Unconventional Supercondutivity in UTe_2 in Extreme Conditions

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G. Gabarino, J.P. Sanchez, F. Wilhelm

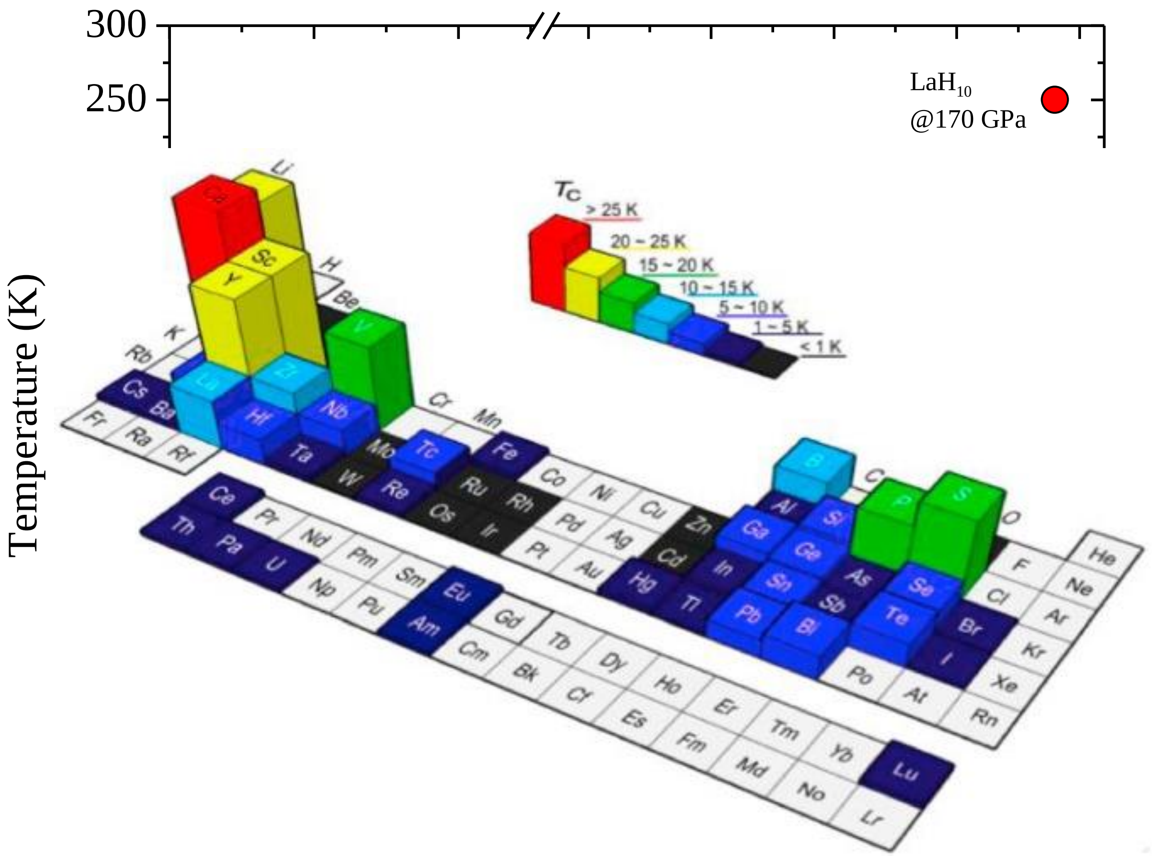
ISIS, UK
P. Manuel

Topical review:
D. Aoki, J.-P. Brison, J. Flouquet, K. Ishida, G. Knebel, Y. Tokunaga, and Y. Yanase,
J. Phys.: Condens. Matter **34** (2022) 243002

Progress report on high fields
S. K. Lewin, C.E. Frank, S. Ran, J. Paglione, N. Butch
Rep. Prog. Phys. 86 (2023) 114501

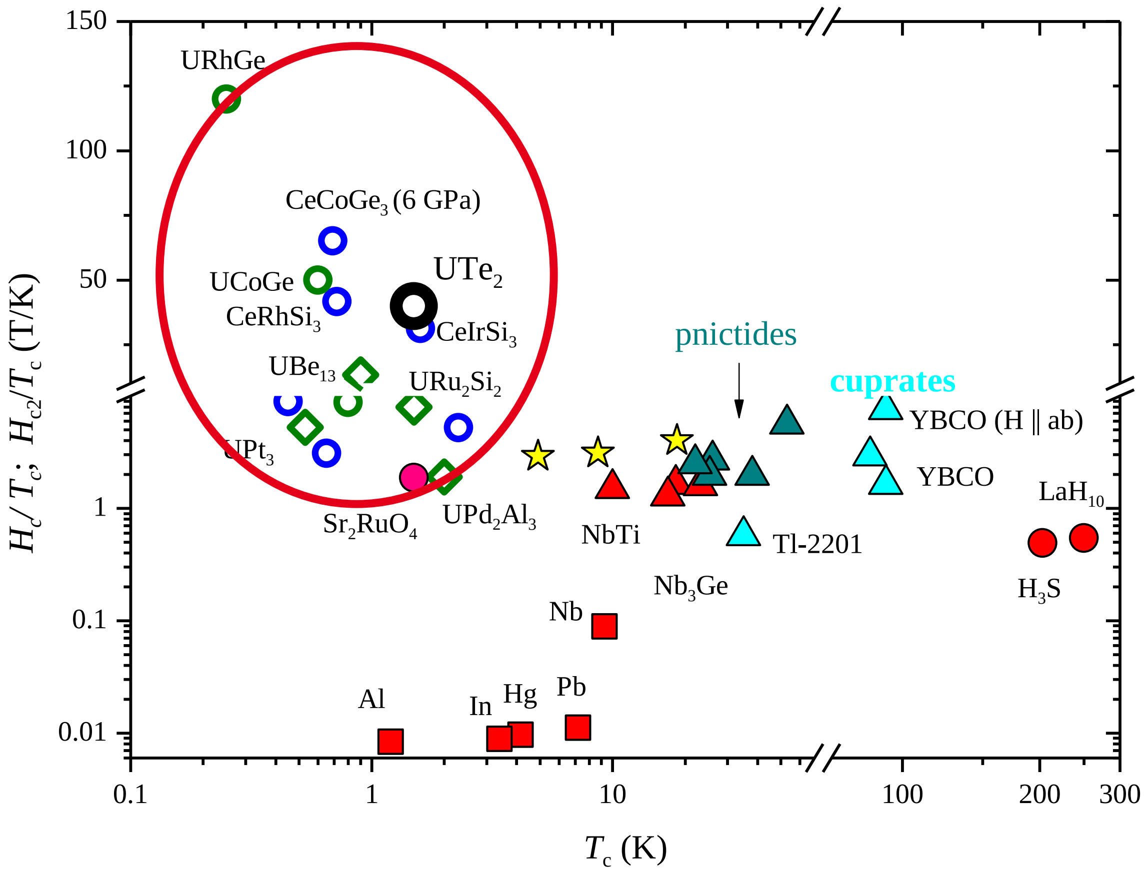
Thanks to : Y. Tokunaga, K. Ishida, J. Ishizuka, Y. Yanase, H. Harima

Superconductors



from K. Shimizu, Physica C, 552, 30 (2018)

magnetic field effect :



heavy fermion superconductors:
Cooper pairs formed by electrons with high effective masses ⇒ high critical fields

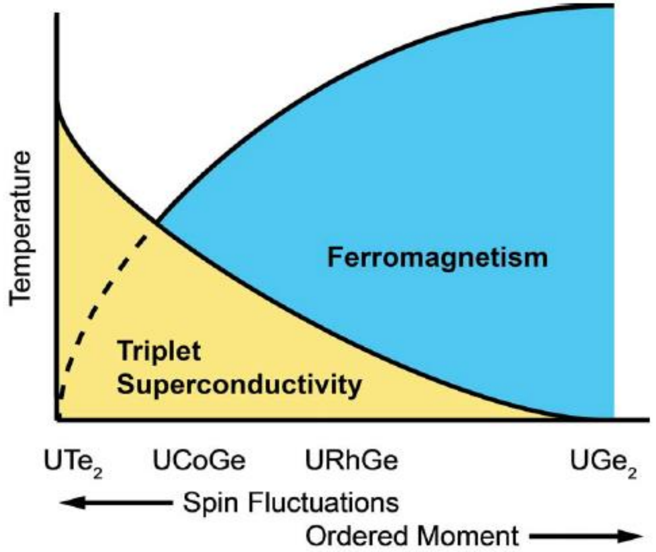
New heavy fermion superconductor: UTe$_2$

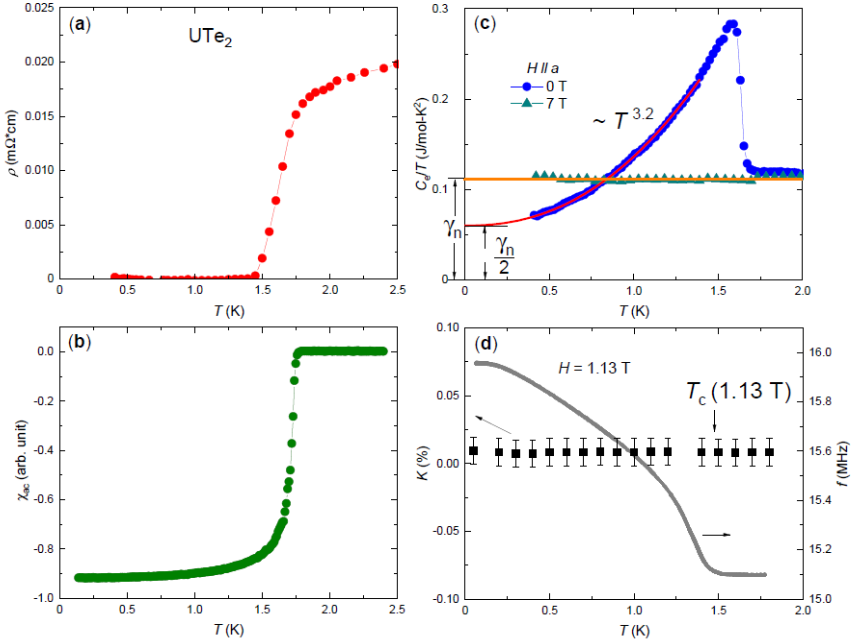
Science **365**, 684–687 (2019) 16 August 2019

SUPERCONDUCTIVITY

Nearly ferromagnetic spin-triplet superconductivity

Sheng Ran[1,2]*, Chris Eckberg[2], Qing-Ping Ding[3], Yuji Furukawa[3], Tristin Metz[2], Shanta R. Saha[1,2], I-Lin Liu[1,2,4], Mark Zic[2], Hyunsoo Kim[2], Johnpierre Paglione[1,2], Nicholas P. Butch[1,2]*





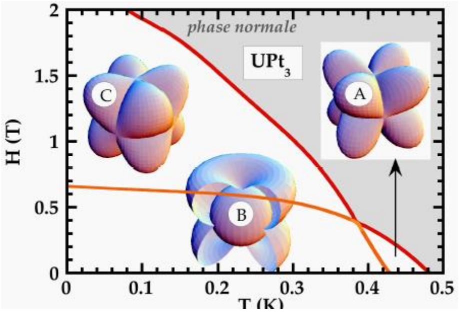
$$
\begin{aligned}
T_{sc} &= 1.6\text{ K}\\
\gamma &= 117\text{mJ/molK}^2\\
\gamma_0 &\approx 50-60\text{mJ/molK}^2\\
C/T &\propto T^{3.2}
\end{aligned}
$$

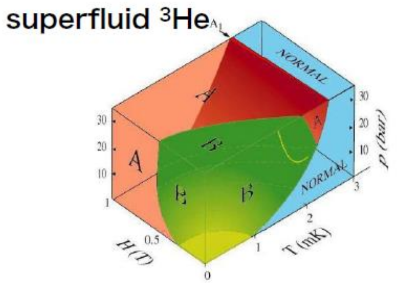
- ➢ no change in Knight shift
- ➢ point nodes in the gap ?

