Quantized photocurrents in chiral nodal semimetals

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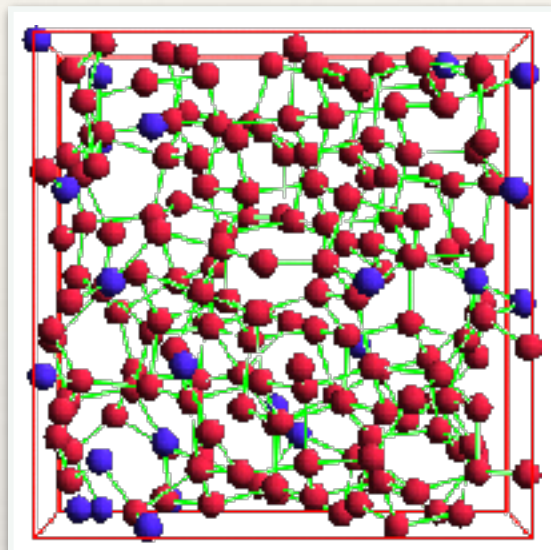
Workshop on Weyl metals
IFT, Madrid

de Juan et al, Nat. Commun. 8, 15995 (2017)
Flicker et al, PRB 98, 155145 (2018)
Schroeter et al, arxiv:1812.03310 (Nat. Phys. in press)

Preamble: Topology and quantization

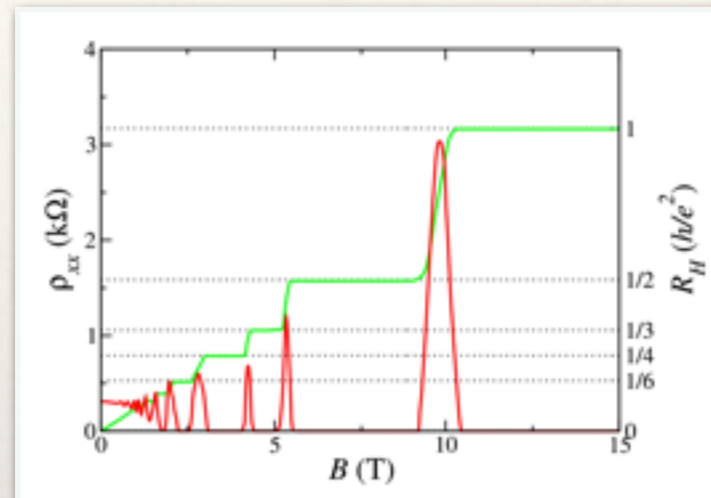
Condensed matter



Bulk observables can be anything!

And yet…

Quantum Hall Effect

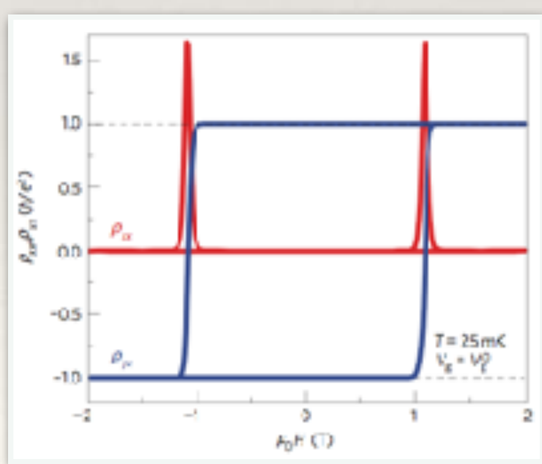


von Klitzing, RMP **58**, 519 (1986)

$$\sigma_{xy} = \frac{e^2}{h} C$$

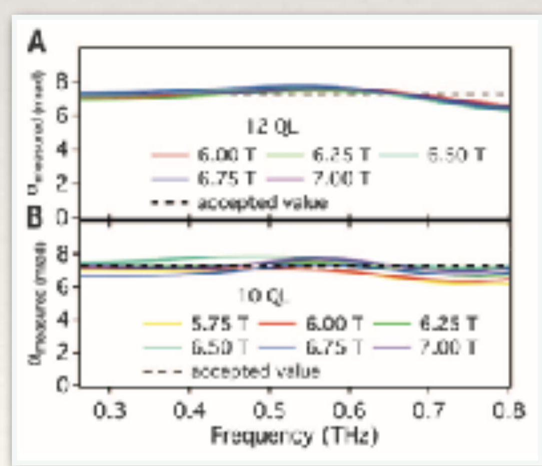
Topological invariant

Quantized Anomalous Hall Effect



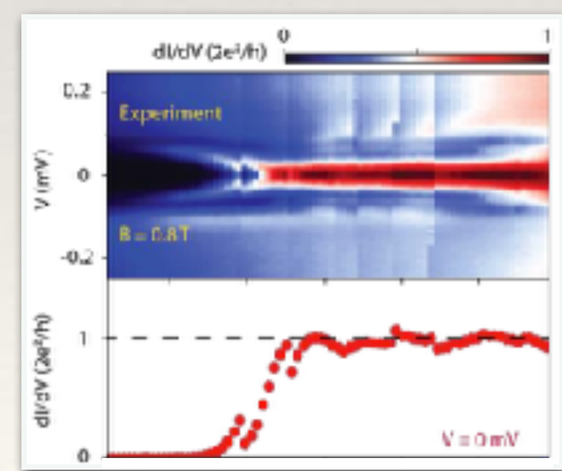
Chang, Nature Mater. **14**, 473–477 (2015)

Quantized Kerr / Faraday rotation

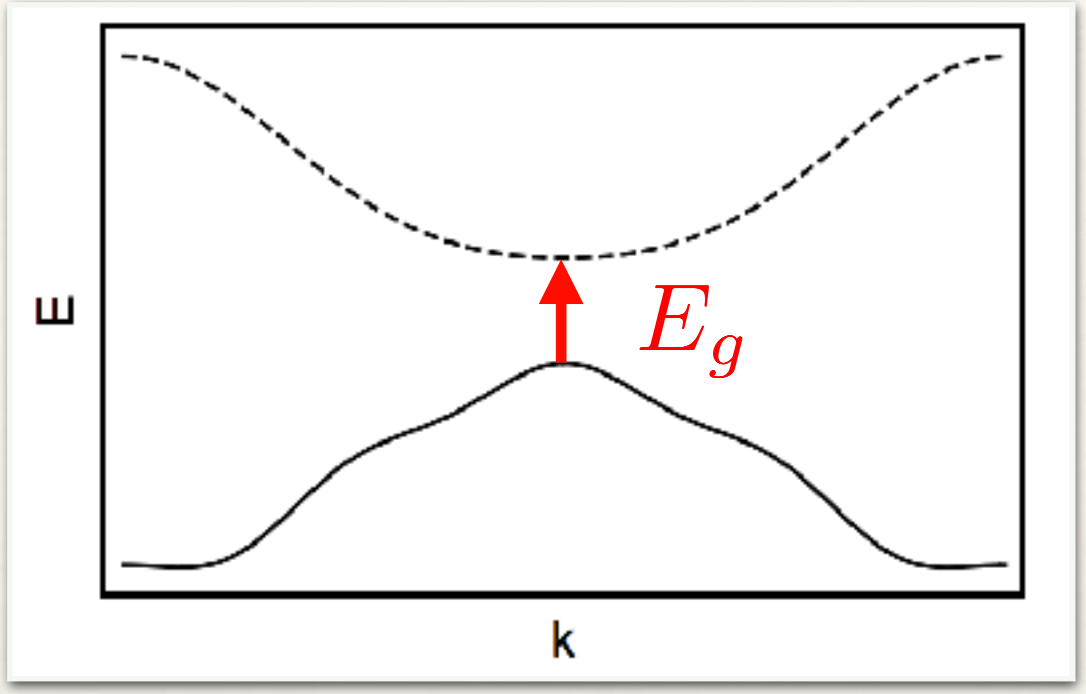


Wu et al, Science **354**, 1124 (2016)

Quantized Andreev reflection



Kouwenhoven group, arxiv:1710.10701



All these examples are for insulators (with an energy gap to excitations)

Gap protects quantization

The question in this talk

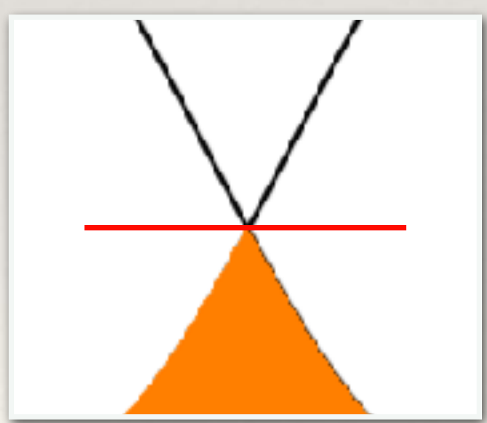
Is there a quantized observable in gapless systems (i.e. metals)?

