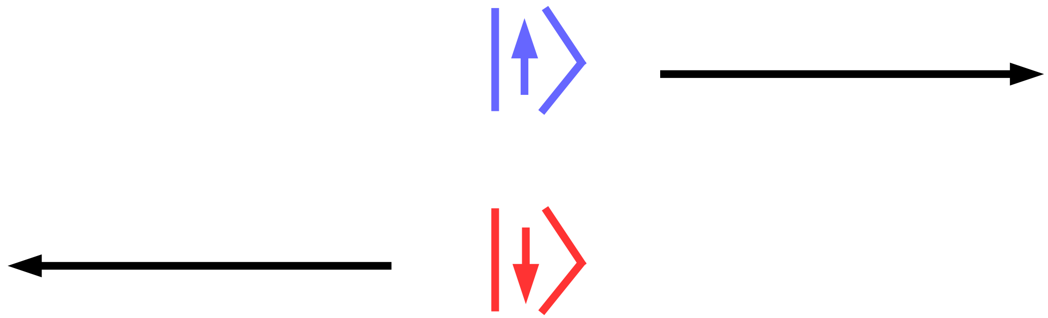
Disorder-robust helical coupled resonator waveguides

Daniel Leykam



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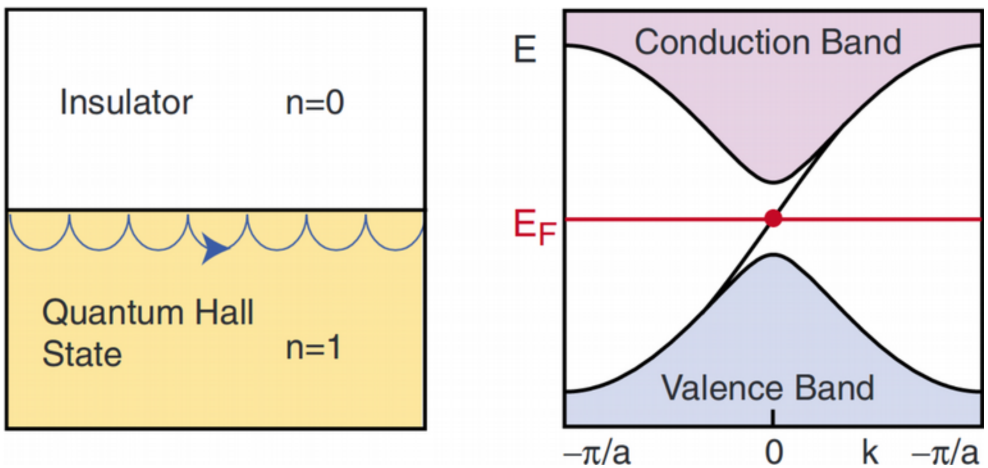
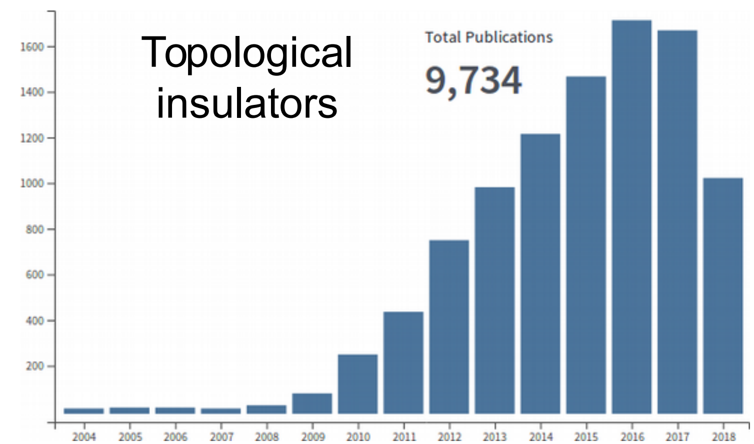
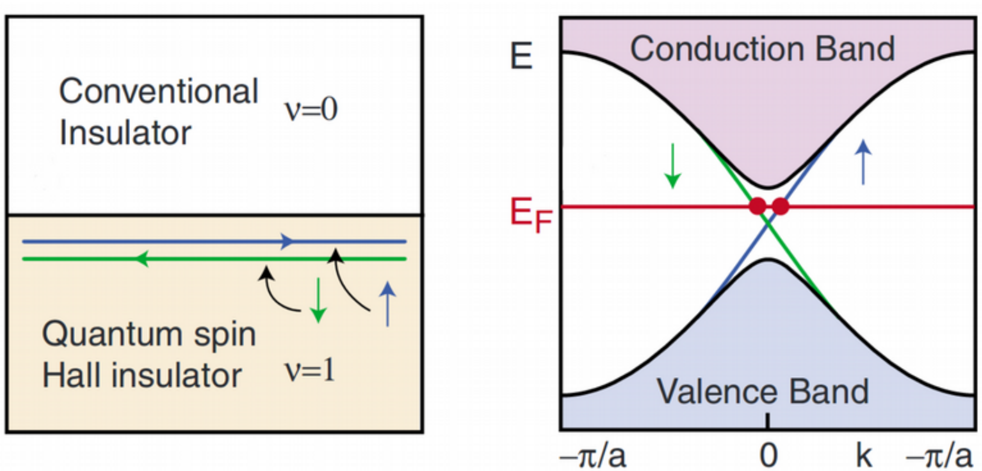
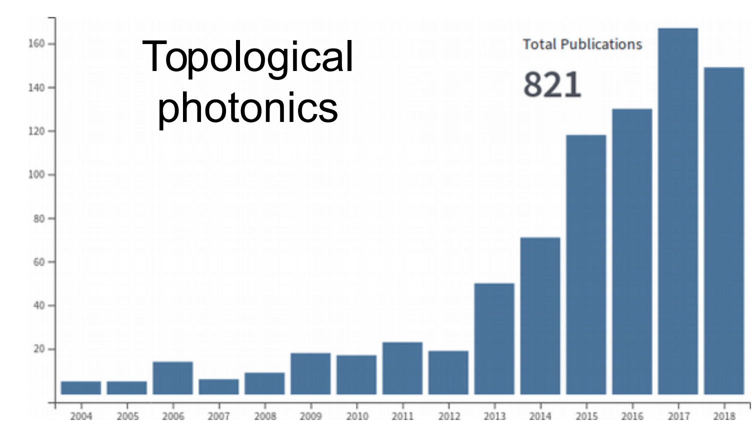
Topological protection against disorder

- Engineer 2D system with “topological” band structures
- One-way or spin-momentum locked edge modes
- Topological insulators, photonics, acoustics, ….





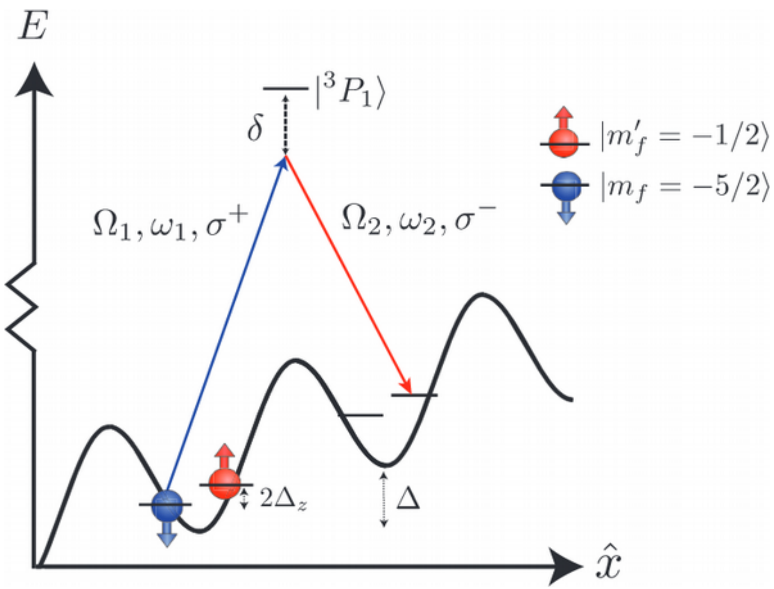




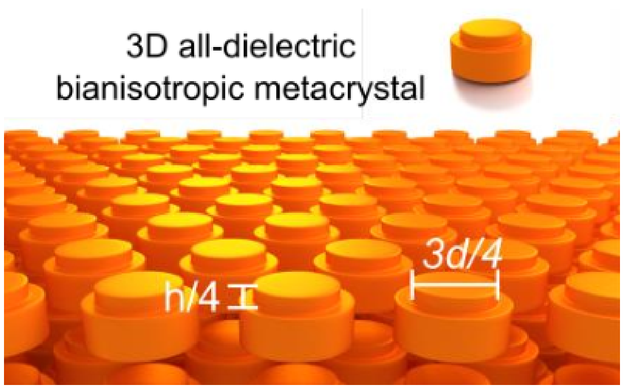
Kane & Mele, Phys. Rev. Lett. 95, 226801 (2005); Hasan & Kane, Rev. Mod. Phys. 82, 3045 (2010)

Motivation

- Are topological phases the “best” way to achieve disorder-robust transport?
- Drawbacks: system dimension, require exotic band structure engineering
- Can we use band structure engineering to directly achieve disorder robustness, without using topological phases?
- Benefits: reduced device size, can exploit fine-tuning



Budich et al., Phys. Rev. B 92, 245121 (2015)



Slobozhanyuk et al, Nature Photonics 11, 130 (2017)

Outline

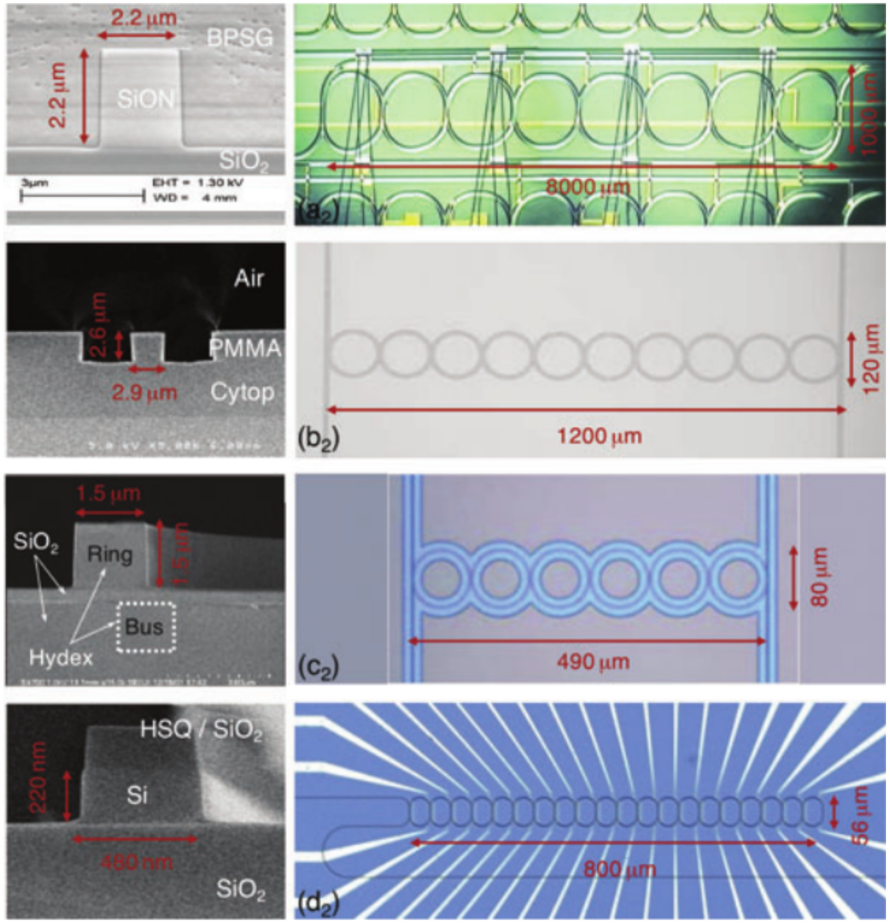
1. Coupled resonator optical waveguides (CROWs)

