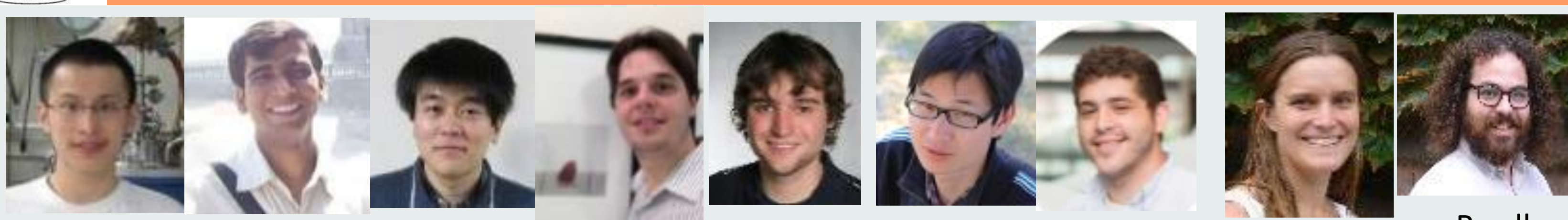
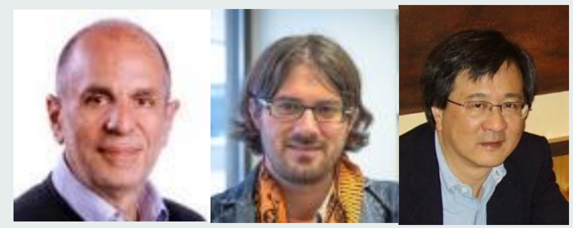
Workshop Topological Quantum Matter, KITP-UCSB Oct. 2016

The chiral anomaly in Dirac and Weyl Semimetals



Jun Xiong Kushwaha Tian Liang Jason Krizan Hirschberger Zhijun Wang Quinn Gibson Cano Bradlyn

S.H. Liang



Bob Cava Bernevig NPO

Princeton University

1. Chiral anomaly in Na_3Bi and the half-Heusler GdPtBi
2. Thermopower of Weyl fermions
3. Prelim results on nonsymmorphic semimetal KHgSb

Support from

Moore Foundation, ARO, NSF

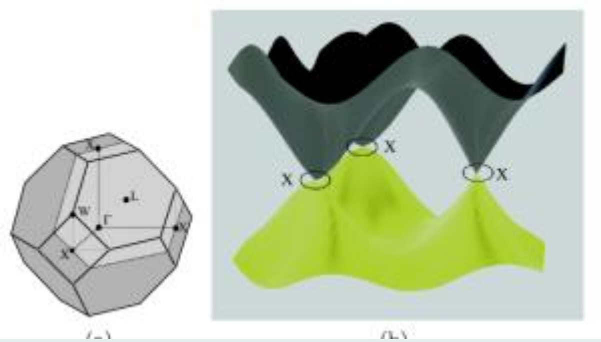
Search for (3+1)d Dirac cones with protected nodes

Topological semimetal and Fermi-arc surface states in pyrochlore iridates

Wan, Turner, Vishwanath and Savrasov, PRB 2011

Dirac Semimetal in Three Dimensions

Young, Zaheer, Teo, Kane, Mele and Rappe PRL 2012



Time reversal symmetry (TRS) and Inversion symmetry (IS) protect a Dirac node if it is pinned at zone corner *X*

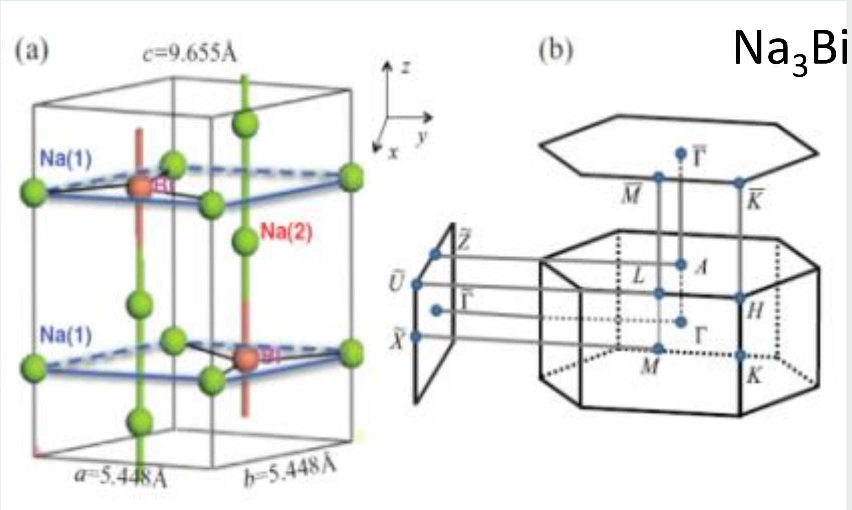
Candidate: β cristobalite BiO_2

Add point group symmetry to TRS and IS to unpin from BZ vertex

(Bernevig, XiDai, PRL 2013)

Topological Dirac semimetals Na3Bi and Cd3As2

Na_3Bi and Cd_3As_2 (Wang *et al.*)

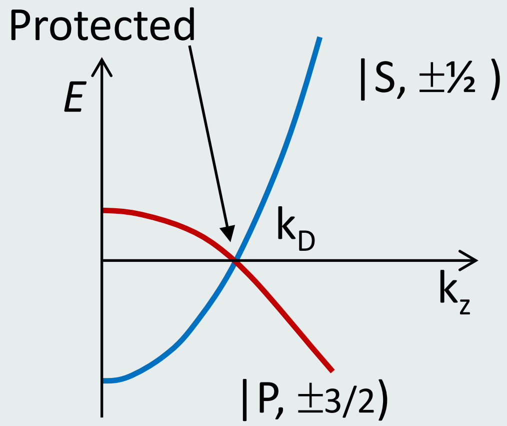


C_3

Zhijun Wang, Xi Dai et al, PRB 2012

Wan, Turner, Vishwanath, *PRB* 2011
Burkov, Hook, Balents, *PRB* 2011
Son, Spivak, *PRB* 2013

Dirac cone resolves into two Weyl nodes with opposite chiralities $\chi = \pm 1$



The low-E Hamiltonian, close to node $\mathbf{K}_+$, reduces to

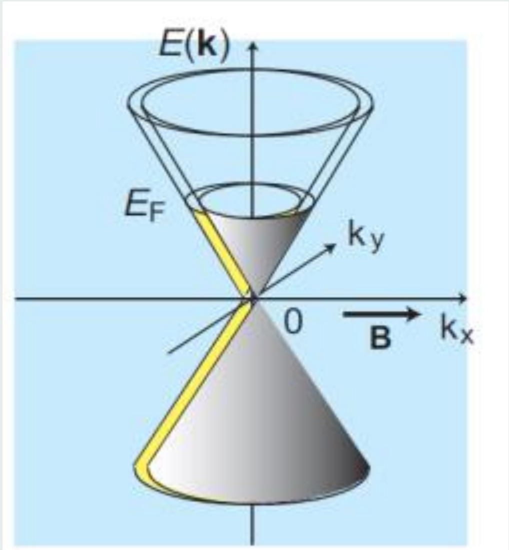
$$H = v\begin{bmatrix} k_z & k_+ & 0 & 0 \\ k_- & -k_z & 0 & 0 \\ 0 & 0 & k_z & -k_- \\ 0 & 0 & -k_+ & -k_z \end{bmatrix} \qquad \begin{pmatrix} S, ½ \\ P, 3/2 \\ S, -½ \\ P, -3/2 \end{pmatrix}$$

H resolves into two 2x2 Weyl Hamiltonians H_1, H_2

Calculate chirality from velocity matrix $\widetilde{\boldsymbol{v}}$

$$H_1 = \mathbf{k} \cdot \widetilde{\mathbf{v}}_1 \cdot \boldsymbol{\tau} = \mathrm{v}(k_x\tau_1 - k_y\tau_2 + k_z\tau_3)$$

$$\tilde{\mathbf{v}}_1 = v\begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

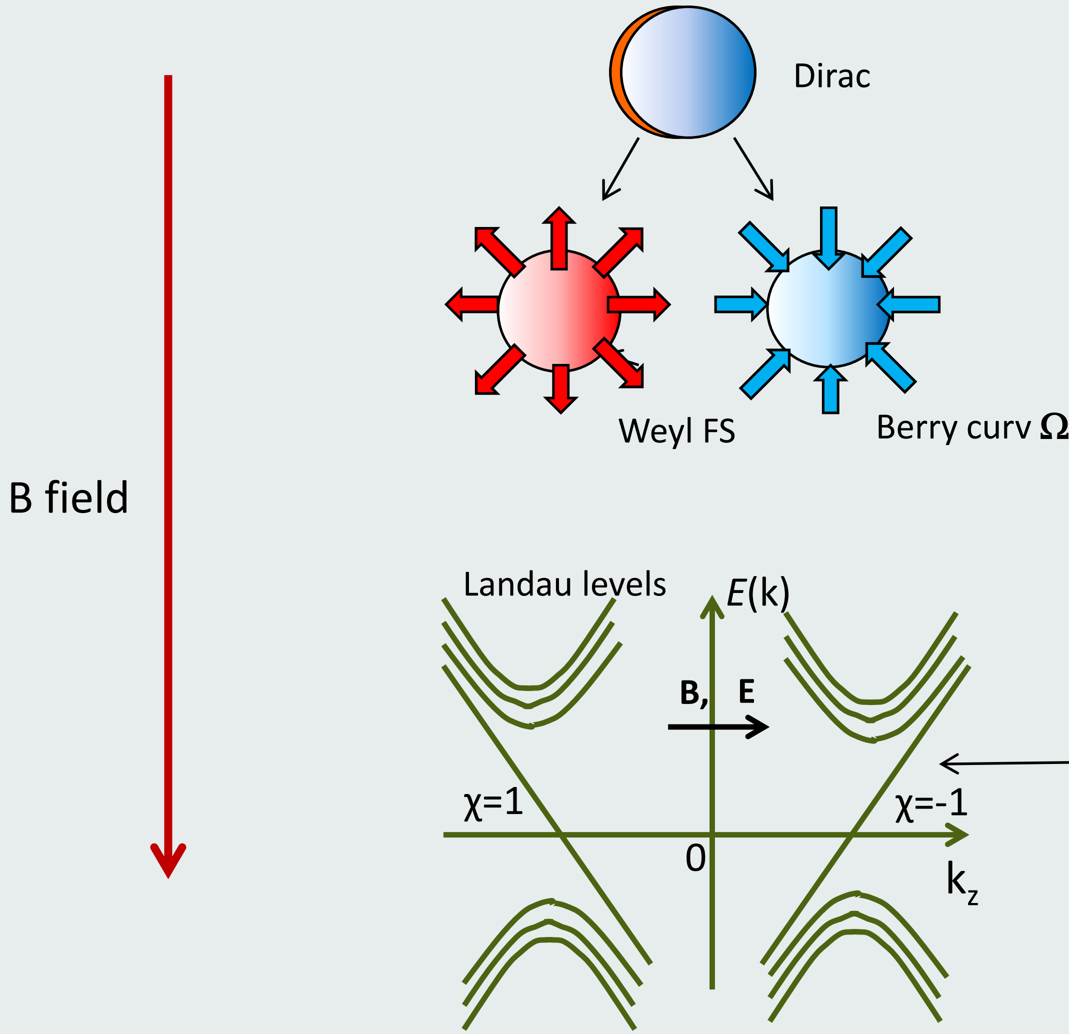


The chirality is $\chi = \dfrac{\det[\tilde{\mathbf{v}}]}{\mathrm{v}}$

$$\chi_1 = -1, \qquad \chi_2 = +1$$

We have a superposition of two Weyl nodes at B = 0

Creation of Weyl states in applied magnetic field



Lowest Landau level
Schwinger model

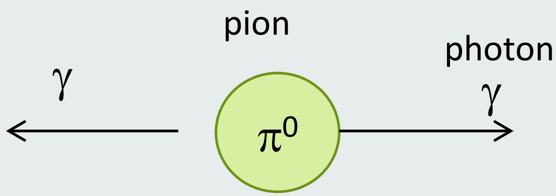
Detect axial current

$$A = -\left(\frac{L^2}{2\pi\ell_B^2}\right)\left(\frac{Le\dot{k}_z}{2\pi}\right) = -V\frac{e^3}{4\pi^2\hbar^2}\mathbf{E}.\mathbf{B}$$

The chiral (or Adler Bell Jackiw) anomaly

An anomaly in QFT is the breaking of a classically allowed symmetry by quantum effects.

