Interplay of magnetism and band structure in $EuCd_2As_2$

Ana Akrap, University of Fribourg, Switzerland

February 23, 2023
23.02.2023.
02.23.2023.

Low-energy degrees of freedom

Topological materials

2007: 2D topological insulators

M. König et al., Science 318, 766 (2007)

2008: 3D topological insulators

D. Hsieh et al., Nature 452, 970 (2008)

2012: 3D topological crystalline insulators

P. Dziawa et al., Nature Mater. 11, 1023 (2012)

2014: Symmetry-protected 3D Dirac semimetals

Z. K. Liu et al., Science 343, 864 (2014)

2015: 3D Weyl semimetals

B. Q. Lv et al., Nature Phys. 11, 724 (2015)

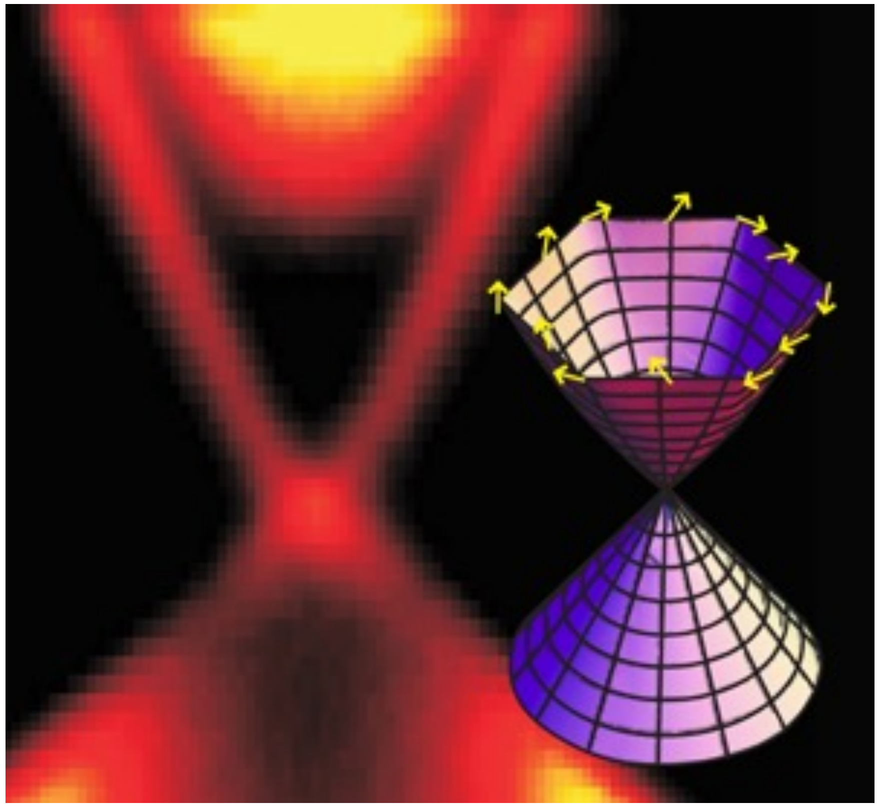
2016: Nodal line/loop Dirac semimetals

Wu, Y. et al., Nature Phys. 12, 667 (2016)

2019: Multifold massless electrons

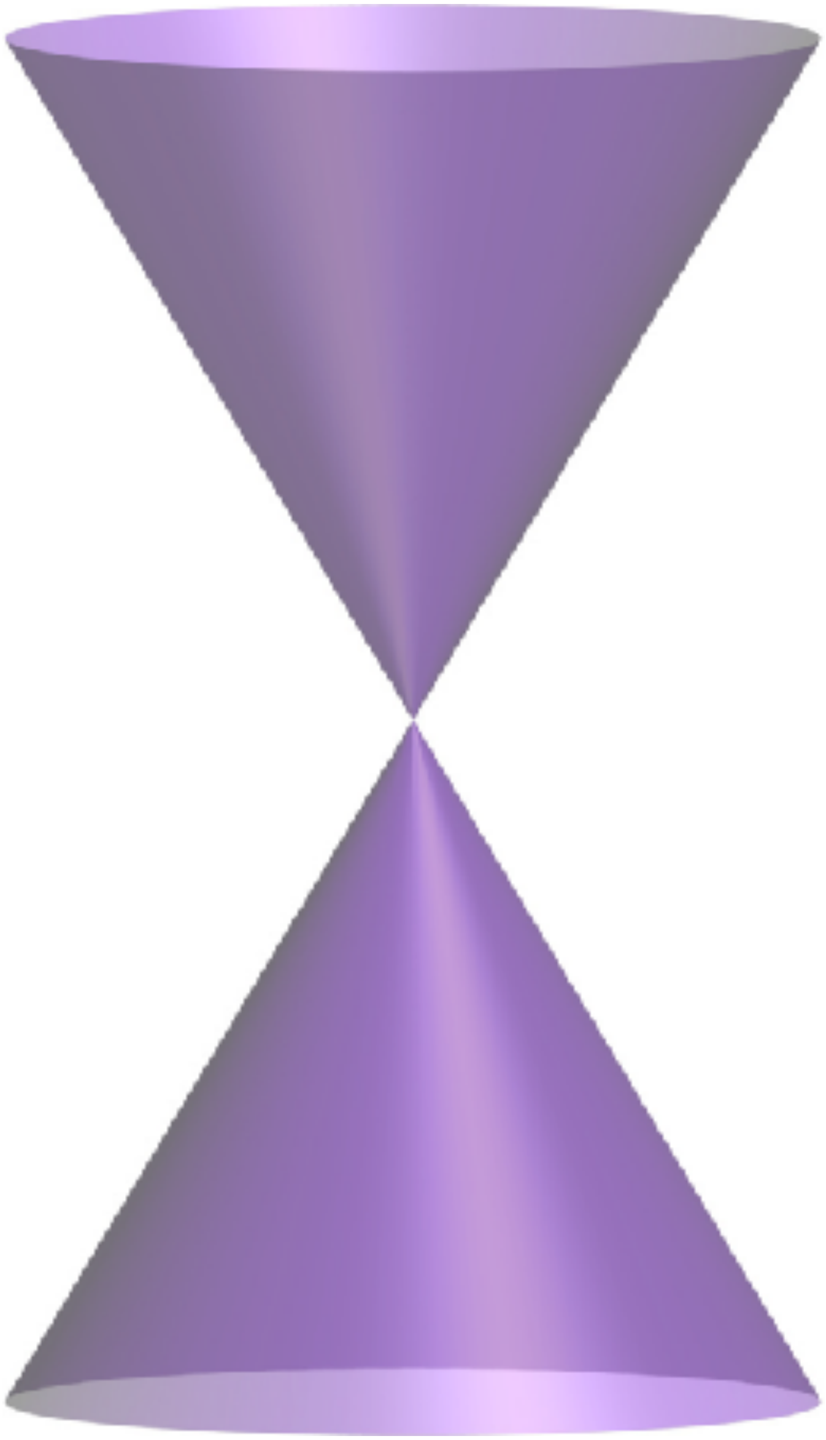
D. S. Sanchez et al., Nature 567, 501 (2019)

2023: …



M. Z. Hasan and C. L. Kane, RMP 82, 3045 (2010)

Topological semimetals



conical bands

small energy scales

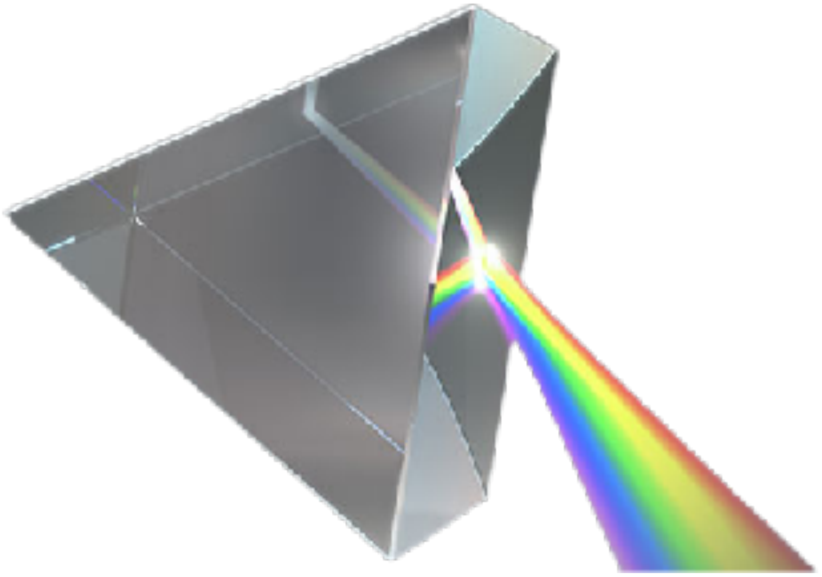
can be tuned
externally

exotic quasiparticles:
eg Weyl fermions

can be coupled
to magnetism

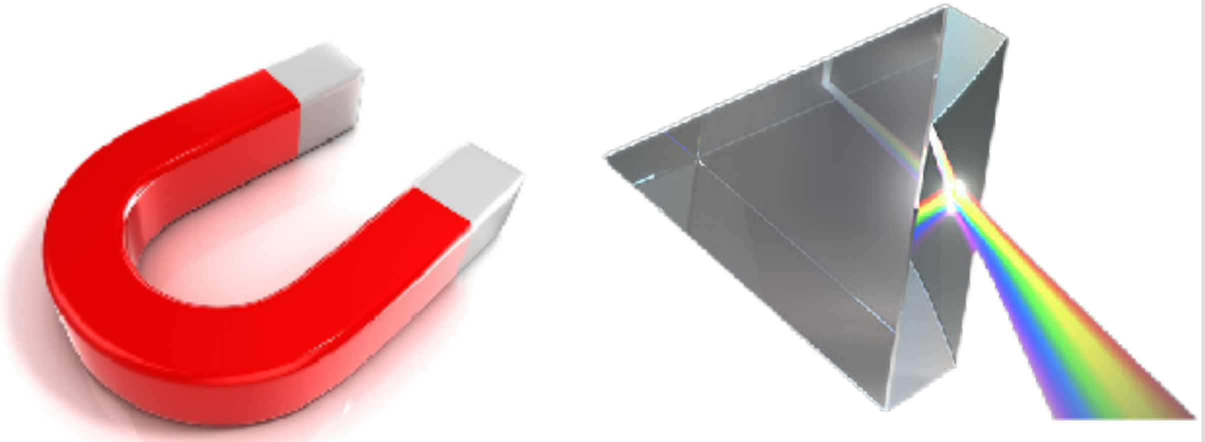
correlations

Our techniques



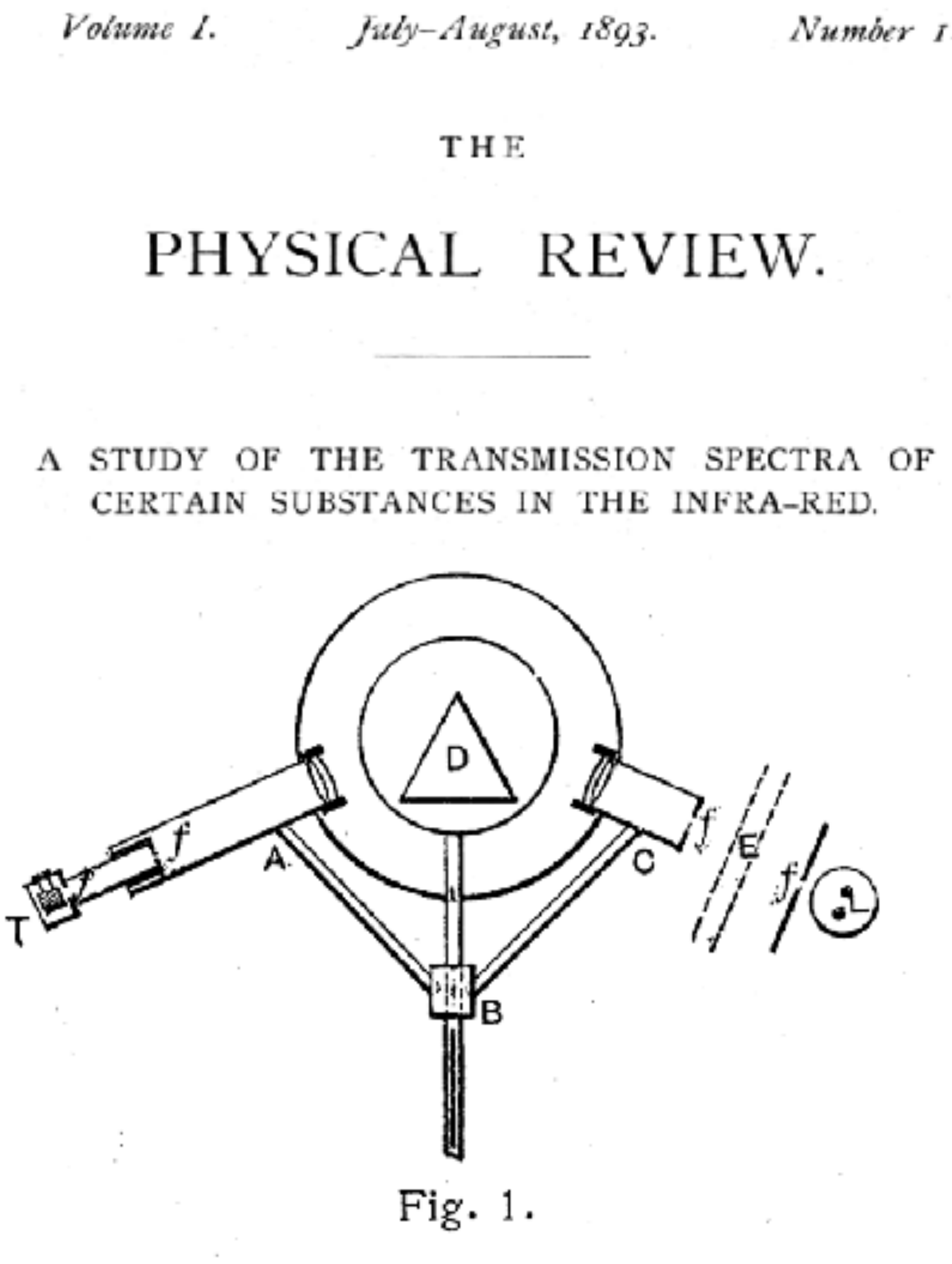
infrared spectroscopy

high-pressure
IR spectroscopy



magneto-optics

Infrared spectroscopy



Volume I. *July–August, 1893.* *Number 1.*

THE

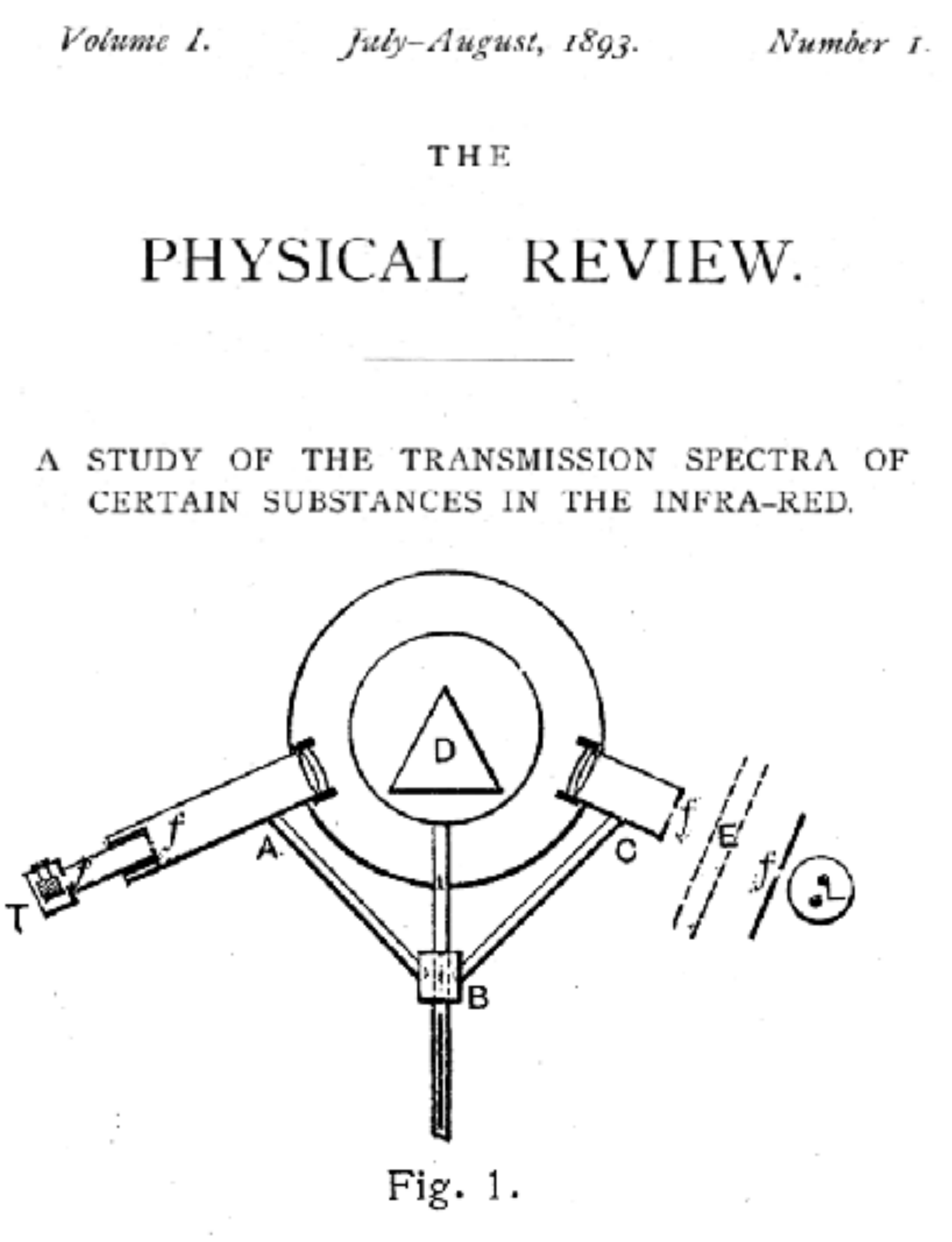
PHYSICAL REVIEW.

A STUDY OF THE TRANSMISSION SPECTRA OF CERTAIN SUBSTANCES IN THE INFRA-RED.

Fig. 1.

Physical Review 1, 1 (1893)

Infrared spectroscopy



Volume I. *July–August, 1893.* *Number 1.*

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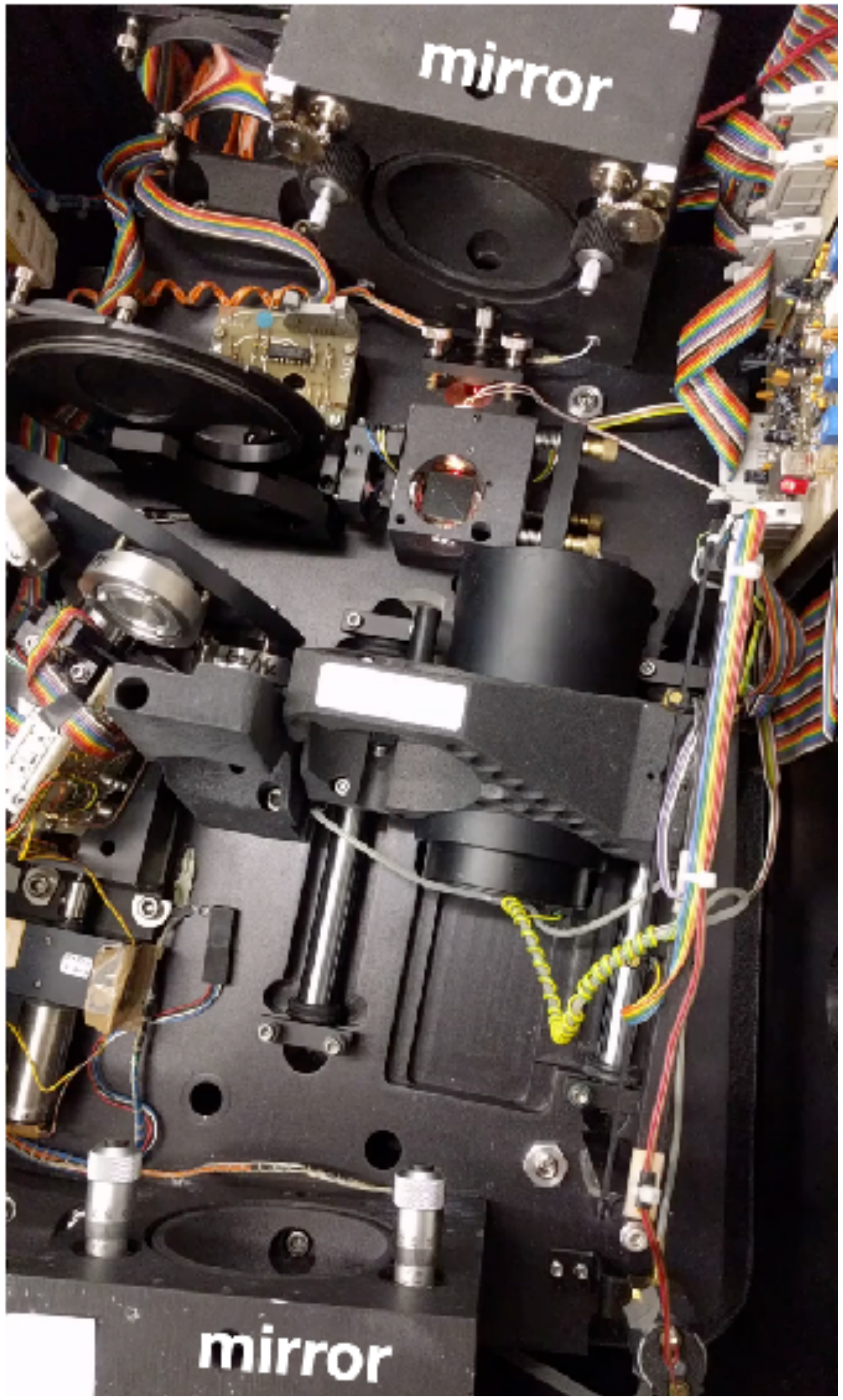
Fig. 1.

