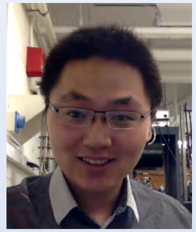
Transport signatures of 3D topological matter: Glide Hall in nonsymmorphic metal and chiral anomaly


S.H. Liang


S. Kushwaha


T. Gao


M. Hirschberger


Z.J. Wang


Bernevig


Bob Cava

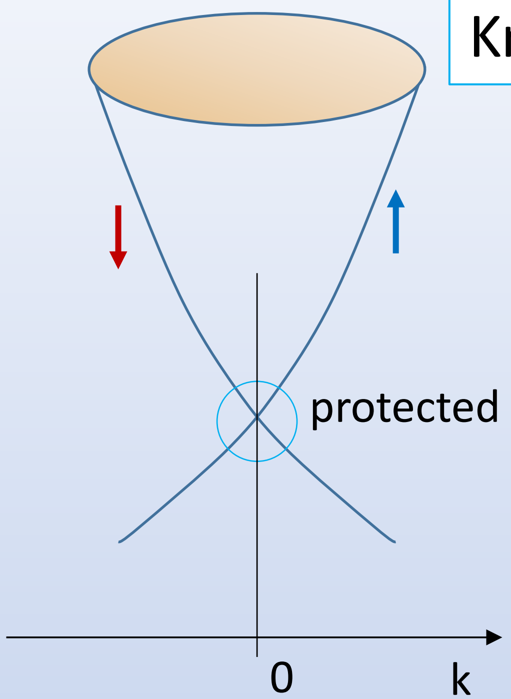

NP Ong

S.H. Liang, S. Kushwaha, T. Gao, M. Hirschberger, J. Li, Z.J. Wang, K. Stolze, B.A. Bernevig, R.J. Cava, N. P. Ong
Departments of Physics and Chemistry, Princeton Univ.

1. Glide symmetry protection
2. The nonsymmorphic metal KHgSb
3. A novel zero Hall state at lowest Landau level
4. The chiral anomaly in Na_3Bi and GdPtBi
5. Tests for chiral anomaly

Support from
Moore Foundation, ARO, NSF

2D Dirac node protected by time-reversal symmetry (TRS)



Kramer's theorem

When Hamiltonian is time reversal symmetric (TRS)

$$H\varphi = E\varphi, \qquad H\psi = E\psi$$

$$\Theta\varphi = \psi, \qquad \Theta\psi = -\varphi$$

$$(\Theta\varphi, \Theta\psi) = (\varphi, \psi)^* = (\psi, \varphi)$$ antiunitarity

$$-(\psi, \varphi) = (\psi, \varphi) = 0$$

φ, ψ are orthogonal (hence 2-fold degenerate)

To apply to **k** space, need the little group.

Little group $\mathcal{G}_{\mathbf{k}}$ and symmetry protection

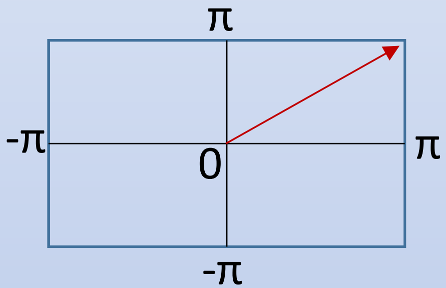
For space group $\mathcal{G}$, the subset of operations g that leave **k** invariant define the **little group** $\mathcal{G}_{\mathbf{k}}$. We have the equation

$$g\,\mathbf{k} \doteq m\,\mathbf{k} \quad \text{mod } \mathbf{G} \qquad\qquad (\,g \in \mathcal{G}_{\mathbf{k}}\,)$$

To apply Kramer's theorem at **k**, we need its little group $\mathcal{G}_{\mathbf{k}}$ (to return to **k**)

Example: In 2D topological insulators, the TR operator Θ returns **k** → **-k** = **k+G** ≐ **k**

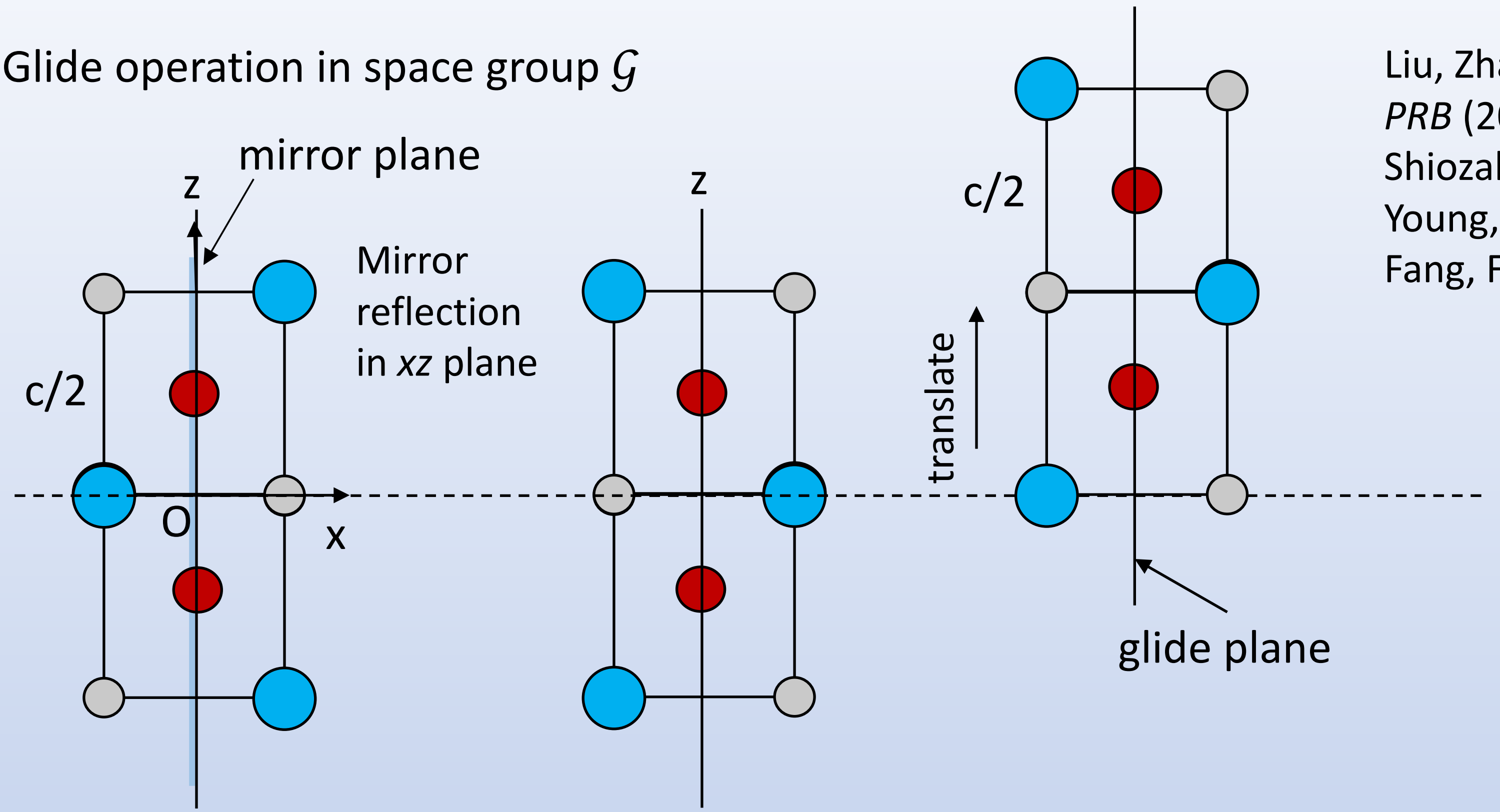
$$\Theta\,|\mathbf{k},\alpha) = \pm i\,|-\mathbf{k},\bar{\alpha})$$



provided **k** is a time-reversal invariant momentum **TRIM** (Γ and corners of BZ). The surface Dirac cone is protected only if **pinned** at a TRIM.

Nonsymmorphic space groups $\mathcal{G}$ have glide and screw operations

Glide operation in space group $\mathcal{G}$



Liu, Zhang, Vanleuven, *PRB* (2014)
Shiozaki, Sato, *PRB* (2014)
Young, Kane, *PRL* (2015)
Fang, Fu, *PRB* (2015)

Glide combines mirror reflection and translation by half a lattice parameter

$$\boxed{g_x = \{M_x|\boldsymbol{\tau}\}} \qquad \boldsymbol{\tau} = \frac{c}{2}\hat{\mathbf{z}}$$

Mirror reflection = Rotation by π and Inversion *P*

$$\boxed{M_x = -Pi\sigma_x}$$

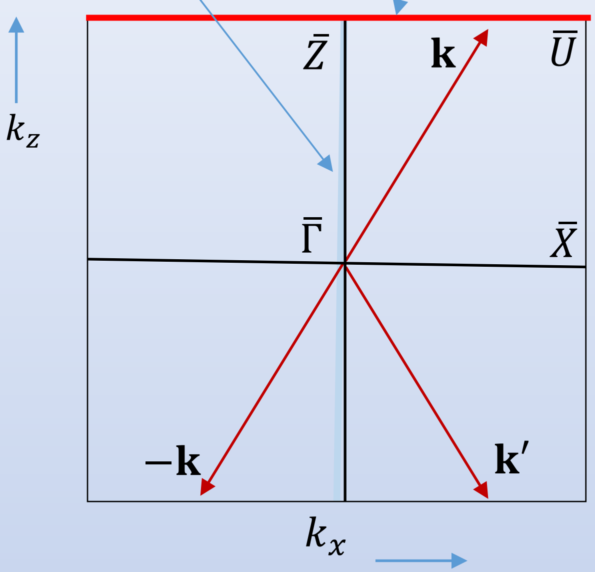
The power of glide 1

1. "Sticking" of bands on BZ surface when Θg_x is in little group

C. Herring (1937)

Glide protection of degenerate bands all along *UZU*

mirror plane



1. Under TR operation Θ, **k** → **-k**

2. Under glide operation g_x, **-k** → **k′** $\doteq$ **k**

$$(\Theta g_x)\,|\,\mathbf{k}\rangle = p\,|\,\mathbf{k}\rangle$$

(Θg_x) returns **k** to itself, but what is the "eigenvalue" *p*?

$$(g_x)^2 = (M_x)^2 \mathrm{e}^{ik_z c} = +1$$

$$(\Theta g_x)^2 = (-1)(g_x)^2 = -1$$

Mirror reflection

$$M_x = Pi\sigma_x$$

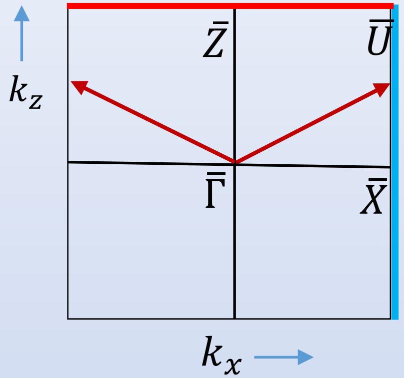
Eigenvalue p^2 is -1 for all **k** on *UZU* --- Kramer's doublet at each **k**!

