Max-Planck Institute
for the Science
of Light

Friedrich-Alexander
Universität
Erlangen-Nürnberg

QUANTUM MEASUREMENT THROUGH PARAMETRIC AMPLIFICATION

Maria Chekhova

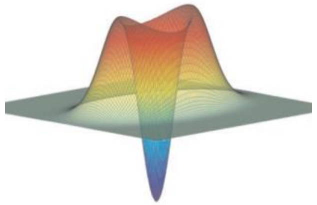
GdR TeQ, Grenoble, November 14, 2025

QUANTUM STATES AND THEIR MEASUREMENT

Pillars of quantum technology

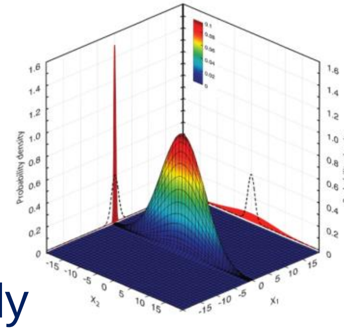
Quantum simulation	Quantum computation	Quantum communication	Quantum sensing and metrology

Non-Gaussian states:
very fragile!



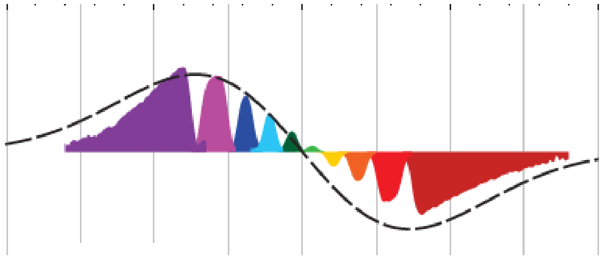
Ourjoumtsev et al., Science 312, 83 (2006)

Squeezed states



Mehmet et al., PRA 81, 013814 (2010)

Spatially and temporally multimode states

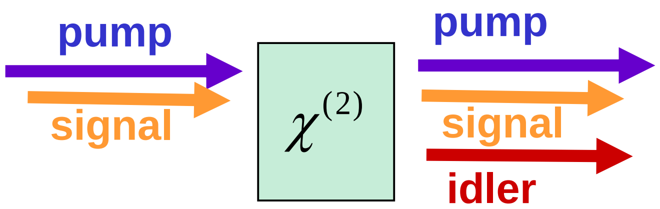


Roslund et al., Nature Photonics 8, 109 (2014)

HOW TO MEASURE?

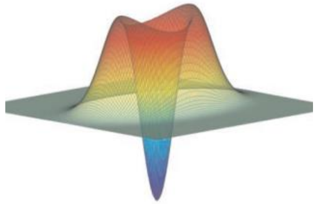
OUTLINE

Optical parametric amplifier instead of homodyne detection



Simultaneous characterization of multiple modes

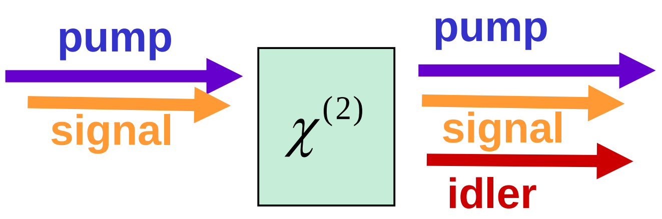
Wigner function tomography



Conclusions

OUTLINE

Optical parametric amplifier instead of homodyne detection



Simultaneous characterization of multiple modes

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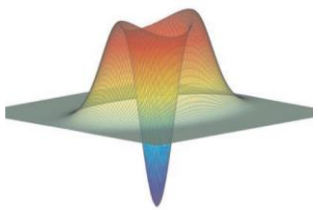
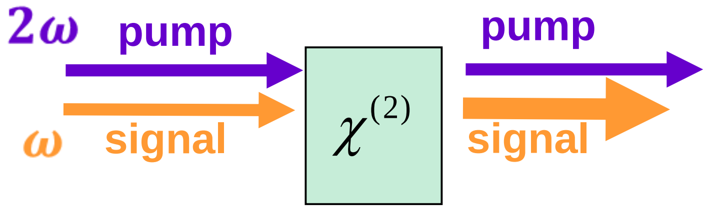


Conclusions

PHASE-SENSITIVE OPTICAL PARAMETRIC AMPLIFIER



Amplification or de-amplification depending on the phase: phase-sensitive OPA

Swing: frequency ω

Pump: frequency 2ω

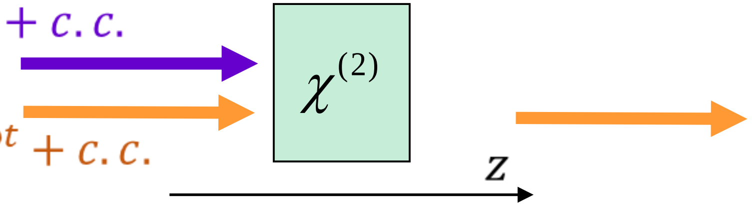
You can amplify or de-amplify the swing oscillations

AMPLIFICATION OF AN OPTICAL FIELD

Nonlinear optics:

Pump: $E_p = E_{p0}e^{-2i\omega t} + c.c.$

Signal: $E_s = E(z)\, e^{-i\omega t} + c.c.$



$$\frac{dE(z)}{dz} = \Gamma E^*(z)$$

Nonlinear polarization:

$$P^{(2)} \sim \chi^{(2)}\left[E_{p0}e^{-2i\omega t} + E_0 e^{-i\omega t} + c.c.\right]^2$$

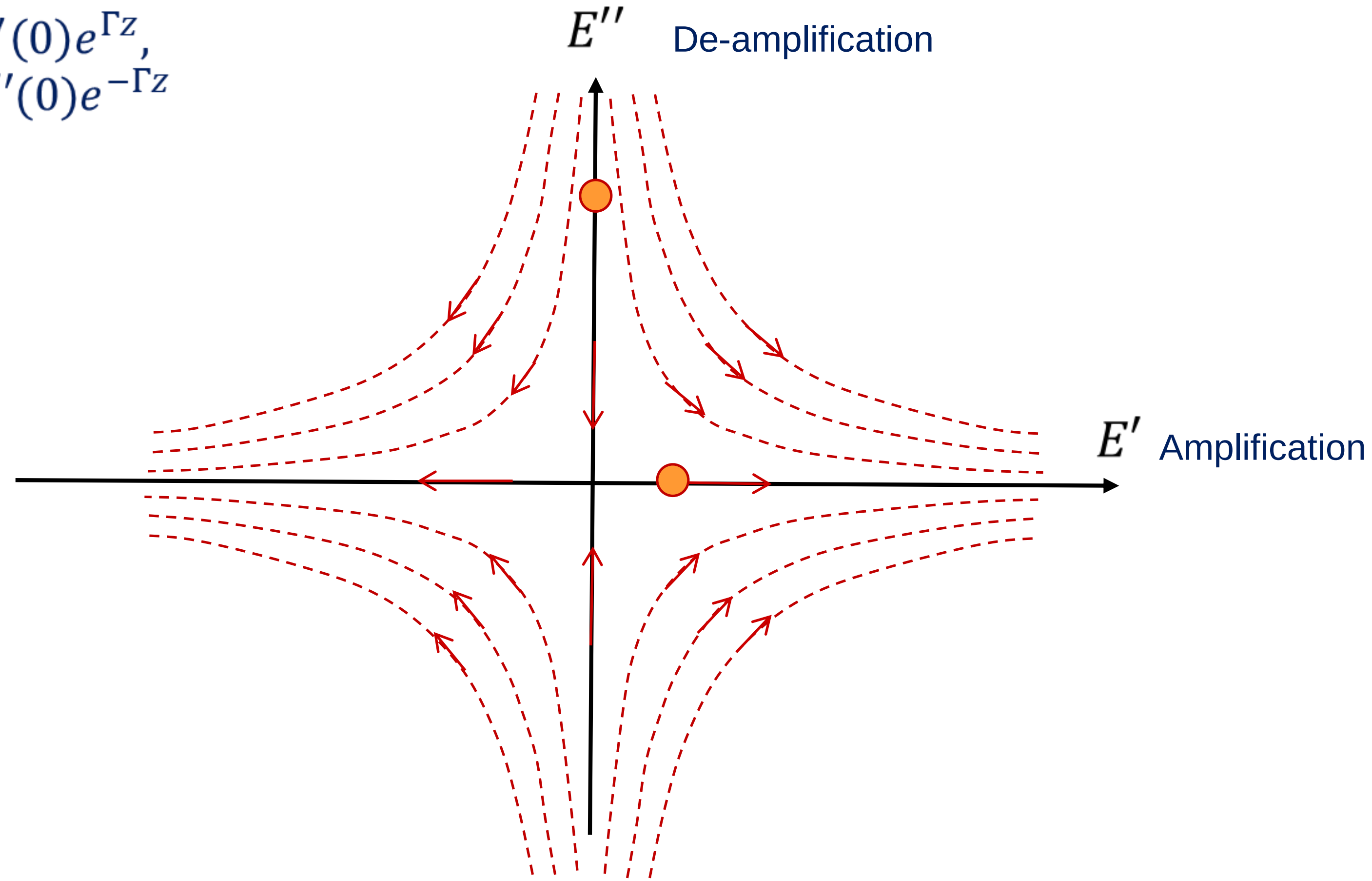
$$E(z) = \mathrm{E}'(\mathrm{z}) + \mathrm{i}\mathrm{E}''(\mathrm{z})$$

$$\frac{dE'(z)}{dz} = \Gamma E'(z), \qquad \frac{dE''(z)}{dz} = -\Gamma E''(z)$$

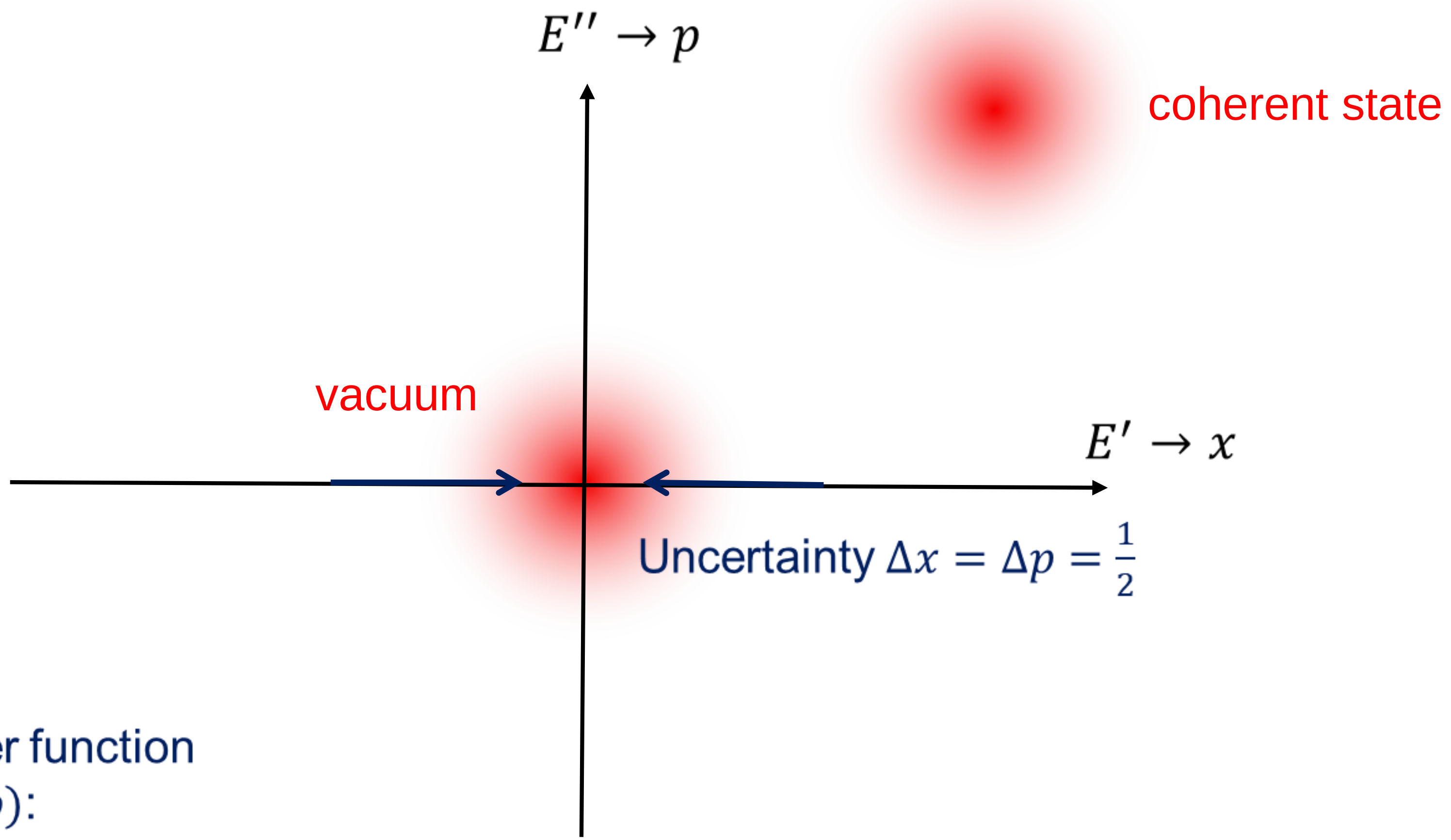
$$E'(z) \sim e^{\Gamma z}, \qquad E''(z) \sim e^{-\Gamma z}$$

