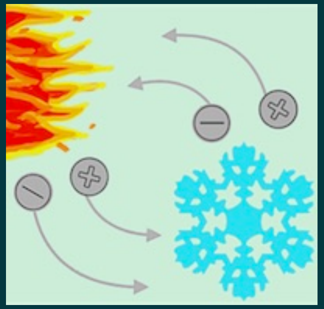


Chiral waves in WSMs

María A. H. Vozmediano

Instituto de Ciencia de Materiales de Madrid, CSIC

Condensed matter collaborators

High energy collaborators

A. Cortijo

Y. Ferreiros

D. Kharzeev

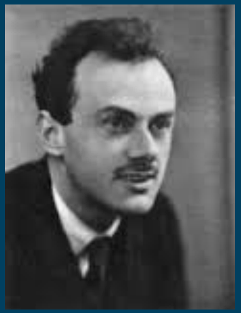
K. Landsteiner

M. Chernodub

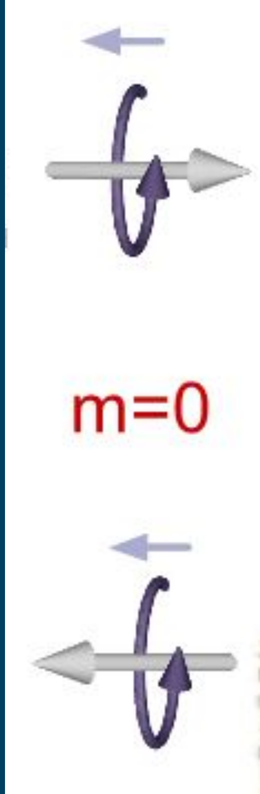
https://wp.icmm.csic.es/field-theories-in-condensed-matter-physics/

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

La Suma de Todos Comunidad de Madrid www.madrid.org



Dirac and Weyl fermions



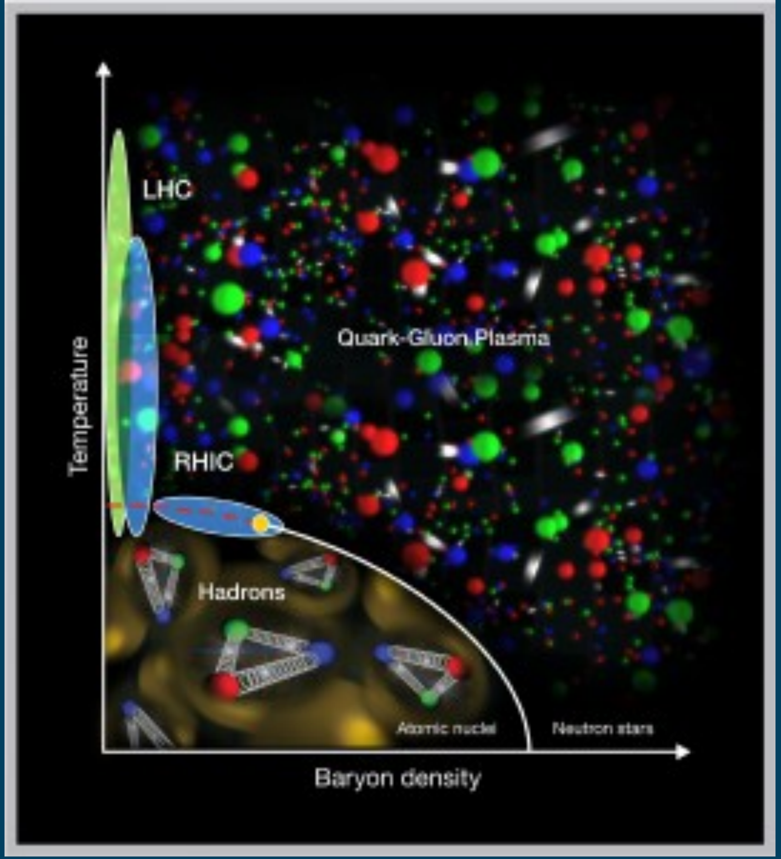
1. Massless fermions **in (3+1) dimensions** are 4 component Dirac spinors which split into two 2 component Weyl fermions of well defined **chirality.**

$$\boxed{H = \pm v_F \vec{\sigma}.\vec{p}}$$

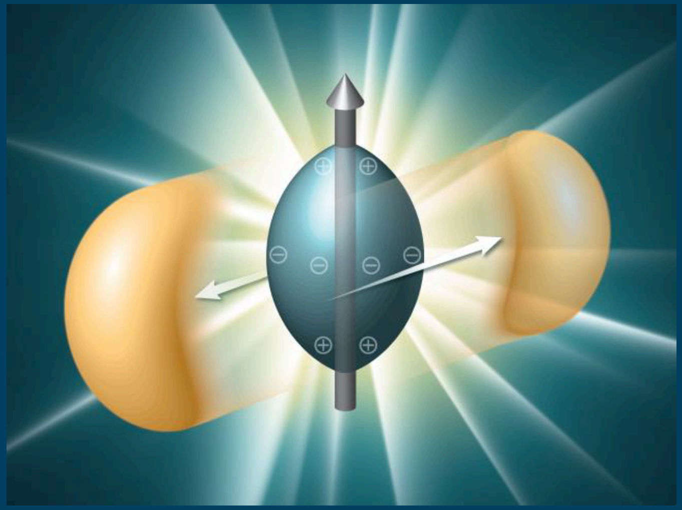
(1929)

2. These Weyl have very special properties (chiral anomaly).

3. There are no Weyl fermions as free particles (neutrinos have mass).



High energy labs



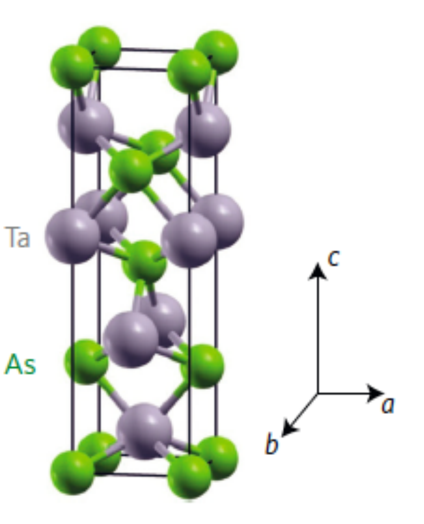
Physics "accesible" at very high energies and temperatures (mass comparatively negligible):

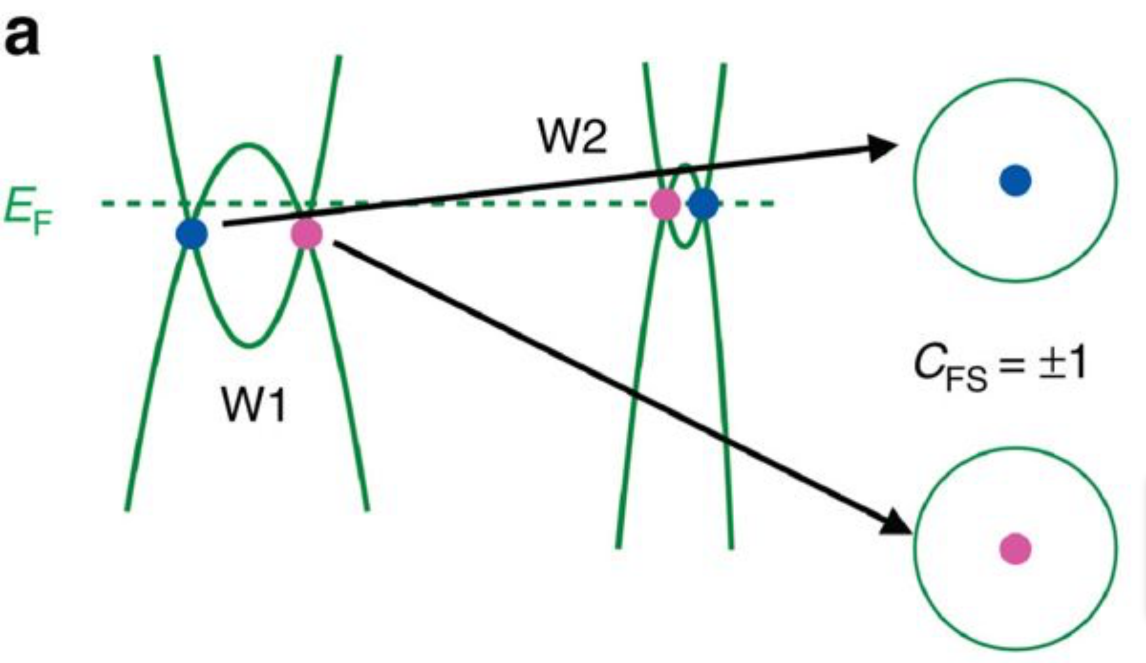
Quark-gluon plasma

- early universe
- heavy ion collisions

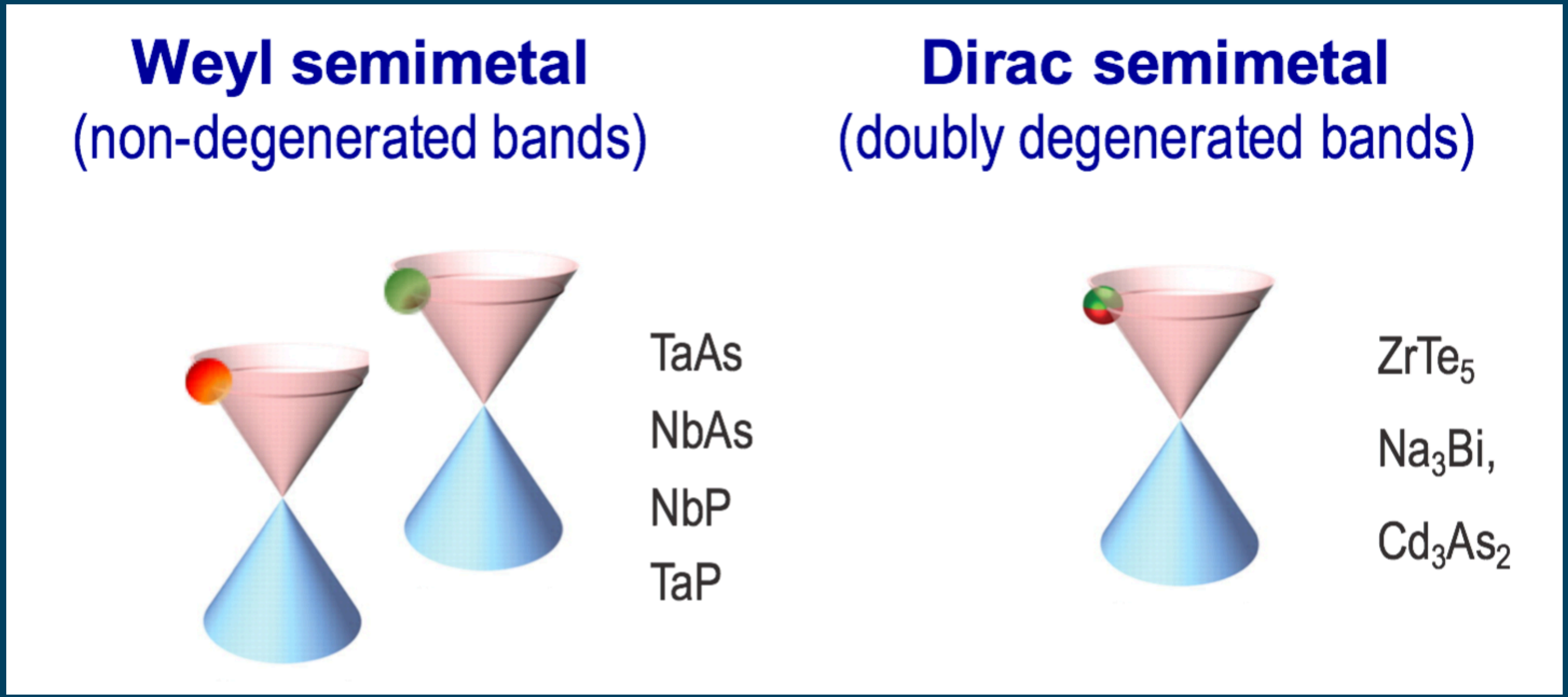
Weyl fermions in condensed matter

Effective low energy description around band crossings in 3D crystals.