Weyl fermions

HEP

$$\mathcal{L} = \bar{\psi}\gamma^\mu i\partial_\mu \psi$$

$$\mathcal{H} = \psi^\dagger \begin{pmatrix} \sigma_i & 0 \\ 0 & -\sigma_i \end{pmatrix} k_i \psi$$

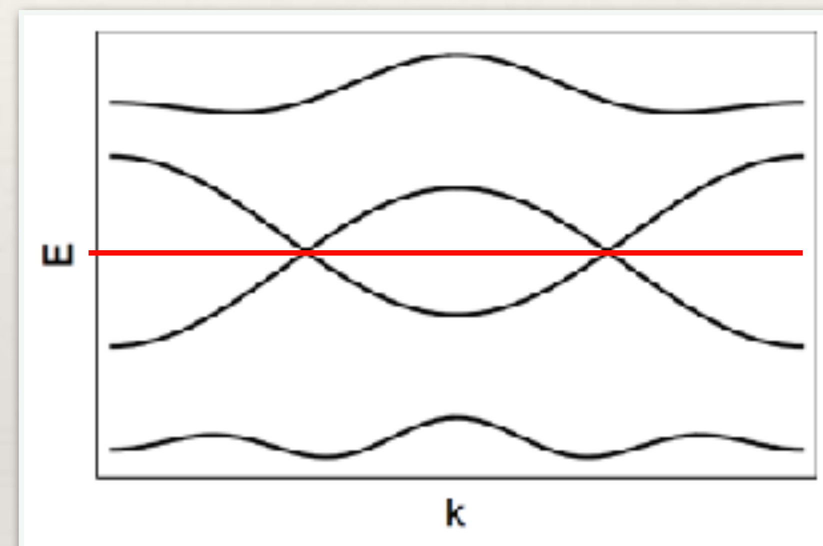


$$E_k = \pm c|k|$$

Dirac sea

CMP

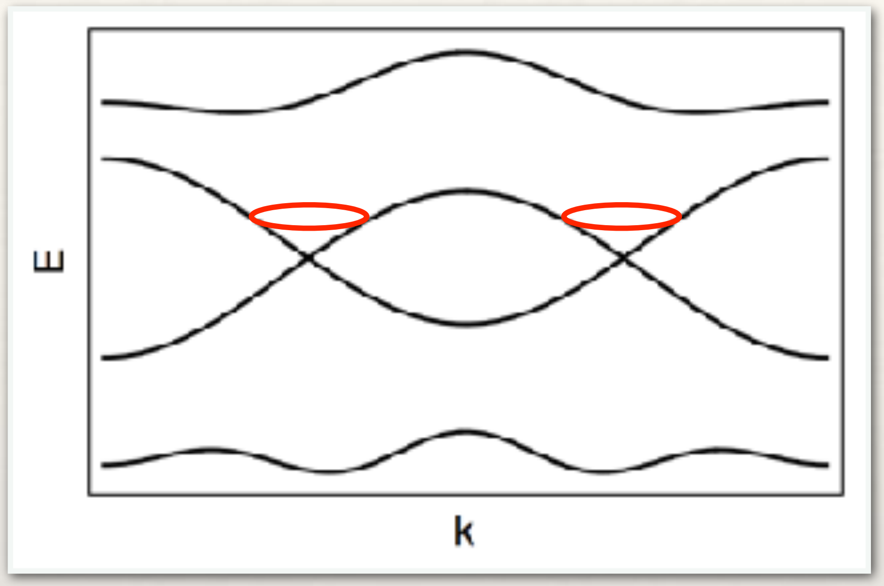
$$H_k |u_k\rangle = E_k |u_k\rangle$$



- "Accidental Degeneracy in the Energy Bands of Crystals" Herring Phys. Rev. **52**, 365 (1937)

Similar discussion in the context of lattice fermions:
Nielsen, Ninomiya, Nucl. Phys. **B** 193, 173 (1981)

Weyl fermions in crystals



$$H = v_F(\sigma_x k_x + \sigma_y k_y + \sigma_z k_z)$$

$$\vec{\Omega}_k = \vec{\nabla} \times \langle u_k | i\vec{\nabla} | u_k \rangle$$

$$\vec{\Omega} = \pm \frac{\vec{k}}{2k^3}$$ Berry curvature monopole

1) Monopole charge is a topological invariant of the node

2) Nodes cannot gap out except in pairs

3) In finite systems, Berry monopoles require surface states knows as Fermi arcs

Berry, Proc. R. Soc. Lond. A **392** 45 (1984), Volovik JETP **46**, 81 (1987),
Murakami *New J. Phys.* **9** 356 (2007), Wan, Phys. Rev. B **83**, 205101 (2011)

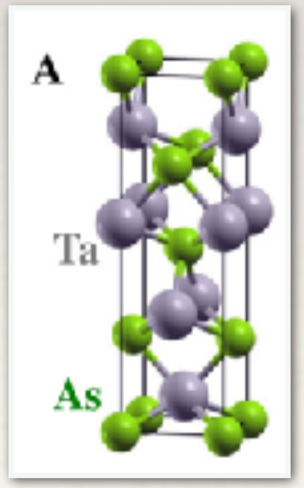
Materials realizing Weyls

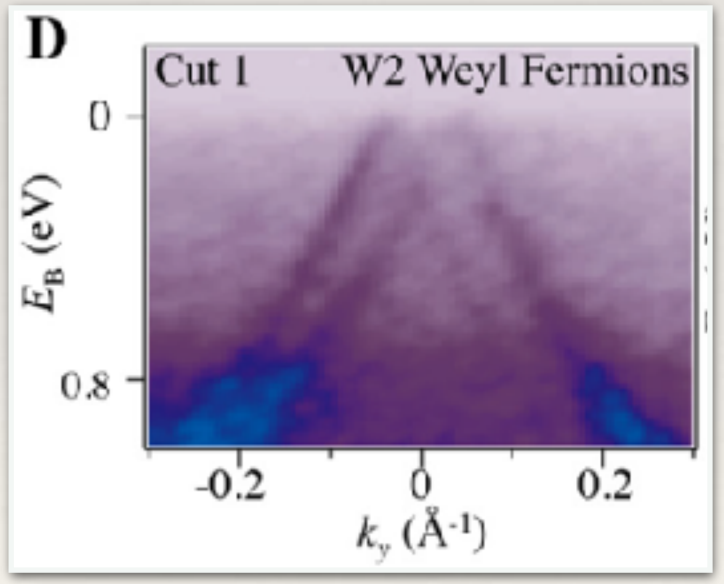
Time reversal + inversion symmetry -> No isolated Weyl points

Therefore: Two classes of Weyl semimetals

Inversion breaking Weyl semimetal
TaAs, NbAs

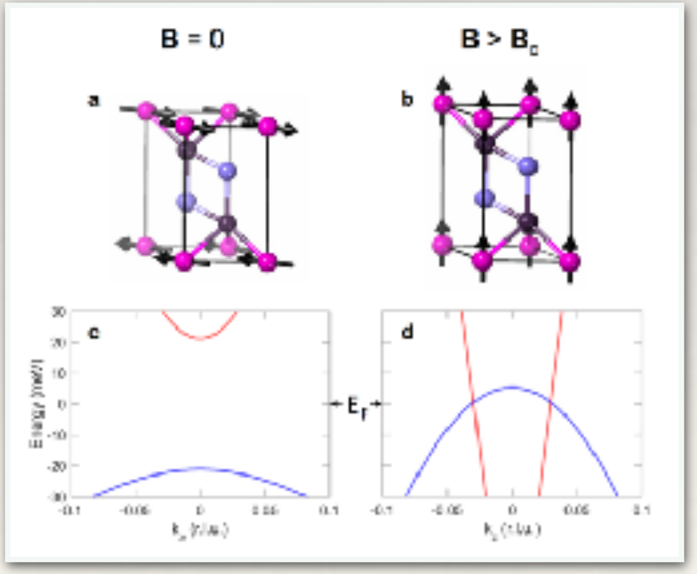
TaAs





Xu, Science **349**, 613 (2015)

Magnetic Weyl semimetal
GdPtBi, EuCd2As2



Soh et al, arxiv:1901.10022

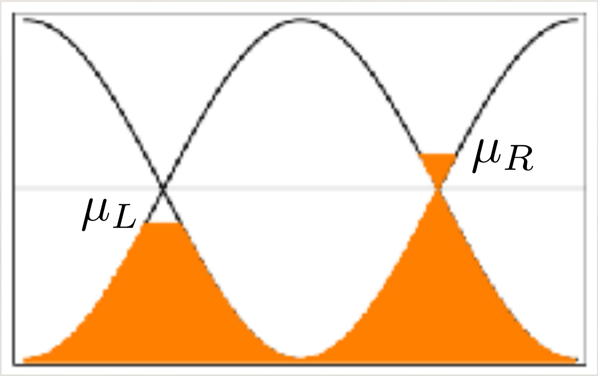
Probing the Weyl node

Chiral anomaly

$$\partial_\mu (j^\mu_L - j^\mu_R) = \frac{1}{2\pi^2} \vec{E} \cdot \vec{B}$$

Exact coefficient, but only measured indirectly

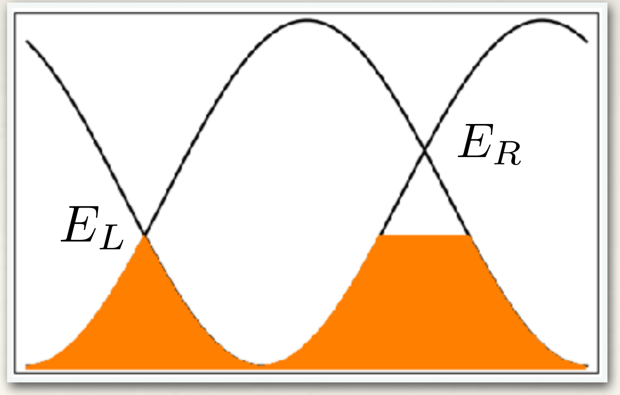
Chiral magnetic effect



$$\vec{j} = \frac{C}{4\pi^2} (\mu_L - \mu_R) \vec{B}$$

Intrinsically non-equilibrium effect. Hard!