AMPLIFICATION ON THE PHASOR DIAGRAM

$$E'(z) = E'(0)e^{\Gamma z},$$
$$E''(z) = E''(0)e^{-\Gamma z}$$

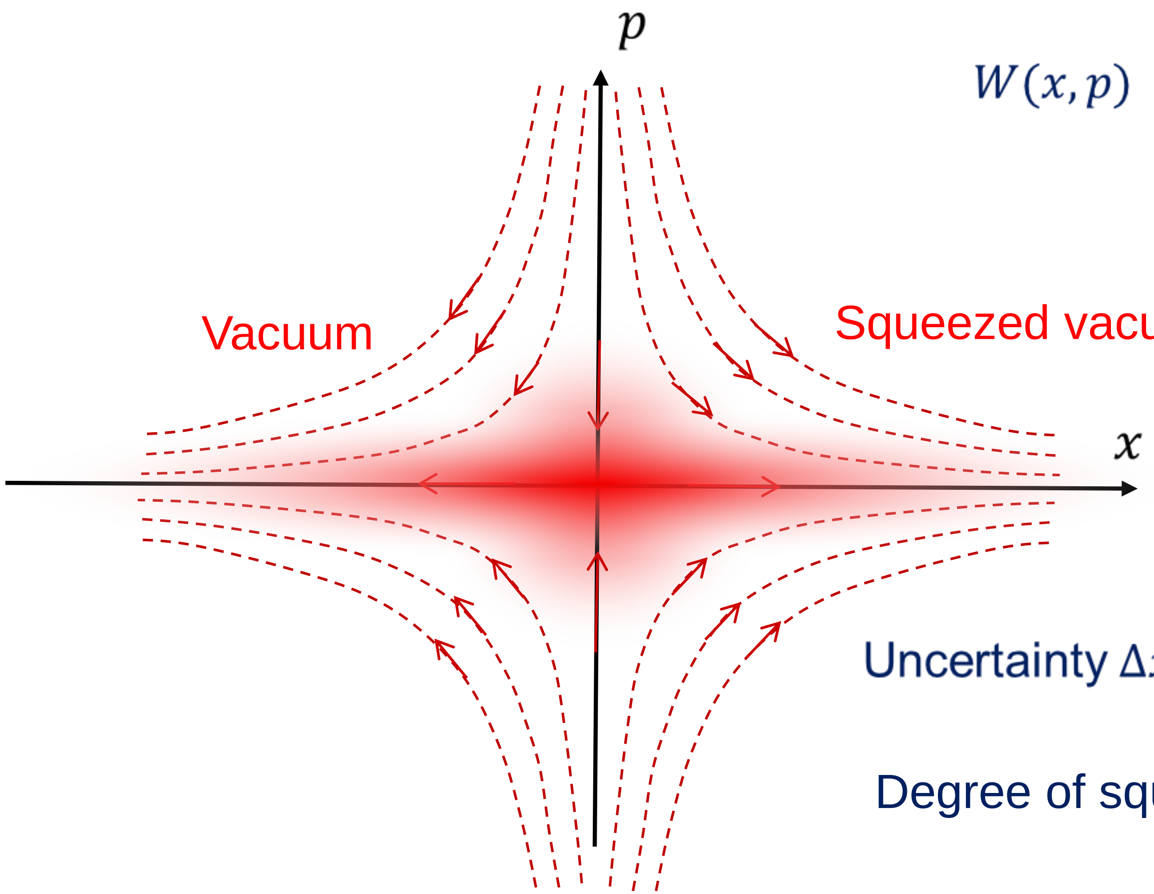


QUANTUM PICTURE: UNCERTAINTY



Wigner function
$W(x, p)$:

a quasiprobability
$$[\hat{x}, \hat{p}\,] \neq 0$$



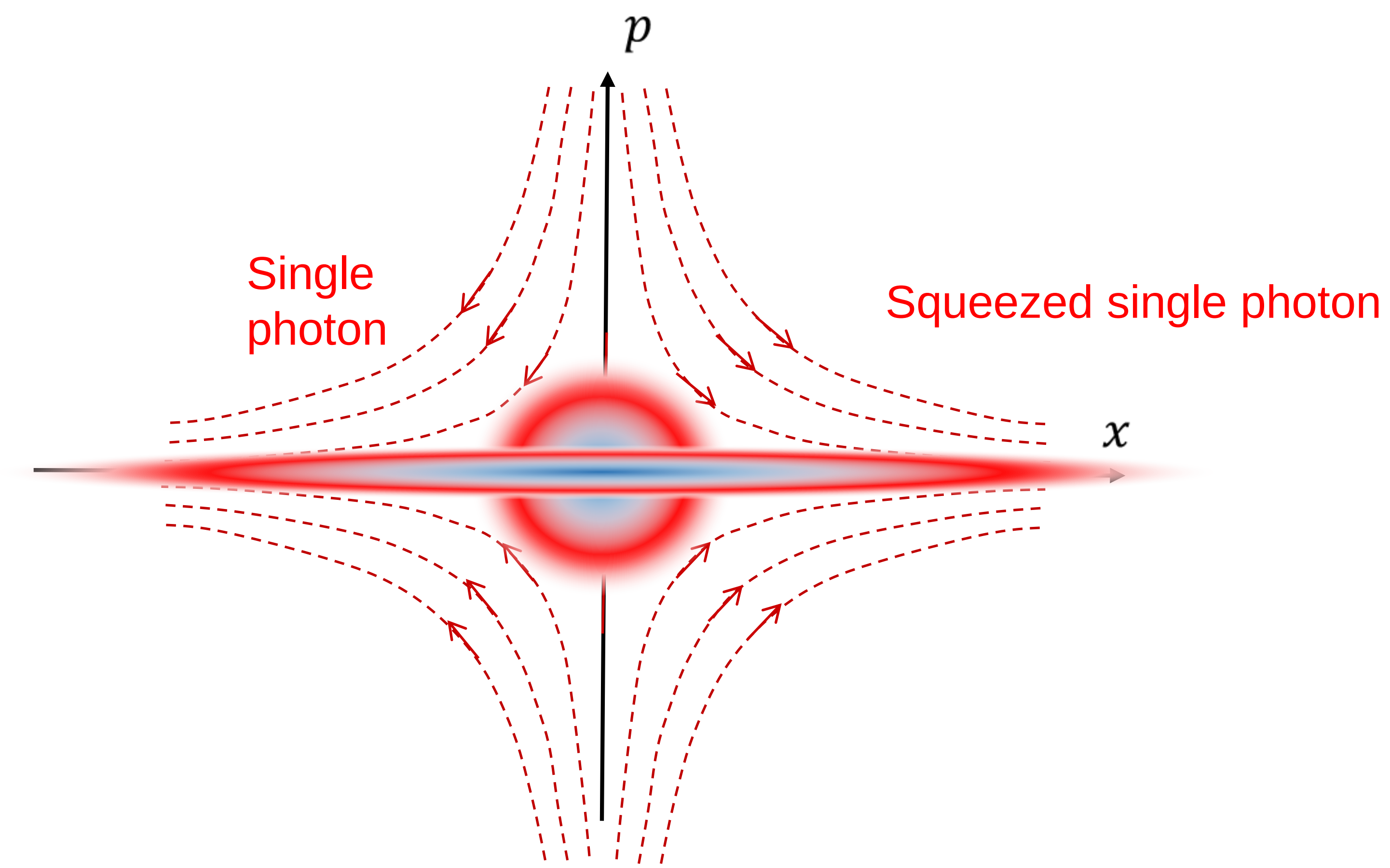
$W(x,p)$ Wigner function

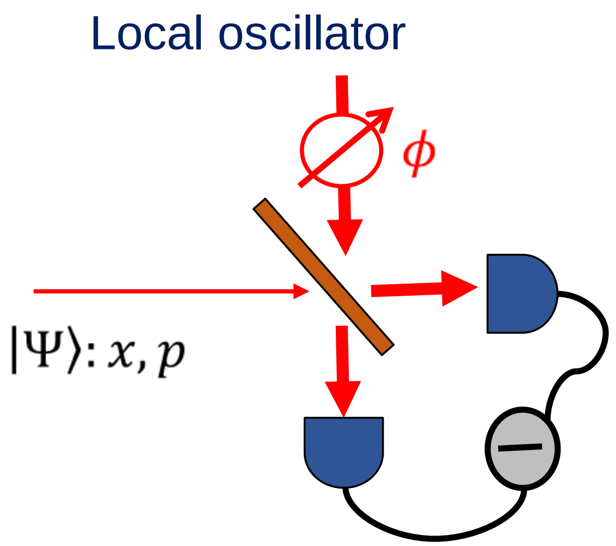
Uncertainty $\Delta x = \Delta p = \frac{1}{2}$

Degree of squeezing: $\Delta p^2/\Delta p_{vac}^2$

'Rubber sheet'

PARAMETRIC AMPLIFICATION: SQUEEZED SINGLE PHOTON





Difference signal

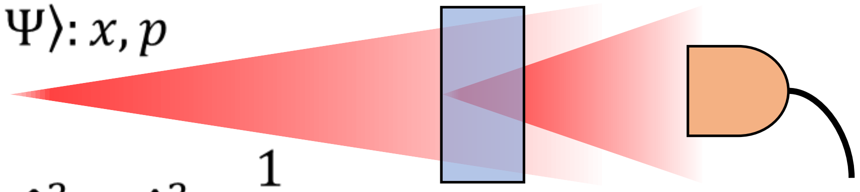
$$i_- \propto x\cos(\phi) + p\sin(\phi)$$

$$x(\phi)$$

The local oscillator should have the same spectrum as the state under study. Difficult for broadband and multimode radiation.

Detection inefficiency strongly affects the performance; crucial for squeezing measurement!

‘PARAMETRIC HOMODYNE’ TO MEASURE SQUEEZING



A phase-sensitive OPA performs as an optical homodyne detector:

$$\langle N\rangle = \underbrace{e^{2G}\langle x^2\rangle}_{\text{large}} + \underbrace{e^{-2G}\langle p^2\rangle}_{\text{small}} - \frac{1}{2}$$

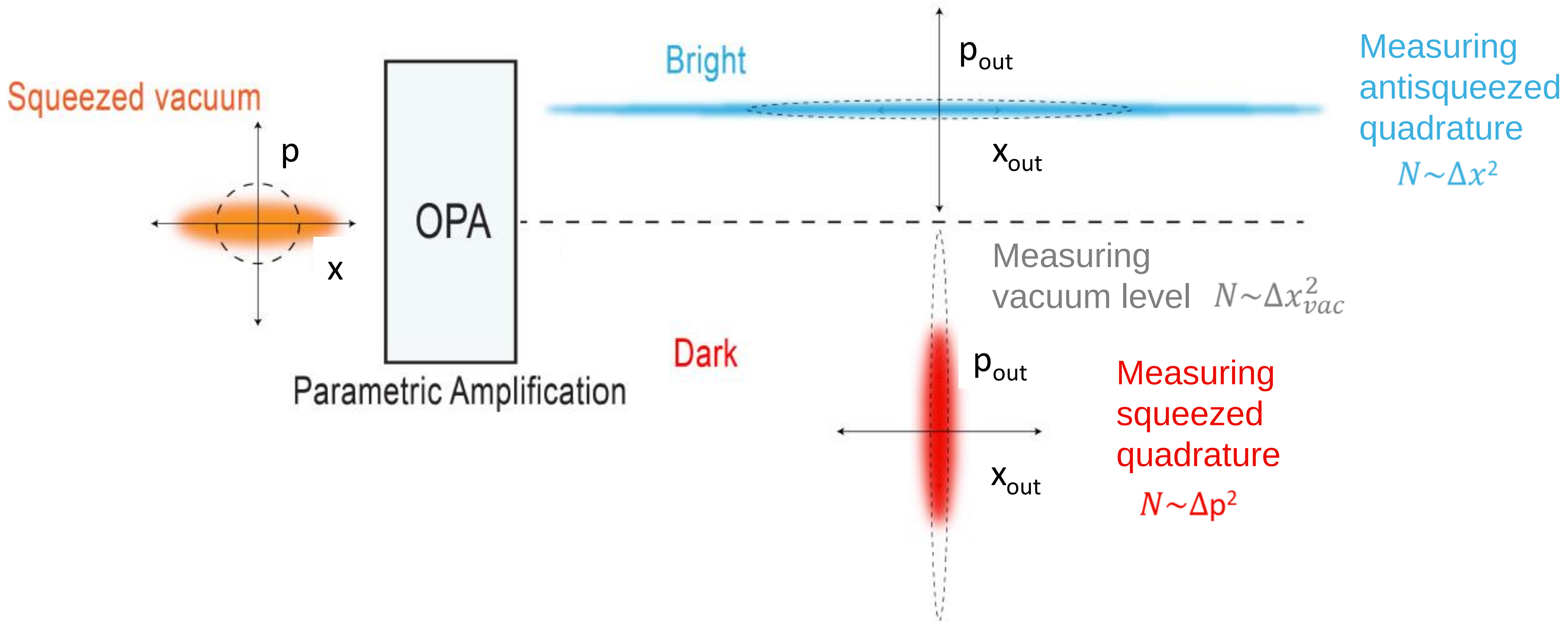
High parametric gain, $\langle N\rangle \approx e^{2G}\langle x^2\rangle = e^{2G}\Delta x^2$

Shot noise level: no input state, $\langle\hat{N}\rangle \approx \frac{1}{4}e^{2G}$

Advantages:
- broadband;
- no need for local oscillator;
- detection loss can be overcome;
- can work simultaneously for multiple modes

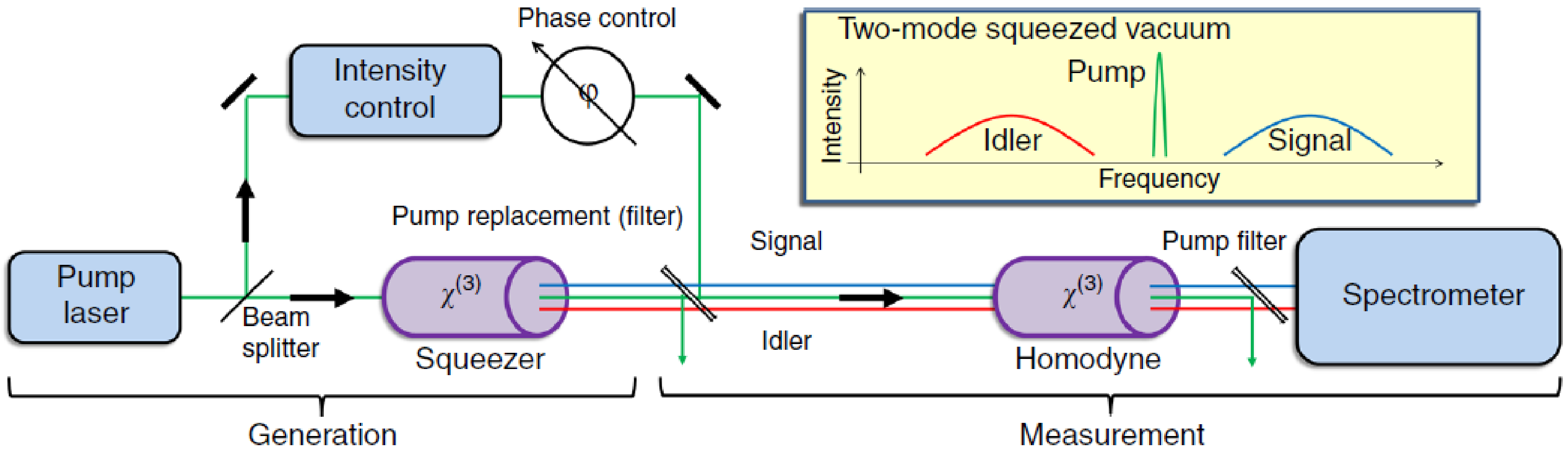
Y. Shaked, Y. Michael, R. Z. Vered, L. Bello, M. Rosenbluh, and A. Pe’er, Nature Comm. 9:609 (2018)

