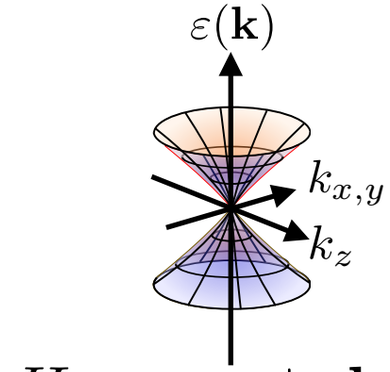
Quantum Oscillations in Weyl and Dirac Semimetals

Andrew C. Potter
UC Berkeley

1. ***ACP,*** *I Kimchi, A. Vishwanath Nat. Comm '14*
2. *P. Moll, N.L. Nair, T. Helm,* ***ACP****, I. Kimchi, A. Vishwanath, J. Analytis arXiv:1505.02817*

Berkeley UNIVERSITY OF CALIFORNIA
GORDON AND BETTY MOORE FOUNDATION

A flurry of Weyl materials

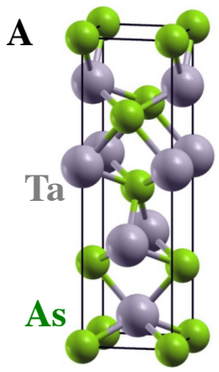


$$H_{\mathrm{Weyl}} = \pm v\mathbf{k}\cdot\boldsymbol{\sigma}$$

Original proposal: pyrochlore iridates

Wan, Turner, Vishwanath, Savrasov; Witzcak-Krempa, YB Kim

Weyl - TaAs, NbAs, NbP



TaAs ARPES

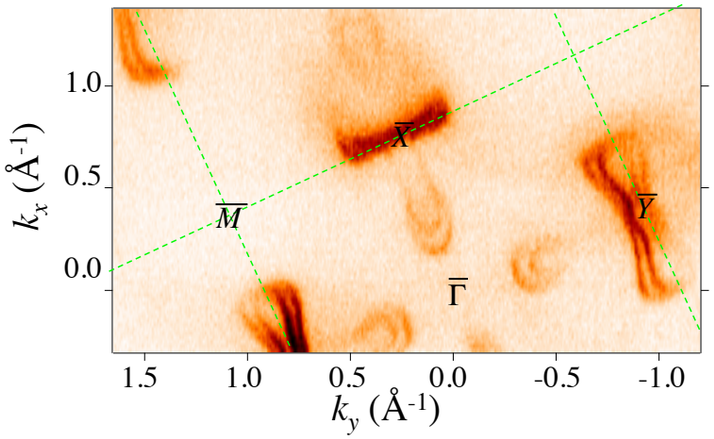
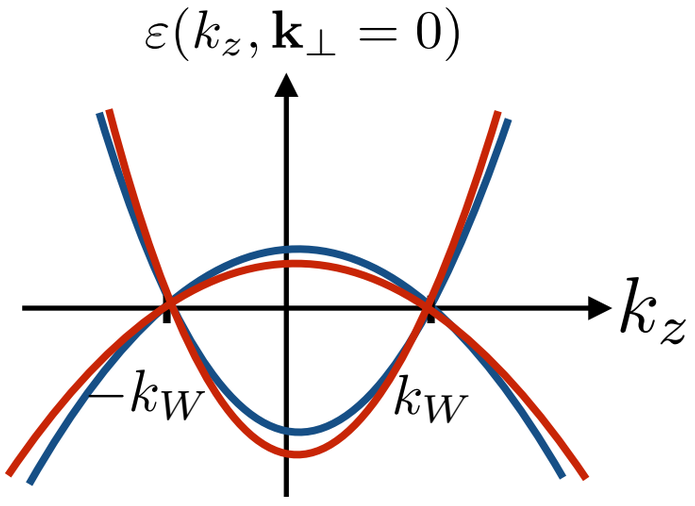


Figure - Xu et al. arXiv '15 (Hasan group)

Xu et al. 'Science '15; Lv et al. PRX '15; Huang et al. Nat Comm '15;

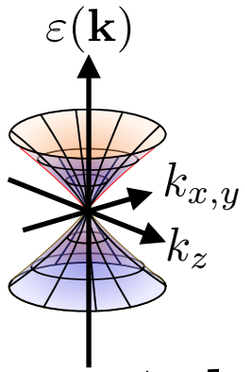
Dirac - Cd_3As_2, Na_3Bi



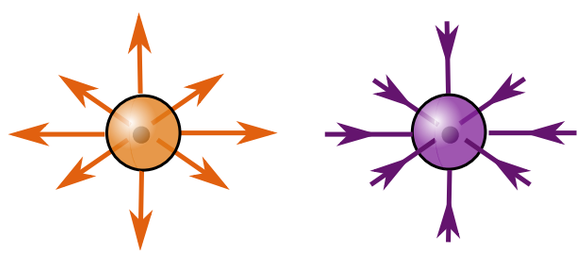
Z Wang, et al. PRB '13; Neupane et al. Nat Comm '13; Borisenko et al. PRL '14; Liu et al. '13; Xu et al. '13; many others…

Topology without a band-gap

Chirality <=> Chern monopoles

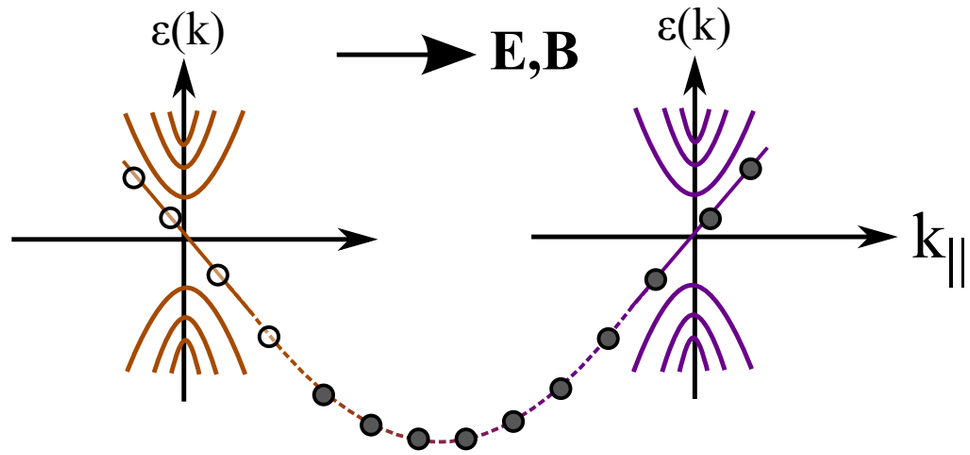


$$H_{\mathrm{Weyl}} = \pm v\mathbf{k}\cdot\boldsymbol{\sigma}$$



$$\chi = \pm 1$$

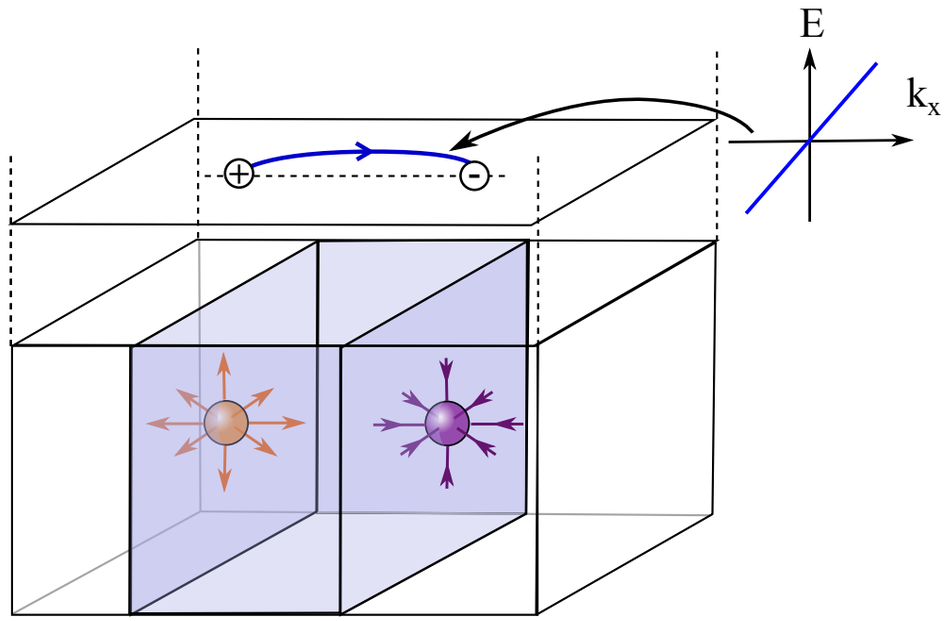
Chiral Anomaly



$$\partial_\mu j^{(\chi)}_\mu = -\chi \frac{1}{4\pi^2}\mathbf{E}\cdot\mathbf{B}$$

Adler, Bell, Jackiw

Fermi arcs



Wan, Turner, Vishwanath, Savrasov

Key players:

- Chiral bulk Landau level
- Surface Fermi-arcs

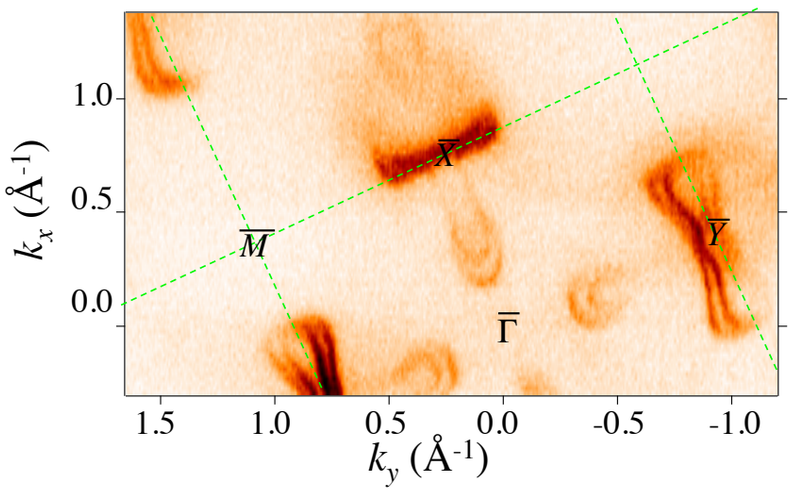
Plan

Goal: Experimental probe of surface topology and bulk chiral anomaly physics

Quantum oscillations in a magnetic field

1. Semiclassical description - *ACP, Kimchi, Vishwanath Nat Comm '14*
2. Experimental data (Cd_3As_2) -

P. Moll, et al. (Analytis group) arXiv:1505.02817



1. Theory - Oscillations from Weyl surface arcs

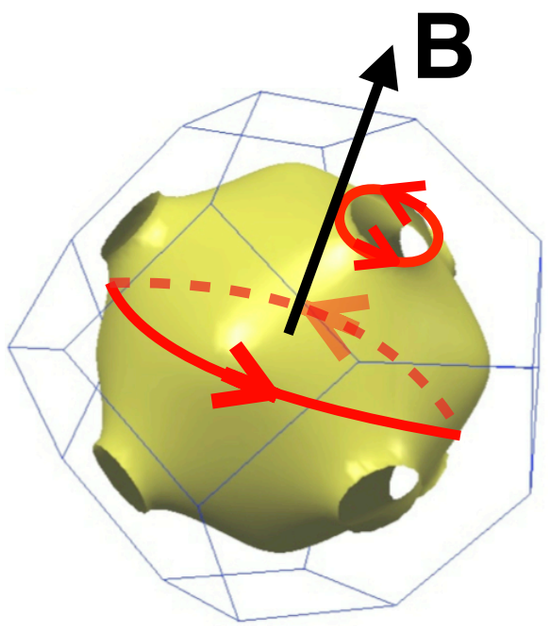
ACP, I Kimchi, A. Vishwanath Nat. Comm '14

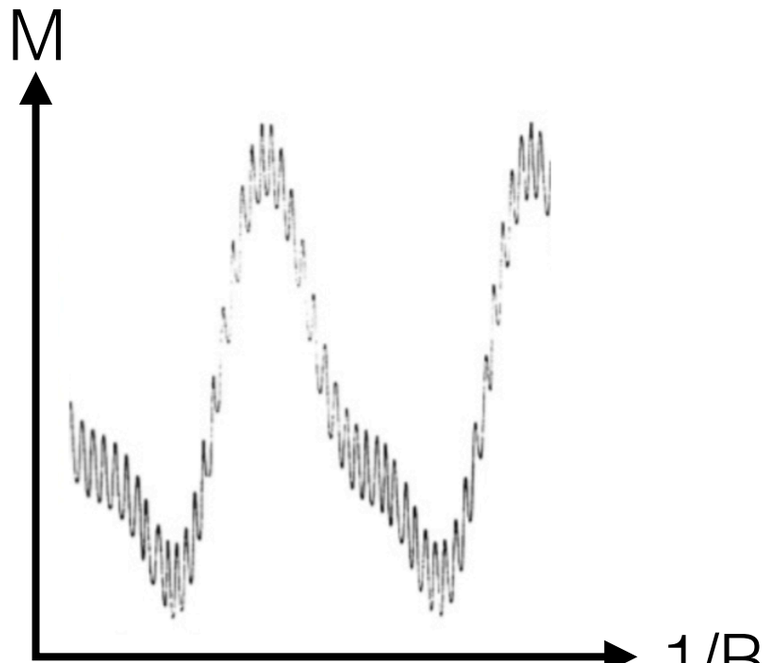
(Berkeley -> MIT)

Berkeley UNIVERSITY OF CALIFORNIA

GORDON AND BETTY MOORE FOUNDATION

Reminder - Quantum Oscillations in a Field





$$\mathbf{k} = e\mathbf{v} \times \mathbf{B}$$

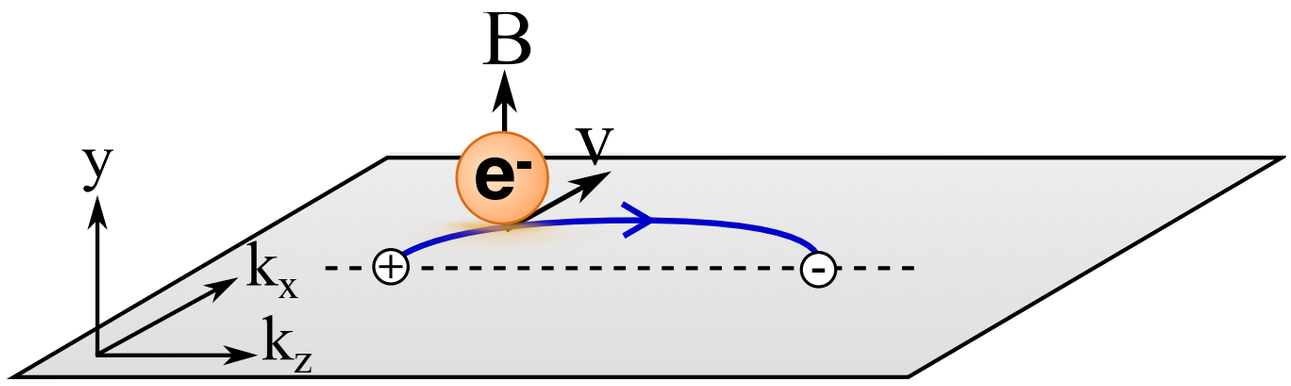
Quantized Magnetic orbits => Periodic-in-1/B modulation of DOS

- 1/B Frequency ~ k-space area

Observable in:

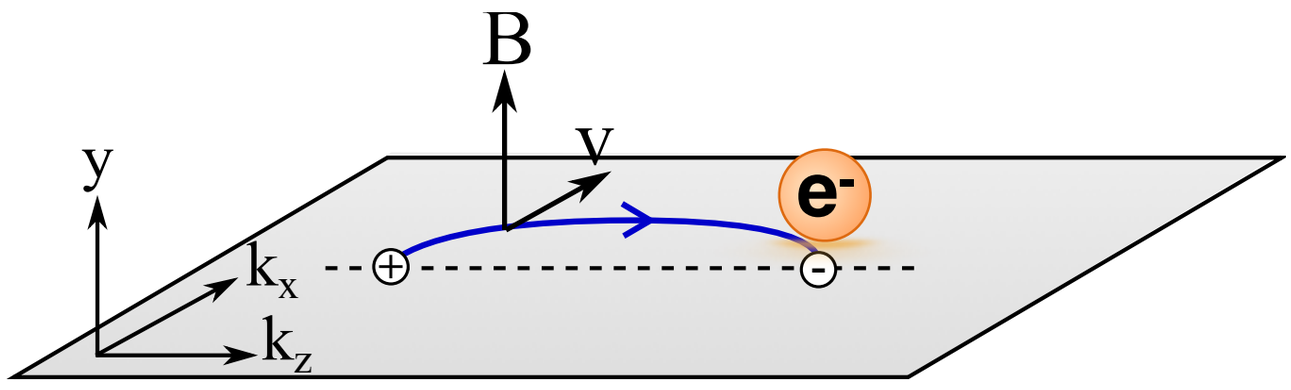
- Magnetization (de Haas van Alphen)
- Conductivity (Shubnikov de Haas)
- Tunneling density of states (Landau level spectroscopy)
- etc…

Quantum Oscillations from Fermi Arcs?



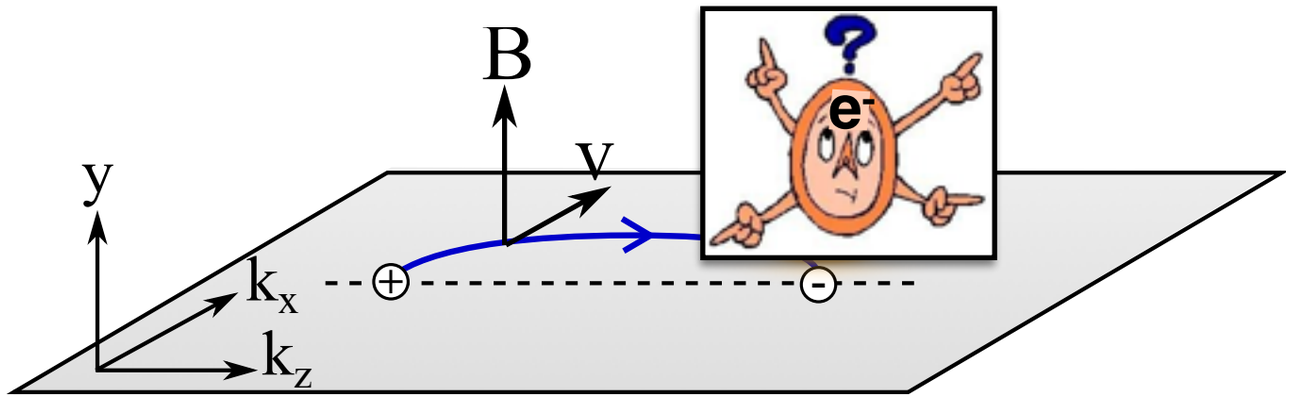
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?



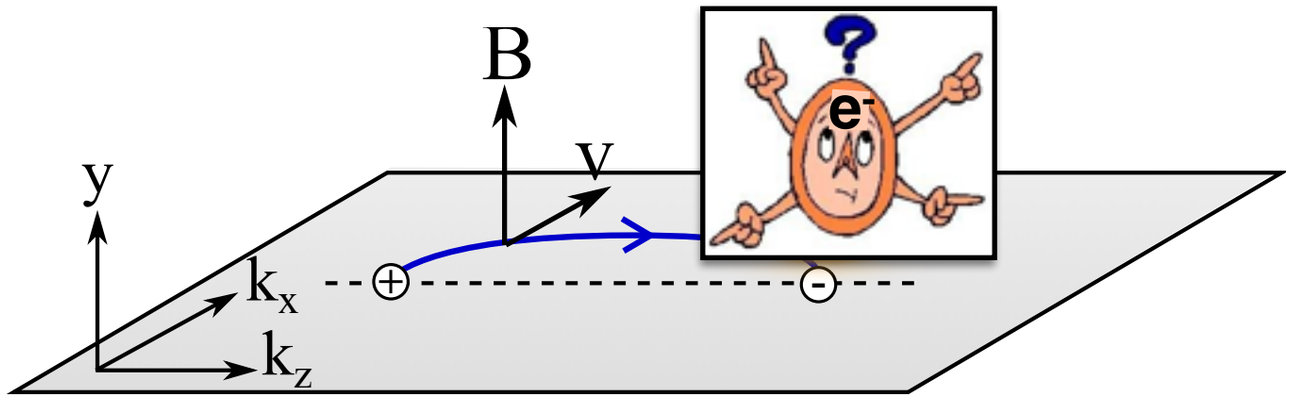
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

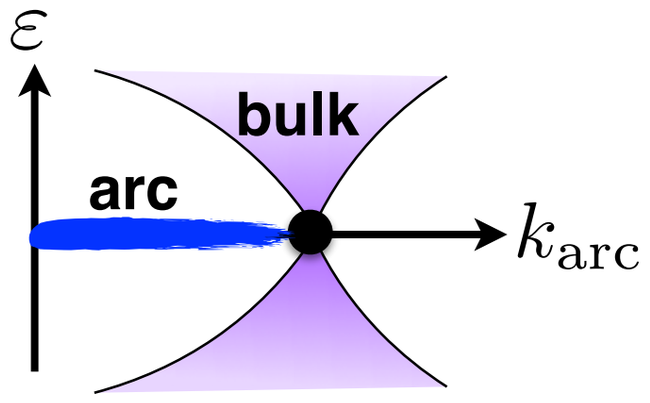
Quantum Oscillations from Fermi Arcs?



ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?

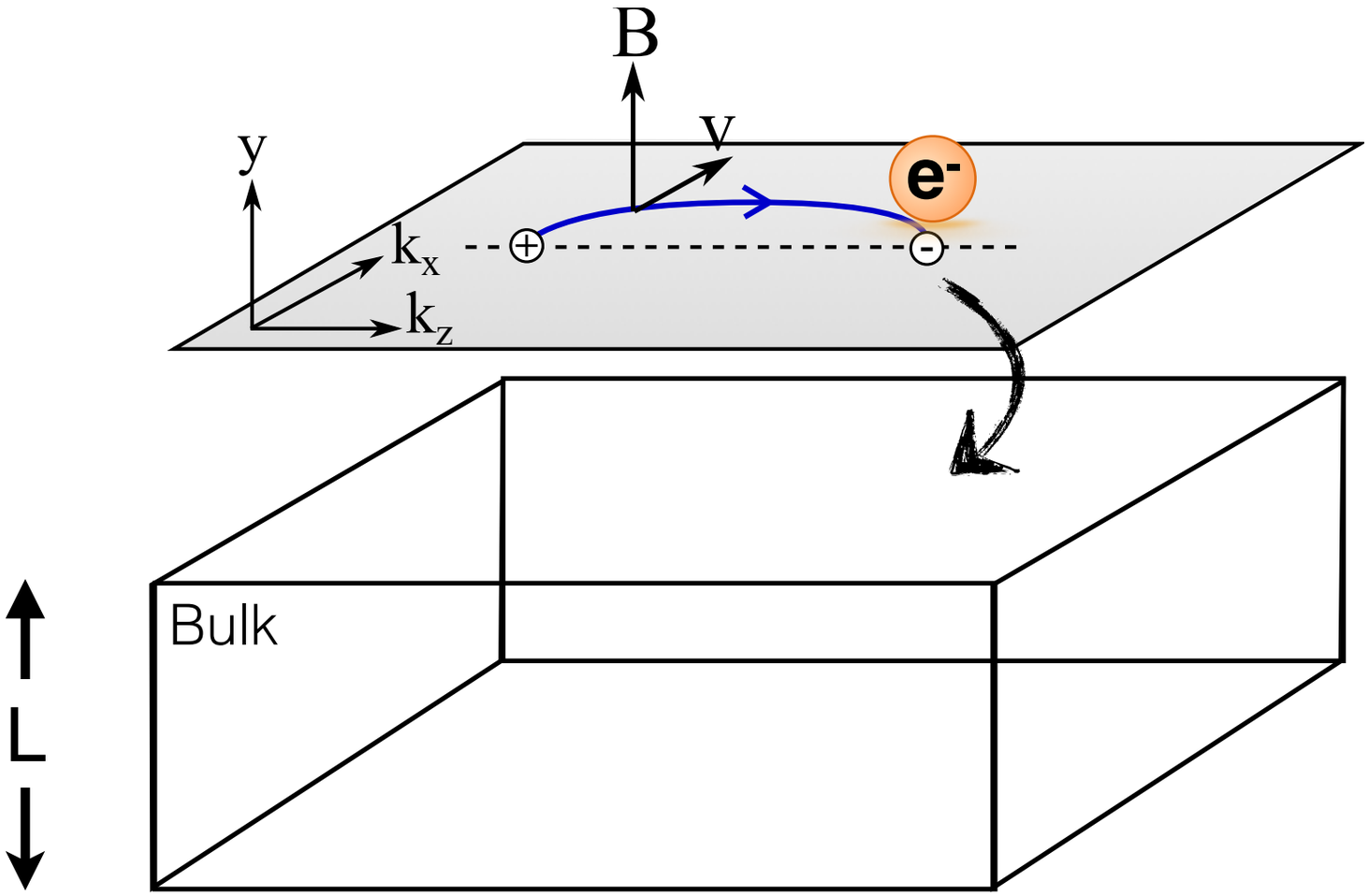


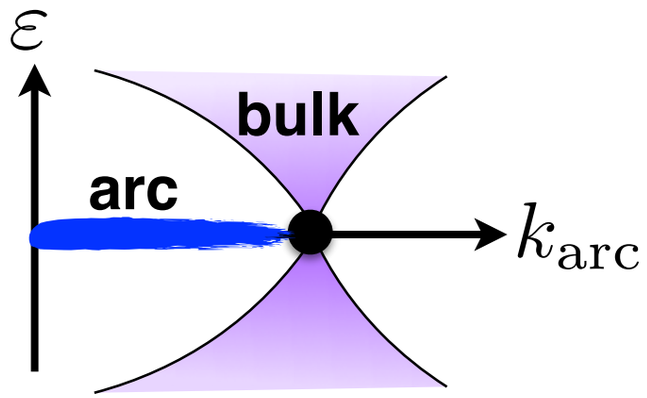


Surface-to-Bulk Transfer

ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?

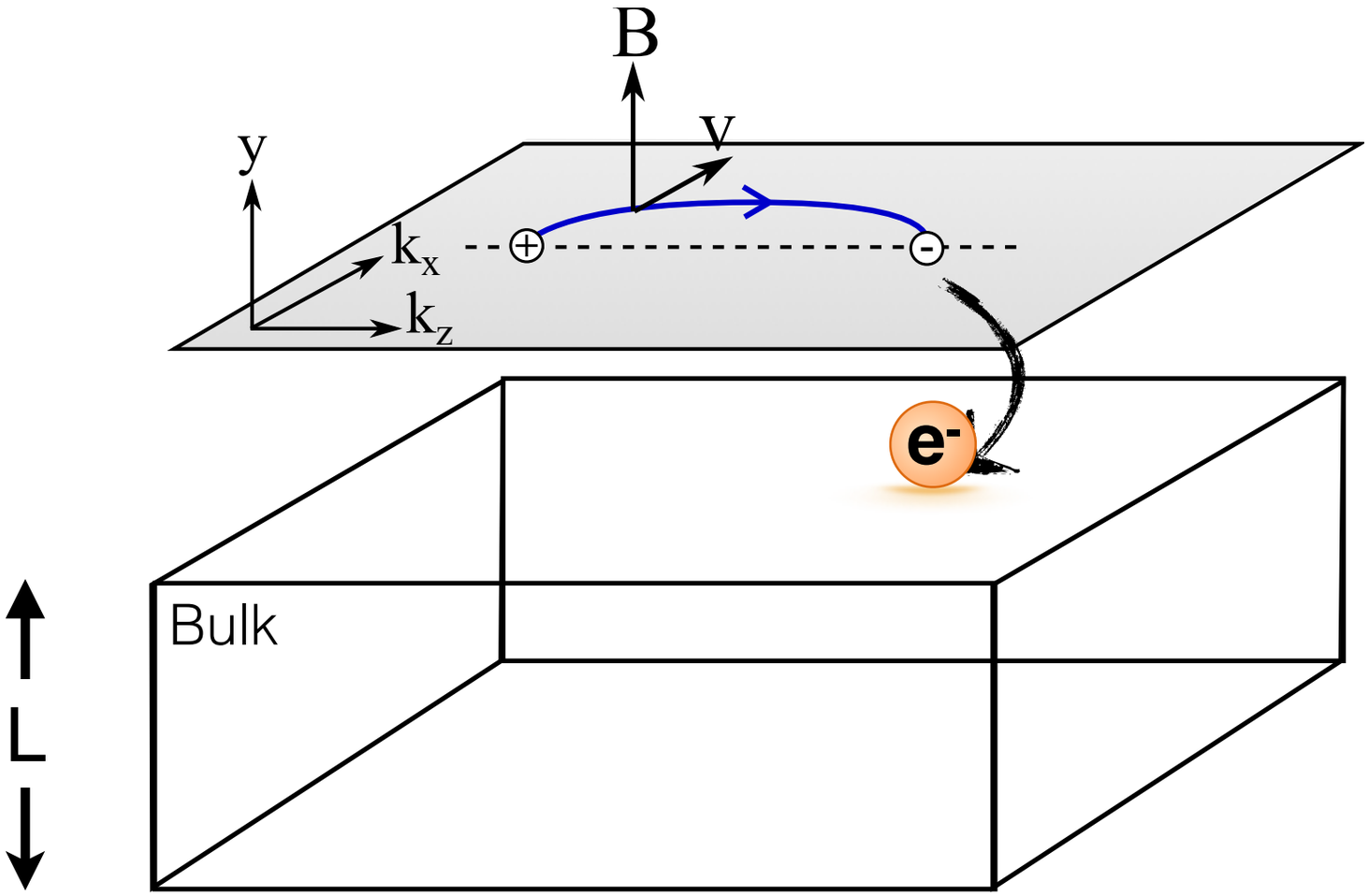


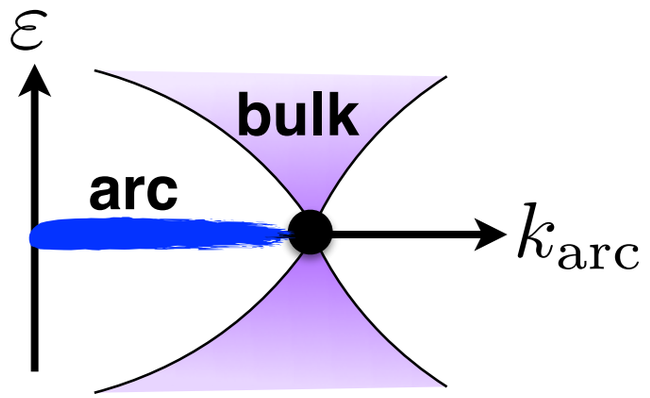


Surface-to-Bulk Transfer

ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?

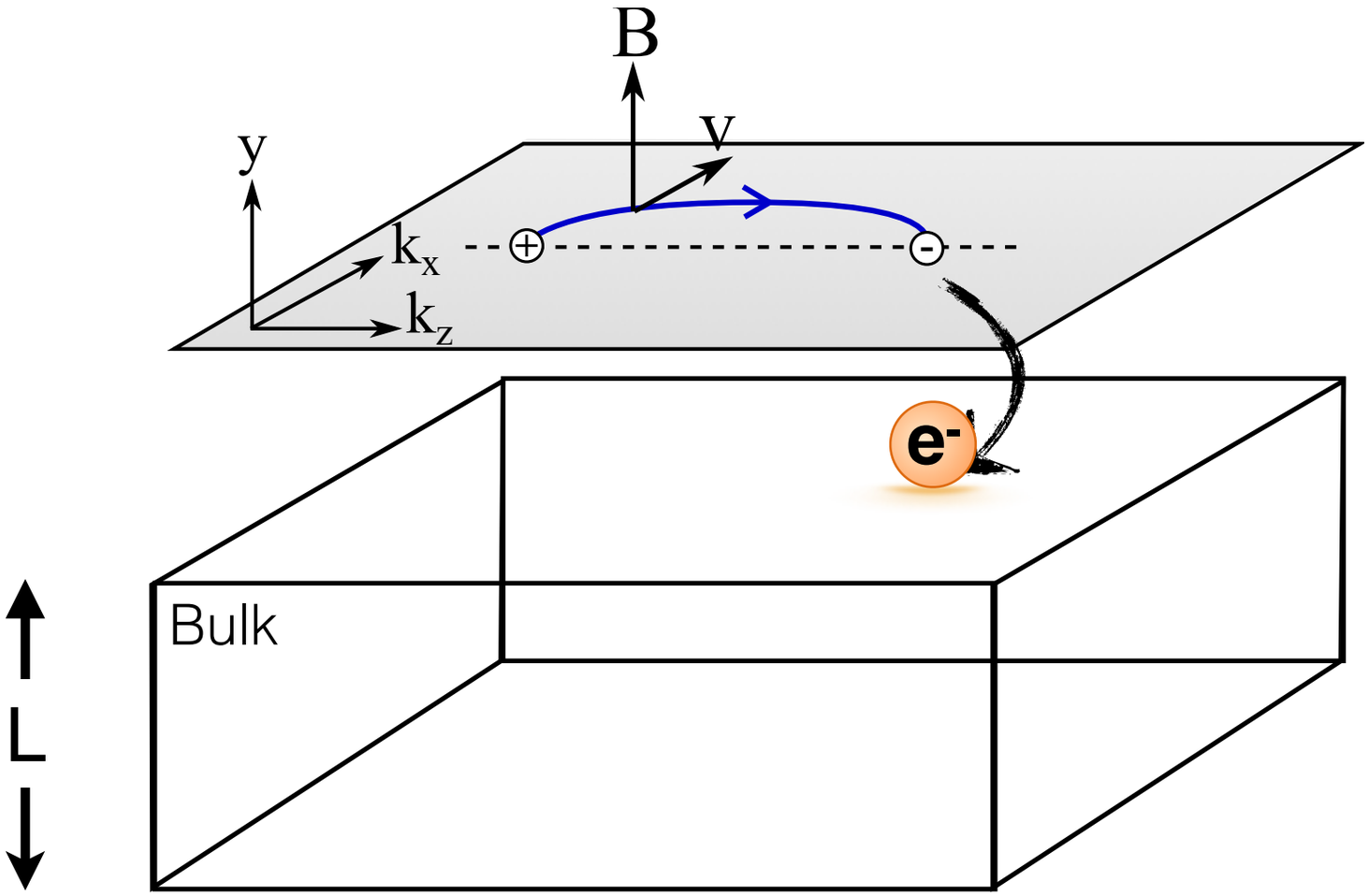


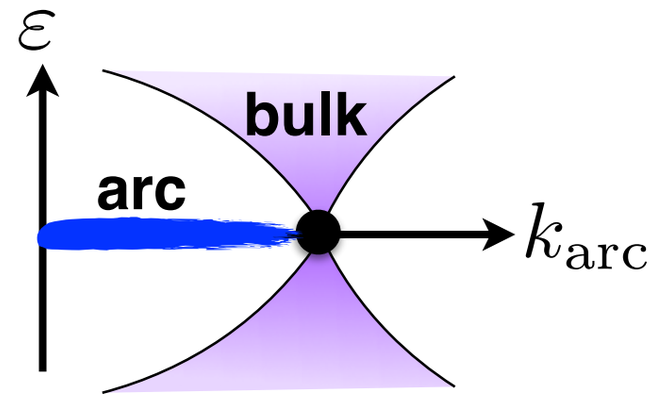


Surface-to-Bulk Transfer

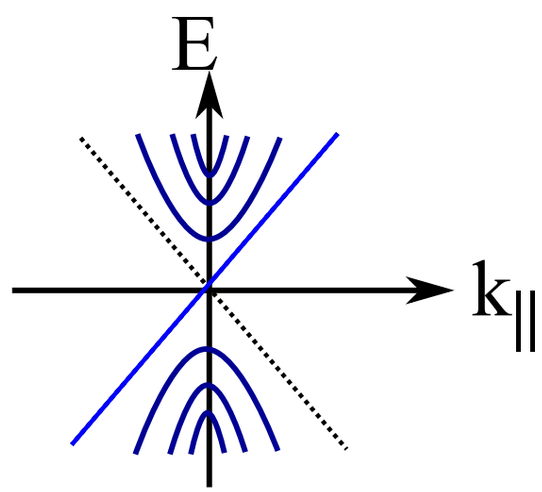
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?





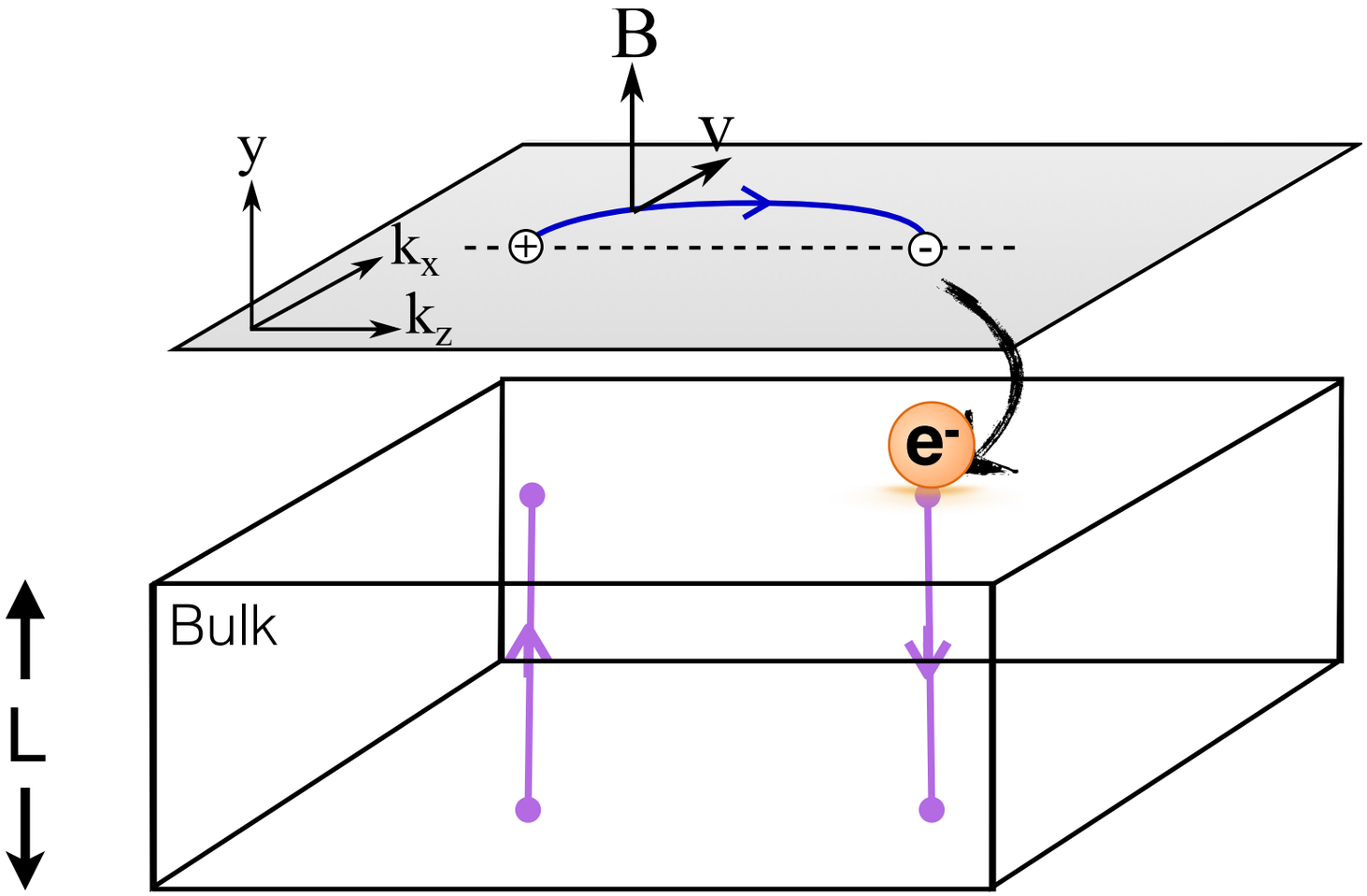
Surface-to-Bulk Transfer

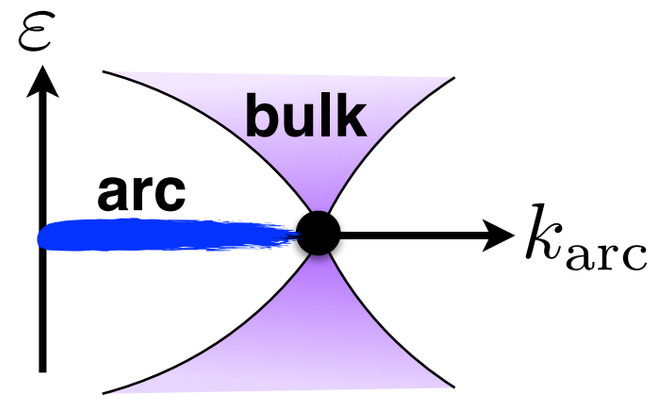


Bulk Landau Levels

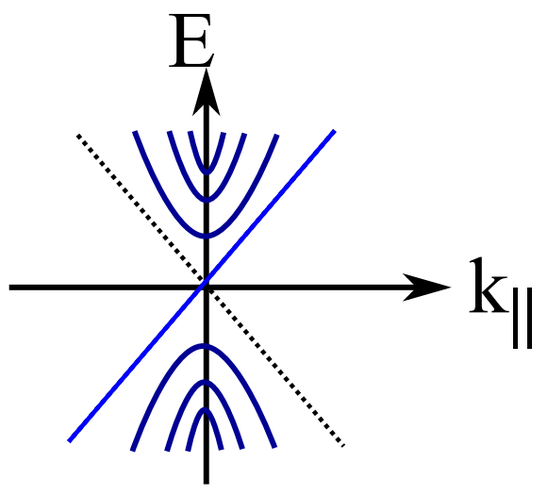
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?





