Evidence of 3D Dirac dispersion in PbSnSe by the de Haas - van Alphen oscillations

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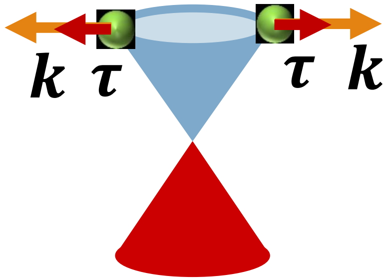
GRAPHENE vs TOPOLOGICAL INSULATORS

$$\hat{H}_{2D} = \hbar v_F \boldsymbol{\tau} \cdot \boldsymbol{k}$$

- ❑ Latice pseudospin
- ❑ Pseudospin – momentum locking - helicity

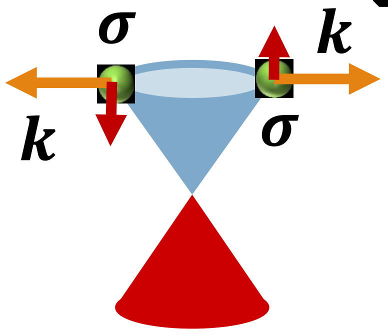


- ❑ 2D system
- ❑ Weak S-O interaction
- ❑ Lattice symmetry protection

By Google 10^7

$$\hat{H}_{2D} = \hbar v_F \boldsymbol{\sigma} \cdot \boldsymbol{k}$$

- ❑ Real spin
- ❑ Spin – momentum locking: $\boldsymbol{k} \perp \boldsymbol{\sigma}$ ***in plane***



- ❑ 2D QSH
- ❑ 3D $\boldsymbol{Z}_2$ invariants
- ❑ Strong S-O interaction
- ❑ TRS protection

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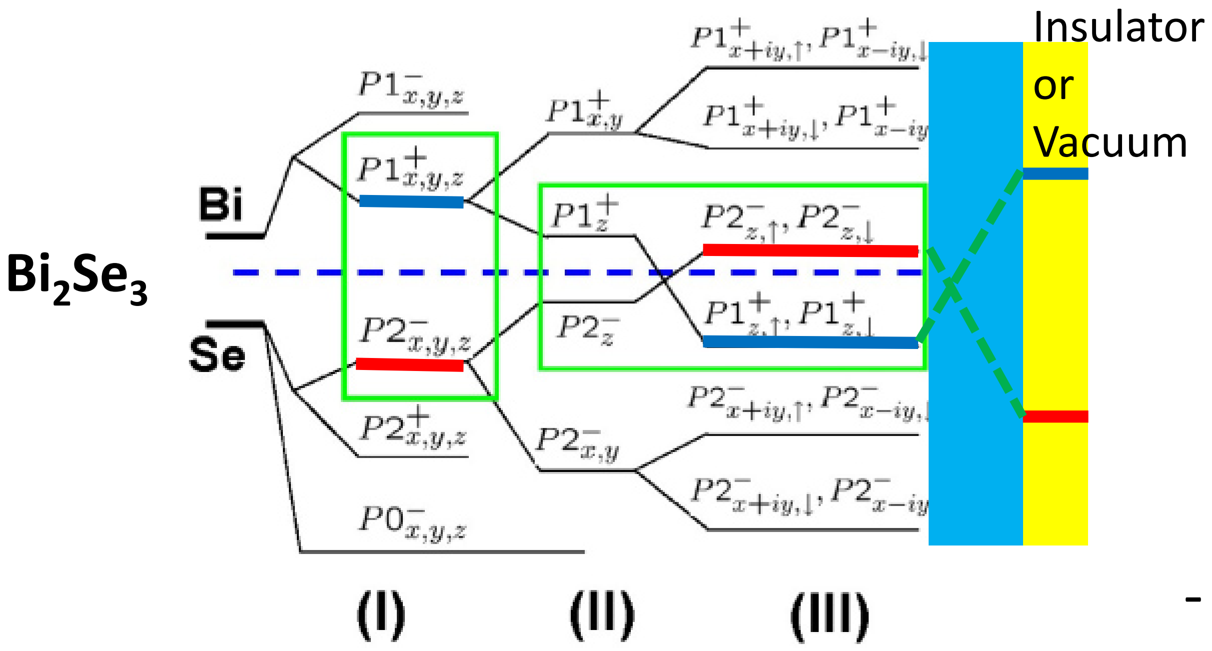
What are Topological insulators

