



# 3<sup>rd</sup> colloquium of the GdR TeQ "Quantum Technologies"



Grenoble  
Maison Minatec, Amphi. Palladium  
November 12-14 2025  
<https://gdrteq2025.sciencesconf.org/>







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# 1 What is GDR TEQ ?

## 1.1 A CNRS “Research Network” on Quantum Technologies

The acronym **GDR TEQ** stands for "**G**roupement de **R**echerche **T**echnologies **Q**uantiques". It is a research network supported by the Centre National de la Recherche Scientifique (**CNRS**<sup>1</sup> GDR n°2149) through the **CNRS Physics**<sup>2</sup>, **CNRS Engineering**<sup>3</sup>, **CNRS Mathematics**<sup>4</sup> and **CNRS Computer Science**<sup>5</sup>).

The goal of the GDR TEQ is to bring together the French community whose research activities fall within the broad spectrum of quantum technologies, ranging from physics to computer science, mathematics or chemistry. The GDR TEQ encompasses all the different types of physical support for quantum information, such as photons, trapped atoms and ions, quantum dots and point defects at the solid state, superconducting circuits, hybrid quantum systems... In particular, its scientific perimeter combines theoretical and experimental developments, including both very exploratory aspects and engineering aspects on mature technologies. The GDR TEQ network gathers more than 1000 researchers spread over ~100 French laboratories.

**GDR TEQ is organized along six research axes (ART<sup>6</sup>)** that currently underlie the development of quantum technologies all around the world, in particular within the European Quantum Flagship project and the French Quantum Plan :

- QUANTUM COMMUNICATION & CRYPTOGRAPHY – QCOM,
- QUANTUM SENSING & METROLOGY – QMET,
- QUANTUM PROCESSING, ALGORITHMS, & COMPUTATION – QPAC,
- QUANTUM SIMULATION – QSIM,
- FUNDAMENTAL QUANTUM ASPECTS – FQA,
- TRANSVERSE ENGINEERING AND METHODS – TEM.

More details on these research axes are provided on the GDR TEQ webpage : <https://gdr-teq.cnrs.fr/>.

## 1.2 Scientific Committee of the GDR TEQ

Audrey Bienfait (CNRS, ENS Lyon),  
Juliette Billy (LCAR Toulouse),  
Cyril Branciard (CNRS, Institut Néel Grenoble),  
Anaïs Dréau (CNRS, Laboratoire Charles Coulomb Montpellier),  
Jean Etesse (CNRS, Institut de Physique de Nice),  
Omar Fawzi (INRIA, LIP Lyon),  
Michele Filippone (CEA Grenoble),  
Hanna Le Jeannic (CNRS, Laboratoire Kastler Brossel),  
Anthony Leverrier (INRIA Paris),  
Damian Markham (CNRS, LIP6 Paris),  
Alexei Ourjountsev (CNRS, Collège de France),  
Sylvain Ravets (CNRS, C2N Palaiseau),  
Matias Urdampilleta (CNRS, Institut Néel Grenoble),  
Jérémie Viennot (CNRS, Institut Néel Grenoble),  
Christophe Vuillot (INRIA, LORIA),  
Mattia Walschaers (CNRS, LKB Paris).

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1. <http://www.cnrs.fr/>

2. <https://www.inp.cnrs.fr>

3. <https://www.insis.cnrs.fr>

4. <https://www.insmi.cnrs.fr>

5. <https://www.ins2i.cnrs.fr>

6. In French : Axes de Recherche Thématiques.

## 2 TEQ#3 Colloquium – Scientific Information

### 2.1 Welcome !

TEQ#3 is organized by the GDR TEQ Scientific Committee and by the Institut Néel<sup>7</sup>.

Its main goal is to gather members of various communities involved in Quantum Technologies and to foster exchanges about the latest advances in the field. The colloquium will feature four types of presentations :

- 3 tutorial talks (50'+10' discussion), providing the participants with a clear and pedagogical perspective on significant recent advances in specific branches of fundamental and applied research in the field,
- 4 invited talks (25'+5' discussion) on results that struck the most the scientific committee during the past year ;
- 30 contributed talks (15'+5' discussion), representative of the different themes of GDR TEQ and selected among the 122 contributions received by the scientific committee for their scientific quality and for their general interest ;
- 92 contributed posters, presented during two poster sessions according to their theme.

You will find in this book the abstracts of all of these contributions.

We would like to express our warmest thanks to the CNRS, University Grenoble Alps, the Institut Néel and all our sponsors for their support in enabling us to organize the TEQ#3 colloquium.

We wish all the 200 participants a fruitful colloquium.

On behalf of GDR TEQ's Scientific Committee,

The organizers :

**Cyril BRANCIARD** (CNRS scientist, Institut Néel),  
**Michele FILIPPONE** (CEA scientist, IRIG),  
**Matias URDAMPILLETA** (CNRS scientist, Institut Néel),  
**Jérémie VIENNOT** (CNRS scientist, Institut Néel),  
**Alyssa ARNOUD** (CNRS admin, Institut Néel),  
**Anna KUNIKOWSKA** (CNRS admin, Institut Néel),  
**Angélique SIMOËS** (CNRS admin, Institut Néel),  
**Florence FERNANDEZ** (CNRS admin, Institut Néel),  
**Anaïs DRÉAU** (CNRS researcher, L2C, Director of GDR TEQ),  
**Alexei OURJOUNTSEV** (CNRS, Collège de France & Deputy Director of GDR TEQ).

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7. <https://neel.cnrs.fr/>

## 2.2 Program of the colloquium

| Wednesday, Nov. 12                                                                                                                                                       | Thursday, Nov. 13                                                                                                                                        | Friday, Nov. 14                                                                                                                                              |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                                                                                          | <b>09:00 - 09:40: V. Vilasini - Invited (FQA)</b><br><i>Quantum causality meets spacetime</i>                                                            | <b>09:00 - 10:00: Alexei Ourjoumtsev - Tutorial (QCOM)</b><br><i>Non-linear quantum optics</i>                                                               |
|                                                                                                                                                                          | 09:40 - 10:00: Uta Meyer - <i>Robustly self-testing all maximally entangled states in every finite dimension</i>                                         |                                                                                                                                                              |
|                                                                                                                                                                          | 10:00 - 10:20: Xiangling Xu - <i>Quantitative quantum soundness for all multipartite compiled nonlocal games</i>                                         | 10:00 - 10:20: Kiara Hansenne - <i>No quantum advantage without classical communication: fundamental limitations of quantum networks</i>                     |
| <b>10:15 - 10:45</b><br>Welcome Coffee                                                                                                                                   | 10:20 - 10:40: Romaric Journet - <i>Iterative generation of free-propagating superposition of coherent states of light using a quantum memory cavity</i> | 10:20 - 10:40: Hugo Jacinto - <i>Network Requirements for Distributed Quantum Computation</i>                                                                |
| <b>10:45 - 11:10</b><br>Opening session                                                                                                                                  | 10:40 - 11:00: David Theidel - <i>Certifying Non-Classicality of High-Harmonic Generation in Semiconductors</i>                                          | <b>10:40 - 11:10</b><br>Coffee break                                                                                                                         |
|                                                                                                                                                                          | <b>11:00 - 11:30</b><br>Coffee break                                                                                                                     | 11:10 - 11:30: Enky Oudot - <i>Long-distance device-independent quantum key distribution</i>                                                                 |
| <b>11:10 - 12:10: Andreas Wallraff - Tutorial (QPAC)</b><br><i>Superconducting circuits</i>                                                                              | 11:30 - 11:50: Carlos De Góis - <i>Overlapping tomography of fermionic simulators</i>                                                                    | 11:30 - 11:50: Yoann Piétri - <i>High-Performance Heterodyne Receiver for Quantum Information Processing in a Laser Written Integrated Photonic Platform</i> |
|                                                                                                                                                                          | 11:50 - 12:10: Jean-Samuel Tettekpoe - <i>Coherence Limits in Interference-Based <math>\cos(2\phi)</math> Qubits</i>                                     | 11:50 - 12:10: Abel Hugot - <i>Approaching optimal microwave-acoustic transduction on lithium niobate using SQUID arrays</i>                                 |
| 12:10 - 12:30: Lucas Ruela - <i>High fidelity at high power and suppression of measurement induced state transitions in transmon readout using a non-linear coupling</i> | 12:10 - 12:30: Baptiste Carles - <i>Experimental quantum reservoir computing with a circuit quantum electrodynamics system</i>                           | 12:10 - 12:30: Lorenzo Lazzari - <i>Biphoton state generation and engineering with hybrid III-V/Silicon photonic devices</i>                                 |
| <b>12:30 - 14:00</b><br>Lunch break                                                                                                                                      | <b>12:30 - 14:00</b><br>Lunch break                                                                                                                      | <b>12:30 - 14:00</b><br>Lunch break                                                                                                                          |
| <b>14:00 - 14:40: André Chailloux - Invited (QPAC)</b><br><i>Quantum Algorithms Inspired by Regev's Reduction</i>                                                        | <b>14:00 - 14:40: Alberto Amo - Invited (QSIM)</b><br><i>Topology and noise in networks of photonic unitary operators</i>                                | <b>14:00 - 15:00: Maria Chekhova - Tutorial (TEM)</b><br><i>Quantum measurement through parametric amplification</i>                                         |
| 14:40 - 15:00: Andreas Bluhm - <i>Efficient learning and simulation of quantum continuous variable systems</i>                                                           | 14:40 - 15:00: Alessandro Zecchetto - <i>High-dimensional entanglement and topological protection in nonlinear waveguide arrays</i>                      |                                                                                                                                                              |
| 15:00 - 15:20: Paul Hermouet - <i>On the Quantum Equivalence between S(LWE) and ISIS</i>                                                                                 | 15:00 - 15:20: Eloi Flament - <i>Unitary Transformations using Robust Optimal Control on a Cold Atom Qudit</i>                                           | 15:00 - 15:20: Hani Naim - <i>High-performance solid-state quantum memory in a low-vibration in-house built cryostat</i>                                     |
| 15:20 - 15:40: Sami Abdul Sater - <i>Verification of Universal Quantum Computations with single-qubit Pauli measurements</i>                                             | <b>15:20 - 15:50</b><br>Coffee break                                                                                                                     | 15:20 - 15:40: Antoine Covolo - <i>Protecting collective qubits from non-Markovian dephasing</i>                                                             |
| <b>15:40 - 16:10</b><br>Coffee break                                                                                                                                     |                                                                                                                                                          | <b>15:40 - 16:10</b><br>Closing session                                                                                                                      |
|                                                                                                                                                                          | <b>15:50 - 16:30: Franck Pereira Dos Santos - Invited (QMET)</b><br><i>Measuring short range forces with quetconewton stability</i>                      |                                                                                                                                                              |
|                                                                                                                                                                          | 16:30 - 16:50: Ali Moshiri - <i>Deterministic nuclear spin squeezing and squeezing by continuous measurement using vector and tensor light shifts</i>    |                                                                                                                                                              |
|                                                                                                                                                                          | 16:50 - 17:10: Emilio Annoni - <i>Optimal characterization of multi-photon distinguishability</i>                                                        |                                                                                                                                                              |
| 17:10 - 17:30: Young Aurore - <i>Non-destructive optical read-out and manipulation of circular Rydberg atoms</i>                                                         |                                                                                                                                                          |                                                                                                                                                              |
| <b>17:30 - 19:30</b><br>Poster session                                                                                                                                   | <b>17:10 - 19:00</b><br>Poster session                                                                                                                   |                                                                                                                                                              |
|                                                                                                                                                                          | <b>19:00 - ...</b><br>Banquet + After party                                                                                                              |                                                                                                                                                              |

|      |      |     |      |      |     |
|------|------|-----|------|------|-----|
| QPAC | QSIM | FQA | QMET | QCOM | TEM |
|------|------|-----|------|------|-----|





## 4 Host institution & sponsors of the colloquium

### 4.1 Parent institution



The Centre National de la Recherche Scientifique (CNRS) is an interdisciplinary public research organisation under the administrative supervision of the French Ministry of Higher Education, Research, and Innovation (MESRI). The CNRS chooses to pursue research excellence that explores natural and social phenomena in greater depth, in an effort to push back the frontiers of knowledge.

The research network “Quantum Technologies” (GdR TeQ) is linked to and supported by CNRS Physics. CNRS Physics’s research themes relate to the fundamental laws of physics, understanding radiation, matter, and their interactions. Those studies come with two main motivations : understanding the world, and answering current societal challenges.

The GdR TeQ also benefits from secondary support from the CNRS Engineering, CNRS Mathematics and CNRS Computer Science.

### 4.2 Institutionnal support



The Néel Institute (Institut Néel) is a leading French research center in condensed matter physics, located in Grenoble and operating under the CNRS in association with Université Grenoble Alpes. It conducts fundamental and applied research on the physical properties of materials, spanning quantum phenomena, magnetism, superconductivity, nanoscience, and quantum technologies. Created in 2007 from the merger of several long-established CNRS laboratories, the institute unites a large multidisciplinary community of researchers, engineers, and students, combining theory, advanced experiments, and technological development. It also plays an active role in education and innovation, collaborating closely with academic and industrial partners in France and abroad.



Université Grenoble Alpes (UGA) is one of France’s leading research universities, located in Grenoble. It brings together a wide range of disciplines across science, engineering, medicine, humanities, and social sciences. UGA is known for its strong focus on research and innovation, hosting numerous national laboratories in partnership with organizations such as CNRS, CEA, and INRIA. The university plays a central role in Grenoble’s internationally recognized ecosystem for advanced technologies, particularly in microelectronics, materials science, and quantum research.



CEA (Commissariat à l’Énergie Atomique et aux Énergies Alternatives) is a leading French public research organization focused on energy, defense, information technologies, and health. It conducts both fundamental and applied research, supporting innovation from basic science to industrial applications. The CEA plays a central role in developing technologies for nuclear and renewable energy, microelectronics, materials science, and quantum technologies. With strong collaborations across academia and industry, it is a key actor in France’s scientific and technological landscape.



QuantAlps (Quantum Technologies Alpes) is a research federation based in Grenoble, France, dedicated to advancing quantum science and technology. It brings together academic and industrial partners — including the CNRS, Université Grenoble Alpes, CEA, and INRIA — to coordinate research in quantum materials, quantum communication, quantum computing, and quantum sensing. The initiative supports collaboration, shared infrastructure, and innovation to strengthen the regional and national quantum ecosystem within the French and European quantum strategy.



QuantEdu-France, led by Université Grenoble Alpes, brings together a consortium of 21 academic institutions nationwide, professionals in initial and continuing education, and players in industry and innovation. QuantEdu-France aims to meet the objectives set out in the national strategy for quantum technologies, as part of a drive to accelerate the development of skills and human capital. QuantEdu-France is implementing concrete actions to meet the growing need for quantum technology skills among engineers, researchers, teacher-researchers and professors, technicians and managers, while consolidating interactions between academics, researchers and local and national economic players. Indeed, the emergence of new professions encouraged by the national quantum strategy, such as quantum engineer-doctors, calls for in-depth reflection on the teaching methods to be adopted. These methods preserve the generalist nature of disciplinary and fundamental teaching, while promoting interdisciplinarity, a spirit of innovation and integration into the job market.



Inria (Institut National de Recherche en Informatique et en Automatique) is the French national research institute dedicated to computer science, applied mathematics, and digital technologies. It focuses on both fundamental research and technological innovation, often in collaboration with universities and industry. Inria's teams develop cutting-edge work in areas such as algorithms, artificial intelligence, data science, cybersecurity, and quantum computing. Through its interdisciplinary approach and partnerships, Inria plays a key role in advancing France's and Europe's digital and technological competitiveness.

### 4.3 Sponsors



Alice & Bob is a quantum computing company based in Paris and Boston whose goal is to create the first universal, fault-tolerant quantum computer. Founded in 2020, Alice & Bob has already raised €130 million in funding, hired over 140 employees and demonstrated experimental results surpassing those of technology giants such as Google or IBM. Alice & Bob specializes in cat qubits, a pioneering technology developed by the company's founders and later adopted by Amazon. Demonstrating the power of its cat architecture, Alice & Bob recently showed that it could reduce the hardware requirements for building a useful large-scale quantum computer by up to 200 times compared with competing approaches. Alice & Bob cat qubit is available for anyone to test through cloud access.

## EVIDEN

Eviden, a leader in advanced digital technologies, offers Qaptiva™, a comprehensive and modular quantum computing solution. This full-stack offering includes on-premises emulation appliances, a powerful programming platform, HPC-cluster emulation software, expert consulting, and a free starter toolkit. Designed to be fully hardware-agnostic, Qaptiva™ enables users to develop, optimize, emulate, and run quantum applications across a wide range of infrastructures and technologies. It is tailored for both researchers and businesses looking to explore the potential of quantum computing today.

## QUANDELA

Quandela, a leader in the field of quantum computing, offers industrial-grade solutions. Quandela designs, builds, and provides ready-to-use quantum systems for data centers, quantum processors accessible via the cloud, and algorithm access services. Quandela employs over 100 people from 20 different nationalities, the majority of whom are researchers and engineers in optics, algorithms, and information sciences.

Quandela is committed to making advanced quantum computing accessible to all, empowering innovators to solve the most pressing industrial and societal challenges.



Quantum Design is a global leader in scientific instrumentation, offering advanced cryogenic solutions tailored to the needs of quantum technologies. In collaboration with specialized partners, we provide a comprehensive portfolio of tools for low-temperature research and quantum device characterization. Our offering includes high-precision temperature sensors, closed-cycle cryostats, cryogenic probe stations, and versatile measurement platforms designed for demanding environments. Integrated electronics solutions support low-noise transport studies, precise temperature control, and stable current/voltage sourcing—even at millikelvin temperatures and under magnetic fields. These systems are ideally suited for quantum optics, spintronics, nanoscale device testing, and the study of quantum materials. They enable cryogen-free operation with variable temperature and magnetic field control, ensuring flexibility and reproducibility in experimental setups. With dedicated technical teams across Europe and worldwide, Quantum Design ensures close support and collaboration with research institutions, providing expert guidance and responsive service. Together with our partners, we empower researchers to explore quantum phenomena with precision, reliability, and flexibility.



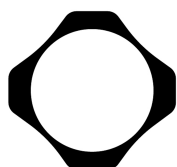
Opton Laser International is a French distributor of high technology products operating in the field of Photonics. For over 30 years, Opton Laser has built a reputation for innovation and service excellence, particularly in the fields of lasers, microscopy and spectroscopy, as well as opto-mechanical components, laser instrumentation and quantum optics. Opton Laser offers a 360° customer experience, from pre-sales to after-sales.



Quobly is a pioneer in quantum microelectronics. The company is developing a quantum chip on silicon using the existing industrial semiconductor manufacturing process. Founded in 2022, the company draws on 15 years of collaborative research between internationally renowned Research and Technology Organizations (RTO), CEA-Leti and CNRS. Based in Grenoble, Quobly was co-founded by Maud Vinet, Ph.D. in quantum physics, author or co-author of over 300 papers and holder of more than 70 nanotechnology-related patents, Tristan Meunier, a world-renowned expert in semiconductor quantum engineering, trained under Serge Haroche, winner of the 2012 Nobel Prize in Physics, and François Perruchot, PhD in solid-state physics, engineer, expert in sensor development, modeling and characterization of MEM micro-sensors. Quobly has signed several strategic and operational partnerships with Soitec, Orano, Air Liquide and recently with ST Microelectronics to accelerate the manufacturing process of its “silicon quantum chip”. In 2023, Quobly raised €19 million, setting a new record for seed financing for a European start-up in the quantum sector. In 2025, Quobly secured a €21 million funding package for its Q100T project.



Silent Waves, founded in 2022 by Baptiste Planat, Nicolas Roch and Luca Planat, is a spin-off company of the Institut Néel, a CNRS laboratory based in Grenoble. Silent Waves is specialising in the development, fabrication and commercialisation of ultra-low noise superconducting amplifiers. Its first products, the Argo and the Carthago, are Josephson traveling-wave parametric amplifiers, reaching near quantum-limited amplification, over GHz bandwidth and with high saturation power. These products are instrumental in experiments requiring fast and accurate detection of low-power microwave signals generated at ultra-low temperatures ( $< 100$  mK). Today, the primary use of these products is fast, high-fidelity readout of superconducting qubits.



Spaictra is a quantum optics company pioneering a novel light-matter interaction for blood analysis. Its technology combines nonlinear optics with non-classical states of light to enable comprehensive, multiparametric quantification from a single biological sample. By making light accurate in complex media, Spaictra aims to free analytics from the burden of reagents, along with the overhead, costs, and time they entail. The company is working toward a new era for clinical and research settings, one where accessibility is not simply a matter of decentralization, but of radically reducing the cost and time required to access molecular information, beyond traditional chemical processing. The team, composed of quantum physicists and physicians, is currently building its first prototype and validating it on real biomarkers.



THORLABS, a vertically integrated photonics products manufacturer, was founded in 1989 to serve the laser and electro-optics research market. As that market has spawned a multitude of technical innovations, Thorlabs has extended its core competencies in an effort to play an ever-increasing role to serve the Photonics Industry at the research end, as well as the industrial, life science, medical, and defense segments. The organization's highly integrated and diverse manufacturing assets include semiconductor fabrication of Fabry-Perot, DFB, and VCSEL lasers; fiber towers for drawing both silica and fluoride glass optical fibers; MBE/MOCVD epitaxial wafer growth reactors; extensive glass and metal fabrication facilities; advanced thin film deposition capabilities; and optomechanical and optoelectronic shops.

## 5 Abstracts, Participants and Authors

The following section contains the abstracts of the tutorial talks, the invited talks, the contributed talks, and all the posters sorted according to their session and theme. They are followed by the list of authors of the presented papers.



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# Tutorials

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# Quantum Error Correction for Superconducting Quantum Information Processors

Andreas Wallraff<sup>1</sup>

<sup>1</sup> *Department of Physics, ETH Zurich, Switzerland*

Superconducting electronic circuits are ideally suited for studying quantum physics and its applications [1]. Since complex circuits containing hundreds or thousands of elements can be designed, fabricated, and operated with relative ease, they are one of the prime contenders for realizing quantum computers. Currently, both academic and industrial labs vigorously pursue the realization of universal fault-tolerant quantum computers. However, building systems which can address commercially relevant computational problems continues to require significant conceptual and technological progress. For fault-tolerant operation quantum computers must correct errors occurring due to unavoidable decoherence and limited control accuracy. In this talk, after a brief introduction to superconducting qubits, I will discuss quantum error correction using the surface code, which is known for its exceptionally high tolerance to errors. Using 17 physical qubits in a superconducting circuit we encode quantum information in a distance-three logical qubit. In an error correction cycle taking only 1.1  $\mu\text{s}$ , we demonstrate the preservation of four cardinal states of the logical qubit with a low logical error probability of 3 % per cycle [2]. In addition, the realization of universal fault-tolerant quantum computation requires the implementation of logical entangling gates. Lattice surgery is an approach for implementing such gates in planar quantum processor architectures. If time allows, I will also touch upon how we perform lattice surgery between two distance-three repetition-code qubits [2] by splitting a single distance-three surface-code qubit [1]. These insights support our understanding that fault-tolerant quantum computation will be practically realizable.

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## **Quantum geometry, dichroism and sum rules : a Tutorial**

Nathan Goldman

*Center for Nonlinear Phenomena and Complex Systems,  
Université Libre de Bruxelles, CP 231, Campus Plaine, 1050 Brussels, Belgium  
International Solvay Institutes, 1050 Brussels, Belgium  
Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-Université PSL,  
Sorbonne Université, 11 Place Marcelin Berthelot, 75005 Paris, France*

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## **Non-linear quantum optics**

Alexei Ourjoumtsev  
*Collège de France*

Light is an excellent carrier of quantum information, but photonic non-classical states and multi-qubit gates remain challenging to realize. Both rely on non-linear effects acting at a single-photon level. In this tutorial I will present different techniques used to create such effects, with a focus on the fundamental physics and on the experimental challenges. Finally, I will show that they can be advantageously combined.

---

## Quantum measurement through parametric amplification

Maria Chekhova

*Max Planck Institute for the Science of Light, Staudtstr. 2, 91058 Erlangen, Germany,  
Friedrich-Alexander Universität Erlangen-Nürnberg, 91058 Erlangen, Germany*

Quantum states of light are central to photonic quantum technologies, which makes their measurement very important. But quantum states are extremely fragile. Fortunately, a nonlinear-optical device known as the optical parametric amplifier comes to rescue when measurement over a fragile quantum state is needed. It protects the measurement against optical losses and imperfect detection, enables addressing several modes simultaneously, and can substitute homodyne detection with direct detection.

In my talk I will show examples of fully reconstructing a single-mode squeezed vacuum state, simultaneously measuring squeezing in many spatial or temporal modes, and even addressing a non-Gaussian state – a heralded single photon.

## Invited talks

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## Quantum Algorithms Inspired by Regev's Reduction

André Chailloux  
*Inria Paris, France*

Shor's quantum algorithm for integer factorization compels us to rethink currently deployed cryptographic schemes in order to make them post-quantum, that is, resistant even to adversaries equipped with a functional quantum computer. These new schemes rely on novel computational assumptions, notably those based on Euclidean lattices and error-correcting codes. In recent years, a new family of quantum algorithms targeting these lattice and code-based problems has been discovered. These algorithms are inspired by Regev's reduction, which constitutes one of the theoretical foundations of post-quantum cryptography. This presentation will offer an overview of this family of algorithms, along with a discussion of their implications for post-quantum cryptography and, more broadly, for quantum algorithms.

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## Quantum causality meets spacetime

V. Vilasini

*Université Grenoble Alpes, Inria, 38000 Grenoble, France*

Causality is central to explaining and understanding the world around us, yet it takes on fundamentally distinct forms within quantum and relativity theories : the former related to information-flow discernible via agents’ operations and the latter to spacetime structure. Reconciling these causality notions is essential for the fundamental interface of these theories and for describing real quantum experiments in spacetime. I will present a framework that defines and connects quantum and relativistic notions of causality, providing a physical spacetime perspective on the abstract phenomenon of indefinite causal order (ICO) quantum processes, via no-go theorems. In particular, I will show how ICO experiments can be causally unraveled in an acyclic fine-grained quantum description compatible with relativistic principles, and how relativistic causality constrains the landscape of physically realizable quantum processes, allowing to exclude processes violating causal inequalities. If time permits, I will outline an new operational approach towards defining events and their causal relations relationally, without assuming a background spacetime—rather relative to agents’ “Labs” equipped with physical references (e.g., clocks). This reconciles diverging proposals on the physical interpretation of ICOs, while shedding light on the distinctions between their optical and quantum gravitational realizations. The talk will conclude with an outlook on open directions for the study quantum causality and information processing within and beyond spacetime.



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# Topology and noise in networks of photonic unitary operators

Alberto Amo

Université de Lille, CNRS, UMR 8523 – PhLAM – Physique des Lasers Atomes et Molécules, F-59000 Lille  
alberto.amo-garcia@univ-lille.fr

Discrete-step walks define the dynamics of particles in a lattice subject to splitting events at discrete times. They are described by a cascade of unitary operations and are at the core of the architecture of quantum computers and in the physics of quantum walks. Despite their importance, the topological properties arising from the discrete-step evolution of lattices of cascaded unitary operators have been hardly explored [1–3]. In this presentation we report the observation of two-dimensional topological phases unique to discrete-step walks [4]. We use light pulses in a two-fibre ring setup whose dynamics maps into a two-dimensional lattice model subject to discrete splitting events [5]. We show that the bulk edge-correspondence is broken and the number of edge states is not simply described by the bulk invariants of the lattice but also by a topological invariant associated to the discrete-step unitary operators acting at the edges of the lattice [6]. We also study the robustness of the evolution of an initial state in the lattice to noise in the unitary operators. Our results open new perspectives for the engineering of topological modes for particles subject to quantum walks.

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## Measuring short range forces with quectonewton stability

Franck Pereira Dos Santos

*Laboratoire Temps Espace, Observatoire de Paris, Université PSL,  
Sorbonne Université, Université de Lille, LNE, CNRS, 75014 Paris, France*

I will present quantum sensing of short-range forces with a force sensor based on trapped atom interferometry. Ultracold atoms are first transported with a Bloch elevator close to the surface of a dielectric mirror before being trapped in a vertical lattice. Raman pulses are then used to split the atoms across different wells and recombine them, creating a Ramsey-type interferometer. The phase of the interferometer depends on the difference of potential energy between neighbouring wells, and thus to the force exerted on the atoms. The stability of the local force measurement reaches  $3 \cdot 10^{-28}$  N at 1s measurement time, and decreases down to about  $4 \cdot 10^{-30}$  N after a few hours of averaging. With this sensor, we measure an attractive force of order of  $10^{-27}$  N when bringing the atoms at a few micrometers from the surface, larger than the expected Casimir Polder force of about  $0.4 \cdot 10^{-27}$  N. We attribute the difference to parasitic electric fields created by adsorbed atoms, which we characterize and model. Correcting for this effect, we put into evidence the Casimir Polder force below  $20 \mu\text{m}$ .

## Contributed talks

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# High fidelity at high power and suppression of measurement induced state transitions in transmon readout using a non-linear coupling

C. Mori<sup>1</sup>, F. D’Esposito<sup>1</sup>, A. Petrescu<sup>2</sup>, L. Ruela<sup>1</sup>, V. Milchakov<sup>1</sup>, S. Kumar<sup>1</sup>, V. N. Suresh<sup>1</sup>, W. Ardati<sup>1</sup>, D. Nicolas<sup>1</sup>, G. Cappelli<sup>1</sup>, A. Ranadive<sup>1</sup>, G. Le Gal<sup>1</sup>, M. Esposito<sup>1</sup>, T. Ramos<sup>3</sup>, Q. Ficheux<sup>1</sup>, N. Roch<sup>1</sup>, O. Buisson<sup>1\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*

<sup>2</sup>*Laboratoire de Physique de l’Ecole Normale Supérieure, Inria, ENS, Mines ParisTech, Université PSL, Sorbonne Université, Paris, France*

<sup>3</sup>*Institute of Fundamental Physics IFF-CSIC, 28006 Madrid, Spain*

The field of superconducting qubits is constantly evolving with new types of circuit and designs but, when it comes to qubit readout, the use of simple transverse linear coupling is overwhelmingly prevalent. This type of coupling intrinsically limits the readout mode’s dispersive shift and is known to cause Purcell effect. We propose here to overcome these limitations by engineering a non-linear  $\cos\varphi$ -coupling between the transmon qubit and a dedicated readout mode. This is based upon previous published work[1] on qubit readout with a non-perturbative cross-Kerr coupling engineered by a transmon molecule circuit. A new sample with optimized design and parameters shows a readout fidelity of 99.21% measured using a parametric amplifier and a high Quantum Non-Demolition (QND) fidelity of 97%[2]. Interestingly, these results have been achieved with 89 photons in the readout mode. In addition, we have observed suppression of measurement-induced state transitions (MIST) up to high photon counts above 300[3]. This effect can be explained by the symmetry of the coupling, which is tunable with a magnetic field. All of these measurements were corroborated by a theoretical study, a numerical analysis of the spectra associated with the nonlinearly coupled circuit, and simulations of the corresponding classical dynamics[3]. In conclusion, we show that the  $\cos\varphi$ -coupling is more robust to measurement photons than the usual linear coupling, making it a compelling alternative for high fidelity and non-destructive transmon readout.

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\* olivier.buisson@neel.cnrs.fr

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## Efficient learning and simulation of quantum continuous variable systems

Tim Möbus<sup>1</sup>, Andreas Bluhm<sup>2,\*</sup>, Tuvia Gefen<sup>3</sup>, Yu Tong<sup>4</sup>, Albert H. Werner<sup>5</sup>, and Cambyse Rouzé<sup>6</sup>

<sup>1</sup>*Department of Mathematics, University of Tübingen, 72074 Tübingen, Germany*

<sup>2</sup>*Univ. Grenoble Alpes, CNRS, Grenoble INP, LIG, 38401 Saint Martin d'Hères, France*

<sup>3</sup>*Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Givat Ram, Israel*

<sup>4</sup>*Department of Mathematics, Department of Electrical and Computer Engineering, and Duke Quantum Center, Duke University, Durham, NC 27708, USA*

<sup>5</sup>*QMATH, Department of Mathematical Sciences, University of Copenhagen, 2100 Copenhagen, Denmark*

<sup>6</sup>*Inria Saclay, Télécom Paris - LTCI, Institut Polytechnique de Paris, 91120 Palaiseau, France*

Hamiltonian learning is the task of identifying the unknown Hamiltonian governing the evolution of a quantum system. Besides being a fundamental problem for our understanding of quantum systems, it is useful for tasks ranging from quantum simulation to quantum error correction.

While Hamiltonian learning has been studied in a large number of works, most focus on quantum spin systems with finite local Hilbert space dimension. However, many quantum systems involve infinite-dimensional Hilbert spaces and unbounded Hamiltonians. Examples include superconducting circuits, integrated photonic circuits or optomechanical platforms. Previous works on Hamiltonian learning for bosonic systems either restrict to special models, e.g., generalized Bose-Hubbard model, or do not achieve the Heisenberg-limited scaling.

More general forms of bosonic Hamiltonians are challenging. Notably, the squeezing terms, quadratic in the bosonic creation and annihilation operators and commonly seen in the quantum metrology setting, can cause the particle number to grow exponentially in time, leading to the breakdown of the Lieb-Robinson bound that governs the information propagation speed in the system [1]. Higher-order polynomials of the creation and annihilation operators present even greater challenges.

In this work, we use engineered dissipation not only to regularize the dynamics in order to address the issues mentioned above, but also to drive the Hamiltonian into a projected, finite-dimensional subspace in which it becomes decoupled. This enables us to construct a phase estimation scheme, similar to [2], combined with Chebyshev interpolation to learn an  $m$ -mode low-interaction Hamiltonian with total evolution time  $\mathcal{O}(\varepsilon^{-1} \log(m/\delta))$ , where  $\varepsilon$  denotes the maximum error in each Hamiltonian coefficient and  $\delta$  is the allowed failure probability.

The same adiabatic limit also underlies the stability of the cat code, where a bosonic mode is stabilized within the subspace spanned by  $|\pm\alpha\rangle$  through engineered dissipation, significantly reducing the phase-flip error rate (and sometimes also the bit-flip error rate). Previous works have analyzed such adiabatic limits, but have so far focused either on optimal convergence rates in finite dimensions or on bounded Lindbladians. Recently, [3] proved a convergence result for an unbounded driving term with a bounded supplementary Lindbladian, albeit with a slightly suboptimal convergence rate.

Our work is the first to rigorously address the adiabatic limit in the cat qubit setting. We establish an explicit bound showing that Hamiltonians are projected exponentially fast onto the cat codespace. For a driving Hamiltonian defined by the position operator, the effective dynamics reduces to a rotation around the  $x$ -axis [4], which has been experimentally realized. The techniques developed in this work pave the way for a mathematically rigorous analysis of the effects of strong dissipation in quantum control and learning settings. The submission is based on the arXiv preprint 2506.00606 (<https://arxiv.org/abs/2506.00606>).

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\* andreas.bluhm@univ-grenoble-alpes.fr

# On the Quantum Equivalence between $S|LWE\rangle$ and ISIS

André Chailloux<sup>1</sup>, Paul Hermouet<sup>1\*</sup>

<sup>1</sup>*COSMIQ Team, Inria of Paris, 48 Rue Barrault, 75013 Paris*

## I. CONTEXT

A cornerstone of lattice-based cryptography is Regev's reduction [1] that reduces the *Short Integer Solution* (SIS) problem to the *Learning With Errors* (LWE) problem. That is, it shows that given an algorithm solving LWE, one can solve SIS. These are arguably two of the most important problems in post-quantum cryptography and they are somehow dual to each other. LWE asks to find a random secret  $s$  given a noisy linear samples  $(A, As + e)$ , while SIS asks to find a *short*, non-zero solution  $x$  to a linear system  $Ax = 0$  — the short condition being usually defined as an upper-bound on the solution's ( $\ell_2$  or  $\ell_\infty$ ) norm. Regev's reduction uses a (classical or quantum) algorithm solving LWE in order to create a superposition of noisy lattice points and then performs a measurement in the Fourier basis to obtain a short dual lattice point.

As noted in [2], this reduction does not strictly need an LWE solver, but an algorithm solving an easier problem, later defined as  $S|LWE\rangle$  [3], where the errors in the samples are in quantum superposition, that is one is given  $(A, \sum_e f(e)|As + e\rangle)$  where  $f$  is an amplitude function that concentrates on small inputs. This was first explicitly used by Brakerski, Kirshanova, Stehlé and Wen [4] where they extend this reduction and introduced the Extended Dihedral Coset Problem.

A few years later, Chen Liu and Zhandry [3] revisited this reduction for algorithmic purposes, and showed that in some regimes, this  $S|LWE\rangle$  problem can be significantly easier than the standard LWE problem. They showed how to construct, for some parameters, a quantum polynomial time algorithm for  $SIS_\infty$  — where the upper-bound is on the  $\ell_\infty$  norm of the solution. While these parameters are still very far from those used in lattice-based cryptography, this result shows the very promising nature of this family of algorithms.

