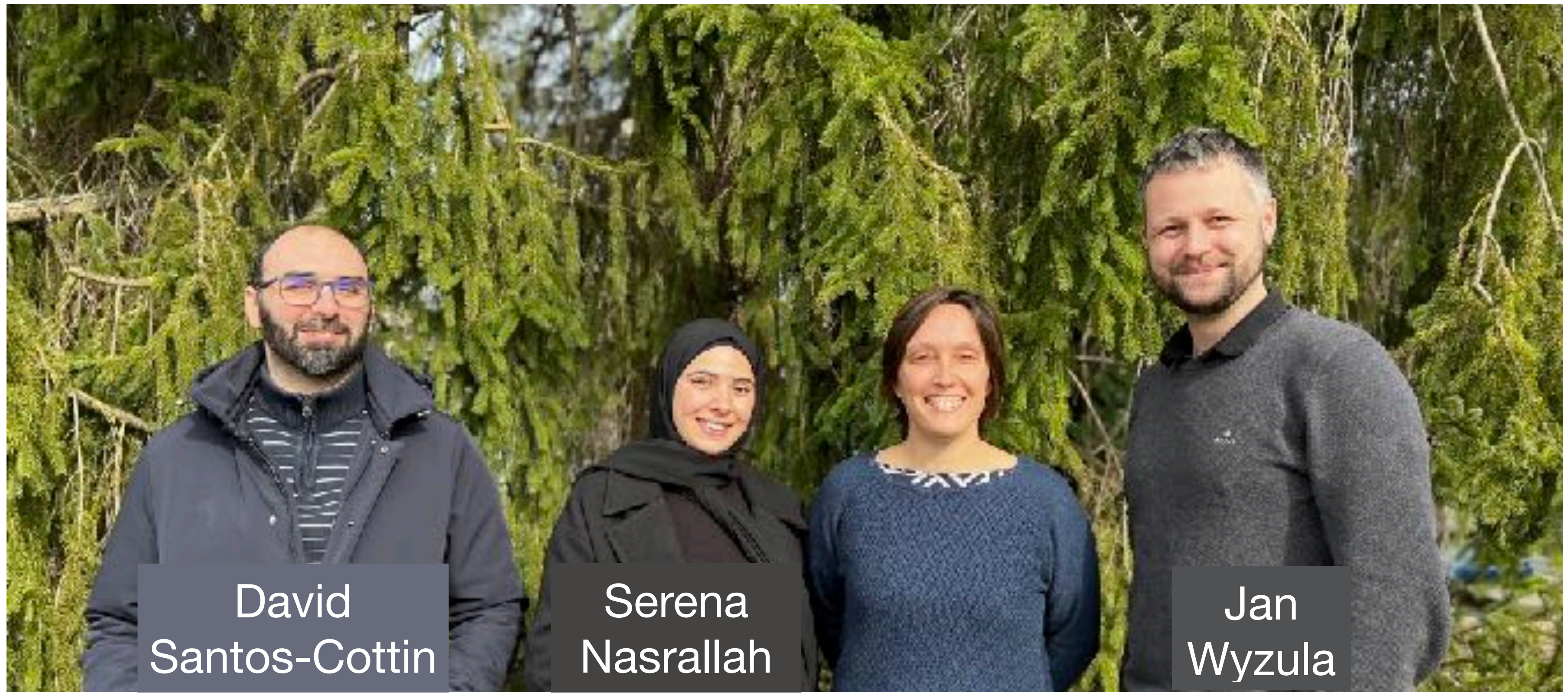
Interplay of magnetism and band structure in $EuCd_2As_2$

Ana Akrap, University of Fribourg, Switzerland

March 3, 2023

Light Fermion Spectroscopy & Collaborators



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Jiri Novak

Uni Paris Sud
Mark O. Goerbig

ABB
Edoardo Martino

Stanford Uni
Megan Loh

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)

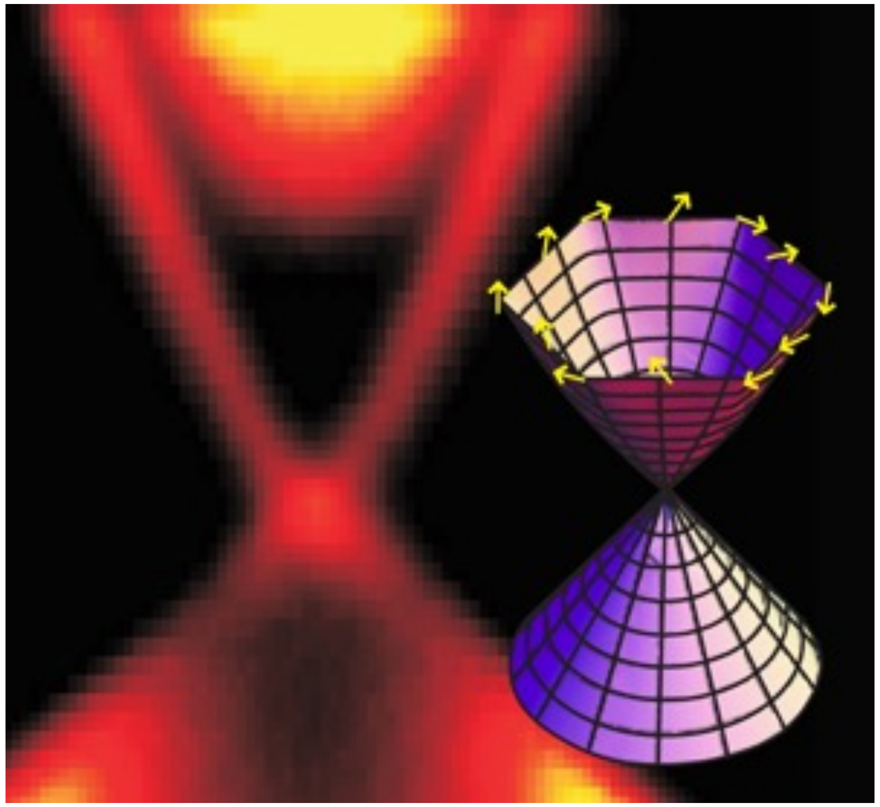
2016: Nodal line/loop Dirac semimetals

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

2019: Multifold massless electrons

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

2023: …



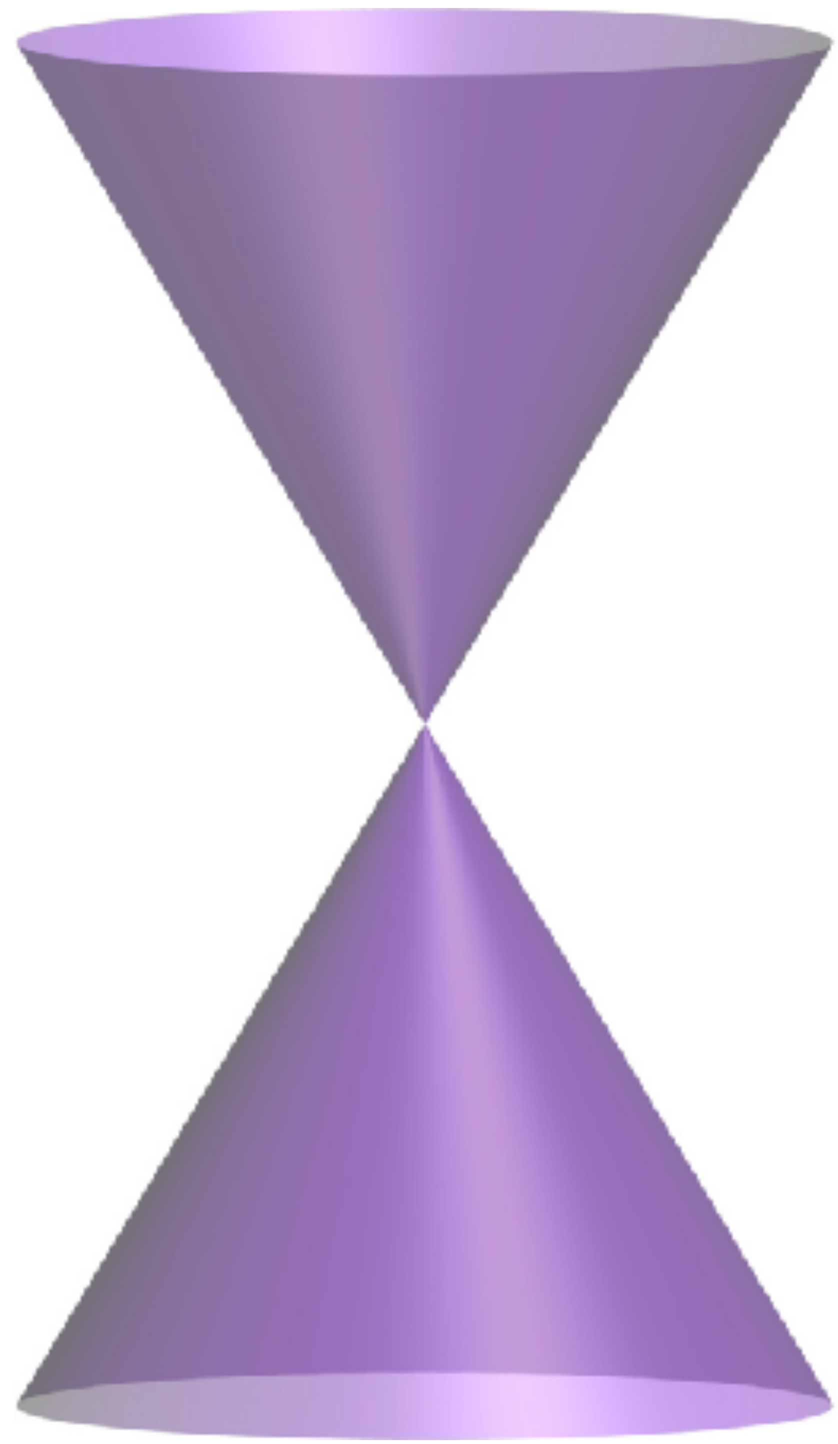
M. Z. Hasan and C. L. Kane, RMP 82, 3045 (2010)

Topological semimetals

conical bands

small energy scales

can be tuned externally

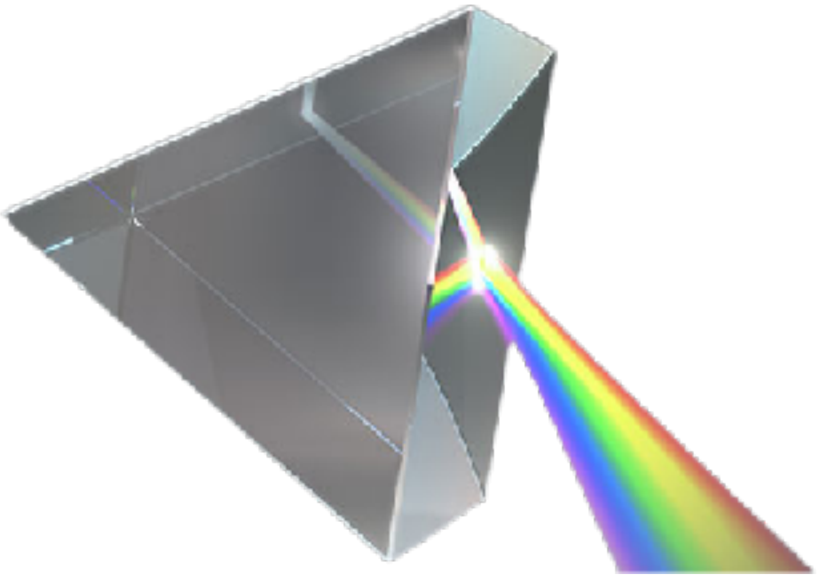


exotic quasiparticles: eg Weyl fermions

can be coupled to magnetism

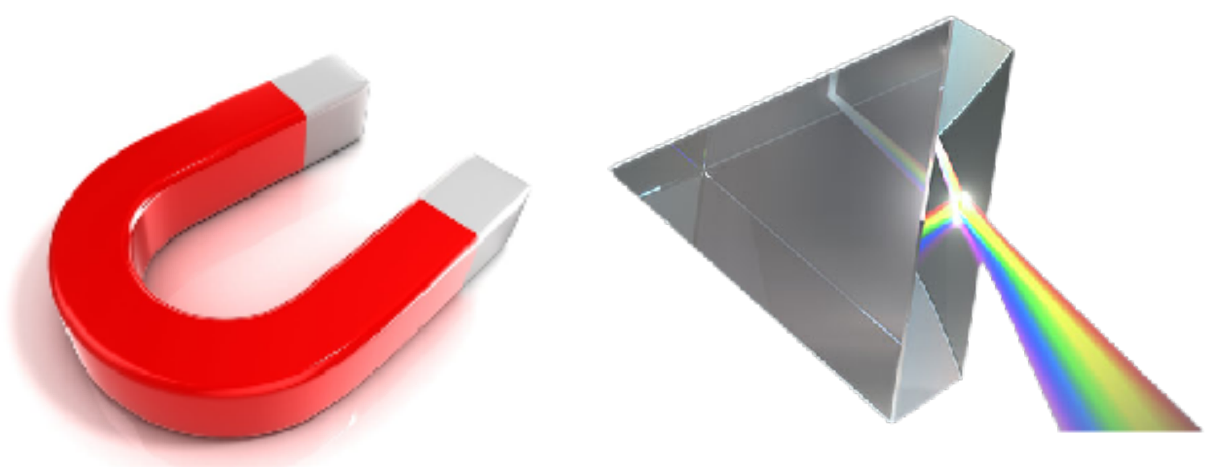
correlations

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.

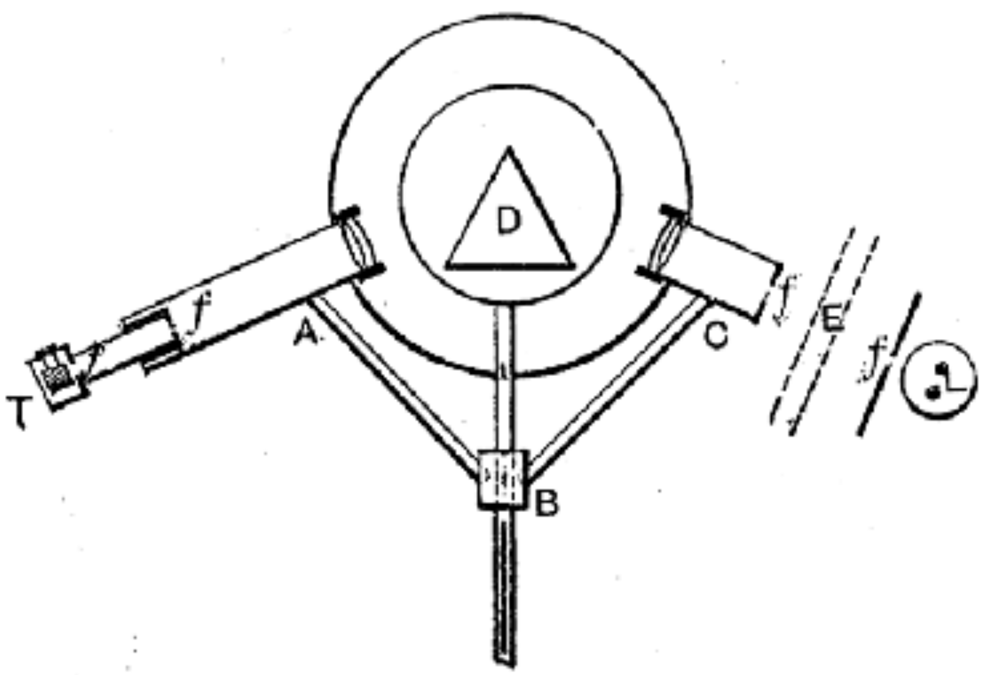
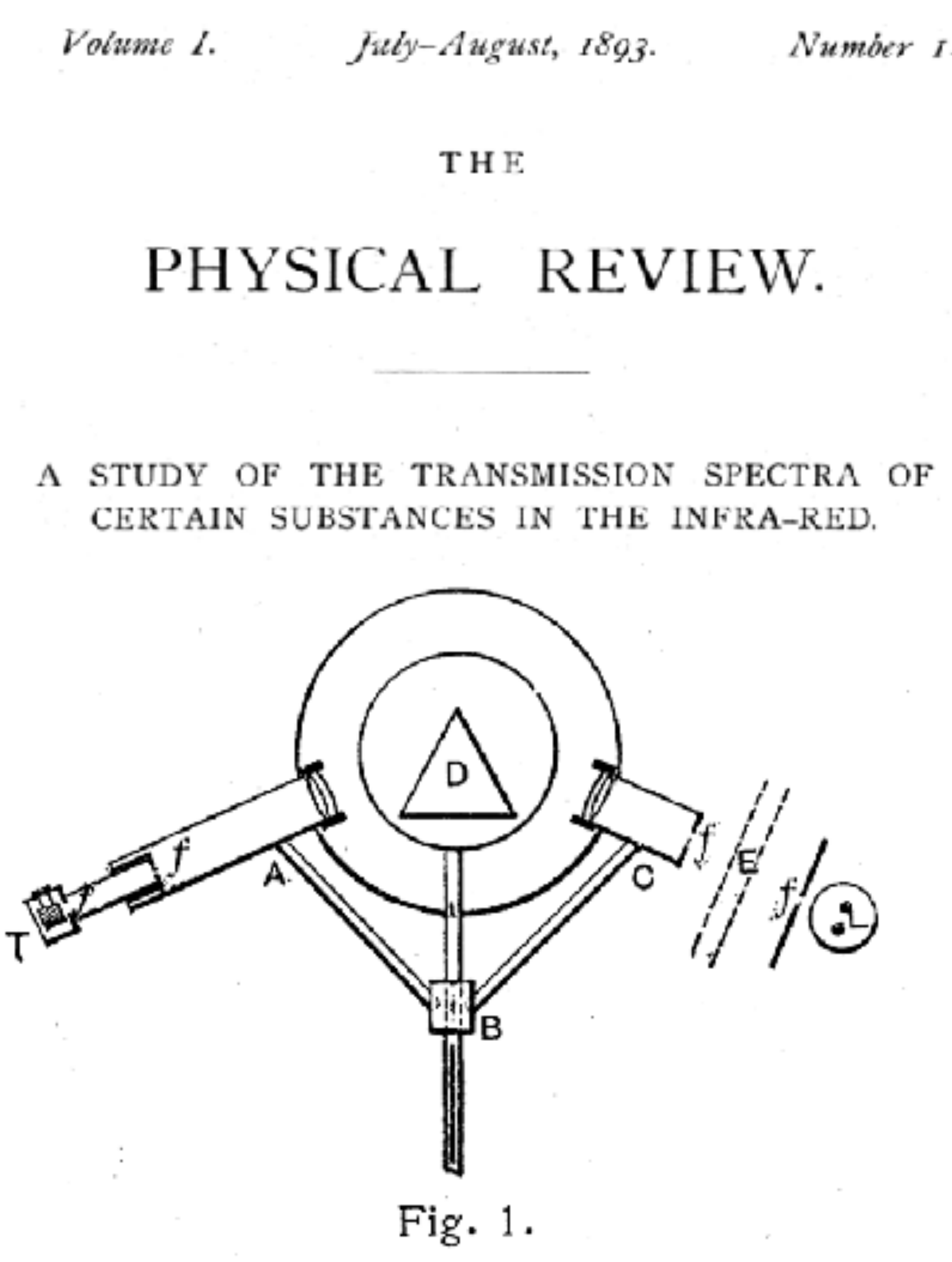


Fig. 1.

Physical Review 1, 1 (1893)

Infrared spectroscopy


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

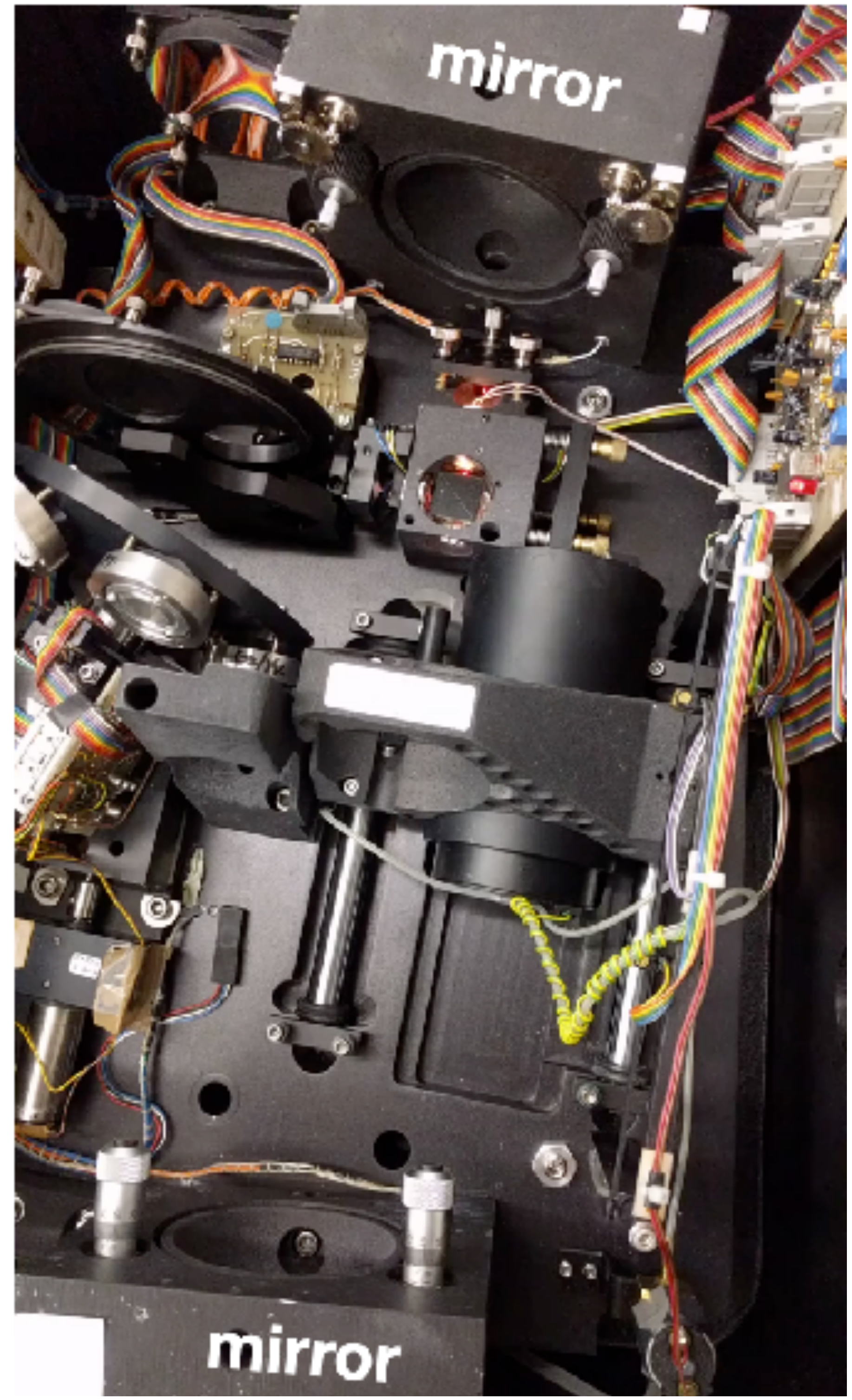
THE

PHYSICAL REVIEW.

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

Fig. 1.

