High Field Properties of Uranium Ferromagnetic Superconductors

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Review paper of FM-SC

D. Aoki and J. Flouquet: JPSJ **81** (2012) 011003

Collaborators

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H. Kotegawa (present: Kobe Univ.)
E. Hassinger (present: Sherbrooke)
L. Malone (present: Bristol)
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Funding

NewHeavyFermion

CORMAT, SINUS

Outline

Introduction

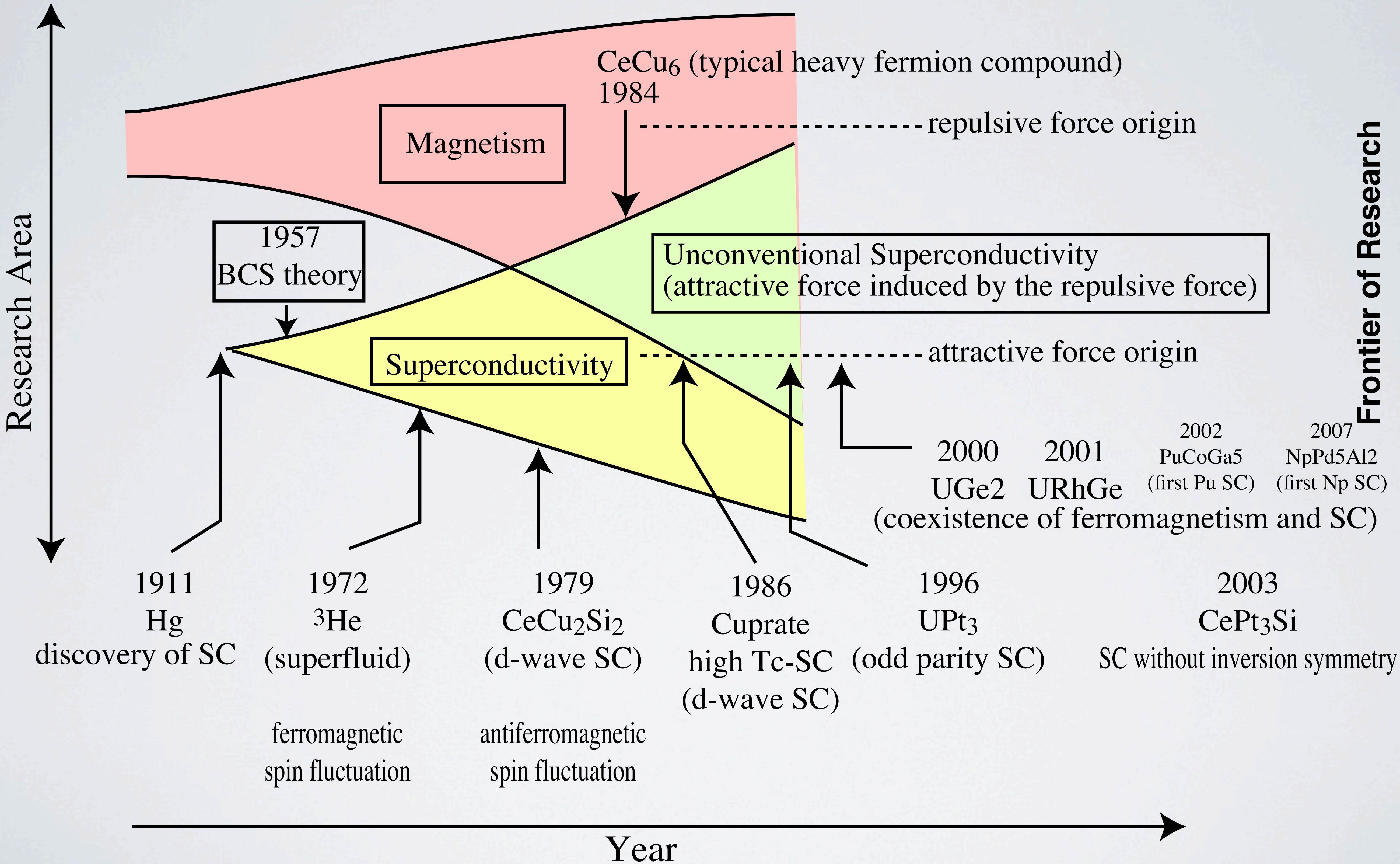
- Heavy Fermion Superconductivity
- Ferromagnetism & Superconductivity
- UGe_2, URhGe, UCoGe

Results

- FM-QCEP
- Re-entrant superconductivity
- Fermi surfaces

Summary

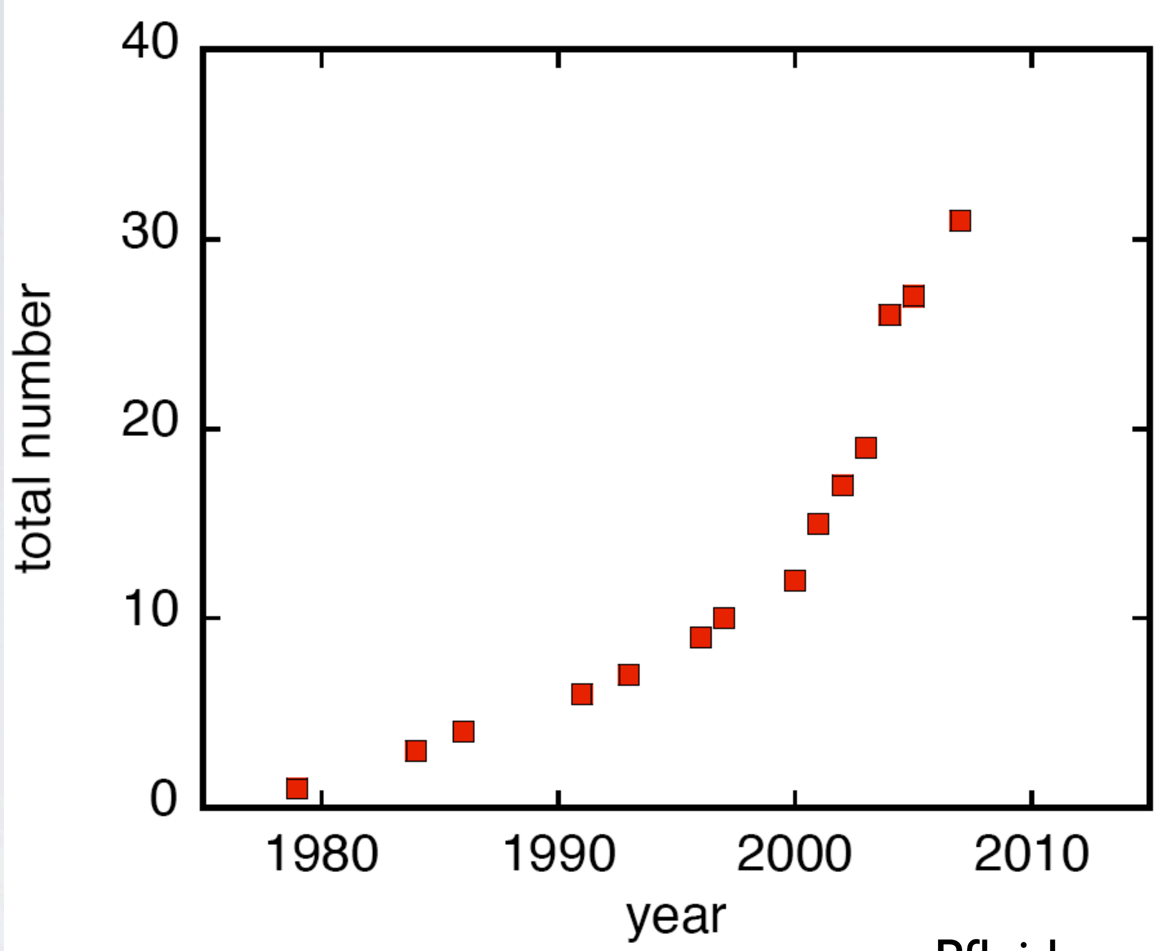
Magnetism & Superconductivity



New materials open the frontiers of research

After K. Miyake

Number of heavy fermion superconductors (f-electron system)



Pfleiderer , Rev. Mod. Phys.

