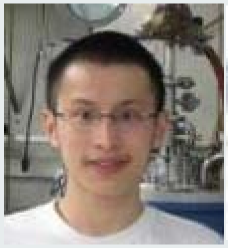
Talk 1: Boulder Summer School, July 2016

Dirac and Weyl Semimetals and the chiral anomaly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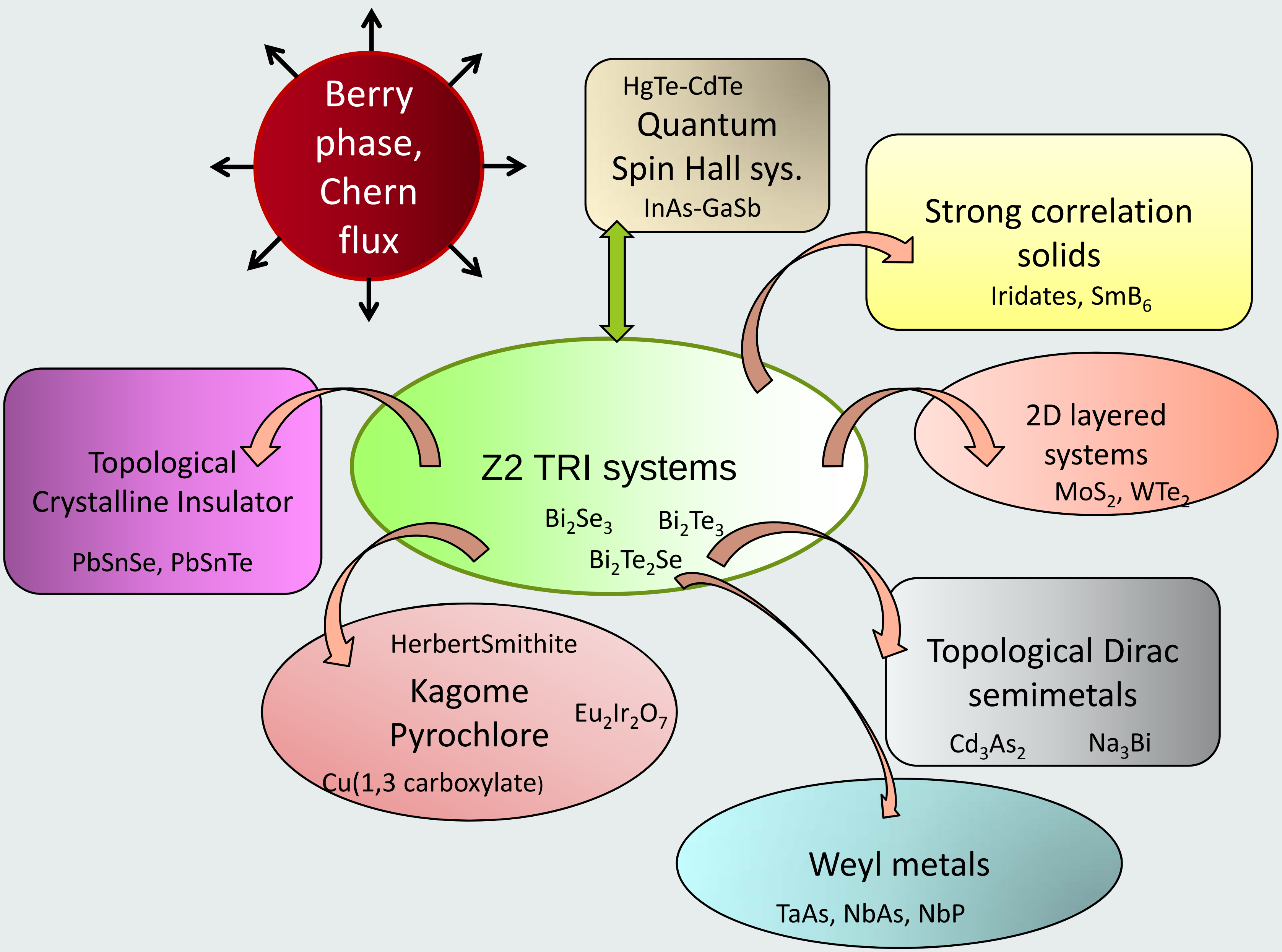
1. Introduction protected Dirac nodes in (3+1)D
2. Dirac and Weyl states in Na_3Bi
3. The Chiral anomaly
4. Charge pumping in Na_3Bi
5. An axial current plume

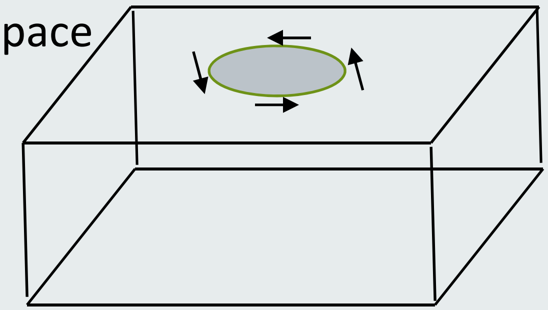
GORDON AND BETTY MOORE FOUNDATION

Support from
Moore Foundation, ARO, NSF

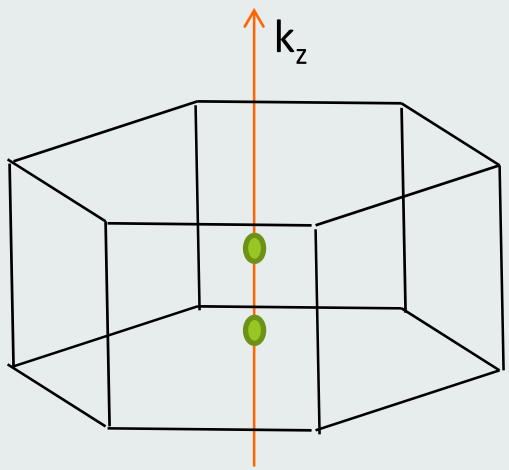
Topological Matter Cornucopia



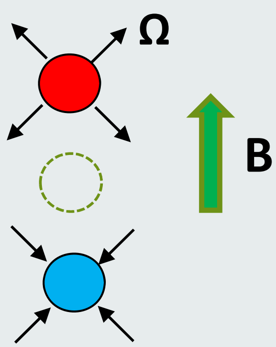
2D and 3D Topological Matter



Topological Insulator
2D Spin-locked states on surface
Bulk insulating
Bi_2Se_3, Bi_2Te_3, Bi_2Te_2Se …

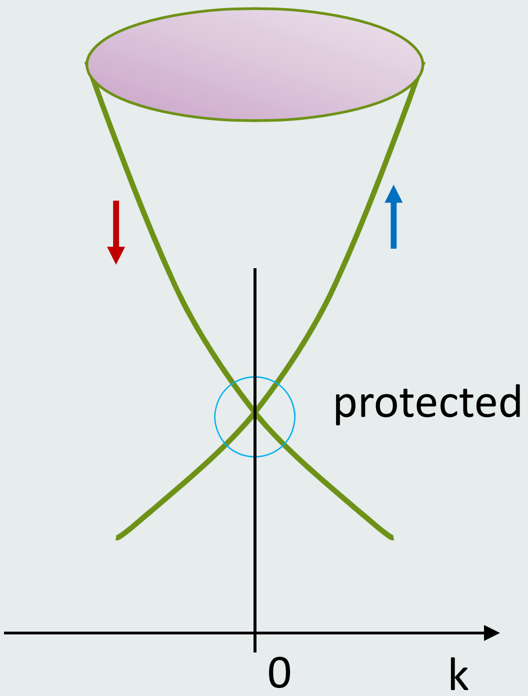


Topological Dirac semimetal
Bulk Dirac states are conducting
3D protected nodes on symmetry axis
Each Dirac node is comprised of 2 Weyls
Na_3Bi, Cd_3As_2



Weyl nodes
In applied **B**, Weyl nodes move apart. Act as monopole source and sink of Berry curvature **Ω** (an eff. magnetic field in **k** space).

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



Kramer's theorem

H is 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 must be orthogonal (hence 2-fold degenerate)

Slight generalization

$$M = (\varphi, V\psi) = 0$$

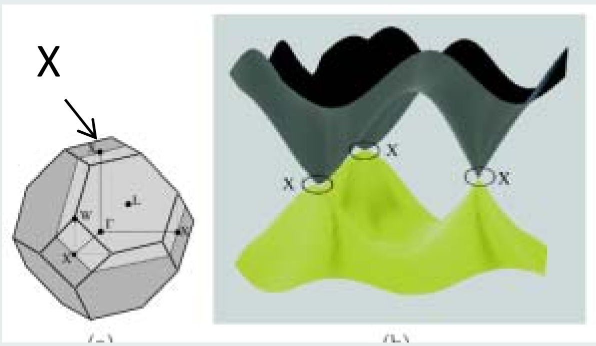
All matrix elements of TRS potentials *V* must vanish.
Therefore, node is protected against gap formation.

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

Kane Mele

Dirac Semimetal in Three Dimensions

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



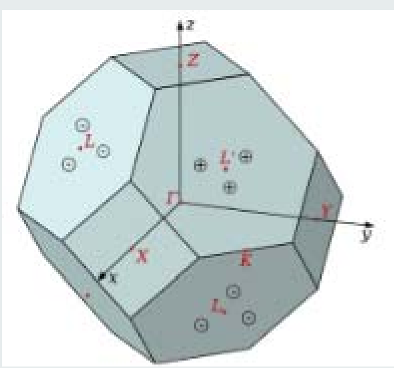
Time reversal symmetry (TRS) *and* Inversion symmetry (IS) protect a Dirac node if it is pinned at zone corner *X*

Candidate: β cristobalite BiO_2
(unfortunately, chem. unstable)

Vishwanath

Topological semimetal and Fermi-arc surface states in pyrochlore iridates

Wan, Turner, Vishwanath and Savrasov, PRB 2011

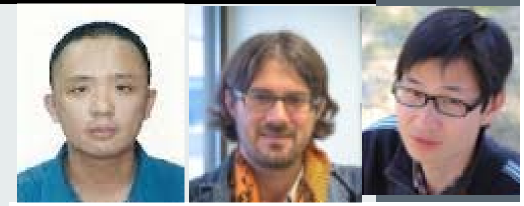


Predicted $Y_2Ir_2O_7$ should exhibit multiple **Weyl** nodes

Experimental progress has been slow

Na3Bi and Cd3As2 are topological Dirac semimetals

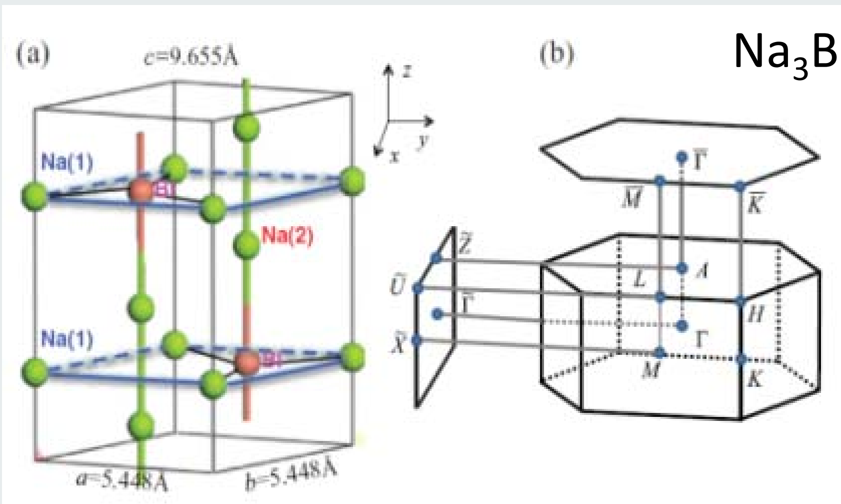
The key: Add *point-group symmetry* C_n to TRS and IS! (Bernevig, XiDai)

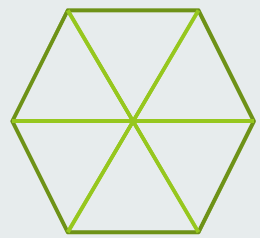


XiDai Bernevig Z. Wang

Called *Topological* Dirac Semimetal

Na_3Bi and Cd_3As_2 (Wang *et al.*)





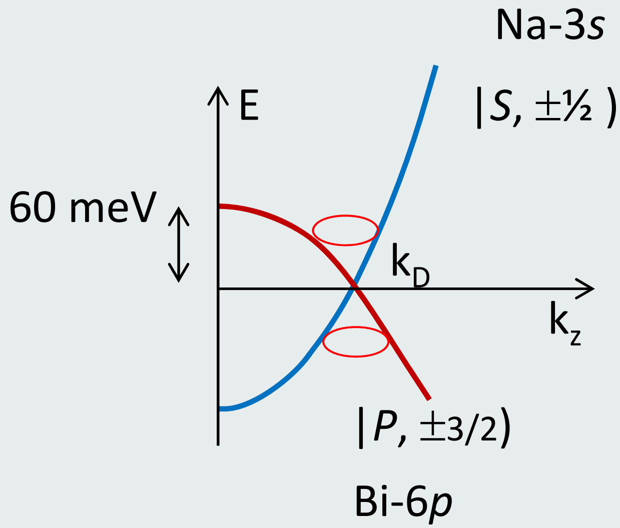
C_3

Zhijun Wang, Xi Dai et al, PRB 2012

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

Sparked massive renewed interest in search for the chiral anomaly

The band structure of Na_3Bi (Wang, Dai, Fang et al. *PRB* 2012)

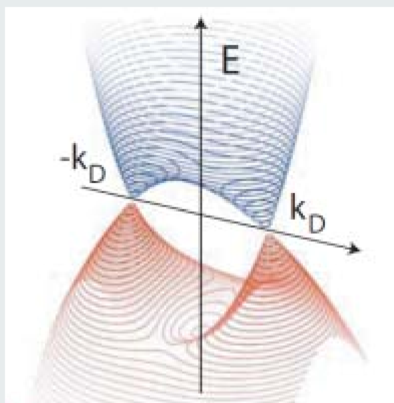


Only 2 bands, derived from Na-3*s* and Bi-6*p*, lie near Fermi energy.

Spin orbit interaction leads to crossings at $\mathbf{K}_{\pm} = (0, 0, \pm k_D)$

Crossings protected against gap formation --- |S) and |P) states belong to different irreducible representations of C_3.