Spin – triplet superconductivity

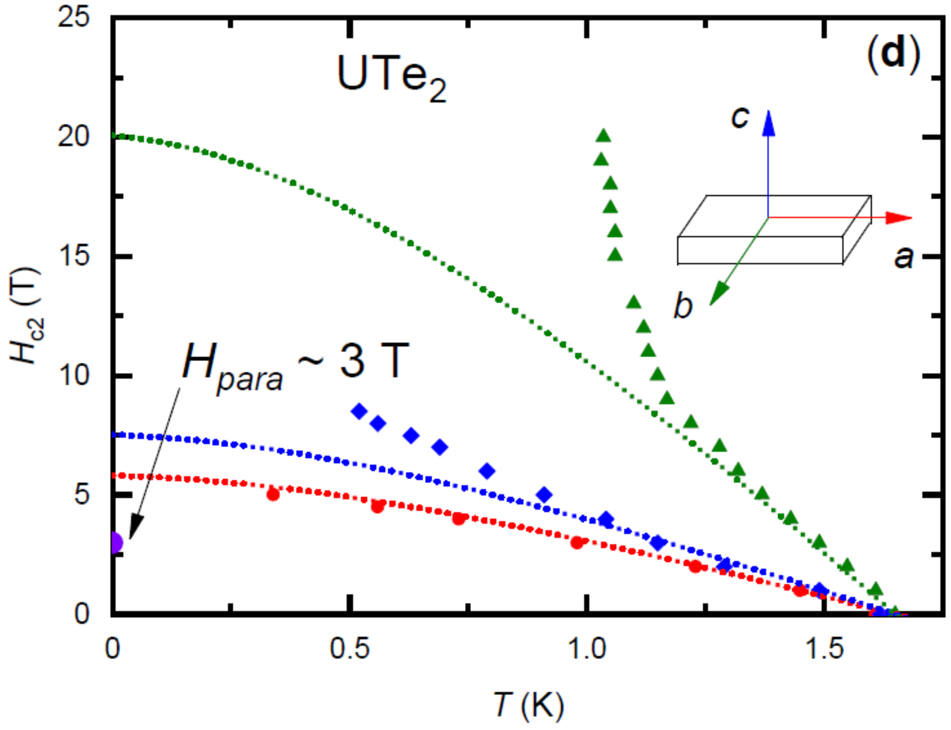
- Cooper pair with spin S = 1, (*p* – wave)
- spin degree of freedom
  - $\Rightarrow$ multiple superconducting phases
- chiral *p*-wave states, topological superconductivity

Multiple superconducting phases





Extremely high superconducting upper critical field



Ran et al. Science 365, 684 (2019)

Pauli – limit : polarization = condensation energy

$$H_P = \sqrt{2}\Delta / g\mu_B$$

$$H_{c2}^P = 1.86\ T_c = 3\ \mathrm{T}$$

orbital – limit : Lorentz force on Cooper pairs

$$H_{\mathrm{orb}}(T) = \Phi_0 / 2\pi\xi^2(T)$$

$$H'_{\mathrm{c2}} = (\mathrm{d}H_{\mathrm{c2}}/\mathrm{d}T)_{T=T_{\mathrm{c}}} \approx T_{\mathrm{c}}/v_{\mathrm{F}}^2$$

$$H_{c2}^{orb} = -0.7\frac{dH_{c2}}{dT}|_{T_c} T_c$$

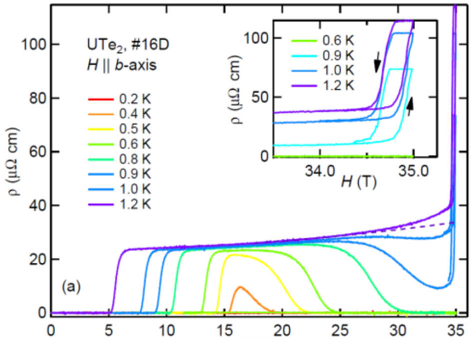
$$\approx 20\mathrm{T} \quad (H\|b)$$

- ⇒ very large upper critical field
- ⇒ spin triplet superconductivity
- ⇒ mechanism enhancing superconductivity under field

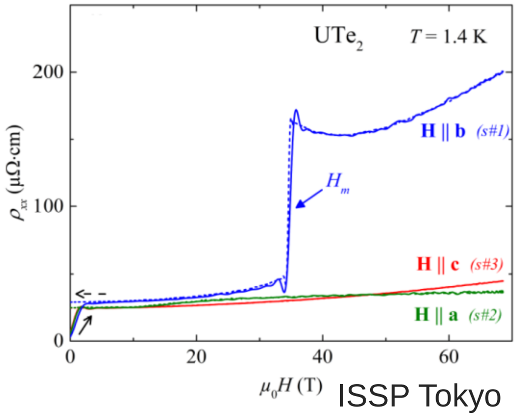
Phase diagram *H* || *b* axis at zero pressure

March-April 2019

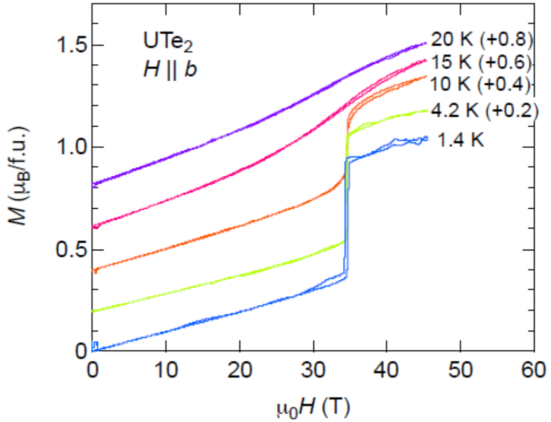
Grenoble



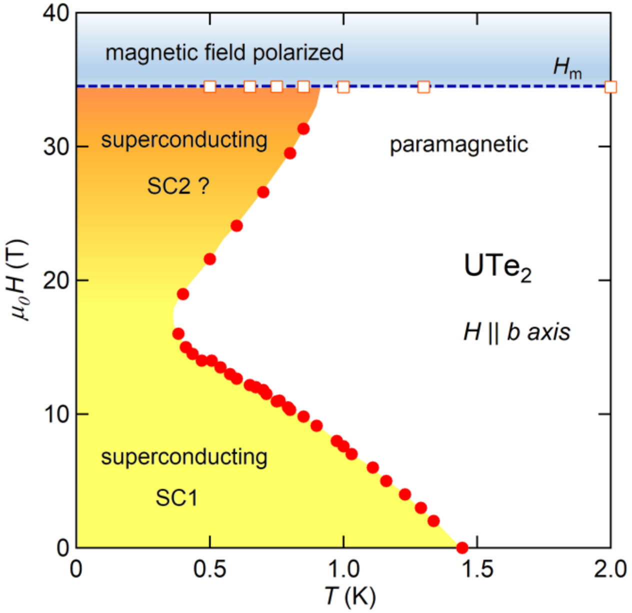
Toulouse



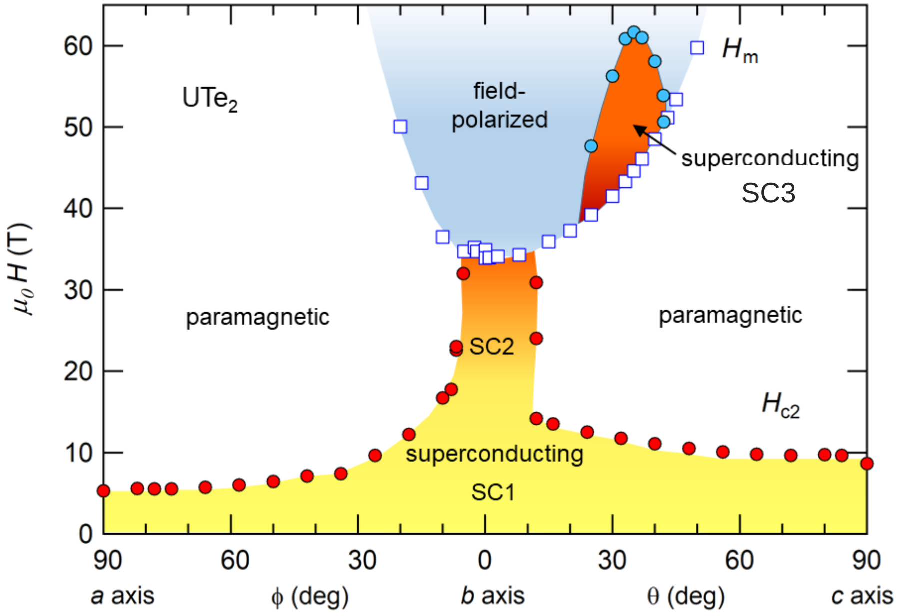
ISSP Tokyo



upper critical field *H* || *b* axis



angular dependence of upper critical field



Ran et al. Nat. Phys. 2019

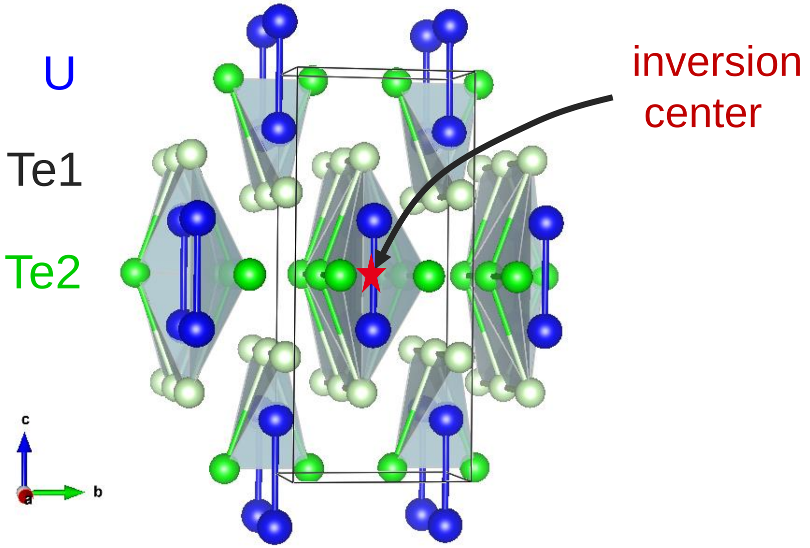
Phase diagram only determined by transport, no thermodynamic measurement !

