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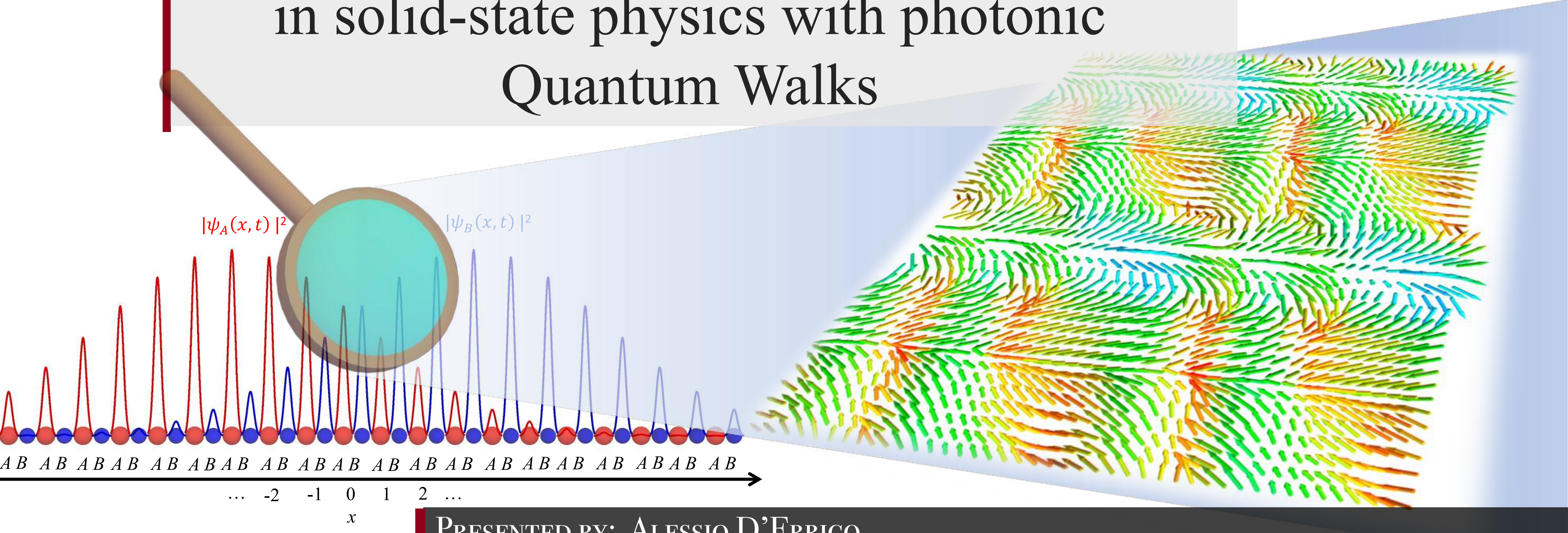
Understanding topology and geometry in solid-state physics with photonic Quantum Walks

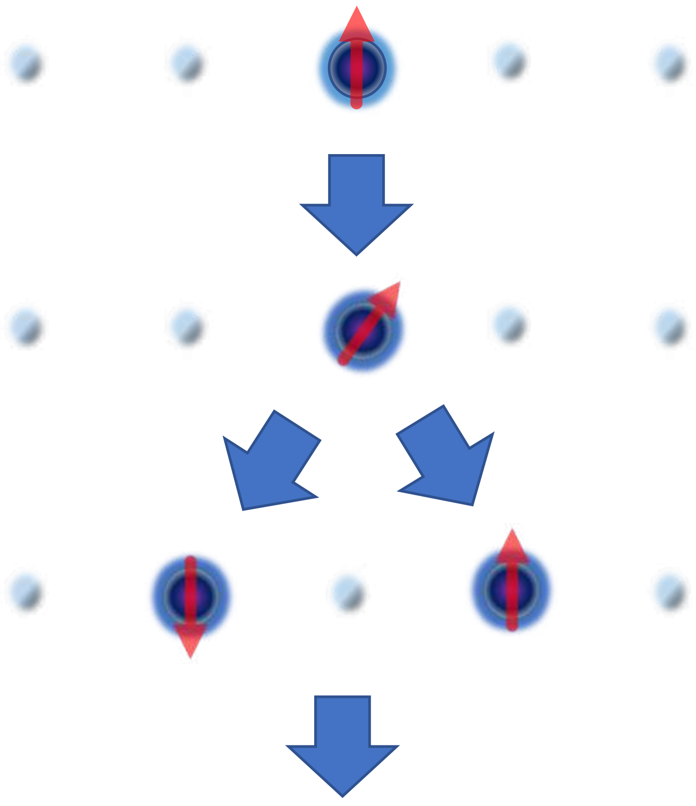


PRESENTED BY: ALESSIO D'ERRICO

Quantum Walks as iterated Unitary processes

$C(\theta)$

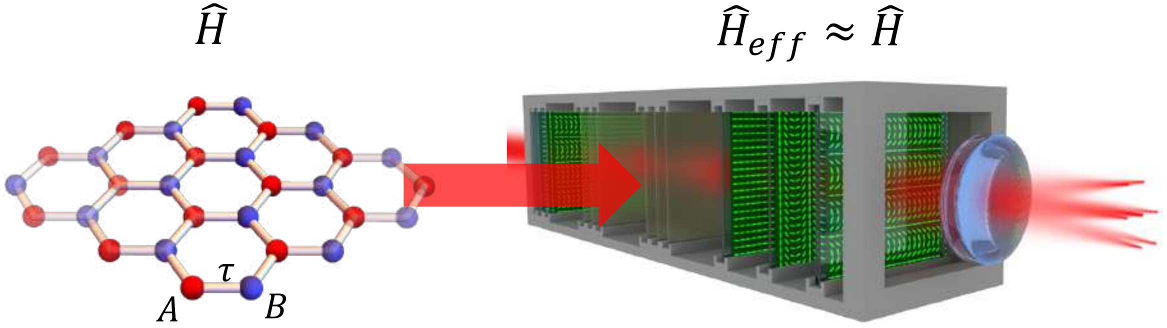
S



Repeat!

$$U = S \cdot C(\theta); \ \ |\psi(t)\rangle = U^t |\psi(0)\rangle$$

$$U^t = Exp\left(-\frac{iH_{eff}}{\hbar}t\right)$$

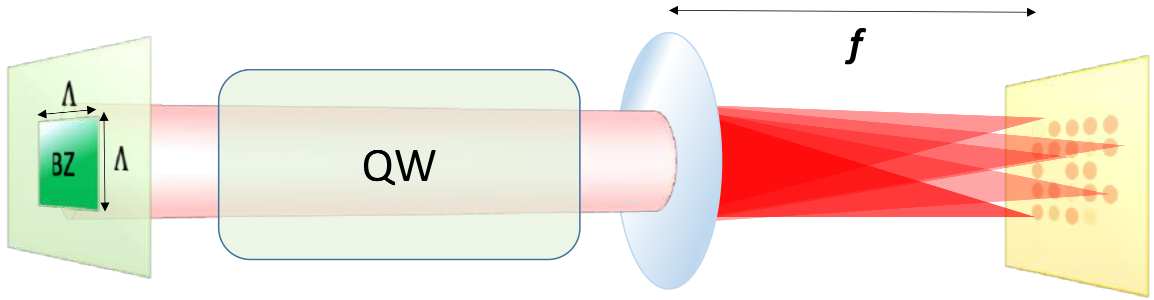


D'Errico, Alessio, et al. Two-dimensional topological quantum walks in the momentum space of structured light. *Optica*, 2020 7.2: 108-114.

Quantum Walks as iterated Unitary processes

$$U^t = \int_{-\pi}^{\pi} \mathcal{U}^t(q) \otimes |q\rangle\langle q| \frac{dq}{2\pi}$$

$$|q\rangle := \sum_X e^{iqX} |X\rangle$$



Real space ↔ quasi-momentum space

Fourier plane ↔ lattice space

Kitagawa, Takuya. "Topological phenomena in quantum walks: elementary introduction to the physics of topological phases." *Quantum Information Processing* 11 (2012): 1107-1148.