Physical Review 1, 1 (1893)



Interferometer inside a Bruker 113v

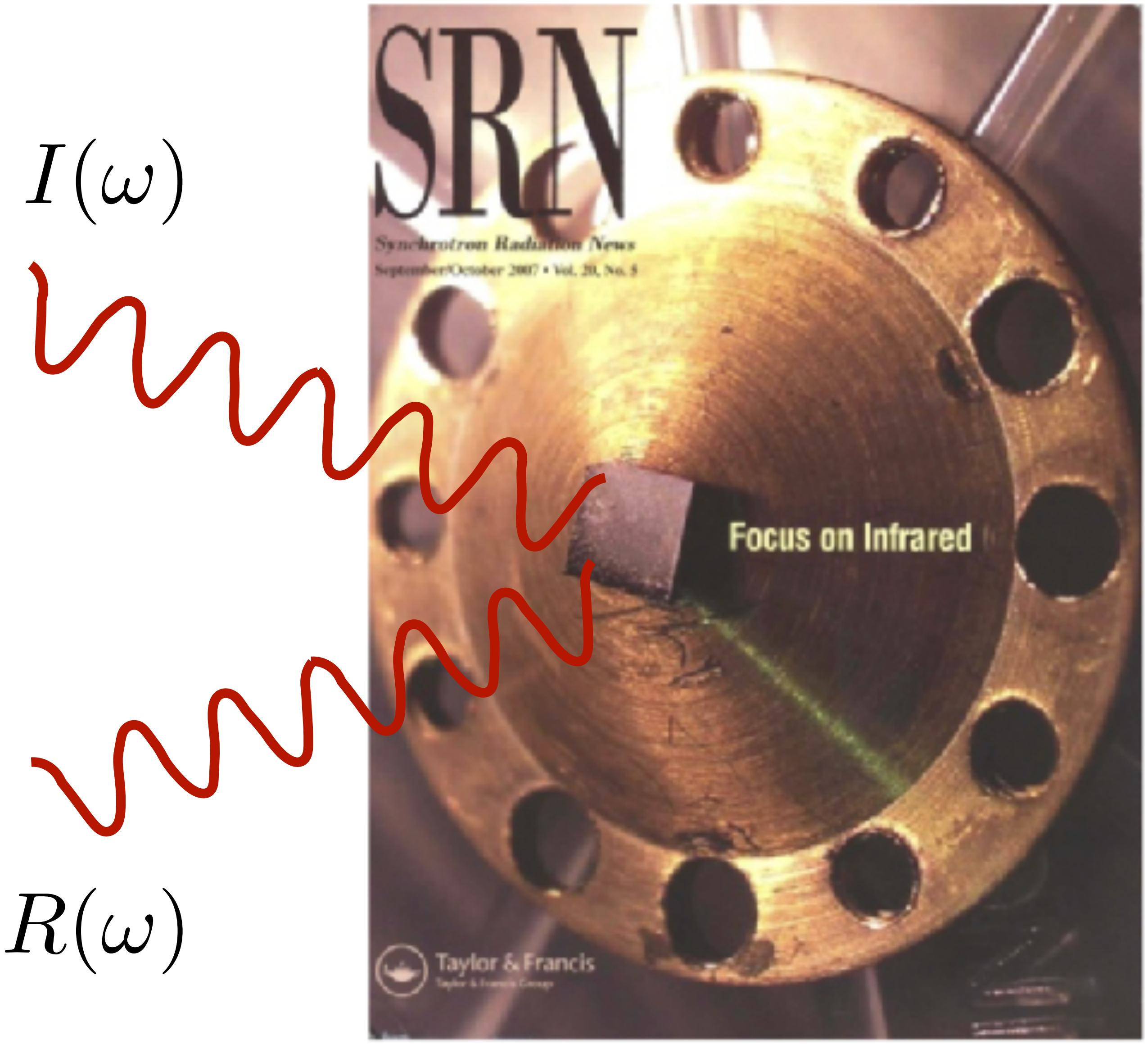
Infrared spectroscopy

$$R = \left|\frac{E_R}{E_0}\right|^2 = \left|\frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}\right|^2$$

Kramers-Kronig relations

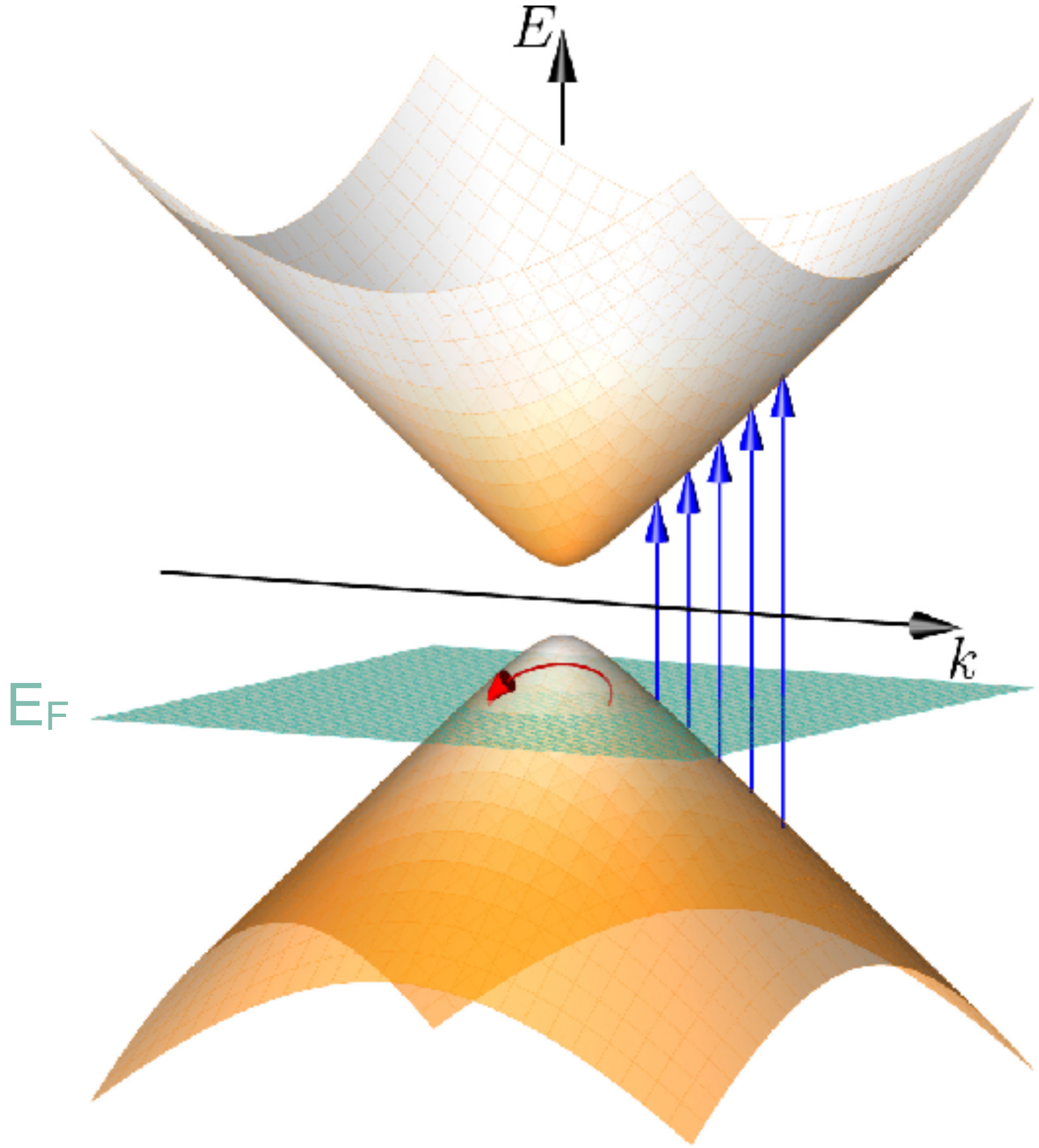
Complex optical conductivity

$$\sigma(\omega) = \sigma_1(\omega) + i\sigma_2(\omega)$$



Chris Homes

Optical spectroscopy tells about jDOS

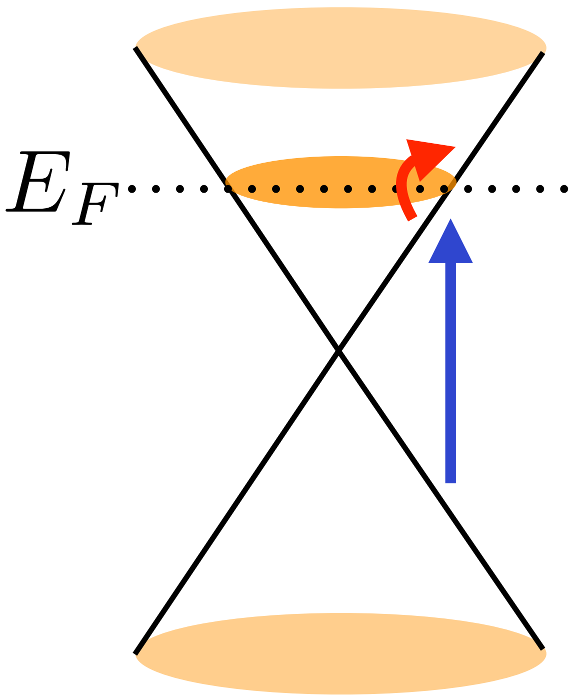


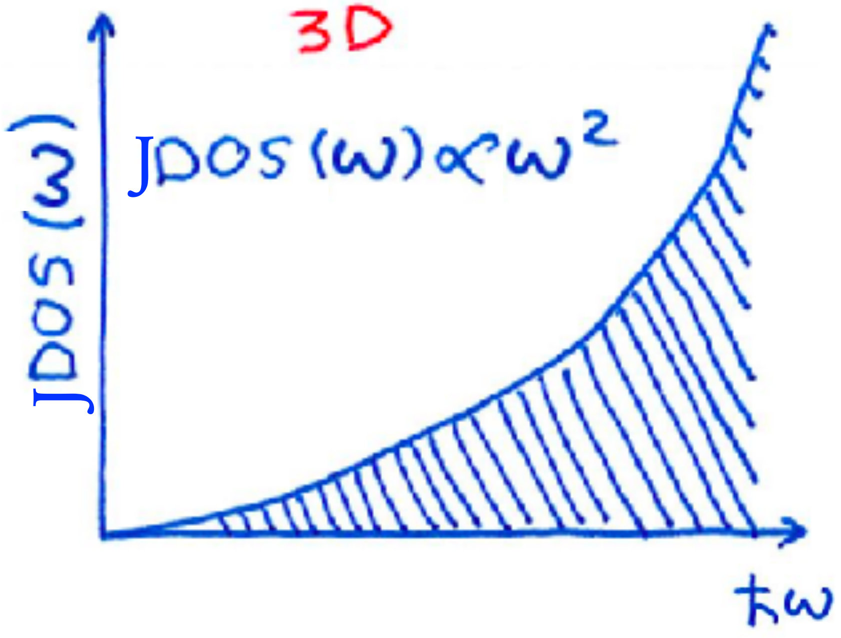
intraband (Drude)

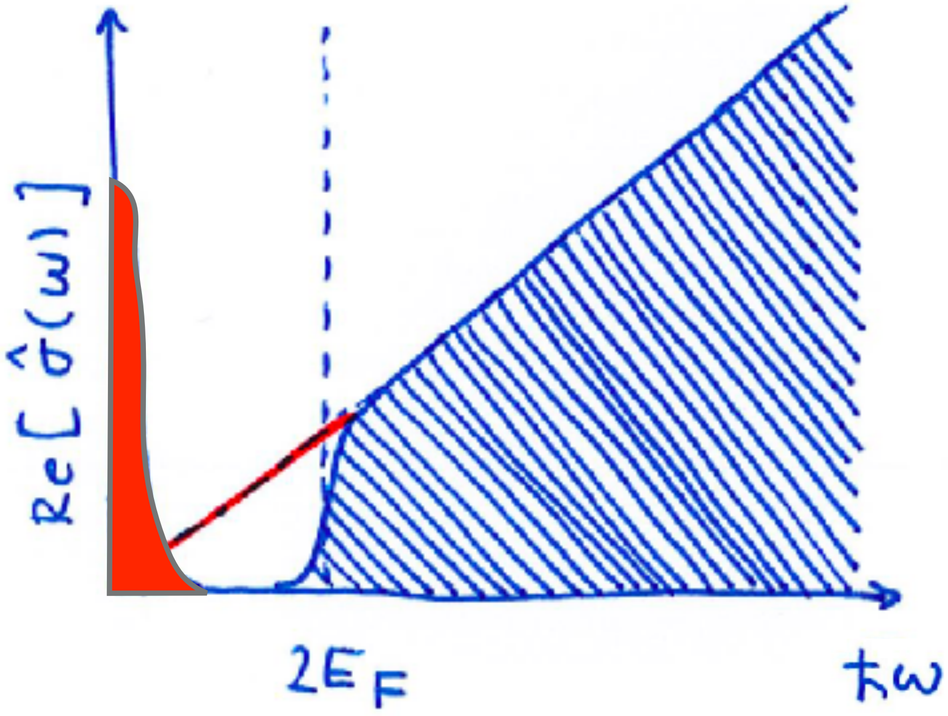
interband excitations

Optical conductivity tells about jDOS

3D linear bands



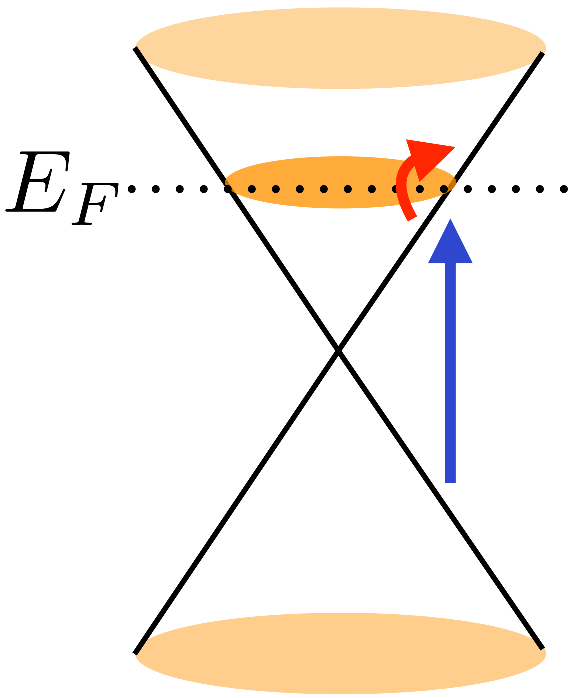


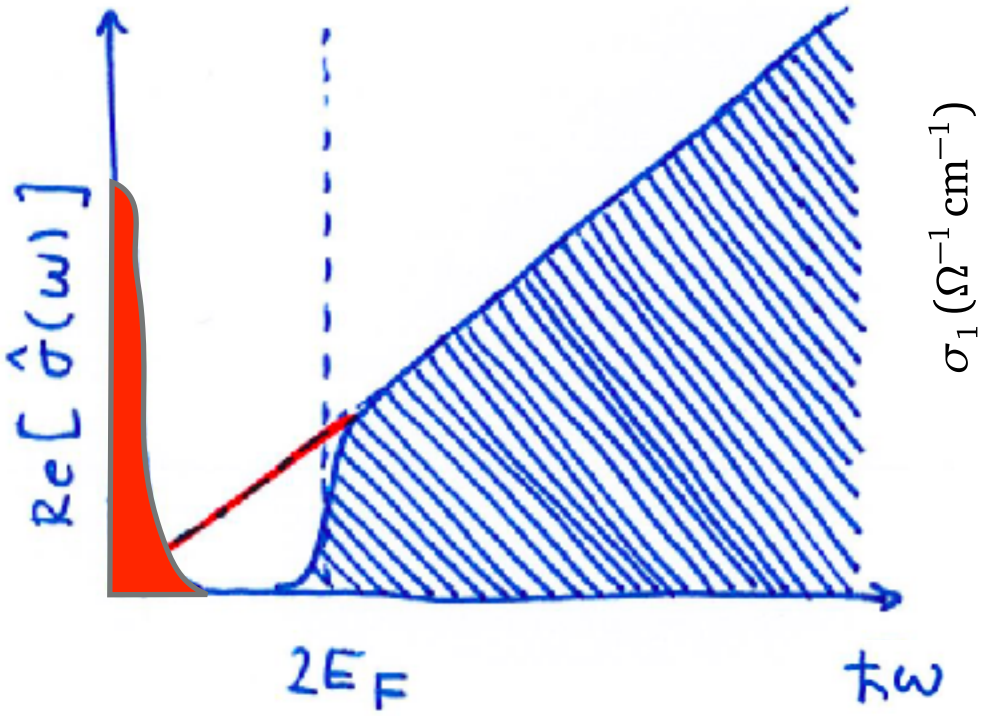


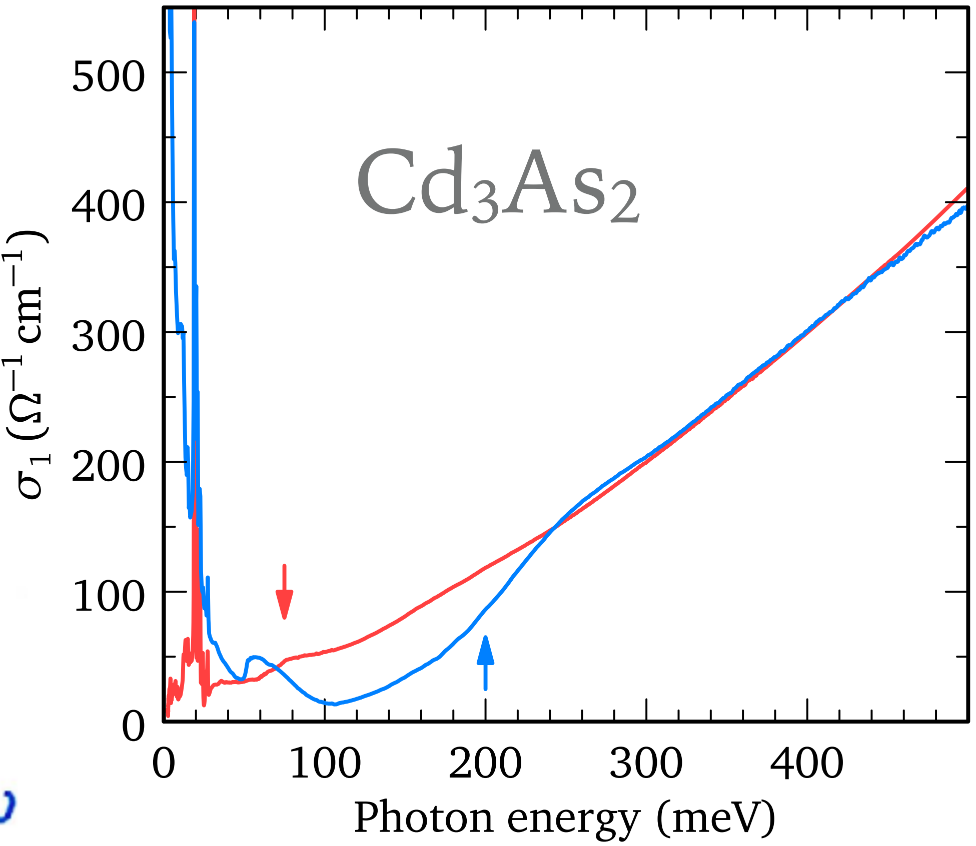
$$\sigma_1(\omega) \propto \frac{jDOS}{\omega}$$

Optical conductivity tells about jDOS

3D linear bands



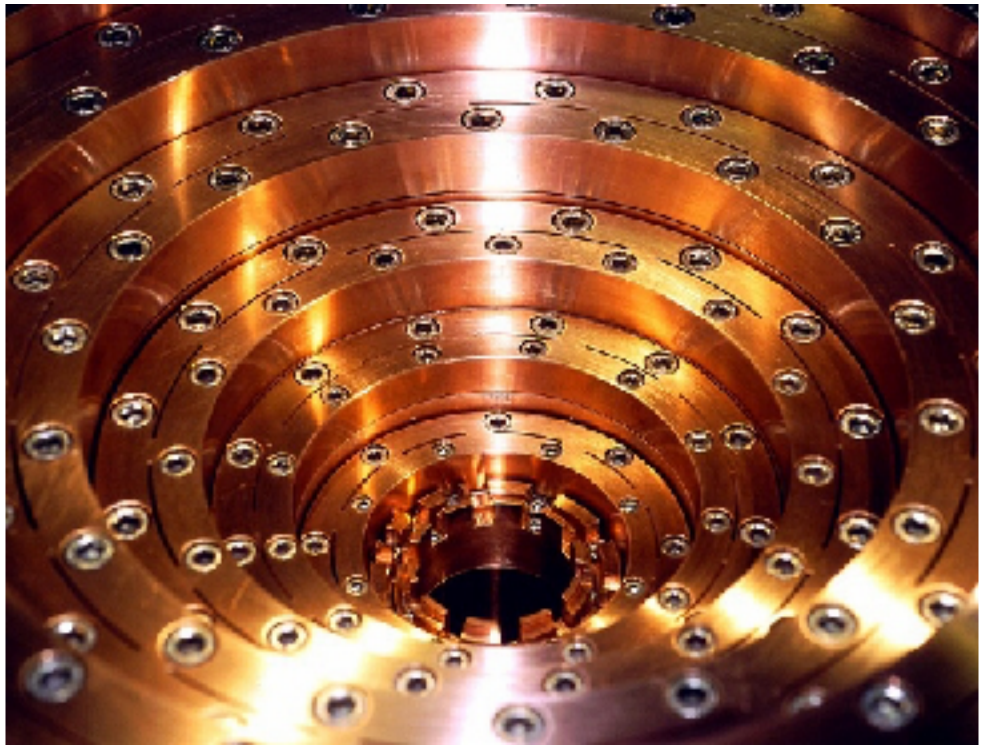




$$\sigma_1(\omega) \propto \frac{jDOS}{\omega}$$

AA et al, Phys. Rev. Lett. **117**, 136401 (2016)

Also in high magnetic fields

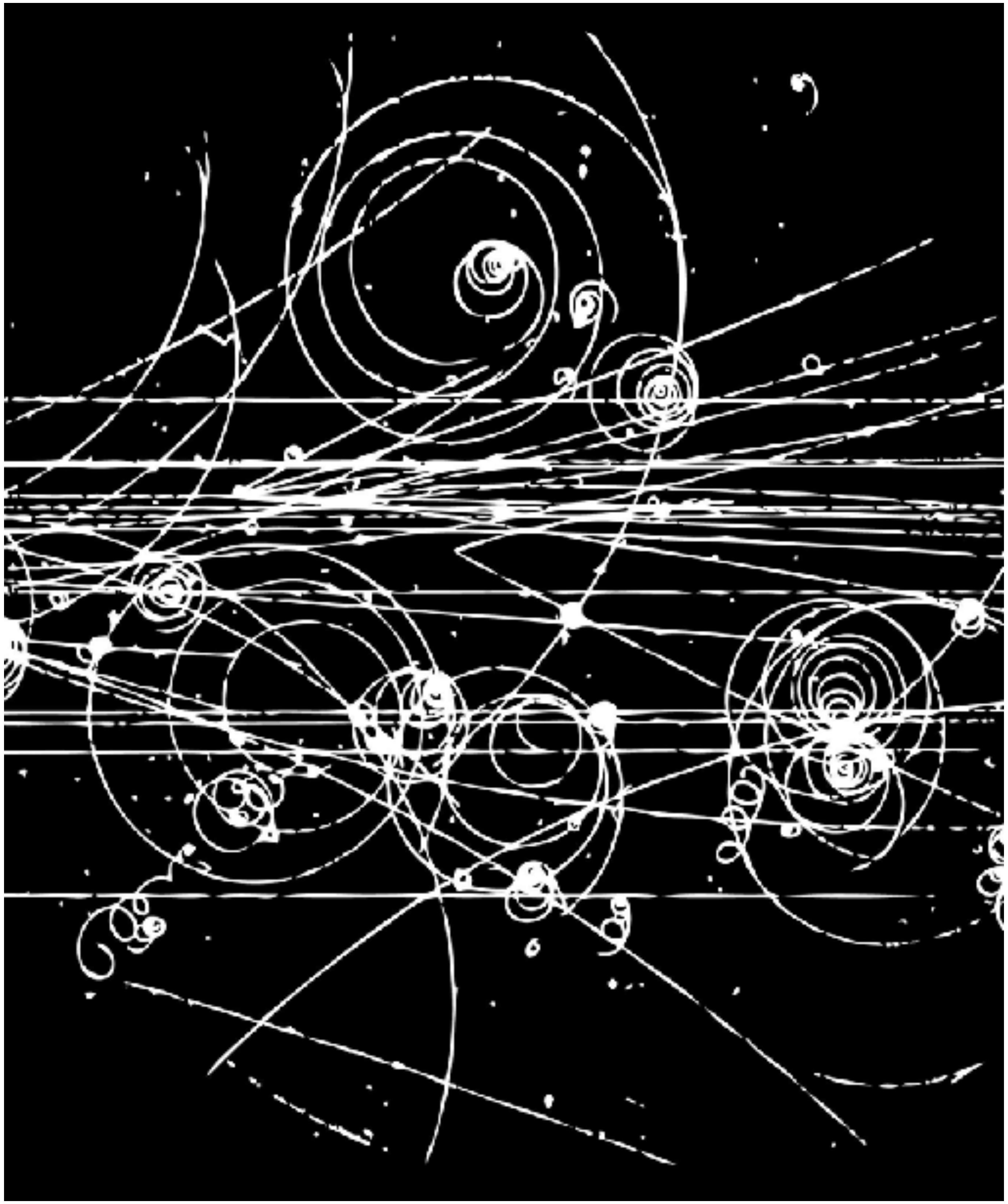


14’000 amps through
4 copper alloy coils

25 MW for 36 T
static magnetic field

LNCMI Grenoble

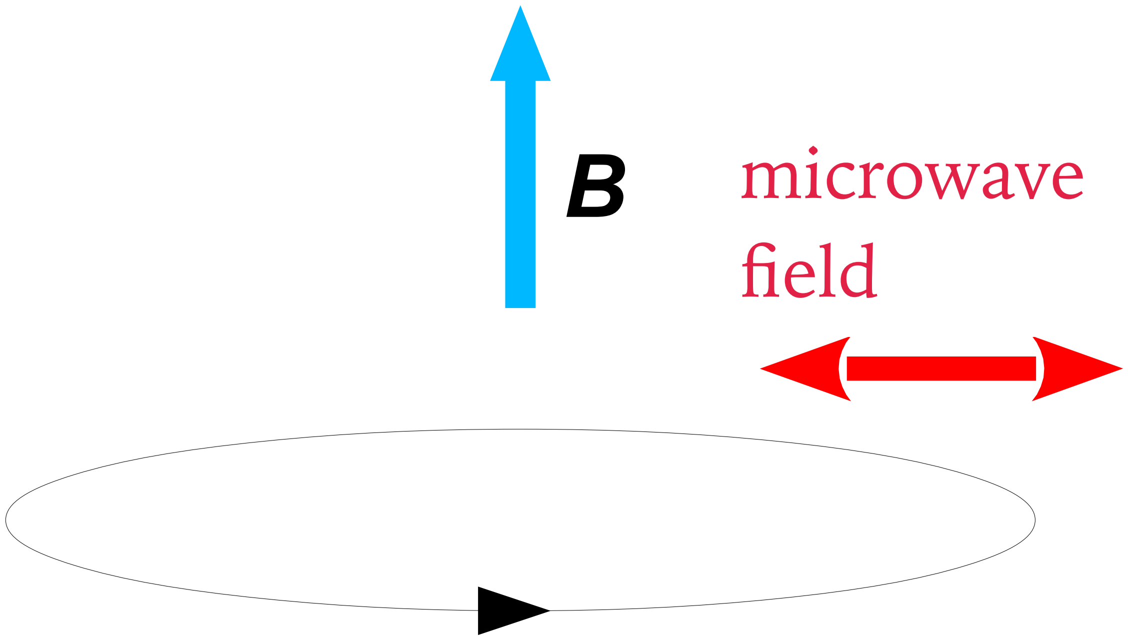
Cyclotron motion



CERN bubble chamber (1960)

