Chiral Fermion Transport and THz Spectroscopy in Dirac/Weyl Semimetals

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BROOKHAVEN NATIONAL LABORATORY
a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Weyl Metal Workshop, IFT-Madrid, Feb. 24, 2019

Outline:

- **3D chiral fermions in condensed matters**

- **Chiral fermion transport in 3D Dirac/Weyl semimetals**
  - Chiral magnetic effect
  - Anomalous Hall effect and Nernst effect

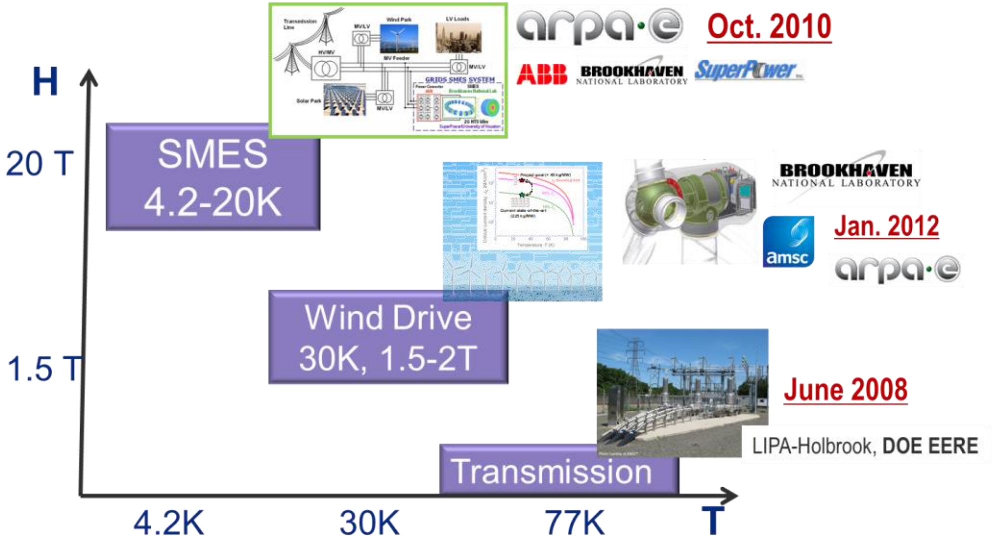
- **Light and chiral fermion interaction**
  - Chiral qubit
  - Coherent THz emission
  - Dark matter detection

Topological photonics – review on Nat. Photon. (2014); Chiral phonons - Science (2018)

Superconductivity

Seven Nobel Prizes

Applications of high temperature superconductor in electricity generation, transmission, and storage

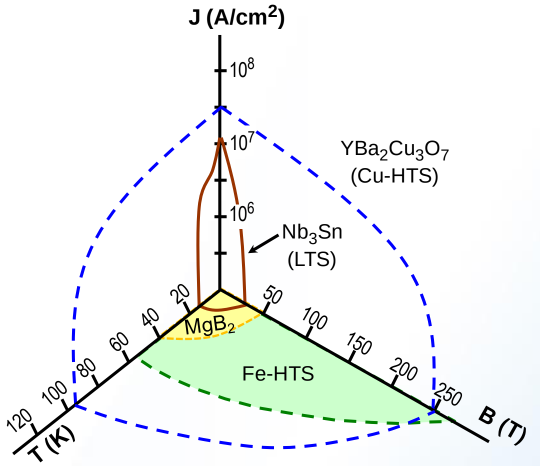


Oct. 2010

Jan. 2012

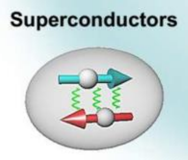
June 2008

LIPA-Holbrook, **DOE EERE**



Li, Rep. Prog. Phys. **74** 124510 (2011)

The BCS Theory (1957)



- Paired electrons
- Medium to provide the “glue” for the Cooper pairs
- Condensates in the ground state

Bardeen, Cooper, Schrieffer,
Phys. Rev. **106**, 162; **108**, 1175 (1957).

Other way to transfer charge without dissipation?

(single) fermion? at higher (or room) temperature?

Other way to build a more robust qubit?

Higher gate/coherence ratio? at higher (or room) temperature?

- **Edge states in topological insulators**
- **Chiral magnetic effect* (3D)**

  The generation of electric current by the chirality imbalance between left- and right-handed fermions in a magnetic field.

$$\vec{J} = \sigma_{\mathrm{CME}}\,\vec{B}$$

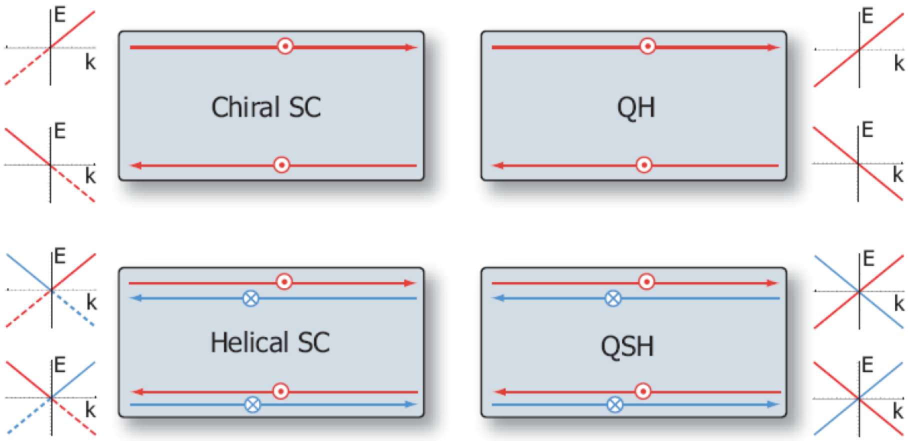
*In the case of conserved chirality, or below the chiral flipping time

○ Edge states in TI (0D*, 1D, 2D) and Chiral SC

Full pairing gap in the bulk, gapless Majorana edge and surface states

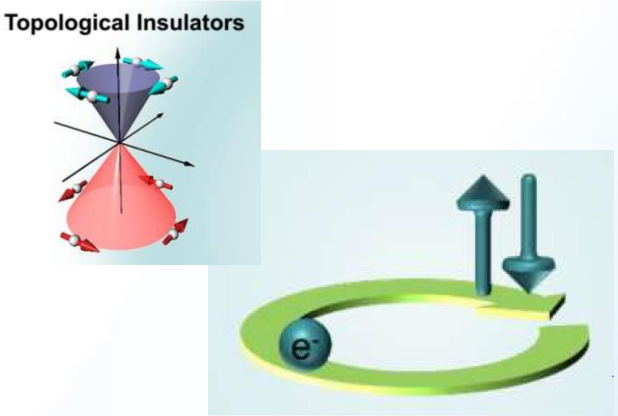
Chiral fermions in TI

Chiral Majorana fermions   Chiral fermions



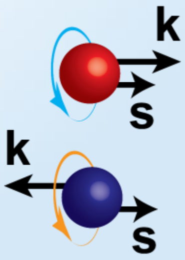
massless Majorana fermions   massless Dirac fermions

(Qi, Hughes, Raghu and Zhang, PRL, 2009)



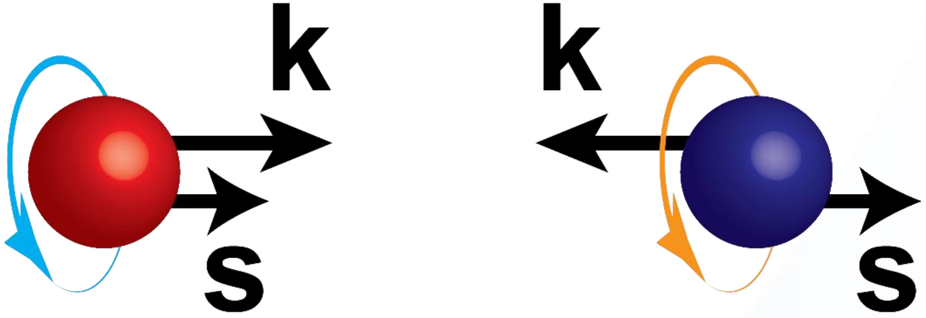
○ Chiral magnetic effect (3D)

The generation of electric current by the chirality imbalance between left- and right-handed fermions in a magnetic field.



Massless Fermions – Parity odd system (P, CP)

Chirality: (electrons, quarks, and neutrinos)



Right-handed

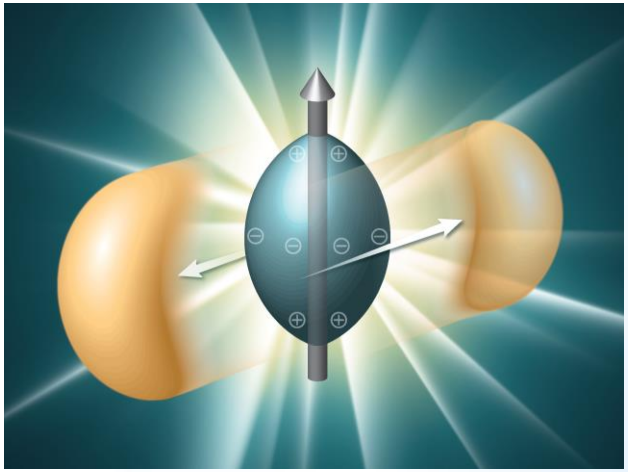
Left-handed

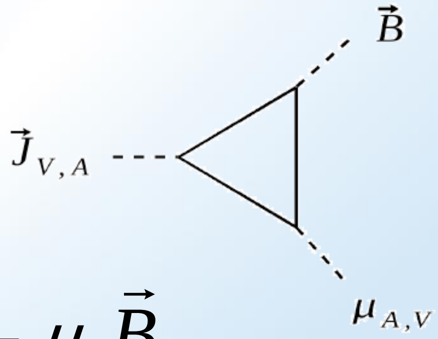
Chiral charge conservation

Quark-gluon plasma in heavy-ion collisions

(RHIC and LHC)

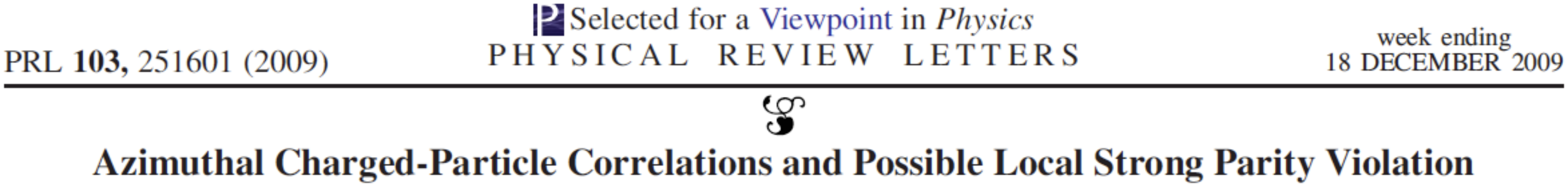
- Extreme relativistic u and d quarks (~ massless fermions)
- Chirality imbalance due to rapid topological transitions mediated by QCD sphalerons (the axial anomaly)
- Huge magnetic field (> 10^{12} Tesla) due to noncentral collisions
- The induced electric current in the quark-gluon plasma is proportional to the chiral chemical potential μ_5 which controls imbalance between left-handed and right-handed quarks.





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

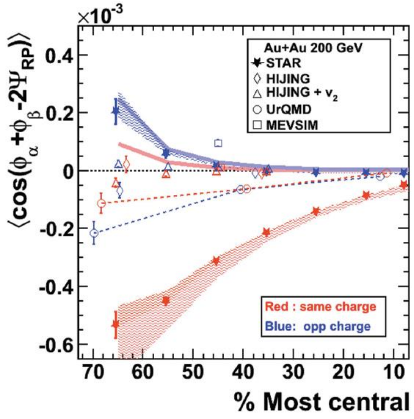
Quark-gluon plasma in heavy-ion collisions



Selected for a Viewpoint in *Physics*

PRL **103,** 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation



(STAR Collaboration)

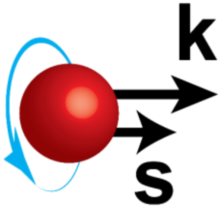
PRL **113,** 052302 (2014) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2014

Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au + Au Collisions at RHIC

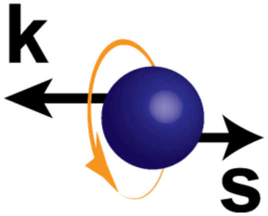
PRL **114,** 252302 (2015) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2015

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

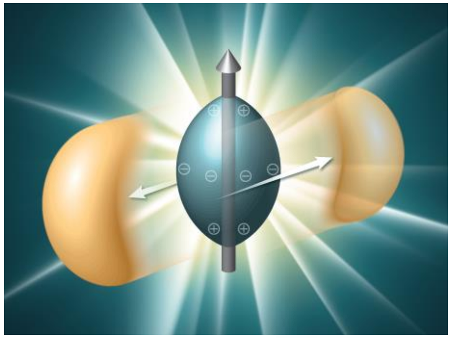
Chiral particles: (ultra-relativistic electrons, quarks, and neutrinos)



Right-handed



Left-handed



Quark-gluon plasma in heavy-ion collisions

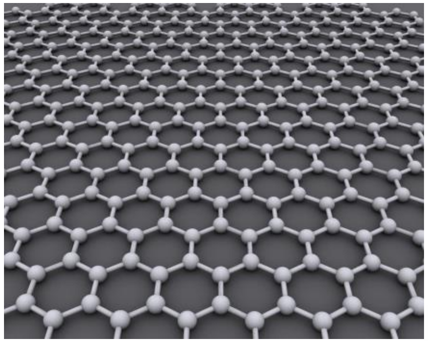
Chiral quasiparticles in condensed matters

3D semimetals with quasi-particles that have a linear dispersion relation have opened a fascinating possibility to study the quantum dynamics of relativistic field theory in condensed matter experiments.

Graphene and 2D Dirac Fermions

-a single atomic plane of graphite*

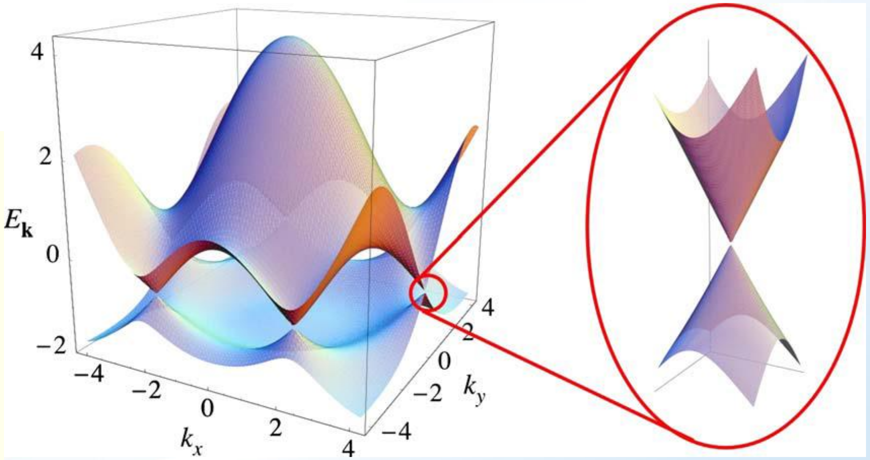
Novoselov, et al. Science 306, 666–669 (2004).