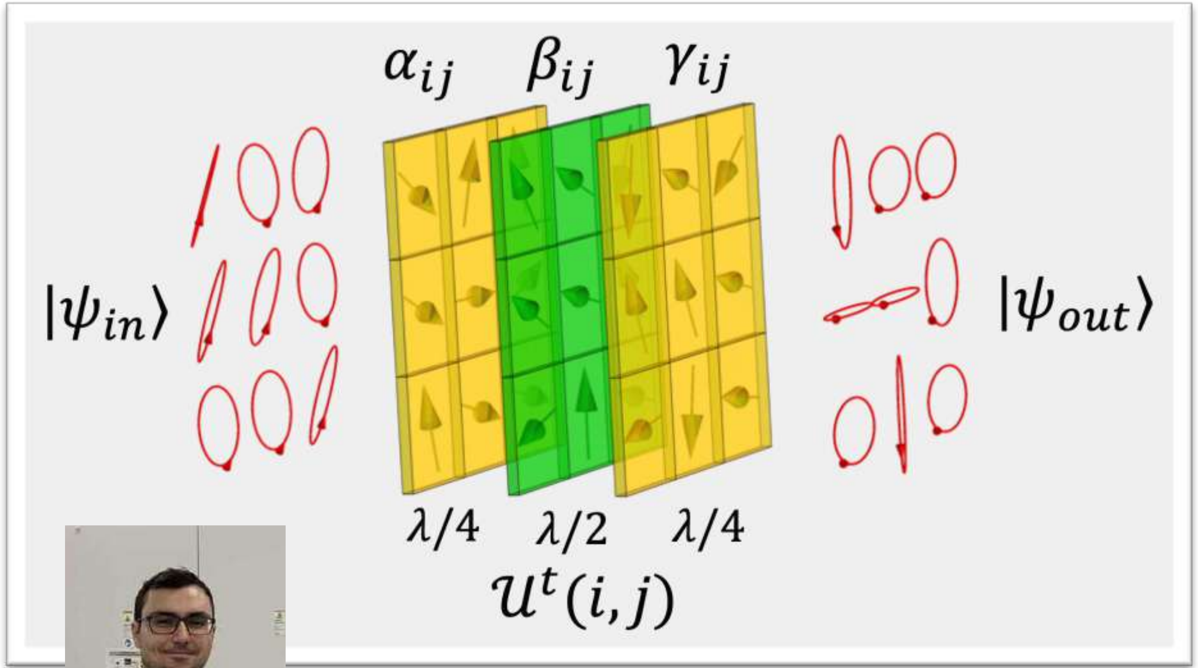
Customizing space dependent unitaries

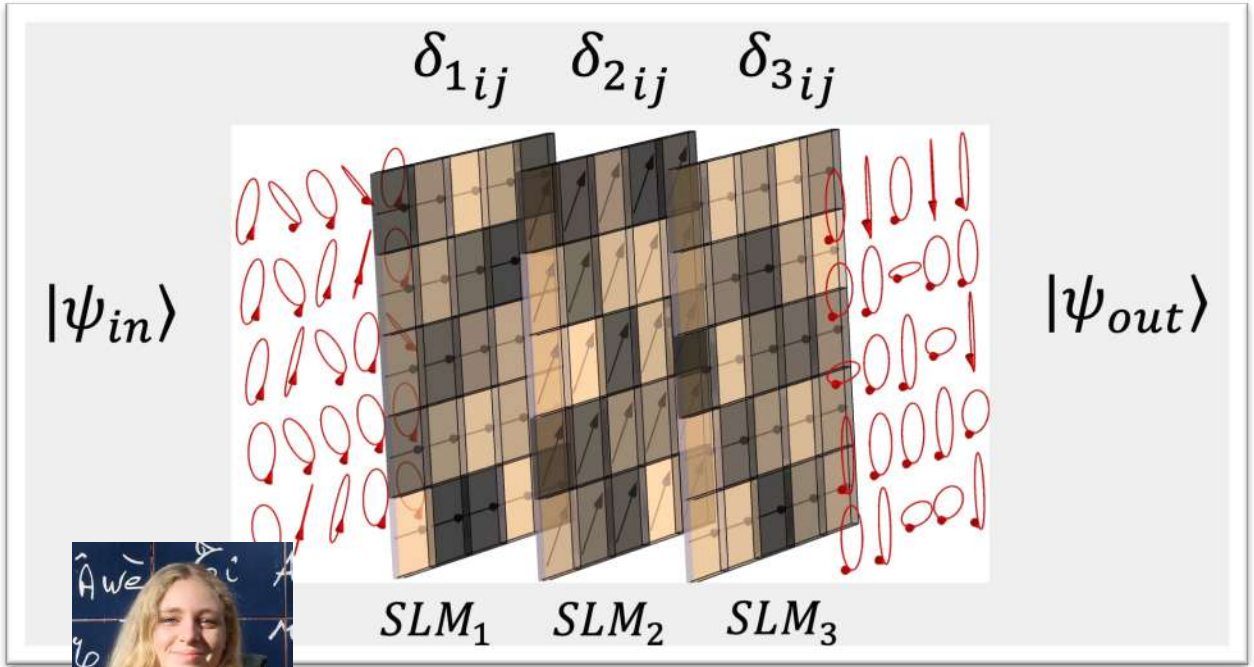
Liquid crystal metasurfaces

- Fixed retardation
- Variable optical axis

Spatial light modulators

- Variable retardation
- Fixed optical axis



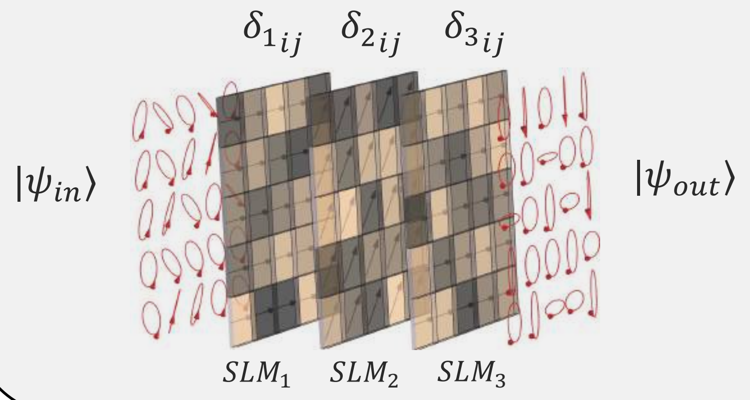


P_28 Maria G. Ammendola

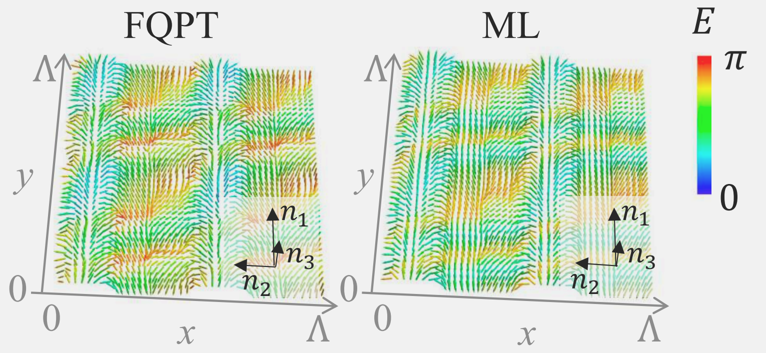
Di Colandrea, Francesco, et al. "Ultra-long quantum walks via spin–orbit photonics." *Optica* 10.3 (2023): 324-331.
M.G. Ammendola et al. *In preparation*

QW with structured light

Reconfigurable photonic processors

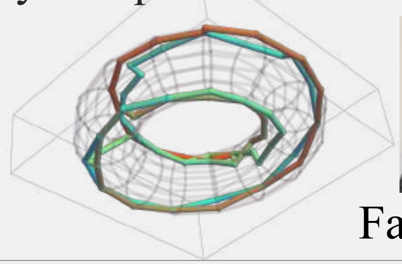


Process tomography

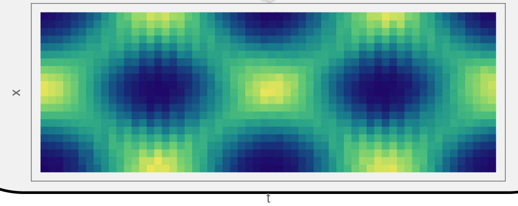


npj Quantum Information 10.1 (2024): 49.