Cyclotron resonance

Classical picture

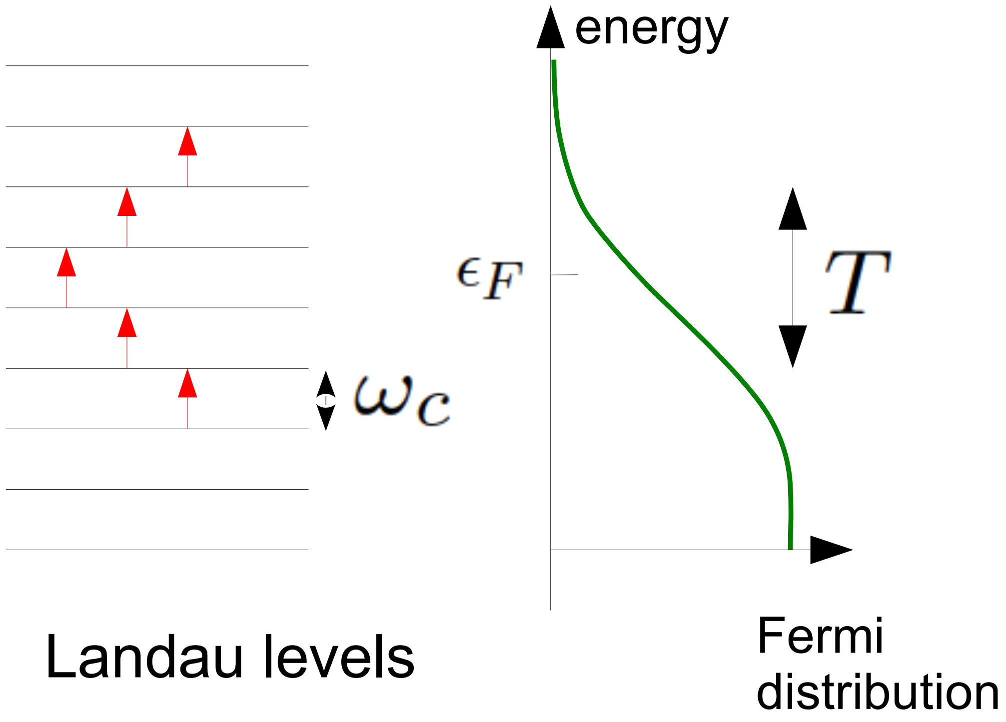


$$\frac{d\mathbf{p}}{dt} = \frac{e}{c}\left[\mathbf{v} \times \mathbf{B}\right] + \mathbf{F}_0 \cos \omega t$$

Cyclotron motion
with the frequency ω_c

Resonance
when $\omega = \omega_c$

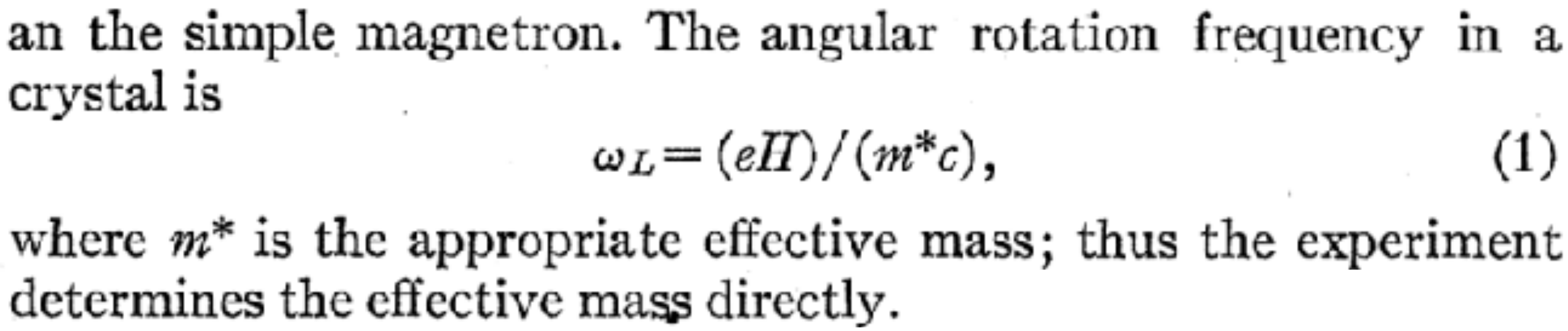
Quantum picture



Transitions
between Landau
levels

Cyclotron resonance = resonant absorption of light at the cyclotron frequency

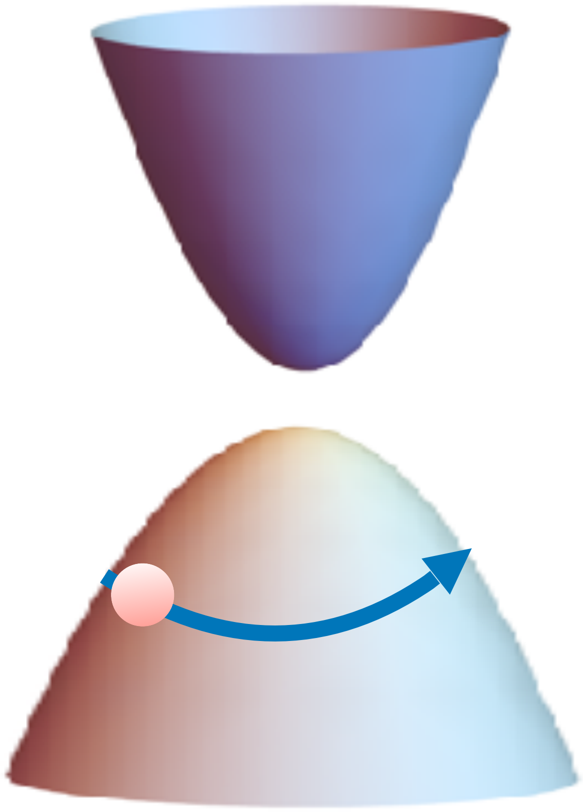
Observation of Cyclotron Resonance in Germanium Crystals*



an the simple magnetron. The angular rotation frequency in a crystal is

$$\omega_L = (eH)/(m^*c), \qquad (1)$$

where m^* is the appropriate effective mass; thus the experiment determines the effective mass directly.

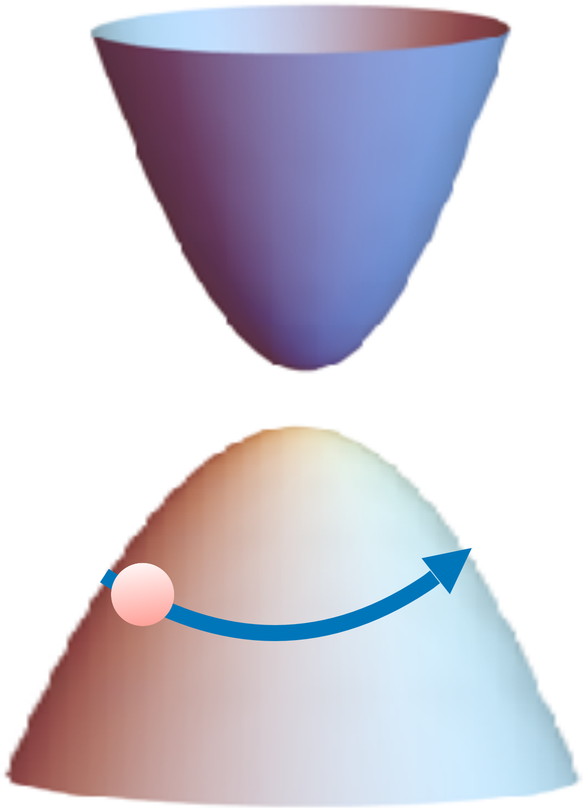


G. Dresselhaus, A.F. Kip, C. Kittel, Phys. Rev. 92, 827 (1953).

M.L. Cohen, AIP Conference Proceedings 772, 3 (2005).

Observation of Cyclotron Resonance in Germanium Crystals*

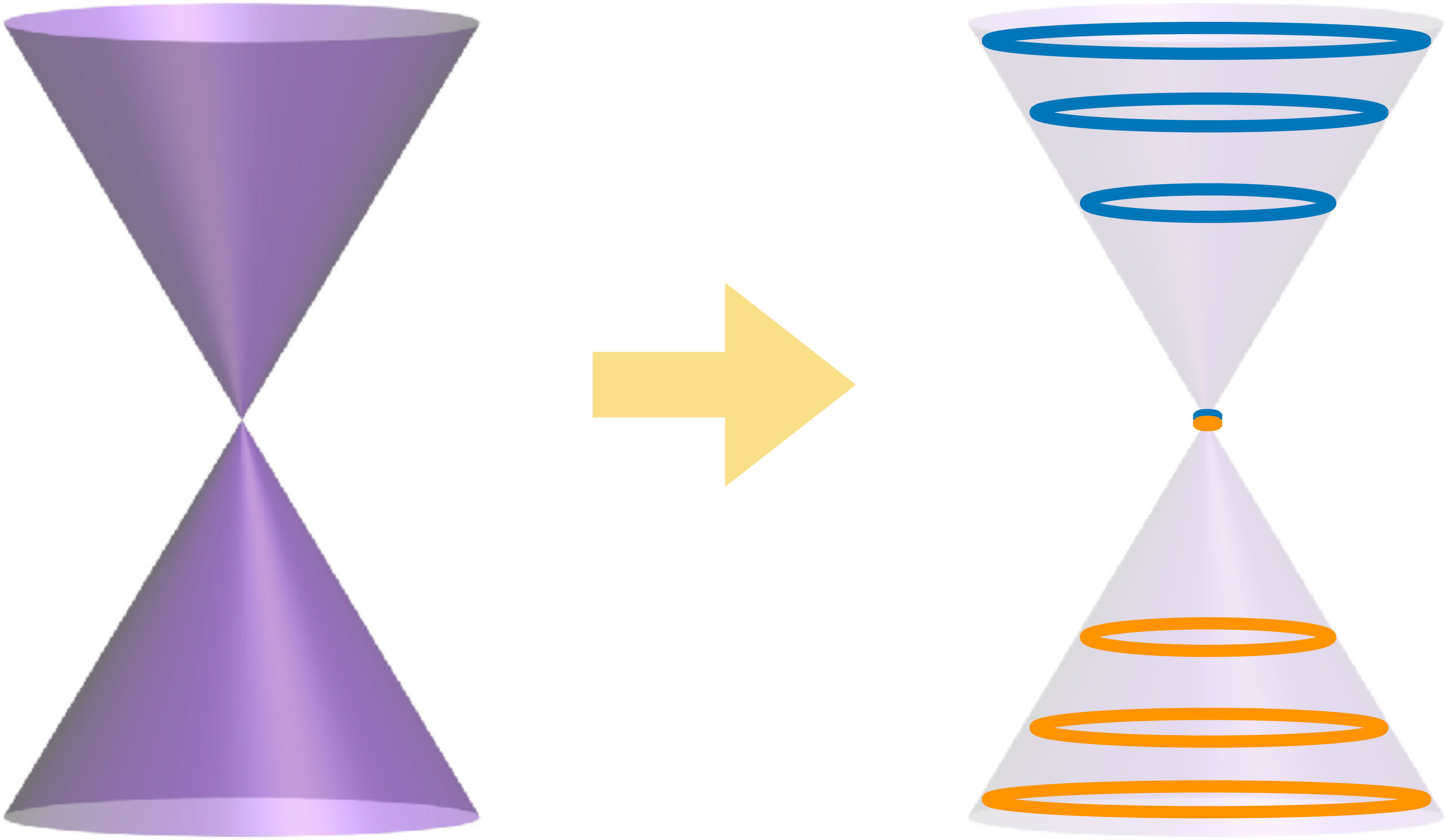
> "The first experimental observation of cyclotron resonance in Ge was very exciting. A.F. Kip was at the controls of the spectrometer while Kittel and I, along with other members of the research group, were offering lots of advice and encouragement in the background.



G. Dresselhaus, A.F. Kip, C. Kittel, Phys. Rev. 92, 827 (1953).

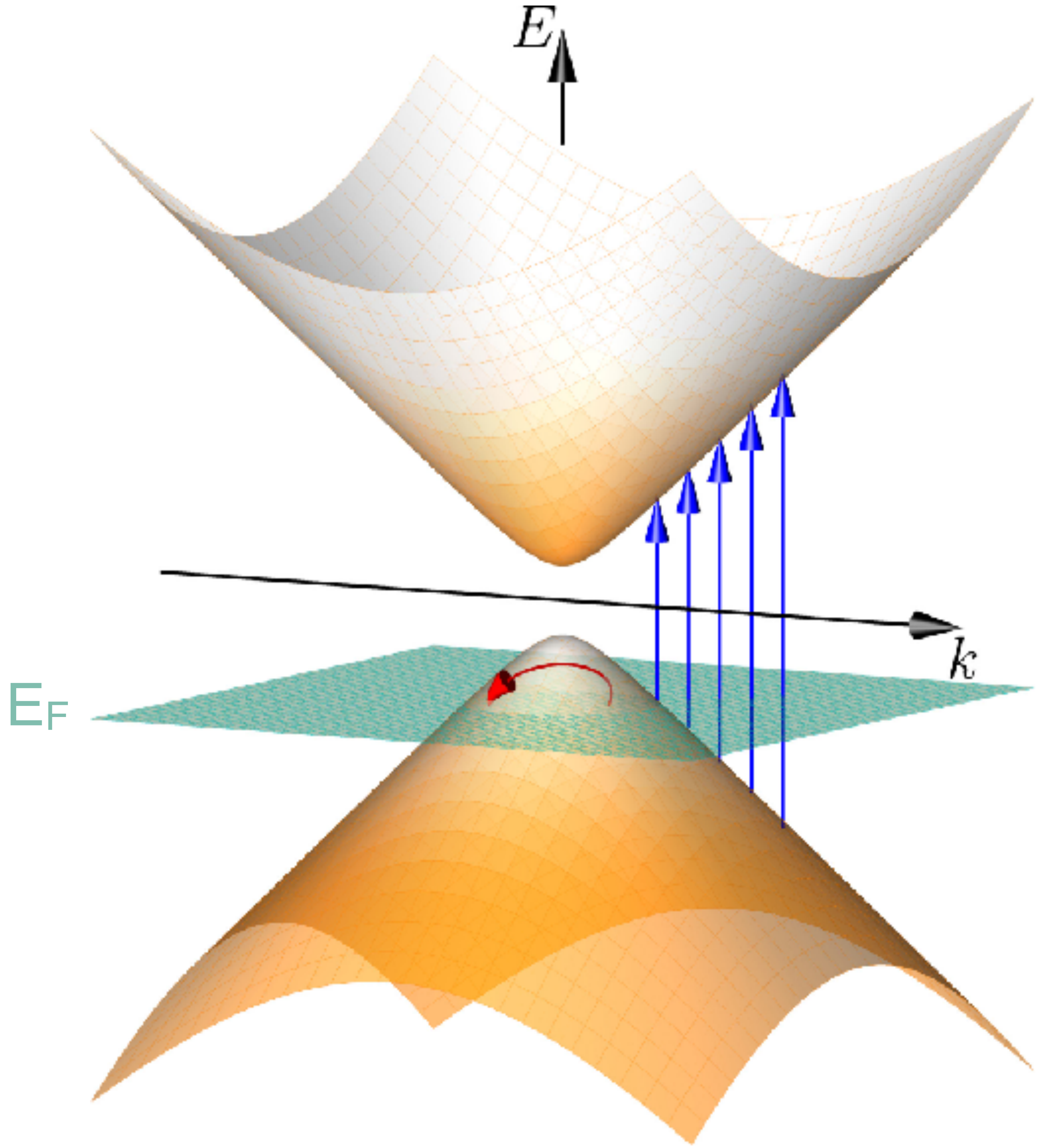
M.L. Cohen, AIP Conference Proceedings 772, 3 (2005).

Nonequidistant Landau levels



The nature of interband transitions is preserved.
Precise access to very low energy features.

