Weyl semimetals in high magnetic fields

Fermi arcs and magnetic torque in the quantum limit

Philip J. M. W. Moll, Nityan Nair, James G. Analytis

University of California, Berkeley

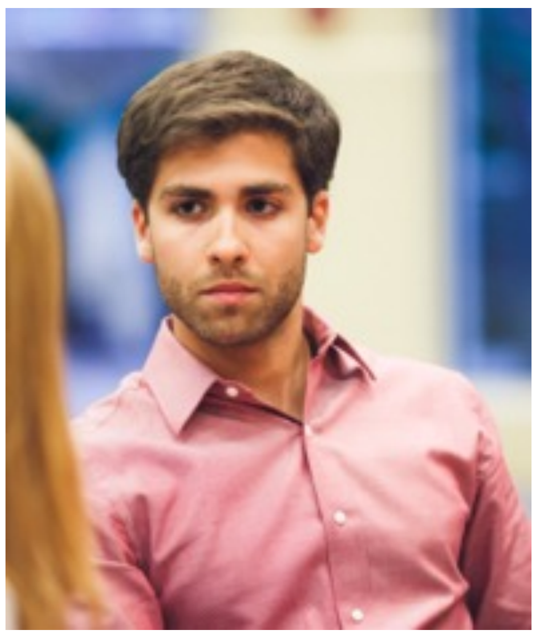
GORDON AND BETTY MOORE FOUNDATION

Rectangle

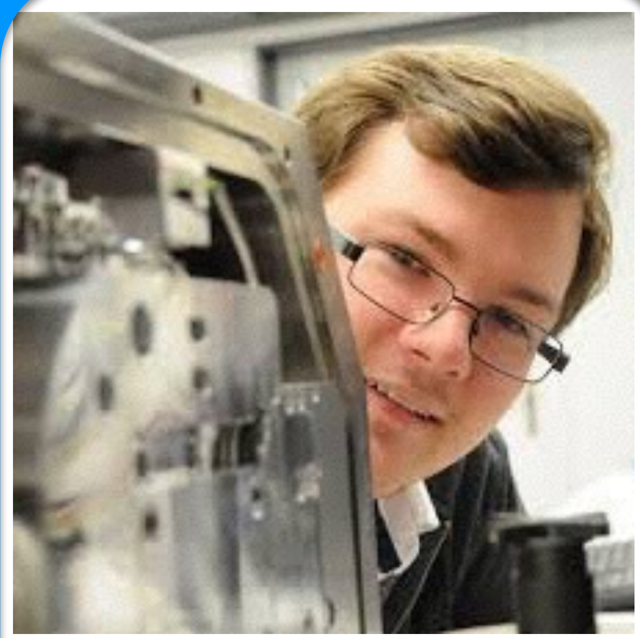
Triangle

50μ

Key players @ UCB



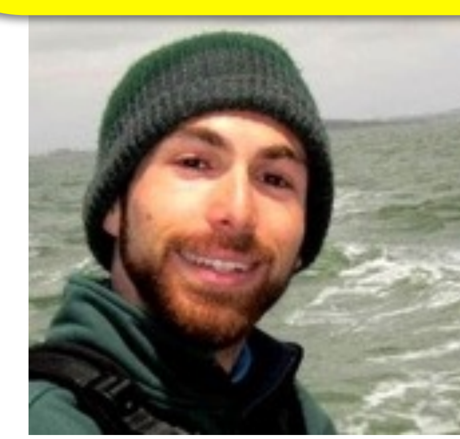
Nityan Nair



Philip Moll

Ashvin Vishwanat

Drew Potter



Itamar Kimchi

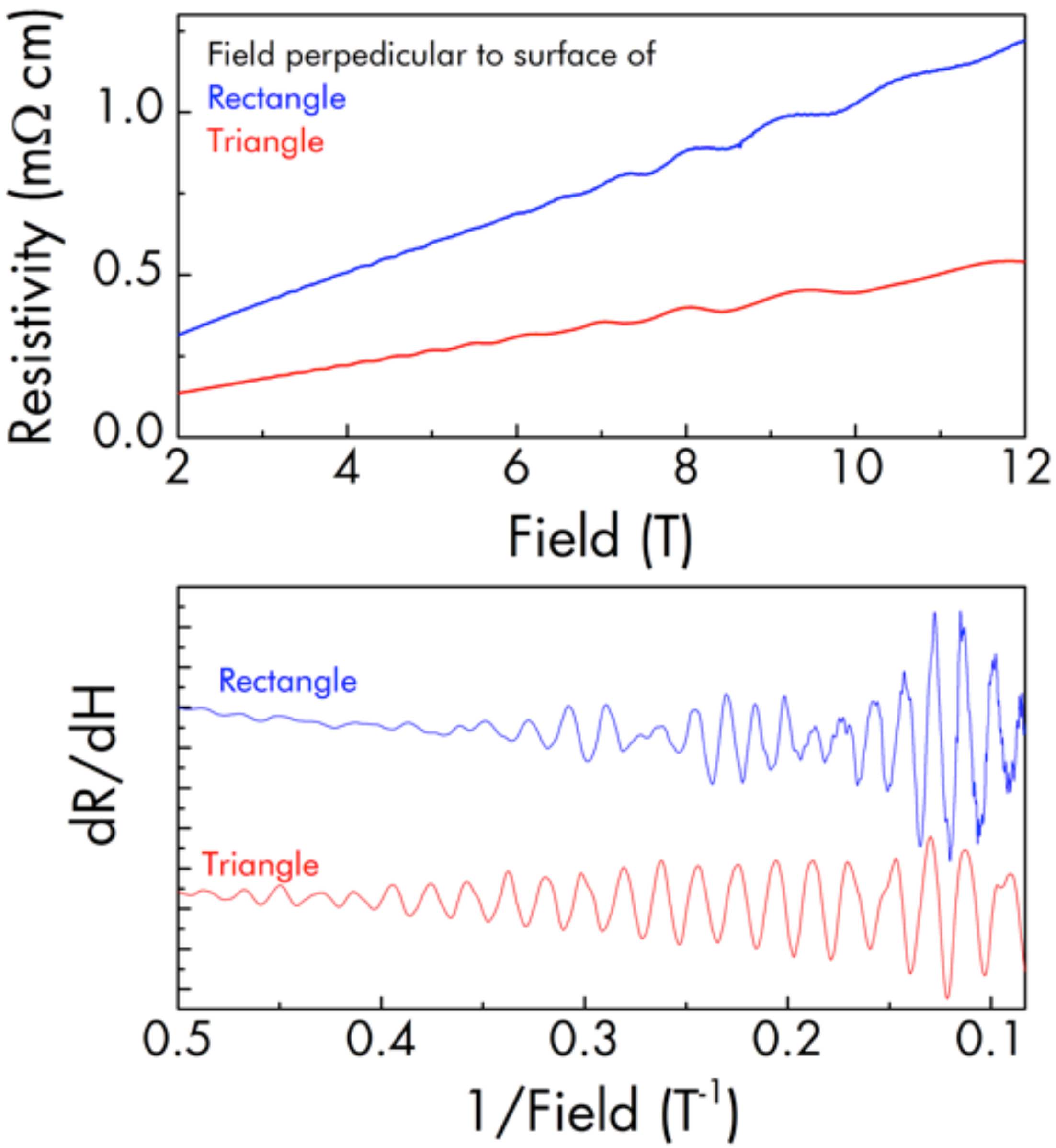
GORDON AND BETTY MOORE FOUNDATION

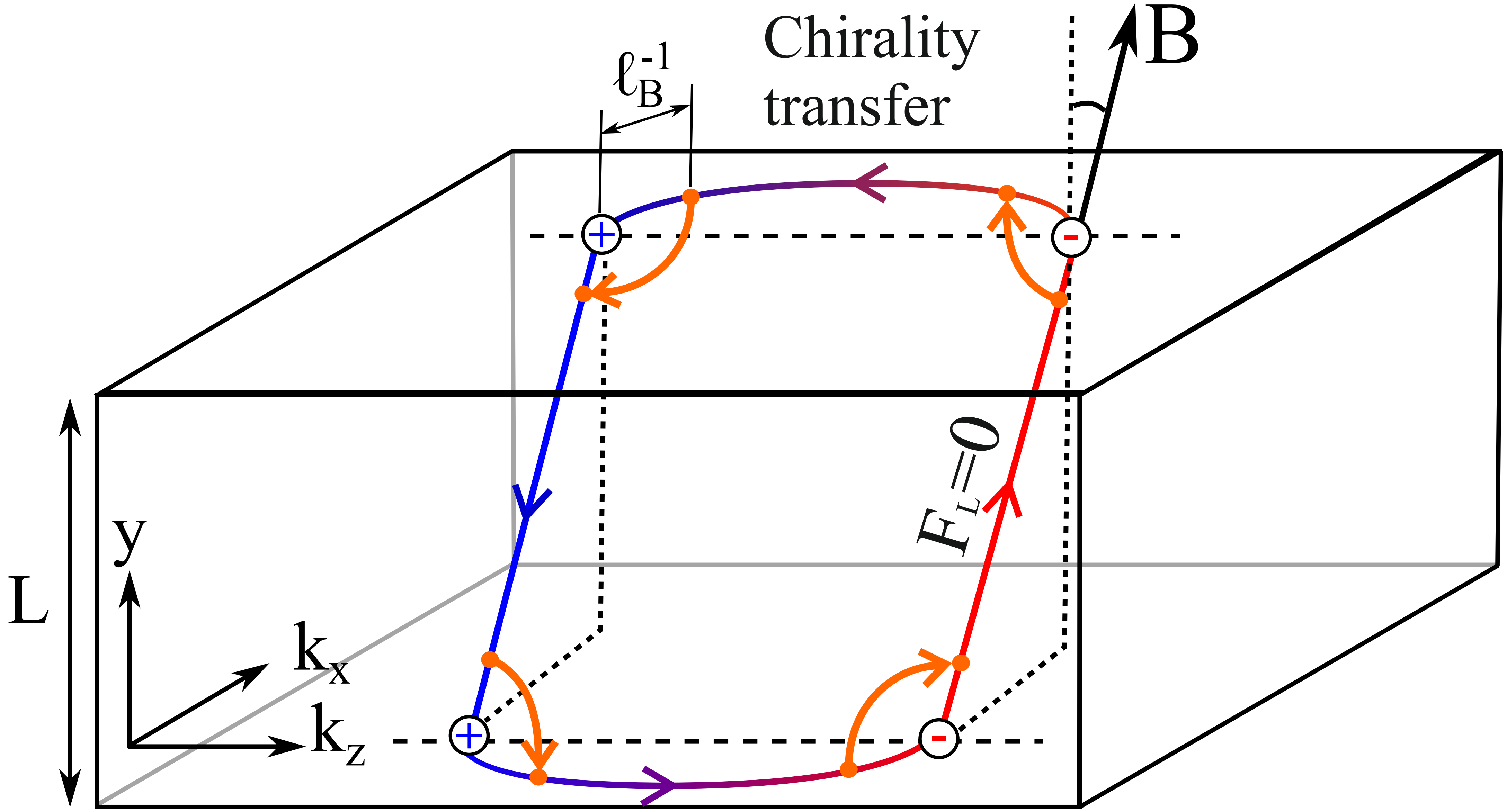
Weyl systems in high magnetic fields

PART I: Introduction

PART II: Weyl orbits and the observation of Shubnikov-de Haas from Fermi Arcs.

PART III: Berry-paramagnetism, torque in the quantum limit and a new tool for the search for Weyl and Dirac systems.

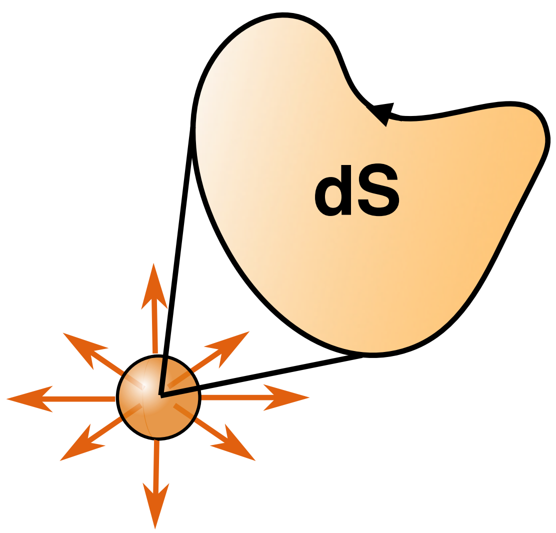




PART I: Introduction

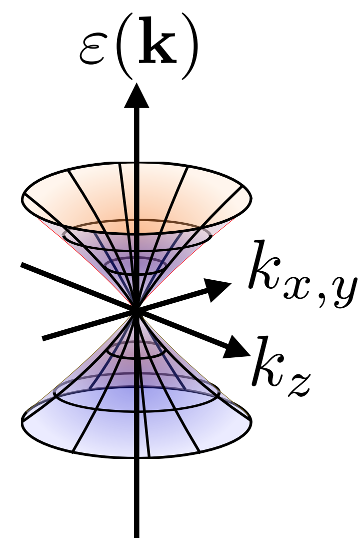
Wan, Turner, Vishwanath, Savrasov; Burkov & Balents; Witczak-Krempa & Y-B Kim; ….
Andrew C. Potter, I.Kimchi, A. Vishwanath, Nature Communications (2014)

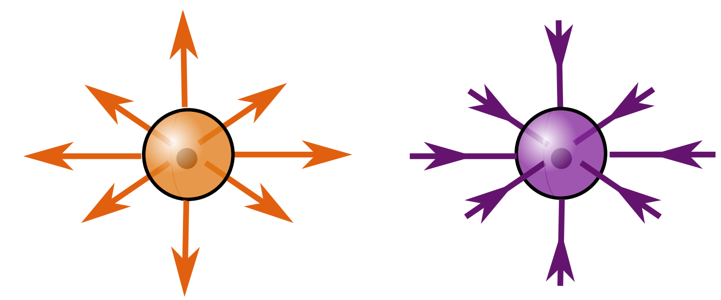
Monopoles and Berry curvature



$$\oiint \mathbf{B}\cdot d\mathbf{S} = 2\pi n$$

$$H_{\mathrm{Weyl}} = \pm v\mathbf{k}\cdot\boldsymbol{\sigma}$$

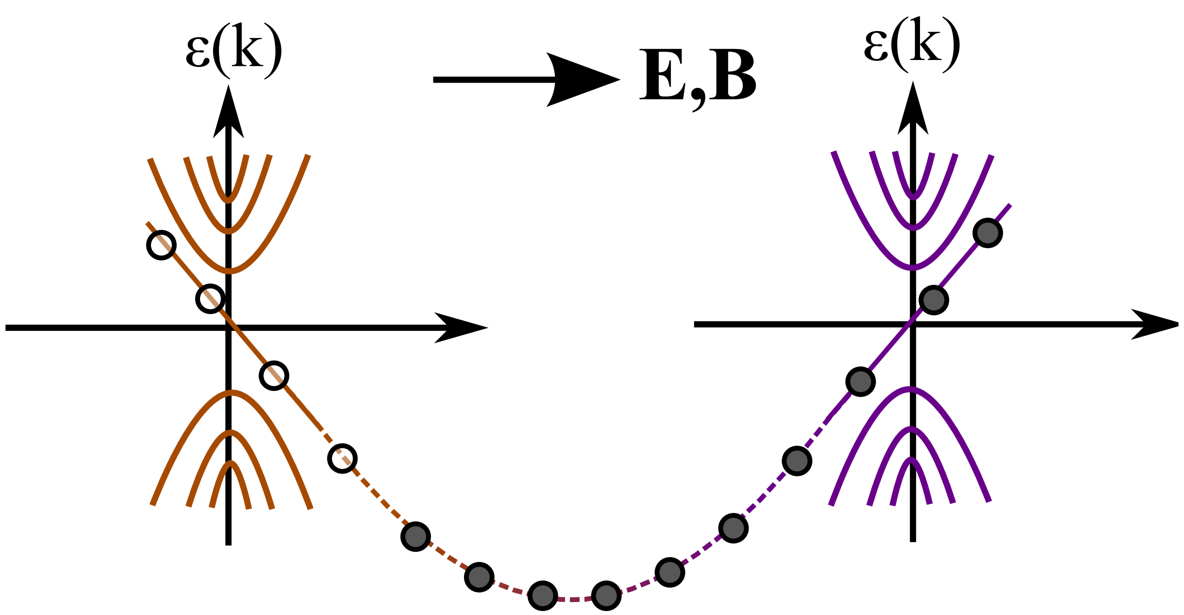




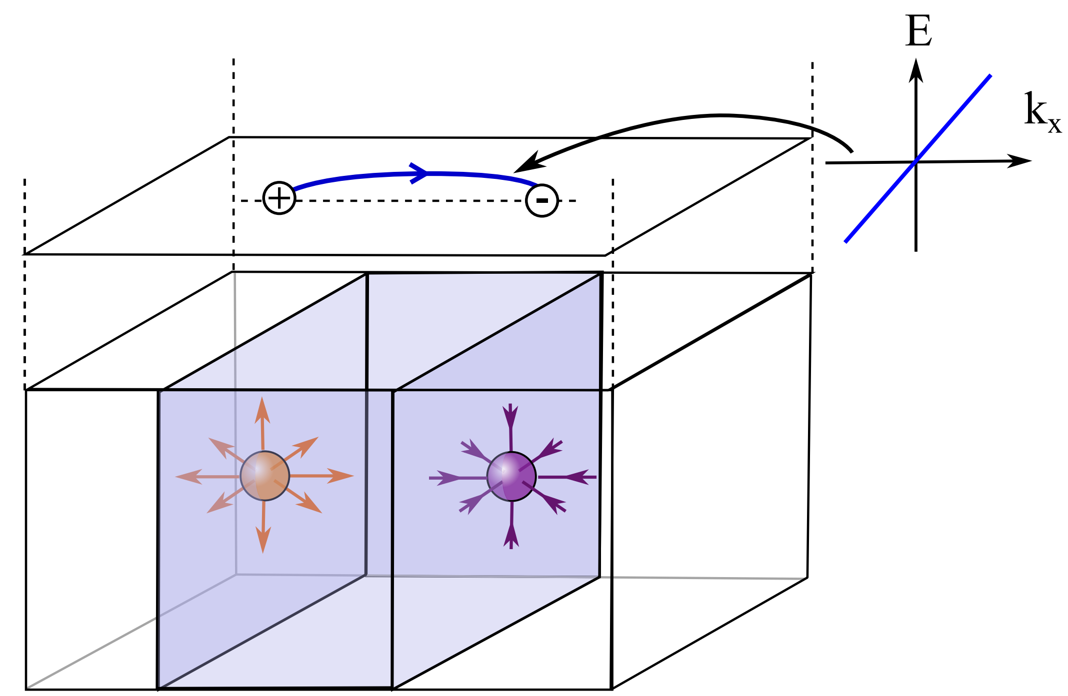
$$\chi = \pm 1$$

- Degeneracies act like monopoles and are associated with a Chern number
- A Weyl node is a source of Berry curvature in *k*-space. Chirality is a good quantum number.