This framework has then been successfully used. Yamakawa and Zhandry [5] provided a first quantum advantage without structure in the Random Oracle Model. It was also used in a somewhat different context to construct quantum oblivious sampling [6] and extended to the setting of linear codes [7, 8], as well as structured codes in order to obtain a quantum advantage [9, 10]. All these results use an algorithm for  $S|LWE\rangle$  to construct an algorithm for SIS and perform an ad hoc analysis of this reduction. This is in part due to the fact that we cannot have a generic reduction from SIS to  $S|LWE\rangle$  using this approach (see [8]). The only notable exception is the work of Chailloux and Tillich [10] that provided the first generic reduction, but from Inhomogeneous-SIS (ISIS) to  $S|LWE\rangle$  — where ISIS is a variant of SIS that asks to find a short so-

lution to an *inhomogeneous* linear system  $Ax = y$ . This reduction does however have some assumptions on the  $S|LWE\rangle$  algorithm, which are satisfied by classical algorithms but not necessarily by quantum algorithms. A first natural question arises :

*Is it possible to have a fully generic reduction from ISIS to  $S|LWE\rangle$  that is robust to failures in the decoder ?*

Also, because of the importance of  $S|LWE\rangle$ , recent works directly construct quantum algorithms for this problem. First, a generic quantum algorithm for  $S|LWE\rangle$  was presented in [11], running in subexponential time and requiring a subexponential number of queries. Then [12] presented a slightly superpolynomial algorithm for  $S|LWE\rangle$  in the case the alphabet size  $q$  is a small power of 2. These results both use variants of the quantum Kuperberg sieve [13] for the Dihedral Coset Problem. When looking at these algorithms more carefully, one can notice that they are actually very similar to some known classical algorithm for ISIS and this raises a second question :

*Is there a way to construct algorithms for  $S|LWE\rangle$  from algorithms for ISIS ? More generally, are the problems  $S|LWE\rangle$  and ISIS equivalent ?*

## II. CONTRIBUTIONS

We present three main contributions in our work :

1. First, we construct a fully generic reduction from ISIS to  $S|LWE\rangle$ . This new reduction is robust to errors in the  $S|LWE\rangle$  solver, and removes the assumptions needed in [10].
2. We then tackle the reverse reduction. We introduce a quantum version of ISIS :  $|ISIS\rangle$  and show that one can solve  $S|LWE\rangle$  given access to a solver for  $|ISIS\rangle$ . This is, to the best of our knowledge, the first work investigating this direction of the reduction.
3. Finally, we show that such a solver for  $|ISIS\rangle$  can be constructed by a solver for its classical counterpart ISIS, provided that this solver meets a specific condition, that we call *randomness-recoverability*.

In conclusion, our results give for the first time a full forward reduction between ISIS and  $S|LWE\rangle$  and a partial reverse reduction. This clarifies the landscape of reductions between  $S|LWE\rangle$  and ISIS, as well as the remaining barrier for showing full equivalence.

\* paul.hermouet@inria.fr

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## Verification of universal quantum computations with single-qubit Pauli measurements

Sami Abdul-Sater<sup>1</sup>, Ulysse Chabaud<sup>1</sup>, Maxime Garnier<sup>1</sup>, Thierry Martinez<sup>1</sup>, Harold Ollivier<sup>1</sup>

<sup>1</sup> DIENS, Ecole Normale Supérieure, PSL University, CNRS, INRIA. *first.last@inria.fr*

**Context.** As quantum technologies mature, checking the state produced by a quantum experiment or the result of a quantum computation becomes impractical with standard techniques such as tomography. Both experimentalists and clients in cloud-based quantum computing face the common challenge of certifying quantum states and verifying quantum computations. The most important criteria in their approach are the complexity of the setup and the number of samples required to confidently certify the produced state or computation result. In the literature, this has given rise to candidate solutions to this problem. For instance, the state-of-the-art solution using only single-qubit Pauli measurements [1] gives a generic procedure to certify quantum states in which the number of required samples scales in a parameter that depends on the target state. In particular, it is proven to be polynomial in the size of the state for different class of states, such as Haar-random states, graph states, *i.e* classes that are of a particular interest in quantum information processing tasks.

**Main results.** In this work, we introduce new protocols for certifying another important class of quantum states – one that enables universal quantum computations – using only Pauli measurements and where the sample complexity is polynomial in the size of the target state/width of computation.

**Contributions.** Our contributions are three-fold, and for each we examine the scaling of the number of samples  $N$  with respect to the size of the target state/width of the computation  $n$ , in different scenarios. The security of the protocols is captured by a fidelity error  $\varepsilon$  and a failure probability  $\delta$ .

1. We propose a protocol that allows to certify a  $n$ -qubit quantum state of the form  $|\Psi\rangle = C(\bigotimes_{i=1}^n |\psi_i\rangle)$ , where  $C$  is a known Clifford circuit and the  $|\psi_i\rangle$  are arbitrary single-qubit states, possibly including magic states, where all samples are *i.i.d*, resulting in  $N \sim O(n^3, \log(1/\delta)/\varepsilon^2)$ . The main interest of this class is that together with adaptive single-qubit Pauli measurements, it enables universal quantum computation [2].
2. We refine this protocol for specific families of Clifford circuits, showing that the required number of samples becomes quadratic in the computation size :  $N \sim O(n^2, \log(1/\delta)/\varepsilon^2)$ . We also show that any quantum computation can be reduced to this setting thus preserving universality.
3. We extend the protocol to the general non-*i.i.d*. setting, in which states might be entangled or correlated across rounds. This version remains efficient and sound under adversarial behavior producing the states.

**Techniques.** Our protocols rely on an optimal fidelity estimation technique [3] to estimate the single-qubit fidelities of the pre-Clifford product state, using Pauli measurements on the tested state. This is enabled by the fact that Pauli observables can be efficiently propagated backward through the Clifford circuit  $C$  in the Heisenberg picture (in practice equivalent to a classical post-processing of measurement outcomes). The resulting local fidelity estimates are then combined into a *robust fidelity witness* [4] for the global state, yielding a fidelity error  $\varepsilon$  and a failure probability  $\delta$ . In the third setting, we further show that by applying a quantum de Finetti reduction [5], the protocol remains sound even against a malicious server employing arbitrary, non-*i.i.d*. strategies across rounds.

**Discussion.** While robust fidelity witnesses have previously been used in continuous-variable quantum systems, this work demonstrates their first application to discrete-variable systems. Although originally motivated by experimentalist needs, we show that techniques from quantum state certification also enable efficient verification of quantum computations in cryptographic settings. Lastly, the required setup involves only single-qubit Pauli measurements, which not only offer practical simplicity but also pave the way for fault-tolerant implementations with limited overhead. Our certification protocol applies to a large class of target states and is compatible with quantum with magic state injection, a prominent model for realizing universal quantum computations.

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## Non-destructive optical read-out and manipulation of circular Rydberg atoms

Yohann Machu<sup>1</sup>, Andrés Durán-Hernández<sup>1</sup>, Gautier Creutzer<sup>1</sup>, Aurore-Alice Young<sup>1</sup>,  
Abderrahmane Kassid<sup>1</sup>, Jean-Michel Raimond<sup>1</sup>, Clément Sayrin<sup>1,2</sup>, and Michel Brune<sup>1</sup>

<sup>1</sup>*Laboratoire Kastler Brossel, Collège de France, CNRS, ENS-Université PSL,  
Sorbonne Université, 11 place Marcelin Berthelot, F-75231, Paris, France*

<sup>2</sup>*Institut Universitaire de France, 1 rue Descartes, 75231 Paris Cedex 05, France*

Among the thriving quantum computation and quantum simulation platforms based on arrays of Rydberg atoms, those using circular Rydberg atoms are particularly promising. These atoms uniquely combine the strong dipole-dipole interactions typical of Rydberg states with long lifetimes. However, low-angular-momentum ( $\ell$ ) laser-accessible Rydberg levels have been so far mostly used, because circular Rydberg atoms have no optical transitions, hindering their individual detection and manipulation. We remove this limitation with a hybrid platform, combining an array of logical circular Rydberg atoms (CRA) of rubidium with an auxiliary array of Rb ancilla atoms transiently excited to a low- $\ell$  Rydberg level.

In our platform, we prepare arrays of individual circular Rydberg atoms trapped in optical bottle beams [1, 2]. We now couple the circular atoms to an array of ancillas trapped in optical tweezers. We use a Förster resonance between one circular state and the ancilla laser-accessible Rydberg level to engineer a strong dipole-dipole interaction between the circular and ancilla atoms [3]. This induces a circular-state-dependent Rydberg blockade of the optical excitation of a nearby ancilla. Subsequent fluorescence detection on the ancilla performs a QND measurement of the circular state. Similarly, we use an ancilla excited to the low- $\ell$  Rydberg level to block a microwave excitation of the circular atom. This effectively performs an optical manipulation of the circular Rydberg state.

This dual-Rydberg platform enables quantum simulation with circular Rydberg atoms. I will eventually show how we have used it to observe a spin exchange between two circular states.

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# Robustly self-testing all maximally entangled states in every finite dimension

Uta Isabella Meyer<sup>1</sup>, Ivan Šupić<sup>2</sup>, Frédéric Grosshans<sup>1</sup>, and Damian Markham<sup>1\*</sup>

<sup>1</sup>*Sorbonne Université, CNRS, LIP6, 75005 Paris, France*

<sup>2</sup>*Université Grenoble Alpes, CNRS, Grenoble INP, LIG, 38000 Grenoble, France*

Device-independent self-testing certifies quantum states and measurements directly from Bell correlations, without trusting the devices. While qubit self-tests are well established, extending *robust*, *universal* certificates to *qudits* has been challenging : many approaches decompose into qubits, tailor inequalities dimension-by-dimension, or lack explicit error tolerance [1]. We give a *single, fully robust* protocol that self-tests all maximally entangled states in every finite local dimension, via a constant-size Bell test built from non-diagonal Heisenberg-Weyl (HW) observables that generalize CHSH to higher dimensions [2].

Let  $d$  be an odd prime (composites follow by a tensor-factor lift), the experiment uses measurements in the eigenbases of the HW displacement operators with  $T_{(x,z)} = \omega^{2^{-1}xz} X^x Z^z$ ,  $\omega = e^{2\pi i/d}$ , and  $Z^z X^x = \omega^{xz} X^x Z^z$ . The target state is a locally rotated maximally entangled state  $|\Phi\rangle = \frac{1}{\sqrt{d}} (U_\nu \otimes \mathbb{1}) \sum_{k \in \mathbb{Z}_d} |kk\rangle$  where  $U_\nu$  is a non-Clifford unitary, diagonal in the computational basis, injecting the required non-stabilizer “magic”. The associated Bell operator reads

$$\mathcal{B}_d = \sum_{n \in \mathbb{Z}_d^\times} \sum_{j,k \in \mathbb{Z}_d} g(j,k,n) A_j^n \otimes B_k^n, \quad (1)$$

with explicitly computable coefficients  $g(j,k,n)$ . On the target state,  $\langle \Phi | \mathcal{B}_d | \Phi \rangle = d(d-1)$ .

We give an *exact* sum-of-positive-operator decomposition for the gap  $d(d-1) - \mathcal{B}_d$ . Almost saturating the decomposition with a given physical state furnishes algebraic constraints directly on the physical operators from near-optimal correlations. Combining these linear relations with power identities for the unitary measurement blocks yields *twisted commutation* on the support of the state,

$$(A_j A_k - \omega^{j-k} A_k A_j) |\psi\rangle = 0, \quad (B_j B_k - \omega^{j-k} B_k B_j) |\psi\rangle = 0, \quad \forall j, k \in \mathbb{Z}_d, \quad (2)$$

which pins down the operator algebras. An explicit local isometry (a qudit SWAP built from the generalized Fourier transform and HW generators) then extracts a maximally entangled pair and maps the physical observables to canonical HW operators.

If a bipartite strategy achieves  $\langle \psi | \mathcal{B}_d | \psi \rangle \geq d(d-1) - \varepsilon$ , then there exist local unitaries  $V_A, V_B$  such that

$$|(V_A \otimes V_B) |\psi\rangle - |\Phi\rangle \otimes |\text{aux}\rangle| \leq \delta(\varepsilon), \quad \delta(\varepsilon) = \sqrt{\varepsilon} d(d-1) (\mu_d(4 + 1/d) + 1), \quad (3)$$

with  $\mu_d = \sqrt{d}(\sqrt{d} + 2)$  for  $d > 3$  (and an explicit bound for  $d = 3$ ). Under the same isometry,  $A_j \mapsto T_{(1,j)} \otimes \mathbb{1}$  and  $B_j \mapsto T_{(1,j)} \otimes \mathbb{1}$ . Hence, both the state and the implemented HW measurements are certified up to local isometries, with  $O(\sqrt{\varepsilon})$  robustness.

The construction extends to arbitrary  $d = \prod_\ell p_\ell^{k_\ell}$  by applying the prime-dimensional test on each factor, with controlled (essentially linear) error accumulation. All ingredients are available in high-dimensional photonic and atomic platforms, yielding implementation-friendly targets and explicit error bars.

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\* uta-isabella.meyer@lip6.fr

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## Quantitative quantum soundness for all multipartite compiled nonlocal games

Matilde Baroni, Siniša Janković, Igor Klep, Dominik Leichtle, Connor Paddock, Marc-Olivier Renou, Simon Schmidt, Ivan Šupić, Lucas Tendick, Xiangling Xu, and Yuming Zhao

Nonlocal games are central to the study of quantum nonlocality since Bell’s groundbreaking work [1]. The standard setup involves multiple players, typically spatially separated to ensure no-signaling, sharing quantum entangled quantum systems. Each player measures their own system according to a measurement selected according to an input provided by a referee. Famously, shared entanglement allows quantum players to achieve correlations, and thus higher scores, that are classically infeasible.

In practice, ensuring that multiple players are truly unable to communicate is a significant experimental challenge. This raises a compelling question : can we witness this quantum advantage using just a *single*, untrusted quantum device, called *quantum prover* ? To this end, the authors of [2] introduced *compiled nonlocal games*, which transform the multi-player setup into a single-device protocol : the spatially separated players are replaced by a single quantum prover, who interacts with a *verifier* (the protocol’s referee). This compiler is built on quantum homomorphic encryption (QHE) [3, 4], a technique allowing computation on encrypted quantum data. The authors showed this compilation to be *classically sound* (a dishonest classical prover cannot exceed the classical score) and *quantum complete* (an honest quantum prover can achieve the optimal nonlocal quantum score).

However, the original proposal left a crucial question open : what happens with dishonest quantum provers ? Could they achieve a score significantly higher than what is physically possible in the original, multi-player nonlocal game ? Proving that this is impossible, a property called *quantum soundness*, has been a major research challenge.

This talk presents the cumulative results from three works [5–7] that resolve this question by providing the *first quantitative upper bounds* on the achievable scores for *all* multipartite compiled nonlocal games. For all games that admit finite-dimensional optimal quantum strategies, we show that the compilation is quantitatively sound, meaning the optimal compiled score can exceed the true nonlocal maximum by only a negligible amount. More generally, we establish a bound for all compiled nonlocal games using a novel generalization of the celebrated Navascués-Pironio-Acín (NPA) hierarchy [8, 9], a systematic computational tool for characterizing quantum correlations.

This is a highly significant and technical result, as it elevates compiled games into a provably secure framework. It makes it possible to explore and certify genuinely multipartite quantum phenomena, such as the self-testing of multipartite states, within a practical single-device model, opening new perspectives for both theoretical and experimental research.

As mentioned, the key to our results is the development of a *convergent multi-round sequential NPA hierarchy*, which was done in multiple steps. First, it required establishing a new operator-algebraic framework to correctly describe multipartite quantum steering. This framework resolves a long-standing challenge in generalizing steering beyond the bipartite case, where naive approaches were known to fail [10]. Building on this, our hierarchy is the first computational tool capable of handling quantum sequential processes by modeling quantum instruments and imposing appropriate constraints on the level of completely positive maps, which may be of independent interest.

The goal of this talk is to make the concepts of compiled nonlocal games and their quantitative quantum soundness accessible to a broad audience of theorists and experimentalists. We will focus on the high-level ideas to provide a clear picture of this interesting intersection of quantum information, cryptography, and mathematics.

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# Iterative generation of free-propagating superposition of coherent states of light using a quantum memory cavity

Romaric Journet<sup>1</sup>, Lucas Caron<sup>1</sup>, Hector Simon<sup>1</sup>, Hugo Basset<sup>1</sup> and Rosa Tualle-Brouri<sup>1\*</sup>

<sup>1</sup>*Laboratoire Charles Fabry, Institut d'Optique Graduate School,  
Université Paris Saclay, 2 avenue Augustin Fresnel,  
91127, Palaiseau, France*

Schrödinger cat states — coherent superpositions of coherent states with opposite phases — constitute valuable resources for quantum information processing [1], quantum communication [2], and quantum metrology [3]. Their controlled generation and storage remain major challenges in the development of scalable quantum technologies.

In this work, we report the experimental realization of a source of Schrödinger cat states using an iterative protocol. Our approach combines a heralded single-photon source based on parametric fluorescence with a low-loss “quantum memory” cavity integrating a fast Pockels cell and a polarizing beam splitter. This architecture allows the storage of a first single photon while waiting for the heralding of a second one. The stored and incoming photons are subsequently entangled through polarization manipulations via the Pockels cell and recombination at the beam splitter. A homodyne detection is then used to perform a quadrature measurement on one mode of the entangled state. When the measured quadrature satisfies the condition  $X = 0$ , the other mode is projected onto a Schrödinger cat state.

Using this method, we achieve high-fidelity ( $> 60\%$ ) state generation at a repetition rate of 1 kHz [4], which represents, to the best of our knowledge, the current state of the art. Furthermore, the quantum memory cavity enables the storage of the generated state, opening the way for the iterative synthesis of increasingly more complex non-classical states [4].

The key feature of this experiment is therefore the quantum memory cavity, which simultaneously enhances the generation rate and provides the necessary architecture for iterative generation protocols.

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\* romaric.journet@institutoptique.fr

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# Certifying Non-Classicality of High-Harmonic Generation in Semiconductors

David Theidel<sup>\*1</sup>, Mateusz Weis<sup>1</sup>, Mackrine Nagra<sup>1</sup>, Philip Heinzel<sup>2</sup>, Viviane Cotte<sup>1</sup>, Houssna Griguer<sup>1</sup>, Ilya Karuseichyk<sup>1</sup>, Jens Biegert<sup>3</sup>, René Sondenheimer<sup>2,4</sup>, and Hamed Merdji<sup>5</sup>

<sup>1</sup>Laboratoire d'Optique Appliquée, ENSTA ParisTech, CNRS, École Polytechnique – Laboratoire d'Optique Appliquée, ENSTA ParisTech, CNRS, École Polytechnique – France

<sup>2</sup>Fraunhofer Institute for Applied Optics and Precision Engineering IOF – Germany

<sup>3</sup>Institut de Ciències Fòniques [Castelldefels] – Spain

<sup>4</sup>Friedrich Schiller University Jena – Germany

<sup>5</sup>Laboratoire d'optique appliquée – École Nationale Supérieure de Techniques Avancées, Ecole Polytechnique, Centre National de la Recherche Scientifique, Centre National de la Recherche Scientifique : UMR7639 – France

## Abstract

Non-classical sources of light in the perturbative interaction regime are well established and the workhorses of quantum optics. Only recently it has been shown that also emission of photons from strong-field interaction can contain non-classical effects (1). We present our work on the first experimental verification of intrinsic non-classical effects from radiation created in the strong-field regime (2, 3). Our unique experimental platform is based on solid-state high-harmonic generation (SHHG) driven by classical light. By measuring Glauber correlation functions with a single photon resolving setup, we characterize the photon statistics of the emission, revealing a super-Poissonian distribution and non-classical inter-harmonic correlations. We show these results are well-described by an effective model based on displaced squeezed states. Furthermore, we present recent work extending these investigations to higher harmonic orders. Here, conditional measurements between harmonic modes show the generation of anti-bunched light. We rigorously certify its quantum non-Gaussian (QNG) character by measuring a witness operator (4). Indeed, the creation of a QNG state via conditional measurements on an otherwise Gaussian state is only possible if the initial harmonic modes are entangled (5). This makes these results the most direct hint of the presence of entanglement between the high-order harmonics up to now. Our work firmly establishes laser-driven SHHG as a promising new source for generating complex, entangled quantum states of light.

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<sup>\*</sup>Speaker

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## Overlapping tomography of fermionic simulators

Ahana Ghoshal,\* Otfried Gühne, and Hai-Chau Nguyen

*Naturwissenschaftlich-Technische Fakultät, Universität Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany*

Carlos de Gois\*

*Inria Paris-Saclay, Bâtiment Alan Turing, 1 rue Honoré d'Estienne d'Orves, 91120 Palaiseau, France*

Kiara Hansenne

*Université Paris-Saclay, CEA, CNRS, Institut de Physique Théorique, 91191 Gif-sur-Yvette, France*

Simulating many-body fermionic systems on conventional qubit-based quantum computers involves significant overhead due to the fermion-to-qubit encodings required to capture fermionic exchange statistics. Motivated by their potential applications in quantum chemistry, condensed matter physics, and materials science, recent proposals have introduced native fermionic quantum simulators [1–5]. Designed to naturally incorporate fermionic statistics without the overhead of fermion-to-qubit encodings, they suggest a potentially scalable and more direct platform for simulating fermionic problems. However, they also introduce unique constraints, a notable example being the difficulty in implementing particle non-conserving operations. This raises a key challenge : How can we efficiently characterize the state of a fermionic simulator given their operational constraints ?

We address this challenge by pairing fermionic modes to form "second-quantized qubits." Crucially, we show that native fermionic gates act as rotations on these qubits, enabling direct adaptation of qubit-based methods. Our approach utilizes only particle-number-preserving operations, aligning with the natural capabilities of current fermionic simulators and avoiding the need for challenging non-conserving gates.

As a key application, we adapt overlapping tomography to fermionic simulators. We map the measurement of two- and four-point correlators onto the second-quantized qubits and represent the set of target correlators and the constraints imposed by the pairing scheme as a graph problem. Optimizing the number of measurement settings is then analyzed using analytical and algorithmic graph-theoretic methods. Our results demonstrate :

1. Determining single-body observables in an  $n$ -mode system require only  $O(n)$  measurement settings, and we provide an explicit construction.
2. Measuring all two-body observables requires at least  $\Omega(n^2)$  settings and optimal solutions can be constructed with graph covering algorithms.
3. For common lattice geometries (square, triangular, hexagonal, Kagome), two-body observables within individual tiles (local regions) can be recovered using a constant number of settings, independent of system size.

By exploiting only particle-number-conserving native gates, our approach offers a scalable and natural method for state characterization in emerging fermionic quantum simulators. Future work includes extending the framework to higher-order correlators and refined statistical analysis of sample complexity.

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\* These authors contributed equally to this work.



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## Coherence Limits in Interference-Based $\cos(2\varphi)$ Qubits

S. Messelot<sup>1\*</sup>, A. Leblanc<sup>2,3</sup>, J.-S. Tettekpoe<sup>1,4</sup>, F. Lefloch<sup>2</sup>, Q. Ficheux<sup>1</sup>, J. Renard<sup>1</sup>, É. Dumur<sup>2\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CNRS, Grenoble INP,  
Institut Néel, 38000 Grenoble, France*

<sup>2</sup>*Univ. Grenoble Alpes, CEA, Grenoble INP,  
IRIG, PHELIQS, 38000 Grenoble, France*

<sup>3</sup>*Present address : Center for Quantum Information Physics,  
Department of Physics, New York University,  
New York, NY 10003, USA*

<sup>4</sup>*DGA, Paris, France*

The search for new superconducting qubit designs is driven by the need to overcome the coherence bottlenecks of transmons and related architectures. Among the many proposals, the  $\cos(2\varphi)$  qubits[1], where only pairs of Cooper pairs can tunnel, leads to states of different parity and, consequently, to a suppression of energy relaxation. Such elements can be engineered using multi-harmonic Josephson junctions in interference-based circuits, including semiconductor–superconductor[3, 4] devices, rhombus[2] circuits, and KITE[1] structures. Despite their promise, experimental progress has been limited, and the true coherence potential of this class of qubits remains an open question.

In this work, we present a comprehensive theoretical study of interference-based  $\cos(2\varphi)$  qubits, focusing on their relaxation and dephasing properties under realistic experimental conditions and attainable circuit parameters. We first show that the commonly accepted picture of “parity protection” in  $\cos(2\varphi)$  qubit does not hold in the context of finite experimental accuracy. Furthermore we show that these out-of-experimental-reach qubit can only leads to extreme charge noise sensitive qubit.

Then, using numerical simulations, we evaluate in more detail the impact of junction asymmetry, magnetic flux bias, and charge offset on coherence times. We find that such finite experimental accuracies lead to an experimentally attainable qubit where a more complex picture of parity protection is present. We show that such energy relaxation protection is remarkably robust, with qubit lifetimes  $T_1$  potentially exceeding milliseconds for realistic circuit parameter and experimental finite accuracy.

Finally, we identify a fundamental trade-off between sensitivity to flux noise and charge noise that constrains the dephasing time  $T_\varphi$  to the microsecond range. This limitation persists across the whole experimentally attainable parameter space making interference-based  $\cos(2\varphi)$  an inadequate qubit candidate.

Our results clarify why demonstrations of  $\cos(2\varphi)$ -based qubits have so far struggled to achieve long coherence times, and they establish quantitative bounds on what can realistically be expected from this approach. These findings are relevant to a variety of interference-based  $\pi$ -periodic circuit elements, providing design guidelines and highlighting key challenges for future experiments.

By outlining both the opportunities and inherent limits of  $\cos(2\varphi)$  qubits, this work aims to inform the ongoing search for hardware-efficient quantum processors.

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\* [simon.messelot@neel.cnrs.fr](mailto:simon.messelot@neel.cnrs.fr), [etienne.dumur@cea.fr](mailto:etienne.dumur@cea.fr)

# Experimental quantum reservoir computing with a circuit quantum electrodynamics system

Baptiste Carles<sup>1</sup>, Julien Dudas<sup>1</sup>, Léo Balembois<sup>2</sup>, Julie Grollier<sup>1</sup>, Danijela Marković<sup>1\*</sup>

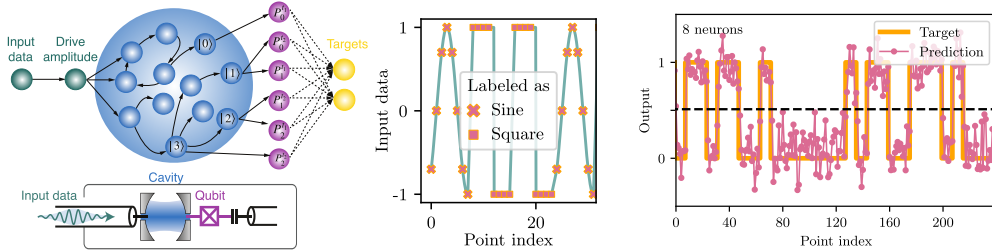
<sup>1</sup>Laboratoire Albert Fert, CNRS, Thales,  
Université Paris-Saclay, Palaiseau, France

<sup>2</sup>CEA, SPEC, Gif-sur-Yvette, France

Quantum computing suffers from a lack of quantum algorithms, a challenge that could be mitigated by learning-based approaches. Circuit QED allows easy quantum interactions engineering, such as superposition and entanglement through nonlinear processes, which can be trained to implement neural networks [1]. Interestingly those quantum properties should improve learning capabilities [2]. Most approaches are based on two level systems for which high coupling density is hard to obtain and have less tunable parameters. Our approach exploits the energy levels of quantum oscillators as neurons [3]. In this work, we implement experimentally a quantum neural network on a minimal system consisting of the fundamental mode of a superconducting resonator, coupled to a transmon qubit for its readout. To test the potential of this system for quantum neural networks, we use the reservoir computing architecture, which benefits from the physical system properties, training only a final layer.

We experimentally implement a benchmark task for reservoir computing : the sine-square wave classification task. This task specifically tests the non-linearity of the neural network, arising from the measurement in our case. By measuring 8 output neurons corresponding to some occupation probabilities of 0 to 4 photons after four different time steps we obtain a classification accuracy of 98.6 %. Despite the presence of quantum and experimental noise, this result is an improvement in terms of the number of necessary neurons compared to simulations of a reservoir computing with classical oscillators [4]. Since the system non-linearity is the key property for reservoir computing, we also investigated the impact of Kerr non-linearity. Simulations show that the Kerr effect, inherent to the resonator-transmon coupling, improves the task performance as its strength increases.

This experiment shows that projecting a Gaussian state onto the Fock basis enables the extraction of a large number of nonlinear features. It demonstrates the potential of quantum measurement as a source of nonlinearity for quantum neural networks.



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\* baptiste.carles@cnrs-thales.fr

# High-dimensional entanglement and topological protection in nonlinear waveguide arrays

Alessandro Zecchetto<sup>1</sup>, Arnault Raymond<sup>1</sup>, Jean-René Coudevylle<sup>2</sup>, Martina Morassi<sup>2</sup>,  
Aristide Lemaître<sup>2</sup>, Fabrice Raineri<sup>2,3</sup>, Maria Amanti<sup>1</sup>, Sara Ducci<sup>1</sup>, and Florent Baboux<sup>1</sup>

<sup>1</sup>Université Paris Cité, CNRS, MPQ, Paris, France

<sup>2</sup>Université Paris-Saclay, CNRS, C2N, Palaiseau, France

<sup>3</sup>Université Côte d'Azur, CNRS, InPhyNi, Nice, France

Harnessing high-dimensional entangled states of light presents a frontier for advancing quantum information technologies, from fundamental tests of quantum mechanics to enhanced computation and communication protocols. In this context, the spatial degree of freedom stands out as particularly suited for on-chip integration. But while traditional demonstrations produce and manipulate path-entangled states sequentially with discrete optical elements, continuously coupled nonlinear waveguide systems offer a promising alternative where photons can be generated and interfere along the entire propagation length, unveiling novel capabilities within a reduced footprint. We have exploited this concept to implement a compact and reconfigurable source of path-entangled photon pairs based on parametric down-conversion in semiconductor nonlinear waveguide arrays (Fig. 1a,b). We use a double-pump configuration to engineer the output quantum state and implement various types of spatial correlations (Fig. 1c,d), exploiting a quantum interference effect between the biphoton state generated in each pumped waveguide [1].

We then investigate more complex geometries by alternating two coupling distances in the array to implement the Su-Schrieffer-Heeger (SSH) Hamiltonian. In the center of the lattice, a topological defect is introduced by inserting an additional long coupling distance. This results in the emergence of a topologically protected mode localized at the interface. In contrast to a trivial defect mode, the existence of this topological mode as well as its modal refractive index are expected to be protected against disorder. We investigated experimentally the topological protection of the resonance spectrum of the SPDC process in these arrays. For this, we systematically compared different lattice geometries: periodic arrays, arrays featuring a trivial localized mode, and topological SSH arrays. While in the first two cases, disorder is shown to strongly affect the SPDC spectrum, giving rise to sensible fluctuations in the shape and/or the maximum resonance position, the resonance spectrum of topological arrays remains protected up to significant levels of disorder. Our experimental results supported by numerical simulations along with a simplified analytical model that captures these different behaviors and trace them back to the band structure properties of the interacting modes [2]. This rich phenomenology highlights nonlinear waveguide arrays as a promising platform for exploring the interplay between nonlinearity, disorder and topology in quantum photonic circuits.

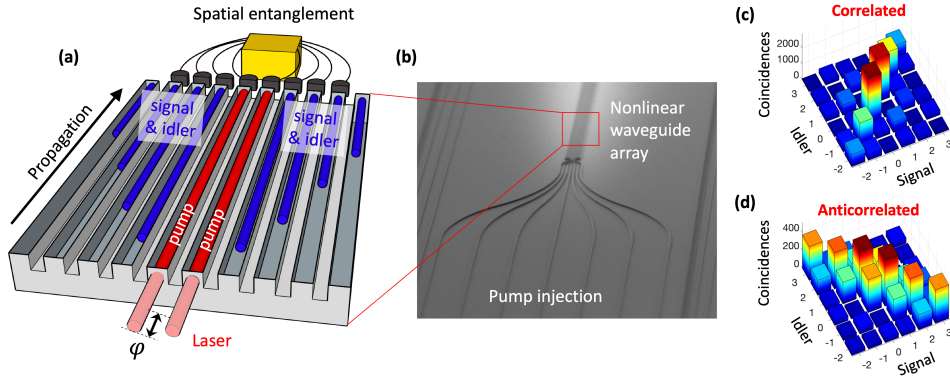


FIG. 1: (a) Sketch and (b) SEM image of an AlGaAs nonlinear waveguide array. (c-d) Measured coincidence maps at the array output, corresponding to a spatially correlated and anticorrelated state, respectively.

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## Unitary Transformations using Robust Optimal Control on a Cold Atom Qudit

E. Flament, N. Ombredane, F. Arrouas, D. Ronco, B. Peaudecerf, and D. Guéry-Odelin  
*Laboratoire Collisions, Agrégats, Réactivité, FeRMI, Université de Toulouse,  
CNRS, 118 Route de Narbonne, F-31062 Toulouse Cedex 09, France\**

D. Sugny  
*Laboratoire Interdisciplinaire Carnot de Bourgogne, CNRS UMR 6303,  
Université Bourgogne Europe, BP 47870, F-21078 Dijon, France*

In this work [1], we design and experimentally implement various robust quantum unitary transformations (gates) acting on  $d$ -dimensional vectors (qudits) by tuning a single control parameter using optimal control theory. The quantum state is represented by the momentum components of a Bose-Einstein condensate (BEC) placed in an optical lattice, with the lattice position varying over a fixed duration serving as the control parameter. To evaluate the quality of these transformations, we employ standard quantum process tomography. In addition, we show how controlled unitary transformations can be used to extend state stabilization to global stabilization within a controlled vector subspace. Finally, we apply them to state tomography, showing how the information about the relative phase between distant momentum components can be extracted by inducing an interference process.

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\* eloi.flament@utoulouse.fr

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# Deterministic nuclear spin squeezing and squeezing by continuous measurement using vector and tensor light shifts

Ali Moshiri<sup>1\*</sup> and Alice Sinatra<sup>2†</sup>

<sup>1</sup>*Laboratoire Kastler Brossel, ENS-Université PSL, CNRS,  
Université de la Sorbonne et Collège de France,  
24 rue Lhomond, 75231 Paris, France*

<sup>2</sup>*Laboratoire Kastler Brossel, ENS-Université PSL,  
CNRS, Université de la Sorbonne et Collège de France,  
24 rue Lhomond, 75231 Paris, France*

We study the joint effects of vector and tensor light shifts in a set of large spin atoms, prepared in a polarized state and interacting with light. Depending on the ratio  $\epsilon$  between tensor and vector coupling and a measurement rate  $\Gamma$ , we identify a regime of quantum non-demolition measurement squeezing for times shorter than  $(\sqrt{\epsilon}\Gamma)^{-1}$ , and a deterministic squeezing regime for times longer than  $(\epsilon\Gamma)^{-1}$ . We apply our results to fermionic isotopes of strontium, ytterbium, and helium, which are atoms with purely nuclear spin in their ground state, benefiting from very low decoherence. For ytterbium 173, with a cavity such as that of [1], it would be possible to achieve an atomic spin variance reduction of 0.03 in  $\simeq 50$ ms.

Used directly, the spin squeezed state for helium 3 could be used in magnetometry and improve the accuracy of fundamental physics experiments [2]. As for alkaline earth atoms or similar atoms, the squeezed state could be transferred to an optical transition [3], to benefit atomic clocks [4, 5].

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\* ali.moshiri@lkb.ens.fr

† alice.sinatra@lkb.ens.fr

# Optimal characterization of multi-photon distinguishability

Rodrigo Martínez<sup>1,3</sup>, Emilio Annoni<sup>2,3</sup>, Stephen C. Wein<sup>3</sup>, Carmen G. Almudéver<sup>1</sup>, Shane Mansfield<sup>3</sup>, Ellen Derbyshire<sup>3</sup> and Rawad Mezher<sup>3</sup>

<sup>1</sup>Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain

<sup>2</sup>Centre for Nanosciences and Nanotechnology, 10 Boulevard Thomas Gobert, 91120, Palaiseau, France

<sup>3</sup>Quandela SAS, 7 Rue Léonard de Vinci, 91300 Massy, France

The quest for the perfect single photon source is yielding devices that are bright enough to explore the capabilities of multi-photon interference protocols. In this context, clean interference between indistinguishable photons is a key requirement to implement meaningful Quantum Information Processing. Notably, in order to correctly account for imperfections and assess the quality of these experiments, it becomes necessary to access quantities that are not measurable with standard Hong-Ou-Mandel-type experiments [1, 2].

The relevant distinguishability properties can be measured by the state-of-the-art Cyclic Interferometer (CI) protocol [1], with the pitfall that only 1 out of every  $2^n$  photocounting events it produces are useful. We introduce a novel scheme based on the linear-optical Quantum Fourier Transform (QFT) which overcomes this limitation, demonstrating the measurement of the distinguishability spectrum of a multi-photon state without any post-selection [3], ultimately providing an exponential improvement in sample efficiency compared to the state of the art.