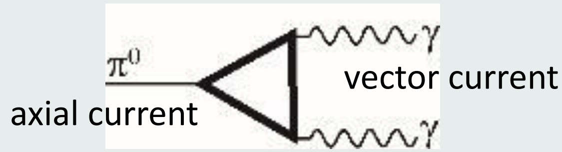
First appeared in pion decay -- discrepancy of 300 million between neutral and charged pions



Pions, the lightest hadrons, are long-lived.
Charged pions can decay only into leptons $\pi^+ \rightarrow \mu^+ + \nu$

However, *neutral* pions can decay into 2 photons ($3\text{x}10^8$ faster)

$$\pi^0 \rightarrow \gamma + \gamma$$



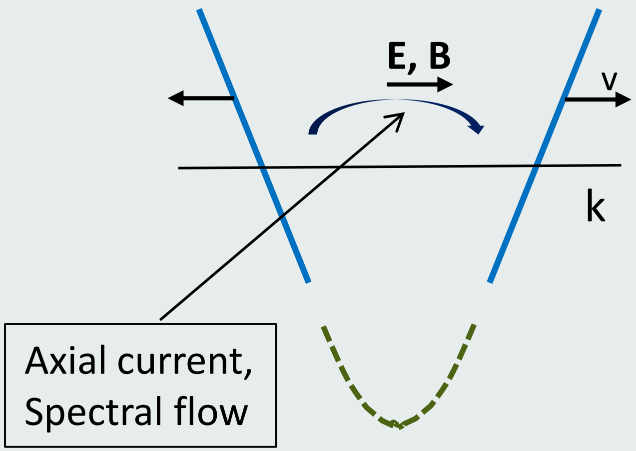
Adler Bell Jackiw anomaly

(Adler, Bell, Jackiw, 1969)[1]

Coupling to EM field breaks chiral symmetry of pions
Leads to decay of axial current into photons

1. Axial Anomaly, R. Jackiw, *Scholarpedia*

chiral Landau Level



Adler Bell Jackiw anomaly

$$A = \frac{1}{16\pi^2} \varepsilon^{\mu\nu\alpha\beta} \, \mathrm{tr} F_{\mu\nu} F_{\alpha\beta}$$

B quantizes Dirac states into Landau levels

Rate at which charge is pumped in **E** field

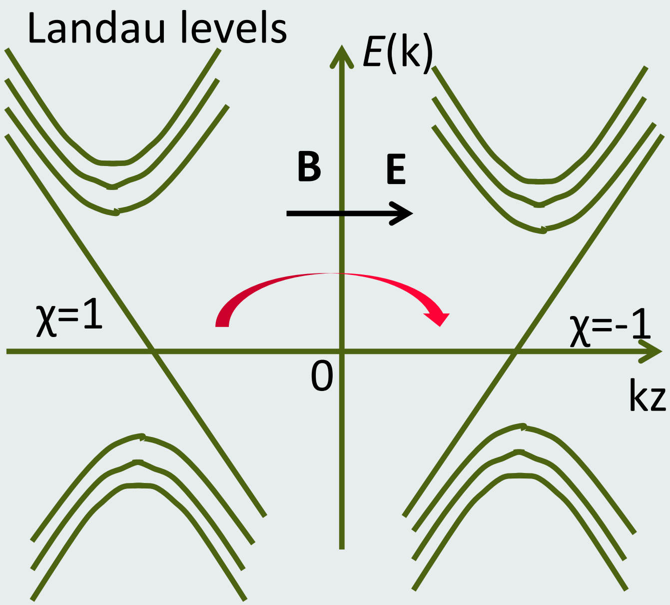
$$A = -\left(\frac{L^2}{2\pi\ell_B^2}\right)\left(\frac{Le\dot{k}_z}{2\pi}\right) = -V\frac{e^3}{4\pi^2\hbar^2}\mathbf{E}.\mathbf{B}$$

DOS of one Landau level

Rate of increase of states along k_z in **E** field

Chiral anomaly is observable as a large, negative longitudinal magnetoresistance (Nielsen and Ninomiya, *Phys. Lett.* 1983)

Charge pumping and the chiral anomaly



Nielsen, Ninomiya, *Phys. Lett.* 1983
Wan, Turner, Vishwanath, *PRB* 2011
Burkov, Hook Balents, *PRB* 2011
Son, Spivak, *PRB* 2013
Parameswaran et al. *PRX* 2014

Chiral anomaly engenders
large, negative longitudinal MR
Locked to B field

In large-*B* regime, with **E||B,** charge is pumped between Weyl nodes at the rate

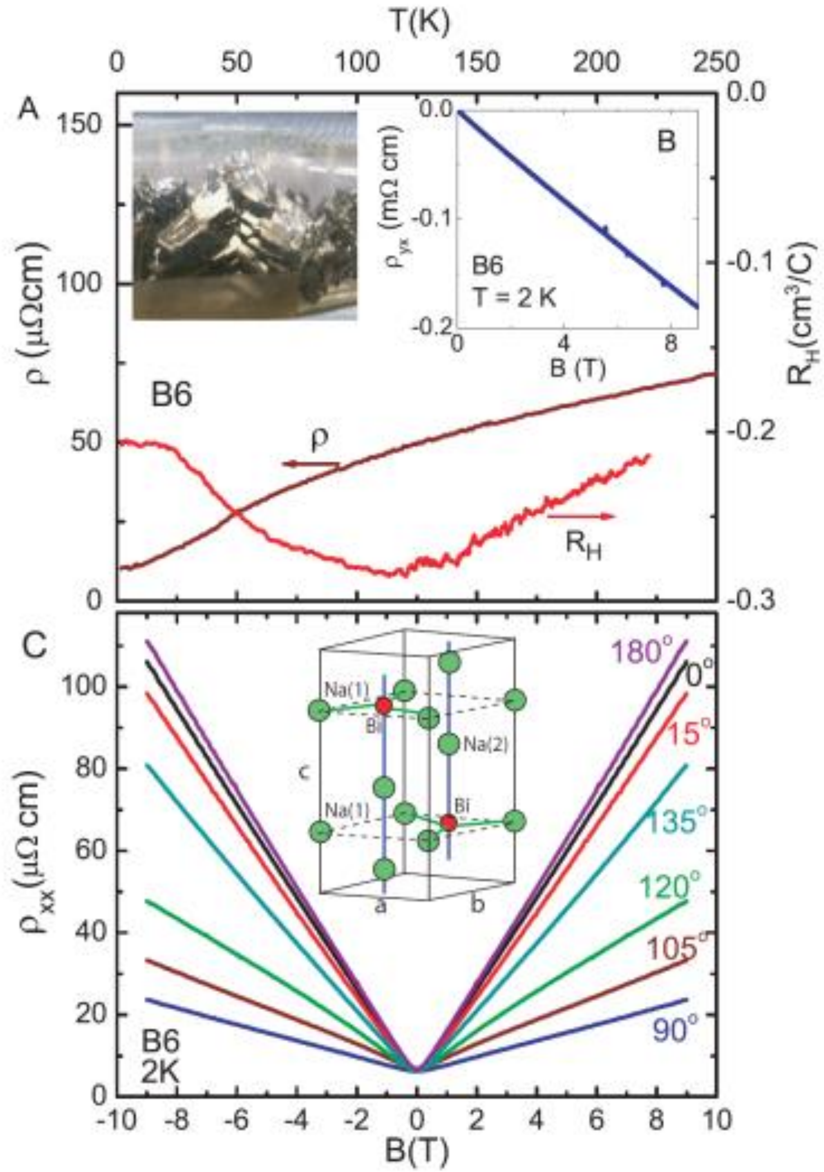
$$A = -\frac{L^2}{2\pi\ell_B^2}\frac{Le\dot{k}}{2\pi} = -V\frac{e^3}{4\pi^2\hbar^2}\mathbf{E}.\mathbf{B}$$

In weak *B*, charge pumping gives (Son and Spivak, *PRB* 2013)

$$\sigma_\chi = \frac{e^2}{4\pi^2\hbar c}\frac{v}{c}\frac{(eBv)^2}{\epsilon_F^2}\,\tau_a$$

τ_a is relaxation time for pumped current

Initial results on Na_3Bi



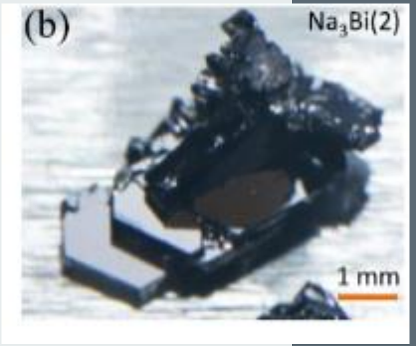
S. Kushwaha *et al.*, *APL* 2015

Jun Xiong *et al.*, EPL 2015

Jun Xiong Kushwaha Krizan

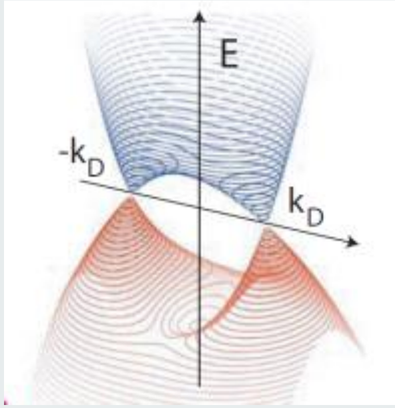
Deep purple crystals

Rapidly oxidizes in ambient air (30 s)

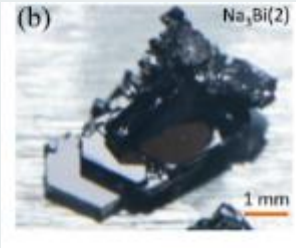


Large linear MR similar to Set B Cd_3As_2 samples

E_F 400 mV above node



Non-metallic Crystals of Na_3Bi with lower carrier density

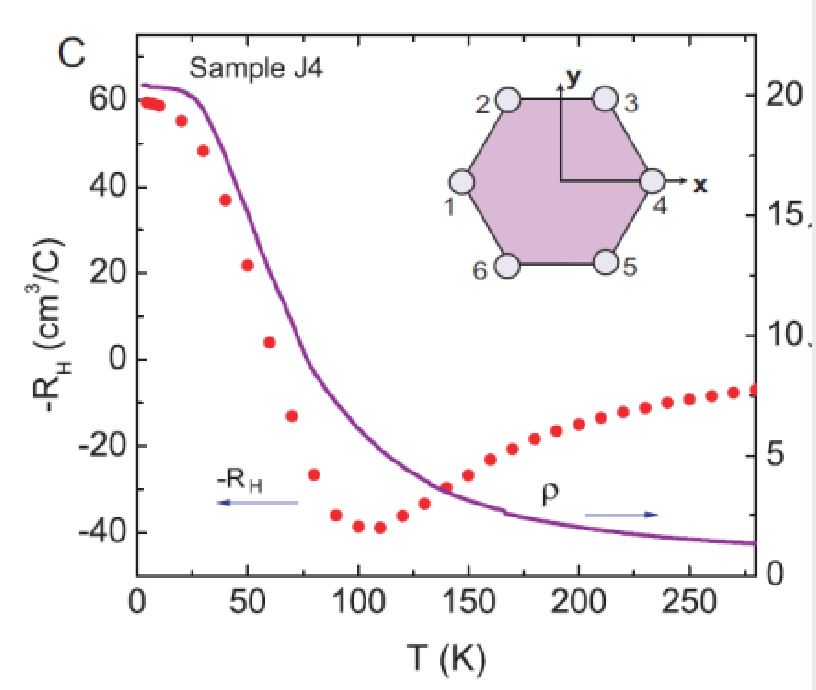


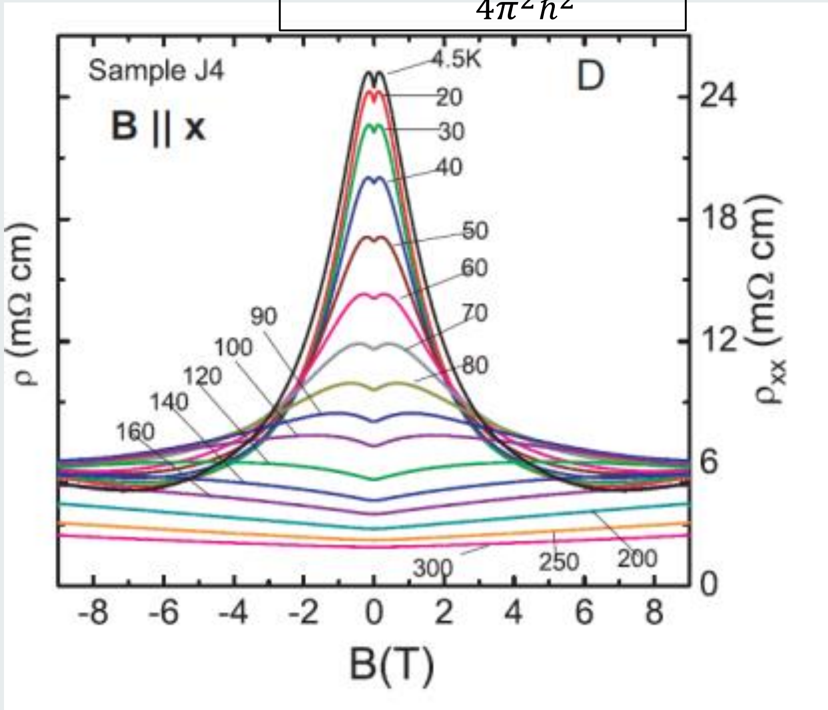
Jun Xiong, S. Kushwaha et al., *Science* 2015