Connecting particles with different chirality



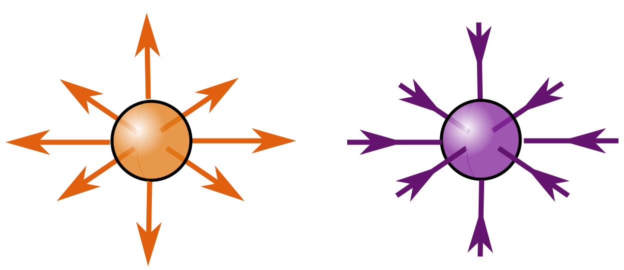
Chiral Anomaly



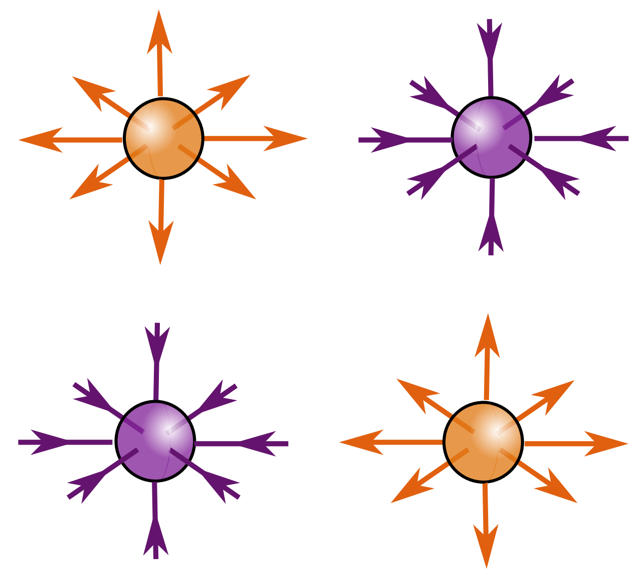
Fermi Arcs

- Breaking translational symmetry of the system, chirality can be transferred from one Weyl node to another via a Fermi arc

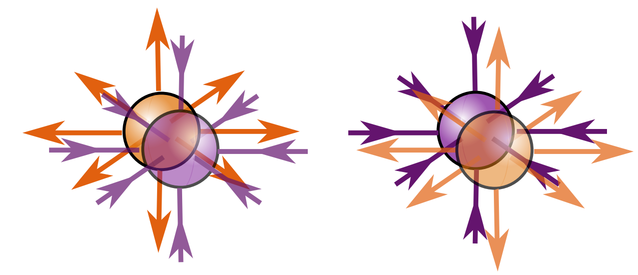
Weyl and 3D Dirac



Time-reversal SB
Weyl

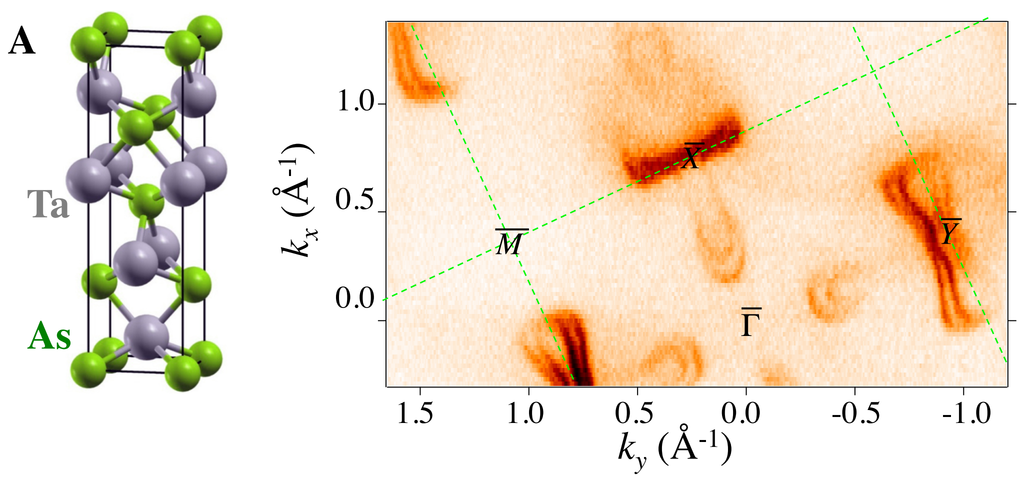


Inversion SB
Weyl
e.g. TaAs



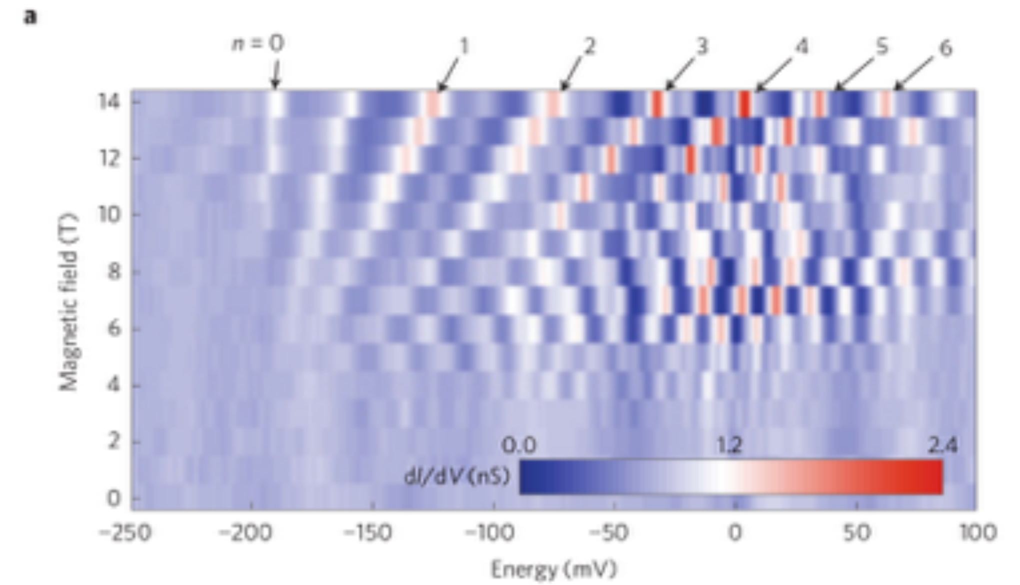
Symmetry protected
3D Dirac
e.g. Cd3As2, Na3Bi

Experimental observations



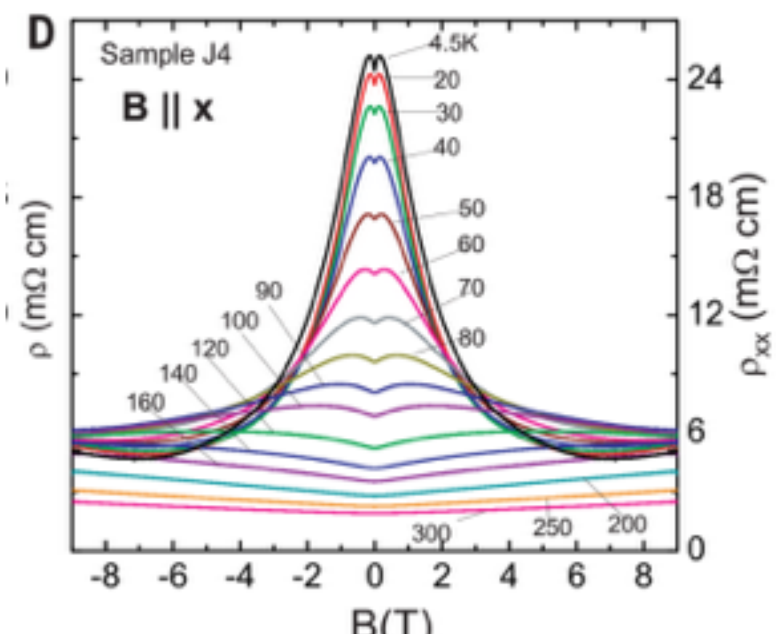
ARPES on TaAs

(Hasan group, Nat. Comm. '15)



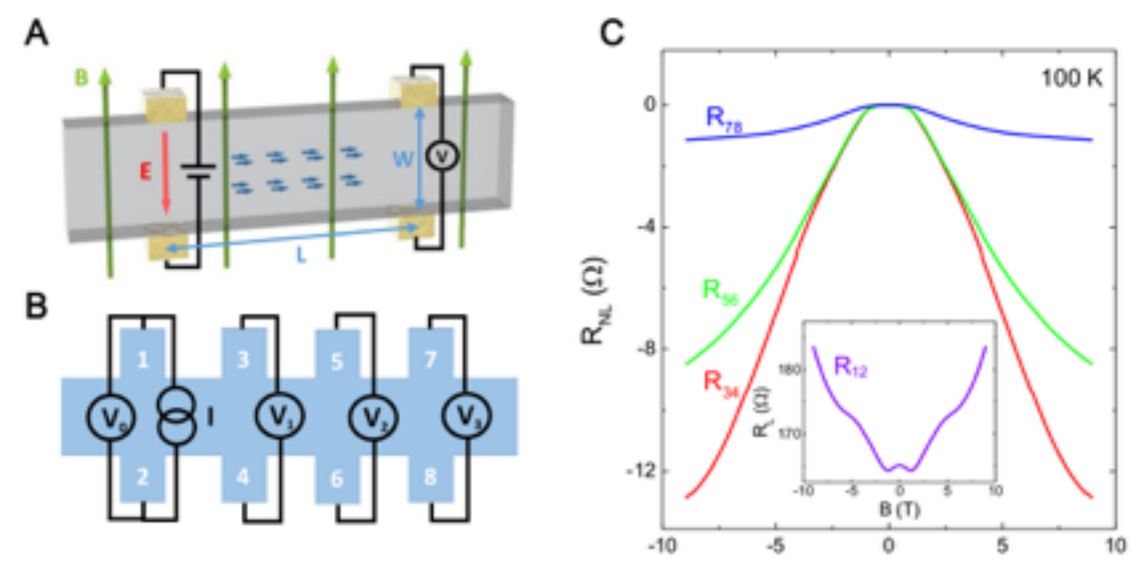
STM on Cd_3As_2

(Yazdani group, Nat. Mat. '14)



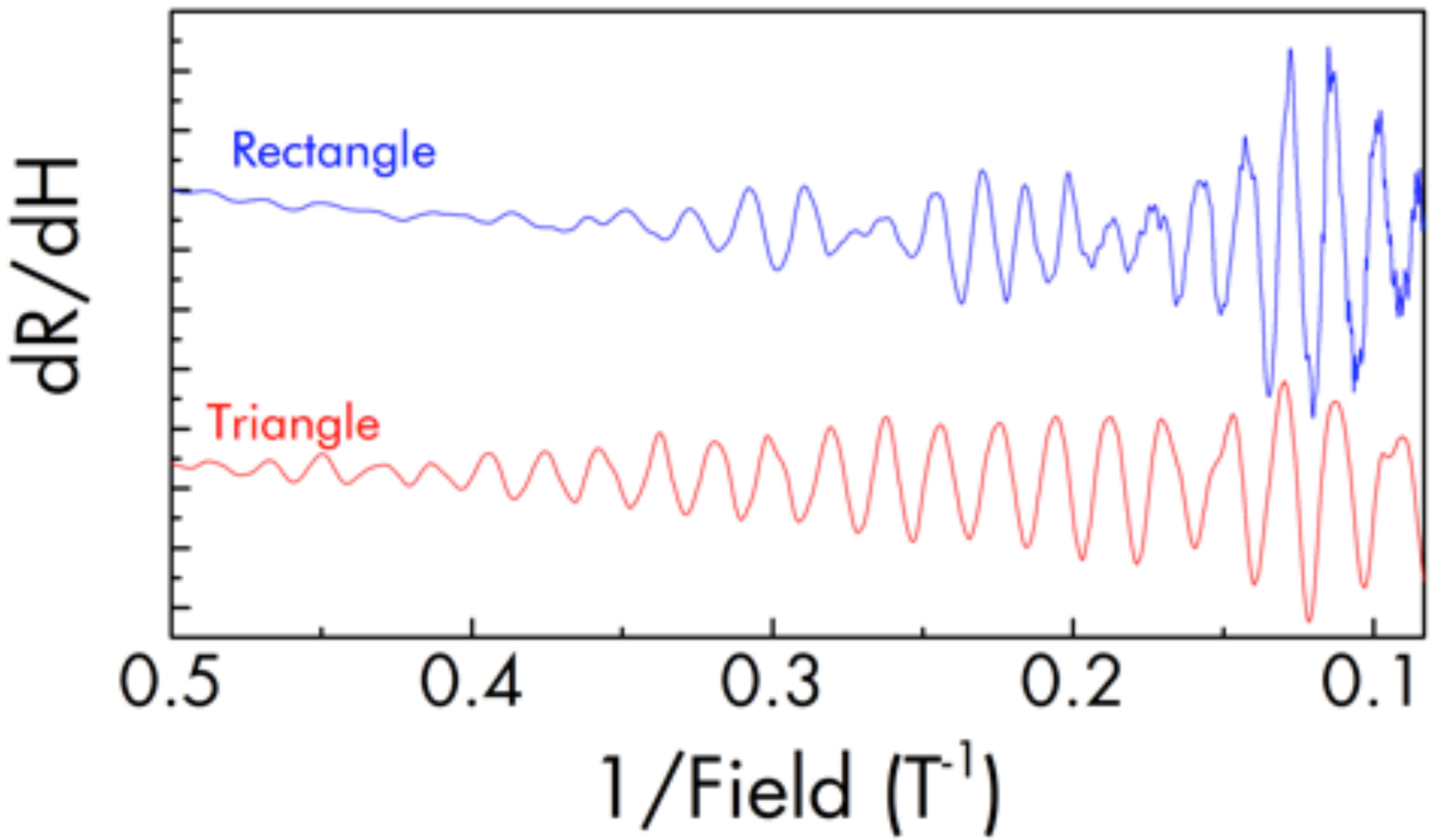
Negative MR on Na_3Bi

(Ong group, Science '15)



Non-local transport

(Xiu group, Fudan '15)



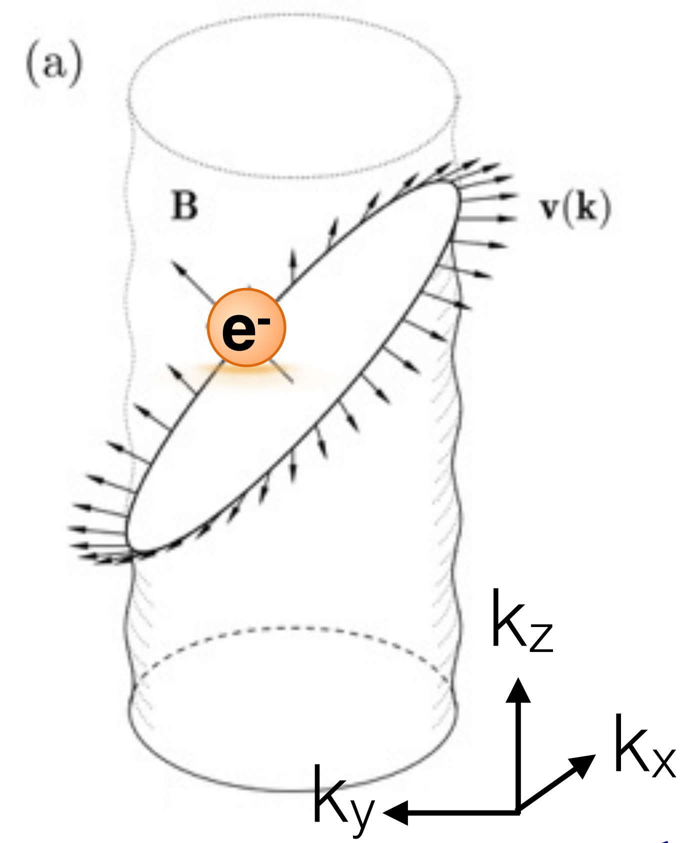
Part II: Quantum oscillations from Weyl orbits

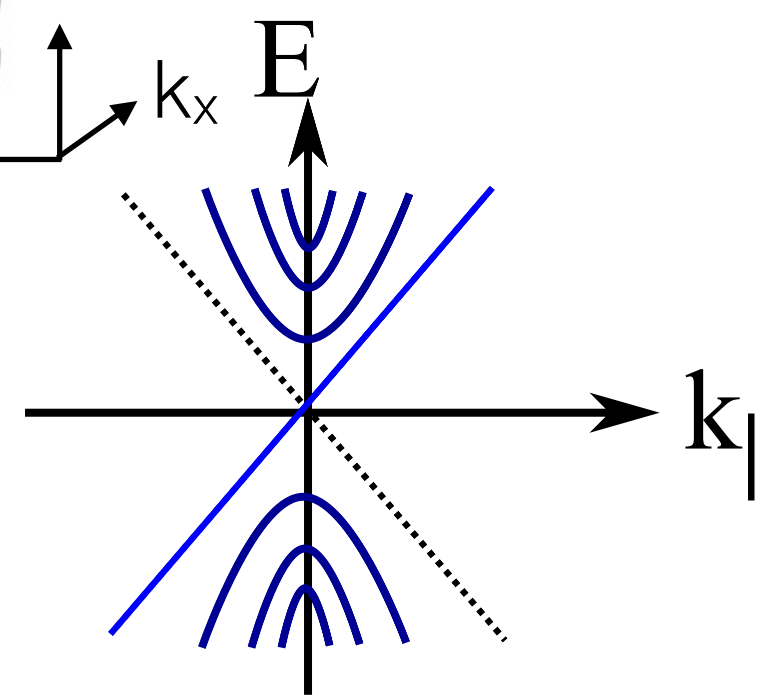
3D Dirac system Cd_3As_2

Philip J. W. Moll, JGA et al. arXiv:1505.02817

Intro to Weyl orbits

- Potter-Kimchi-Vishwanath theory (PKV) proposed quantum oscillations as a possible probe of Fermi arcs.
- Closed quasiparticle orbits result in Landau quantization of the energy spectrum, arising from the Bohr-Sommerfeld quantization.
- Oscillations in the density of states observable in magneto-transport, magnetization, heat capacity…….

