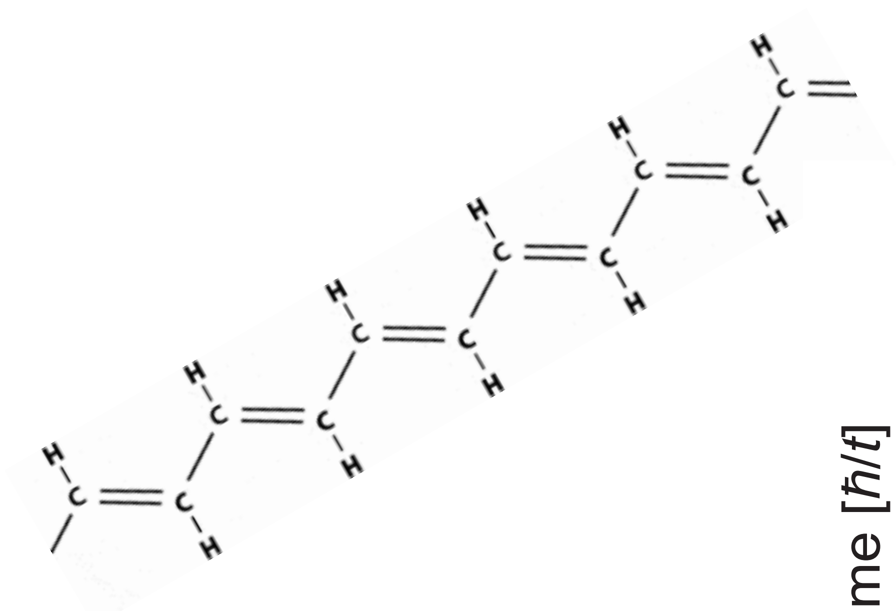
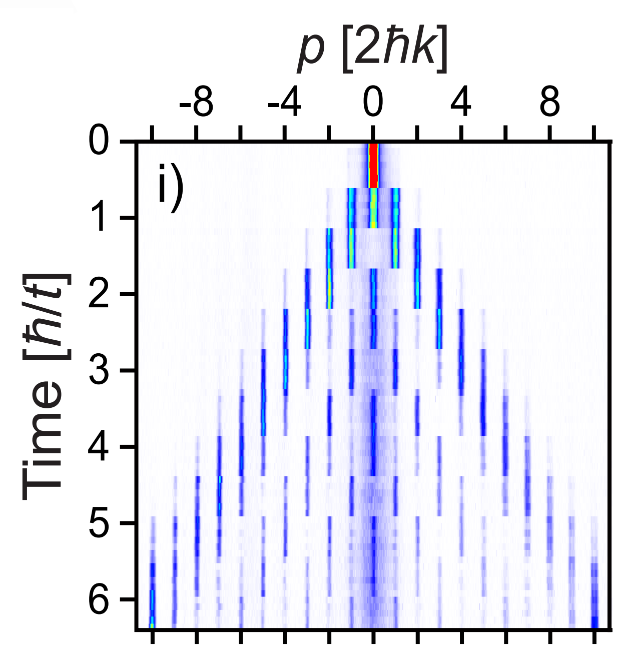
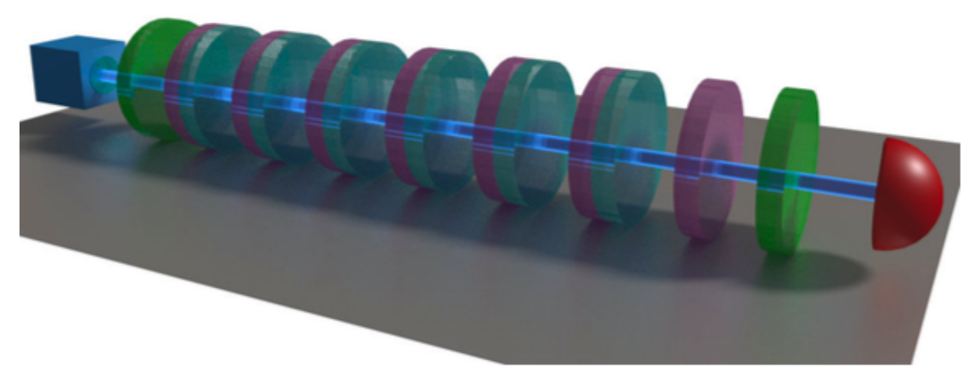
Observation of Topological Anderson & Floquet Insulators

Pietro Massignan







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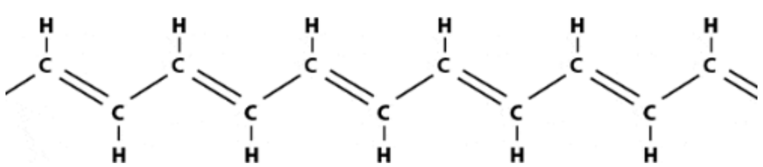
ICFO The Institute of Photonic Sciences

PHYSICS ILLINOIS

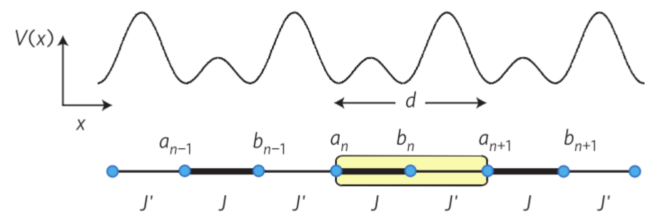
SLAM group

1D chiral systems



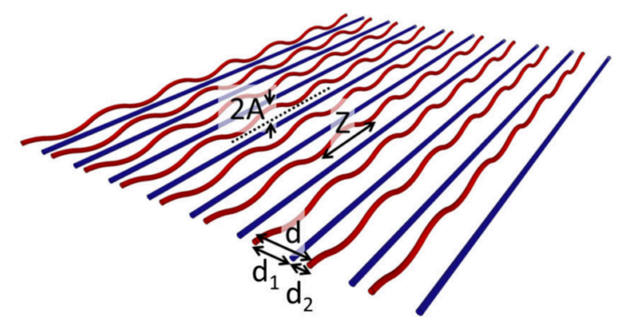
polyacetilene

[Nobel prize in Chemistry 2000]



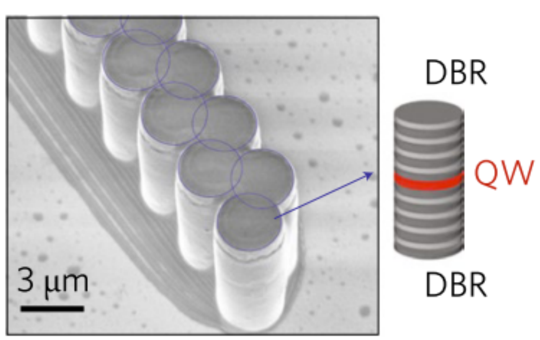
ultracold atoms
in superlattices

[M. Atala *et al.*, Nature Phys. 2013]