Gyrotropic magnetic effect

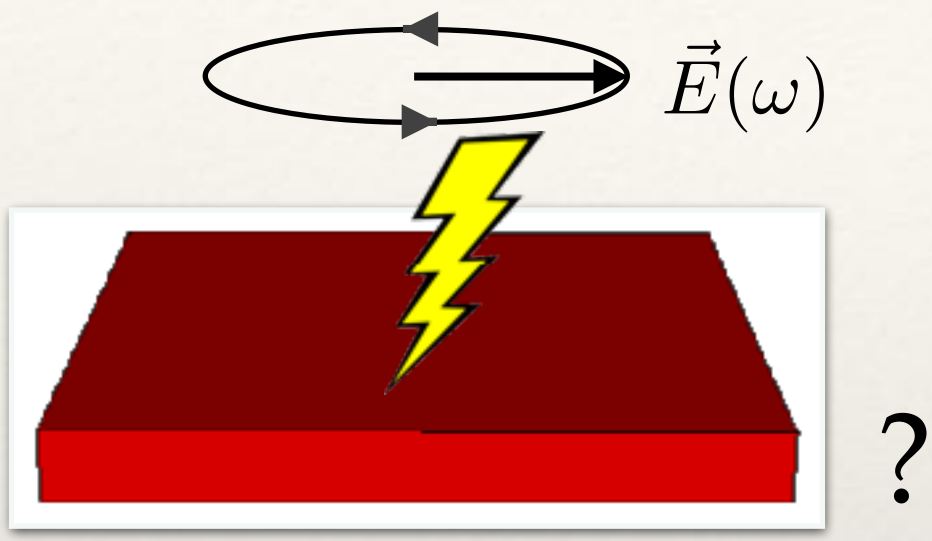


$$\vec{j}(\omega) = \chi \vec{q} \times \vec{A}(\omega) = \chi \vec{B}(\omega)$$

$$\chi \propto (E_L - E_R)$$

Finite frequency, linear response. More standard, but: Not generic to Weyl nodes!

Circular Photogalvanic effect

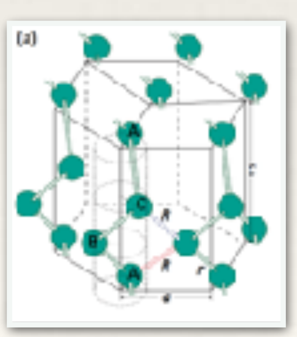


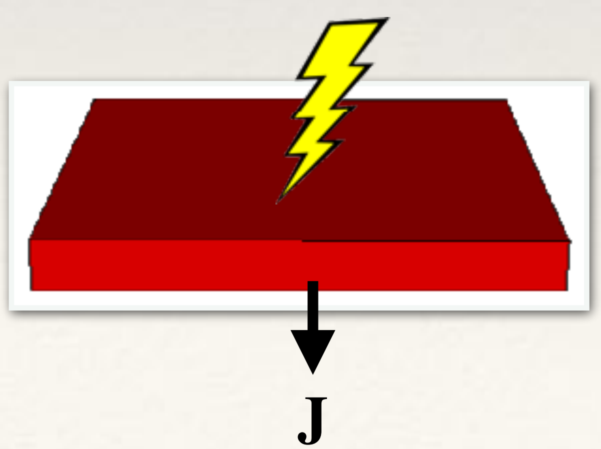
Circular photogalvanic effect (CPGE):
In homogeneous, inversion-breaking system current grows linearly in time (injection current)

$$\partial_t J_i = \beta_{ij}[\vec{E}(\omega) \times \vec{E}^*(\omega)]_j$$

Transverse CPGE: Any gyrotropic crystal class

- **GaAs** quantum wells, SSC 128, 283–286 (2003)
- **Bi_2Se_3** TIs surfaces, Nature Nanotech. **7**, 96–100 (2012)
- **BiTeBr** Bulk Rashba semiconductor PRB **90**, 125122 (2014)
- **Si** nanowires: Science **349**, 726 (2015)
- Gated **WSe_2**, Nat. Nanotech **9**, 851 (2014)
- …





Longitudinal CPGE: Any chiral crystal class

Elemental Te, SSC **30**, 565 (1979)

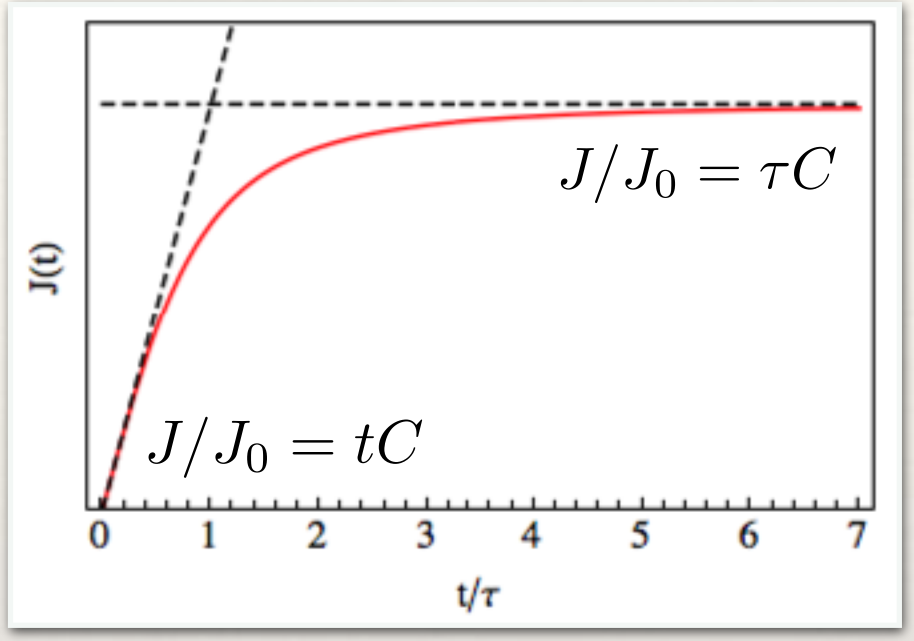
Injection current in experiment

Short time: rate of current growth (slope)