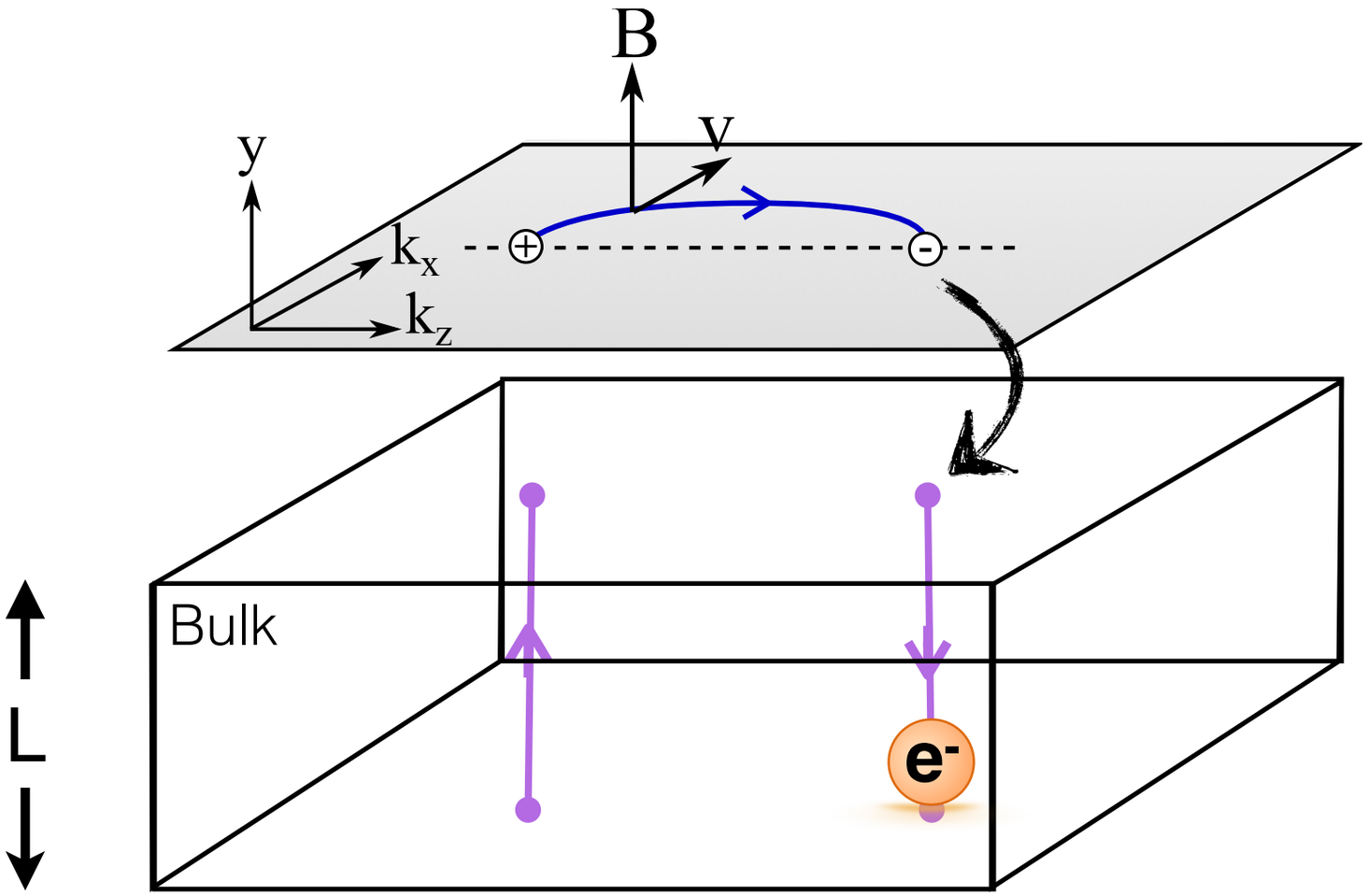
Surface-to-Bulk Transfer

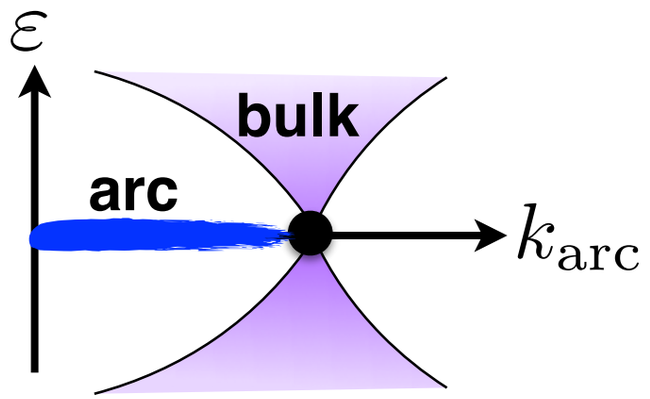


Bulk Landau Levels

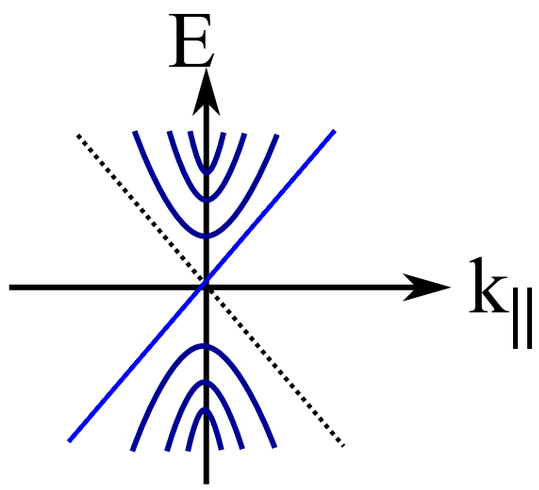
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?





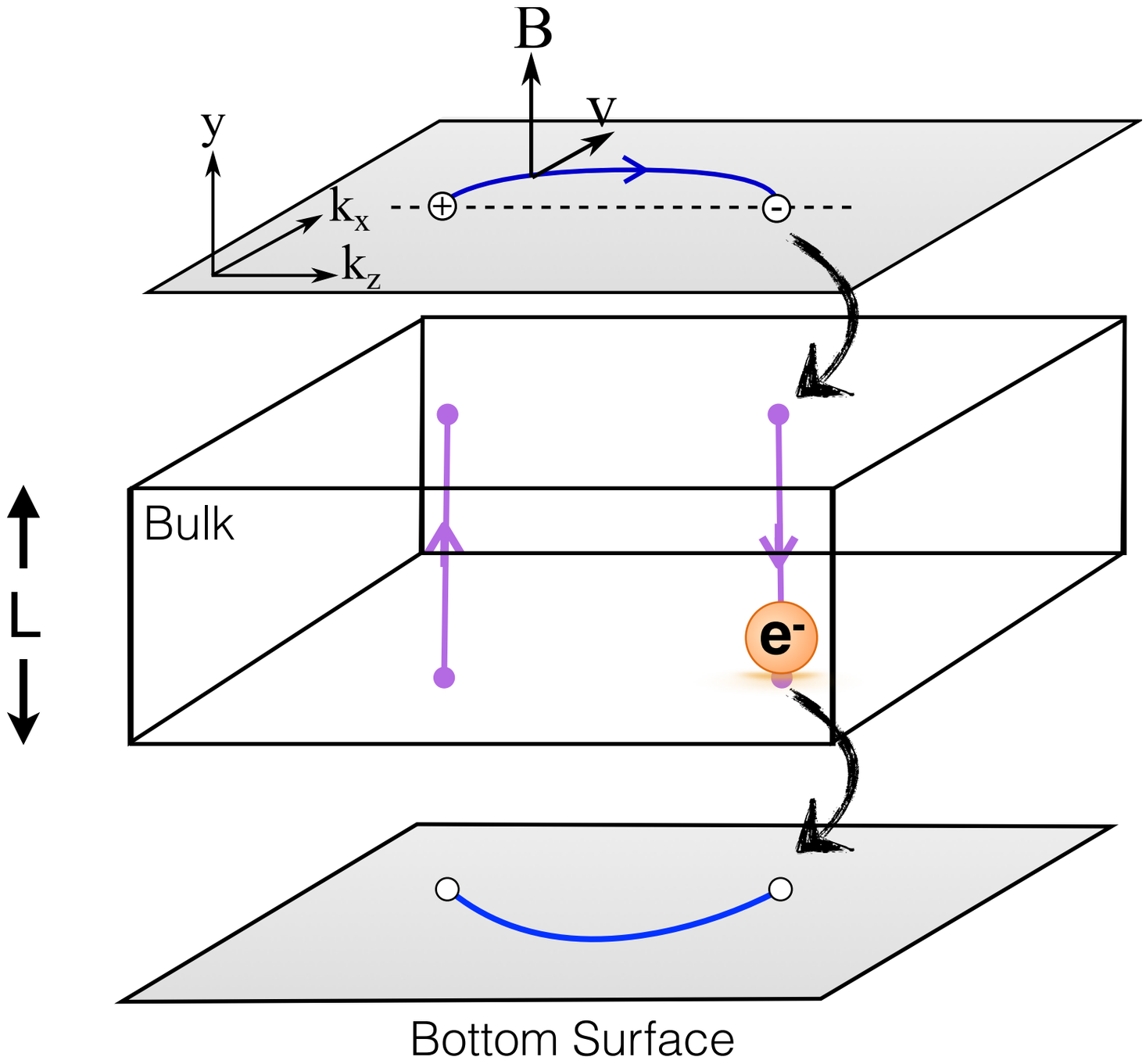
Surface-to-Bulk Transfer

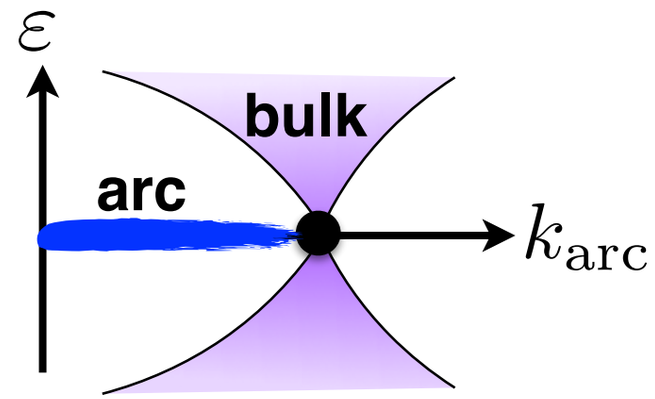


Bulk Landau Levels

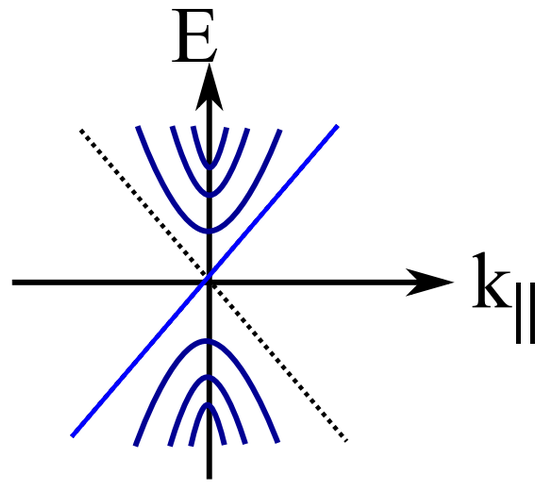
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?





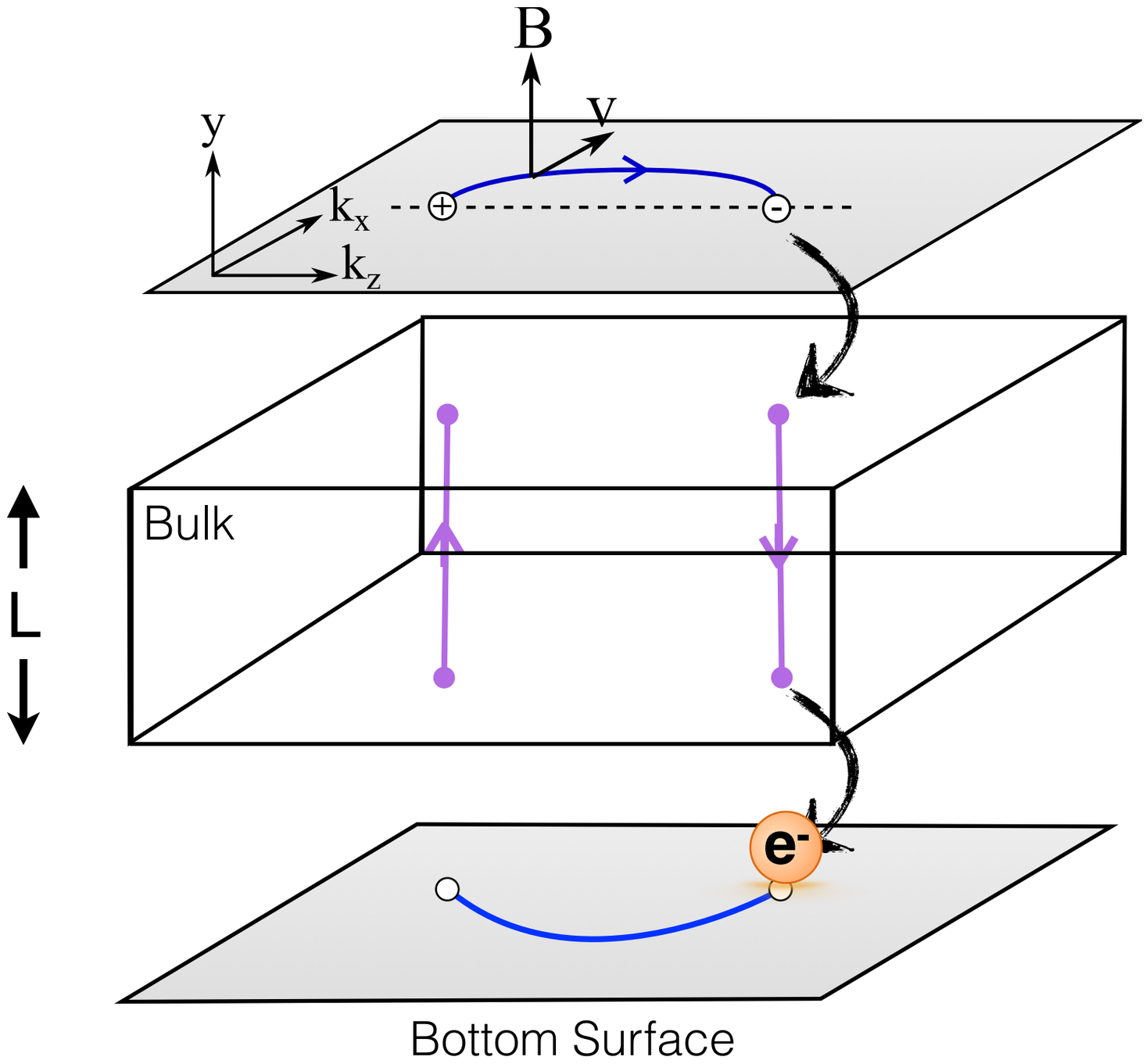
Surface-to-Bulk Transfer

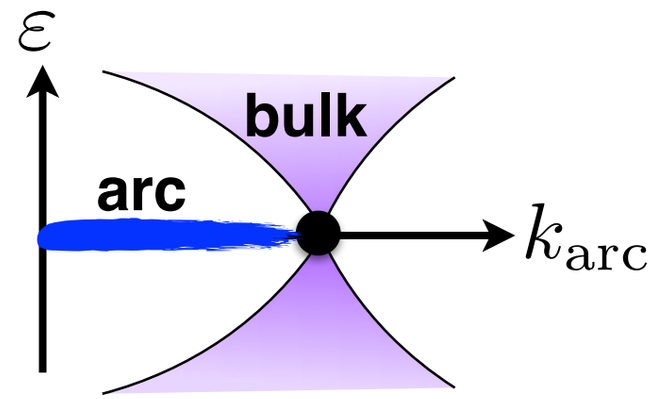


Bulk Landau Levels

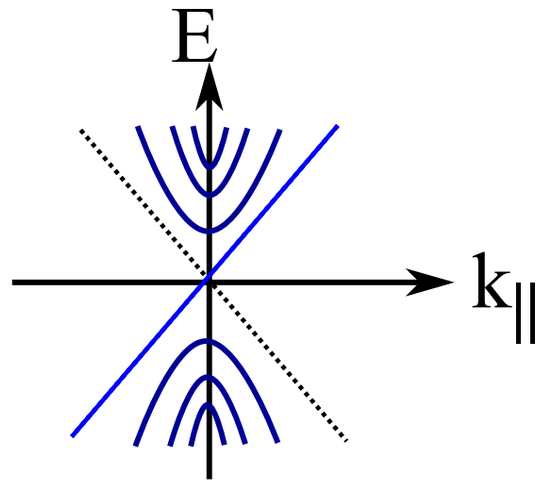
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum Oscillations from Fermi Arcs?





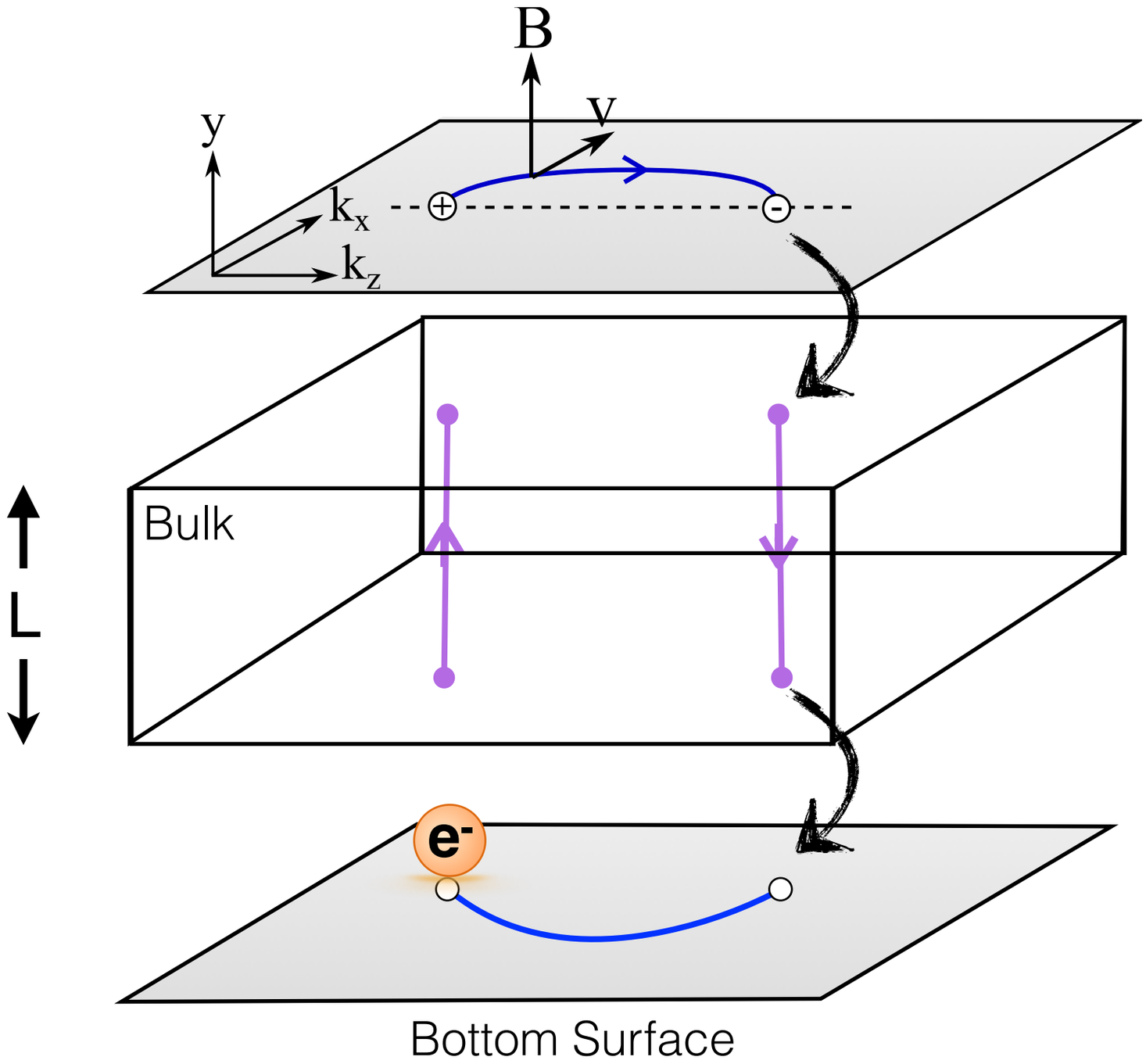
Surface-to-Bulk Transfer



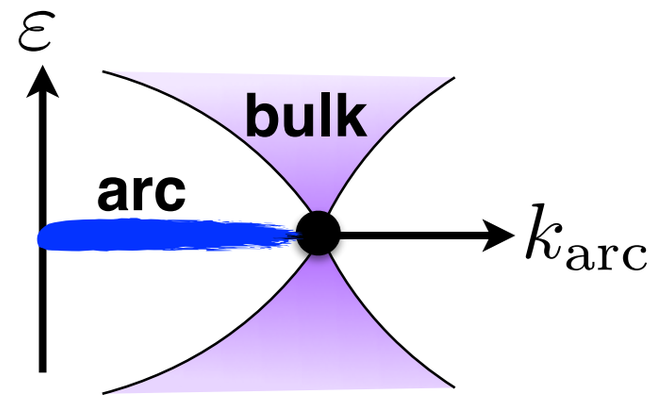
Bulk Landau Levels

ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

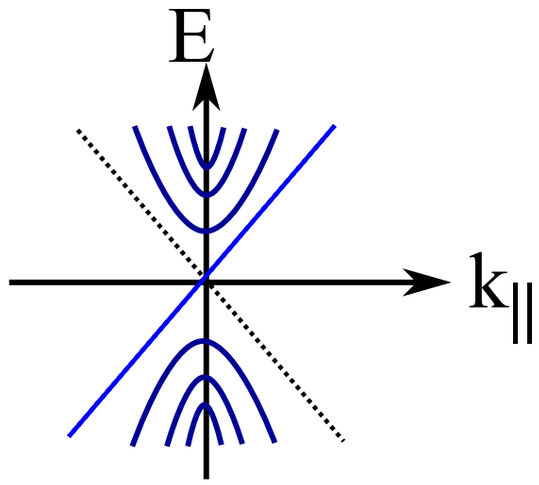
Quantum Oscillations from Fermi Arcs?