❖ Special materials with insulating balk and conducting surface

❖ Origin of metallic surface lies special properties of bulk wave function

Bulk surface correspondence



Rep. Prog. Phys. **75** 096501 (2012)
Binghai Yan and Shou-Cheng Zhang

❖ Band inversion is curtail – NONTRIVIAL TOPOLOGY
❖ Dirac cones at TRS points
❖ Odd number of Dirac cones in the band gap

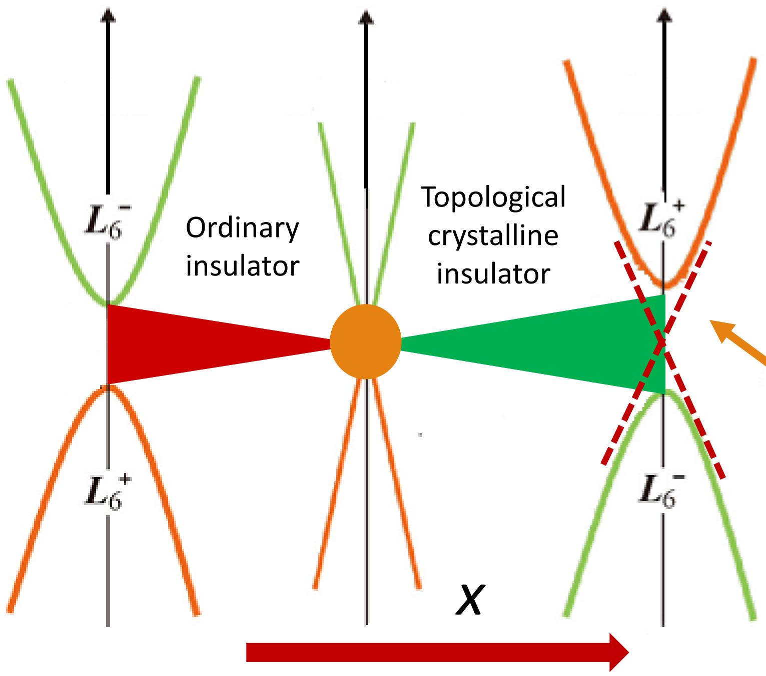
Interesting field for testing Elemental Particle Physics concepts

- Dirac, Weyl and Majorana fermion, magnetic monopoles and axion dynamics

PbSnSe and Topological Crystalline Insulators

❖ Topological Crystalline Insulators $\boldsymbol{TRS \leftrightarrow Crystal\ Symetry}$

$$Pb_{1-x}Sn_xSe$$



Band inversion

For *x*=0.17 critical point

- band inversion pint

I. Zeljkovic et al.
Nature Materials **14**, 318 (2015)

Topological SS

@ *x*= 0.17

-Topological phase transition

- 3D Dirac dispersion?

3D Dirac semimetals

- 3D equivalent of graphene

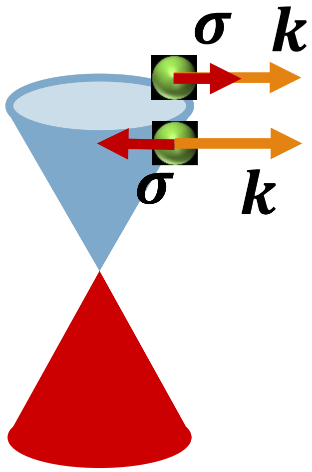
$$\hat{H}_{3D} = \hbar v_F \boldsymbol{\sigma} \cdot \boldsymbol{k}$$

$\sigma_x, \sigma_y, \sigma_z$ Spin Pauli matrix

k_x, k_y, k_z kristal momentum

- **Robust to perturbation**
- **Dirac cone is spin degenerated**
- **Helicity**

$$\chi = \frac{\boldsymbol{\sigma} \cdot \boldsymbol{k}}{\sigma k}$$



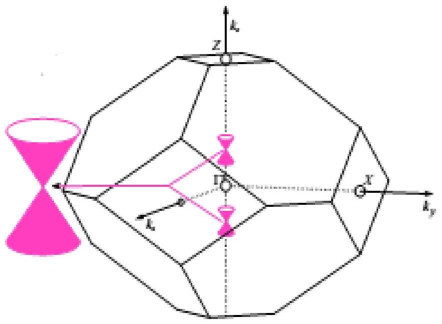
- 3D Dirac semimetals have nontrivial topology – due to band inversion- strong S-O interaction

