Title: Exotic superconductivity in UTe2

Speakers: Sheng Ran

Collection/Series: Quantum Matter

Subject: Condensed Matter

Date: November 05, 2024 - 3:30 PM

URL: https://pirsa.org/24100142

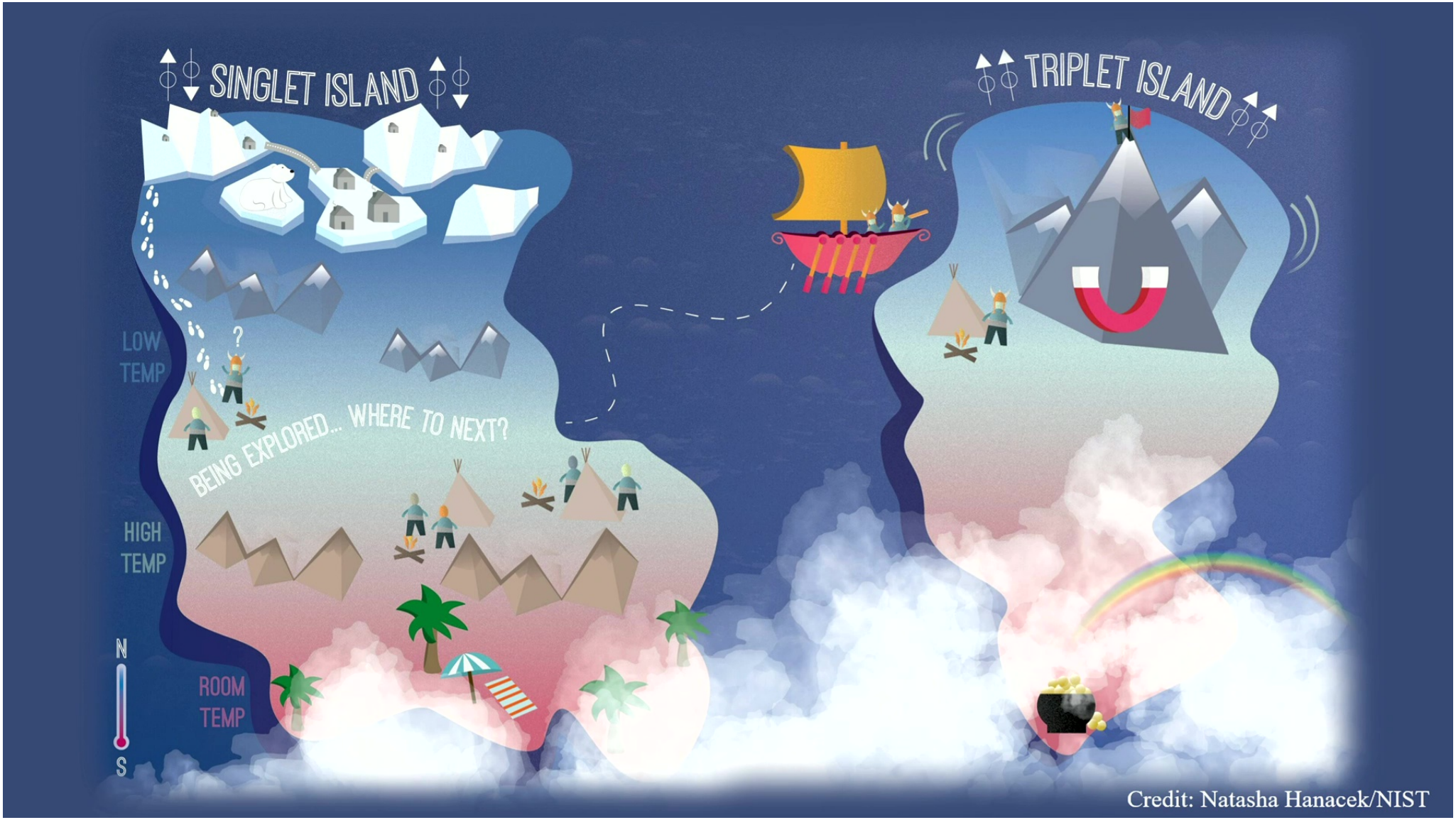
Abstract:

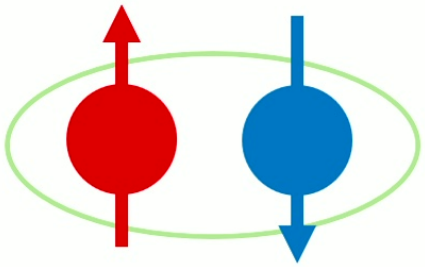
UTe_2 is an intriguing recently discovered superconductor that exhibits a wide range of exotic properties. Experimental evidence increasingly supports spin-triplet pairing, and under pressure or in magnetic fields, UTe_2 displays multiple superconducting phases, including a remarkable reentrant phase above 40 T. However, conflicting results persist regarding the presence of chiral and time-reversal symmetry breaking. Recent STM measurements have identified a charge density wave in the normal state, which couples with the superconducting state at lower temperatures to form a pair density wave. In this talk, I will provide an overview of the latest developments in understanding the unconventional superconductivity of UTe_2.

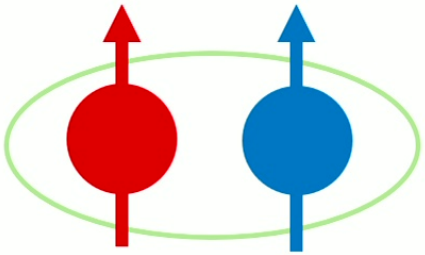
Exotic Superconductivity in UTe_2

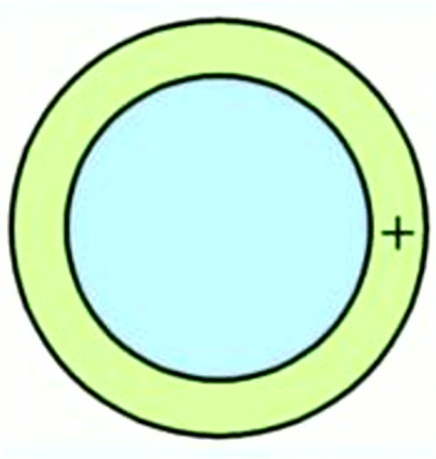
Sheng Ran
Assistant Professor

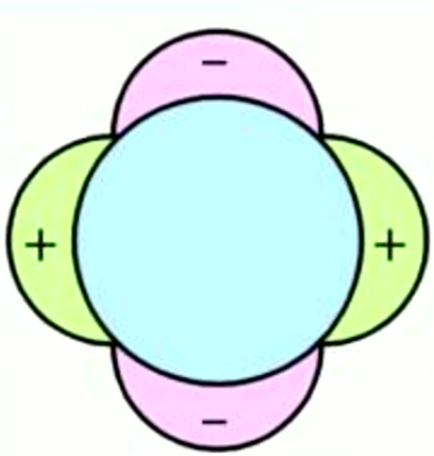
Washington University in St. Louis

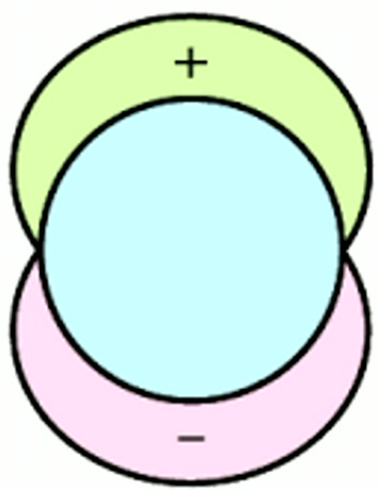

SINGLET ISLAND
TRIPLET ISLAND
LOW TEMP
HIGH TEMP
ROOM TEMP
N
S
?
BEING EXPLORED... WHERE TO NEXT?
Credit: Natasha Hanacek/NIST



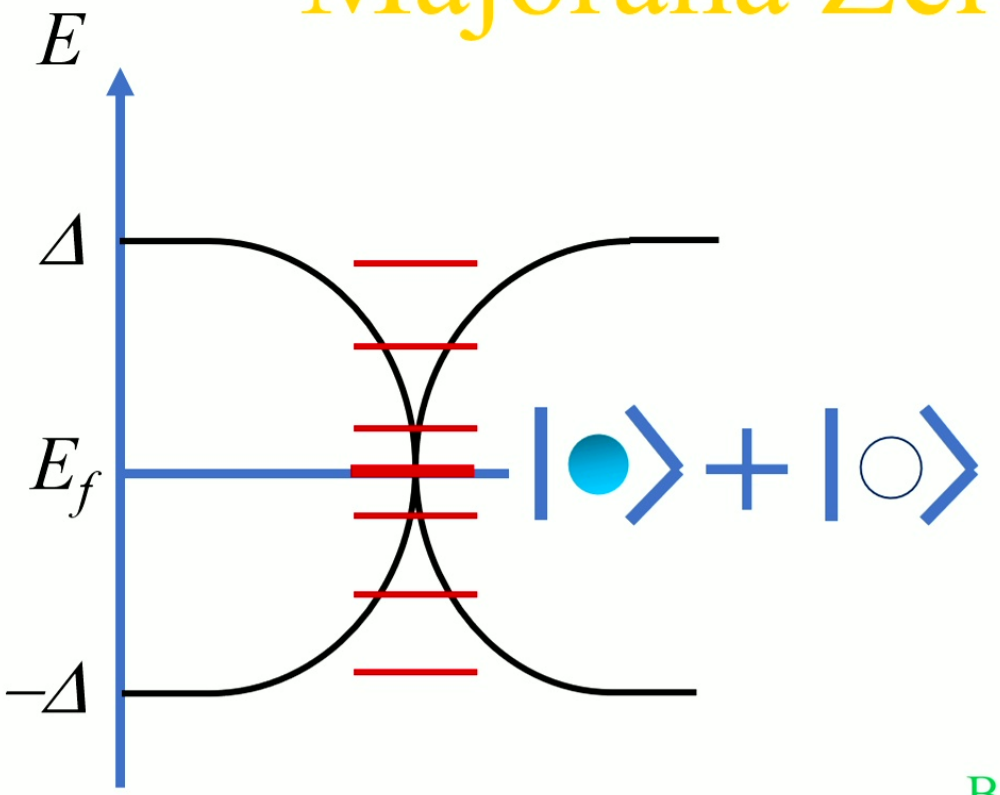




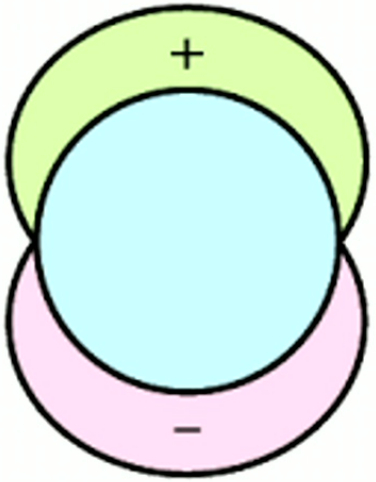




Majorana Zero Mode

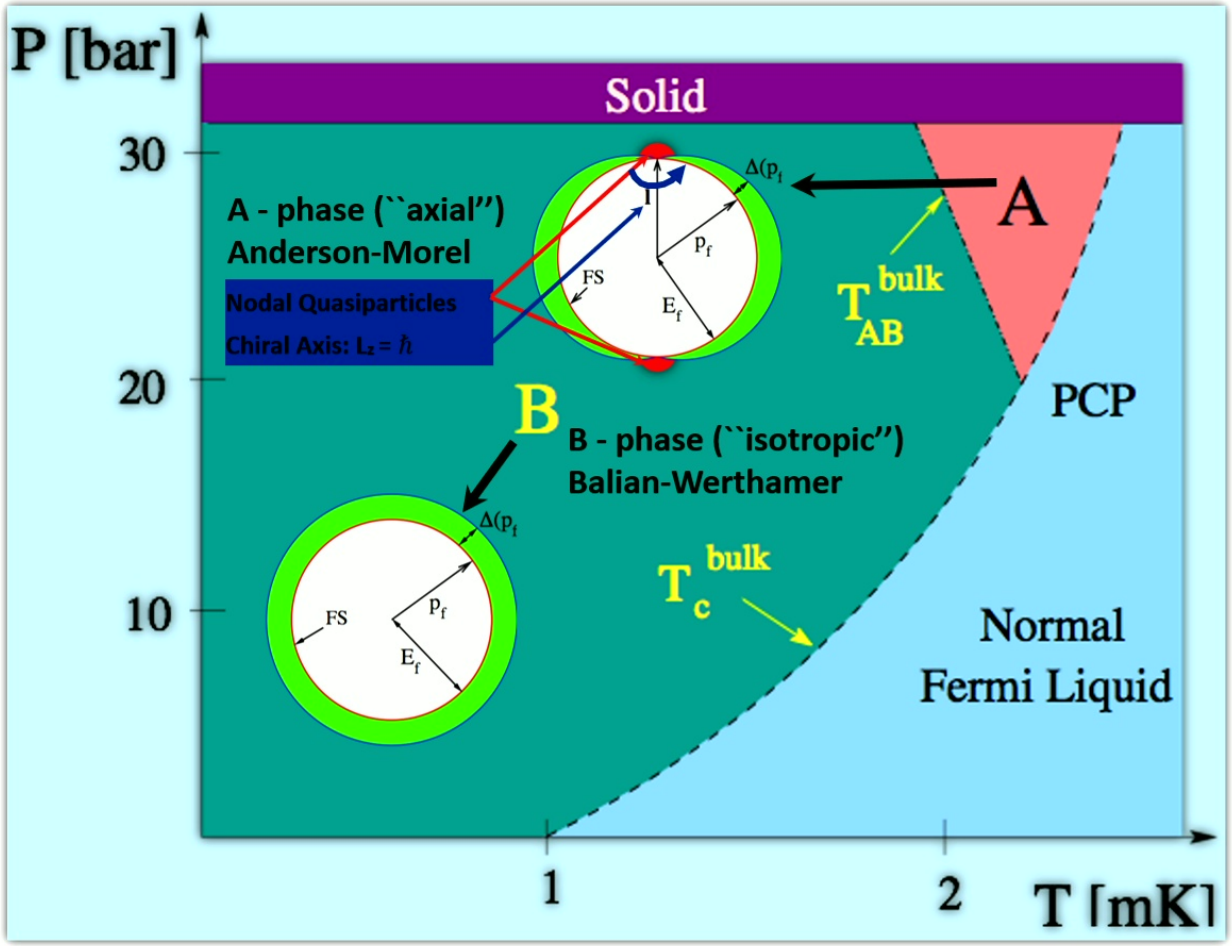


P-wave (triplet) superconductor



Berry phase cancel zero point motion

G.E. Volovik, JETP letters, 70, 609 (1999)

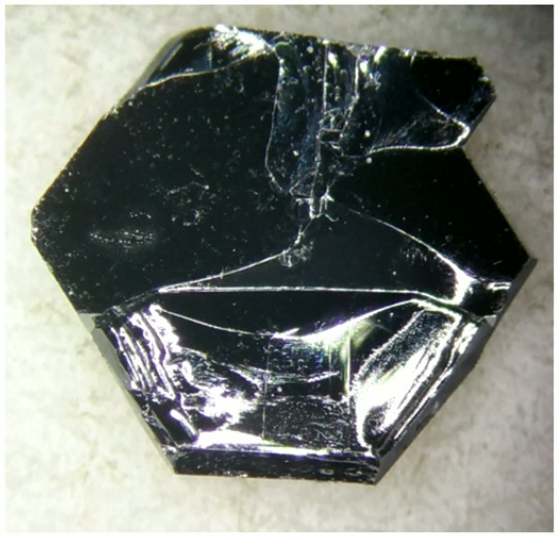


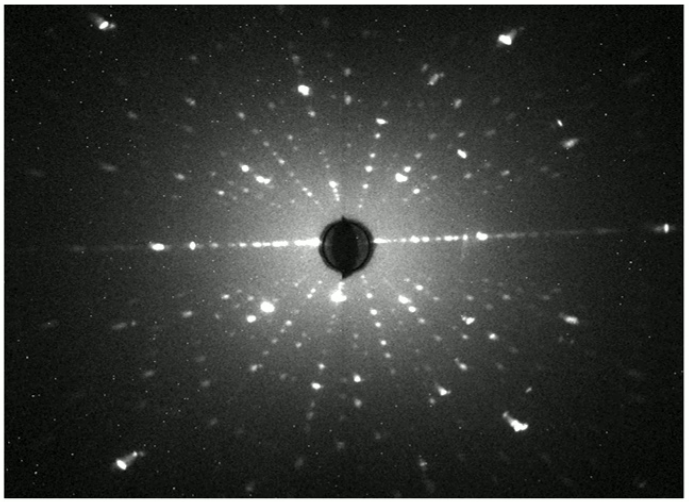
A phase (or ABM phase) :

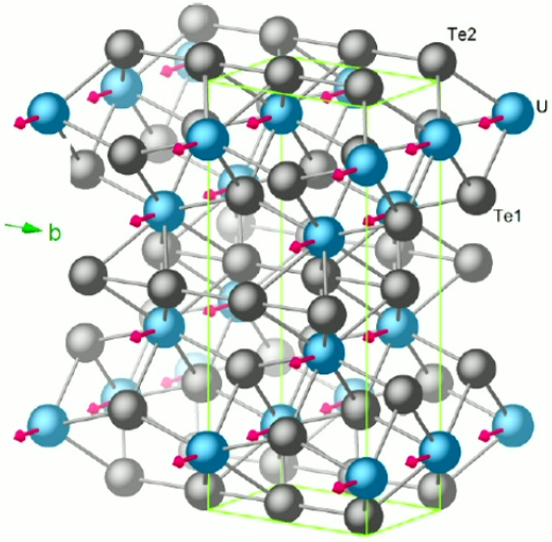
↑↑, ↓↓-equal spin pairing
d=Δ(0,k_x+*i*k_y,0)
Breaks time reversal
Point nodes

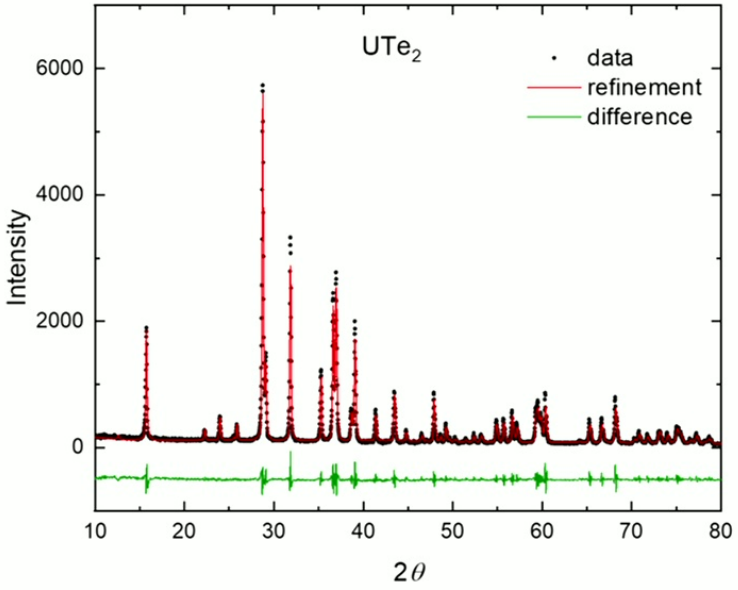
B phase (or BW phase) :

↑↑, ↓↓, (↑↓+↓↑) –not equal spin pairing
d=Δ(k_x,k_y,k_z)
Time reversal symmetric
Isotropic gap

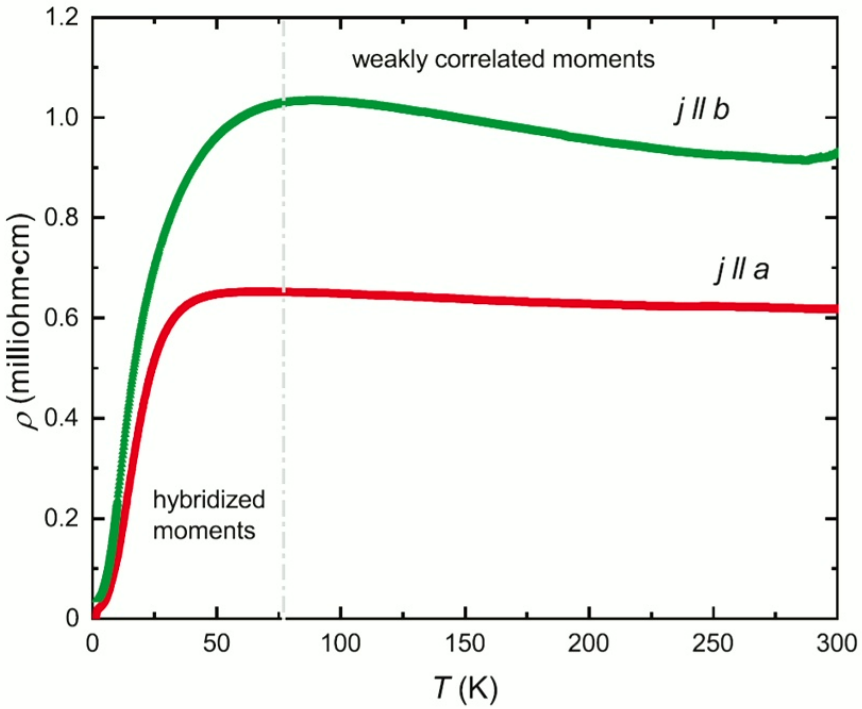


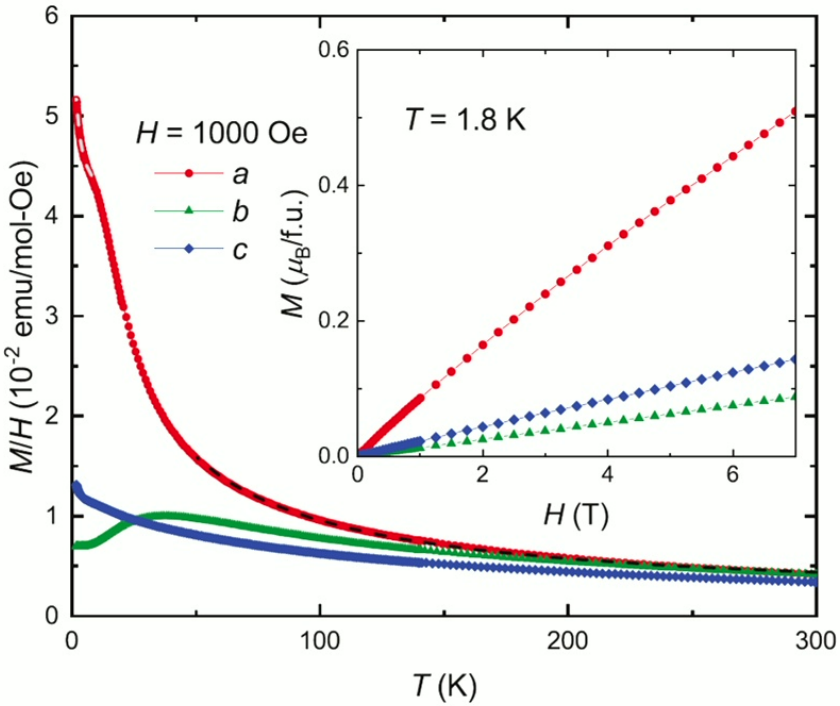



Te2
U
Te1
b


UTe2
data
refinement
difference
Intensity
6000
4000
2000
0
10
20
30
40
50
60
70
80
2θ