Physical Review 1, 1 (1893)



Interferometer inside a Bruker 113v

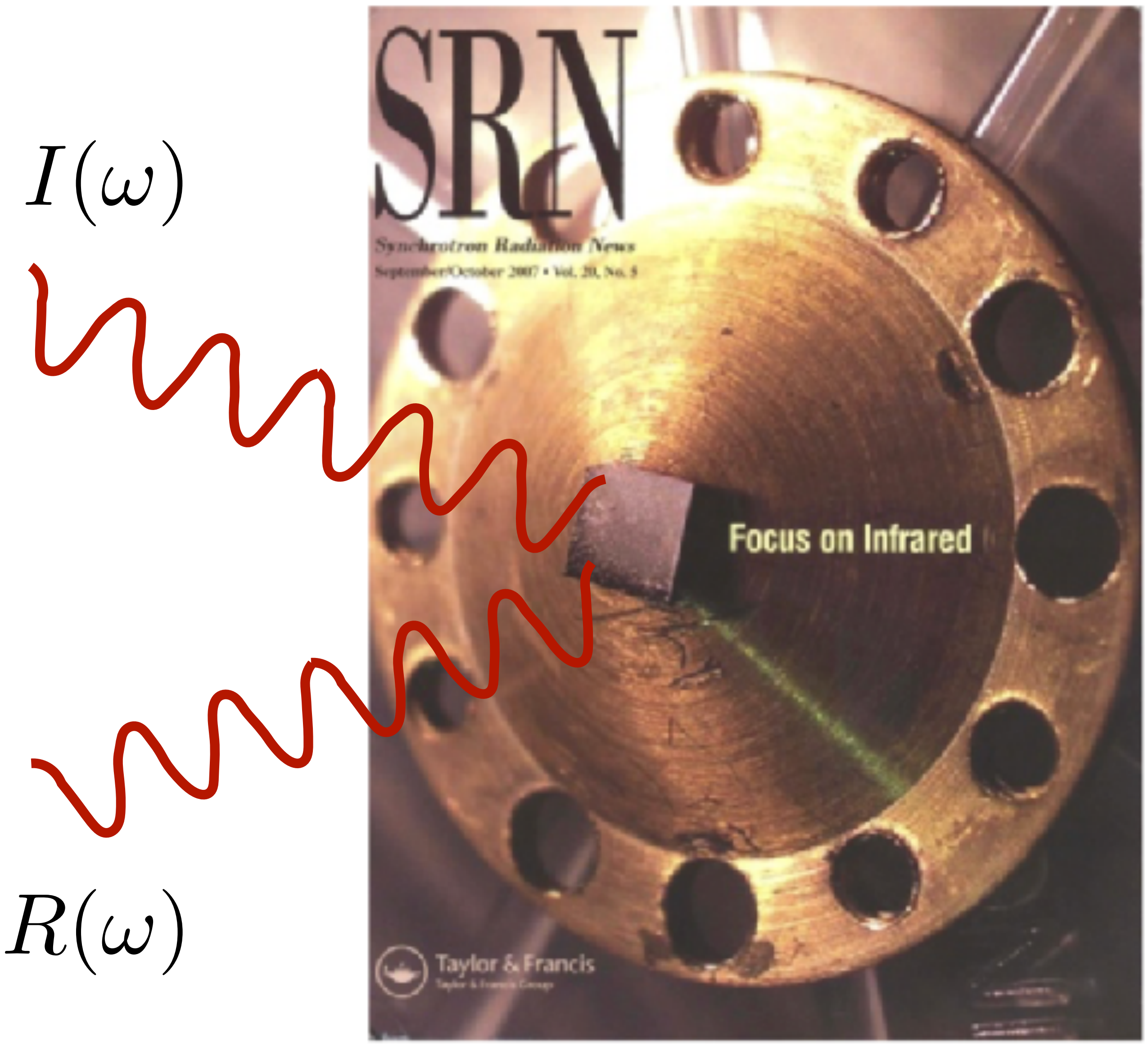
Infrared spectroscopy

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

Kramers-Kronig relations

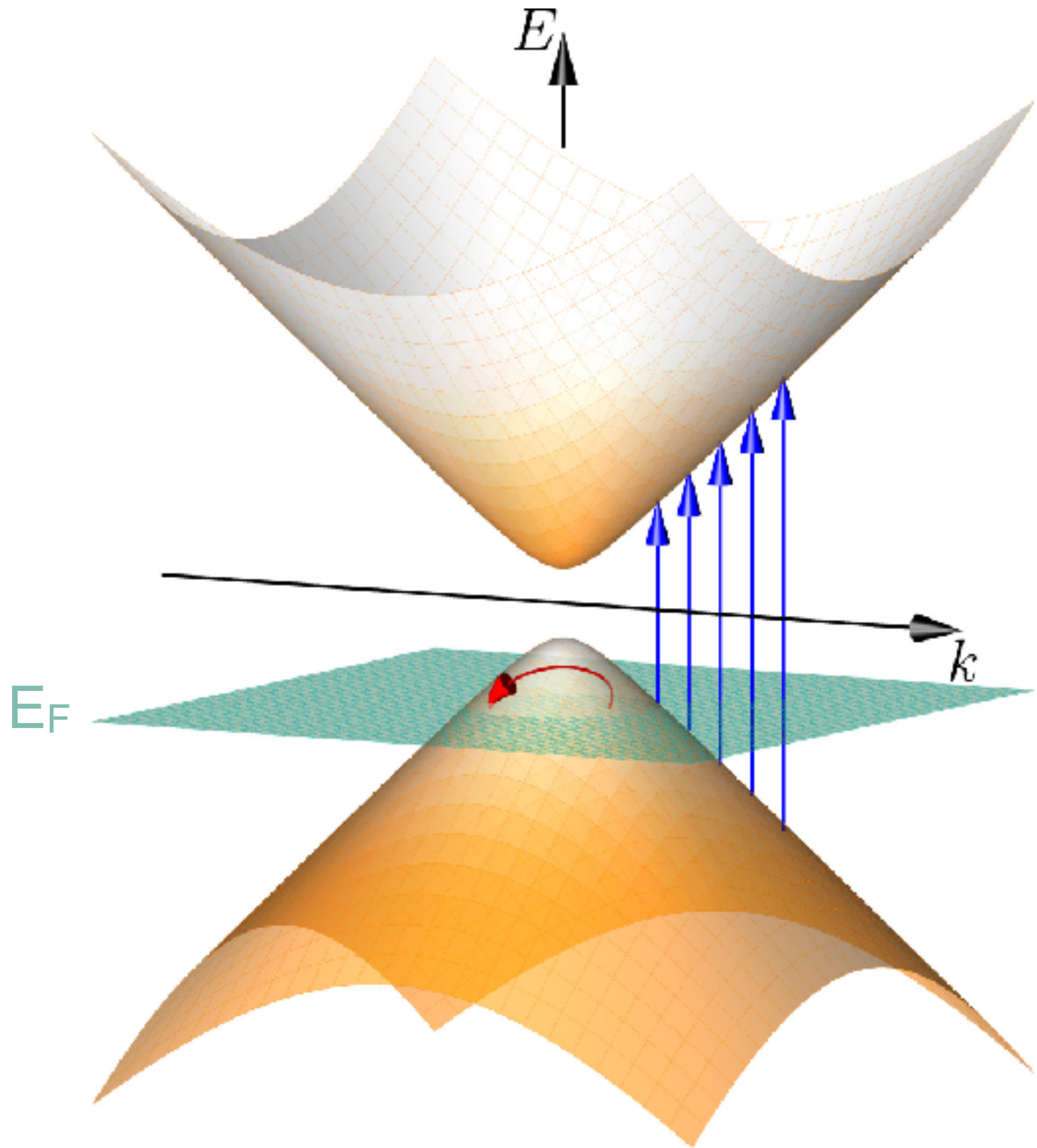
Complex optical conductivity

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



Chris Homes

Optical conductivity tells about jDOS



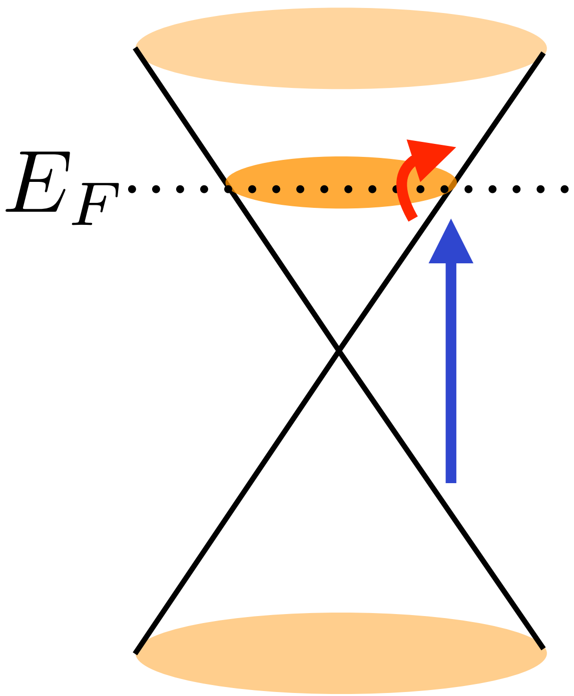
intraband (Drude)

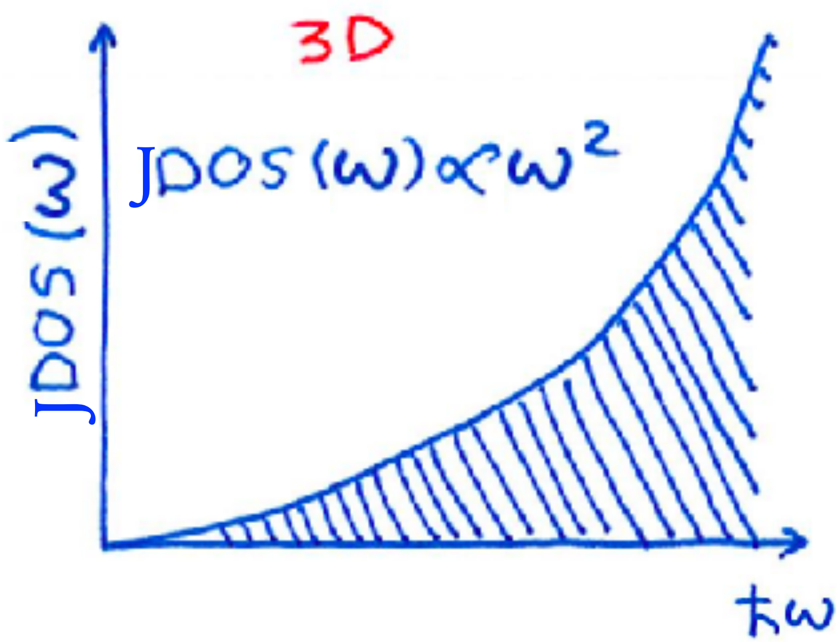
interband excitations

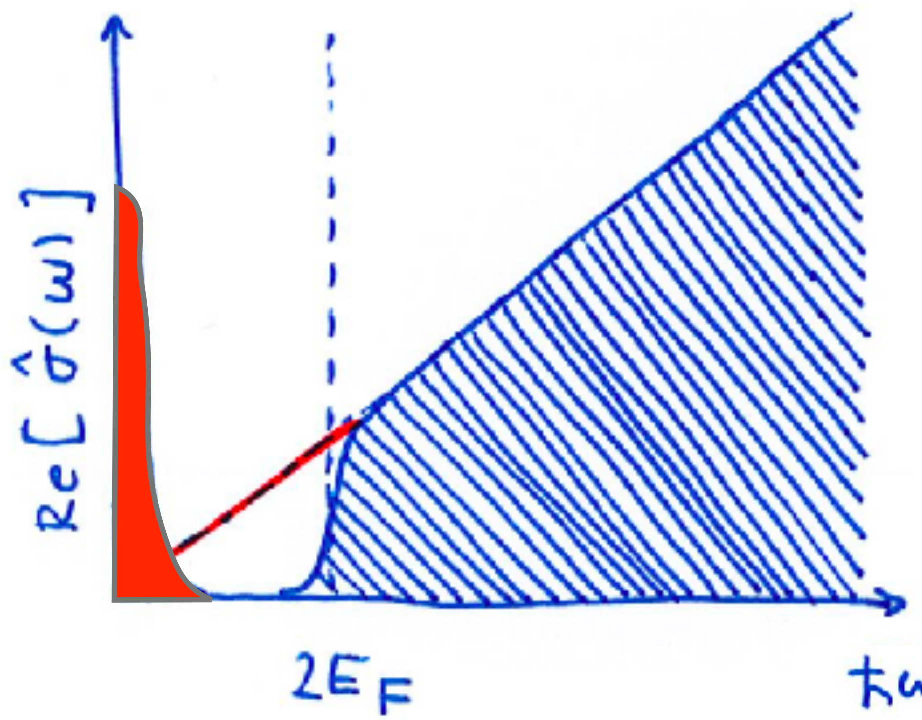
Florian Le Mardelé

Optical conductivity tells about jDOS

3D linear bands





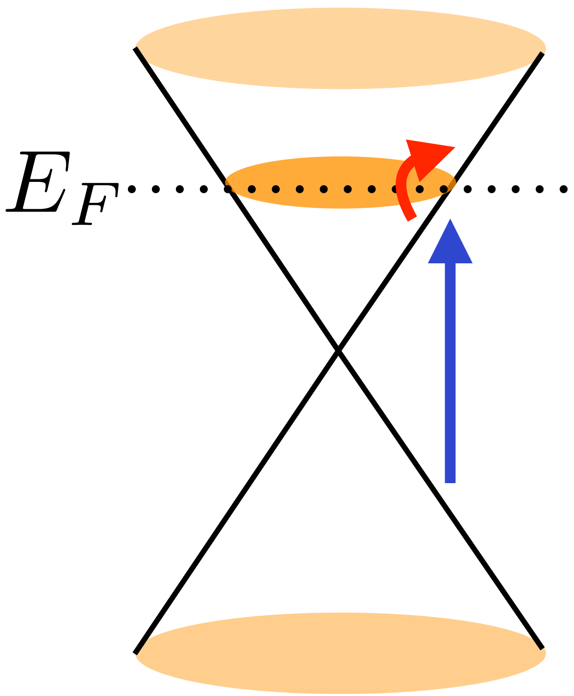


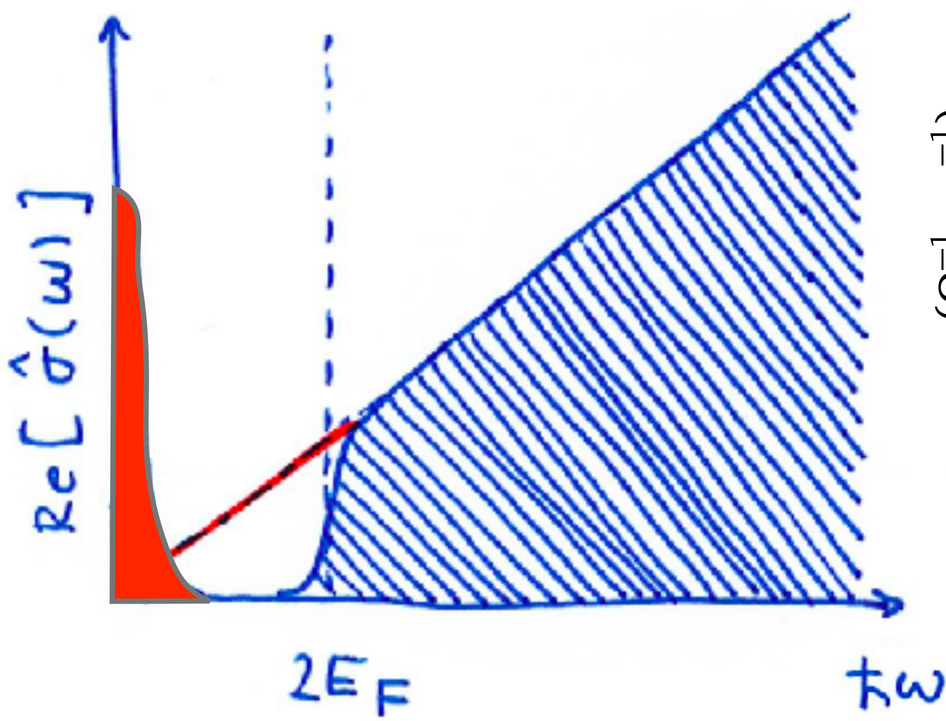
$$\sigma_1(\omega) \propto \frac{jDOS}{\omega}$$

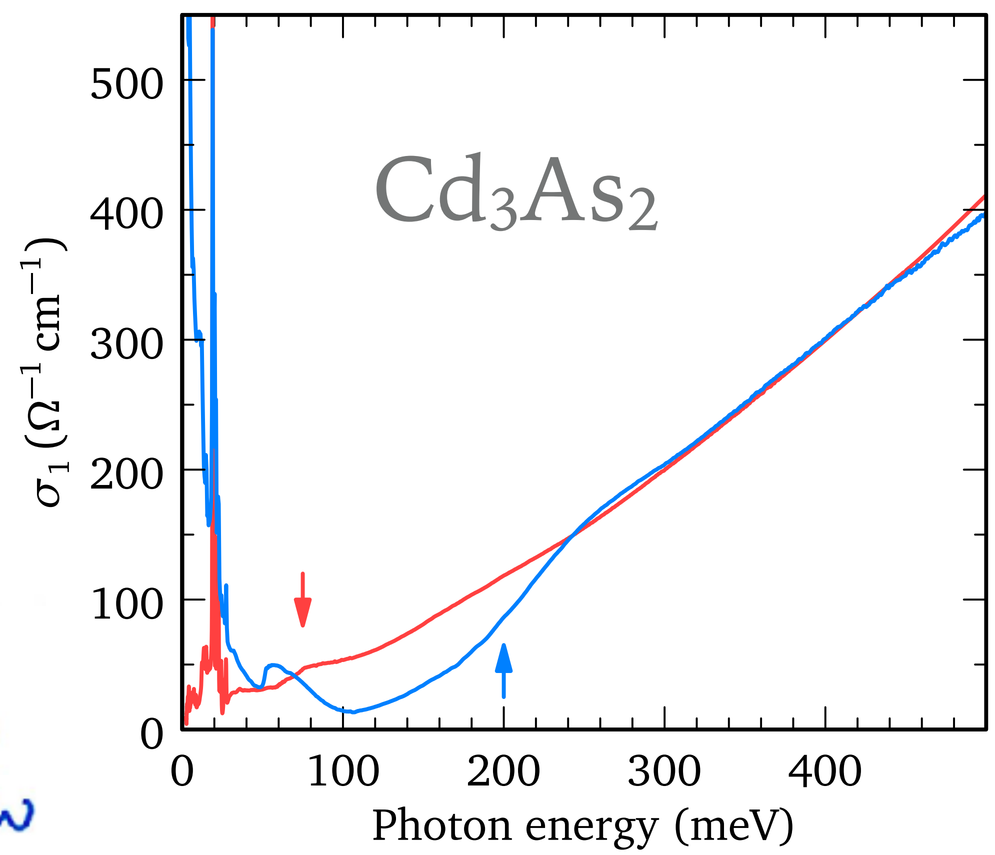
$$JDOS(\omega) = \frac{1}{V} \sum_{k,\sigma} \delta(\hbar\omega - (\epsilon_2 - \epsilon_1))$$