2. Topological protection in 2D resonator lattices

3. New approach: 1D CROWs with spin-momentum locking

Coupled resonator optical waveguides (CROWs)

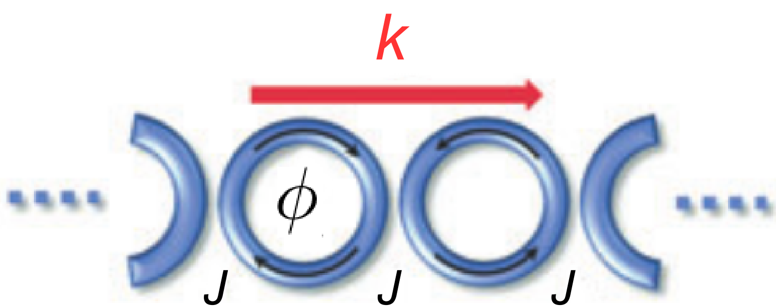
- Evanescently coupled high Q microresonators
- Applications: optical filtering & buffering, slow light, nonlinear signal processing

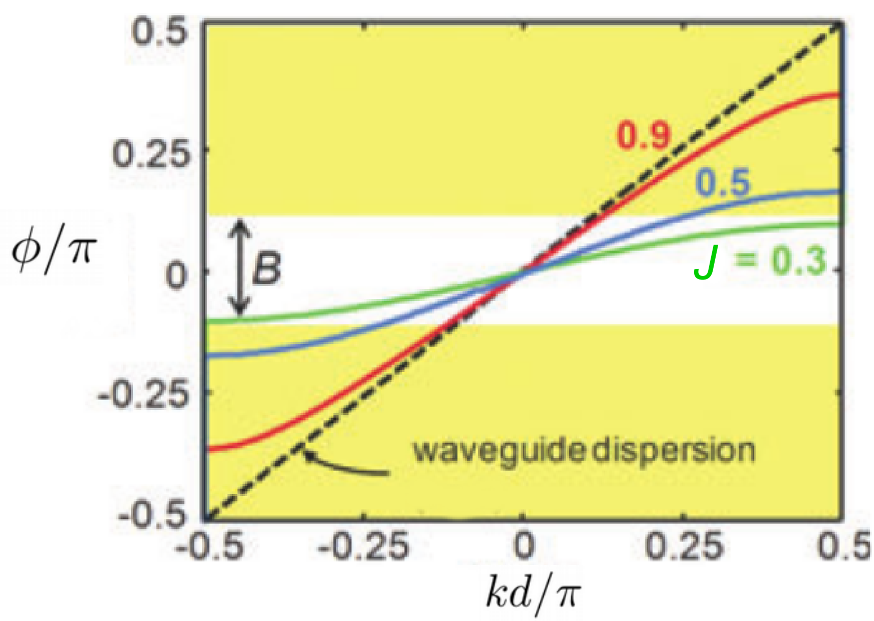


Yariv, et al., Opt. Lett. 24, 711 (1999); Morichetti et al., Laser & Photonics Rev. 6, 74 (2012)

Coupled resonator optical waveguides (CROWs)

- Resonator modes: clockwise or anticlockwise (negligible intra-ring backscattering)
- Coupling between neighboring rings: scattering matrices, coupling angle ~ *J*/FSR
- Weak coupling limit *J* << FSR: tight binding Hamiltonian





Energy $\phi = \omega n d / c$

Free spectral range $\mathrm{FSR} = c/2nd$

Bloch momentum $\cos(kd) = \frac{\mathrm{FSR}}{J} \sin\phi$

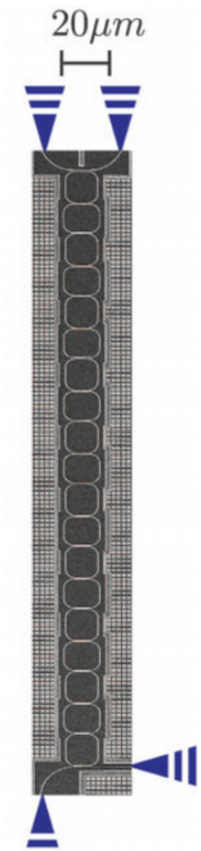
Bandwidth $B = \frac{2\mathrm{FSR}}{\pi} \sin^{-1}(J/\mathrm{FSR})$

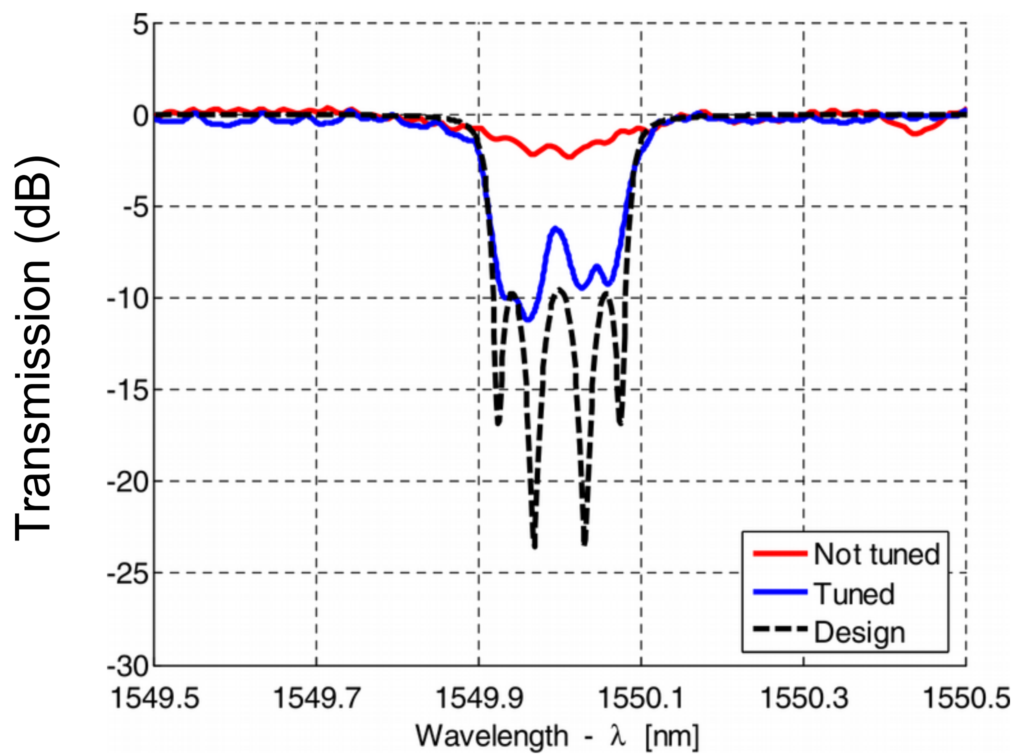
$$\hat{H} a_n = J(a_{n-1} + a_{n+1})$$

Yariv, et al., Opt. Lett. 24, 711 (1999); Morichetti et al., Laser & Photonics Rev. 6, 74 (2012)

Limits to CROWs: absorption & disorder

- Intrinsic absorption κ~ 2GHz
- Coupling (off-diagonal) disorder ΔJ~ 1 GHz
- Resonance misalignment (on-site disorder) Δω ~ **30 GHz**
- Thermal tuning of Δω: additional power consumption, limited bandwidth

