The Golden Age of Chirality And Quantum Mechanics

Karl Landsteiner
Instituto de Física Teórica UAM-CSIC

Instituto de Física Teórica UAM-CSIC

EXCELENCIA SEVERO OCHOA

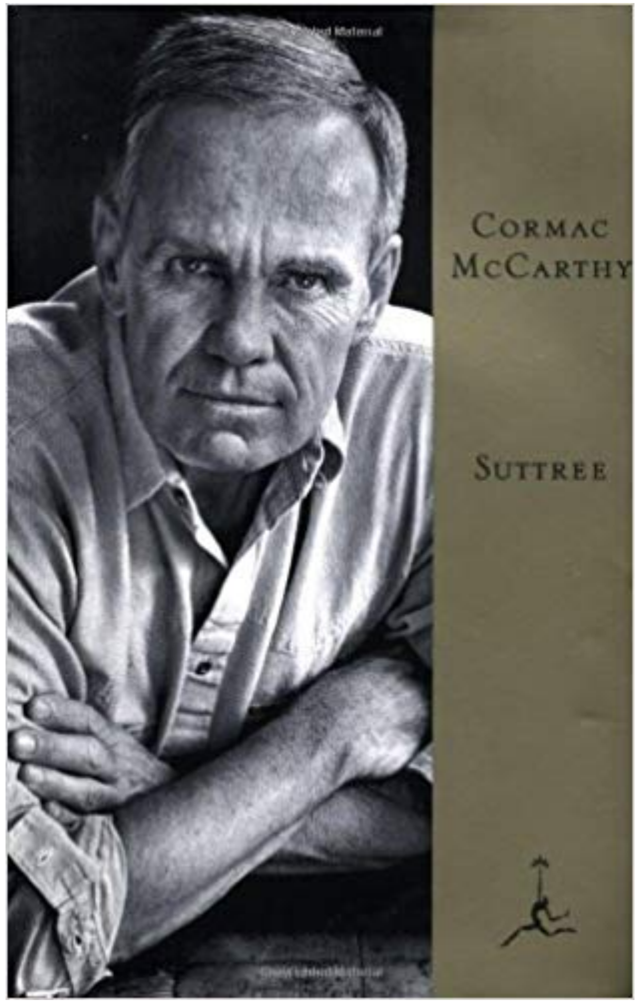
Campus Internacional excelencia UAM CSIC+

Southampton, 21.02.2019

Outline

- Explain Title
- Anomalies
- Anomaly induced Currents (CME & CVE)
- Applications: Black Holes, QGP, WSMs
- Summary and Outlook

Last year: chiral fluid workshop in Santa Fe, NM:



"On the right temple a mauve halfmoon. 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

Levomethamphetamin

Dextromethamphetamin
"crystal meth"

Nobel Prize in Chemistry 2016: Bernard L. Feringa

"for the design and synthesis of (chiral) molecular machines." [Nobel committee]

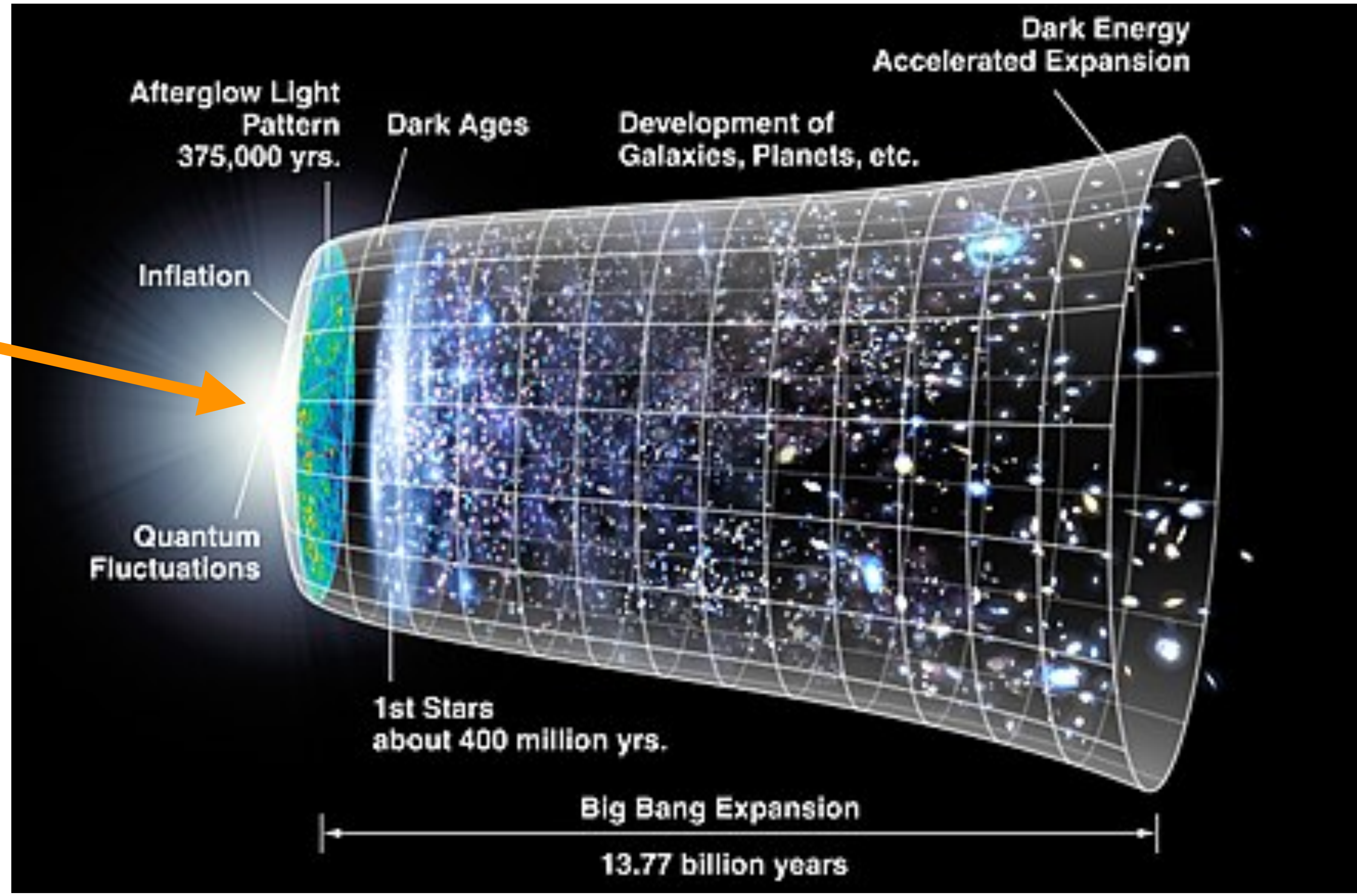
…"chiral electromagnetic radiation to generate enantioselectivity"… [from Wikipedia]

"Zilch"

Physics:

Golden age
of chirality starts
somewhere here

GUTs,
Standard Model:
Chiral gauge theories



This talk: chiral *states* (not theories),
anomalies and *applications*

Anomalies

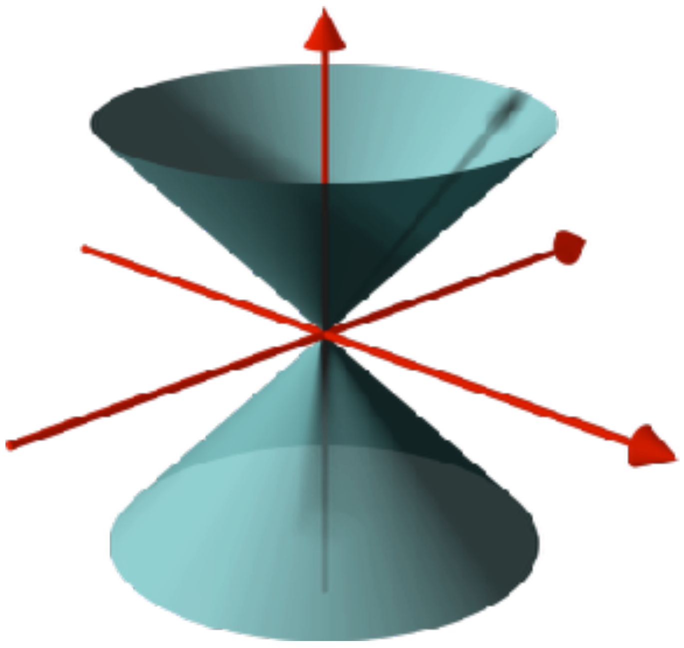
-- Do you ever run across a fellow that even you can't understand?"

"Yes," says he.