Optical conductivity tells about jDOS

3D linear bands



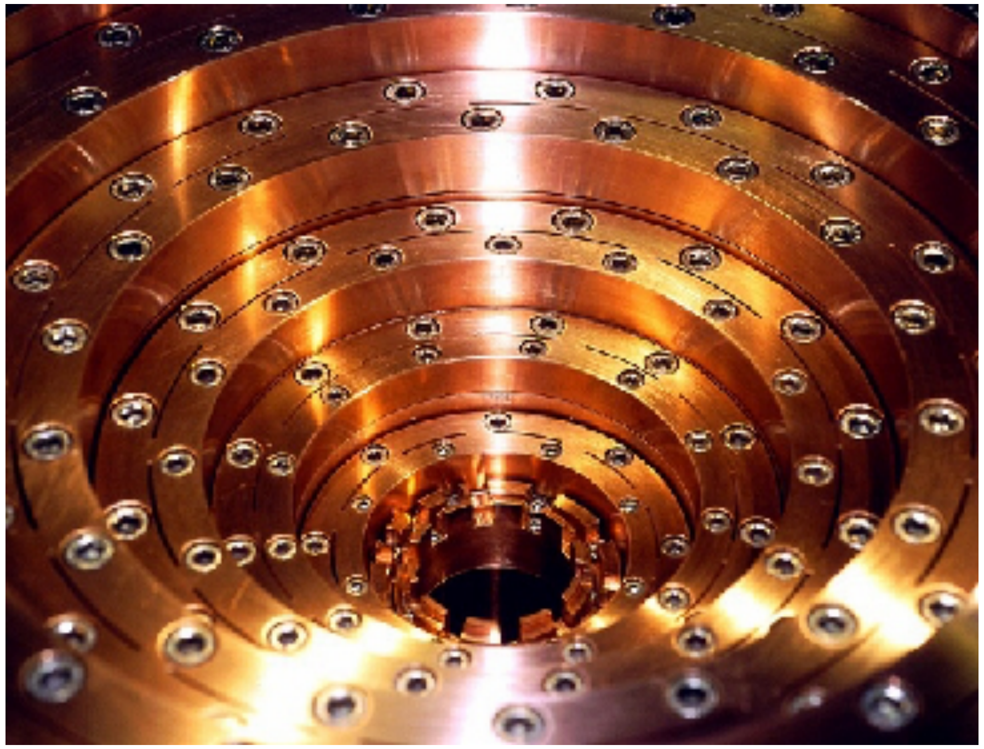




$$\sigma_1(\omega) \propto \frac{jDOS}{\omega}$$

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

Also in high magnetic fields

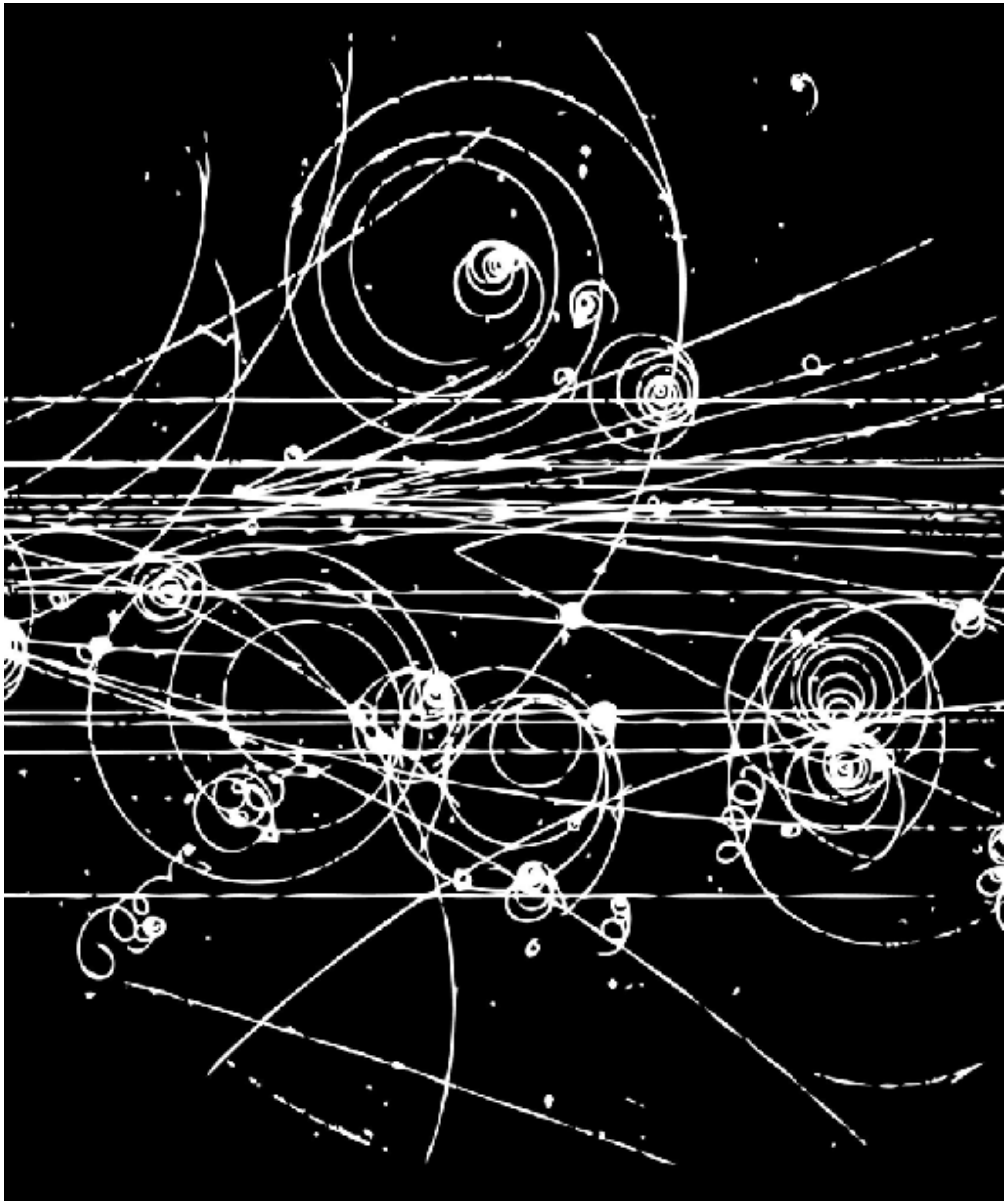


14’000 amps through
4 copper alloy coils

25 MW for 36 T
static magnetic field

LNCMI Grenoble

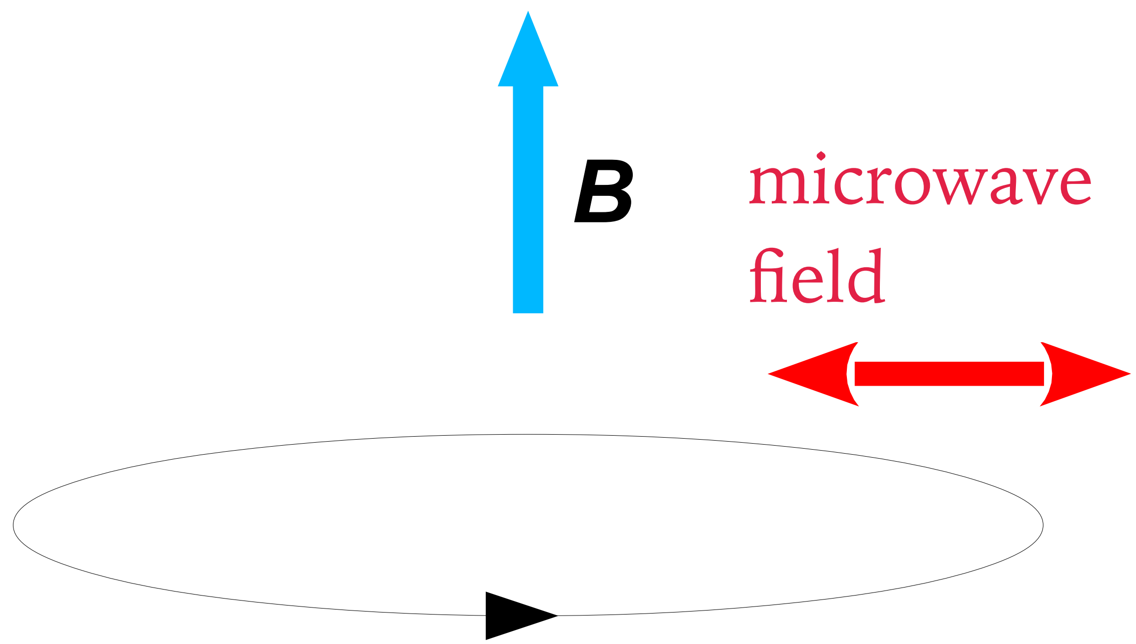
Cyclotron motion



CERN bubble chamber (1960)

Cyclotron resonance

Classical picture

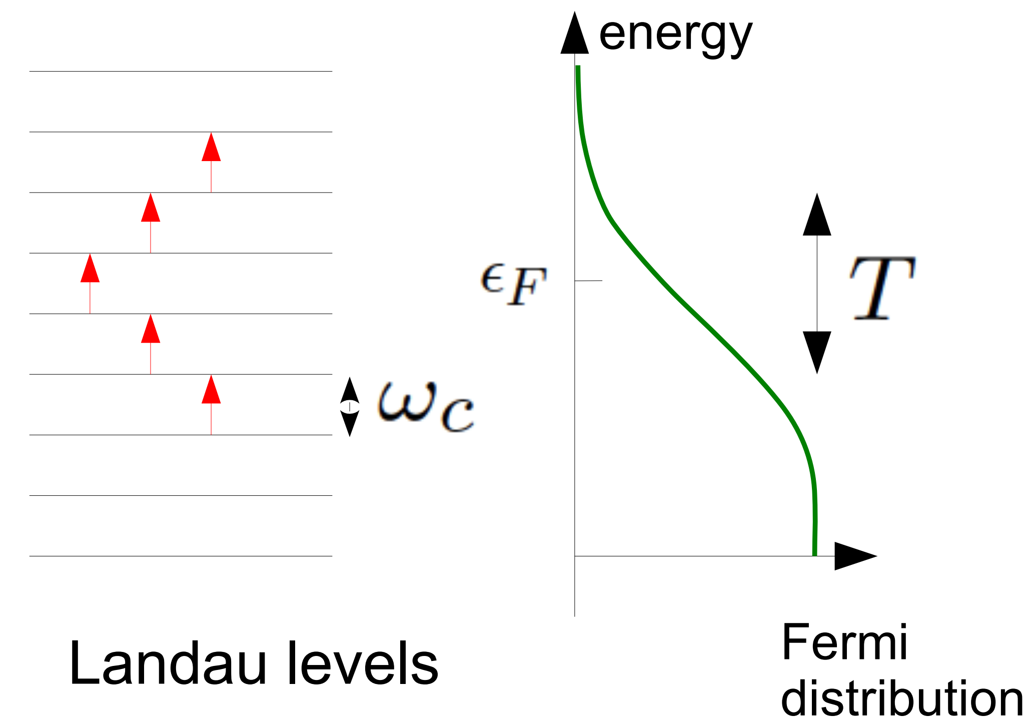


$$\frac{d\mathbf{p}}{dt} = \frac{e}{c}\left[\mathbf{v} \times \mathbf{B}\right] + \mathbf{F}_0 \cos \omega t$$

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

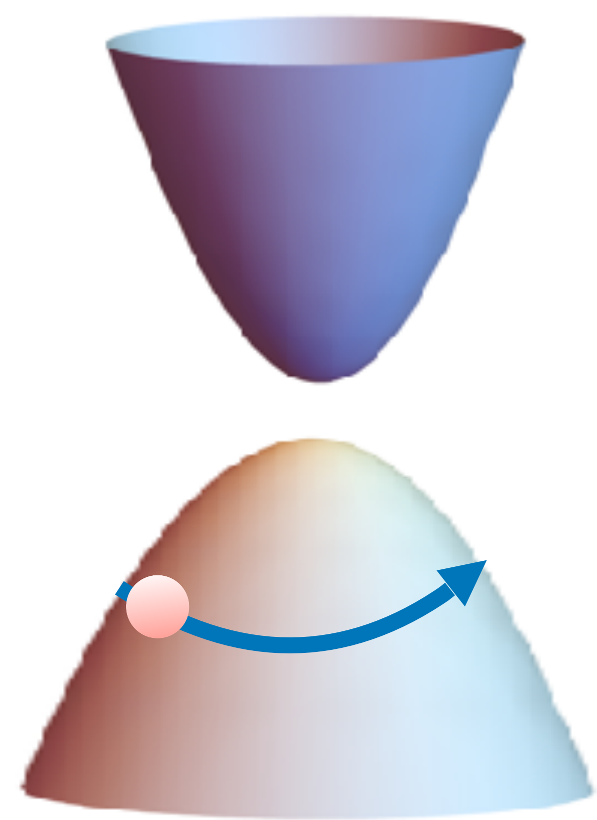
Denis M. Basko

Observation of Cyclotron Resonance in Germanium Crystals*

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

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

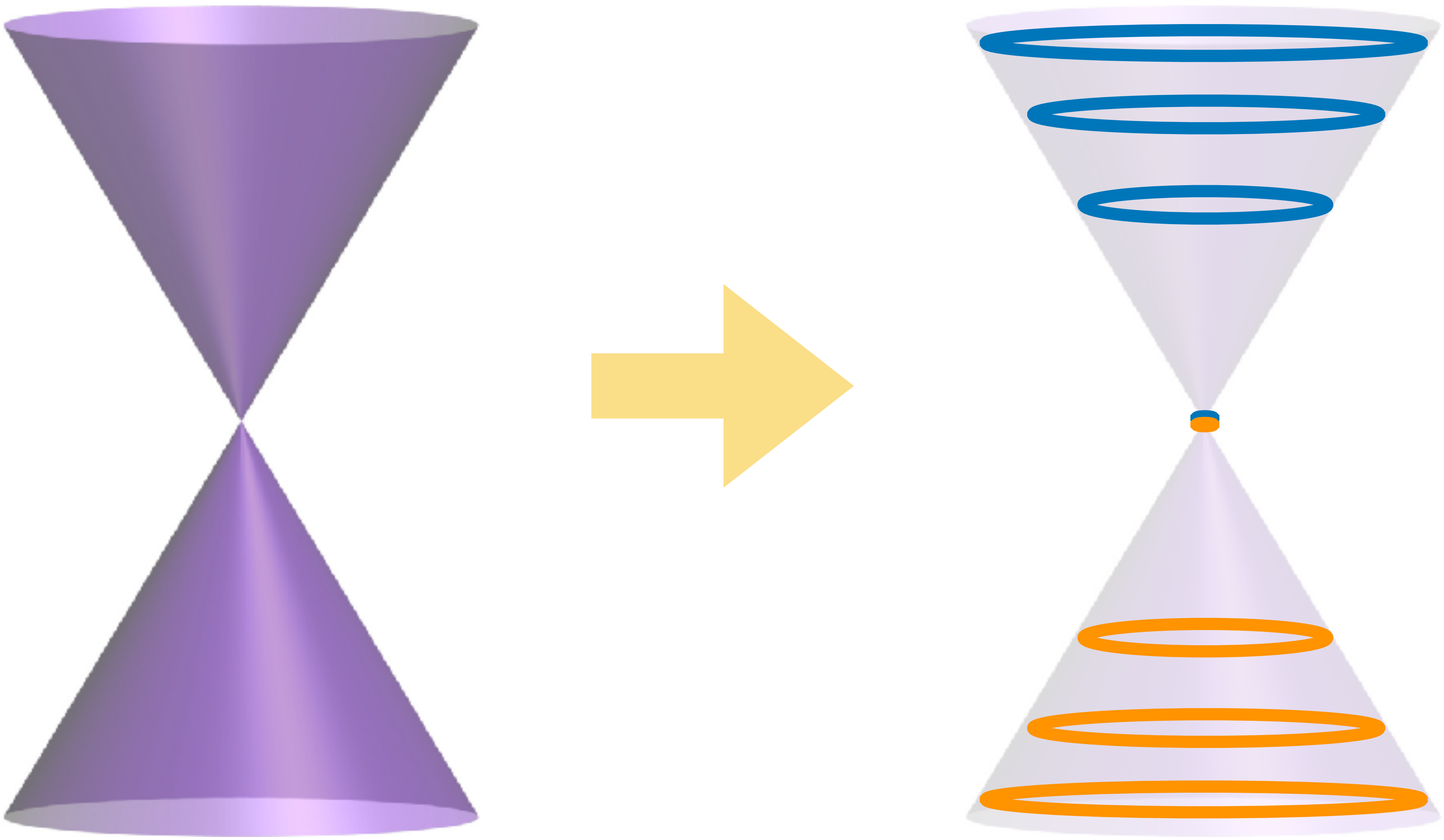
where m^* is the appropriate effective mass; thus the experiment determines the effective mass directly.



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

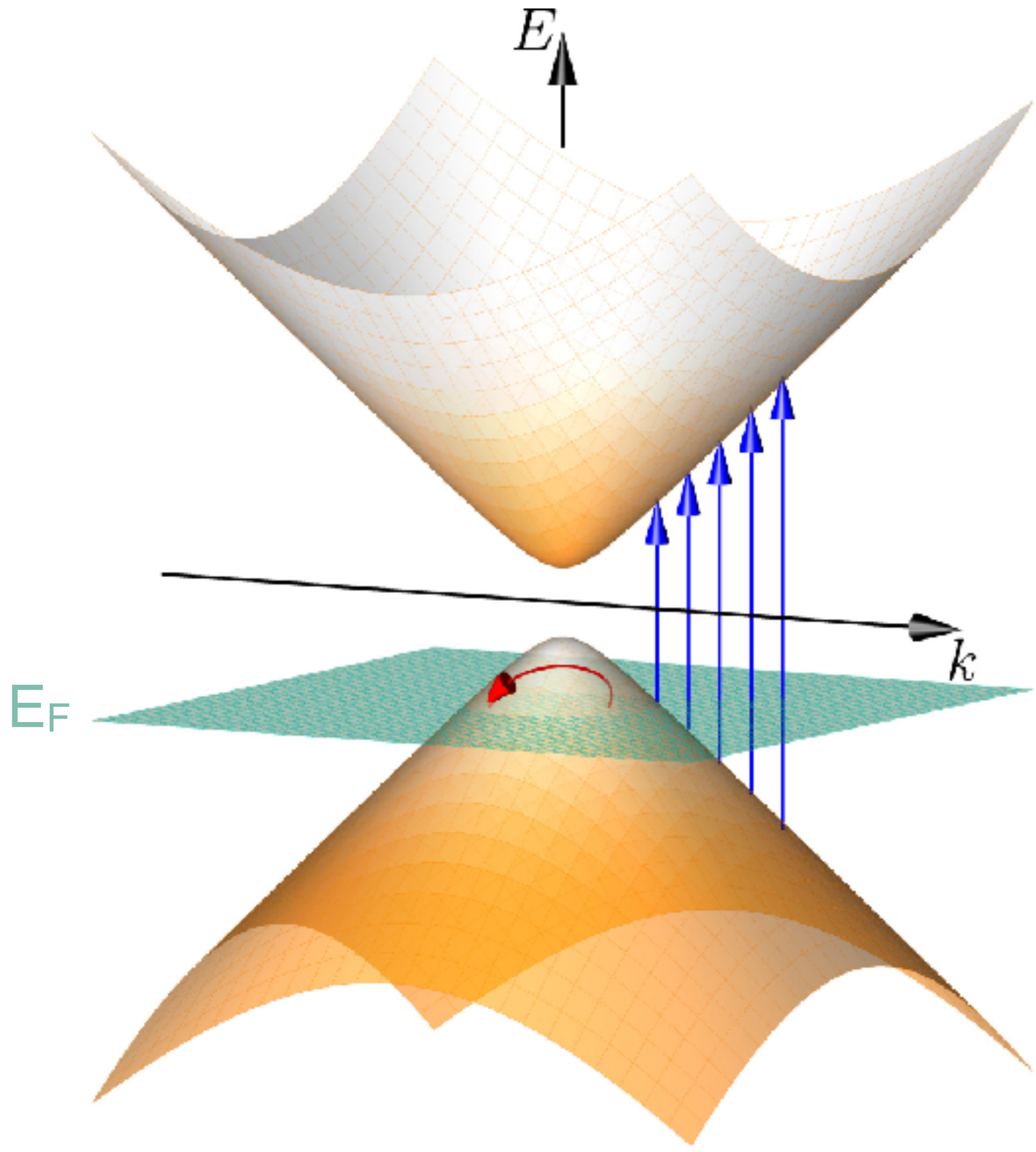
M.L. Cohen, AIP Conference Proceedings 772, 3 (2005).