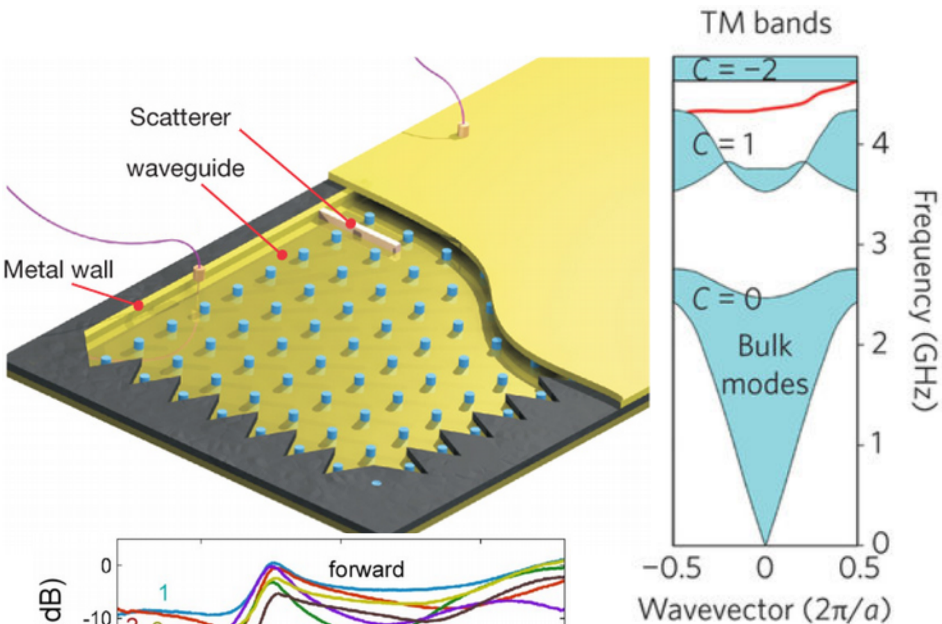


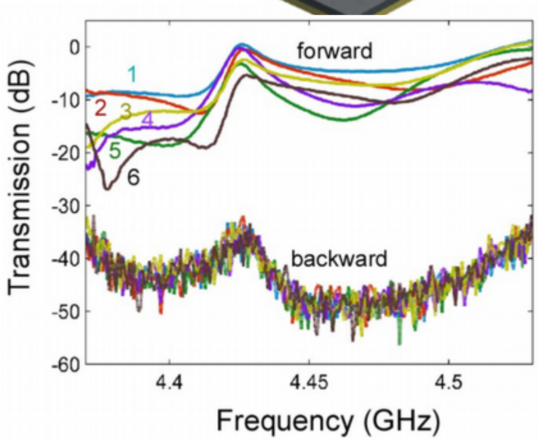


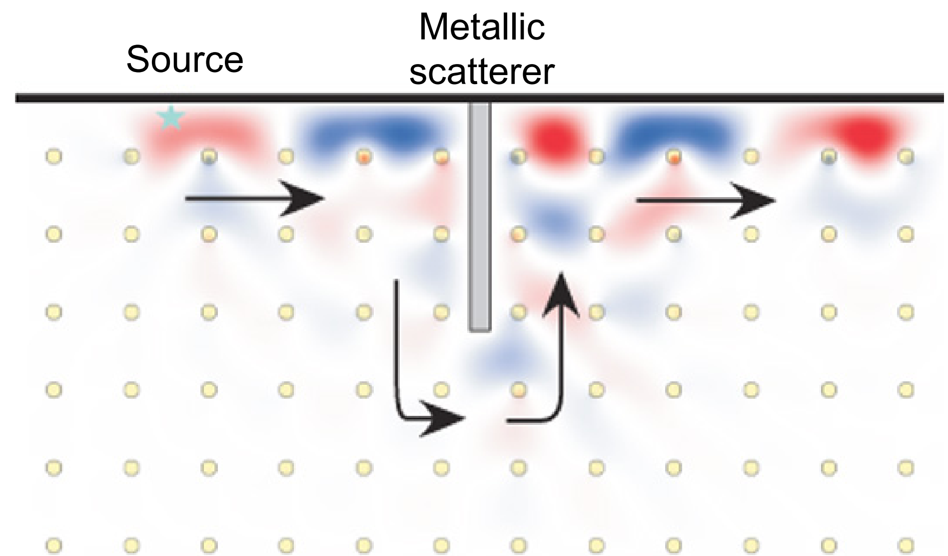
Mittal et al., Phys. Rev. Lett. 113, 087403 (2014); Canciamilla et al., J. Opt. 12, 104008 (2010)

Topological photonics

- Photonic lattices: “insulators” for light, can have topological band structures
- Photonic crystals, waveguide arrays, resonator lattices, metamaterials
- Device applications: Disorder-robust waveguides, lasers, ...

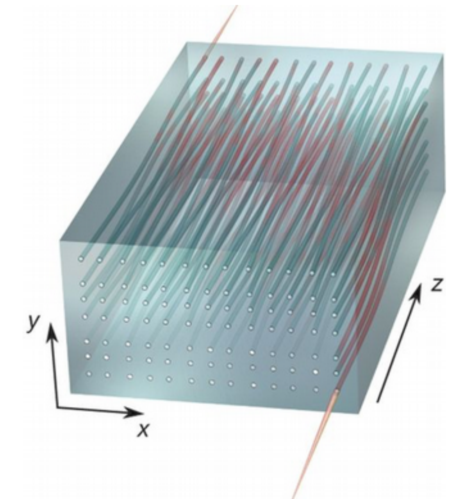




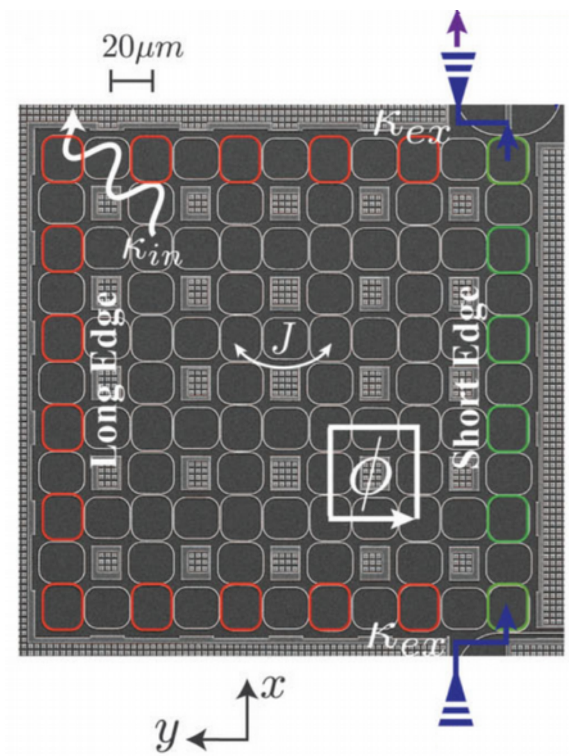


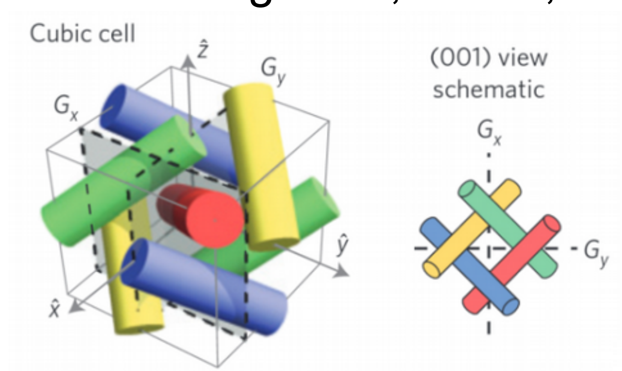
Haldane & Raghu, Phys. Rev. Lett. 100, 013904 (2008)
Wang, Chong, Joannopoulos, & Soljacic, Phys. Rev. Lett. 100, 013905 (2008)
Wang, Chong, Joannopoulos, & Soljacic, Nature 461, 772 (2009)

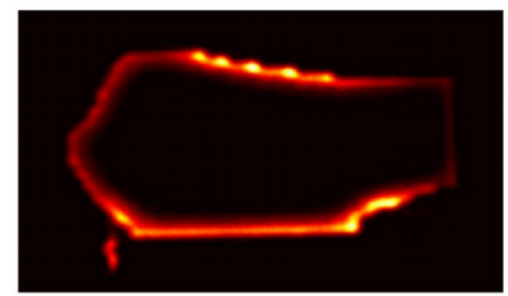
Photonic topological insulators

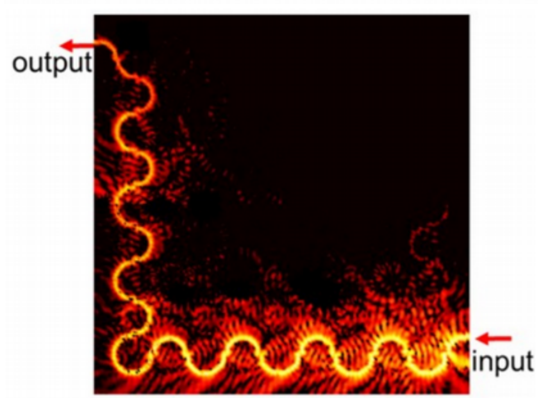


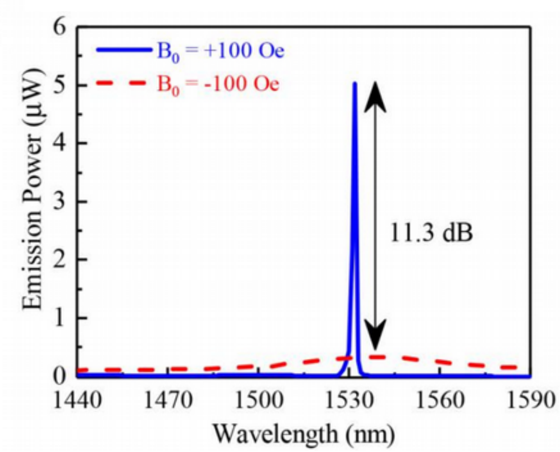
- Now generalized to various non-magnetic designs
- Waveguide arrays, resonator lattices, metamaterials
- 1D, 2D, 3D, 4D (!)
- New physics, inaccessible in condensed matter?
- Device applications? Unidirectional waveguides, lasers, ...









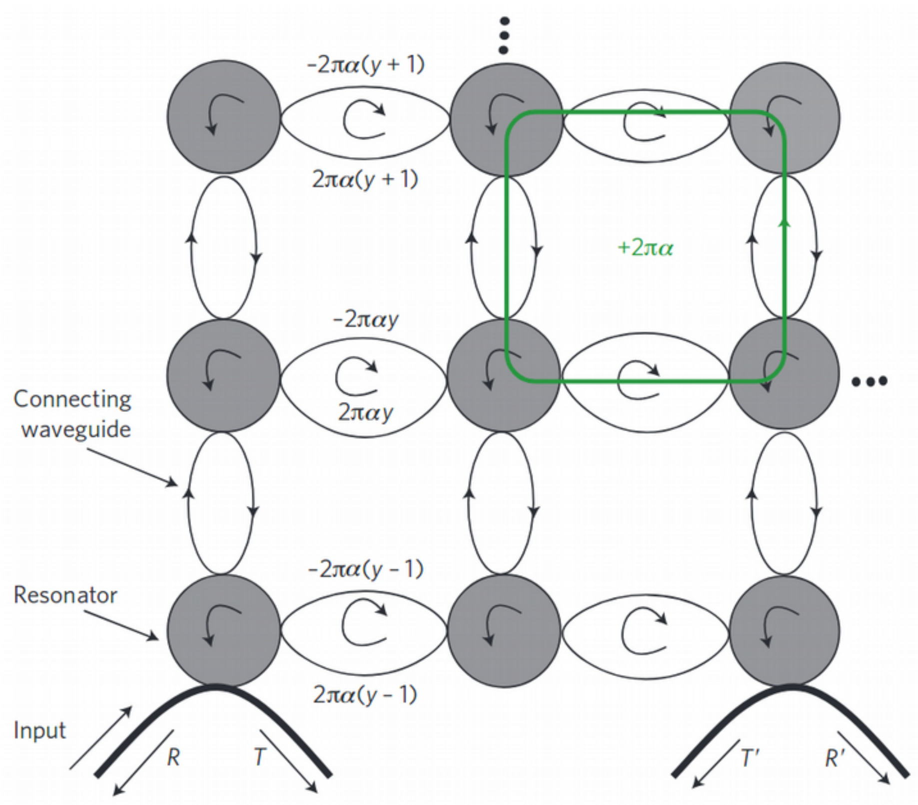


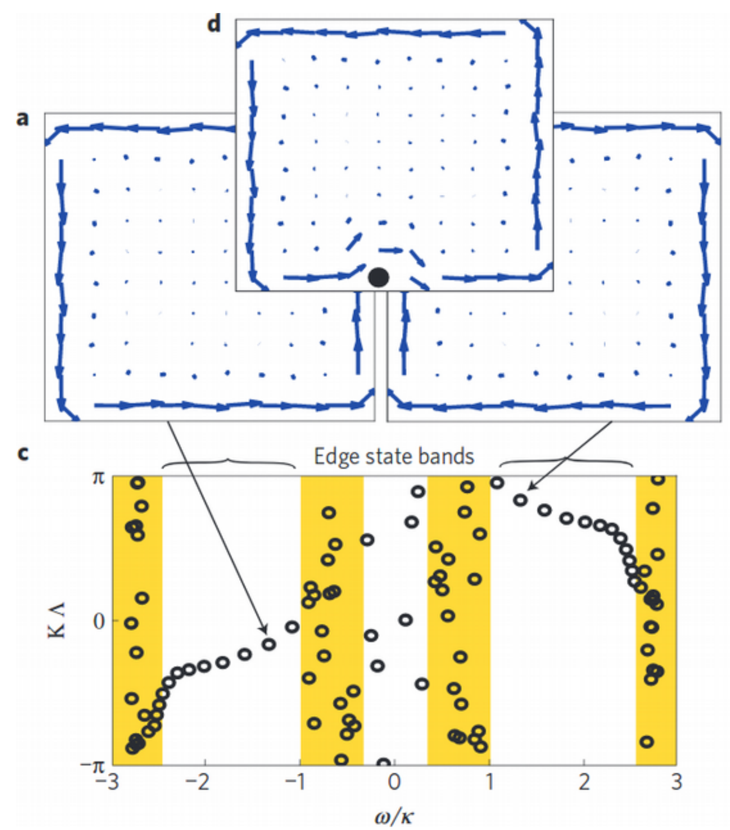
Hafezi et al., Nature Photon. 7, 1001 (2013); Gao et al., Nature Comm. 7, 11619 (2016); Lu et al, Nature Physics 12, 337 (2016); Bahari et al, Science eaao4551 (2017); Zilberberg et al, Nature 553, 59 (2018);
Lu, Joannopoulos, & Soljacic, Nature Photon. 8, 821 (2014); Ozawa et al., arXiv:1802:04173

