Illinois Center for Advanced Studies of the Universe

Dynamic magneto-chiral instability in a semiconductor

Nick Abboud

Y. Huang*, NA*, Y. Lv, P. Zhu, A. Murzabekova, C. Lee, E. A. Pappas, D. Petruzzi, J. Y. Yan, D. Chauduri, P. Abbamonte, D. P. Shoemaker, R. M. Fernandes, J. Noronha, F. Mahmood

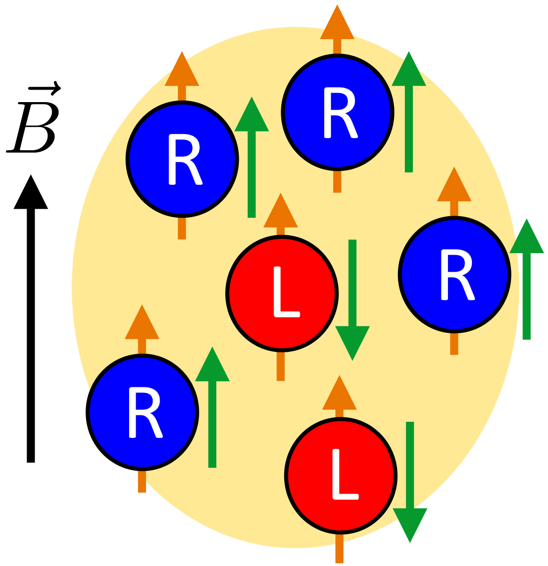
arXiv:2502.05170

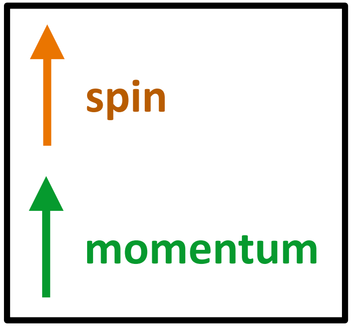
9^{th} Conference on Chirality, Vorticity, and Magnetic Fields in Quantum Matter

July 2025

São Paulo, Brazil

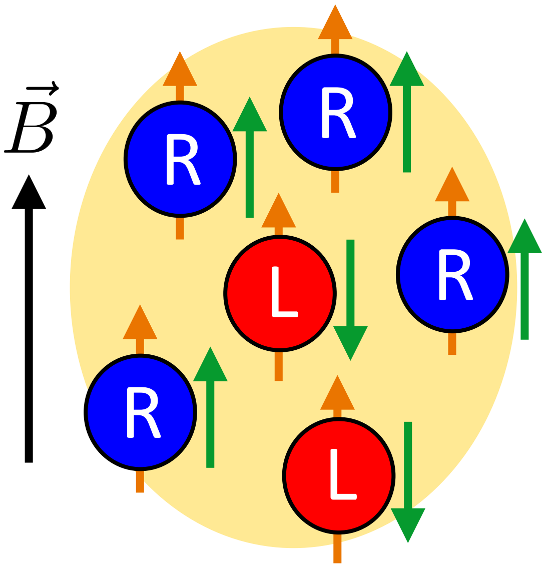
Motivation: the chiral magnetic effect





Chirally imbalanced plasma
of massless fermions
in a magnetic field

Motivation: the chiral magnetic effect



Chirally imbalanced plasma
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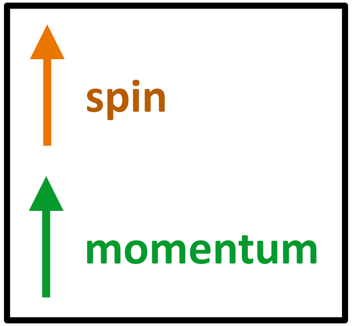
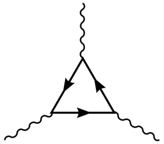
$\Longrightarrow$ Electric current $\vec{J} \propto \vec{B}$



Consequence of chiral anomaly



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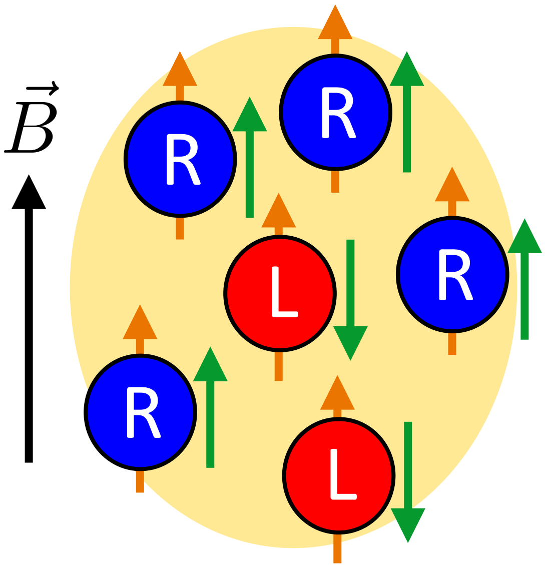

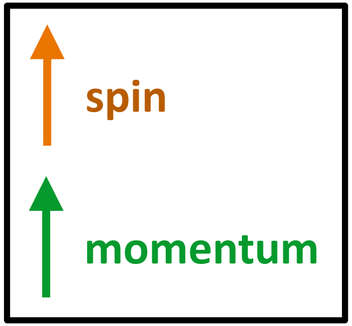

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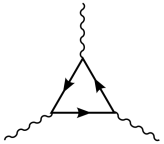
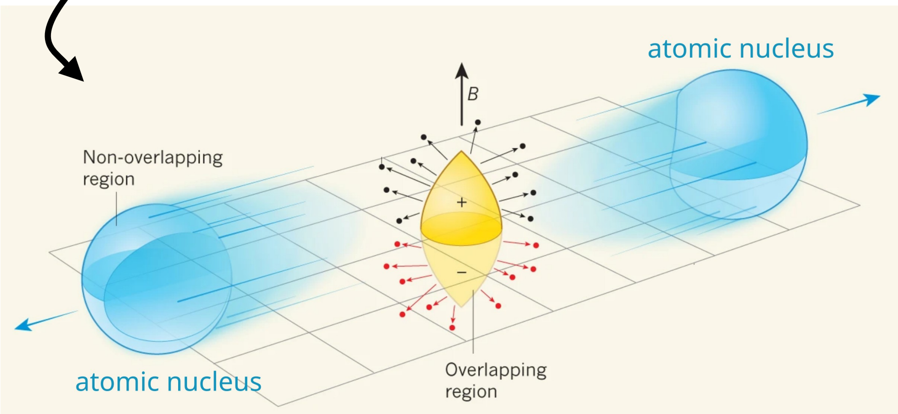


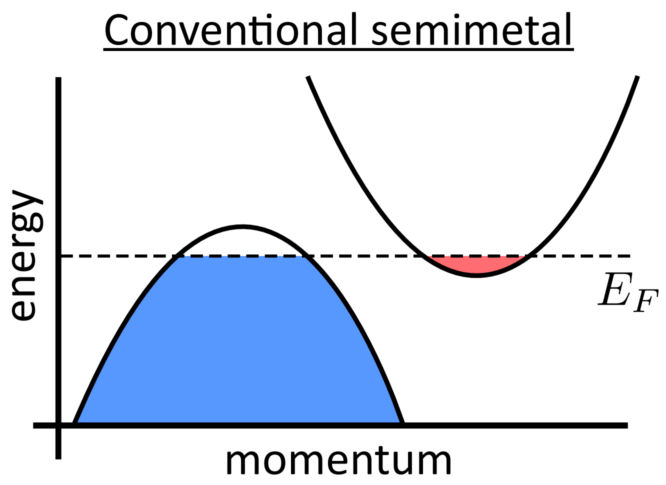
- Manifestation of deconfined quarks and CP-violation in ultra-relativistic nuclear collisions?
  e.g. Kharzeev et al., Nucl. Phys. A 803 227-253 (2008)



A. F. Dobrin, Nature 546, 477

electrically conductive crystalline materials

Weyl semimetals host massless fermions



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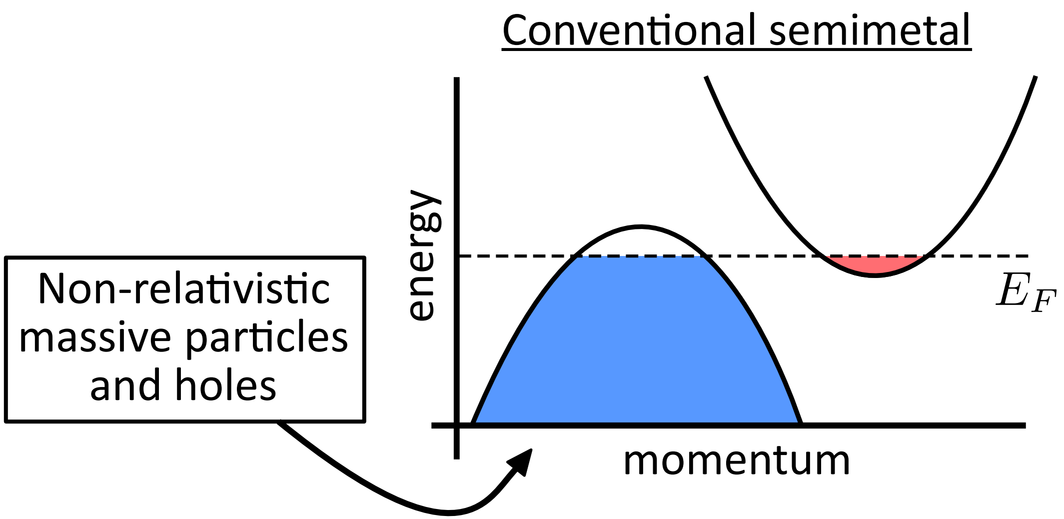
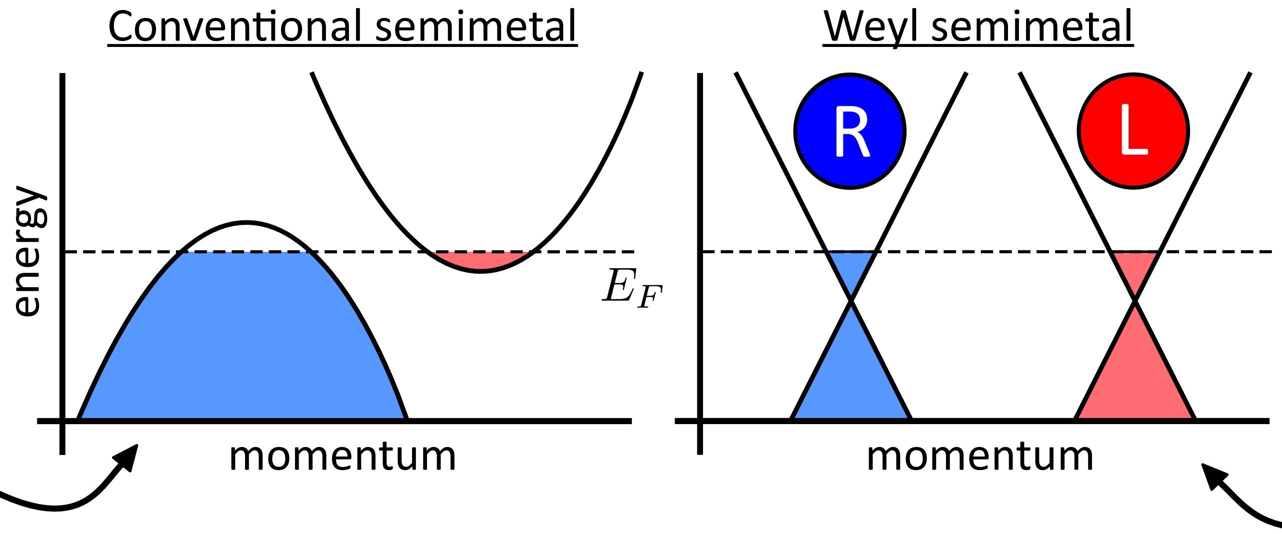


