Réunion Plénière du GDR,
Lastresne 2023

Spin triplet superconductivity in bulk strongly correlated materials.

J.P. Brison

Collaborations between:

Univ. Grenoble Alpes:

Pheliqs/MEM-CEA

LNCMI-CNRS

Institut Néel-CNRS

IMR-Toku university

Interplay with … all electronic instabilities ?

- Magnetism (all SCES families ?) Erik Linnér
- Charge order ($NbSe_2$, Cuprates, Nickelates) Alvaro Adrian Carrasco Alvarez
- *Nematicity (iron pnictides)*
- *Multipolar ordering (URu_2Si_2, $PrOs_4Sb_{12}$)*
- Topological properties (band structure) Valentin Taufour

Between Fields:

- “Nano-physics”:
  - *Phase manipulation (meso phys. – quantum engineering)*
  - Current manipulation (non reciprocal superconductivity) *Shamashis Sengupta*
  - Thin films / surface spectroscopies Florent Condaminas
  - *Topological properties (Majorana modes)*
- Solid-State Chemistry (novel/high quality materials !) Araceli Gutiérrez Llorente, Alain Demourgues

Outline: spin-triplet superconductivity

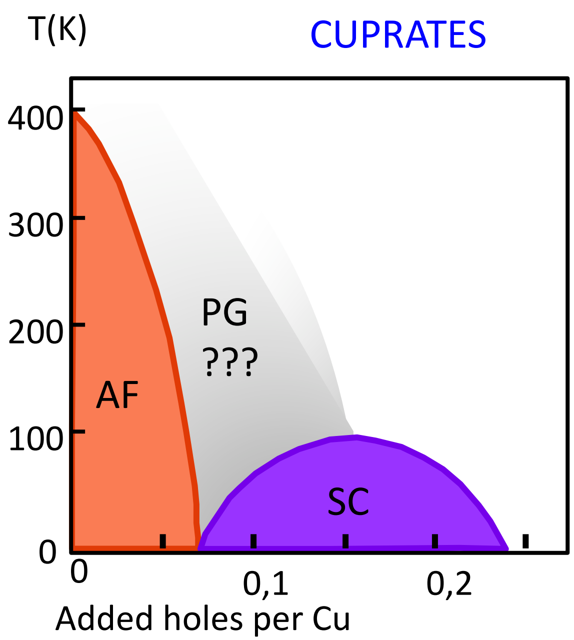
1. Superconducting state in FM-SC
    - Spin-triplet superconductivity
    - Effect of transverse fields
    - Field dependence of the pairing

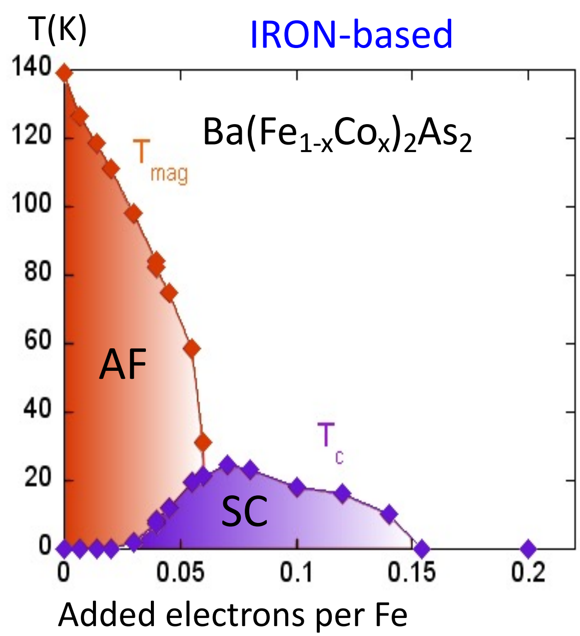
2. UTe_2
    - Spin triplet superconductor (T_{sc} ~2K)
    - Field reinforced superconductivity
    - Multiple superconducting phases
    - Comparison with FM superconductors

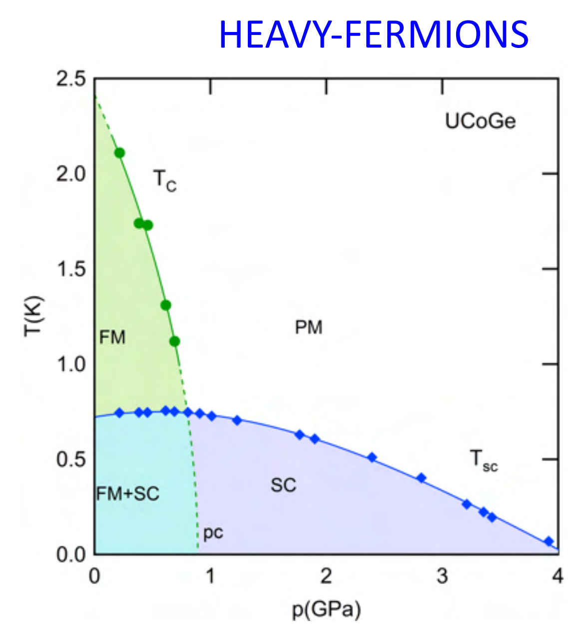
Unconventional superconductivity in SCES

Superconductivity the verge of “magnetic instabilities”:

- Pairing mechanism related to the exchange of magnetic excitations ?
- Competing interactions : which one controls pairing ?

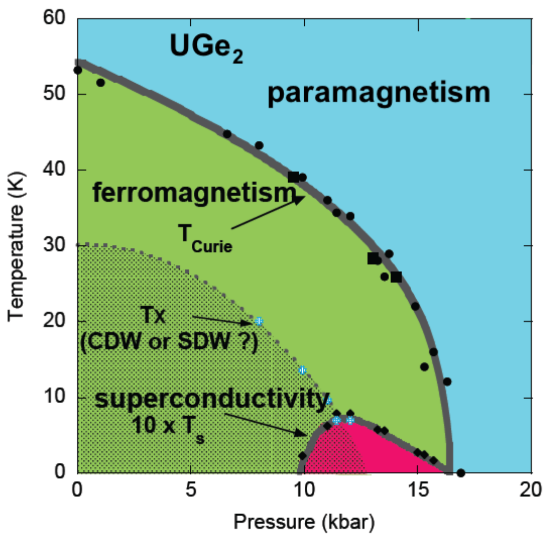




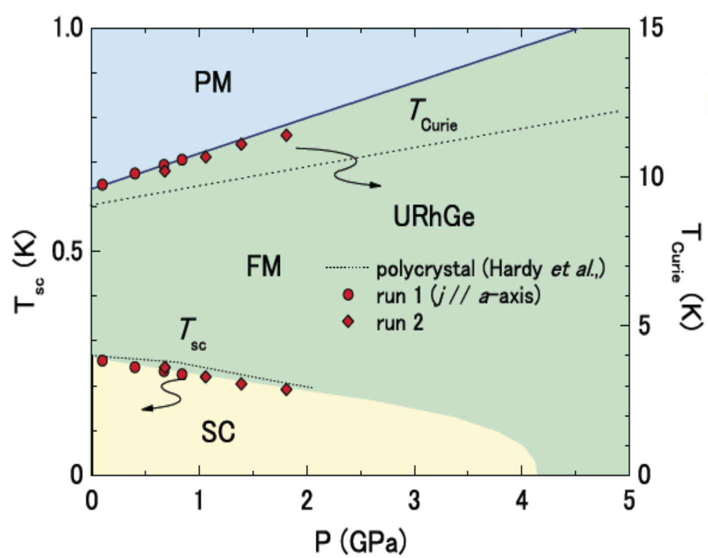


FM-SC in uranium-based systems

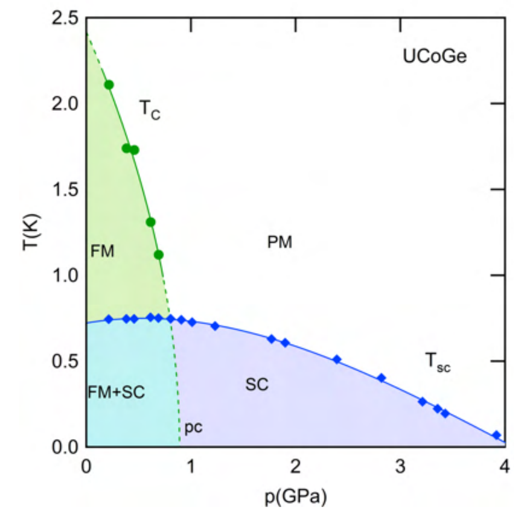
Three known systems, always with $T_{Curie} > T_{sc}$



Saxena et al. Nature 2000
Huxley et al. PRL 2003



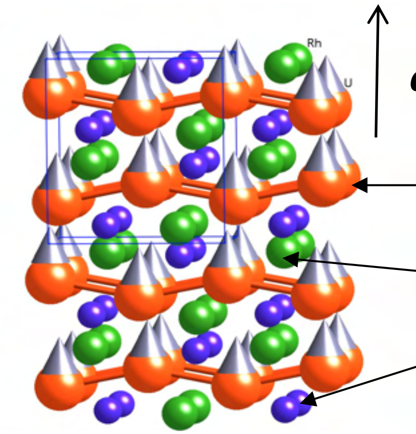
Aoki et al Nature 2001
Hardy et al. PRL 2005



Huy et al, PRL 2007
E. Hassinger *et al.*, PRB 2008
E. Slooten *et al.*, PRL 2009
G Bastien *et al.* PRB 2016

Uranium-based FM-SC

- Orthorhombic, with « zig-zag» U-chains
- Uranium: ~ $5f^3$ (Fujimori JPSJ 2012, *81*, 014703)
- 5f bands at E_F (Fujimori et al. PRB 2014-2015)
- « **Ising** type » , **weak** itinerant (?) ferromagnets
- SCES: m*/m0 ≥ 50



UGe_2: T_{c_max}~0.8K,

T_{curie}~35K, at 12kbars

m_s~1.4μ_B at 0kbar.

S. Saxena et al. Nature 406 (2000) 587

URhGe: T_{sc}~0.25K,

T_{Curie}~9.5K, **m_s~0.4μ_B**

n_e^{5f}~2.61, μ_L/μ_S~-2.1

D. Aoki et al. Nature 413 (2001) 613

UCoGe: T_{sc}~0.5K,

T_{Curie}~2.5K, **m_s~0.04μ_B**

n_e^{5f}~2.84, μ_L/μ_S~-2.3

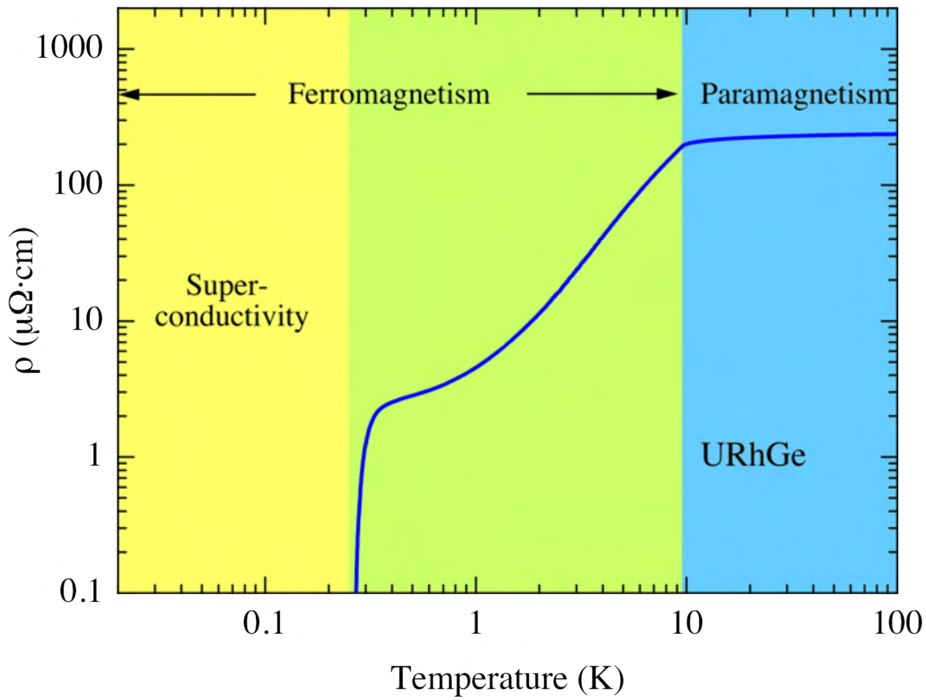
N.T. Huy et al.: Phys. Rev. Lett. 99 (2007) 067006

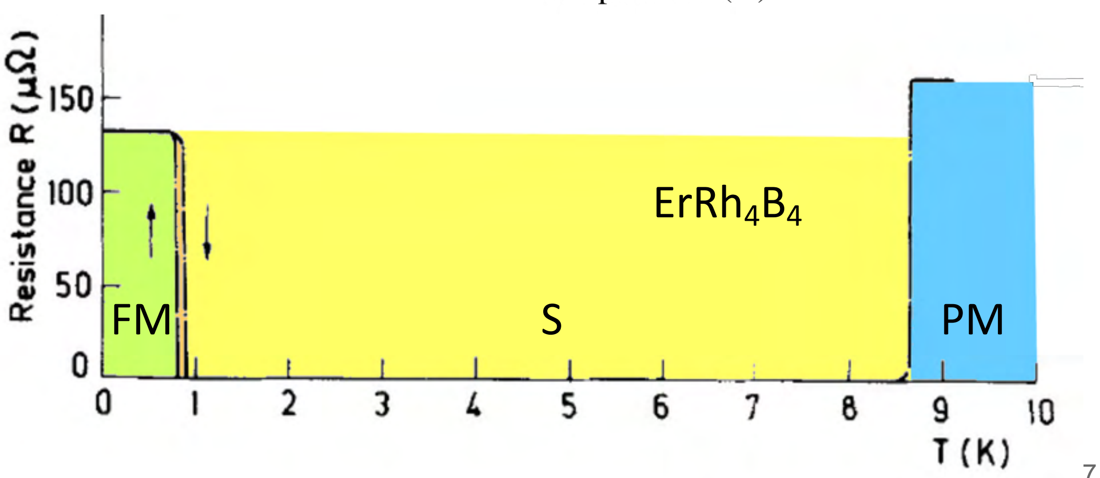
Superconductivity in FM-SC

In heavy fermion systems:

- $T_{Curie} > T_{sc}$
- true coexistence (e.g. muons:
  Huy et al. PRL **2007**, *99*, 067006)
- the same 5f-electrons yield
  - ferromagnetism
  - superconductivity

Why/how is it possible ?