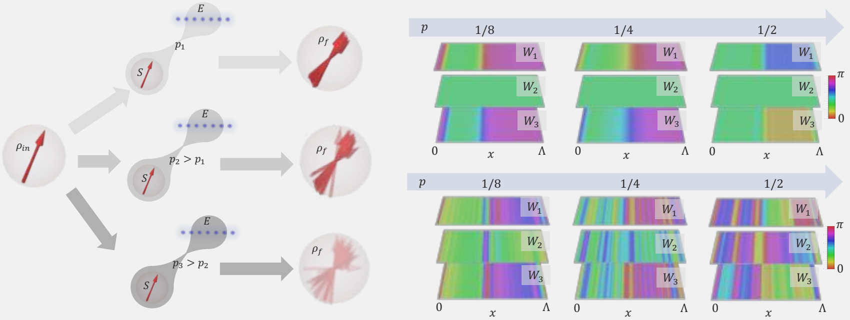
Cyclic quantum walks



Farid Ghobadi

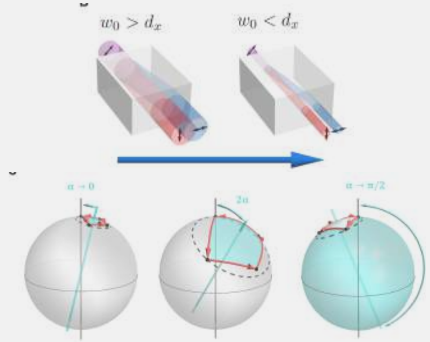


Open systems



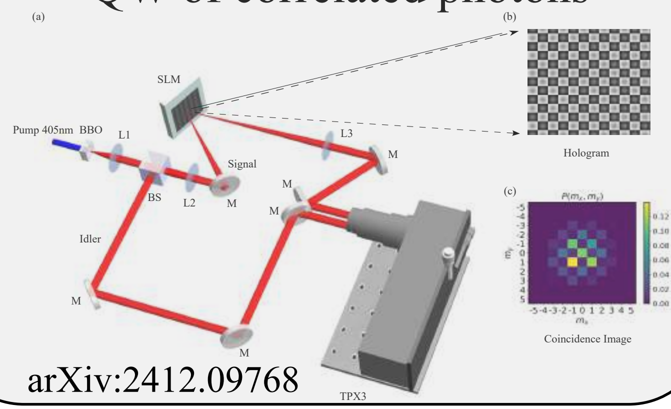
arXiv:2412.04701

Topology and geometric phases



Science advances, *9*(47), eadg6810

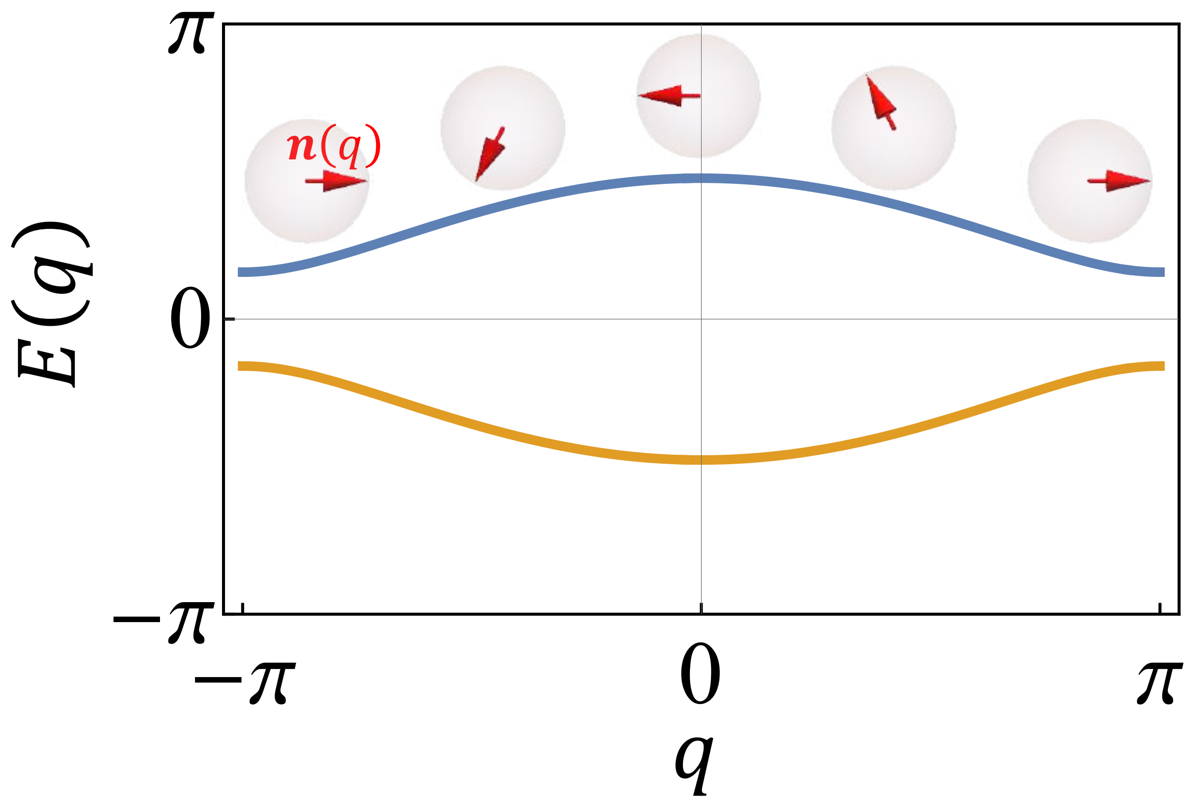
QW of correlated photons



arXiv:2412.09768

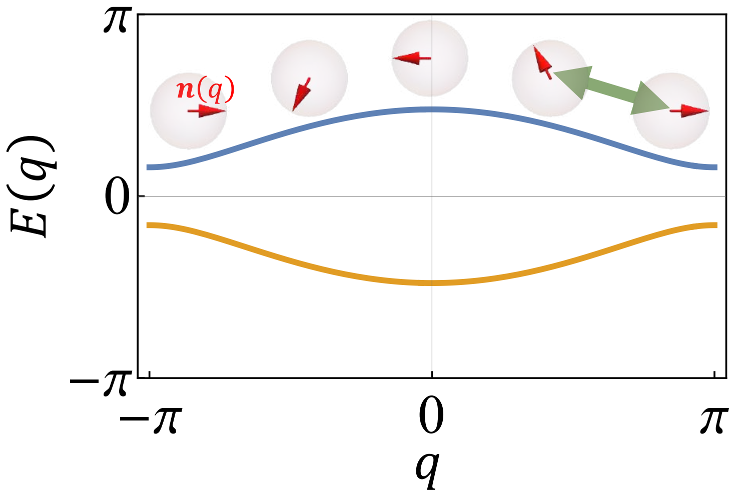
Geometry of $\mathcal{U}(q)$

$$\mathcal{U}^t(q) = \exp(-i\, t\, E(q)\, \boldsymbol{n}(q) \cdot \boldsymbol{\sigma})$$



Kitagawa, Takuya. "Topological phenomena in quantum walks: elementary introduction to the physics of topological phases." *Quantum Information Processing* 11 (2012): 1107-1148.

Geometry of $\mathcal{U}(q)$: quantum metric

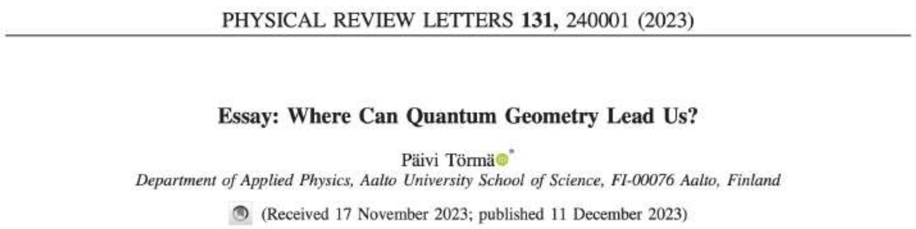


$$distance(|\boldsymbol{n}(q_1)\rangle, |\boldsymbol{n}(q_2)\rangle) = ?$$

Quantum Geometric Tensor (Fubini Study metric)

$$\eta_{ij}(q) = \langle \partial_i \boldsymbol{n} | \partial_j \boldsymbol{n} \rangle - \langle \boldsymbol{n} | \partial_i \boldsymbol{n} \rangle \langle \boldsymbol{n} | \partial_j \boldsymbol{n} \rangle$$

$$d\ell^2 = Re\left[\eta_{ij}(q)\right] dq_i dq_j$$


PHYSICAL REVIEW LETTERS **131**, 240001 (2023)

Essay: Where Can Quantum Geometry Lead Us?

