Dynamics of chiral fermions and chiral magnetic effect*

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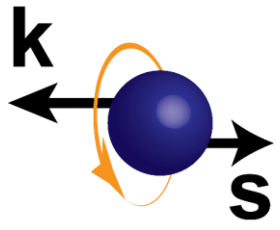
Outline

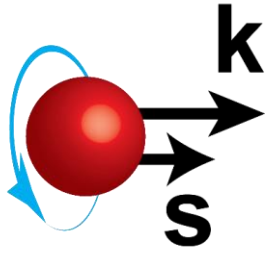
- A brief review of chiral magnetic effect
- Control of topological states in condensed matters
- Massive Dirac semimetals for axions and dark matters detection
- Quantum computing with chiral fermions

Chirality:

(Relativistic electrons, quarks, and neutrinos)

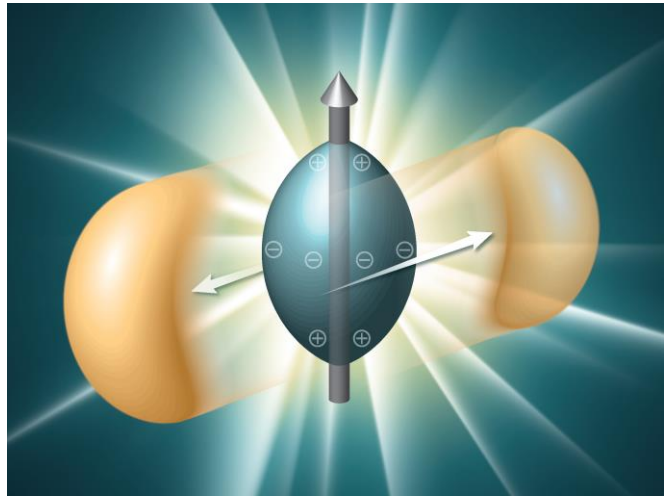


Left-handed



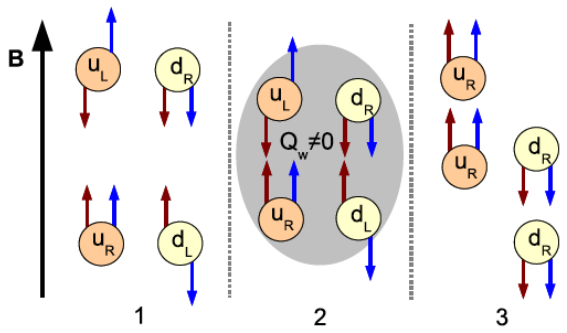
Right-handed

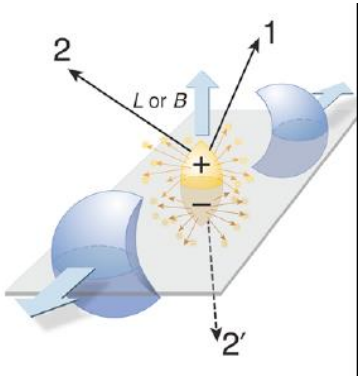
Quark-gluon plasma in heavy-ion collisions
(RHIC and LHC)



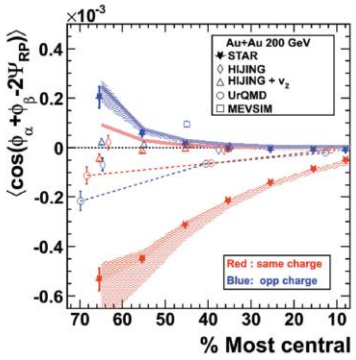
Chiral magnetic effect (CME)

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





(STAR Collaboration)

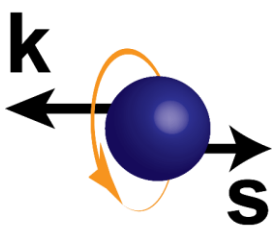


D. Kharzeev, L.McLerran, H.Warringa, 2007
K. Fukushima, D. Kharzeev, and H. Warringa. Phys. Rev. D, 78, 074033 (2008).

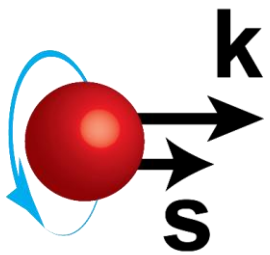
3D semimetals with quasi-particles that have a linear dispersion relation have opened a fascinating possibility to study the quantum dynamics of relativistic field theory in condensed matter experiments.

Chirality:

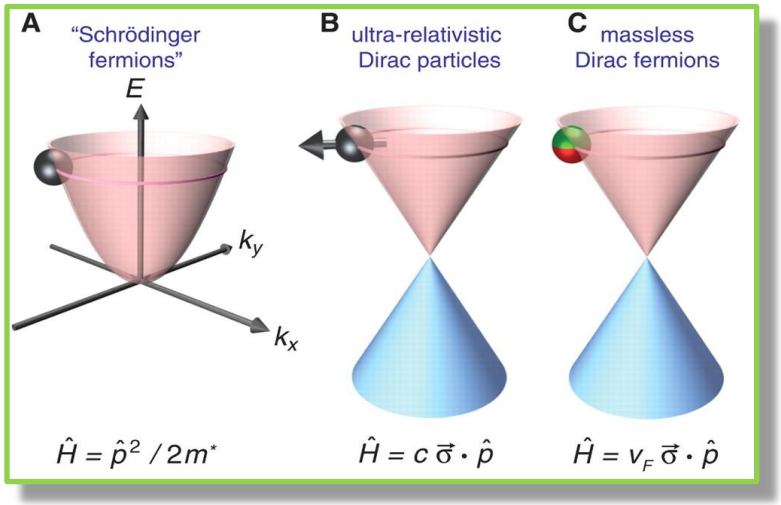
(electrons, quarks, and neutrinos)



Left-handed



Right-handed

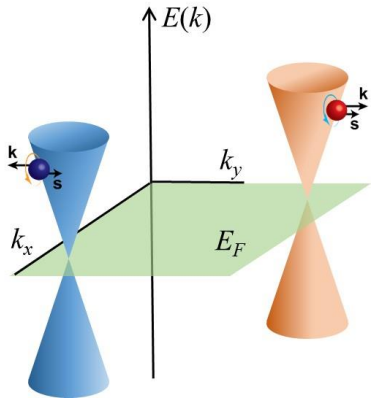


A. K. Geim, Science 324,1530 (2009)

3D semimetals with linear dispersion

Weyl semimetal

(non-degenerated bands)



TaAs

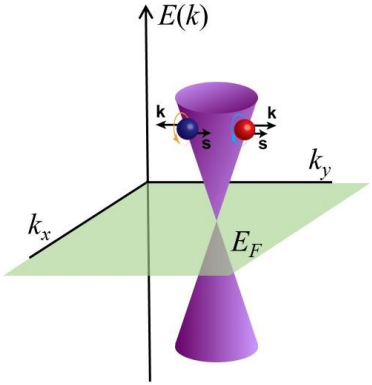
NbAs

NbP

TaP

Dirac semimetal

(doubly degenerated bands)

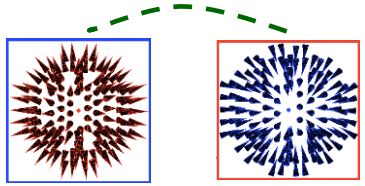


$ZrTe_5$

Na_3Bi,

Cd_3As_2

- 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

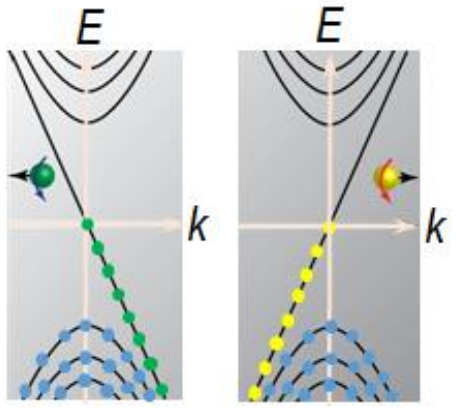


Chiral anomaly and chiral magnetic effect

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

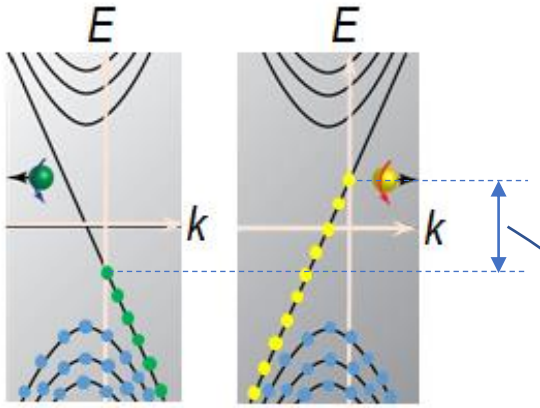
$\vec{B}$

$\vec{E} = 0$



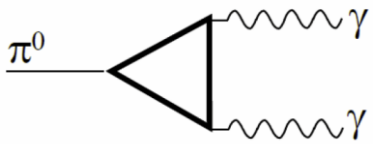
$\vec{B}$

$\vec{E}$



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

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



Rapid decay of π^0 into two photons γ

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

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

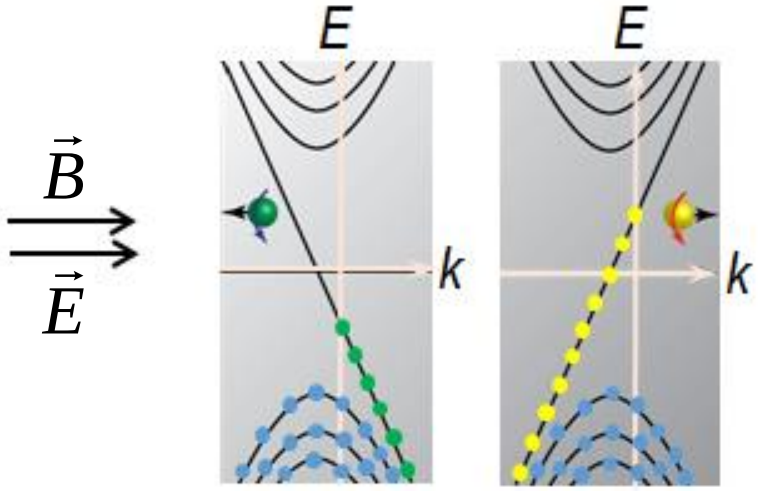
Son and Spivak (2013) - Phys. Rev. B, 88, 104412 (2013).

"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".