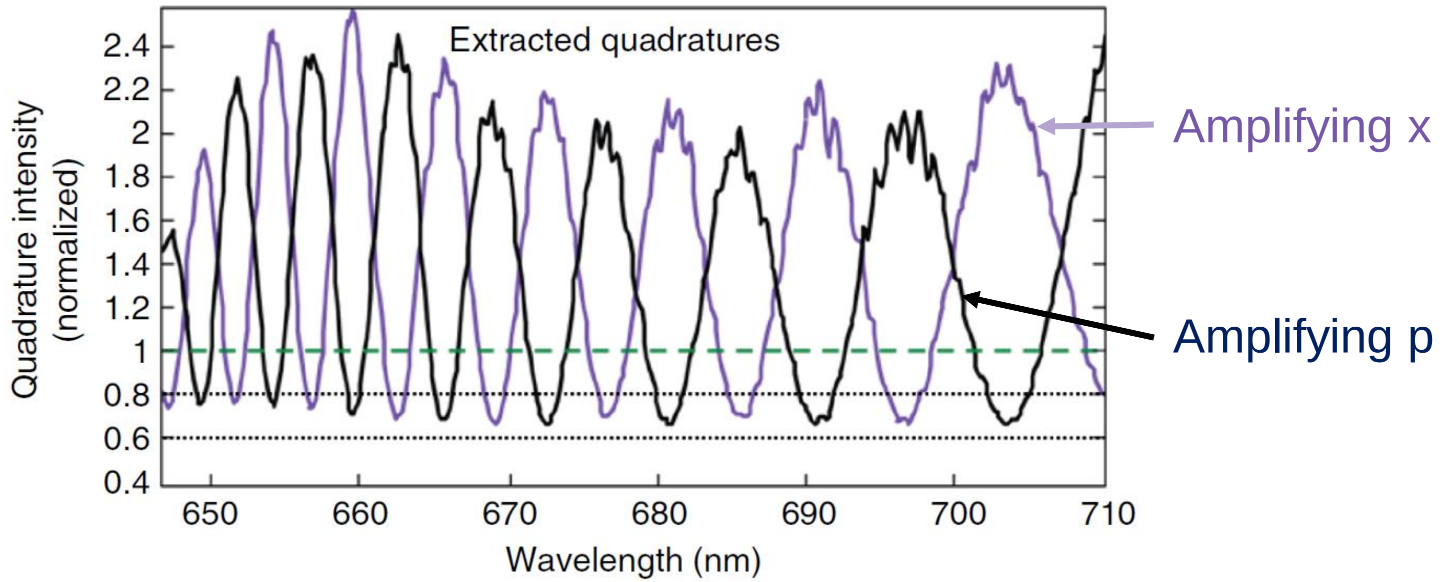
HOW IT WORKS



Squeezed vacuum
p
x
OPA
Parametric Amplification
Bright
p_{out}
x_{out}
Measuring antisqueezed quadrature
$N \sim \Delta x^2$
Measuring vacuum level $N \sim \Delta x_{vac}^2$
Dark
p_{out}
x_{out}
Measuring squeezed quadrature
$N \sim \Delta p^2$

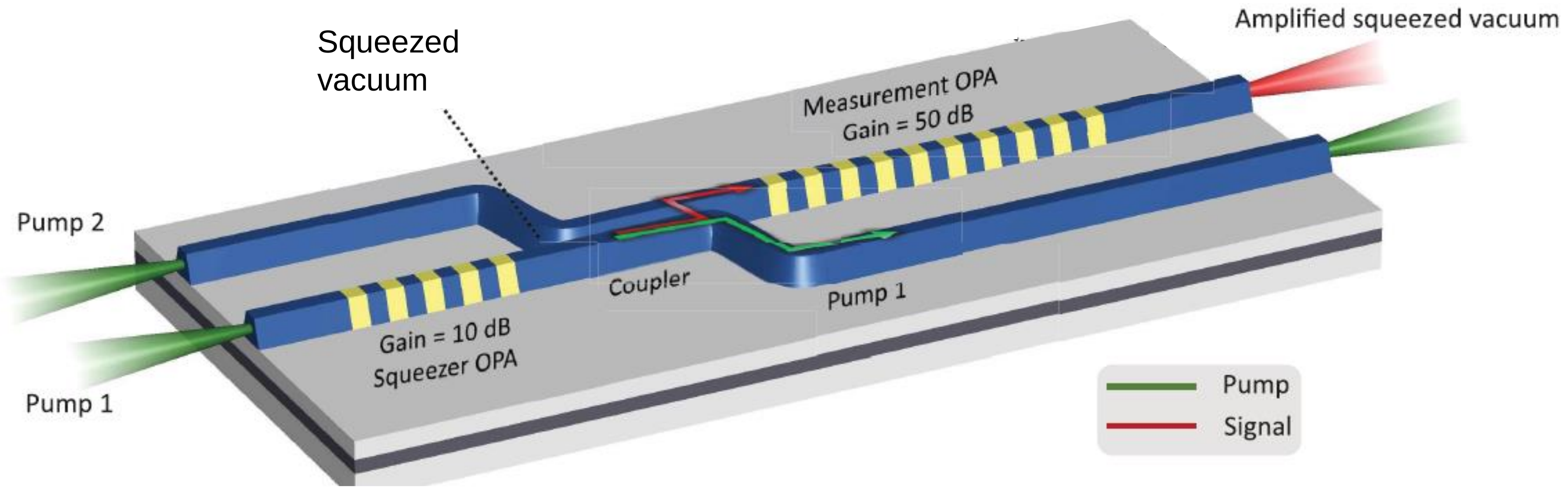
‘PARAMETRIC HOMODYNE’

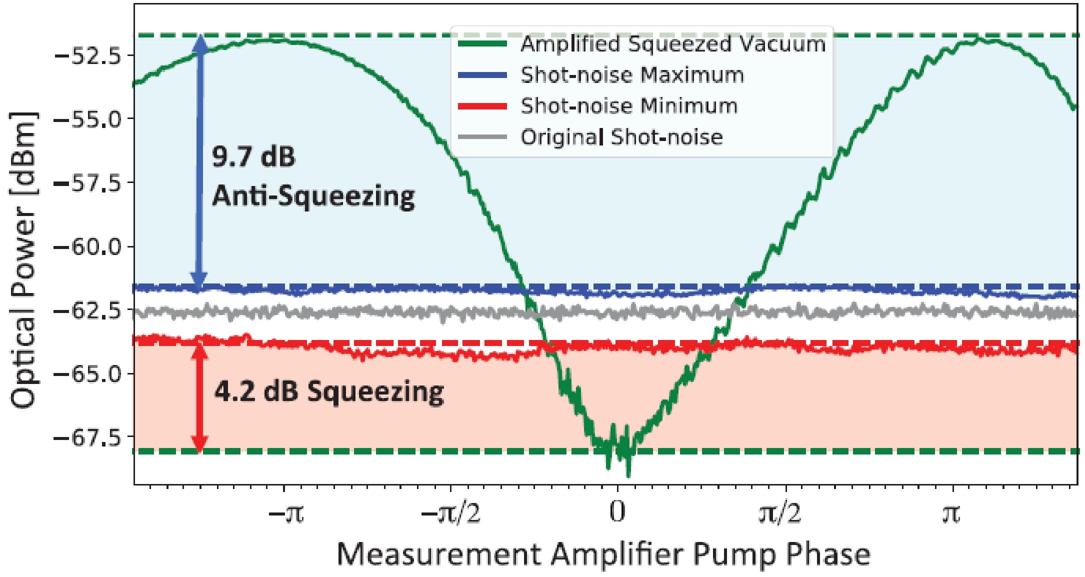




Y. Shaked, Y. Michael, R. Z. Vered, L. Bello, M. Rosenbluh, and A. Pe’er, Nature Comm. 9:609 (2018)

VERY USEFUL FOR NANOPHOTONICS





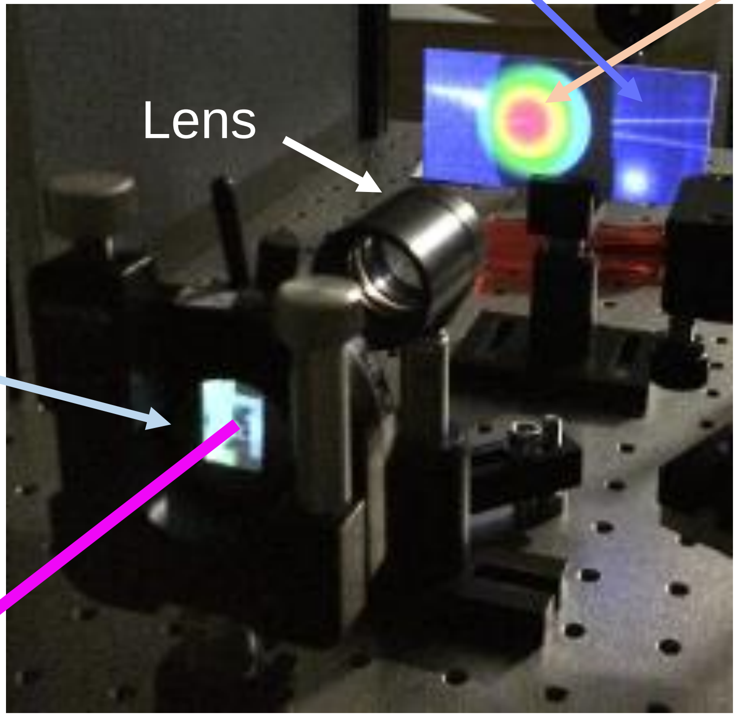
R. Nehra, R. Sekine, L. Ledezma, Q. Guo, R. M. Gray, A. Roy, A. Marandi, Science ***377****, 1333 (2022)*

HOW IT LOOKS IN MY LAB

Paper screen

Squeezed vacuum centered at 800 nm but broadband in frequency and angle

Nonlinear crystal $\left(\chi^{(2)}\right)$

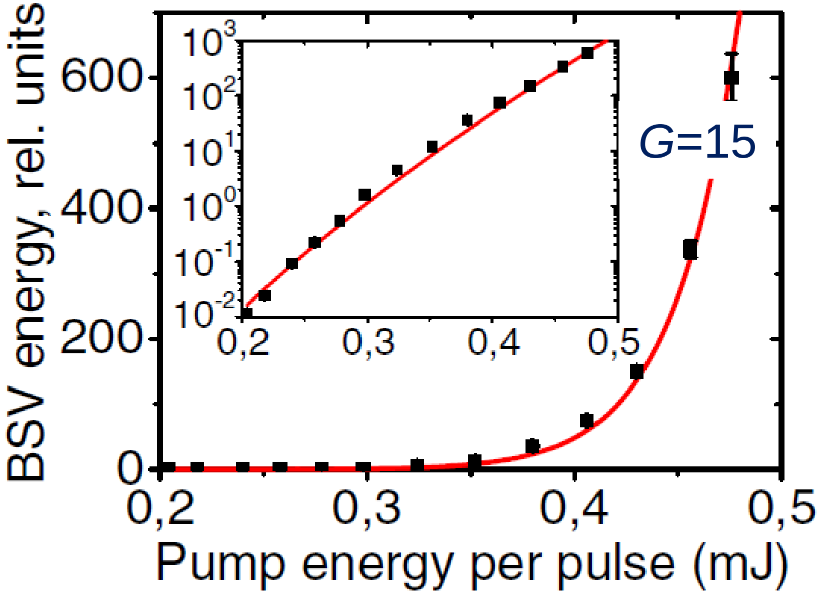


Pump: 1.5 ps pulses at 400 nm, focused

G. Frascella, PhD thesis (Erlangen, 2021).

$$\langle N\rangle = \sinh^2(G), G = \Gamma L \sim E_p \sim \sqrt{P_p}$$

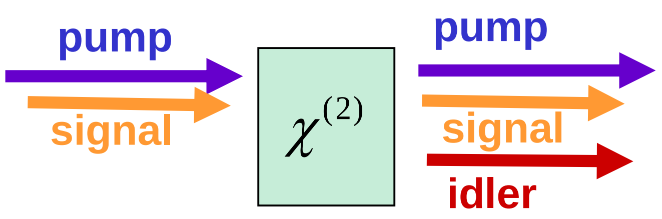
Parametric gain



M. Manceau, K. Yu. Spasibko et al., PRL 123, 123606 (2019).

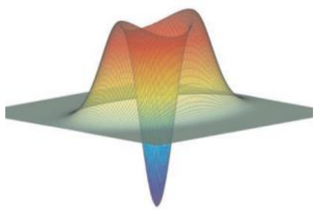
OUTLINE

Optical parametric amplifier instead of homodyne detection



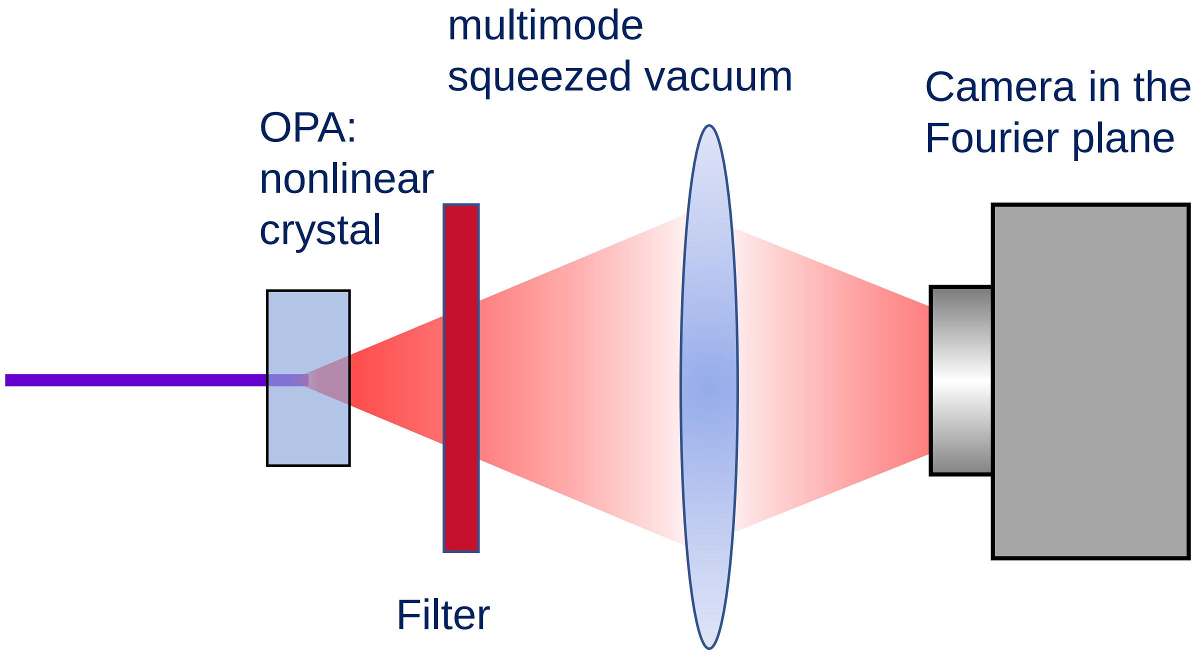
Simultaneous characterization of multiple modes