- Band gap is not open to crate Topological Insulator

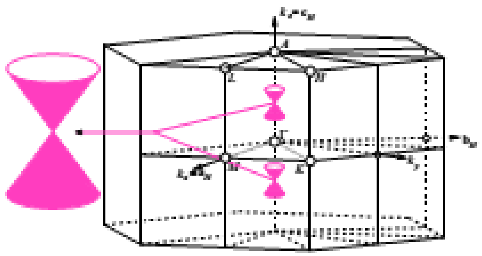
Intrinsic 3D Dirac semimetal

- Crystal symmetry protection from gap opening

Cd_3As_2, Na_3Bi, BaAgBi....



Cd_3As_2



Na_3Bi

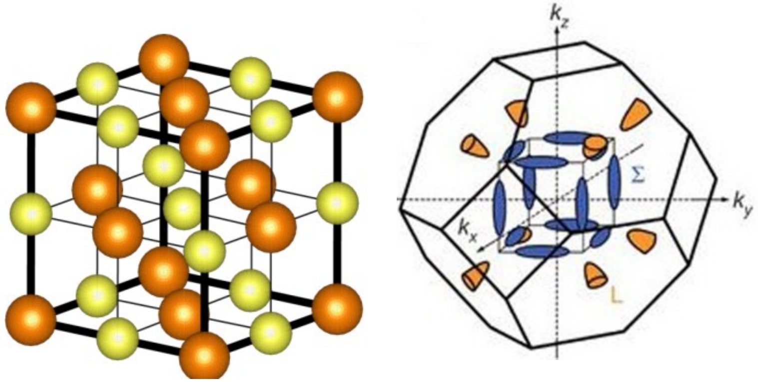
Q. D Gipson et al. arXiv:1411.0005

- High mobility 10^7 cm^2/Vs
- Very strong MR
- Giant diamagnetism

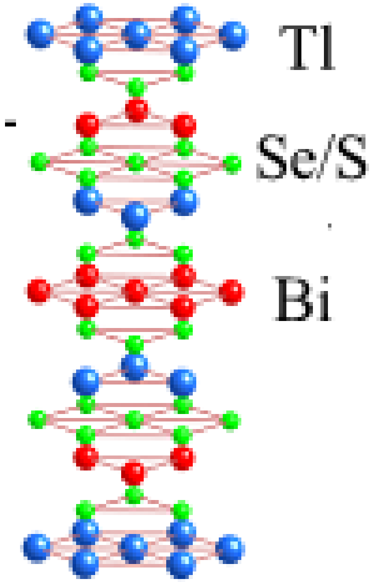
Accidental band touching

- Nontrivial topology
- CB and VB touching by composition tuning
- Always at Topological critical point