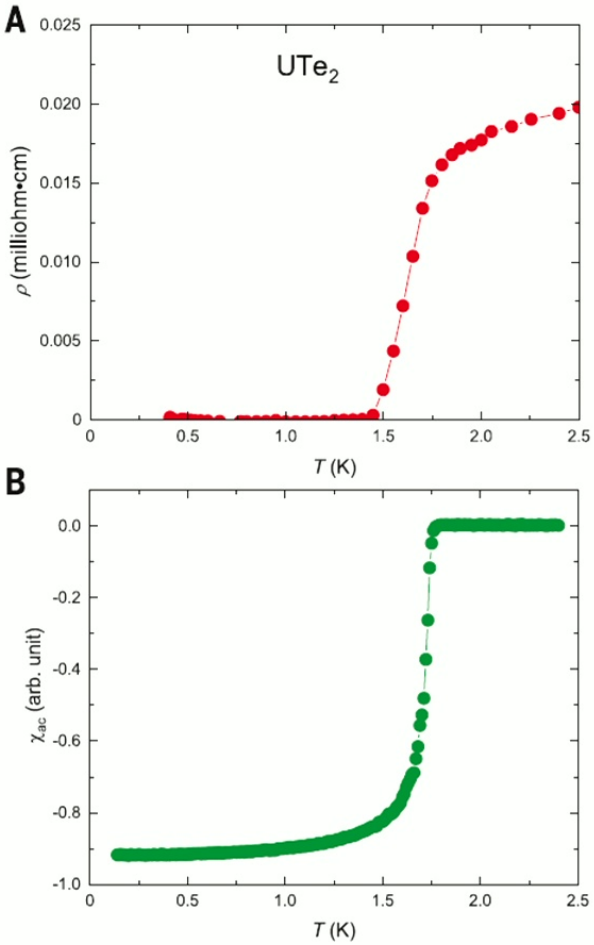
Kondo lattice with no magnetic order

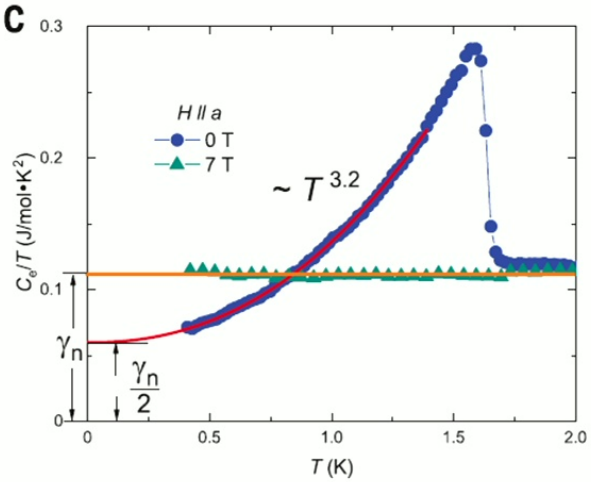




Sheng Ran et al., Science, 365, 684-687 (2019)

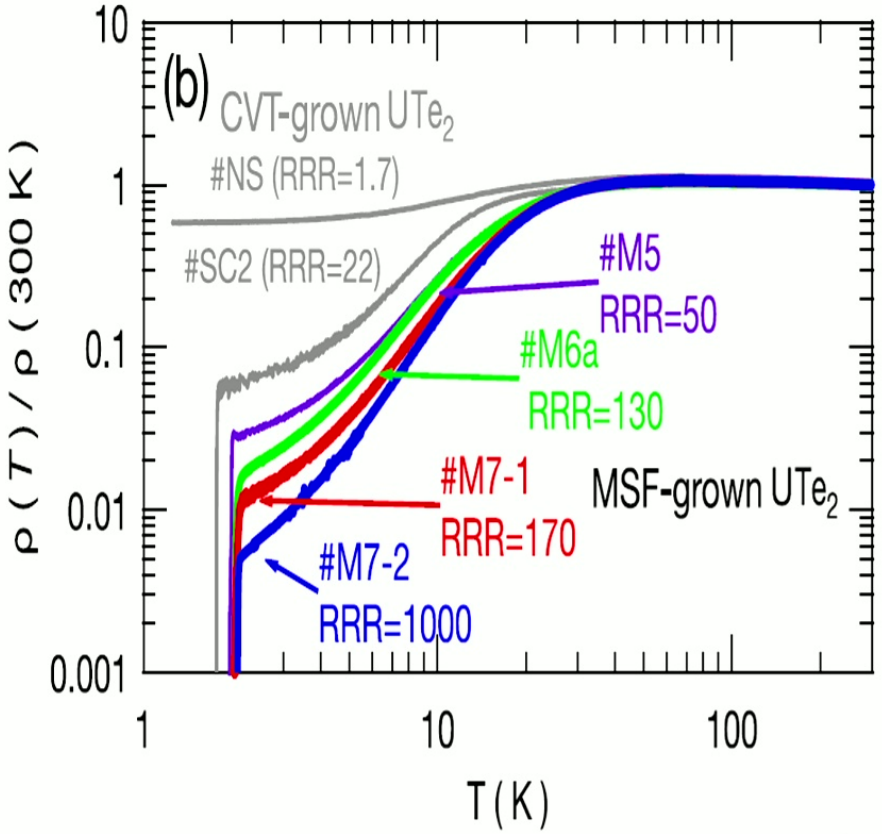
Superconductivity below 1.6 K

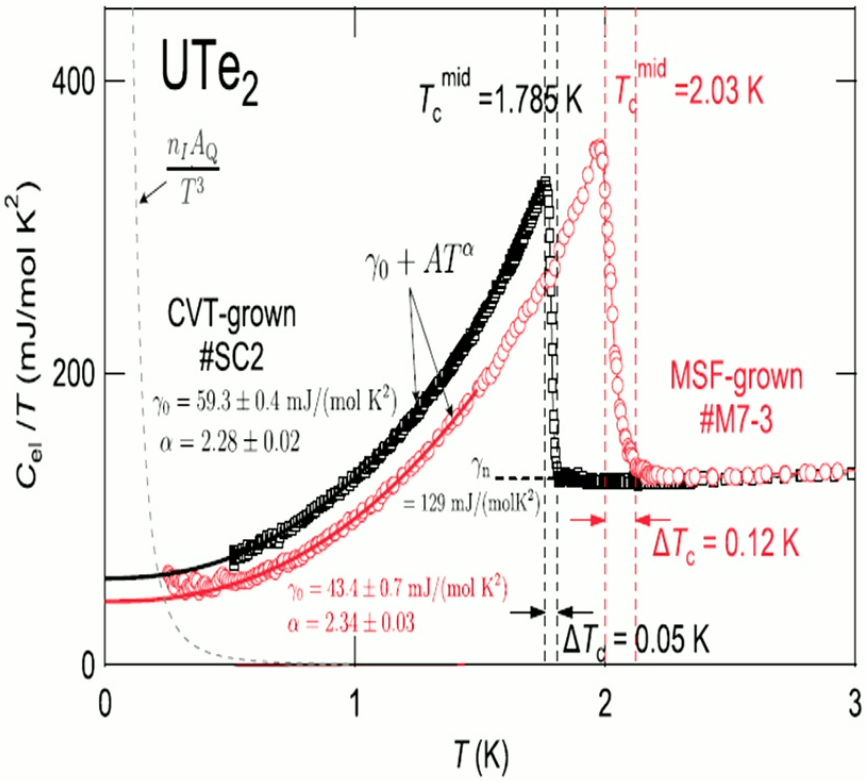




Sheng Ran et al., Science, 365, 684-687 (2019)

2nd generation sample with T_c of 2.1 K

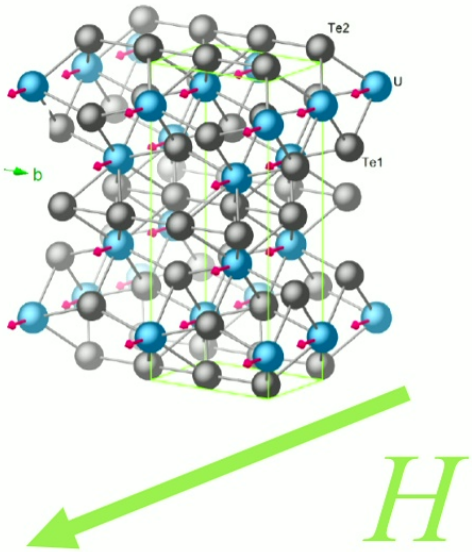


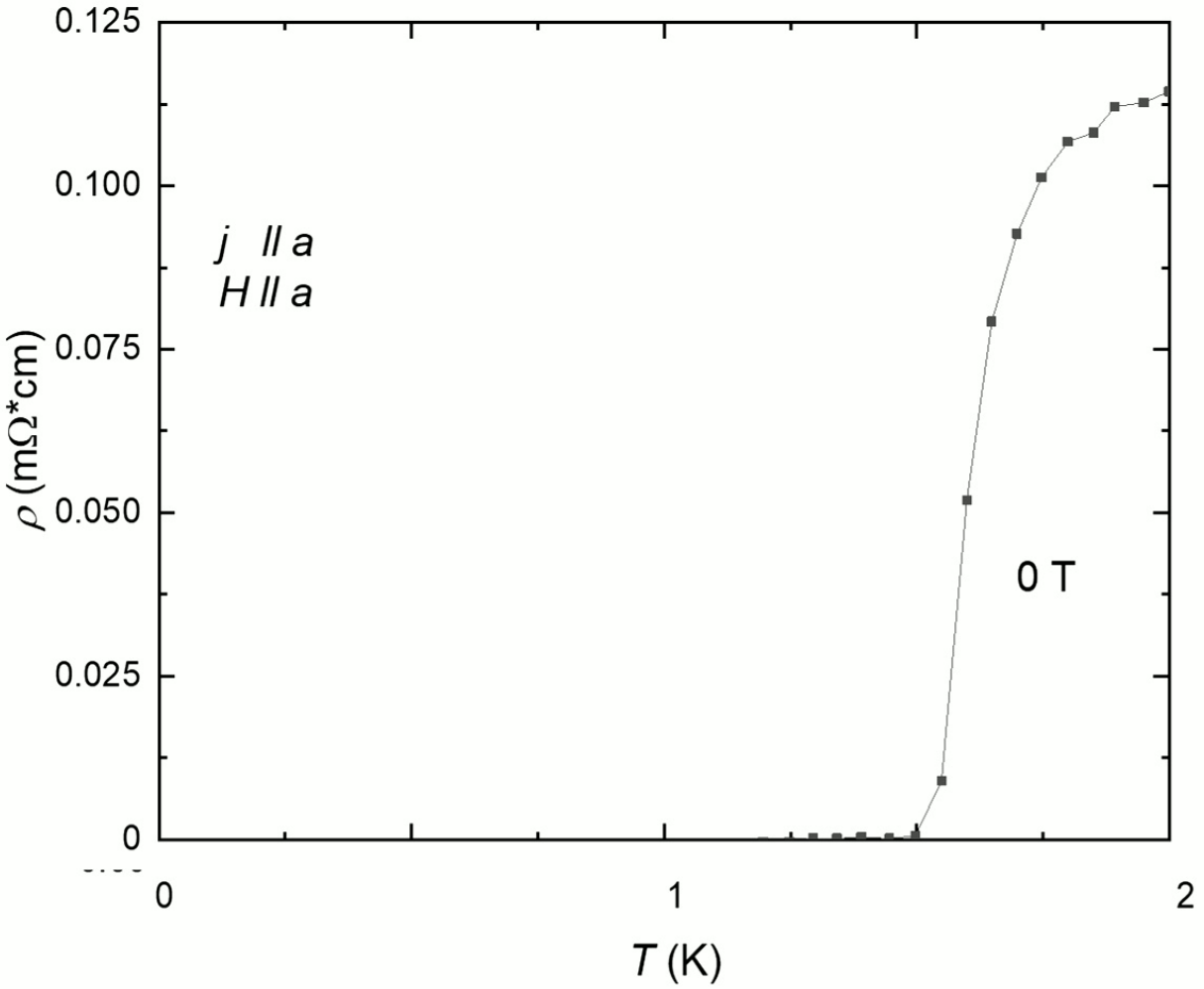


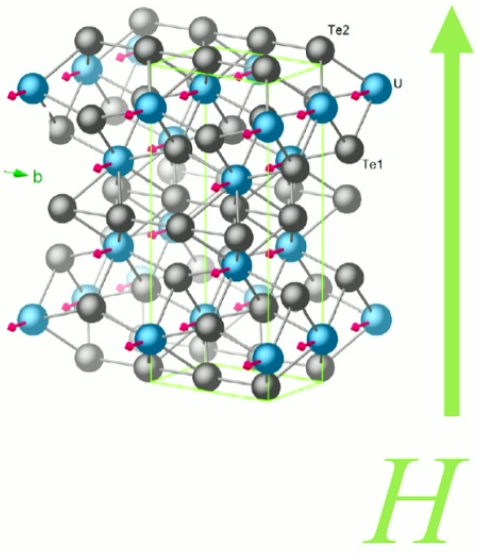
H. Sakai et al., PR Materials, 6, 073401 (2022)

Superconductivity 101

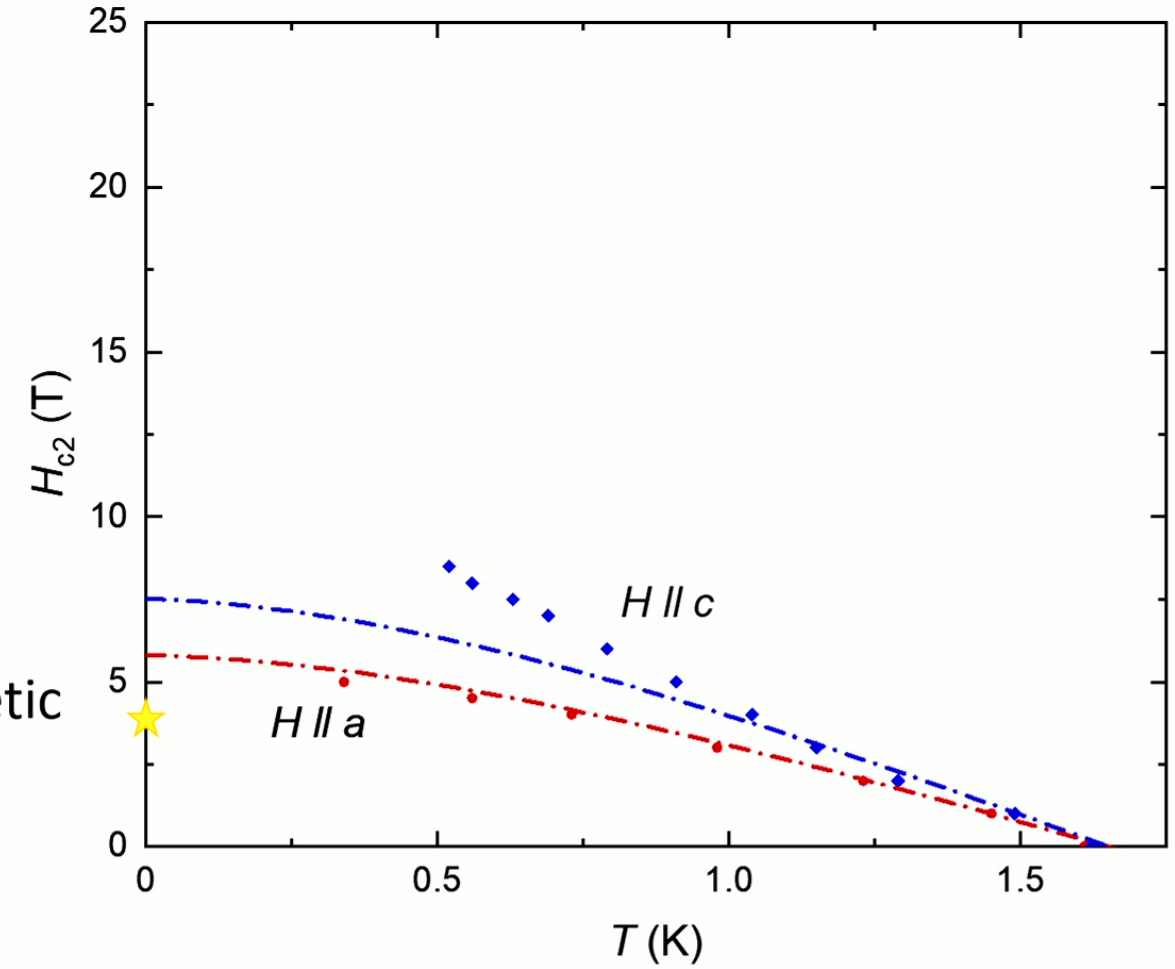
Magnetic field suppresses superconductivity

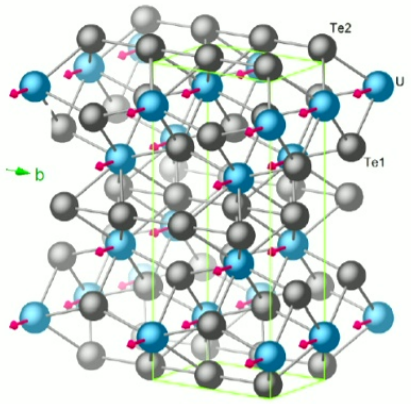

Te2
U
Te1
b
H


0.125
0.100
0.075
0.050
0.025
0
ρ (mΩ*cm)
j ll a
H ll a
0 T
0
1
2
T (K)



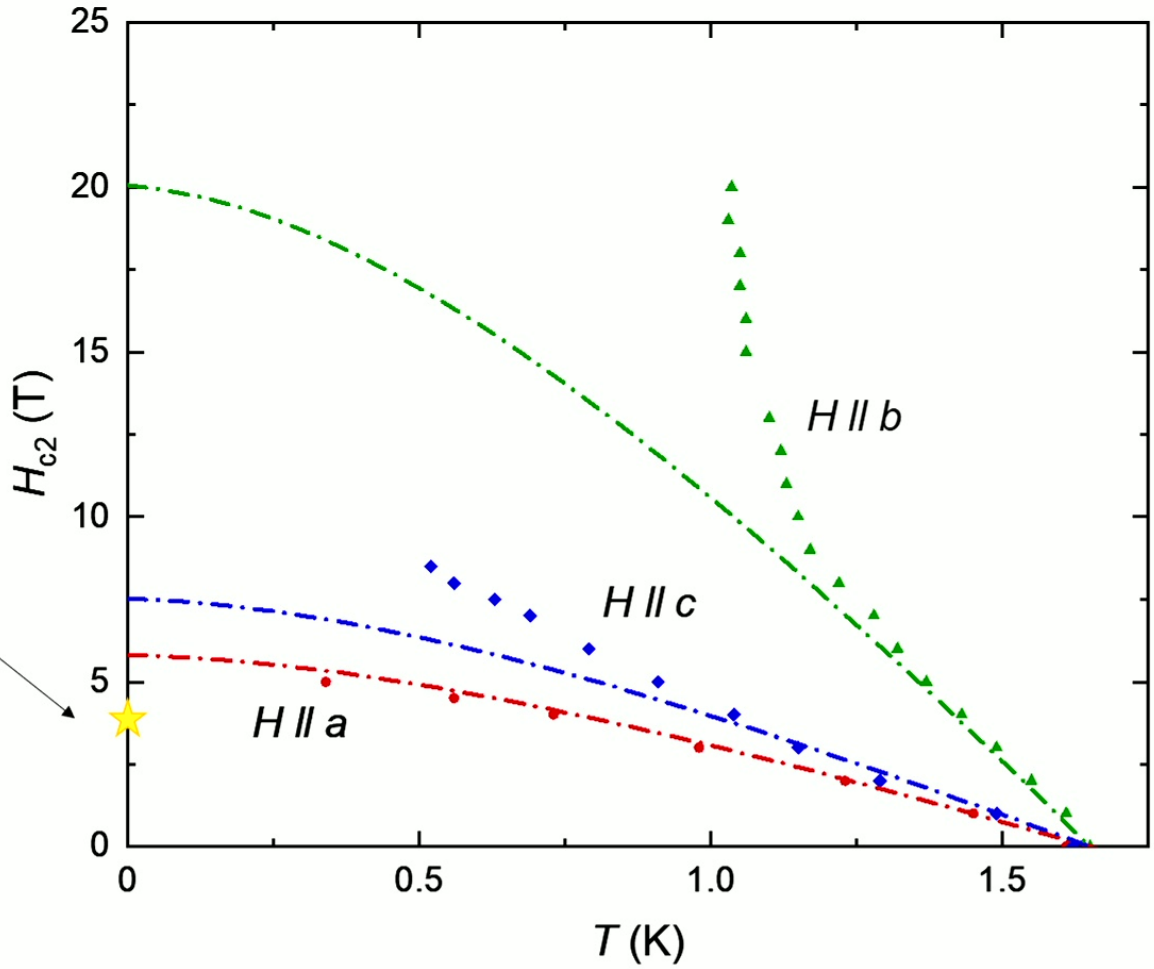
Paramagnetic Limit



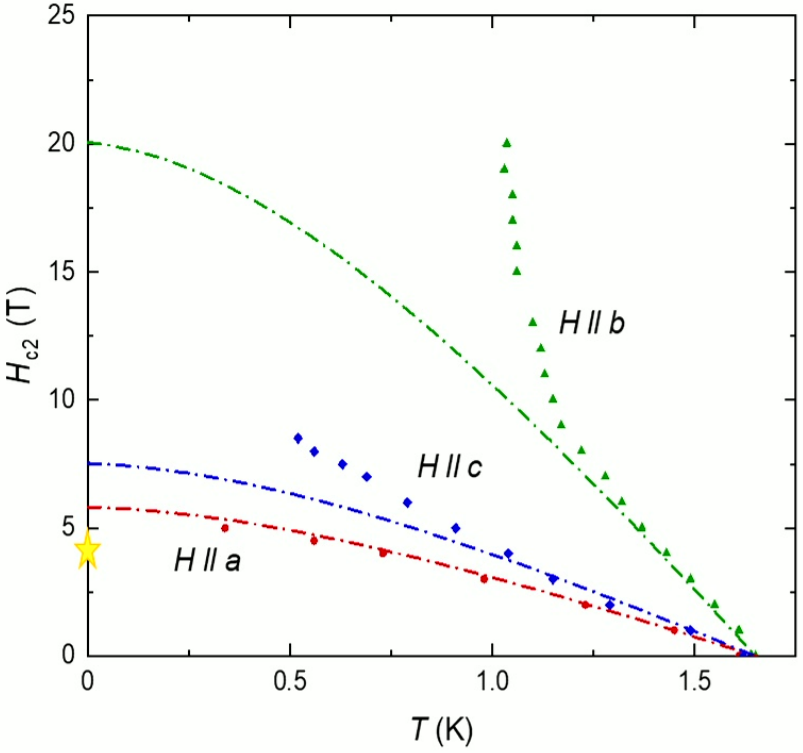


H

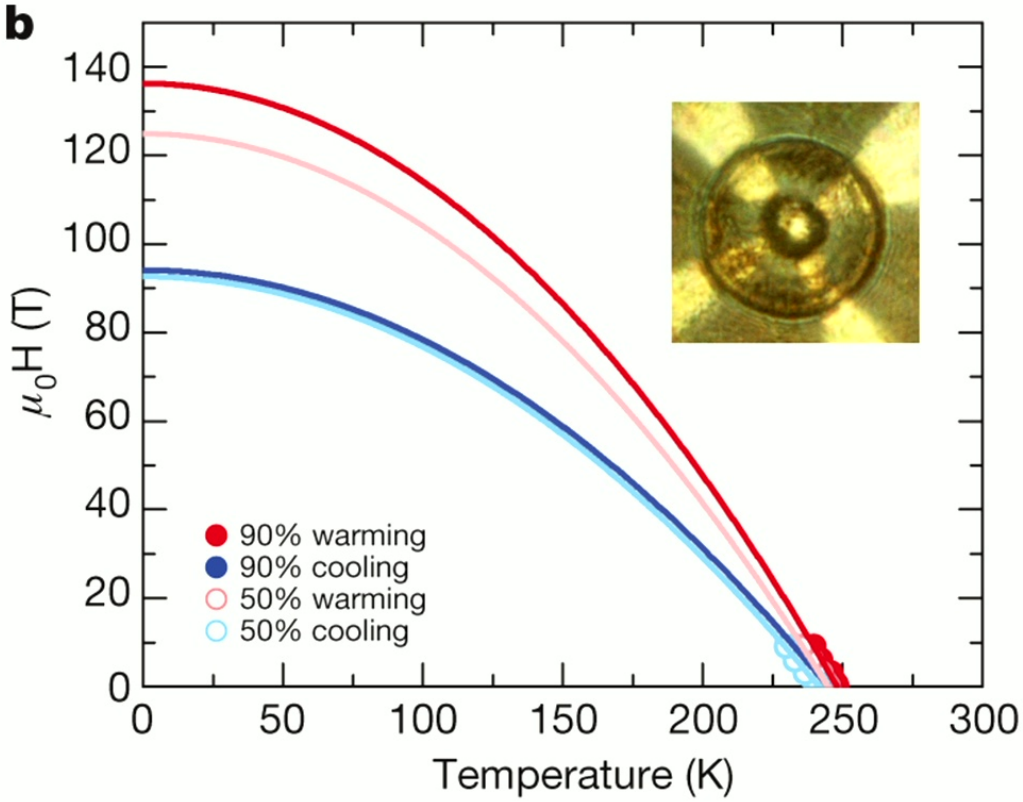
Paramagnetic Limit



Sheng Ran et al., Science, 365, 684-687 (2019)