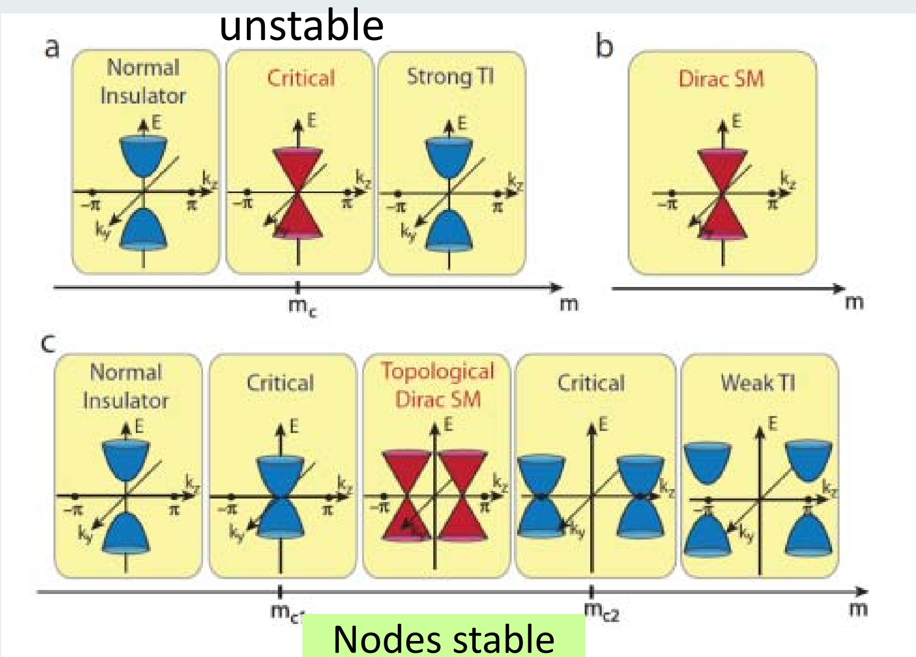
We end up with 2 Dirac nodes centered at $\mathbf{K}_{\pm}$

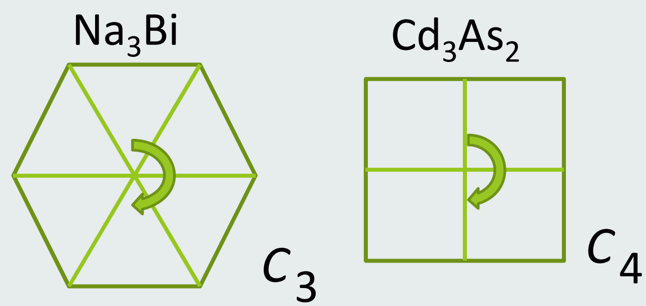


Dirac node protection by Point-Group Symmetry

Wan, Turner, Vishwanath, Savrasov, *PRB* 2011
Young, Kane, Mele et al. *PRL* 2012
Wang, Dai et al., *PRB* 2012
Fang, Gilbert, Dai, Bernevig, *PRL* 2012

B.J. Yang and N. Nagaosa, Nat Comm.2014



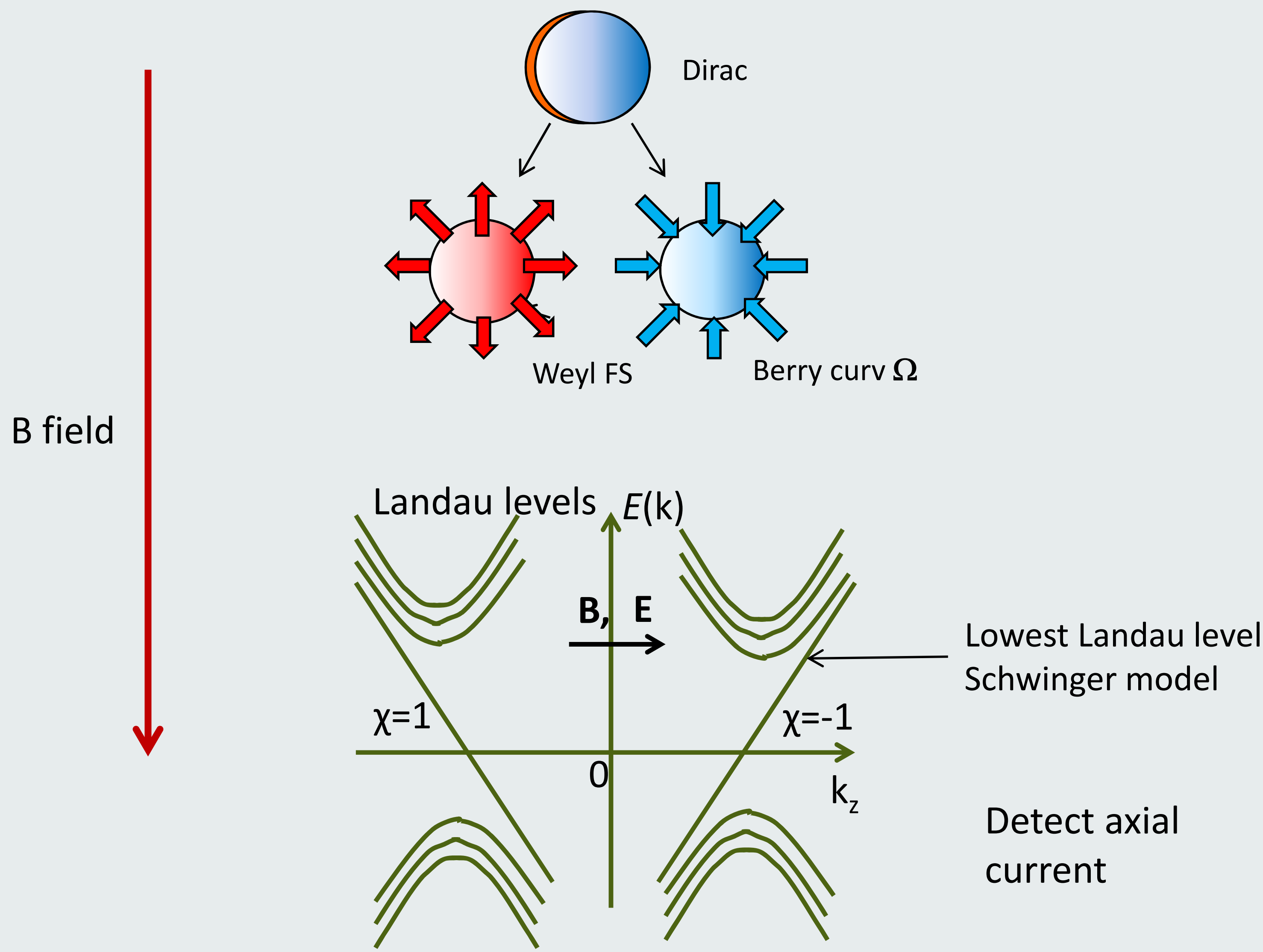


Two Cases

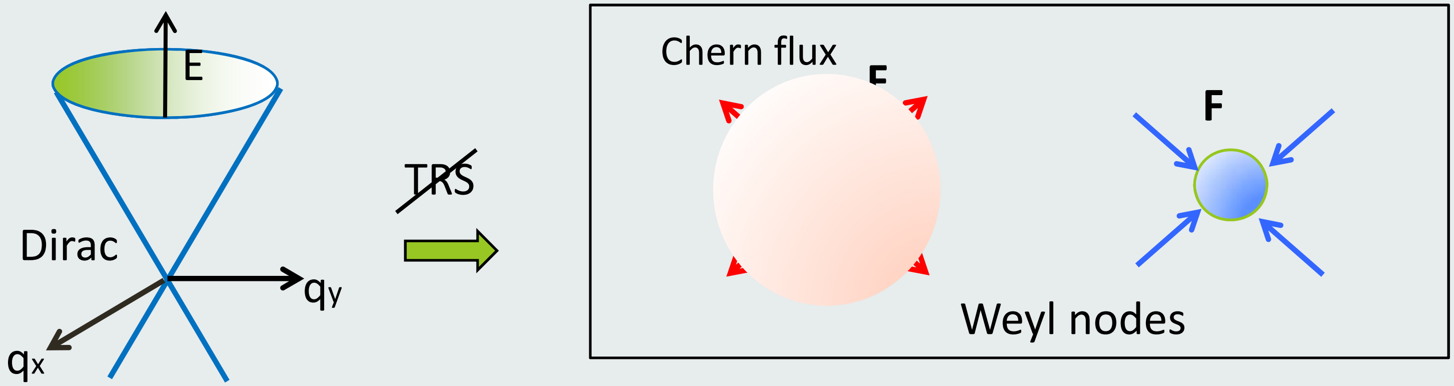
1. Dirac node is protected by TRS and IS if *pinned* to zone corners (non-symorphic case; has glide planes or screw axes).

2. Inclusion of point-group symmetry C_n extends protection to *anywhere* on symmetry axis (topological Dirac semimetal).

Creation of Weyl states in applied magnetic field



Berry curvature of Weyl nodes



$$\mathbf{A} = -i\langle u_{\mathbf{k}}|\nabla_{\mathbf{k}}|u_{\mathbf{k}}\rangle$$

Berry curvature $$\mathbf{\Omega}(\mathbf{k}) = \nabla \times \mathbf{A}(\mathbf{k})$$

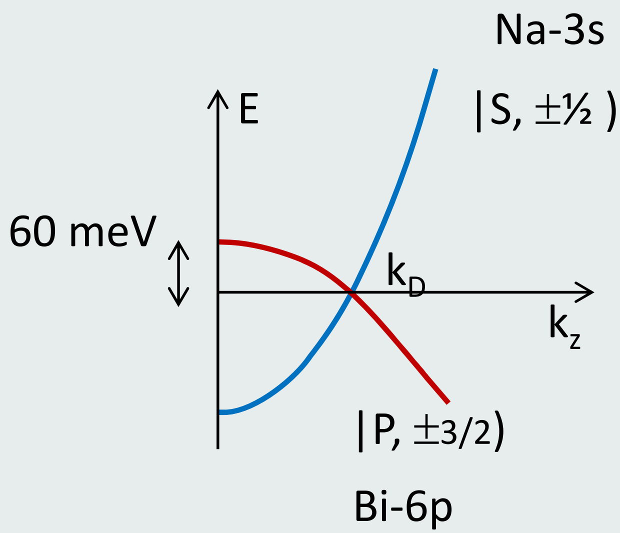
Chirality $$\chi = \frac{1}{2\pi}\oint \mathbf{\Omega}\cdot \mathbf{dS}(\mathbf{k})$$

Proposed (2011) existence of Weyl nodes in iridates (Vishwanath et al.) reawakened strong interest in the Nielsen Ninomiya prediction.

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

… and 80+ theory uploads on arXiv

The band structure of Na_3Bi (Wang, Dai, Fang et al. *PRB* 2012)

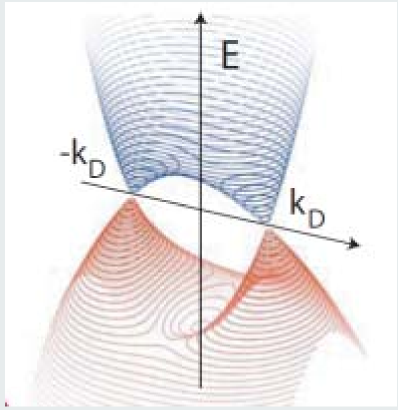


Only 2 bands, derived from Na-3*s* and Bi-6*p*, lie near Fermi energy.

Large spin-orbit coupling (SOC) leads to band crossing at $\mathbf{K}_{\pm} = (0, 0, \pm k_D)$

Crossings protected against gap formation --- |S) and |P) states belong to different irreducible representations of C_3.

We end up with 2 Dirac nodes centered at $\mathbf{K}_{\pm}$

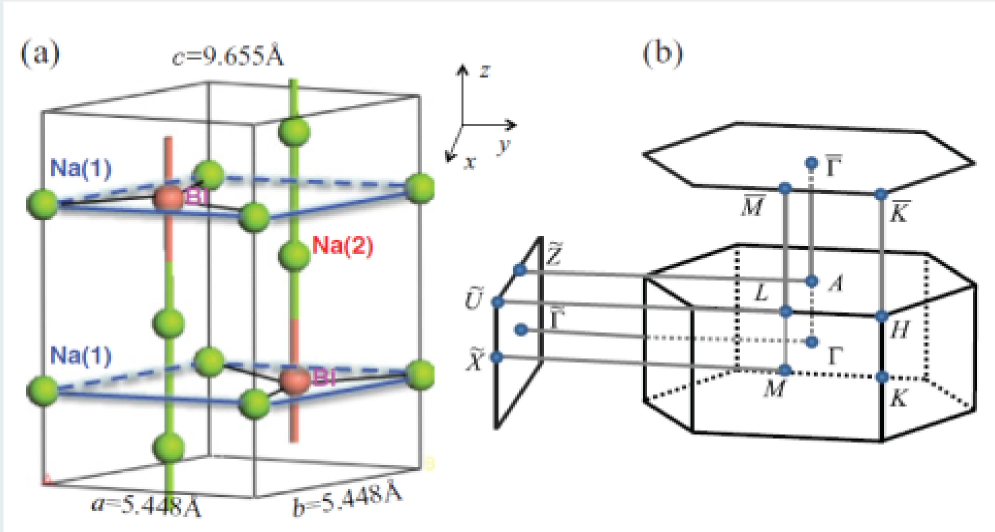


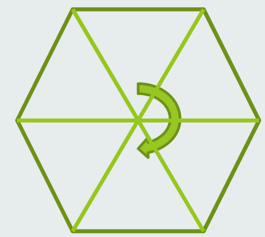
Protected Dirac nodes in semimetal Na_3Bi

Identified by Wang, Dai, Fang et al. *PRB* 2012
Wang, Dai, Fang et al. *PRB* 2013

