Condensed Matter Axion Modes: Experimental Status & Future Work

Weyl and Dirac Semimetals as a Laboratory for High-Energy Physics Workshop

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26 June 2025

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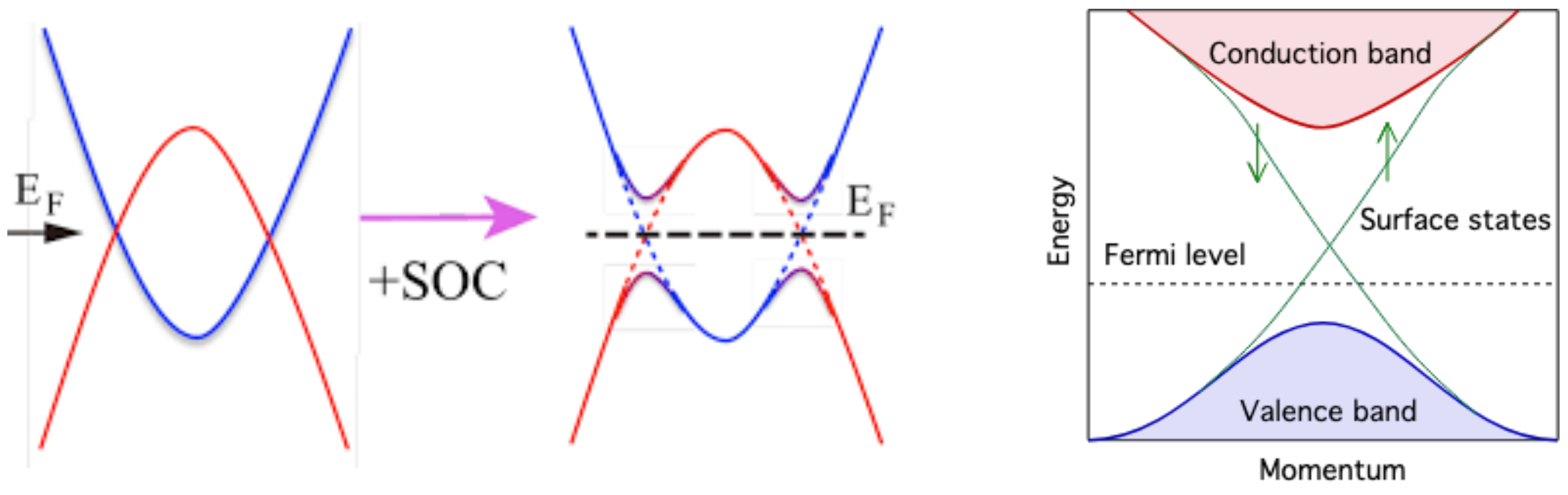
NARANGLAB

Topological materials which host axion physics

Topological insulators

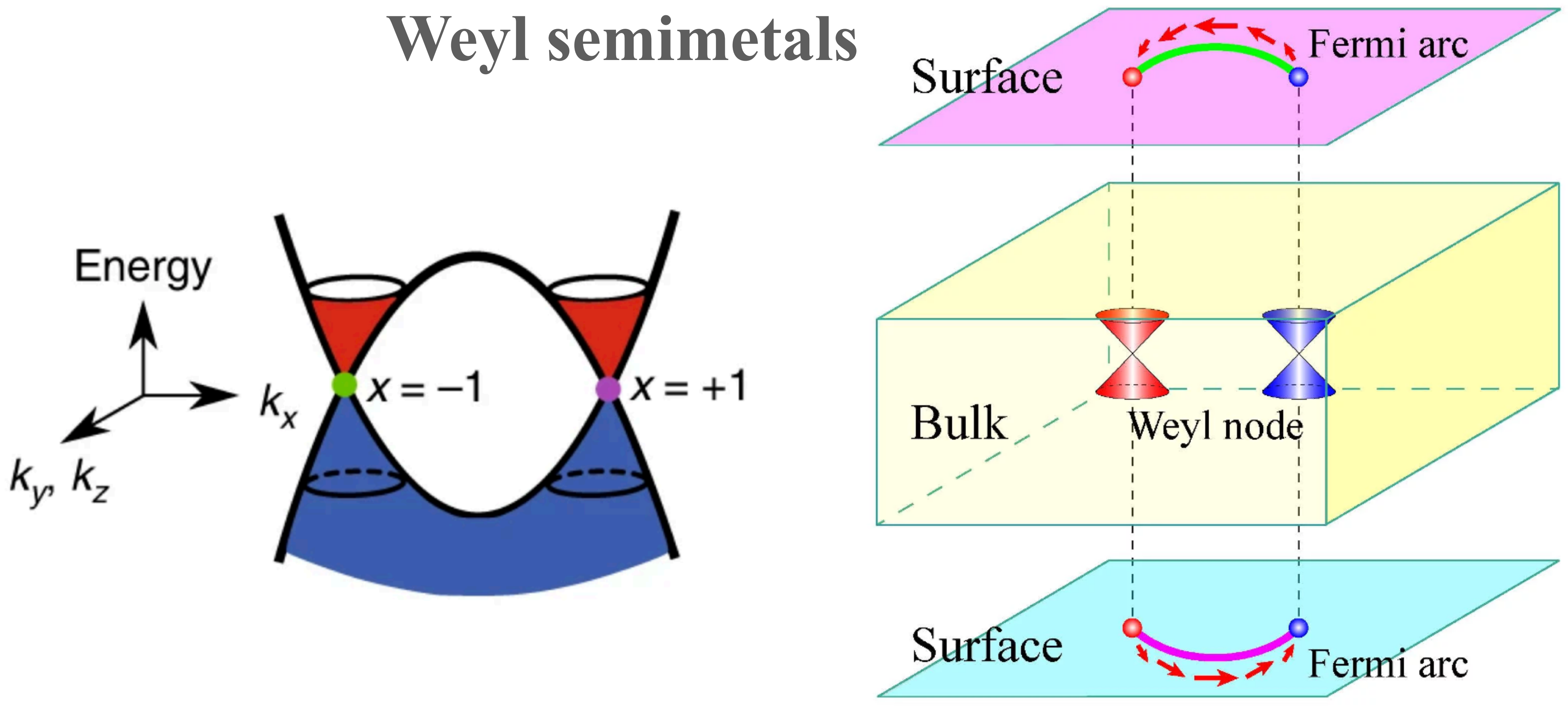


Characterized by insulating in the bulk, with conducting surface states

$$H_{TI}(\boldsymbol{k}) = \hbar v_F \boldsymbol{\sigma} \cdot \boldsymbol{k}$$

Quantized / static background axion $\theta_0 = \pi$

Weyl semimetals



Characterized by pairs of linear band crossings (Weyl nodes) and Fermi surface states arcs i.e. chiral surface states

$$H_{Weyl}(\boldsymbol{k}) = b_0 \pm v\boldsymbol{\sigma} \cdot (\boldsymbol{k} - \boldsymbol{b})$$

Background axion $\theta_0(\boldsymbol{r}, t) = \boldsymbol{b} \cdot \boldsymbol{r} - b_0 t$

Axion as a framework for *topological magnetoelectrics*

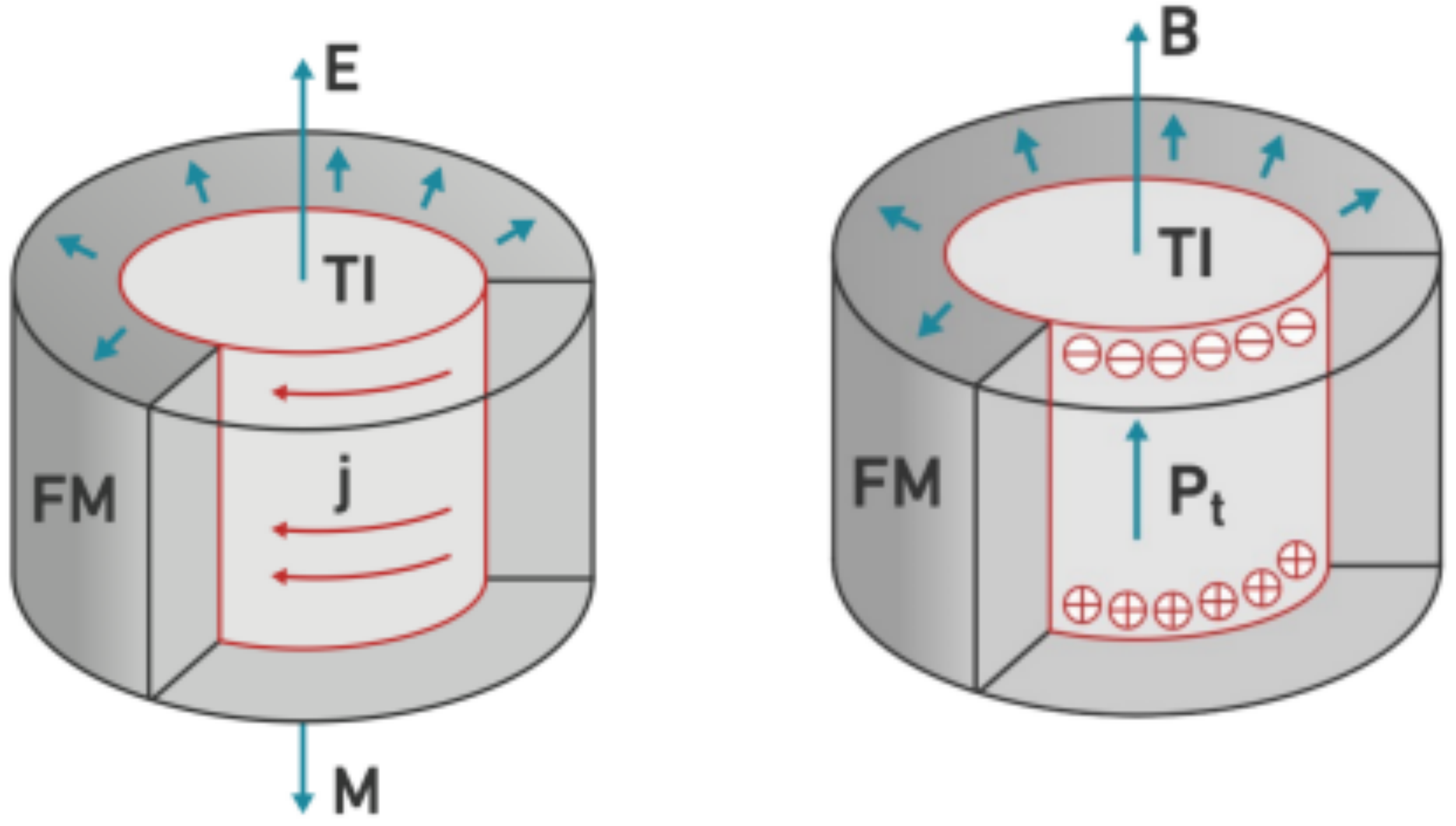
Axion term modifies how electric and magnetic fields couple, leading to modified form of Maxwell's equations

θ: topological magnetoelectric coupling $$S_\theta = \int d^3r dt \frac{\theta(\boldsymbol{r}, t) e^2}{4\pi^2 \hbar c} \boldsymbol{E} \cdot \boldsymbol{B}$$

Unusual transport properties in topological materials:

Compactly described by
axion framework ✓

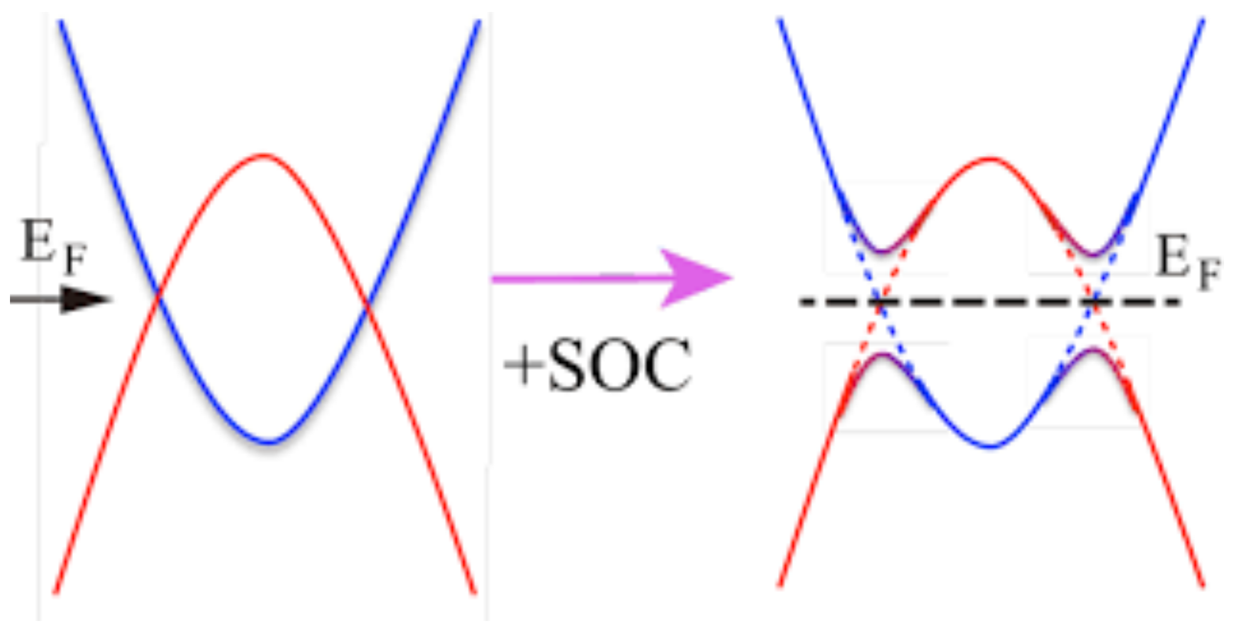
- Anomalous Hall currents ($\nabla\theta$)
- Chiral magnetic effect ($\partial_t\theta$)
- Signature of axion is magnetoelectric response $\boldsymbol{P} \propto \theta \boldsymbol{B}, \boldsymbol{M} \propto \theta \boldsymbol{E}$

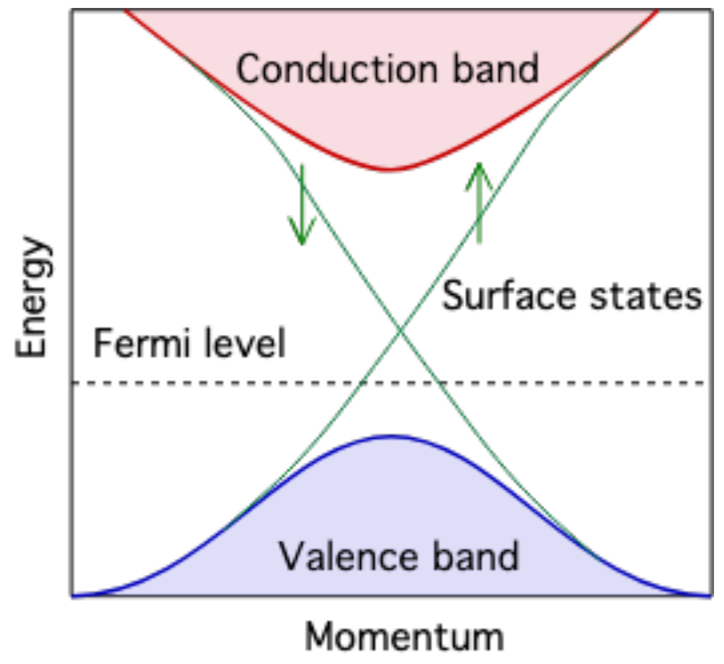


Nenno et. al., Nat. Rev. Phys. (2020)