Wigner function tomography

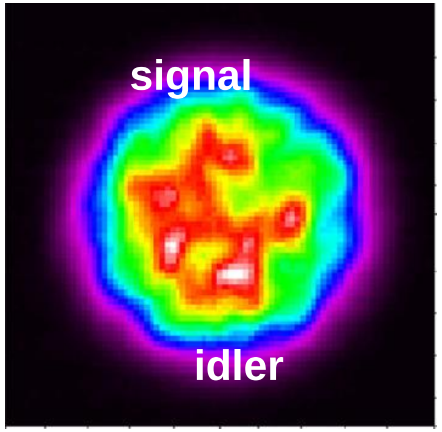


Conclusions

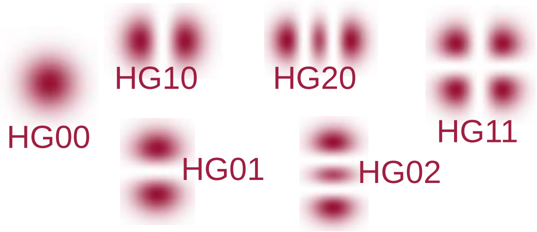
SPATIAL MODES OF AN OPA



Single-shot angular distribution: speckles

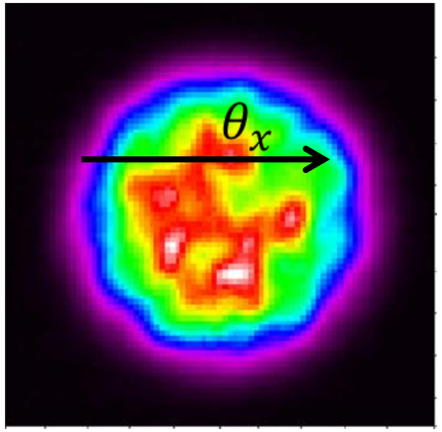


Modes of a traveling-wave OPA:
to a good approximation,
Hermite-Gaussian

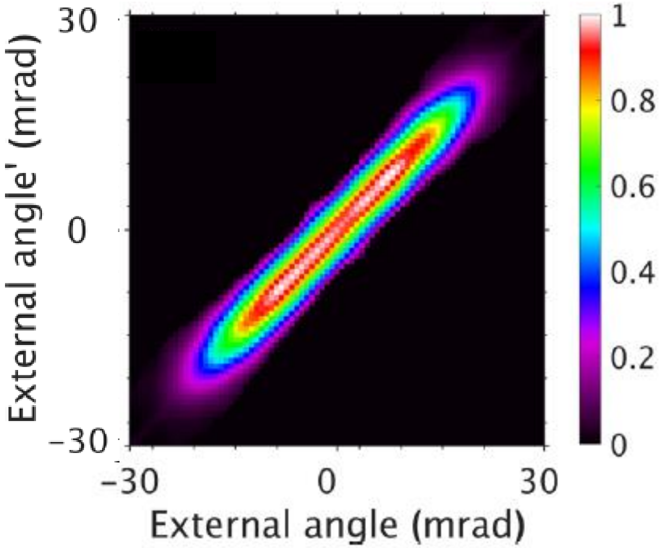


1D MODE DECOMPOSITION

Single-shot angular distribution: speckles

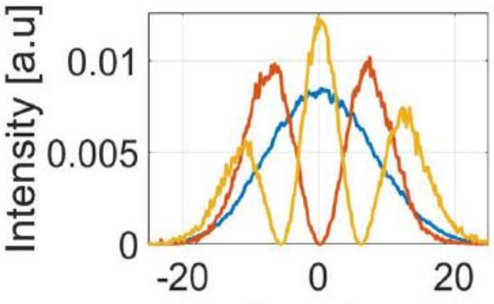


$$\mathrm{Cov}\{I(\theta_x), I(\theta_x')\} = \langle I(\theta_x) I(\theta_x') \rangle - \langle I(\theta_x) \rangle \langle I(\theta_x') \rangle$$

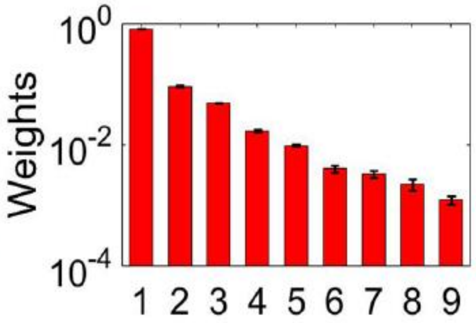


$$\sqrt{\mathrm{Cov}\{I(\theta_x), I(\theta_x')\}} = |G^{(1)}(\theta_x, \theta_x')|$$

Singular-value decomposition => shapes and weights of the modes



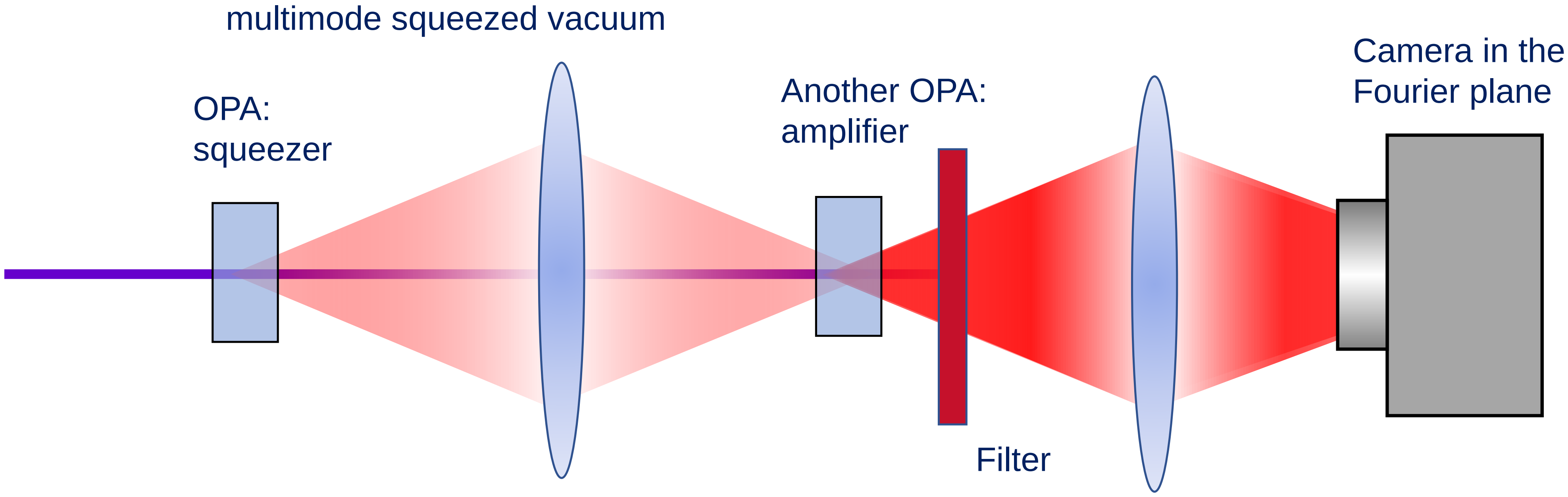
Mode shapes



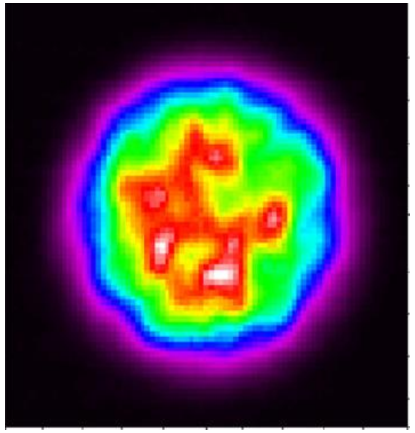
Mode weights

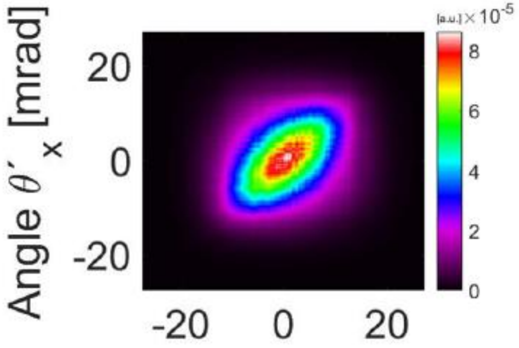
V. A. Averchenko, G. Frascella, M. Kalash, A. Cavanna, M. Chekhova, PRA 102, 053725 (2020).