Dipolar and exchange fields

Ferromagnet/paramagnet: exchange or dipolar-governed

$$\boldsymbol{B_{dip}} \sim \mu_0 \boldsymbol{M} \sim \frac{\mu_0 \mu_{ord}}{V_{at}} \approx 0.3\ T/\mu_B$$

$$\boldsymbol{B_{ex}} \text{ from Coulomb interaction: can be} \sim 100\ T$$

$$\widehat{\mathcal{H}}^{spin} = -g\mu_B \boldsymbol{B_{ex}} \cdot \boldsymbol{S}$$

***B**_{dip}*: real magnetic field, acts on orbital & Pauli limits

***B**_{ex}*: effective field, acts on spins only => Pauli limit ONLY.

Superconductivity in FM heavy-fermions

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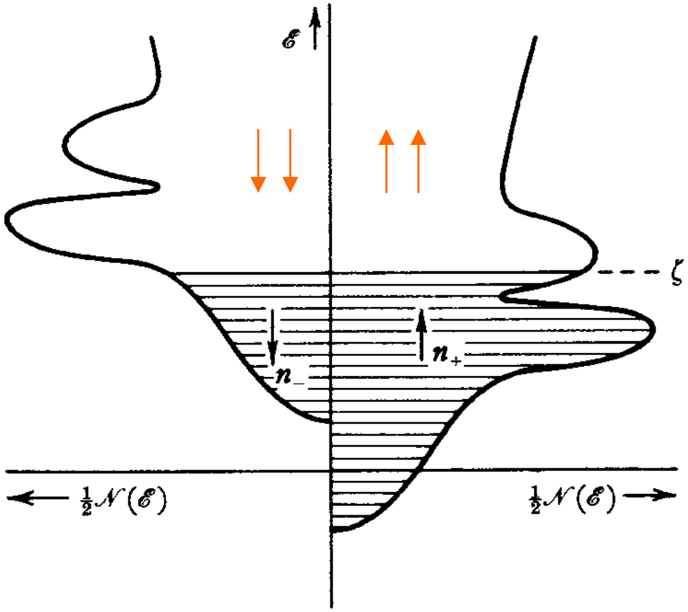

	UGe_2	URhGe	UCoGe
μ_{ord} / uranium	~1 μ_B	~0.4 μ_B	~0.045 μ_B
$B_{dip} \sim \mu_0 M$	0.2T	0.09T	0.01T
$B_{ex} > (k_B/\mu_B) T_{Curie}$	>50T	>13T	>4.5T

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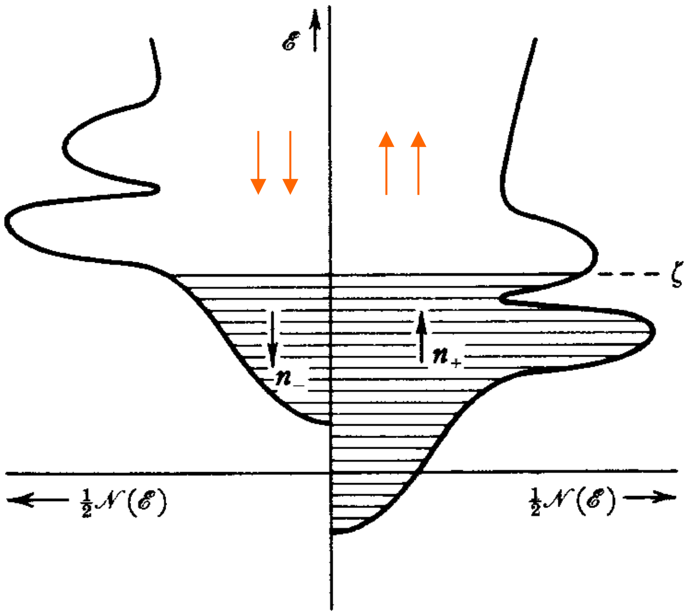

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$B_{ex} > (k_B/\mu_B) T_{Curie}$	>50T	>13T	>4.5T

→ << H_{c2}^{orb} : no problem for HF

Always in the mixed state : Paulsen et al. PRL **109** 237001 (2012),
Deguchi et al. JPSJ, ***79***, 083708 (2010)

Superconductivity in FM heavy-fermions

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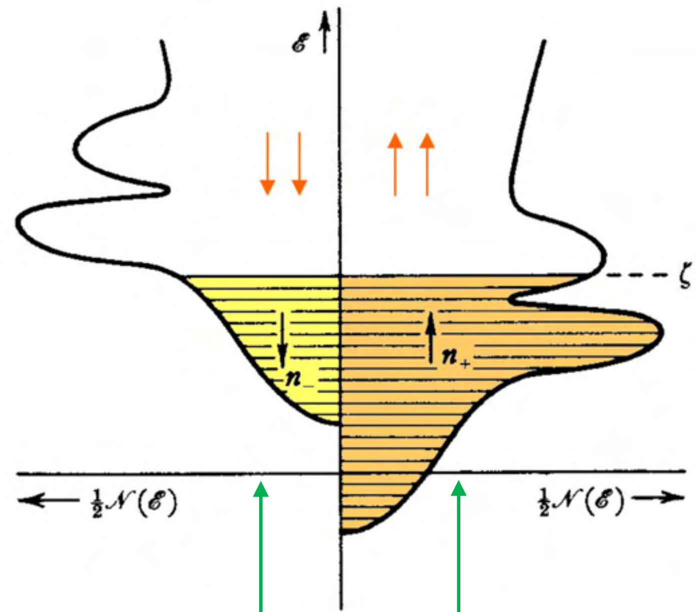

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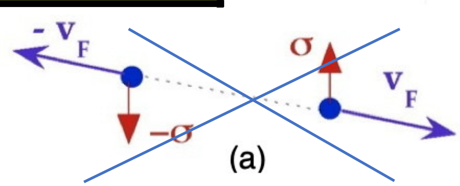
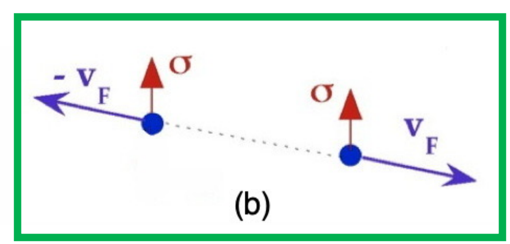
B_{Pauli} (~$2T_{sc}$)	1.6T	.5T	1T

→ $\ll H_{c2}^{orb}$

→ $\gg H_P$



(a)



(b)

Superconductivity in FM heavy-fermions

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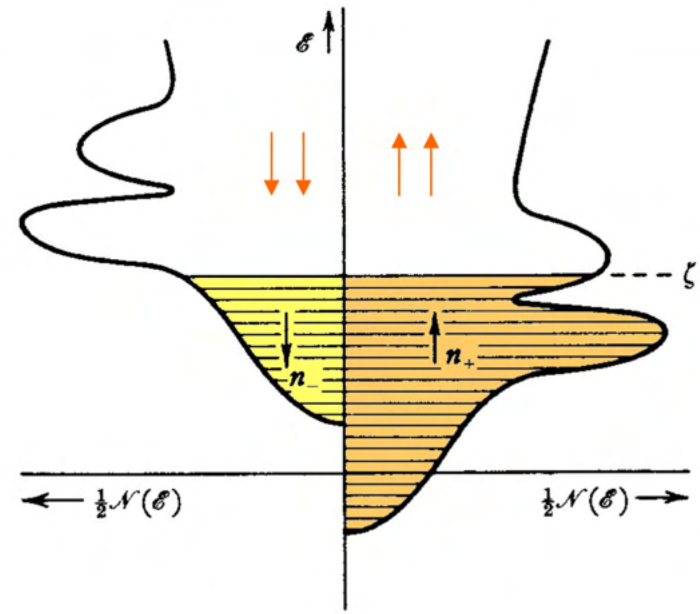

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$B_{ex} > (k_B/\mu_B) T_{Curie}$	>50T	>13T	>4.5T

→ $\ll H_{c2}^{orb}$

→ $\gg H_P$

$T_{Curie} \gg T_{sc}$ implies **a different superconducting state :**

a spin-**triplet**, **ESP**, superconducting state

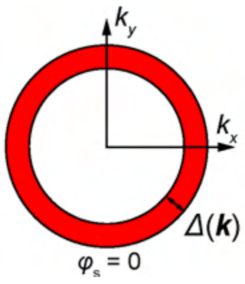
Spin-singlet Superconductors

Conventional superconductors

- **s-wave** (singlet) superconductors
- pairing mechanism: phonons

$$(k,\uparrow) \quad (-k,\downarrow) \quad \text{with:} \quad |\psi>= \varphi(\boldsymbol{k})(|\uparrow\downarrow> - \downarrow\uparrow>)$$

$$\varphi(\boldsymbol{k}) = \varphi(-\boldsymbol{k}) \quad \text{and} \quad \varphi(\boldsymbol{k}) \text{ isotropic (s-wave)}$$



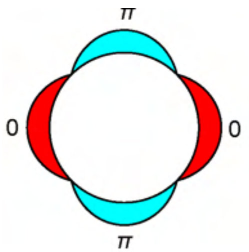
Unconventional Superconductors (e.g. cuprates):

- **d-wave** (singlet) superconductivity
- pairing mechanism: AF correlations

$$(k,\uparrow) \quad (-k,\downarrow) \quad \text{with:} \quad |\psi>= \varphi(\boldsymbol{k})(|\uparrow\downarrow> - \downarrow\uparrow>)$$

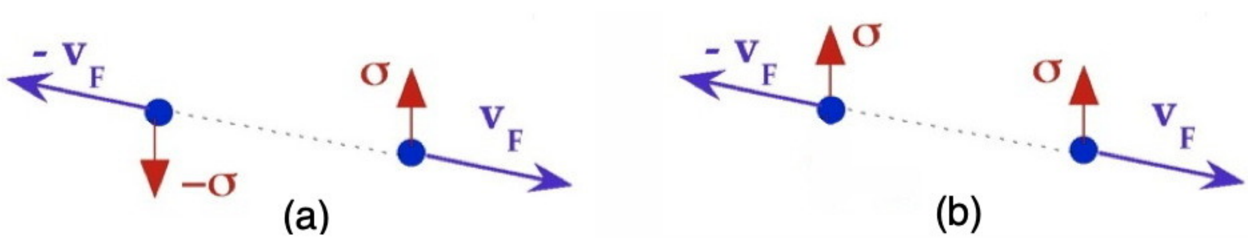
$$\varphi(\boldsymbol{k}) = \varphi(-\boldsymbol{k}) \quad \text{and} \quad \varphi(\boldsymbol{k}) \text{ anisotropic (d-wave)}$$

$$\Delta(\hat{\boldsymbol{k}}) = \Delta_0 \left|\hat{k}_x^2 - \hat{k}_y^2\right| = \Delta_0 \left|cos(2\theta)\right|$$



Spin-triplet superconductors

- **Unconventional superconductors (uranium based…)**
  - p-wave (triplet) superconductivity
  - pairing mechanism: ferromagnetic fluctuations (FM superconductors)



$$(k,\uparrow) \quad (-k,\uparrow) \quad \text{or:}(k,\downarrow) \quad (-k,\downarrow)\ldots$$

$$|\psi>=\varphi(\boldsymbol{k})|\uparrow\uparrow> \quad \text{or} \quad |\psi>=\varphi(\boldsymbol{k})|\downarrow\downarrow> \quad \text{or}$$

$$|\psi>=\varphi(\boldsymbol{k})(|\uparrow\downarrow>+|\downarrow\uparrow>)$$

$$\varphi(\boldsymbol{k})=-\varphi(-\boldsymbol{k}) \quad \text{and} \quad \varphi(\boldsymbol{k}) \text{ anisotropic (p-wave, f-wave...)}$$

Odd/ triplet

ESP spin-triplet superconducting state

- Most general form (Cooper pair wave function or Order Parameter):

$$|\Psi(\hat{\boldsymbol{k}}) >= \varphi(\hat{\boldsymbol{k}})|S = 1 >$$

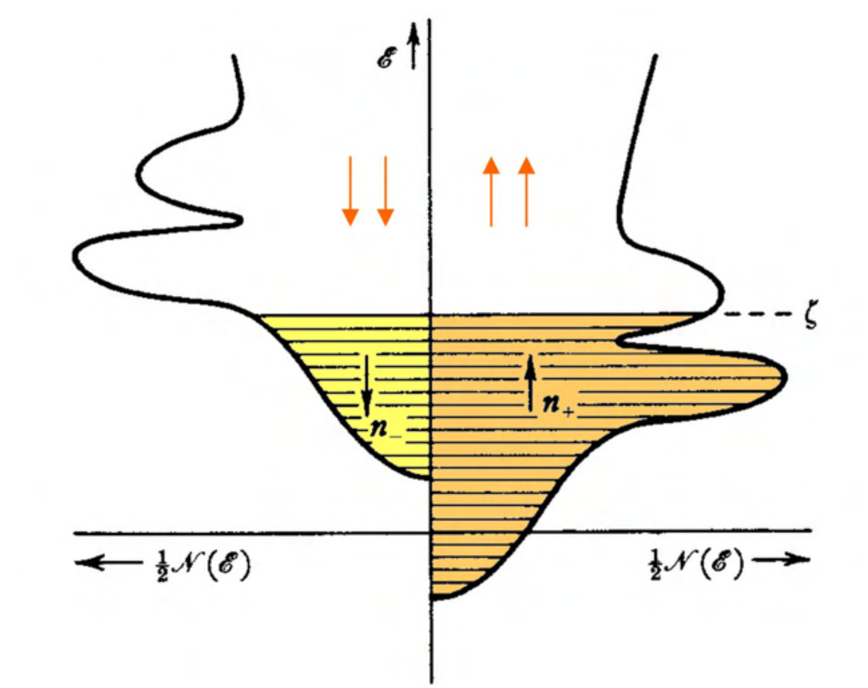
$$|\Psi >= \varphi_{11}(\boldsymbol{k})| \uparrow\uparrow> +\varphi_{22}(\boldsymbol{k})| \downarrow\downarrow> +\varphi_{12}(\boldsymbol{k})| \uparrow\downarrow + \downarrow\uparrow>$$

ESP spin-triplet superconducting state

- Most general form (Cooper pair wave function or Order Parameter):

$$|\Psi> = \varphi_{11}(\boldsymbol{k})|\uparrow\uparrow> + \varphi_{22}(\boldsymbol{k})|\downarrow\downarrow> + \varphi_{12}(\boldsymbol{k})|\uparrow\downarrow + \downarrow\uparrow>$$

- **ESP** = Equal Spin Pairing:
  Cooper pairs with only $|\uparrow\uparrow>$ or $|\downarrow\downarrow>$ spin states