Our results build on previous work which explored the Zero Transmission Laws (ZTL [4]) that characterize the photocounting statistics of a QFT interferometer and its strong dependence on distinguishability properties. We extend the description of these suppression laws to arbitrary input photons with mixed spectral states, developing a basis-independent description of the measurement procedure based on distinguishability observables. Finally, we implement the QFT and CI protocols for  $n = 3$  and  $n = 4$  photons on Quandela's *Ascella* QPU [5] (see Fig. 1) comparing the performance and requirements of each approach.

Our protocol enables rigorous benchmarking of multi-photon distinguishability and provides a powerful diagnostic tool for photonic quantum technologies.

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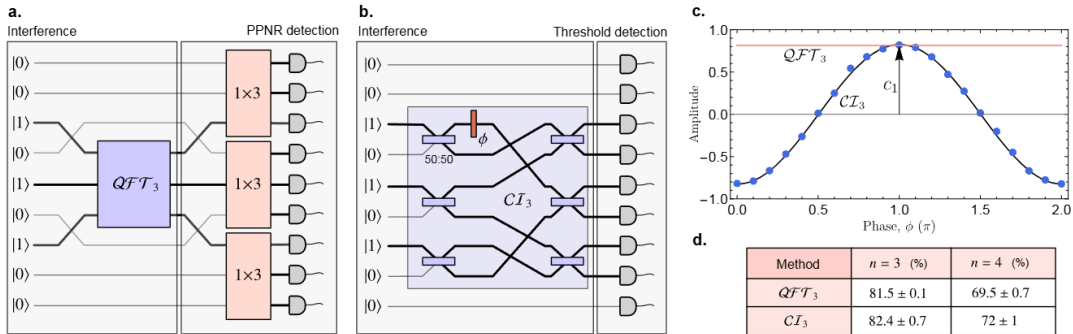


FIGURE 1. Implementation scheme of the QFT (a.) and CI (b.) protocols on Quandela's *Ascella* QPU for  $n = 3$  photons. CI and QFT protocol datapoints (c.,  $n = 3$ ) and final  $n$ -photon indistinguishability measurements (d.,  $n = 3, 4$ ). The QFT protocol achieves better precision in estimating GI for comparable acquisition times.

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## No quantum advantage without classical communication : fundamental limitations of quantum networks

Justus Neumann<sup>1</sup>, Tulja Varun Kondra<sup>1</sup>, Kiara Hansenne<sup>2,3</sup>, Lisa T. Weinbrenner<sup>3</sup>,  
Hermann Kampermann<sup>1</sup>, Otfried Gühne<sup>3</sup>, Dagmar Bruß<sup>1</sup>, and Nikolai Wyderka<sup>1\*</sup>

<sup>1</sup>*Heinrich Heine Universität Düsseldorf, Germany*

<sup>2</sup>*Université Paris-Saclay, CNRS, CEA,  
Institut de Physique Théorique, France*

<sup>3</sup>*Universität Siegen, Germany*

Quantum networks connect systems at separate locations via quantum links, enabling a wide range of quantum information tasks between distant parties. A key requirement for many such applications is the generation and distribution of multipartite entangled states (most notably quantum graph states such as GHZ and cluster states) used in tasks ranging from blind quantum computation and quantum metrology to quantum key distribution and clock synchronisation. Yet creating these states across a large network remains experimentally demanding : it requires precise control of high-dimensional systems and typically relies on quantum memories and real-time classical communication.

To model what is feasible with present-day hardware, one often considers local operations and shared randomness (LOSR) networks. Here, distant parties are connected by bipartite entangled sources and can perform only local quantum operations assisted by pre-shared classical correlations, without time-critical classical communication. These networks are experimentally attractive and have been intensely investigated [1–6], yet existing results mostly concern (almost) pure states or focus on specific target states.

In this work we ask whether LOSR networks can truly harness the full potential of distributed quantum information processing. We provide a largely negative answer. Focusing on the task of preparing highly entangled multipartite states, we show that the maximum fidelity achievable within the LOSR model does not significantly exceed the best fidelity attainable by purely classical (or separable) networks. In other words, when it comes to producing useful multipartite entanglement for distant parties, the quantum advantage of bipartite sources alone is negligible. To go beyond this limitation, additional resources such as quantum memories, classical communication, or direct distribution of multipartite entanglement are indispensable. Our findings generalise and strengthen earlier observations for symmetric output states [4], where LOSR networks were shown to produce only fully separable states.

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\* kiara.hansenne@ipht.fr

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## Network Requirements for Distributed Quantum Computation

Hugo Jacinto,<sup>1,2,\*</sup> Élie Gouzien,<sup>1</sup> and Nicolas Sangouard<sup>2</sup>

<sup>1</sup>*Alice & Bob, 53 boulevard du Général Martial Valin, 75015 Paris, France*

<sup>2</sup>*Université Paris–Saclay, CNRS, CEA, Institut de Physique Théorique, 91191 Gif-sur-Yvette, France*

Physical constraints and engineering challenges, including wafer dimensions, classical control cabling, and refrigeration volumes, impose significant limitations on the scalability of quantum computing units. As a result, a modular quantum computing architecture, comprising small processors interconnected by quantum links, is emerging as a promising approach to fault-tolerant quantum computing. Recent theoretical work showed that logical qubits encoded in unrotated surface code patches in distinct processing units can be fault-tolerantly connected with a noise threshold along their shared interface reaching up to 10% [1]. Although these results are encouraging, the central questions about how many Bell pairs are required and how faithful they need to be to execute a quantum algorithm in a distributed way, with comparable space and time resources with respect to the monolithic approach, remain open. To answer these questions, in [2], we considered an architecture tailored for qubits with nearest-neighbor physical connectivity, leveraging the rotated surface code for error correction and enabling fault-tolerant operations through lattice surgery and magic state distillation. We derived resource estimations with the following steps.

The first step was to build a model for the logical error rate during a memory experiment on a rotated surface code patch shared across two processors through a fit of an ansatz. On top of usual fully depolarizing circuit-level noise, we model Bell state preparation infidelity by a 2-qubit depolarizing noise. This ansatz has been built upon an analytical bound in a phenomenological noise model originally developed for the unrotated surface code in [1] that we adapted for the rotated surface code.

Using this fitted model, we have been able to evaluate the probability of failure and the duration of each logical quantum operation (initializations, gates and measurements) on a minimalist chain-like architecture of processors. This chain-like architecture ensures logical all-to-all logical connectivity but limits parallelization as only one surface code patch at the same time can be shared between two nearest-neighbors processors on the chain. Particularly, we carefully designed the lattice surgery implementation of CNOT, CX...X, and Toffoli gates on this layout by taking into account errors occurring in merged patches of the lattice surgery operations. We have made the conservative assumption that each logical CNOT is performed between two logical qubits located at both extremities of the chain by using a very long routing patch that crosses every interface.

Leveraging this logical noise model, we’ve made a resource estimation for 2048-RSA number factoring using Ekerå and Håstad [3] version of Shor’s algorithm on both monolithic and distributed architectures. As a result, for a characteristic physical gate error rate of  $10^{-3}$ , a processor cycle time of 1  $\mu$ s, factoring a 2048-bit RSA integer is shown to be possible with 379 processors, each made with 89 781 qubits, with negligible space and time overhead with respect to a monolithic approach without parallelization, if 70 Bell pairs are available per cycle time between each processors with a fidelity exceeding 98.1 %.

Recent experiments of Bell state preparation via microwave links have reached a fidelity above 90 %, e.g [4] achieved a fidelity up to 96.4 % over 60 cm link. Our findings are pertinent for informing how networks’ quality should progress to scale up quantum computing.

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\* hugo.jacinto@alice-bob.com



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# Long-distance device-independent quantum key distribution using single-photon entanglement

Anna Steffinlongo<sup>1</sup>, Mariana Navarro<sup>1</sup>, Marina Cenni<sup>1</sup>, Xavier Valcarce<sup>2</sup>, Antonio Acín<sup>1</sup> and Enky Oudot<sup>1,3\*</sup>

<sup>1</sup>ICFO - Institut de Ciències Fòniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain

<sup>2</sup>Université Paris-Saclay, CEA, CNRS, Institut de physique théorique, 91191, Gif-sur-Yvette, France

<sup>3</sup>LIP6, CNRS, Sorbonne Université, 4 place Jussieu, F-75005 Paris, France

Quantum key distribution (QKD) has demonstrated the ability to enable secure communication between users with information-theoretic security. The security of a QKD protocol depends critically on the level of control over the quantum states prepared during the protocol. This control can now be achieved with very high precision, allowing QKD to be secure even in the presence of source flaws [3]. However, such security imposes a limit on the maximum distance over which the protocol remains secure. Indeed, at long distances, the communicating parties may only share a very small fraction of the initially prepared quantum states. If this fraction becomes smaller than the degree of control over the state preparation, the protocol can no longer be considered secure. Thus, while QKD has reached a level of maturity that makes it secure for short and medium distances, its security over long distances remains fundamentally limited by imperfections in state preparation.

Device-independent quantum key distribution (DIQKD) offers the strongest form of quantum security, as it allows two honest users to establish secure communication even when using fully uncharacterized quantum devices. It is therefore inherently robust against attacks stemming from imperfect state preparation. The security proof of DIQKD is derived from the violation of a Bell inequality, mitigating side-channel attacks by asserting the presence of nonlocality. This enhanced security comes at the cost of a challenging implementation. As photons in fibers are the natural carriers of quantum information, channel losses represent the main challenge for DIQKD : growing exponentially with distance, they become already at short distances too large for the honest users to be able to observe any Bell inequality violation. To circumvent channel losses, a heralding scheme can be used, where entanglement is generated between the parties' systems conditioned on the detection of photons at a central heralding station performing a joint measurement. Losses therefore reduce the key generation rate, but not its security. Heralding schemes have been used in recent proof-of-principle demonstrations of DIQKD [1]. In this experiment, the honest users locally generate light-matter entanglement, so that the state at the local stations is encoded in material qubits. Despite these successful demonstrations, the light-matter entanglement generation process required in this approach typically has low repetition rates, limiting its scalability over large distances. Purely photonic platform can offer a good repetition rate but they typically require 2 photon interference at the central station which make the key rate proportional to the efficiency of the channel between the two parties and thus limit the maximum distance at which one can perform DIQKD.

Photonic heralding scheme requires a Bell state measurement at a central station and usually rely on the arrival of two photons at a central station where the states are encoded in polarisation or time bin. We propose a photonic realization of DIQKD [2], utilizing single photon sources and linear optics which heralds a single-photon path entangled state between the honest users. Being based on single-photon interference effects, the obtained secret key rate scales with the square root of the quantum channel transmittance. This leads to positive key rates over distances of up to hundreds of kilometers with large improvement for loss tolerance. We also proposed recently a DIQKD experiment with only SPDC sources and linear optics[4], it has square root scaling of the key rate with the transmittance and use tailored Bell inequalities optimized for finite size analysis.

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\* enky.oudot@lip6.fr

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# High-Performance Heterodyne Receiver for Quantum Information Processing in a Laser Written Integrated Photonic Platform

Andrea Peri<sup>1</sup>, Giulio Gualandi<sup>2,3</sup>, Tommaso Bertapelle<sup>1</sup>, Mattia Sabatini<sup>1</sup>, Giacomo Corrielli<sup>3</sup>, Yoann Piétri<sup>1</sup>, Davide Giacomo Marangon<sup>1,4</sup>, Giuseppe Vallone<sup>1,5,4</sup>, Paolo Villorosi<sup>1,5,4</sup>, Roberto Osellame<sup>3</sup> and Marco Avesani<sup>1,4\*</sup>

<sup>1</sup>Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Padova, Via Gradenigo 6B, 35131 Padova (Italy)

<sup>2</sup>Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano (Italy)

<sup>3</sup>Istituto di Fotonica e Nanotecnologie, CNR, Piazza Leonardo da Vinci 32, 20133 Milano (Italy)

<sup>4</sup>Padua Quantum Technologies Research Center, Università degli Studi di Padova, via Gradenigo 6B, IT-35131 Padova (Italy)

<sup>5</sup>Istituto di Fotonica e Nanotecnologie - CNR, Via Trasea 7, 35131 Padova (Italy)

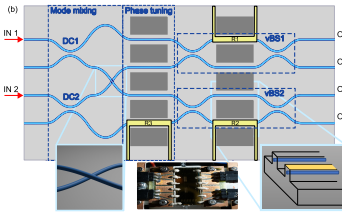
Among the most mature protocols of quantum technologies, Continuous-Variable Quantum Random Number Generation (CV-QRNG) and Continuous-Variable Quantum Key Distribution (CV-QKD) are critical technologies offering a viable solution to the security threats posed by the rapid advancement of quantum computing [1]. While impressive and numerous experimental demonstrations have been made in the past few years in these domains, there is an important need for reducing the cost and size of those systems before a potential large scale deployment [2].

In this context, optical integration plays a key role by enabling scalable, cost-effective, and mass-producible quantum systems that meet the demands of real-world deployment. In this work, we introduce Femtosecond Laser Micromachining (FLM) on borosilicate glass as a novel platform for producing photonic chips tailored toward quantum communication applications [3]. This technique consists of permanently increasing the index of refraction by focusing femtosecond pulses on a glass substrate, creating buried waveguides. The advantages of the FLM glass platform include low propagation losses, high stability and high mode matching efficiency with standard single mode telecom fibers. To the best of our knowledge, this work represents the first demonstration of FLM technology utilized for CV quantum communication protocols.

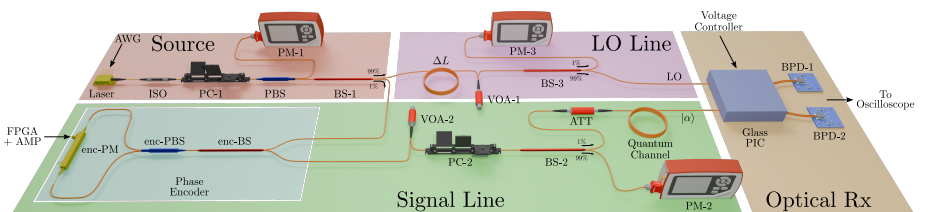
The layout of the integrated photonic circuit is shown in Fig. (a). It consists of two 50 : 50 beam splitters followed by a phase tuning stage for one of the arm and two variable beam splitters based on Mach-Zehnder Interferometers. The chip functionality is a 90° hybrid for coherent detection with adjustable balance and phase. The phase shifts are done with Thermo-Optic Phase Shifters (TOPSs). The phase can be adjusted to 90° a precision of  $\pm 0.9^\circ$  and maintained over several hours within this precision. The Common-Mode Rejection Ratio of the detection can also be optimized using the variable beam splitters, reaching up to 73.8 dB. Both these values, along with the impressive input-to-output losses, including coupling, of 1.05 dB, surpass state-of-the-art values for comparable bulk and integrated optical hybrids.

The circuit was then used in a CV-QRNG/CV-QKD setup, see Fig. (1b). Specifically, the platform demonstrated excellent performance in random number generation for CV-QRNG, reaching a generation rate of more than 40 Gbps, currently the record for any Source-Device-Independent QRNG. We also employed the same chip as a receiver in a CV-QKD experiment, obtaining high secret key rates exceeding 3 Mbps. Both these values were enabled by the high performance and stability of the chip-based receiver.

The intrinsic performance of the chip in terms of losses, stability, and tunability, along with the reported performance of the QKD and QRNG protocols demonstrate the large potential of the FLM glass platform for future integrated quantum technologies.



(a) Layout of the integrated photonic circuit.



(b) CV-QKD/CV-QRNG Experimental scheme.

\* Yoann.Pietri@unipd.it

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## Approaching optimal microwave-acoustic transduction on lithium niobate using SQUID arrays

Abel Hugot,\* Q. Greffe, G. Julie, E. Eyraud, F. Balestro, and J. J. Viennot  
*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Neel, 38000 Grenoble, France*

Acoustic waves play an essential role in a variety of classical and quantum electronic devices. Central to these devices is the transducer, which enables the exchange of signals between electrical and acoustic networks. Among the various transduction mechanisms, piezoelectricity remains the most widely used. For surface acoustic waves and Lamb waves, control and detection are commonly achieved using interdigital transducers (IDTs). However conventional IDTs are either inefficient or have narrow bandwidth, because their impedance is generally not  $50\ \Omega$  matched. These limitations restrict their utility in many applications operating at microwave frequencies.

We propose and demonstrate a strategy to realize piezoelectric microwave-acoustic transducers showing both high efficiency, wide bandwidth, and *in-situ* tunability [1]. These transducers are based on wide-band IDTs on suspended lithium niobate in conjunction with SQUID arrays. These SQUID arrays serve as tunable impedance transformers that match the large complex impedance of IDTs to  $50\ \Omega$ . We demonstrate this technique for various transducers : plane-wave, single-mode and unidirectional transducers. We achieve a maximum efficiency of 62% at 5.7 GHz with an unprecedented efficiency-bandwidth product of  $\approx 440$  MHz. This approaches the maximal values allowed by the piezoelectric properties of lithium niobate. Moreover, leveraging the flux dependence of SQUIDs, we realize transducers with *in-situ* tunability across nearly an octave around 5.5 GHz.

Our transducers could be used in a variety of hybrid quantum devices, since they are directly compatible with standard superconducting quantum circuits. They could find applications in microwave-to-optics conversion schemes, quantum-limited phonon detection, acoustic spectroscopy and fast acoustic coherent control.

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\* [abel.hugot@neel.cnrs.fr](mailto:abel.hugot@neel.cnrs.fr)

# Biphoton state generation and engineering with hybrid III-V/Silicon photonic devices

L. Lazzari<sup>1,2,3</sup>, J. Schuhmann<sup>1,2,3</sup>, O. Meskine<sup>1</sup>, M. Morassi<sup>2</sup>, A. Lemaître<sup>2</sup>,  
M.I. Amanti<sup>1</sup>, F. Boeuf<sup>3</sup>, F. Raineri<sup>2,4</sup>, F. Baboux<sup>1</sup>, and S. Ducci<sup>1</sup>

<sup>1</sup>MPQ, Université Paris Cité, 75013 Paris, France

<sup>2</sup>C2N, Université Paris Saclay, 91120 Palaiseau, France

<sup>3</sup>STMicroelectronics, 38190 Crolles, France

<sup>4</sup>INPHYNI, Université Côte d'Azur, 06200 Nice, France

Hybrid quantum photonics is a rapidly evolving field that combines different material platforms to harness their complementary optical properties for quantum information processing [1]. By integrating materials such as III-V semiconductors with silicon photonics, hybrid devices can leverage the efficient nonlinearities, direct bandgap and quantum light generation of III-V compounds [2] alongside the scalability and mature fabrication processes of silicon [3]. This approach enables the realization of compact, robust, and versatile photonic circuits capable of generating, manipulating, and routing quantum states of light on a single chip.

We present a hybrid AlGaAs/silicon-on-insulator (SOI) source operating at room temperature [4], whose working principle is sketched in Fig. 1.a: the photon pairs are generated, upon optical pumping, via spontaneous parametric down-conversion in an AlGaAs waveguide based on Bragg reflectors and then transferred, through evanescent adiabatic coupling, to the SOI circuitry, preserving the properties of the produced quantum state, while the pump beam is automatically filtered out.

By employing a nonlinearly shaped multi-mode taper, we improve the transmission efficiency and polarization independence, exceeding by an order of magnitude the previously reported performances [4], both in terms of generation rate and signal-to-noise ratio (Fig. 1.b), hence establishing the new state of the art. Furthermore, the implemented coupling scheme induces strong transformations on both the amplitude and phase of the joint spectral amplitude of the produced quantum state: this is measured via a Hong-Ou-Mandel (HOM) interference measurement. In Fig. 1.c we show the experimental data superimposed on the theoretical predictions, for three tapers with distinct geometrical characteristics. The capability to accurately predict such transformations opens the way to direct biphoton state engineering at the design stage, within a compact device and without requiring complex external components. In particular, we investigated the potential of the current device in modifying the photon exchange statistics and in enhancing the metrological gain for a time delay measurement, achieving performances comparable to those reported in the Literature using wave-shapers or spatial light modulators.

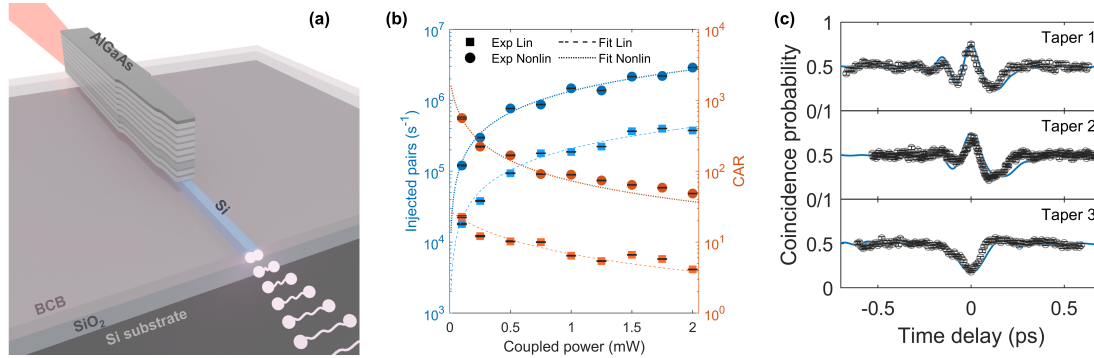


Figure 1. (a) Sketch of the device. (b) Rate of injected pairs into the silicon waveguide and coincidence-to-accidental ratio (CAR), for linearly and nonlinearly shaped tapers. (c) HOM interferograms - experimental data are superimposed on theoretical predictions.

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# High-performance solid-state quantum memory in a low-vibration in-house built cryostat

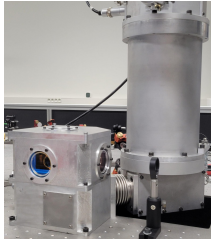
H. Naim<sup>1</sup>, M. Khelifa<sup>1</sup>, J. Le Meur<sup>1</sup>, C. Pitiot<sup>1</sup>, F. Zumbo<sup>1</sup>, A. Tempel<sup>2</sup>, S. Bosio<sup>1</sup>, S. Tanzilli<sup>1</sup>, and J. Etesse<sup>1\*</sup>

<sup>1</sup>Université Côte d'Azur, CNRS,  
Institut de Physique de Nice, UMR 7010,  
17 rue Julien Lauprêtre, 06200 Nice, France  
<sup>2</sup>Université de Bordeaux, CNRS, LOMA,  
UMR 5798, 33400 Talence Cedex, France

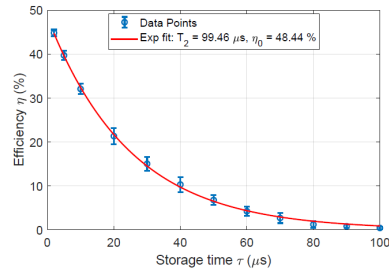
Quantum memories have been an active research in quantum optics, for they are essential for quantum information processing. One of the most prominent platforms is rare-earth ion-doped crystals, used with the atomic frequency comb (AFC) protocol [1]. To reach the highest coherence times, these crystals need to be cooled down at cryogenic temperatures ( $\sim 3$  K), but current state-of-the-art commercially available closed-cycle systems suffer from inevitable vibrations, caused either by mechanically moving pieces or gas turbulences. Such vibrations induce detrimental piezospectroscopic shifts, that hinder the preparation of fine population structures, as required for the AFC protocol [2].

We present here the development of a cryostat whose architecture is designed for minimizing vibration propagation between the cold head and the sample. The body of the cryostat shown on Figure 1, the radiation shieldings as well as sample pieces were all machined in order to achieve high precision adjustment in the space-constrained volume. Our realization aims at being simultaneously low vibration, compact as well as modular, while reaching a base temperature below 4 K. The key vibration isolation feature is a mechanical decoupling between the cold head part and the experimental chamber via the joint use of elastic vacuum connections and copper braids for thermal connection.

We estimate the performances of the cryostat by two means. The first means consists in burning a narrow hole in the inhomogeneously broadened absorption line of a praseodymium-doped yttrium orthosilicate (Pr :YSO) crystal. By monitoring in real time the hole width and position, we assess the effect of vibration on spectral features. With our setup we reach hole widths of 15 kHz, monitored with a free-induction-decay (FID) protocol, for durations of the order of 400 ms, and estimate drifts smaller than this value over the whole measurement. The second characterization means consists in implementing the AFC protocol in the Pr :YSO crystal for optical storage of coherent states of light, for fixed delay-like storage durations ranging between 2 and 100  $\mu$ s. By fitting the exponential decay of the efficiency  $\eta$  as a function of the storage time  $\tau$ , we reach a coherence time  $T_2$  of 99  $\mu$ s and an efficiency of 48 % which overcomes state-of-the-art value for Pr :YSO, as shown in Figure 2 [3].



**Figure 1** The cryostat : chamber (left) and cold head housing (right)



**Figure 2** AFC efficiency decay

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\* jean.ettesse@univ-cotedazur.fr

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## Protecting collective qubits from non-Markovian dephasing

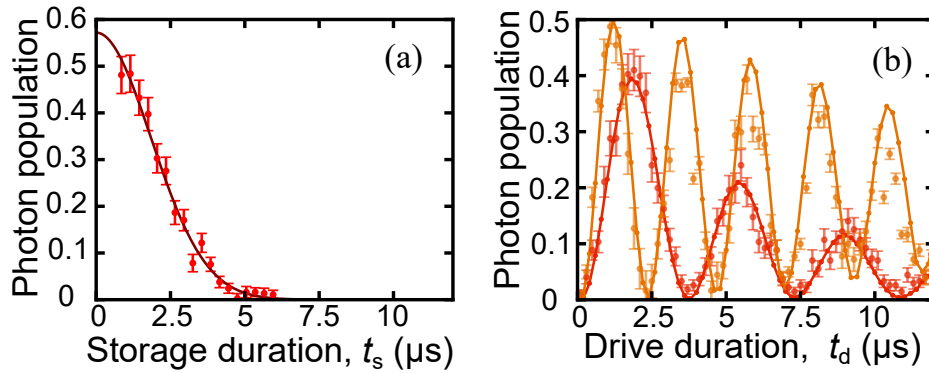
Antoine Covolo<sup>1</sup>, Valentin Magro<sup>1</sup>, Mathieu Girard<sup>1</sup>, Sébastien Garcia<sup>1</sup>, Alexei Ourjoumtsev<sup>1</sup>

<sup>1</sup>*Jeunes Equipe de l'Institut de Physique du Collège de France, Paris, 11 Pl. Marcelin Berthelot, France*

Collective atomic or solid-state excitations present important advantages for encoding qubits, such as strong directional coupling to light. Unfortunately, they are plagued by inhomogeneities between the emitters, which make the qubit decay into a quasi-continuum of dark states. In most cases, this process is non-Markovian. Through a simple and resource-efficient formalism, we unveil a regime where the decay is suppressed by a combination of driving and non-Markovianity [1].

We experimentally demonstrate this “driving protection” using a Rydberg superatom : a small ensemble of cold atoms where interactions between Rydberg-state atoms limit the number of excitations to one, thus defining a collectively-encoded qubit [2]. We achieved to extend its coherent dynamics beyond the characteristic free decay time by an order of magnitude.

This remarkable behavior is reminiscent of a phenomenon previously observed in systems with cavity coupled to inhomogeneous ensemble of emitters, commonly referred to as cavity protection [3][4].



**Fig. 1** We can access the excited population of our collectively encoded qubit by mapping it onto a cavity photon. (a) Free evolution of the qubit excited state. (b) Experimental evolutions for two different Rabi frequencies (data points with error bars) and corresponding numerical simulations using our dephasing model (points connected by lines).

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**Poster Session 1**  
**(QPAC, QSIM, QMET)**



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# Benchmarking Decoder Accuracy against Optimal Decoding

Anthony Benois<sup>\*1</sup>, Kiara Hansenne<sup>1</sup>, Pierre Cussenot<sup>1,2</sup>, Grégoire Misguich<sup>1</sup>, and Nicolas Sangouard<sup>1</sup>

<sup>1</sup>Institut de Physique Théorique - UMR CNRS 3681 – Université Paris-Saclay, Centre National de la Recherche Scientifique, Direction de Recherche Fondamentale (CEA) – France

<sup>2</sup>DGA – Direction générale de l’armement [France] – France

## Abstract

Quantum error correction (QEC) is widely recognised as the key component for achieving fault-tolerant quantum computing. Indeed, physical qubits are highly sensitive to environmental perturbations (such as temperature fluctuations or electromagnetic field variations) which lead to decoherence and prohibits the implementation of quantum circuits with large number of qubits and great depth. In QEC, logical qubits are encoded across many noisy physical qubits to protect quantum information, and errors are detected through non-destructive syndrome measurements. The measurement syndrome is then decoded : a classical algorithm (the decoder) maps the syndrome to a recovery operation. The quality of the decoder has a strong impact on the QEC procedure : if the recovery operations is chosen poorly, the logical error rate increases and thus the physical error threshold beyond which QEC becomes feasible becomes smaller.

In recent year, a variety of decoders have been proposed, ranging from fast heuristic methods like minimum-weight perfect matching to more computationally intensive but highly accurate methods such as tensor-network-based approaches. However, most benchmarking studies rely on stochastic error sampling under simplified circuit-level noise models (1), which fails to assess the true performance of a decoder, especially at low logical error rates.

In this work, we compare the performances of several decoding strategies, including minimum-weight perfect matching and recent decoders such as those proposed in Refs. (2, 3), against optimal decoding for a range of codes, starting with the repetition code and small low-density parity check codes from Ref. (4). To do so, we perform full density matrix simulations, allowing us to reach arbitrarily small error rates. Although this limits the exploration to small code distances, our results provide essential benchmarks for current decoders.

This decoder can also be formulated using mixed matrix product states (MPS) (5), which opens the door for a promising decoding strategy : compressing the full noisy state into a tensor network before syndrome measurement shifts the computational cost ahead of the QEC procedure. Once the syndrome is known, a fast projection onto the corresponding subspace gives access to the optimal recovery operation in real time.

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<sup>\*</sup>Speaker

# Certifying Gaussian States Without the i.i.d. Assumption

Anton L. Andersen<sup>1\*</sup> and Damian Markham<sup>1</sup>

<sup>1</sup>LIP6, CNRS, Sorbonne Université, 4 Place Jussieu, Paris F-75005, France

Continuous-variable (CV) states play a pivotal role in quantum technologies, offering unique advantages for quantum computation, communication, and sensing due to their inherent compatibility with optical systems and their ability to encode and process information in the infinite-dimensional Hilbert space of bosonic modes. In this poster, we present a protocol for the certification of a specific subclass of CV states. The protocol relies on local homodyne detection and does not assume that the source produces identical and independently distributed (i.i.d.) states. It is therefore well suited to adversarial network scenarios, where an entangled state is produced by an untrusted source and distributed to spatially separated parties via an untrusted network. The protocol applies to the subclass of Gaussian states  $|\Psi\rangle = \hat{U}|\emptyset\rangle$  generated by unitaries  $\hat{U}$  that act separately and linearly on the position and momentum quadratures. Specifically,  $\hat{U}$  must satisfy  $\hat{U}\hat{x}_i\hat{U}^\dagger = \sum_j \alpha_{ij}\hat{x}_j$ , and  $\hat{U}\hat{p}_i\hat{U}^\dagger = \sum_j \beta_{ij}\hat{p}_j$ , where  $\alpha_{ij}$  and  $\beta_{ij}$  are real coefficients. Despite this restriction, the protocol enables the certification of resource states relevant to both quantum computing [1] and quantum metrology [2]. We analyze the performance of the certification protocol in terms of the certified fidelity of the output state, considering the presence of realistic noise sources. Our results indicate that an experimental demonstration of the protocol is within experimental reach.

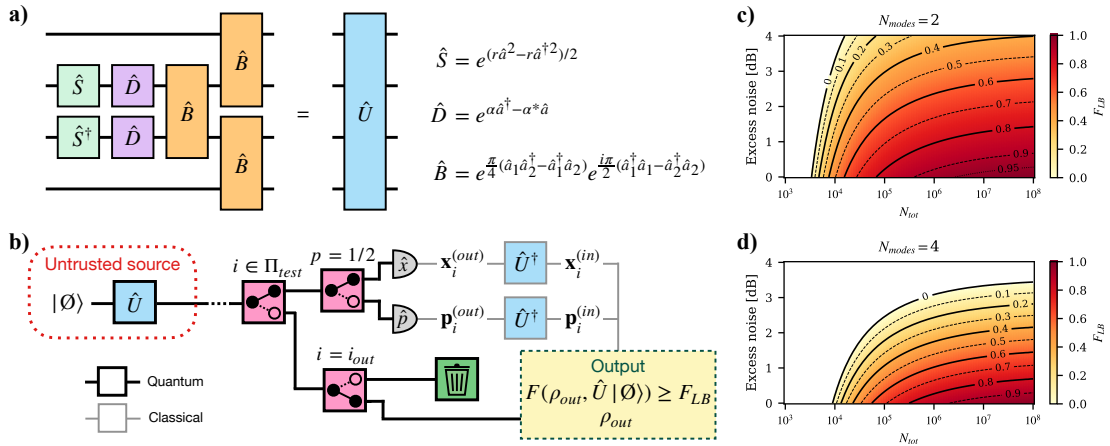


FIGURE 1 – Overview of the protocol. **a)** Circuit used to produce the resource states for metrology in [2], which serve as examples of states certifiable by this protocol. **b)** Schematic representation of the certification protocol. The untrusted source provides  $N_{tot}$  copies of the target state. A randomly chosen subset of these copies is used for test measurements via local homodyne detection. From the remaining states, one output state  $\rho_{out}$  is selected at random, for which a lower bound on the fidelity with the target state is computed. **c-d)** Lower bound  $F_{LB}$  on the fidelity guaranteed by the protocol, shown as a function of noise level and the total number of resource states  $N_{tot}$  used. Results are presented for two-mode states (**c**) and four-mode states (**d**).

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\* anton.andersen@lip6.fr

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## Circulator-free, near-quantum-limited qubit readout using the Traveling Wave Parametric Amplifier Isolator

Bekim Fazlji<sup>1,2</sup>, Vishnu Narayanan Suresh<sup>1</sup>, Arpit Ranadive<sup>1</sup>, Gwenael Le Gal<sup>1</sup>,  
Giulio Cappelli<sup>1</sup>, Wael Ardati<sup>1</sup>, Luca Planat<sup>2</sup>, Quentin Ficheux<sup>1</sup> and Nicolas Roch<sup>1\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CNRS, Grenoble INP,*

*Institut Néel, 38000 Grenoble, France*

<sup>2</sup>*Silent Waves, 38000 Grenoble, France*

Traveling wave parametric amplifiers (TWPAs) are now widespread for near-quantum-limited broadband amplification of microwave signals. Due to imperfect impedance matching with their environment and unwanted non-linear processes, they can exhibit significant backward emission and reverse gain. Therefore, isolators between the device under test (DUT) and the TWPA are used in order to protect the DUT from radiation from the measurement line. These isolators are bulky, magnetic and add losses before the first amplifier, resulting in the degradation of the noise performance of the amplification chain.

We will present the TWPAI (traveling wave parametric amplifier isolator) that utilizes four-wave mixing for amplification and three-wave mixing to upconvert backward propagating mode to a frequency band that can be easily discarded, effectively providing forward amplification and reverse isolation. It exhibits 20 dB of gain and -35 dB of isolation over 500 MHz. We will also discuss the implementation of the TWPAI in a qubit measurement setup without standard isolators, using the TWPAI to provide amplification and isolation. Along with this discussion, we will present qubit measurements for different configurations of the TWPAI.

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\* bekim.fazlji@neel.cnrs.fr

In the photonics continuous variable framework, encoding generally relies on electric field quadratures [1]. The time-frequency approach [2] on the other hand exploits *time-of-arrival* and *frequency* (modes) in the single-photon subspace. These variables are strictly speaking continuous but they do not rely on photon number statistics in a given mode as the field quadrature-based approach. Non-Gaussian operations - that are challenging in quadrature-based systems and require offline measurements or nonlinear interactions - are straightforward in this time-frequency encoding. However, while modes entanglement in quadratures is deterministic, achieving time-frequency entanglement between single photons, a specific case of photon-photon entanglement, is notoriously challenging. More specifically, time-frequency entanglement gate has been shown [2] to be quartic in the bosonic creation and annihilation operators that is *a priori* complicated to carry out experimentally. Yet, time-frequency entanglement naturally arises in the photon pairs generated via spontaneous parametric down-conversion (SPDC) and spontaneous four-wave mixing (SFWM) in pumped nonlinear crystals. Nevertheless, these processes have significant drawbacks : (i) they are highly inefficient and not scalable for large-scale quantum protocols. (ii) they do not directly entangle preexisting photons but rather produce entangled pairs, preventing cascaded entanglement for cluster states. (iii) they also generate higher-order states and are thus imperfect sources of true frequency-correlated photon pairs. To circumvent these pitfalls, experimental [3] and theoretical [4] schemes have been investigated. Alushi *et al.* [4] investigated the time-frequency photon-pair correlations originating from a light-matter quadratic Hamiltonian. Their derivation was however based on a generic toy-model without taking into account the requirements of a specific system. We fill this gap by rigorously showing that in the adiabatic elimination limit, the light-matter interaction in the weak regime yields a genuine quadratic light-matter coupling between a QD and a waveguide continuum of modes (see Figure 1) of the same form as that of Alushi *et al.*. Using a Schmidt decomposition to analyze the continuous frequency entanglement, we further showcase a tradeoff between entanglement generation efficiency and entanglement quality (see Figure 2). We therefore consolidate a route for efficient entanglement of preexisting photons harnessing an effective non-linearity with no need of intense pump or postselection.