Weyl semimetals host massless fermions

Non-relativistic massive particles and holes



Weyl fermions of opposite chirality

$$\mathcal{L} = \bar{\psi}[i\partial\!\!\!/ - eA\!\!\!/]\psi$$

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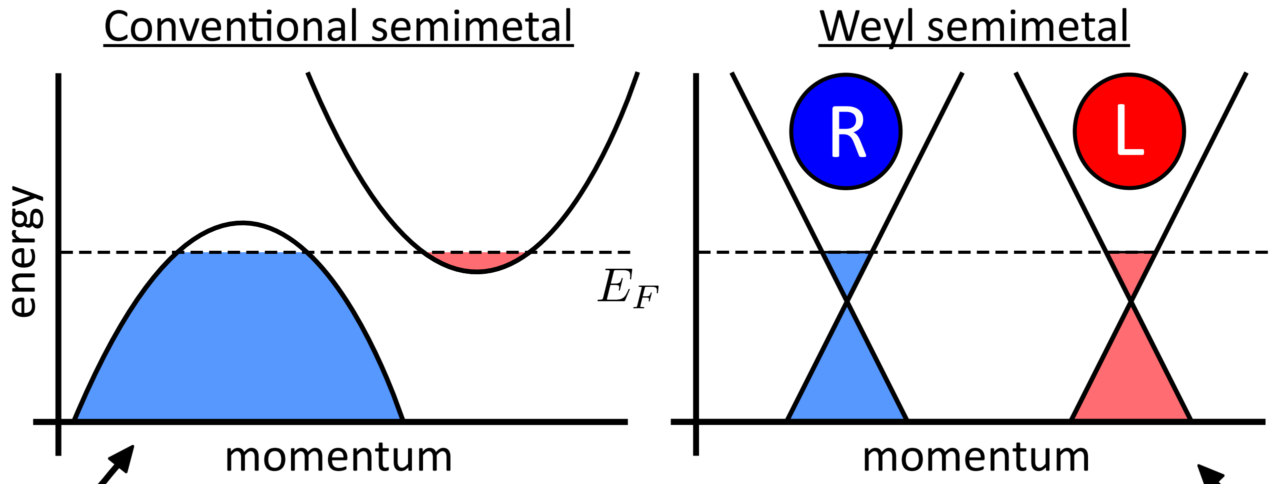


Weyl fermions of opposite chirality

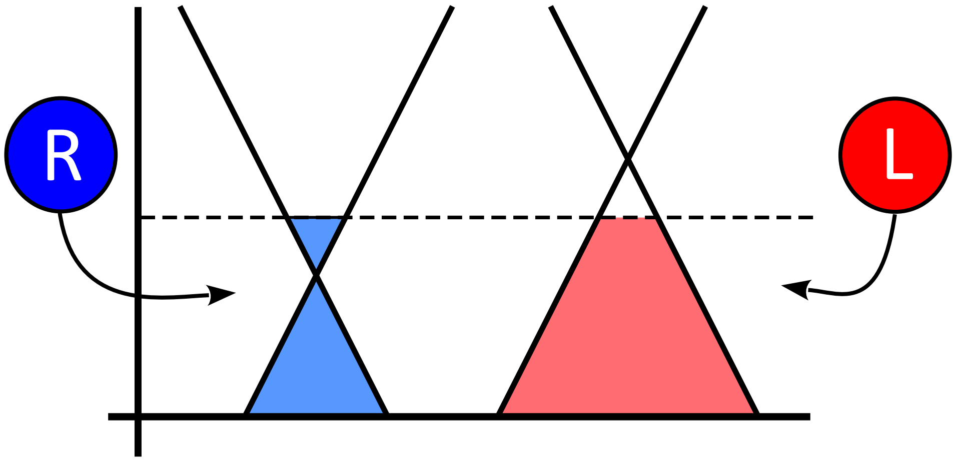
$$\mathcal{L} = \bar{\psi}[i\not{\partial} - e\not{A}]\psi$$

The emergent low-energy degrees of freedom of a Weyl semimetal are massless fermions.

$\Longrightarrow$ Chiral magnetic effect?

Chiral magnetic effect in Weyl semimetals

Weyl semimetal in equilibrium



No current in equilibrium!

$$\vec{J} = \vec{J}_R + \vec{J}_L = 0$$

Vazifeh & Franz (2013)
Basar et al. (2014)
and others

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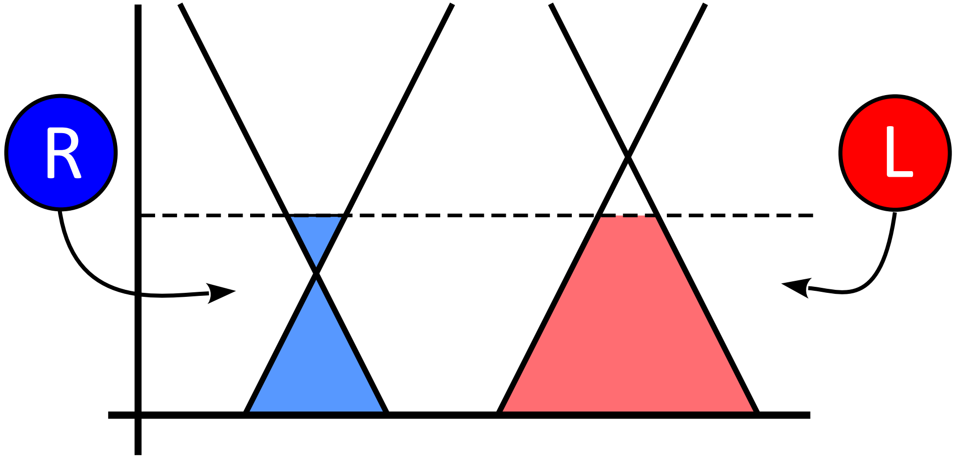

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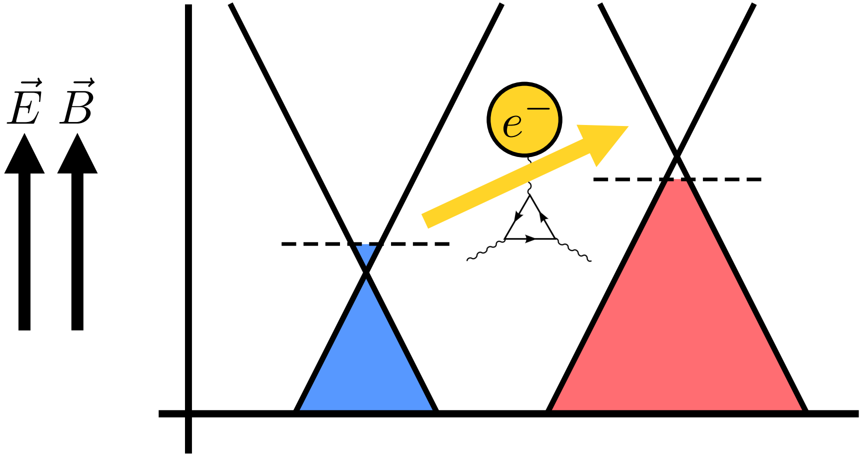
Chirally pumped Weyl semimetal



Created and maintained by external fields

$\vec{E} \parallel \vec{B}$ and chiral anomaly

Steady-state non-eq chiral magnetic effect

$$\vec{J} \propto \vec{B}$$

Son & Spivak (2013)

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No cu

$\vec{J} =$

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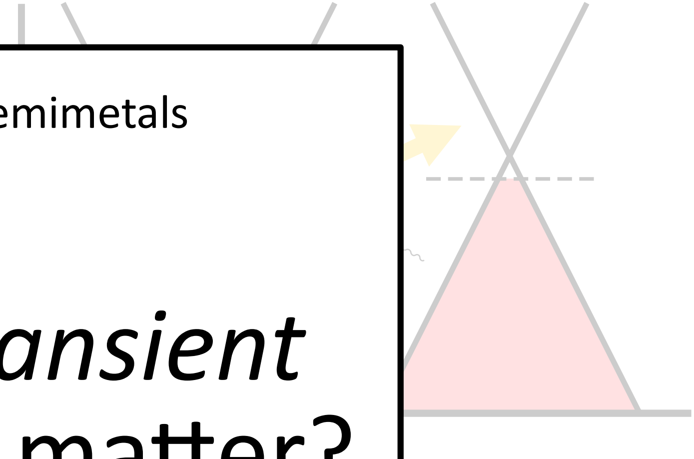

external fields

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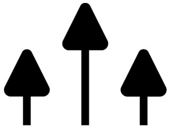
Transport in **chirally pumped** Weyl semimetals

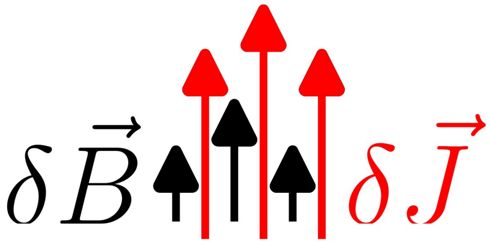
X. Huang et al., PRX 5, 031023 (2015)
Q. Li et al., Nat. Phys. 12, 550 (2016)

Manifestation in *transient* states in condensed matter? (beyond steady states)

Chiral magnetic instability

$\delta\vec{B}$ 

Chiral magnetic instability



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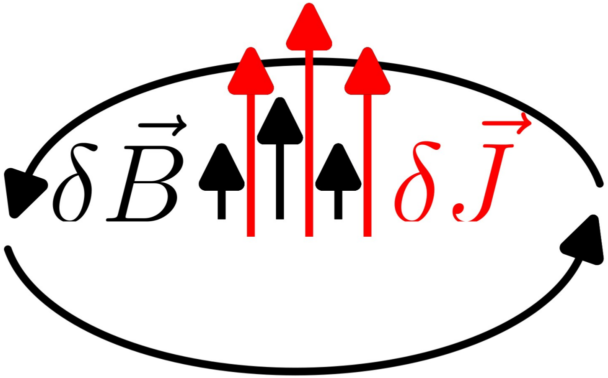