Chiral Magnetic Effect (CME) in Condensed Matters (CM)



Rate of chiral charge generaton:

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

Chiral anomaly

Chirality-changing scattering time
(chirality flipping time)

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

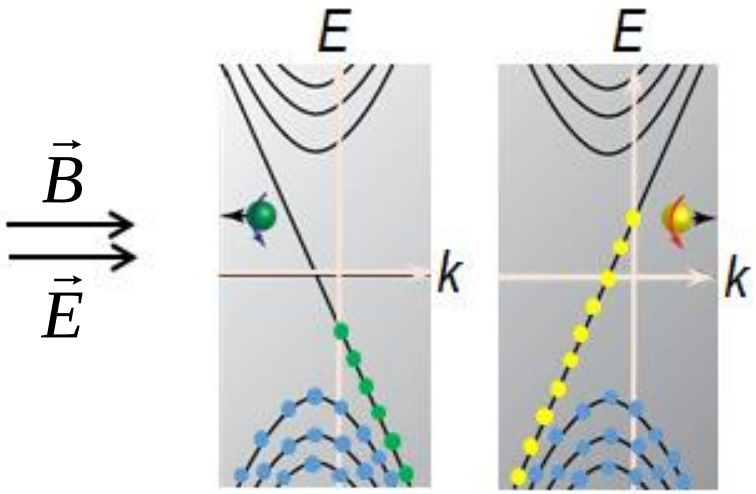
at $t >> \tau_v$ (steady state)

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

Chiral Magnetic Effect (CME) in Condensed Matters (CM)

Dmitri Kharzeev
(SBU/BNL)

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



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

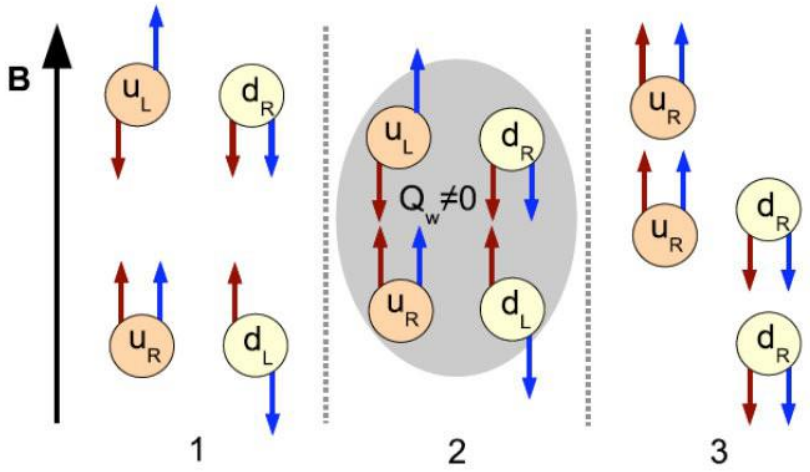
$$J^i_{CME} = \boxed{\frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_v}{T^2+\frac{\mu^2}{\pi^2}}B^iB^kE^k} = \boxed{\sigma^{ik}_{CME}}E^k$$

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

A negative longitudinal magnetoresistance (NLMR) at $(\vec{B}//\vec{E})$ in Dirac/Weyl semimetals

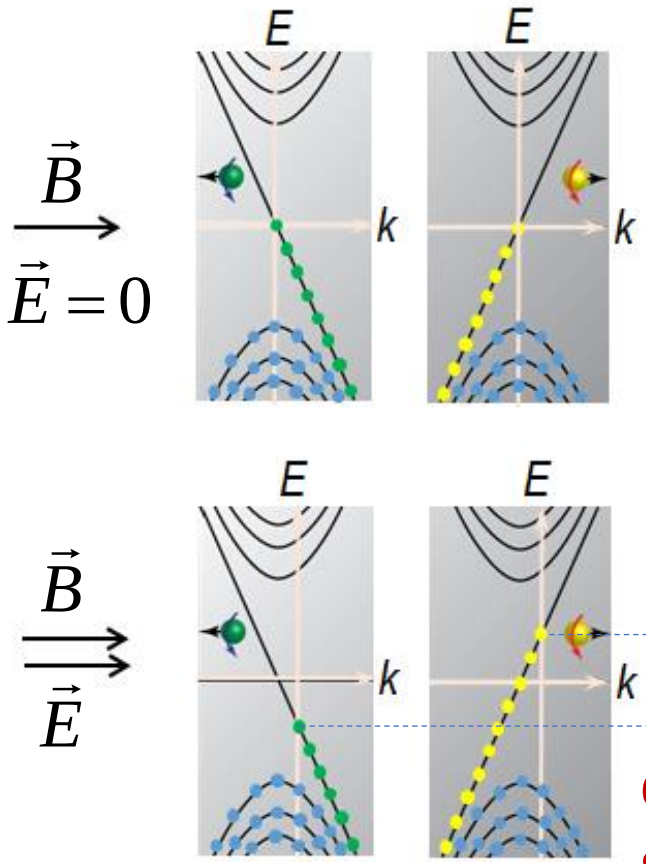
Chiral magnetic effect

Quark-gluon plasma in heavy-ion collisions



- 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 is proportional to the chiral chemical potential μ_5 which controls imbalance between left-handed and right-handed quarks

Chiral fermions in 3D Dirac semimetals

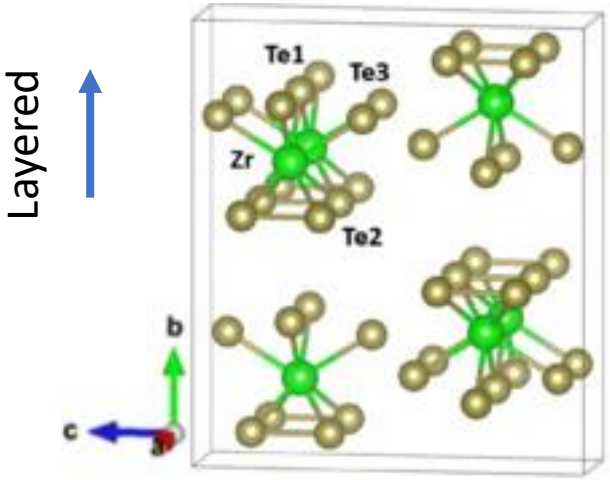


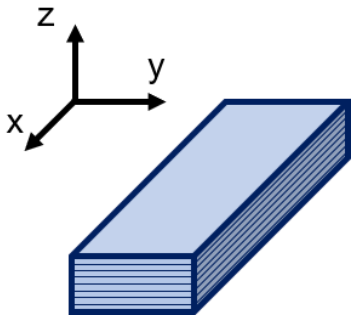
$$\vec{J}_{CME} = \frac{e^2}{2\pi^2}\mu_5\vec{B}$$

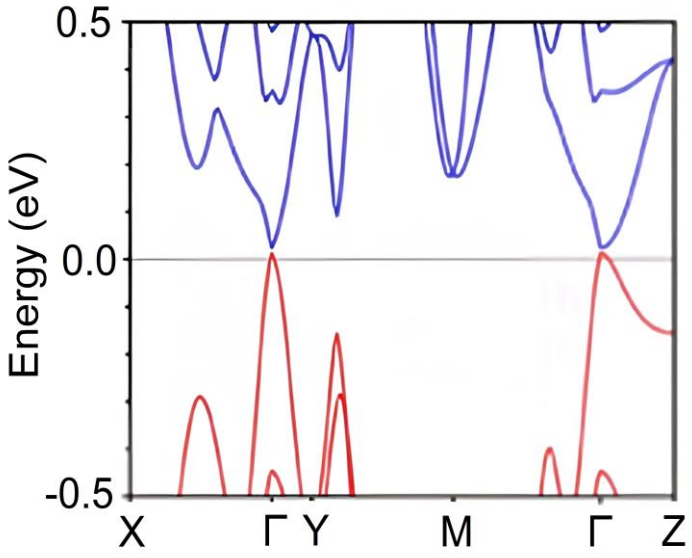
$$\mu_5 \equiv \mu_R - \mu_L$$

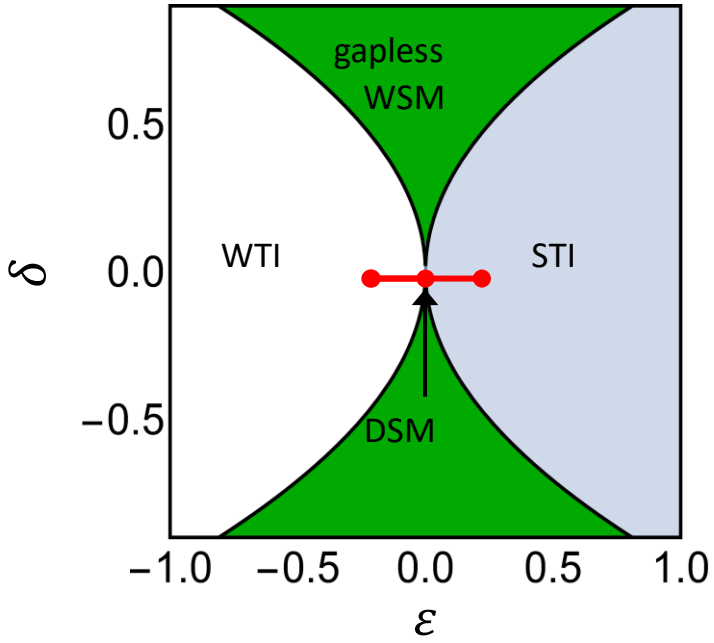
CME is dynamic, not a ground state property

Discovery of chiral magnetic effect in $ZrTe_5$



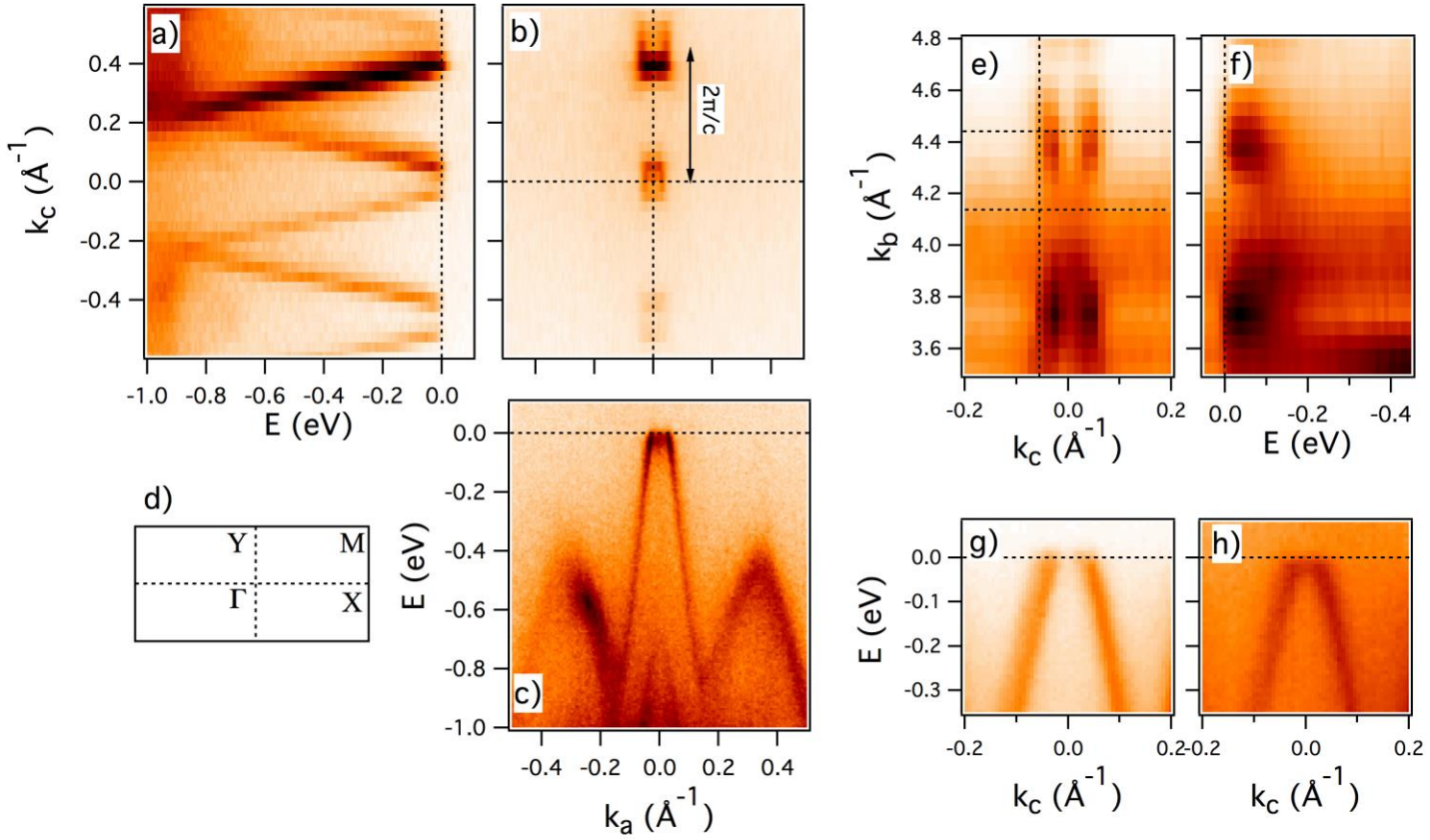


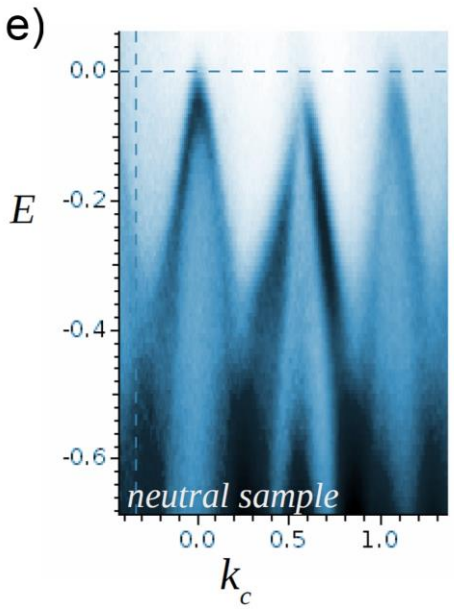




Ref. P. Zhang QL et al., Nat. Commun. 12, 406 (2021)
N. Aryal, QL et al., Phys. Rev. Lett. 126, 016401 (2021)