Bottom Surface



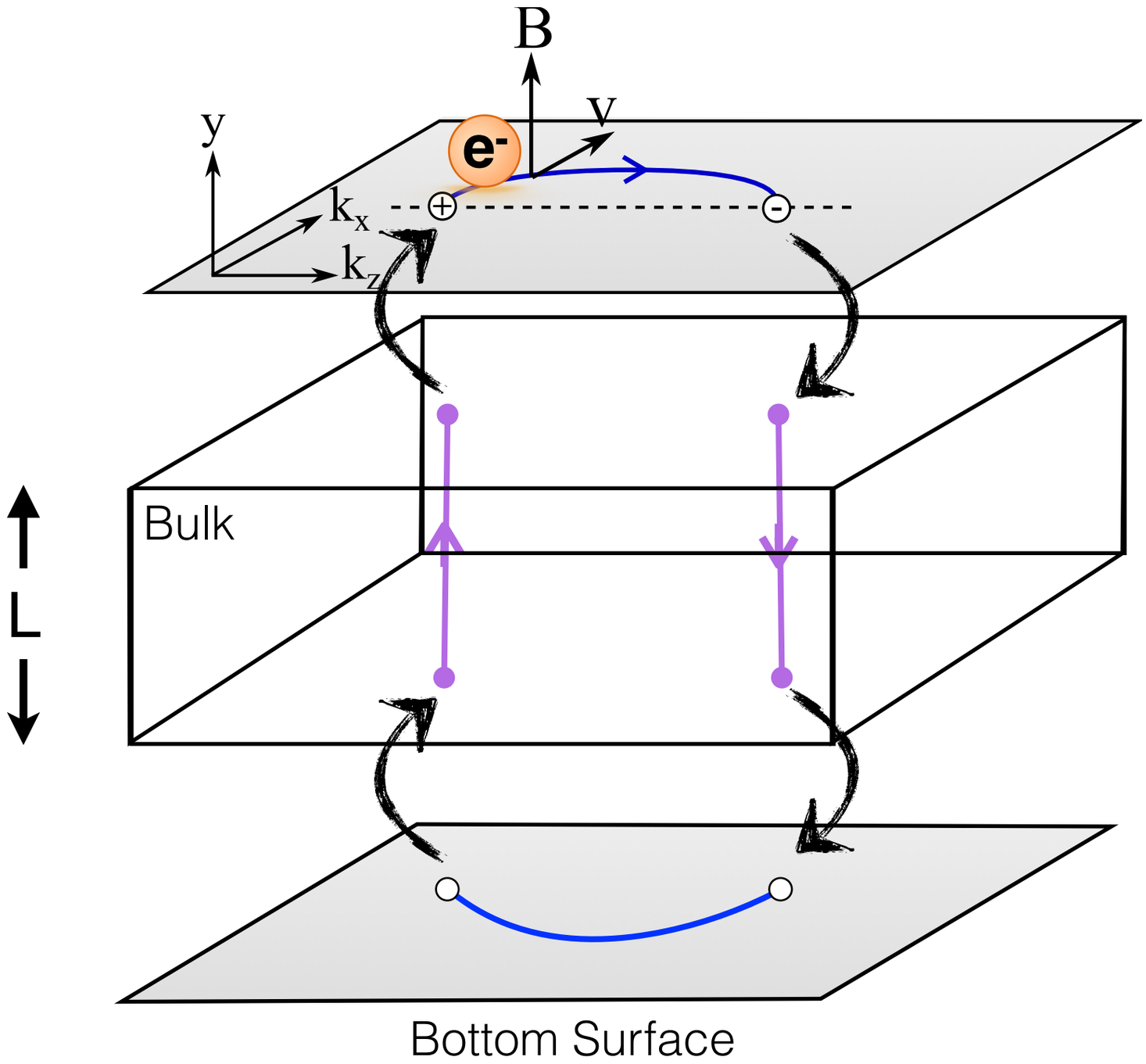
Surface-to-Bulk Transfer



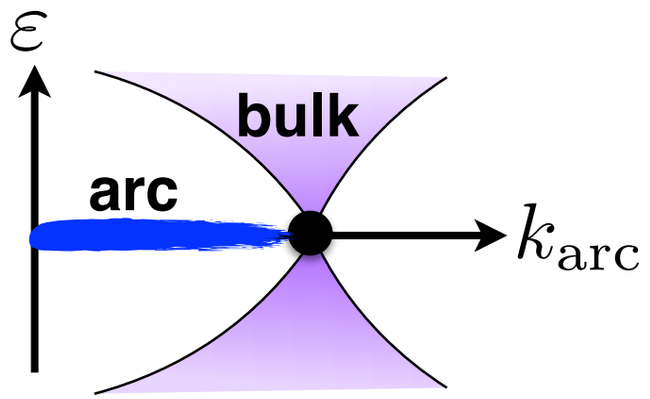
Bulk Landau Levels

ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

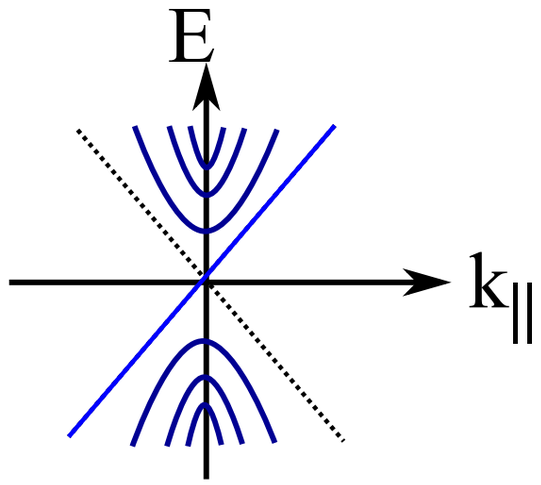
Quantum Oscillations from Fermi Arcs?



Bottom Surface



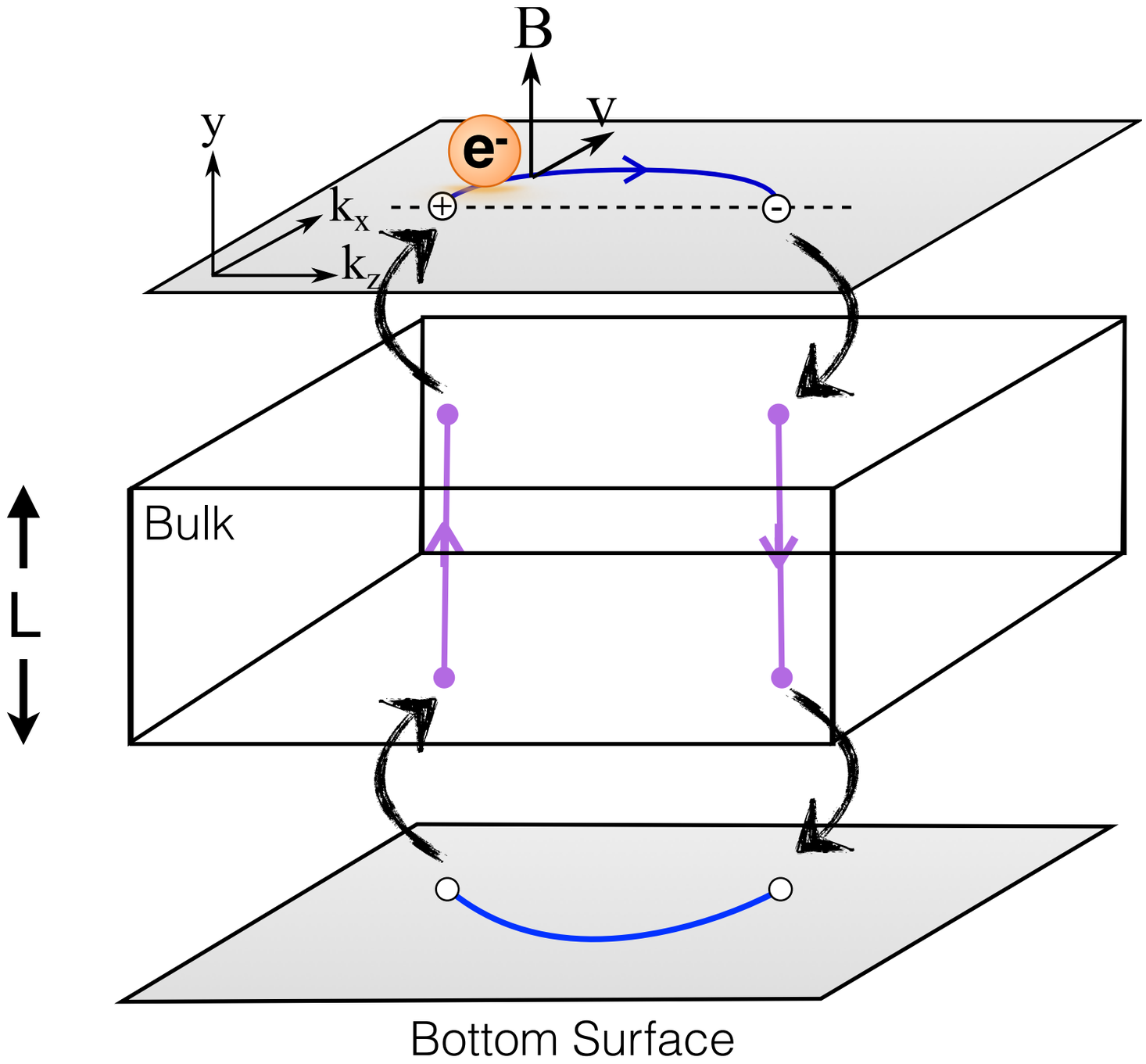
Surface-to-Bulk Transfer



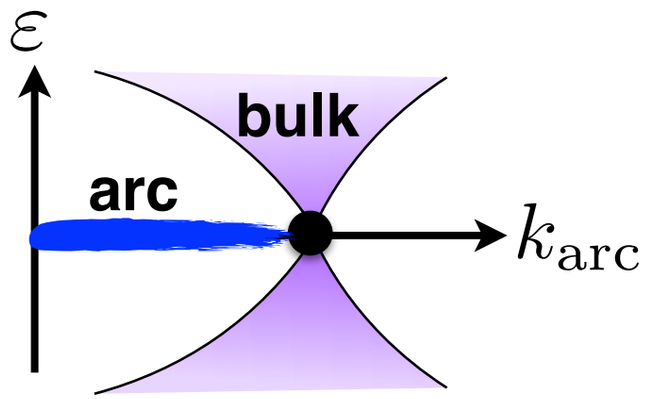
Bulk Landau Levels

ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

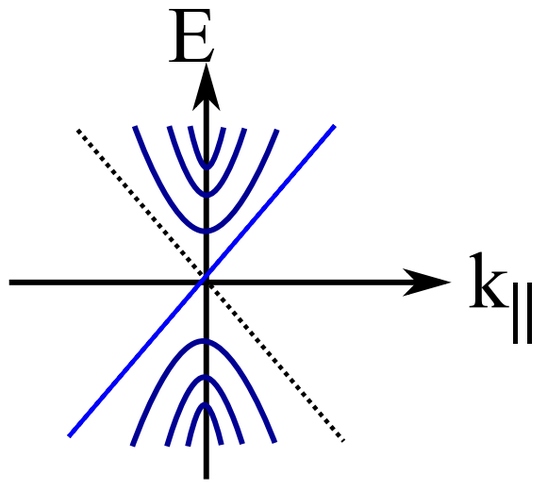
Quantum Oscillations from Fermi Arcs?



Bottom Surface



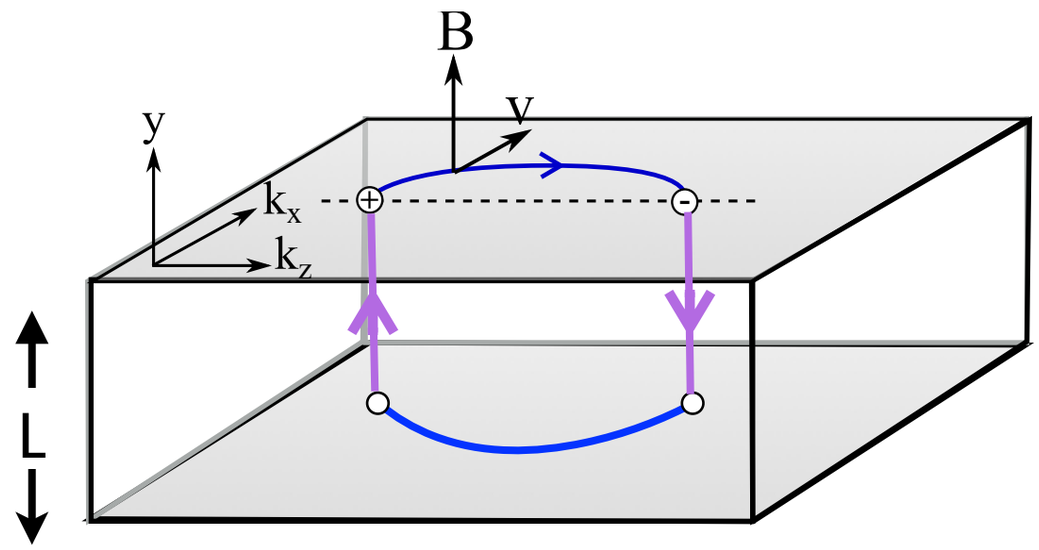
Surface-to-Bulk Transfer

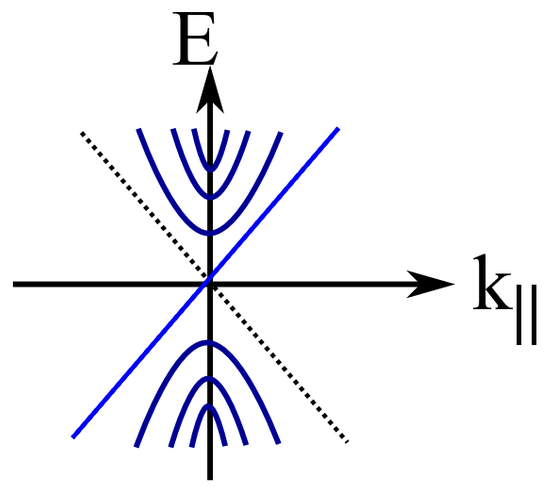


Bulk Landau Levels

ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Some remarks





Bulk Landau Levels

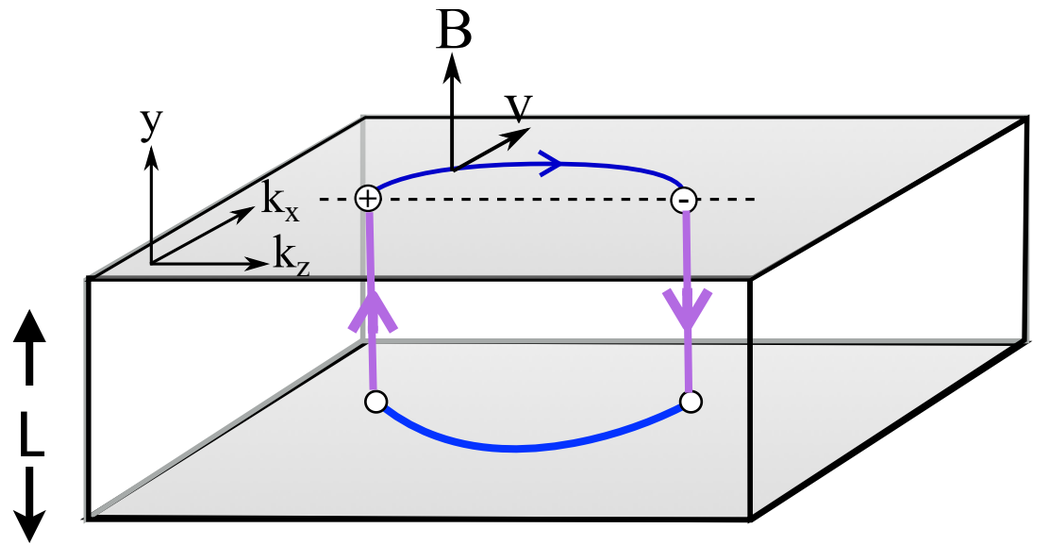
- Closed magnetic orbit around non-local Fermi surface
- Real space trajectory encloses no flux
- Occurs at all energies where there is a Chiral bulk LL

Quantum oscillations from a non-local Fermi surface

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

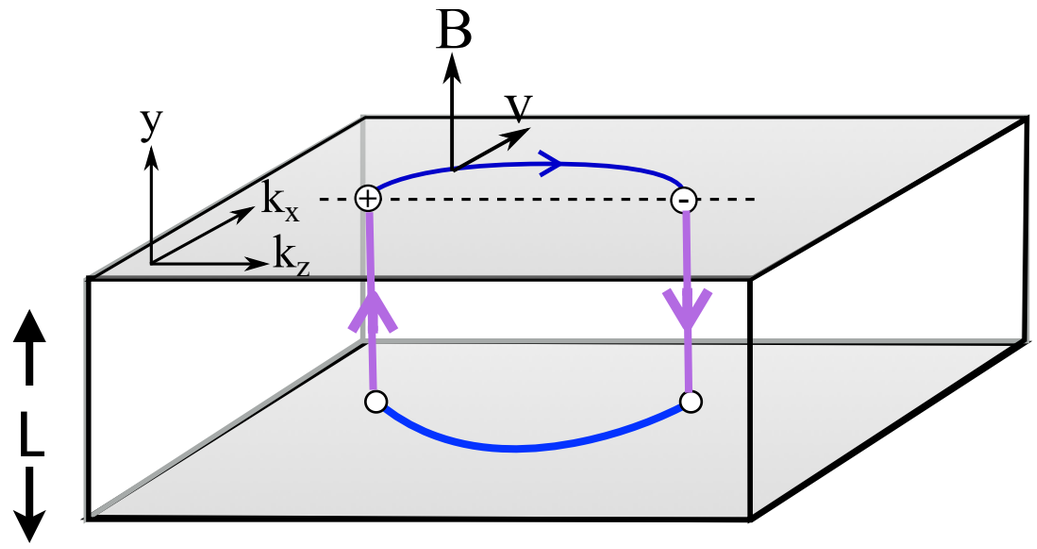
ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Quantum oscillations from a non-local Fermi surface

