

Quantum geometry, dichroism and sum rules: Some recent developments

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TeQ3 Grenoble, November 12th 2025

OUTLINE

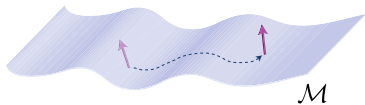
- From geometry to quantum geometry
- Dichroism and quantum geometry
- Relation to electric conductivity and sum rules
- Dichroic approach in quantum-engineered systems
- Correlated topological insulators : from bulk to edge
- Recent work at LKB (Collège de France)

From geometry to quantum geometry

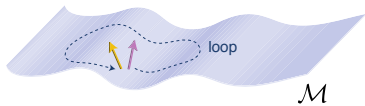


$\mathcal{M}$

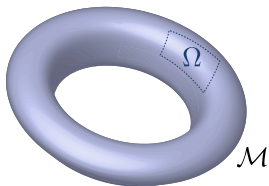




displacement $\longrightarrow$ **parallel transport**

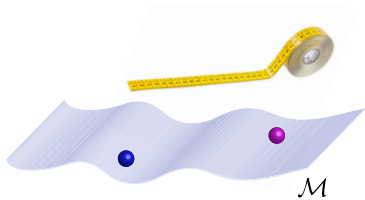


transport mismatch $\longrightarrow$ **curvature** Ω



Gauss-Bonnet theorem: $\frac{1}{2\pi} \int_{\mathcal{M}} \Omega \, dS = 2(1 - \nu)$

topological invariant



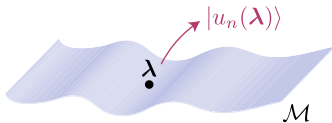
distances $\longrightarrow$ **metric** $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

- **Quantum system** described by Hamiltonian $\hat{H}(\lambda)$ with $\lambda \in \mathcal{M}$

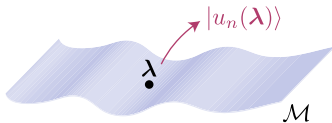


- Some examples :
 - 2-level system :
 $(\lambda_1, \lambda_2) \rightarrow (\theta, \varphi) \in S^2$ (Bloch sphere)
 - Particle moving on 2D lattice :
 $(\lambda_1, \lambda_2) \rightarrow (q_x, q_y) \in \mathbb{T}^2$ (first Brillouin zone)
 - Many-body system with twisted boundary conditions :
 $(\lambda_1, \lambda_2) \rightarrow (\theta_x, \theta_y) \in \mathbb{T}^2$ ("twist-angle space")

- Consider the Hamiltonian $\hat{H}(\lambda)$ with $\lambda \in \mathcal{M}$
- Local eigenstates : $\hat{H}(\lambda)|u_n(\lambda)\rangle = \varepsilon_n(\lambda)|u_n(\lambda)\rangle$



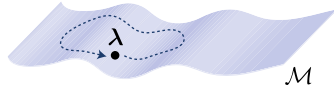
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- **Projection** onto a single band ε_n (adiabatic evolution) :

$\Rightarrow$ **emergent geometric structure**

- **Geometry (i)** : the curvature (Berry's geometric phase)

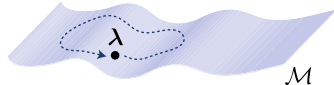
$$|u_n(\boldsymbol{\lambda})\rangle \longrightarrow |u_n(\boldsymbol{\lambda})\rangle \exp \left(i \int_{\Sigma} \Omega^{(n)} \right)$$


The diagram shows a light blue, wavy surface representing a manifold $\mathcal{M}$. A dashed blue loop is drawn on the surface, with an arrow indicating a counter-clockwise direction. A black dot is located on this loop and is labeled with the symbol $\boldsymbol{\lambda}$.