AMPLIFICATION OF EACH SPATIAL MODE

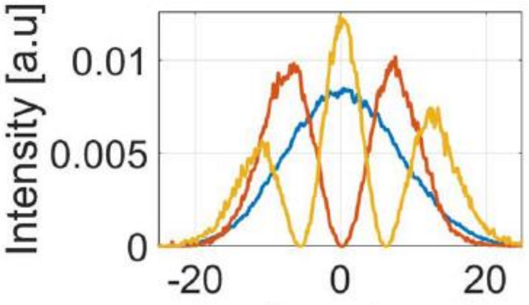


Single-shot angular distributions

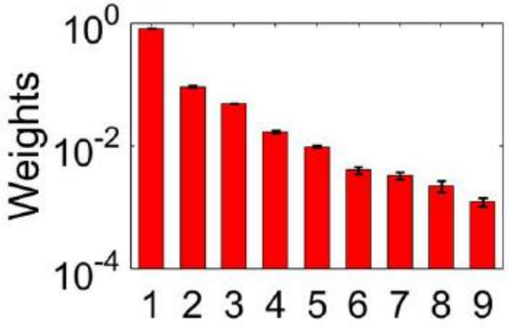




Covariance



Mode shapes

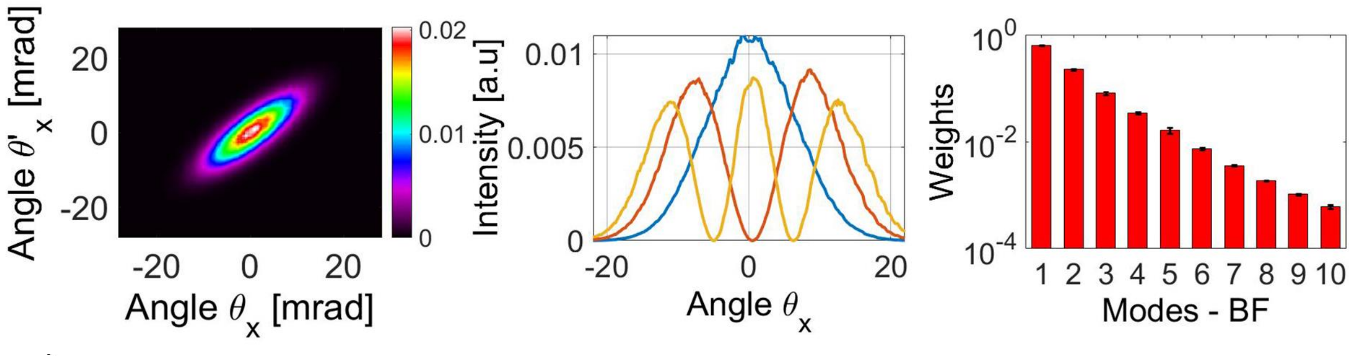


Mode weights

MEASUREMENT OF SQUEEZING IN SPATIAL MODES

Covariance | Mode shapes | Mode weights

Bright fringe

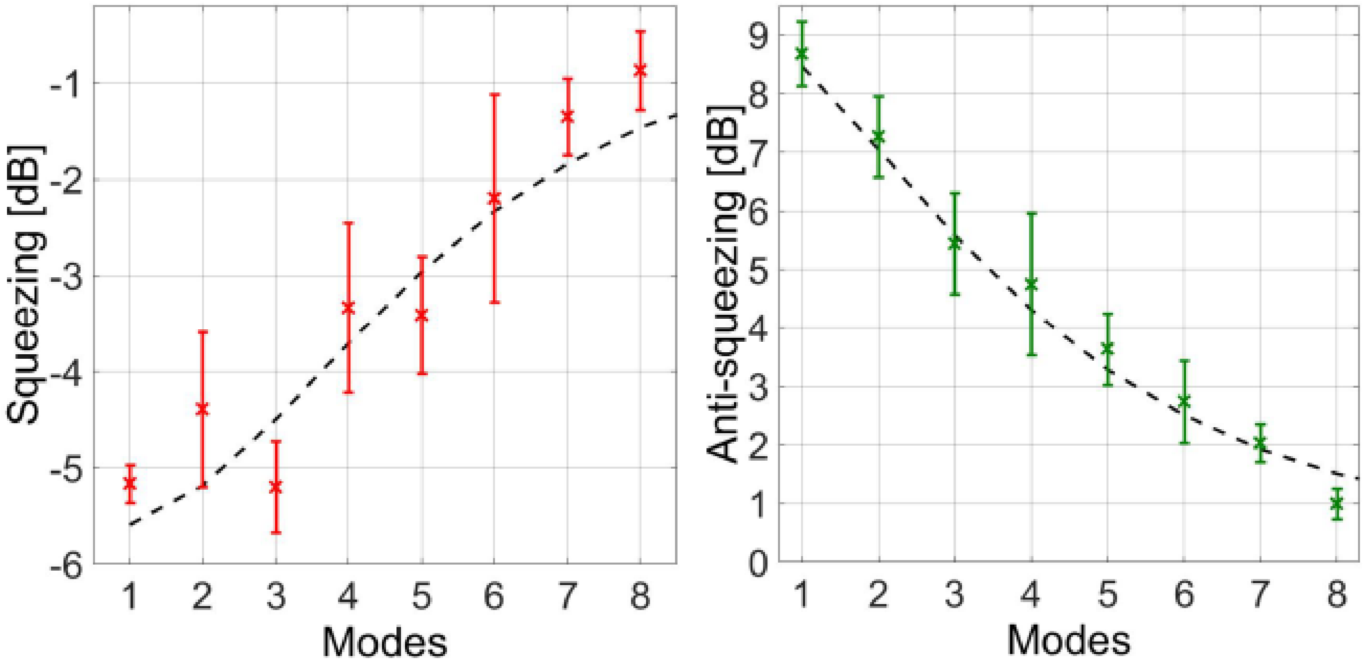


Antisqueezing

Squeezing

I. Barakat, M. Kalash, D. Scharwald, P. Sharapova, N Lindlein, M. Chekhova, Optica Quantum 3, 36 (2025)

SQUEEZING AND ANTISQUEEZING FOR DIFFERENT MODES

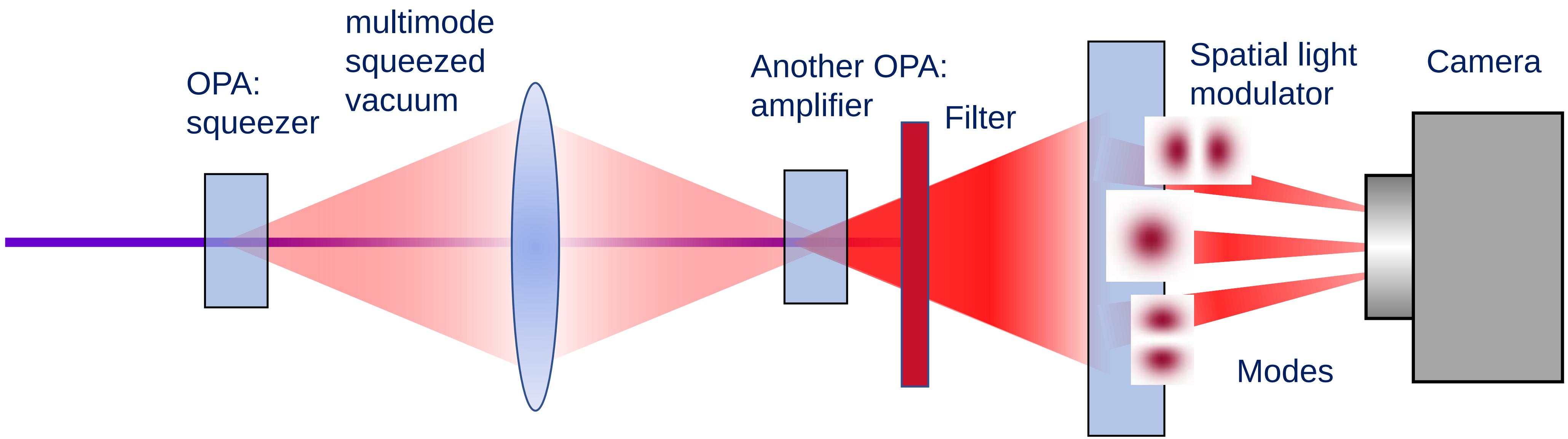


Record squeezing
for multiple modes

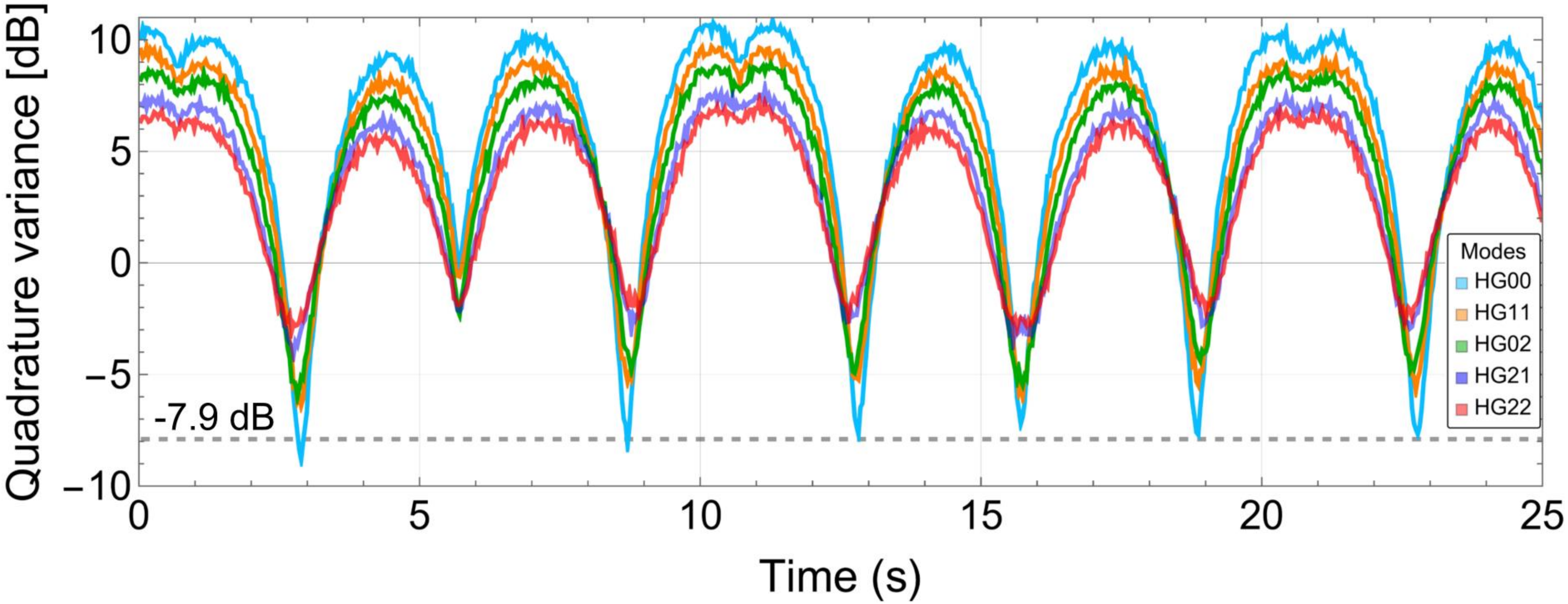
Losses ~50%

I. Barakat, M. Kalash, D. Scharwald, P. Sharapova, N Lindlein, M. Chekhova, Optica Quantum 3, 36 (2025)

MODE DEMULTIPLEXING

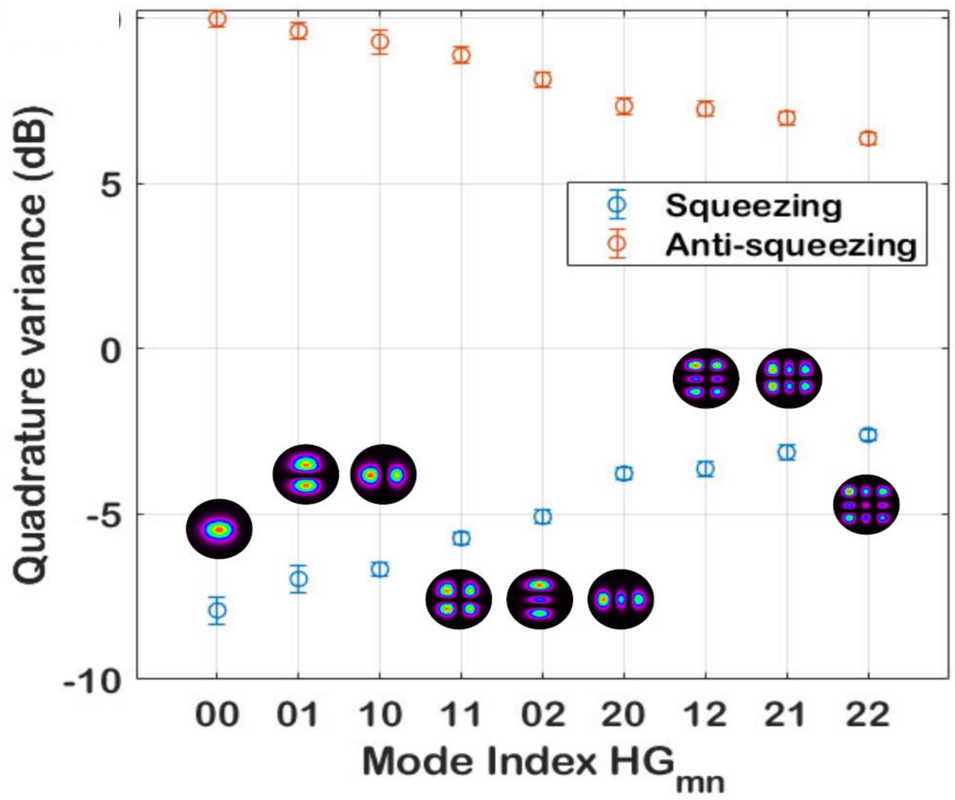


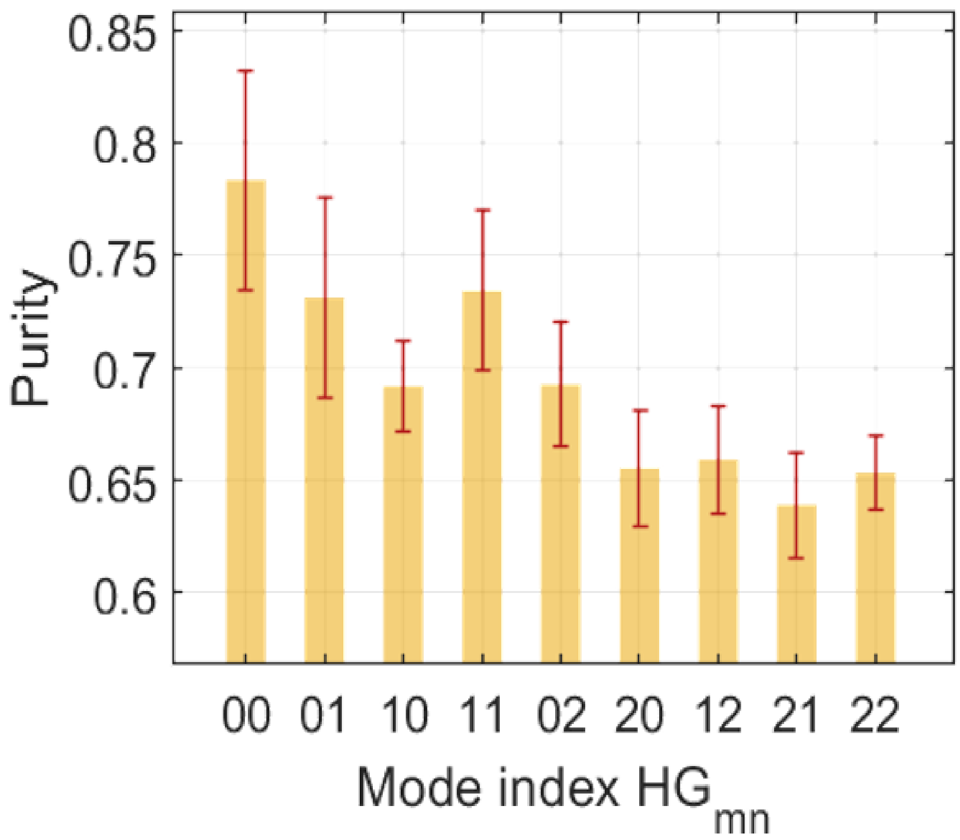
RESULTS: SIMULTANEOUS MONITORING OF MODES



M. Kalash, A. Sudharsanam, M. H. M. Passos, V. Parigi, M. Chekhova, arXiv:2503.07486v1 [quant-ph]

RESULTS: DEGREES OF SQUEEZING





Up to 8 dB squeezing: a new record value for multimode light

Measurement ‘on the fly’

High purity for such a measurement

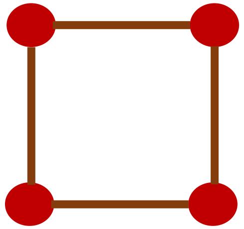
M. Kalash, A. Sudharsanam, M. H. M. Passos, V. Parigi, M. Chekhova, arXiv:2503.07486v1 [quant-ph]

CLUSTER STATES

Resource for measurement-based quantum computation

2-node
(EPR-like)

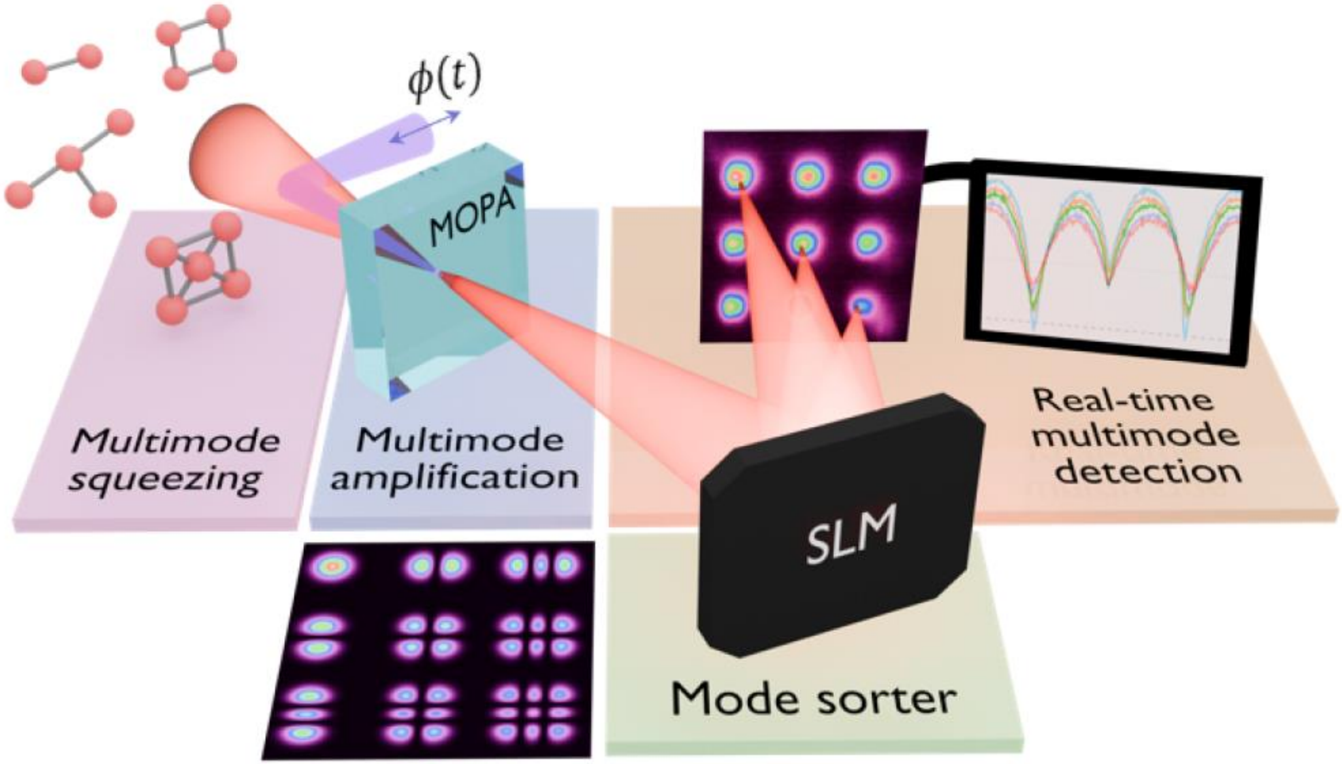
3-node

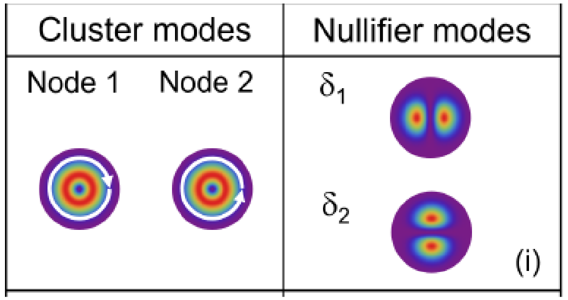


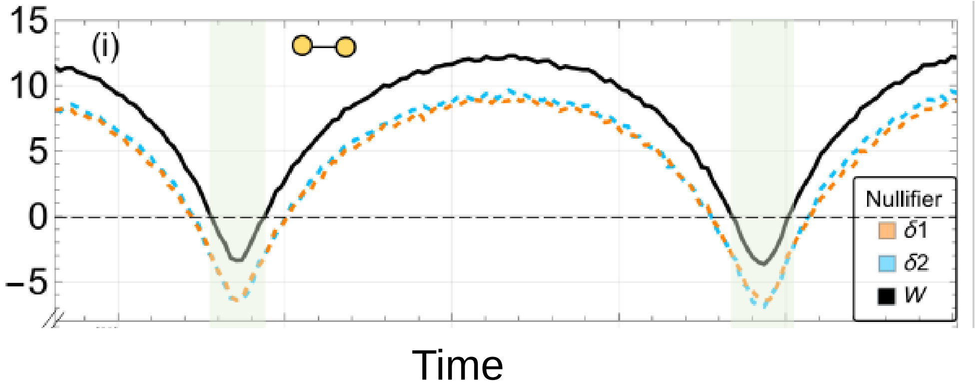
4-node

Nullifiers $$\delta_i = \frac{p_i - \sum_j x_j}{\sqrt{1 + n_j}}$$ Number of neighbouring nodes