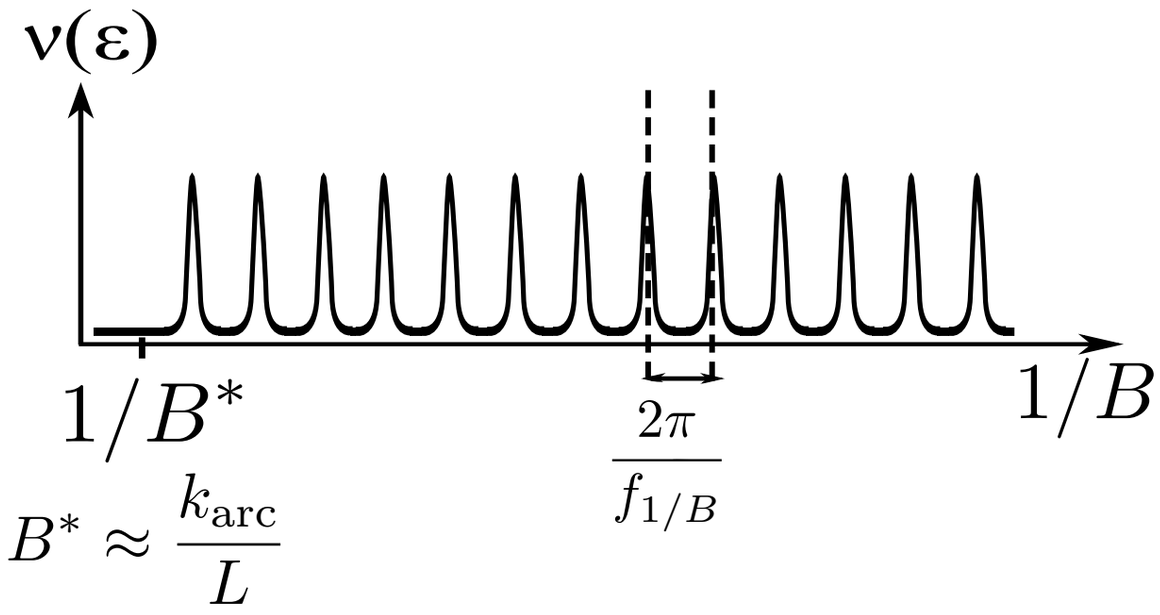
Quantization of semiclassical orbits

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

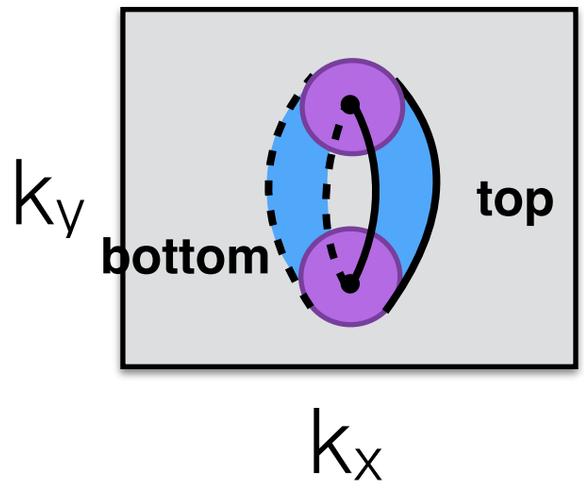
Arc **Bulk**



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

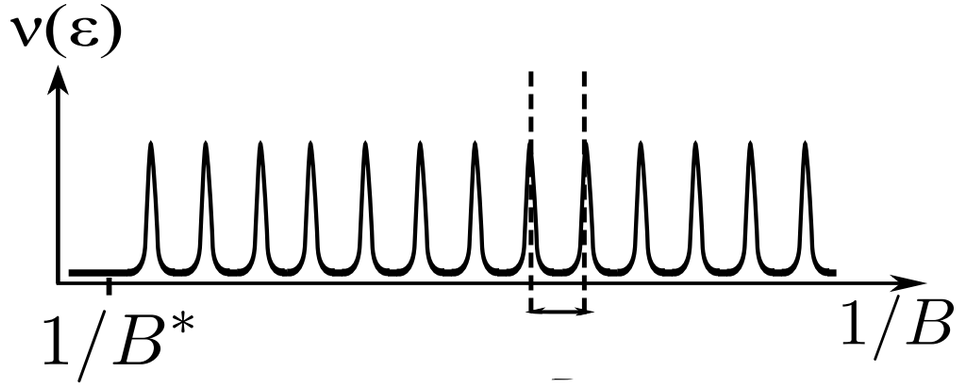


$f_{1/B}$



ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

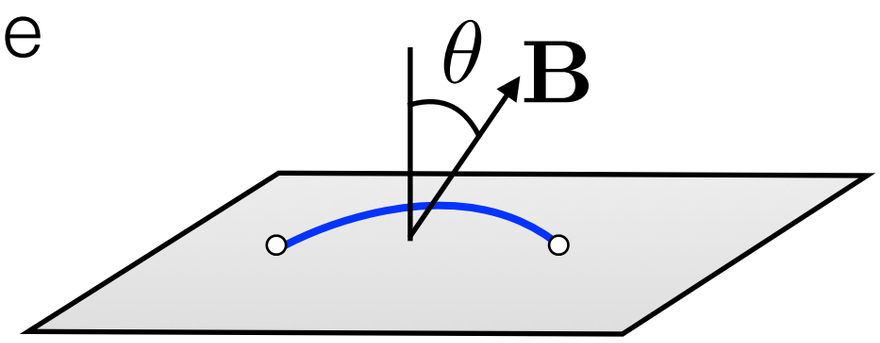
Fermi Arc Quantum Oscillations - Remarks



Experimental signature of topological surface-bulk connection

- Characteristic thickness dependence

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

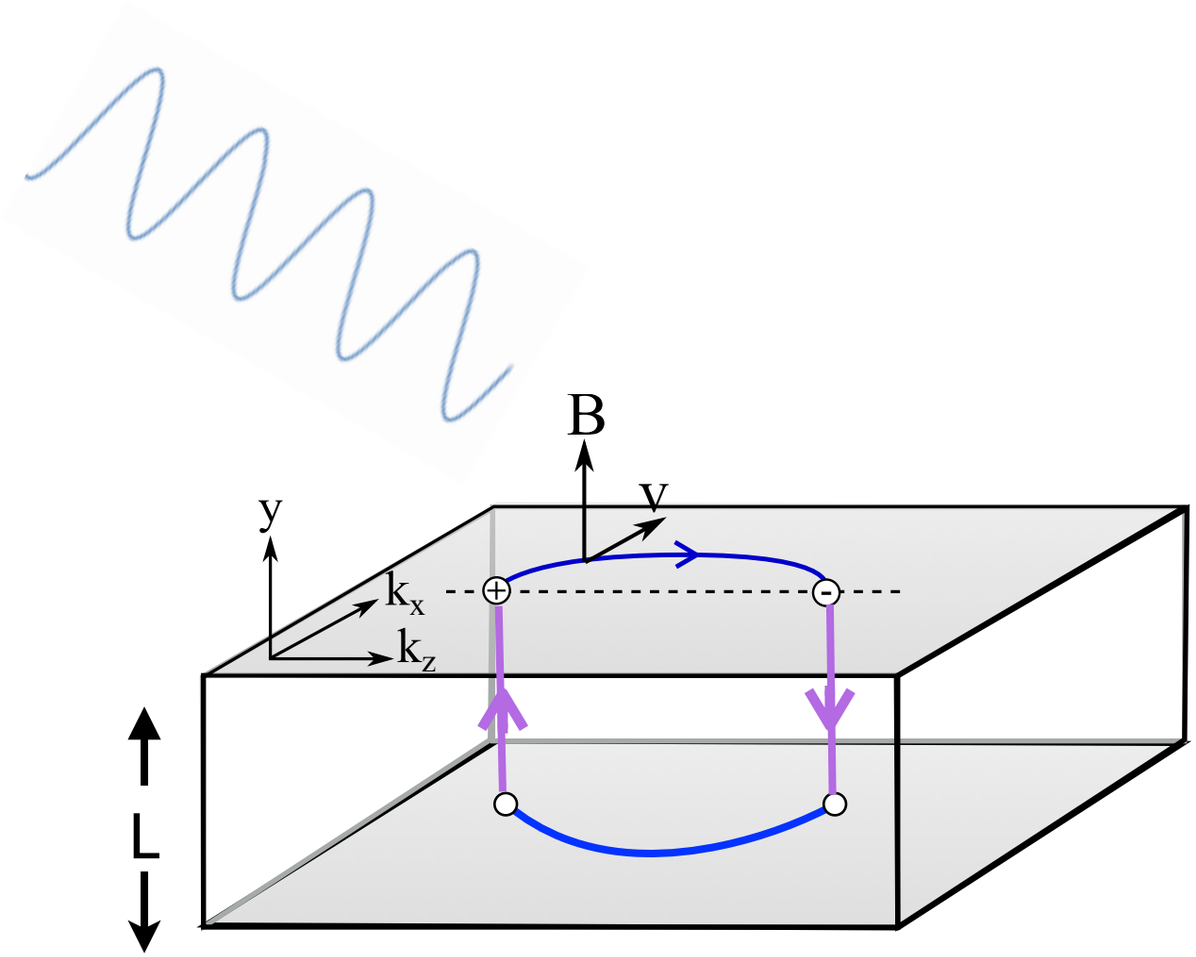


Practical consideration - Disorder

- Need L < MFP (can be 100's of nm, e.g. Cd_3As_2)

ACP, I.Kimchi, A. Vishwanath, Nature Communications (2014)

Related Measurement - Cyclotron resonance



$$\omega_{\mathrm{res}} \approx \frac{\pi}{\frac{k_{\mathrm{arc}}}{evB} + L/v}$$

$$\lambda_{\mathrm{res}} \gtrsim \frac{c}{v} L$$

- Cyclotron frequency saturates at B ~ 1/L
- Polarization dependence
- Anomalous skin-depth effect => surface sensitivity

Y Baum, E Berg, SA Parameswaran, A Stern unpublished

2. Experiment - Cd3As2 magnetotransport

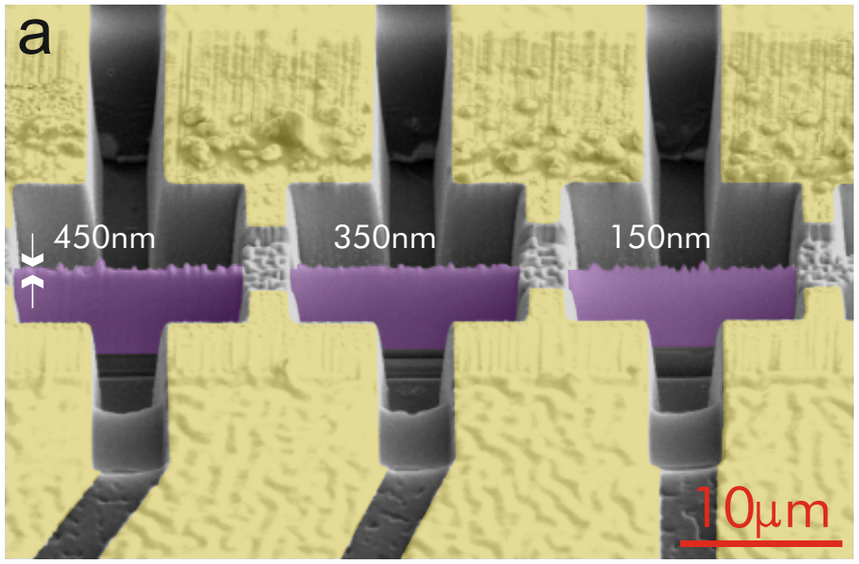
P. Moll, N.L. Nair, T. Helm, A.C. Potter, I. Kimchi, A. Vishwanath, J. Analytis arXiv:1505.02817

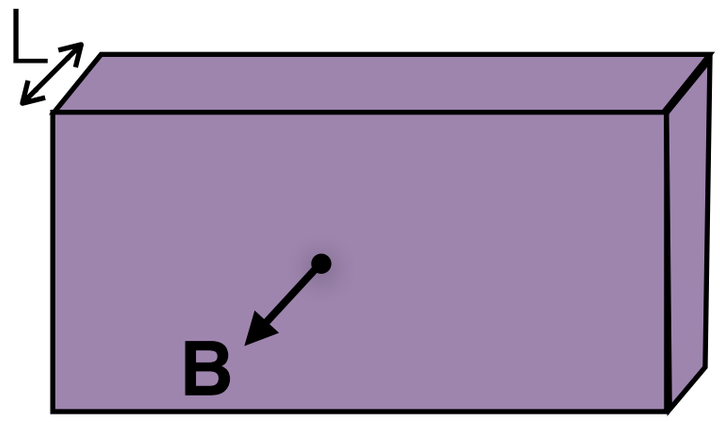
Berkeley UNIVERSITY OF CALIFORNIA

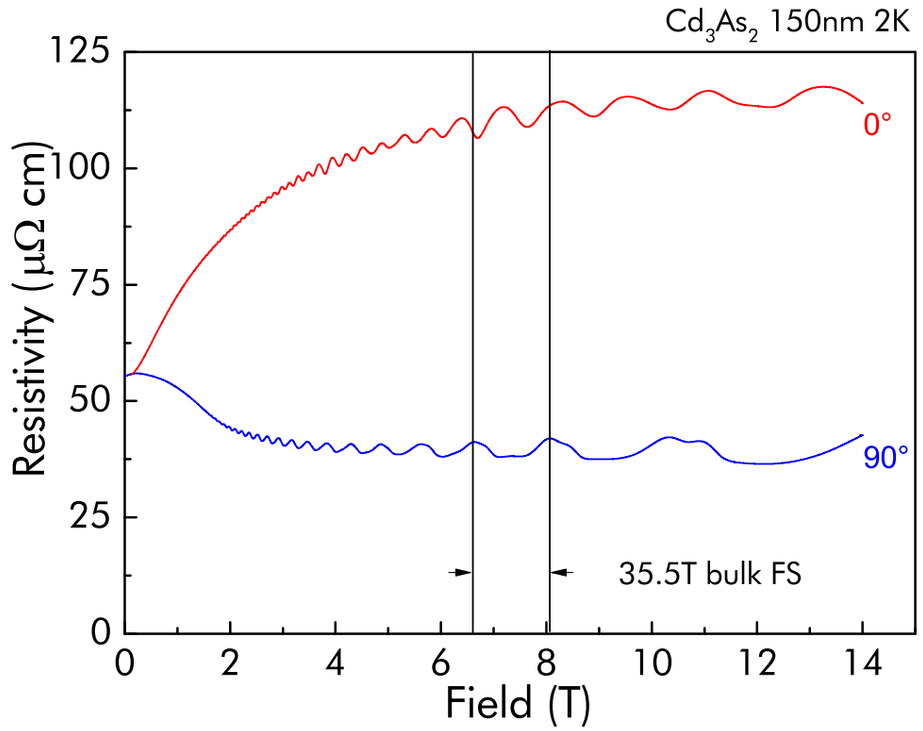
GORDON AND BETTY MOORE FOUNDATION

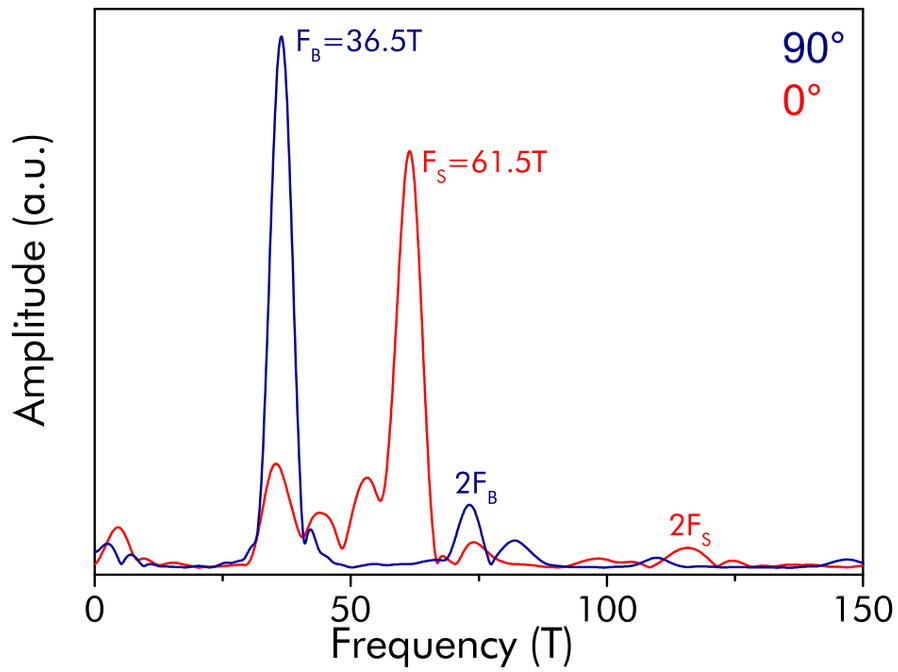
(Berkeley -> MPI)

