Chiral Anomaly and Weyl Semimetals

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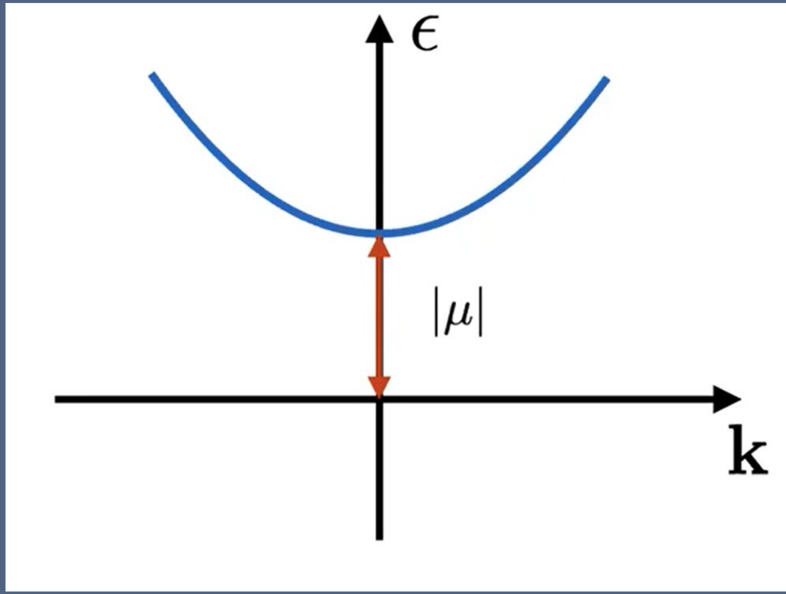
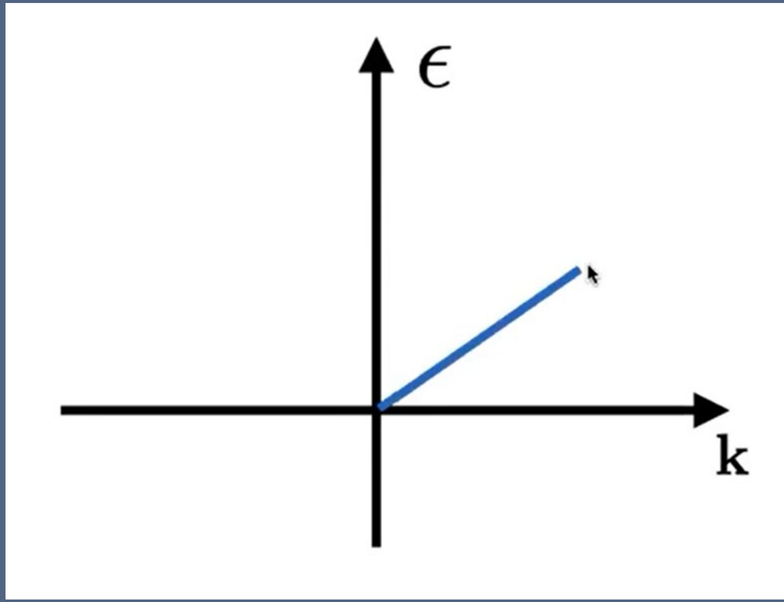
Gapless excitations

- Example: superfluid
  - When μ-> 0, dispersion changes drastically
- Gapless excitations created from **spontaneous symmetry breaking**

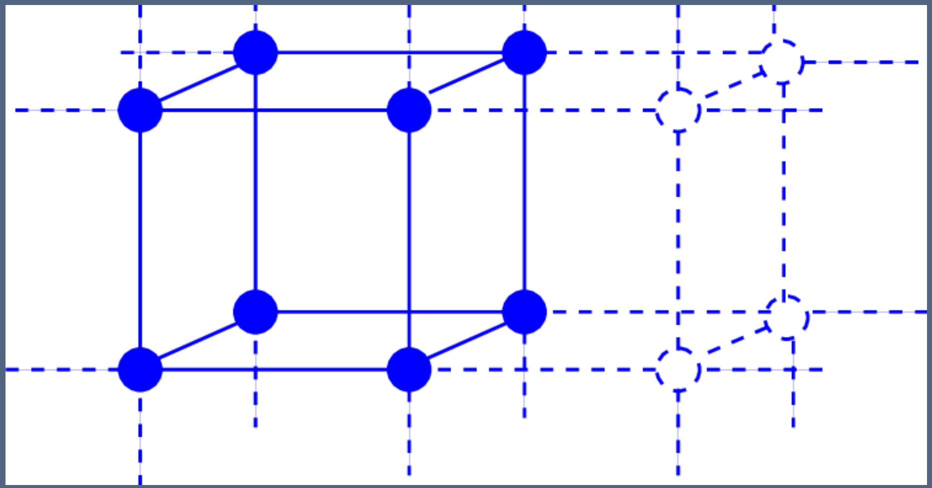




(Burkov)

Gapless excitations

- Lattices naturally break translation symmetry, leading to gapless excitations (acoustic phonons)
  - Spontaneous symmetry breaking helps us understand new phases!
- Gapless excitations may also arise from **topology**



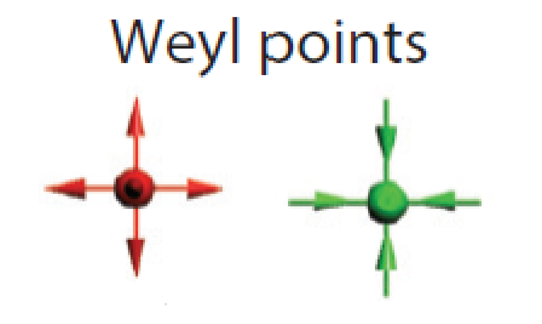
(Saad)

