Introduction to Topological Photonics

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AMOLF Nanophotonics Summer School, June 2019

The group


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Jonathan Guglielmon


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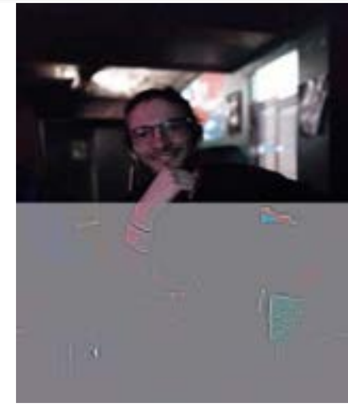
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The Pennsylvania State University 1855

Alfred P. Sloan Foundation 1934

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Part 1: Introduction to Photonic Topological Insulators

[collaboration with group of M. Segev and A. Szameit]

Nobel prize for physics: 2016

Photo: A. Mahmoud

David J. Thouless

Prize share: 1/2

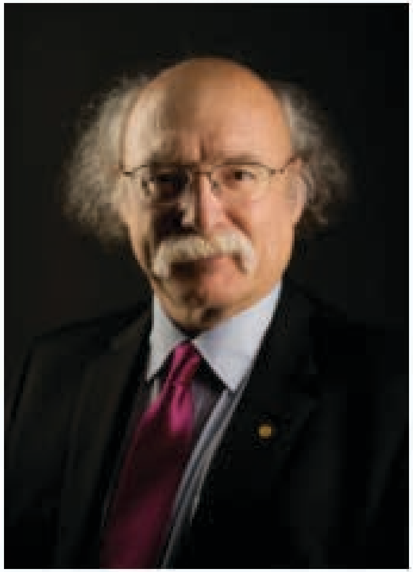


Photo: A. Mahmoud

F. Duncan M. Haldane

Prize share: 1/4

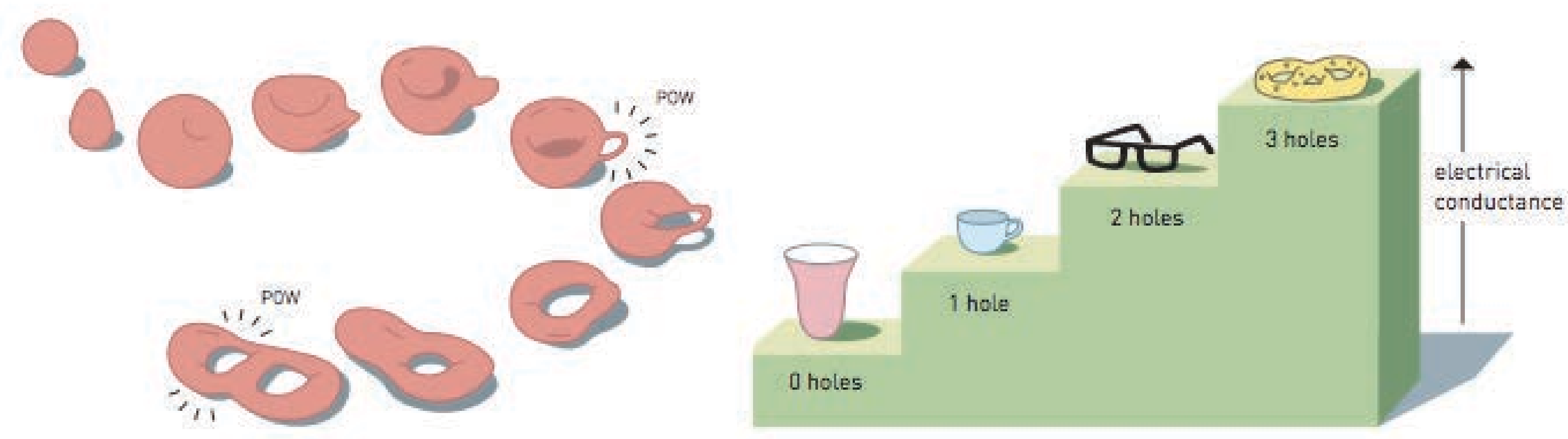
Photo: A. Mahmoud

J. Michael Kosterlitz

Prize share: 1/4

"For theoretical discoveries of topological phase transitions and topological phases of matter."

Topological physics



Royal Swedish Academy

A system described by a topological number must be robust

Quantum Hall effect

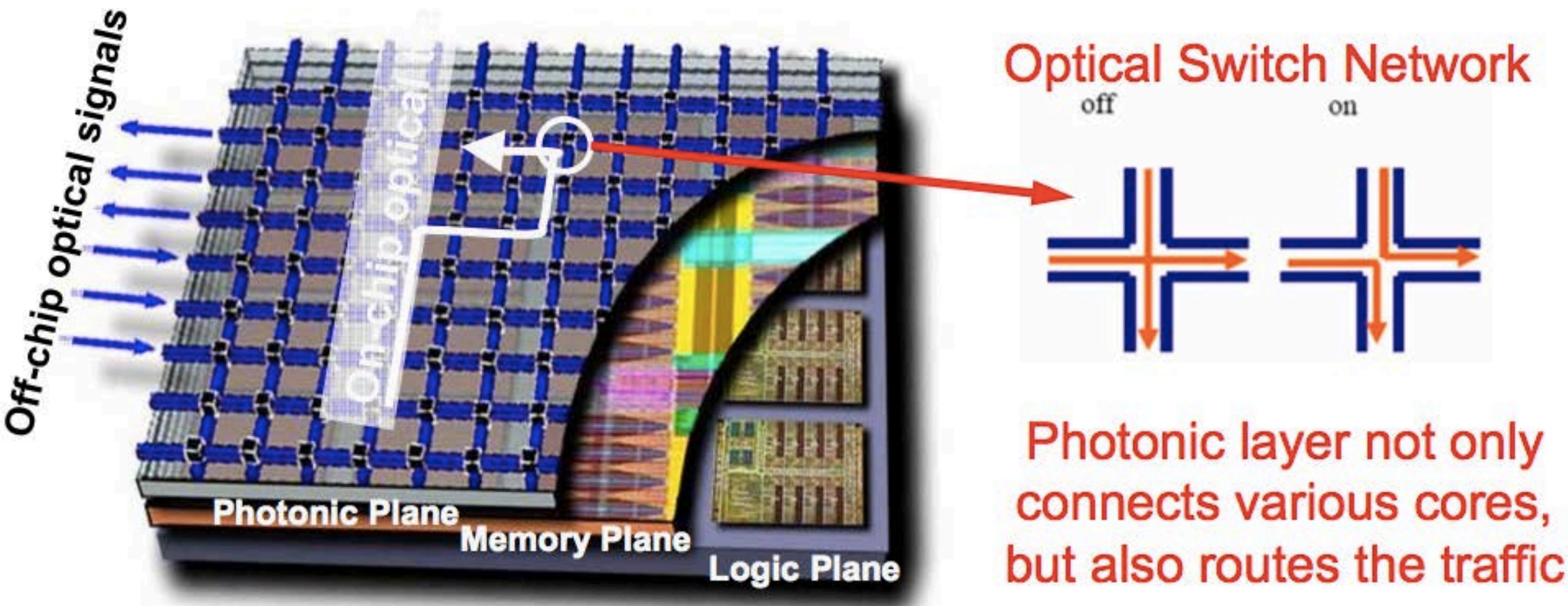
VOLUME 45, NUMBER 6 PHYSICAL REVIEW LETTERS 11 AUGUST 1980

New Method for High-Accuracy Determination of the Fine-Structure Constant Based on Quantized Hall Resistance

K. v. Klitzing
Physikalisches Institut der Universität Würzburg, D-8700 Würzburg, Federal Republic of Germany, and Hochfeld-Magnetlabor des Max-Planck-Instituts für Festkörperforschung, F-38042 Grenoble, France

uncommongoods.com

Motivation: bring topological robustness into photonics

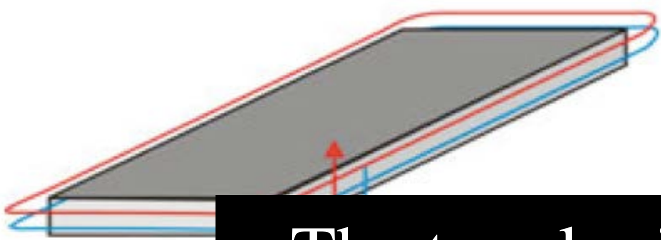


Dr. Gary Patton, IBM: “Innovations for Next Generation Scaling” Industry Strategy Symposium, Napa, CA, Jan 15, 2013

What are topological insulators?

- Topological insulators are insulators in the bulk but metallic on the edges.

- Most importantly: the edge states are scatter-free!



Kane and Mele, Phys. Rev. Lett. 95, 226801 (2005)

Hughes et al., Science 314, 5806, 1757-1761 (2006)

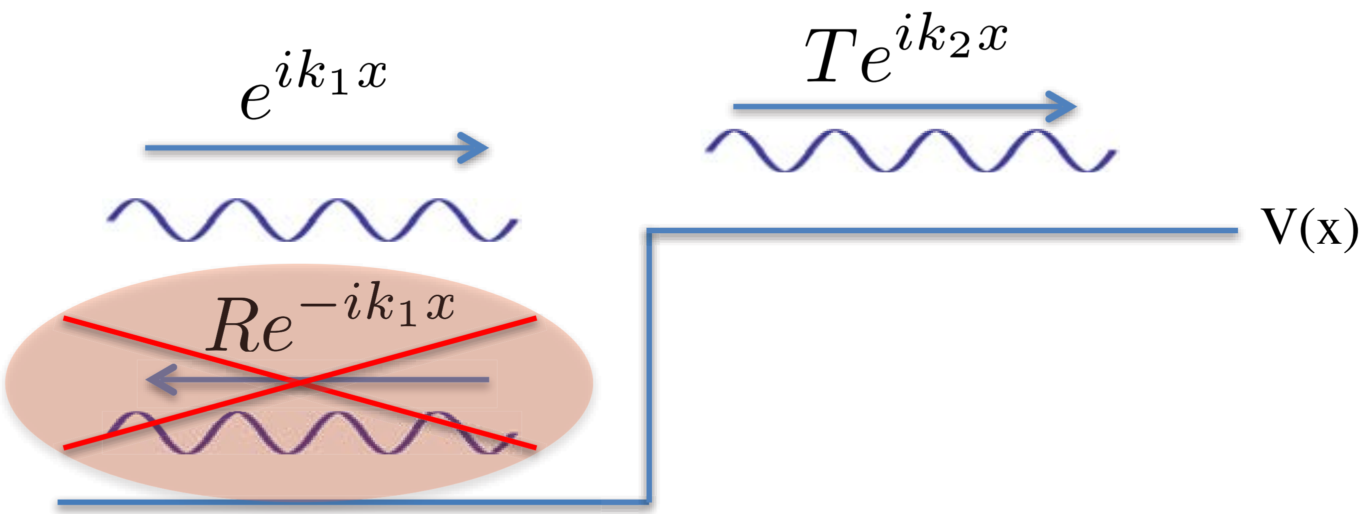
Hsieh et al., Nature 452, 970-974 (2008)

(2009)

09)

The topological robustness arises from the edge states

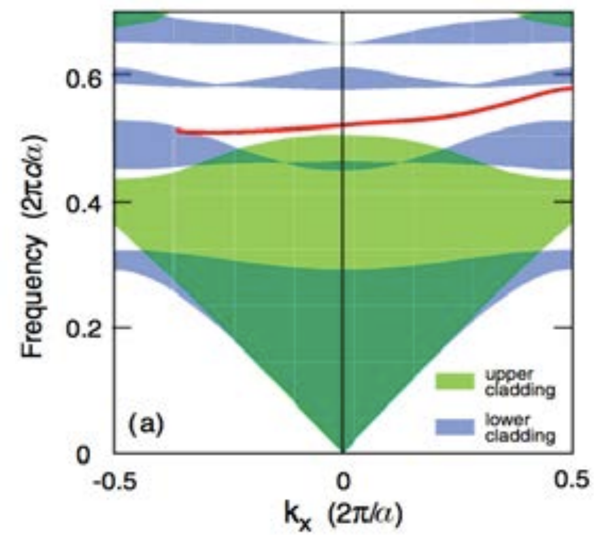
- Why?



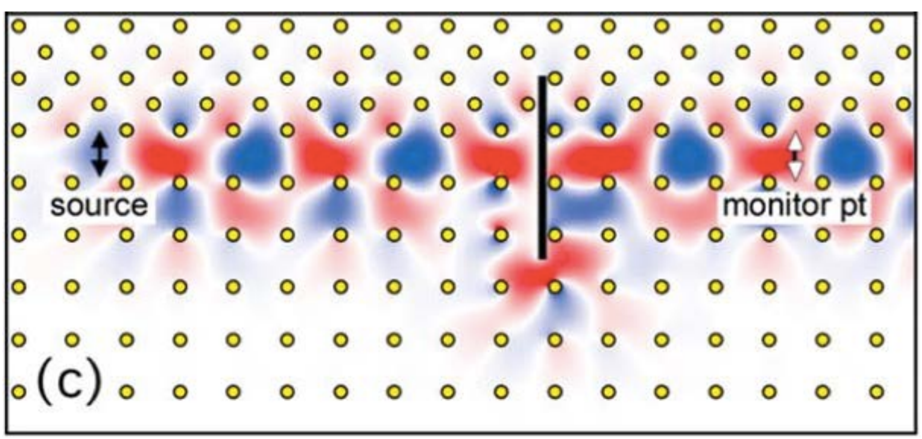
M. Soljacic's microwave experiment: 2009

Raghu and Haldane, 2008

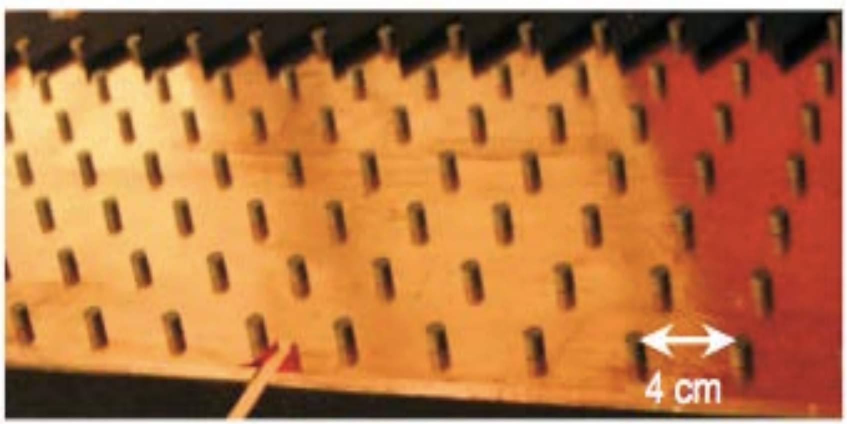
$$\tilde{\mu} = \begin{pmatrix} \mu_1 & i\mu_2 & 0 \\ -i\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_1 \end{pmatrix}$$



Wang et. al., PRL (2008)



Wang et. al., Nature (2009)



Magnetism in photonics

The big question:
How can we strongly break time-reversal symmetry in optics?