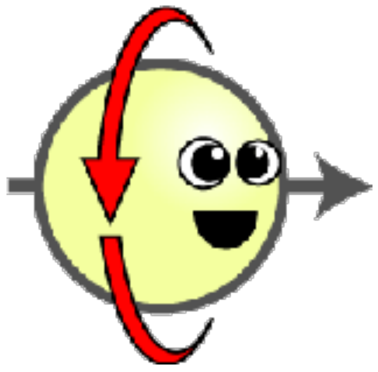
"This well make a great reading for the boys down at the office," says I. "Do you mind releasing to me who he is?"

"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

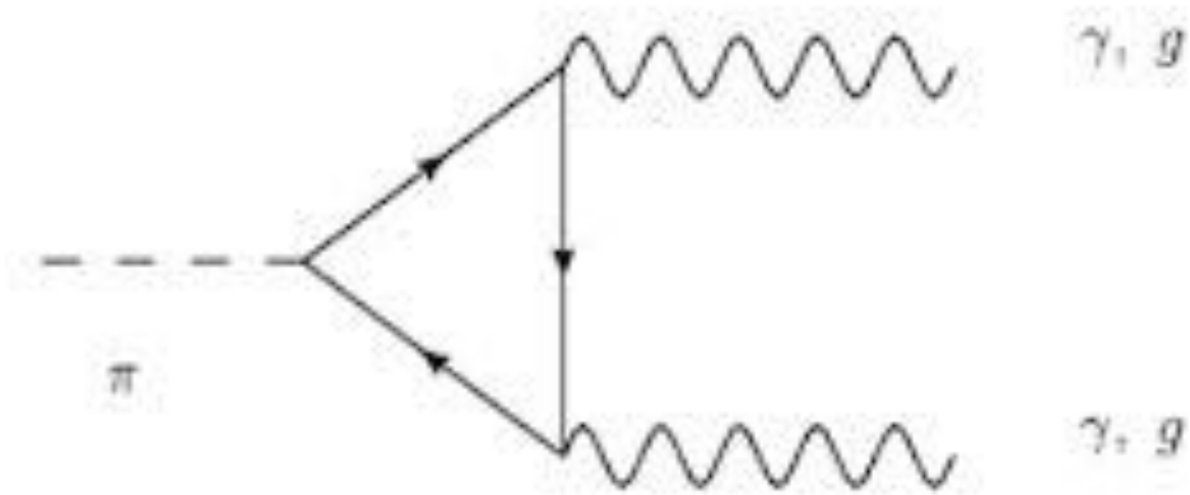
- Symmetry (Noether)
- Quantum Mechanics

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

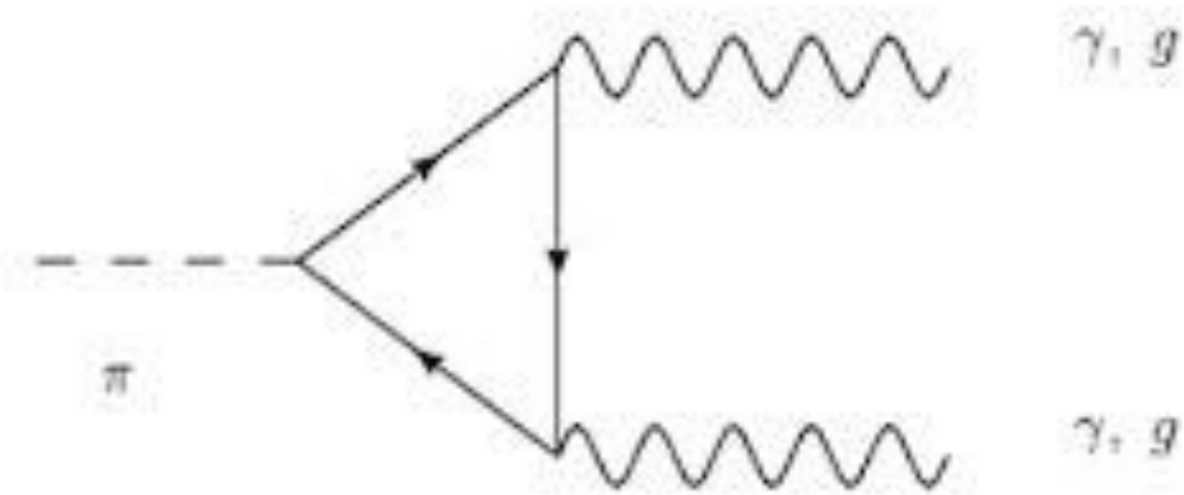
$$\partial_\mu J_5^\mu = -\frac{\alpha}{8\pi}\epsilon^{\mu\nu\rho\lambda}F_{\mu\nu}F_{\rho\lambda}$$

Quantum corrections destroy symmetry

[Adler], [Bell,Jackiw] 1969

Anomalies

Decay of neutral pion into gravitons

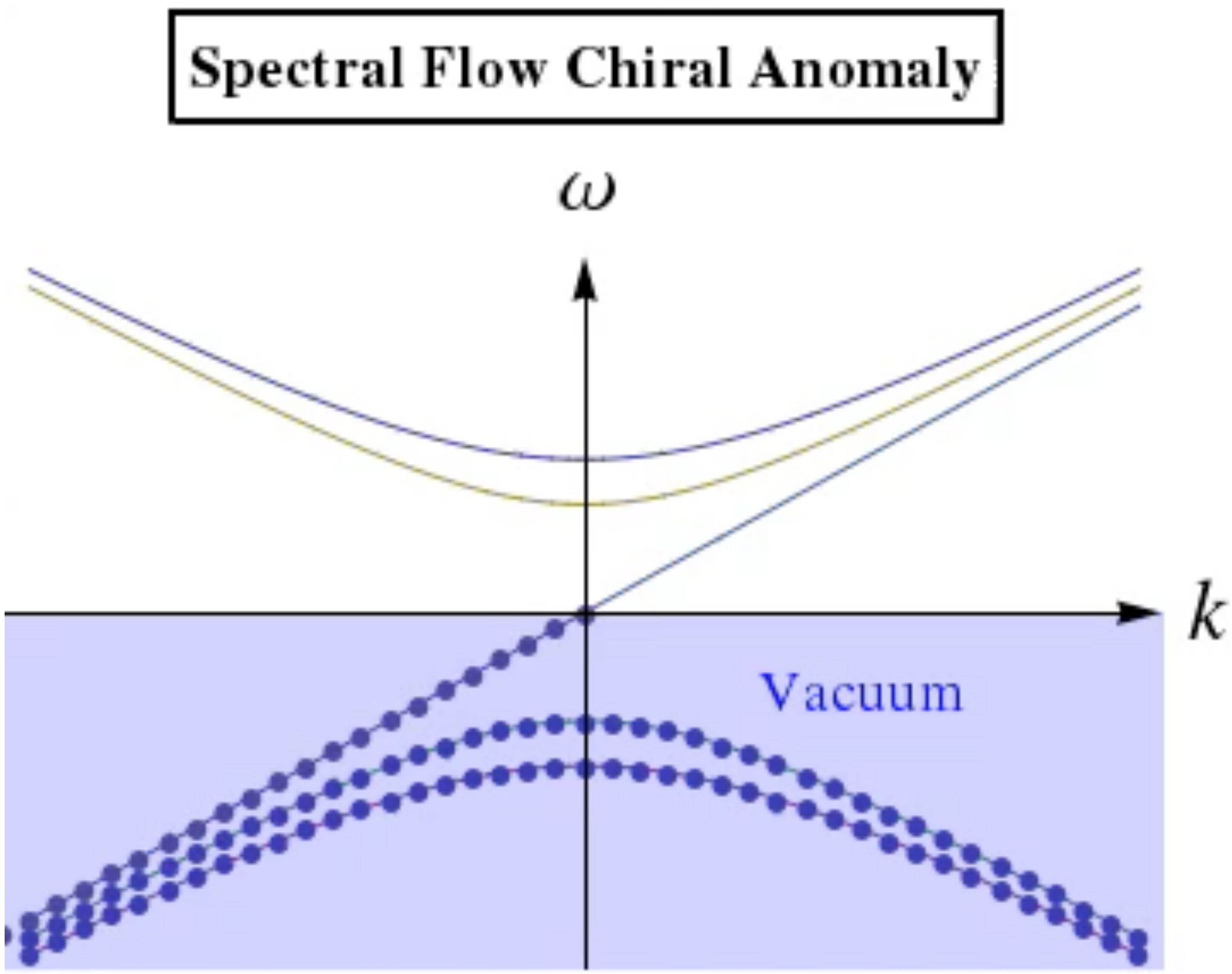


$$\partial_\mu J_5^\mu = \frac{1}{384\pi^2}\epsilon^{\mu\nu\rho\lambda}R^a{}_{b\mu\nu}R^b{}_{a\rho\lambda}$$