Optical spectroscopy tells about jDOS

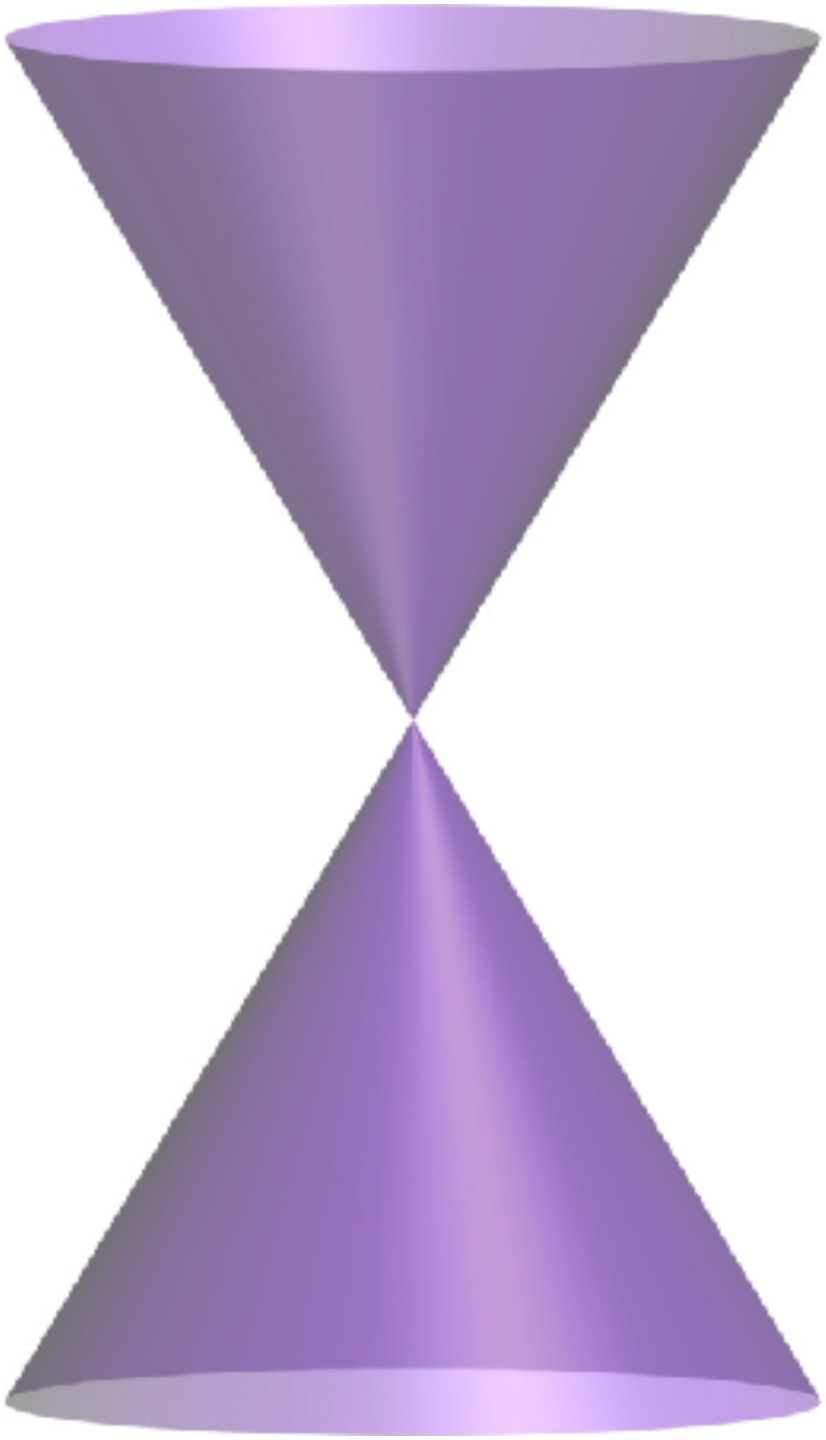


intraband (Drude) —
Cyclotron resonance

interband excitations —
interband inter-Landau level
transitions

Florian Le Mardelé

Topological semimetals



conical bands

small energy scales

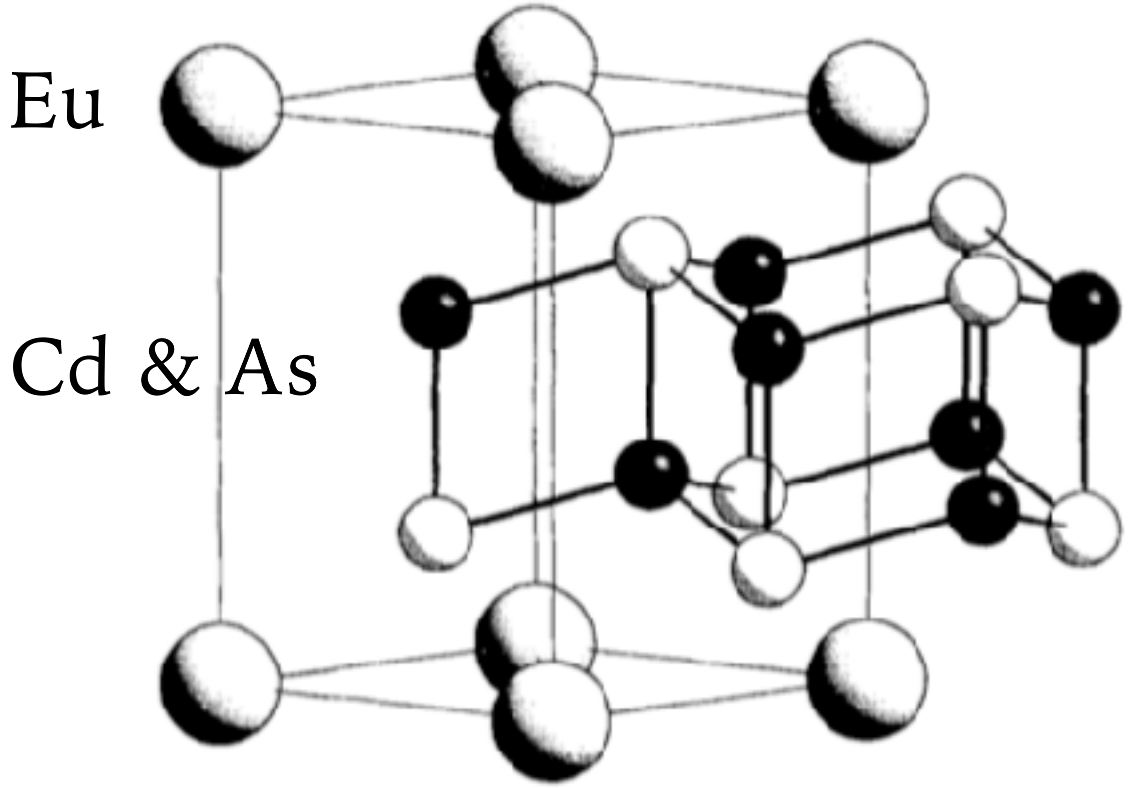
can be tuned
externally

exotic quasiparticles:
eg Weyl fermions

**can be coupled
to magnetism**

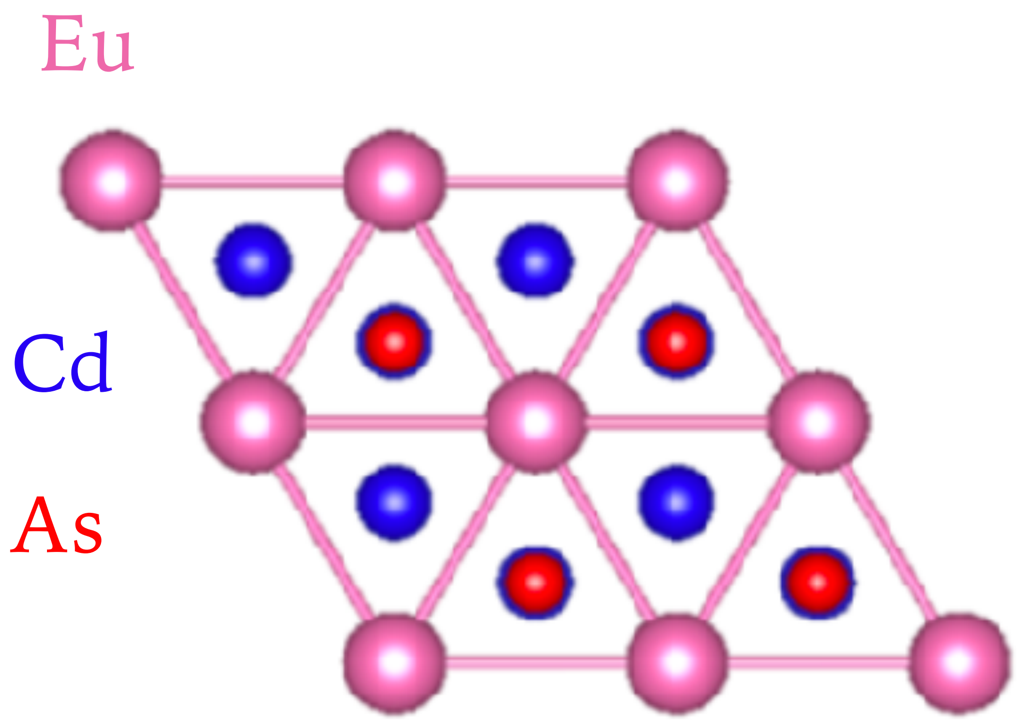
correlations

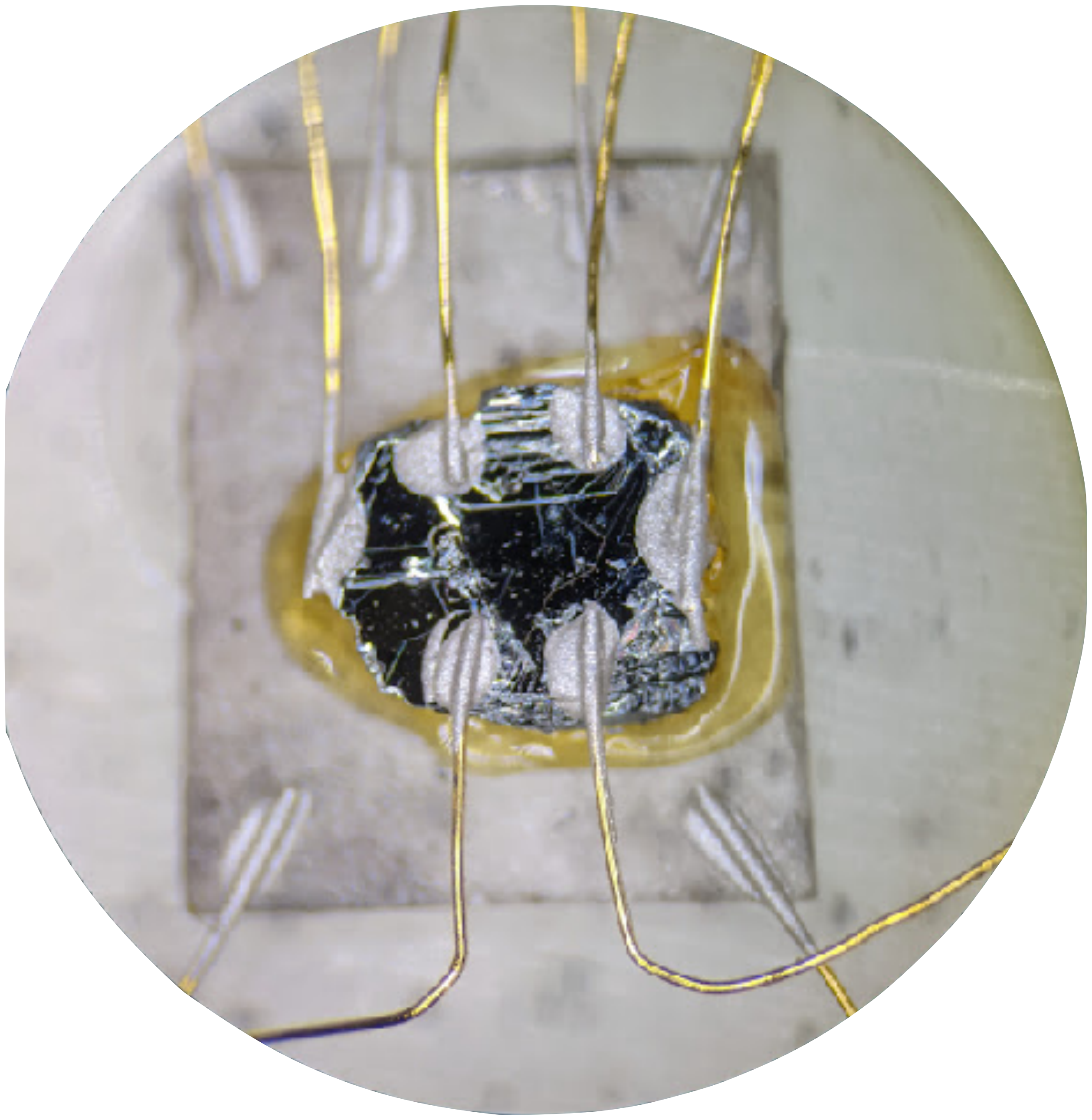
Topological semimetal $EuCd_2As_2$



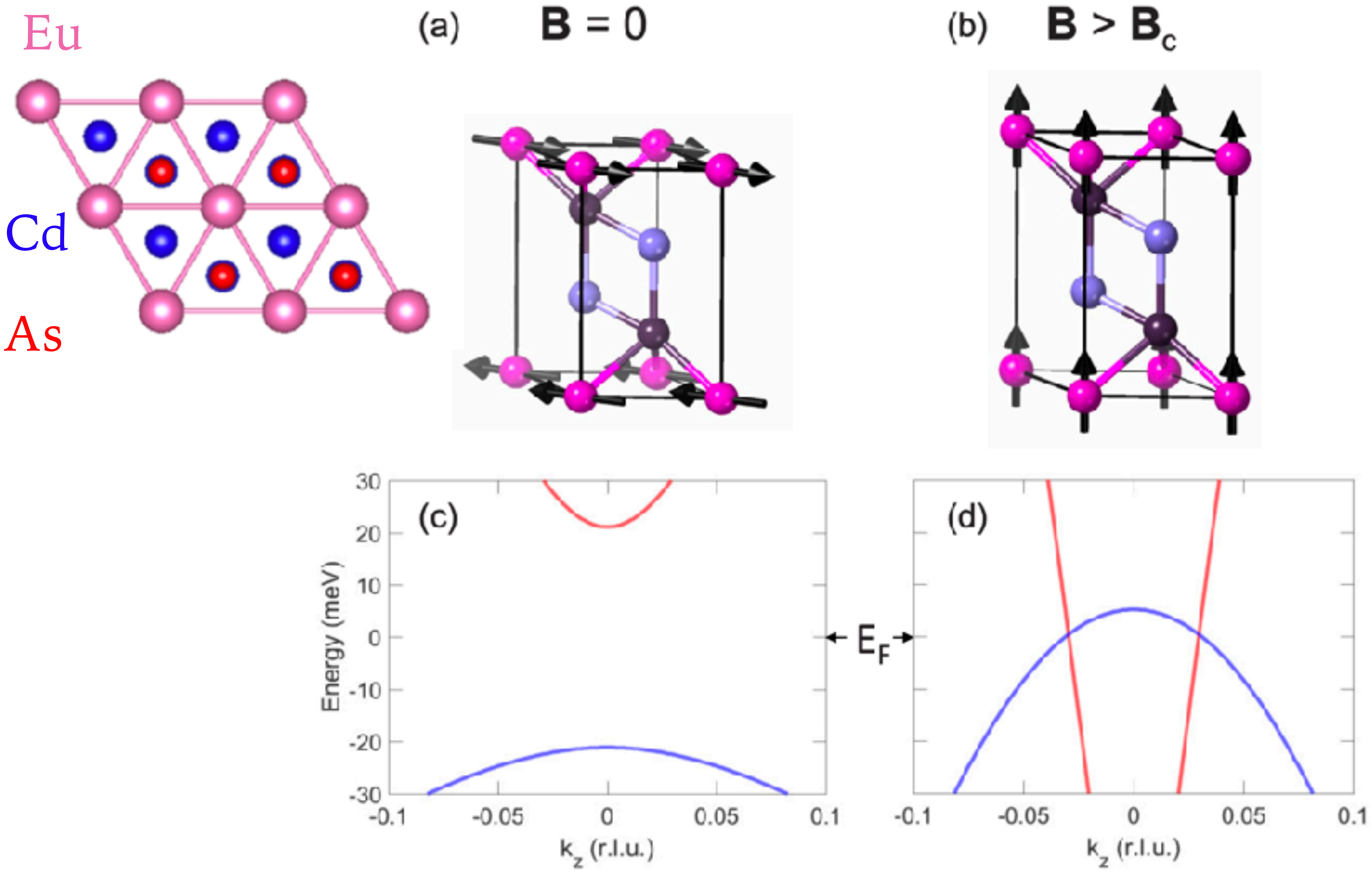
- Eu valence is 2+
  spin state S=7/2
- DFT says semimetal
  (U = 5 eV, by hand)

Topological semimetal $EuCd_2As_2$



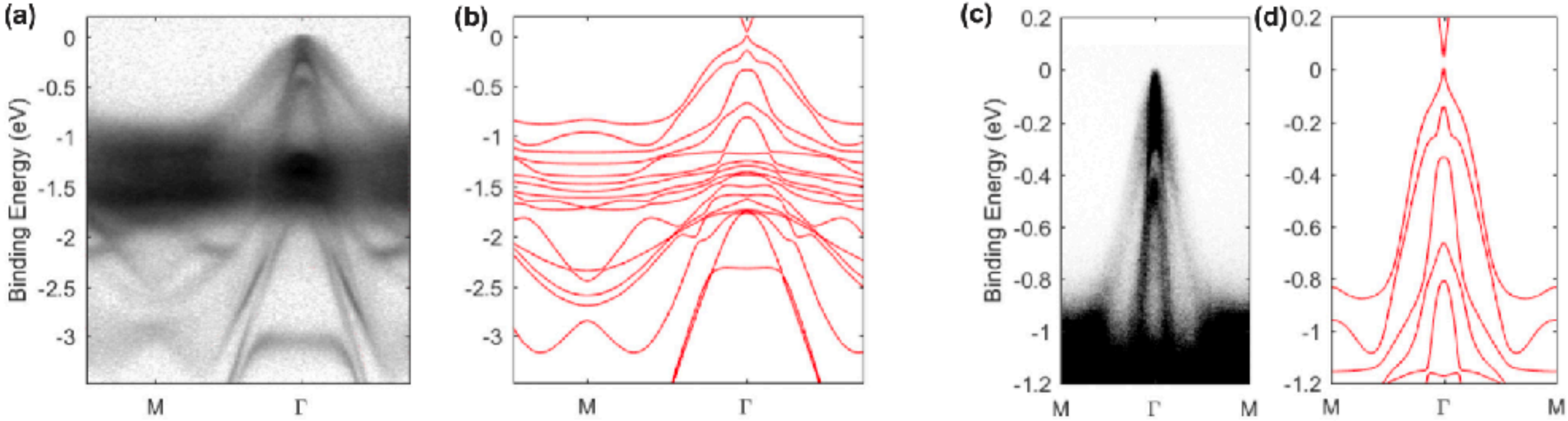


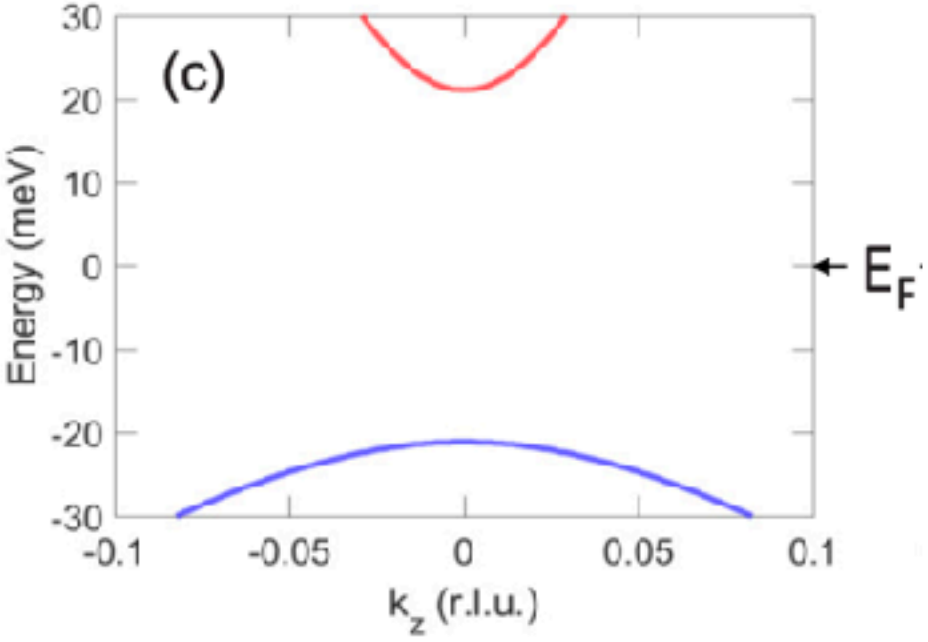
Topological semimetal $EuCd_2As_2$



J.R. Soh et al, Physical Review B **100**, 201102(R) (2019)

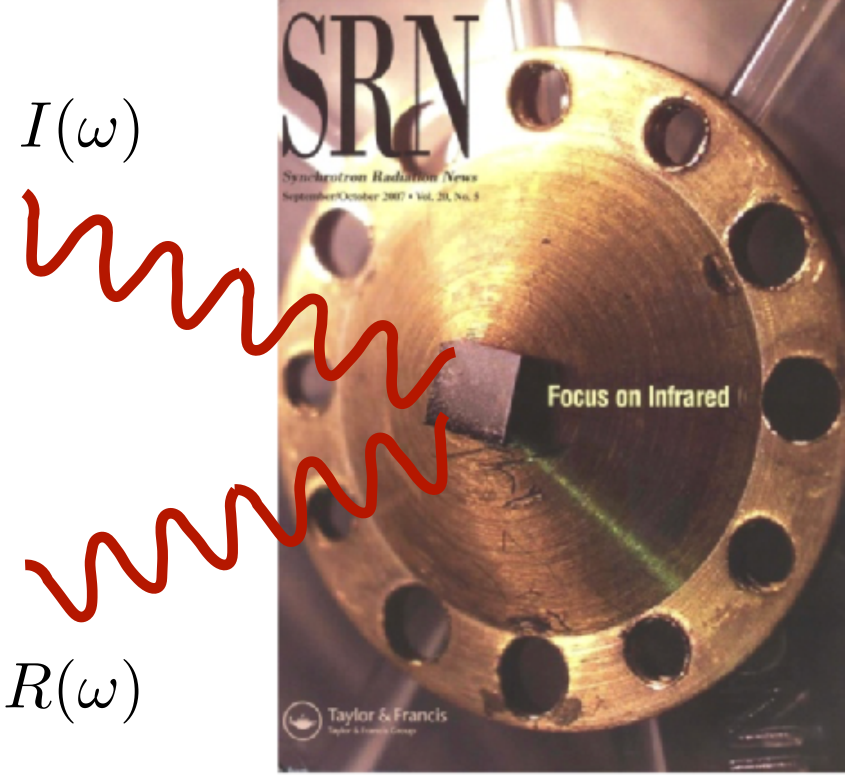
Topological semimetal $EuCd_2As_2$

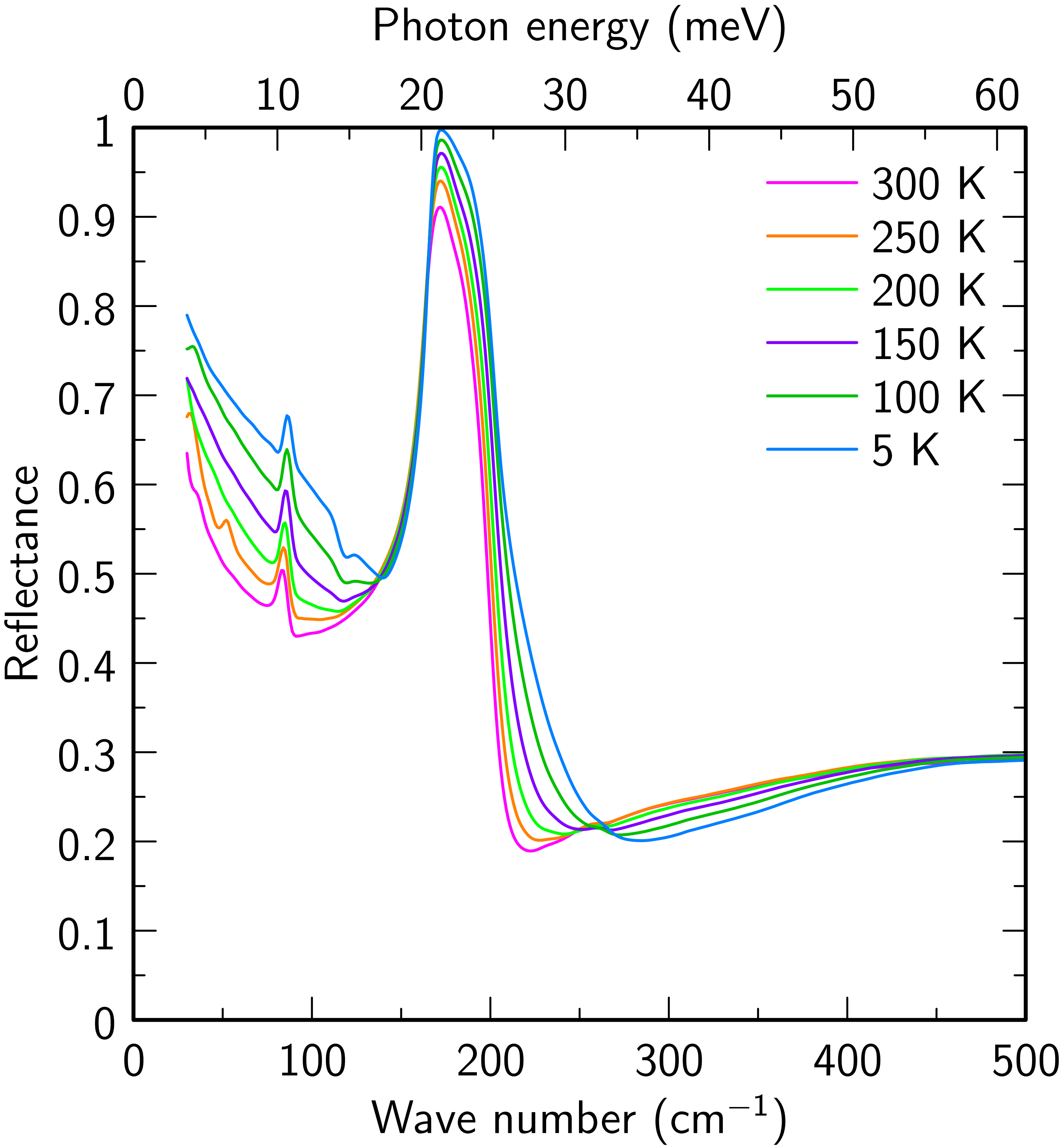




J.R. Soh et al, Physical Review B **100**, 201102(R) (2019)

Surprise

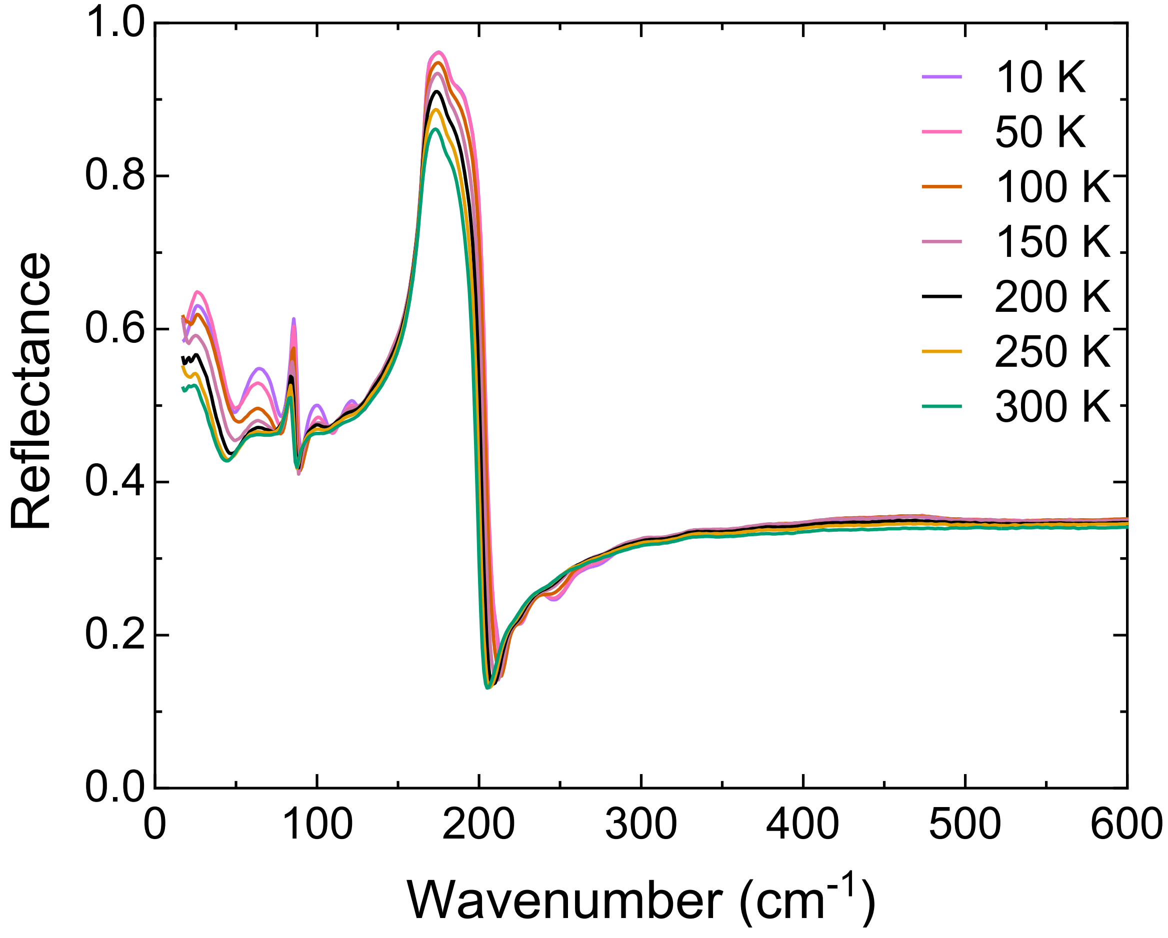




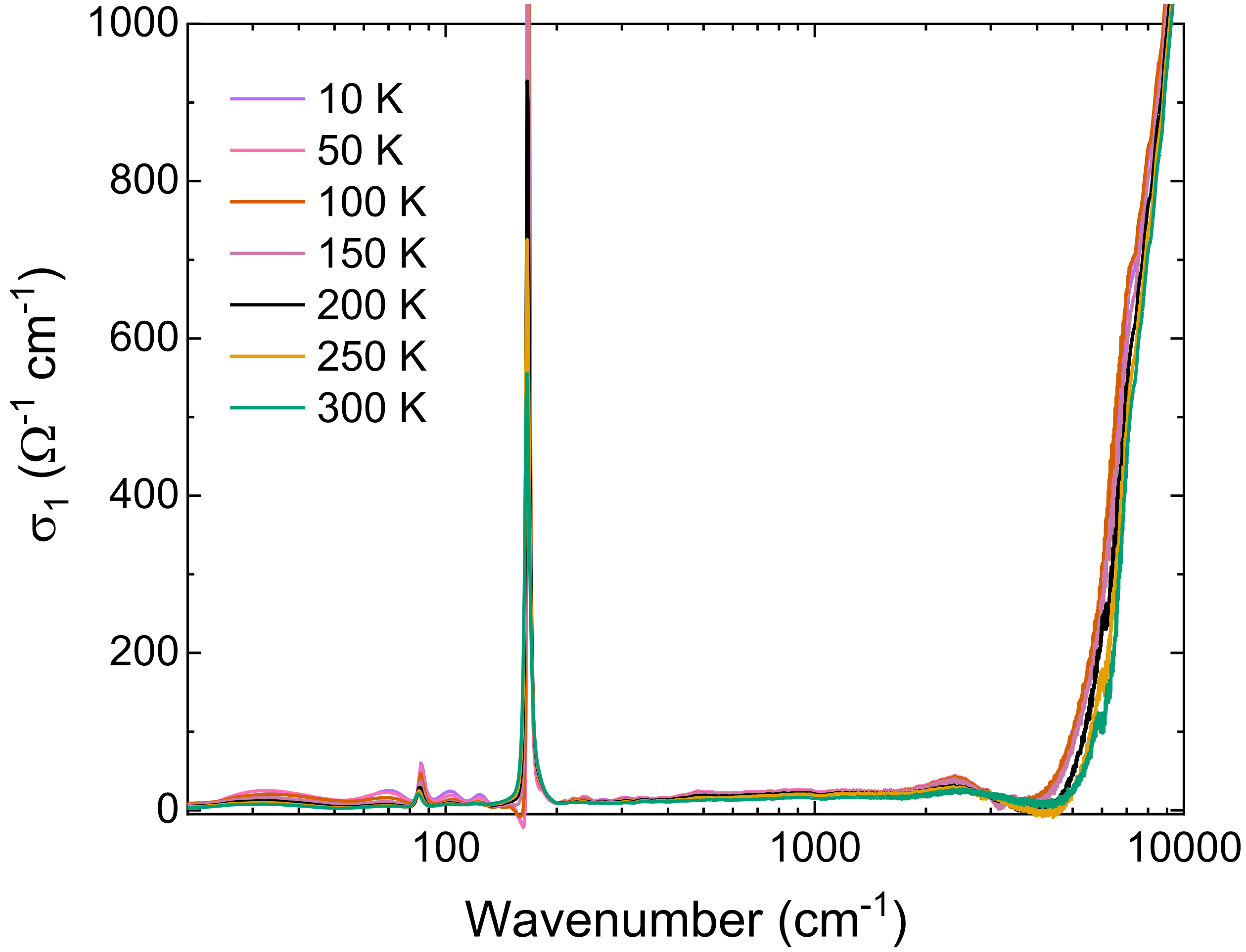
- weakly screened phonon modes
- low reflectance

Is this really a semimetal?