Jun Xiong, S. Kushwaha, Krizan,

Long-term annealed crystals with E_F much closer to node

$$A = -V \frac{e^3}{4\pi^2\hbar^2} \mathbf{E}.\mathbf{B}$$



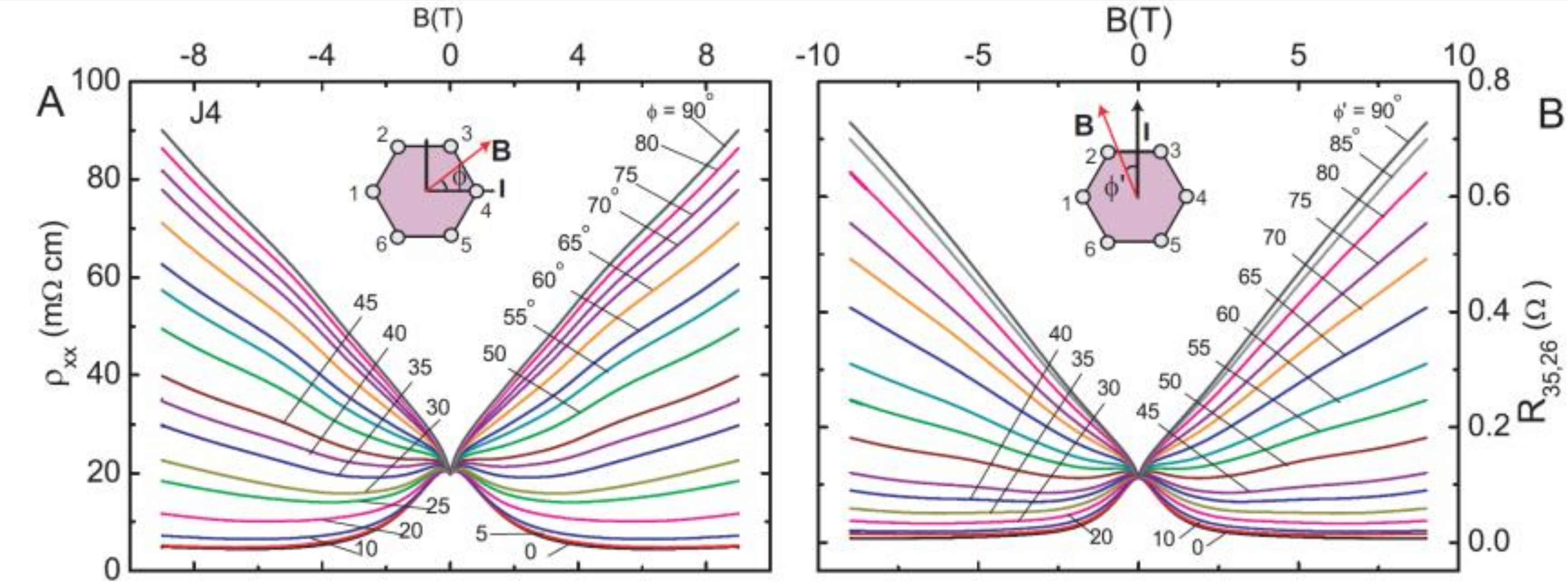


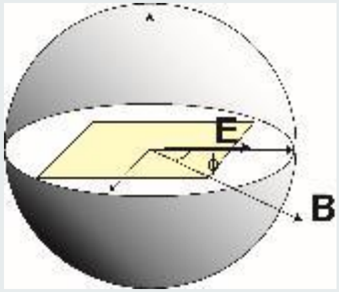
Fermi energy lies 30 meV above node

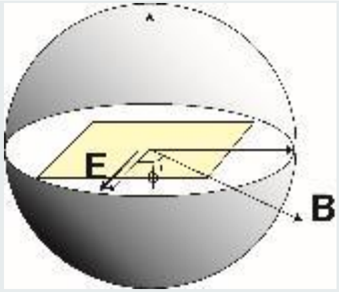
Striking negative longitud. MR (LMR)

A test for the chiral anomaly -- **B** is locked to **E**

Jun Xiong, S. Kushwaha et al., Science 2015





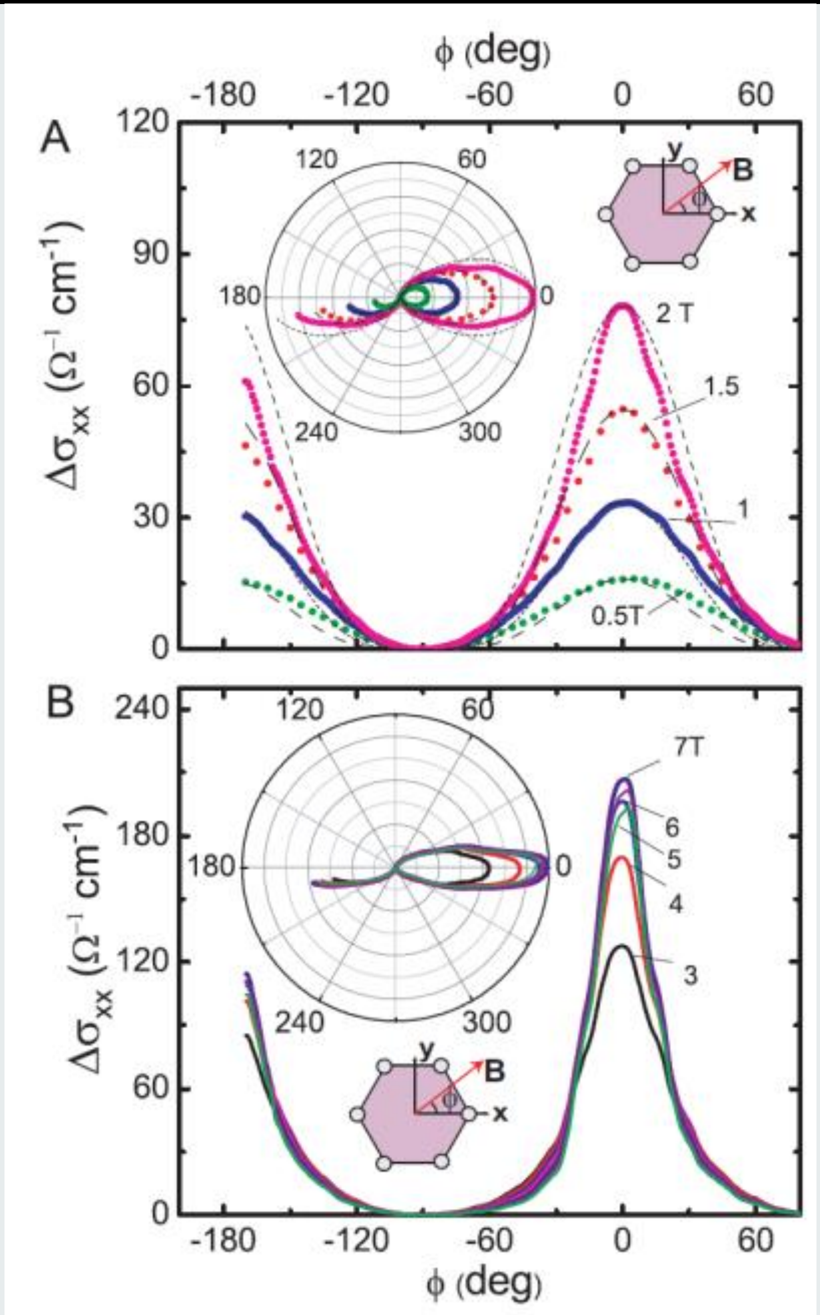


Negative MR appears only when **B** is locked to **E.**

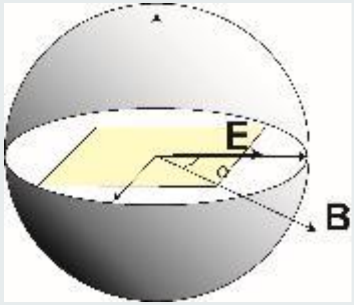
Test: if **E** is rotated by 90^o (right panel), neg. MR shifts to new direction of **E.**

For weak B, this locking is novel and unexpected in semiclasscl transport

A narrow plume of chiral current, B in-plane



Jun Xiong, S. Kushwaha et al., Science 2015



Enhanced cond. in a narrowly collimated beam for **B** in the *x*-*y* (horizontal) plane

Chiral anomaly and thermopower of Weyl fermions in half-Heusler GdPtBi

Max Hirschberger, S. Kushwaha, ZJ Wang, Quinn Gibson, C. Belvin, B. A. Bernevig, R. J. Cava and N. P. O

Nature Materials, 2016

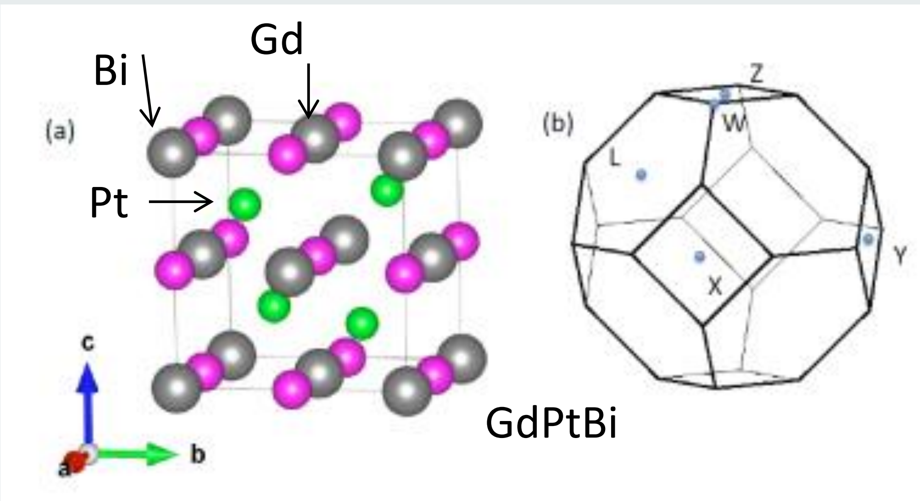
M. Hirschberger

S. Kushwaha

Zhijun Wang

Cano

Bradlyn



Zinc blende structure (like GaAs)

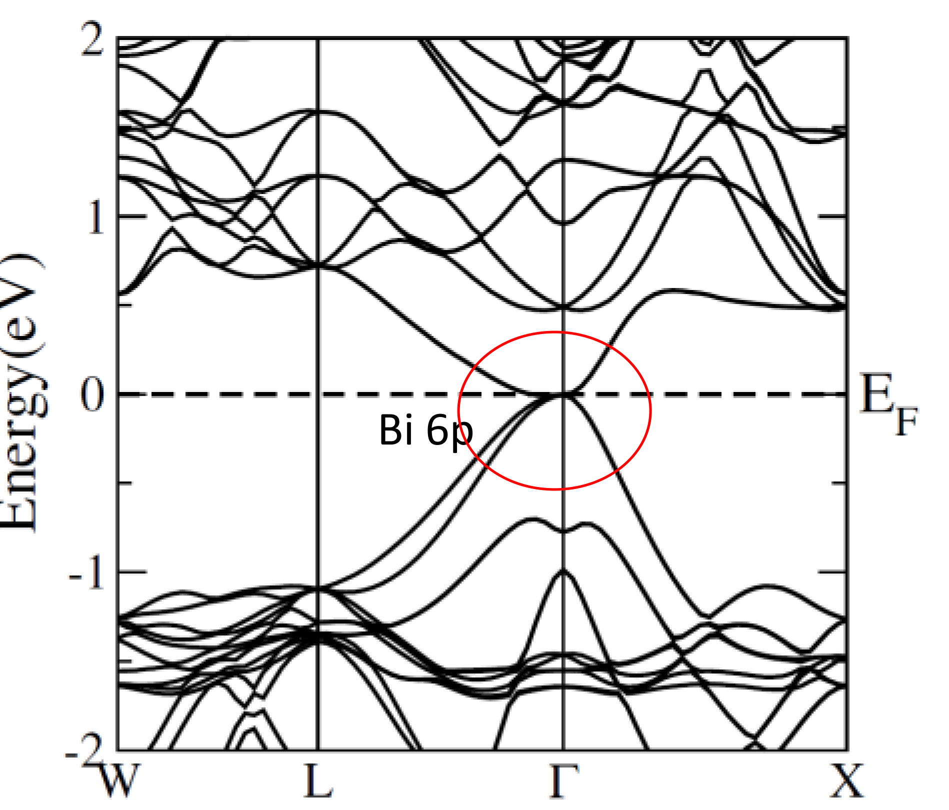
Except Bi is "stuffed" in fcc sublattice