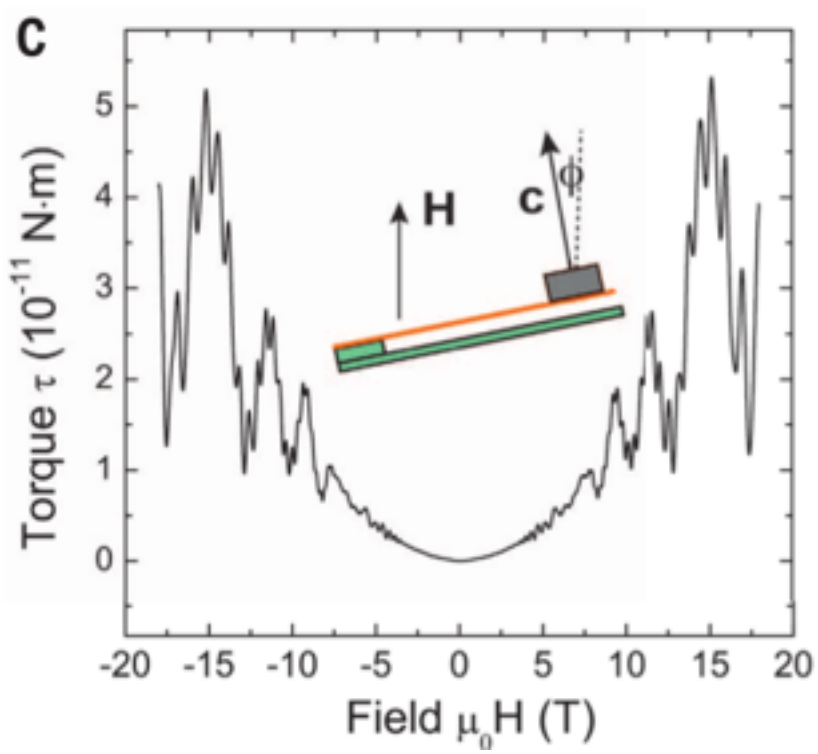


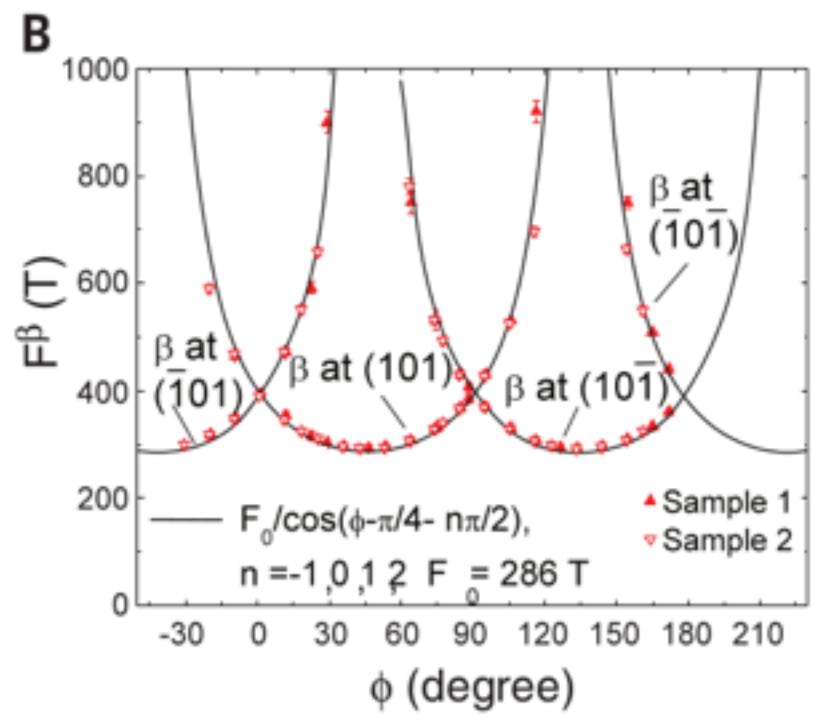


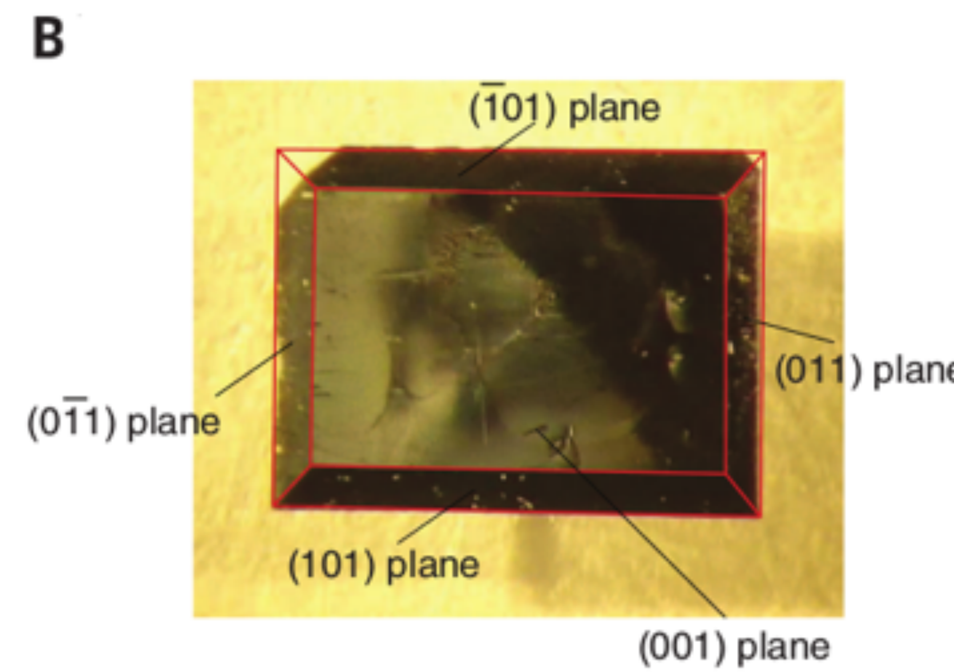
Bulk Landau Levels

Quantum oscillations as a probe of surface states

e.g. Li group SmB_6 (Science 2014)

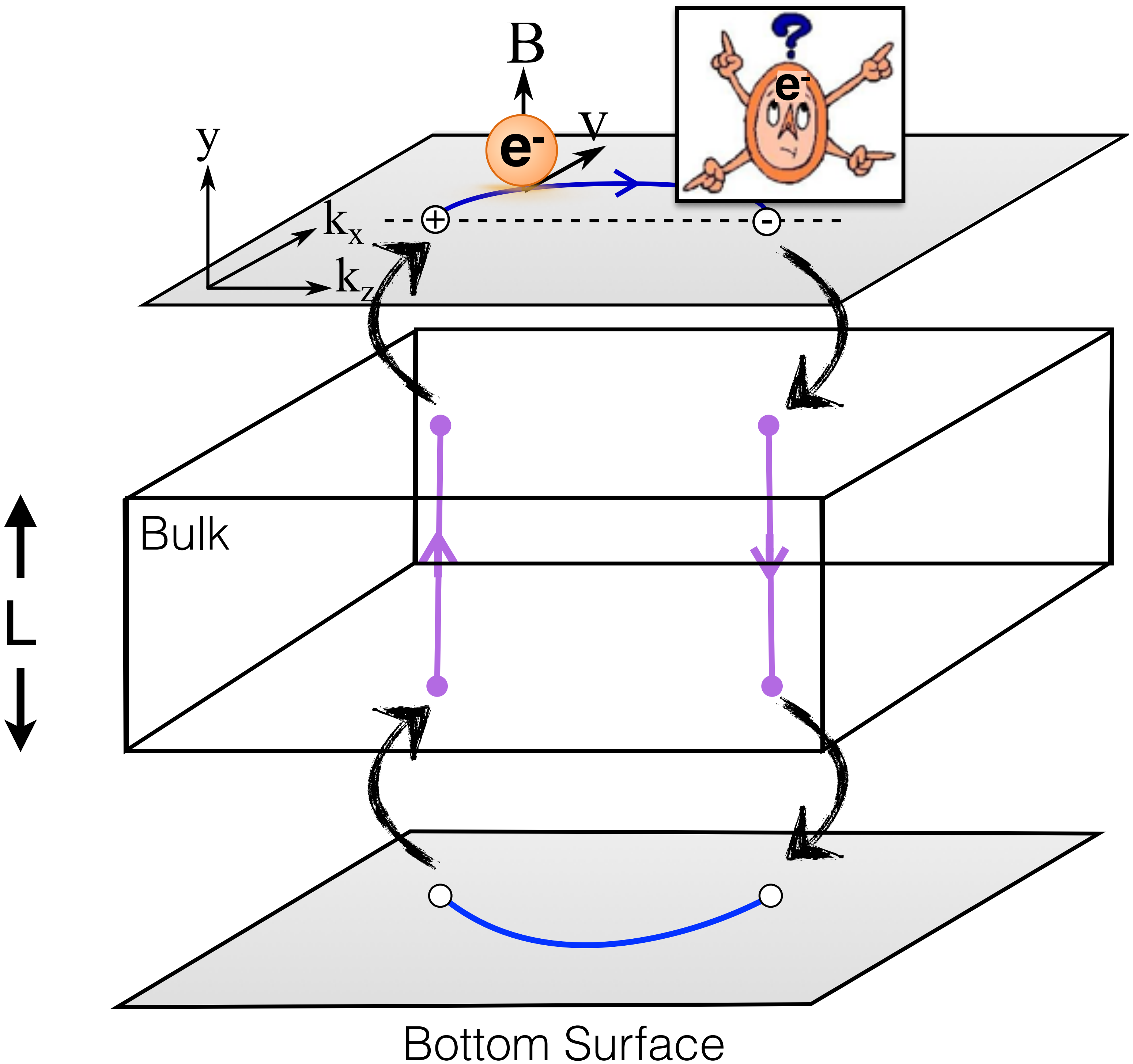


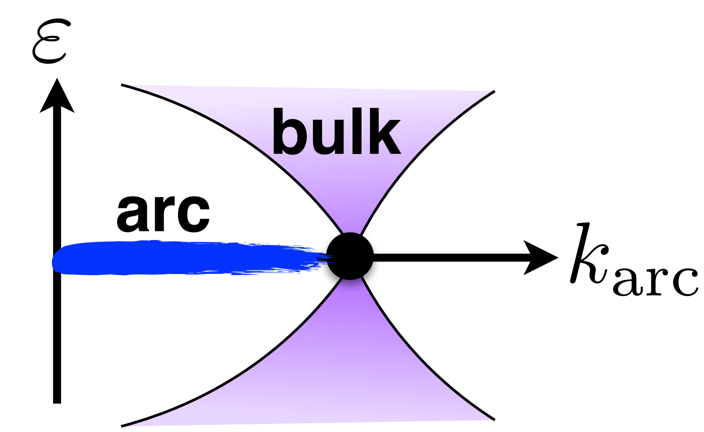




The chirality conveyor belt

Andrew C. Potter, I.Kimchi, A. Vishwanath, Nature Communications (2014)





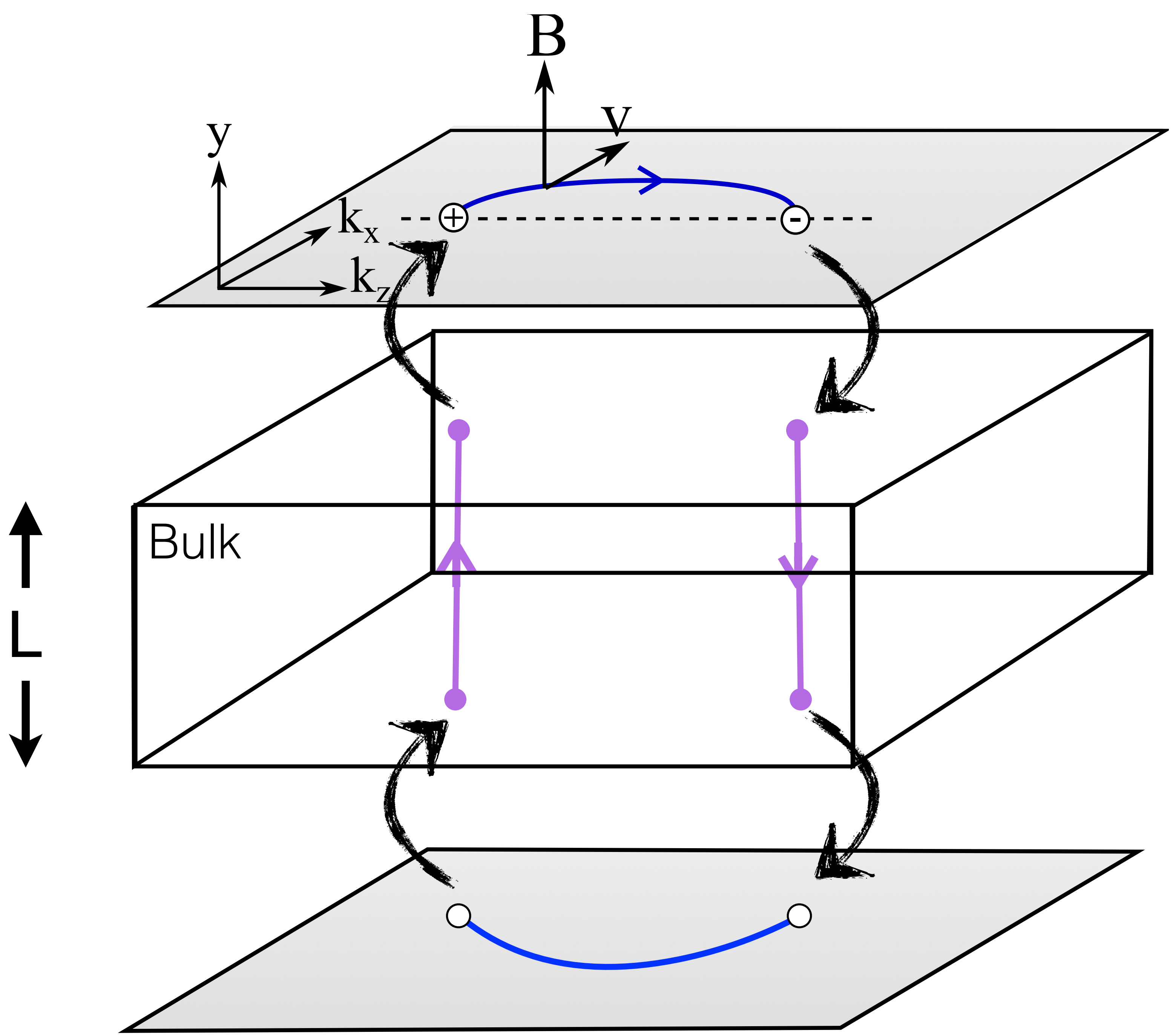
Surface-to-Bulk Transfer

$$t = 2\left(\frac{k_{\rm arc}}{evB} + \frac{L}{v}\right)$$

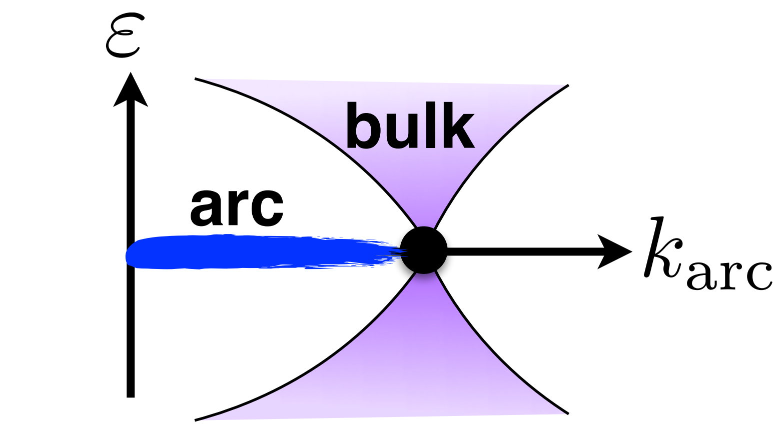
Arc **Bulk**

Weyl orbits

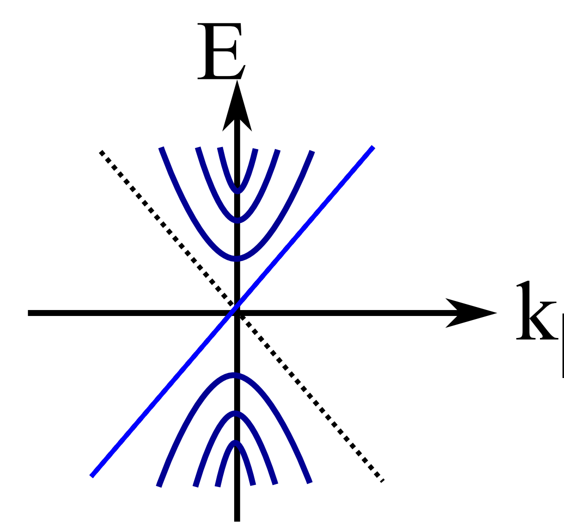
Andrew C. Potter, I.Kimchi, A. Vishwanath, Nature Communications (2014)



Bottom Surface

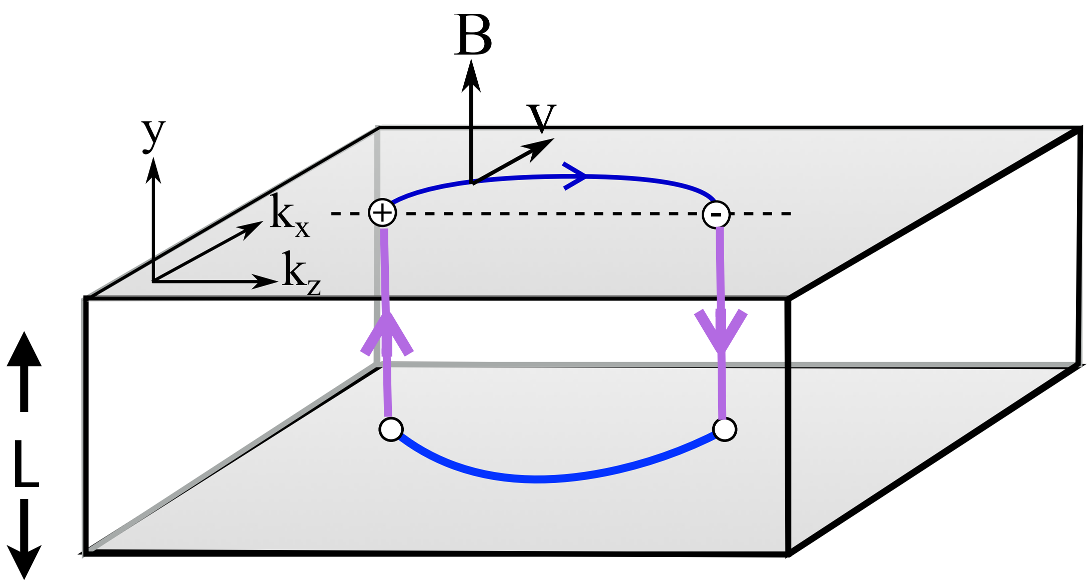


Surface-to-Bulk Transfer

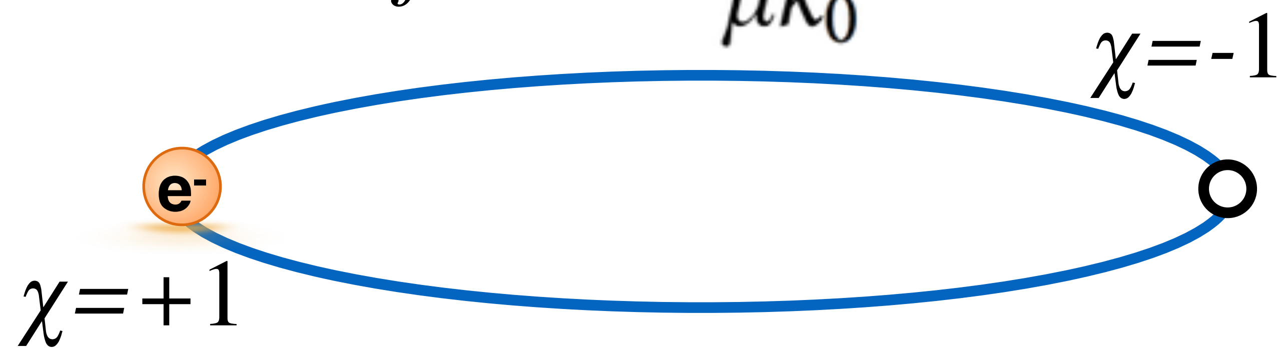


Bulk Landau Levels

Some remarks

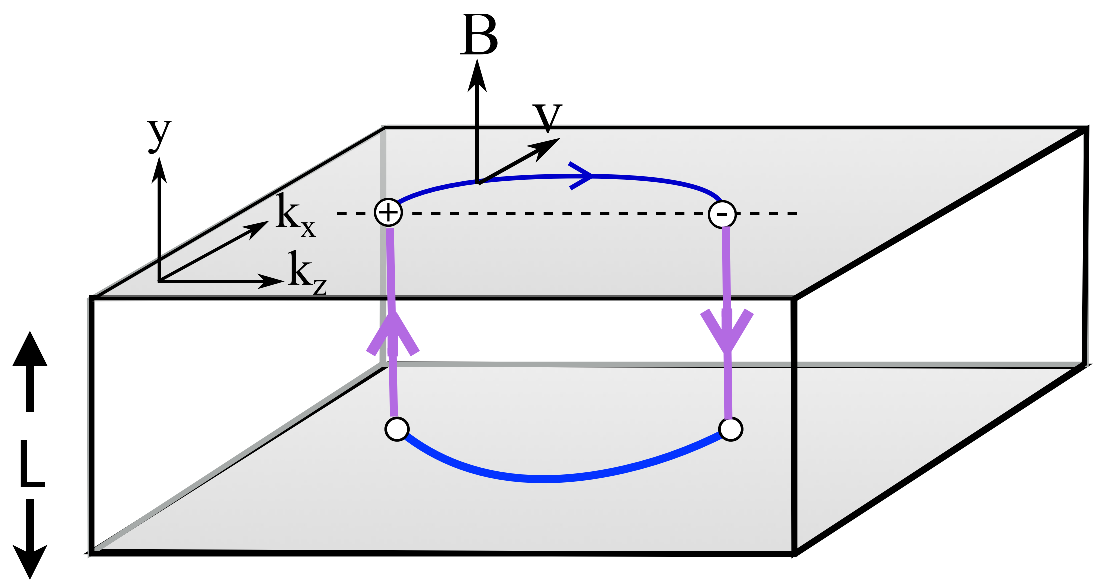


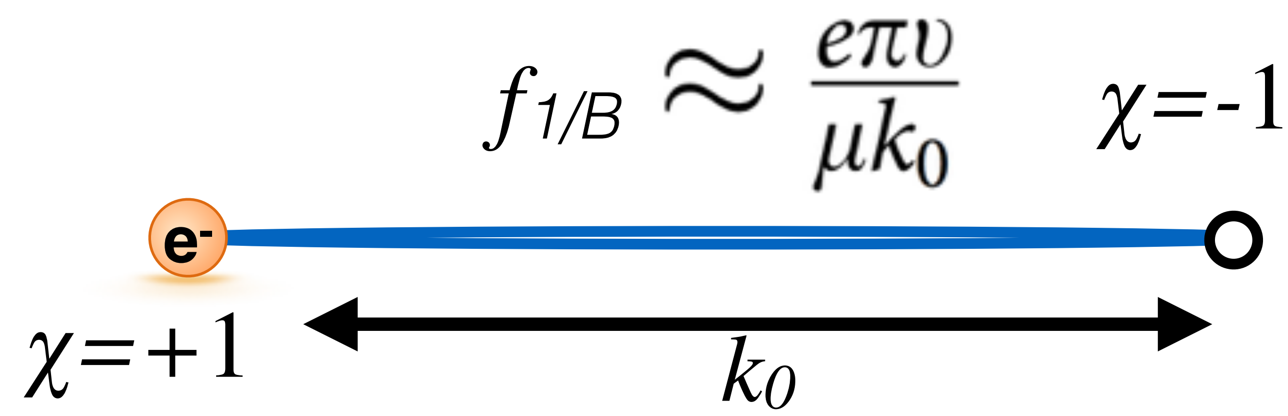
$$f_{1/B} \approx \frac{e\pi v}{\mu k_0}$$