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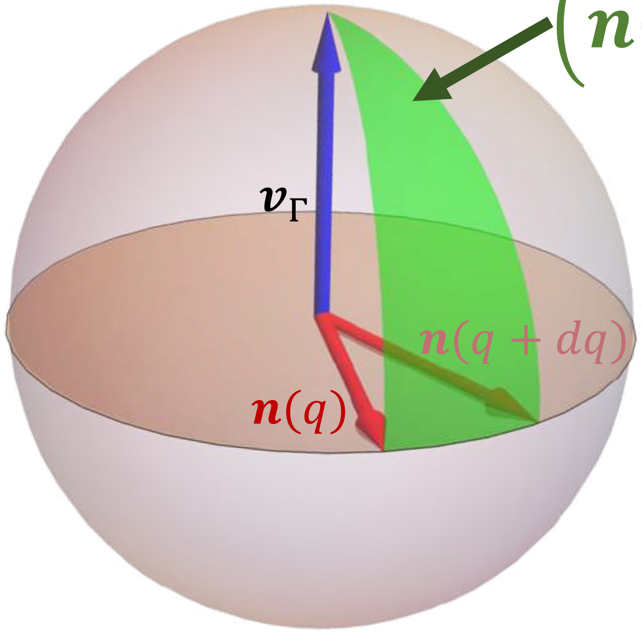
Kang, M., Kim, S., Qian, Y. *et al.* Measurements of the quantum geometric tensor in solids. *Nat. Phys.* (2024). https://doi.org/10.1038/s41567-024-02678-8

Provost, J. P., and G. Vallee. "Riemannian structure on manifolds of quantum states." *Communications in Mathematical Physics* 76 (1980): 289-301.

Quantum metric under chiral symmetry

chiral (or sublattice)symmetry: $\boldsymbol{n}(q) \perp \boldsymbol{v}_\Gamma$ for each q



$$\left(\boldsymbol{n}(q)\times\partial_q\boldsymbol{n}(q)\right)\cdot\boldsymbol{v}_\Gamma\, dq = \sqrt{\eta(q)}dq$$

For higher dimensions

$$\sqrt{\eta(q)} \rightarrow \sqrt{\eta_{ii}(q)}$$
$$\partial_q \rightarrow \partial_{q_i}$$

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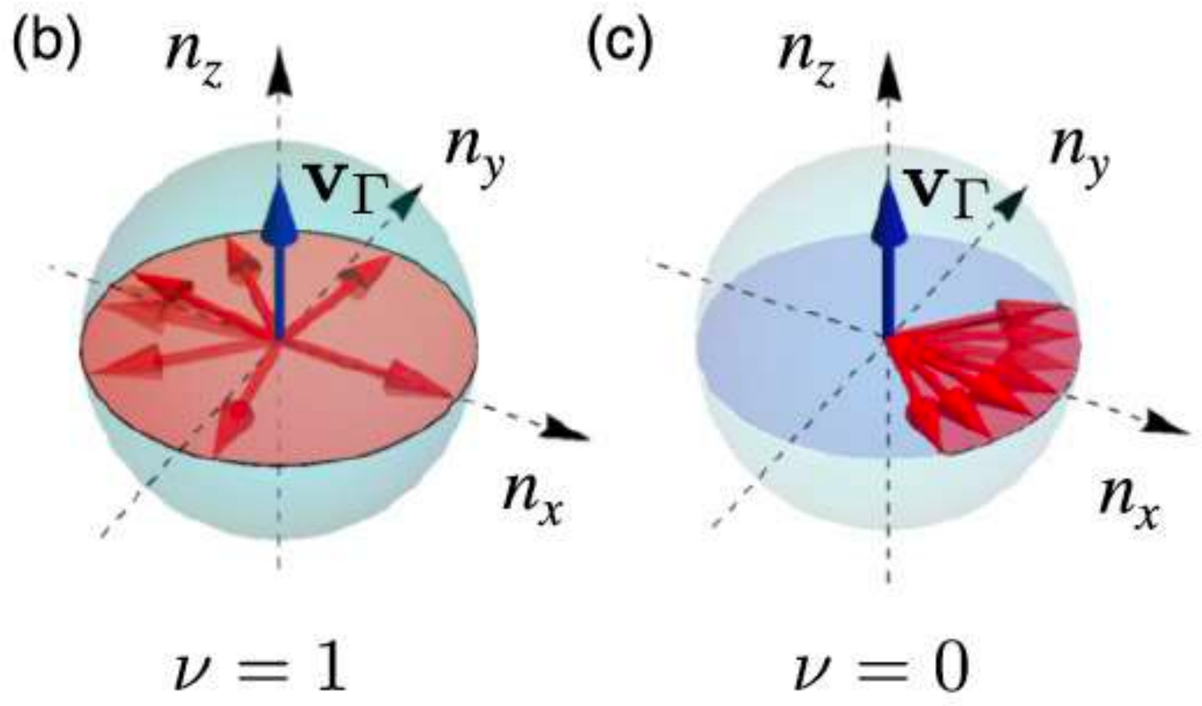
Nazanin Dehghan

Filippo Cardano

Di Colandrea, Francesco, et al. "Manifestation of the quantum metric in chiral lattice systems." *Communications Physics* 7.1 (2024): 265.

Topology of $\mathcal{U}(q)$ (in 1D)

chiral symmetry: $\boldsymbol{n}(q) \perp \boldsymbol{v}_\Gamma$ for each q



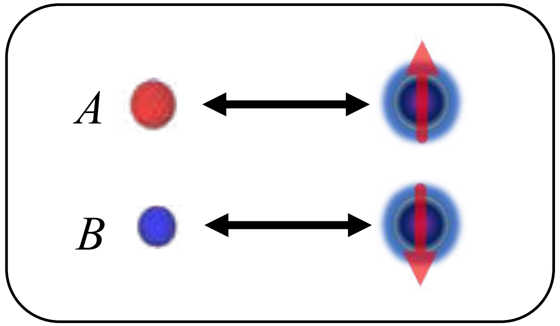
Winding number:

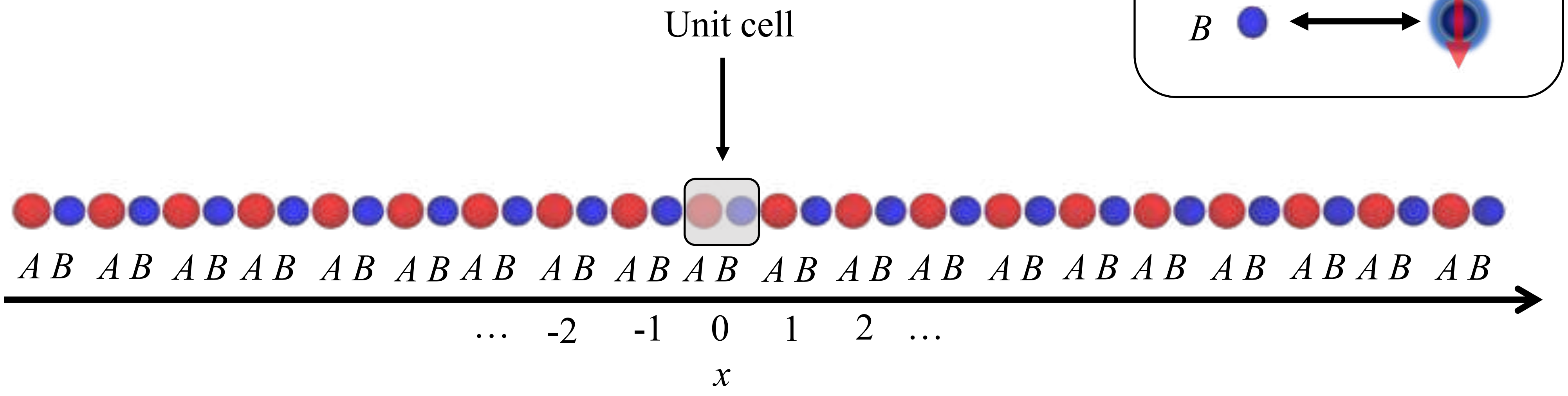
$$\nu = \int_{-\pi}^{\pi} \sqrt{\eta(q)} \frac{dq}{2\pi}$$

