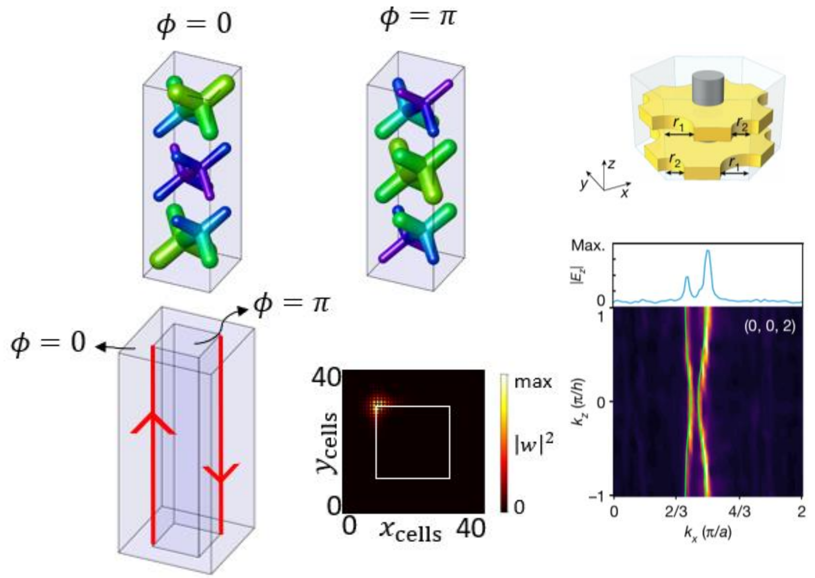
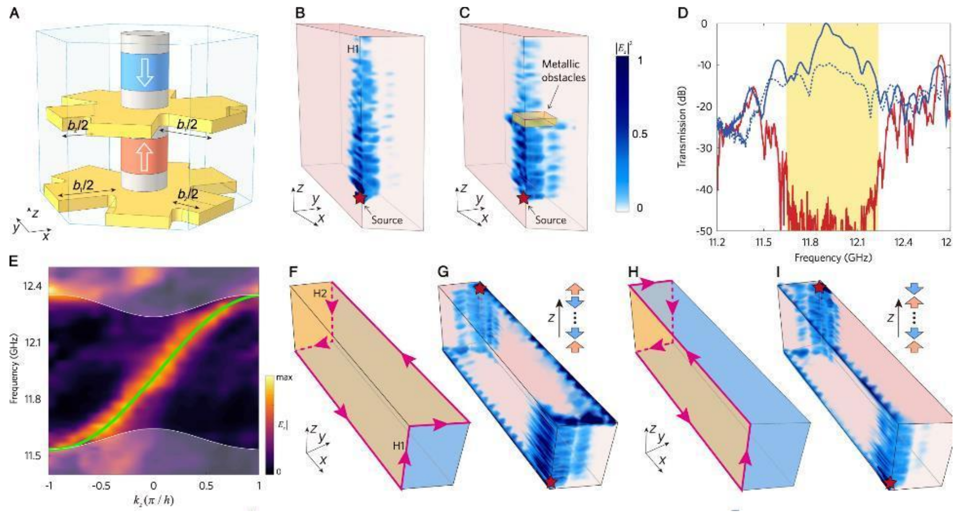
Photonic axion domain walls and insulators

Chiara Devescovi (ETH Zurich)





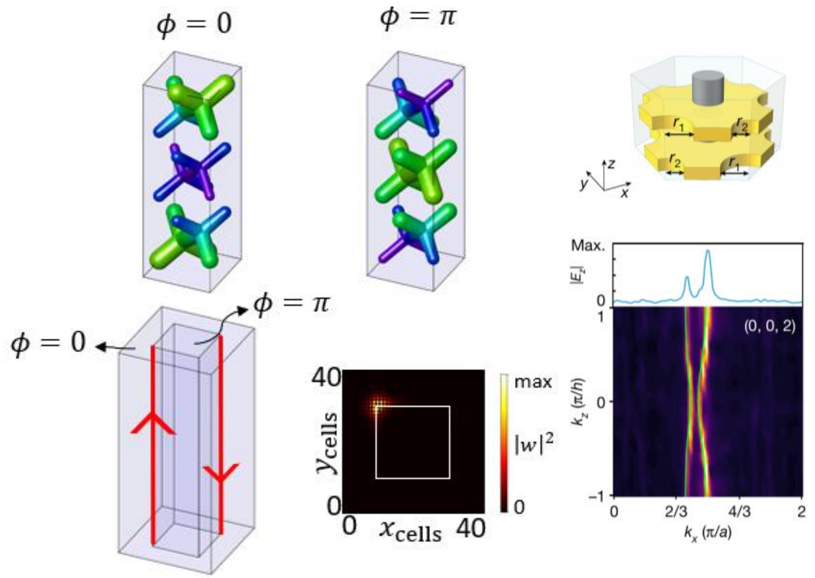
Aitzol García Etxarri
Maia García Vergniory
Antonio Morales Perez

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Gui-Geng Liu
Subhaskar Mandal
Yidong Chong
Baile Zhang

In this presentation:

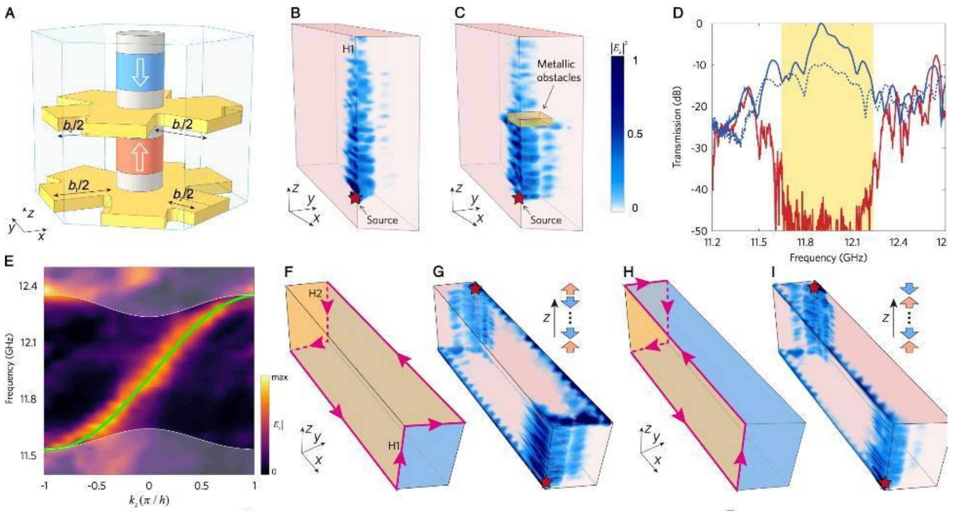
Realizing an AXI **for light**



Axion topology in photonic crystals

Nat. Comm. 15, 6814 (2024)

From **Relative** to **Instrinsic** photonic AXI



Photonic Axion Insulator

Science 387, 162–166 (2025)

Outline

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3D magnetic
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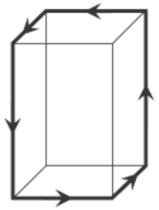

$\theta = \pi$

$$\theta = \frac{1}{12\pi}\int_{BZ} Tr\varepsilon^{\mu\nu\rho}\left[A_\mu\partial_\nu A_\rho - \frac{2i}{3}A_\mu A_\nu A_\rho\right]d^3k$$

X.L. Qi, T. L. Hughes, and S.C. Zhang, "Topological field theory of time-reversal invariant insulators" PRB 78, 195424 (2008)

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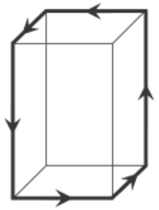

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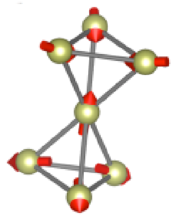
Invariant quantization:

$\theta \to -\theta$

e.g. Inversion (I)



Varnava et al., Phys. Rev. B 98, 245117 (2018)

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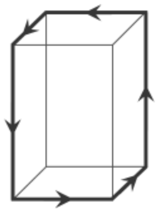

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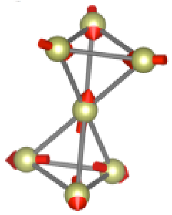


Varnava et al., Phys. Rev. B 98, 245117 (2018)

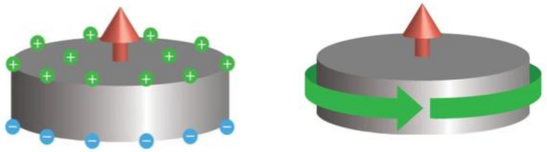
Axion-modified electrodynamics

$\mathcal{L} \propto \theta \boldsymbol{E} \cdot \boldsymbol{B}$

$$\begin{cases} \nabla \cdot (\varepsilon \boldsymbol{E}) = -\nabla\theta \cdot \boldsymbol{B} \\ \nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \cdot \boldsymbol{B} = 0 \\ \nabla \times \mu^{-1}\boldsymbol{B} = \frac{\partial(\varepsilon \boldsymbol{E})}{\partial t} + \nabla\theta \times \boldsymbol{E} + \frac{\partial\theta}{\partial t}\boldsymbol{B} \end{cases}$$

F. Wilczek, "Two applications of axion electrodynamics", PRL letters 58, 1799 (1987)

$\boldsymbol{P} = \theta\boldsymbol{B}$ $\boldsymbol{M} = \theta\boldsymbol{E}$



Topological quantized magnetoelectric effects

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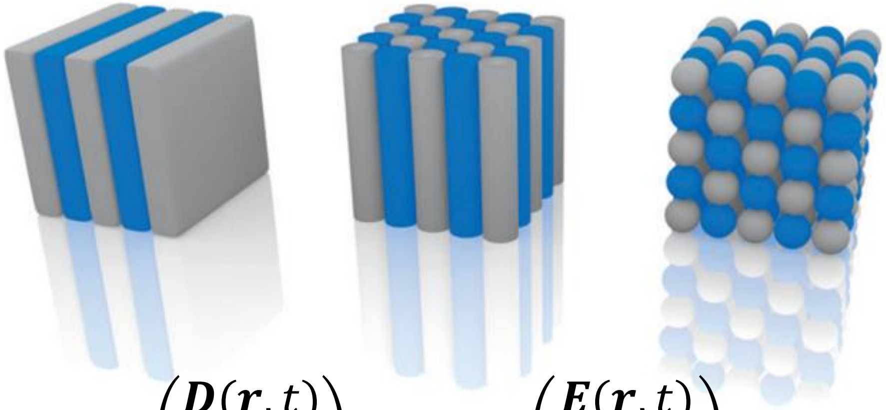
What is a Photonic Crystal?



$$\begin{pmatrix} \boldsymbol{D}(\boldsymbol{r},t) \\ \boldsymbol{B}(\boldsymbol{r},t) \end{pmatrix} = \boldsymbol{\mathcal{K}}(\boldsymbol{r}) \begin{pmatrix} \boldsymbol{E}(\boldsymbol{r},t) \\ \boldsymbol{H}(\boldsymbol{r},t) \end{pmatrix}$$

$$\boldsymbol{\mathcal{K}}(\boldsymbol{r}) = \begin{pmatrix} \overleftrightarrow{\varepsilon}(\boldsymbol{r}) & \overleftrightarrow{\xi}(\boldsymbol{r}) \\ \overleftrightarrow{\chi}(\boldsymbol{r}) & \overleftrightarrow{\mu}(\boldsymbol{r}) \end{pmatrix}$$

Constitutive dielectric tensor is periodic $\boldsymbol{\mathcal{K}}(\boldsymbol{r}) = \boldsymbol{\mathcal{K}}(\boldsymbol{r}+\boldsymbol{R})$

Periodic Maxwell equations: bandgaps for light

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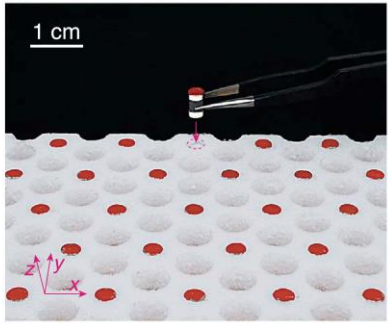
Clean and flexible platform

- Tunable symmetries (TRS, inversion)
- No stringent material constraints
- Compatible with inverse-design



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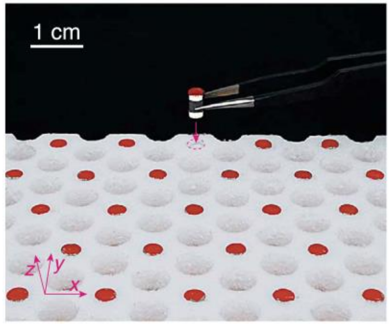
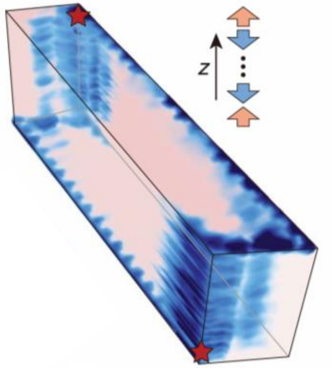


Direct access to electromagnetic response

- Field-resolved experiments possible
- All **measurable via optical probes**



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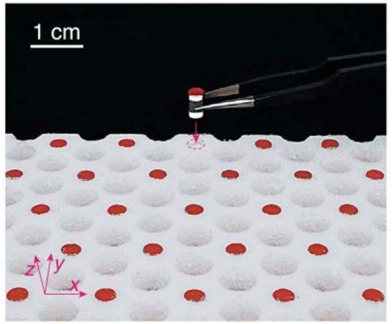

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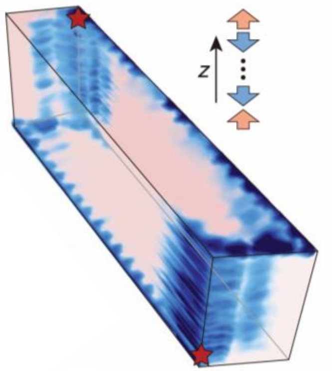
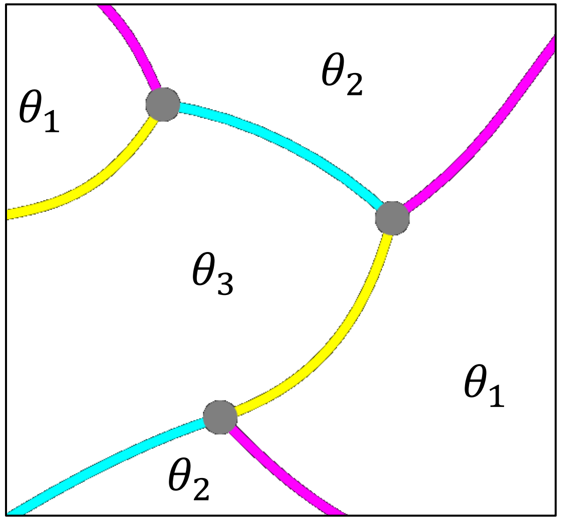


Can implement $\boldsymbol{\theta}$ **as a spatially varying parameter** $\boldsymbol{\theta(x)}$**:**
something **not feasible in particle physics experiments**

Simulating Axion Domain Walls

Can implement $\boldsymbol{\theta}$ **as a spatially varying parameter** $\boldsymbol{\theta(x)}$**:** enabling direct exploration of topological domain-wall physics

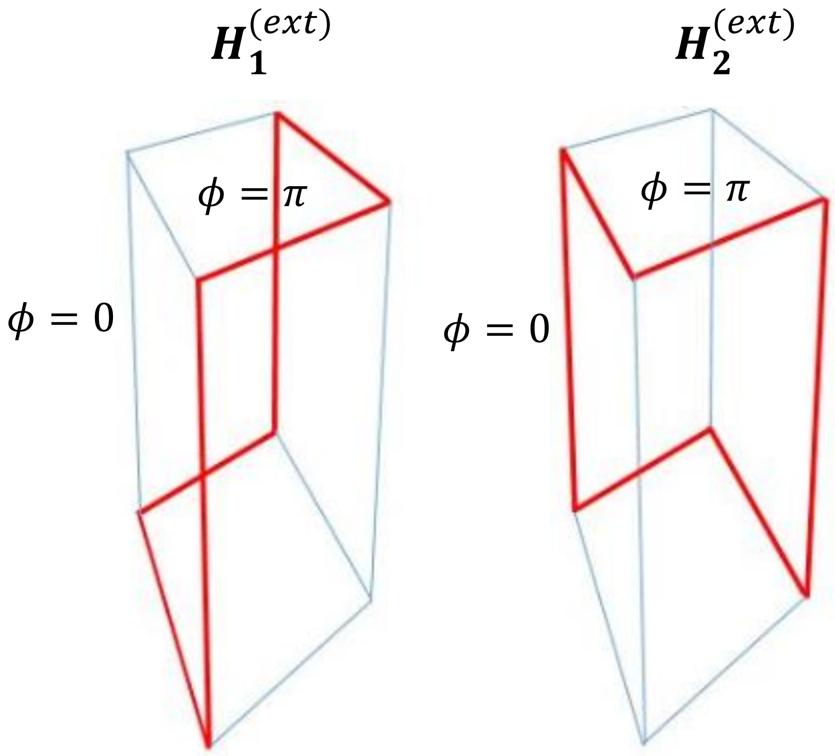
Axion strings



Armengaud, Journal of Cosmology and Astroparticle Physics, 2019(06), 047.

Manipulating Axion Domain Walls

Propose physically accessible ways to control the axion string **connectivity**



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Design strategy

How to open an AXI gap in a PhC? I-symmetric and T-broken

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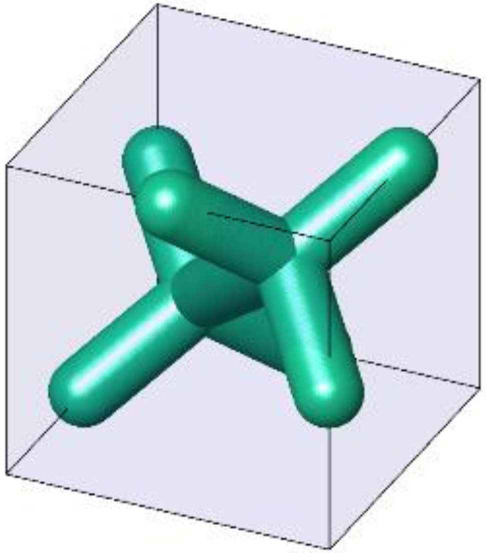
inversion center
+
3-fold axis



$$\overleftrightarrow{\varepsilon} = \begin{pmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}$$

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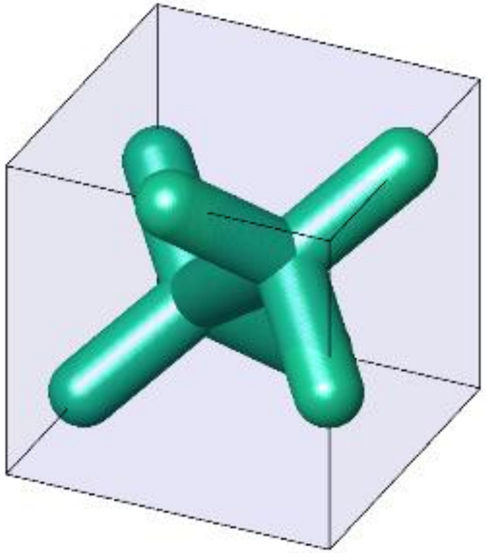

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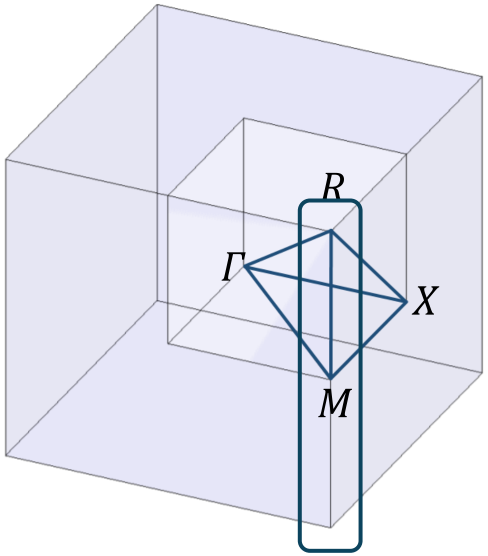

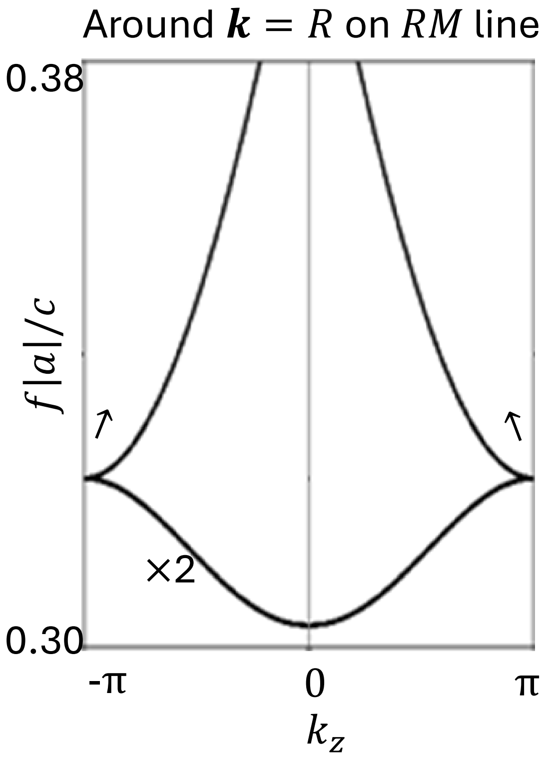

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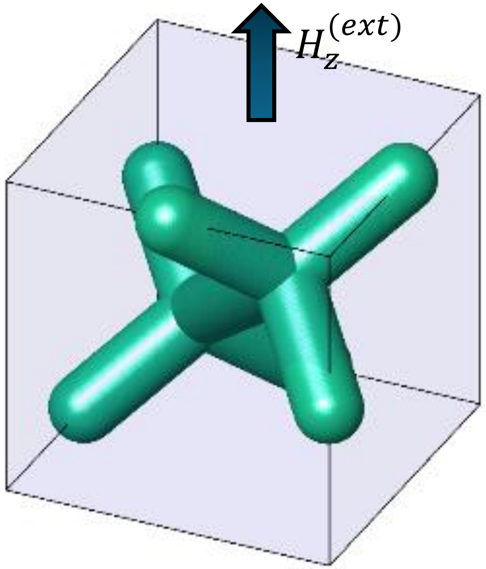
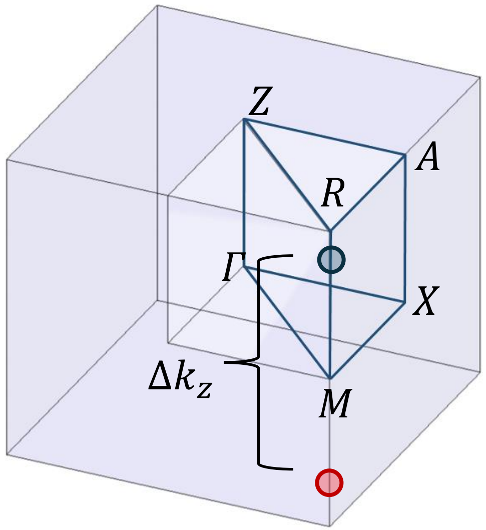
Step 1: Gyrotropy via Yittrium Iron Garnets (YIGs)