Reflectance



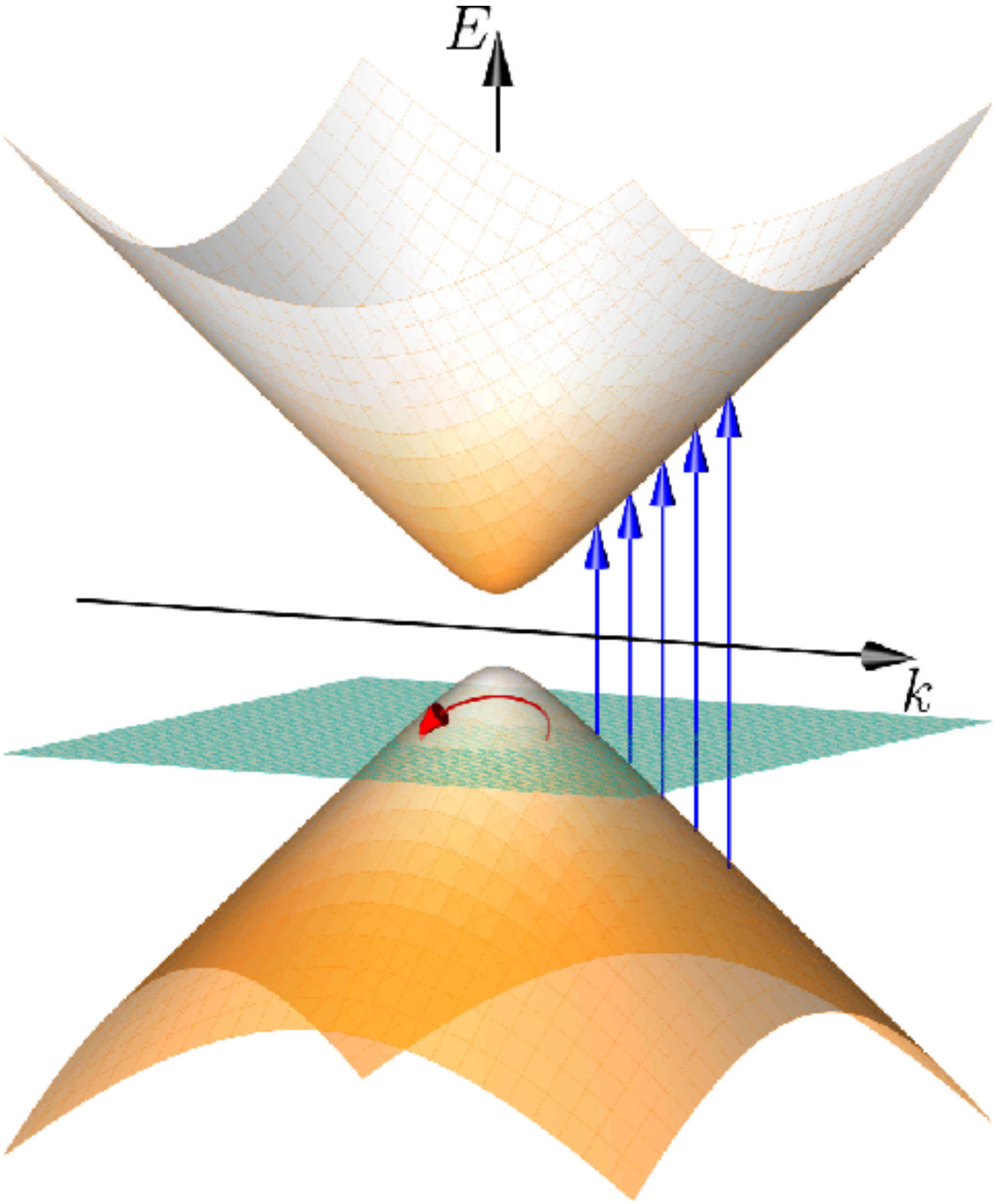
Optical conductivity

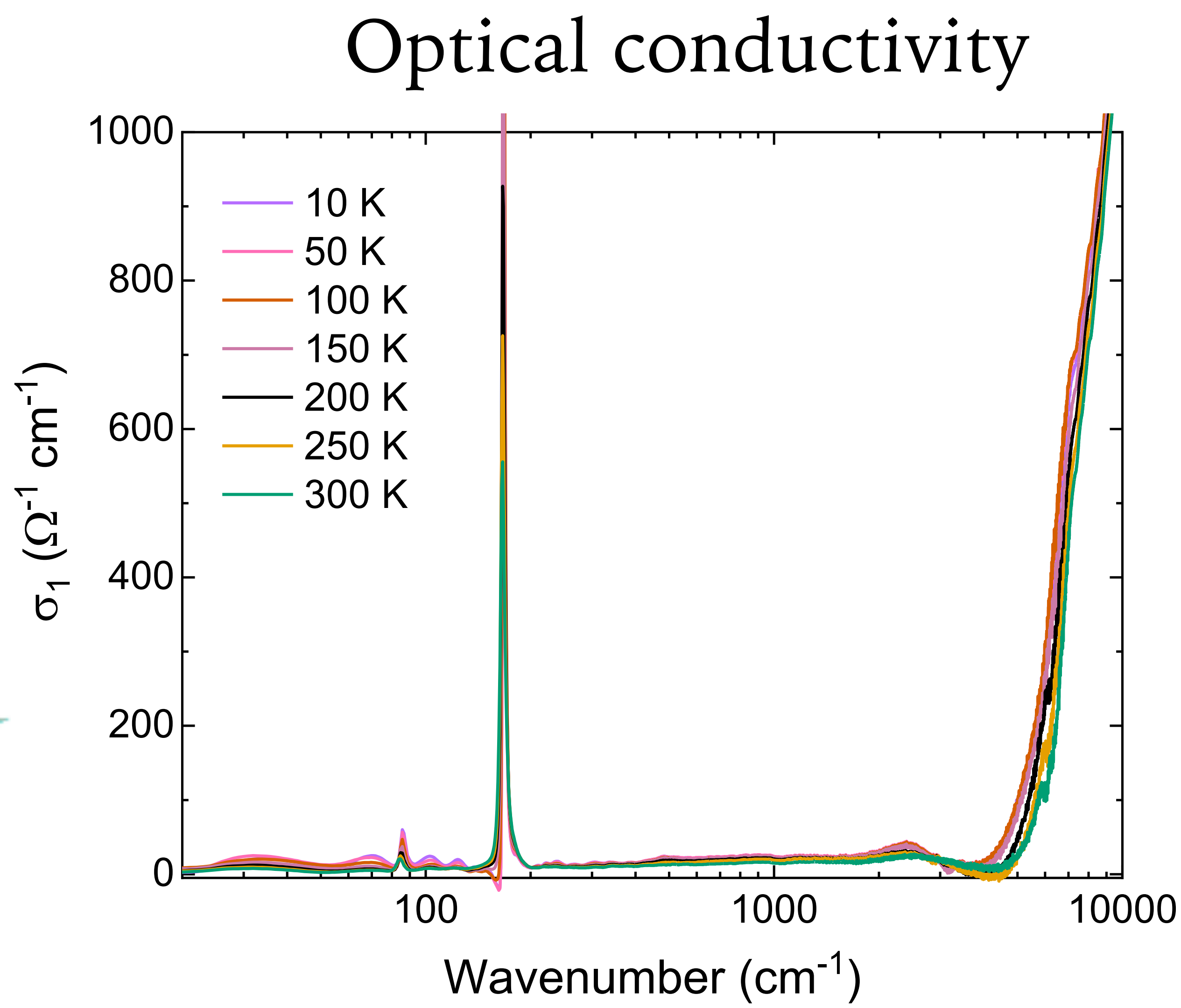


- weak temperature dependence of R

- weak Drude contribution
- gap-like feature above 0.5 eV

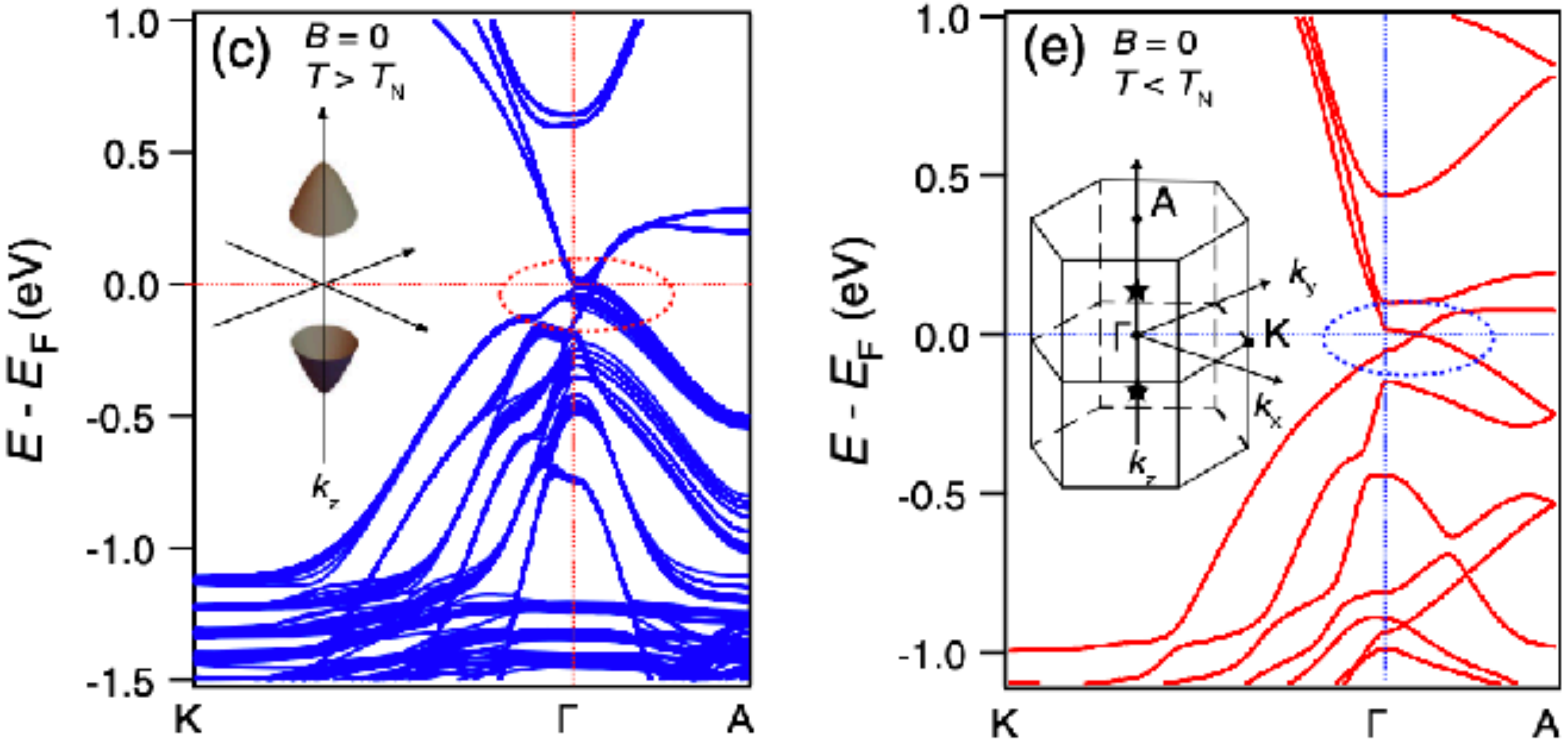
Is this really a semimetal?





- weak Drude contribution
- gap-like feature above 0.5 eV

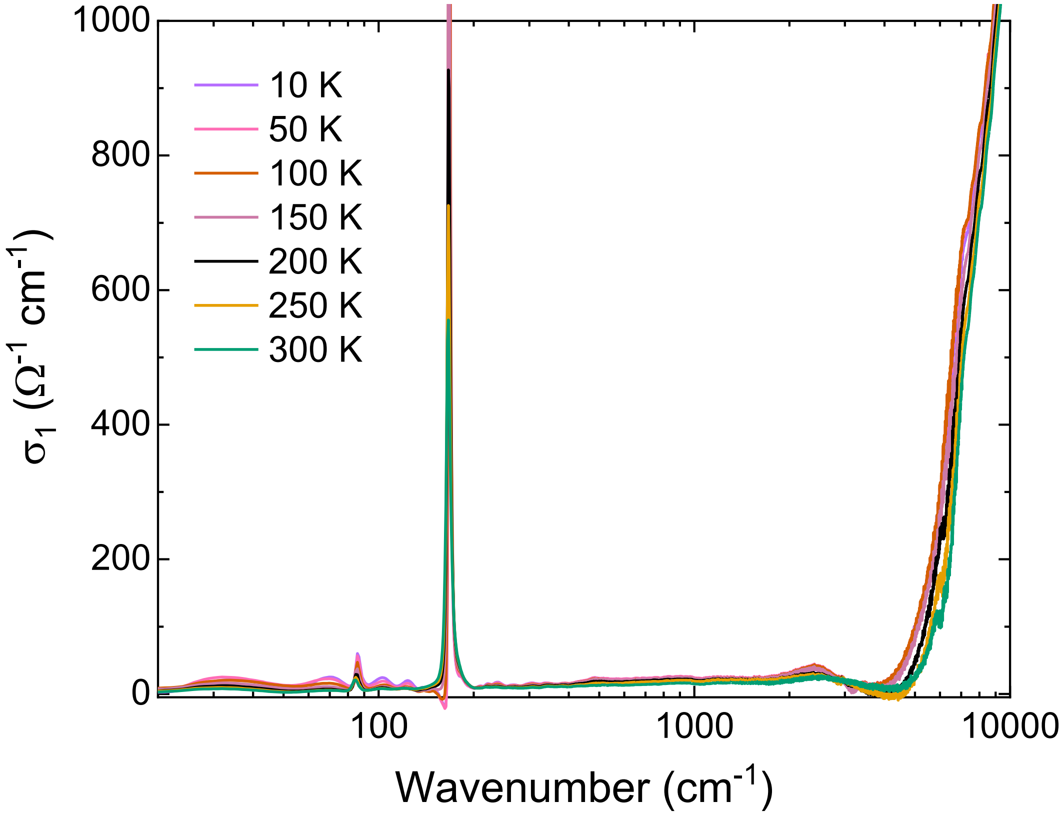
How to understand this?



DFT:
Small or zero gap

Optical conductivity:
No interband transitions below 0.5 eV

Weird selection rule?



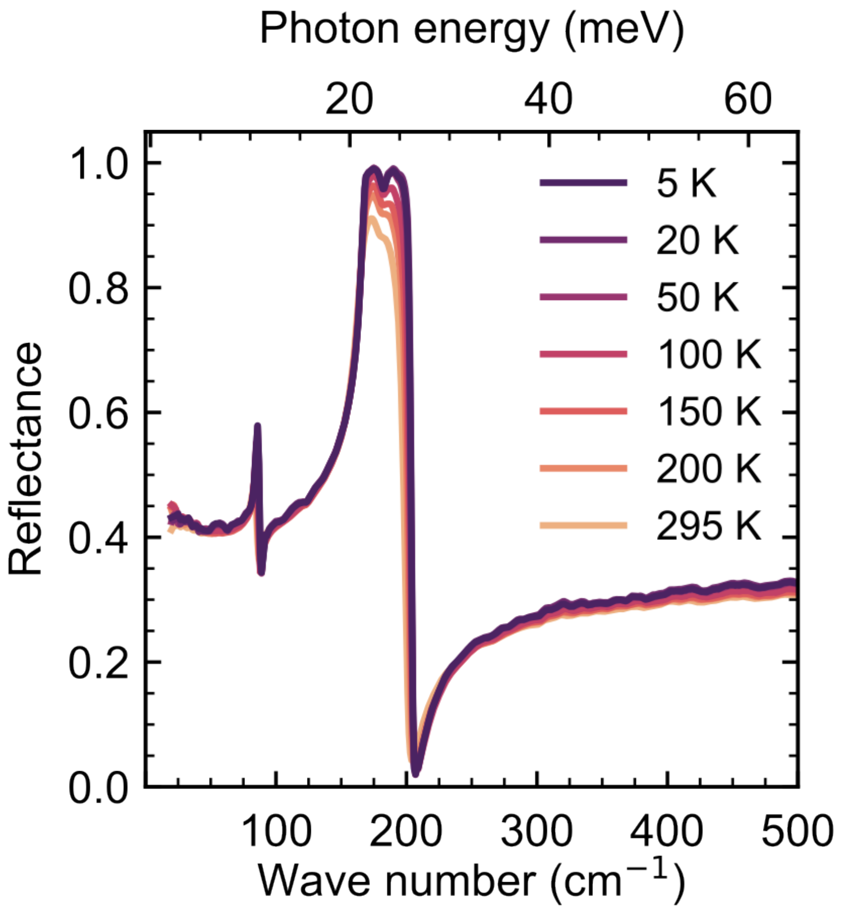
Y. Xu et al, Physical Review Letters 126, 076602 (2021)

Better samples

New batch

Old batch

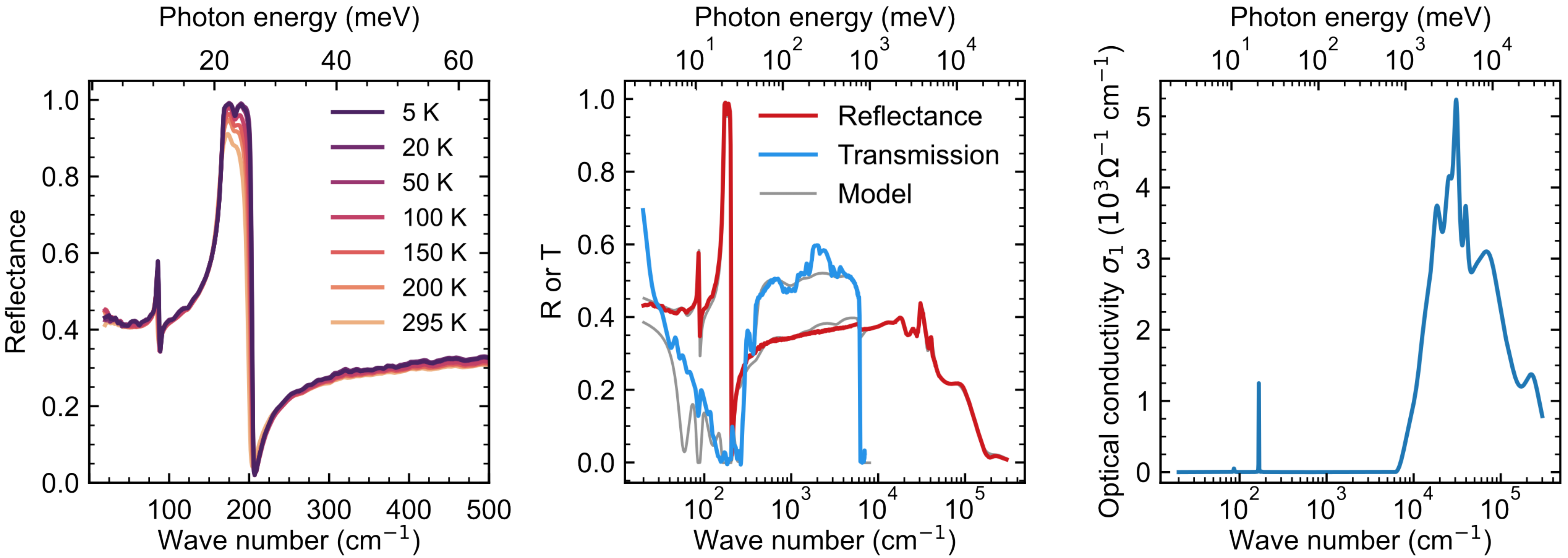
Even fewer carriers



No Drude component.
Reststrahlen band between TO and LO frequencies

D. Santos-Cottin, … T. Dietl, M. Orlita, AA, arXiv:2301.08014 (2023)

Even fewer carriers

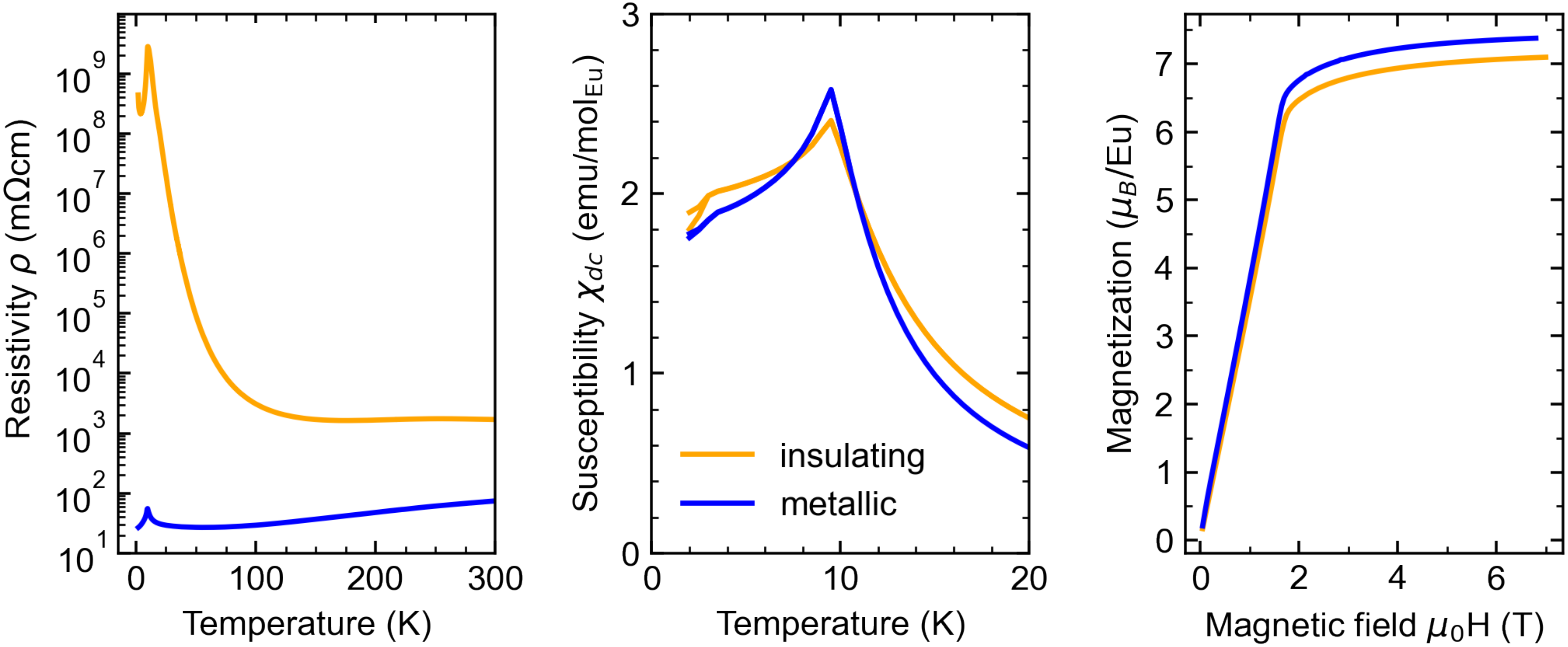


No Drude component.
Reststrahlen band between TO and LO frequencies.

Can’t use simple Kramers-Kronig analysis!

D. Santos-Cottin, … T. Dietl, M. Orlita, AA, arXiv:2301.08014 (2023)

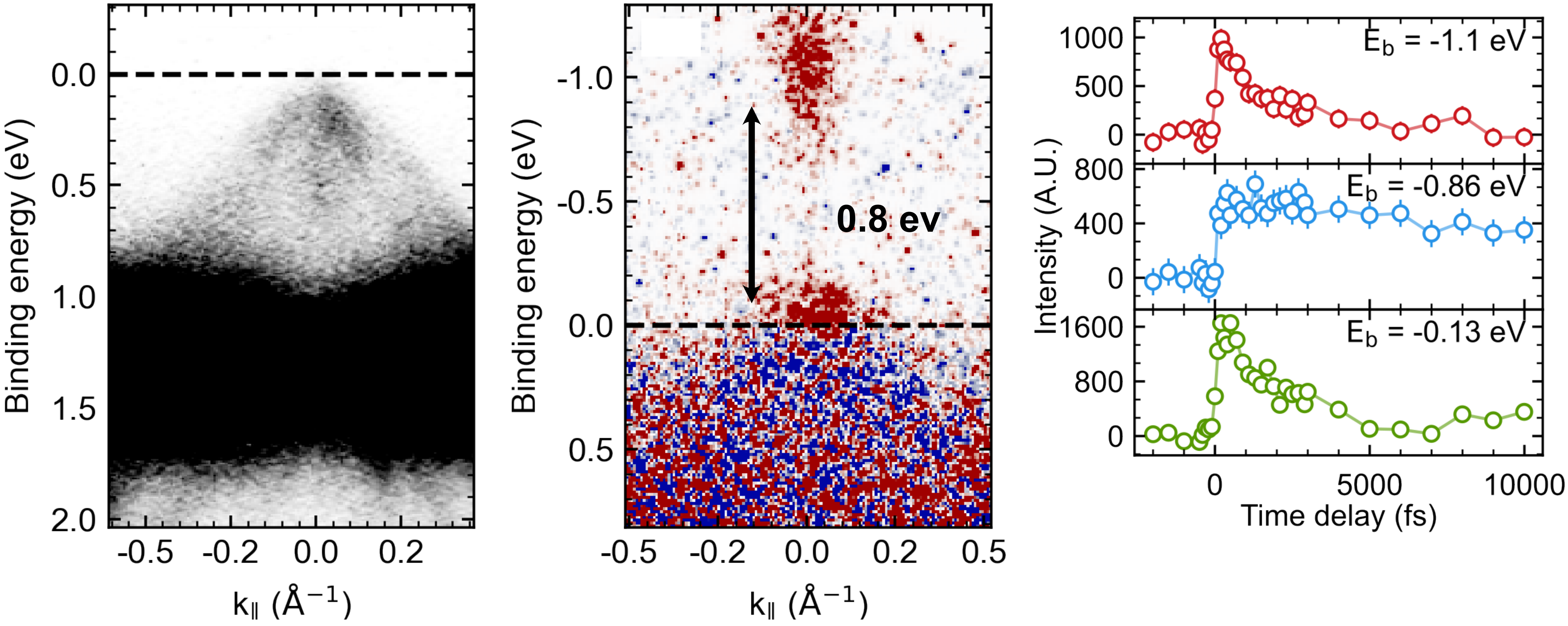
Not a semimetal…



Drude doesn’t know about topology!
This cannot be a semimetal.