ARPES results - band dispersion of $ZrTe_5$

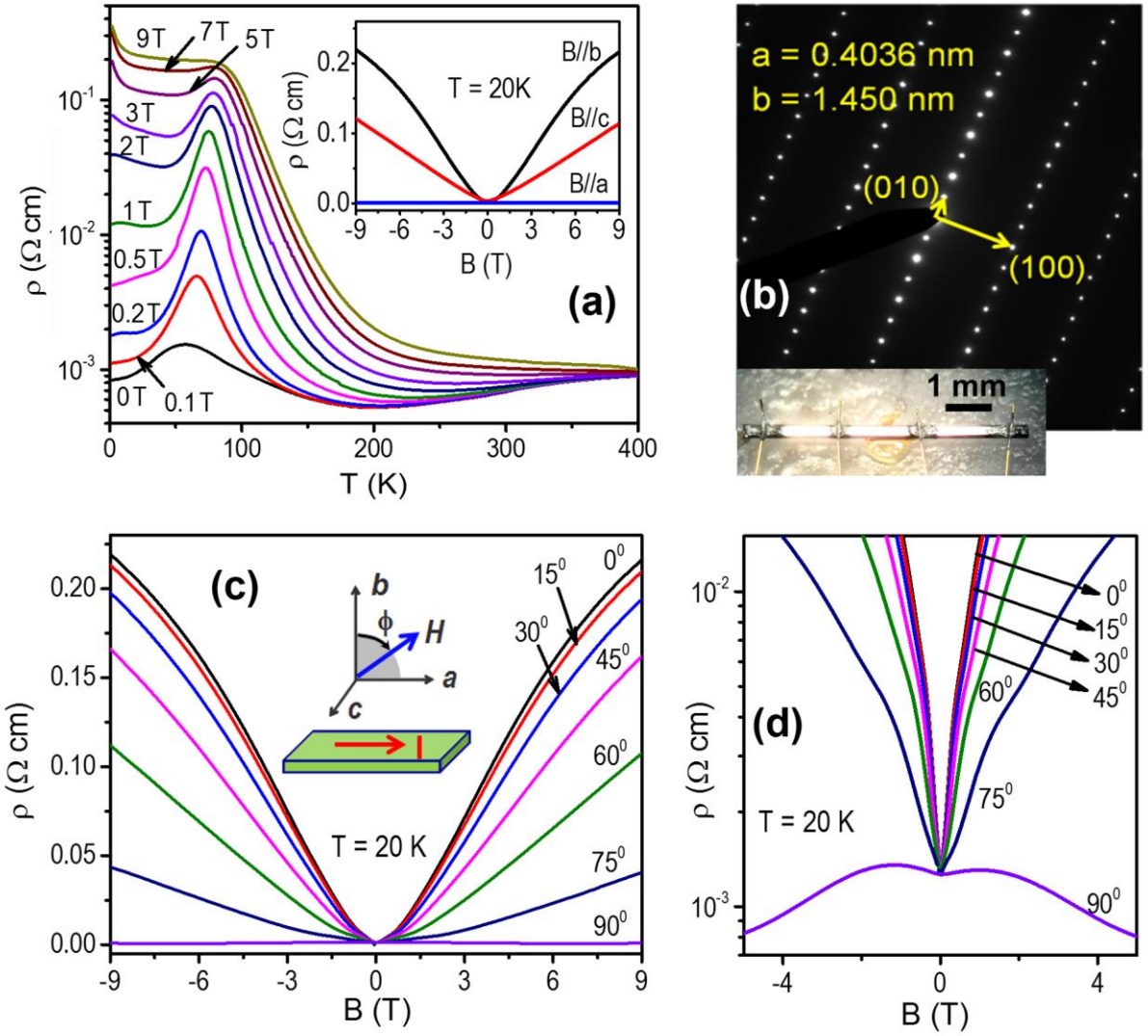




Tonica Valla
(BNL)

More line 3D Dirac semimetal

Magneto-transport properties of $ZrTe_5$

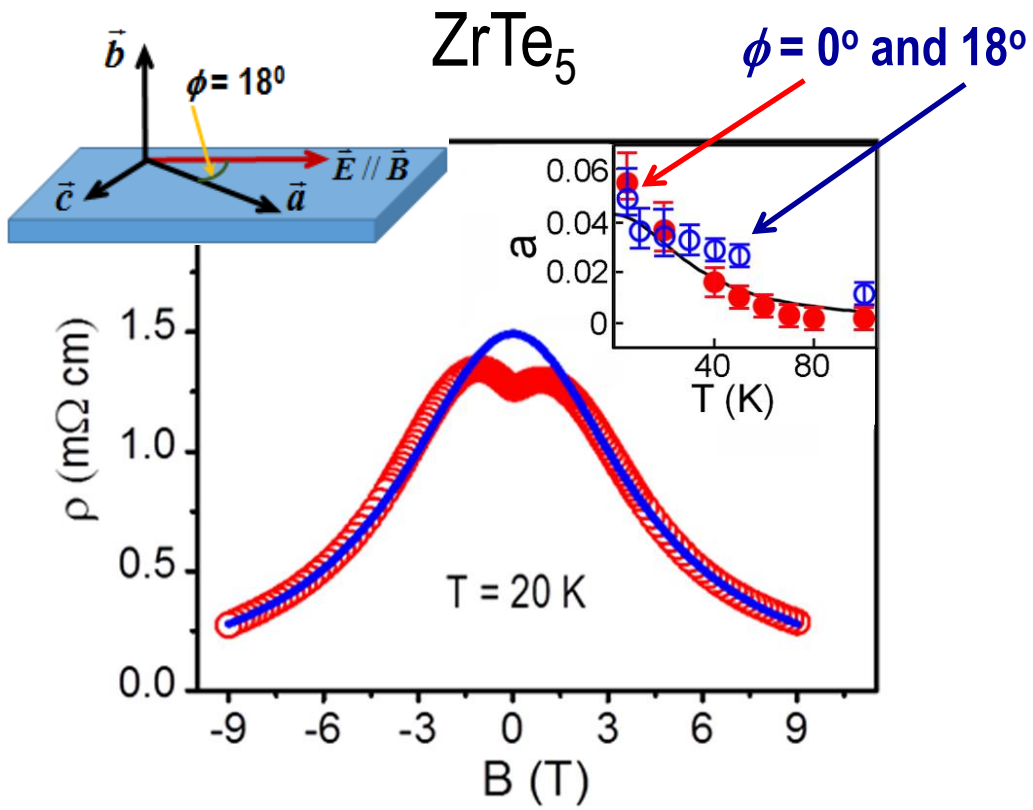


Measurable parameter from CME

Large negative magnetoresistance when B//E (ϕ = 90°)

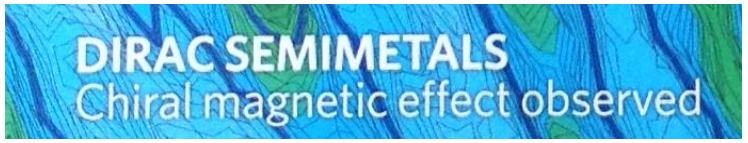
Li, et al arXiv:1412.6543, Nature Physics (2016) doi:10.1038/nphys3648

Chiral Magnetic Effect (Chiral Anomaly)



$\sigma = \sigma_0 + \sigma_{CME}$

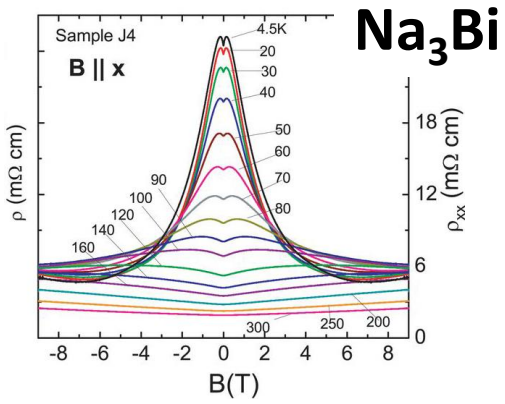
$$\sigma_{CME}^{zz} = \frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_V}{T^2 + \frac{\mu^2}{\pi^2}}B^2 = a(T)B^2$$



QL, et al arXiv:1412.6543, Nature Physics 12 550 (2016)

Chiral magnetic effect (chiral anomaly) in Dirac/Weyl semimetals

Dirac semimetals:



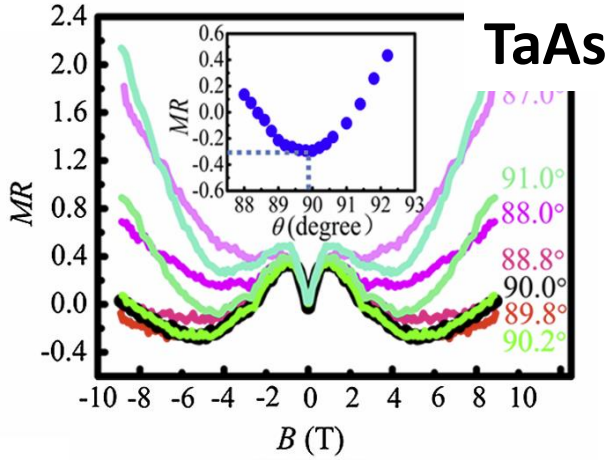
Na_3Bi

$ZrTe_5$ - QL, D. Kharzeev et al (BNL and Stony Brook Univ.)
arXiv:1412.6543; Nat. Phys. 12 550 (2016)

Na_3Bi - J. Xiong, N. P. Ong et al (Princeton Univ.)
arxiv:1503.08179; Science 350 413 (2015)

Cd_3As_2 - C. Li et al (Peking Univ. China)
arxiv:1504.07398; Nat. Commun. 6, 10137 (2015).

