

# The Golden Age of Chirality And Quantum Mechanics



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*Vienna Central European Seminar, Vienna, 30.11–01.12. 2018*

# Outline

- Explain Title
- Anomalies
- Anomaly induced Currents (CME & CVE)
- Weyl semi-metals
- Zilch
- Summary and Outlook

# Earlier this year: chiral fluid workshop in Santa Fe, NM:

Topic: Chirality in McCarthy | CormacMcCarthy.com - Mozilla Firefox

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## Chirality in McCarthy

Posted on by Glass

This topic contains 18 replies, has 7 voices, and was last updated by Candy Minx 6 months, 1 week ago.

Viewing 10 posts - 1 through 10 (of 19 total) 1 2 →

Author	Posts	Mark Topic Read
	09 Aug 2013 at 11:15 pm	#3745
 Glass Member	<a href="http://en.m.wikipedia.org/wiki/Chirality">http://en.m.wikipedia.org/wiki/Chirality</a>	
	<a href="http://en.m.wikipedia.org/wiki/Situs_inversus">http://en.m.wikipedia.org/wiki/Situs_inversus</a>	
	<a href="http://www.youtube.com/watch?v=3Cc5KXHxoFU&amp;feature=youtube_gdata_player">http://www.youtube.com/watch?v=3Cc5KXHxoFU&amp;feature=youtube_gdata_player</a>	
	<a href="http://en.m.wikipedia.org/wiki/Drawing_Hands">http://en.m.wikipedia.org/wiki/Drawing_Hands</a>	
	I've been researching the concept of "Chirality" and thinking of how it might resonate in McCarthy. An object or a system is chiral if it is not identical to	

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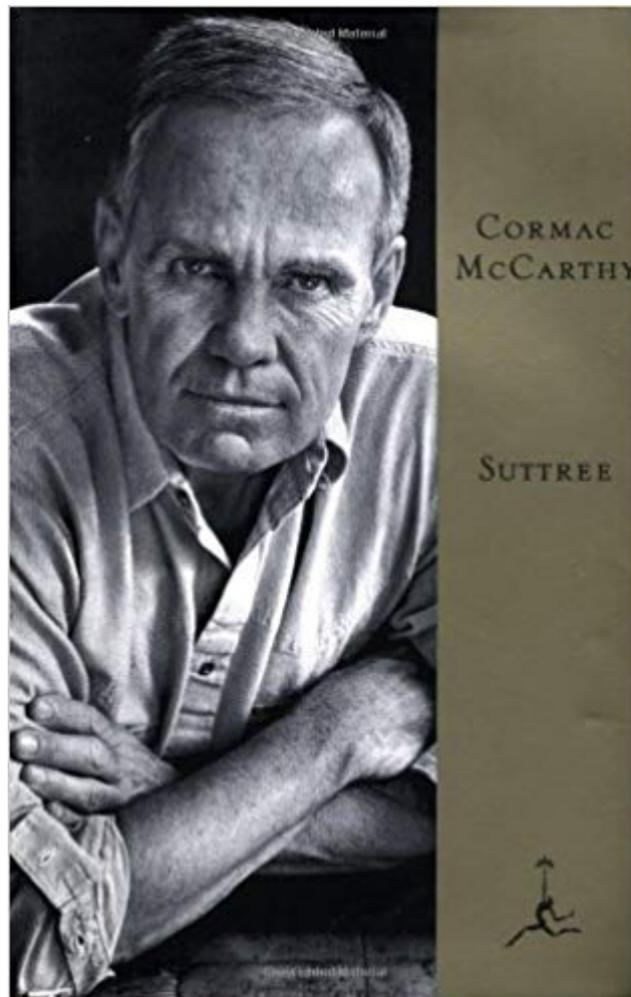
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I made a soundtrack to go along with Blood Meridian.  
8 hours, 11 minutes ago



*“On the right temple a mauve half moon. Suttree turned and lay staring at the ceiling, touching a like mark on his own left temple gently with his fingertips. The ordinary of the second son. Mirror image. Gauche carbon.”*

*“Gray vines coiled leftward in the northern hemisphere, what winds them shapes the dogwhelk’s shell.”*

*“A dextrocardiac, said the smiling doctor. Your heart’s in the right place.”*

**Bryan Giemza : “Mirror Image, Asymmetry, Chirality and Suttree”,  
Special Issue of the European Journal of American Studies:  
Cormac McCarthy Between Worlds**

**“For now, suffice it to say that we may be in something of a golden age of chirality, from Breaking Bad to Nobel Prize-winning areas of scientific enquiry.”**

# Breaking Bad to Nobel Prize



Levometamphetamin



Dextromethamphetamin  
"crystal meth"

## Nobel Prize in Chemistry 2016: Bernard L. Feringa

"for the design and synthesis of (chiral) molecular machines."

[Nobel committee]

...“chiral electromagnetic radiation to generate enantioselectivity”...

[from Wikipedia]

➔ "Zilch"

# Anomalies

-- Do you ever run across a fellow that even you can't understand?"

"Yes," says he.

"This will make a great reading for the boys down at the office," says I. "Do you mind releasing to me who he is?"

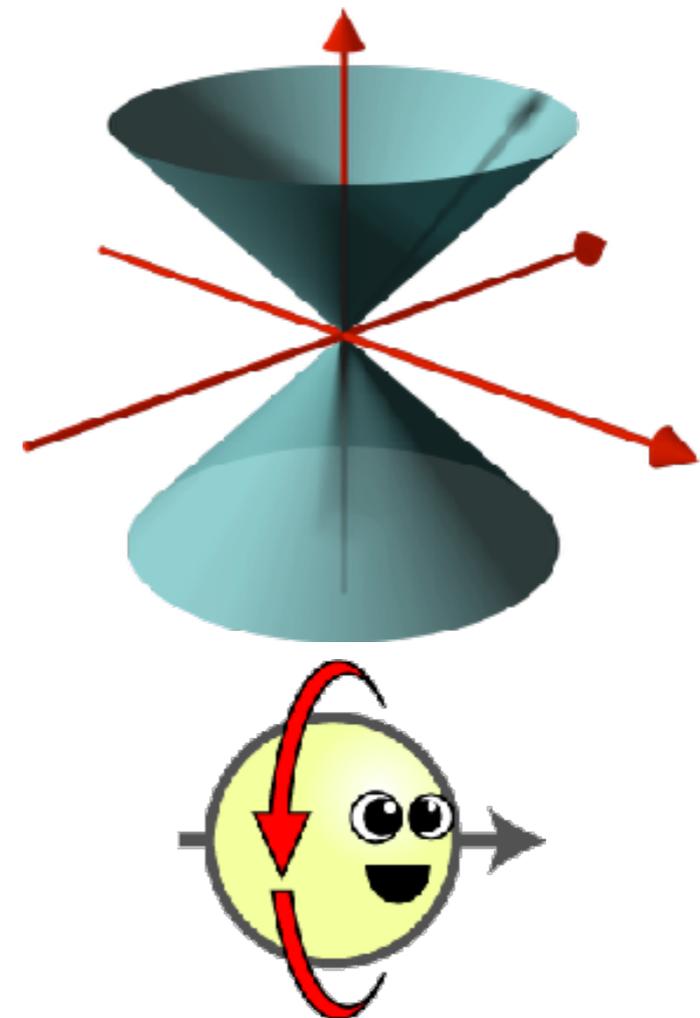
"Weyl," says he.