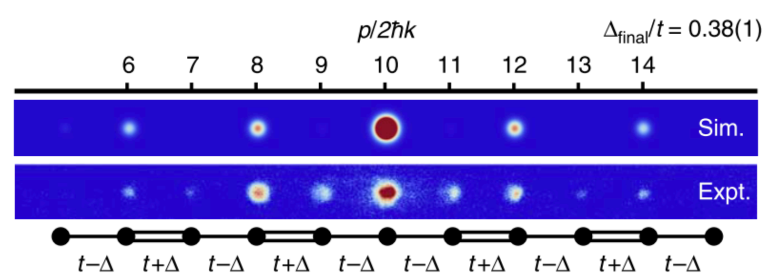
optical waveguides

[Zeuner *et al.*, PRL 2015]



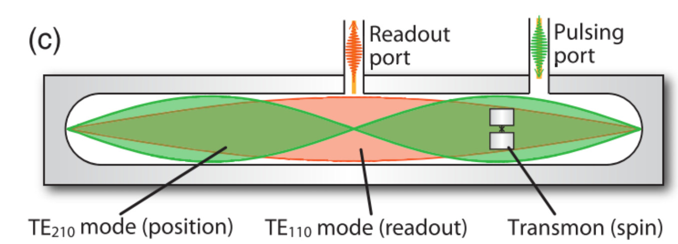
cavity polaritons

[St. Jean *et al.*, Nature Phot. 2017]



ultracold atoms
in k-space lattices

[Meier *et al.*, Nature Comm. 2016]

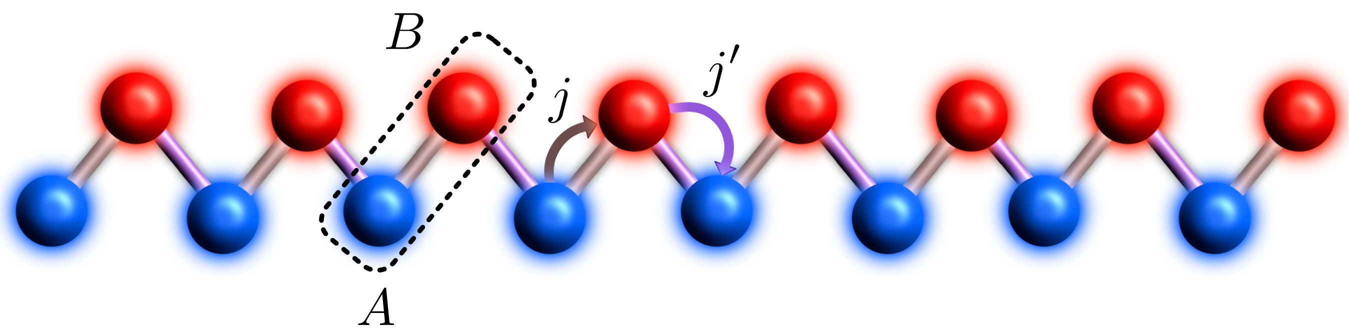


SC qubits
in mw-cavities

[Flurin *et al.*, PRX 2017]

SSH model

- Spinless fermions with staggered tunnelings:



Su, Schrieffer & Heeger
Phys. Rev. Lett. (1979)

Asbóth, Oroszlány, & Pályi
Lecture Notes in Physics (2016)

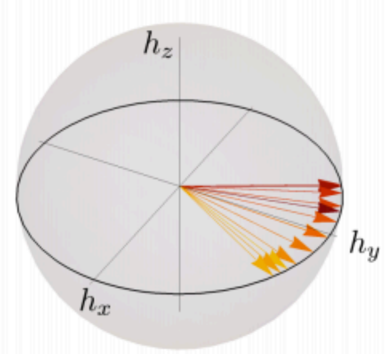
- ∃ two sublattices
  ∃ a "canonical basis" where H is purely off-diag: $H = \begin{pmatrix} 0 & h^\dagger \\ h & 0 \end{pmatrix}$

- Chiral symmetry: $\Gamma H \Gamma = -H$ (Γ: unitary, Hermitian, local)

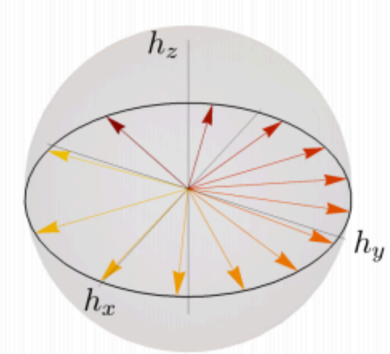
- In momentum space: $H_k = E_k \mathbf{n}_k \cdot \boldsymbol{\sigma}$

- In the canonical basis, $\mathbf{n}_k \perp \hat{\mathbf{z}} \quad \forall k$ and $\Gamma = \sigma_z$

- Winding:



$\mathcal{W} = 0$



$\mathcal{W} = 1$

The winding *W*

- $\mathcal{W}$ may be calculated:

$$H_k = E_k \mathbf{n}_k \cdot \boldsymbol{\sigma}$$

  - from n : $\mathcal{W} = \oint \frac{\mathrm{d}k}{2\pi} \left(\mathbf{n} \times \partial_k \mathbf{n}\right)_z$
  - from the *eigenstates* : $\mathcal{W} = \oint \frac{\mathrm{d}k}{\pi} \mathcal{S},$ $\quad \mathcal{S} = i\langle \psi_+ | \partial_k \psi_- \rangle$

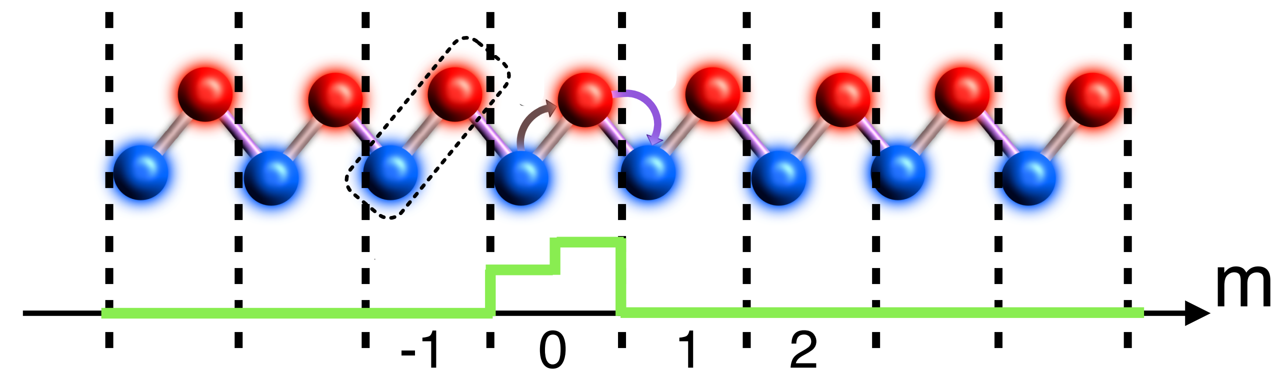
skew polarization

- What if the Hamiltonian is not known?
  Can one *measure* the winding?

  Yes, and it's simple!