Topological coupled resonator lattices

- Light localized to resonant “site” rings, weak coupling via off-resonant “link” rings
- Asymmetric link rings: relative hopping phase ~ vector potential
- Effective magnetic flux emulates quantum Hall effect

$$H_0 = -\kappa\left(\sum_{\sigma,x,y} \hat{a}^{\dagger}_{\sigma x+1,y}\hat{a}_{\sigma x,y}\mathrm{e}^{-i2\pi\alpha y\sigma} + \hat{a}^{\dagger}_{\sigma x,y}\hat{a}_{\sigma x+1,y}\mathrm{e}^{i2\pi\alpha y\sigma} + \hat{a}^{\dagger}_{\sigma x,y+1}\hat{a}_{\sigma x,y} + \hat{a}^{\dagger}_{\sigma x,y}\hat{a}_{\sigma x,y+1}\right)$$

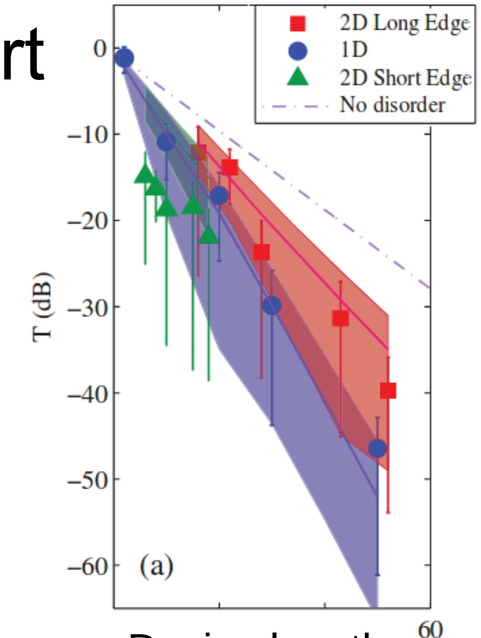




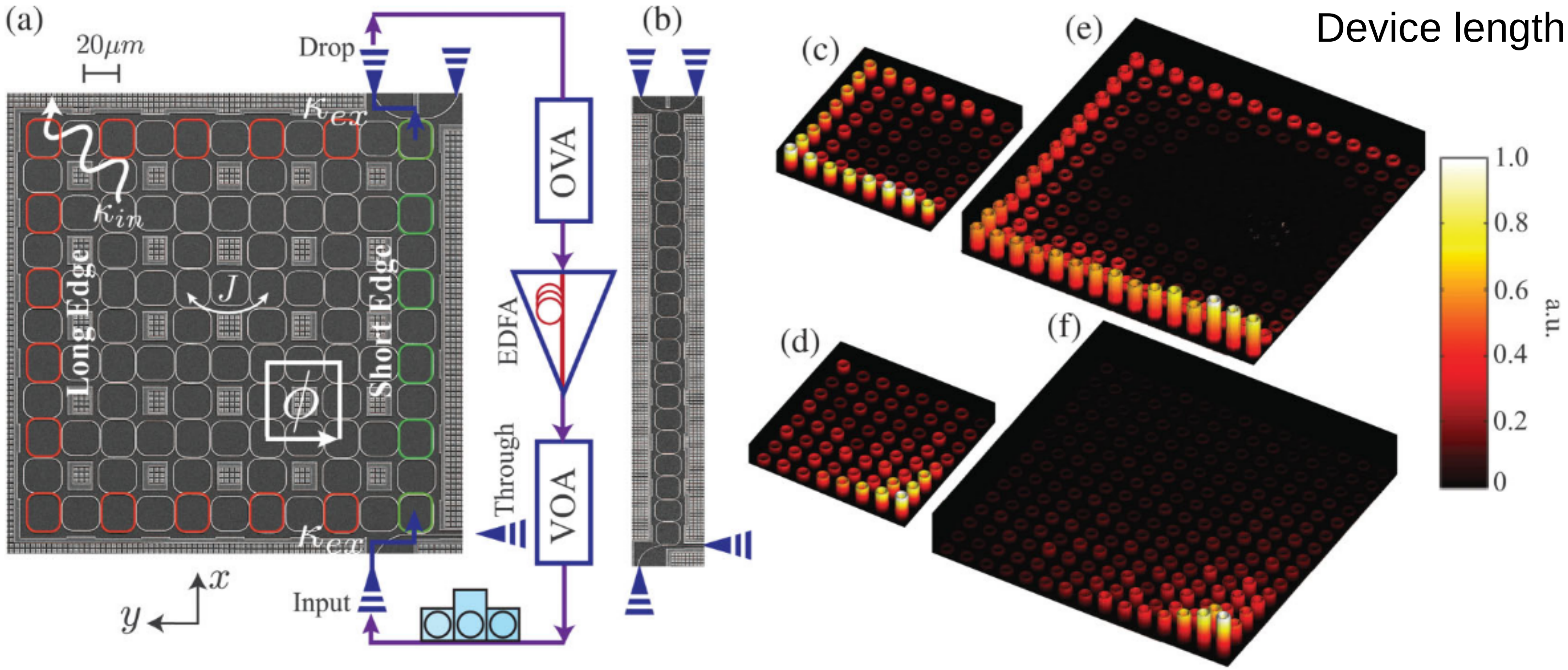
Hafezi et al., Nature Phys. 7, 907 (2011)

Topologically-protected transport

- Transmission: 1D vs topological 2D devices
- Both have similar losses due to absorption
- 2D edge states protected against disorder-induced localization



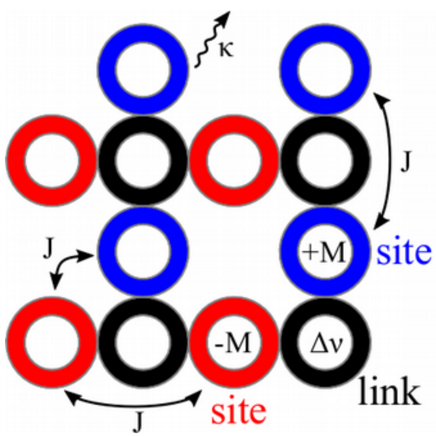
Device length

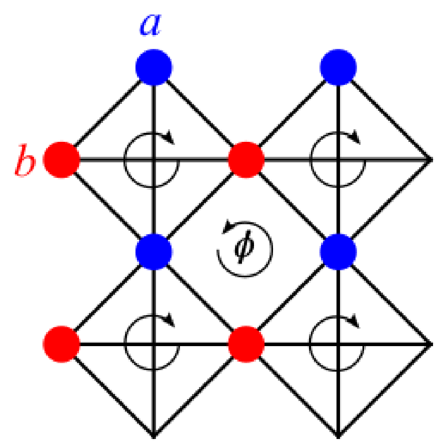


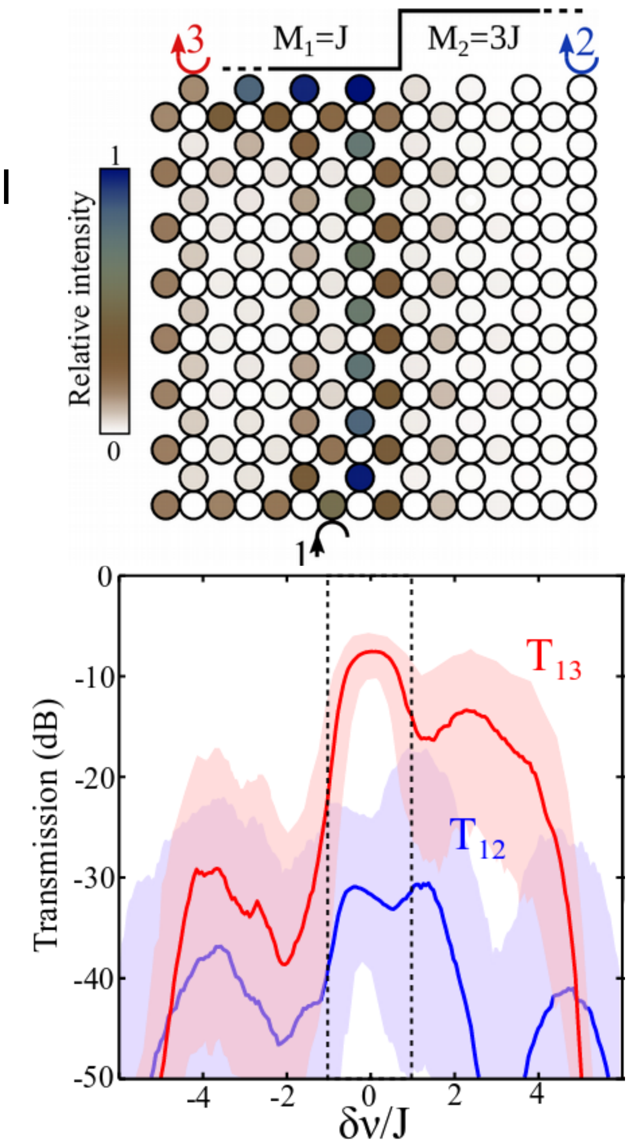
Hafezi et al., Nature Photon. 7, 1001 (2013); Mittal et al., Phys. Rev. Lett. 113, 087403 (2014)