$$\partial_t J_i = \beta_{ij}[\vec{E} \times \vec{E}^*]_j$$

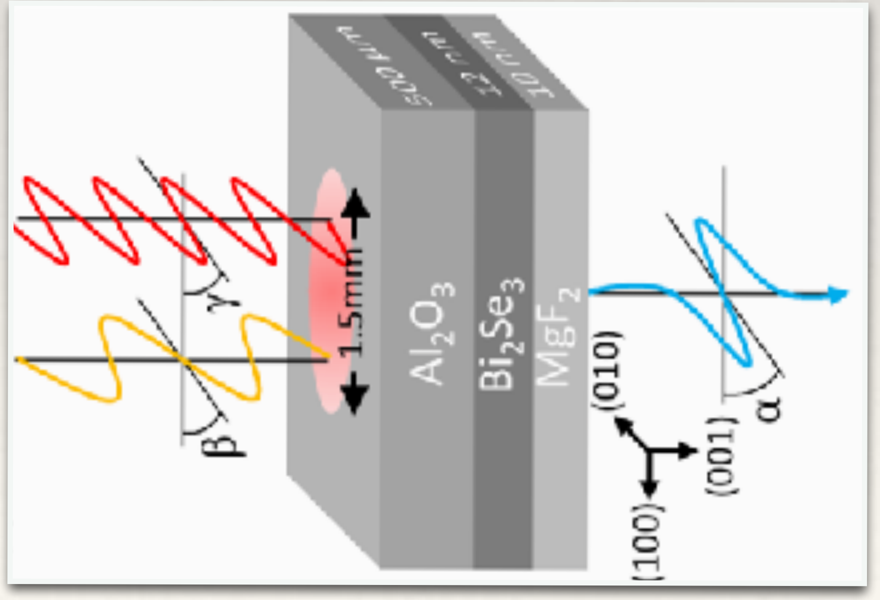
Long time: saturation due to scattering

$$J_i = \tau\beta_{ij}[\vec{E} \times \vec{E}^*]_j$$



$\vec{E}(\omega_1)$

$\vec{E}(\omega_2)$



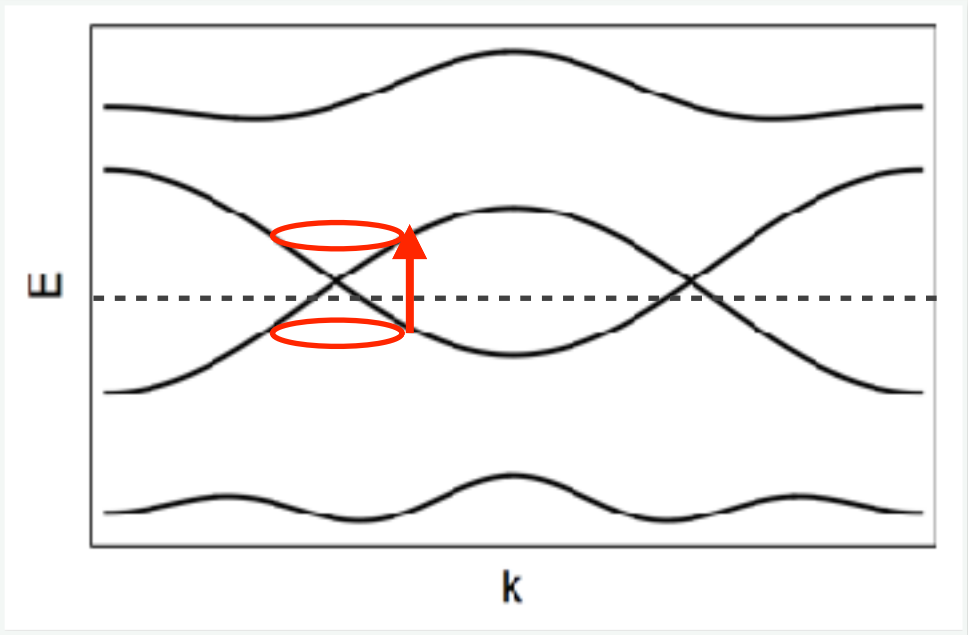
arxiv:1602.01074

All optical alternative: 1) Use two beams with similar but not equal frequencies

2) Response oscillates at $\omega_1 - \omega_2$

3) J_i and $\partial_t J_i$ have relative phase of $\pi/2$ and can be separated

Circular photogalvanic effect



$$\beta(\omega) = 4\pi^2\beta_0 \int \frac{d^3k}{(2\pi)^3} \sum_{n,m} f_{nm}\partial_{k_i}E_{nm}R^i_{nm}\delta(\hbar\omega - E_{mn})$$

$$\equiv 4\pi^2\beta_0 \sum_{n,m} \int d\vec{S}_{nm}\cdot\vec{R}_{nm}$$

$$\beta_0 = \frac{\pi e^3}{h^2}$$

$$\vec{\Omega}_n = i\sum_{m\neq n}\vec{R}_{nm}$$

$$\vec{R}_{nm} = \vec{r}_{nm}\times\vec{r}_{mn}$$

$$\vec{r}_{mn} = i\langle n|\partial_{\vec{k}}|m\rangle$$

Two bands $\vec{R}_{12} = -i\vec{\Omega}_1$

$$\beta = i\beta_0 C$$

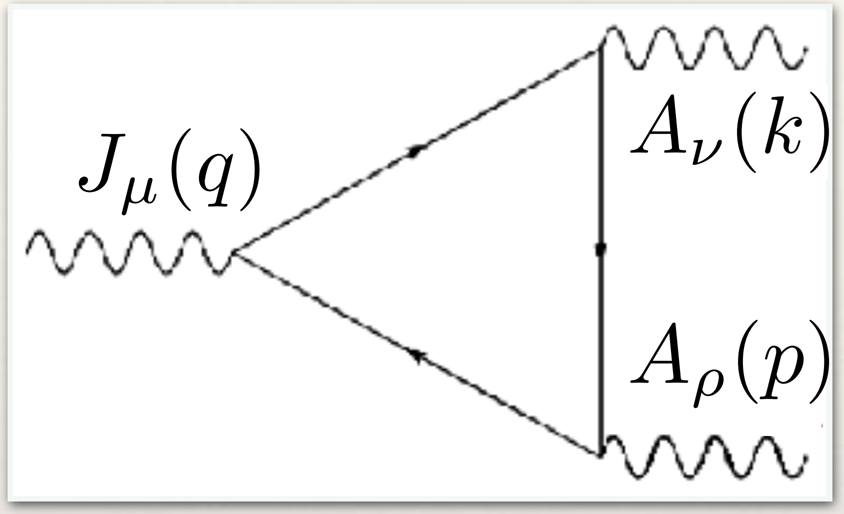
Quantized CPGE!

Three bands $\vec{R}_{12} = -i\vec{\Omega}_1 - \vec{R}_{13}$

$$\frac{|\vec{R}_{13}|}{|\Omega_1|} \approx \frac{\vec{v}_{13}\times\vec{v}_{31}}{v_F^2}\frac{\omega^2}{E_3^2}$$

…

Diagrams



$$J^\mu = J^\mu_L + j^\mu_R = \langle \bar\psi\gamma^\mu\psi \; \bar\psi\gamma^\nu\psi \; \bar\psi\gamma^\rho\psi \rangle \, A_\nu A_\rho$$
$$= \Pi^{\mu\nu\rho} A_\nu A_\rho$$
$$J^\mu_5 = J^\mu_L - j^\mu_R = \langle \bar\psi\gamma^\mu\gamma_5\psi \; \bar\psi\gamma^\nu\psi \; \bar\psi\gamma^\rho\psi \rangle \, A_\nu A_\rho$$
$$= \Pi^{\mu\nu\rho}_5 A_\nu A_\rho$$

Chiral anomaly

$$q_\mu J^\mu_5 = q_\mu \Pi^{\mu\nu\rho}_5 A_\nu A_\rho$$

vs

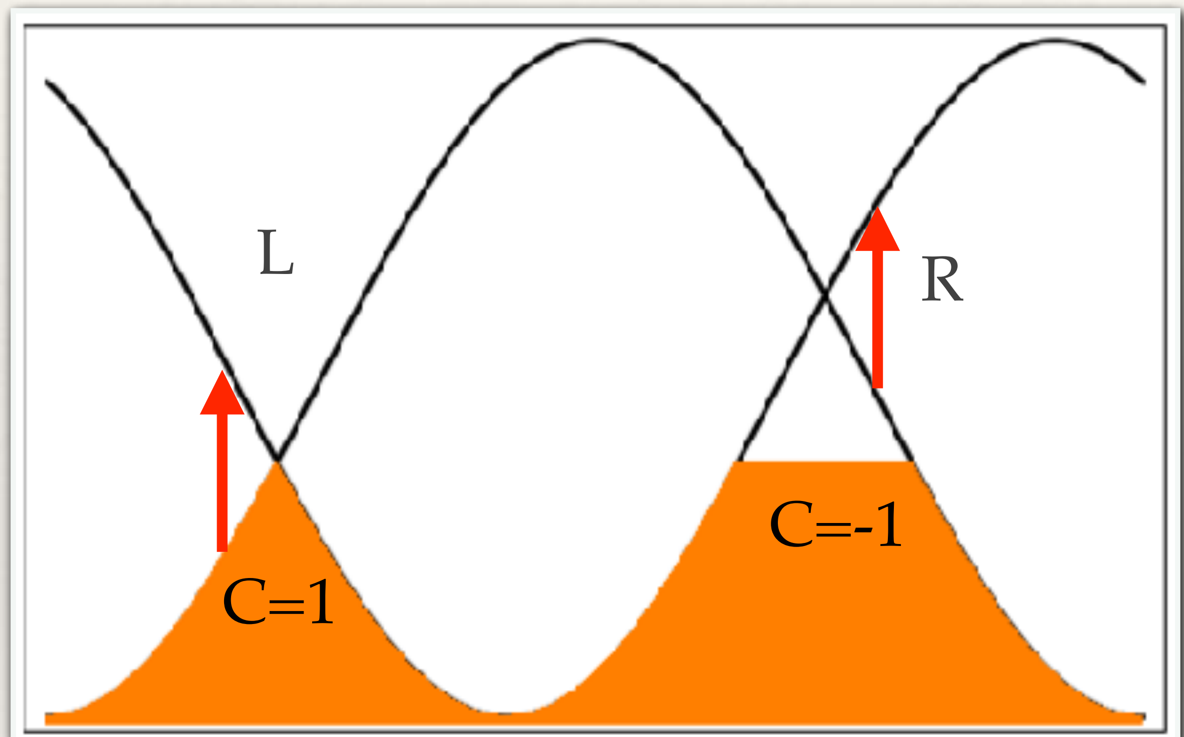
Injection current (CPGE)