Nullifiers should be squeezed below the shot-noise level







Two-node clusters: already measured

Larger clusters: requires shaping of the pump

M. Kalash, A. Sudharsanam, M. H. M. Passos, V. Parigi, M. Chekhova, arXiv:2503.07486v1 [quant-ph]

OUTLINE

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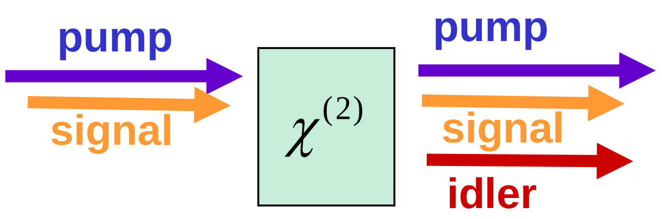
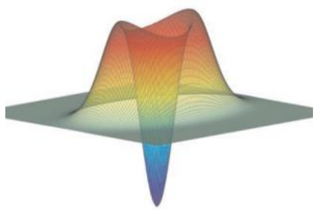


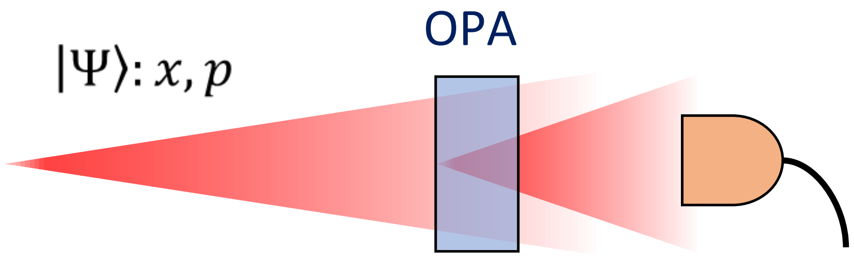
Simultaneous characterization of multiple modes

Wigner function tomography



Conclusions

WIGNER FUNCTION TOMOGRAPHY

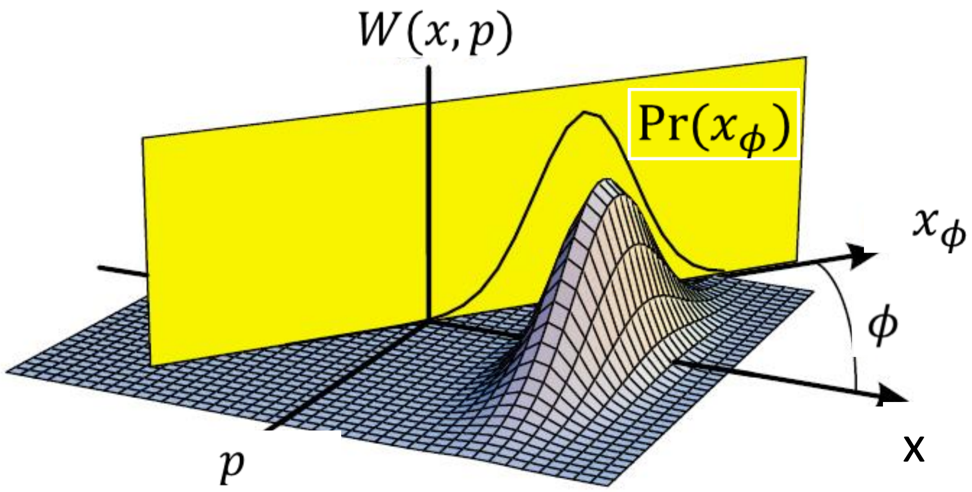


$$N = e^{2G} x^2$$

Probability distribution:

$$\Pr(N) = e^{2G} \Pr(x^2)$$

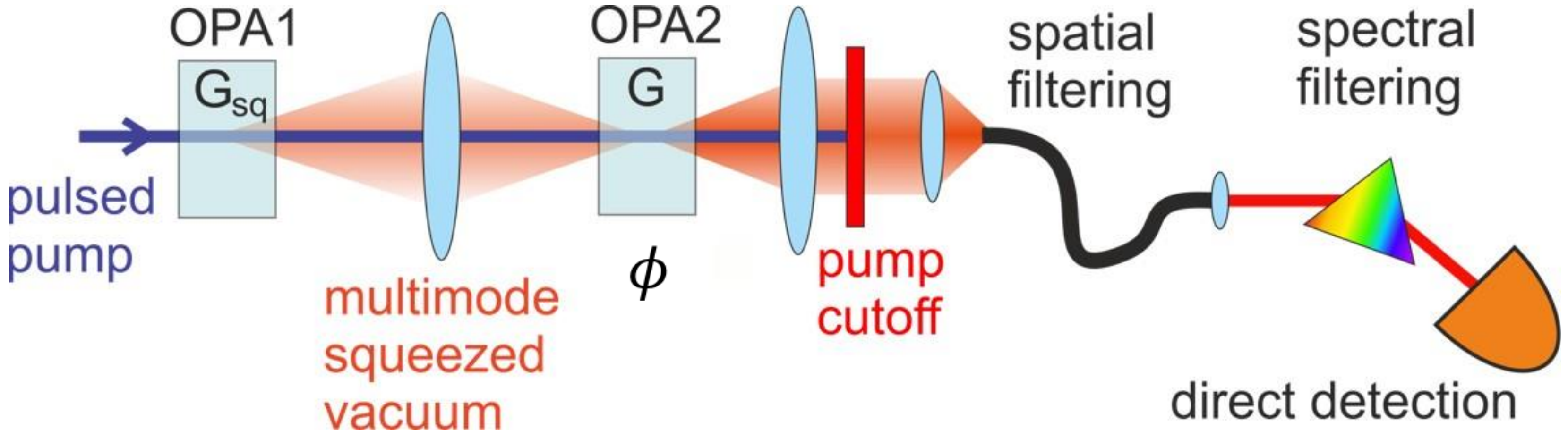
$\Pr(x^2) \Rightarrow \Pr(x)$ if it is an even function $\Pr(-x) = \Pr(x)$



A. I. Lvovsky and M. G. Raymer, Rev. Mod. Phys. 81, 299 (2009).

A SINGLE MODE OF MULTIMODE SQUEEZED VACUUM

Choice of the phase of the quadrature

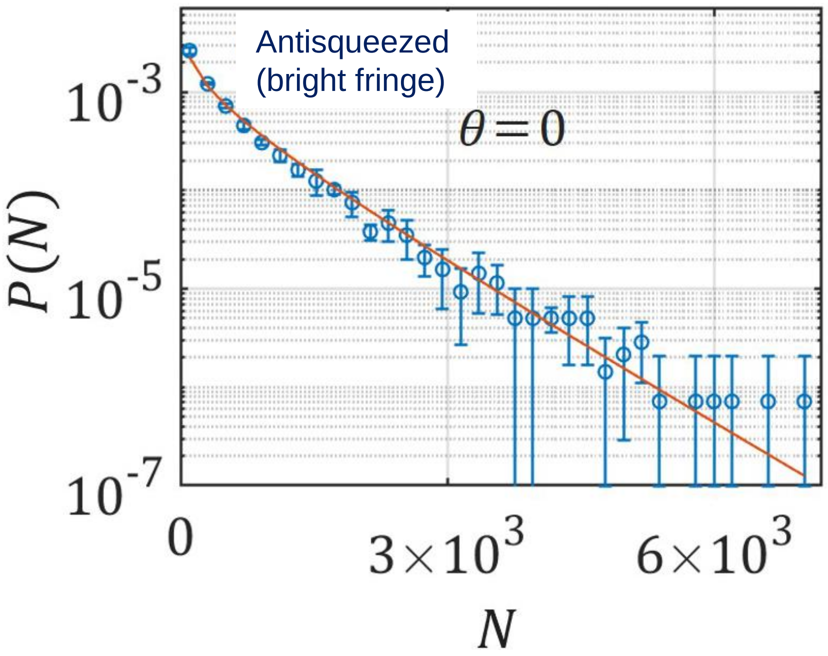


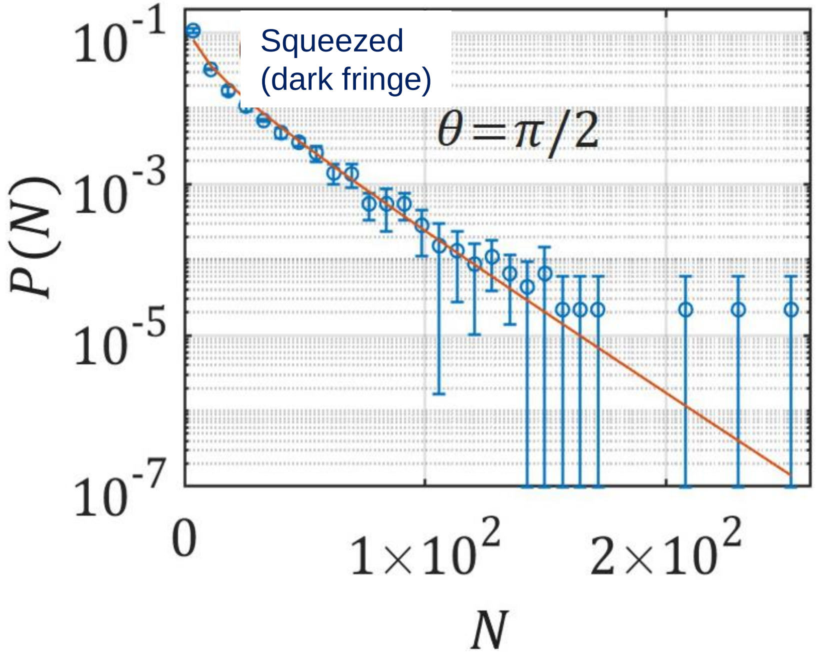
Calibration: no input, $\langle \hat{N} \rangle \approx \frac{1}{4} e^{2G}$

Number of photons in one mode => probability distribution

M. Kalash and M. V. Chekhova, Optica 10, 1142 (2023)

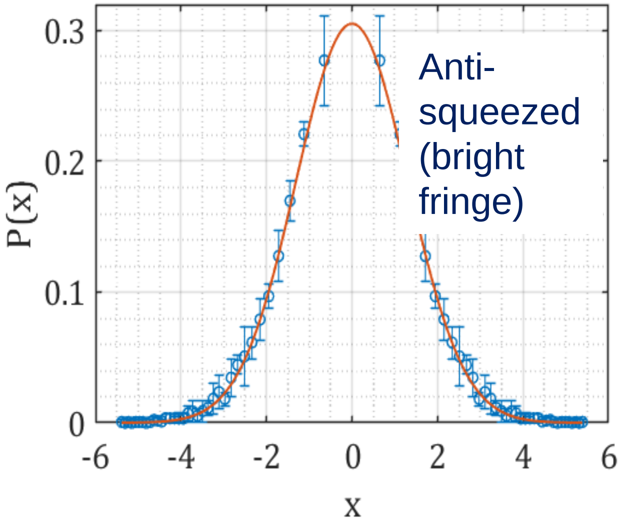
PHOTON-NUMBER DISTRIBUTIONS

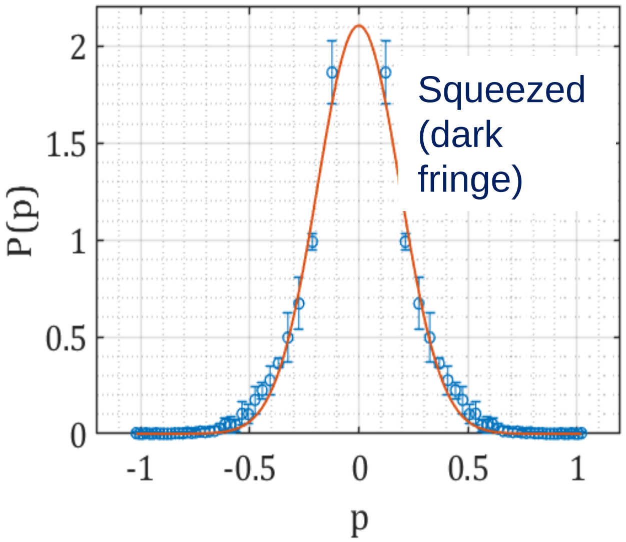


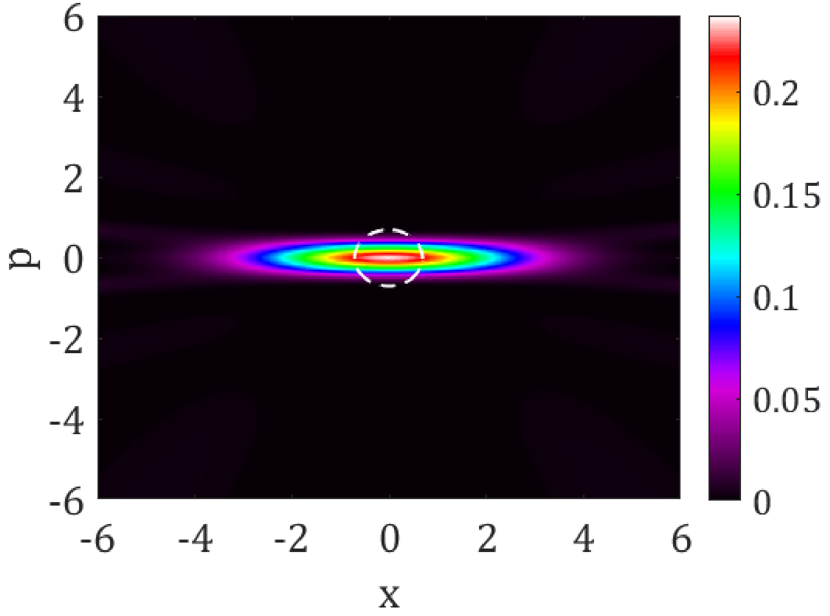


M. Kalash and M. V. Chekhova, Optica 10, 1142 (2023)

QUADRATURES AND WIGNER FUNCTION



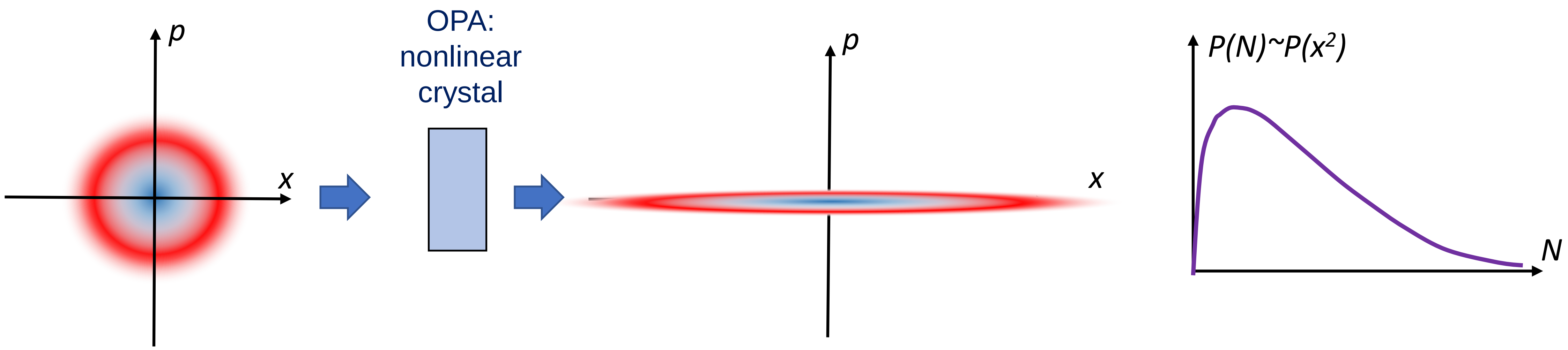




7.7 dB squeezing and 8.5 dB anti-squeezing measured with the detection efficiency <10%