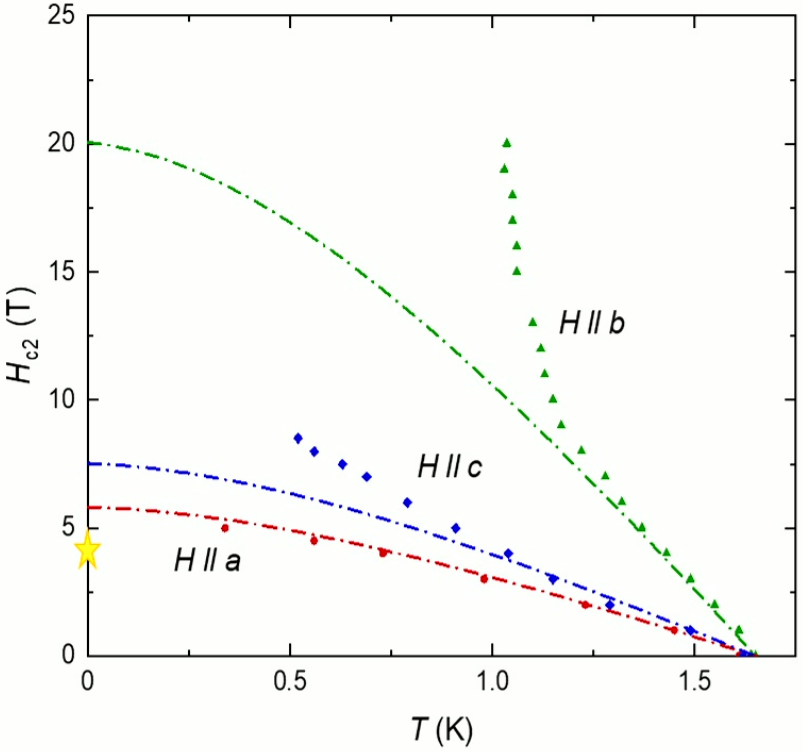


Sheng Ran et al., Science, 365, 684-687 (2019)

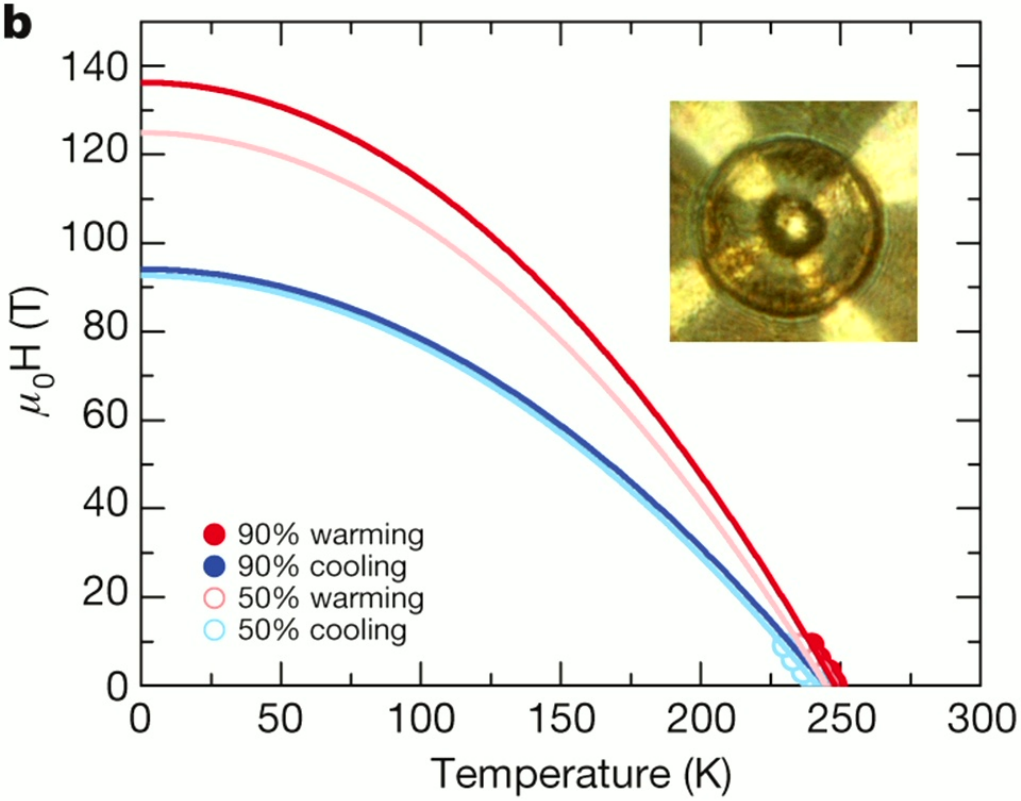


A. P. Drozdov et al., Nature Vol. 569, 528-531 (2019)

Critical magnetic field would be 5000 Tesla!

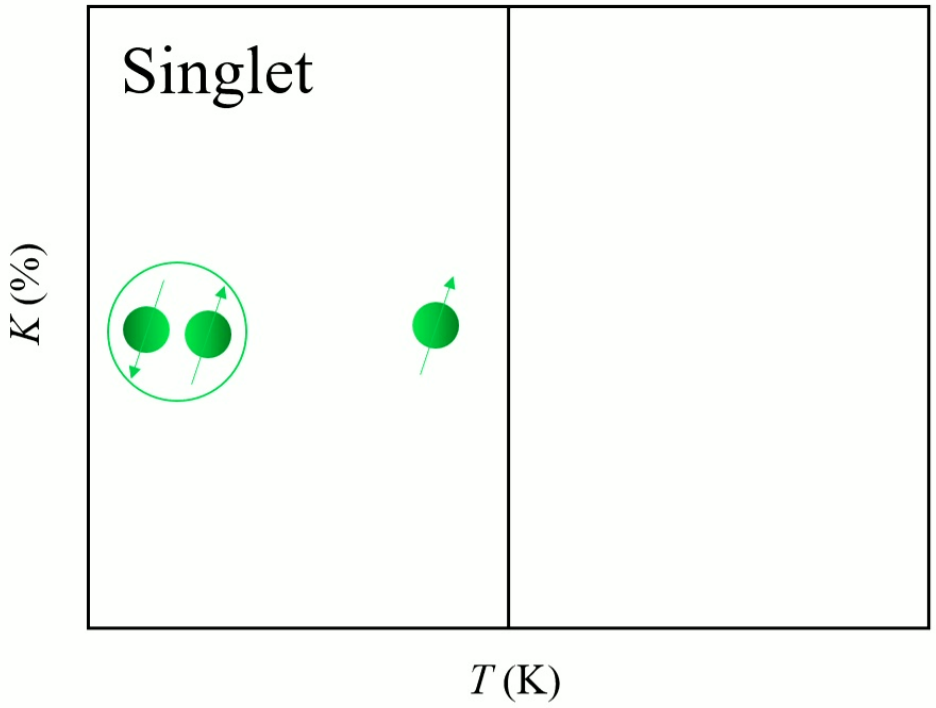


Sheng Ran et al., Science, 365, 684-687 (2019)

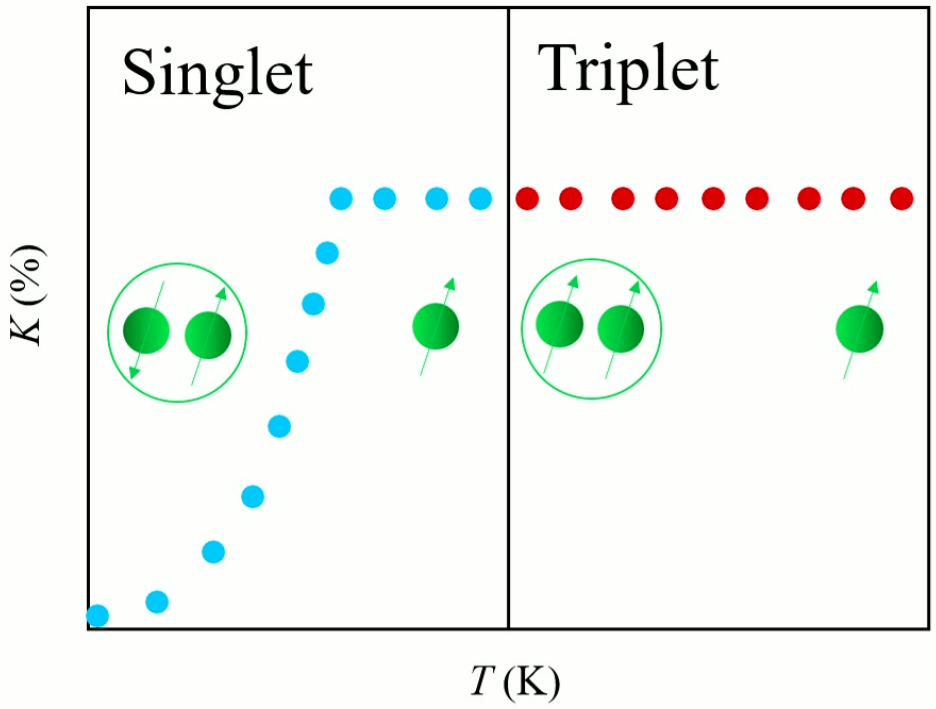


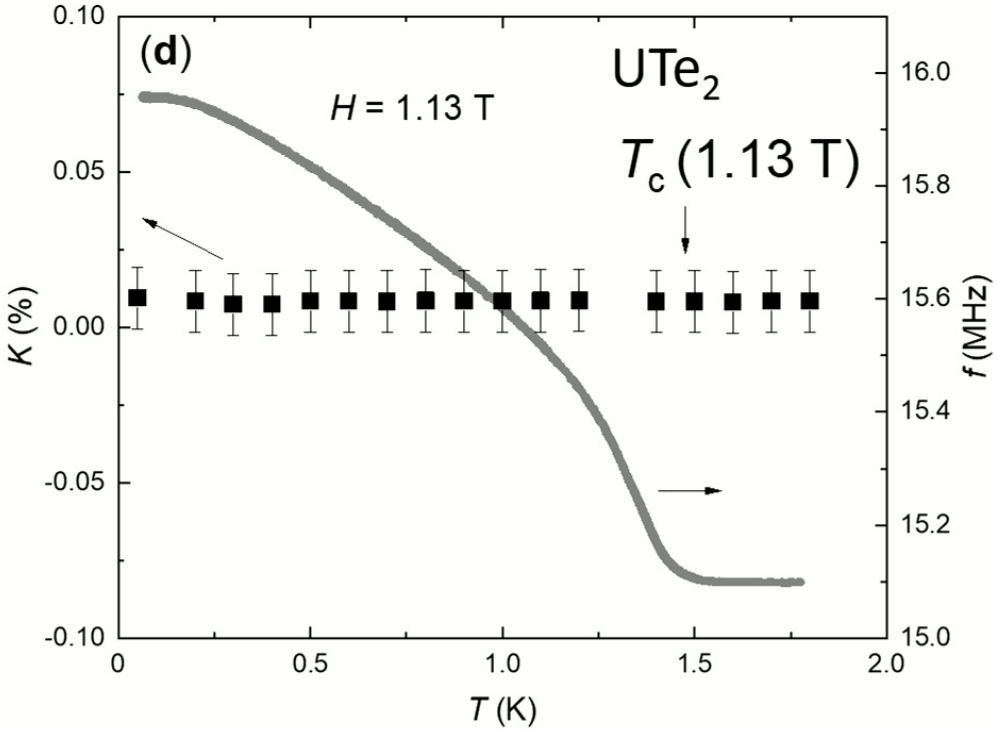
A. P. Drozdov et al., Nature Vol. 569, 528-531 (2019)

NMR - #2 evidence for spin triplet superconductor

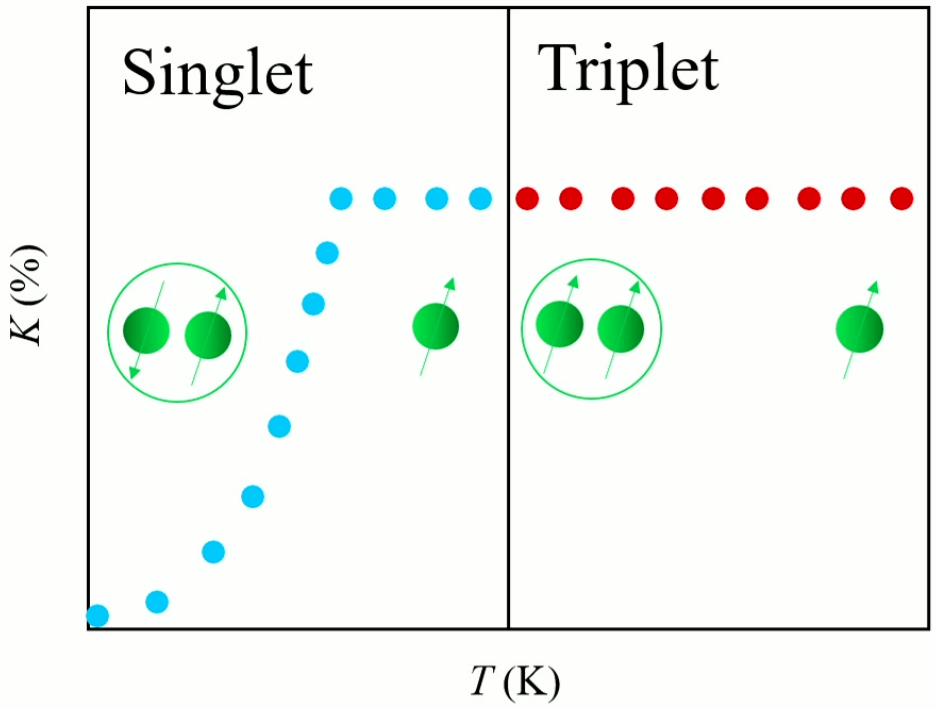


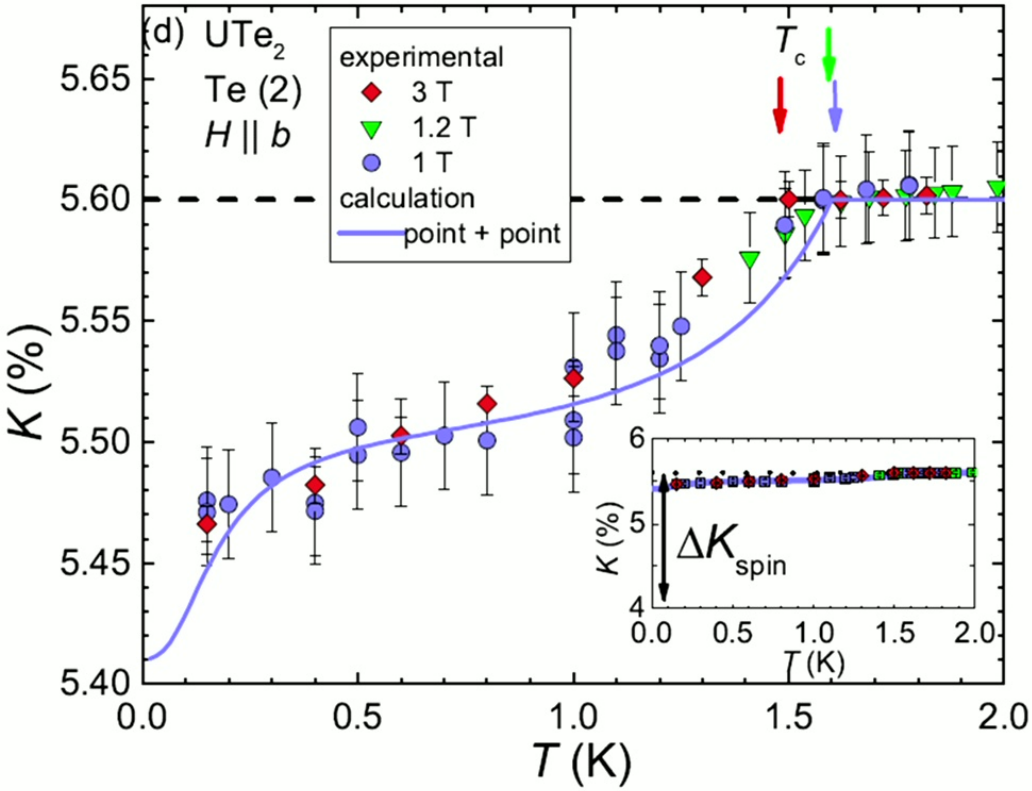
NMR - #2 evidence for spin triplet superconductor





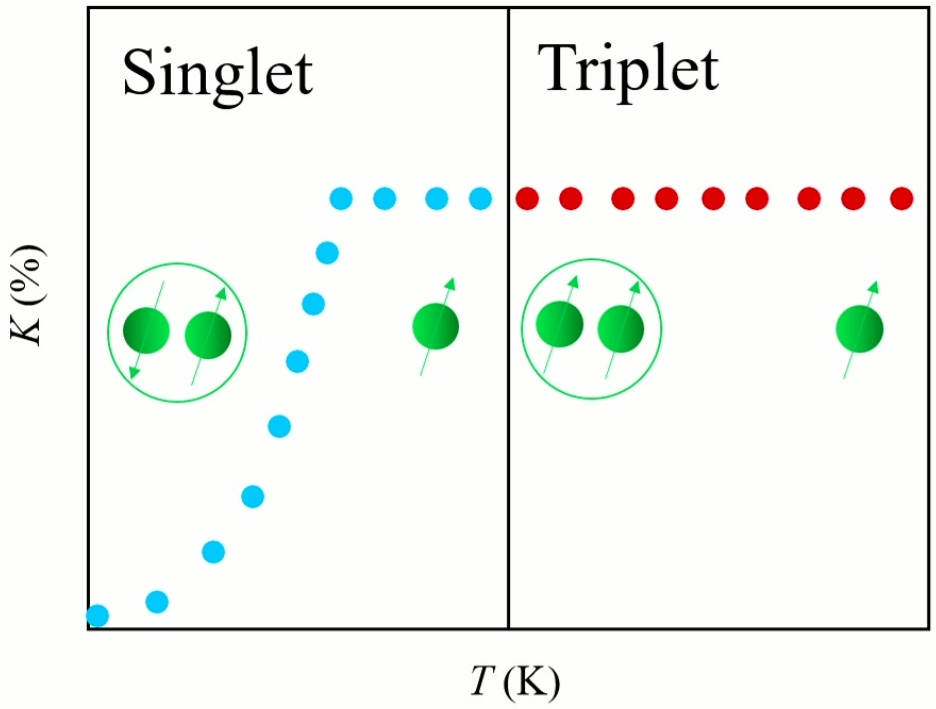
NMR - #2 evidence for spin triplet superconductor

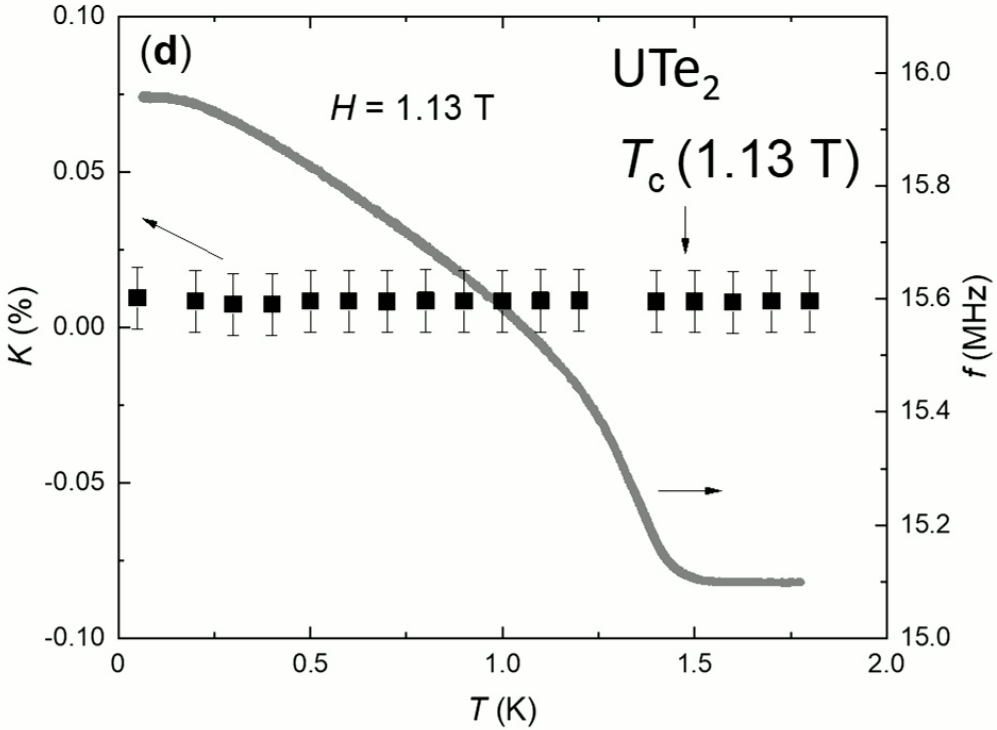




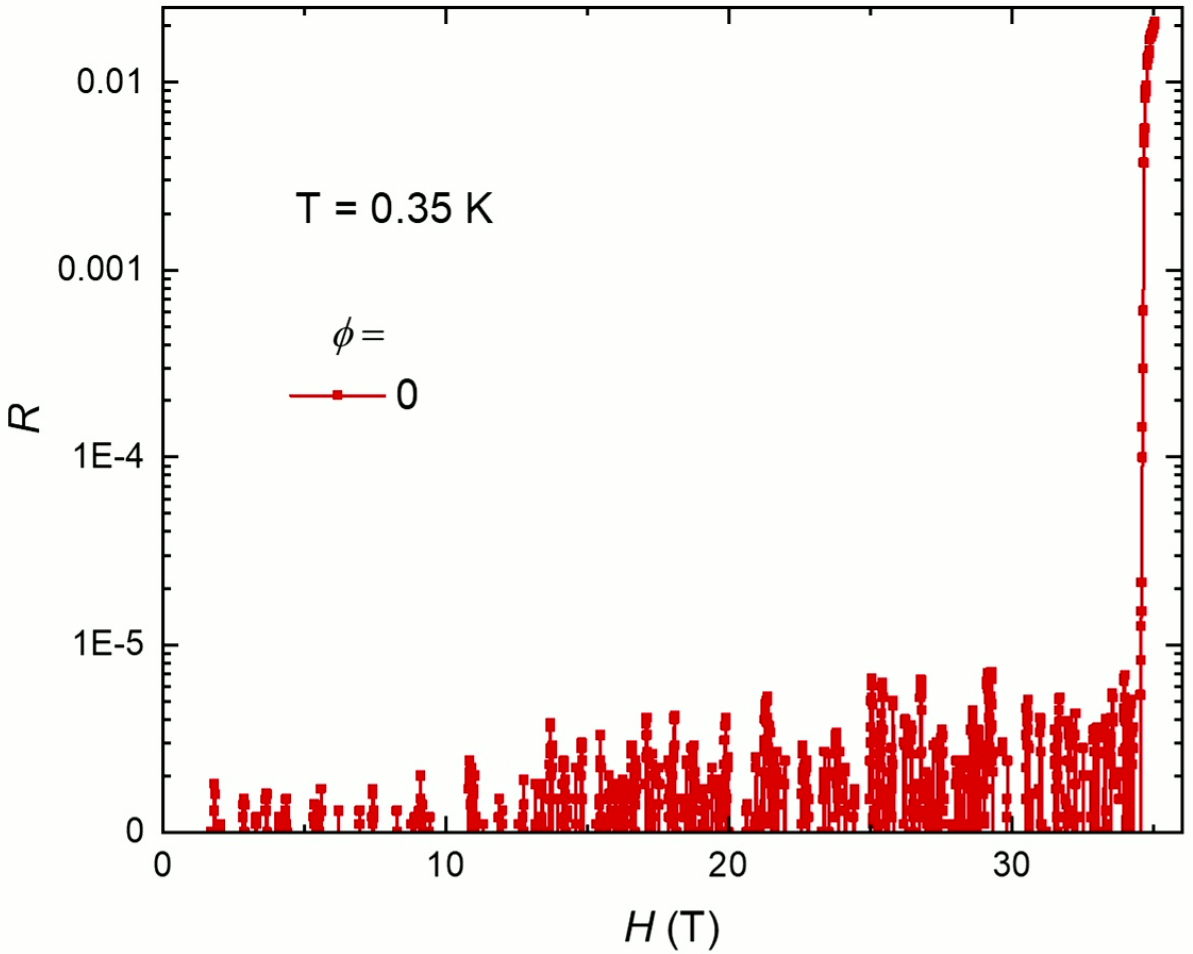
Genki Nakamine et al., J. Phys. Soc. Jpn. 88, 113703 (2019)

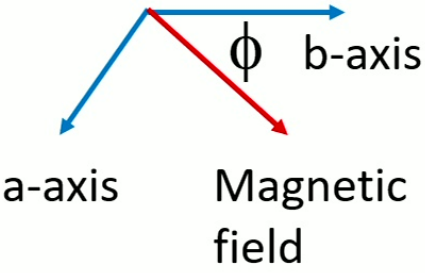
NMR - #2 evidence for spin triplet superconductor