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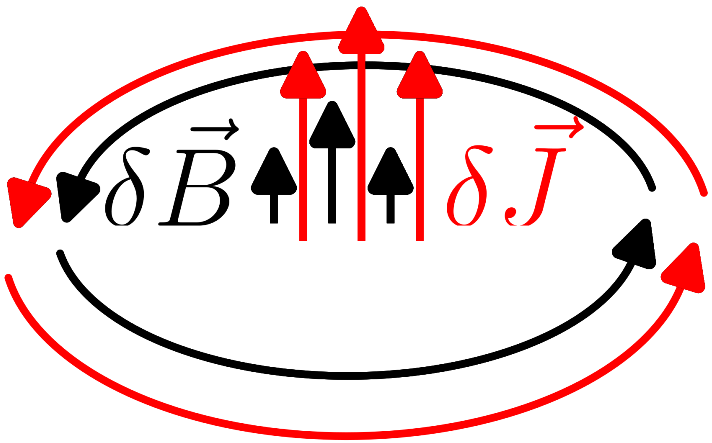

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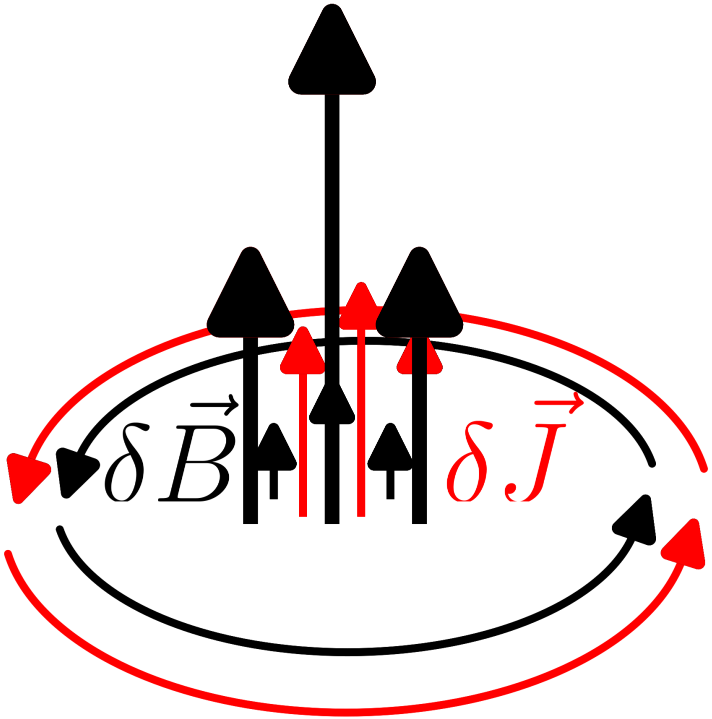

Self-amplifying magnetic fluctuations

Y. Akamatsu & N. Yamamoto, PRL 111, 052002 (2013)

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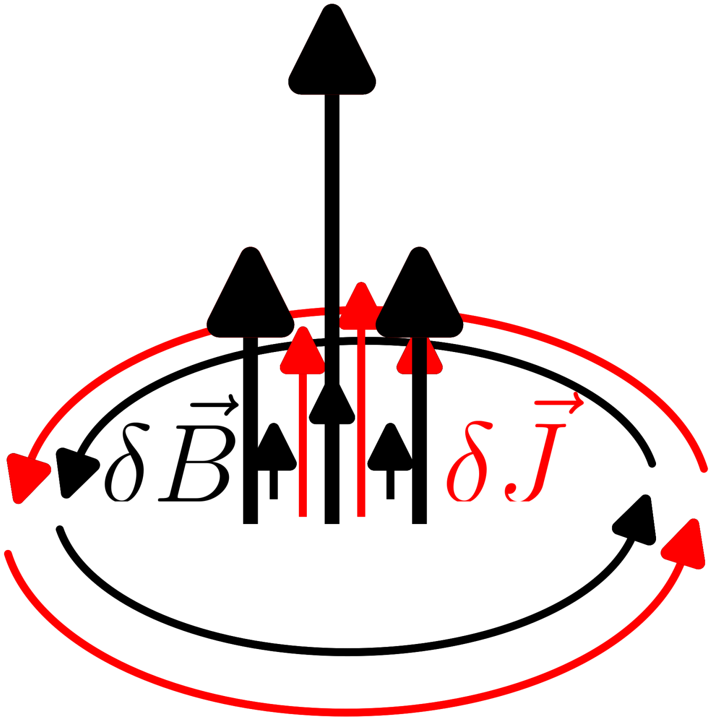

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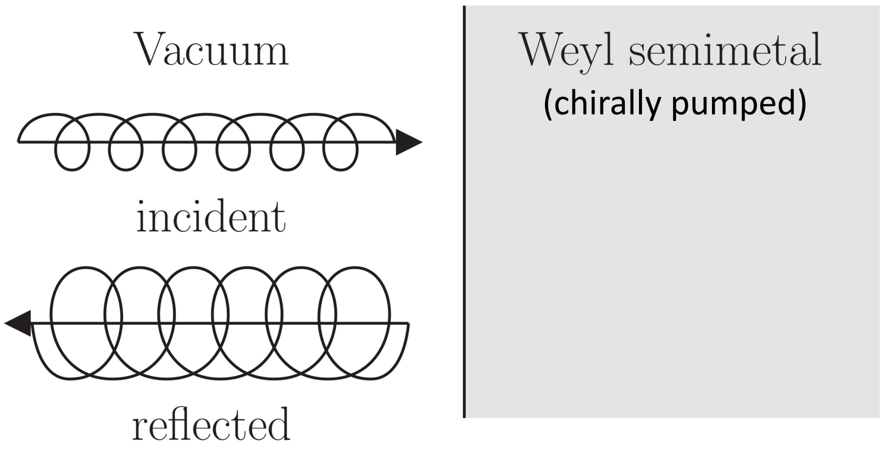
Weyl semimetal as a chiral light amplifier

Y. Nishida, PRL 130, 096903 (2023)
T. Amitani & Y. Nishida, PRB 107, 014302 (2023)



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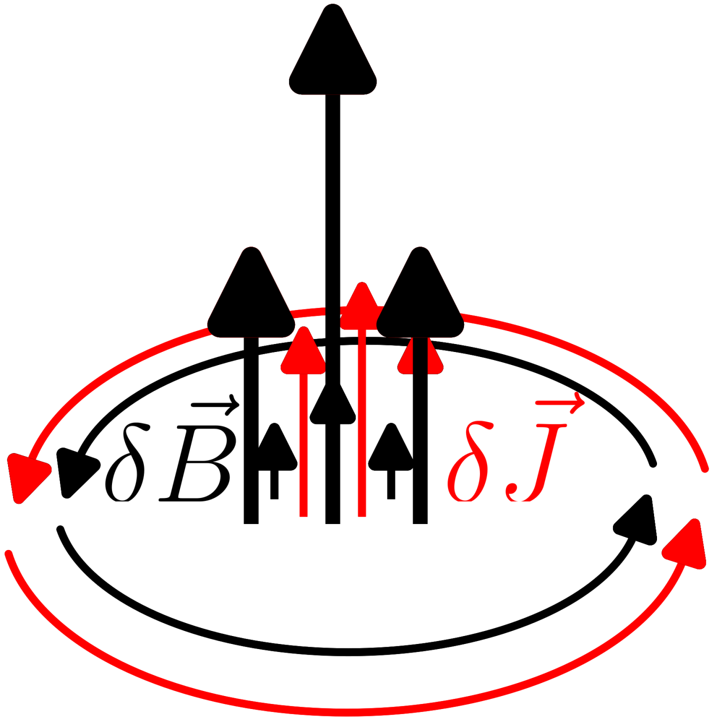

Self-amplifying magnetic fluctuations

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Essential ingredients:

- $\vec{J} \propto \vec{B}$
- Maxwell's equations

Chiral magnetic instability

The chiral anomaly is not necessary!

Stellar dynamo: "alpha effect"

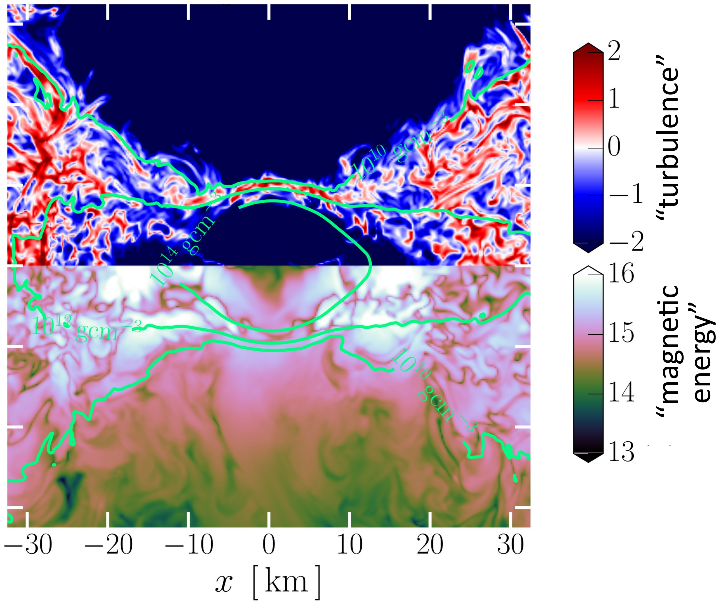
Helical turbulence in rotating bodies

$\longrightarrow$ macroscopic $\vec{J} \propto \vec{B}$

Can generate astrophysical magnetic fields

Neutron star merger (cross section)

E. R. Most, PRD 108, 123012 (2023)



nts:

Self-

Y. Akam

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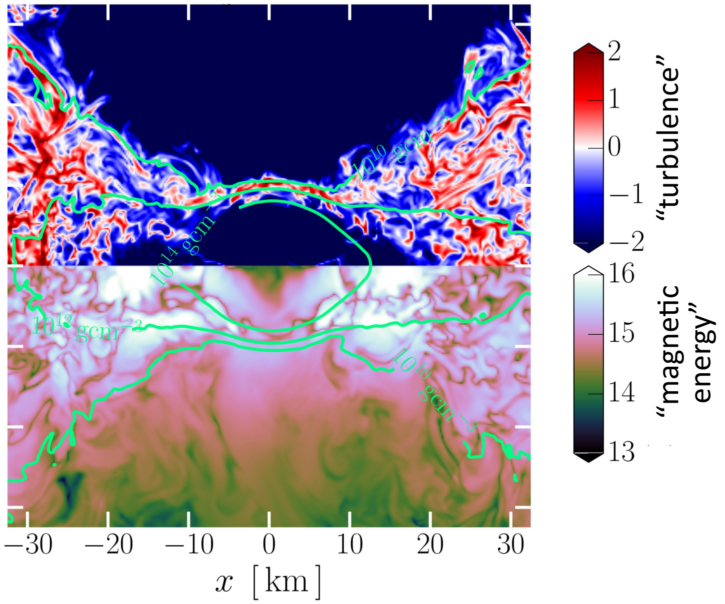