ESP spin-triplet superconducting state

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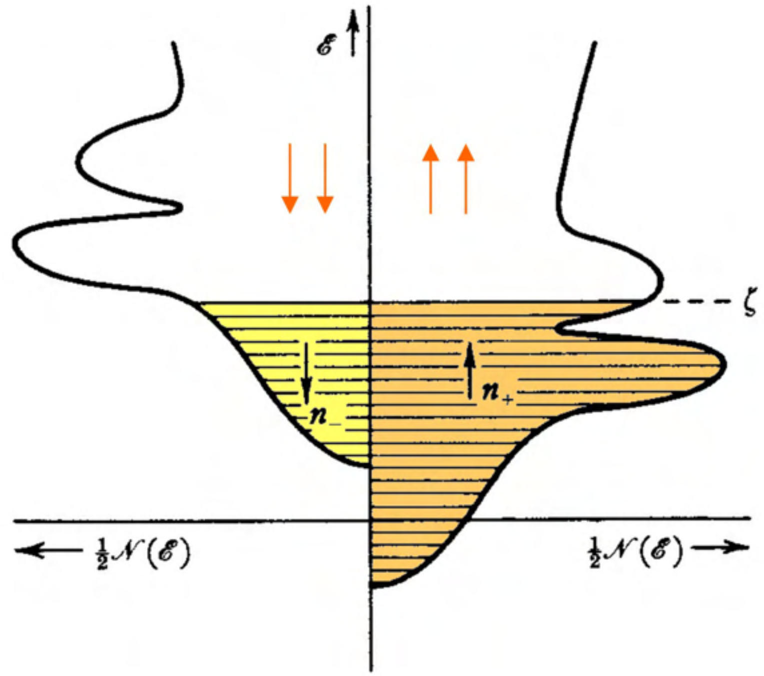
- **ESP** = Equal Spin Pairing:
  Cooper pairs with only $|\uparrow\uparrow>$ or $|\downarrow\downarrow>$ spin states

$$|\Psi> = \Delta^{\uparrow}|\uparrow\uparrow> + \Delta^{\downarrow}|\downarrow\downarrow>$$

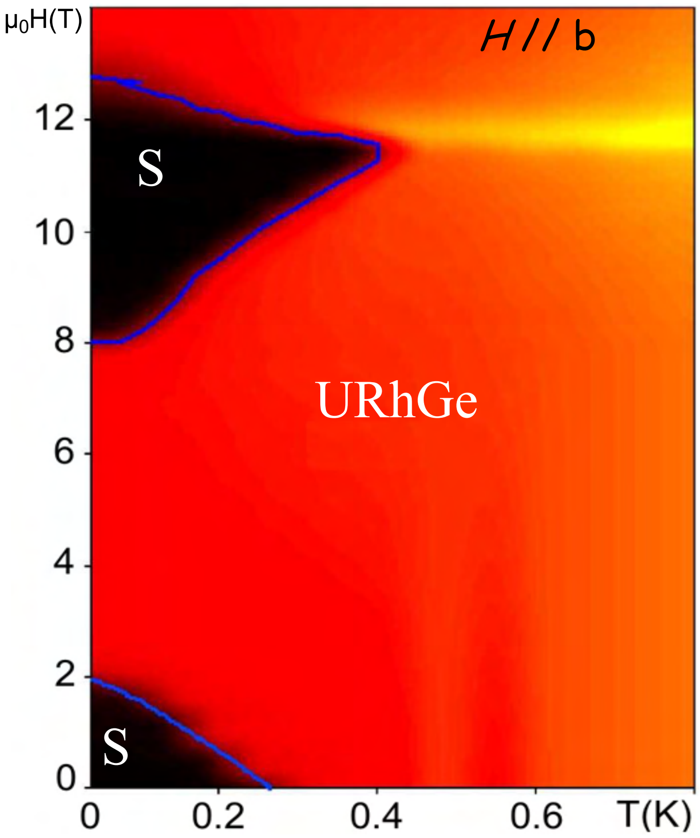
Phase & amplitude of $\Delta^{\uparrow}$ and $\Delta^{\downarrow}$ may change on the F.S.

"Explains" the coexistence FM-SC (survival to B_{ex})

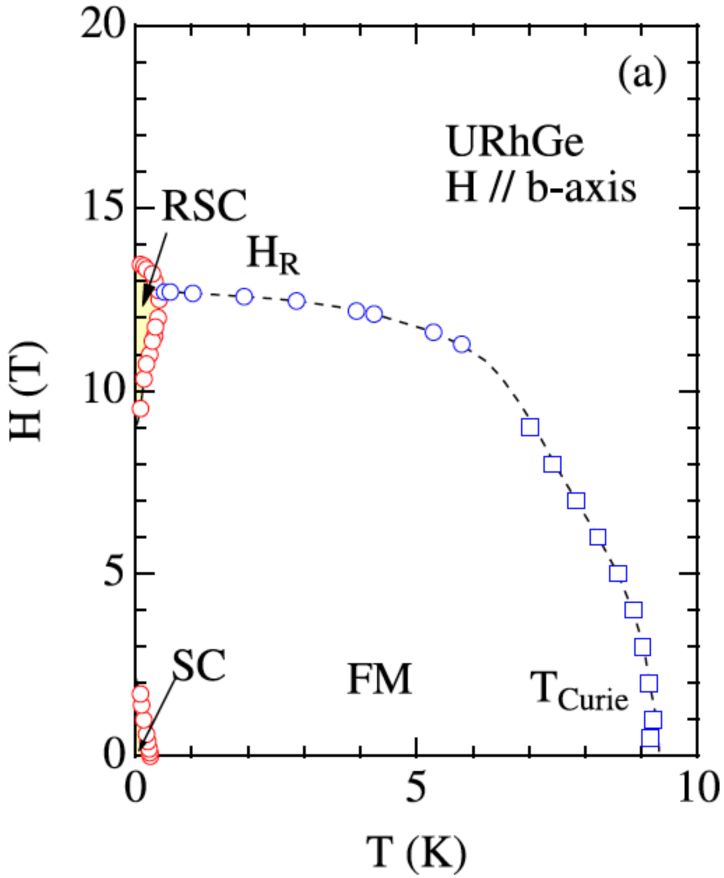
But it does not explain everything…



Effect of transverse field: reinforced superconductivity



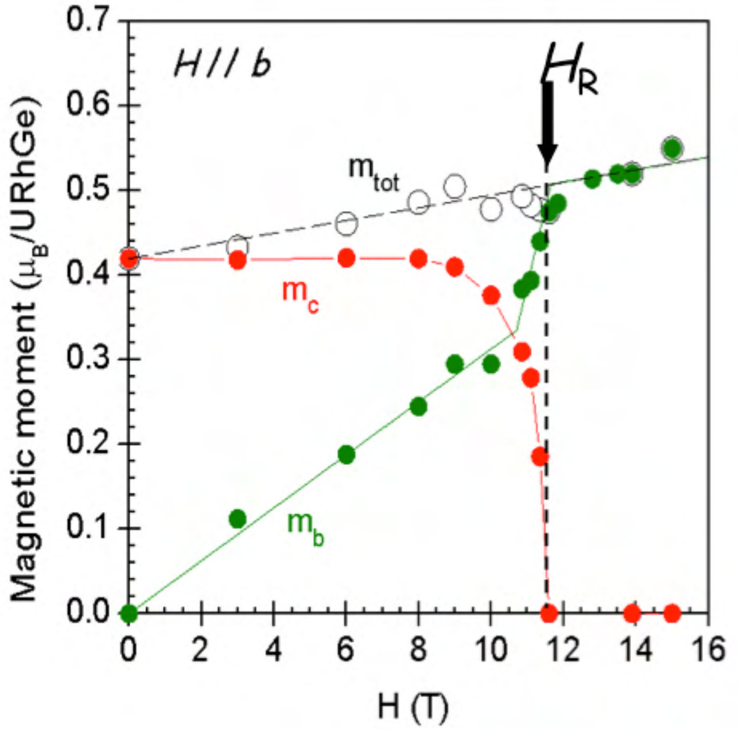
Levy et al. Science, **2005**, *309*, 1343-1346



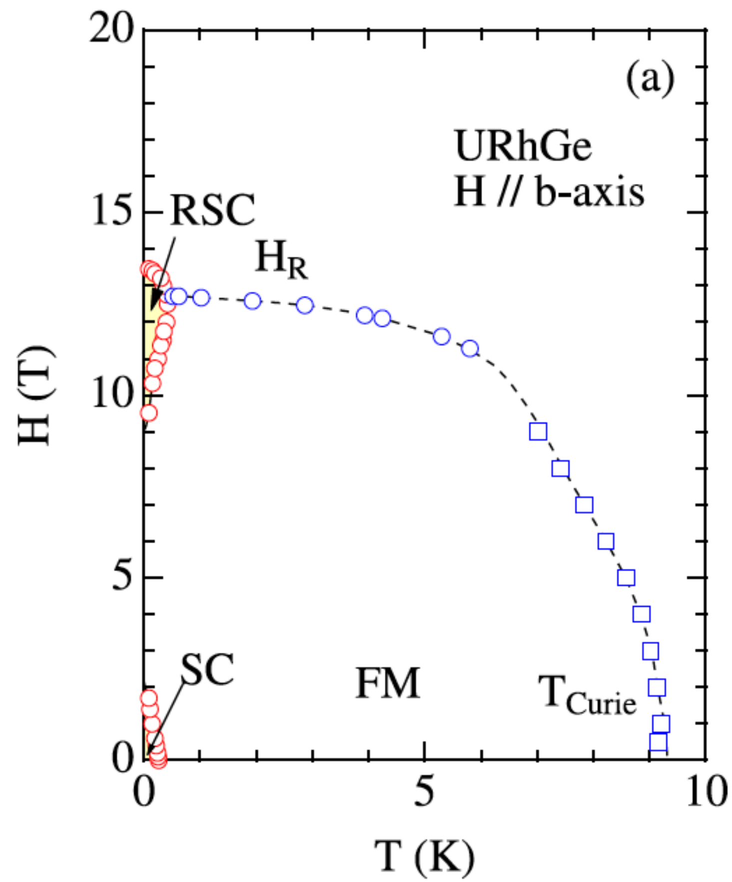
D. Aoki et al., Compt. Rendus. Phys. 12, 573 (2011)

The re-entrant superconducting phase, at the collapse of T_{Curie}

Effect of transverse field: moment re-orientation

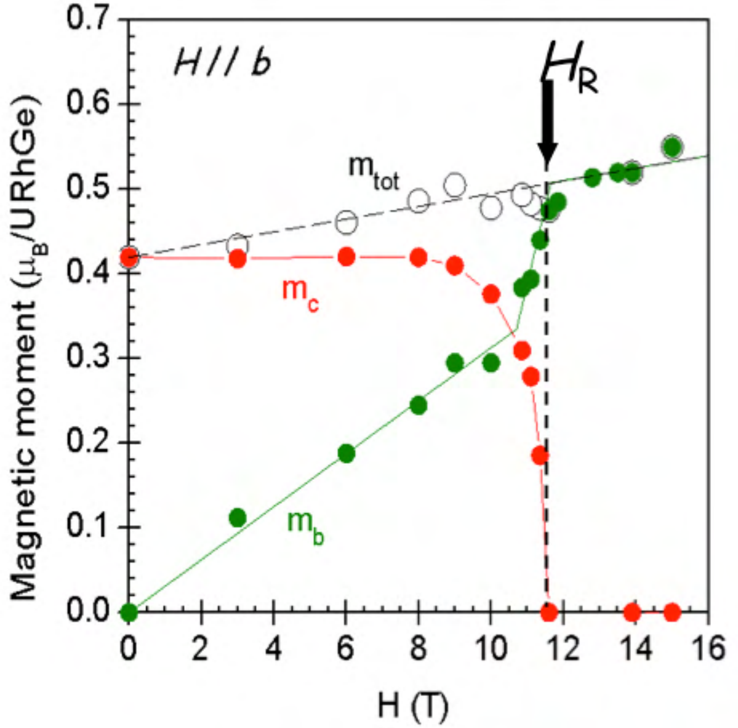


Levy et al. Science, **2005**, *309*, 1343-1346

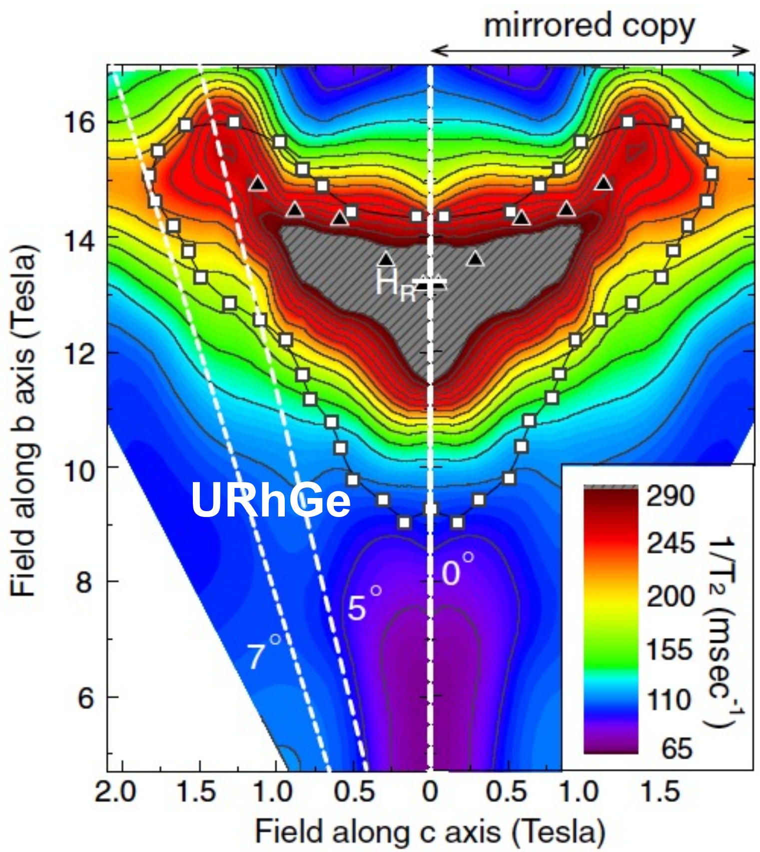


- Easy axis = c-axis; changed to b-axis for fields ~12T//b

Effect of transverse field: magnetic fluctuations



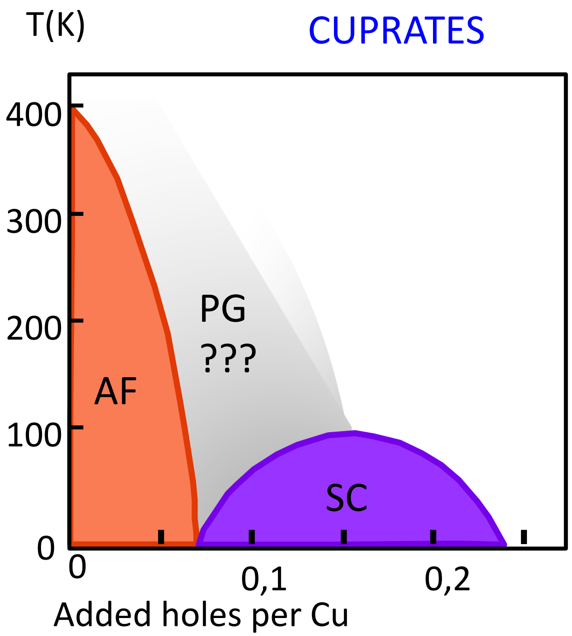
Levy et al. Science, **2005**, *309*, 1343-1346