Weyl semimetals



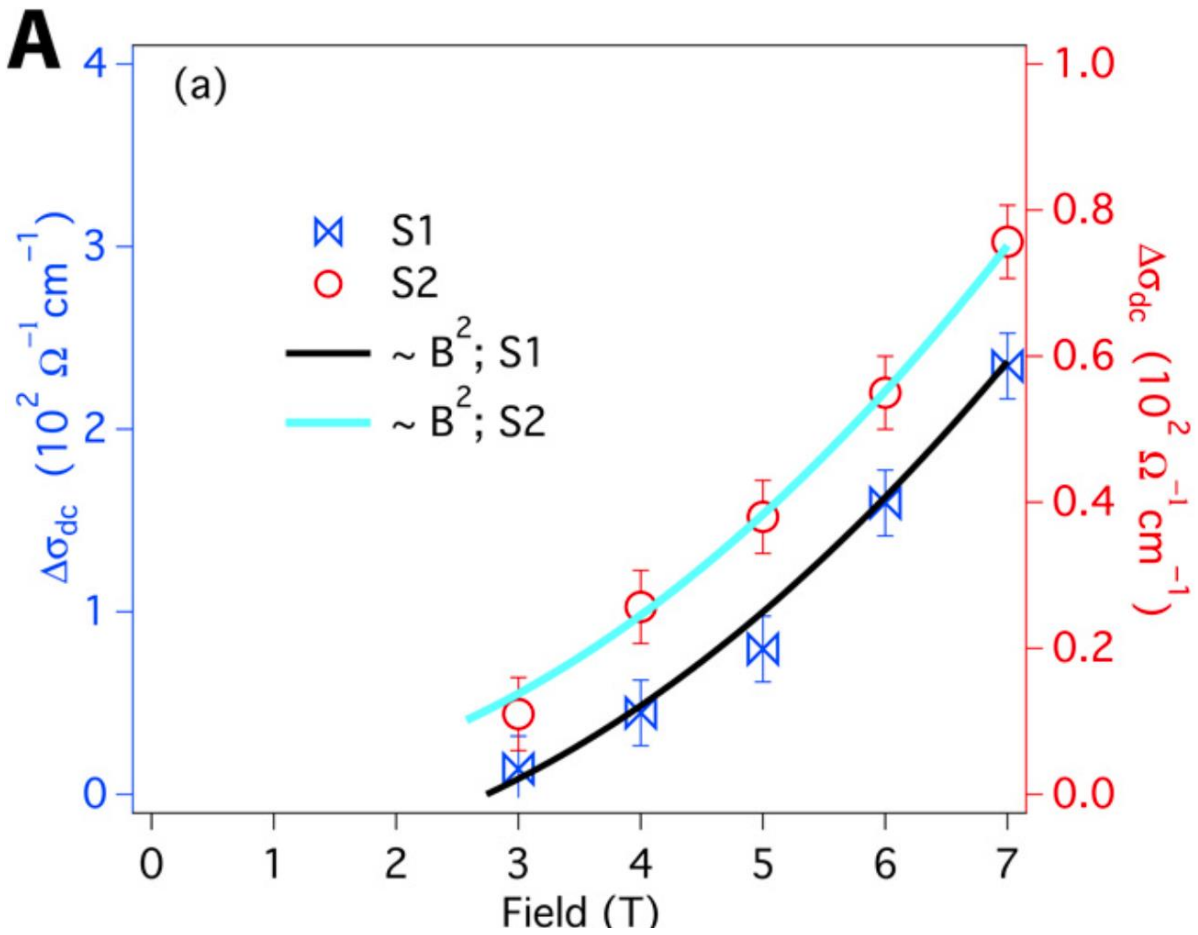
TaAs

TaAs - X. Huang et al (IOP, China)
arxiv:1503.01304; Phys. Rev. X 5, 031023

TaP - Shekhar, C. Felser et al (MPI-Dresden)
arxiv:1506.06577, Nat. Commun. 7, 11615 (2016).

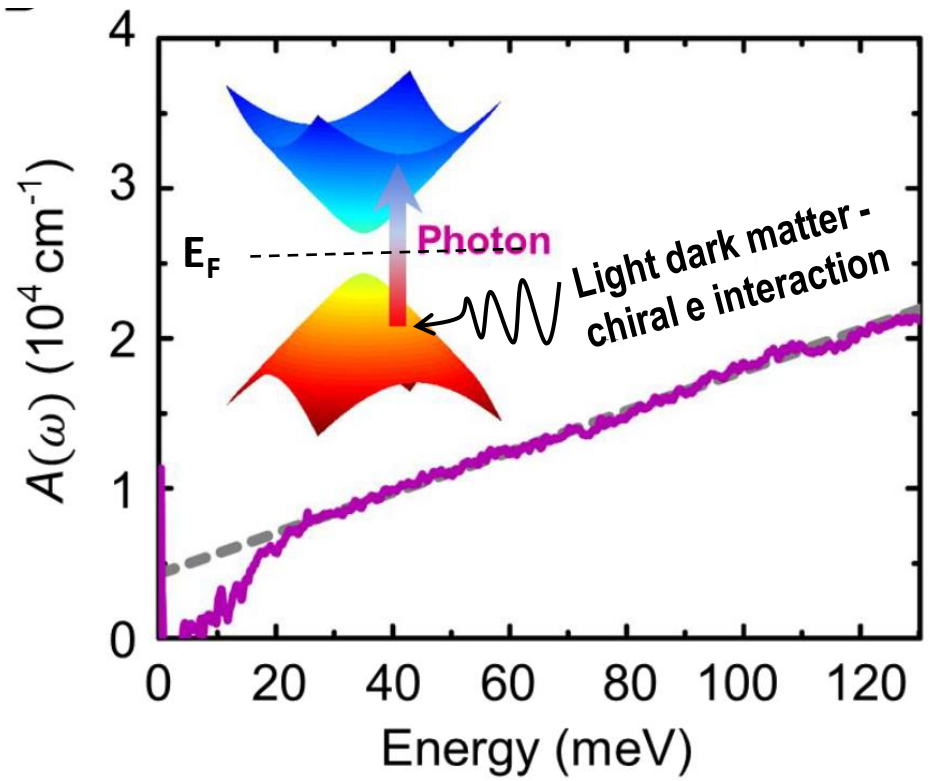
Magneto-terahertz spectroscopy (non contact) confirmed the chiral anomaly in a Dirac semimetal Cd_3As_2

"Intrinsic dc magnetoconductivity from chiral anomaly in sample S1 (blue) and sample S2 (red). In both samples, Δσ follows B^2"



Cheng, Armitage et al., SCIENCE ADVANCES, 7 abg0914 (2021)

$ZrTe_5$ - Light dark matter detection



- At no thermal excitation
- Fermi level in the gap Δ
  (12.4 meV ~ 3 THz)

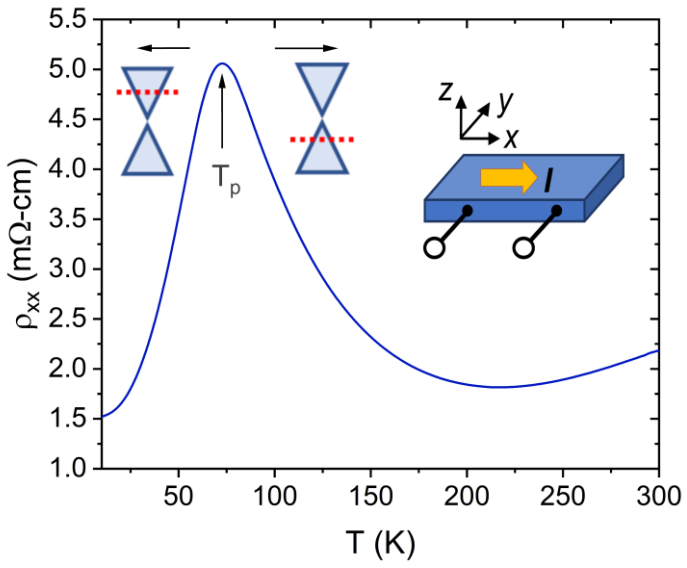
$ZrTe_5$

↓

Light dark matter detection

Temperature induced Lifshitz transition in $ZrTe_5$

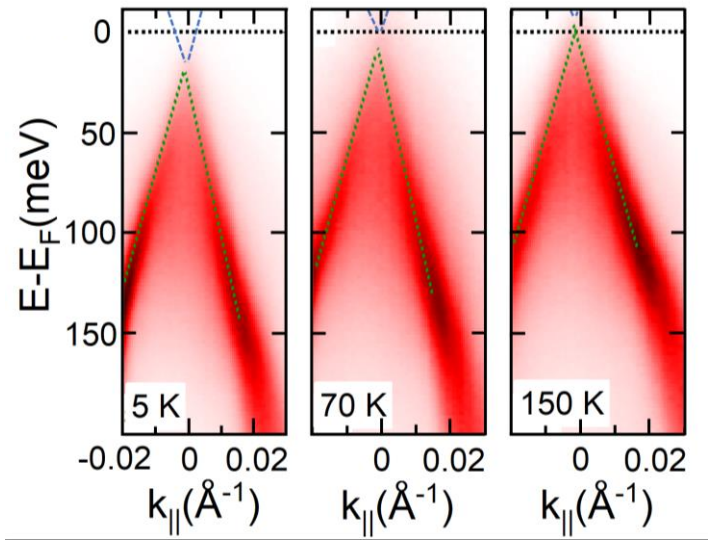
Anomalous resistivity peak in $ZrTe_5$



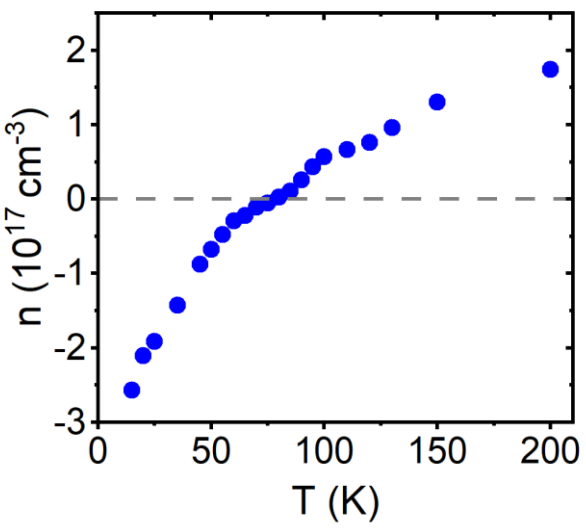
H Chi, QL et al, New Journal of Physics 19, 015005 (2017)

The Fermi level shifts with temperature from the bottom of the conduction band to the top of the valence band.

From ARPES measurements:



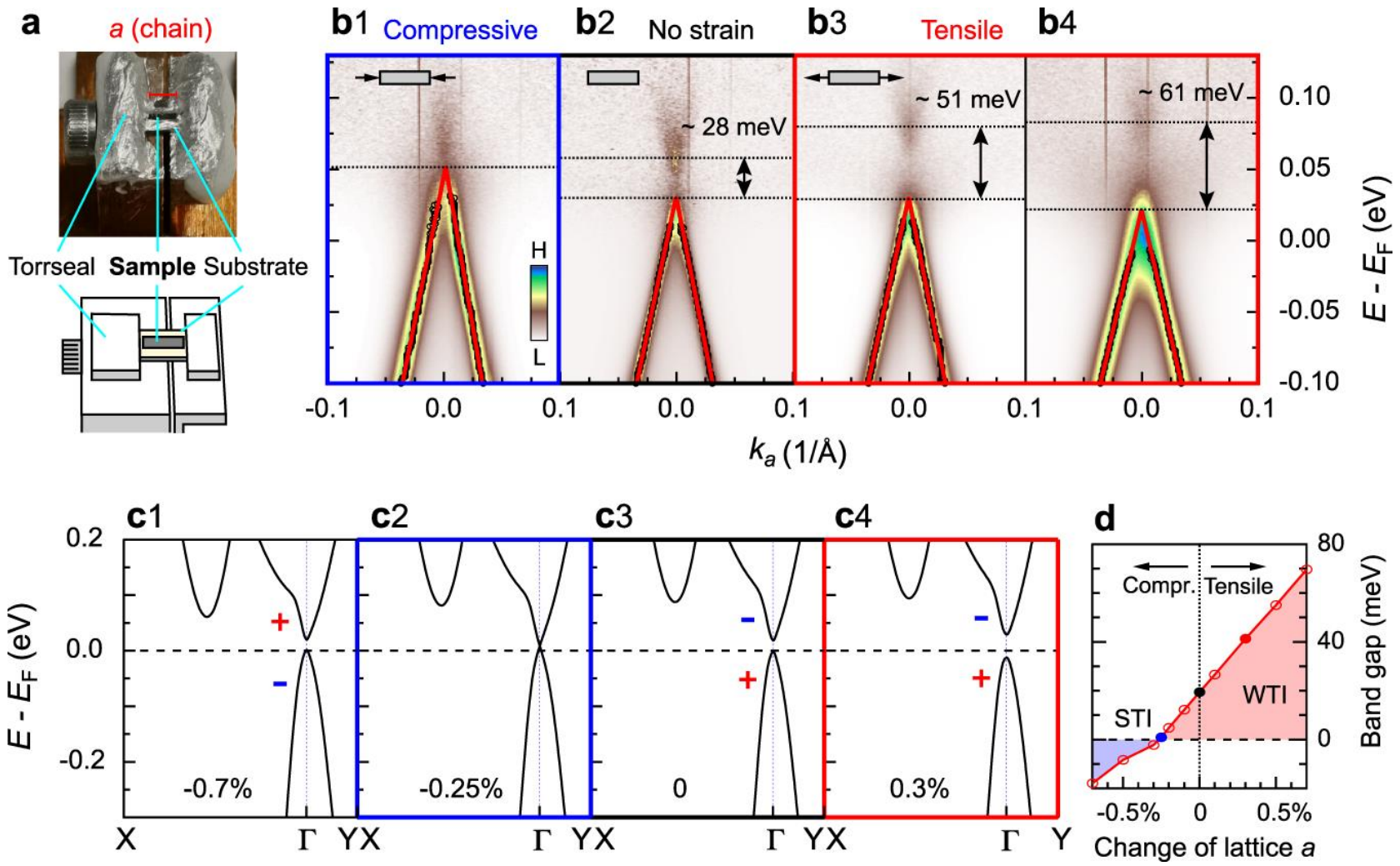
From transport measurements:



P. Lozano, QL et al., Phys. Rev. B 106, L081124 (2022)

For magnetic-field-induced Lifshitz transition in $ZrTe_5$ See S Galeski, QL et al Nature Communications 13, 7418 (2022)

Strain Induced Topological Phase Transition in $ZrTe_5$



a) The strain device.