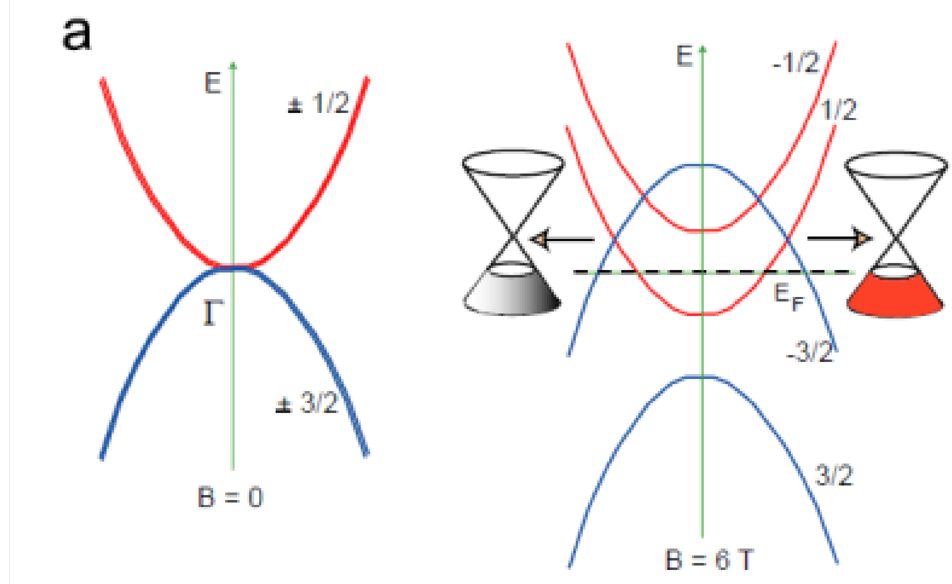
See also, Checkelsky *Nat. Mat*. 2016

Felser, Parkin arXiv 2016

LDA calculations – effect of **B** on bands in GdPtBi

Zhijun Wang

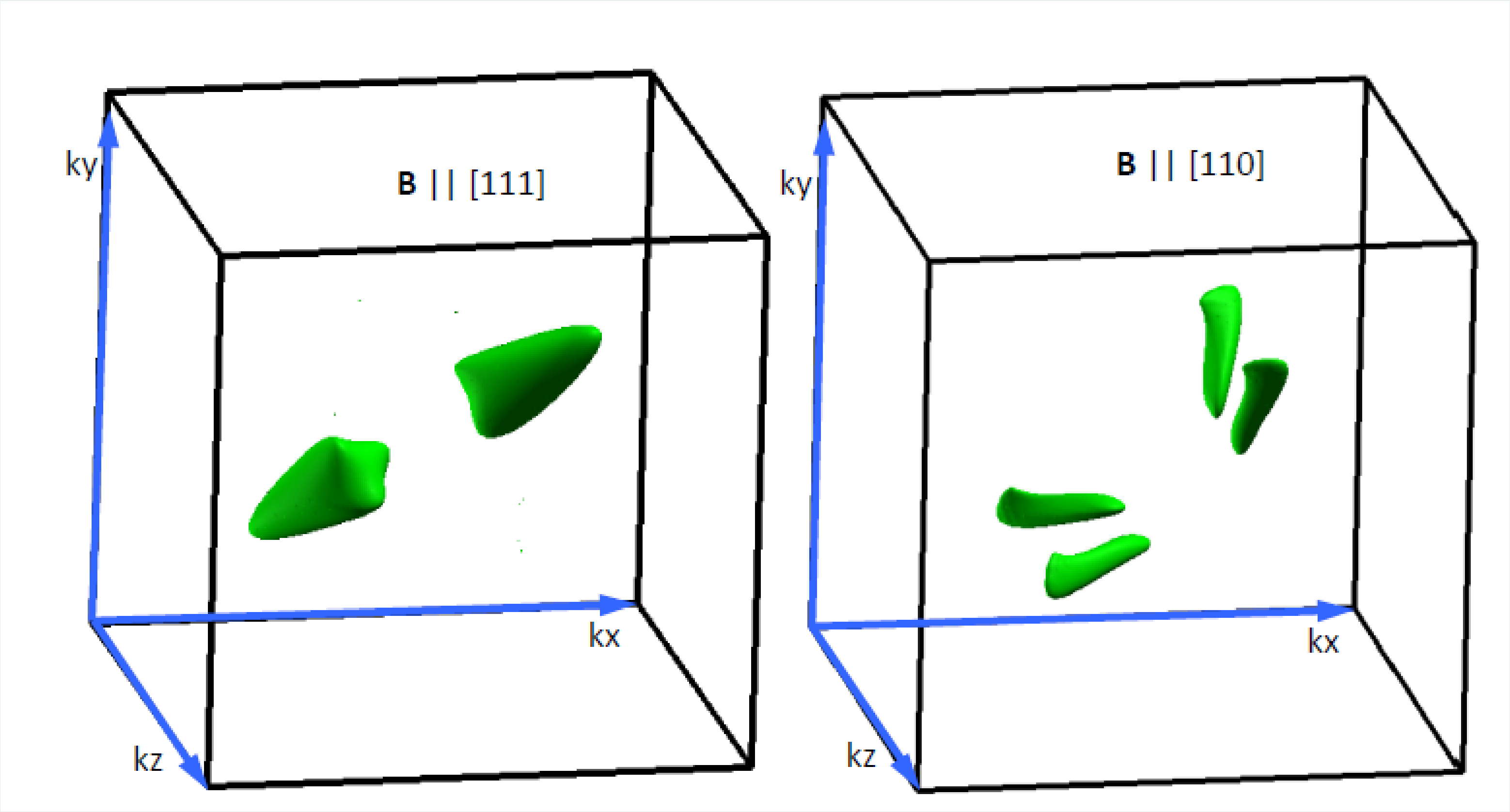




Low-lying states (4) are derived from Bi 6p
Quadratic bands touch at Γ to form zero gap
Large spin orbit coupling

In finite B, large Zeeman field lifts degeneracies
Leads to creation of two Weyl nodes

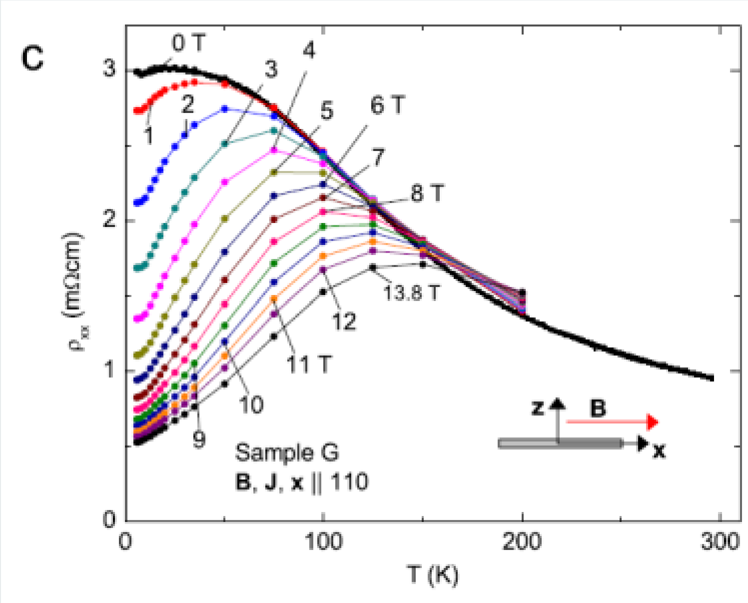
Weyl nodes created in magnetic field

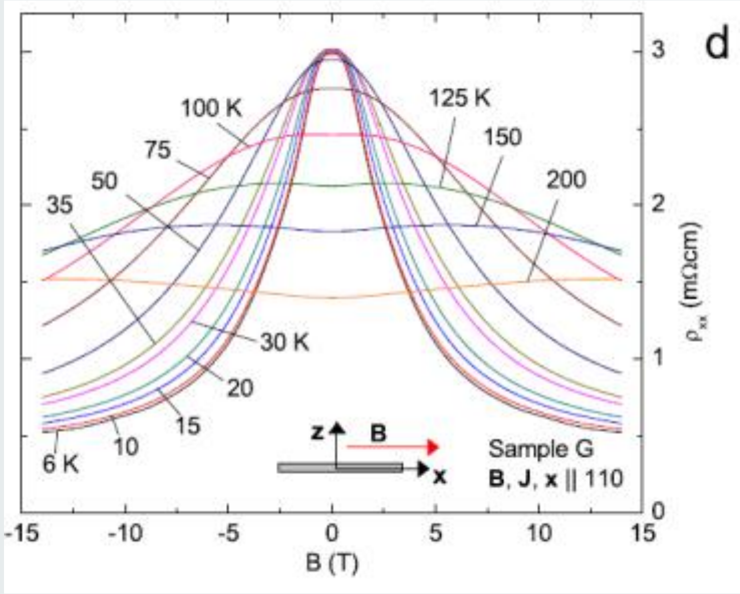


Weyl nodes in a 10-Tesla B (along 111 and 110)
Derived from LDA calculations (Zhijun Wang)

Evidence for chiral anomaly in GdPtBi

Max Hirschberger et al., Nat. Mat. 2016





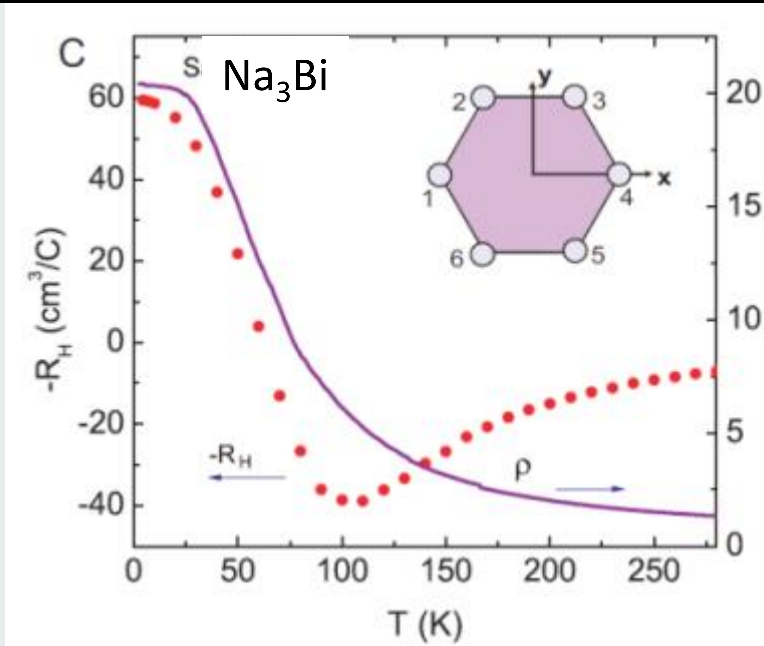
Longitudinal resistivity ρ_{xx} vs. *T* at selected *B*

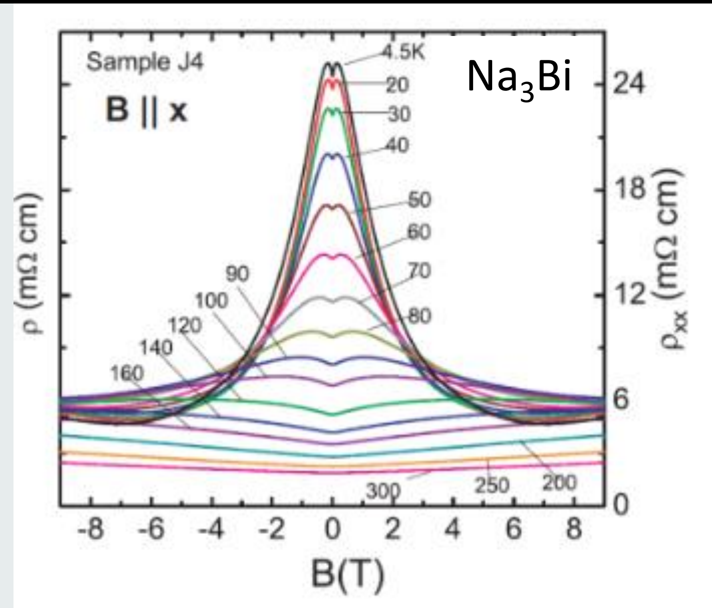
Large suppression of ρ_{xx} at low *T* and large *B*