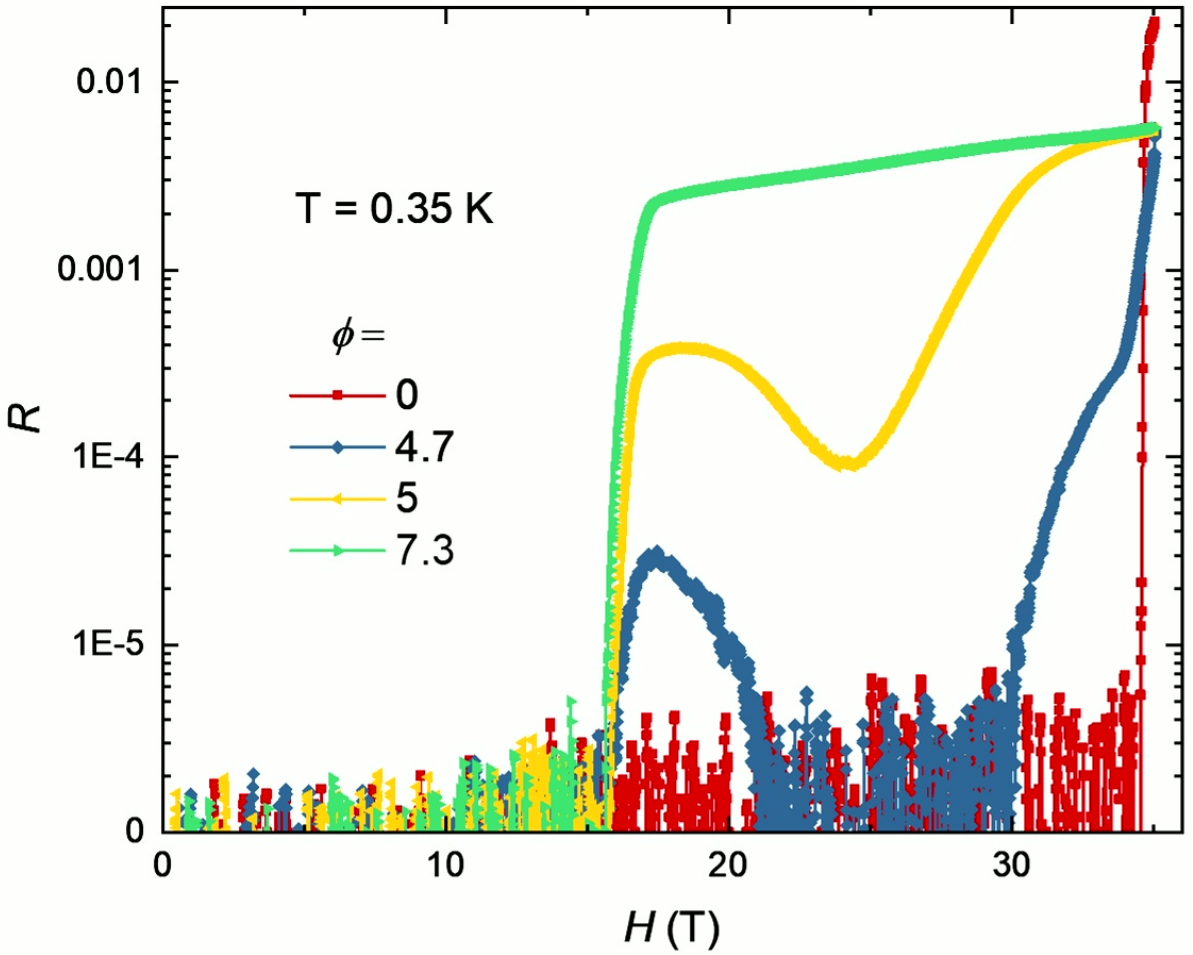
Field induced SC

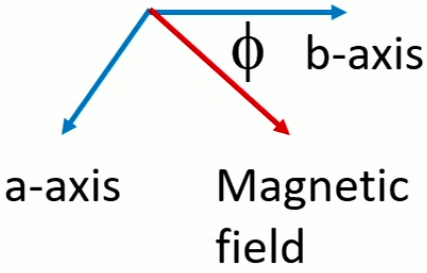




Sheng Ran et al., Nature Physics, 15, 1250-1254 (2019)

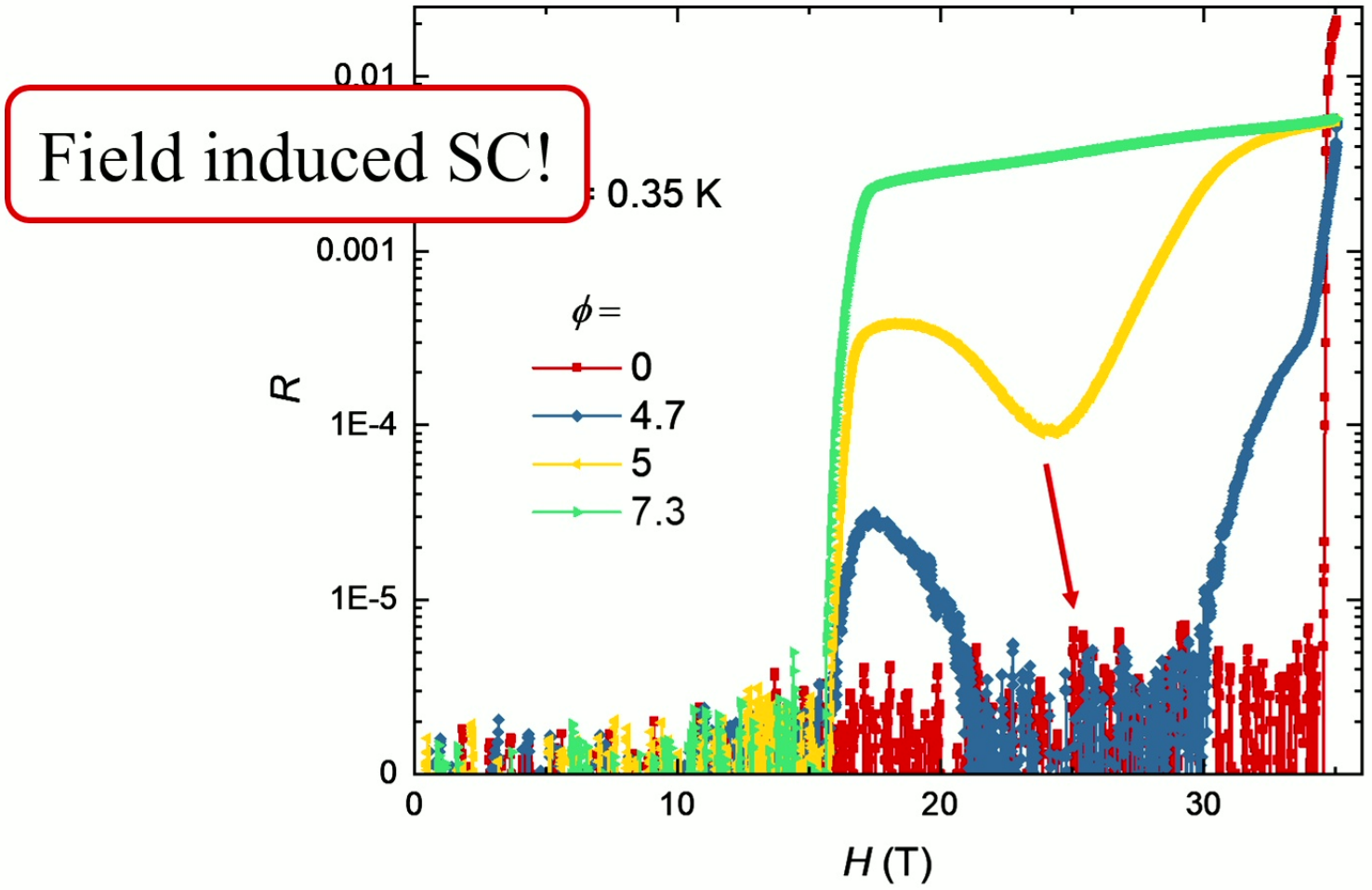
Field induced SC

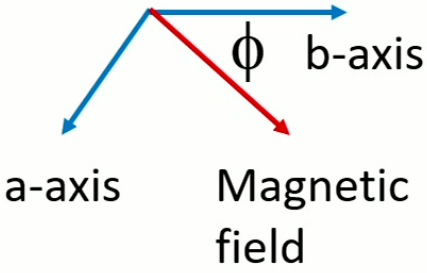




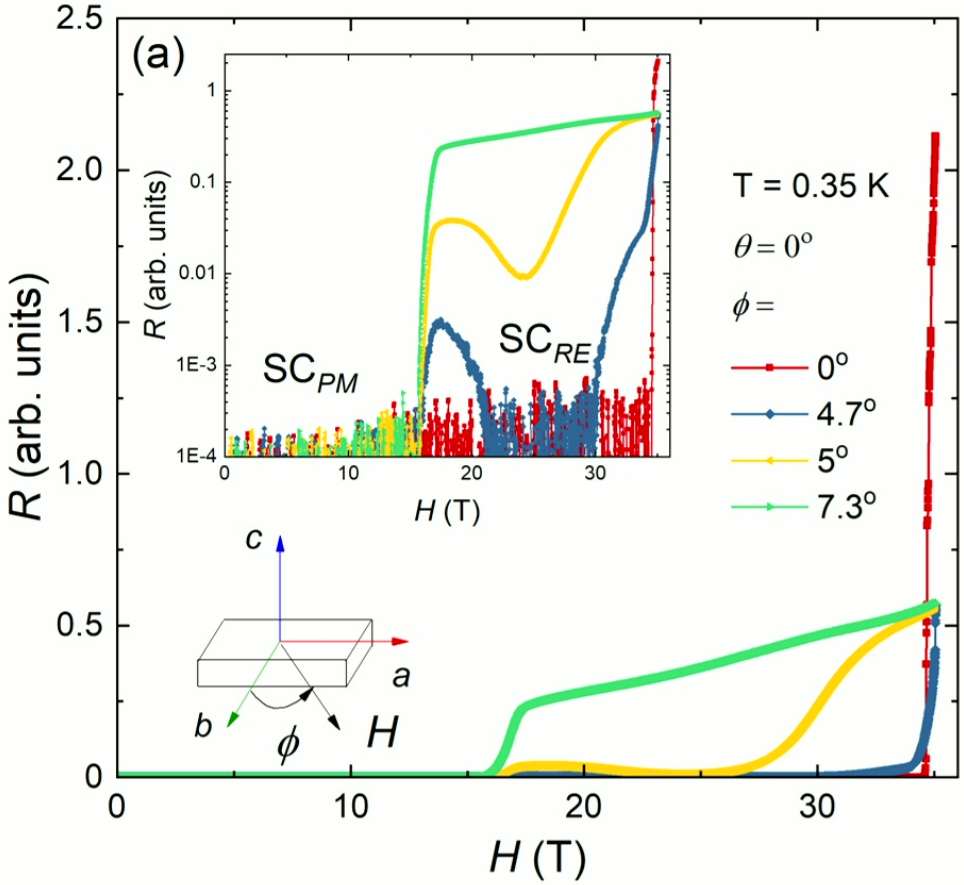
Sheng Ran et al., Nature Physics, 15, 1250-1254 (2019)

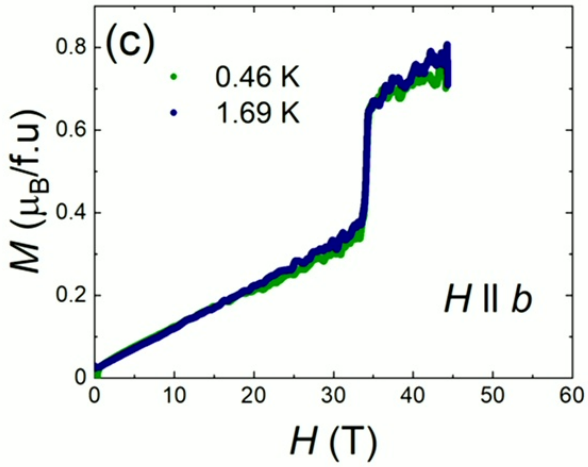
Field induced SC

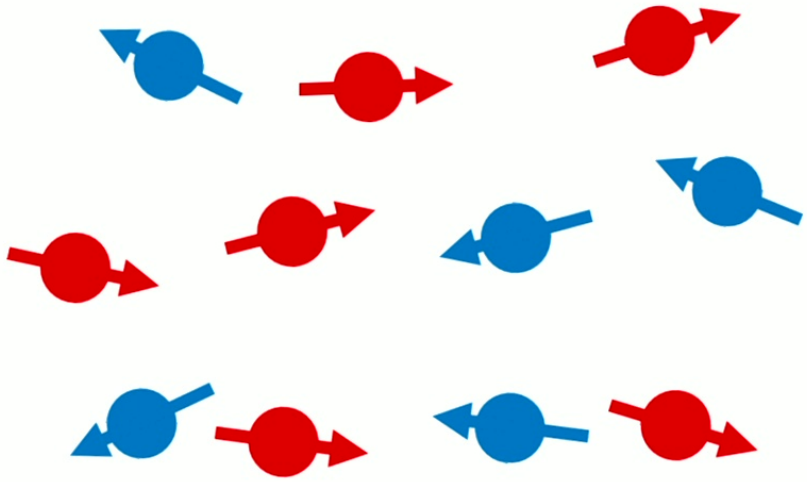


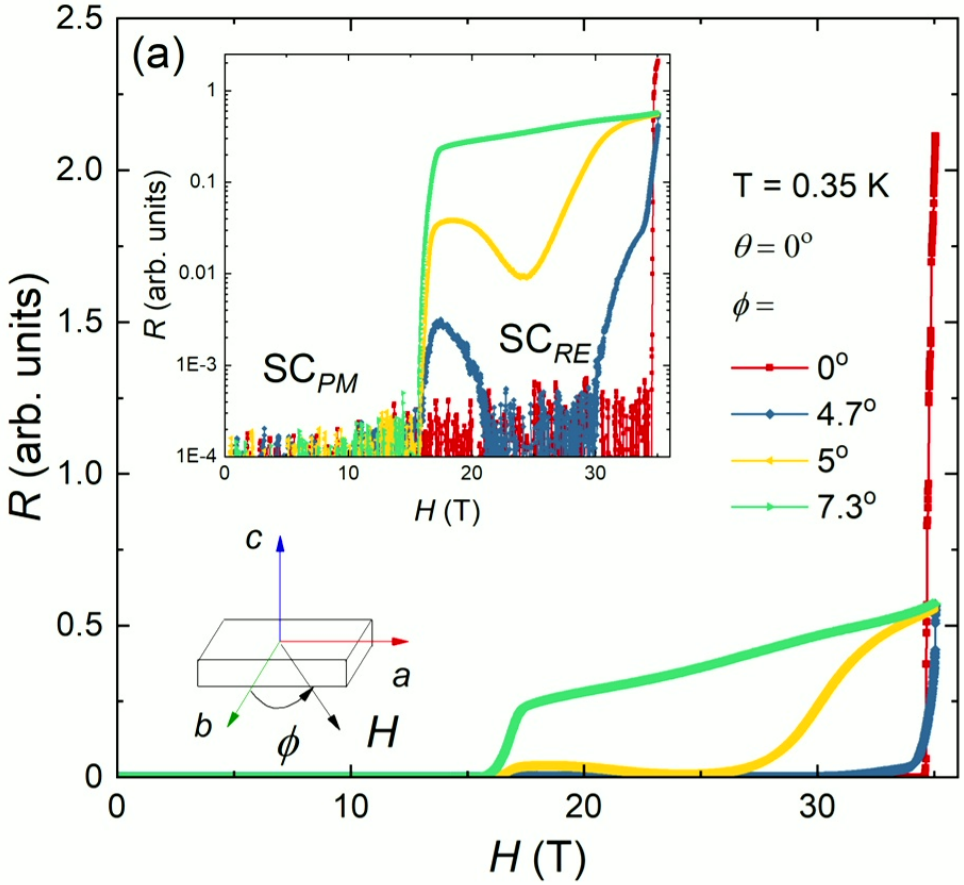


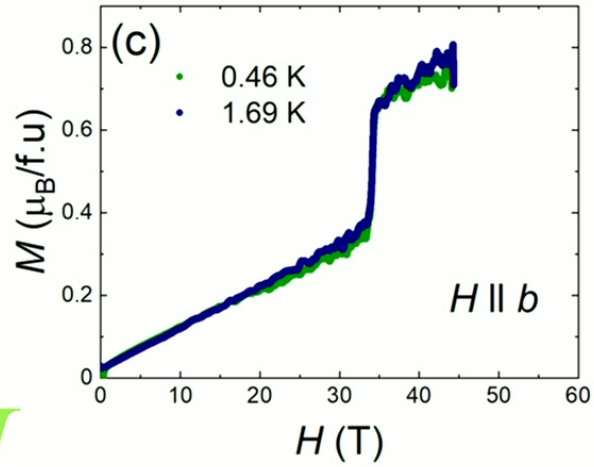
Sheng Ran et al., Nature Physics, 15, 1250-1254 (2019)


(a)
R (arb. units)
H (T)
T = 0.35 K
θ = 0°
ϕ =
0°
4.7°
5°
7.3°
SC_PM
SC_RE
c
a
b
ϕ
H