Heavy fermion superconductors of uranium compounds

Material	T_c (K)	Year of discovery	Number of publication
UPt_3	0.54	1984	1166
UBe_{13}	0.9	1984	382
URu_2Si_2	1.5	1986	629
UPd_2Al_3	1.9	1991	452
UNi_2Al_3	1.0	1991	94
UGe_2	0.7	2000	245
URhGe	0.25	2001	75
UIr	0.33	2004	22
UCoGe	0.6	2007	16

ISI web of science (2009)

Transuranium compounds
PuCoGa5, PuRhGa5,
NpPd5Al2, PuCoIn5,
PuRhIn5

Early study in 1980s'

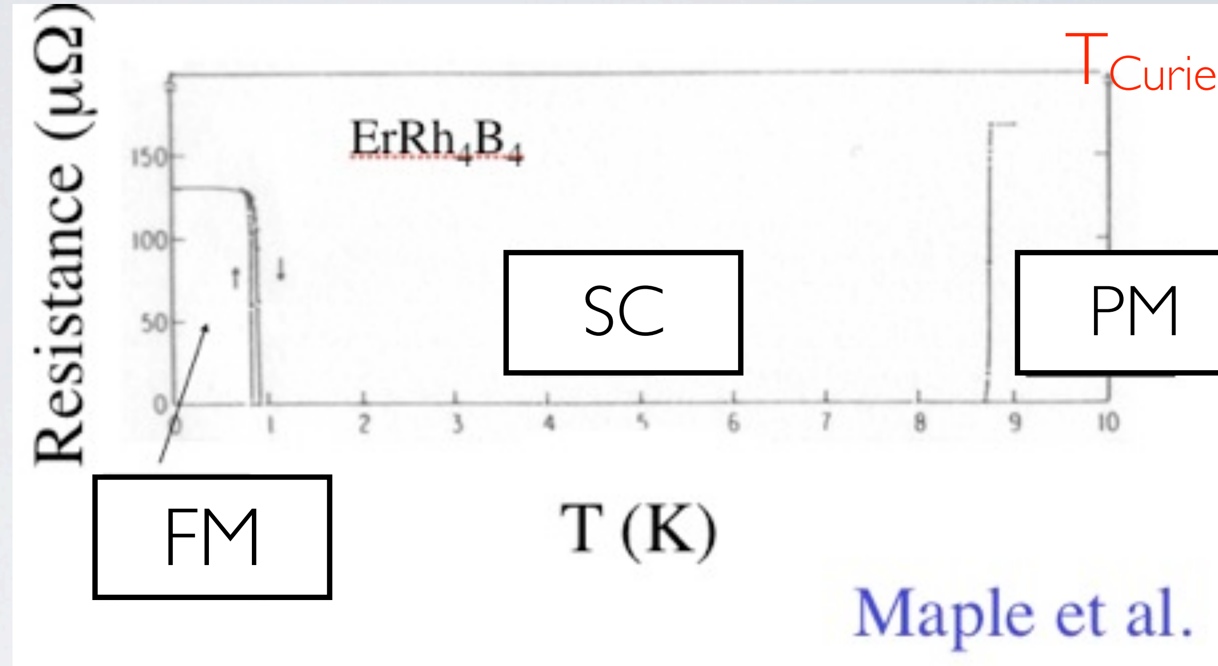
Competitive phenomena: FM & SC

FM excludes SC

Large internal field destroys Cooper pair

$ErRh_4B_4$, $HoMo_6S_8$, etc …

- large moment
- 4f-localized system
- $T_{Curie} < T_{SC}$



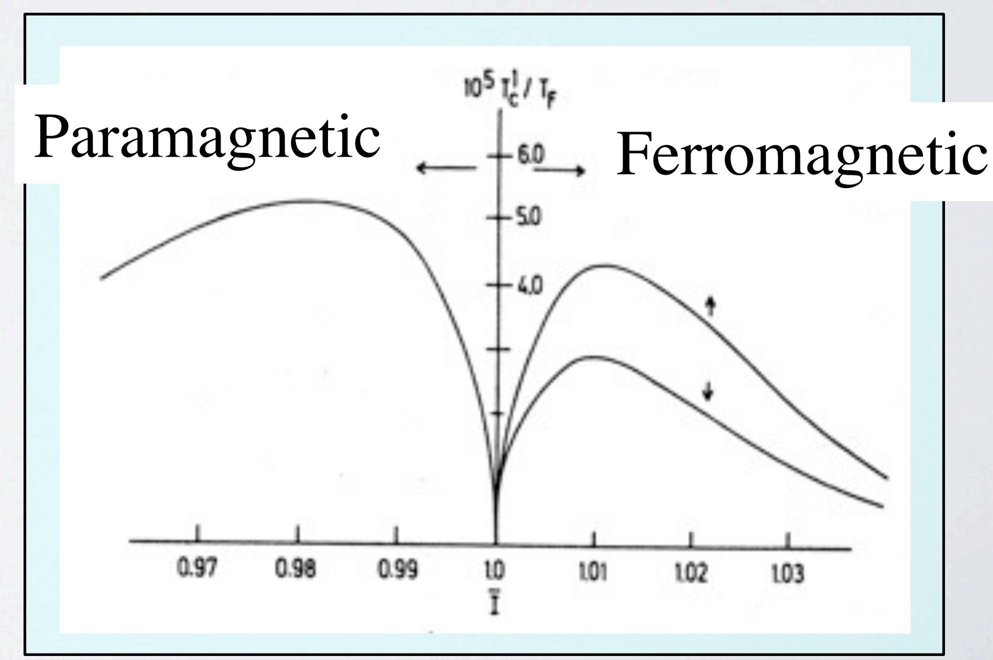
Theoretical prediction near FM-QCP

Weak ferromagnet: $ZrZn_2$

SC Cooper pair

~~spin singlet ↑↓~~

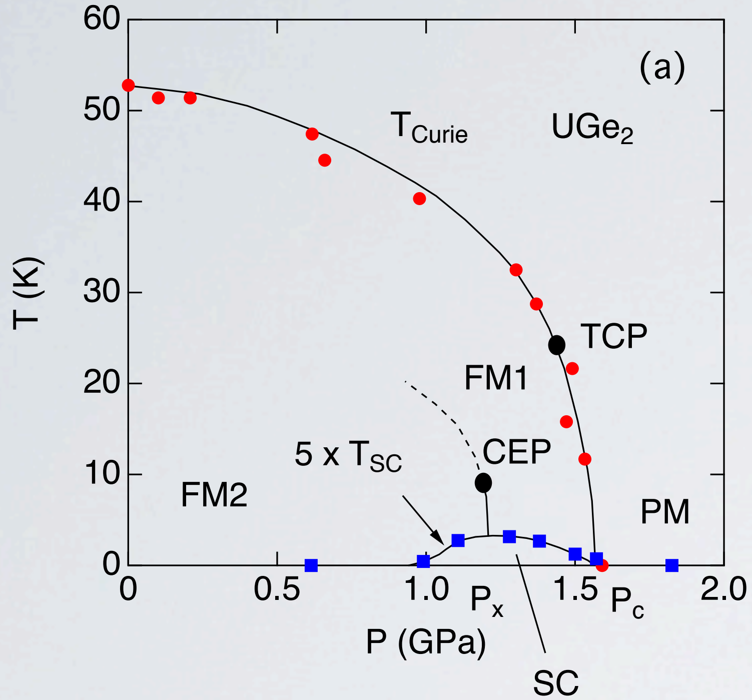
✓ spin triplet ↑↑ ↓↓



Fay & Appel **1980** (PRB 22, 3173)