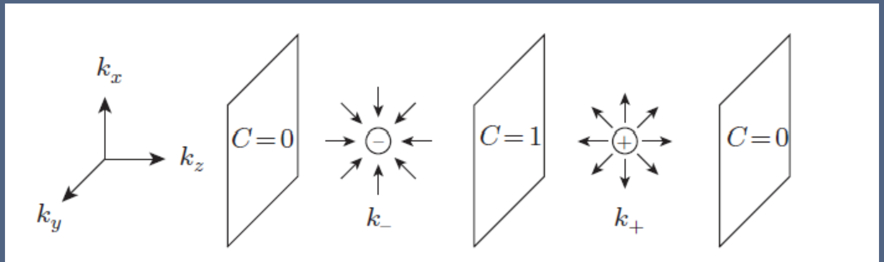
Weyl semimetals (WSM)

- Arise from 3D metal that either lacks time-reversal symmetry or inversion symmetry
- WSM differ from “accidental” SM in that they are **topologically protected**

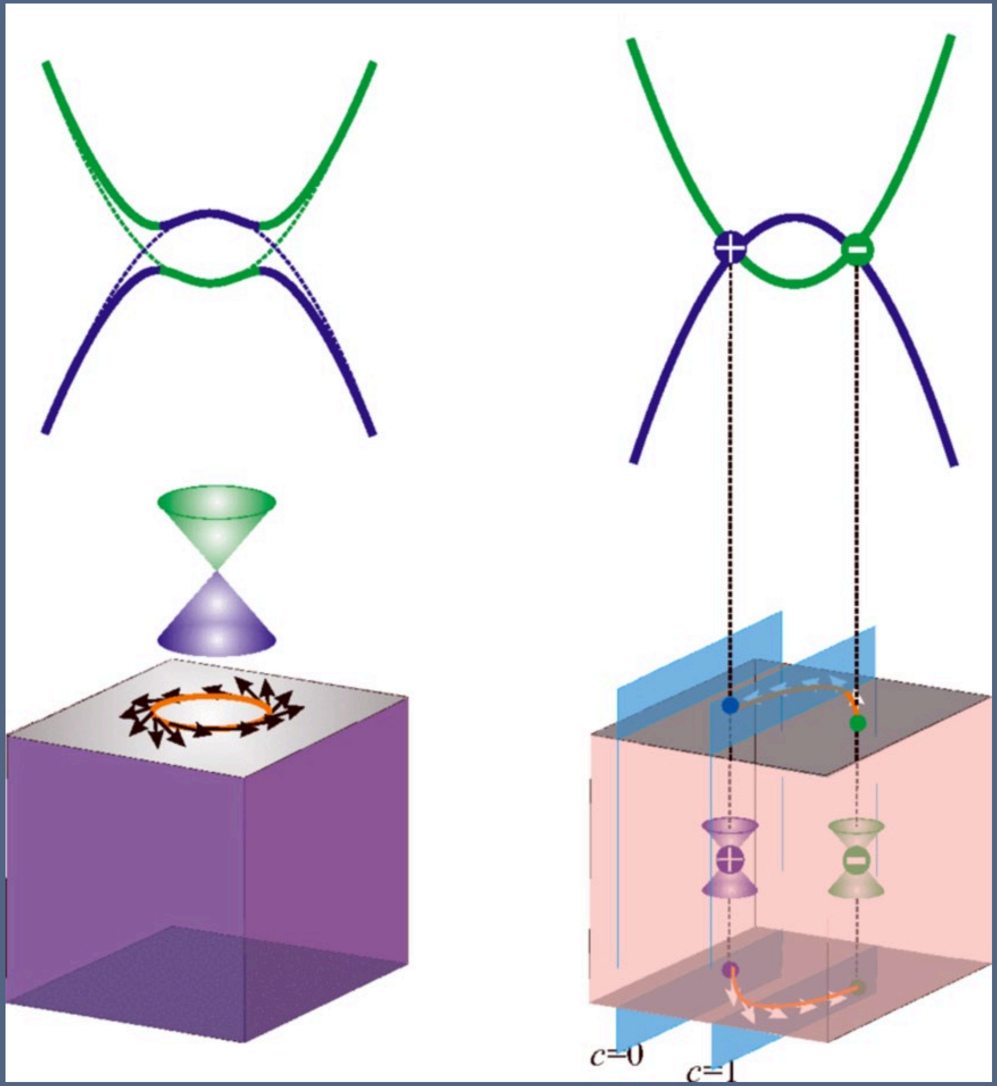
Weyl semimetals

- Forms by breaking time-reversal or inversion symmetry





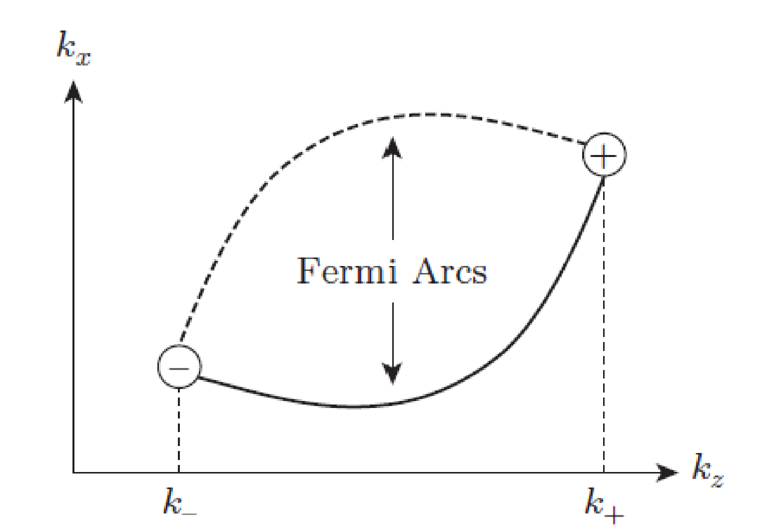
Topological insulator + **symmetry breaking** = **Weyl semimetal (or Dirac semimetal)**