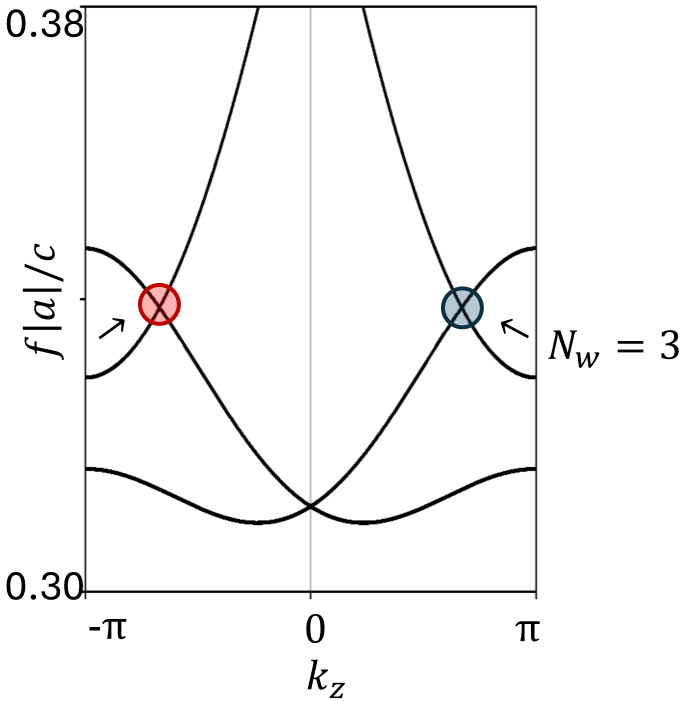


$$\overleftrightarrow{\varepsilon} = \begin{pmatrix} \varepsilon_\perp & i\eta_z & 0 \\ -i\eta_z & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}$$

→

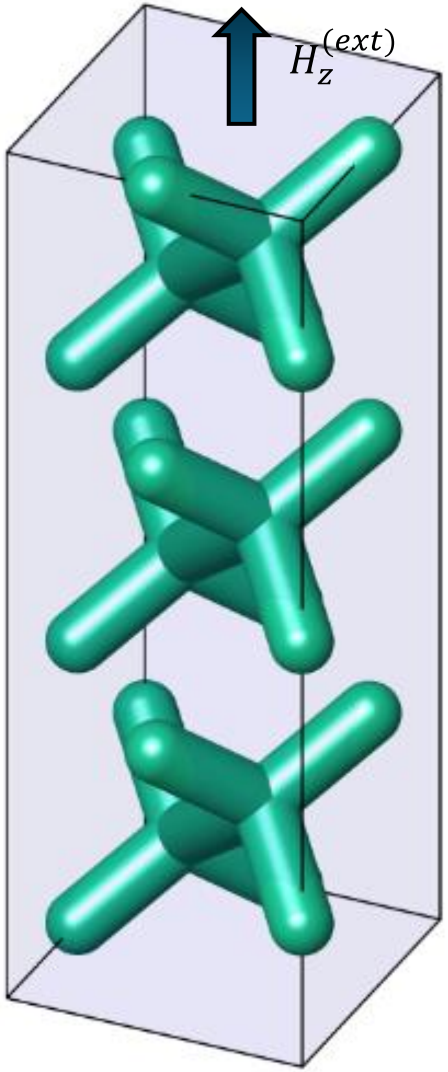


$$\Delta k_z = 2\pi / N_w$$



Weyl splitting at integer fractions of the BZ

Step 2: Commensurate supercell



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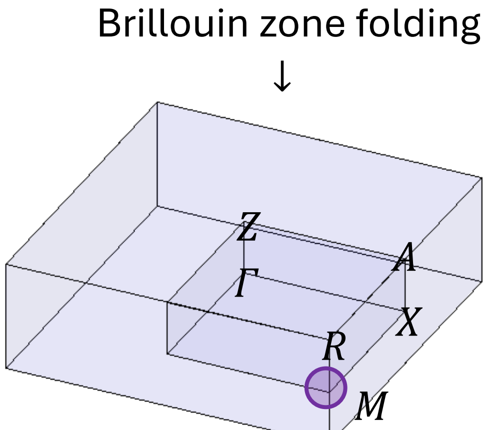
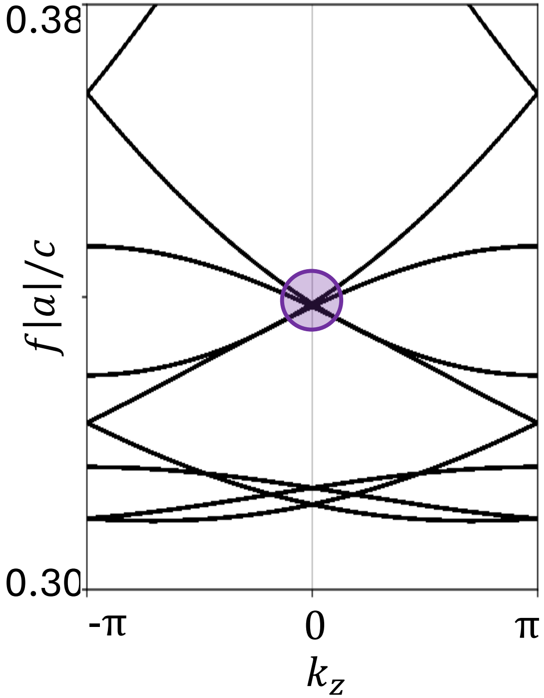
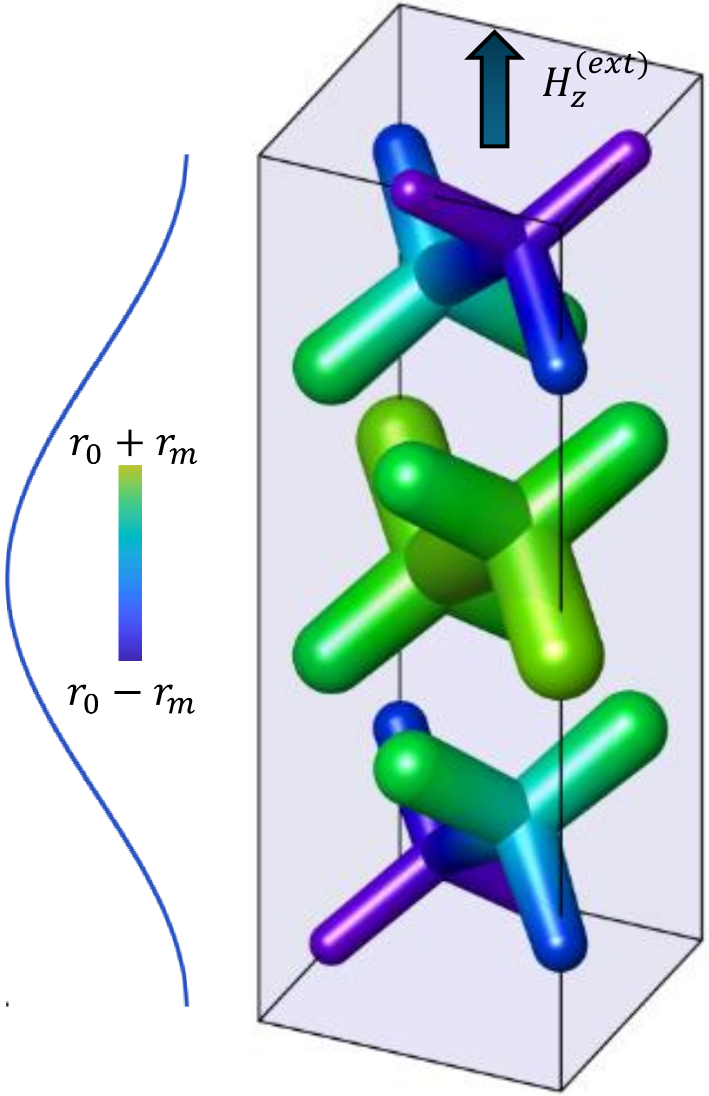




Step 3: Dielectric modulation



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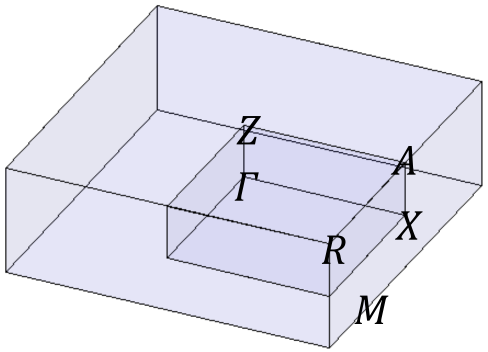
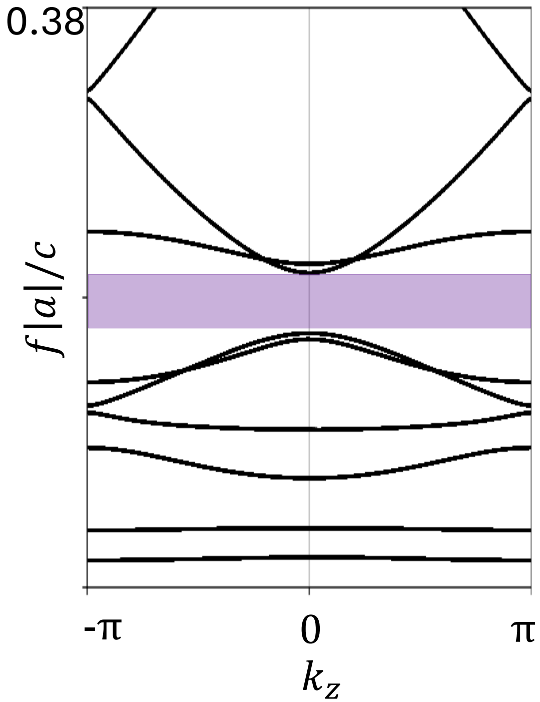
Weyl annihilation





ϕ : Supercell Modulation (SM) Phase

$$\Delta r = r_m \cos\left(\frac{2\pi z}{N} + \phi\right)$$

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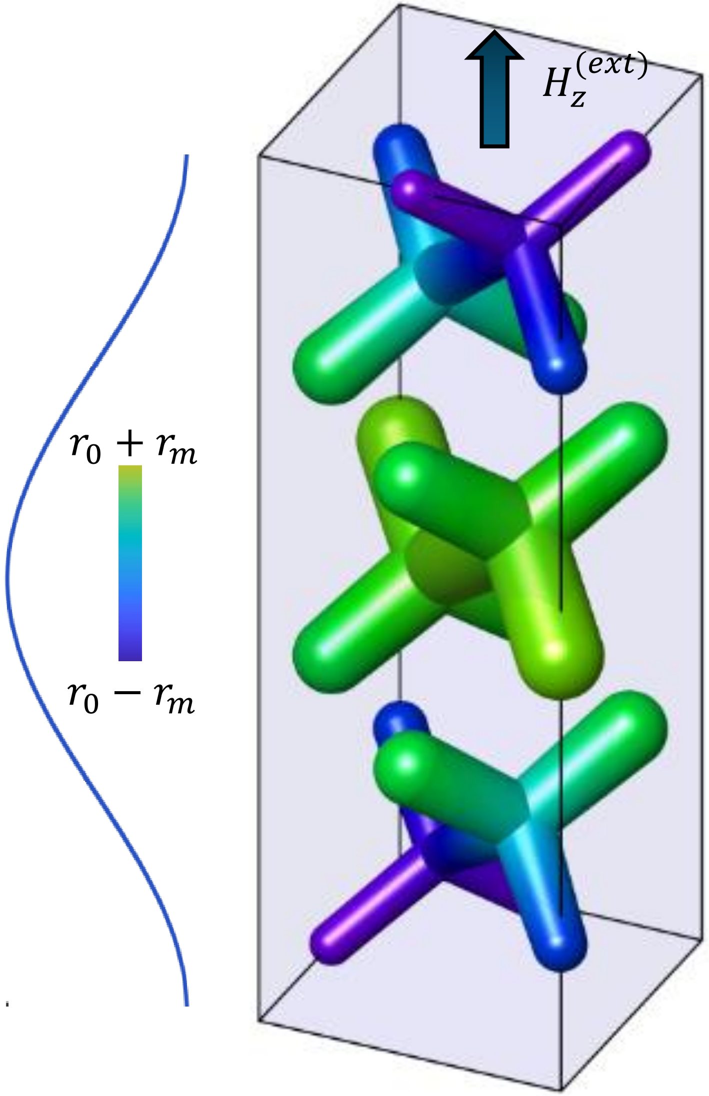

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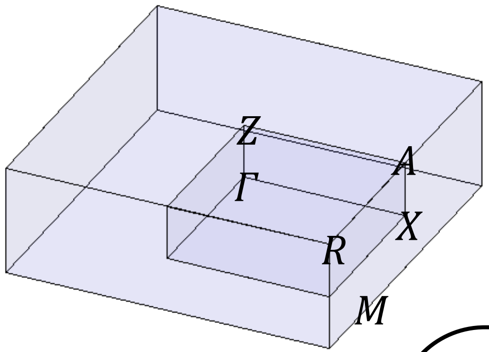

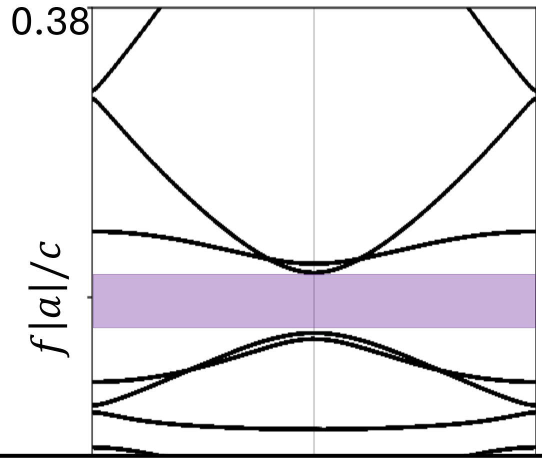

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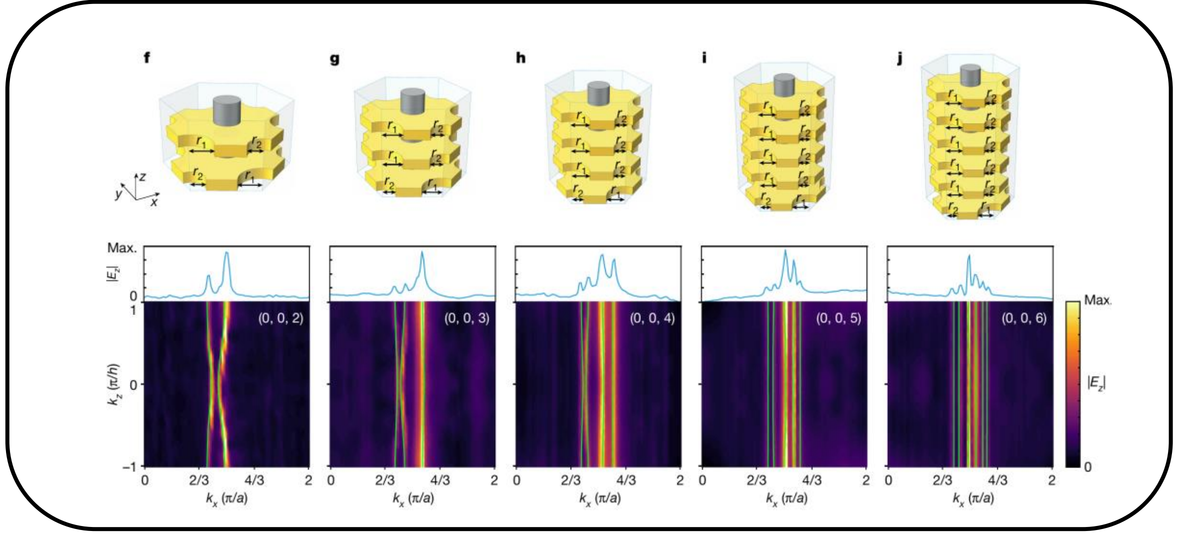
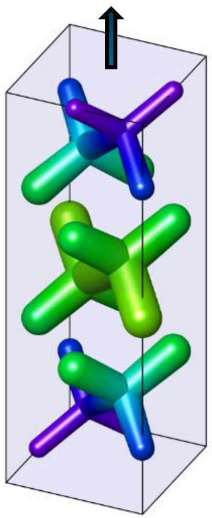
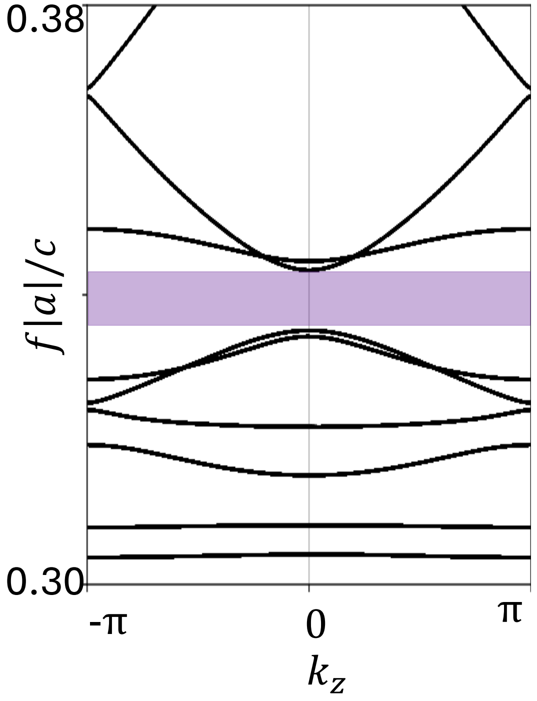


Final Step 4: Inversion symmetry pinning

Relative SM phase

$\phi = 0$





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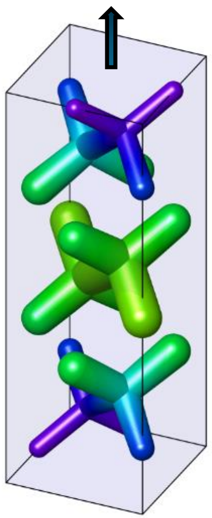

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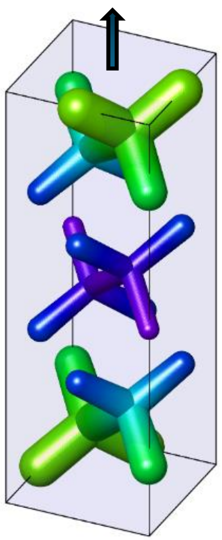

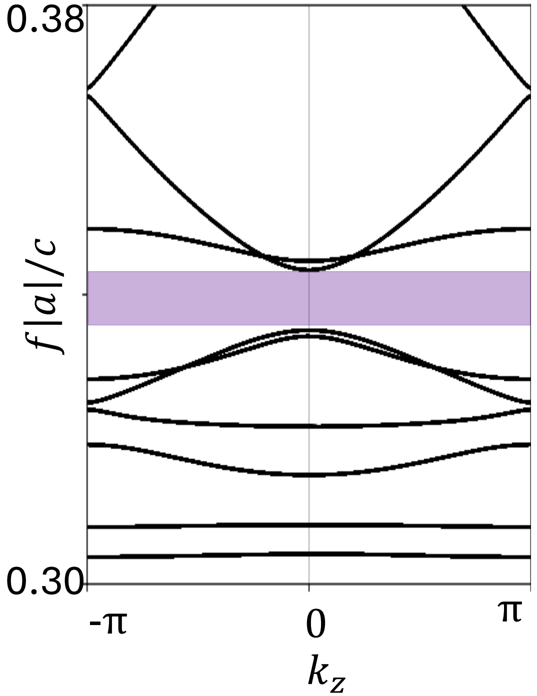

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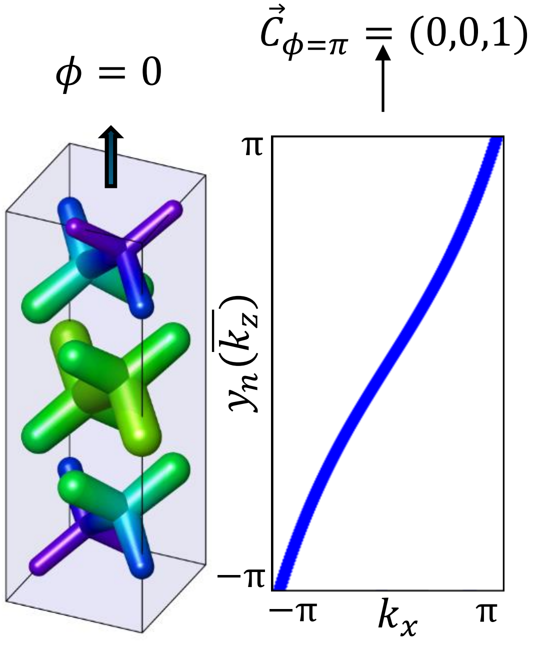

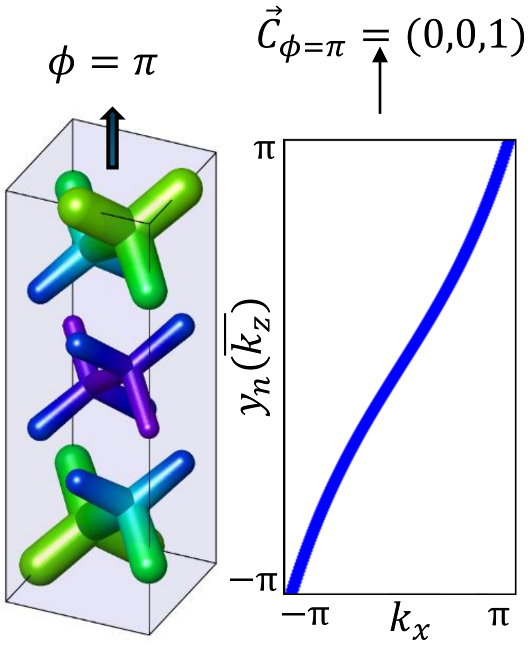

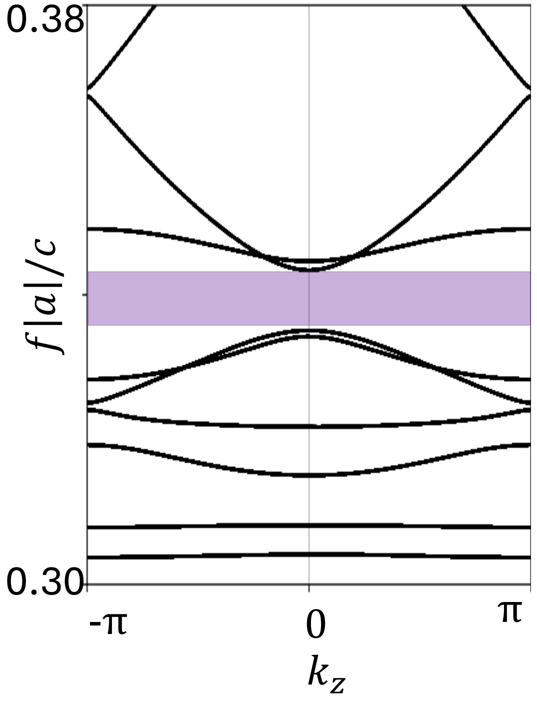

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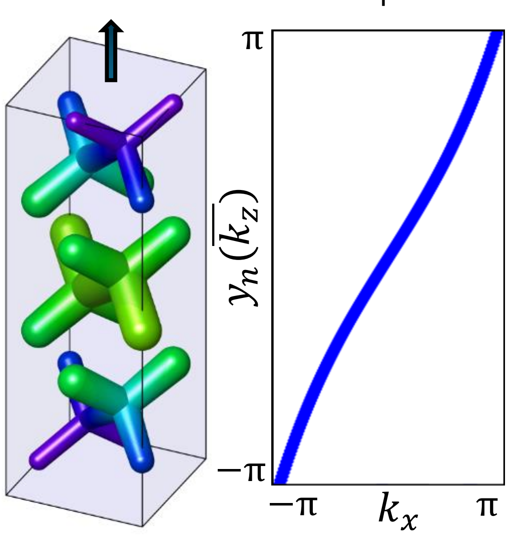