( ROUNDY INTERVIEWS PROFESSOR DIRAC )

Weyl fermions (massless Dirac):

$$H = \pm \vec{\sigma} \vec{p}$$

Spin is either aligned or anti-aligned with momentum



# Anomalies

Early 20th century: 2 key concepts of physics

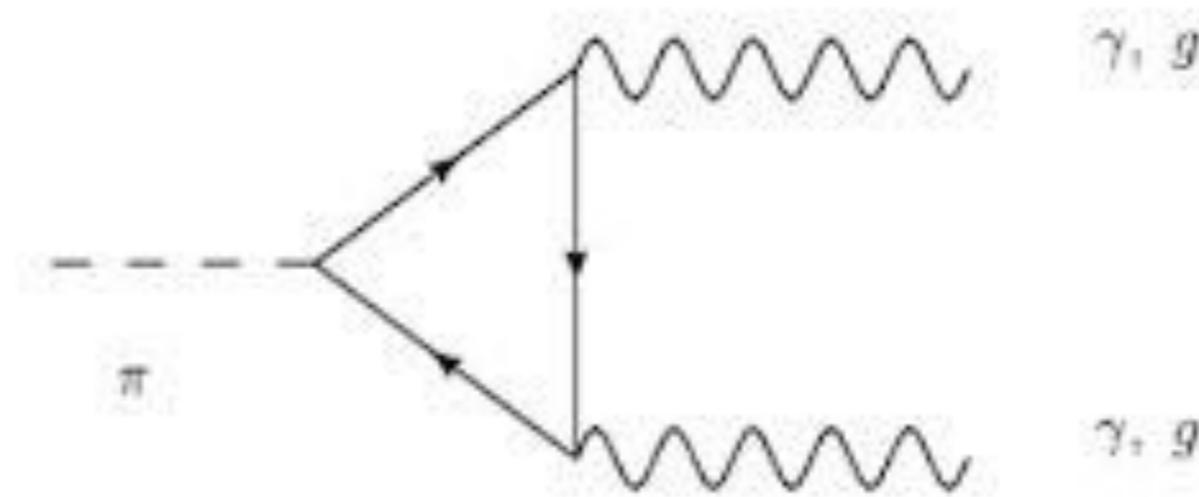
- Symmetry (Noether)
- Quantum Mechanics

Second half of 20th century: not always compatible

- Chiral Anomalies (Adler-Bell-Jackiw)

# Anomalies

High energy physics: decay of neutral pion



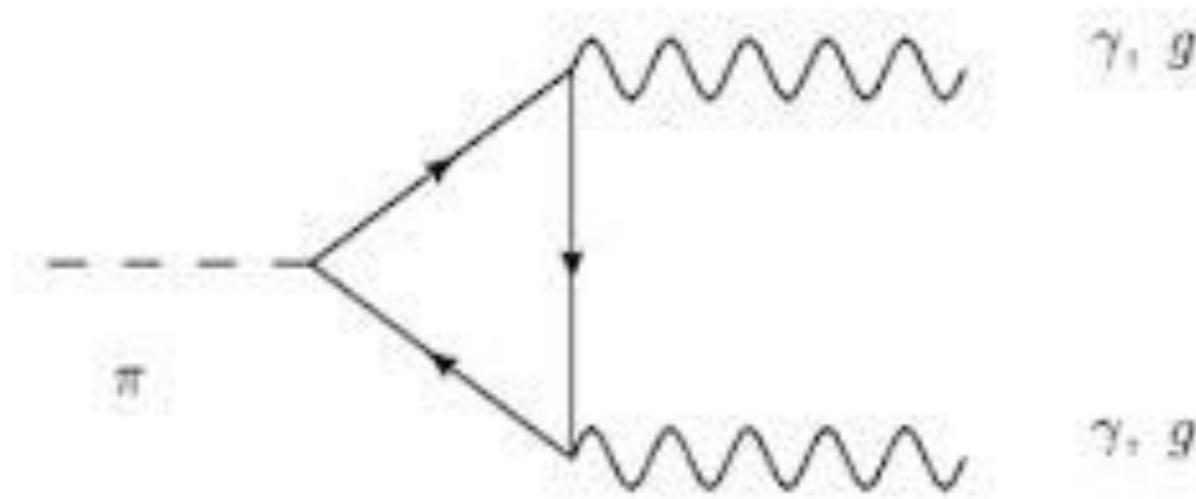
Symmetries suggest process is strongly suppressed

$$\partial_\mu J_5^\mu = -\frac{\alpha}{8\pi} \epsilon^{\mu\nu\rho\lambda} F_{\mu\nu} F_{\rho\lambda}$$

Quantum corrections destroy symmetry

# Anomalies

Decay of neutral pion into gravitons



$$\partial_{\mu} J_5^{\mu} = \frac{1}{384\pi^2} \epsilon^{\mu\nu\rho\lambda} R^a{}_{b\mu\nu} R^b{}_{a\rho\lambda}$$

Suppressed by Planck scale, impossible to detect at LHC + successors

# Anomalies

$$D_\mu J_a^\mu = \epsilon^{\mu\nu\rho\lambda} \left( \frac{d_{abc}}{96\pi^2} F_{\mu\nu}^b F_{\rho\lambda}^c + \frac{b_a}{768\pi^2} R^\alpha{}_{\beta\mu\nu} R^\beta{}_{\alpha\rho\lambda} \right)$$

$$d_{abc} = \sum_r q_a^r q_b^r q_c^r - \sum_l q_a^l q_b^l q_c^l$$

$$b_a = \sum_r q_a^r - \sum_l q_a^l$$

- Exact properties of the theory (non-renormalization)

# Anomalous Transport

- Chiral Magnetic and Vortical effects

$$\vec{J}_A = d_{ABC} \frac{\mu_B}{4\pi^2} \vec{B}_C + \left( d_{ABC} \frac{\mu_B \mu_C}{4\pi^2} + b_A \frac{T^2}{12} \right) \vec{\Omega}$$

$$\vec{J}_\epsilon = \left( d_{ABC} \frac{\mu_B \mu_C}{8\pi^2} + b_A \frac{T^2}{24} \right) \vec{B}_A + \left( d_{ABC} \frac{\mu_A \mu_B \mu_C}{6\pi^2} + b_A \frac{\mu_A T^2}{6} \right) \vec{\Omega}$$

- **Dissipationless**
- **State vs. Theory**



# Anomalous Transport

$$\delta_\lambda \Gamma = \mathcal{A}_\lambda$$

↑                      ↑

**Non-local**                      **local**

But anomaly can be written as **local in 5 dimensions**:

$$\delta_\lambda \int_{\mathcal{M}} A \wedge F \wedge F = \int_{\partial \mathcal{M}} \lambda F \wedge F$$

$$\int_{\mathcal{M}} d\lambda R \wedge R = \int_{\partial \mathcal{M}} \lambda (R^{(4)} \wedge R^{(4)} + D(K \wedge DK))$$

# Anomalous Transport

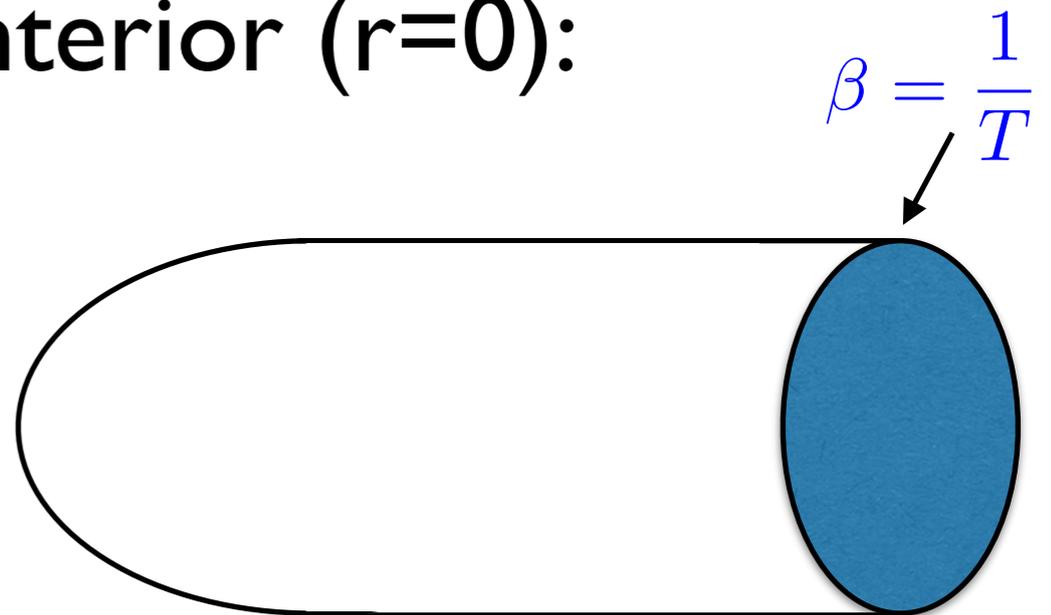
Thermal equilibrium = constraint on topology