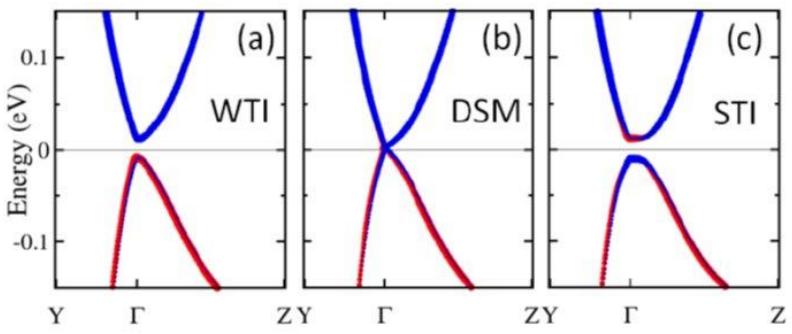
b) Bulk band gap change with compressive and tensile strain. The data are taken with p-polarized photons. The black markers are extracted from the MDC peaks, and the red solid lines are the fitting results

c) Calculated band structure with different lattice constant a. + and − signs indicate the parity of the two bands.

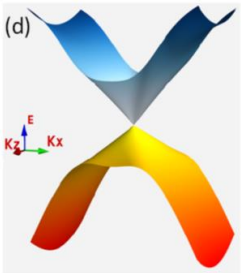
d) Calculated phase diagram with different lattice constant (strain). Blue, black, and red solid markers roughly indicate the experimental values in b.

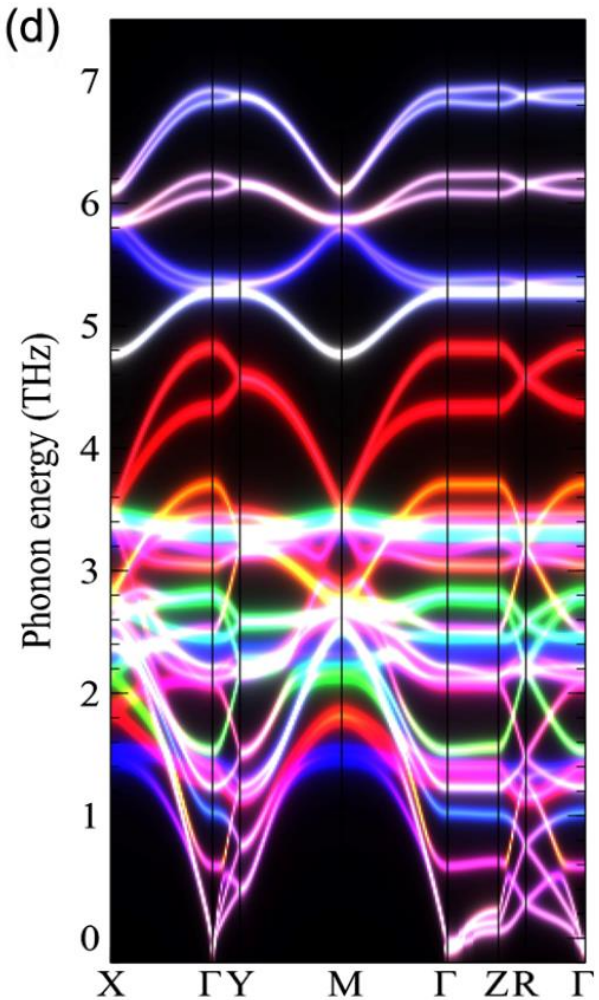
Zhang, QL, et al. Nature Communications 12, 406 (2021)

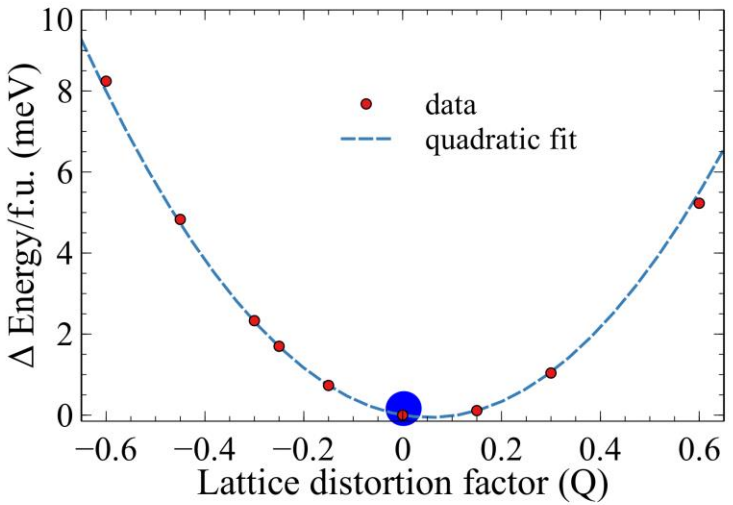
Coherent Phonon Control of Topological Phase Transition in $ZrTe_5$

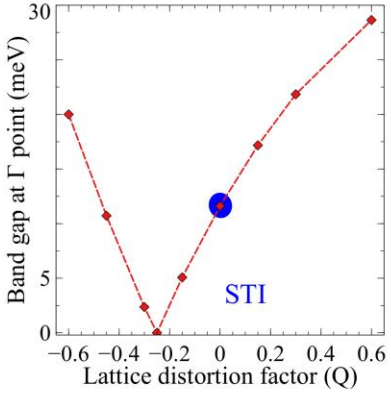


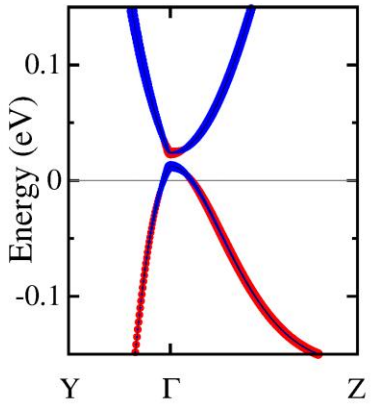
Evolution of the band structure around the Γ point for different values of the normal coordinate Q corresponding to the Ag-27 Raman-active phonon mode.







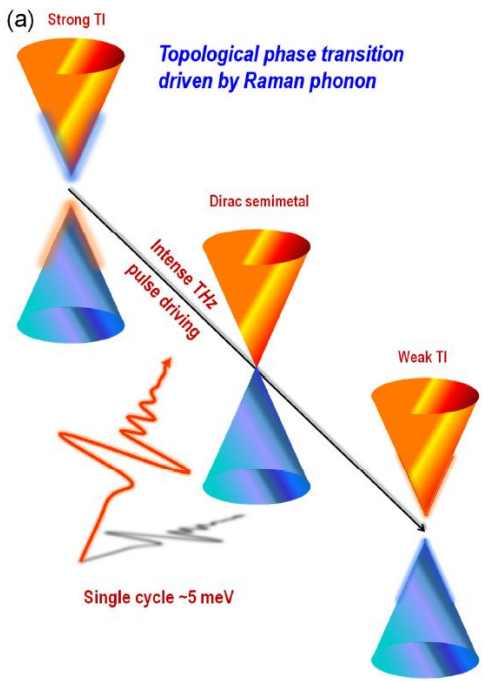


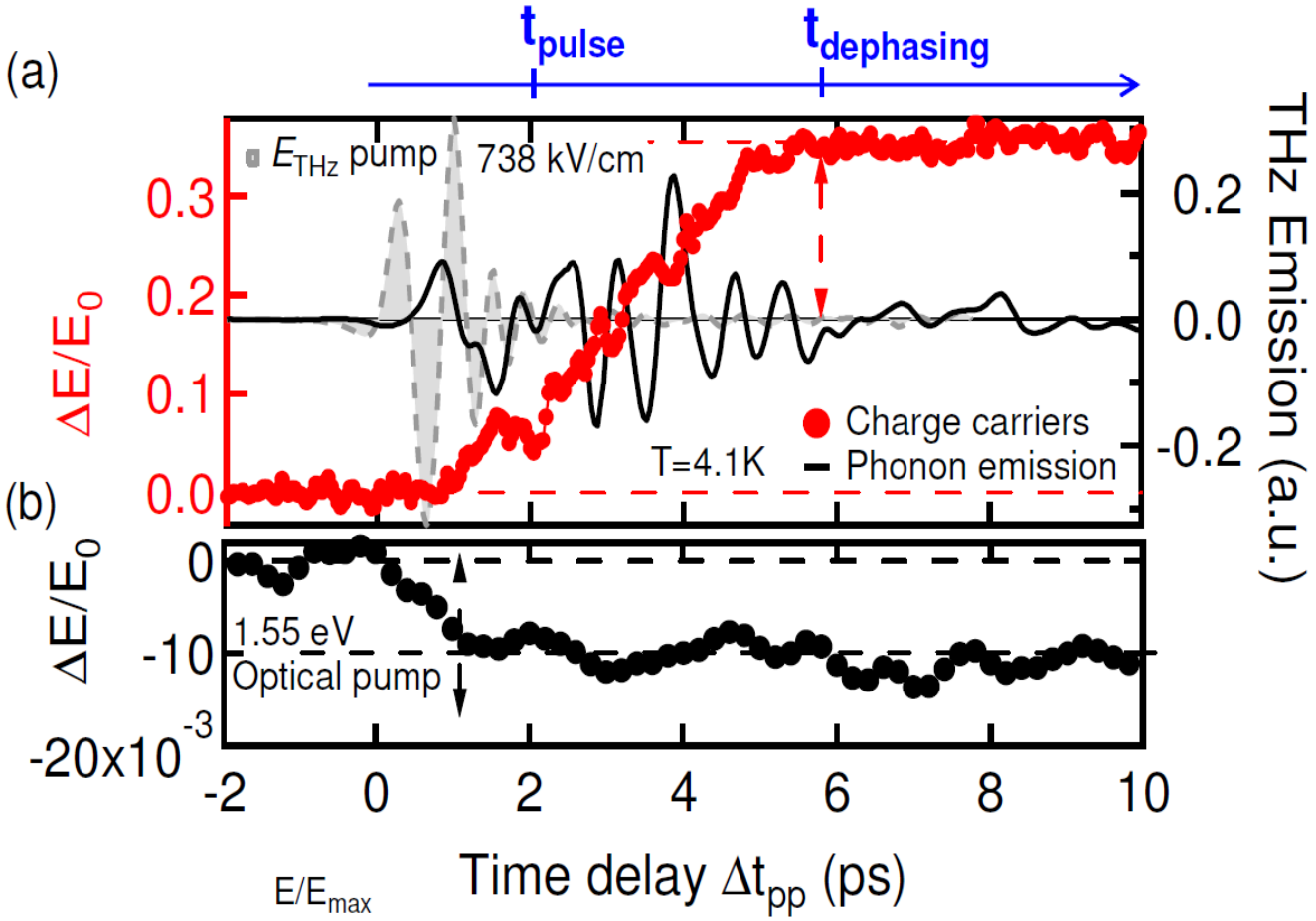


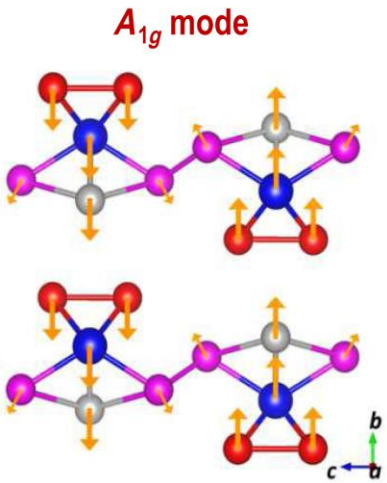
Aryal, Lin, QL, Tsvelik, Yin, Phys. Rev. Lett. 126, 016401 (2021)