Wikipedia.org

Geim and Novoselov
The Nobel Prize in Physics 2010

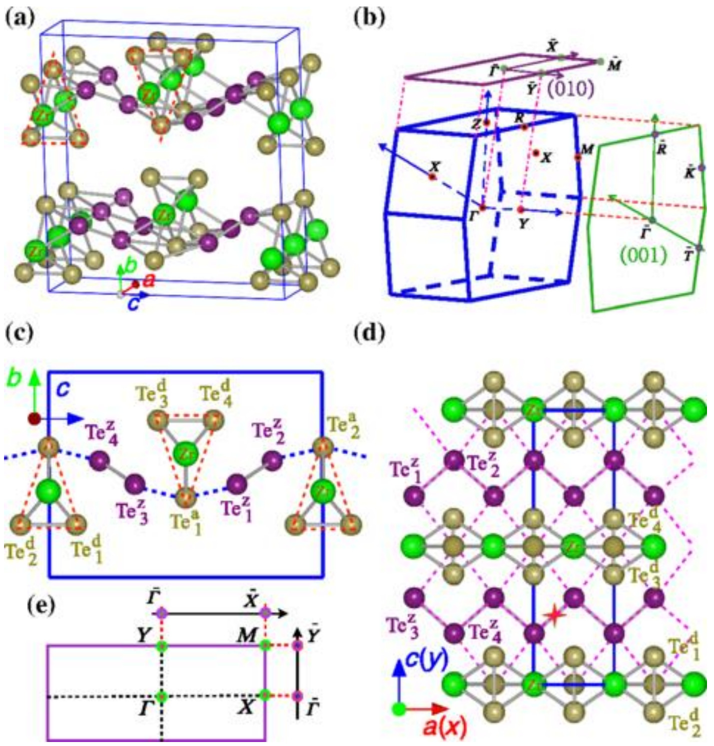
- zero effective mass,
- High mobility - quantum effects robust and survive even at room temperature
- High electrical current, thermal conductivity and stiffness
- Impermeable to gases



Castro Neto, et al Rev. Mod. Phys. 81, 109 (2009)

3D Dirac Semimetals: $ZrTe_5$

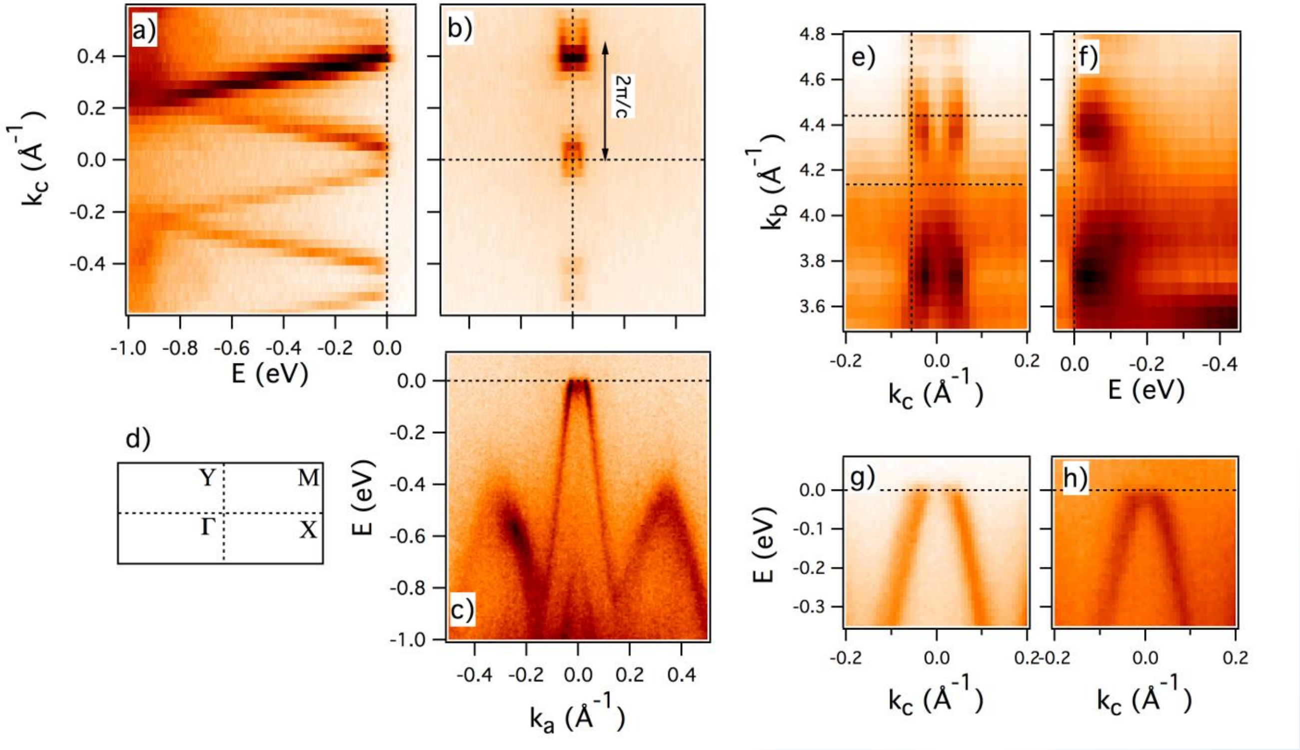
- Crystal structure



Weng, Dai, Fang Phys. Rev. **X** 4, 011002 (2014)

3D Dirac Semimetals: $ZrTe_5$

- Electronic structure by ARPES

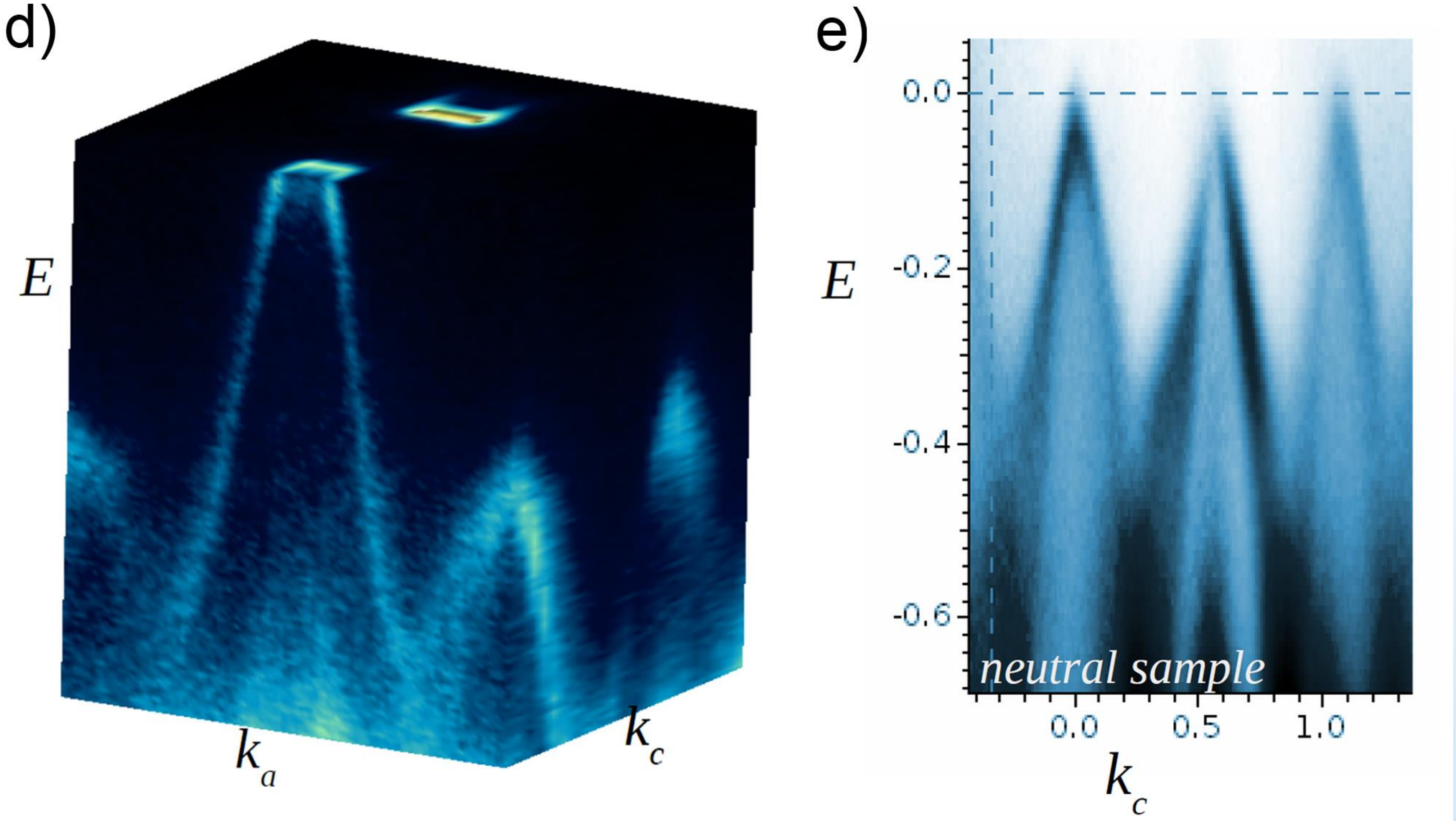


- The states forming the small, hole-like Fermi surface (FS) disperse linearly over a large energy range, indicating a Dirac-like dynamics of carriers
- The velocity, or the slope of dispersion, is very large, v_a ~ 6.4 eVÅ(~ *c*/300), v_c ~ 4.5 eVÅ

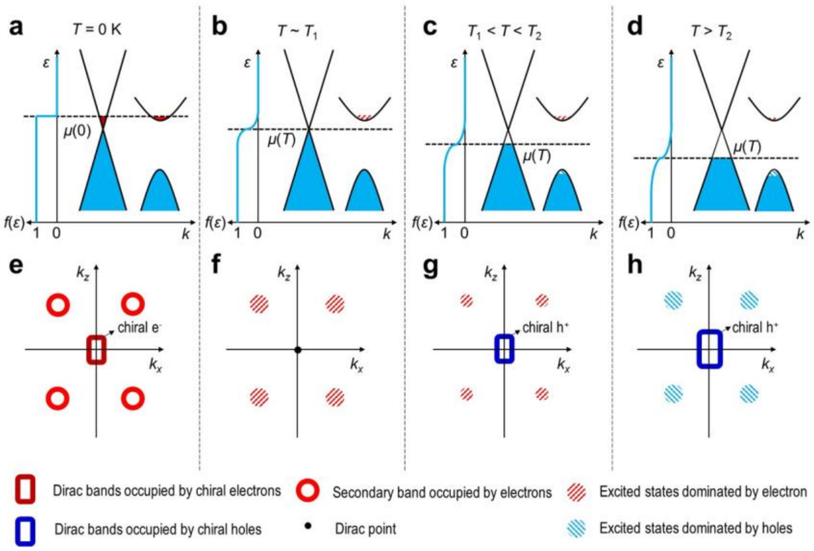
Li, et al arXiv:1412.6543, Nature Physics (2016) doi:10.1038/nphys3648

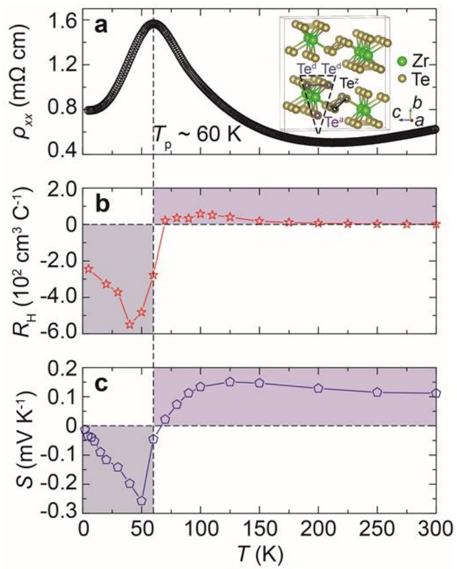
3D Dirac Semimetals: $ZrTe_5$

- Electronic structure by ARPES

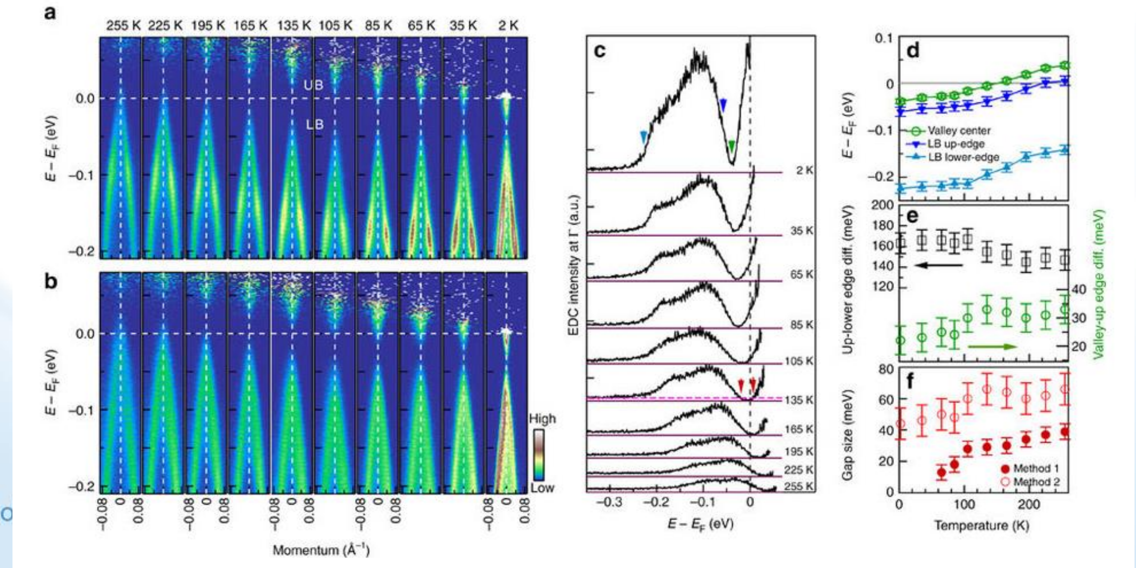


Temperature-induced Lifshitz transition in $ZrTe_5$*





H. Chi, QL et al New J. Phys. **19** 015005 (2017)

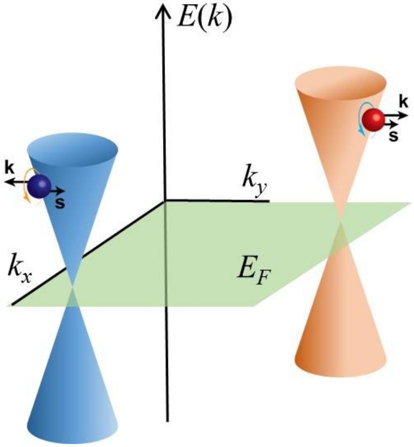


Y. Zhang, et al Nature Communications doi:10.1038/ncomms15512 (2017)

3D semimetals with linear dispersion

Weyl semimetal

(non-degenerated bands)



TaAs

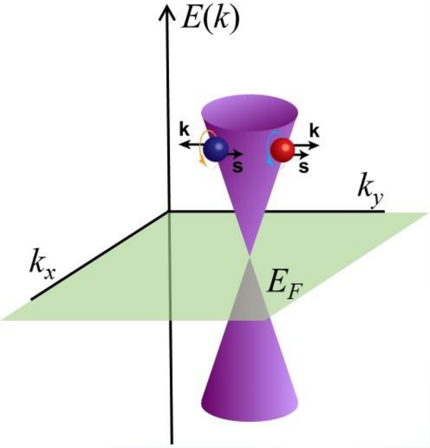
NbAs

NbP

TaP

Dirac semimetal

(doubly degenerated bands)

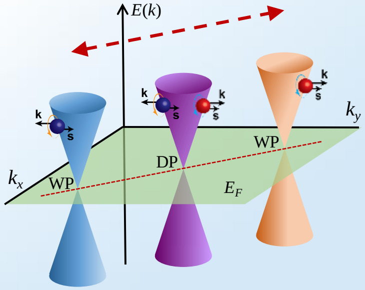


$ZrTe_5$

Na_3Bi,

Cd_3As_2

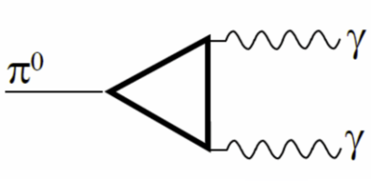
$$2\pi/l_B = 2\pi/\sqrt{\frac{\hbar c}{eB}}$$



- The Dirac point can split into two Weyl points either by breaking the crystal inversion symmetry or time-reversal symmetry.
- Each Weyl point acts like a singularity of the Berry curvature in the Brillion Zone – magnetic monopole in *k*-space

Chiral anomaly (Adler-Bell-Jackiw anomaly)

Rapid decay of π^o into two photons γ



Adler, Phys. Rev. 177, 2426 (1969)
Bell & Jackiw, Nuov Cim 60, 47–61 (1969)

Nielsen and Ninomiya (1983) - Physics Letters B130, 389 (1983)

“The Adler-Bell-Jackiw anomaly and **Weyl** fermions in a crystal”

Son and Spivak (2013) - Phys. Rev. B, 88, 104412 (2013).