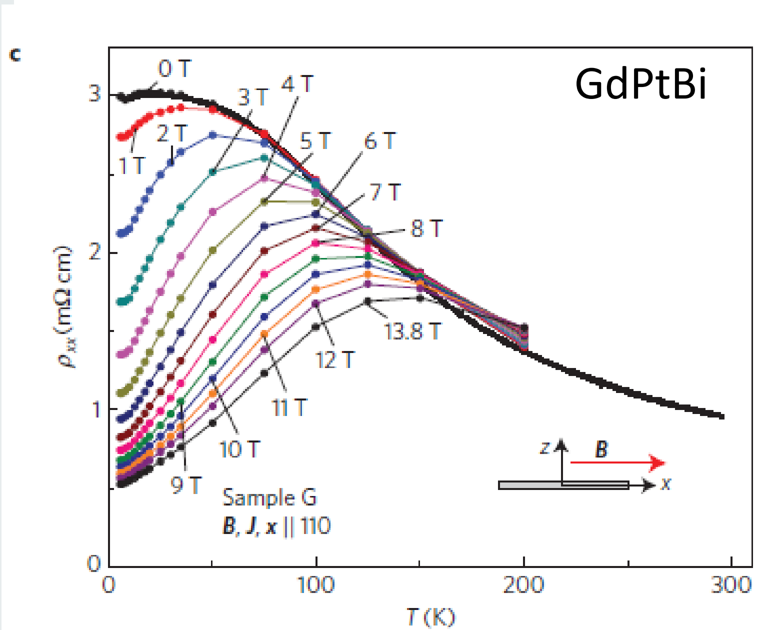
MR profile shows large suppression of ρ_{xx} when *B* exceeds ~3 T

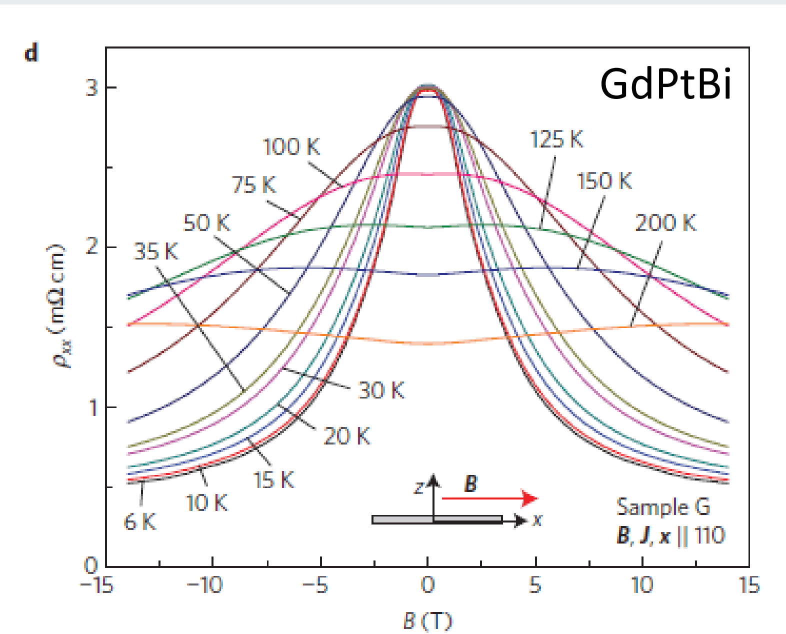
Comparison with Na_3Bi suggests existence of chiral anomaly

Resemblance between long. MR in Na_3Bi and GdPtBi



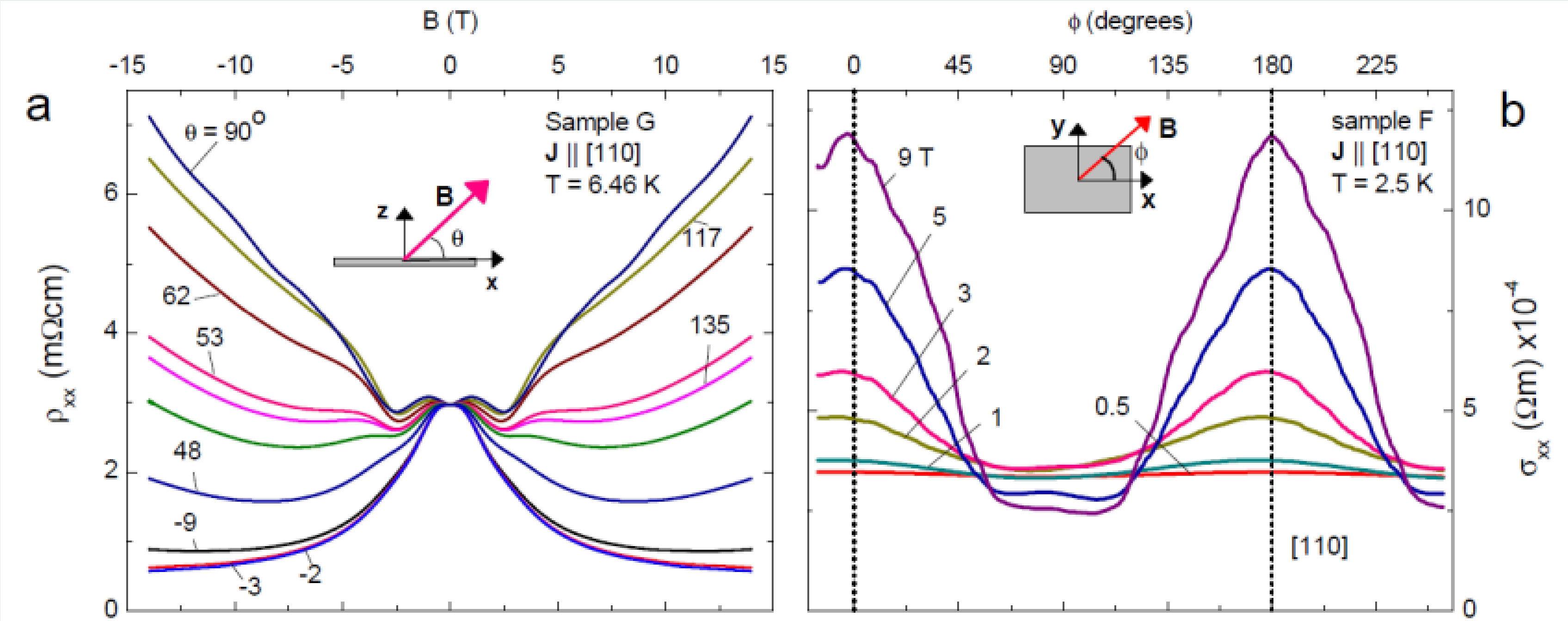






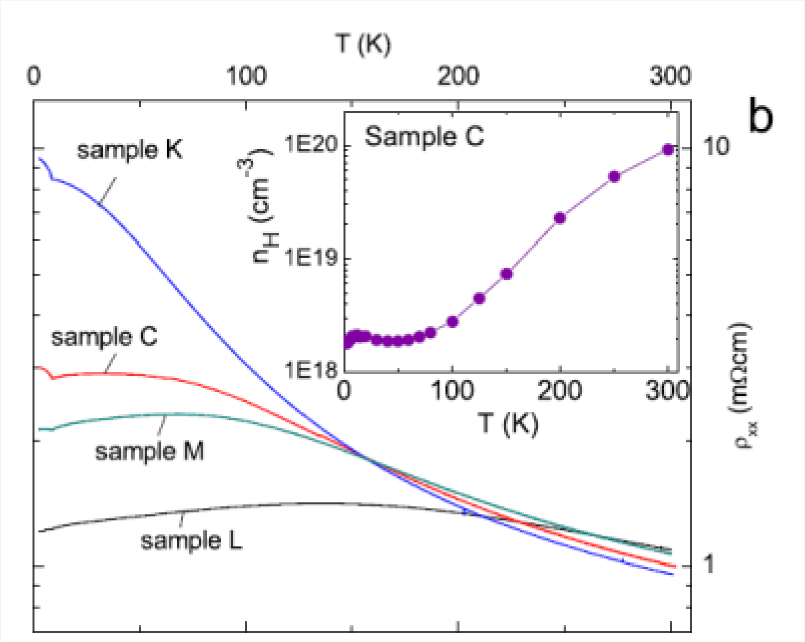
Angular dependence of current plume

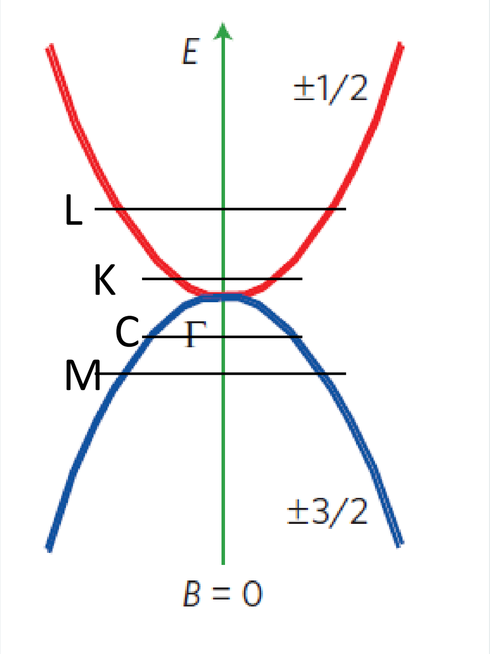
Max Hirschberger et al., Nat. Mat. 2016



Axial current plume is largest when **B** approaches alignment with **J**

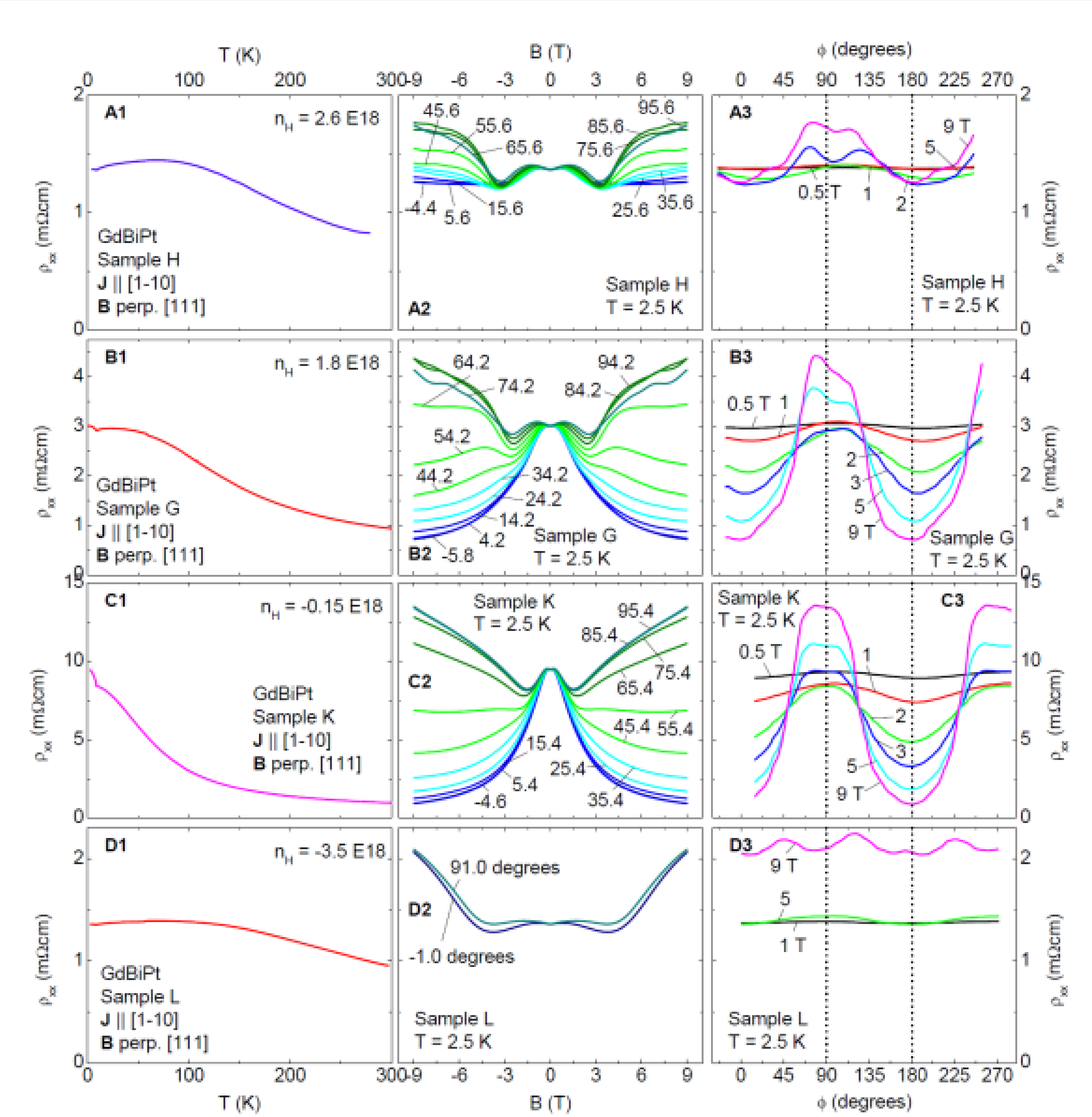
Dependence of resistivity profile on distance of E_F from node