Special issue
NATURE MATERIALS | VOL 15 |
NOVEMBER 2016



Weyl semimetal
(non-degenerated bands)

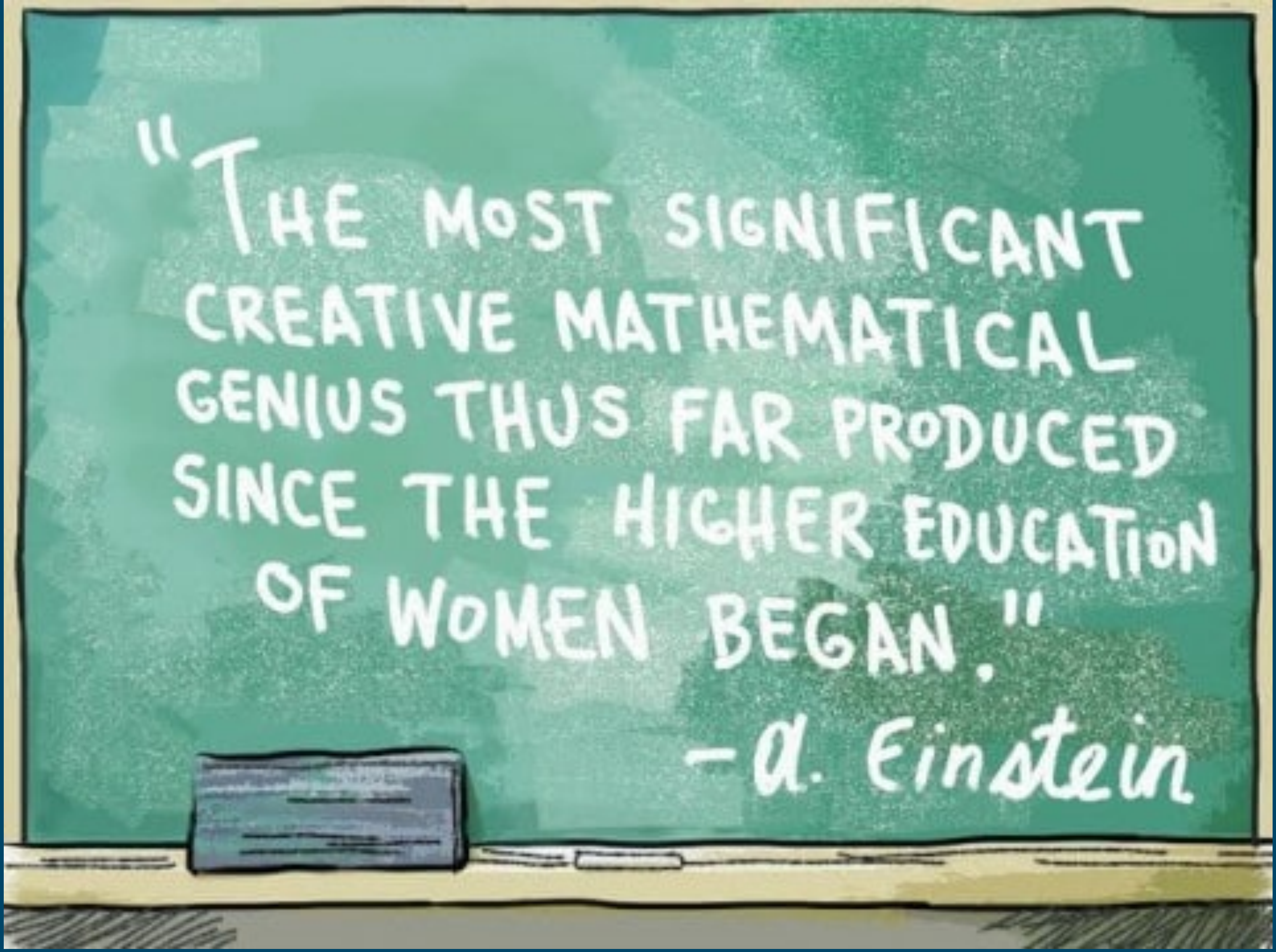
TaAs
NbAs
NbP
TaP

Dirac semimetal
(doubly degenerated bands)

$ZrTe_5$
Na_3Bi,
Cd_3As_2

They exist!
See coming talks on new materials

Advertising



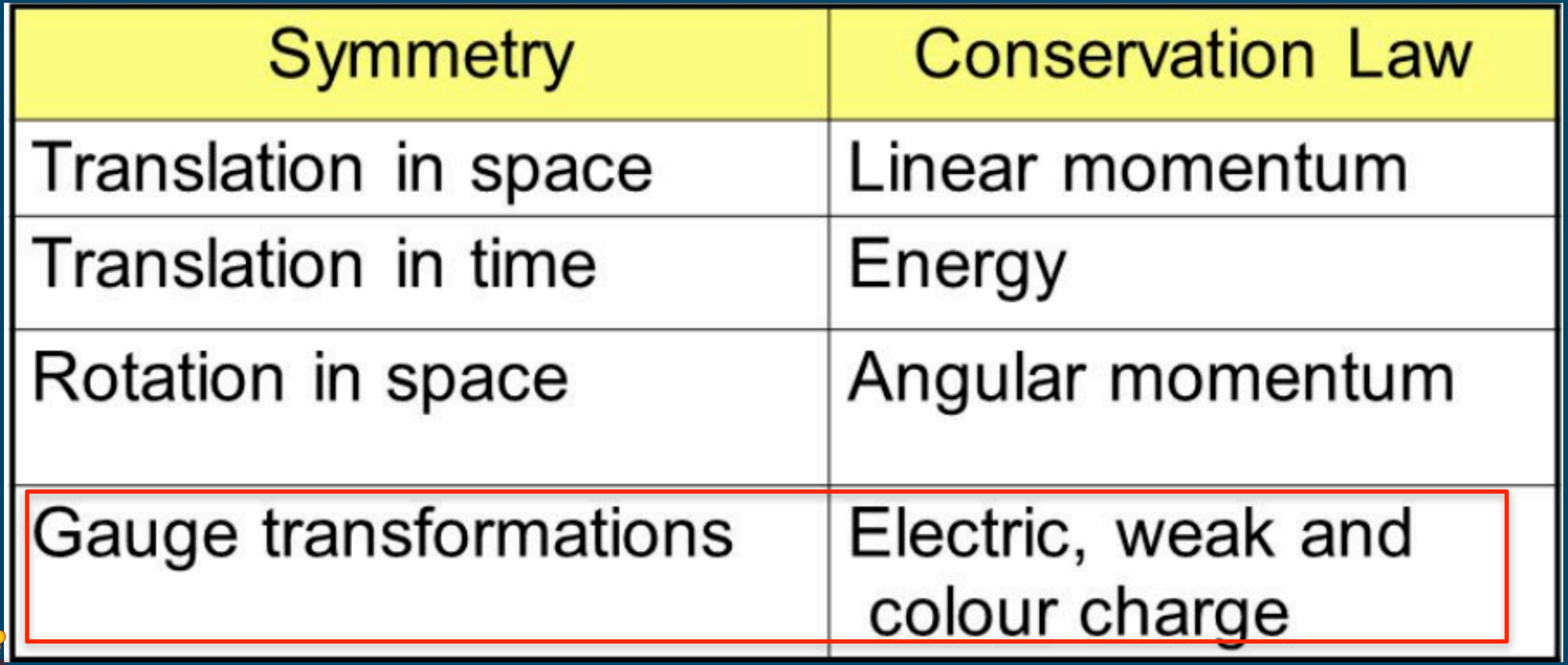
"THE MOST SIGNIFICANT CREATIVE MATHEMATICAL GENIUS THUS FAR PRODUCED SINCE THE HIGHER EDUCATION OF WOMEN BEGAN."

-A. Einstein

The Washington post

Symmetries and anomalies

Noether theorem: a continuum symmetry of the action implies a **conserved current and a conserved charge.**



Symmetry	Conservation Law
Translation in space	Linear momentum
Translation in time	Energy
Rotation in space	Angular momentum
Gauge transformations	Electric, weak and colour charge

$$T_{\mu\nu} = \frac{1}{\sqrt{g}} \frac{\delta S}{\delta g^{\mu\nu}}$$

Quantum anomaly: the classical action is invariant under a symmetry transformation that can not stay after quantization.

Chiral anomaly

$$L = \bar{\Psi}\gamma^{\mu}\partial_{\mu}\Psi \ , \ \bar{\Psi} = \gamma^{o}\Psi^{+}$$

$$\Psi = (\Psi_L, \Psi_R)$$

Action classically invariant under independent L and R rotations:

$$\Psi_{L,R} \rightarrow e^{i\alpha_{L,R}}\Psi_{L,R}$$

Two conserved currents: $J_{L,R}$. **Define $J_{V,A} = J_{\pm}J_R$**

$$j^{\mu} = \bar{\Psi}\gamma^{\mu}\Psi \ , \ \mathrm{Q} = \int \mathrm{j}^{0}(x)d(x)$$

Electric (vector) current.

Electric charge: e (N_L+N_R)

$$j_5^{\mu} = \bar{\Psi}\gamma^{\mu}\gamma_5\Psi \ , \ \mathrm{Q}_5 = \int \mathrm{j}_5^{\,0}(x)d(x)$$

Axial current.

Axial charge: e (N_L-N_R)

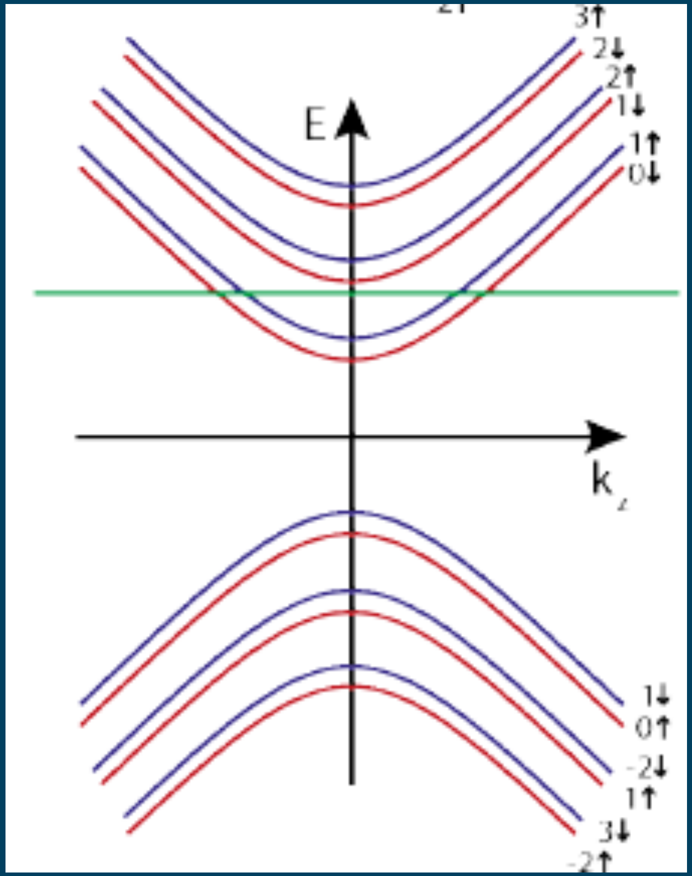
$$\partial_{\mu} \rightarrow \partial_{\mu} + ieA_{\mu}$$