SdH Oscillations in Cd_3As_2 Microstructures

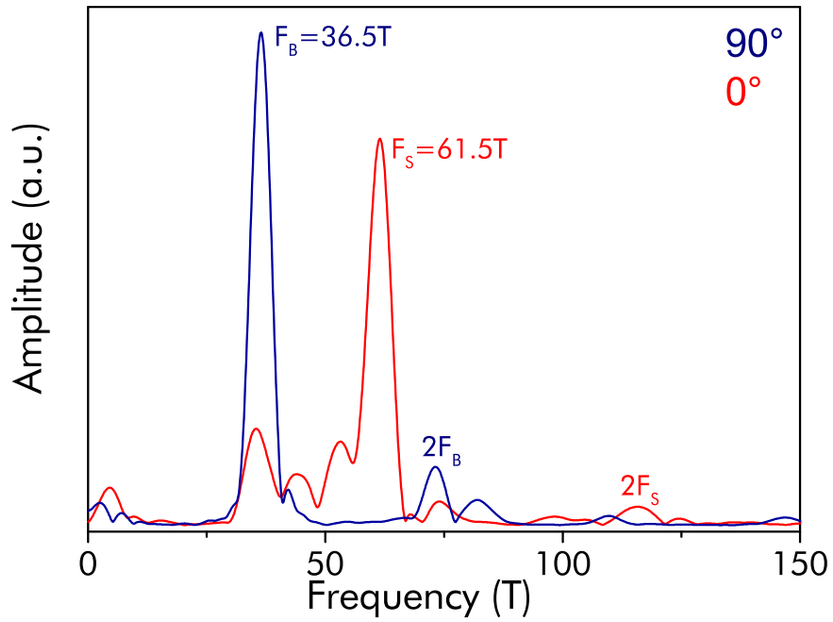


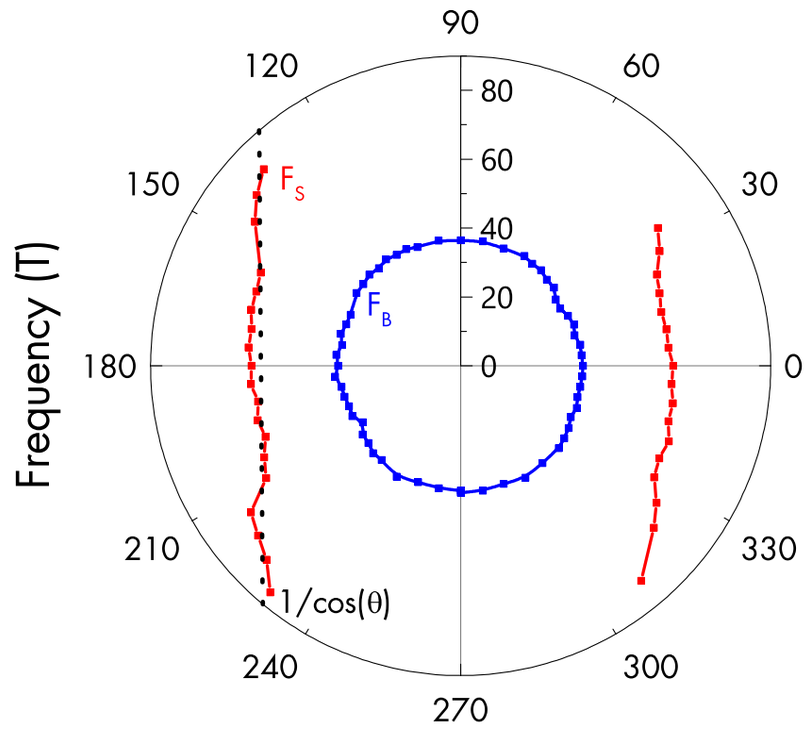




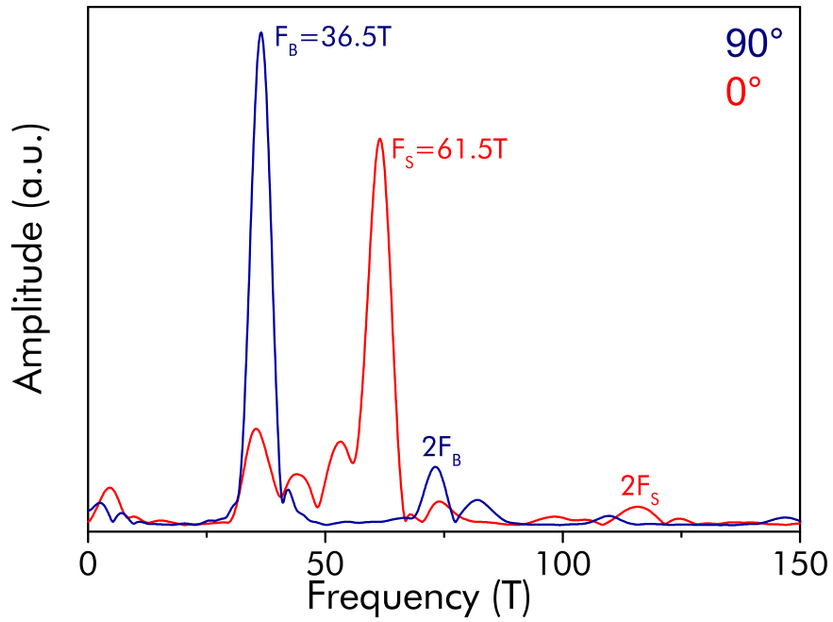


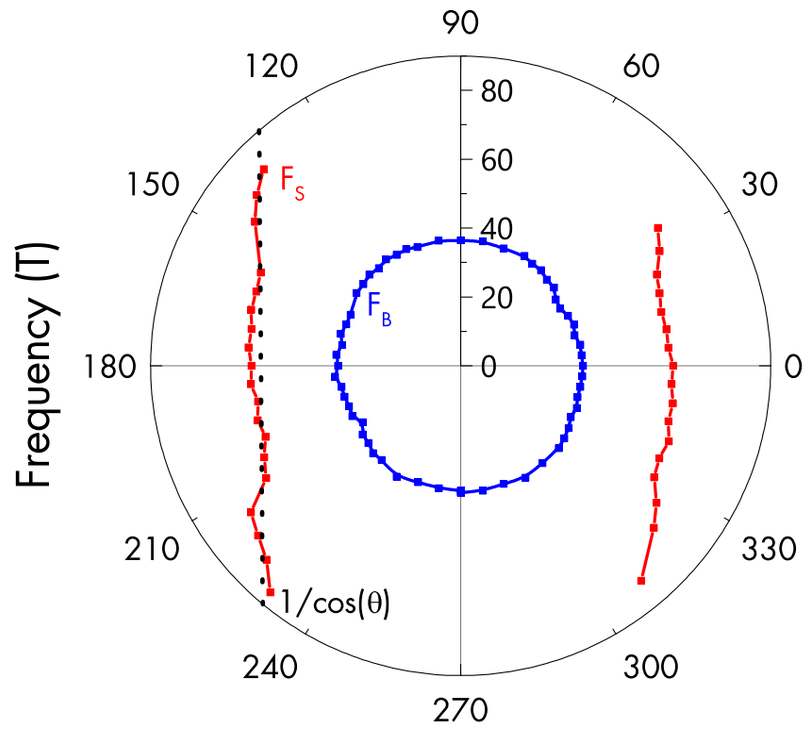
Surface and Bulk Oscillations





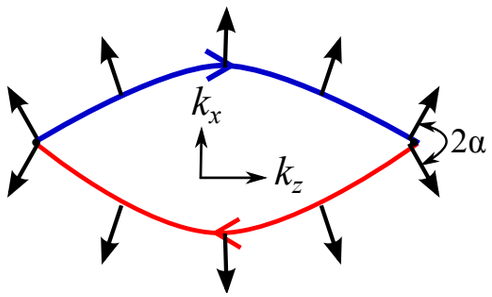
Surface and Bulk Oscillations

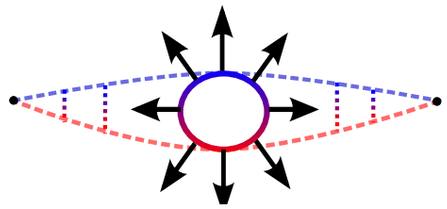


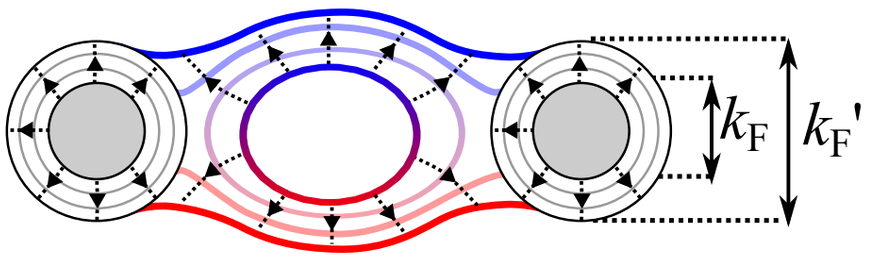


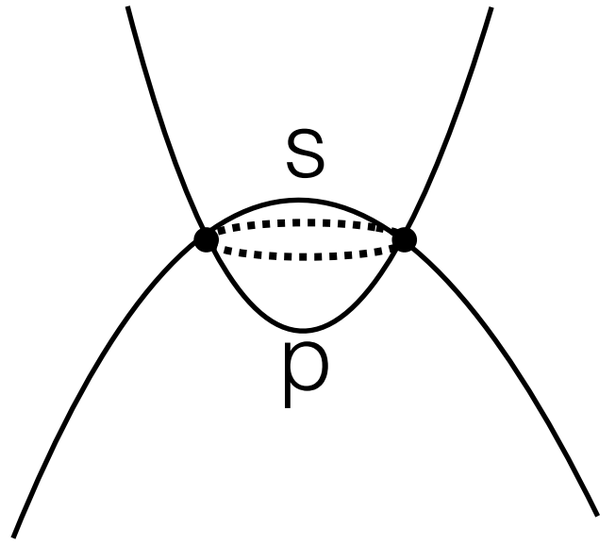
What is the source of the surface signal?

Surface States of Dirac Semimetals



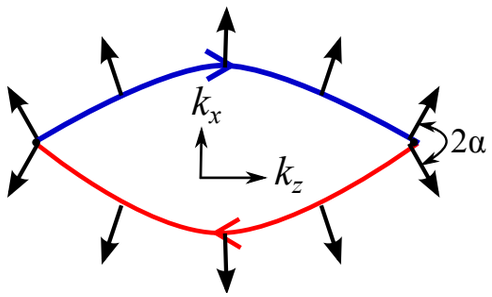


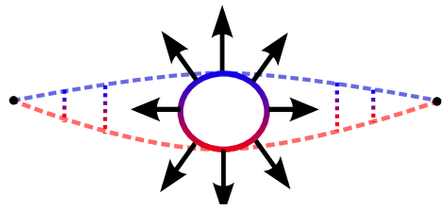


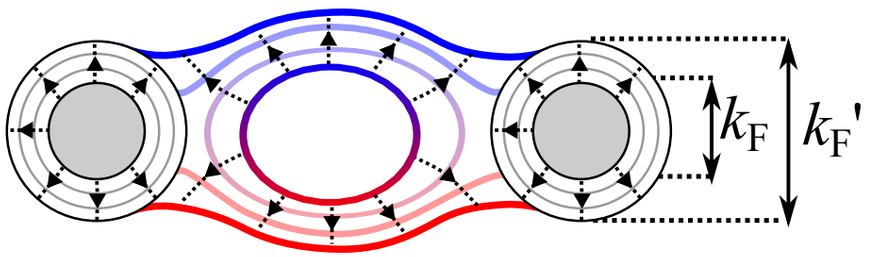


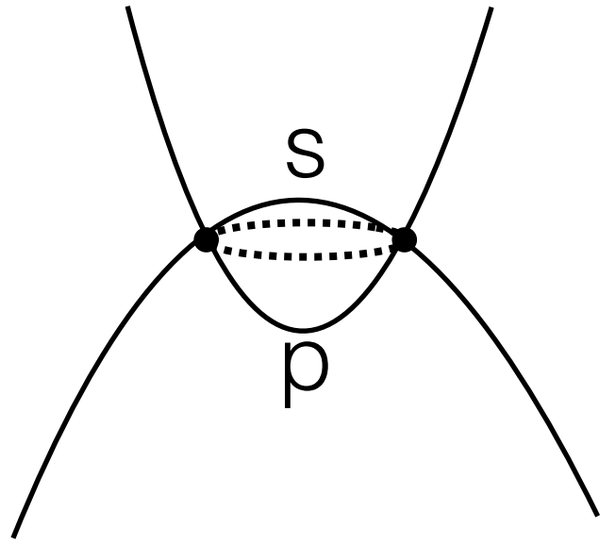
ACP, I.Kimchi, A. Vishwanath, Nat. Comm '14
see also Yang & Nagaosa Nat. Comm '14

Surface States of Dirac Semimetals







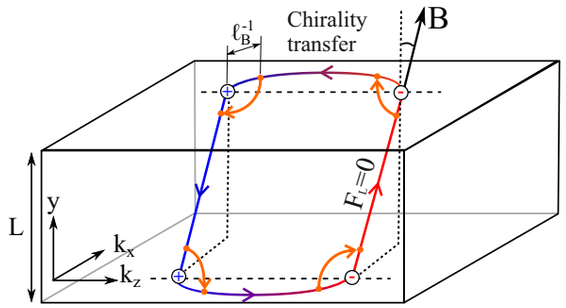


Possible Surface States:

1. Arcs (Weyl-like)
2. Helical (TI-like)
3. Conventional (non-topological)

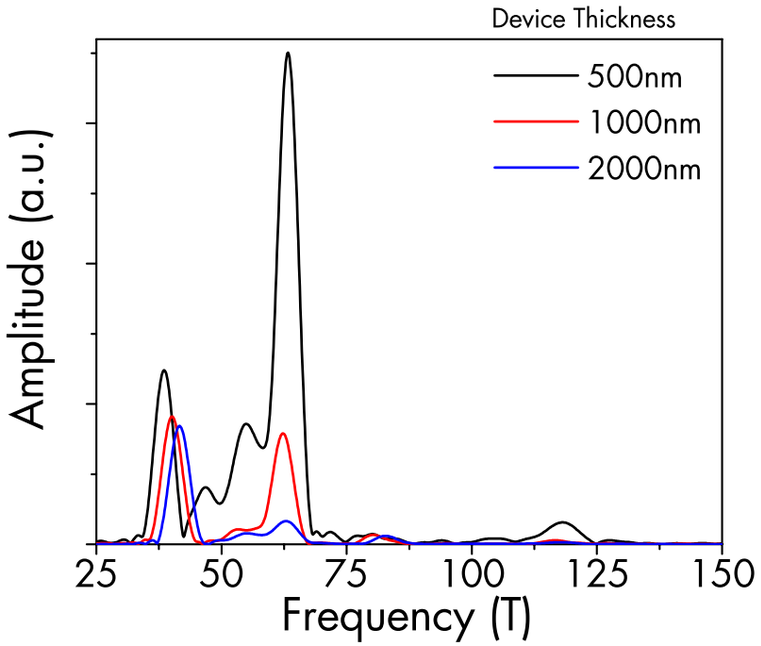
ACP, I.Kimchi, A. Vishwanath, Nat. Comm '14
see also Yang & Nagaosa Nat. Comm '14

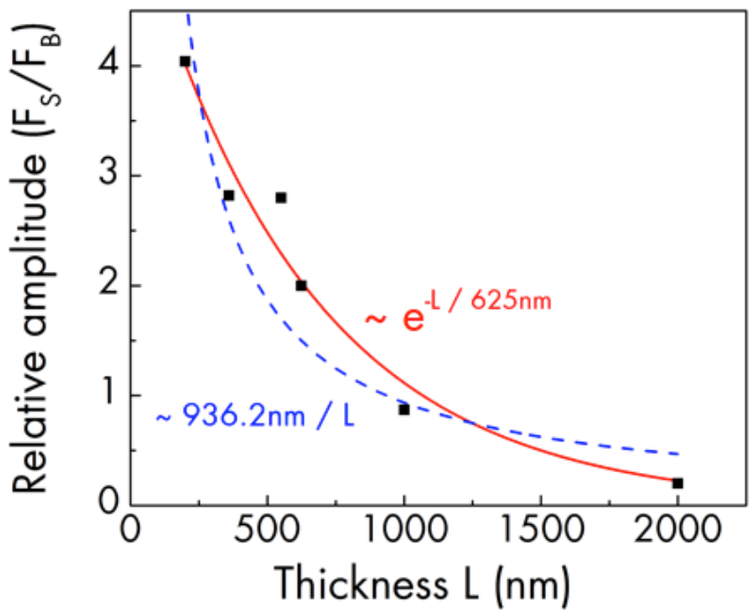
Thickness Dependence



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

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



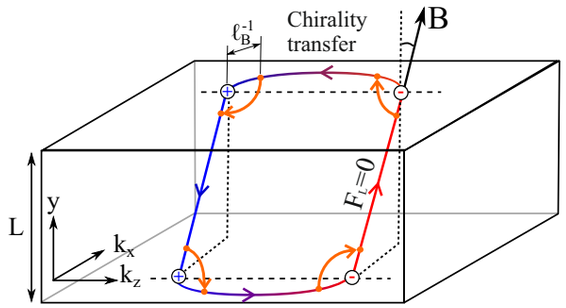


(B Parallel to surface only)

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

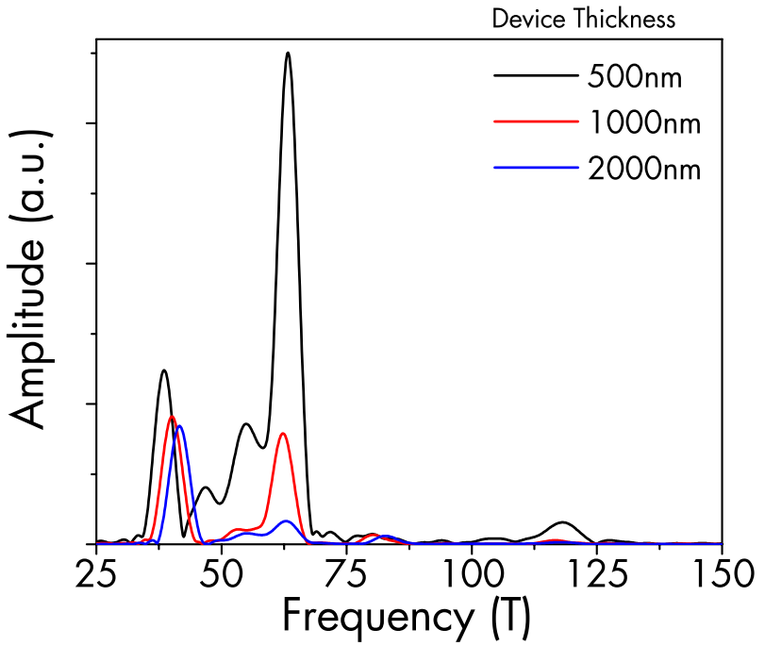
Thickness Dependence

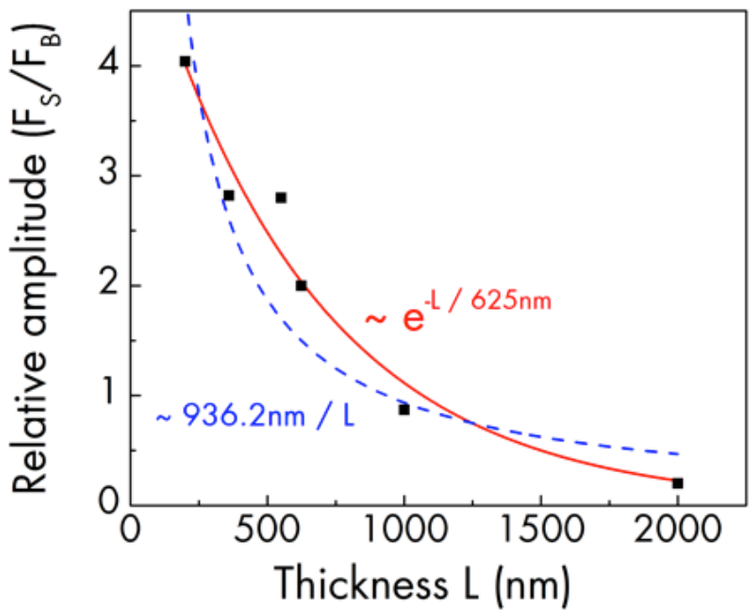
(B Parallel to surface only)

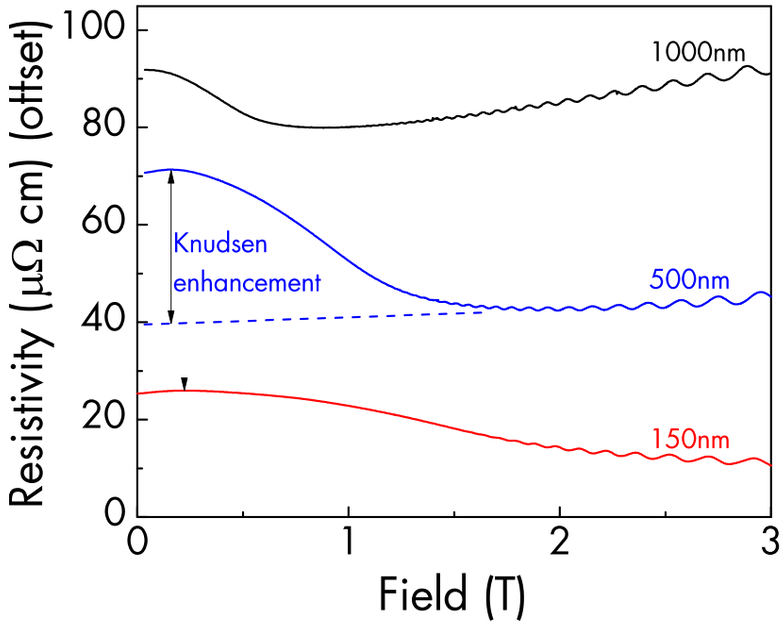


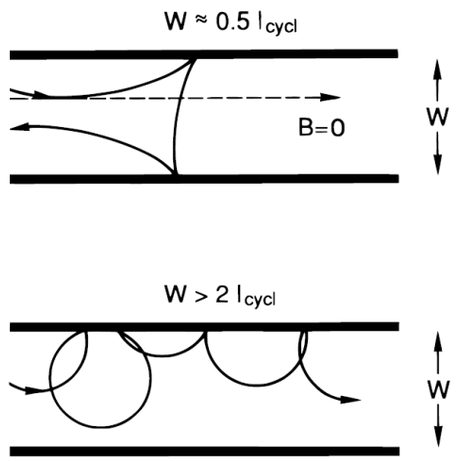
$$A_{\mathrm{SdH}} \sim e^{-1/\omega_c \tau}$$