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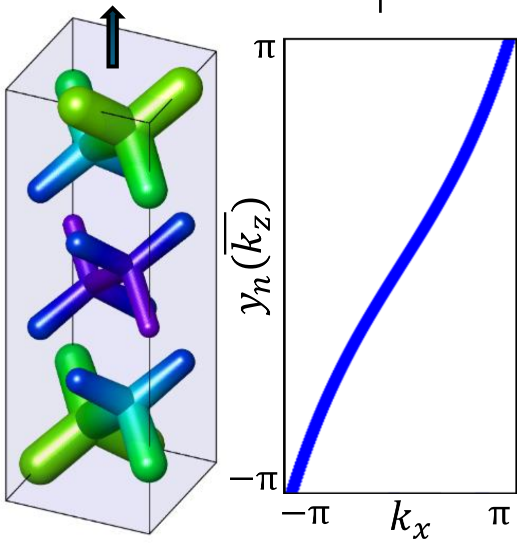

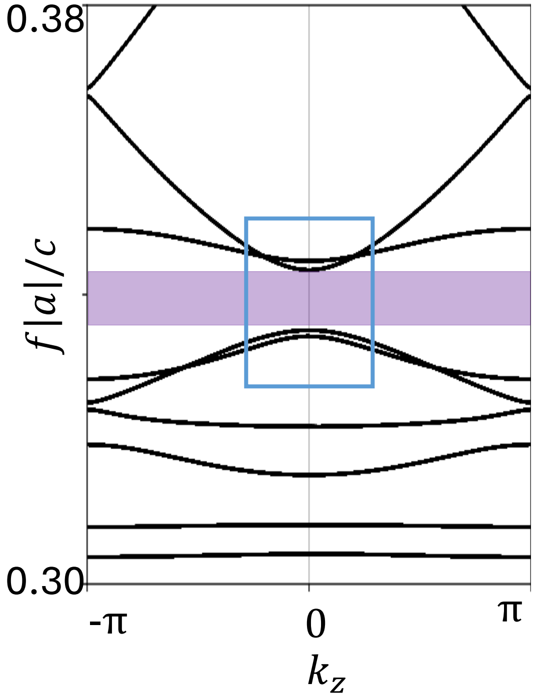

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$$\Delta r = r_m \cos\left(\frac{2\pi z}{N} + \phi\right)$$

$$\mathrm{n}_{\phi=0}^{k=V} = [2V_1^+ + 4V_1^-]$$

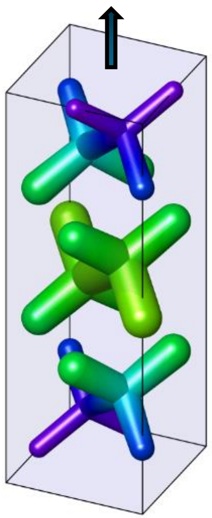
$$\mathrm{n}_{\phi=\pi}^{k=V} = [4V_1^+ + 2V_1^-]$$

Double band-inversion at $V = (\pi, \pi, 0)$

Obstructed magnetic symmetry indicators

Parity obstruction

$\phi = 0$



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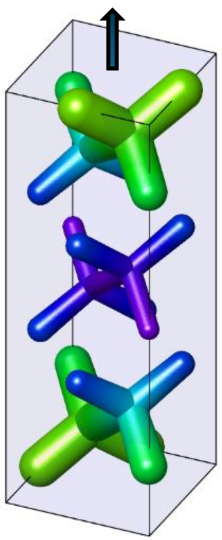
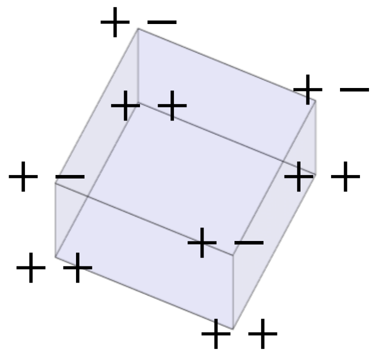


Magnetic symmetry indicators

Phys. Rev. B 85, 165120 (2012)

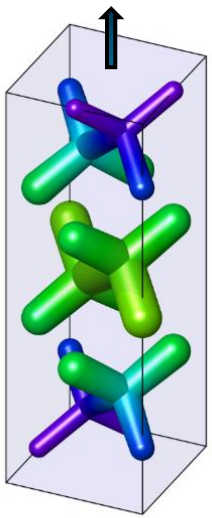


$$\nu = \left\{\underbrace{\bar{z}_{2,x}, \bar{z}_{2,y}, \bar{z}_{2,z}}_{\text{Chern number parity}} \middle| \underbrace{\bar{z}_4}_{\text{Weyl/Axion}}\right\}$$

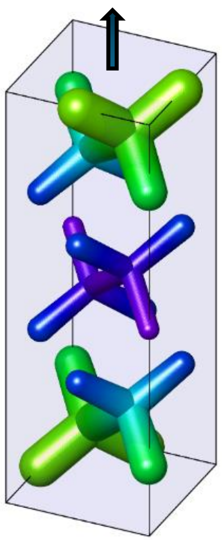
Obstructed magnetic symmetry indicators

Parity obstruction

$\phi = 0$

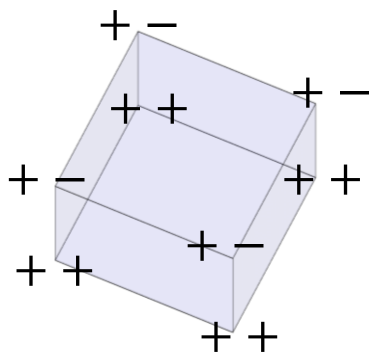


$\phi = \pi$



Magnetic symmetry indicators

Phys. Rev. B 85, 165120 (2012)



$$\nu = \{\underbrace{\bar{z}_{2,x}, \bar{z}_{2,y}, \bar{z}_{2,z}}_{\text{Chern number parity}} | \underbrace{\bar{z}_4}_{\text{Weyl/Axion}}\}$$

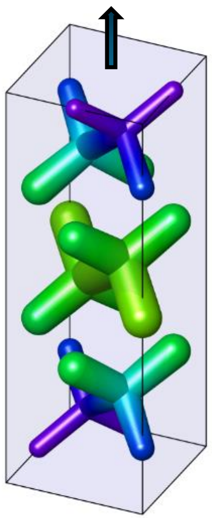
Intrinsic axion insulator

$$\nu_{AXI} = \{0,0,0|2\}$$

Obstructed magnetic symmetry indicators

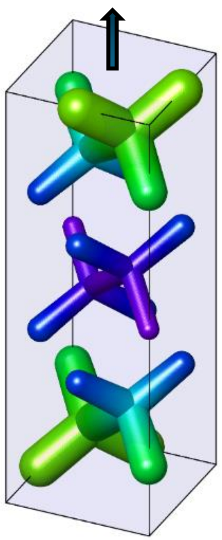
Parity obstruction

$\phi = 0$



$\nu_{\phi=0} = \{0,0,1|0\}$

$\phi = \pi$



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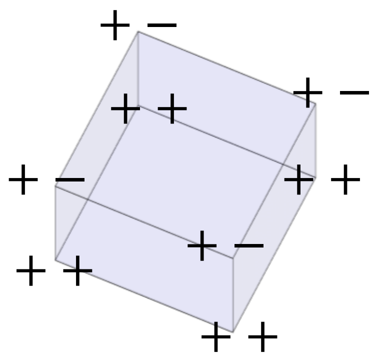
Phys. Rev. B 85, 165120 (2012)



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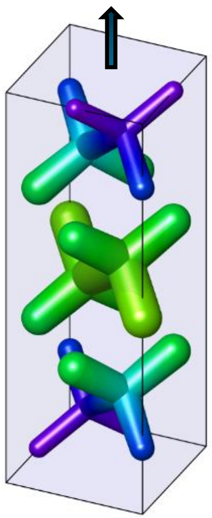

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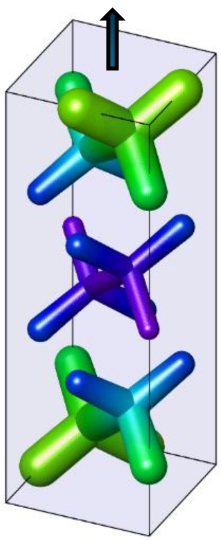


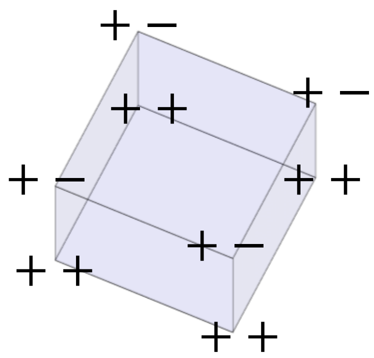
$$\nu_{\phi=\pi} = \{0,0,1|2\}$$

Relative axion topology

$$\nu_{\phi=\pi} - \nu_{\phi=0} = \{0,0,0|2\}$$

Magnetic symmetry indicators

Phys. Rev. B 85, 165120 (2012)



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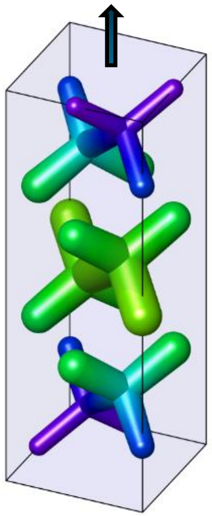
Intrinsic axion insulator

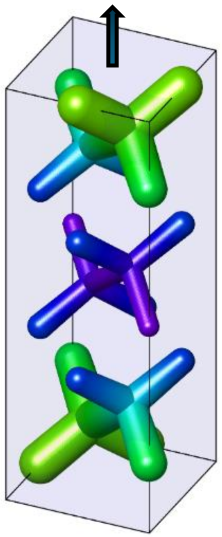
$$\nu_{AXI} = \{0,0,0|2\}$$

Relative axion angle

$\phi = 0$

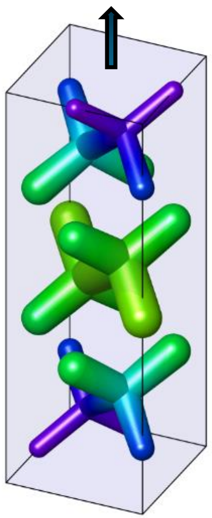


$\phi = \pi$

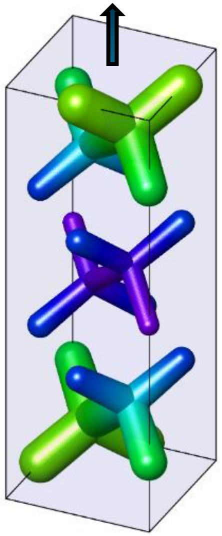


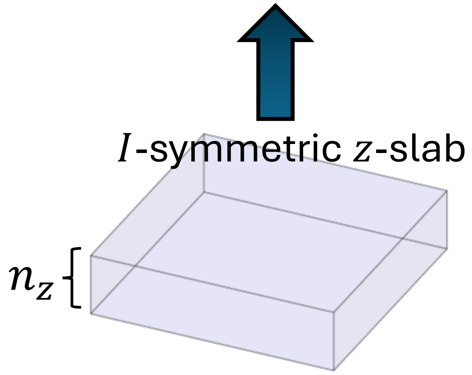
Relative axion angle

$\phi = 0$



$\phi = \pi$

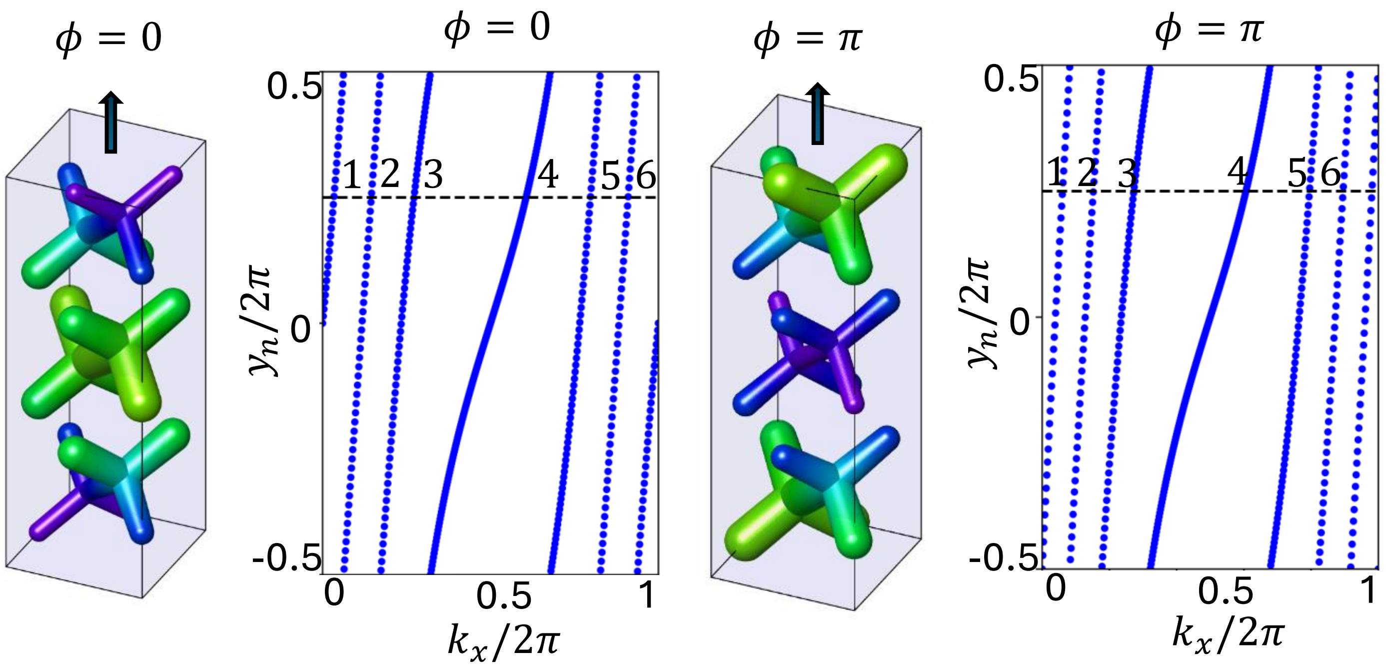


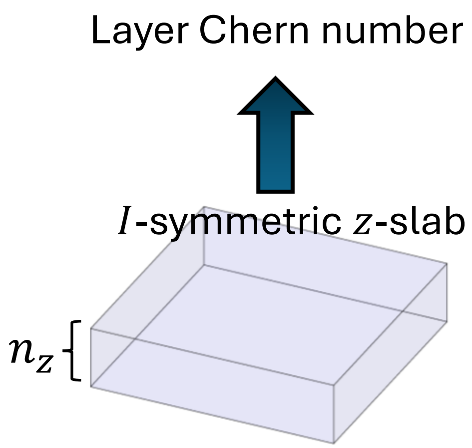


$$G_z = C_z n_z + \theta/\pi$$

Phys. Rev. B 98, 245117 (2018)
Phys. Rev. B 101, 155130 (2020)

Relative axion angle





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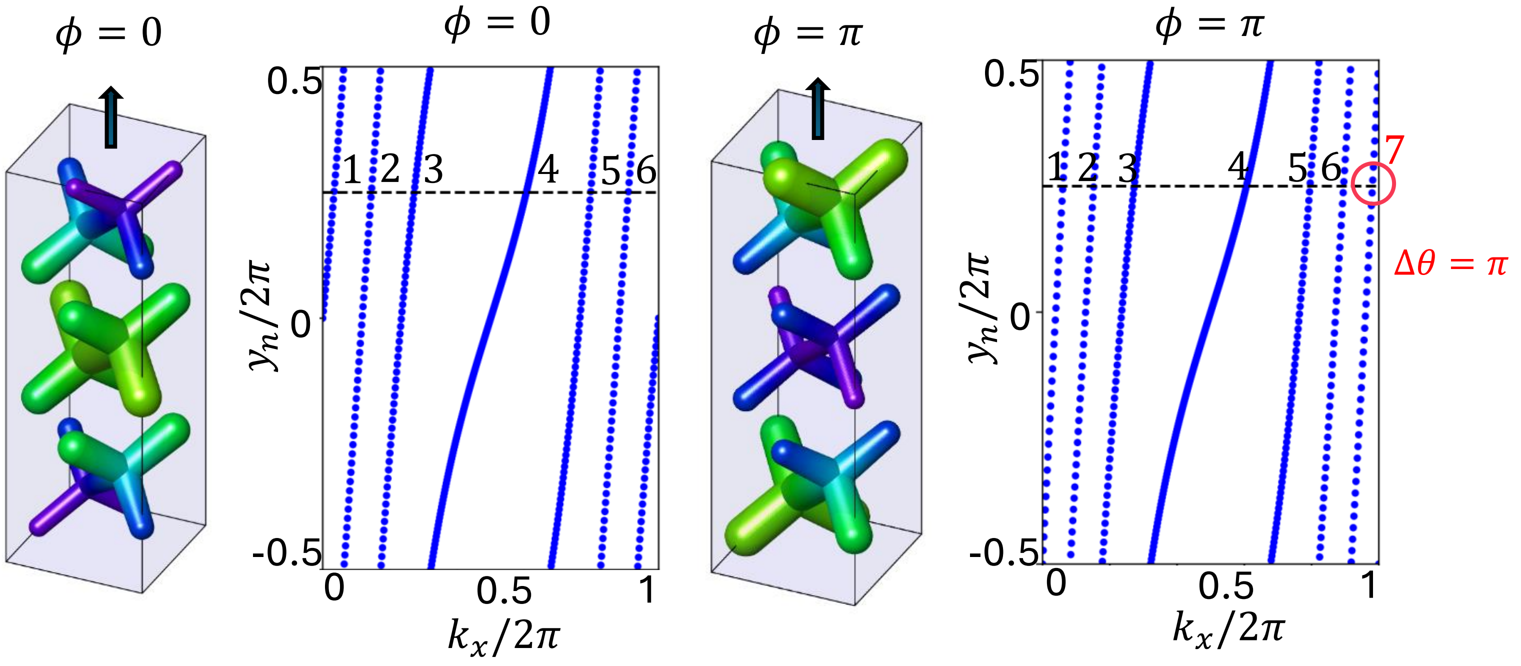
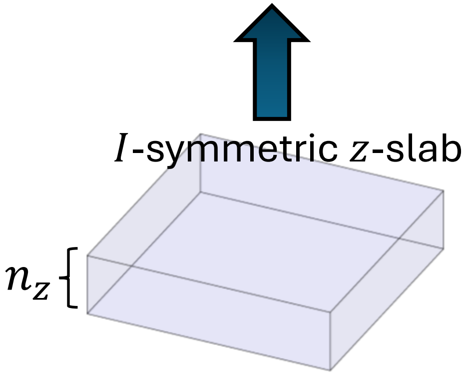


Layer Chern number

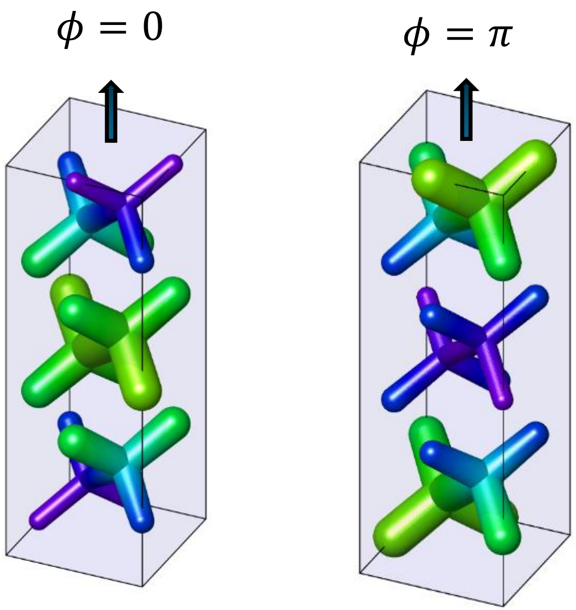


$$G_z = C_z n_z + \theta/\pi$$

Phys. Rev. B 98, 245117 (2018)
Phys. Rev. B 101, 155130 (2020)

Making relative AXI topology manifest

Relative AXI



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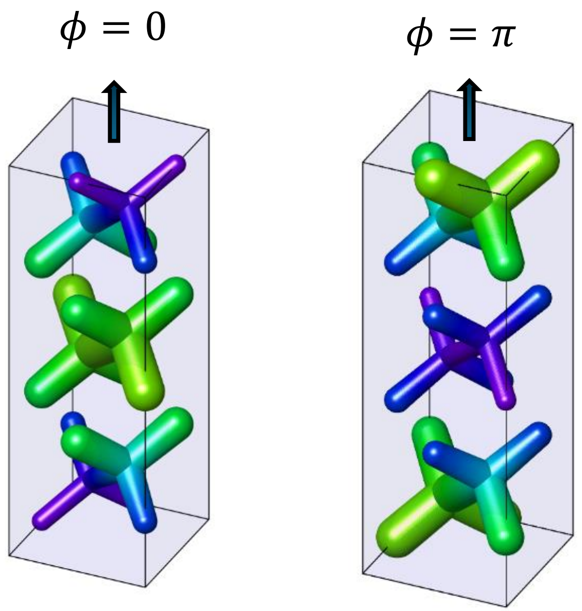
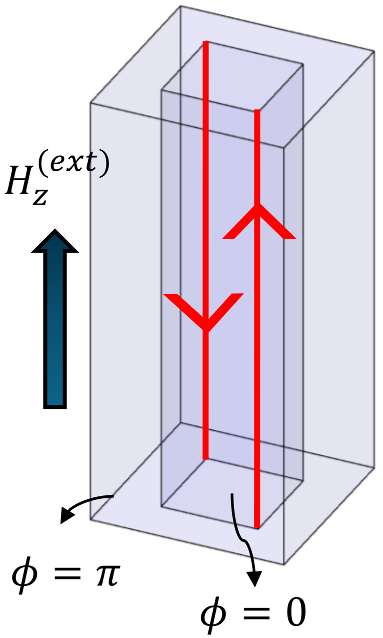