Light-Driven Ultrafast Topology Switching in $ZrTe_5$

Prof. Jigang Wang
(Ames Lab and
Iowa State University)







Vaswani, QL, Wang, et al., Physical Review X 10, 021013 (2020)

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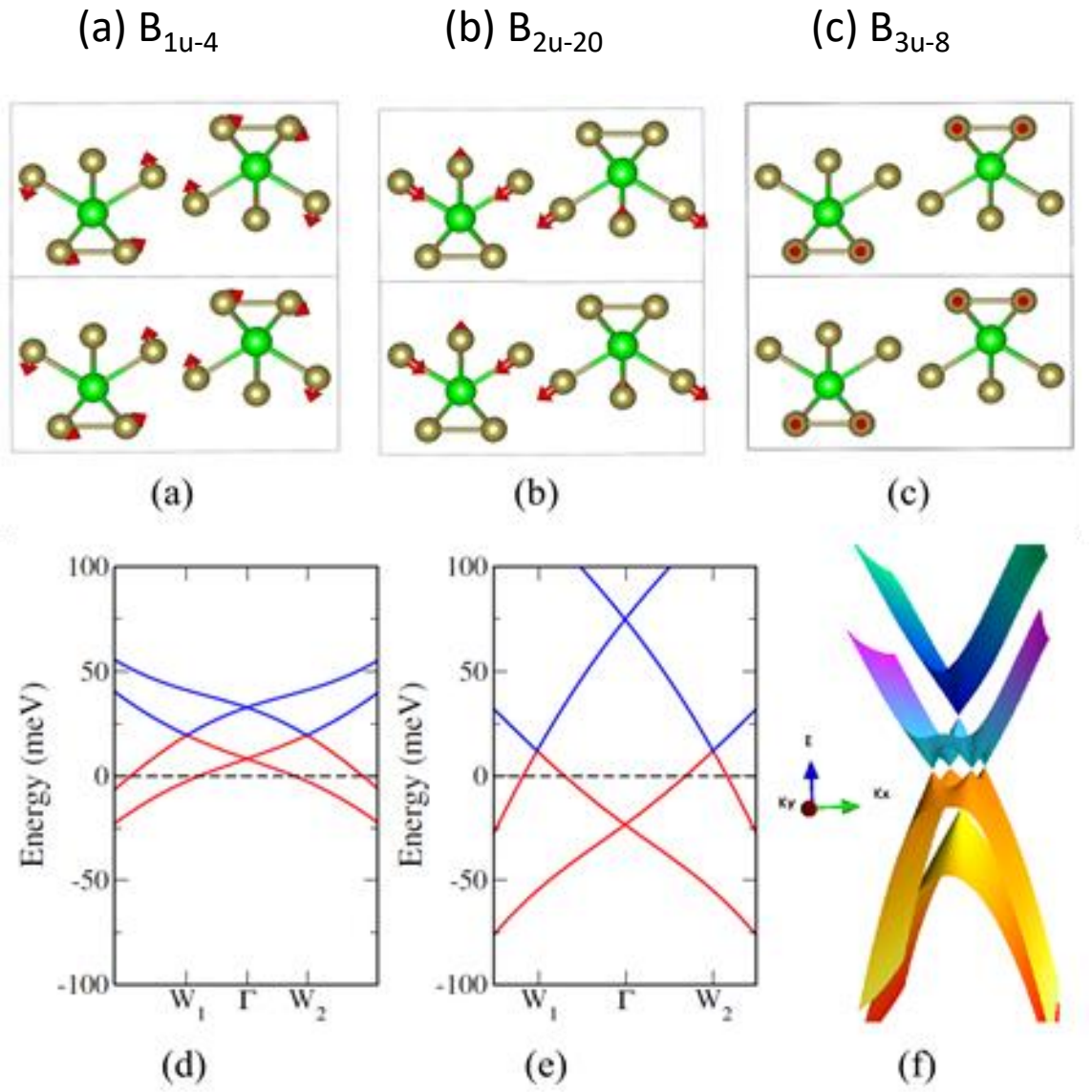
Phonon induced Weyl phases in $ZrTe_5$

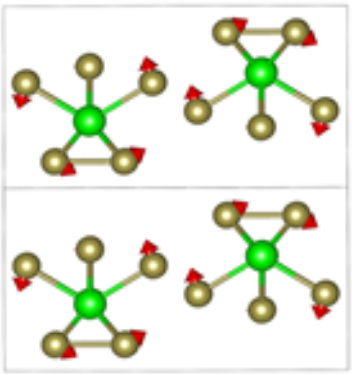


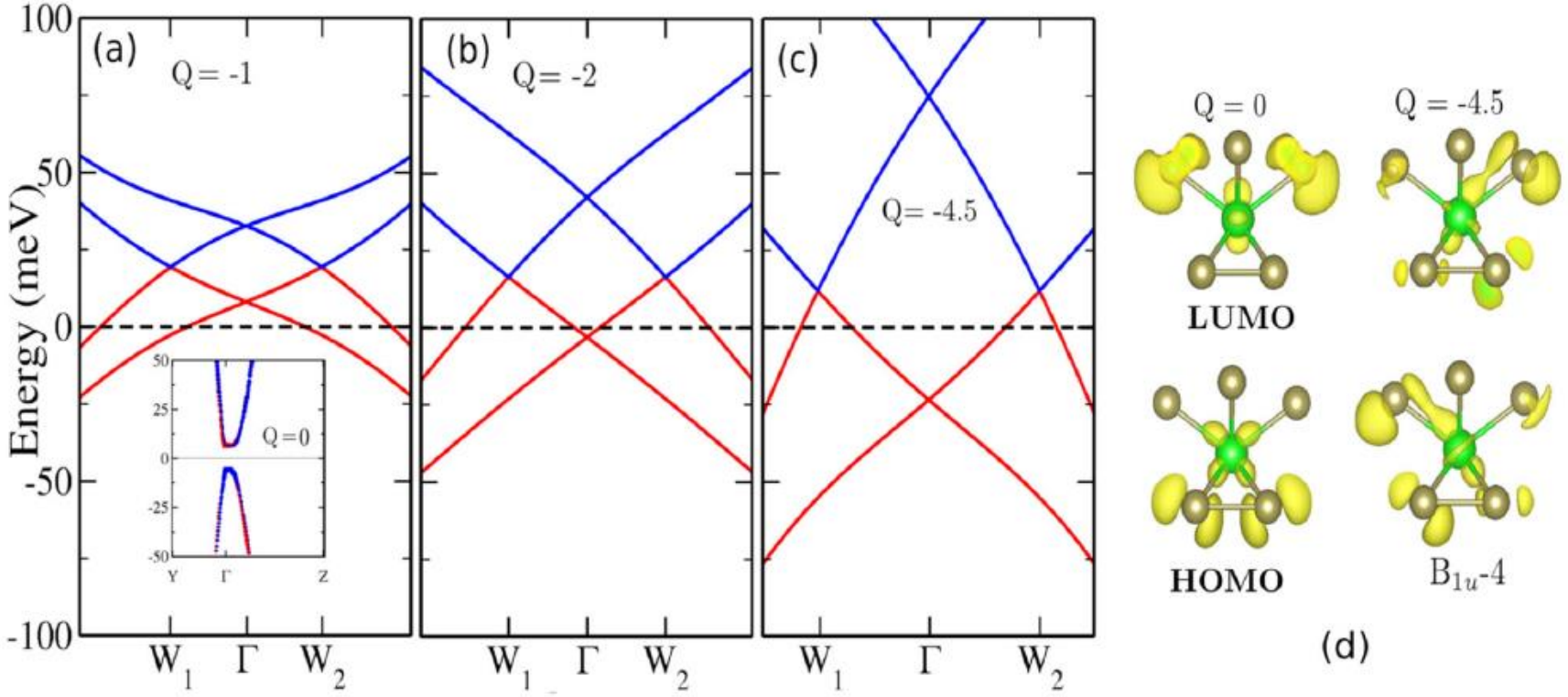
IR modes in $ZrTe_5$ projected on the b-c plane: (a) B_{1u-4} (b) B_{2u-20} and (c) B_{3u-8}; (d), (e) Band structure along W1-Γ-W2 direction for Q values of 1 and 4.5 respectively calculated from DFT for B_{1u-4} mode. (f), the bands forming the WPs are shown on the k_x - k_y.

Aryal, Jin, QL, M. Liu. Tsvelik, and W. Yin, "Robust and tunable Weyl phases by coherent infrared phonons in $ZrTe_5$," npj Computational Materials 8, 113 (2022).