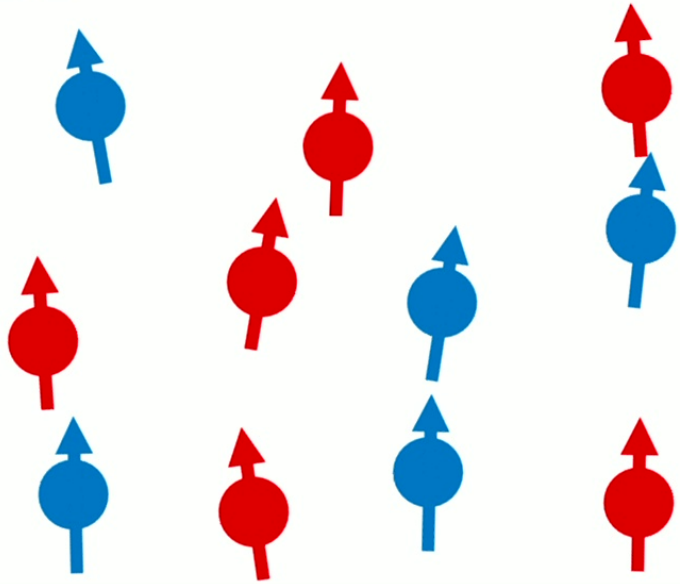

(c)
0.46 K
1.69 K
M (μB/f.u)
H (T)
H ∥ b



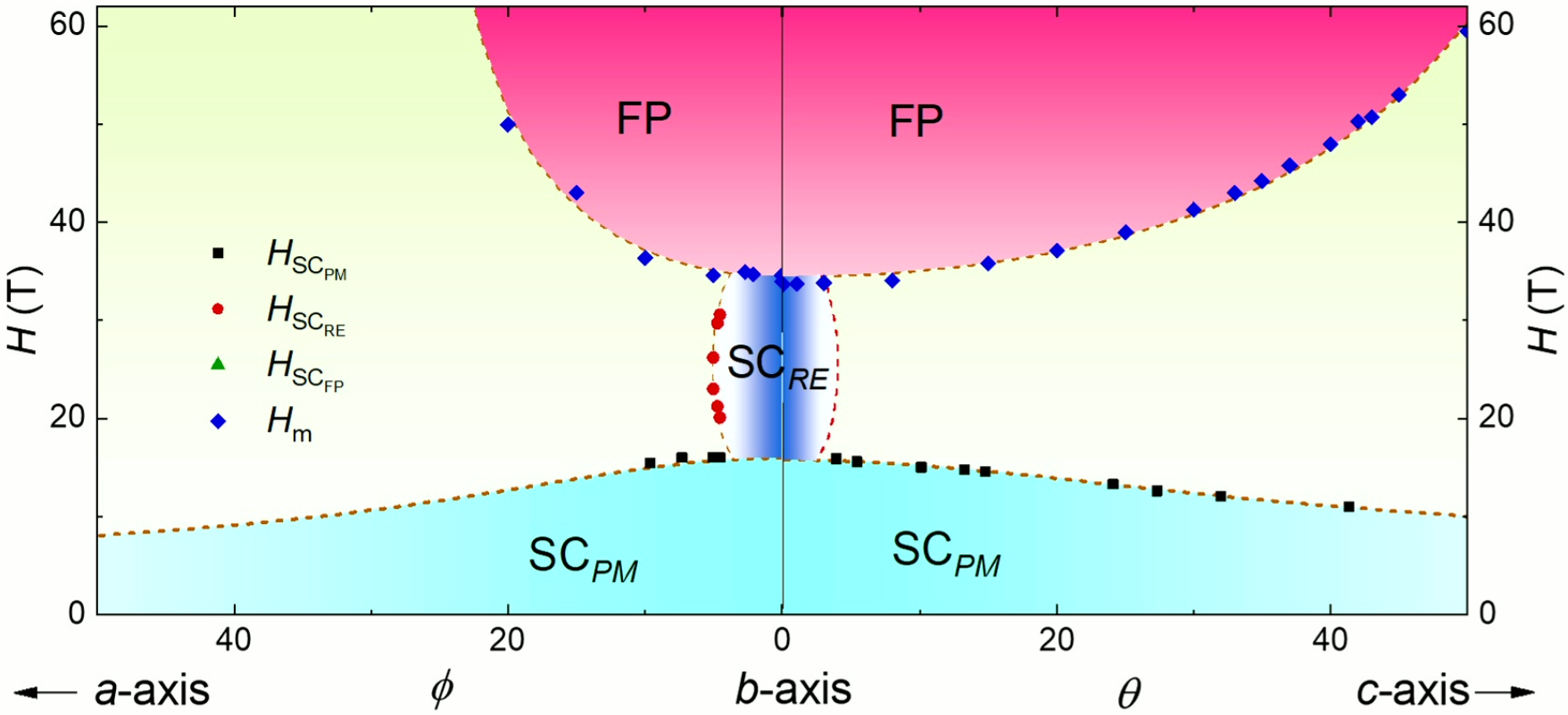




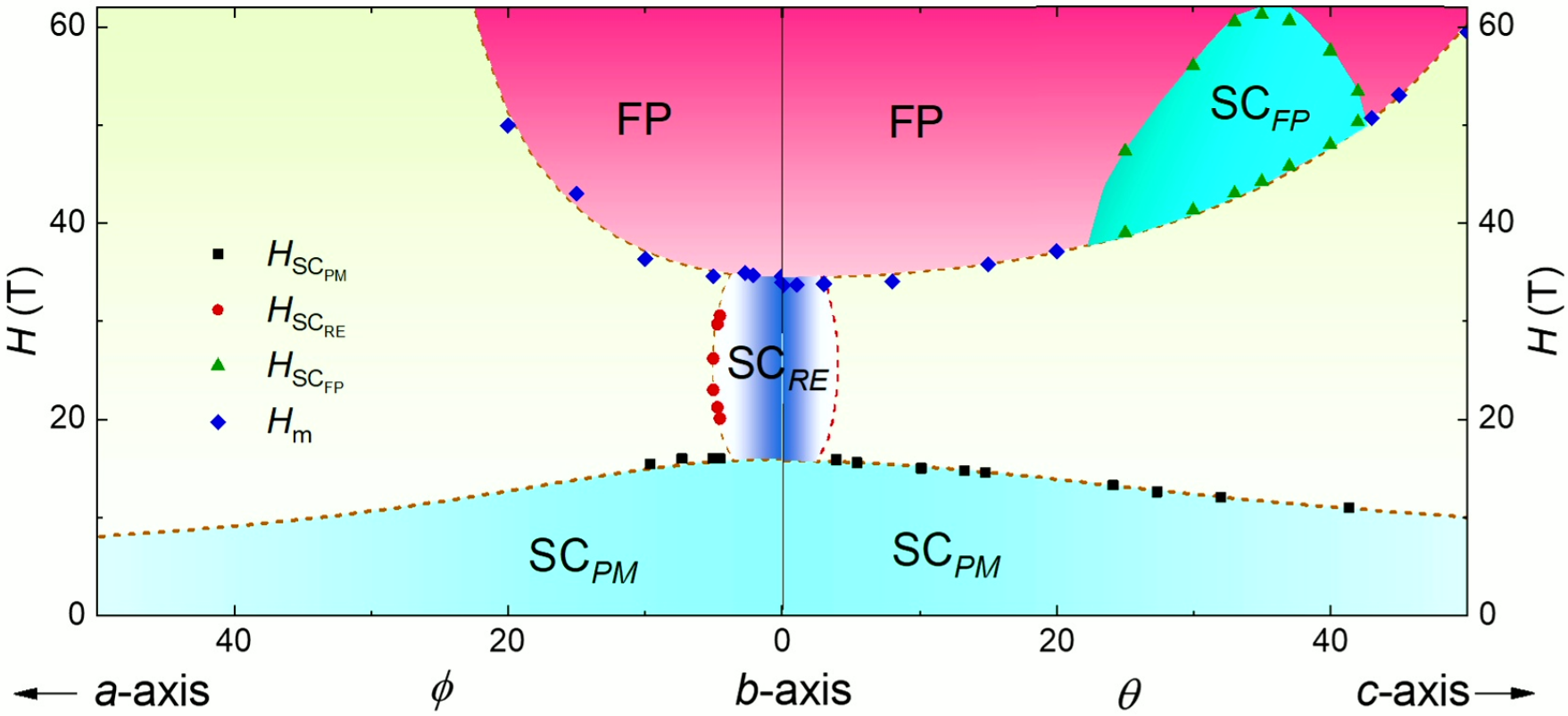
H



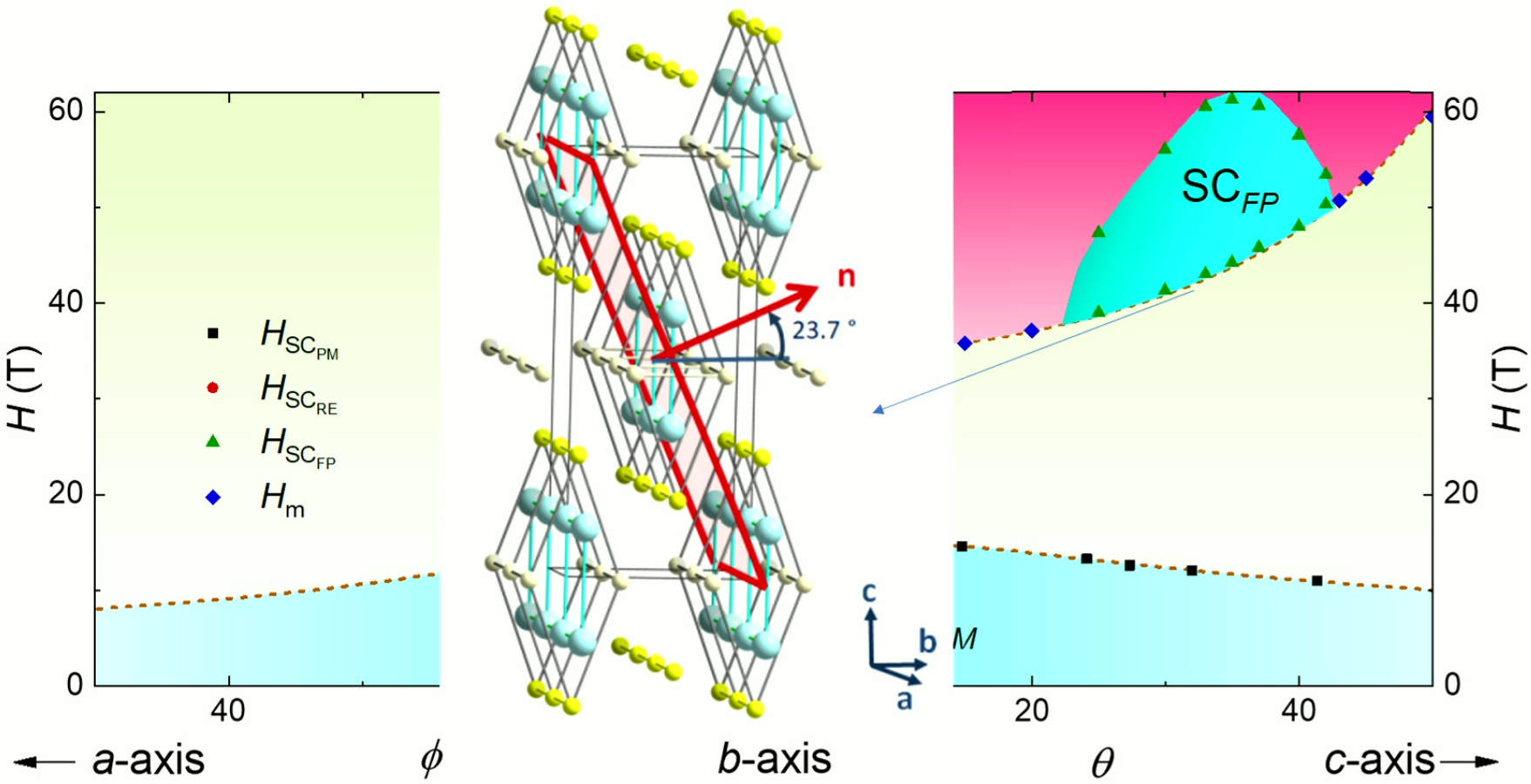
Field induced FM



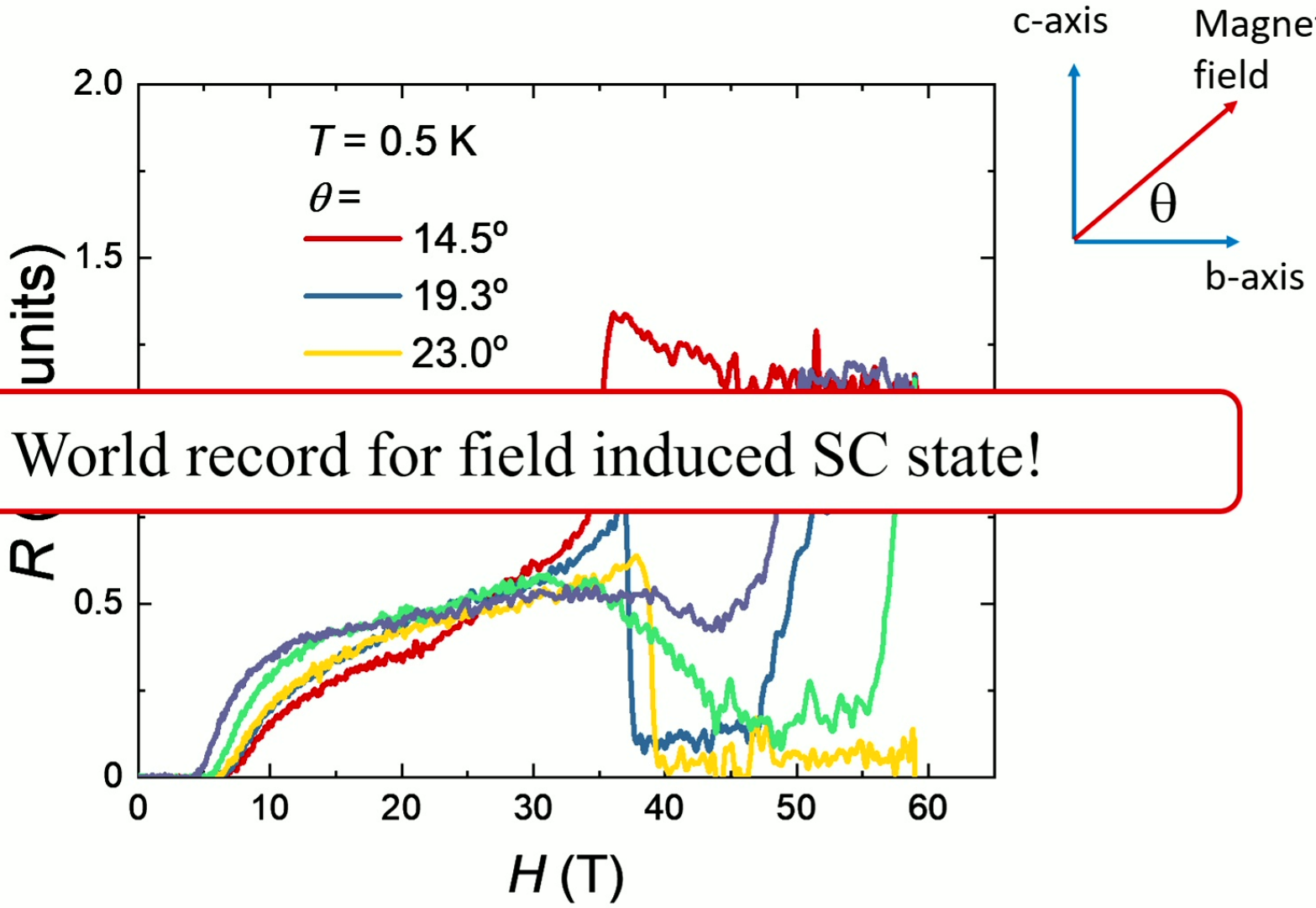
Sheng Ran et al., Nature Physics, 15, 1250-1254 (2019)



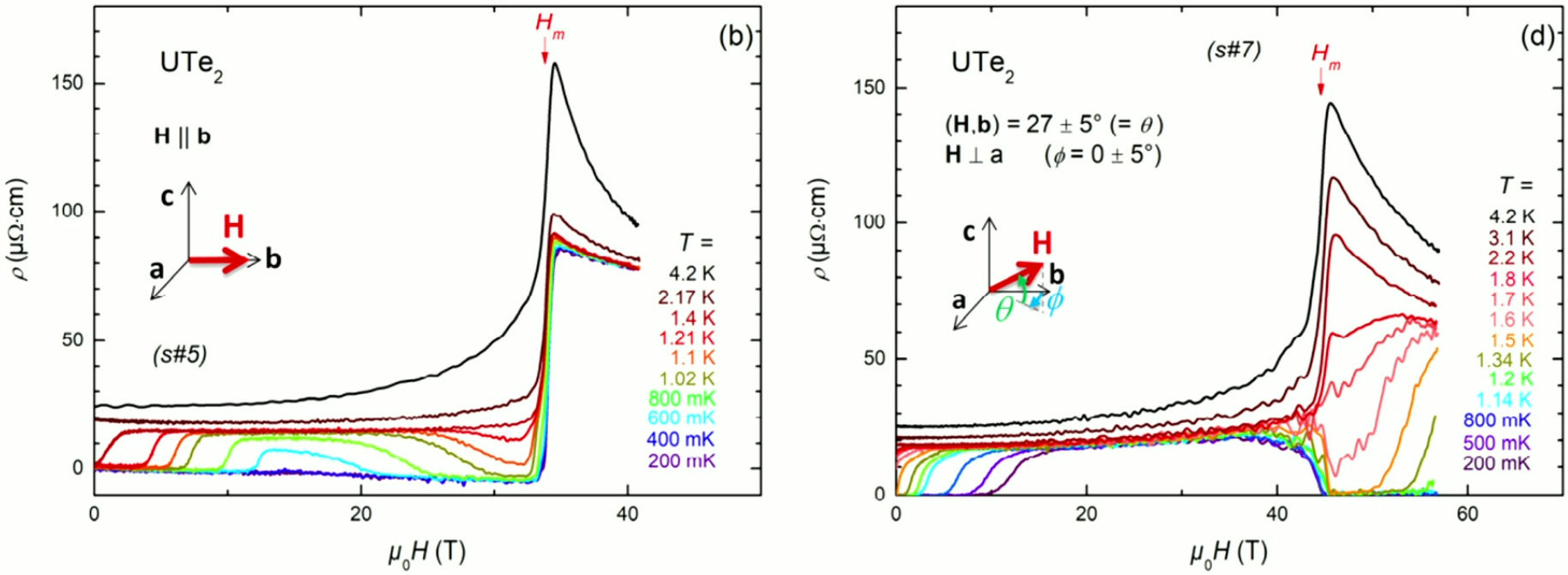
Sheng Ran et al., Nature Physics, 15, 1250-1254 (2019)



Sheng Ran et al., Nature Physics, 15, 1250-1254 (2019)

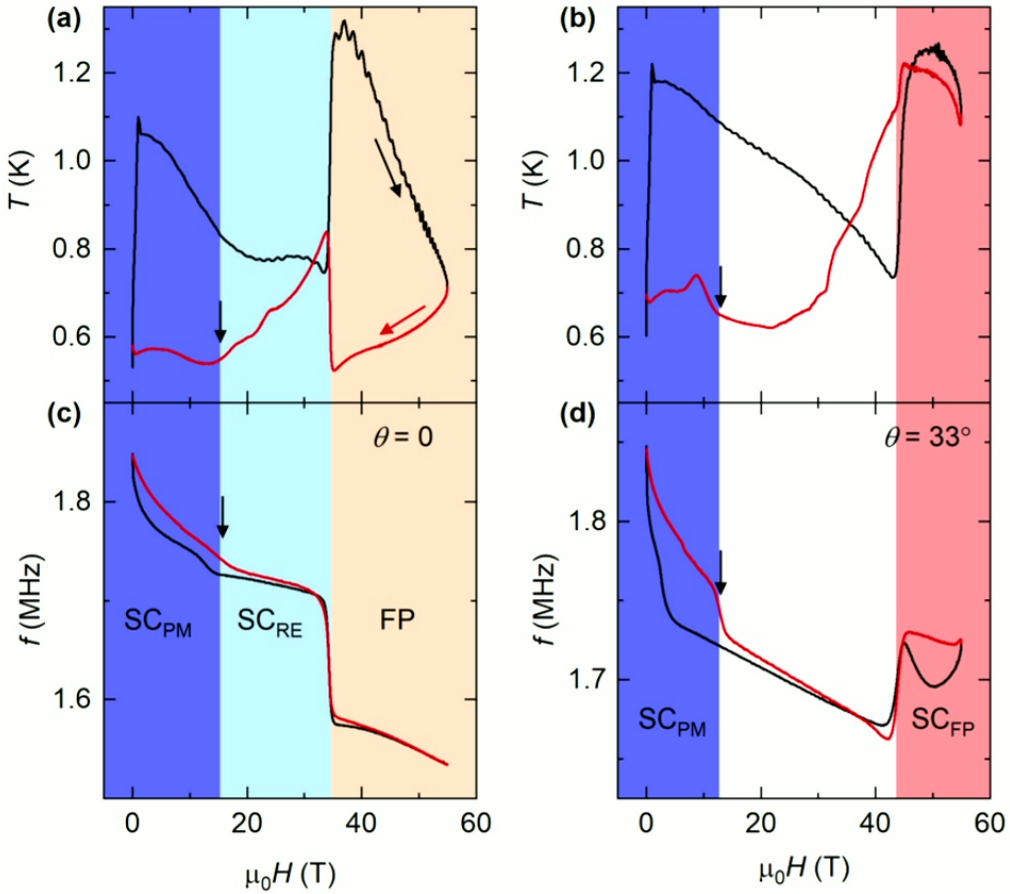


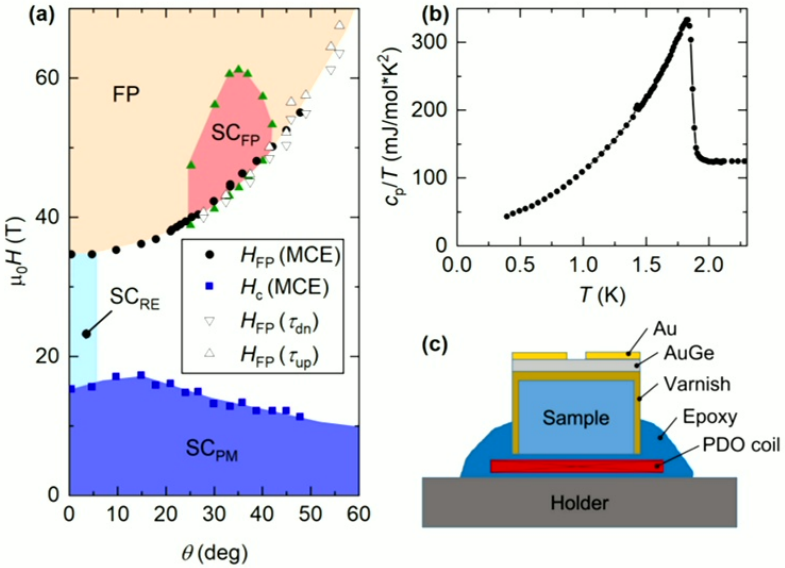
World record for field induced SC state!



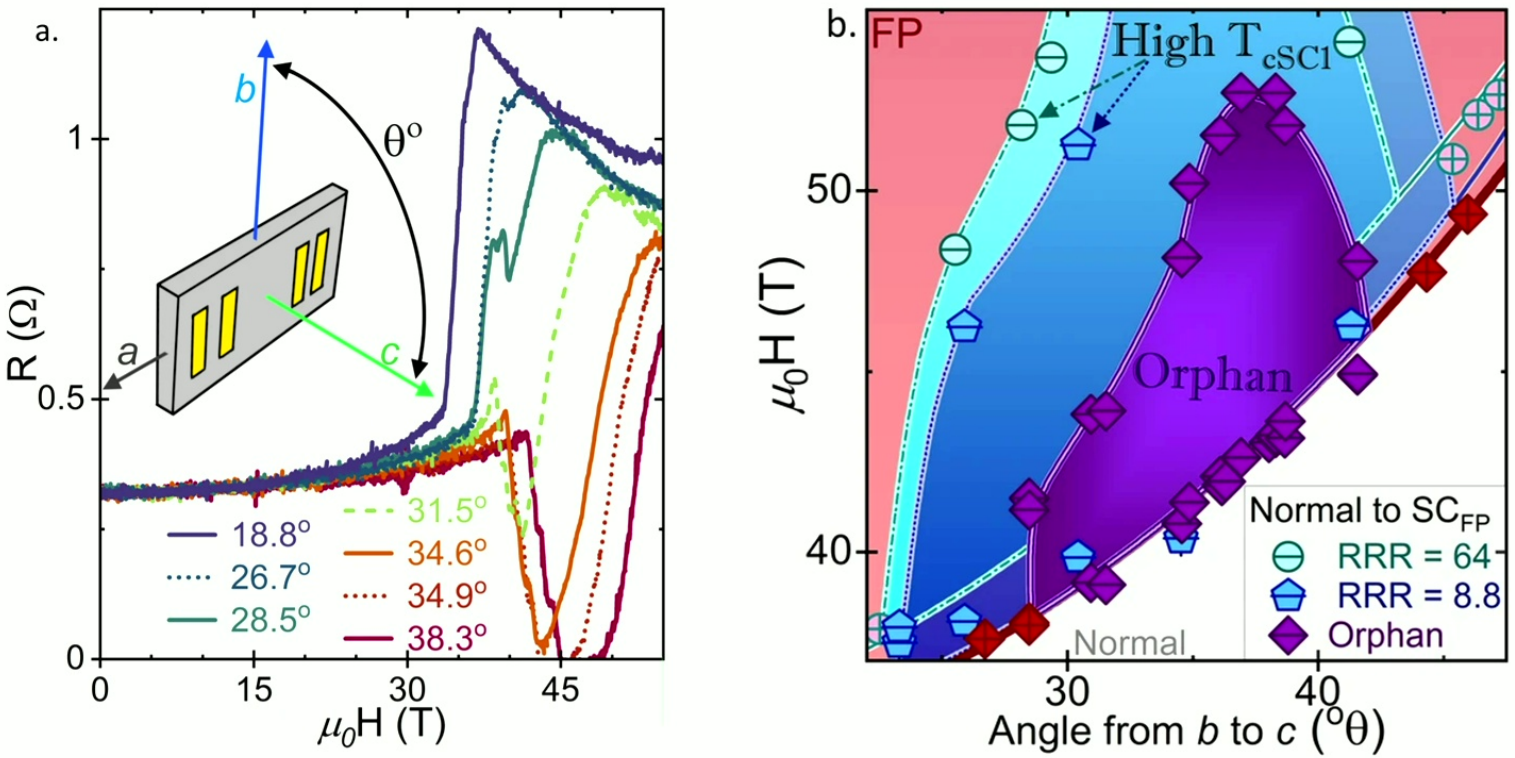
W. Knafo et al., Communications Physics 4, 40 (2021)

Thermodynamic evidence for SC_{FP}





Rico Schönemann et al., arXiv:2206.06508



C. E. Franket al., Nature Communications 15, 3378 (2024)

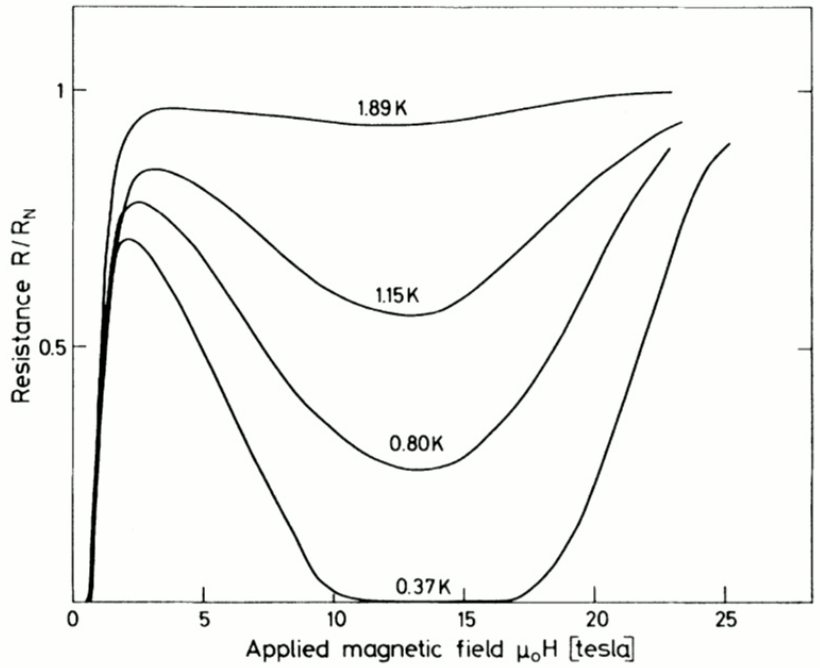


FIG. 2. Normalized resistance R/R_N of $Eu_{0.75}Sn_{0.25}Mo_6S_{7.2}Se_{0.8}$ vs field ($H \leq 25$ T) at various temperatures.

Meul, H. W. et al. Phys. Rev. Lett. 53, 497–500 (1984).

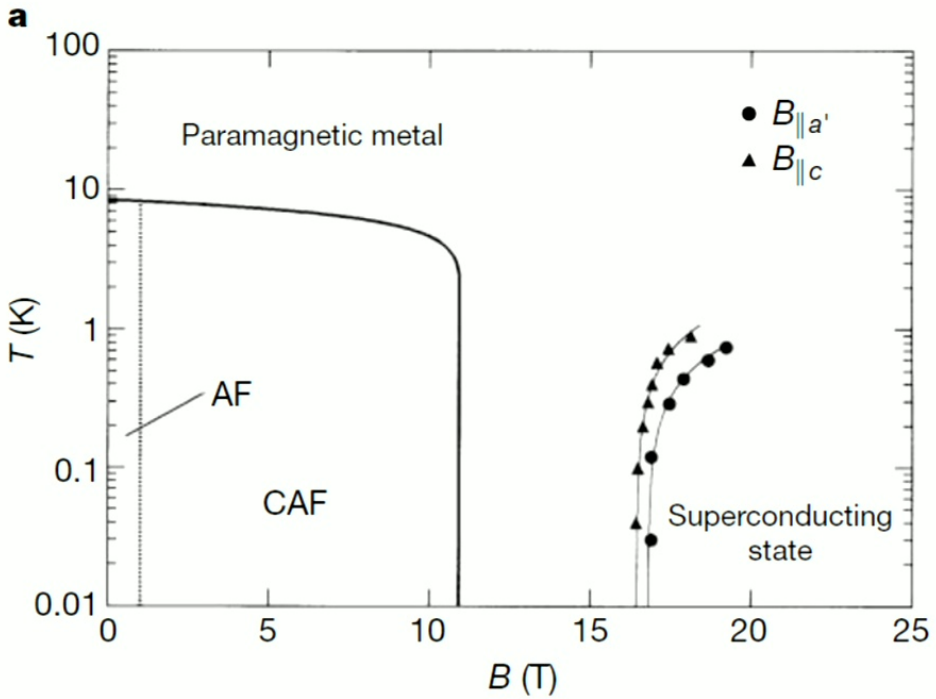


Figure 1 a, Temperature versus magnetic field phase diagram for λ-$(BETS)_2FeCl_4$

Uji, S. et al. Nature 410, 908–910 (2001).

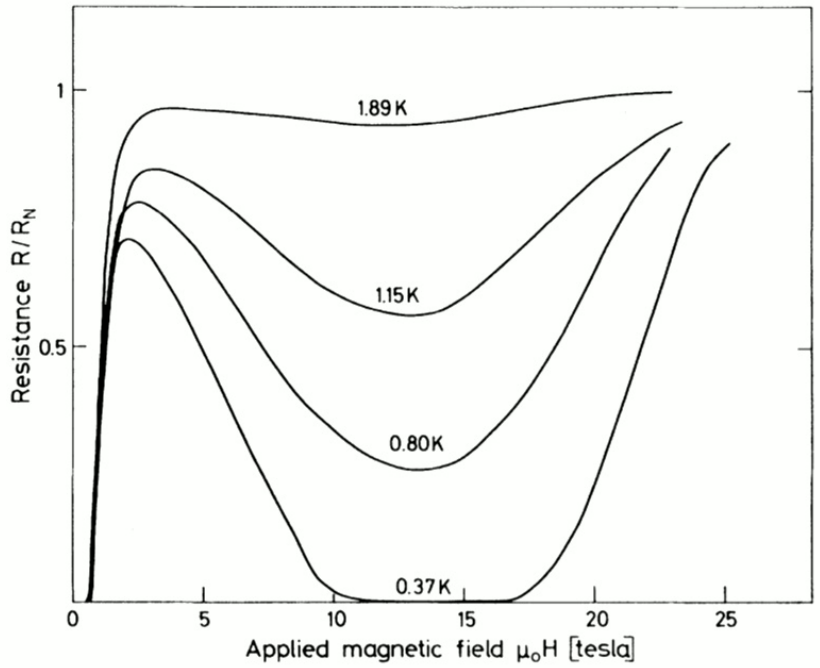


FIG. 2. Normalized resistance R/R_N of $Eu_{0.75}Sn_{0.25}Mo_6S_{7.2}Se_{0.8}$ vs field ($H \leqslant 25$ T) at various temperatures.