Topological phases from next-nearest neighbor coupling

- Off-resonant “link” rings induce NNN coupling
- Checkerboard lattice with effective gauge field
- Tunable Chern insulator, emulates the Haldane model







$$\hat{H} = \sum_{x,y}\left(\hat{H}_a + \hat{H}_b + \hat{H}_{ab} + \hat{H}_{ab}^\dagger\right)$$

$$\hat{H}_a = \hat{a}_{x,y}^\dagger\left[(2J\cot\frac{\phi}{2} + M)\hat{a}_{x,y} + J\csc\frac{\phi}{2}\sum_{\pm}\hat{a}_{x,y\pm1}\right]$$

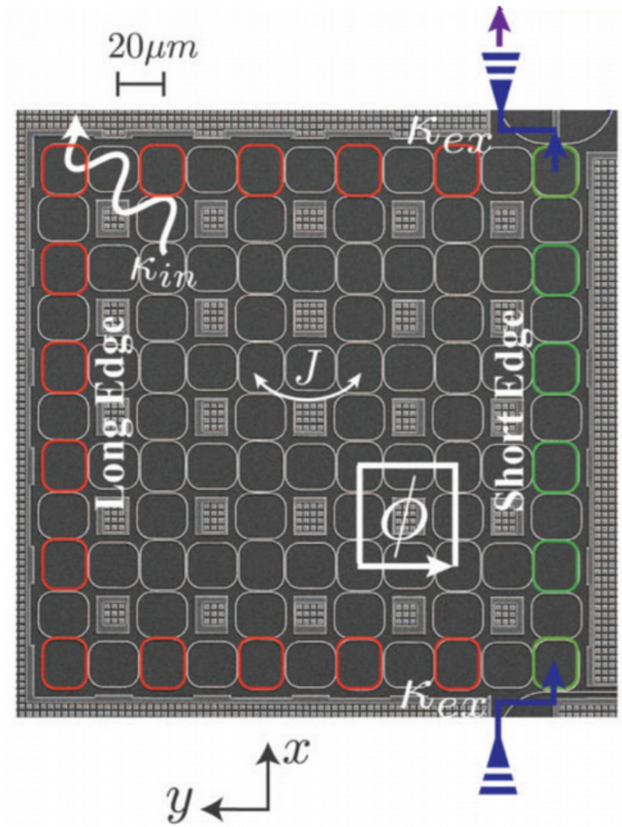
$$\hat{H}_b = \hat{b}_{x,y}^\dagger\left[(2J\cot\frac{\phi}{2} - M)\hat{b}_{x,y} + J\csc\frac{\phi}{2}\sum_{\pm}\hat{b}_{x\pm1,y}\right]$$

$$\hat{H}_{ab} = Je^{i\phi/4}\csc\frac{\phi}{2}\left[\hat{a}_{x,y}^\dagger(\hat{b}_{x,y} + \hat{b}_{x+1,y+1}) + \hat{b}_{x,y}^\dagger(\hat{a}_{x-1,y} + \hat{a}_{x,y-1})\right]$$

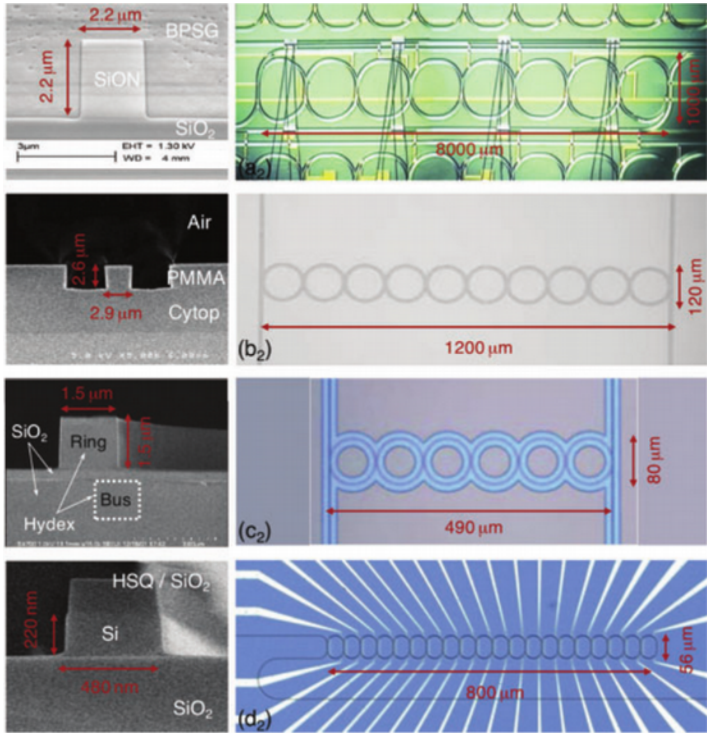
D. Leykam, S. Mittal, M. Hafezi, and Y. D. Chong, Phys. Rev. Lett. 121, 023901 (2018)

Limits to topological protection

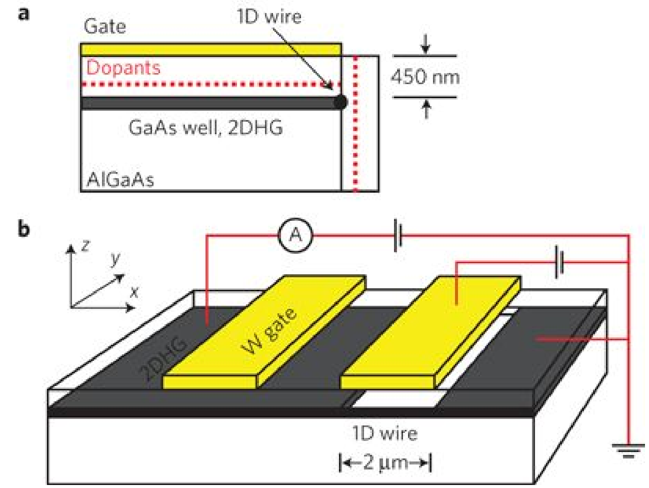
- Topological protection requires a 2D bulk
- Overhead: delay line of length ~L requires ~c*L lattice sites
- Increased device footprint compared to 1D CROWs
- Can we find a way to eliminate backscattering in 1D systems?



VS



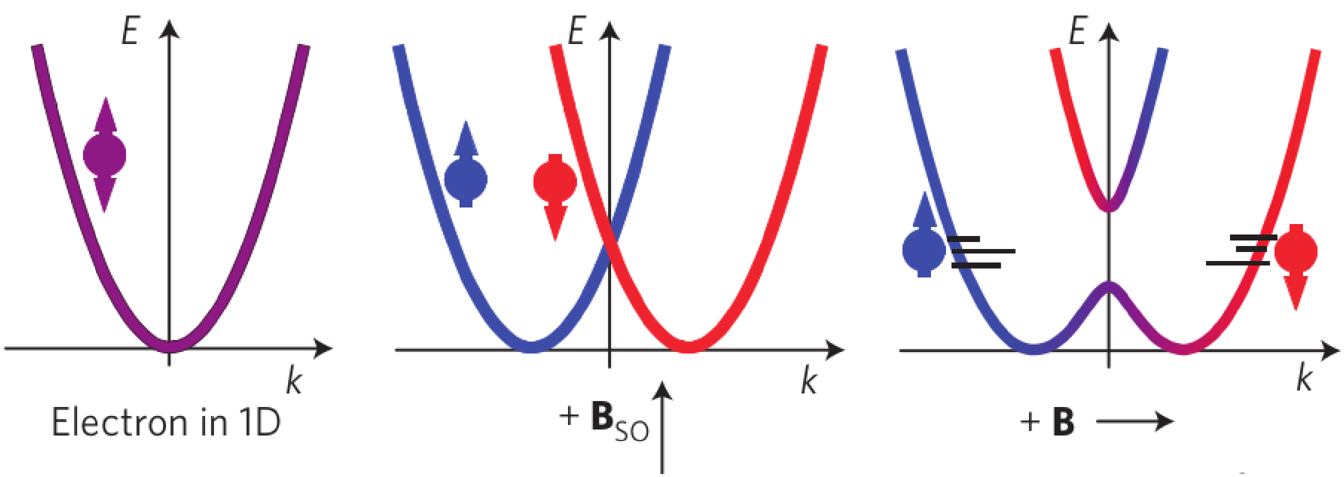
1D helical transport



- Spin-orbit coupling + magnetic field = “spin-orbit gap”
- Backscattering requires a spin flip
- Analogous to edge states of 2D topological insulators

$$H_{\text{tot}} = H_0 + H_{\text{SO}} + H_Z$$

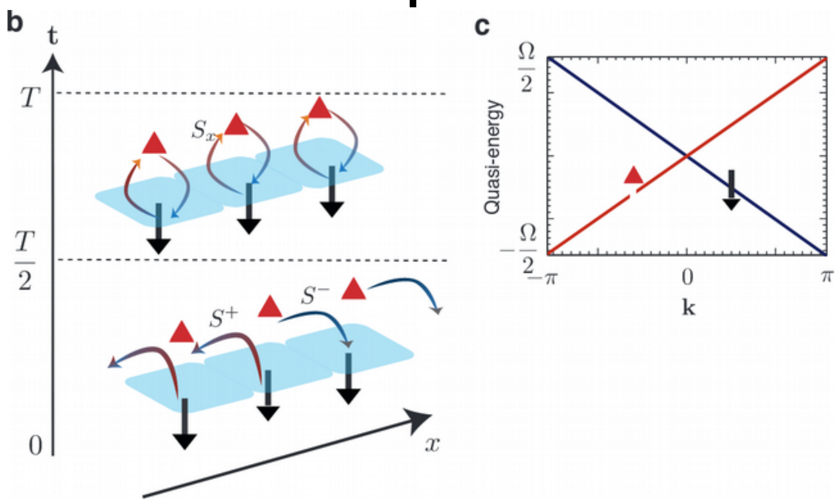
$$H_0 = \hbar^2 k^2 / 2m \qquad H_{\text{SO}} = \beta \boldsymbol{\sigma} \cdot (\mathbf{k} \times \nabla V) \qquad H_Z = g\mu_B \boldsymbol{B} \cdot \hat{\boldsymbol{\sigma}}$$