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Y. Akam

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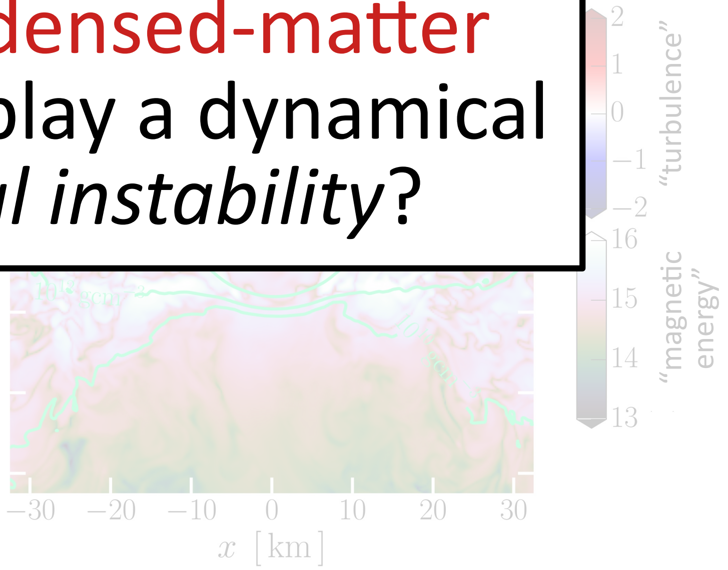
What other condensed-matter systems could display a dynamical *magneto-chiral instability*?

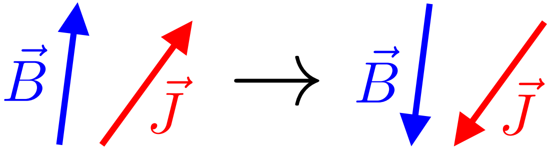
Can generate astrophysical magnetic fields



Crystal symmetry requirements

Magneto-chiral current: $J_i = \sigma_{B,ij} B_j$

Time reversal



$\sigma_{B,ij}$
time-reversal-even

Time-reversal breaking
not necessary

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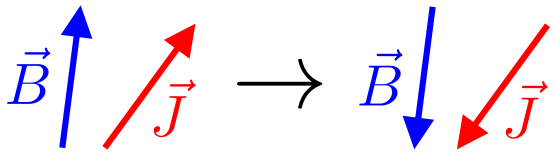
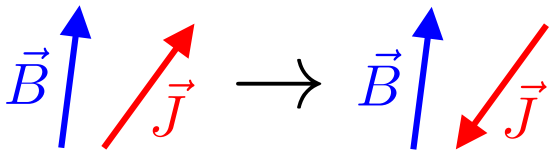


$\sigma_{B,ij}$
time-reversal-even

Time-reversal breaking not necessary

Spatial inversion



$\sigma_{B,ij}$
inversion-odd

Non-centrosymmetric crystal

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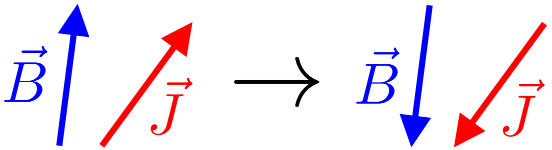

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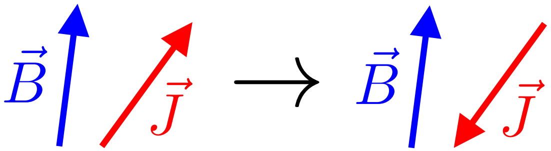

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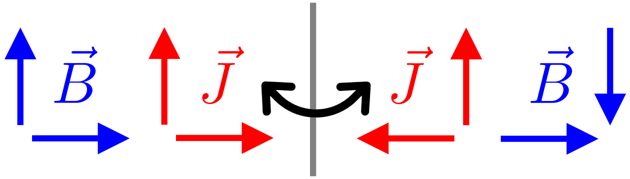
Non-centrosymmetric crystal

Mirror plane



To get a longitudinal effect

$\vec{J} \cdot \vec{B} \neq 0$

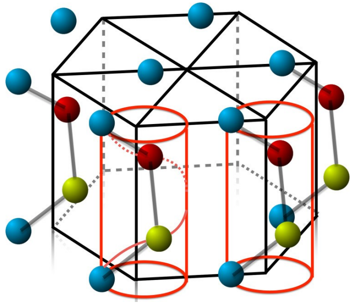
No mirrors

Crystal symmetry requirements

Time-reversal symmetric materials with chiral crystal structure

Structurally chiral semiconductor tellurium

Y. Huang, NA, et al., [2502.05170](https://arxiv.org/abs/2502.05170)



space group

$P3_121$

$$\Longrightarrow \quad \sigma_{B,ij} = \begin{pmatrix} \sigma_B^{\perp} & 0 & 0 \\ 0 & \sigma_B^{\perp} & 0 \\ 0 & 0 & \sigma_B^{\parallel} \end{pmatrix}$$

Crystal symmetry requirements

Magneto-

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Spatial

ane

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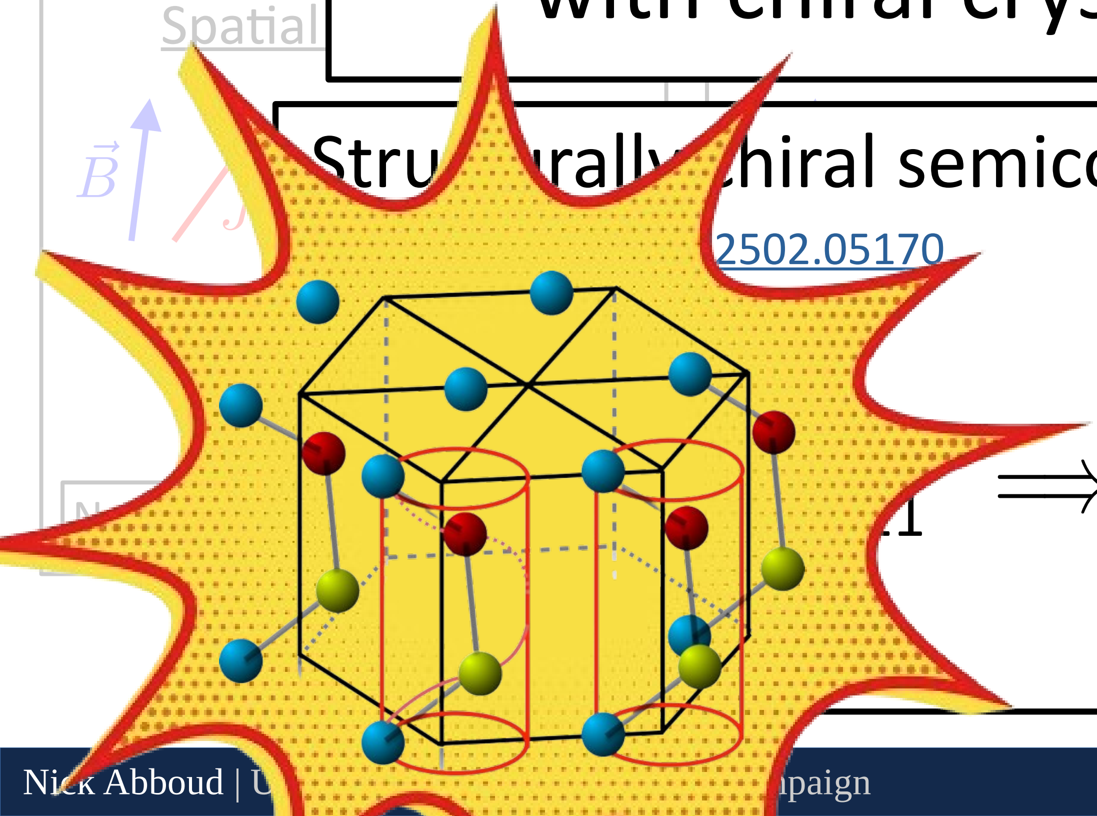
2502.05170



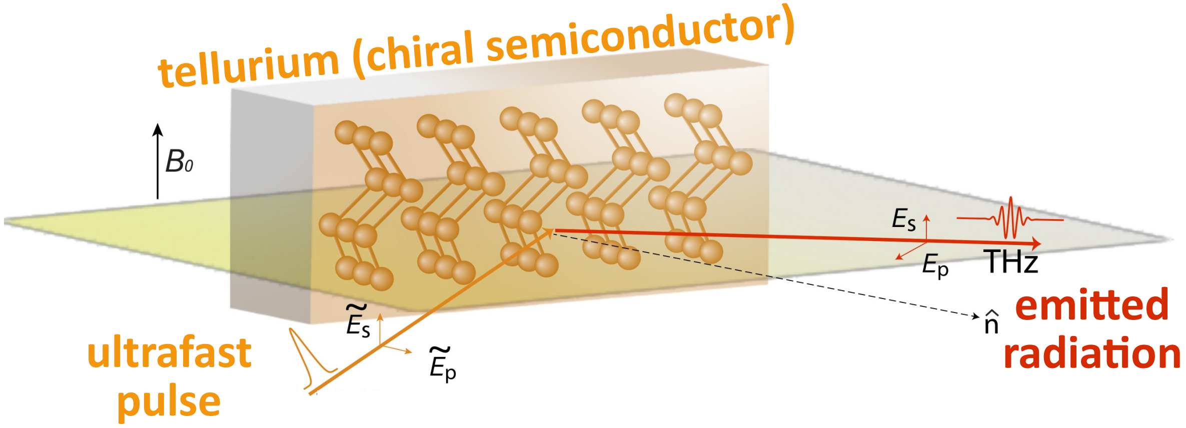
$$\implies \sigma_{B,ij} = \begin{pmatrix} \sigma_B^{\perp} & 0 & 0 \\ 0 & \sigma_B^{\perp} & 0 \\ 0 & 0 & \sigma_B^{\parallel} \end{pmatrix}$$