Finite T Euclidean:  $\partial M = S^1 \otimes \mathbb{R}^3$

$$ds^2 = dr^2 + f(r)^2 d\tau^2 + g(r)^2 d\vec{x}^2$$

Smooth geometry in the interior ( $r=0$ ):

$$\begin{aligned} f(0) &= 0 \\ f'(0) &= 2\pi T \end{aligned} \rightarrow$$



# Anomalous Transport

Thermal equilibrium = 5D black hole !

Calculate current due to rotation from CS action in slowly rotating black hole

$$ds^2 = dr^2 - f(r)^2 [dt - (\vec{\omega} \times \vec{x}) \cdot d\vec{x}]^2 + g(r)^2 d\vec{x}^2$$

$$\delta\Gamma_{CS} = \int \delta A \wedge R \wedge R = \int \delta A_\mu \langle J^\mu \rangle_{\text{non-local}}$$

$$\vec{J} = 4f'(0)^2 \vec{\omega} = 16\pi^2 T^2 \vec{\omega}$$

Fixed by  
Topology!

# Anomalous Transport

## Chiral Magnetic Effect:

$$\delta\Gamma_{CS} = 3 \int_{\mathcal{M}} \delta A \wedge F \wedge F + 2 \int_{\partial\mathcal{M}} \delta A \wedge A \wedge F$$

“Covariant” current

“Bardeen-Zumino” current

$$F = B dx \wedge dy + F_{0r} dt dr$$

[Bardeen, Zumino] ‘84

$$A_r = 0$$

$$A_0 = A_0(r) \quad , \quad A_0|_{\partial} = \mu \quad , \quad A_0(0) = 0$$

$$\vec{J}_{\text{cov}} = 6\mu\vec{B}$$

$$\vec{J}_{\text{BZ}} = -4\mu\vec{B}$$

← In general not unique !

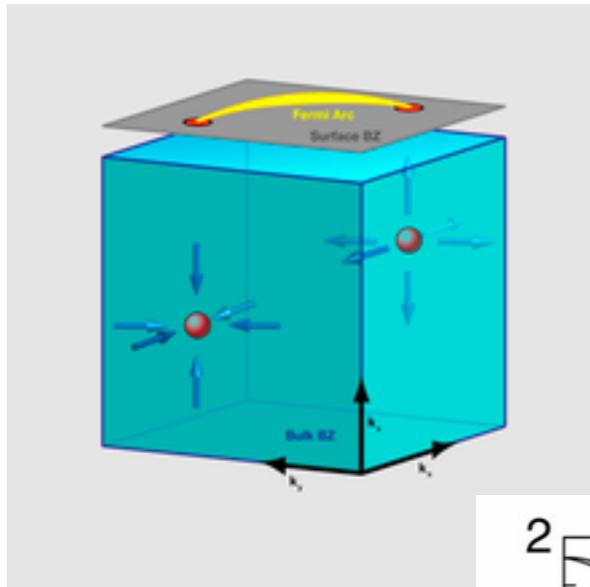
# Anomalous Transport

## Remarks:

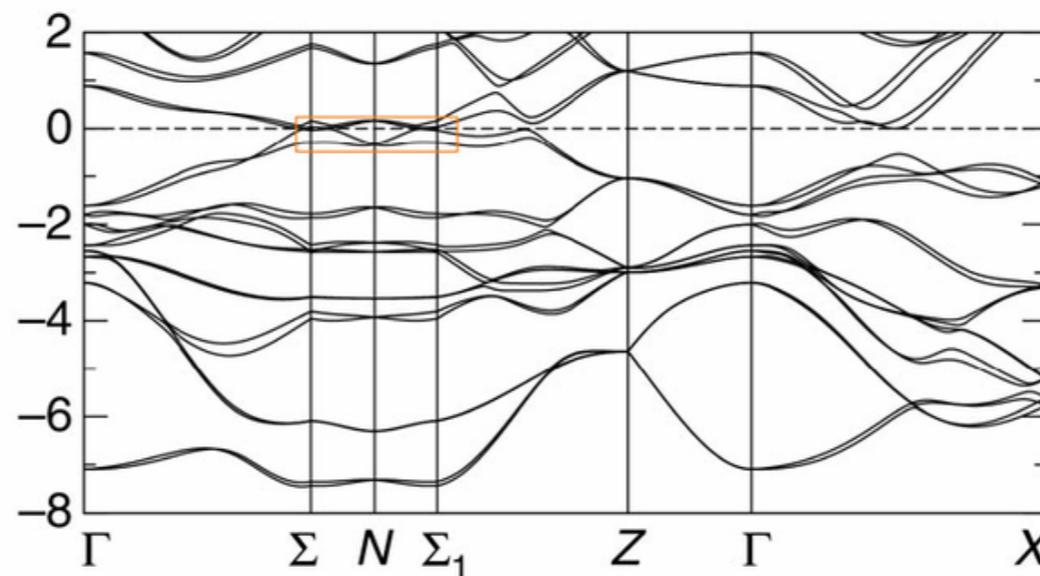
- Not crazy! Results can be obtained in free field theory
- Holography: Non-renormalization of anomaly
- Exact holography for the sector governed by anomaly
- Topology of thermal state = Black hole in 5D
- Derivative mismatch: topology and non-locality
- Bardeen-Zumino terms have physical meaning

[Megias, K.L., Pena-Benitez], [Megias, K.L., Pena-Benitez, Melgar] [Jensen, Loganayagam, Yarom] [Stone, Kim]  
[Vilenkin, 80's], [Alekseev, Cheianov, Froehlich] [Shaposhnikov, Giovannini]  
[Fukushima, Kharzeev, Warringa], [Son, Surowka], [Erdmenger, Haack, Kaminski, Yarom],  
[Banerjee, Bhattacharya, Bhattacharyya, Dutta, Loganayagam, Surowka]