$Pb_{1-x}Sn_xSe$, $Pb_{1-x}Sn_xTe$

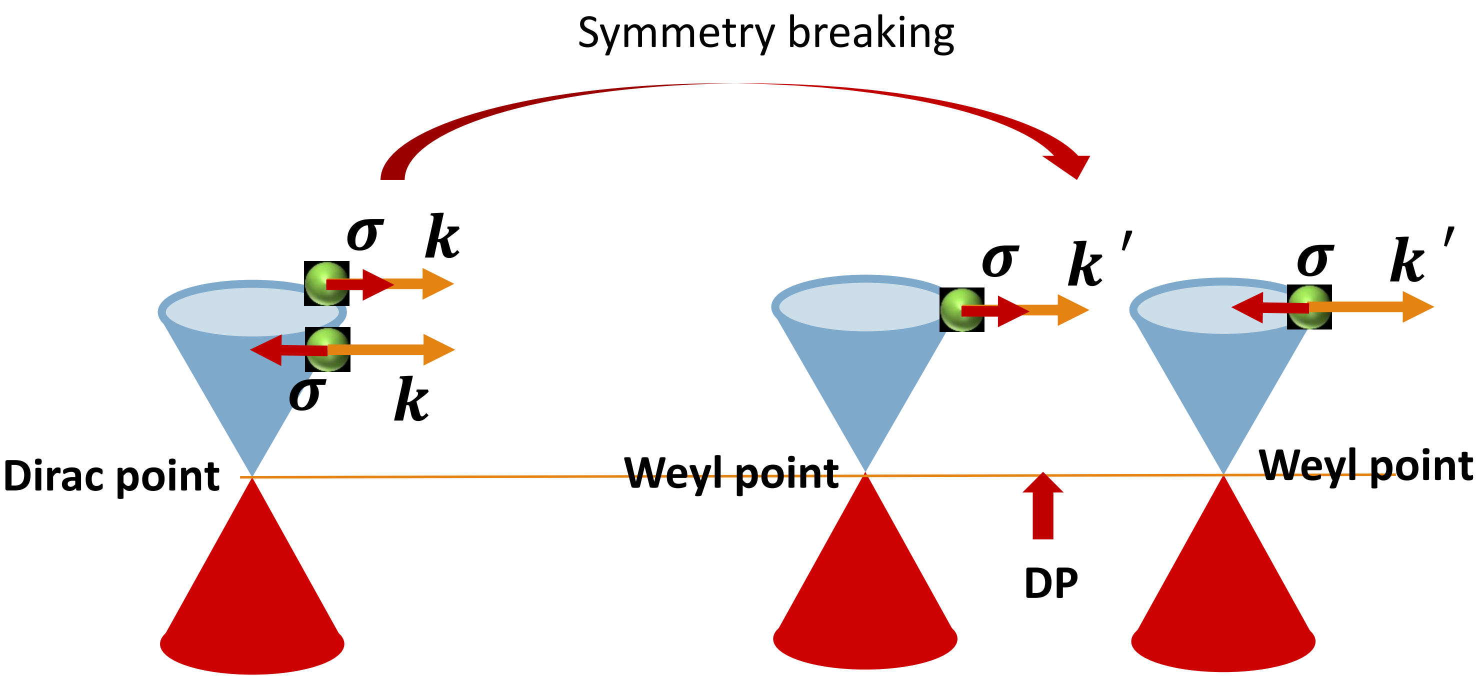


TlBiSSe



Beyond 3D Dirac systems: Weyl semimetals

❖New state of matter – <u>Chiral Dirac particles</u> $\hat{H}_{3D} = \pm\hbar v_F \boldsymbol{\sigma}\cdot\boldsymbol{k}'$



Spin degenerate
3D Dirac

Left and right Dirac electrons

Family of recently predicted WSM

TaAs, TaP, NbAs, NbP

arXiv: 1501.00755

How to get information on type dispersion by magnetic and transport measurements?

- Lanadu quantization and de Haas von Alphon oscillations (dHvA)

- **Osanger's relation** $A_{\boldsymbol{k}}(\epsilon_{\boldsymbol{k}}) = (n+\gamma)2\pi eB/\hbar$