D. Santos-Cottin, … T. Dietl, M. Orlita, AA, arXiv:2301.08014 (2023)

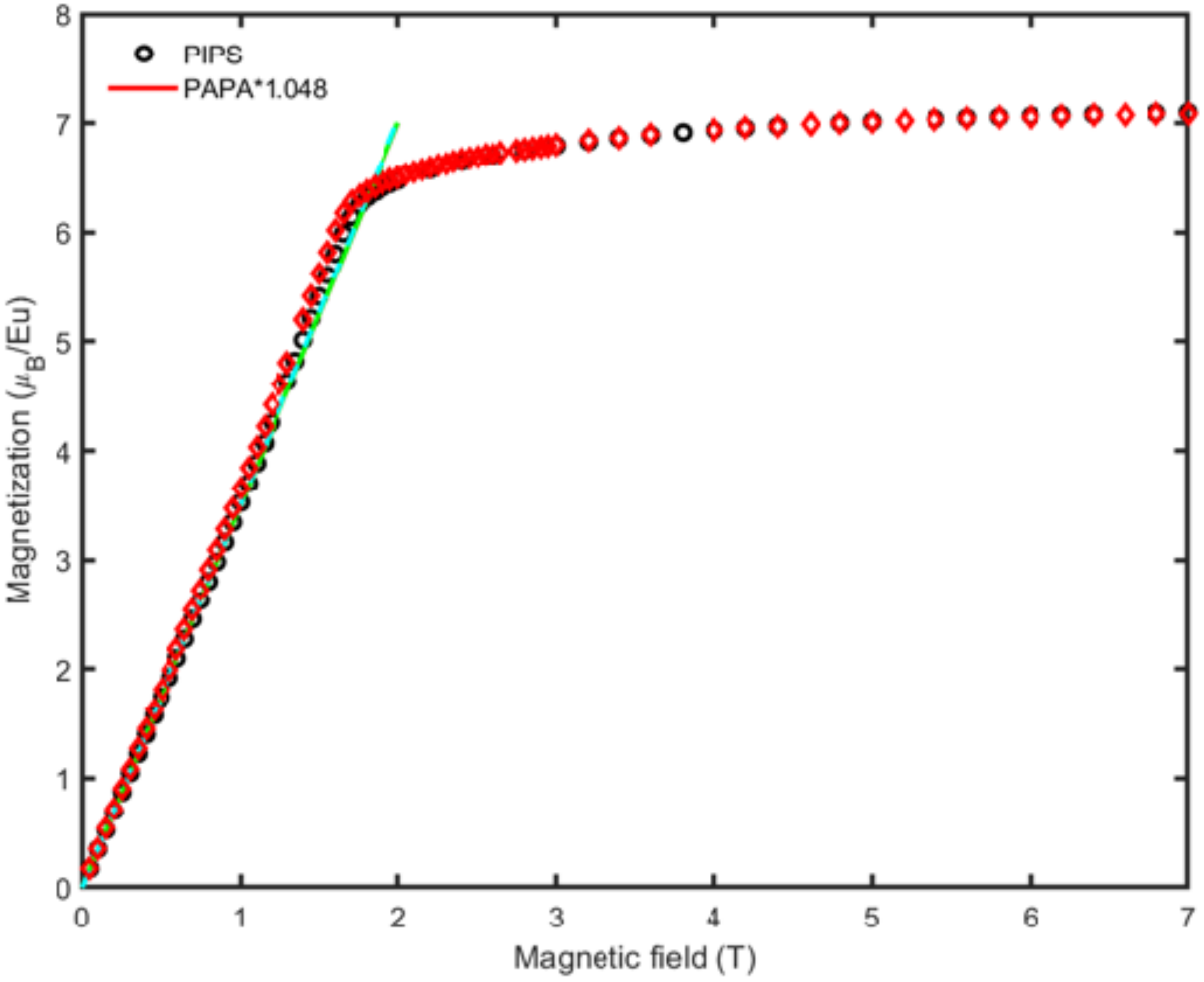
Not a semimetal...

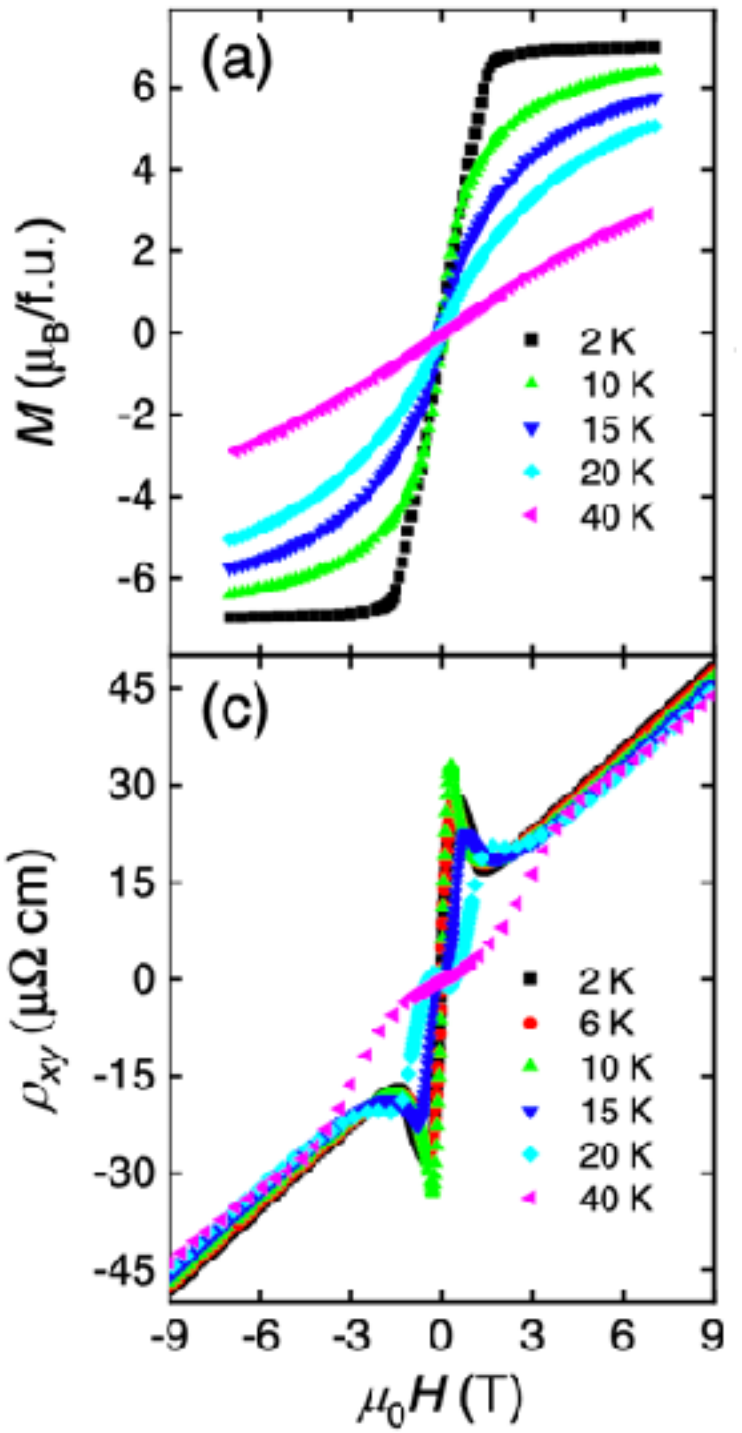


Hugo Dil's group, EPFL

D. Santos-Cottin, … T. Dietl, M. Orlita, AA, arXiv:2301.08014 (2023)

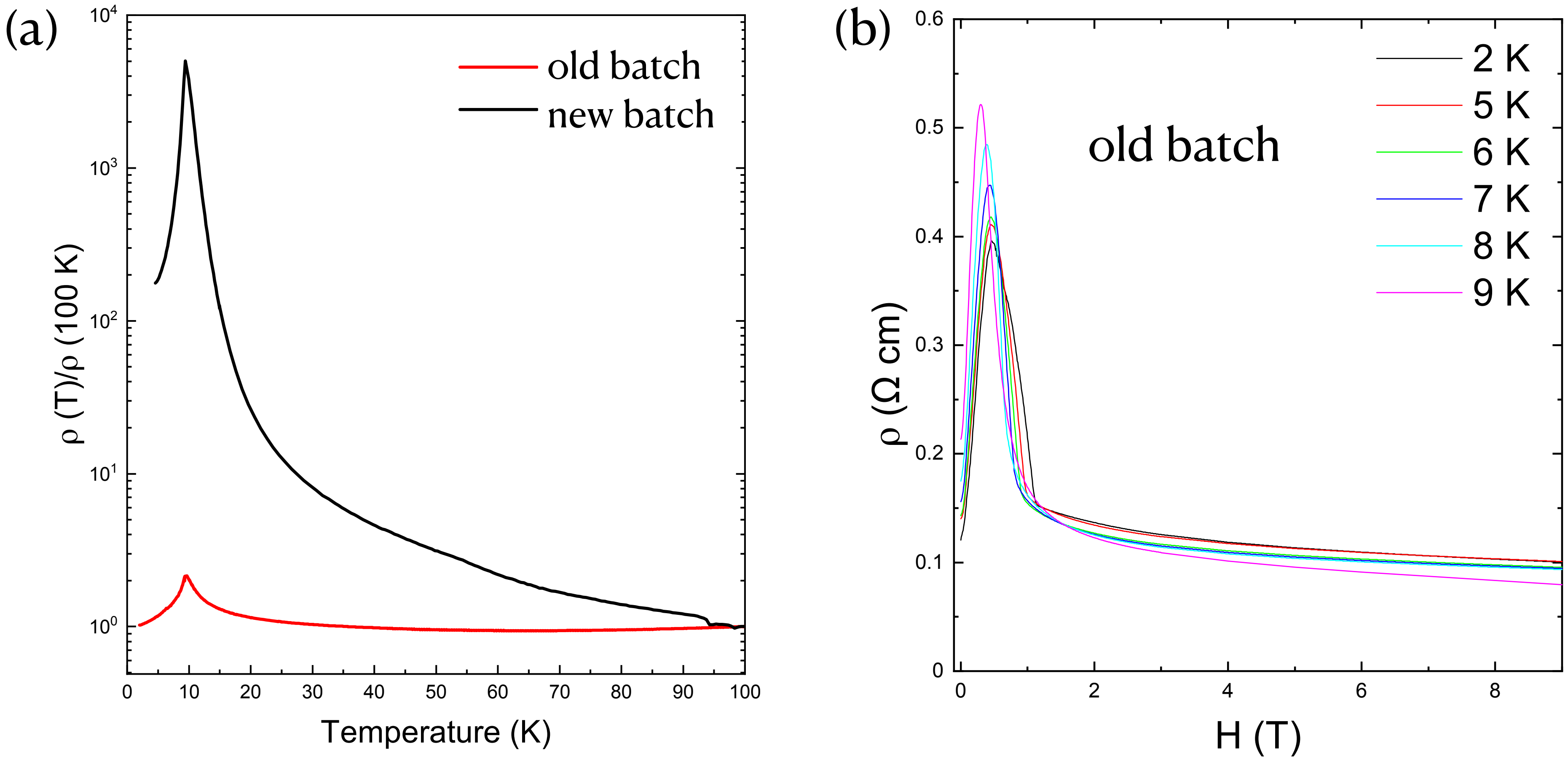
Magnetic properties

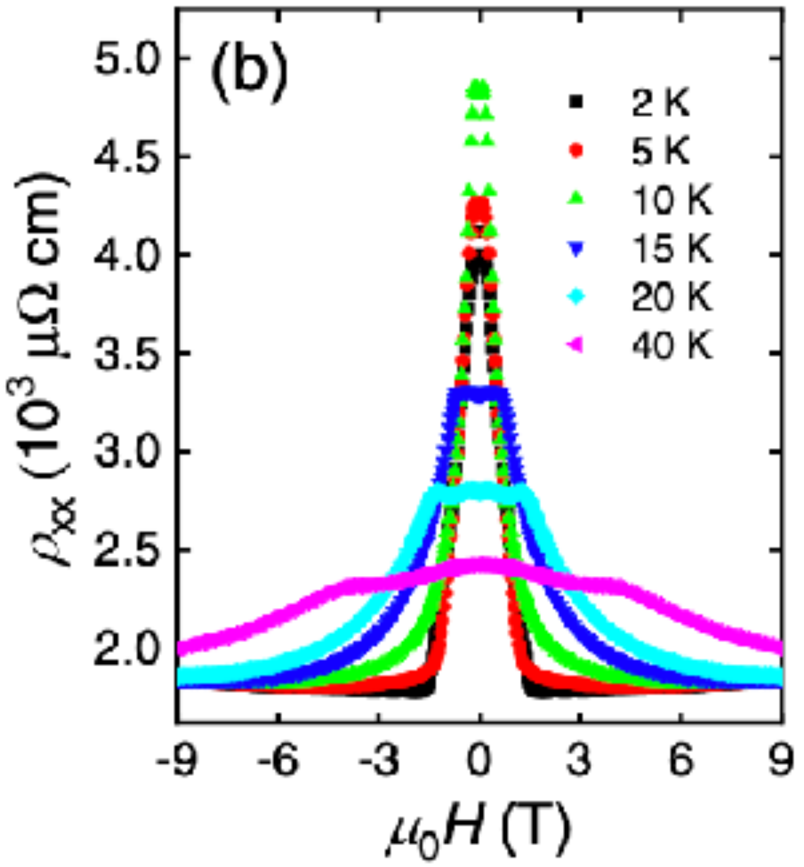




Y. Xu et al, Physical Review Letters 126, 076602 (2021)

Resistivity

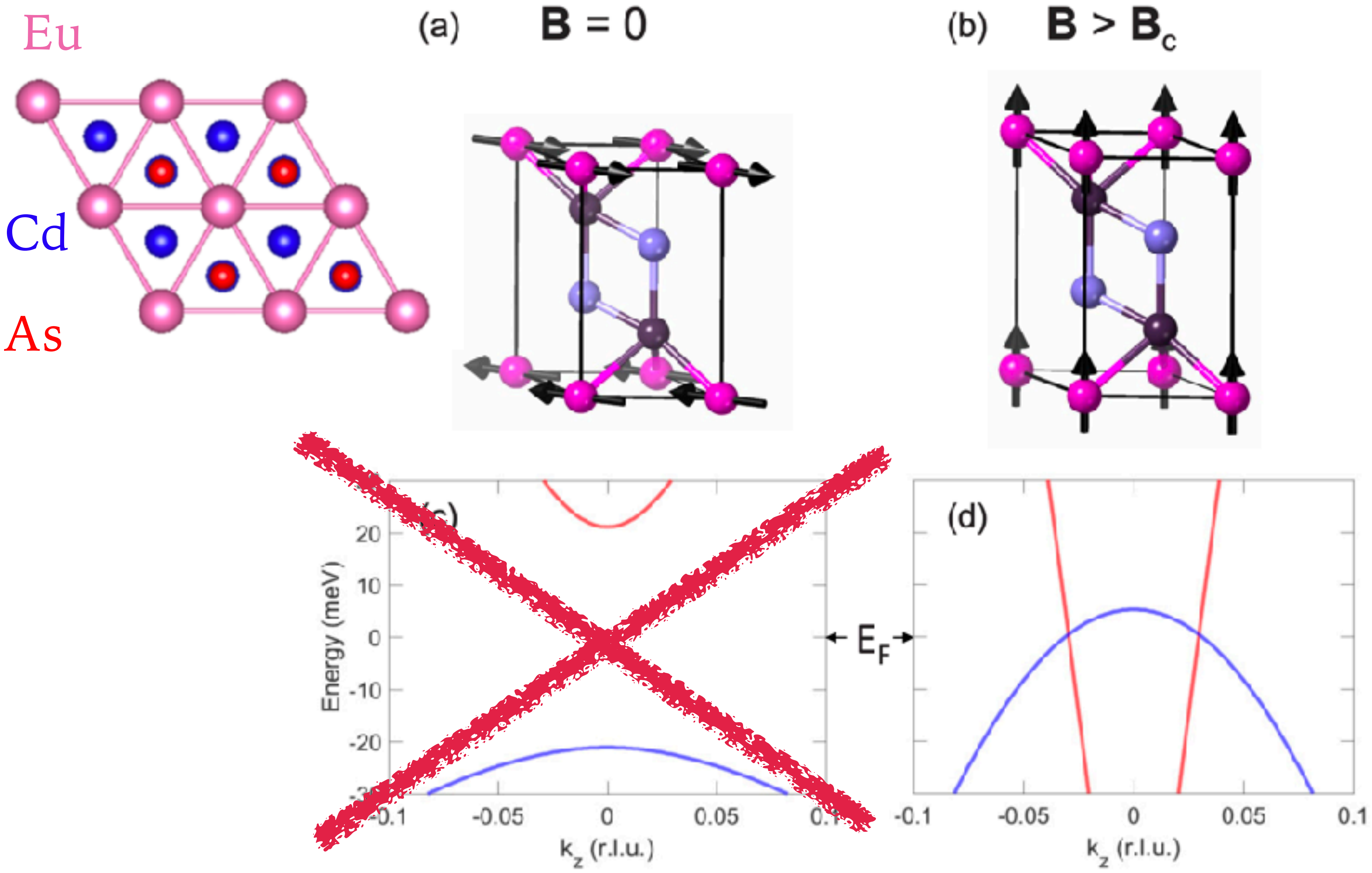




This cannot be a semimetal.

Y. Xu et al, Physical Review Letters 126, 076602 (2021)

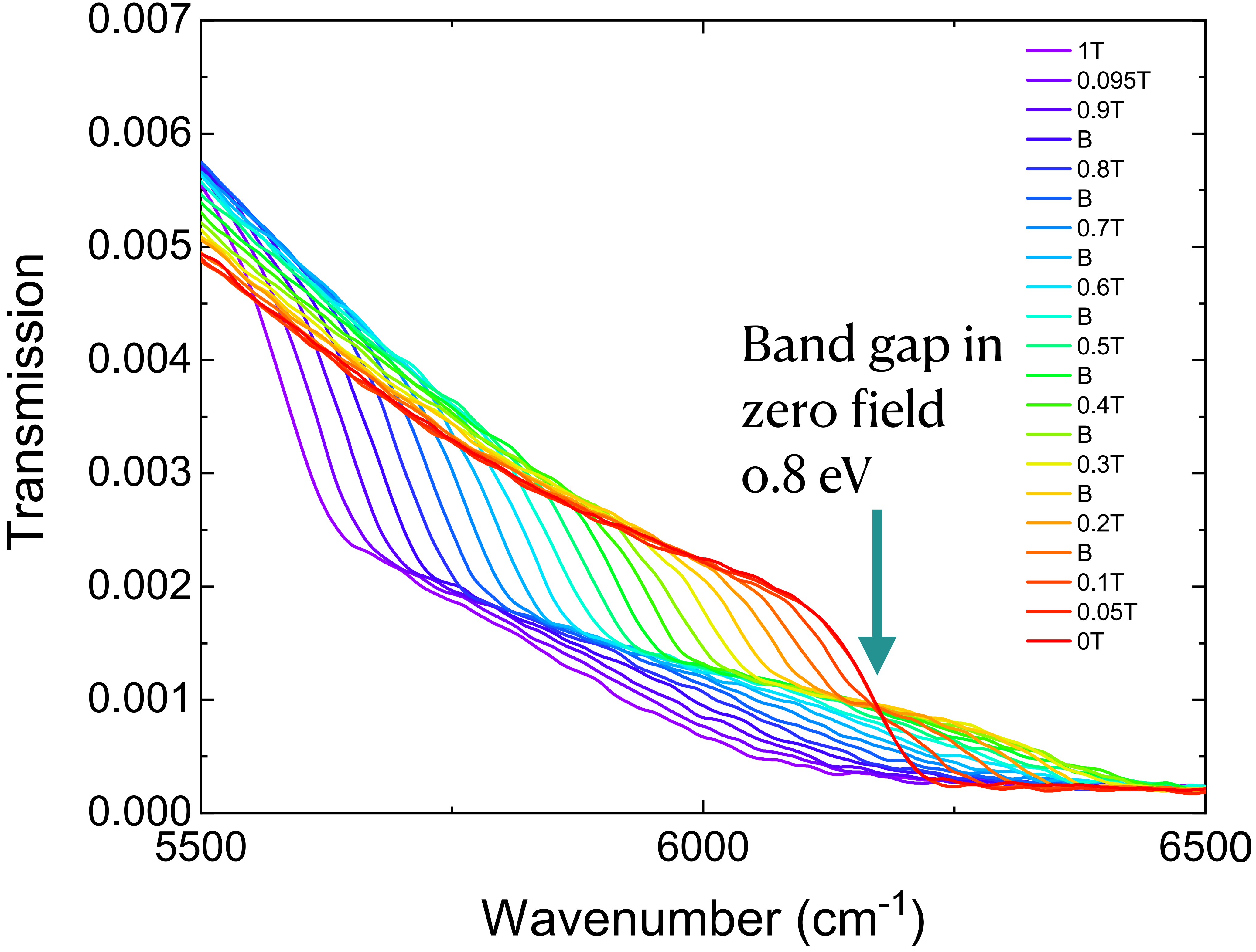
~~Topological semimetal~~ EuCd$_2$As$_2$



J.R. Soh et al, Physical Review B **100**, 201102(R) (2019)