Knebel et al. JPSJ 2019, W. Knafo et al. JPSJ **88**, 063705 (2019), A. Miyake et al. JPSJ **88**, 063705 (2019)
Ran et al. Nat. Phys. 2019, Knafo et al. Commun, Phys. 2021, Helm et al Nature Communications | (2024)15, 37

UTe_2 crystal structure: local inversion symmetry broken

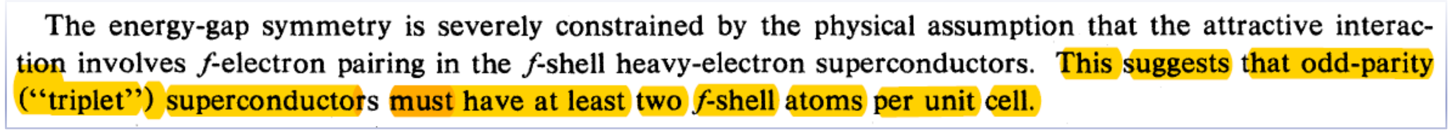
body centered orthorhombic
space group Immm (#71, D_{2h}^{25})

- two leg ladder structure of U atoms
- Te2 chains along the *b* axis
- local inversion symmetry broken



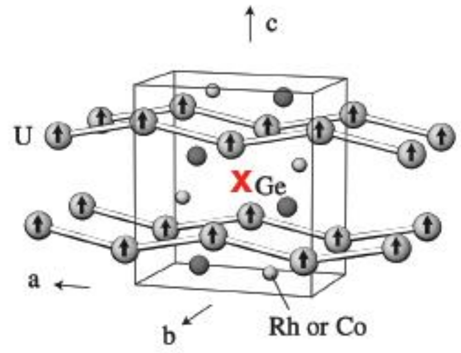
a=4.161 Å, b=6.122 Å, c =13.955 Å
$d_{U\text{-}U}$ = 3.78 Å on ladder rung > Hill – limit
(U localized, no superconductivity)

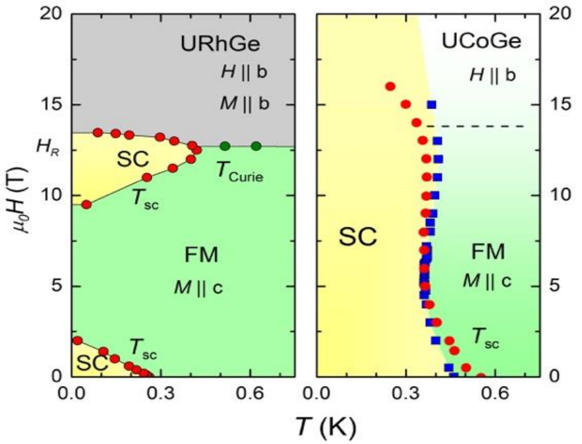
P.W. Anderson PRB 32, 499 (1985)



The energy-gap symmetry is severely constrained by the physical assumption that the attractive interaction involves *f*-electron pairing in the *f*-shell heavy-electron superconductors. This suggests that odd-parity (“triplet”) superconductors must have at least two *f*-shell atoms per unit cell.

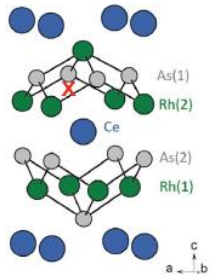
URhGe, UCoGe
Pnma

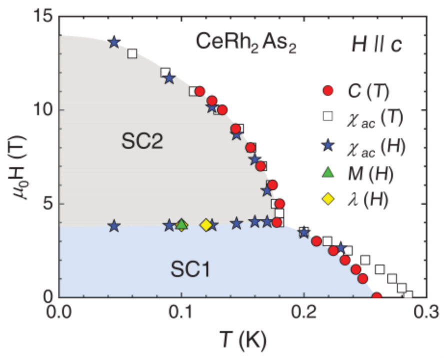


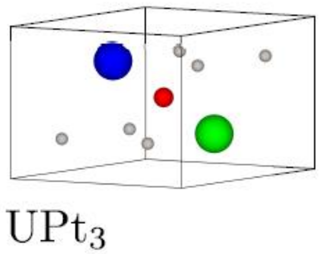


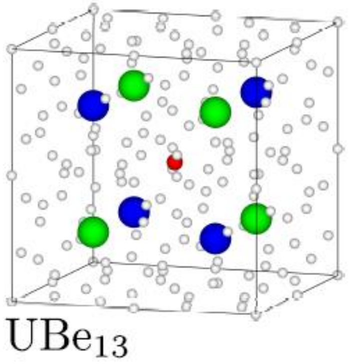
$CeRh_2As_2$

P4/nmm



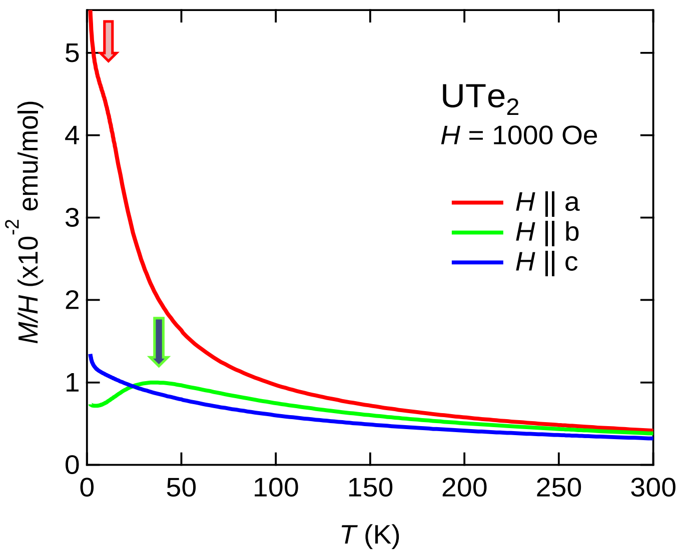




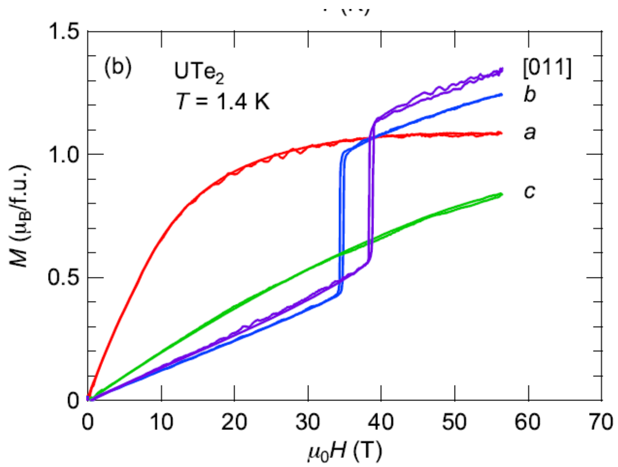


See theory: M. H. Fischer, M. Sigrist, D. F. Agterberg, and Y. Yanase, Annu. Rev. Condens. Matter Phys. **14**:153–72 (2023)
T. Hazra. P. Colman, Phys. Rev. Lett. **130**, 136002 (2023)

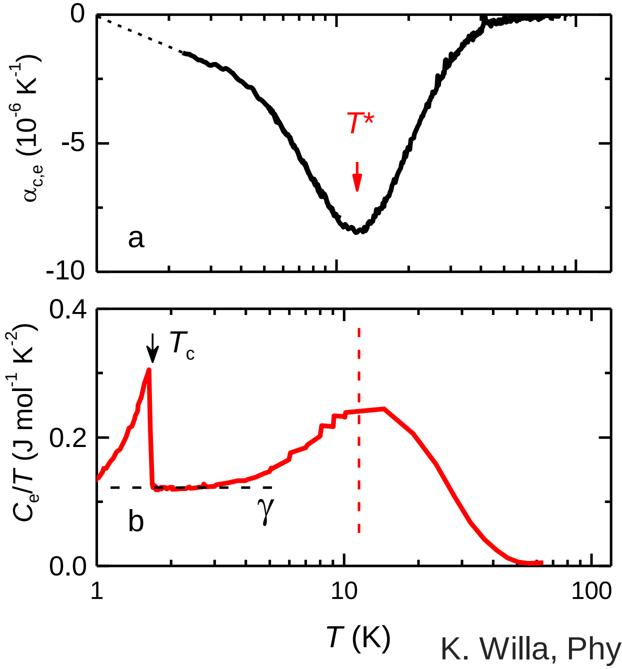
UTe$_2$: normal state properties



- paramagnet
- strong magnetic anisotropy, a-axis easy axis
- maximum in M/H near 35 T for $H \parallel b$
- 1st order metamagnetic transition at 35 T
- negative Curie-Weiss temperatures ⇒ antiferromagnetic exchange at high temperatures

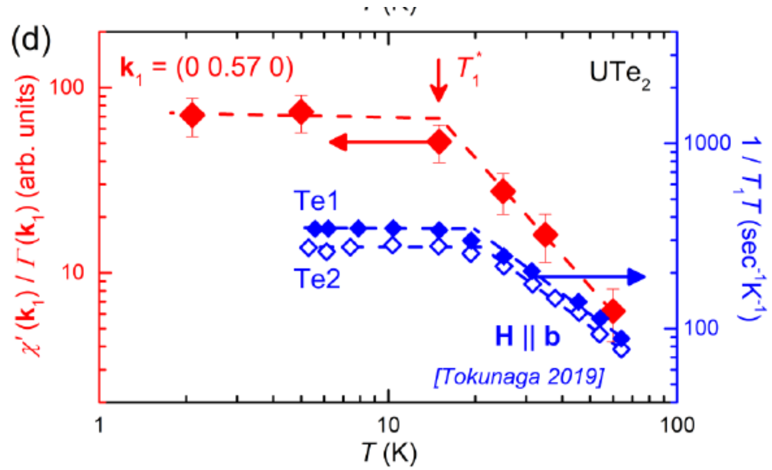


A. Miyake et al. JPSJ 2021



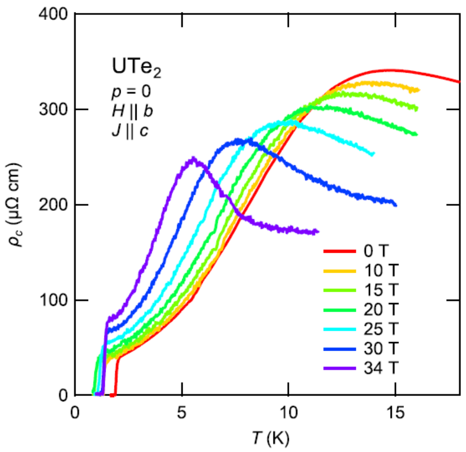
K. Willa, PhysRevB.104.205107

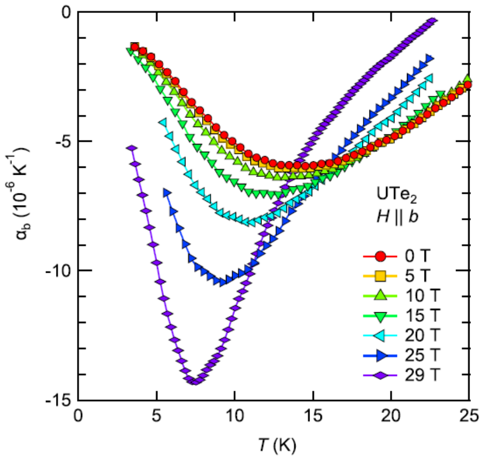
- “Schottky”-like anomaly at T* ~12 K in thermodynamics and transport properties
- T* ~ 12 – 15 K characteristic energy scale in microscopic esperiments.



Knafo et al. Phys. Rev. B **104**, L100409 (2021)

Characteristic energy scales under field

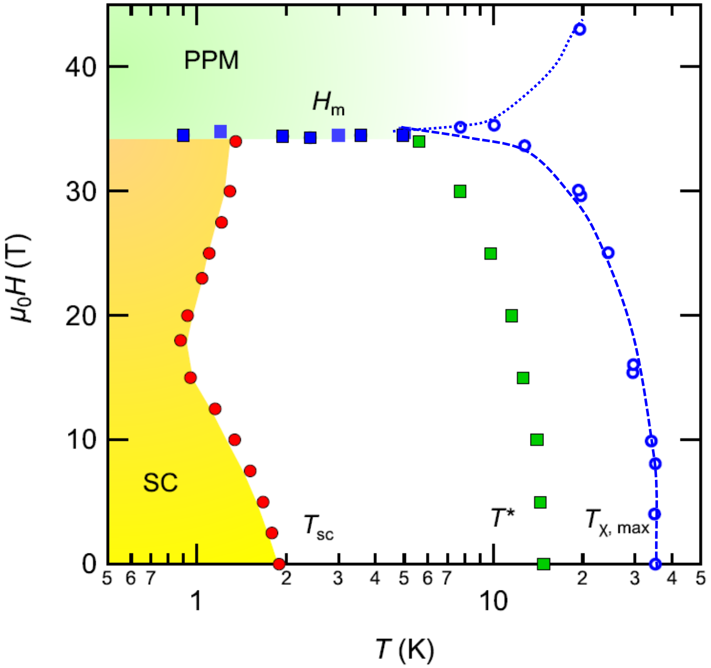




- 1st order metamagnetic transition
- critical point of the 1st order transition
- superconductivity suppressed at metamagnetic transition H_m

Mechanism for field enhancement of superconductivity ?