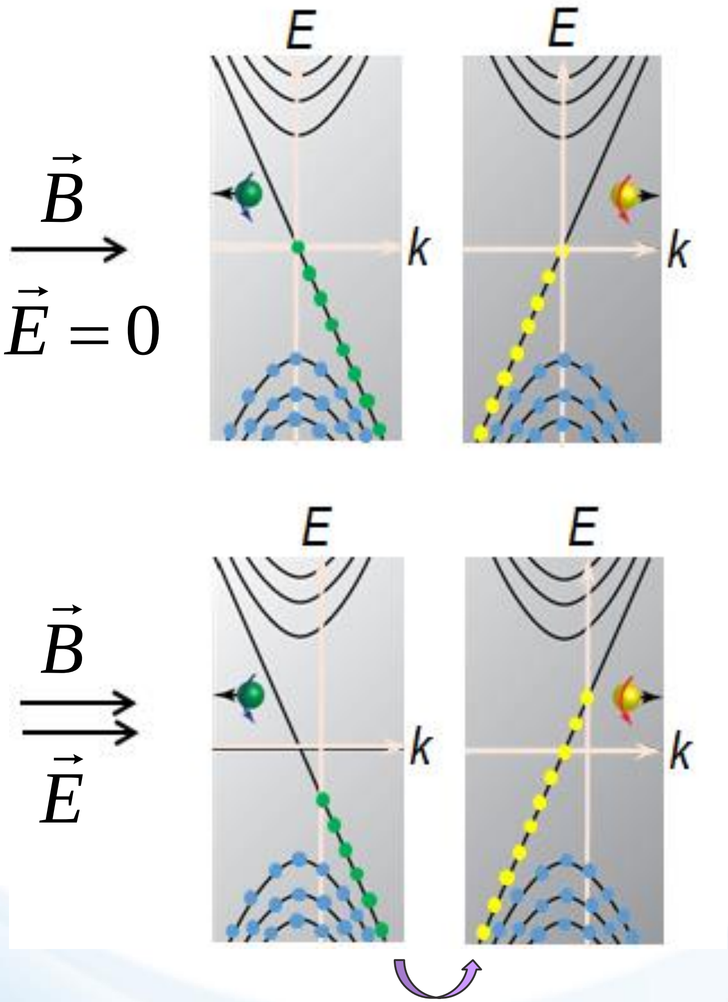
“Chiral anomaly and classical negative magnetoresistance of Weyl metals.”

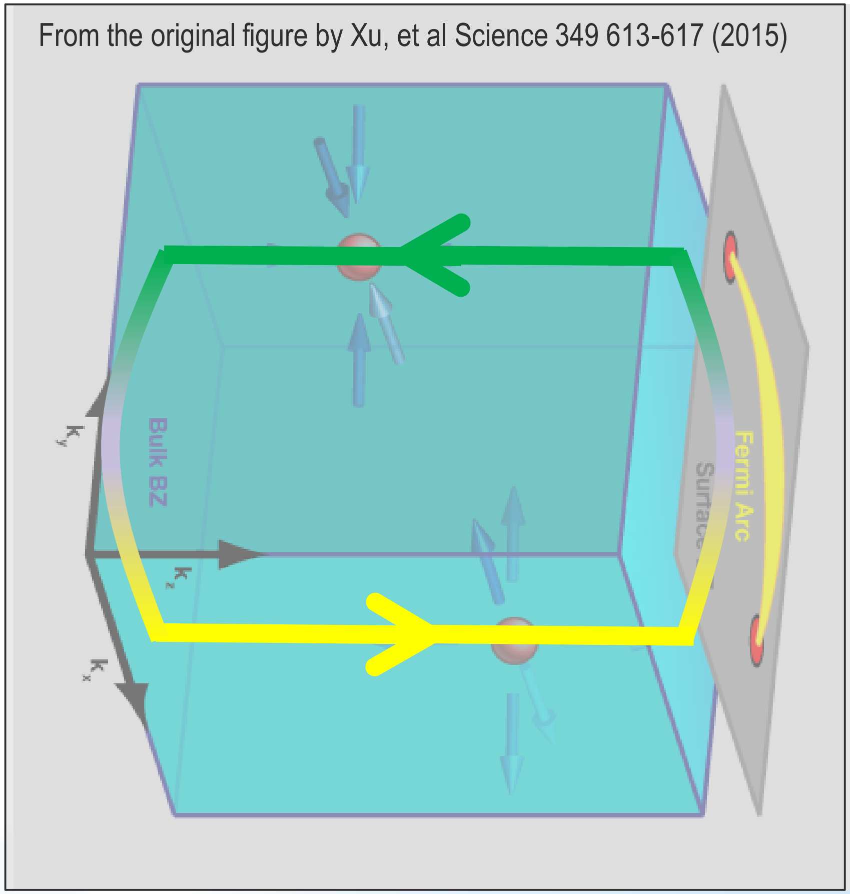
Burkov (2014) -Phys. Rev. Lett., 113, 247203 (2014).

“Chiral anomaly and diffusive magneto-transport in Weyl metals”.

Observable: a large, negative longitudinal magnetoresistance ($\vec{B}//\vec{E}$) in Dirac/Weyl semimetals

Chiral magnetic effect, “Weyl orbits”, charge pumping




From the original figure by Xu, et al Science 349 613-617 (2015)

Chiral charges in Dirac semimetals

Chiral chemical potential:

$$\mu_5 \equiv \mu_L - \mu_R$$

Density of chiral charge:

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

Rate of chiral charge generaton:

$$\frac{d\rho_5}{dt} = \frac{e^2}{4\pi^2\hbar^2 c}\vec{E}\cdot\vec{B} - \frac{\rho_5}{\tau_v}$$

$$\partial_\mu j_5^\mu = \frac{e^2}{4\pi^2\hbar^2 c} F^{\mu\nu}\tilde{F}$$

Chiral anomaly

Chirality-changing scattering time

For $t >> \tau_v$

$$\rho_5 = \frac{e^2}{4\pi^2\hbar^2 c}\vec{E}\cdot\vec{B}\tau_v$$

K. Fukushima, D. Kharzeev, and H. Warringa. Phys. Rev. D, 78, 074033 (2008).

D. E. Kharzeev. “The chiral magnetic effect and anomaly-induced transport”. Progress in Particle and Nuclear Physics **75**, 133 (2014).

Chiral Magnetic Effect in Condensed Matter

Chiral chemical potential:

$$\mu_5 = \frac{3}{4}\frac{v^3}{\pi^2}\frac{e^2}{\hbar^2 c}\frac{\vec{E}\cdot\vec{B}}{T^2+\frac{\mu^2}{\pi^2}}\tau_v$$

Chiral magnetic current:

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

$$J^i_{CME} = \boxed{\frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_v}{T^2+\frac{\mu^2}{\pi^2}}B^i B^k} E^k = \boxed{\sigma^{ik}_{CME}} E^k$$

CME conductivity
for ***B***//***E***:

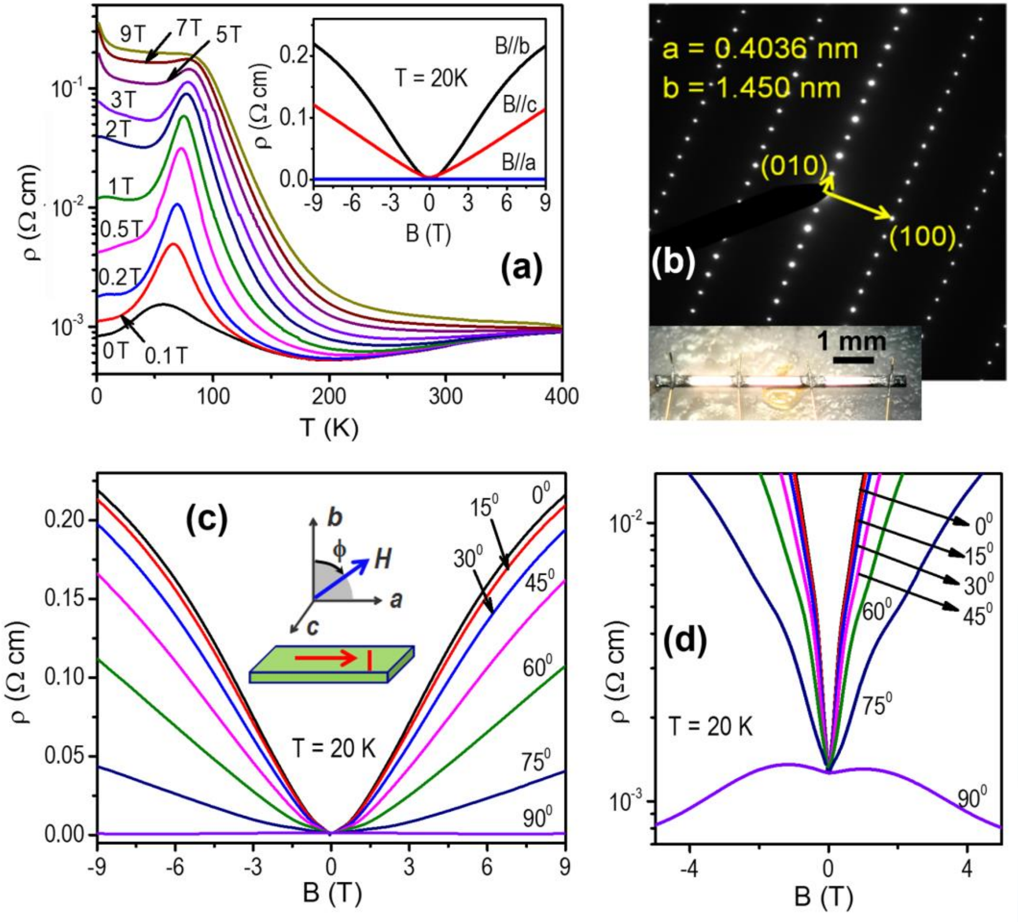
$$\sigma^{zz}_{CME} = \frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_v}{T^2+\frac{\mu^2}{\pi^2}}B^2 = \alpha(T)\cdot B^2$$

$$J = J_{\mathrm{Ohm}} + J_{\mathrm{CME}} = (\sigma_{\mathrm{Ohm}} + \sigma_{\mathrm{CME}})E$$

K. Fukushima, D. Kharzeev, and H. Warringa. Phys. Rev. D, 78, 074033 (2008).

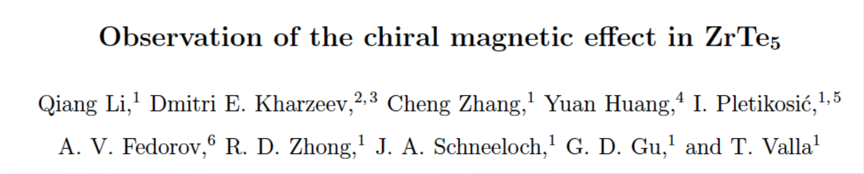
D. E. Kharzeev, Progress in Particle and Nuclear Physics **75**, 133 (2014).

Magneto-transport properties of $ZrTe_5$



- Huge positive magnetoresistance when magnetic field is perpendicular to the current ($\phi = 0$)
- Large negative magnetoresistance when magnetic field is parallel with the current ($\phi = 90^o$)

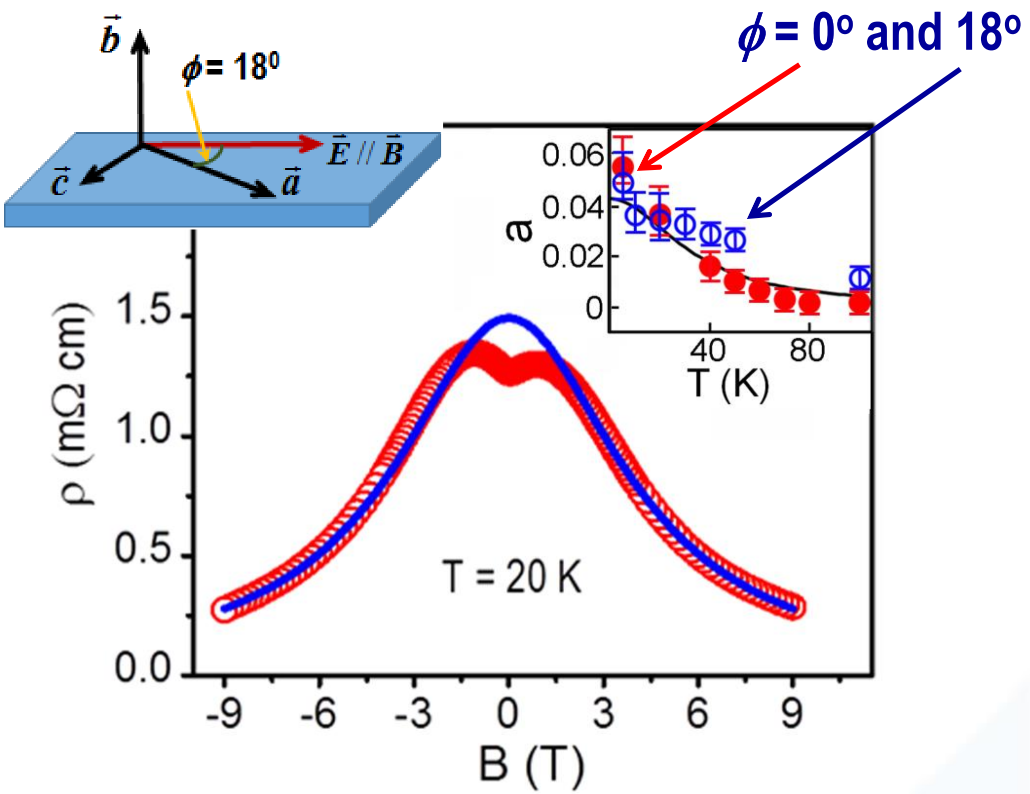
arXiv:1412.6543

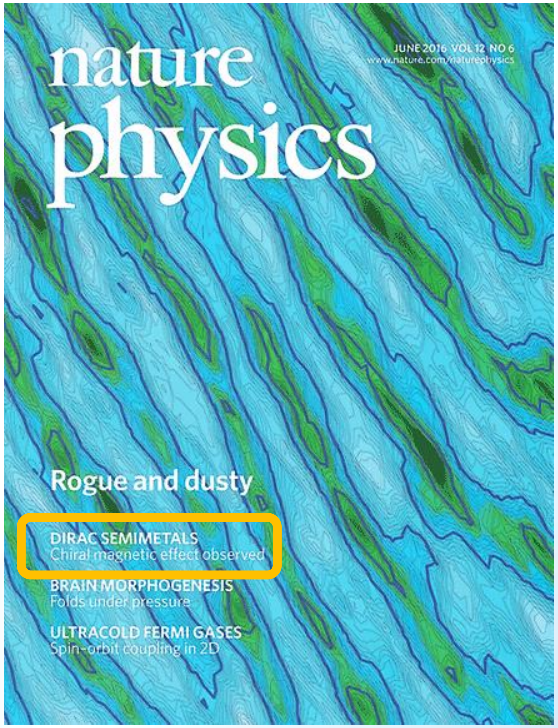


Observation of the chiral magnetic effect in $ZrTe_5$

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]