Magneto-transmission at 4 K

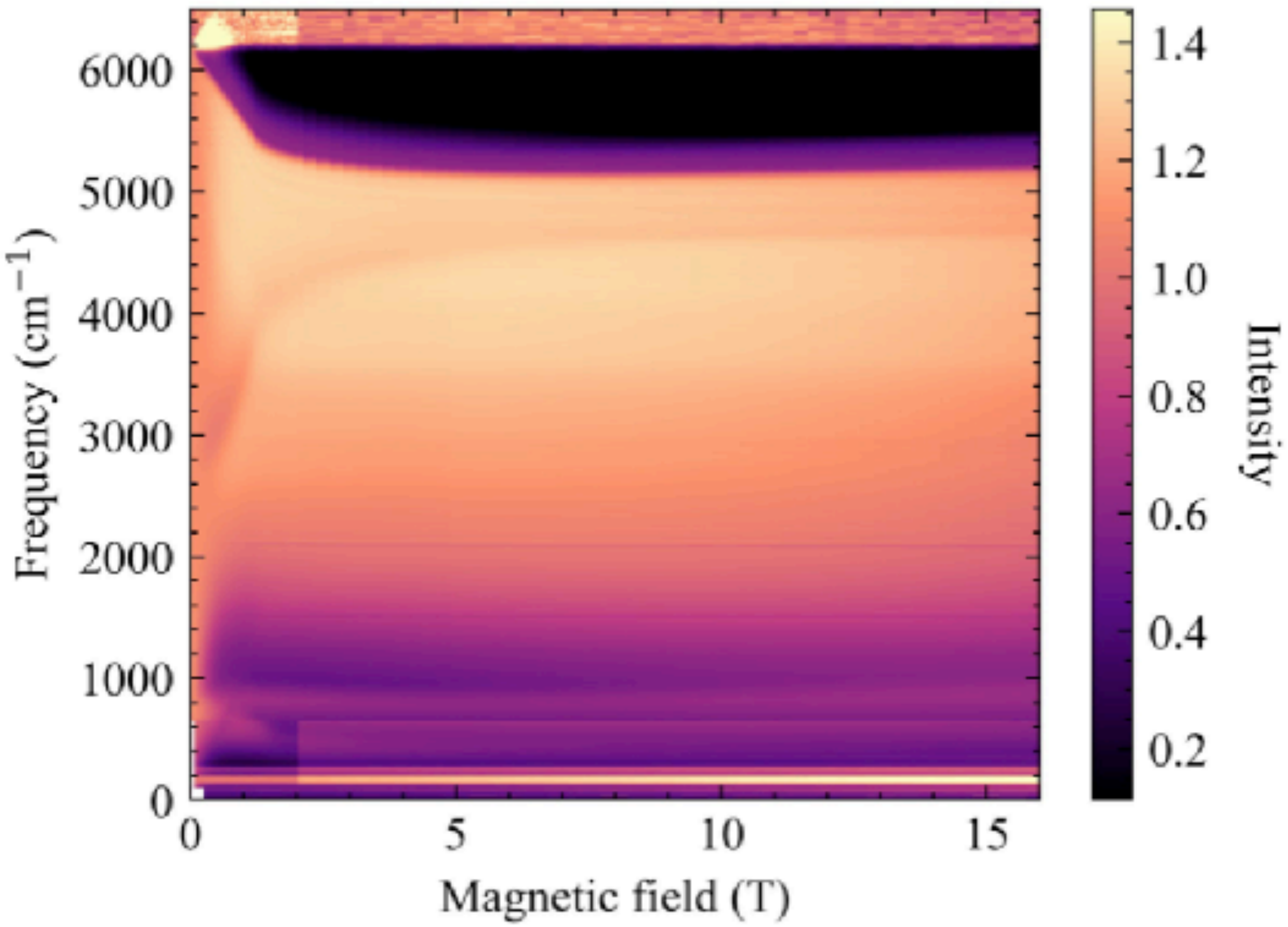
Magneto-transmission below 1 T



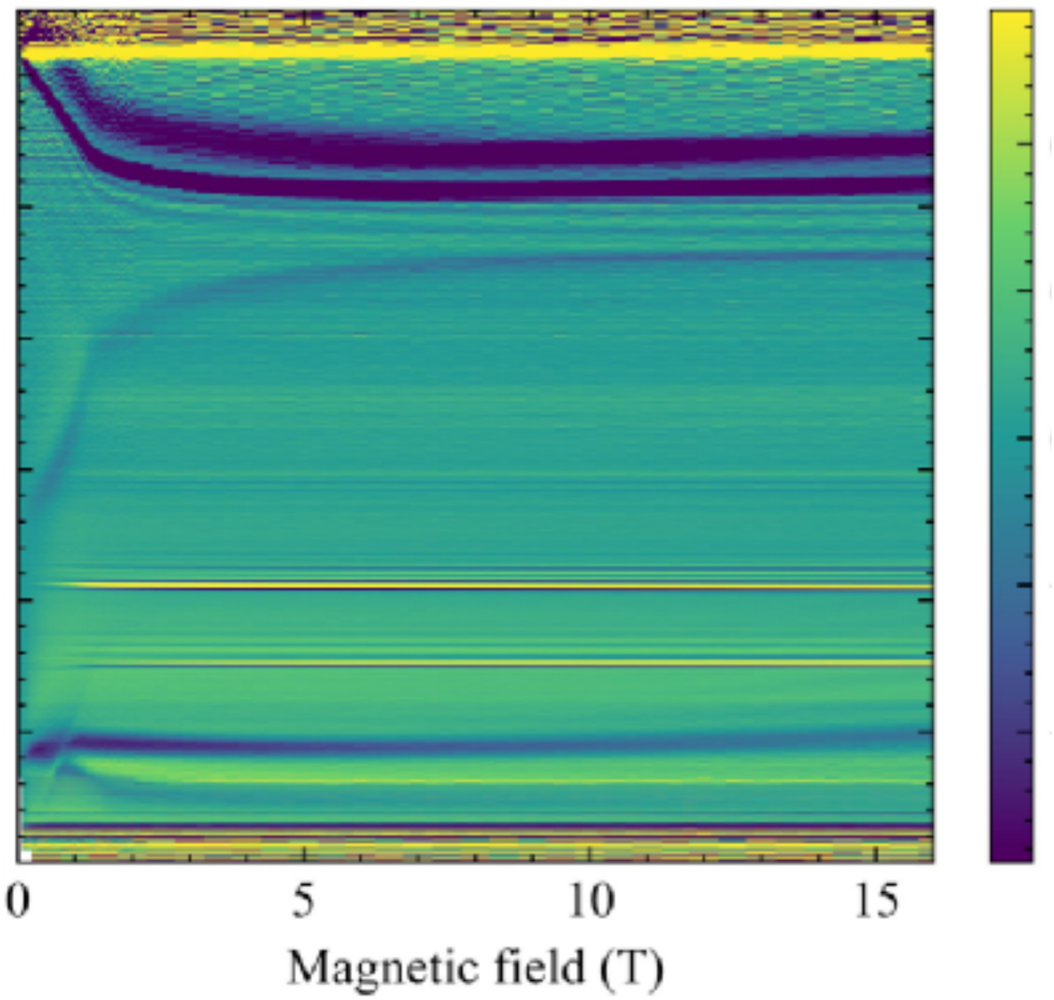
Band gap in zero field 0.8 eV

T_B/T_0 in the mid infrared

Relative transmission



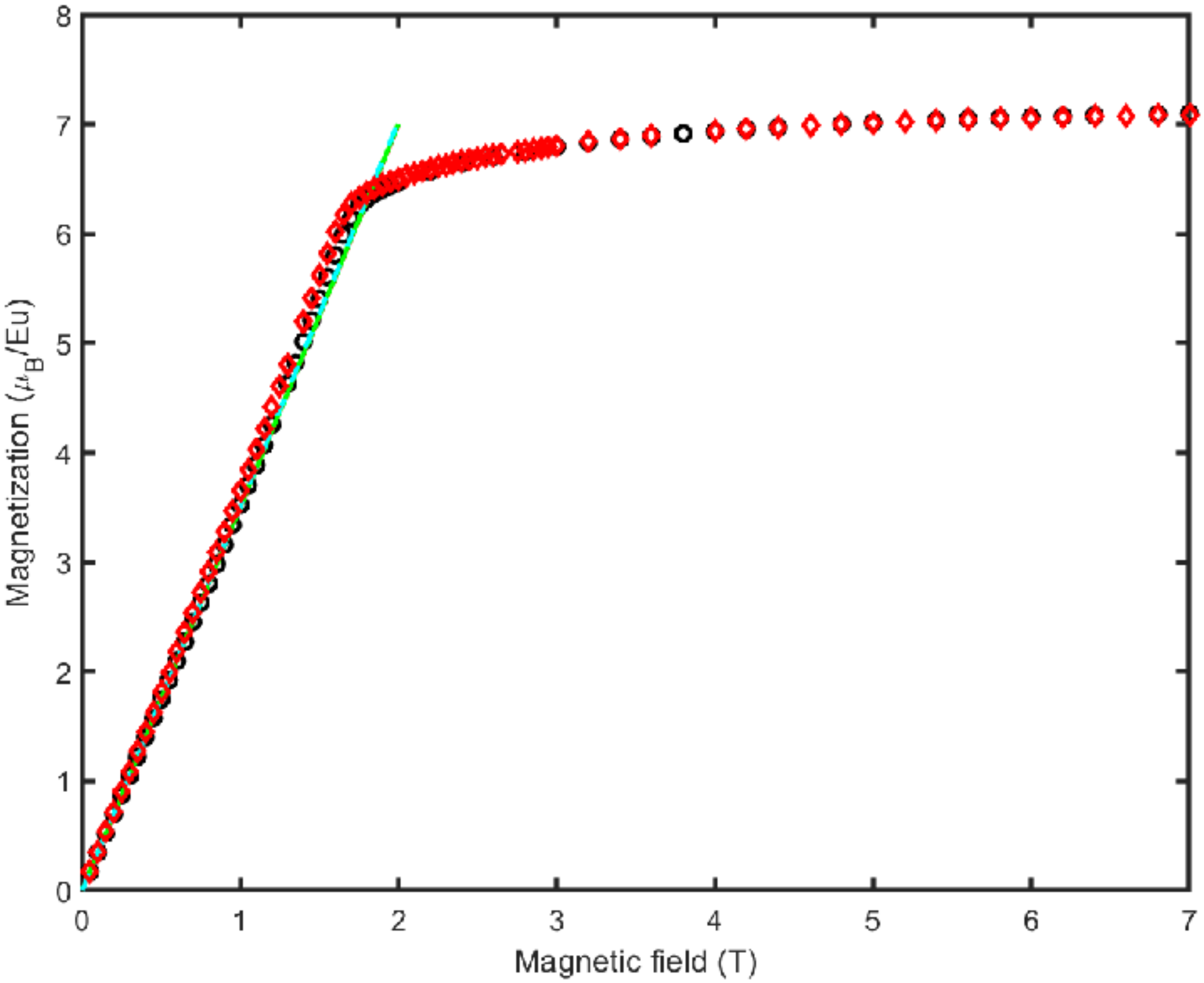
Derivative of relative transmission



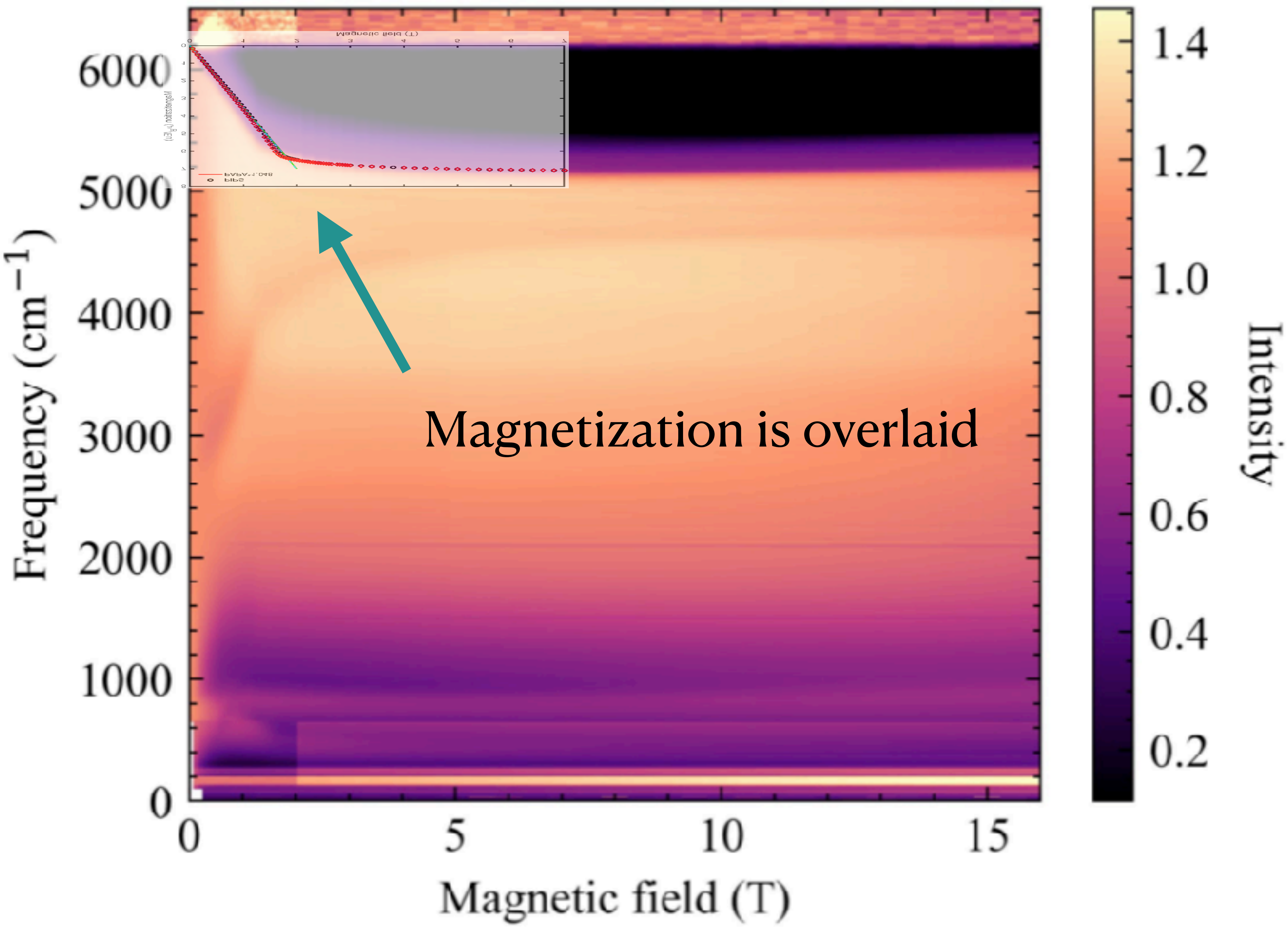
Gap of 0.8 eV decreases by 125 meV, under applied ~4 T.

Spin polarized bands. In-gap "stuff".

Magnetization

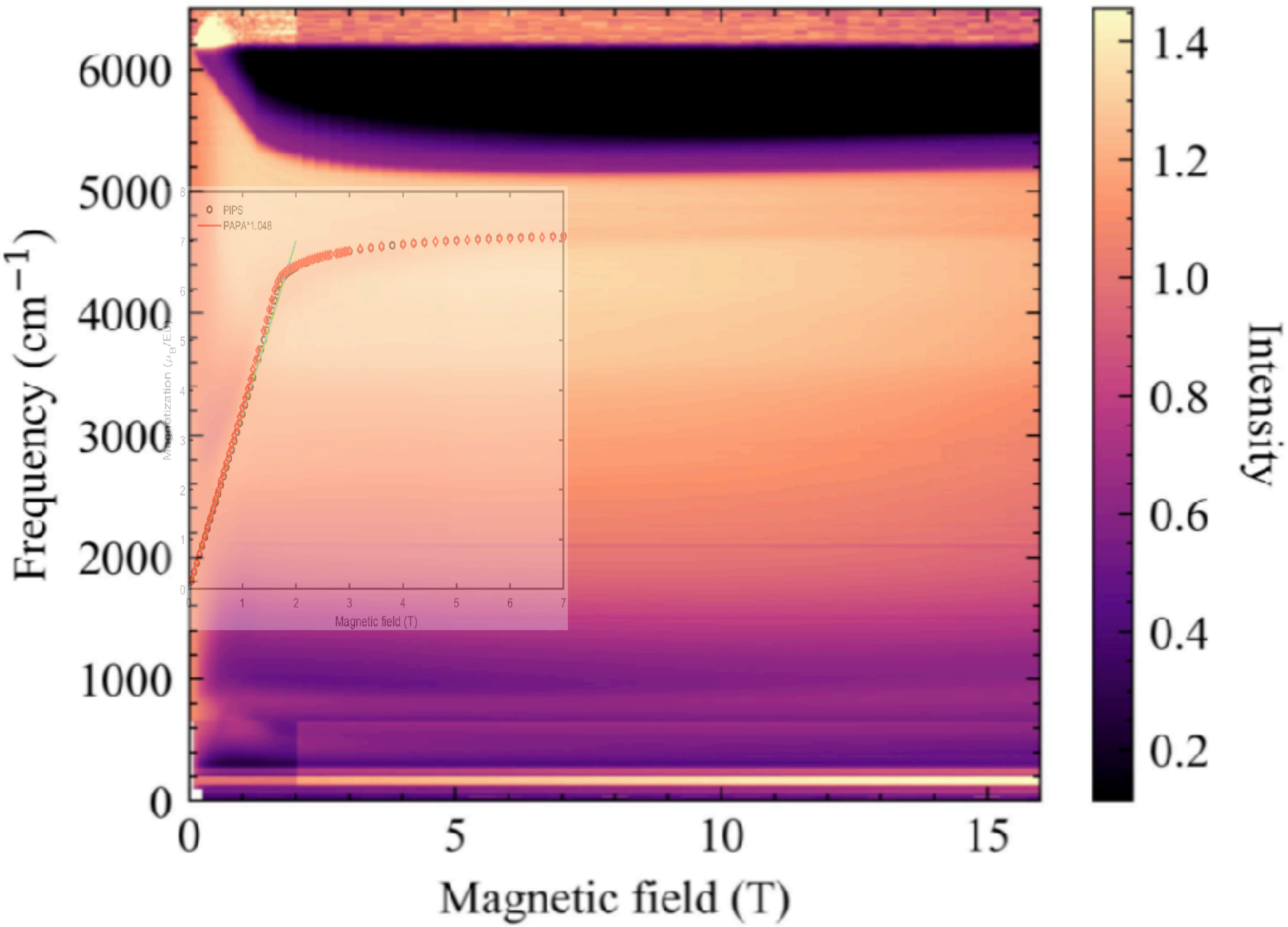


T_B/T_0 in the mid infrared



Magnetization is overlaid

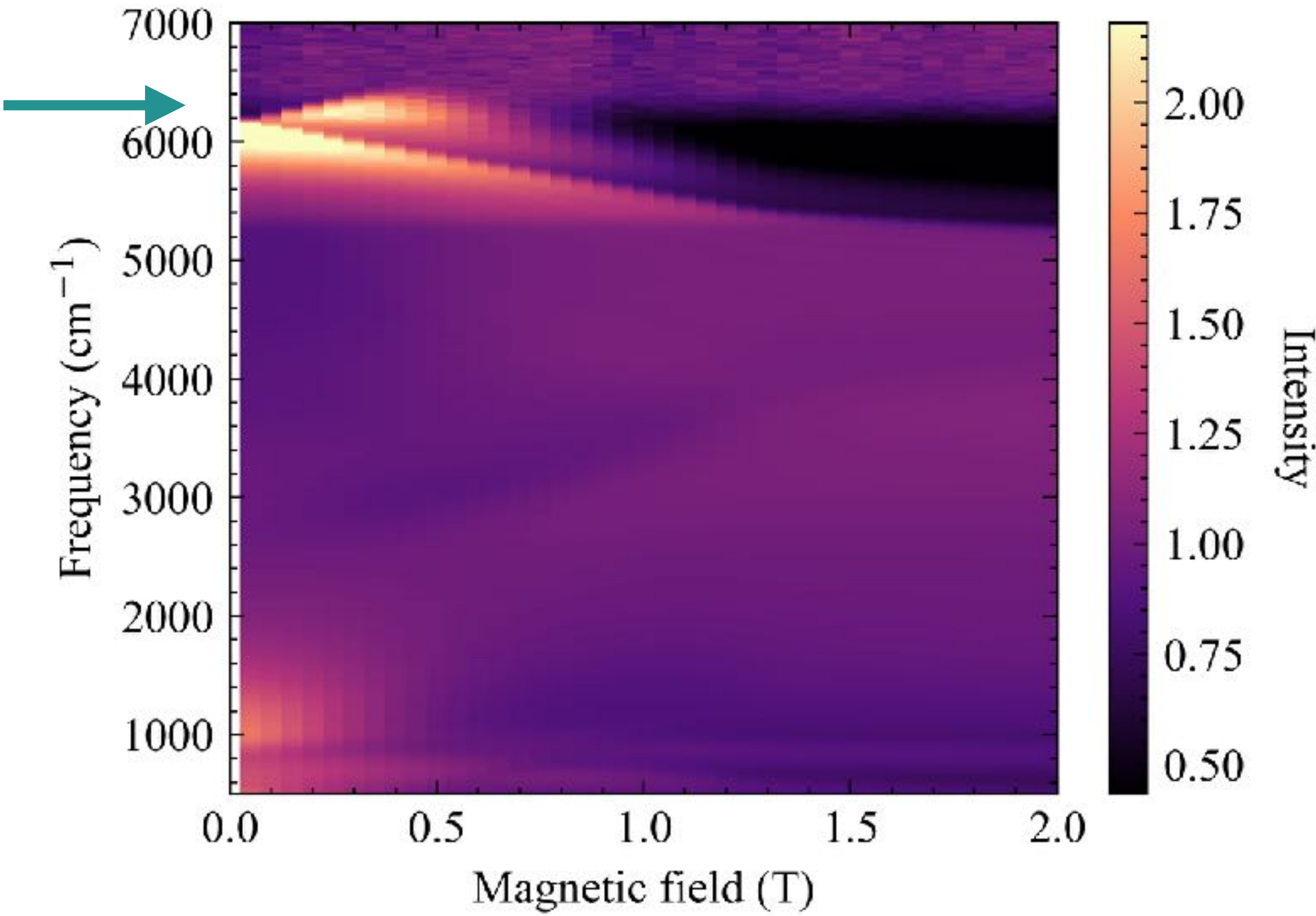
T_B/T_0 in the mid infrared



T_B/T_{avg}

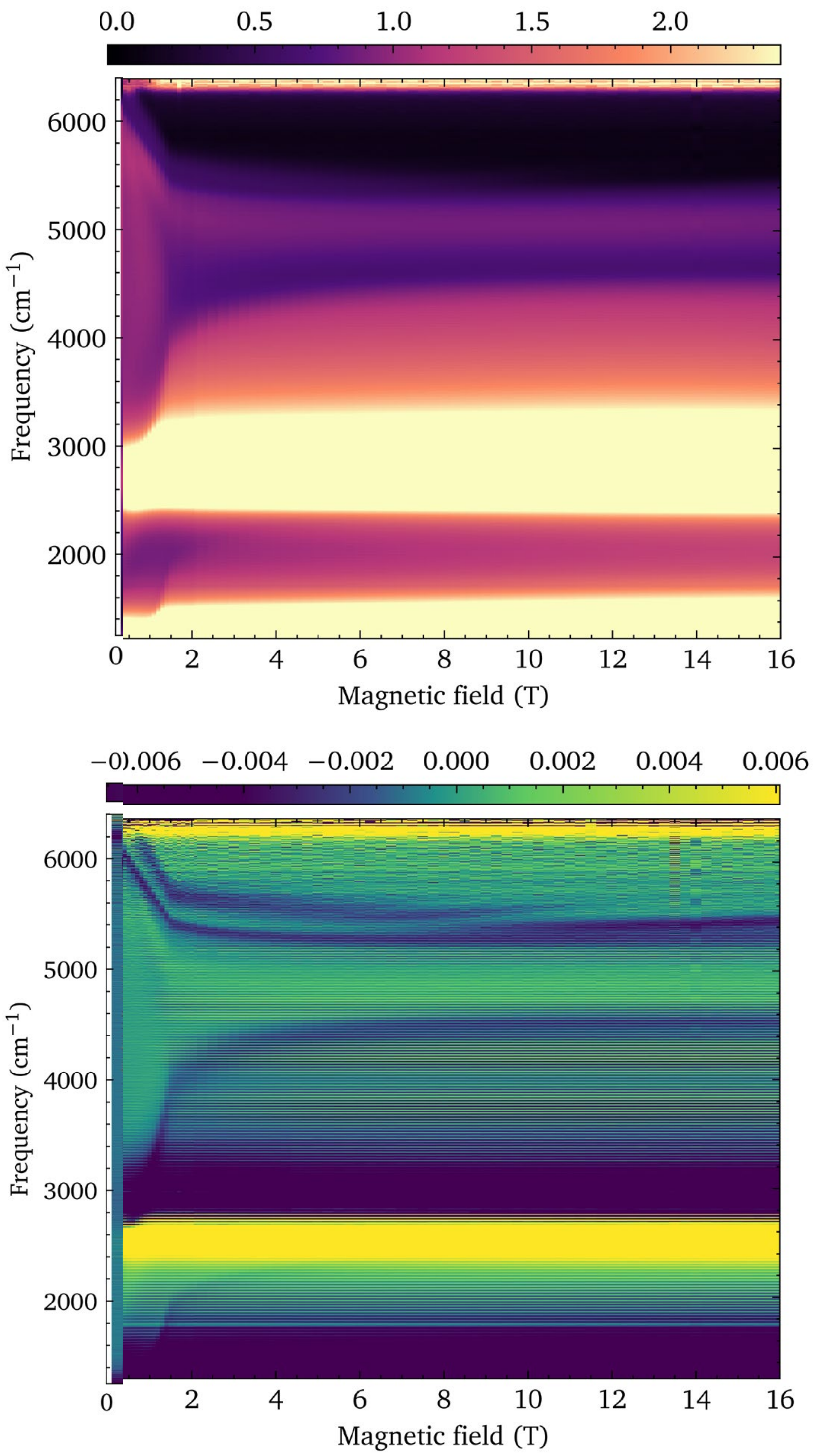
The effective g factor is above 1500.