- Enhancement bulk property ?
- Requires increase of pairing strength !
  - Noted by experimentalist (Ran et al. Supp. Science 2019, ***365***, 684)
  - Ignored by theoretical models !
- different superconducting phases ?
  - symmetry OP, change of OP with magnetic field ? Rotation of ***d*** vector?
  - Connection with (p,T) phase diagrams ?



Knebel et al., Phys. Rev. B 109, 155103 (2024)

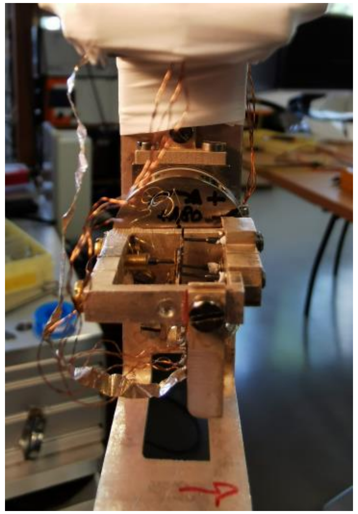
Thermodynamic probes under (static) high fields

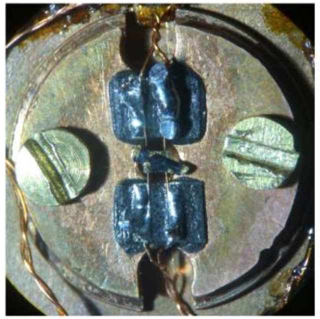
❑ Specific heat – semi-adiabatic (10mg UTe_2) CEA

- two axes rotation
- 0.06mK / 15T (A. Rosuel, J.-P. Brison)

❑ Specific heat – ac (10µg UTe_2)

- 0.4K / 36T (A. Rosuel, C. Marcenat, T. Klein)





Ac calorimetry

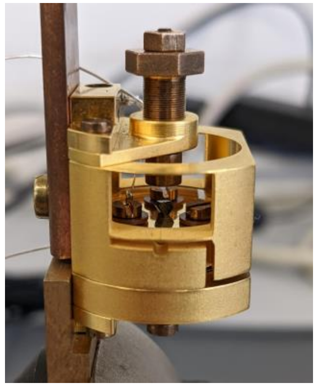
❑ Thermal dilatation/magnetostriction

$$\alpha = \frac{1}{V}\frac{\partial V}{\partial T}\Big|_{p,B} \Leftrightarrow -\frac{1}{V}\frac{\partial S}{\partial p}\Big|_{T,B}$$

$\Rightarrow$ phase transition
kink in $\Delta L/L$
discontinuity in $\alpha(T)$

$$\lambda = \frac{1}{V}\frac{\partial V}{\partial B}\Big|_{p,T} \Leftrightarrow -\frac{1}{V}\frac{\partial M}{\partial p}\Big|_{T,B}$$

$\Rightarrow$ magnetic properties
irreversibilities
vortex pinning

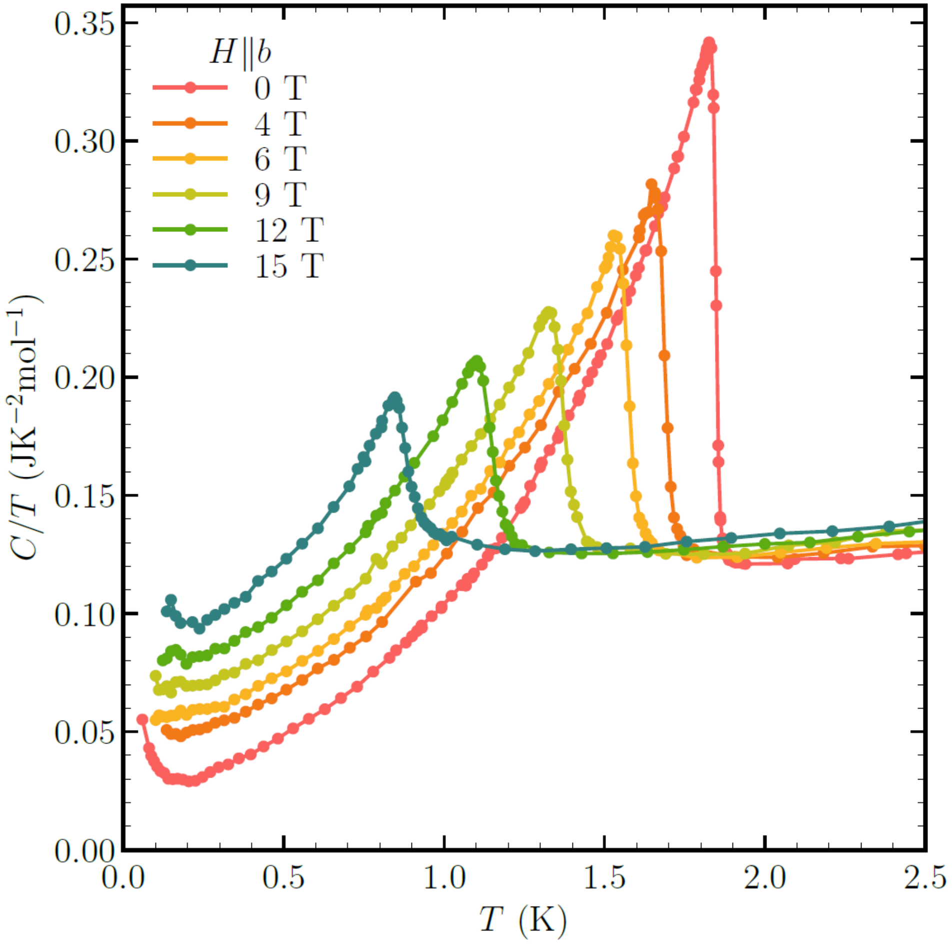


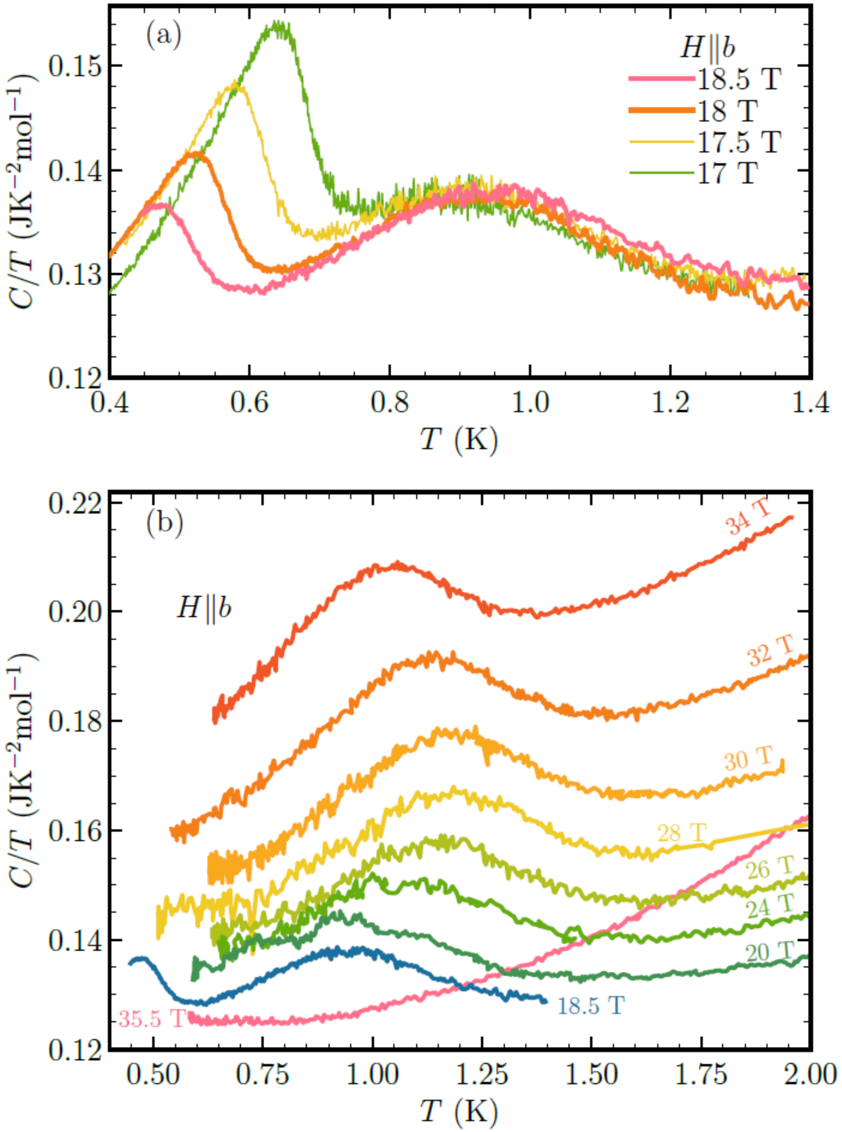
capacitive dilatometer

$$: \frac{\Delta L_i}{L_i} = \frac{1}{L_i}\,\epsilon_0\epsilon_r A\,\frac{C-C_i}{C\cdot C_i}$$

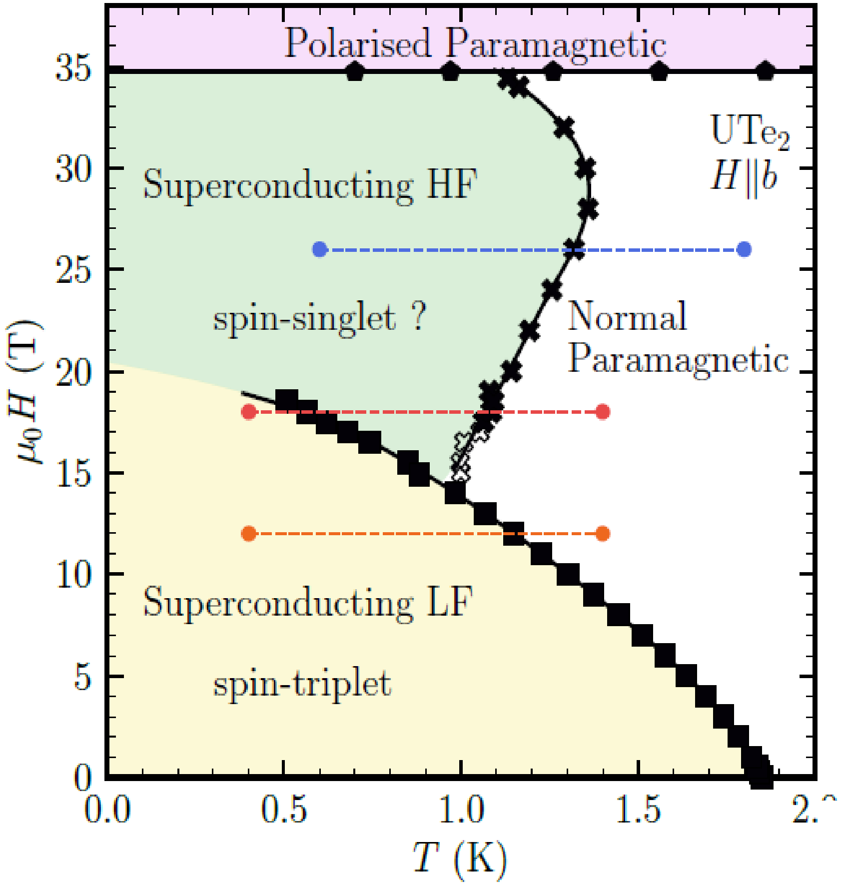
Rosuel et al. Phys. Rev. X **13**, 011022 (2023)

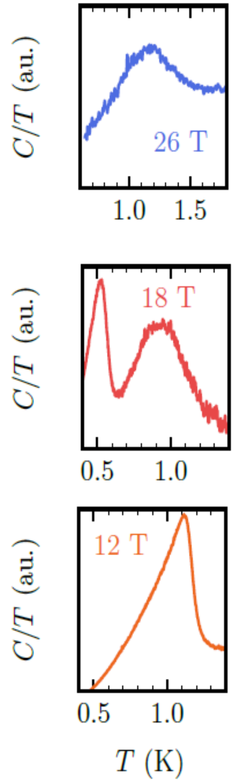
Determination of phase diagram by specific heat





Two distinct superconducting phases !