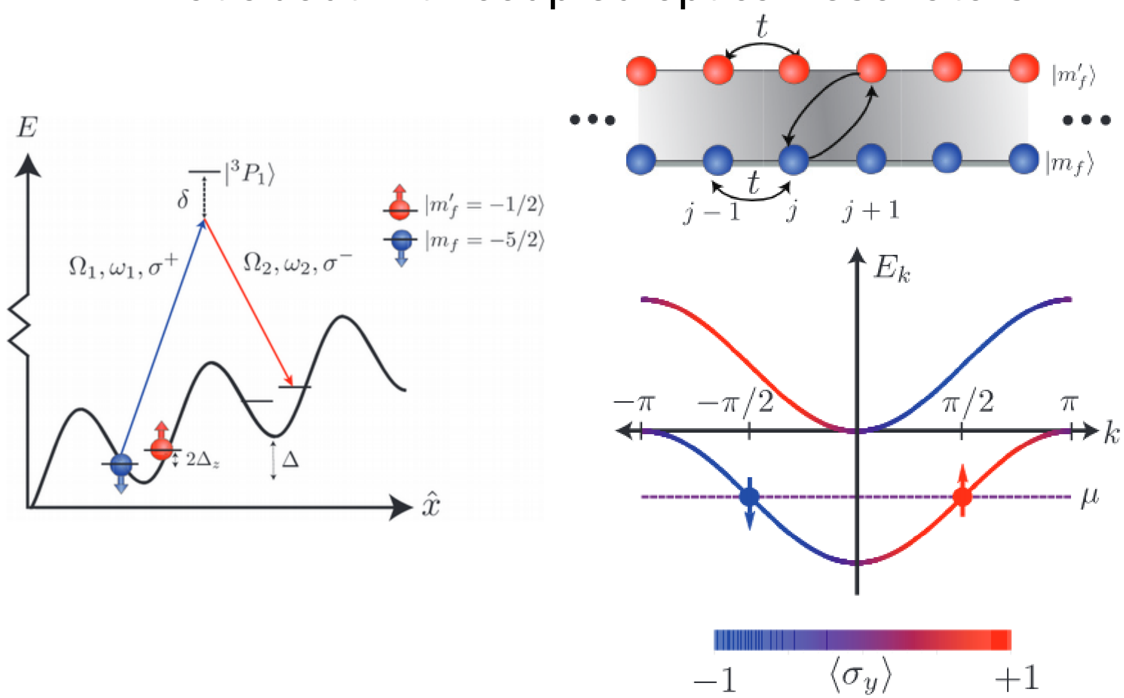
Quay et al., Nature Physics 6, 336 (2010)

Other mechanisms for 1D helical transport

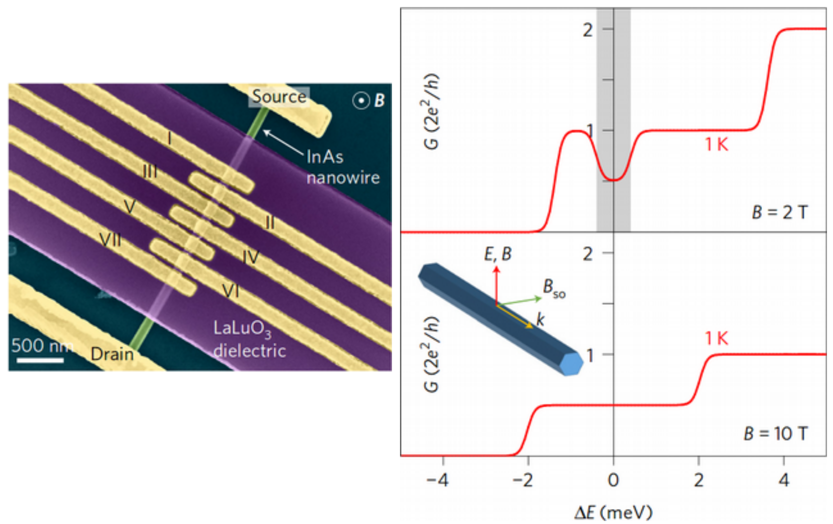
- Strong electron-electron interactions
- Cold atoms + Raman-assisted tunneling
- Periodic driving
- What about with coupled optical resonators?



Budich et al, Phys. Rev. Lett. 118, 105302 (2017)



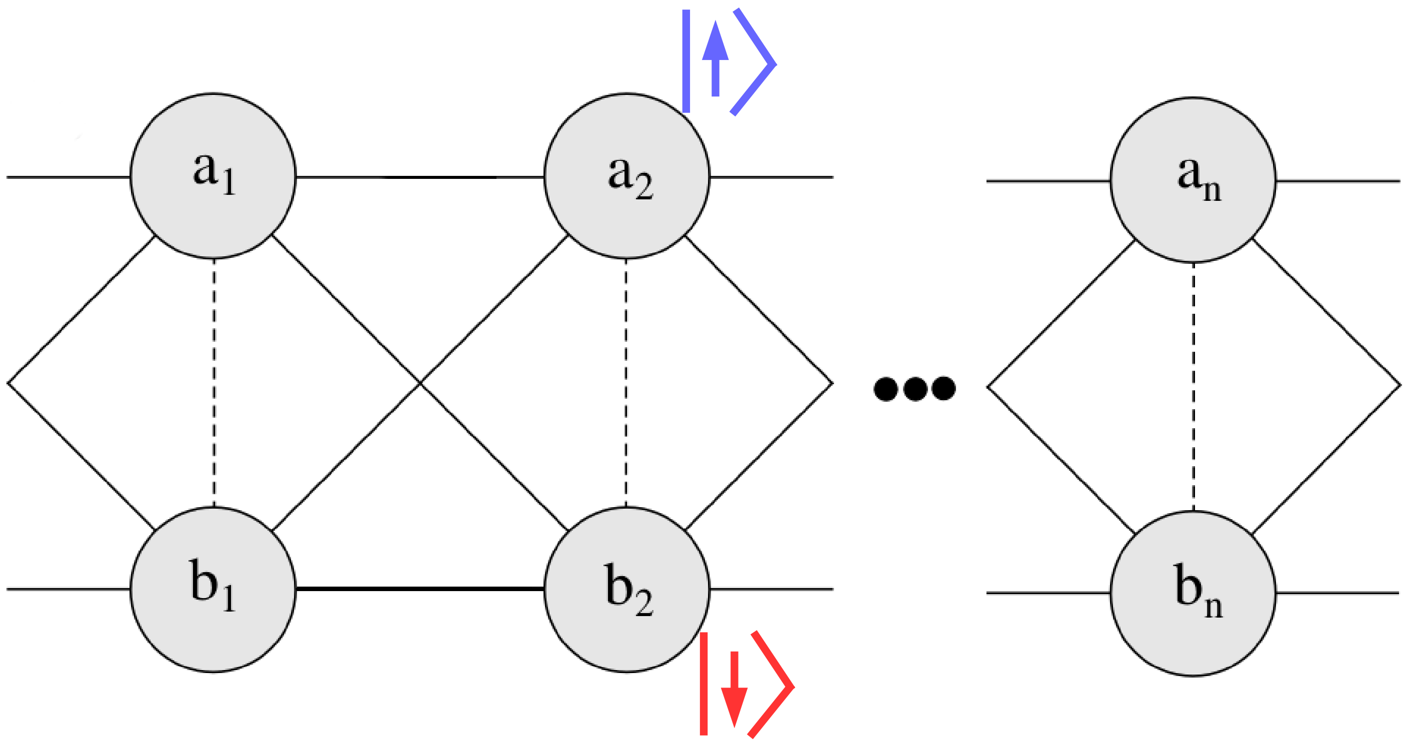
Budich et al., Phys. Rev. B 92, 245121 (2015)



Heedt et al., Nature Physics 13, 563 (2017)

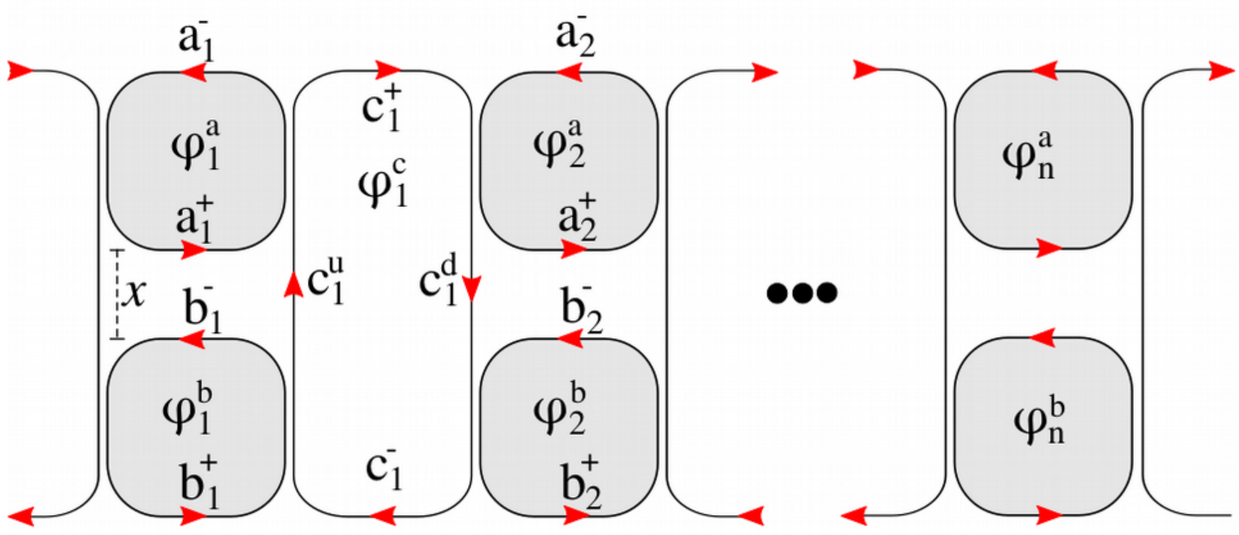
Pseudospin-orbit coupling in a two leg ladder

- Sublattice degree of freedom: pseudo-spin
- Generic Bloch wave Hamiltonian: $\hat{H}(k) = J\boldsymbol{d}(k) \cdot \hat{\boldsymbol{\sigma}}$
- d_0 : intra-leg, symmetric hopping ~ H_0 (effective mass)
- d_x : intra-leg, leg-dependent hopping ~ H_{SO} (spin-orbit coupling)
- d_z : inter-leg hopping ~ H_Z (Zeeman shift of magnetic field Bx)



Coupled resonator implementation

- Two sublattices formed by resonant site rings
- Coupling mediated by an anti-resonant link ring