- The cyclotron “Weyl” orbit involves a real space and k-space path.
- Real space trajectory encloses no flux (Lorentz force free path).
- From a quantum oscillatory point of view, it looks a lot like a 2D orbit with area A_k, or equivalently frequency $f_{1/B}$

Some remarks





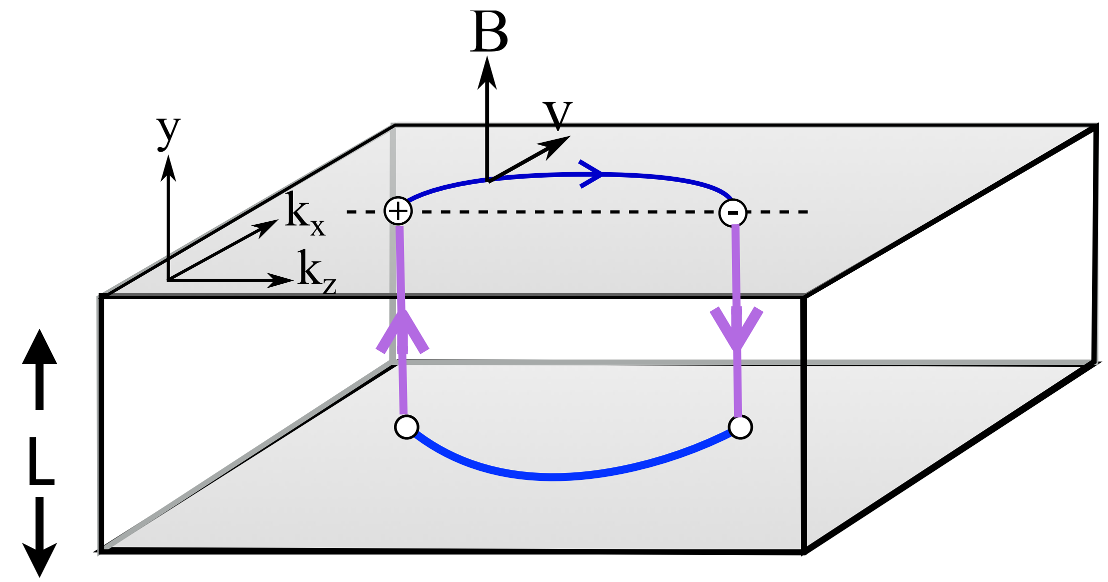
- The cyclotron “Weyl” orbit involves a real space and k-space path.
- Real space trajectory encloses no flux (Lorentz force free path).
- From a quantum oscillatory point of view, it looks a lot like a 2D orbit with area A_k, or equivalently frequency $f_{1/B}$

Distinguishing features

Quantization of semiclassical orbits

$$\varepsilon_n \approx \frac{2\pi n + \gamma}{t} \approx \frac{2\pi n + \gamma}{2\left(\frac{k_{\mathrm{arc}}}{evB} + \frac{L}{v}\right)}$$

Arc **Bulk**

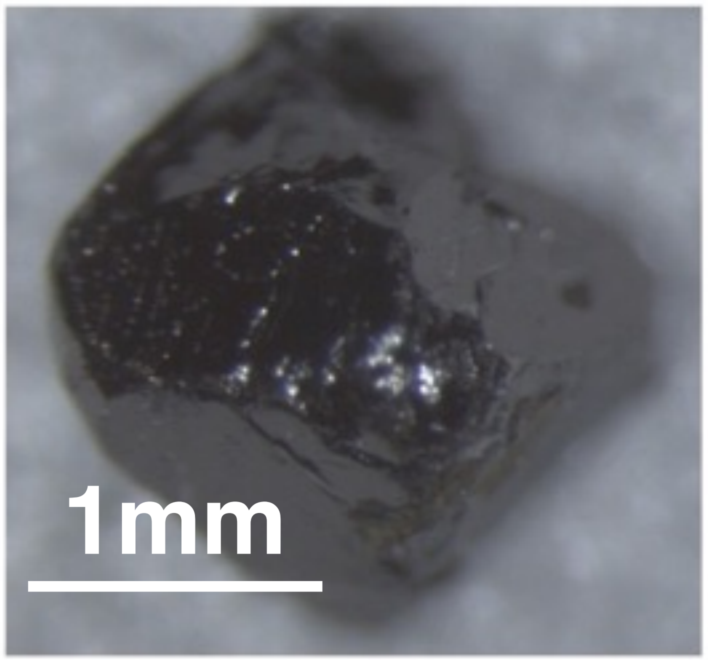


Quantum oscillations $\frac{1}{B_n} = \frac{2\pi n}{f_{1/B}} - \frac{e}{k_{\mathrm{arc}}} L$

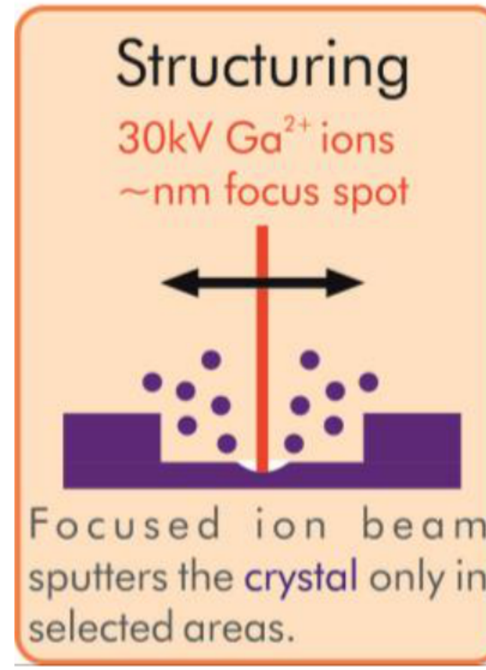
$f_{1/B}$

$B^* \approx \frac{k_{\mathrm{arc}}}{L}$

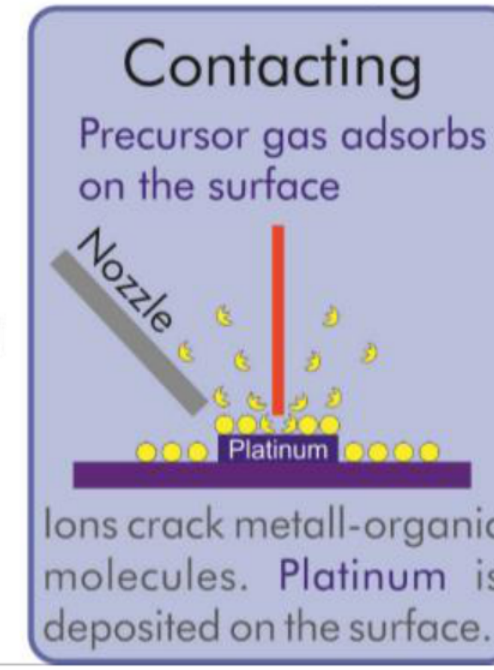
Thickness-dependent quantum oscillatory study in Cd_3As_2



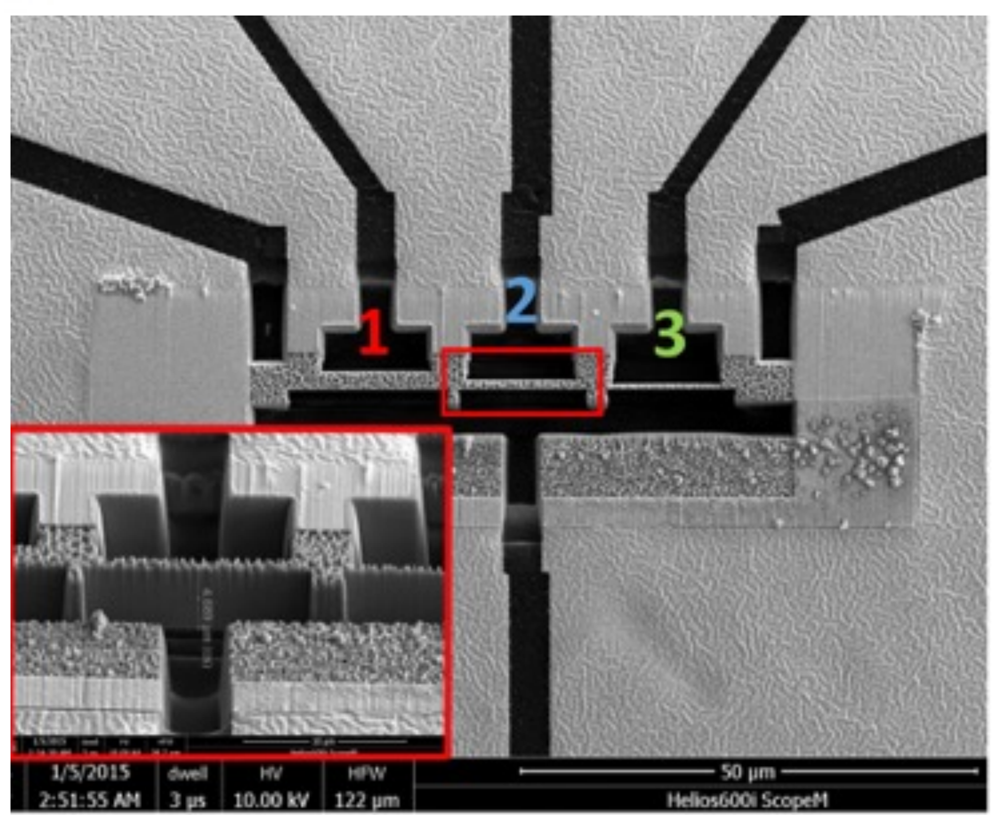
+



+

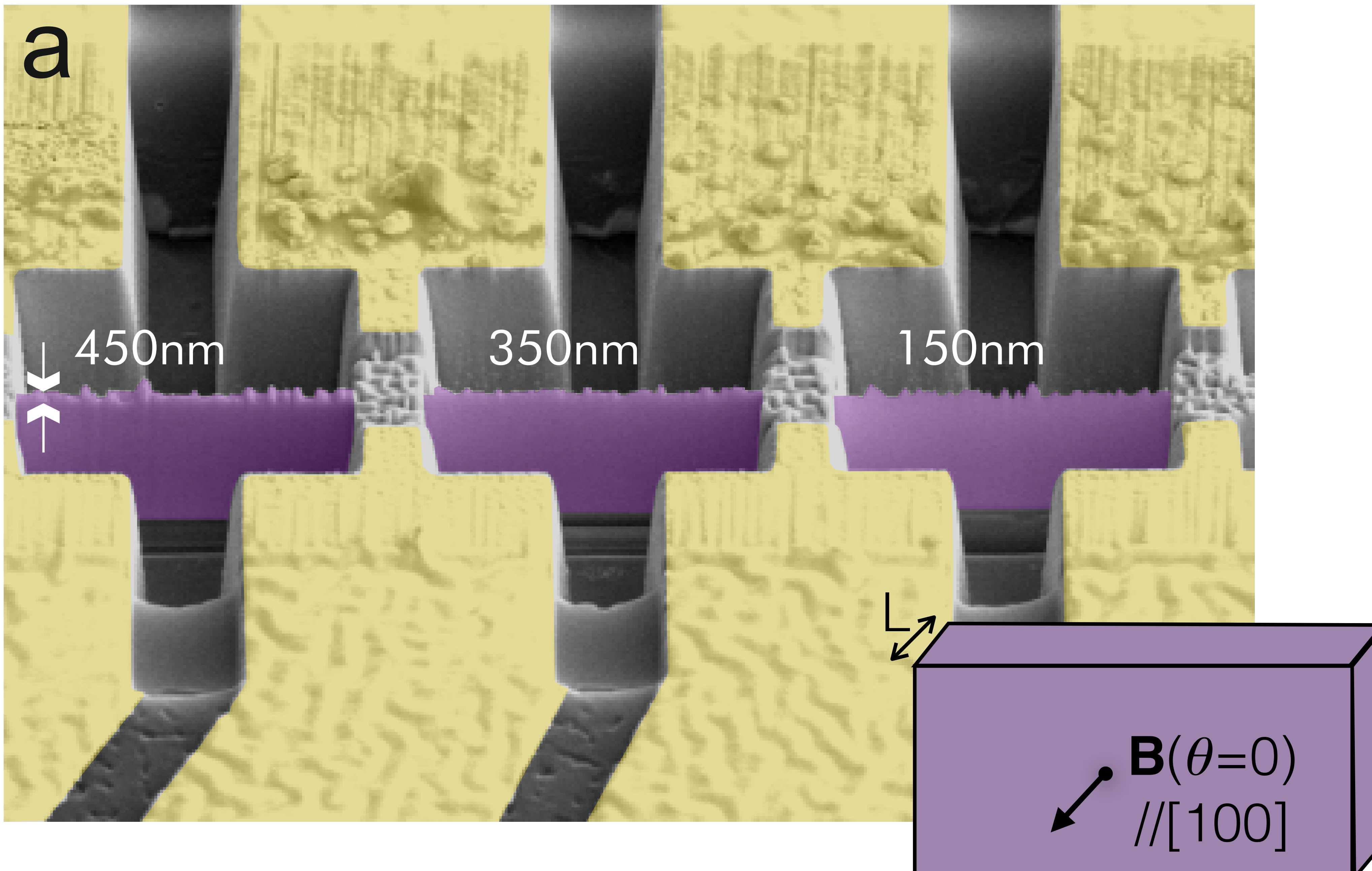


=

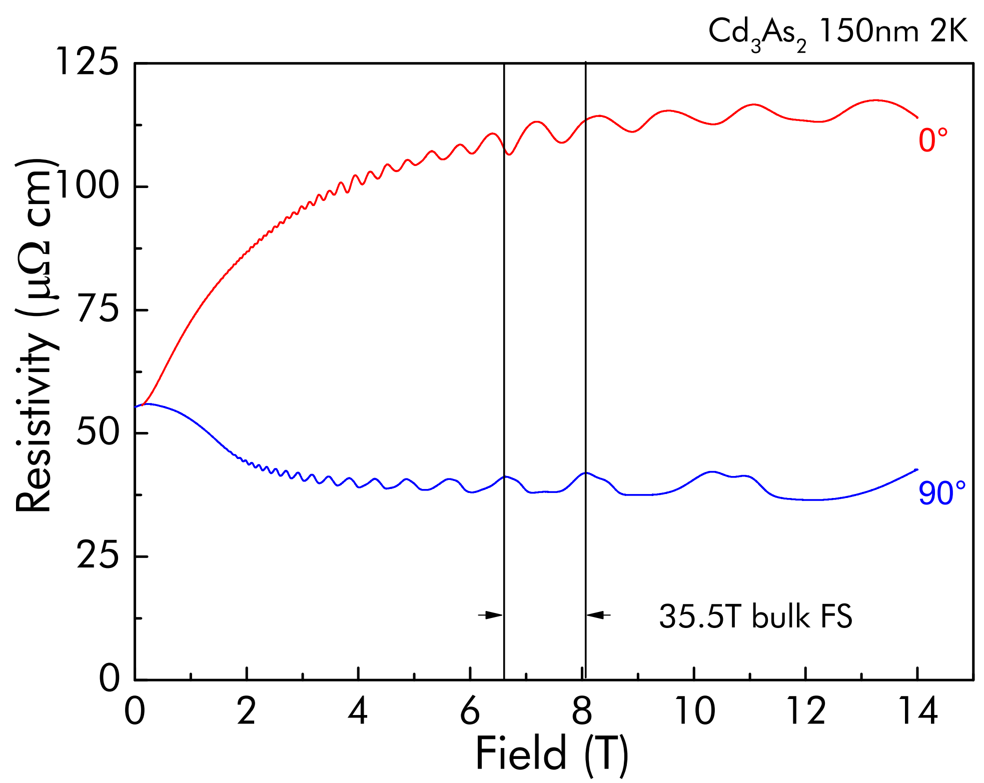


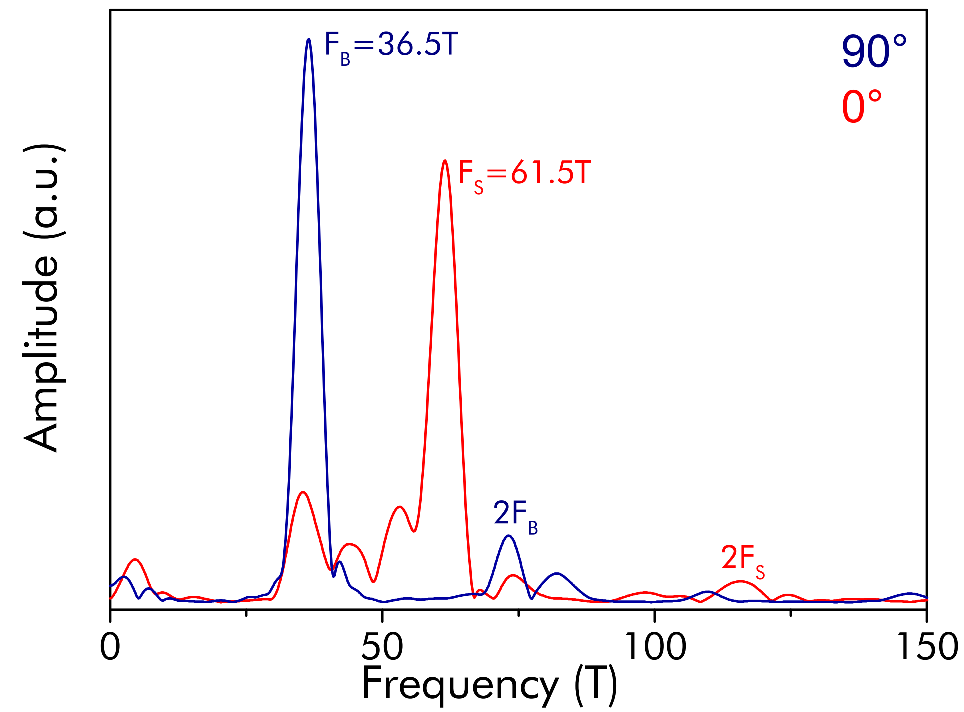
Thickness-dependent quantum oscillatory study in Cd_3As_2

Philip J. W. Moll, JGA *et al.* *arXiv:1505.02817*



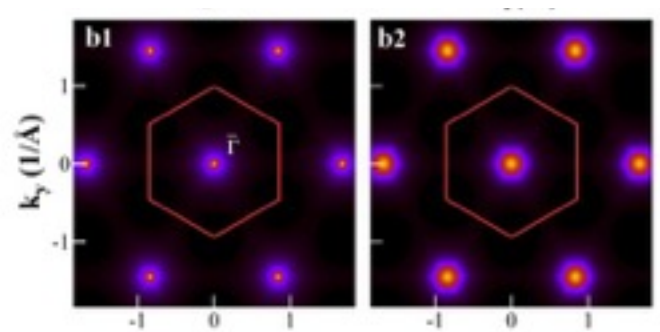
New quantum oscillatory frequency at ~60T (k_0~$0.08Å^{-1}$)