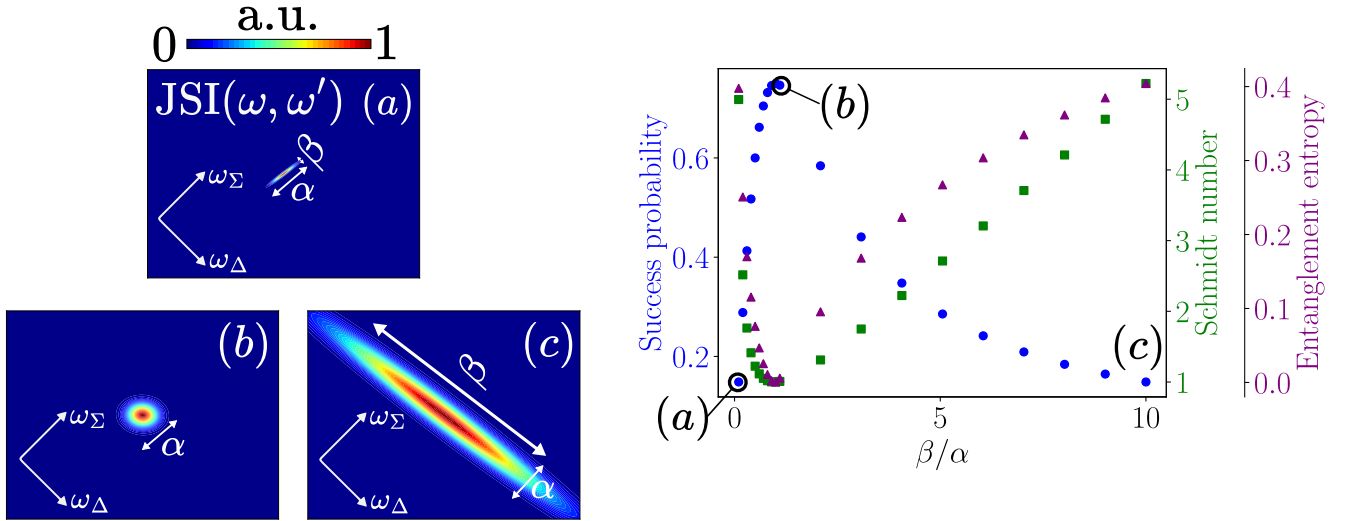


Figure 1: Trade-off between the probability of successfully outputting an entangled two-photon distribution and the quality of the entanglement measured with the Schmidt number and entanglement entropy with respect to the ratio  $\beta/\alpha$  of the Gaussian coupling term width  $\beta$  to the two-photon input width  $\alpha$ . The entanglement entropy is given with respect to its maximum value. The illustrative joint spectral intensities (JSIs) (panels (a), (b), (c)) are all on the same linear scale. The panel (a) depicts a regime where  $\beta \ll \alpha$  (frequency-anti-correlated photons), the panel (c) where  $\beta \gg \alpha$  (frequency-correlated photons) and the panel (b) where  $\beta = \alpha$  (no frequency correlations).

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## High $Q_i$ Tantalum for superconducting qubit implementation

F. D'Esposito, C. Mori, Lucas Ruela, G. Cappelli, S. Kumar, D. Nicolas, V. N.Suresh, W. Ardati, J.-S. Tettekpoe, E. Mossang, L-D. Simon, B. Fernandez, T. Crozes, N. Roch, Q. Ficheux, J. Renard, F. Rouxinol, W. Hash-Guichard, C. Naud, O. Buisson

Institut Néel, University Grenoble Alpes, CNRS, Grenoble INP, F-38000 Grenoble, France  
Gleb Wataghin Institute of Physic, State University of Campinas, 13082-859 Campinas, SP-Brazil

Superconducting qubits performance is limited by decoherence mechanisms such as dielectric losses. We are investigating a transmon molecule design featuring an original coupling mechanism that produces a non-perturbative cross-Kerr interaction between the qubit and the readout microwave cavity [1]. This setup has already achieved high readout fidelity (99.2% [2]) and long coherence times ( $T_1 \cong 120\mu s$ ,  $T_2 \cong 23\mu s$  [2]). Our current objective is to implement such a transmon molecule, utilizing tantalum capacitive pads in conjunction with aluminum junctions. Indeed, recent advancements suggest that tantalum (Ta) on sapphire substrates can significantly enhance qubit performance, achieving relaxation times ( $T_1$ ) in the millisecond range [3]. The tantalum film is grown on sapphire substrate using electron gun evaporation in an ultra-high vacuum chamber, with a static pressure of approximately  $10^{-10}$  mbar and a substrate temperature of  $400^\circ\text{C}$ . We employ a combination of characterization techniques including x-ray diffraction, atomic force microscopy (AFM), and resistance versus temperature ( $R(T)$ ) measurements, to assess the structural, surface, and superconducting properties of the Ta films. In order to evaluate microwave losses, we fabricated superconducting resonators. We measured quality factors ranging up to  $6 \times 10^6$  in the low photon number limit to more than 60 million at large power, placing our results close to the current state-of-the-art. I will present systematic measurements of the internal quality factor and resonance frequency as functions of temperature and microwave power, providing insights into dielectric losses and superconducting properties.

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## Hole Spin-Photon Coupling in Silicon and Germanium Double Quantum Dots

Ahmad Fouad Kalo<sup>1</sup>, Yann-Michel Niquet<sup>1</sup>, Esteban A. Rodriguez-Mena<sup>1</sup>, Michele Filippone<sup>1\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CEA, IRIG-MEM-L Sim, Grenoble, France.*

In recent years, there has been tremendous progress in systems capable of probing and harnessing spin degrees of freedom in solid-state environments. Notably, hybrid architectures have experimentally demonstrated the potential to strongly couple single photons confined in superconducting resonators with the spin of single electrons or holes in quantum dots. These experiments provide significant opportunities for the development of novel hybrid circuit Quantum Electrodynamics (cQED) architectures, where in photons can probe, entangle, and control the states of multiple spins. Here we model cQED systems comprising a silicon or germanium double quantum dot hosting a single hole and a resonator coupled to one of the dots, and assess the strength of spin-photon coupling. For that purpose, we devise a methodology to extract the relevant parameters of the double dot from numerical finite difference calculations (g-tensors, detuning, spin-conserving and spin-flipping tunnel couplings), and to tune the device to a suitable sweet spot. We analyze the physics of the spin-photon interactions in both materials. In planar germanium heterostructures, the spin-photon coupling is dominated by the difference between the g-tensors of the two dots due to the asymmetries and to the inhomogeneous cool-down strains in the system. Significant spin-photon couplings ( $> 100$  MHz) can be achieved for in-plane magnetic fields with a proper engineering of the devices. In silicon MOS devices, linear Rashba spin-orbit interactions may dominate spin-photon coupling for strongly squeezed dots, as shown experimentally.

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\* ahmad-fouad.kalo@cea.fr

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# Hybrid Algorithms for Dynamical Correlation Functions: A Sampling-Based Subspace Diagonalization Approach for Strongly Correlated Electron Systems

Nathan Moumigue,\* Thomas Ayrat, Corentin Bertrand, and Filippo Vicentini

Accurately computing dynamical correlation functions — such as the retarded Green’s function — is vital for understanding the properties of strongly correlated electron systems within embedding and dynamical mean-field approaches. This task, at zero temperature, require both a precise ground state approximation and a reliable method to time-evolve perturbed states.

On the one hand, existing classical algorithms — such as Density Matrix Renormalization Group (DMRG) for Matrix Product States (MPS) or Natural Gradient Descent (NGD) for Neural Quantum States (NQS) — can provide good approximations of ground states. However, simulating real-time dynamics is a hard classical task, especially on perturbed states, where e.g. the MPS simulation faces a quick entanglement growth with time and its associated increase in computational cost — via the bound dimension.

On the other hand, variational Quantum algorithms for ground state estimation seem to be doomed by Barren plateaus and decoherence. Inversely, entanglement growth during the time-evolution of perturbed states is naturally handled by quantum computers.

This poster introduces a sampling-based subspace diagonalization algorithm for computing retarded Green’s functions. The algorithm leverages a hybrid paradigm: the ground state is approximated classically, while the time evolution of selected Gaussian states is performed using quantum circuits. This strategy uses the respective strengths of both classical and quantum platforms.

*Detailed description* The conception of this algorithm has been inspired by the work in [2], where a sampling-based subspace diagonalization algorithm is used to approximate the ground state of a system by, starting from a reference state, sampling Gaussian states from Quantum Krylov states. Indeed, the approximated ground state is computed by diagonalizing exactly the Hamiltonian of the system in the subspace spanned by all the sampled Gaussian states. But this algorithm relies on the ability to prepare the initial reference state with a non-trivial overlap with the true ground state of the system on a quantum computer, which is known to be a difficult task.

In our algorithm, the ground state is computed classically — with DMRG for MPS or NGD for NQS — and expressed in its associated Natural Orbitals (NO) basis to improve its sparsity. Because we are interested in computing the retarded Green’s function, the approximated ground state is classically perturbed with a creation or an annihilation operator. Then, important Gaussian states in the perturbed state are individually loaded on quantum circuits and time-evolved for sampling new Gaussian states and defining a subspace in which the Hamiltonian of the system is projected and exactly diagonalized. An approximated Green’s function in the subspace of sampled Gaussian states is finally computed.

The Single Impurity Anderson Model is used as a benchmark model for this new numerical method. In [1], Bravyi & Gosset proven the exponential decay of the Natural Orbitals Occupation Numbers (NOONs), i.e. the few-body nature or the sparsity of the ground state of impurity models in their NO basis. This limits the number of initial Gaussian states to be individually loaded on quantum circuits and the overall cost of the method for impurity models.

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\* nathan.moumigue@eviden.com

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## Improving Quantum Memory Efficiency with Approximate Error Correction

Thibault Desrousseaux<sup>1,\*</sup>, Eva M. González-Ruiz<sup>1</sup>, Pierre Cussenot<sup>1,2</sup>, Audrey Bienfait<sup>3</sup>, and Nicolas Sangouard<sup>1</sup>

<sup>1</sup>*Université Paris–Saclay, CEA, CNRS, Institut de Physique Théorique, 91 191 Gif-sur-Yvette, France*

<sup>2</sup>*Direction Générale de l'Armement, 75 015 Paris, France*

<sup>3</sup>*Ecole Normale Supérieure de Lyon, CNRS, Laboratoire de Physique, F-69342 Lyon, France*

Quantum architectures that integrate quantum memories offer a scalable path to fault-tolerant quantum computing. By leveraging long-lived storage, they enable the execution of large-scale algorithms with processors that are several orders of magnitude smaller than those required in conventional processor-only architectures [1, 2]. In envisioned implementations, standard solid-state qubits – such as superconducting circuits or silicon spin qubits, which naturally couple to microwave photons – are interfaced with solid-state memories functioning as a microwave-photon qubit register, where the address of each qubit is identified by a temporal and a spatial index [3–5]. Photon-echo storage techniques are particularly promising, as they intrinsically provide large photon storage capacity [6], high efficiency [7–9], and long storage times [10, 11]. A central question in this context, and a crucial step toward fault tolerance, is how the processor can be exploited to actively enhance the performance of the memory. Here, we first identify the dominant source of noise in photon-echo techniques and show that it can be modeled as an amplitude-damping channel. We propose using the  $[[4,1,2]]$  Leung's code [12] to perform approximate quantum error correction of amplitude-damping and improve the memory efficiency and storage time. We suggest implementing error-correction-enhanced microwave storage using a four-transmon-qubit processor coupled to a solid-state memory based on a  $\text{CaWO}_4$  crystal doped with  $^{171}\text{Yb}^{3+}$  [11]. We demonstrate that approximate error correction beyond the break-even point is achievable, even when realistic noise sources in the processor are taken into account. This proposal paves the way for a short-term experimental demonstration of a quantum light storage improved with error correction.

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\* [thibault.desrousseaux@ipht.fr](mailto:thibault.desrousseaux@ipht.fr)



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# Systematic description of 1D interacting spin chain using phase-space and tensor networks methods

Christian de Correc,\* Denis Lacroix, and Corentin Bertrand

Quantum computer technologies have significantly progressed in the last decades, allowing for the simulation of more and more qubits. We have reached a milestone today where around a hundred noisy qubits can be manipulated to simulate complex systems. In this context, the parallel development of efficient classical computer methods to treat at least approximately huge Hilbert spaces is crucial both for (i) pushing the limits of today's more powerful classical computer capabilities and (ii) for providing benchmark comparisons with results obtained using novel quantum platforms. A good candidate of classical methods, although restricted to systems having low entanglement evolution, is tensor-network-based approaches, such as Matrix-Product States (MPS) [7]. Recently, following a technique developed previously in many-body systems [4], the Phase-Space Approximation (PSA) has been proposed as a way to simulate qubits entanglement, keeping the numerical cost extremely low compared to other classical computer techniques. The PSA is a technique to connect the quantum and classical worlds [1]. This method can also be used to map a quantum evolution into a statistical average of classical evolution. The approach of [4] has been exported with some success in Ref [3, 5] to describe neutrino oscillations on qubits, and more recently on qutrits [6]. Due to its polynomial computational cost, it has proved to be tractable even for several hundred neutrinos with accurate results (up to 300 qutrits equivalent to 450 qubits have been simulated so far). It has been successfully applied to many problems ranging from condensed matter, nuclear physics, and astrophysics. The PSA approach is not exact, and its predictive power still needs to be carefully analyzed against other classical computer approaches dedicated to a large number of qubits.

In this contribution, the PSA and tensor network (MPS) approximations are used to simulate 1D interacting spin chains. Specifically, we used the Ising model with  $k$  nearest neighbor interactions, with varying  $k$  from the nearest neighbor case (relevant for condensed matter [8]) to the all-to-all interaction case (relevant for nuclear physics [9]). We systematically analyze the predictive power of both approaches, also varying the interaction strength between spins, from the perturbative to the strong interaction regimes. We show that the PSA approach improves the mean-field picture by being able to describe accurately dissipative effects in one-body observables, regardless of the interaction strengths and types. However, although it improves in the limit of all-to-all interaction, it is not suitable for describing the entanglement entropy of a subsystem formed of more than one qubit. The MPS approach [2], depending on the bond dimension that is used, was also able to describe all types of entanglement, for all Hamiltonians, including the all-to-all case, provided that the entropy does not grow too fast as expected.

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\* c.de-correc@eviden.com

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## Interference in the double Kibble-Zurek mechanism

Francesco Poggio<sup>1</sup> and Kyrylo Snizhko<sup>1,2,3\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France*

<sup>2</sup>*Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, 76100 Israel*

<sup>3</sup>*Institute for Quantum Materials and Technologies, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany*

Quantum simulation of dynamical systems is one of the most promising directions for near-term quantum computing. Our aim is to investigate the crossing of a phase transition in the Ising chain on a Rydberg quantum simulator.

For a slow enough evolution, this is described by the Kibble-Zurek mechanism that predicts universal results linked to the critical indices of the phase transition. Due to technical reasons it is not possible to simulate the phase transition from Paramagnetic to Ferromagnetic state on this neutral atom platform. Previous works have overcome this difficulty by simulating a phase transition belonging to the same universality class [1].

Instead we propose to cross twice the phase transition, starting and finishing in the Ferromagnetic state. Preliminary numerical simulations showed us that the number of defects is independent by the direction of crossing the phase transition, therefore we would expect to double the density of defects in the adiabatic limit. Instead we find a more rich mechanism, the excited states generated by the first crossing accumulate a relative phase which causes interference during the second crossing.

By making use of the free fermions representation of the Ising chain we are able to average out the oscillations, but still the density of defects does not follow the expected behaviour. We are currently investigating the nature of the discrepancy between our first prediction and the numerical simulations.

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\* francesco.poggio@cea.fr

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# Noise tailoring for error mitigation and for diagnosing digital quantum computers

Thibault Scoquart<sup>1</sup>, Hugo Perrin<sup>2</sup>, and Kyrylo Snizkho<sup>3\*</sup>

<sup>1</sup>*Laboratoire de Physique Théorique, Université de Toulouse, CNRS, France*

<sup>2</sup>*University of Strasbourg and CNRS, CESQ and ISIS (UMR 7006), aQCess, Strasbourg, France*

<sup>3</sup>*Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France*

Error mitigation (EM) is essential for extracting reliable physics from noisy intermediate-scale quantum (NISQ) processors [1]. Popular EM techniques such as zero-noise extrapolation (ZNE) [2] work best when hardware noise matches simplified models (e.g. purely stochastic Pauli or depolarizing channels). In practice, device noise often departs from those assumptions, limiting EM efficacy.

In this work [3], we introduce *Noise Tailoring* (NT) : a sampling-based strategy that reshapes the effective noise on two-qubit gates to any arbitrary Pauli channel (typically depolarizing), thereby aligning hardware noise with the assumptions of a chosen EM protocol. Our workflow couples (i) randomized compiling (RC) to suppress coherent errors and convert raw gate noise into an effective Pauli channel [4, 5]; (ii) a lightweight Pauli noise tomography (PNT) to estimate local Pauli rates on each junction; and (iii) NT, which draws additional Pauli dressings so that averaging over the dressed circuit ensemble implements the target channel. In our implementation, NT is paired with noise estimation circuits (NEC) [6], an EM method previously validated by the present authors on NISQ hardware [5].

Two key features make NT practical. First, the target depolarizing strength on each junction is chosen to minimize the error-amplification factor  $\sigma = \gamma^{N_{\text{CNOT}}} / F_{\text{NEC}}$  (here  $\gamma$  is the NT sampling overhead per CNOT and  $F_{\text{NEC}}$  the NEC fidelity), balancing sampling cost against mitigation gain. Second, we deploy a crosstalk-aware variant (cRC + cNT) that includes nearest-neighbor couplings in the tomography and tailoring steps.

We benchmark NT on a three-qubit BCS-quench simulation at depths exceeding  $10^2$  CNOTs. Classical emulations using PNT-calibrated Pauli noise show that NT+NEC reduces the average error (over a set of local Pauli observables and times) by up to a factor  $\sim 5$  compared to NEC alone, with improvements attributable both to a moderate reduction of overall noise strength and, crucially, to *structural* homogenization into a depolarizing form. Hardware runs on IBM devices reveal that finite-sampling NT amplifies small non-Pauli contributions (e.g. residual coherent errors from incomplete RC, non-Markovian drift, and single-qubit noise), which can offset the mitigation gains at practical shot budgets. We show that this same sensitivity turns NT into a diagnostic : by contrasting classical and experimental traces and exploiting the  $\gamma^{N_{\text{CNOT}}}$  amplification, one can isolate and quantify coherent vs. stochastic components, providing guidance for hardware optimization.

Beyond NEC, NT is compatible with ZNE and other mitigation strategies that benefit from depolarizing models ; it also enables noise engineering, suggesting applications to the near-term simulation of open quantum systems where aligning device noise with a desired bath model is advantageous. Overall, NT offers a flexible bridge between characterization, mitigation, and benchmarking in the NISQ regime.

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\* thibault.scoquart@irsamc.ups-tlse.fr

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## Photon catalysis for general multimode multi-photon quantum state preparation

Andrei Aralov,<sup>\*</sup> Émilie Gillet, Mattia Walschaers,<sup>†</sup> and Massimo Frigerio<sup>‡</sup>  
*Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL,  
Collège de France, 4 place Jussieu, F-75252 Paris, France*

Viet Nguyen and Andrea Cosentino  
*Sorbonne Université, F-75006 Paris, France*

Multimode multiphoton states are at the center of many photonic quantum technologies, from photonic quantum computing to quantum sensing. In our work [1], we derive a procedure to generate exactly, and with a controlled number of steps, any such state using a bounded number of experimentally feasible optical operations, namely multiport interferometers, photon additions and photon-number-resolving (PNR) detectors. At variance with the previous attempts [2–4], our result is the first fully general and concise solution to this problem, allowing for precise estimation of the necessary resources – a task of practical significance that extends beyond quantum-state engineering.

Our approach draws an exceptional connection between ideas from quantum information theory and algebraic geometry, relying on established but previously unrelated correspondences: between quantum states and polynomials (via the stellar formalism), and between polynomials and tensors. This connection, beyond its application to our problem, opens a fertile and novel bridge between state engineering and algebraic methods: first, using Waring decomposition, we derive a general photon catalysis protocol that can be reinterpreted either as an instance of boson sampling or Gaussian boson sampling, depending on the concrete setup chosen to implement the photon additions; then, by invoking the Alexander-Hirschowitz theorem, we establish upper bounds on the number of required catalysis photons and Gaussian operations. Furthermore, we formulate a new tensor decomposition method leading to the optimal preparation protocol, for which the analytical solution is provided for general multimode 2-photon states. Finally, we note that this bridge extends beyond merely theoretical territories: on the one hand, transformations on polynomials map to experimentally accessible operations; on the other hand, existing numerical and symbolic tensor decomposition algorithms can be leveraged for computational purposes, which we confirm by a flexible implementation using JAX library.

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<sup>\*</sup> andrei.aralov@etu.sorbonne-universite.fr

<sup>†</sup> mattia.walschaers@lkb.upmc.fr

<sup>‡</sup> massimo.frigerio@lkb.upmc.fr

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## Plasma Modes in Fluxonium Qubits

Shelender Kumar<sup>1</sup>, Waël Ardati<sup>1</sup>, Dorian Nicolas<sup>1</sup>, Vishnu Narayanan Suresh<sup>1</sup>, Francesca D’Esposito<sup>1</sup>, Lucas Ruela<sup>1</sup>, Olivier Buisson<sup>1</sup>, Quentin Ficheux<sup>1</sup> and Nicolas Roch<sup>1\*</sup>

<sup>1</sup>*Institut Néel, CNRS 38042 Grenoble, France*

The fluxonium qubit [1], consisting of a small Josephson junction (JJ) shunted by a large inductance from a long junction array [2], combines long coherence times with strong anharmonicity. However, such arrays also introduce stray capacitances to ground. The interplay of stray capacitances with the inductance leads to collective excitations of the JJ array, known as plasma modes, whose frequencies decrease as the array size increases, thereby opening additional loss channels that limit coherence [3, 4]. To address this, we introduce a dry-etching step that removes silicon substrate around the fluxonium loop, reducing stray capacitance by 60–70%. This shifts plasma modes to higher frequencies while preserving qubit coherence, providing a simple route to engineer the electromagnetic environment of superconducting qubits.

To interpret our measurements, we developed a microscopic model of the fluxonium circuit and its electromagnetic environment. Following the approach of Nigg *et al.* [5] and Smith *et al.* [6], we compute the circuit’s linear admittance—using an ABCD-matrix description—to extract the resonance frequencies, impedances, and zero-point phase fluctuations of the plasma modes. These quantities are incorporated into the effective fluxonium Hamiltonian [5], enabling direct quantitative comparison with spectroscopy data. From this analysis, we extract key device parameters, including capacitances, inductances, and quality factors that identify microscopic loss channels.

Our framework captures the observed qubit–mode hybridization and avoided crossings, and links them directly to device parameters. By combining optimized fabrication with microscopic modeling, we establish a path to designing fluxonium qubits with engineered environments and reduced losses.

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\* shelender.kumar@neel.cnrs.fr

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## Quantum Maxwell Decoder for CSS codes

Bruno C. A. Freire<sup>1,2</sup>, François-Marie Le Régent<sup>2</sup>, and Anthony Leverrier<sup>1\*</sup>

<sup>1</sup>*Inria Paris, COSMIQ, 48 Rue Barrault 75013 Paris, France*

<sup>2</sup>*Pasqal, 28 Av. Émile Baudot, 91120 Palaiseau, France*

In quantum computing, quantum error correction techniques are essential to render quantum systems sufficiently robust to noise and capable of performing useful digital algorithms. One particularly simplified and widely studied noise model is the quantum erasure channel [1], in which qubits can independently at random be sent to the maximally-mixed state, undergoing a random Pauli error to be determined upon syndrome measurement, and with the decoder being aware of the erasure positions. Although simplified, the erasure channel provides valuable insights for analyzing the performance of quantum codes and decoding algorithms, which can prove useful for more realistic noise models. Moreover, some physical platforms can transform their native errors into erasures [2], which greatly simplifies the task of syndrome decoding.

In both the classical and quantum settings, the erasure decoding problem admits a maximum-likelihood decoder based on Gaussian elimination. However, its cubic complexity becomes prohibitive for large systems, and the same approach is not applicable to more realistic channels, which has motivated the development of iterative decoding algorithms with lower computational complexity at the expense of some loss in decoding performance. Among those are message-passing algorithms such as belief propagation (BP), which has many variations and can be applied to different noise models, including in the quantum setting. For the erasure channel, the simplest form of BP is the peeling decoder.

The peeling decoder iteratively solves a linear system by solving equations with a single unknown variable, potentially giving rise to new single-variable equations, until it completely solves the erasure or reaches a stopping set, for which no such single-variable equations remain. In the context of classical LDPC codes, the peeling decoder performs well [3], but in the quantum setting the very presence of low-weight stabilizers hinders its performance by inducing small stopping sets.

To counter this issue, peeling variants such as pruning [4] were proposed, along with BP variants such as BP with Guided Decimation [5]. Building on the idea of the VH decoder introduced in [4] for HGP codes, the cluster peeling decoder was proposed in [6] generalizing the idea to the broader class of CSS codes, and providing a mechanism to balance runtime complexity and decoding performance by tuning a parameter.

In a similar fashion, this work aims to adapt the Maxwell decoder [7] to the quantum CSS case, by introducing guessing mechanisms to the peeling and pruned-peeling decoders. The resulting decoder attains maximum likelihood performance, with complexity no larger than that of Gaussian elimination. By limiting the number of available guesses, one can obtain a linear time decoder, in exchange for some of the decoding performance.

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\* bruno.costa-alves-freire@inria.fr

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## Robust Optimal Control for a Two-Level System using GRAPE

Mohammed Bilal<sup>1,\*</sup>, Camille L. Latune<sup>1</sup>, and Dominique Sugny<sup>1</sup>

<sup>1</sup>*Université Bourgogne Franche-Comté, CNRS, Laboratoire Interdisciplinaire  
Carnot de Bourgogne (ICB) UMR 6303, F-21000 Dijon, France\**

The precise control of quantum systems is crucial for advancing quantum technologies. However, practical implementations often suffer from uncertainties in system parameters, which can degrade control performance. Additionally, energy cost of quantum technologies is a matter of increasing importance, which naturally leads to the question of energy cost of quantum control. To address these challenges, we investigate how to design control protocols which are energetically efficient and which remain effective in the presence of small perturbations.

We consider a two-level quantum system and formulate the control problem using the Pontryagin Maximum Principle (PMP) [1]. To solve it, we apply the GRAPE algorithm—a gradient-based numerical method—to optimize the control field that drives the system from a chosen initial state to a desired target state. Robustness is ensured by modeling an ensemble of systems with small variations in a key Hamiltonian parameter, and the control field is optimized to maximize the average fidelity across the ensemble while simultaneously minimizing its energy cost.

Our results demonstrate that high-fidelity quantum control can be achieved despite parameter uncertainties, and at a lower energy cost when compared to standard methods like STA (shortcut-to-adiabaticity). We also observe a trade-off between robustness and energy cost, which can be adjusted based on the needs of specific applications. This framework opens pathways for robust control in more complex systems and with alternative optimization techniques.

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\* mohammed-bilal\_puthuvedu-shebeek@u-bourgogne.fr

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## Robust Quantum Optimal Control in a Two-Level System

O. Fresse-Colson<sup>1</sup>, C. Babin<sup>1</sup>, D. Sugny<sup>1\*</sup>

<sup>1</sup>*Laboratoire Interdisciplinaire Carnot de Bourgogne,  
CNRS UMR 6303, Université Bourgogne Europe,  
BP 47870, F-21078 Dijon, France*

Quantum Optimal Control (QOC) [1] is a powerful framework to design tailored control fields that steer quantum systems efficiently while minimizing cost functions such as operation time and infidelity. These optimized controls enable high-fidelity operations that are robust against common experimental imperfections, including decoherence from environmental coupling [2, 3]. Thus, the development of this toolkit is a requirement for large-scale industry-ready quantum technologies.

The optimal control fields obtained however can vary greatly depending on the system parameters (energy levels, coupling strength, etc.). Experimentally, those parameters are known up to a given precision and fluctuate over time. To circumvent this limitation, and obtain experimental-compatible control fields, robustness conditions can be introduced in the formulation of the QOC. In that case, the control field steers the studied system with a high fidelity despite small perturbations in the system parameters.

In our proof-of-concept study, we focus on a two-level quantum system including a static fluctuation on the driving field power. We solved analytically the robust optimal control problem in terms of Jacobi integrals and elliptic functions, up to one free parameter that can be found numerically [4]. This greatly reduces the complexity of the original analytical problem, with a qualitative understanding of the robust control problem.

Those advancements can be directly applied to state-of-the-art quantum system such as the NV center in diamond [5], a promising platform for advanced quantum information processing [6–9]. As a preliminary demonstration, we apply standard quantum optimal control techniques to multi-spin systems –here two coupled spins– and report performance that significantly surpasses conventional Rabi-based protocols in both speed and fidelity. These results highlight the essential role of optimal quantum control in advancing spin-based architectures toward large-scale quantum technologies.

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\* dominique.sugny@u-bourgogne.fr



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## Strategies for new-generation ion trap devices dedicated to quantum computing

Sacha Guesne<sup>1,2,\*</sup>, Luca Guidoni<sup>2</sup>, and Quentin Bodart<sup>1</sup>

<sup>1</sup>*Crystal Quantum Computing SAS, Incubateur Télécom Paris, 9 rue Dareau, 75014 Paris, France*

<sup>2</sup>*Laboratoire Matériaux et Phénomènes Quantiques, Université Paris-Cité-CNRS, 10 rue A. Domon et L. Duquet, 75013 Paris, France*

Trapped-ion platforms are leading-edge technologies for various applications in the quantum field, such as optical atomic clocks [1] and quantum information processing devices [2]. They are also used to study fundamental aspects of quantum physics, such as high-precision spectroscopy [3] or sympathetic cooling [4], which have applications for antimatter studies [5]. Trapped-ion based qubits offer long coherence times and high-fidelity gates [6], which are advantageous for the development of large-scale quantum computers. One of the remaining challenges for the trapped-ion platform is achieving high-fidelity entanglement and precise control of qubits as their number grows. To tackle this challenge, several developments are being implemented : including the integration of photonic circuits into ion surface traps in order to steer all the laser beams required for the preparation, control and detection of individual qubits [7]. On the qubit connectivity side, two-dimensional ion trap arrays could implement the so-called QCCD architecture [8]. .

We will present the investigation of some of these strategies in the frame of our project aiming at the building of a universal quantum computer based on dipolar Rydberg interaction gates. This type of quantum gate benefits from a sub-microsecond gate time, which makes it among the fastest gates realized in trapped-ion systems [9]. Despite a relatively low two-qubit gate fidelity, experimental improvements are expected to reduce the two-qubit gate error to 0.19 % [9], making this system a strong candidate for the realization of an universal trapped-ion quantum computer. We will discuss how to build a new-generation trap suitable for a large-scale quantum computer, by incorporating most of the optical beam steering into integrated photonic circuits and expanding the number of entanglement zones within a surface Paul trap. State-of-the-art integrated photonic circuit enable the propagation of the wavelengths required for the preparation, 1-qubit gate and detection of Sr88+ ions using Si3N4-based waveguides [7]. Furthermore, to expand the number of entanglement zones in a single device, we will discuss the assests of the trap designs for the implementation of QCCD architecture through an adiabatic transport protocol. [10]

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\* sacha.guesne@etu.u-paris.fr

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## Theory of Multi-photon Processes for Applications in Quantum Control

Longxiang Huang<sup>1,2</sup>, Jacquelin Luneau<sup>1,2,3</sup>, Johannes Schirk<sup>1,2</sup>, Florian Wallner<sup>1,2</sup>,  
Christian M. F. Schneider<sup>1,2</sup>, Stefan Filipp<sup>1,2,3</sup>, Klaus Liegener<sup>1</sup>, and Peter Rabl<sup>1,2,3\*</sup>

<sup>1</sup>*Technical University of Munich, TUM School of Natural Sciences, Department of Physics, 85748 Garching, Germany*

<sup>2</sup>*Walther-Meissner-Institute, Walther-Meissner-Strasse 8, 85748 Garching, Germany*

<sup>3</sup>*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*

Multi-photon processes in periodically driven quantum systems have been identified as a versatile tool for engineering and controlling nontrivial interactions in various quantum technology platforms. Compared to resonant control, they offer the advantage that novel effective interactions can be mediated via the virtual population of other off-resonant states, and also that the control frequency can be far removed from the relevant system frequencies. This crucial feature breaks the usual trade-off between the ability to apply fast control operations and the requirement to shield the quantum system from its environment. For example, in Ref. [1], a subharmonic driving scheme was used to induce Rabi oscillations between two states of a heavily shielded fluxonium qubit, by applying a control signal at only one-third to one-eleventh of the qubit's transition frequency.

We present a general theoretical framework for evaluating multi-photon processes in periodically driven quantum systems [2]. While in many use cases, the effective dynamics that is generated by a periodic modulation can already be well approximated by second-order perturbation theory, this is clearly no longer possible for the higher-order processes mentioned above. To achieve the accuracy required for such applications, the resulting effective coupling rates, as well as any drive-induced frequency shifts, must be determined with very high precision. Here, we employ degenerate Floquet perturbation theory together with a diagrammatic representation of multi-photon processes to develop a systematic and automatable approach for evaluating the effective dynamics of driven quantum systems to arbitrary orders in the drive strength. We provide a sample Python code that automates the evaluation of higher-order processes for arbitrary system Hamiltonians and perturbation operators [3].

As a specific example, we demonstrate the effectiveness of this framework by applying it to the study of multi-photon Rabi oscillations in a superconducting fluxonium qubit, finding excellent agreement between our theoretical predictions and exact numerical simulations, even in parameter regimes where previously known methods are no longer applicable.

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\* jacquelin.luneau@wmi.badw.de

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## Towards a measurement based model of computation for electronic flying qubits

Thomas Perez\*

INRIA, LIX, CPHT, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

In his book *Understanding Quantum Technologies*, Ezratty [9] identifies nine categories of *quantum objects* used to implement quantum hardware, grouped into three families : *atomic systems*, *electrons and microwave cavities*, and *flying carriers*. Atomic platforms (ions, neutral atoms, Rydberg arrays) exploit laser-controlled interactions for high-fidelity gates, while electrons and microwave cavities encompass superconducting circuits, spin qubits, and hybrid cavity-QED setups.

*Flying carriers* include photons and electrons propagating in guided structures. In photonic platforms—considered serious candidates for scalable quantum computing [15]—photons act as mobile qubits that can be easily routed, entangled via beam splitters, and locally measured. Their mobility naturally supports quantum communication and distributed computation. To exploit these features, an alternative to the circuit model, *Measurement-Based Quantum Computing* (MBQC) [14], performs computation through adaptive measurements on pre-entangled cluster states. *Diagrammatic calculi* such as the ZX-calculus [5, 11] offer a formal tool for translating between MBQC and circuits, and clarify the correction protocols ensuring determinism [1]. They also apply to fusion-measurement schemes for fault-tolerant photonic architectures [7].

A resembling scenario emerges with *electronic flying qubits* [8], where information is carried by fermions whose antisymmetric statistics demand a shift from bosonic to fermionic computation. Following Lloyd’s early ideas of *unconventional devices* [13] and the resulting *Local Fermionic Mode* model of Bravyi and Kitaev [2], fermionic circuits can be given a universal gate set. Building on the ZW-calculus [4, 10], de Felice et al. introduced a diagrammatical calculus for LFM circuits [6]. More recently, Carette et al. gave an axiomatisation of a fragment of this calculus encapsulating *matchgate circuits* [3], which are known to correspond to *local fermionic optics* (LFO) [12]. As the one-way model of MBQC is particularly well-suited to photonic computing, it is natural to wonder whether a similar model could be developed for fermions. In this poster, we investigate how such diagrammatic tools could lead to a measurement-based framework for fermionic flying qubits.

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\* [thomas.perez@inria.fr](mailto:thomas.perez@inria.fr)

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## Towards a quantum Kapitza pendulum with voltage-biased Josephson junctions

Jean-Samuel Tettekpoe<sup>1</sup>, Samuel Cailleaux<sup>2</sup>, Anas Chadli<sup>1</sup>, Olivier Buisson<sup>1</sup>, Wiebke Hasch-Guichard<sup>1</sup>, Julien Renard<sup>1</sup>, Denis M. Basko<sup>3</sup>, Nicolas Roch<sup>1</sup>, and Quentin Ficheux<sup>1\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France,*

<sup>2</sup>*Laboratoire de Physique de l'École Normale Supérieure,*

*ENS-PSL, CNRS, Sorbonne Université, Université Paris Cité,*

*Centre Automatique et Systèmes, Mines Paris, Université PSL, Inria, Paris, France,*

<sup>3</sup>*Univ. Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France*

Creating protected superconducting qubits is essential for building a quantum computer with limited resources. This can be achieved by exploiting a symmetry in the system [1] and encoding the  $|0\rangle$  and  $|1\rangle$  wavefunctions in different parities. An example is known as the  $\cos 2\hat{\phi}$  protected qubit [2], which exploits the parity of the number of Cooper pairs on a superconducting island. This qubit is the quantum version of the Kapitza pendulum [3], and can be viewed as an oscillator with two stable positions. Various implementations of this qubit have been proposed and realized [4–9]; however, while very exciting, their performances are inherently limited for reasons I will discuss.

