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Using symmetry and topology to confine and control light

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Outline

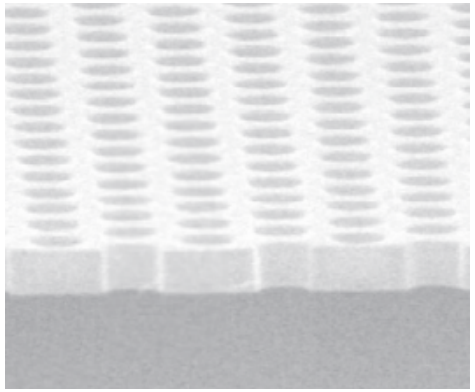
1) Using environmental engineering to create bound states in the continuum (BICs)
   - What are BICs?
   - What sets the energy scale of BICs? (the Bragg-diffraction limit)
   - Overcoming these limitations using environmental design
2) Higher-order topological bound states in the continuum
   - Create cavities in low-index photonic materials
3) Quick rundown of other interests
   - Topological photonics
   - Non-Hermitian systems
   - New kinds of topological phenomena in non-Hermitian systems

Types of states in photonic crystal slabs

Outside the slab:

$$\omega = c|\boldsymbol{k}|$$

Conservation of momentum during radiation, $\boldsymbol{k}_{\parallel,\mathrm{in}} = \boldsymbol{k}_{\parallel,\mathrm{out}}$

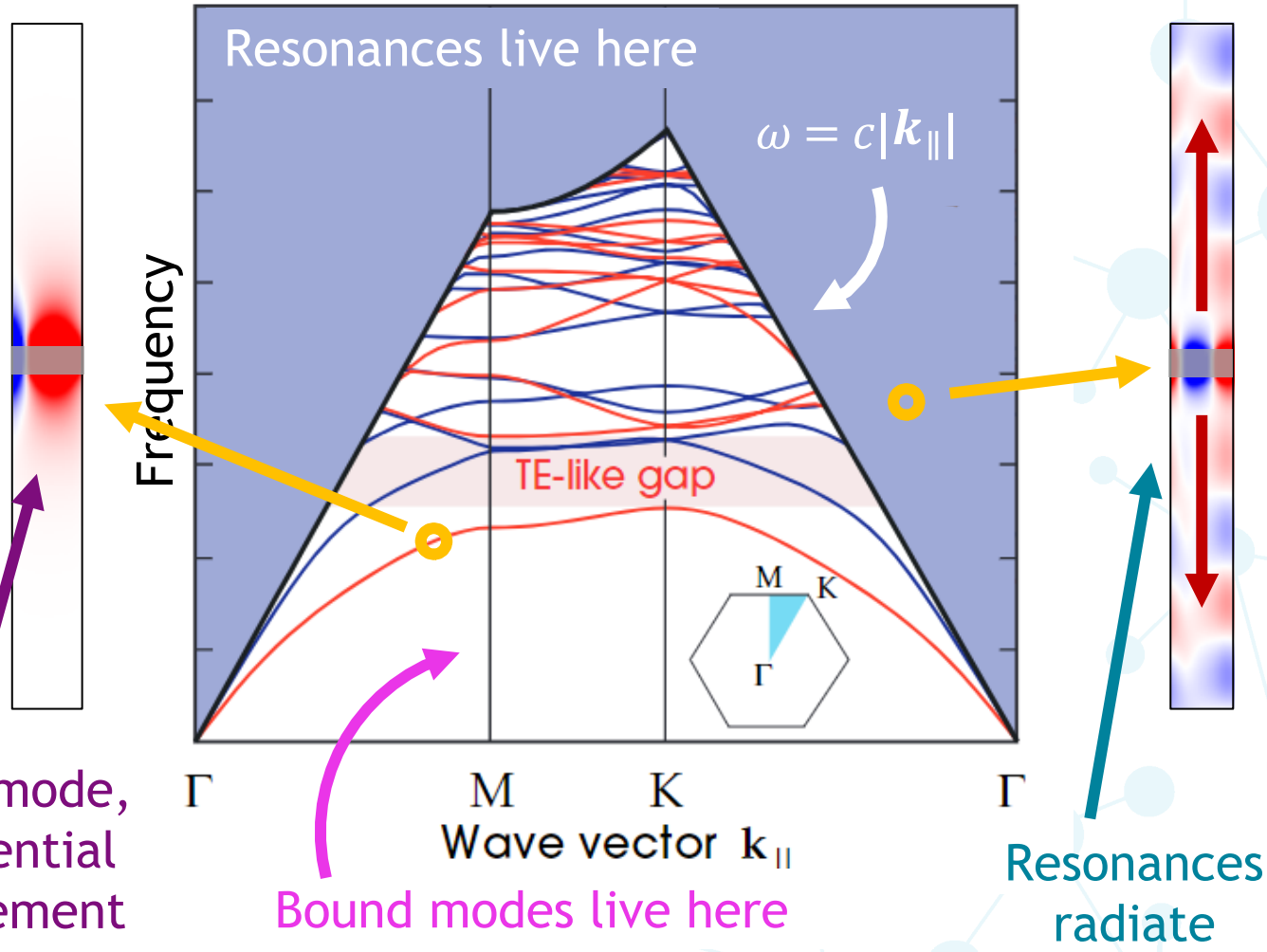


Sugimoto et al., *Opt. Express* 2004

Minimum allowed frequency to radiate $\omega = c|\boldsymbol{k}_{\parallel}|$

Bound modes: $\omega < c|\boldsymbol{k}_{\parallel}|$

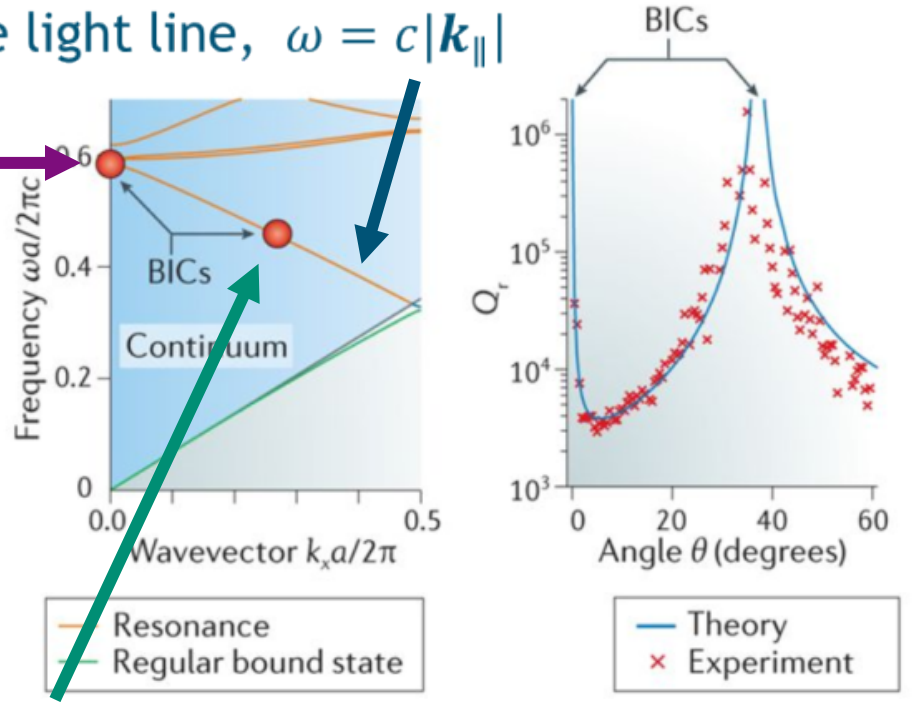
Resonances: $\omega > c|\boldsymbol{k}_{\parallel}|$



Joannopolous, Johnson, Winn, and Meade, *Photonic Crystals: Molding the flow of light*, 2007

Bound states in the continuum (BICs)

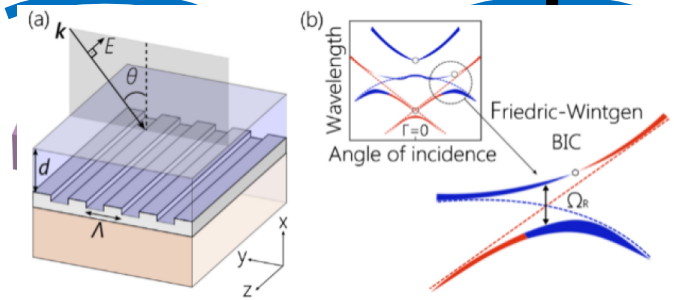
Bound modes above the light line, $\omega = c|\boldsymbol{k}_{\parallel}|$



Could be symmetry protected from leaking

- Common in slabs at $k_x = k_y = 0$
- Requires rotational symmetry about z-axis
  - ➢ Results in a BIC

Friedrich-Wintgen



Azzam et al., *PRL* **121**, 253901 (2018)

- Avoided crossing of two non -Hermitian resonances

Could not leak 'accidentally'

- 2 constraints, d_s, d_p
- 2 degrees of freedom, k_x, k_y
  - ➢ Results in a BIC

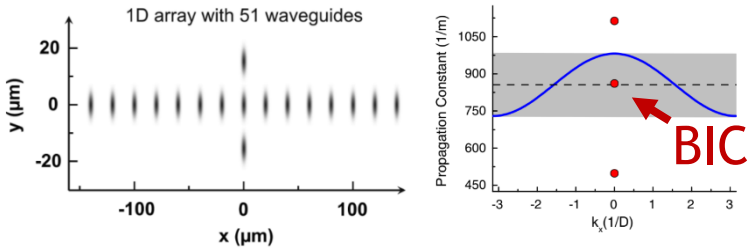
➢ BIC when $d_s = d_p = 0$

Hsu, Zhen et al., *Nature* **499**, 188 (2013)
Hsu, Zhen et al., *Nat. Rev. Mater.* **1**, 16048 (2016)

Modern introduction to an old topic

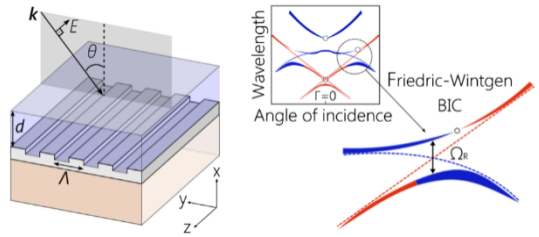
First system with a BIC was predicted in 1929 by von Neumann and Wigner *Phys. Z.* **30**, 465 (1929)