Inst. of Physics

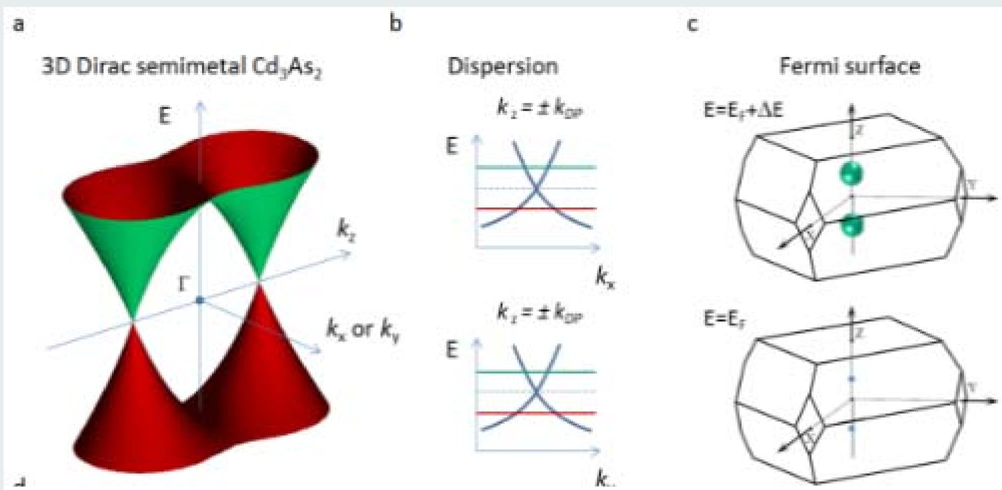
Na_3Bi

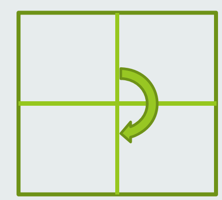




C_3

Cd_3AS_2

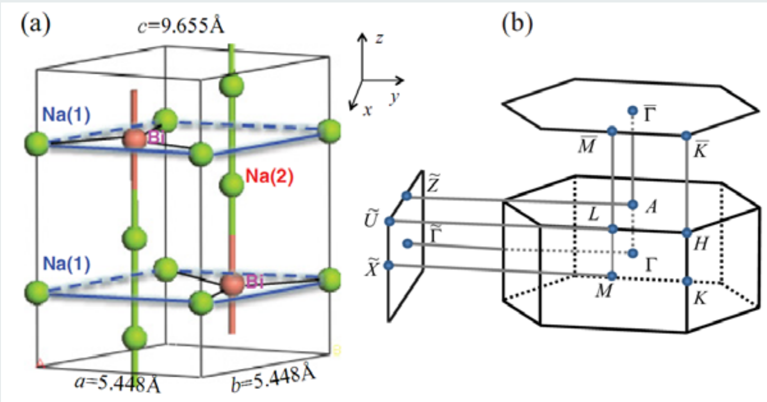


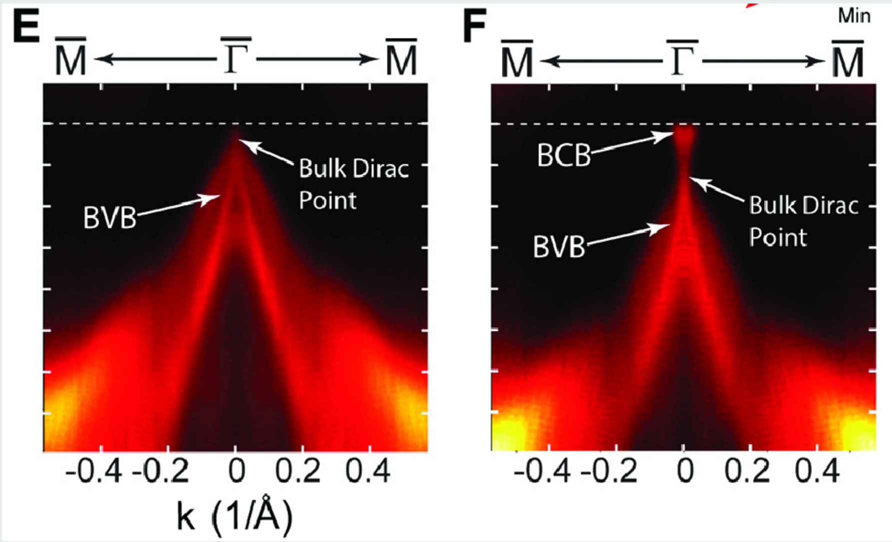


C_4

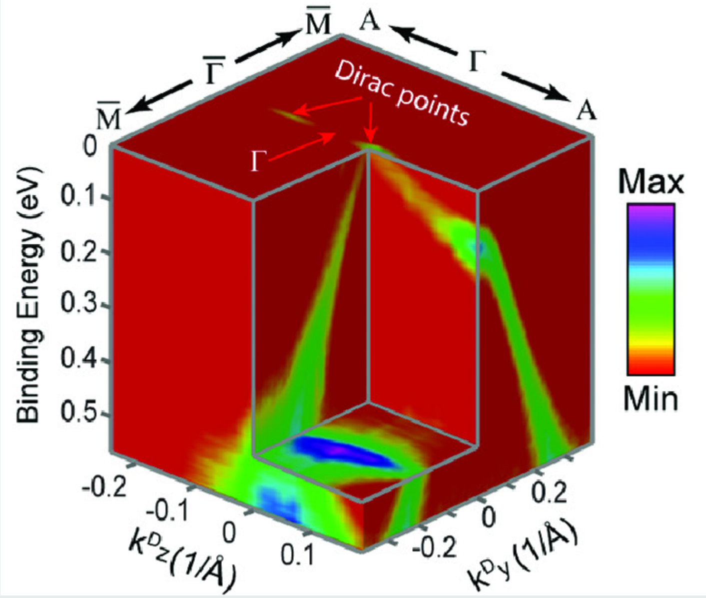
Photoemission on Na_3Bi and Cd_3As_2

Point group C3





Liu, Chen *et al*, *Science* 2014
Neupane, Hasan et al., *Nat Comm.* 2014
Borisenko, Cava et al., *PRL* 2014



$V_x \approx V_y = 3.74 \times 10^5$ m/s, $V_z = 2.89 \times 10^4$ m/s

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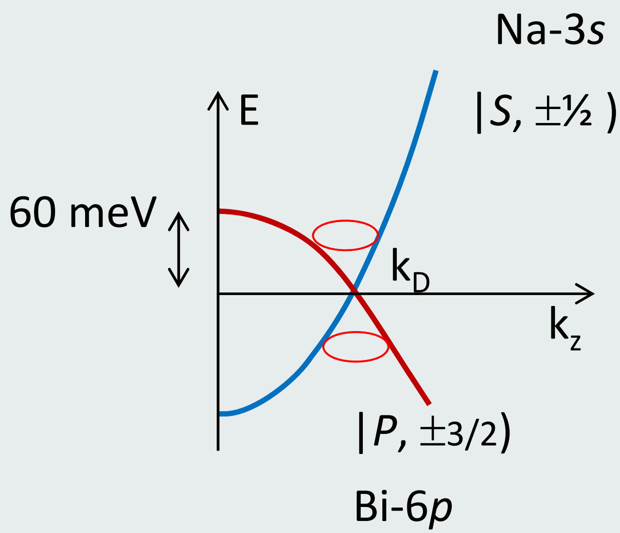

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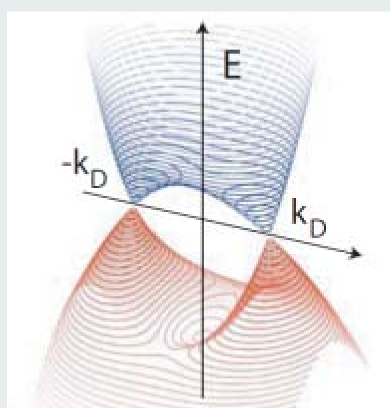


Dirac Equation and Weyl states

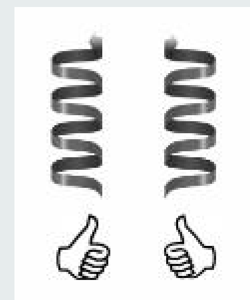
Herman Weyl

Dirac equation $(i\gamma^{\mu}\partial_{\mu} + m)\Psi = 0$

Weyl representn

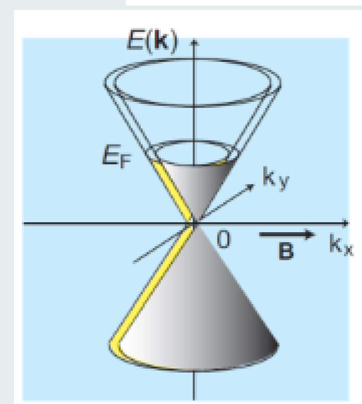
$\Psi_R = \frac{1}{2}(1+\gamma^5)\Psi \qquad \Psi_L = \frac{1}{2}(1-\gamma^5)\Psi$

$$L = \bar{\Psi}_L\, i\gamma^{\mu}\partial_{\mu}\Psi_L + \bar{\Psi}_R\, i\gamma^{\mu}\partial_{\mu}\Psi_R$$



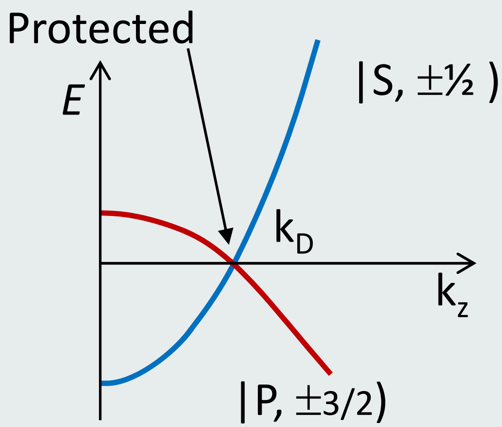
If $m = 0$, the Dirac Hamiltonian describes two massless populations.

$$H = \begin{bmatrix} H_+ & 0 \\ 0 & H_- \end{bmatrix}$$



i) Each has permanent handedness (chirality = ± 1)
ii) Opposites do not mix (chiral symmetry holds)

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



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

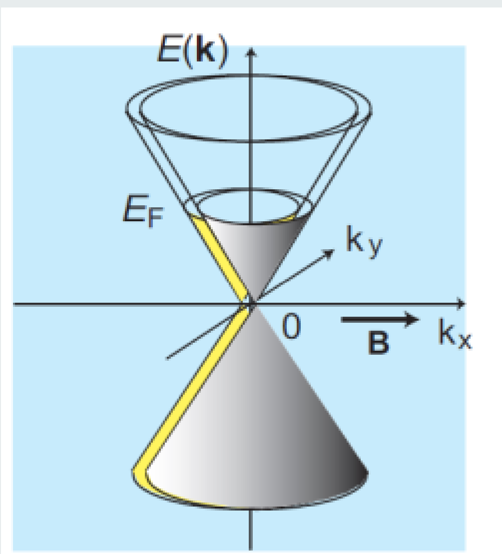
$$H = v\begin{bmatrix} k_z & k_+ & 0 & 0 \\ k_- & -k_z & 0 & 0 \\ 0 & 0 & k_z & -k_- \\ 0 & 0 & -k_+ & -k_z \end{bmatrix} \quad \begin{pmatrix} S, ½ \\ P, 3/2 \\ S, -½ \\ P, -3/2 \end{pmatrix}$$

H resolves into two 2x2 Weyl Hamiltonians H_1, H_2

Calculate chirality from velocity matrix $\tilde{v}$

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

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



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

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

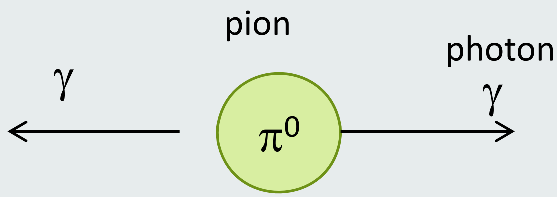
We have a superposition of two Weyl nodes at *B* = 0

1. Introduction protected Dirac nodes in 3D
2. Dirac and Weyl states in Na_3Bi
3. The Chiral anomaly
4. Charge pumping in Na_3Bi
5. An axial current plume

The Adler Bell Jackiw (or chiral, axial) anomaly

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

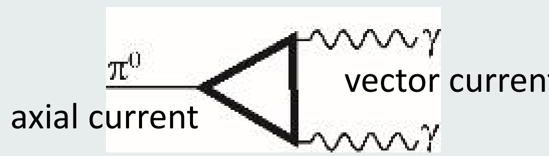
First appeared in pion decay -- discrepancy of 300 million between neutral and charged pions



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 (3x10^8 faster!)

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



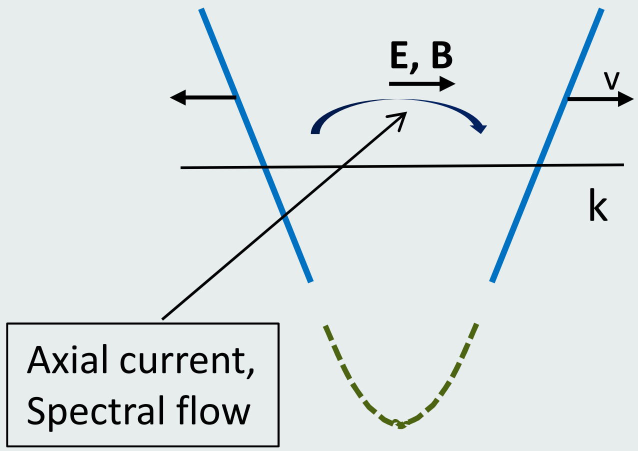
Adler Bell Jackiw anomaly

(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*

Landau quantized



Adler Bell Jackiw anomaly

$$A = \frac{e^2}{16\pi^2}\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu}F_{\alpha\beta}$$

B quantizes Dirac states into Landau levels

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

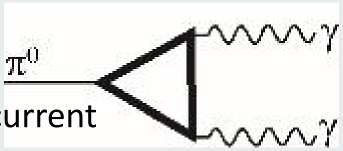
$$A = -\left(\frac{L^2}{2\pi\ell_B^2}\right)\left(\frac{Le\dot{k}_z}{2\pi}\right) = -V\frac{e^3}{4\pi^2\hbar^2}\mathbf{E}.\mathbf{B}$$

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)

Chiral anomaly as spoiler



axial current

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

Spoiler role and Anomaly-free condition

All the anomalies must cancel for a theory to be renormalizable.

In Glashow-Weinberg-Salam theory, exact cancellation of all anomalies in each generation of quarks and leptons has been called “magical” (Peskin[1]).

Triangle diagram has no further corrections to infinite order in perturb theory (Adler Bardeen)

1. *Intro to QFT*, Peskin Schroeder
2. *Anomalies in QFT,* Bertlmann
3. *Geometry* … , Nakahara

Chiral anomaly in non-Abelian gauge theories

1. *Anomalies in QFT,* Bertlmann
2. *Geometry, Topology and Physics*, Nakahara
3. *Classical Theory Gauge Fields,* Rubakov

Topological in origin (Jackiw, Rebbi, Romer, Nielsen, Fujikawa)

The chiral anomaly term is product of $F_{\mu\nu}$ with its dual

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

1) Euclidean action S_E of Yang Mills gauge theory

$$S_E = -\frac{1}{2}\int d^4\,x\ \ \mathrm{tr}\,F_{\mu\nu}F^{\mu\nu} \sim \int(\mathbf{E}^2 - \boldsymbol{B}^2)$$

compare Maxwell action

$$S = \frac{-1}{4}\int d^4\,x\ F_{\mu\nu}F^{\mu\nu}$$

If, instead, we multiply $F_{\mu\nu}$ by its dual we have the anomaly *A(x*). On integrating we get *q.*

2) Winding number and topological charge of instanton

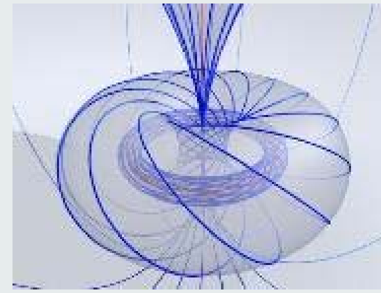
$$q = \int d^4x\ 2A(x) \sim \int \mathbf{E}.\,\mathbf{B}$$

3) Index of Dirac/Weyl operators -- *q* counts the number of zero chiral modes

Chiral anomaly, instanton and index theorem

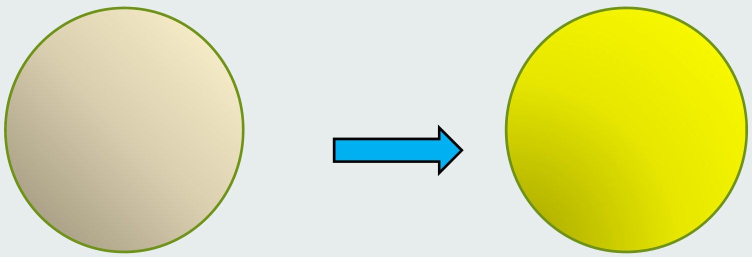
In Yang Mills theory, the Euclidean action S_E is a map: $S^3 \rightarrow S^3$

Cross section of S^3



$z_1^2 + z_2^2 = 1$

instanton　　　　　Gauge group SU(2)



S^3　　　　　S^3

$$A = \frac{e^2}{16\pi^2} \varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta}$$

Euclidean action is the integral of tr $F_{\mu\nu}F^{\mu\nu}$ over all x^μ. This yields the winding number of the map $S^3 \rightarrow S^3$

$$S_E = -\frac{1}{2} \int d^4x \;\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$$

The topological charge q (an integer) is integral of A(x). Equal to the index (n+ - n-)