Phase-obstructed rod-like geometry

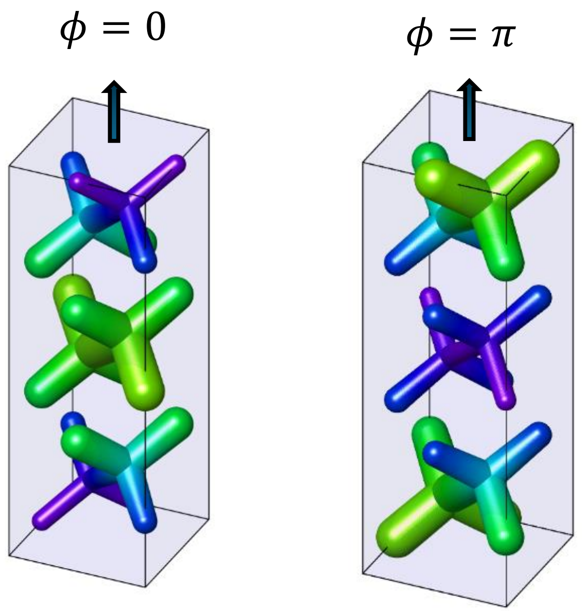


Chiral channels embedded in the bulk

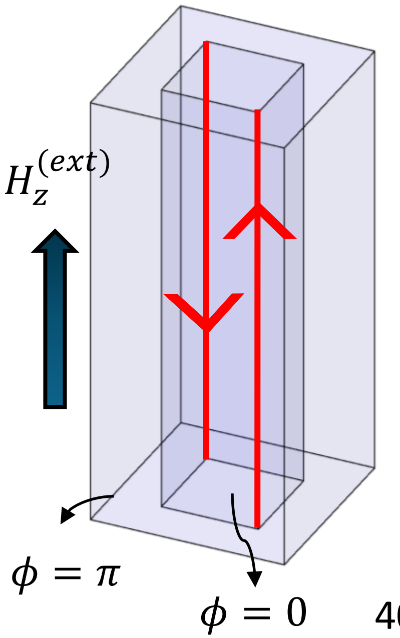
- Protected against radiation the EM continuum
  - Fully 3D connected PhC geometry

Making relative AXI topology manifest

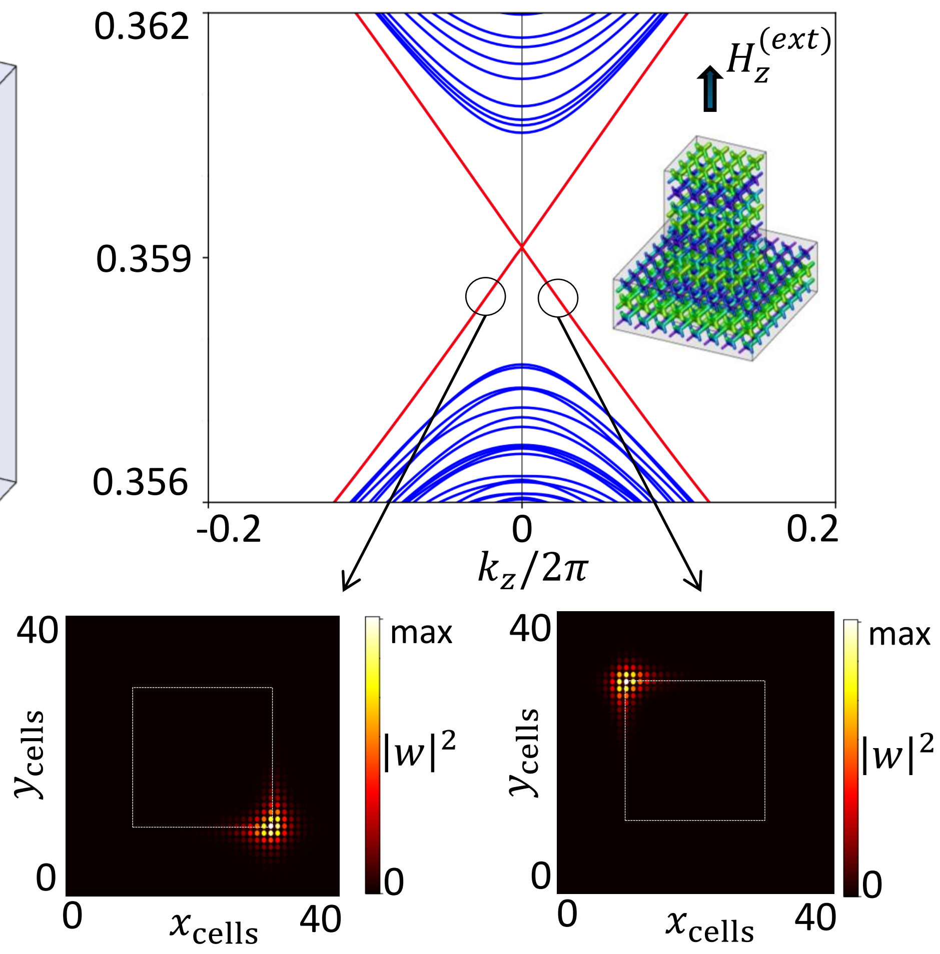
Relative AXI



Phase-obstructed rod-like geometry



Phase-obstructed domain-walls



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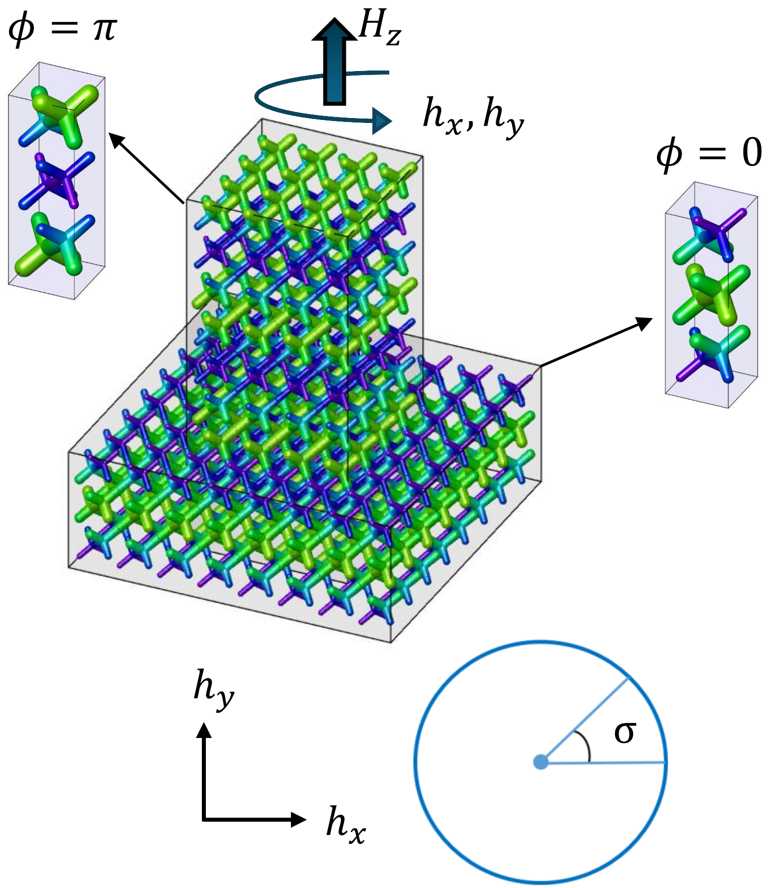
External control of the hinge localization

External control of the hinge localization

Manipulation of the axion chiral channels



$$\boldsymbol{H}^{(ext)} = (|h|\cos(\sigma), |h|\sin(\sigma), H_z)$$

External control of the hinge localization

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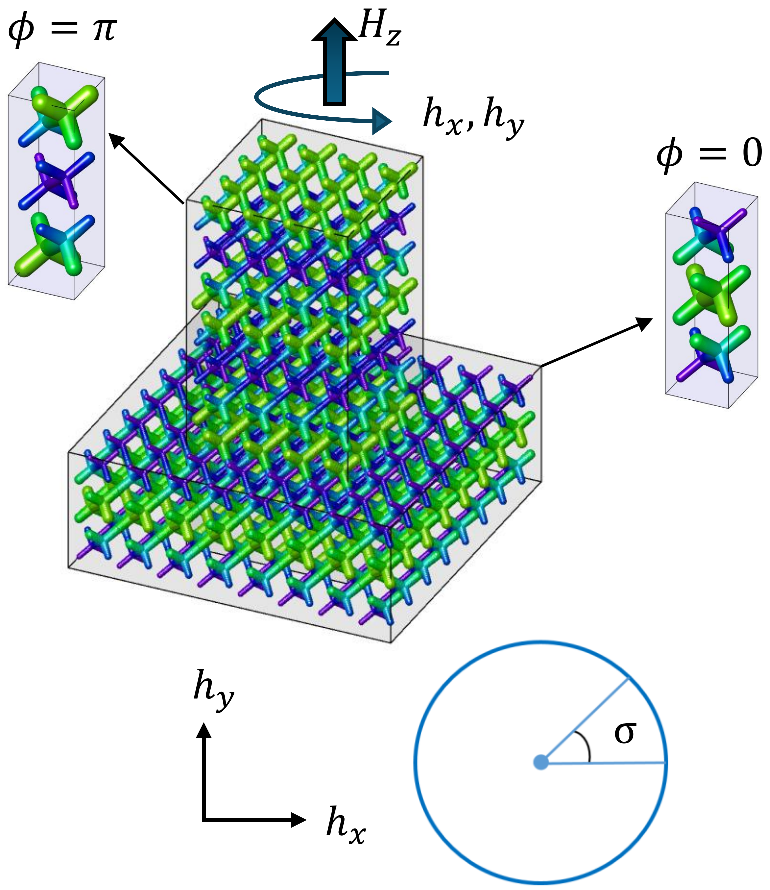
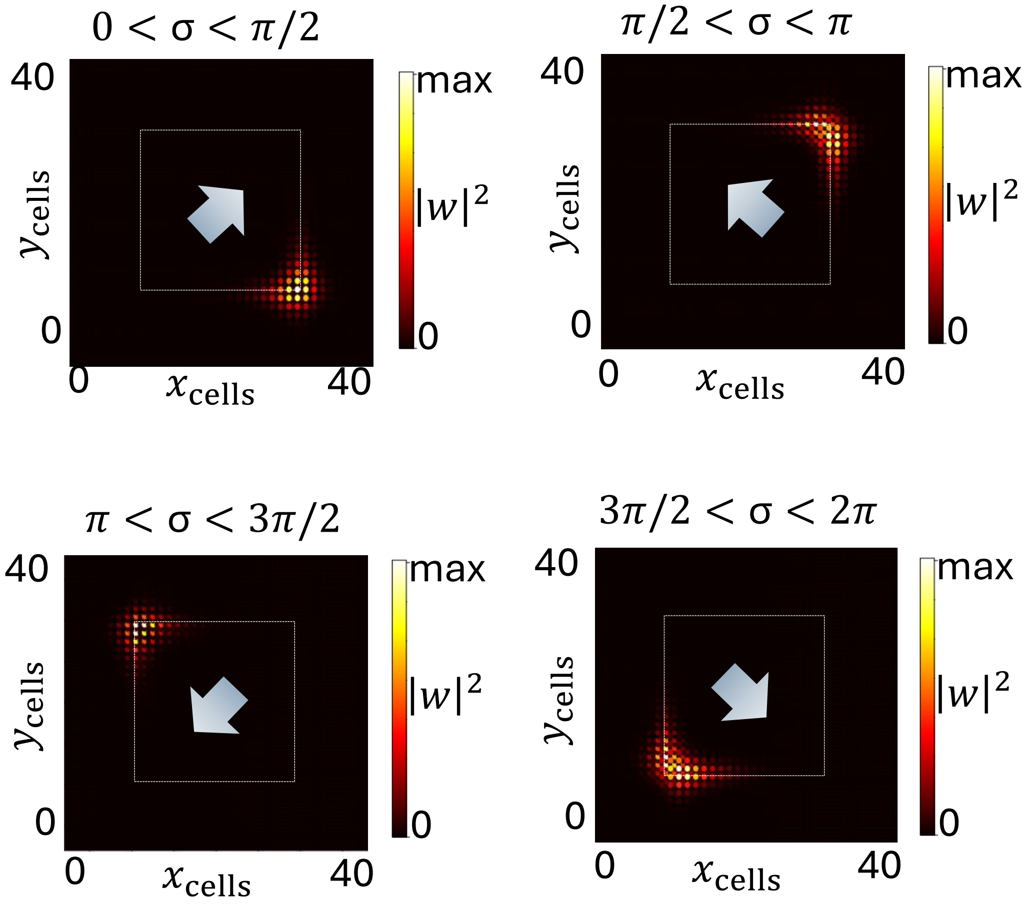


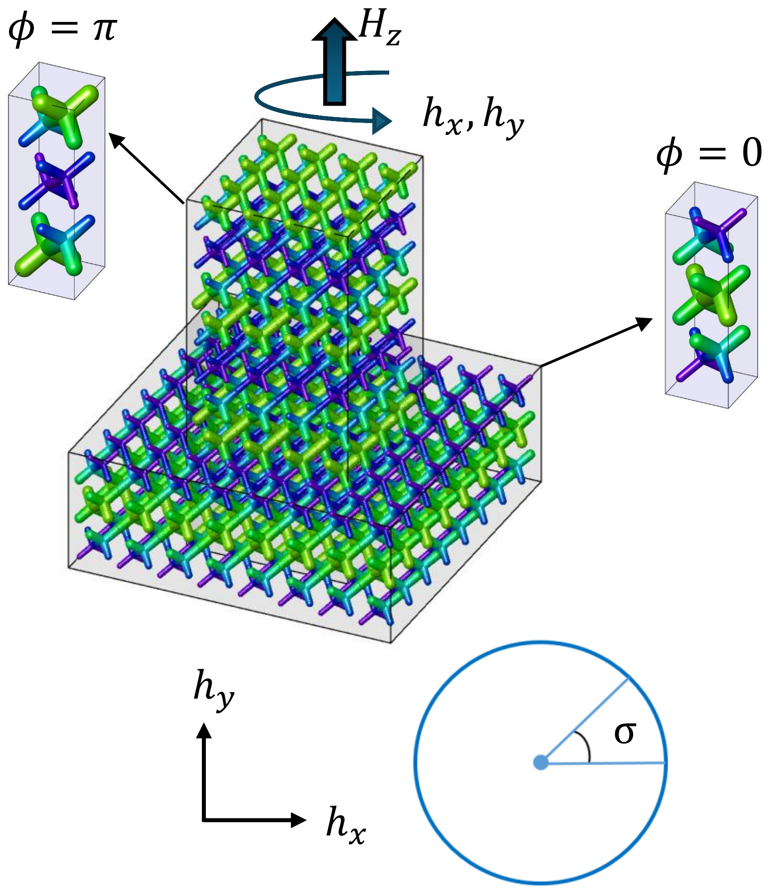
$\boldsymbol{H}^{(ext)} = (|h|\cos(\sigma), |h|\sin(\sigma), H_z)$

$v_z > 0$ upwards moving:



Gyrotropy-induced switching of AXI states

Manipulation of the axion chiral channels



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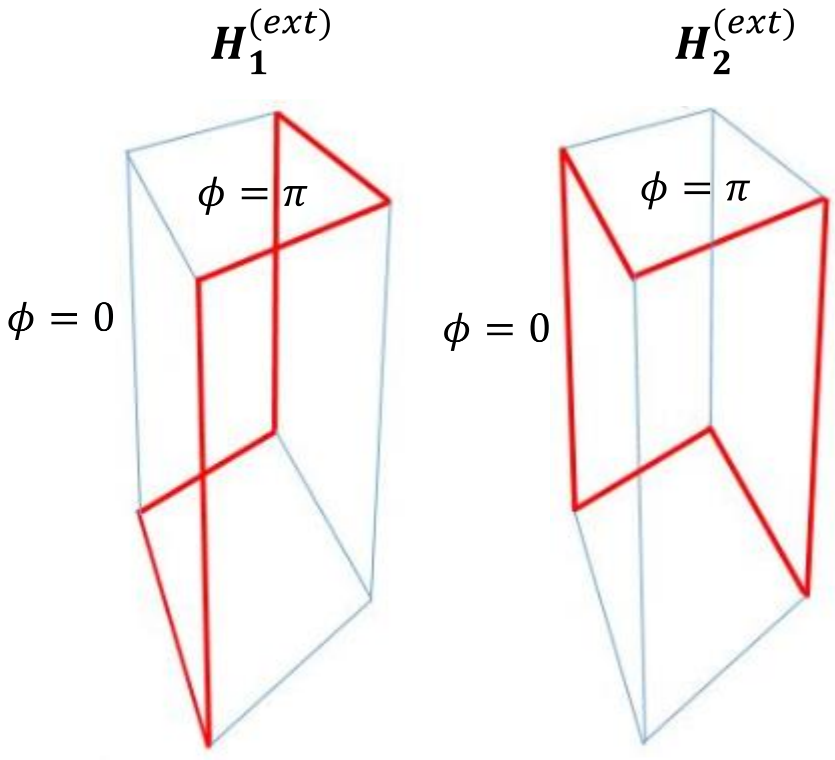

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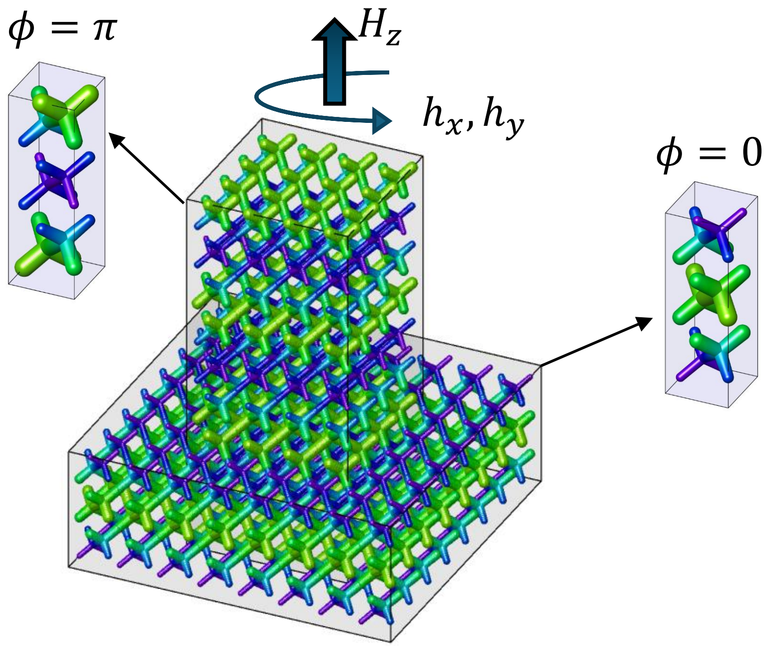
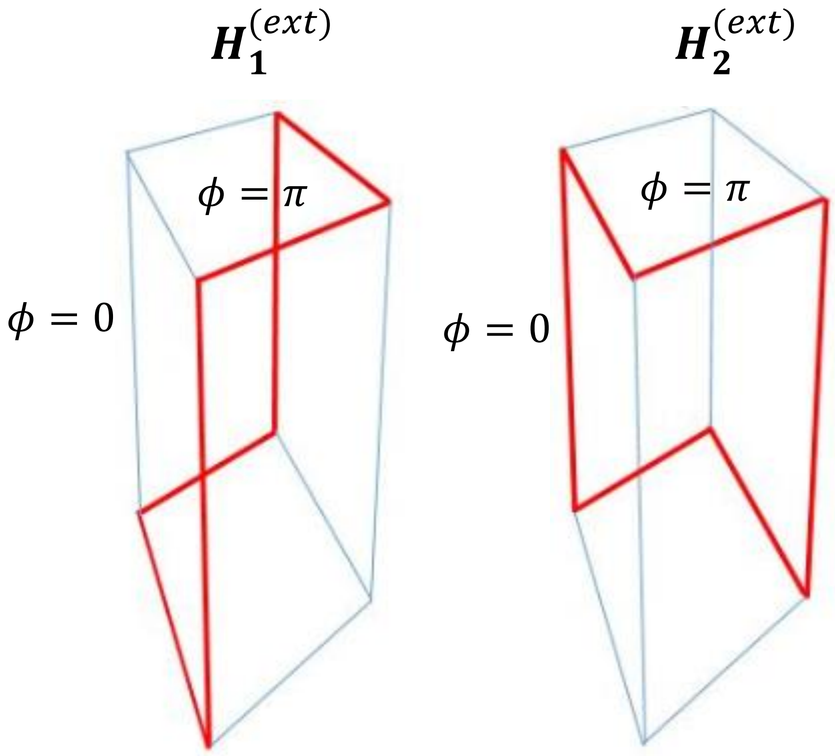


$$\overleftrightarrow{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & i\eta_z & -i\eta_y \\ -i\eta_z & \varepsilon_{yy} & i\eta_x \\ i\eta_y & -i\eta_x & \varepsilon_{zz} \end{pmatrix}$$



So far…

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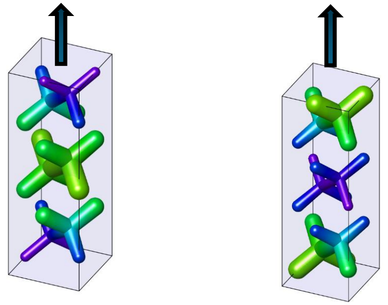
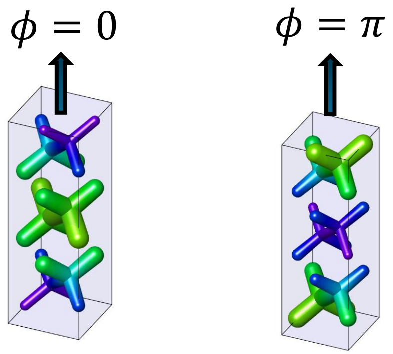
$\phi = 0$ $\phi = \pi$



- Dielectric SM induces EM energy redistribution and opening of a relative axion gap

So far...