Resistivity profiles are most non-metallic close to node

Dependence of chiral anomaly on distance of E_F from node



Maximum anomaly ampl. when closest to node

Hole density $+2.6 \times 10^{18}$

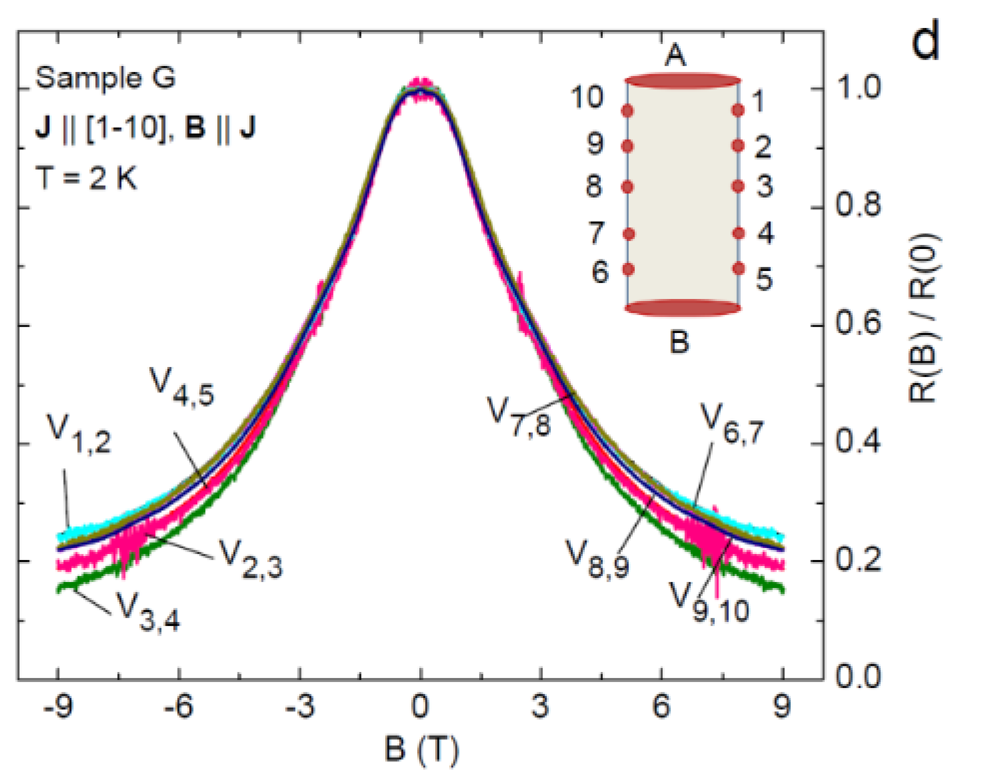
Hole density $+1.8 \times 10^{18}$

Electron density -0.15×10^{18}

Electron density -3.5×10^{18}

Check for uniformity of current density

Max Hirschberger et al., Nat. Mat. 2016



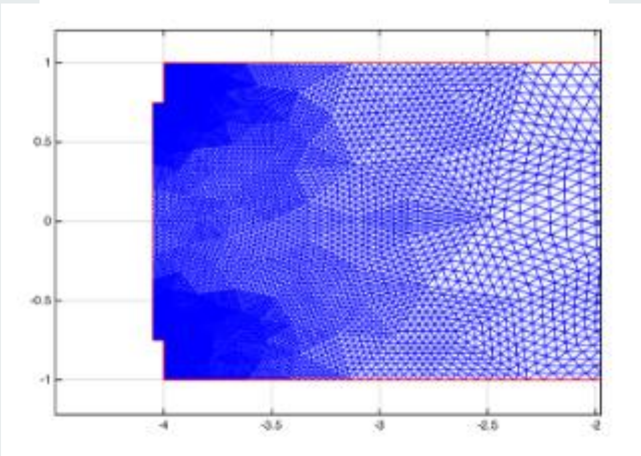
Repeat measmt. on Sample G with 10 voltage contacts
Longitud. MR profiles plotted as relative change are closely similar across all 8 nearest neighbor pairs of contacts

Conclusion: Negative longitude. MR is an intrinsic electronic effect, not a spurious result of inhomogeneity.

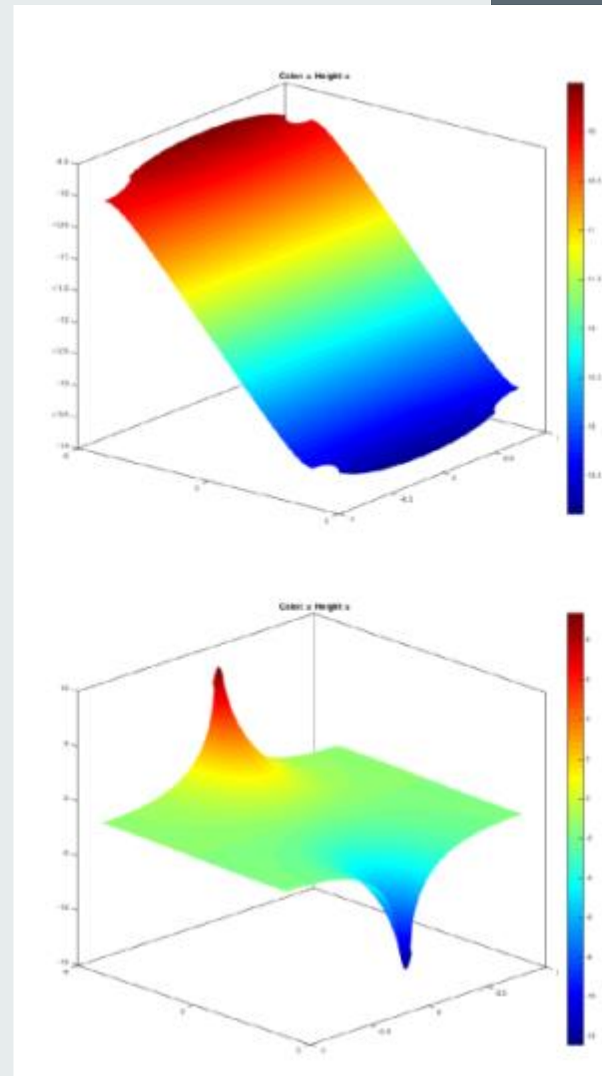
"Current jetting"

Current jetting can produce spurious, negative longitud. MR but only in high mobility samples in intense B (μB>>1)

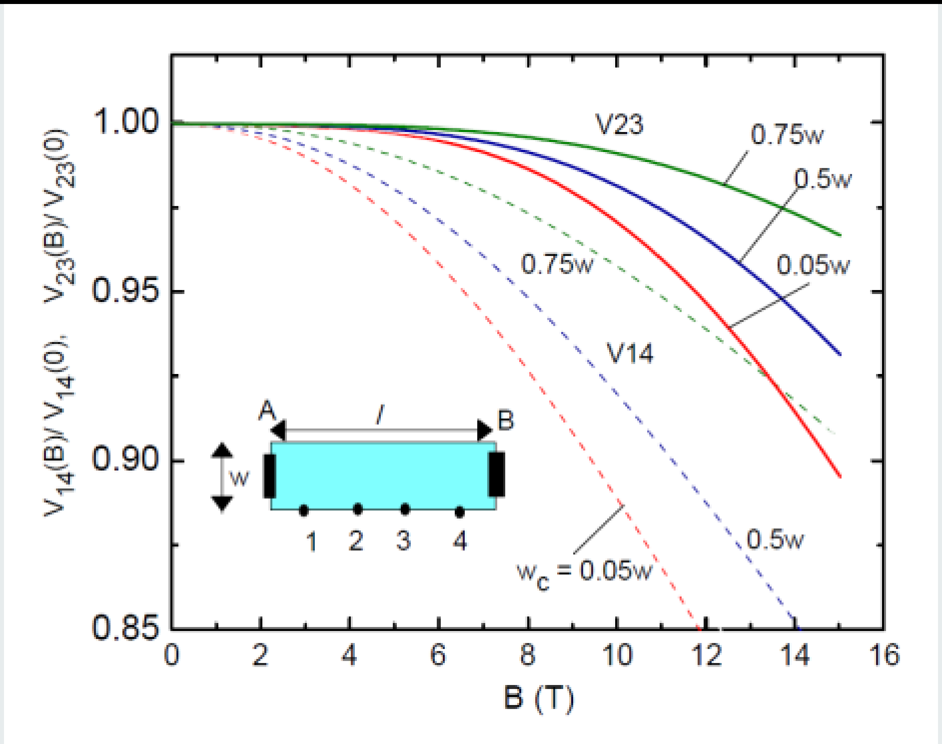
$$[\partial_x \sigma_{xx} \partial_x + \partial_y \sigma_{yy} \partial_y]\psi(x,y) = 0.$$

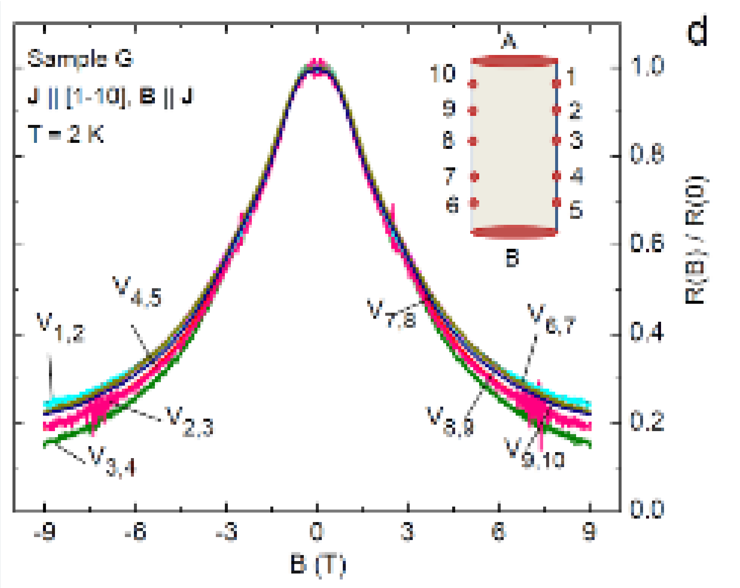


Numerically calculate potential function ψ(x,y) with Drude conductivity tensor in **B** ‖ **E**.
Current jetting is unimportant for small μB and broad current contacts (upper panel). However, for point contacts and large μB (lower panel), get current focusing and jetting (imitates very large contact resistance).



The case against "current jetting" in GdPtBi





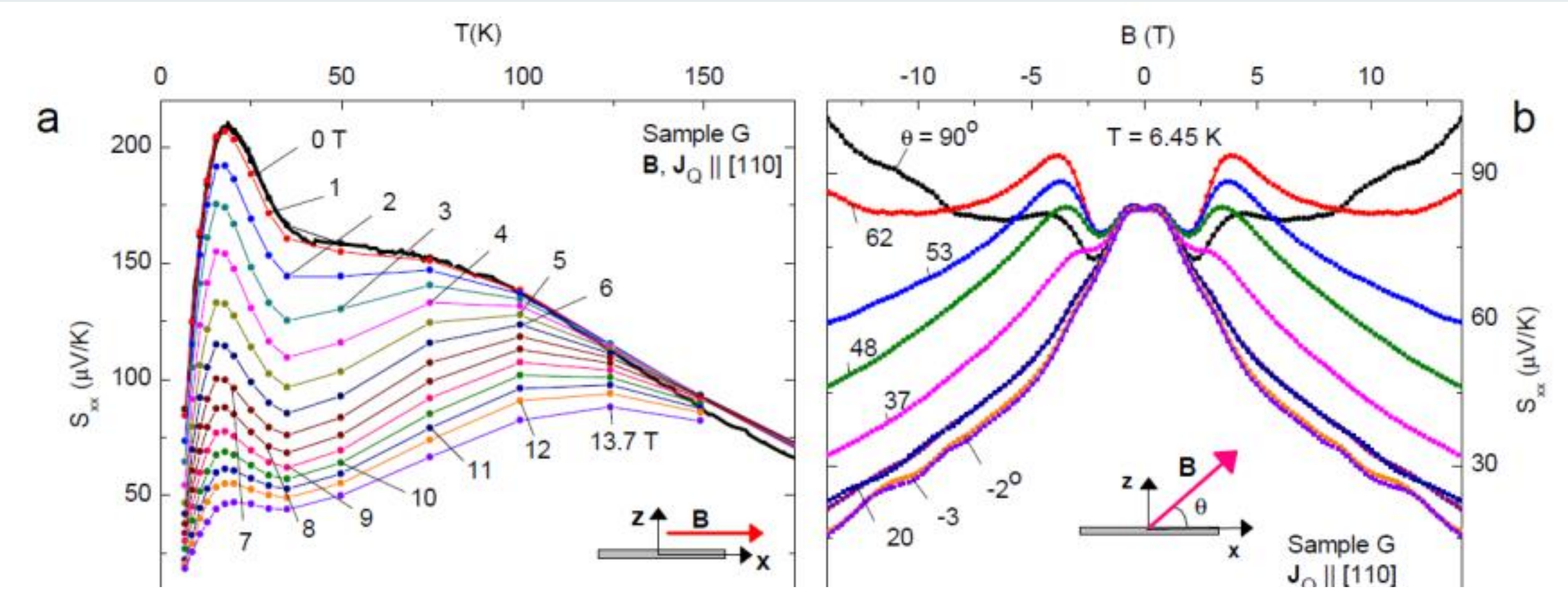
Max Hirschberger et al., Nat. Mat. 2016

Upper panel:
Calculated $V_{ij}(B)$ curves using "current jetting" assumptions for mobility of 2,000 cm^2/Vs and various current contact widths.