Phonon induced Weyl phases in $ZrTe_5$

$B_{1u\text{-}4}$

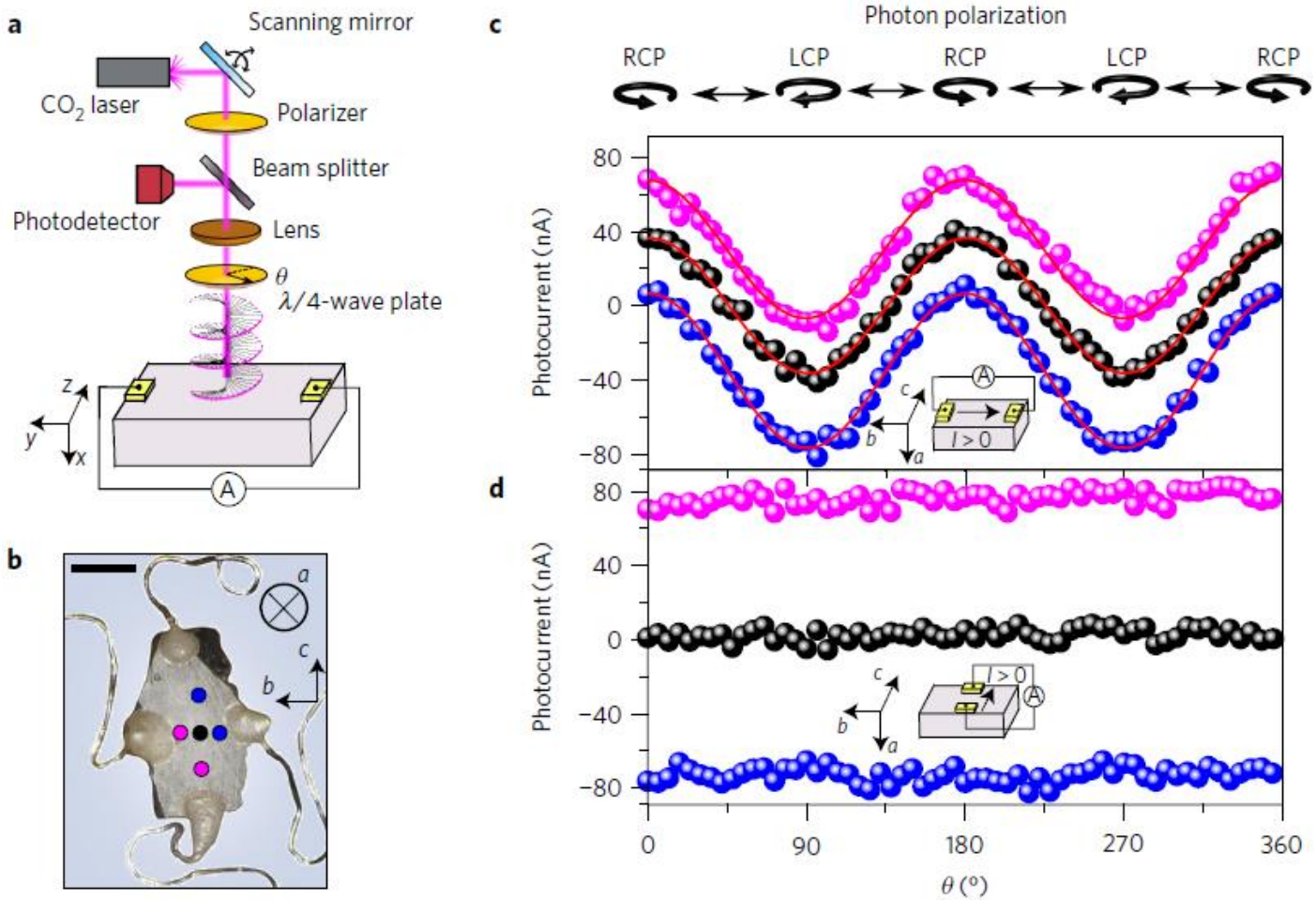


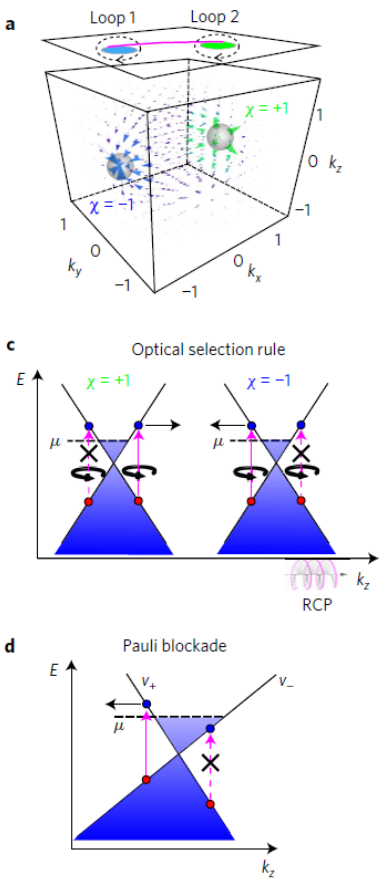


Aryal, Jin, QL, M. Liu. Tsvelik, and W. Yin, “Robust and tunable Weyl phases by coherent infrared phonons in $ZrTe_5$,” npj Computational Materials 8, 113 (2022).

Detection and manipulation of chirality in Weyl semimetal TaAs

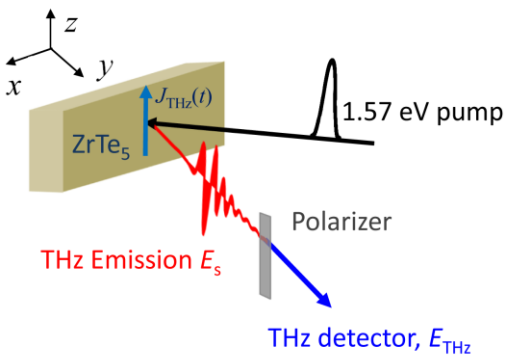
TaAs

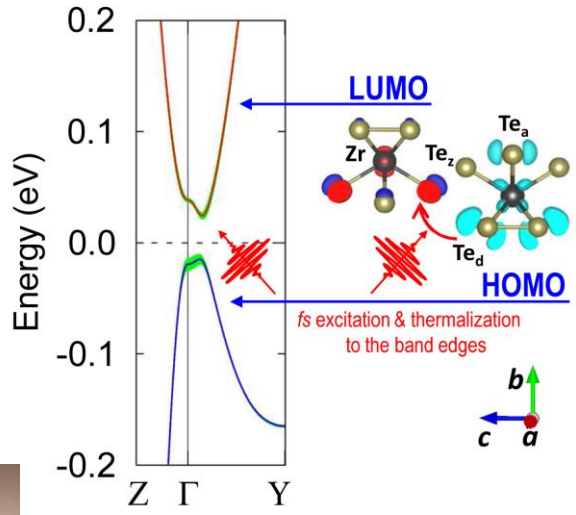


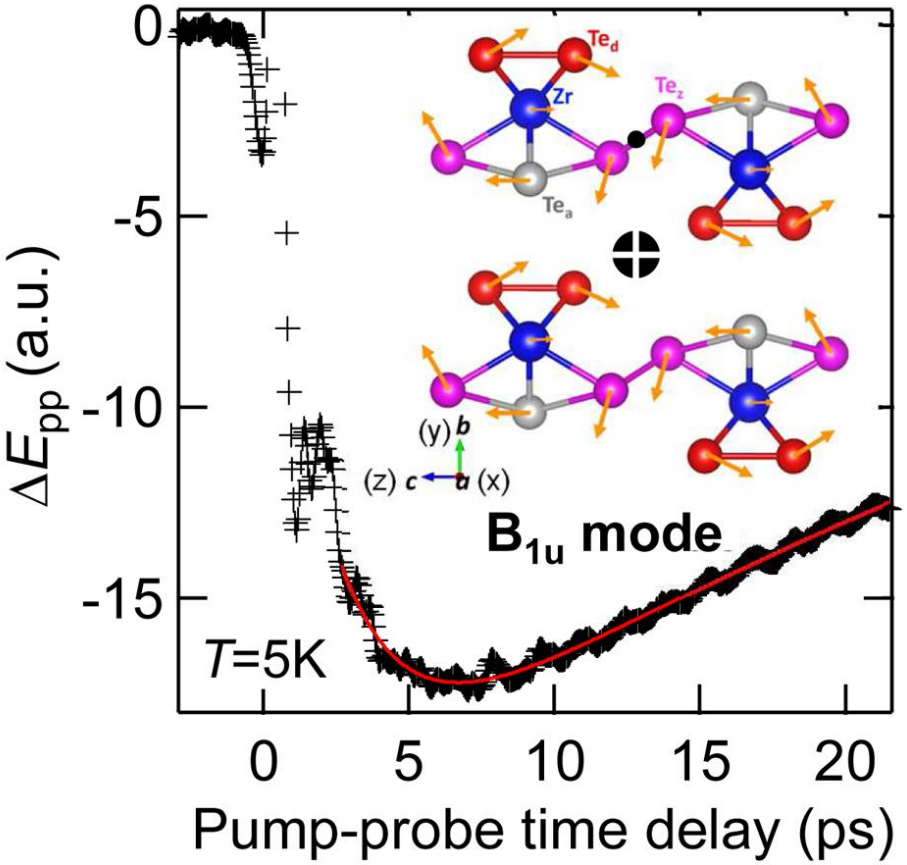


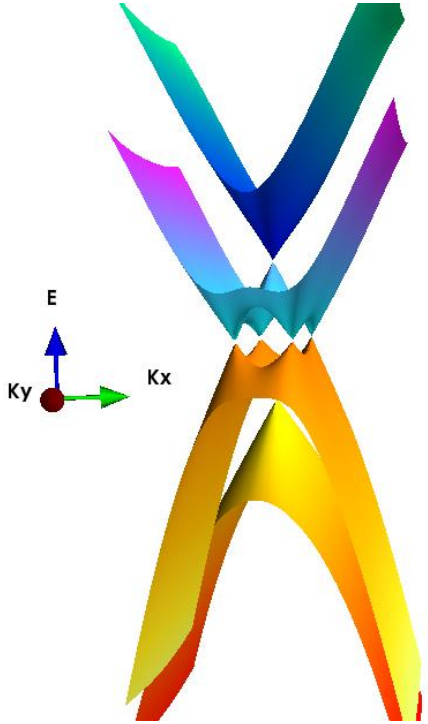
Ma, et al., Nature Physics **13**, 842 (2017)

A Light-induced Giant Dissipationless Topological Photocurrent in $ZrTe_5$*









Aryal, QL, et al., npj Computational Materials 8, 113 (2022).

*Luo, ..QL, Wang, et al., Nature Materials 20, 329 (2021)

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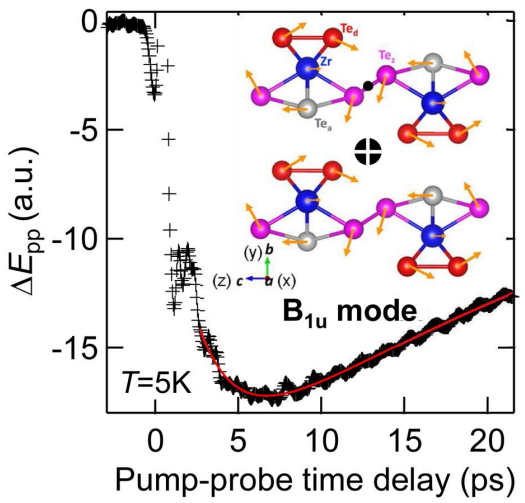
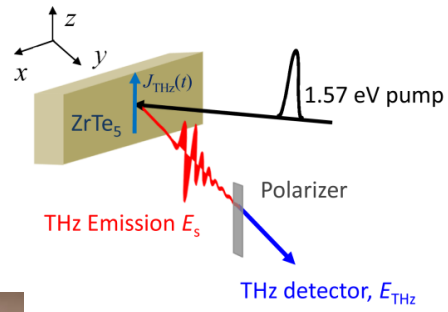
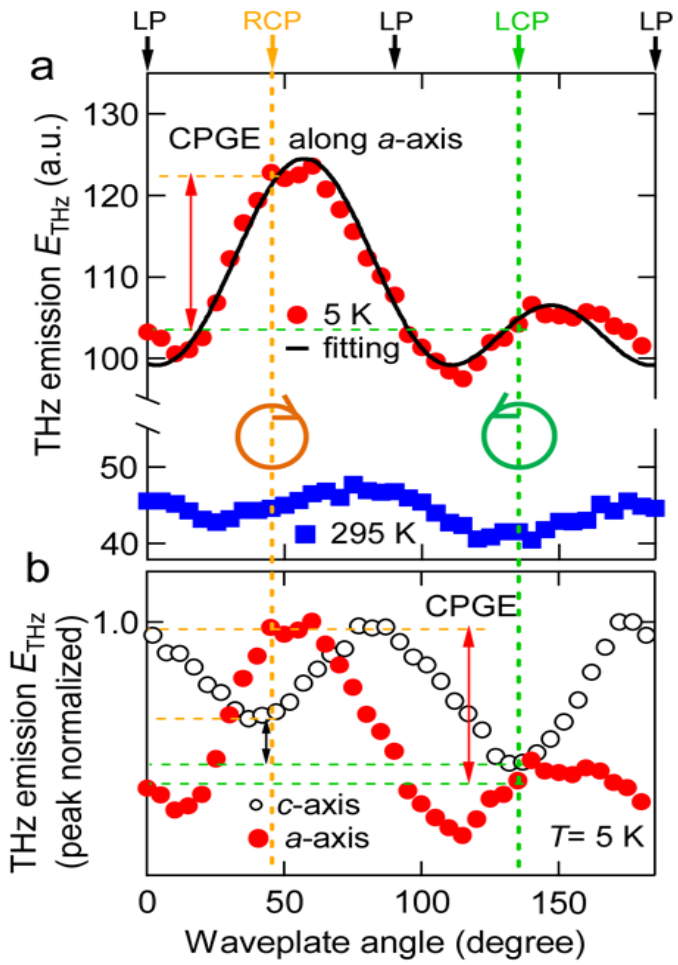
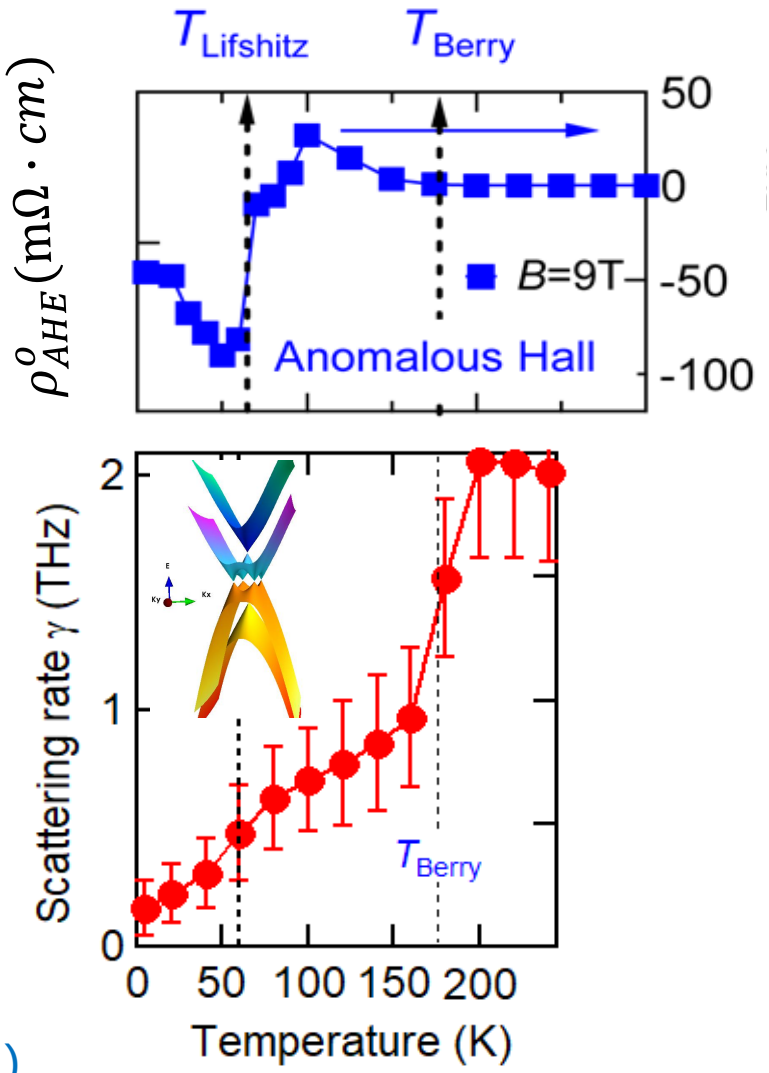
A Light-induced Giant Dissipationless Topological Photocurrent in $ZrTe_5$*