Θg_x in little group of **k** on *UZU* → states **k** are doubly degenerate ("stick" together).

The power of glide 2

2. Möbius band topology (in g_x is part of little group)

All states **k** on *UXU* are eigenstates of g_x with eigenvalues $m_{\pm}(k_z)$

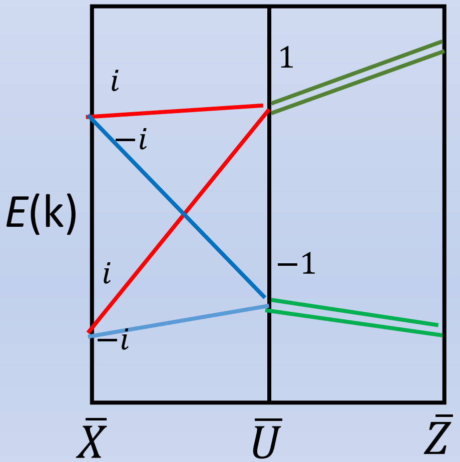


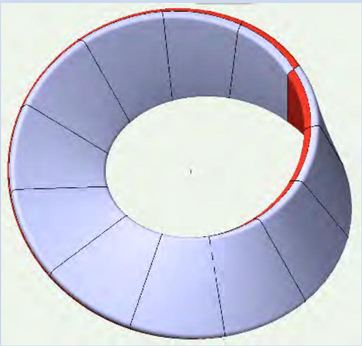
$$g_x|\mathbf{k}\rangle = m_{\pm}|\mathbf{k}\rangle$$

$$m_{\pm} = \pm i\, e^{ik_z c/2}$$

$m_{\pm}(k_z)$ has 2 distinct branches both with period 4π.

After translation of 2π, $m_{+}(k_z)$ becomes $m_{-}(k_z)$
(topology of edges of a Möbius band)





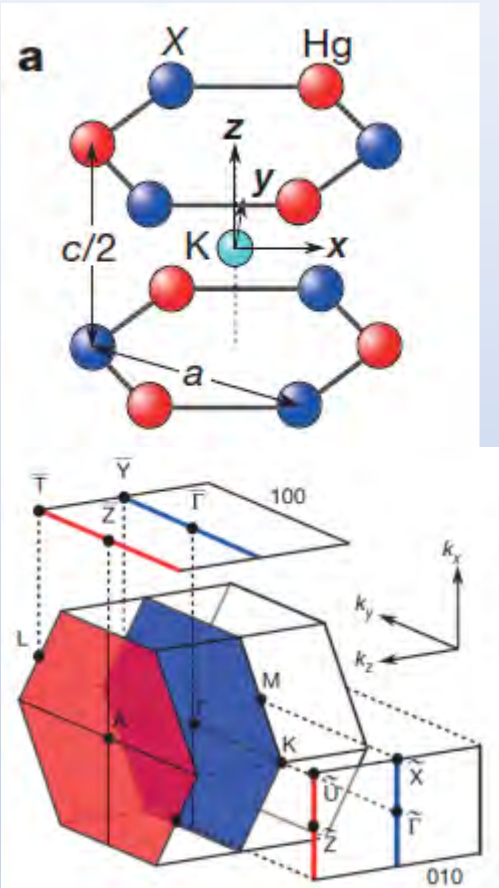
Leads to exchange of states and hourglass fermions
(edges exchange in Möbius band after 2π)

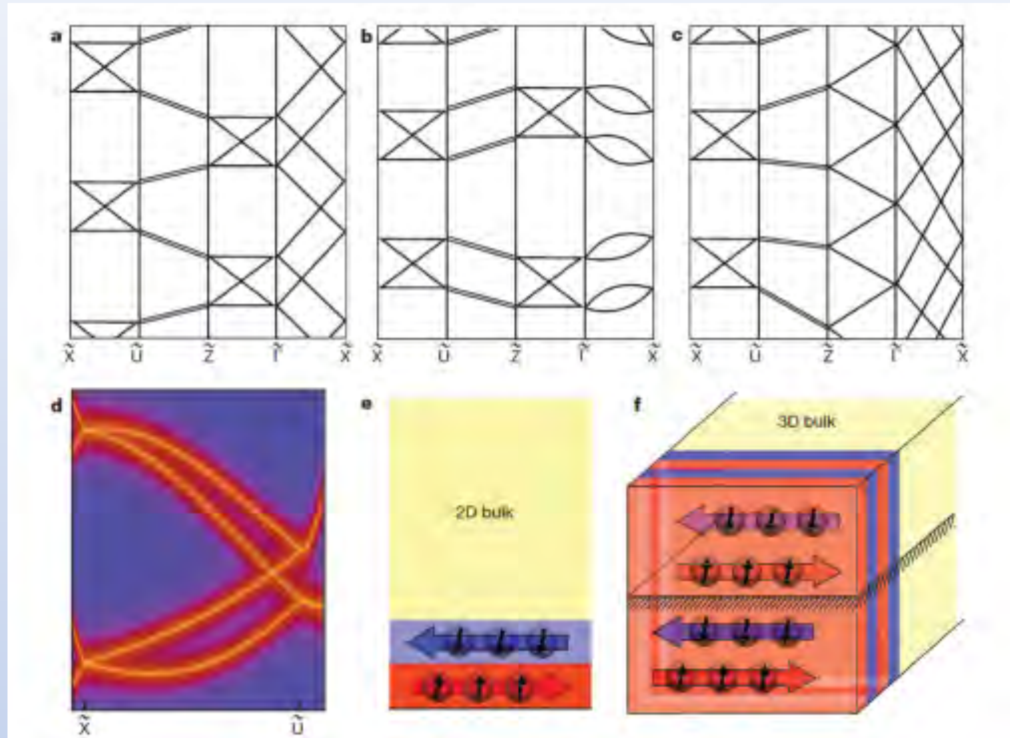
Hourglass fermions

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

Nature (2016)

KHgSb, KHgAs



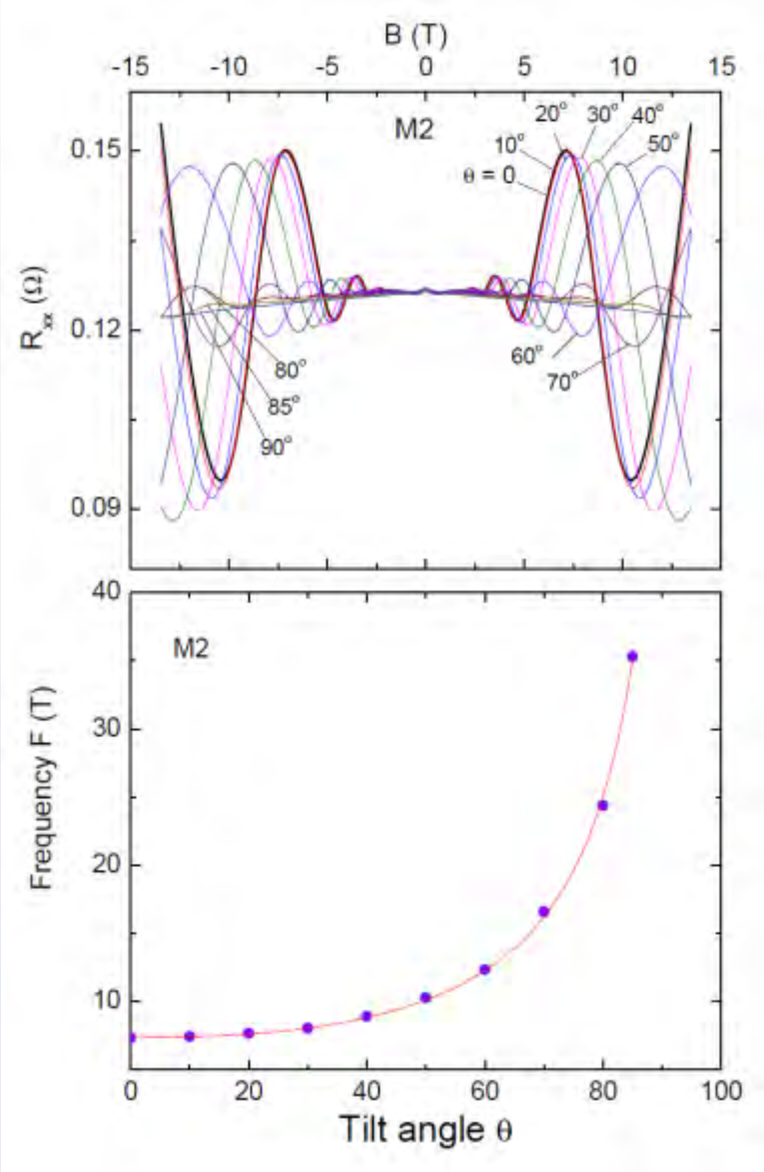


Nonsymmorphic

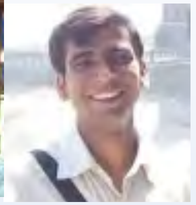
Two pairs of helical states wrap around sides

Hourglass fermions exist on Z-Γ face

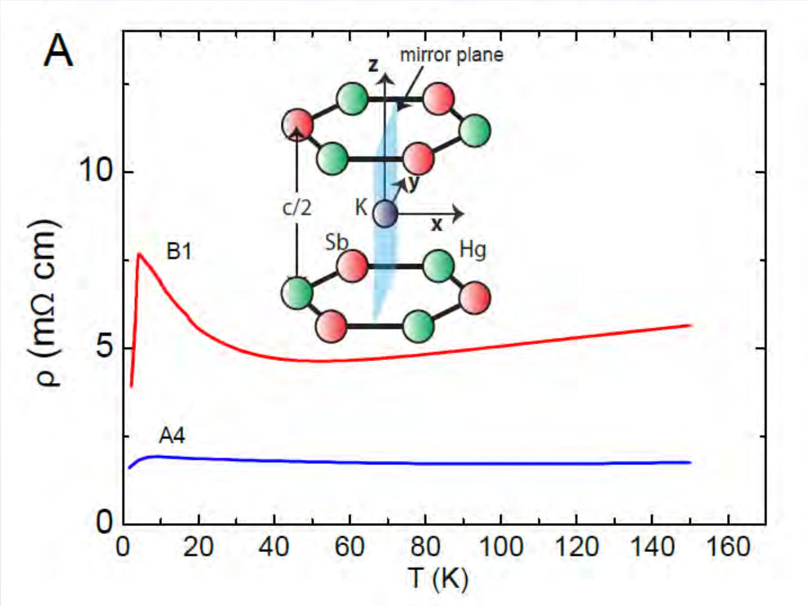
Resistivity and Shubnikov de Haas oscillations