Here I propose a novel approach using two voltage-biased Josephson junctions connected to a single superconducting island, which forms a pure  $\cos 2\hat{\phi}$  element robust against disorder and insensitive to flux. I will discuss our progress towards its implementation and the impact of voltage noise. Our proposal shows an alternative approach to qubit protection that circumvents the usual limitations.

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\* jean-samuel.tettekpoe@neel.cnrs.fr

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## Towards microwave-activated Controlled-Z gate with Fluxonium

Dorian Nicolas, Vishnu Narayanan Suresh, Shelender Kumar, Waël Ardati, Supriya Mandal, Francesca D’Esposito, Jean-Samuel Tettepoe, Cyril Mori, Olivier Buisson, Nicolas Roch, Quentin Ficheux  
*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, Grenoble, France*

Recently, the Fluxonium [1] has emerged as a promising superconducting qubit due to high coherence times achieving the millisecond [2, 3] and by the demonstration of high-fidelity single-qubit [2] and two-qubits gates [3–6]. However, the mitigation of the residual qubit-qubit interaction remains an important challenge. Dynamical control of the residual interaction is usually achieved via tunable-coupling elements [3] but the high anharmonicity of the Fluxonium allows for a coupler-free approach where microwaves tones are used to leverage the AC Stark shift and effectively suppress the qubit-qubit coupling. This effect can also be used to increase the interaction naturally implementing a Controlled-Z (CZ) gate [5, 6]. The present project aims at investigating the scalability of this approach in a three-Fluxonium architecture. As for now, we have characterized a device hosting two-capacitively coupled Fluxonium qubits. The qubits have demonstrated relaxation times  $T_1 = 16.03 \mu s$ , Ramsey decoherence time  $T_2^R = 9.4 \mu s$  and Echo decoherence time  $T_2^R = 9.07 \mu s$ . Individual single qubit randomized benchmarking have also been performed showing an average physical single-qubit gate fidelity of  $F = 99.1 \%$ . Additionally, we measured a qubit-qubit interaction rate of  $\eta_{ZZ} = 0.507$  MHz and we have shown that driving the system close to the  $|00\rangle - |30\rangle$  transition suppresses the interaction rate below  $\eta_{ZZ}^{\min} = 110$  kHz while driving it close to the  $|10\rangle - |20\rangle$  and  $|01\rangle - |02\rangle$  transitions was resulting in a coupling  $\eta_{ZZ} = 7.277$  MHz.

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# Towards Quantum Energetic Advantage in Boson Sampling

Ariane Soret<sup>†\*</sup>, Nessim Dridi<sup>†,‡</sup>, Stephen C. Wein<sup>†</sup>, Valérian Giesz<sup>†</sup>, Shane Mansfield<sup>†</sup>, Pierre-Emmanuel Emeriau<sup>†</sup>

<sup>†</sup> *Quandela SAS, 7 Rue Léonard de Vinci, 91300 Massy, France*

<sup>‡</sup> *Eidgenössische Technische Hochschule Zürich,  
Rämistrasse 101, 8092 Zürich, Switzerland*

<sup>\*</sup> *ariane.soret@quandela.com*

Understanding the energetic efficiency of quantum computers is essential for their scalability and implementation. While the computational advantage of quantum computers has been widely studied and has motivated their development, the concept of a quantum energetic advantage—where a quantum computer completes tasks using less energy than the best classical counterparts—has recently emerged, adding a new layer of motivation for advancing quantum technologies [1].

In this work, we examine the energy cost required by a photonic quantum computer to solve the boson sampling problem. Boson sampling involves generating samples from the output distribution of indistinguishable photons passing through a linear optical network – a problem that quickly becomes intractable for classical computers, and showcases a quantum computational advantage. Using the Metric-Noise-Resource (MNR) framework – a systematic approach to quantify and optimize resource consumption of quantum devices [1] – we identify the control parameters, performance metric, noise processes and resource consumption of the problem, and perform a quantitative analysis of the trade-off between the quality and quantity of the photons. Moreover, we compare the energetic cost per sample for classical and quantum implementations, see Fig.1. Using state of the art classical algorithms [2] and supercomputers [3] as a baseline for classical energy consumption, we show the existence of a quantum energetic advantage of photonic computers for boson sampling, even before the regime of computational advantage (grey area in Figs. 1 and 2). In addition, we compare the energetic cost of generating samples for Boson Sampling with samples from Random Circuit Sampling – a sampling task showcasing a quantum advantage for gate-based quantum computers – and we find that photonic computers are more energy efficient than superconducting computers for these tasks.

This study underscores the importance of integrating energy efficiency into the design of quantum technologies. Demonstrating the potential for a quantum energetic advantage in boson sampling extends the value of quantum computation beyond mere speed-up, emphasizing energy efficiency as a critical factor in the future of scalable quantum systems. As quantum devices evolve toward practical applications, energy considerations should play a pivotal role in their development and optimization.

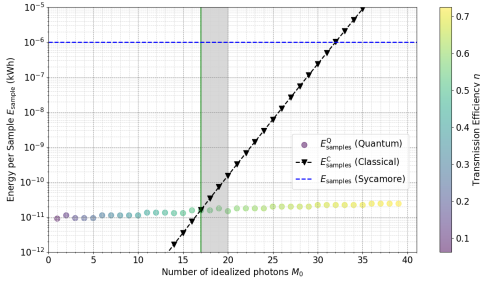


FIGURE 1 – Energy per sample for quantum ( $E_{\text{samples}}^Q$ ) and classical ( $E_{\text{samples}}^C$ ) computers as a function of the number of idealized photons  $M_0$ . The quantum energy per sample points are colored according to the transmission efficiency, as indicated by the color bar. The horizontal blue line is the energy consumed by the Sycamore processor to produce one random circuit sample [4].

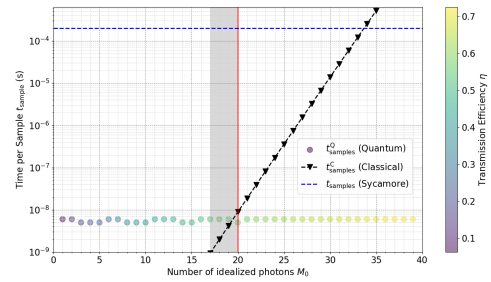


FIGURE 2 – Time per sample for the quantum ( $t_{\text{samples}}^Q$ ) and classical ( $t_{\text{samples}}^C$ ) computers. The gray area shows the regime where the photonic quantum computer is slower but more energy efficient than the classical one.

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## Trapped and cooled $^{88}\text{Sr}^+$ ions in a cylindrical potential provided by a micro-fabricated ring trap

L. Gros-Désormeaux<sup>1</sup>, J.-P. Likforman<sup>1</sup>, L. Guidoni<sup>1</sup>, P. Zhao<sup>2</sup>, Y. D. Lim<sup>2</sup>, C. S. Tan<sup>2</sup>, and H. Y. Li<sup>3\*</sup>

<sup>1</sup>*Laboratoire Matériaux et Phénomènes Quantiques, Université Paris-Cité / CNRS, F-75013 Paris, France*

<sup>2</sup>*Nanyang Technological University, Singapore 639798*

<sup>3</sup>*Institute of Microelectronics, Agency for Science, Technology and Research (A\*STAR), Singapore 117685*

Laser-cooled trapped ions platform is one of the best candidates for the development of future quantum computing. This has generated a major worldwide research effort aimed at scaling and integrating trapping devices. As part of this effort, we are developing miniature atomic ion traps in the laboratory : Paul linear surface traps manufactured in collaboration with Nanyang Technology University and the Microelectronics Institute of Singapore. An original feature of the manufacturing process is that all the electrical contacts of the trap electrodes are made through the Silicon substrate (TSV : through silicon vias). In this way, the wire-bondings usually soldered directly to the electrodes can be offset or completely eliminated [1]. This opens the way to complex architectures, in particular cylindrically symmetrical ring traps, which cannot be made with surface connections that would break the desired symmetry.

The trapping and laser cooling of ions in cylindrically symmetrical linear Paul traps (called "ion storage rings" in their macroscopic version, diameters of around 100 mm) was demonstrated in pioneering work at Garching [2] and subsequently extended to microfabricated traps (multilayer technology) at Sandia National Labs (diameter 2.5 mm) [3] and Berkeley (diameter 95  $\mu\text{m}$ ) [4]. These devices are of interest because, in the absence of defects, they enable rotational symmetry for the trapped ions and thus periodic boundary conditions for the confined cold ion system (Coulomb crystal). They are also candidates for observing and manipulating the rotational quantum state of trapped ion ensembles [4].

We will present our latest results concerning the performance of TSV surface ring traps (diameters between 150 and 210  $\mu\text{m}$ ) manufactured in Singapore. In particular, we loaded these traps with Doppler-cooled  $^{88}\text{Sr}^+$  ions (from a single ion to several hundreds). Laser cooling and image acquisition enable us to estimate the defects of the trapping potential with respect to perfect rotational symmetry. The application of DC voltages to a set of segmented electrodes then makes it possible to compensate for most of these defects, which nevertheless remain the major problem to be solved in order to achieve sub milikelvin free motion.

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\* lilay.gros-desormeaux@etu.u-paris.fr



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# Unifying Floquet Theory of Longitudinal and Dispersive Readout

Alessandro Chessari<sup>1</sup>

<sup>1</sup>*Université Grenoble Alpes,  
IRIG-MEM-L\_Sim, 38000 Grenoble, France*

In the context of circuit quantum electrodynamics (cQED), fast qubit measurements rely on the mechanism of dispersive readout [1, 2] : a transverse interaction between the two lowest levels of a superconducting artificial atom and a resonator shifts the frequency of the resonator, enabling quantum non-demolition (QND) measurements. Recently, a longitudinal interaction had been proposed as a way to perform faster-than-dispersive measurements [3].

Longitudinal interactions have been demonstrated across platforms ranging from superconducting qubits to quantum dots, and rely on driving the qubit at the resonator frequency. In different regimes, the coupling emerges parametrically in the drive strength, allowing to increasing its strength increasing the drive strength. However, existing theories rely on small-drive approximations, leaving open the question of whether this parametric scaling persists at strong drive.

Such a situation calls for a unified description, embracing different devices and regimes. We devise a Floquet theory [4] to establish a universal connection between AC Stark shift, longitudinal coupling and dispersive readout in cQED. We find that an effective longitudinal interaction arises from the slope of the Floquet spectrum while a dispersive shift arises from the curvature.

We derive semi-analytical results supported by exact numerical calculations, which we apply to superconducting and spin cQED settings, providing a unifying, seamless and simple description of longitudinal and dispersive readout in generic cQED systems.

Our approach unifies the adiabatic limit, where the cavity dynamics is so slow that the longitudinal coupling results from the static spectrum curvature, with the diabatic one, where the static spectrum plays no role. We find that the parametric regime breaks down at strong drive, where it overestimates the longitudinal coupling emerging from the Floquet spectrum. In particular, we find sudden degradations of the readout at very particular frequencies in the adiabatic regime. These arise from anticrossings in the Floquet spectrum due to couplings between distant replicas in the Floquet spectrum which causes the suppression of the longitudinal coupling. On the other hand, these suppressions are absent in the diabatic regime, where higher replica processes at strong drives play no roles.

We have already experimentally demonstrated the breakdown of the parametric regime in a two-level quantum dot charge qubit [5] and we plan to investigate spin-qubit architectures where strong spin-photon coupling enables an experimental realization of our theory [6].

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## Using Bifluxon tunneling to protect the fluxonium qubit

Wael Ardati,<sup>\*</sup> Shelender Kumar, Vishnu Narayanan Suresh, Dorian Nicolas, Cyril Mori, Francesca D'Esposito, Olivier Buisson, Quentin Ficheux,<sup>†</sup> and Nicolas Roch<sup>‡</sup>  
*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*

Sébastien Léger

*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*

Encoding quantum information in quantum states with disjoint wave-function support and noise insensitive energies is the key behind the idea of qubit protection. While fully protected qubits are expected to offer exponential protection against both energy relaxation and pure dephasing, simpler circuits may grant partial protection with currently achievable parameters. Here, we study a fluxonium circuit in which the wave-functions are engineered to minimize their overlap while benefiting from a first-order-insensitive flux sweet spot. Taking advantage of a large superinductance ( $L \sim 1 \mu\text{H}$ ), our circuit incorporates a resonant tunneling mechanism at zero external flux that couples states with the same fluxon parity, thus enabling bifluxon tunneling. The states  $|0\rangle$  and  $|1\rangle$  are encoded in wave-functions with parities 0 and 1, respectively, ensuring a minimal form of protection against relaxation. Two-tone spectroscopy reveals the energy level structure of the circuit and the presence of  $4\pi$  quantum-phase slips between different potential wells corresponding to  $m = \pm 1$  fluxons, which can be precisely described by a simple fluxonium Hamiltonian or by an effective bifluxon Hamiltonian. Despite suboptimal fabrication, the measured relaxation ( $T_1 = 177 \pm 3 \mu\text{s}$ ) and dephasing ( $T_2^E = 75 \pm 5 \mu\text{s}$ ) times not only demonstrate the relevance of our approach but also opens an alternative direction towards quantum computing using partially-protected fluxonium qubits.

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<sup>\*</sup> wael.ardati@neel.cnrs.fr

<sup>†</sup> quentin.ficheux@neel.cnrs.fr

<sup>‡</sup> nicolas.roch@neel.cnrs.fr

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## A new interconnection platform for neutral atom arrays

Yi Li,\* Sébastien Garcia, and Alexei Ourjoumtsev

*JEIP, Collège de France, PSL University, 11 Place Marcelin Berthelot 75231 Paris, France*

Advances in the manipulation of arrays of individual Rydberg atoms have demonstrated the potential of the latter for quantum information[1]. However, actual applications in quantum computing will require millions of logical qubits, themselves encoded on tenths of single atoms. The number of atoms in a single array will reach a limit (on the order of  $10^4$ ), defined by the available laser power, the field of view offered by high-NA optics or the resolution of spatial light modulators defining the geometry of the array. This limit calls for the development of distributed quantum processing, which requires quantum interconnections. Our proposal for this necessary development is a platform that will allow the connection of atomic processors through an intracavity Rydberg superatom.

By coupling an atomic cloud to a medium-finesse cavity and driving it to a highly excited state, we can achieve a collective two-level system called a superatom [2]. The main advantage of such a platform is that the collective coupling of the atomic cloud to the cavity bypasses the challenges for a high-finesse cavity and the high sensitivity of Rydbergs atoms to nearby dielectric surfaces. In our group, the coherent mapping of the state of the superatom onto a free-propagating photonic qubit has been demonstrated [3].

Building on this scheme, we propose trapping an array of atoms, via optical tweezers, next to the atomic cloud within the cavity mode. The aim is to entangle the individual atom with the superatom, then map the superatom onto a free-propagating light mode. This will result in an entangled single-atom single-photon state, forming a building block to distribute entanglement between distant single-atom arrays.

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\* yi.li@college-de-france.fr

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# Quantum Hydrodynamics with paraxial fluid of light in hot atomic vapor

Quentin Glorieux<sup>\*1</sup>

<sup>1</sup>Laboratoire Kastler Brossel (LKB (Jussieu)) – École normale supérieure - Paris, Université Pierre et Marie Curie - Paris 6, Centre National de la Recherche Scientifique : UMR8552 – Case 74 - Tour 12, 4 place Jussieu, F-75252 Paris CEDEX 05, France

## Abstract

An emerging topic in modern quantum optics is the study of light as a many-body system. When photons acquire an effective mass (in cavities or in paraxial geometries), and interactions through the presence nonlinear media, they display collective behaviors similar to those of quantum fluids. This perspective has given rise to two complementary approaches: microcavity polaritons and paraxial propagation in nonlinear media. Building on a long tradition of quantum optics at LKB, I will review some landmark achievements of the paraxial fluids of light platform (1): from the observation of superfluidity (2) and solitons (3) to analog models of out-of-equilibrium phase transitions (4). I will then focus on recent works with rubidium vapors, where we study turbulent dynamics (5), dispersive shock waves and Bose-Bose mixture (6).

Future works about the generation of a macroscopic states of Mott insulator of light will be presented as an outlook for the field.

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<sup>\*</sup>Speaker

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Spin and density modes in a binary fluid of light  
Physical Review Letters 134 (22), 223403 (2025)

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# Variational Quantum Subspace Construction via Symmetry-Preserving Cost Functions

Alexandre Perrin<sup>1</sup>, Hamzat A. Akande<sup>2,3</sup>, Bruno Senjean<sup>3</sup> and Matthieu Saubanère<sup>1\*</sup>

<sup>1</sup>*Université de Bordeaux, CNRS, LOMA, UMR 5798, F-33400 Talence, France*

<sup>2</sup>*ICTP-East African Institute for Fundamental Research, University of Rwanda, Kigali, Rwanda*

<sup>3</sup>*ICGM, Univ Montpellier, CNRS, ENSCM, Montpellier, France*

The accurate determination of low-energy eigenstates in strongly correlated quantum systems is a long-standing challenge in quantum chemistry and condensed matter physics, as classical methods face exponential scaling with system size. Hybrid quantum-classical strategies have emerged as practical alternatives for noisy intermediate-scale quantum (NISQ) devices, but they often suffer from either deep circuit requirements or large measurement overheads. In this work, we introduce the Variational Quantum Subspace Method (VQSM), a variational approach that combines the efficiency of symmetry-preserving cost functions with the robustness of subspace diagonalization. The method iteratively generates variational trial states that span an orthonormal reduced subspace, within which the Hamiltonian is classically diagonalized to extract ground and low-lying excited-state properties. By construction, the symmetry-preserving cost functions ensure that only states within the targeted quantum-number sector contribute to the optimization, allowing the use of shallow hardware-efficient ansätze without sacrificing accuracy. Furthermore, the iterative subspace expansion naturally leads to a tridiagonal structure reminiscent of Lanczos-based approaches, enabling fast geometric convergence toward the dominant eigenvalues.

We benchmark the VQSM on hydrogen chain and ring systems ( $H_4$ ), demonstrating that chemical accuracy is achieved with very shallow circuits and a limited number of iterations. Beyond ground-state energies, the method also provides reliable estimates of excited-state observables, including charge and spin gaps, thereby extending its applicability to spectroscopic and correlation-driven phenomena. Importantly, the algorithm exhibits enhanced resilience to noise compared to standard variational approaches, owing to the explicit subspace construction and the reduced depth of the quantum circuits. These results establish VQSM as a versatile and scalable variational framework that bridges the gap between current NISQ capabilities and the long-term goal of accurate quantum simulations of many-body systems. [1]

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\* alexandre.perrin.1@u-bordeaux.fr

# A Generalized Framework for Hong-Ou-Mandel Interferometry and its Applications to Quantum Metrology

Eloi Descamps<sup>1</sup>, A. Keller<sup>1,2</sup>, P. Milman<sup>1\*</sup>

<sup>1</sup>Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Cité, CNRS UMR 7162, 75013, Paris, France

<sup>2</sup>Département de Physique, Université Paris-Saclay, 91405 Orsay Cedex, France

The Hong-Ou-Mandel (HOM) effect, originally observed as a two-photon interference phenomenon, has proven to be a cornerstone in quantum optics and an insightful tool in quantum metrology. While numerous extensions of the HOM effect have been proposed, they often lack a unified theoretical perspective that accounts for their metrological implications. In this work, we present a comprehensive and hierarchical framework that generalizes the HOM effect and systematically connects it to precision measurement.

Our approach is built upon the central idea that the symmetry of the input quantum state under the exchange of spatial modes is the fundamental feature underlying HOM interference [1]. Starting from this principle, we first revisit the standard two-photon HOM effect and extend the concept to multi-photon scenarios. We demonstrate that by characterizing the symmetry properties of arbitrary input states, one can predict and control interference effects analogous to HOM, even beyond the traditional two single-photon regime.

Building on this, we explore higher-order generalizations involving multi-mode interferometers [2]. By considering the rotational symmetry of the interferometer modes, we establish a new framework that encompasses our previously studied extensions and reveals new interference phenomena. Crucially, our formalism maintains a metrological focus throughout, allowing us to derive explicit expressions for the achievable precision in parameter estimation tasks.

This unified viewpoint not only clarifies the operational meaning of extended HOM effects but also paves the way for designing advanced quantum interferometric devices with enhanced metrological capabilities.

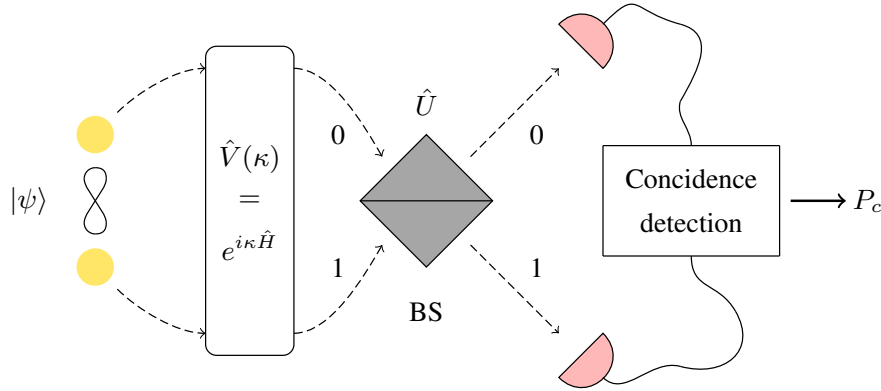


FIGURE 1. Schematics of the HOM interferometer.

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\* eloi.descamps@u-paris.fr

# Biphoton engineering with structured light on an AlGaAs chip

T. PERSON<sup>\* 1</sup>, I.P. DE SIMEONE<sup>1</sup>, O. MESKINE<sup>1</sup>, M. RAVARO<sup>1</sup>, P. MILMAN<sup>1</sup>, F. BABOUX<sup>1</sup> and S. DUCCI<sup>1\*</sup>

<sup>1</sup>Université Paris Cité, CNRS, Laboratoire Matériaux et Phénomènes Quantiques, F-75013 Paris, France

Integrated quantum optics plays a key role in the development of quantum technologies : photons propagate at the speed of light in optical fibers and are highly robust to decoherence, making them an ideal platform for quantum communication. Furthermore, Their high sensitivity and versatility, both in terms of controllability and the breadth of accessible degrees of freedom, make them highly promising candidates for quantum metrology, quantum simulation, and quantum computing. Our platform consists of a waveguide microcavity emitting quantum states of light in a transverse pump configuration via spontaneous parametric down-conversion (SPDC). In this configuration, a pump beam at around 775 nm impinges on the top of the waveguide and generates counterpropagating photon pairs in the C-band telecom window, which can be entangled in different degrees of freedom [1].

This architecture establishes a strong link between the spatial characteristics of the pump beam and the properties of the generated quantum states. By exploiting standard beam-shaping techniques, biphoton states can be finely tailored. For example, manipulating the pump beam phase enables control over the exchange symmetry of the two-photon wavefunction, allowing a continuous transition from bosonic to anyonic exchange statistics [2]. Likewise, adjusting the pump beam intensity can be exploited to generate hybrid polarization-frequency entangled states [3].

Building upon this control, here we investigate applications in quantum metrology by comparing the performance obtained by pumping the source with structured light to engineer different biphoton wavefunctions. We demonstrate in particular that engineered Hermite-Laguerre-Gauss (HHLG) modes exhibit remarkable robustness, enabling reliable information extraction even in finite visibility configurations. The ability to tune spectral and temporal correlations further enhances the sensitivity of measurement protocols, highlighting the potential of our platform for advanced quantum sensing [5].

Altogether, these results highlight the versatility of AlGaAs chips as a source of tailored non-classical states of light. Beyond fundamental control over biphoton properties, this approach opens the way to the on-demand generation of complex quantum states—such as Schrödinger cat states or compass states—that provide powerful new resources for both quantum metrology and quantum information processing [4, 6].

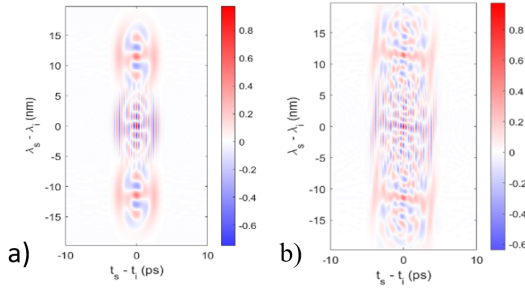


FIGURE 1 – Chronocyclic Wigner functions of hybrid modes : (a)  $HG_{2,0} - LG_{0,0}$ ; (b)  $HG_{4,4} - LG_{4,4}$ . Higher-order mode exhibiting a broader distribution of temporal and spectral interference patterns

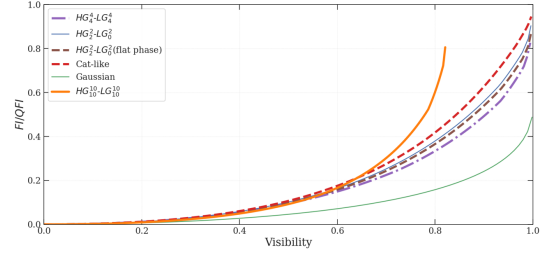


FIGURE 2 – Evolution of the ratio of Fisher Information (FI) to Quantum Fisher Information (QFI) as a function of visibility for different biphoton wavefunctions.

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\* till.person@u-paris.fr



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## From optimal microwave-to-acoustic transduction to wide-band acoustic spectroscopy

Maxime Tomasian<sup>\*1</sup>, Abel Hugot<sup>1</sup>, Quentin Greffe<sup>1</sup>, Franck Balestro<sup>1</sup> and Jeremie Viennot<sup>1\*</sup>

<sup>1</sup>*Institut Néel – Centre National de la Recherche Scientifique, Université Grenoble Alpes,  
Institut polytechnique de Grenoble - Grenoble Institute of Technology,  
Centre National de la Recherche Scientifique : UPR2940 – France*

### Abstract

Spin defects in 2D materials have the potential to exhibit strong coherent coupling to acoustic phonons at GHz frequencies. However, opto- and electro-mechanical techniques have not enabled the coupling to such high frequency modes at very low temperature. We have recently demonstrated piezoelectric microwave-acoustic transduction on lithium niobate acoustic waveguides [1]. Our technique is based on SQUID arrays, and by using a small magnetic flux, our transducers are tunable in-situ across the 4-7 GHz band.

Equipped with these transducers we are now aiming to perform the acoustic spectroscopy of 2D materials and thin films in the quantum regime. We are developing devices that harness thermal contractions and piezoelectric actuation in order to control the static stress while probing the acoustic response at GHz frequencies. This technique could be instrumental for the study of new spin defects in 2D materials.

I will present our optimal microwave-acoustic transducers as well as our progress towards acoustic spectroscopy under controlled static stress.

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(arXiv.2501.09661)

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\* maxime.tomasian@neel.cnrs.fr

# Integrated Photonics for Quantum Sensing Applications

Abdelali HAMMOUTI<sup>1</sup>, Rahul Chembra Vasudevan<sup>1</sup>, Julie Le

pouliquen<sup>1</sup>, Parastesh Pirasteh<sup>1</sup>, Yannick Dumeige<sup>1</sup>, and Paul Huillery<sup>1\*</sup>

<sup>1</sup>Univ Rennes, INSA Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France

Diamond technology is undergoing remarkable expansion across diverse technological domains. Diamond has established itself in power electronics due to its ultra-wide bandgap (5.5 eV) and exceptional thermal conductivity (2200 W/m-K) [1]. Beyond electronics, its optical properties including a large transparency window (225 nm to 25  $\mu\text{m}$ ), a high refractive index ( $n \approx 2.4$ ) and minimal birefringence make it a material of choice for integrated photonics applications [2]. The presence of optically active nitrogen-vacancy (NV) color centers further enables room-temperature quantum sensing with nanometric spatial resolution, particularly for magnetometry [3, 4]. Recent development of NV-doped thin-film growth by a few specialized groups has created new opportunities for integrated photonic quantum sensing platforms.

In this work, we focus on the fabrication of submicron diamond structures for quantum sensing applications including neuronal signal detection [5] (Fig. 1) and endoscopic NV magnetometry (Fig. 2) [6, 7]. We developed optimized reactive ion etching (RIE) protocols that achieve good selectivity and minimal surface roughness. Our process enables deep etching up to 6  $\mu\text{m}$  while maintaining smooth sidewalls, critical for high-performance photonic devices. We have successfully optimized RIE-ICP etching parameters for improved submicron structuring of diamond, achieving high-quality microdisks (Fig. 3a) and nanopillar arrays (Fig. 3b, c) while minimizing the redeposition of residual products. As perspectives, we are working on the development of under-etching techniques for the fabrication of diamond pedestal structures and on the development of hybrid photonic structures combining diamond and ZnS materials for improved light-matter interaction [8].

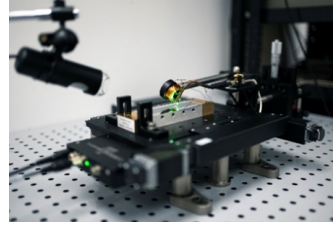
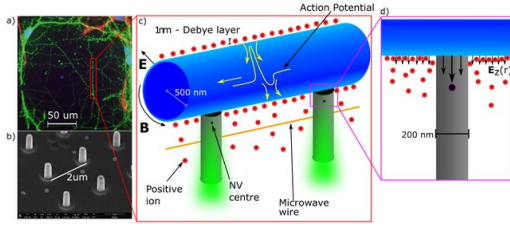


Figure 1: Diamond nanopillar arrays for quantum microscopy of neuronal signals [5] Figure 2: Fiber endoscope for NDT-Kwantek [6]

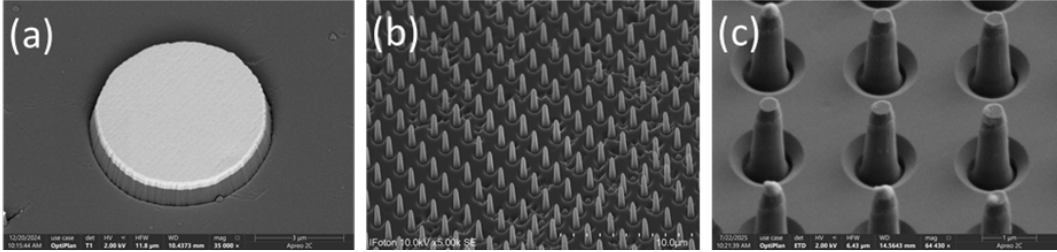


Figure 3: (a) Diamond microdisk with a top layer of resist, (b) Diamond nanopillars etching, (c) Zoom in nanopillars.

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\* Paul.Huillery@insa-rennes.fr

# Privacy in distributed sensing with Gaussian graph states

Jason Pereira<sup>1</sup> and Damian Markham<sup>1\*</sup>

<sup>1</sup>LIP6, CNRS, Sorbonne Université, 4 Place Jussieu, Paris F-75005, France

Distributed sensing is the task of estimating a global function of parameters of remote systems. In the discrete variable (DV) setting, graph states can be used for this task [1, 2]. Various parties, each holding a qudit of a graph state, can use their local state as a probe of some local, parametrised, unitary dynamics. That is (as illustrated in Fig. 1), party  $x$  applies the unitary  $e^{i\phi_x H_x}$  to their local state, for some unknown local parameter  $\phi_x$  and known, fixed Hamiltonian  $H_x$ . Then, via an appropriate choice of local measurements, the parties are able collaborate to estimate a linear function of the local parameters,  $f(\{\phi_x\}) = \sum_x a_x \phi_x$  (for some coefficients  $\{a_x\}$ ). Crucially, for certain encoding unitaries, this protocol has two important properties : enhanced sensitivity and privacy.

Enhanced sensitivity means that the parties can learn the function  $f(\{\phi_x\})$  more efficiently (in terms of the number of uses of the encoding unitary) than could be achieved by any strategy that estimates the individual, local parameters and then calculates  $f(\{\phi_x\})$  using the estimates. This is true even if the local strategy uses entanglement with an idler system.

Privacy means that it is not possible to gain any information about the local parameters that is not contained in the value of  $f(\{\phi_x\})$ . In other words, if we calculate the QFI matrix of the encoded state (with regard to the parameters  $\{\phi_x\}$ ), it will have only one non-zero eigenvalue, corresponding to the eigenvector with components  $\{a_x\}$ . We can also phrase this as “any party can hide any other party’s local parameter value”.

In the continuous variable (CV) setting, distributed sensing protocols have been proposed using Gaussian graph states [3]. These demonstrate enhanced sensitivity (now defined in terms of local strategies with probes of the same energy), but do not have privacy in the same sense as in the DV case [4]. A natural question is therefore whether there can exist a distributed sensing protocol, using Gaussian graph states as a resource, that can demonstrate both privacy and enhanced sensitivity.

We show, with a simple no-go result, that Gaussian states do not allow perfect privacy for any set of encoding unitaries. We therefore study how close we can get to privacy using Gaussian graph states as a resource, in order to bound the maximum level of privacy achievable for a Gaussian distributed sensing protocol.

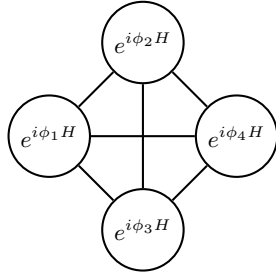


FIGURE 1. Each party locally applies an encoding unitary with an unknown parameter. Here,  $H$  is the same Hamiltonian for every party, but more generally it could be specific to each party. The goal is to estimate  $\sum_x \phi_x$ , rather than the individual parameter values.

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\* Jason.Pereira@lip6.fr

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## Probing direct spin-phonon interactions with bulk acoustic wave resonators

Q. Greffe, T. Chanelière, and J. J. Viennot

*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Neel, 38000 Grenoble, France*

Understanding spin-phonon interactions is essential for solid-state quantum technologies that exploit the spin degree of freedom. In order to probe the resonant coupling of solid-state spin defects to strain fields, we developed a technique to bond thin-film lithium niobate transducers onto arbitrary samples. We then engineer high overtone bulk acoustic wave resonators (HBAR) in crystals hosting spin defects and we probe them at microwave frequencies and 50 mK. Our technique does not require fabrication processes on the target crystal and only requires two parallel polished faces to achieve relatively high quality factors. In  $\text{CaWO}_4$  crystals doped with  $\text{Er}^{3+}$  ions,  $\text{Y}_2\text{SiO}_5$  crystals doped with  $\text{Er}^{3+}$  ions, we demonstrate acoustic paramagnetic resonance and we unveil the anisotropy of spin-phonon interactions.

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# Probing the quantum motion of a macroscopic mechanical oscillator with a radio-frequency superconducting qubit

K. Gerashchenko<sup>1</sup>, R. Rousseau<sup>1,2</sup>, L. Balembois<sup>1</sup>, H. Patange<sup>1</sup>, P. Manset<sup>1</sup>,  
W. C. Smith<sup>3,4</sup>, Z. Leghtas<sup>3</sup>, E. Flurin<sup>5</sup>, T. Jacqmin<sup>1</sup>, and S. Deléglise<sup>1\*</sup>

<sup>1</sup>*Laboratoire Kastler Brossel, Sorbonne Université, CNRS,  
ENS-Université PSL, Collège de France, Paris, France*

<sup>2</sup>*Alice & Bob, 53 Bd du Général Martial Valin, 75015 Paris, France*

<sup>3</sup>*Laboratoire de Physique de l'Ecole Normale Supérieure,  
ENS-PSL, CNRS, Sorbonne Université,  
Université Paris Cité, Centre Automatique et Systèmes,  
Mines Paris, Université PSL, Inria, Paris, France*

<sup>4</sup>*Google Quantum AI, Santa Barbara, CA*

<sup>5</sup>*Quantronics group, Université Paris-Saclay, CEA,  
CNRS, SPEC, 91191 Gif-sur-Yvette Cedex, France*

Long-lived mechanical resonators like drums oscillating at MHz frequencies and operating in the quantum regime offer a powerful platform for quantum technologies and tests of fundamental physics [1]. Yet, quantum control of such systems remains challenging, particularly owing to their low energy scale and the difficulty of achieving efficient coupling to other well-controlled quantum devices. Here, we demonstrate repeated, and high-fidelity interactions between a 4 MHz suspended silicon nitride membrane and a resonant superconducting heavy-fluxonium qubit [2–4], representing, to our knowledge, the first realization of resonant coupling in such a hybrid system at record-low frequencies. The qubit is initialized at an effective temperature of 21  $\mu$ K and read out with 77 % single-shot fidelity. During the 6 ms lifetime of the membrane the two systems swap excitations more than 300 times. After each interaction, a state-selective detection is performed, implementing a stroboscopic series of weak measurements that provide information about the mechanical state. The accumulated records reconstruct the position noise-spectrum of the membrane, revealing both its thermal occupation at 10 mK and the qubit-induced back-action. By preparing the qubit either in its ground or excited state before each interaction, we observe an imbalance between the emission and absorption spectra, proportional to  $n_{\text{th}}$  and  $n_{\text{th}}$  respectively, a hallmark of the non-commutation of phonon creation and annihilation operators. Since the predicted Diósi–Penrose gravitational collapse time [5, 6] is comparable to the measured mechanical decoherence time, our architecture enters a regime where gravity-induced decoherence could be tested directly [7].