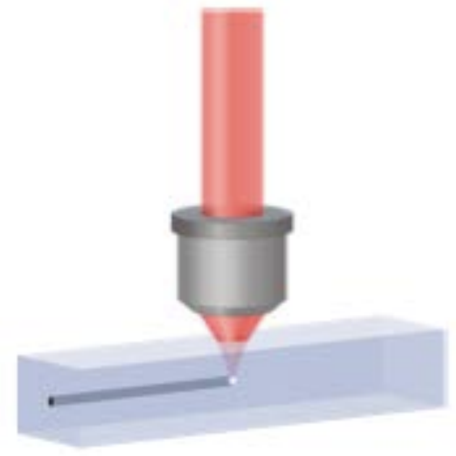

Thus there is ... cal frequencies
onward, and in ... ish between **B**
and **H** in this fr... ame is true for

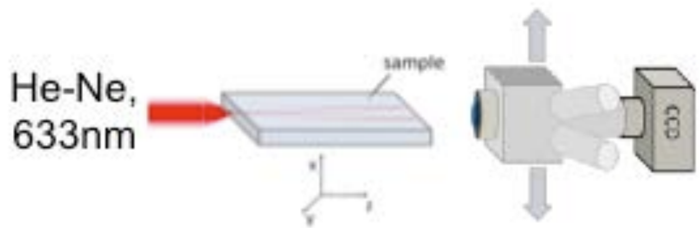
Magnetic response is inherently weak at optical frequencies

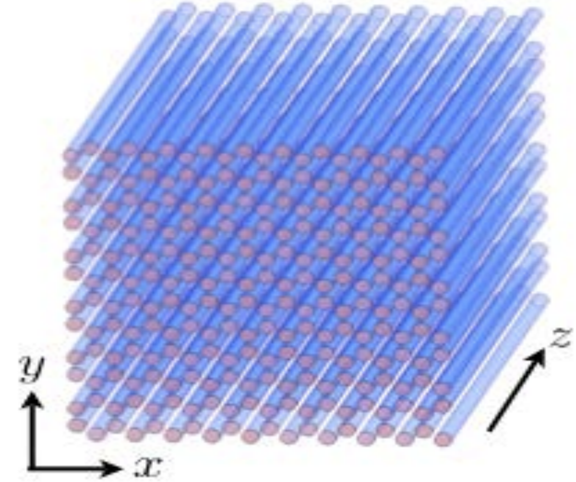
(1) Hafezi, Demler, Lukin, Taylor, Nature Phys. (2011): CROWS [+ Nature Photon. (2013)]
(2) Umucalilar and Carusotto, PRA (2011): using spin as polarization in PCs
(3) Fang, Yu, Fan, Nature Photon. (2012): electrical modulation of refractive index in PCs
(4) Khanikev et. al. Nature Mat. (2012): birefringent metamaterials [+ Nature Mater. (2016)]

Experimental system: photonic lattices

Array of coupled waveguides







Peleg et. al., PRL (2007)

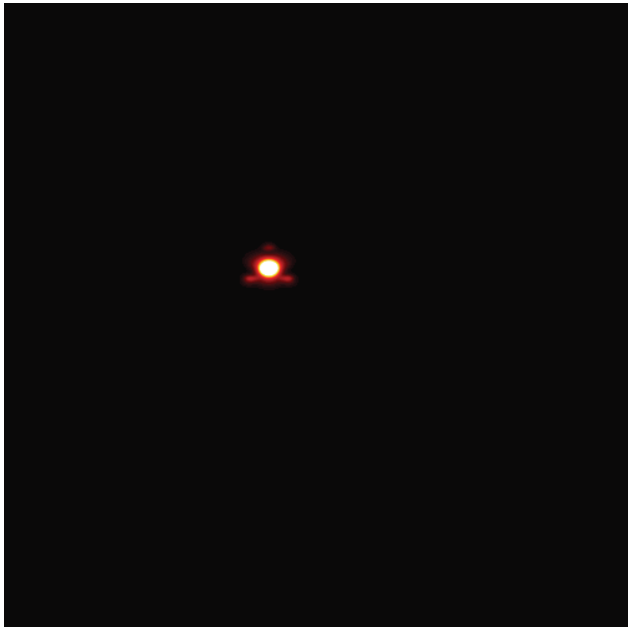
Envelope approximation for electric field:

$$\mathbf{E}(x, y, z) = \hat{x}\psi(x, y, z)e^{i(k_0 z - \omega t)}$$

$$|\partial_z^2 \psi| \ll 2k|\partial_z \psi|$$

Paraxial Schrödinger equation:

$$i\partial_z \psi = -\frac{1}{2k}\nabla^2 \psi - \frac{k}{n_0}\Delta n(x, y, \mathbf{z})\psi$$



Derivation of paraxial approximation

Maxwell $$\nabla \times \nabla \times \mathbf{E} = \varepsilon(x, y, z) \left(\frac{\omega}{c}\right)^2 \mathbf{E}$$

id. $$\nabla \times \nabla \times \mathbf{E} = -\nabla^2 \mathbf{E} + \nabla \left(\nabla \cdot \mathbf{E}\right)$$

Maxwell $$\nabla \cdot (\varepsilon \mathbf{E}) = \nabla \varepsilon \cdot \mathbf{E} + \varepsilon \nabla \cdot \mathbf{E} = 0$$

$$\nabla \cdot \mathbf{E} = -\frac{\nabla \varepsilon \cdot \mathbf{E}}{\varepsilon} = -\nabla \ln \varepsilon \cdot \mathbf{E}$$

$$-\nabla^2 \mathbf{E} - \nabla \left(\nabla \ln \varepsilon \cdot \mathbf{E}\right) = \varepsilon(x, y, z) \left(\frac{\omega}{c}\right)^2 \mathbf{E}$$

Derivation of paraxial approximation

$$-\nabla^2 \mathbf{E} = \varepsilon(x, y, z) \left(\frac{\omega}{c}\right)^2 \mathbf{E}$$

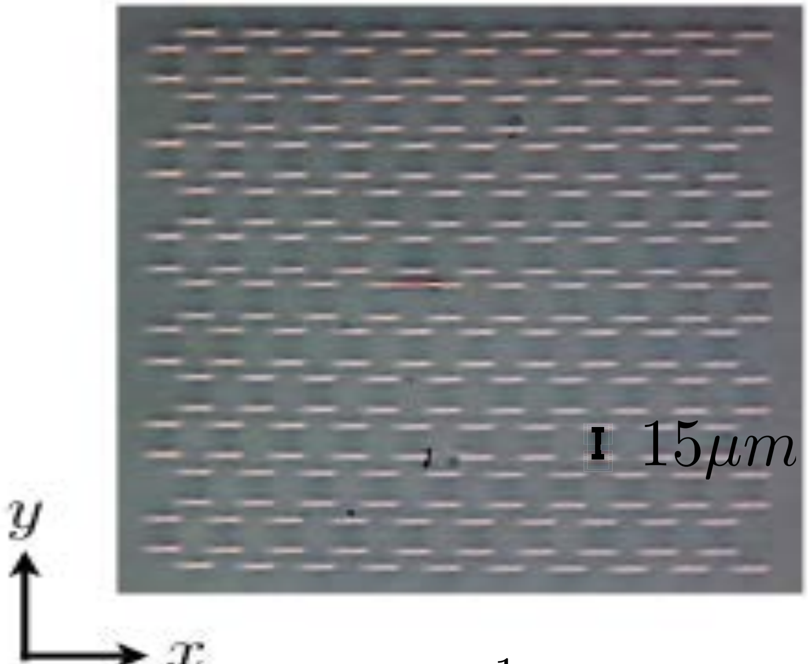
envelope approx: $\mathbf{E} = \psi(x, y, z) e^{ik_0 z} \hat{x}$ (with $k_0 = \sqrt{\epsilon_1}\omega/c$)

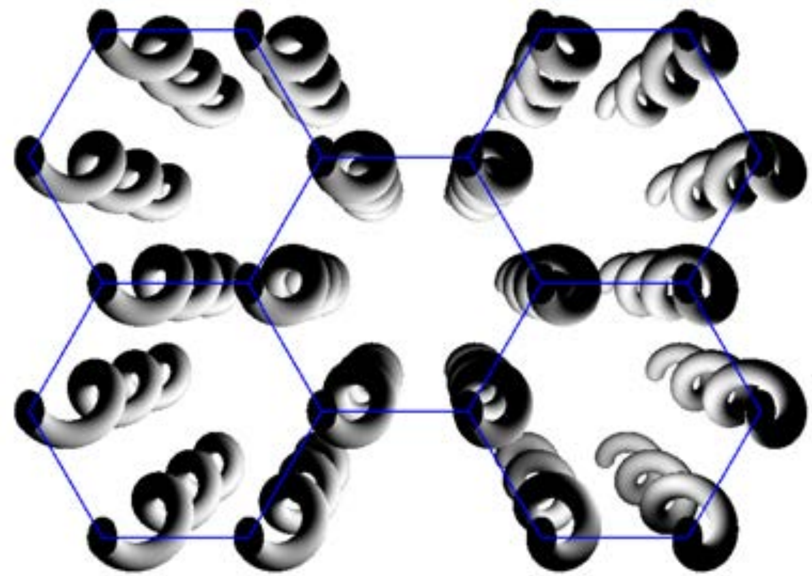
$$\underbrace{-(\partial_x^2 + \partial_y^2)\psi}_{\nabla_\perp^2 \psi} - \underbrace{\partial_z^2 \psi}_{\to 0} - 2ik_0 \partial_z \psi + \underbrace{k_0^2 \psi = \varepsilon_1 \left(\frac{\omega}{c}\right)^2 \psi}_{0} + \Delta\varepsilon(x, y, z) \left(\frac{\omega}{c}\right)^2$$

$$i\partial_z \psi = -\frac{1}{2k_0} \nabla_\perp^2 \psi - \frac{k_0}{2} \Delta\varepsilon(x, y, z)$$

$$i\partial_z \psi = -\frac{1}{2k_0} \nabla_\perp^2 \psi - \frac{k_0}{n_0} \Delta n(x, y, z)$$

Helical rotation induces a gauge field





$$i\partial_z\psi = \frac{1}{2k_0}\left(i\nabla + \mathbf{A}(z)\right)^2\psi - \frac{k_0\Delta n(x,y)}{n_0}\psi - \frac{k_0 R^2\Omega^2}{2}\psi$$

$$A(z) = k_0 R\Omega(\sin\Omega z, \cos\Omega z)$$

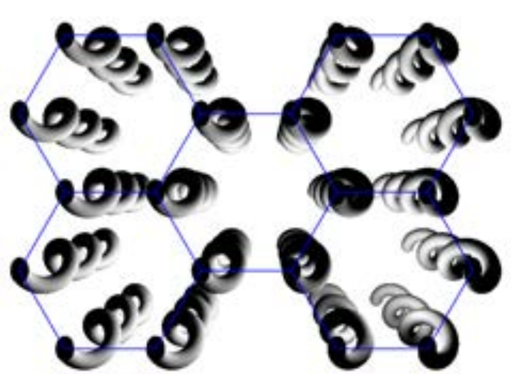
$$\boxed{\begin{aligned} x' &= x + R\cos\Omega z \\ y' &= y + R\sin\Omega z \\ z' &= z \end{aligned}}$$

$$\boxed{\mathcal{H}(z) = \sum_{m,\langle n\rangle} e^{i\mathbf{A}(z)\cdot\mathbf{r}_{mn}}\psi_n^\dagger\psi_m}$$

- Floquet TIs: Kitagawa et al., PRB (2010); Lindner et al., Nature Phys. (2011).

Gauge field through helicity

$$\boxed{\begin{aligned} x' &= x + R\cos\Omega z \\ y' &= y + R\sin\Omega z \\ z' &= z \end{aligned}}$$



$$\partial_z = \partial_z' - R\Omega\sin(\Omega z)\partial_x' + R\Omega\cos(\Omega z)\partial_y'$$

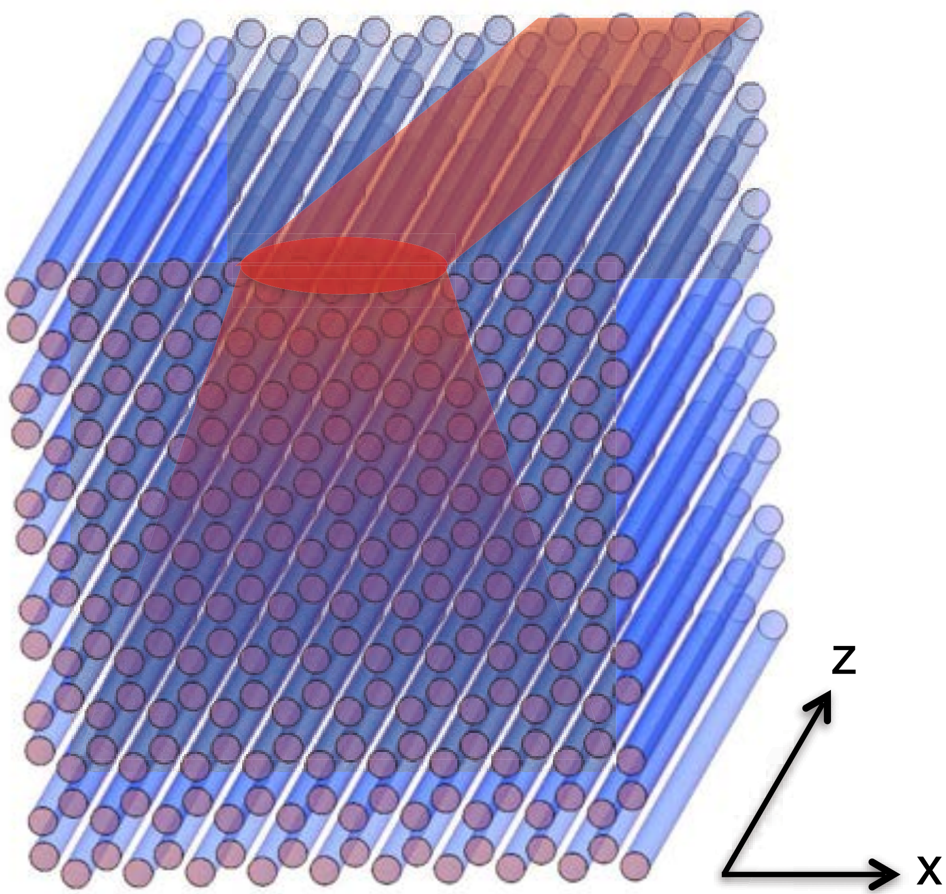
Complete the square

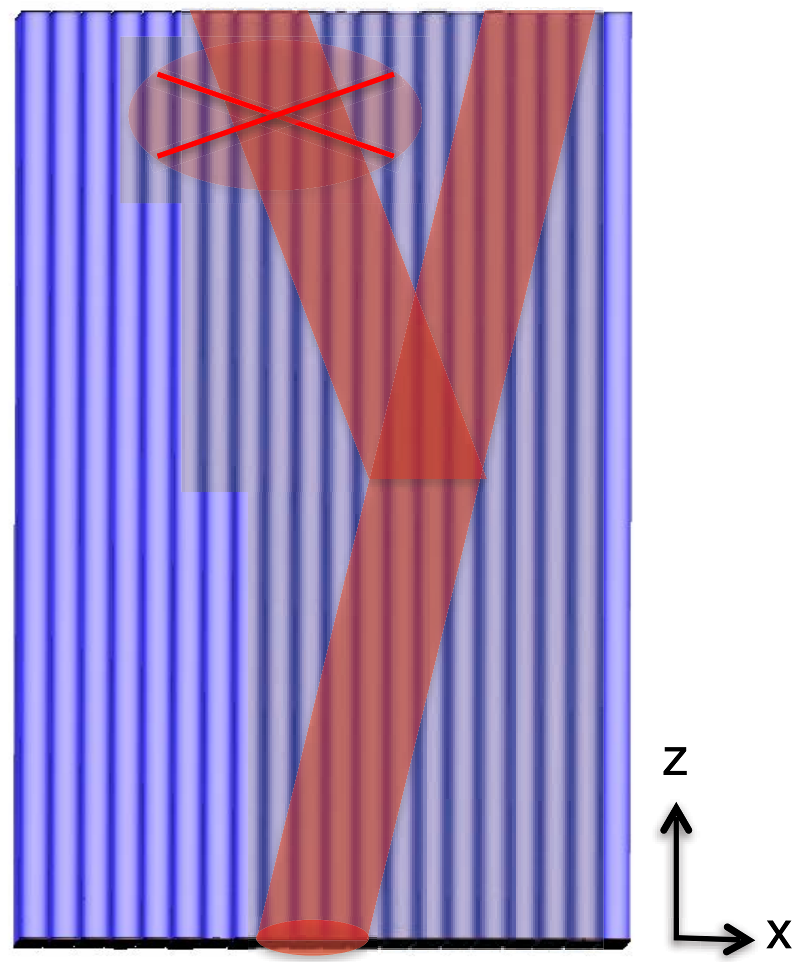
$$i\partial_z'\psi = \frac{1}{2k_0}\left(i\partial_\perp' - k_0 R\Omega(-\sin\Omega z, \cos\Omega z)\right)^2\psi - \frac{k_0 R^2\Omega^2}{2}\psi$$