# Applications: WeylSemiMetal

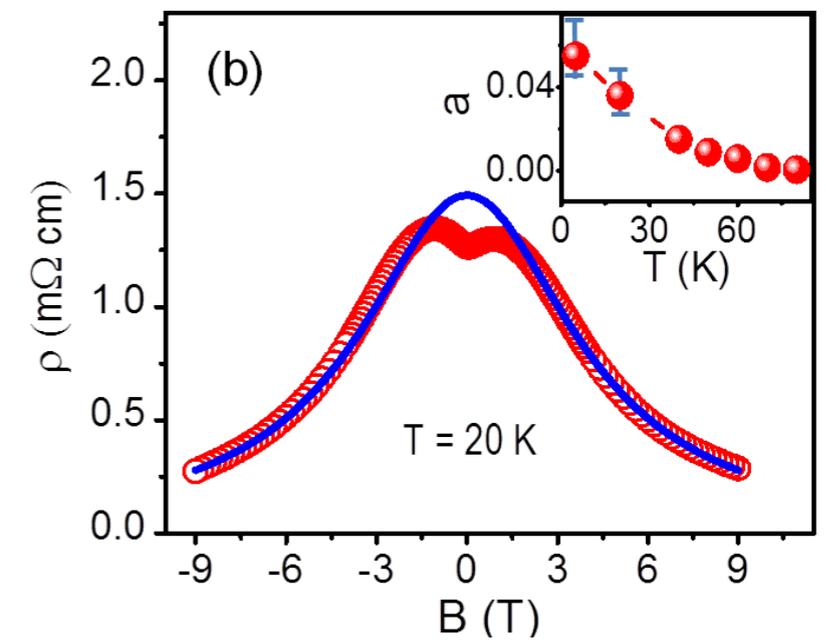
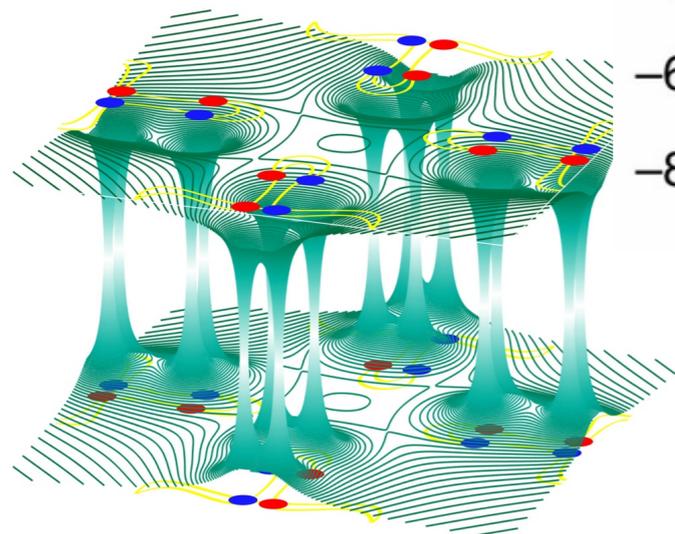


Wikipedia

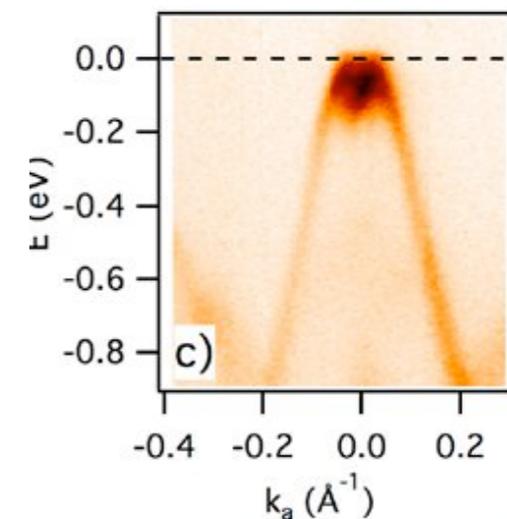


TaAs

[Huang, Xu, Belopolski, Hasan] Nature Comm.



Zr<sub>5</sub>Te

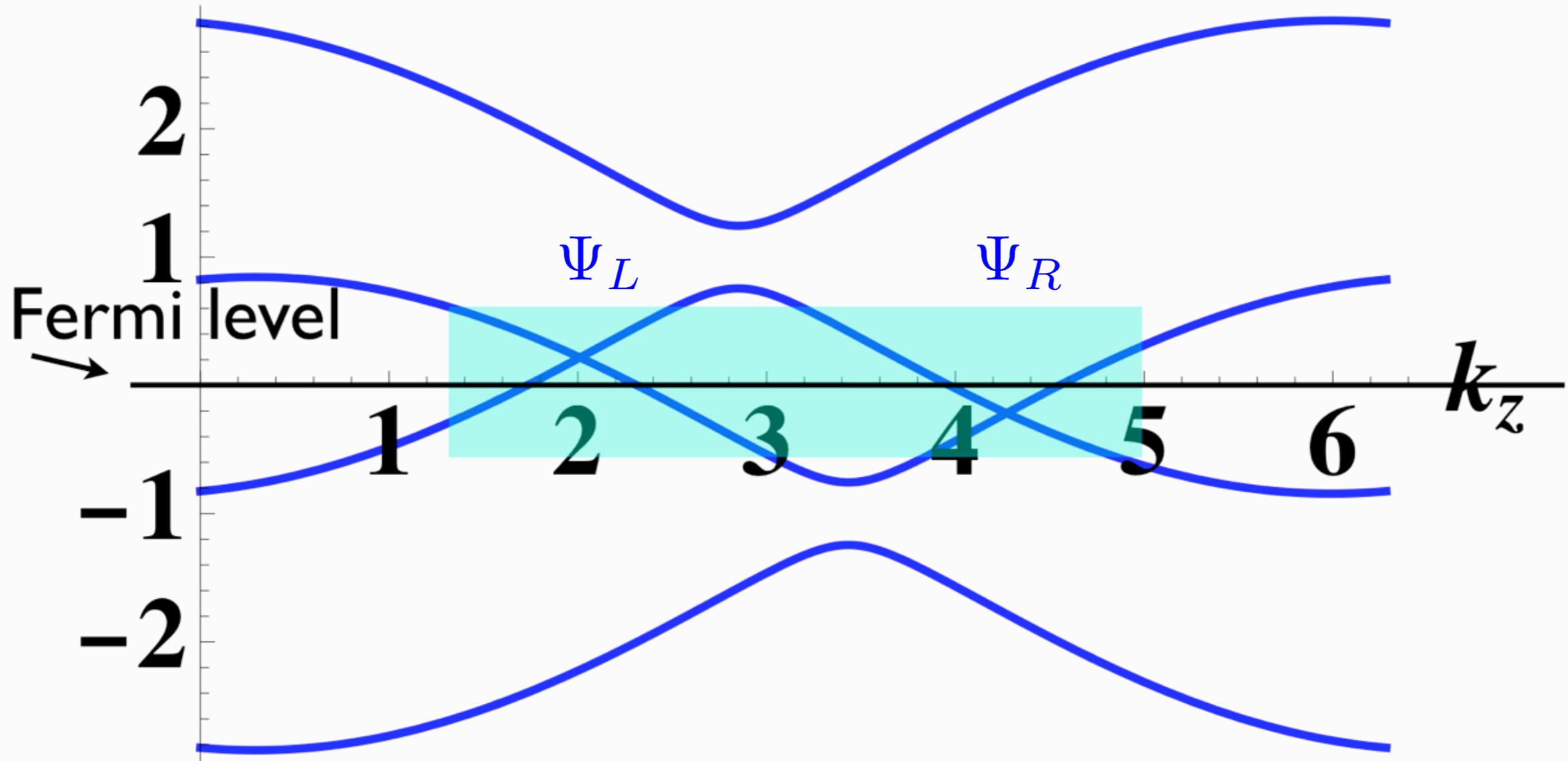


Hiroyuki Inoue, András Gyenis, Zhijun Wang, Jian Li, Seong Woo Oh, Shan Jiang, Ni Ni, B. Andrei Bernevig, and Ali Yazdani, was published in the March 11, 2016 issue of the journal *Science*

[Qiang Li](#) (Brookhaven Natl. Lab.), [Dmitri E. Kharzeev](#) (Brookhaven Natl. Lab. & SUNY, Stony Brook), [Cheng Zhang](#), [Yuan Huang](#) (Brookhaven Natl. Lab.), [I. Pletikosic](#) (Brookhaven Natl. Lab. & Princeton U.), [A.V. Fedorov](#) (LBNL, ALS), [R.D. Zhong](#), [J.A. Schneeloch](#), [G.D. Gu](#), [T. Valla](#)