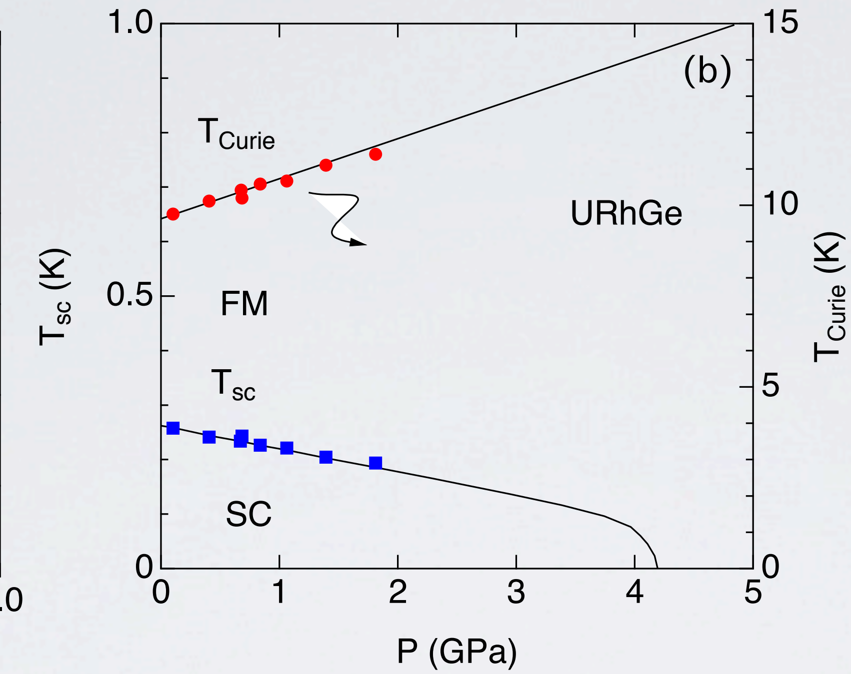
Coexistence of FM and SC in uranium compounds

UGe_2



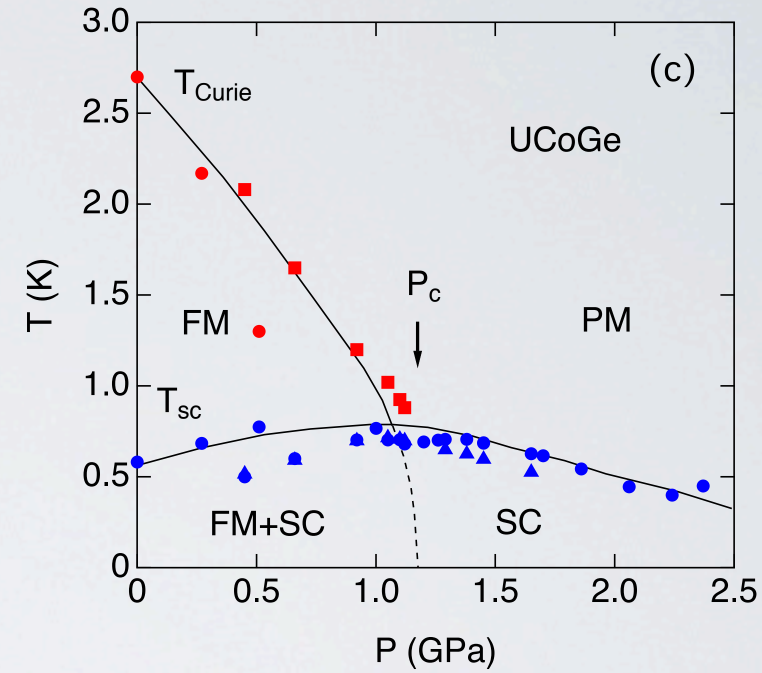
Saxena et al. Nature 406 (2000) 587

URhGe



D. Aoki et al. Nature 413 (2001) 613.
F. Hardy et al. Physica B (2005)
A. Miyake et al. JPSJ (2009)

UCoGe



N.T. Huy et al.: PRL 99 (2007) 067006.
E. Hassinger et al. JPSJ (2008)

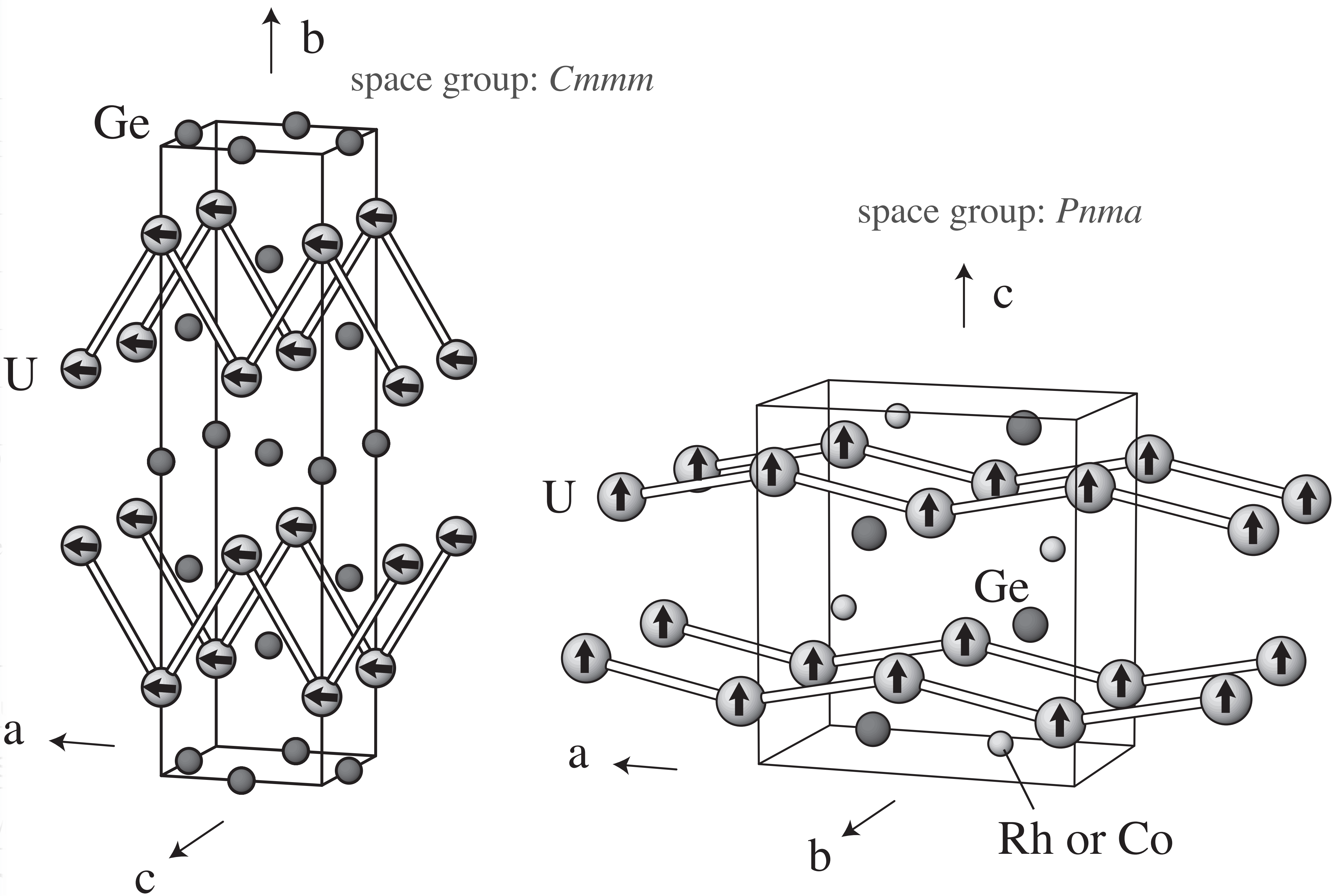
T_{Curie}	52 K	9.5 K	3 K
T_{SC}	0.8 K	0.25 K	0.6 K
γ (mJ/K²mol)	30	160	55
m_0	1.5 μ_B	0.4 μ_B	0.05 μ_B