$$\mathbf{A} = k_0 R\Omega\left(-\sin\Omega z, \cos\Omega z\right)$$

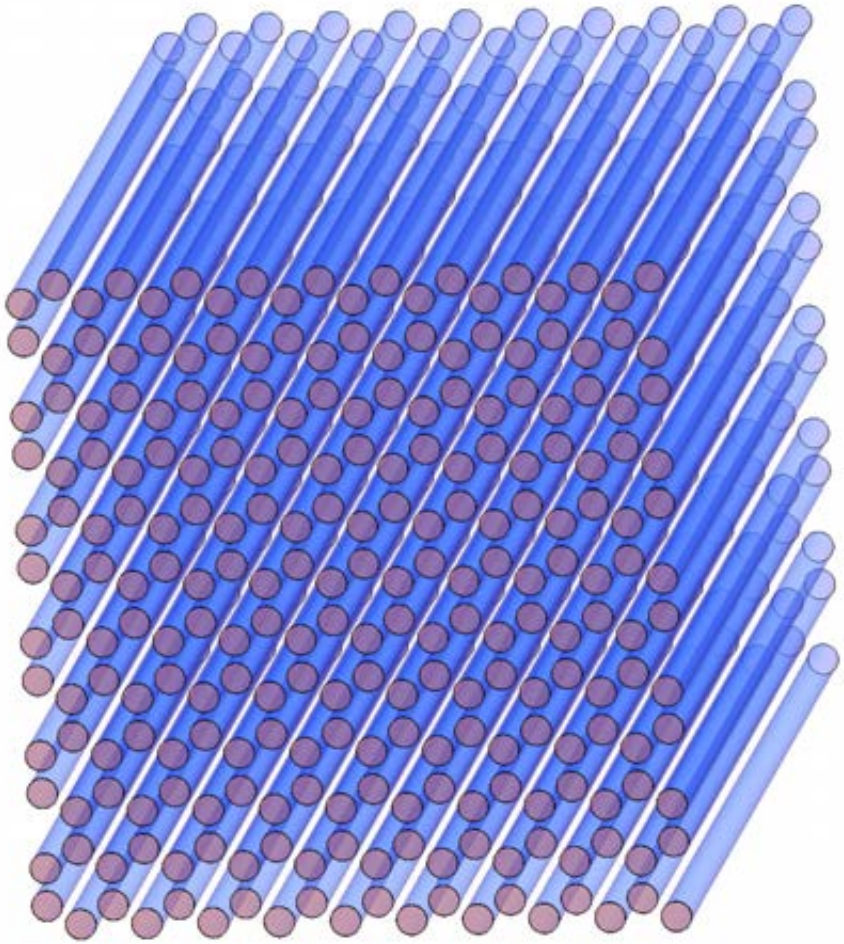
Experimental system: photonic lattices

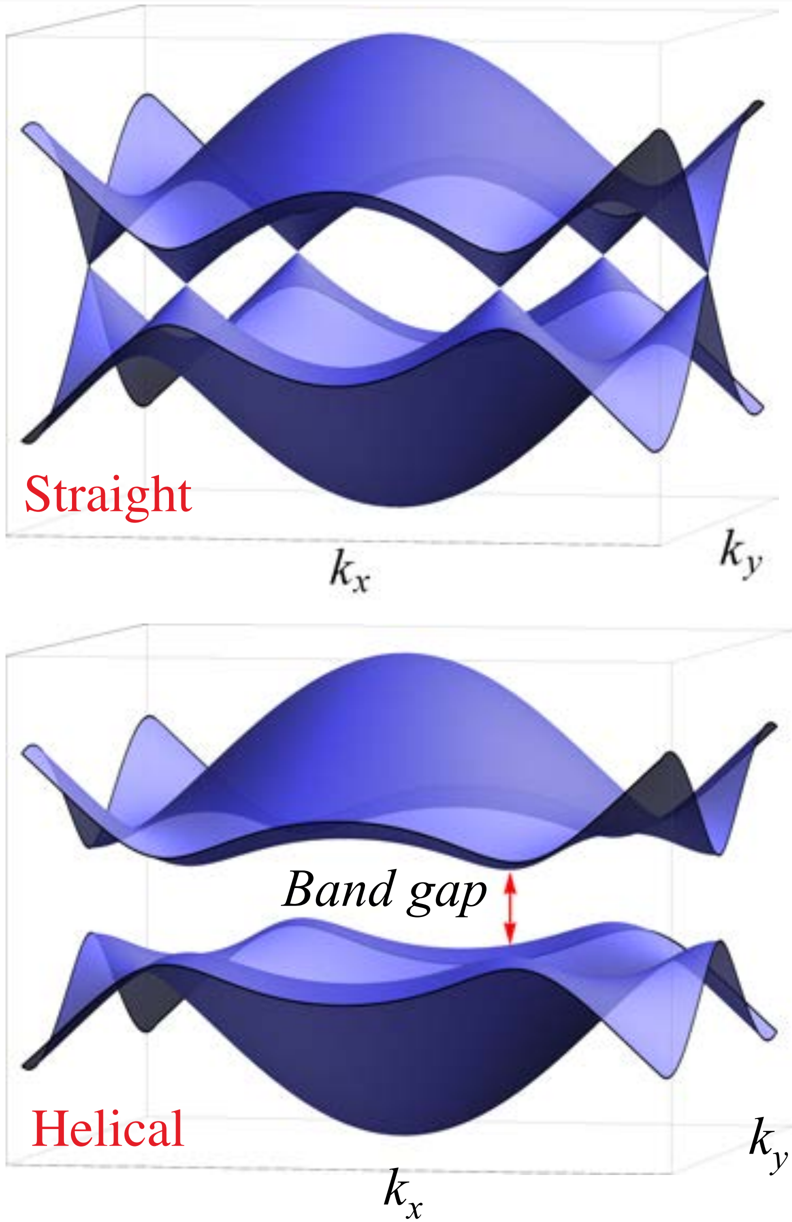
Our system: topological protection against transverse backscattering



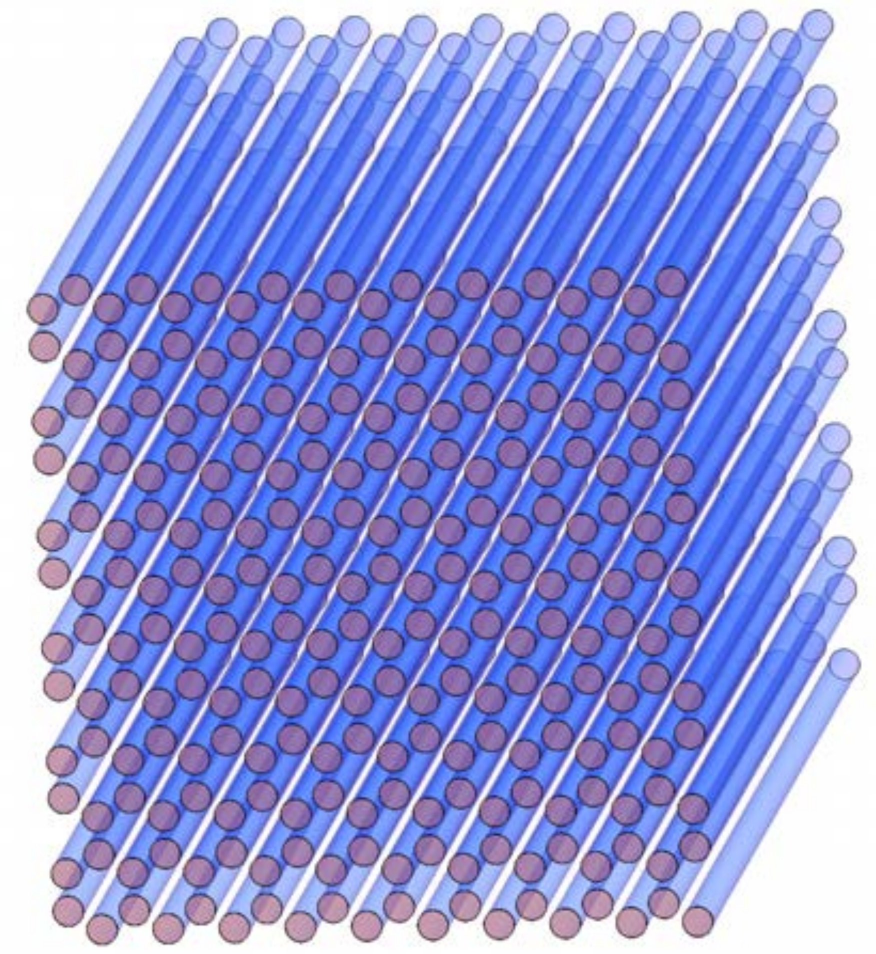


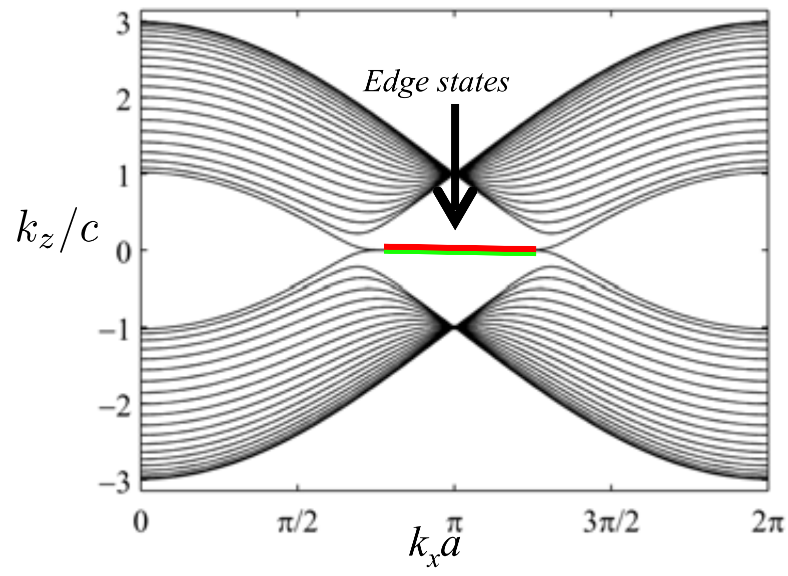
Graphene opens a Floquet gap for helical waveguides

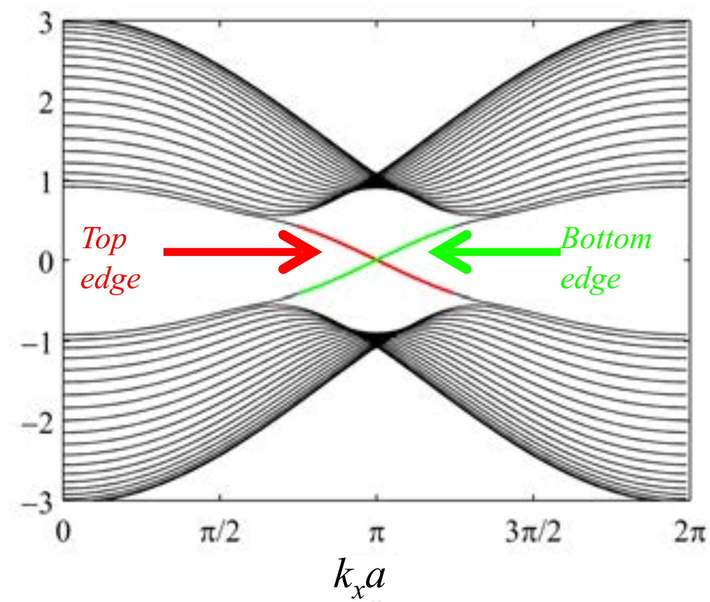




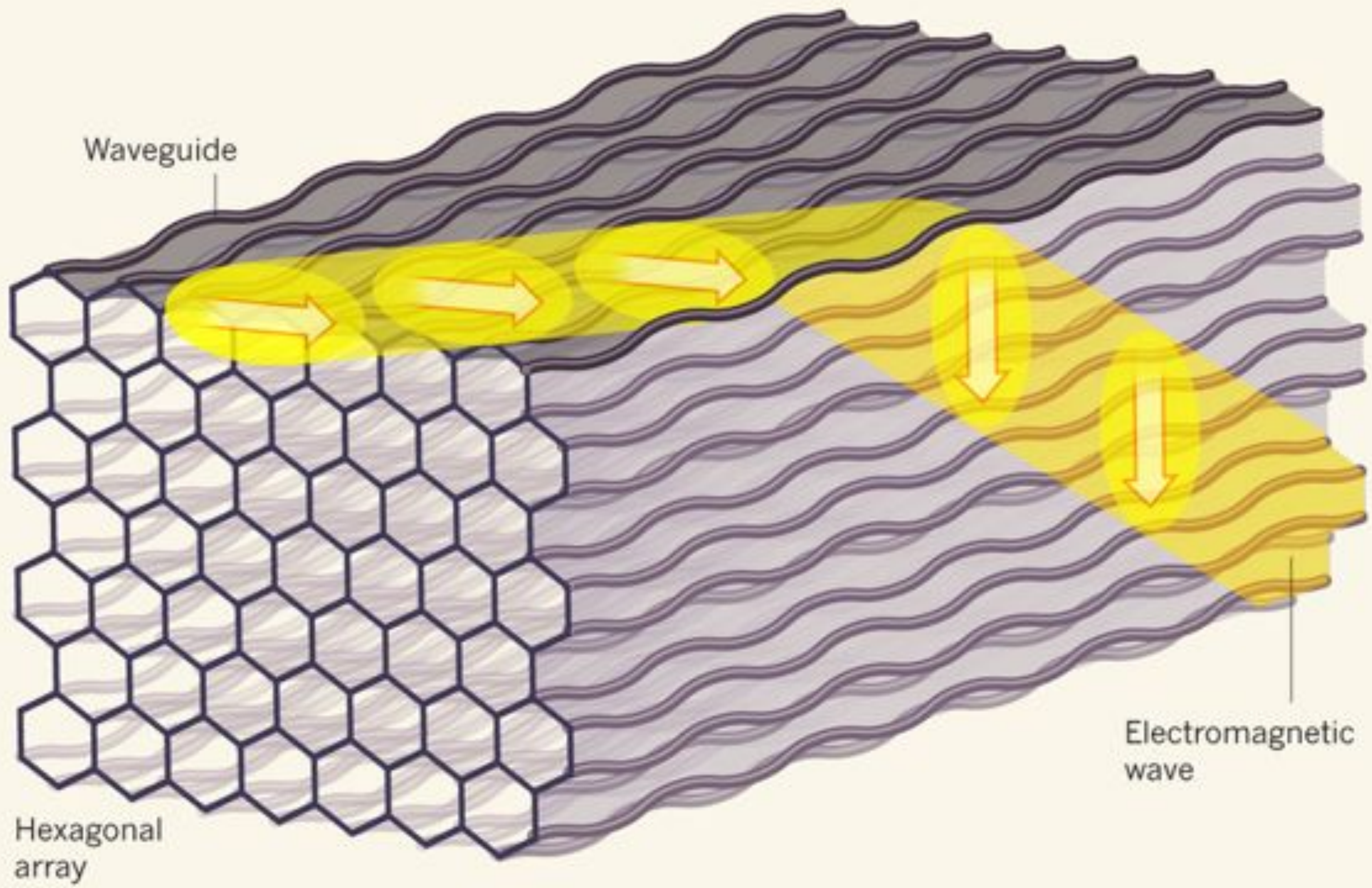
Graphene opens a Floquet gap for helical waveguides