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

[Kimura] 1969, [Delbourgo, Salam] 1972, [Eguchi,Freund] 1976

Anomalies:



In magnetic field: Landau Levels

In additional electric field fermions feel Lorentz force

$$\frac{d}{dt}p_z = eE_z$$

The density of states changes as

$$dn = \frac{dp}{2\pi}\frac{eB}{2\pi}$$

[Nielsen, Ninomiya], [Gribov]

Anomaly →

$$\frac{dn}{dt} = \frac{e^2 \vec{B}\vec{E}}{4\pi^2}$$

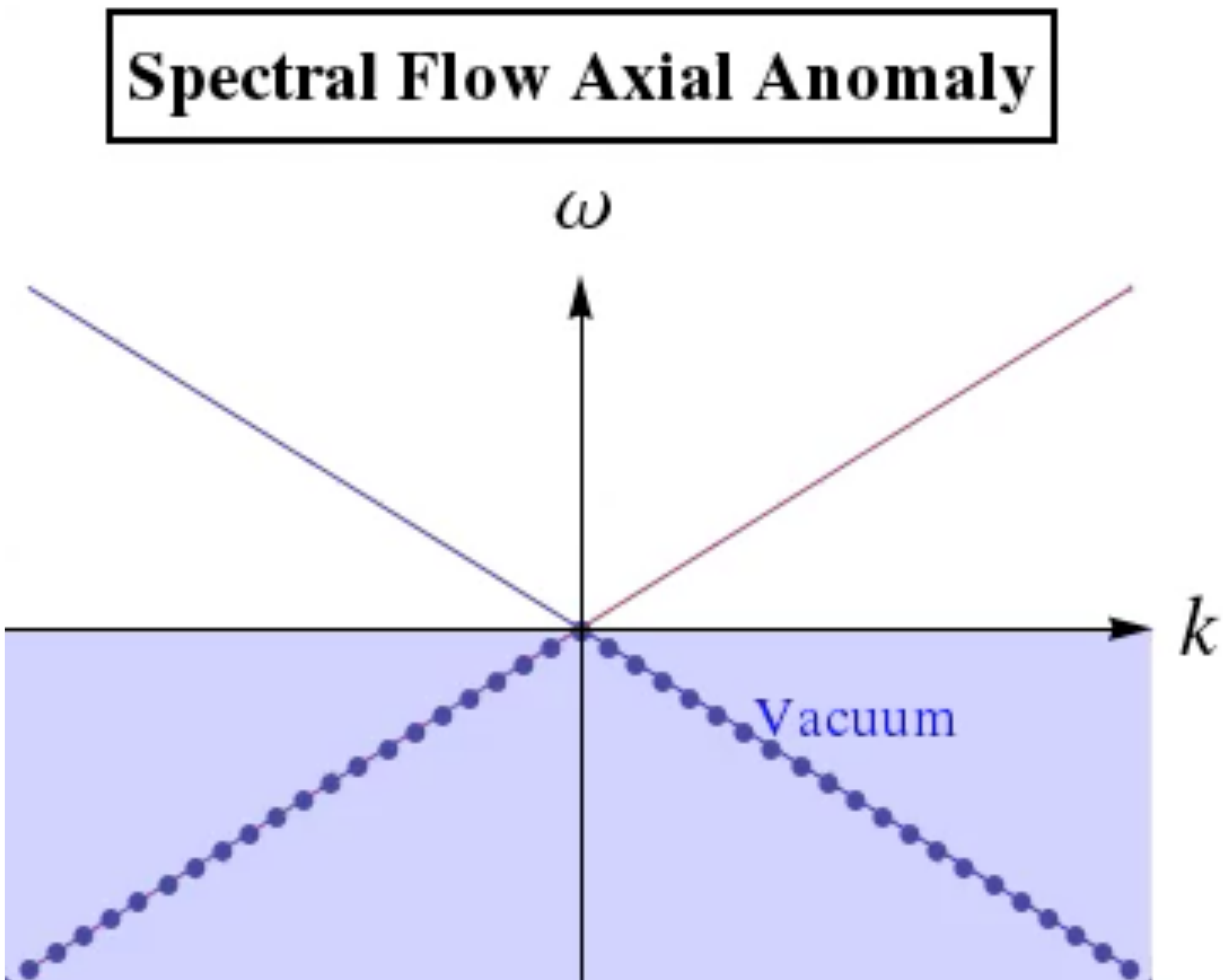
Anomalies:

$$n = n_R + n_L$$

$$n_5 = n_R - n_L$$

$$\frac{d(n_L + n_R)}{dt} = 0$$

$$\frac{d(n_L - n_R)}{dt} = \frac{1}{2\pi^2}(\vec{E}\vec{B})$$



Anomalies

$$D_\mu J^\mu_a = \epsilon^{\mu\nu\rho\lambda}\left(\frac{d_{abc}}{96\pi^2}F^b_{\mu\nu}F^c_{\rho\lambda} + \frac{b_a}{768\pi^2}R^\alpha{}_{\beta\mu\nu}R^\beta{}_{\alpha\rho\lambda}\right)$$

$$d_{abc} = \sum_r q^r_a q^r_b q^r_c - \sum_l q^l_a q^l_b q^l_c$$

$$b_a = \sum_r q^r_a - \sum_l q^l_a$$

- Exact properties of the theory (non-renomalization)

Anomalous Transport

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

Non-local → $\delta_\lambda \Gamma$ local → $\mathcal{A}_\lambda$

But anomaly can be written as local in 5 dimensions:

(applications: anomaly inflow, Hall effect, topological insulators)

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

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

Anomalous Transport

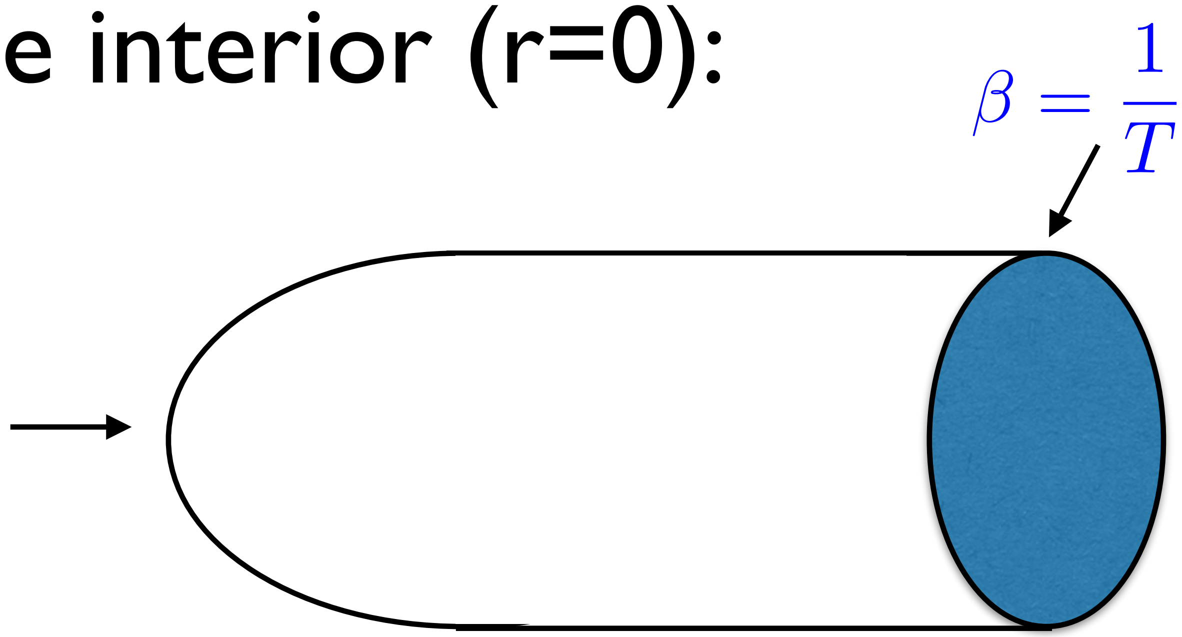
Thermal equilibrium = constraint on topology

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

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

Smooth geometry in the interior (r=0):

$$f(0) = 0$$
$$f'(0) = 2\pi T$$



Anomalous Transport

Thermal equilibrium = 5D black hole !

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

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

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

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

Non-locality + Topology!

(not captured in conventional effective action approaches)

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

$$F = Bdx \wedge dy + F_{0r}dtdr$$

[Bardeen, Zumino] '84

$$A_r = 0$$

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

More generally: $\mu = \int_0^1 dr F_{tr}$

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

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

← In general not unique !