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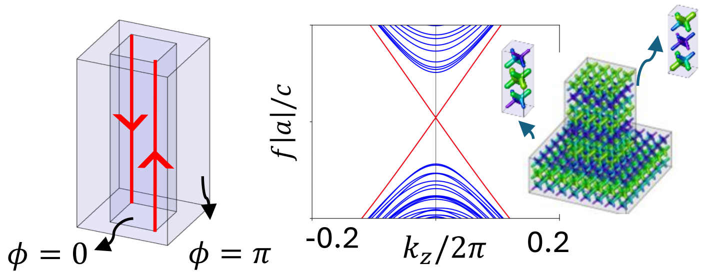
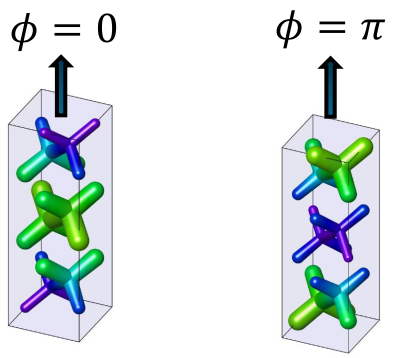


- Manifest axion topology at phase-obstructed domain walls

So far...



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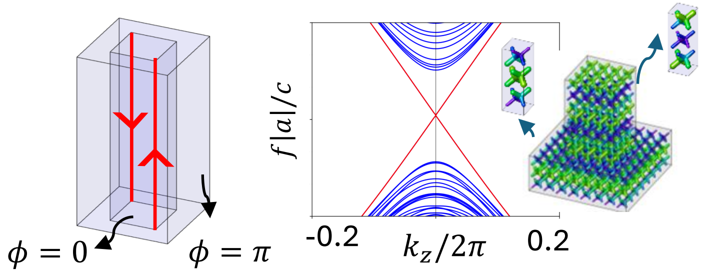
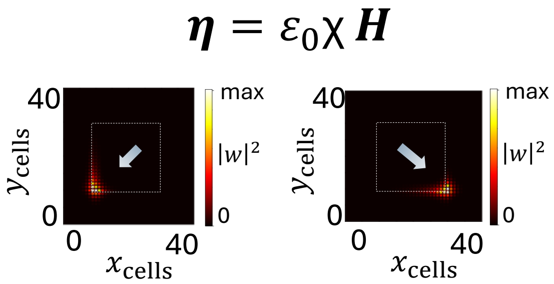


- Manifest axion topology at phase-obstructed domain walls



- Propose a physically accessible way to control of the chiral channels of light via gyromagnetism

Outline

- Context:
  - Axion Insulator (AXI)
  - Photonic crystals (PhC)
  - Why do we seek an AXI in a PhC

1- From 3D Chern insulators to Relative AXI

2- From Relative to Intrinsic AXI

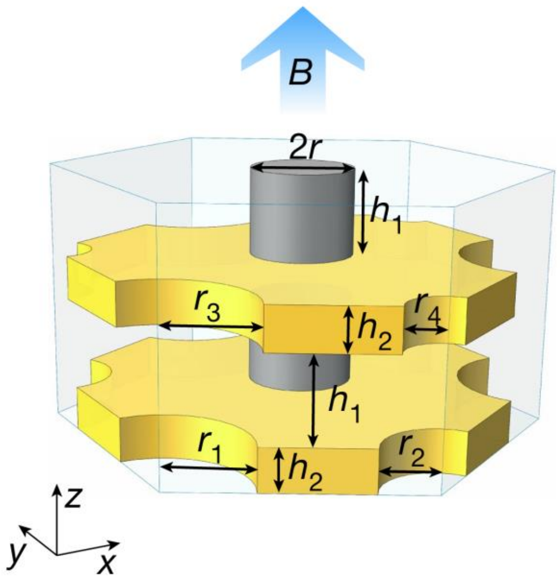
- Outlook and conclusions

From relative to intrinsic axion

From relative to intrinsic axion

External Magnetic field

- YIG gyromagnetic cylinders
- Metallic plates



From relative to intrinsic axion

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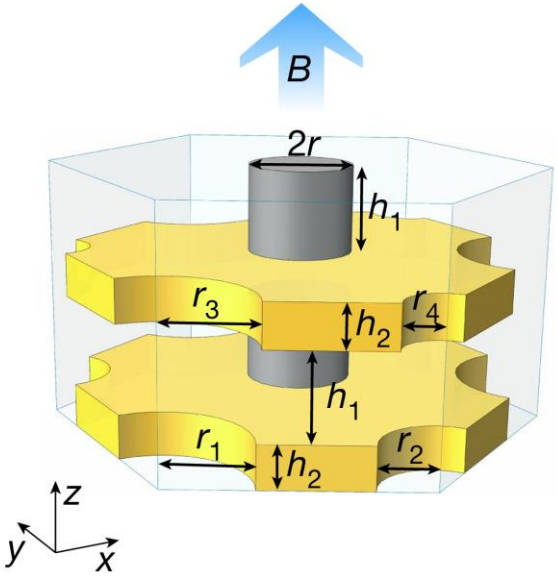
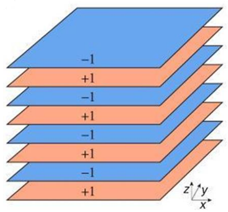
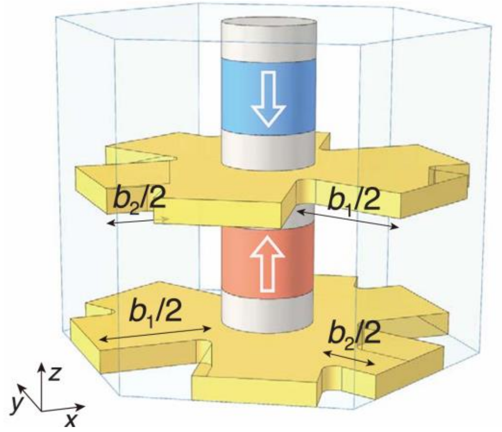


Alternating permanent magnets

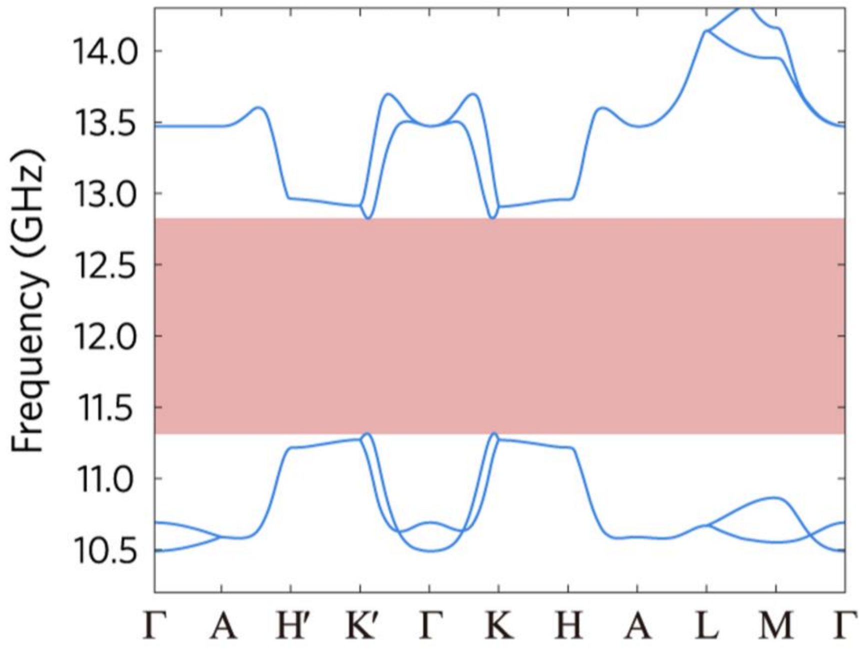


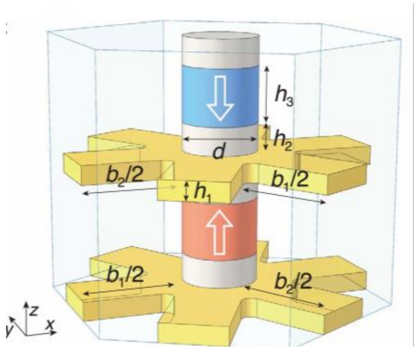


Net zero Chern

Gapped bulk

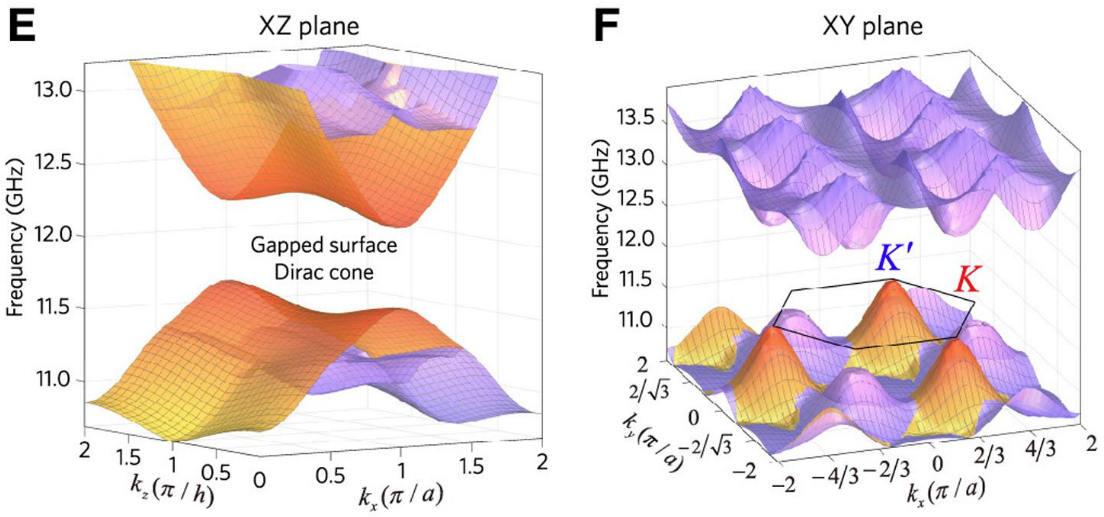
b_1=10 mm; b_2=5 mm



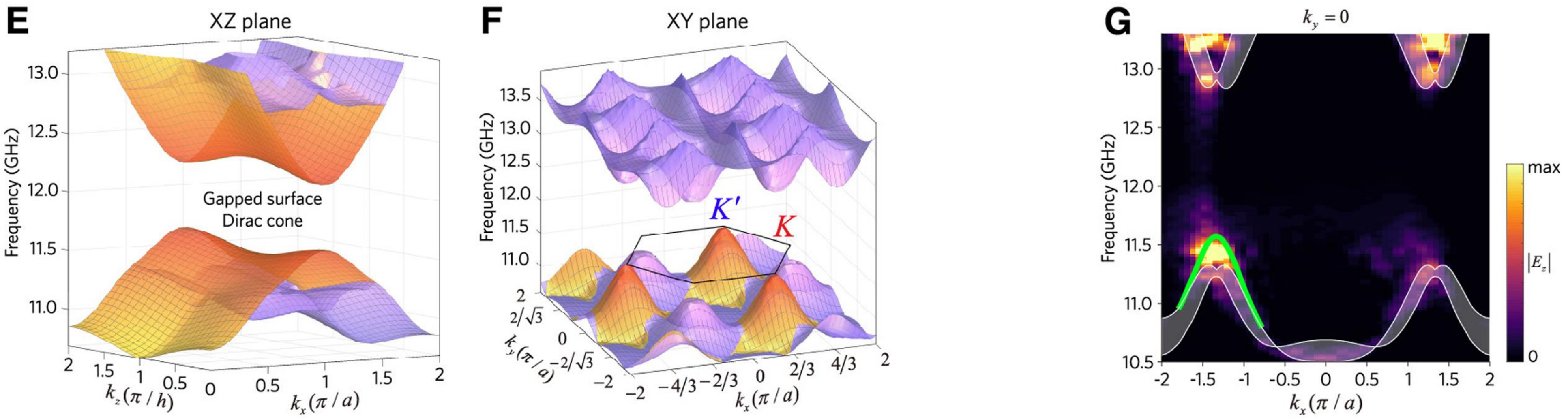


Gapped surface

Gapped surface

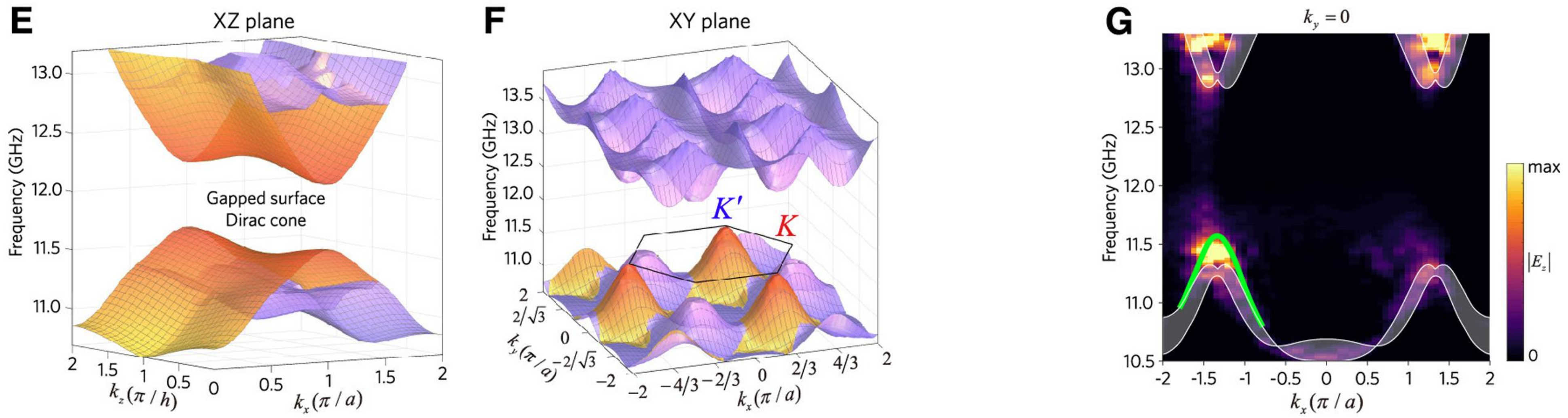


Gapped surface



Top surface measurement

Gapped surface



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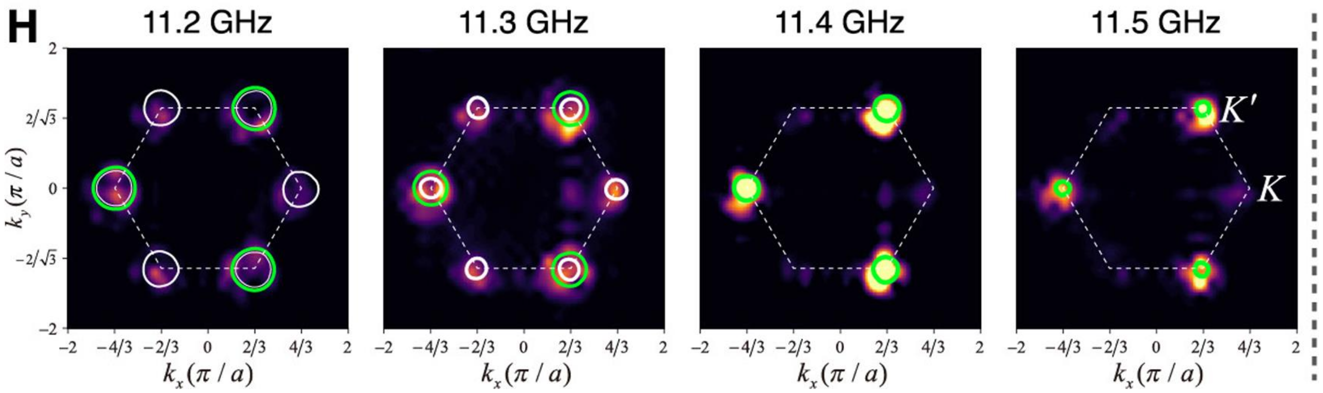
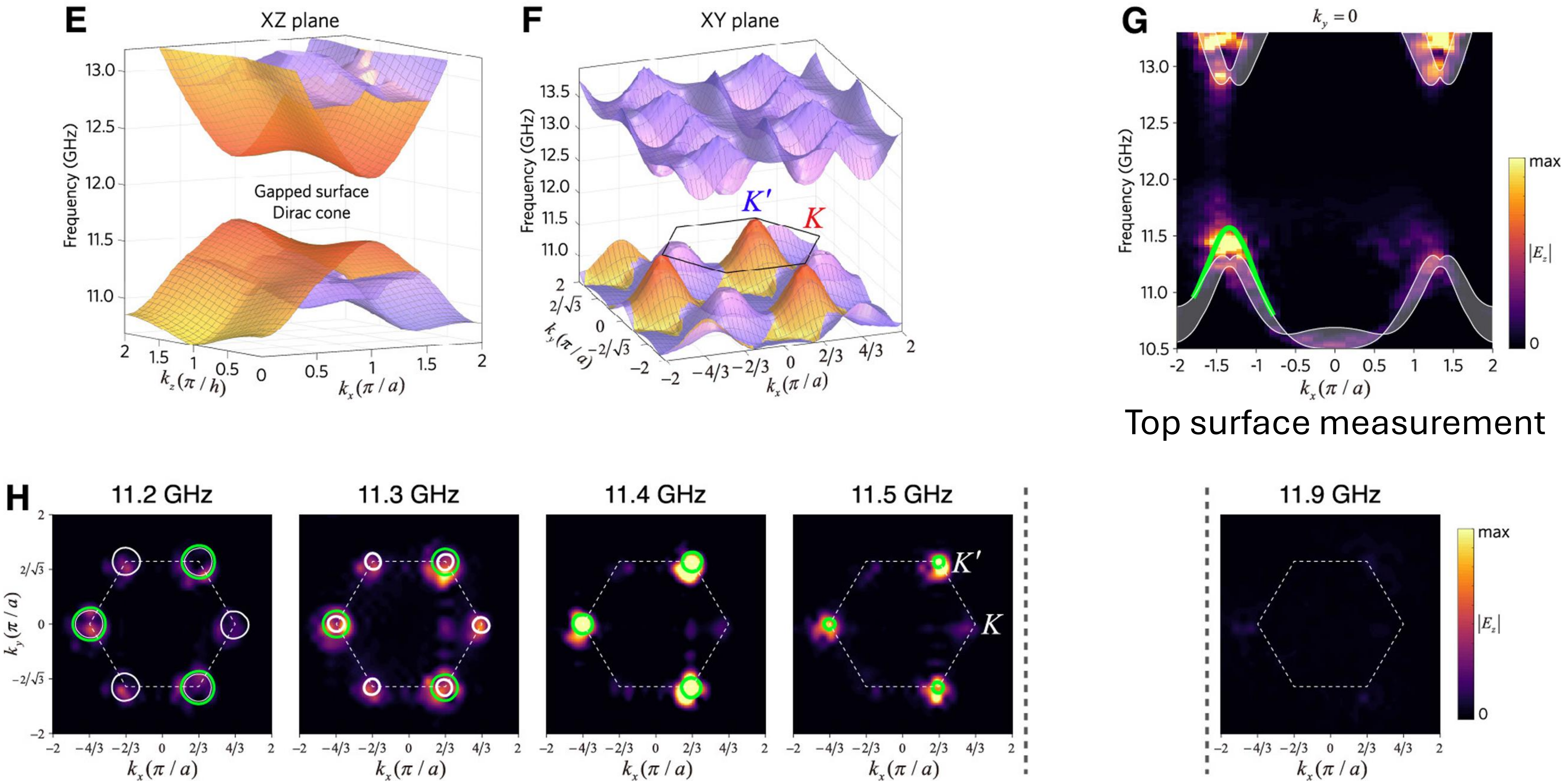


only one valley for surface state

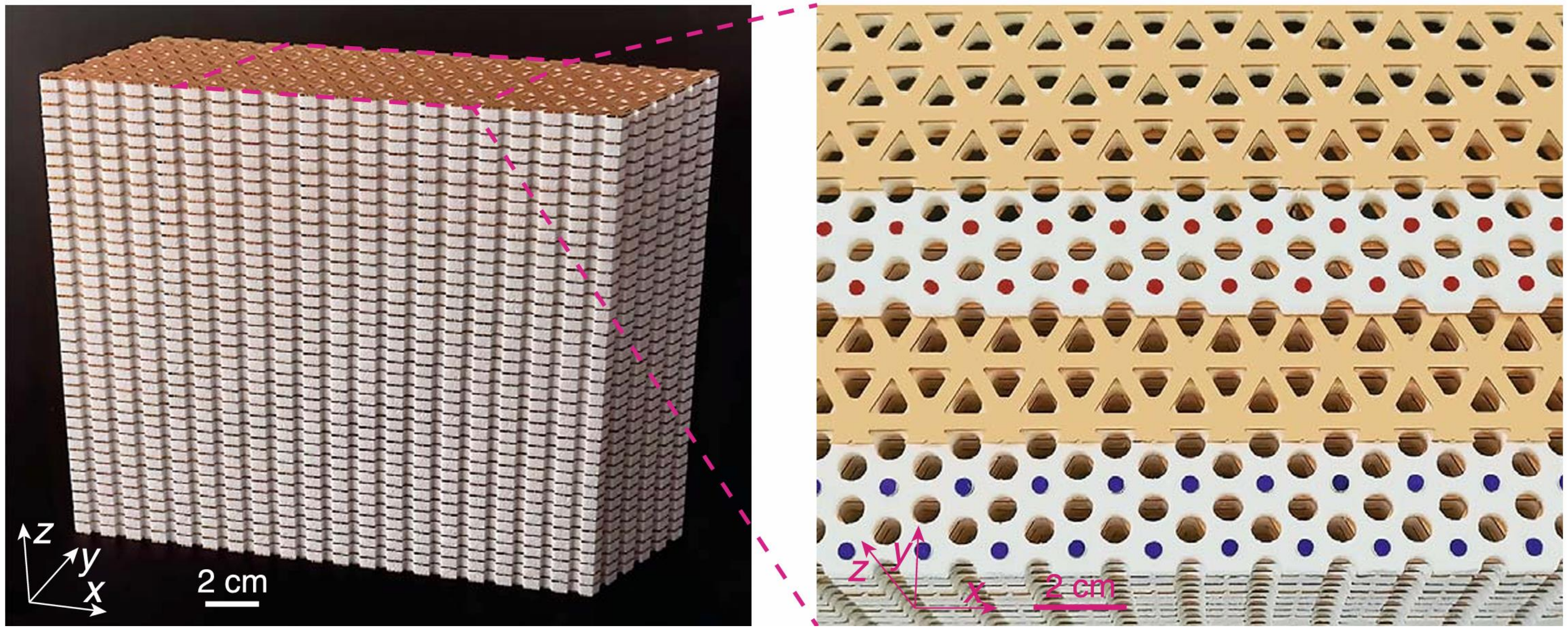
Gapped surface



only one valley for surface state

frequency used to observe hinge states

Finite 3D PhC



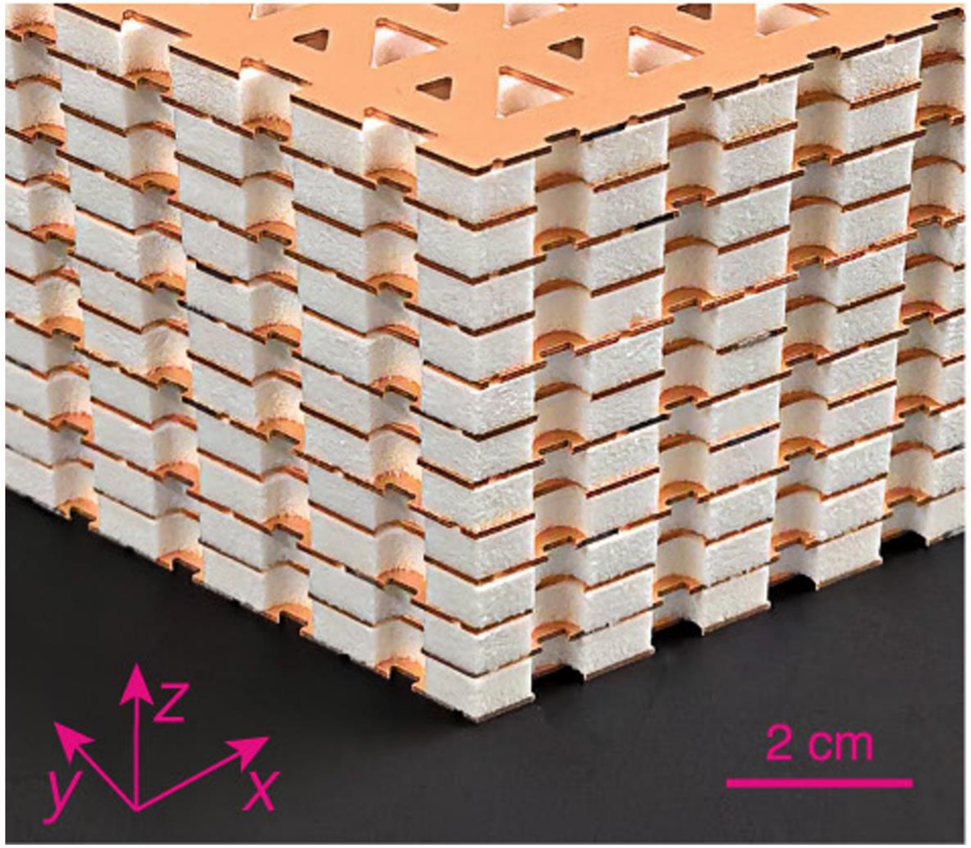
Copper plate (3shift)