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

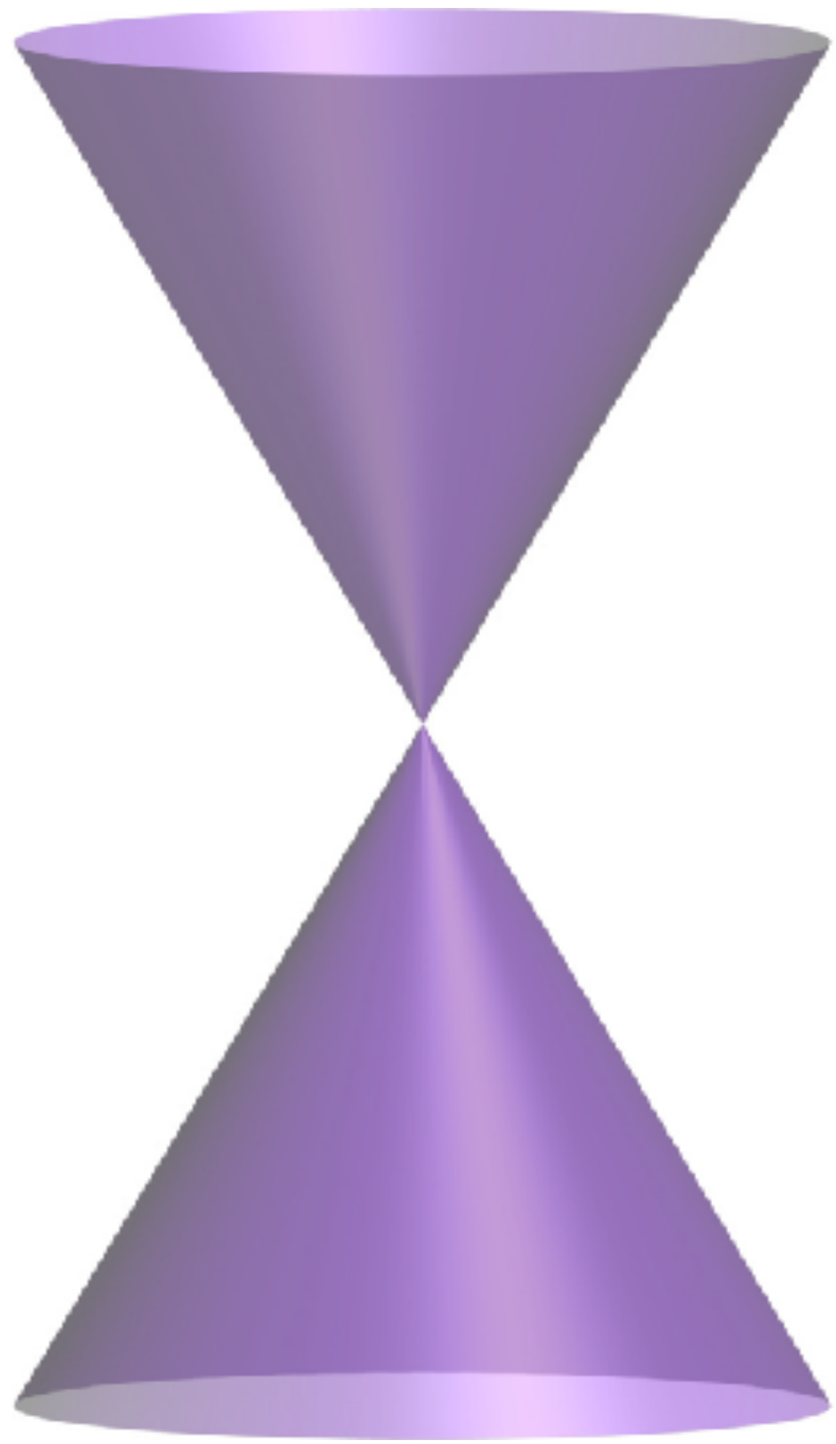
Florian Le Mardelé

Topological semimetals

conical bands

small energy scales

can be tuned externally

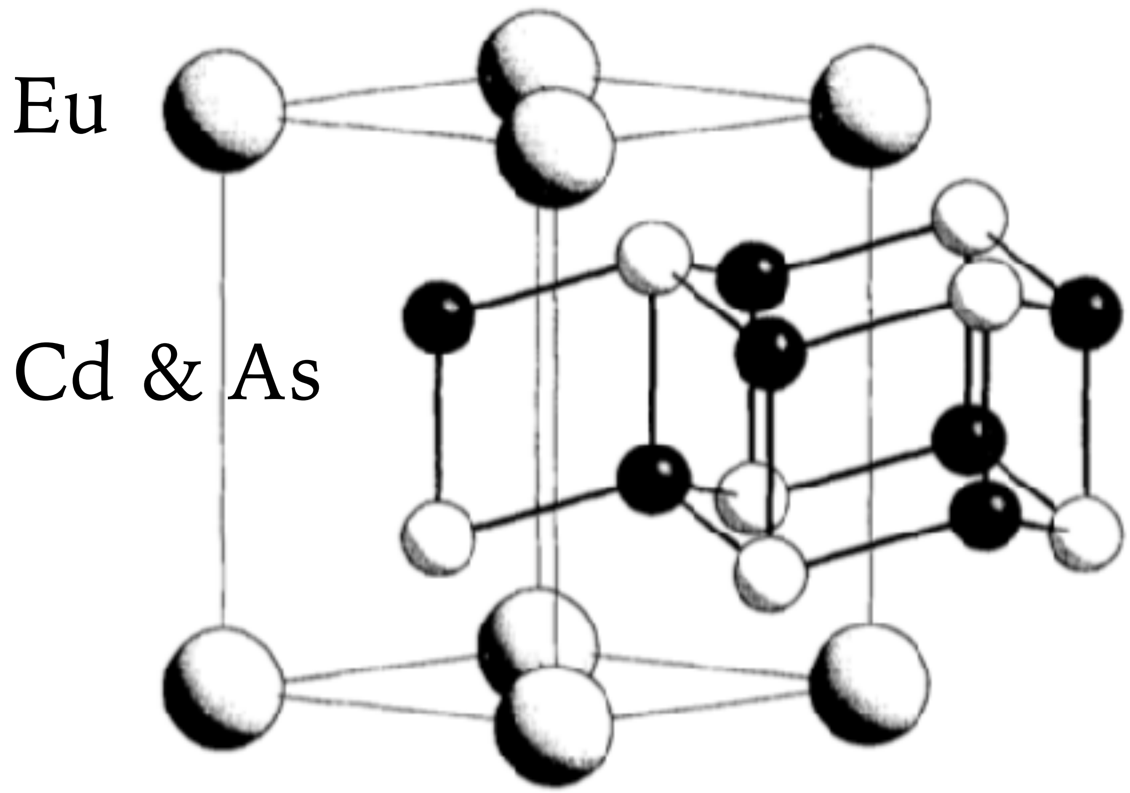


exotic quasiparticles: eg Weyl fermions

can be coupled to magnetism

correlations

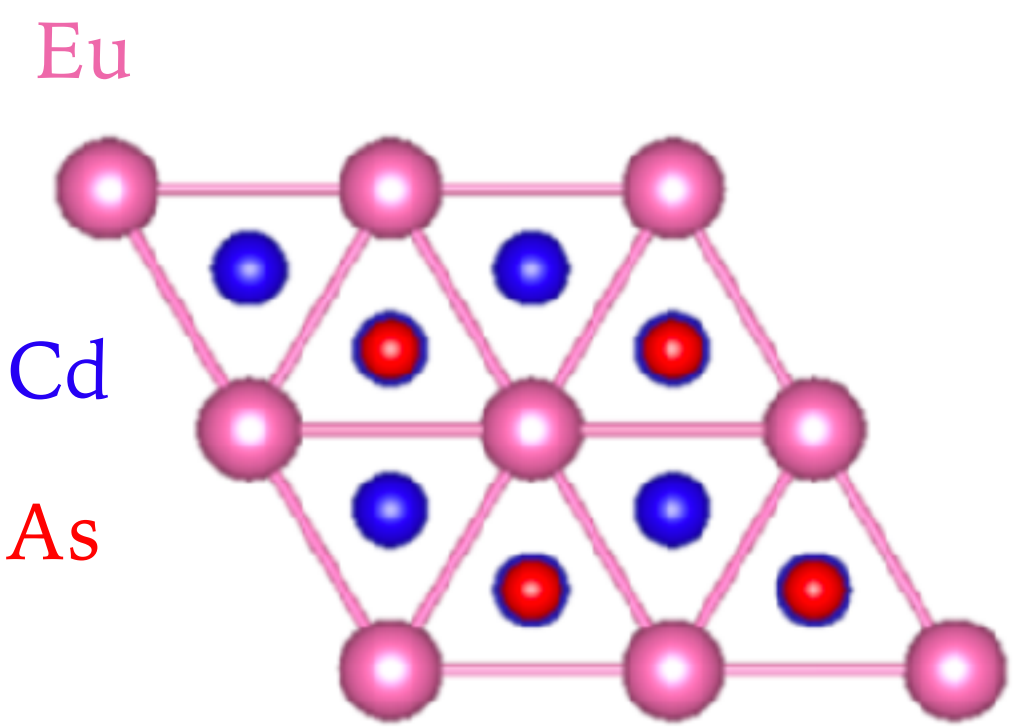
Topological semimetal $EuCd_2As_2$

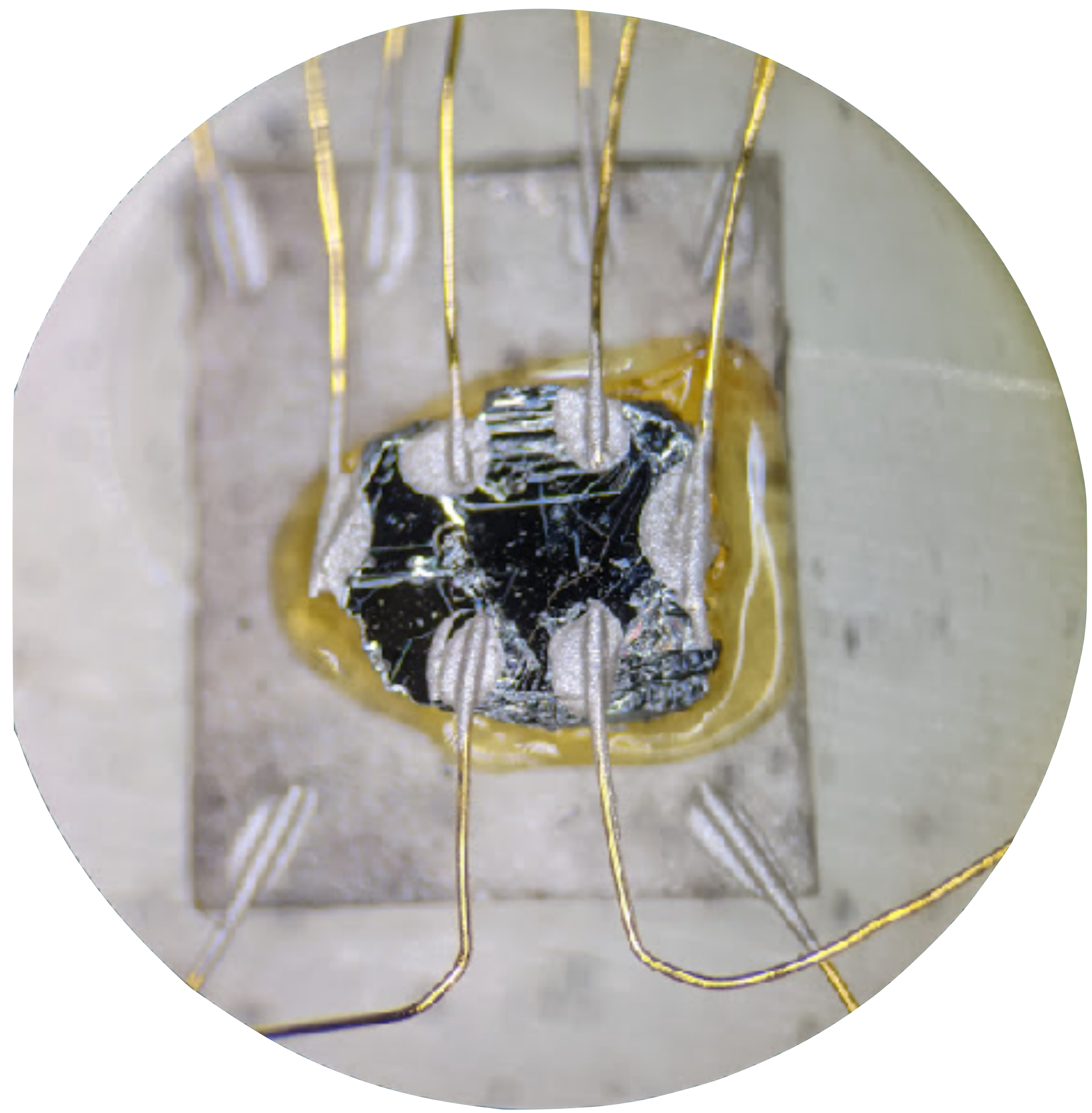


- Eu valence is 2+
  spin state S=7/2
- Néel transition at 9.5 K
- DFT says semimetal
  (U = 5 eV, by hand)

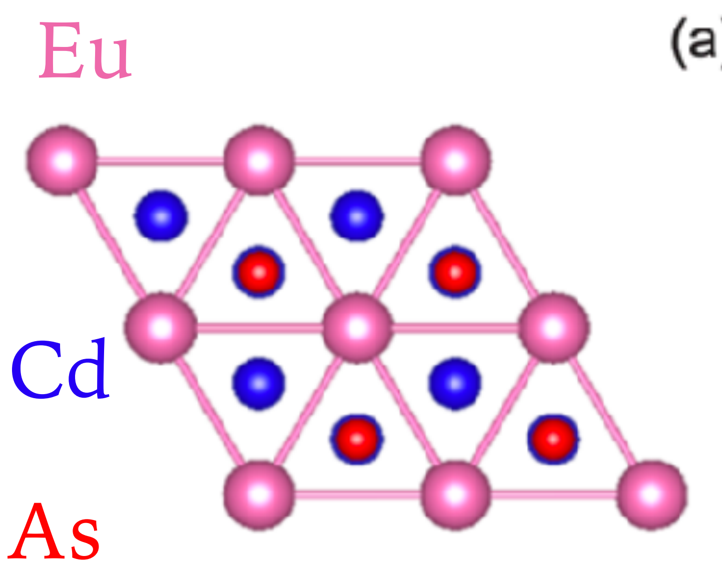
Currently, > 25 papers calling it a "topological semimetal" in their title/abstract.

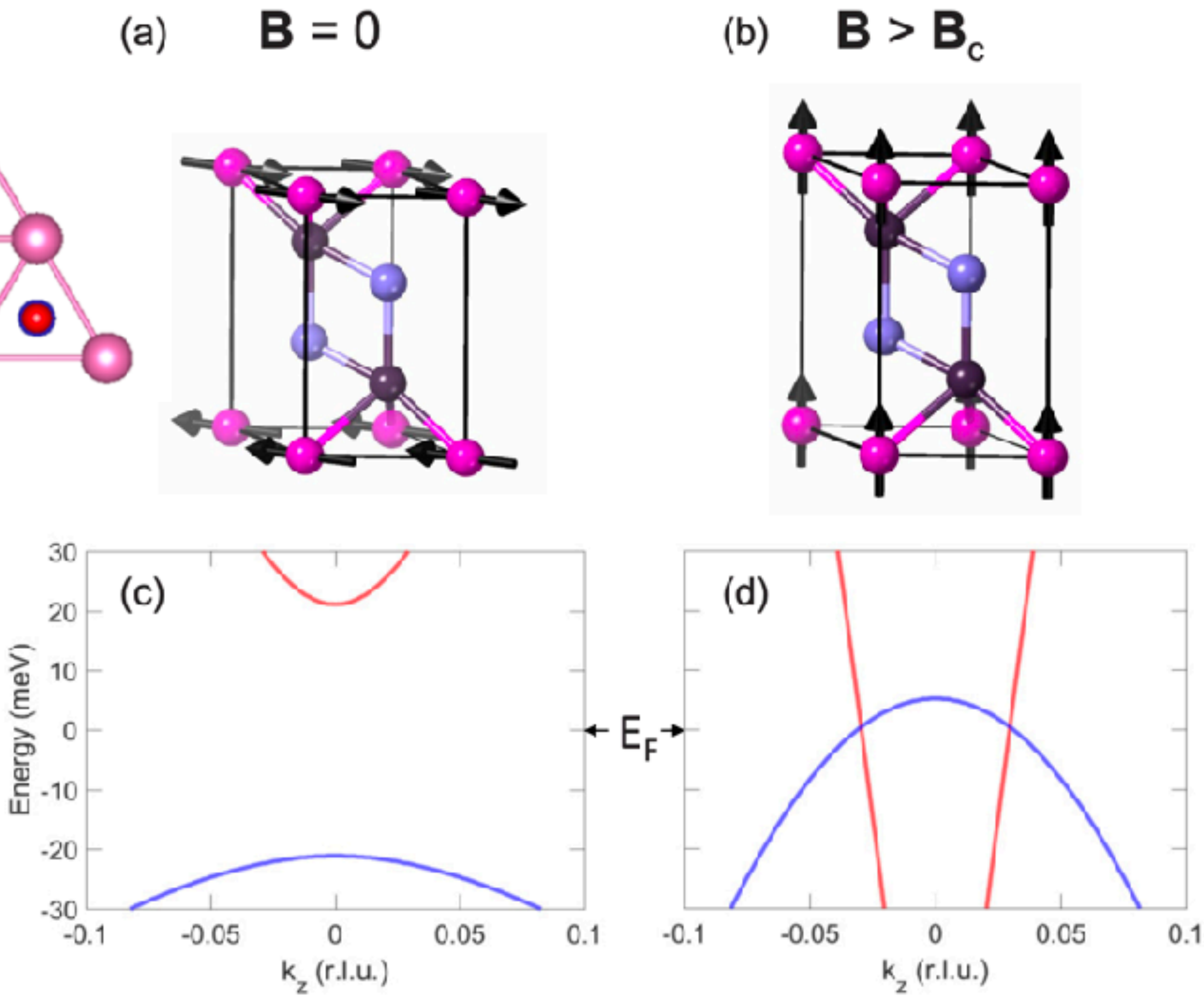
Topological semimetal $EuCd_2As_2$





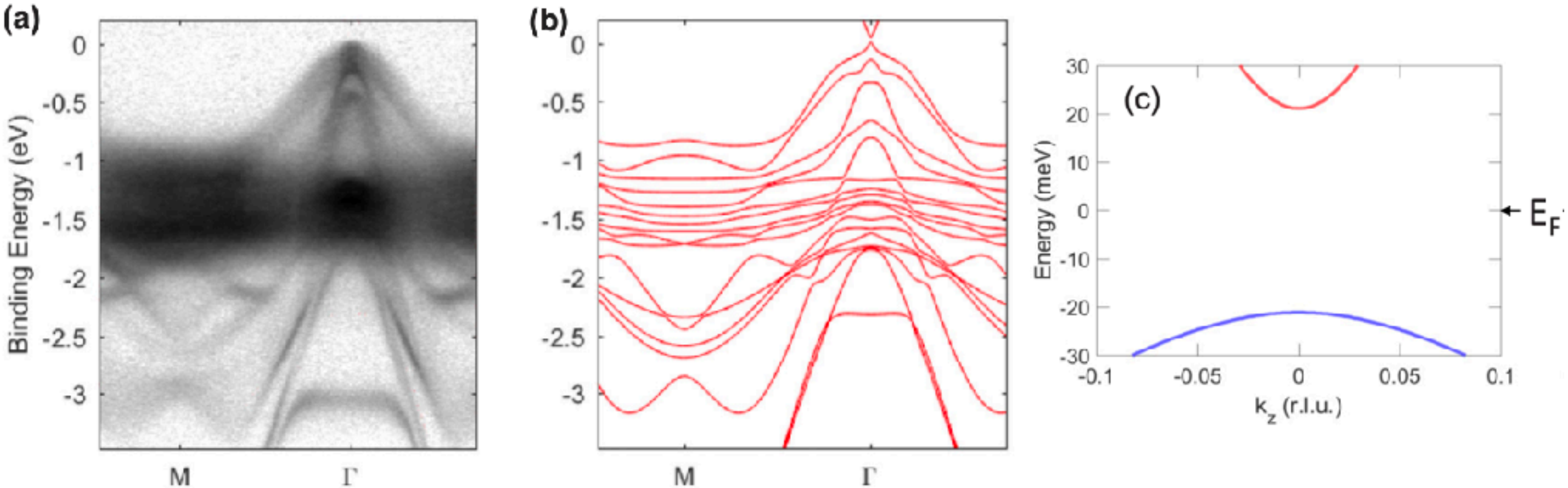
Topological semimetal $EuCd_2As_2$





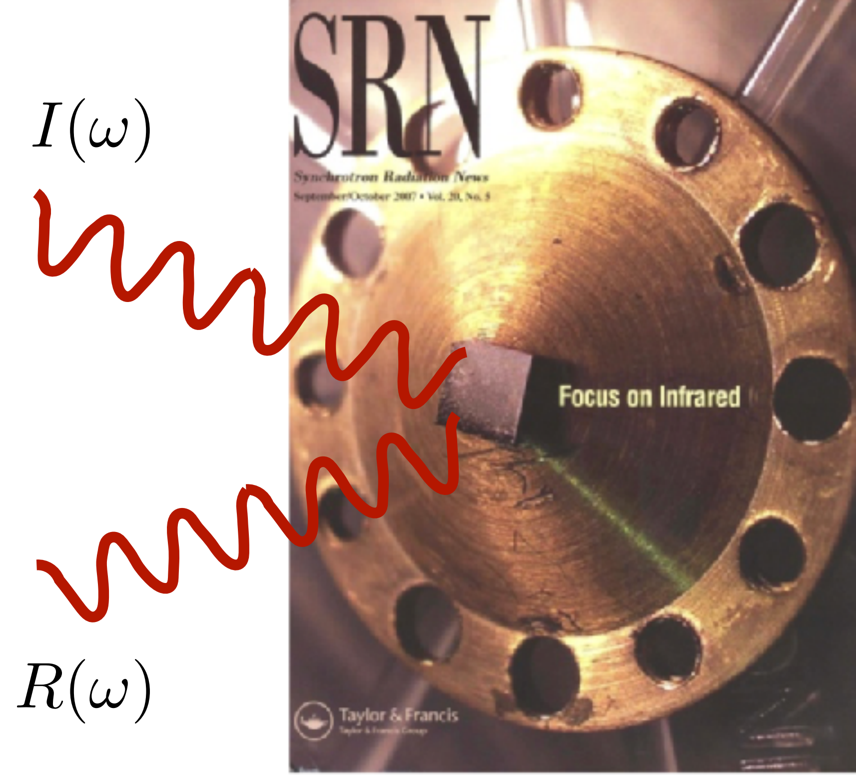
J.R. Soh et al, Physical Review B **100**, 201102(R) (2019)