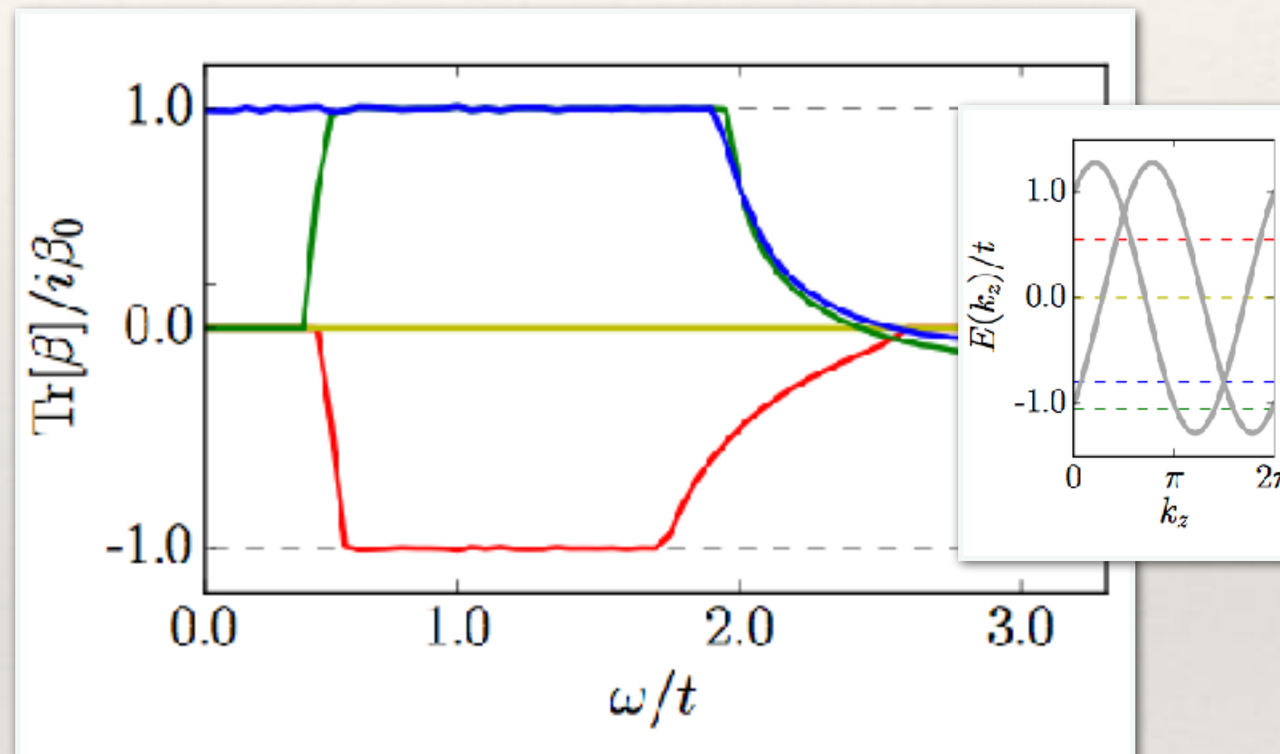
$$q_0 J_i = q_0 \Pi^{ijk} A_j A_k$$

Quantization in two band model

Chiral system (no mirrors)

Mirror symmetric





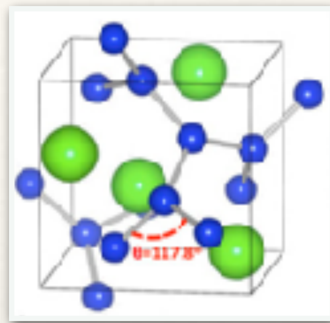
In a **chiral Weyl semimetal** CPGE measures monopole charge when:

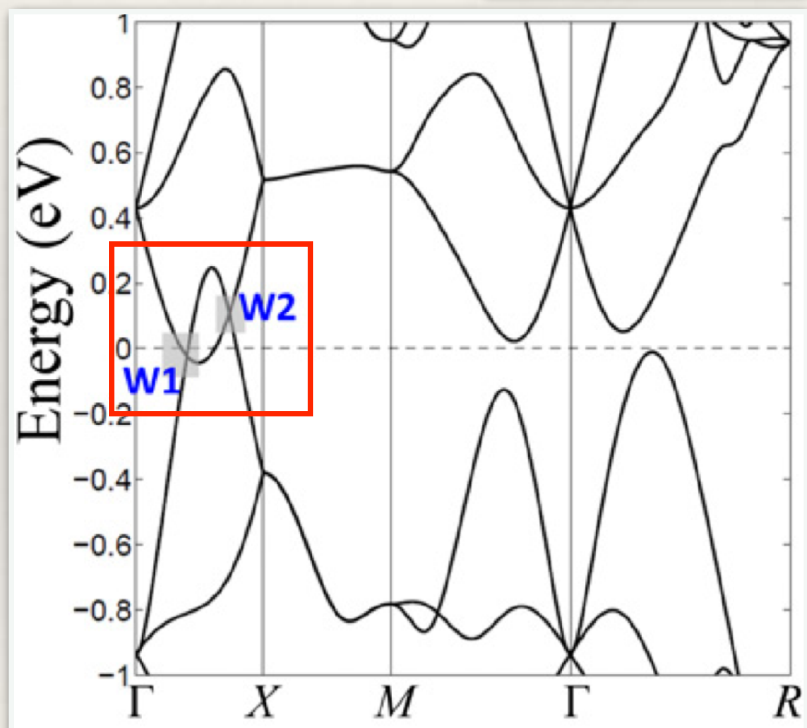
$$2|E_L| < \omega < 2|E_R|$$

F de Juan et al., Nat. Commun. 8, 15995 (2017)

Chiral Weyl semimetals

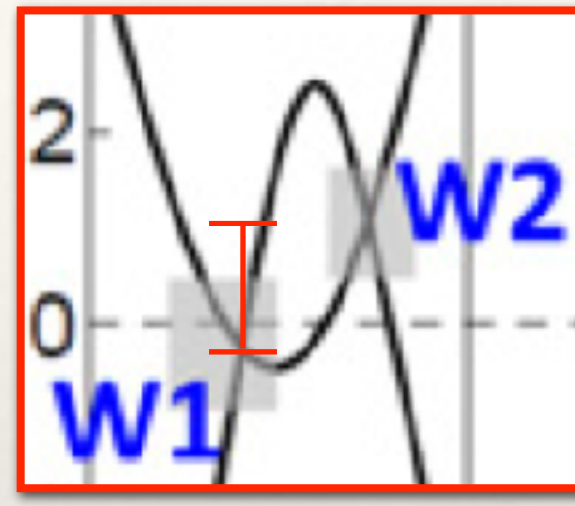
$SrSi_2$ (SG 212)





Huang, PNAS **113** 1180 (2015)

See also Kramers-enforced Weyl fermions like Ag2Se$_x$Te$_y$, arxiv:1611.07925, and elemental Te, PRL **114**, 206401 (2015)



$\Delta E \sim 150$ meV

We need roughly $$\frac{1}{\tau} < \omega < \Delta E$$

TaAs Lifetimes of order 1 ps:
Scattering rate 1 THz = 4 meV

Phys. Rev. B **93**, 075114 (2016)

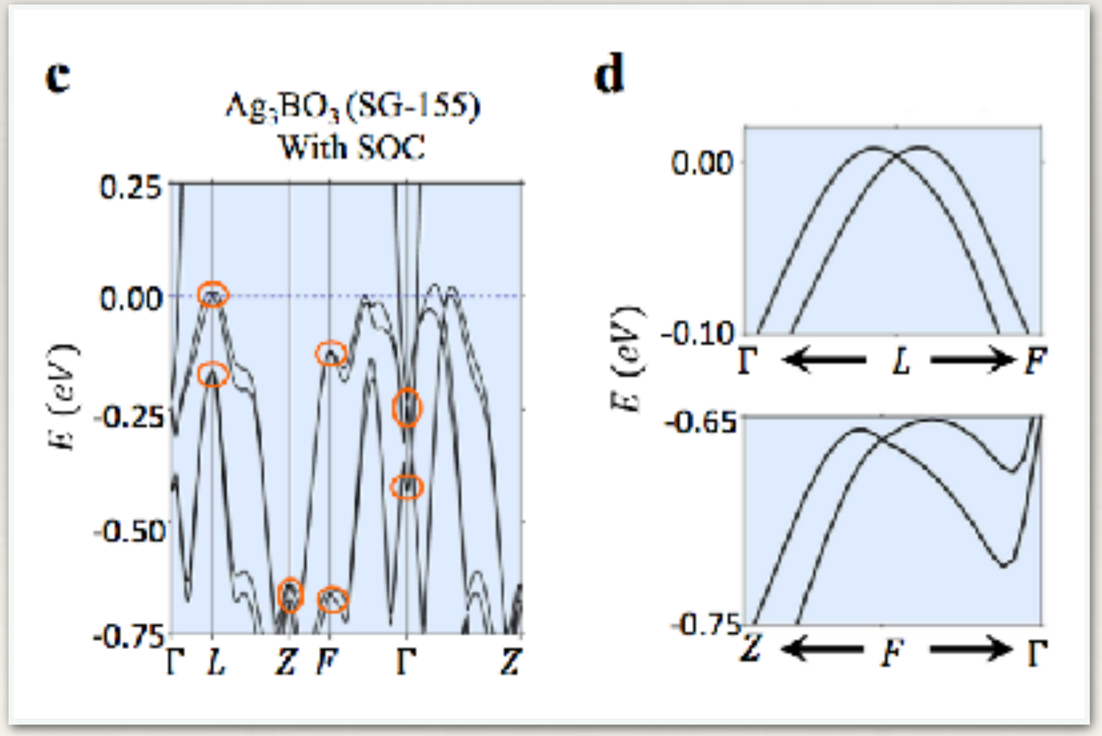
$$I = \frac{c\epsilon_0}{2}|\vec{E}|^2 \quad J = \frac{2\pi e^3}{h^2 c\epsilon_0} I = 22.2 \frac{A}{W\ ps} I$$

They refuse to exist!