- The **Berry curvature** (in band ε_n) :

$$\Omega_{\mu\nu}^{(n)}(\boldsymbol{\lambda}) = i \left(\left\langle \frac{\partial u_n}{\partial \lambda^\mu} \middle| \frac{\partial u_n}{\partial \lambda^\nu} \right\rangle - \left\langle \frac{\partial u_n}{\partial \lambda^\nu} \middle| \frac{\partial u_n}{\partial \lambda^\mu} \right\rangle \right)$$

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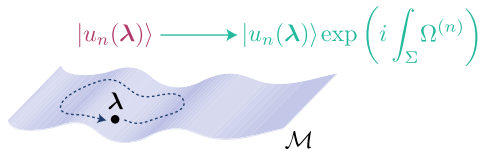
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- Physical manifestation : **Hall response** in a Bloch band $\varepsilon_n(\mathbf{q})$

$$v_x^{(n)}(\mathbf{q}) = \frac{\partial \varepsilon_n}{\partial q^x} - F_y \Omega_{xy}^{(n)}(\mathbf{q}) : \text{velocity in Bloch band}$$

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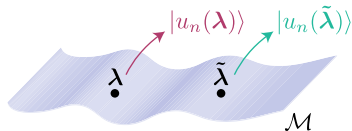
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- Topological invariant (**Chern number** or TKNN number) :

$$\nu_{\text{Ch}}^{(n)} = \frac{1}{2\pi} \int_{\mathcal{M}} \Omega_{\mu\nu}^{(n)} d\lambda^\mu d\lambda^\nu \in \mathbb{Z}$$

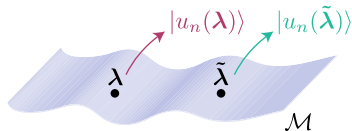
- **Geometry (ii)** : distance between states



- The **quantum (Fubini-Study) metric** :

$$g_{\mu\nu} d\lambda^\mu d\lambda^\nu = 1 - |\langle u_n(\lambda) | u_n(\lambda + d\lambda) \rangle|^2$$

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- Various physical manifestations :
 - Imaginary part of susceptibility (Kubo's linear response theory)
 $\implies$ fluctuations & dissipation
 - Quantum Fisher information $\implies$ Cramér-Rao bound, multi-partite entanglement
 - Contributes to transport, superconductivity, optical responses, quantum Hall physics, ...

Refs : Kolodrubetz et al., Phys. Rep. **697**, 1-87 (2017)
 Jiabin Yu et al., arXiv :2501.00098 (2025)

- **Metric and curvature united** : the quantum geometric tensor (QGT)

$$G_{\mu\nu}^{(n)} = \sum_{m \neq n} \frac{\langle u_n | \partial_{\lambda_\mu} \hat{H} | u_m \rangle \langle u_m | \partial_{\lambda_\nu} \hat{H} | u_n \rangle}{(\varepsilon_n - \varepsilon_m)^2} \quad (\text{in band } \varepsilon_n)$$

- Quantum metric : $g_{\mu\nu}^{(n)} = \mathcal{R} \left(G_{\mu\nu}^{(n)} \right)$
- Berry curvature : $\Omega_{\mu\nu}^{(n)} = -2 \mathcal{I} \left(G_{\mu\nu}^{(n)} \right)$

$\implies$ metric and curvature are related (**Kähler geometry**) !

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- **Experimental studies** of QGT since 2018

$\implies$ solid-state qubits, cold atoms, photonics, solid-state materials, ...

Refs : Yu et al. (Jianming Cai's group), arXiv :1811.12840 (2018)
 Asteria et al. (Weitenberg/Sengstock group), arXiv :1805.11077 (2018)

Dichroism and quantum geometry

- Generic system with Hamiltonian $\hat{H}(\boldsymbol{\lambda})$ with $\boldsymbol{\lambda} = (\lambda_1, \lambda_2) \in \mathcal{M}$



- Local eigenstates : $\hat{H}(\boldsymbol{\lambda})|\Psi_n(\boldsymbol{\lambda})\rangle = E_n(\boldsymbol{\lambda})|\Psi_n(\boldsymbol{\lambda})\rangle$

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- **Prepare** system in a local eigenstate (gapped) : $|\Psi_0(\boldsymbol{\lambda})\rangle$
- **Time-modulate** a parameter : $\lambda_\mu(t) = \lambda_\mu + (2\mathcal{E}/\hbar\omega) \cos(\omega t)$

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- **Excitation rate** : Fermi's Golden Rule with $\delta\hat{H} = (\mathcal{E}/\hbar\omega)(\partial_{\lambda_\mu}\hat{H})e^{-i\omega t} + \text{h.c.}$