Magneto-transport properties at H//I





nature physics

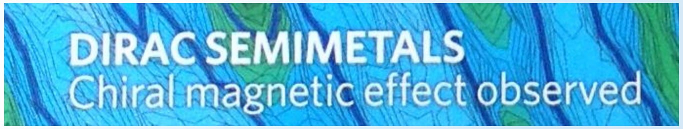
JUNE 2016 VOL 12 NO 6
www.nature.com/naturephysics

Rogue and dusty

DIRAC SEMIMETALS
Chiral magnetic effect observed

BRAIN MORPHOGENESIS
Folds under pressure

ULTRACOLD FERMI GASES
Spin-orbit coupling in 2D



DIRAC SEMIMETALS
Chiral magnetic effect observed

$$\sigma = \sigma_0 + \sigma_{\mathrm{CME}} \qquad \sigma^{zz}_{CME} = \frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_V}{T^2+\frac{\mu^2}{\pi^2}}B^2 = a(T)B^2$$

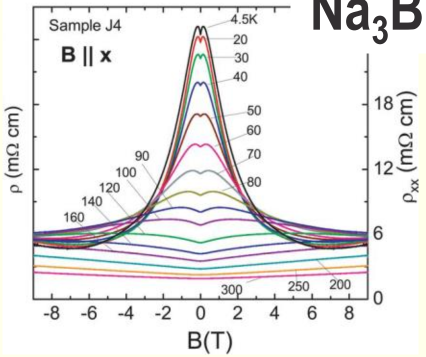
At 20K, ρ_0 ~ 1.2 mΩcm, Δ ≈ 50 meV, μ ~ 9 meV, ν ~ 1/300c.

Li, et al arXiv:1412.6543,
doi:10.1038/nphys3648

Chiral magnetic effect in Dirac/Weyl semimetals

Dirac semimetals:

Na_3Bi



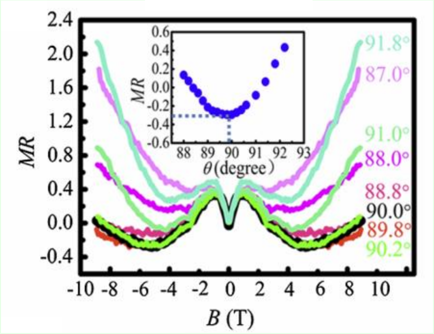
$ZrTe_5$ - Q. Li, et al (BNL and Stony Brook Univ.)
arXiv:**1412.6543**; Nat. Phys., doi:10.1038/NPHYS3648
G. Zheng, M. Tian et al (CHMFL, USTC et al)
arXiv:**1603.05351**; Phys. Rev. B

Na_3Bi - J. Xiong, N. P. Ong et al (Princeton Univ.)
arxiv:**1503.08179**; Science

Cd_3As_2- C. Li et al (Peking Univ. China)
arxiv:**1504.07398**; Nat. Commun

Weyl semimetals

TaAs



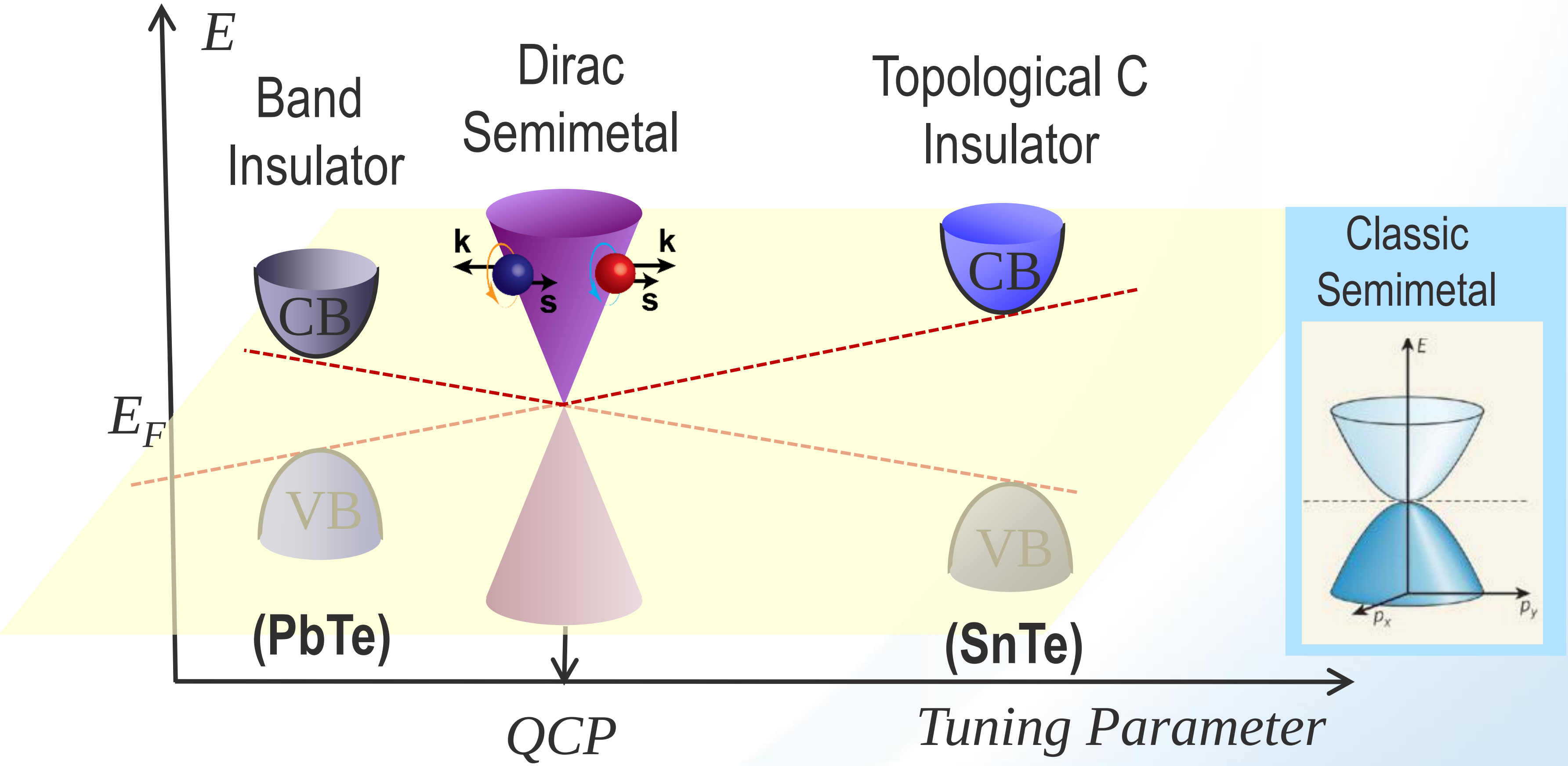
TaAs - X. Huang et al (IOP, China)
arxiv:**1503.01304**; Phys. Rev. X

NbP - Z. Wang et al (Zhejiang Univ. China)
arxiv:**1506.00924**, Phys. Rev. B

TaP - Shekhar, C. Felser, B. Yang et al (MPI-Dresden)
arxiv:**1506.06577**, Nat. Commun.

$Bi_{1-x}Sb_x$ at $x \approx 0.03$ - Kim, et al. “Dirac versus Weyl Fermions in Topological Insulators: Adler-Bell-Jackiw Anomaly in Transport Phenomena” Phys. Rev. Lett., 111, 246603 (2013).

Topological phase transition



TCI : Topological Crystalline Insulator (SnTe and SnSe)

- **PbTe**

-- one of the first materials studied by Ioffe and colleagues in 1950s

A. F. Ioffe, Semiconductor Thermoelements and Thermoelectric Cooling (Infosearch, London,1957)

- **$PbTe_xSe_{1-x}$ (p-type) $Pb_{1-x}Sn_xTe$ (n-type)**

-- suggested by S. V. Airapetyants et al *- Zh. Tekh. Fiz. 27 2167 (1957)*

- **$Pb_{1-x}Sn_xTe$**

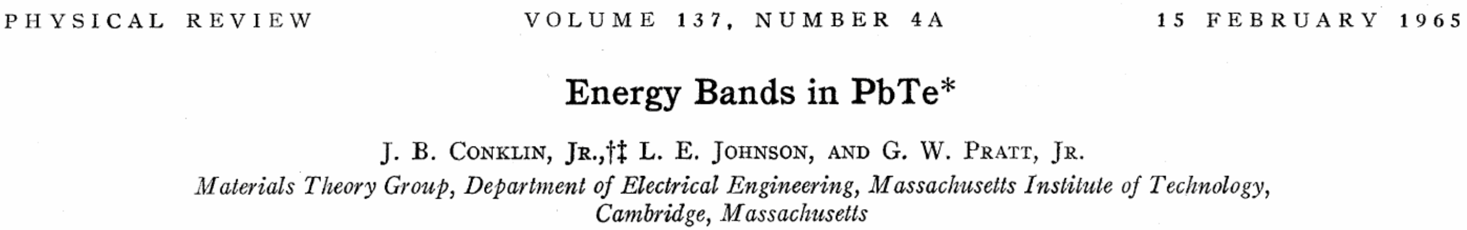
-- can be both n- and p-type *- D. A. Wright, Metall. Rev. 15 147 (1970)*

Energy gap goes to zero at x = 0.4

- **$Pb_{0.75}Sn_{0.25}Te$ (x=0.25)**

-- recommended by Rosi et al

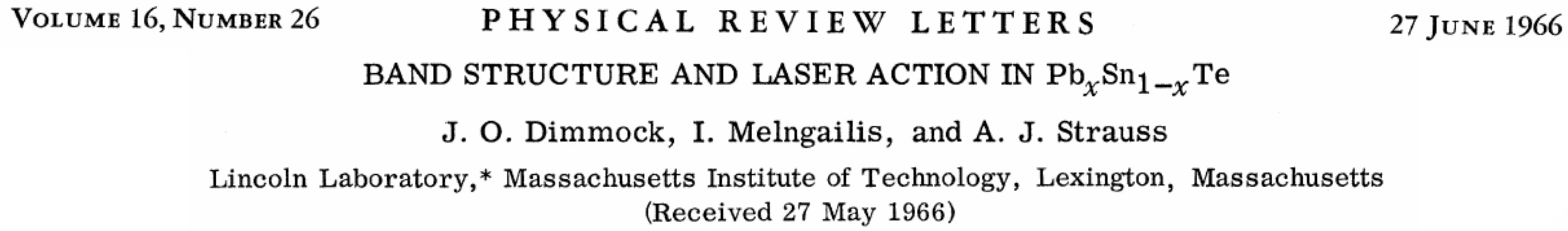
- *F.D. Rosi, E. F. Hocking, N. E. Lindernbald: RCA Rev. 22, 82 (1961)*



PHYSICAL REVIEW VOLUME 137, NUMBER 4A 15 FEBRUARY 1965

Energy Bands in PbTe*

J. B. CONKLIN, JR.,†‡ L. E. JOHNSON, AND G. W. PRATT, JR.
Materials Theory Group, Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

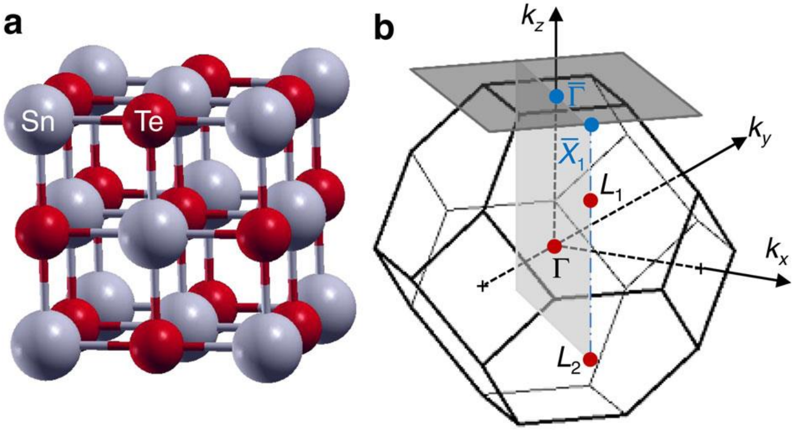


VOLUME 16, NUMBER 26 PHYSICAL REVIEW LETTERS 27 JUNE 1966

BAND STRUCTURE AND LASER ACTION IN $Pb_xSn_{1-x}Te$

J. O. Dimmock, I. Melngailis, and A. J. Strauss
Lincoln Laboratory,* Massachusetts Institute of Technology, Lexington, Massachusetts

(Received 27 May 1966)



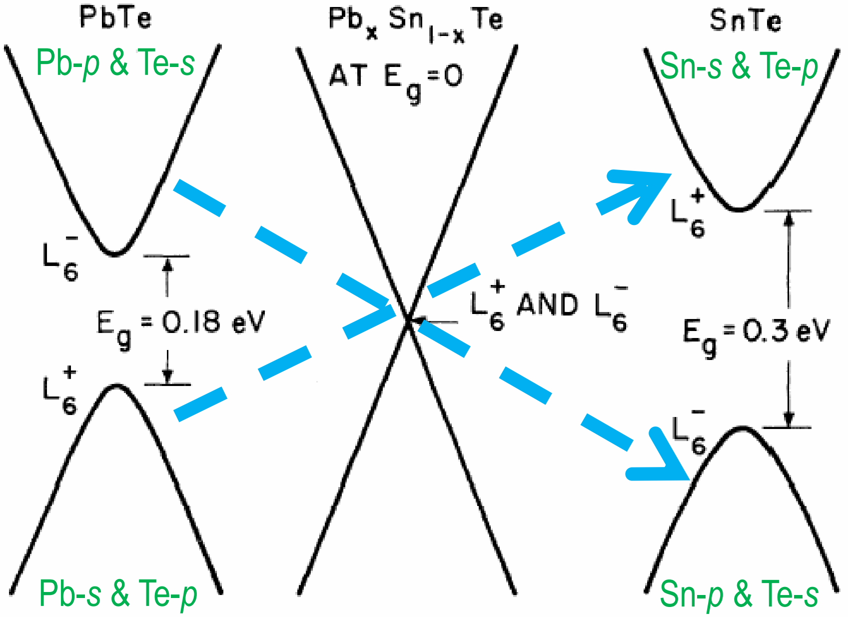
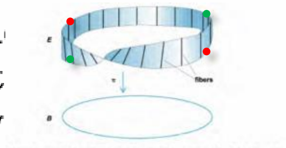


FIG. 2. Schemati ı of the valence and
conduction bands at for the composition
at which the energy d for SnTe.