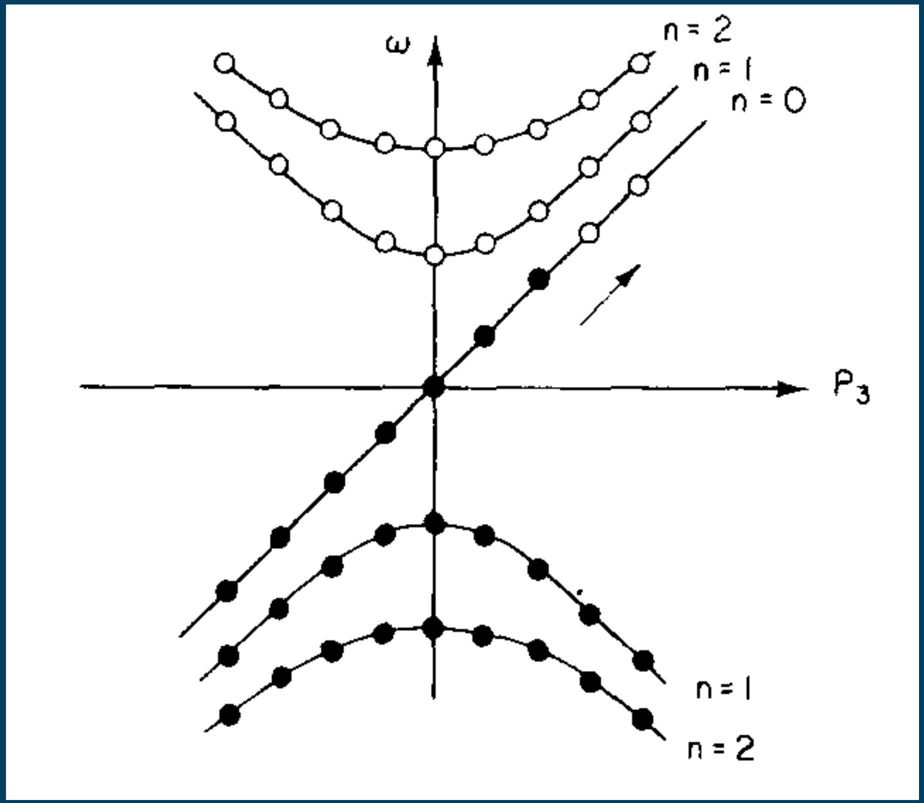
The quantum system can not keep both: axial charge not conserved **in the presence of an external electromagnetic potential A.**

$$\partial_{\mu}J_{\mu}^{A} = \frac{1}{4\pi^2}\vec{E}.\vec{B}$$

Dirac versus non-relativistic

Behavior in magnetic field (a digression)





$$\epsilon_n = \frac{\hbar^2 k_z^2}{2m_e} + (n + \frac{1}{2})\hbar\omega_c \qquad \omega_c = \frac{eB}{m_e}$$

$$\epsilon_n = \pm\sqrt{\Omega_c^2 n + v_f^2 k_z^2}, \qquad \Omega_c = v_F\sqrt{2eB}$$

Very important:

Zero Landau level: (1+1) chiral fermion

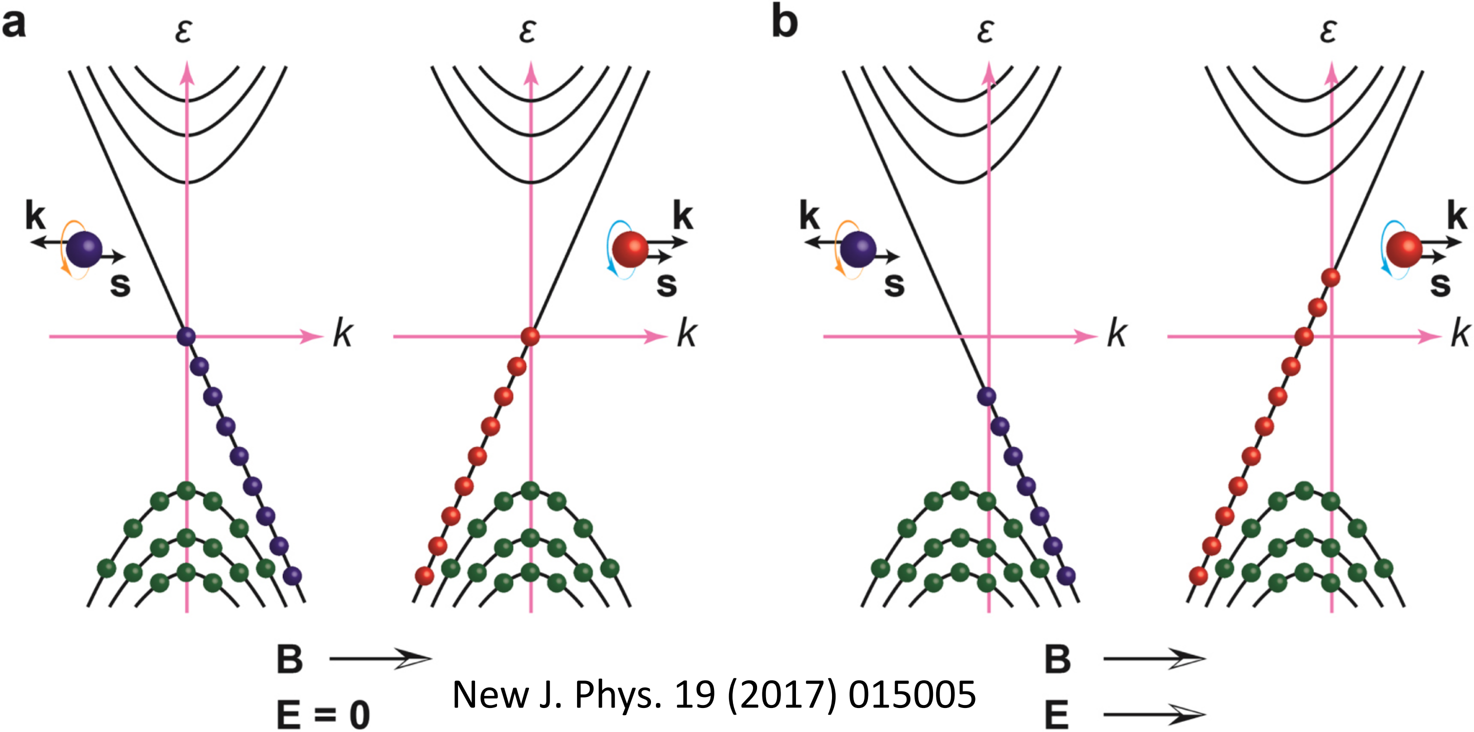
$$\varepsilon_\pm(k) = \pm \mathrm{v} k$$

Physical consequences

(anomay-induced transport phenomena)

The Adler-Bell-Jackiw anomaly and Weyl fermions in a crystal, Phys. Lett. B'83

$$\partial_\mu J_5^\mu = \frac{1}{2\pi^2}\vec{E}.\vec{B} \Rightarrow$$ **Charge is pumped from L to R points**



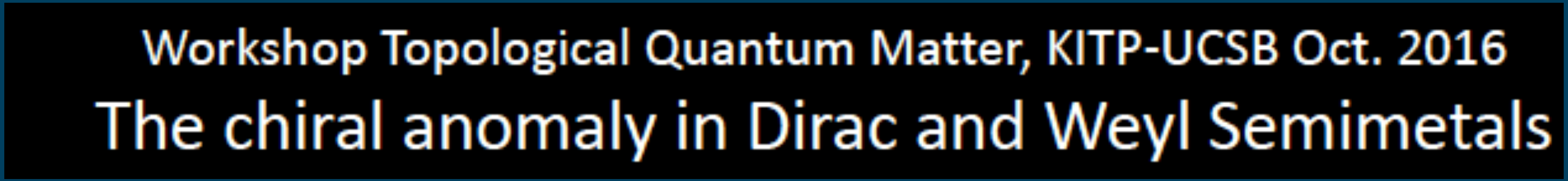
New J. Phys. 19 (2017) 015005

$$Q_5 = N_L - N_R$$

$$\frac{dQ_5}{dt} = \frac{e^2}{2\pi^2}\vec{E}\cdot\vec{B}$$

It generates large negative MR locked to the B field.

A good discussion on the experimental situation in Ong's talk at

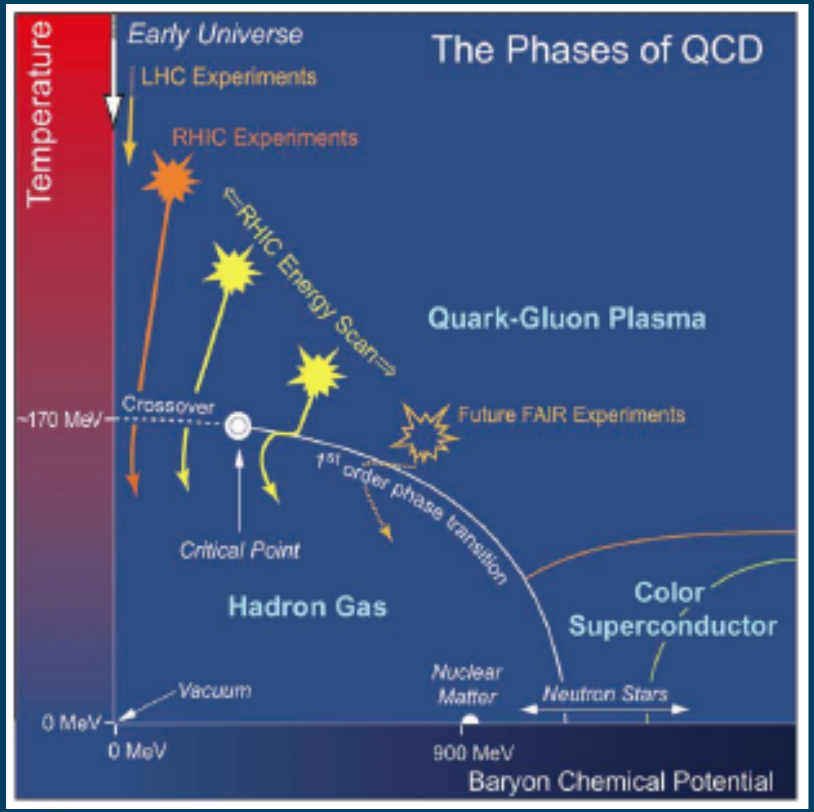


Workshop Topological Quantum Matter, KITP-UCSB Oct. 2016

The chiral anomaly in Dirac and Weyl Semimetals

Anomaly related transport

The quark-gluon **plasma**



- Chiral magnetic effect: $\vec{J} = \frac{\mu_5}{2\pi^2}\vec{B}$
- Axial magnetic effect: $J_\varepsilon = \frac{\mu^2+\mu_5^2}{4\pi^2}\boxed{B_5}$
- Chiral vortical effect: $\vec{J} = \frac{\mu_5\mu}{\pi^2}\vec{\omega}$
- Chiral separation effect: $\vec{J}_5 = -\frac{e\mu}{\pi^2}\vec{B}$

No axial gauge fields in particle physics

LETTERS

PUBLISHED ONLINE: 8 FEBRUARY 2016 | DOI: 10.1038/NPHYS3648

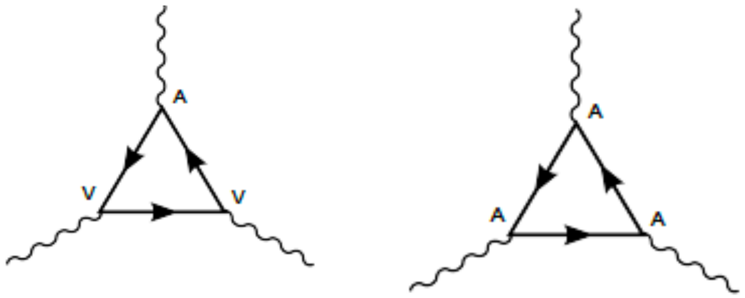
nature physics

Chiral magnetic effect in ZrTe$_5$

Qiang Li[1]*, Dmitri E. Kharzeev[2,3]*, Cheng Zhang[1], Yuan Huang[4], I. Pletikosić[1,5], A. V. Fedorov[6], R. D. Zhong[1], J. A. Schneeloch[1], G. D. Gu[1] and T. Valla[1]*