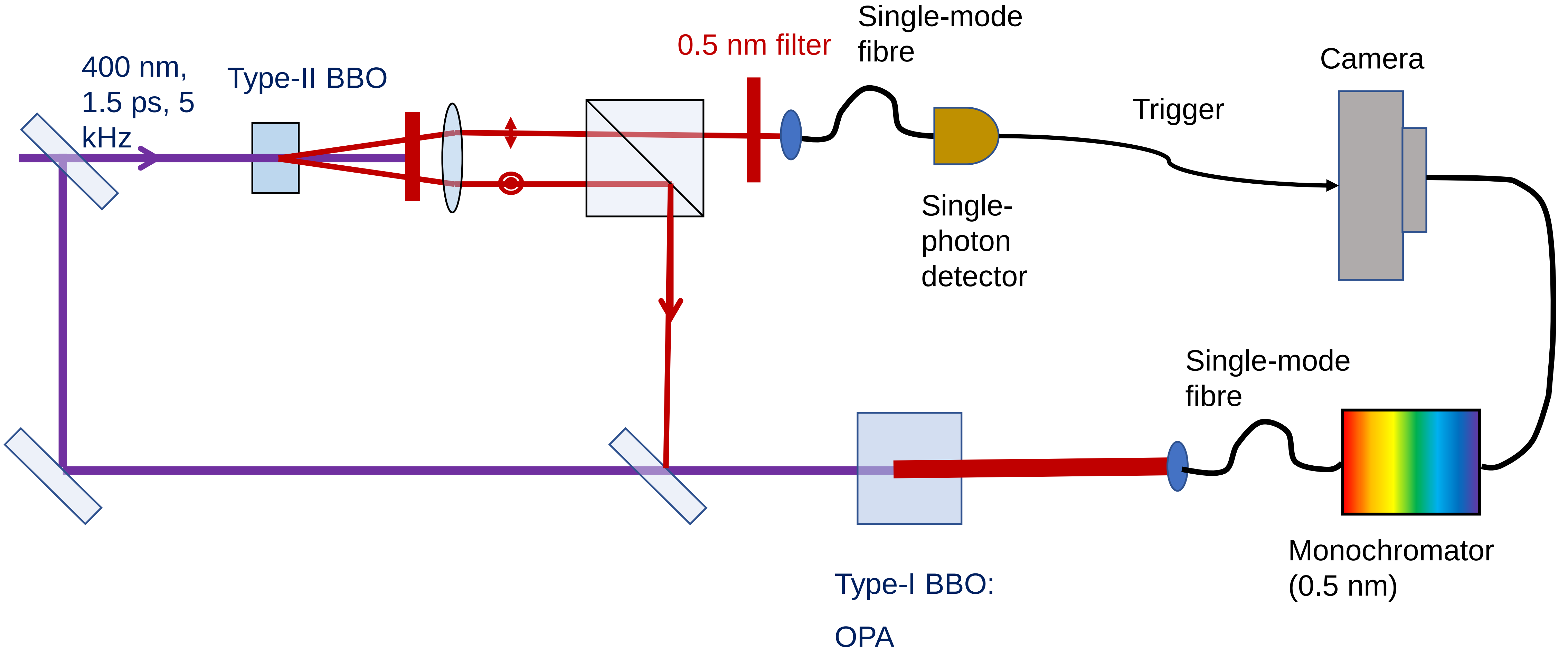
M. Kalash and M. V. Chekhova, Optica 10, 1142 (2023)

A SINGLE-PHOTON STATE AT THE INPUT

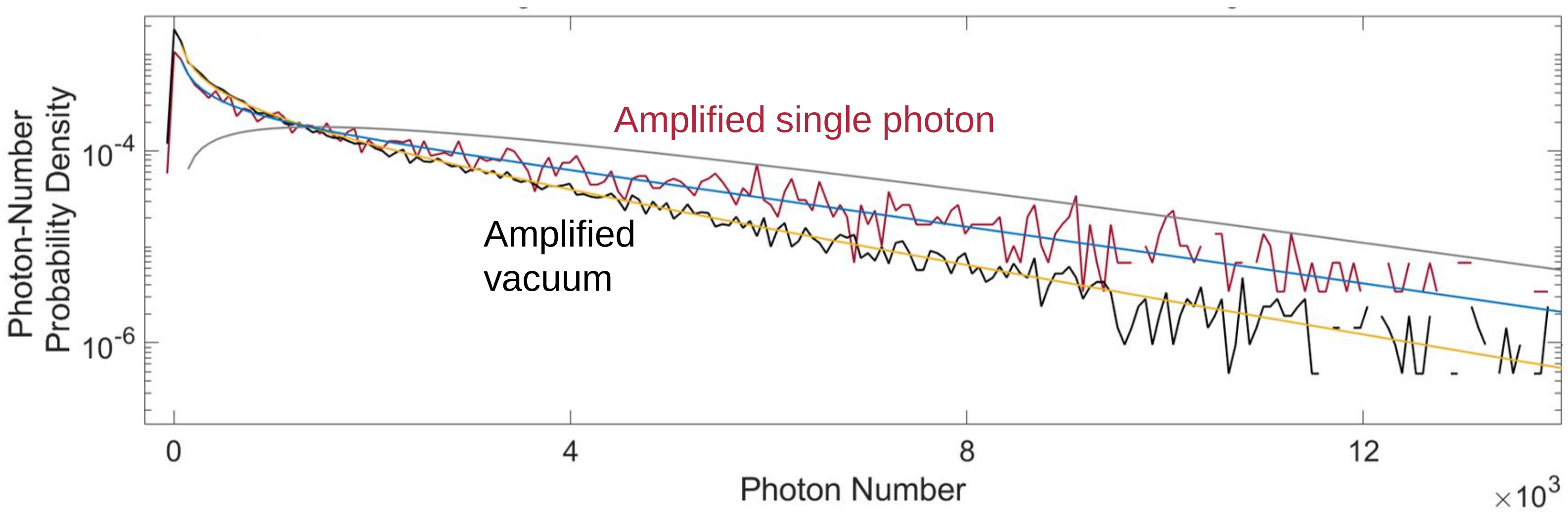


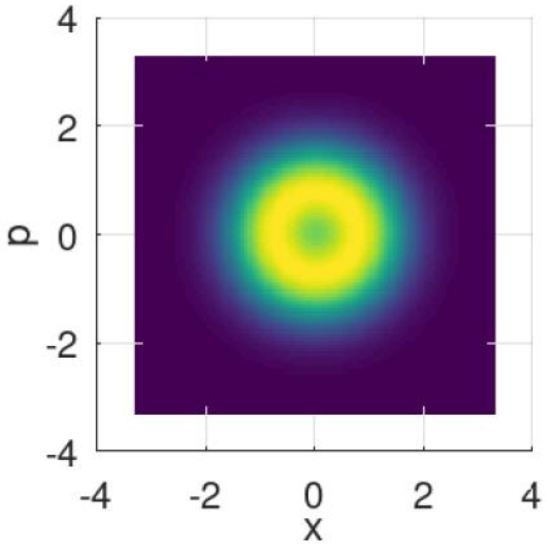
$$P(x^2) \to P(x) \to W(x, p)$$

EXPERIMENT: HERALDED SINGLE PHOTON



RESULTS



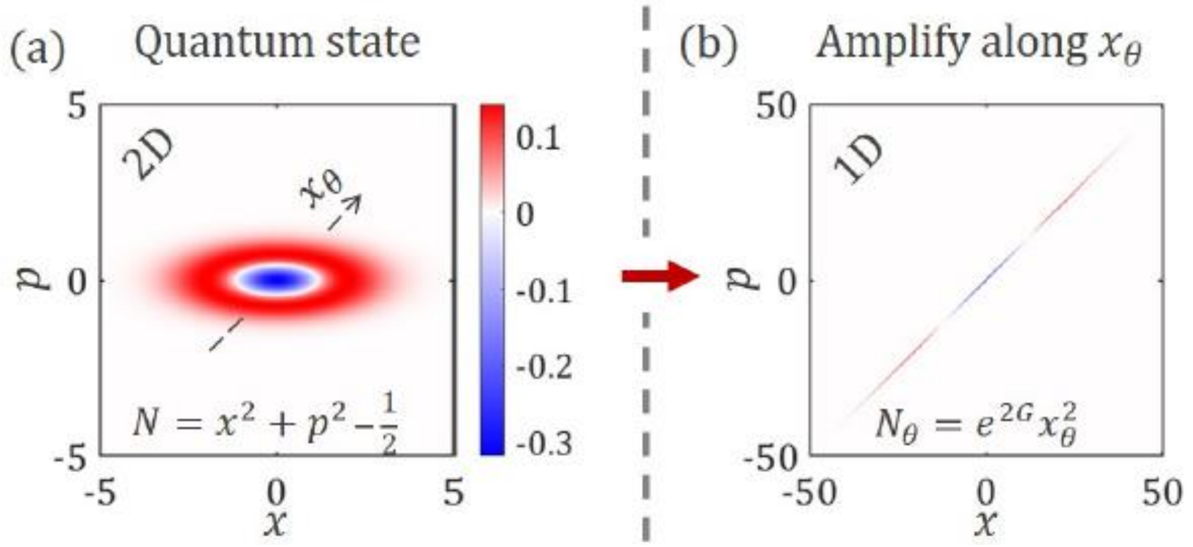


Singularity in the squeezed vacuum P(N)=> no dip in P(x) and no negativity in W(x,p) ☹

Nevertheless, the WF can be reconstructed using the tail of the distribution ☺

M. Kalash, M. H. M. Passos, E. Racz, L. Ruppert, R. Filip, M. Chekhova, arXiv:2507.18296v2 [quant-ph]

OUTLOOK: A BRIGHT NON-GAUSSIAN STATE



A squeezed single photon

THANKS TO

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MAX PLANCK SCHOOL of photonics

QUANTERA

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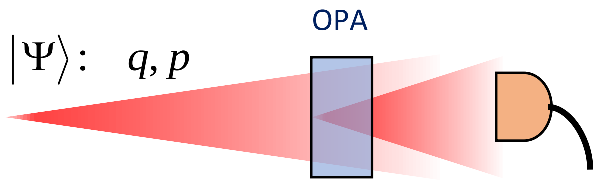
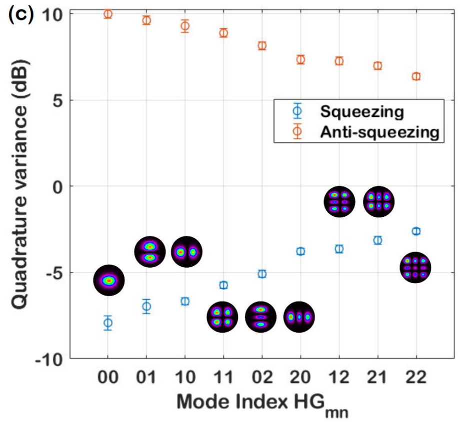
CONCLUSIONS

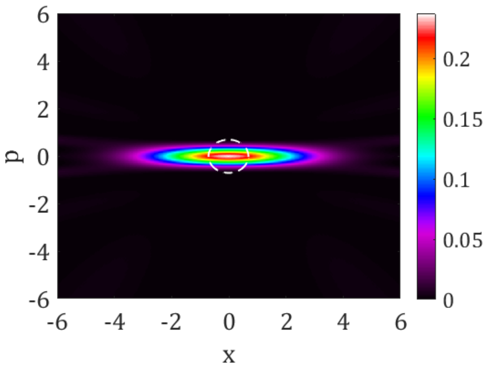
Phase-sensitive optical parametric amplification followed by direct detection as an alternative to homodyne detection: broad bandwidth, tolerance to loss and noise;



… simultaneous characterization of multiple spatial modes;

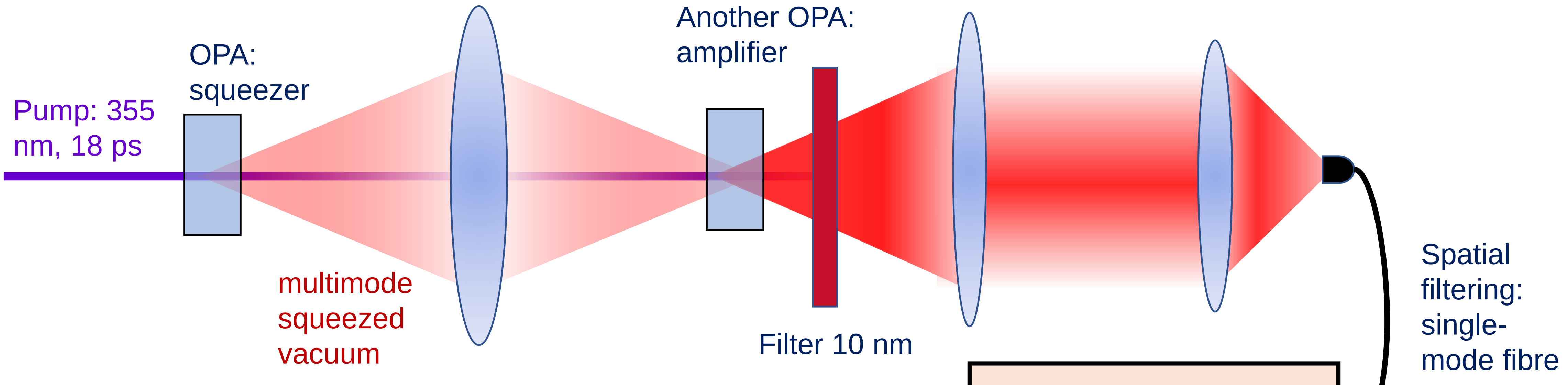


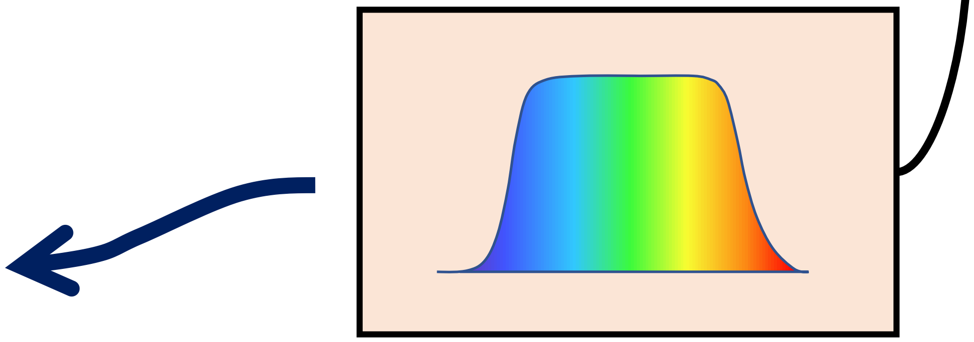
… quantum tomography of squeezed and even non-Gaussian states.