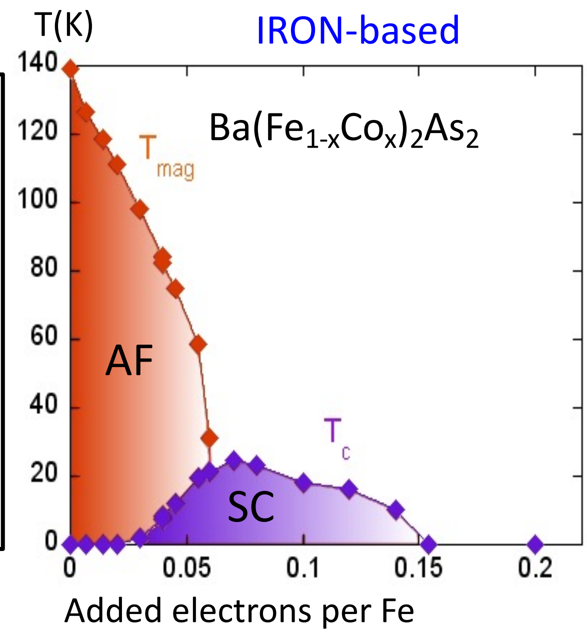


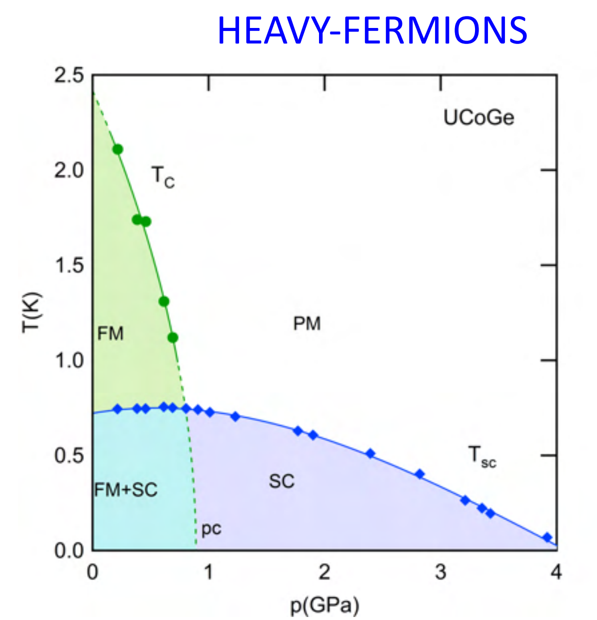
Tokunaga et al. PRL **2015**, *114*, 216401

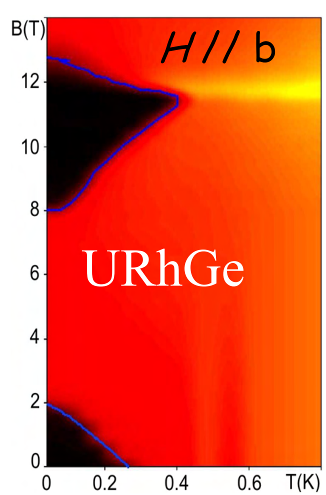
- Easy axis = c-axis; changed to b-axis for fields ~12T//b
- Increase of the magnetic fluctuations (NMR)

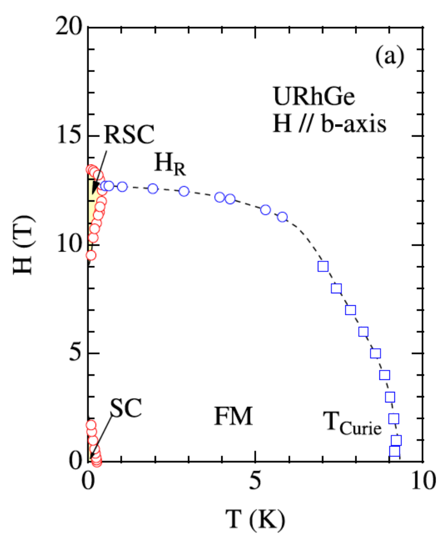
Effect of a transverse field: **a field-induced QCP**



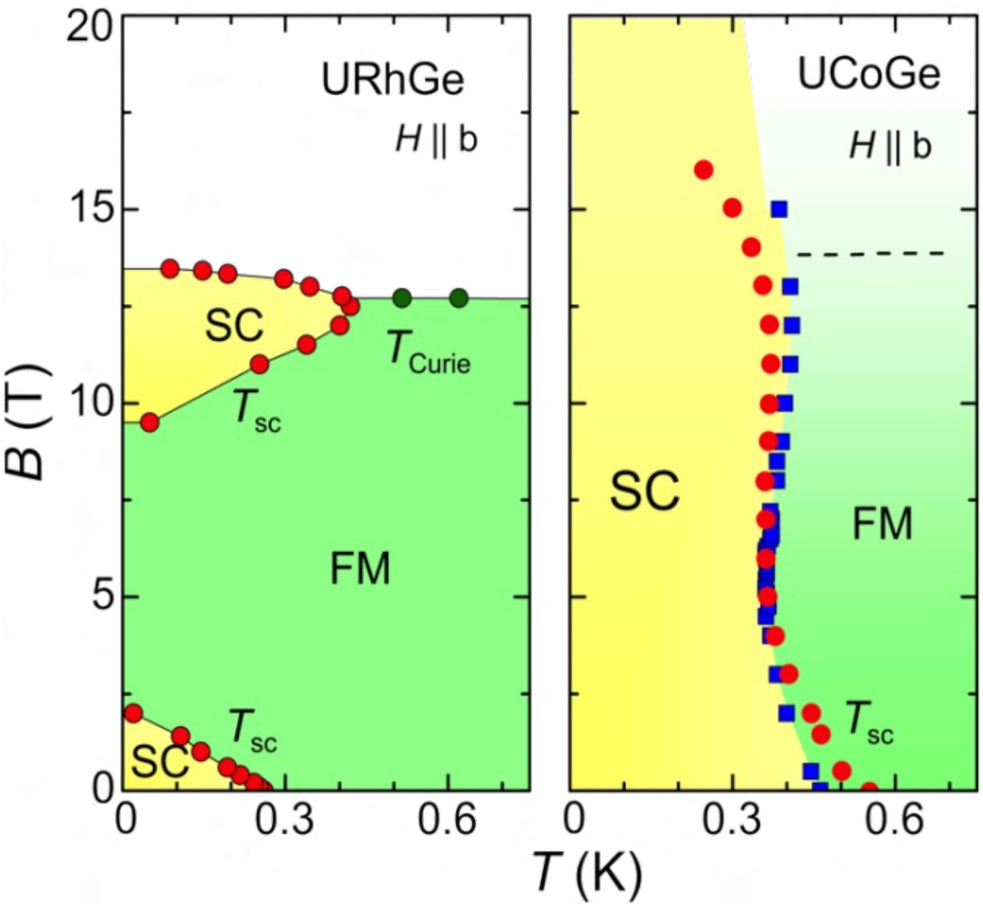






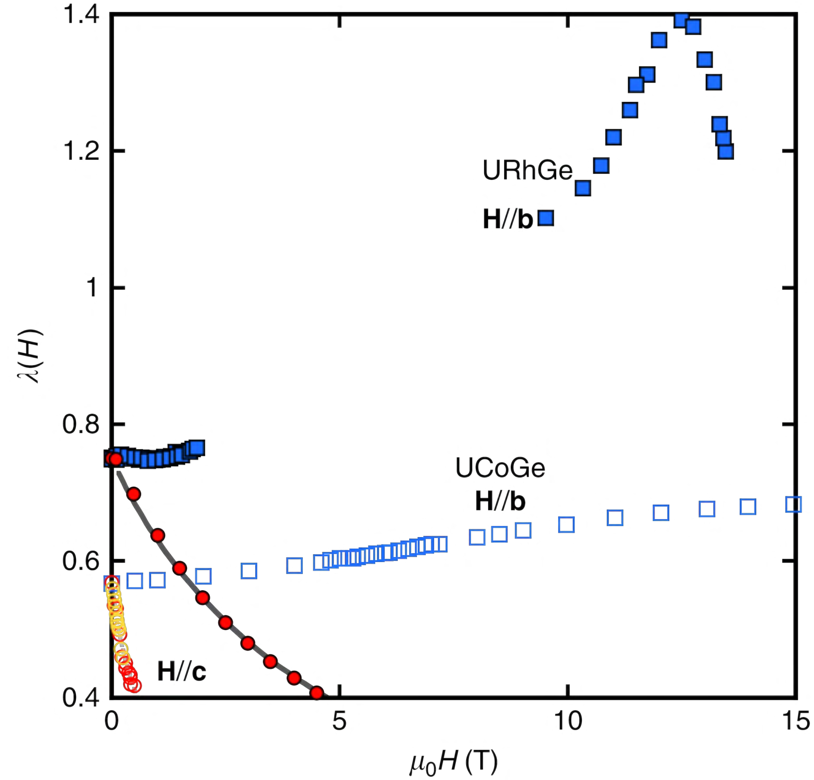


Field dependence of the pairing in FM-SC



Levy et al Science 2005, Nature 2007

Aoki et al. JPSJ 2009



B. Wu et al., Nature Com. **2017**, *8*, 14480

Precise microscopic theoretical model still missing…

Summary – FM-SC

- FM imposes an ESP spin-triplet state:

  Chiral and non-unitary (TRS breaking by orbital & spin)

- Pairing due to FM fluctuations:

  Reinforced when $T_{curie} \longrightarrow 0$ (B $\perp$ easy axis)

  Suppressed when B // easy axis

- 2 gap superconductor ($\Delta^{\uparrow}$ and $\Delta^{\downarrow}$):

  T_{sc} larger for “non-Ising” type fluctuations

- No microscopic model for:
  - the magnetic state
  - **d(k)** under transverse fields !

“New” system: **UTe_2**

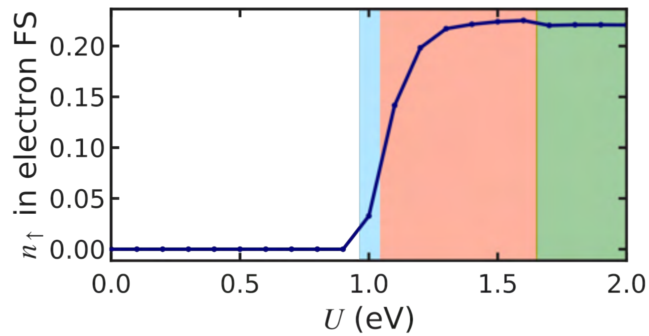
PhD work of **Adrien Rosuel**
Diplomarbeit **Nils Marquardt -> see poster this afternoon**

Collaboration with **C Marcenat** and **T Klein**
(High field experiments)

+ Pheliqs/CEA team: G Knebel, D Braithwaite, A Pourret, G Lapertot.
+ D Aoki (IMR Sendai)

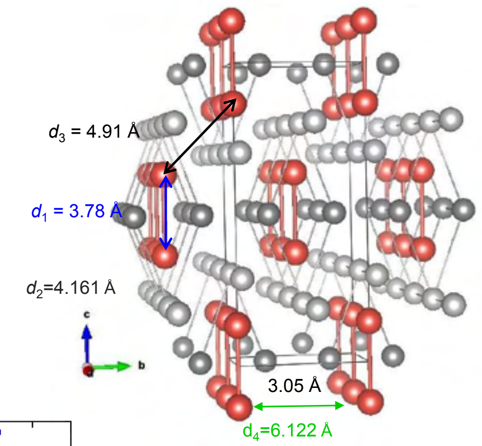
UTe_2 a correlated anisotropic metal

- Superconductivity discovered in 2018 (Ran et al. Science 2019)
- A band insulator, metallic thanks to correlations !



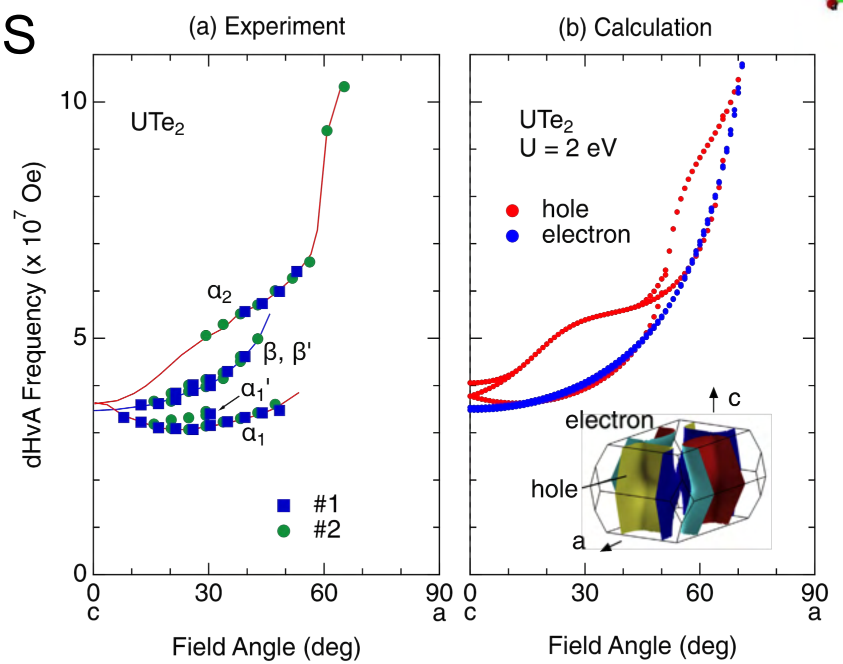
Ishizuka et al. PRL 2019

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



- 3D metal but quasi 2D FS

$m^*/m_0 \sim 50$



Aoki et al. JPSJ 2022

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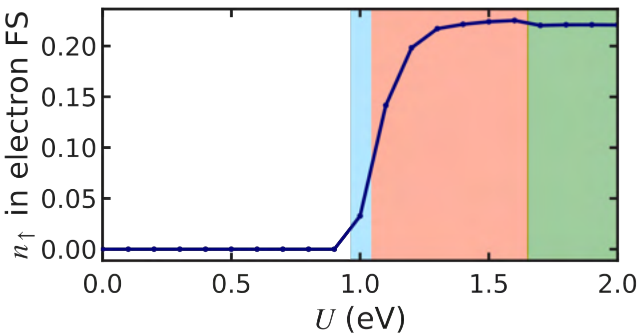