Meul, H. W. et al. Phys. Rev. Lett. 53, 497–500 (1984).

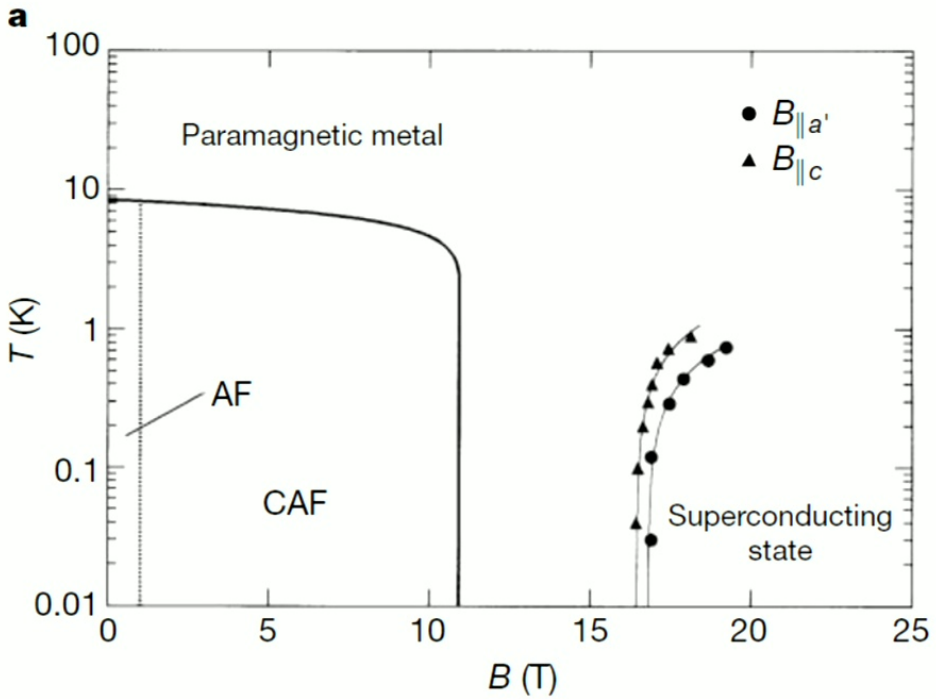
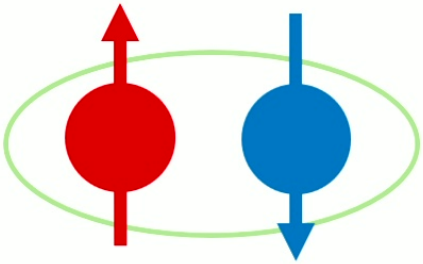


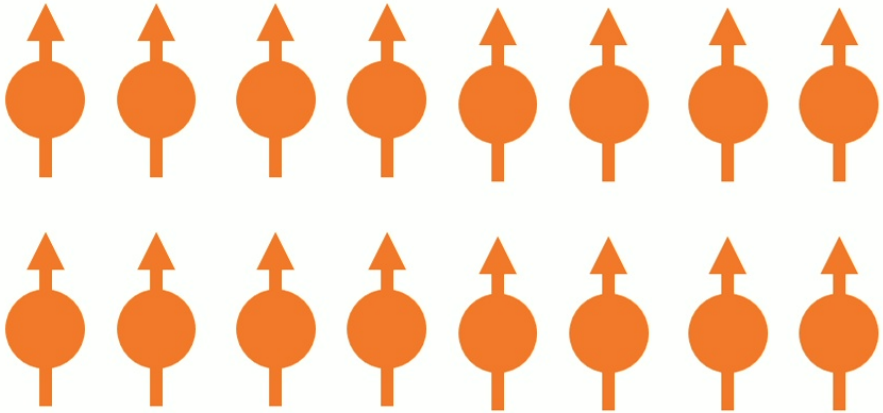
Figure 1 a, Temperature versus magnetic field phase diagram for λ-$(BETS)_2FeCl_4$

Uji, S. et al. Nature 410, 908–910 (2001).

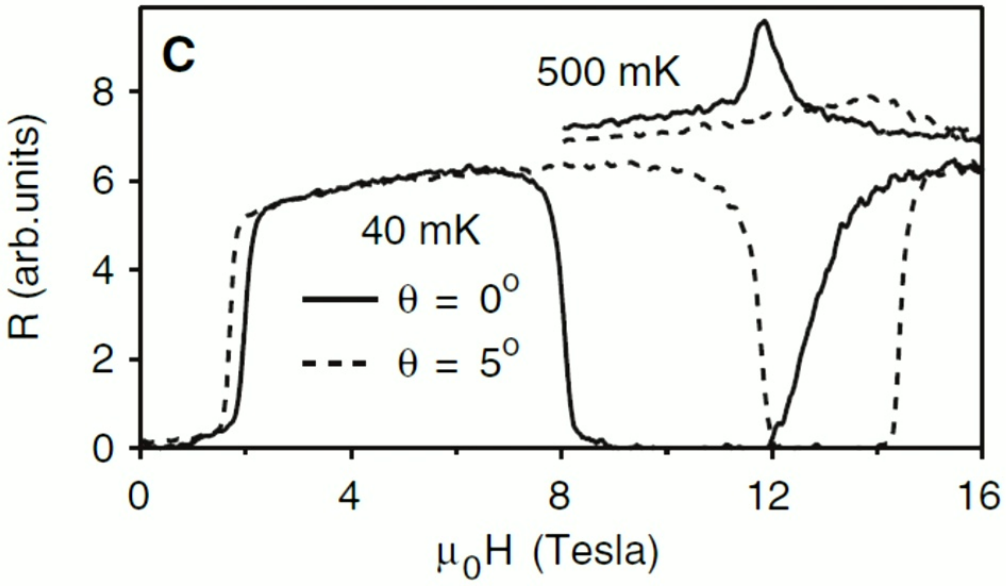
Jaccarino-Peter effect



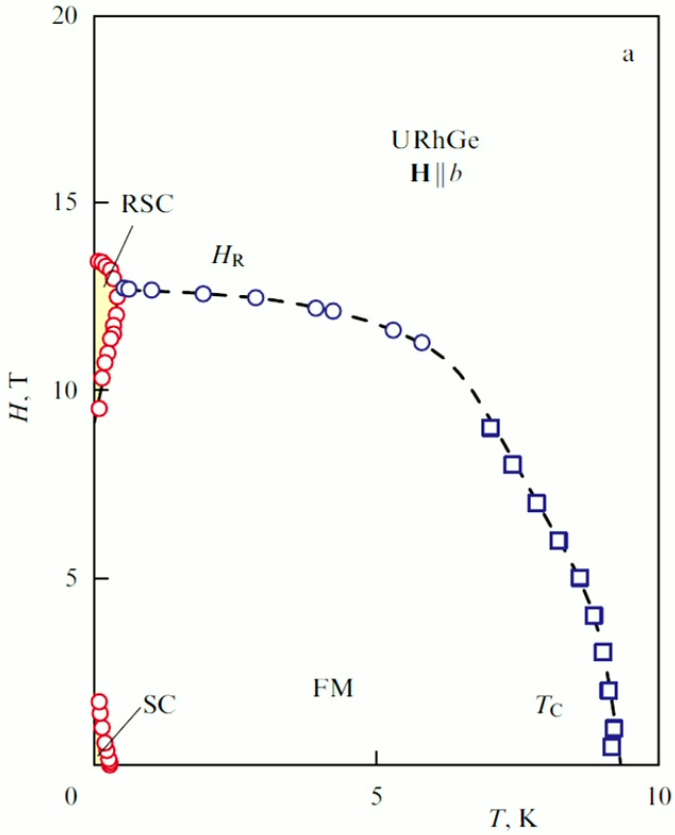
$J \sim -$



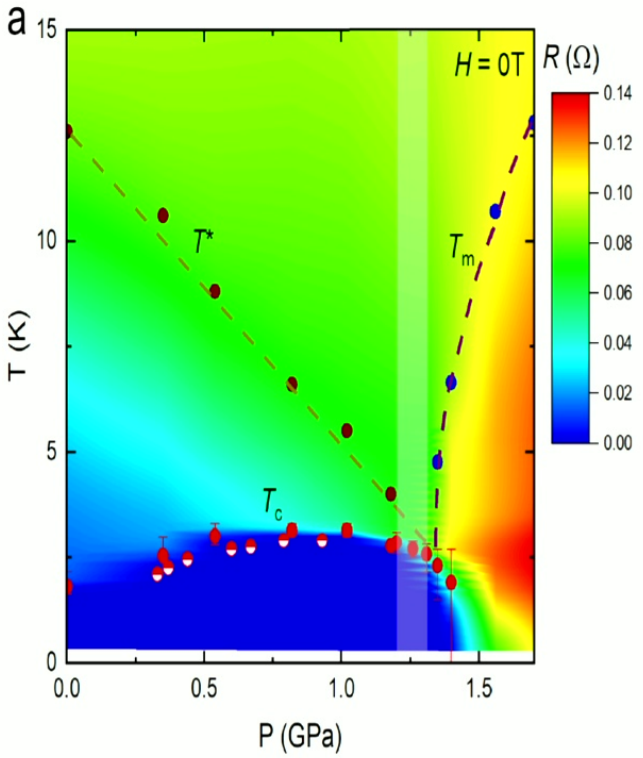
URhGe



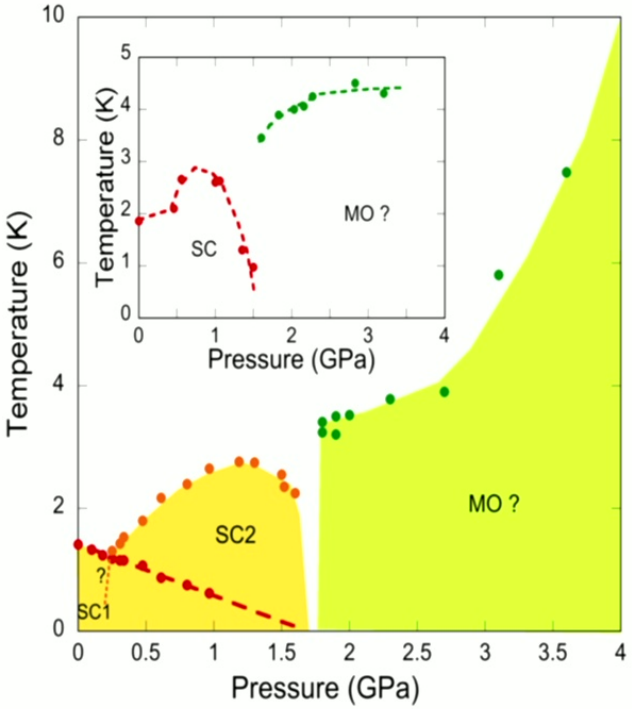
Lévy, F. et al. Science 309, 1343–1346 (2005).



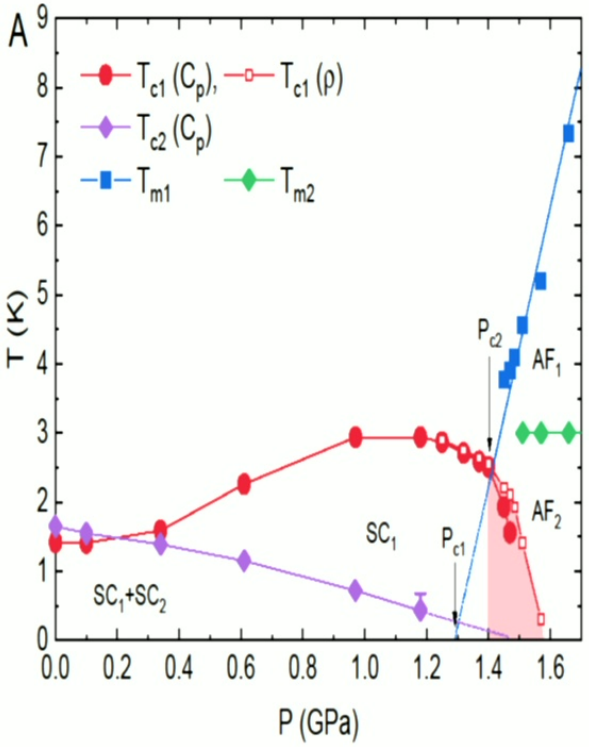
Multiple SC phases under pressure



S. Ran et al., PRB, 101, 140503 (2020)

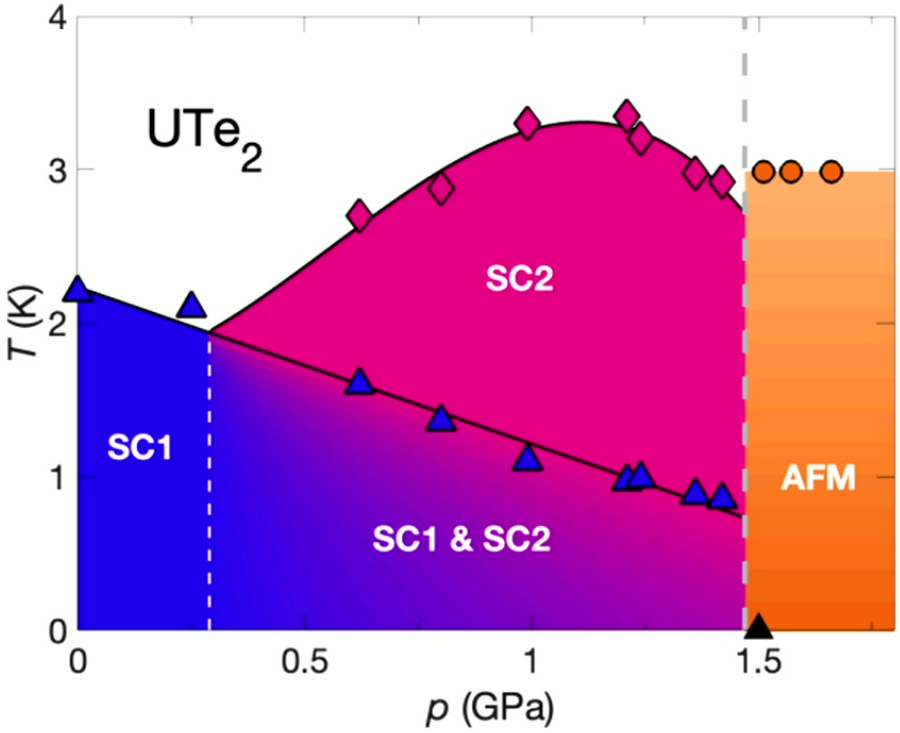


D. Braithwaite et al., Communications Physics, 2, 147 (2019)



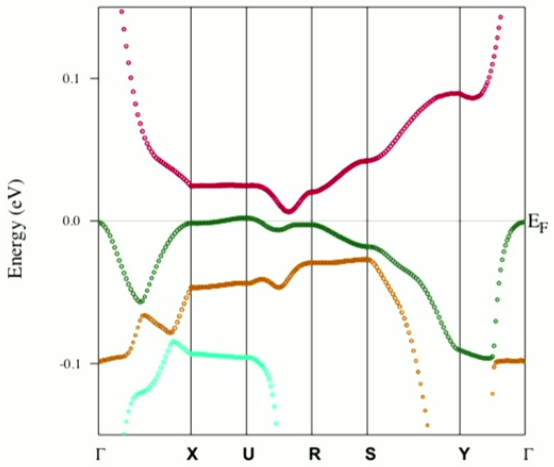
S. M. Thomas et al., Sci. Adv. 2020; 6 : eabc8709 (2020)

Multiple SC phases under pressure



Z. Wu et al., arXiv:2403.06650v1 (2019)

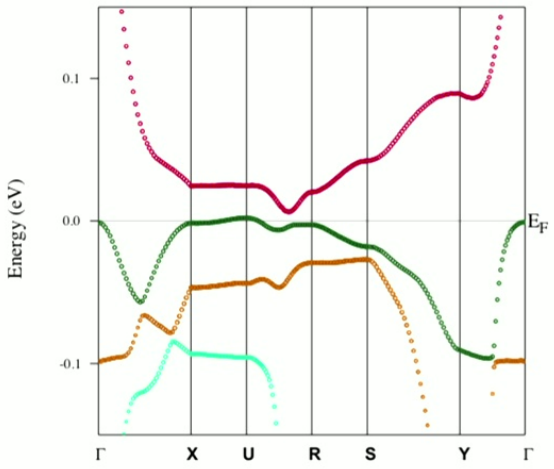
Band structure of UTe_2



A.. Shicket et al., PRB 100, 134502 (2019)

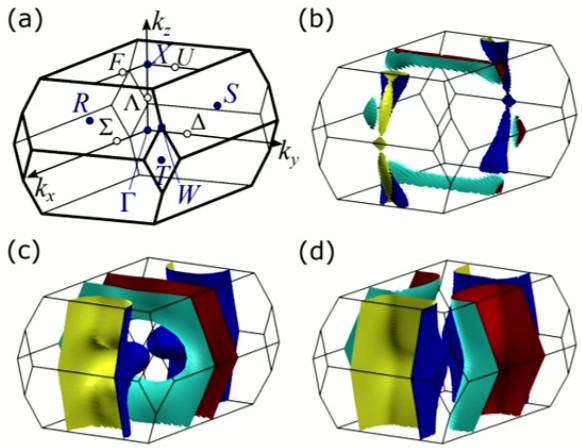
Initial DFT+U : insulator

Band structure of UTe_2

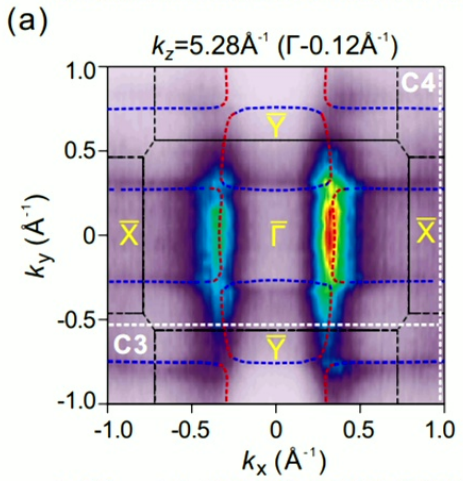


A.. Shicket et al., PRB 100, 134502 (2019)

Initial DFT+U : insulator

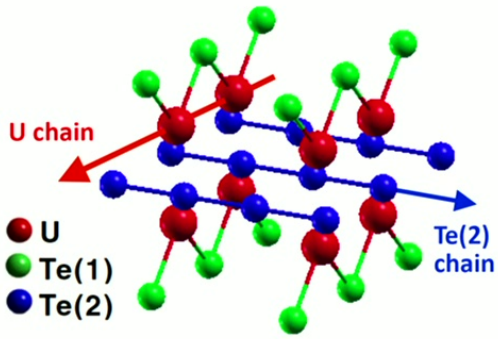


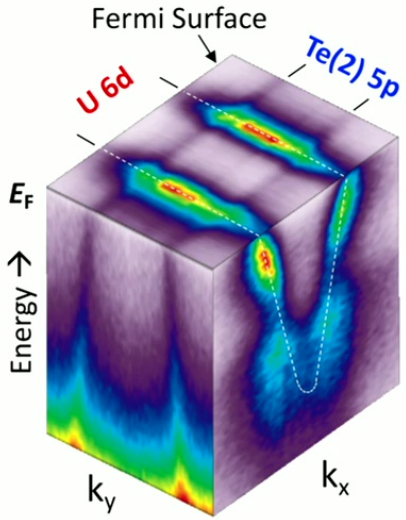
Jun Ishizuka et al., PRL 123, 217001 (2019)



L. Miao et al., PRL 124, 076401 (2020)

Strongly depends on value of U

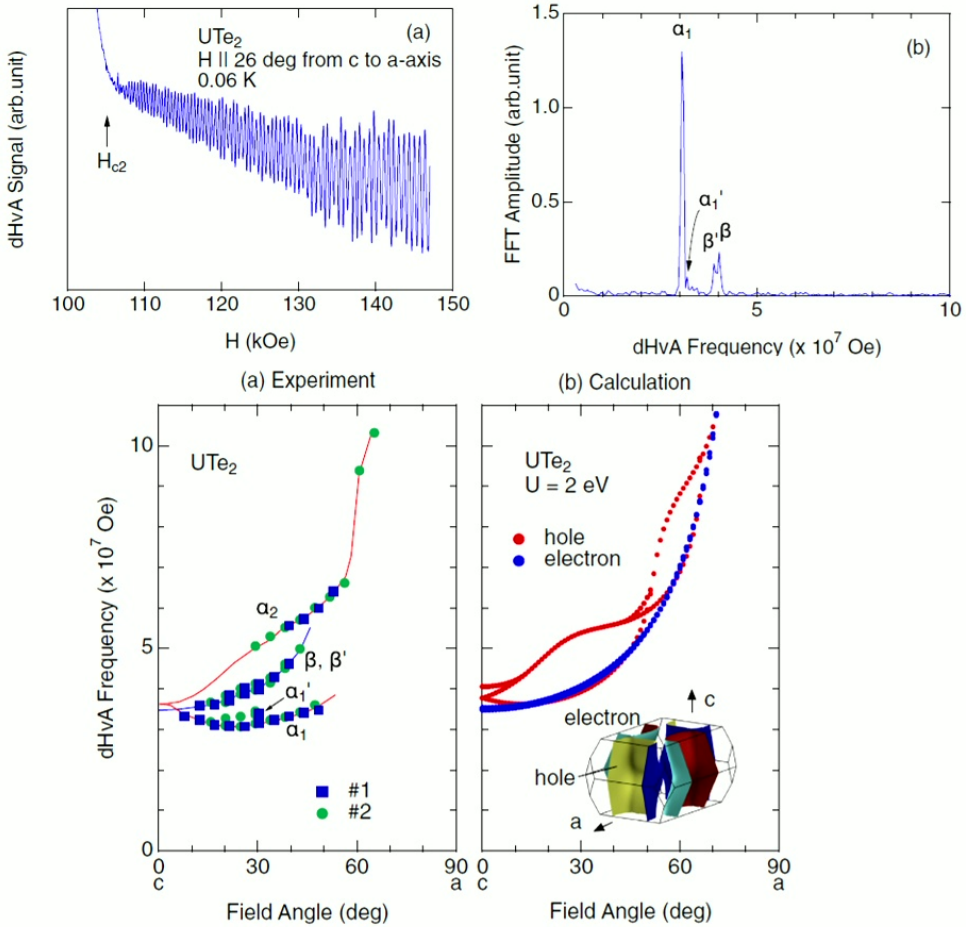




U-6d and Te5p orbitals of the perpendicular U chains and Te chains

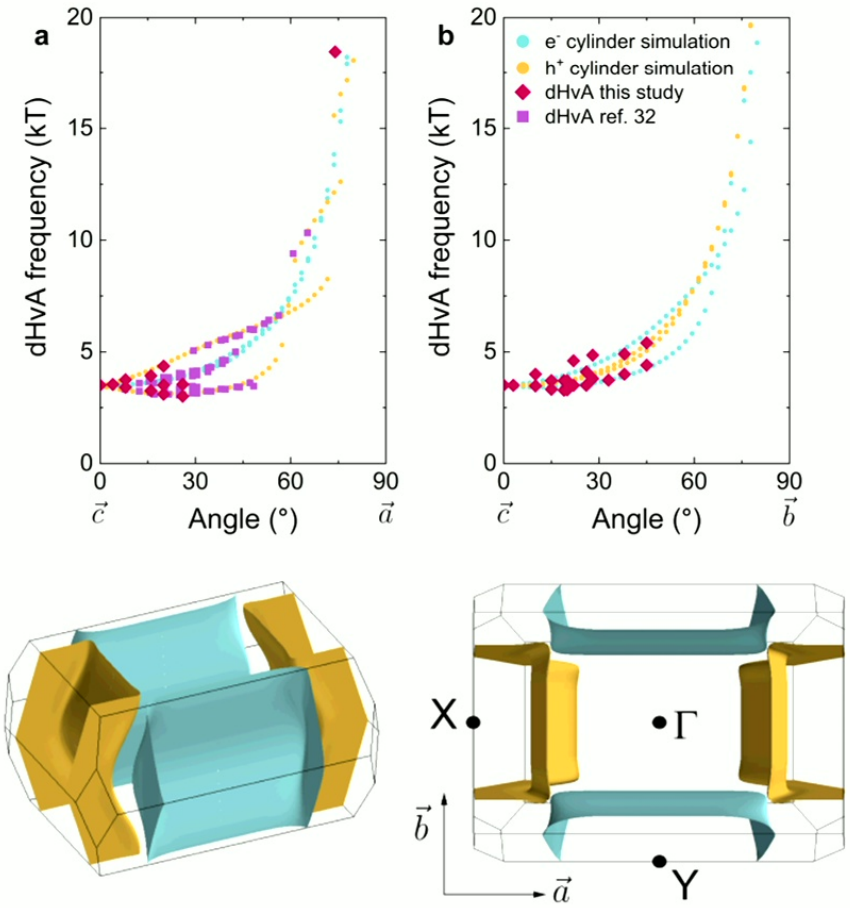
Fermi surface of UTe_2 from quantum oscillations

Magnetization



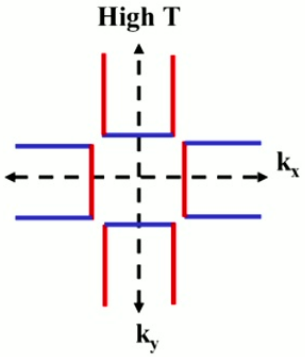
Dai Aoki et al., JPSJ 91, 083704 (2022)

Magnetic torque



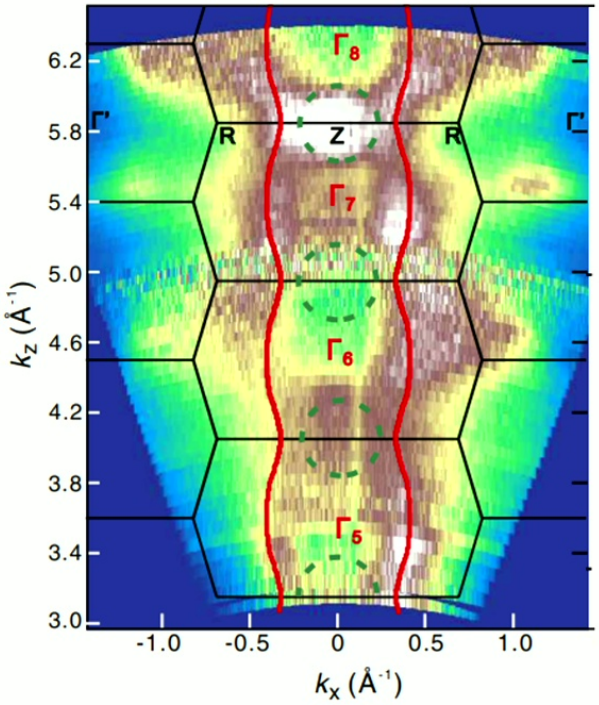
A. G. Eaton et al., arXiv:2302.04758

Is there a 3D Fermi surface pocket?