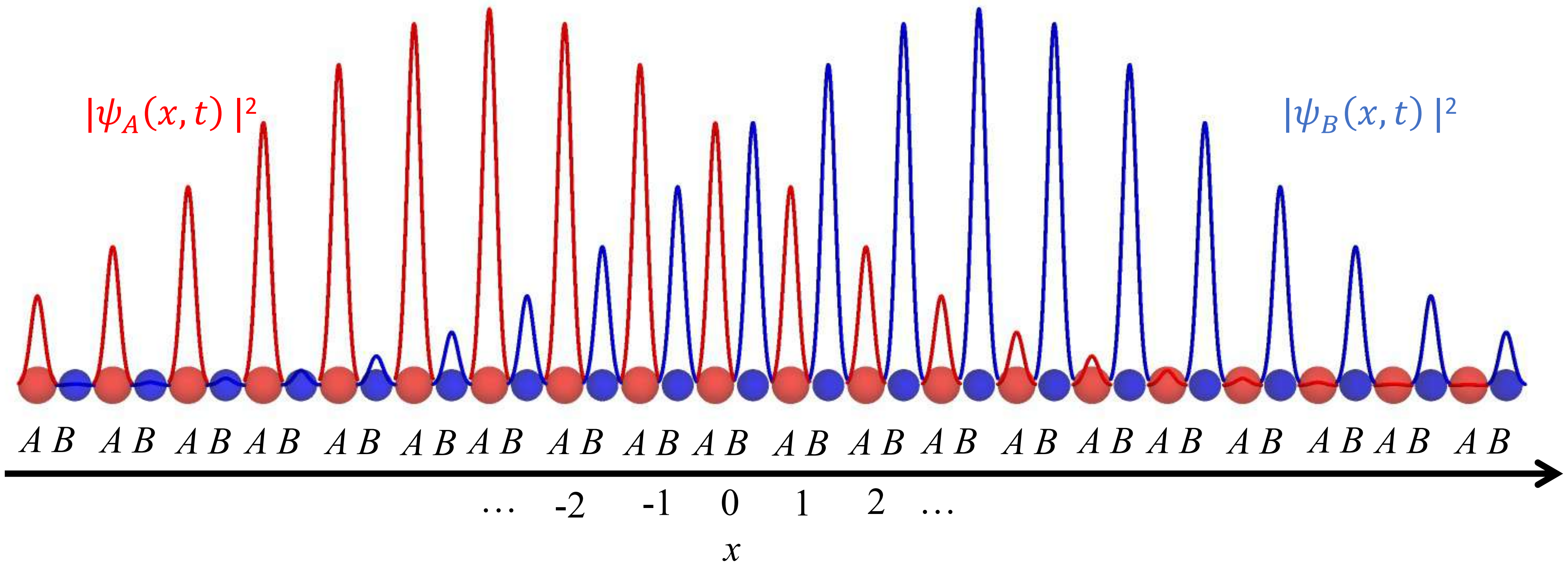
$$\sqrt{\eta(q)} = \partial_q \phi$$

Kitagawa, Takuya. "Topological phenomena in quantum walks: elementary introduction to the physics of topological phases." *Quantum Information Processing* 11 (2012): 1107-1148.

Topology and Geometry in Chiral symmetric Systems



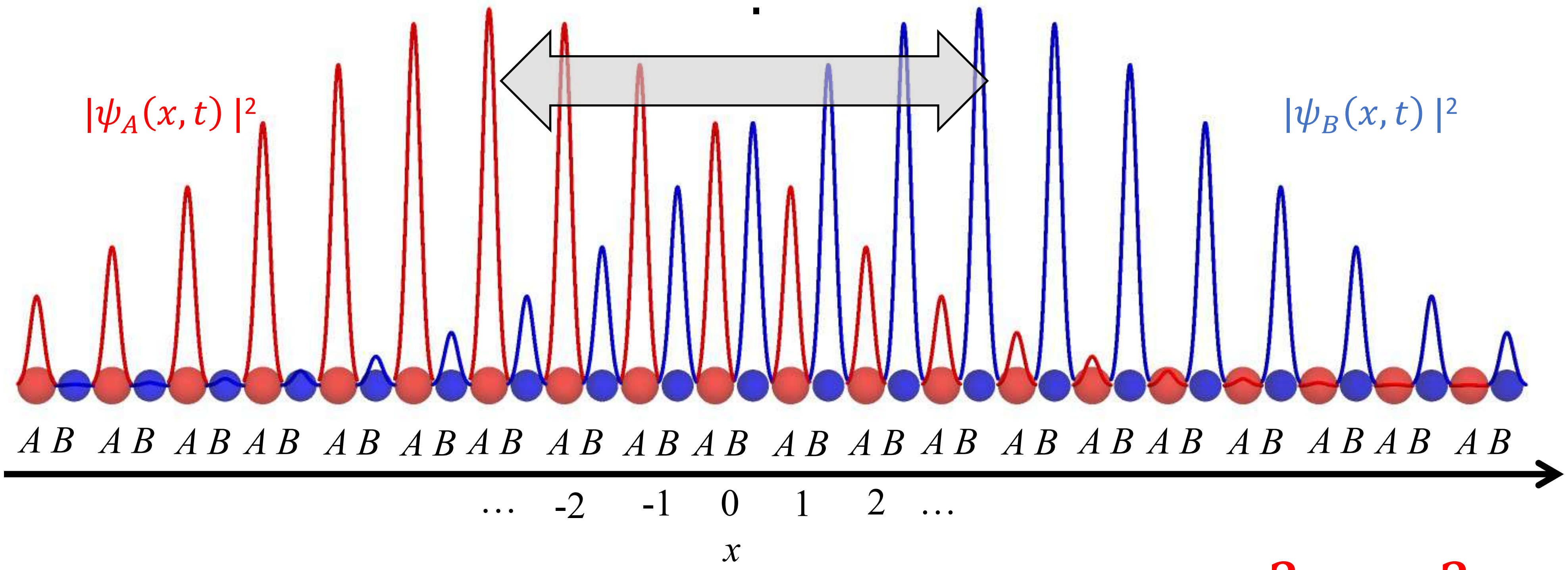




$|\psi_A(x,t)|^2$
$|\psi_B(x,t)|^2$
A B A B A B A B A B A B A B A B A B A B A B A B A B A B A B A B A B A B A B A B
… -2 -1 0 1 2 …
x

Mean chiral displacement

$$\mathcal{C}(t) \coloneqq \langle x \rangle_B - \langle x \rangle_A$$



$\eta_{ij} = ?, \nu = ?$

Cardano, Filippo, et al. "Detection of Zak phases and topological invariants in a chiral quantum walk of twisted photons." *Nature communications* 8.1 (2017): 15516.

Mean chiral displacement measures winding numbers

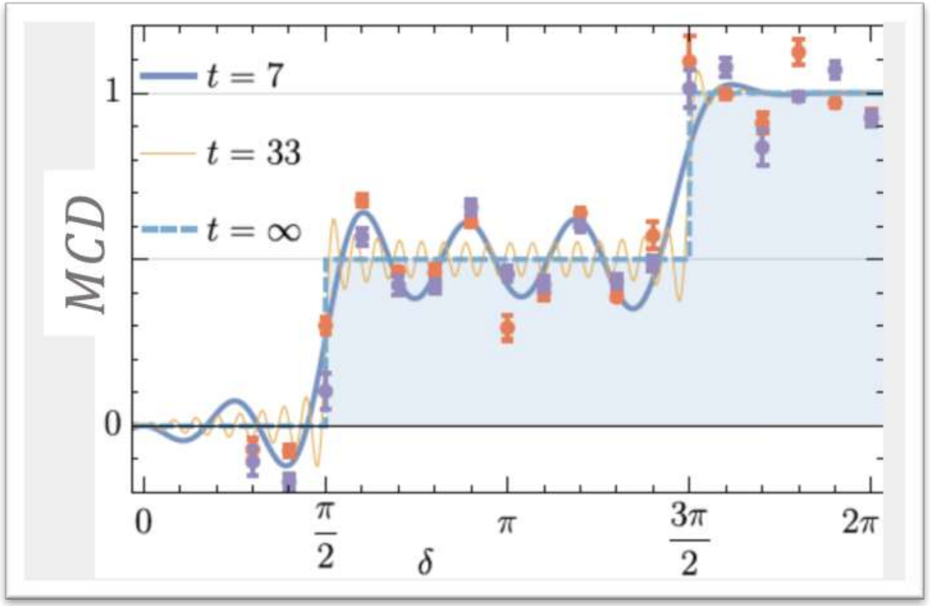
$$\mathcal{C}(t) \coloneqq \langle \psi(t) | \Gamma x | \psi(t) \rangle$$

$$\Gamma \coloneqq |B\rangle\langle B| - |A\rangle\langle A|.$$

$$\mathcal{C}(t) \overset{t \gg 0}{\sim} \nu/2$$

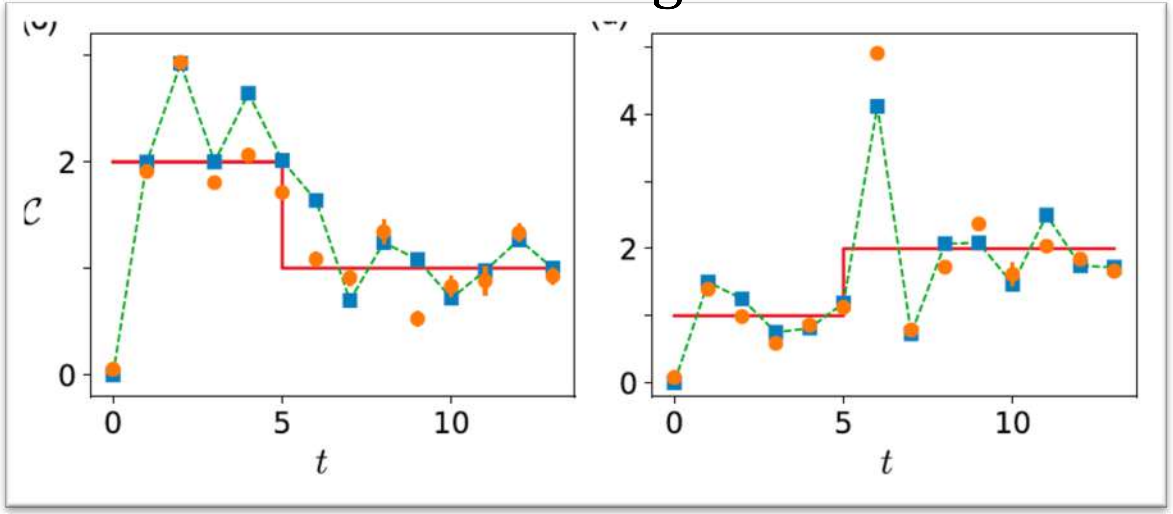
$$|\psi(t=0)\rangle = |x=0\rangle \otimes |c_0\rangle$$