Evolution in real time

- Initial condition
  localized on the $m=0$ cell:



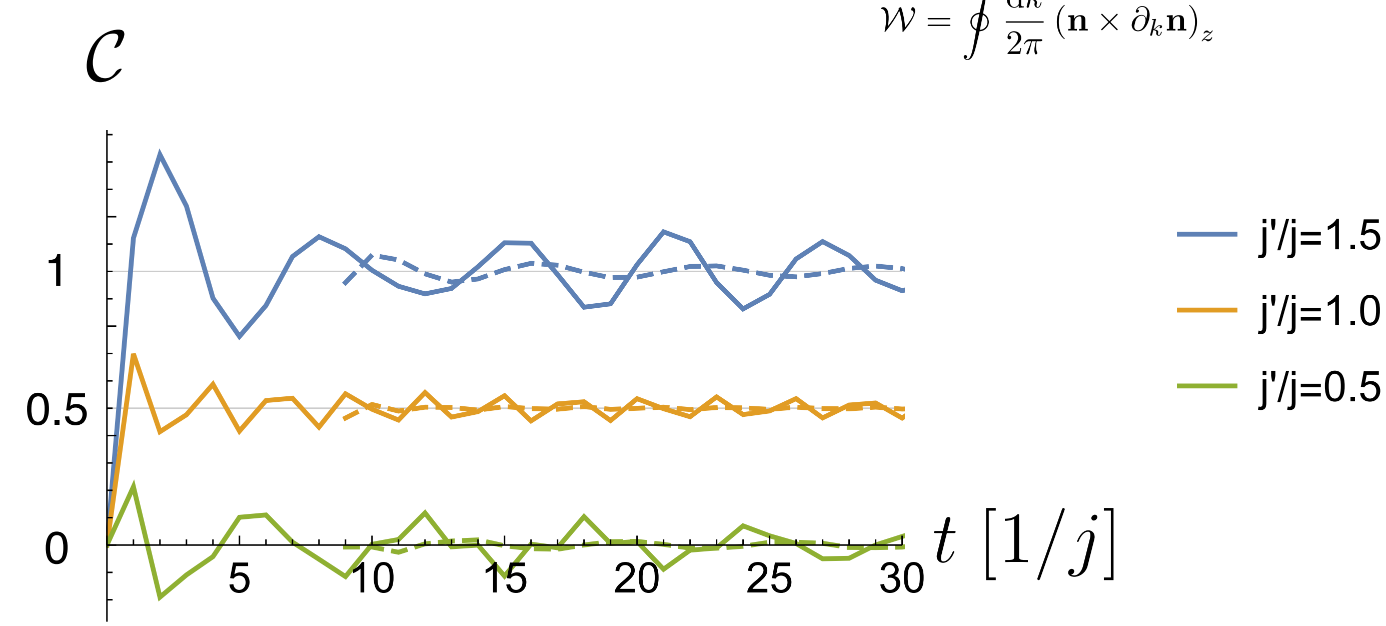
- **Mean Chiral Displacement:** $\mathcal{C}(t) \equiv 2\langle\widehat{\Gamma m}(t)\rangle = 2\Big[\langle m_A(t)\rangle - \langle m_B(t)\rangle\Big]$

$$\mathcal{C}(t) = 2\int_{-\pi}^{\pi}\frac{\mathrm{d}k}{2\pi}\,\langle U^{-t}\sigma_z(i\partial_k)U^t\rangle_{\psi_0} = 2\int_{-\pi}^{\pi}\frac{\mathrm{d}k}{2\pi}\sin^2(Et)\,|\mathbf{n}\times\partial_k\mathbf{n}| \xrightarrow{t\to\infty} \mathcal{W}$$

$$\mathcal{W} = \oint\frac{\mathrm{d}k}{2\pi}\,(\mathbf{n}\times\partial_k\mathbf{n})_z$$

- *Bulk* measurement

- Fast convergence



Cardano, Dauphin, … & PM
Nature Comm. (2017)

Resistance to disorder

SSH model in the topological phase $\quad j' = 2j \quad \rightarrow \quad \begin{cases} \mathcal{W} = 1 \\ \Delta_{\text{gap}} = 2j \end{cases}$

+

independent disorder of amplitude Δ on ***all*** tunnelings

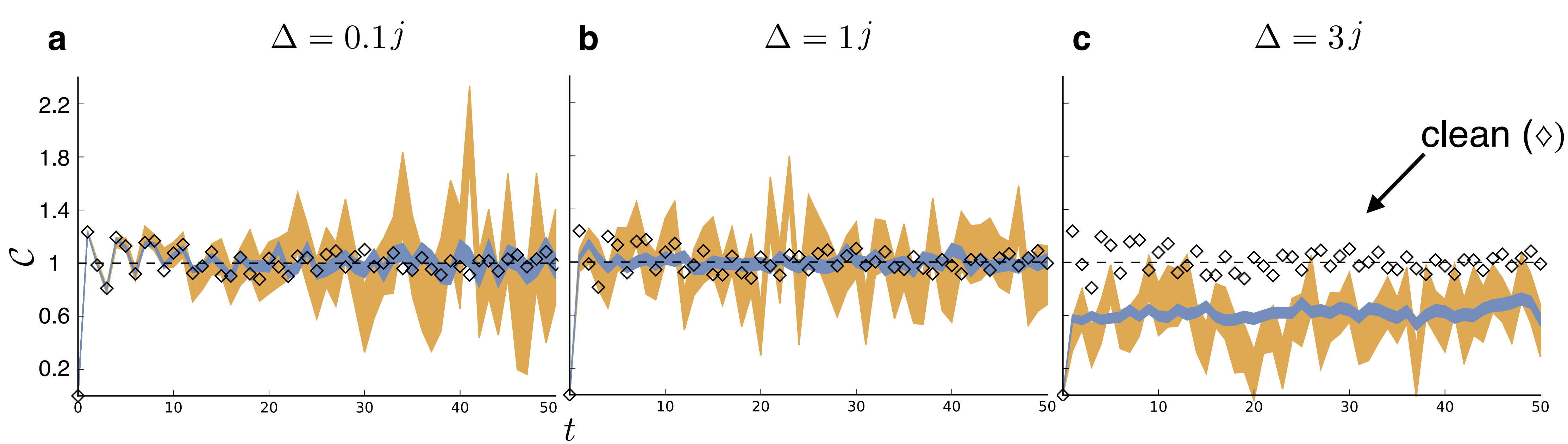
+

localized initial condition (randomly-polarized)