- All Weyls synthesized to date have mirror symmetry (in I-breaking or T-breaking classes)

- $SrSi_2$ would work but too hard to make a good crystal

- Engineering one is hard: remember Weyl points are "accidental"

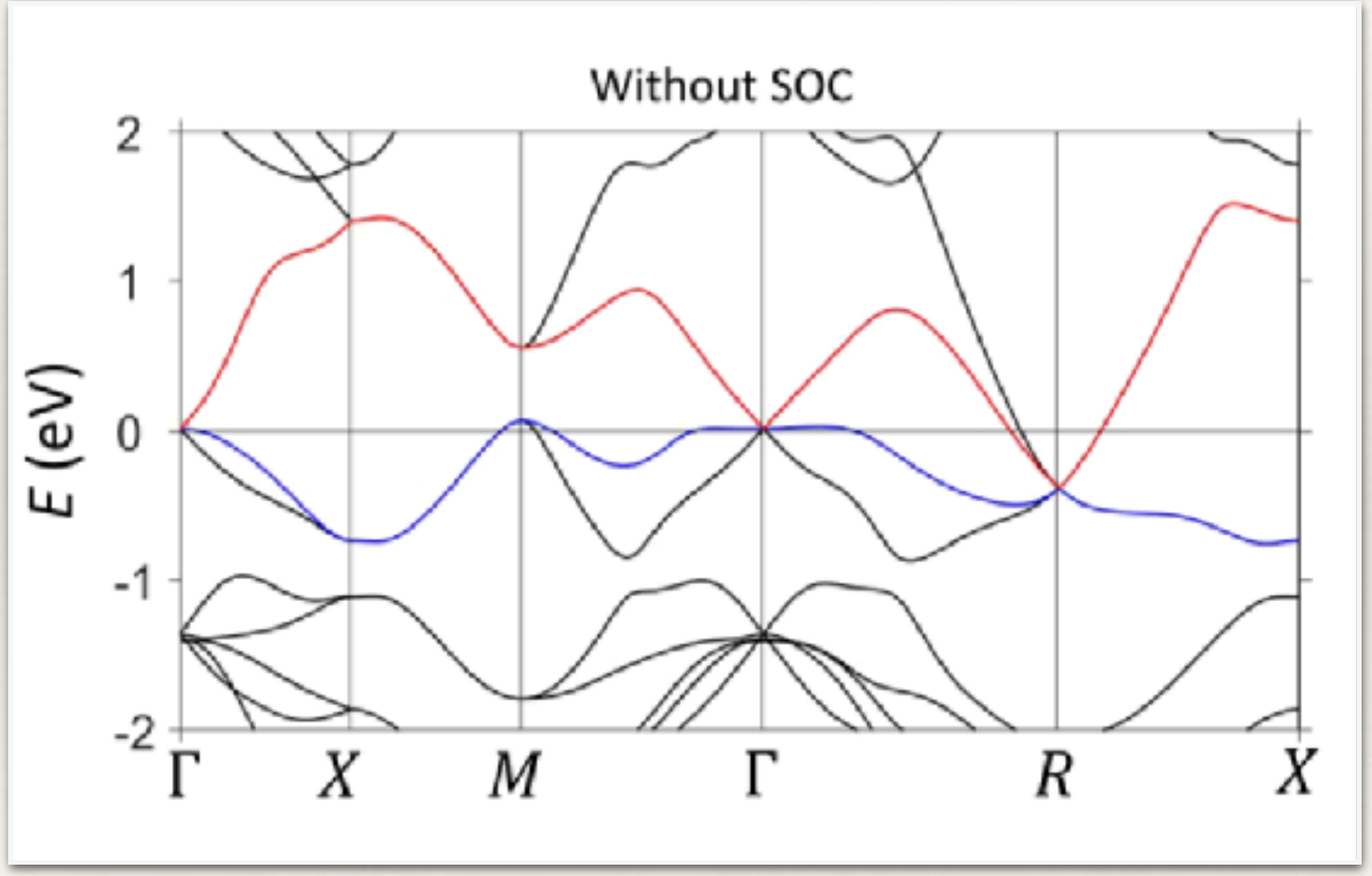


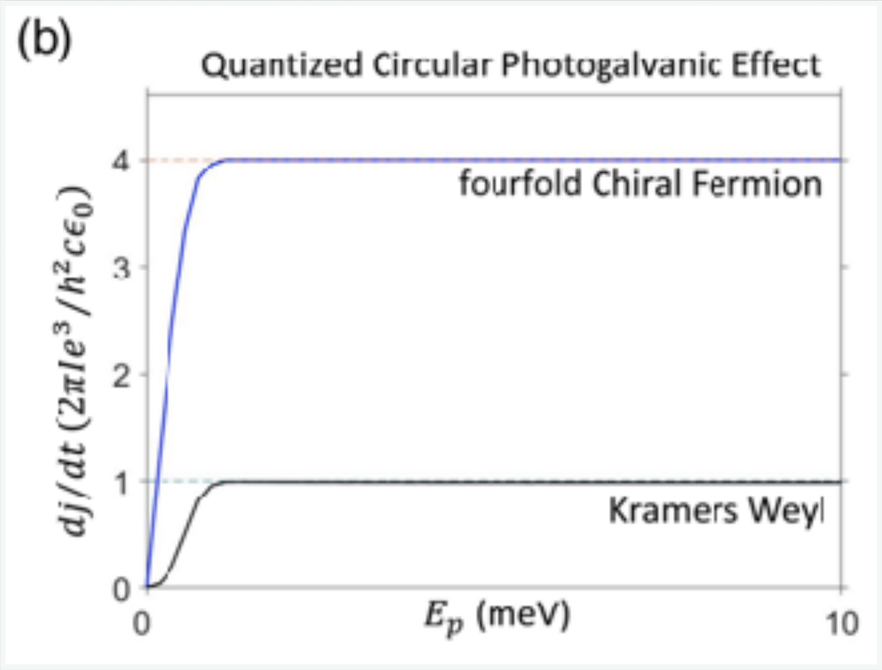
"We identify representative chiral materials in 33 of the 65 chiral space groups in which Kramers–Weyl fermions are relevant to the low-energy physics".

"Topological quantum properties of chiral crystals" Nat. Mater. 17, 978 (2018)

Multifolds in RhSi

We were minding our own business trying to design a chiral Weyl semimetal when:

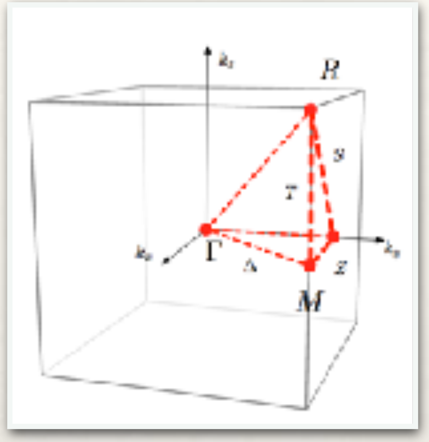




Quantization should not work for more than two bands!

Chang, PRL **119**, 206401 (2017)
Tang, PRL **119**, 206402 (2017)

Symmetry protected chiral nodes

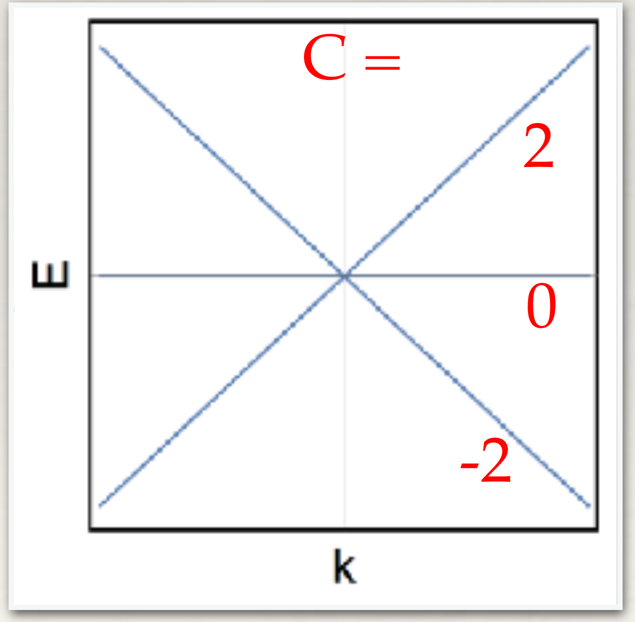


In certain chiral space groups, at certain high symmetry points:

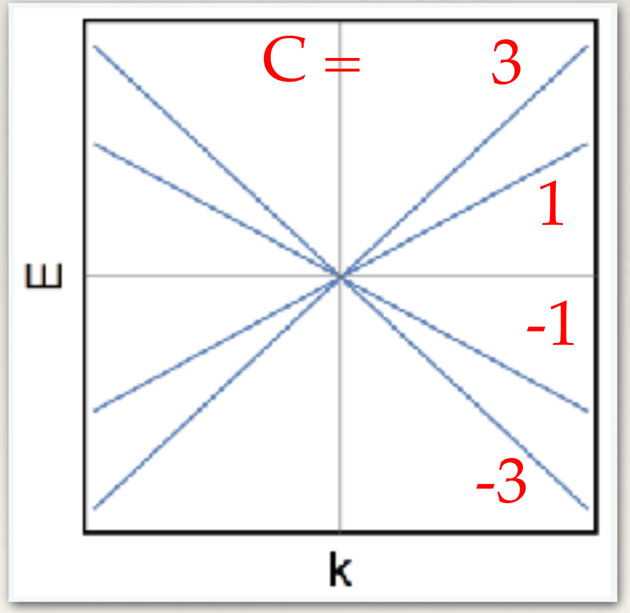
$$H(\phi, \vec{k}) = \vec{S}(\phi) \cdot \vec{k}$$

$$[S_i(0), S_j(0)] = i\epsilon_{ijk} S_k(0)$$

Spin 1
(3x3 matrices)