l effect,

THz emission from photoexcited Te

Y. Huang, NA, et al., 2502.05170

Mahmood lab, University of Illinois



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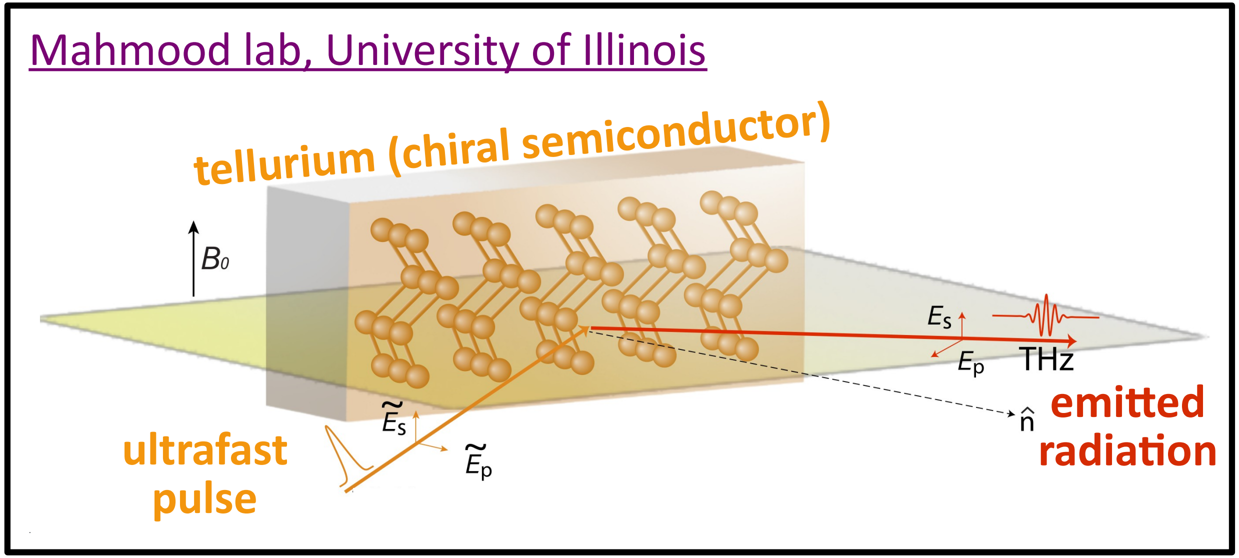

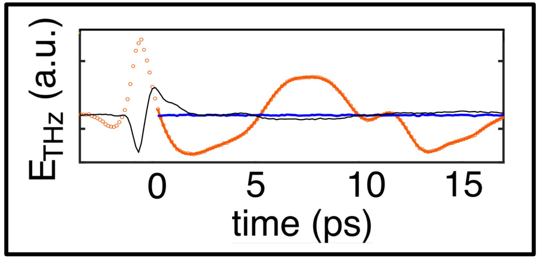

- Sum of four exponentially decaying oscillations…

  → Impurity levels

  K. Natori et al., JPSJ 34, 1263 (1973)

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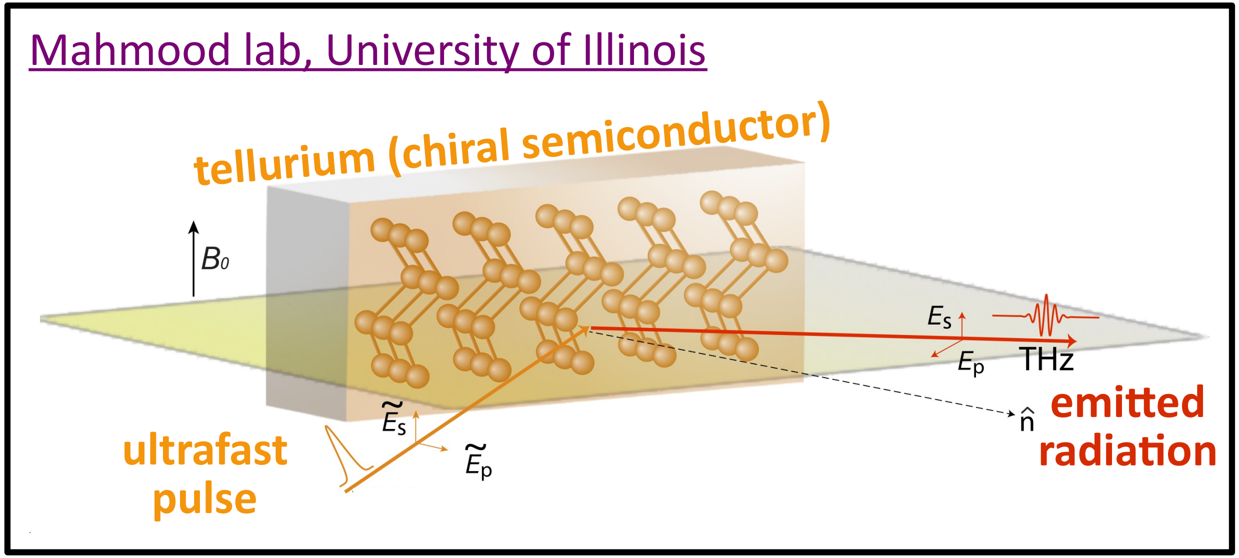
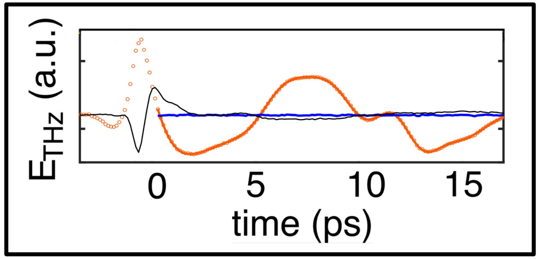
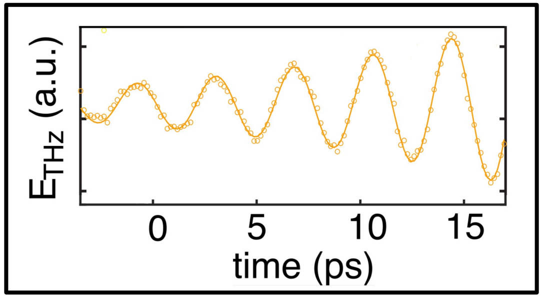




- Sum of four exponentially decaying oscillations…

  → Impurity levels
  K. Natori et al., JPSJ 34, 1263 (1973)

- ...AND one *growing* oscillation!



A first attempt: ~~condensed matter~~

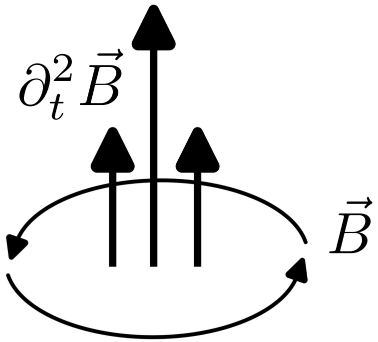
Magneto-chiral current

$$\vec{J} = \sigma_B \vec{B}$$

constant and isotropic

From Maxwell's equations,

$$\left(\partial_t^2 - \nabla^2\right) \vec{B} = \sigma_B \vec{\nabla} \times \vec{B}$$



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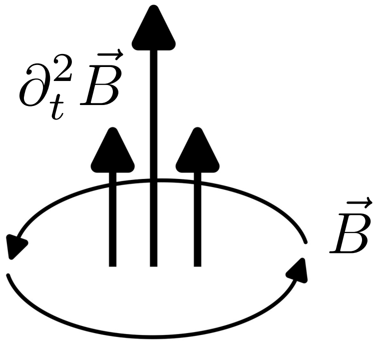

plane wave solutions $\vec{B} \sim e^{i(\vec{k}\cdot\vec{r}-\omega t)}$

$$\vec{k} \in \mathbb{R}^3$$

$\mathrm{Im}[\omega] > 0 \implies$ instability

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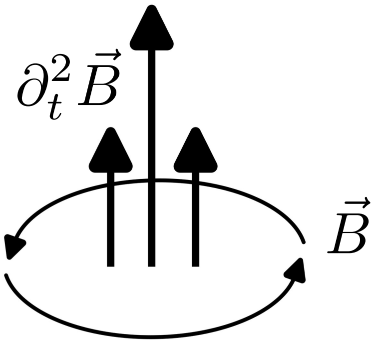

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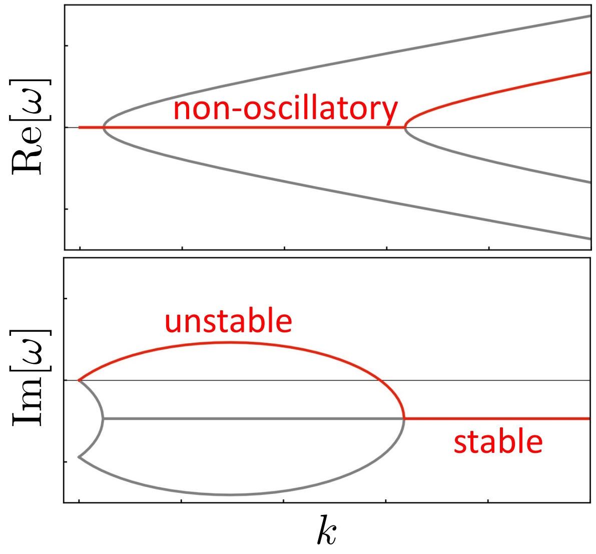
circularly polarized

$$\vec{\nabla} \times \vec{B} = k\vec{B}$$

$$\implies \omega = \sqrt{k(k - \sigma_B)}$$

non-oscillatory instability

e.g. Shovkovy, 2111.11416



New ingredient: impurity oscillators

Recall, the observed frequency of the instability is characteristic of an **impurity level**.