Chiral anomaly with axial gauge fields

$$S = \int d^4x \bar{\psi}\gamma^\mu (i\partial_\mu + eA_\mu + b_\mu\gamma^5)\psi.$$



The AAA triangle anomaly

$$\partial_\mu J^\mu_5 = \frac{1}{2\pi^2}\left(\vec{E}\vec{B} + \vec{E}_5\vec{B}_5\right)$$

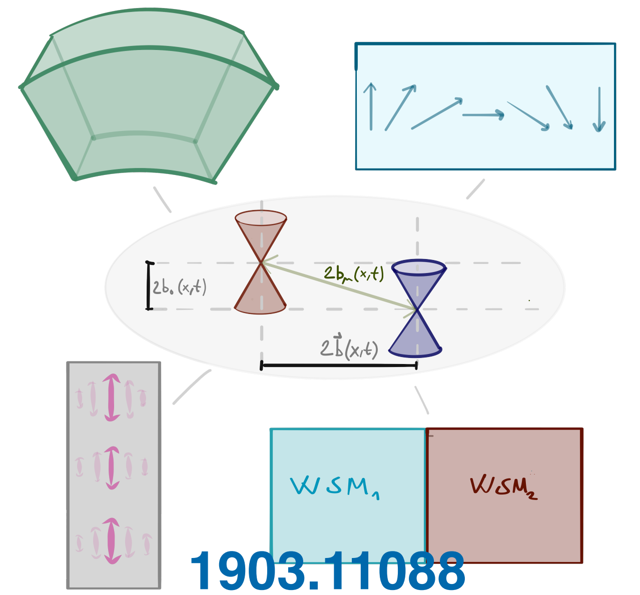
No axial fields in particle physics

$$H = \begin{pmatrix} -\vec{\sigma}(\vec{k} - \frac{\vec{b}}{2}) & 0 \\ 0 & \vec{\sigma}(\vec{k} + \frac{\vec{b}}{2}) \end{pmatrix}.$$

$$\mathcal{L} = \bar{\Psi}\gamma^\mu(i\partial_\mu + \gamma^5 b_\mu)\Psi,$$

The nodes separation acts as a (constant) axial gauge field

A nice review



1903.11088

How to promote b to a dynamical field?

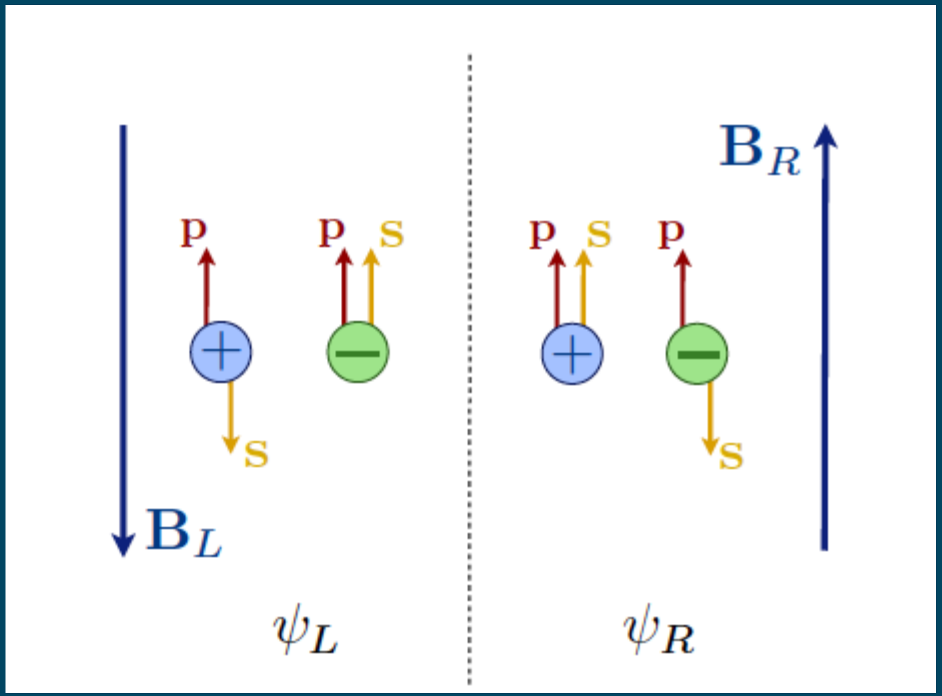
1. Elastic deformations of the lattice
2. Boundaries
3. Non-uniform magnetization

See talk by R. Ilan

Axial magnetic effect

(From boundaries)

Generation of an energy current in the direction of an axial magnetic field.



$$S = \int d^4k \bar{\Psi}_k (\gamma^\mu k_\mu - b_\mu \gamma^\mu \gamma^5) \Psi_k$$

b_0: Energy separation

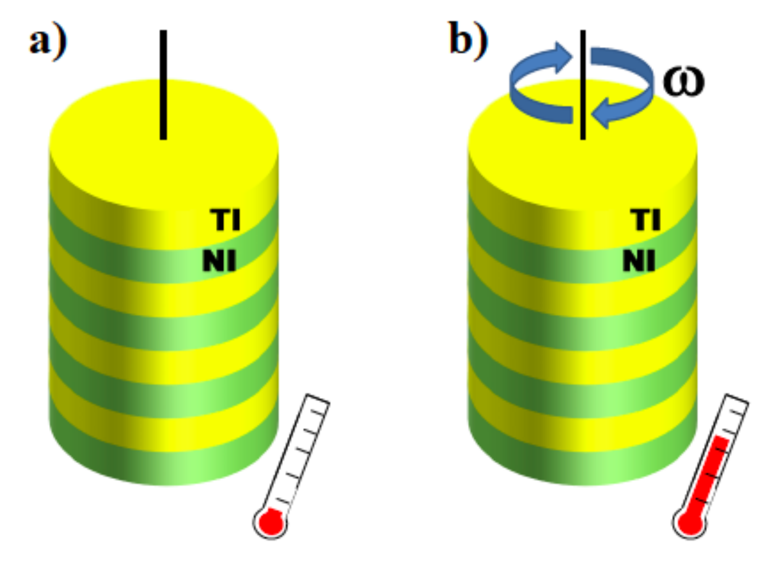
b_i: k separation. b(x) → B_5(x).

$$\mathbf{b} = \hat{z} b_z \Theta(a - |r|). \qquad B_\theta \sim b_z \delta(|r| - a).$$

$$T^{0i} = J^i_\epsilon = \sigma_{AME} B^i_5.$$

$$\sigma_{AME} = \frac{\mu^2 + \mu_5^2}{4\pi^2} \boxed{+ \frac{T^2}{12}},$$

$$L_z = \frac{N_f}{6} T^2 b_z \mathcal{V},$$



Experimental confirmation of the gravitational anomaly?

Cortijo, Grushin, Landsteiner, MAHV, PRB 89, 081407R (2014)

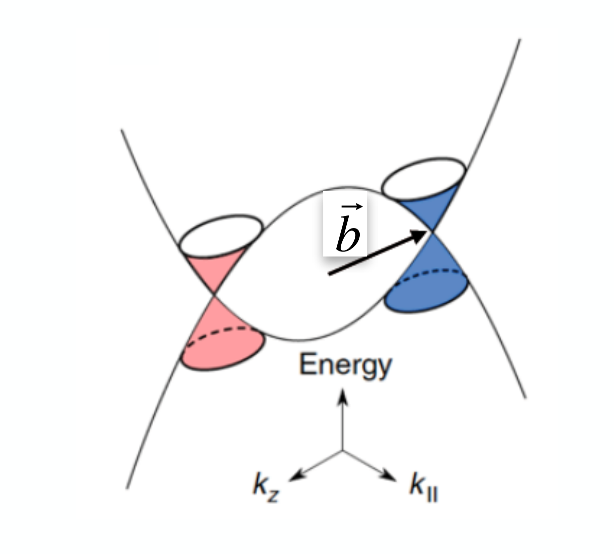
Axial gauge fields from strain

(Effective action)

$$S_0 = \int d^4k \bar{\Psi}_k \gamma^\mu [k_\mu - \beta\gamma^5 A_\mu(x)]\Psi_k$$

Building blocks

$$\sigma_i, k_j, u_{ij}, \boxed{\mathrm{b}_i}$$



Elastic gauge field $A_i^5 \approx u_{ij} b_j$

Opposite signs at opposite chiralities: Axial gauge field

A tight binding derivation provides values for the coupling.

A. Cortijo, Y. Ferreiros, K. Landsteiner, M.V.,
- Elastic gauge fields in Weyl semimetals PRL **115**, 177202 (2015).
- Visco elasticity in 2D materials, 2D Materials **3**, 011002 (2016).

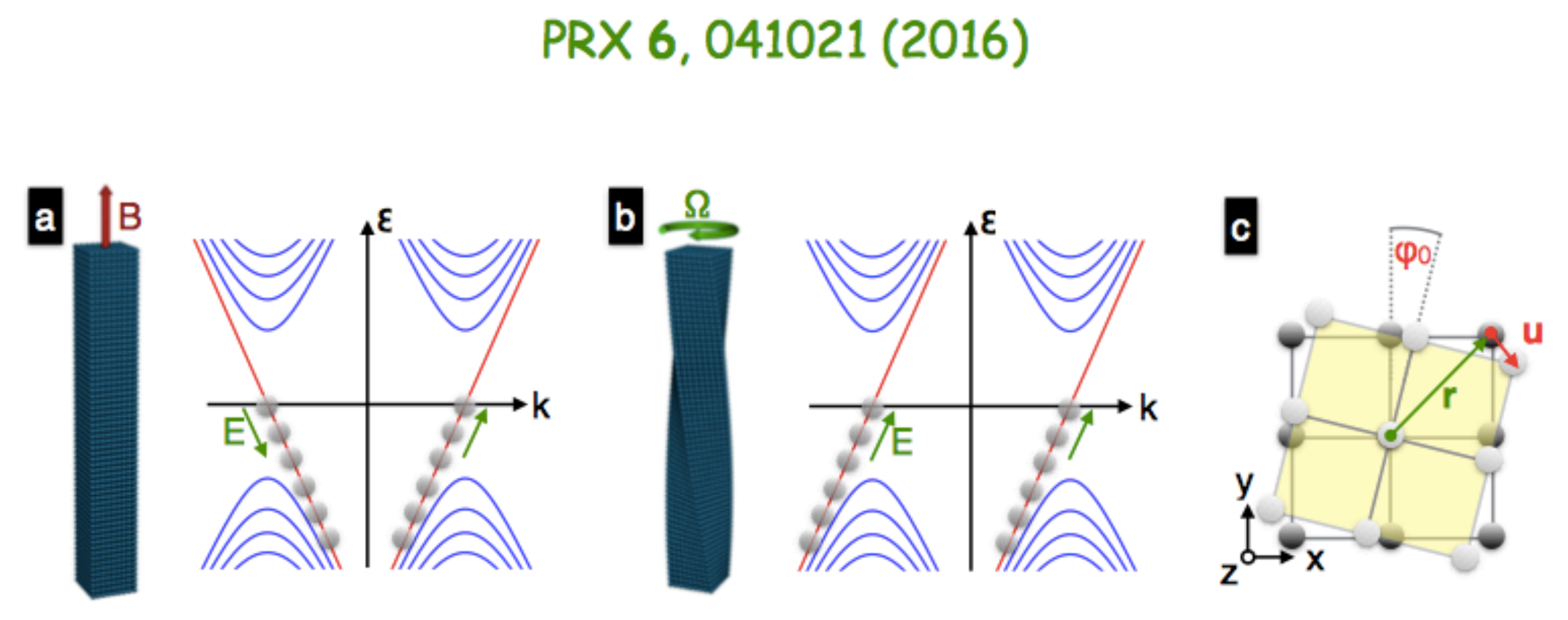
In the presence of b_0 get a new A_0 component (not present in graphene)