(Damascelli), (Doniach), (Girvin)

Surface Fermi arcs

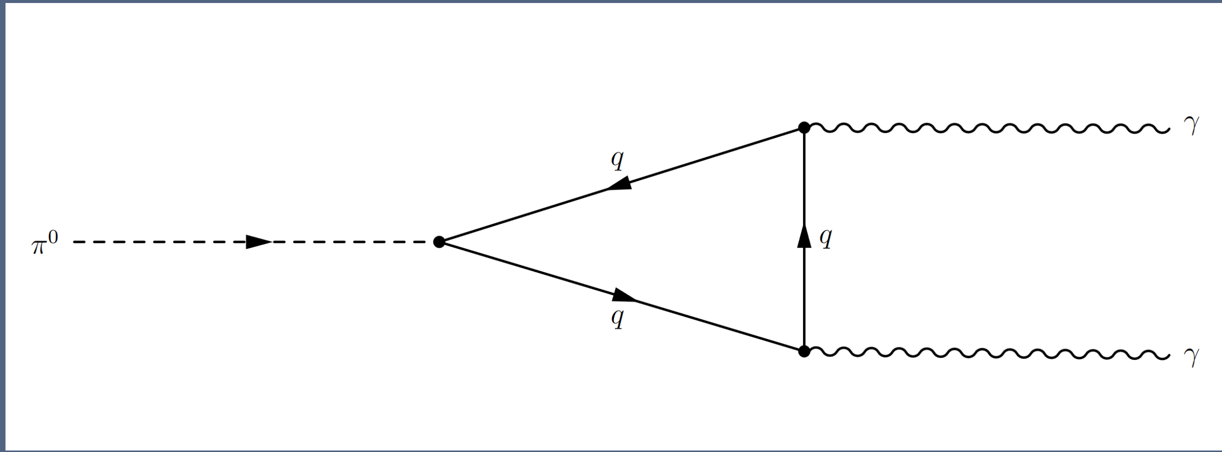
- The bulk of a WSM *is* conductive, but the WSM state is still protected by Fermi arcs
- Chern number can only change at band crossings



(Girvin)

Chiral anomaly in field theory

- The **Adler–Bell–Jackiw anomaly** or **chiral anomaly** describes pion decay that violates chiral charge conservation
  - Theorized in field theory, this has now become a hot topic in condensed matter!



(Wikipedia page for chiral anomaly)

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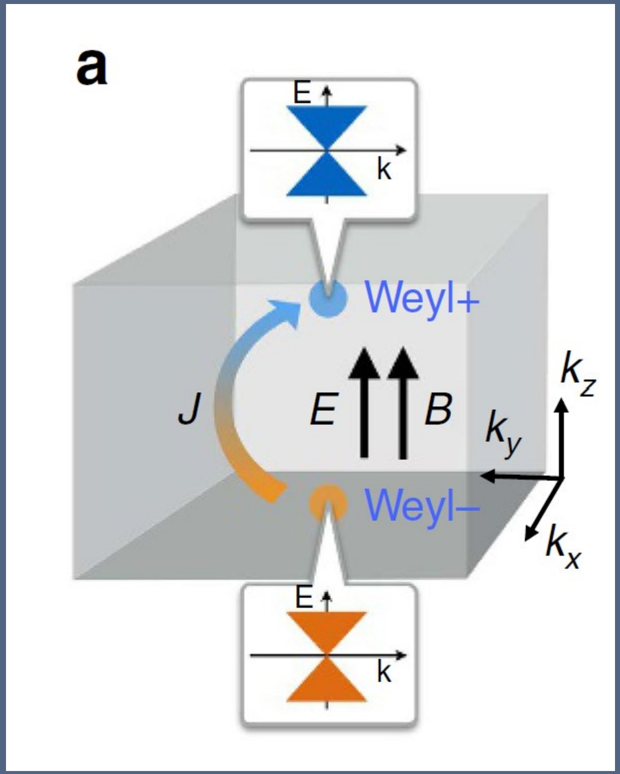
Signatures of the Adler–Bell–Jackiw chiral anomaly in a Weyl fermion semimetal

Cheng-Long Zhang[1,*], Su-Yang Xu[2,*], Ilya Belopolski[2,*], Zhujun Yuan[1,*], Ziquan Lin[3], Bingbing Tong[1], Guang Bian[2], Nasser Alidoust[2], Chi-Cheng Lee[4,5], Shin-Ming Huang[4,5], Tay-Rong Chang[2,6], Guoqing Chang[4,5], Chuang-Han Hsu[4,5], Horng-Tay Jeng[6,7], Madhab Neupane[2,8,9], Daniel S. Sanchez[2], Hao Zheng[2], Junfeng Wang[3], Hsin Lin[4,5], Chi Zhang[1,10], Hai-Zhou Lu[11], Shun-Qing Shen[12], Titus Neupert[13], M. Zahid Hasan[2] & Shuang Jia[1,10]