$$g \propto \frac{\Delta E}{\Delta B}$$

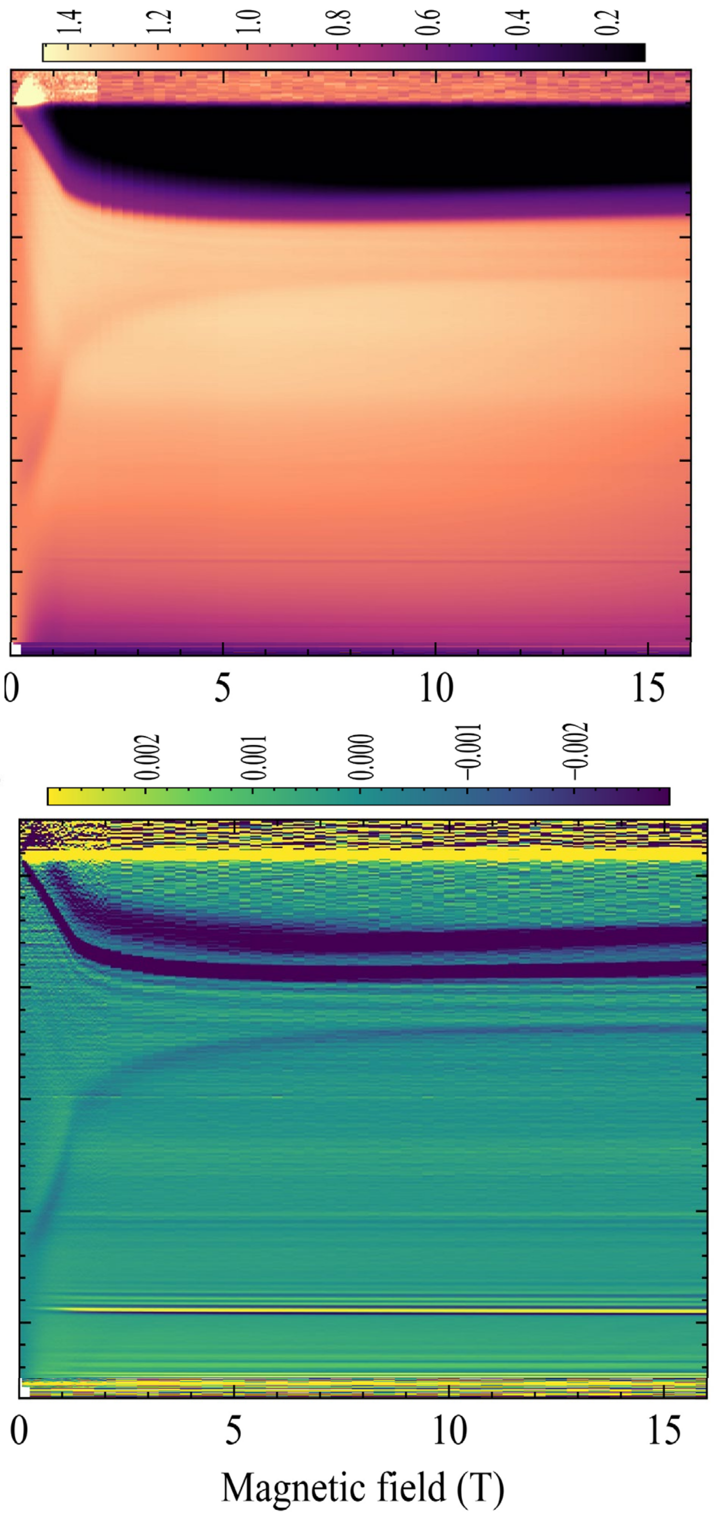


Metallic vs insulating samples

Metallic

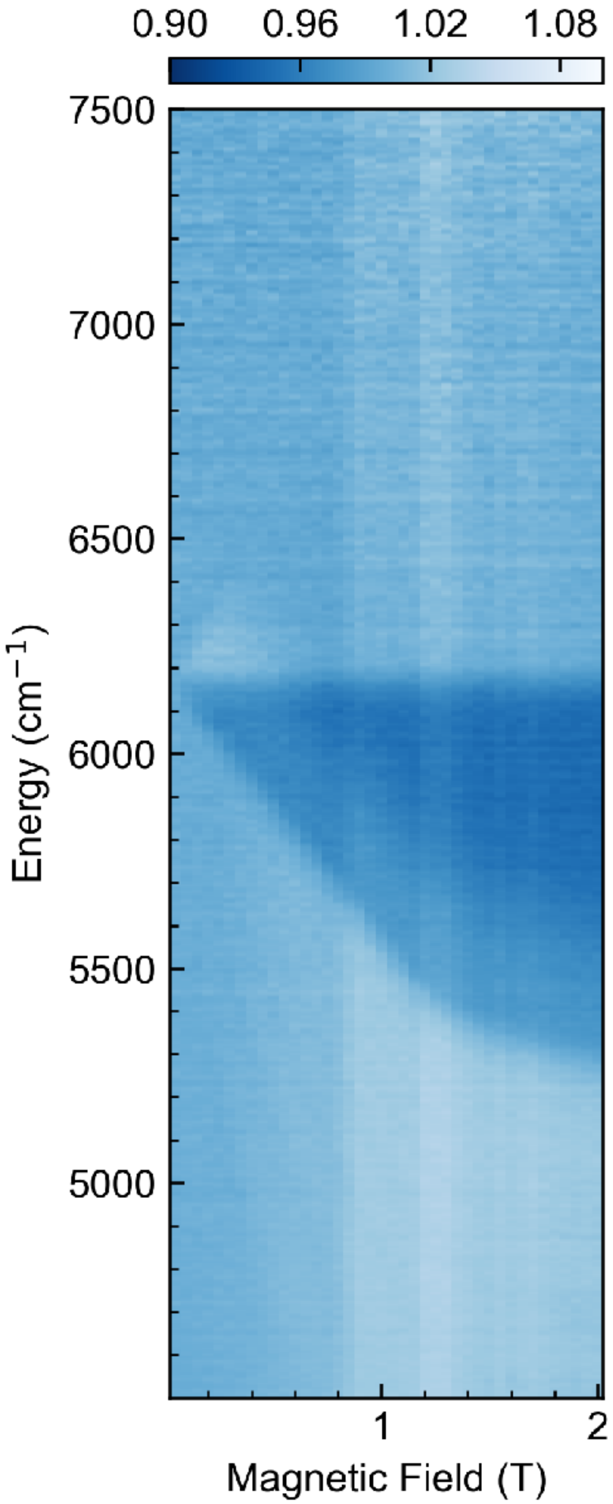


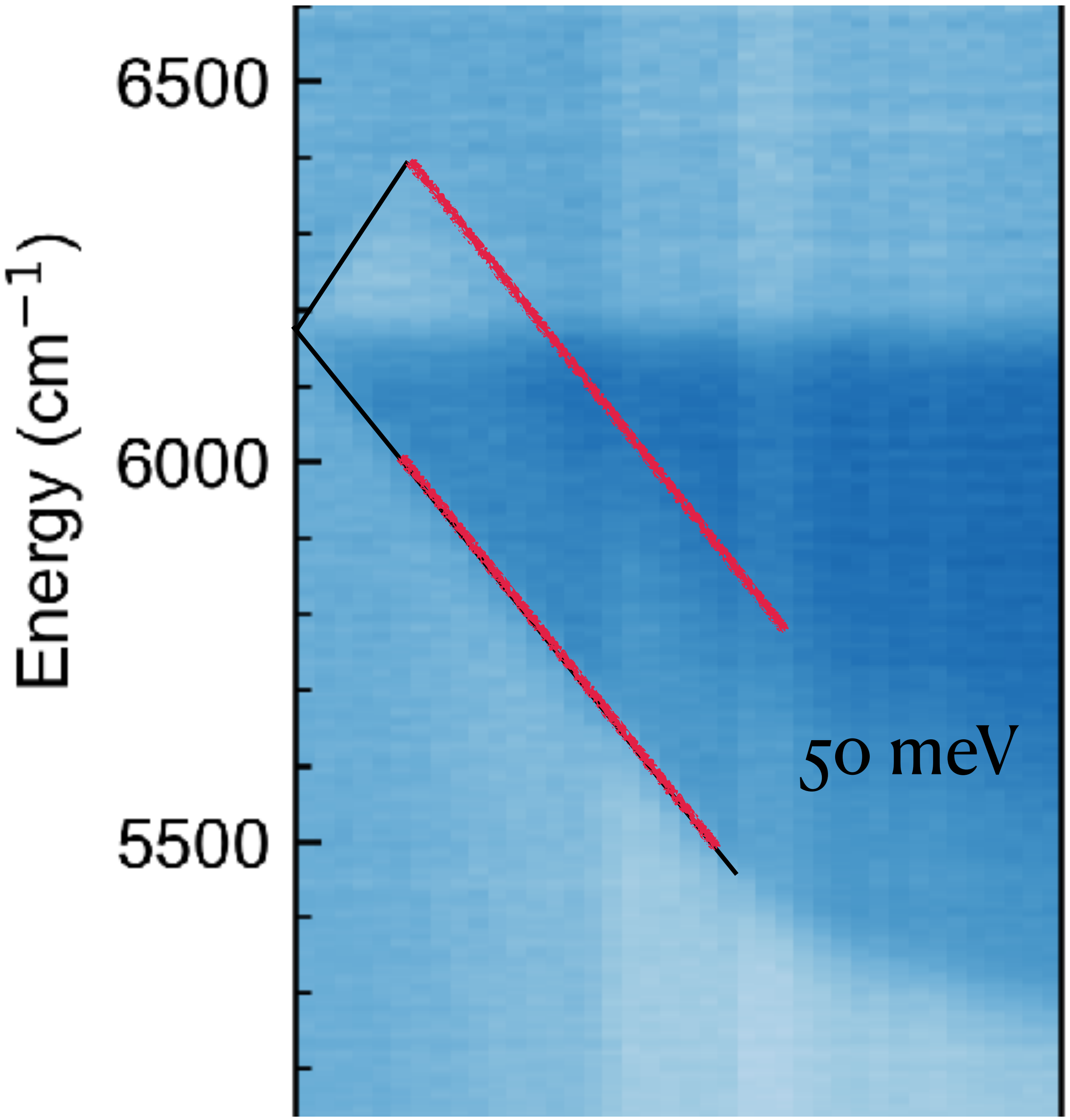
Insulating



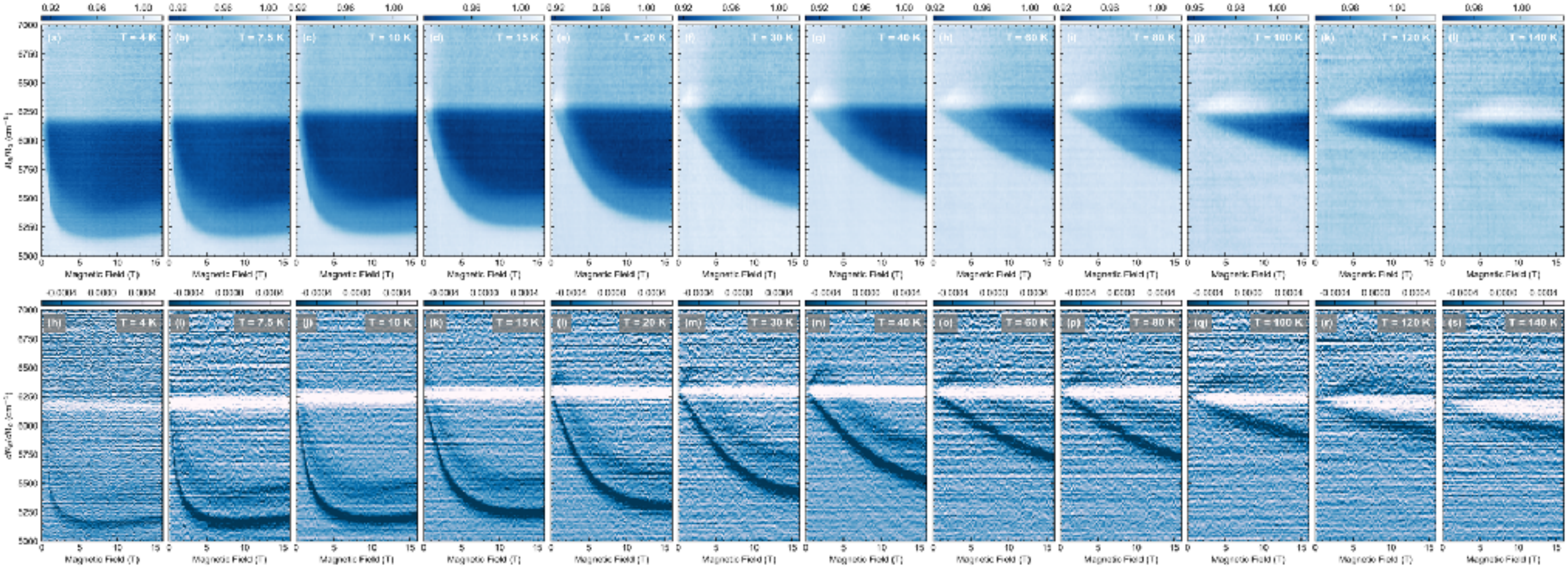
Magneto-reflection from 4 K to 140 K

Gap splitting and decrease in field: 4 K

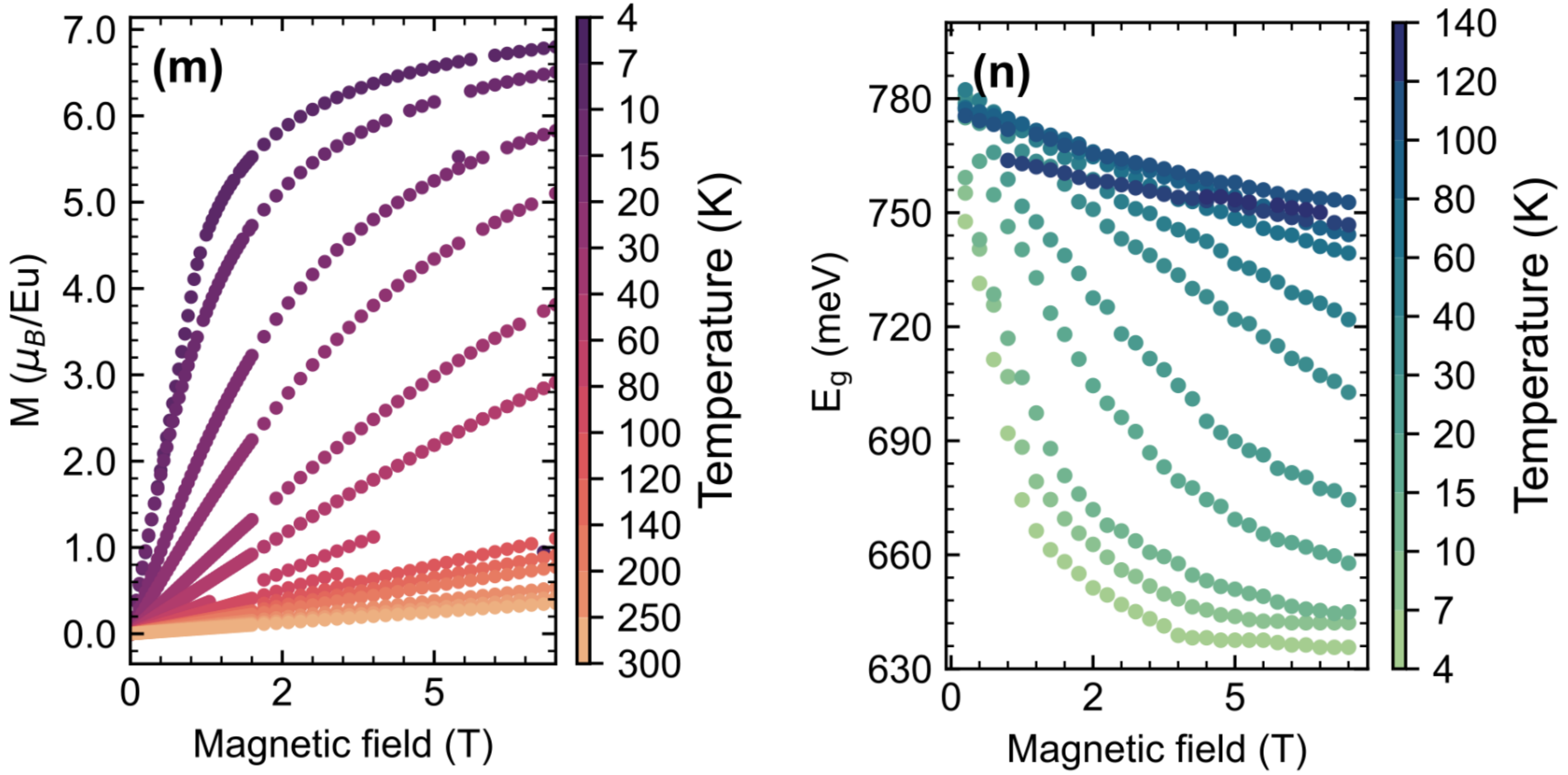




R_B/R_0 up to 140 K - high field



Gap decrease mimics magnetization



$$\Delta E_{\mathrm{g}} = -\frac{1}{2}\mathcal{J}_{\mathrm{eff}} S M(T,H)/M_S$$

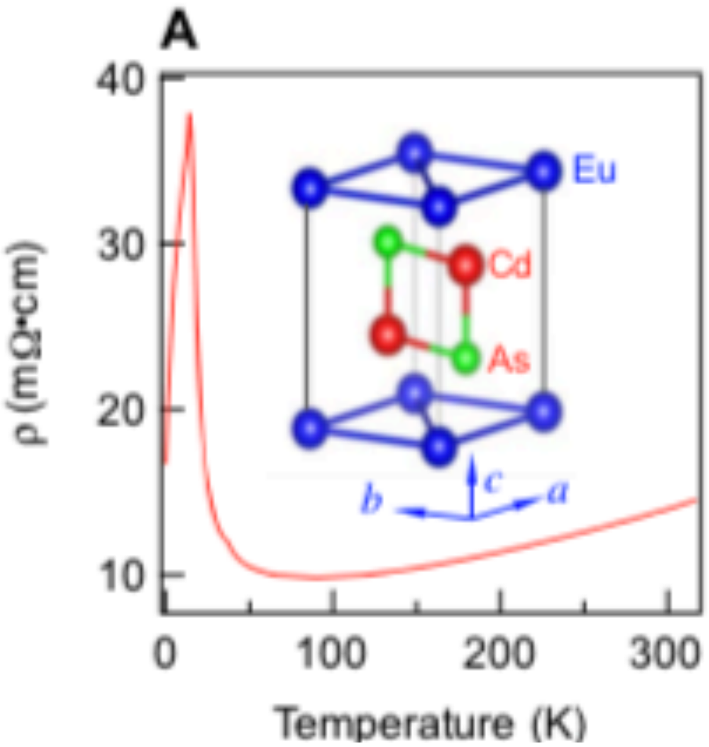
$$\mathcal{J}_{\mathrm{eff}} = 80\ \mathrm{meV}$$

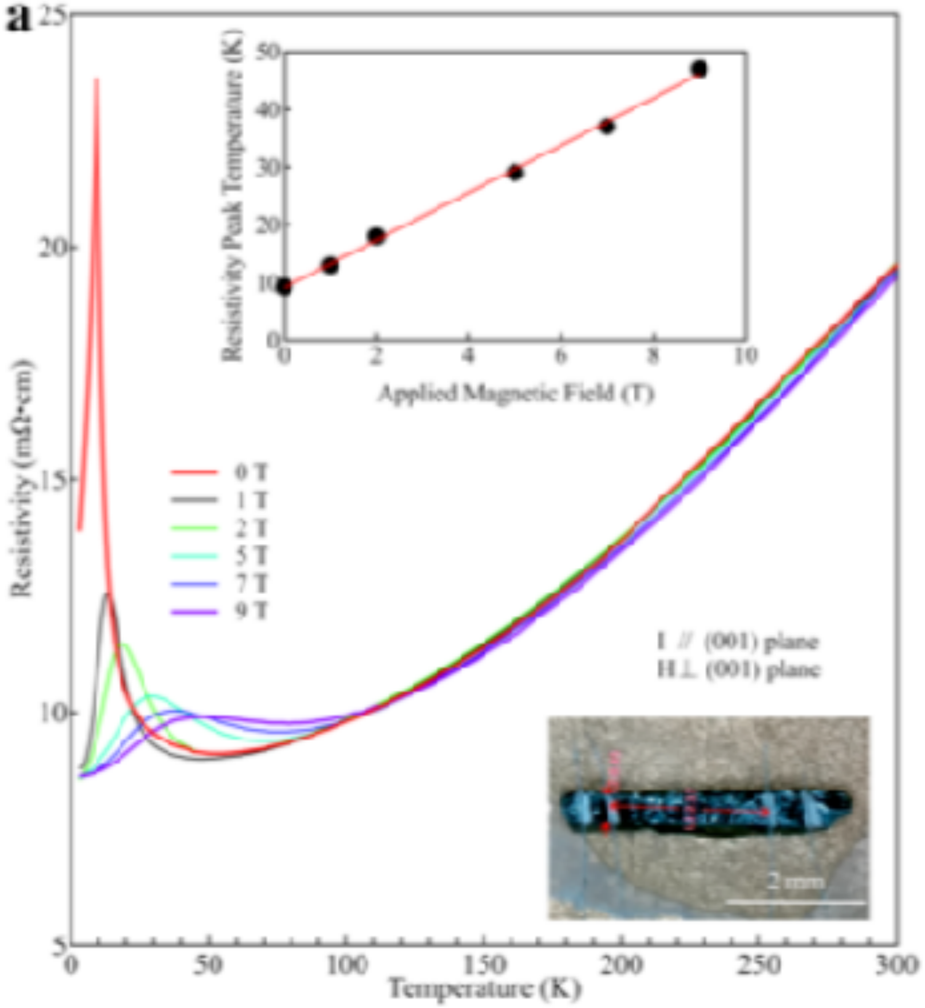
D. Santos-Cottin, … T. Dietl, M. Orlita, AA, arXiv:2301.08014 (2023)

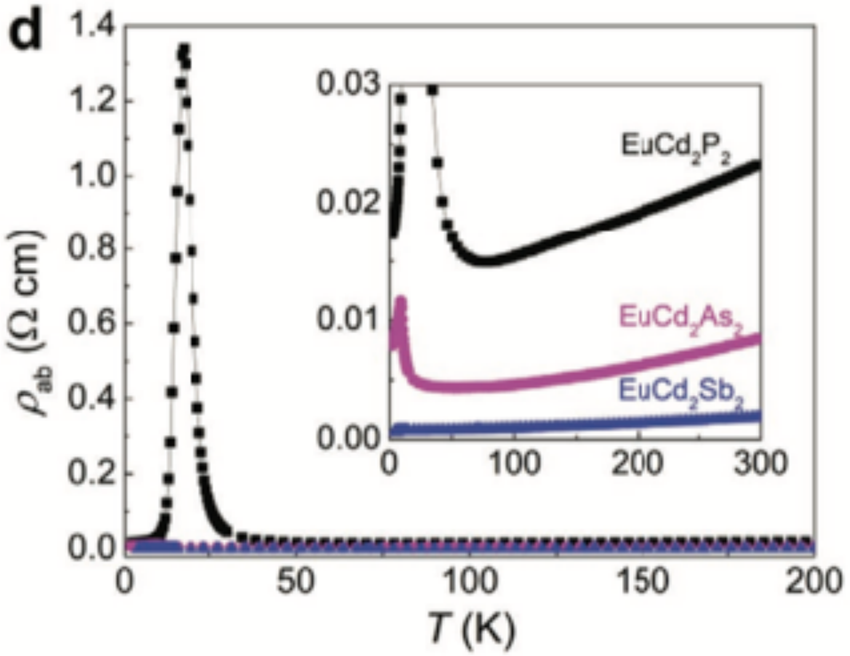
Exchange coupling dictates band structure

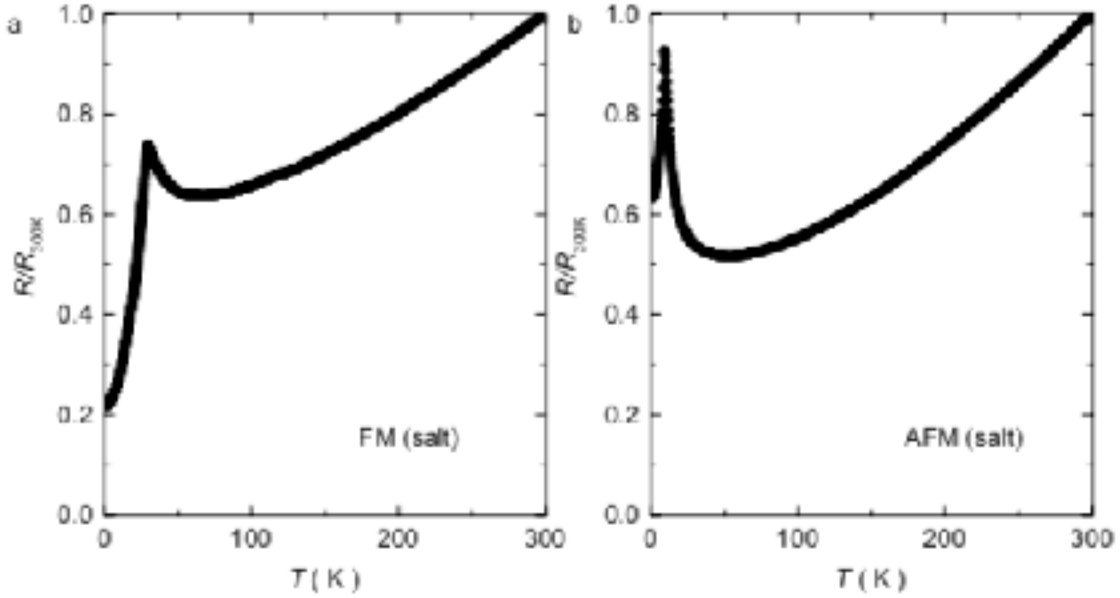
Local Eu magnetism strongly influences the band gap.

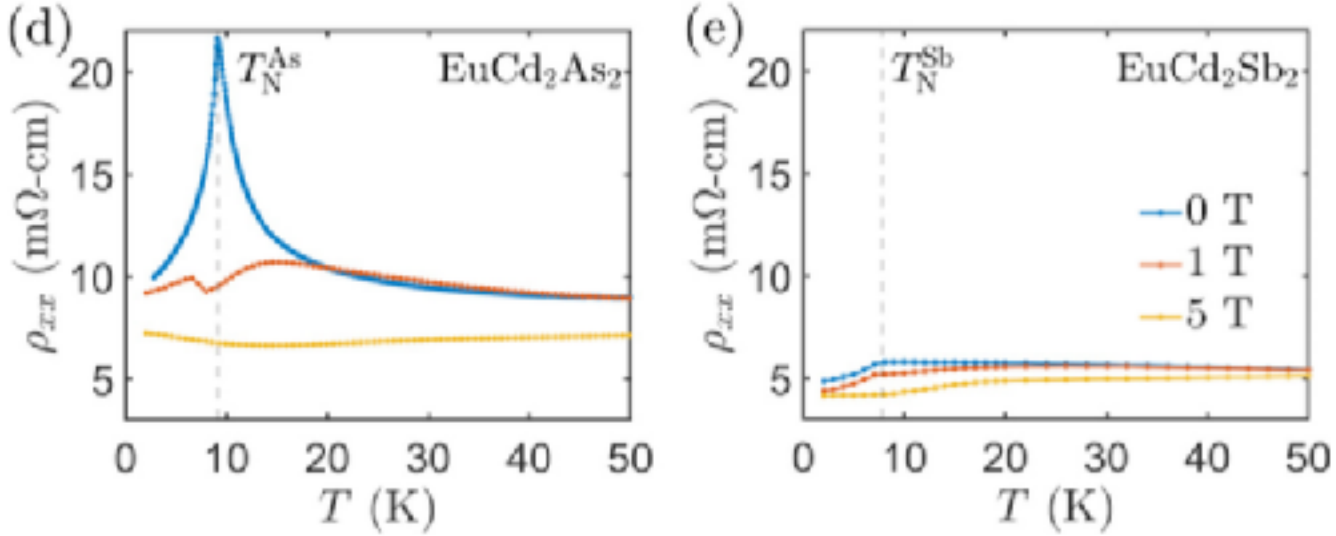
What about transport?











Conclusions

$EuCd_2As_2$ is a semiconductor with a 0.8 eV gap.

Clean samples are insulating.

The band structure is remarkably sensitive to magnetic fields.

Probably no topology involved.