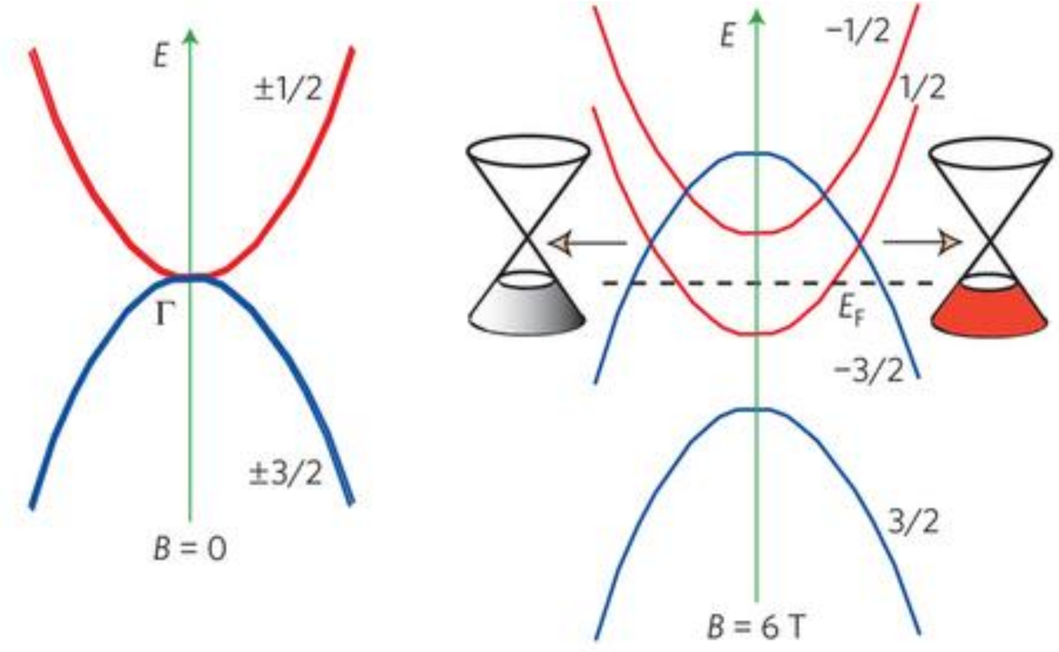


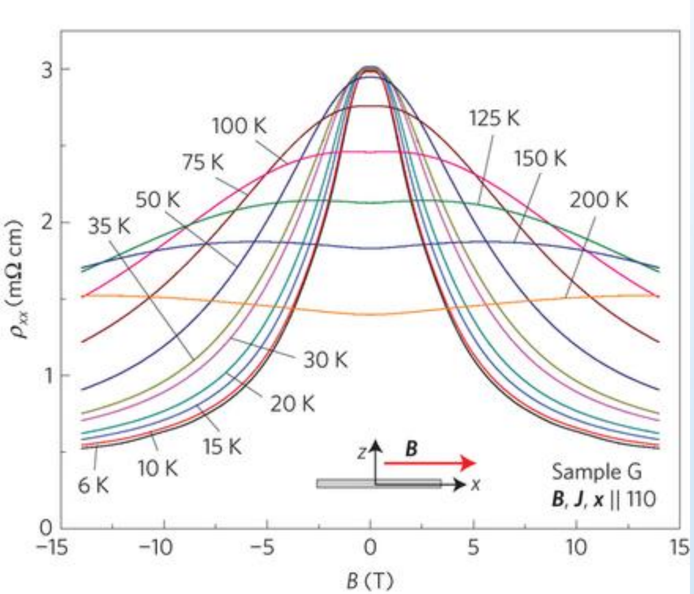
Möbius strip, the simplest nontrivial example of a fiber bundle

$Pb_{1-x}Sn_xTe$

The field-induced band crossing in GdBiPt and CME

- Half-Heusler GdPtBi is a semimetal with quadratic bands.
- In a magnetic field, the Zeeman energy leads to Weyl nodes

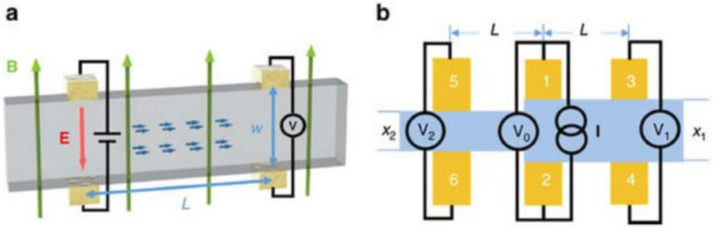


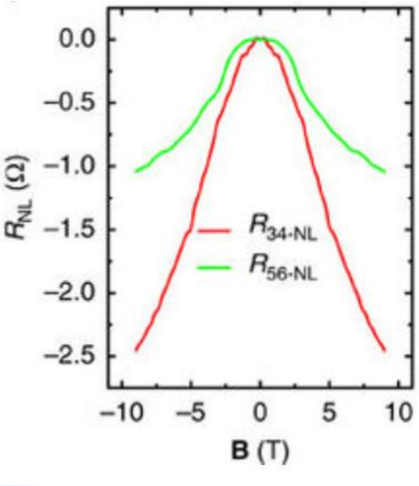


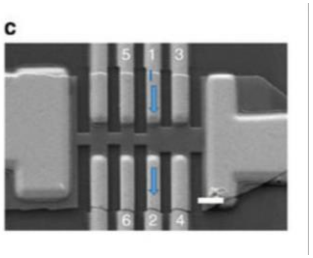
Hirschberger, et al, Nature Materials (2016) doi:10.1038/nmat4684

Room-temperature chiral charge pumping

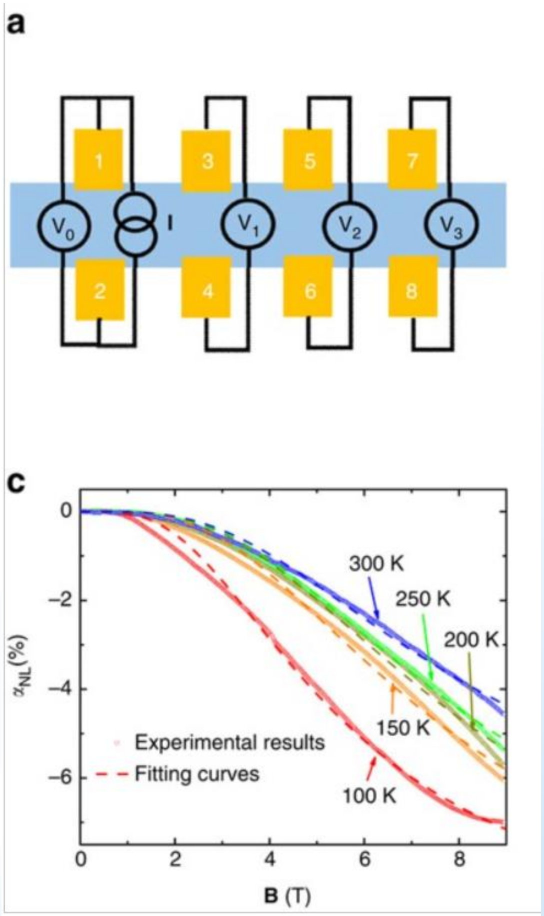
Chiral length: L_c > a few μm







In Cd_3As_2



Zheng et al, Nature Communications **8**, 13741 (2017)

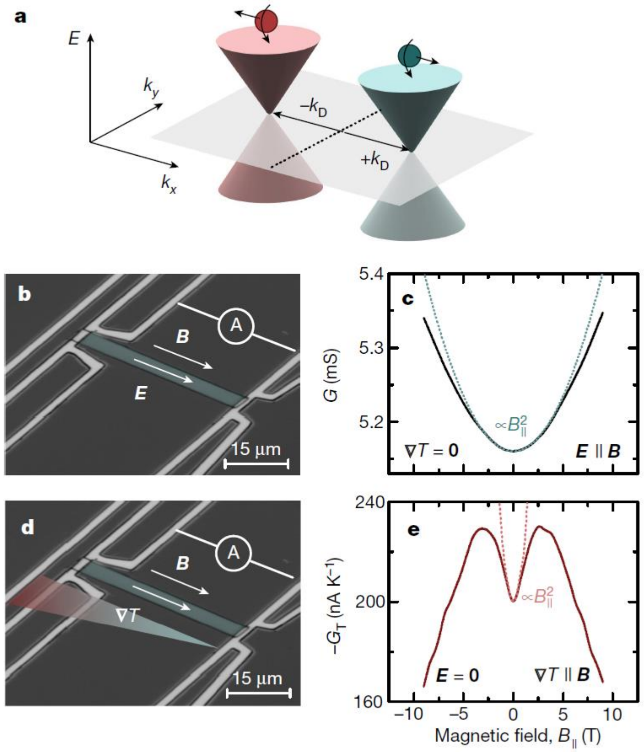
Robustness of chiral fermion transport

- **Known:**
  - Chiral flipping is a rare event that involves large quasi-momentum transfer in Weyl semimetals or scattering between different point-group

    $\boldsymbol{\tau_v}$ – **chirality-change scattering relaxation time**
  - Long chiral charge scattering length $L_v (= v_F \cdot \tau_v)$
  - CME exists at room temperature in Dirac semimetals, even with small band gap, band non-linearity, and crystal deformation
- **Unknown:**
  - What determines $\boldsymbol{\tau_v}$? – chiral fermion-phonon interaction, defects, etc
  - Chiral flipping mechanism

Mixed Axial–Gravitational Anomaly

– Thermopower of NbP in a magnetic field



Gooth et al Nature **547** 324 (2017)

- ○ Mixed axial–gravitational anomaly: Curved space-time provides a distinct contribution to a chiral imbalance,
- ○ A mixed axial–gravitational anomaly in flat space-time leads to a positive magneto-thermoelectric conductance for Weyl fermions

Low field limit: $$G = \frac{J}{E} = G_x + c_1 a_c^2 B_\parallel^2$$

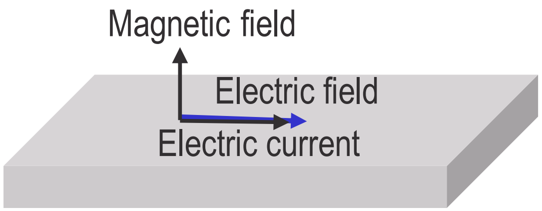
$$G_T = \frac{J}{|\nabla T|} = G_{T,x} + c_2 a_c a_g B_\parallel^2$$

Theoretical References:

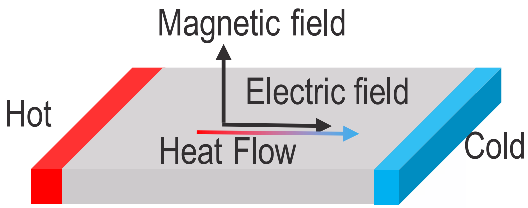
Landsteiner et al “Gravitational Anomaly and Transport Phenomena” Phys. Rev. Lett. **107**, 021601 (2011)

Lucas et al “Hydrodynamic theory of thermoelectric transport and negative magnetoresistance in Weyl semimetals.” Proc. Natl Acad. Sci. USA **113**, 9463 (2016).

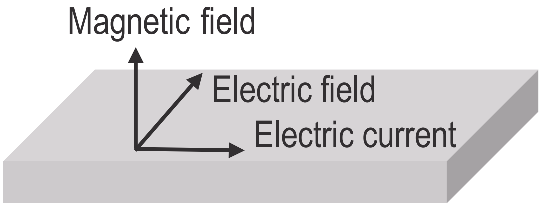
Transport coefficients in condensed matters



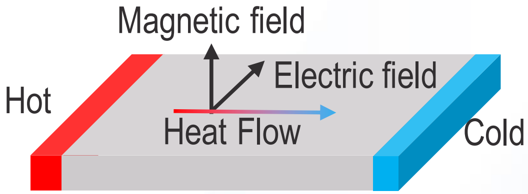
Magneto-resistance



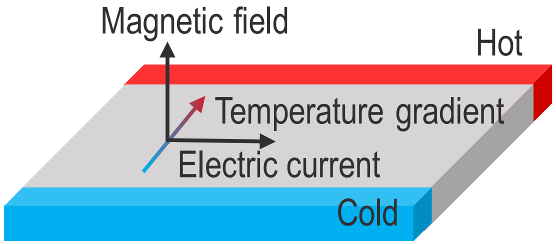
Thermopower (Seebeck)