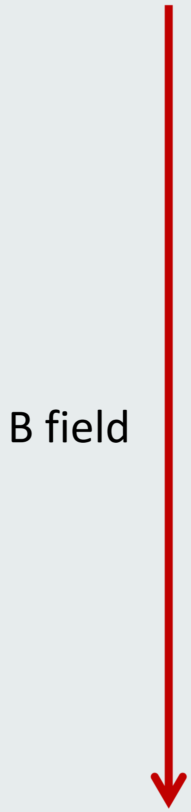
$$q = \int d^4x \;\; 2A(x)$$

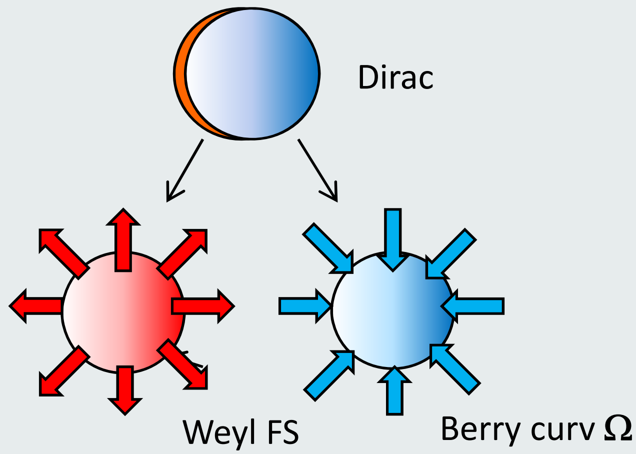
$$q = \int d^4x \;\; 2A(x) = n_+ - n_-$$

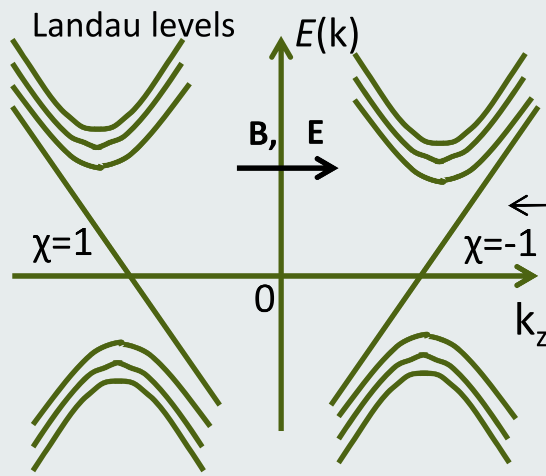
Atiyah Singer Index theorem

1. *Anomalies in QFT,* Bertlmann
2. *Geometry, Topology and Physics*, Nakahara
3. *Classical Theory Gauge Fields,* Rubakov

Creation of Weyl states in applied magnetic field





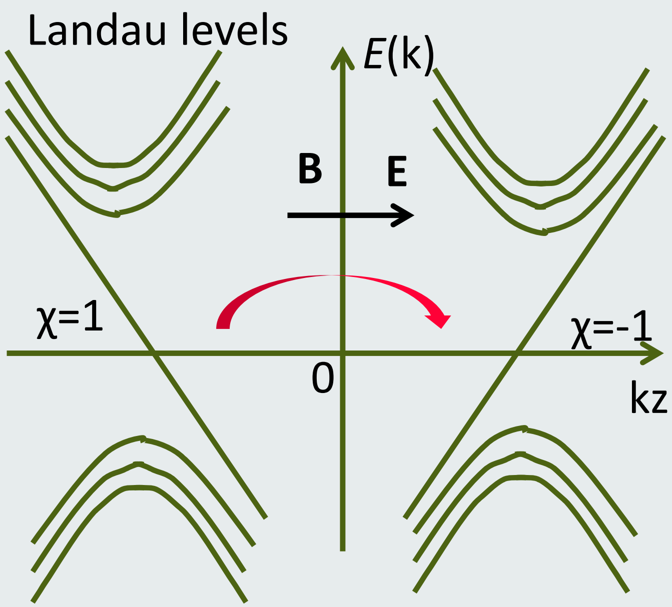


Lowest Landau level
Schwinger model

Detect axial current

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

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)

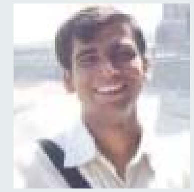
$$\sigma_\chi = \frac{e^2}{4\pi^2\hbar c}\frac{v}{c}\frac{(eBv)^2}{\epsilon_F^2}\,\tau_a$$

τ_a is relaxation time for pumped current

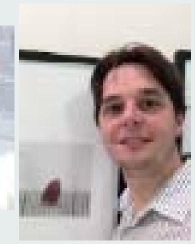
1. Introduction protected Dirac nodes in 3D
2. Dirac and Weyl states in Na_3Bi
3. The Chiral anomaly
4. Charge pumping in Na_3Bi
5. An axial current plume

Bulk crystal growth and electronic characterization of the 3D Dirac semimetal Na_3Bi

S. Kushwaha, J. Krizan … **Yazdani**, **Ong** and **Cava,** *APL Materials* 2015

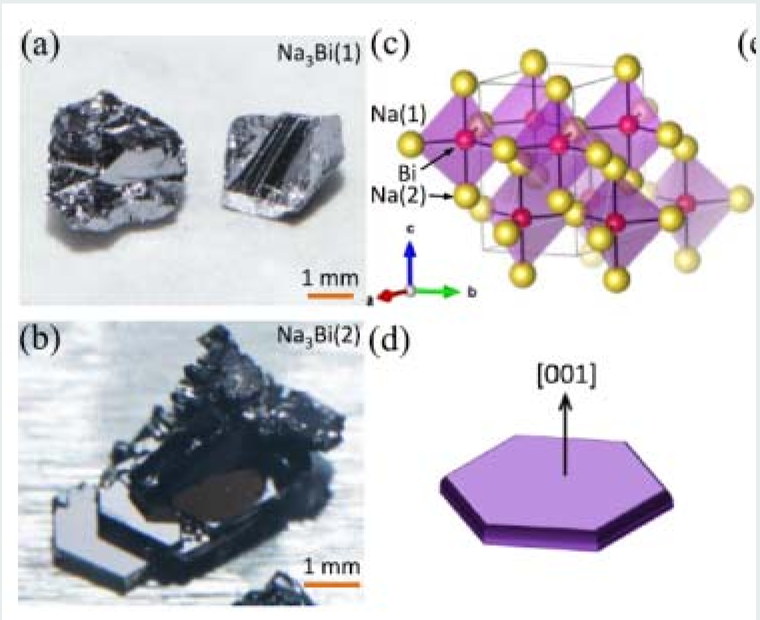


S. Kushwaha



J. Krizan

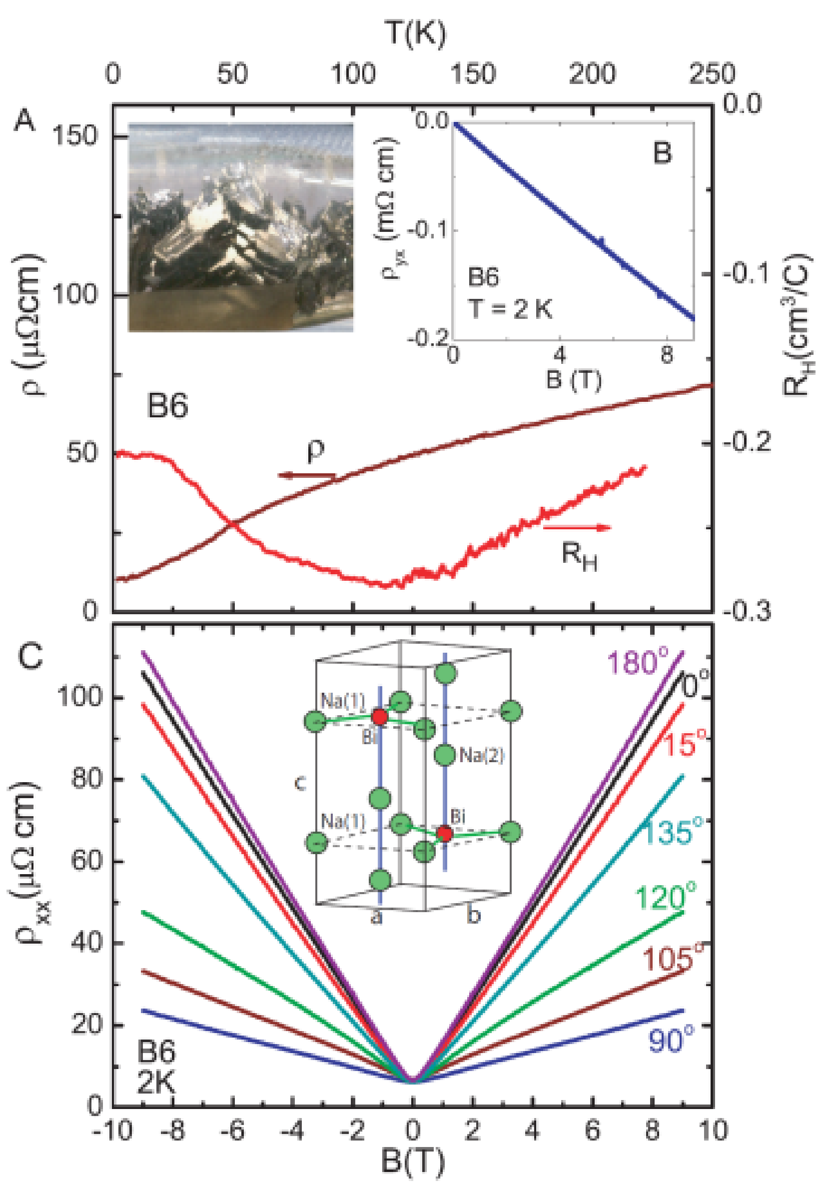
Cava



Deep purple crystals, that rapidly oxidize in ambient air (30 s)

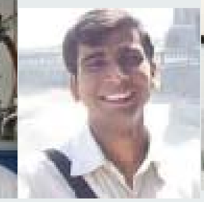
Initial growth produced highly metallic crystals, but no anomaly

Initial results on Na_3Bi



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

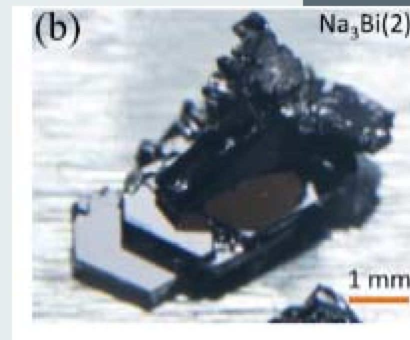
Jun Xiong *et al.*, submitd



Jun Xiong Kushwaha Krizan

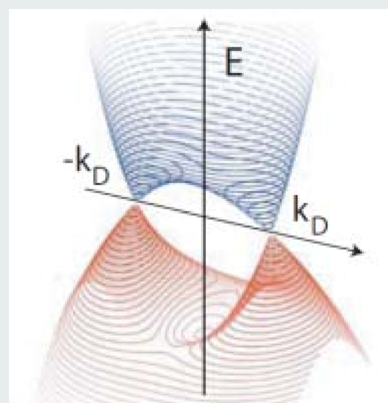
Deep purple crystals

Rapidly oxidizes in ambient air (30 s)



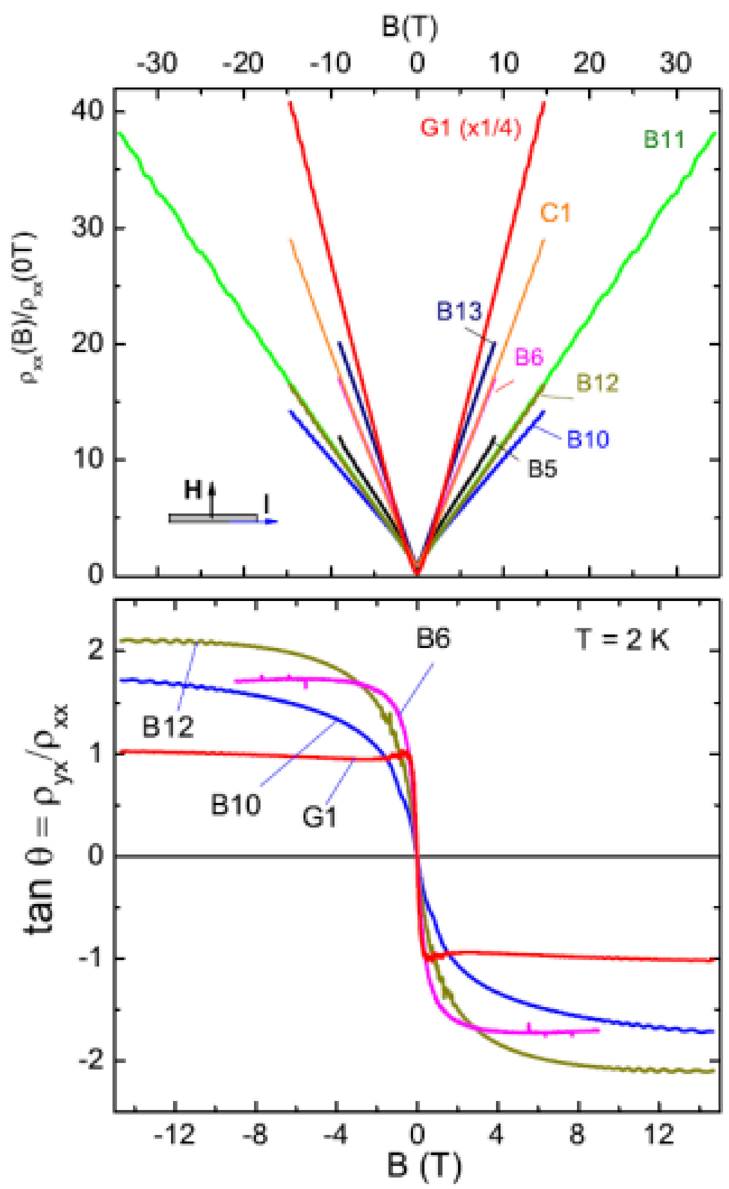
Large linear MR similar to Set B Cd_3As_2 samples