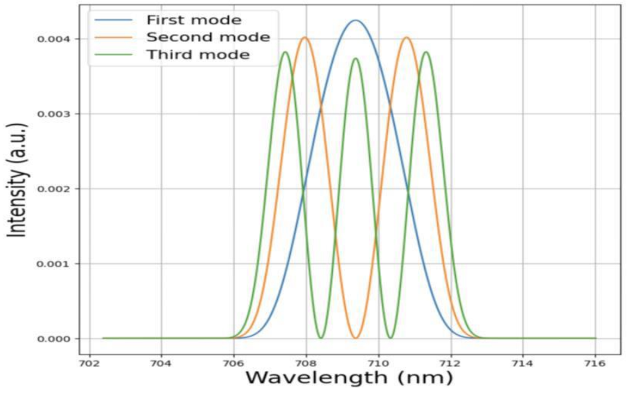
THANK YOU FOR YOUR ATTENTION!

FREQUENCY MODES



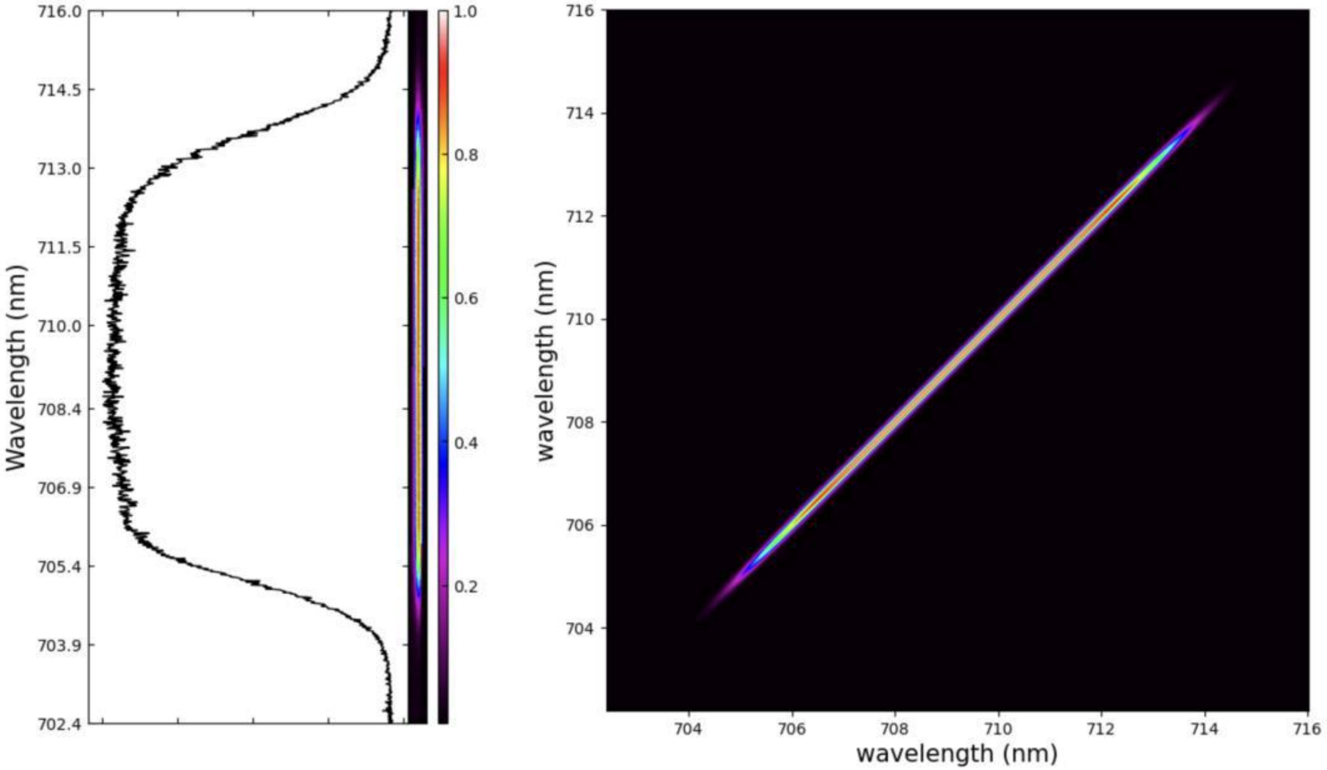


Home-made spectrometer

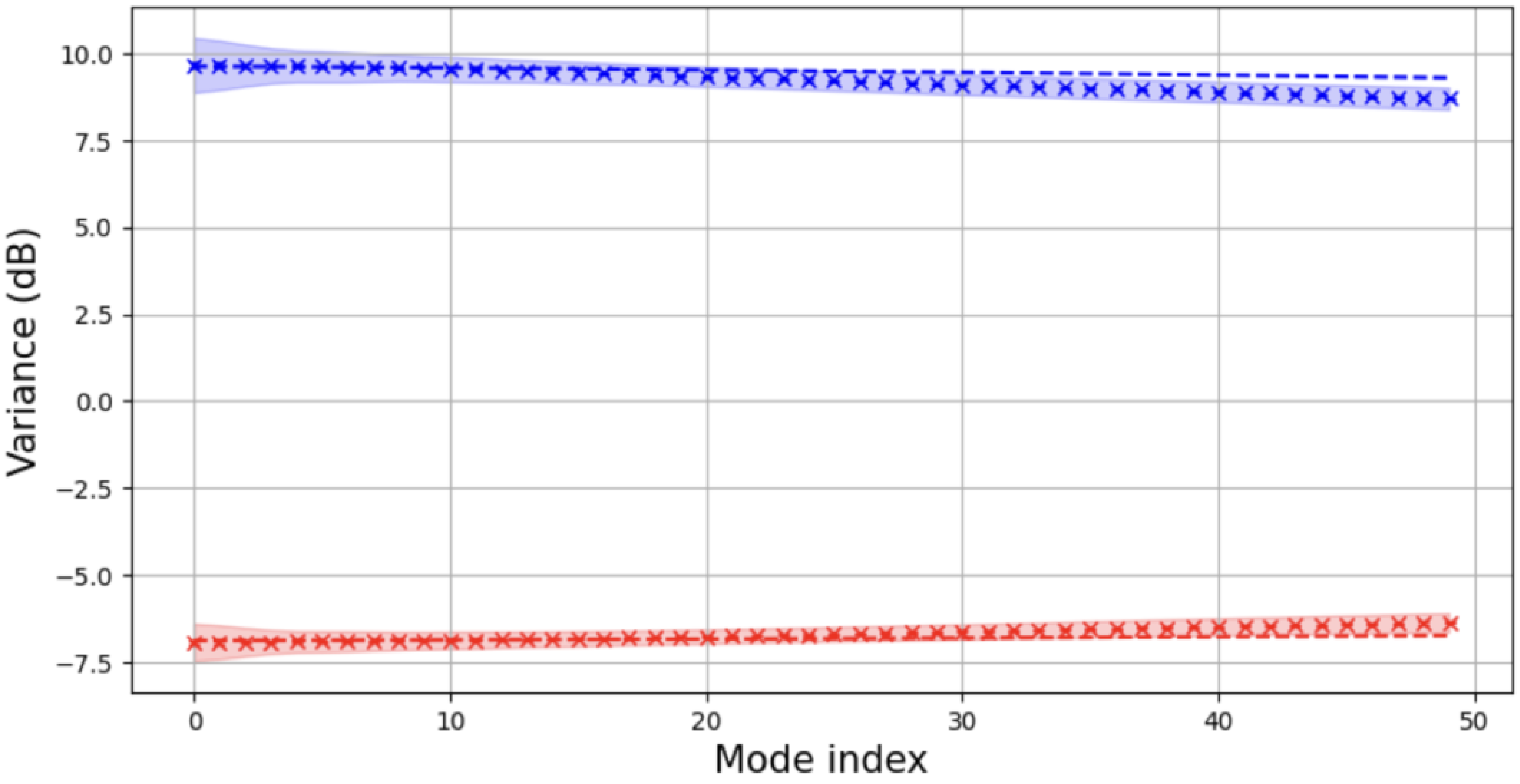


Mode reconstruction

MODE RECONSTRUCTION

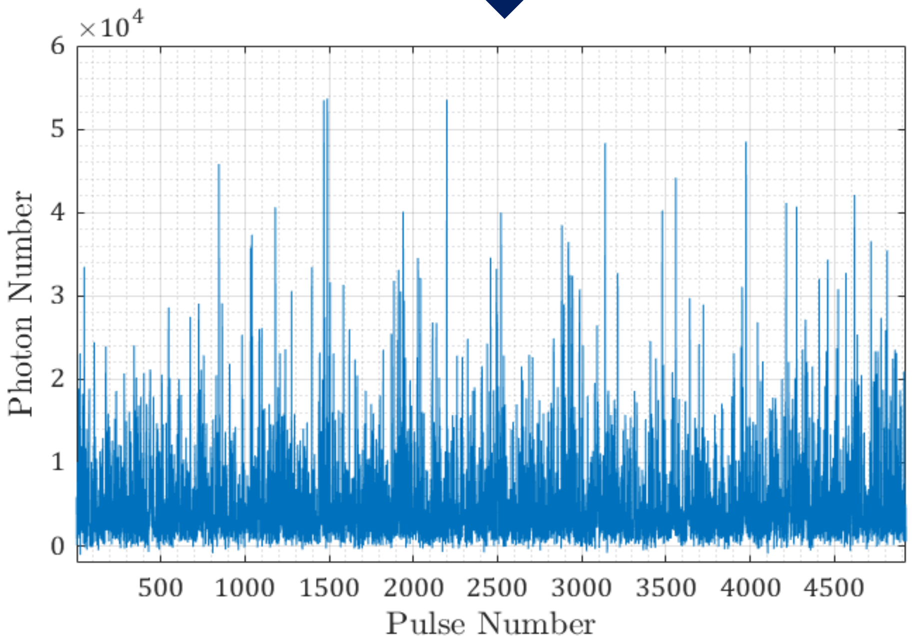


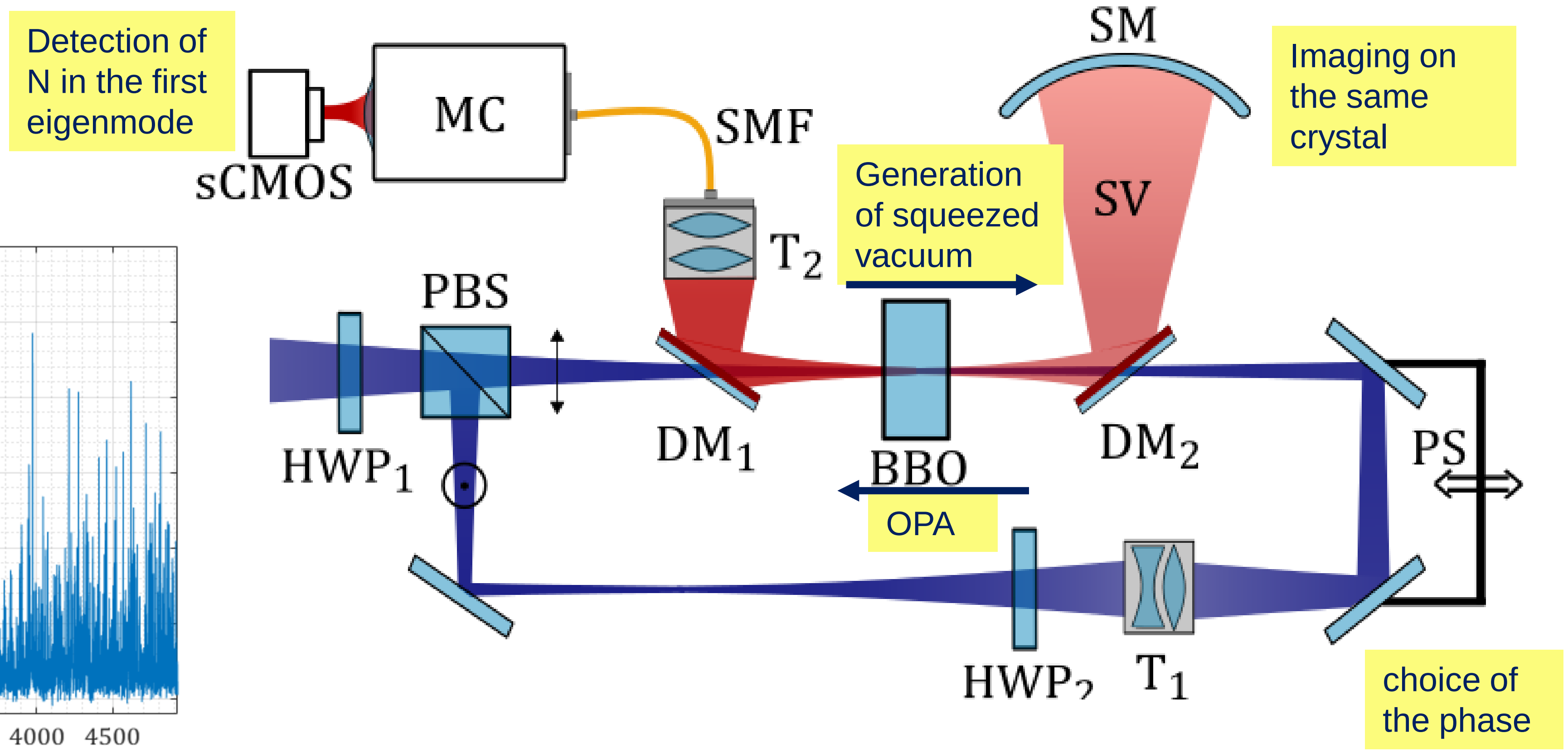
SQUEEZING IN 50 FREQUENCY MODES



M. Kalash, U.-N. Han, Y.-S. Ra, M. Chekhova, arXiv:2508.04502 [quant-ph]

THE REAL SETUP





Detection losses >90%

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