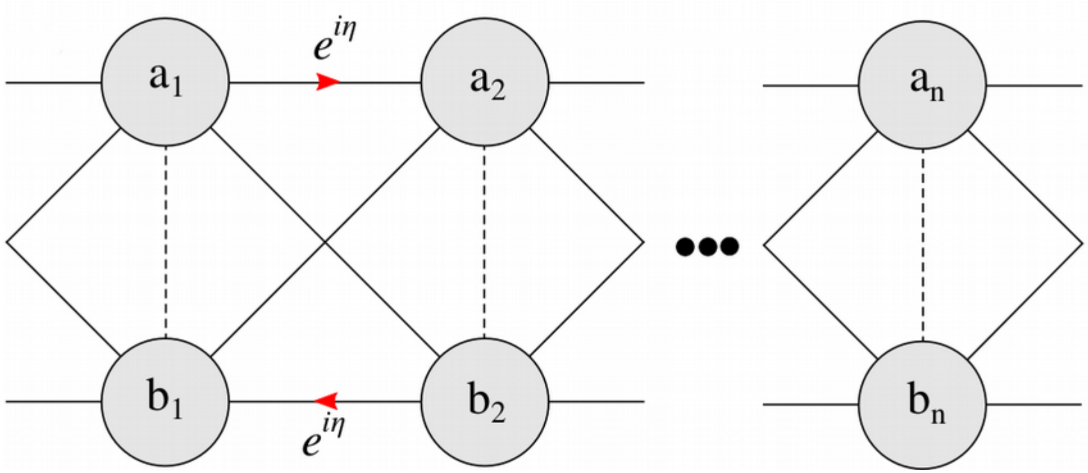


$$\begin{pmatrix} a_n^- e^{-i\varphi_n^a/2} \\ c_n^+ e^{-i(\varphi_n^c/2-\eta)/2} \end{pmatrix} = \hat{S} \begin{pmatrix} a_n^+ e^{i\varphi_n^a/2} \\ c_n^u e^{i\eta/2} \end{pmatrix}, \quad \begin{pmatrix} a_{n+1}^+ e^{-i\varphi_{n+1}^a/2} \\ c_n^d e^{-i\eta/2} \end{pmatrix} = \hat{S} \begin{pmatrix} a_{n+1}^- e^{i\varphi_{n+1}^a/2} \\ c_n^+ e^{i(\varphi_n^c/2-\eta)/2} \end{pmatrix},$$

$$\begin{pmatrix} b_n^- e^{-i\varphi_n^b/2} \\ c_n^u e^{-i\eta/2} \end{pmatrix} = \hat{S} \begin{pmatrix} b_n^+ e^{i\varphi_n^b/2} \\ c_n^- e^{i(\varphi_n^c/2-\eta)/2} \end{pmatrix}, \quad \begin{pmatrix} b_{n+1}^+ e^{-i\varphi_{n+1}^b/2} \\ c_n^- e^{-i(\varphi_n^c/2-\eta)/2} \end{pmatrix} = \hat{S} \begin{pmatrix} b_{n+1}^- e^{i\varphi_{n+1}^b/2} \\ c_n^d e^{i\eta/2} \end{pmatrix},$$

Weak coupling limit: tight binding model

- Effective SOI strength η tunable via link ring parameters

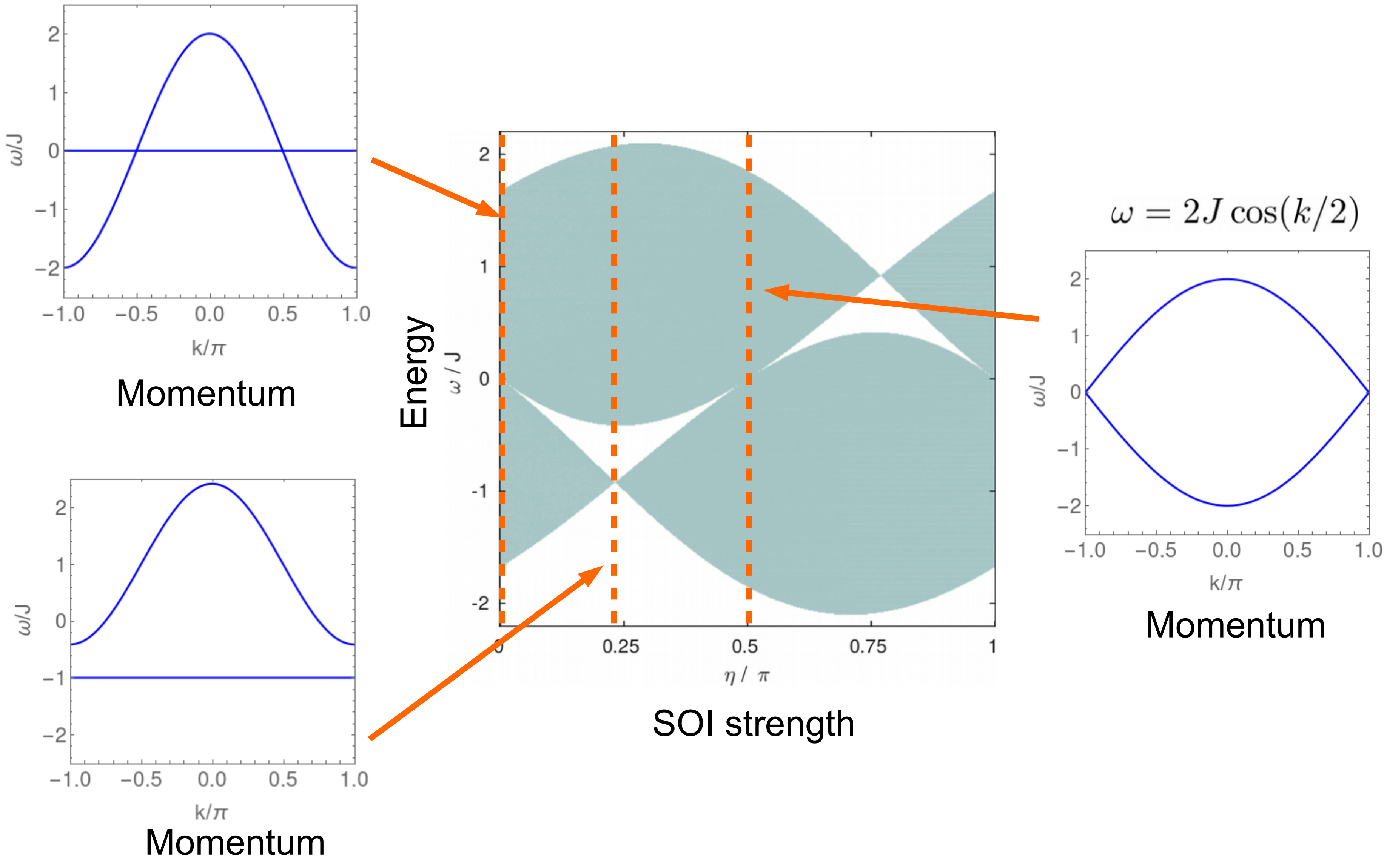


$$\omega a_n = \epsilon_n^a a_n + J \sin \eta b_n + \frac{J}{2}(e^{-i\eta} a_{n-1} + e^{i\eta} a_{n+1} + b_{n-1} + b_{n+1})$$

$$\omega b_n = \epsilon_n^b b_n + J \sin \eta a_n + \frac{J}{2}(e^{i\eta} b_{n-1} + e^{-i\eta} b_{n+1} + a_{n-1} + a_{n+1})$$

Band structure

- Effective SOI strength η tunes between flat band, gapped, & gapless dispersions

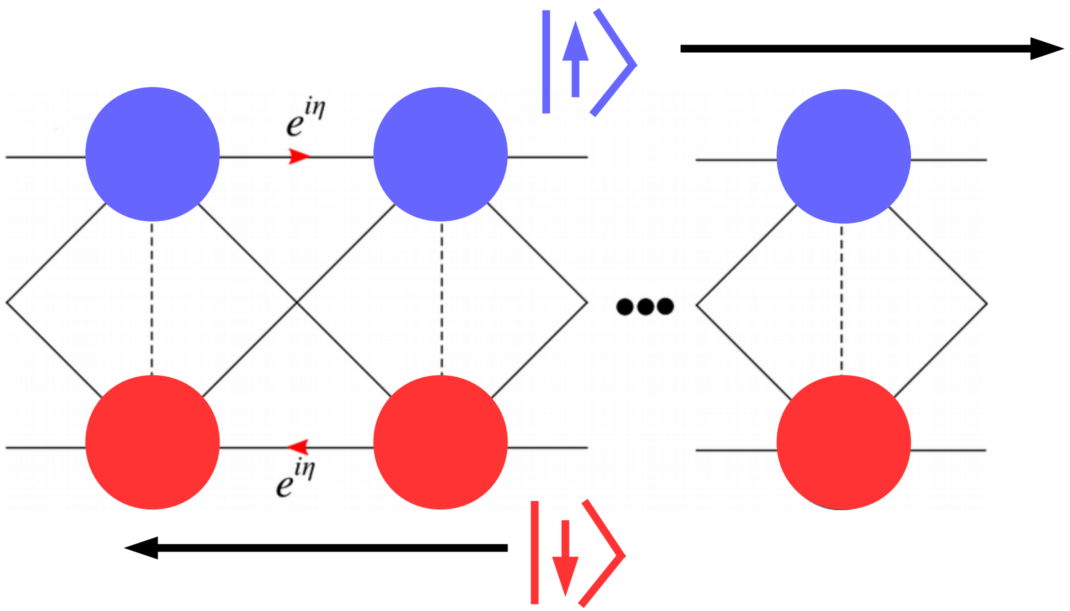


Helical Bloch waves

$$\hat{H}(k) = J\boldsymbol{d}(k)\cdot\hat{\boldsymbol{\sigma}}$$

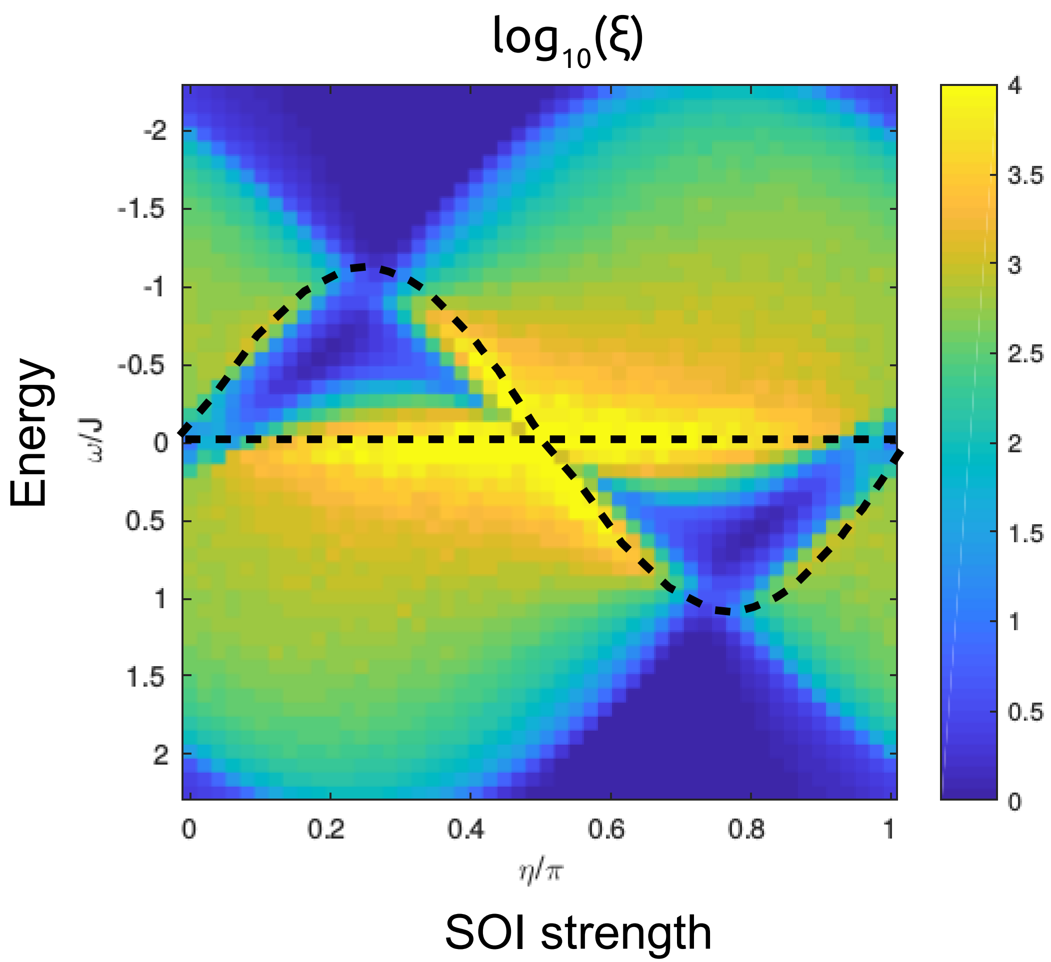
$$d_0 = (\epsilon^a + \epsilon^b)/(2J) + \cos\eta\cos k,$$
$$d_x = \sin\eta + \cos k,$$
$$d_z = (\epsilon^a - \epsilon^b)/(2J) - \sin\eta\sin k.$$