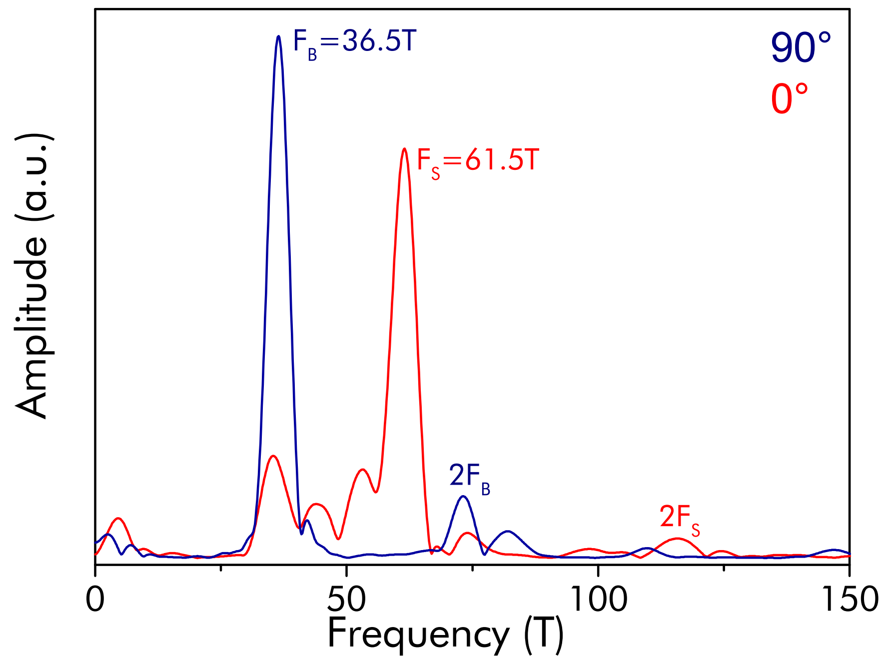


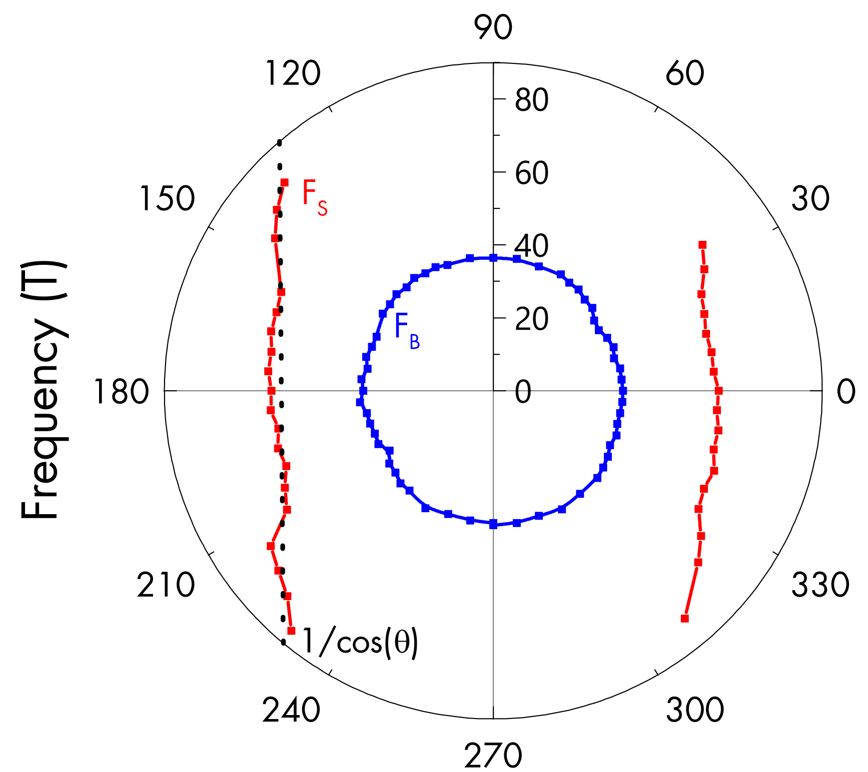
Note this is approximately the k_0 measured by ARPES

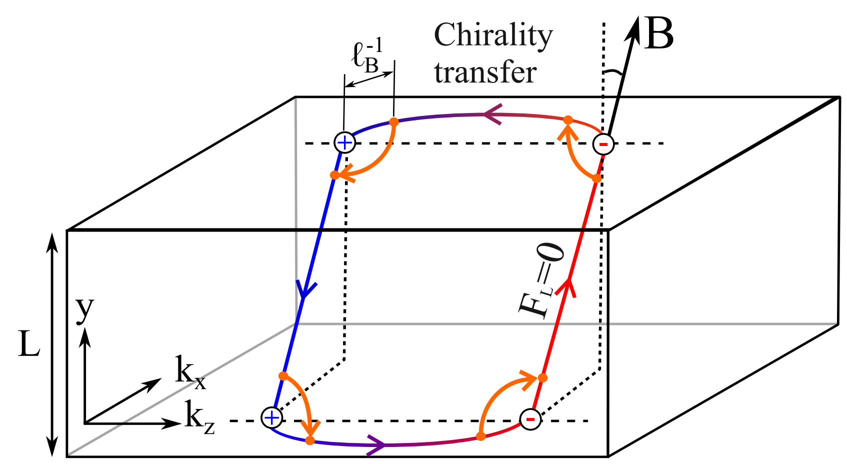
Yi et al. *Sci. Rep.* **4**, 6106 (2014)



Oscillations are 2D



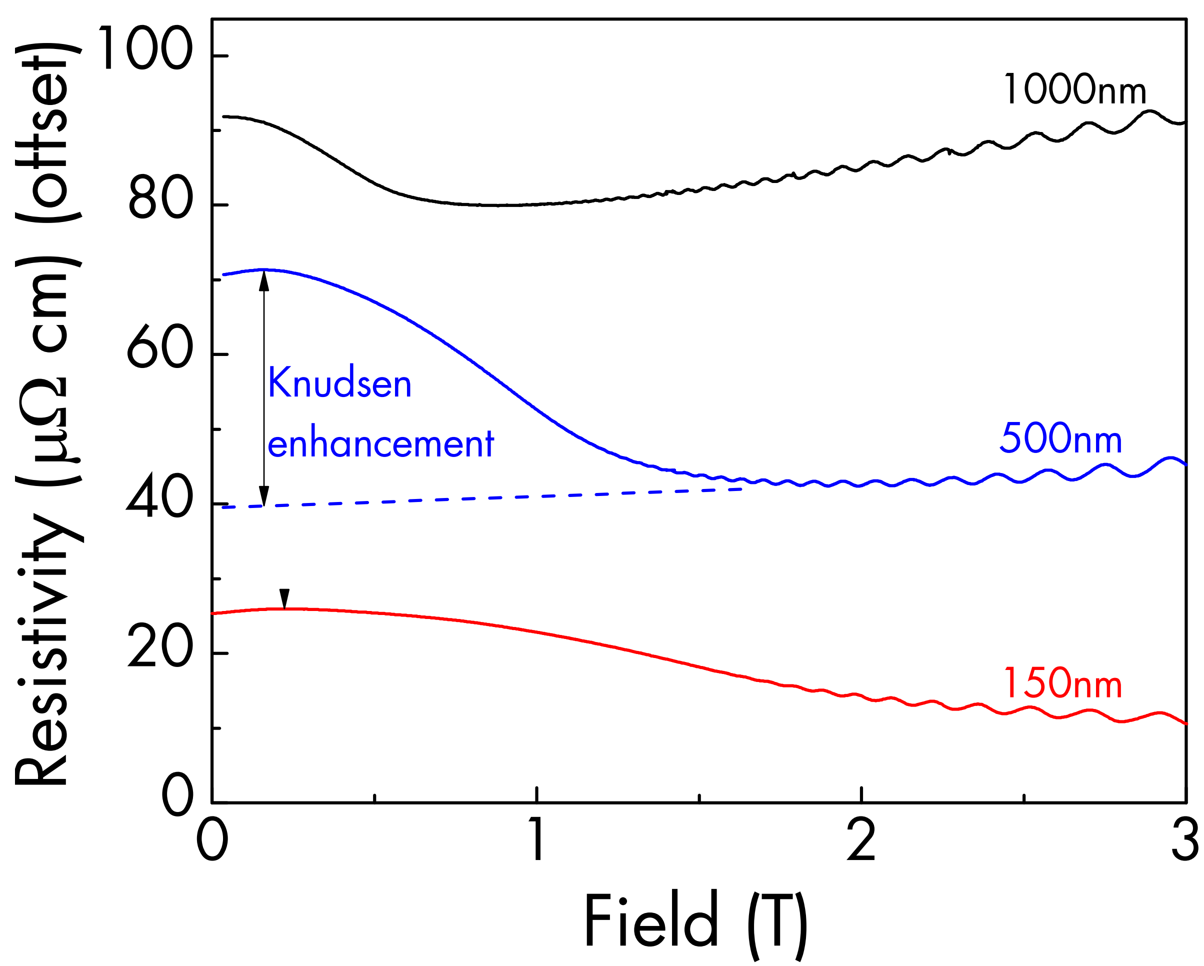


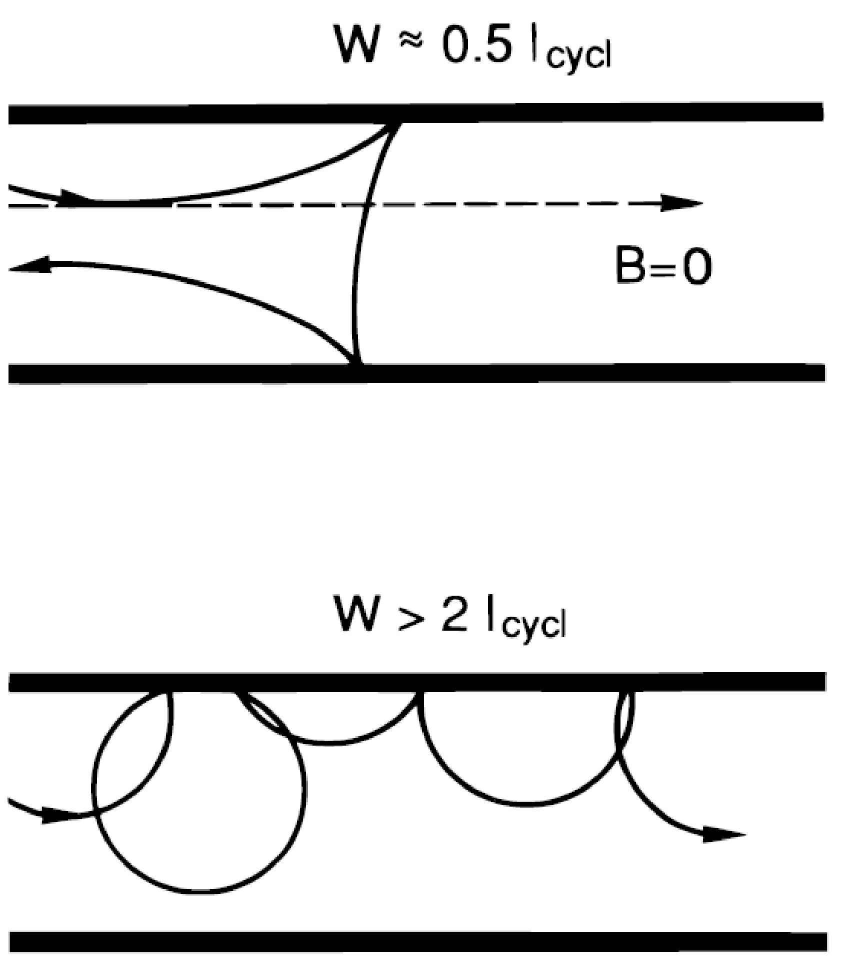


Philip J. W. Moll, JGA et al. arXiv:1505.02817

Amplitude onsets at $L \sim 2l$ (Knudsen effect)

(*B* Parallel to surface only)

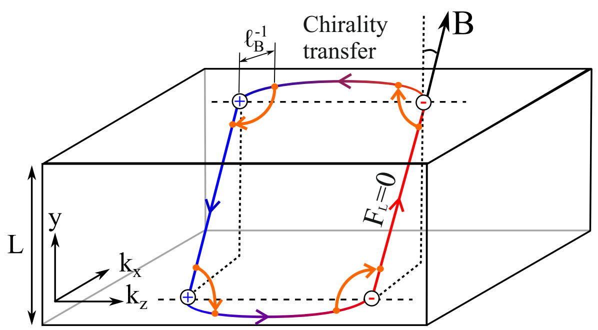




$\ell_{\rm MFP} \approx 1.2\mu m$

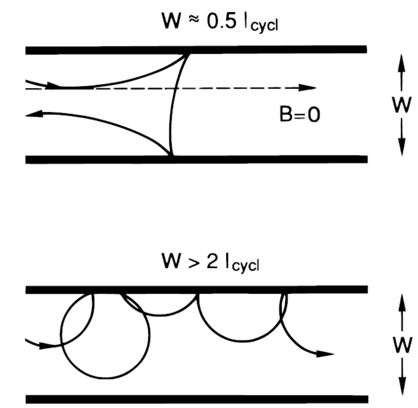
Philip J. W. Moll, JGA et al. arXiv:1505.02817

And grows exponentially with thinness

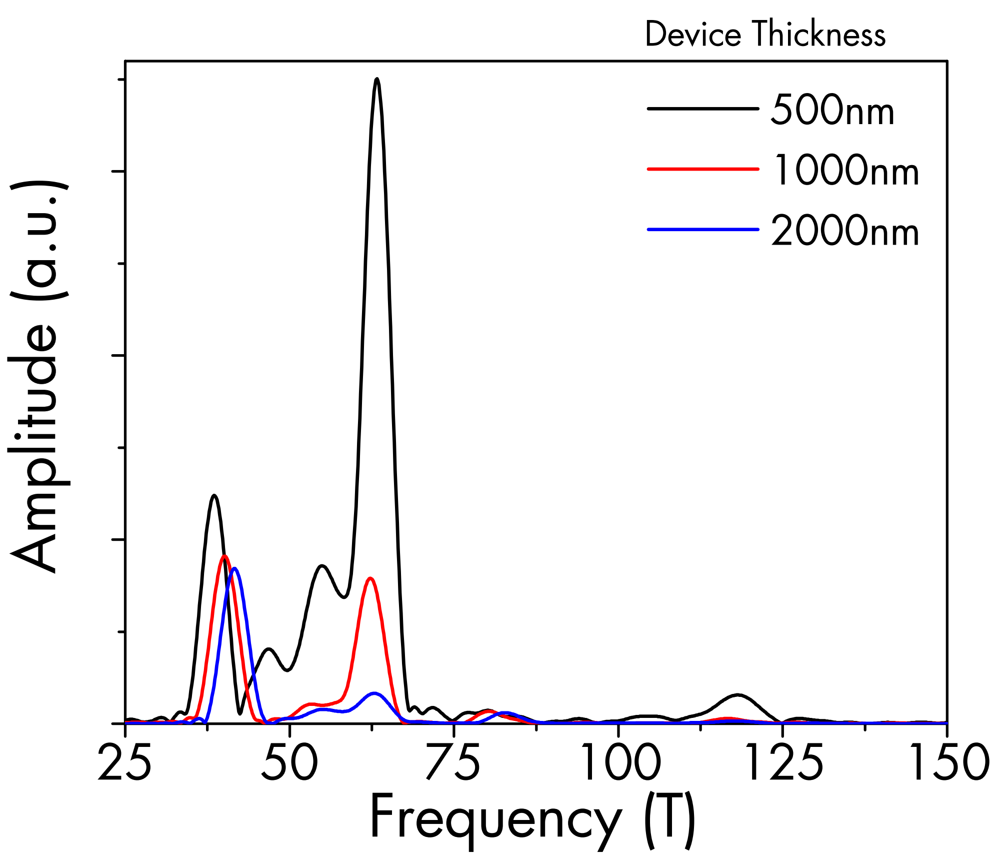


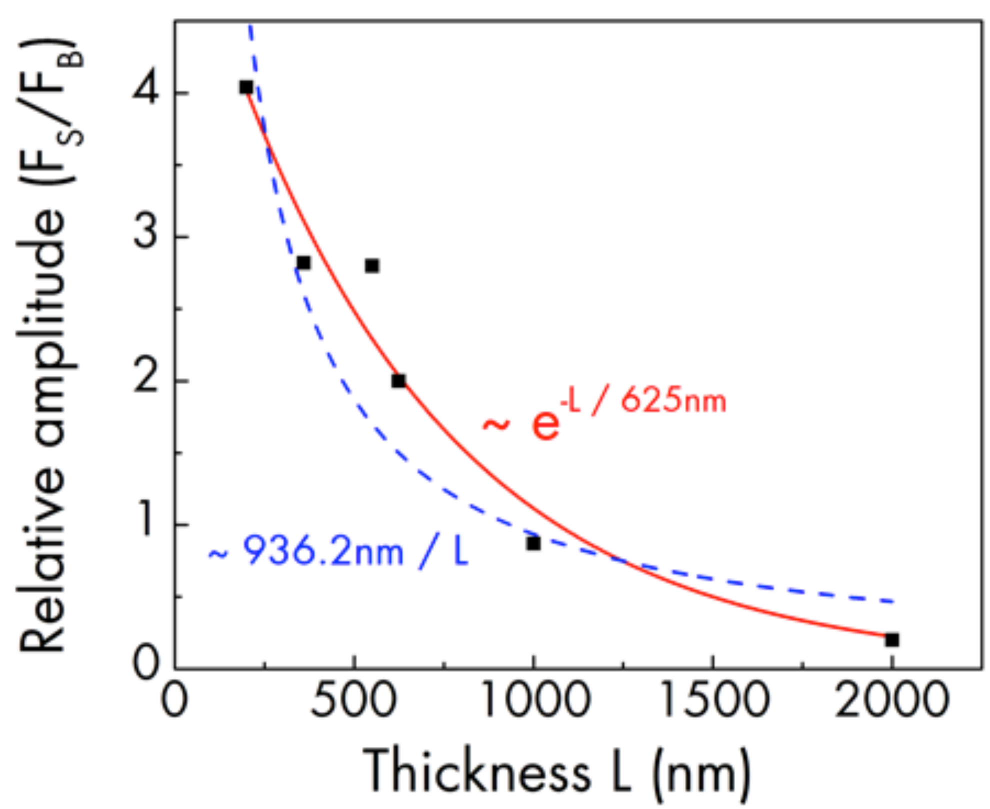
$$A_{\mathrm{SdH}} \sim e^{-1/\omega_c \tau}$$

$$\text{“}\frac{1}{\omega_c \tau}\text{”} \approx \frac{k_0}{e v_s B}\tau_s^{-1} + \frac{L}{v_B}\tau_B^{-1}$$



$$\ell_{\mathrm{MFP}} \approx 1.2\mu m$$

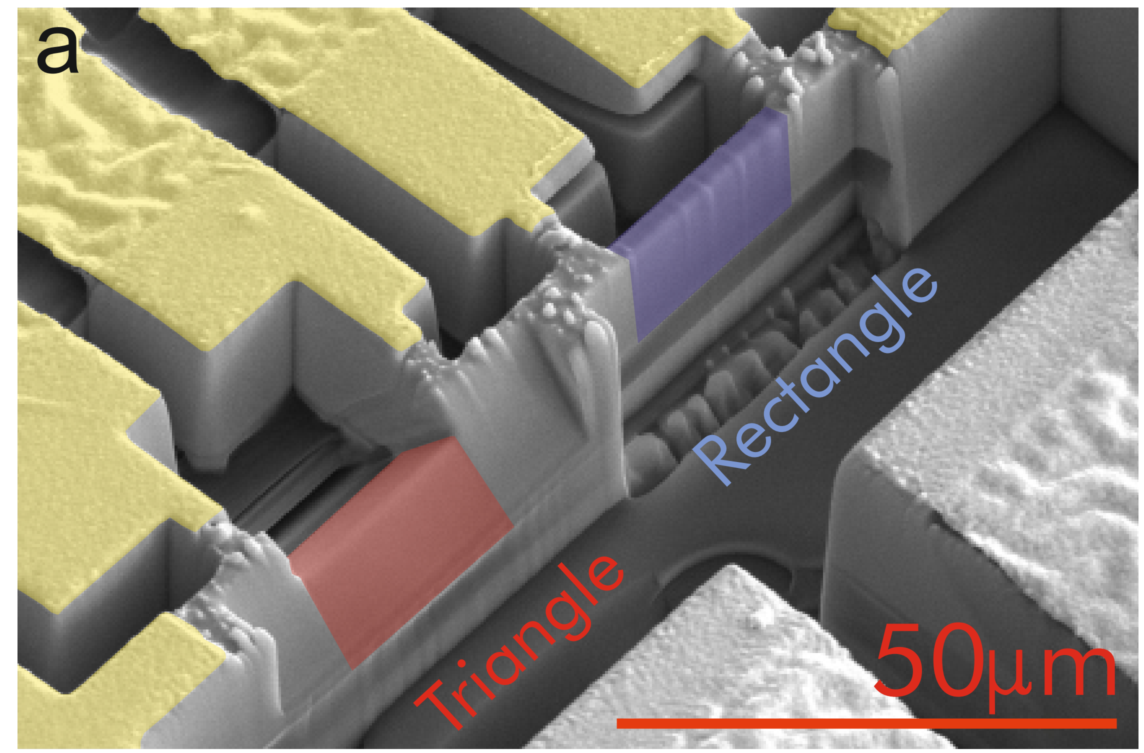


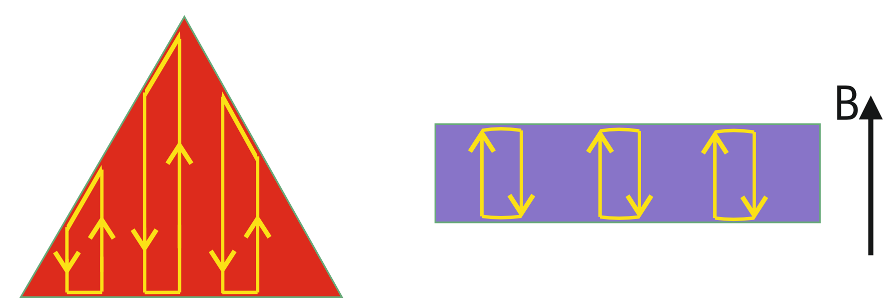


Philip J. W. Moll, JGA et al. arXiv:1505.02817

Does the phase of the oscillations depend on thickness?