+

average over 50 (1000) disorder realizations

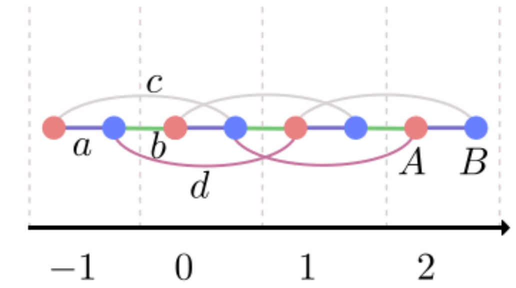
⬇

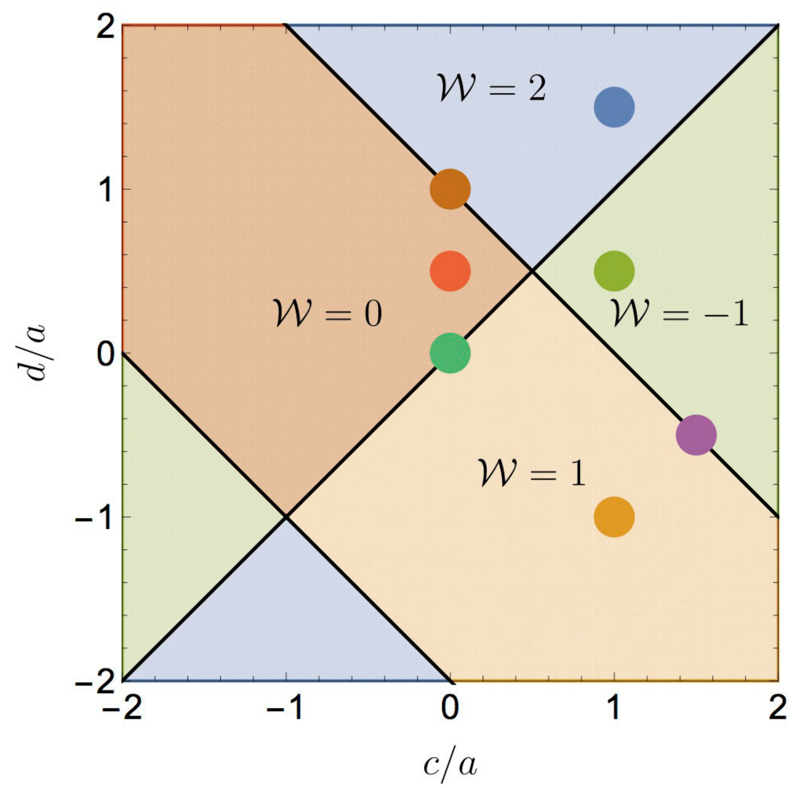


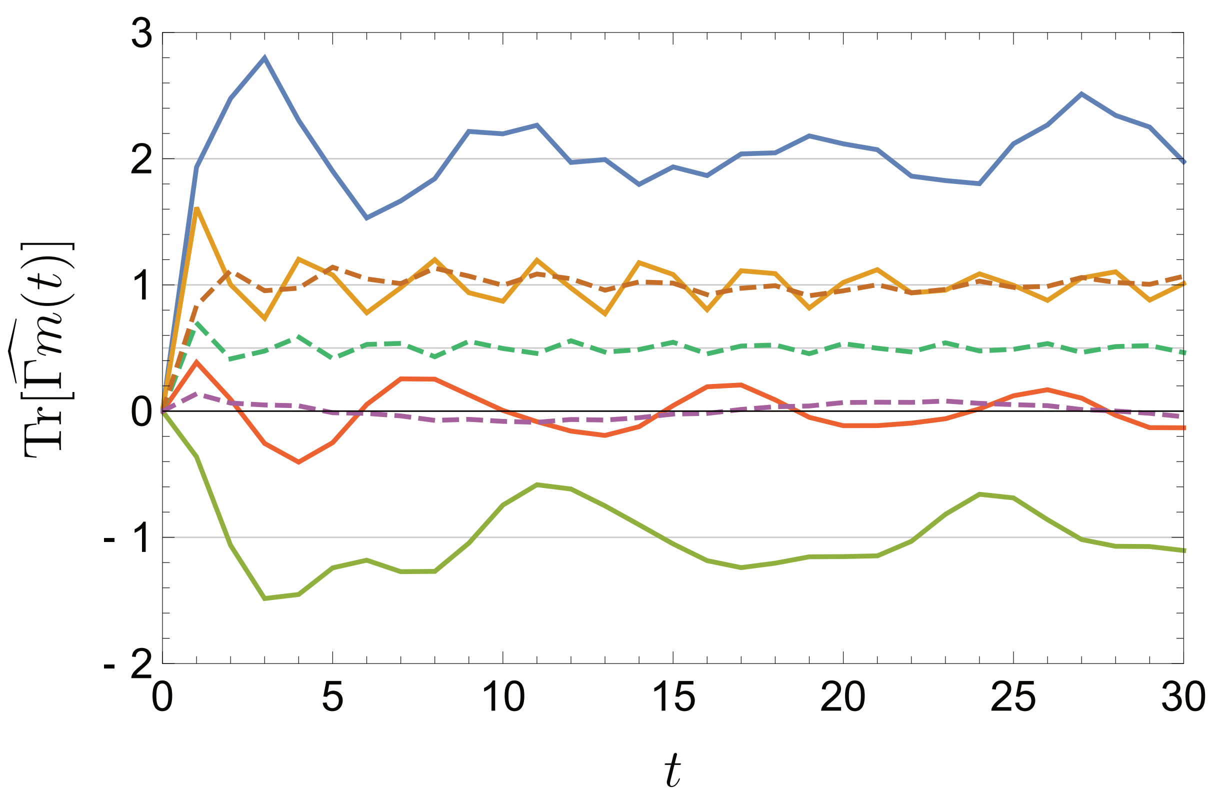
the MCD stays locked to the topological invariant as long as $\Delta < \Delta_{\text{gap}}$

Higher windings

- Extension to long-ranged models:





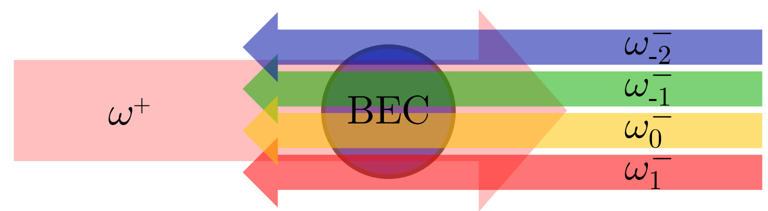


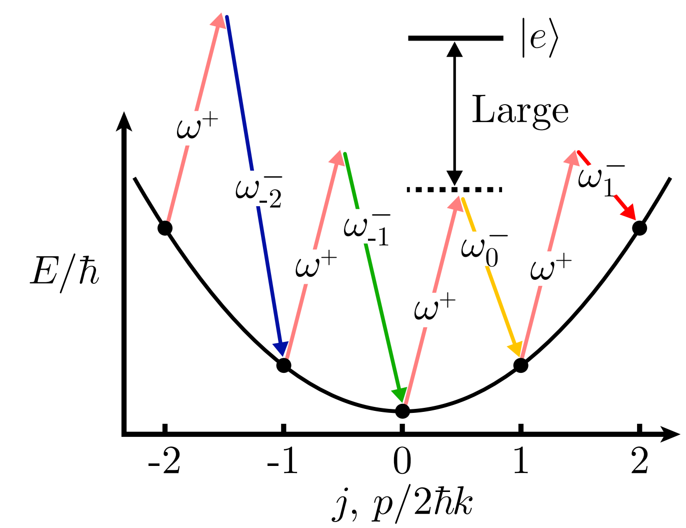
- At critical boundaries: MCD converges to the mean of the winding in the neighboring phases

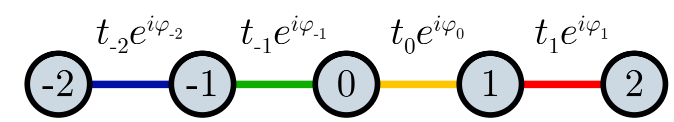
Maffei, Dauphin, Cardano, Lewenstein & PM
New J. Phys. 2018

Atomic wires in Urbana

- Atomic, ~ideal BEC







- Laser-driven coupling
  of discrete-momentum states

$$H_{\text{eff}} \approx \sum_j t_j (e^{i\varphi_j} |\widetilde{\psi}_{j+1}\rangle\langle\widetilde{\psi}_j| + \text{h.c.})$$