S.H. Liang



S. Kushwaha

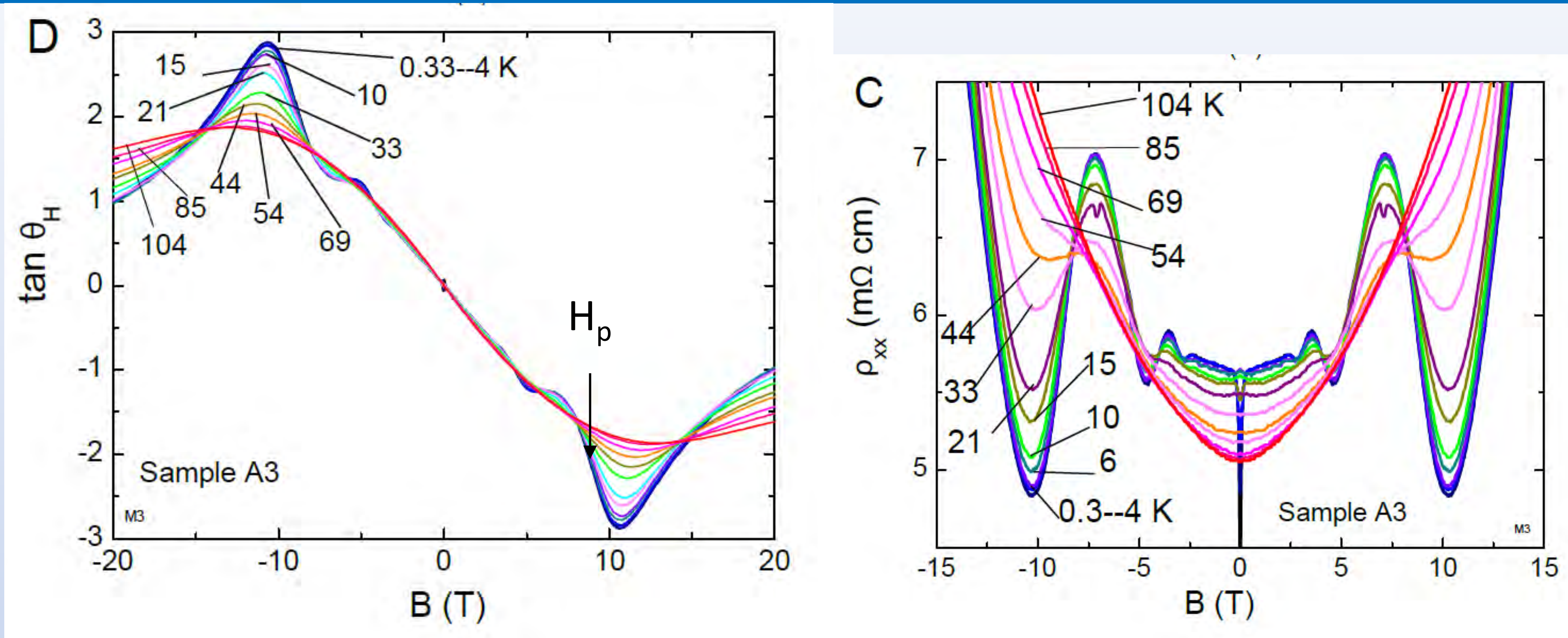


Special handling needed:
Hg exudes to surface, extreme air sensitivity

Residual density of *n*-type carriers (loss of Hg) occupy a ellips. FS at Γ

Large SdH oscillations. Enters lowest Landau level at ~10 Tesla

First hint: A sharp anomaly in Hall angle

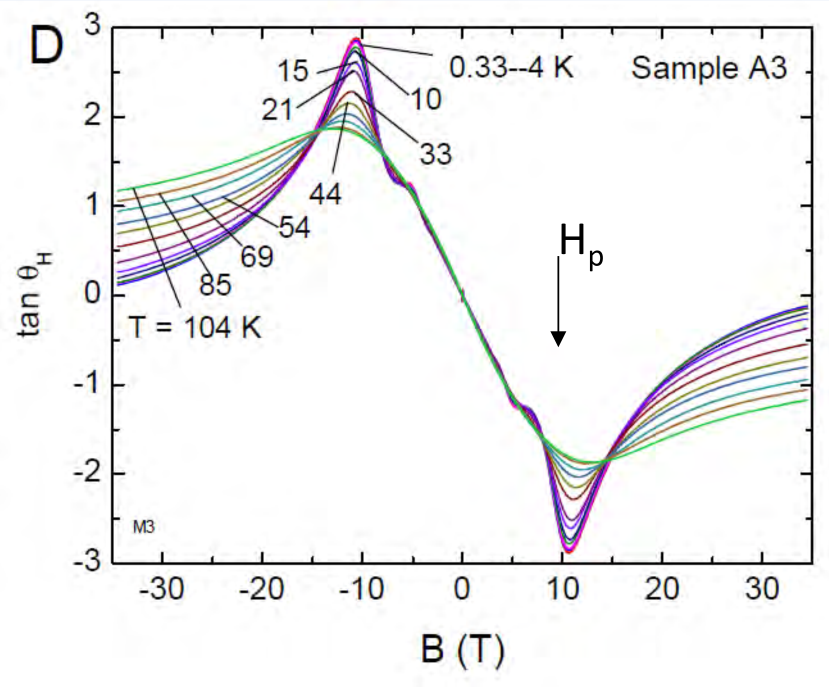


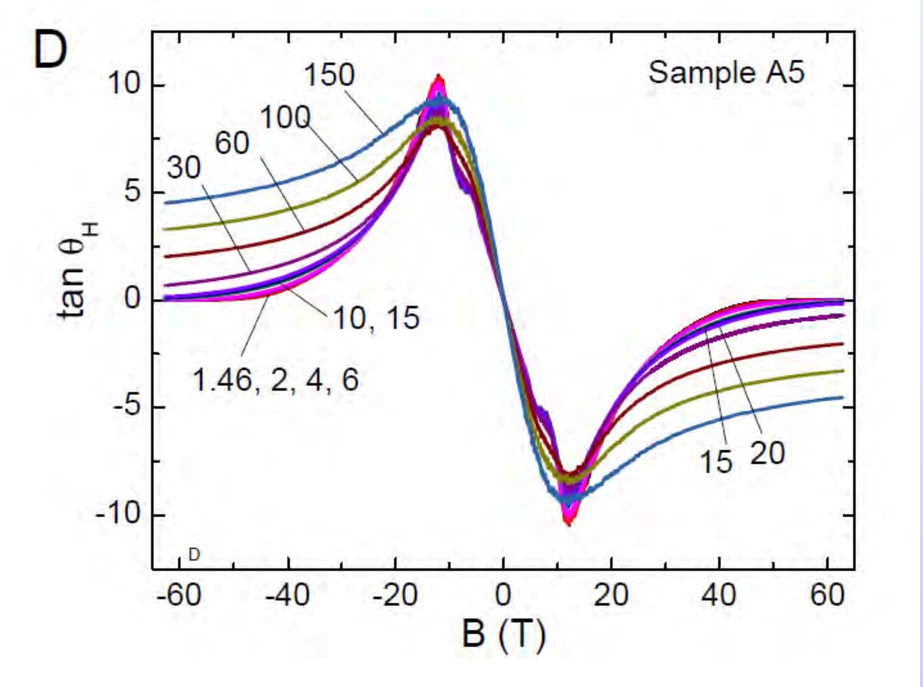
H_p is close to where E_F enters lowest Landau level (LLL).

In conventional metal, tan θ_H is generally linear in B even in quantum limit.

Clearer picture emerges in pulsed fields

Above H_p, tan θ_H is strongly T dependent



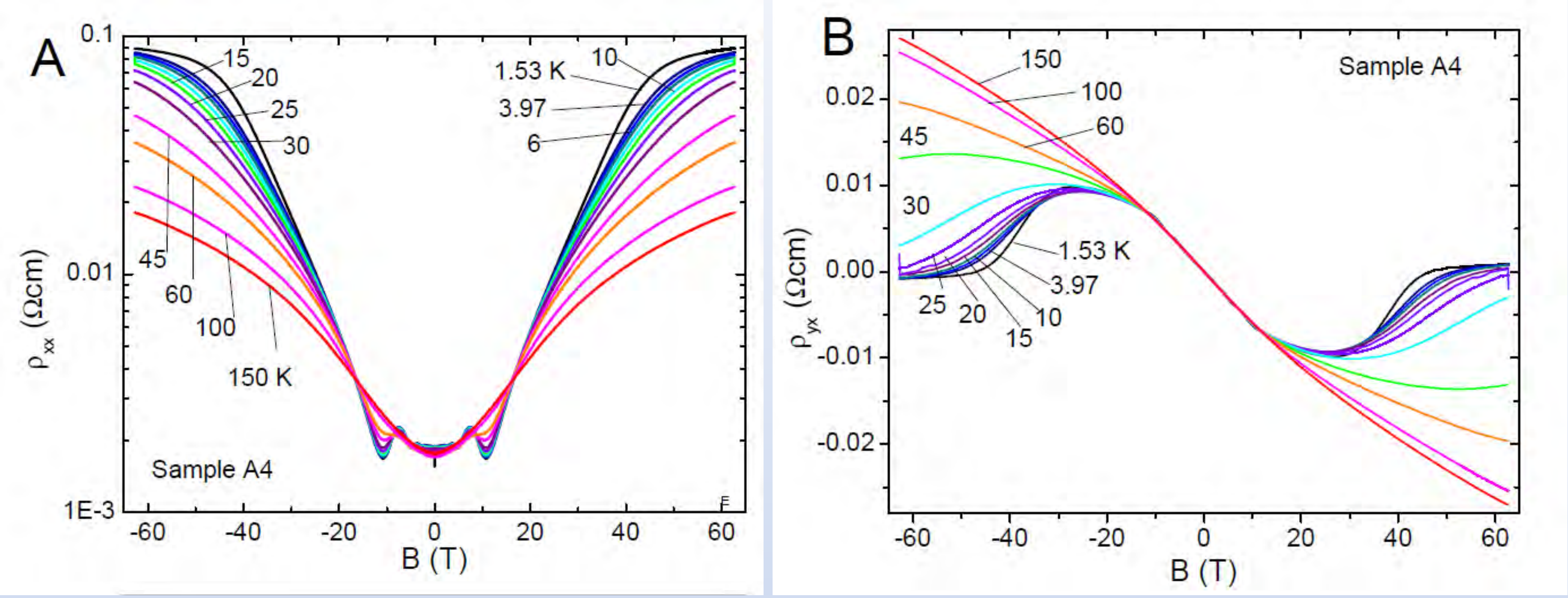


Further unusual features:

Hall response reaches zero in large B and is locked to zero.