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\* kyrylo.gerashchenko@lkb.upmc.fr

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# Quantum sensing of a quantum field

Ricard Ravell<sup>\*1</sup>, Martí Perarnau-Llobet<sup>2</sup>, and Pavel Sekatski<sup>3</sup>

<sup>1</sup>IFISC – Spain

<sup>2</sup>UAB – Spain

<sup>3</sup>UNIGE – Switzerland

## Abstract

Estimating a parameter encoded in unitary dynamics is a fundamental and well-understood task in quantum metrology. A textbook scenario where it is encountered is the estimation of the amplitude of a classical field with a two-level probe, as exemplified in the semi-classical Rabi model. Starting with this example, we here explore its fully quantum analog where a two-level atom is coupled to a coherent quantized field via the resonant Jaynes-Cummings interaction. To compare the limits of field amplitude in the semi-classical and the fully quantum models we focus on the quantum Fisher information (QFI) of the reduced state of the atomic probe after the interaction.

In the semi-classical Rabi model the QFI is independent from the field amplitude and grows quadratically with the interaction time. In contrast, when the atom interact with a single field mode prepared in a coherent state, the QFI has a complicated dependence on time and field amplitude, and is furthermore bounded by a constant that can only be attained in the weak field limit. When the atom interacts with a sequence of coherent states, the QFI can increase with time, but is ultimately bound to a linear scaling due to the production of entanglement between the atom and the radiation (back-action). Finally, in the continuous limit, where the atom interacts with many weak coherent states, this back-action has a simple interpretation as spontaneous emission, giving rise to an optimal interaction time.

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<sup>\*</sup>Speaker

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## Quantum-State Tomography of Ultrafast High-Harmonic Light from Solids

Houssna Griguer<sup>1</sup>, David Theidel<sup>1</sup>, Ilya Karuseichyk<sup>1</sup>, Mateusz Weis<sup>1</sup>, Mackrine Nagra<sup>1</sup>, and Hamed Merdji<sup>1\*</sup>

<sup>1</sup>*Laboratoire d'Optique Appliquée, CNRS – ENSTA Paris – Institut Polytechnique de Paris,  
828 Boulevard des Maréchaux, 91762 Palaiseau, France*

High-harmonic generation (HHG) in solids has become a central platform for attosecond science, providing access to strong-field electron dynamics in condensed matter and enabling the generation of broadband frequency-comb-like coherent light in the IR–UV range [1, 2]. Recent experiments have challenged the pure coherent-state hypothesis by showing that HHG emission exhibits intrinsic quantum features, including multi-mode squeezing and violations of Cauchy–Schwarz-type inequalities [3, 4], firmly establishing the presence of non-classical correlations between harmonic orders.

While photon-correlation measurements certify the non-classical nature of the emission, the underlying quantum state of HHG light remains unknown, as full quantum-state tomography has not yet been achieved. Performing tomography on such sources presents major experimental challenges : the short pulse duration, low photon flux, broad spectral bandwidth inherent to solid-state HHG pose immense constraints on the quality and stability of the local oscillator required for phase-sensitive quadrature measurements.

To address this gap, we have developed a homodyne detection platform optimized for HHG photons emitted from semiconductor materials. Combined with spatially resolved correlation imaging, it will enable reconstruction of the Wigner function and density matrix of individual harmonic orders, providing the first phase-space characterization of light generated in the strong-field non-perturbative regime. As a perspective, we explore quantum-enhanced imaging schemes leveraging the unique spectral and temporal properties of HHG photons, extending attosecond metrology into the quantum domain.

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\* houssna.griguer@ensta-paris.fr

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# Resources for bosonic metrology: quantum-enhanced precision from a superselection rule perspective

Astghik Saharyan<sup>\*1</sup>, Eloi Descamps<sup>2</sup>, Arne Keller<sup>3</sup>, and Perola Milman<sup>4</sup>

<sup>1</sup>Laboratoire Matériaux et Phénomènes Quantiques – Université Paris Cité – France

<sup>2</sup>Laboratoire Matériaux et Phénomènes Quantiques – Centre National de la Recherche Scientifique,  
Université Paris Cité, Centre National de la Recherche Scientifique :  
UMR7162, *Université Paris Cité : UMR7162 – France*

<sup>3</sup>Matériaux et Phénomènes Quantiques (MPQ) – Université Paris Diderot - Paris 7, CNRS : UMR7162  
– Université Paris Diderot, Bât. Condorcet , 10 rue Alice Domon et Leonie Duquet, Case 7021, 75205  
Paris cedex 13, France

<sup>4</sup>Matériaux et Phénomènes Quantiques (MPQ) – CNRS : UMR7162, Université Paris VII - Paris  
Diderot – Université Paris Diderot, Bât. Condorcet , 10 rue Alice Domon et Leonie Duquet, Case 7021,  
75205 Paris cedex 13, France

## Abstract

Quantum optics and atomic systems are prominent platforms for exploiting quantum-enhanced precision in parameter estimation. However, not only are quantum optical and atomic systems often treated separately, but even within quantum optics, identifying optimal probes (quantum states) and evolutions (parameter-dependent dynamics) typically relies on case-by-case analyses. Mode, and sometimes only particle entanglement, can yield quantum enhancement of precision in continuous-

and discrete-variable regimes, yet a clear connection between these regimes remains elusive. In this work, we present a unified framework for quantum metrology that encompasses all known precision-enhancing regimes using bosonic resources. We introduce a superselection rule compliant representation of the electromagnetic field that explicitly incorporates the phase reference, enforcing total particle number conservation. This approach provides a description of the electromagnetic field which is formally equivalent to the one employed in atomic systems, and we show how it encompasses both the discrete and the continuous limits of quantum optics. Within this framework, we consistently recover established results while offering a coherent physical interpretation

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<sup>\*</sup>Speaker



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of the  
quantum resources responsible for precision enhancement. Moreover, we develop general  
strategies to  
optimize precision using arbitrary multimode entangled probe states. Finally, our formalism  
readily  
accommodates noise, measurement strategies and non-unitary evolutions, extending its ap-  
plicability  
to realistic experimental scenarios.

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## Towards Direct Detection of Dark Matter by Precision Molecular Spectroscopy

Florin Lucian Constantin<sup>1\*</sup>

<sup>1</sup>*Laboratoire PhLAM, CNRS UMR 8523, Université de Lille, 59655 Villeneuve d'Ascq, France*

Dark matter makes the majority of the matter in our Universe, but its nature is unknown. Ultra-light bosonic dark matter (UBDM), formed of 0-spin, sub-eV-mass particles, is expected to behave as a classical field coherently oscillating at the corresponding Compton frequency. UBDM couples to the Standard Model (SM) particles and yields oscillations of the fundamental constants (FC), that translate into oscillations of the frequencies of atomic and molecular transitions and of the lengths of solids.

The experiment [1] aims to monitor oscillations of the fine structure constant  $\alpha$  and proton-electron mass ratio  $\mu$  by absorption spectroscopy at 1.5  $\mu\text{m}$  of gas-phase acetylene. A laser emitting at frequency  $f_L$  probes an acetylene transition at frequency  $f_{mol} \approx f_L$ , and provides a spectroscopic signal proportional with the fractional frequency detuning :

$$(f_L(t) - f_{mol}(t))/f_L(t) = (Q_\alpha^L - Q_\alpha^{mol}) \Delta\alpha(t)/\alpha + (Q_\mu^L - Q_\mu^{mol}) \Delta\mu(t)/\mu \quad (1)$$

that is expressed here with the sensitivity coefficients  $Q_X^{L,mol} = \frac{\partial \ln f_{L,mol}}{\partial \ln X}$  to the variation of  $X = \alpha, \mu$ . The rovibrational transitions of the acetylene are sensitive to  $\mu$ -variations with sensitivity coefficients calculated by the molecular theory in ref. [2].

The experiment exploits a laser at 1542 nm, stabilized on a Fabry-Perot cavity resonance with  $10^{-15}$ -level fractional stability at 1 s, continuously referenced against a hydrogen maser at Observatoire de Paris, and disseminated to remote geographical locations through REFIMEVE's stabilized optical fiber links [3]. The acetylene spectrometer developed at PhLAM performs linear absorption spectroscopy measurements that are synchronized against the time reference provided by the GPS. The spectral components of the noise of the spectroscopic signal, sensitive to FC oscillations in a frequency range from 1 Hz and 1 GHz, can be subsequently converted into constraints of the couplings of UBDM to SM particles.

This contribution will present the projections for the performances of this approach, ongoing experimental developments, data recording and exploitation procedures, and an evaluation of the performances reached with the simplest experimental setup.

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\* FL.Constantin@univ-lille1.fr

## Poster Session 2 (FQA, QCOM, TEM)

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## A Fine-Grained Perspective on Indefinite Causal Order : Modelling Agents in Spacetime

E. de Bank<sup>1</sup>, V. Vilasini<sup>1</sup> and C. Branciard<sup>2\*</sup>

<sup>1</sup> *Inria and Université Grenoble Alpes, 38042 Grenoble Cedex 9, France*

<sup>2</sup> *CNRS and Université Grenoble Alpes, 38042 Grenoble Cedex 9, France*

Causality is a fundamental concept that takes on markedly different forms in quantum and relativistic theories. Yet in quantum information protocols implemented in spacetime, both notions must coexist consistently. This raises compelling questions : How can we describe a measurement on a quantum system in a superposition of spacetime locations ? Can an agent locally extract an outcome from such a system without collapsing its spatiotemporal coherence ? We explore how such measurements can be modelled within quantum information theory in a manner consistent with relativistic causality.

This connects closely to questions about the physicality of indefinite causal order (ICO) [1] processes, where the ordering of agents' operations is not fixed or acyclic. Broadly, two categories of approaches exist in this context :

(1) A coarse-grained perspective which exhibits indefinite causal order. For example, the framework of quantum circuits with quantum control of causal order (QCQCs) [2] captures scenarios in which a quantum system coherently controls the order of operations.

(2) A fine-grained perspective, in which such processes are embedded in spacetime in a way that respects relativistic causality, where the process can be unravelled into one with a definite and acyclic causal order between operations. The process box framework [3] is representative of this approach.

Our modelling of quantum measurements in spacetime informs how agents' interventions can be described within the fine-grained, definite-order picture, while still capturing the operational correlations found in the coarse-grained ICO framework—ensuring each agent acts only once on a quantum system that may be non-localised in spacetime.

Additionally, QCQCs are known not to violate causal inequalities. Our results investigate an alternative derivation of QCQC correlations, based on quantum and relativistic causality principles in spacetime, which can shed light on the limits of attainable correlations in quantum protocols in spacetime. Finally, considering recent experimental claims for certifying non-classical correlations in ICO processes, we analyse how they align with a fine-grained, spacetime-consistent interpretation which can involve superpositions of arrival times. This can enable a better understanding of the physical resources responsible for these non-classical features in the fine-grained picture which accounts for both quantum information and relativistic aspects.

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\* emilien.de-bank@inria.fr

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## A Higher Order Theory for Fermions

Ved Kunte<sup>1\*</sup>

<sup>1</sup>*Université Grenoble Alpes, CNRS, Institut Néel, 38000 Grenoble, France*

The circuit architecture of a typical quantum process can be theoretically formulated as a ‘box with holes’ in which a party can plug in their local choice of transformations[1]. Such a box is often called a ‘quantum supermap’ as it behaves as a map between maps. This way of formulating quantum processes as supermaps allows us to study the causal relations between any given parties in the process. By generalizing the notion of supermaps, one can even conceive processes that no longer have a well-defined causal structure between the parties, leading to a phenomenon called ‘indefinite causal order’ [4]. The theoretical framework to study all such processes, and supermaps in general, is the ‘higher-order quantum theory’ [2].

We want to extend this analysis to indistinguishable quantum systems, specifically to fermionic systems, by defining fermionic processes as higher order transformations in a similar fashion to quantum theory. To that end, we construct a higher order theory for fermionic systems that generalizes fermionic theory and can accommodate higher order transformations. This theory, which we dub HOFT is constructed in an operational way by definition higher-order systems and the corresponding state space as being isomorphic to transformations in fermionic theory. We then construct a channel state map for fermions that allows us to derive a Fock space representation and of the ‘higher-order states’ à la the second quantization formalism of the fermionic theory or the ‘mode picture’[3]. We lay out the admissibility criteria for valid higher order states and define the composition rules, and characterize higher order transformations. Finally, we look at ways to express fermionic processes as higher order transformations and then derive the admissibility criteria for them as well.

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\* ved.kunte@neel.cnrs.fr

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## Communication-complexity of Quantum Distributed Algorithms

Pedro Lauand<sup>1</sup>, Marc-Olivier Renou<sup>2,3,4,5</sup>, Lucas Tendick<sup>2,3,4</sup>, Isadora Veeren<sup>2,3,4</sup>, Juliette Vlieghe<sup>6\*</sup>

<sup>1</sup>*Perimeter Institute for Theoretical Physics, Waterloo, Canada*

<sup>2</sup>*Inria, Université Paris-Saclay, Palaiseau, France*

<sup>3</sup>*CPHT, Ecole Polytechnique,  
Institut Polytechnique de Paris, Palaiseau, France*

<sup>4</sup>*LIX, Ecole Polytechnique,  
Institut Polytechnique de Paris, Palaiseau, France*

<sup>5</sup>*LINCS, Telecom Paris, Palaiseau, France*

<sup>6</sup>*Technical University of Denmark, Denmark*

Quantum computing is advancing rapidly, with breakthroughs bringing us closer to reliable devices performing efficient high-end computation. Nowadays agents are connected globally through networks to perform complex joint tasks, and the next highly anticipated step is establishing a Quantum Internet - operating in quantum networks. However, most current algorithms are designed for centralized architectures - where a single processor implements the task - and do not translate directly to the decentralized structure of quantum networks. While classical distributed networks already support telecommunications, it remains unclear whether quantum methods can deliver concrete advantages under realistic constraints. Since efficiency in distributed structures depends strongly on latency restrictions, quantum advantage can be achieved with strategies that require fewer communication rounds between agents in the network; yet, there currently exists no method that can systematically determine the communication complexity of quantum distributed tasks, and consequently there is no way to assert that a given task can have a quantum advantage in the distributed scenario.

In order to properly shape the future quantum internet and guide resource allocation as well as the development of adequate algorithms, this work takes the first steps toward a robust mathematical framework to determine communication-complexity of quantum distributed algorithms. We will discuss the current challenges and what can be learned from classical distributed algorithms - as well as the limitations that this approach imposes. The current state of the art is presented in our paper [1], where we can show quantum advantage to a specific task, but now we go beyond and introduce recent results that pave the way to a general framework that can evaluate a quantum advantage to any general task.

We adapt techniques from the field of quantum network nonlocality, namely *quantum inflation* [2], to model communication between agents in a network. Using technique native to the community of quantum information [3], we are able to obtain analytical results indicating the communication-round complexity of the task we dub "cascaded CHSH-game". In this task, a network of  $N$  agents connected in a line must cooperate to win a collection of bipartite CHSH games, while only being allowed to send messages in one direction of the line. With this simple task, we are able to apply our framework and derive a quantum communication-complexity bound. We also present other network tasks that could be analyzed with our framework, and the next steps that must be taken to bring our method to a fully developed analytical and numerical tool.

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\* isadora.veeren@polytechnique.edu

# Complete Self-Testing of a System of Remote Superconducting Qubits

Simon Storz, Anatoly Kulikov, Josua D. Schär, Florence Berterottière, and Andreas Wallraff  
*Department of Physics, ETH Zurich, 8093 Zurich, Switzerland and  
Quantum Center, ETH Zurich, 8093 Zurich, Switzerland*

Victor Barizien, Xavier Valcarce, Nicolas Sangouard, and Jean-Daniel Bancal  
*Institute of Theoretical Physics, University of Paris-Saclay, CEA, CNRS, Gif-sur-Yvette, France*

Self-testing protocols enable the certification of quantum systems in a device-independent manner, i.e. without knowledge of the inner workings of the quantum devices under test. Here, we demonstrate this high standard for characterization routines with superconducting circuits, a prime platform for building large-scale quantum computing systems. We first develop the missing theory allowing for the self-testing of Pauli measurements. We then self-test Bell pair generation *and* measurements at the same time, performing a *complete* self-test in a system composed of two entangled superconducting circuits operated at a separation of 30 meters. In an experiment based on 17 million trials, we measure an average CHSH (Clauser-Horne-Shimony-Holt) S-value of 2.236. Without relying on additional assumptions on the experimental setup, we certify an average Bell state fidelity of at least 58.9% and an average measurement fidelity of at least 89.5% in a device-independent manner, both with 99% confidence. This enables applications in the field of distributed quantum computing and communication with superconducting circuits, such as delegated quantum computing.

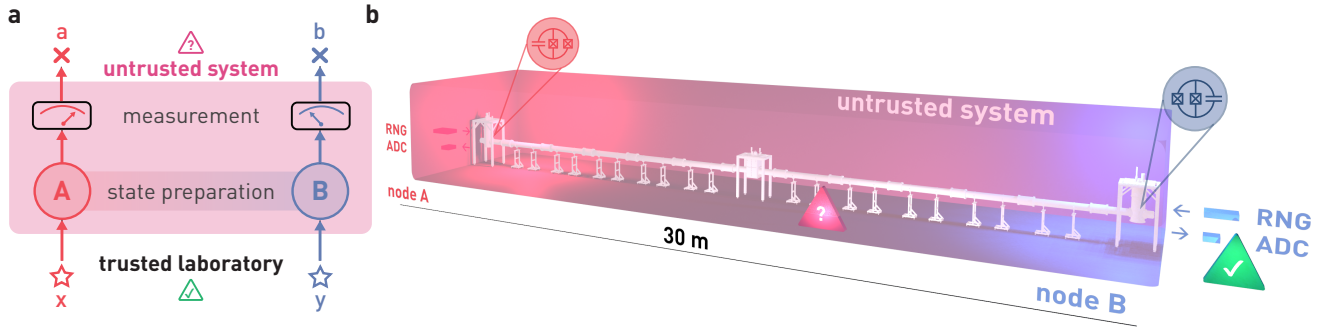


FIGURE 1. **Experimental setup.** a, Schematic representation of a self-testing scheme. In each trial, A and B choose the measurement bases  $x$  and  $y$  using trusted random number generators, and the two parties record the measurement outcomes  $a$  and  $b$ . The untrusted setup (magenta) consists of all devices relevant for generating a Bell state and for performing a Bell test. b, Schematic illustration of the experimental setup. At the two nodes A and B each, a superconducting circuit qubit is operated in a dilution refrigerator. The two nodes are remotely connected through a 30-meter-long microwave waveguide to generate entanglement between the two qubits. Each node operates a trusted random number generator (RNG) and measurement signal detection device (analog-to-digital converter, ADC). The untrusted setup, represented in a magenta box, is marked with a magenta triangle, the trusted part with a green triangle.

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## Difficulties in learning quantum strategies with variational quantum circuits : a differential approach to the geometry of the quantum set

Sacha Cerf, Harold Ollivier\*  
*QAT team, DIENS, École Normale Supérieure, PSL University,  
CNRS, INRIA, 45 rue d'Ulm, Paris 75005, France*

The quantum correlations set, often denoted  $\mathcal{Q}$ , is the collection of all possible probability distributions on measurement outcomes achievable by space-like separated parties sharing a quantum state. It is well established that this set is larger than what can be explained by classical physics. In his seminal work, Tsirelson [1] initiated the systematic study of the quantum set as a mathematical construct, which has so far mainly been conducted using algebraic and convex geometry techniques. In this work, we explore a more analytical approach to  $\mathcal{Q}$  by considering infinitesimal perturbations of state-measurement combinations, and the induced response on the associated correlation. Using this technique in the  $n22$  scenario ( $n$  parties, two dichotomic measurements), we mathematically prove a hardness result on the learning of quantum strategies for nonlocal games. Learning a quantum strategy can be understood as optimizing, over a parametrized family of quantum states and measurements, the expected payoff of a nonlocal game. This problem can typically be approached using a variational quantum circuit, combining a parametrized state preparation stage with input-adaptive measurement angles. Nonlocal games thus provide a controlled and analytically tractable setting to study generic features of quantum variational optimization. In this setting, we show that any variational circuit ansatz using parametrized unitaries only exhibits a local optimum at points corresponding to optimal classical strategies, even when the game admits a strictly better quantum strategy. Our results indicate that local optima may arise purely from constraining the optimization to pure states, implying that incorporating parametrized non-unitary CPTP maps could enhance the trainability of quantum machine-learning models. Apart from this practical outreach, we believe that this result has theoretical consequences for the geometry of  $\mathcal{Q}$ , specifically that its faces are flat around any local deterministic point.

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\* sacha.cerf@inria.fr, harold.ollivier@inria.fr



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# Explicit Renormalization Group Flow from Perturbed Matrix Product Operators Using Random Walks

Léo Le-Nestour<sup>1</sup>, David Pérez-García<sup>2,3</sup>, and Alberto Ruiz-de-Alarcón<sup>4\*</sup>

<sup>1</sup>*École normale supérieure de Lyon, 69342 Lyon Cedex 07, France*

<sup>2</sup>*Faculty of Mathematics, Complutense University of Madrid, 28040 Madrid, Spain*

<sup>3</sup>*Institute of Mathematical Sciences, CSIC-UAM-UC3M-UCM, 28049 Madrid, Spain*

<sup>4</sup>*Department of Mathematics, CUNEF Universidad, 28040 Madrid, Spain*

We study a class of Matrix Product Density Operators endowed with an algebraic structure [1] and address the problem of defining a meaningful coarse-graining procedure for the corresponding tensor networks. We then analyze the trajectories that emerge from generic perturbations of known fixed points, tracing their flow toward potential new fixed points. Beginning with the case of group algebras, which is closely related to Toric Code states, we identify all possible new fixed points. Building on this, we propose a generalization to arbitrary finite-dimensional Hopf algebras, where the coarse-graining steps are naturally described in terms of successive convolutions of states. In this framework, the classification of new fixed points is tied to the characterization of idempotent states in Hopf algebras.

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\* leo.le\_nestour@ens-lyon.fr

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## Fermionic Nonlocality Beyond Bell : The Fundamental Fermion–Boson Distinction

Fatemeh Moradi Kalarde<sup>1,2</sup>, Sadra Boreiri<sup>3</sup>, Xiangling Xu<sup>1,2</sup>, Tommaso Guiata<sup>4</sup>, Salman Beigi<sup>5</sup>, Lucas Tendick<sup>1,2</sup>, Marc-Olivier Renou<sup>1,2\*</sup>

<sup>1</sup>*Inria de Saclay, Palaiseau, France*

<sup>2</sup>*CPHT, École Polytechnique, Palaiseau, France*

<sup>3</sup>*University of Geneva, Geneva, Switzerland*

<sup>4</sup>*Freie Universität Berlin, Germany*

<sup>5</sup>*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*

Feynman [1] remarked that the spin–statistics theorem is one of the few rules in physics that can be simply stated yet whose proof requires the full machinery of relativistic quantum field theory. A central implication of this theorem is that fermions cannot be composite bosons. This naturally raises the question : *can there exist an elementary, non-relativistic proof of this fact ?*

Bell’s theorem [2] provides a paradigm for such elementary arguments : it rules out classical (local hidden-variable) models under the minimal assumption of causality. It proves that quantum systems such as qubits—carried, for instance, by bosons—cannot be simulated by classical bits of information, and hence that bosonic correlations cannot be reproduced by any composition of classical particles. Inspired by this framework, we devise a fermionic thought experiment whose outcome shows that fermions cannot be composite bosons, following reasoning analogous to that of Bell’s theorem.

Our thought experiment is framed in the context of distributed quantum networks and based on concepts from Distributed Computing. Within this setting, we prove the existence of a set of fermionic correlations that admits no local hidden-qubit model and is stronger than Bell nonlocal correlations obtained with qubits. This demonstrates that standard Quantum Information Theory is not sufficient to represent information carried by indistinguishable fermions in distributed contexts. The assumptions of our thought experiment remain simple : causality is preserved, and the parties involved are distributed and therefore have no knowledge of the network topology. Hence, our result provides an information-theoretic, non-relativistic proof of the fundamental fermion–boson distinction implied by the spin–statistics theorem.

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\* fatemeh.moradi-kalarde@inria.fr

# From subwavelength quantum state control to collective incoherent scattering in ultracold atoms

Eliott Béraud<sup>1,\*</sup>, Ruiyang Huang<sup>1</sup>, Romain Veyron<sup>2</sup>, and Simon Bernon<sup>1</sup>

<sup>1</sup>LP2N, Laboratoire Photonique, Numérique et Nanosciences,

Université de Bordeaux-IOGS-CNRS :UMR 5298, rue F. Mitterrand, Talence F-33400, France and

<sup>2</sup>ICFO - Institut de Ciències Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain

Major recent developments in quantum technologies have been driven by advances in quantum state engineering. Our team uses cold atoms whose quantum states can be shaped by light fields over distances of the order of the optical wavelength (typically less than one micron). In our setup, an optical lattice acts as a dressing field to sinusoidally modulate the excited state. The induced light shift maps an atomic transition frequency onto a 1D array of subwavelength volumes (Fig. 1a)). This method allows us to image ground-state wavefunctions of the lattice with a spatial resolution down to 31 nm, well below the diffraction limit. In addition, atoms trapped in the lattice can coherently tunnel between neighboring sites separated by half the optical wavelength (511 nm in our setup). We are able to observe and control these single-site tunneling dynamics, and even suppress them using the quantum Zeno effect (Fig. 1b)).

In parallel, we investigate light scattering in regimes where the single-particle picture breaks down. We show that the atomic scattering cross section is strongly modified by the mean incoherent field arising from the collective response to light, with a significant dependence on the cloud optical density. This effect has important implications for absorption imaging in dense ultracold atomic samples : ignoring the contribution of incoherent scattering leads to systematic underestimation of the atom number [1].

Finally, we present preliminary results on the guiding behavior of a 1D ultracold atomic cloud. Our observations indicate that such a system behaves as a continuous medium with a well-defined refractive index, despite its relatively low density (1e19atoms/m<sup>3</sup>). Our ongoing goal is to investigate the role of incoherent scattering in this guiding regime.

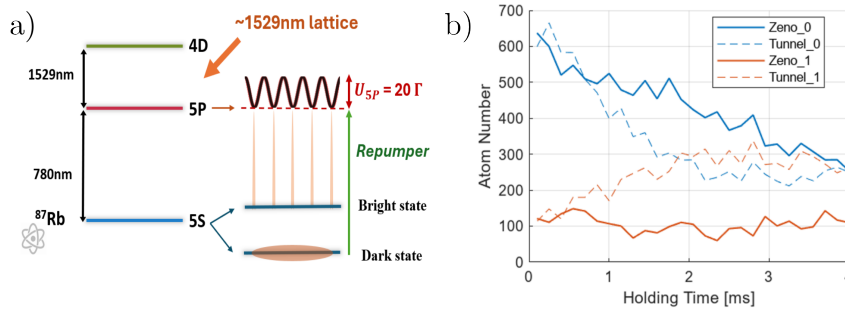


FIGURE 1. a) Representation of Rubidium electronic levels, a 1529 lattice modulates periodically the 5P-4D transition. Subwavelength volumes are pumped to a cycling transition depending on the specific frequency of the repumper beam b) Tunneling dynamics of one lattice site to its nearest neighbour and suppression of tunneling using the quantum Zeno effect.

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\* eliott.beraud@institutoptique.fr

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# Interaction of atoms in free space with quantum pulses of light with

Adrien Gavalda<sup>1,2</sup>, Sara Pancaldi<sup>1</sup>, Guillaume Tremblier<sup>1</sup>, Igor Ferrier-Barbut<sup>1</sup>, Antoine Browaeys<sup>1</sup>

<sup>1</sup> Universite Paris-Saclay, Institut d'Optique Graduate School, ' CNRS, Laboratoire Charles Fabry, 91127 Palaiseau Cedex, France

<sup>2</sup> PASQAL SAS, 7 Rue Leonard de Vinci, 91300 Massy, France

In the context of quantum technologies , there is a strong interest in interfacing quantum systems such as atoms, quantum dots, etc. with photons. In particular, research is driven by the desire to transfer the quantum states produced by these systems to propagating photons : This could allow for deterministic entanglement between static quantum systems and photons or the generation of specific quantum states of light. This is also useful in various quantum computing and quantum cryptography schemes. To make predictions and investigate various scenarii, one needs a theoretical framework to calculate the quantum state of the light emitted by a quantum system itself driven by quantum light.

Quite surprisingly, the task of developing a general framework describing the full quantum interaction of a simple 2-level system with propagating photons has only been undertaken recently [1,2]. However, so far the formalism does not include the spatial modes of the photons as is necessary when driving an atom in free space. In this work, we generalize the recently developed framework of a 2-level system interacting with pulses of photons to any spatial mode of light. This generalization is required to apply the current formalism to the textbook example of a free space atom interacting with a laser beam. We further illustrate the versatility of this approach by numerically computing the state of radiated light of a 2-level atom in any direction, in any temporal mode. This paves the way for the full quantum description of an ensemble of  $N$  atoms interacting with any pulse of photons.

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# Measurement-Induced Relaxation in Superconducting Qubits

Prakritish Gogoi<sup>1</sup>, Angela Riva<sup>1</sup>, and Alex Chin<sup>1,3</sup>

<sup>1</sup>*Sorbonne Université, CNRS, Institut des NanoSciences de Paris, 4 Place Jussieu, 75005 Paris, France.*

<sup>2</sup>*LPENS, Département de Physique, École Normale Supérieure, Centre Automatique et Systèmes (CAS), MINES ParisTech, Université PSL, Sorbonne Université, CNRS, Inria, 75005 Paris, France.*

<sup>3</sup>*Sorbonne Université, CNRS, Institut des NanoSciences de Paris, 4 Place Jussieu, 75005 Paris, France*

## Abstract

Within the domain of open quantum systems, measurement induced relaxation of qubits [1] is a prevalent problem in superconducting circuits which are one of the leading platforms for quantum computing. Much of the present work involves the use of Lindblad master equation [2] that consists of a qubit coupled to a cavity and the dissipation only acts on the cavity mode. This approach has led to some disagreements between what has been observed experimentally and the theoretical results. We devise a new approach to this problem which involves using the Bloch-Redfield equation that allows us to model the dissipation in the eigen-basis of the coupled qubit-cavity system. This approach enables us to take entanglement into account and also model rich spectral features into the environment which are very important while considering a realistic scenario [3]. We aim to understand the underlying mechanism of this phenomena of relaxation of the qubit as a result of coupling it to a cavity which in turn, is used to read out the state of the qubit. Preliminary results show that under the same parameter regime, these two approaches can give strikingly different results. Understanding this problem will allow us to formulate methods to limit qubit relaxation while maximizing the readout fidelity.

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# Plug-and-play preparation of non-local superpositions between non-classical light states

Antoine Petitjean<sup>1</sup>, Sébastien Tanzilli<sup>1</sup>, Anthony Martin<sup>1</sup>, Jean Etesse<sup>1</sup> and Virginia D'Auria<sup>1\*</sup>

<sup>1</sup>Université Côte d'Azur, CNRS, Institut de Physique de Nice, 17 av. J. Laupretre, 06200 Nice, France

Squeezed states of light represent a key resource for continuous-variable (CV) quantum optics [1]. They enable protocols such as quantum teleportation, entanglement distribution, quantum-enhanced metrology, and measurement-based quantum computation [2, 3]. Beyond Gaussian operations, non-Gaussian resources—such as photon-subtracted states, Schrödinger cat states, or entangled coherent states—are required to achieve universality and to reveal strong non-classical features through negativity in their Wigner functions.

Optical Schrödinger cat states, defined as superpositions of coherent states  $|\alpha\rangle \pm |-\alpha\rangle$ , are of particular interest since they can be considered as logical qubits in a coherent state encoding. Their richer structure provides advantages for teleportation, universal computation, and loophole-free Bell tests. However, they are extremely fragile with respect to losses. One strategy, demonstrated in [4], is to generate non-local entanglement probabilistically via photon subtraction on two modes. By this method, losses only reduce the success probability without impacting the fidelity of the prepared state.

This work aims to develop a compact, fibre-based platform that integrates Gaussian squeezed-light sources with discrete-variable heralding. It enables plug-and-play generation and characterization of non-Gaussian states that are robust to losses and suitable for scalable quantum networks. The plug-and-play architecture minimizes alignment requirements and phase drifts, providing a testbed for fibre-integrated non-Gaussian state generation.

The experimental setup is based on a compact fibre network whose principle is illustrated in figure 1. The initial squeezed vacuum states are generated by Spontaneous Parametric Down Conversion (SPDC) in two waveguided periodically poled lithium niobate (ppLN) nonlinear crystals. We use two homodyne detections implemented with independent local oscillators, providing access to quadrature statistics of the heralded state. A central experimental challenge is maintaining phase and frequency stability in the delocalised photon subtraction process. The latter is described by the operator  $\hat{a}_1 - e^{i\Delta\phi}\hat{a}_2$ , where  $\Delta\phi$  is the phase difference between the two paths of the dual-wavelength central Mach-Zehnder interferometer. We implement a hybrid stabilization approach combining Pound–Drever–Hall (PDH) locking [5] applying a low-frequency dither modulation to a frequency-shifted probe laser. This ensures a fixed relative phase during photon subtraction and enables systematic studies of the generated state at controlled phase differences.

This experiment can be viewed as a practical, fibre-integrated analogue of non-local photon subtraction schemes demonstrated in [4]. By interfering heralding modes and conditioning on single-photon detections, we approximate the preparation of entangled coherent superpositions robust to losses. Such states are potential resources for coherent-state qubits, long-distance teleportation, and phase-space quantum gates.

The roadmap includes optimizing the PDH/dither stabilization loops, performing full Wigner-function reconstruction, implementing heralded photon subtraction to generate cat-like states, and demonstrating conditional operations as resources for coherent-state quantum computing.

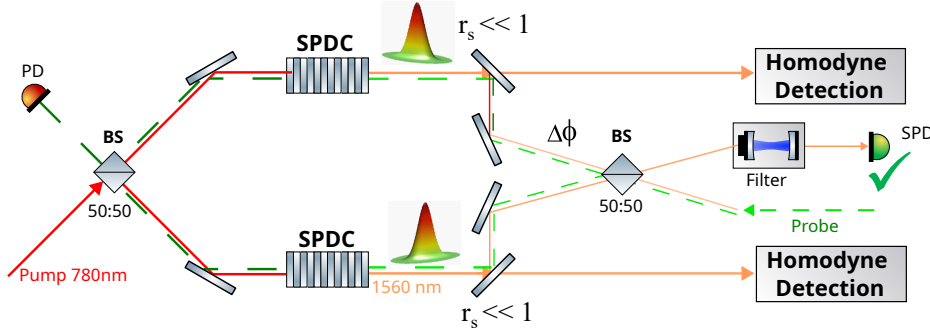


FIGURE 1. Fibre-integrated setup for non-local photon subtraction. Two SPDC sources generate squeezed states combined on a balanced beam splitter (BS). Single-photon detections (SPD) herald the preparation of non-Gaussian states, which are characterized via independent homodyne detections using independent local oscillators.

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# Quantum-to-classical transition seen through quantum signals : reconstruction of a classical image from a network of observers.

Benjamin Souaille\* and Alexandre Feller†  
*Université de Lille, Laboratoire PhLAM, 59655 Villeneuve d'Ascq cedex, France*

Benjamin Roussel‡  
*Department of Applied Physics, Aalto University, Aalto, Finland*

Pascal Degiovanni§  
*Univ Lyon, Ens de Lyon, Université Claude Bernard Lyon 1,  
CNRS, Laboratoire de Physique, F-69342 Lyon, France*

The main way of exploring the quantum-to-classical transition in distinguishable particle systems is through decoherence. To take observers into account and understand how they can reconstruct an objective classical picture of a quantum system, the quantum darwinism framework shifts the perspective to the study of the multipartite entanglement between the system, the observers and the environment, hoping to reconstruct a coherent classical image of the system. To characterize this spread of information, Zurek theory [1–3] identified the mutual information as a relevant tool. However, this quantity is not easily accessible experimentally. One shot quantum information can answer this challenge and be used to put these ideas to the test. The present work explores this approach in the context of cavity and circuit QED through the comparison of the mutual information and the Helstrom bound in a model of a system of a qubit coupled to an environment of multimode bosonic signal. Our goal is to extend this study to electronics systems and to different tools of the one-shot approach.