Gyro rod (up) (2shift)

Copper plate (1shift)

Gyro rod (down)

Hinge close up



Hinge states robust to metallic obstacles

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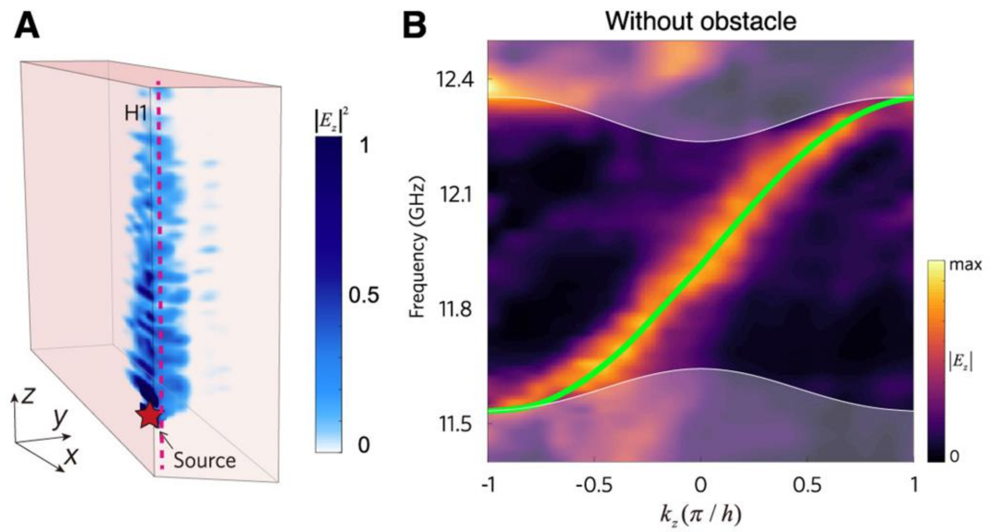
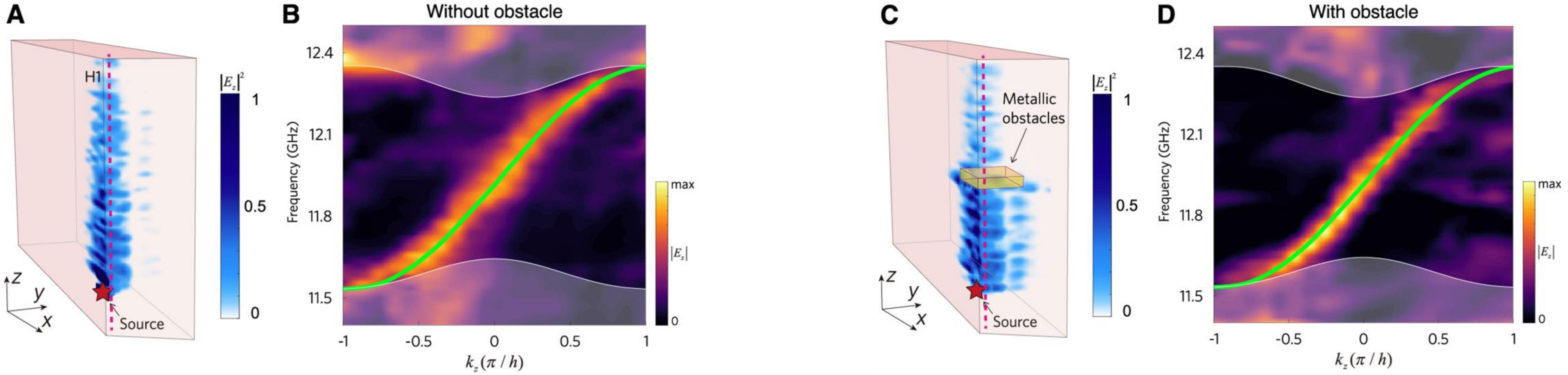


Hinge states robust to metallic obstacles



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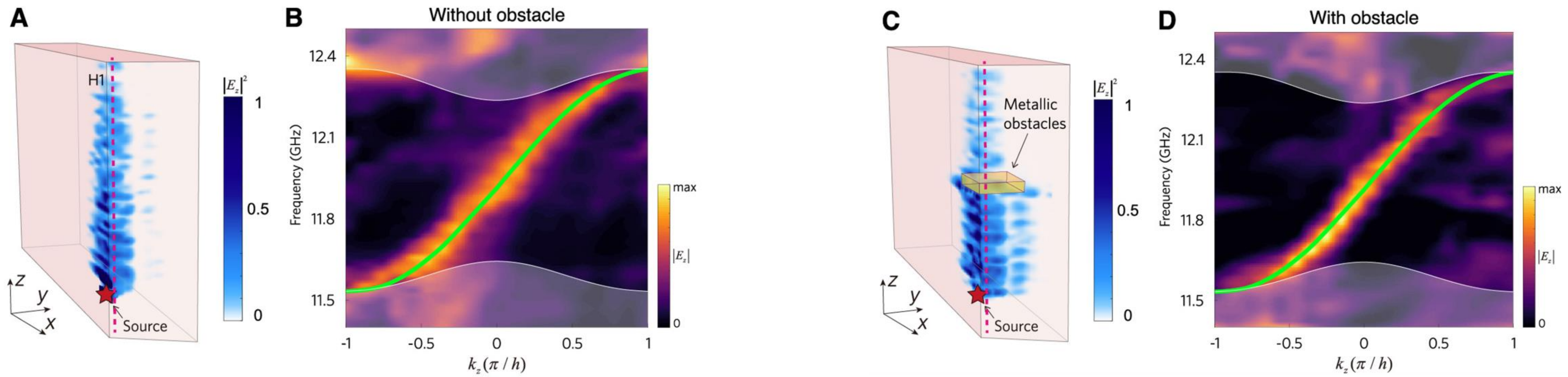

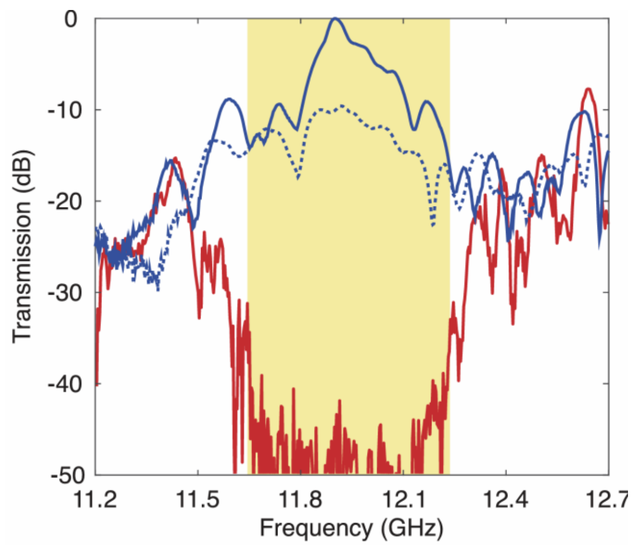

Even/odd layers: half-quantized Chern numbers

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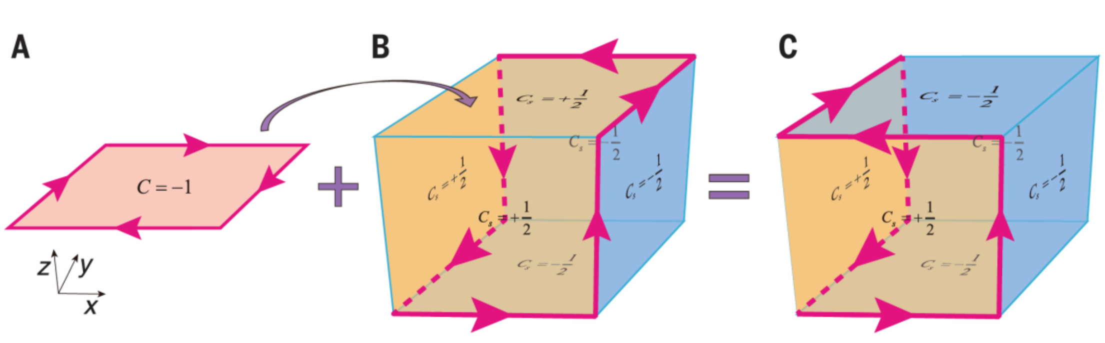

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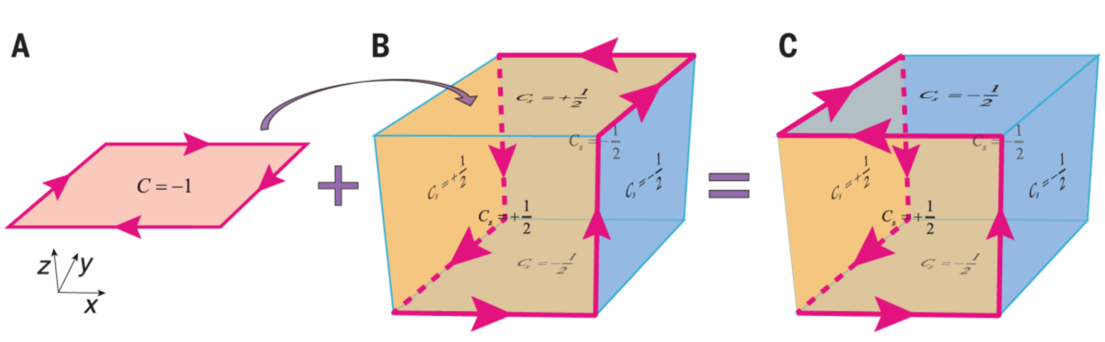

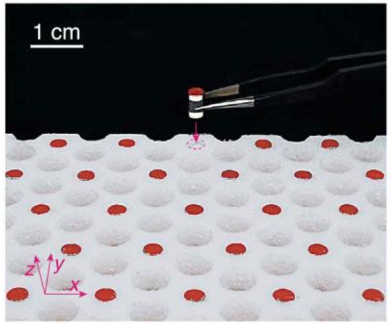

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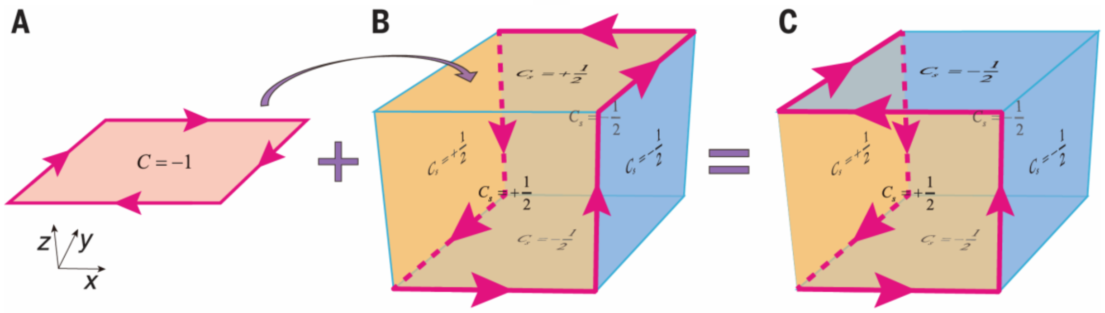
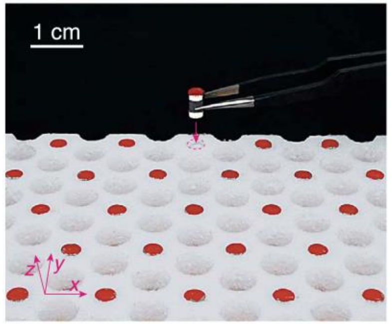
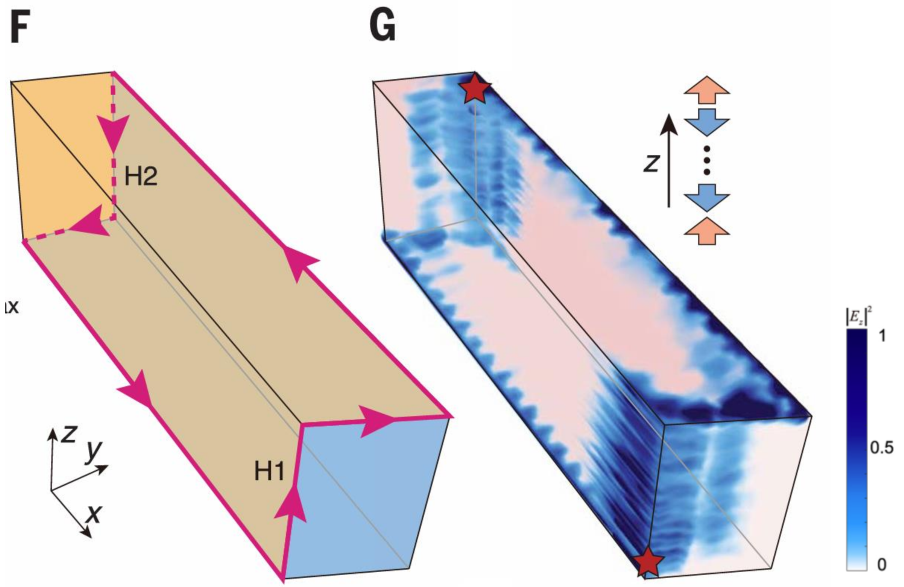




39 layers



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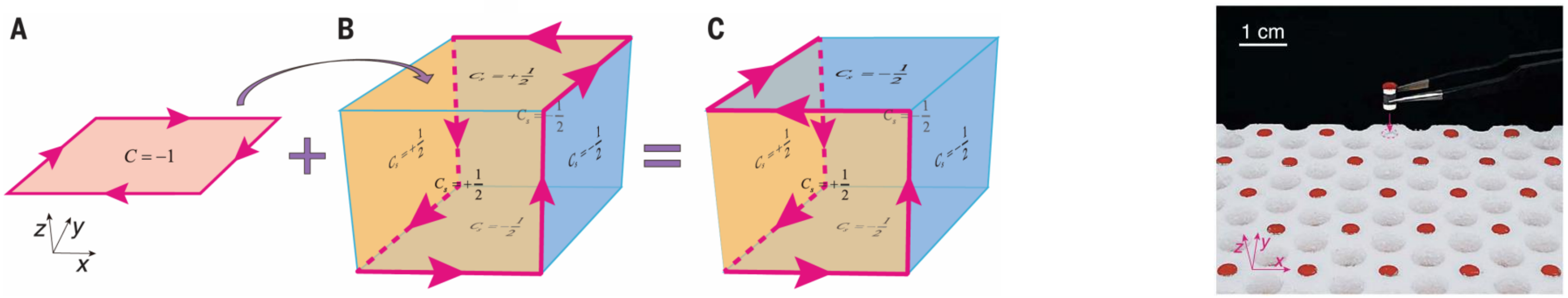
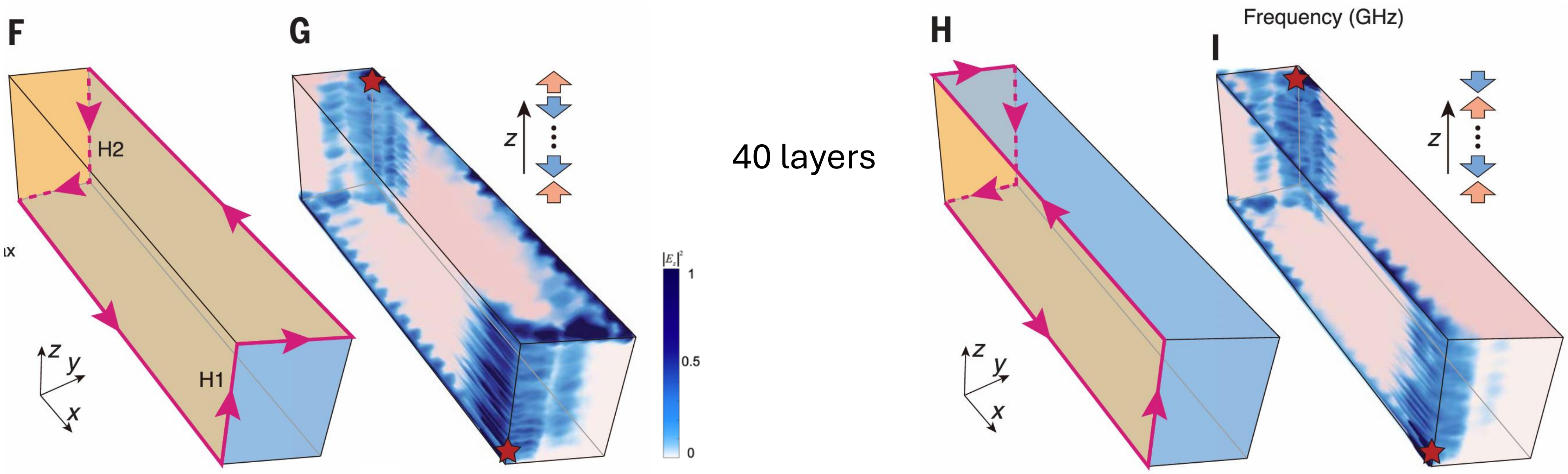


39 layers

40 layers



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2- From Relative to Intrinsic AXI

- **Outlook and conclusions**

Surface topological photonic gaps

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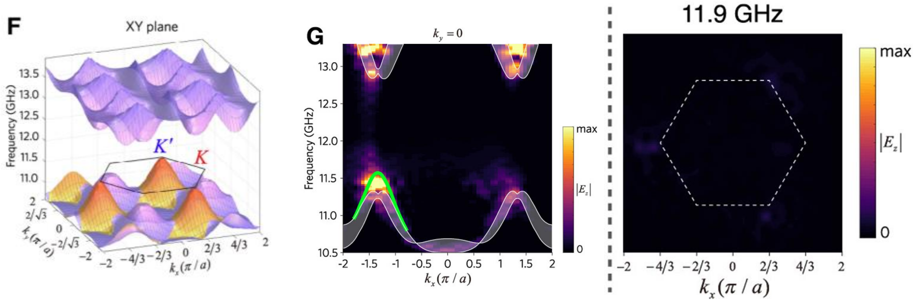
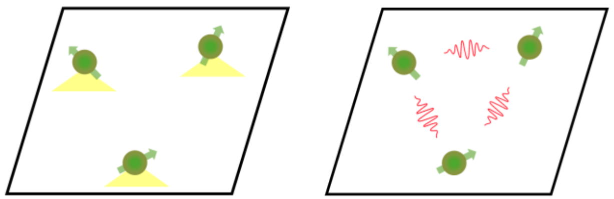
Surface photonic gap with non-trivial topological properties:



Coupling of emitters to the surface:



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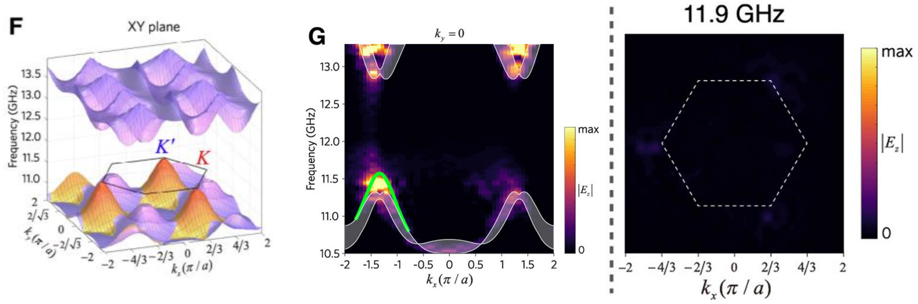

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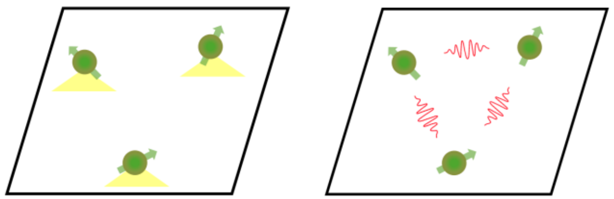

In contrast to coupling of QE in the bulk of….e.g.