- **Berry phase** $\phi_B = 2\pi\left(\frac{1}{2} - \gamma\right)$

- **dHvA** $\Delta M \sim A(T,B)\ \sin(\frac{2\pi\ F}{B} + \emptyset(\gamma))$

Phase factor

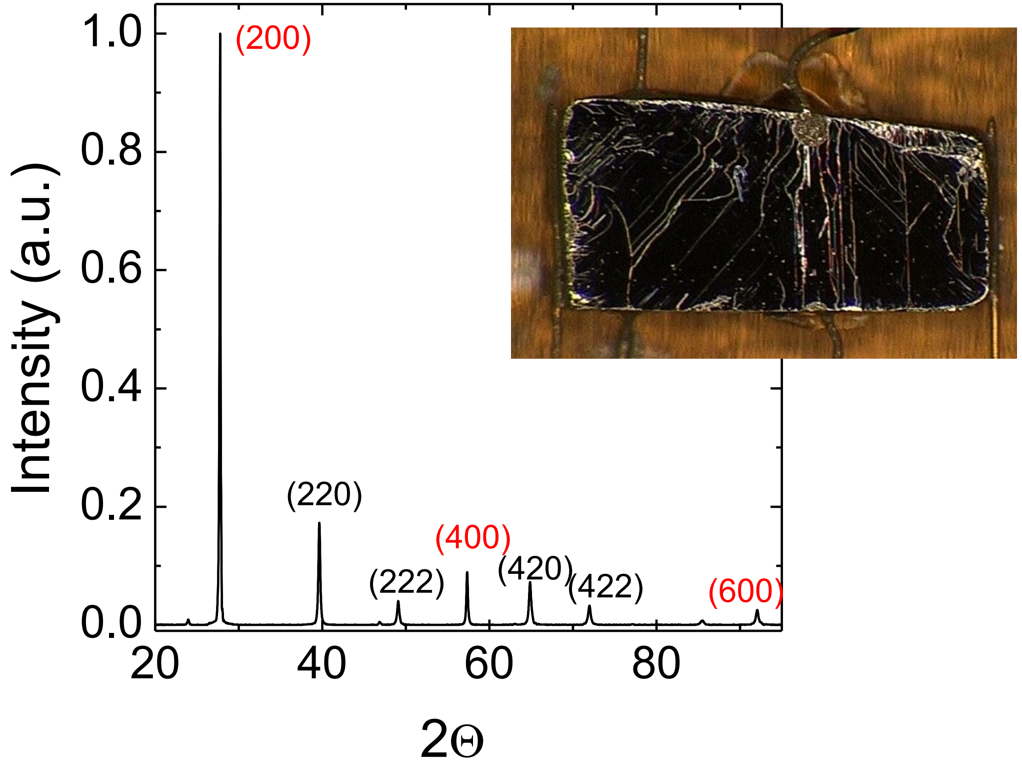
$$\emptyset(\gamma) = 2\pi(\frac{1}{4} \pm \frac{1}{4} - \gamma \pm \frac{1}{8})$$

$\gamma =$ 1/2 Parabolic

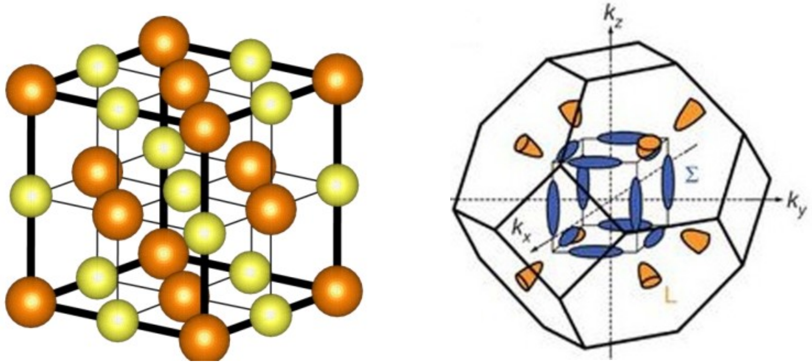
0 Linear

Sample information

❖Sample: Monocrystal of Pb0.83Sn0.17Se with reduced charge carriers $\sim 10^{17}$ cm^3