$T_{sc} < T_{Curie}$

small ordered moment (cf. free ion ~3.6 μ_B for $5f^2$ or $5f^3$)

- weak ferromagnets (5f-itinerant)
- strong Ising anisotropy

orthorhombic structure



UGe_2 URhGe, UCoGe

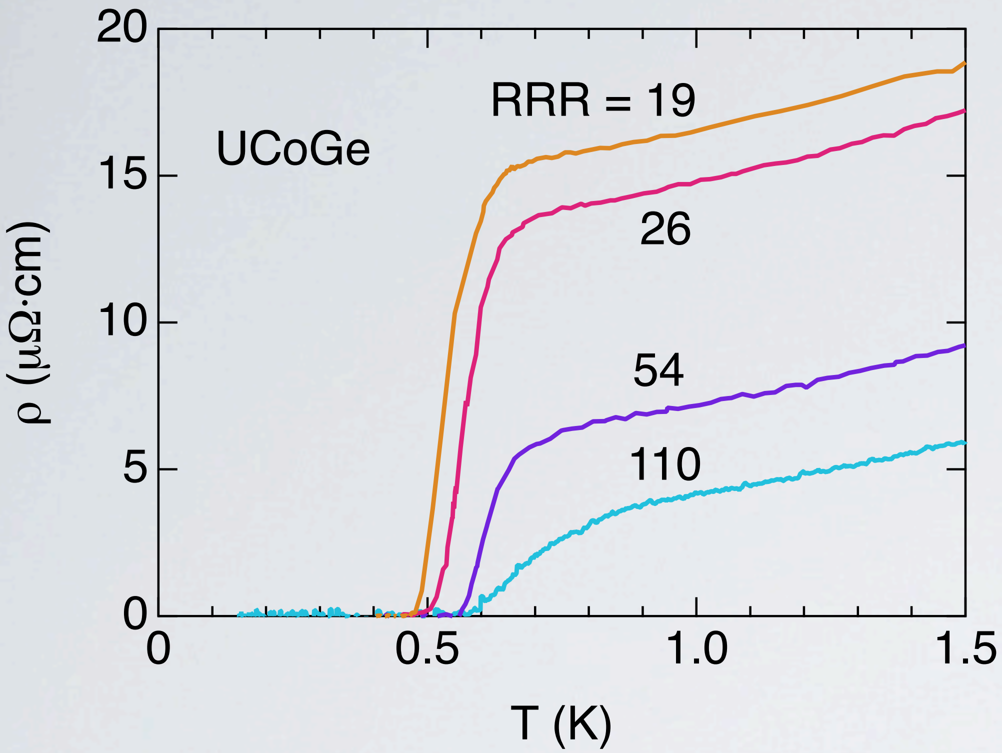
Zigzag chain → No inversion symmetry (local)

Inversion symmetry (global)

Parity mixing & Strong spin-orbit interaction

T_{Curie}

High quality single crystals are essential

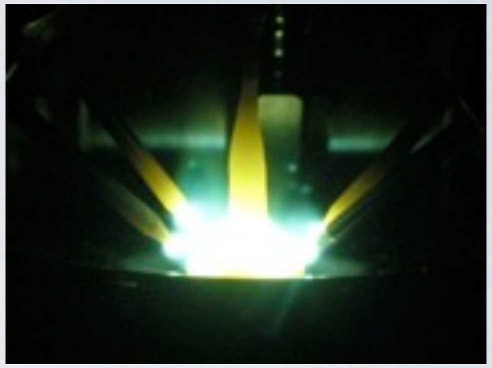


UGe_2: high quality easily available (RRR> 300)

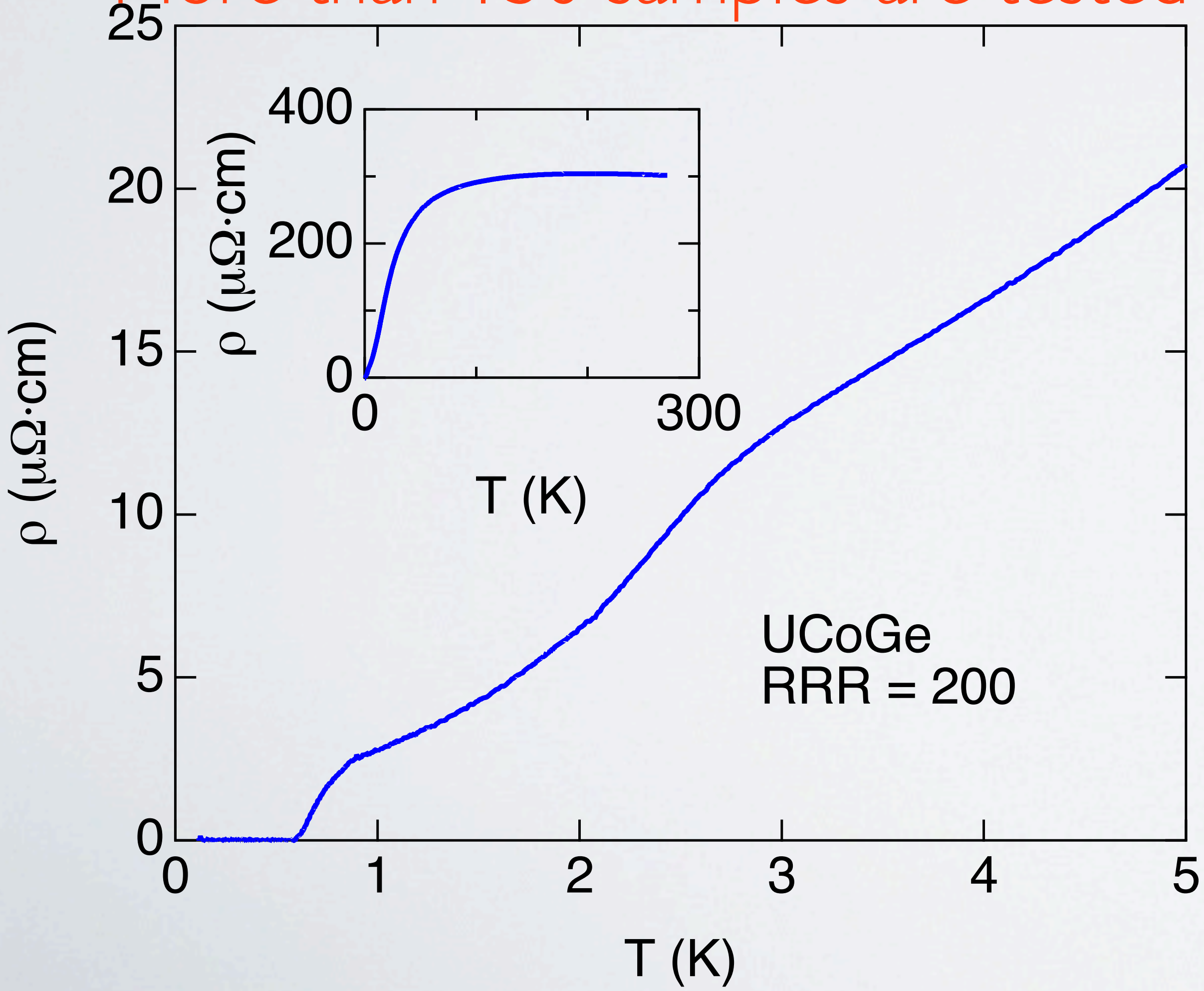
URhGe, UCoGe: very difficult (usually RRR=3–10)