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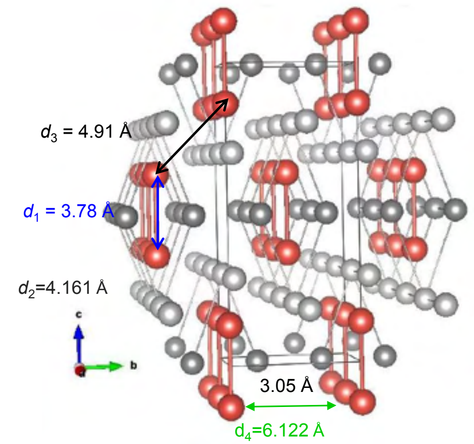
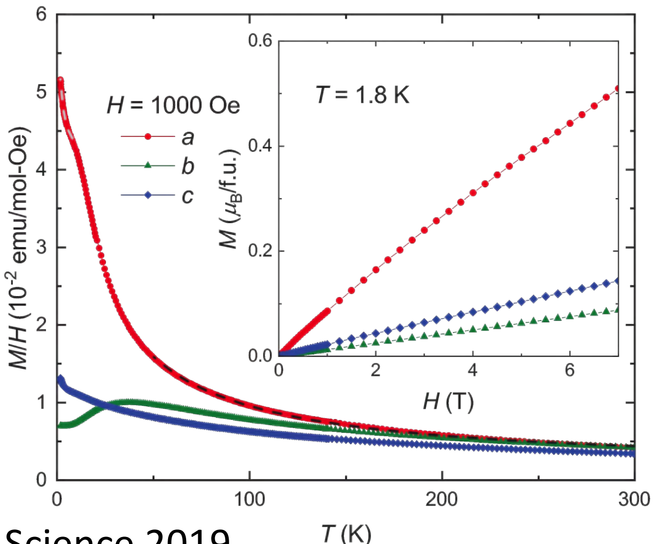
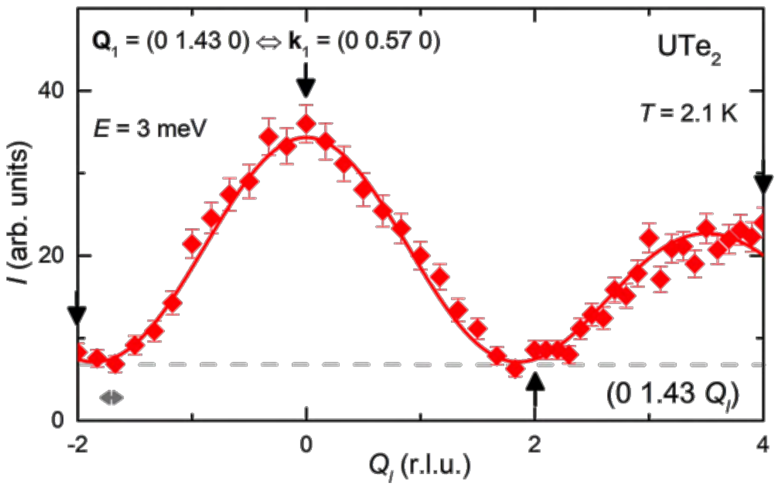


- 3D anisotropic paramagnet, with low-D fluctuations

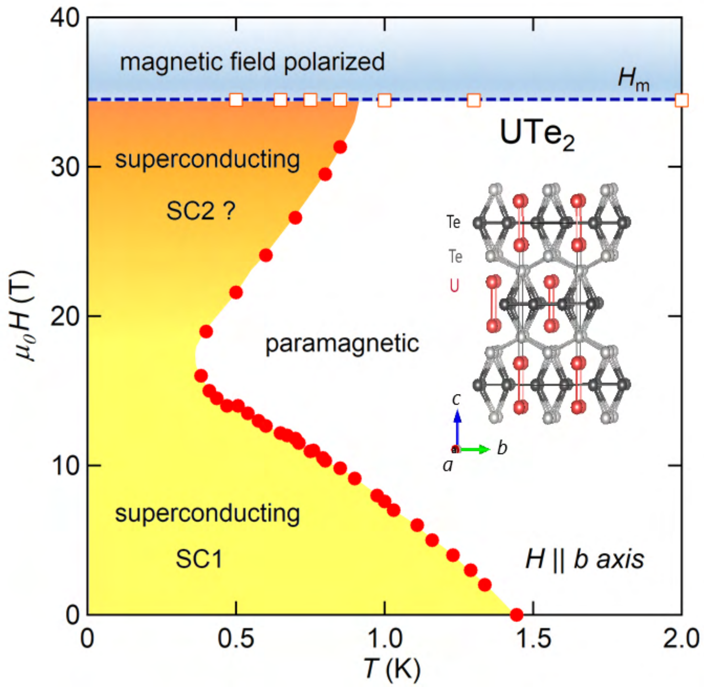




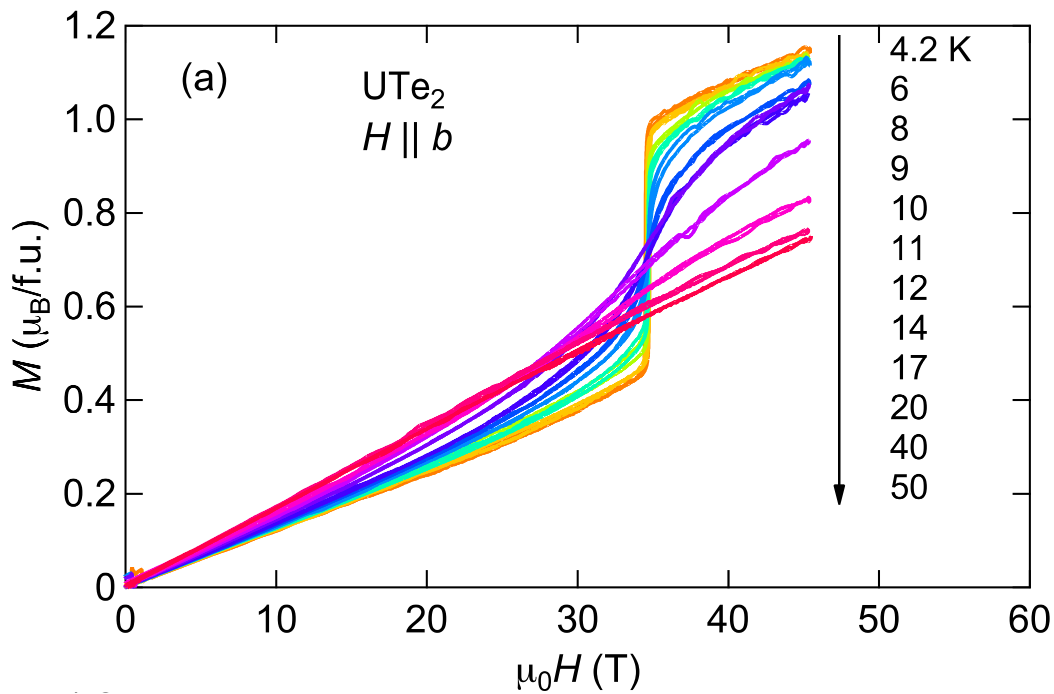
Ran et al. Science 2019

Knafo et al. PRB 2021

UTe_2: field reinforced and field induced phases !



Knebel et al. JPSJ 88 063707 (2019)
Ran et al. Science 2019
Ran et al. Nature Phys 2019

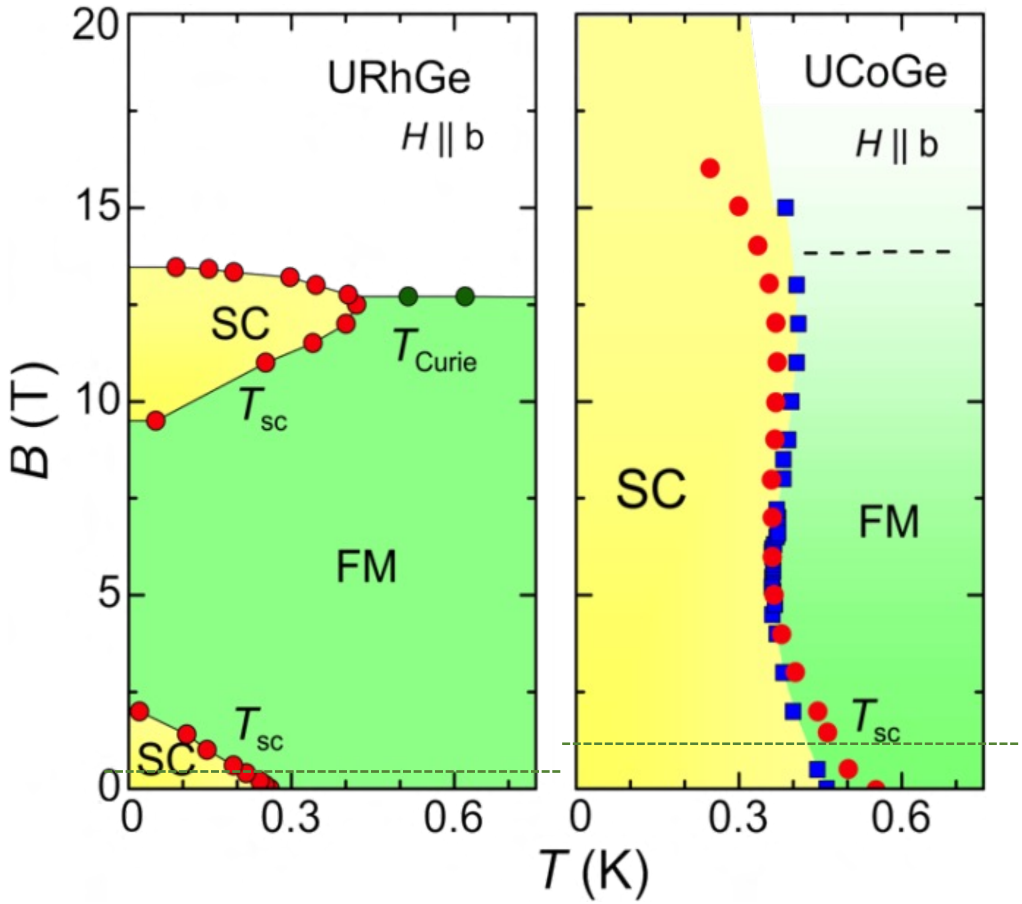


K. Miyake et al. et al. JPSJ 88 063706 (2019)

- Spin triplet superconductivity: violation of Pauli limit in the three directions.
- Field-reinforced SC for transverse field (H//b)
- SC stopped by metamagnetic transition

4- UTe_2 and FC-SC

Re-entrant or reinforced superconductivity under applied field



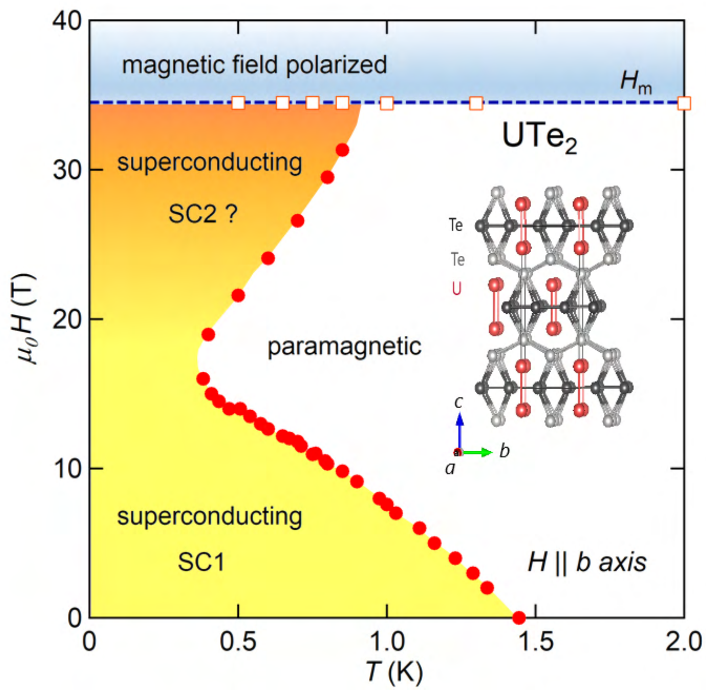
H_{Pauli}

Levy et al Science2005, Nature 2007

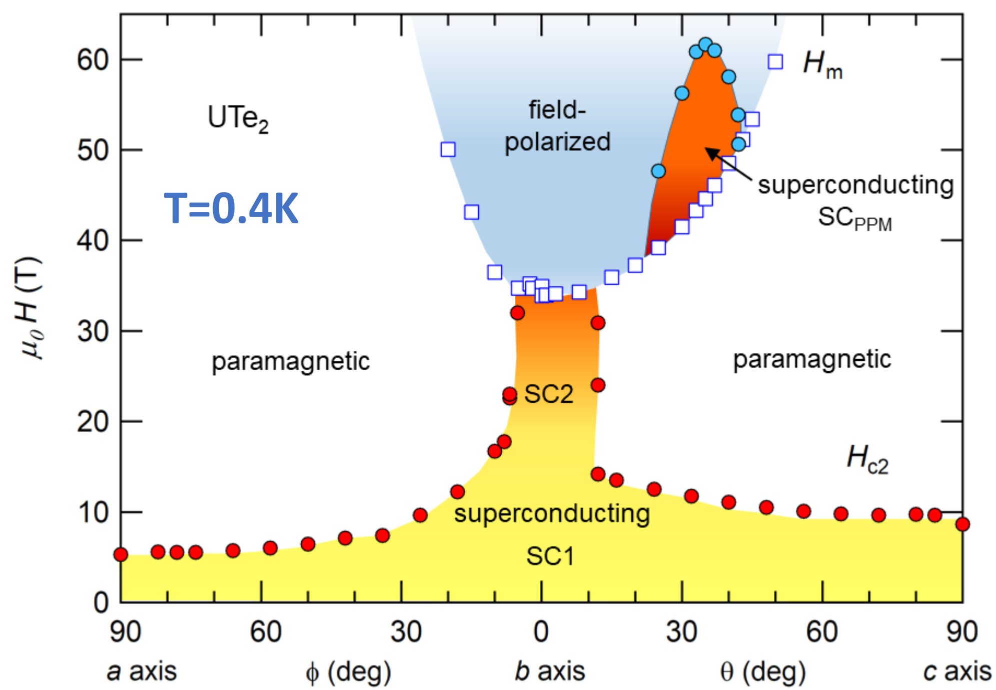
Aoki et al. JPSJ 2009

G Knebel et al. JPSJ 2019

UTe_2: field reinforced and field induced phases !