$$A_0^{el} \sim \beta b_0 tr(u)$$

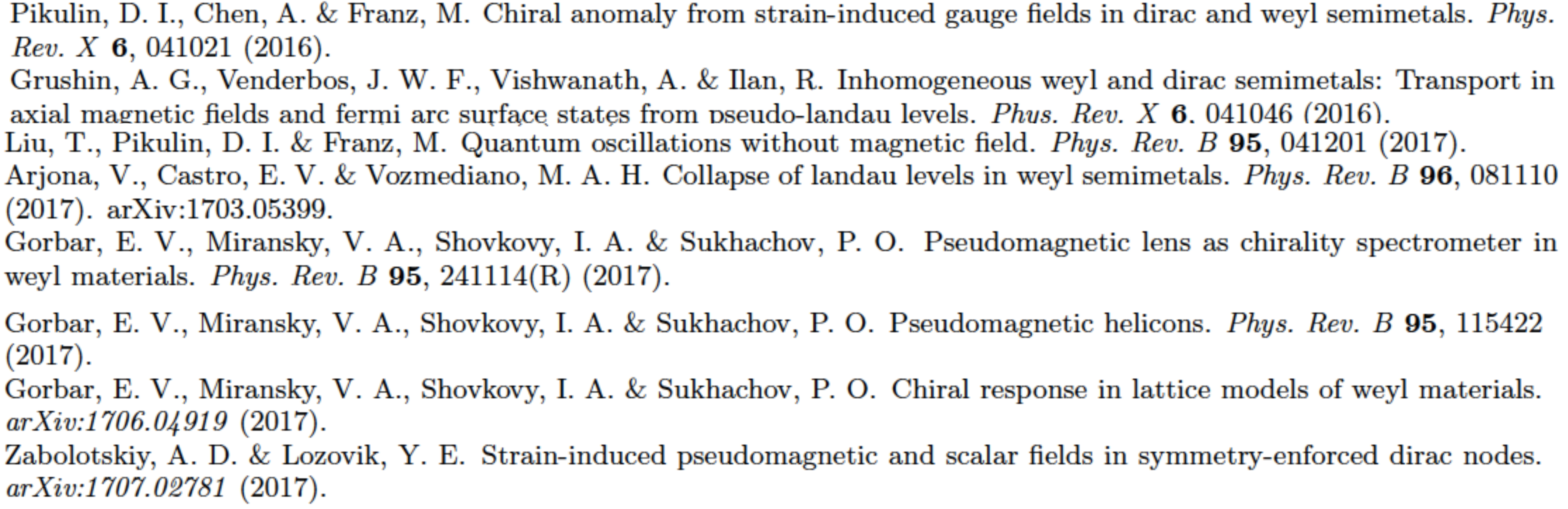
A. Cortijo, D. Kharzeev, K. Landsteiner, M.V.
Strain-induced CME in Weyl semimetals, PRB**94** (R) (2016).

A complete list of couplings: *Rotational strain in WSM: A continuum approach, V. Arjona, MV* , PRB**97**(R) (2018).

WSM straintronics (theory)



PRX 6, 041021 (2016)



Pikulin, D. I., Chen, A. & Franz, M. Chiral anomaly from strain-induced gauge fields in dirac and weyl semimetals. *Phys. Rev. X* **6**, 041021 (2016).

Grushin, A. G., Venderbos, J. W. F., Vishwanath, A. & Ilan, R. Inhomogeneous weyl and dirac semimetals: Transport in axial magnetic fields and fermi arc surface states from pseudo-landau levels. *Phys. Rev. X* **6**, 041046 (2016).

Liu, T., Pikulin, D. I. & Franz, M. Quantum oscillations without magnetic field. *Phys. Rev. B* **95**, 041201 (2017).

Arjona, V., Castro, E. V. & Vozmediano, M. A. H. Collapse of landau levels in weyl semimetals. *Phys. Rev. B* **96**, 081110 (2017). arXiv:1703.05399.

Gorbar, E. V., Miransky, V. A., Shovkovy, I. A. & Sukhachov, P. O. Pseudomagnetic lens as chirality spectrometer in weyl materials. *Phys. Rev. B* **95**, 241114(R) (2017).

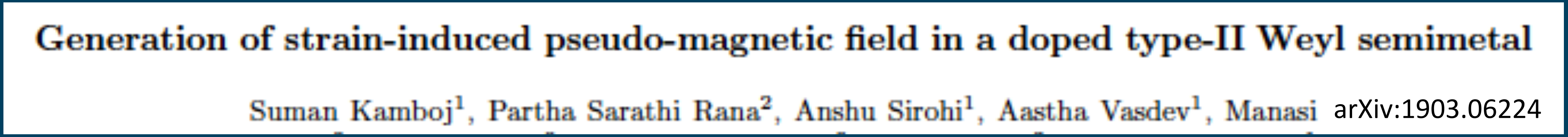
Gorbar, E. V., Miransky, V. A., Shovkovy, I. A. & Sukhachov, P. O. Pseudomagnetic helicons. *Phys. Rev. B* **95**, 115422 (2017).

Gorbar, E. V., Miransky, V. A., Shovkovy, I. A. & Sukhachov, P. O. Chiral response in lattice models of weyl materials. *arXiv:1706.04919* (2017).

Zabolotskiy, A. D. & Lozovik, Y. E. Strain-induced pseudomagnetic and scalar fields in symmetry-enforced dirac nodes. *arXiv:1707.02781* (2017).

And a long etc. including bosonic analogs: magnons, phonons, photons..

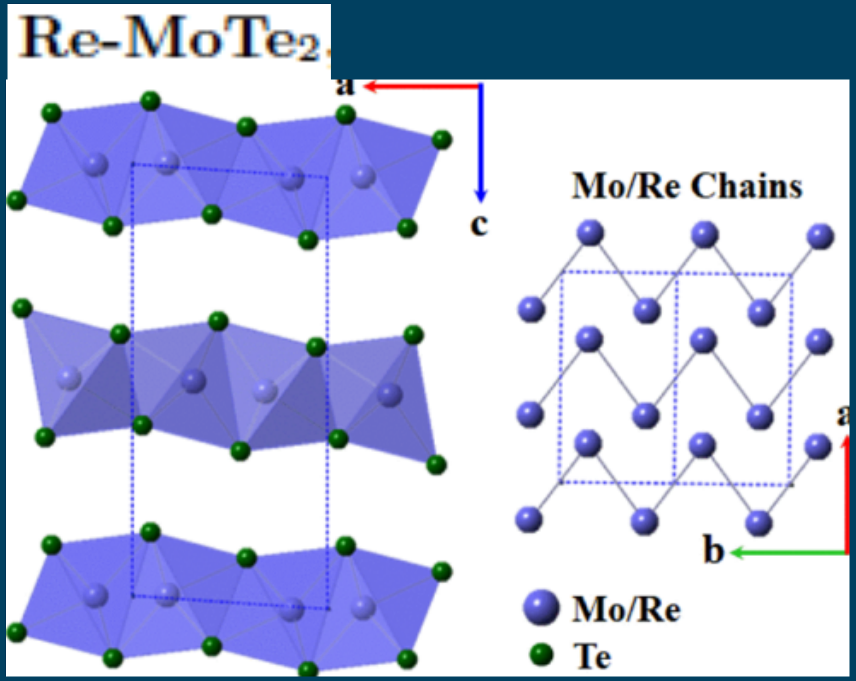
Experimental evidence?



Generation of strain-induced pseudo-magnetic field in a doped type-II Weyl semimetal

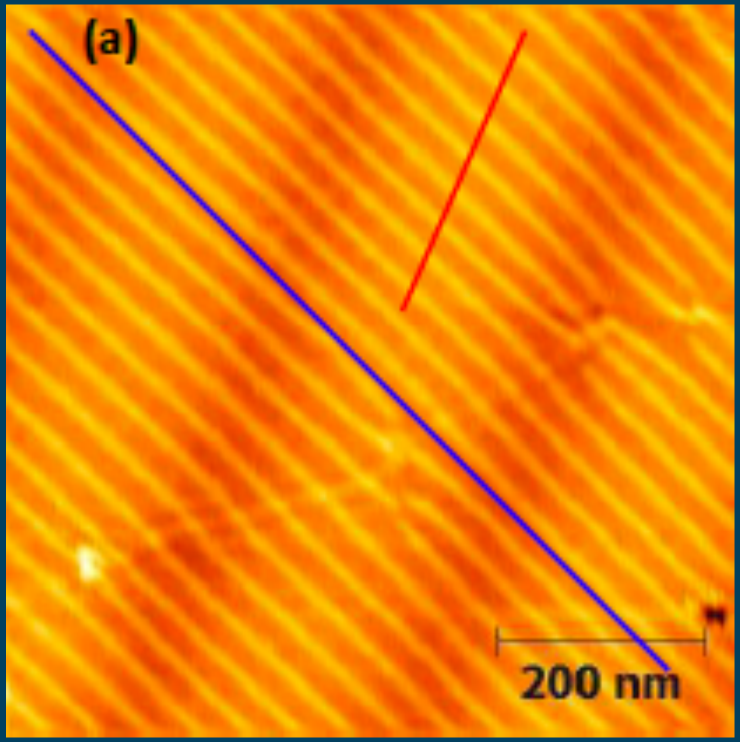
Suman Kamboj[1], Partha Sarathi Rana[2], Anshu Sirohi[1], Aastha Vasdev[1], Manasi arXiv:1903.06224