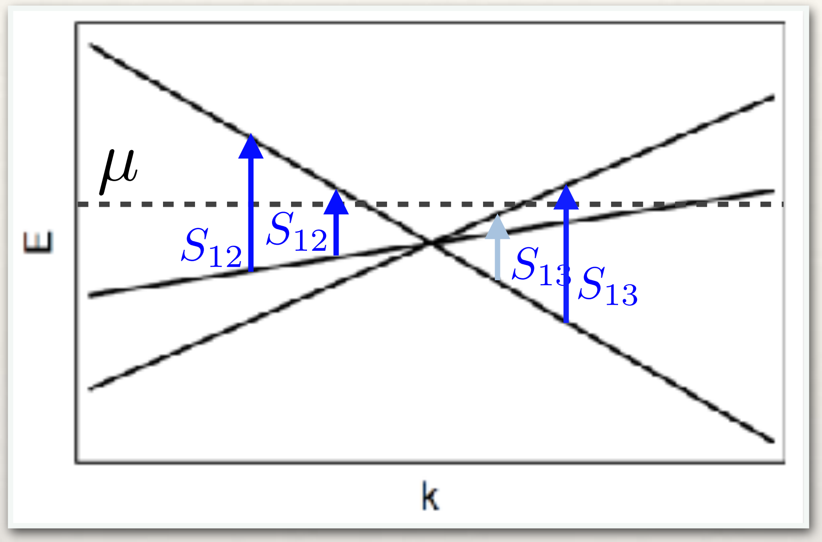


Spin 3/2
(4x4 matrices)



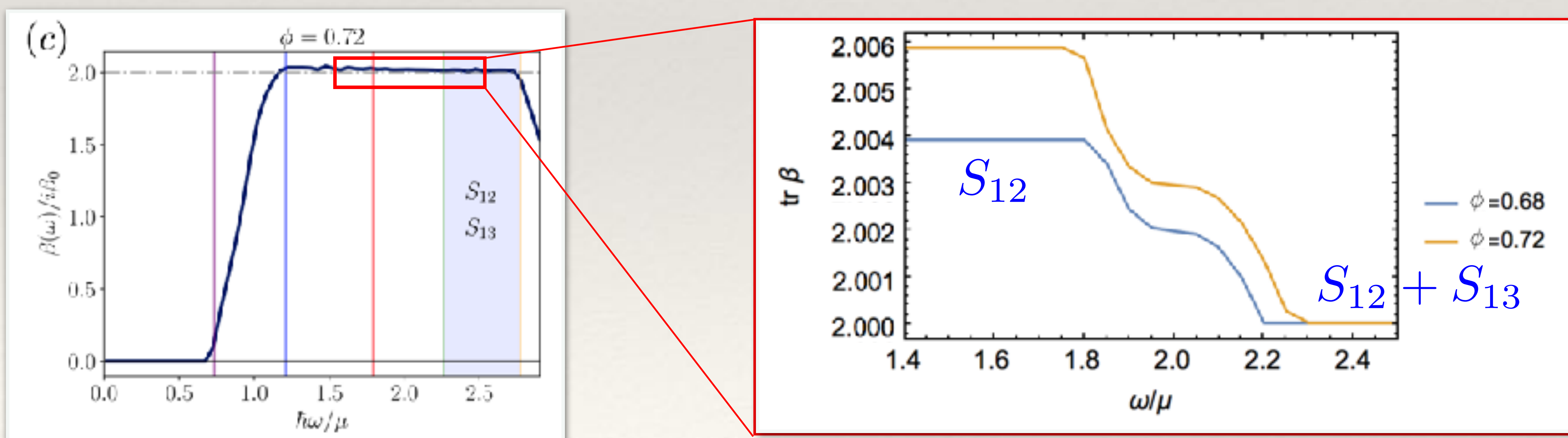
Mañes, PRB 85, 155118 (2012), Bradlyn et al, Science 353, aaf5037 (2016), Chang, PRL 119, 206401 (2017), Tang, PRL 119, 206402 (2017), Flicker et al, PRB 98, 155145 (2018)

Quantization in linear models

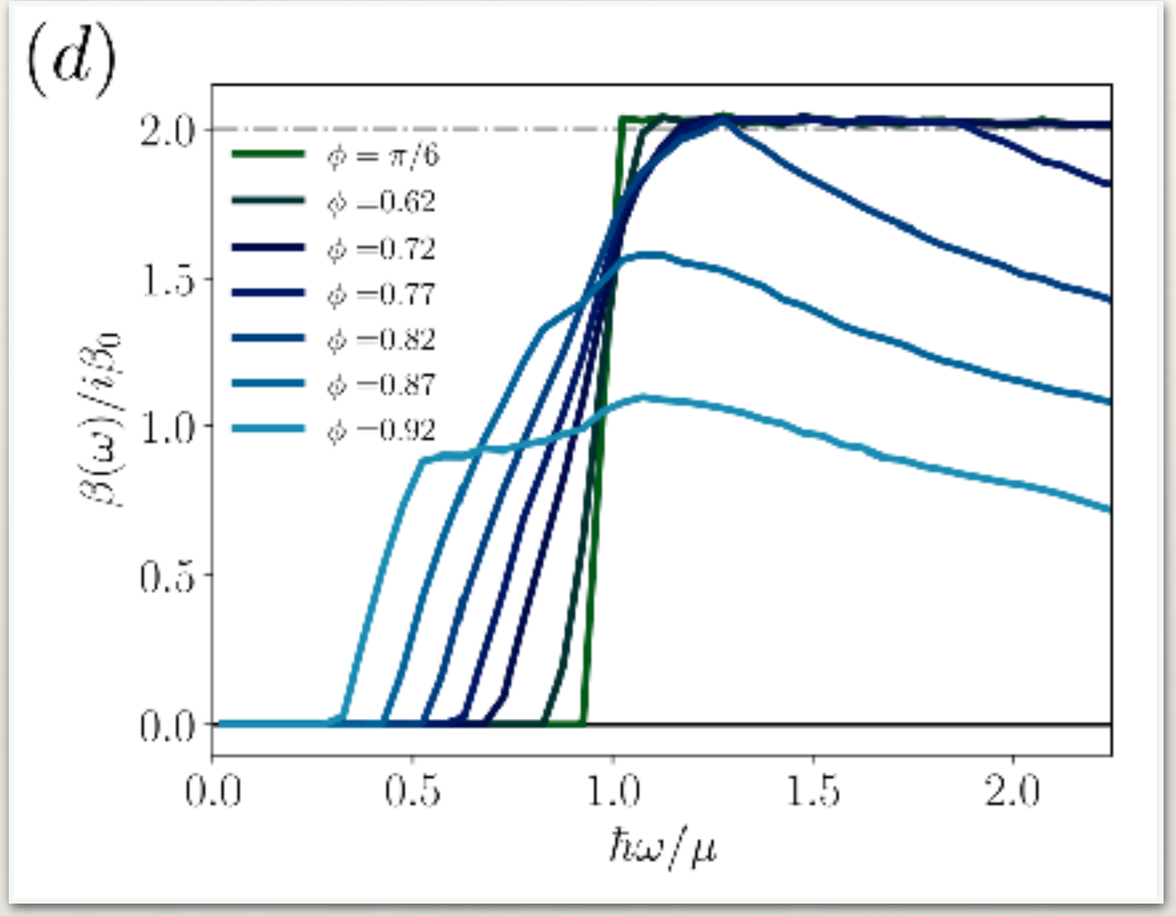


$$\beta(\omega) \equiv 4\pi^2\beta_0 \sum_{n,m} \int d\vec{S}_{nm} \cdot \vec{R}_{nm}$$

$$\begin{aligned}\beta(\omega) &= 4\pi^2\beta_0 \left(\int d\vec{S}_{12} \cdot \vec{R}_{12} + \int d\vec{S}_{13} \cdot \vec{R}_{13} \right) \\ &= 4\pi^2\beta_0 \left(-i \int d\vec{S}_{12} \cdot \vec{\Omega}_1 \quad + \left[-\int d\vec{S}_{12} + \int d\vec{S}_{13} \right] \cdot \vec{R}_{13} \right)\end{aligned}$$



Quantization in linear models



1) All chiral multifolds **can have** a quantization window

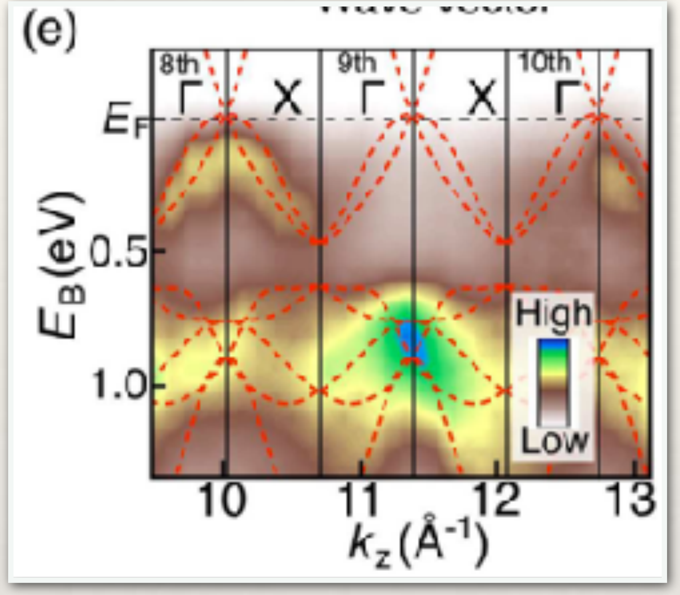
2) As in Weyls, quantization window is material dependent (might be zero!)

3) Corrections to quantization from non-linear dispersion **and** remote extra bands

This greatly enlarges the material classes to show quantized CPGE!