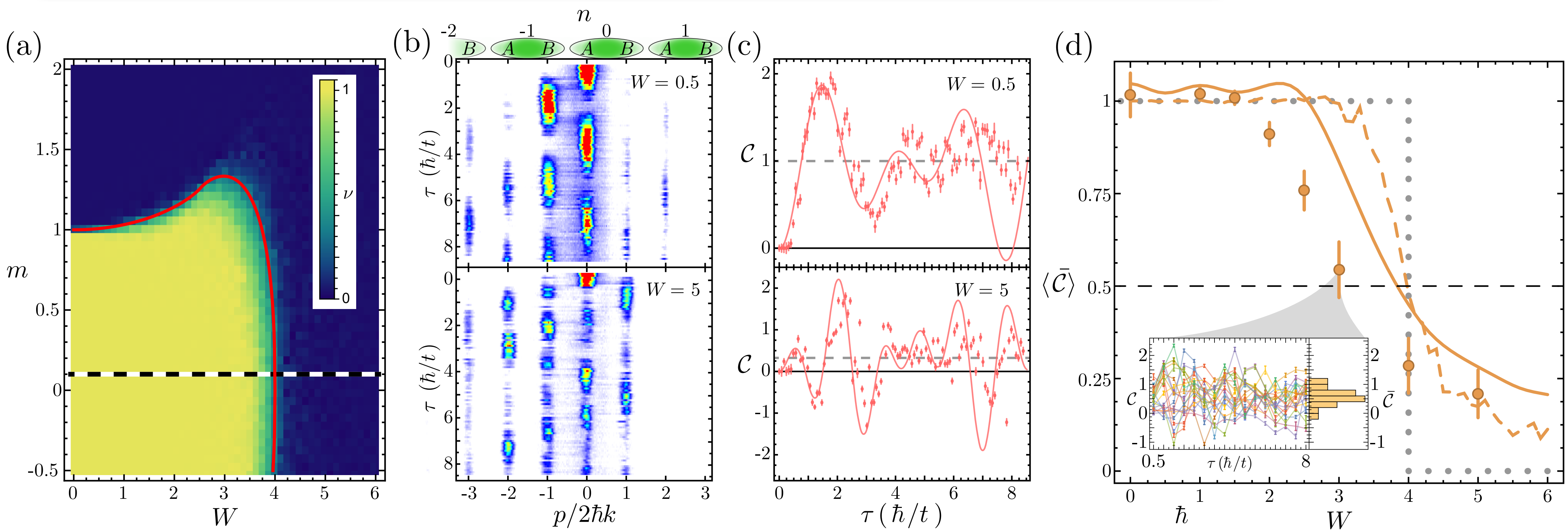
- 1D Hubbard model with full control on each
  tunneling strength and phase

- Built-in chiral symmetry

Detecting topology

A topological wire becomes trivial by adding disorder

intra-/inter-cell coupling



disorder strength | time evolution | MCD | phase diagram

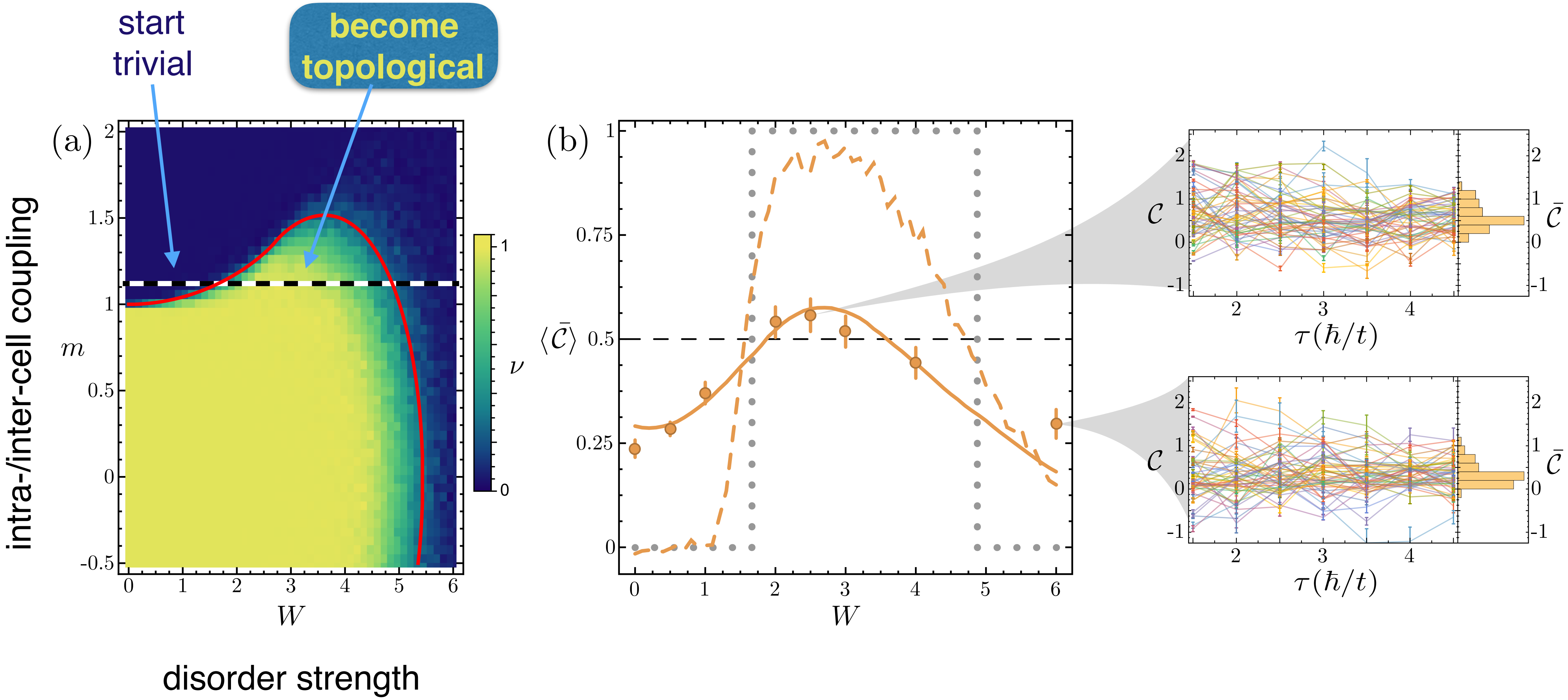
color map: real-space computation of the winding

red line: critical boundary (diverging localization length)

datapoints: experimental measurement of the MCD

Topological Anderson transition

A trivial wire is driven into the topological phase by adding disorder



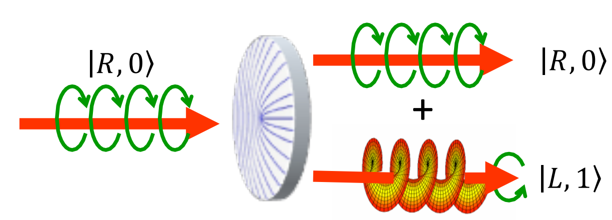
Meier, An, Dauphin, Maffei, PM, Taylor and Gadway,
arXiv:1802.02109