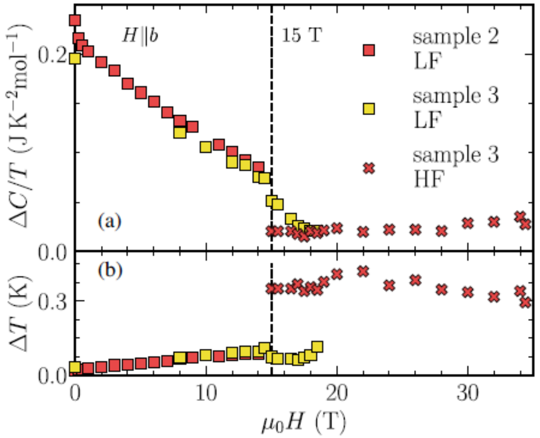




large

two

sharp



Two distinct superconducting phases with different pairing mechanisms:

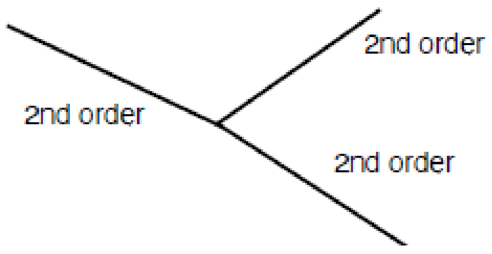
proposal :

spin-triplet at low field

new pairing mechanism (spin singlet) at high field, driven by critical fluctuations related to the metamagnetic transition ?

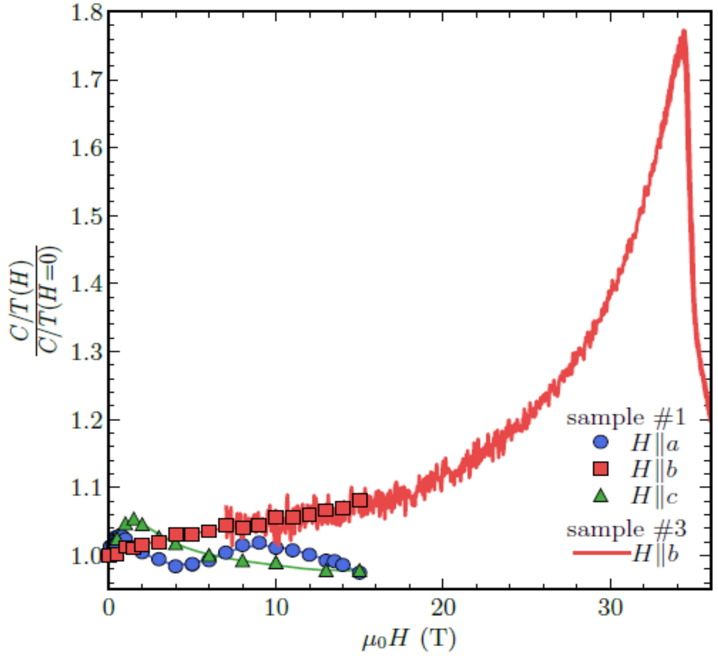
field enhancement of pairing mechanism

Problem :

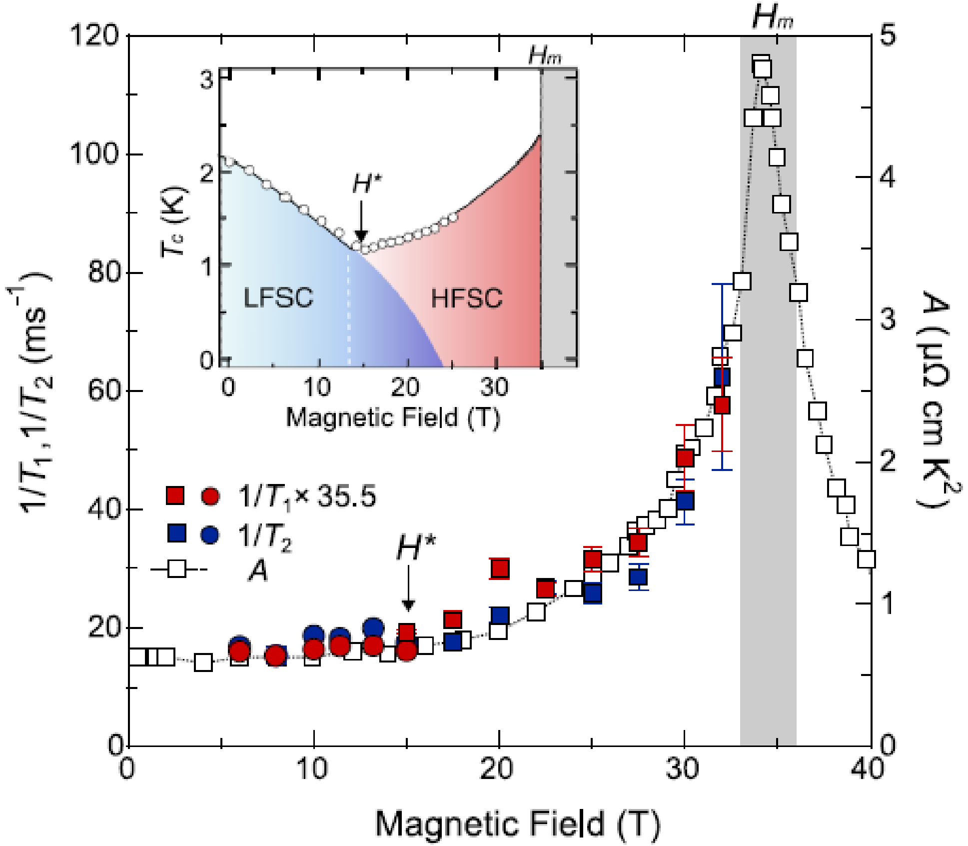


thermodynamically forbidden

Enhancement of fluctuations approaching the metamagnetic transition

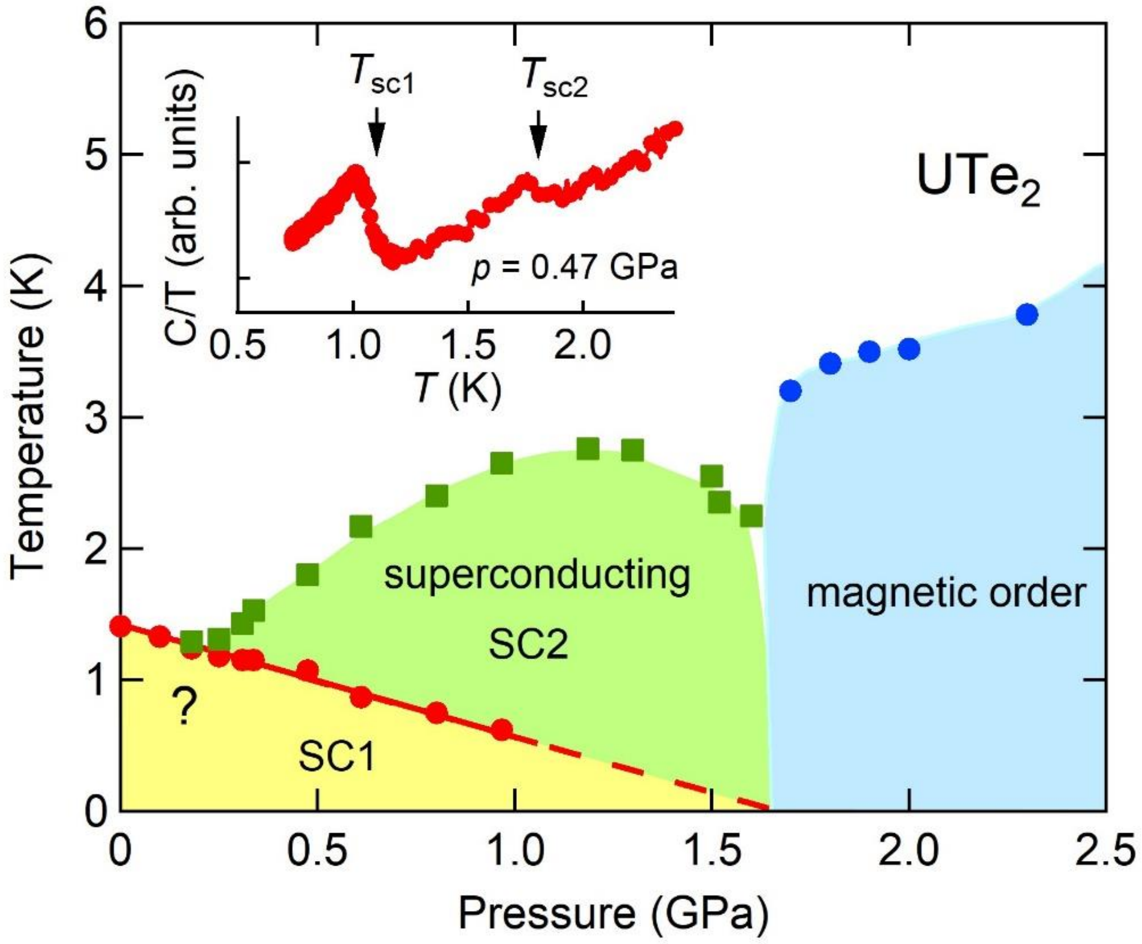


Strong enhancement of the γ coefficient on approaching H_m
⇒ strong enhancement of magnetic fluctuations