# Applications: WSM

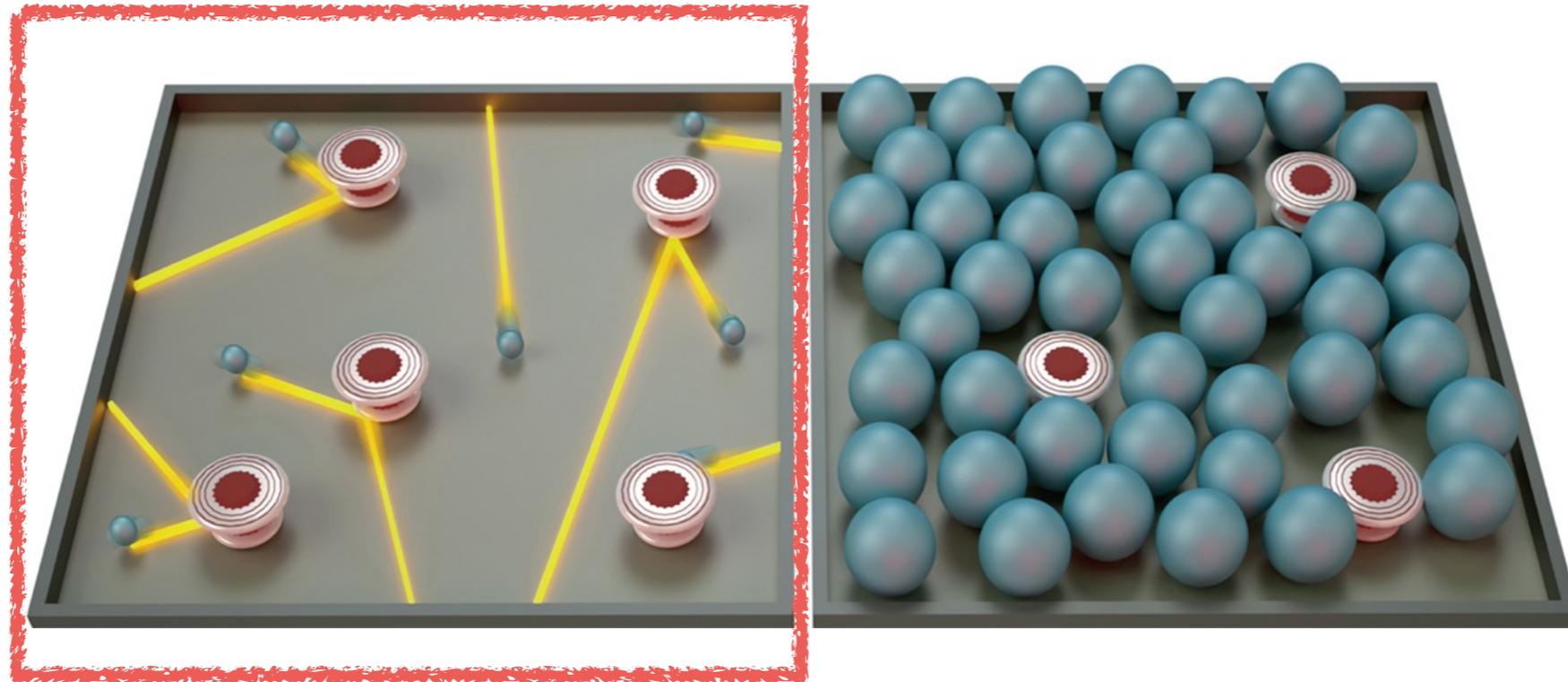
Band structure of WSM



$$\gamma^\mu (iD_\mu + \gamma_5 A_\mu^5) \Psi = 0$$



# NMR and NTMR in WSM



[J. Zaanen, “Electrons go with the flow in exotic materials”, Science Vol. 351, 6277]

If WSM is not strongly coupled,  
hierarchy of scattering times

$$\tau_{\text{inner}} < \tau_{\text{inter}} < \tau_{ee}$$



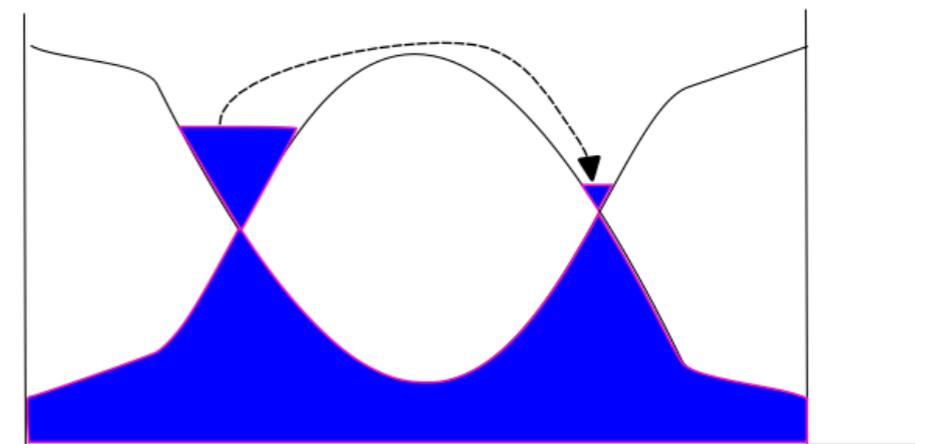
Kills  $\vec{P}$



Kills  $\rho_5, \epsilon_5$



Is irrelevant



# NMR and NTMR in WSM

NMR = **N**egative **M**agneto**R**esistivity

In equilibrium CME vanishes,

Induce non-equilibrium steady state

$$\dot{\rho}_5 = \frac{1}{2\pi^2} \vec{E} \cdot \vec{B} - \frac{1}{\tau_5} \rho_5$$

$$\rho_5 = \chi_5 \mu_5 \quad \vec{J} = \sigma \vec{E} + \frac{\mu_5}{2\pi^2} \vec{B}$$

$$J = \left( \sigma + \frac{\tau_5 B^2}{4\pi^4 \chi_5} \right) E$$

# NTMR via CME

Coupled charge and energy transport of chiral currents

$$\begin{aligned} \vec{J}_\epsilon &= \left( \frac{a_\chi}{2} \mu^2 + a_g T^2 \right) \vec{B} \\ \vec{J} &= a_\chi \mu \vec{B} \end{aligned} \quad \Longrightarrow \quad \vec{J} = G_E (\vec{E} - \vec{\nabla} \mu) + G_T \vec{\nabla} T$$

$$\begin{aligned} G_E &= \tau_5 \frac{a_\chi^2}{\det(\Xi)} \left( \frac{\partial \epsilon}{\partial T} - \mu \frac{\partial \rho}{\partial T} \right) B^2 \\ G_T &= \tau_5 \frac{2a_g a_\chi}{\det(\Xi)} \frac{\partial \rho}{\partial T} B^2 \end{aligned}$$