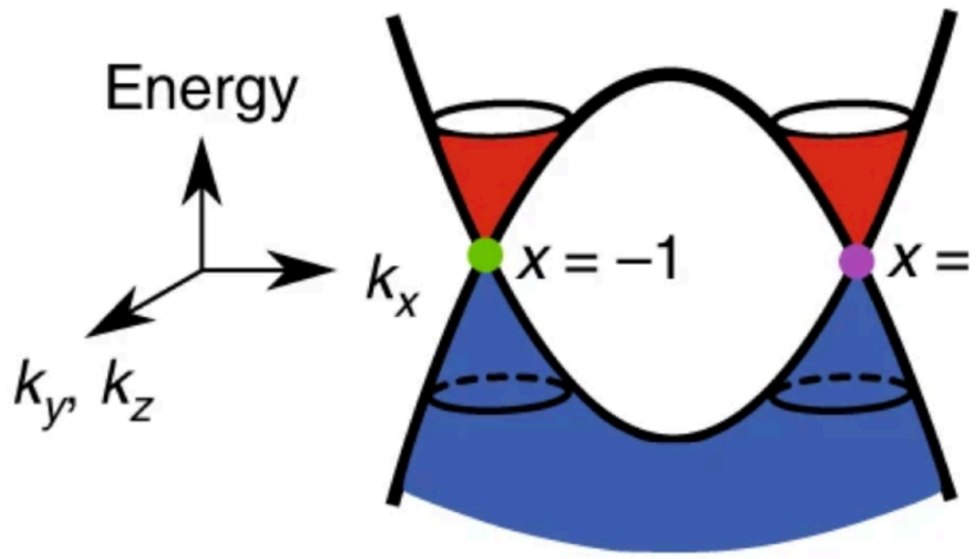
Topological materials which host *dynamical* axion quasiparticles

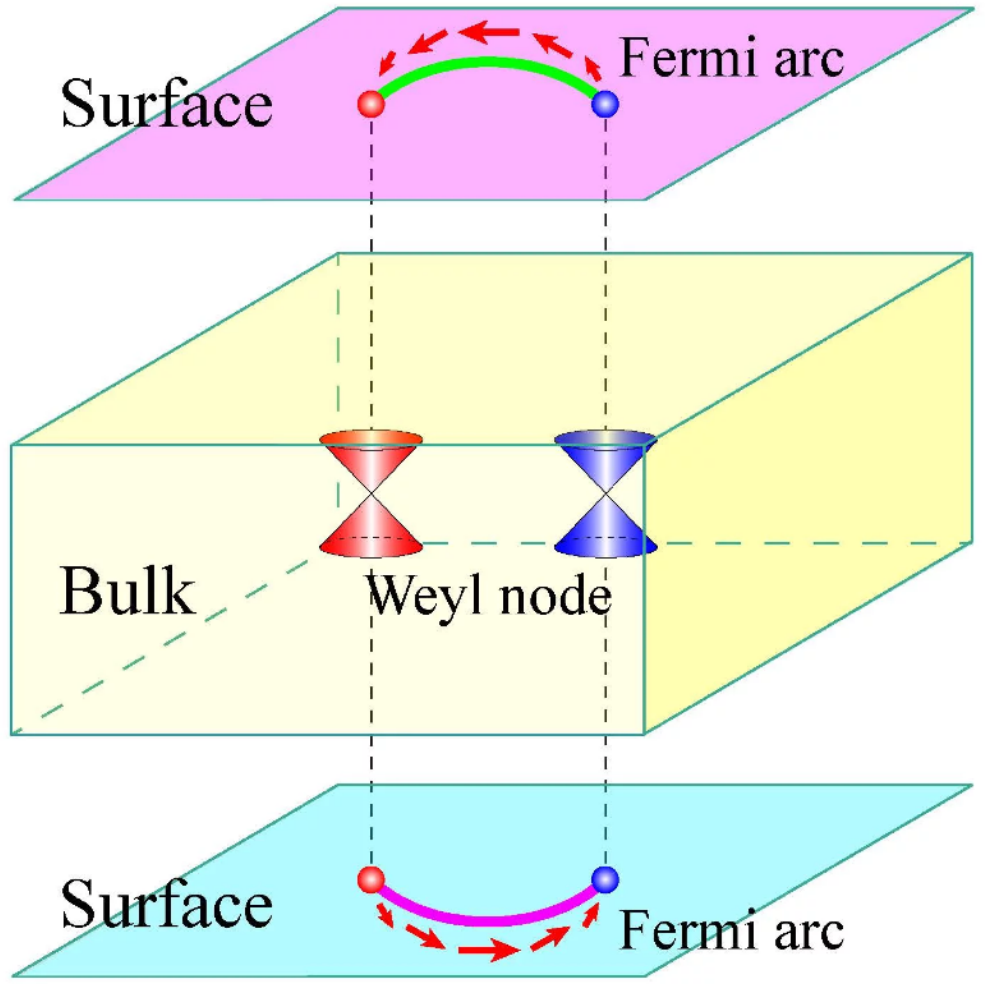
Topological insulators





Weyl semimetals





Antiferromagnetic topological insulators

$$\theta(\vec{r}, t) = \theta_0 + \delta\theta$$

Charge density wave Weyl semimetals

Dynamical axion $\delta\theta$ **-** topological insulators with AFM ordering

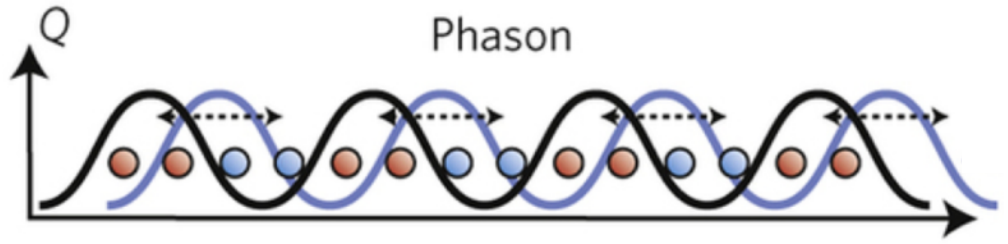
$\delta\theta$ = collective spin wave excitations of AFM OP

e.g. $MnBi_2Te4$

Dynamical axion $\delta\theta$ **-** arises due to strong correlations in the bulk

Weyl semimetal with charge density wave order, $\delta\theta$ = phason of CDW

e. g. $(TaSe_4)_2I$



Condensed matter axion

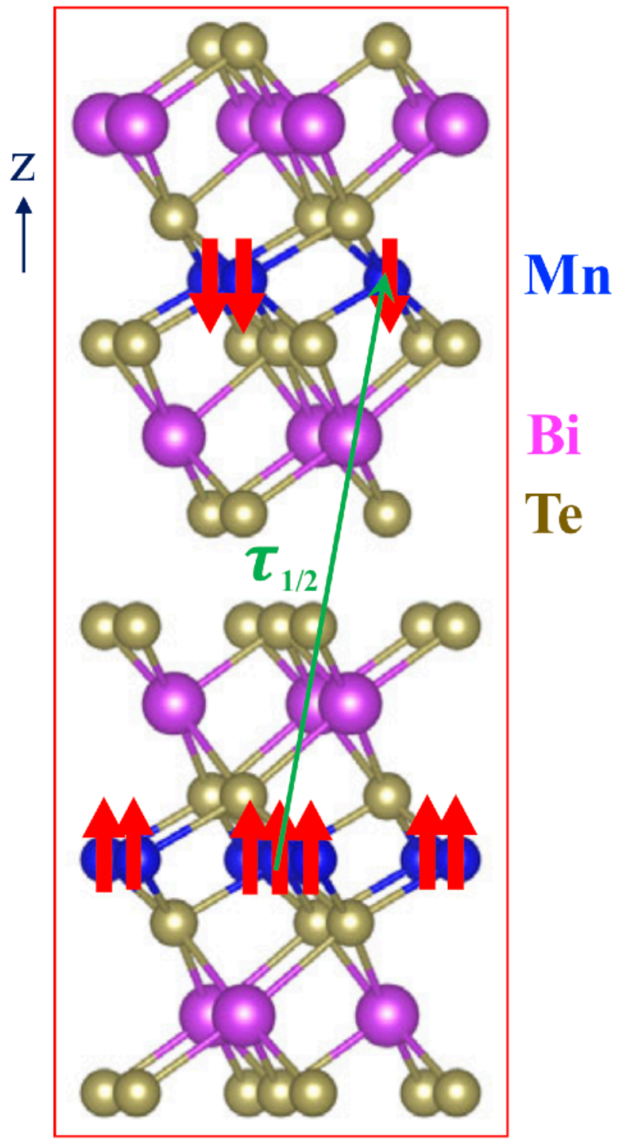
Axion-modified Maxwell's equations

$$\nabla \cdot \mathbf{E} = \rho - \frac{e^2}{4\pi^2 \hbar c} \nabla\theta \cdot \mathbf{B}$$

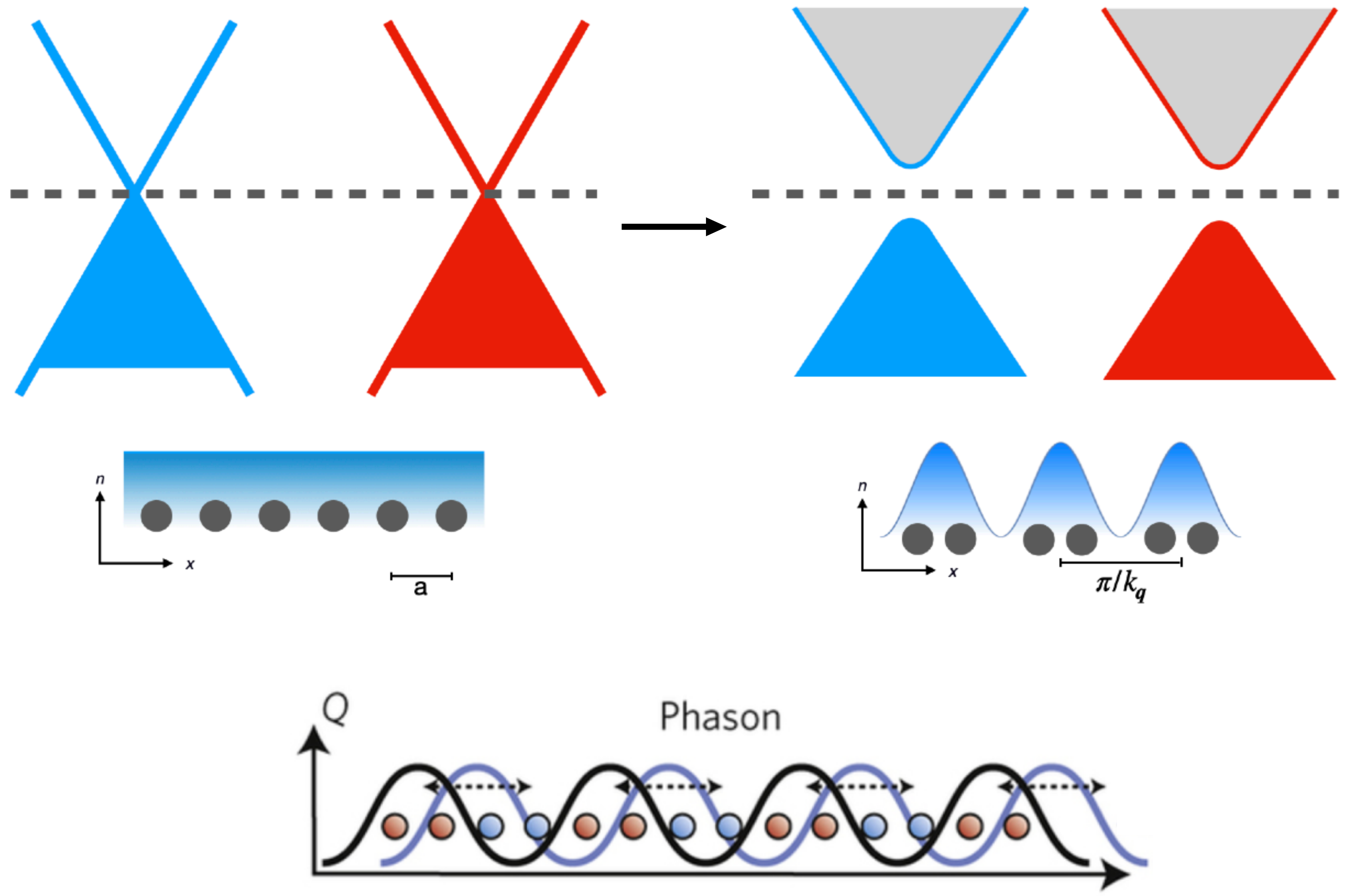
$$\nabla \times \mathbf{B} - \frac{1}{c^2}\partial_t \mathbf{E} = \mathbf{J} + \frac{e^2}{4\pi^2 \hbar c}\left(\nabla\theta \times \mathbf{E} + \partial_t \theta\, \mathbf{B}\right)$$

$$\mathcal{L}_\theta = \frac{e^2}{4\pi^2 \hbar}\theta(\mathbf{r}, t)\,\mathbf{E}\cdot\mathbf{B} \longrightarrow \boldsymbol{J}_\theta = \frac{\alpha}{\pi}\nabla\theta \times \boldsymbol{E} + \frac{\alpha}{\pi}\partial_t \theta \boldsymbol{B}$$

…dynamical axion contribution



$$\theta(\vec{r}, t) = \theta_0(\vec{r}) + \delta\theta(\vec{r}, t)$$



Why call these collective modes "axions"?