Anomalous Transport

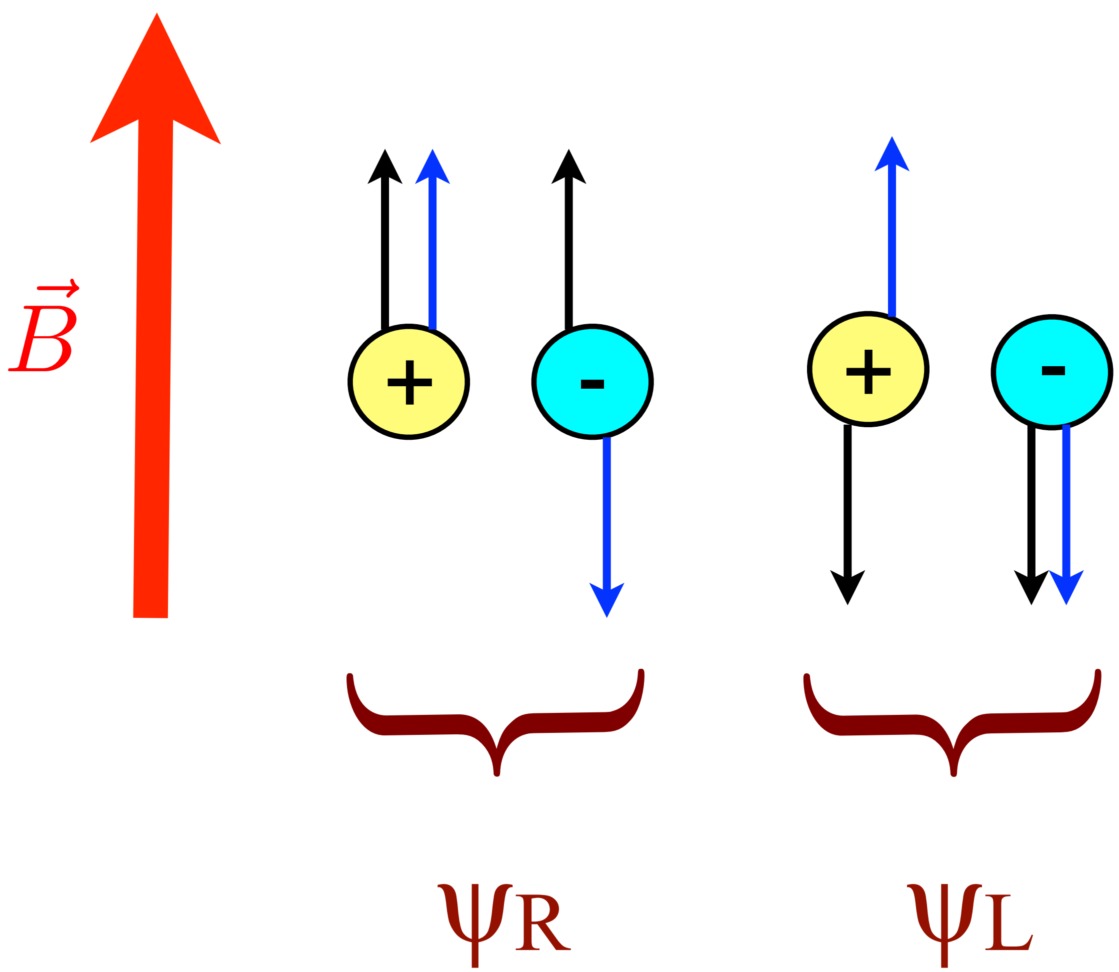
- Chiral Magnetic and Vortical effects

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

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

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

Chiral Magnetic Effect :



$$\vec{J}_{\rm cov} = \frac{\mu_5}{2\pi^2}\vec{B}$$

$$\mu_5 = \frac{1}{2}(\mu_R - \mu_L)$$

Axial chemical potential: counts occupied states above vacuum!

[Vilenkin], [Shaposhnikov, Giovannini], [Alekseev, Chaianov, Fröhlich] [Newman] [Kharzeev, Fukushima, Warringa],[Son,Surowka]

Anomalous Transport

- 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

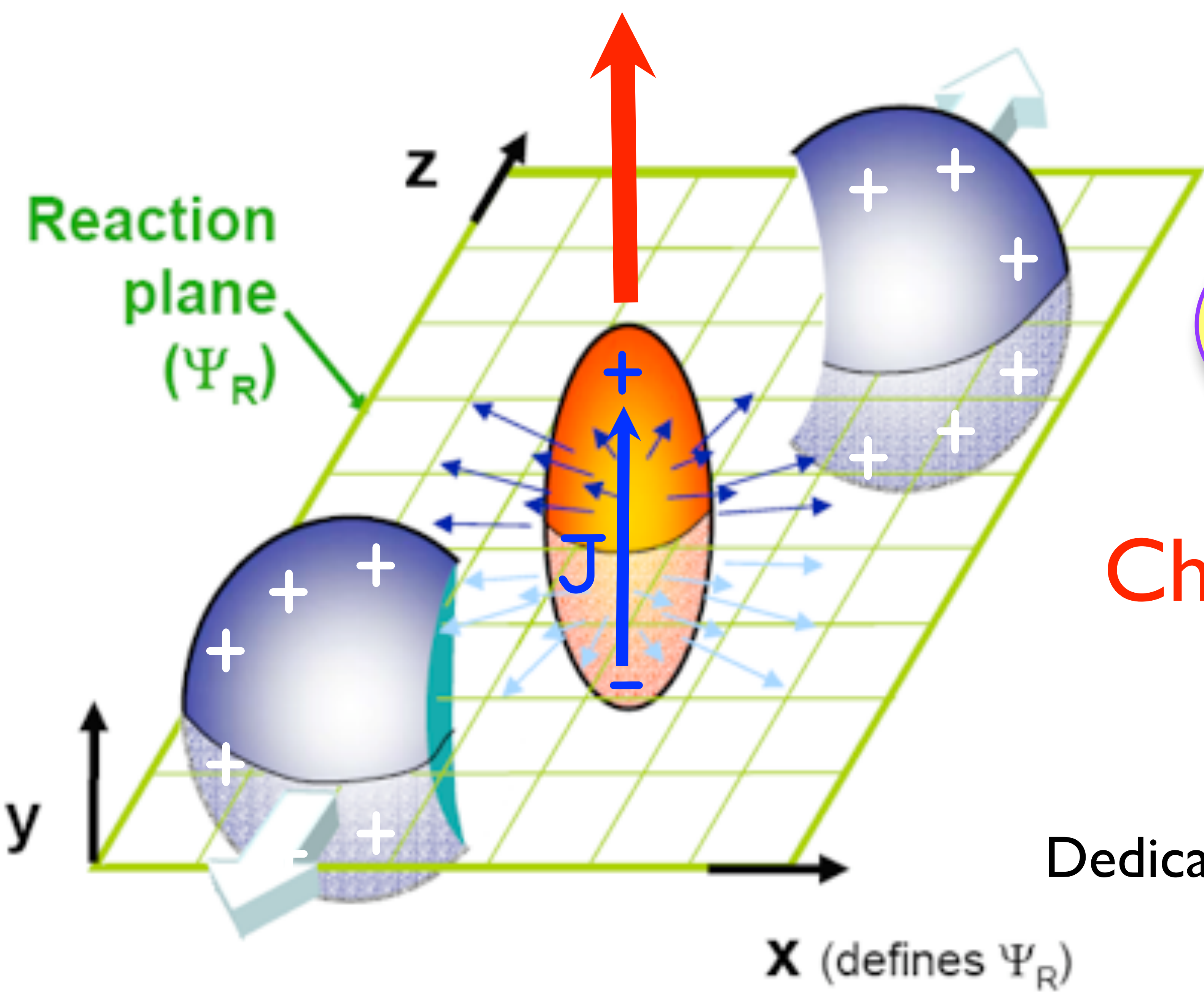
[Vilenkin, 80's], [Alekseev, Cheianov, Froehlich] [Shaposhnikov, Giovannini]
[Fukushima, Kharzeev, Warringa], [Son, Surowka], [Erdmenger, Haack, Kaminski, Yarom],
[Banerjee, Bhattacharya, Bhattacharyya, Dutta, Loganayagam, Surowka] [Rebhan ,Schmitt, Stricker]
[Hoyos, Fukyoka, O'Bannon] [Gynther, K.L.,Pena-Benitez, Rebhan], [Amado, K.L., Pena-Beniteez]
[Megias, K.L., Pena-Benitez], [Megias, K.L., Pena-Benitez, Melgar] [Jensen, Loganayagam, Yarom] [Stone, Kim]

Applications:QGP

strongest Magnetic field in the Universe 10^{15}T!!!