Large B (ultra-quantum limit):  $\rho = \frac{|B|}{4\pi^2} \mu$

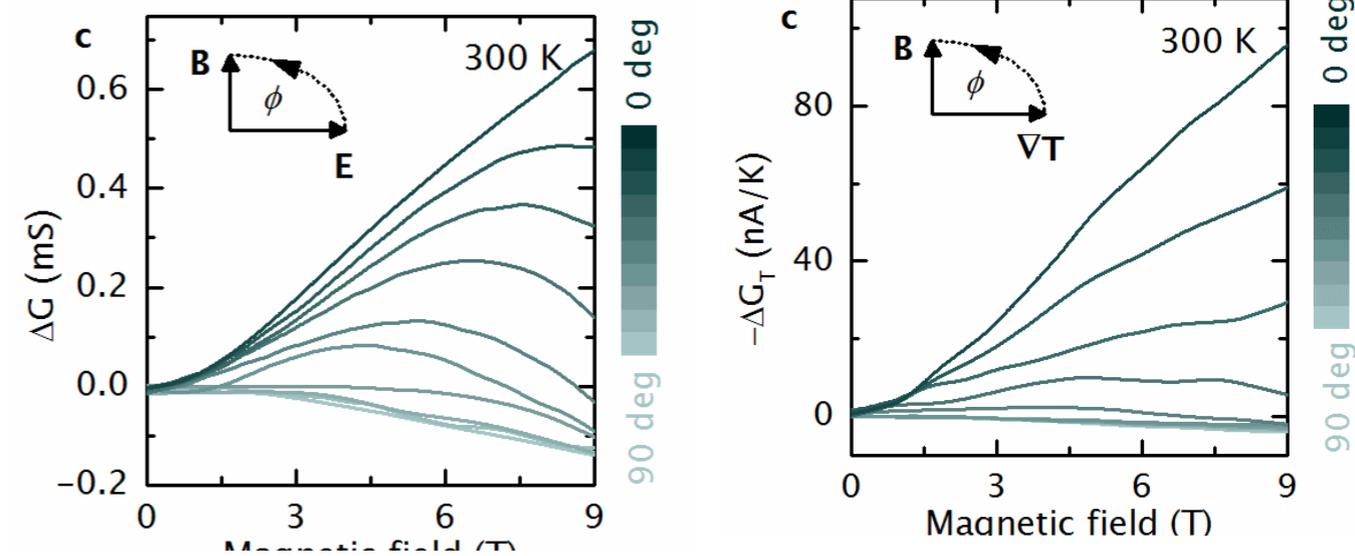
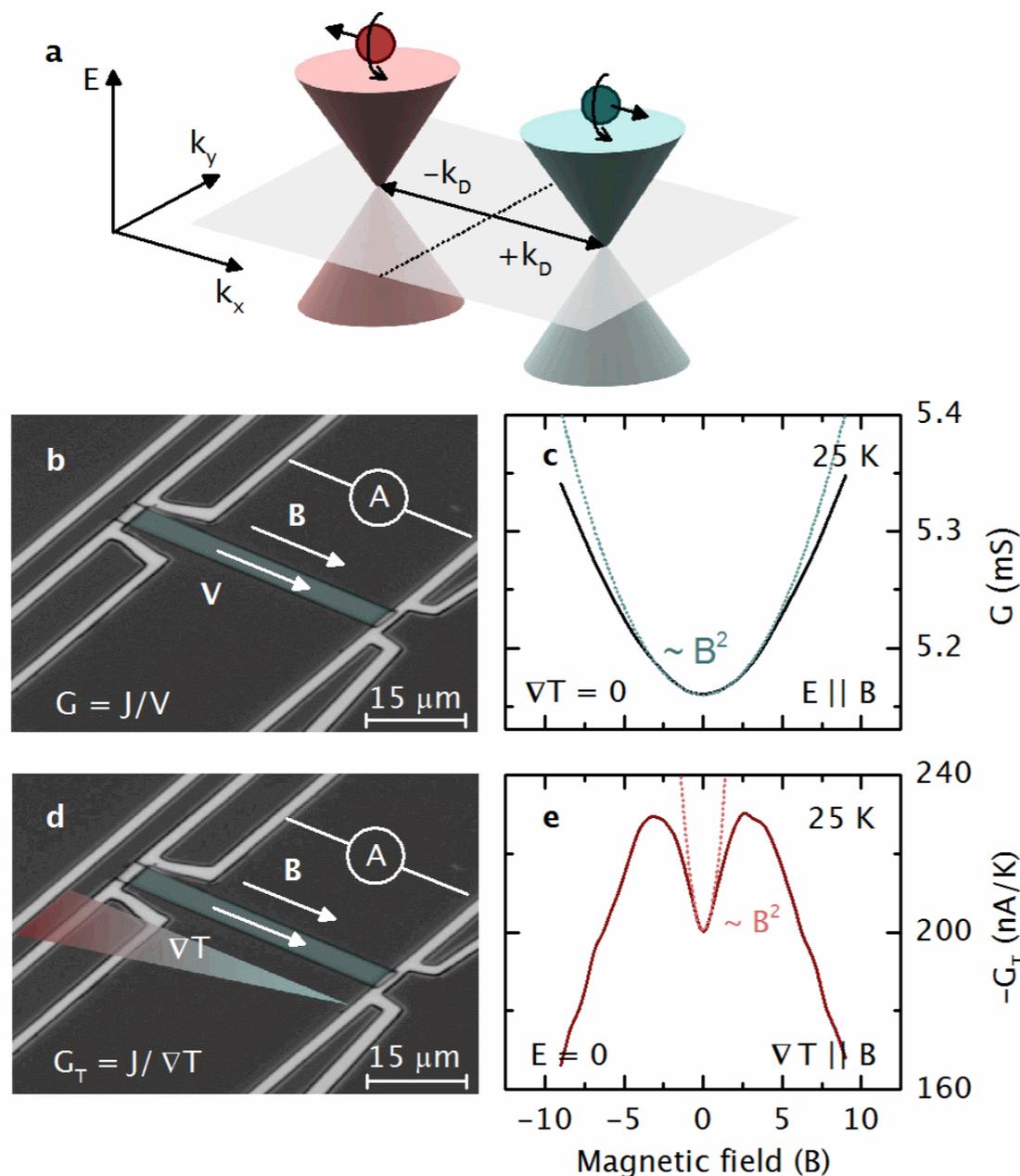
- $G_E$  linear in B
- $G_T$  vanishes

# NMR and NTMR in NbP

## Experimental signatures of the mixed axial-gravitational anomaly in the Weyl semimetal NbP

Johannes Gooth, Anna Corinna Niemann, Tobias Meng, Adolfo G. Grushin, Karl Landsteiner, Bernd Gotsmann, Fabian Menges, Marcus Schmidt, Chandra Shekhar, Vicky Sueß, Ruben Huehne, Bernd Rellinghaus, Claudia Felser, Binghai Yan, Kornelius Nielsch

[arXiv:1703.10682](https://arxiv.org/abs/1703.10682) (Nature)