Knebel et al. JPSJ 88 063707 (2019)



Ran et al. Science 365 684 (2019)

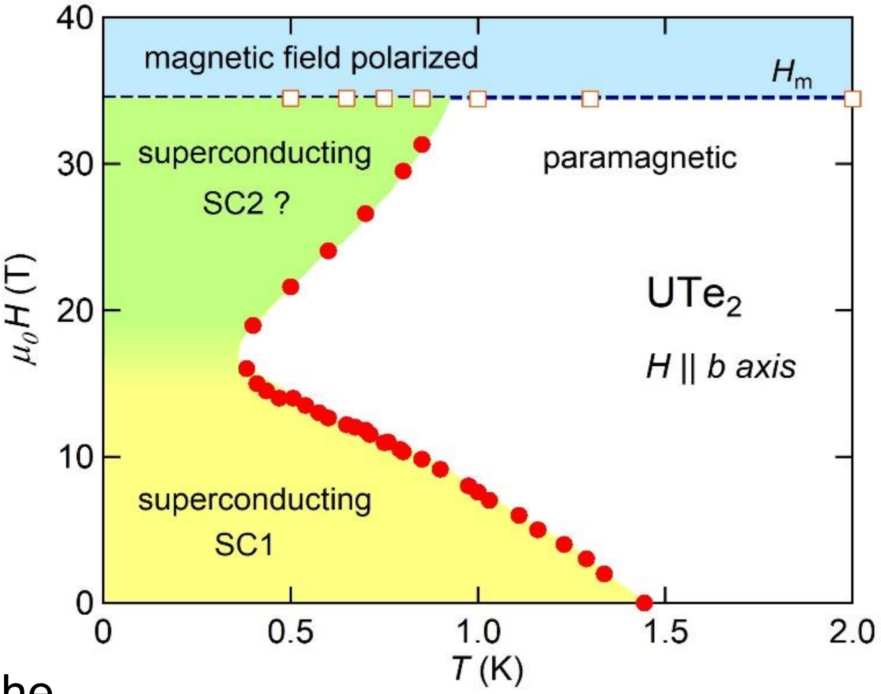
- At 34T, metamagnetic transition “stopping” superconductivity for H//b
- With re-entrant phase above 40T at 30° between b and c

(some) Questions in UTe_2

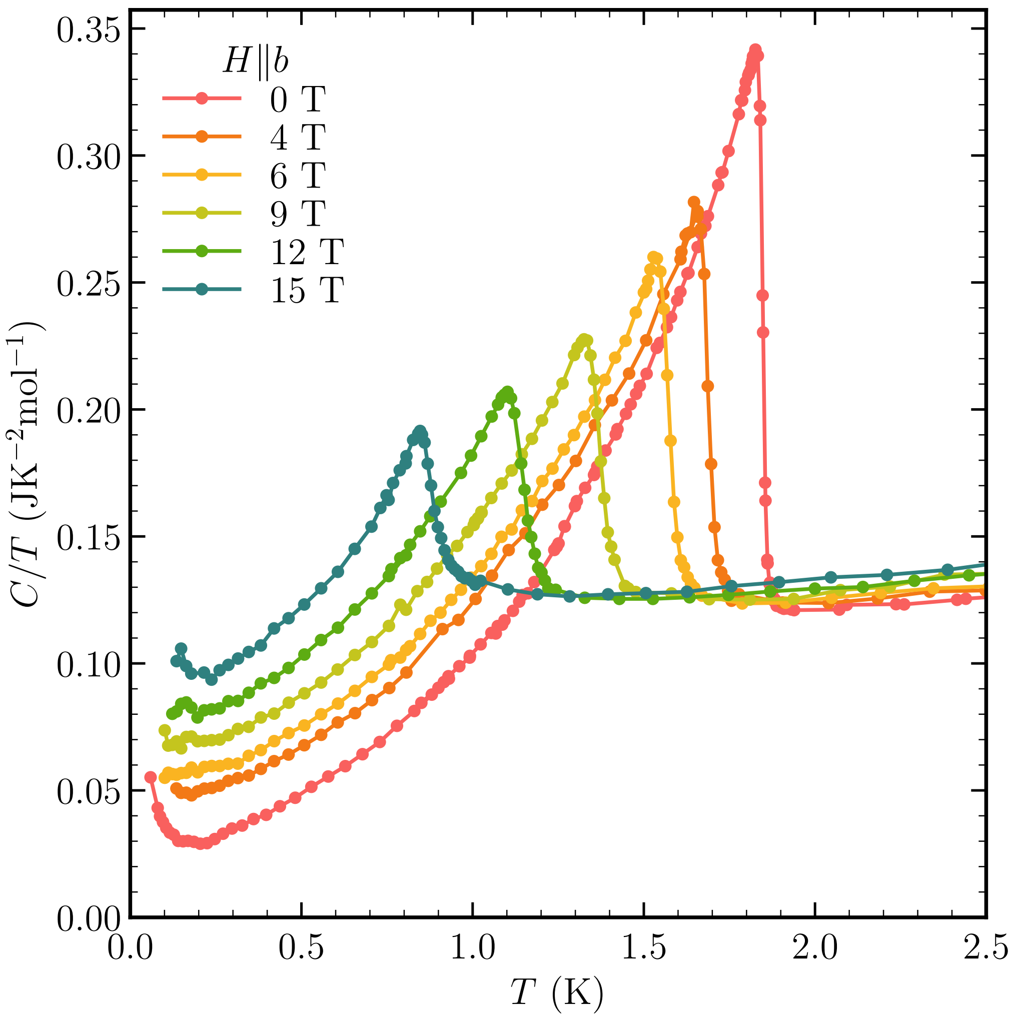
Questions (H//b) :

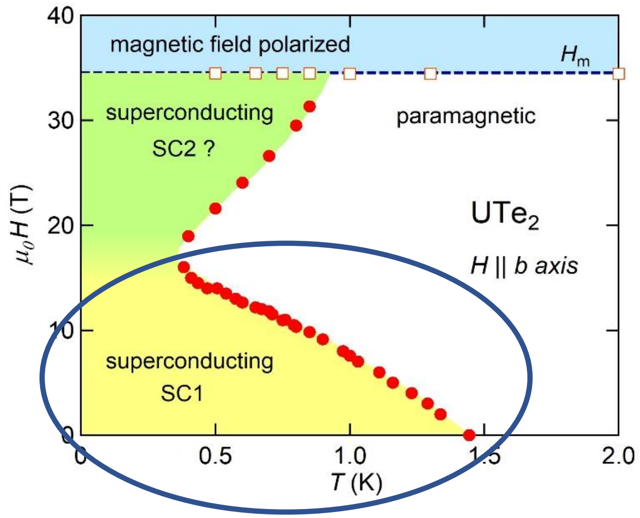
- Two different phases ?
- Difference SC1 / SC2 ?
- Comparison to FM SC ?

Reinforcement of the zero-field pairing

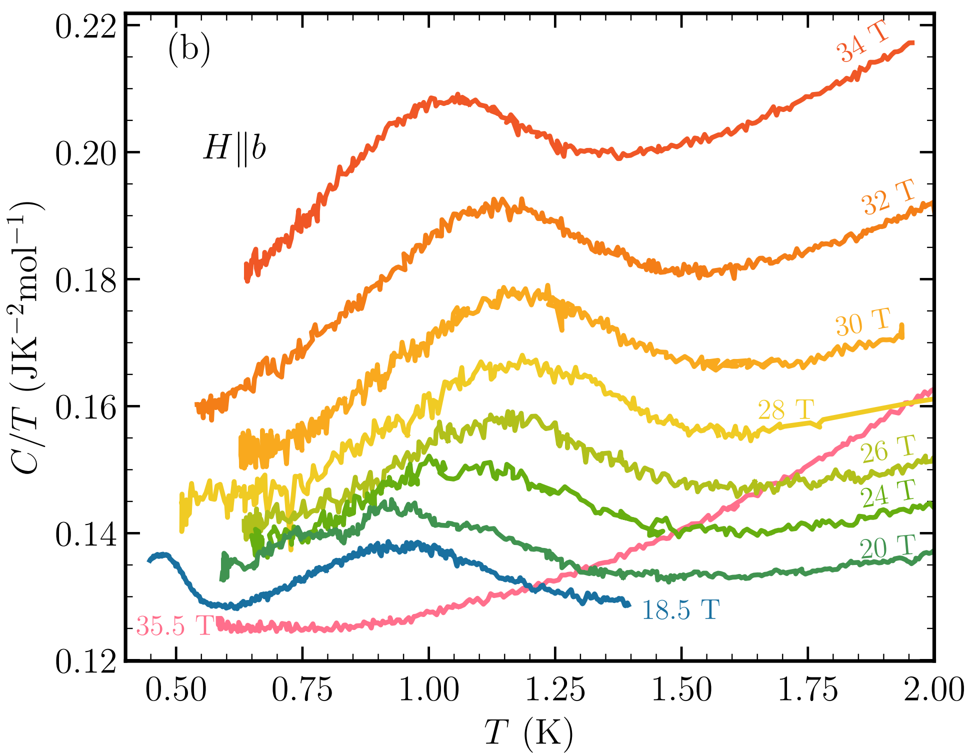


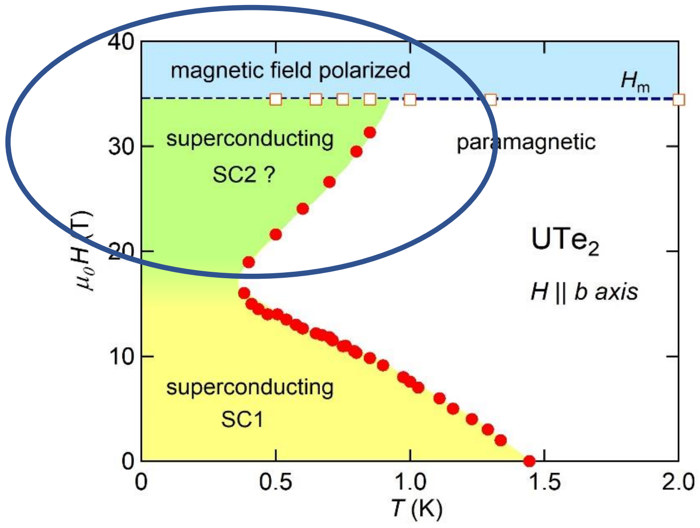
Specific heat under magnetic field, H//b