Chiral anomaly: breaking chiral charge conservation in presence of $E \cdot B$



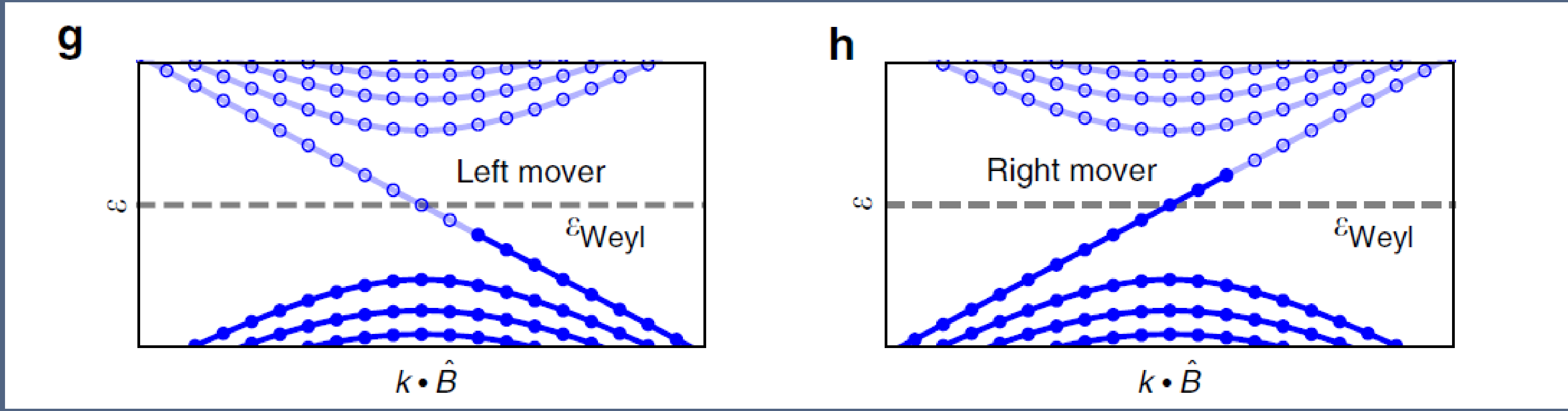
(Zhang)

Axial charge pumping

- Charge imbalance caused by chiral anomaly
  - Balanced by axial charge relaxation
- An axial current can be measured since Weyl points are separated in momentum space

$$\frac{\partial n_R}{\partial t} = \frac{1}{4\pi^2}\mathbf{E}\cdot\mathbf{B}$$

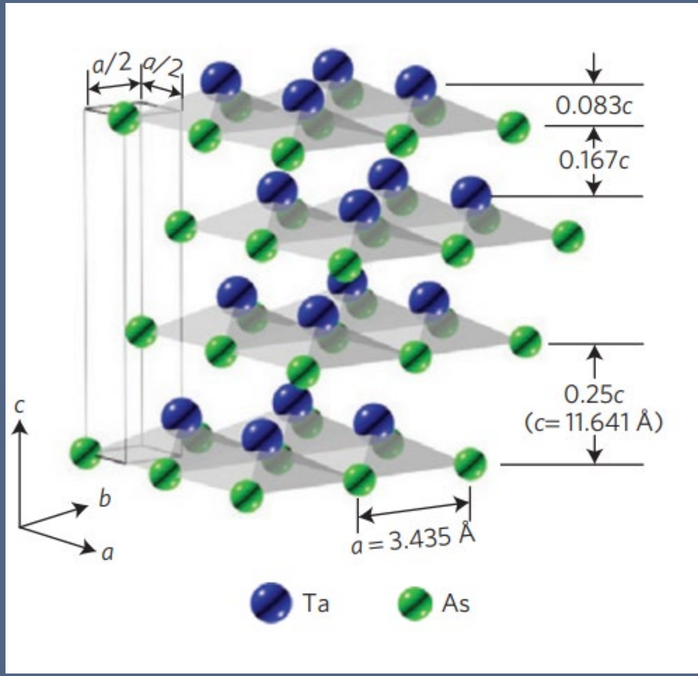
$$\frac{\partial n_L}{\partial t} = -\frac{1}{4\pi^2}\mathbf{E}\cdot\mathbf{B}$$



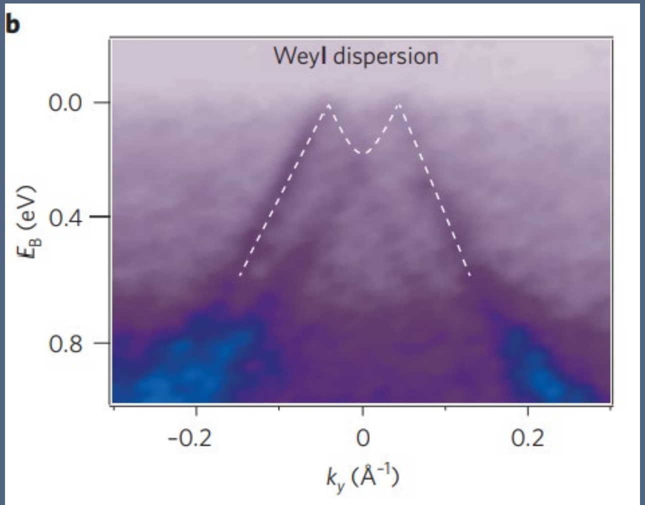
(Zhang)

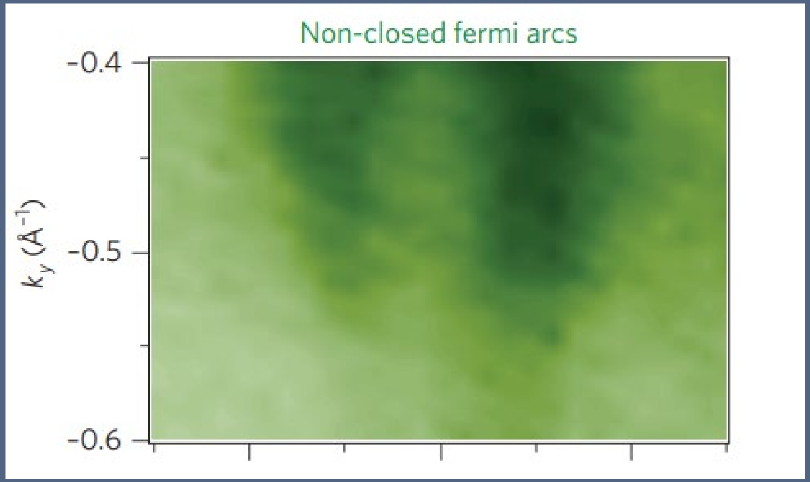
TaAs as a Weyl semimetal

- Body-centered tetragonal
  - Non-centrosymmetric (breaks **inversion symmetry)**
- ARPES shows evidence of WSM state