Bulk measurement of ν



Nature communications 8.1 (2017): 15516.

time tracking of ν



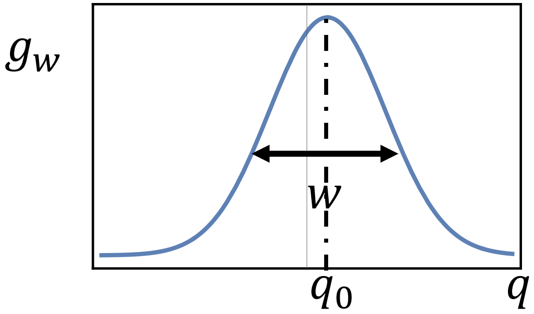
Physical Review Research 2.2 (2020): 023119

Mean chiral displacement

$$\mathcal{C}(t) \coloneqq \langle\psi(t)|\Gamma x|\psi(t)\rangle$$

$$\Gamma \coloneqq |B\rangle\langle B| - |A\rangle\langle A|.$$

$$|\psi(t=0)\rangle = \int g_w(q-q_0)|q\rangle dq \otimes |c_0\rangle$$



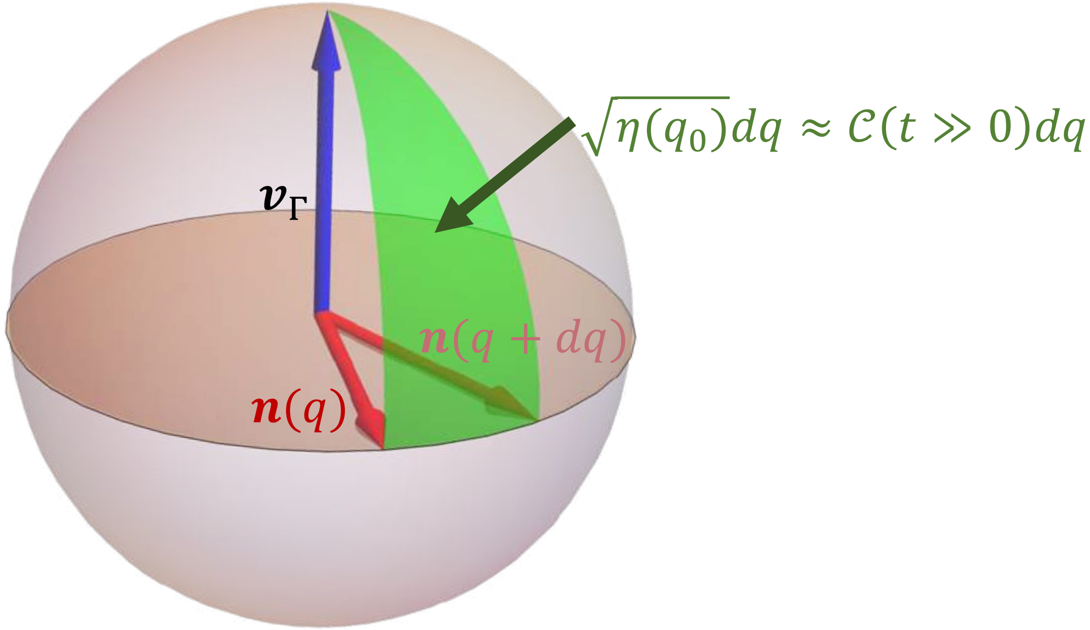
$$\mathcal{C}(t) = \int g_w^2(q-q_0)\sqrt{\eta(q)}\frac{dq}{2} + \frac{f(t)}{\sqrt{t}}$$

Di Colandrea, Francesco, et al. "Manifestation of the quantum metric in chiral lattice systems." *Communications Physics* 7.1 (2024): 265.

Mean chiral displacement of initially delocalized states

$$\mathcal{C}(t) \overset{t \gg 0}{\sim} \int g_w^2(q - q_0)\sqrt{\eta(q)}\,dq/2$$

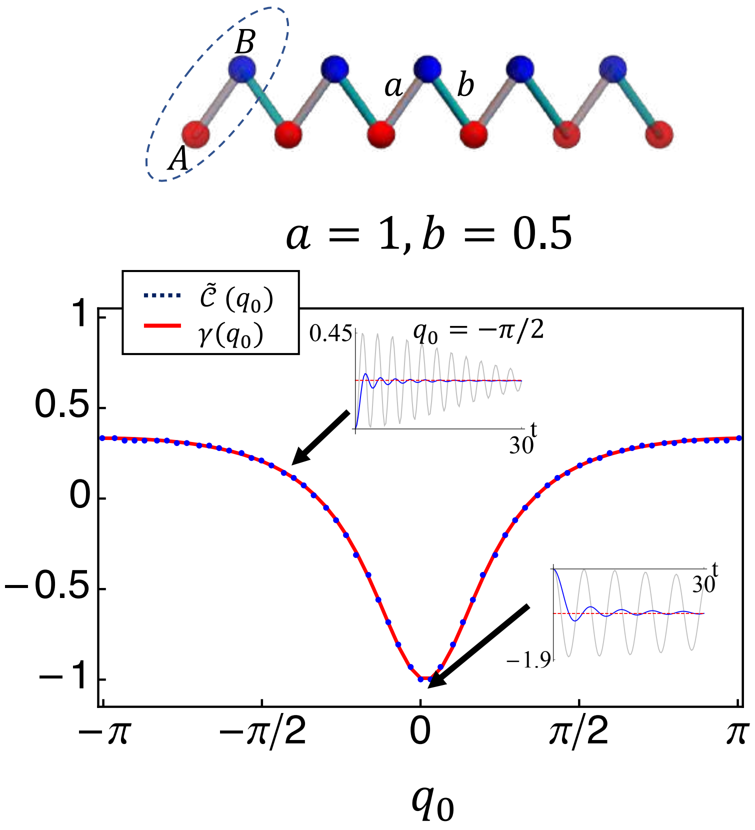
$$w \approx 0 \rightarrow \mathcal{C}(t \gg 0) \sim \sqrt{\eta(q_0)}$$