Strategy

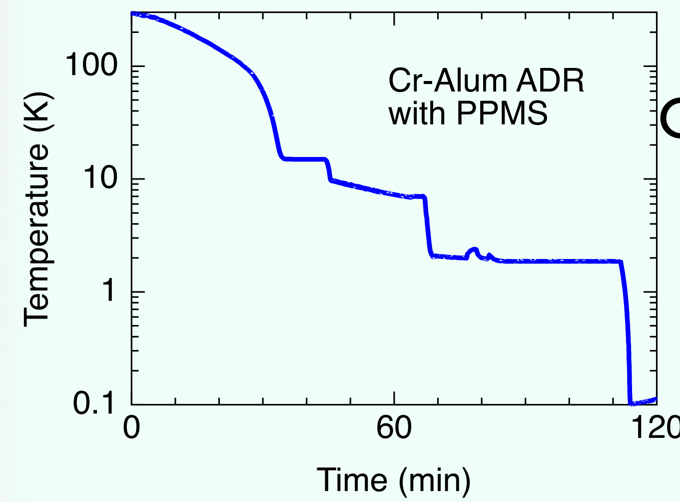
- Optimize growth condition
- Rapid feedback
  crystal growth ↔ characterization
- Work hard



More than 150 samples are tested



Rapid Resistivity Measurement

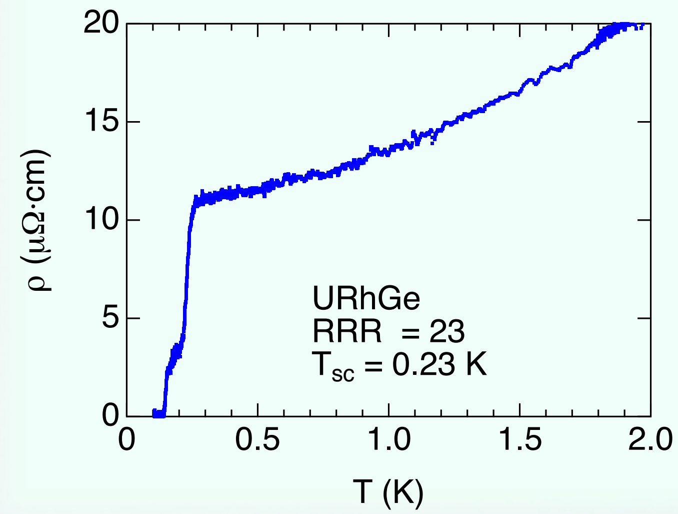


Homemade ADR with PPMS
(costs < 100 euros)