- Detailed thickness dependence prohibitively difficult at the moment (frequency is too high and would require 1nm thickness dependence)
- So we came up with something different - a triangular geometry.
- The orbit is averaging over all length scales, causing the QOs to destructively interfere.





$$\frac{1}{B_n} = \frac{2\pi n}{f_{1/B}} - \frac{e}{k_{\rm arc}} L$$

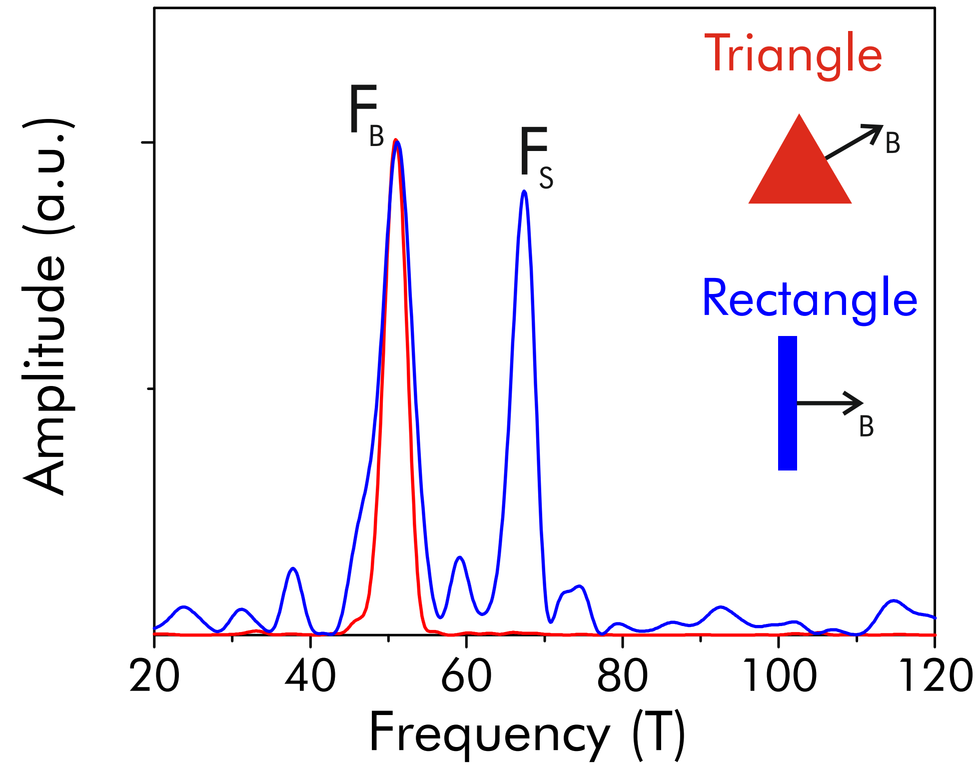
Philip J. W. Moll, JGA et al. arXiv:1505.02817

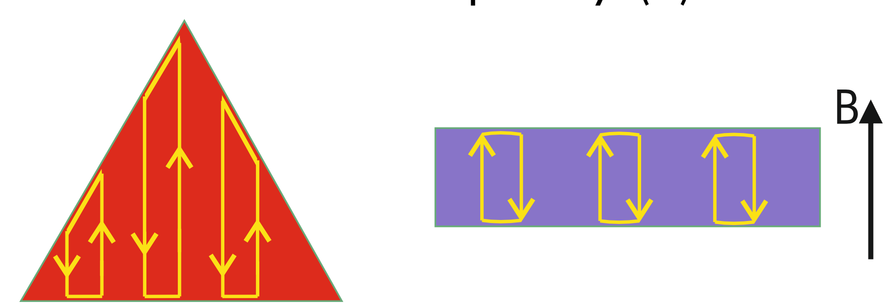
Does the phase of the oscillations depend on thickness?

- Detailed thickness dependence prohibitively difficult at the moment (frequency is too high and would require 1nm thickness dependence)

- So we came up with something different - a triangular geometry.

- The orbit is averaging over all length scales, causing the QOs to destructively interfere.

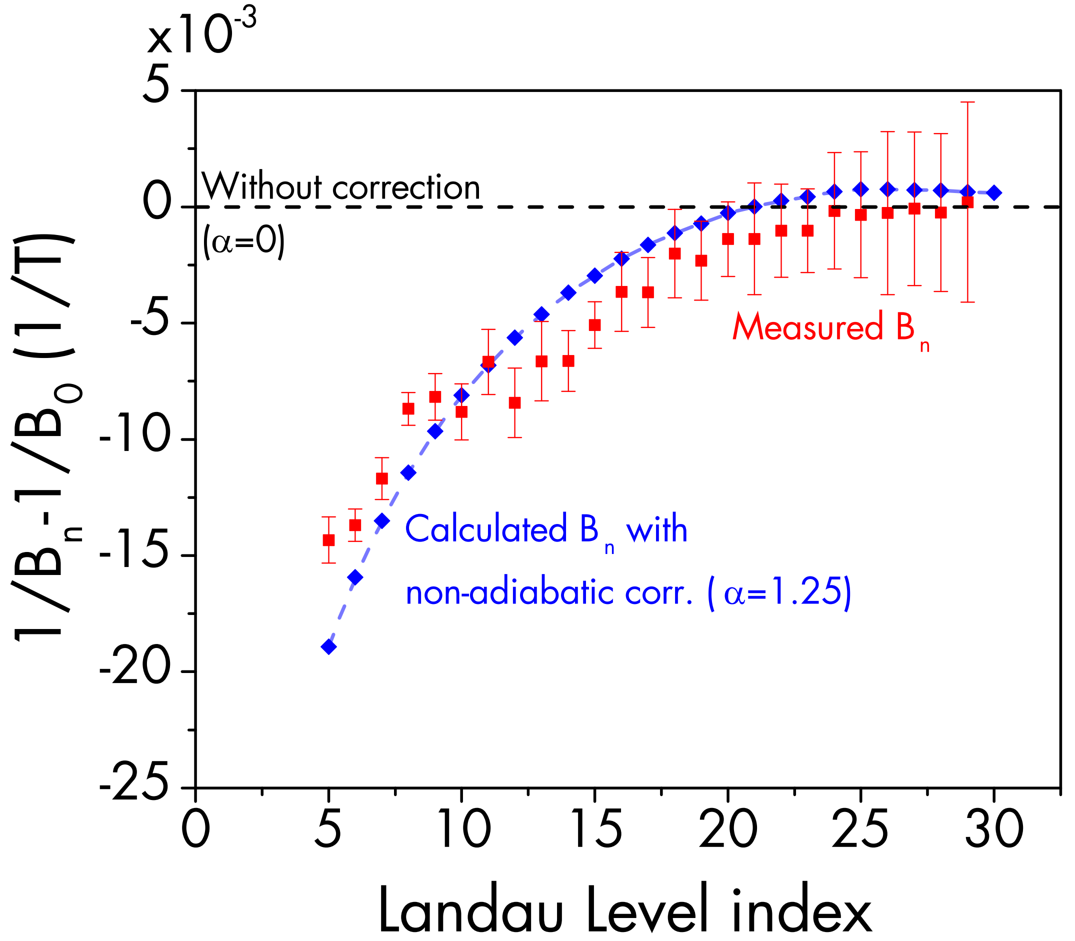


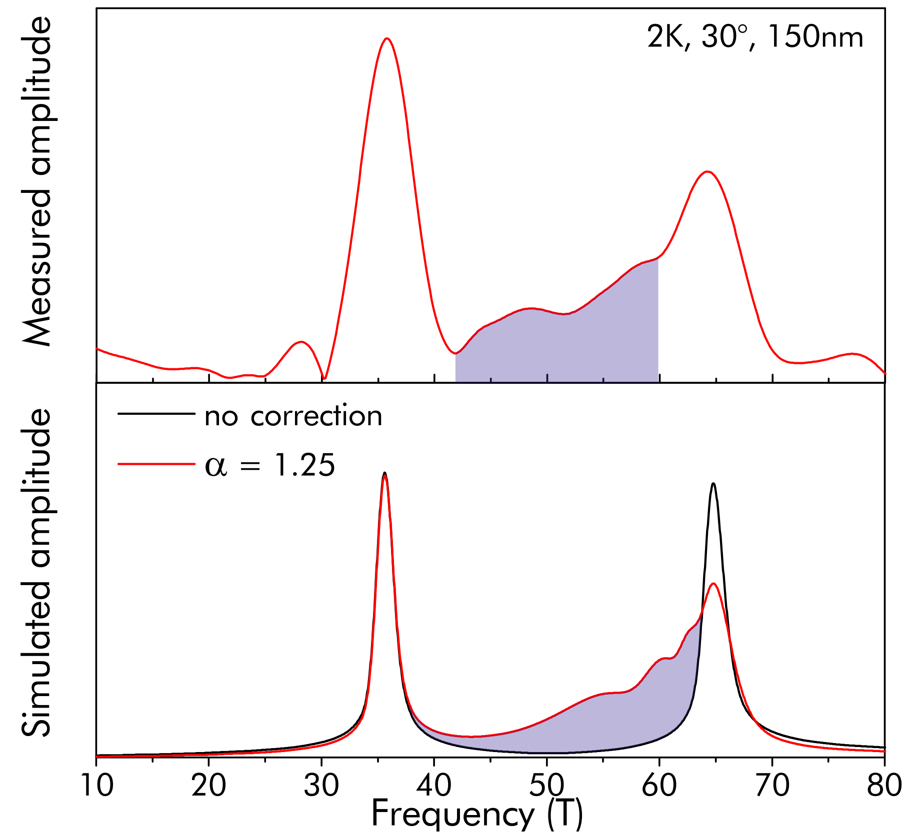


$$\frac{1}{B_n} = \frac{2\pi n}{f_{1/B}} - \frac{e}{k_{\mathrm{arc}}} L$$

Philip J. W. Moll, JGA et al. arXiv:1505.02817

Some other, unexpected details





Philip J. W. Moll, JGA et al. arXiv:1505.02817

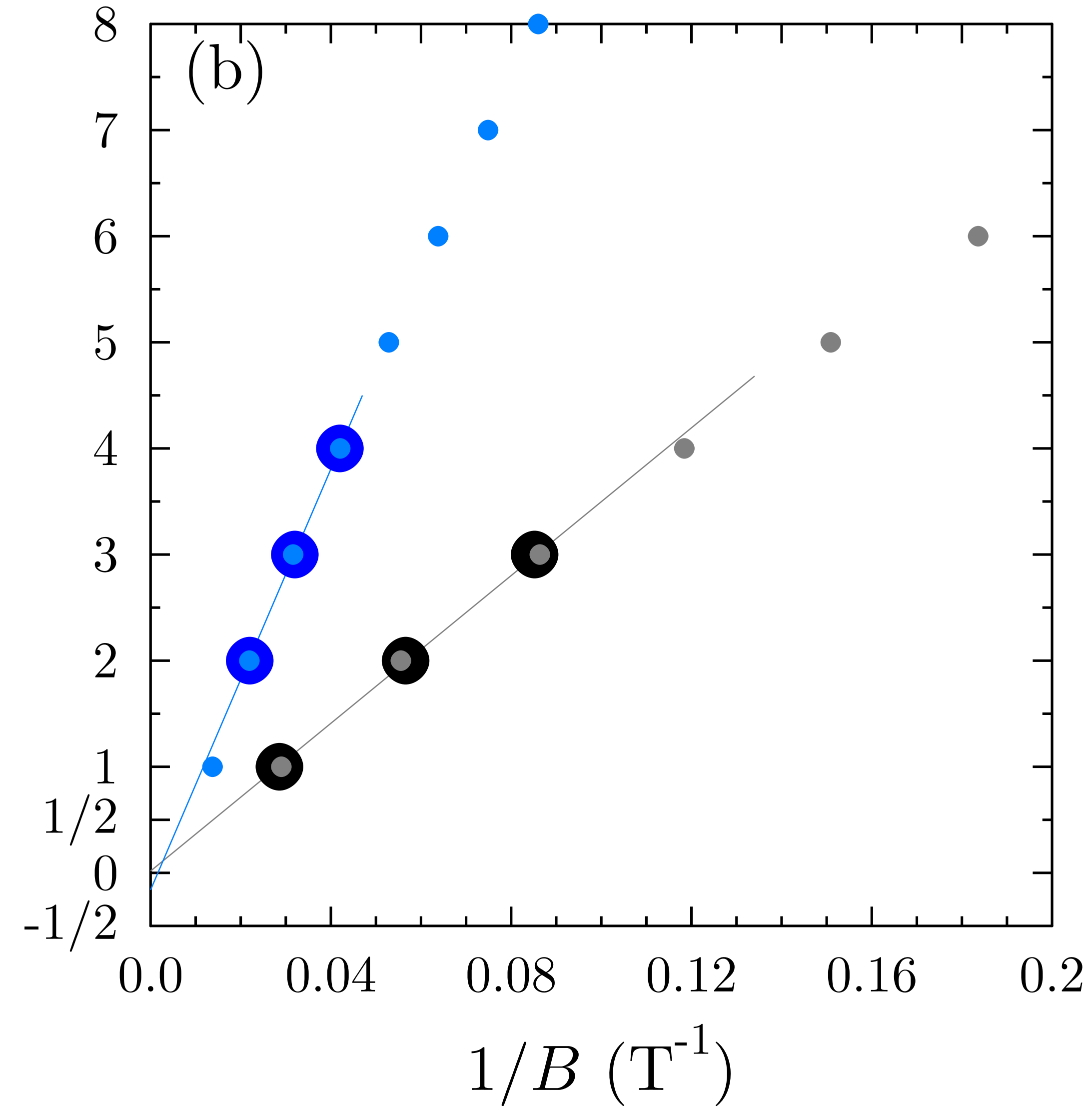
Mass corrections in TI surface states?

- Seen in Rashba systems (BiTeI) and TIs

- But….

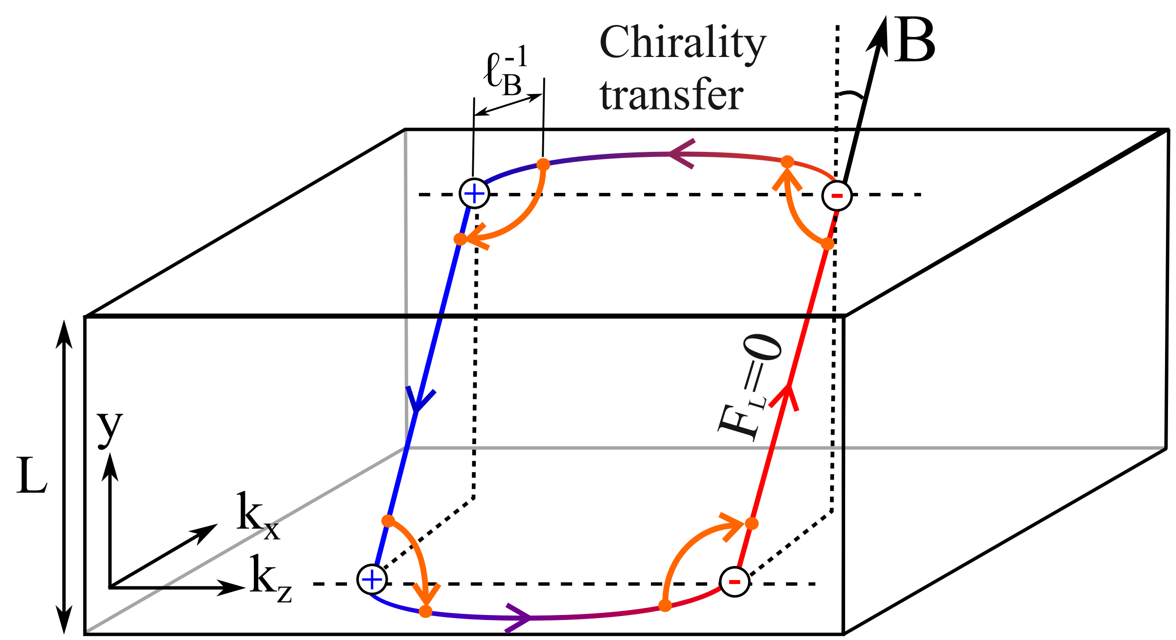
    1. the effect seems to go in the wrong direction

    2. The g-factor required is 300 (10x anything measured in these compounds)



Analytis et al Nature Physics 2010

Non-adiabatic corrections in Weyl orbits?