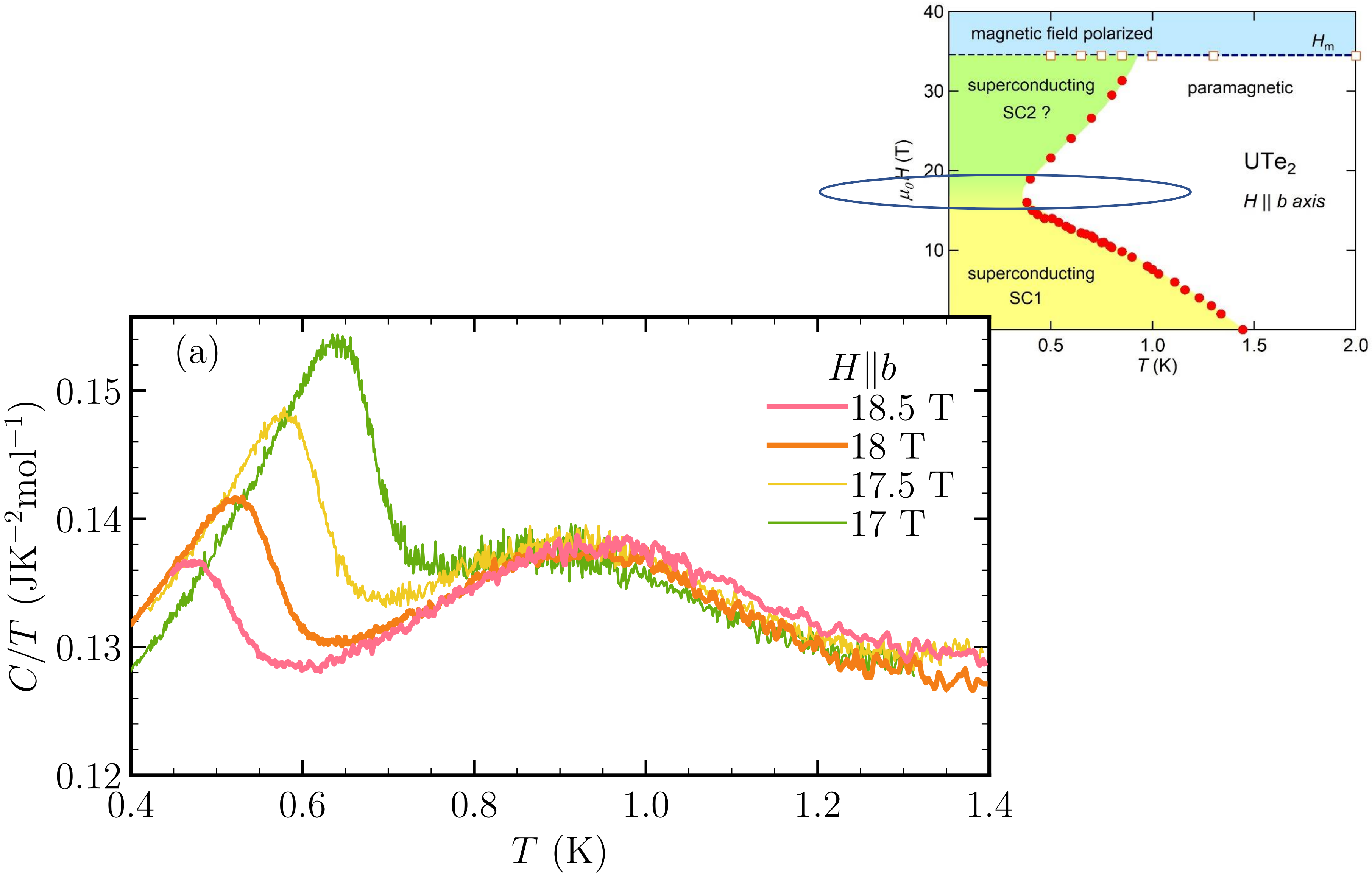


Specific heat under magnetic field, H//b

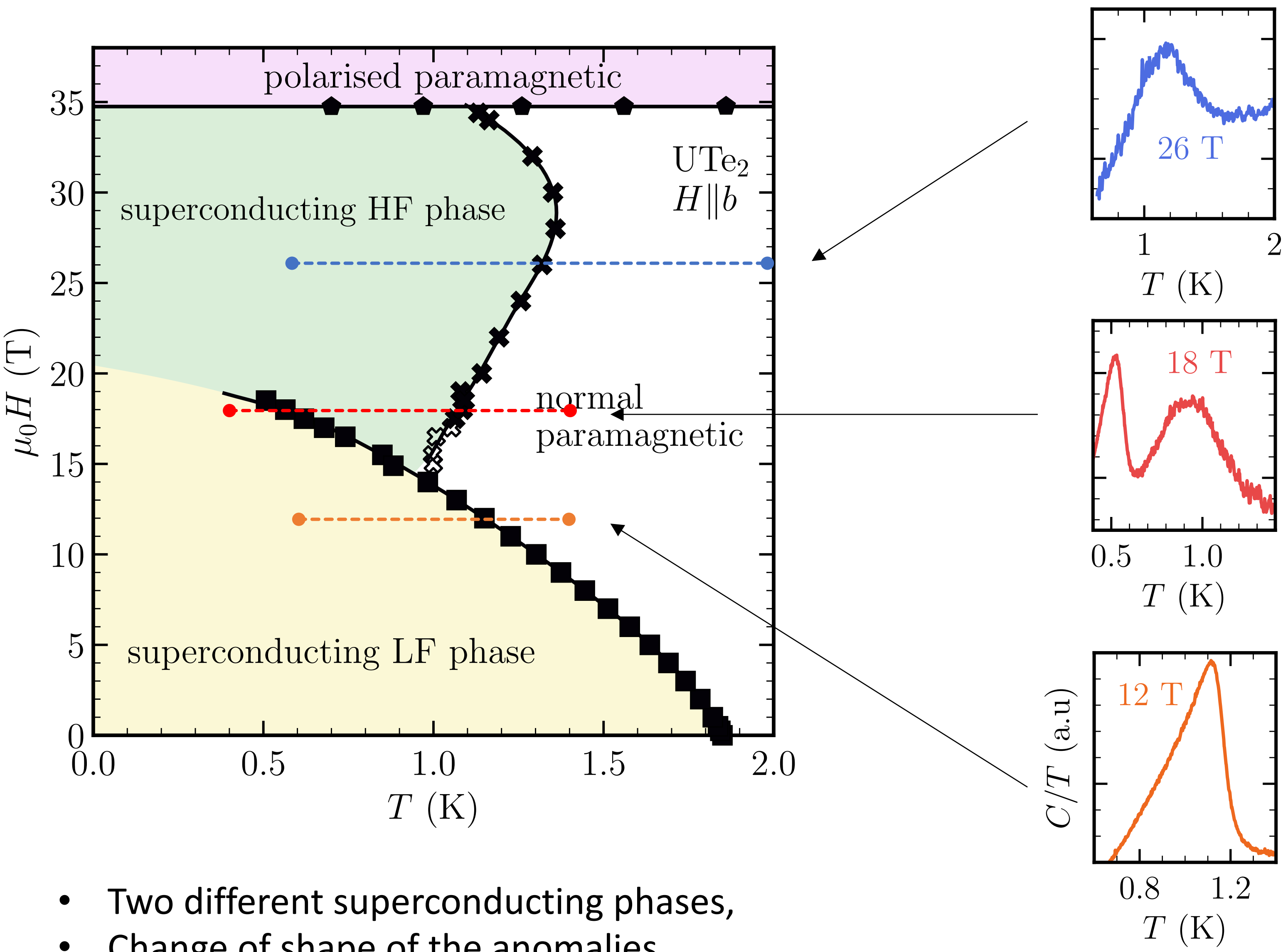




Specific heat under magnetic field, H//b



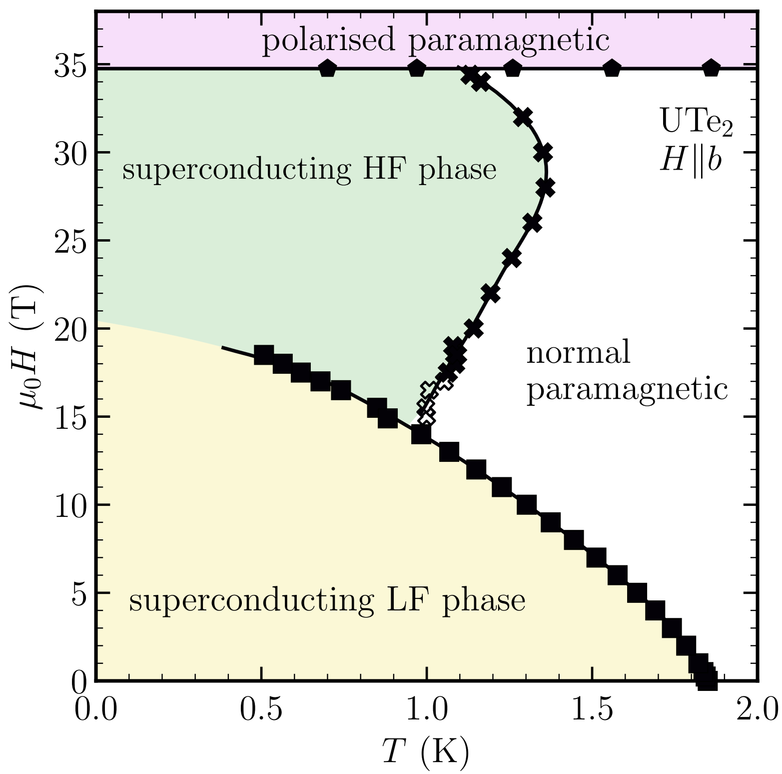
Phase diagram by specific heat

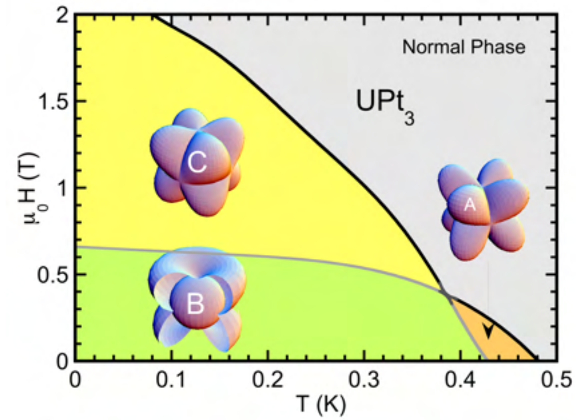


- Two different superconducting phases,
- Change of shape of the anomalies

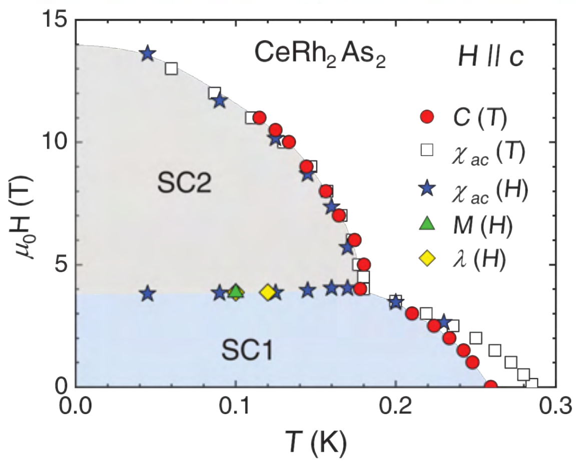
A.Rosuel et al. PRX 2023

Multiphase superconductivity





Physica B 280, 165 (2000)



Khim et al., Science, **2021**, *373*, 1012-1016

In UTe_2, H//b:

- LF phase weakly enhanced under field & narrow transition
- HF phase strongly reinforced by field & wide transition

} Different mechanism

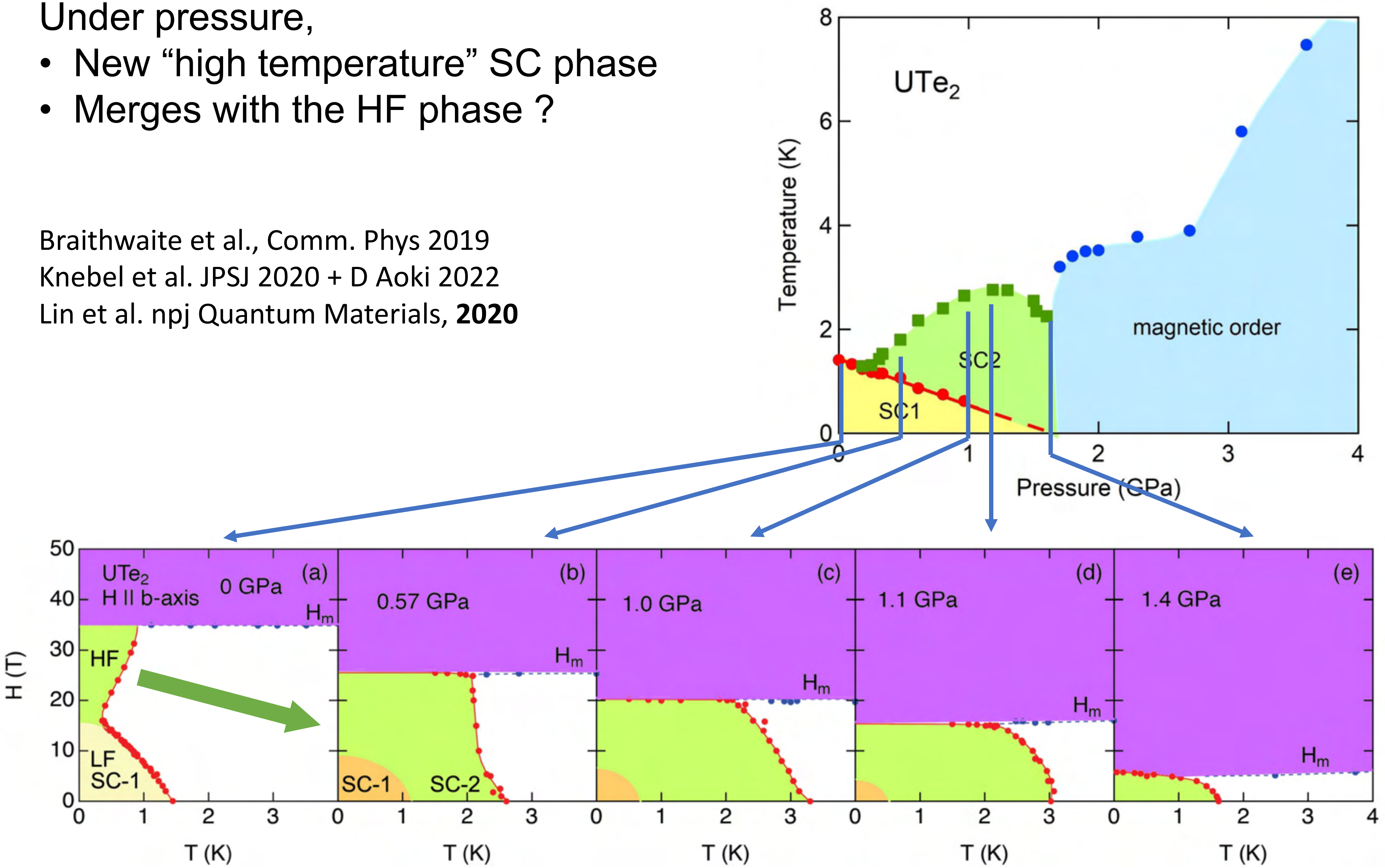
- Different from **UPt_3, $CeRh_2As_2$**… transition triggered by change of T, H, p => different symmetry favoured for the same pairing mechanism

Connection with pressure phase diagram ?

Under pressure,

- New “high temperature” SC phase
- Merges with the HF phase ?

Braithwaite et al., Comm. Phys 2019
Knebel et al. JPSJ 2020 + D Aoki 2022
Lin et al. npj Quantum Materials, **2020**

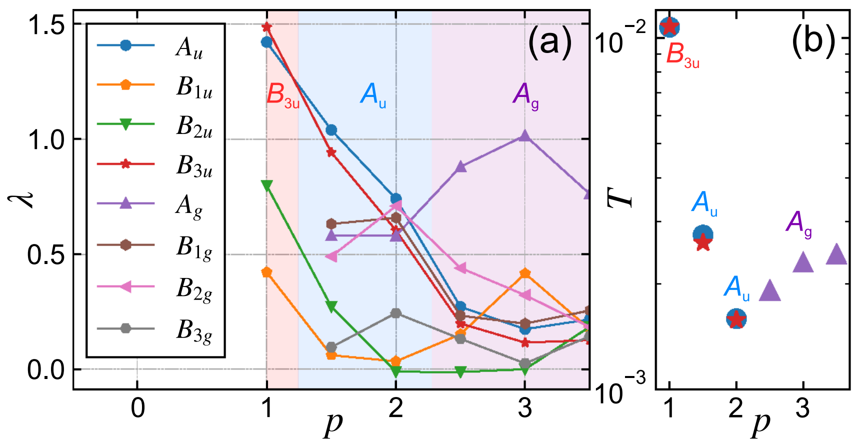


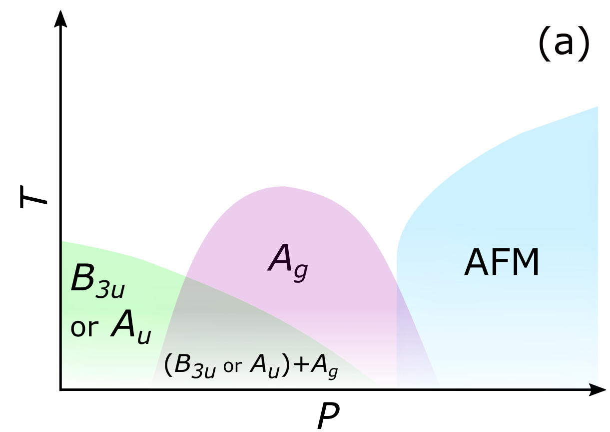
UTe$_2$ competing (pairing) interactions ?