To reproduce observed long. MR curves (lower panel) we would need *B* to exceed 50 to 70 Tesla.

Conclusion: Current jetting is not the origin of observed chiral anomaly.

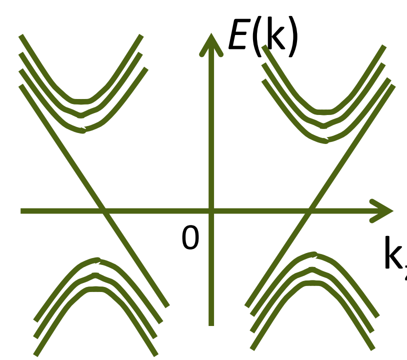
Max Hirschberger et al., Nat. Mat. 2016

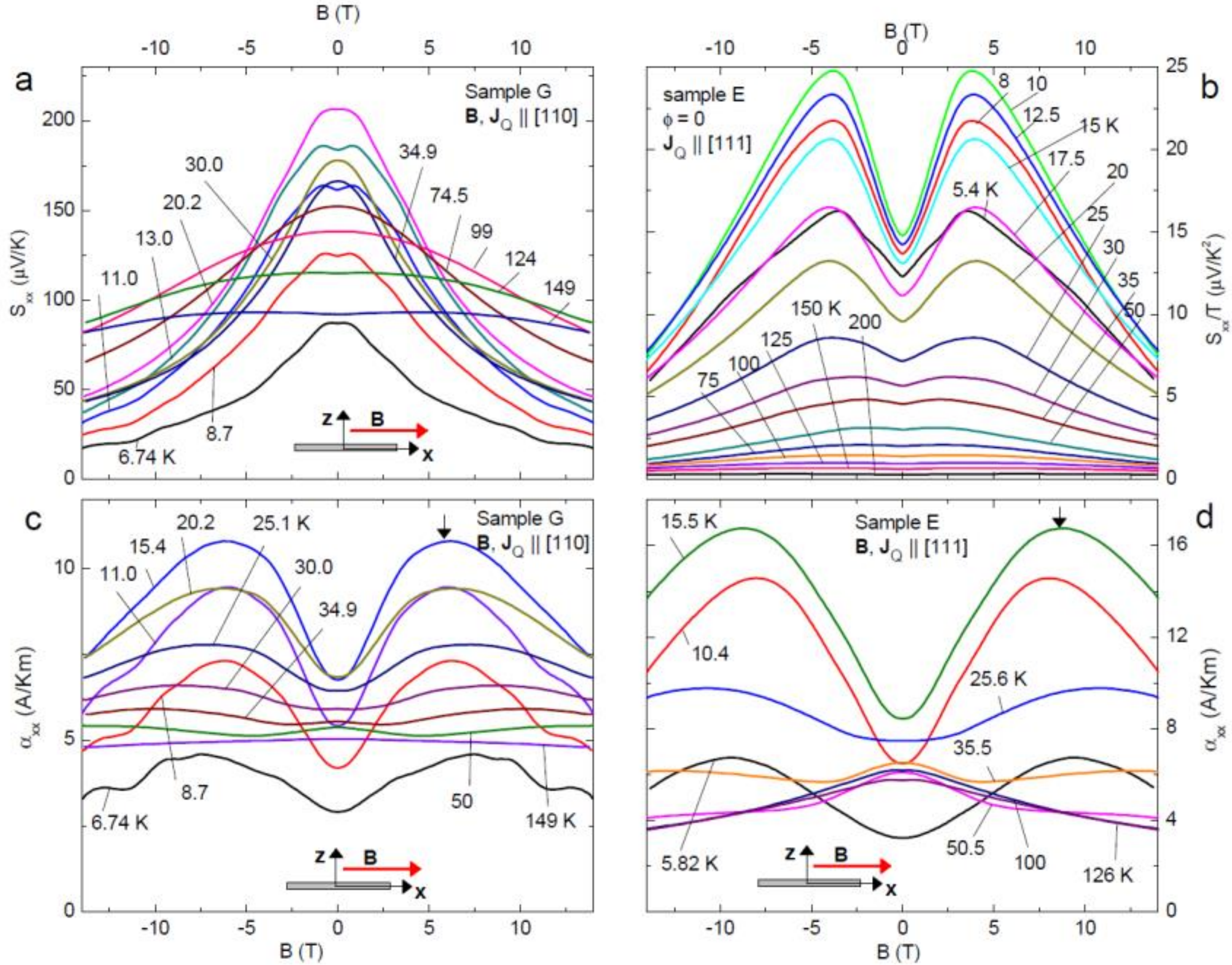


Thermoelectric response is strongly suppressed when axial current appears.

A consequence of chiral n=0 Landau level?

Reflects the “flat” DOS vs. E in the lowest Landau level





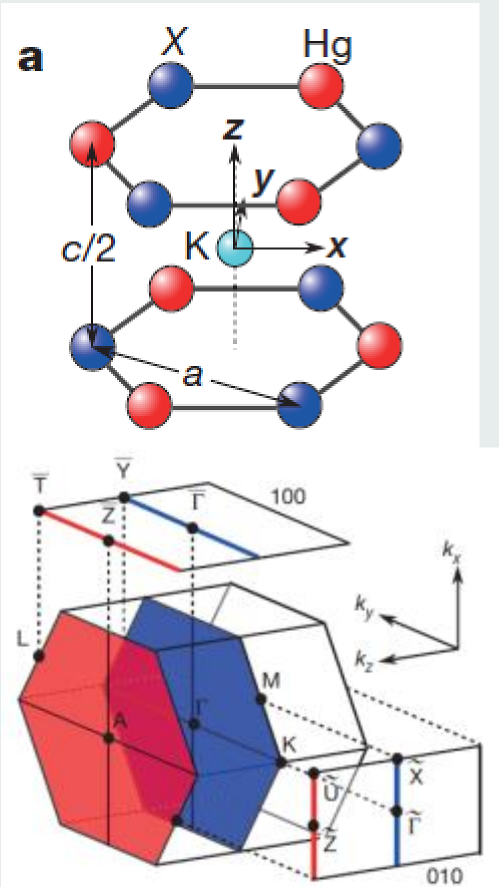
a
Sample G
B, J_Q || [110]
B (T)
S_{xx} (μV/K)
6.74 K
8.7
11.0
13.0
20.2
30.0
34.9
74.5
99
124
149
b
sample E
φ = 0
J_Q || [111]
S_{xx}/T (μV/K^2)
5.4 K
8
10
12.5
15 K
17.5
20
25
30
35
50
75
100
125
150 K
200
c
Sample G
B, J_Q || [110]
α_{xx} (A/Km)
6.74 K
8.7
11.0
15.4
20.2
25.1 K
30.0
34.9
50
149 K
d
Sample E
B, J_Q || [111]
α_{xx} (A/Km)
15.5 K
10.4
25.6 K
35.5
5.82 K
50.5
100
126 K
z
B
x

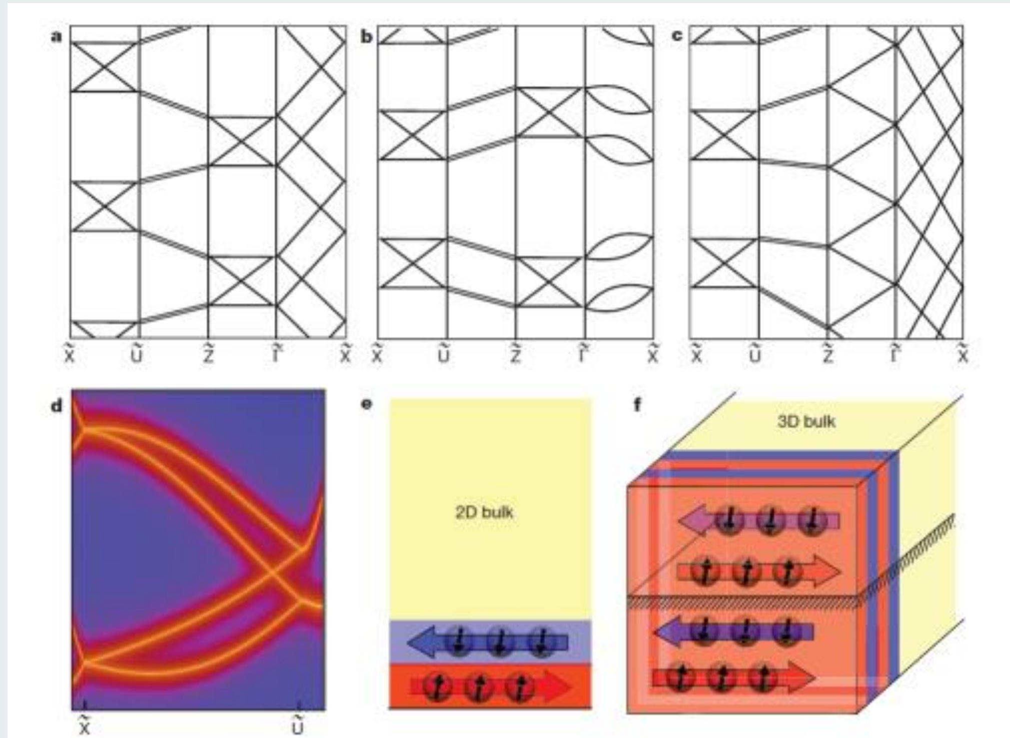
Hourglass fermions

Zhijun Wang[1]*, A. Alexandradinata[1,2]*, R. J. Cava[3] & B. Andrei Bernevig[1]

ZJ Wang et al., *Nature* (2016)

KHgSb, KHgAs





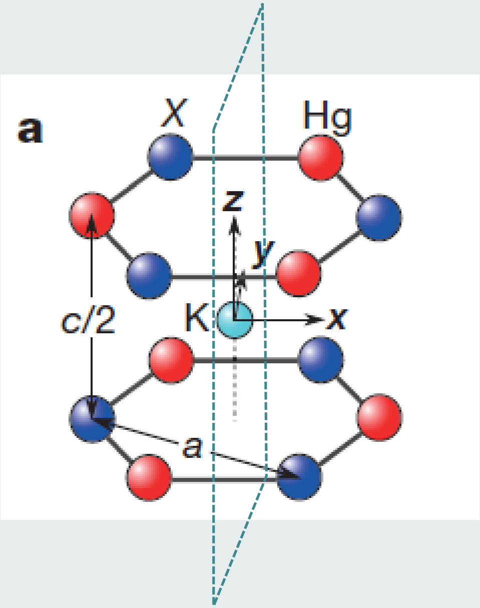
Nonsymmorphic

Two pairs of helical states wrap around sides

Hourglass fermions exist on Z-Γ face

Nonsymmorphic group and protected bands on BZ surface

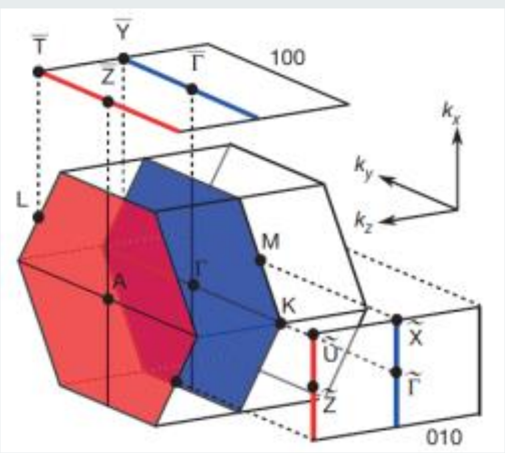
Nonsymm space groups include glide planes and screw oper.