One click

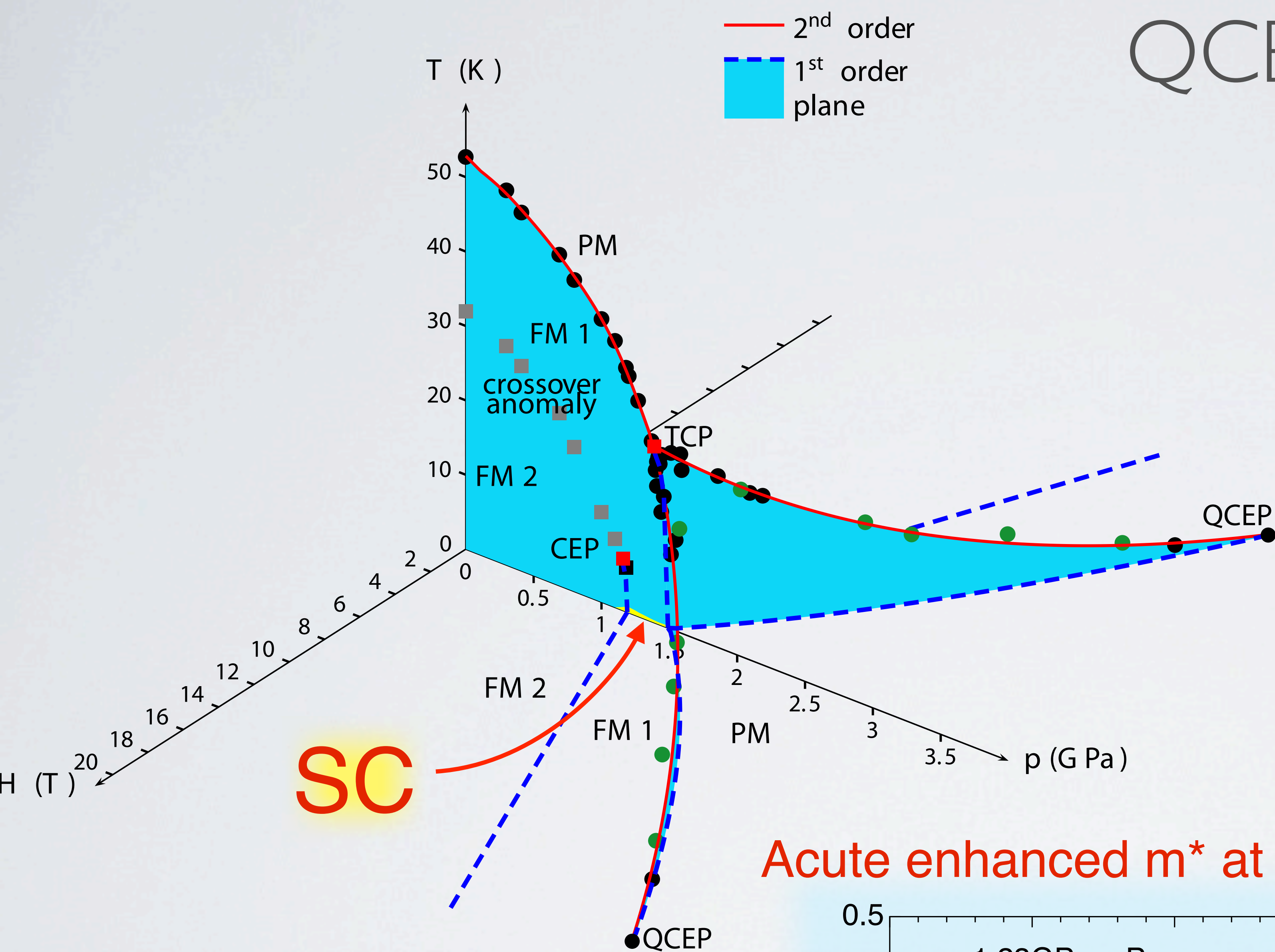
300 K → 100 mK

< 2 hours



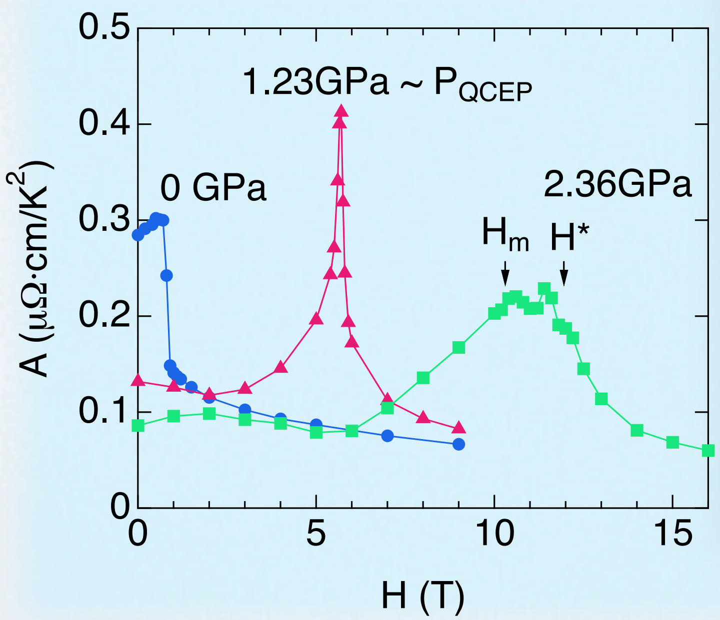
FM-Quantum Critical Endpoint of UGe_2

QCEP (P~3.5 GPa, H ~ 20T)