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$$\Rightarrow \Gamma(\omega) = \frac{2\pi}{\hbar} \sum_{n \neq 0} \left| \frac{\mathcal{E}}{\hbar\omega} \left\langle n \left| \frac{\partial \hat{H}}{\partial \lambda_\mu} \right| 0 \right\rangle \right|^2 \delta(E_n - E_0 - \hbar\omega)$$

$$\Rightarrow \Gamma^{\text{int}} = \int_0^\infty \Gamma(\omega) d\omega = \frac{2\pi\mathcal{E}^2}{\hbar^2} g_{\mu\mu}(\boldsymbol{\lambda}) : \text{quantum Fisher information (F-D theorem)}$$

- Time-modulate **two** parameters :

$$\lambda_{\mu}(t) = \lambda_{\mu} + (2\mathcal{E}/\hbar\omega) \cos(\omega t)$$

$$\lambda_{\nu}(t) = \lambda_{\nu} \pm (2\mathcal{E}/\hbar\omega) \cos(\omega t)$$

- Introduce the **differential** excitation rate : $\Delta\Gamma(\omega) = (\Gamma^{+}(\omega) - \Gamma^{-}(\omega)) / 2$

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where $g_{\mu\nu}(\boldsymbol{\lambda}) = \mathcal{R}[G_{\mu\nu}]$: quantum metric in band $E_0(\boldsymbol{\lambda})$

$$G_{\mu\nu} = \sum_{n \neq 0} \frac{\langle 0 | \frac{\partial \hat{H}}{\partial \lambda_{\mu}} | n \rangle \langle n | \frac{\partial \hat{H}}{\partial \lambda_{\nu}} | 0 \rangle}{(E_n - E_0)^2} : \text{quantum geometric tensor}$$

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$\Rightarrow$ entire **quantum metric** can be **probed** by monitoring the Γ 's !

- Time-modulate **two** parameters : **circular** drive in λ -space

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$\Rightarrow$ entire **quantum geometric tensor** can be **probed** by monitoring the Γ 's!

$\Rightarrow$ applications in quantum-engineered settings

Ref : Tran, Dauphin, Grushin, Zoller and NG, Sci. Adv. **3**, e1701207 (2017)
Ozawa and NG, PRB **97**, 201117(R) (2018)

Relation to electric conductivity and sum rules

- 2D insulator irradiated by **circularly**-polarized light

$$\mathbf{E}_{\pm}(\omega) = 2\mathcal{E} [\cos(\omega t)\mathbf{1}_x \pm \sin(\omega t)\mathbf{1}_y] = -\partial_t \mathbf{A}(t)$$

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- Insulator : completely **filled Bloch band**

$$\Rightarrow \Delta\Gamma^{\text{int}}/A_{\text{syst}} = (\mathcal{E}/\hbar)^2 \nu_{\text{Ch}}$$

where $\nu_{\text{Ch}} = \frac{1}{2\pi} \int_{\text{BZ}} \Omega_{xy} d^2q$: **Chern number** of band $E_0(\mathbf{q})$

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$\Rightarrow$ dichroic response is **quantized** by the Chern number

- 2D insulator irradiated by circular light : **Power absorbed** (Joule heating)

$$P_{\pm}(\omega) = 4A_{\text{syst}}\mathcal{E}^2 \left(\sigma_{\text{R}}^{xx}(\omega) \pm \sigma_{\text{I}}^{xy}(\omega) \right)$$

$$= \hbar\omega \Gamma^{\pm}(\omega)$$

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- The differential integrated rate reads

$$\Delta\Gamma^{\text{int}}/A_{\text{syst}} = \frac{4\mathcal{E}^2}{\hbar} \int_0^{\infty} \frac{\sigma_{\text{I}}^{xy}(\omega)}{\omega} d\omega$$

$$= \frac{2\pi\mathcal{E}^2}{\hbar} \sigma_{\text{H}} \quad : \text{ **Hall response** (Kramers-Kronig)}$$

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- Combined with the result : $\Delta\Gamma^{\text{int}}/A_{\text{syst}} = (\mathcal{E}/\hbar)^2 \nu_{\text{Ch}}$

$$\implies \sigma_{\text{H}}/\sigma_0 = \nu_{\text{Ch}}$$

$\implies$ **TKNN** obtained through FGR and Kramers-Kronig only !