- CDW phason in WSM / AFM spin wave in TI
  - Pseudoscalar
  - CP-violating
  - Couples to $\vec{E} \cdot \vec{B}$

Experimental status:

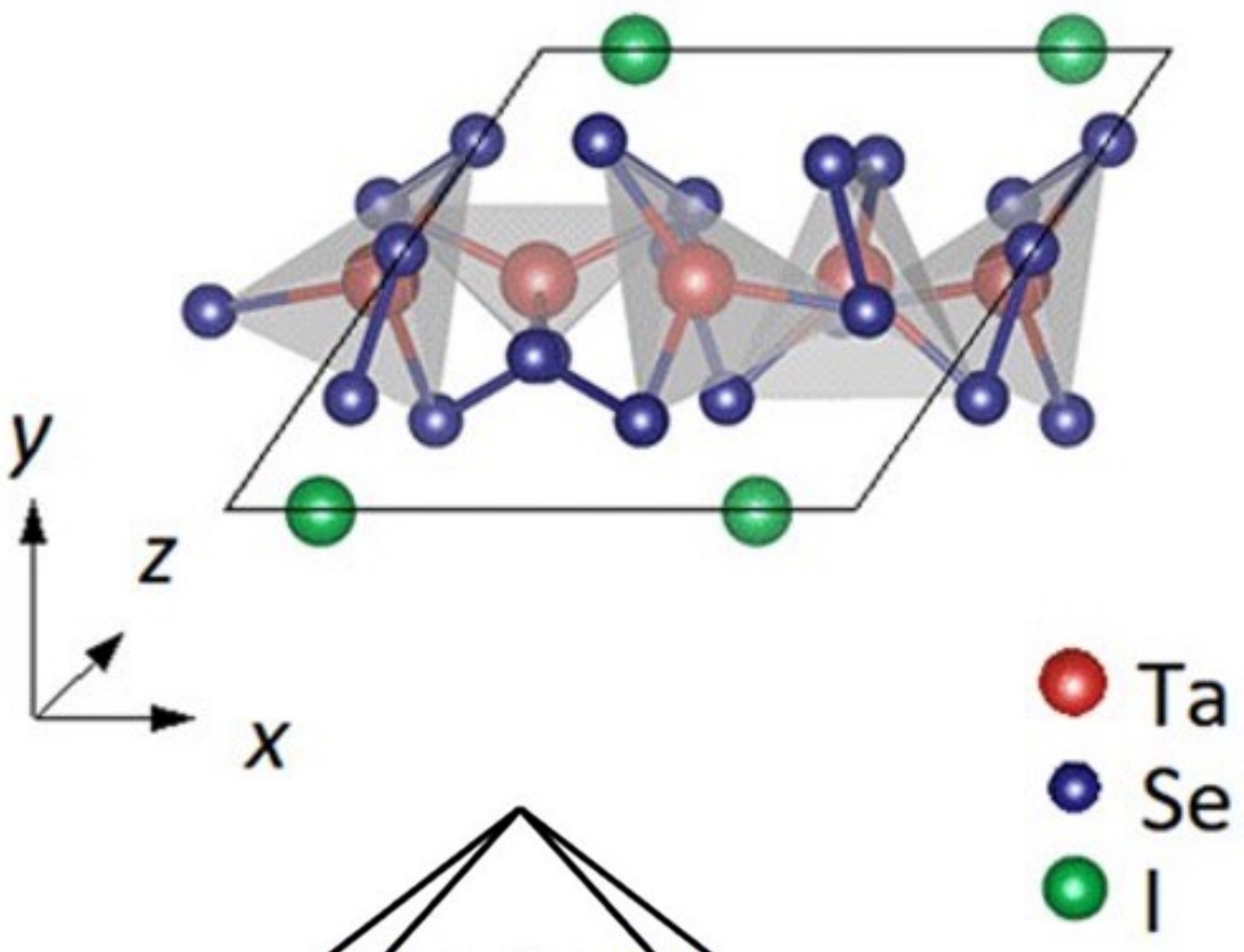
1. ***Dynamical axion detection in charge density wave Weyl semimetal $(TaSe_4)_2I$***
2. ***Observation of the axion quasiparticle in 2D $MnBi_2Te_4$***

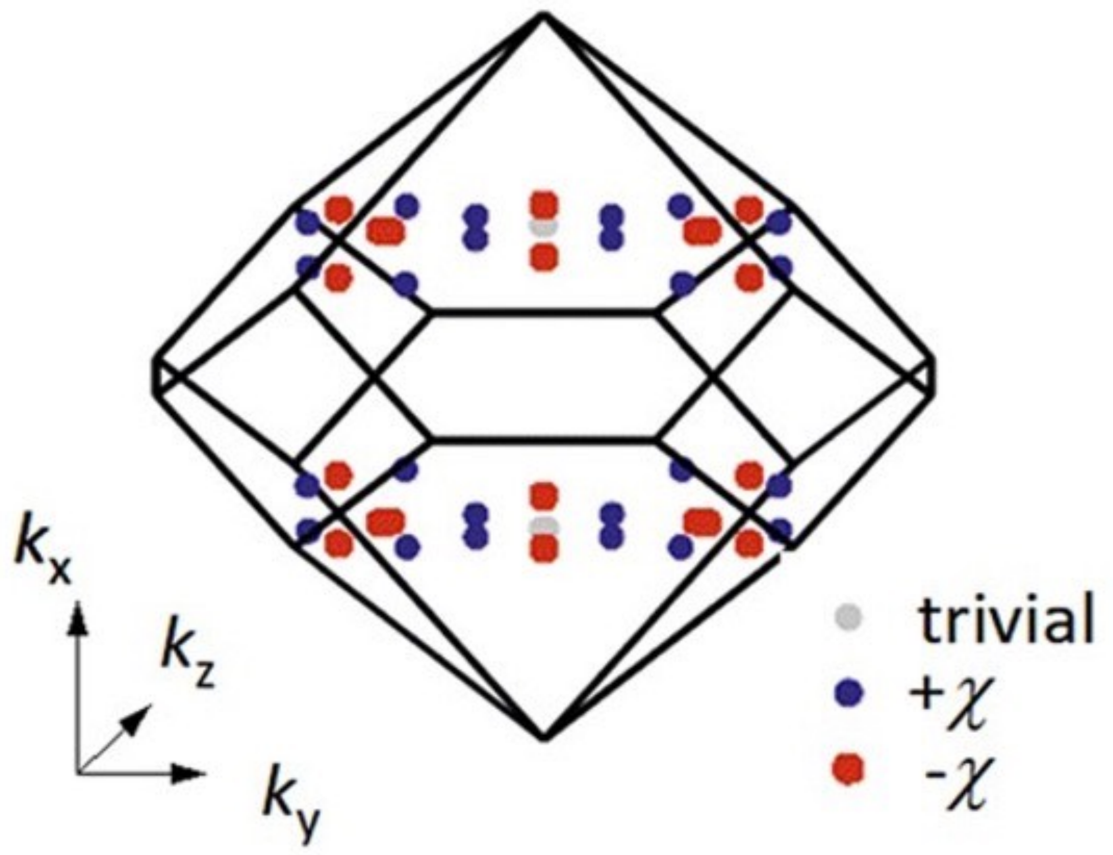
…and experimental proposals for future work

Dynamical axion detection in charge density wave Weyl semimetal $(TaSe_4)_2I$

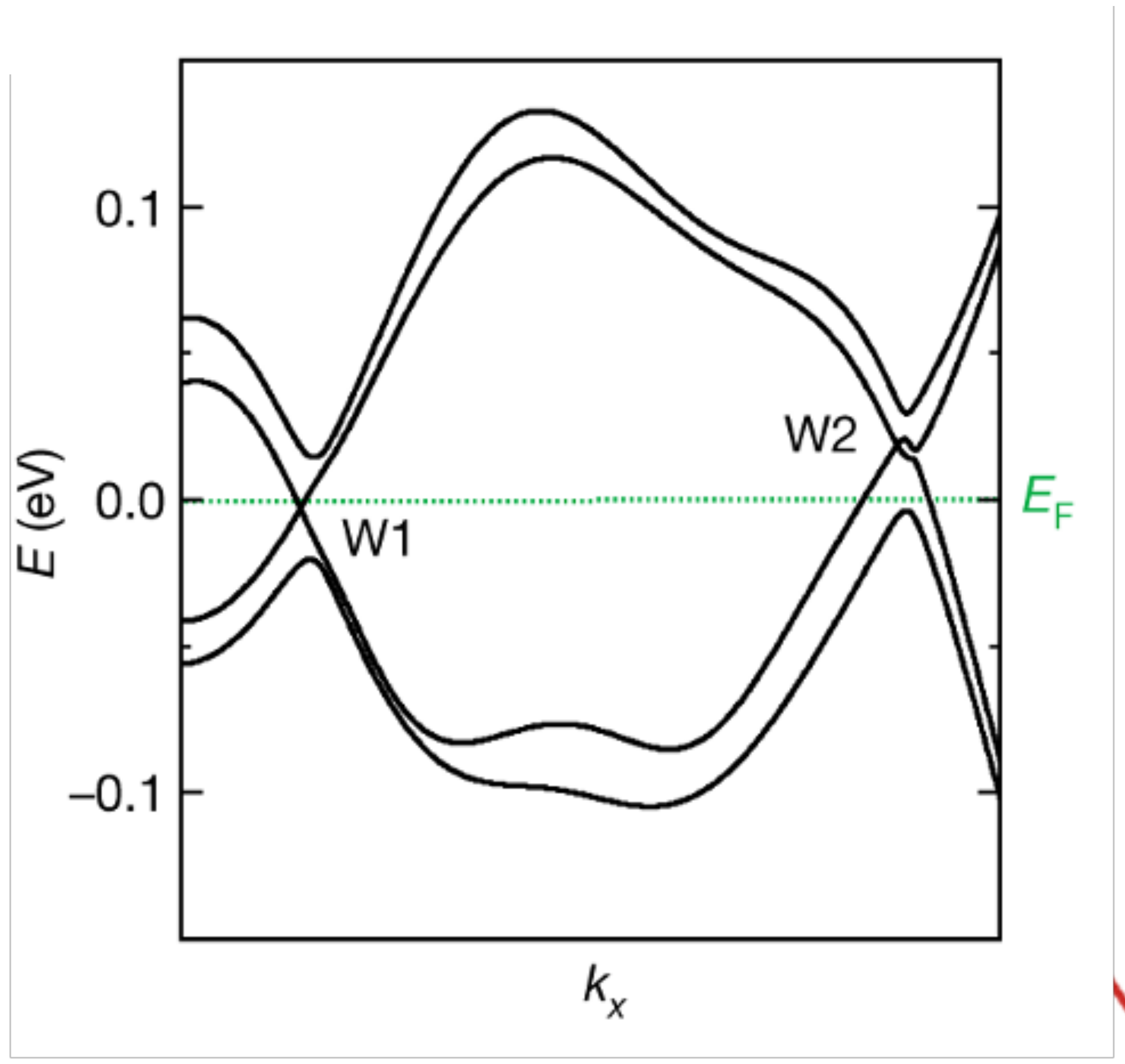
J. Gooth, B. Bradlyn, S. Honnali, C. Schindler, N. Kumar, J. Noky, Y. Qi, C. Shekhar, Y. Sun, Z. Wang, B. A. Bernevig, & C. Felser

Nature 575, 315–319 (2019). doi:10.1038/s41586-019-1630-4



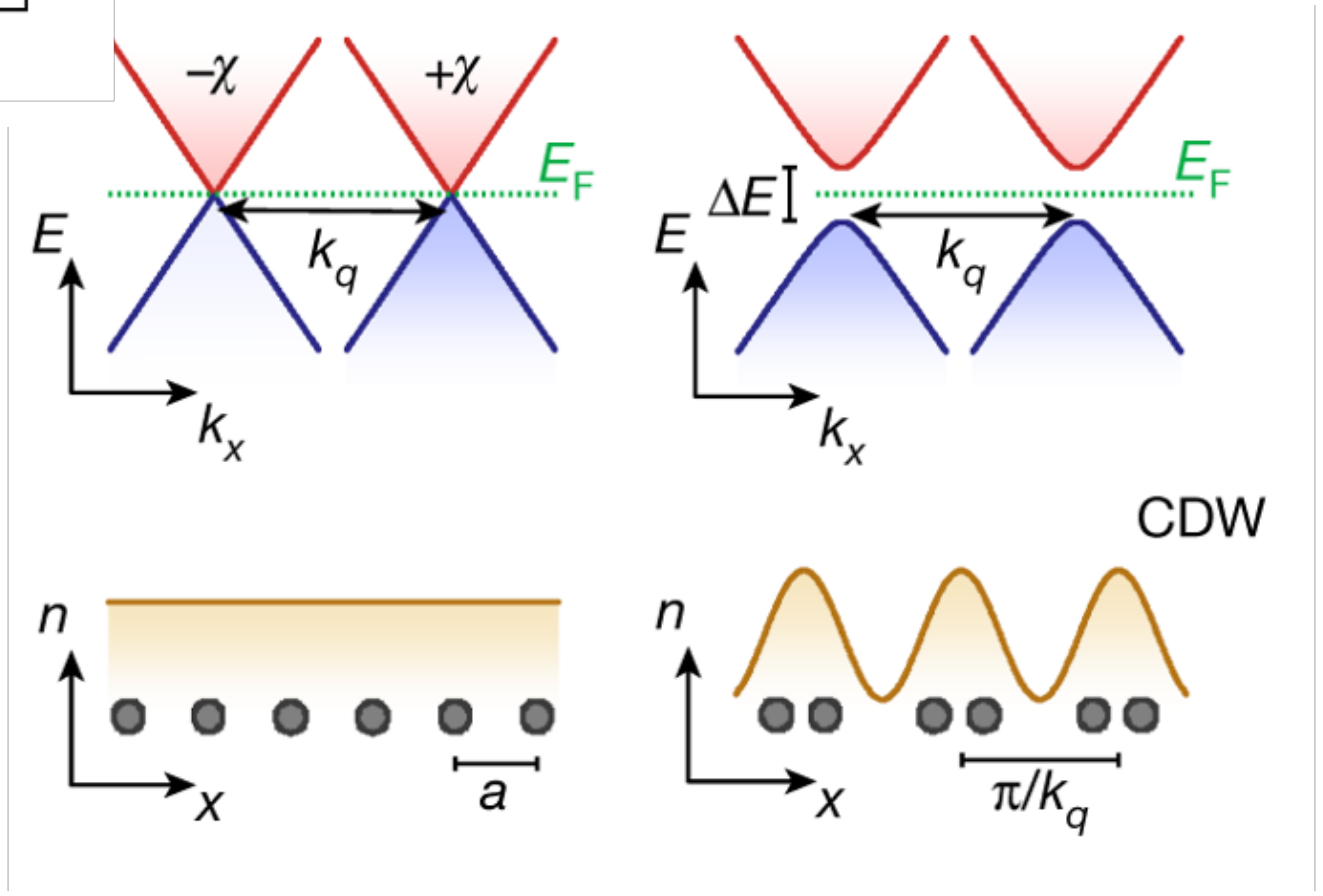


Distribution of Weyl nodes in k-space



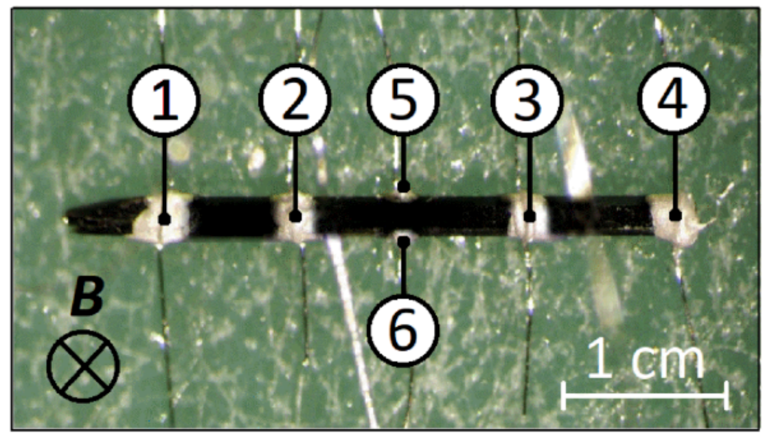
Relevant features of $(TaSe_4)_2I$:

- Weyl semimetal
- Quasi-1D structure
- CDW transition temperature $T_c \approx 263K$
- Incommensurate CDW