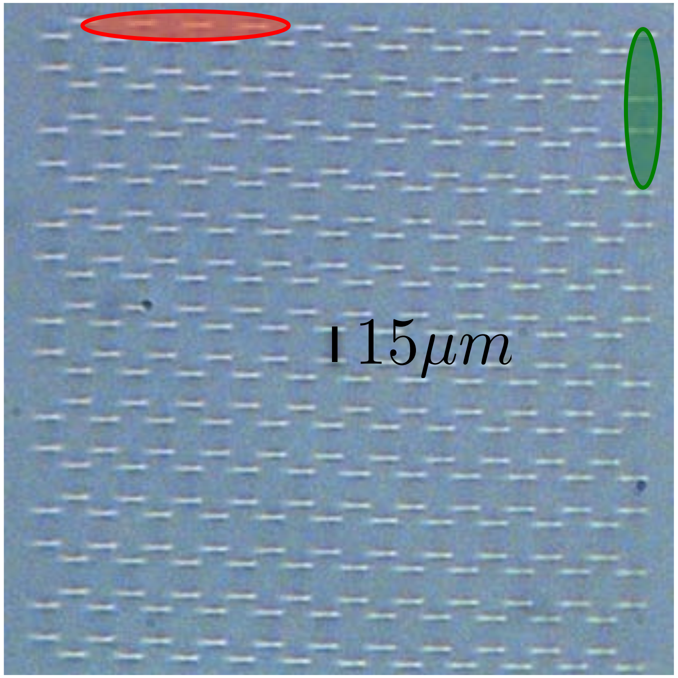
“Time”-domain continuous simulations

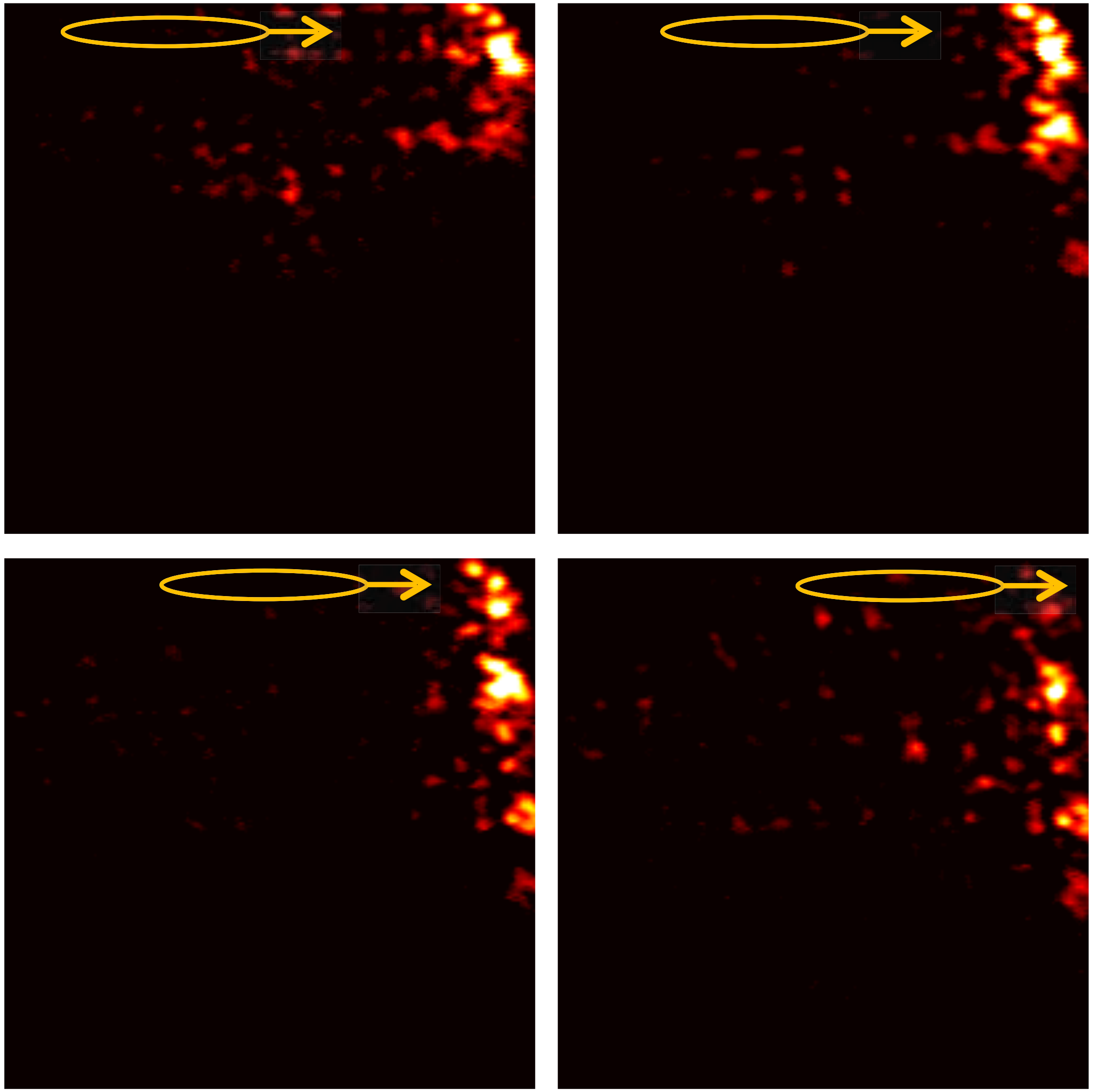


Y. Chong, “Photonic Insulators with a Twist” Nature News and Views, 496, 173-174 (2013)

Experimental results: rectangular arrays

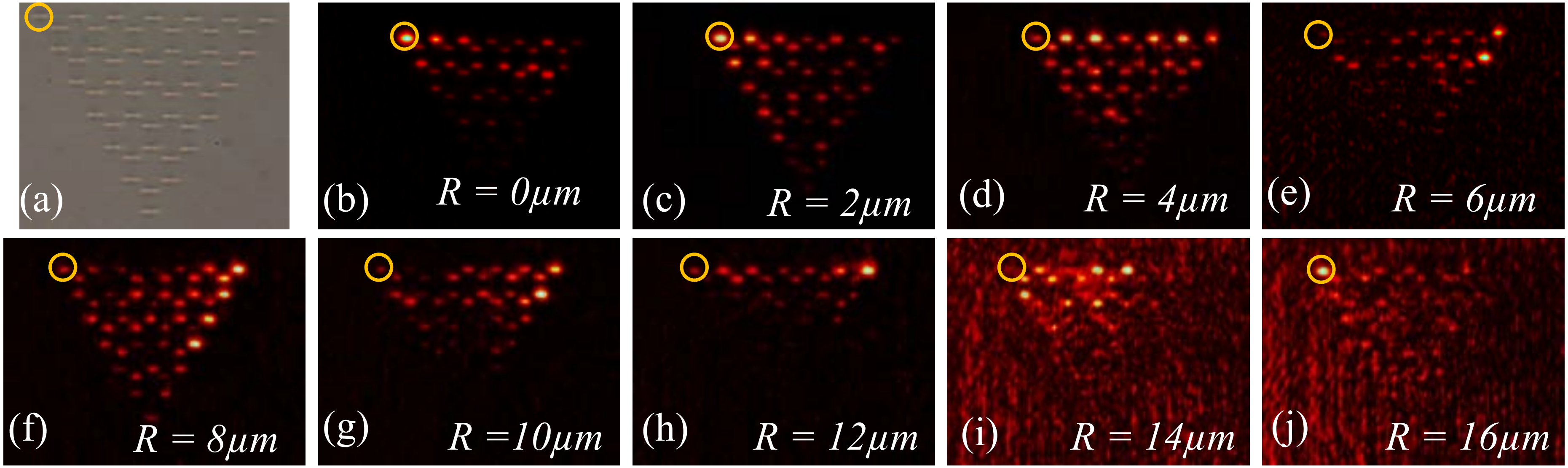
Microscope image

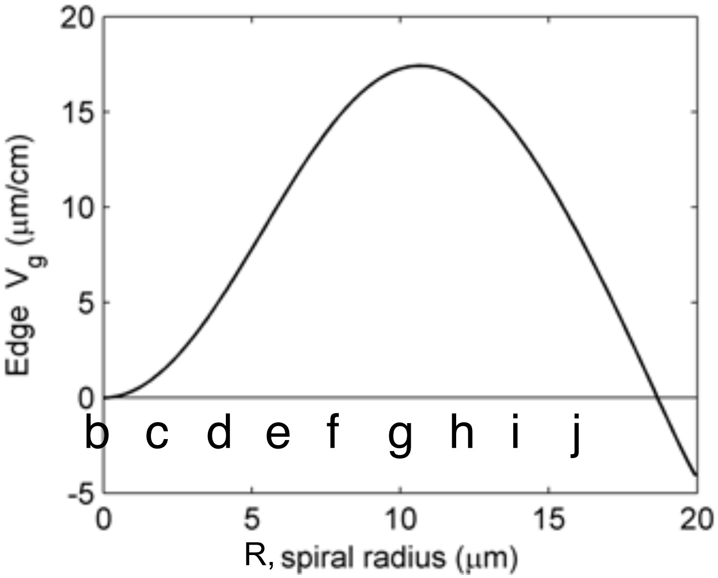




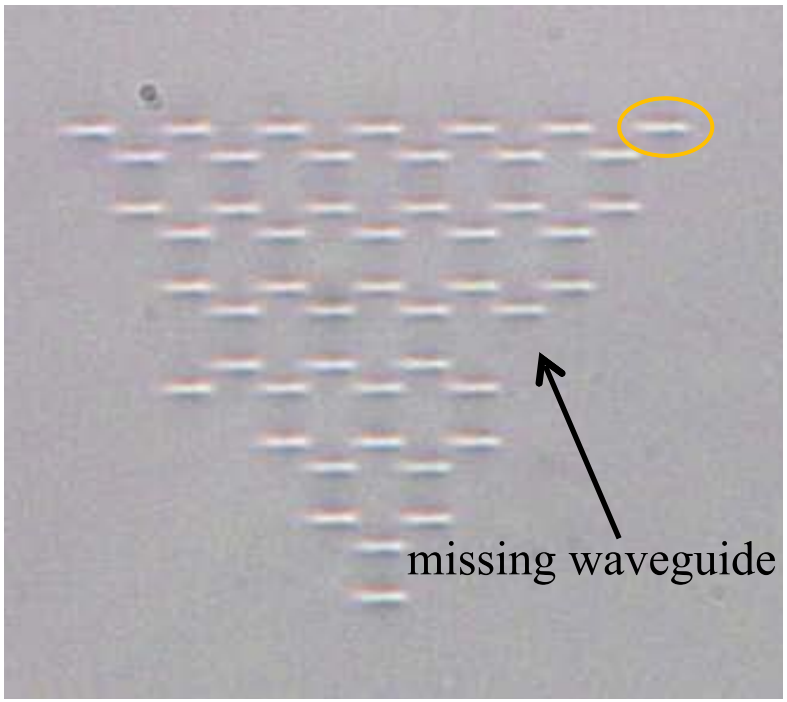
MCR et al., Nature 496, 196-200 (2013)

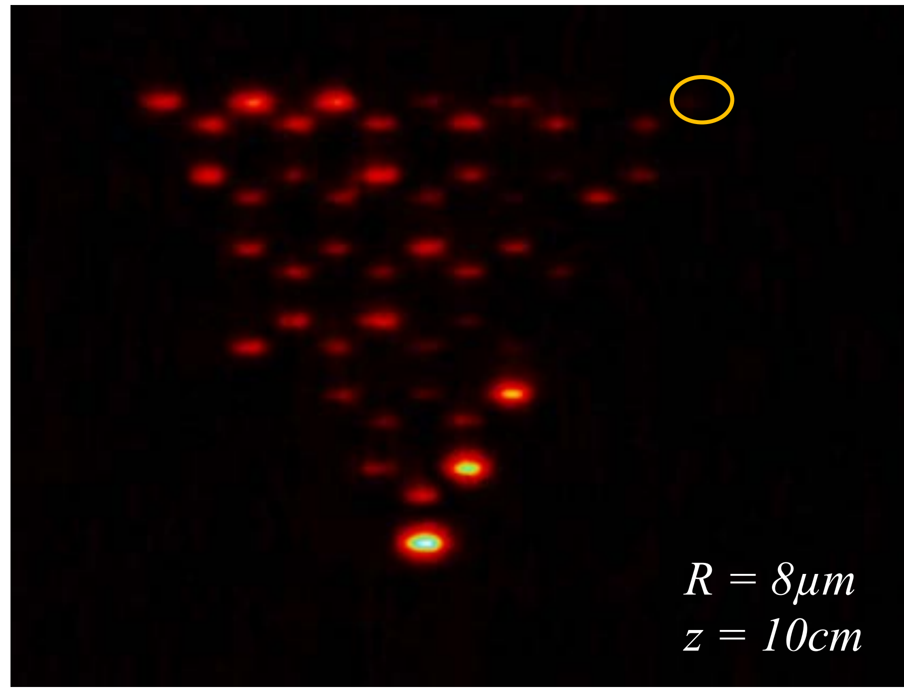
Experimental results: group velocity vs. helix radius, R