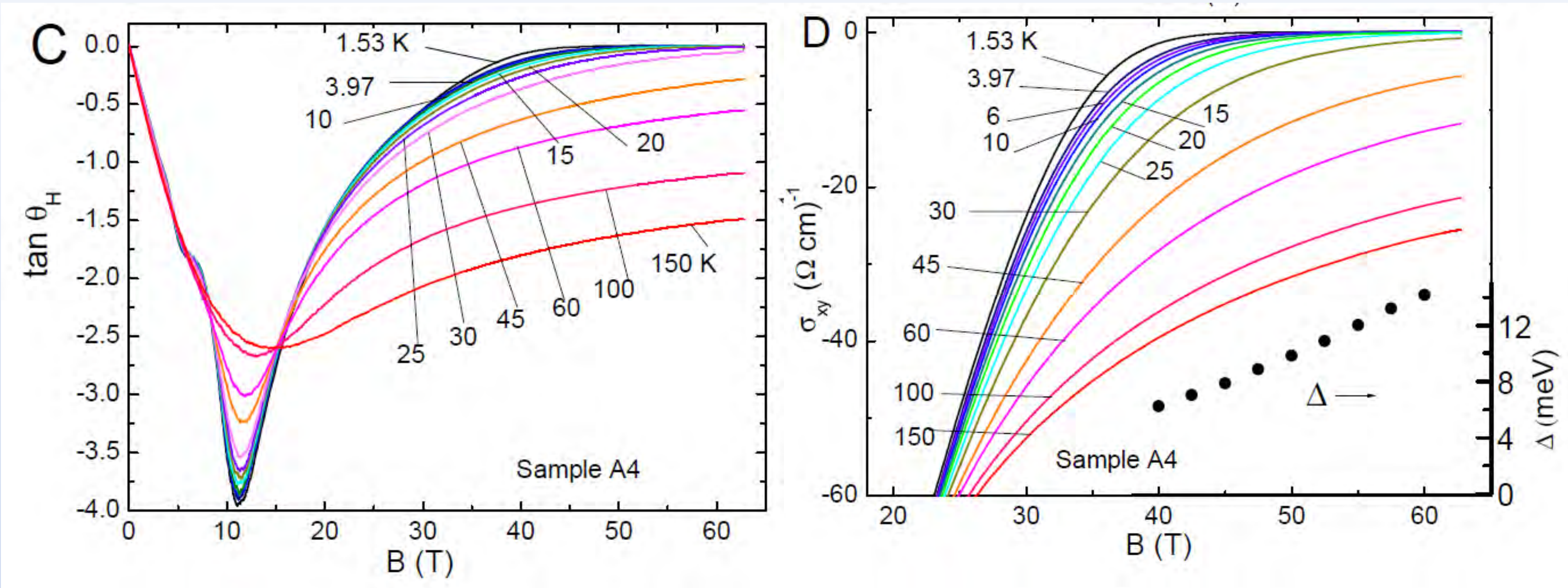
Exponential sensitivity of Hall response to temp.

Anomalous Hall conductivity in pulsed field to 63 T



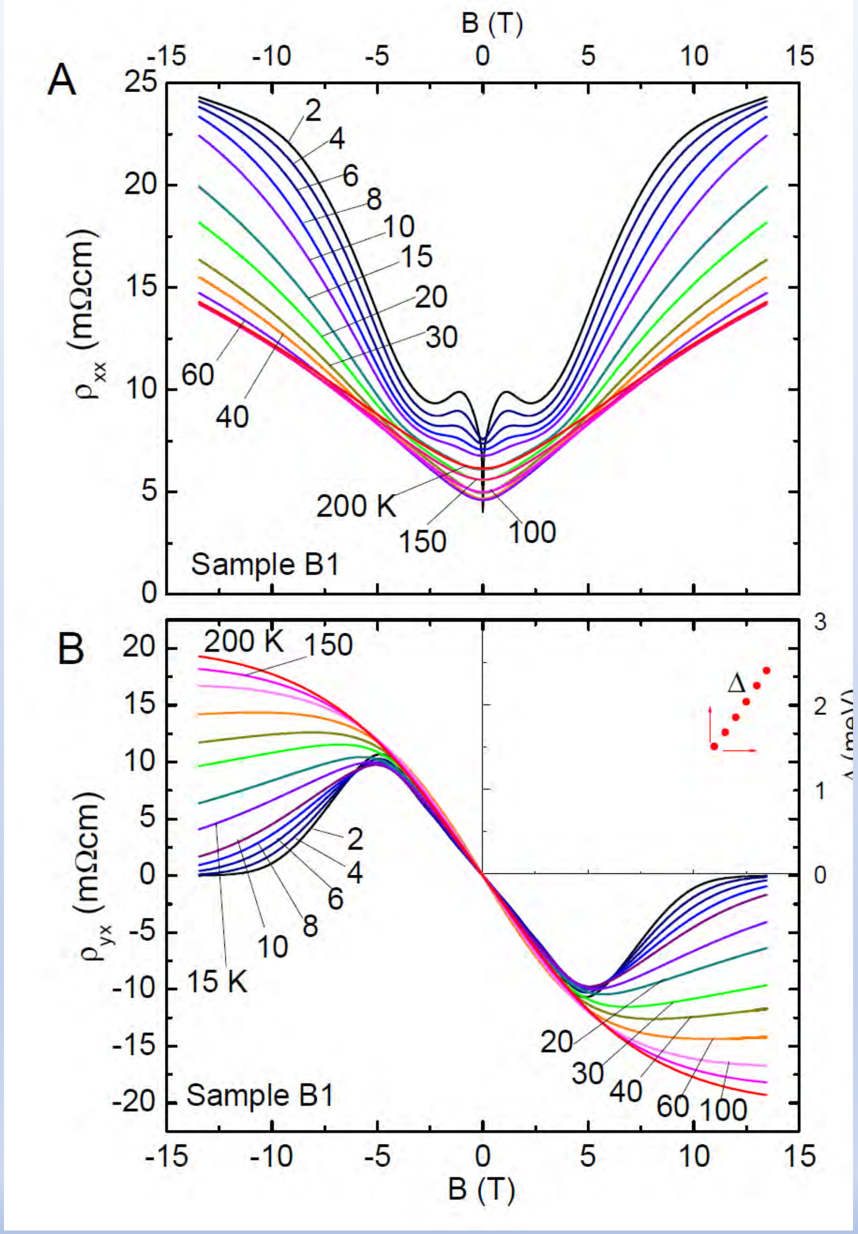
At lowest T (1.53 K), resistivity ϱ_{xx} tends towards saturation.
Hall resistivity ϱ_{yx} approaches zero exponentially.

tan θ_H and σ_{xy} decrease *exponentially* to zero as *B* incr.



Both quantities "stick" to zero over a large field interval.

Dope with bismuth to lower H_p= to 3 -- 4 Tesla

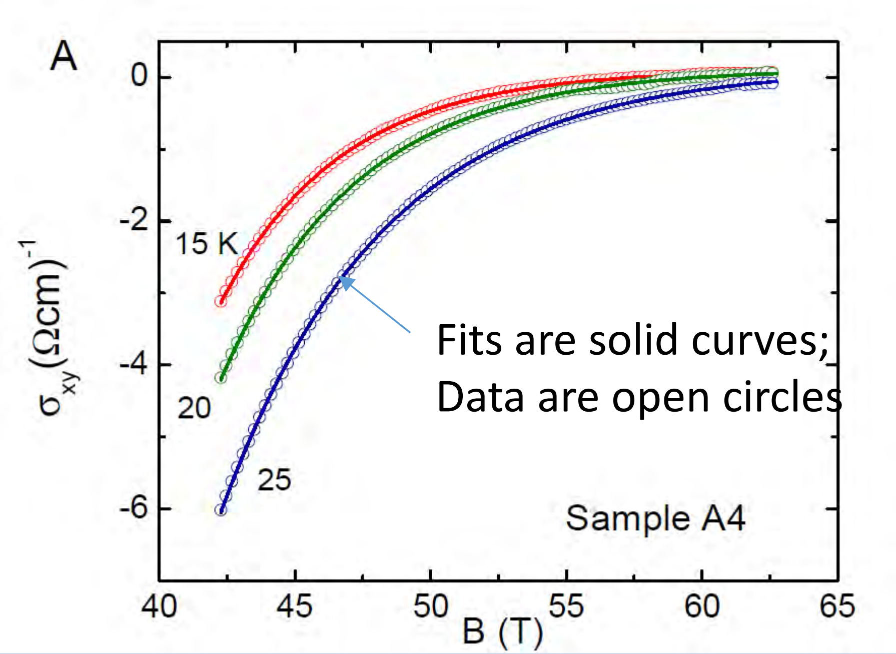


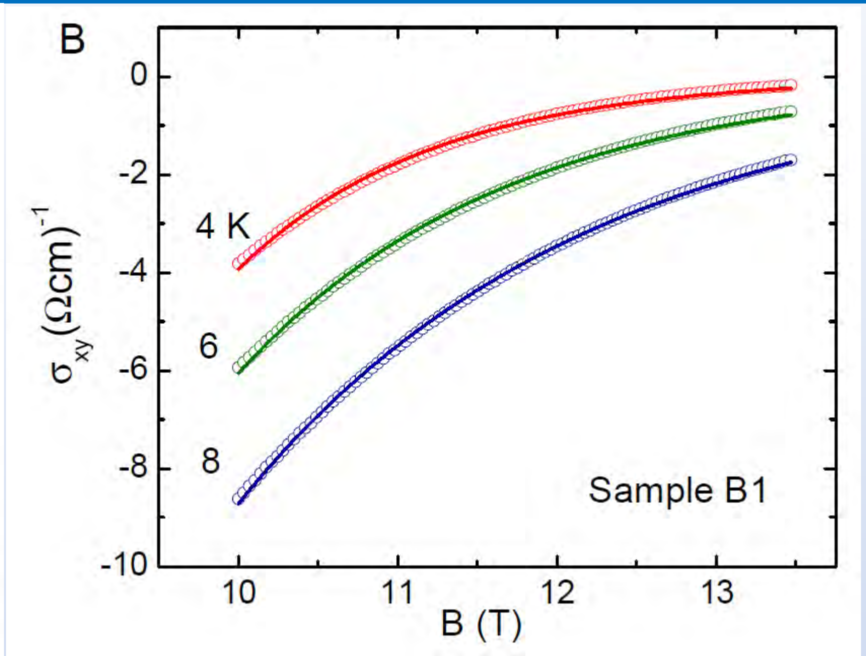
The zero-Hall state is intrinsic to lowest Landau level (LLL).

A large gap Δ separates LLL from excited state.