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\* benjamin.souaille@univ-lille.fr

† alexandre.feller@univ-lille.fr

‡ benjamin.roussel@aalto.fi

§ pascal.degiovanni@ens-lyon.fr

# Realistic Bell tests and DIQKD with homodyne detectors

Gaël Massé<sup>1</sup>, Enky Oudot<sup>1</sup>, Xavier Valcarce<sup>2</sup> and Antonio Acín<sup>3\*</sup>

<sup>1</sup> Laboratoire d'informatique de Paris 6, 4 Pl. Jussieu, 75005, Paris, France

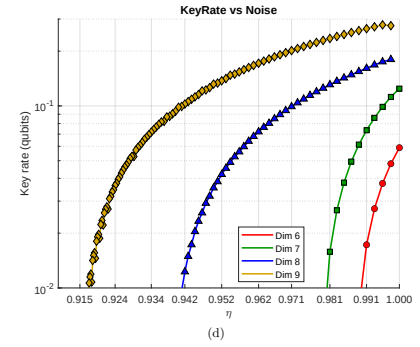
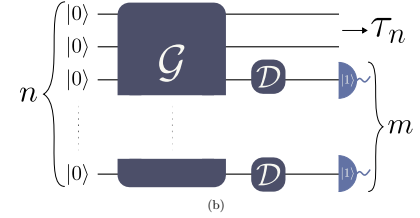
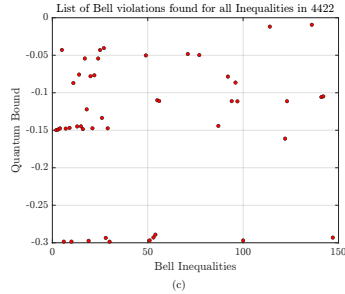
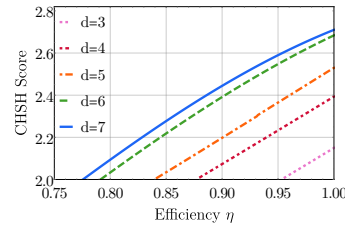
<sup>2</sup> Université Paris-Saclay, CEA, CNRS, Institut de physique théorique, 91191, Gif-sur-Yvette, France

<sup>3</sup> The Institute for Photonic Sciences, Quantum Information Team, Mediterranean Technology Park, Avinguda Carl Friedrich Gauss, 3, 08860 Castelldefels, Barcelona, Espagne

Bell non-locality is a core resource for quantum communication in a device-independent (DI) manner, *i.e.* without making assumptions about the underlying quantum model [1, 2]. By 2017, three Bell experiments closed the main "loopholes", *i.e.* experimental problems that affect the validity of Bell tests [3–5]. However, these tests involve measurements devices relying on superconducting nanowire single-photon detectors, which require cryogenic temperatures to operate efficiently. This stands in contrast with the practical and commercial expectations for the implementation of DI protocols.

We consider standard photonic devices, notably restricting the detecting apparatus to homodyne detectors. We numerically found the largest possible Bell violations for local qudit Fock spaces of increasing dimensions in the literature [6]. We focus on the experimental feasibility by deriving thresholds of efficiency (Fig.(a)) and by deriving realistic set-ups (Fig.(b)).

We extend that work by computing quantum bounds for all the Bell Inequalities that involve 2 players and up to 4 measurements, discovering 21 inequalities for which the resistance to noise is comparable to CHSH (Fig (c)). Besides, we verify that multiple-outcomes POVMs do not yield an advantage. Finally, we derived key-rates for Device Independent Quantum Key Distribution (DIQKD) protocols, using cutting-edge analytical proves (Fig d).



(a) CHSH score with respect to the overall efficiency of the noise  $\eta$ , for various dimension of the local Fock space. (c) Quantum violation for the list of all Bell Inequalities for 2 players and up to 4 measurements.

(b) Circuit generating non-local states with respect to our protocol, using  $n$ -mode bosonic parameterized circuits and a Gaussian process  $\mathcal{G}$  (d) Keyrate for growing dimensions of subsystems

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\* gael.masse@lip6.fr



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## Routing Quantum Control of Causal Order

Maarten Grothuis,<sup>1,2</sup> Alastair A. Abbott,<sup>1</sup> Augustin Vanrietvelde,<sup>3</sup> and Cyril Branciard<sup>2</sup>

<sup>1</sup>Univ. Grenoble Alpes, Inria, 38000 Grenoble, France

<sup>2</sup>Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France

<sup>3</sup>Télécom Paris-LTCI, Inria, Institut Polytechnique de Paris, 91120 Palaiseau, France

**arXiv:2507.08781**

In recent years, various frameworks [1–8] have been proposed for the study of quantum processes with indefinite causal order, going beyond simple yet (comparatively) well-known examples like the *quantum switch* [9], which has been subject of intense study [9–12].

In particular, *quantum circuits with quantum control of causal order* (QC-QCs) [4] form a well-characterised, broad class of physical supermaps [13] (or process matrices [14]) obtained from a bottom-up construction and are believed to represent all quantum processes physically realisable in a fixed spacetime [15]. Complementarily, the formalism of *routed quantum circuits* [7, 16] introduces quantum operations constrained by “routes” to represent processes in terms of a more fine-grained routed circuit decomposition. This decomposition, formalised using a so-called *routed graph*, represents the information flow within the respective process, using a precise and intuitive diagrammatic representation. However, the existence of routed circuit decompositions has only been established for a small set of processes so far, including both certain specific QC-QCs and more exotic processes [17, 18], violating causal inequalities, as examples.

In this work, we remedy this fact by connecting these two frameworks. We prove that for any given  $N$ , one can use a single routed graph to systematically obtain a routed circuit decomposition for any QC-QC with  $N$  parties. We detail this construction explicitly and contrast it with other routed circuit decompositions of QC-QCs, which we obtain from alternative routed graphs. We conclude by pointing out how this connection can be useful to tackle various open problems in the field of indefinite causal order. Particularly, this includes establishing circuits representations of subclasses of QC-QCs, like for *non-dynamical* processes [19] – where the causal order is not determined from the start but is instead established on the fly – or the class of *agent-local* processes, where we restrict the supermap to act as local pre- and post-processing for the respective agents.

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## Optical control of excitonic states in GaAs/AlGaAs and InAs/GaAs quantum dot molecules

A. Chapuis<sup>1</sup>, P. Atkinson<sup>1</sup>, A. Raymond<sup>1</sup>, B. Eble<sup>1</sup>, V. Voliotis<sup>1\*</sup>

<sup>1</sup> Sorbonne University, CNRS, Institut des NanoSciences de Paris, 4 Place Jussieu, 75252, Paris, France

Qubits with long coherence times, when used with strong light-matter coupling, allow for transferring quantum information between static, matter qubits and flying, light qubits. Semiconductor quantum dots (QD) systems are promising candidates for quantum communication protocols. Moreover, the specific transitions' optical selection rules allow for a mapping between light polarization and spin states' transitions which is a valuable tool for coherent control with light pulses. We propose to build such a spin-photon interface on an InAs/GaAs double quantum dot structure embedded in a diode, where the thin tunnel barrier between the dots allows for coherent coupling of the electronic states. Our goal is to define robust spin qubits with one or two charge carriers on the ground state that present long coherence times [1] and can be manipulated with optical pulses [2].

Quantum dot molecules (QDMs) are systems that allow the existence of excitons, either direct (where both electron and hole are confined within the same QD) or indirect (where they are confined in different QDs [3]). Since indirect excitons present a much stronger dipole moment, their energy can be easily tuned with the application of an electric field along the growth axis of the structure.

By performing micro-photoluminescence maps as a function of the applied bias, one can observe an anticrossing between direct and indirect neutral exciton transitions. But with singly-charged or multiple-charged exciton states, one can see more complex structures arising. Indeed, the 3 charges of a trion can either be confined with the same QD or shared across both, when the energy levels are in resonance for a given value of the applied field.

One can also observe "X-patterns", signatures of tunnelling of the hole left after electron-hole recombination. We analyze such a pattern to measure tunnel coupling and to probe the fine structure of the hole states [4].

Using numerical simulation tools, we recreate the measured X-pattern and explain the different photoluminescence lines. Resonances between excited states in the different dots are evidenced allowing to map the electronic structure of the coupled QDs.

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\* chapuis@insp.jussieu.fr

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# Superposition and Maximal Causal Indefiniteness in a Maximally Nonlocal Theory

Kuntal Sengupta<sup>1\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38000 Grenoble, France*

This abstract is based on [1].

Quantum theory not only allows for superposition of states but also of causal orders between operations, i.e., for an indefinite causal order [2]; an implication of the principle of quantum superposition. Since a more fundamental theory might also admit this feature, an understanding of superposition and indefinite causal order in an operational framework, such as that of generalised probabilistic theories (GPTs) [3], is needed. In particular, such an understanding should not rely on the mathematical formalism used to describe the theory (for instance Hilbert spaces for quantum theory), but in terms of operational outcomes that users of the theory can observe. We present a candidate definition of superposition in the framework of GPTs and show that in maximal theories, respecting non-signalling relations, (i.e., consistent with no superluminal signalling), single system state-spaces do not admit superposition; however, composite systems do. Additionally, we show that superposition does not imply entanglement. Next, we provide a concrete example of a maximally Bell-nonlocal theory, which not only admits the presented notion of superposition, but also allows for post-quantum violations of theory-independent inequalities that certify indefinite causal order [4]; even up to an algebraic bound. These findings might point towards potential connections between a theory's ability to admit indefinite causal order, Bell-nonlocal correlations and the structure of its state spaces.

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\* [kuntal.sengupta@neel.cnrs.fr](mailto:kuntal.sengupta@neel.cnrs.fr)

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## System–Bath Correlations and Bath Dynamics in Quantum Spin Chains

Amanda E. Seedhouse\* and Robert S. Whitney

*Université Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France*

Understanding the flow of information and energy in quantum systems is of interest in both quantum thermodynamics and quantum technologies. Here, we investigate a single spin coupled to a spin chain, with the latter acting as a bath. Inspired by previous works [1, 2] we study the entropy production in terms of the two contributions : information exchange with the bath and shifts of the bath away from its initial state. We find that coupling geometry and interaction type govern the trade-off between these two contributions with an initial creation of system–bath correlations and their subsequent dissipation into the bath.

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\* amanda.seedhouse (at) lpmmc.cnrs.fr

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# Time travels with freedom of choice and unambiguous nonlocal product measurements are equivalent

Hippolyte Dourdent<sup>1</sup>, Kyrylo Simonov<sup>2</sup>, Andreas Leitherer<sup>1</sup>, Ravi Kunjwal<sup>3</sup>, Saronath Halder<sup>4</sup>, Remigiusz Augusiak<sup>4</sup>, and Antonio Acín<sup>1,5\*</sup>

<sup>1</sup>*ICFO-Institut de Ciències Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels, Barcelona, Spain*

<sup>2</sup>*Fakultät für Mathematik, Universität Wien, Oskar-Morgenstern-Platz 1, 1090 Vienna, Austria*

<sup>3</sup>*Aix-Marseille University, CNRS, LIS, Marseille, France*

<sup>4</sup>*Center for Theoretical Physics, Polish Academy of Sciences, Aleja Lotników 32/46, 02-668 Warsaw, Poland*

<sup>5</sup>*ICREA, Passeig Lluís Companys 23, 08010 Barcelona, Spain*

Indefinite causal structures challenge the traditional notion that physical processes unfold according to a fixed global order of events [1]. In this context, process functions have been introduced as a noncausal generalization of deterministic classical communications [2], capturing logically consistent scenarios where each party's input may depend on the outputs of others without generating paradoxes, and interpreted as information-theoretic "non-trivial time travel compatible with freedom of choice" [3, 4]. Recently, Kunjwal and Baumeler showed that the Lugano process—a tripartite process function without a global past—is equivalent to the SHIFT measurement, a canonical example of quantum nonlocality without entanglement (QNLWE) [5]. QNLWE arises from product bases whose states are locally indistinguishable, meaning they cannot be perfectly discriminated using local operations and classical communication (LOCC) [6]. Moreover, they demonstrated that any set of local operations with a Boolean process function lacking a global past can be used to implement a QNLWE multiqubit product measurement. In this work, we elevate extensively this result by demonstrating a precise equivalence between all process functions and unambiguous QNLWE product measurements, for any dimension and any number of parties.

Our main result shows that the condition ensuring logical consistency of process functions — the existence of a unique fixed point under arbitrary local operations — is exactly mirrored by a simple unambiguity requirement on product bases, namely that each local quantum state is uniquely associated with a local basis. We demonstrate that every unambiguous product basis defines a unique process function, and that every process function can be encoded into an unambiguous product basis. We also show that noncausal process functions — those lacking any global past — are equivalent to unambiguous product bases exhibiting QNLWE, revealing that the operational content of the exotic noncausal correlations is precisely the ability to perform such measurements.

This equivalence thus shows that “time travel with freedom of choice”, as embodied by non-causal process functions, is mathematically indistinguishable from the ability to distinguish perfectly the states of unambiguous QNLWE product bases. We provide a systematic toolbox for generating new examples of noncausal process functions and corresponding QNLWE bases across arbitrary dimensions and multipartite scenarios. Remarkably, our result also shows an equivalence between causal inequalities that can be maximally violated by process functions and trivial nonsignalling inequalities that cannot be violated by non-signalling probabilistic theory [7].

Finally, our equivalence illuminates the relation between structural limits : e.g. bipartite process functions are always causal, so no bipartite unambiguous product basis can display QNLWE. It provides both a new perspective on indefinite causal order and practical tools for constructing resources beyond LOCC, with potential applications to quantum information processing, and even insights into spatiotemporal closed timelike curves [8].

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\* hippolyte.dourdent@icfo.eu

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## Analog to digital converters in the quantum regime

Thomas Pousset,<sup>\*</sup> Romain Alléaume,<sup>†</sup> and Nicolas Fabre<sup>‡</sup>

*Telecom Paris, Institut Polytechnique de Paris, 19 Place Marguerite Perey, 91120 Palaiseau, France*

In continuous variable quantum key distribution, the information is encoded in the intensity and phase of the optical field in the quantum regime where the signal power is comparable to quantum fluctuations and the prevalent noise is the shot noise. In this context, DSP allows for performing certain coherent detectors [1], correcting linear setup impairments [2] and performing digital mode projection to extract the information encoded in the optical field. To take advantage of the computational power offered by DSP, it is necessary to convert the analog optical signal into a digital signal by using an electronic processing stage followed by an analog to digital converter (ADC). A model defining the detector sample modes accounting for DSP, has been developed in [3] in the case of linear electronics and ideal ADC assuming no noise sources other than the quantum fluctuations of the signal. They assume that DSP can be backpropagated to the optical domain which allows to define an effective optical mode which can be compared to the emitted mode to define a mode-matching coefficient equivalent to an optical transmission coefficient.

Considering a coherent state detection with the model of [3], we show that Nyquist-Shannon criterion must account for the signal quantum fluctuations and not just the emission bandwidth. We assume an electronic bandwidth (BW) larger than the coherent state BW and a sampling frequency larger than twice the coherent state BW but smaller than twice the electronic BW and show that although this situation allows lossless reconstruction of the signal in the classical regime, in the quantum regime the measurement is impeded by extra vacuum noise corresponding to unused sidebands. Then to quantitatively compute the losses due to the ADC, we consider the modes reconstructible by linear processing of the ADC samples, and derive the one that maximizes the mode-matching coefficient. We illustrate our results by considering a raised root cosine (RRC) as the emitted mode as shown in Fig. 1 and show the need to oversample the signal higher than the electronic BW.

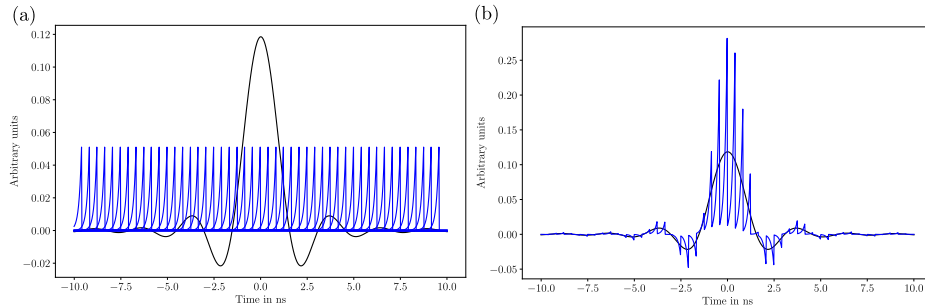


FIGURE 1. (a) Emitted RRC superposed with samples modes measured by the detector and (b) Emitted RRC superposed with the best mode reconstructible by the detector. In solid black line is plotted the raised root cosine mode. In solid blue line of (a), each peak corresponds to the mode of a sample measured by the detector. The sample modes are linearly combined in order to reconstruct the mode plotted in solid blue line of figure (b) which maximizes the overlap with the RRC while remaining in the reconstructible mode set.

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<sup>\*</sup> thomas.pousset@telecom-paris.fr

<sup>†</sup> romain.alleaume@telecom-paris.fr

<sup>‡</sup> nicolas.fabre@telecom-paris.fr

# Brightness measurement of the single-photon emission from a nanowire quantum dot in the blue-green spectral range

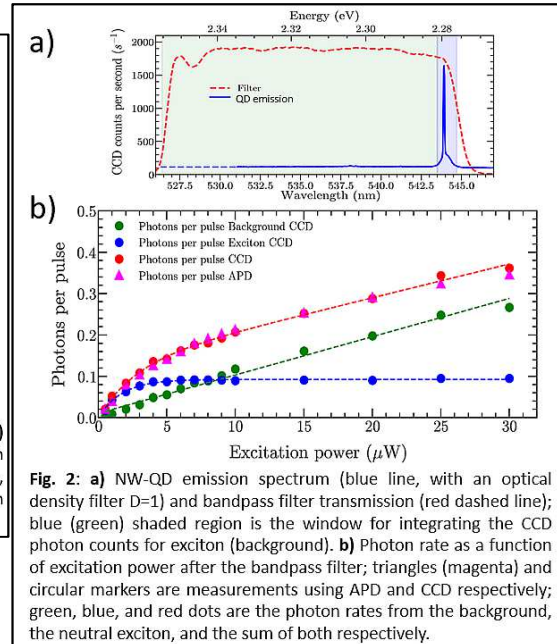
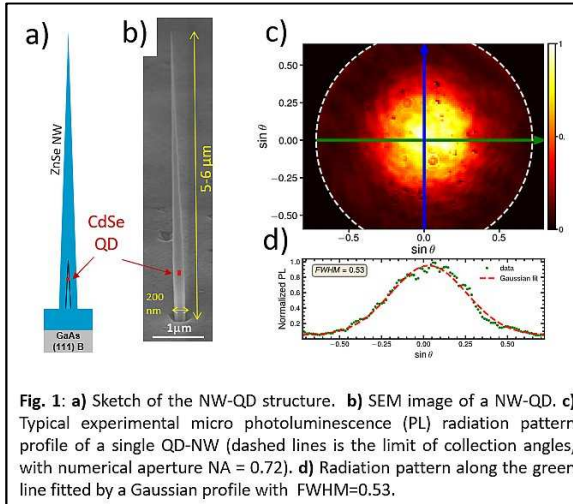
F. Granger<sup>1</sup>, L. Vallejo<sup>1</sup>, G. Nogues<sup>2</sup>, E. Bellet-Amalric<sup>1</sup>, J. Cibert<sup>2</sup>, D. Ferrand<sup>2</sup> and K. Kheng<sup>1\*</sup>

<sup>1</sup> Univ. Grenoble-Alpes, CEA, Grenoble-INP, IRIG, PHELIQS, 38000 Grenoble, France.

<sup>2</sup> Univ. Grenoble-Alpes, CNRS, Inst. NEEL, 38042 Grenoble, France.

We investigate the single-photon emission efficiency of a CdSe a quantum dot (QD) embedded in a bottom-up ZnSe nanowire (NW) grown by Molecular Beam Epitaxy. This system emits in the blue-green spectral range (450-580 nm) which offers major benefits for free-space quantum communication compared to longer wavelengths such as compatibility with both airborne and submarine communications, smaller optics size, and better spatial filtering [1].

The NW acts as a photonic wire (Fig. 1a) and has a tapered shape which gradually expands the confined optical mode  $HE_{11}$ , reducing the far-field emission angle (Fig. 1c), enhancing collection efficiency. The brightness measurements are carried out at low temperature (6 K), under pulsed excitation (above the ZnSe bandgap) at 76 MHz, collecting photons from the top facet of the NW. As a first step, we use a spectrometer and a CCD camera to characterize the emission spectra, the pulse excitation power dependence, and the intensity saturation regime of the neutral exciton (Fig. 2). We observe single-photon emission from the neutral exciton with an anti-bunching value  $g^{(2)}(0) < 0.07$ . We then apply a direct, practical method, bypassing the spectrometer and using a bandpass filter (20 nm spectral window) and an avalanche photodiode (APD) to measure the photon count rate from neutral exciton recombination. This approach yields **2.9 MHz (0.04 photon per pulse)** of single photons just before the detector (Fig. 2b). This value would be higher if the QD did not trap an electron from time to time, changing the neutral exciton into a charged exciton. Including contributions from both the neutral and charged excitons, the total photon detection rate could reach **11 MHz (0.15 photon per pulse)**. After calibration of the setup, we obtained a brightness of **0.18 photon per pulse** at the first lens from both the neutral and charged excitons. These outstanding values from an as-grown quantum emitter demonstrate the benefit of the NW photonic geometry for efficient photon extraction, underlining the strong potential of this nanowire-based system for scalable quantum communication applications.



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\* kkheng@cea.fr

# Design of integrated ion-photon interfaces : a neural network approach

I.P. De Simeone<sup>1</sup>, G. Maltese<sup>2</sup>, M.Ravaro<sup>1</sup>, M.Amanti<sup>1</sup>, F. Baboux<sup>1</sup> and , S. Ducci<sup>1\*</sup>

<sup>1</sup>*Laboratoire Matériaux et Phénomènes Quantiques,  
Université Paris Cité, 75013 Paris, France*

<sup>2</sup>*Microsoft Azure Fiber, Romsey, United Kingdom*

Photons exhibit excellent resilience to decoherence and negligible crosstalk, making them particularly suitable as flying qubits for quantum information transmission. Trapped ions, on the other hand, offer strongly interacting qubits via Coulomb forces, enabling high-fidelity quantum logic gates and applications in quantum metrology. In this context, the development of integrated ion-photon interfaces would pave the way to scalable quantum networks with trapped ions as stationary quantum nodes and photons as carriers of quantum information. Designing such an interface requires navigating a high-dimensional, multi-objective design space. For this task, traditional grid-search methods become computationally prohibitive.

In this work, we leverage neural networks for their differentiability and ability to exploit gradient-descent optimization. We develop a U-Net Convolutional Neural Network [1] to design an ion-photon interface based on an AlGaAs microcavity for non-degenerate spontaneous parametric down-conversion (SPDC). The proposed device consists of a multilayer AlGaAs waveguide operating in a transverse pump configuration [2] generating entangled photon pairs at respective wavelengths of 1550 nm and 1092 nm. The 1092 nm photon is resonant with a specific atomic transition of the  $\text{Sr}^+$  ion, allowing coherent interaction between the photon and the ion. Consequently, its entangled partner at 1550 nm—within the telecom band—can serve as a flying qubit, while preserving entanglement with the stationary ion qubit.

Our design tool enables the prediction of the spatial mode profiles and effective refractive indices of the signal and idler photons, based on the underlying AlGaAs multilayer epitaxial structure. The optimized device exhibits an estimated conversion efficiency of approximately  $10^{-11}$  pairs per pump photon, which is comparable to state-of-the-art degenerate SPDC sources based on the same geometry [3]. Thanks to the versatility of the proposed design tool, ongoing efforts focus on applying it to a broader class of waveguide-based photon-pair sources, particularly targeting copropagating configurations [4].

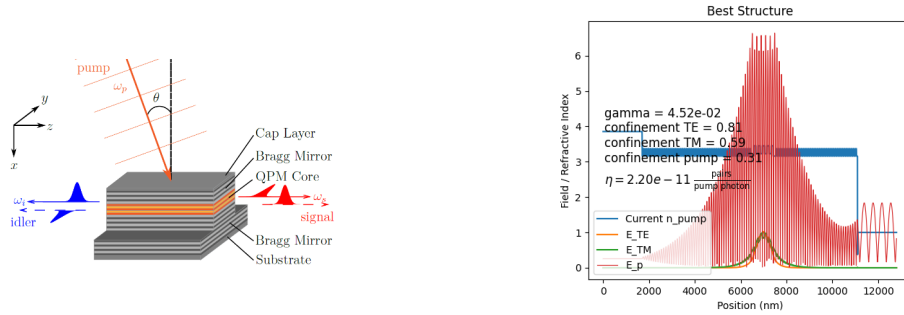


FIGURE 1. (Left) Sketch of the AlGaAs waveguide microcavity in the transverse pump configuration. (Right) Spatial profiles of the optical fields involved in the SPDC process within the optimized ion-photon interface.

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\* sara.ducci@u-paris.fr



# Engineering and measuring multimode entanglement in the continuous-variable regime

W. Zeidan<sup>1</sup>, R. Dalidet<sup>1</sup>, A. Petitjean<sup>1</sup>, L. Labonté<sup>1</sup>, S. Tanzilli<sup>1</sup>, J. Etesse<sup>1</sup>, G. Patera<sup>2</sup>, A. Martin<sup>1</sup>, V. D'Auria<sup>1\*</sup>

<sup>1</sup>*Institut de Physique de Nice, CNRS, UMR 7010, Université Côte d'Azur, 06108 Nice Cedex 2, France*

<sup>2</sup>*Physique des Lasers Atomes et Molécules, CNRS, UMR 8523, University of Lille, 59000 Lille, France*

Developing new models of quantum computing and quantum communication protocols requires advanced technologies that are more compact, loss tolerant, and that allow us to have higher scalability to match the complexity of tasks [1]. This can be done in quantum optics with observables in the Continuous-Variables regime (CV) by encoding information on the entanglement of frequency-time modes of the electromagnetic field [2]. An example of this approach is the use of highly multimodal states, called cluster states, which can be used for one-way quantum computing protocols [3].

For our project, we aim to generate and engineer these highly multimodal states by tailoring the quantum correlations between modes of light we generate via the process of Parametric Down Conversion (PDC). We are engineering the spectral envelope of the pump that we send to a periodically poled KTP crystal (ppKTP). These correlations are fully described by the Joint Spectral Amplitude (JSA). This function is governed by the spectral envelope of the pump and the phase-matching function of the crystal (PMF). Consequently, spectral modulations of the pump will modulate the JSA and engineer correlations between multiple modes [4].

In our experimental setup, the pump of the ppKTP is a pulsed 778 nm beam generated via second harmonic generation in a periodically poled Lithium Niobate (ppLN). The measured Joint Spectral Intensity (JSI =  $|JSA|^2$ ) is presented in Fig.1(a) where we can see the result of the product of the gaussian spectral envelope of the pump and the *sinc* function of the PMF. This JSI is obtained by performing a stimulated parametric down conversion by seeding our crystal with a CW tunable telecom laser sent together with the pulsed pump. To inspect the modal composition of our JSI, we make a singular value decomposition (SVD), known as the Schmidt decomposition. This decomposition gives us information on the number of effective spectral modes composing the state, called the Schmidt number. For this first JSI, the Schmidt number is  $K = 1.10$ , which means that we just excited one spectral mode. Then, we tailored the pump spectral envelope by adding a wave shaper to the setup. The resulting tailored JSIs are presented in Fig.1(b) and (c). We can see how, by engineering the pump spectral envelope, the Schmidt number of the JSI gets higher, which proves the excitation of additional spectral modes. These preliminary results confirm our ability to successfully engineer multimode correlations in the spectral domain.

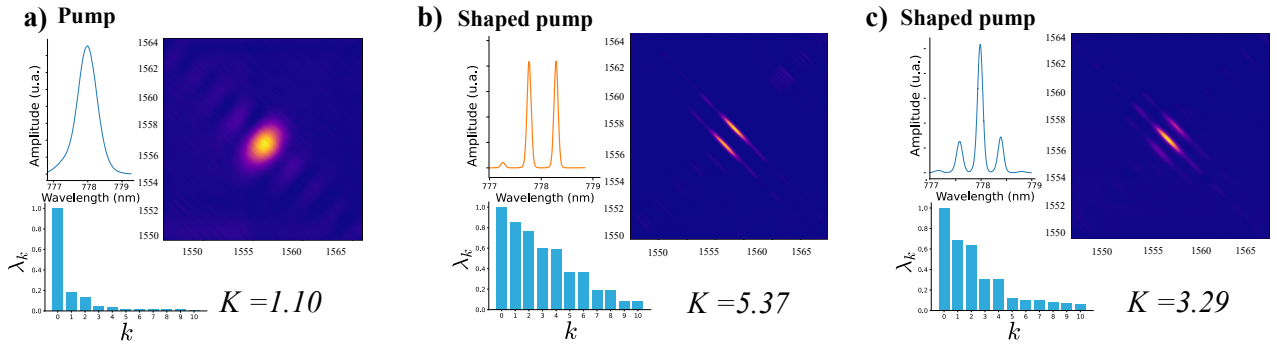


FIGURE 1 – Measured JSI of generated states in the ppKTP crystal with different pump spectral envelopes. (a) Untailored pump yielding a Schmidt number of  $K = 1.10$  modes composing the state. (b-c) Tailored pumps that result in higher Schmidt numbers of  $K = 5.37$  and  $K = 3.29$ , respectively.

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\* wadad.zeidan@univ-cotedazur.fr

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## Experimental Implementation of Quantum Oblivious Transfer from One-Way Functions

Adriano Innocenzi<sup>1</sup>, Verena Yacoub<sup>1</sup>, Álvaro Yángüez<sup>1</sup>, Pascal Lefebvre<sup>2</sup>, Alex B. Grilo<sup>1</sup> and Eleni Diamanti<sup>1</sup>

<sup>1</sup> Sorbonne Université, CNRS, LIP6, 4 Place Jussieu, Paris F-75005, France

<sup>2</sup> KTH Royal Institute of Technology, Stockholm, Sweden

Secure multiparty computation (SMPC) is a cryptographic protocol that allows the communicating parties to compute the result of a given function without disclosing their input parameters. It has been shown that SMPC [1] can be based on the oblivious transfer (OT) functionality. In OT, Alice has two messages  $\{m_0, m_1\}$  while Bob has a choice bit  $b \leftarrow \{0, 1\}$ . At the end of the interaction, Bob retrieves only  $m_b$  and Alice has no information on  $b$  [2]. As shown in [3], classically, one-way functions (OWF) do not imply OT. In the attempt of overcoming this limit, [4] proposed the first quantum OT (QOT) scheme, which exploited BB84 [5] and a bit commitment (BC) subroutine to guarantee security against a malicious receiver. Unfortunately, unconditional security for BC (and consequently for QOT) is prevented by [6, 7]. However, [8] proved the possibility of achieving computational security in a simulation-based framework by providing BC schemes with two properties : *extractability* and *equivocality*. For the first time, [9, 10] showed how to build computationally-secure BC schemes from OWF by leveraging quantum communication, hence obtaining computationally-secure QOT from OWF and surpassing the classical limit of [3]. Unfortunately, both [9] and [10] constructions are not noise tolerant and their resource consumption scales rapidly with the required security, making an experimental implementation unpractical. To solve these problems, we proposed a practical, noise-tolerant QOT protocol [11], based on *equivocal* and *relaxed-extractable* bit commitments and proven secure in a simulation-based framework. In our scheme, Alice and Bob exchange BB84 states bidirectionally over a quantum channel. Experimentally, we implement it by allowing the parties to send transmission and reception queries to the *Control Station* of a single polarization-based weak coherent pulse source, which prepares the qubits polarization states and measures them with a passive setup. The *Transmitter* uses an electro-optic amplitude modulator to carve ns-pulses in a 4 mW continuous-wave laser at 1550 nm. Two variable optical attenuators are then used to simulate single-photon pulses and their polarization is changed via an electro-optic polarization modulator. The *Receiver* passively measures the states through two polarizing beam splitters, then the photons are detected with a superconducting nanowire single-photon detector (SNSPD), with a maximum detection rate of 10 MHz. The performance of our protocol has been assessed by comparing several figures of merit with BCKM21 benchmark. The number of queries to computationally-demanding functions – such as PRGs, hashes and RNGs – is a crucial aspect for determining the protocol execution time and memory consumption and has been reduced by seven orders of magnitude. However, the key factor has been identified in the total number of required BB84 states, as the major bottleneck is represented by the SNSPD detection rate. In fact, while in BCKM21 the total number of states is given by  $N_{BB84} \in \Omega(\lambda_{CK88}^2)$ , our protocol only requires  $N_{BB84} \in \Omega(\lambda_{CK88})$ , allowing for a remarkable reduction of the qubits acquisition time, from 19 days to 210 ms.

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Nicolas Laurent-Puig,<sup>1</sup> Laura dos Santos Martins,<sup>1</sup> Luis Bugalho,<sup>2</sup> Santiago Scheiner,<sup>1</sup> Majid Hassani,<sup>3</sup> Sean Moore,<sup>1</sup> Damian Markham,<sup>1</sup> and Eleni Diamanti<sup>1</sup>

<sup>1</sup>*Sorbonne Université, CNRS, LIP6, 4 Place Jussieu, Paris F-75005, France*

<sup>2</sup>*Instituto Superior Técnico, Universidade de Lisboa, Portugal*

<sup>3</sup>*Instituut-Lorentz, Universiteit Leiden, P.O. Box 9506, 2300 RA Leiden, The Netherlands*

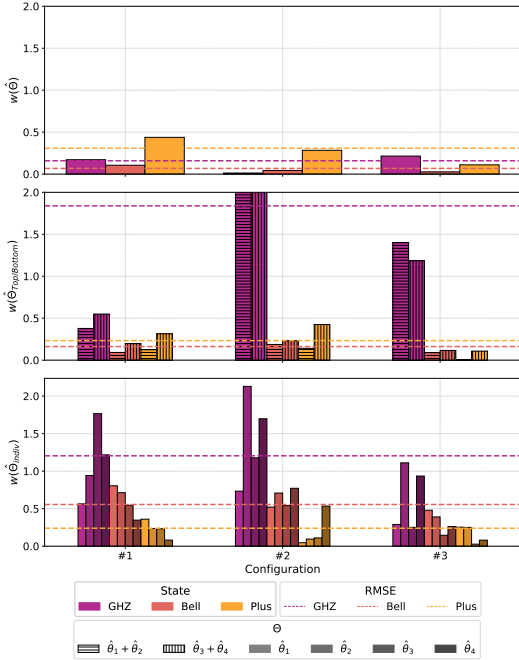


Figure 1: Distance of the estimation of  $w(\hat{\Theta})$ ,  $w(\hat{\Theta}_{top/bottom})$  and  $w(\hat{\Theta}_i)$  using the density matrix method with the real encoded value. The dotted lines represent the RMSE for each state over the 3 configurations.

perform measurements in the  $X$ -basis, share their outcomes, and compute the global parity of the joint measurement results. To find the true value of  $w(\Theta)$ , based on the measurement outcomes, we can rely on maximum likelihood estimation, for which we need to select a joint probability distribution. Relying on a description of the states' density matrix, obtained via quantum state tomography, performed at the beginning of each configuration, we build the joint probability distribution. Finally, to confirm the advantage of GHZ states in terms of both precision of the estimation and privacy of the protocol, we perform the same protocol using Bell and  $|+\rangle$  (Plus) states and compare the estimation results. For this purpose, we consider the estimation of  $w(\Theta_{top/bottom}) = \theta_i + \theta_j$  and  $w(\Theta_{indiv}) = \theta_i$ . We were able to deduce the FI for each estimator;

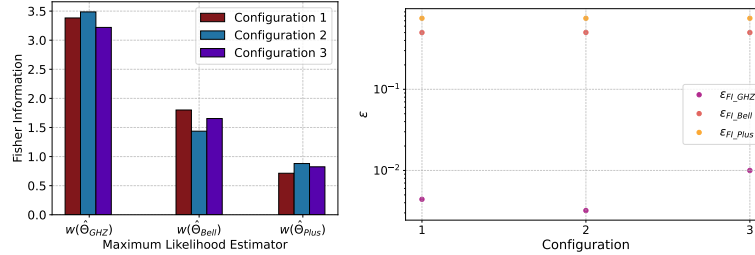


Figure 2: **Left:** Fisher Information for each configuration. **Right:** Privacy  $\epsilon$  for the GHZ, Bell, and Plus states.

as shown in Fig. 2 (left), the precision of our estimation is better for GHZ states as the corresponding FI is larger. Once the global function is estimated, we explore the feasibility of retrieving individual parameters. We compute estimates for each of the functions, as shown in Fig. 1. All states feature good estimates of the total sum of the angles; the Plus and the Bell states perform well for the sum two by two of the individual angles. Finally, for the GHZ and Bell states, the individual estimated values deviate significantly from the true parameters. This discrepancy highlights that the protocol preserves the privacy of the individual parameters, as no accurate single-parameter estimation can be extracted from the available data even using a cheating strategy. Finally, we estimate the privacy parameter  $\epsilon$ . As shown in Fig. 2 (right), the GHZ state exhibits high privacy, with negligible information leakage. In contrast, when using Bell and Plus states, the observed privacy is significantly reduced, reflecting greater information leakage.