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



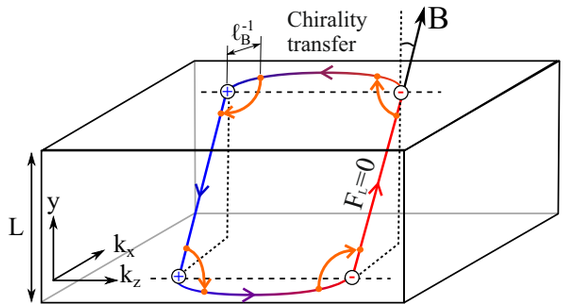






$$\ell_{\mathrm{MFP}} \approx 1.2\mu m$$

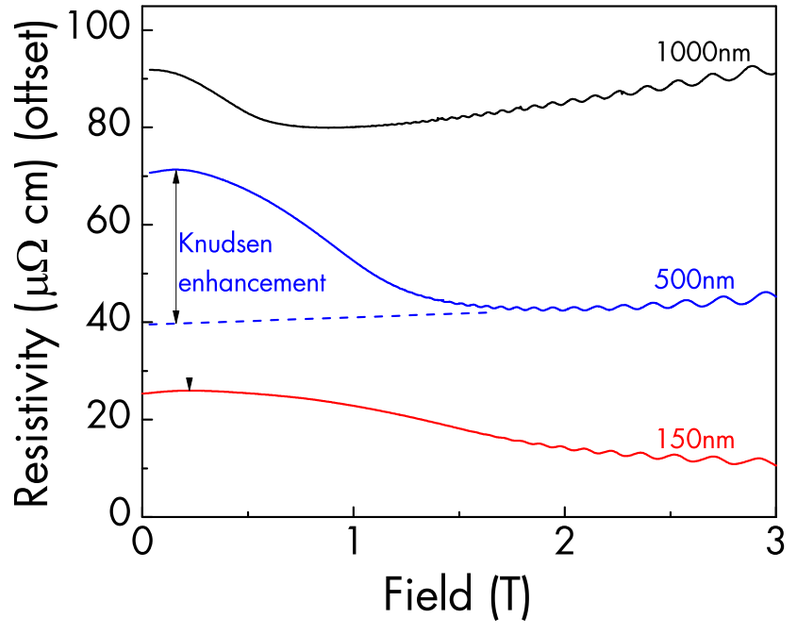
Thickness Dependence

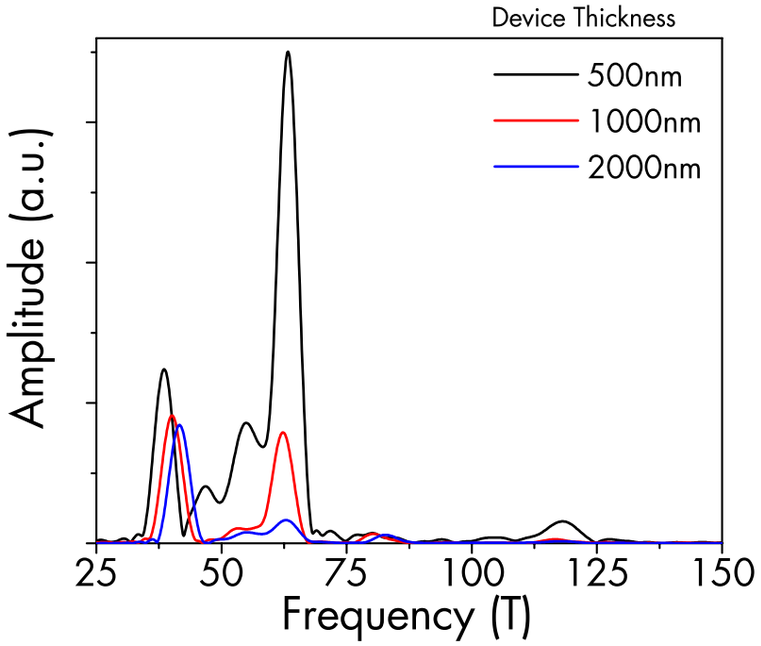


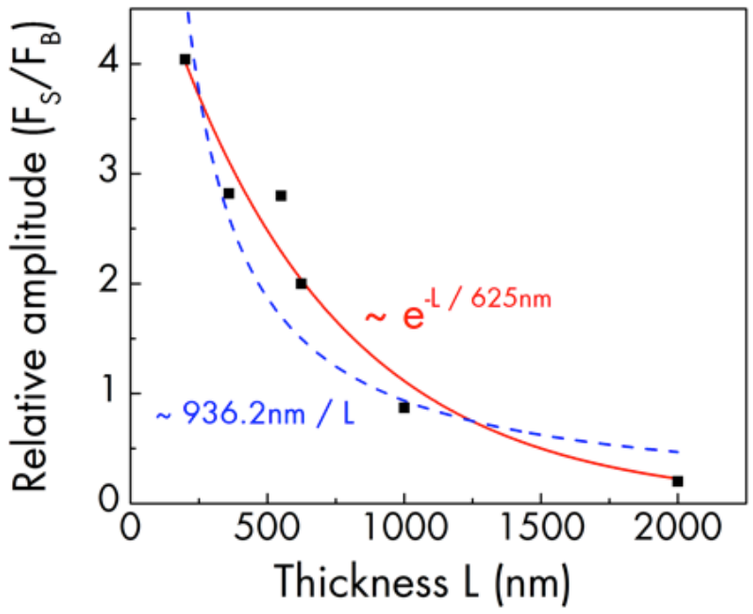
$$A_{\mathrm{SdH}} \sim e^{-1/\omega_c \tau}$$

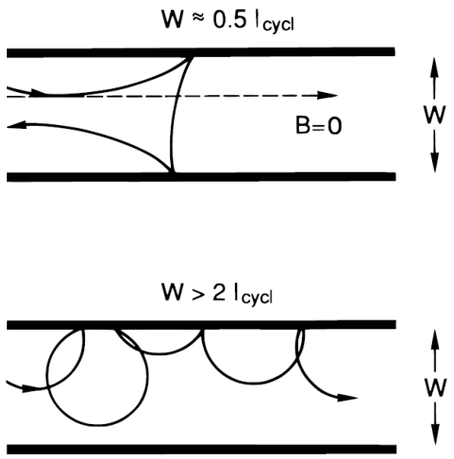
$$\text{“}\frac{1}{\omega_c \tau}\text{”} \approx \frac{k_0}{e v_s B}\tau_s^{-1} + \frac{L}{v_B}\tau_B^{-1}$$

(B Parallel to surface only)





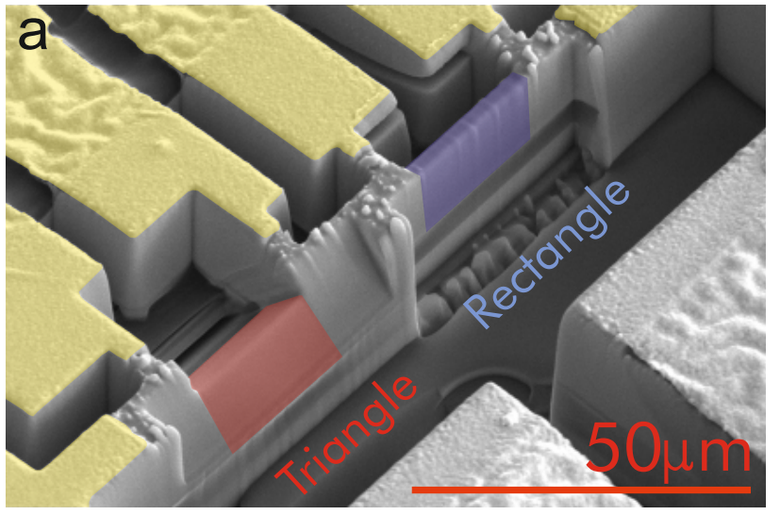




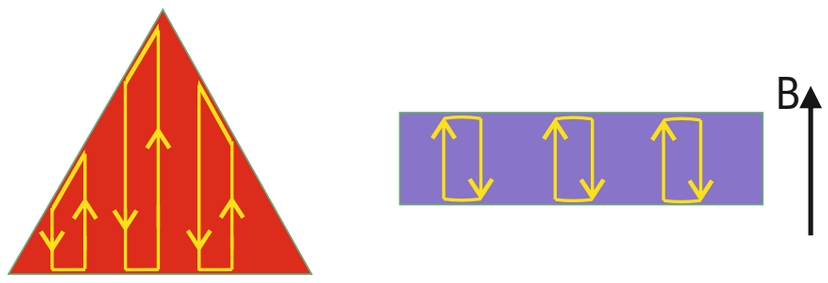
But… $$\frac{1}{\rho_{\mathrm{tot}}} = \frac{1}{\rho_s} + \frac{1}{\rho_b}$$

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

Geometric Interference - Triangle Device



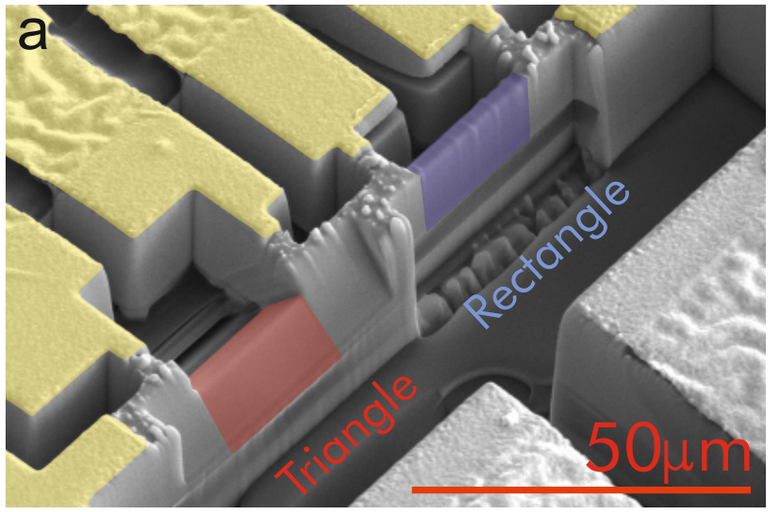
(same surface-bulk ratio)



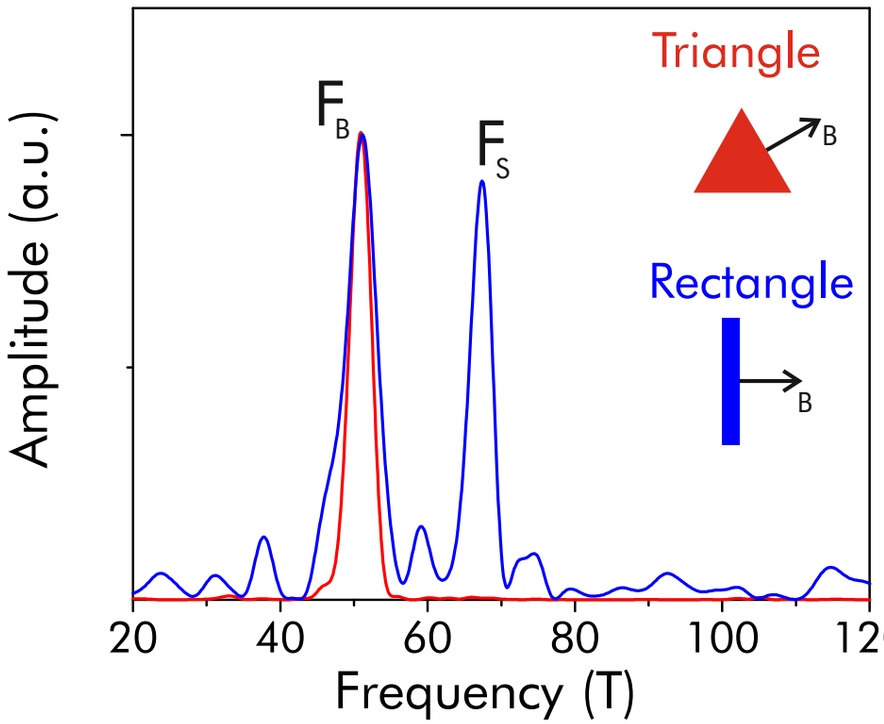
$$\frac{1}{B_n} = \frac{2\pi n}{f_{1/B}} - \frac{e}{k_{\mathrm{arc}}} L$$

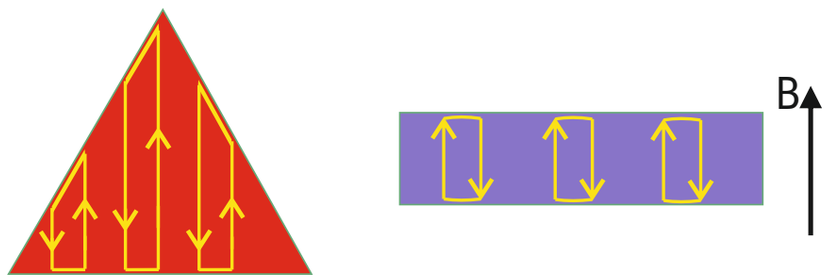
Analogy: Josephson junction in magnetic field

Geometric Interference - Triangle Device



(same surface-bulk ratio)

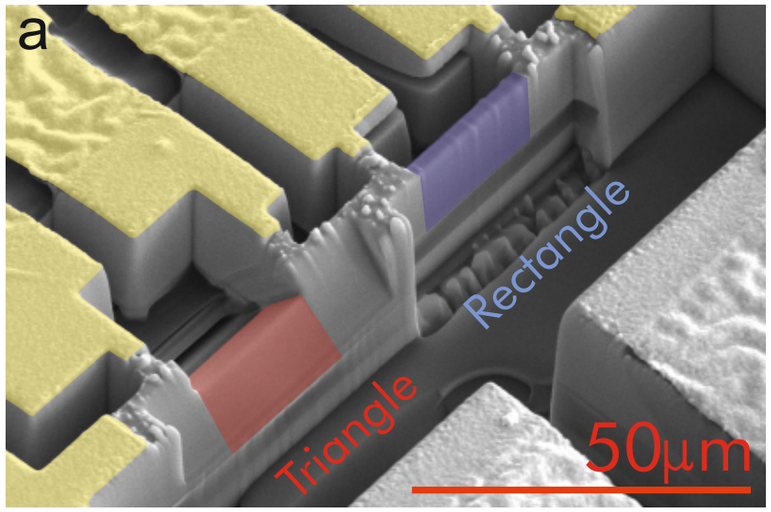




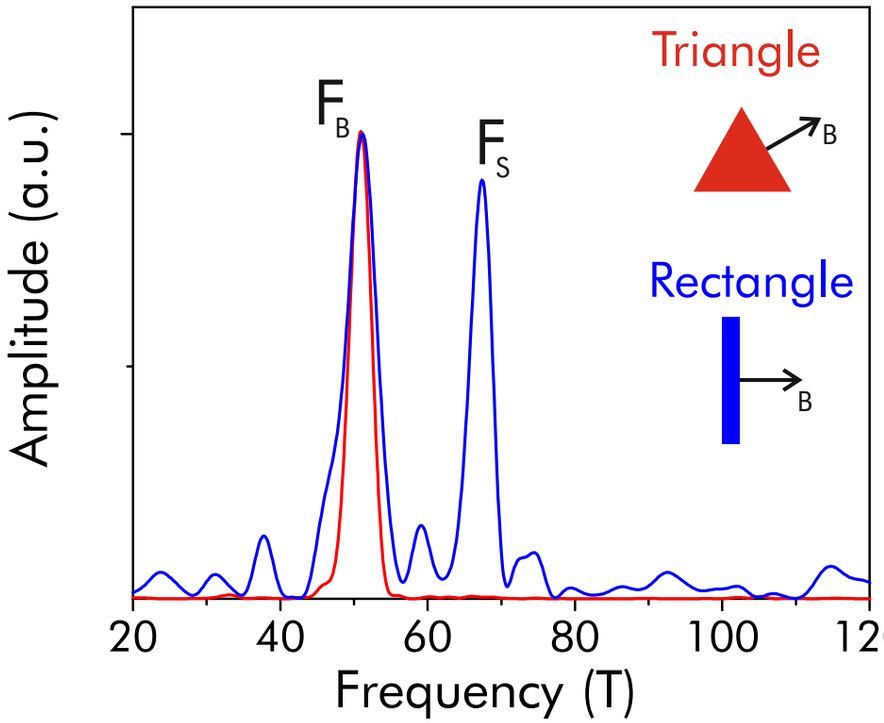
$$\frac{1}{B_n} = \frac{2\pi n}{f_{1/B}} - \frac{e}{k_{\mathrm{arc}}} L$$

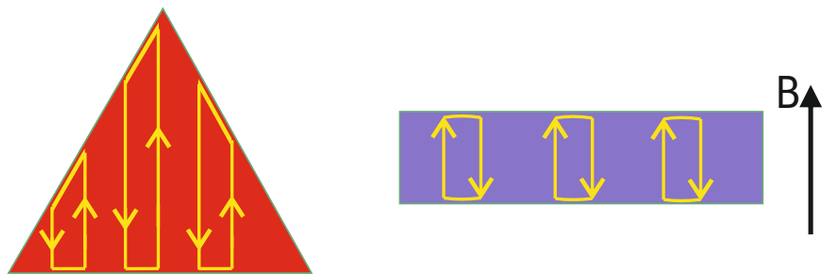
Analogy: Josephson junction in magnetic field

Geometric Interference - Triangle Device



(same surface-bulk ratio)



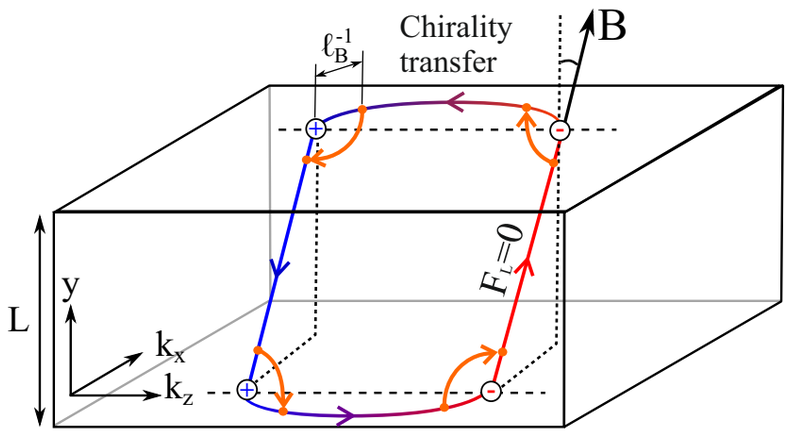


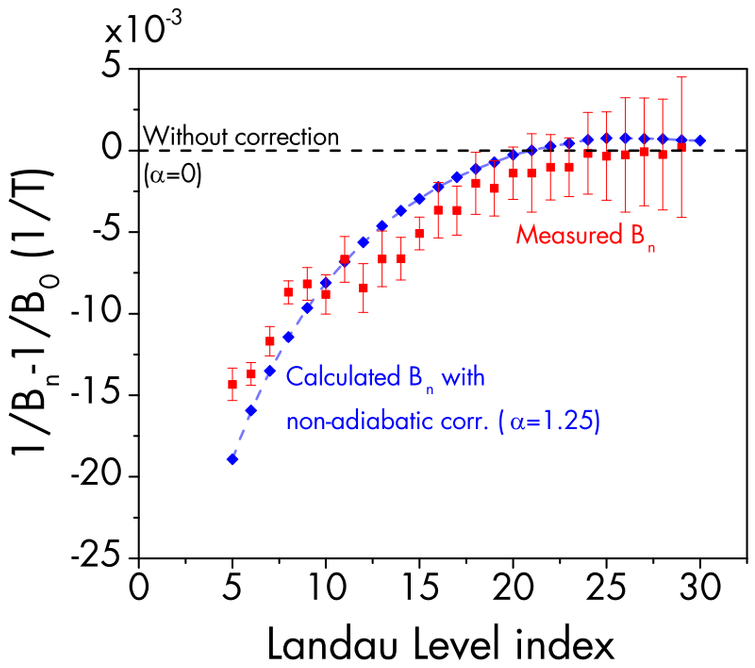
$$\frac{1}{B_n} = \frac{2\pi n}{f_{1/B}} - \frac{e}{k_{\mathrm{arc}}} L$$

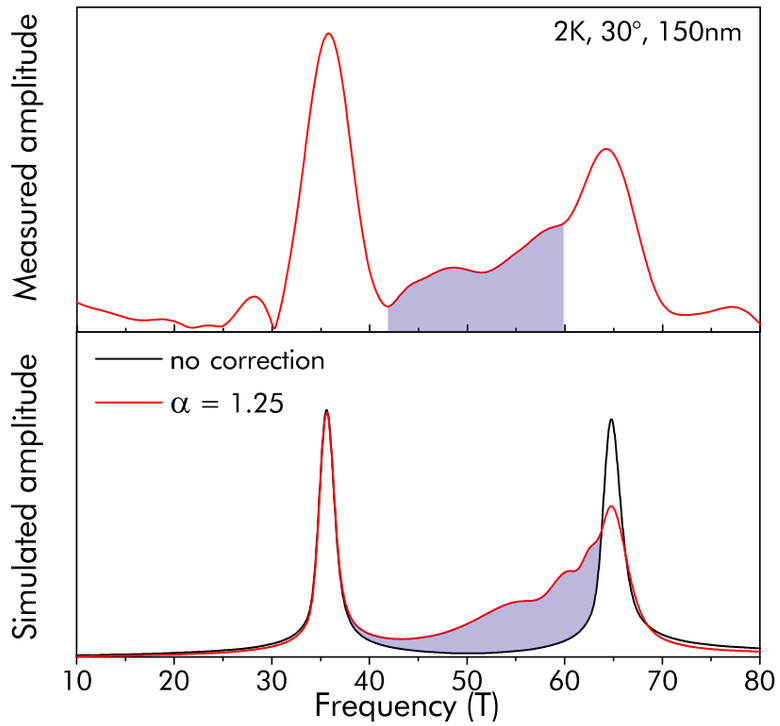
Analogy: Josephson junction in magnetic field

1. Conventional ✗
2. Helical (TI-like) ✗
3. Arcs (Weyl-like) ✓

Non-Adiabatic Corrections







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

Not spin-splitting

- asymmetric lineshape,
- wrong sign for TI,
- magnitude requires unphysically large g~300

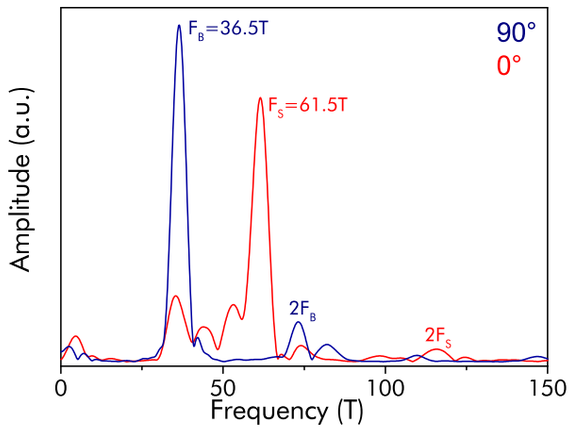
Theory Predictions vs Observations

Thickness Dependence

- Seen in thin films
- Oscillations require parallel surfaces
- Thickness dependent saturation field: $B_{sat} \sim 1/L$

Angle dependence

- Surface state 1/cos dependence
- Thickness dependent offset of peak positions (Lower doping?)