E_F 400 mV above node



H-linear MR and step-profile of Hall angle tan θ_H

Jun Xiong et al., PRL submitd



Conventional

$\rho_{xx}(B) \sim [1+ (\mu B)^2]$

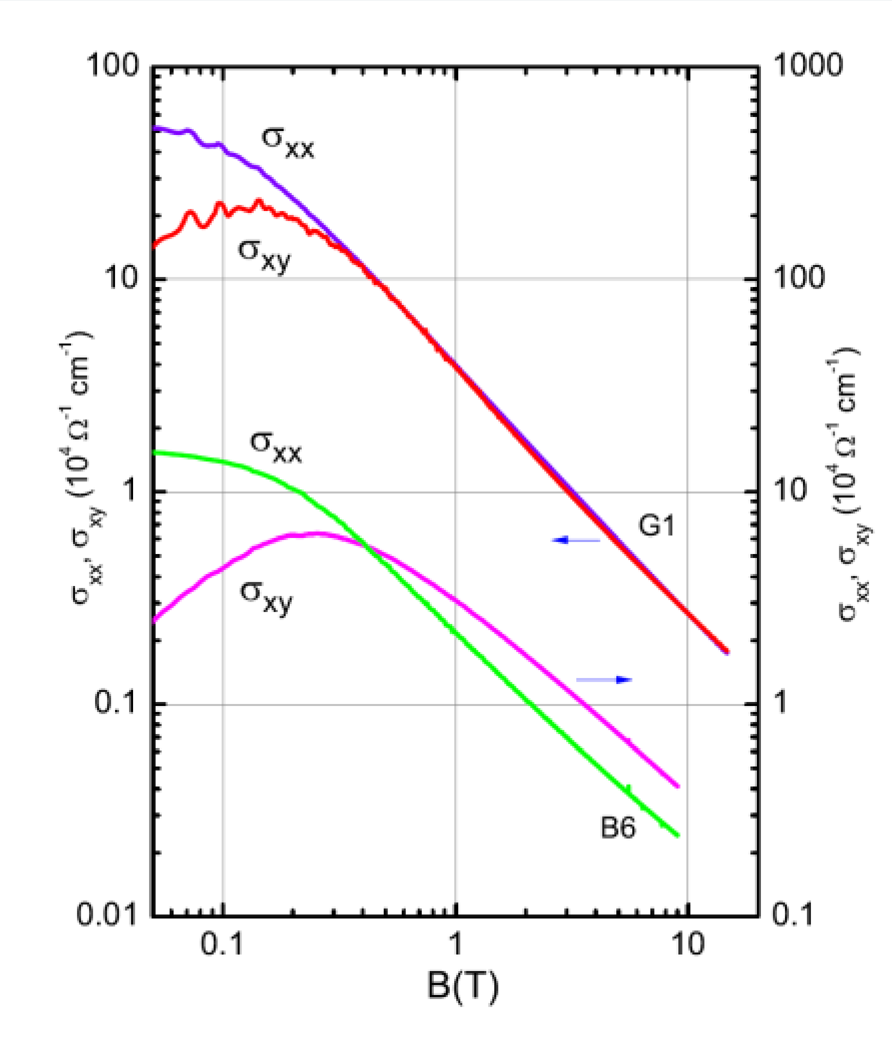
$\tan\theta_H \sim \mu B$

In Na_3Bi

$\rho_{xx}(B) \sim B$, linear MR

$\tan\theta_H$ has a *step-function* profile

Conductivity tensor is anomalous



Conventional

$\sigma_{xx}(B) = ne\mu/[1+(\mu B)^2] \sim 1/B^2$

$\sigma_{xy}(B) = ne\mu^2 B/[1+ (\mu B)^2] \sim 1/B$

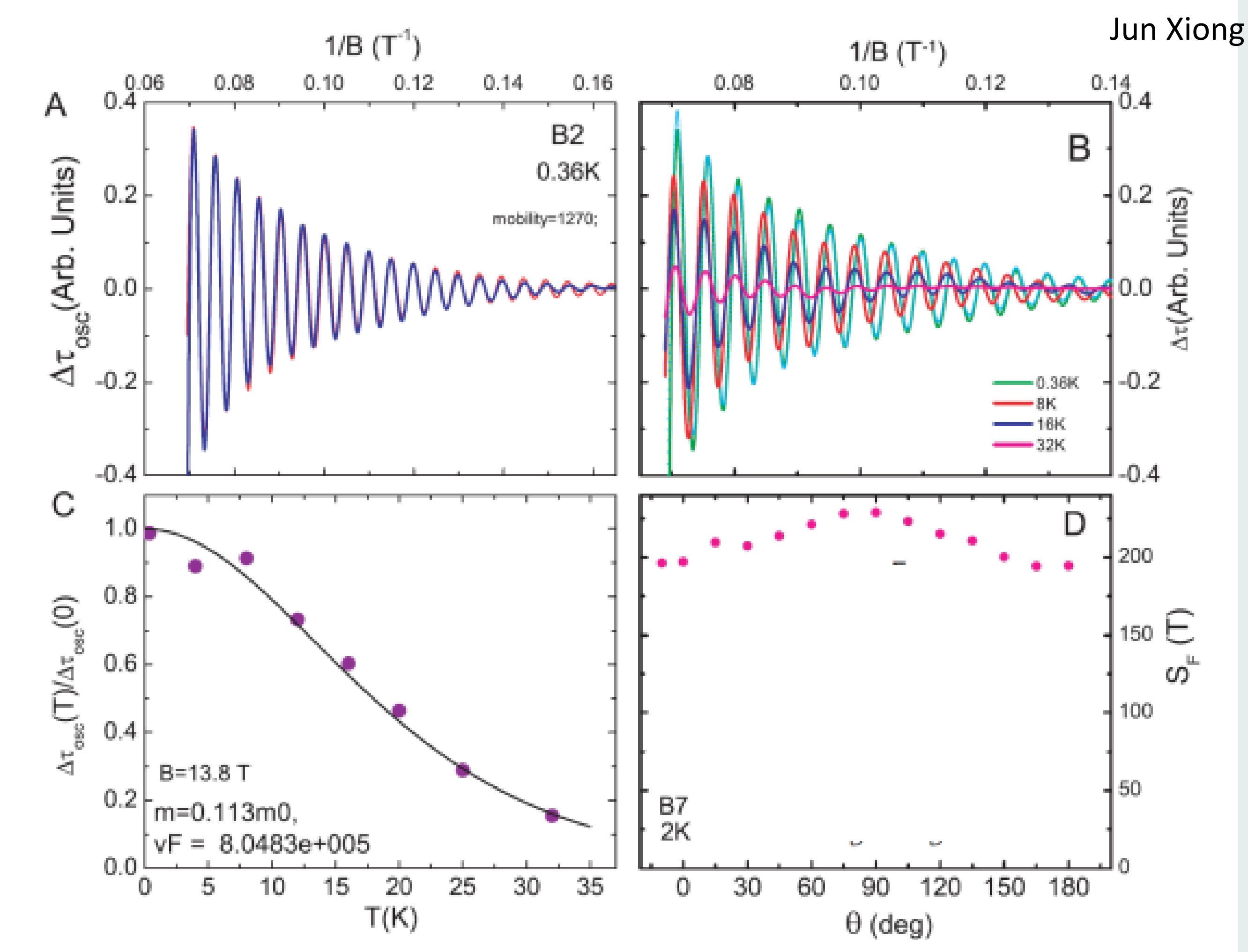
Differ by one power of B

In Na_3Bi

Both σ_{xx} and $\sigma_{xy} \sim 1/B$

Prominent de Haas van Alven oscillations

Jun Xiong et al., PRL submitd

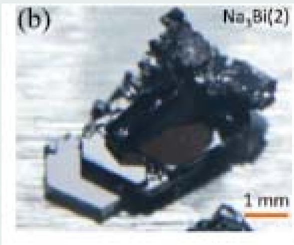


From dHvA oscillations, we infer k_F, m^* and T_{dingle}

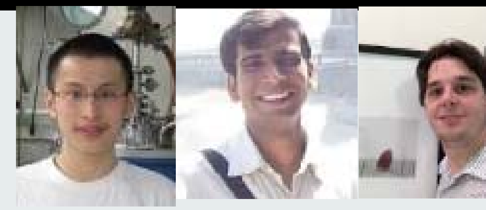
E_F (400 mV) lies above the Lifshitz energy E_L (60 mV)

Non-trivial inverted band regime

Non-metallic Crystals of Na_3Bi with lower carrier density



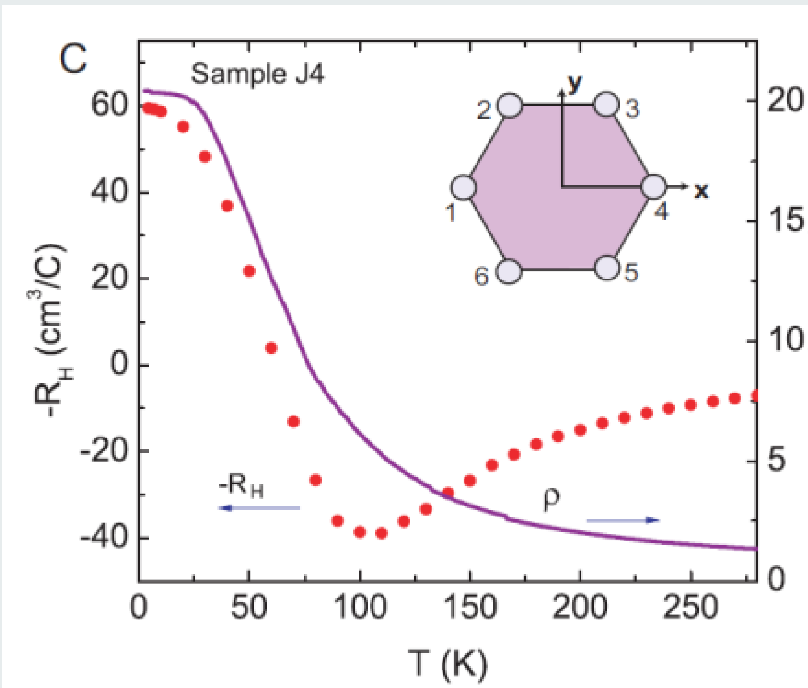
Jun Xiong, S. Kushwaha et al., Science 2015

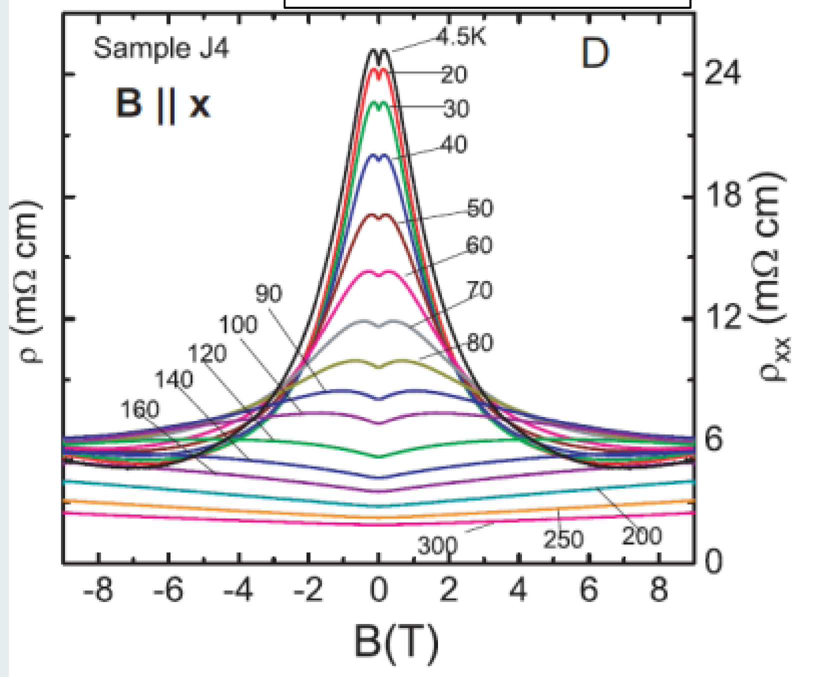


Jun Xiong, S. Kushwaha, Krizan,

Long-term annealed crystals with E_F much closer to node

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





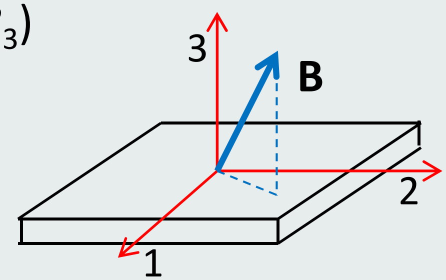
Fermi energy lies 30 meV above node

Striking negative longitud. MR (LMR)

Longitudinal MR is rare in conventional metals

A conventional 1-band model does not lead to MR, regardless of band anisotropy.

Standard Boltzmann equation with anisotropic mass tensor (elliptical FS) in *arbitrarily large*, tilted, field **B** = (B_1, B_2, B_3)



$$e\mathbf{E}\cdot\mathbf{v}\frac{\partial f^0_{\mathbf{k}}}{\partial \epsilon_{\mathbf{k}}} + e\mathbf{v}\times\mathbf{B}\cdot\frac{\partial g_{\mathbf{k}}}{\partial \mathbf{k}} = -\frac{g_{\mathbf{k}}}{\tau},$$

$$\hat{m} = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}$$

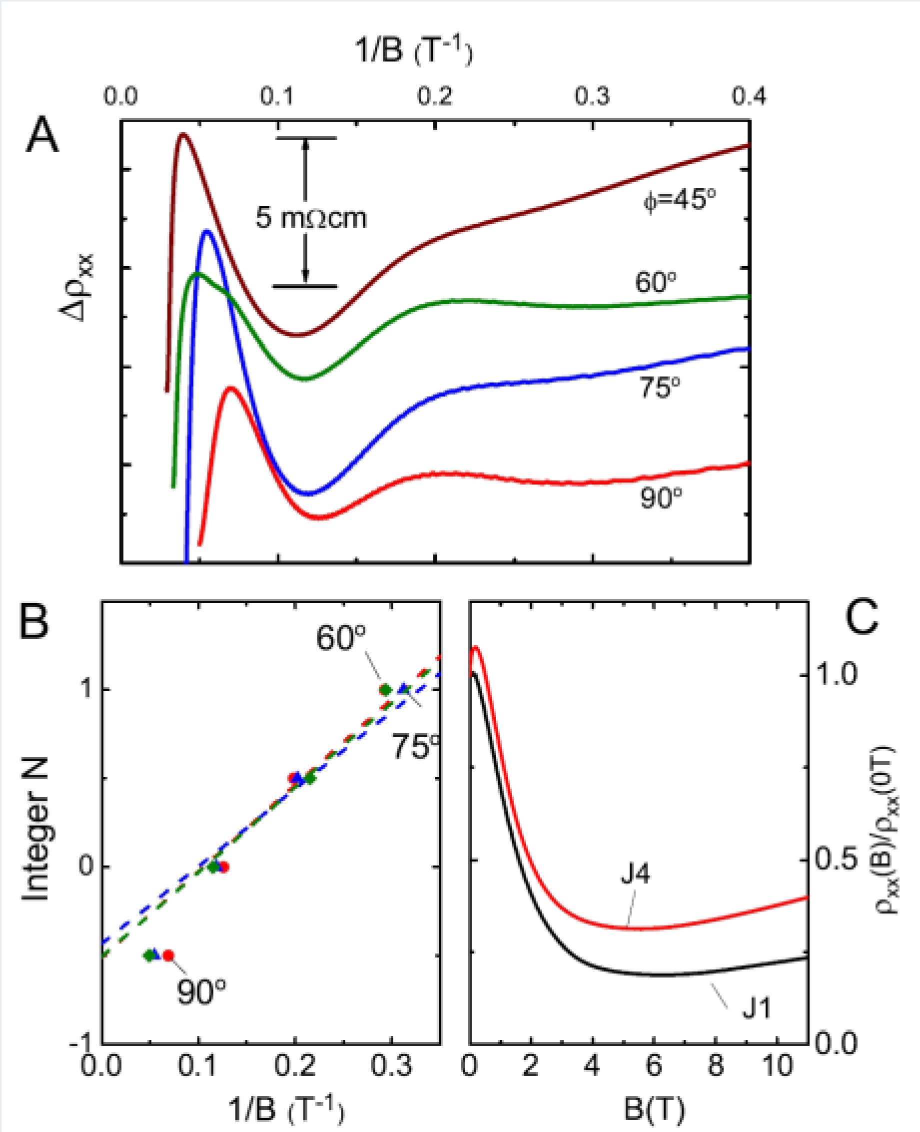
Solution for resistivity tensor

$$\hat{\rho} = \begin{bmatrix} \rho_1 & -B_3/ne & 0 \\ B_3/ne & \rho_2 & -B_1/ne \\ 0 & B_1/ne & \rho_3 \end{bmatrix}$$