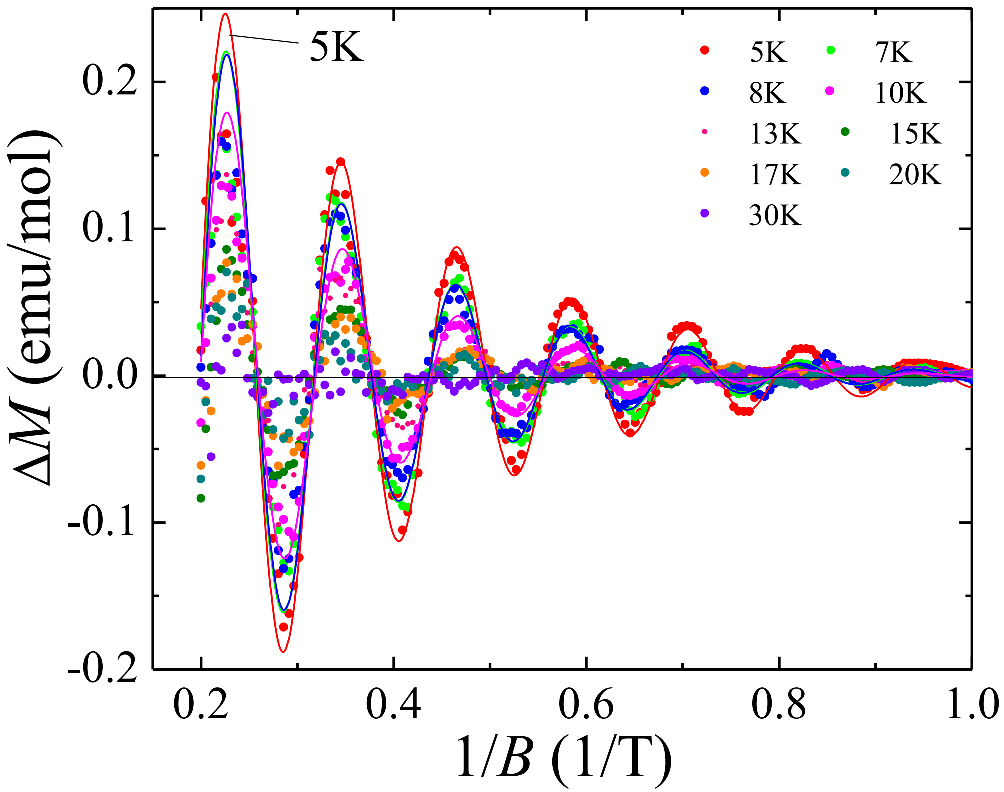


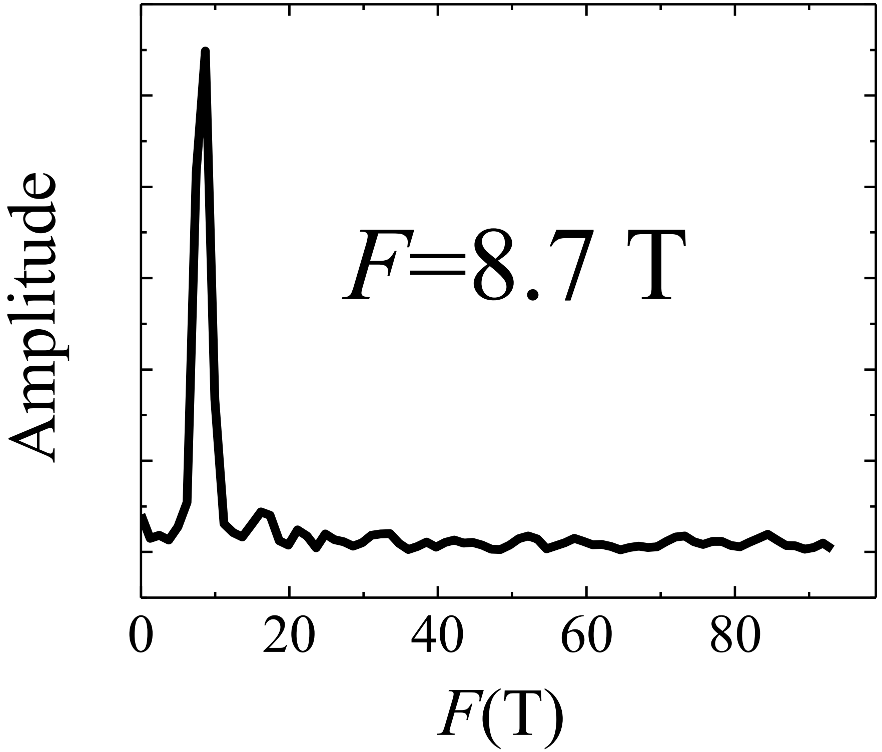
❖ Samples were grown by modified Bridgman method