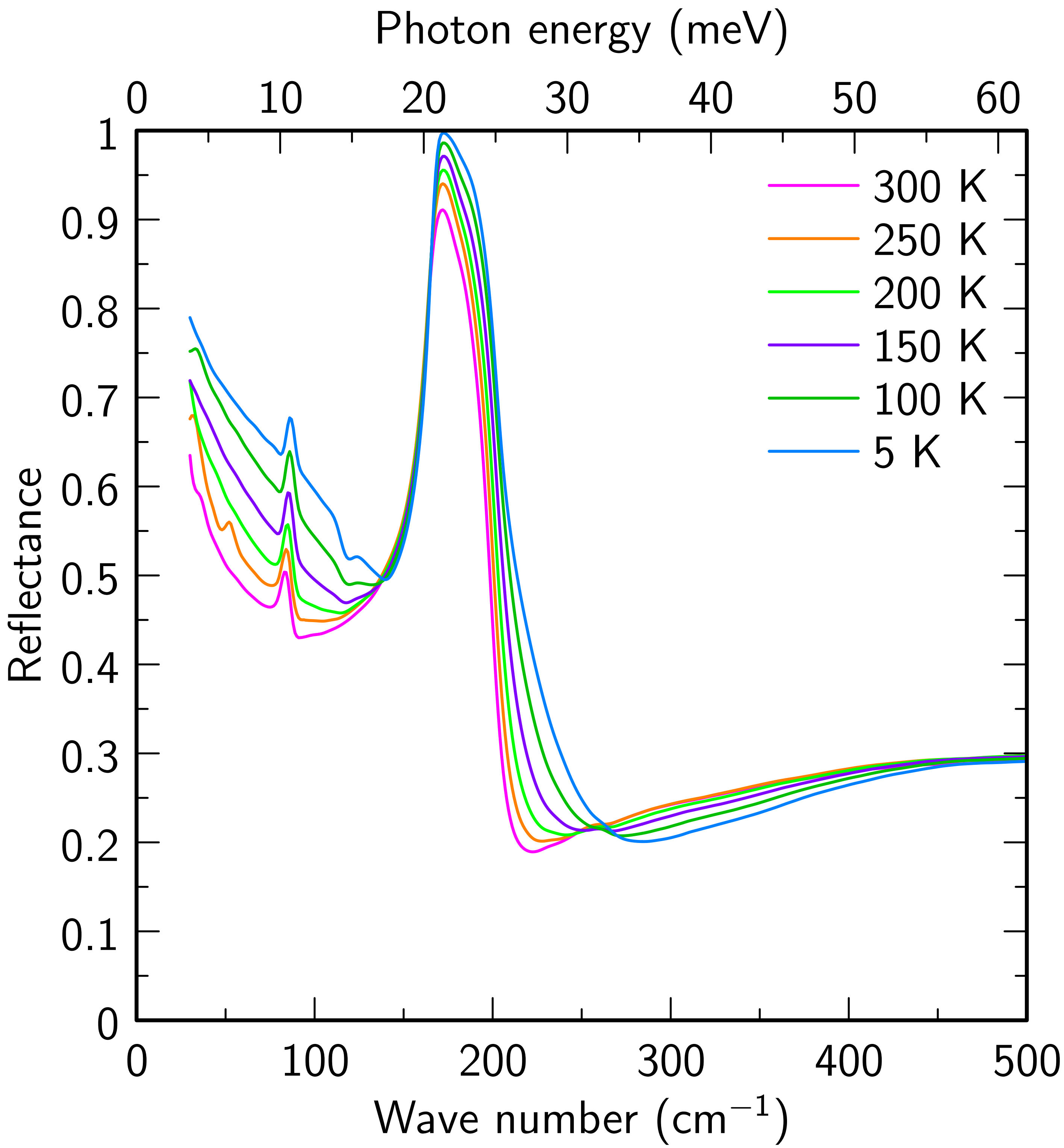
Topological semimetal $EuCd_2As_2$



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

Surprise

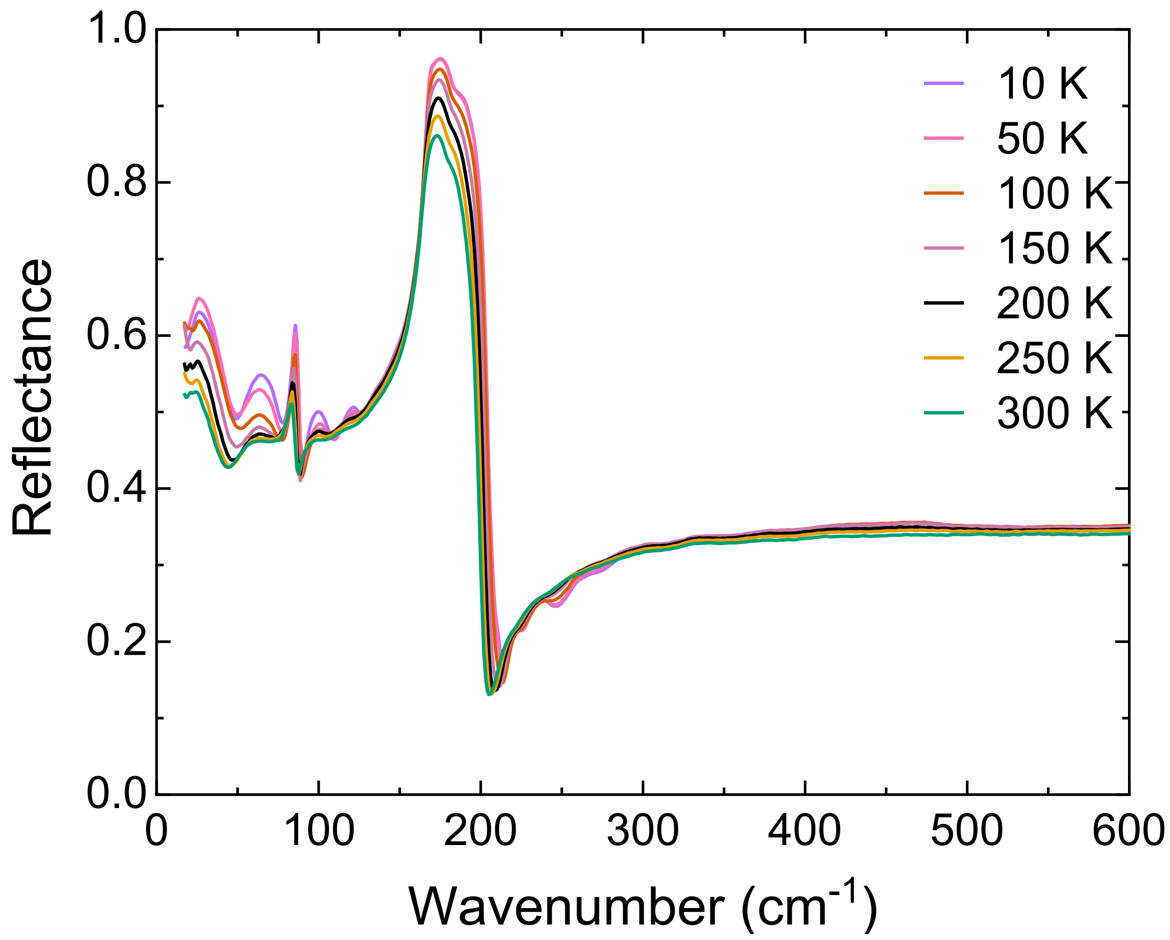




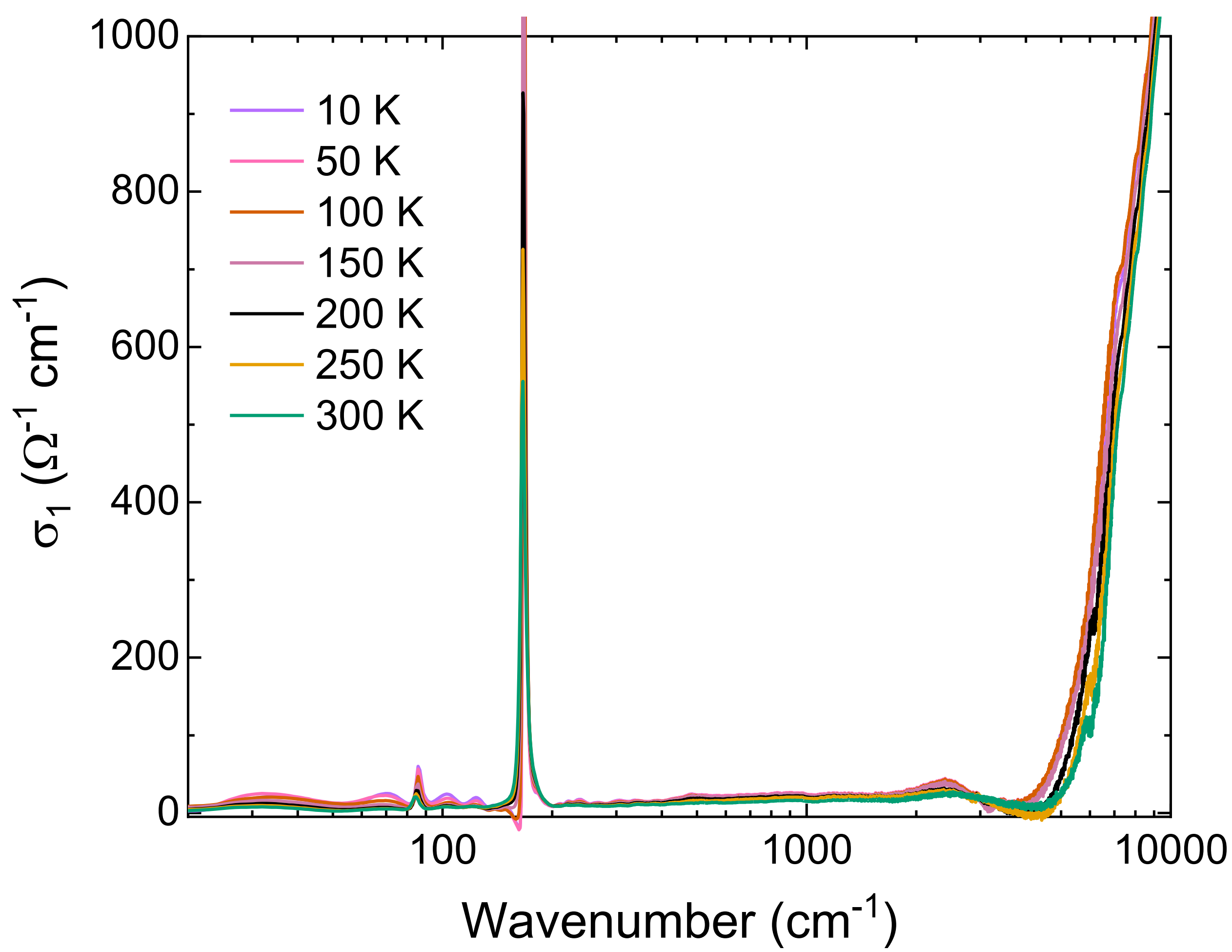
- weakly screened phonon modes
- low reflectance

Is this really a semimetal?

Reflectance

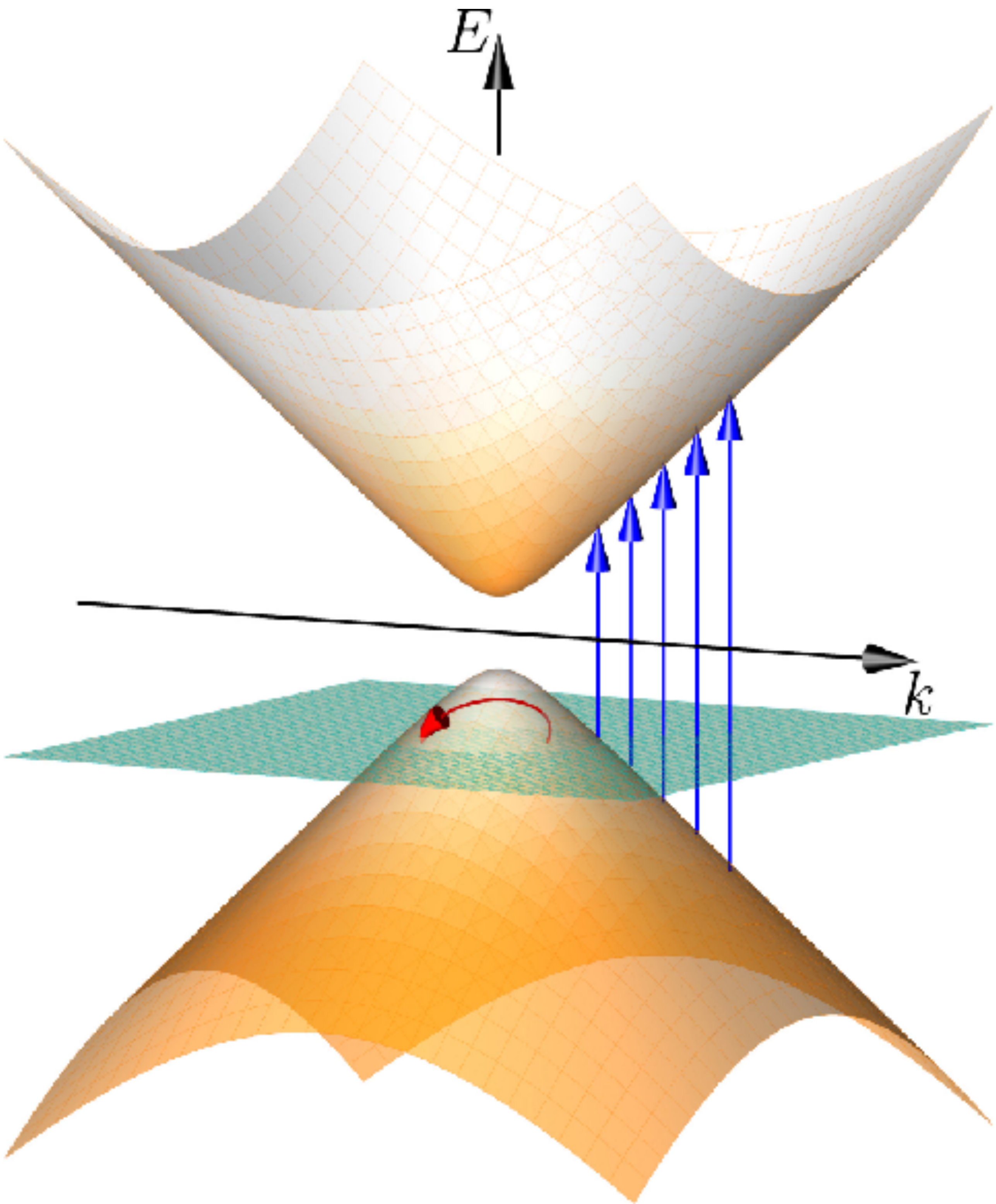


Optical conductivity

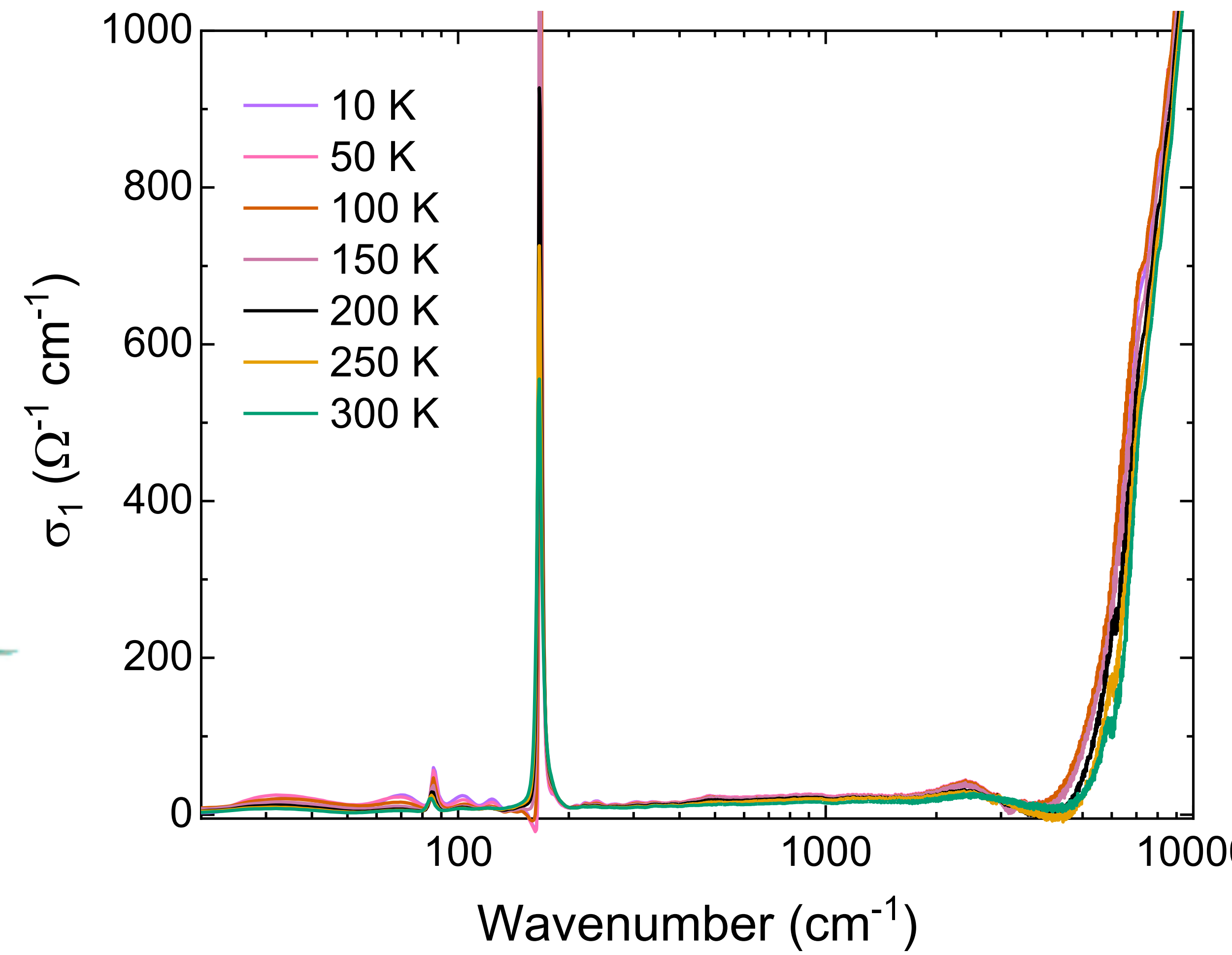


- weak temperature dependence of R
- weak Drude contribution
- gap-like feature above 0.5 eV

Is this really a semimetal?

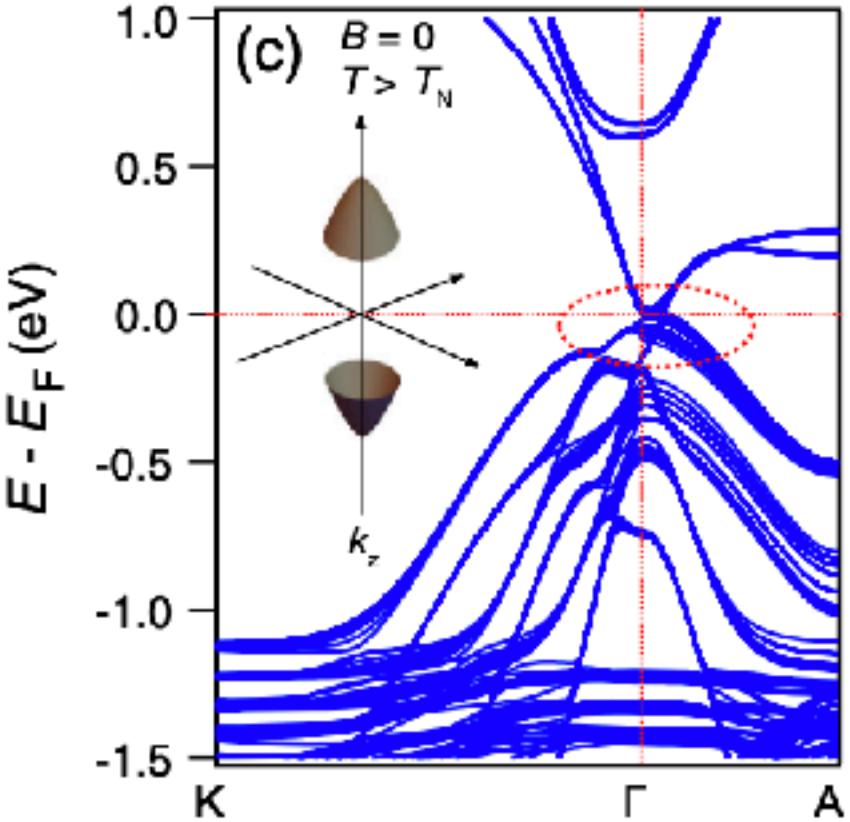


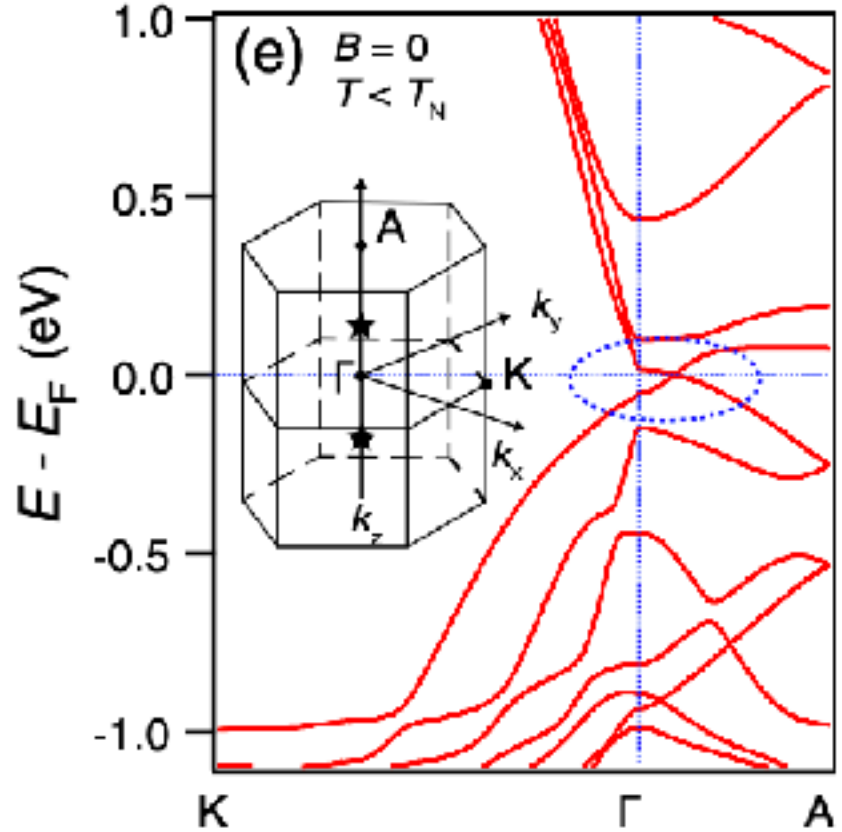
Optical conductivity



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

How to understand this?

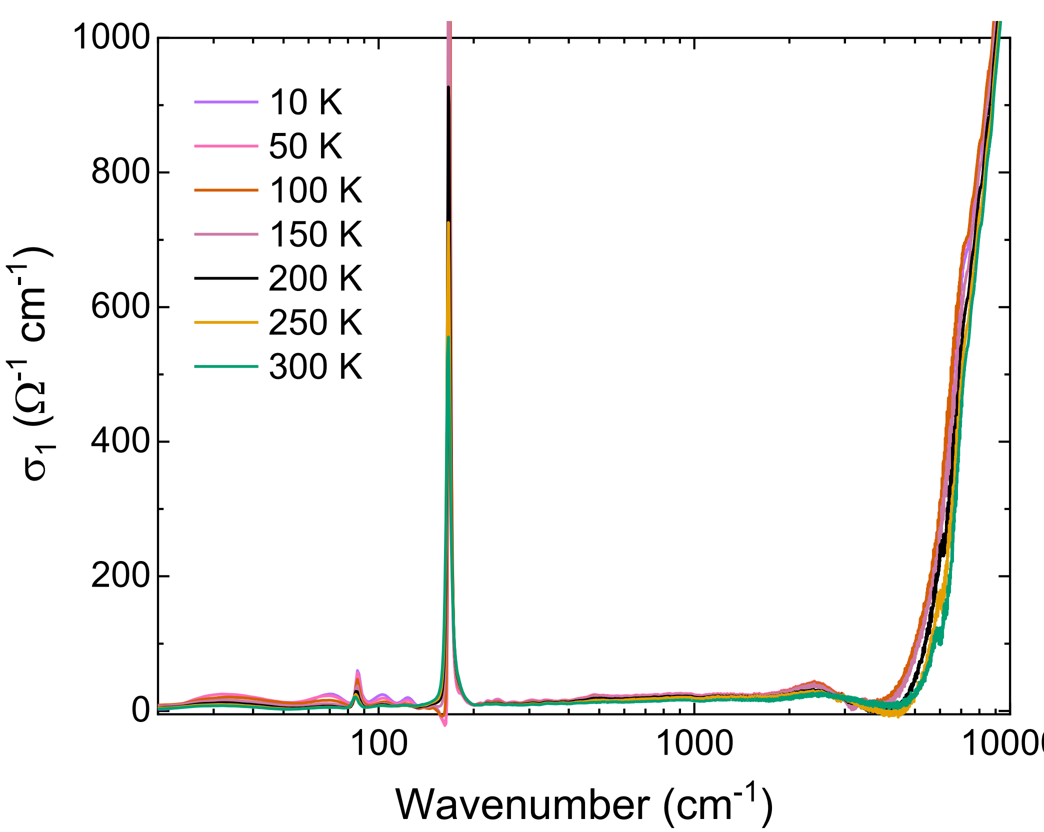




DFT:
Small or zero gap

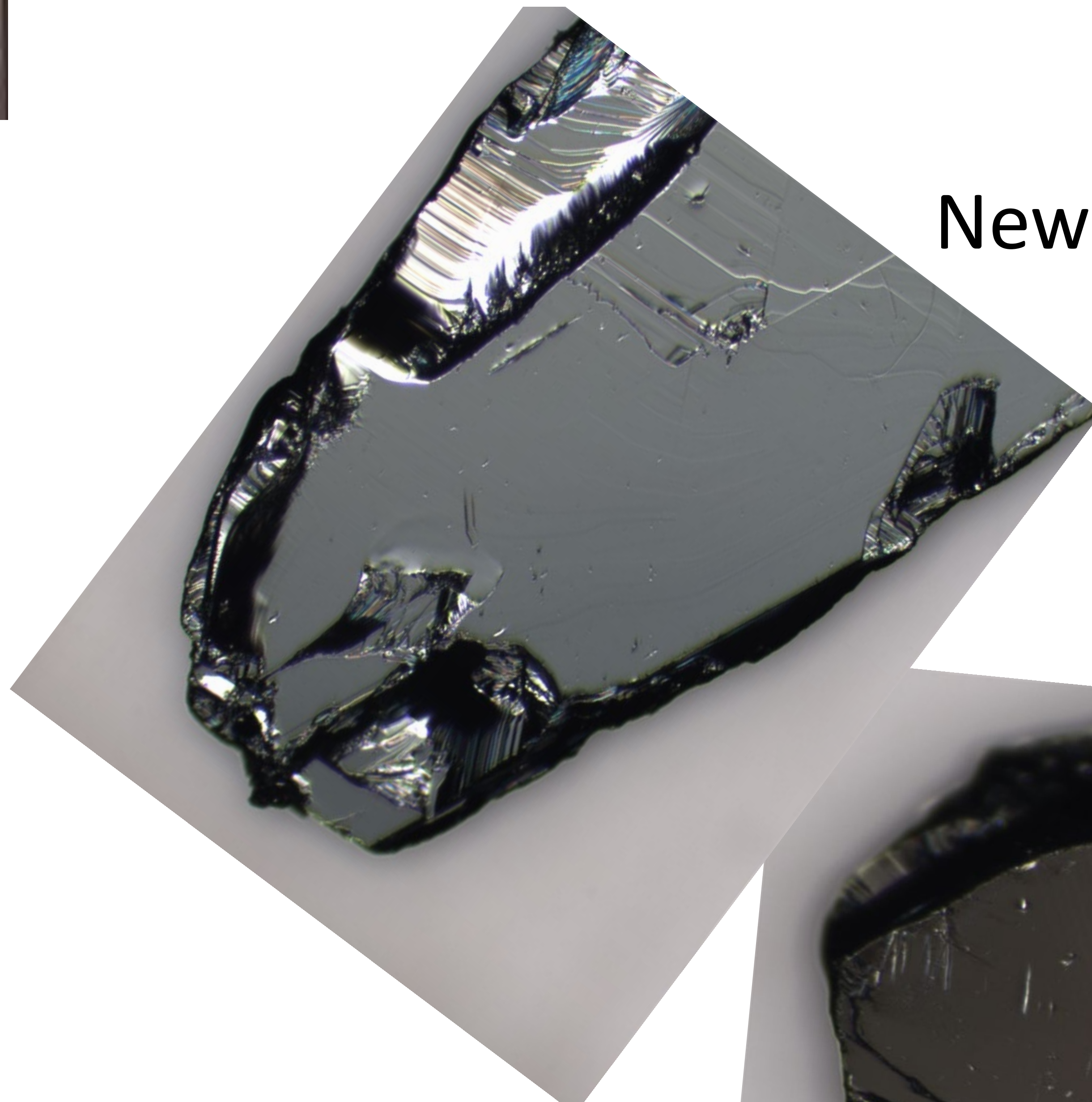
Optical conductivity:
No interband transitions below 0.5 eV

Weird selection rule?