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# Integrated Electro-Optic Effect and Polarization Routing in AlGaAs Photon-Pair Sources

Michael Choquer<sup>1</sup>, Célia Smai<sup>1</sup>, Othmane Meskine<sup>1</sup>, Marco Ravarolo<sup>1</sup>, Maria Amanti<sup>1</sup>, Florent Baboux<sup>1</sup>, and Sara Ducci<sup>1\*</sup>

<sup>1</sup>Université Paris Cité, CNRS,

Laboratoire Matériaux et Phénomènes Quantiques, 75013 Paris, France

<sup>2</sup>Université Paris-Saclay, CNRS,

Centre de Nanosciences et de Nanotechnologies,

91120 Palaiseau, France

Quantum photonic integrated circuits (QPICs) are a promising technological platform for various applications, ranging from secure long-distance communications to the simulation of complex phenomena. QPICs based in III-V semiconductors, in general and in AlGaAs in particular, are especially attractive for the monolithic integration of active and passive photonic components; recent work in AlGaAs QPICs has demonstrated electrically injected photon pair sources [1] as well as a high degree of photon indistinguishability [2] and entanglement [3]. These results are encouraging further development in AlGaAs QPICs towards more complex multi-entangled photon states, notably by engineering two-photon interference between the emitted photon pairs from multiple nominally identical SPDC sources; such states will expand the applications of these sources in quantum networking, computing, and simulation [4]. Controlling this interference requires a low-loss and reconfigurable interface between classical and quantum photonic degrees of freedom: in particular, photon modulation via the linear electro-optic effect is commonly exploited in classical optical communications networks and benefits from straightforward integration within the standard fabrication processes of many QPIC platforms. Although several experiments utilizing the electro-optic effect have demonstrated the on-chip control of photon-pair phase and polarization degrees of freedom [5–7] these works either used external SPDC sources or integrated nonlinear ferroelectric crystals, namely LiNbO<sub>3</sub>, for photon pair generation. Combining direct-bandgap III-V quantum state sources with integrated electro-optic modulation has been proposed [4, 7] but not yet demonstrated. In this talk, we show the design, development and characterization of electro-optic tuners integrated on-chip with state-of-the-art AlGaAs photon-pair sources. Operating in the quantum regime, we realize tunable electro-optic delay lines, polarizing beamsplitters, and polarization rotators, validating that entangled photon pairs can be both efficiently generated and manipulated on-chip. These results constitute a step further in the landscape of complex fully integrated quantum photonic circuits and will increase the potential of AlGaAs photonic chips for quantum networks [8].

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\* sara.ducci@u-paris.fr

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## GdR TeQ Quantum Abstract

Essowéréo TCHAO<sup>1,2</sup>, Mauricio GOMEZ-ROBLES<sup>1,2</sup>, Margoth CORDOVA-CASTRO<sup>3</sup>, Robert W. BOYD<sup>3</sup>, and Rafael SALAS-MONTIEL<sup>1,2\*</sup>

<sup>1</sup>Laboratory Light, nanomaterials, and nanotechnologies - L2n CNRS UMR 7076,  
Université de Technologie de Troyes, 10004, Troyes, France

<sup>2</sup>EUT+ Institute of Nanomaterials and Nanotechnologies-EUTINN, European University of Technology, European Union

<sup>3</sup>Department of Physics, University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada

This work proposes the design, fabrication, and characterization of an integrated photon-pair source using Spontaneous Four Wave Mixing (SFWM) in a silicon nitride microring resonator. The goal is to generate a signal photon at 606 nm, compatible with the transitions of praseodymium ions  $\text{Pr}^{3+}$ , and an idler photon at 1430.5 nm, corresponding to a Coarse Wavelength Division Multiplexing (CWDM) channel in the E-band. Building upon previous studies [1] that used a waveguide with a height of  $h=430$  nm and a width of  $w=818$  nm, we theoretically demonstrate that a waveguide with a height of 500 nm and a width of approximately 996 nm can achieve equivalent phase-matching conditions, resulting in a spectral bandwidth close to 3.98 MHz. Furthermore, we determined the resonator radius to ensure phase matching at the target wavelengths and calculated the ideal gap region for efficient coupling between the bus waveguide and the resonator. After validating the device in the classical domain, we are working on improving the quality factor, particularly in fabrication. We are also proceeding with quantum characterization and plan to extend this approach toward the generation of photon triplets via nonlinear processes. This work aims to overcome the current limitations in terms of efficiency and source integration, bringing us closer to realizing integrated photon triplet sources that are efficient, stable, and suitable for quantum photonic architectures, especially those compatible with telecommunications.

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\* rafael.salas@utt.fr

## Permutationally decodable CSS quantum codes

Massinissa Zenia<sup>1</sup>, Yannick Saouter<sup>2</sup>, Gilles Burel<sup>1</sup> and Roland Gautier<sup>1</sup>

<sup>1</sup>Lab-STICC (CNRS UMR 6285), Université de Bretagne Occidentale, SI3 team, Brest, France and

<sup>2</sup>Lab-STICC (CNRS UMR 6285), IMT-Atlantique, CODES team, Brest, France

Quantum technology is a rising and promising technology. It has many possible applications in various domains of science. A major problem in the design of quantum devices is the decoherence of quantum states. As for classical telecommunications, quantum error correcting codes have been proposed as a solution to this problem [1]. Following this seminal work, quantum CSS codes [2] have been proposed. They have the advantage of enabling the construction of quantum codes with desired minimum distance.

Quantum CSS codes are built upon two classical binary linear error-correcting codes  $C_1$  and  $C_2$  such that  $C_1$  is self-orthogonal and  $C_2 \subset C_1^\perp$ . A code  $C$  such that  $C = C^\perp$  is said to be self-dual. Any subcode of  $C$  is then self-orthogonal. A classical method for the search of linear codes with a large minimum distance is to select codes with large automorphism groups. A typical example of self-dual codes having large minimum distances is given by the class of extended quadratic residue codes of length  $p + 1$  where  $p$  is a prime number of the form  $p = 4k + 3$ . These codes are stable under the action of  $PSL(2, p)$ .

In our work, we have relied on this family of codes to construct new self-orthogonal codes and related quantum CSS codes. More precisely, for each extended quadratic residue code, the set of its minimum distance codewords have been partitioned by the action of each maximal subgroup of the automorphism group. For any set of a partition, the code generated by linear combinations was considered and sometimes, strict subcodes were generated. These codes are then self-orthogonal and have a large automorphism group by construction. Their relative dual code is also invariant on the same automorphism group and therefore good CSS codes can be built.

Obtained results are depicted in Figure 1. Each table gives the parameters of the obtained quantum  $[[n, q, d^\perp]]$  codes. Parameter  $m$  is the multiplicity of minimum distance codewords while  $Aut(C)$  describe the structure of the automorphism group. In [4], the authors describe an alternative to syndrome decoding when algebraic decoding is possible. The technique of the article can be used here when considering permutation decoding [3]. Parameter  $G$  is the Gordon bound which gives a lower bound on the number of permutations required for complete decoding. Finally, parameter  $P$  gives the number of permutations allowing complete decoding, as found by the authors.

| $n$ | $k$ | $q$ | $d^\perp$ | $m$ | $Aut(C)$      | $G$ | $P$ |
|-----|-----|-----|-----------|-----|---------------|-----|-----|
| 24  | 8   | 8   | 3         | 8   | $PSL(2, 7).2$ | 3   | 4   |
| 23  | 11  | 1   | 7         | 253 | $M_{23}$      | 15  | 24  |
| 22  | 10  | 2   | 6         | 77  | $M_{22}.2$    | 7   | 9   |
| 16  | 5   | 6   | 4         | 140 | $2^4.A_8$     | 4   | 4   |

Extended (24,12,8) Golay code

| $n$ | $k$ | $q$ | $d^\perp$ | $m$ | $Aut(C)$      | $G$ | $P$ |
|-----|-----|-----|-----------|-----|---------------|-----|-----|
| 32  | 15  | 2   | 6         | 32  | $2^2.3.2$     | 7   | 11  |
| 32  | 9   | 14  | 4         | 216 | $2^7.3.2^2$   | 4   | 5   |
| 31  | 15  | 1   | 7         | 155 | $31.3.5$      | 15  | 32  |
| 24  | 8   | 8   | 3         | 8   | $PSL(2, 7).2$ | 3   | 4   |

EQR(32, 16, 8) code

| $n$ | $k$ | $q$ | $d^\perp$ | $m$  | $Aut(C)$    | $G$ | $P$ |
|-----|-----|-----|-----------|------|-------------|-----|-----|
| 48  | 20  | 8   | 8         | 810  | $2^3.3.2^2$ | 20  | 77  |
| 48  | 12  | 24  | 4         | 132  | $2^2.3.2$   | 4   | 9   |
| 47  | 23  | 1   | 11        | 4324 | $47.23$     | 66  | 332 |

EQR(48, 24, 12) code

FIGURE 1 – Parameters of new self-orthogonal codes extracted from extended quadratic codes.

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## Resonant Spectroscopy of W Centers in Silicon

Alicia Morandini<sup>1\*</sup> and Krithika V. R.<sup>1</sup>, Giuliano Coppola<sup>2</sup>, Félix Cache<sup>1</sup>, Baptiste Lefaucher<sup>2</sup>, Yoann Baron<sup>2</sup>, Jean-Baptiste Jager<sup>3</sup>, Frédéric Mazon<sup>2</sup>, Sébastien Kerdilès<sup>2</sup>, Isabelle Robert-Philip<sup>1</sup>, Vincent Jacques<sup>1</sup>, Guillaume Cassabois<sup>1,4</sup>, Jean-Michel Gérard<sup>3</sup> and Anaïs Dréau<sup>1</sup>

<sup>1</sup>Laboratoire Charles Coulomb, Université de Montpellier and CNRS, 34095 Montpellier, France

<sup>2</sup>Université Grenoble Alpes, CEA-LETI, 38000 Grenoble, France

<sup>3</sup>Université Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France

<sup>4</sup>Institut Universitaire de France, 75231 Paris, France

Single-photon generation, processing and detection are routinely performed in silicon-based quantum photonic chips [1]. However, the highly probabilistic nature of the single-photon generation relying on non-linear optical processes limits the efficient generation of large entangled photonic states [1]. The recent isolation in silicon of atomic-like single-photon sources (SPS) based on individual fluorescent defects [2], such as G centers [3], T centers [4], Er dopants [5], could open new perspectives for the realization of on-demand sources of indistinguishable photons directly integrated into silicon. In this prospect, the W center has emerged as a particularly promising candidate [6, 7]. Its emission features a strong, linearly polarized zero-phonon line (ZPL) at 1218 nm, close to the telecom O-band, originating from a single emission dipole and greatly facilitating integration into nanophotonic structures such as waveguides and cavities. This tri-interstitial complex can be created at the single-defect scale with nanoscale positioning using silicon-focused ion beam [8] or silicon implantation through a mask with nanoholes [7]. The recent integration of a single W center in a circular Bragg grating (CBG) microcavity has demonstrated a detected single-photon count rate exceeding  $1.3 \text{ Mcounts.s}^{-1}$ , as well as a proportion of photons emitted in the ZPL that reaches  $\sim 99\%$  [7]. The next milestone is to control the W center's optical coherence to achieve indistinguishable single-photon emission.

In this context, we will present preliminary results on the resonant excitation of W centers in silicon, expected to cause less perturbation to the defect emission compared to the above-bandgap optical excitation used to date [6–8]. We perform photoluminescence excitation (PLE) spectroscopy using an ultra-fine tunable laser ( $< 1 \text{ MHz}$  resolution) on an ensemble of W centers integrated within a CBG cavity. Through resonant time-resolved photoluminescence measurements, we investigate ionization and charge-state fluctuation processes affecting the W center's emission. These developments will serve as the basis for a detailed study of the spectral diffusion limiting the photon coherence of W centers integrated into photonic structures.

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\* alicia.morandini@umontpellier.fr

# Secure Delegated Sensing with polarization-entangled Bell states

Daniel Carvalho de Salles<sup>1,\*</sup>, Sean William Moore<sup>2</sup>, R. Dalidet<sup>1</sup>, T. Troisi<sup>1</sup>,  
A. Martin<sup>1</sup>, G. Sauder<sup>1</sup>, S. Tanzilli<sup>1</sup>, D. Markham<sup>2</sup>, and L. Labonté<sup>1,†</sup>

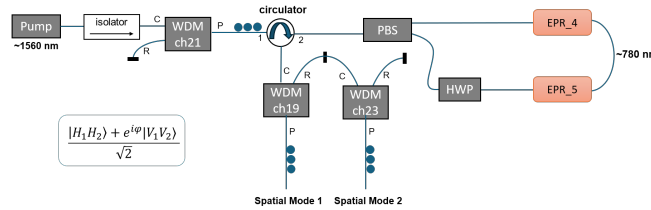
<sup>1</sup>Université Côte d'Azur, CNRS, Institut de Physique de Nice, 17 rue Julien Lauprêtre, 06200 Nice, France

<sup>2</sup>Sorbonne Université, CNRS, LIP6, F-75005 Paris, France

On the eve of global implementation of quantum networks with remote nodes separated by hundreds of kilometers and supported by the existing telecommunications fiber infrastructure, applications beyond Quantum Key Distribution are emerging. These include Blind Quantum Computing and Distributed Quantum Sensing, which are developing at a rapid pace. The context in which our work is placed is akin to both of the latter examples : a Network of Quantum Sensors, where each user locally encodes a parameter to be estimated individually or as part of a function of multiple parameters. Results can be shared secretly due to informational asymmetry created by the entanglement shared between nodes or the use of non-orthogonal quantum states/measurements. The implementation of an appropriate network protocol ensures the security against adversarial interferences for specific applications.

The graph interpretation of networks of quantum sensors represents vertices containing one qubit and edges portray entanglement shared between the different nodes. The resource consumption for making a fully interconnected graph scales unfavorably if each vertex contains one qubit, since making multiphoton entangled states — e.g. GHZ — poses significant challenges for obtaining high generation rate and fidelity. The application versatility and enhanced precision achieved by using states such as GHZ can be traded off by the implementation of entangled states with fewer photons, which are distributed in the network as a superposition of 2-photon states delocalized over pairs of nodes [1]. This restricts protocols to be implemented only in a pairwise manner, but enables speeding up and scaling of networks.

We aim to use a polarization-entangled photonic state, distributed between couples of nodes as a superposition of Bell states. This allows for implementation of delegated sensing tasks, where a user of the network can request to estimate another's parameter. The verification protocol to be used has been proposed in the context of quantum teleportation [2], but fits well with the task at hand to ensure a secure transfer of the parameter-encoded results between remote users. An experimental implementation of a remote quantum sensing protocol that is undeniably secure against man-in-the-middle-type of attacks and with thorough analyses of the security parameters has yet to be demonstrated. The EQUINE project, jointly conducted between INPHYNI (Nice) and LiP6 (Paris), aims to break this barrier and lay the foundations for the implementation of experiments in this emerging field of research.



**Figure 1** : Sagnac loop configuration for generating polarization-entangled Bell states.

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\* Daniel.CARVALHO-DE-SALLES@univ-cotedazur.fr

† Laurent.LABONTE@univ-cotedazur.fr



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## Towards entanglement-based quantum communication over a field deployed fiber-network in Paris

C. Smar<sup>1</sup>, O. Meskine<sup>1</sup>, A. Lemaître<sup>2</sup>, M. Morassi<sup>2</sup>, M. Ravaro<sup>1</sup>, M.I. Amanti<sup>1</sup>, F. Baboux<sup>1</sup> and S. Ducci<sup>1\*</sup>

<sup>1</sup>Laboratoire Matériaux et phénomènes quantiques, Université Paris Cité, CNRS, 75013 Paris, France

<sup>2</sup>Centre de Nanosciences et de Nanotechnologies, Université Paris Saclay, Palaiseau, France

Entanglement-based quantum key distribution (QKD) is one of the most secure quantum communication protocols, relying on the fundamental properties of quantum entanglement to ensure security against eavesdropping. These protocols can operate without the need for trusted nodes and are source-independent, making them strong candidates for device-independent QKD. Significant efforts are currently being made to bring these protocols out of the laboratory and into real-world networks [1].

To support practical deployment, it is essential to rely on existing telecommunication infrastructure while addressing several technical challenges. Chromatic dispersion must be compensated to preserve temporal correlations, and distributing entangled states between distant measurement stations requires precise clock synchronization, often at the picosecond level. It is also necessary to encode quantum information in photonic degrees of freedom that are both robust and compatible with long-distance transmission. Among the most common encodings, polarization stands out for its simplicity : polarization states are relatively easy to generate, manipulate, and measure.

In this work, we demonstrate the distribution of polarization-entangled photon pairs over a 30 km deployed fiber link. The quantum source is based on an AlGaAs Bragg-reflection waveguide. This III-V semiconductor platform combines strong second-order nonlinearity leading to efficient photon-pair generation ( $\sim 2.7 \times 10^6$  pairs/s/mW) and a large electro-optic effect enabling on-chip state manipulation at room temperature [2]. Moreover, AlGaAs direct bandgap has already led to the monolithic integration of laser action and internal parametric down-conversion on a single chip [3].

The generated biphoton state exhibits a broad bandwidth of 93 nm, centered in the telecom C-band, allowing for entanglement distribution based on dense wavelength multiplexing across several 100 GHz ITU channels. We report a fidelity exceeding 96.7% (85%) to the polarization Bell state  $|\Psi^+\rangle$  over 11 (20) energy-matched pairs of 100 GHz ITU channels, demonstrating the source's high entanglement quality and its suitability for multi-user quantum networks. We further conducted quantum state tomography after transmission through the deployed fiber link and observed that a 12 nm-broad two-photon state maintains a fidelity exceeding 91%. These results highlight the potential of polarization encoding in real-world conditions and illustrate the interest of AlGaAs-based integrated sources for scalable, practical entanglement-based quantum communication over existing telecommunication infrastructure.

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\* sara.ducci@u-paris.fr

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# Transmission of entangled two-photon states through scattering media using coherence-entanglement transfer

Shaurya Aarav<sup>\*1,2</sup> and Hugo Defienne<sup>3</sup>

<sup>1</sup>Postdoctoral Researcher – CNRS – France

<sup>2</sup>Institut des Nanosciences de Paris – Sorbonne Université, Centre National de la Recherche Scientifique, Centre National de la Recherche Scientifique : UMR7588 – France

<sup>3</sup>Institut des nanosciences de Paris – Institut des NanoSciences de Paris, CNRS UMR 7588, Sorbonne Université, F-75005 Paris – France

## Abstract

Transmission of high-dimensional quantum states through real-world environments is essential for quantum communication and imaging, but aberrations and scattering scramble the signal and hinder practical use. A common solution employs a classical beacon beam to measure the transmission matrix and correct distortions, relying on the high-contrast speckle patterns of coherent light (1,2). In contrast, entangled photon pairs do not produce such speckles in intensity, making them unsuitable for direct wavefront correction. Moreover, introducing an auxiliary beacon increases system overhead, as it must be carefully matched to the quantum state in polarization, wavelength, and bandwidth.

Here, we present a fast, efficient approach that eliminates the need for external reference light by using the quantum state itself for wavefront correction. By shaping the pump beam, we tune the degree of spatial entanglement so that the two-photon state behaves either as a high-dimensional entangled state or as a low-dimensional, classical-like state. In the latter regime, speckles emerge in the two-photon intensity itself, enabling direct transmission matrix measurement with a spatial light modulator. Once the matrix is obtained, appropriate phase patterns restore the correlations of the high-dimensional state. By exploiting the fundamental coherence-entanglement duality (3), we demonstrate recovery and shaping of two-photon correlations through scattering, paving the way toward scalable quantum imaging and communication in complex environments.

Associated paper: Shaurya Aarav, Hugo Defienne. Wavefront correction of high-dimensional two-photon states via coherence-entanglement transfer. *arXiv:2509.04170* (2025)

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\*Speaker

# Violating Bell inequalities using photon path encoding

Alexis Rosio<sup>1\*</sup>, Verena Yacoub<sup>1</sup>, Ahmad Hasan<sup>1</sup>, and Enky Oudot<sup>1\*</sup>

<sup>1</sup>LIP6, Sorbonne Université, CNRS, 4 place Jussieu, 75005 Paris, France

Bell non locality is at the heart of Device Independent (DI) protocols such that DI Quantum Random Number Generators (DI QRNG) and DI Quantum Key Distribution (DI QKD). They offer higher security by removing assumptions about practical implementations of states and measurements. Moreover the sole violation of a Bell inequality to run a DI protocol is not sufficient, as a larger violation is needed to ensure security [3]. Therefore, finding an implementation of a Bell game which allows for high violation of a Bell inequality with a large loss robustness is of central interest for DI protocols. Photons are a natural information carrier choice as they allow for high speed distribution. Many violations of Bell inequalities using photons have been proposed [2] using intrinsic degrees of freedom of photons such as polarisation or time bin.

In this work we investigate the use of path entanglement for the violation of a Bell inequality. The advantage of this encoding is that Bell pairs can be distributed with a rate scaling as the square root of the transmittivity of the channel in an heralding protocol [1]. The drawback is that it is hard to implement generic Pauli measurements. In the literature those measurements are implemented using displacements and single photon counting [4, 5]. One noticeable improvement used a squeezing operation [1]. We display in Figure 1 the violation of the CHSH inequality with different encodings and in Figure 2 a proposed DI QKD scheme using path encoding. In this ongoing project we aim to reduce the gap between theoretical performances and practical implementations of DI protocols using path encoding by exploring new measurement schemes based on gaussian operations, conditioning and photon counting.

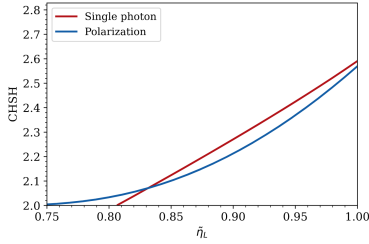


FIGURE 1. The difference of resistance to loss between polarisation and single photon/path encoding. [1]. We see that path encoding performs better on a large range of losses.

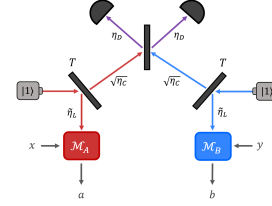


FIGURE 2. The DI QKD scheme proposed in [1]. Highly unbalanced beamsplitters combined with a Bell state measurement at the central station project Alice and Bob's local modes on e.g.  $\frac{|01\rangle + |10\rangle}{\sqrt{2}}$ , where  $|0\rangle$  and  $|1\rangle$  are Fock states.

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\* alexis.rosio@lip6.fr

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## An ultra-compact dilution refrigerator for rapid quantum device characterization and education

Clément Geffroy<sup>1</sup>, Éric Eyraud<sup>1</sup>, Dorian Nicolas<sup>1</sup>, Julien Jarreau<sup>1</sup>, Laura Kowalski<sup>1</sup>, Laurent Del-Rey<sup>1</sup>, Didier Dufeu<sup>1</sup>, Wolfgang Wernsdorfer<sup>2,3</sup>, Franck Balsetro<sup>1</sup>, Quentin Ficheux<sup>1</sup>, and Matias Urdampilleta<sup>1\*</sup>

<sup>1</sup>*Université Grenoble Alpes, CNRS, Grenoble INP, Institut Néel, 38402 Grenoble, France*

<sup>2</sup>*IQMT, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

<sup>3</sup>*PHI, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

As quantum technologies become increasingly complex, the demand for integrated electronics at cryogenic temperatures rises. This evolution requires cryogenic systems to support greater electronic integration, inevitably leading to the development of large-scale, high-cooling-power systems. However, quantum technologies are still in their early development stage, where trial-and-error procedures still help to optimize fabrication process or select hero-sample. Moreover, training personnel in cryostat operation and basic quantum characterization requires user-friendly, rapid-cycling platforms, a feature often lacking in large-scale systems.

To meet these demands, we have developed an ultra-compact, home-built cryogenic platform optimized for nanoelectronic device characterization. This system achieves a base temperature of 70 mK in 40 minutes, with a 15-minute cooldown to 4 K followed by a 25-minute condensation to 70 mK. The experimental stage offers sufficient volume for integrating DC and RF electronics, including attenuators, circulator and amplifier. In contrast to large-scale systems, this platform facilitates rapid cooldown-warmup cycles within a single day, significantly reducing the time required for characterization and benchmarking.

In addition, training future scientists on how to run quantum devices in a cryogenic equipment is vital for the solid state qubit community. In this context, our tabletop solution is currently being used by master students as part of their educational program.

This work is supported by CRYONEXT [1] and QUANTEDU [2].



FIGURE: Photograph of the *sionludi XS*, an ultra-compact dilution refrigerator. It features standard cryogenic components, including three precooling stages at 100 K, 20 K, and 4 K, as well as a base stage at 70 mK.

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[1] <https://quantique.france2030.gouv.fr/recherche-innovation/programme-cryonext/>

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\* [matias.urdampilleta@neel.cnrs.fr](mailto:matias.urdampilleta@neel.cnrs.fr)

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## Design and Conception of cryogenic attenuators for superconducting circuits

Evan Ichir<sup>1,2</sup>, Biswajit Dutta<sup>1</sup>, Sébastien Jézouin<sup>1</sup>, Alexis Jouan<sup>1</sup>, Audrey Bienfait<sup>1</sup>, Sylvain Hermelin<sup>1</sup>, Benjamin Huard<sup>1</sup>

<sup>1</sup>*Ecole Normale Supérieure de Lyon, CNRS,*

*Laboratoire de Physique, F-69342, Lyon, France*

<sup>2</sup>*Radiall, 642 Rue Emile Romanet, 38340 Voreppe, France*

Control and readout of superconducting circuits inside dilution fridges require bringing RF signals generated at room temperature to the last stage of the fridge which is typically below 20 mK. It is necessary to reduce the thermal noise produced by blackbody radiation at 300 K down to much less than a photon of noise at the device input. The use of attenuators, which are anchored at each stage of the dilution refrigerator, addresses this issue by swapping hot incoming signals with photons emitted at their own temperature.

While commercial dilution refrigerators offer a base plate temperature around 10 mK, thermalizing the microwave modes themselves turns out to be more challenging than simply anchoring the superconducting circuit to the mixing chamber plate. Indeed, some studies report an effective temperature of the incoming RF field comprised between 50 and 100 mK [1–3], drastically reducing the coherence time [5]. The coldest attenuator, which is usually anchored at the mixing chamber plate, plays a critical role because it is its temperature that will mainly determine the amount of black-body thermal noise incoming onto the superconducting circuit. Recent progress has been made using NiCr resistive thin films [4] or a 3D brass cavity [6].

Below 1 K, few phonons are available to conduct heat while the electrons have non negligible thermal conductivity at these temperatures [7]. The current commercial attenuators mainly rely on electron phonon coupling to thermalize them, but this coupling scales like  $T^5$  and is therefore suppressed below 1 K. This phenomena together with the Wiedemann-Franz law which links the electrical conductivity and the thermal conductivity of electrons in a normal metal [7] explains the unperfect thermalization of the attenuators at 10 mK.

We propose a coplanar waveguide geometry that efficiently cools down the electrons which heat up as a resistive thin film dissipates incoming microwave. In this poster, the fabrication process of the attenuator, simulations and measurements of the attenuation will be presented, together with thermometry protocol for an attenuator

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## Engineering of isolated G-centers in silicon with deterministic positioning

Krithika V R<sup>1\*</sup> and Alicia Morandini<sup>1</sup>, Yoann Baron<sup>2</sup>, Félix Cache<sup>1</sup>, Jean-Baptiste Jager<sup>3</sup>, Frédéric Mazen<sup>2</sup>, Frédéric Milési<sup>2</sup>, Sébastien Kerdiles<sup>2</sup>, Isabelle Robert-Philip<sup>1</sup>, Jean-Michel Gérard<sup>3</sup>, Vincent Jacques<sup>1</sup>, Guillaume Cassabois<sup>1,4</sup>, Anaïs Dréau<sup>1</sup>

<sup>1</sup>Laboratoire Charles Coulomb, Université de Montpellier and CNRS, 34095 Montpellier, France

<sup>2</sup>Université Grenoble Alpes, CEA-LETI, 38000 Grenoble, France

<sup>3</sup>Université Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 38000 Grenoble, France

<sup>4</sup>Institut Universitaire de France, 75231 Paris, France

Silicon is an ideal candidate for developing quantum technologies since, in addition to being the foundation of the photonics and microelectronics industries, it boasts mature fabrication protocols and seamless integration with existing CMOS architectures [1]. Silicon wafers have recently been shown to host a diverse range of near-infrared single-photon emitters [2], such as G center [3], W center [4], T center [5], Er dopant [6] and many other unidentified defect centers [8]. The integration of single fluorescent defects in silicon-based photonic cavities has developed considerably in recent years, enabling the demonstration of bright near-infrared single-photon sources [4], coherent control of spin-qubits interfaced with telecom single photons [5–7] and even remote entanglement generation between distant spins [5]. Among the detected single color centers, the G center is of particular interest due to its emission at 1.28  $\mu\text{m}$  in the telecom O-band [9], and a metastable spin triplet that could be used as a qubit [7, 10]. While single G center integration has been demonstrated for several photonic resonators [7, 11], the defects were randomly distributed over the silicon-on-insulator (SOI) wafers, thus drastically limiting the probability to get G centers well-coupled to the cavity mode. A fundamental requirement for further large scale applications is the controlled fabrication of G defects with deterministic positioning compatible with existing ion implantation semiconductor foundries.

In this work, we investigate the engineering of isolated G centers in SOI samples with up to sub-100-nm spatial resolution. To achieve this goal, our strategy is to adapt the co-implantation method carbon + proton [9] - which has proven successful to produce exclusively G centers - to the implantation through PMMA masks with nanoholes. The defect properties are characterized by their zero-phonon line spectra, single-photon count rates, and second-order auto-correlation functions to identify the optimal nanohole diameters and annealing conditions for creating well-isolated G centers. In the course of this fabrication protocol, we also observe and characterize other fluorescent defects created by this method. We further compare the defects created by this technique with wafer-wide implantation methods to understand how different fabrication procedures influence defect formation. This study can further be extended to develop nanophotonic cavities around the fabricated single G centers for enhanced single-photon emission properties [4] and opens up prospects for scalable integration of color centers in silicon quantum photonic chips.

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\* krithika.velliyur-ramachandran@umontpellier.fr

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## Flip-chip integration of high-impedance resonators for Si hole spin cQED

Sébastien Granel<sup>1</sup>, Simon Zihlmann<sup>1</sup>, Cécile Yu<sup>1,2</sup>, Étienne Dumur<sup>1</sup> and Romain Maurand<sup>1\*</sup>

<sup>1</sup>*Univ. Grenoble Alpes, CEA, Grenoble INP, IRIG-Pheligs, Grenoble, France and*

<sup>2</sup>*QuTech and Kavli Institute of Nanoscience, Delft University of Technology,  
P.O. Box 2046, Delft, 2600 GA, Delft, The Netherlands.*

Coupling photons with solid-state qubits in circuit quantum electrodynamics (cQED) would pave the way for long-range on-chip connectivity [1] and high fidelity quantum non-demolition (QND) readout [2]. Especially, 330 MHz strong coupling achieved between a microwave photon in superconducting resonator and a hole spin in a silicon-based double quantum dot issued from a foundry-compatible MOS fabrication demonstrates that silicon hole spin qubits are a promising platform for cQED [3].

This state-of-the art hole-spin cQED architecture relies on transferring a high-impedance resonator to an NbN layer sputtered on the Si-MOS wafer. However, that co-integration degrades the internal resonator quality factor to  $Q_i = 600$  which is detrimental to reaching a fast and high fidelity QND readout [3]. Si-MOS substrate loss and extra bias lines patterned on the chip close to the high-impedance resonator are identified as sources of photon loss and quality factor decrease [4].

The presented work aims at building a new hole spin cQED architecture that takes up those microwave challenges for integrating high quality factor resonators. On the one hand, we move to a flip-chip assembly which consists of splitting the cQED architecture into two chips, one hosting the Si-MOS transistor and the other hosting the resonator and readout circuit and connecting both galvanically with soldering In bumps [5]. This configuration enables to delocalize the resonator on a Sapphire substrate, which is less loss than the Si-MOS wafer. In that scope, characterization of the bump interconnects down to mK temperature and under B-field has been carried out, showing that they still provide low-loss connection under spin cQED experimental conditions. Especially, 100 000-high quality factors have been demonstrated in the single photon limit for flip-chip 1.7 k $\Omega$  high-impedance resonators bridged to another chip. On the other hand, work has been performed to improve the filtering of the DC lines which connect to the transistor gates by engineering lumped 5<sup>th</sup> order low-pass filters. This proof of concept of flip-chip technology and on-chip microwave filtering enables to envision the integration of a low-loss resonator with a Si hole-based spin qubit for fast and high fidelity QND readout.

**Keywords :** cavity QED, 3D integration, high-impedance resonators, silicon quantum dots, on-chip microwave filters

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\* sebastien.granel2@cea.fr

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## Tailoring Novel Group IV Quantum Materials

M. Turmel<sup>1</sup>, N. Pauc<sup>1</sup>, V. Calvo<sup>1</sup>, S. De Franceschi<sup>1</sup>, S. Assali<sup>1\*</sup>

<sup>1</sup>*University Grenoble Alpes, CEA, Grenoble INP, IRIG, PHELIQS, Grenoble (FR)*

Materials engineering is at the foundation of the plethora of solid-state devices that are now driving the second quantum revolution. Combining metals, insulators, semiconductors (SEMI), superconductors (SC), and topological (TOP) materials in quantum material heterostructures opened new avenues in condensed matter physics [1]. Superconducting qubits, superconducting spin qubits, and topological qubits systems are often fabricated using Josephson junction field-effect transistors (JoFETs) made of hybrid SC/SEMI and SC/TOP junctions [2]. Here, any disorder at the interface between two materials is a detrimental source of noise and dissipation, hence compromising the ability to generate, detect, and manipulate quantum states. Avoiding structural defects, impurities, oxides, and roughness at these hybrid interfaces is a major challenge in materials science.

Herein, we develop novel group IV quantum materials and their future integration into superconducting qubits. We focus our attention on Tin grown in the body-centered tetragonal  $\beta$ -phase ( $\beta$ -Sn), which is a superconductor with a critical temperature  $T_C=3.7$  K. Compared to superconducting Aluminum ( $T_C=1.2$  K) that is widely used in quantum devices, the higher  $T_C$  of  $\beta$ -Sn results in a larger SC gap and enhanced resilience to external magnetic fields, hence more robust qubits with a longer coherence time may be fabricated using  $\beta$ -Sn. We developed the epitaxial growth of  $\beta$ -Sn on a Ge (100) wafer using molecular beam epitaxy (MBE) and probed the crystalline quality in-situ during growth using RHEED. A detailed correlation between morphology, dislocations, grain sizes, and strain of the  $\beta$ -Sn samples was obtained by combining SEM, Raman, XRD, and TEM. In-plane XRD  $2\theta\chi$  study demonstrates that  $\beta$ -Sn is epitaxial on the Ge substrate, with the presence of  $\beta$ -Sn diffraction peaks with its (200) plane parallel to the (220) plane of the Ge substrate, while no peaks associated with the diamond cubic  $\alpha$ -Sn phase are visible. Magnetotransport measurements at a temperature  $< 1$  K will be discussed to evaluate the superconducting properties of epitaxial  $\beta$ -Sn and correlate them with the crystalline quality of the material. Next, we discuss the selective area growth of  $\beta$ -Sn on Ge from a patterned SiOx mask to provide a straightforward path for the future fabrication of JoFETs-based gatemons using Ge/SiGe QWs [3]. To this end, we will discuss the MBE growth of Ge/SiGe QWs grown on a Ge wafer, which have been proven as a high (hole) mobility material when grown by chemical vapor deposition (CVD) [4]. The structural and quantum transport properties of the MBE Ge QW will pave the way for their use in a  $\beta$ -Sn JoFET device.

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\* mathieu.turmel2@cea.fr



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## Towards Large Scale Quantum Computers : More than just CryoCMOS

Gabriel Zerbib<sup>1\*</sup>

<sup>1</sup>*CEA Grenoble, LIST, Université Grenoble Alpes,  
17 av. des Martyrs Grenoble, France*

Quantum computers operate on qubits to solve problems that current computer can't hope to solve in our lifetimes. Among all current qubit types, we'll focus on semiconductor qubits, which operate at temperatures very close to absolute zero, and require electrical connections to be manipulated and read out. This extremely cold environment, provided by the use of a cryostat, imposes power and communication constraints on the electronics.

Furthermore, current qubit technologies are far from the reliability required for quantum algorithms. As such, quantum error correction algorithms need to be used, which increases the required number of physical qubits necessary to run those algorithms. The high number of qubit needed to run a useful algorithm makes the design of control electronics a real challenge, due to the sheer amount of wiring and the density of quantum dots causing fanout issues.

To assess the feasibility and scalability of currently proposed control architectures, we first developed a cryostat efficiency model. This model, roughly linear (in log-log space) with respect to the operating temperature, gives us a better understanding of the power constraints associated with cryogenic environments. Cryostat efficiency as low as  $10^{-6}$  at 1K is reported, highlighting the very low power budget for cryo-electronics embedded near the qubits.

We extracted the power consumption and area figures of CryoCMOS functions from 30 state-of-the-art publications. The values are then scaled with respect to the number of qubits controllable in each publication. We show that only a few of those publications allow for a function of a large scale quantum computer to be built from those components, within the previously defined affordable power budget.

Finally, we open the discussion towards the use of other technologies and we challenge that, for some function, CryoCMOS is the most suitable one. We explored the following technologies : RSFQ, Optoelectronics, Electrostatic and Piezoelectric MEMS, Beamforming and HEMTs.

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\* gabriel.zerbib@cea.fr

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