(Zhang)

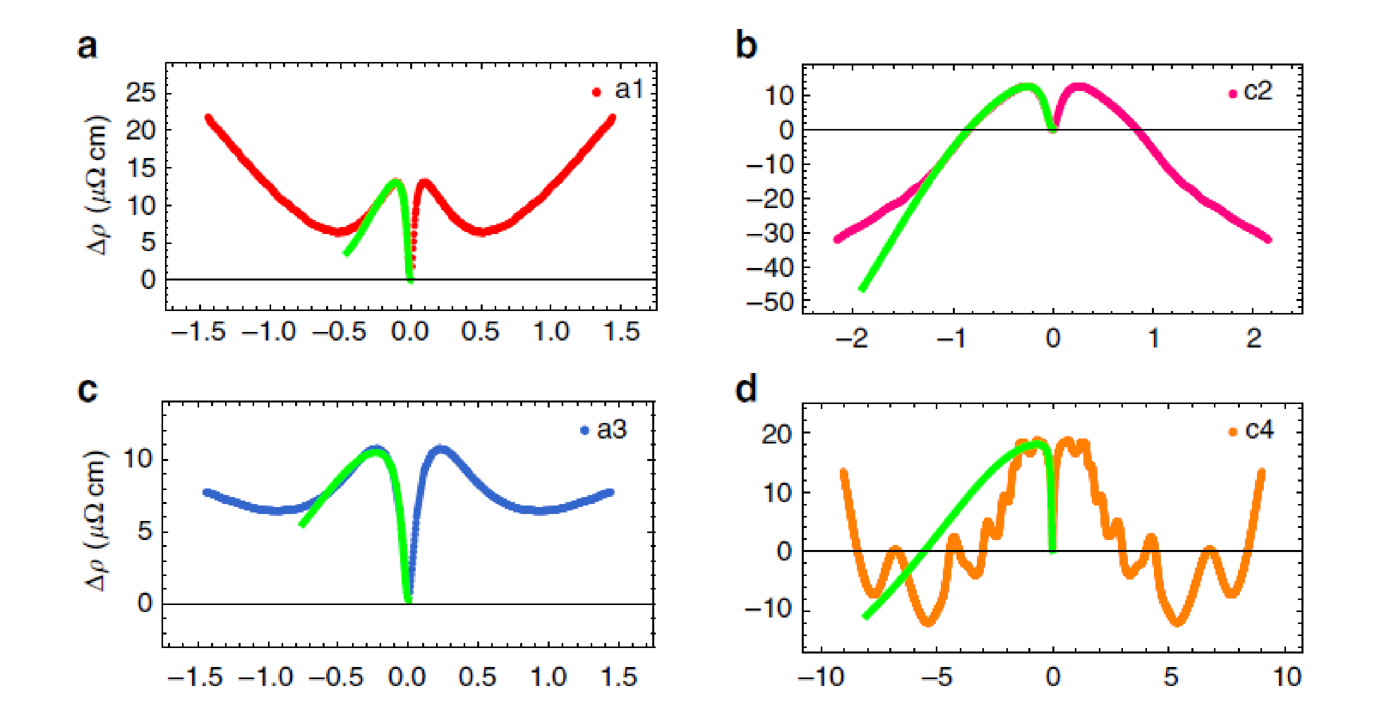




(Jia)

Observation of negative LMR

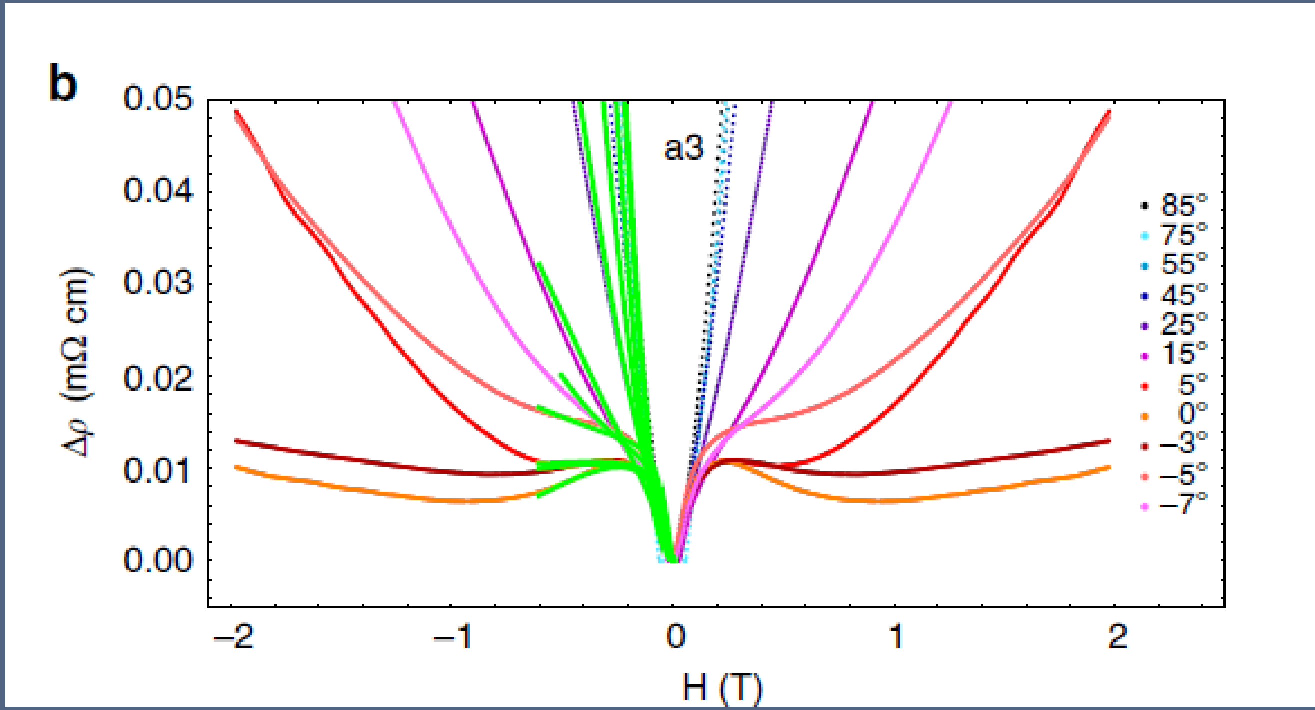
- In this paper, “negative longitudinal magnetoresistance (LMR)” means decreasing ρ with increasing B