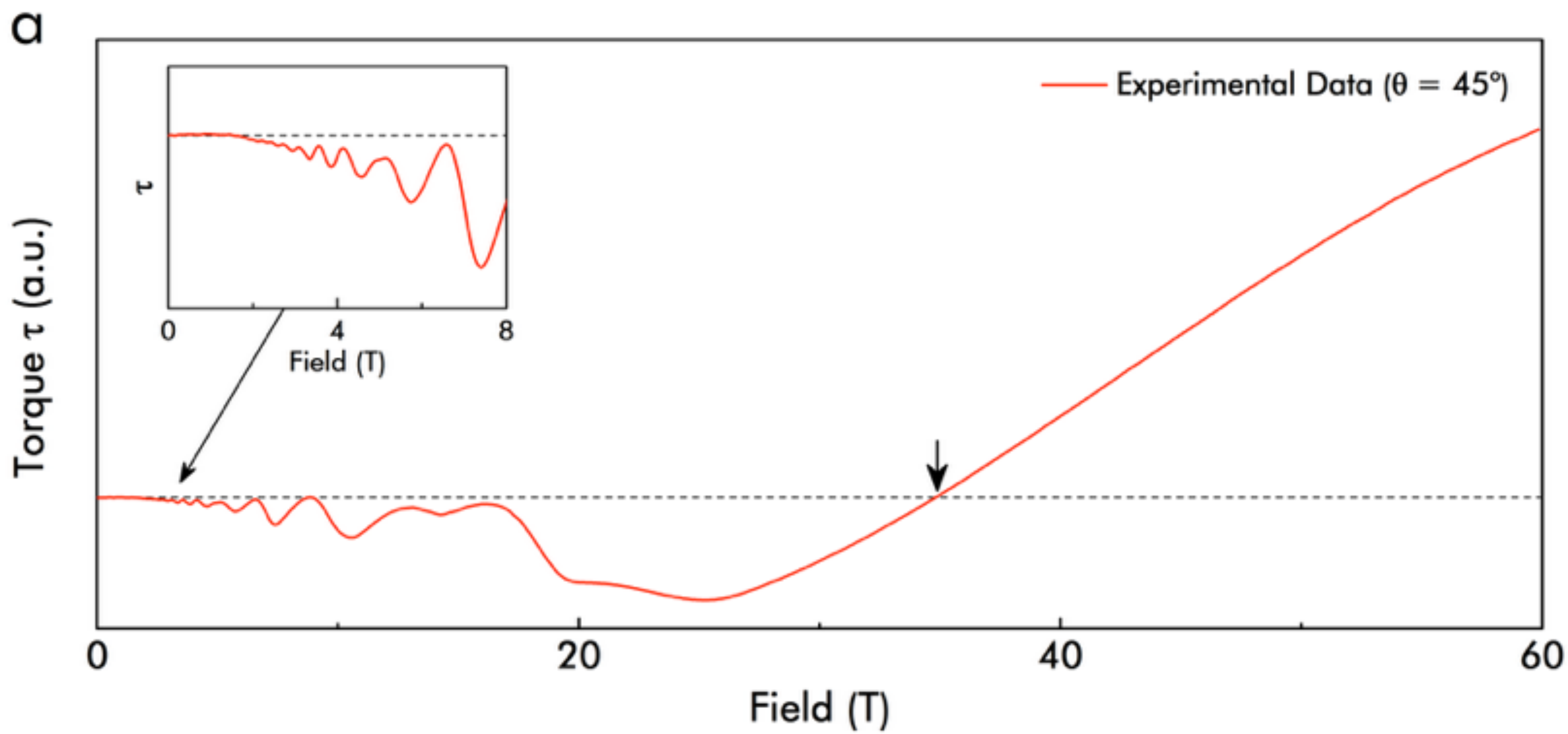
$$\delta F_s(B) \approx -4\alpha \frac{\ell_B}{k_{\rm arc}}$$

Andrew C. Potter, I.Kimchi, A. Vishwanath, Nature Communications (2014)

We get α~1.2

Philip J. W. Moll, JGA et al. arXiv:1505.02817

Observation	Trivial	Weyl
2D QOs	Y	Y
Frequency ~56T	Coincidence	Y
Amplitude exponential with L	Close	Y
Onset at L=2l	Coincidence	Y
Parallel surface required	N	Y
Field dependent phase.	Unphysical	Y
Saturation field B*	N	N (not yet)

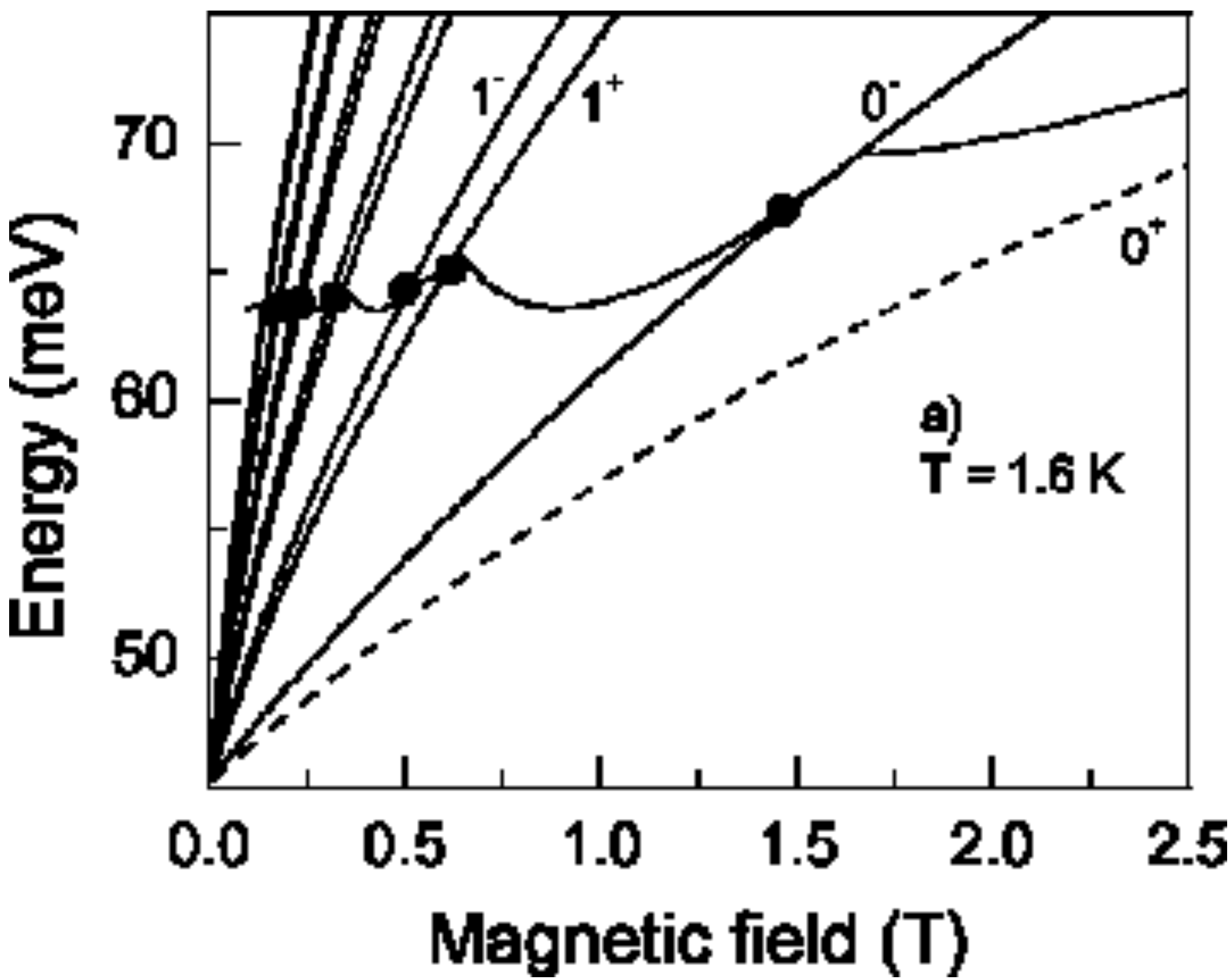


Part III: Berry paramagnetism and the quantum limit torque anomaly.

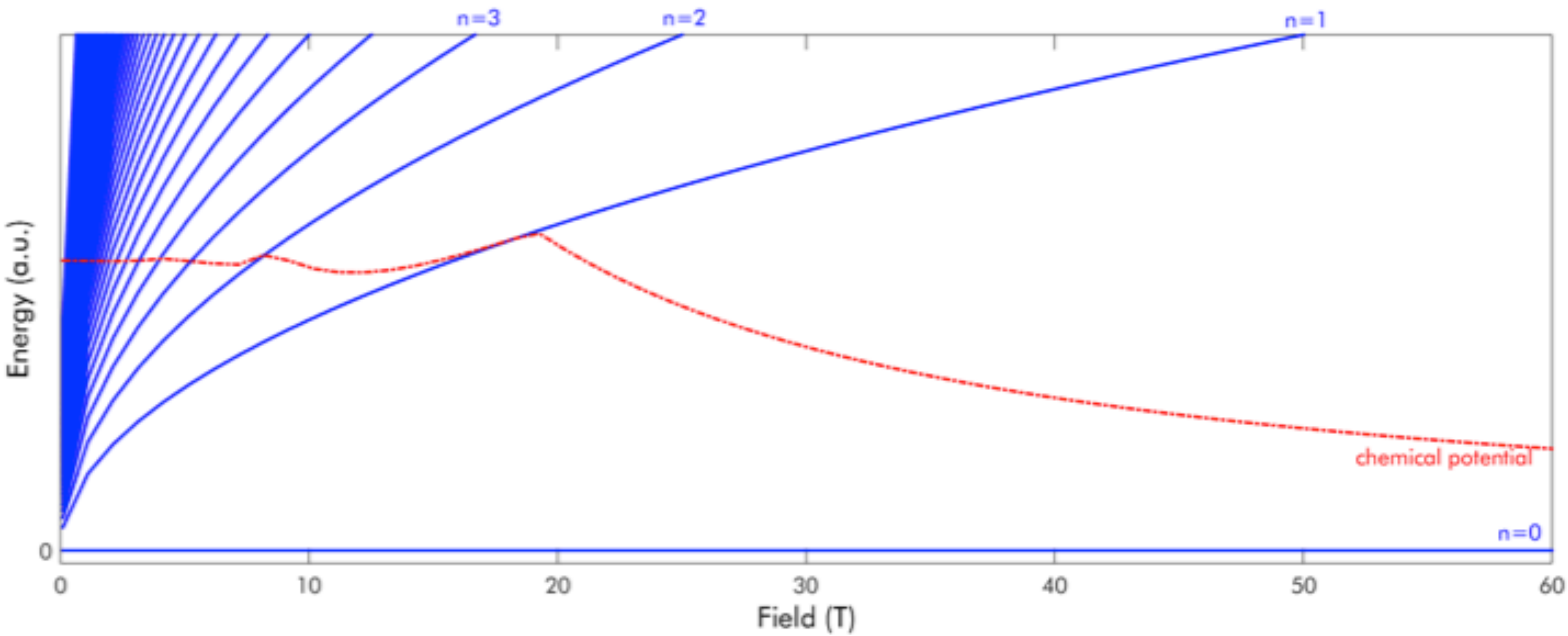
Inversion symmetry breaking NbAs

Philip J. W. Moll, JGA et al. arXiv:1507.06981

Landau diamagnetism



Berry paramagnetism



Philip J. W. Moll, JGA et al. arXiv:1507.06981

The quantum limit n=0

TRIVIAL

Loosely speaking

$E=\hbar\omega(n+\frac{1}{2})$

In the quantum limit

$\mathcal{M}_T=-dE/dB \cong -\hbar\omega/2B$

DIRAC

Loosely speaking

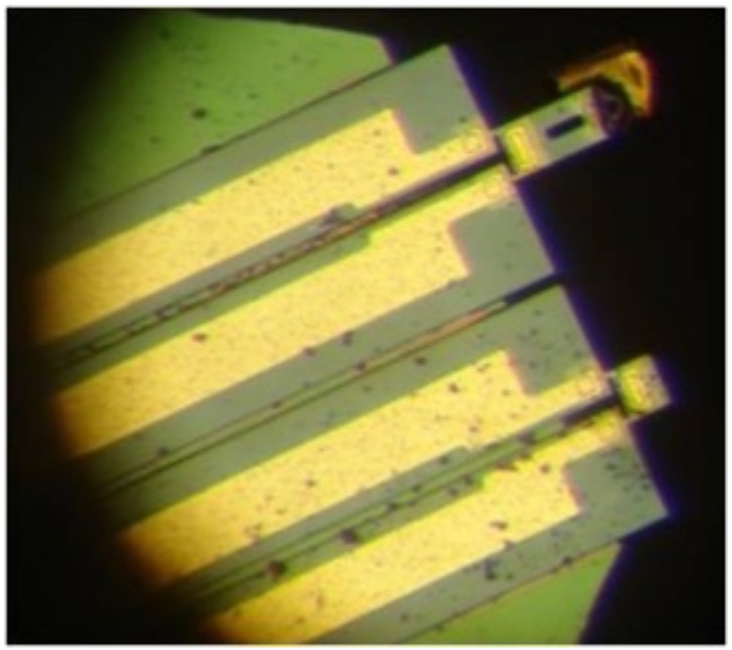
$E=v_F\sqrt{2e\hbar Bn}$

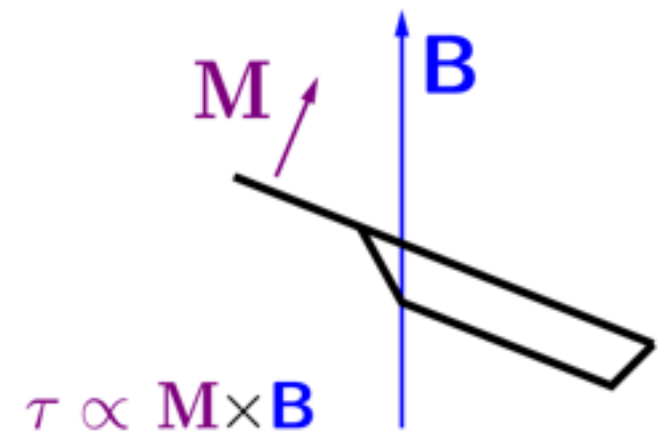
In the quantum limit

$\mathcal{M}_D=-dE/dB=0$

$$\mathcal{M}_{Tot} = \mathcal{M}_T + \mathcal{M}_D$$

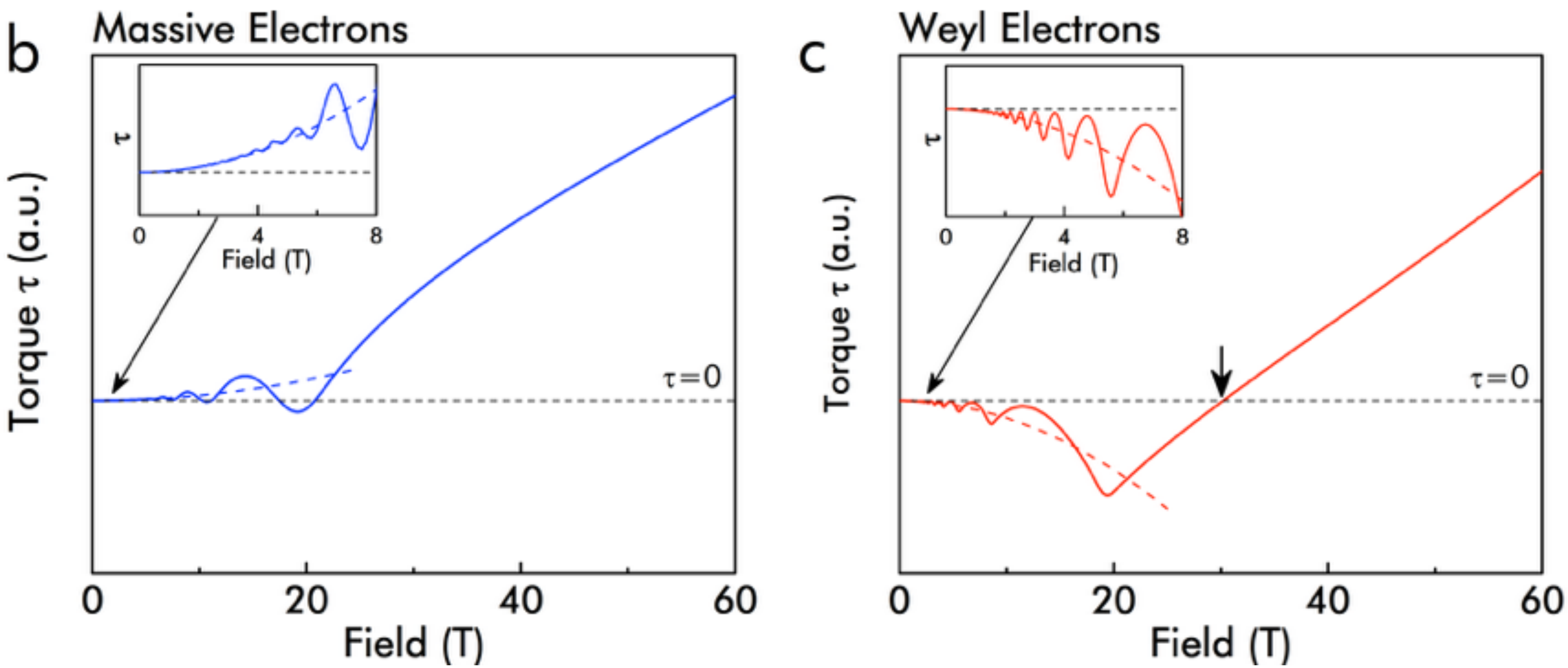
Torque as a measure of magnetic anisotropy





Extremely sensitive to a change of sign in the magnetization

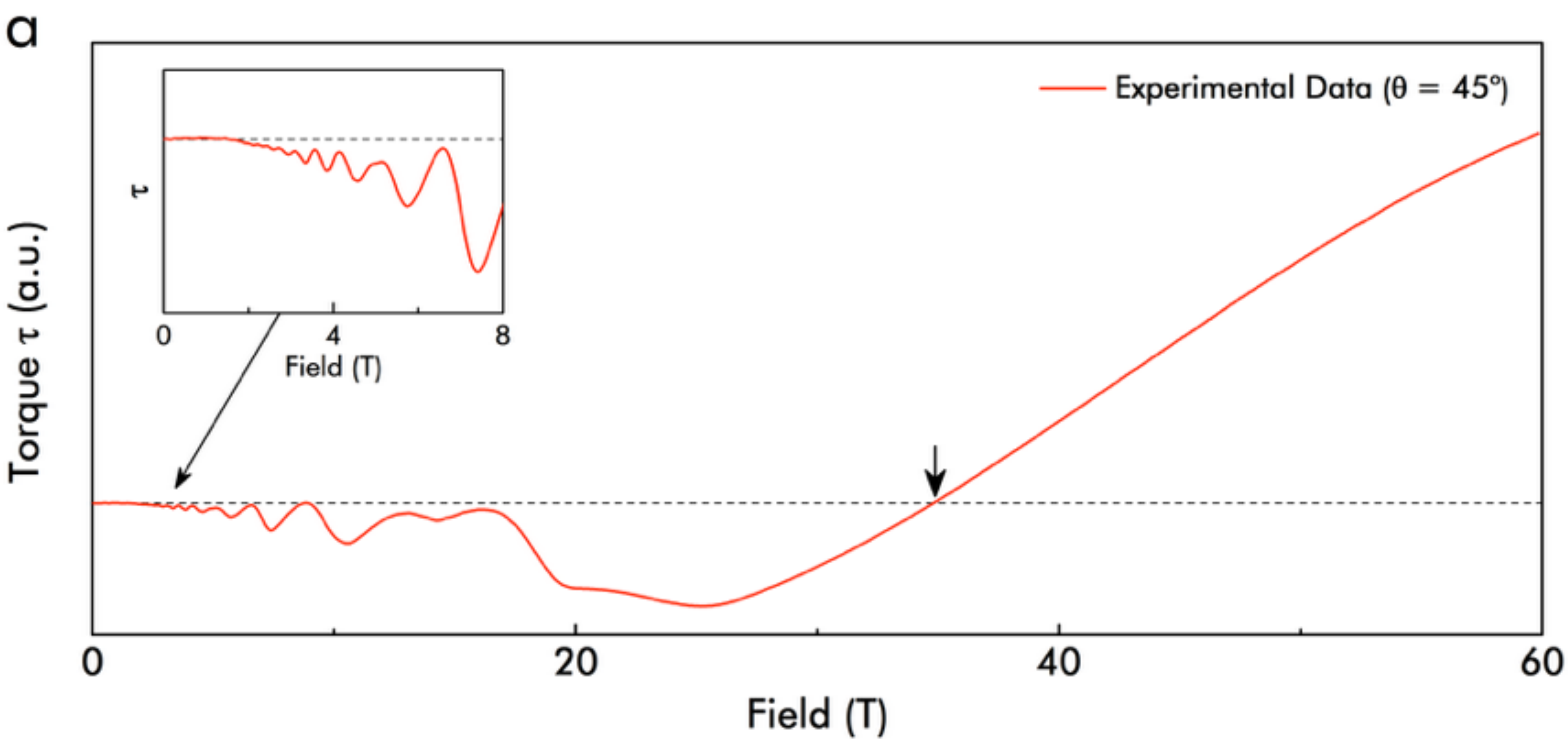
Torque expected in trivial vs Weyl systems