Spin-momentum locking when d_x = 0 => ω=0, -J sin(2η)



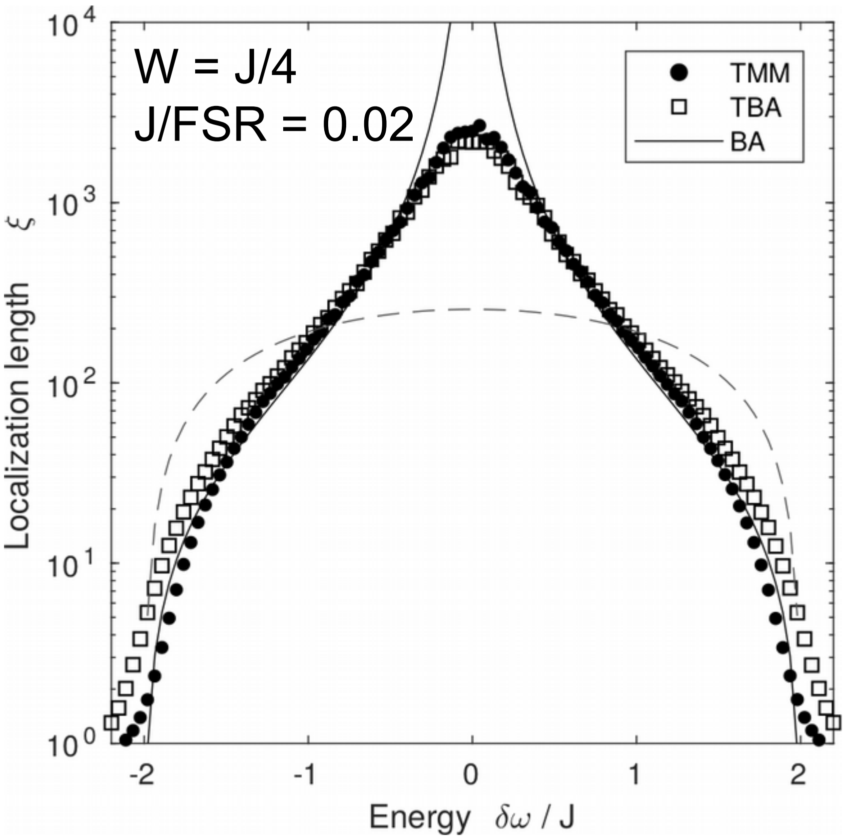
Disorder & Anderson localization

- Fabrication disorder: random resonator detunings ~ W
- Compute localization length ξ using transfer matrix method
- Large enhancement of ξ at spin-momentum locked energies

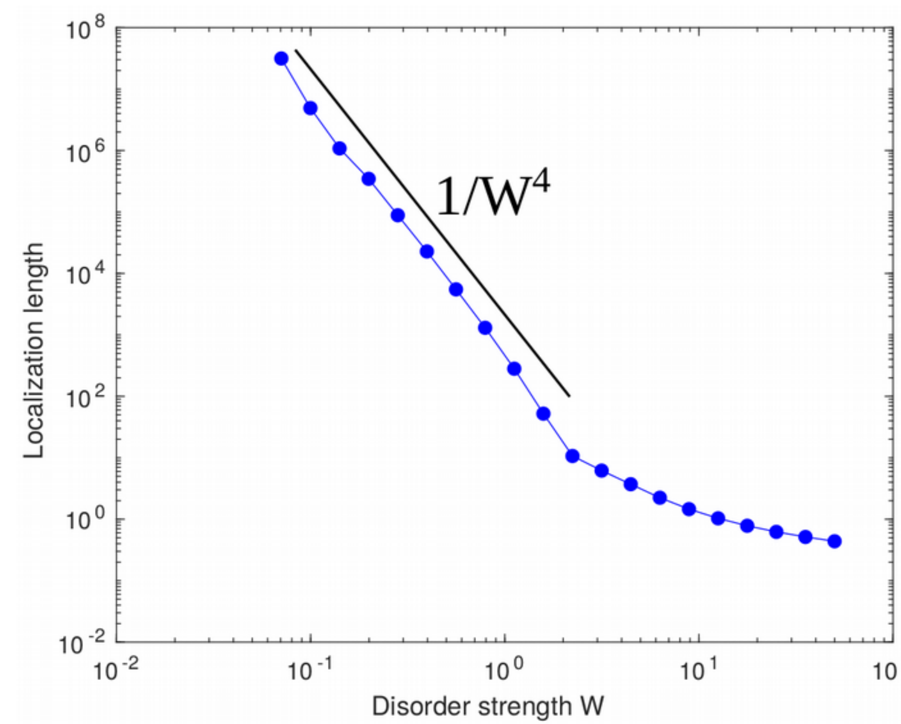


Anderson localization length: η = π/2

- Born approximation: divergence of ξ at ω=0: $\xi = 48J^2(4J^2 - \omega^2)/(W^2\omega^2)$
- Anomalous scaling near band centre: $\xi \sim 1 / W^4$
- Conventional tight binding model: $\xi = 4(4J^2 - \omega^2)/W^2$
- Order of magnitude enhancement of ξ for typical device parameters



ω=0



Locally-correlated disorder

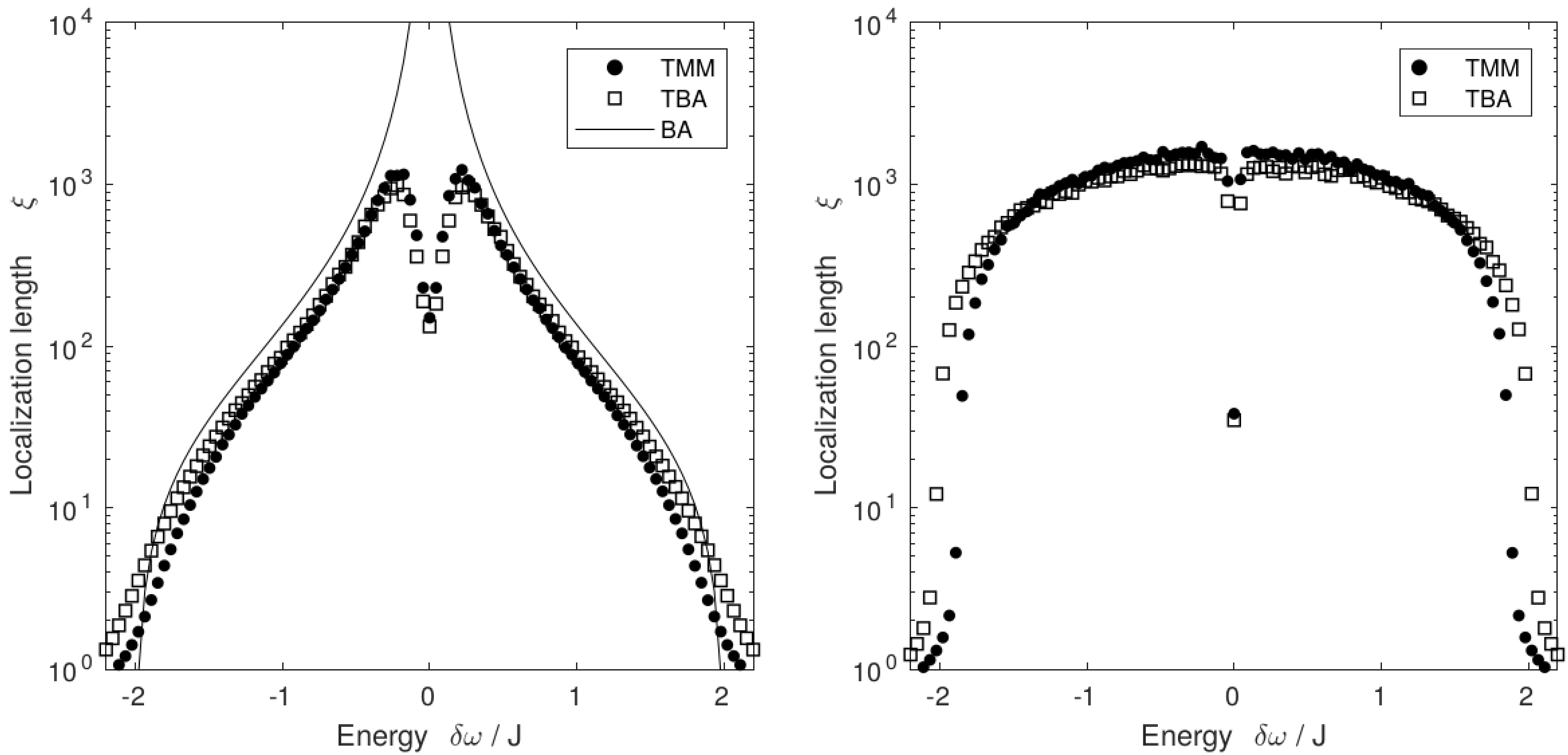
- Disorder can be split into inversion-symmetric and -antisymmetric parts
- Local correlations *enhance* localization at ω=0

Symmetric disorder $\epsilon_n^a = \epsilon_n^b$

BA: $\xi = 24J^2(4J^2 - \omega^2)/(W^2\omega^2)$

Antisymmetric disorder $\epsilon_n^a = -\epsilon_n^b$

BA: $\xi \to \infty$



Summary

- Coupled resonator lattices can exhibit strong next-nearest neighbour coupling
- Novel way to implement topological phases & synthetic spin-orbit coupling
- 1D helical Bloch waves robust to on-site disorder
- Band structure engineering: 2D topological phases not required for robust transport

D. Leykam, S. Mittal, M. Hafezi, & Y. D. Chong, PRL 121, 023901 (2018); arXiv:1802.02253
J. Han, C. Gneiting, & D. Leykam, in preparation

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