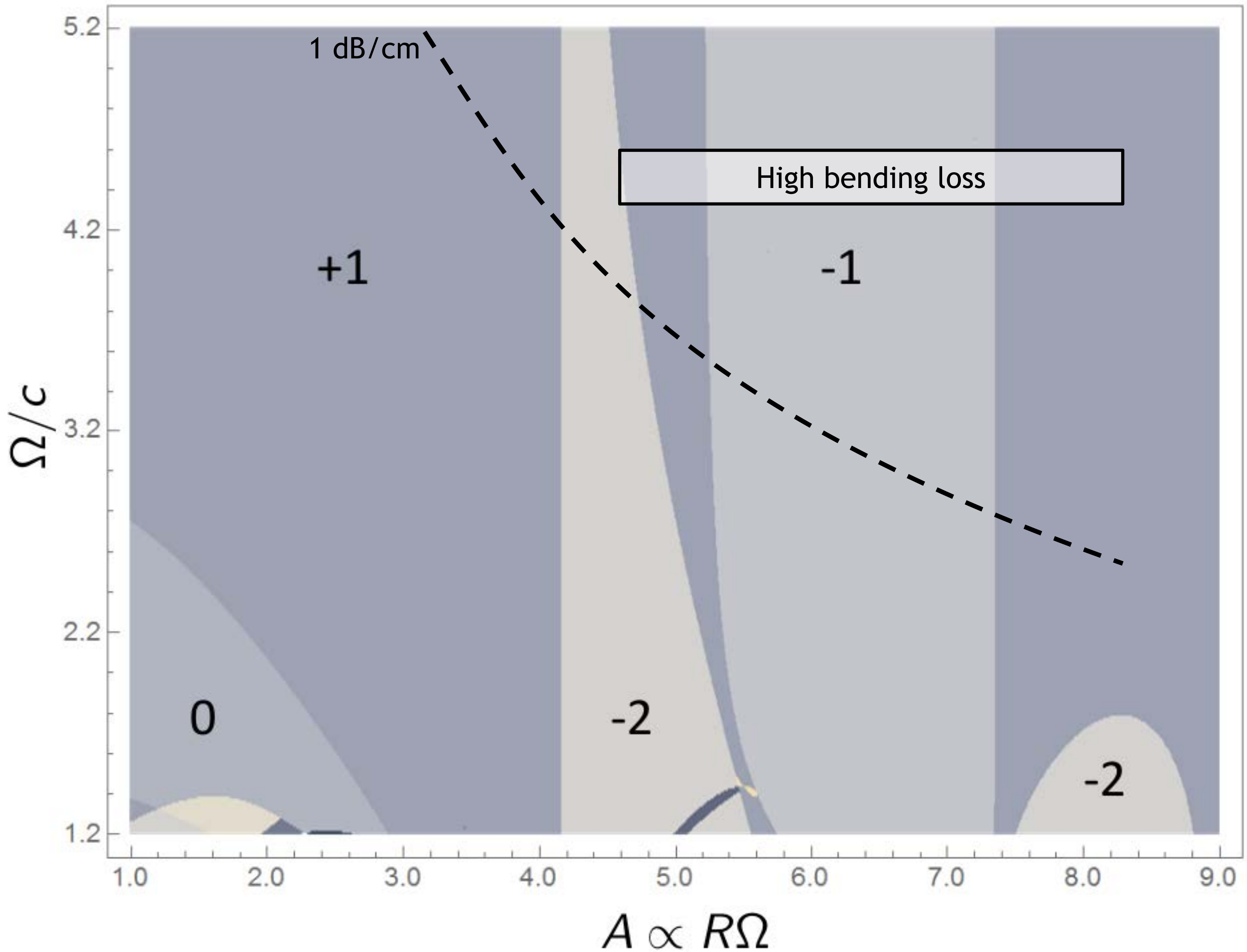


Experimental results: triangular arrays with defects





Observation of a topological transition

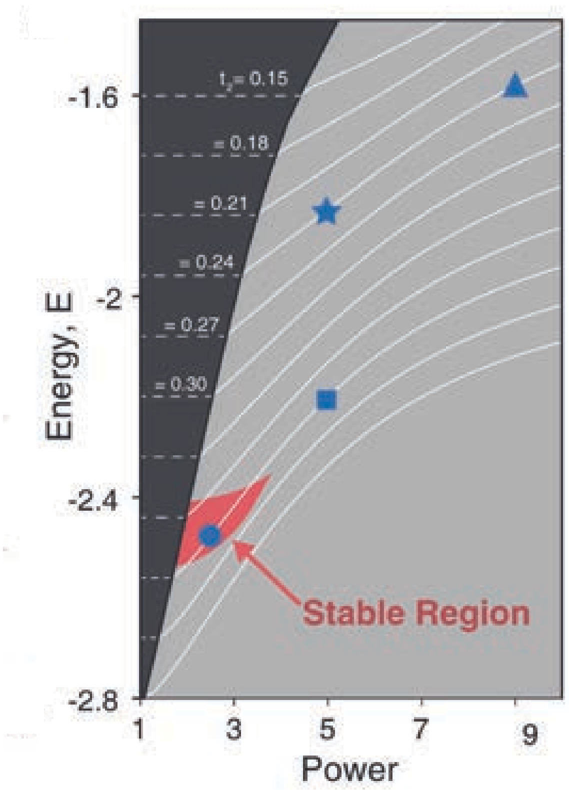


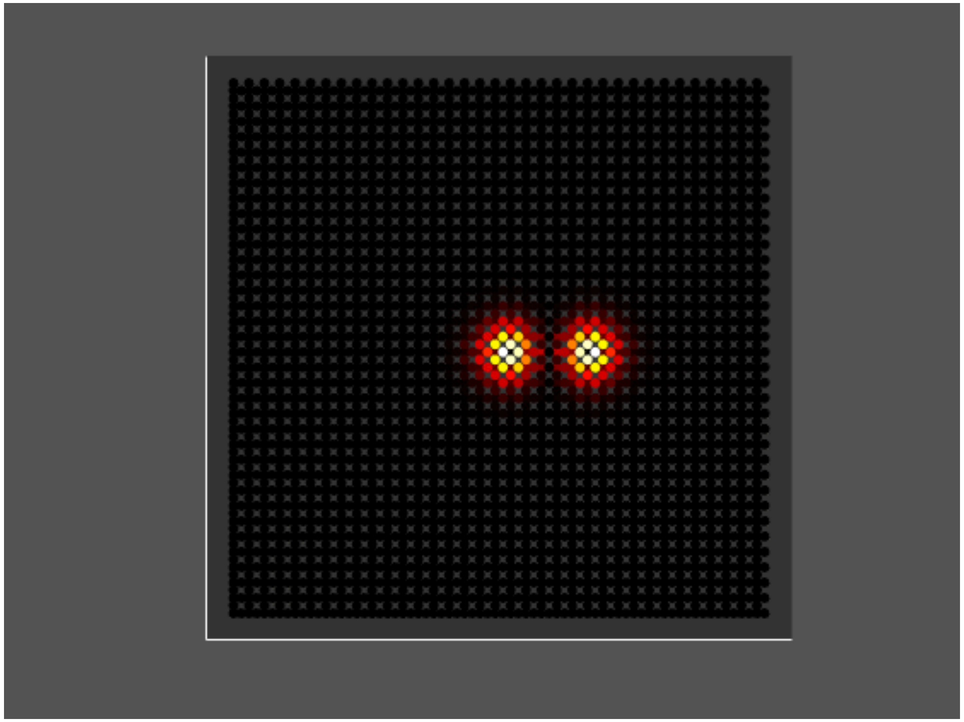
Guglielmon et al., Phys. Rev. A **97**, 031801 (2018)

Interactions/nonlinearity: topological solitons

$$i\partial_z \psi = H_T \psi - |\psi|^2 \psi$$

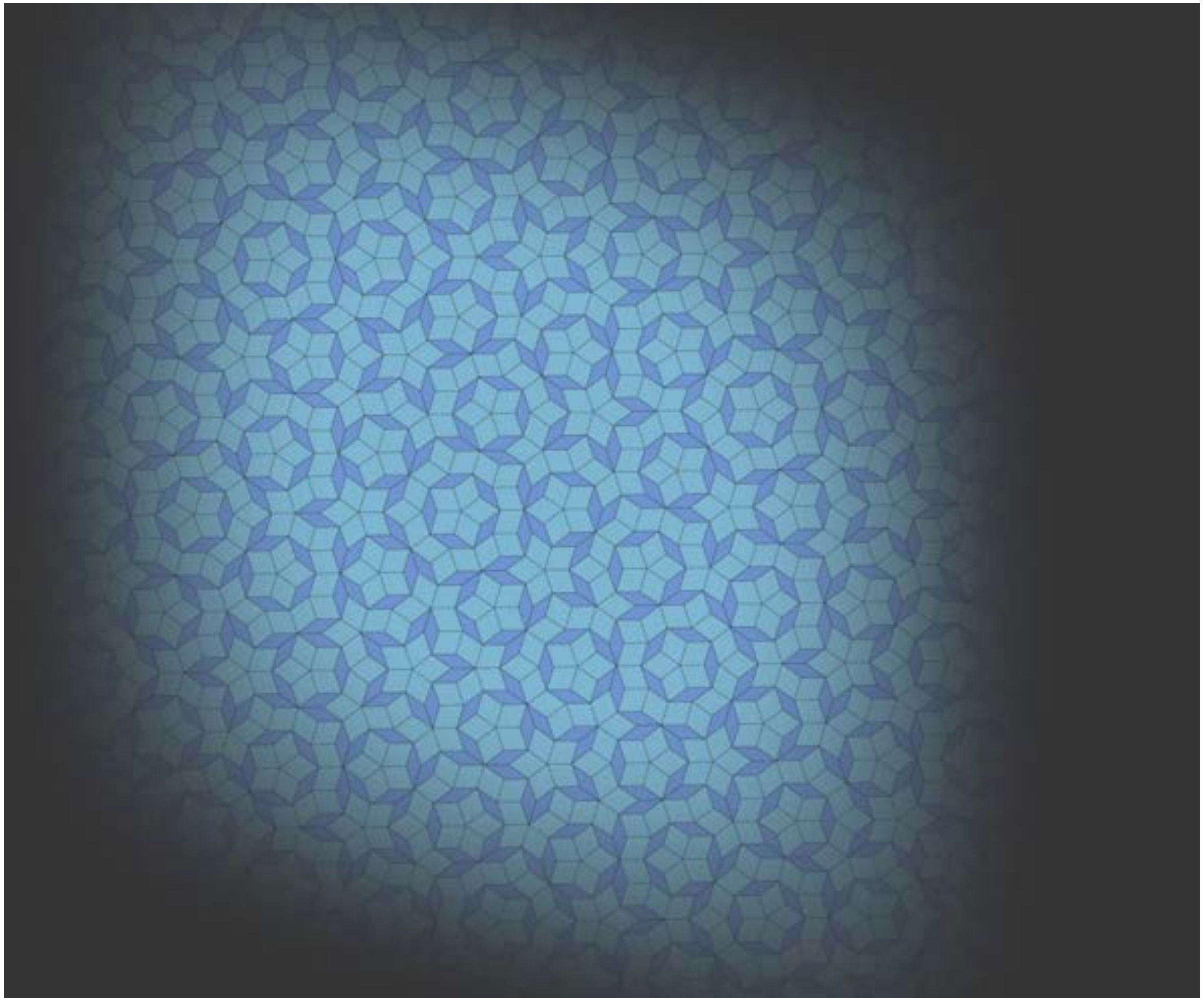
Superfluid like…





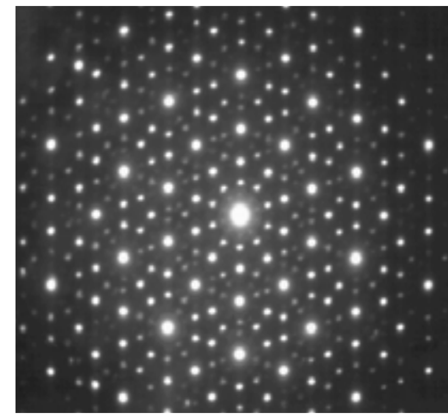
Topological Quasicrystals

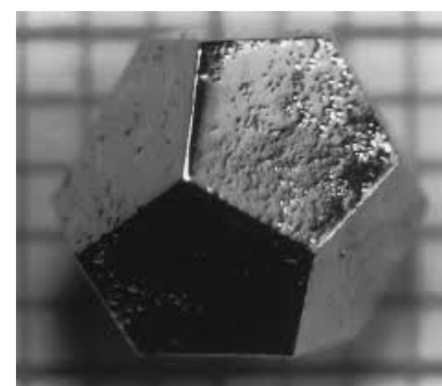
What are quasicrystals?



Dan Shechtman

Nobel Prize
2011





Why study (photonic) quasicrystals?

- Fundamentally interesting: between disorder and periodicity; no k, no Bloch's theorem, rethink the nature of wave physics.

  Chan et al., *Phys. Rev. Lett.* **80,** 956-959 (1998); Tanese et al., PRL 112, 146404 (2014) .

- Isotropic "Brillouin zone" means larger 2d gaps for low $\varepsilon_2/\varepsilon_1$.

  Rechtsman et al., *Phys. Rev. Lett.* **101,** 073902 (2008).

- Open question: do 3d photonic QCs have band gaps?

  Man et al., *Nature* **436,** 993-996 (2005).

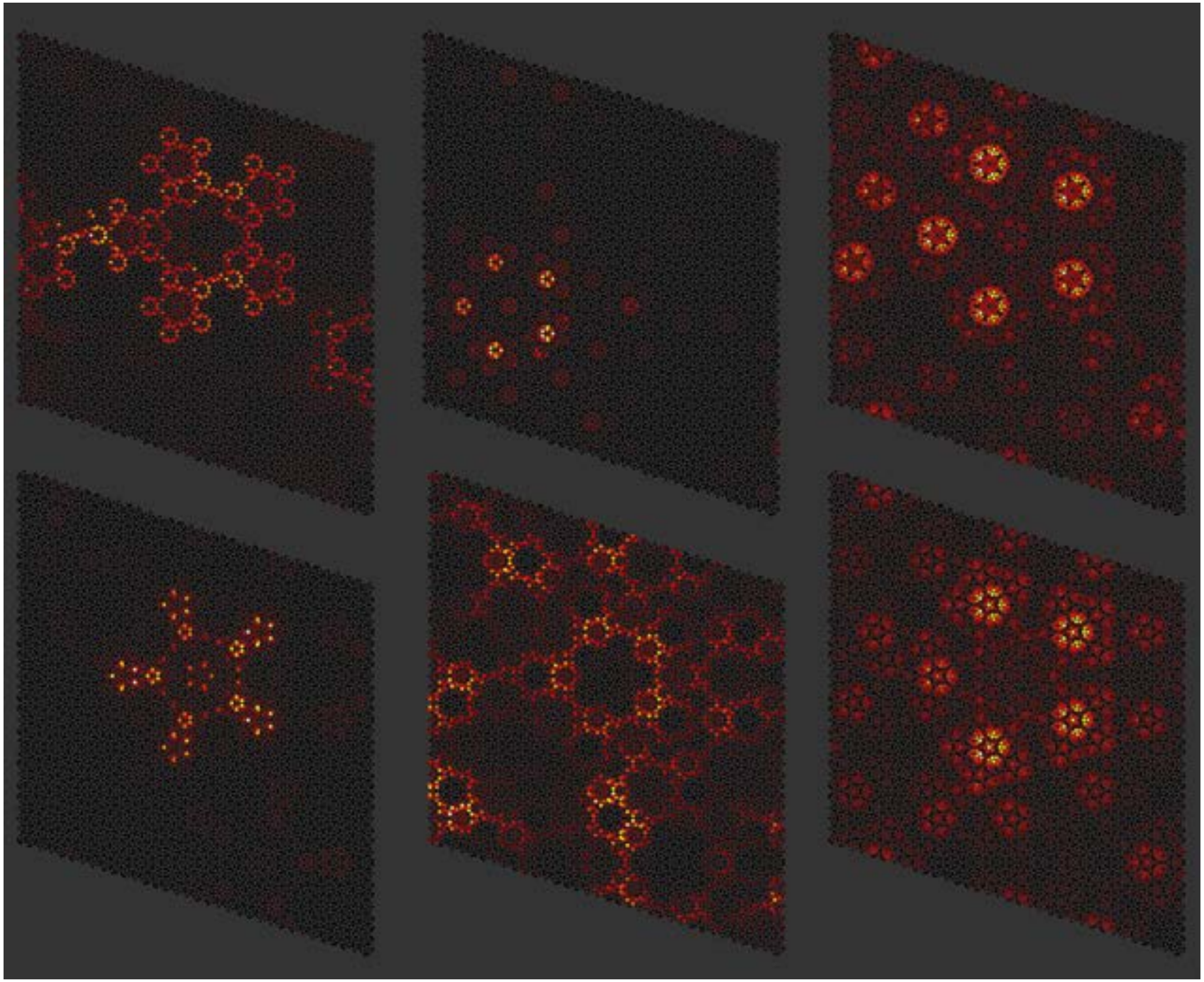
- Novel nonlinear behavior.