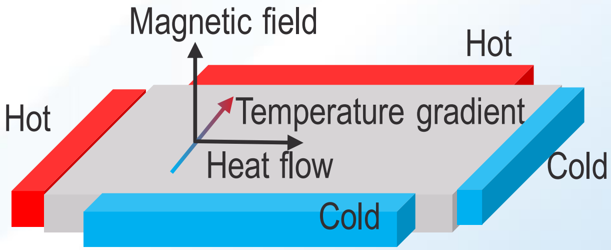
Hall



Nernst



Ettingshausen

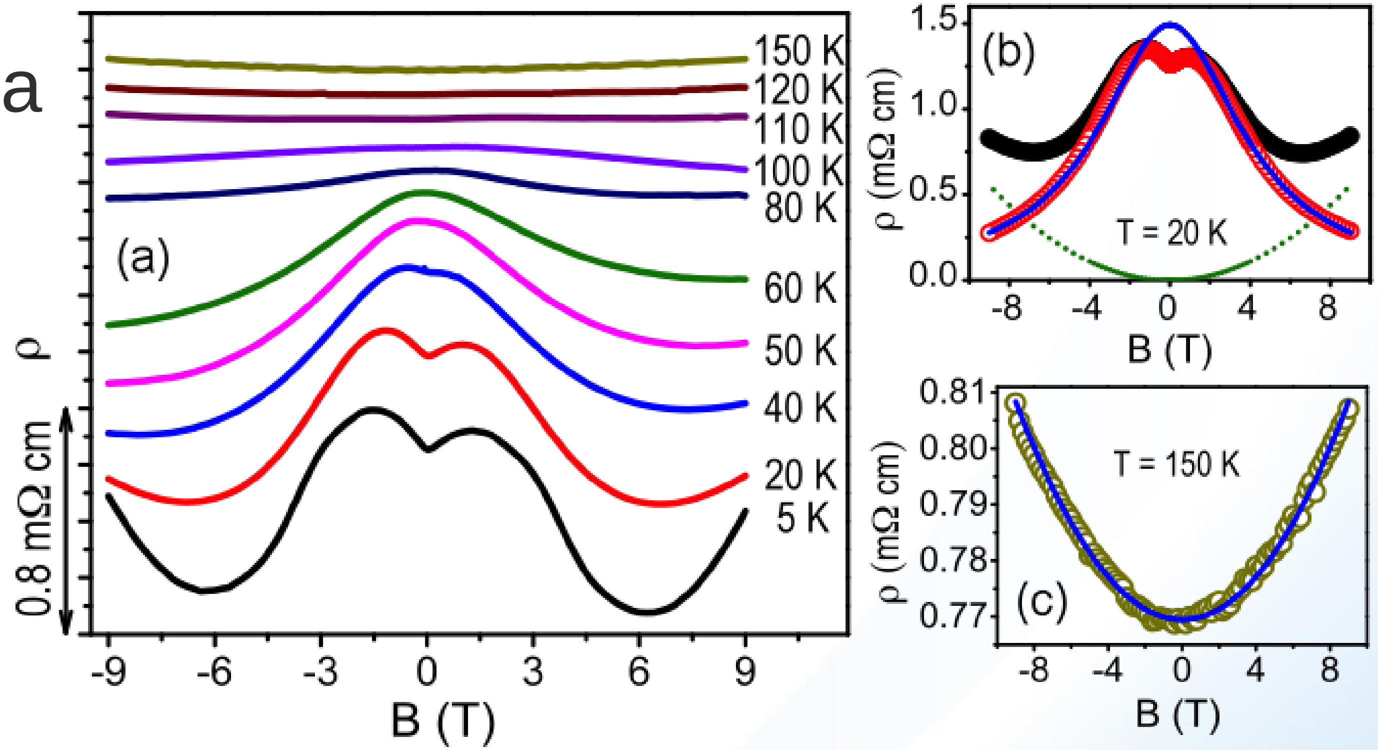


Righi-Leduc

Thermal Hall Effect

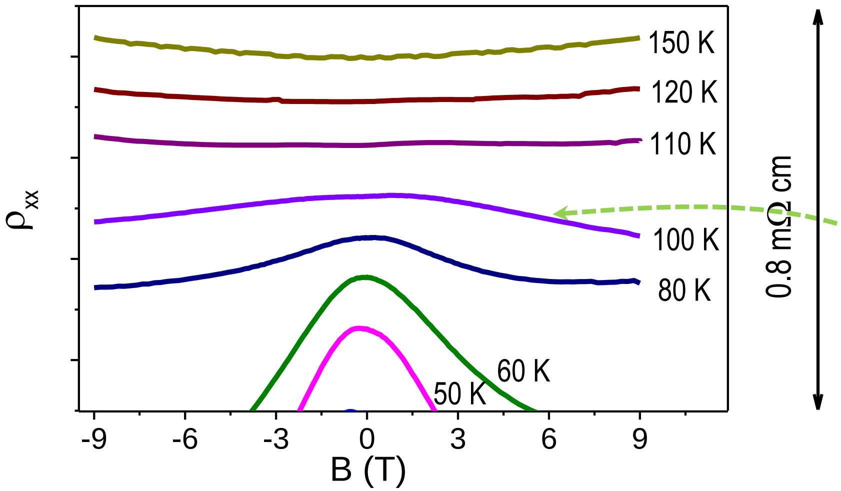
Magneto-resistance at B//E

Raw data



- Negative longitudinal magnetoresistance develops at ~ 100 K

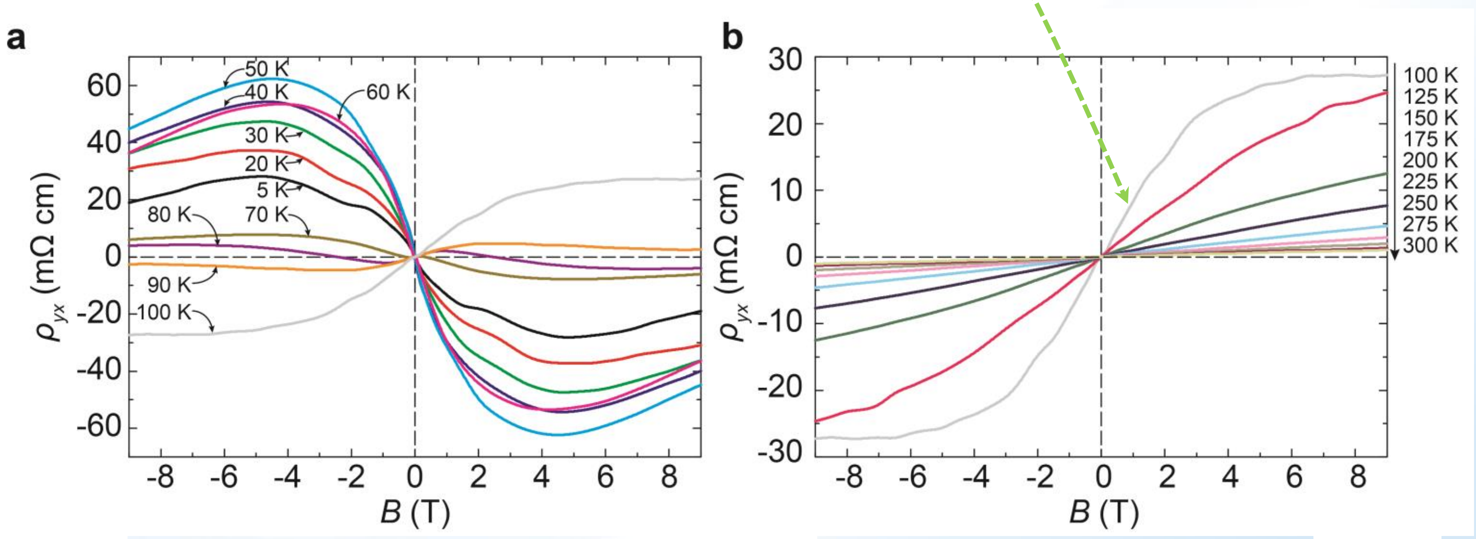
Hall signature at onset of chiral magnetic effect in $ZrTe_5$



Berry curvature leads to anomalous velocity: (no external **B**)

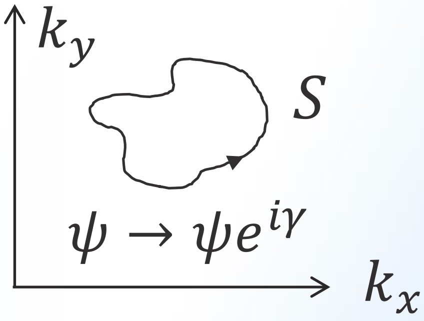
$$\mathbf{v}_{\mathbf{A}} = \mathbf{E}\times\mathbf{\Omega}_{\mathbf{k}}$$

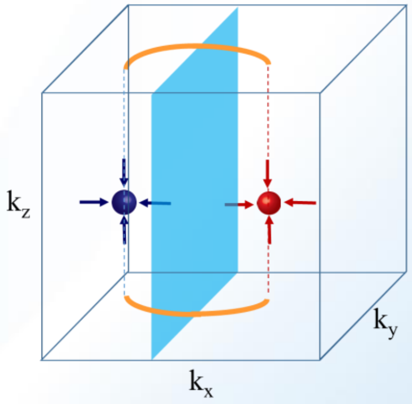
$$\sigma_{xy}^{\mathrm{AHE}} = \sum_{i,\mathbf{k}} n_{i,\mathbf{k}}\,\mathbf{\Omega}_{i,\mathbf{k}}^{z}$$



H. Chi, QL et al New J. Phys. (2017)

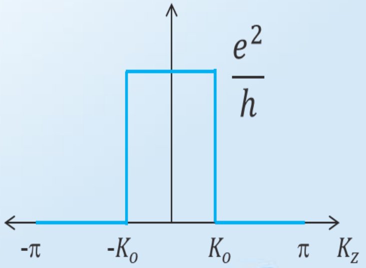
Berry curvature induced anomalous Hall effect and anomalous Nernst effect





- Berry curvature: $\vec{\Omega}_k = i\nabla_k \times \langle \psi(k)|\nabla_k|\psi(k)\rangle$
- Berry phase: $\gamma = \oint_S \vec{\Omega} \cdot d\vec{a}_k$
- Chiral fermion velocity: $\frac{\partial \vec{r}}{\partial t} = \vec{\nabla}_{\vec{k}}\varepsilon + \frac{\partial \vec{k}}{\partial t} \times \vec{\Omega}$
- Force: $\frac{\partial \vec{k}}{\partial t} = q\vec{\nabla}_{\vec{r}}\phi + q\frac{\partial \vec{r}}{\partial t} \times \vec{B}$
- Anomalous Hall effect: $\sigma_{yz} = \frac{e^2}{\hbar}\int d^3k\, \Omega_z f_o$
- Quantized anomalous Hall conductance: $\sigma_{yz}^{3D} = \frac{e^2}{h} 2K_o$

Yang et at PRB 84, 075129 (2011)

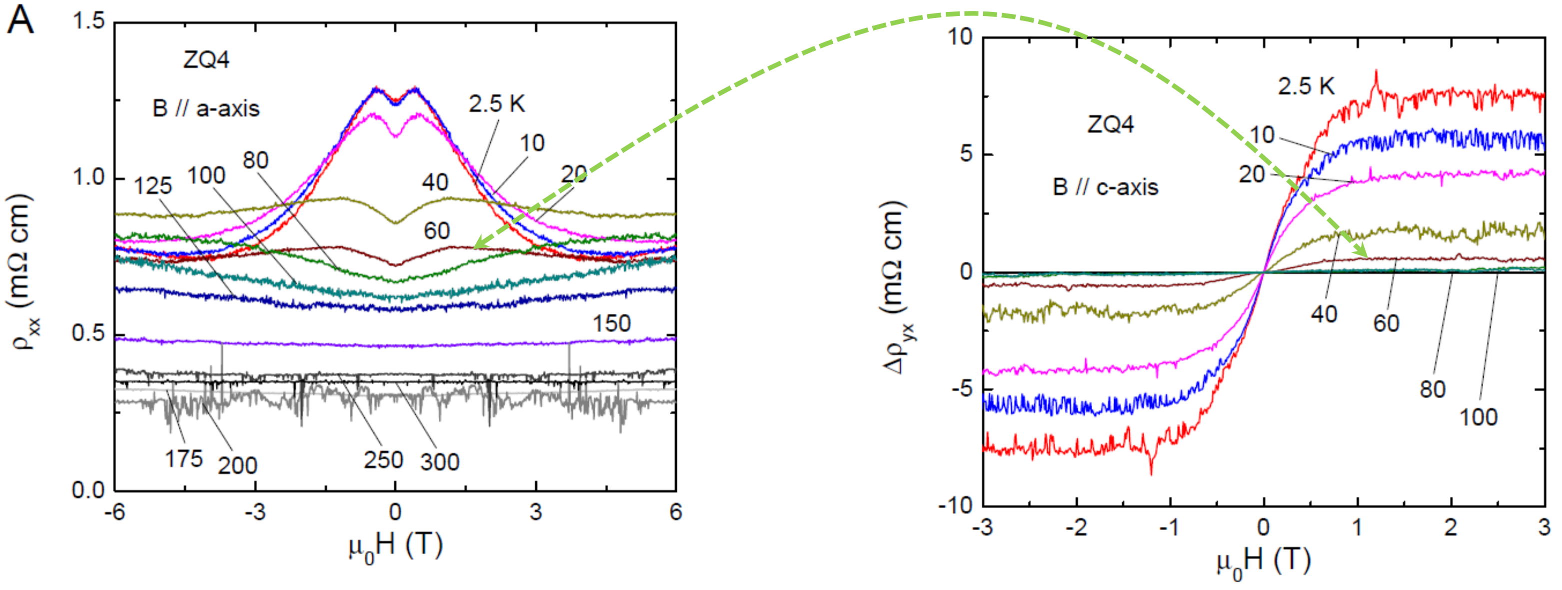


- Anomalous Nernst effect: $\alpha_{yz} = \frac{k_B e}{\hbar}\int d^3k\, \Omega_z S_k$

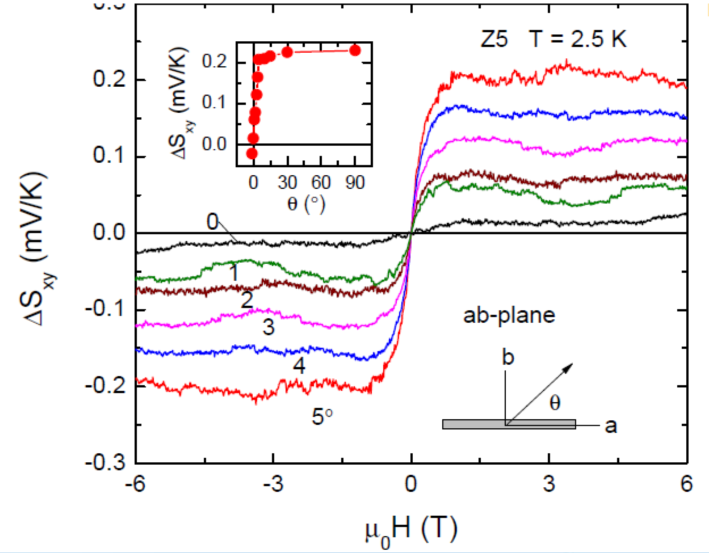
$f_o = (e^{\frac{\varepsilon-\mu}{k_B T}} + 1)^{-1}$ $\quad S_k = -f_o \ln f_o - (1 - f_o)\ln(1 - f_o)$

Anomalous Hall and Anomalous Nernst effect in ZrTe$_5$

(Data and crystals from Princeton U.) **T. Liang, Nat. Phys. 14, 451 (2018)**



- Hall signatures of Berry curvature at onset of chiral anomaly
- Anomalous Hall effect accompanied by anomalous Nernst effect



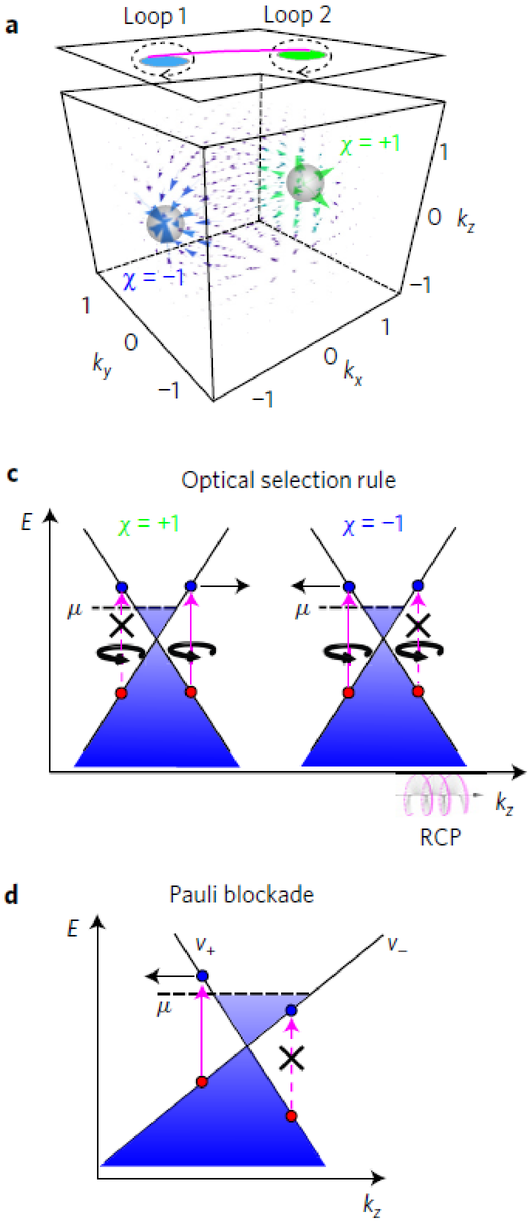
Figures from P. Ong/March meeting 2018

Phase Sensitive Probes to Weyl Fermion Chirality

ARPES, STM, and transport experiments so far are not phase sensitive to the chirality.

One proposal is to use pump probe ARPES (a mid-infrared pump and a soft X-ray probe) to measure the transient spectral weight upon shining circularly polarized pump light.