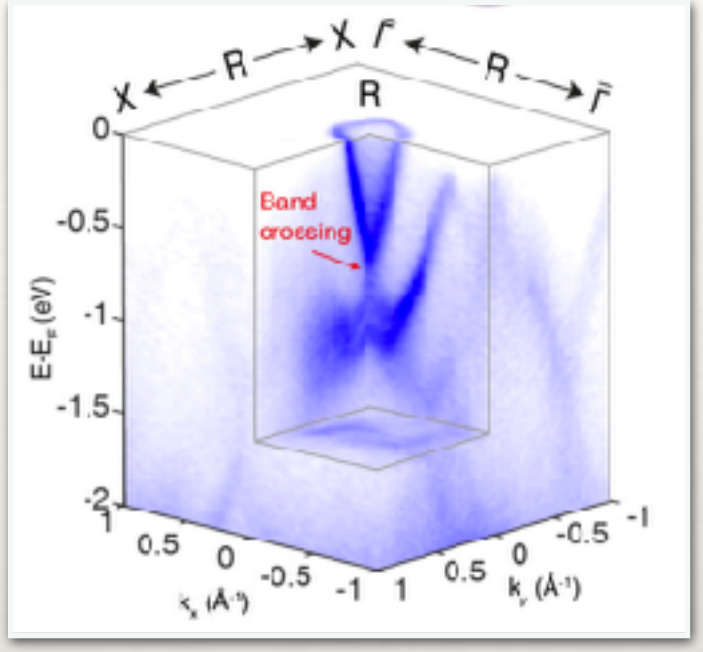
But do these multifolds exist anywhere?

The discovery of multifolds



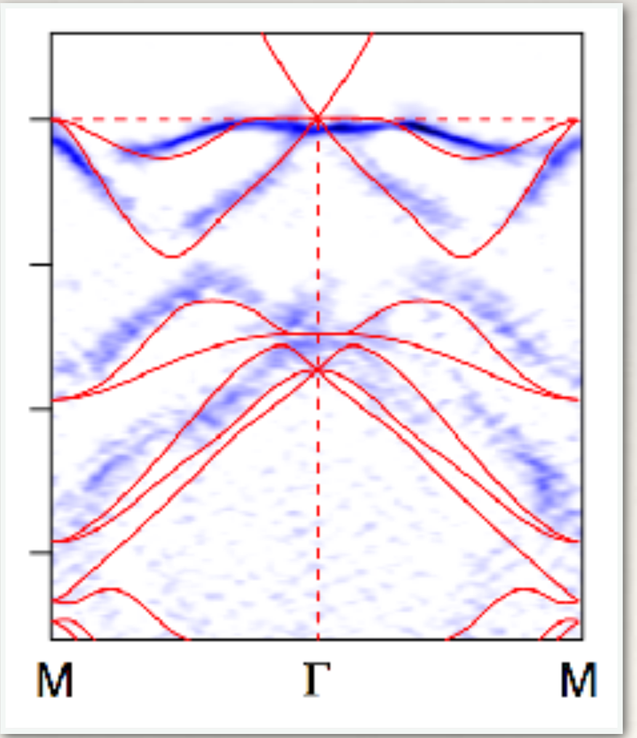
CoSi

arxiv:1809.01312 (to appear in PRL)



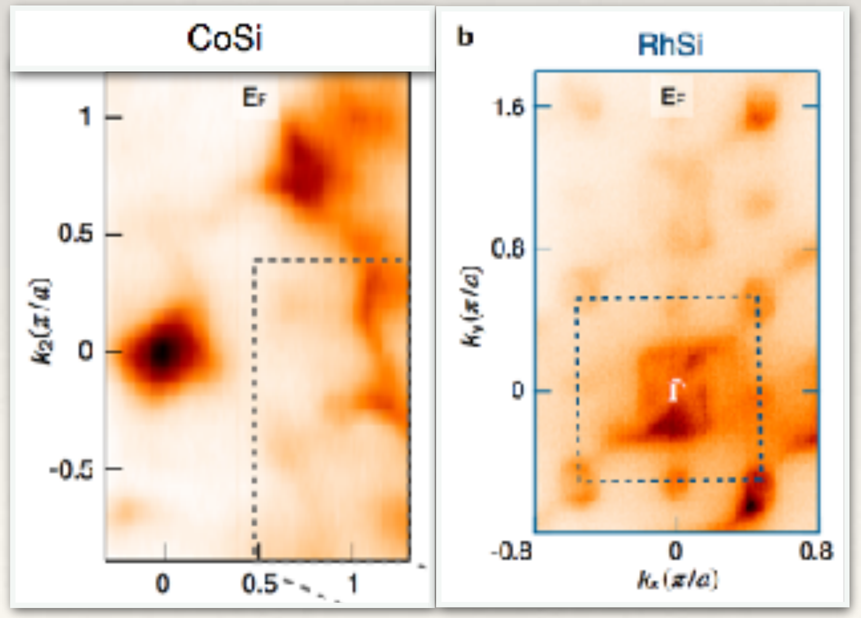
AlPt

arxiv:1812.03310 (to appear in Nat. Phys.)



CoSi

arxiv:1901.03358 (to appear in Nature)

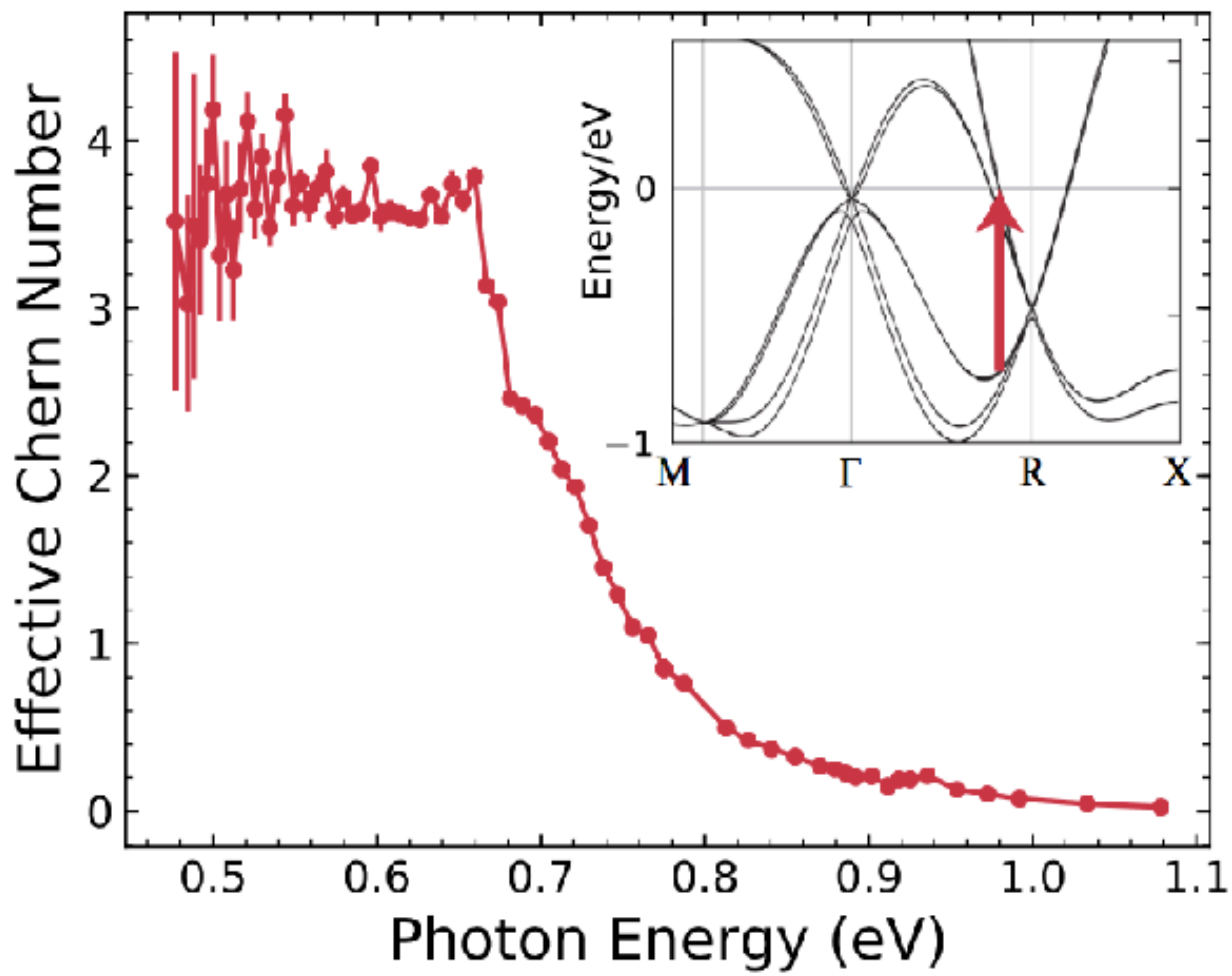


CoSi & RhSi

arxiv:1809.01312 (to appear in Nature)

Quantized Photocurrents in the Chiral Multifold Fermion System RhSi

Dylan Rees[1,2], Kaustuv Manna[3], Baozhu Lu[4], Takahiro Morimoto[1], Horst Borrmann[3], Claudia Felser[3], J. E. Moore[1,2], Darius H. Torchinsky[4*], J. Orenstein[1,2*]



arxiv:1902.03230

Conclusions

Take home message:

Quantized observable in **gapless system** in non-linear response:

Quantization related to Chern number of chiral nodal fermions

Future:

- Will experiments be able to measure quantization? Do we need alternatives?

- Other surprises in the topological structure of finite frequency response?