- Consider **linearly polarized** light

$$q_x(t) = q_x + (2\mathcal{E}/\hbar\omega) \sin(\omega t) \implies \Gamma_x(\omega)$$

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- Insulator : completely **filled Bloch band**

$$\implies \Gamma_x^{\text{int}} + \Gamma_y^{\text{int}} = \frac{2\pi\mathcal{E}^2}{\hbar^2} \Omega_I$$

where $\Omega_I = \sum_{\mathbf{q}} g_{xx}(\mathbf{q}) + g_{yy}(\mathbf{q})$: **Wannier spread functional**

$\implies \Gamma$'s contain information on **spatial localization** in Bloch bands

Ref : Ozawa and NG, PRB **97**, 201117(R) (2018)

Ozawa and NG, PRR **1**, 032019(R) (2019)

- Insulator irradiated by **linearly-polarized** light : **Power absorbed**

$$P_{\pm}(\omega) = 4A_{\text{syst}}\mathcal{E}^2 \sigma_{\text{R}}^{xx}(\omega) = \hbar\omega \Gamma_x^{\pm}(\omega)$$

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- Combined with the result : $\Gamma_x^{\text{int}} + \Gamma_y^{\text{int}} = \frac{2\pi\mathcal{E}^2}{\hbar^2} \Omega_{\text{I}}$

$$\Rightarrow \int_0^{\infty} \frac{\sigma_{\text{R}}^{xx}(\omega) + \sigma_{\text{R}}^{yy}(\omega)}{\omega} d\omega = \frac{\pi}{A_{\text{syst}}\hbar} \Omega_{\text{I}}$$

$\Rightarrow$ we recover the Souza-Wilkens-Martin sum rule !

Dichroic approach in quantum-engineered systems

- Ultracold atoms in a 2D **honeycomb optical lattice** with **circular shaking** :

$$\hat{H} = \hat{H}_{\text{lattice}} + V_0 (\cos(\omega t)\hat{x} \pm \sin(\omega t)\hat{y})$$

Ref : Struck et al. (Sengstock group), Science **333**, 996 (2011)
Jotzu et al. (Esslinger group), Nature **515**, 237 (2014)

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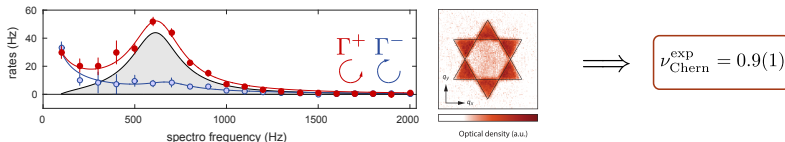
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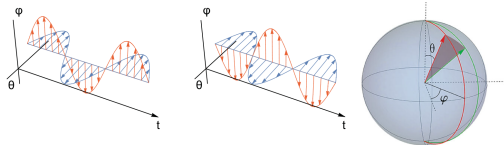


$\Rightarrow$ first experimental observation : $\Delta\Gamma^{\text{int}}/A_{\text{syst}} = (\mathcal{E}/\hbar)^2 \nu_{\text{Ch}}$

- Using a **linear-shaking probe** $\Rightarrow$ Wannier spread functional / **quantum metric**

Ref : Asteria et al. (Sengstock group), Nature Phys. **15**, 449 (2019)

- **Solid-state qubits** : Quantum geometric tensor, metrology & topology



PHYSICS

Experimental measurement of the quantum geometric tensor using coupled qubits in diamond

Min Yu^{1,2,†}, Pengcheng Yang^{1,2,†}, Musang Gong^{1,2}, Qingyun Cao^{3,1,2}, Qiuyu Lu^{1,2}, Haibin Liu^{1,2}, Shaoliang Zhang^{1,2,*}, Martin B. Plenio^{4,2}, Fedor Jelezko^{3,2}, Tomoki Ozawa⁵, Nathan Goldman^{6,*} and Jianming Cai^{1,2,*}

ARTICLE OPEN

Quantum Fisher information measurement and verification of the quantum Cramér–Rao bound in a solid-state qubit

Min Yu¹, Yu Liu¹, Pengcheng Yang^{1,2}, Musang Gong¹, Qingyun Cao^{1,2}, Shaoliang Zhang¹, Haibin Liu¹, Markus Heyl³, Tomoki Ozawa⁵, Nathan Goldman⁶ and Jianming Cai^{1,2,3,4,5,6}

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REPORT

TOPOLOGICAL PHYSICS

A synthetic monopole source of Kalb-Ramond field in diamond

Mo Chen (陈墨)^{1,2,†}, Changhao Li^{1,3,†}, Giamdomenico Palumbo^{4,5}, Yan-Qing Zhu⁴, Nathan Goldman⁶, Paola Cappellaro^{3,5,6}