Y. Tokunaga et al. Phys. Rev. Lett. 131, 226503 (2023)

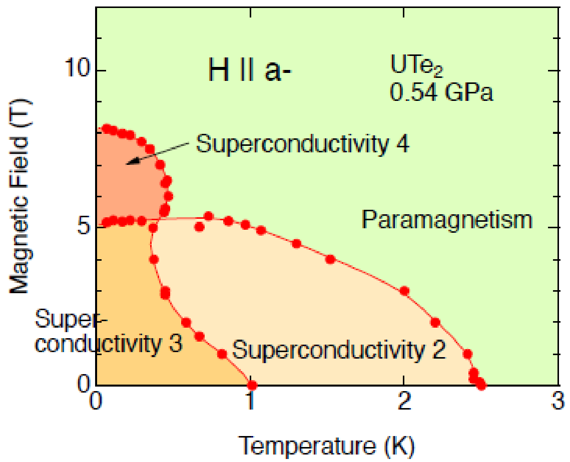
High pressure phase diagram



Braithwaite et al., COMMUNICATIONS PHYSICS | (2019) 2:147

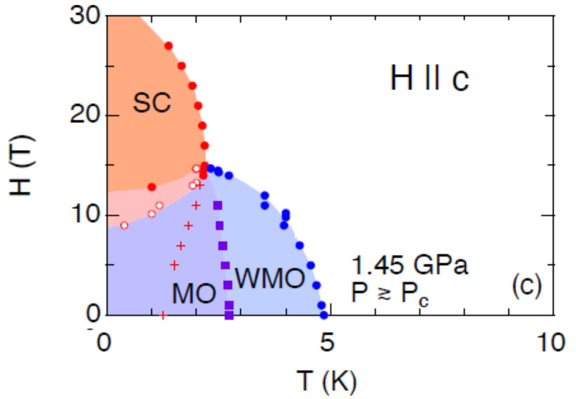
- from ac calorimetry :

for *H* || *a* : multiple superconducting phases



Aoki et al. JPSJ **89**, 053705 (2020)
Aoki et al. JPSJ **90**, 074705 (2021)

for *H* || *c* : field induced SC

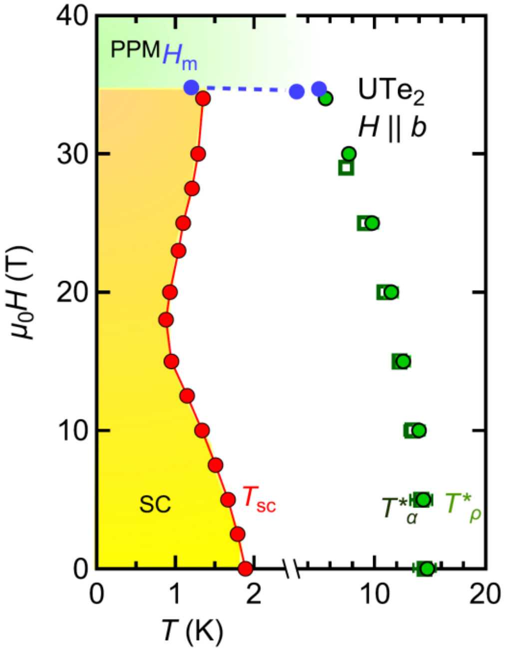


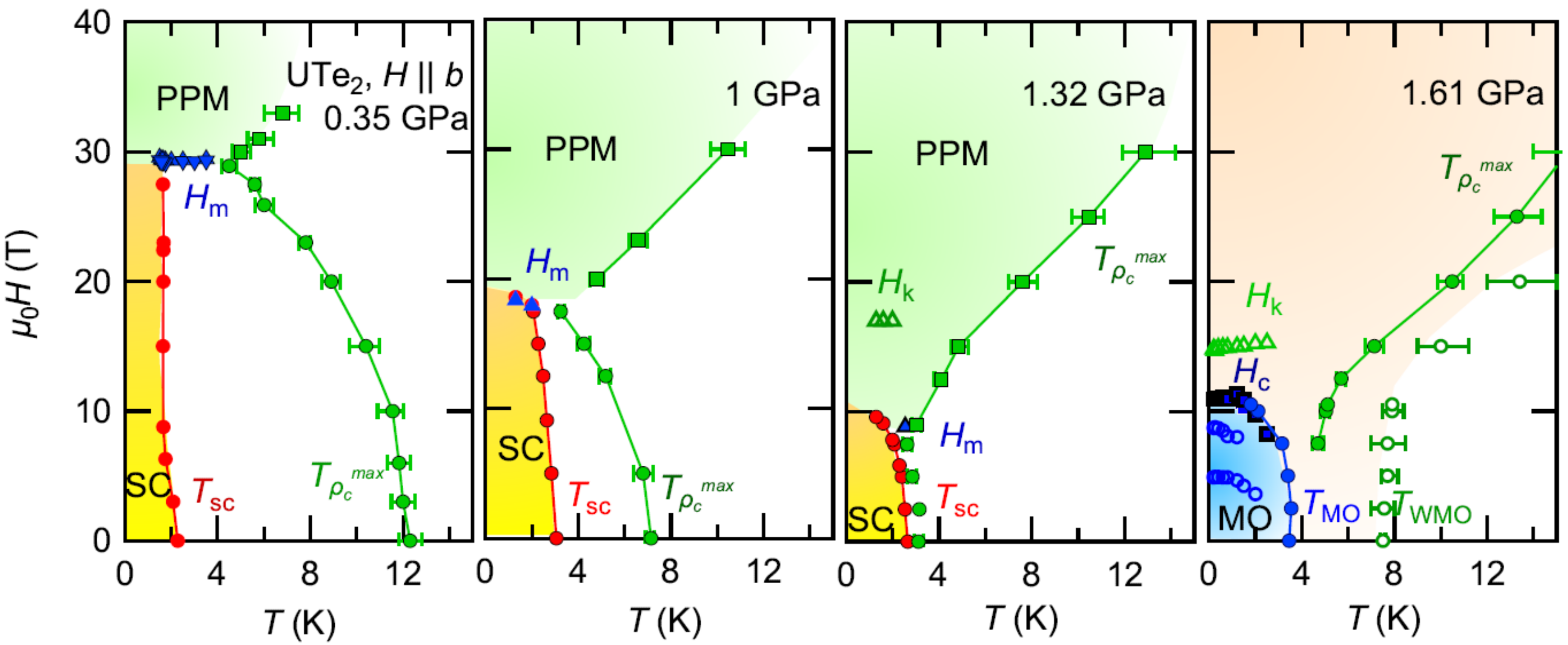
- antiferromagnetic order above p_c

$\mathbf{k}_m$ = (0.07, 0.33, 1) close to the vector of AF fluctuations

Knafo et al. PRX under review

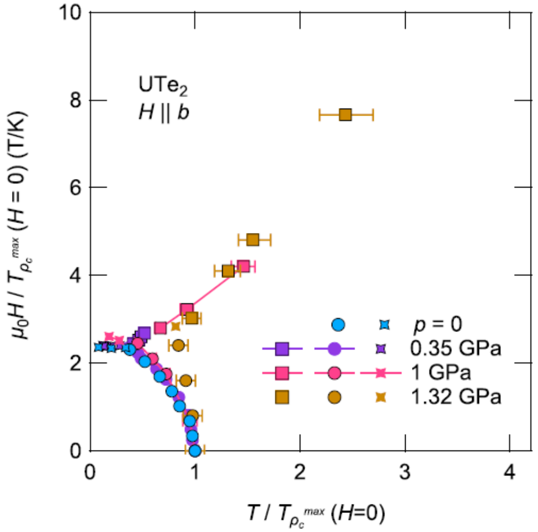
High pressure *H* || *b* axis





H_m scales with *T**

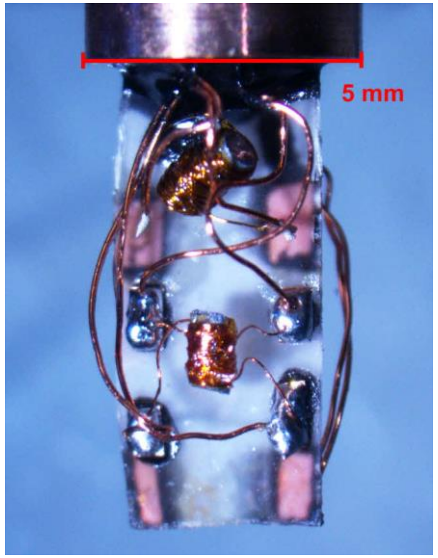
Scaling by T* of phase diagram

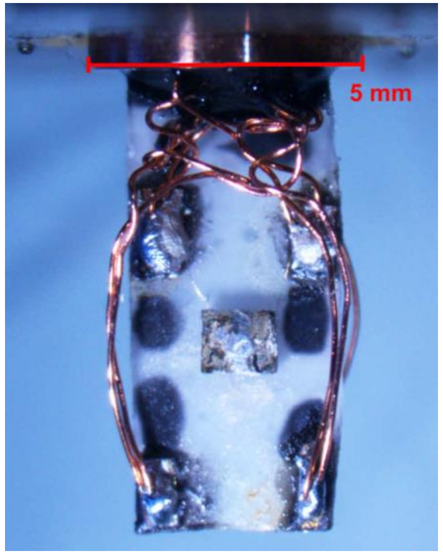


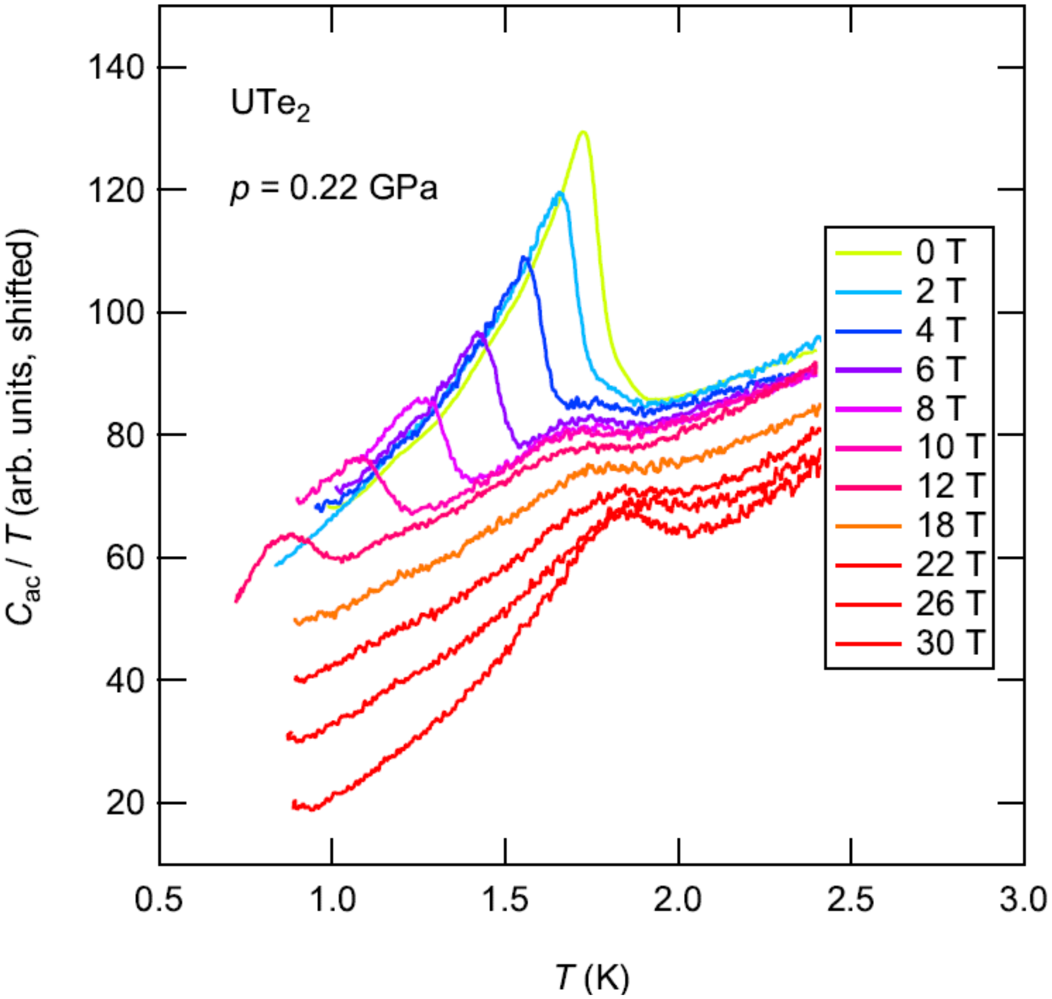
Knebel et al., Phys. Rev. B 109, 155103 (2024)