Δ is roughly linear in B

Fit σ_{xy} vs. *B* and *T* to obtain gap Δ vs *B*



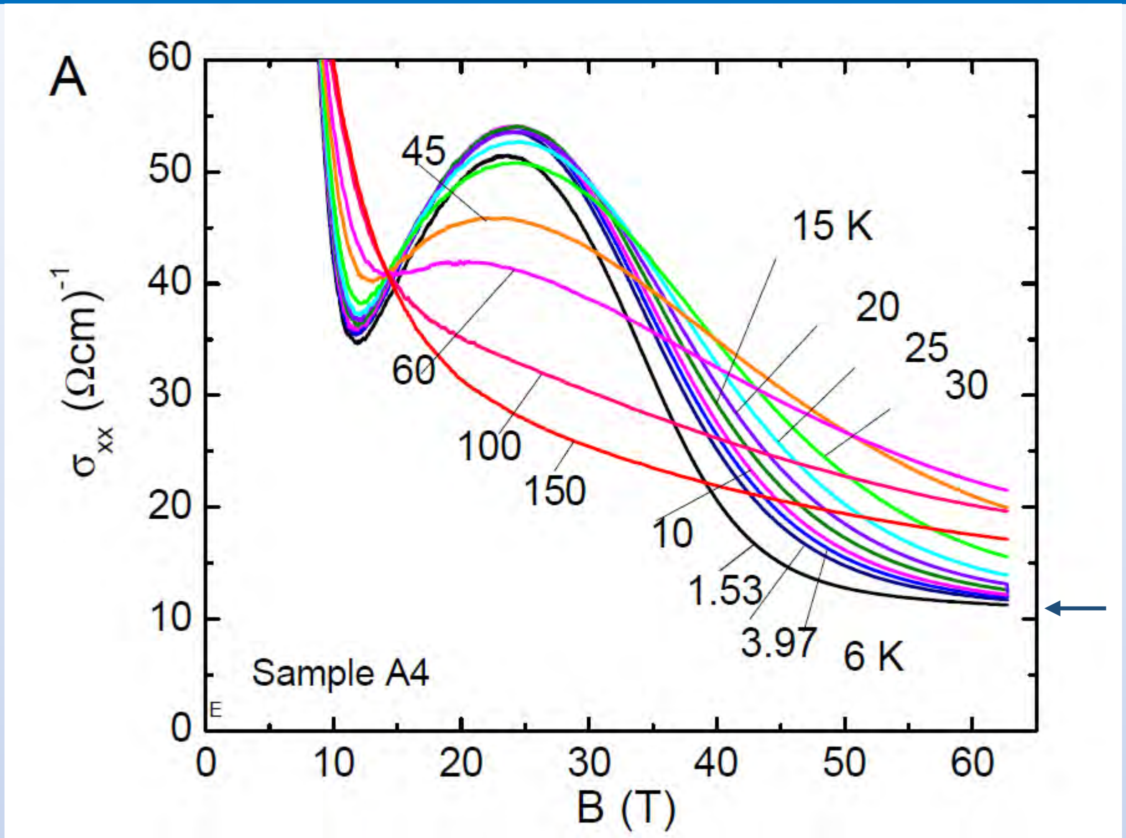


$$\sigma_{xy} = \sigma_{xy}^{(1)} \exp(-\Delta/_{kT}) + \sigma_{xy}^{(0)} \rightarrow 0$$

Gives good fits over broad range of *T* and *B*. Yields Δ at each *B*.

Existence of a gap is **incompatible** with gapless spectrum in 3D Landau states.

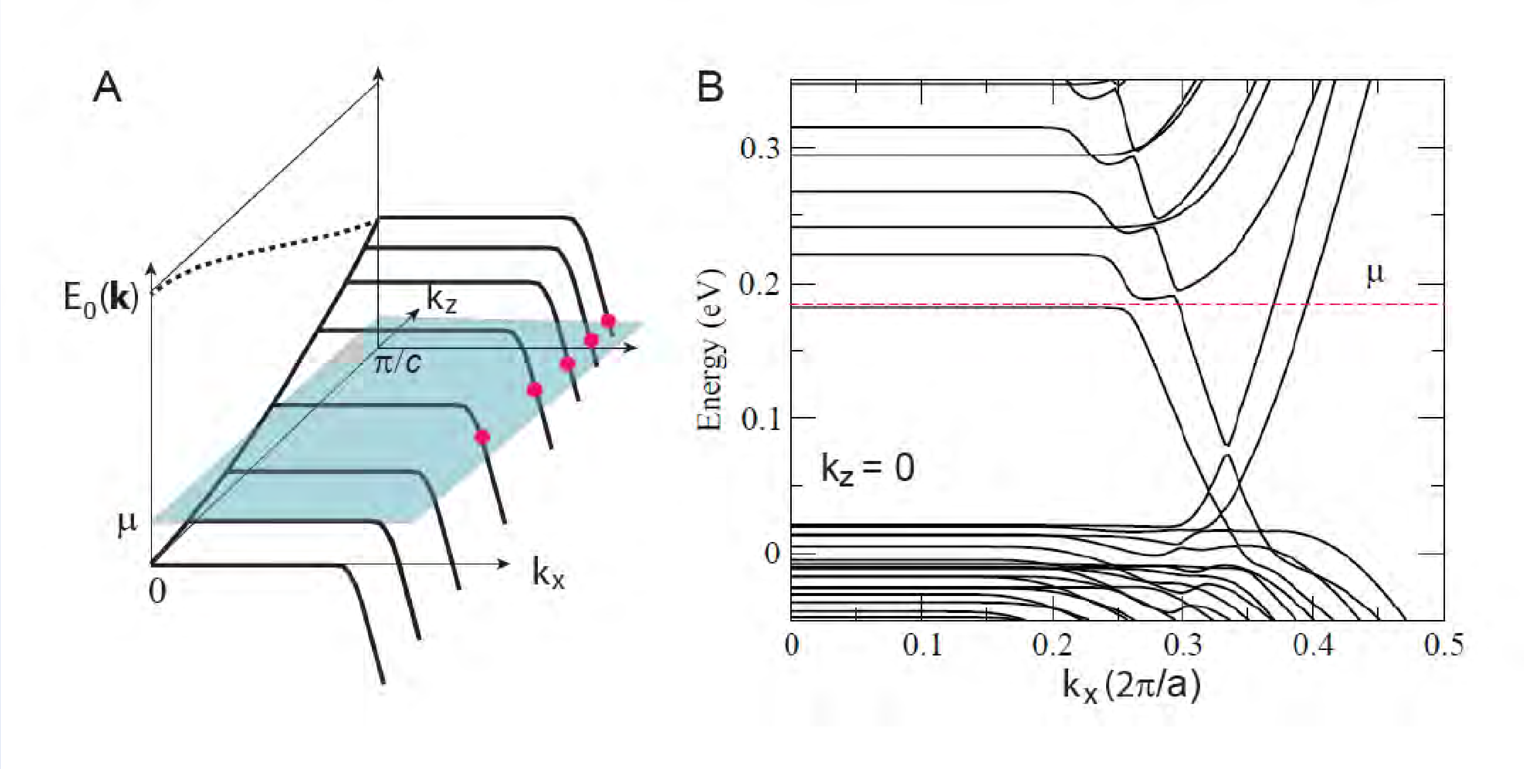
Longitudinal conductivity σ_{xx} remains finite



In high-field limit, σ_{xx} at 1.5 K is finite but small (~ 0.1 e^2/h per QSH mode)

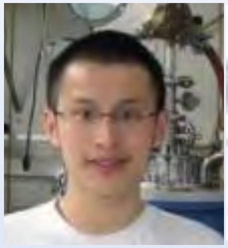
Gapped behavior is restricted to Hall response.

Ab initio calculation of Landau level spectrum in KHgSb



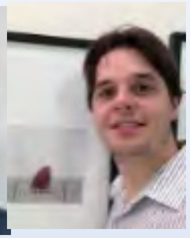
SPICE workshop, Mainz Jun 2017

The chiral anomaly in Dirac and Weyl Semimetals


Jun Xiong


Kushwaha


Tian Liang


Jason Krizan


Hirschberger


S.H. Liang


Bob Cava


NP Ong


Bernevig


Z.J. Wang

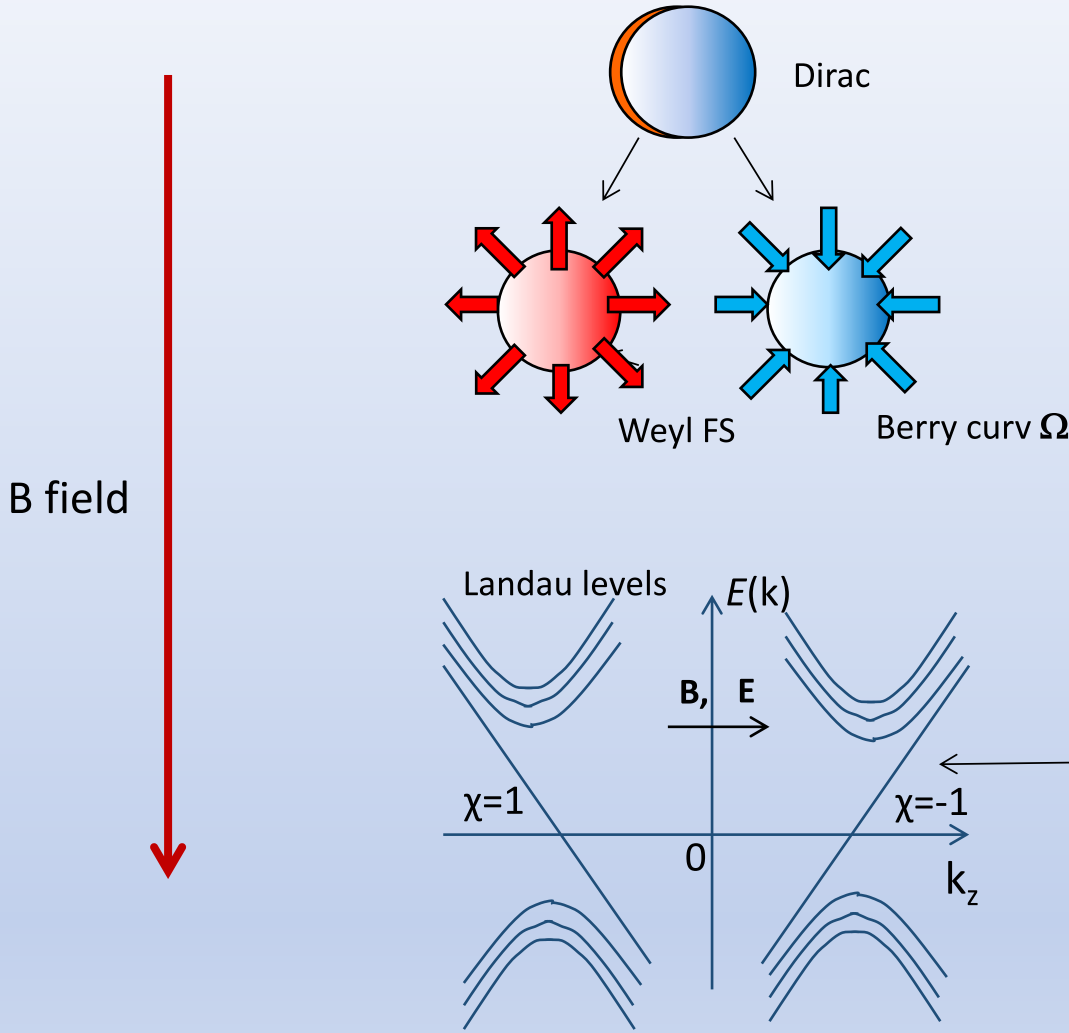
Jun Xiong, Tian Liang, Max Hirschberger, Sihang Liang, N. P. Ong
Department of Physics, Princeton Univ.
Satya Kushwaha, Jason Krizan, R. J. Cava
Department of Chemistry, Princeton Univ.