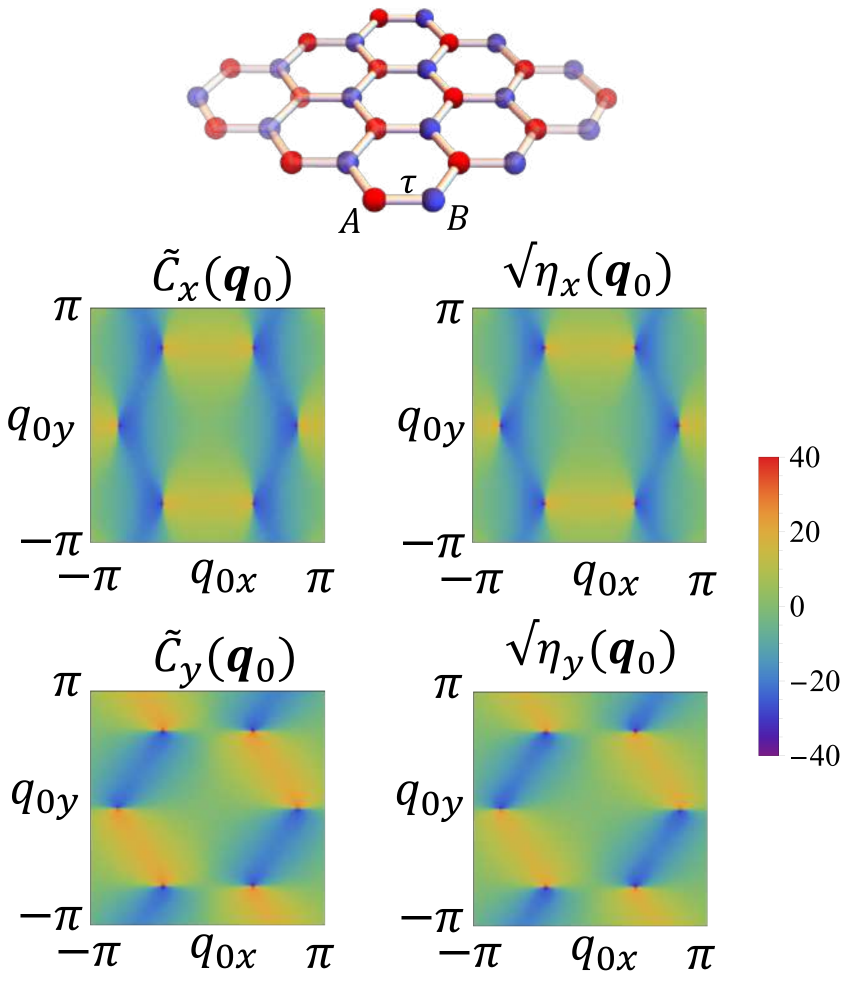
Di Colandrea, Francesco, et al. "Manifestation of the quantum metric in chiral lattice systems." *Communications Physics* 7.1 (2024): 265.

MCD and quantum metric

SSH model

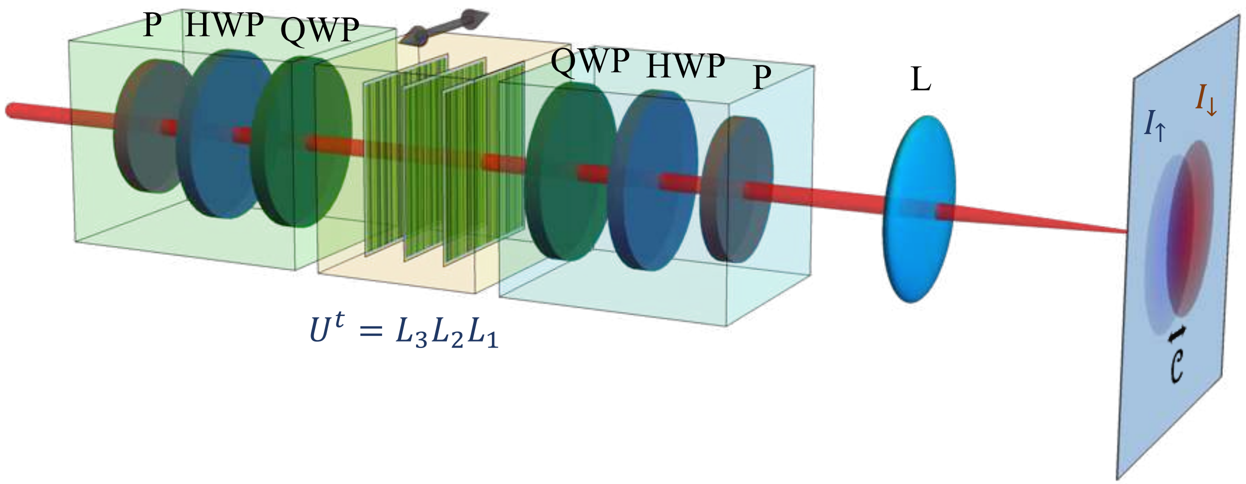


Graphene



Di Colandrea, Francesco, et al. "Manifestation of the quantum metric in chiral lattice systems." *Communications Physics* 7.1 (2024): 265.

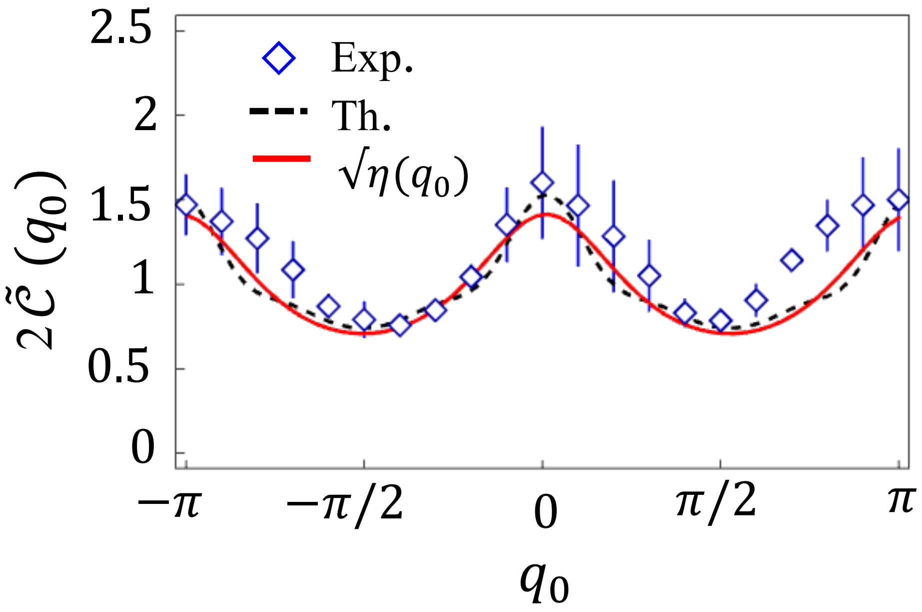
MCD and quantum metric



$$\hat{S} = \sum_x (|x+1\rangle\langle x| \otimes |R\rangle\langle L| + h.c);$$

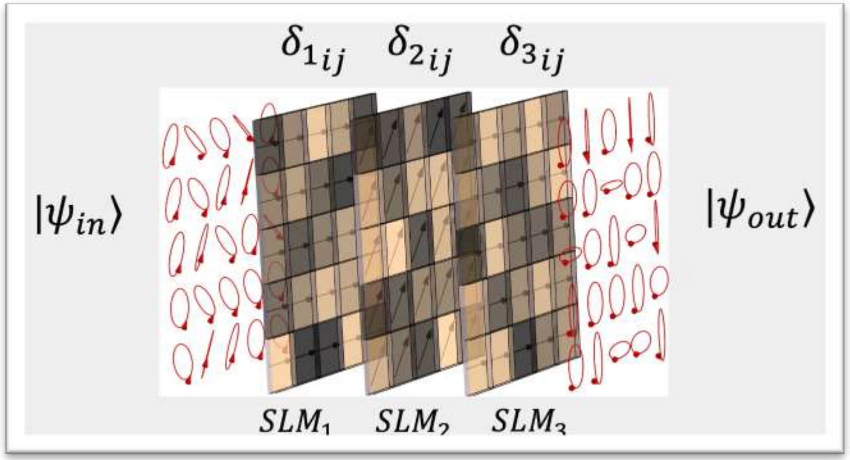
$$\widehat{W} = (1 + i\,\sigma_x)/\sqrt{2}$$

$$\widehat{U} = \hat{S}.\widehat{W}$$

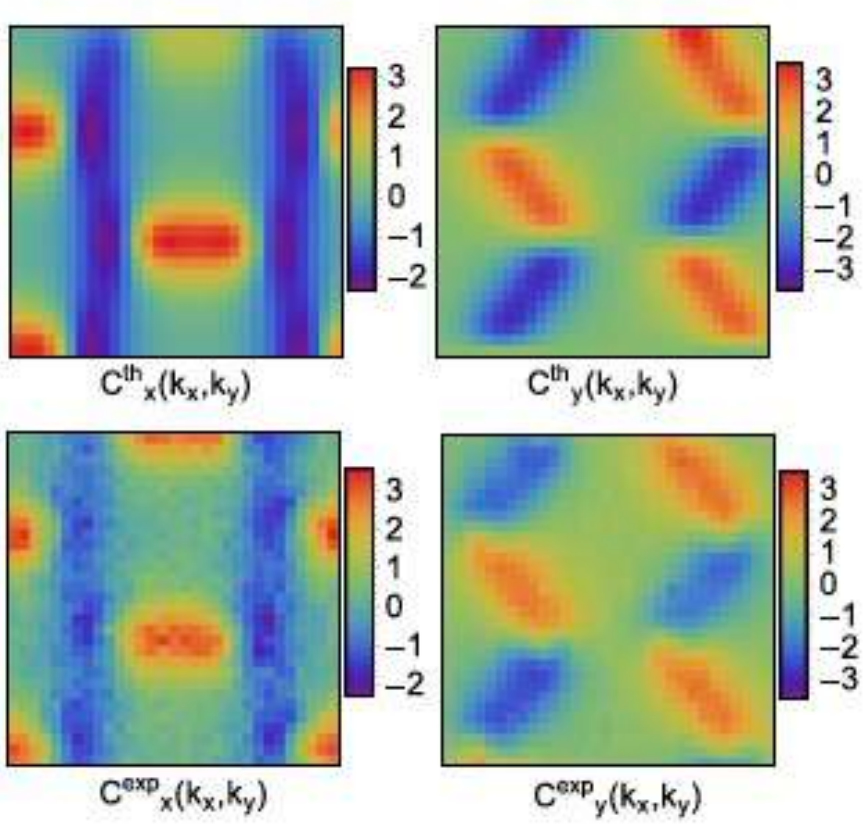


Di Colandrea, Francesco, et al. "Manifestation of the quantum metric in chiral lattice systems." *Communications Physics* 7.1 (2024): 265.