(QHE: 10 T)

(T ~ 10^{12} K)



$$\vec{J} = \frac{\mu_5}{2\pi^2}\vec{B}$$

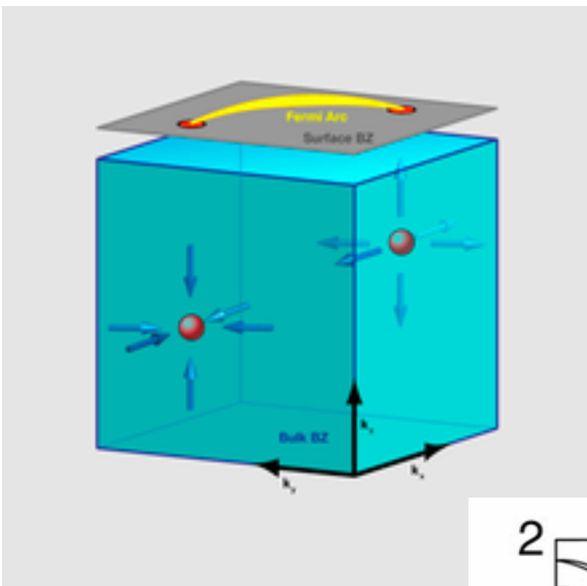
Chiral Magnetic Effect

,[Kharzeev, McLarren, Warringa]
[Fukushima, Kharzeev,, Warringa]

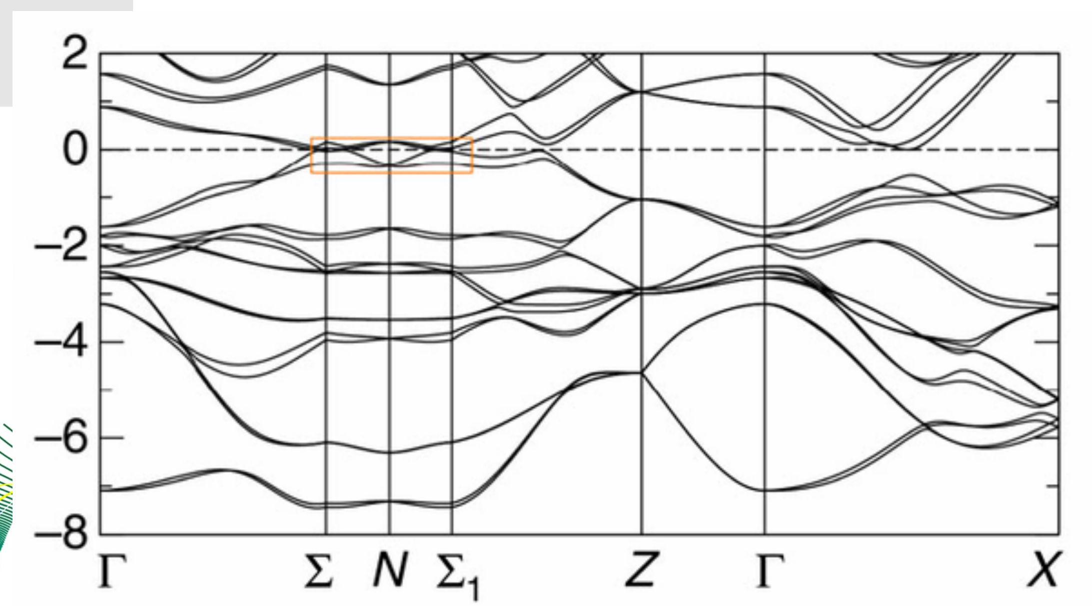
Dedicated Isobar run at RHIC 2018
$^{96}Zr^{44}$ vs. $^{96}Ru^{40}$