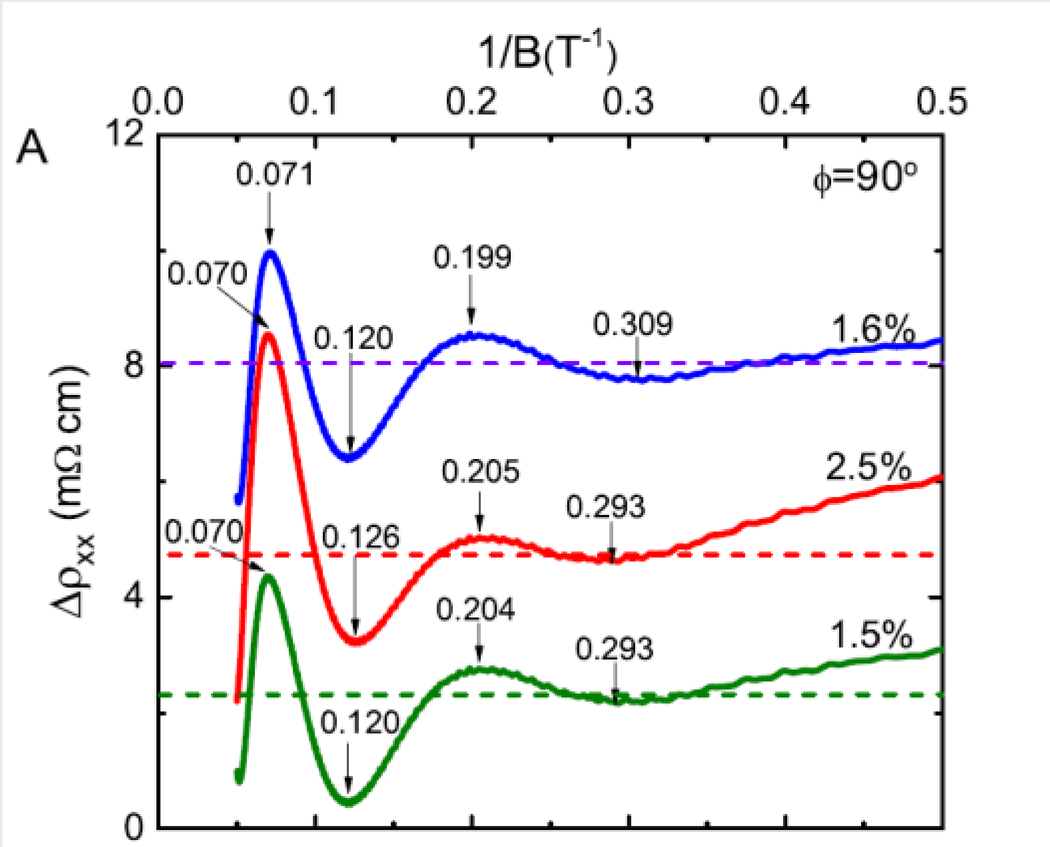
$$\rho_i = \frac{m_i}{ne^2\tau_0}$$

Diagonal elements are independent of **B** → absence of MR

Measure FS caliper by Shubnikov de Haas (SdH) oscillations



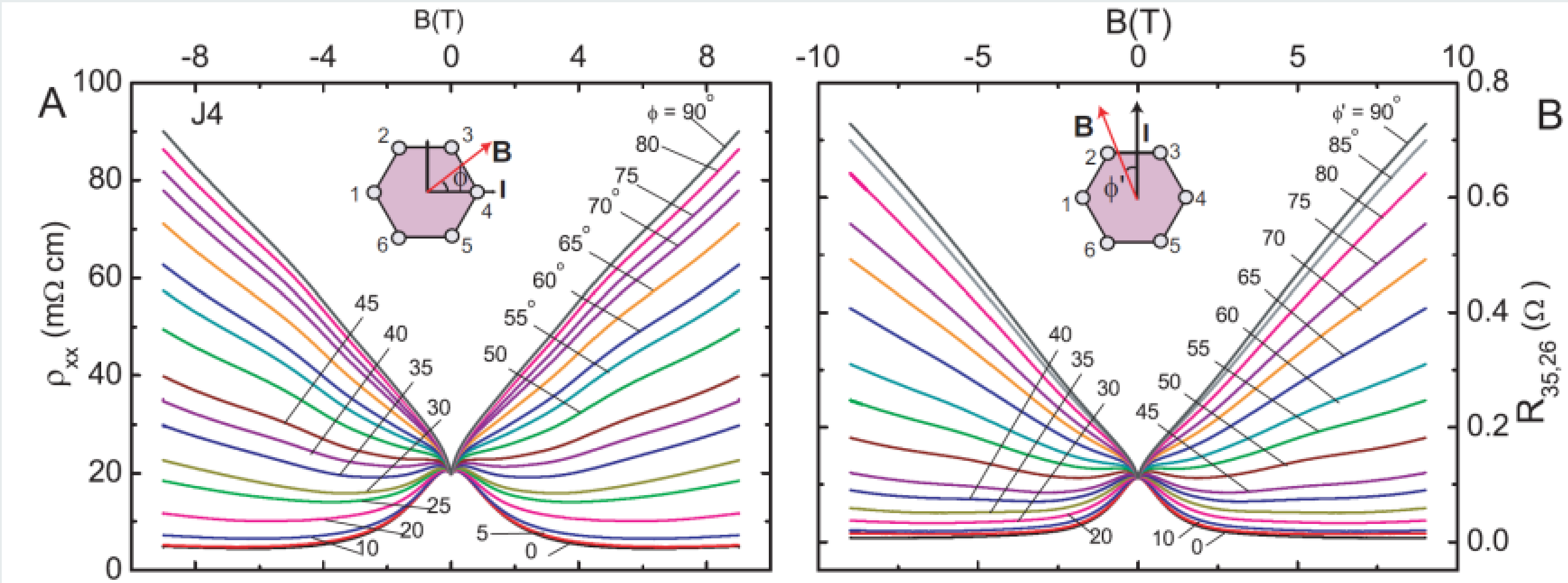
FS volume determined by SF in good agreement with desity n inferred from R_H

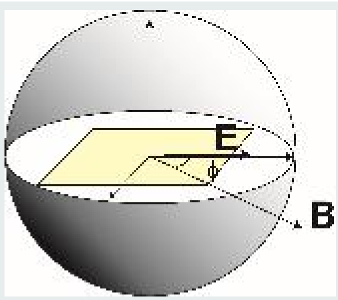


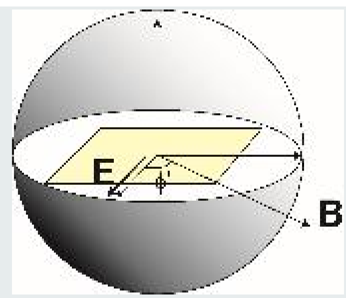
Oscillation amplitude affected by background subtraction,
But extrema positions in field only weakly affected.

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

Jun Xiong, S. Kushwaha et al., submitted





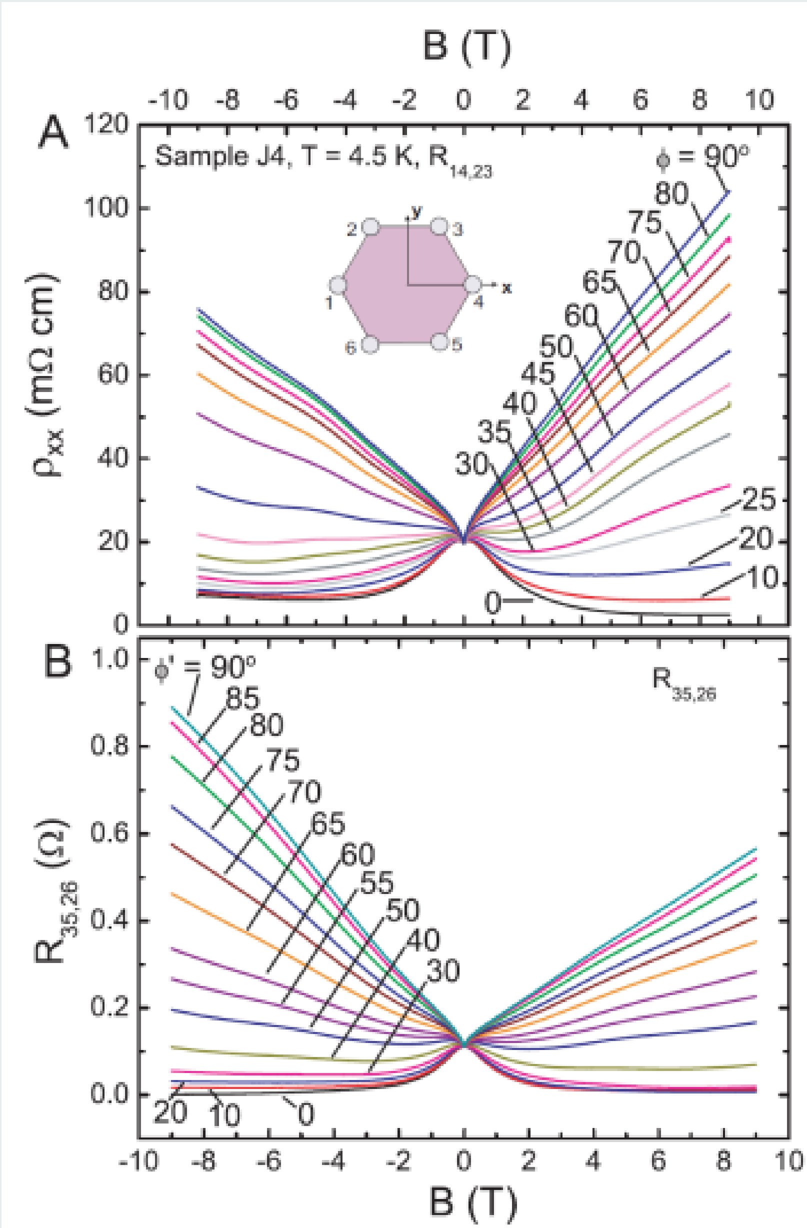


Negative MR appears only when **B** is locked to **E.**

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

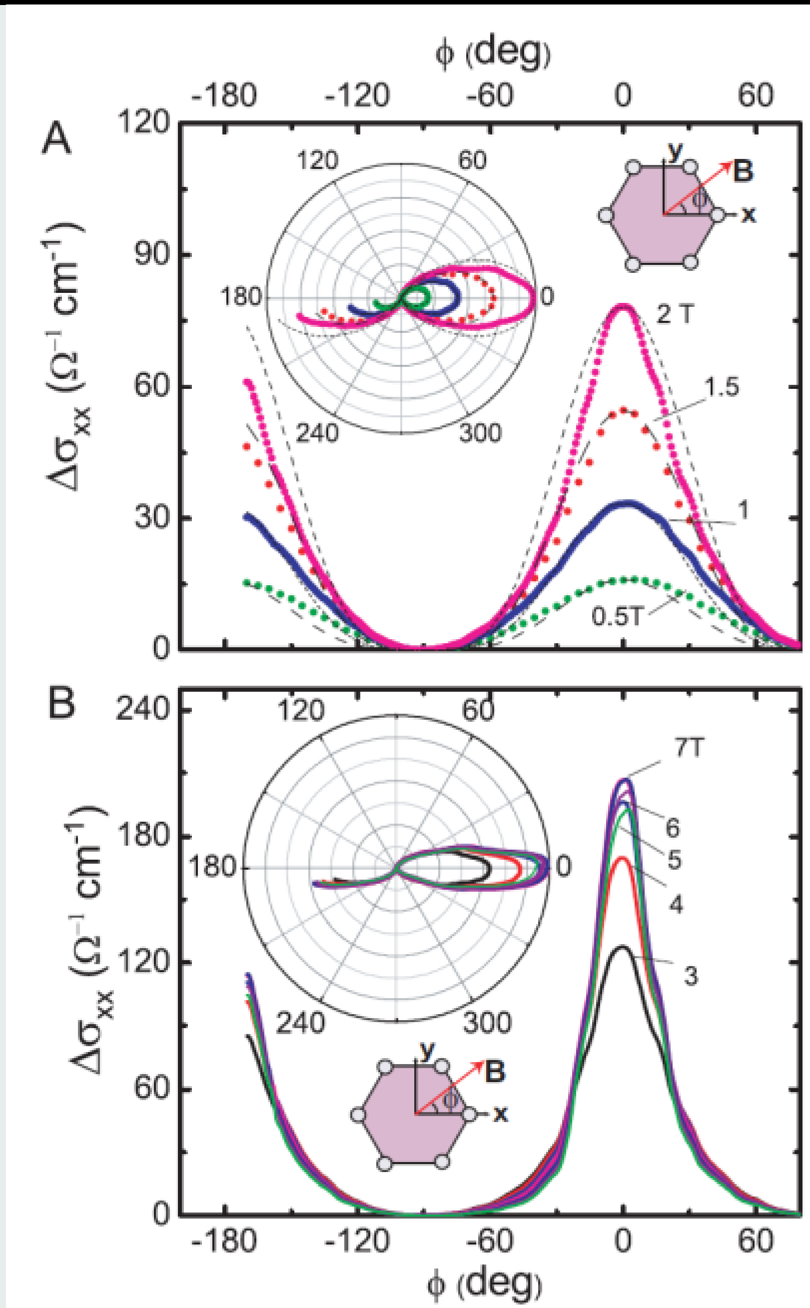
For weak B, this locking is novel and unexpected in semiclasscl transport

Some dirty laundry: Raw curves (unsymmetrized)

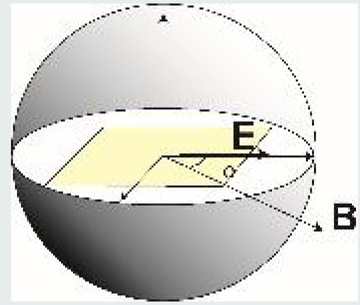


Evidence for some contamination from large Hall signal, but doesn't affect intrinsic MR pattern