Note that these arguments are quite general - there will always be an anomaly in the quantum limit of a topologically non-trivial system (though it won't always manifest as a change of sign)

Philip J. W. Moll, JGA et al. arXiv:1507.06981

Torque observed in NbAs

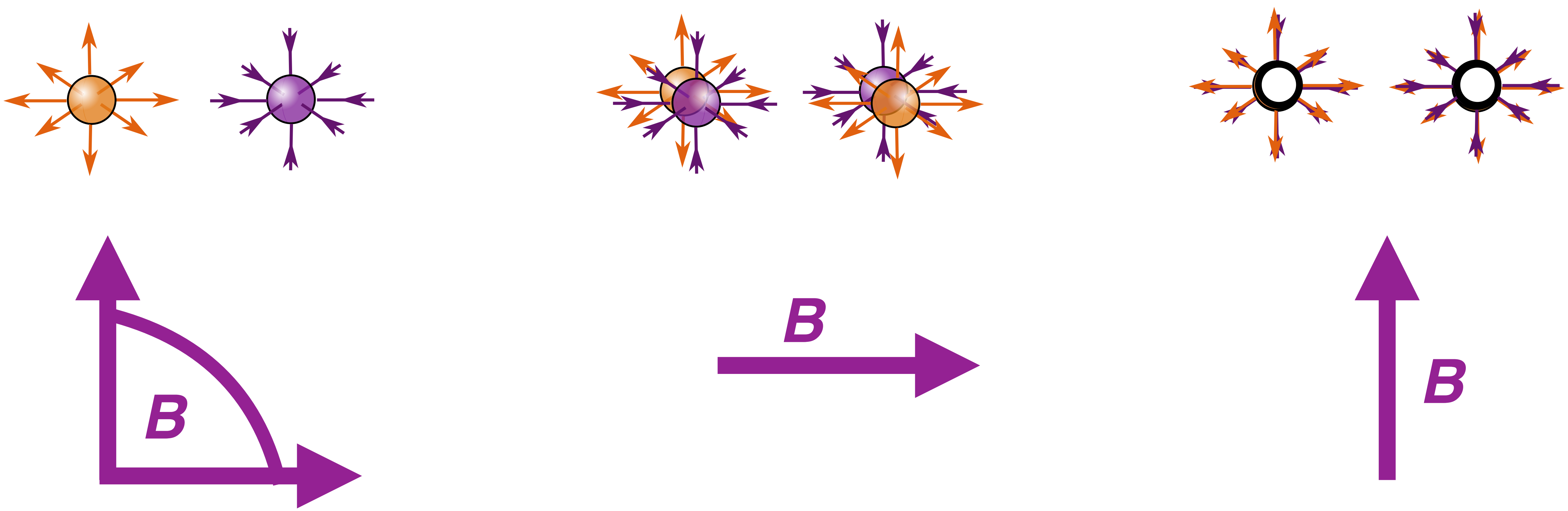


A new probe for topological states of matter, that can be done in any lab without the help of photoemission!

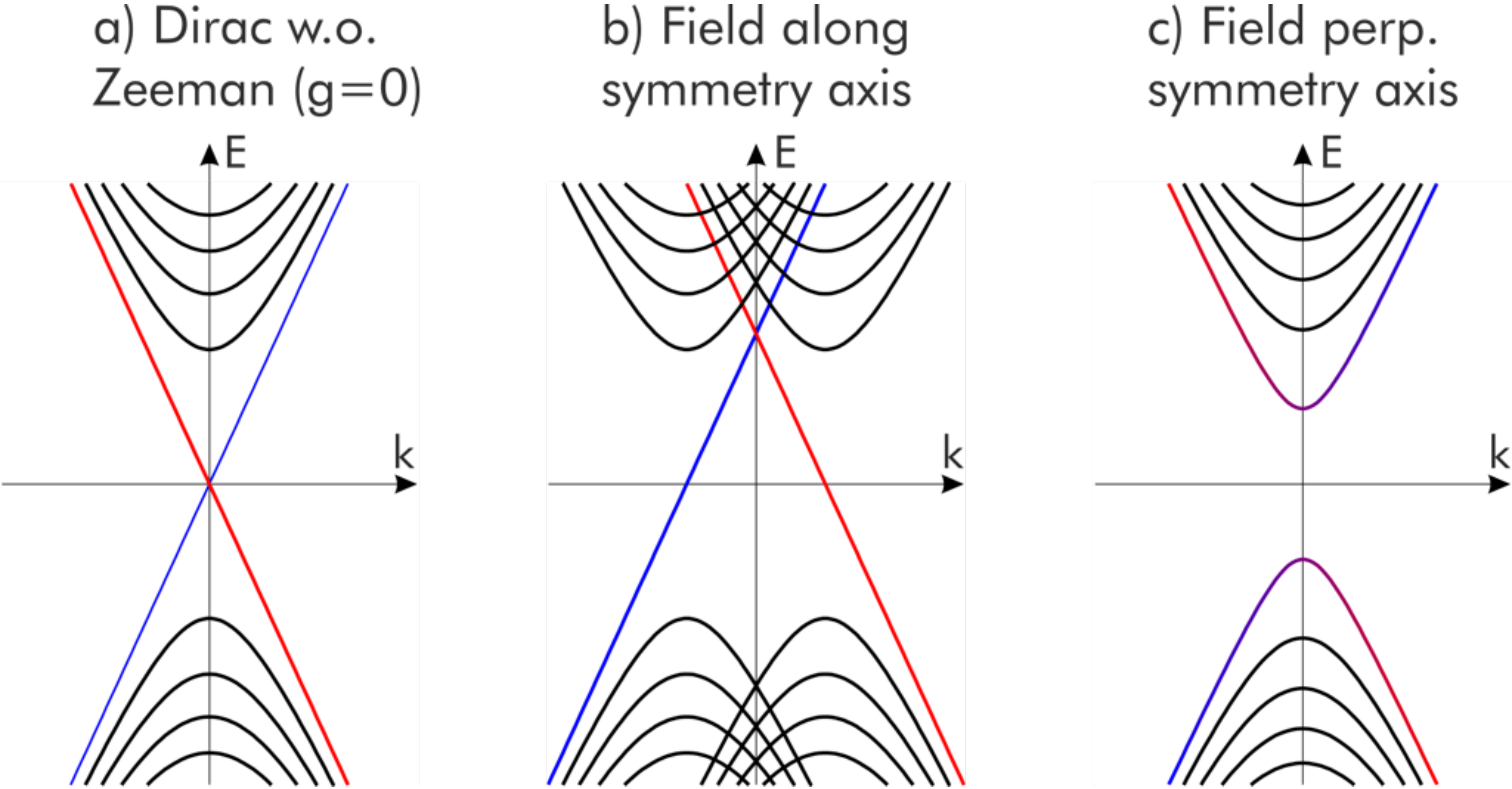
Philip J. W. Moll, JGA et al. arXiv:1507.06981

Distinguishing between 3D Dirac and Weyl systems

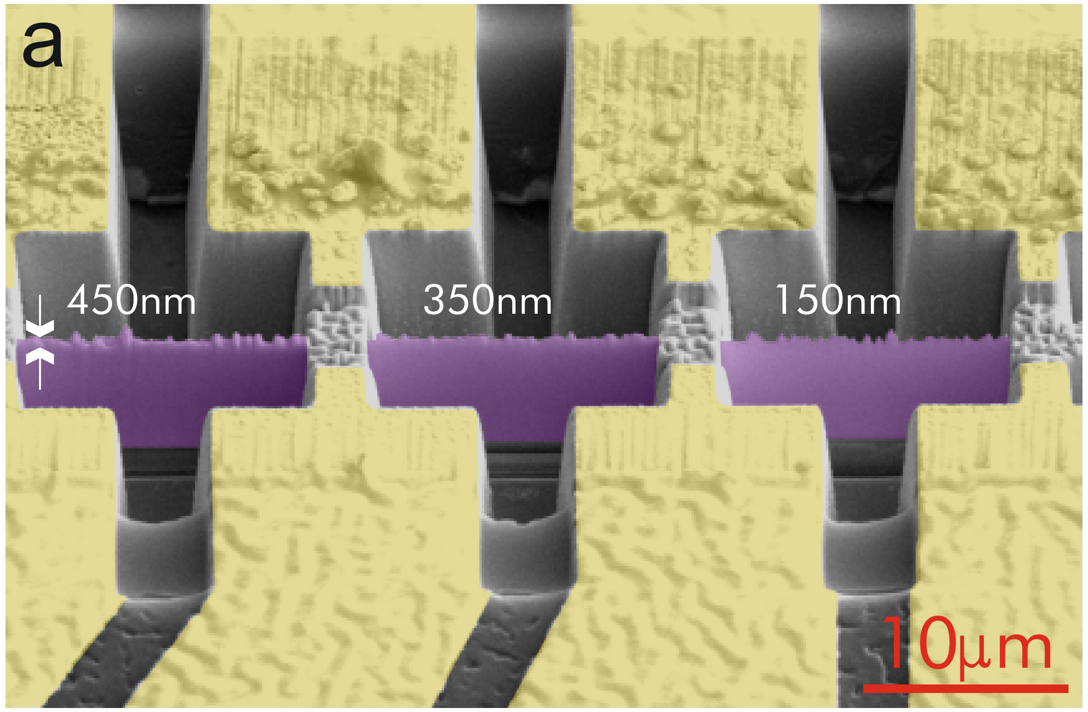
Weyl | Dirac B//[001] | Dirac B⊥[001]

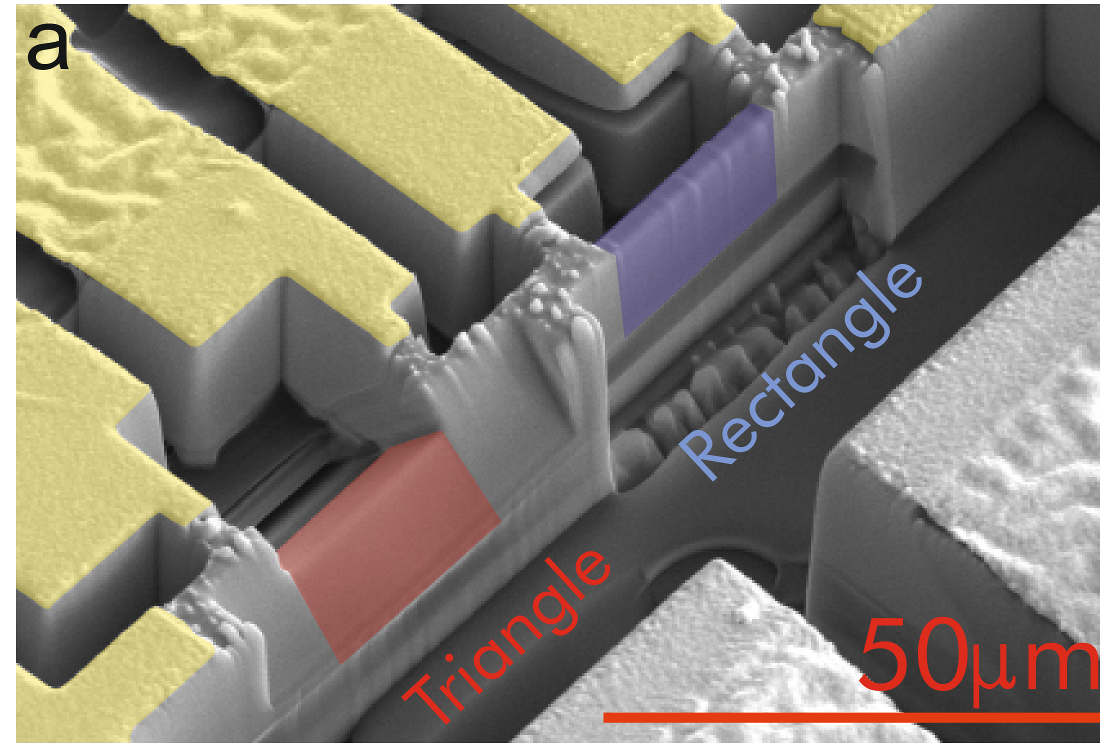


Distinguishing between 3D Dirac and Weyl systems

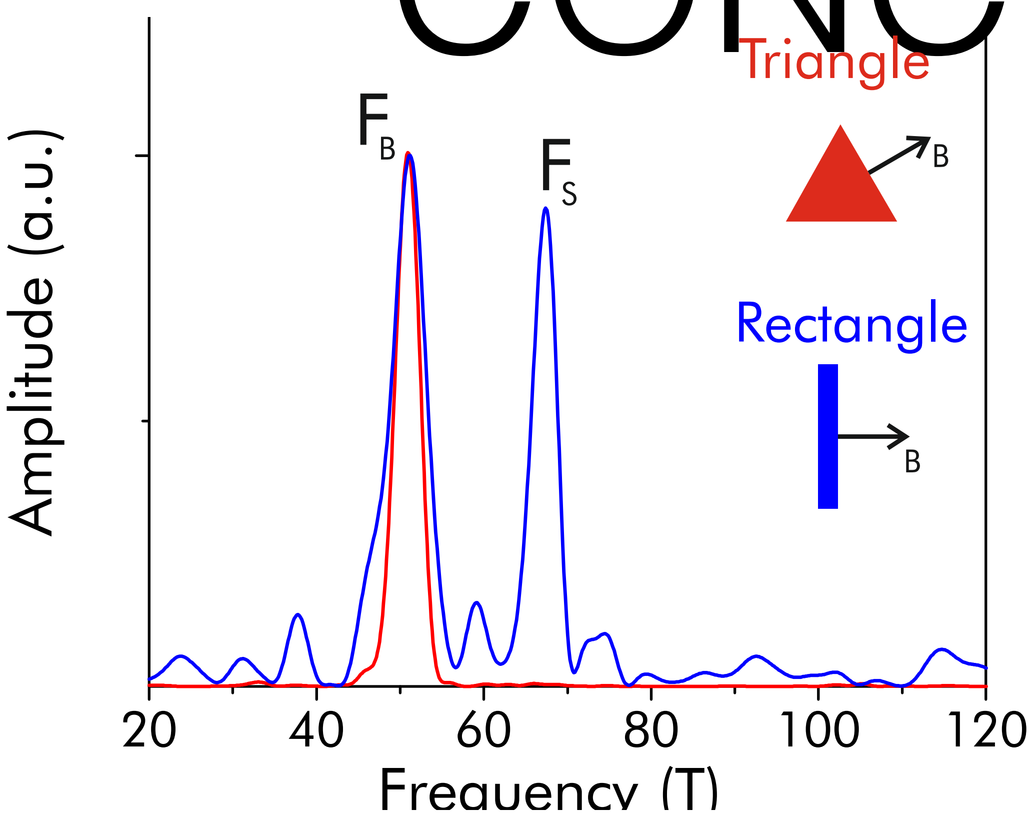


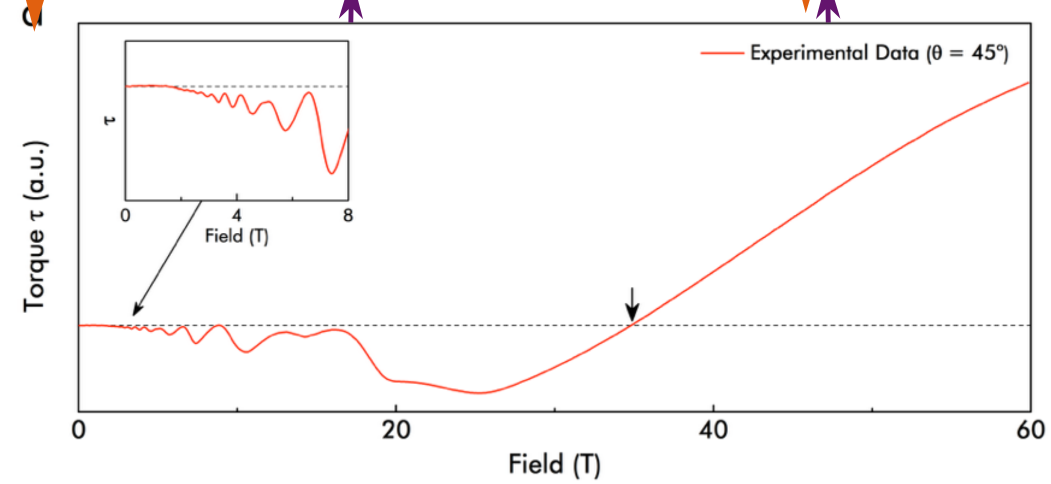
Philip J. W. Moll, JGA et al. arXiv:1505.02817





CONCLUSIONS

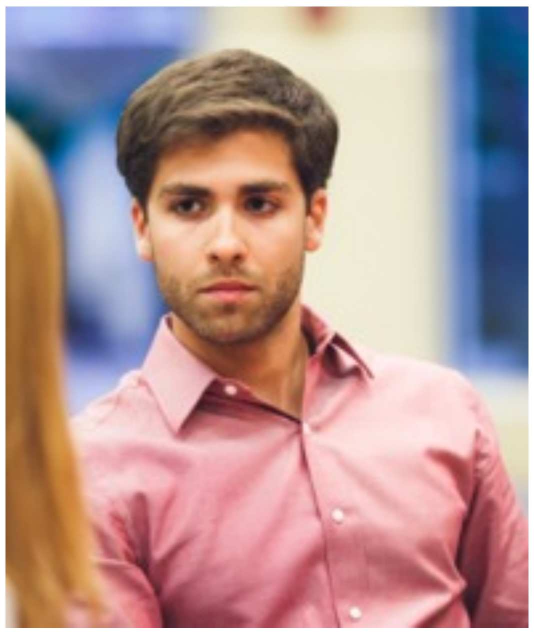




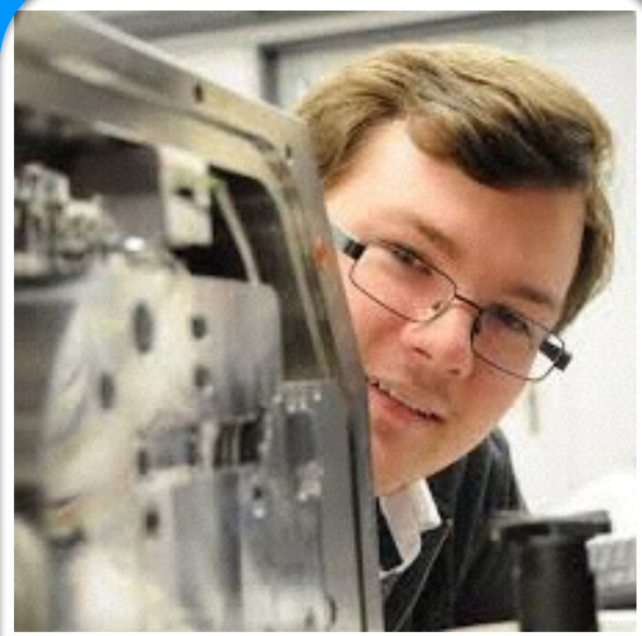
Philip J. W. Moll, JGA et al. arXiv:1507.06981

GORDON AND BETTY MOORE FOUNDATION

Berkeley -> MPI



Nityan Nair



Philip Moll

shvin Vishwanat

Drew Potter

Filip Ronning

Eric Bauer

Los Alamos NATIONAL LABORATORY EST. 1943

Itamar Kimchi

Thanks

Torque angle dependence