Applications: WeylSemiMetals

physicsworld
TOP 10 BREAKTHROUGH 2015

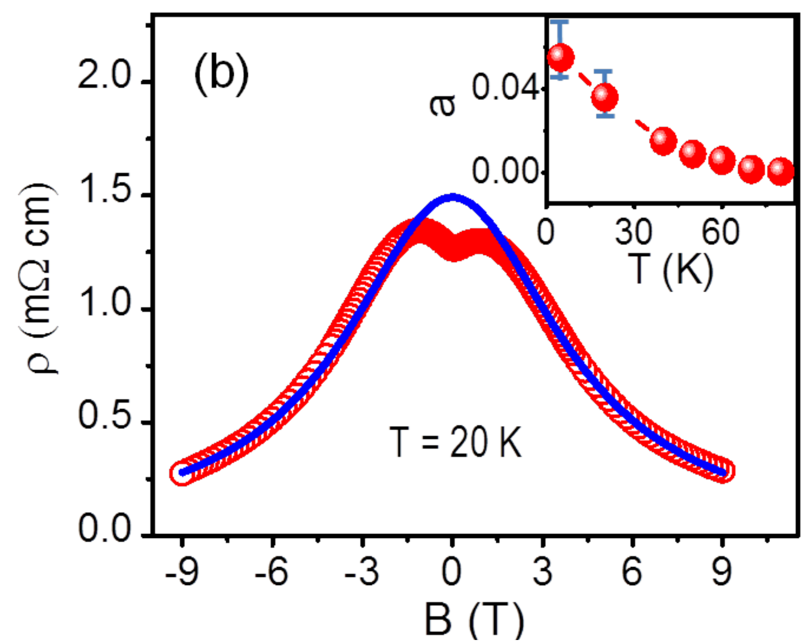


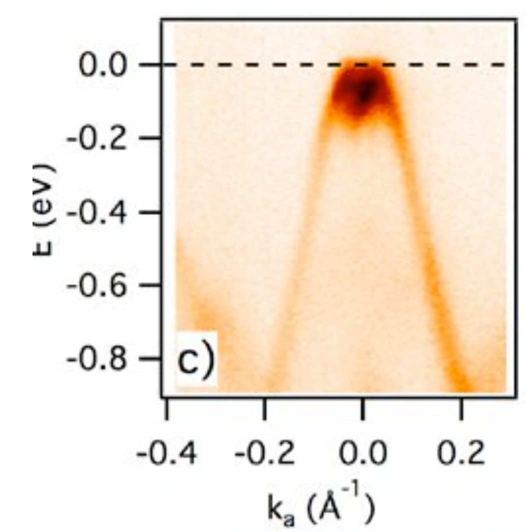
Wikipedia



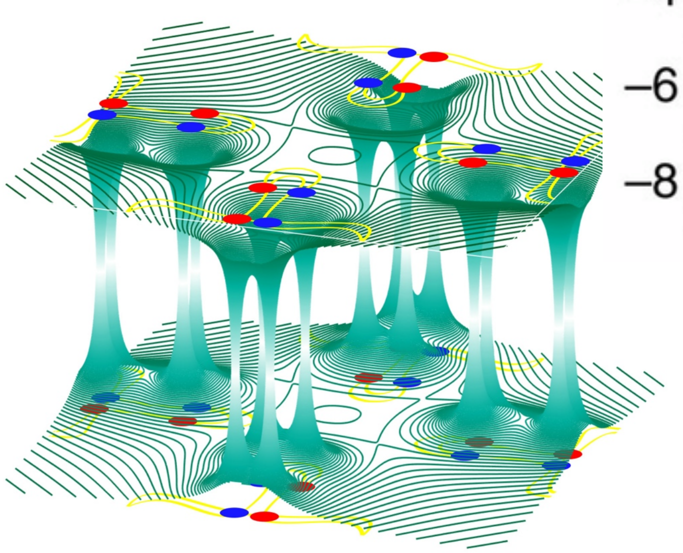
TaAs

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





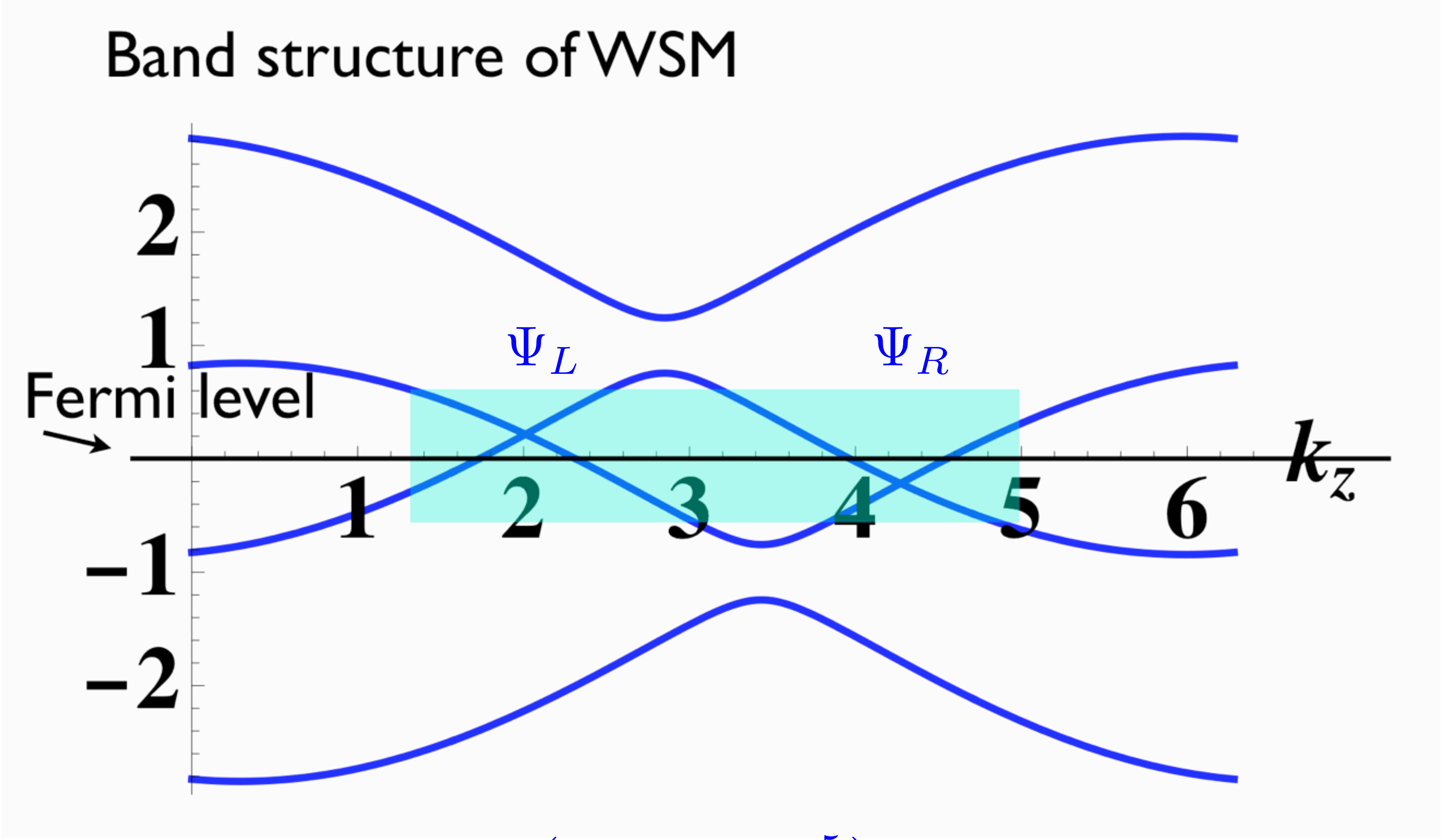
Zr_5Te



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*

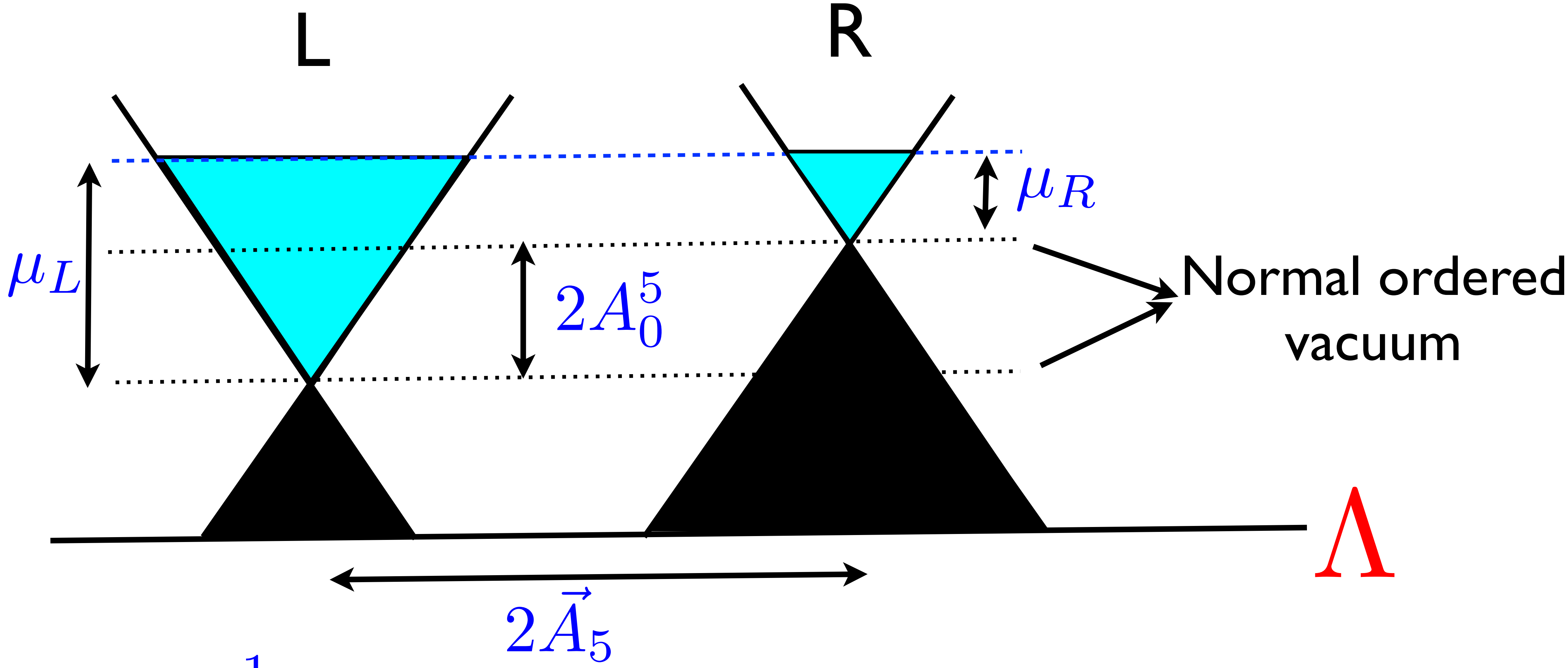
Qiang Li (Brookhaven Natl. Lab.), Dmitri E. Kharzeev (Brookhaven Natl. Lab. & SUNY, Stony Brook), Cheng Zhang, Yuan Huang (Brookhaven Natl. Lab.), I. Pletikosic (Brookhaven Natl. Lab. & Princeton U.), A.V. Fedorov (LBNL, ALS), R.D. Zhong, J.A. Schneeloch, G.D. Gu, T. Valla