CDW formation leads to gapping out of Weyl cones

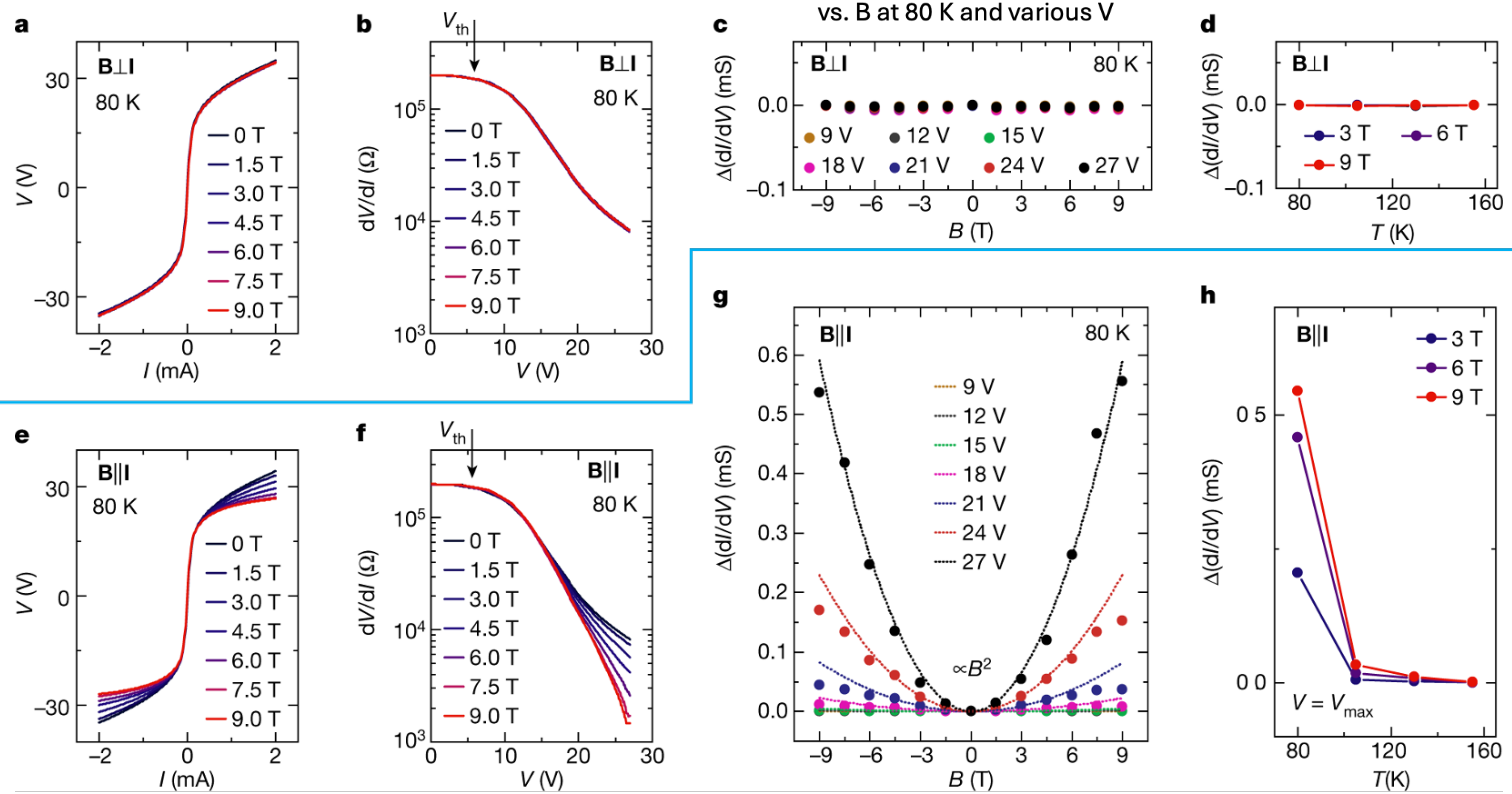
Evidence for axionic phason in $(TaSe_4)_2I$



differential conductance $\Delta(dI/dV)_B = (dI/dV)_B - (dI/dV)_{0\,T}$ vs. B at 80 K and various V

B* ⊥ *I

B* || *I

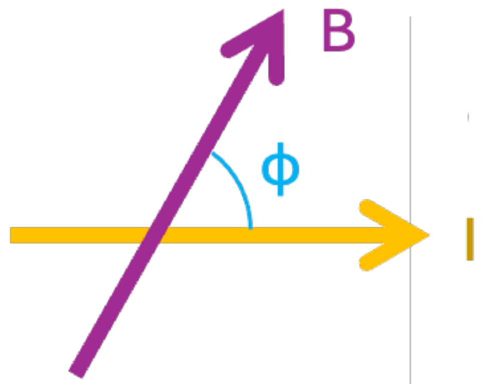


$$J_\theta \propto \partial_t \theta \boldsymbol{B}$$

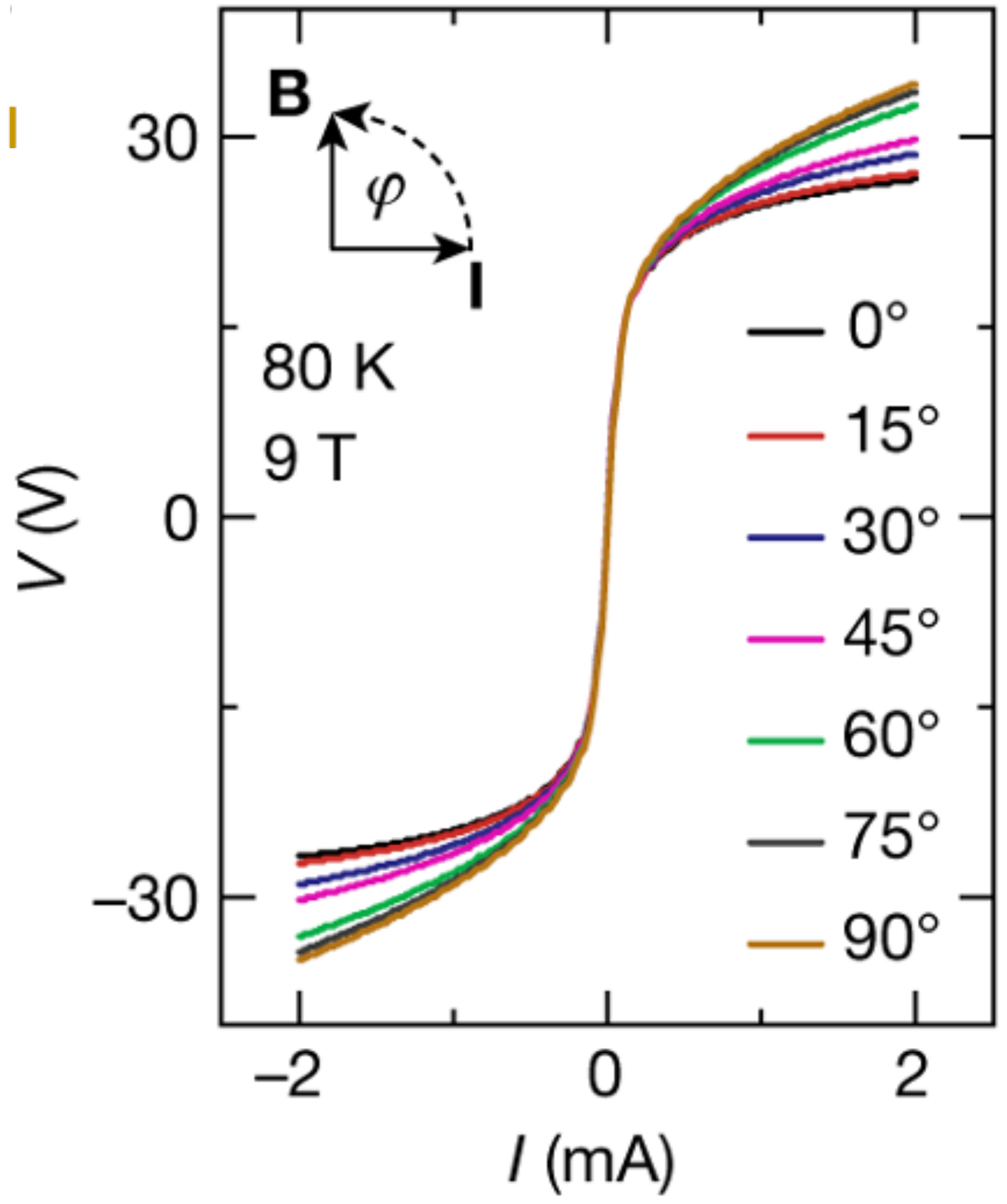
Nonlinear transport: dI/dV increases nonlinearly only when $\boldsymbol{B}||\boldsymbol{I}$

Gooth, et al. Nature 575, pages 315–319 (2019)

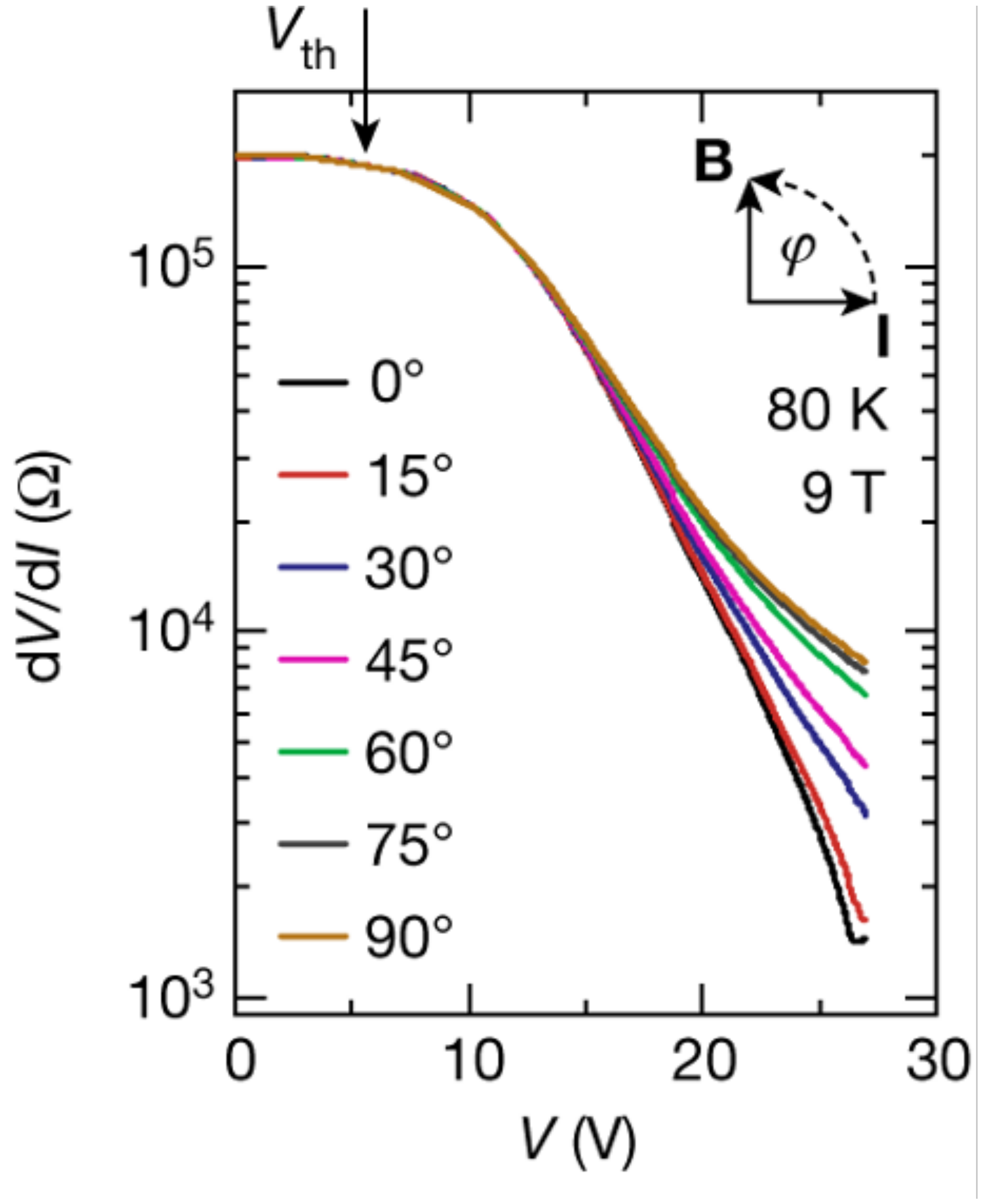
Angular dependence of axial current



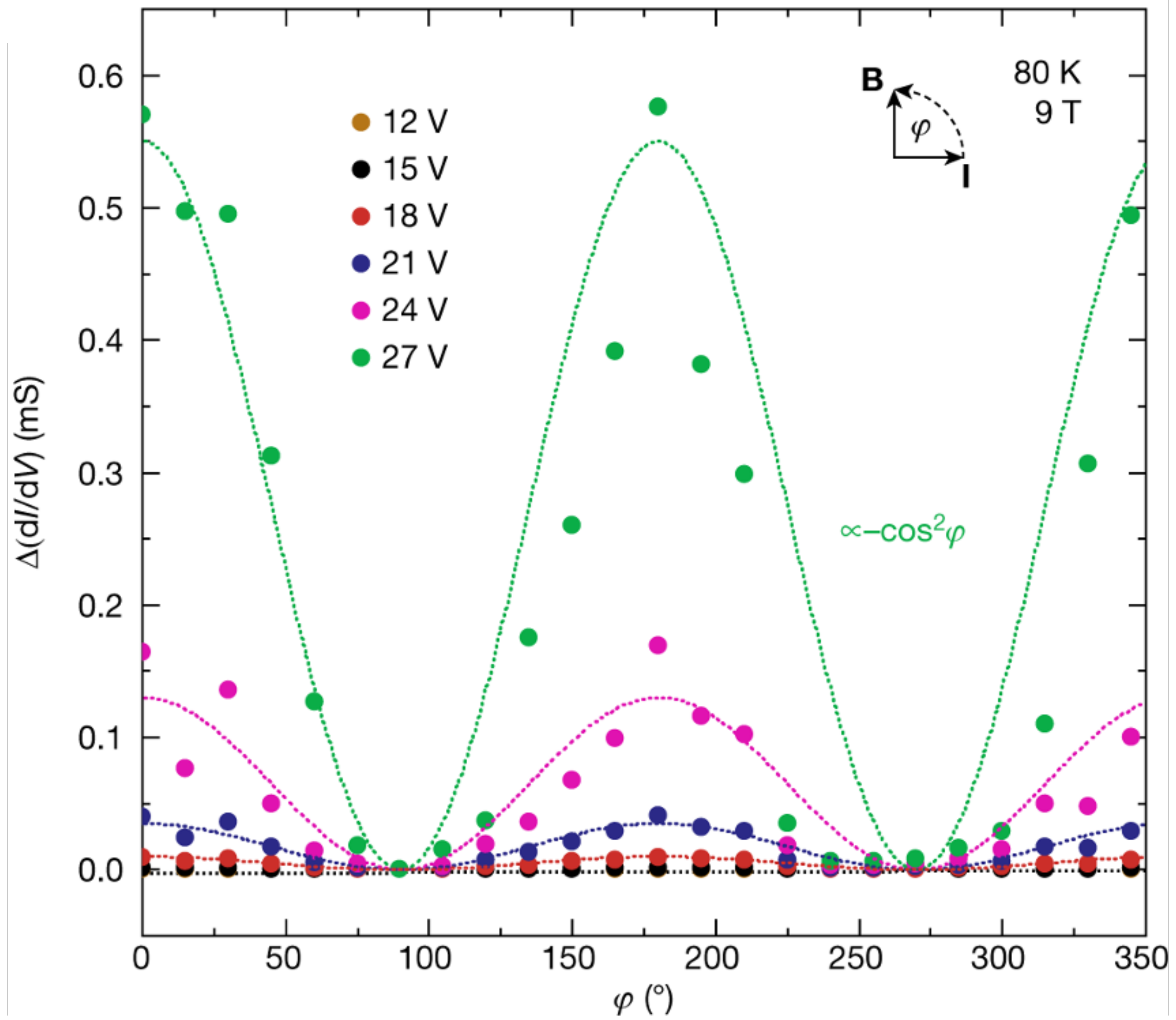
V–I characteristics in tilted B(φ)



dV/dI vs. φ for V>Vth



Δ(dI/dV) vs φ for various V



Reasonable fit with cos2φ with axial current peaks at φ → 0°, 180°

Key findings from Gooth et al:

1. Large negative magnetoconductance only when $\vec{B} \,||\, \vec{I}$
2. Directionally dependent nonlinear magnetotransport behavior under varying B-field configurations
3. Match with axion theory predictions: thermal activation indicative of a CDW gap (gapping of Weyl nodes) i.e. chiral symmetry breaking

Note: axion is inferred from transport measurements, not directly observed via $\boldsymbol{J}_\theta \propto \partial_t \theta \boldsymbol{B}$

Gooth, et al. Nature 575, pages 315–319 (2019)

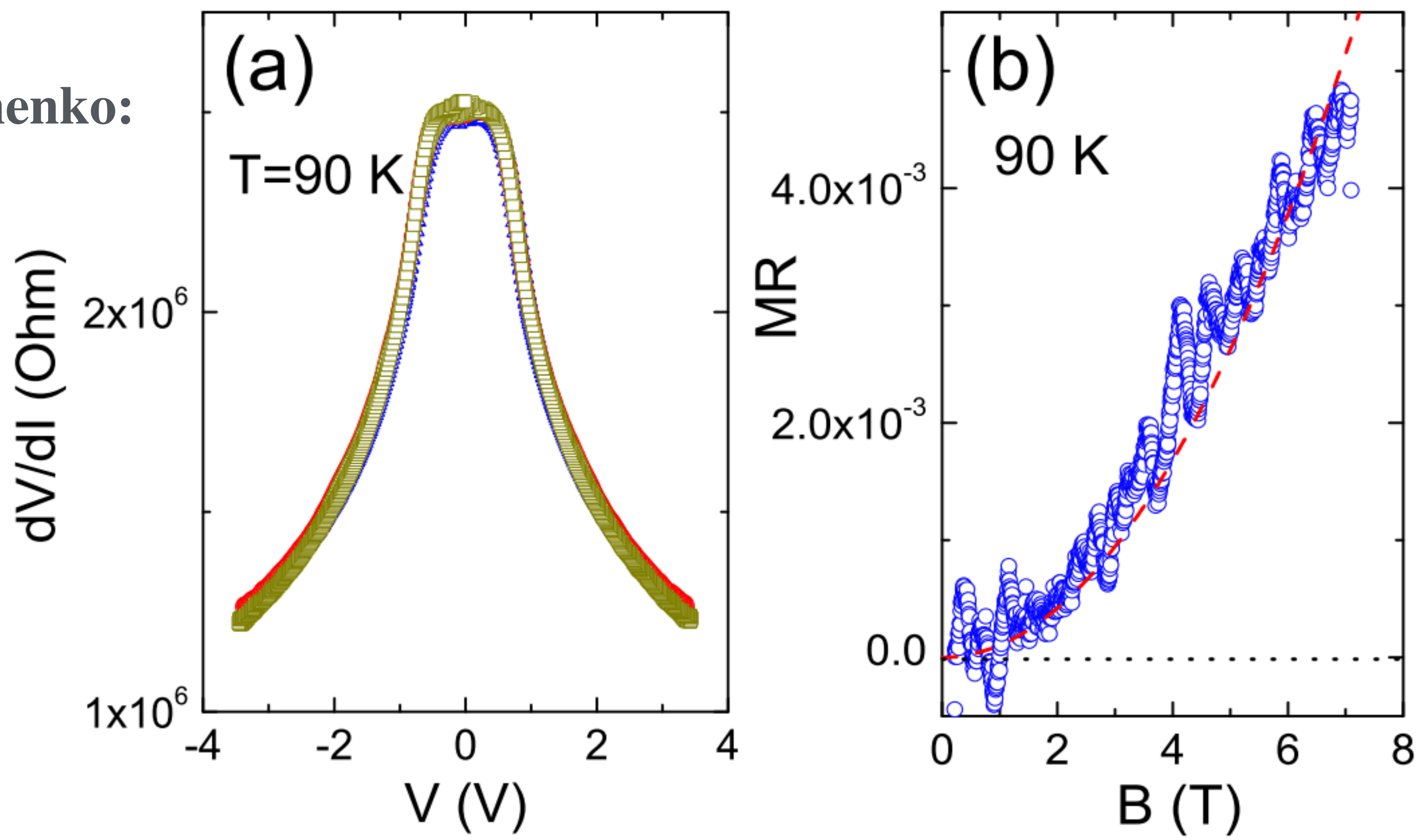
Does $(TaSe_4)_2I$ really harbor an axionic charge density wave?

A.A. Sinchenko, R. Ballou, J.E. Lorenzo, Th. Grenet, P. Monceau

Appl. Phys. Lett. 7 February 2022; 120 (6): 063102. doi:10.1063/5.0080380

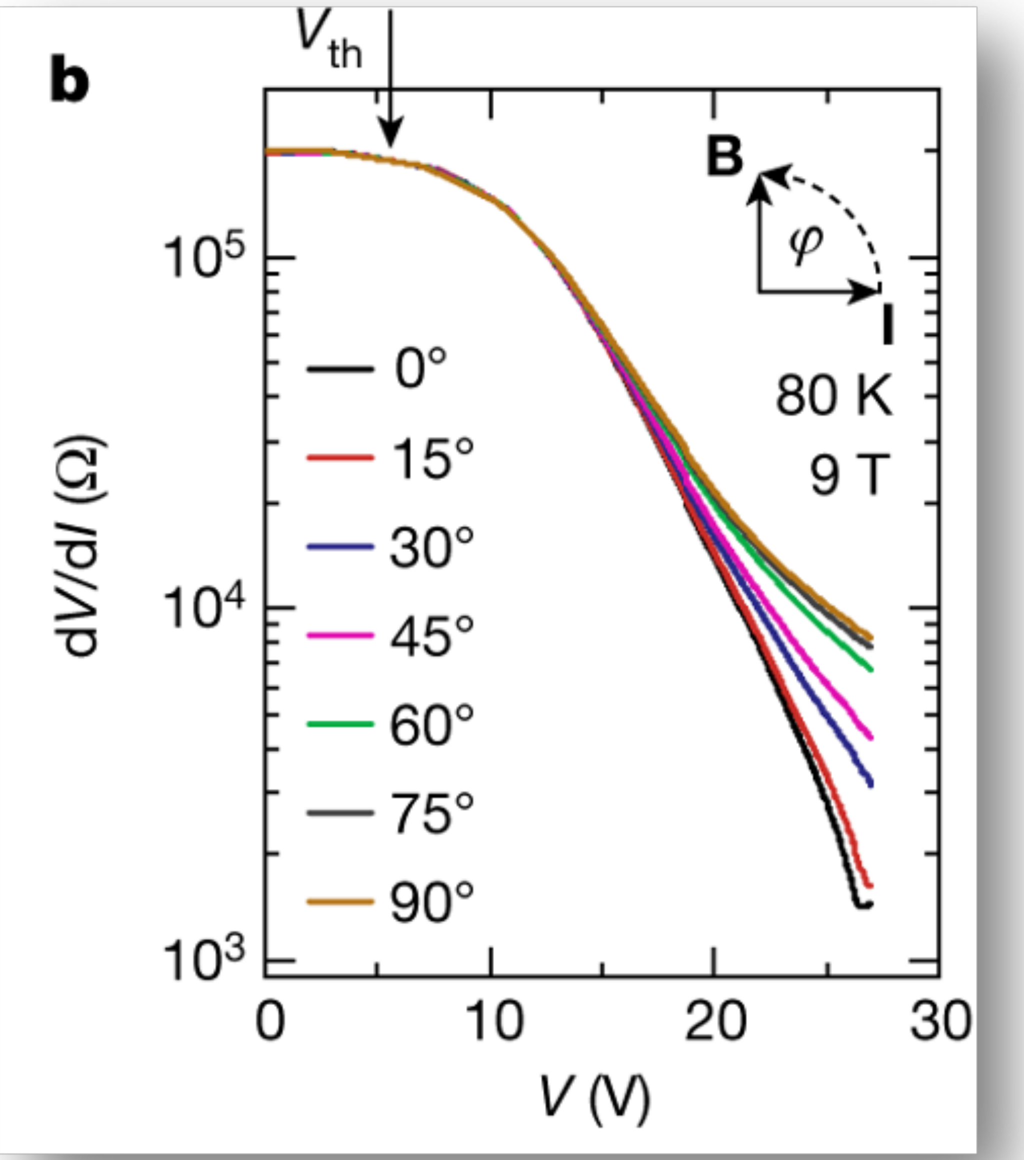
Critical counterpoint: attempted to reproduce results… but couldn't → No observed magnetoresistance

Sinchenko:

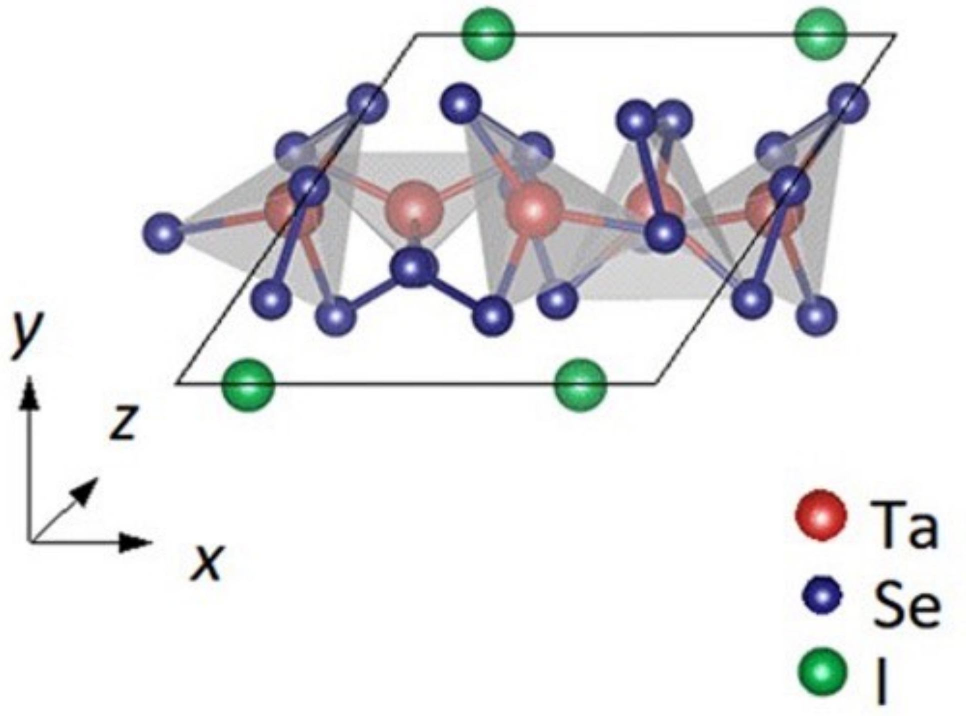


In magnetic fields:
B = 0 T (dark yellow)
B = 7 T parallel to current (red)
B = 7 T perpendicular to current (blue)

Gooth:



Both used chemical vapor deposition to grow crystal



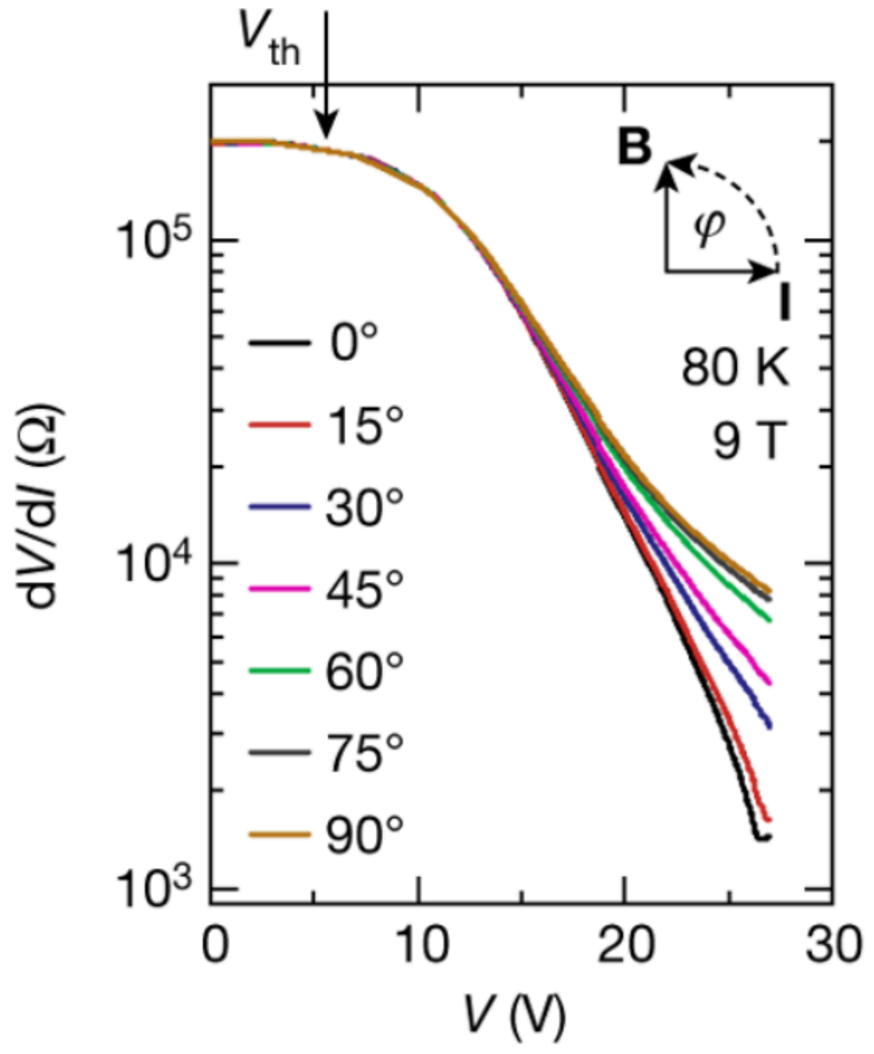
… lack of B-field dependence of CDW in $(TaSe_4)_2I$

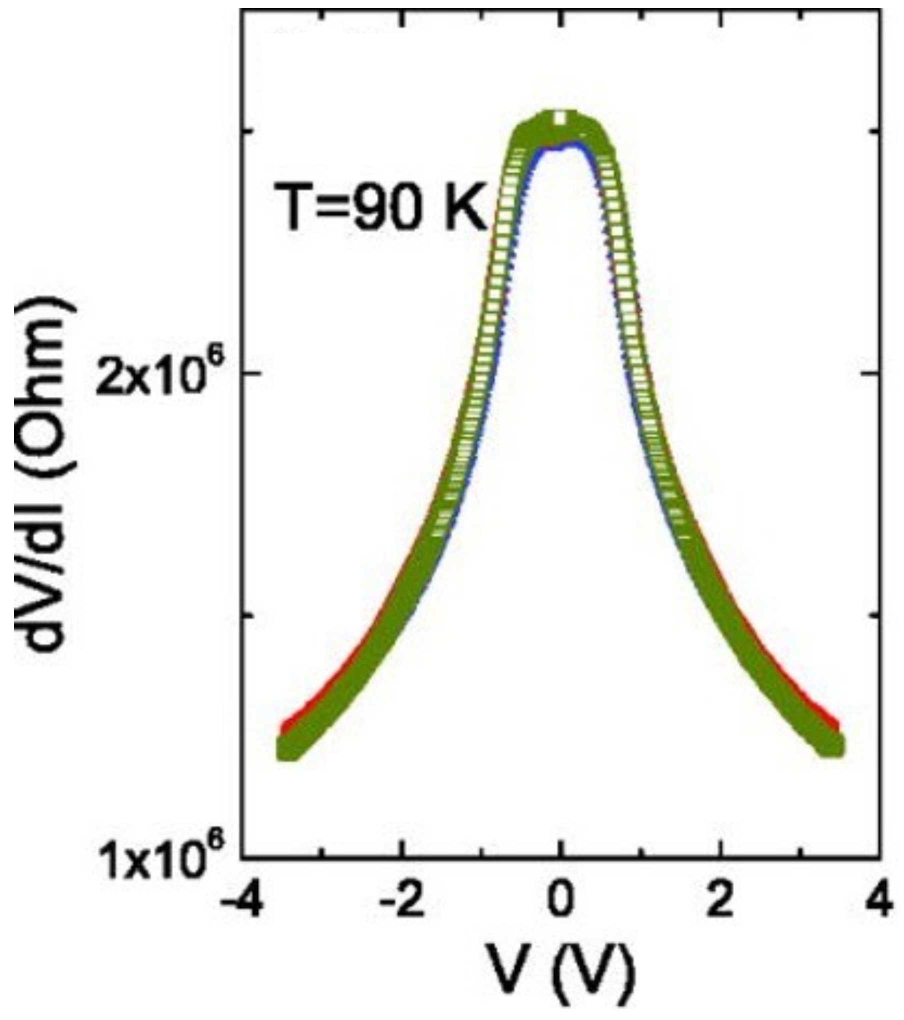
More work is needed for unambiguous detection…

Cohn, et al. Jetp Lett. 112 (2020) also attempted to recreate Gooth results but could not → no negative longitudinal magnetoresistance like Gooth paper claimed

Gooth data:

- Magneto-conductivity data from [Gooth, et al. Nature 575, 315–319 (2019)]
  - Large, positive magnetoconductance only for $E||B$ and above threshold current
  - Also, only included data for a single temperature = 80K
  - Under very high voltage, which induces a large Joule power dissipation





Possible explanation for discrepancy?