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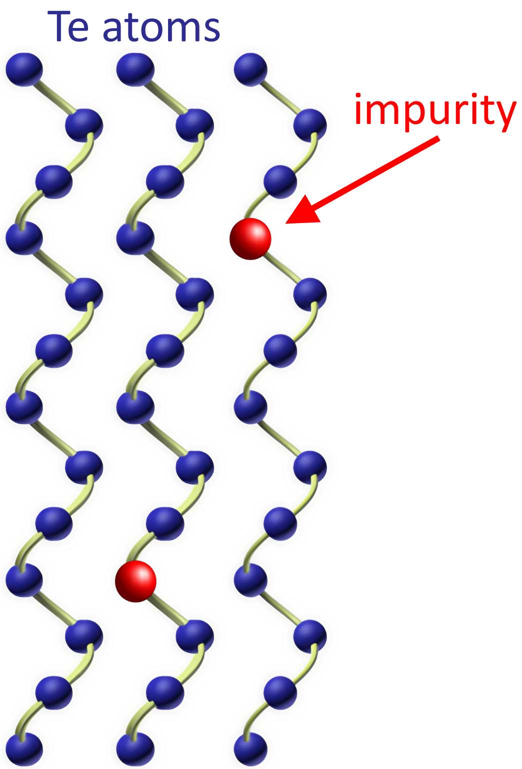

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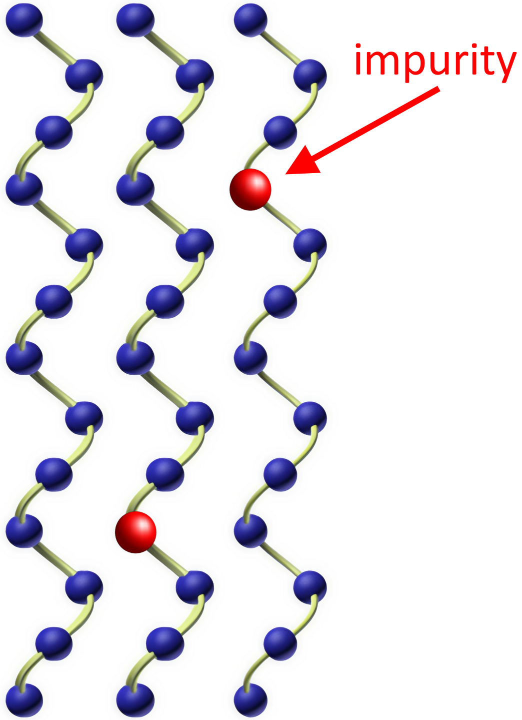

Lorentzian oscillator model for charged impurities

$$\vec{J} \supset -\frac{n_{\mathrm{imp}} e^2}{m^*} \frac{i\omega}{(\omega_0^2 - \omega^2) - i\gamma\omega} \vec{E}$$

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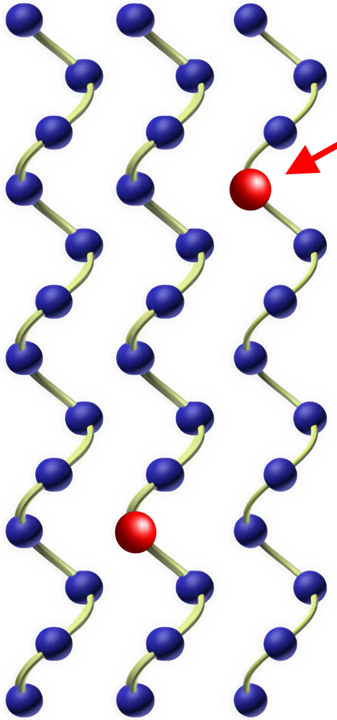

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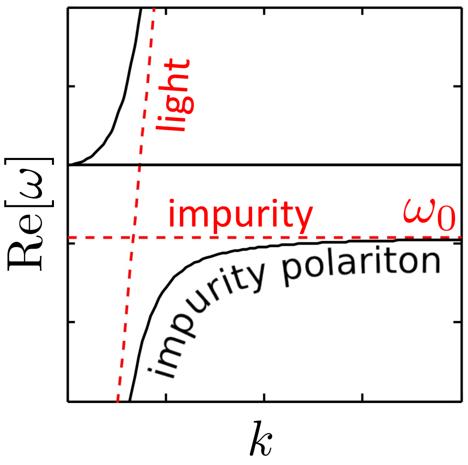
Impurity polariton



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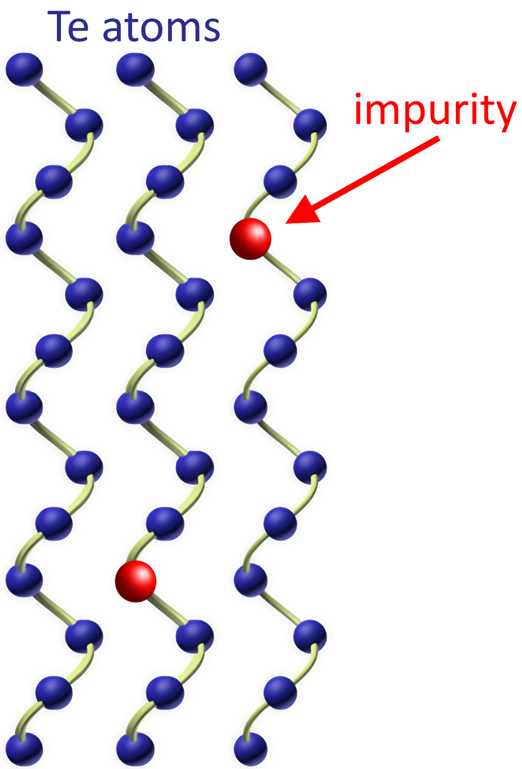
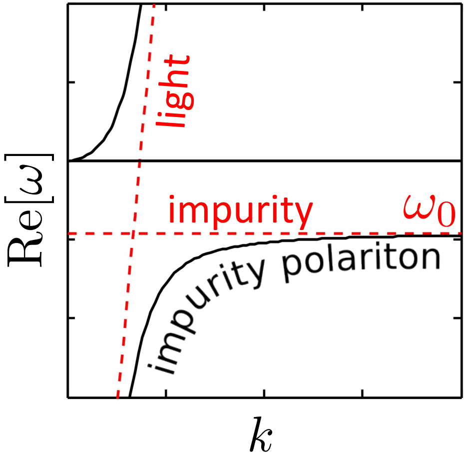
Recall, the observed frequency of the instability is characteristic of an **impurity level**.



<u>Lorentzian oscillator model for charged impurities</u>

$$\vec{J} \supset -\frac{n_{\text{imp}} e^2}{m^*} \frac{i\omega}{(\omega_0^2 - \omega^2) - i\gamma\omega} \vec{E}$$

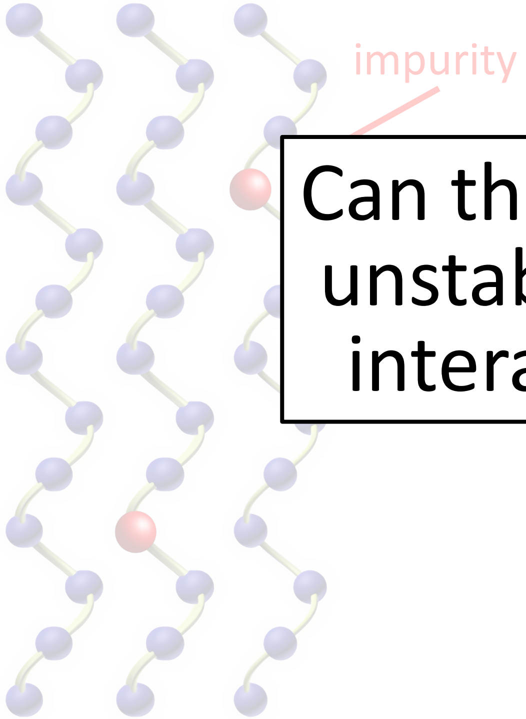
<u>Impurity polariton</u>



One normal mode is a light-impurity hybrid with "pinned" frequency.

New ingredient: impurity oscillators

Recall, the observed frequency of the instability is characteristic of an **impurity level**.



Lorentzian oscillator model for charged impurities

$$\vec{J} \supset -\frac{n_{\text{imp}} e^2}{m^*} \frac{i\omega}{(\omega_0^2 - \omega^2) - i\gamma\omega} \vec{E}$$

Can the impurity polariton become unstable through electromagnetic interaction with charge carriers?

...normal ...is a light-impurity hybrid with "pinned" frequency.

New ingredient: impurity oscillators

Recall, the observed frequency of the instability is characteristic of an impurity level.

Summary of model:

Y. Huang, NA, et al., 2502.05170

$$\vec{J}(\omega,\vec{k}) = \sigma_B(\omega)\vec{B}(\omega,\vec{k}) + \sigma_E(\omega)\vec{E}(\omega,\vec{k})$$

$$\sigma_E(\omega) = \sigma_{E0} - \frac{n_{\text{imp}}e^2}{m^*}\frac{i\omega}{(\omega_0^2-\omega^2)-i\gamma\omega}$$

Ohm's law

Bound current due to impurities

$$\sigma_B(\omega) = \frac{e^2}{4\pi^2\hbar^2}\left(\mu_{\text{DC}} + \mu_{\text{AC}}\frac{\omega\tau}{\omega\tau+i}\right)$$

Unequal left- and right-handed populations

Generic to chiral crystals

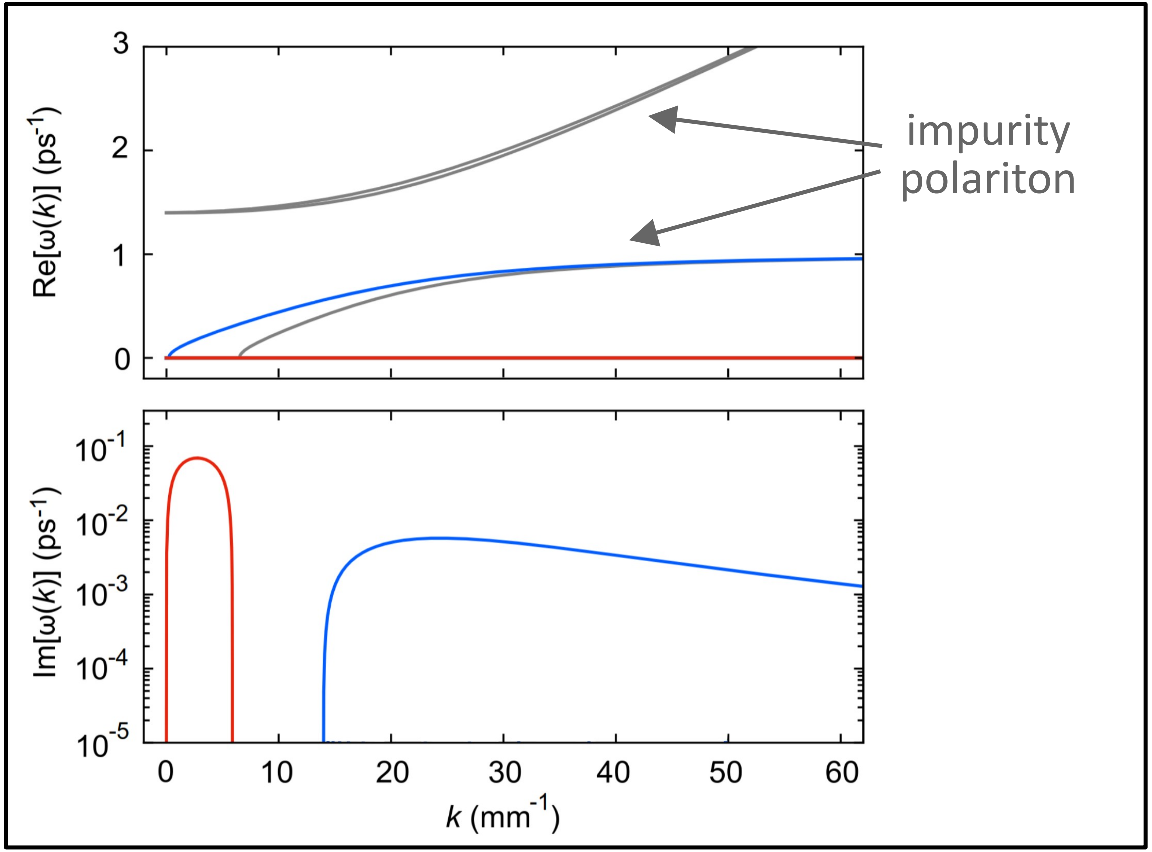
Insert into Maxwell's equations and solve with