  Freedman, B. *et al. Nature* **440,** 1166-1169 (2006).

- Surprising effects, e.g., disorder-enhanced transport.

  Levi et al., Science 332, 1541 –1544 (2011).

Quasicrystal bulk states

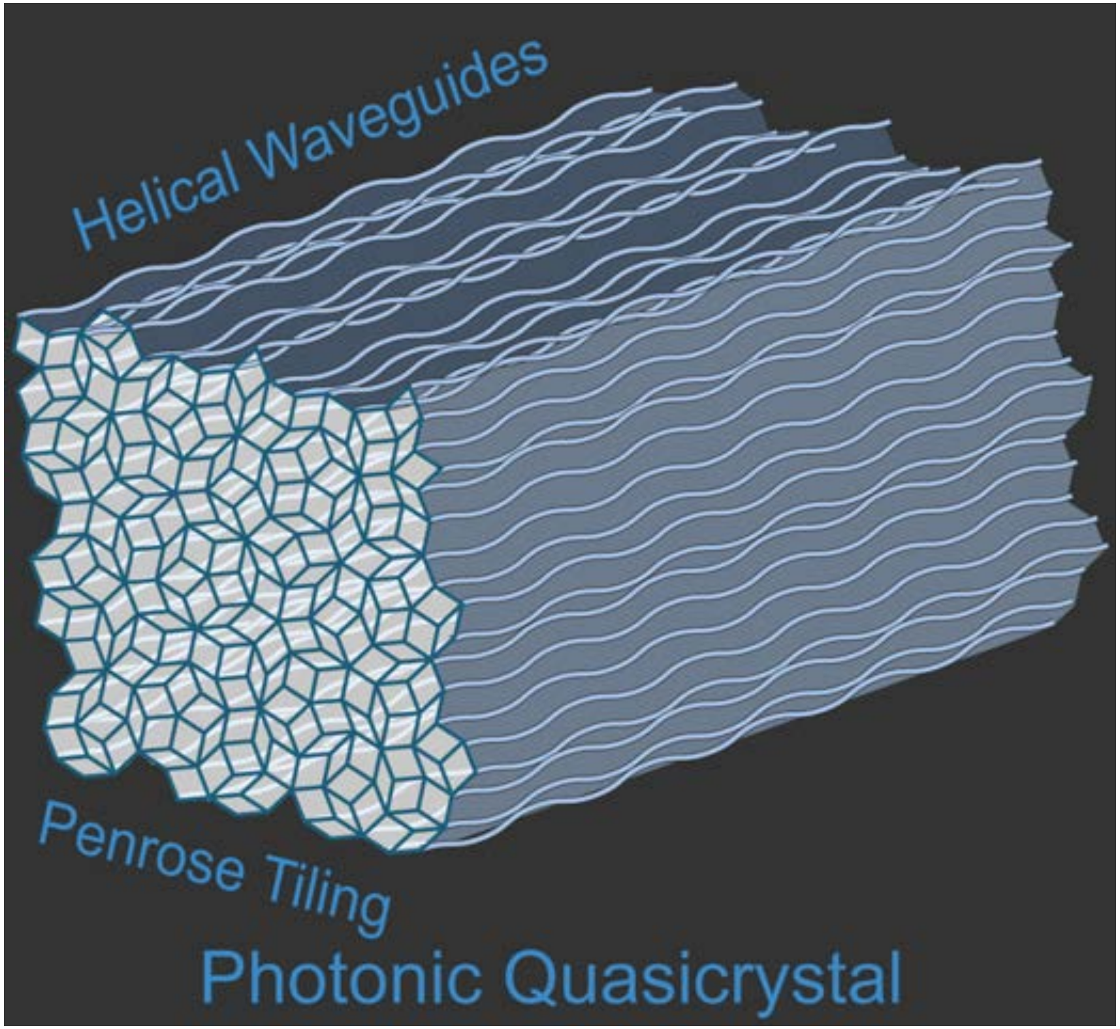


Fractal states

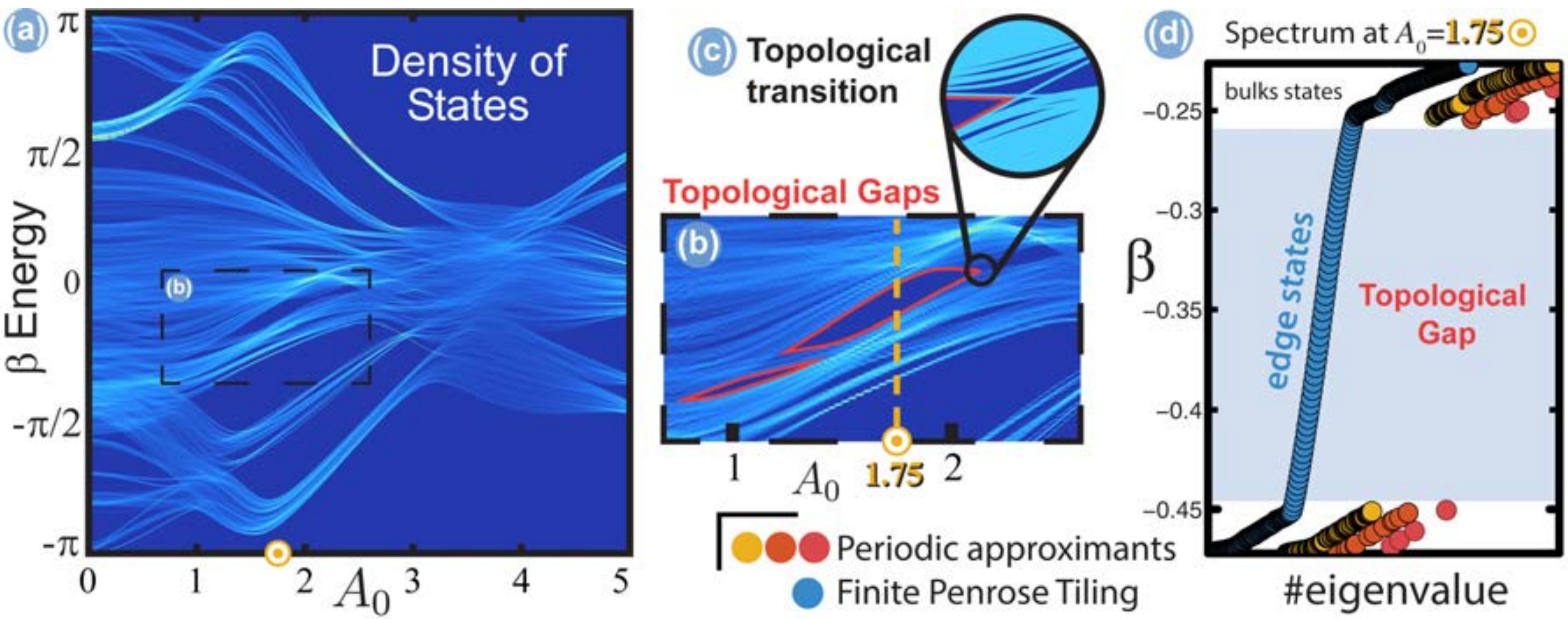
$$\psi \sim \frac{1}{r^n}$$

… strange transport properties

What happens in a Floquet'ed quasicrystal?



Topological gaps!

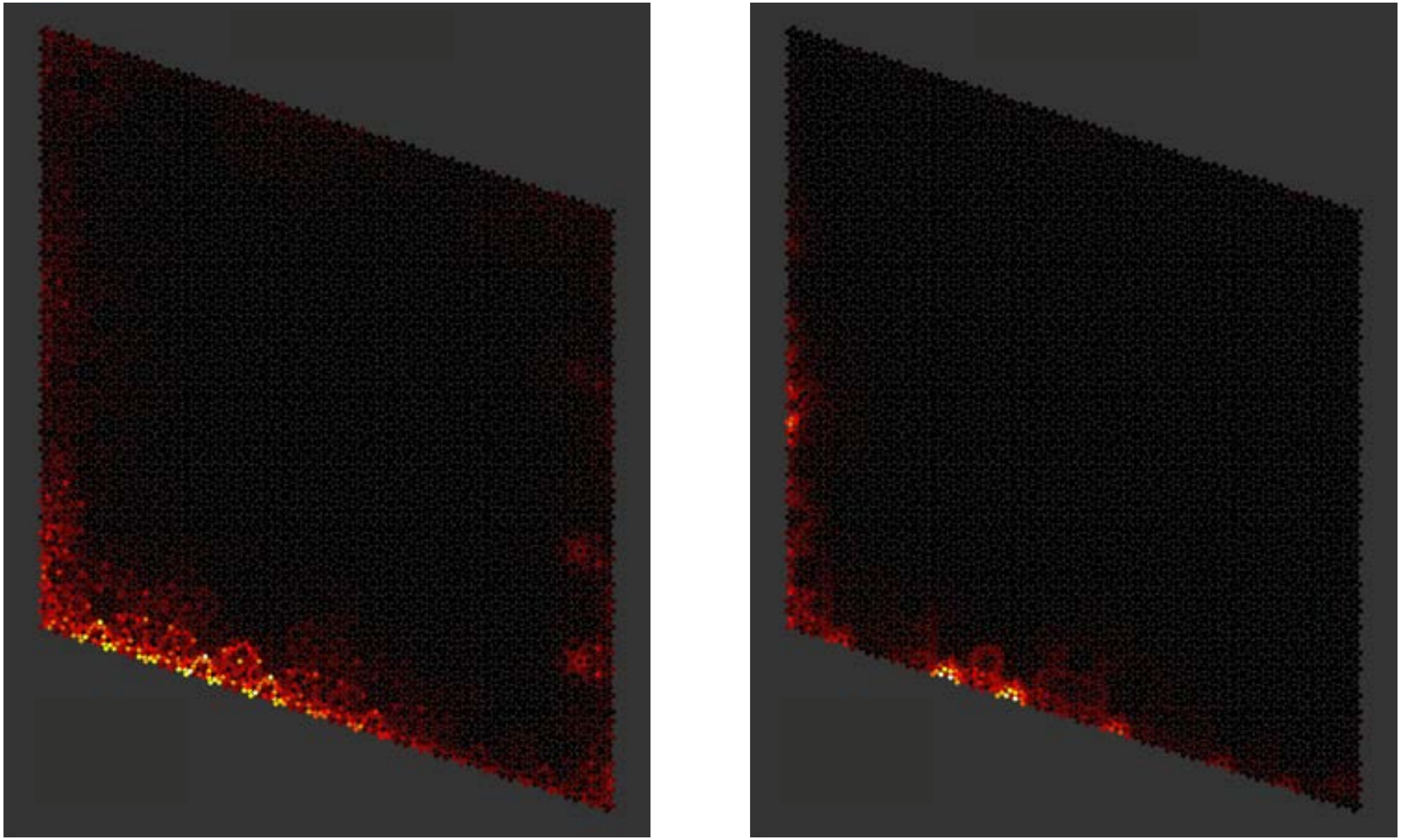


This is a quantum anomalous Hall effect (Haldane model) for quasicrystals!

→ new class of quasicrystalline states

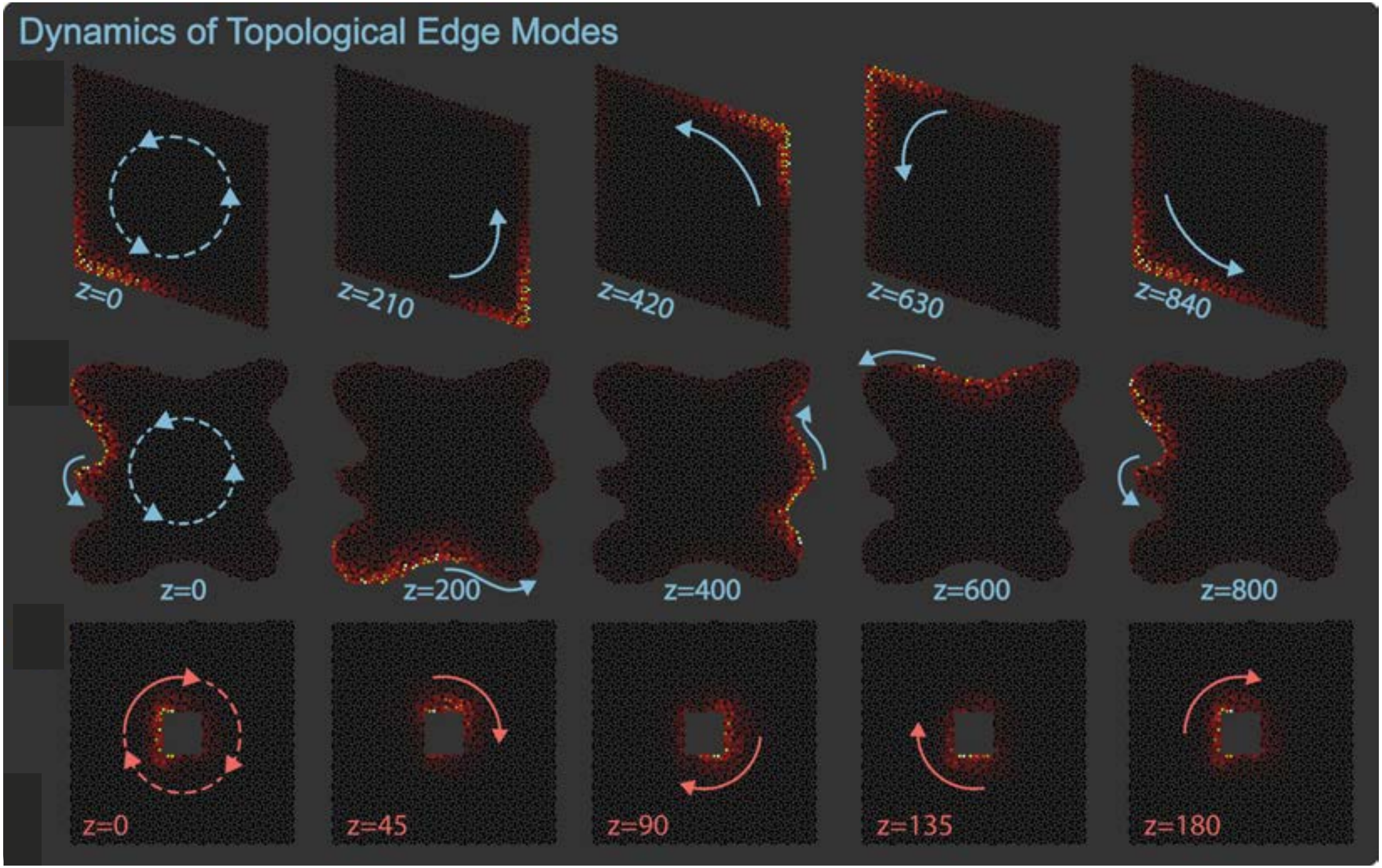
Phys. Rev. X **6**, 011016 (2016)

Topological edge states!