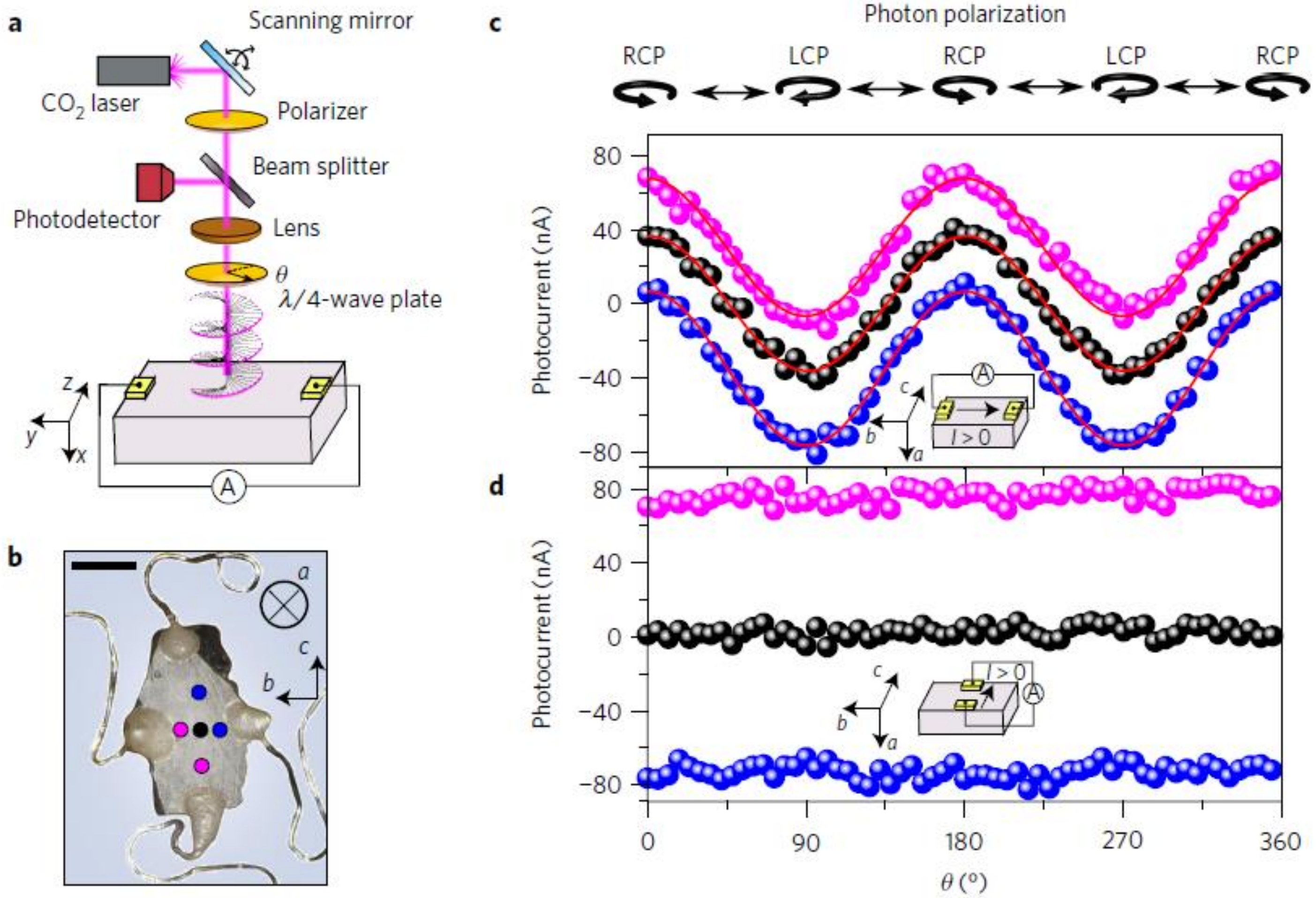
Another proposal is to measure mid-infrared photocurrent response to the chirality. Photocurrents induced by circularly polarized light*



*Ma et al, Nature Physics 13, 842 (2017)

Detection and manipulation of chiral Weyl fermions by optical means

TaAs

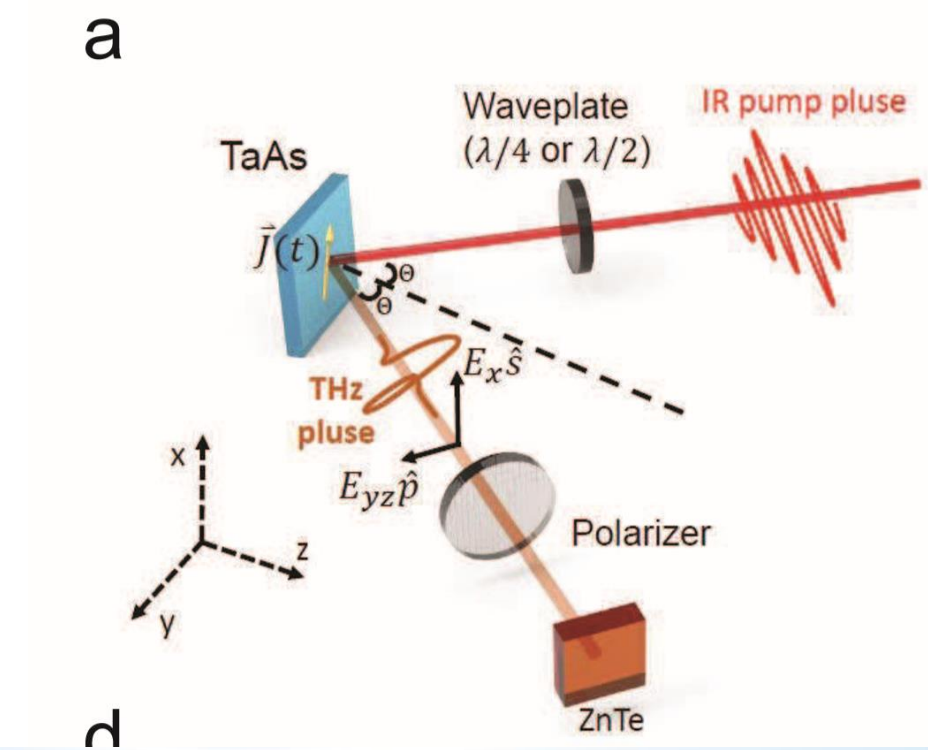


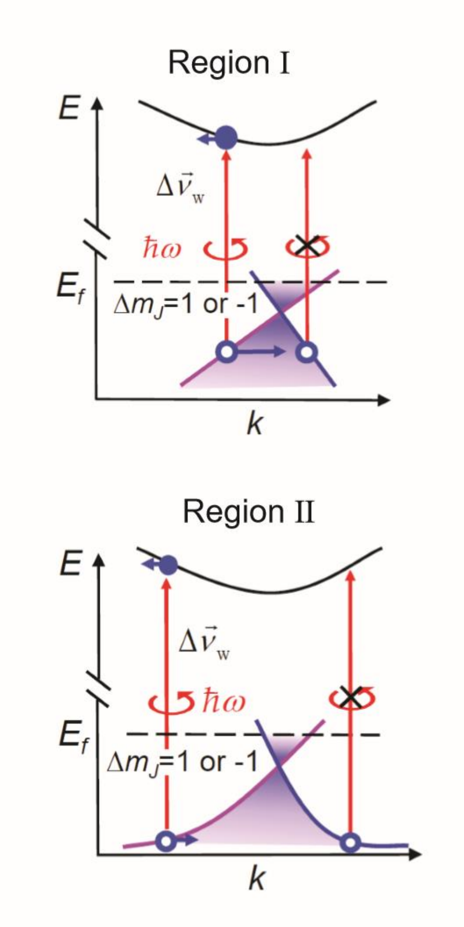
Ma et al, Nature Physics 13, 842 (2017)

Coherent terahertz emission with tunable ellipticity and optical chirality from the Weyl semimetal TaAs

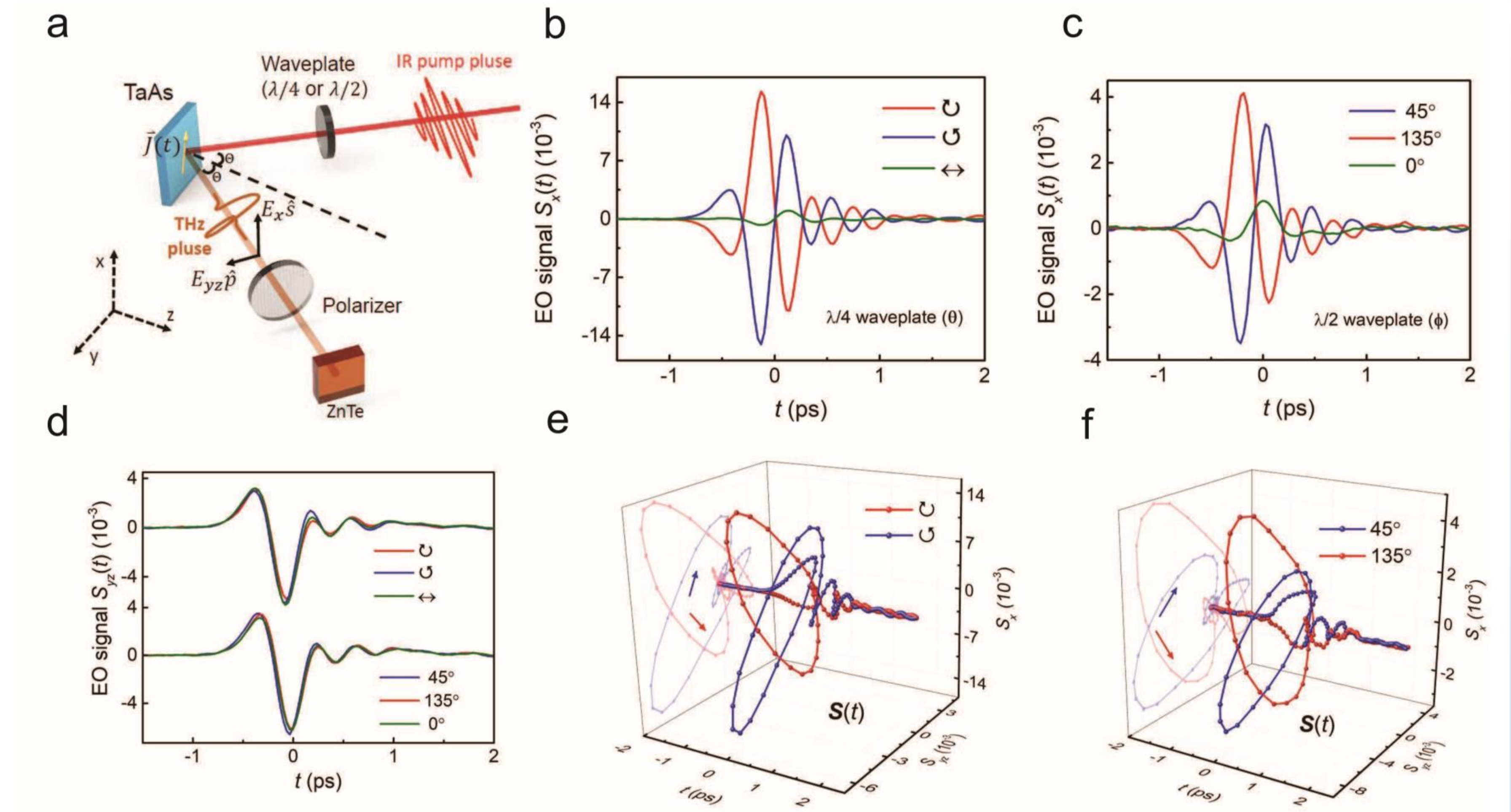
Gao, et al arXiv:1901.00986

An ultrafast change in $\vec{j}(z,t)$ on the ps time scale will result in EM radiation in the THz range



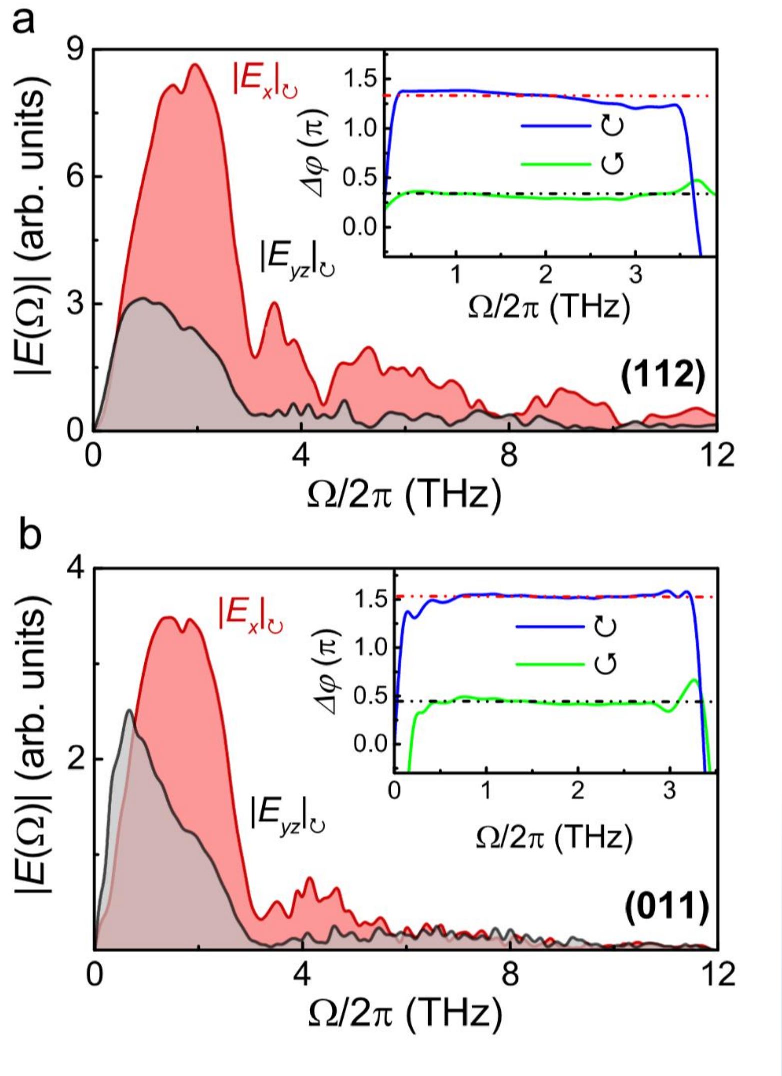


Coherent terahertz emission with tunable ellipticity and optical chirality from the Weyl semimetal TaAs



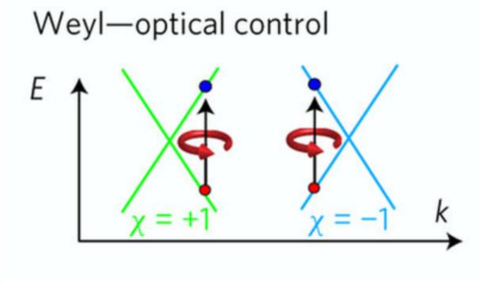
Gao, et al arXiv:1901.00986

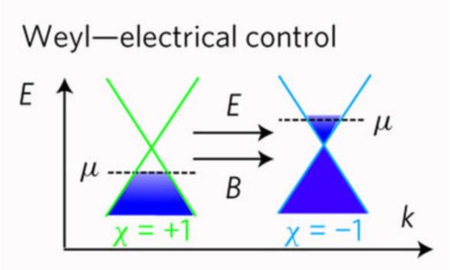
Fourier transform spectra for the THz near-field