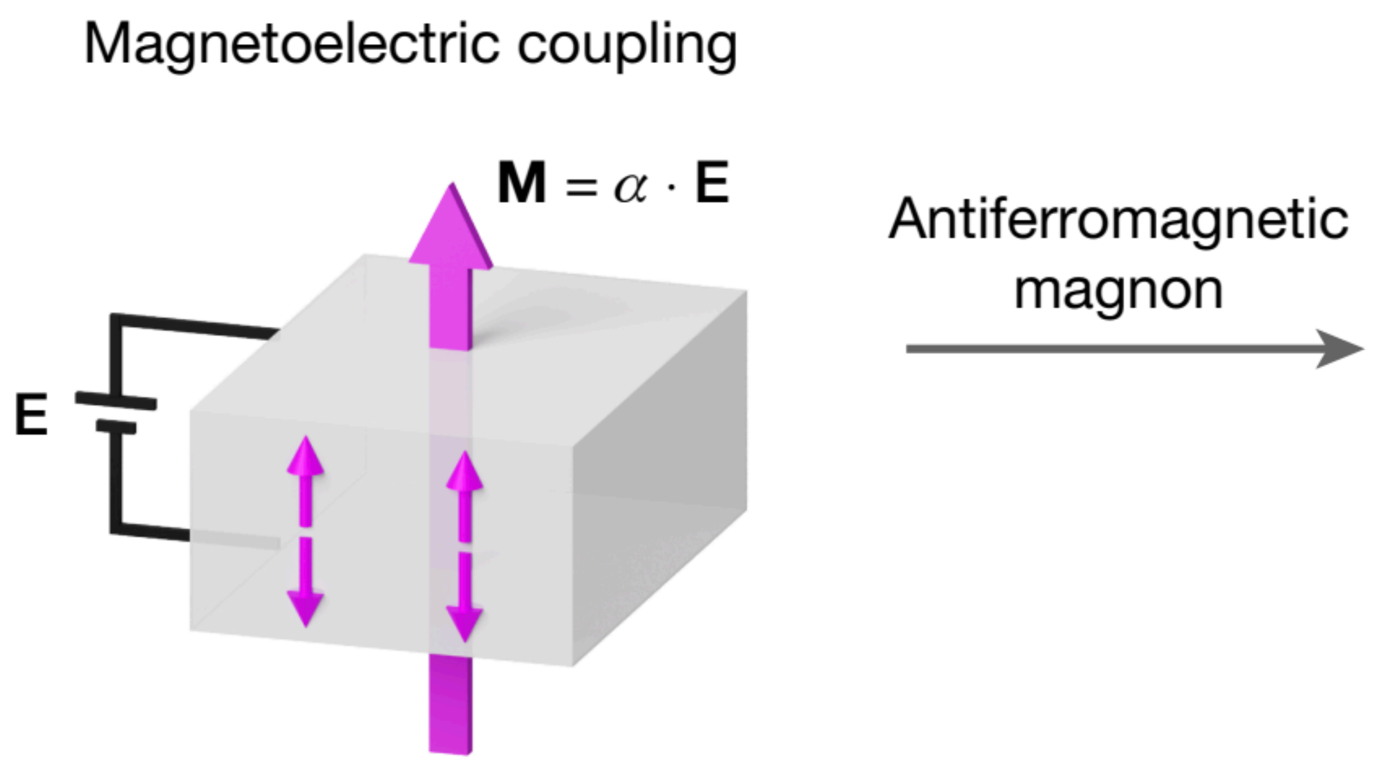
- **Joule power dissipation:** strong heating creates strong thermal inhomogeneities
  - Thermal gradient with corresponding thermoelectric current
  - Gives no Lorentz force to thermo-electrons, but leads to additional scattering + heating
- **Possible hot filaments** with cores having properties of normal state.
- Anisotropic conductance from filaments

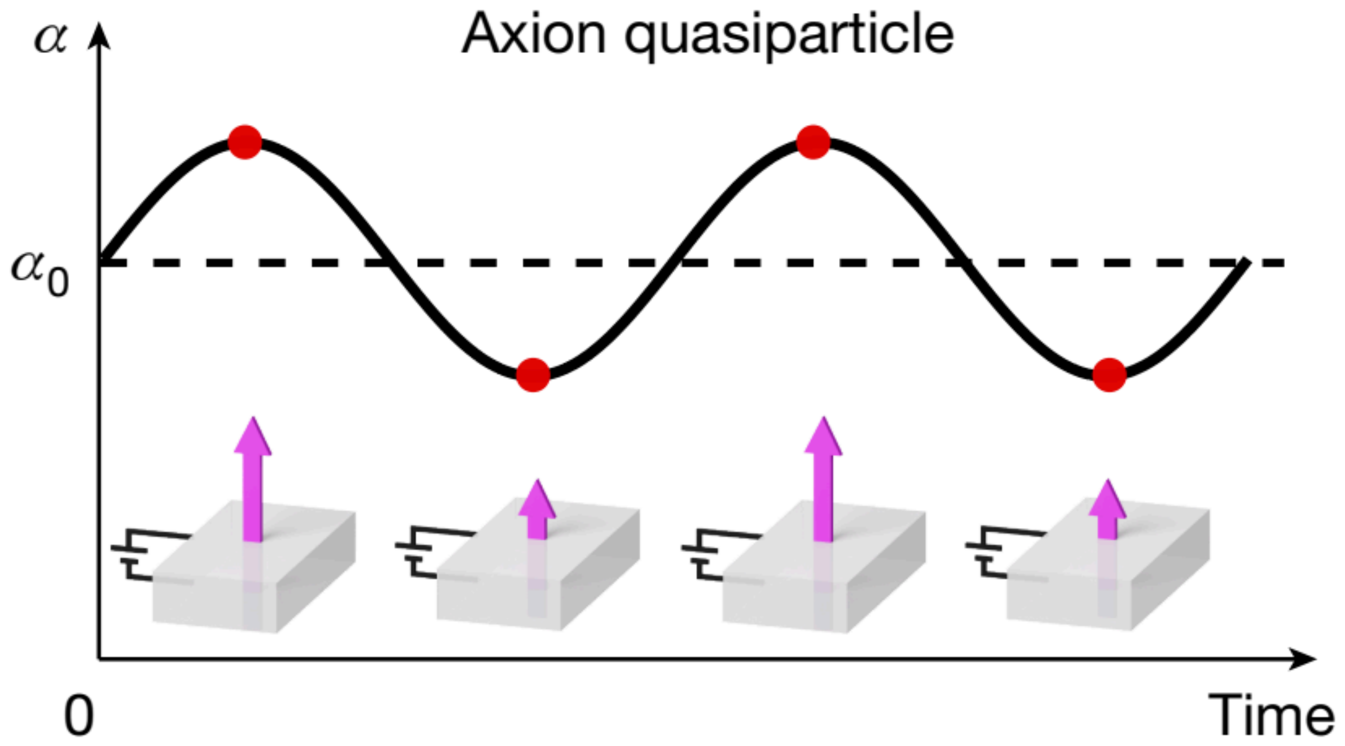
Gooth, et al. Nature 575, pages 315–319 (2019)
Sinchenko, et al. Appl. Phys. Lett. (2022); doi:10.1063/5.0080380

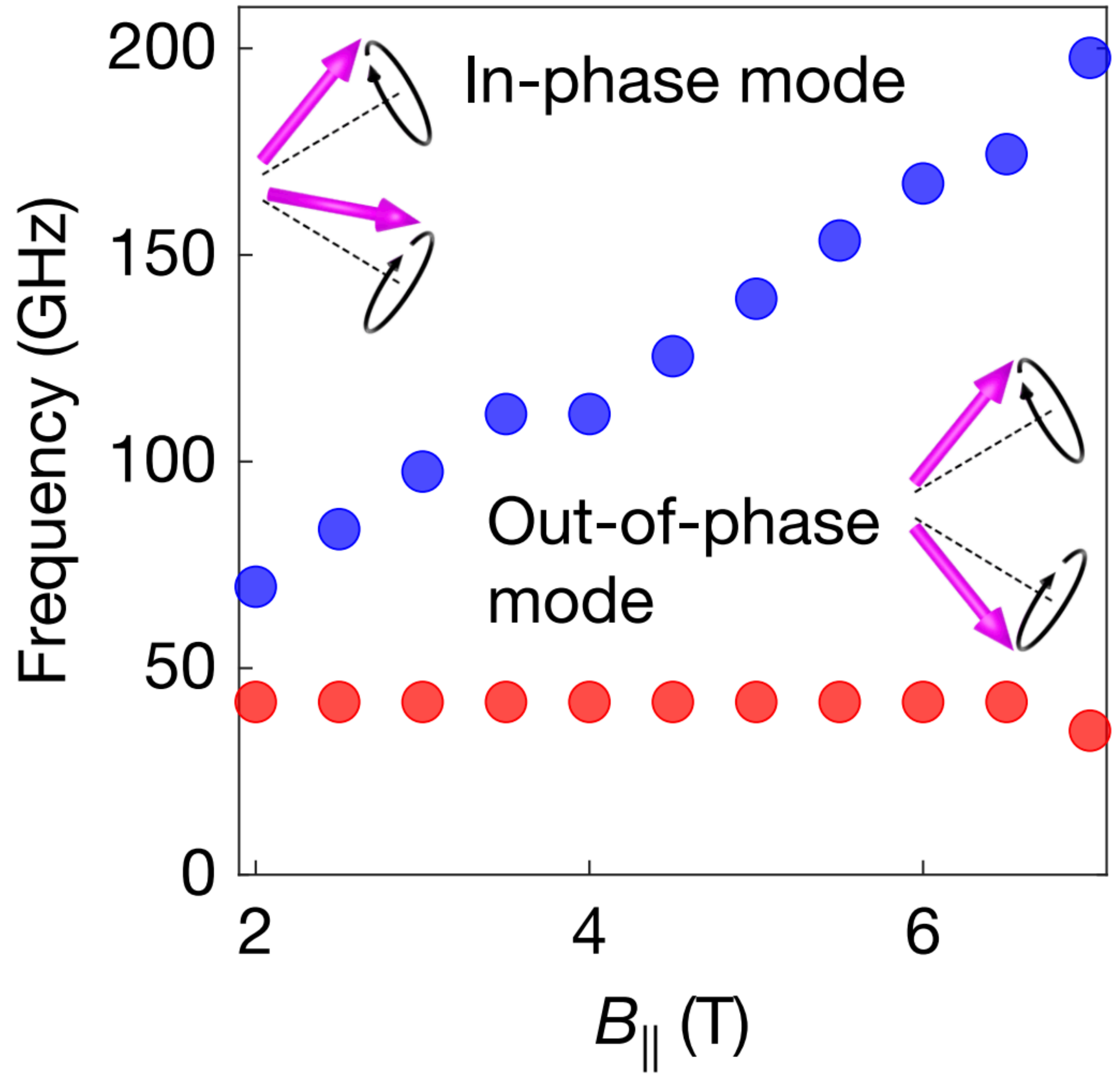
Observation of the axion quasiparticle in 2D $MnBi_2Te_4$

Nature vol. 641,8061 (2025): 62-69. doi:10.1038/s41586-025-08862-x

Jian-Xiang Qiu[1], Barun Ghosh[2,3,4], Jan Schütte-Engel[5,6], Tiema Qian[7], Michael Smith[8], Yueh-Ting Yao[9], Junyeong Ahn[10], Yu-Fei Liu[1,10], Anyuan Gao[1], Christian Tzschaschel[1,11], Houchen Li[1], Ioannis Petrides[12], Damien Bérubé[1], Thao Dinh[1,10], Tianye Huang[1], Olivia Liebman[12,13], Emily M. Been[12], Joanna M. Blawat[14], Kenji Watanabe[15], Takashi Taniguchi[15], Kin Chung Fong[2,3,16], Hsin Lin[17], Peter P. Orth[18,19,20], Prineha Narang[12,21], Claudia Felser[22], Tay-Rong Chang[9,23,24], Ross McDonald[14], Robert J. McQueeney[18,19], Arun Bansil[2,3], Ivar Martin[8], Ni Ni[7], Qiong Ma[25,26], David J. E. Marsh[27], Ashvin Vishwanath[10] & Su-Yang Xu[1]✉