Ac calorimetry *H* || *b* under pressure (end may 2024)

Experimental set up:
20 mm Cu/Be-NiCrAl pressure cell
Daphne 7373 as pressure medium
^{3}He cryostat
Cernox thermometer, carbon past as heater

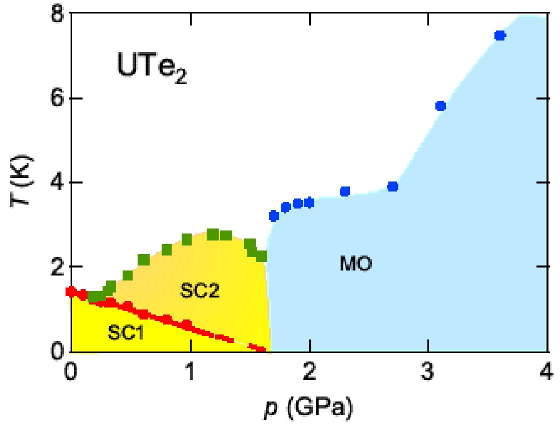


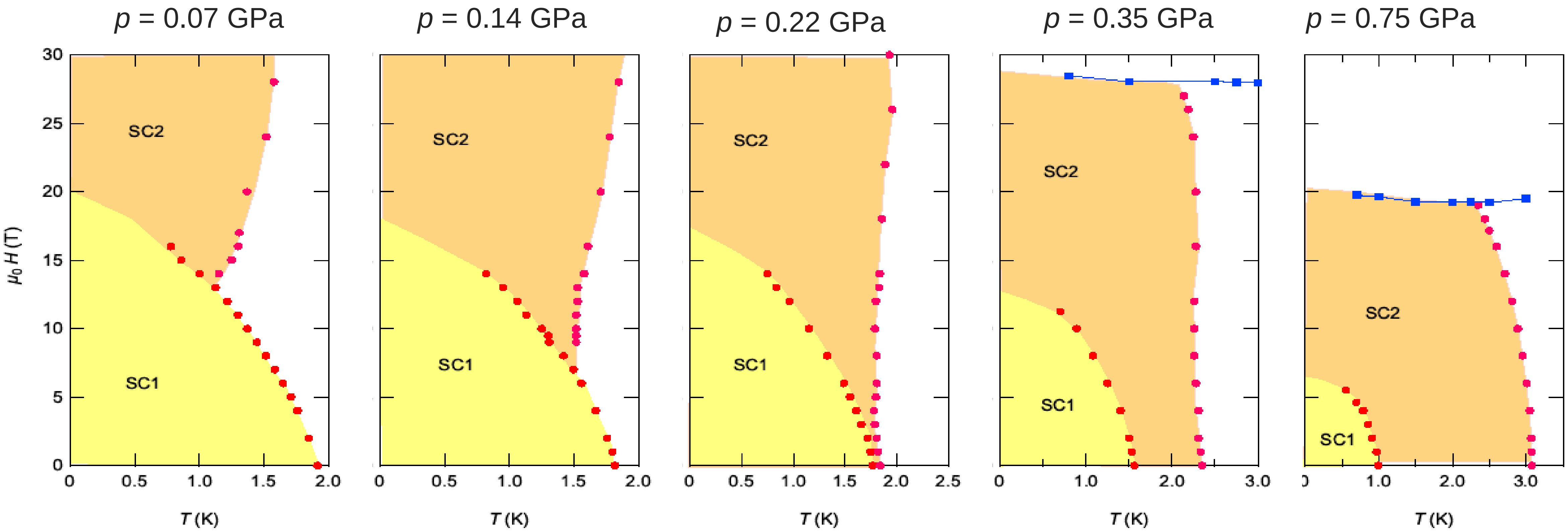




T. Vasina et al., in preparation

Phase diagrams from ac calorimetry

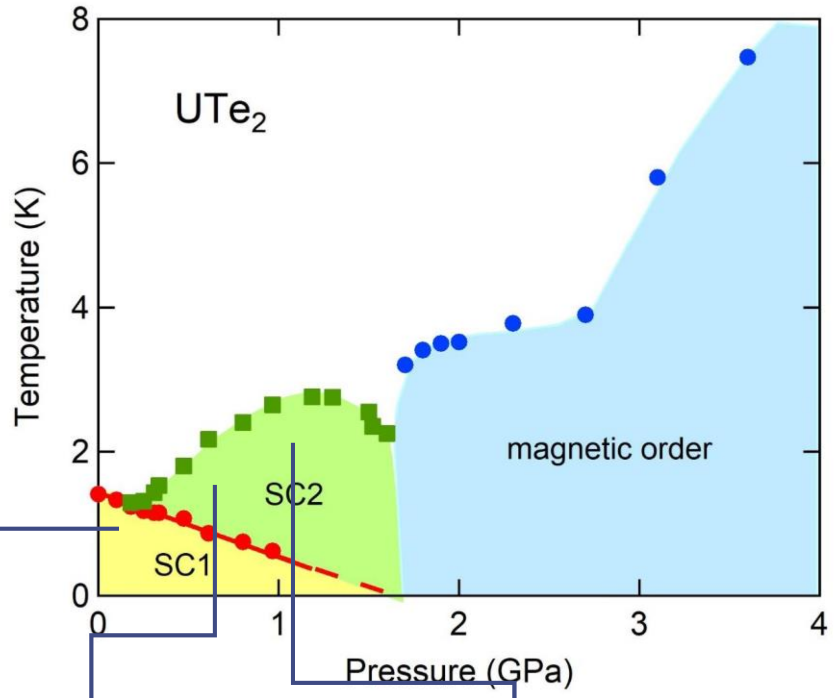




High temperature superconducting phase under pressure corresponds to high field phase at ambient pressure.

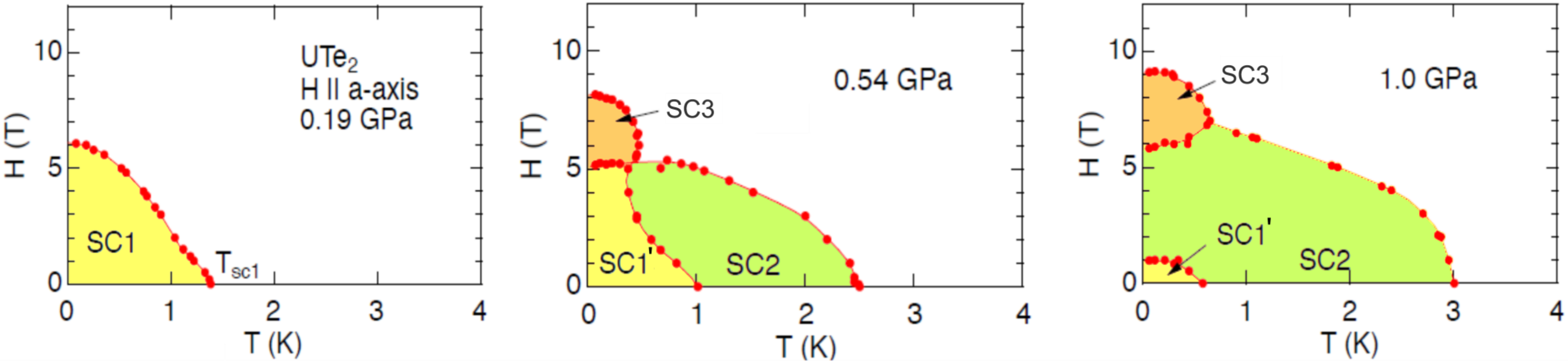
UTe$_2$: Superconductivity tuned by pressure, *H* || *a*

Under pressure,
“high temperature phase” close
to paramagnetic limit (H//a)



Braithwaite et al. Comm. Phys. 2019

Aoki et al. JPSJ 2020
Knebel et al. JPSJ 2020



UTe$_2$: progress in crystal growth

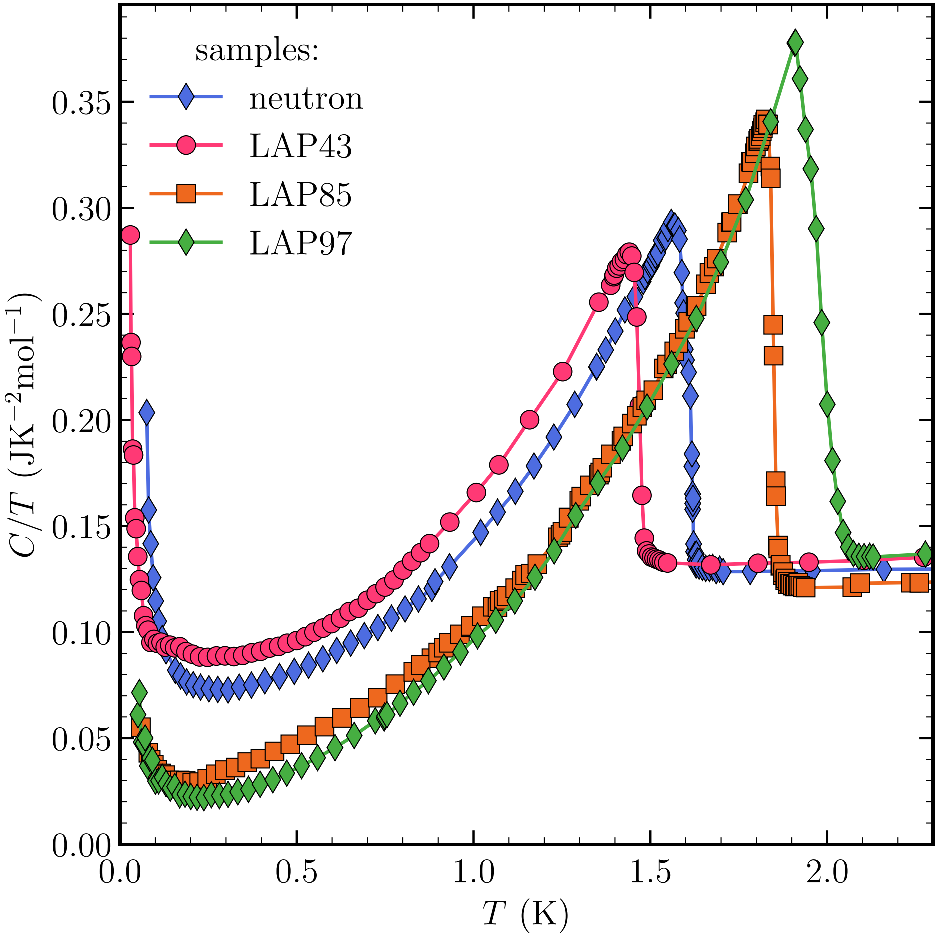
Chemical Vapor Transport optimization
P. F. S. Rosa et al. Comm. Materials 3, 33 (2022)

Molten Salt Flux method (2022)
H. Sakai et al. Phys. Rev. Materials 6, 073401 (2022)

$T_c \rightarrow 2.1$ K
$\gamma_0/\gamma_N \rightarrow 0$

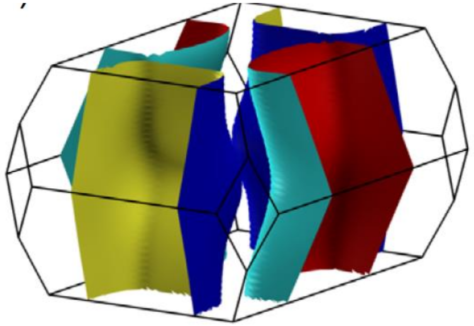
$\Delta C/\gamma T_c \rightarrow 2.7$
$\gamma_0/\gamma_N \rightarrow 0$