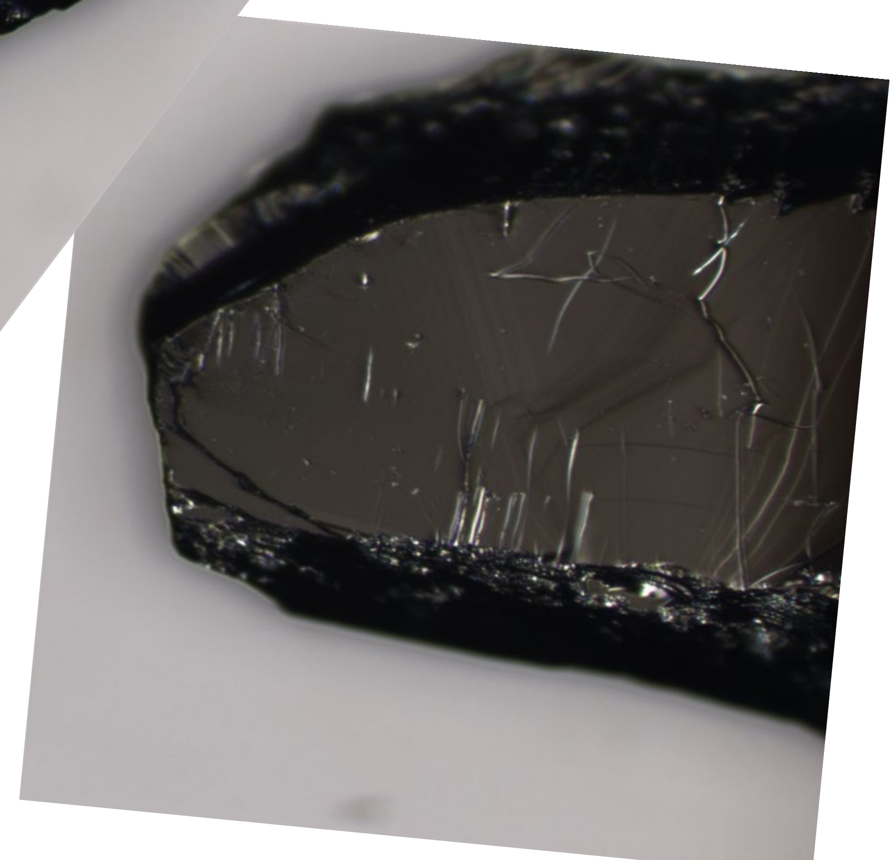


Y. Xu et al, Physical Review Letters 126, 076602 (2021)

Better samples

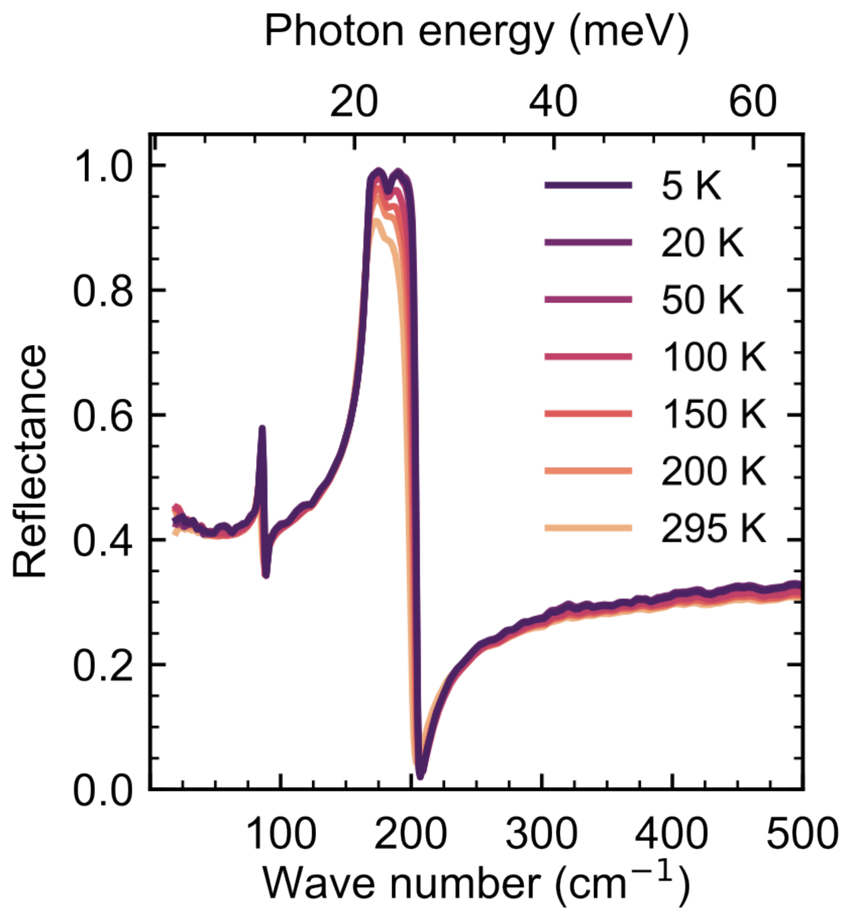


New batch



Old batch

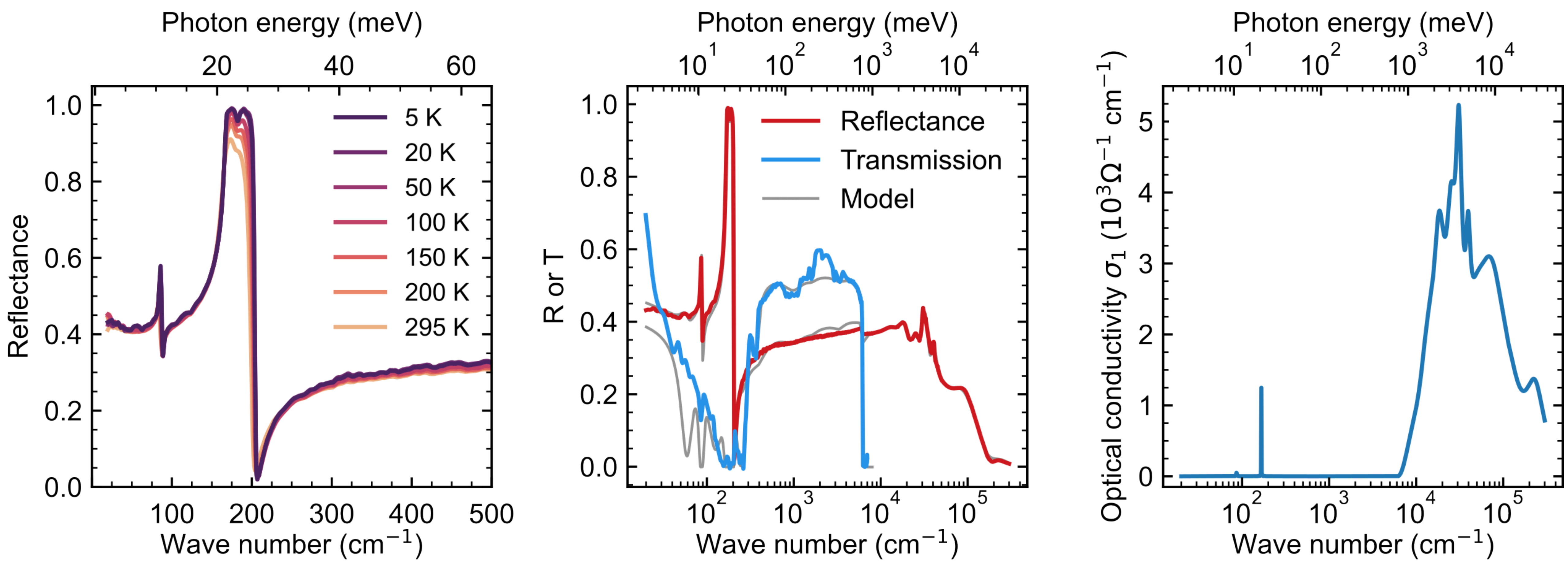
Even fewer carriers



No Drude component.
Reststrahlen band between TO and LO frequencies

D. Santos-Cottin, … A.B. Kuzmenko, M. Orlita, AA, arXiv:2301.08014 (2023)

Even fewer carriers



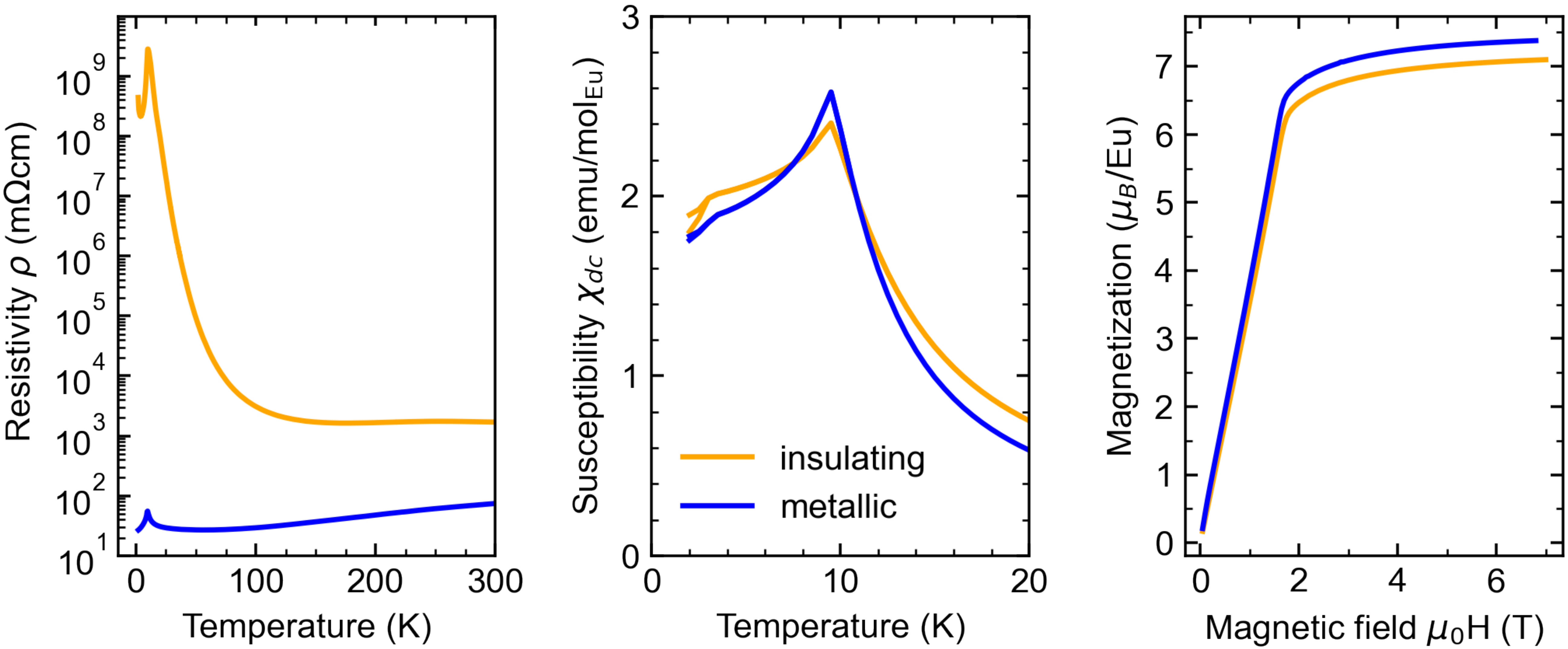
No Drude component.

Reststrahlen band between TO and LO frequencies.

Can't use simple Kramers-Kronig analysis!

D. Santos-Cottin, … A.B. Kuzmenko, M. Orlita, AA, arXiv:2301.08014 (2023)

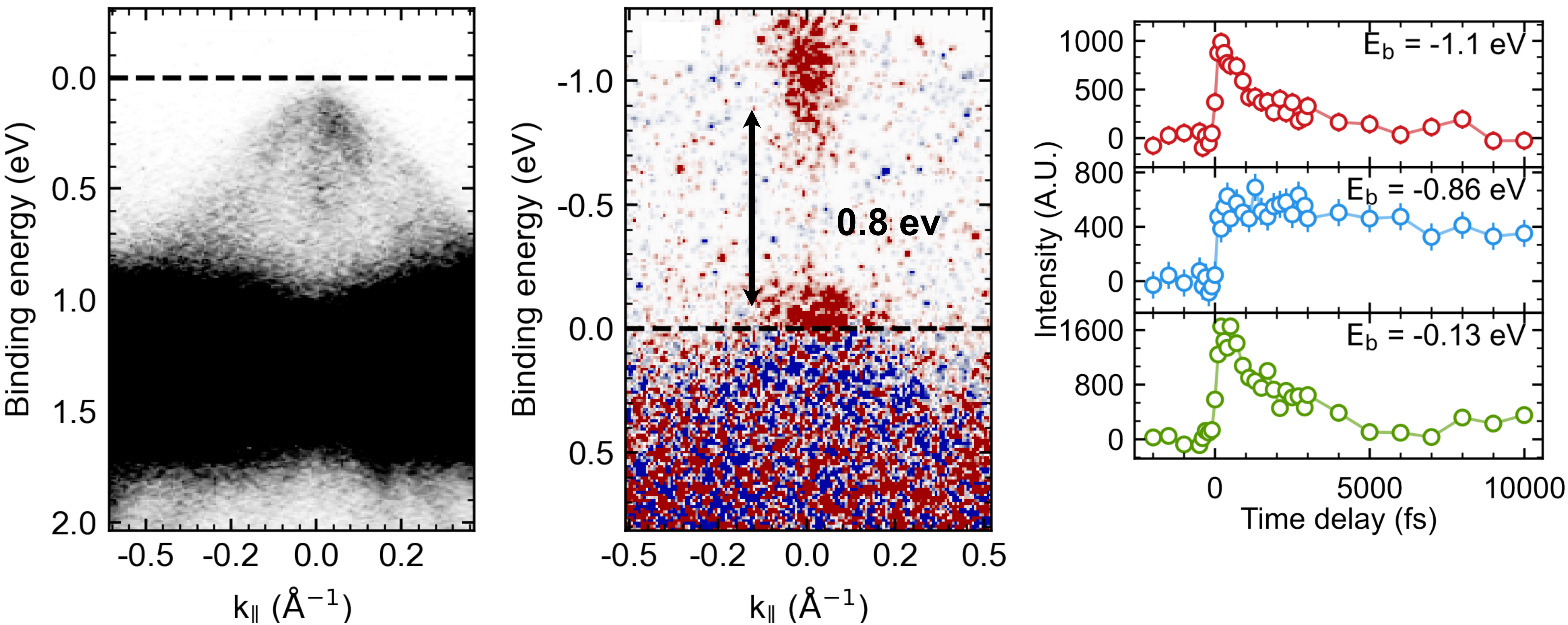
Not a semimetal...



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

D. Santos-Cottin, … A.B. Kuzmenko, M. Orlita, AA, arXiv:2301.08014 (2023)

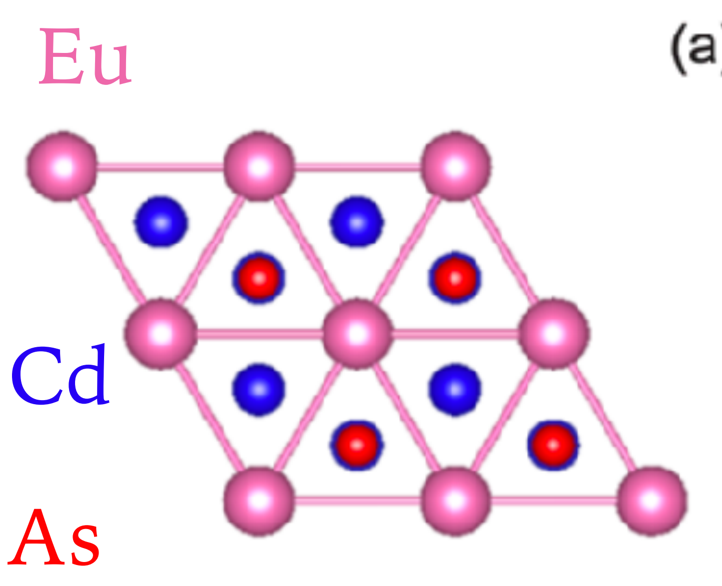
Not a semimetal…

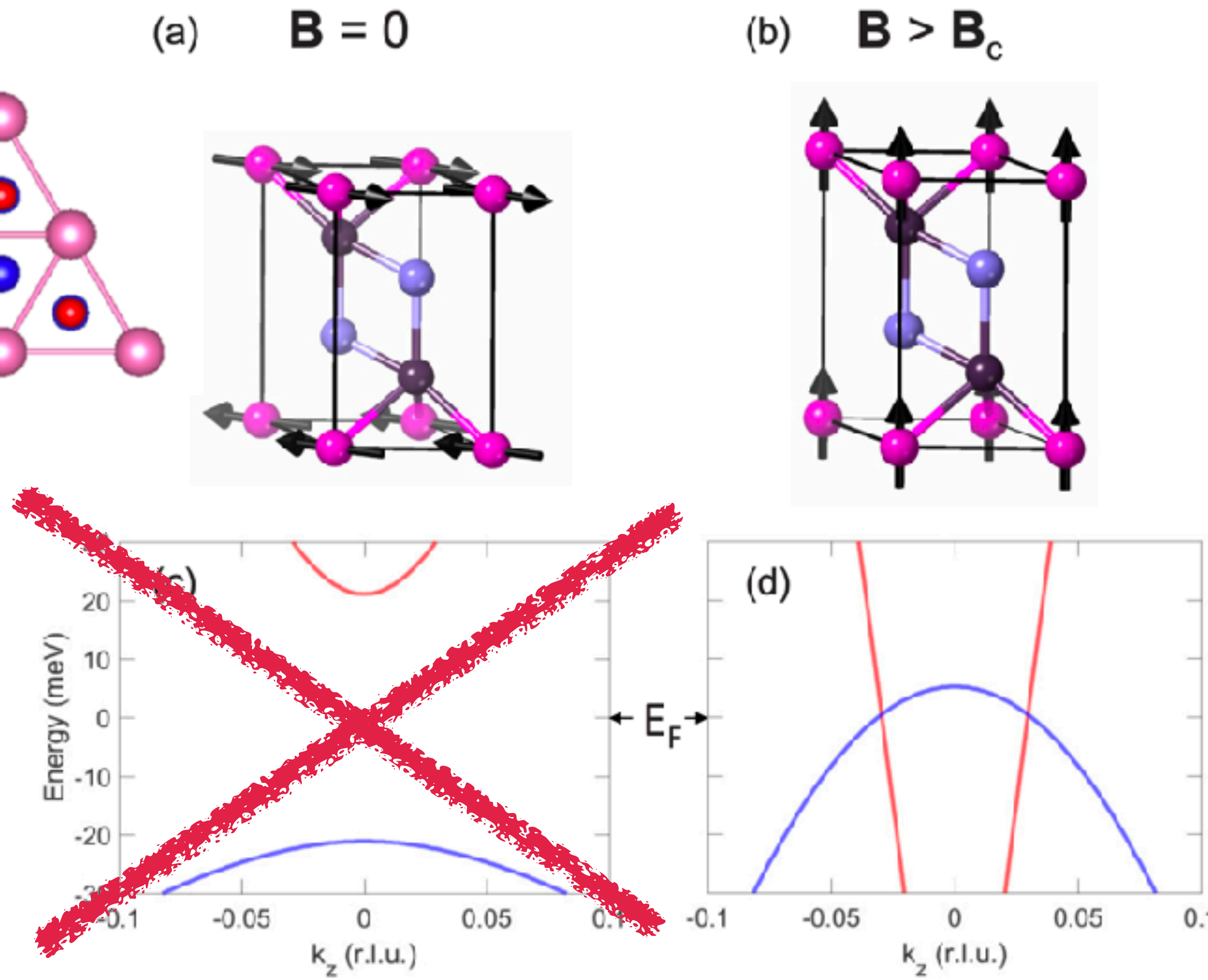


Hugo Dil's group, EPFL

D. Santos-Cottin, … A.B. Kuzmenko, M. Orlita, AA, arXiv:2301.08014 (2023)

~~Topological semimetal~~ $EuCd_2As_2$





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

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Spin fluctuation induced Weyl semimetal state in the paramagnetic phase of $EuCd_2As_2$

Journal of Physics: Condensed Matter

PAPER

Comparative Raman spectroscopy of magnetic topological material $EuCd_2X_2$ (X = P, As)

PHYSICAL REVIEW B **99**, 235119 (2019)

Quantum anomalous Hall effect and gate-controllable topological phase transition in layered $EuCd_2As_2$

PHYSICAL REVIEW B **97**, 214422 (2018)

Coupling of magnetic order and charge transport in the candidate Dirac semimetal $EuCd_2As_2$

PHYSICAL REVIEW B **94**, 045112 (2016)

Anisotropic transport and optical spectroscopy study on antiferromagnetic triangular lattice $EuCd_2As_2$: An interplay between magnetism and charge transport properties

PHYSICAL REVIEW B **104**, 155124 (2021)

npj | quantum materials

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ARTICLE OPEN

Check for updates

Consecutive topological phase transitions and colossal magnetoresistance in a magnetic topological semimetal

Pressure-induced ferromagnetism in the topological semimetal $EuCd_2As_2$

PHYSICAL REVIEW B **102**, 014408 (2020)

PHYSICA

Rapid Communications

Editors' Suggestion

Resonant x-ray scattering study of diffuse magnetic scattering from the topological

ARTICLE

https://doi.org/10.1038/s41467-021-27277-5 OPEN

Check for updates

Visualizing band selective enhancement of quasiparticle lifetime in a metallic ferromagnet

PHYSICAL REVIEW B **101**, 140402(R) (2020)

Rapid Communications

Manipulating magnetism in the topological semimetal $EuCd_2As_2$

Evidence of Ba-substitution induced spin-canting in the magnetic Weyl semimetal $EuCd_2As_2$

RESEARCH ARTICLE

ADVANCED SCIENCE

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Anomalous Hall Conductivity and Nernst Effect of the Idea[l] Weyl Semimetallic Ferromagnet $EuCd_2As_2$

PHYSICAL REVIEW B **106**, 085134 (2022)

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[ev]olution in a magnetic topological material Eu[...]