(Zhang)

LMR as function of E · B

- LMR decreases with $E \cdot B$!



(Zhang)

What is the source of negative LMR?

- Magnetism?
  - TaAs is non-magnetic
- Geometry?
  - Samples shaped to avoid geometric effects
- Anisotropy?
  - Negative LMR observed along both a- and c- axes of tetragonal lattice
- Ultra-quantum limit? ($\omega\tau >> 1$)
  - Samples are in semiclassical limit at low B-fields

LMR data fitting

$$\sigma_{xx}(B) = 8C_W B^2 - C_{WAL}\left(\sqrt{B}\frac{B^2}{B^2+B_c^2} + \gamma B^2 \frac{B_c^2}{B^2+B_c^2}\right) + \sigma_0$$

Chiral coefficient term (goes as B^2)

$$C_W = \frac{e^4 \tau_a}{4\pi^4 \hbar^4 g(E_F)} \propto \frac{1}{E_F^2}$$

Weak anti-localization term (goes as $-B^2$ in low field and $-\sqrt{B}$ in high field (B_c describes crossover)

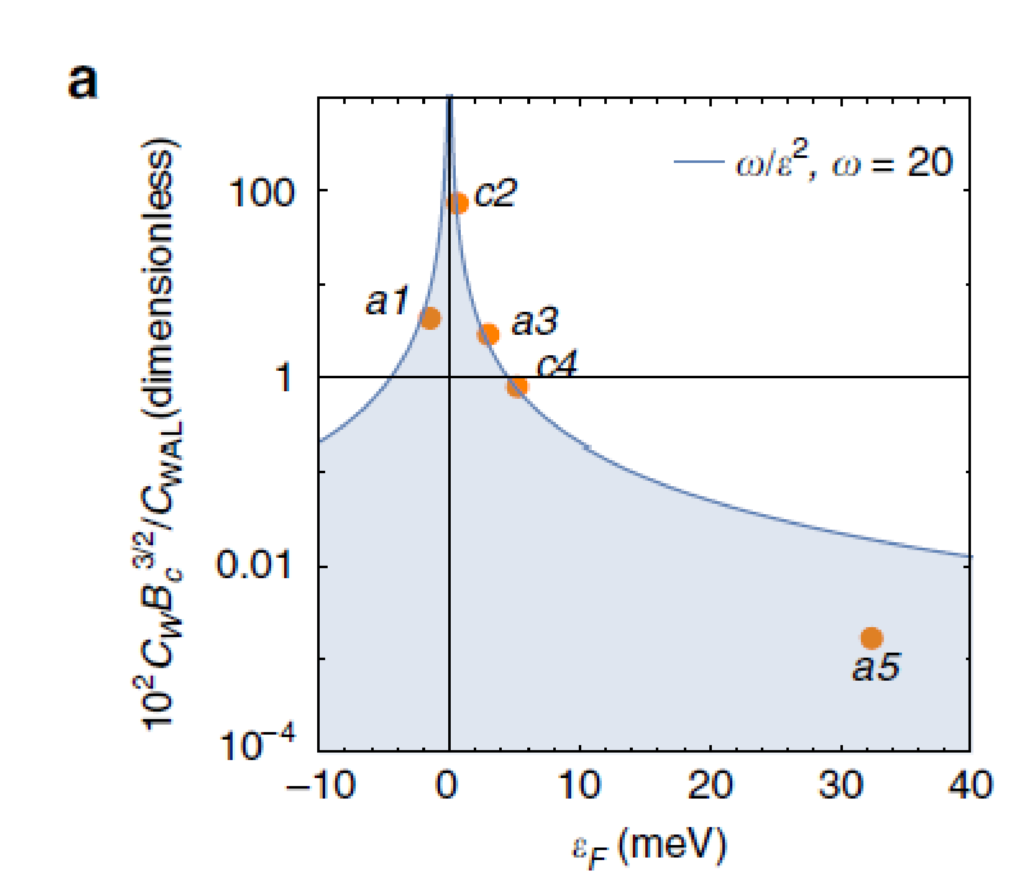
Drude conductivity

(Zhang)

Berry curvature as source of LMR

- How do we know this Berry curvature arises from Weyl nodes?
  - "Chiral anomaly ratio" scales as $1/E_F^2$, as expected for theoretical model of Weyl point
    - $\Omega \propto 1/E_F^2$

$$C_W = \frac{e^4 \tau_a}{4\pi^4 \hbar^4 g(E_F)} \propto \frac{1}{E_F^2}$$



(Zhang)