Re-MoTe$_2$

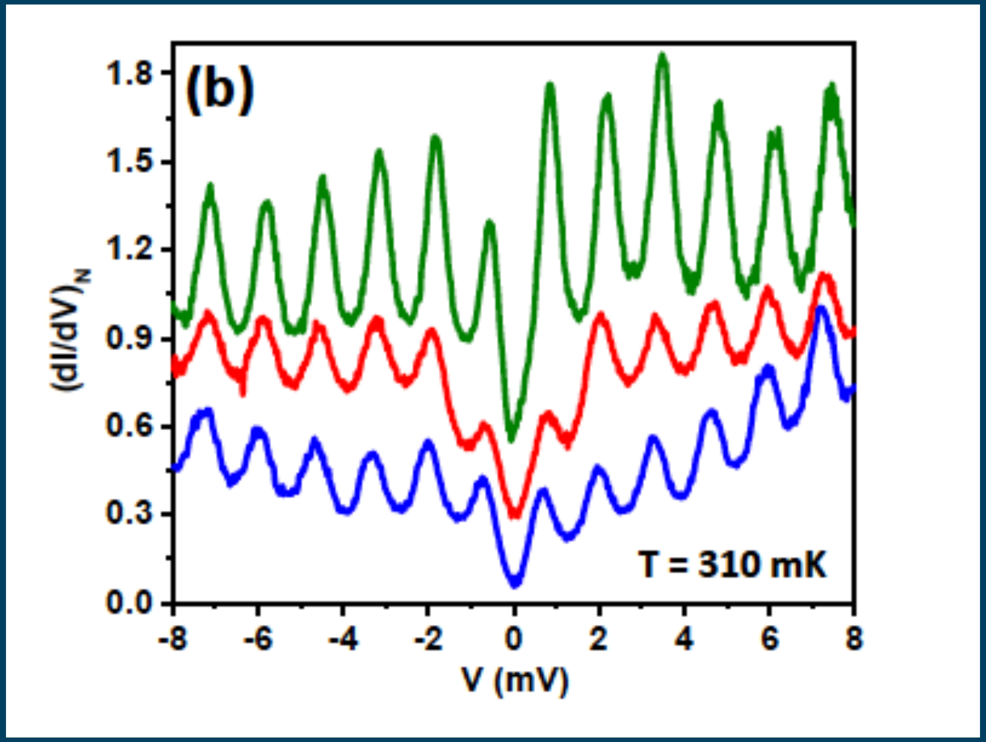


Landau levels from strain

$$\vec{B}_5 = \vec{\nabla} \times \vec{A}_5$$



Stripes λ~35 nm



$B \approx 3T$, 300 mK,

Hydro aspects of Dirac matter

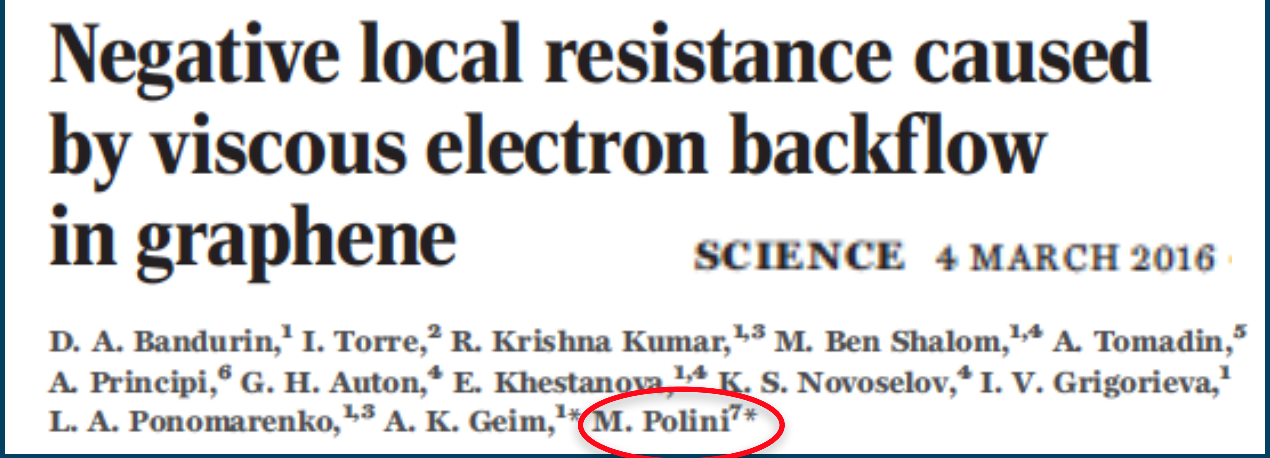
$\tau_{ee} >> \tau_{any}$ Fermi liquids in ultrapure crystals

JHEP

March 24, 2015

Negative magnetoresistivity in chiral fluids and holography

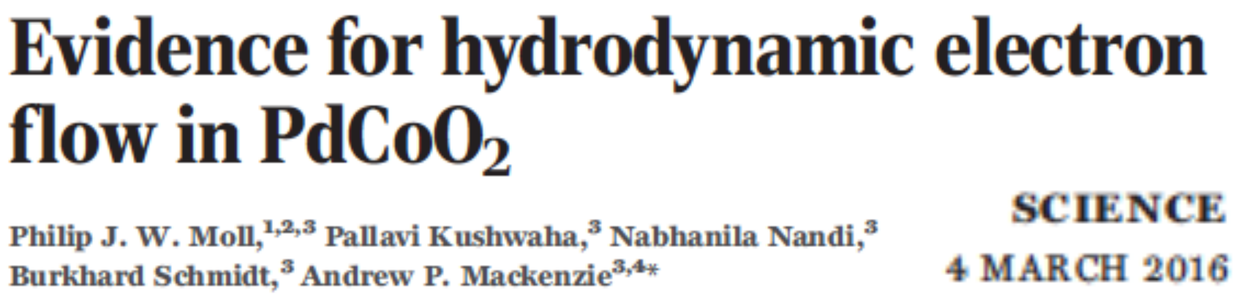
Karl Landsteiner, Yan Liu and Ya-Wen Sun



Negative local resistance caused by viscous electron backflow in graphene

SCIENCE 4 MARCH 2016

D. A. Bandurin,[1] I. Torre,[2] R. Krishna Kumar,[1,3] M. Ben Shalom,[1,4] A. Tomadin,[5] A. Principi,[6] G. H. Auton,[4] E. Khestanova,[1,4] K. S. Novoselov,[4] I. V. Grigorieva,[1] L. A. Ponomarenko,[1,3] A. K. Geim,[1*] M. Polini[7*]



Evidence for hydrodynamic electron flow in $PdCoO_2$

SCIENCE 4 MARCH 2016

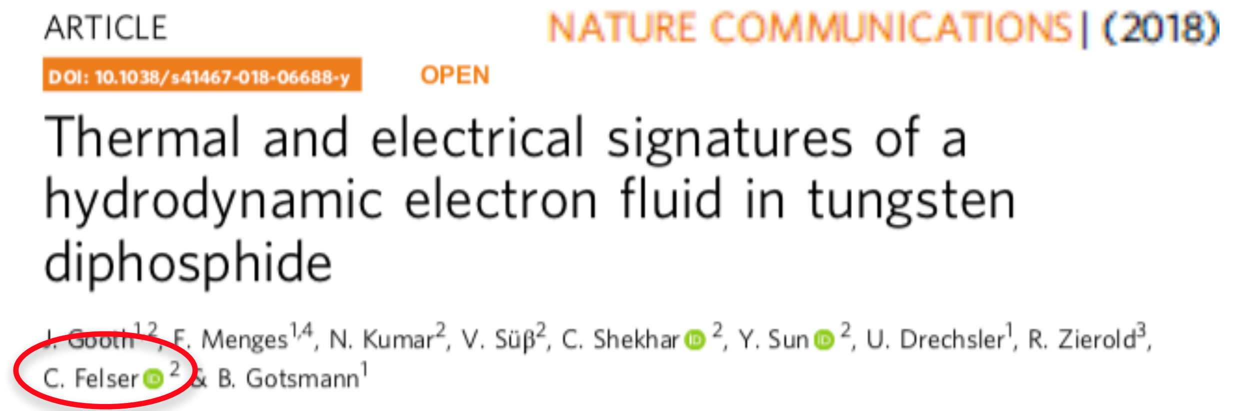
Philip J. W. Moll,[1,2,3] Pallavi Kushwaha,[3] Nabhanila Nandi,[3] Burkhard Schmidt,[3] Andrew P. Mackenzie[3,4*]

ELECTRON TRANSPORT

Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

SCIENCE 4 MARCH 2016

Jesse Crossno,[1,2] Jing K. Shi,[1] Ke Wang,[1] Xiaomeng Liu,[1] Achim Harzheim,[1] Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2*] Takashi Taniguchi,[4] Kenji Watanabe,[4] Thomas A. Ohki,[5] Kin Chung Fong[5*]



ARTICLE

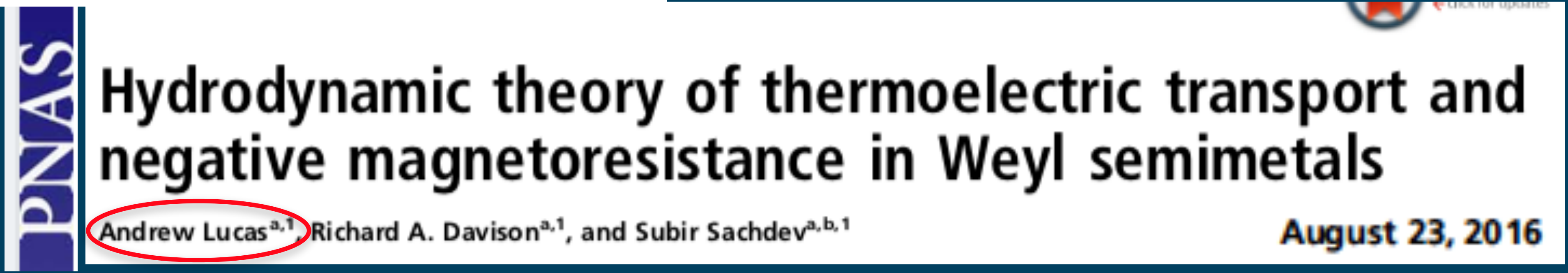
NATURE COMMUNICATIONS | (2018)

DOI: 10.1038/s41467-018-06688-y

OPEN

Thermal and electrical signatures of a hydrodynamic electron fluid in tungsten diphosphide

J. Gooth[1,2], F. Menges[1,4], N. Kumar[2], V. Süβ[2], C. Shekhar[2], Y. Sun[2], U. Drechsler[1], R. Zierold[3], C. Felser[2] & B. Gotsmann[1]



PNAS

Hydrodynamic theory of thermoelectric transport and negative magnetoresistance in Weyl semimetals

Andrew Lucas[a,1], Richard A. Davison[a,1], and Subir Sachdev[a,b,1]

August 23, 2016

Collective modes in chiral fluids

PHYSICAL REVIEW D **83**, 085007 2011

Chiral magnetic wave

Dmitri E. Kharzeev and Ho-Ung Yee

CME

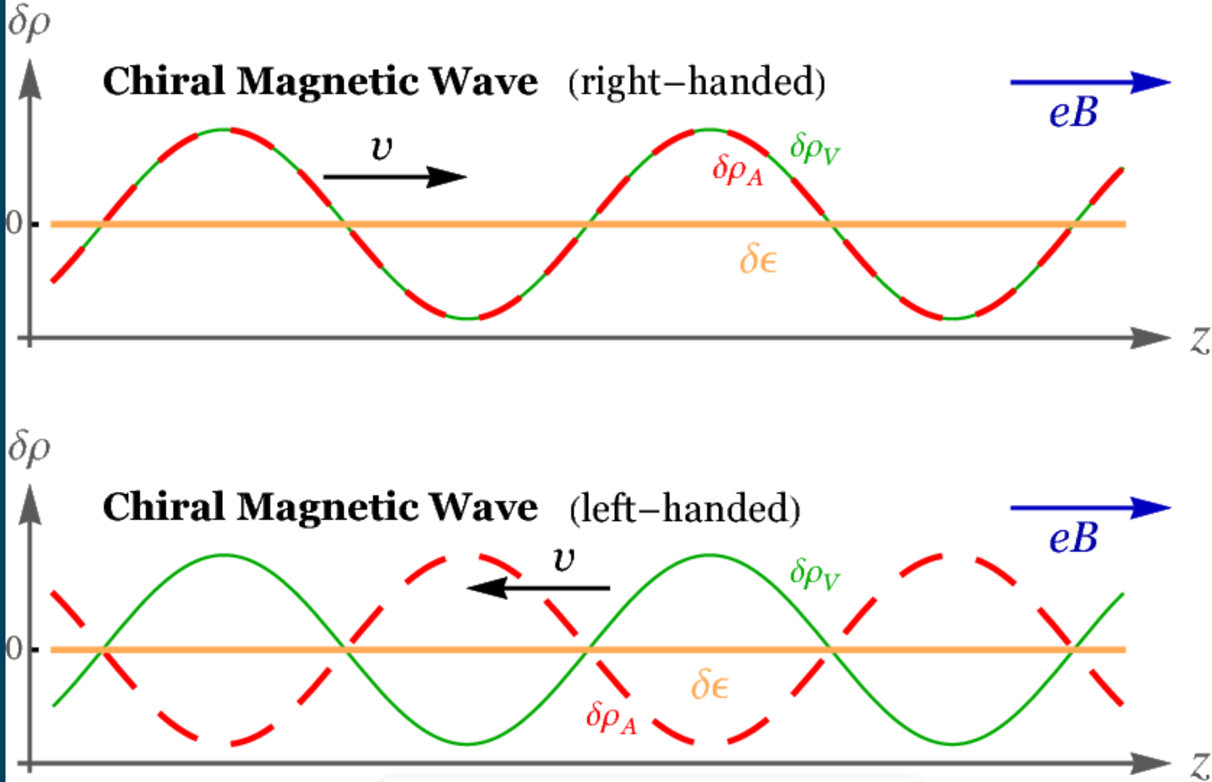
$$\vec{J} = \frac{\mu_5}{2\pi^2}\vec{B}$$

CSE

$$\vec{J}_5 = \frac{\mu}{2\pi^2}\vec{B}$$

$$\left(\partial_t^2 - v_{\mathrm{CMW}}^2\partial_z^2\right)\rho_V(x) = 0$$

$$\left(\partial_t^2 - v_{\mathrm{CMW}}^2\partial_z^2\right)\rho_A(x) = 0$$



M. Chernodub, JHEP 2016

PRL 114, 252302 (2015) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2015

Observation of Charge Asymmetry Dependence of Pion Elliptic Flow and the Possible Chiral Magnetic Wave in Heavy-Ion Collisions (STAR Collaboration)

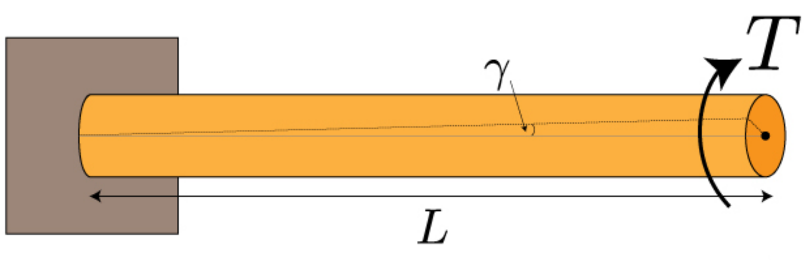
The overdamped chiral magnetic wave

I. Shovkovy et al, arXiv 1811:10635

Hybridization with standard EM wave-> CMW diffusive.