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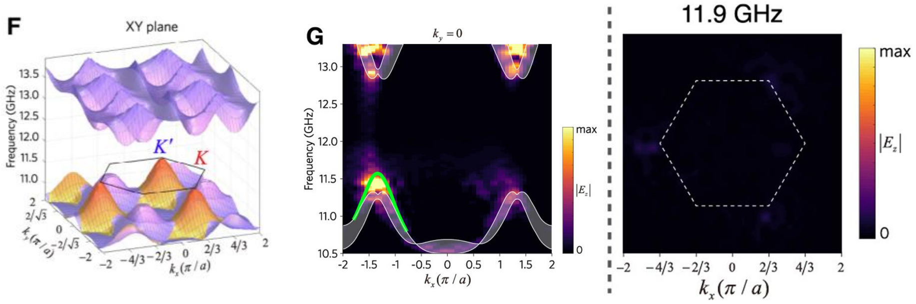

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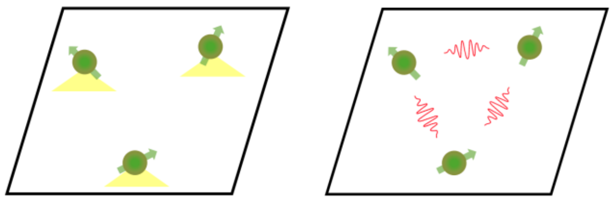

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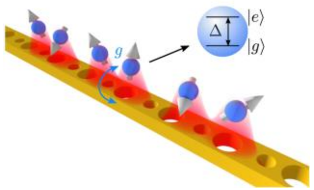

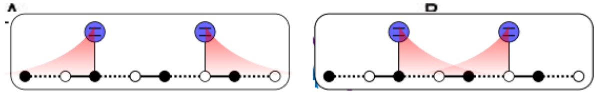

Single QE: chiral bound state
Many emitters: BS mediates topological, tunable interactions

Bello M, Platero G, Cirac JI, González-Tudela A. Unconventional quantum optics in topological waveguide QED. Science advances. 2019

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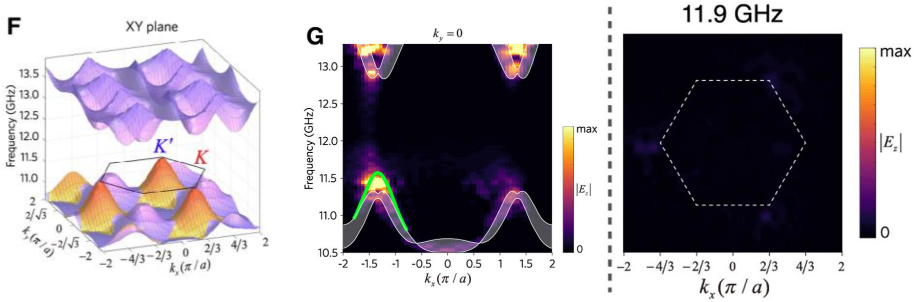

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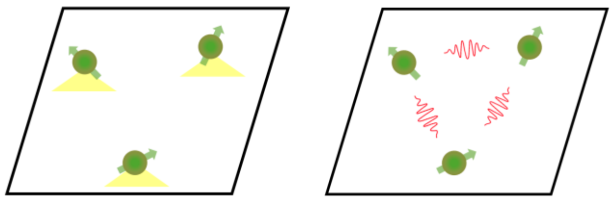

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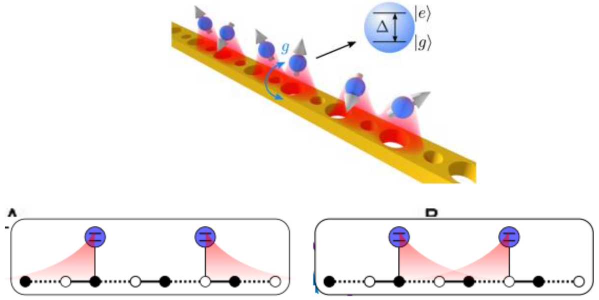

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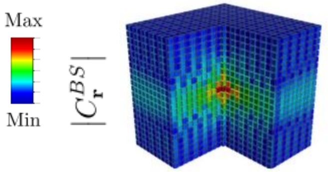
a Weyl Photonic Crystal



$$V_{eff} \propto \frac{1}{r^{\alpha}}$$

Single QE: Weyl bound state
Many emitters: BS mediates coherent, long-range interactions

Iñaki García-Elcano, Alejandro González-Tudela, and Jorge Bravo-Abad. Tunable and robust long-range coherent interactions between quantum emitters mediated by weyl bound states. Physical Review Letters, 125(16):163602, 2020.

Summary

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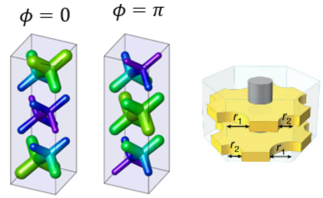

Supercell dielectric ~ inducing EM energy redistribution

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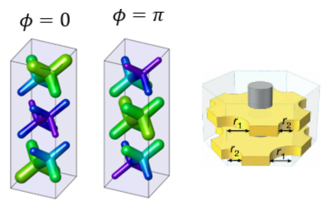

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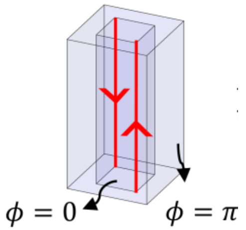
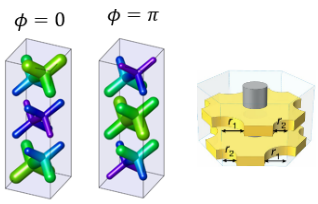


Axion hinge states manifesting at the domain wall

Summary



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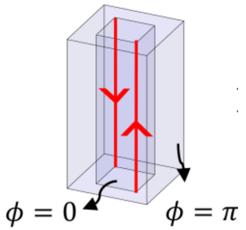

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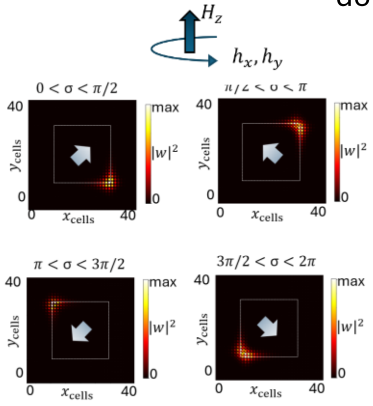

Small in-plane gyromagnetic bias to control hinge string connectivity

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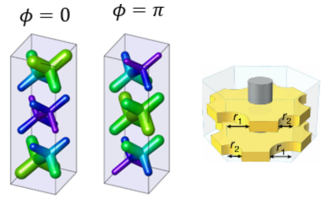

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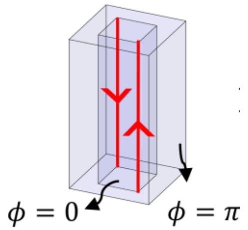

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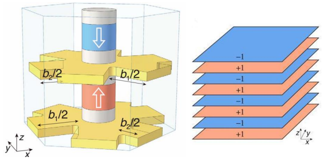
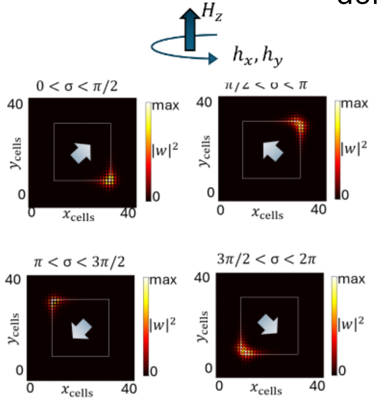


Intrinsic AXI can be realized via an alternating stacking



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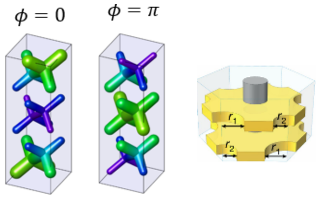

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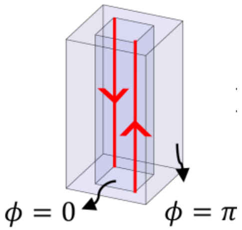

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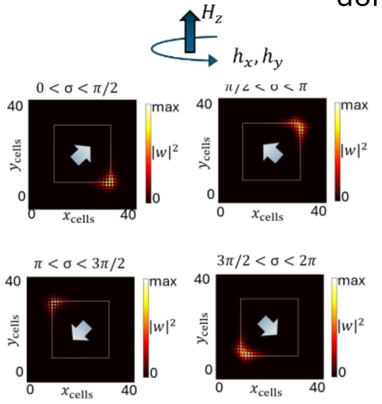

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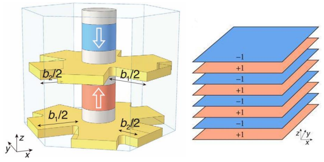

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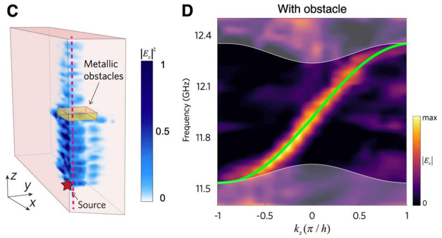

Unidirectional hinge states robust to obstacles

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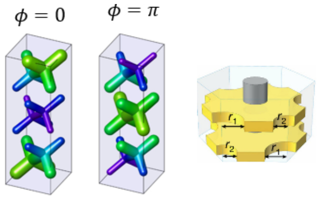

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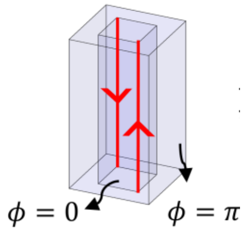

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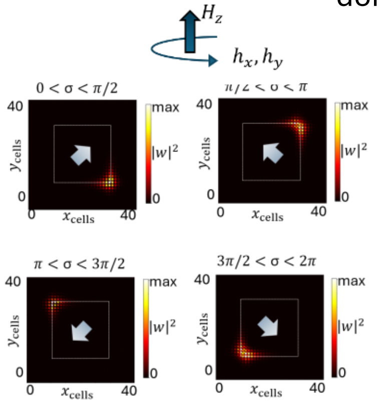

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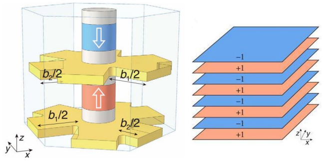

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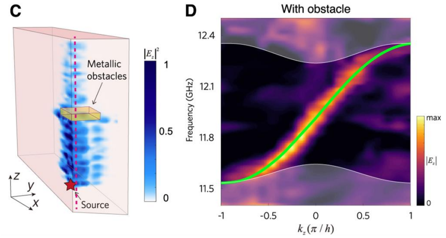

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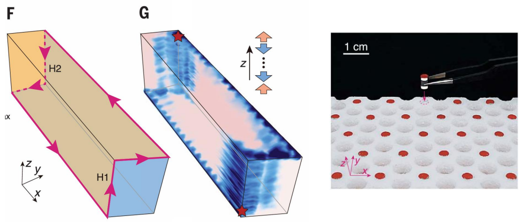

Half quantized anomalous Chern, whose sign can be be probed by addition of physical layers

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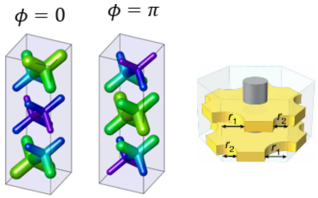

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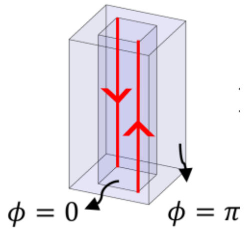

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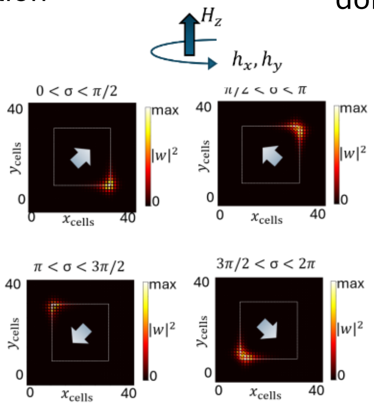

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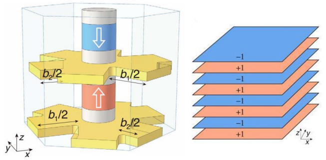

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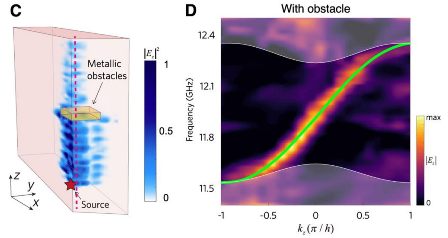

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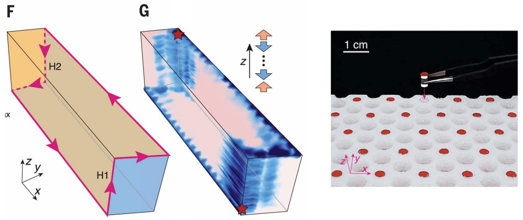

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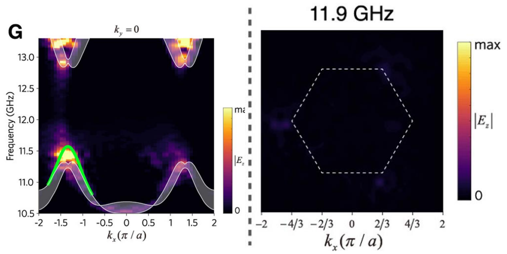
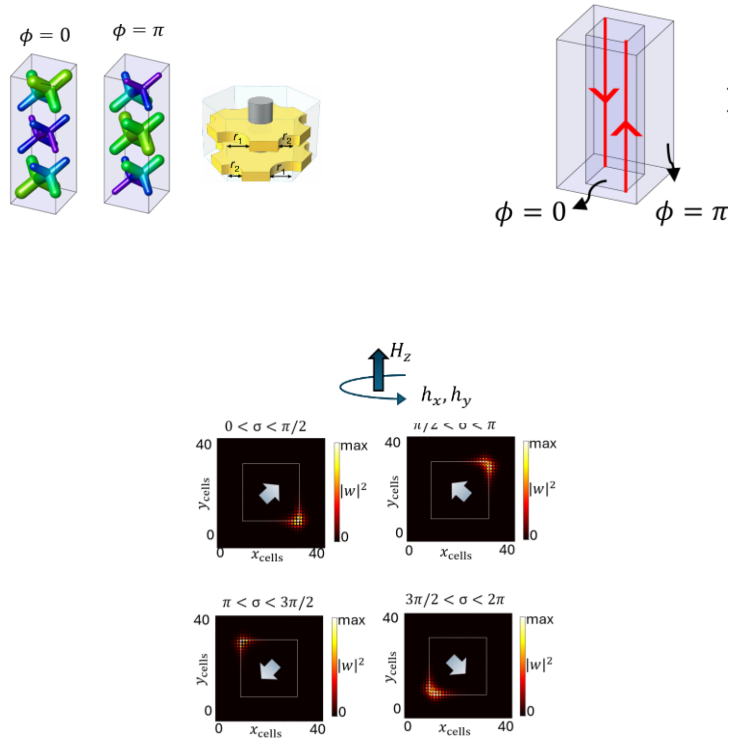
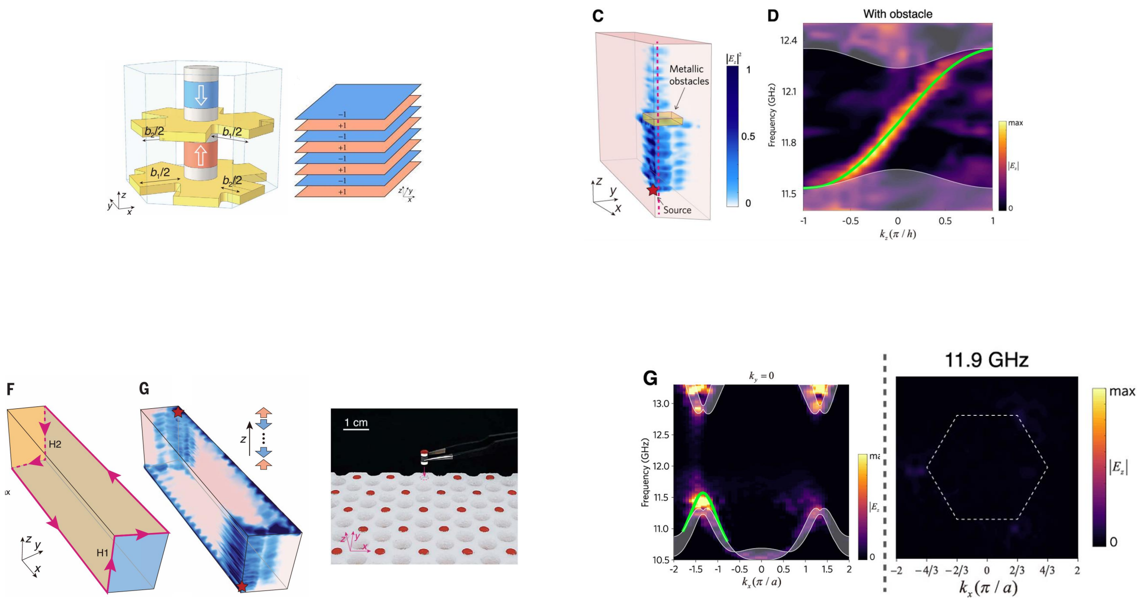


Potential platform to study surface topological order

Thank you for listening!



Axion topology in photonic crystals
Nat. Comm. 15, 6814 (2024)

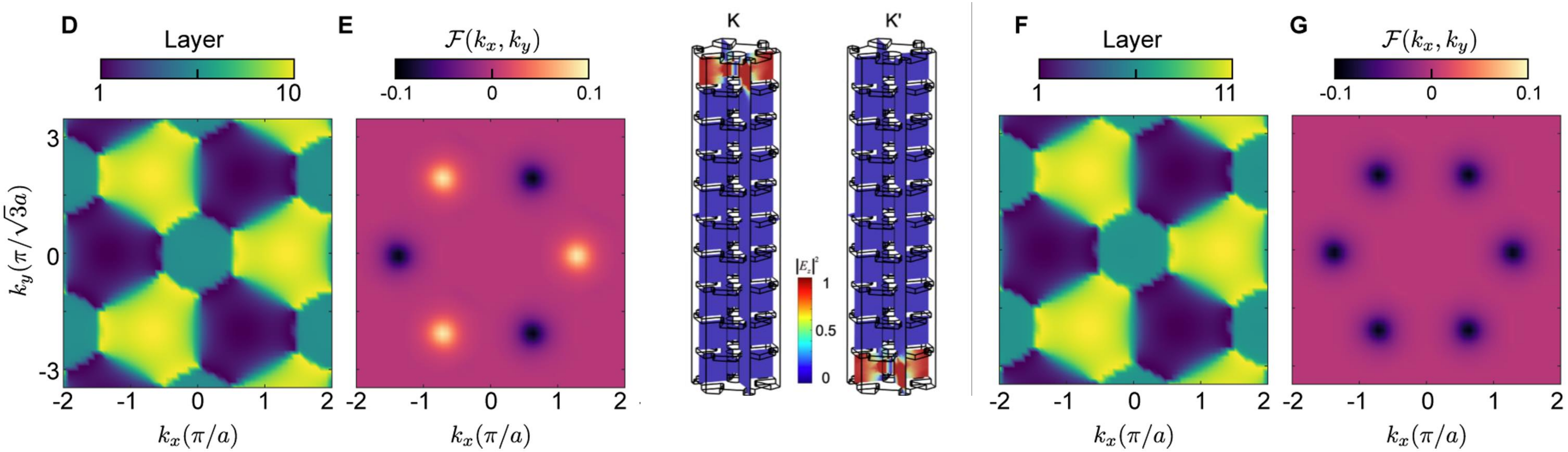


Photonic Axion Insulator
Science 387, 162–166 (2025)

Top/bottom valley contributions

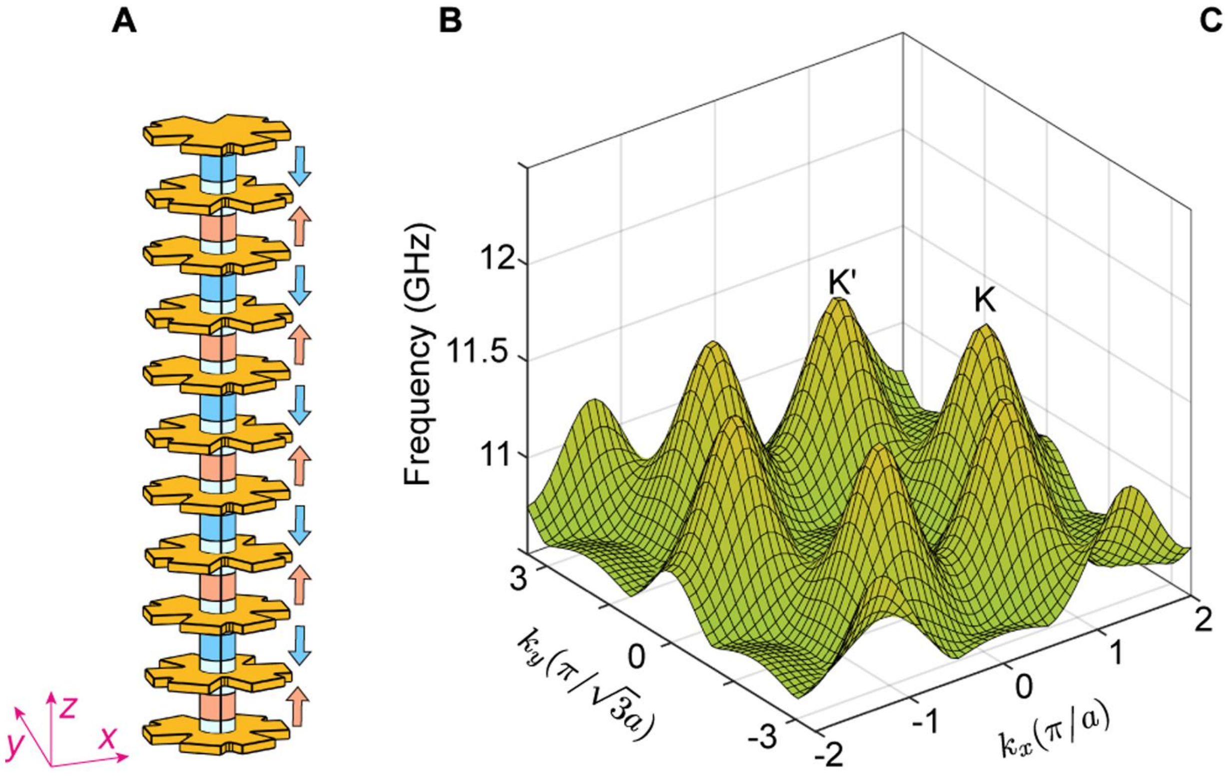
Even number of layers

Odd number of layers

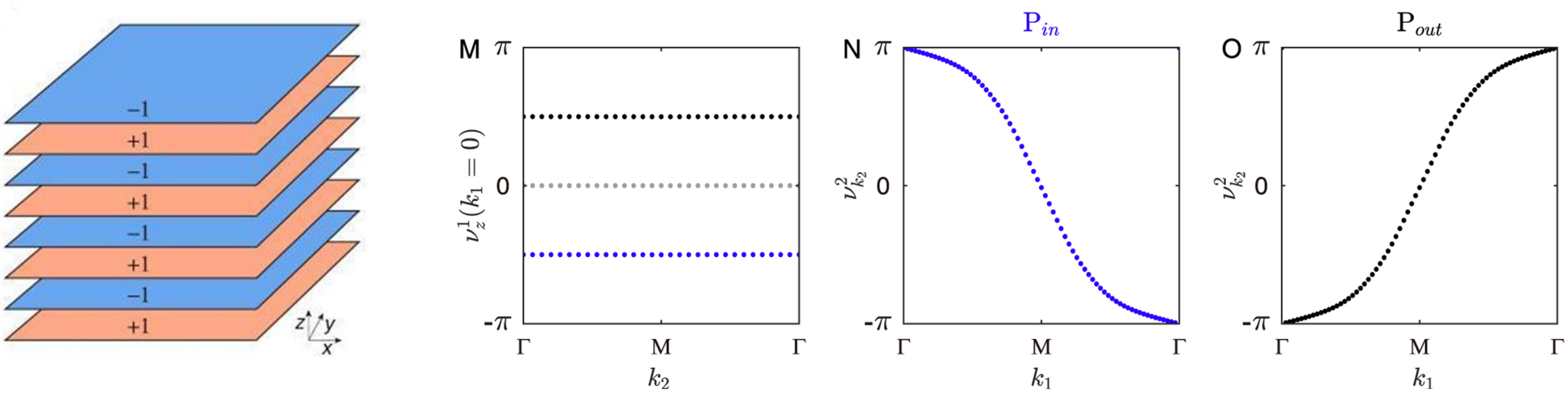


Sign change from positive to negative at the K valley where top surface contributes