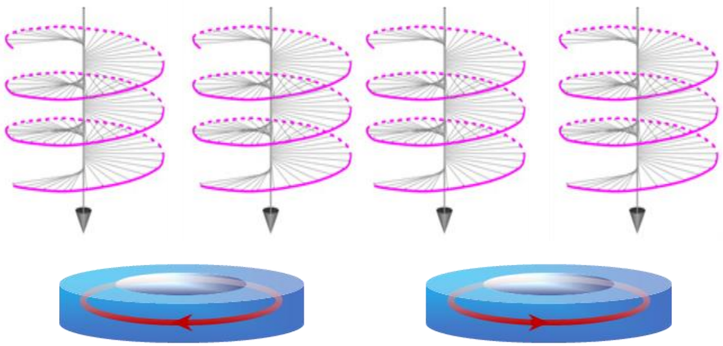


Gao, et al arXiv:1901.00986

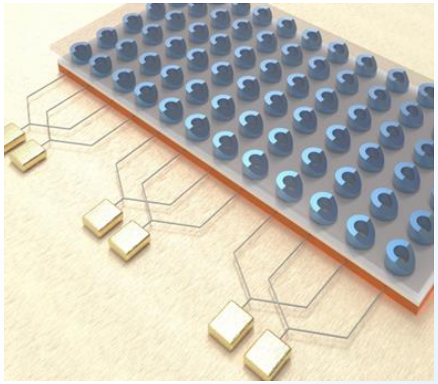
Chiral Qubit*





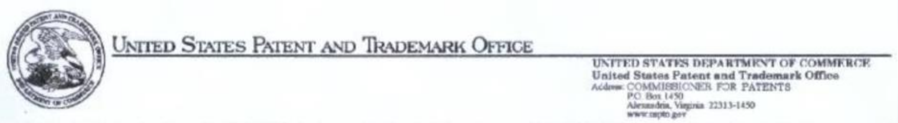


$$\alpha|L\rangle \quad + \quad \beta\,|R\rangle$$



The quantum states corresponding to the non-dissipative CME current circulating counter- and clockwise form the basis of the qubit. Incident circularly polarized light creates quantum superpositions of these states

Kharzeev and QL*



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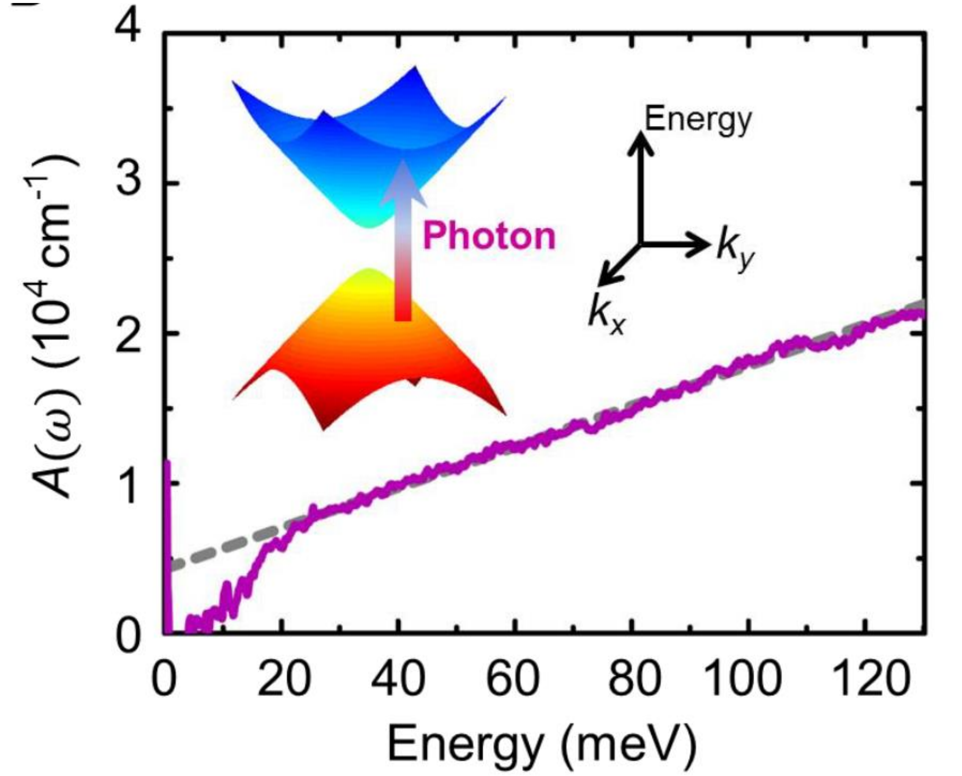
*CHIRAL QUBIT SYSTEM AND METHOD – Provisional patent application # 62685349, confirmation #7192, June 15, 2018

Massless or massive 3D Dirac fermions in $ZrTe_5$

- Infrared spectroscopy study

R. Chen, QL, Gu, Wang et al, PRB (2015)

Z. Chen, QL, Gu, Wang et al. Proc. Natl. Acad. Sci. (2017)

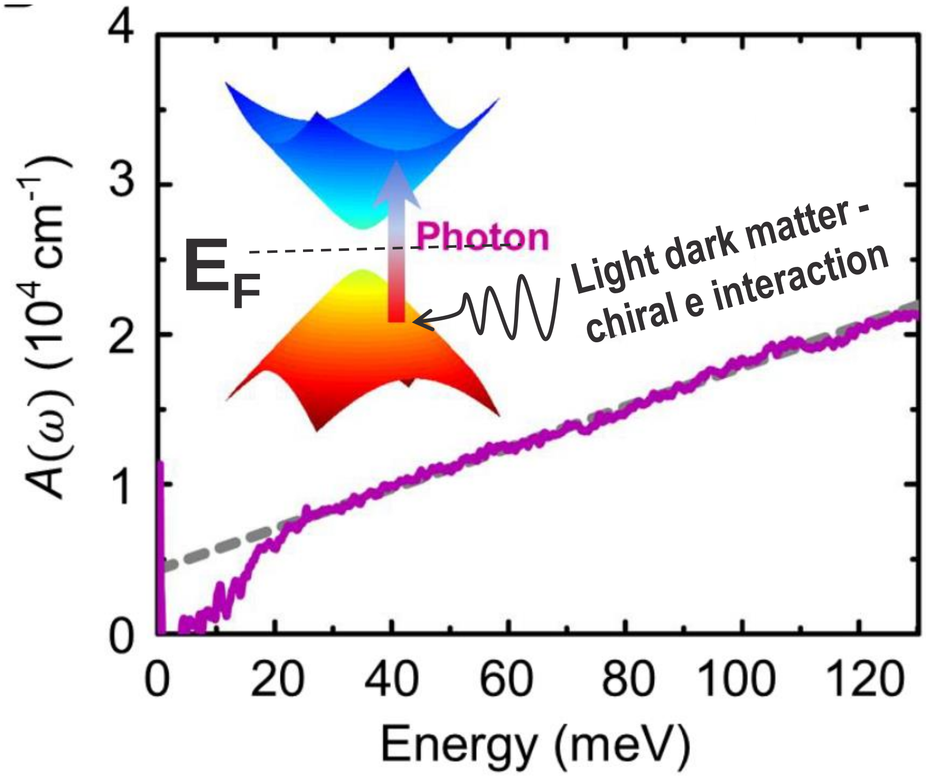


A linear relationship observed between the zero-magnetic-field (B) absorption and the photon energy

A bandgap of ∼10 meV and a $\sqrt{B}$ dependence of the Landau level (LL) transition observed at low B

Reemergence of intra-LL transitions at B > 17 T reveals the energy cross between the two zeroth LLs, which reflects the inversion between the bulk conduction and valence bands.

$ZrTe_5$ - Light dark matter detection



- ○ **At no thermal excitation**
- ○ **Fermi level in the gap Δ**

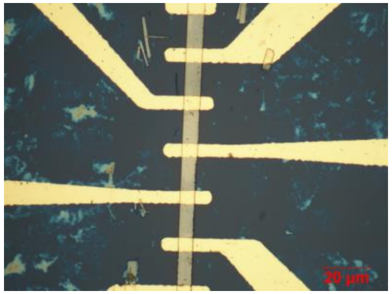
(12.4 meV ~ 3 THz)

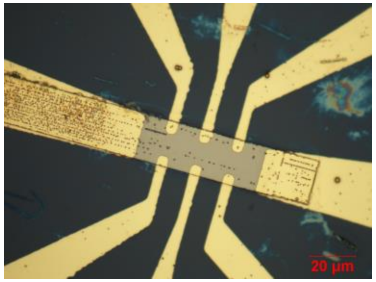
$ZrTe_5$

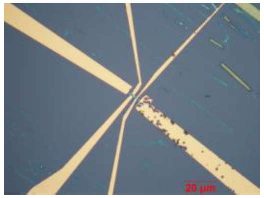
⇩

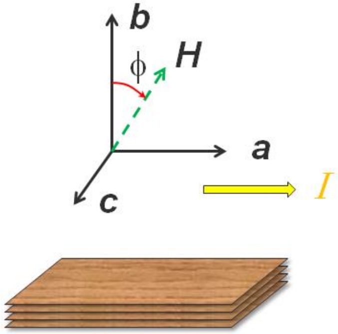
Light dark matter detection

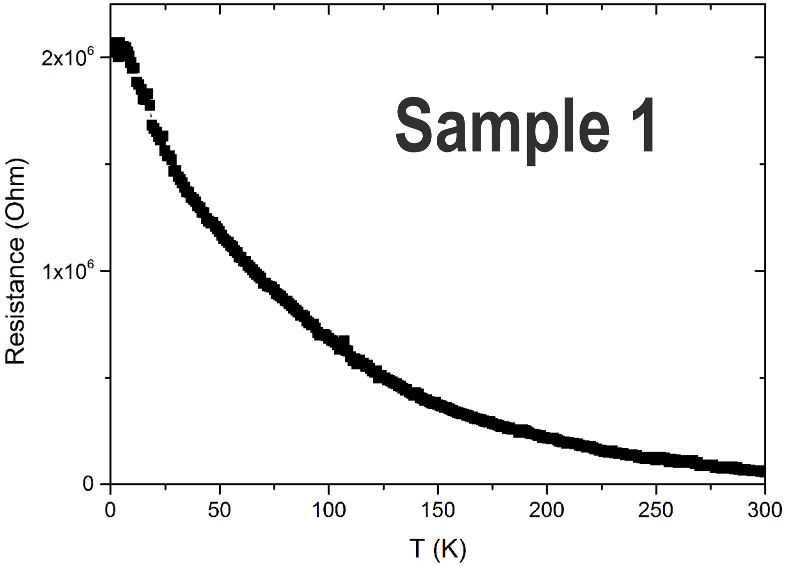
Experiments from the ultra thin crystals (a few to tens of unit cell)

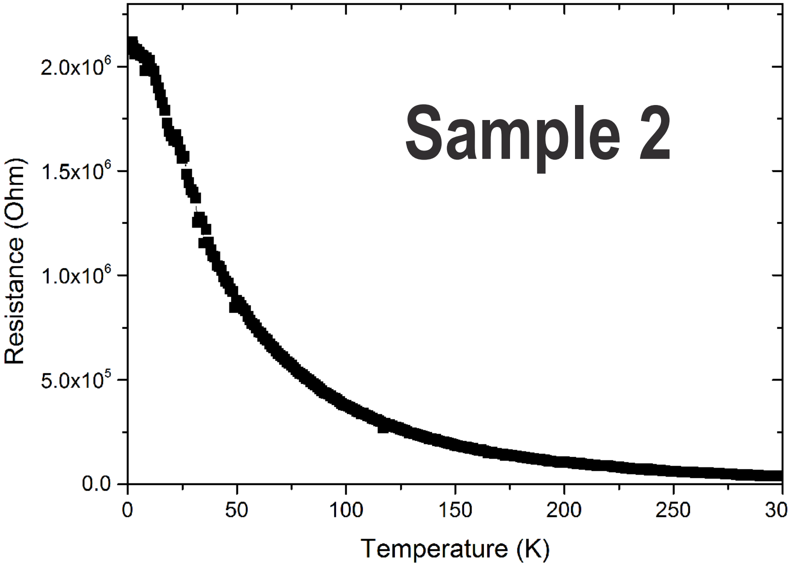




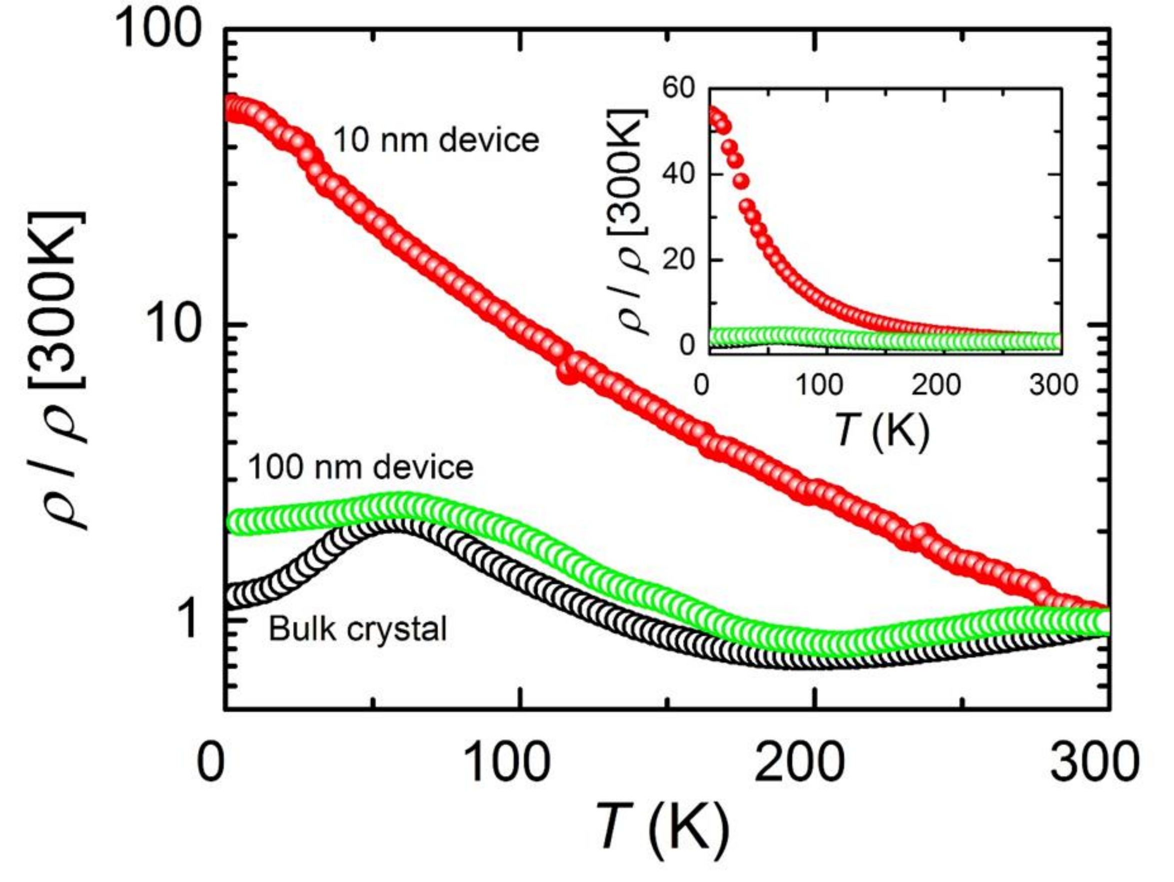








Evolution of temperature dependent resistivity of ZrTe5. Normalized temperature dependent resistivity of 0.2 mm bulk ZrTe5 single crystal sample, 100 nm device and 10 nm device, showed as black open circle, green open circle and red solid circle, respectively. Inset shows the linear scale.



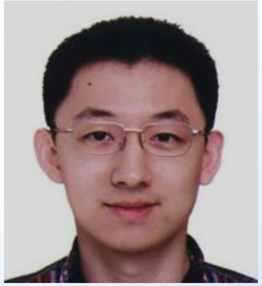
Summary

- 3D Dirac/Weyl semimetals open a new avenue to study the quantum dynamics of relativistic field theory in condensed matter experiments.
- Chiral magnetic effect has been observed in condensed matter systems
- Optical manipulation of Weyl fermions and chiral qubit proposal for quantum information process
- Coherent THz emission and light dark matter detection

Dmitri Kharzeev

Tonica Valla

Genda Gu



Cheng Zhang

Sahal Kaushik