Waveguide arrays



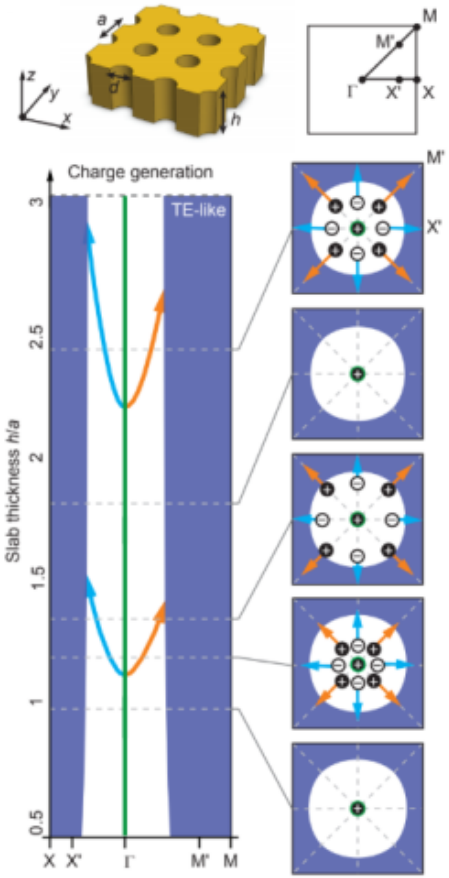
Plotnik et al., *PRL* **107**, 183901 (2011)

Plasmonic-Photonic systems



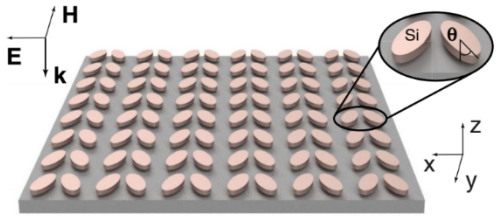
Azzam et al., *PRL* **121**, 253901 (2018)

Photonic crystal slabs



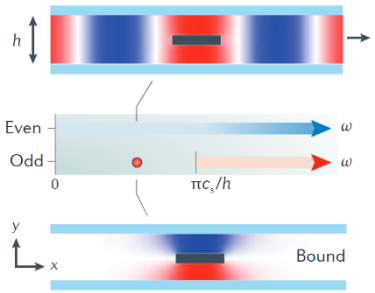
Zhen et al., *PRL* **113**, 257401 (2014)

Metasurfaces



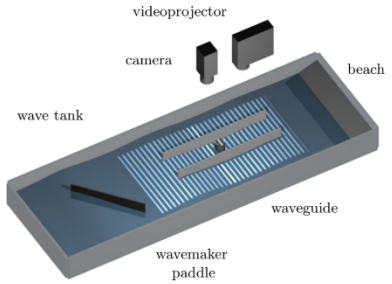
Koshelev et al., *PRL* **121**, 193903 (2018)

Acoustics



Parker and Stoneman, *Proc. Inst. Mech. Eng.* C **203**, 9 (1989)

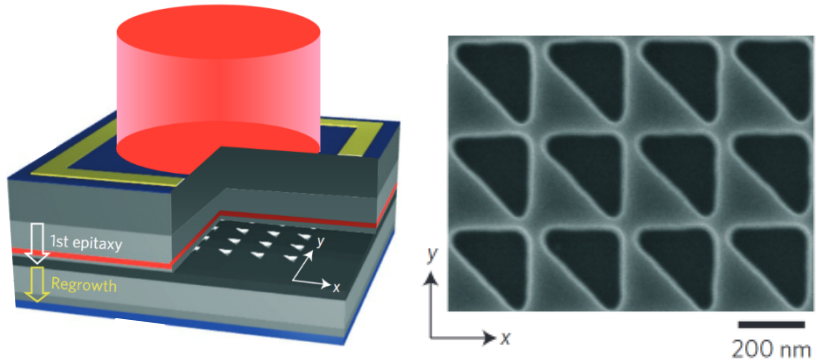
Water Waves



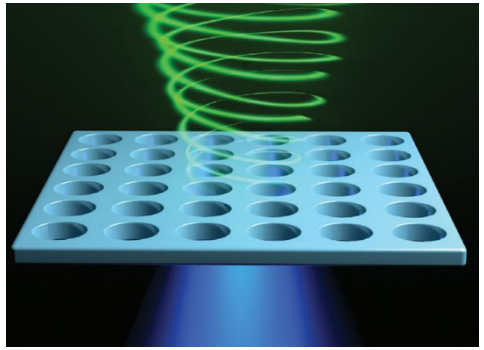
Cobelli et al., *Euro. Phys. Lett.* **8**, 20006 (2009)

Uses of (symmetry-protected) BICs

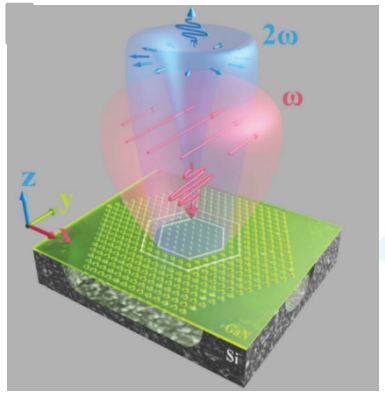
Photonic Crystal Surface Emitting Lasers (PCSELs)



Hirose et al., *Nat. Photonics* **8**, 406 (2014)

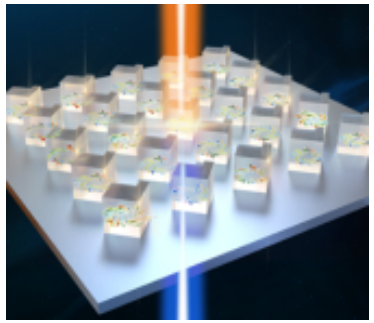


Huang et al., *Science* **367**, 1018 (2020)
Wang et al., *Nat. Photonics* 1 (2020)

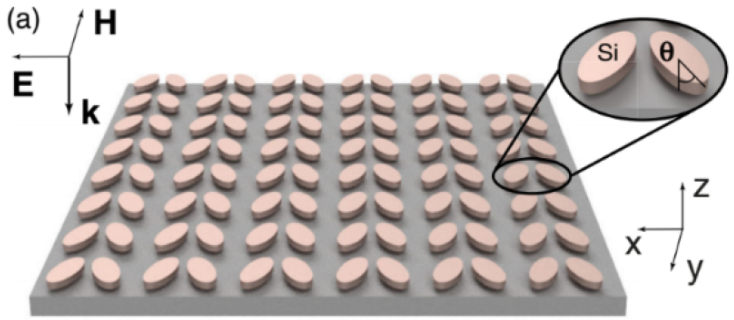


Minkov et al., *Optica* **6**, 1039 (2019)
Wang et al., *Optica* **7**, 1126 (2020)

Controlling reflection and transmission spectra

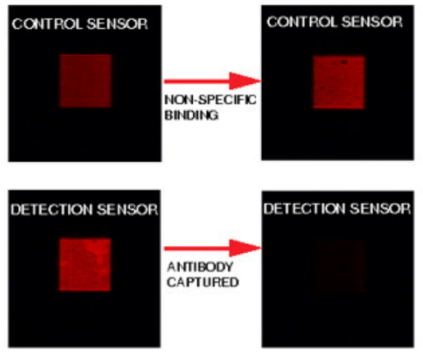


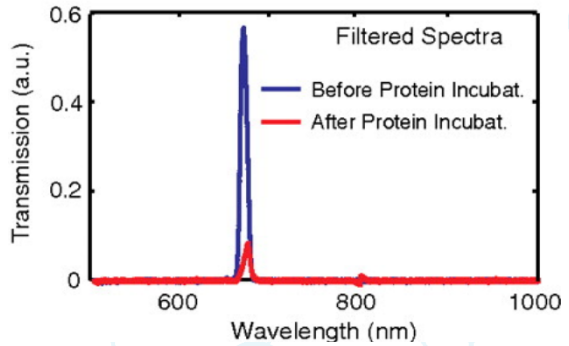
Campione et al., *ACS Photonics* **3**, 2362 (2016)



Koshelev et al., *PRL* **121**, 193903 (2018)

Sensors





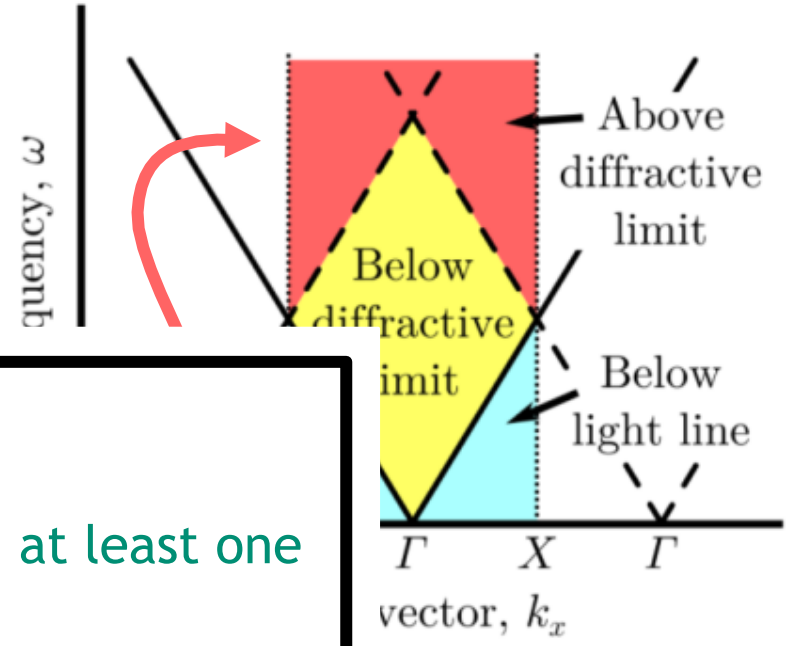
Yanik et al., *Proc. Natl. Acad. Sci.* 108, 11784 (2011)

What sets the energy scale of BICs?

Example: photonic crystal slab surrounded by air

Diffraction limit is

$$\frac{n\omega}{c} \geq \left|\mathbf{k}_{\parallel} \pm \mathbf{b}_m\right|$$



Is this general?

- BICs cannot exist in compact structures
  - ➢ System **must** be infinite and periodic in at least one dimension
  - ➢ **Yes.** There will always be a diffraction limit.

Theorem
possible

- ➢ No
- ➢ Also *strongly* limits other BIC creation mechanisms

$\mathbf{k}_{\parallel}$ is the in-plane wavevector
$\mathbf{b}_m$ are the in-plane reciprocal lattice vectors

AC,* Jörg,* et al., arXiv:2104.09603

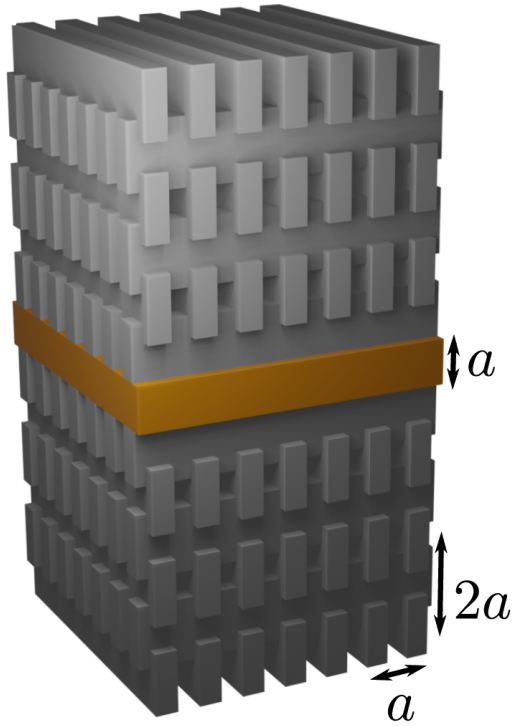
Overcoming this limitation

Need to either break:

isotropy – using birefringent materials in the environment

homogeneity – by patterning the environment

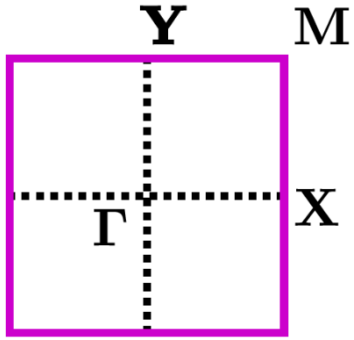
Embed slab in a 3D photonic crystal

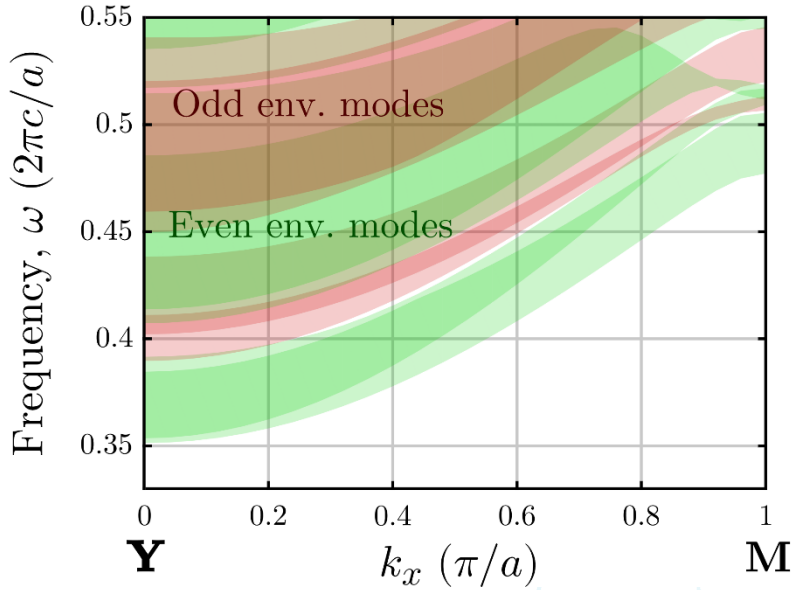


➢ Changes the radiative channels to be the photonic crystal's projected-in-k_z bands, $\omega_n(\mathbf{k}_\parallel)$

Remember – Looking for a slab symmetry not in the environment

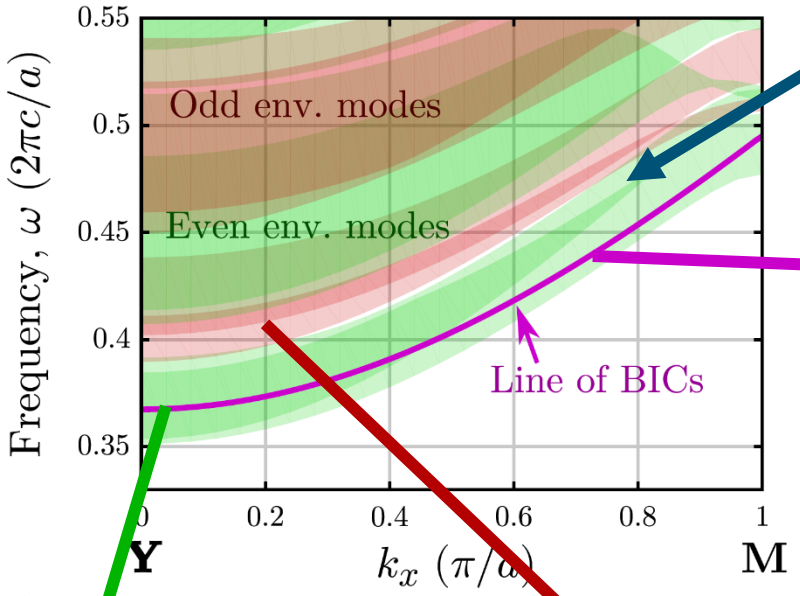
So, look along high-symmetry lines:

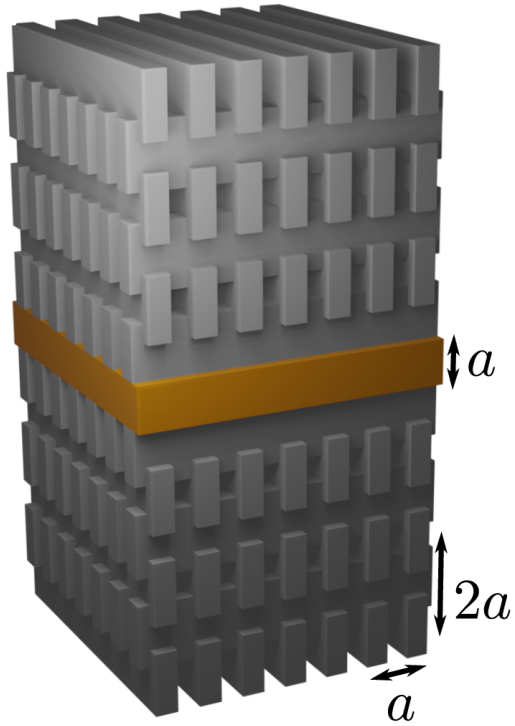




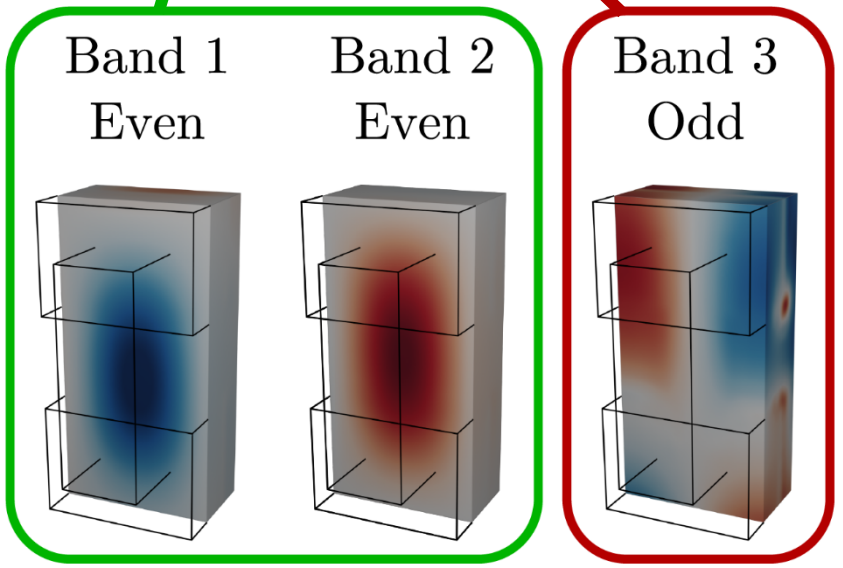
Overcoming this limitation

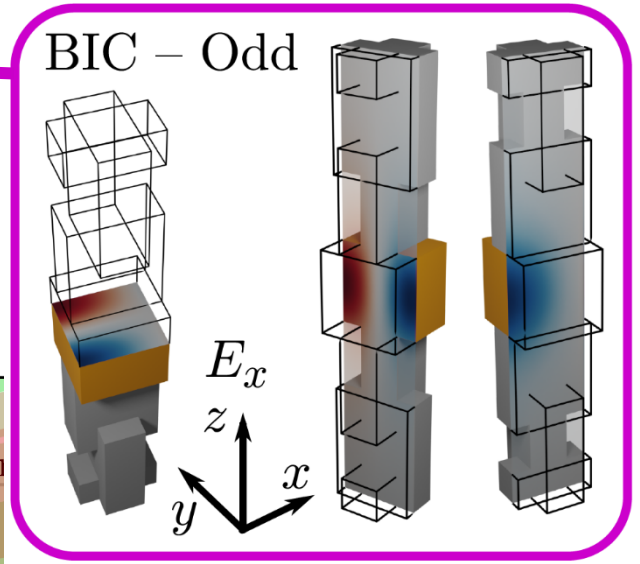
Symmetry bandgap – only one of the two possible symmetries in the environment is present at this ω

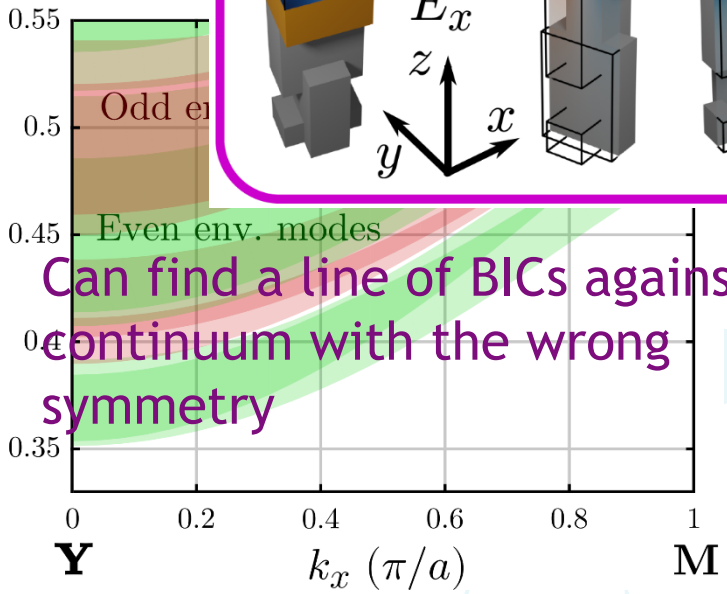




Alo
line
are



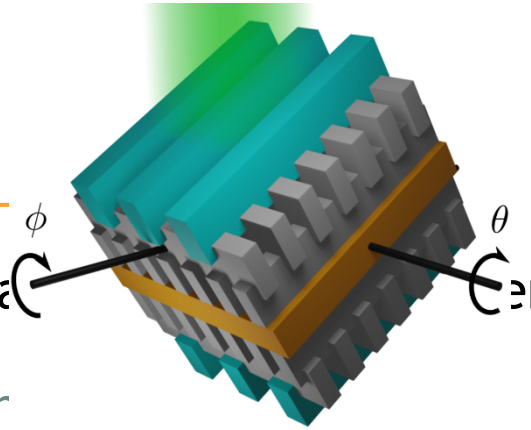




Can find a line of BICs against the continuum with the wrong symmetry

Observing a line of BICs

Effect can still be observed with just a single complete la ent

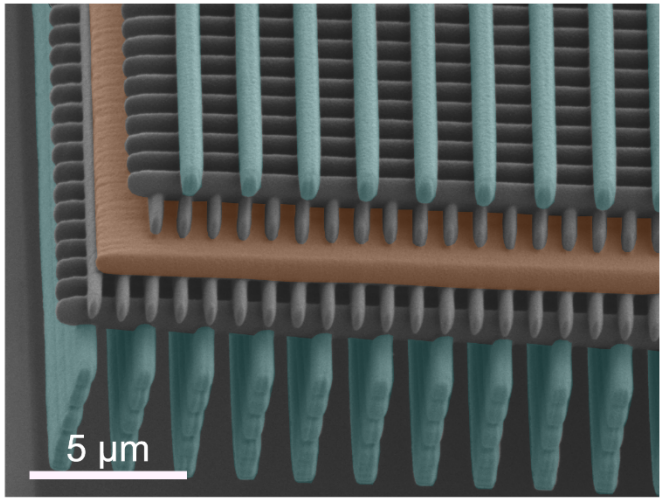


In simulation

θ - k_x ϕ - k_y

$\Gamma - \mathbf{X}$ line at $\phi = 0$

Fabricate using a Nanoscribe

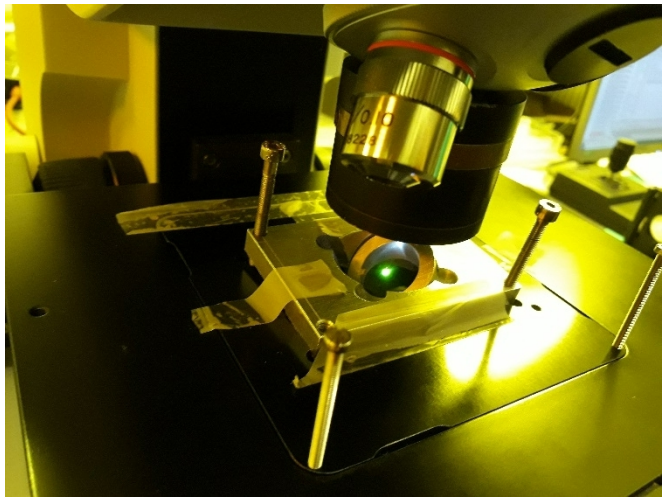


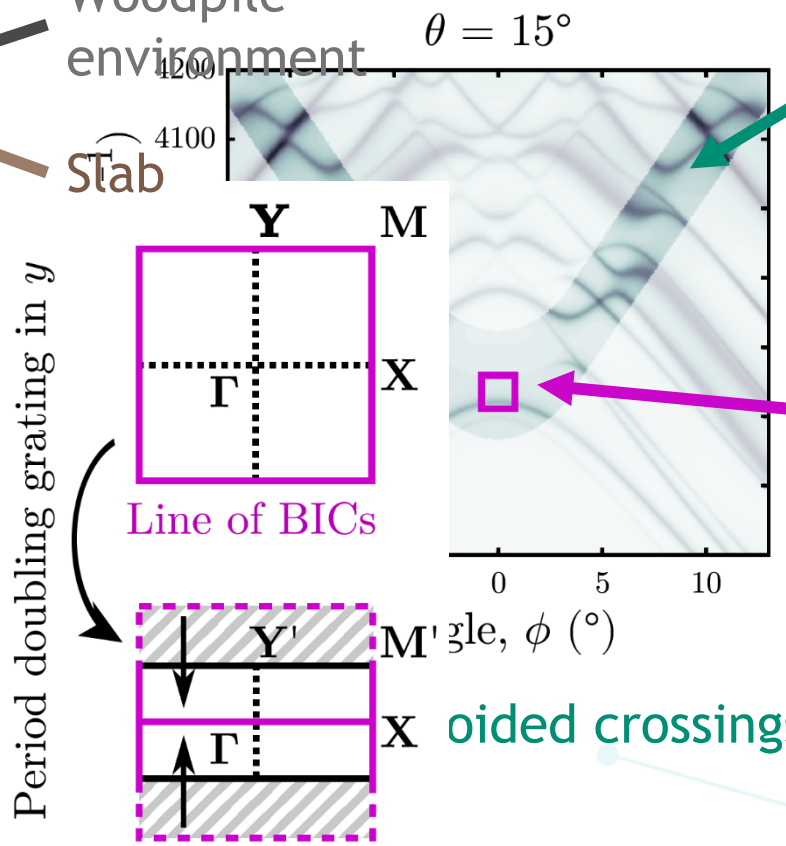
Gratir

Woodpile environment

Slab

Observe with an FTIR





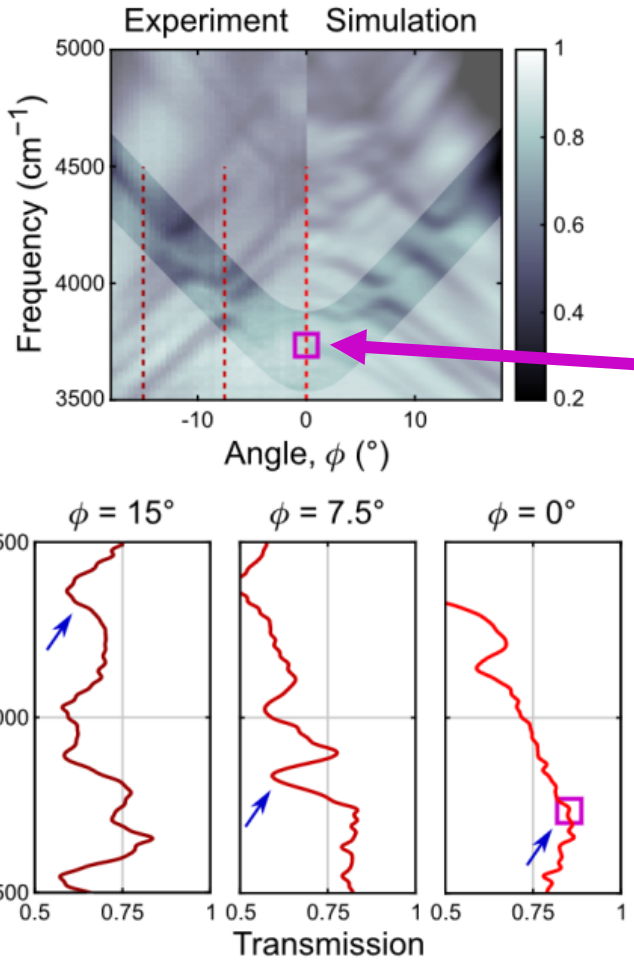
Slab resonance away from BIC

$Q \to \infty$ as $\phi \to 0$
Disappearance implies BIC

oided crossings

AC,* Jörg,* et al., arXiv:2104.09603

Observing a line of BICs



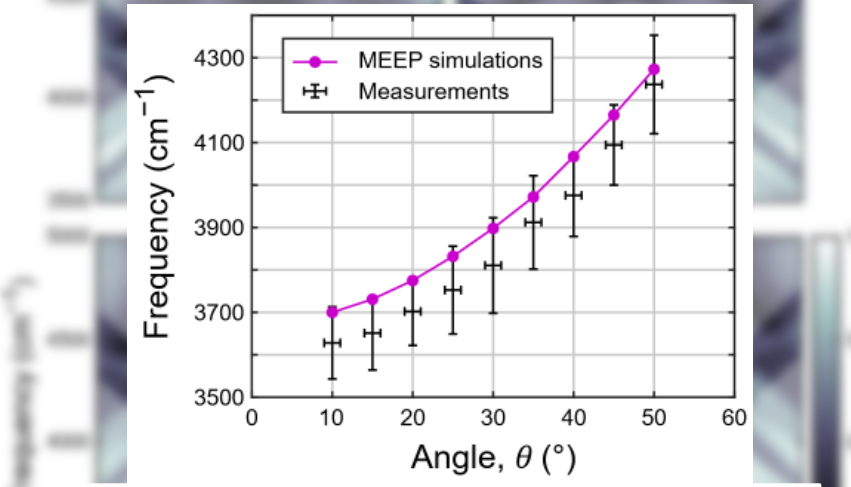
θ - k_x angle

ϕ - k_y angle

$\Gamma - X$ line at $\phi = 0$

BIC at $\phi = 0$

Different θ still yield BICs

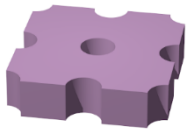


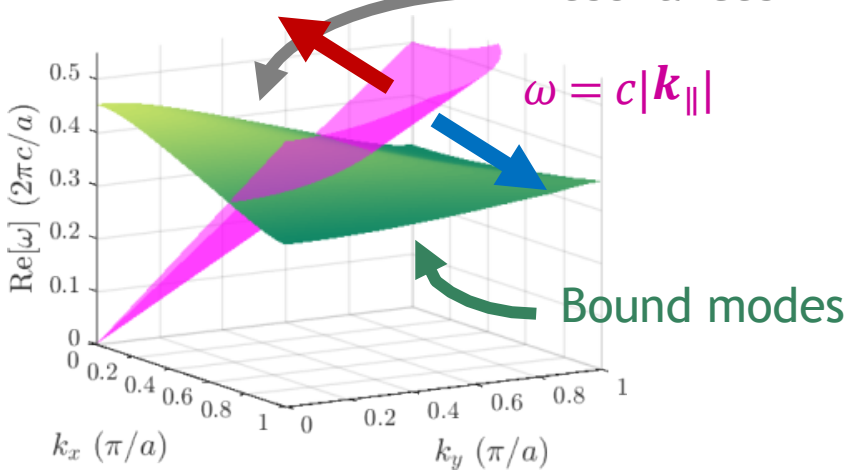
Error of only $\Delta\omega/\omega = 1.84\%$

AC,* Jörg,* et al., arXiv:2104.09603

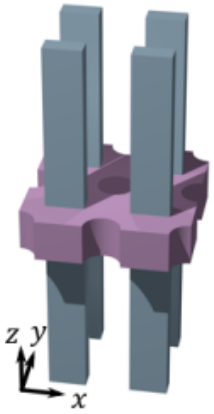
Splitting the light cone to create BICs

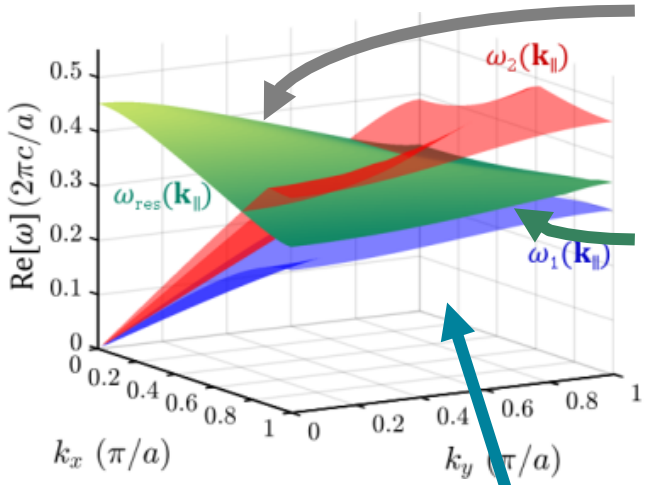
Band of an isolated photonic crystal slab





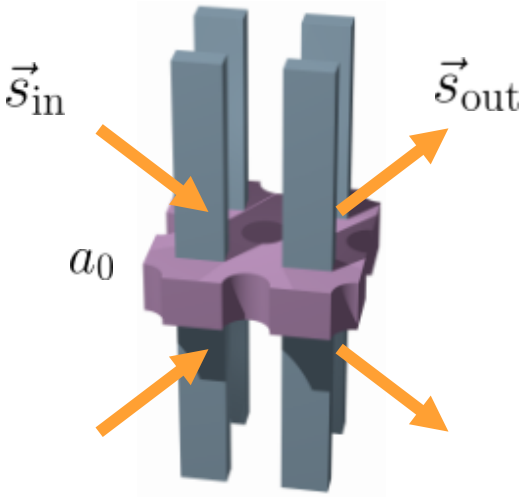
Adding an environment changes the 'light cone' of the system





Resonances above 2 "light lines"

Resonances above only 1 "light line"



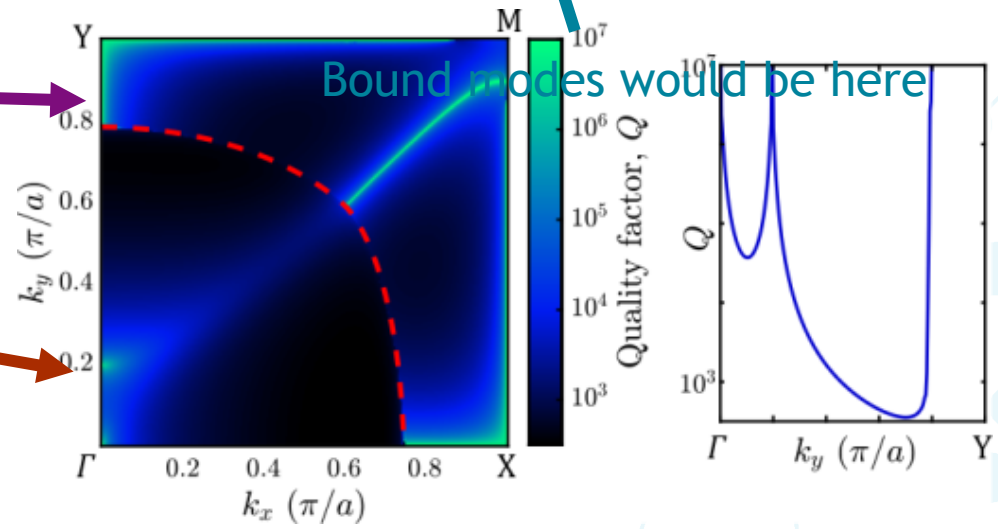
Prove existence using coupled mode theory and symmetry

$$\vec{s}_{\mathrm{out}} = C\vec{s}_{\mathrm{in}} + \vec{D}a_0$$

- BIC when $\vec{D} = 0$

Lines of BICs above 1 light line

Isolate above 2 light lines



AC, Hsu, Rechtsman, *Phys. Rev. Lett.* **123**, 023902 (2019)

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   - Create cavities in low-index photonic materials
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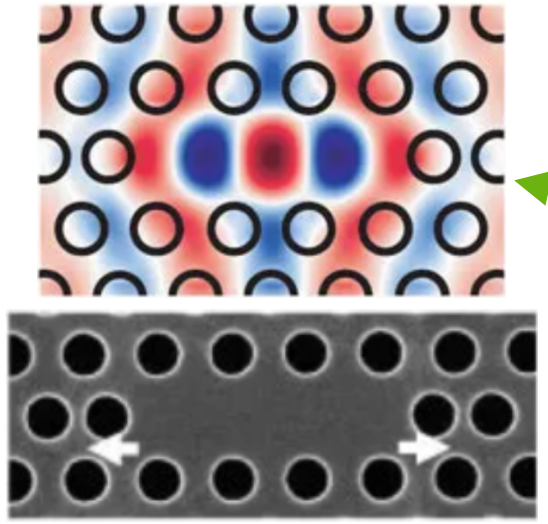
   - Non-Hermitian systems
   - New kinds of topological phenomena in non-Hermitian systems

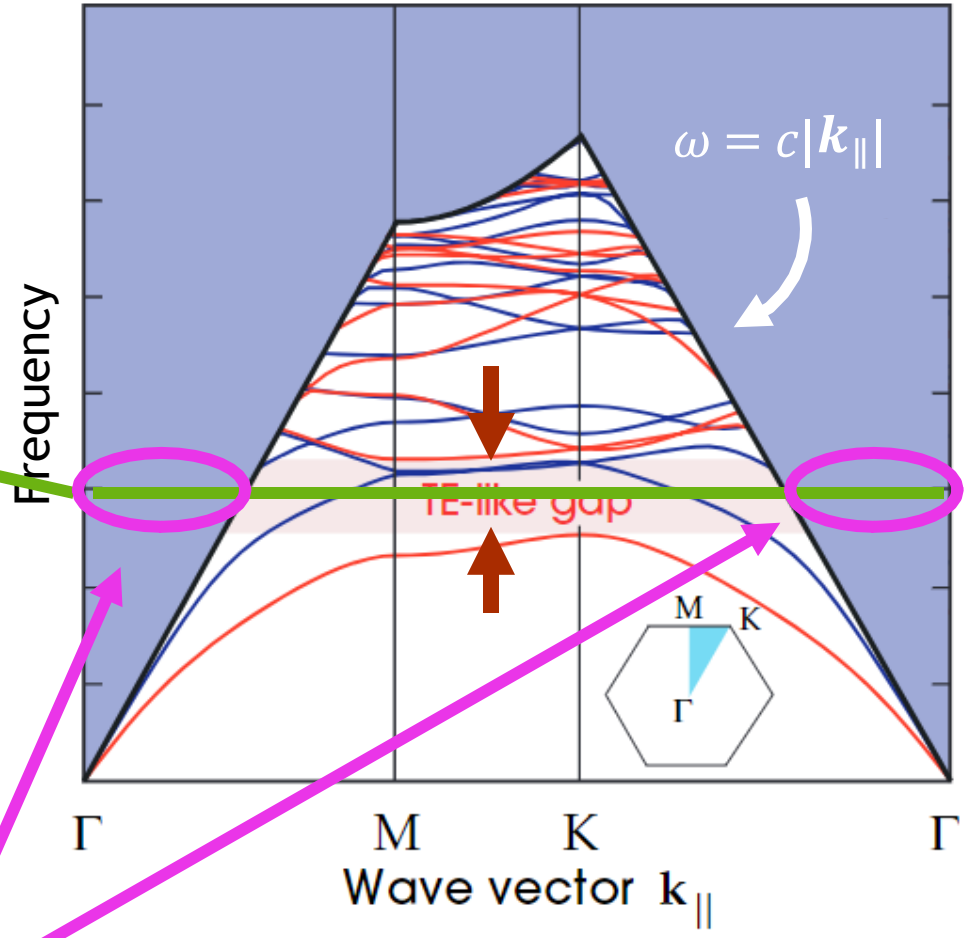
Cavities in photonic crystal slabs



Akahane et al., *Nature* **425**, 944 (2003)

Decreasing index
- Decreasing bandgap

In-plane confinement from bandgap in surrounding crystal



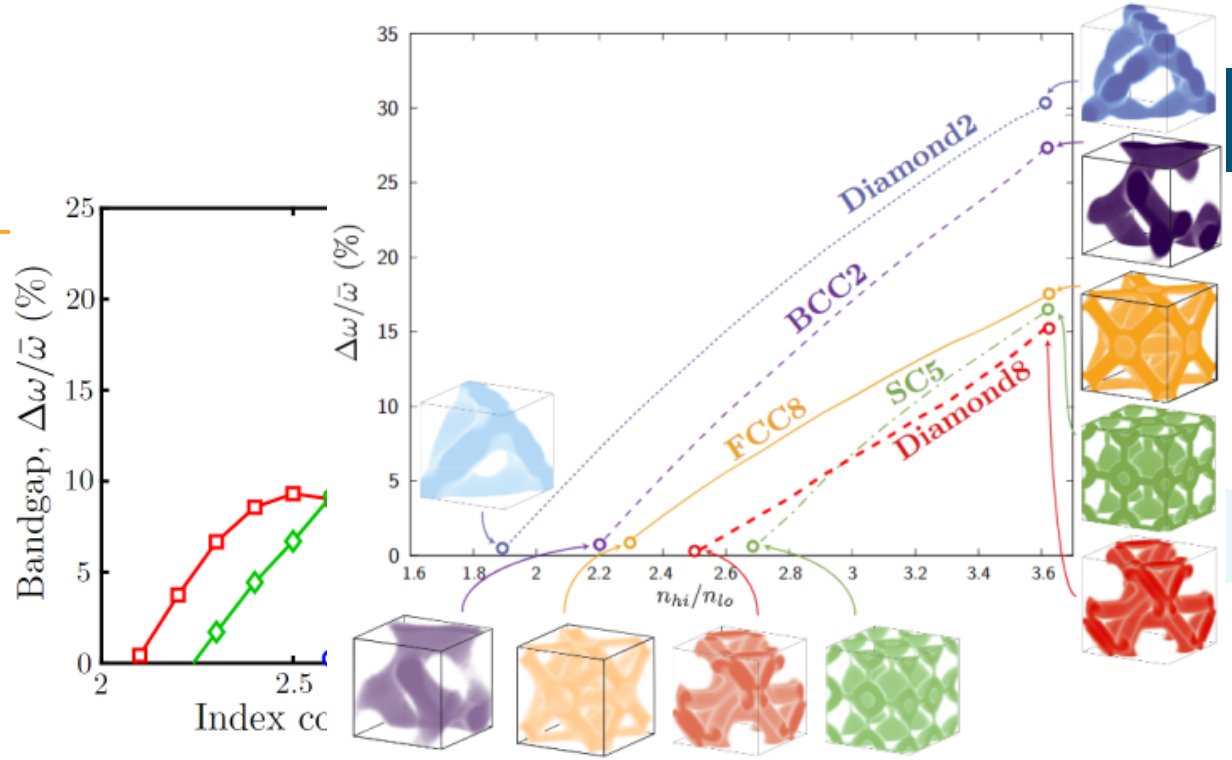
Out-of-plane confinement from total internal reflection (as much as possible)

Energy will still radiate from the cavity

Low-index photonic platforms

- Large area, possibly 3D
- Potential to make monolithic devices,
  - ➢ i.e. ‘optical table on a chip’

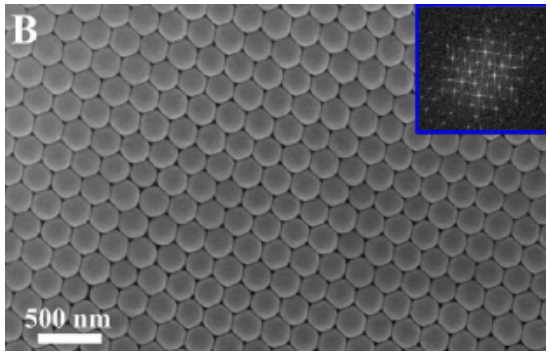
But no complete bandgaps.



AC and Fan, *Phys. Rev. A* **96**, 051802(R) (2017)

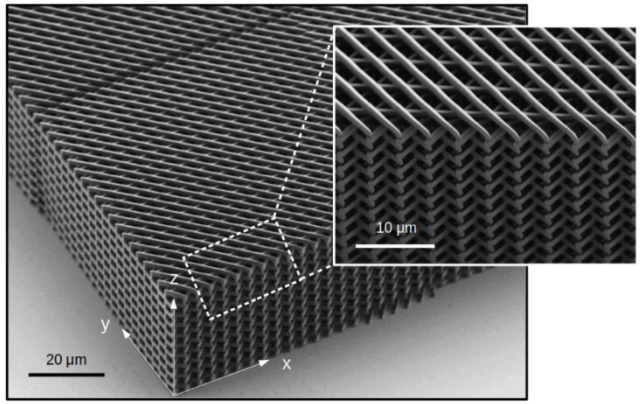
Men et al., *Opt. Express* **22**, 22632 (2014)

Colloids



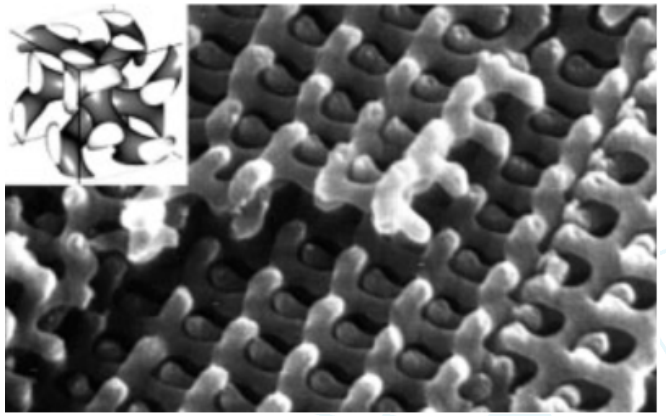
Huang et al., *JACS* **134**, 17053 (2012)

Two-photon polymerization



Vaidya, Noh, AC, and Rechtsman, *Phys. Rev. Lett.* **125**, 253902 (2020)

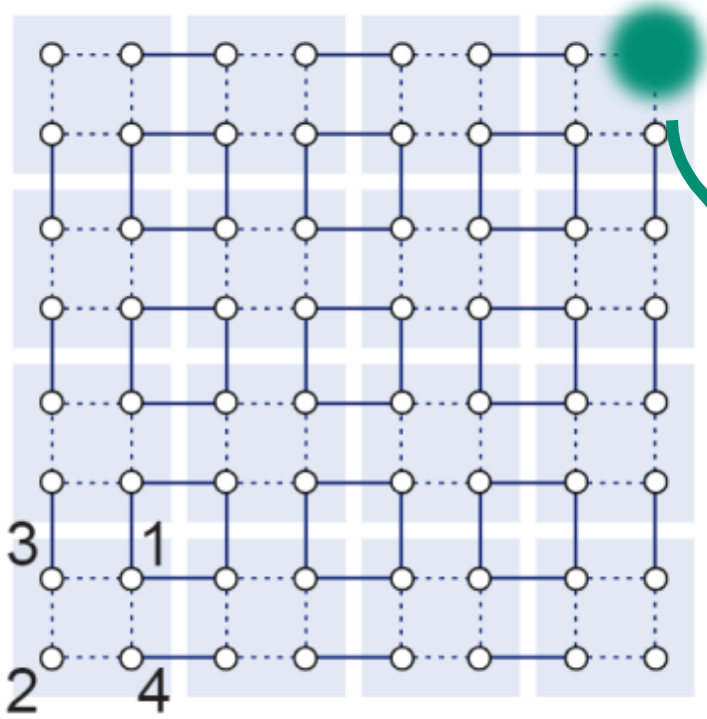
Self-assembled polymers



Urbas et al., *Adv. Mater.* **14**, 1850 (2002)

Similar difficulty in higher order topological systems

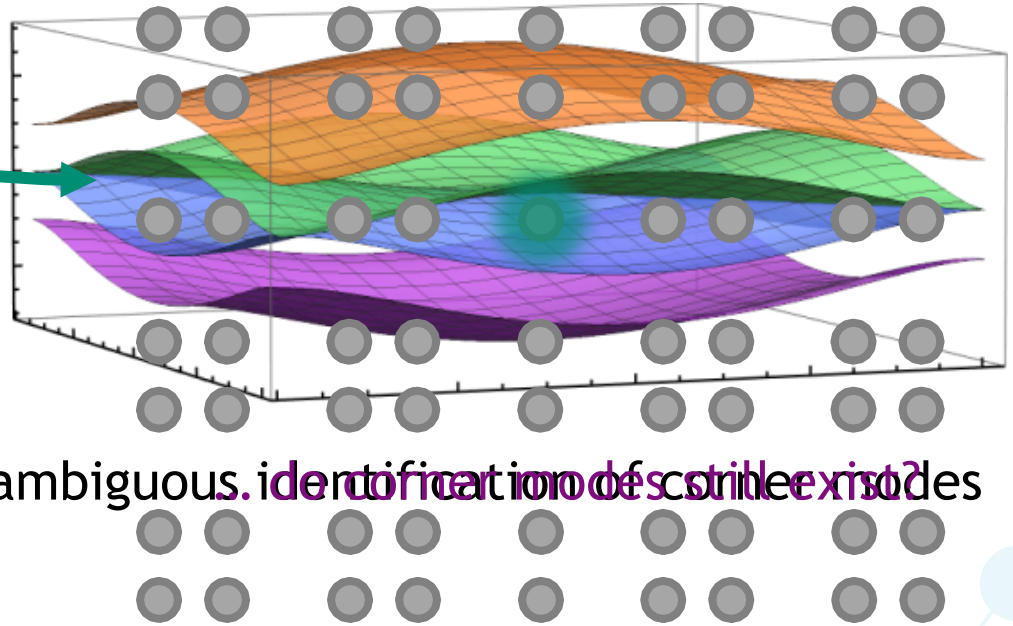
Guaranteed to exist due to crystalline symmetries, i.e. the structure



Could build higher order TI photonic crystals

But, can have these crystal symmetries without a gap…

Originally discovered within complete bandgaps



➢ Unambiguous identification of corner modes

…do corner modes still exist?

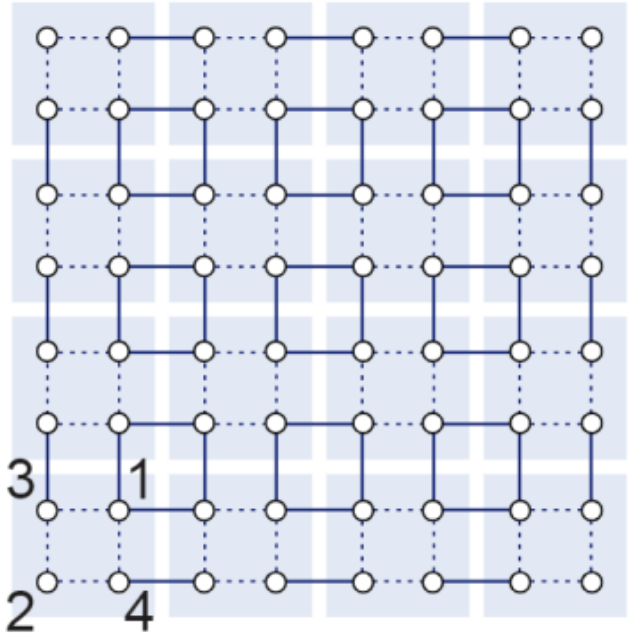
Corner-localized mode in the bulk

Benalcazar, Bernevig, Hughes, *Science* **357**, 61 (2017)

BICs in Higher-order topological systems – Proof

Analytically prove BICs exist using representation theory

System is C_{4v} and Π (chiral) symmetric



(1) In the bulk, the two available modes form the representation: E

(2) The four corner modes form: $A_1 \oplus B_2 \oplus E$

- ➢ Immediately, A_1, B_2 can't mix with E, incompatible symmetries

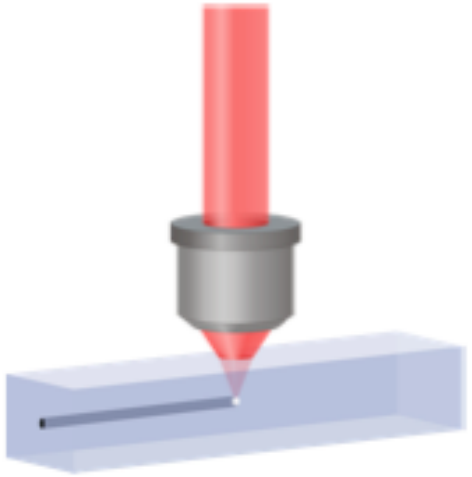
(3) The remaining two modes must have
- Same energy (rotationally symmetric partners)
- Opposite energy (chiral symmetric partners)

➢ Must have energy = 0, and no physical hybridization is possible

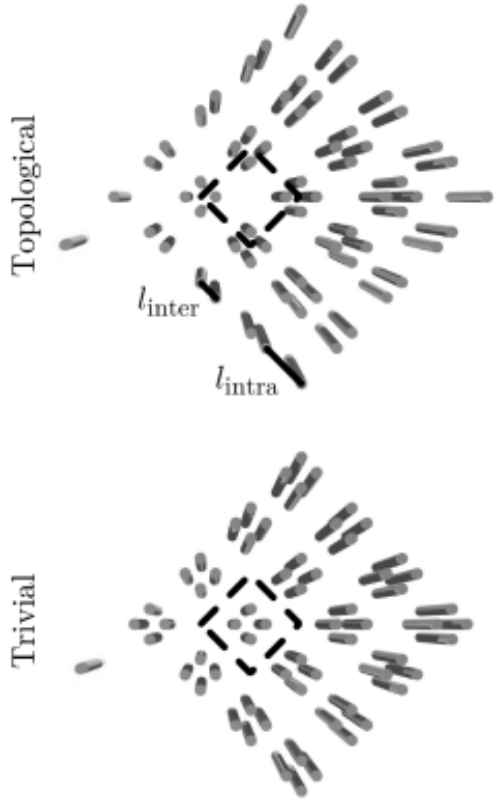
Benalcazar and AC, *Phys. Rev. B* **101** 161116(R) (2020)

Experiments in waveguide arrays

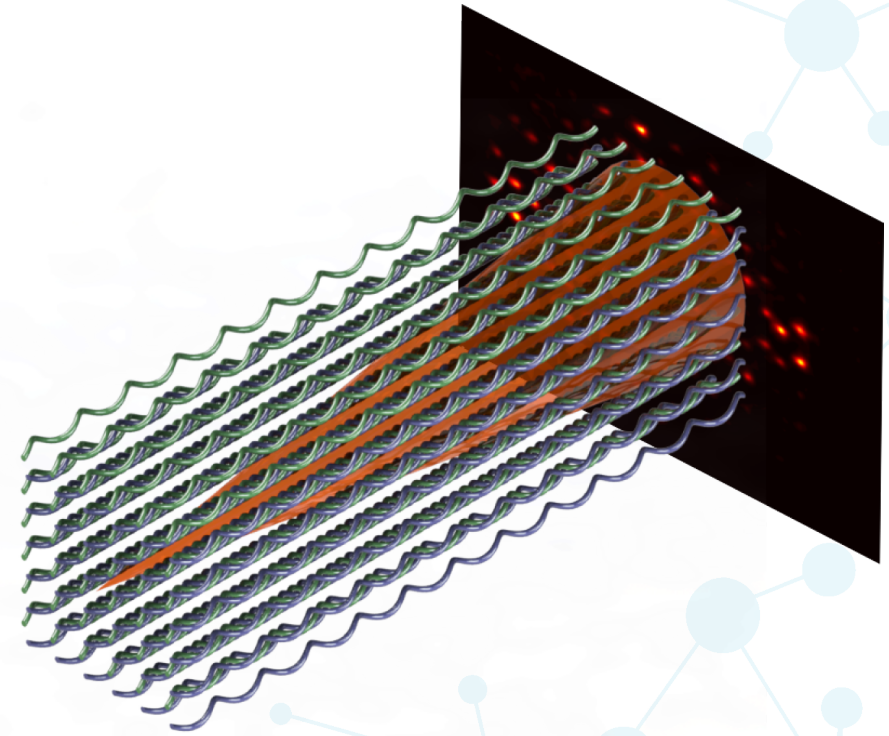
Fabricate waveguides via inscription into glass



Set the topology of the system through its geometry



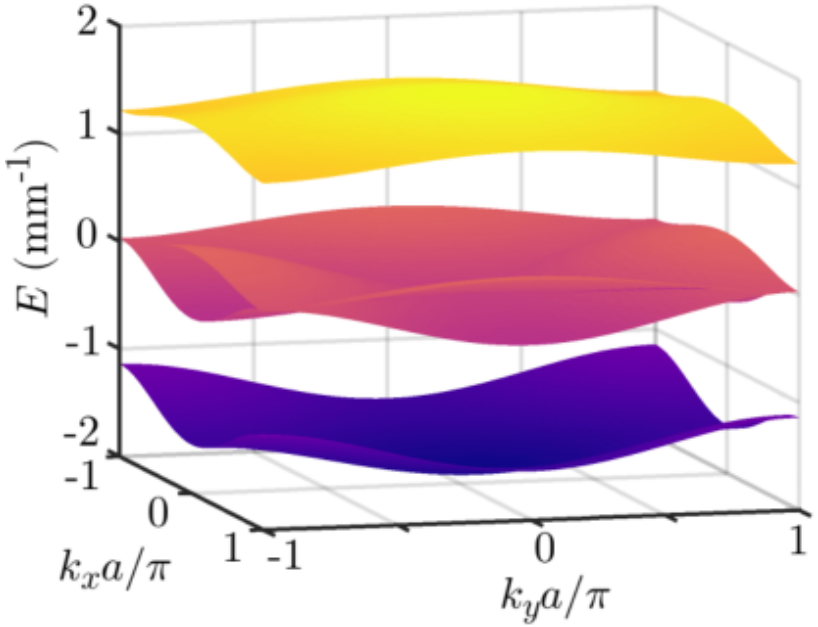
Observe diffraction through the array

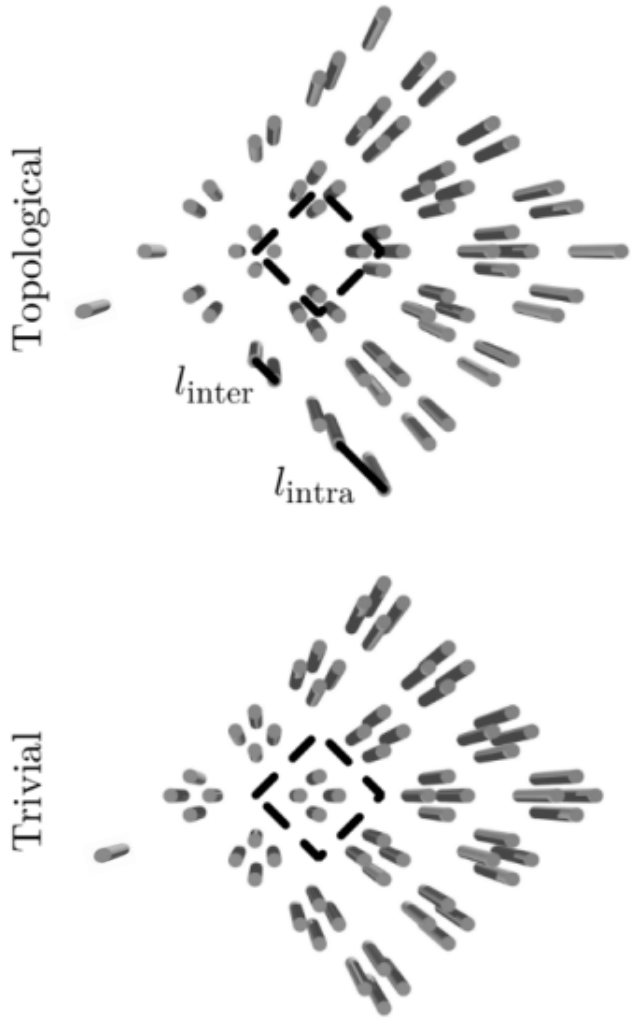


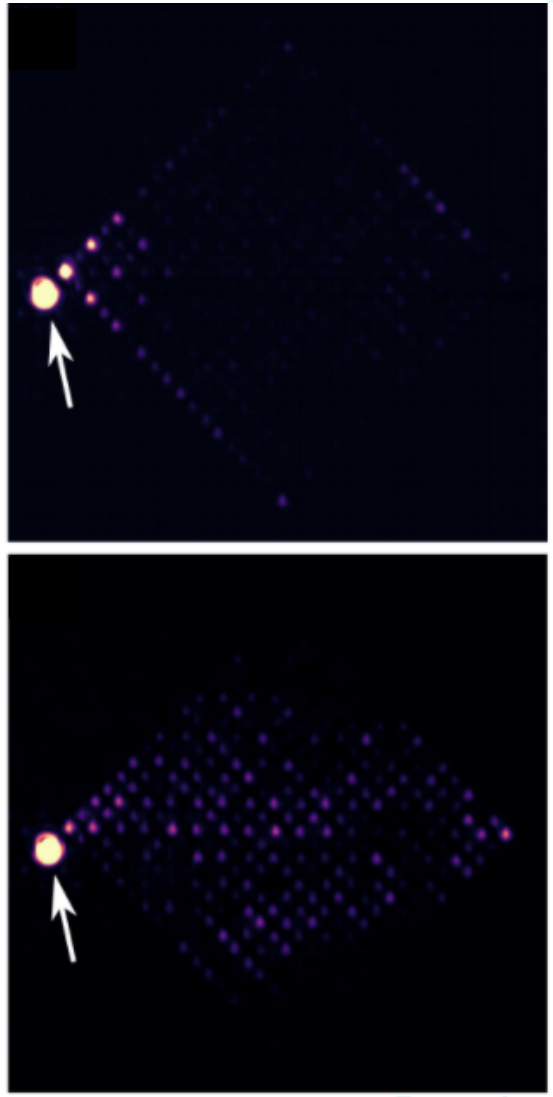
BICs in Higher-order topological systems – Observation

Injecting light with an auxiliary waveguide sets $E = 0$

Letting $l_{\text{intra}} \leftrightarrow l_{\text{inter}}$ maintains the exact same bulk band structure







Topological lattice has a bound state

But the trivial lattice also has states at this energy

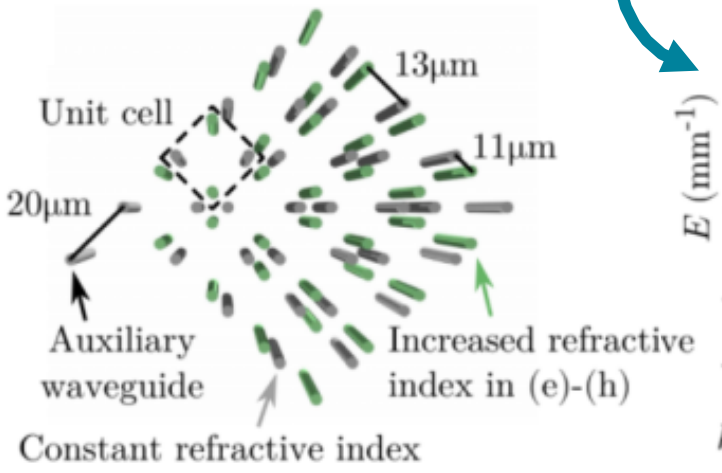
➢ **Higher-order topological BIC**

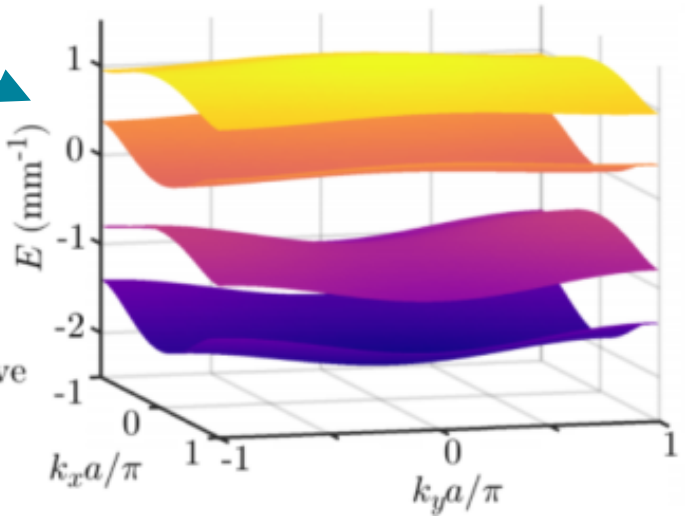
AC et al., *Phys. Rev. Lett.* **125**, 213901 (2020)

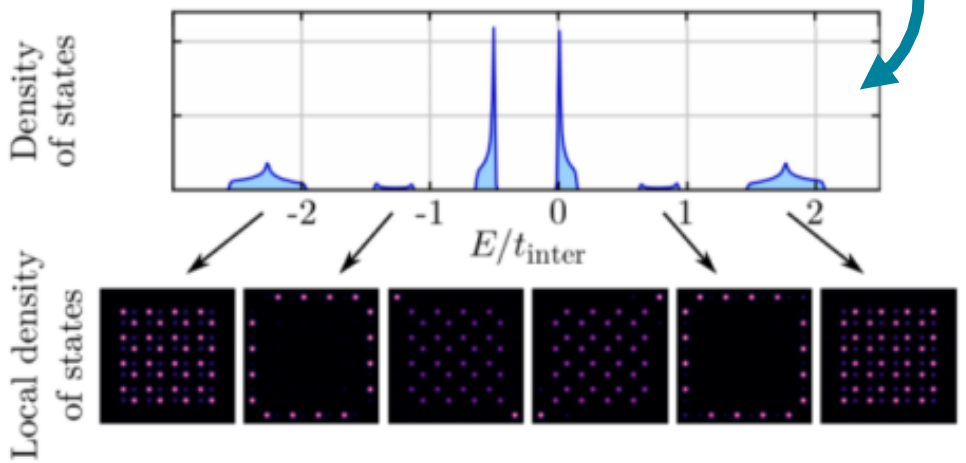
BIC to resonance by breaking symmetry

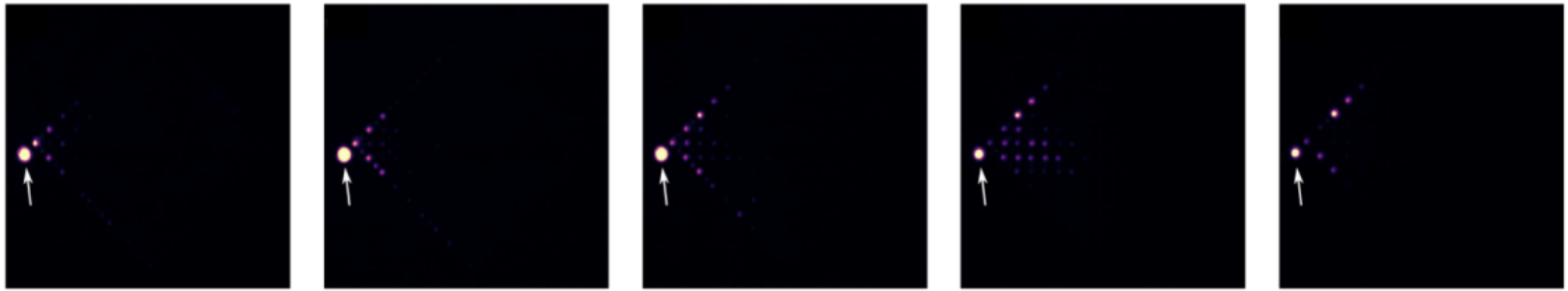
Effect of broken chiral symmetry on the band structure…

…and the local density of states









AC et al., *Phys. Rev. Lett.* **125**, 213901 (2020)

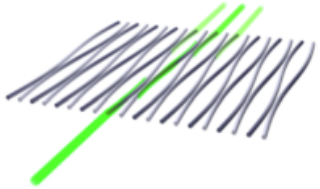
Outline

1) Using environmental engineering to create bound states in the continuum (BICs)
   - What are BICs?
   - What sets the energy scale of BICs? (the Bragg-diffraction limit)
   - Overcoming these limitations using environmental design
2) Higher-order topological bound states in the continuum
   - Create cavities in low-index photonic materials
3) Quick rundown of other interests
   - Topological photonics
   - Non-Hermitian systems
   - New kinds of topological phenomena in non-Hermitian systems

Other fields I'm interested in

- Topological photonics:

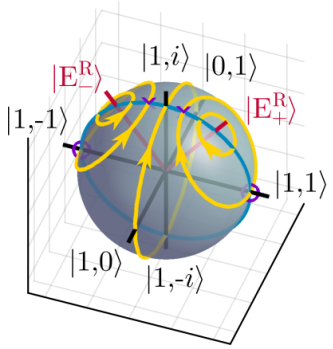
  Thouless pumping:



AC et al., Light Sci. Appl. **9**, 178 (2020)

- Non-Hermitian physics:

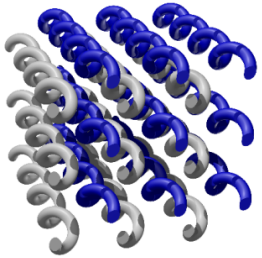
  Polarization control:

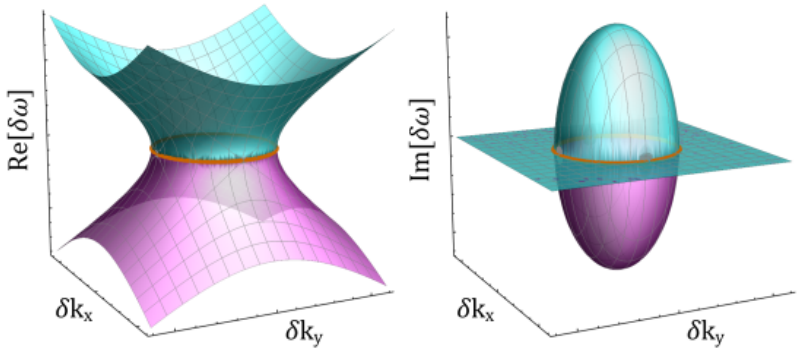


AC and Fan, *Phys. Rev. Lett.* **118**, 253902 (2017)

- And their intersection (Topology + non-Hermiticity)

  Weyl exceptional rings:

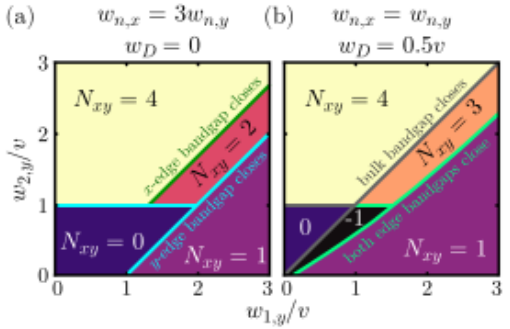




AC et al., *Phys. Rev. B* **97**, 075108 (2018)

AC et al., *Nat. Photonics* **13**, 623 (2019)

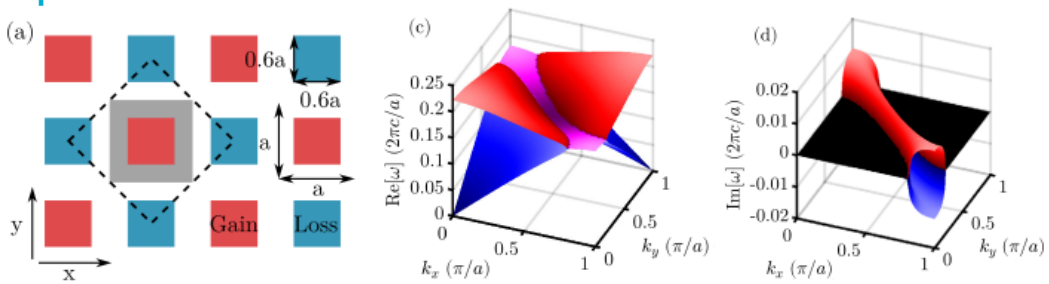
Diagnosing higher-order topological phases:



Benalcazar and AC (in submission)

Terry Loring
UNM

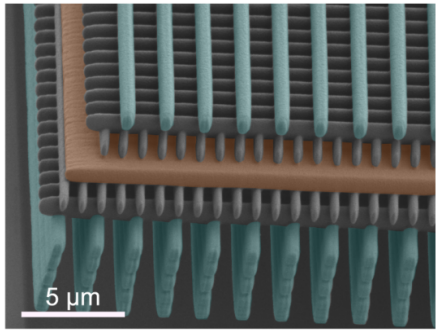
Exceptional contours:

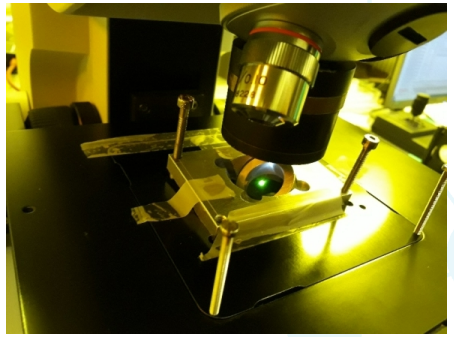


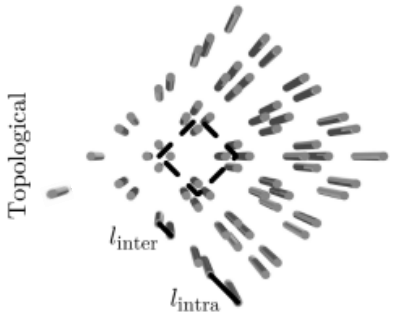
AC, Raman, and Fan, *Phys. Rev. Lett.* **116**, 203902 (2016)

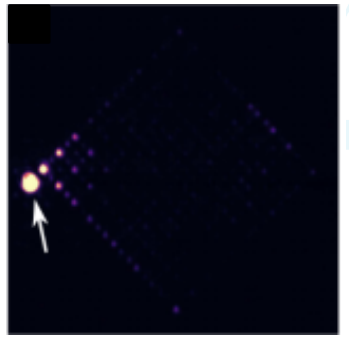
Summary

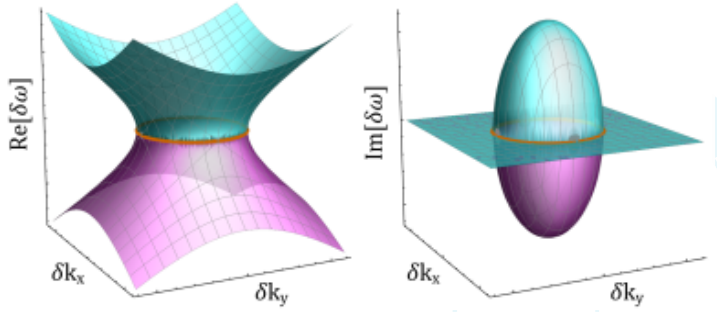
1) Environmental engineering paradigm for creating BICs
   - Limitations of symmetry-protected BICs in homogeneous, isotropic radiative environments
   - Overcoming these limitations using a 3D photonic crystal as the radiative environment
2) Higher-order topological bound states in the continuum
   - Create cavities in low-index photonic materials
3) Quick rundown of other interests
   - Topological photonics
   - Non-Hermitian systems
   - New kinds of topological phenomena in non-Hermitian systems











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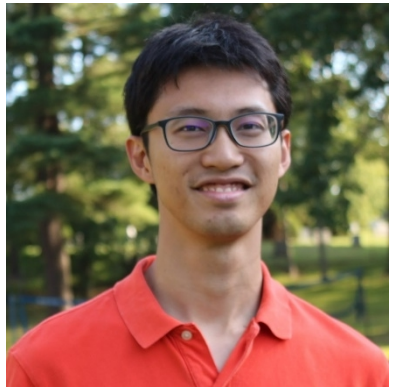

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