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Switchable quantum anomalous and spin Hall effects in honeycomb magnet $EuCd_2As_2$

PHYSICAL REVIEW LETTERS **126**, 076602 (2021)

201116(R) (2018)

[PHYSICAL] REVIEW B **105**, L140401 (2022)

Letter

Unconventional Transverse Transport above and below the Magnetic Transition Temperature in Weyl Semimetal $EuCd_2As_2$

COMMUNICATION

ADVANCED MATERIALS

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Single pair of Weyl nodes in the spin-canted structure of $EuCd_2As_2$

[PHYSICAL] REVIEW B **98**, 125110 (20[18])

PAPER

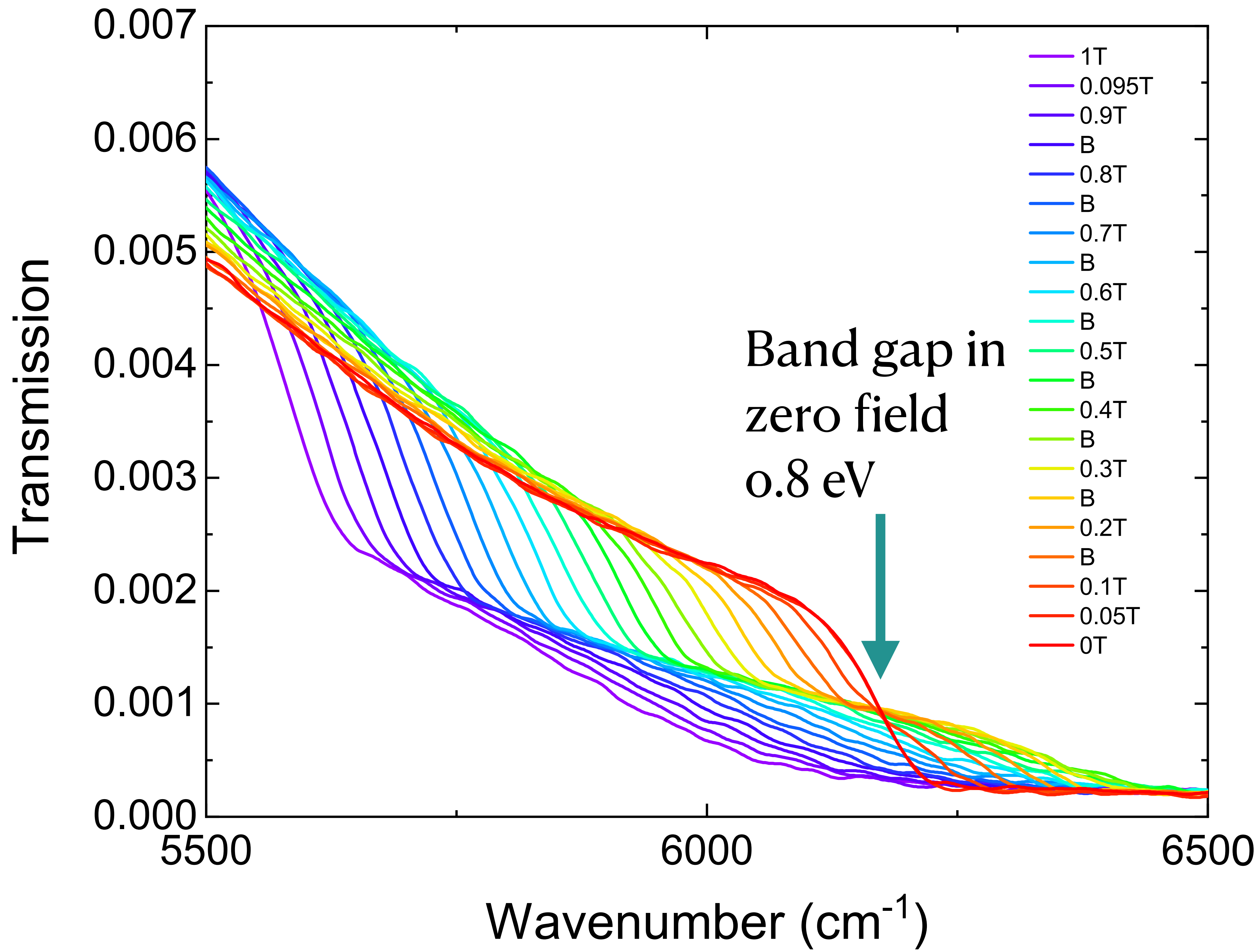
Emergence of Nontrivial Low-Energy Dirac Fermions in Antiferromagnetic $EuCd_2As_2$

[S]tructure, transport, and opti[cal ...]

Long-Time Magnetic Relaxation in Antiferromagnetic Topological Material $EuCd_2As_2$

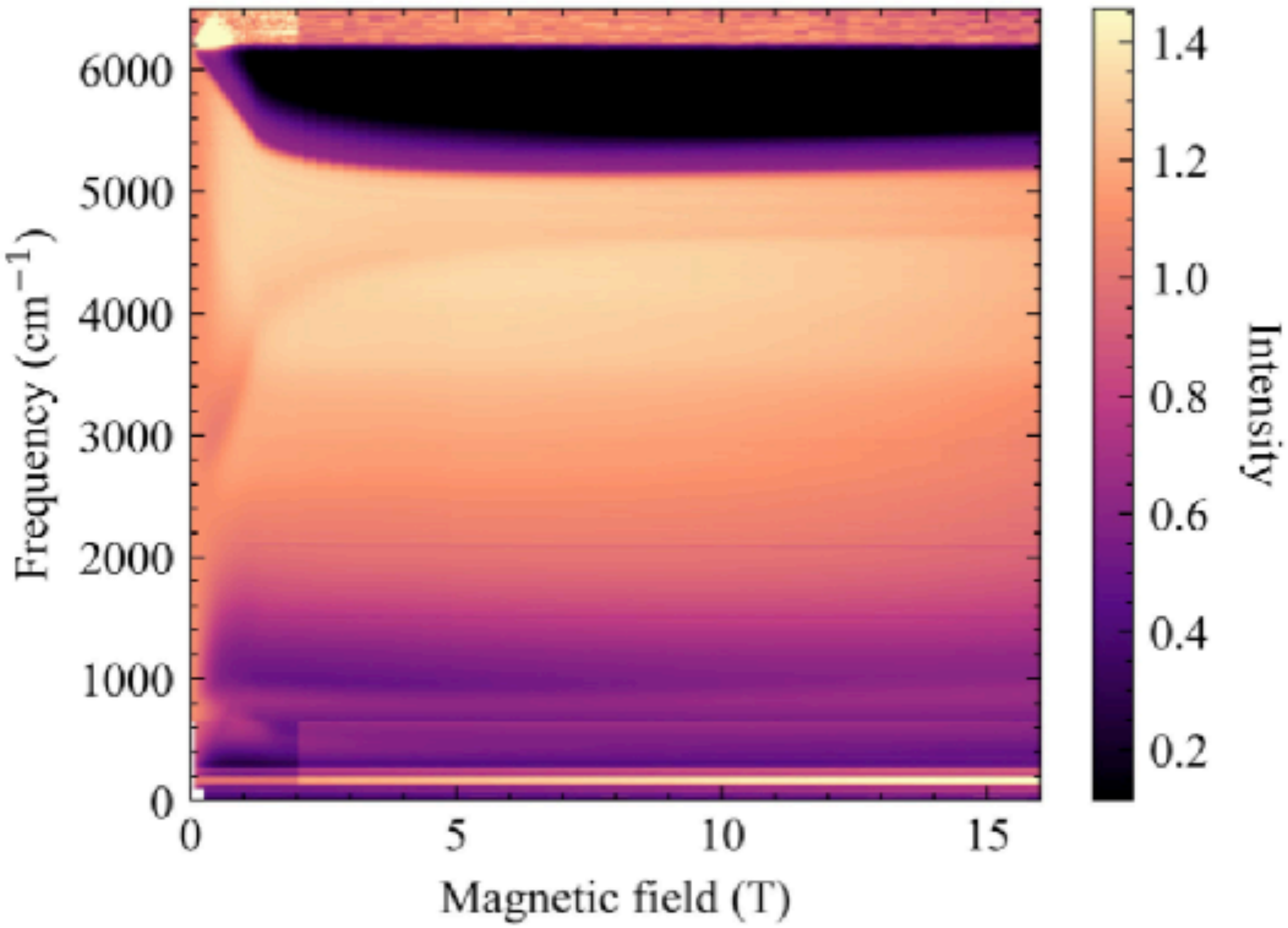
Magneto-transmission at 4 K

Magneto-transmission below 1 T

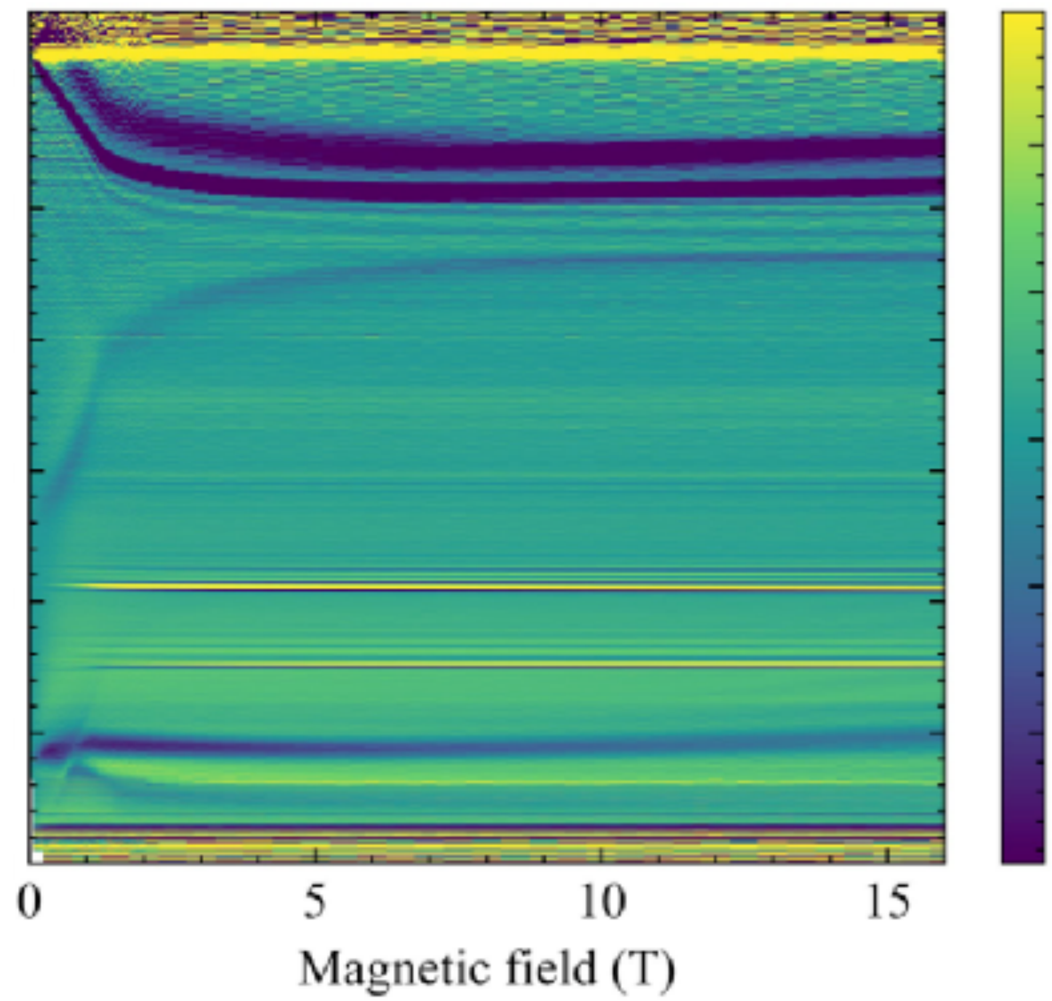


T_B/T_0 in the mid infrared

Relative transmission



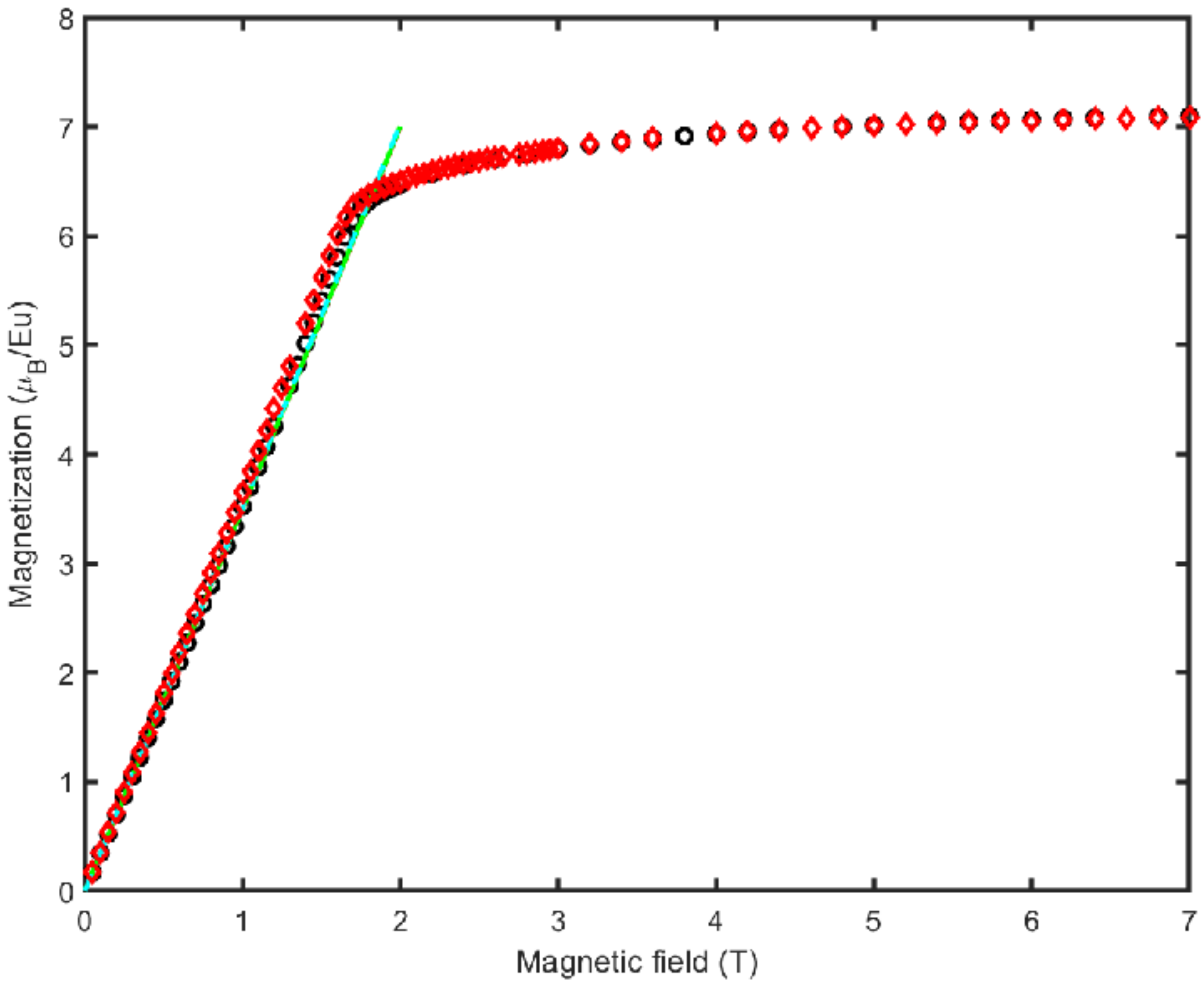
Derivative of relative transmission



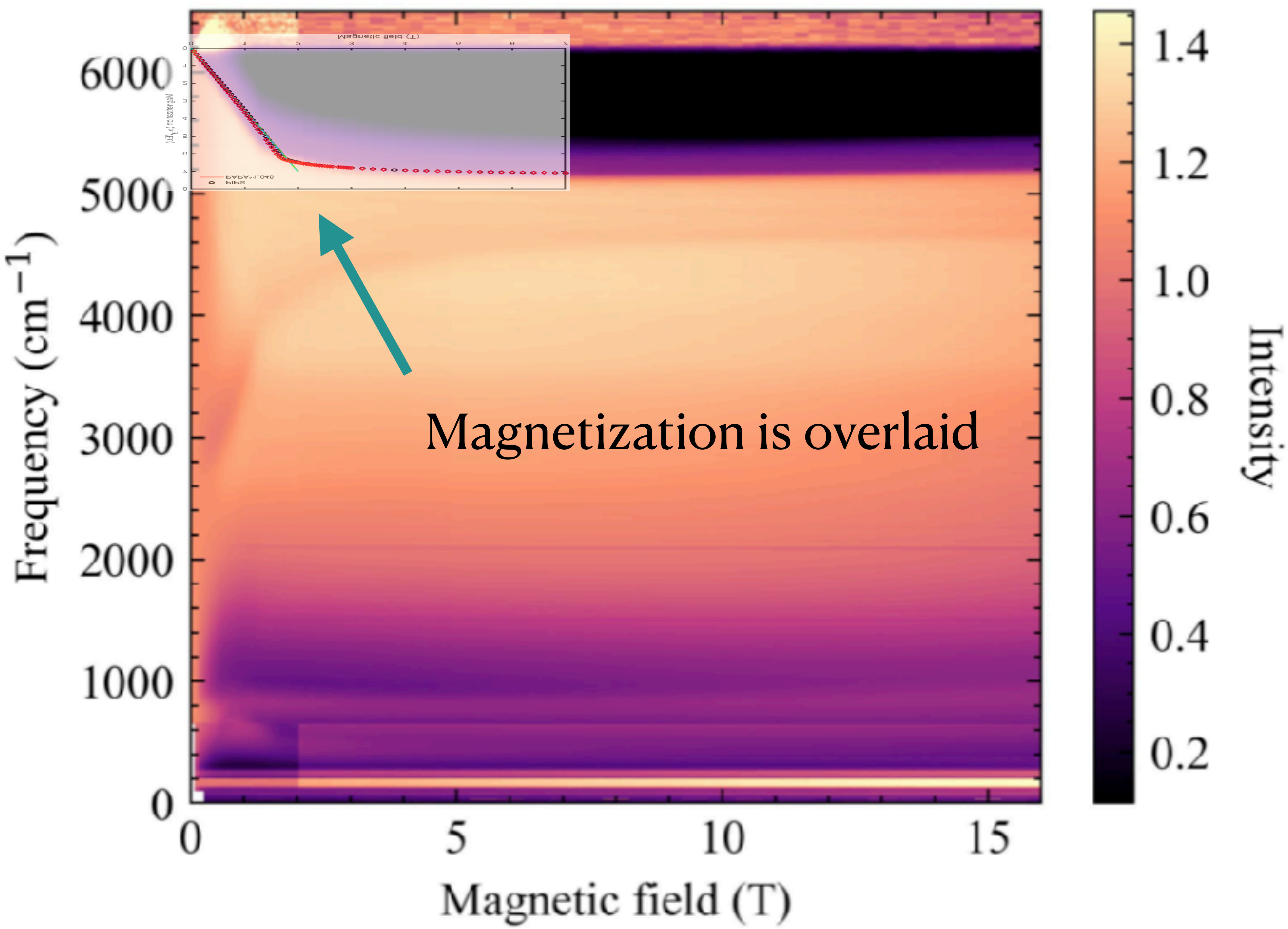
Gap of 0.8 eV decreases by 125 meV, under applied ~4 T.

Spin polarized bands. In-gap "stuff".