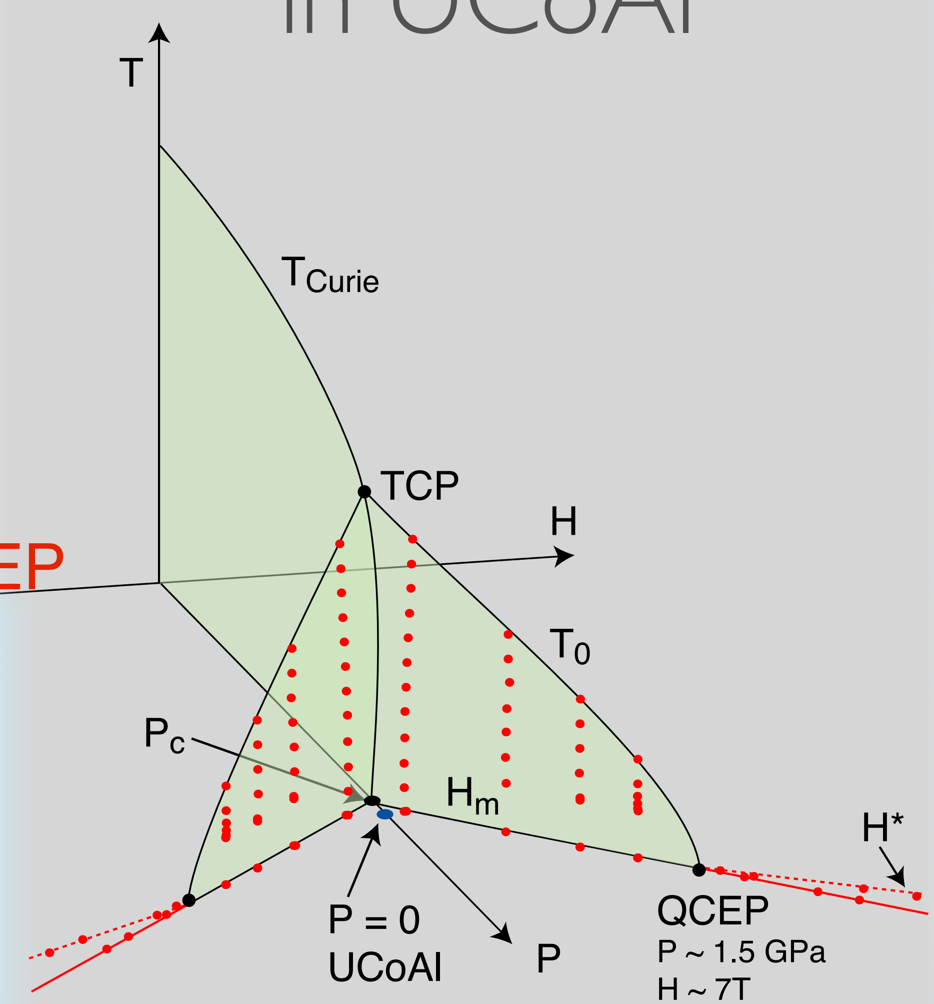


V. Taufour *et al*.: PRL **105** (2010) 217201.
H. Kotegawa *et al*.: JPSJ **80** (2011) 083703.

Acute enhanced m* at QCEP

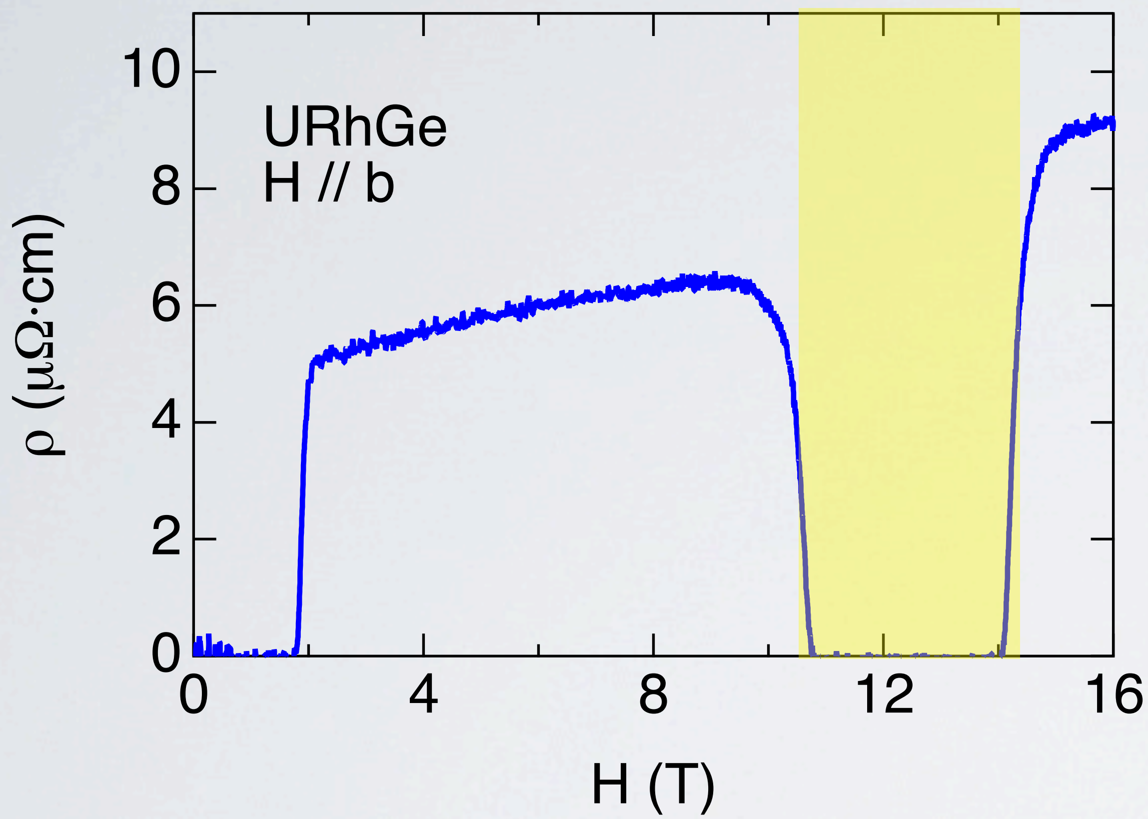


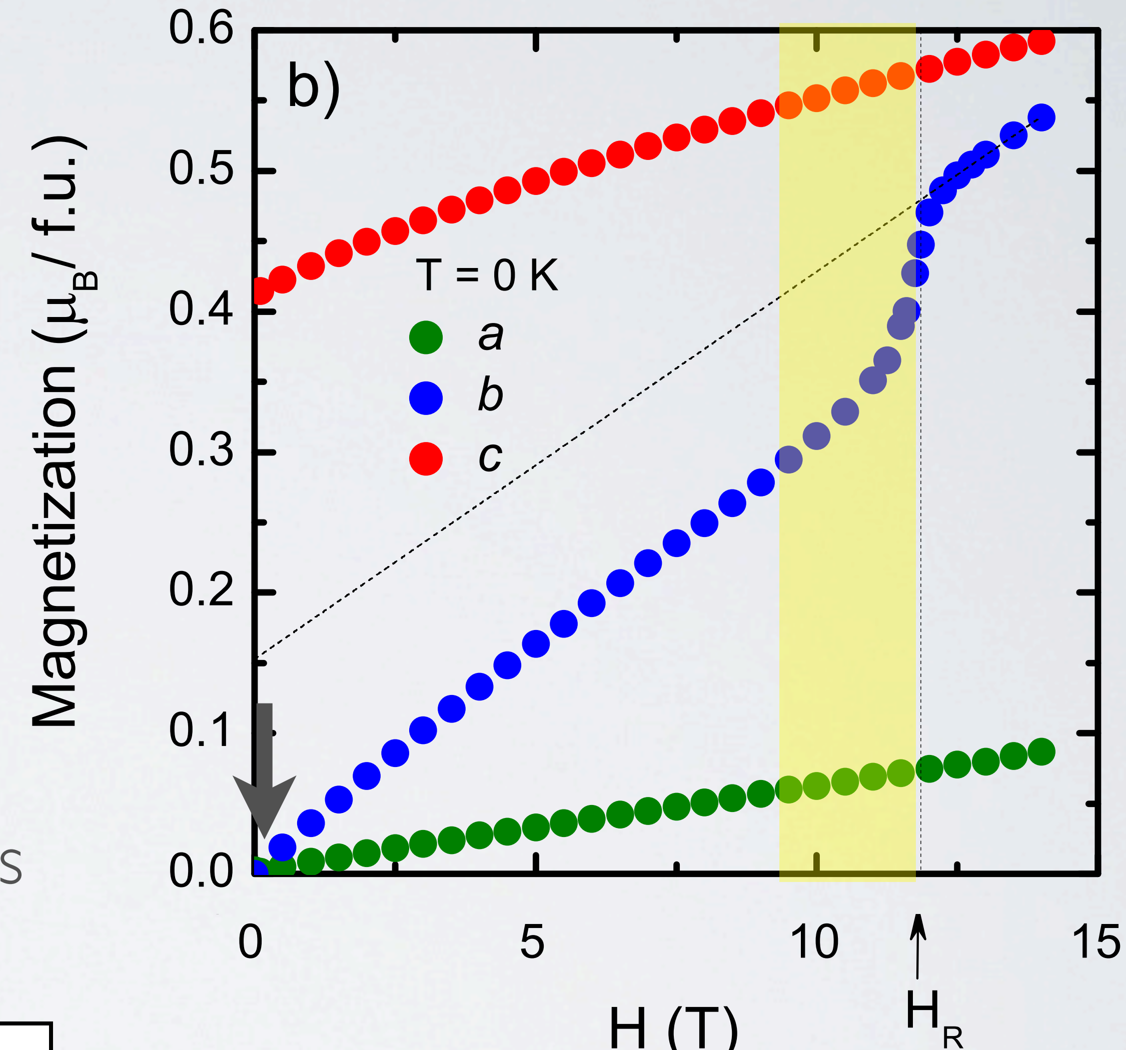
similar (T,P,H) phase in UCoAl

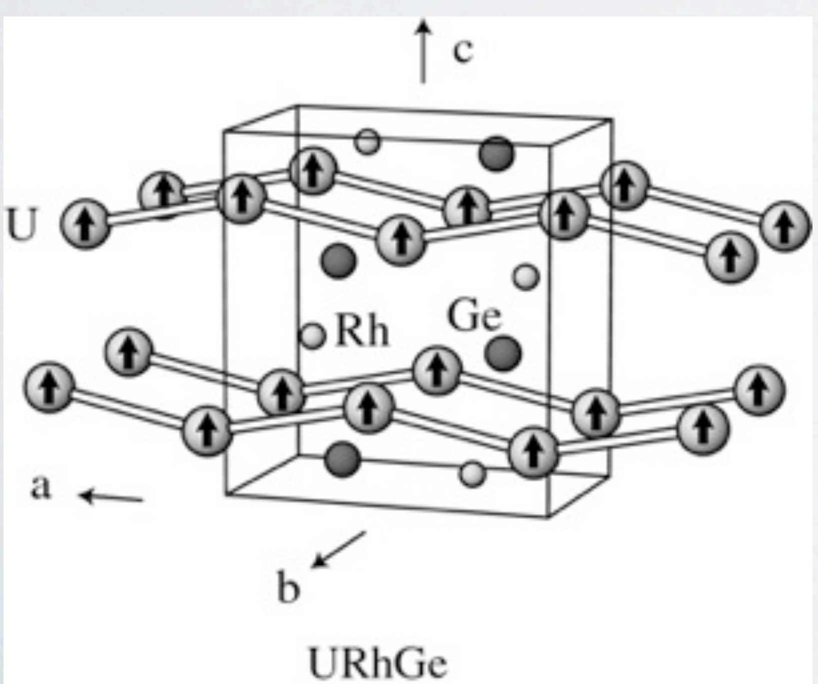


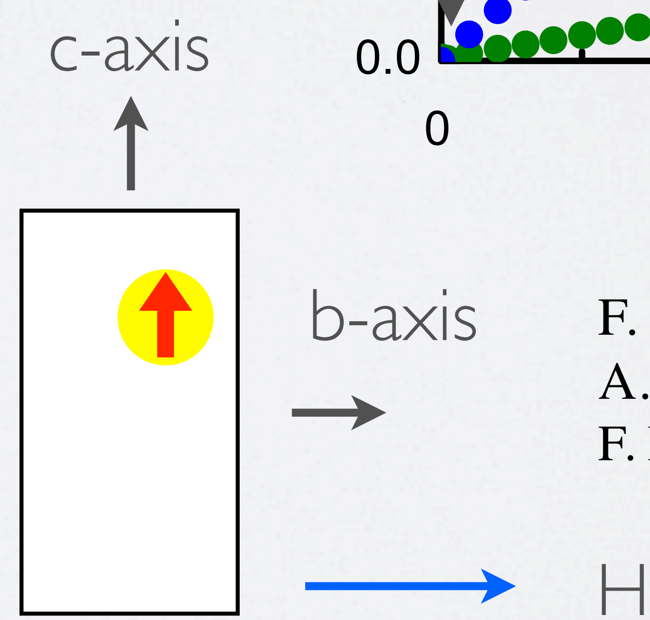
D. Aoki *et al*.: JPSJ **80** (2011) 094711.