MCD and quantum metric

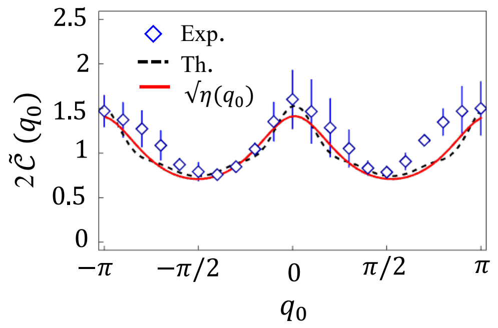


Graphene Hamiltonian

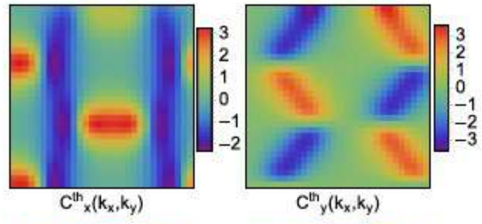


Conclusions and prospects

The quantum metric of chiral symmetric systems can be extracted from the MCD



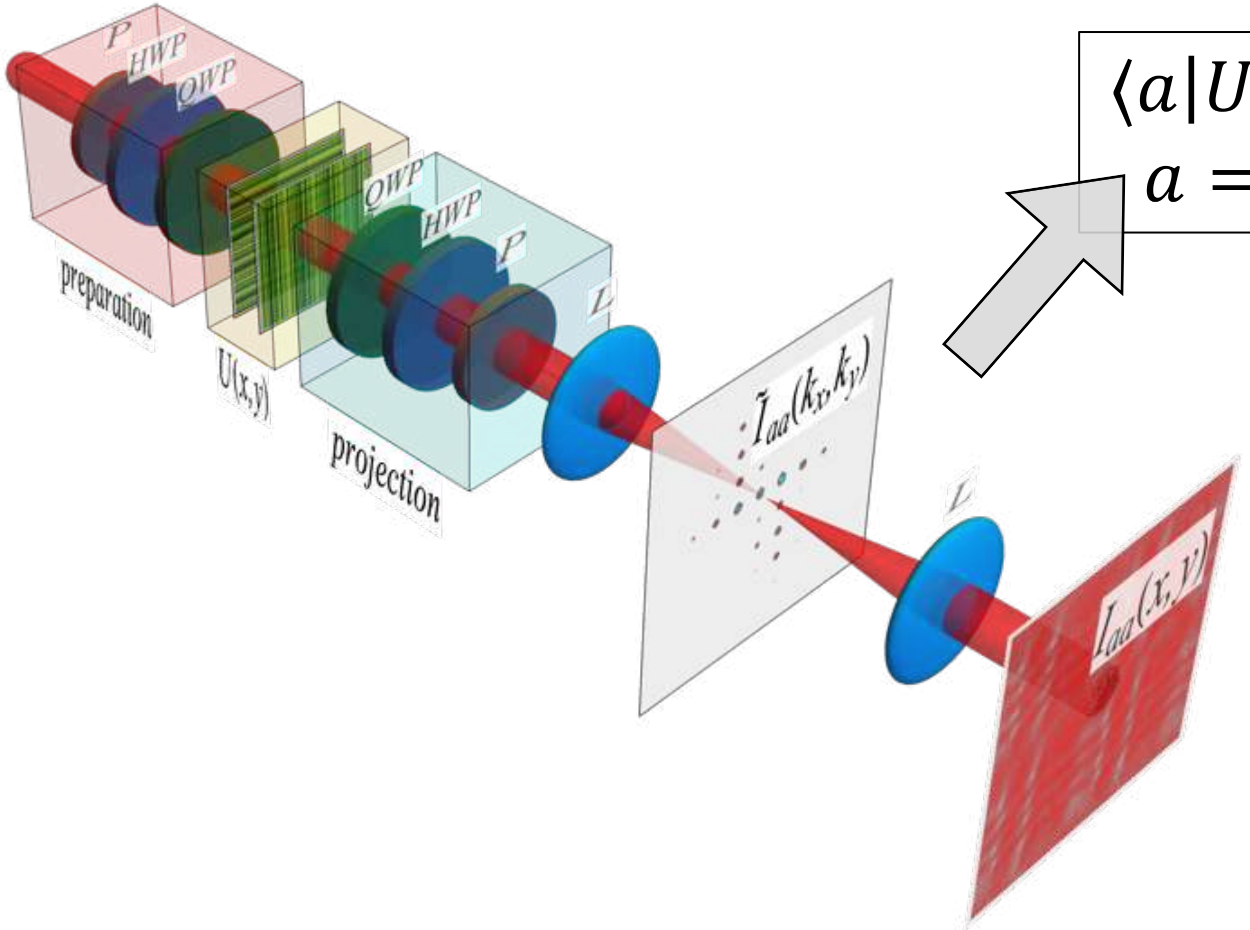
The distribution of a wavepacket on two sublattices is directly affected by the quantum metric



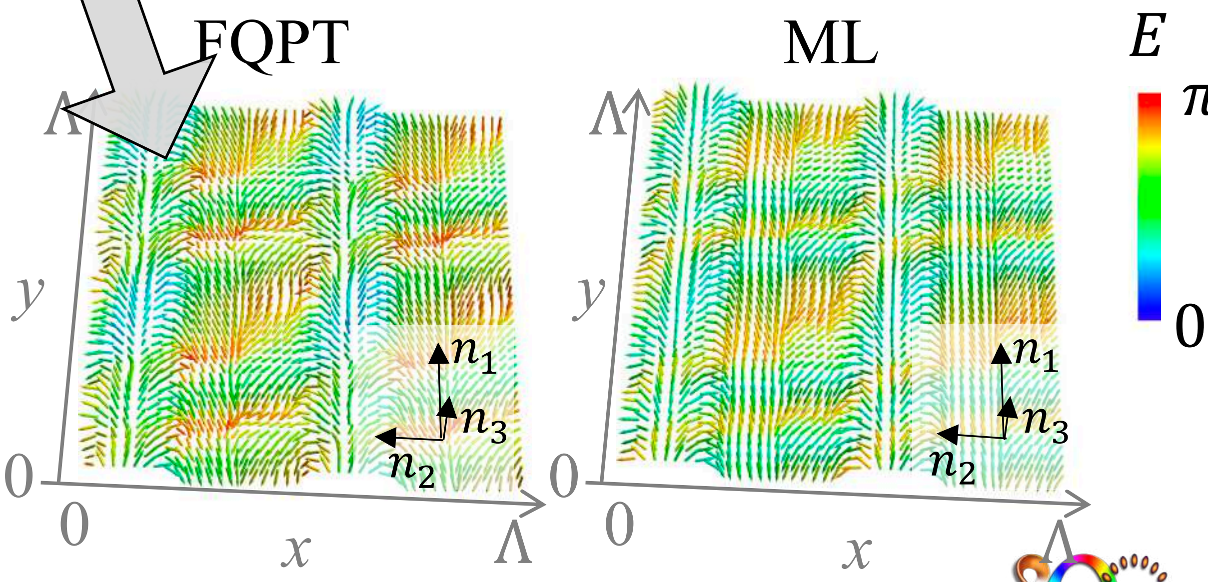
To do: extension of the results to *higher-dimensional internal states*, *non-hermitian dynamics,* and *interacting systems*


PHD and Postdoc Positions Available
ekarimi@uottawa.ca

Reconstructing the full unitary: Fourier Quantum Process Tomography



$$\langle a|U(x,y)|a\rangle$$
$$a = H, D, L$$



Di Colandrea, Francesco, et al. "Fourier quantum process tomography." *npj Quantum Information* 10.1 (2024): 49.