PHYSICS

Experimental demonstration of topological bounds in quantum metrology

Min Yu^{1,2,†}, Xiangbei Li^{1,2,†}, Yaoming Chu^{1,2,*}, Bruno Mera^{3,*}, F. Nur Ünal^{4,*}, Pengcheng Yang^{1,2}, Yu Liu^{2,5}, Nathan Goldman^{6,7,*} and Jianming Cai^{1,2,8,*}

Experimental Measurement of the Quantum Metric Tensor and Related Topological Phase Transition with a Superconducting Qubit

Xinsheng Tan,^{1,*} Dan-Wei Zhang,^{2,†} Zhen Yang,¹ Ji Chu,¹ Yan-Qing Zhu,¹ Danyu Li,¹ Xiaopei Yang,¹ Shuqing Song,¹ Zhikun Han,¹ Zhiyuan Li,¹ Yuqian Dong,¹ Hai-Feng Yu,¹ Hui Yan,² Shi-Liang Zhu,^{1,2,†} and Yang Yu^{1,3}

¹National Laboratory of Solid State Microstructures, School of Physics, Nanjing University, Nanjing 210093, China

²Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, GPETR Center for Quantum Precision Measurement and SPTE, South China Normal University, Guangzhou 510006, China

Correlated topological insulators : from bulk to edge

- Consider a many-body Hamiltonian in 2D space (size $L \times L$) with PBC

$$\hat{H} = \sum_{a=1}^N \left(\frac{[\hat{\mathbf{p}}_a - \mathbf{A}(\hat{\mathbf{r}}_a)]^2}{2m} + V(\hat{\mathbf{r}}_a) \right) + \hat{H}_{\text{int}}(\{\mathbf{r}_a\}),$$

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- Prepare a gapped GS $|\Psi_0\rangle$ and study **response to circular field**

$$\mathbf{E}_{\pm}(\omega) = 2\mathcal{E} [\cos(\omega t)\mathbf{1}_x \pm \sin(\omega t)\mathbf{1}_y] = -\partial_t \mathbf{A}(t)$$

$$A_x \longrightarrow A_x - (2\mathcal{E}/\omega) \sin(\omega t), \quad A_y \longrightarrow A_y \pm (2\mathcal{E}/\omega) \cos(\omega t)$$

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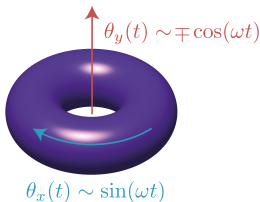
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- In **flux-space** language : Prepare $|\Psi_0(\theta = 0)\rangle$ and evolve with $\hat{H}(\theta_x(t), \theta_y(t))$

$$\theta_x(t) = (2\mathcal{E}L/\omega) \sin(\omega t), \quad \theta_y(t) = \mp (2\mathcal{E}L/\omega) \cos(\omega t)$$



- Dichroic response yields the **many-body Berry curvature**

$$\Delta\Gamma^{\text{int}} = \frac{1}{2} \int_0^\infty \Gamma^+(\omega) - \Gamma^-(\omega) \, d\omega = \left(\frac{\mathcal{E}^2 L^2}{\hbar^2} \right) \times 2\pi \Omega_{xy}^{\text{MB}}(\boldsymbol{\theta} = 0)$$

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$$2\pi \Omega_{xy}^{\text{MB}}(\boldsymbol{\theta} = 0) \longrightarrow 2\pi \langle \Omega_{xy}^{\text{MB}} \rangle_{\boldsymbol{\theta}} = 2\pi \times \frac{1}{(2\pi)^2} \int_{\mathbb{T}^2} \Omega_{xy}^{\text{MB}}(\boldsymbol{\theta}) d^2\theta = \nu_{\text{Ch}}^{\text{MB}}$$

$$\longrightarrow \Delta\Gamma^{\text{int}}/A = (\mathcal{E}/\hbar)^2 \times \nu_{\text{Ch}}^{\text{MB}} : \textbf{quantized topological response !}$$

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$$\nu_{\text{Ch}}^{\text{MB}} = \nu_{\text{Ch}} = \frac{1}{2\pi} \int_{\text{FBZ}} \Omega_{xy}(\mathbf{q}) d^2\mathbf{q} \in \mathbb{Z} \longrightarrow \Delta\Gamma^{\text{int}} \text{ quantized !}$$