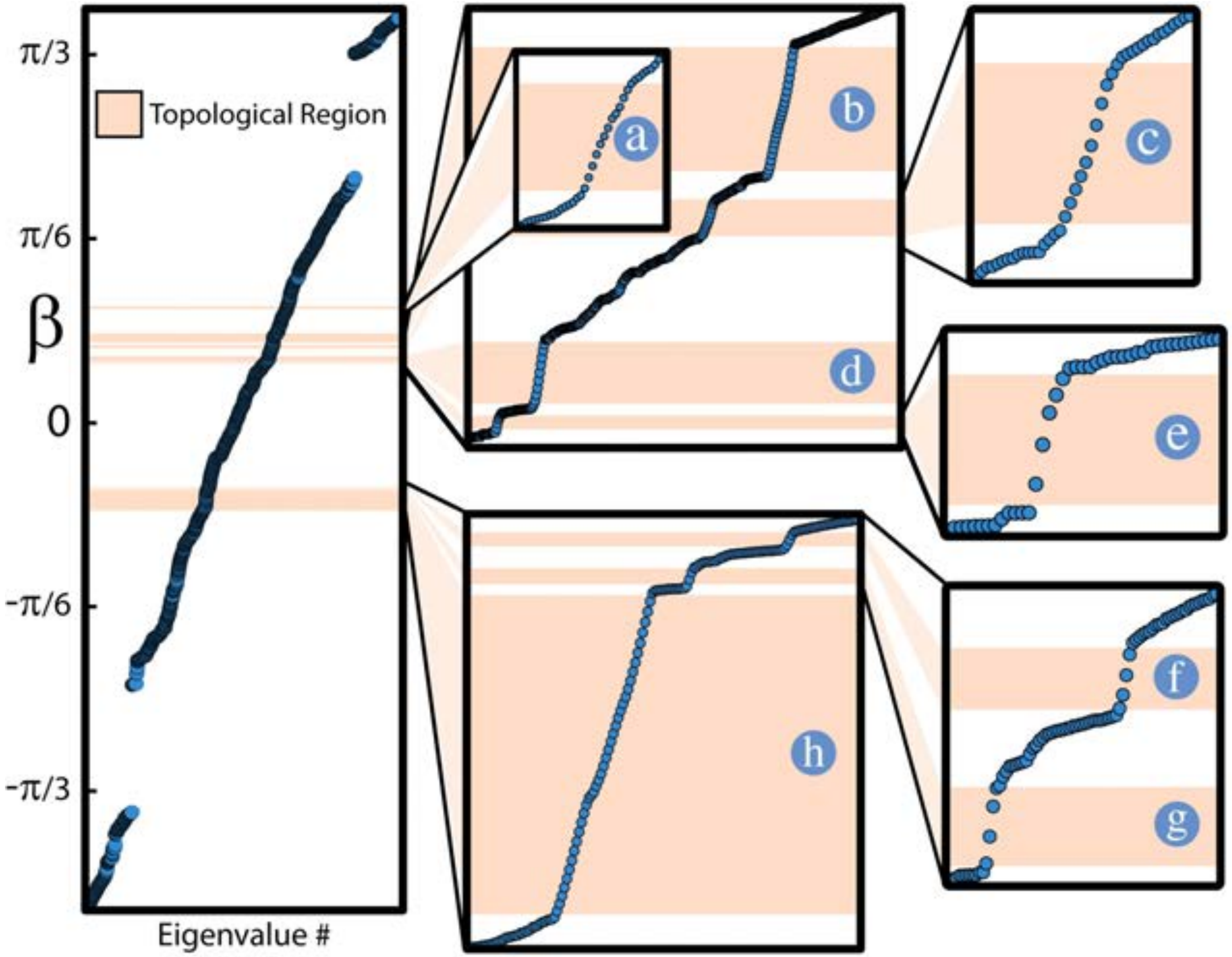


M. Bandres, MCR, M. Segev, PRX (2016)

Topological edge states!



Topological regions are fractal-like

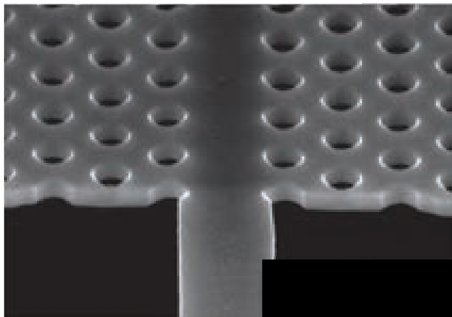


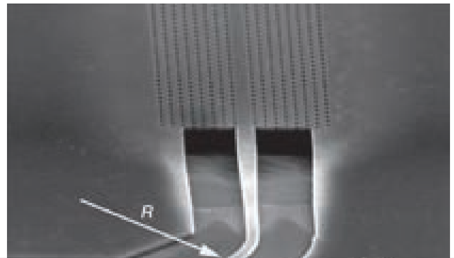
Conjecture: within any band, there are an infinite number of topological gaps

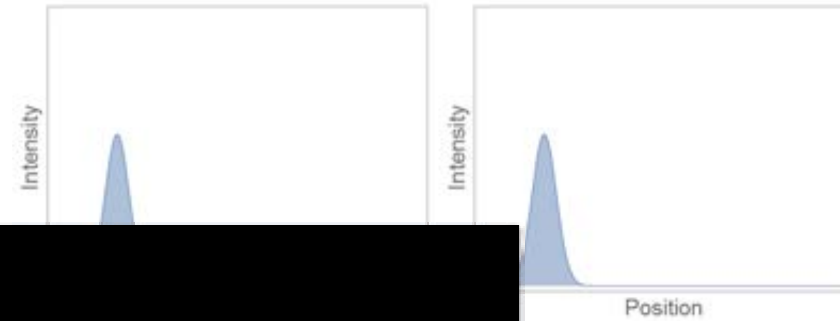
Topological slow light via BZ winding

J. Guglielmon and M. C. Rechtsman, Phys. Rev. Lett. **122**, 153904 (2019).

Idea: topological slow light

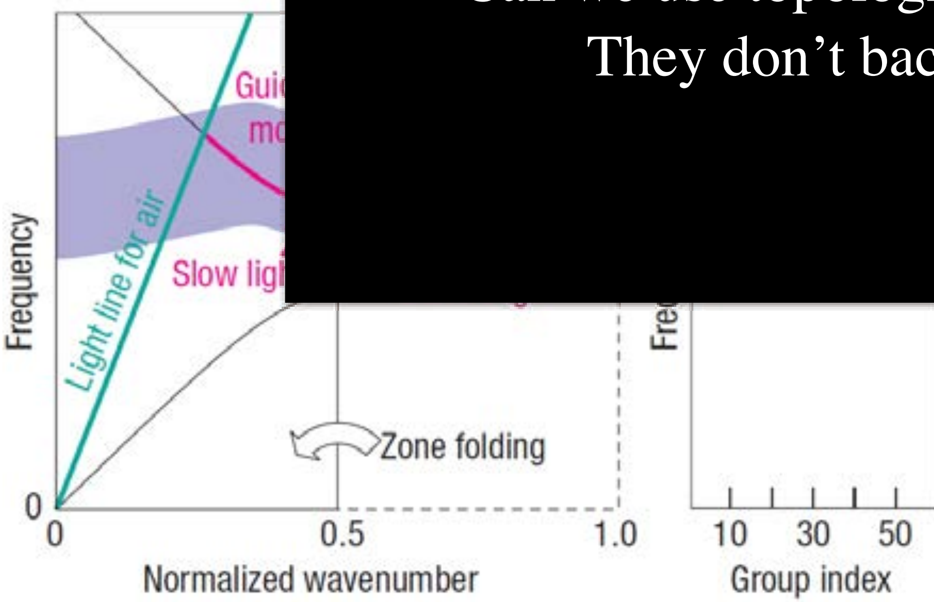






Vlasov, Yurii A.

Can we use topological edge states?
They don't backscatter…



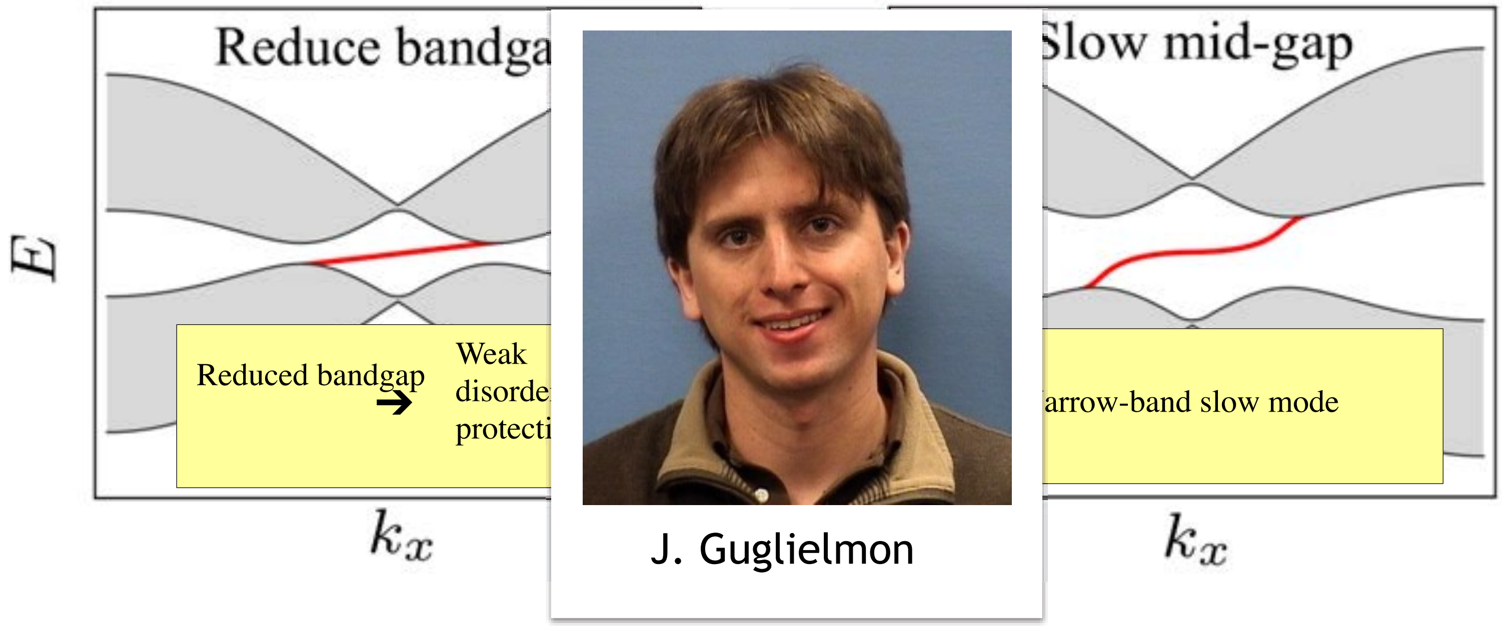
M. Notomi et al. (2001); T. Baba (2008)