Discrete-Time Quantum Walks with twisted photons

- Cascade of Q-plates and quarter-wave plates W

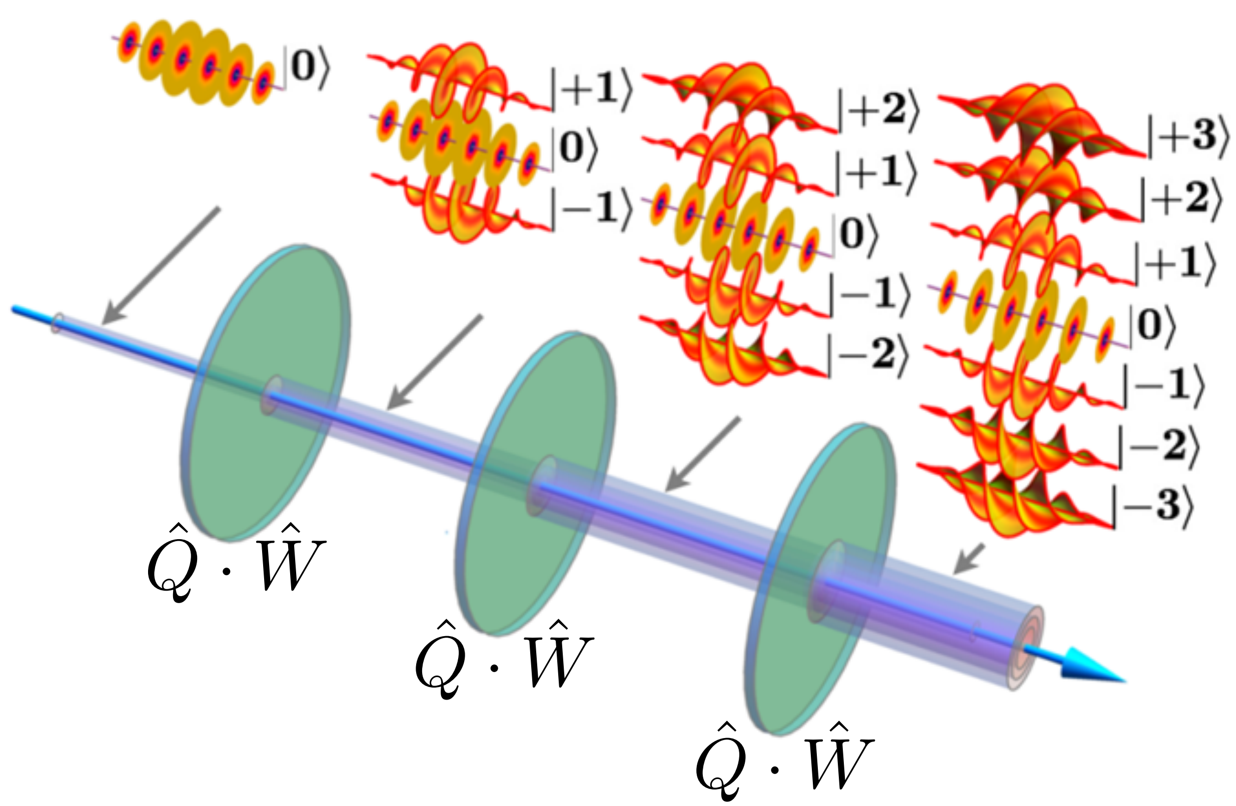
$$\hat{W} = \frac{1}{2}\begin{pmatrix} 1 & -i \\ -i & 1 \end{pmatrix}$$

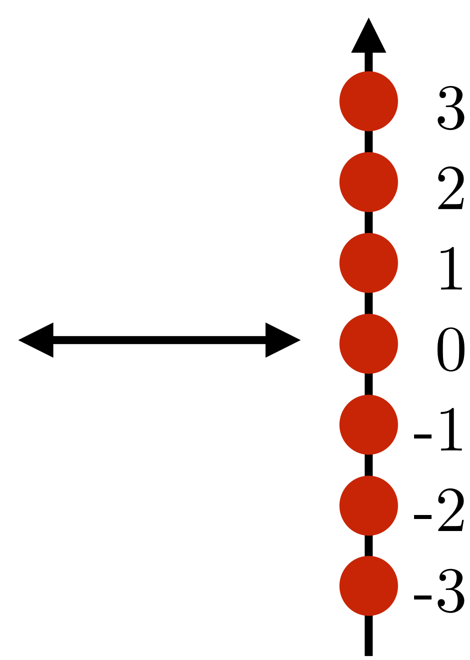
discrete-time QW	Twisted photons
walker's position	OAM (m)
coin state (↑/↓)	polarization (↻/↺)
spin rotation	W-plate
conditional displacement	Q-plate
time	$\hat{\mathbf{z}}$



P$_{stay}$= $\cos^2(\delta/2)$

P$_{flip}$= $\sin^2(\delta/2)$

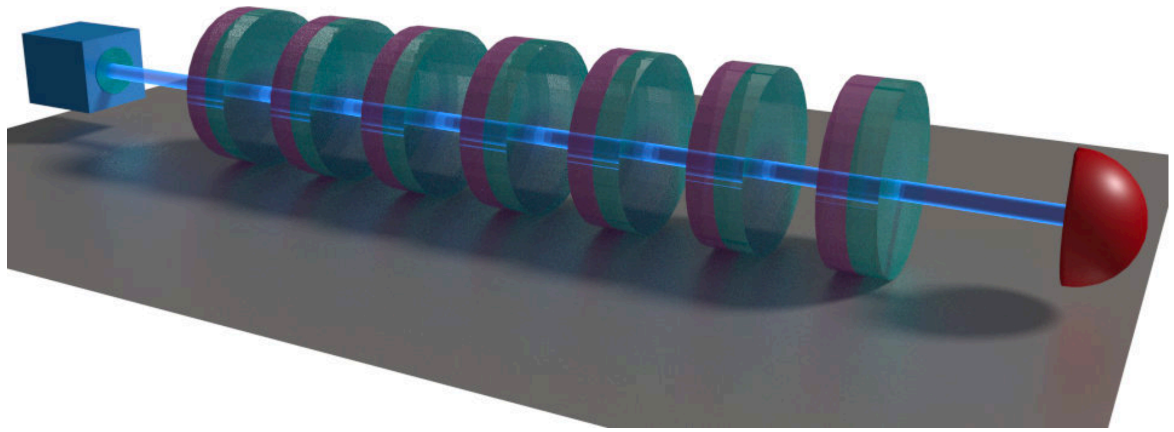


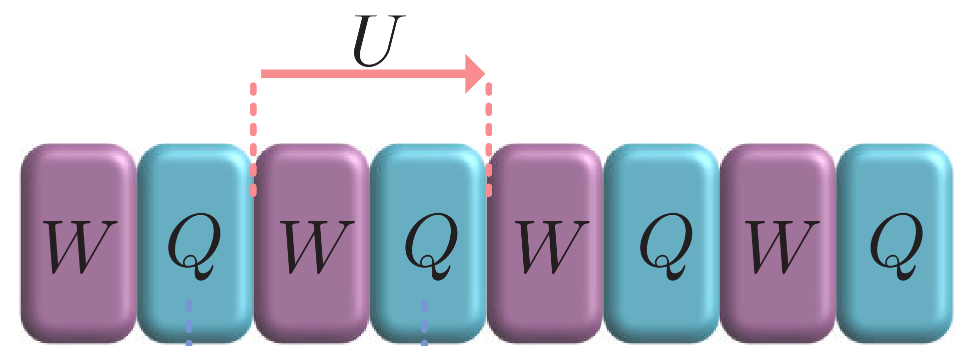


a synthetic dimension!

[Cardano et al., Science Advances (2015)]

Discrete-Time Quantum Walk



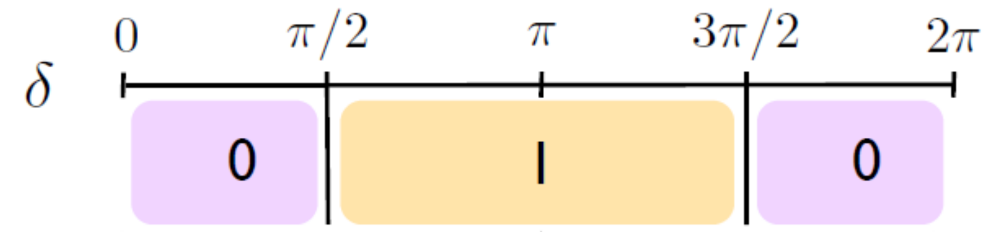


- Periodic evolution: may be treated via Floquet theory
- One-step evolution operator U ➙ $H_{\text{eff}} \equiv \frac{i}{T} \log U$
- In momentum space: $H_{\text{eff}}(k) = E_k \hat{\mathbf{n}}_k \cdot \boldsymbol{\sigma}$
- The spectrum of H_{eff} is 2π-periodic (quasi-energies E_k)
- T+C+S symmetries: BDI class —> same invariant as the static SSH model

Cardano, D'Errico, Dauphin, Maffei, … Marrucci, Lewenstein & PM
Nature Comm. (2017)

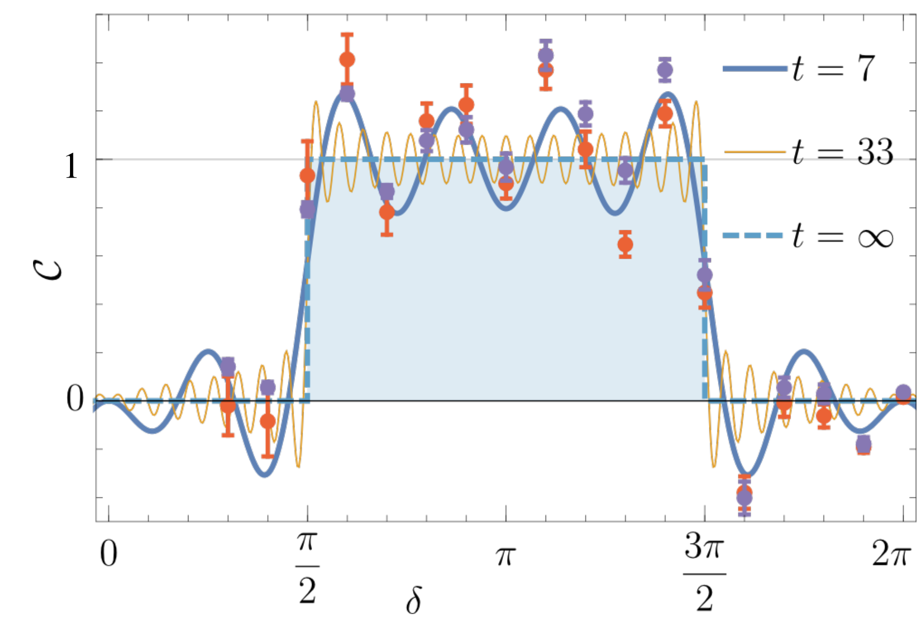
Detecting the invariant

- Winding: $\mathcal{W} = \oint \frac{\mathrm{d}k}{2\pi} \left(\mathbf{n} \times \partial_k \mathbf{n}\right)_z$



- Experimental measurement of the MCD after 7 timesteps of the DTQW with twisted photons:

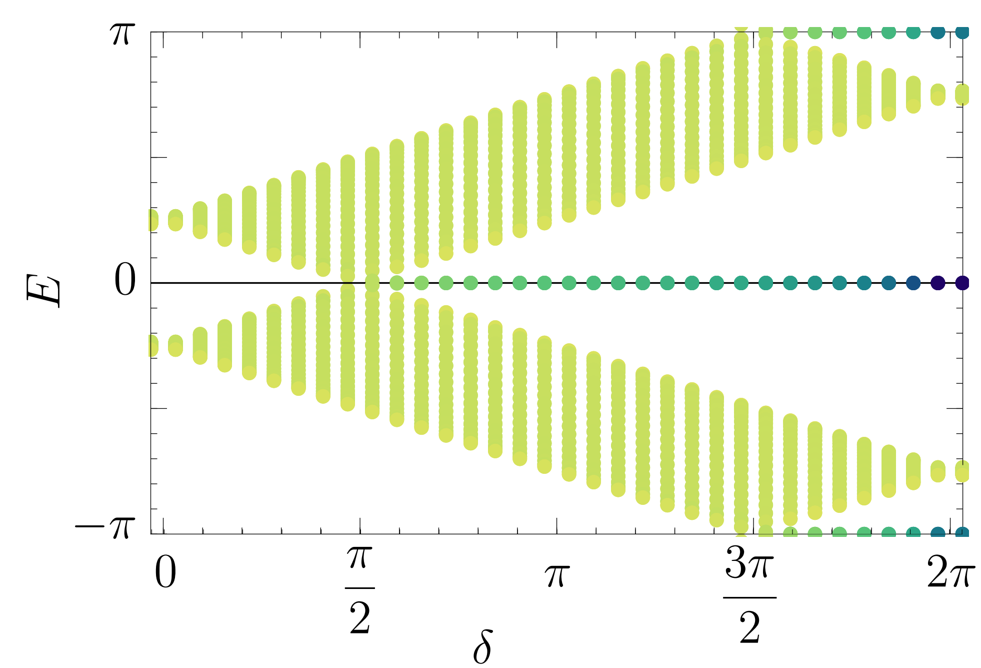
(●/●): different initial polarizations



- Check bulk-boundary correspondence

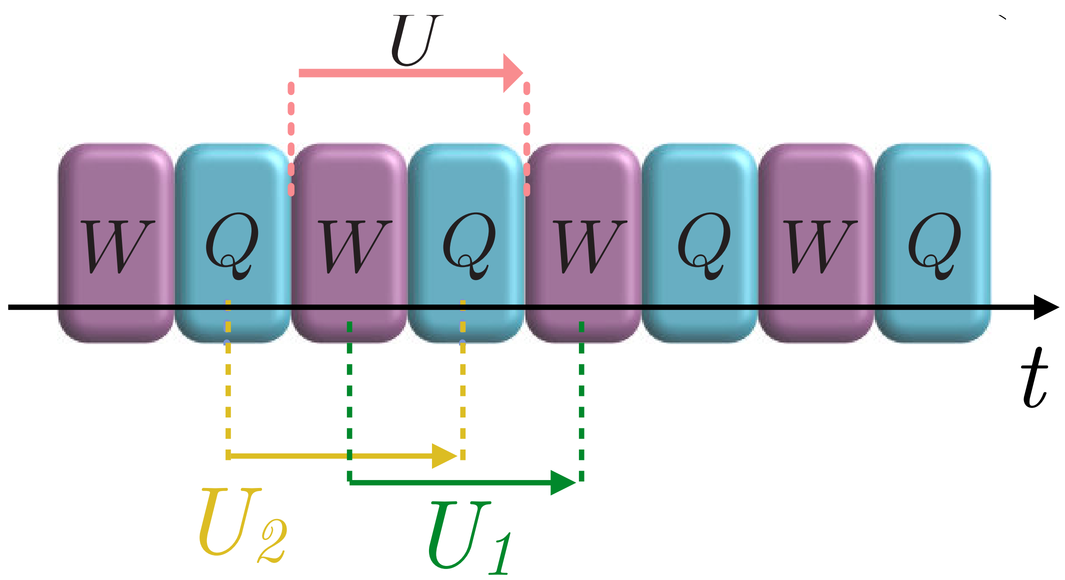
- Spectrum with edges:

darker colors: "edgier" states



- Bulk-boundary correspondence violated?