Conclusions

- Weyl cones can produce observable chiral anomaly
- Chiral anomaly can also arise for other reasons
  - Only TaAs (at time of publish) had been confirmed to have this $1/E_F^2$ signature
  - Other causes were ruled out systematically

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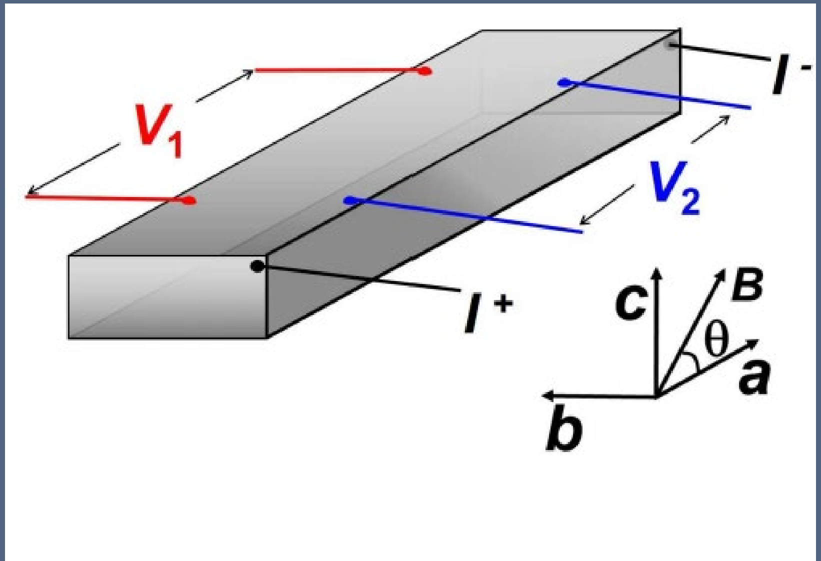
  - Other causes were ruled out systematically

Not so fast…

On the search for the chiral anomaly in Weyl semimetals: The negative longitudinal magnetoresistance

R. D. dos Reis, M. O. Ajeesh, N. Kumar, F. Arnold, C. Shekhar, M. Naumann, M. Schmidt, M. Nicklas, and E. Hassinger
Max Planck Institute for Chemical Physics of Solids, Nöthnitzer Str. 40, 01187 Dresden, Germany

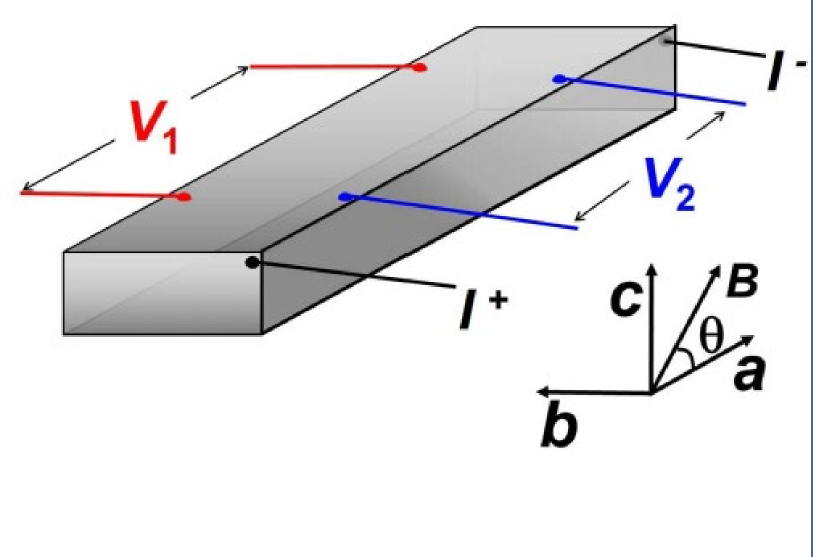
Current jetting as the cause for chiral anomaly?



(dos Reis)

Current jetting

- B-field induces anisotropic resistance
- If B perpendicular to direction of line between current contacts, a “jet” can form
  - Measured voltage decreases with increasing B