Applications: WSM



$$\gamma^\mu \left(iD_\mu + \gamma_5 A^5_\mu \right) \Psi = 0$$

CME in WSMs



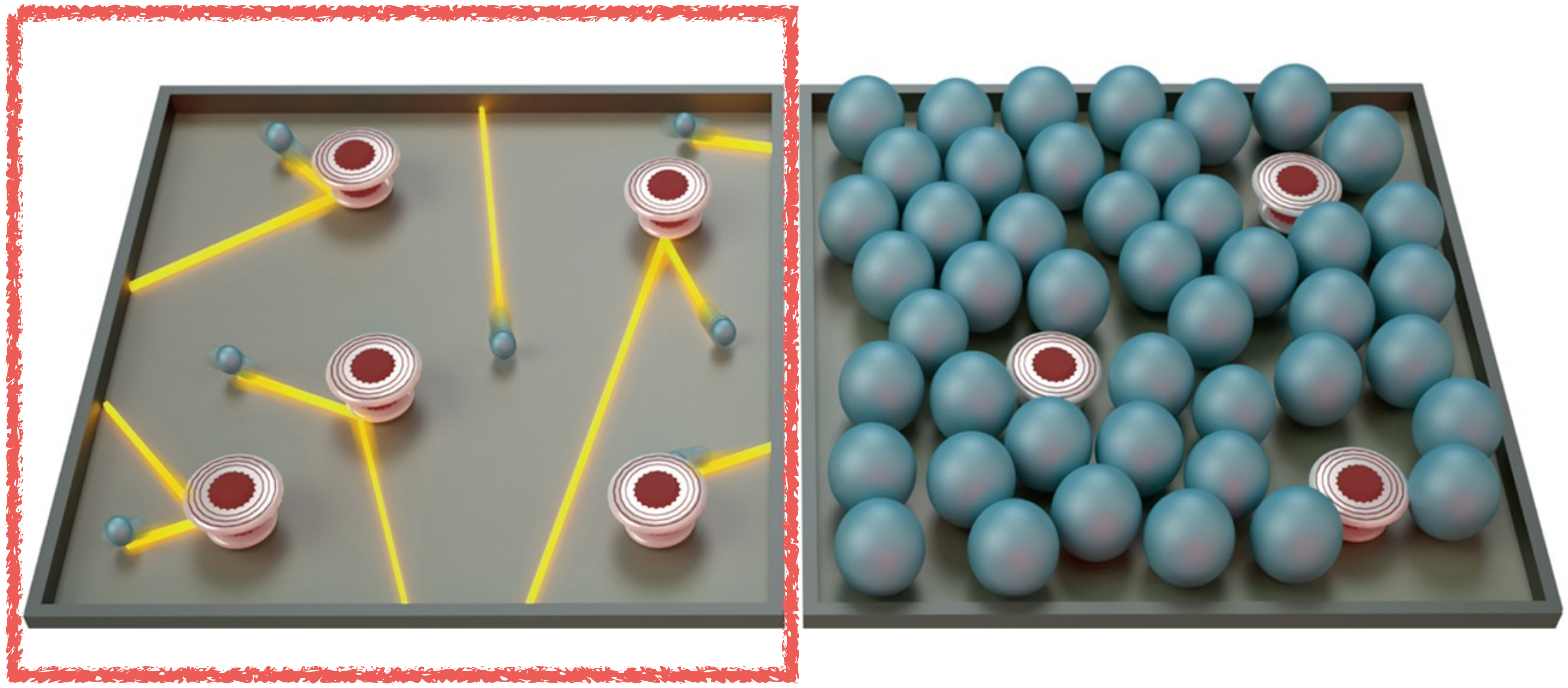
$$\mu_5 = \frac{1}{2}(\mu_L - \mu_R) \qquad \mu = \frac{1}{2}(\mu_R + \mu_L)$$

CME: $\vec{J} = \frac{1}{2\pi^2}\left(\mu_5 - A_0^5\right)\vec{B} = 0$

No electric current in equilibrium (Bloch '30s)

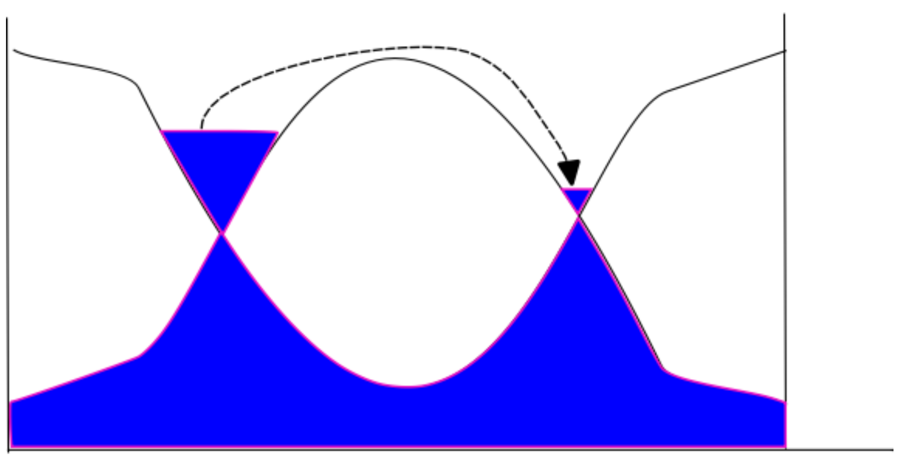
[Rebhan ,Schmitt, Stricker]
[Gynther, K.L., Pena-Benitez, Rebhan]

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 ρ_5, ϵ_5 — Is irrelevant

NMR and NTMR in WSM

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

In equilibrium CME vanishes,
Induce non-equilibrium steady state

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

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

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

[Nielsen, Ninomiya], [Kharzeev],[Spivak, Son]

NTMR via CME

Coupled charge and energy transport of chiral currents

$$\vec{J}_\epsilon = \left(\frac{a_\chi}{2}\mu^2 + a_g T^2\right)\vec{B}$$

$$\vec{J} = a_\chi \mu \vec{B}$$

$\Rightarrow$

$$\vec{J} = G_E(\vec{E} - \vec{\nabla}\mu) + G_T \vec{\nabla} T$$

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

$$G_T = \tau_5 \frac{2 a_g a_\chi}{\det(\Xi)} \frac{\partial \rho}{\partial T} B^2$$

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

- G_E linear in B
- G_T vanishes

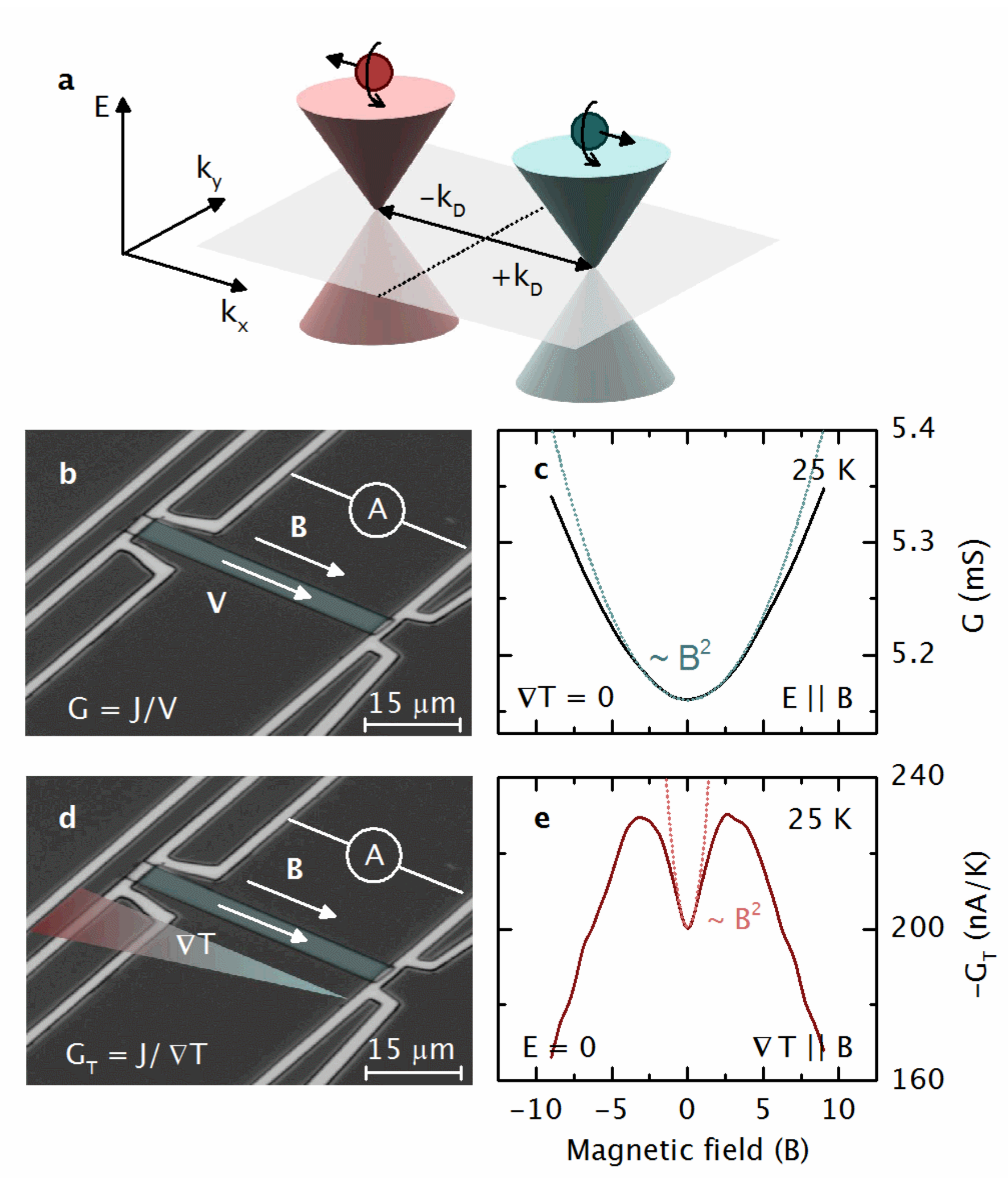
[Spivak, Andreev], [Lundgren, Laurell, Fiete] *kinetic theory*
[Lucas, Davison, Sachdev] *chiral fluids,* [K.L.]