Chiral sound wave

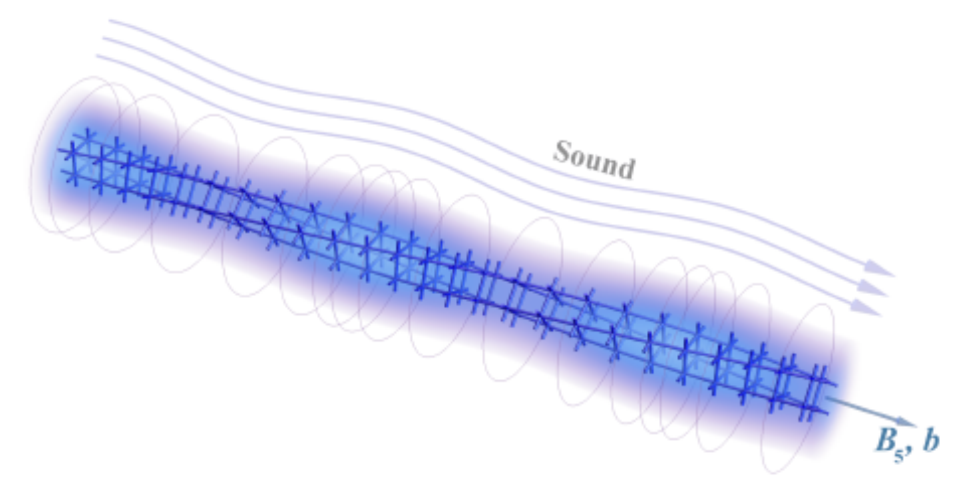
Static torsional strain and dynamical longitudinal phonons



$$\vec{u} = \theta z(\vec{r}\times\hat{z})$$

$$u_{13} = \theta y \; ; \; u_{23} = -\theta x \; . \; \vec{A}_i^5 = u_{ij} b_j \, .$$
$$\vec{A}^5 = b(\theta y, -\theta x, 0) \; . \; \mathrm{B}_3^5 = b\theta \; .$$

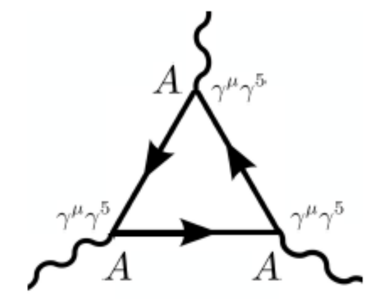
Static torsional strain induces a constant B_5 along the rod[1]



$$\partial_\mu j_5^\mu = \frac{1}{3}\frac{1}{2\pi^2} E_5 \, . \, B_5$$

$$j_5 = \frac{\mu_5}{2\pi^2} B_5,$$

$$\rho_5 = \frac{\mu_5}{3v_F^3}\left(T^2 + \frac{3\mu^2}{\pi^2}\right)$$



$$\left(\frac{\partial}{\partial t} + v_{\rm CSW}\frac{\partial}{\partial z}\right)\rho_5 = 0,$$

$$v_{\rm CSW} = \frac{3B_5 v_F^3}{2\left(\pi^2 T^2 + 3\mu^2\right)}$$

Unidirectional chiral wave.

- Not direct coupling to em fields.
- Damping regulated by τ_5.

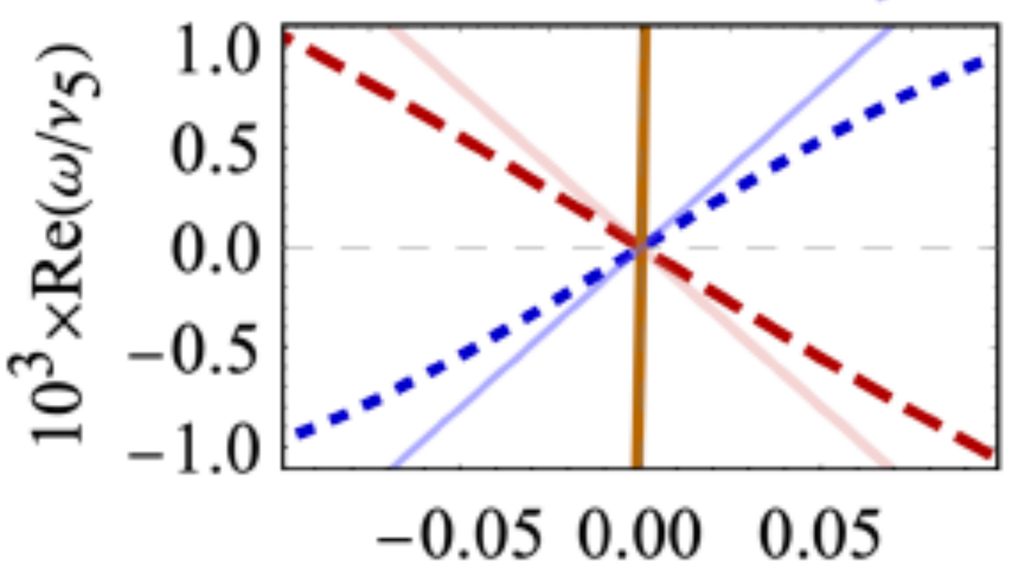
[1] Pikulin et al, PRX (2016).

Chiral sound waves in strained Weyl semimetals M. Chernodub, M. V. arXiv:1904.09113

Experimental signature

It mixes with standard acoustic phonons

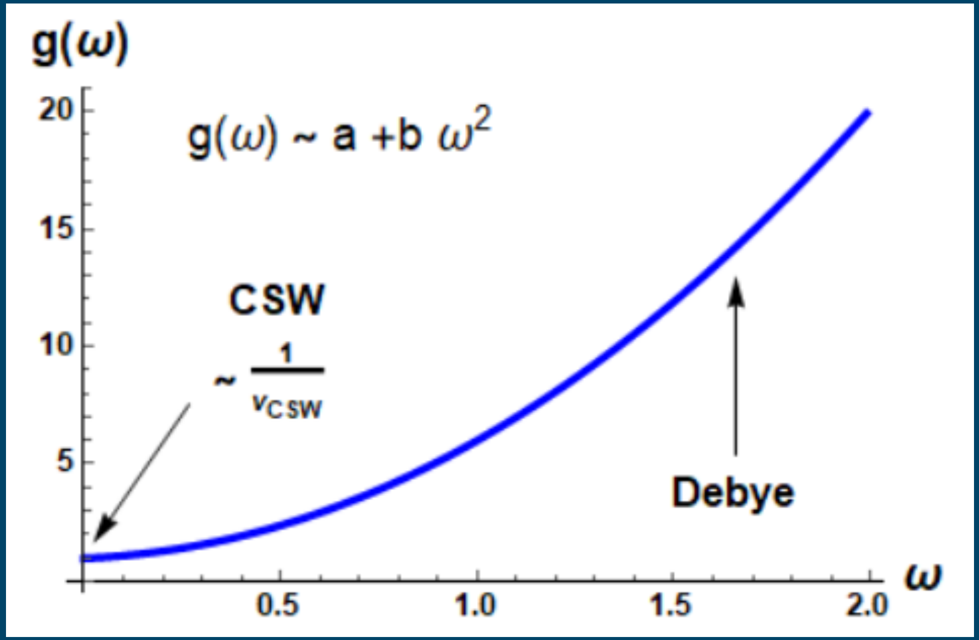
$$\delta v = |v_+| - |v_-| \simeq \frac{v_p^2}{v_{\mathrm{CSW}}} \simeq \frac{\kappa\theta b^3}{2\pi^2 v_F},$$

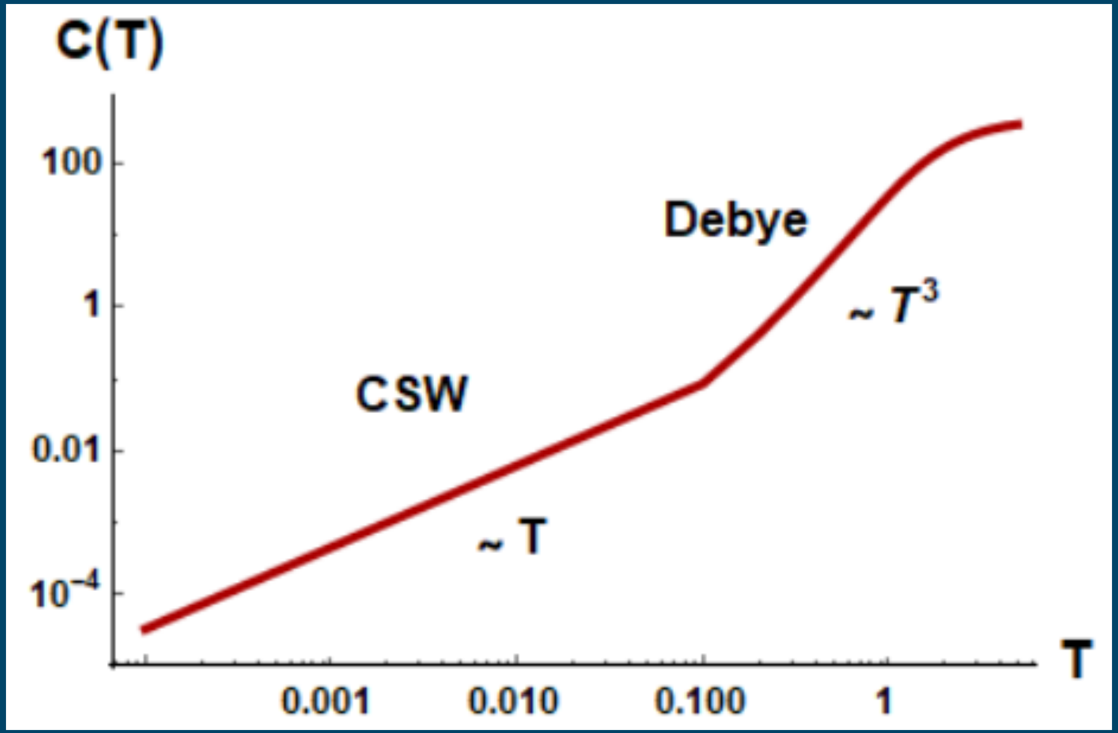


Change θ and measure asymmetry in the phonon branches

Chiral thermal transport?

Very preliminary results!!