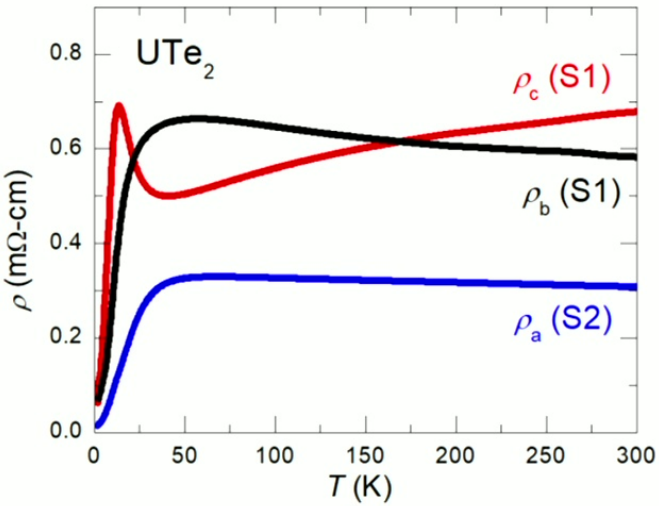
H. C. Choi et al., arXiv:2206.04876v3 (2022)

Renormalized band structure due to Kondo effect



L. Miao et al., PRL 124, 076401 (2020)

Small pocket at Z point



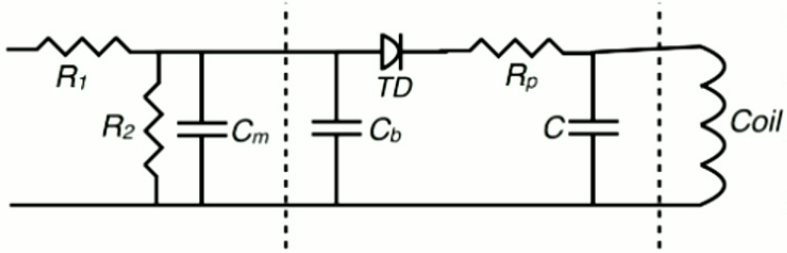
Y. S. Eo et al., PRB 106, L060505 (2022)

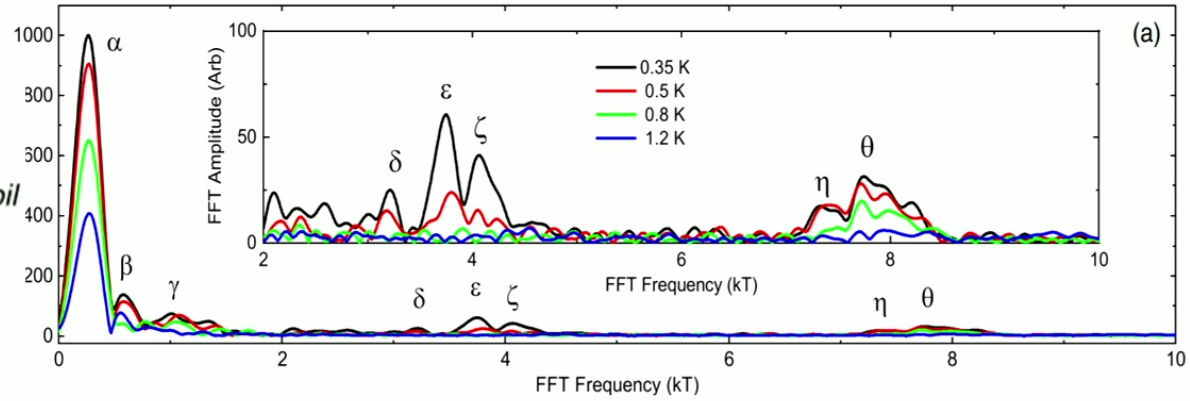
$$\sigma_{ab} = \sigma_{2D} + \sigma_Z$$

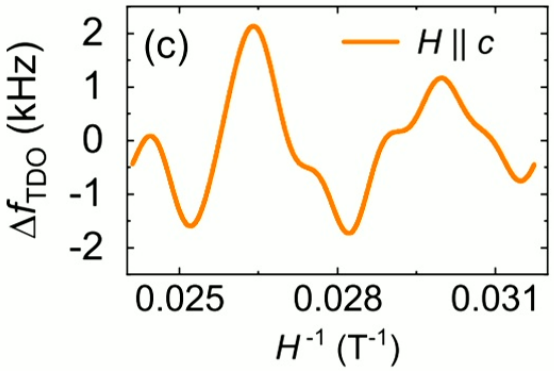
$$\sigma_c \approx \sigma_Z$$

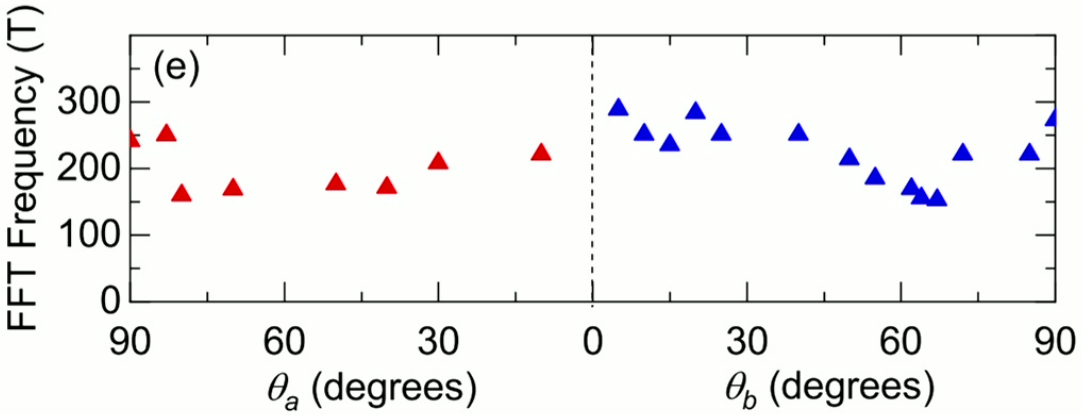
Nearly isotropic transport properties

Low frequency oscillations





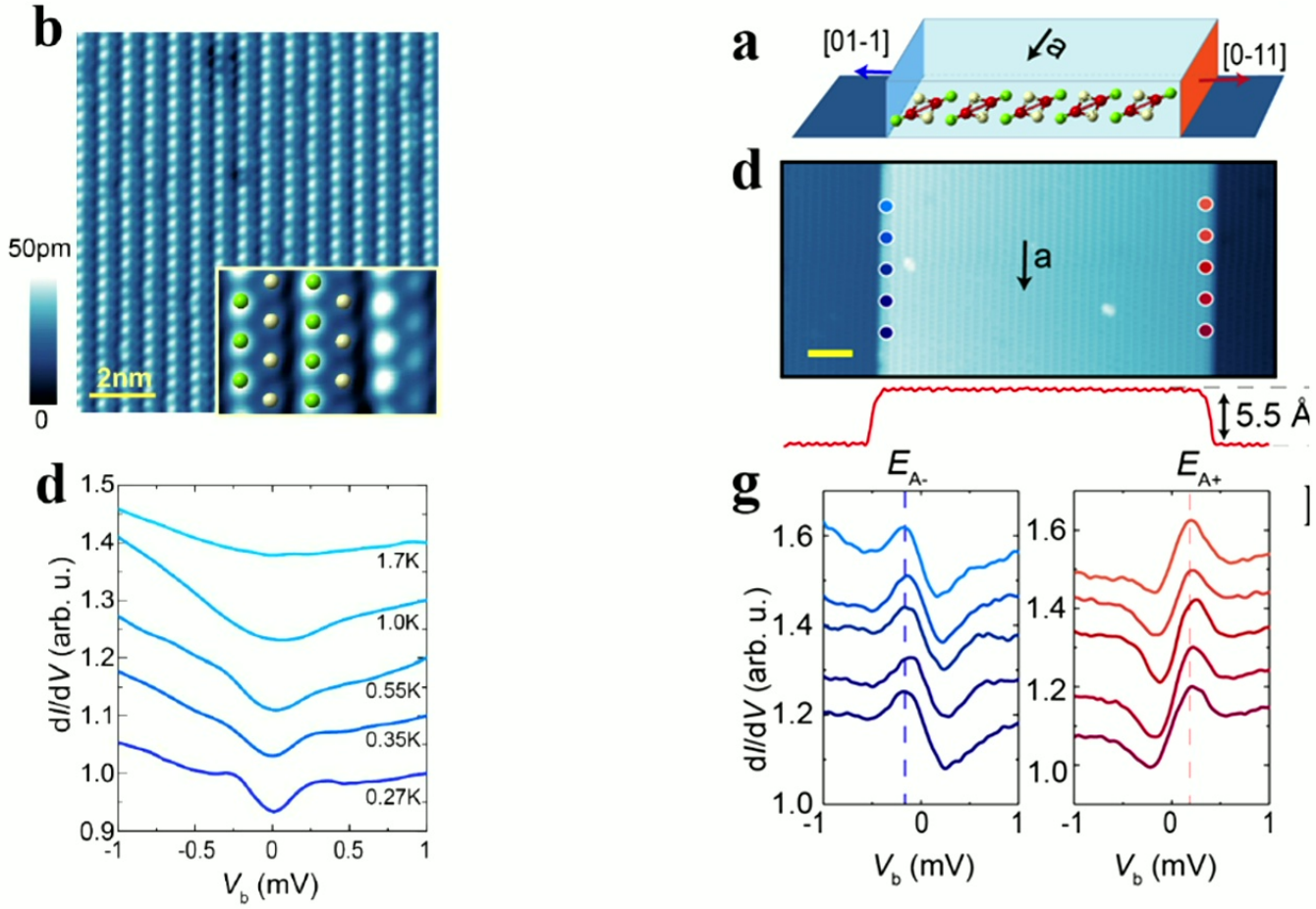




C. Broyles, et al., PRL 131, 036501 (2023)

Is UTe_2 a chiral superconductor?

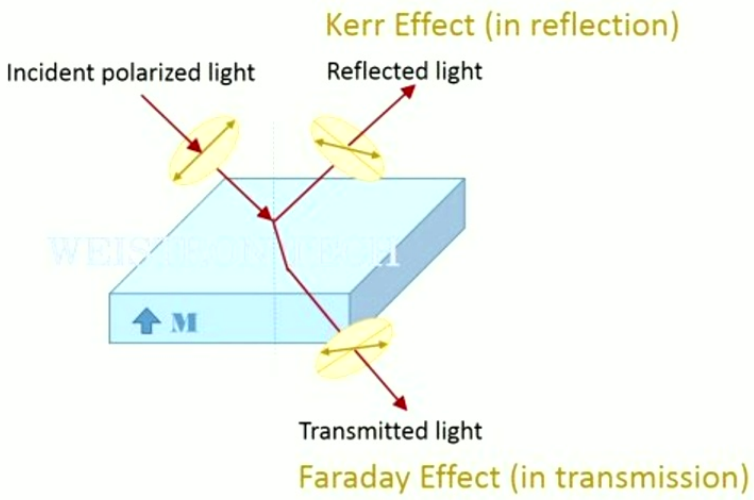
#1 STM

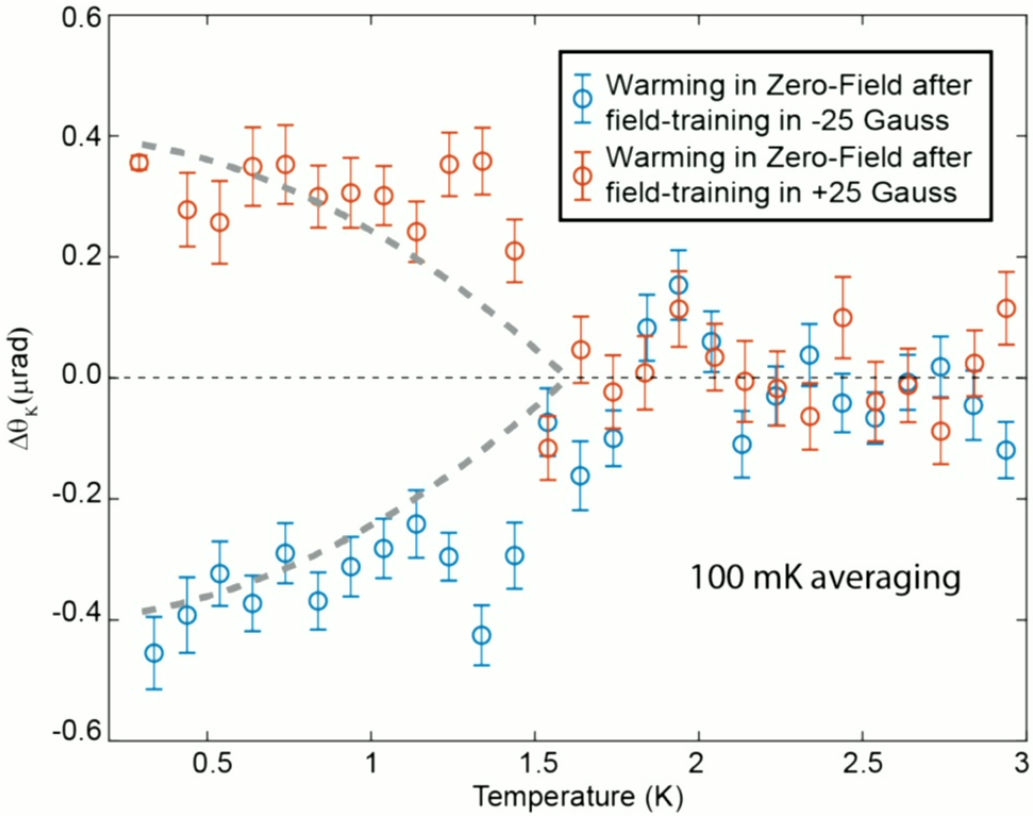


Lin Jiao et al., Nature, 579, 523-527 (2020)

Is UTe_2 a chiral superconductor?

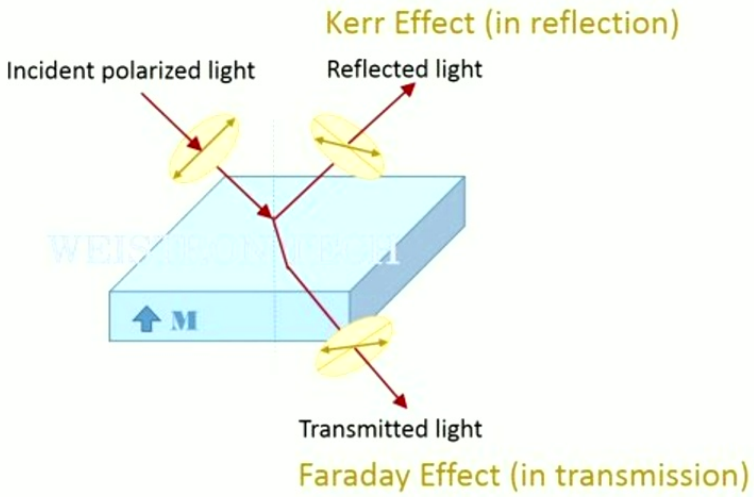
#2 Kerr rotation





Ian Hayes et al., Science 373 (6556), 797-801

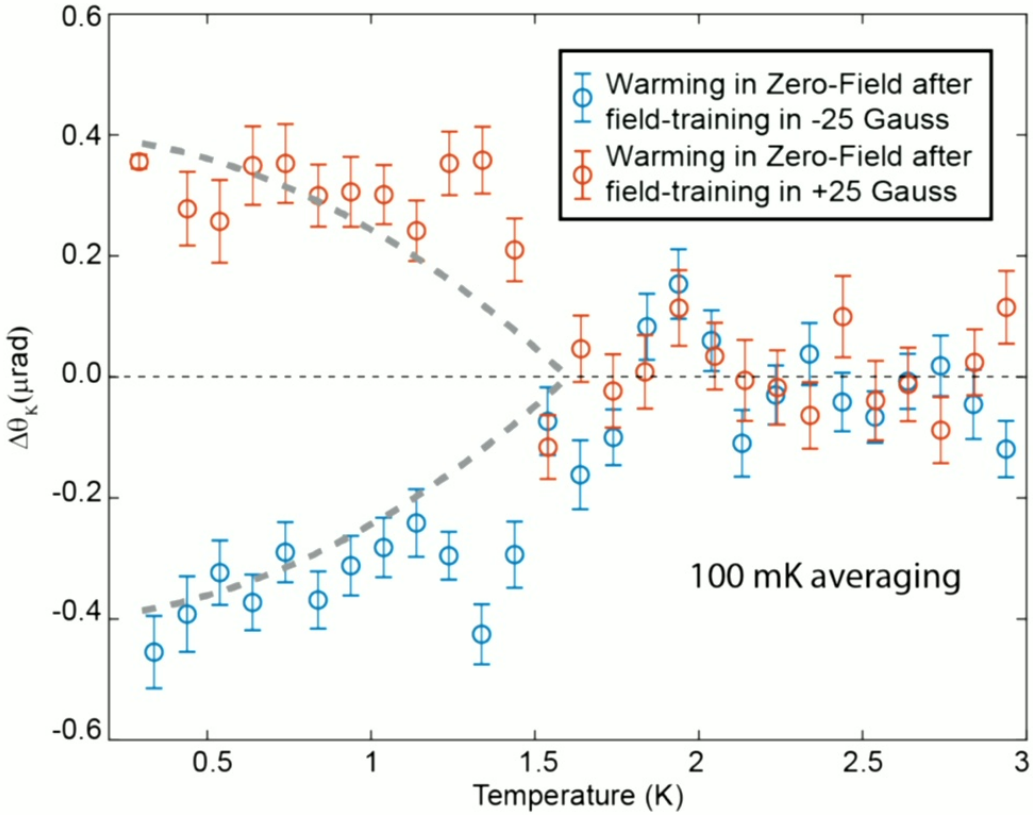
Is UTe_2 a chiral superconductor?



Tetragonal system

$k_x \pm ik_y$

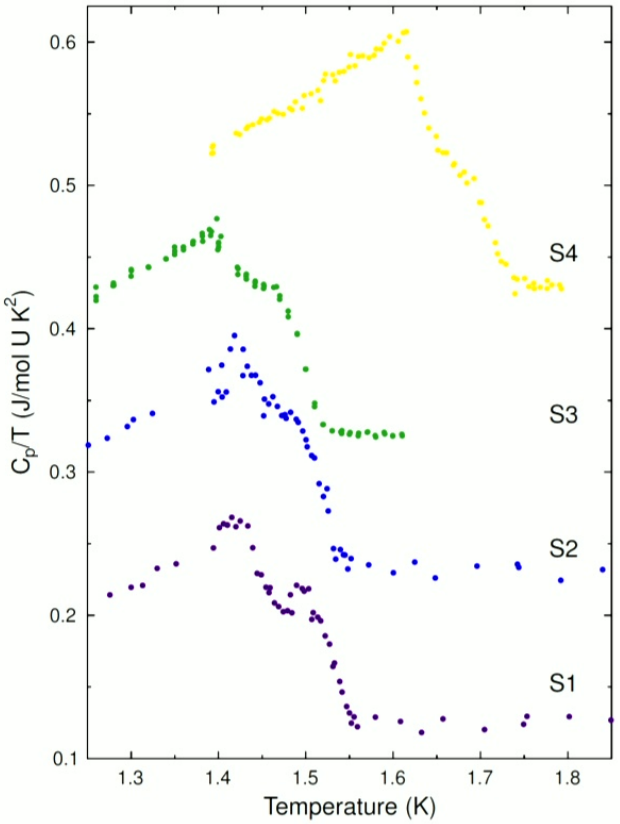
#2 Kerr rotation



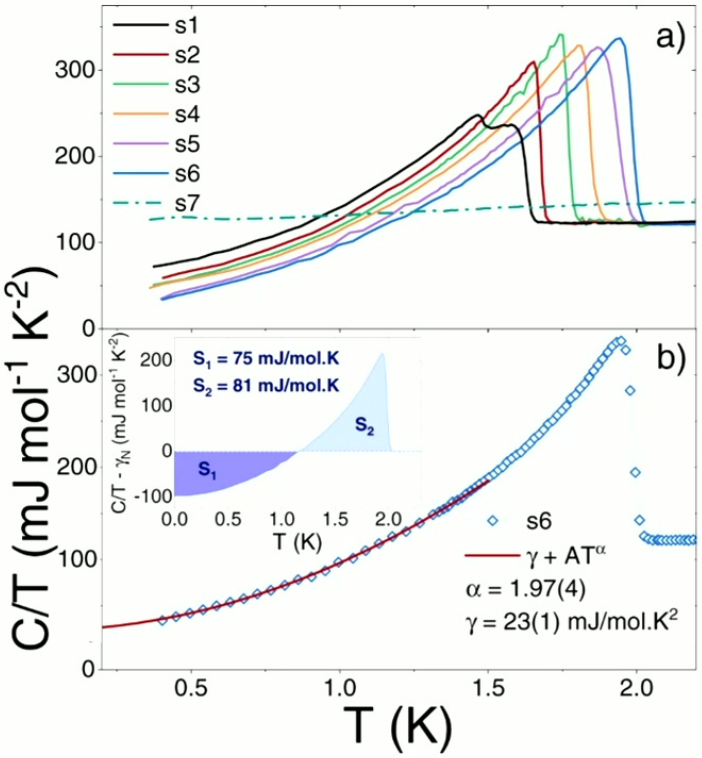
Ian Hayes et al., Science 373 (6556), 797-801

Is UTe_2 a chiral superconductor?