Surface band structure simulation

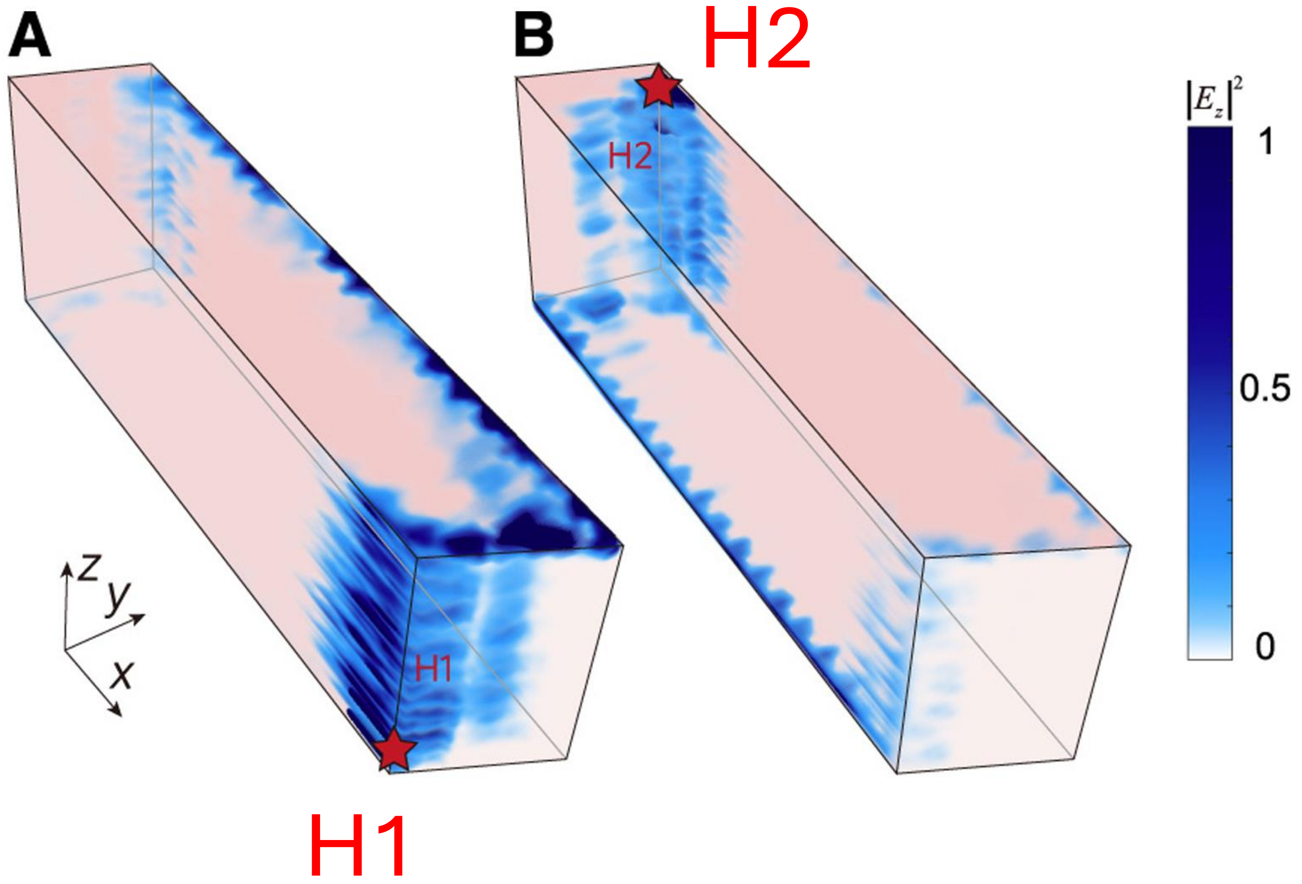


Nested Wilson loops



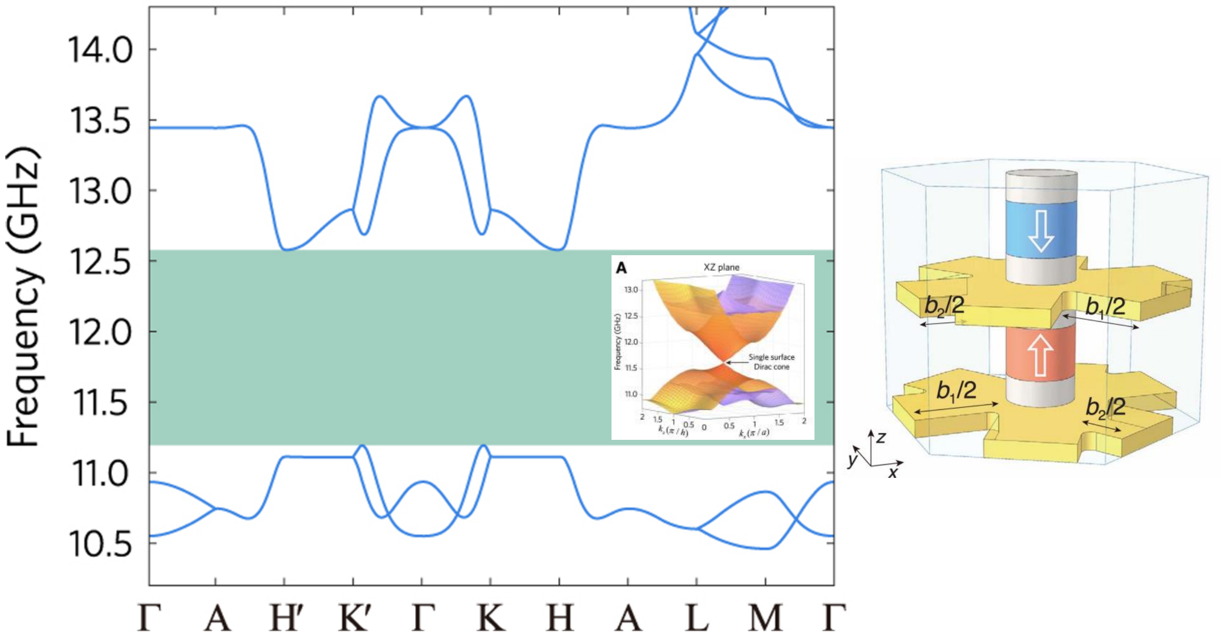
Hinge state profiles

Point source excitation: microwave dipole antennas

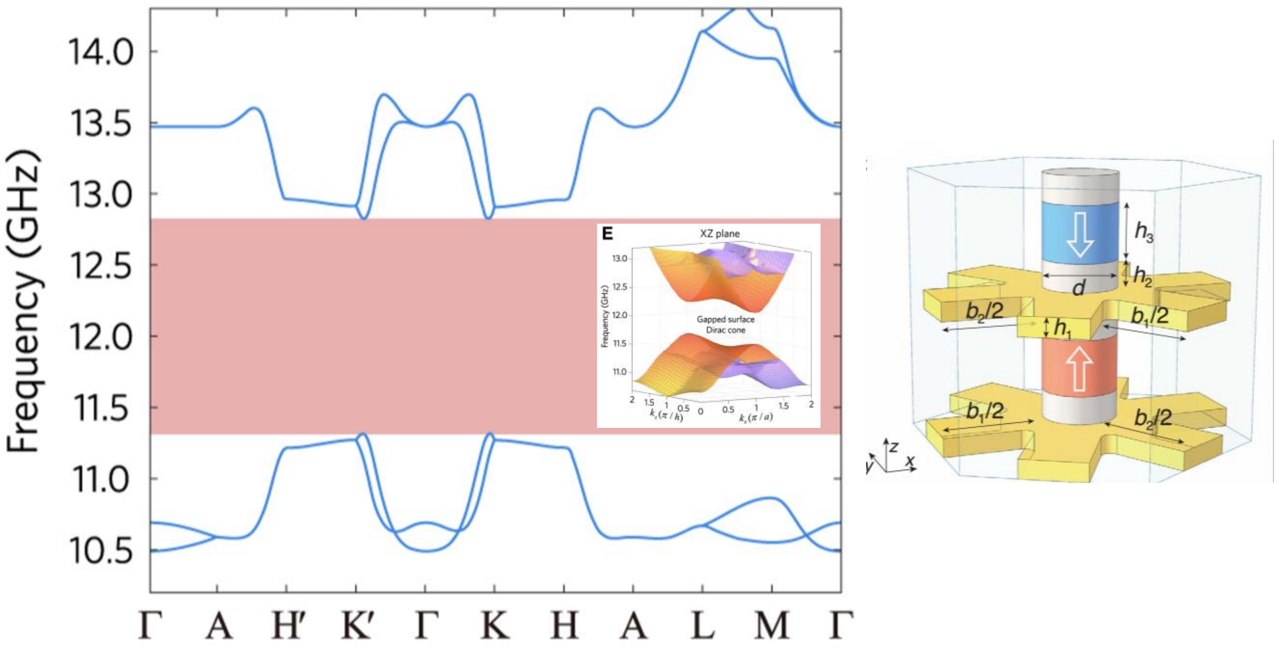


Gapped bulk

b_1=10 mm; b_2=10 mm

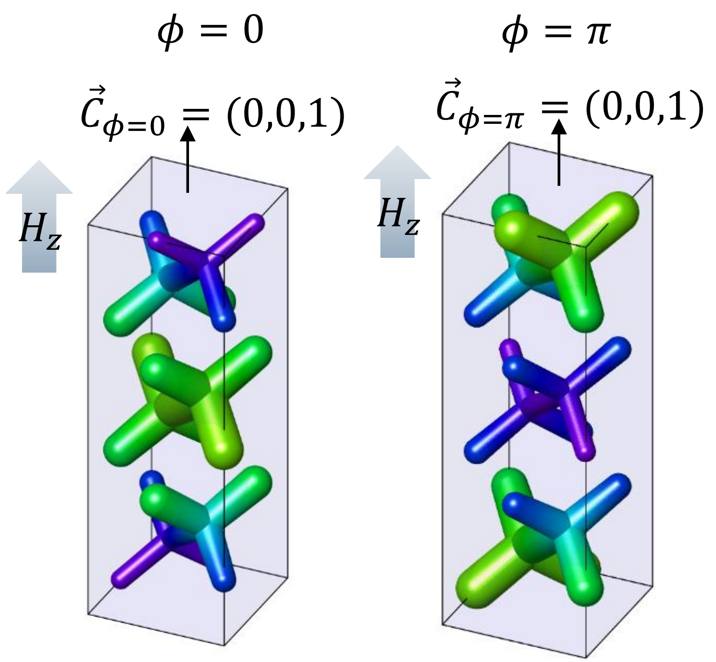


b_1=10 mm; b_2=5 mm



Magnetic space group

Tilted external magnetic field



$Y = (\pi, \pi, 0)$
$Z = (0,0,\pi)$
$C = (\pi, \pi, \pi)$

$\mathbb{Z}_2 \times \mathbb{Z}_2$

$\boldsymbol{n}^T_{\phi=0}$
$= [3A_1, 3B_1, C_1^- + 2C_2^+ + 3C_2^-, 3D_1, 3E_1, (\blacksquare)^{2T} + 2\Gamma_2^+ + 2\Gamma_2^-, Y_1^- + 2Y_2^+ + 3Y_2^-, 3Z_2^+ + 3Z_2^-]$ $\Rightarrow$ $\nu^T_{\phi=0} = (1,0)$

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MSG 67.505

$\{\bar{1}|0\}$
$\left\{C_{2z}\middle|\frac{1}{2},\frac{1}{2},0\right\}$
$\left\{m_z\middle|\frac{1}{2},\frac{1}{2},0\right\}$

$\left\{C'_{2_{110}}\middle|\frac{1}{2},\frac{1}{2},0\right\}$, $\left\{m'_{110}\middle|\frac{1}{2},\frac{1}{2},0\right\}$
$\left\{C'_{2_{1\bar{1}0}}\middle|\frac{1}{2},\frac{1}{2},0\right\}$, $\left\{m'_{1\bar{1}0}\middle|\frac{1}{2},\frac{1}{2},0\right\}$

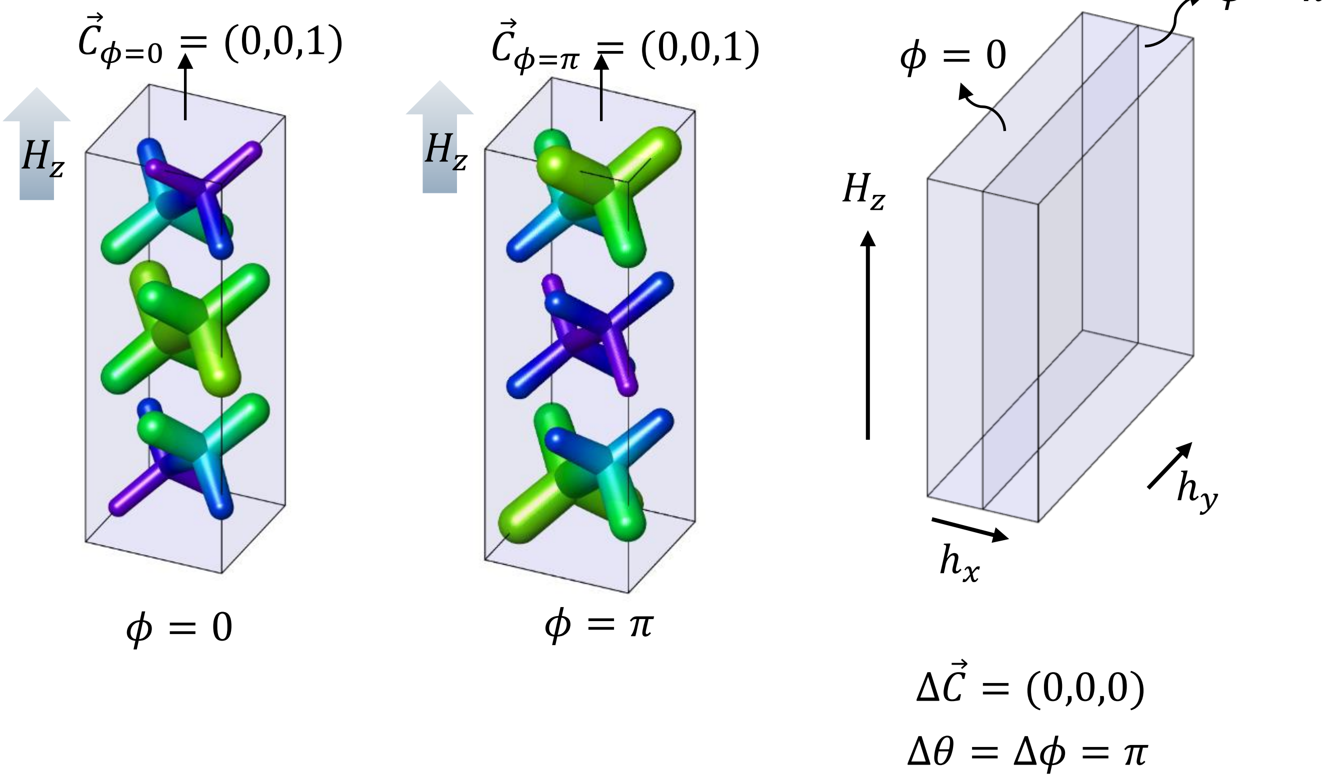
Unitary: P2/c (SG No. 13) Anti-unitary

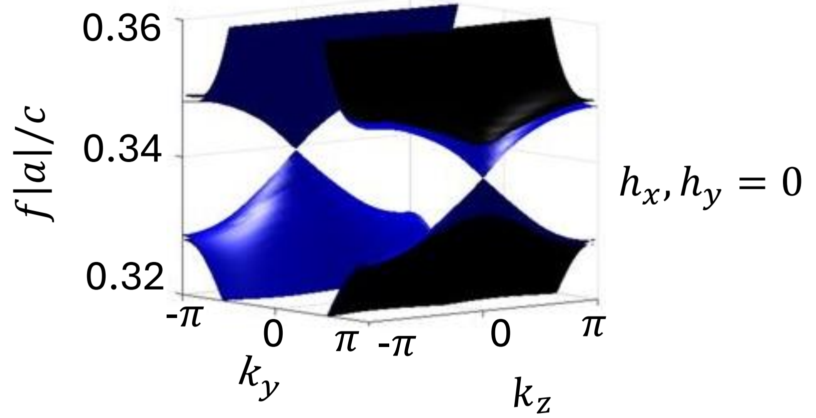
For $\boldsymbol{H} = (h_x, h_y, H_z)$, subduction to *MSG 2.4* without bulk-gap closing while $|h_x|, |h_y| \ll |H_z|$

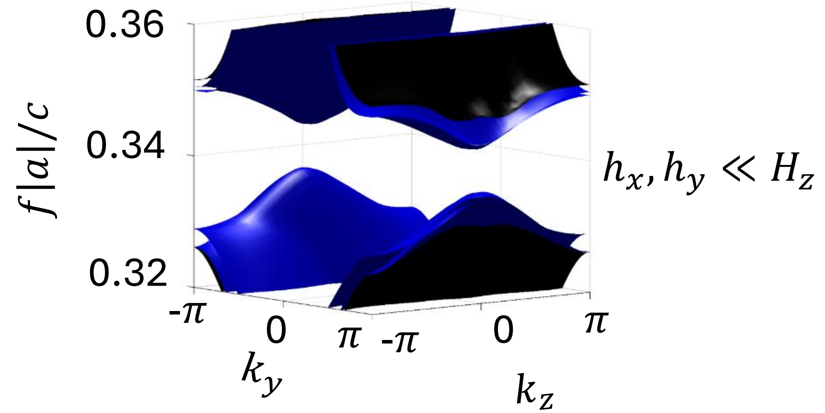
$\bar{z}_{2,x} = \bar{z}_{2,y} = 0 \quad \nu = \left(\bar{z}_{2,z}, \frac{\bar{z}_{24}}{2}\right)$

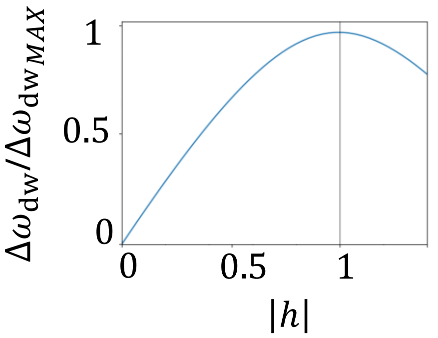
Higher-order response

Opening domain wall surface gap



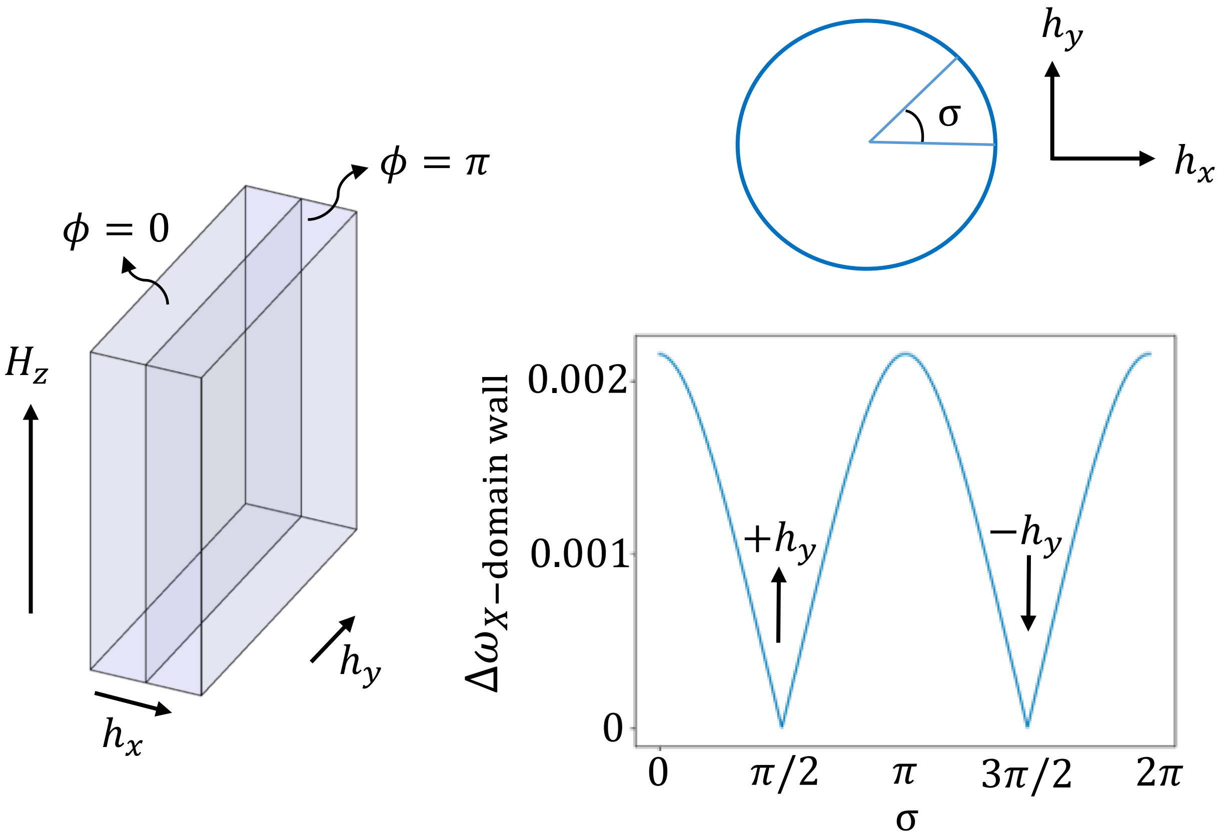






Gyrotropy-induced switching of HOTI states

Boundary-obstructed transitions



$|H_z| \gg |h_x|, |h_y|$