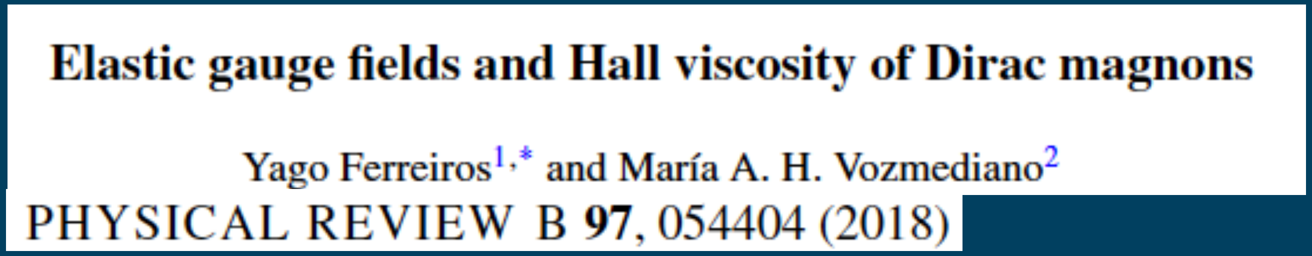
M. Baggioli, M. Chernodub, K. Landsteiner, M. V. **work in progress**

Other very interesting new developments:

Strain-induced nonlinear spin Hall effect in topological Dirac semimetal

Yasufumi Araki[1,2]

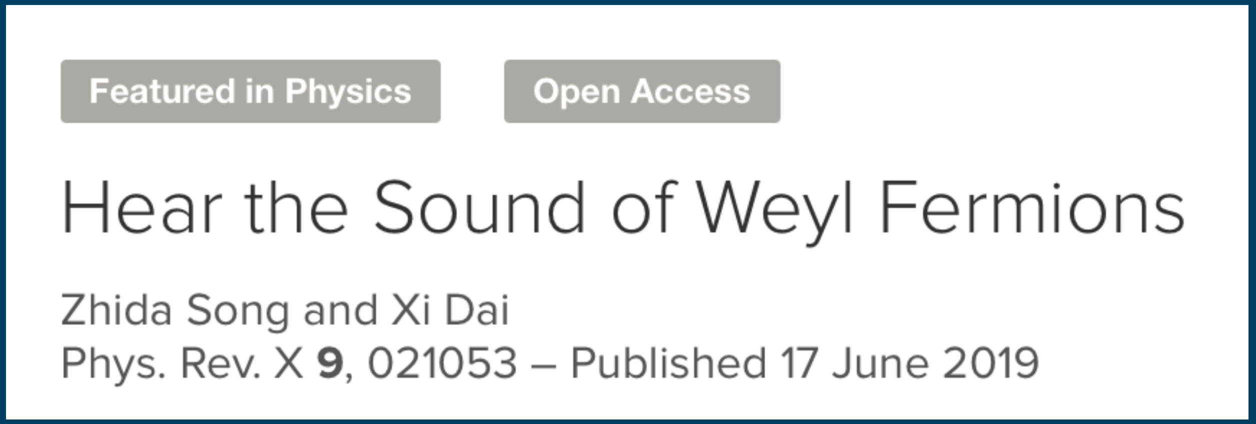
SclentIFIc ReportS I (2018) 8:15236



Elastic gauge fields and Hall viscosity of Dirac magnons

Yago Ferreiros[1,*] and María A. H. Vozmediano[2]

PHYSICAL REVIEW B **97**, 054404 (2018)



Hear the Sound of Weyl Fermions

Zhida Song and Xi Dai

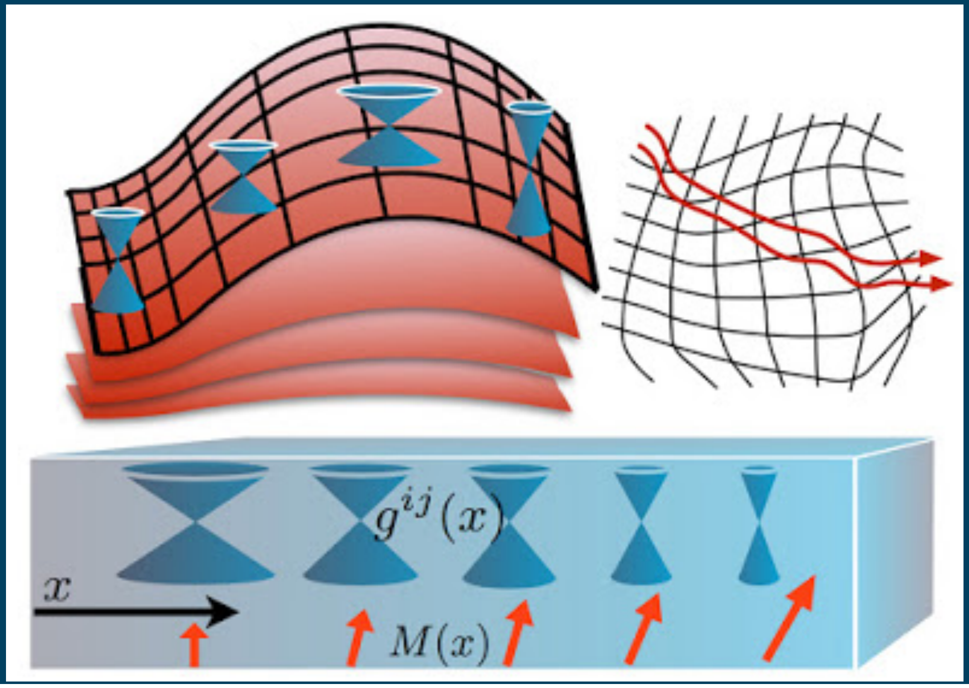
Phys. Rev. X **9**, 021053 – Published 17 June 2019

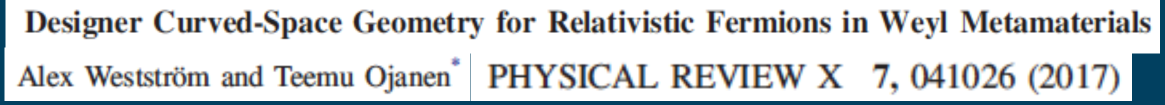
TOPOLOGICAL SEMIMETALS

Sound of Weyl

Nature Physics **15**, 522 (2019)

Yun Li





Designer Curved-Space Geometry for Relativistic Fermions in Weyl Metamaterials

Alex Westström and Teemu Ojanen* PHYSICAL REVIEW X 7, 041026 (2017)

Axial-field-induced chiral channels in an acoustic Weyl system

Valerio Peri, Marc Serra-Garcia, Roni Ilan & Sebastian D. Huber

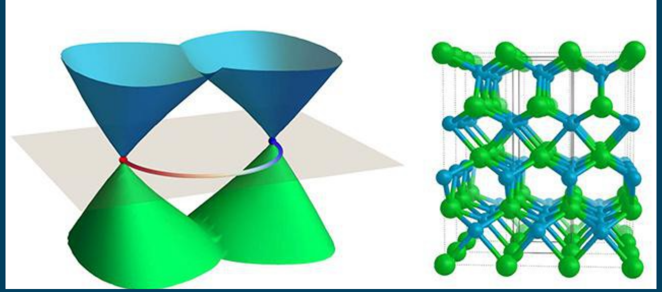
Nature Physics **15**, 357–361(2019) | Cite this article

ACOUSTICS

Audible Landau levels

Boundaries
Elastic deformations
Magnetic moments

Weyl crystals



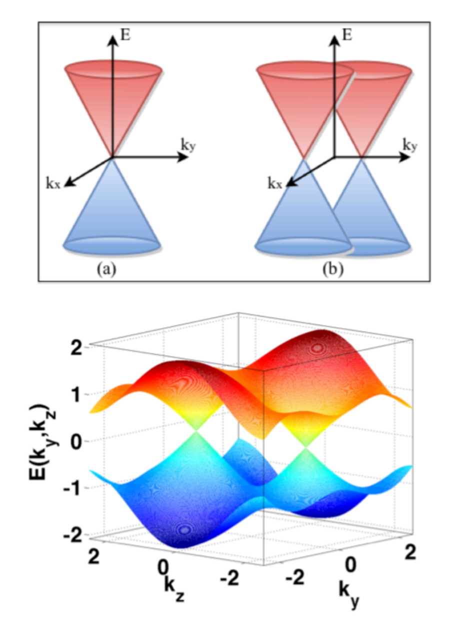
Elasticity

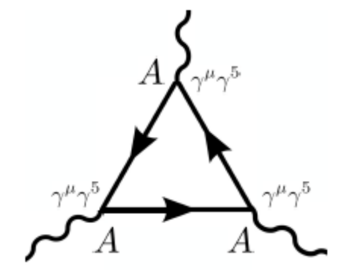
QFT

Effective actions

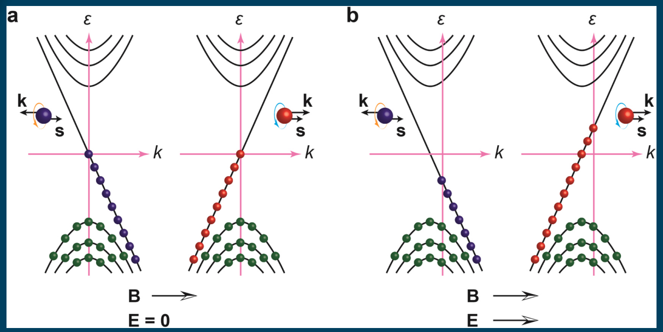
Axial gauge fields

Anomalies





Hydro



Chiral waves

New transport phenomena

DIRAC MATTER
grand unification

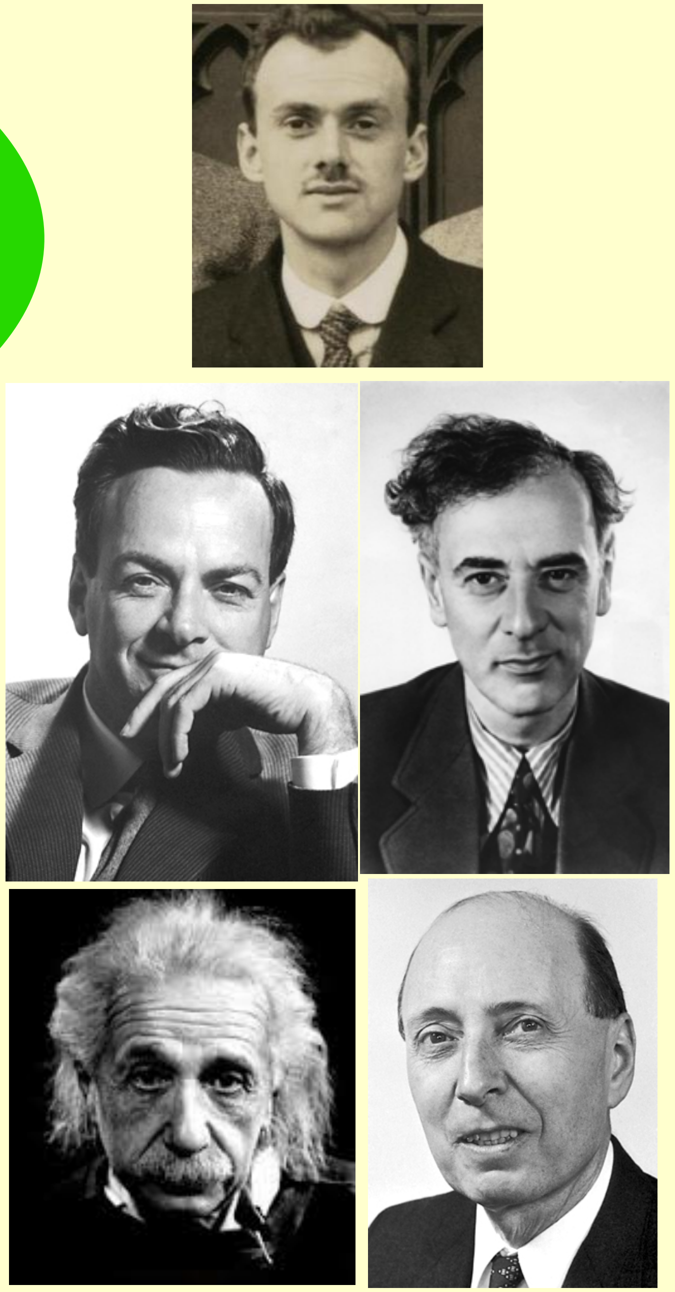
The big picture

Quantum field theory

particle physics

Condensed matter

solid state+stat. physics



Plasma physics

Elasticity

Hydrodynamics

Relativity and cosmology

String theory (holography) ADS/CMT