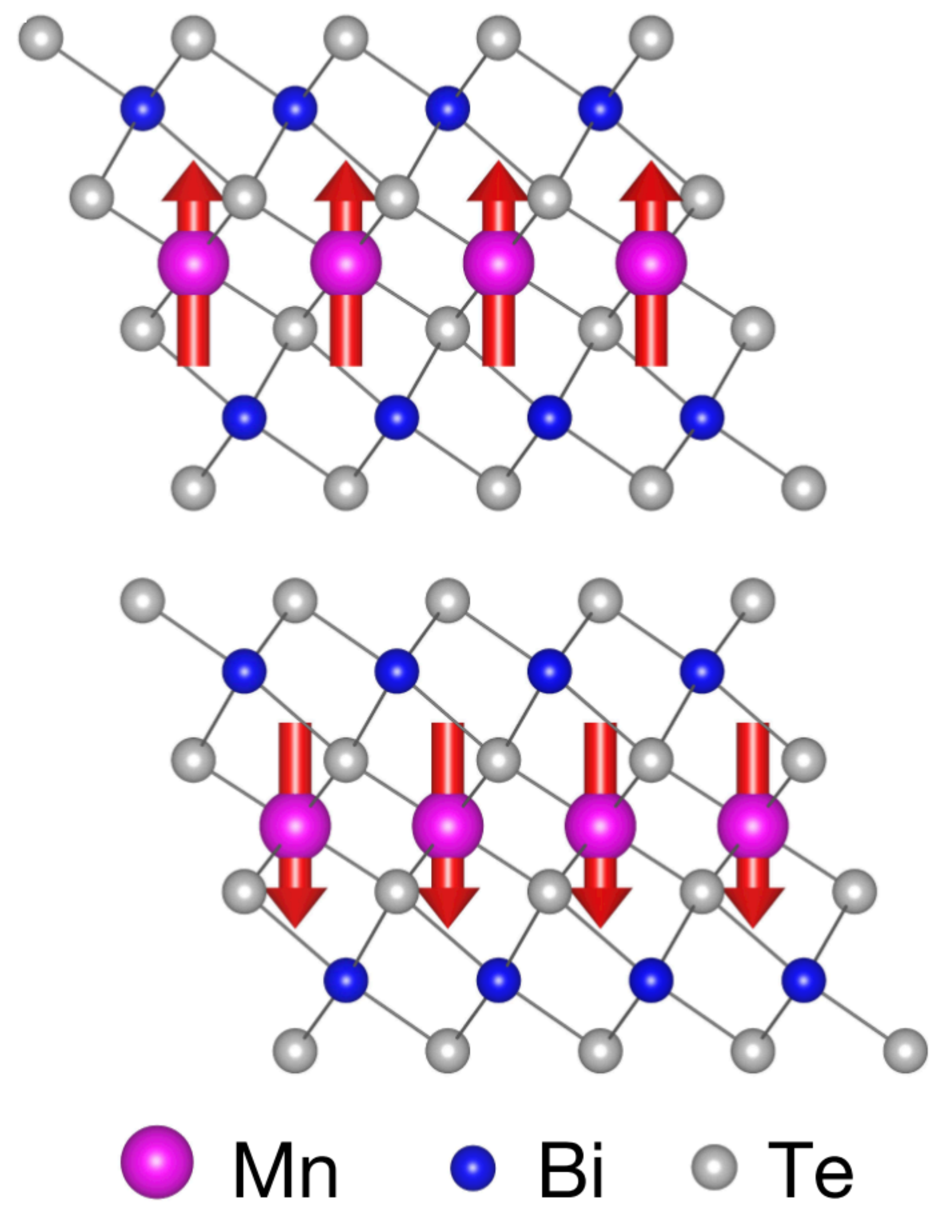






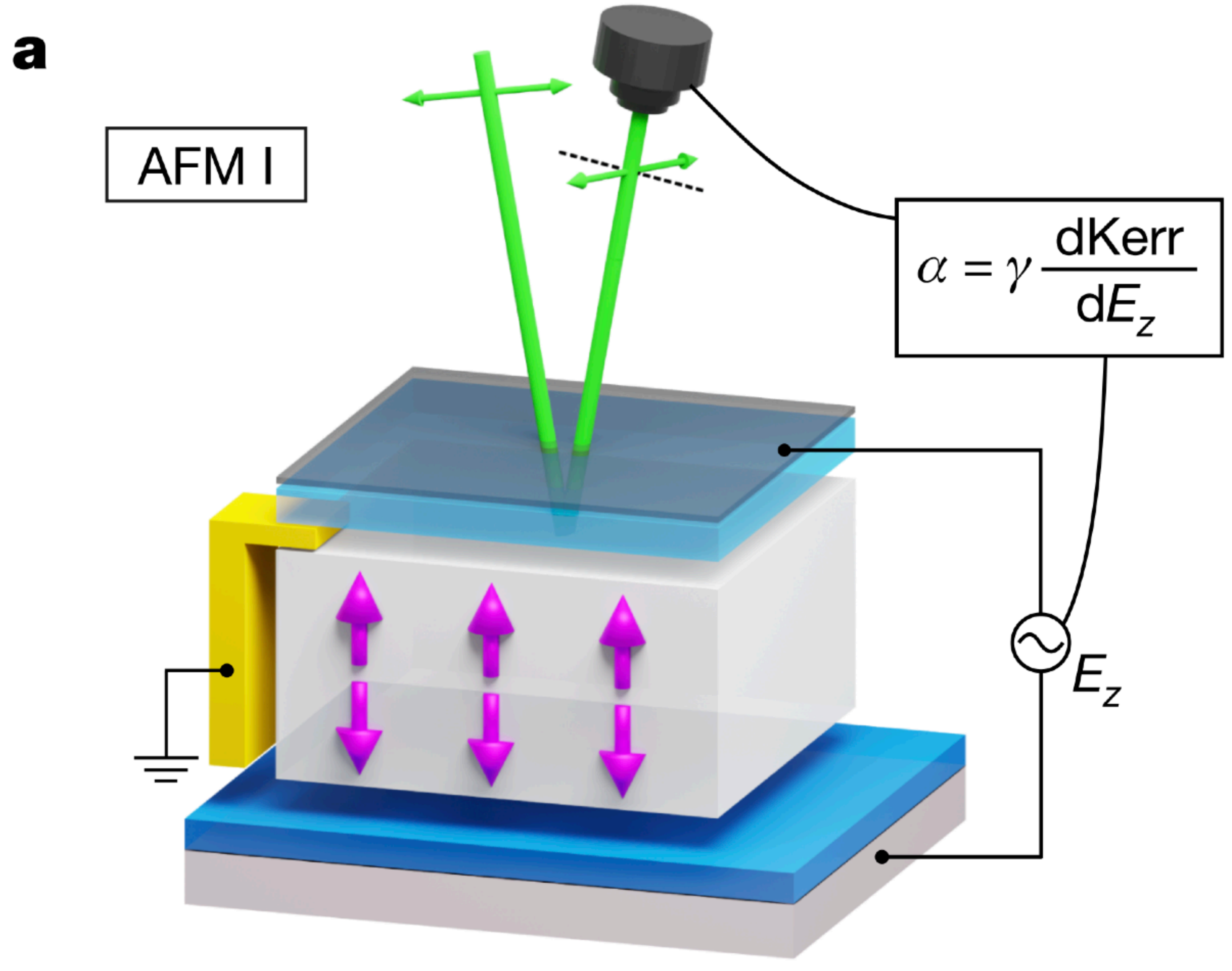
Key results:

- Direct observation of dynamical axion quasiparticle in AFM TI
- Coherent oscillation of the out-of-phase AFM magnon mode i.e. θ-field ~44 GHz



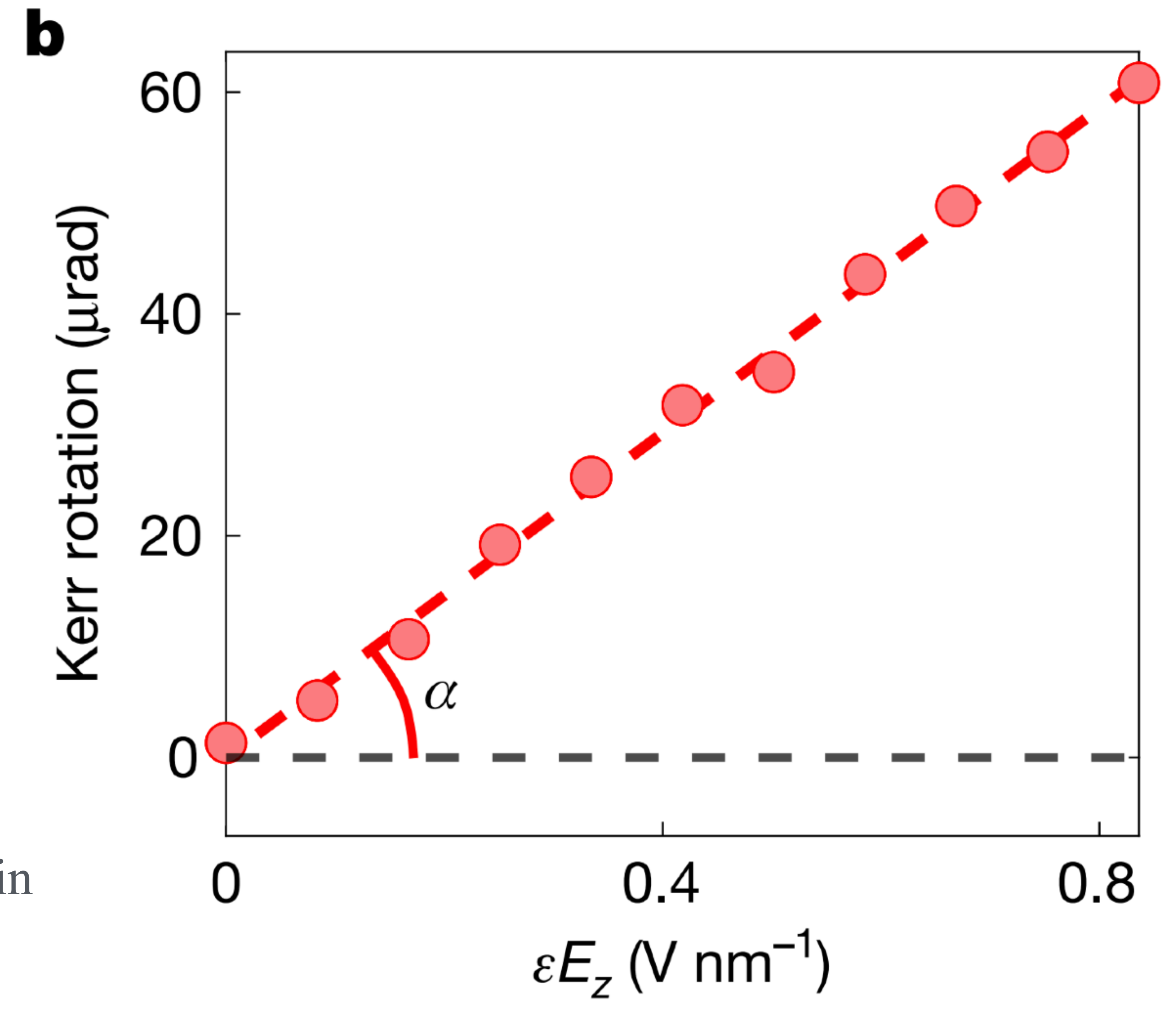
2D, 6-layer $MnBi_2Te_4$

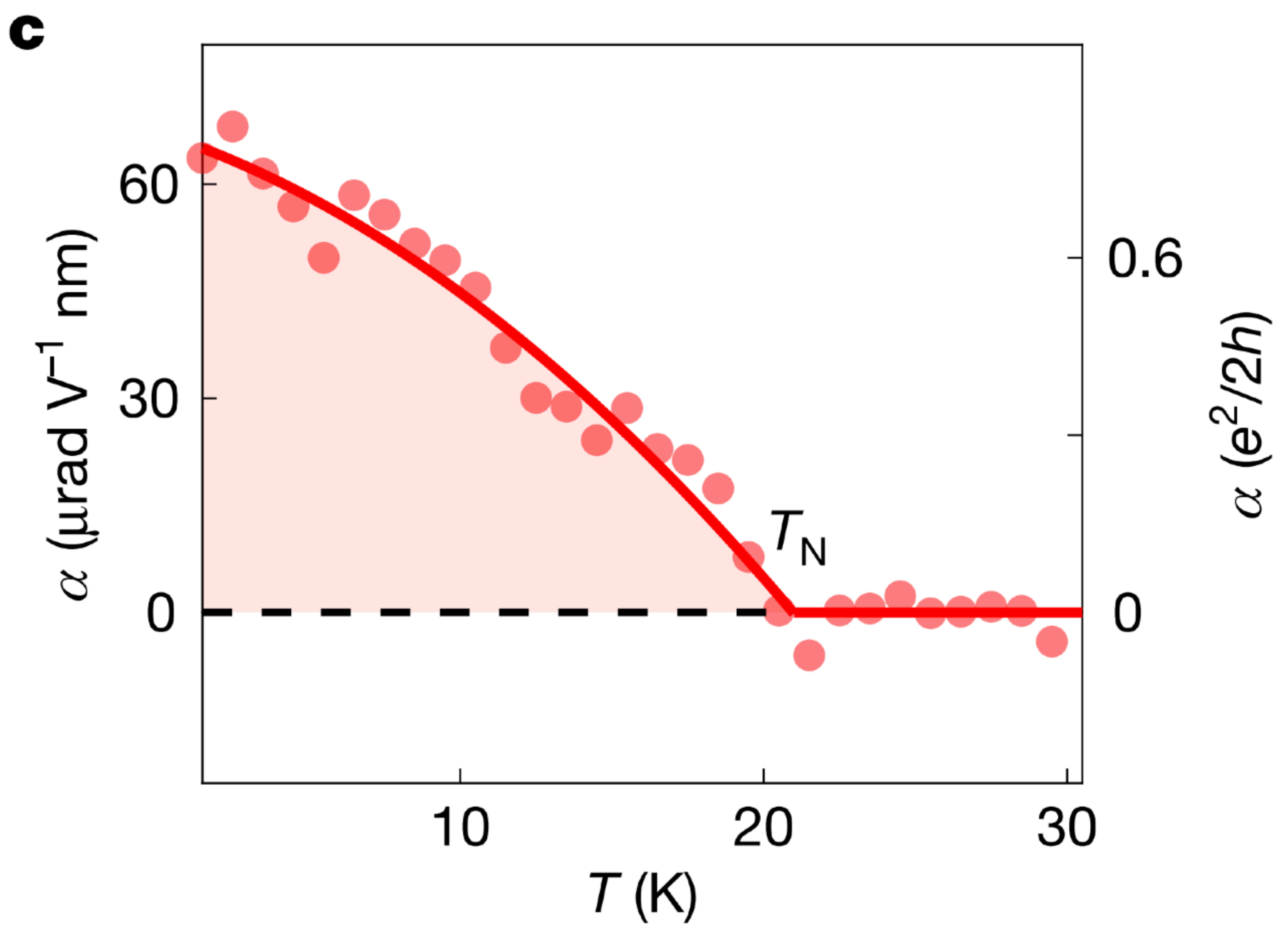
Time-resolve Kerr for dynamical axion detection



Schematic of set-up: apply E_z via top and bottom gates, resultant M_z measured via Kerr rotation

Extract slope α via linear relationship between Kerr angle and E_z





Confirm magnetic origin via temperature dependence of α; vanishes at Néel temperature

Pump: Triggers coherent magnetic excitations (AFM magnons) in the sample.