Timeframes

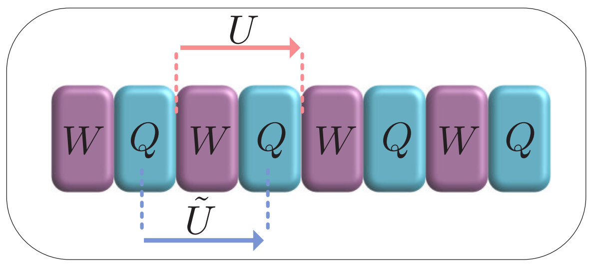


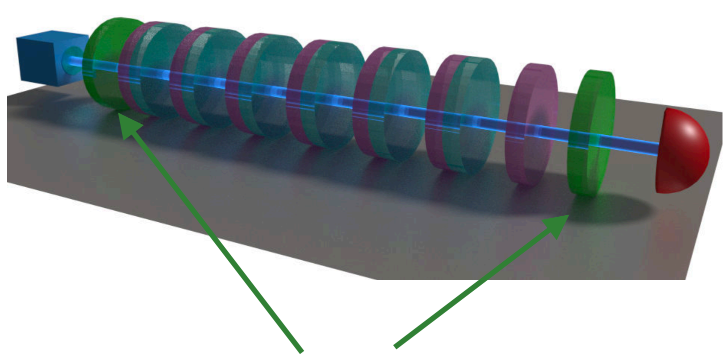
- Different initial t_0 lead to different U
- Eigenvalues of H_{eff} don't depend on t_0
- Eigenstates instead do! And so does the winding: $\mathcal{W} = \mathcal{W}_1 \neq \mathcal{W}_2$
- Timeframes invariant under time-reflection (U_1 and U_2) are special
- # of 0-energy edge states: $C_0 = (\mathcal{W}_1 + \mathcal{W}_2)/2$
- # of π-energy edge states: $C_\pi = (\mathcal{W}_1 - \mathcal{W}_2)/2$

[Asboth and Obuse, PRB (2013)]

Recovering the bulk-boundary correspondence

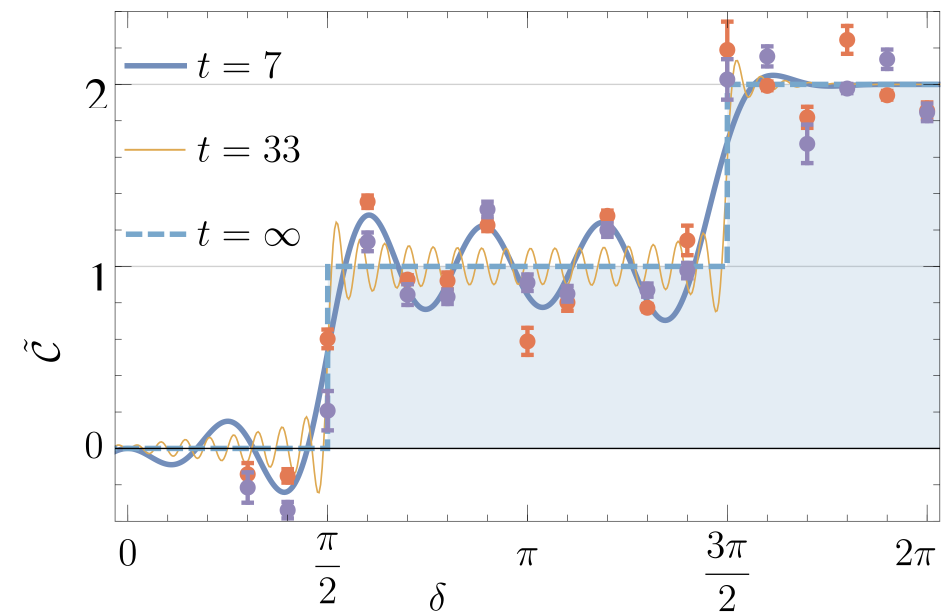
Measurement of the MCD in an alternative timeframe:





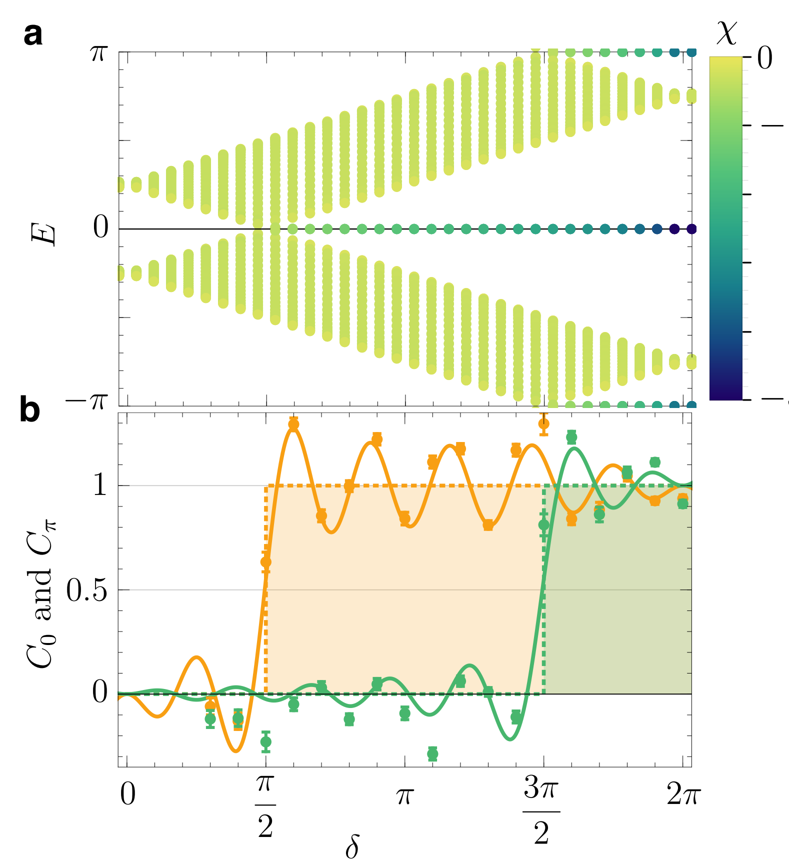
$$\sqrt{Q_\delta} = Q_{\delta/2}$$

(●/●): different initial polarizations



Spectrum (theory):

Measurements of C_0 and C_π:



Complete topological characterization of a Floquet topological insulator