Mirror reflection in *yz* plane M_x = -i$\sigma_1 P$
is not a symm operation of the group

Need to combine with translation by $\boldsymbol{\tau}$ = **c**/2
$t(\boldsymbol{\tau})$ = exp(i**k**· $\boldsymbol{\tau}$)

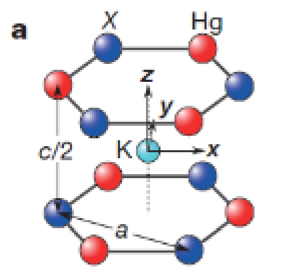
$$\overline{M_x} = t_z\left(\frac{c}{2}\right) M_x = \exp(i\mathbf{k}\cdot\frac{\mathbf{c}}{2})(-i\sigma_1 P)$$



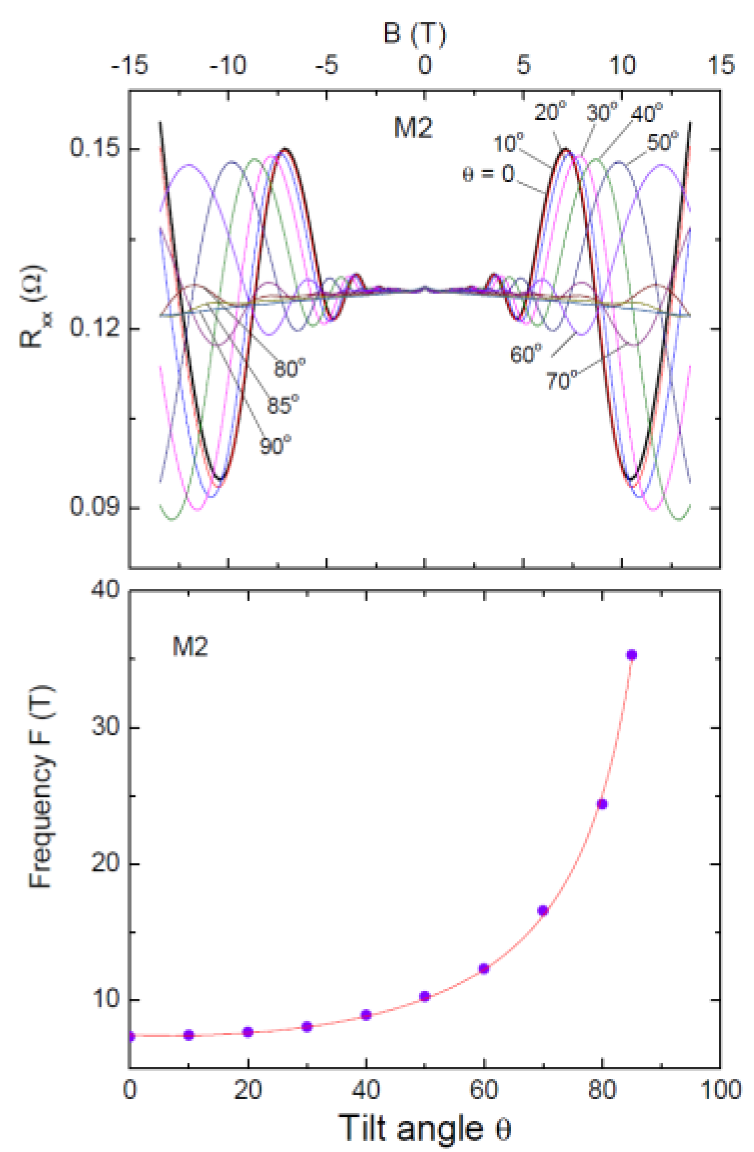
$$\Theta^2\overline{M_x}^2 = \exp(ik_z c)$$

Protects pair of degenerate states on
plane $k_z = \pi/c$

SdH oscillations in KHgSb



S.H. Liang et al., unpublished



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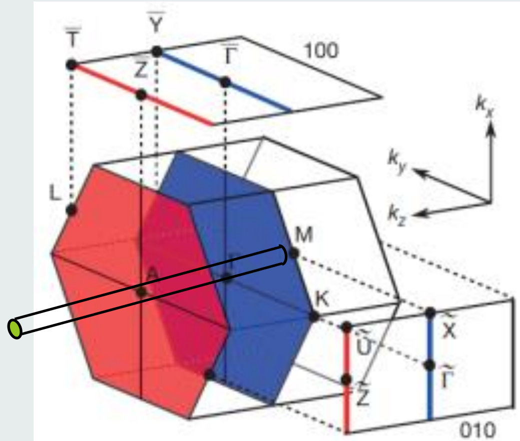
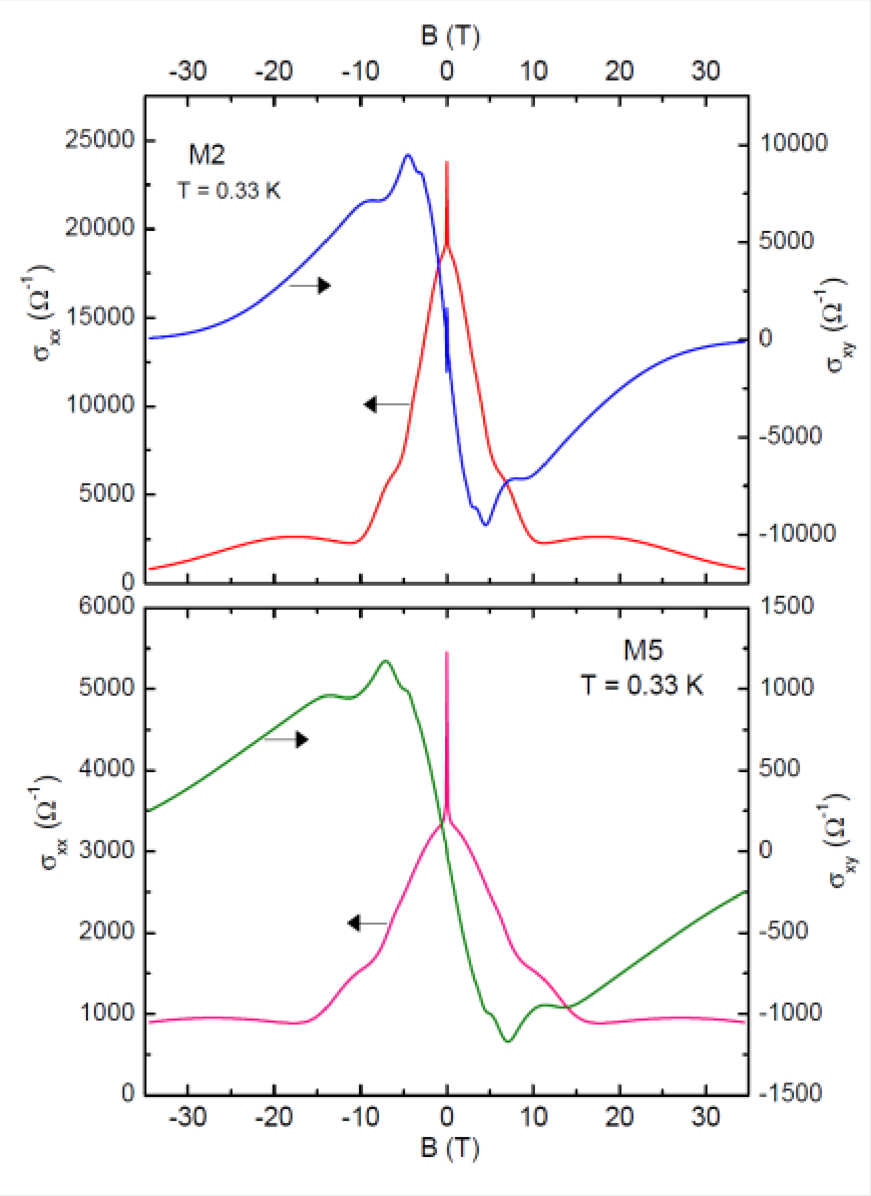
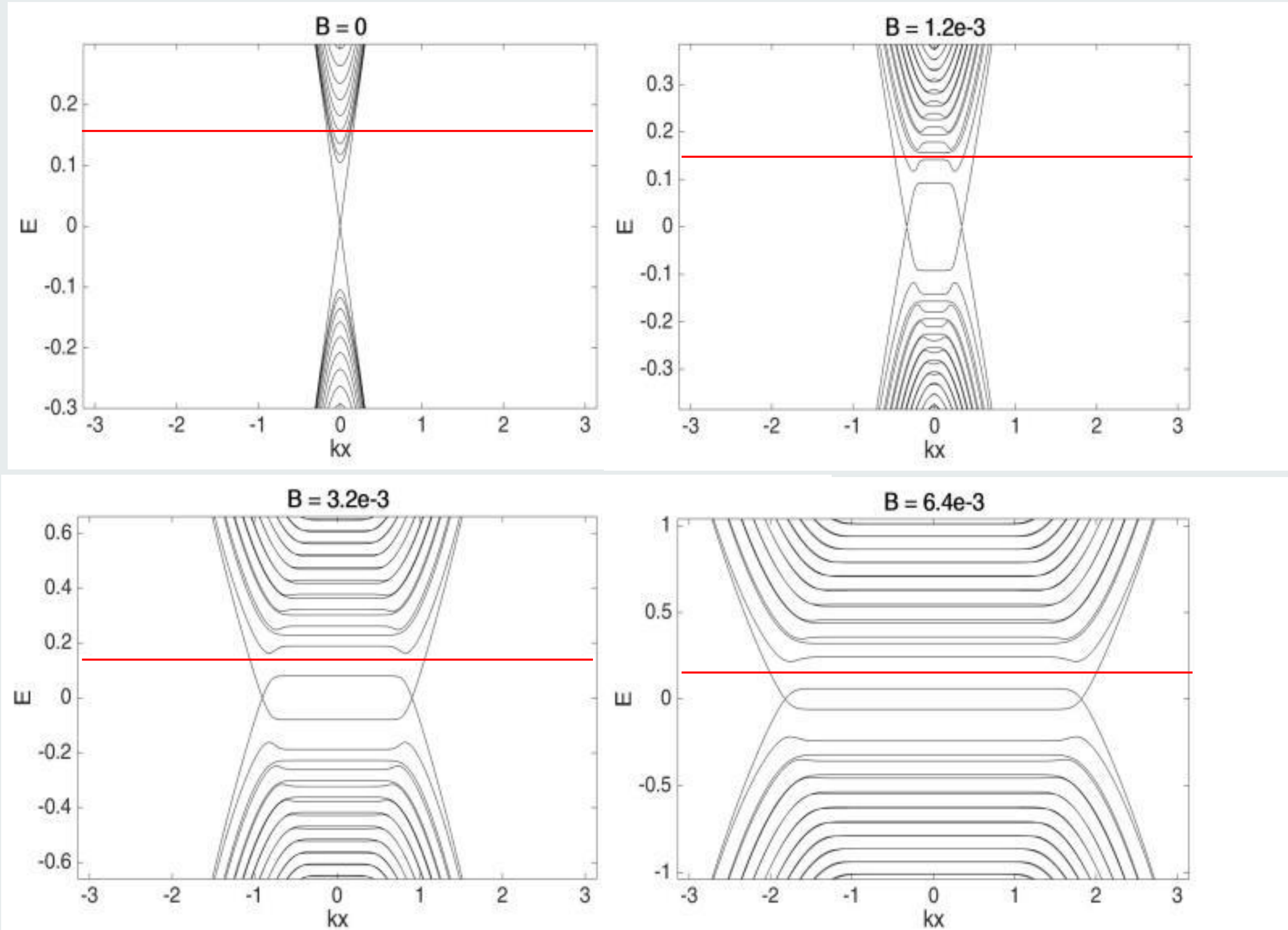


n-type carriers
occupy a narrow
FS cylinder

Abrupt change of conductivity in quantum limit

S.H. Liang et al., unpublished





Calculations: Jian Li, Zhijun Wang, B.A. Bernevig

Summary

1) Evidence for chiral anomaly in Dirac semimetal Na_3Bi

2) Chiral anomaly in a zero-gap semiconductor, half Heusler GdPtBi

   Zeeman field induces band crossing and protected nodes

   Chiral anomaly has strong effect on thermoelectric current

3) Nonsymmorphic semimetal KHgSb – new mode in quantum limit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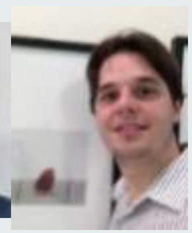
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NPO

Thank you