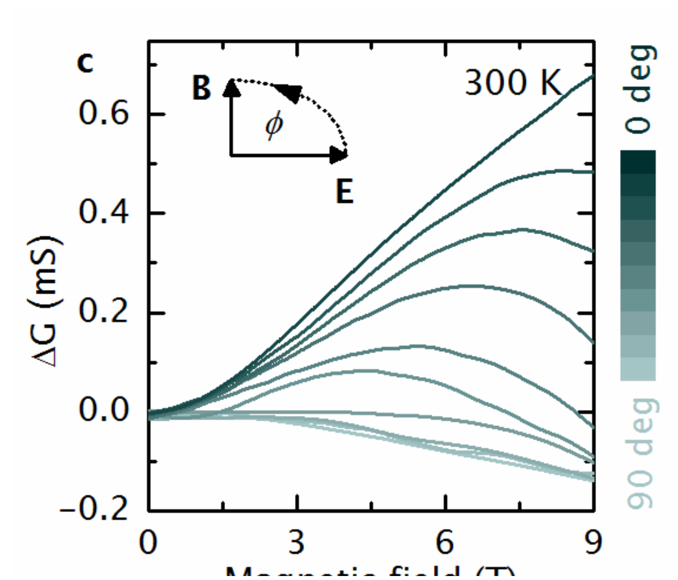
NMR and NTMR in NbP

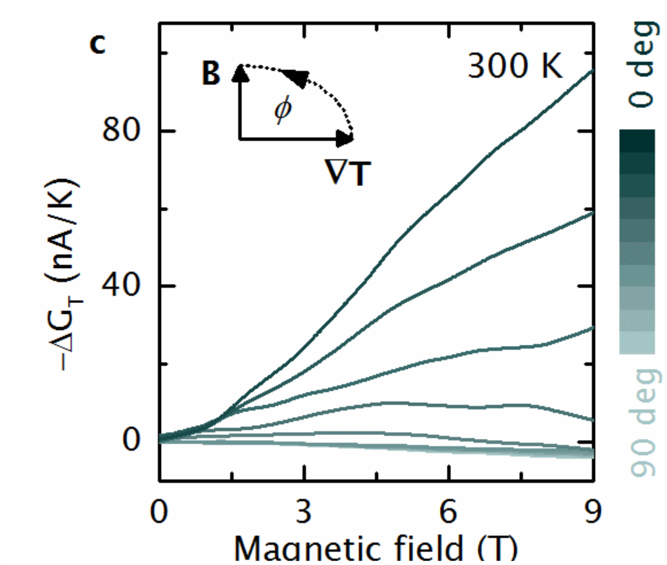
Experimental signatures of the mixed axial-gravitational anomaly in the Weyl semimetal NbP

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 (Nature)







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

NbP very difficult material: Doping, T dependence

Application: Optics

"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

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

Anomaly?

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

BUT: No physical local current or charge density !

Zilch

Zilch - density, current and charge:

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

[Lipkin] 1966

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

Infinite tower of higher spin currents

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

[Kibble] 1967

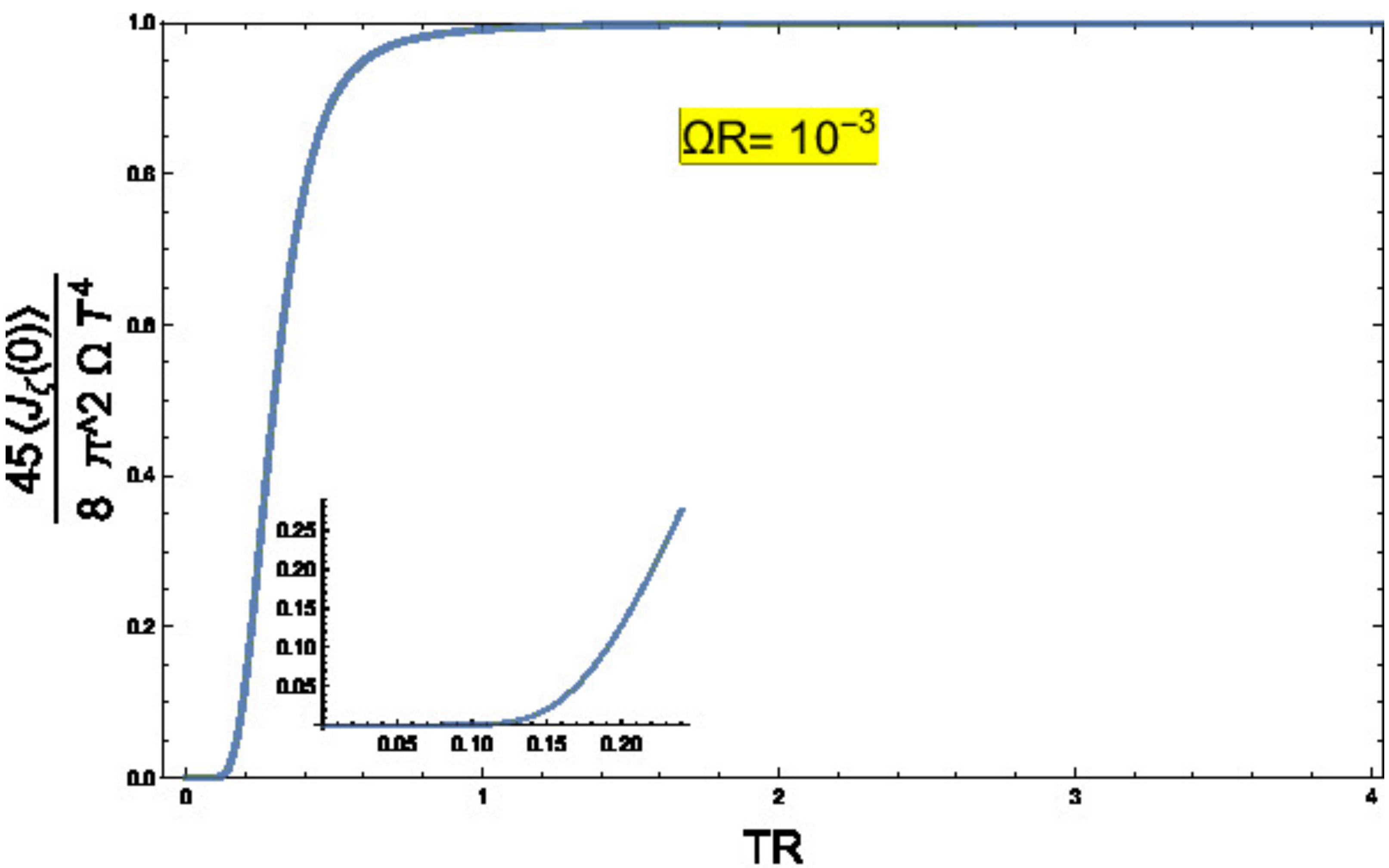
Dictionary: “Zilch”: Nothing, Zero

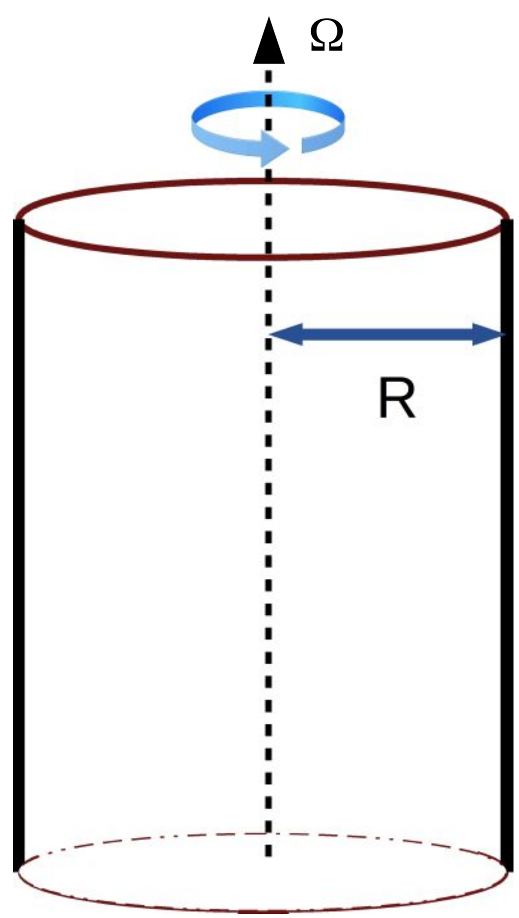
Zilch measures differences in excitation of chiral molecules in polarised light “optical chirality” (enantioselectivity)

[Tang, Cohen] 2010 !!

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
- 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:
    - *Chiral electronics*
    - *Chiral magnetic photocells*
    - *Electromagnetic enantioselectivity*
    - *Chiral qbits*
    - *Quark gluon plasma*
    - *Early universe*

Thank You!