$$\vec{E},\vec{B} \sim e^{i(\vec{k}\cdot\vec{r}-\omega t)}$$

S. Zhong et al., PRL 116, 077201 (2016)
J. Ma & D. A. Pesin, PRB 92, 235205 (2015)

Results

Y. Huang, NA, et al., 2502.05170

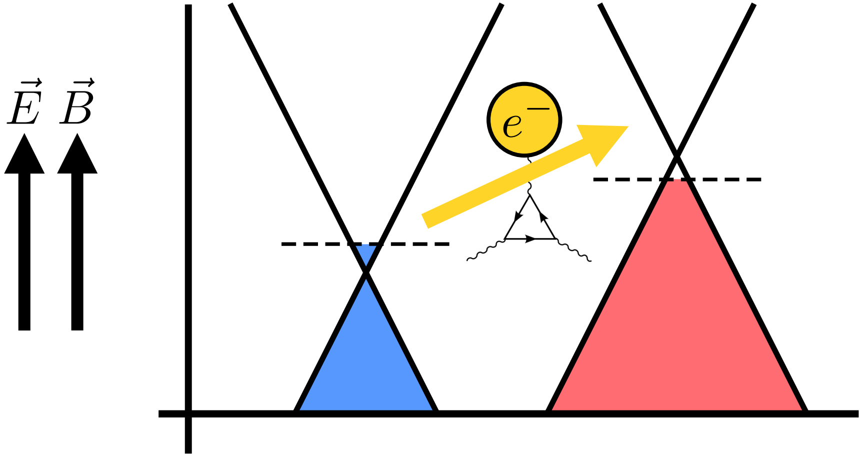


A branch of the impurity polariton is unstable!

- Using reasonable parameter values, some measured on the sample
- Agrees with experiment to order of magnitude
- Damping of the impurity oscillators can render the blue mode stable again

Steady-state vs. transient chiral transport

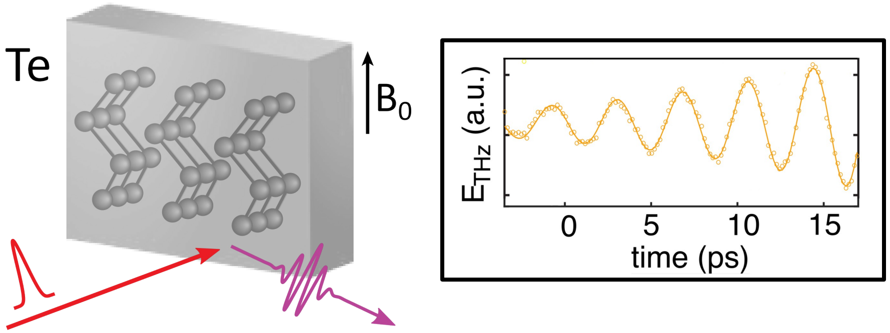
Chirally pumped Weyl semimetal



- Steady non-eq current $\vec{J} \propto \vec{B}$
- Consequence of chiral anomaly
- Property of emergent massless carriers

e.g. X. Huang et al. (2015); Q. Li et al. (2016)

Magneto-chiral instability in Te



Y. Huang, NA, et al., 2502.05170

- Transient non-eq current $\vec{J} \propto \vec{B}$
- Requires only a chiral crystal structure
- Doesn't have a direct analog outside of solid state (due to impurity involvement)

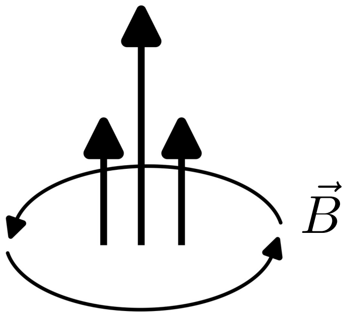
Conclusions & Outlook

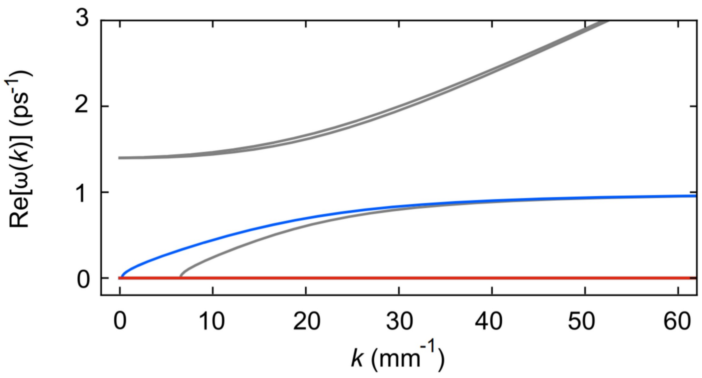
Y. Huang, NA, et al., 2502.05170

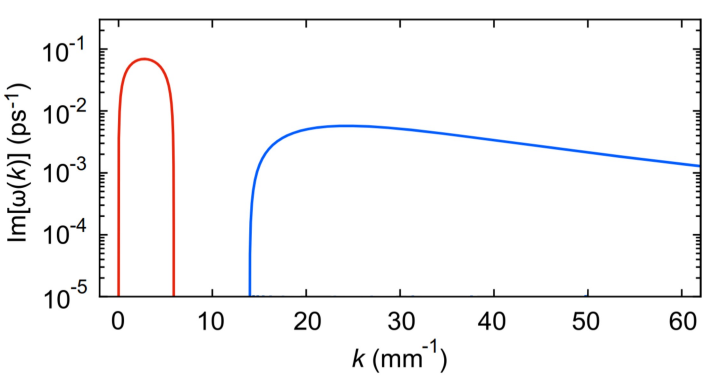
- **We propose a simple electrodynamic model in which an impurity polariton is rendered dynamically unstable by magneto-chiral transport effects in transiently excited chiral materials.**

- **Experimental results highlight the potential to manipulate THz-range radiation in far-from-equilibrium chiral materials, including wave amplification.**

- **Motivates a systematic study of nonlinear dynamics including background fields in far-from-equilibrium microscopic descriptions of chiral semiconductors.**







Bonus slides

Directions for further work

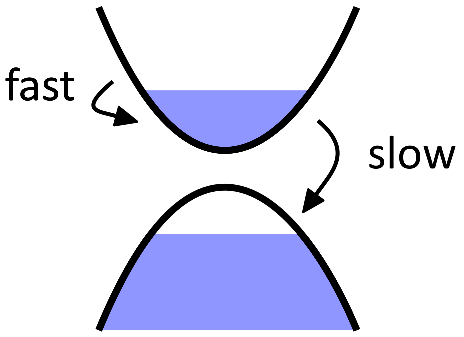
Y. Huang, NA, et al., [2502.05170]

- Our linear response model implicitly assumes a long-lived out-of-equilibrium state.

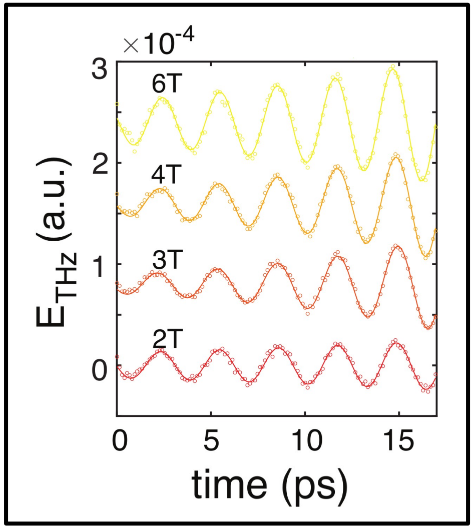
  - Plausible—carrier recombination is slow.

    Jnawali et al., Nat. Comm. 11, 3991 (2020)

  - Calls for a more microscopic approach, e.g. a kinetic theory.



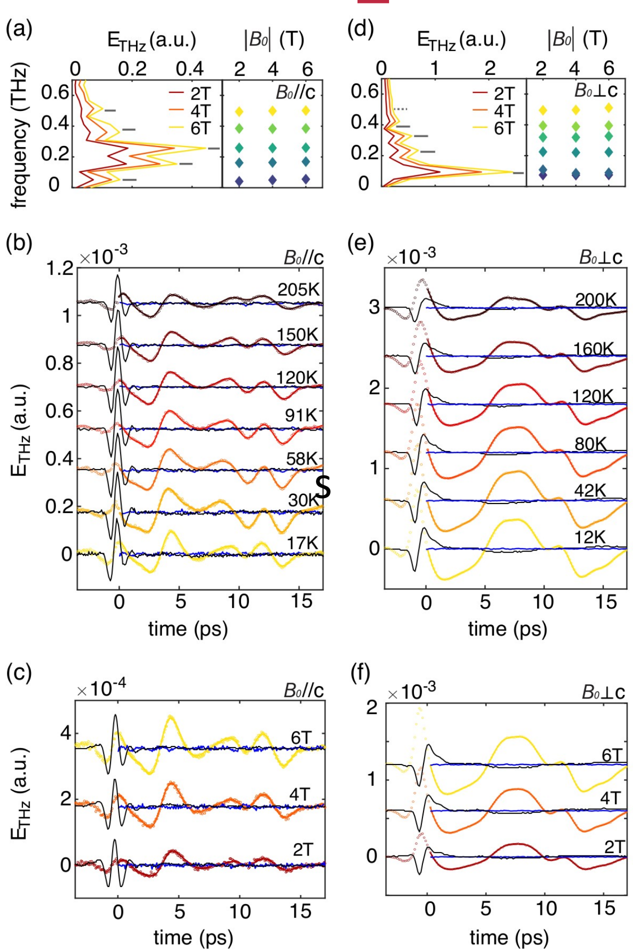
- Understand observed dependence on applied magnetic field
  - Not yet taken into account