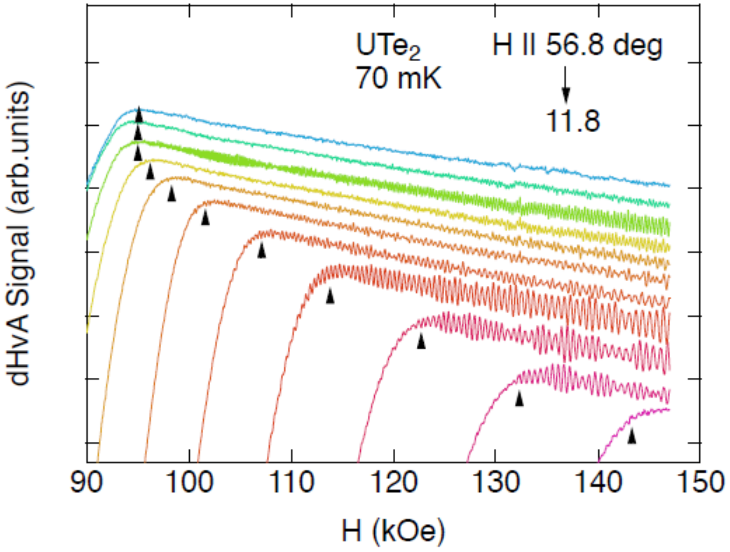
RRR → 800



observation of dHvA

Quasi-2D Fermi surfaces with strong corregation



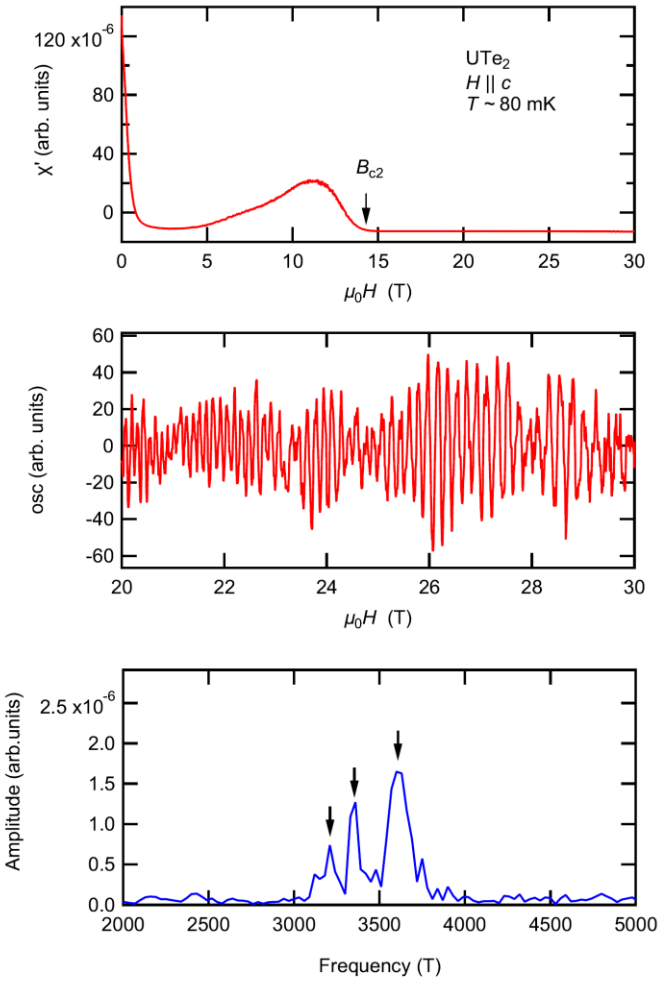


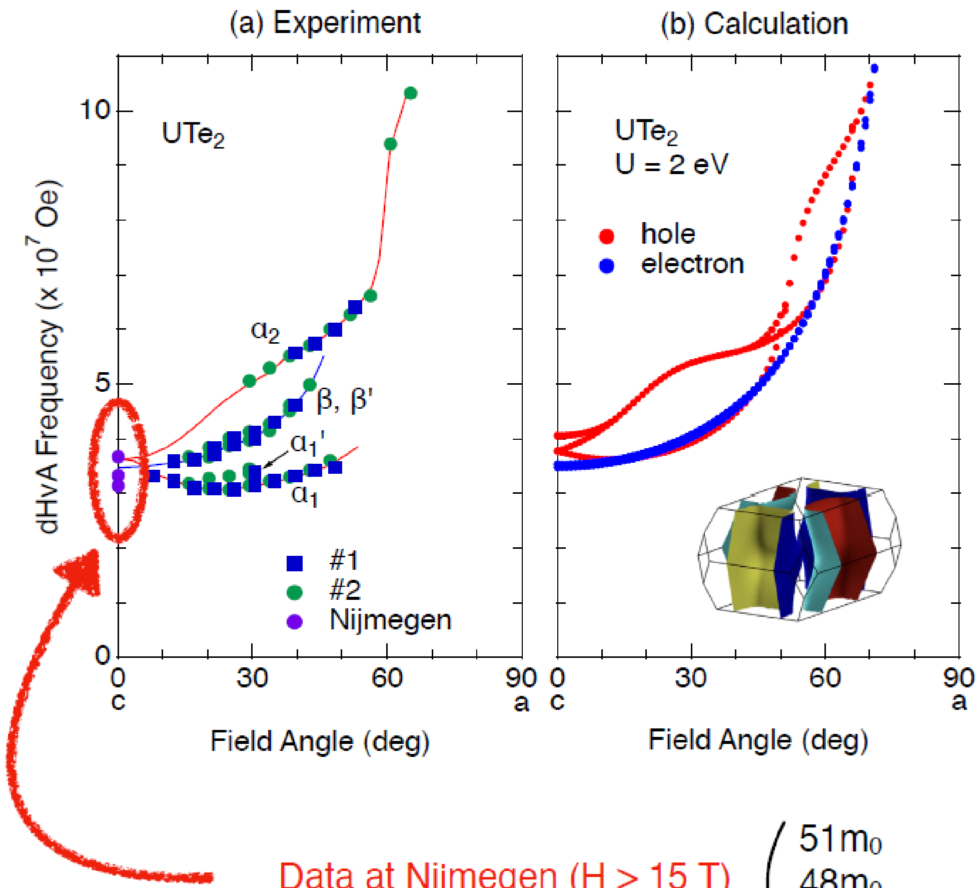
D. Aoki, et al. JPSJ 91, 083704 (2022)
confirmed by Cambridge group A.G. Eaton et al

Studies on crystal LAP85: $T_c \sim 1.85K$

- $\frac{\Delta T_c}{T_c} \sim 0.01$
- $\frac{\gamma_0}{\gamma_N} \sim 0.1 - 0.03$

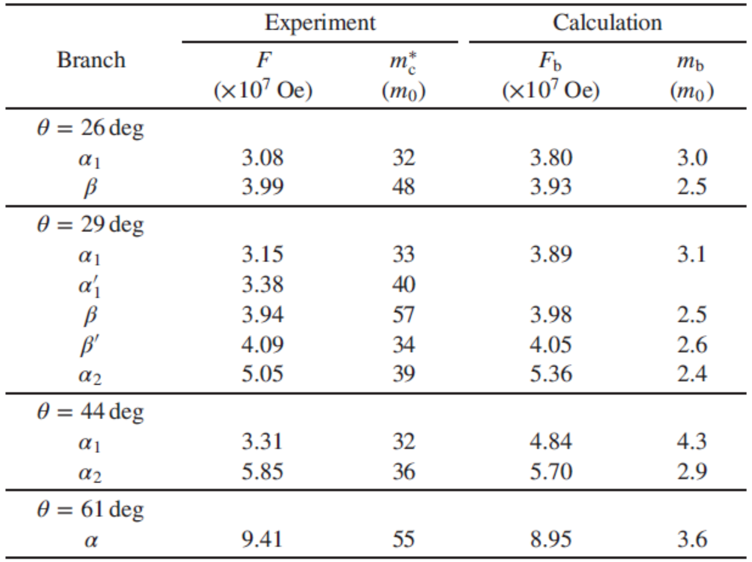
Quantum oscillations in high field





Data at Nijmegen (H > 15 T)

$$\left(\begin{array}{l} 51m_0 \\ 48m_0 \\ 41m_0 \end{array}\right.$$



Branch	Experiment F ($\times 10^7$ Oe)	Experiment m_c^* (m_0)	Calculation F_b ($\times 10^7$ Oe)	Calculation m_b (m_0)
$\theta = 26$ deg				
α_1	3.08	32	3.80	3.0
β	3.99	48	3.93	2.5
$\theta = 29$ deg				
α_1	3.15	33	3.89	3.1
α_1'	3.38	40		
β	3.94	57	3.98	2.5
β'	4.09	34	4.05	2.6
α_2	5.05	39	5.36	2.4
$\theta = 44$ deg				
α_1	3.31	32	4.84	4.3
α_2	5.85	36	5.70	2.9
$\theta = 61$ deg				
α	9.41	55	8.95	3.6

cylindrical FS

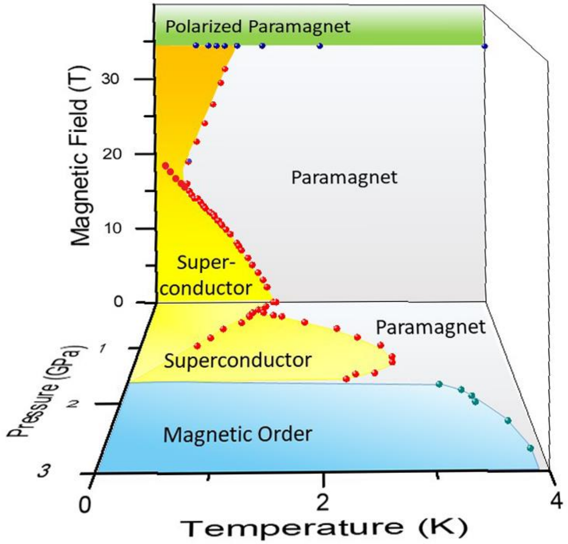
$$\gamma = \frac{k_B^2 V}{6\hbar^2} \sum m^* k_z$$

Important information on the electronic structure.
Main Fermi surface branches are detected.
Existence of a small pocket still under discussion.

Aoki et al., JPSJ **91**, 083704 (2022)
Aoki et al., JPSJ **92**, 065002 (2023)

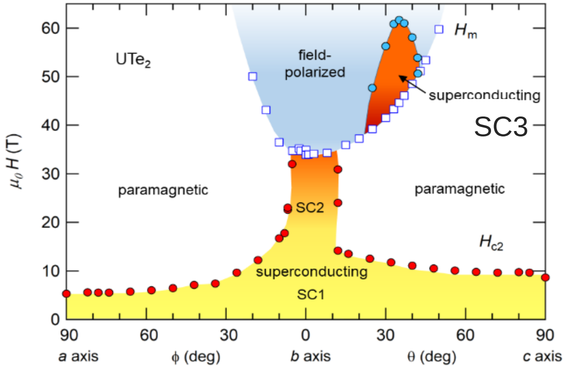
Conclusions

- Extremely rich superconducting phase diagram at ambient pressure
- Multiple superconducting phases
- Antiferromagnetic order under high pressure
- Two cylindrical Fermi surfaces determined by dHvA experiments



many open questions:

- nature/symmetry of the superconducting order parameter in different phases
- triplet ⇔ singlet ⇔ mixture of singlet triplet
- Pairing mechanism, only AF fluctuations competing with “local” FM
- Why so many superconducting phases
- Existence of PDW coupled to CDW



Wishes : “static” fields to reach SC3 superconducting phase !

Many thanks to EMFL for continuous support of experiments !