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- For a **fractional** Chern insulator :

$$\nu_{\text{Ch}}^{\text{MB}} \in \mathbb{Q} \longrightarrow \Delta\Gamma^{\text{int}} \textbf{ fractionally quantized !}$$

Numerical study on FCIs : Repellin and NG, PRL '19

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- Combined with **Kramers-Kronig** :

$$\Delta\Gamma^{\text{int}}/A_{\text{syst}} = \frac{2\pi\mathcal{E}^2}{\hbar} \sigma_{\text{H}} \implies \sigma_{\text{H}}/\sigma_0 = \nu_{\text{Ch}}^{\text{MB}}$$

Ref : NG and Tomoki Ozawa, Comptes Rendus Physique **25**, 289 (2024)

- In a confined and isolated system (“QH system in a box”)

$$\sigma_H = 0 \implies \Delta\Gamma^{\text{int}} = 0 \quad (1)$$

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- From the previous analysis (PBC) :

$$\Delta\Gamma_{\text{bulk}}^{\text{int}} = (\mathcal{E}/\hbar)^2 \times \nu_{\text{Ch}}^{\text{MB}}$$

$\implies$ quantized response requires **isolating the bulk contribution** !

Ref : Tran, Dauphin, Grushin, Zoller and NG, Sci. Adv. **3**, e1701207 (2017)

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- From Eq. (1), the **edge response is quantized** :

$$\Delta\Gamma^{\text{int}} = \Delta\Gamma_{\text{bulk}}^{\text{int}} + \Delta\Gamma_{\text{edge}}^{\text{int}} = 0 \quad \implies \Delta\Gamma_{\text{edge}}^{\text{int}} = -(\mathcal{E}/\hbar)^2 \times \nu_{\text{Ch}}^{\text{MB}}$$

$\implies$ can one **isolate the quantized edge response** ?

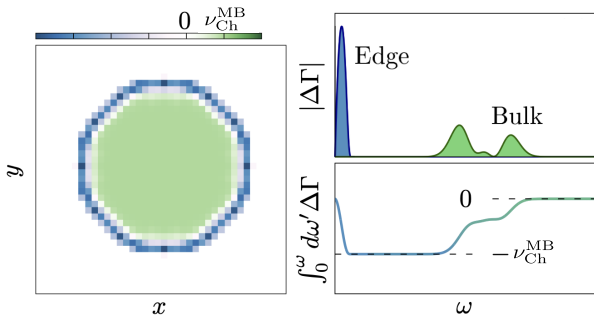


Ref : Nur Ünal, Alberto Nardin and NG, arXiv :2407.04639

- Using Wen's effective theory of **low-energy edge excitations**

$$\Delta\Gamma_{\text{edge}}^{\text{int}} \Big|_{\text{Wen}} = -(\mathcal{E}/\hbar)^2 \times \nu_{\text{Ch}}^{\text{MB}}$$

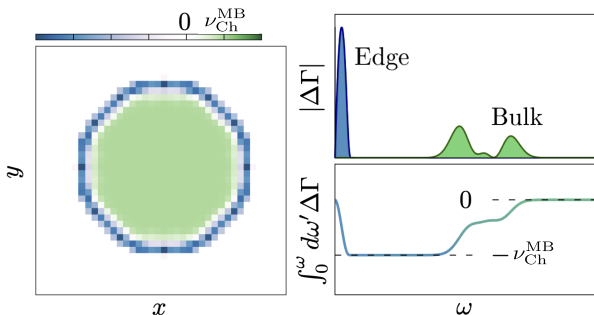
$\Rightarrow$ edge dichroic response entirely captured by **low-energy modes** !



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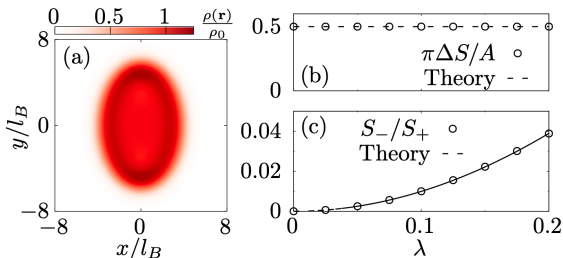


- The quantized edge response can be **spatially and energy resolved** !
- Numerical studies** on various FQH states and edge configurations