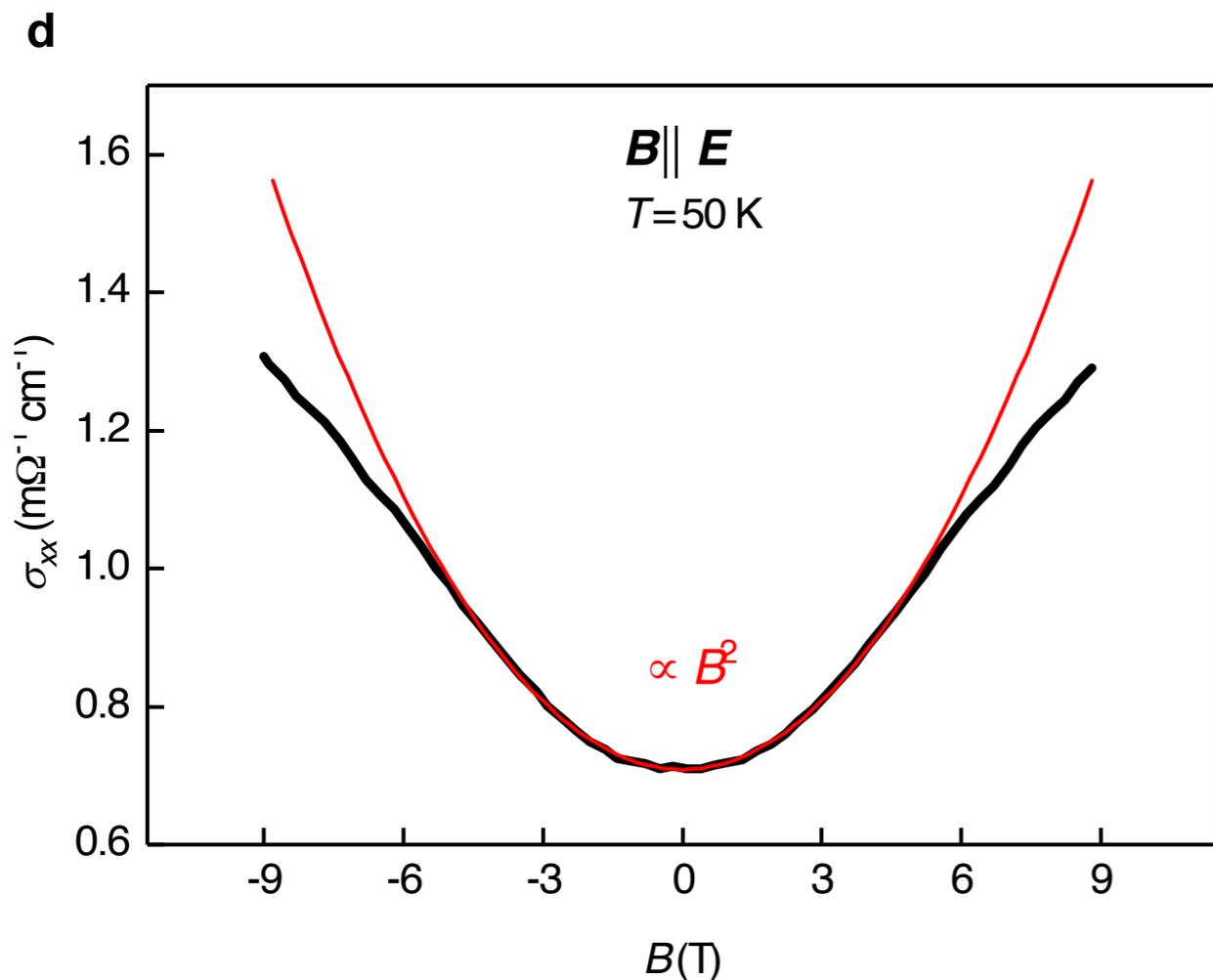


- Angle dependence
- NMR and NTMR show  $B^2$  at small  $B$
- NMR  $\sim$  linear for large  $B$  field
- NTMR vanishes for large  $B$  field

NbP very difficult material: Doping, T dependence

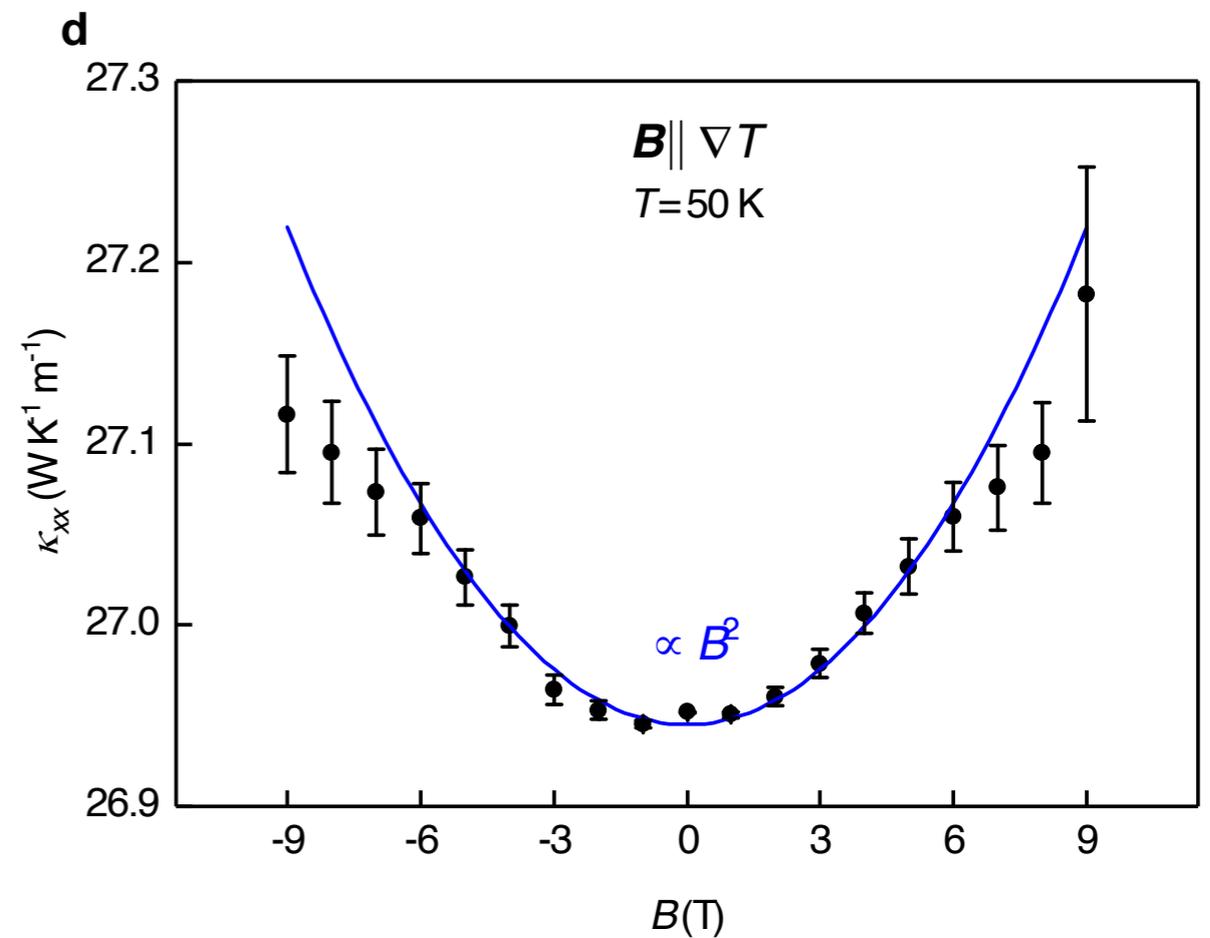
# Heat current in GdPtBi

Clemens Schindler,<sup>1</sup> Satya N. Guin,<sup>1</sup> Walter Schnelle,<sup>1</sup> Nitesh Kumar,<sup>1</sup> Chenguang Fu,<sup>1</sup> Horst Borrmann,<sup>1</sup> Chandra Shekhar,<sup>1</sup> Yang Zhang,<sup>1</sup> Yan Sun,<sup>1</sup> Claudia Felser,<sup>1</sup> Tobias Meng,<sup>2</sup> Adolfo G. Grushin,<sup>3</sup> and Johannes Gooth<sup>1,\*</sup>



Chiral Anomaly  
induced electric current

$$\Delta J_{\text{el}} \propto a_{\chi}^2 B^2$$



Grav. Anomaly  
induced heat current

$$\Delta J_{\text{heat}} \propto a_g^2 B^2$$

# Zilch

“optical helicity” of Maxwell theory

$$J^\mu = \epsilon^{\mu\nu\rho\lambda} \left( A_\nu F_{\rho\lambda} - C_\nu \tilde{F}_{\rho\lambda} \right)$$

Conserved charge

$$Q_h = \int d^3x J^0 = \int \frac{d^3k}{(2\pi)^3} \left( a_+^\dagger(\vec{k}) a_+(\vec{k}) - a_-^\dagger(\vec{k}) a_-(\vec{k}) \right)$$

circularly polarized photons

$$D_\mu J_h^\mu = \frac{1}{48\pi^2} \epsilon^{\mu\nu\rho\lambda} R^\alpha{}_{\beta\mu\nu} R^\beta{}_{\alpha\rho\lambda} \quad \text{Anomaly?}$$