A narrow plume of chiral current, B in-plane

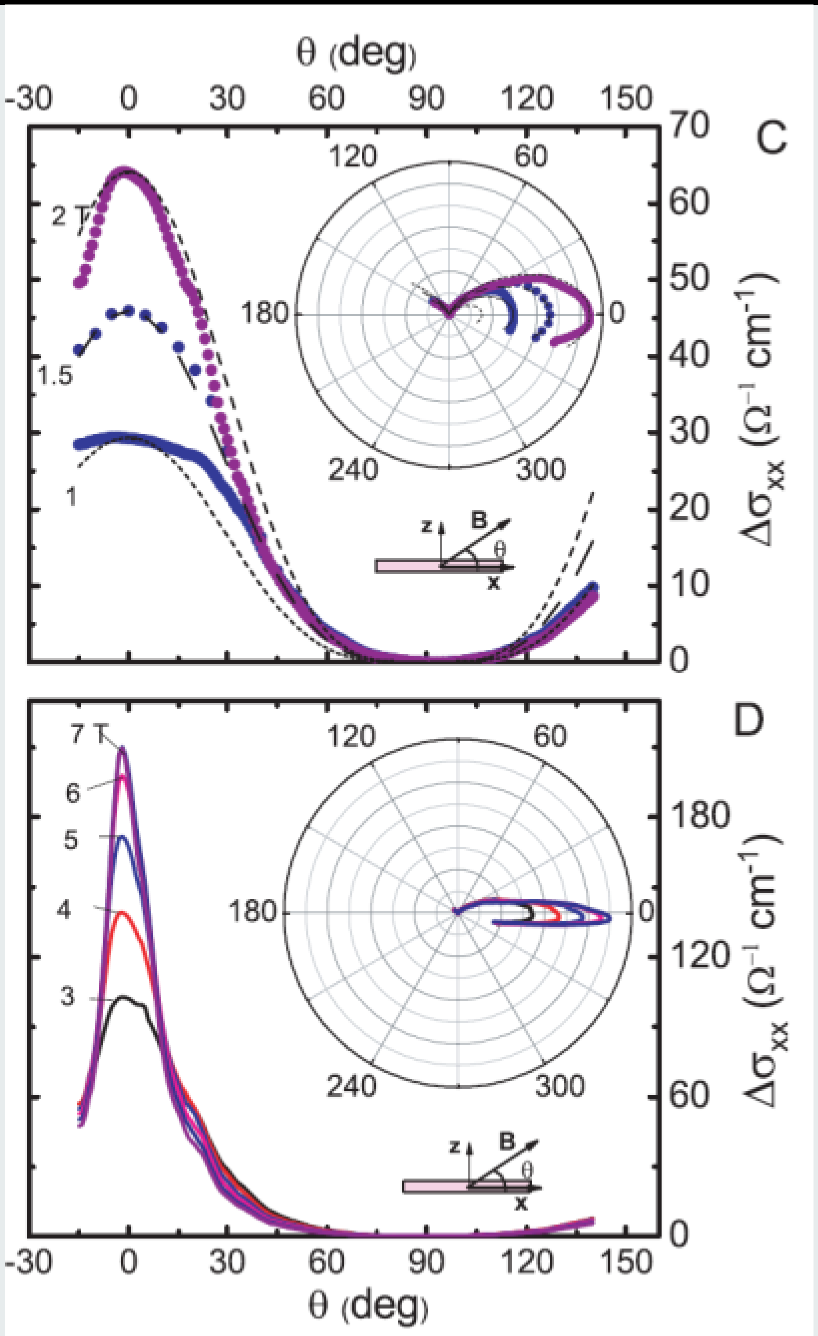


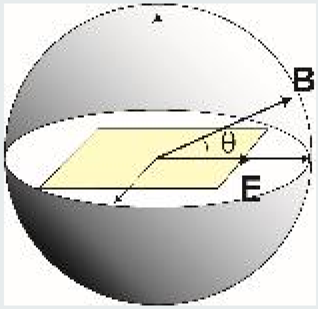
Jun Xiong, S. Kushwaha et al., submitted



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

Width of chiral conductivity "plume", B normal to plane

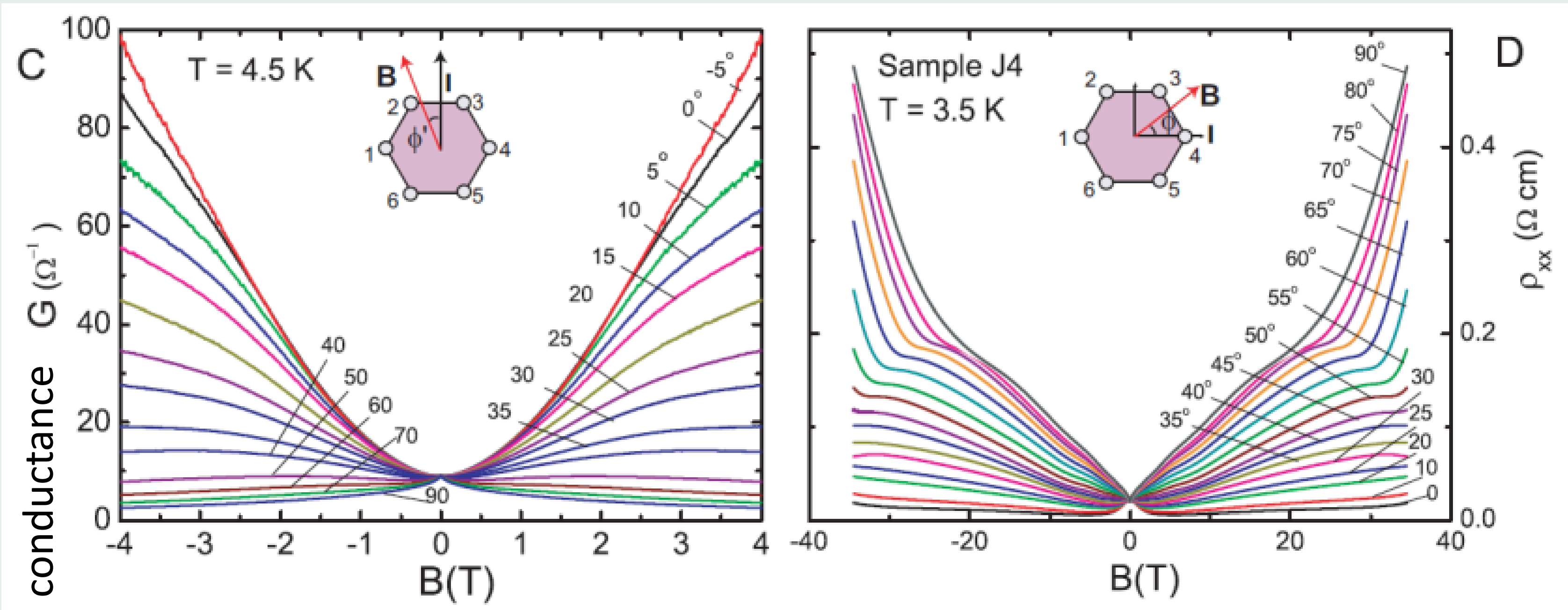




Enhanced cond. in a narrowly collimated beam for **B** rotated in the *x-z* (vertical) plane

Relaxation time τ_a of the pumped axial current

Determine intervalley scat. lifetime using Son-Spivak expression



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

In semiclassical regime, Weyl node conductivity grows as B^2 (Son, Spivak, *PRB* '13)

From fit, we find τ_a = 40-80 τ_0

The axial current relaxation lifetime τ_a

Fit to Son-Spivak expression → $(\tau_a / \tau_0) = 40\text{-}60$, where τ_0 is Drude lifetime

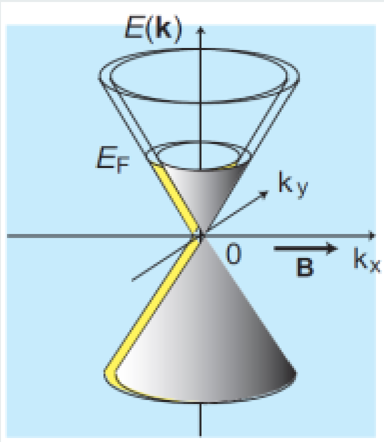
Why is axial current relaxation strongly suppressed?

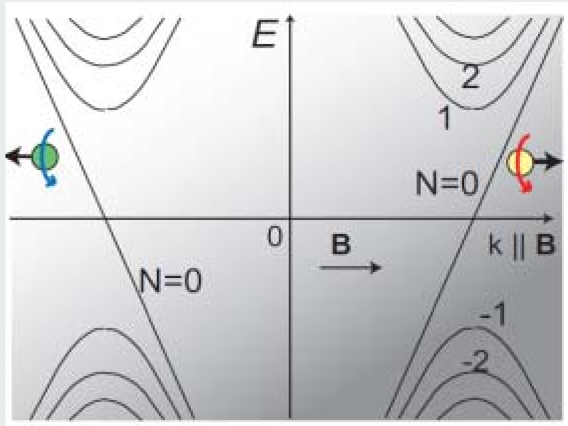
1) Charged impurities are well screened (Thomas-Fermi factor) for large valley scattering ($\Delta k \gg k_F$).

2) Violation of chiral symmetry is weak at low B, so chiral coupling to impurities is weak.

An interesting question:
Does large ratio (τ_a / τ_0) reflect near-conservation of chiral charge?

Zeeman energy and separation of Weyl nodes with B



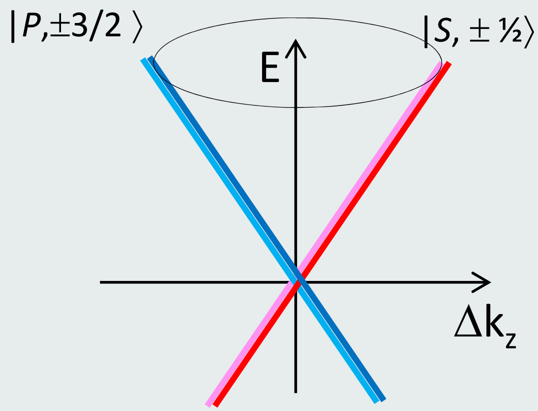


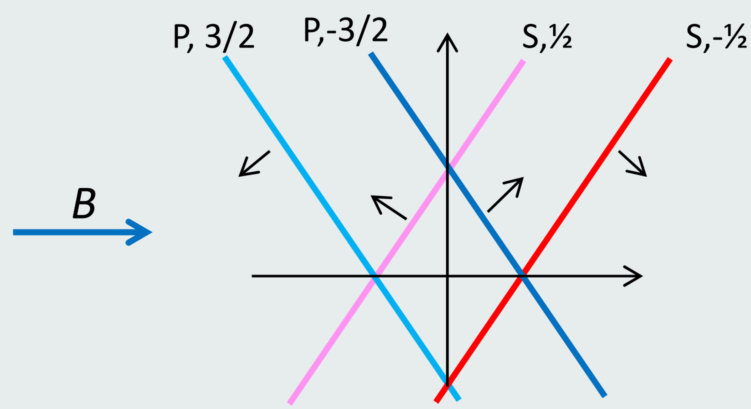
At 6 Tesla, what is node displacement Δk_N?

Zeeman term

$$H_1 = \hbar v \begin{bmatrix} \Pi_z & \Pi_+ \\ \Pi_- & -\Pi_z \end{bmatrix} - \mu_B B \begin{bmatrix} g_s & 0 \\ 0 & g_p \end{bmatrix}$$

$$\delta g = (g_S - g_P)/2 \quad \Rightarrow \quad \Delta k_N = \delta g \mu_B B / \hbar v$$





Separation may be small if $\delta g < 40$

Calculation of lifetime τ_a

Burkov arXiv: 1505.01849v2

Near conservation of chiral charge leads to slow diffusion modes.
Predicts a long axial current relaxation time,
especially for undisplaced Weyl nodes (Dirac case)

$$\frac{\partial n_v}{\partial t} = D\,\frac{\partial^2 n_v}{\partial z^2} + \Gamma\,\frac{\partial n_a}{\partial z}$$

$$\frac{\partial n_a}{\partial t} = D\,\frac{\partial^2 n_a}{\partial z^2} - \frac{n_a}{\tau_a} + \Gamma\,\frac{\partial n_v}{\partial z}$$

$$\frac{\tau_0}{\tau_a} = \frac{{E_F}^2}{20W^2} \ll 1$$

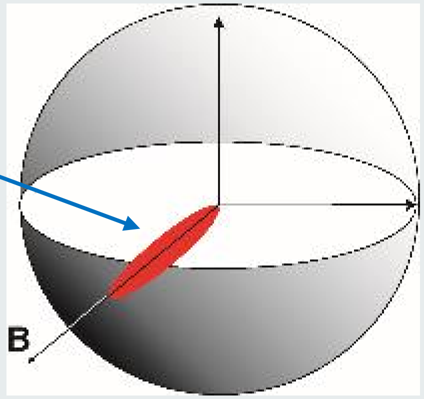
The axial relaxation time τa is currently poorly understood,
but can now be measured in LMR experiments.

Is matrix element for impurity scattering $(+|V_{\mathrm{imp}}|-)$ sensitive to chirality?

Signature of chiral anomaly: **B** locks direction of axial current

In conventional transport, we cannot “rotate” FS parameters, e.g. scattering rate anisotropy, by rotating direction of a weak **B**.

Axial plume



Locking of observed axial to **B** (even in *weak B*) seems to be a signature characteristic of the chiral anomaly.

Axial plume direction fixed by **B** (and **E**)

Observation of negative, longitudinal MR is necessary but insufficient.

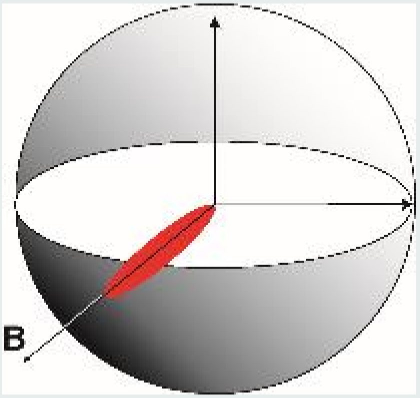
Summary

Transport experiments on Dirac semimetals

In Cd_3As_2, we observe very high mobility (9 million cm^2/Vs) in zero *B*. Appears to be protected by a zero-*B* mechanism. Giant MR observed when protection is lifted.

In Na_3Bi, in samples with E_F ~ 30 mV, we see evidence for the chiral anomaly.

Signature: The enhanced-conductivity "plume" is locked to the direction of **B** (and **E**). **YES**



Estimated inter-valley lifetime is 40-60 x longer than Drude value. Why so large?

A surprise: Width of plume is *much narrower* than anticipated by theory.