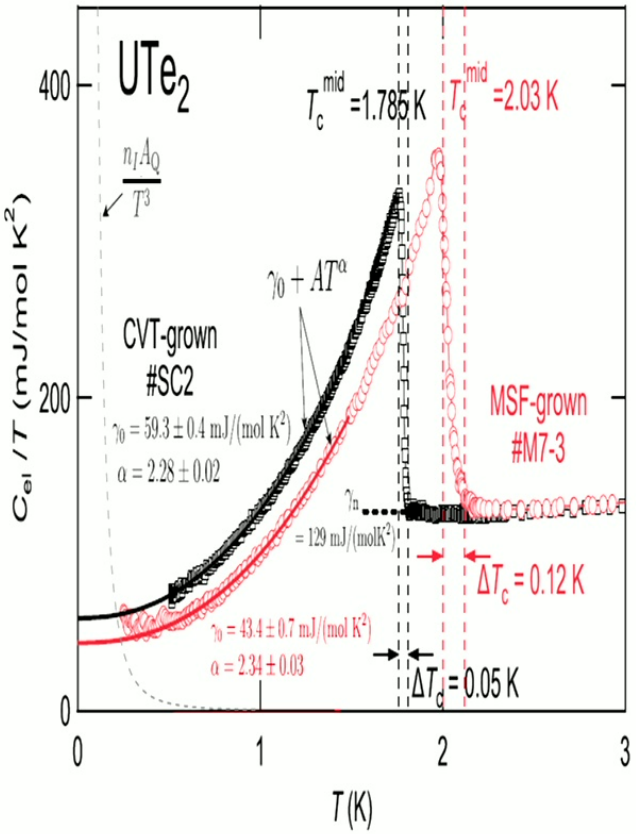
#3 Specific heat



Ian Hayes et al., Science 373 (6556), 797-801



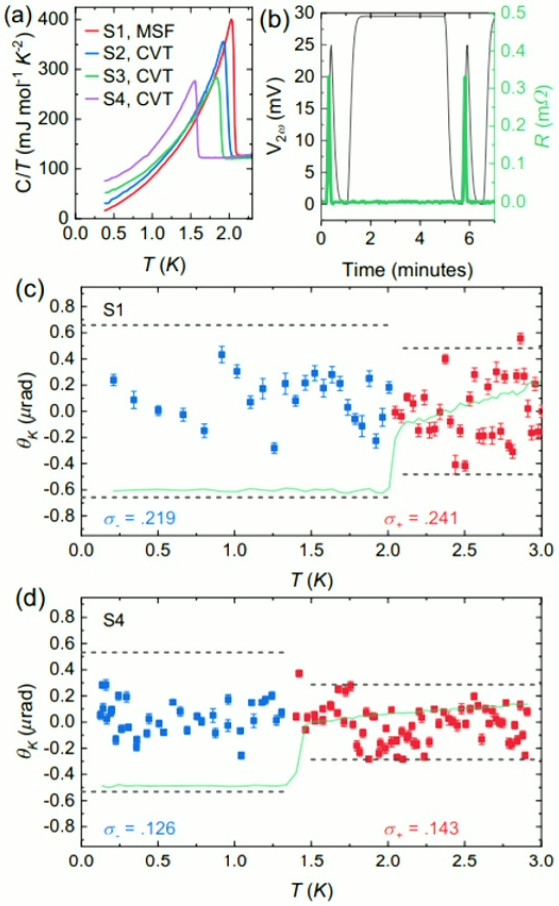
Priscila F. S. Rosa et al., Communications Materials 3, 33 (2022)



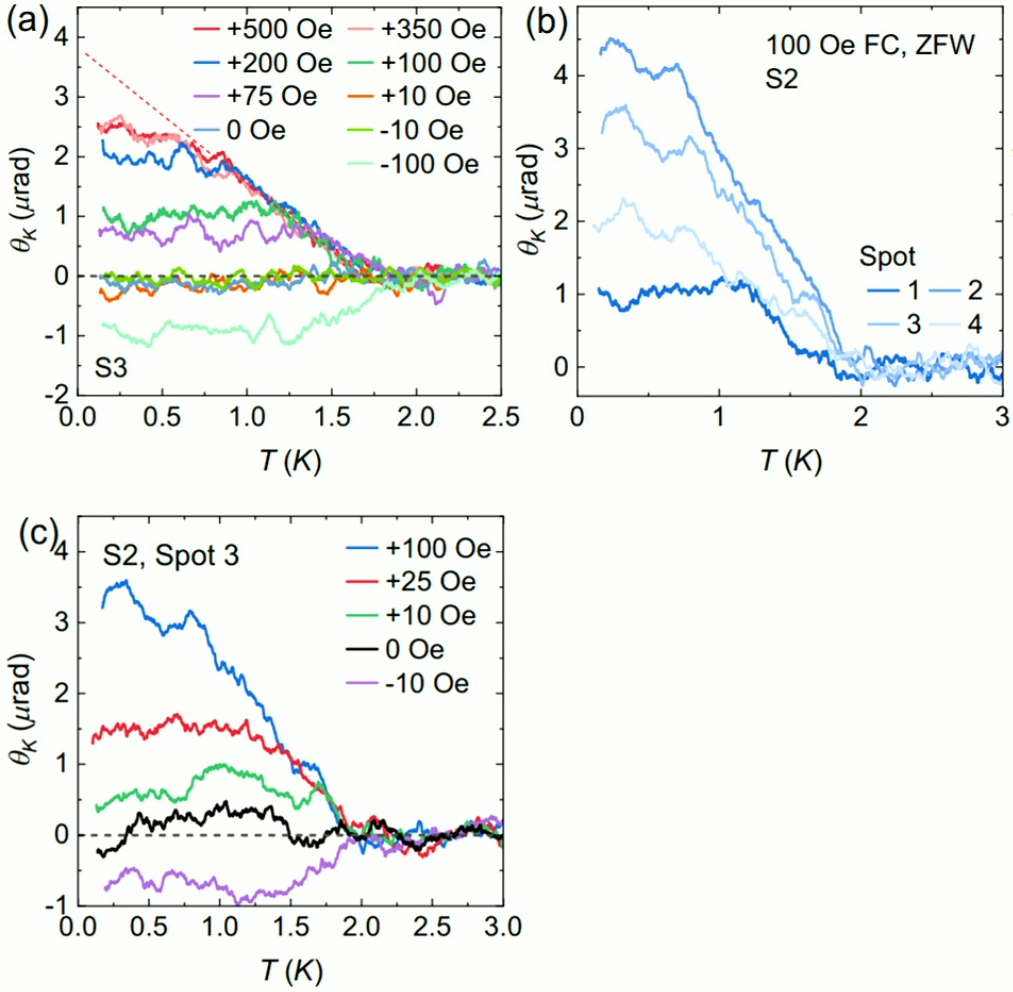
H. Sakai et al., PR Materials 6, 073401(2022)

Is UTe_2 a chiral superconductor?

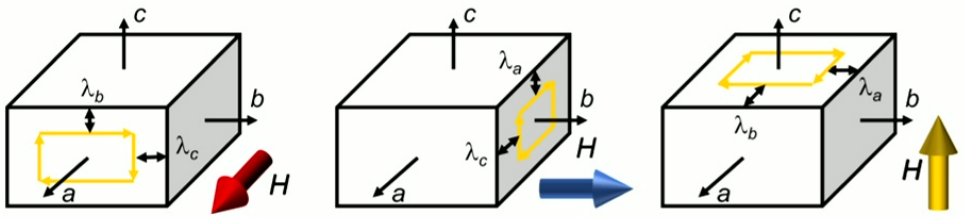
#2 Kerr rotation revisit

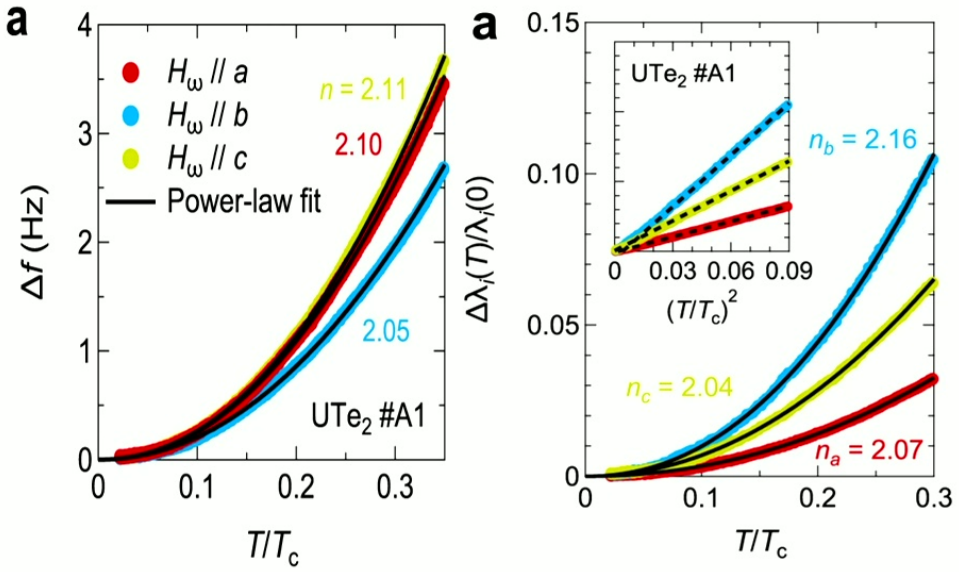


M. O. Ajeesh et a l., PRX 13, 041019 (2023)



Is UTe_2 a chiral superconductor?

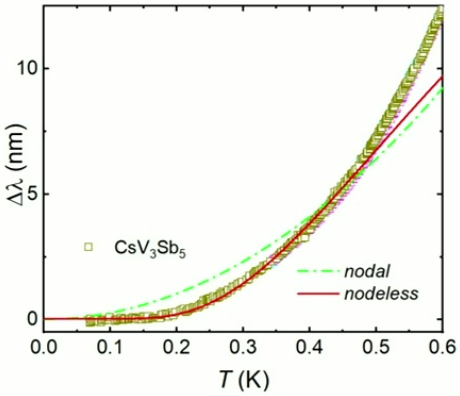




Kota Ishihara et a l., Nature Comm. 14, 2966 (2023)

#4 Penetration depth

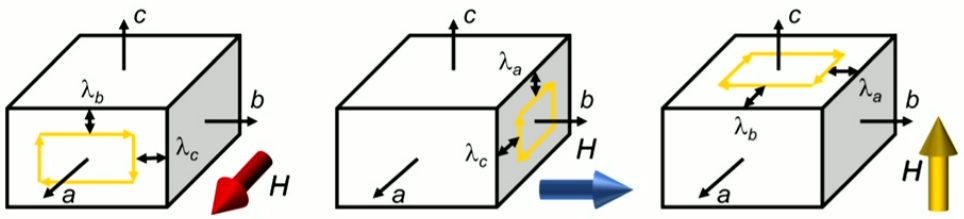
Exp	fully gapped
T^2	point node
T^3	line node

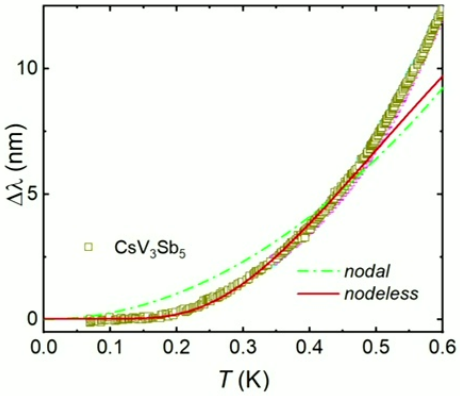


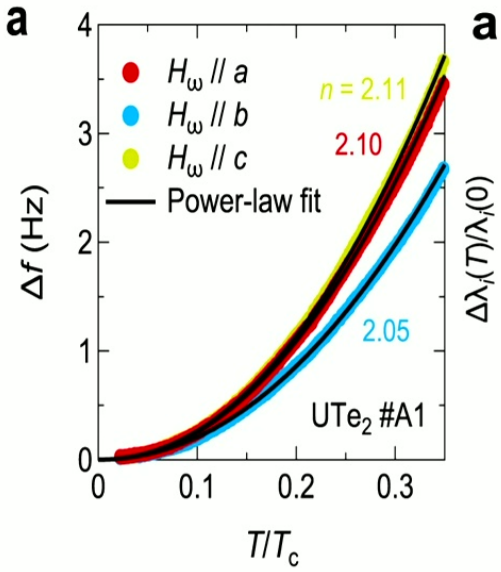
Is UTe_2 a chiral superconductor?

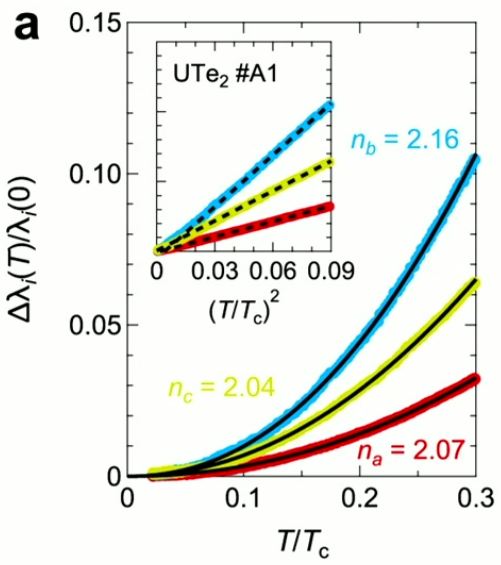
#4 Penetration depth

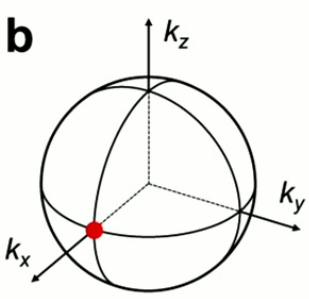
Exp	fully gapped
T^2	point node
T^3	line node

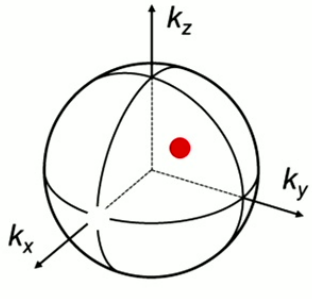


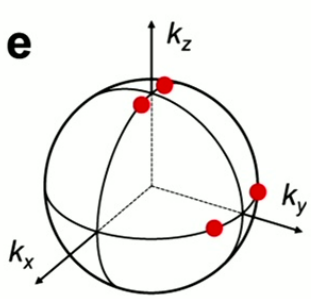






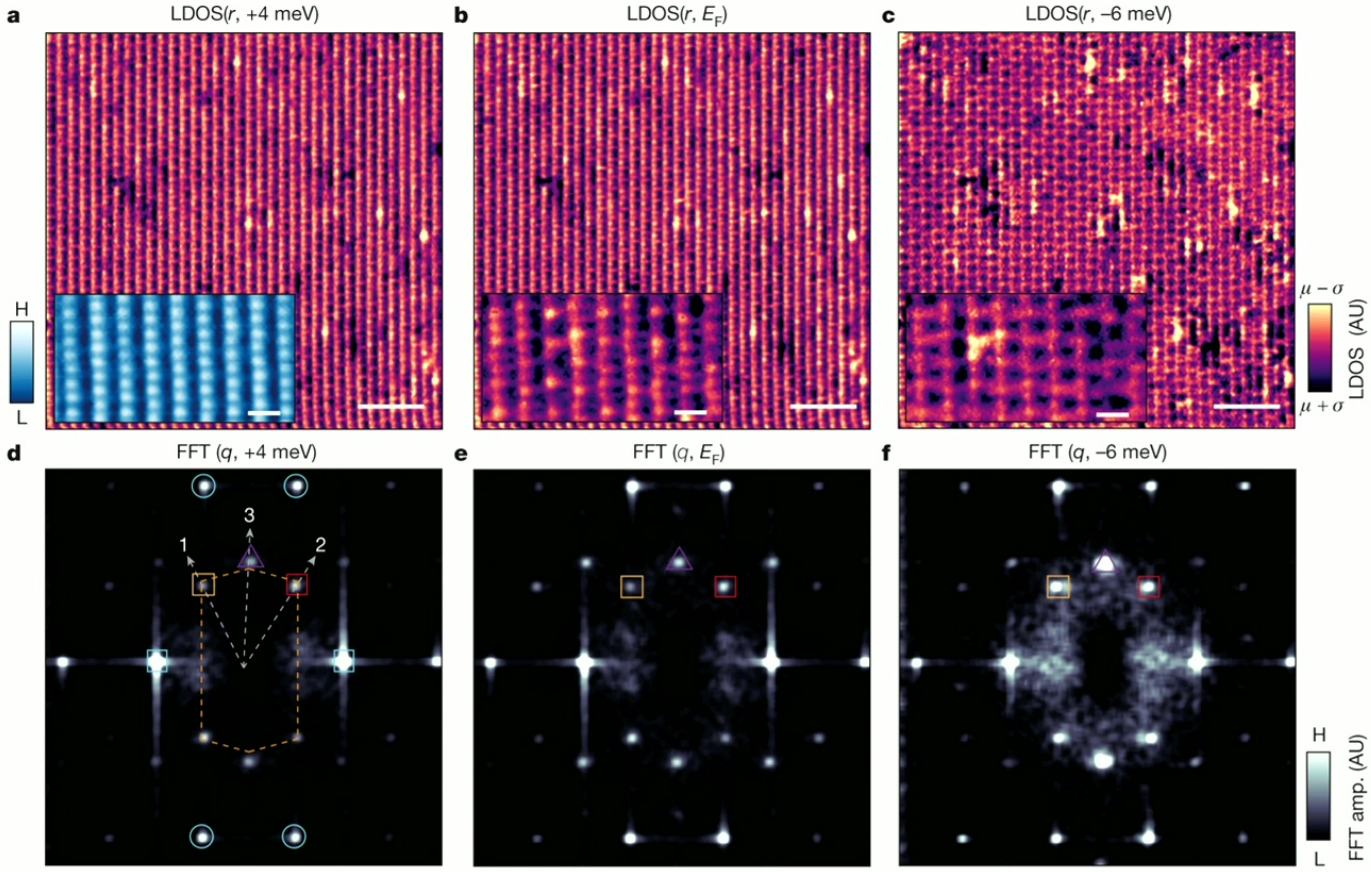






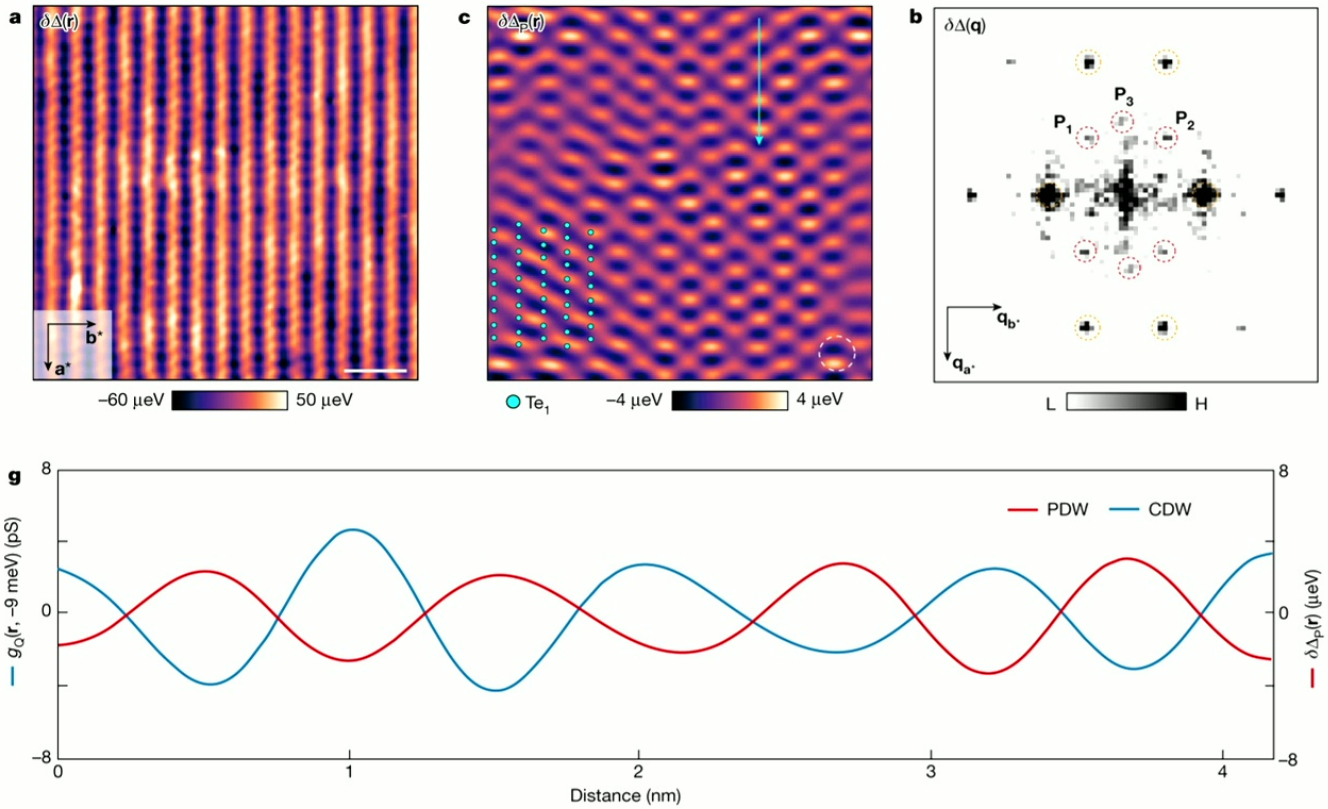
Kota Ishihara et a l., Nature Comm. 14, 2966 (2023)

Charge density wave?



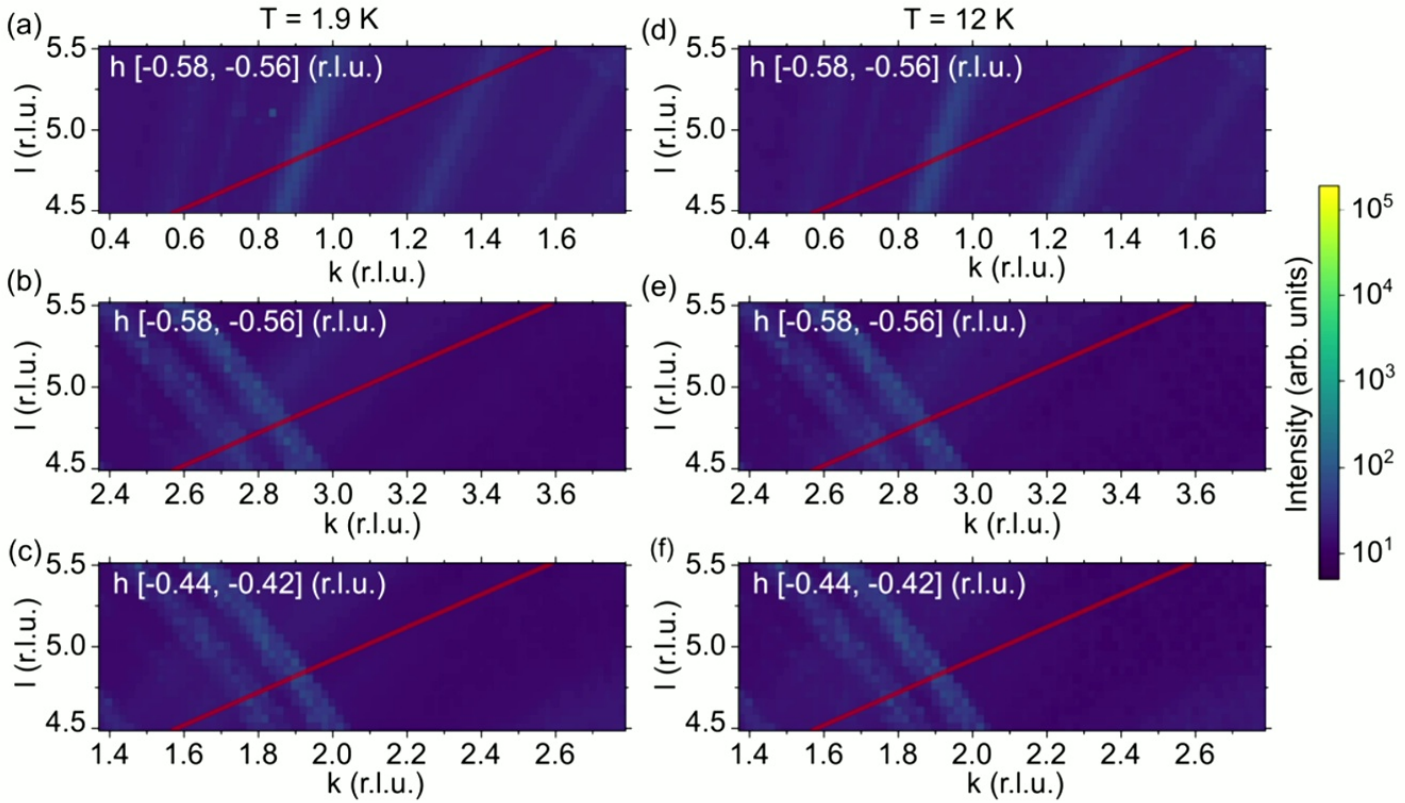
Anuva Aishwarya et al., Nature 618, 928–933 (2023)

Pair density wave?



Qiangqiang Gu et al., Nature 618, 921–927 (2023)

Charge density wave?



Caitlin S. Kengle et al., Phys. Rev. B 110, 145101 (2024)

no charge density wave from Xray

Superconductivity in UTe2

2D vs 3D FS

- Magnetization — 2D
- TDO — 3D

Chiral

- STM — ?
- Kerr — ✗
- Specific heat — ✗
- Penetration depth — ✓

Charge density wave

- STM — ✓
- Xray — ✗