- Edge dichroism is sensitive to the **shape of quantum Hall droplet**
- **Example** : Quantum Hall droplet in an **elliptic** trap :

$$V_{\text{conf}}(x, y) = U_0 \left(e^{2\lambda} x^2 + e^{-2\lambda} y^2 \right) \implies \frac{S_-}{S_+} = \tanh^2(\lambda)$$

where $S_{\pm} = (\hbar^2/2\pi\mathcal{E}^2) \times (\Gamma_{\pm}^{\text{int}})_{\text{edge}}$



A recent work with **Baptiste and Anaïs** at LKB (Collège de France)



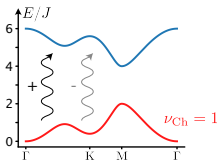
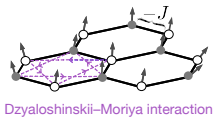
Baptiste Bermond



Anaïs Defossez

- 2D spin systems : **topological magnons and dichroism**

$$\hat{\mathcal{H}} = -J \sum_{\langle ij \rangle} \vec{s}_i \cdot \vec{s}_j + \sum_{\langle\langle ij \rangle\rangle} \vec{D}_{ij} \cdot (\vec{s}_i \wedge \vec{s}_j)$$

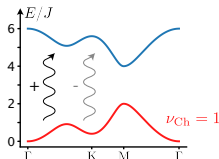
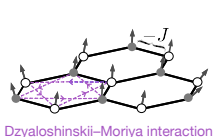


$$\delta \hat{\mathcal{H}}_{\pm}(t) = 2\epsilon [\hat{x} \cos(\omega t) \pm \hat{y} \sin(\omega t)]$$

$$\hat{x} = - \sum_j x_j \hat{s}_j^z$$

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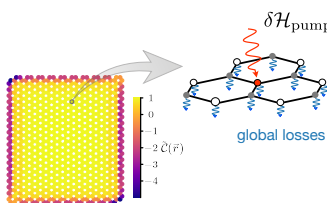
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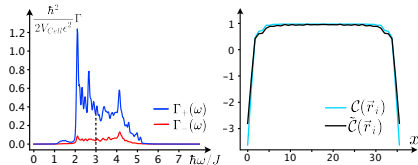
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- Driven-dissipative** preparation and the **local marker**



$$\delta \mathcal{H}_{\text{pump}} = \mu_B \sum_j B_j (e^{i\omega_0 t} s_j^+ + \text{h.c.})$$



Kähler geometry: From topological quantum matter to quantum field theories

workshop

The primary objective of this Workshop is to foster dialogue and collaboration across diverse communities, spanning mathematical physics to condensed matter physics. In particular, we will discuss the role of Kähler structures in topological quantum matter; quantum geometry and optical responses in quantum matter; supersymmetry; string theory; geometric quantization and gravity.

Invited Speakers

Philip Argyres (U. of Cincinnati, USA)
Tristan Collins (U. of Toronto, Canada)
Joel Fine (ULB, Belgium)
Liang Fu (MIT, USA)
Mario Garcia-Fernandez (ICMAT, Spain)
Jutho Haegeman (Ugent, Belgium)
Duncan Haldane (Princeton U., USA)
Chris Hull (Imperial College London, UK)

Magdalena Larfors (Uppsala U., Sweden)
Bruno Mera (U. de Lisboa, Portugal)
Shinsei Ryu (Princeton U., USA)
Robert-Jan Slager (U. of Cambridge & U. of Manchester, UK)
James Sparks (U. of Oxford, UK)
Stefan Vandoren (Utrecht U., The Netherlands)
Ashvin Vishwanath (Harvard U., USA)

Organising Committee

Glenn Barnich (ULB, Belgium)
Nathan Goldman (ULB, Belgium & Collège de France)
Marc Henneaux (ULB, Belgium)

Scientific Committee

Riccardo Argurio (ULB, Belgium)
Andrei Bernevig (Princeton U., USA)
Ben Craps (VUB, Belgium)
Michael Douglas (Stony Brook, USA)
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Boris Pioline (Sorbonne U., France)
Sakura Schafer-Nakemi (U. of Oxford, UK)
Robert-Jan Slager (U. of Cambridge, UK)
Frank Verstraete (Ugent, Belgium)

27 – 29 May 2026
Fondation Universitaire
Salle Félicien Cattier

11, Rue d'Egmont
1000 Bruxelles

Registration