Solid solution with cubic structure

SQUID measurements of dHvA oscillations





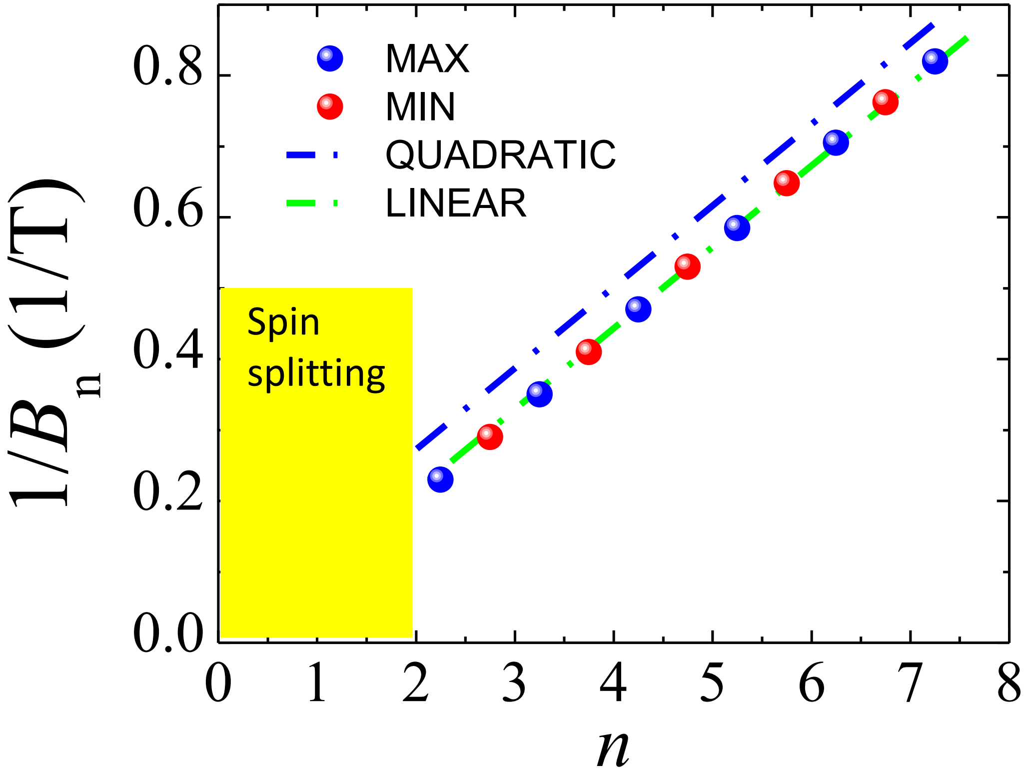
dHvA oscillations

FFT of the oscillations

Phase determination

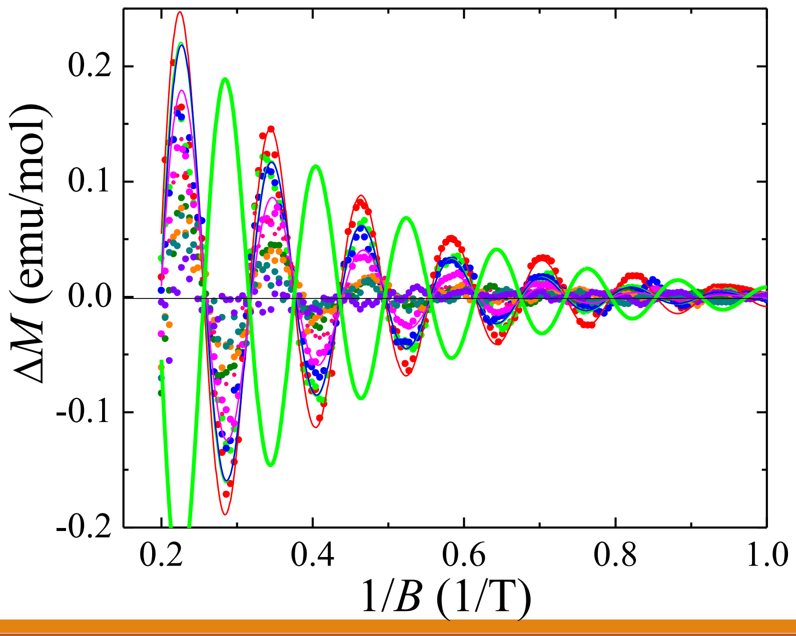
- Landau level indexing

$$\emptyset(\gamma) = 2\pi\left(\frac{1}{4} \pm \frac{1}{4} - \gamma \pm \frac{1}{8}\right)$$