1. Review of the chiral anomaly in Na_3Bi and in GdPtBi
2. Current jetting? The squeeze test
3. Giant planar Hall effect and angular MR

1. Introduction to chiral anomaly
2. Dirac and Weyl states in Na_3Bi
3. The Chiral anomaly in Na_3Bi and in GdPtBi
4. Current jetting? The squeeze test
5. Nonsymmorphic semimetal KHgSb

Support from
Moore Foundation, ARO, NSF

Creation of Weyl states in applied magnetic field

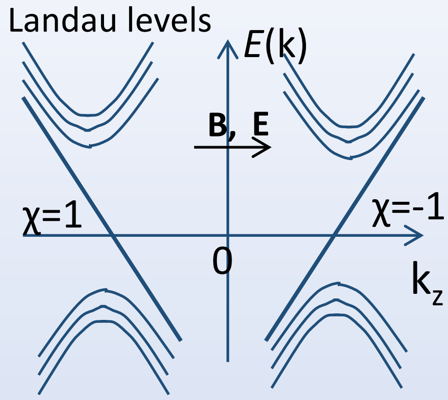


Lowest Landau level
Schwinger model

Detect axial current

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

Chiral anomaly



In strong **B**, the **chiral** lowest Landau levels (LLL) in a Weyl metal realizes the Schwinger model (sea of right-moving and left-moving massless fermions).

With **E** || **B**, we produce a large axial current, observed as negative LMR.

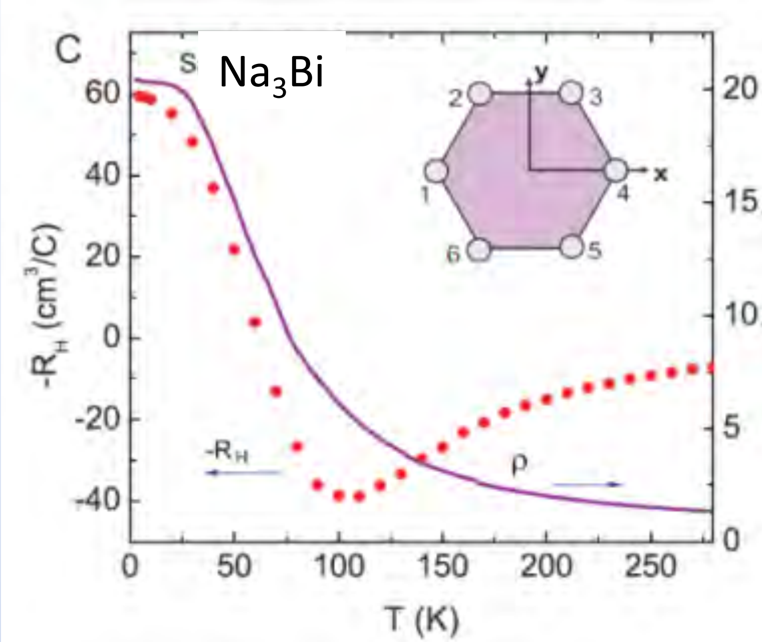
Similar to the Adler-Bell-Jackiw (triangle) anomaly in decay of neutral pions to photons $\pi^0 \longrightarrow 2\gamma$

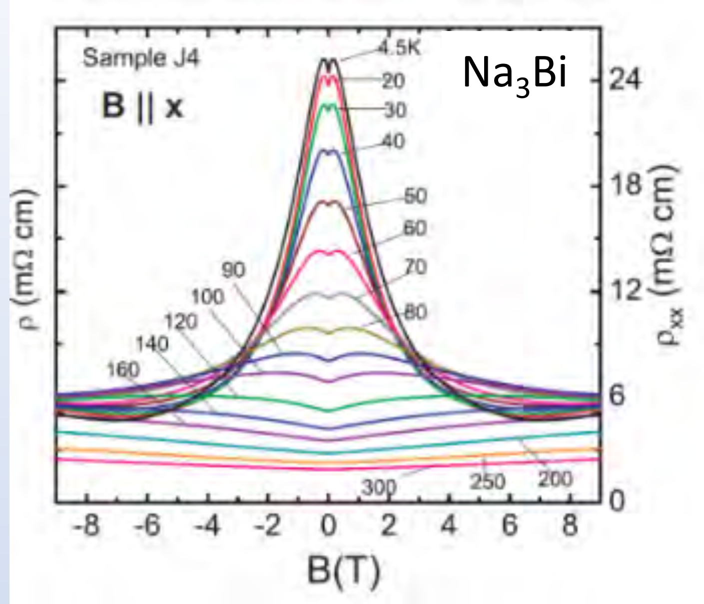
Presence of axial current alters

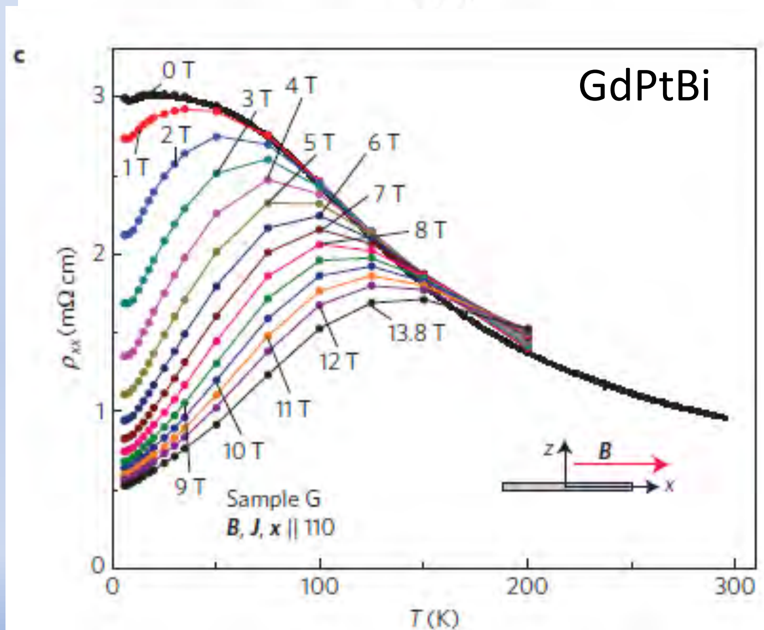
i) Longitudinal MR
ii) Thermoelectric response
iii) Hall effect

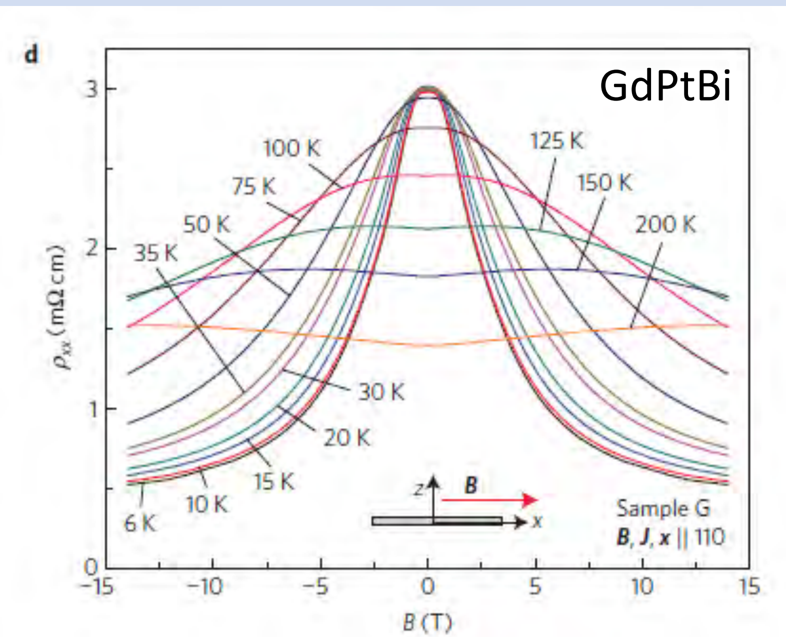
Observed in
Na_3Bi, Xiong *et al., Science* (2015)
GdPtBi, Hirschberger *et al*., *Nat. Mat*. (2016)
$ZrTe_5$, T. Valla *et al*. (BNL), *Nat. Phys*. (2016)