[Dolgov, Kriplovich, Vainstein, Zhakharov], [Agullo, del Rio, Navarro-Salas]

**BUT: No physical local current or charge density !**

# Zilch

Zilch - density, current and charge:

$$\left. \begin{aligned} Z &= \vec{B} \cdot (\vec{\nabla} \times \vec{B}) + \vec{E} \cdot (\vec{\nabla} \times \vec{E}) \\ J_Z &= \vec{E} \times (\vec{\nabla} \times \vec{B}) - \vec{B} \times (\vec{\nabla} \times \vec{E}) \end{aligned} \right\} \dot{Z} + \vec{\nabla} \cdot \vec{J}_Z = 0$$

[Lipkin] 1966

$$Q_Z = \int \frac{d^3k}{(2\pi)^3} \omega^2 (a_+^\dagger a_+ - a_-^\dagger a_-)$$

Infinite tower of higher spin currents

$$Z_{\mu_1 \dots \mu_n} = F^\alpha_{(\mu_1} \overleftrightarrow{\partial}_{\mu_2} \dots \overleftrightarrow{\partial}_{\mu_{n-1}} \tilde{F}_{\mu_n)\alpha}$$

[Kibble] 1967

Dictionary: “Zilch”: **Nothing, Zero**

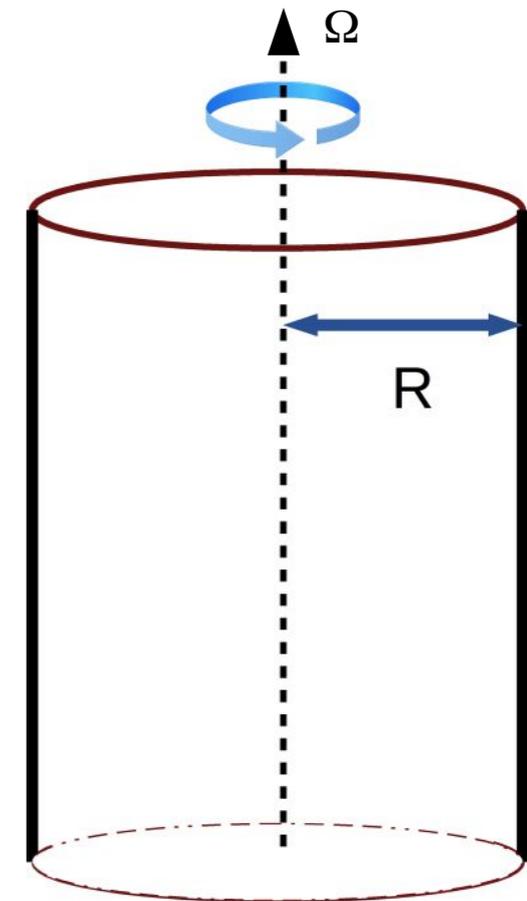
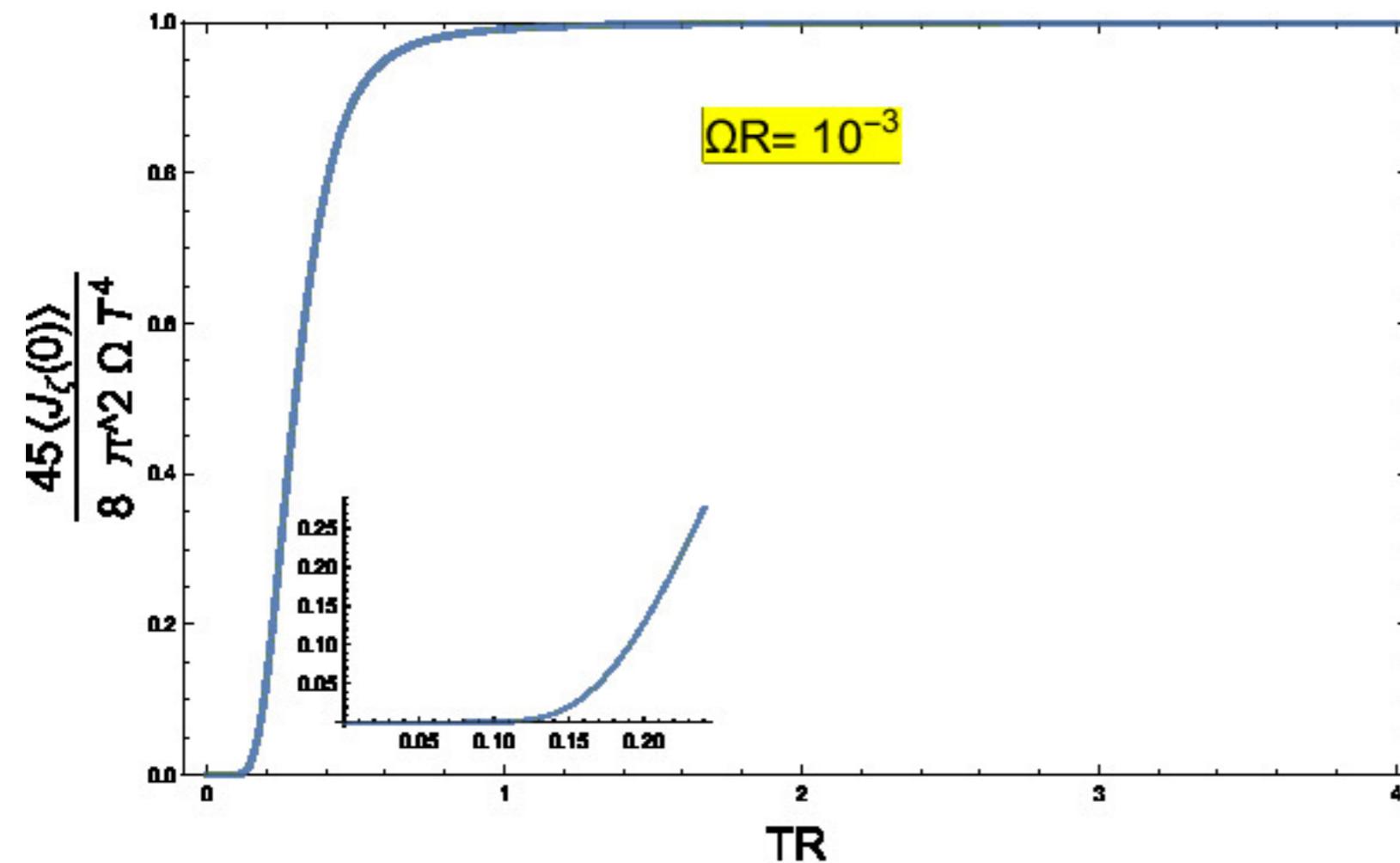
Zilch measures differences in excitation of chiral molecules in polarised light

[Tang, Cohen] 2010 !!

“optical chirality” ( enantioselectivity )

# Zilch vortical effect

$$\vec{J}_Z = \frac{8\pi^2 T^4}{45} \vec{\omega}$$



- Universal result at axis of rotation
- Vanishing Poynting vector !

[Chernodub, Cortijo, K.L.]  
[Fernandez-Pendas, Copetti]  
[Avkhadiev, Sadofyev]  
[N. Yamamoto]

# Summary

- Anomalies: rich anomaly induced transport phenomenology (CME, CVE, CSE, AME, AHE, NMR, NTMR)
- WSMs allow experimental observation of anomalous transport effects
- Maxwell theory shows similar behaviour, chiral current due to rotation - Anomaly?
- Applications might lead to a **new, anomalous golden age of chirality**: *electronics, chiral magnetic photocells, electromagnetic enantioselectivity, quark gluon plasma, early universe, ...*

**Thank You!**