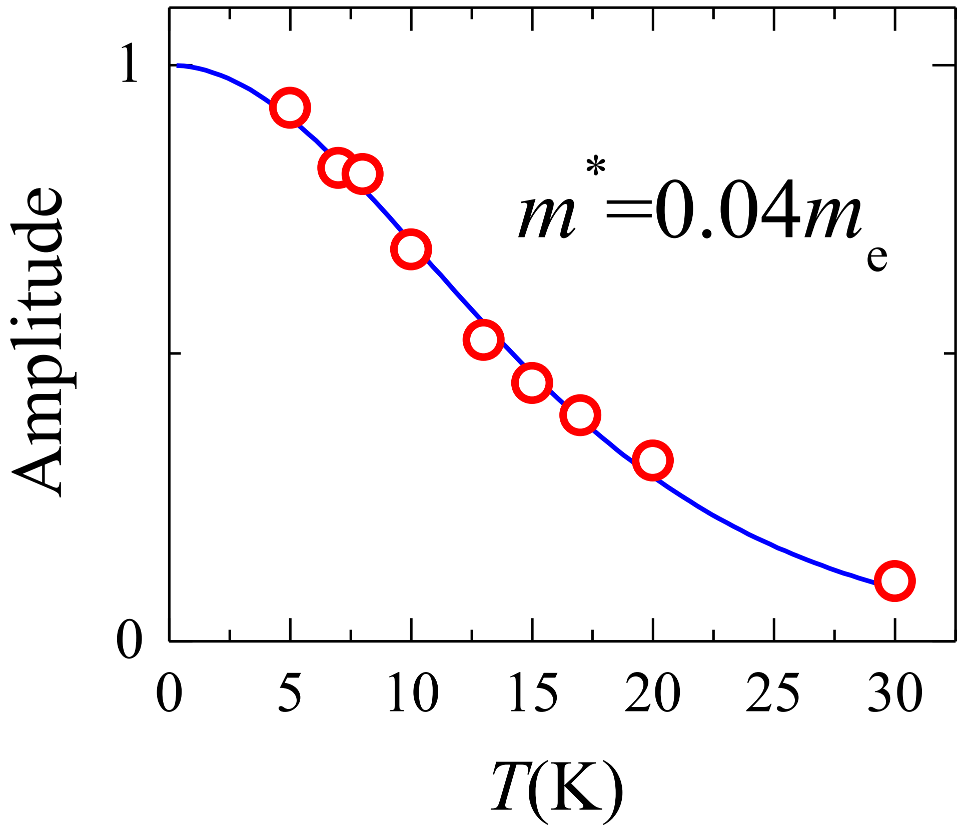


Linear dispersion: Dirac electrons

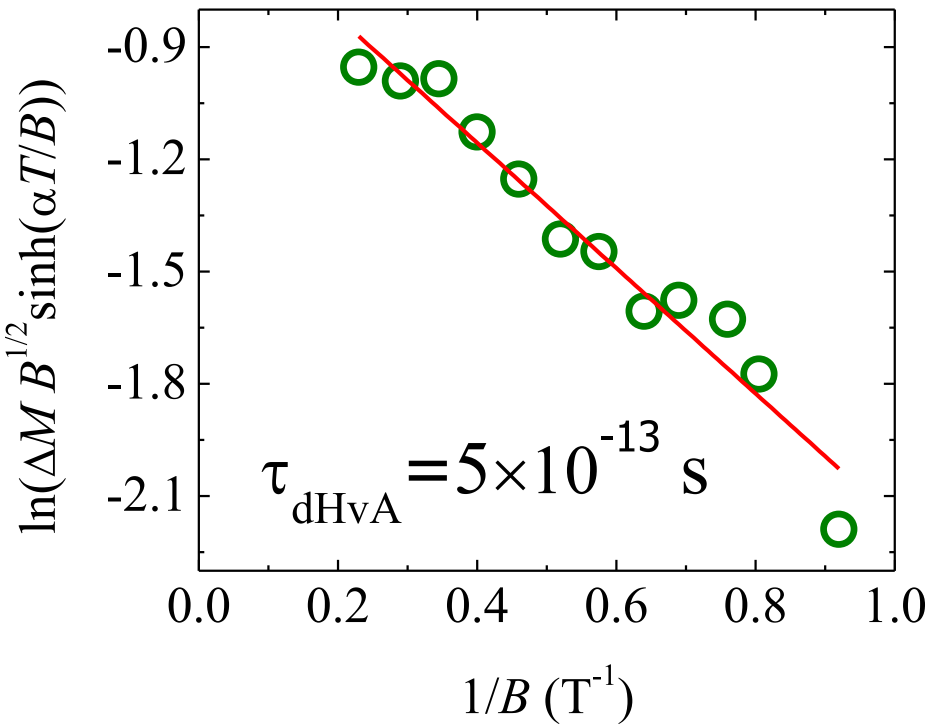
Quadratic dispersion: Schrodinger electrons



❖ Effective mass



❖ Scattering rate



Much stronger than form transport measurements

Thank you for your attention