Resemblance between long. MR in Na_3Bi and GdPtBi

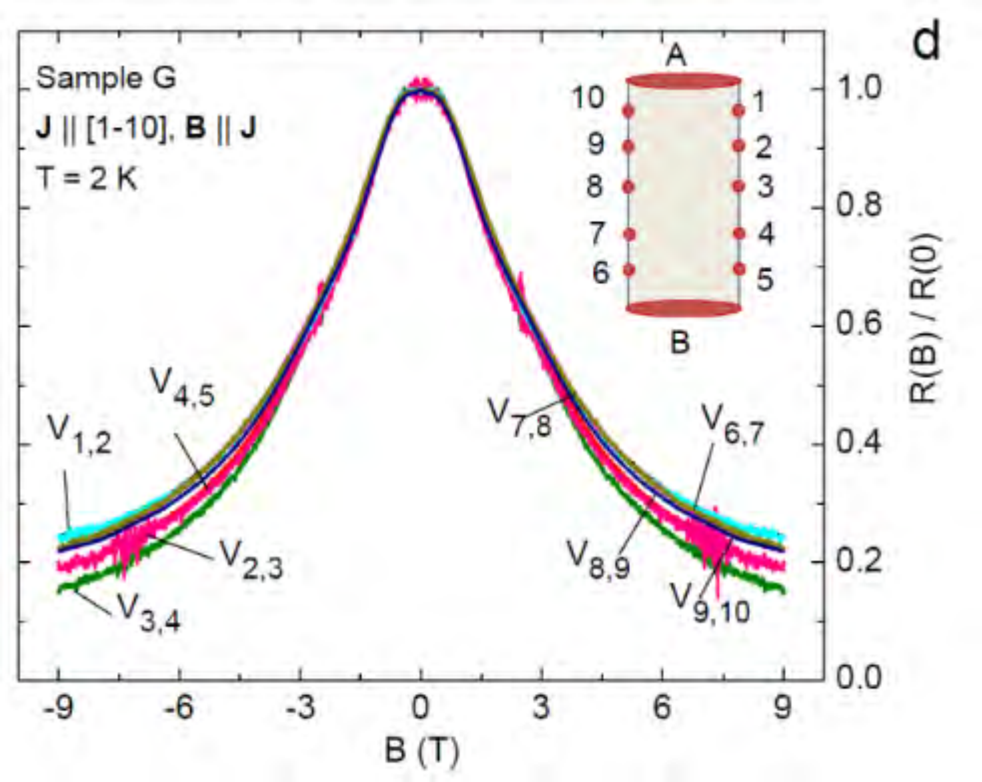


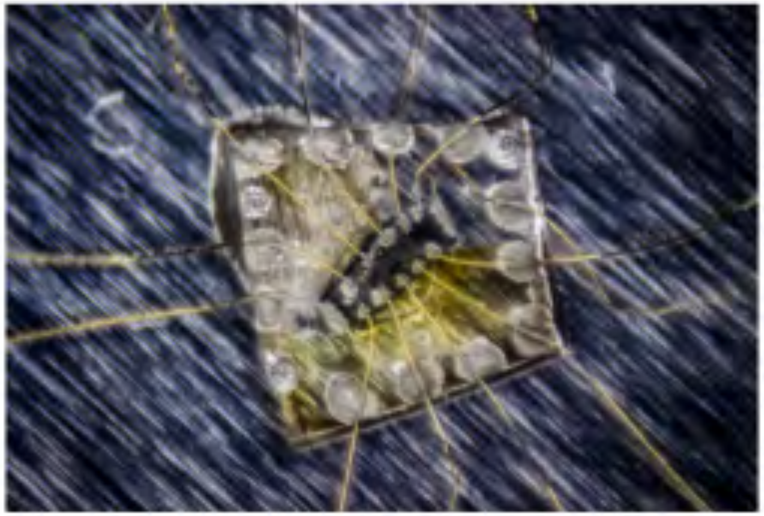






Check for uniformity of current density



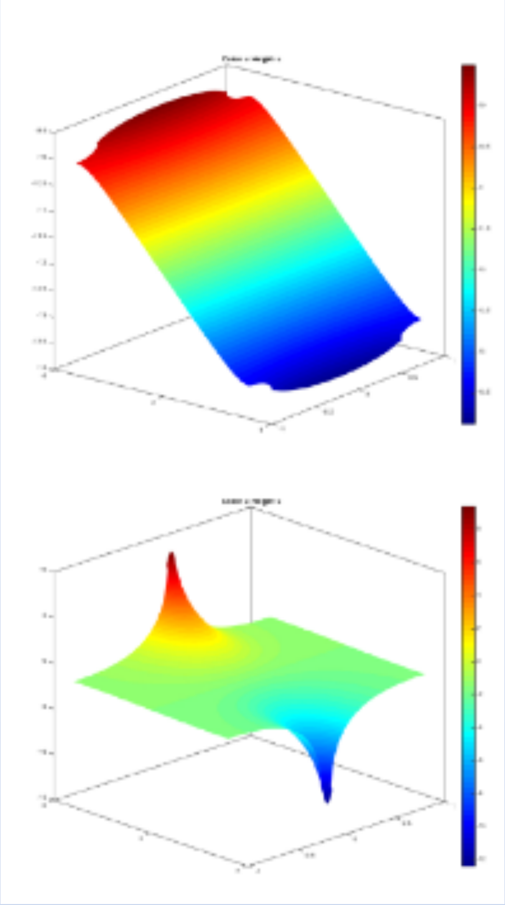


Repeat measmt. on Sample G with 10 voltage contacts
Longitud. MR profiles plotted as relative change are closely similar across all 8 nearest neighbor pairs of contacts

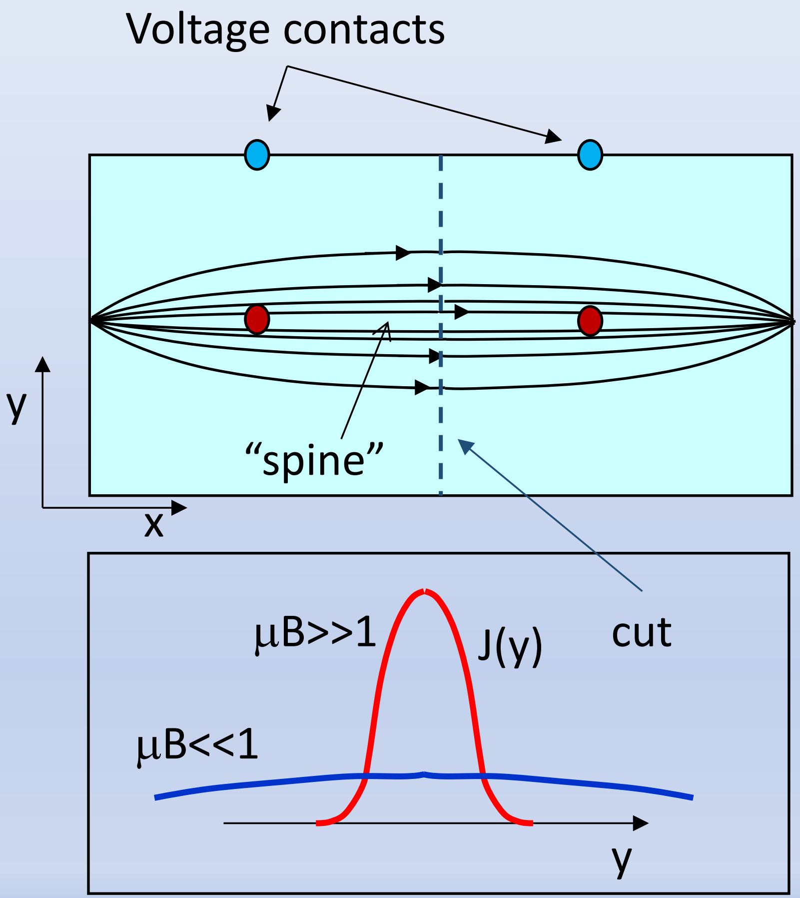
Conclusion: Negative longitude. MR is an intrinsic electronic effect, not a spurious result of inhomogeneity.

The “squeeze” test for current jetting

Chiral anomaly effect: Voltage decreases with B both along spine and side
Pure current jetting: Voltage decreases along side, but **increases** along spine



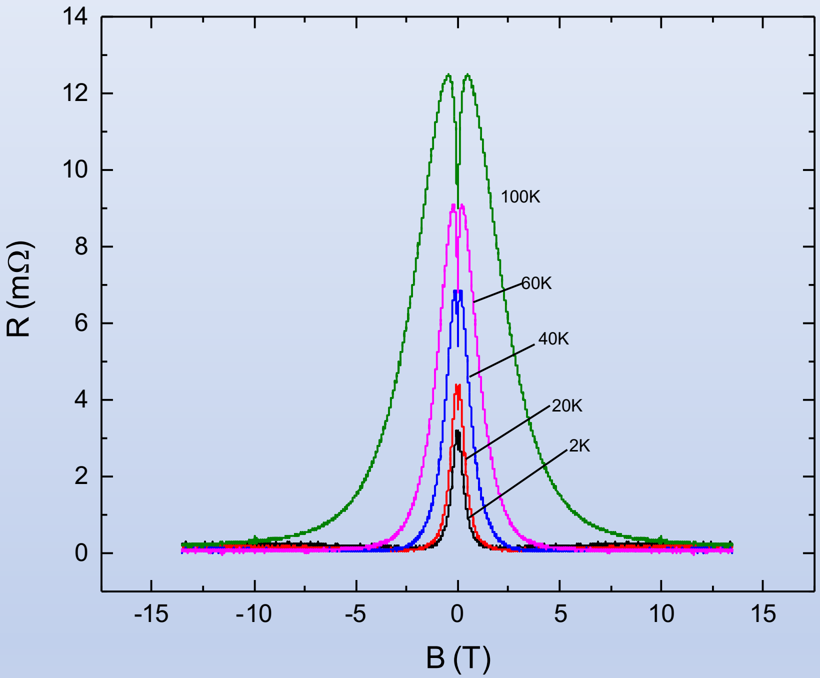
Extreme current jetting



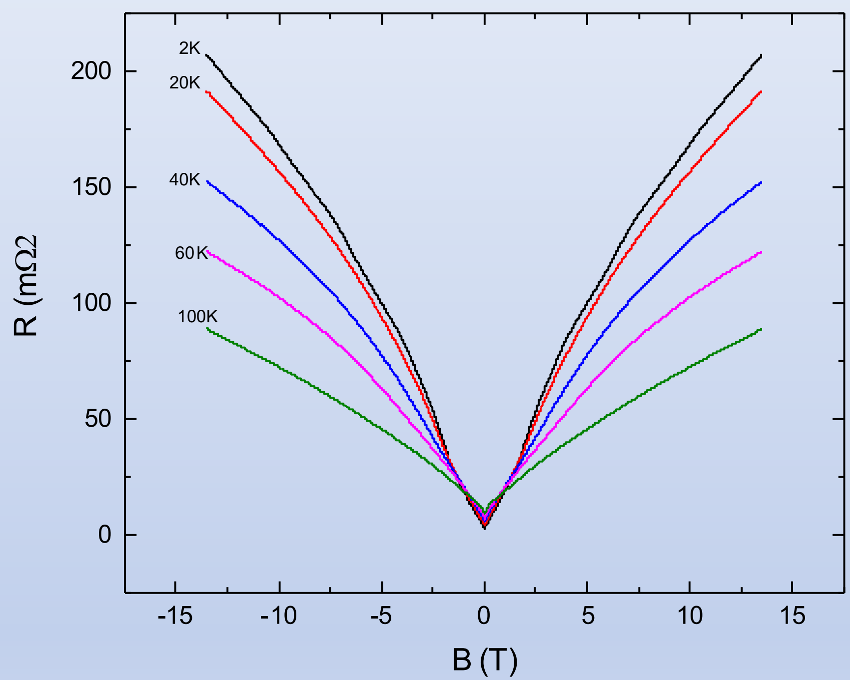
Pure bismuth

Apply squeeze test to high-purity elemental bismuth

Voltage contacts along the edge



Voltage contacts along the spine

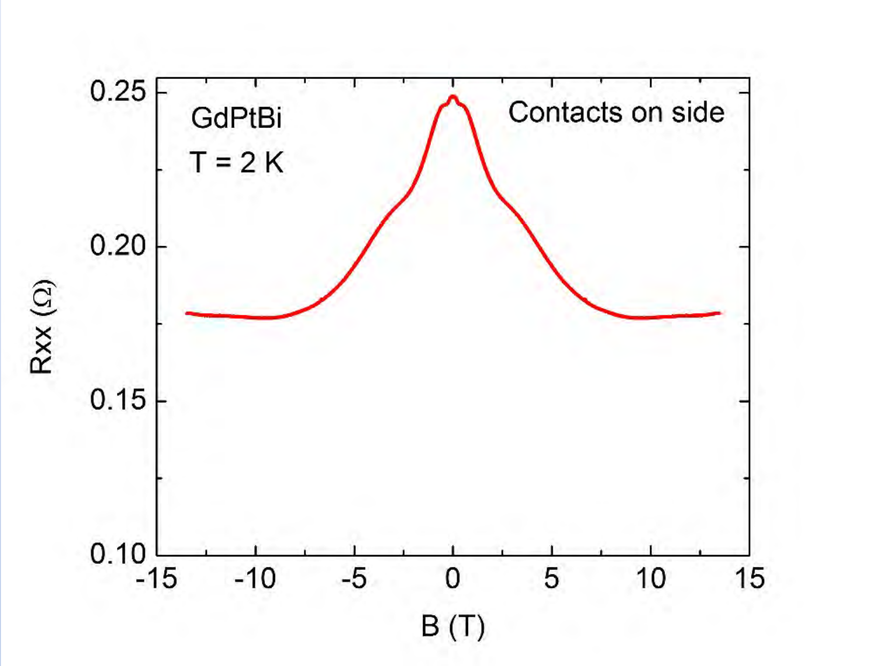


Negative LMR caused by extreme current jetting

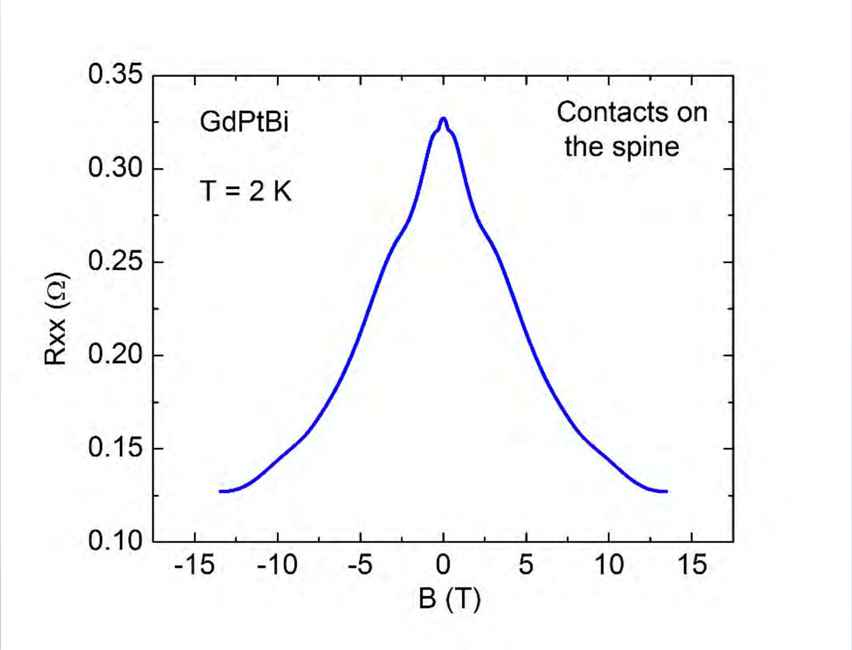
The “squeeze” test applied to GdPtBi

Compare MR measured with spine and edge contacts in GdPtBi

Voltage contacts along the edge



Voltage contacts along the spine



In GdPtBi, negative LMR is intrinsic and uniform
However, tests on TaAs and NbP fail (to date)