Probe: Arrives after a controlled delay t, and detects how the sample's magnetoelectric properties α(t) evolve over time.

$$\alpha = \frac{dM_z}{dE_z}$$

$$\boxed{\theta_{\mathrm{Kerr}} = \frac{1}{\gamma} M_z = \frac{\alpha}{\gamma} E_z}$$

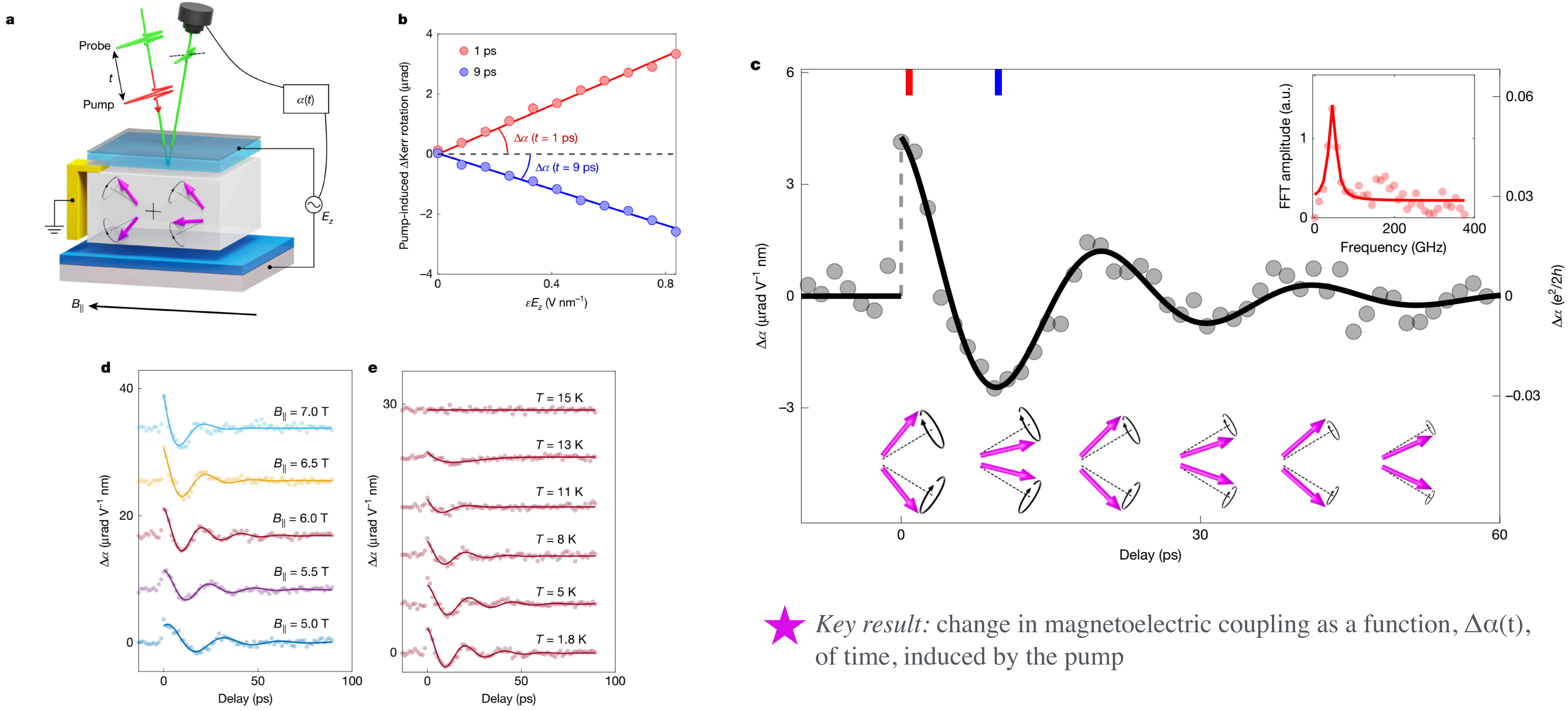
Magnetoelectric coupling

Axion field

$$\boxed{\alpha = \frac{e^2}{2\pi h}\theta}$$

Qiu, Jian-Xiang et al. *Nature* vol. 641,8061 (2025): 62-69. doi:10.1038/s41586-025-08862-x

Observation of DAQ in 2D $MnBi_2Te_4$

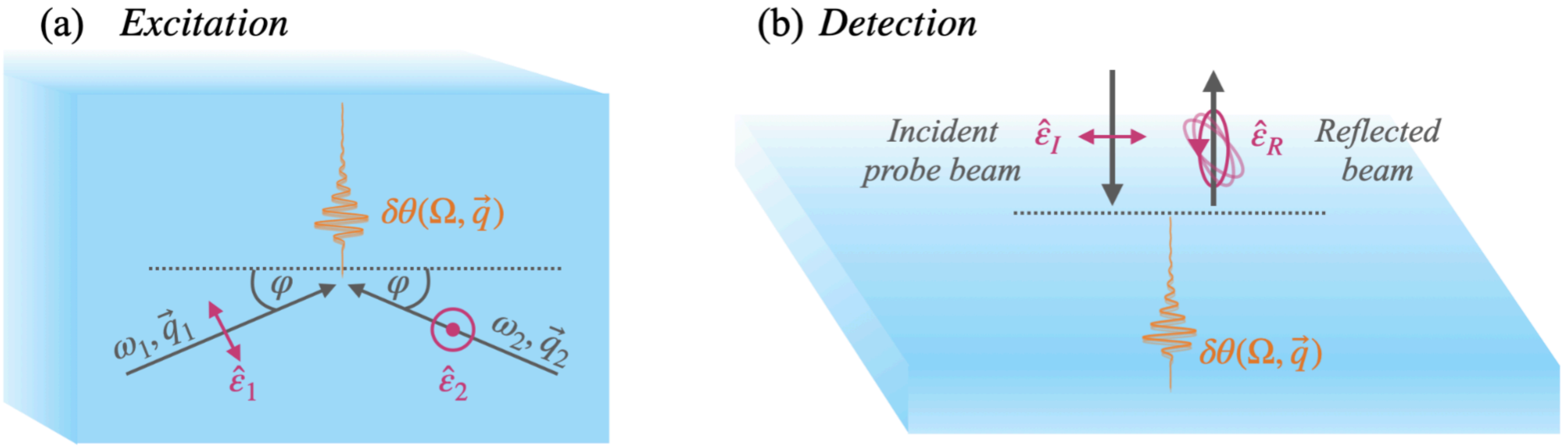


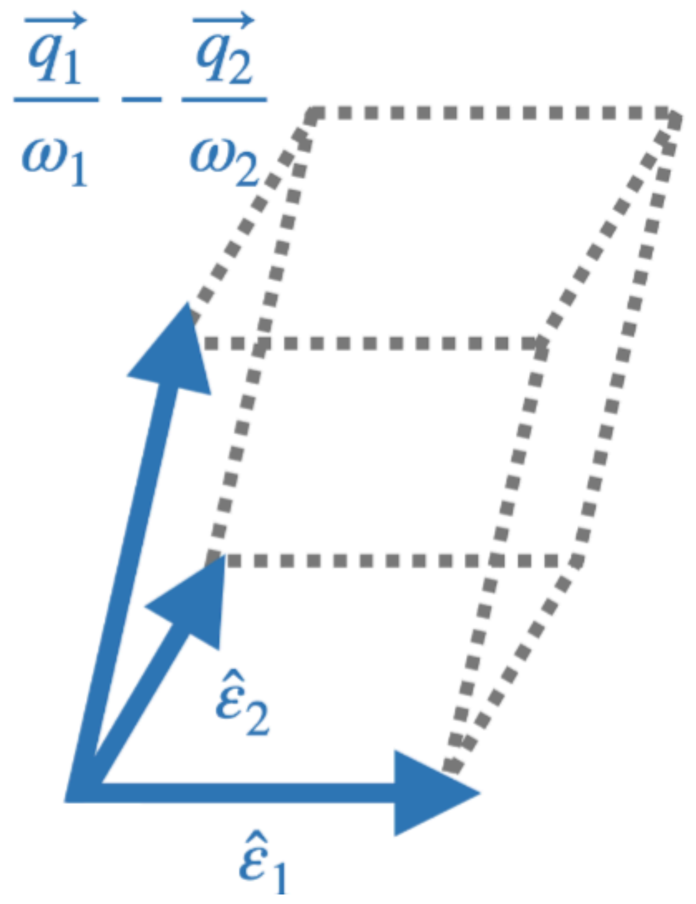
★ *Key result:* change in magnetoelectric coupling as a function, Δα(t), of time, induced by the pump

Qiu, Jian-Xiang et al. *Nature* vol. 641,8061 (2025): 62-69. doi:10.1038/s41586-025-08862-x

Future work: generic optical protocol for detection

- Definitive dynamical axion detection in a Weyl CDW material is needed
- Theoretical proposal for dynamical axion detection for a generic axion insulator system:





Response of dynamical axion $\delta\theta$ to application of external EM fields

$$\boxed{\delta\theta(q) = \frac{(\alpha/\pi\kappa)\omega_1\omega_2\mathcal{A}_1\mathcal{A}_2}{\Omega^2 + i\Omega\gamma - \Omega_0^2}\left(\frac{\boldsymbol{q}_1}{\omega_1} - \frac{\boldsymbol{q}_2}{\omega_2}\right)\cdot(\hat{\boldsymbol{\varepsilon}}_1 \times \hat{\boldsymbol{\varepsilon}}_2)}$$

Intensity of axion response depends on:

- Frequency
- Momenta
- Polarization
- Angle of incident beams

Liebman, Curtis, Petrides, & Narang. In Review: PRL. arxiv:2306.00064

Axion detection

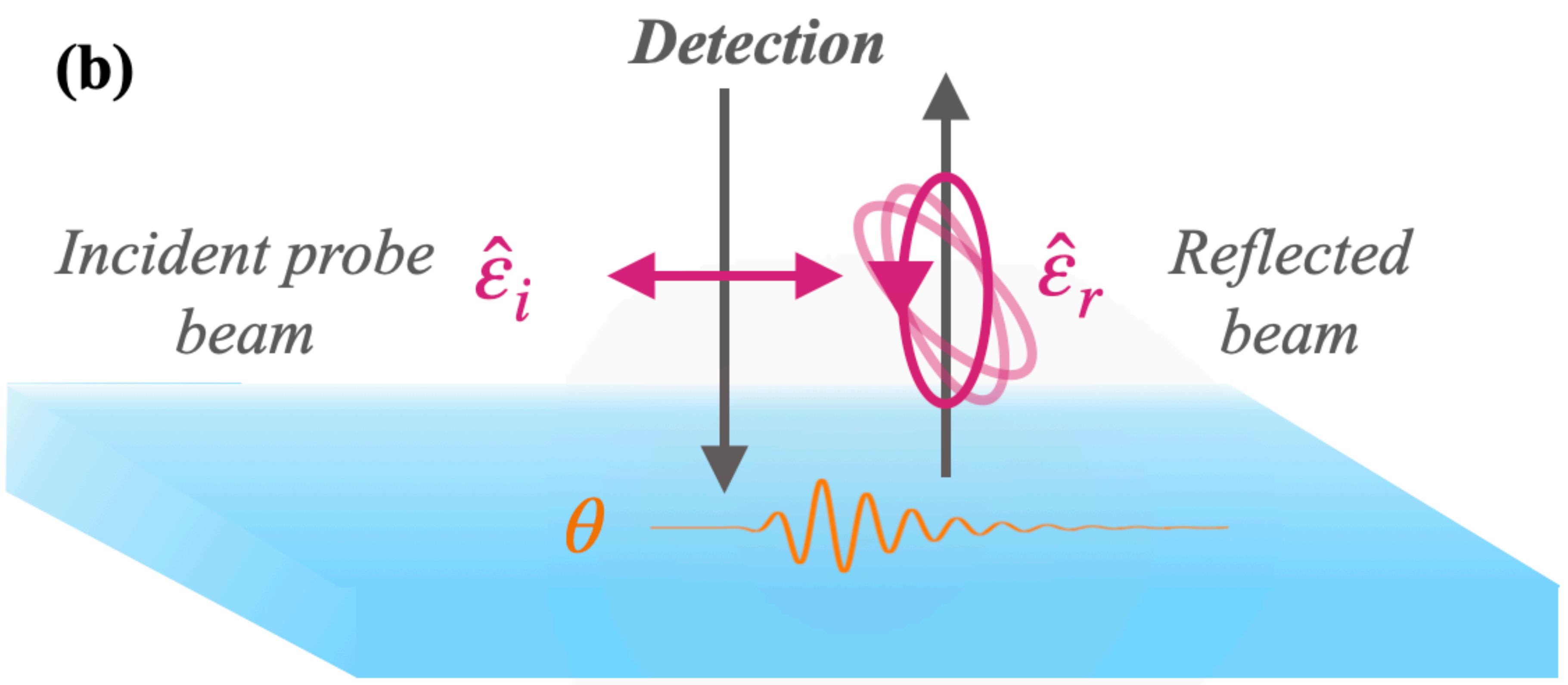
Kerr rotation angle

$$\Theta_K = -\frac{1}{2}(\Delta^+ - \Delta^-)$$

Complex Kerr rotation: $\Phi_{Kerr} = \Theta_K + i\eta_K$

Polar Kerr ellipticity

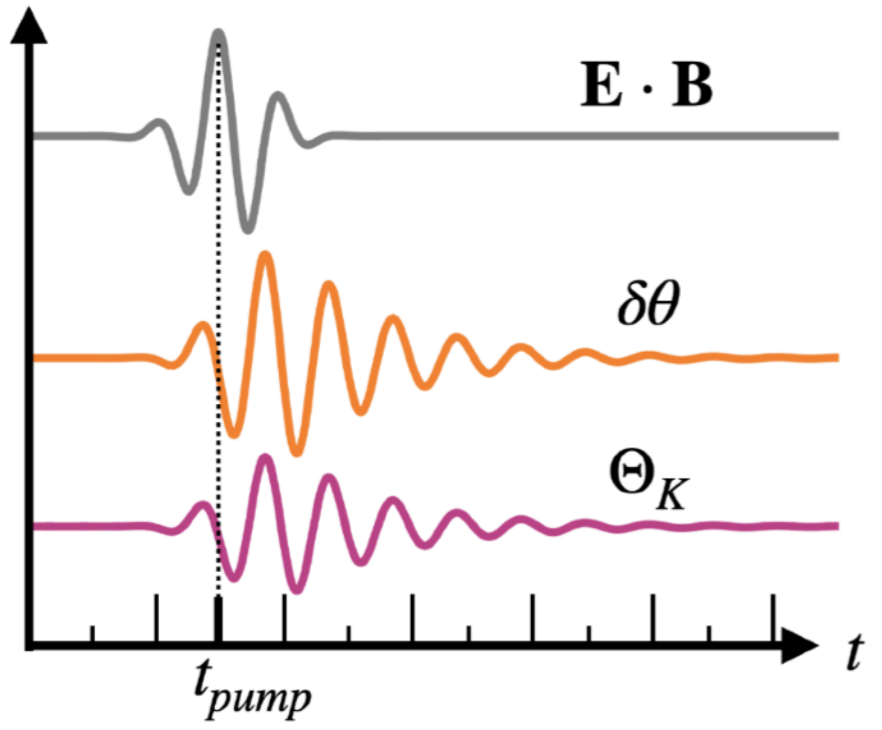
$$\eta_K = \frac{R_+ - R_-}{R_+ + R_-}$$



Linearize for small $\delta\theta$

$$R_\pm = \pm \frac{1 - \left(n_\pm \mp i\frac{\alpha}{\pi}\delta\theta\right)}{1 + \left(n_\pm \mp i\frac{\alpha}{\pi}\delta\theta\right)} = |R_\pm| e^{i\Delta_\pm}$$

$$\Theta_K = -\frac{1}{2}(\Delta_+ - \Delta_-) \approx \frac{\alpha}{\pi}\frac{(-2 + n_+^2 + n_-^2)}{(n_+^2 - 1)(n_-^2 - 1)}\delta\theta.$$



Order of magnitude estimate for $(TaSe_4)_2I$

expected modulation in Kerr angle $\Theta_K \approx 1.5\mu$rads

Liebman, Curtis, Petrides, & Narang. In Review: PRL. arxiv:2306.00064

Thank you!

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