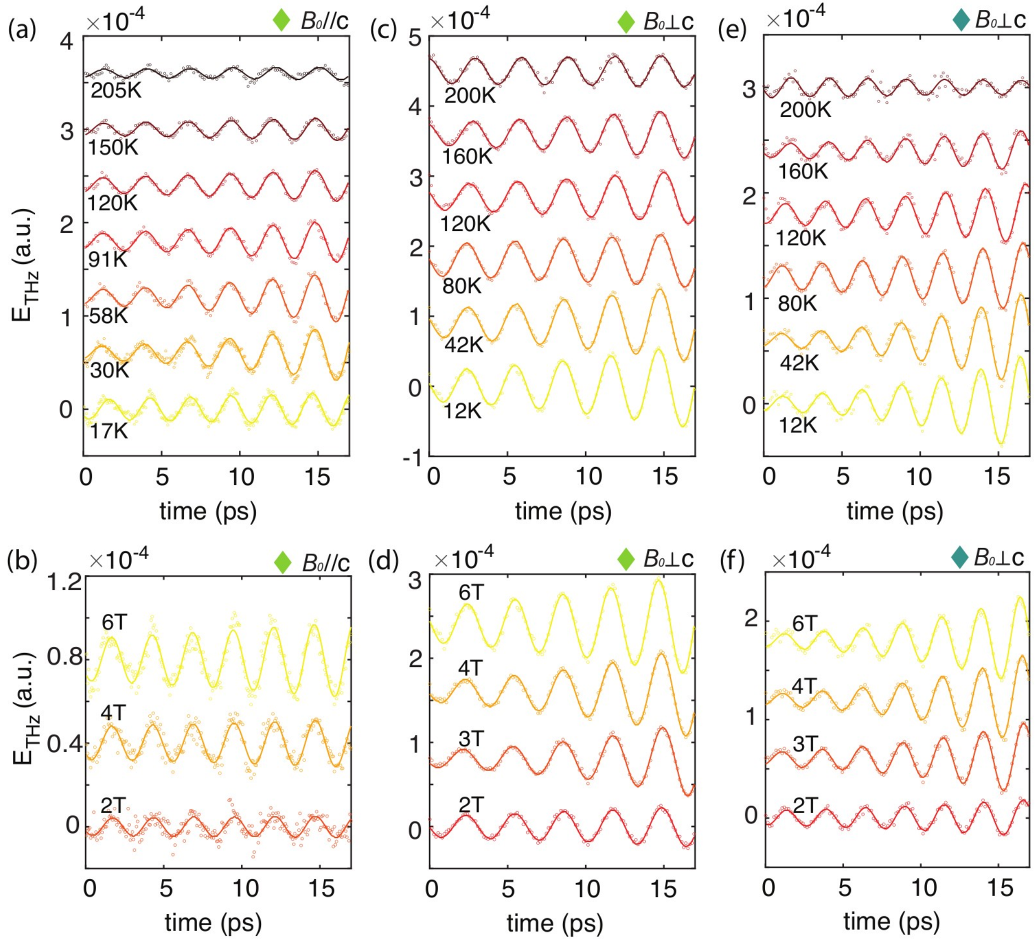


- Better experimentally resolve the polarization of the outgoing radiation.

Some experimental data

Y. Huang, NA, et al., 2502.05170





Other enantiomorphic point groups

Point Groups	matrix representation of Ξ	Cartesian axes
C_1	$\begin{bmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{bmatrix}$	arbitrary
C_2	$\begin{bmatrix} T_{xx} & T_{xy} & 0 \\ T_{yx} & T_{yy} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	two-fold rotation along z
D_2	$\begin{bmatrix} T_{xx} & 0 & 0 \\ 0 & T_{yy} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	rotation axes along (x, y, z)
C_3	$\begin{bmatrix} T_{\|\|} & -T^{-} & 0 \\ T^{-} & T_{\|\|} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	three-fold rotation along z
D_3	$\begin{bmatrix} T_{\|\|} & 0 & 0 \\ 0 & T_{\|\|} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	three-fold rotation along z
C_4	$\begin{bmatrix} T_{\|\|} & -T^{-} & 0 \\ T^{-} & T_{\|\|} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	four-fold rotation along z
D_4	$\begin{bmatrix} T_{\|\|} & 0 & 0 \\ 0 & T_{\|\|} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	four-fold rotation along z
C_6	$\begin{bmatrix} T_{\|\|} & -T^{-} & 0 \\ T^{-} & T_{\|\|} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	six-fold rotation along z
D_6	$\begin{bmatrix} T_{\|\|} & 0 & 0 \\ 0 & T_{\|\|} & 0 \\ 0 & 0 & T_{zz} \end{bmatrix}$	six-fold rotation along z
T	$\begin{bmatrix} T_0 & 0 & 0 \\ 0 & T_0 & 0 \\ 0 & 0 & T_0 \end{bmatrix}$	(x, y, z) along crystal axes
O	$\begin{bmatrix} T_0 & 0 & 0 \\ 0 & T_0 & 0 \\ 0 & 0 & T_0 \end{bmatrix}$	(x, y, z) along crystal axes

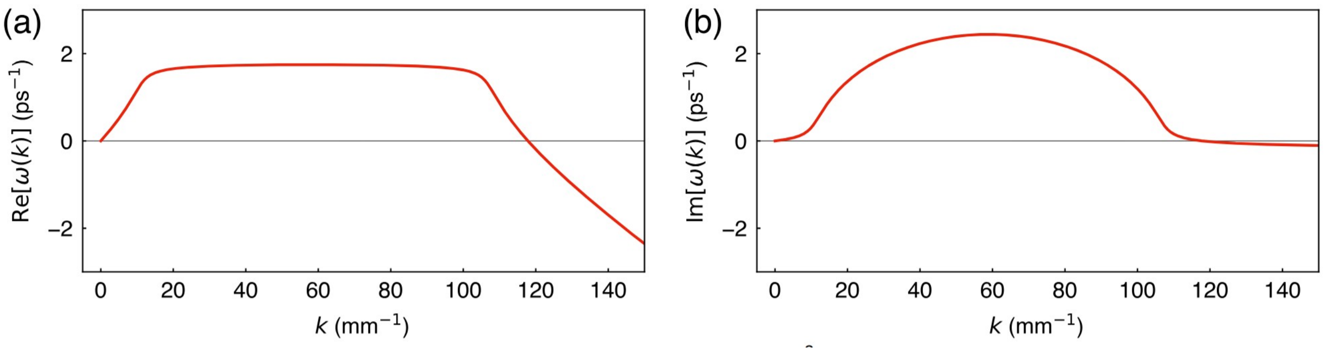
Trying adding Hall effects?

- Classical Hall effect (in large B-field) swamps valley Hall

- No anomalous Hall effect in TR-invariant tellurium

- Classical Hall effect causes instability to propagate (Nishida 2023), but the magnitude of the effect is off by several orders without unrealistic fine tuning

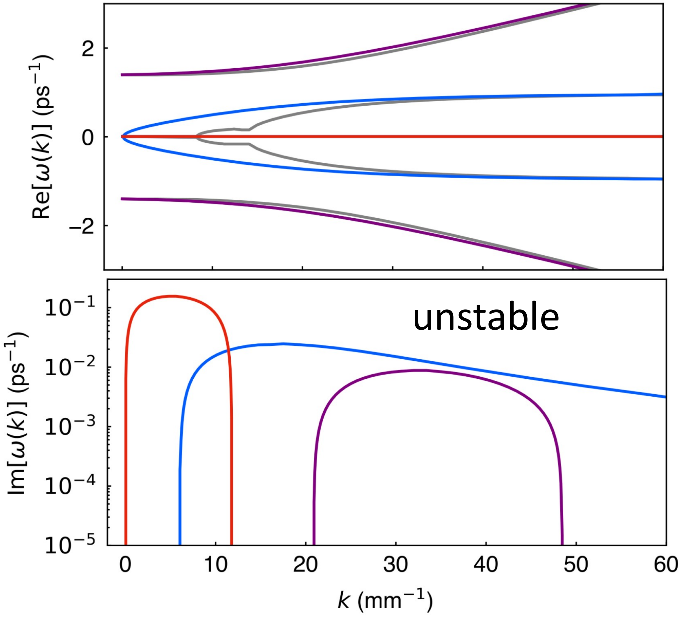
    - Would lead to B-dependent growth rate, contrary to observations



More than one unstable mode

Tweak the parameters?

→ sometimes multiple oscillatory instabilities



Y. Huang, NA, et al., 2502.05170

Speculative mechanism for imbalance

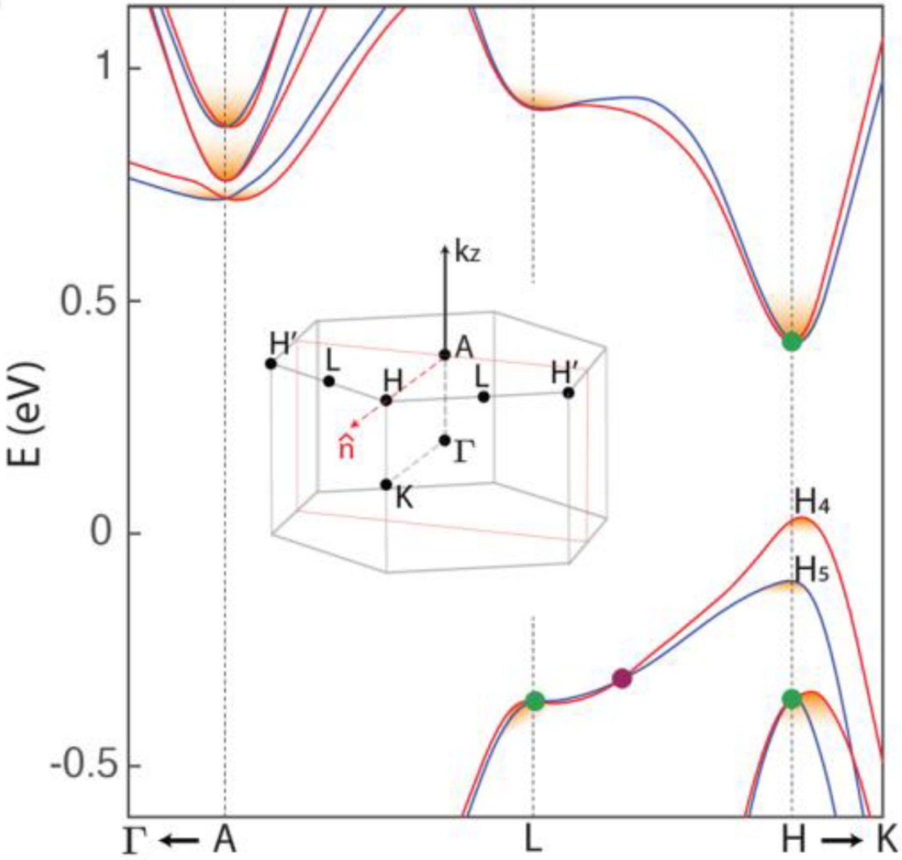


Figure from Jnawali et al., Nat. Comm. 11, 3991 (2020)

Time-reversal-invariant chiral crystal:

→ **Opposite-chirality Weyl nodes** are not related by symmetries, so generically **have different energies**.

→ Hence, photoexcitation by a linearly polarized source populates opposite-chirality nodes differently.

→ Plus, after photoexcitation, the average rate of decay of the right-handed fermions generically differs from that of the left-handed ones.