A new signature of chiral anomaly (A. Burkov)

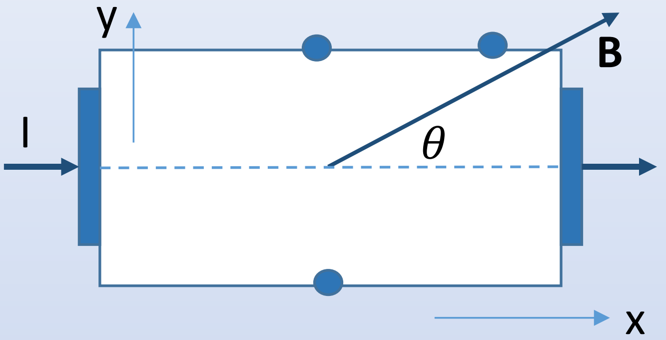
A. Burkov, arXiv:1704.05467

In presence of chiral anomaly, the chemical potential μ for electrons and the "chiral" chemical potential μ_c obey coupled diffusion equations (the chiral charge n_c decays with lifetime τ).

CME current

$$D\nabla^2\mu + \Gamma\mathbf{B}\cdot\nabla\mu_c = 0$$

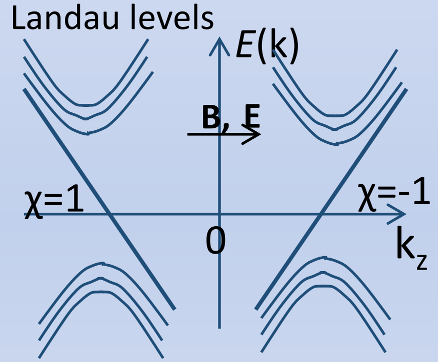
$$D\nabla^2\mu_c + \Gamma\mathbf{B}\cdot\nabla\mu = \mu_c/\tau$$



In a rectangular sample, this leads to an angular magnetoresistance and a giant planar Hall effect.

$$\boxed{\begin{aligned}\rho_{xx} &= \rho_\perp - \Delta\rho\cos^2\theta \\ \rho_{yx} &= -\Delta\rho\sin\theta.\cos\theta,\end{aligned}}$$

$$\Delta\rho = \rho_\perp - \rho_\parallel$$



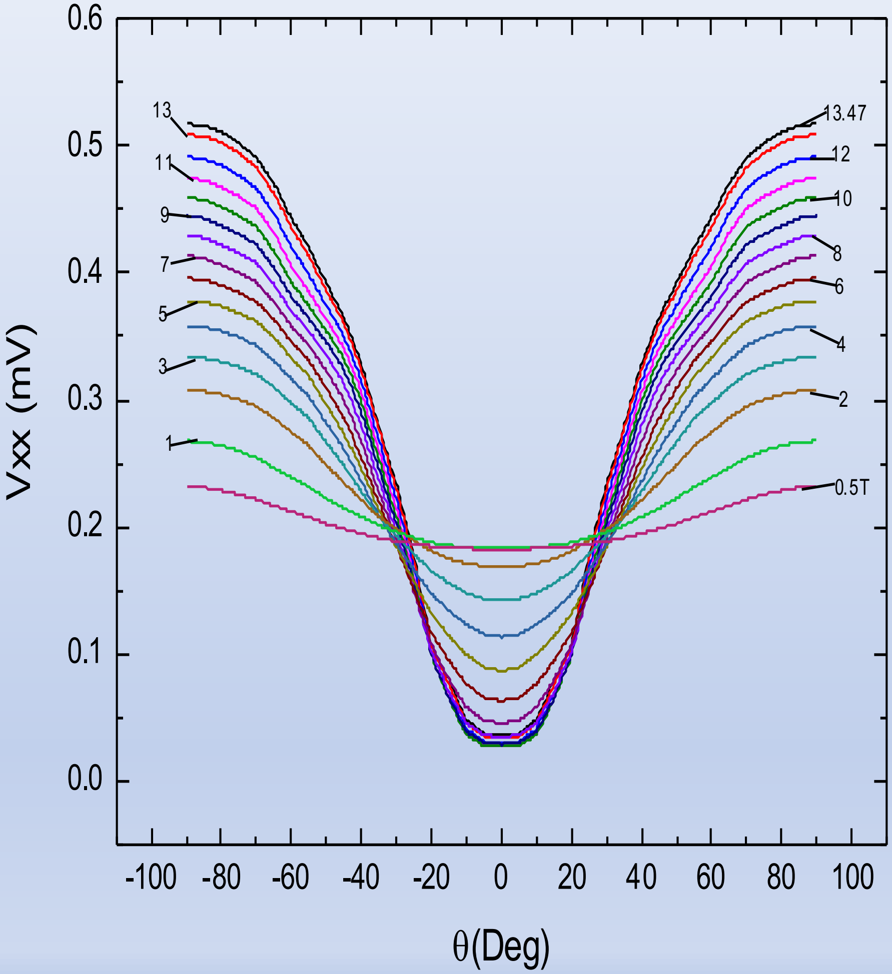
Angular Magnetoresistance in Na_3Bi

Sihang Liang, *unpubl*.

Longitudinal voltage has a $\cos^2\theta$ dependence

$$\rho_{xx} = \rho_{\perp} - \Delta\rho\cos^2\theta$$

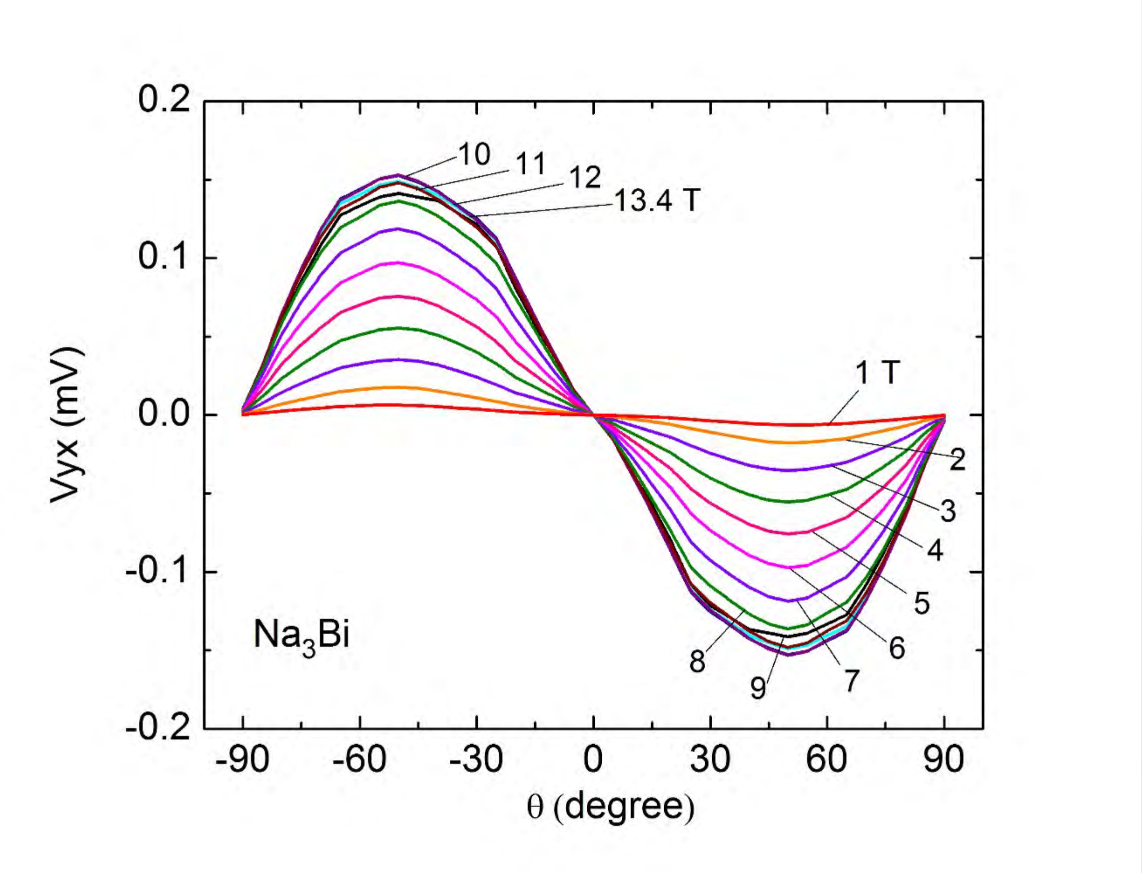
Also seen in GdPtBi



Giant planar Hall effect in Na_3Bi

Transverse voltage displays a component that is $\sin 2\theta$ and symmetric in *B*

$$\rho_{yx} = -\Delta\rho \sin\theta . \cos\theta,$$



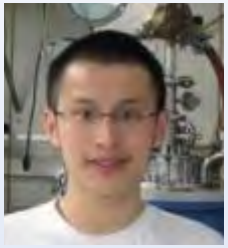
Summary

Zero-Hall state in system with glide protection

- In lowest Landau level (LLL), Hall response approaches zero exponentially in *B* and *T*
- Fits yield a *B*-dependent gap Δ protecting zero-Hall ground state
- Zero-Hall state is intrinsic to LLL (from doping study)
- Longitudinal conductance remains finite (~ 0.1 of surface mode conductance)

Chiral anomaly

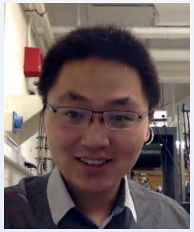
- Observed in Na_3Bi and GdPtBi
- Squeeze test rules out current jetting
- Giant planar Hall effect -- a new signature of the anomaly



Jun Xiong

S.H. Liang

S. Kushwaha



T. Gao

M. Hirschberger

Z.J. Wang

Bernevig

Bob Cava

NP Ong

Thank you