Magnetization



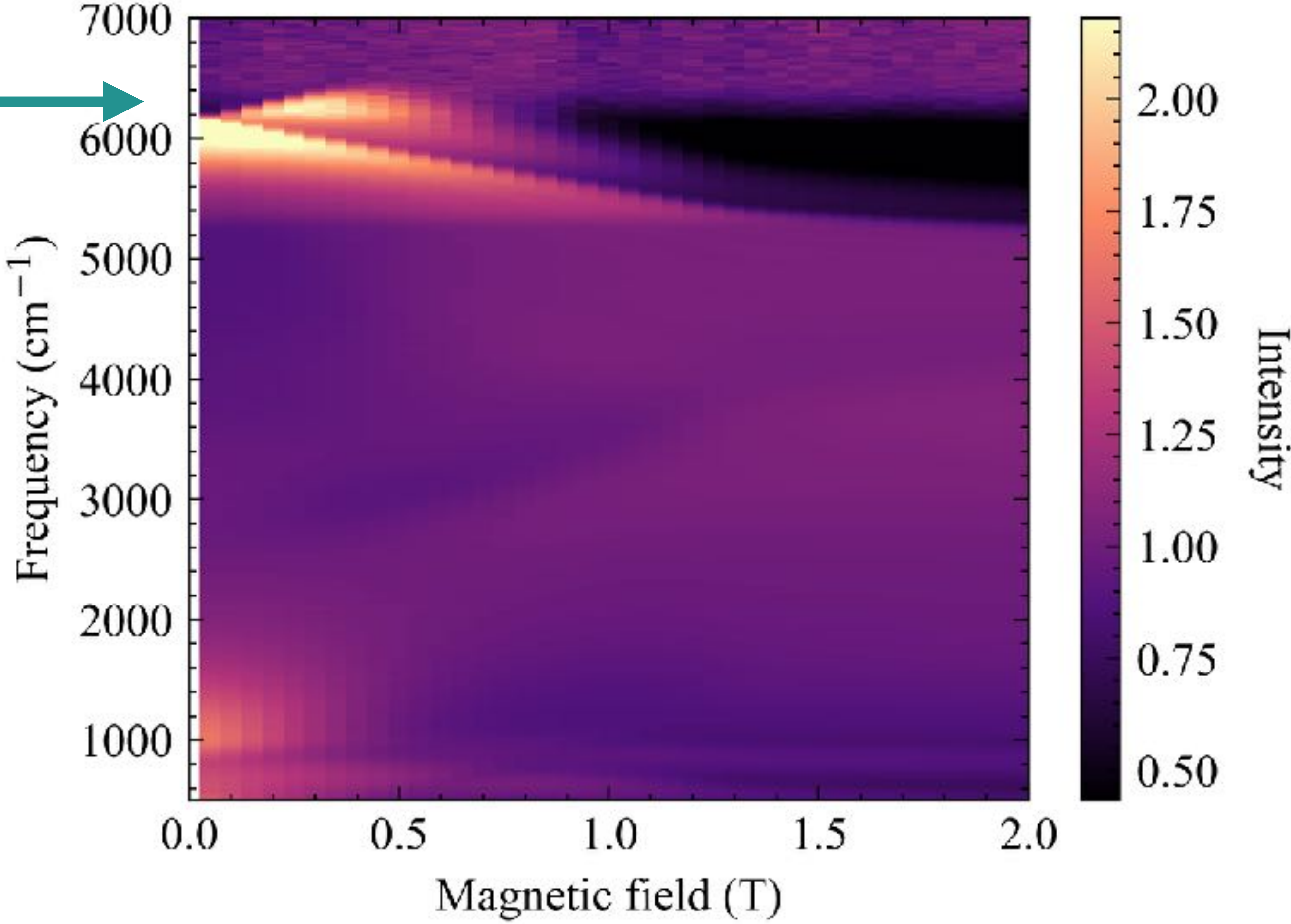
T_B/T_0 in the mid infrared



T_B/T_{avg}

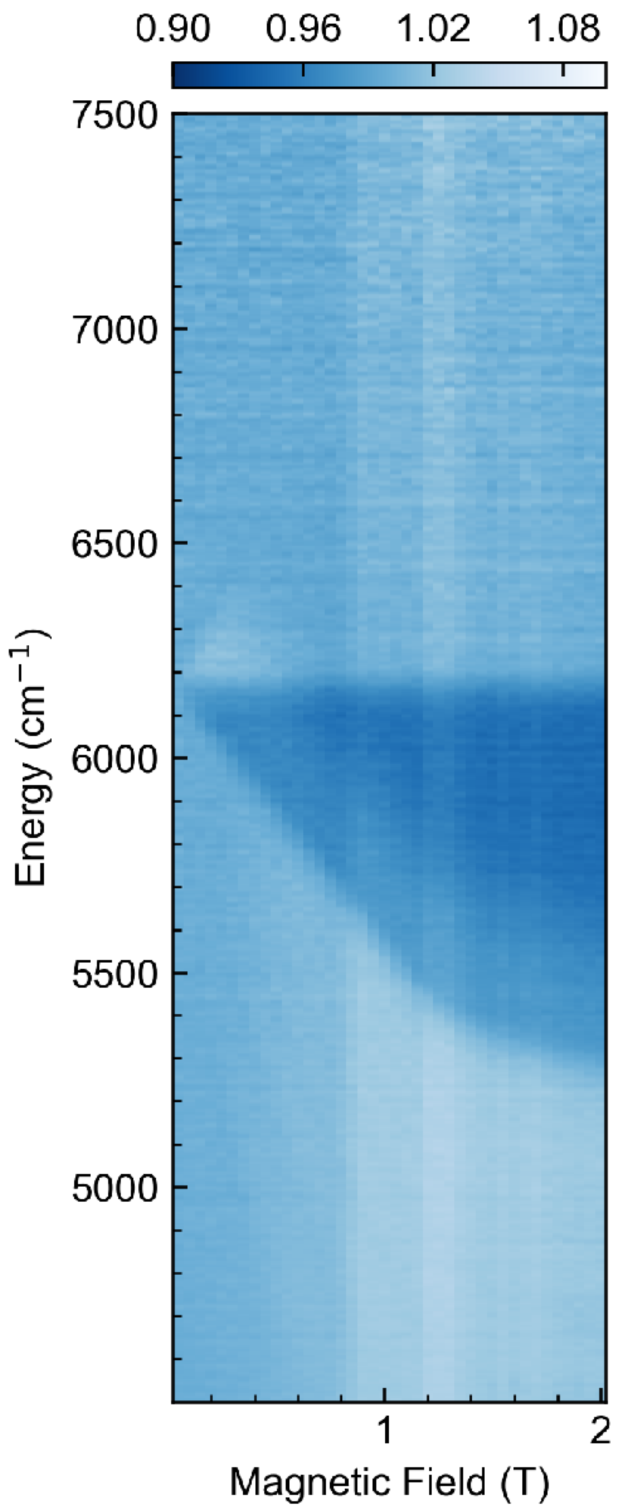
The effective g factor is ~ 1600

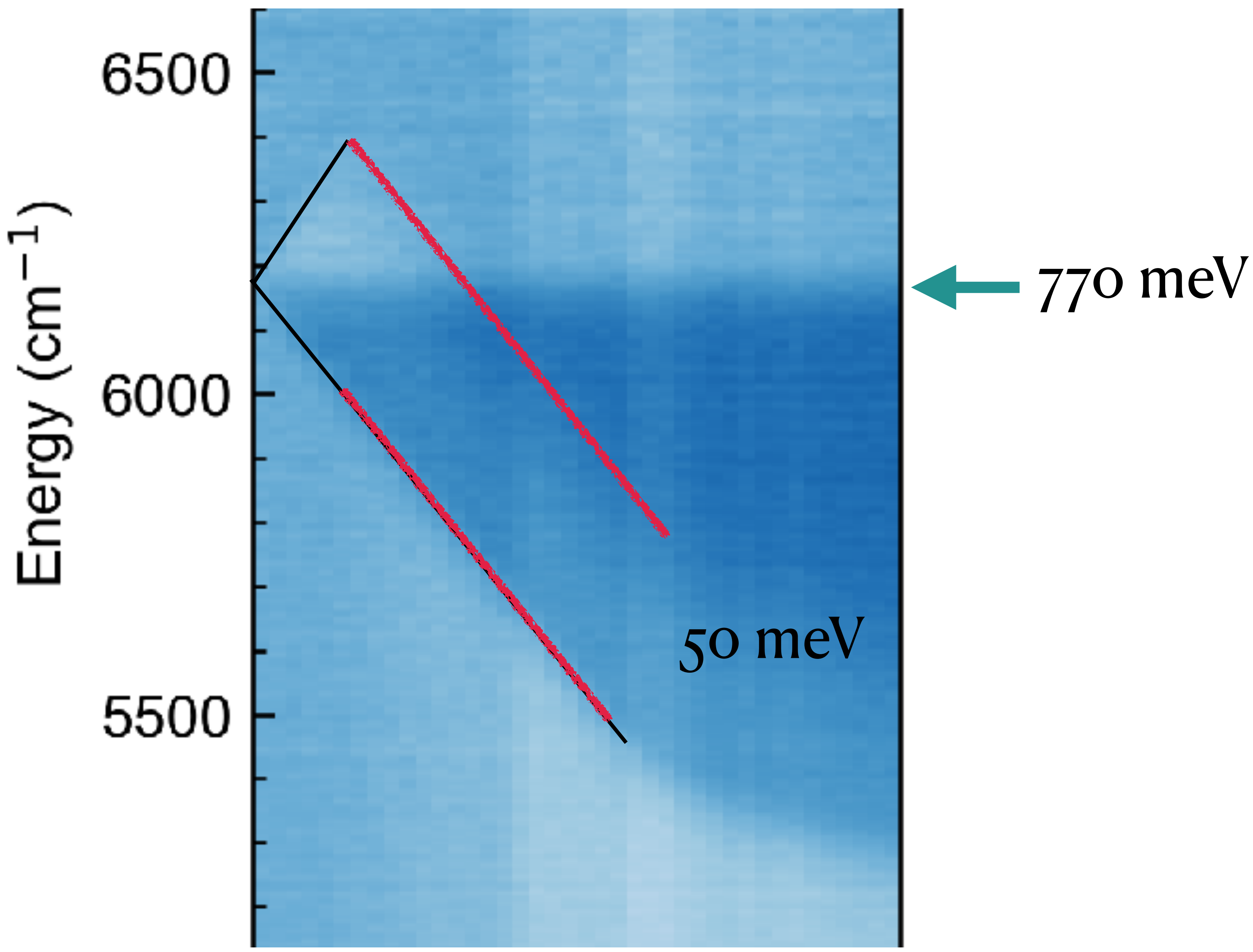
$$g \propto \frac{\Delta E}{\Delta B}$$



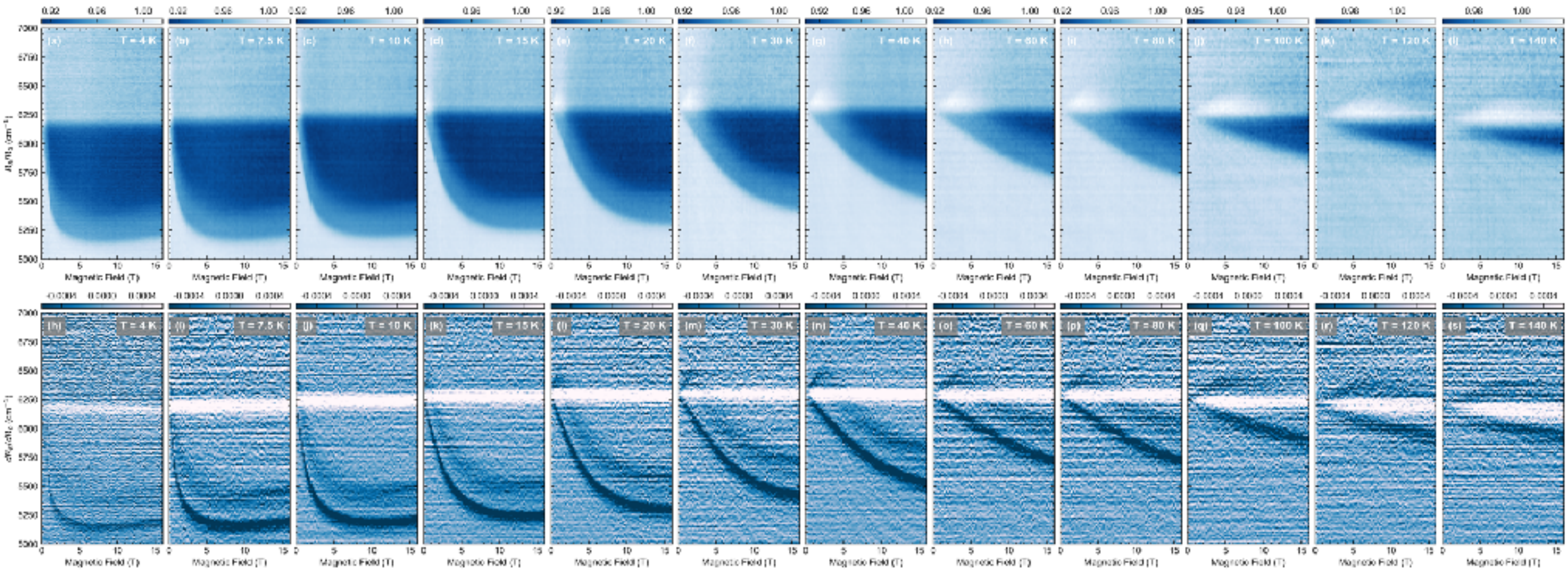
Magneto-reflection from 4 K to 140 K

Gap splitting and decrease in field: 4 K



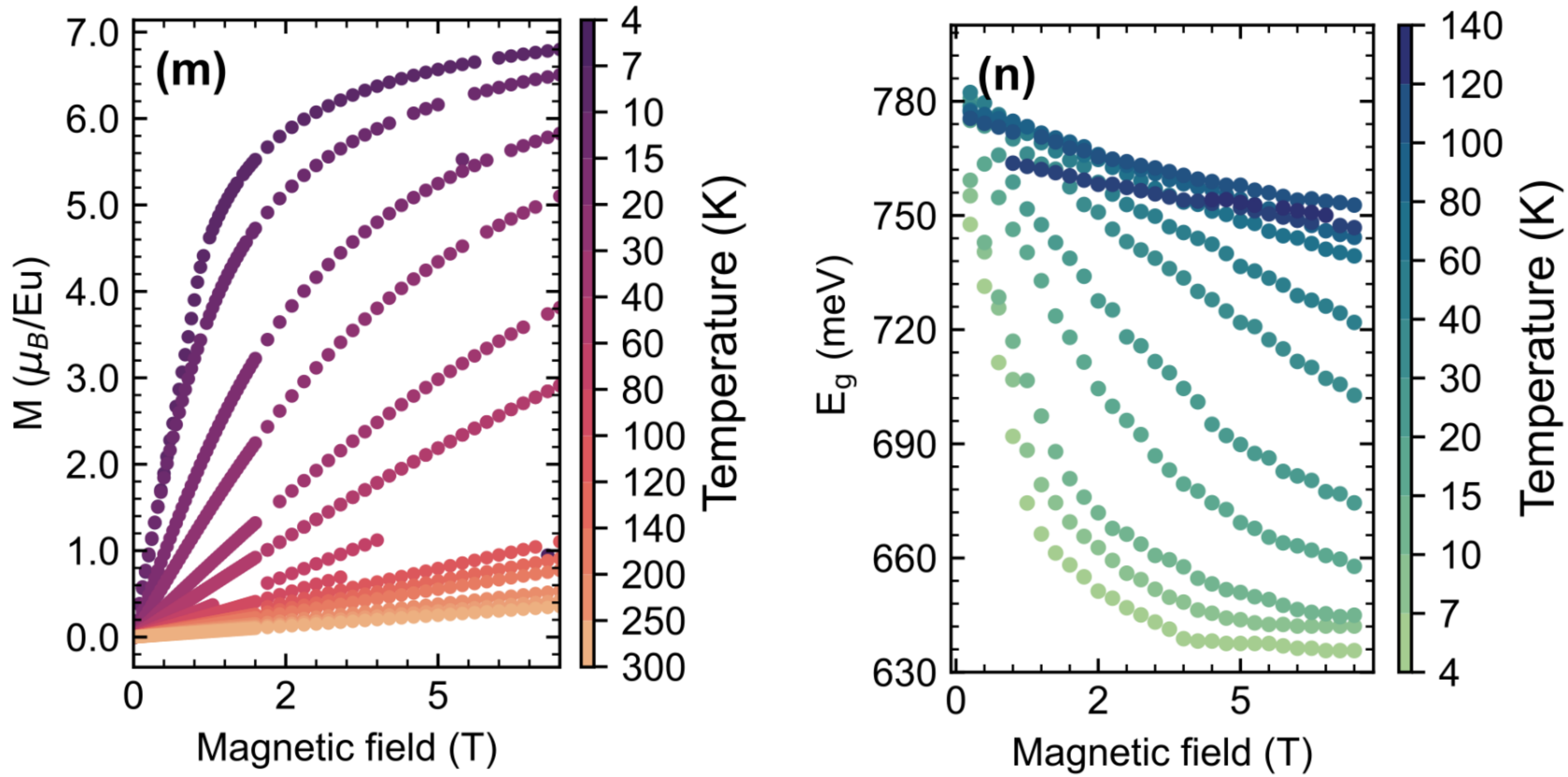


R_B/R_0 up to 140 K - high field



4 K **10 K** **20 K** **40 K** **60 K** **100 K** **140 K**

Gap decrease mimics magnetization



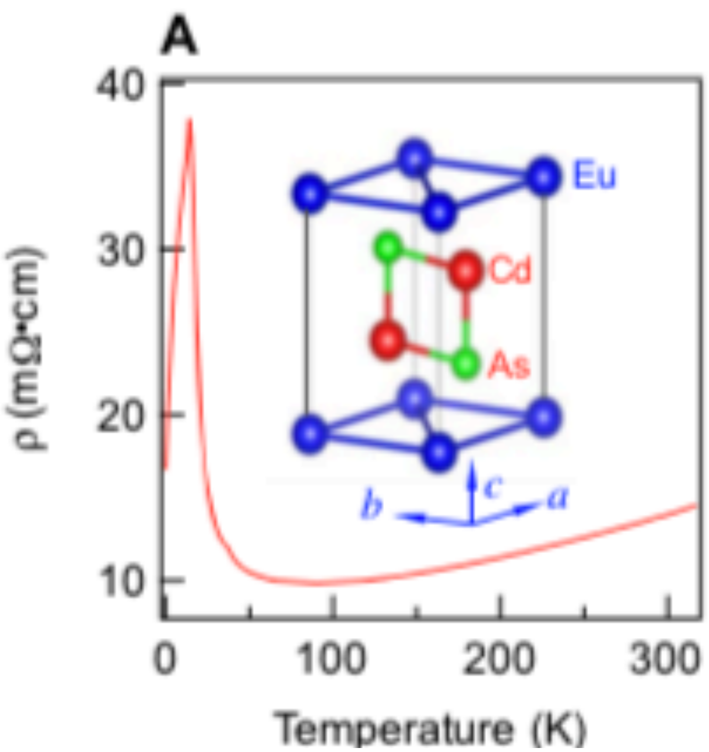
$$\Delta E_{\mathrm{g}} = -\frac{1}{2}\mathcal{J}_{\mathrm{eff}} S M(T,H)/M_S \qquad \mathcal{J}_{\mathrm{eff}} = 80 \text{ meV}$$

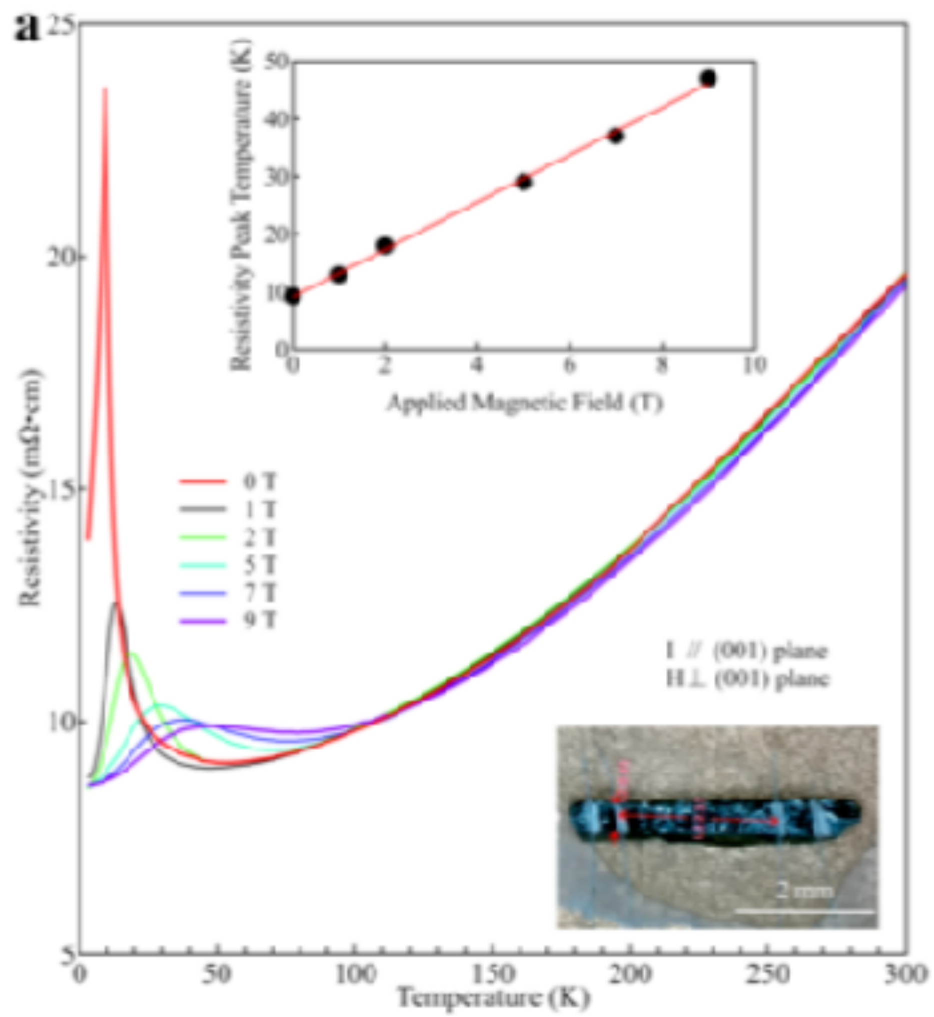
D. Santos-Cottin, … A.B. Kuzmenko, M. Orlita, AA, arXiv:2301.08014 (2023)

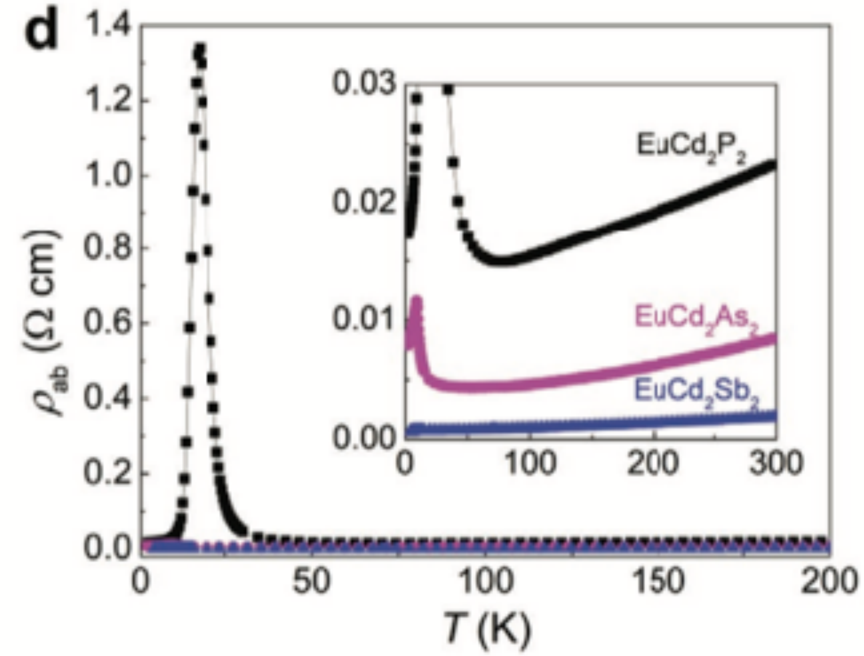
Exchange coupling dictates band structure

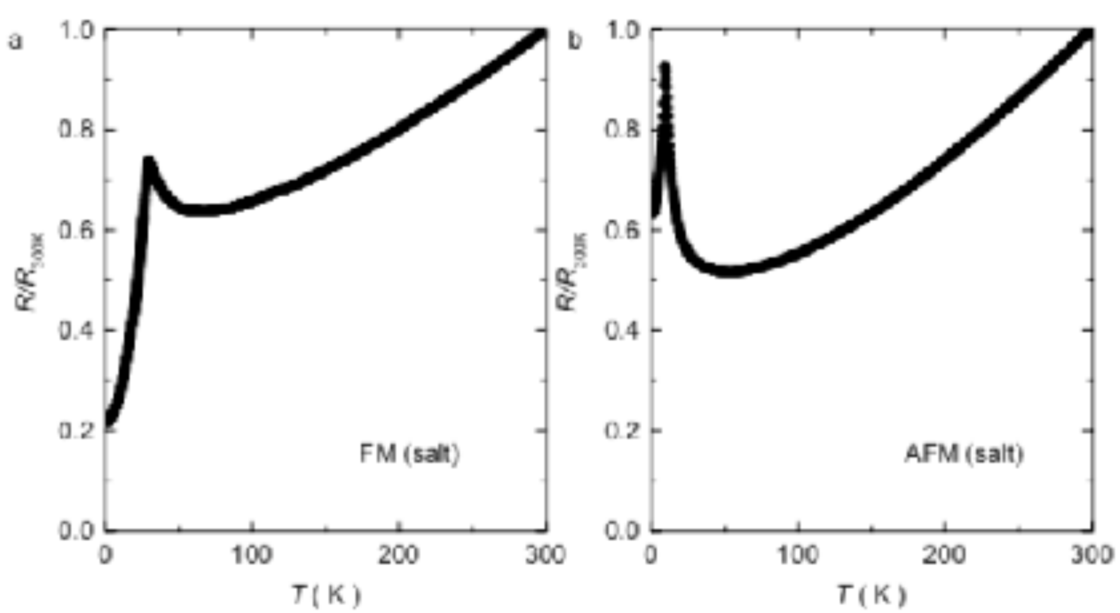
Local Eu magnetism strongly influences the band gap.

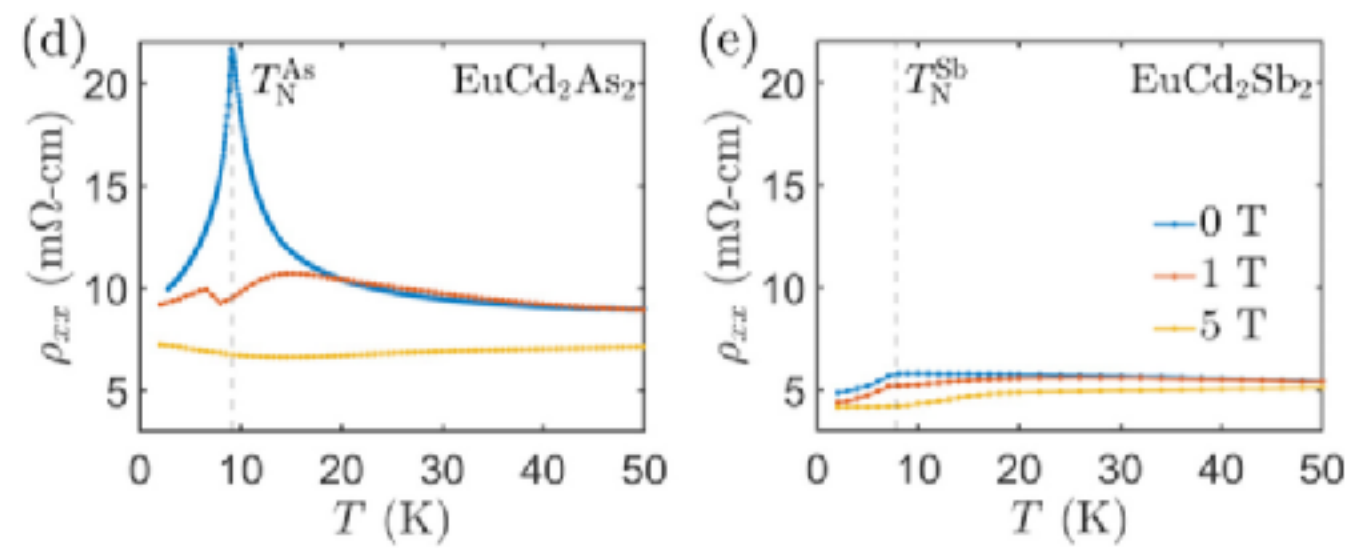
What about transport?











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.