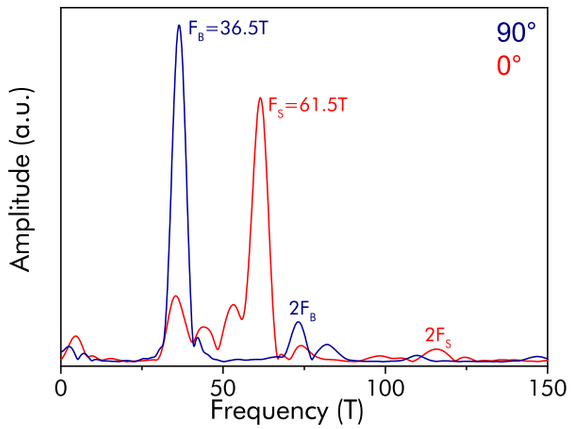
Theory Predictions vs Observations

Thickness Dependence

- Seen in thin films ✓
- Oscillations require parallel surfaces
- Thickness dependent saturation field: $B_{sat} \sim 1/L$

Angle dependence

- Surface state 1/cos dependence
- Thickness dependent offset of peak positions (Lower doping?)



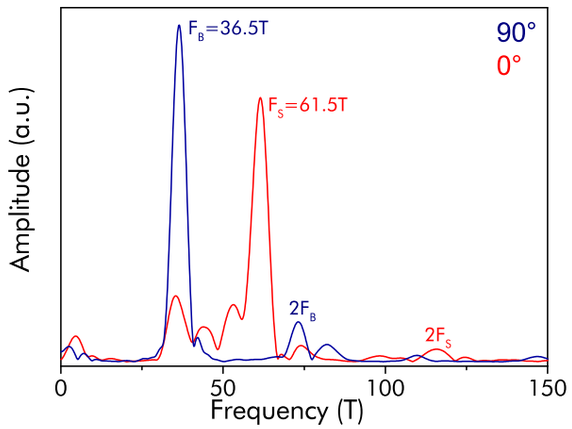
Theory Predictions vs Observations

Thickness Dependence

- Seen in thin films ✓
- Oscillations require parallel surfaces ✓
- Thickness dependent saturation field: $B_{sat} \sim 1/L$

Angle dependence

- Surface state 1/cos dependence
- Thickness dependent offset of peak positions (Lower doping?)



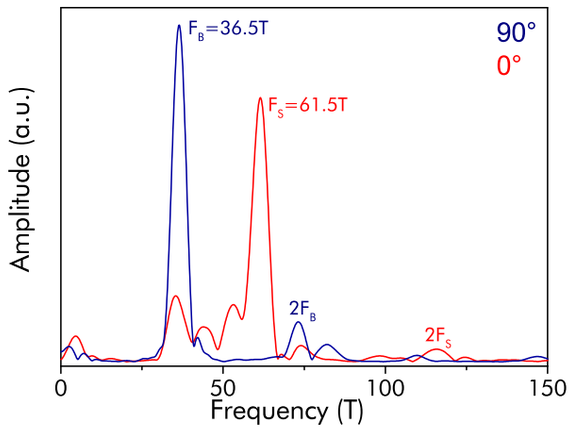
Theory Predictions vs Observations

Thickness Dependence

- Seen in thin films ✓
- Oscillations require parallel surfaces ✓
- Thickness dependent saturation field: $B_{sat} \sim 1/L$ ✗

Angle dependence

- Surface state 1/cos dependence
- Thickness dependent offset of peak positions (Lower doping?)



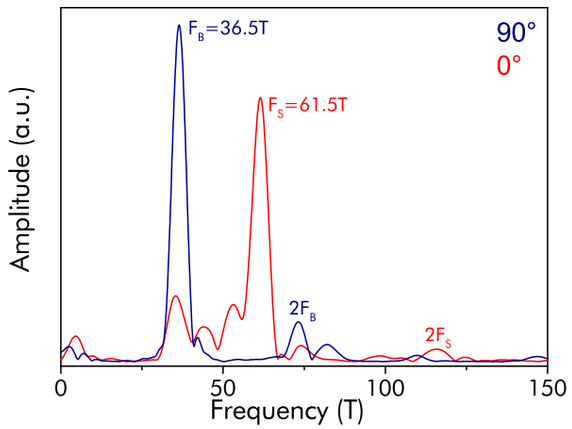
Theory Predictions vs Observations

Thickness Dependence

- Seen in thin films ✓
- Oscillations require parallel surfaces ✓
- Thickness dependent saturation field: $B_{sat} \sim 1/L$ ✗

Angle dependence

- Surface state 1/cos dependence ✓
- Thickness dependent offset of peak positions (Lower doping?)



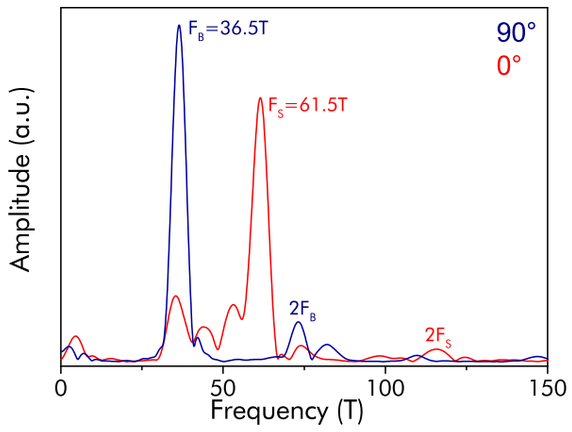
Theory Predictions vs Observations

Thickness Dependence

- Seen in thin films ✓
- Oscillations require parallel surfaces ✓
- Thickness dependent saturation field: $B_{sat} \sim 1/L$ ✗

Angle dependence

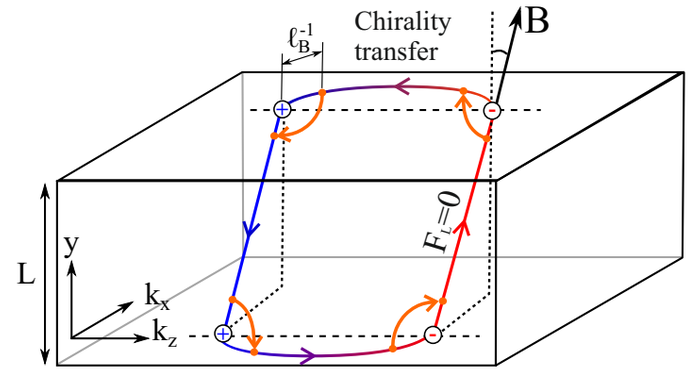
- Surface state 1/cos dependence ✓
- Thickness dependent offset of peak positions **(?)**
  (Lower doping?)



Summary and Open Questions

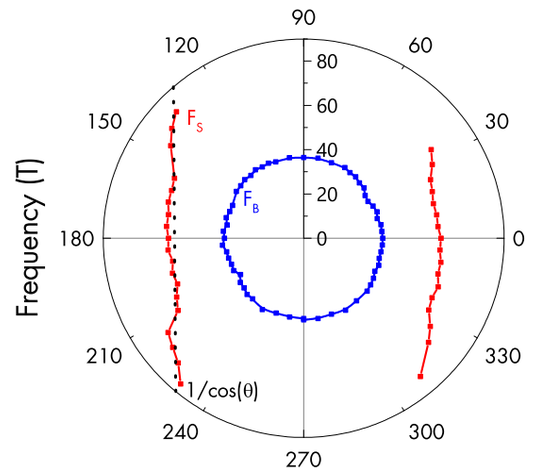
Quantum oscillations

- Experimental probe of surface arcs + Bulk chiral charge pumping (“anomaly” physics)



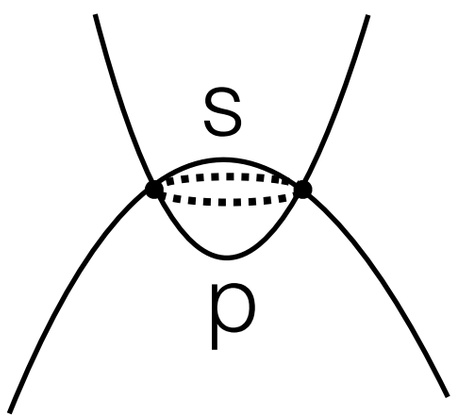
Cd_3As_2 Microstructures

- Clear sign of surface states in SdH oscillations
- Evidence consistent with Fermi-arcs

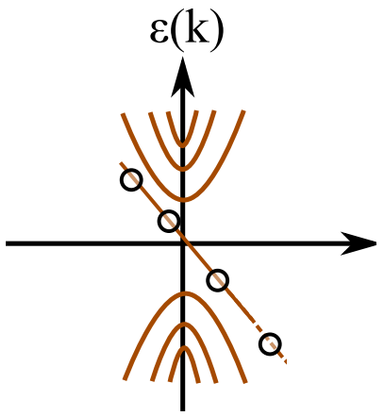


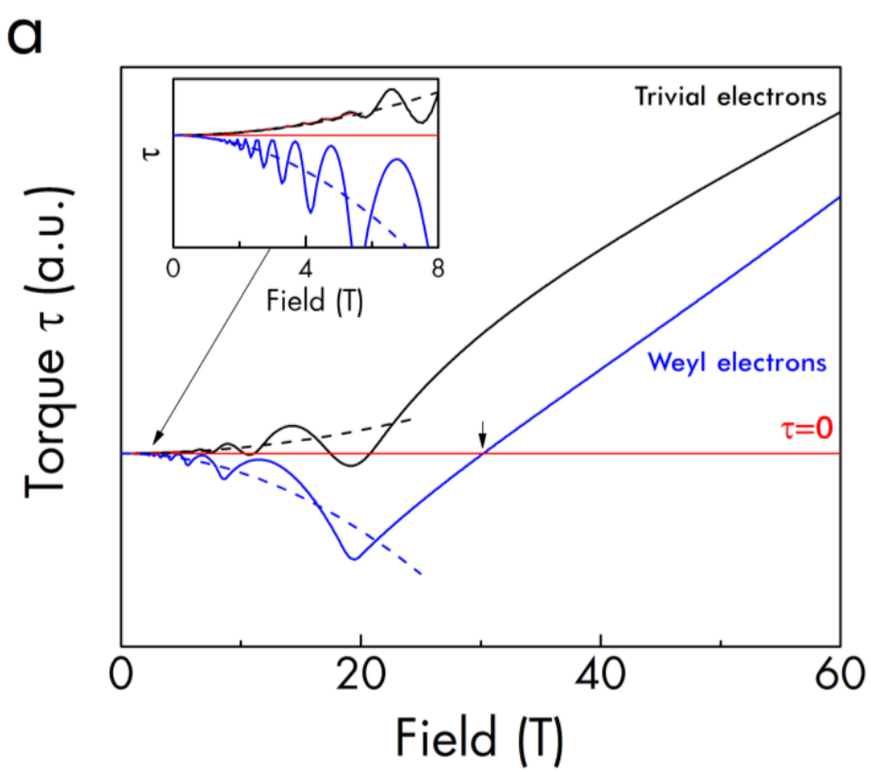
Questions & Future directions:

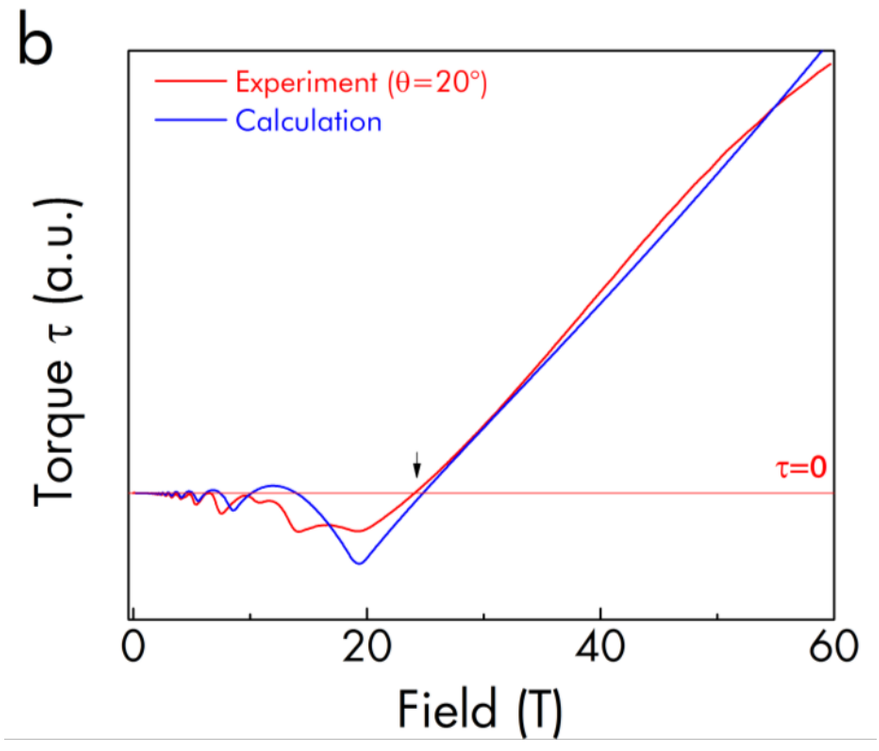
- Other materials?
  TaAs? - many, long arcs - could be complicated
- Related measurements: Cyclotron resonance?



Advertisement - Diagnosing a Weyl semimetal (NbAs)







$$\varepsilon_n(k) = \pm v \ \mathrm{sgn}(n)\sqrt{2|n|B + k^2}$$

$$M = -\frac{\partial E_{\mathrm{GS}}}{\partial B}$$

Torque reversal at quantum limit = symptom of chiral fermions

P. Moll, ACP et al. (J. Analytis Group) arXiv:1507.06981

References:

1. *ACP, I Kimchi, A. Vishwanath Nat. Comm '14*
2. *P. Moll, et al. arXiv:1505.02817, arXiv:1507.06981*

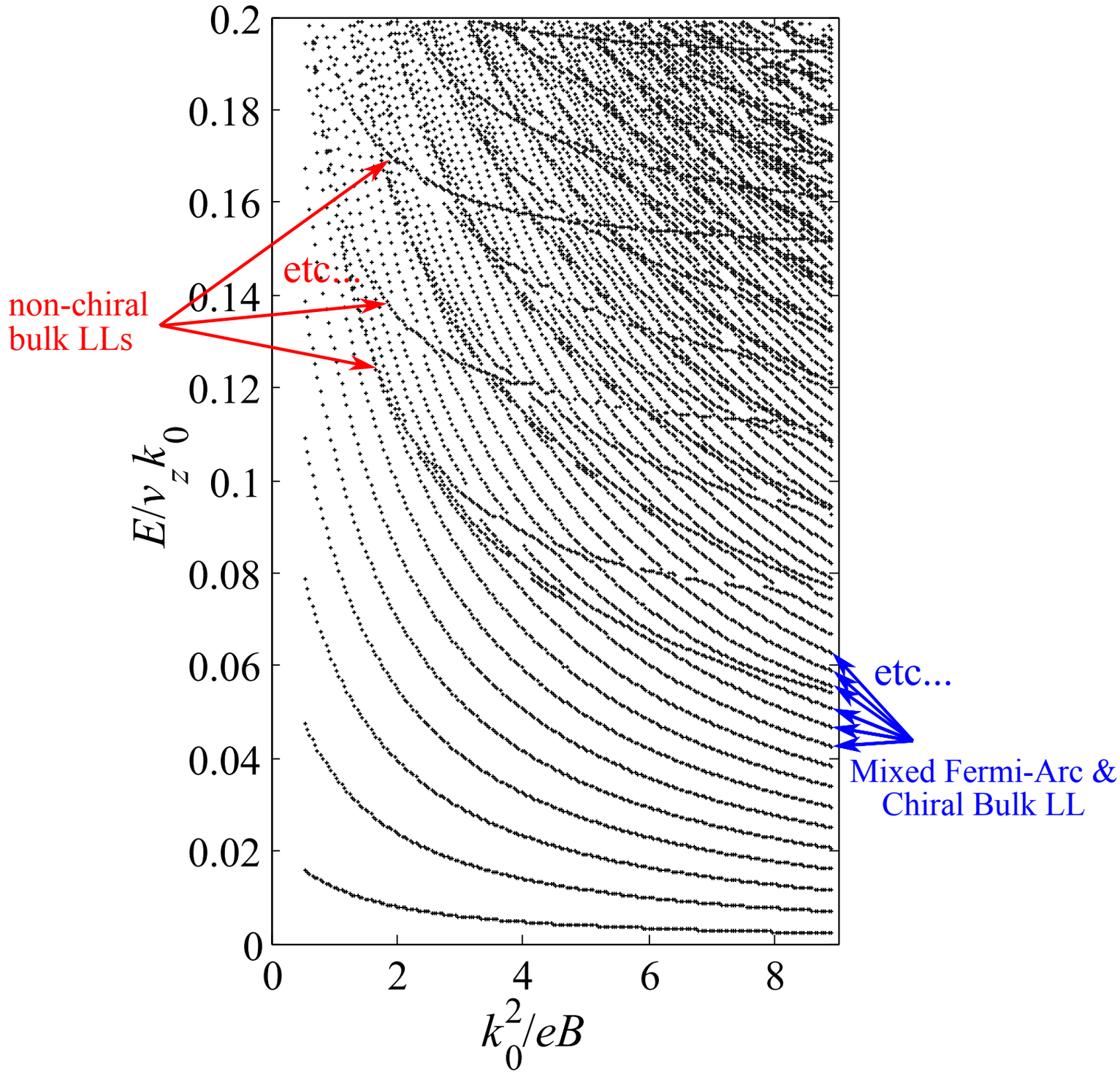
Thank you for your attention

Berkeley UNIVERSITY OF CALIFORNIA

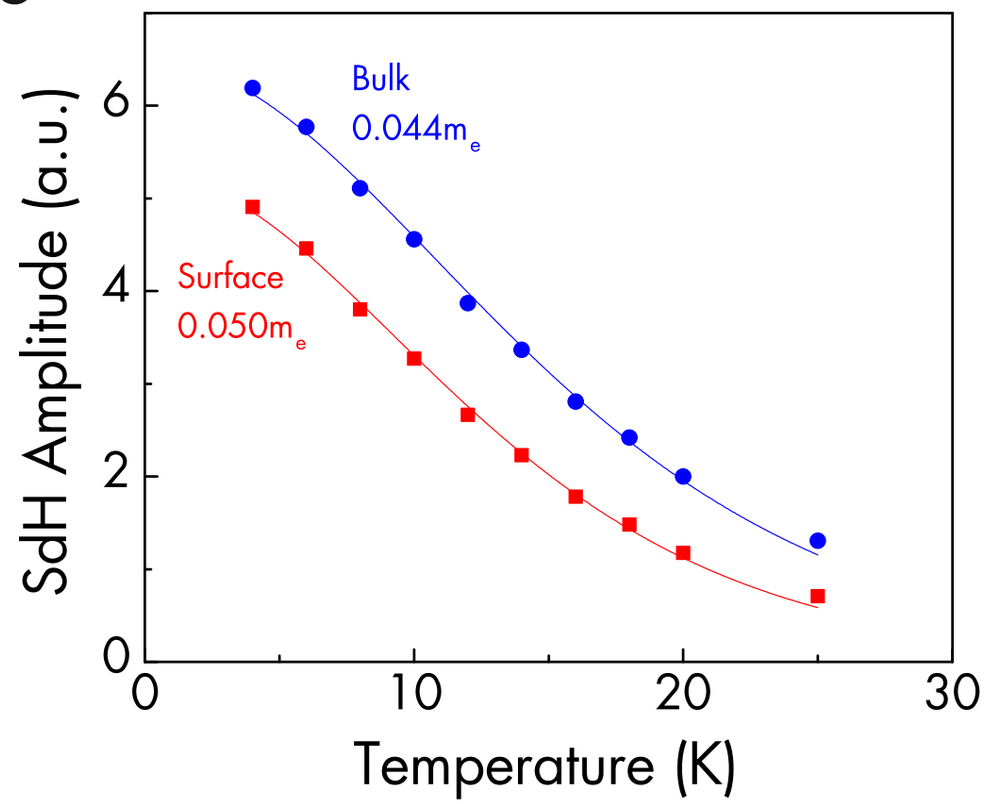
GORDON AND BETTY MOORE FOUNDATION




Weyl Quantum Oscillations - Numerics



c


Bulk
0.044m_e
Surface
0.050m_e
SdH Amplitude (a.u.)
0
2
4
6
0
10
20
30
Temperature (K)