*Luo, ..QL, Wang, et al., Nature Materials 20, 329 (2021)

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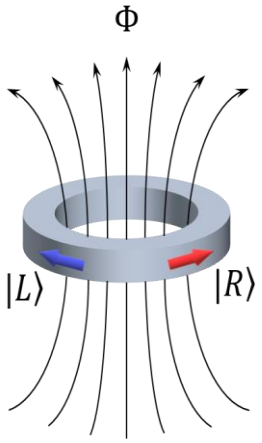
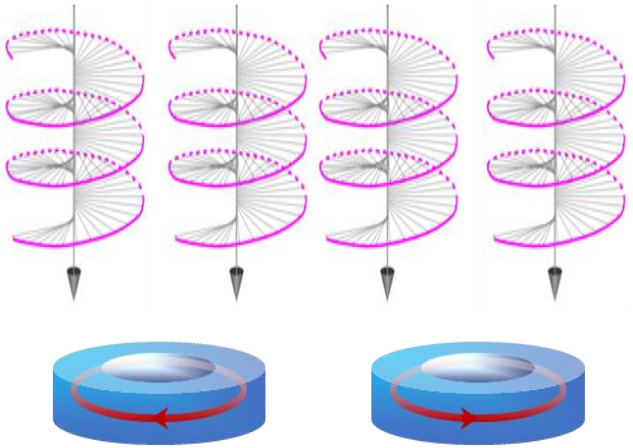
Chiral Qubit*

Chiral Qubit is a micron-scale ring made of a Weyl or Dirac semimetal, with the two base states describing chiral fermions circulating along the ring clockwise and counter-clockwise. A fractional magnetic flux through the ring induces a quantum superposition. The entanglement of qubits can be implemented through the circularly polarized THz frequency electromagnetic fields.

$$\hat{H} = \hbar\omega \left(-i\partial_\theta + \frac{\Phi}{\Phi_0} \right) \hat{\sigma}_z$$

$$|0\rangle = \frac{1}{\sqrt{2}} \left(|R\rangle + |L\rangle \right), |1\rangle = \frac{1}{\sqrt{2}} \left(|R\rangle - |L\rangle \right)$$

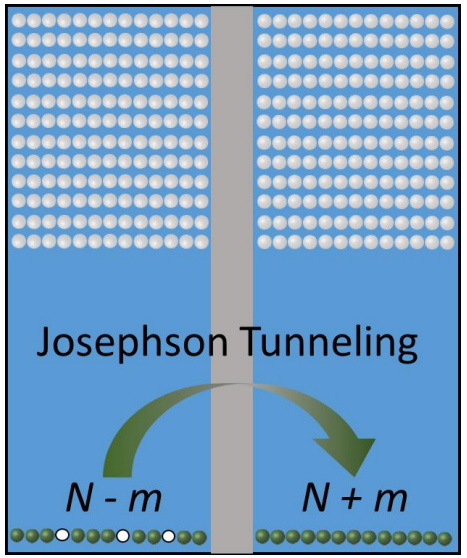




$$\alpha|L\rangle + \beta|R\rangle$$

*D. Kharzeev and QL "Quantum computing using chiral qubits" United States patent #10,657,456 B1 (2020);
D. Kharzeev and QL "The Chiral Qubit: quantum computing with chiral anomaly" arXiv:1903.07133

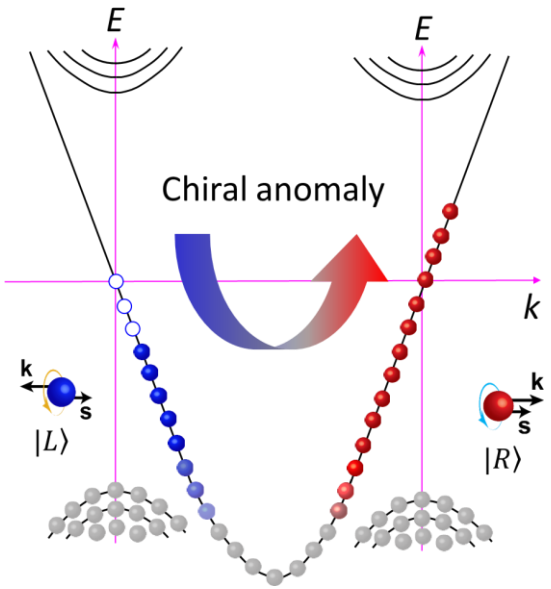
Superconducting qubit



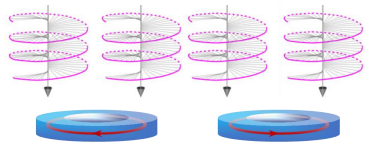
GHz energy gap
Microwave pulse

1 K ~ energy fluctuations 20 GHz

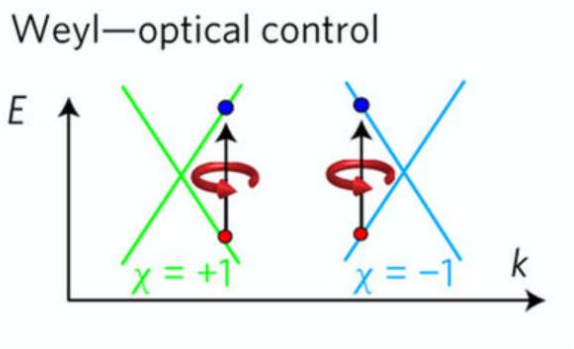
Chiral qubit

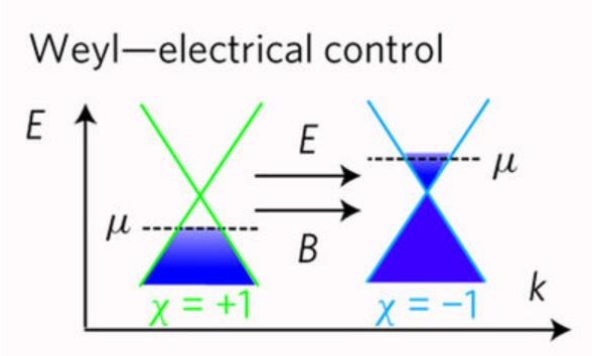


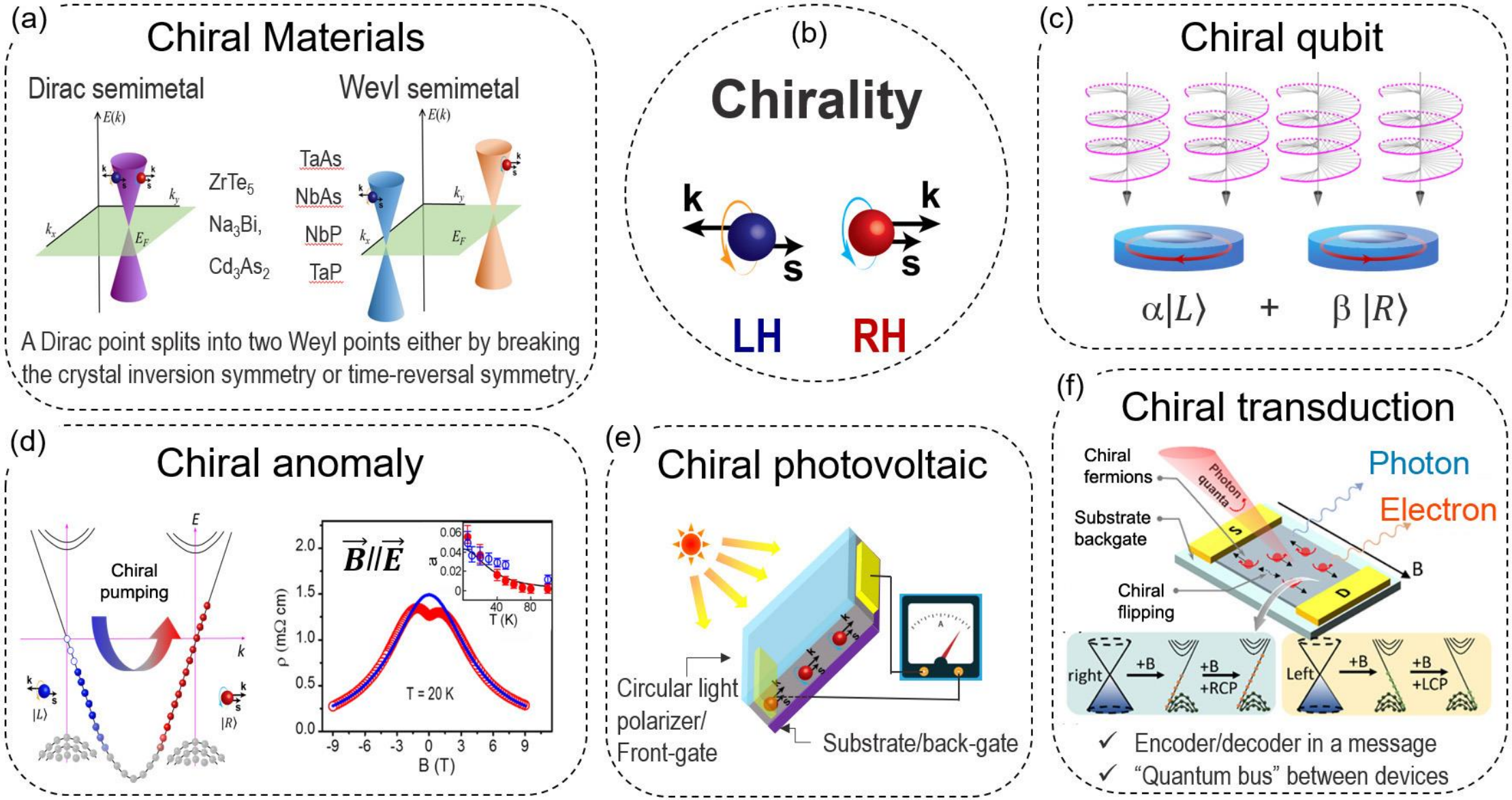
THz pulse



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







Q. Li "Dynamics of chiral fermions in condensed matter systems" Nobel Symposium Proceedings on Chiral Matters (2021)