Theory: competition/coexistence of AF and FM fluctuations

increase of f-character of FS under pressure => AF by nesting

- Low T_{sc} (field) phase: spin-triplet from FM fluctuations
- High T_{sc} (field) phase: spin-singlet from AF fluctuations





(Ishizuka & Yanase PRB 2021 ***103*** 094504)

Experimentally: AF fluctuations are dominant

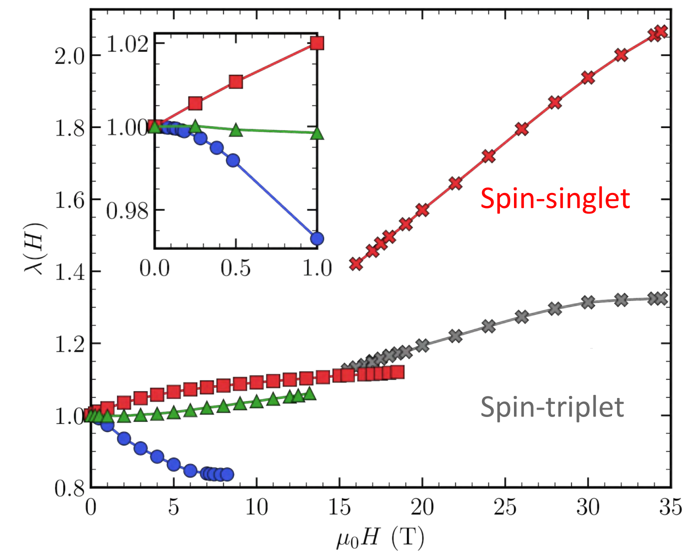
Durst et al. PRL **125** 237003 (2020), Butch et al. *NPJ Qmat.* **2022**, *7*,

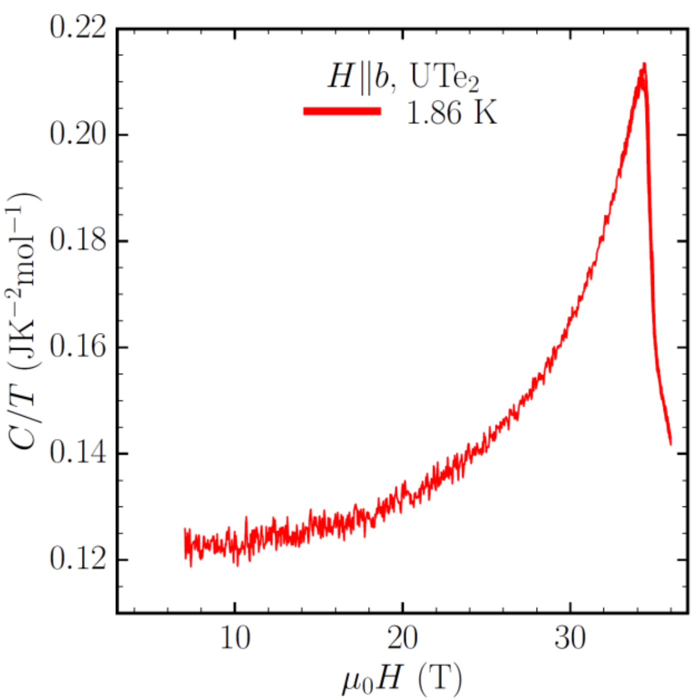
Knafo et al. PRB**104** L100409 (2021) Ambika et al PRB **105**, L220403 (2022)

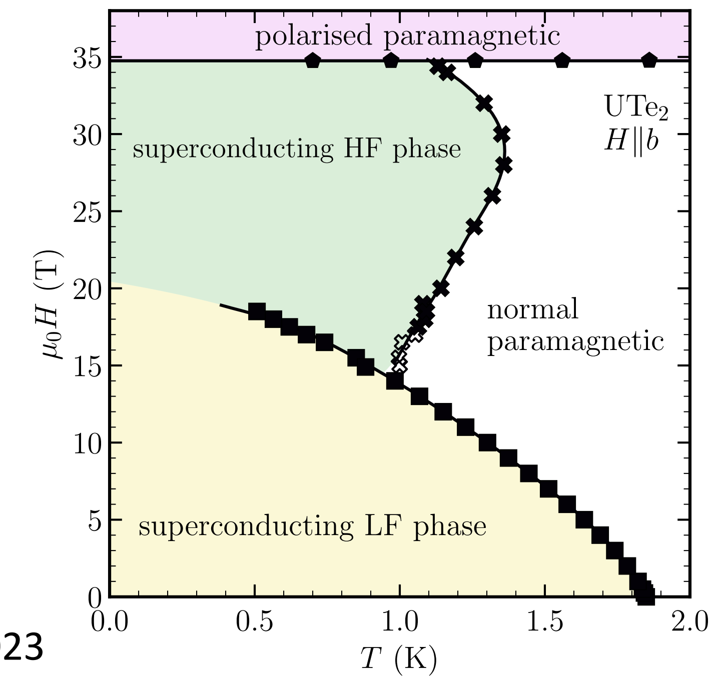
Experimental support for HF-spin singlet

Stronger increase of the pairing required for the spin-singlet scenario

HF phase connected to H_m: $\lambda(H) = \lambda(H/H_m)$
distribution of H_m => distribution of $T_c = T_c(H,\lambda)$







A.Rosuel et al. PRX 2023

Experimental support for HF-spin singlet

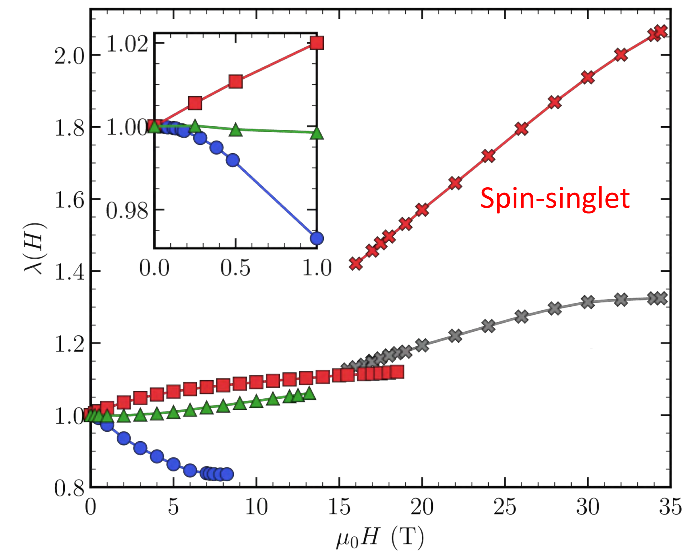
HF phase connected to H_m: $\lambda(H) = \lambda(H/H_m)$

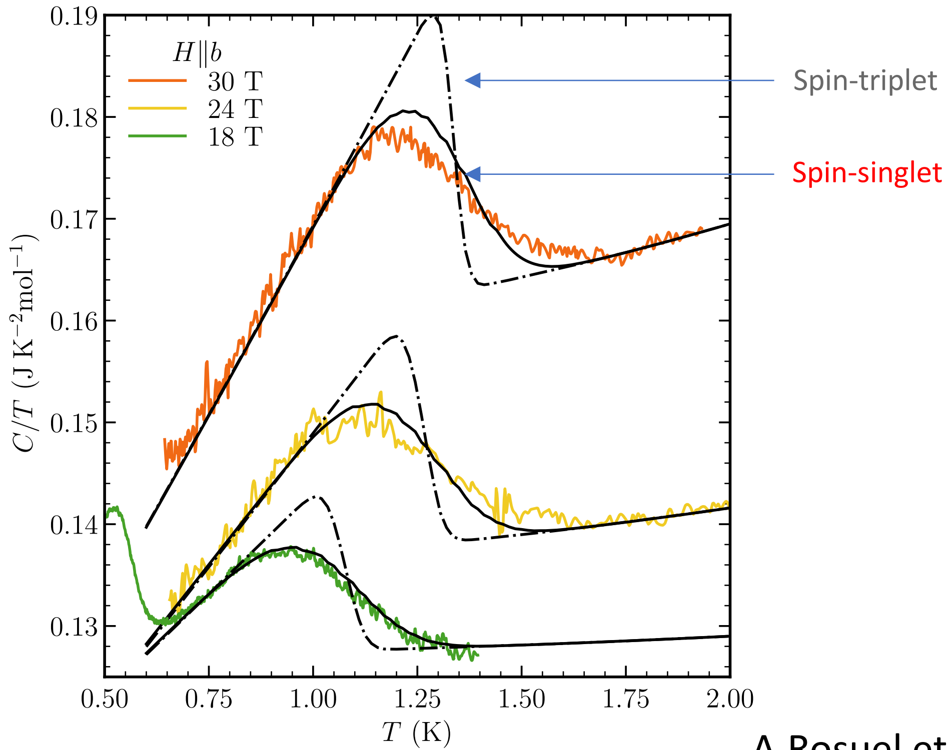
distribution of H_m => distribution of $T_c=T_c(H,\lambda)$

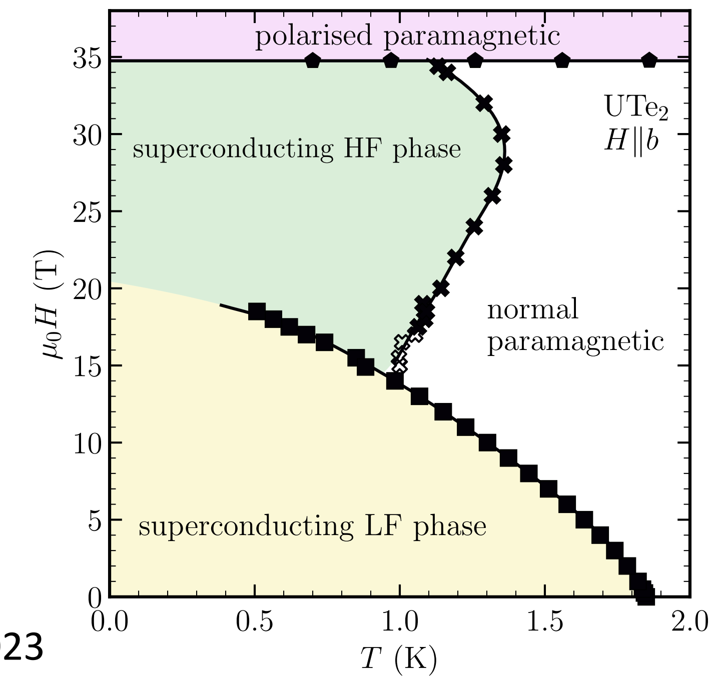
Singlet Phase (saturating Hc2) explains partly

- The large broadening in the HF phase

$$\left.\frac{\partial T_{sc}}{\partial H_m}\right|_H \propto \left.\frac{\partial T_{sc}}{\partial H}\right|_\lambda$$







A.Rosuel et al. PRX 2023

Perspectives

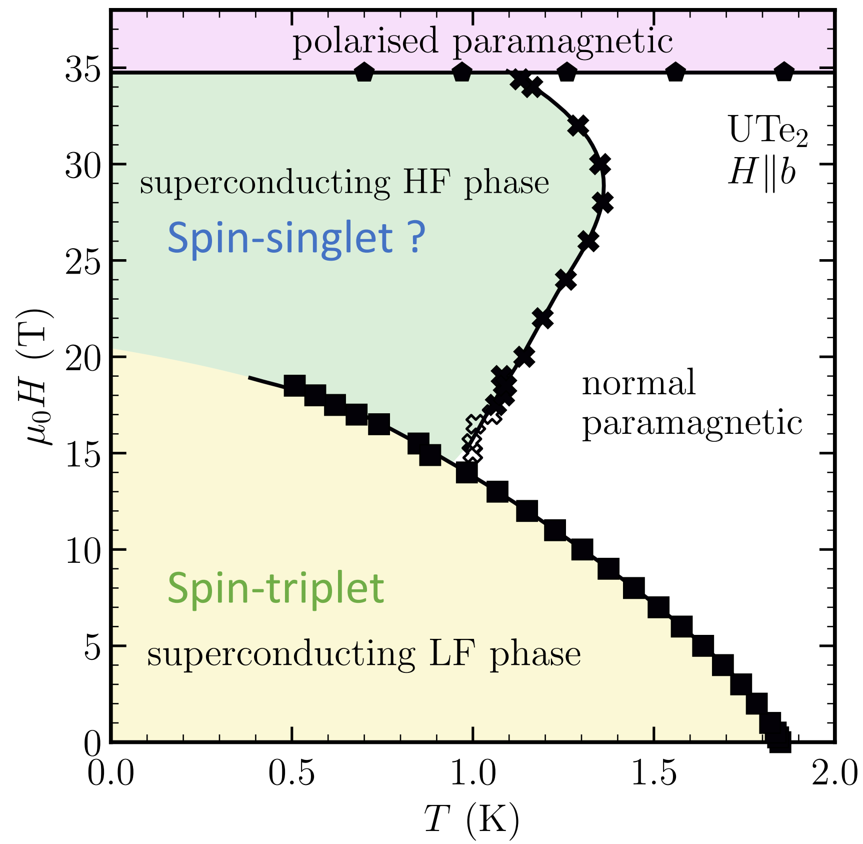
Possible spin-singlet phase at HF:
Competing pairing interactions
(FM/AF or AF and ≠ Q or local interactions ?)

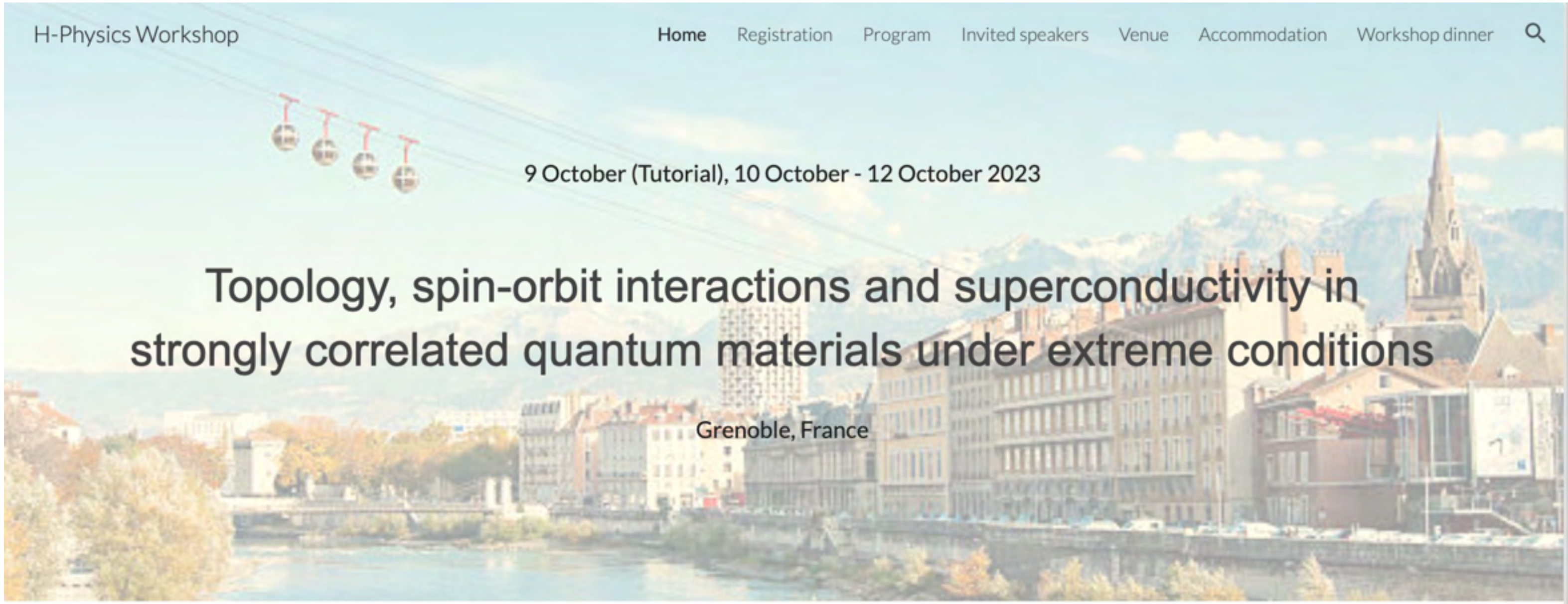
Clear **phase transition** observed between a LF and HF phase.
- Also seen with
  - $\chi(\omega_L)$ Kinjo et al. PRB 2023
  - χ Sakai et al PRL 2023
  - MCE Schönemann et al. ArXiv 2206.06508v1

Open questions:
- Explaining the phase diagram H//b
- Connection with pressure phase diagrams
- Order of transitions

- Theory of field-reinforced phases

And see **Poster Nils Marquardt & Daniel Braithwaite**





Registration

Deadline: 30th June 2023

Registration fee: free

60 participants (maximum)

This workshop aims to discuss and exchange the recent progress on strongly correlated quantum materials under extreme conditions such as high field, high pressure, and low temperature between researchers. The topics include topological phenomena, spin-orbit interactions, superconductivity, multipole order, and fermiology.