ng

- Bandwidth

- Backscattering

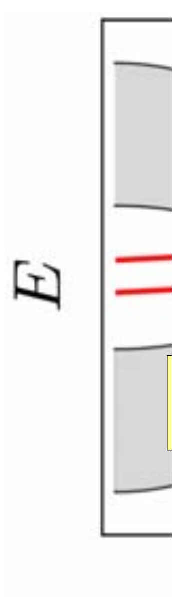
Obvious ideas

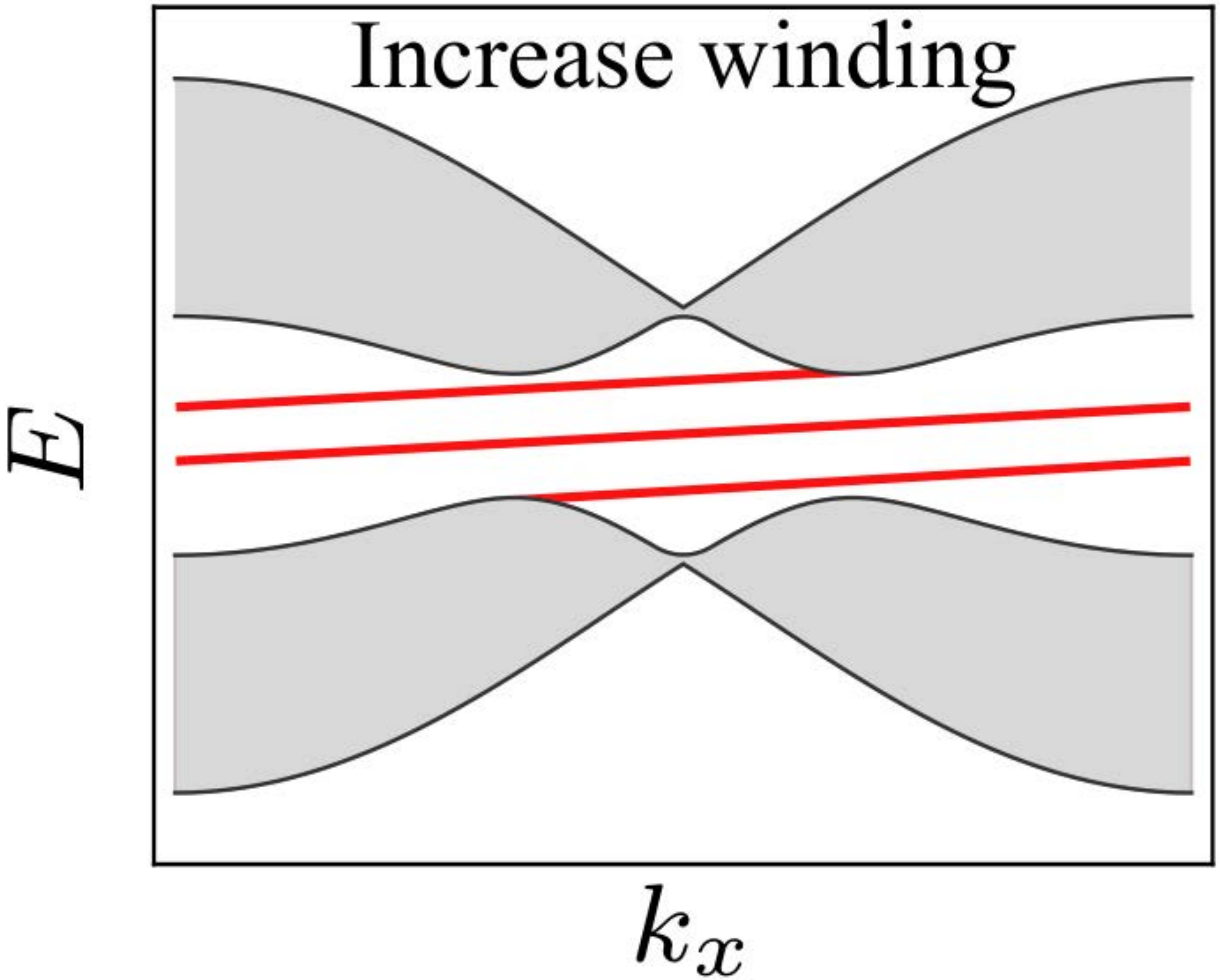


Note that both methods sacrifice bandwidth

Increase winding

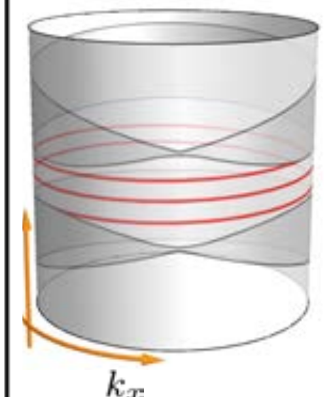
To





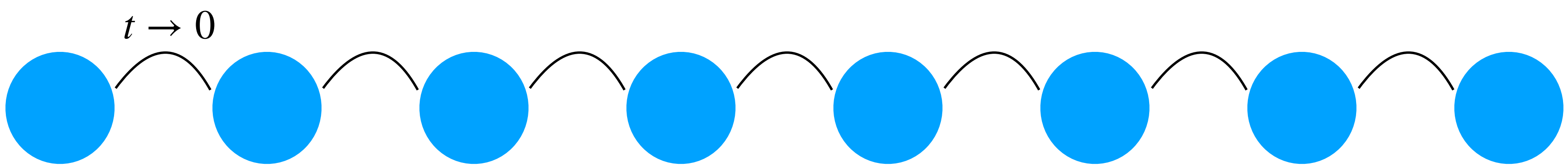
nd BZ

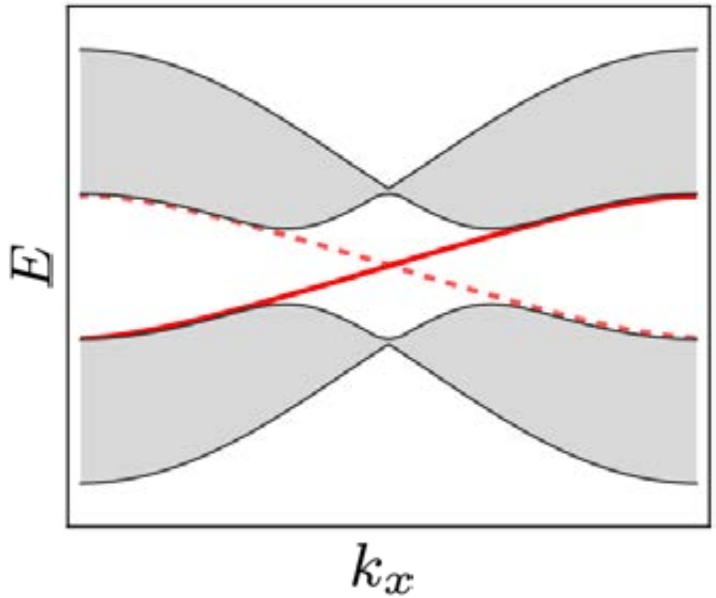
riodic Brillouin Zone



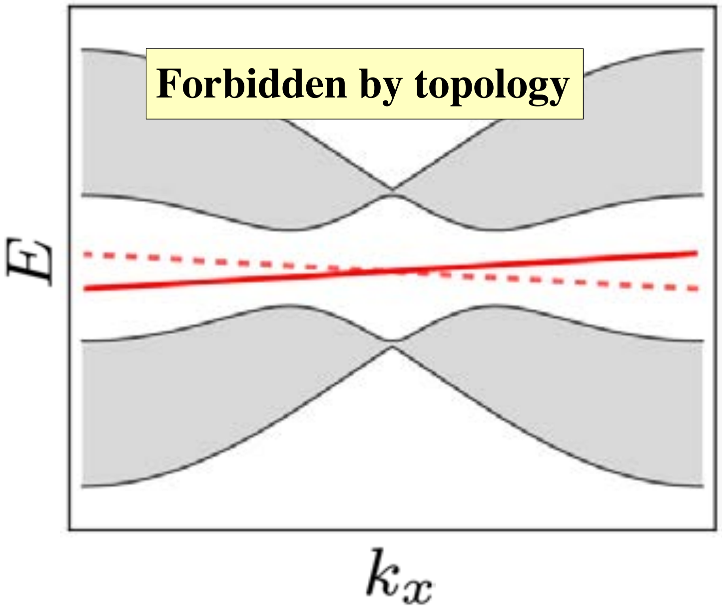
J. Guglielmon and M. C. Rechtsman. Phys. Rev. Lett. **122**, 153904 (2019).

How do we do it?

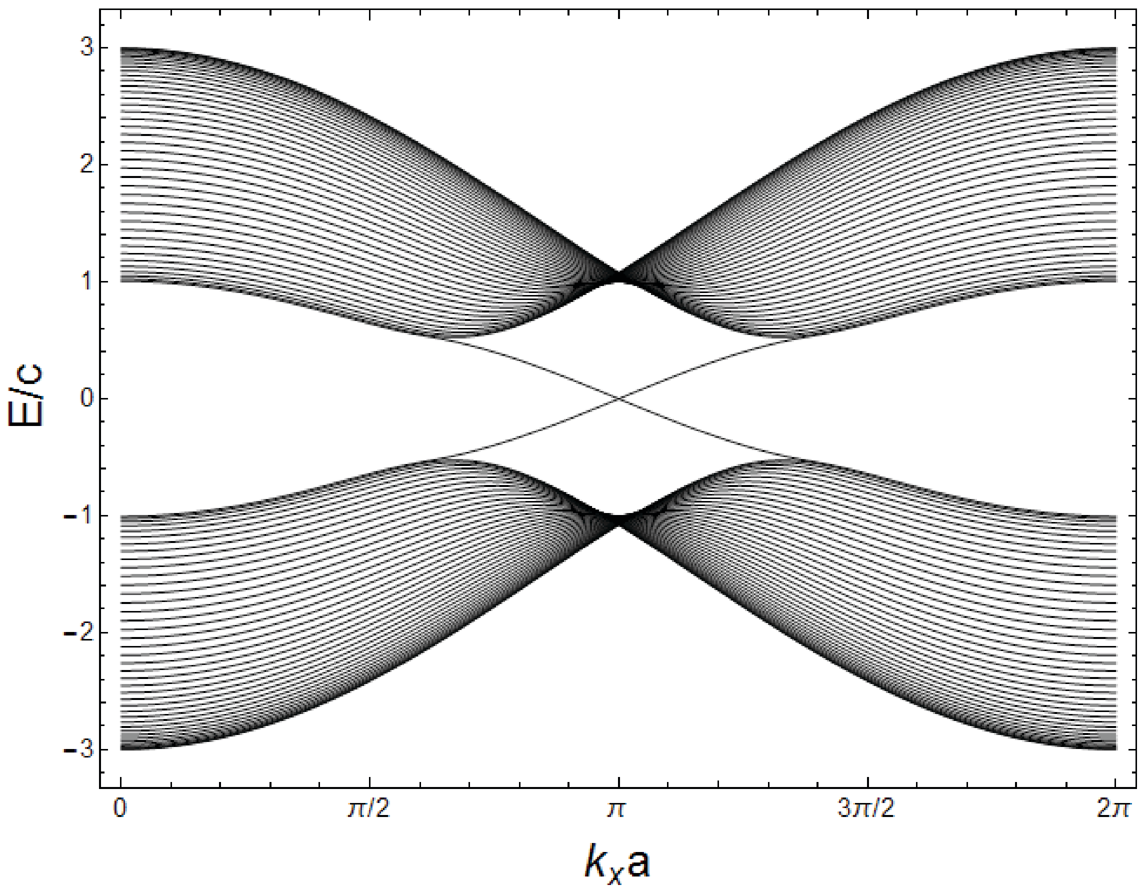


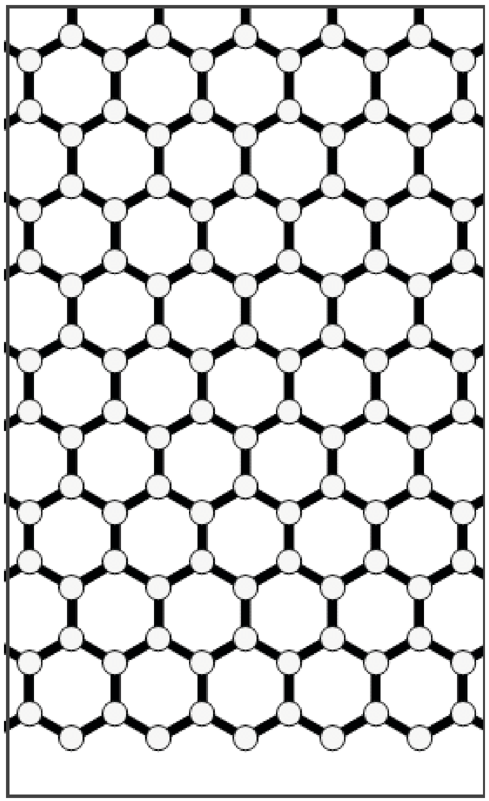


Slow **all** in-gap states



Engineering the edge…

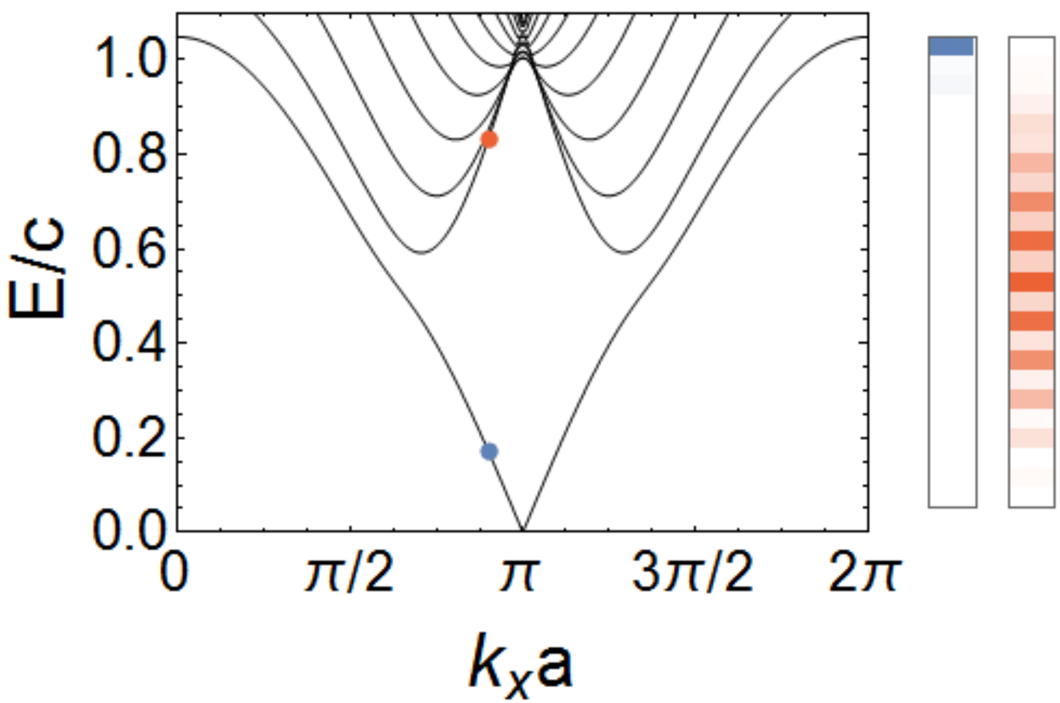




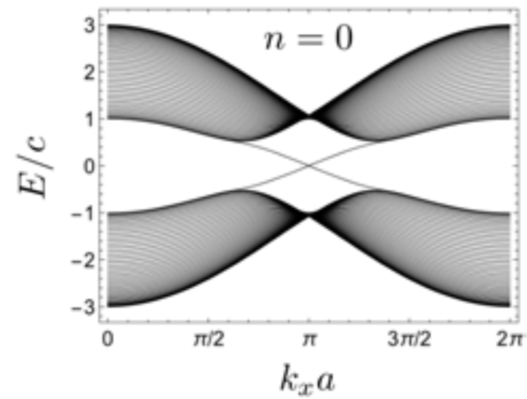
J. Guglielmon and M. C. Rechtsman. Phys. Rev. Lett. **122**, 153904 (2019).

Where do the new edge states come from?

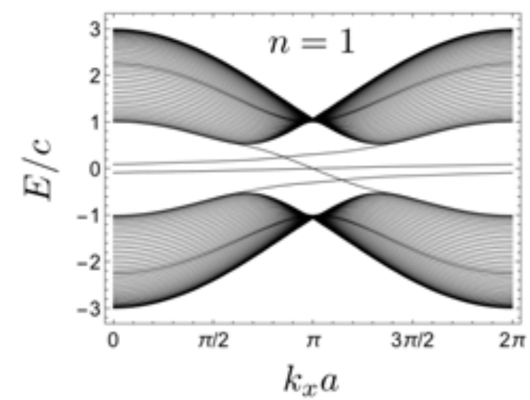
$$H_\lambda(k_x) = (1-\lambda)H_0(k_x) + \lambda H_1(k_x)$$



Initial band structure



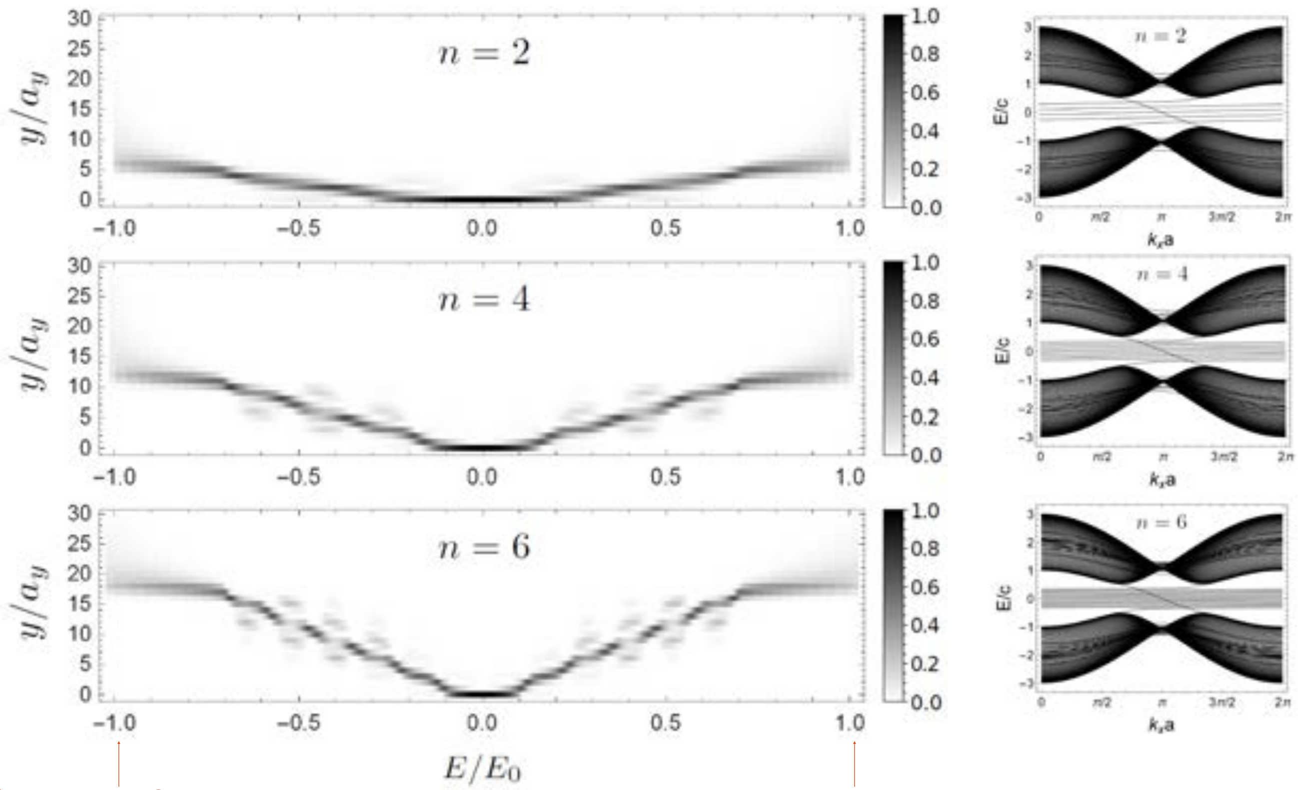
Final band structure



… this defines an invariant

Confinement of slow light edge modes

As winding increases, the edge modes utilizes more bulk sites



"Unused real estate" of a 2D PTI utilized to enable wideband operation

(bottom of gap)

(top of gap)

Robust slow light

These slow chiral edge states resist the severe backscattering associated with a reduced group velocity: