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Using symmetry band reate bound sta in the continuum in nic crystals

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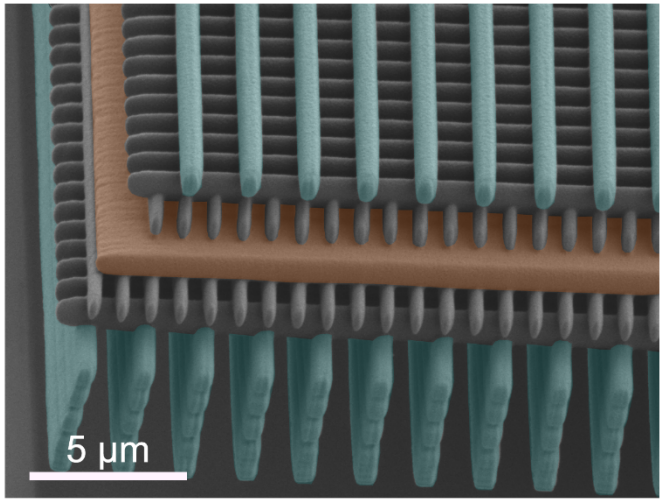
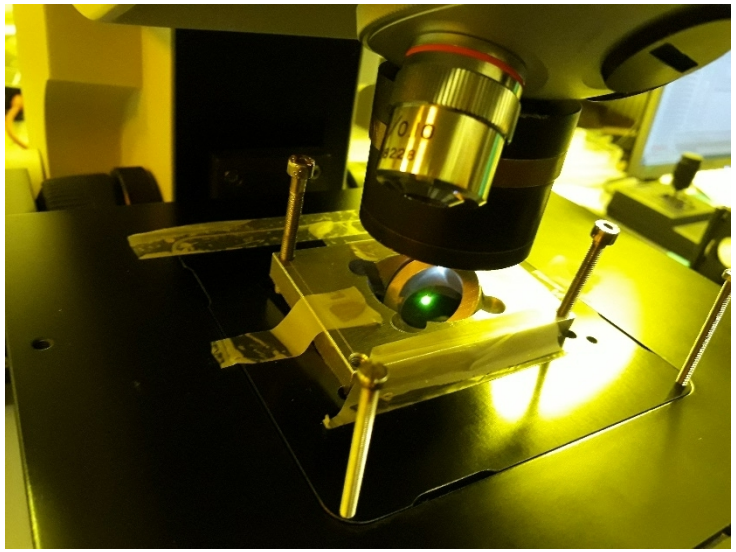
Outline

- Review the differences between resonances and bound states in the continuum (BICs) in photonic crystal slabs and metasurfaces
  - Applications
  - Limitations
- Analytical proof of the limitations of symmetry-protected BICs in homogeneous, isotropic radiative environments
- Overcoming these limitations using a 3D photonic crystal as the radiative environment
  - Theory and experiment





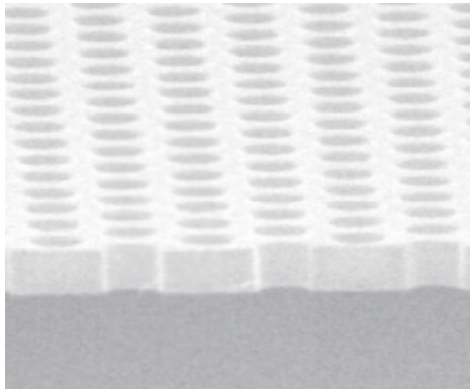
Types of states in photonic crystal slabs

Outside the slab:

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

Conservation of momentum during radiation,

$$\boldsymbol{k}_{\parallel,\mathrm{in}} = \boldsymbol{k}_{\parallel,\mathrm{out}}$$

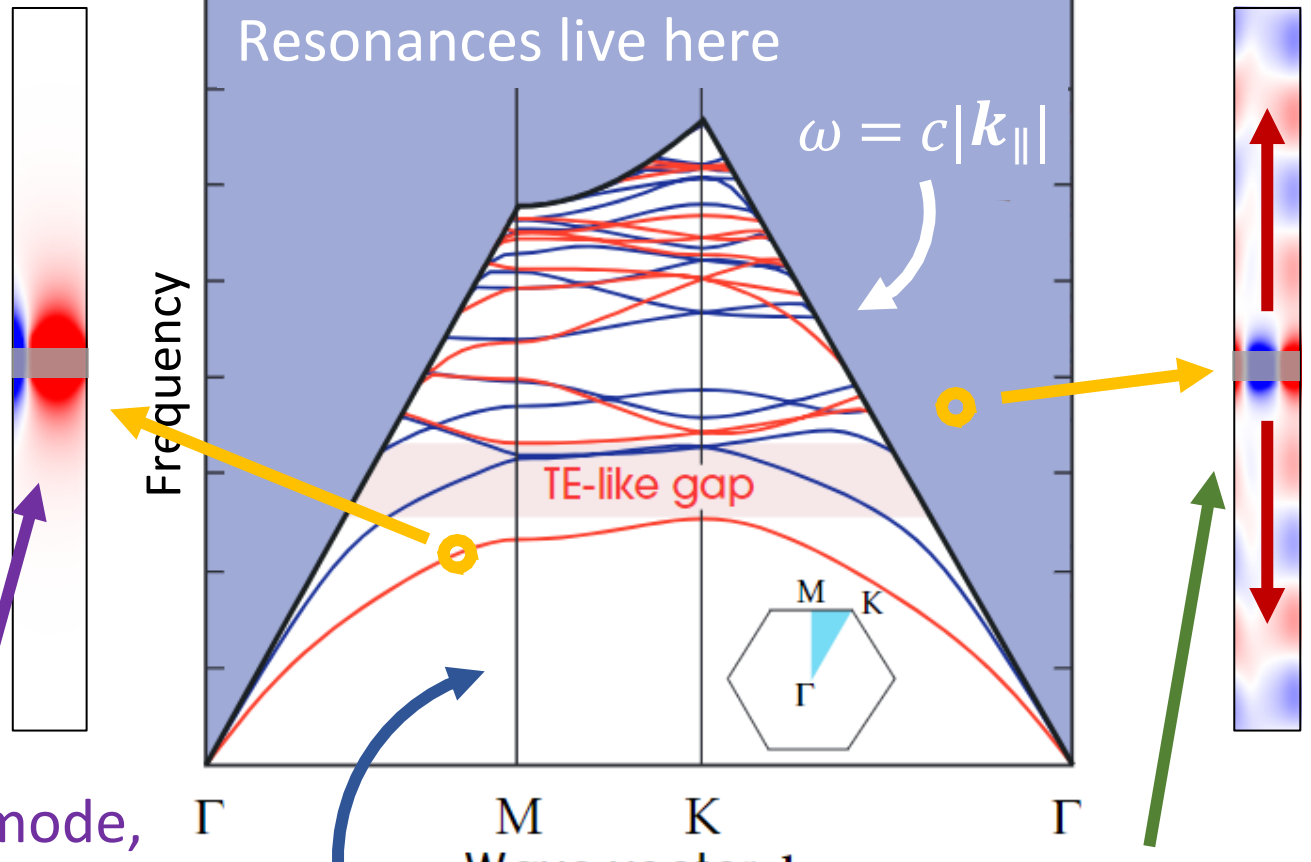


Sugimoto et al., *Opt. Express* 2004

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

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

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



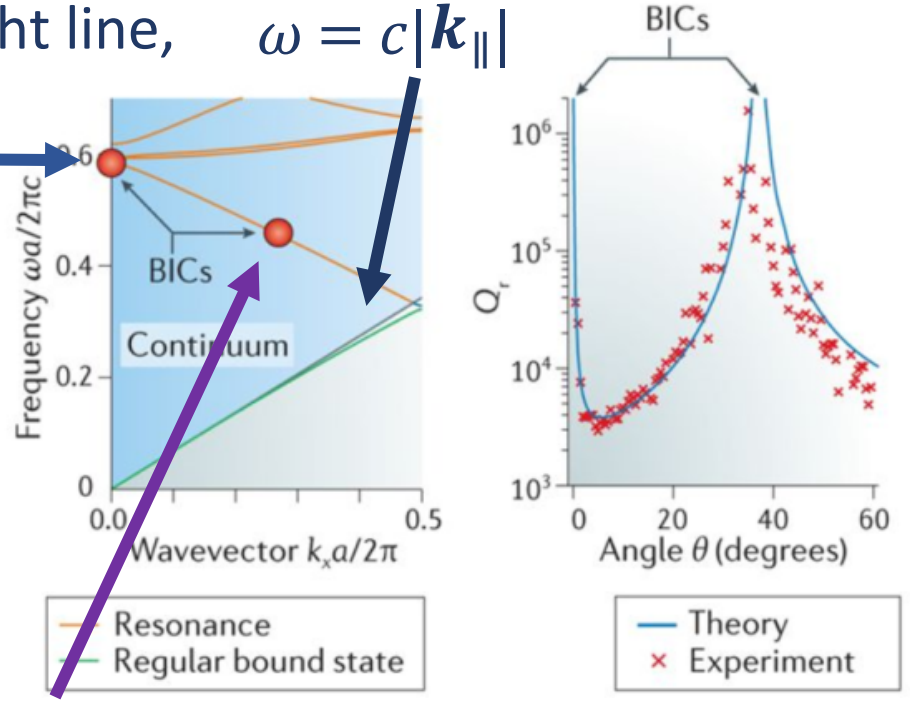
Joannopolous, Johnson, Winn, and Meade, *Photonic Crystals: Molding the flow of light*, 2007

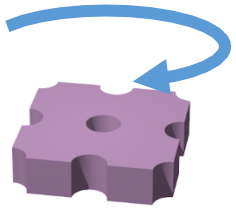
Bound states in the continuum (BICs)

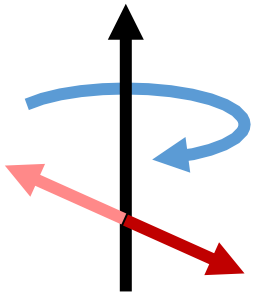
Bound modes above the light line, $\omega = c|\boldsymbol{k}_{\parallel}|$

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







Could not leak 'accidentally'

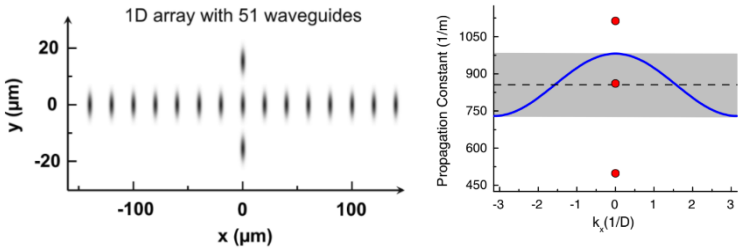
- 2 constraints, d_s, d_p ➢ BIC when $d_s = d_p = 0$
- 2 degrees of freedom, k_x, k_y
  - ➢ Results in a BIC

Hsu, Zhen et al., *Nature* **499**, 188 (2013)

Hsu, Zhen et al., *Nat. Rev. Mater.* **1**, 16048 (2016)

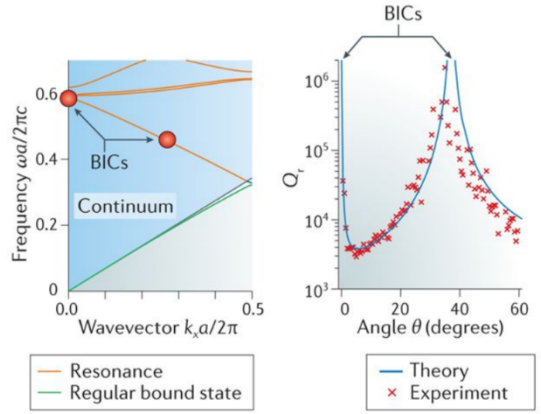
Mechanisms for creating BICs

Symmetry protection



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

Accidentally

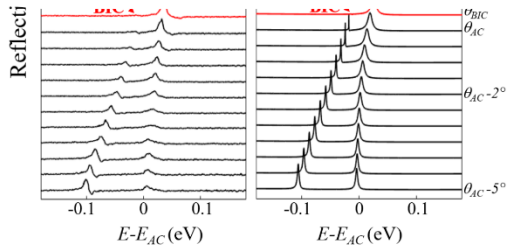


Hsu, Zhen et al., *Nature* **499**, 188 (2013)

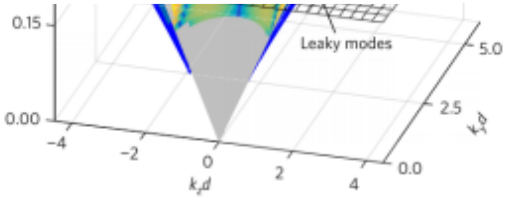
Zhen et al., *PRL* **113**, 257401 (2014)

Applications have almost exclusively focused on symmetry protection

- Predictable
- No fine-tuning required
- Only requires isotropic materials



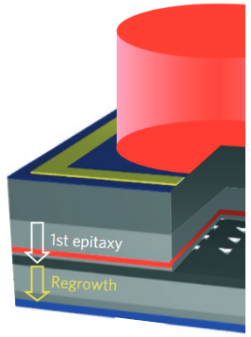
Mermet-Lyaudoz, arXiv:1905.03868



Gomis-Bresco et al., *Nat. Photon.* **11**, 232 (2017)

Uses of symmetry-protected BICs

Photonic Cr



Hirose et al

Limitations of symmetry-protected BICs:

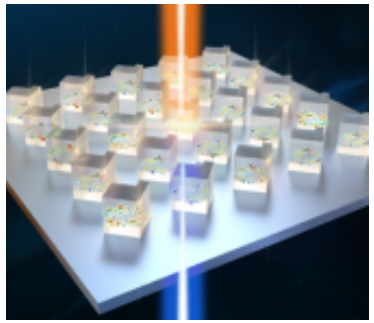
- Only exist at normal incidence
- Always isolated

➢ **Forces single frequency, single wavevector operation**

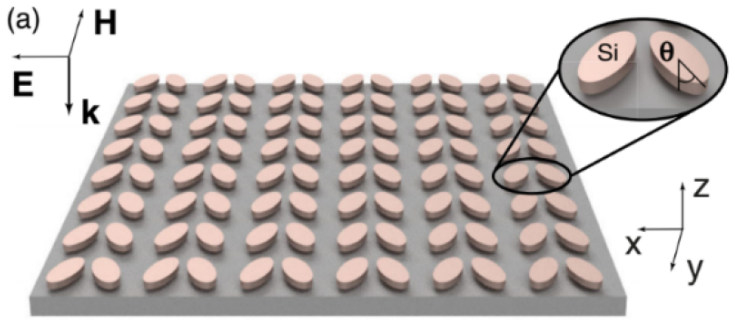
ation

:a **6**, 1039 (2019)
7, 1126 (2020)

Controlling re…

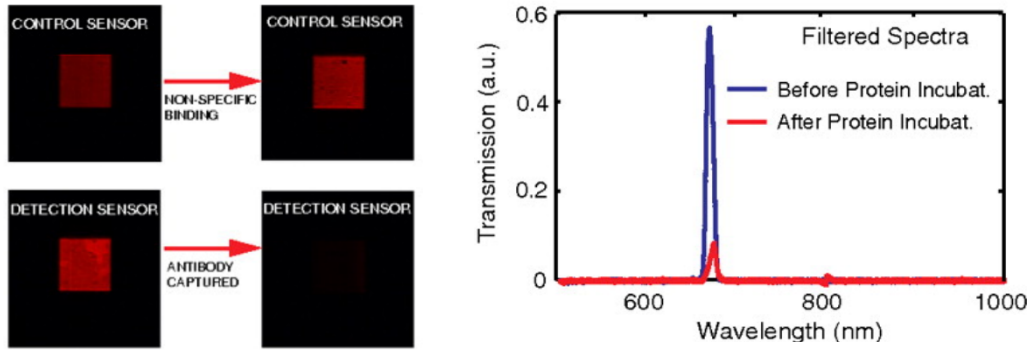


Campione et al., *ACS Photonics* **3**, 2362 (2016)



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

Sensors

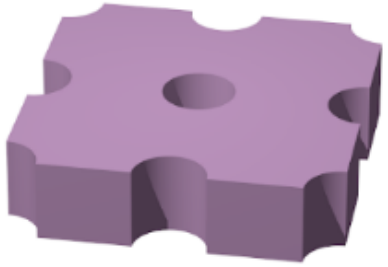


Yanik et al., *Proc. Natl. Acad. Sci.* 108, 11784 (2011)

Limitations on symmetry-protected BICs

Theorem: In a planar system embedded in isotropic, homogeneous environments, symmetry protected BICs only appear at $\mathbf{\Gamma}$, below the diffractive limit.

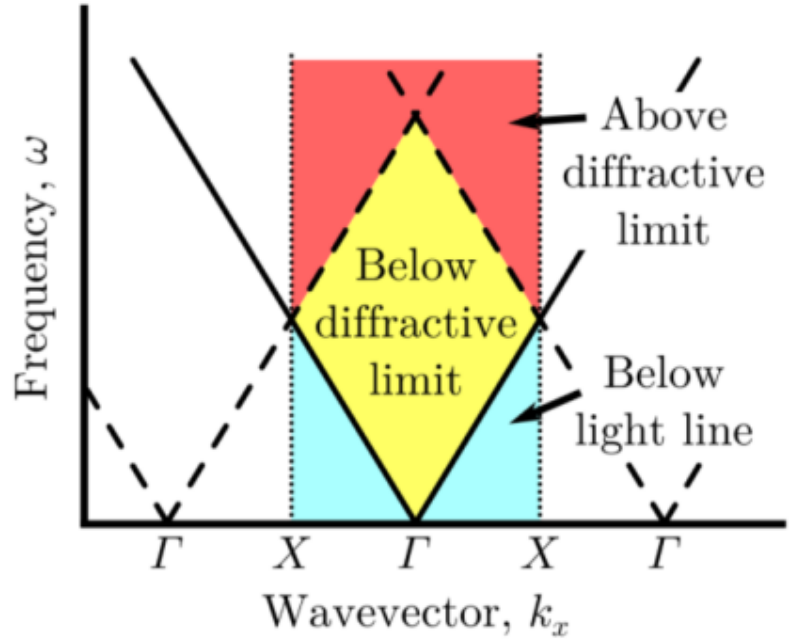
Example: photonic crystal slab surrounded by air



Diffraction limit is

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

(can change momentum when radiating from lattice)



First diffractive order radiative channels span all possible slab symmetries

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

AC,* Jörg,* et al., arXiv:2104.09603

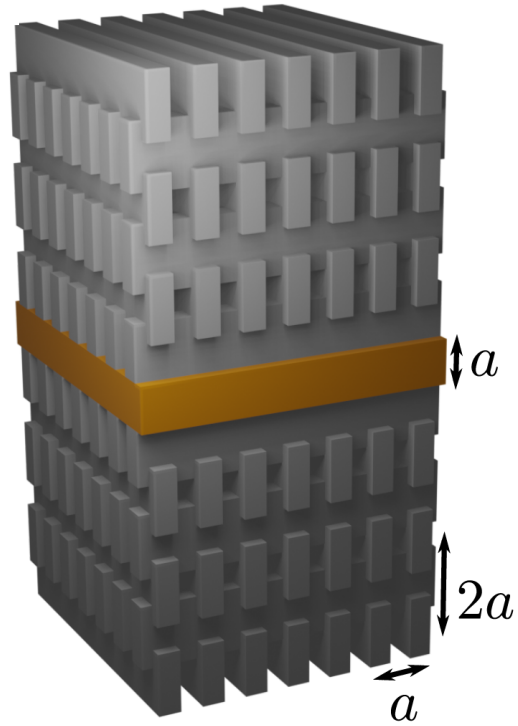
Overcoming this limitation

Need to either break:

isotropy – using birefringent materials in the environment

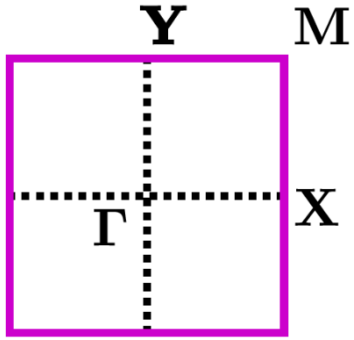
homogeneity – by patterning the environment

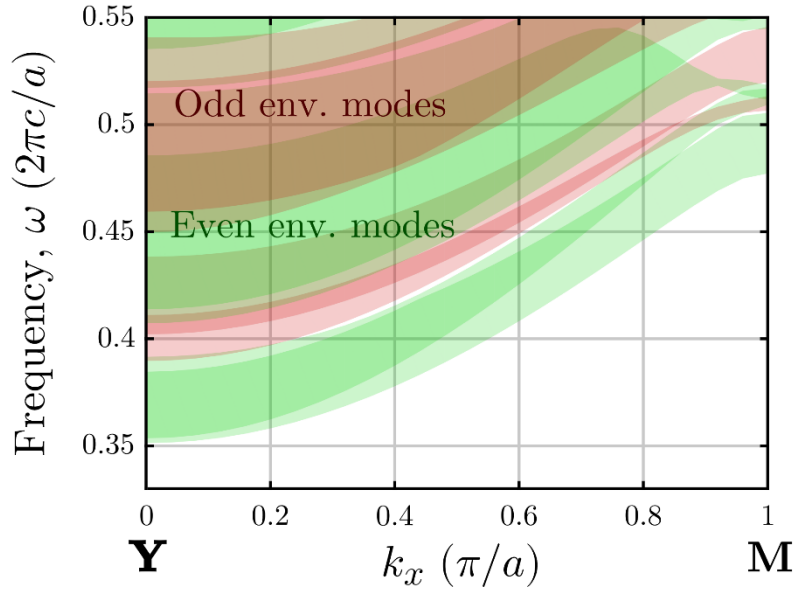
Embed slab in a 3D photonic crystal ➢ Changes the radiative channels to be the photonic crystal's projected-in-k_z bands, $\omega_n(\mathbf{k}_\parallel)$



Remember – Looking for a slab symmetry not in the environment

So, look along high-symmetry lines:

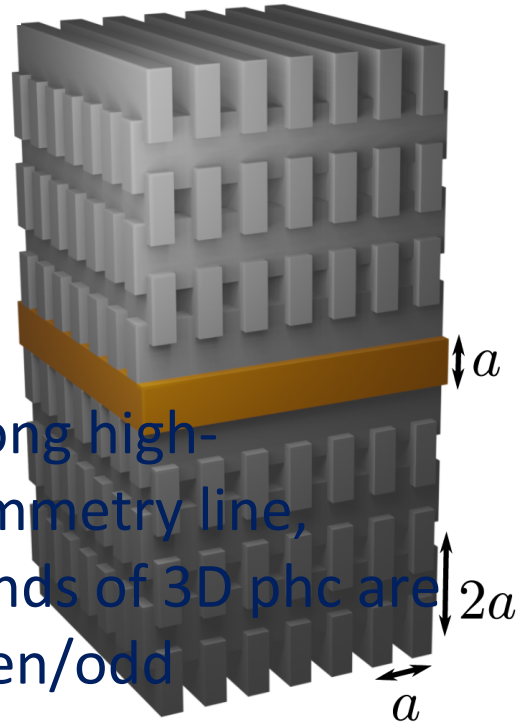




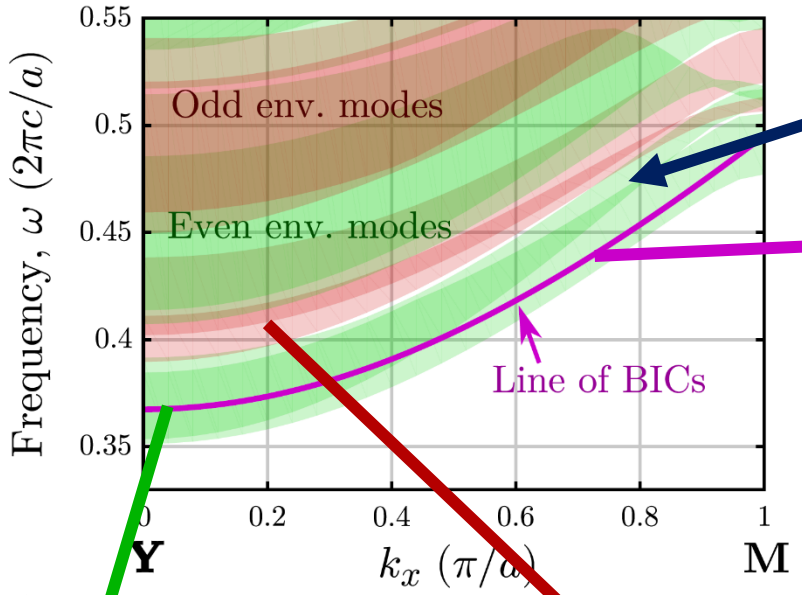
Overcoming this limitation

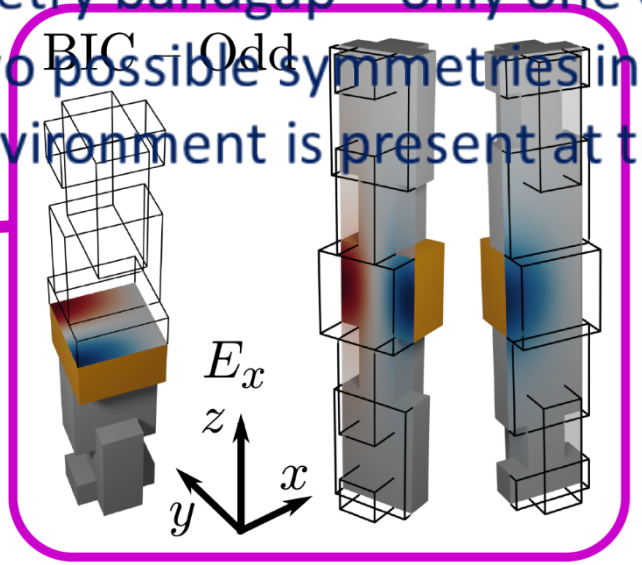
Can find a line of BICs against the continuum with the wrong symmetry

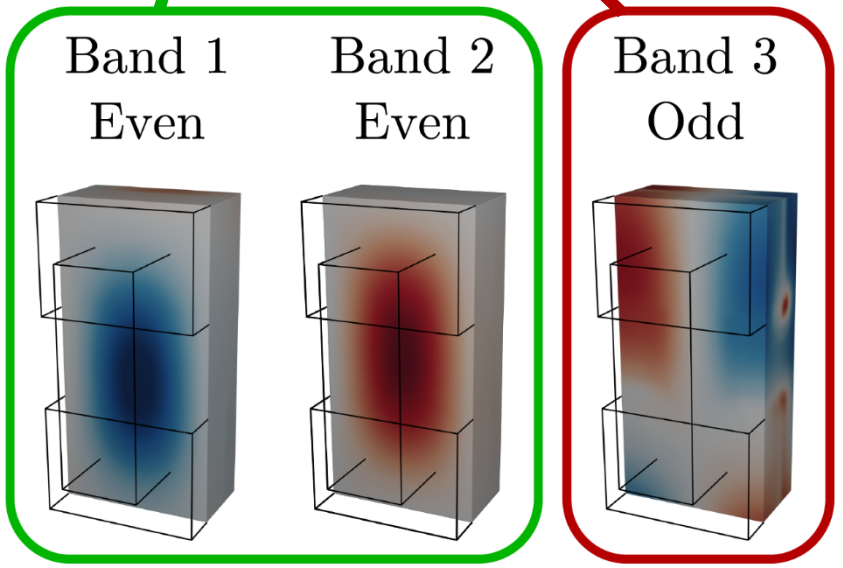
Symmetry bandgap – only one of the two possible symmetries in the environment is present at this ω

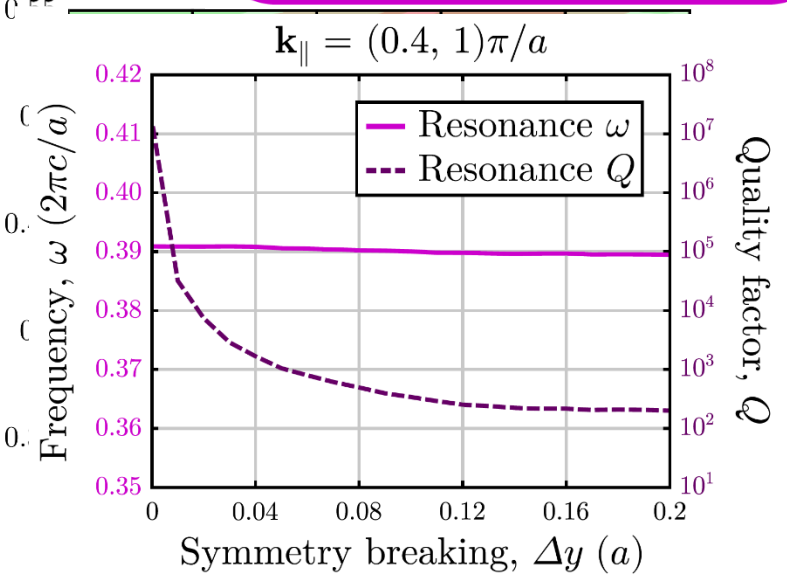


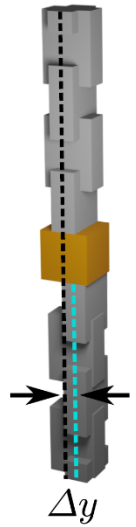
Along high-symmetry line, bands of 3D phc are even/odd





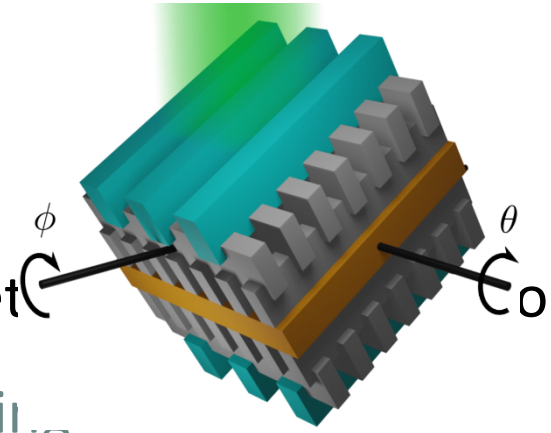






Observing a line of BICs

Effect can still be observed with just a single complet onment

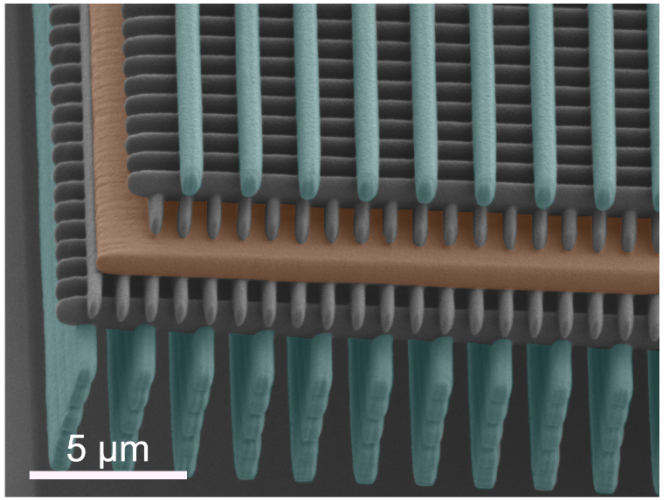


$\theta - k_x$ $\phi - k_y$

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

In simulation

Fabricate using a Nanoscribe



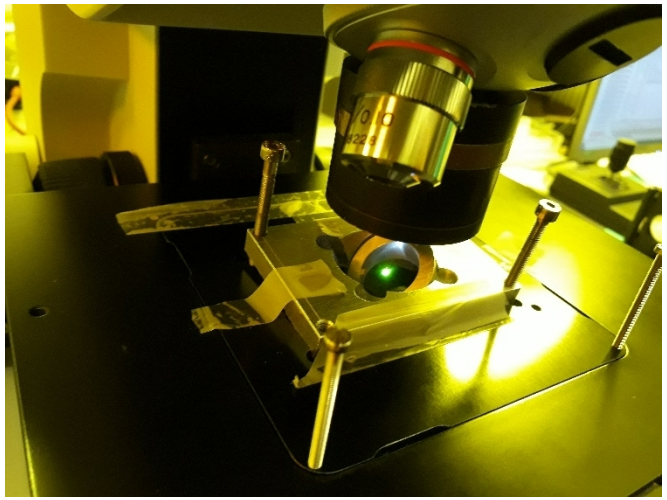
Grati g

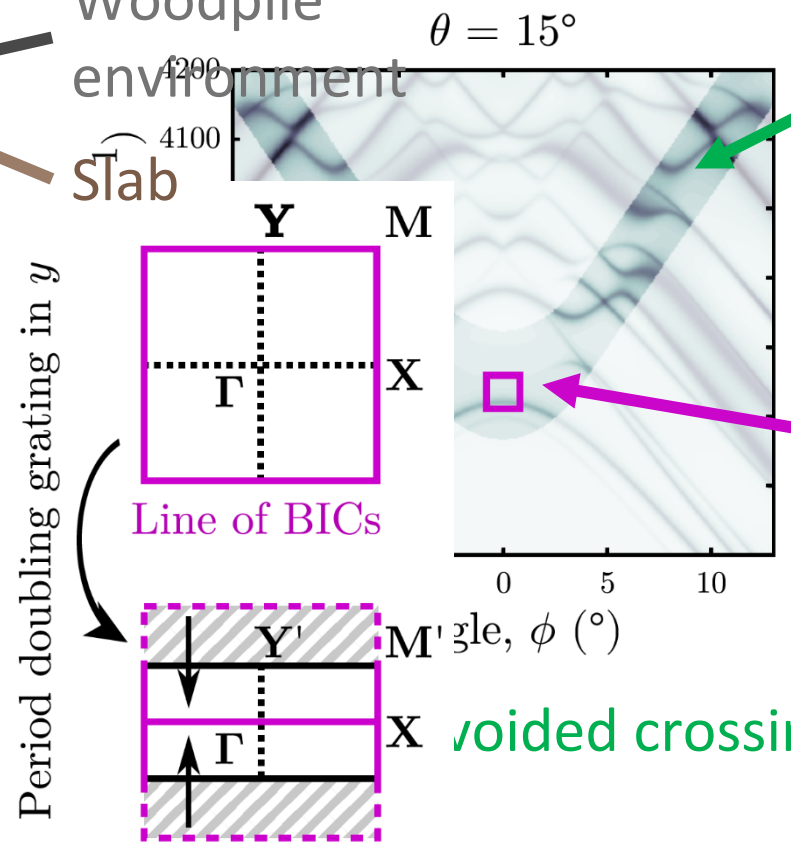
Woodpile

environment

Slab

Observe with an FTIR





Slab resonance away from BIC

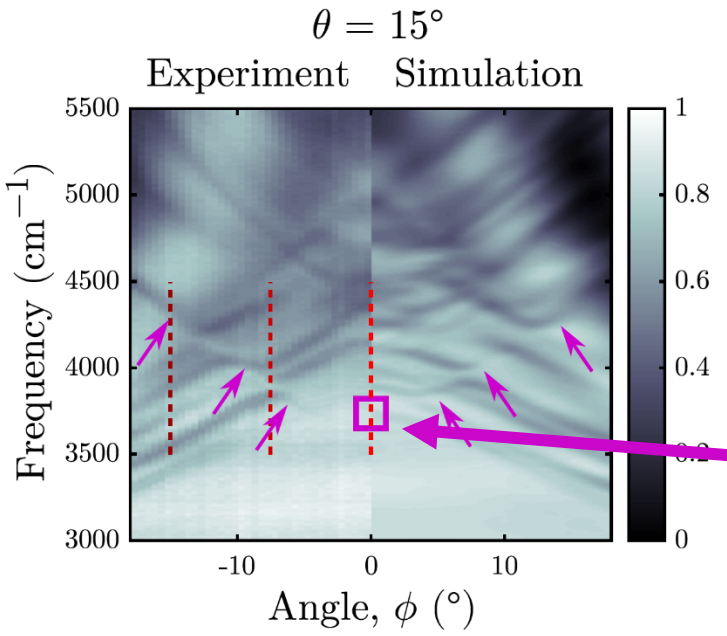
$Q \to \infty$ as $\phi \to 0$

Disappearance implies BIC

voided crossings

AC,* Jörg,* et al., arXiv:2104.09603

Observing a line of BICs

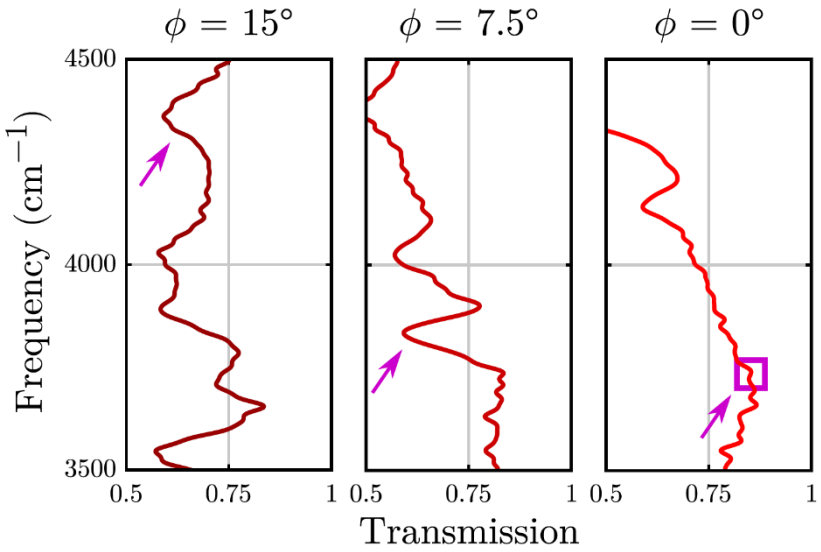


$\theta - k_x$ angle

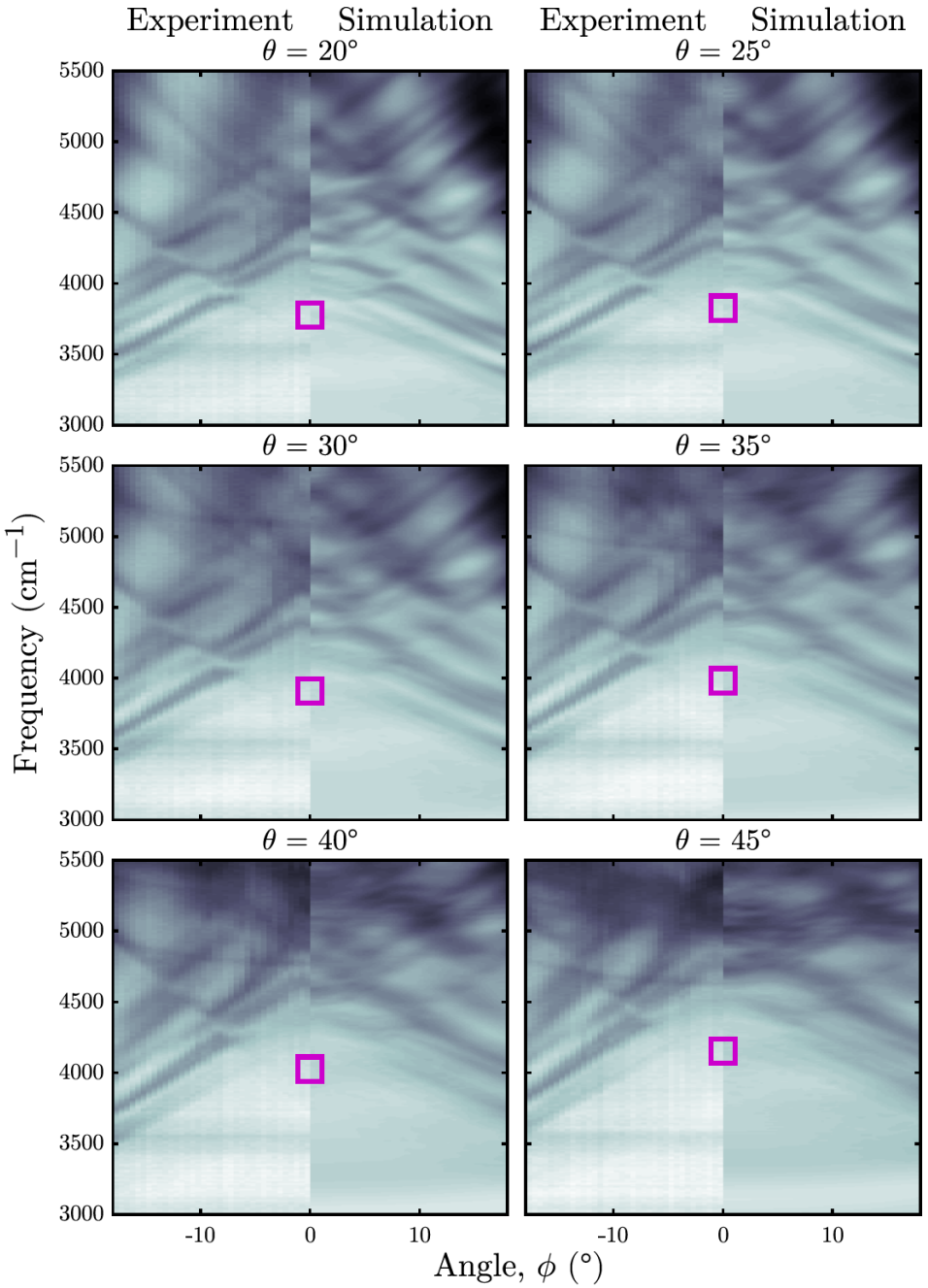
$\phi - k_y$ angle

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

BIC at $\phi = 0$



Different θ still yield BICs



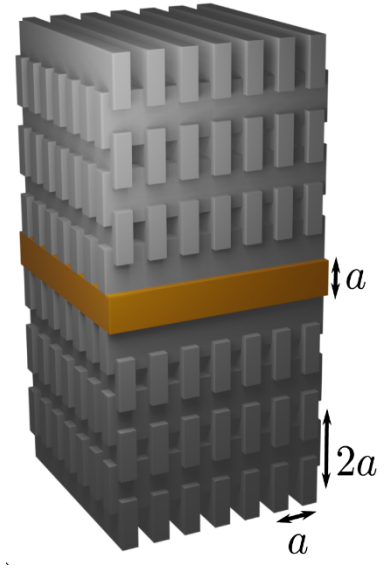
AC,* Jörg,* et al., arXiv:2104.09603

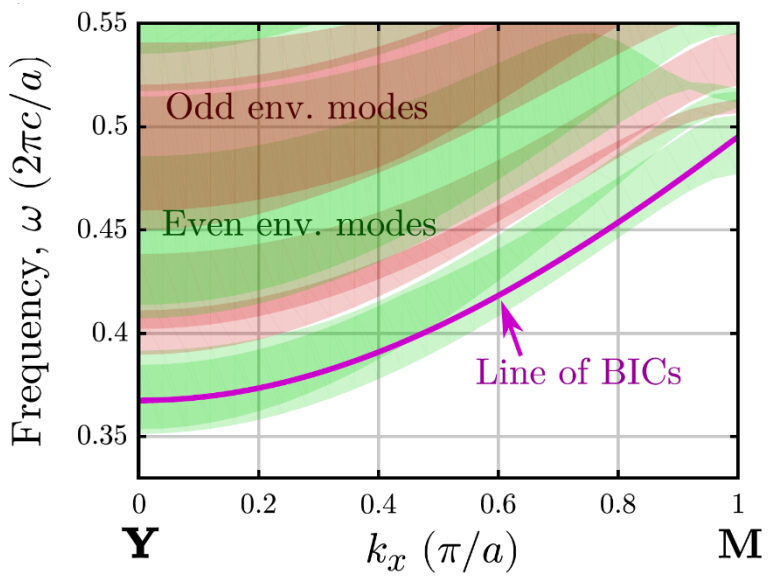
Summary

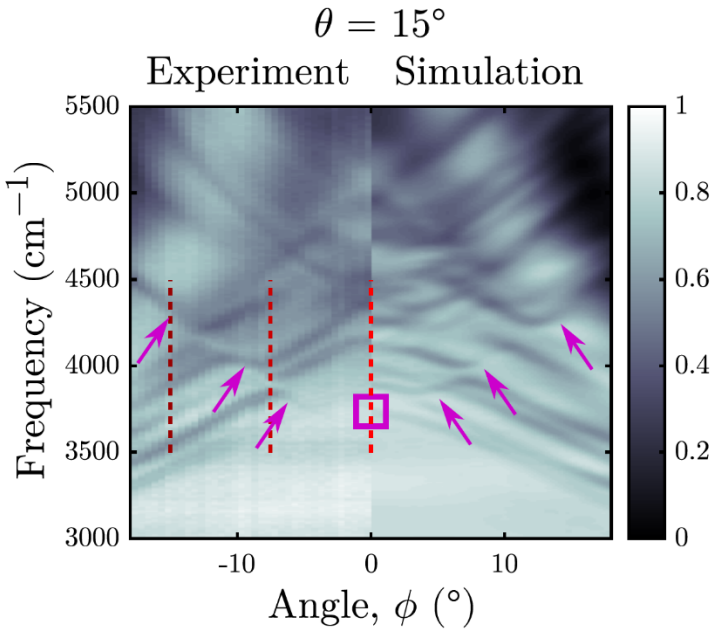
AC,* Jörg,* et al., arXiv:2104.09603

- Analytical argument of the limitations of symmetry-protected BICs in photonic crystal slabs and metasurfaces surrounded by air
  - Full proof can be completed using representation theory

- Can achieve multi-frequency, multi-wavevector BICs in a monolithic device using a single layer of a 3D photonic crystal surrounding the slab







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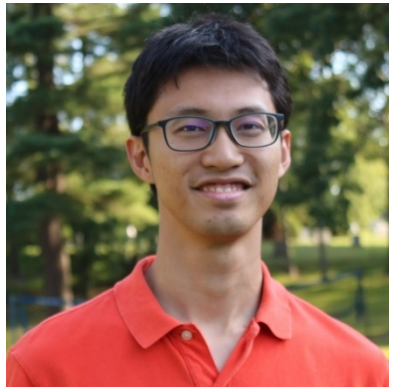

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