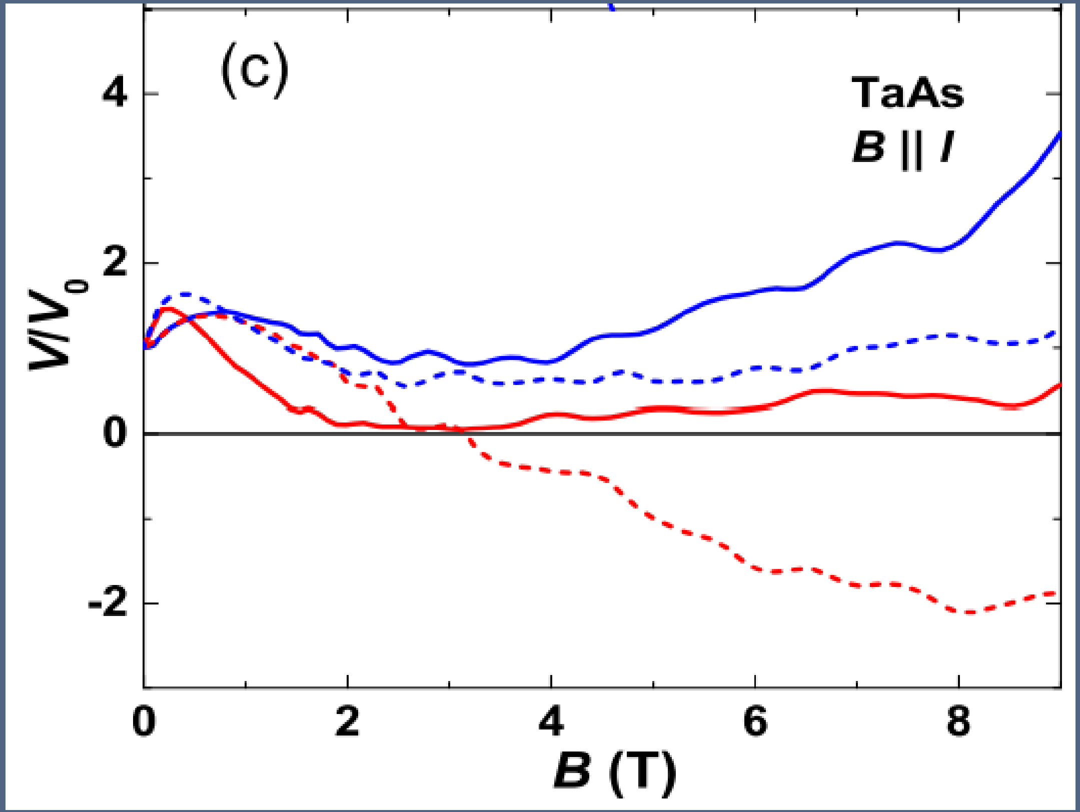


(dos Reis)

Measurement of negative LMR

- Red and blue curves are two sets of voltage contacts
- Solid lines: spot-welded
- Dashed lines: silver paint

- Takeaway: small changes in alignment or contact lead to big changes in results

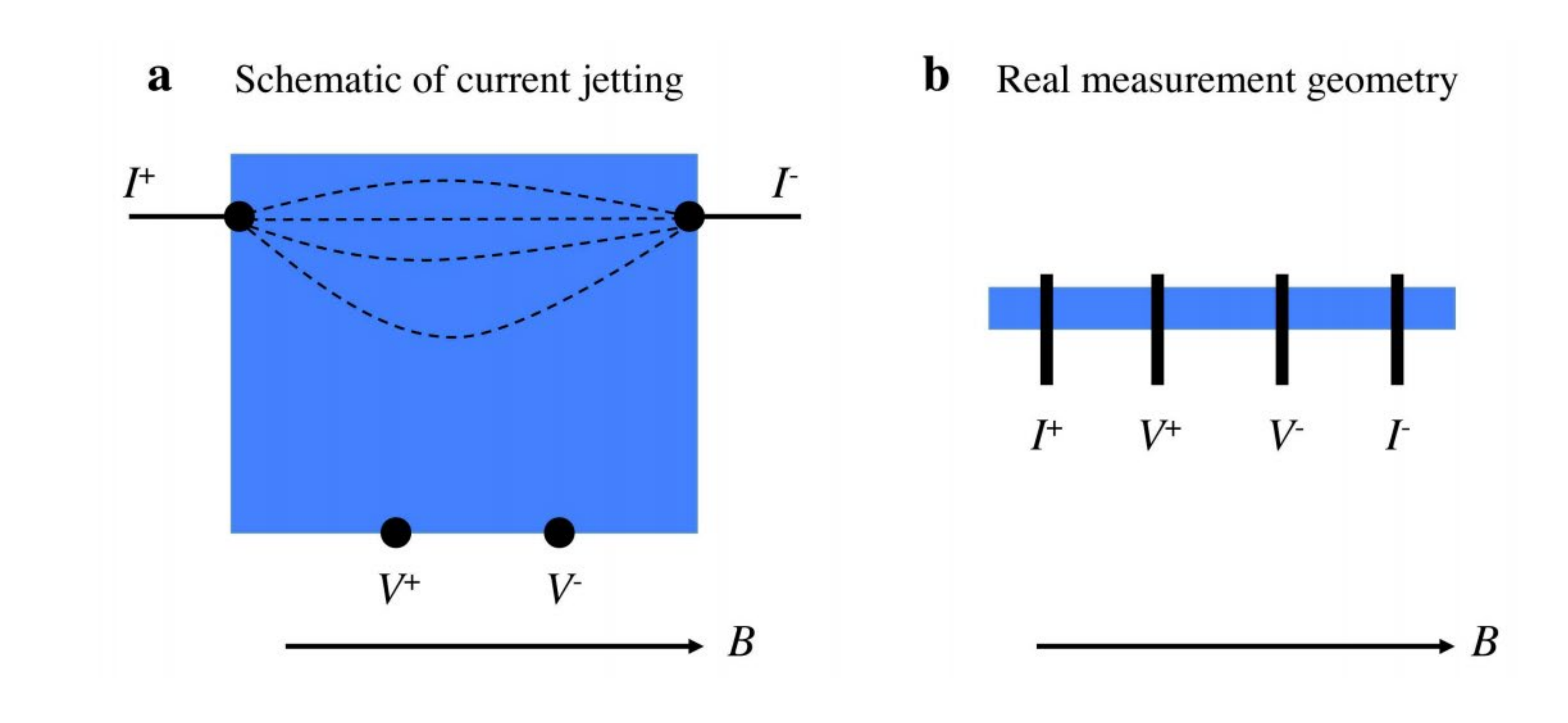


(dos Reis)

Conclusions from Hassinger paper

- It is very difficult to rule out geometrical effects (current jetting) as the source of negative LMR
- They do not deny that TaAs is a WSM, only disputing the observation of chiral anomaly

Experimental setup in original paper



(Zhang)

Questions

- For Jia paper:
  - Were the probes placed at different positions to demonstrate the robustness of measurements?
- For Hassinger paper:
  - Were ARPES measurements done on their samples?

References

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Girvin and Yang. *Modern Condensed Matter Physics.*

Jia et al. *Weyl semimetals, Fermi arcs and chiral anomalies.*

Saad *et al. Numerical Methods for Electronic Structure Calculations of Materials.*

Zhang *et al. Signatures of the Adler–Bell–Jackiw chiral anomaly in a Weyl fermion semimetal.*