Recent reports of Negative Longit MR in semimetals

1. Neg. longit. MR in $Bi_{1-x}Sb_x$, Li et al., PRL 2013 --- Accidl band x'ing

2. Neg. longit MR in Cd_3As_2, Tian Liang et al., Nat Mat. 2015 --- Dirac SM

3. Neg. longit. MR in $ZrTe_5$, Brookhaven Nat. Lab. arXiv --- QSHE?

4. Neg. longit. MR in $PdCoO_2$, Balicas, Maeno, Hussey et al. arXiv --- ??

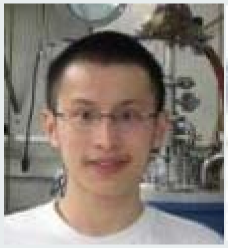
5. Neg. longit. MR in TaAs, NbAs, S. Jia and Hasan, arXiv -- Weyl metals

Other systems showing large, negative MR

6. PbSnTe, Tian Liang --- Topol xtalline insulator

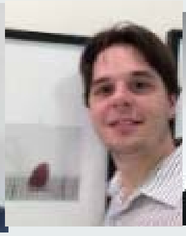
7. GdPtBi Hirschbirger --- Dirac metal with strong exchange

End


Jun Xiong


Kushwaha


Tian Liang


Jason Krizan


Hirschberger


Bob Cava

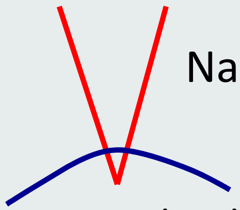

NPO

Thank you

Protection of nodes against gap formation

Dai et al., PRB **85**, 195320 (2012)
Bernevig et al., PRL (2012)

1. Gap inversion pulls (Na 3s) *S* band 0.3 eV below HH (Bi 6p) *P* band



2. Retain the two orbitals |*S*, 1/2) and |*P*, 3/2) near node.
With spin, we have a 4x4 Hamiltonian

$$H_\Gamma(\mathbf{k}) = \epsilon_0(\mathbf{k}) + \begin{pmatrix} M(\mathbf{k}) & Ak_+ & 0 & B^*(\mathbf{k}) \\ Ak_- & -M(\mathbf{k}) & B^*(\mathbf{k}) & 0 \\ 0 & B(\mathbf{k}) & M(\mathbf{k}) & -Ak_- \\ B(\mathbf{k}) & 0 & -Ak_+ & -M(\mathbf{k}) \end{pmatrix}, \qquad \Psi = \begin{pmatrix} |S,\frac{1}{2}\rangle \\ |P,\frac{3}{2}\rangle \\ |S,\frac{-1}{2}\rangle \\ |P,\frac{-3}{2}\rangle \end{pmatrix}$$

Entries fixed by TRS and P (inversion symm.)
At crossing, bands do not mix because they belong to different representations of C_3 rotation group

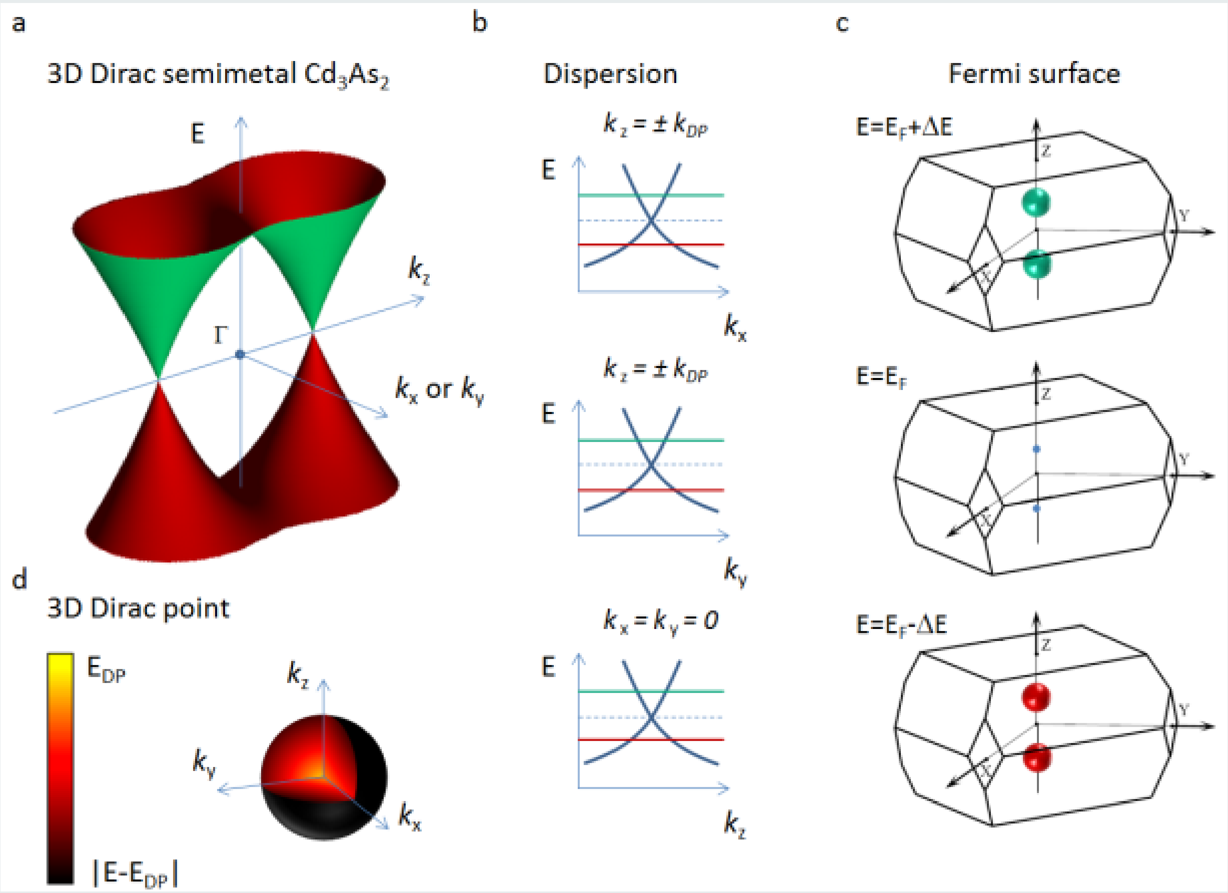
3. Point group symmetry (PGS) e.g. C_3, dictates that off-diagonal terms

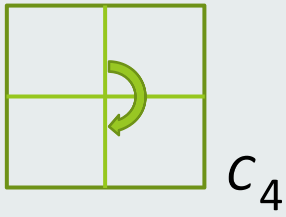
$B(\mathbf{k}) \sim k_z k_+^2$

Near node, *H* decomposes to two diagonal 2x2 blocks (Weyl fermions)

Dual Dirac nodes in Cd_3As_2

Wang, Dai, Fang et al. *PRB* 2012
Wang, Dai, Fang et al. *PRB* 2013



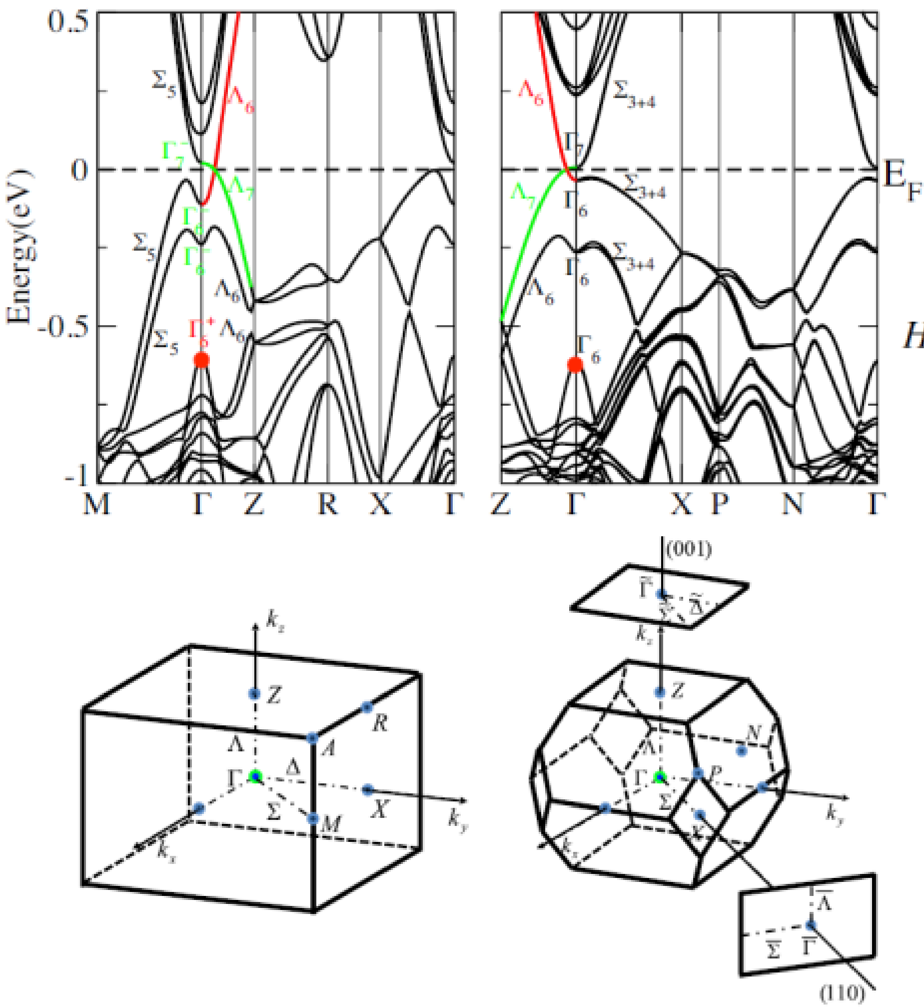


Three Dimensional Dirac Semimetal and Quantum Spin Hall Effect in Cd_3As_2

Zhijun Wang, Hongming Weng,* Quansheng Wu, Xi Dai, and Zhong Fang†

IOP, Beijing

Point Group C4

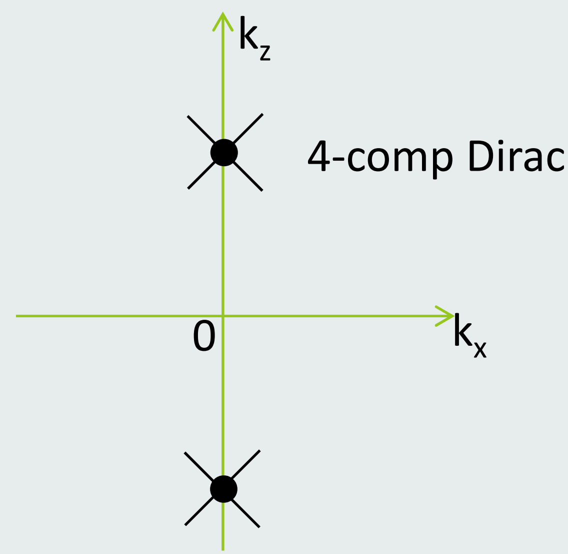


(a) structure I (b) structure II

4x4 basis set

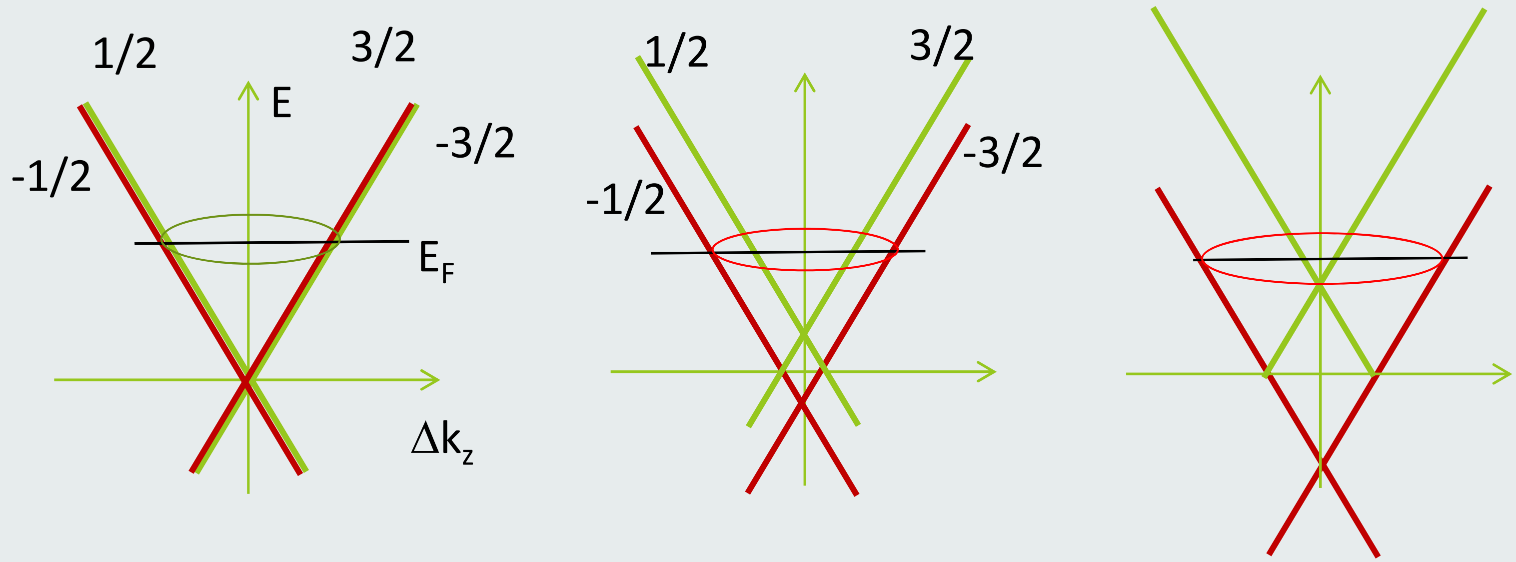
|S,½⟩, |P,3/2 ⟩, |S,-½ ⟩, |P,-3/2 ⟩

$$H_\Gamma(\mathbf{k}) = \epsilon_0(\mathbf{k}) + \begin{pmatrix} M(\mathbf{k}) & Ak_+ & 0 & B^*(\mathbf{k}) \\ Ak_- & -M(\mathbf{k}) & B^*(\mathbf{k}) & 0 \\ 0 & B(\mathbf{k}) & M(\mathbf{k}) & -Ak_- \\ B(\mathbf{k}) & 0 & -Ak_+ & -M(\mathbf{k}) \end{pmatrix},$$

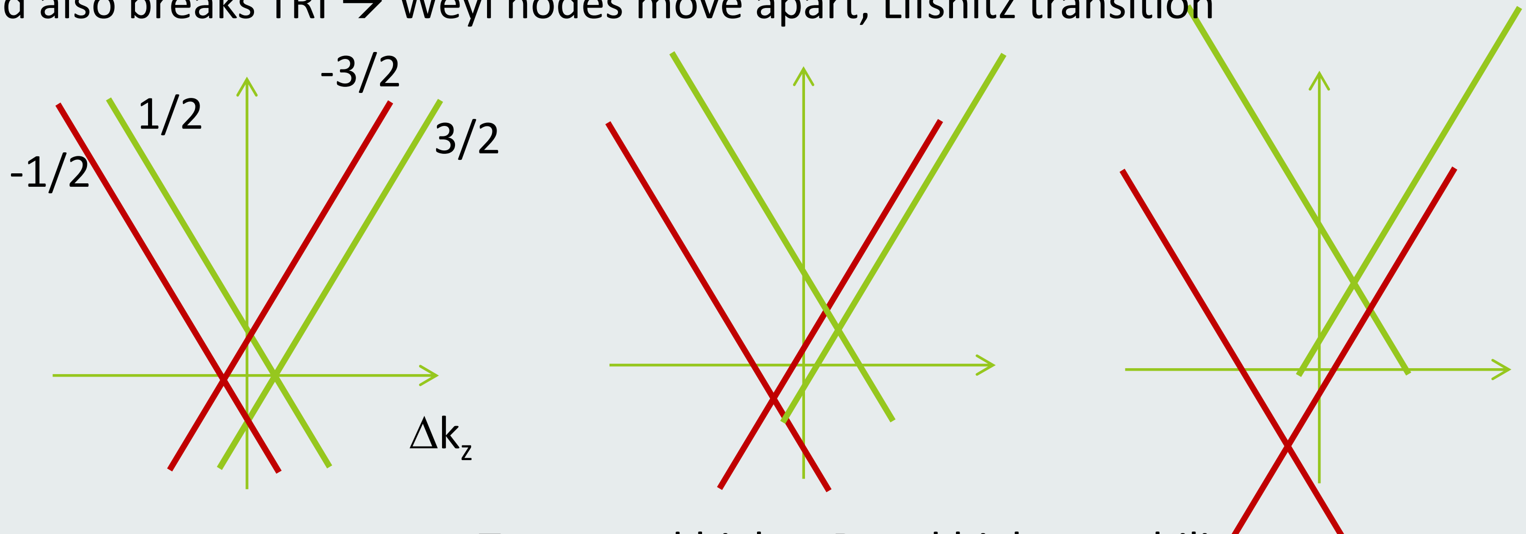


Linear MR from Zeeman splitting of FS? Dai et al, PRL (2012)c

4x4 basis |*S*,½⟩, |*P*,3/2 ⟩, |*S*,-½ ⟩, |*P*,-3/2 ⟩



B field also breaks TRI → Weyl nodes move apart, Lifshitz transition



Tests need higher B and higher mobility