Re-entrant superconductivity and spin reorientation in URhGe



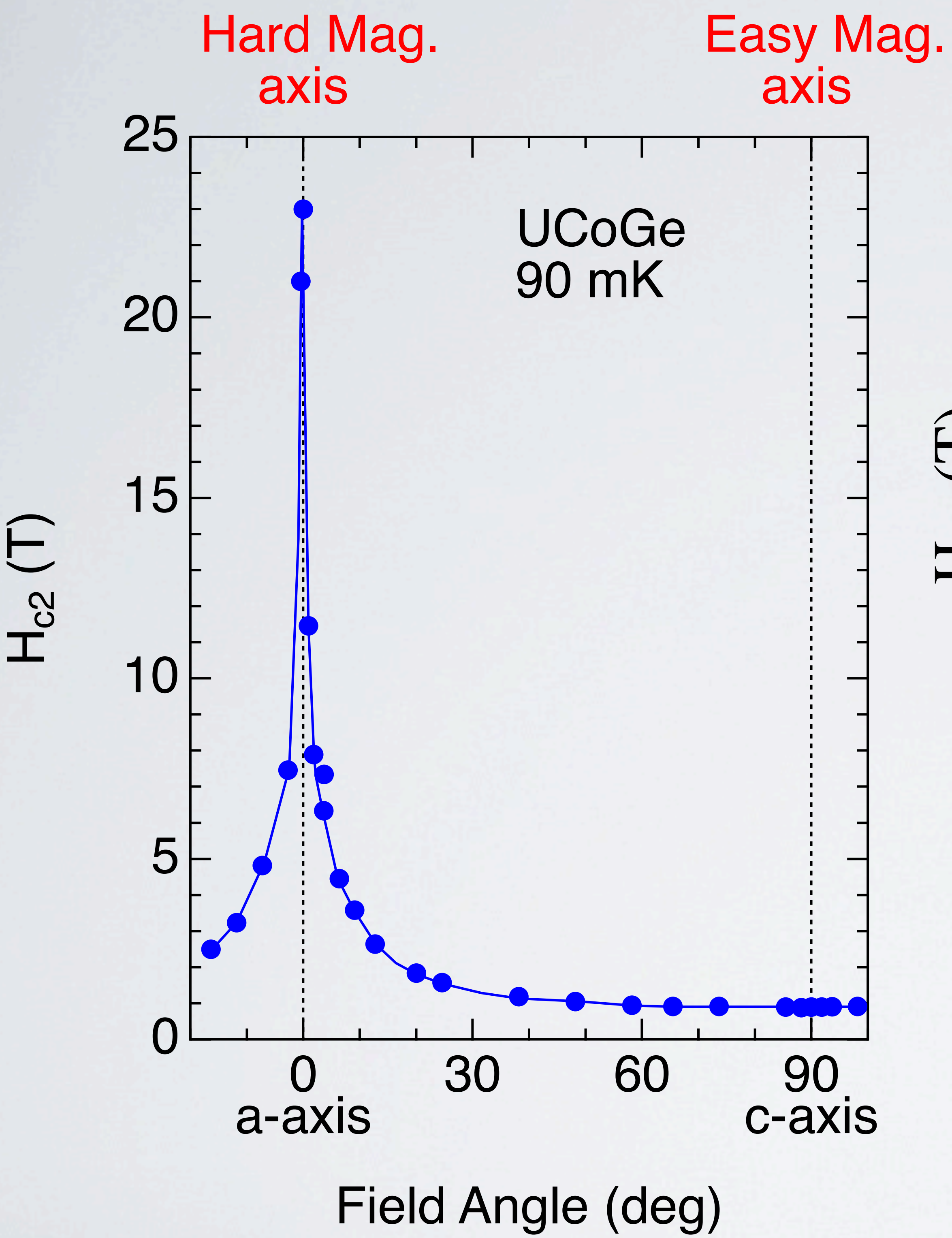


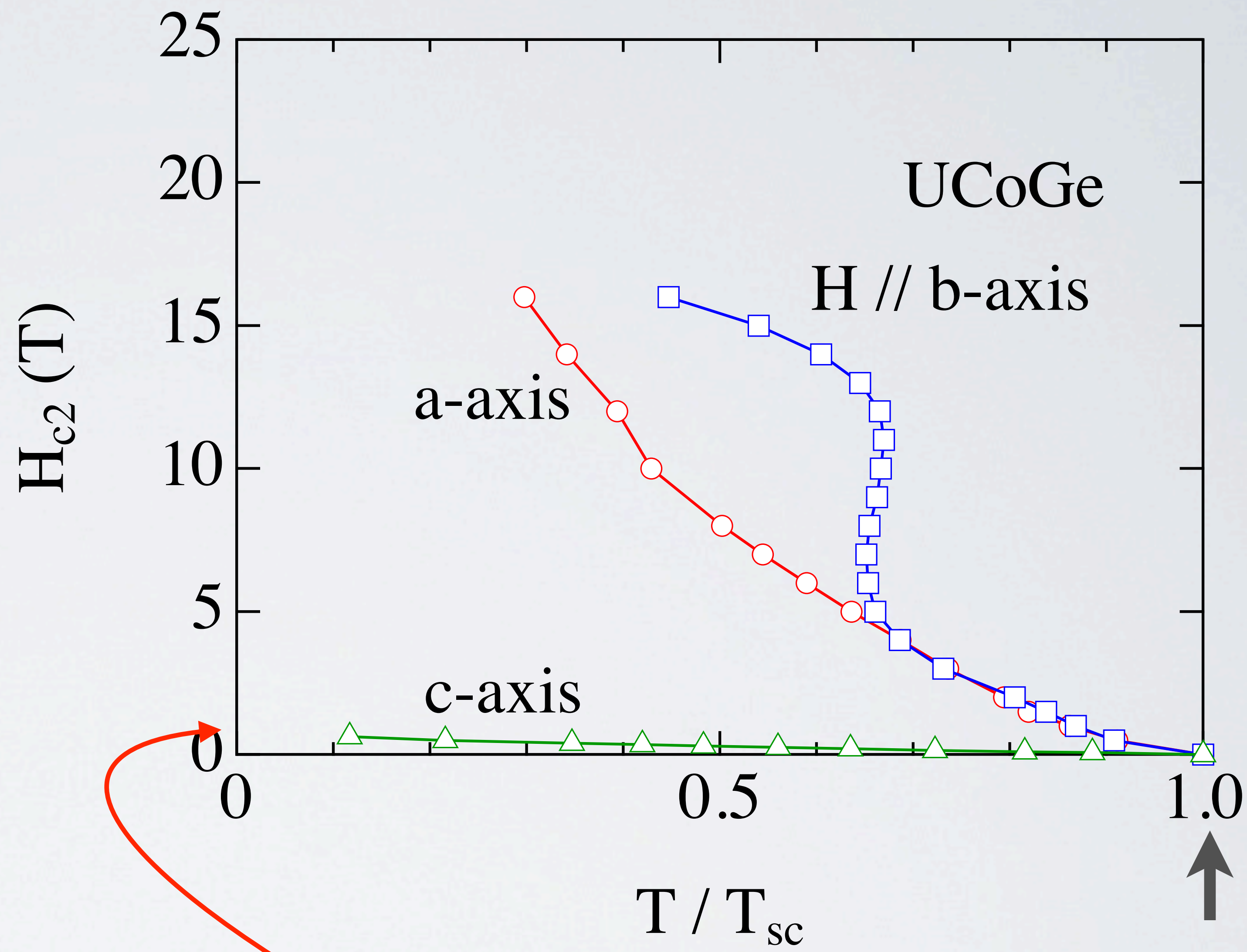




F. Levy et al. Science (2005)
A. Miyake et al. JPSJ (2008)
F. Hardy et al.: PRB 83 (2011) 195107.

Very anisotropic H_{c2} of UCoGe



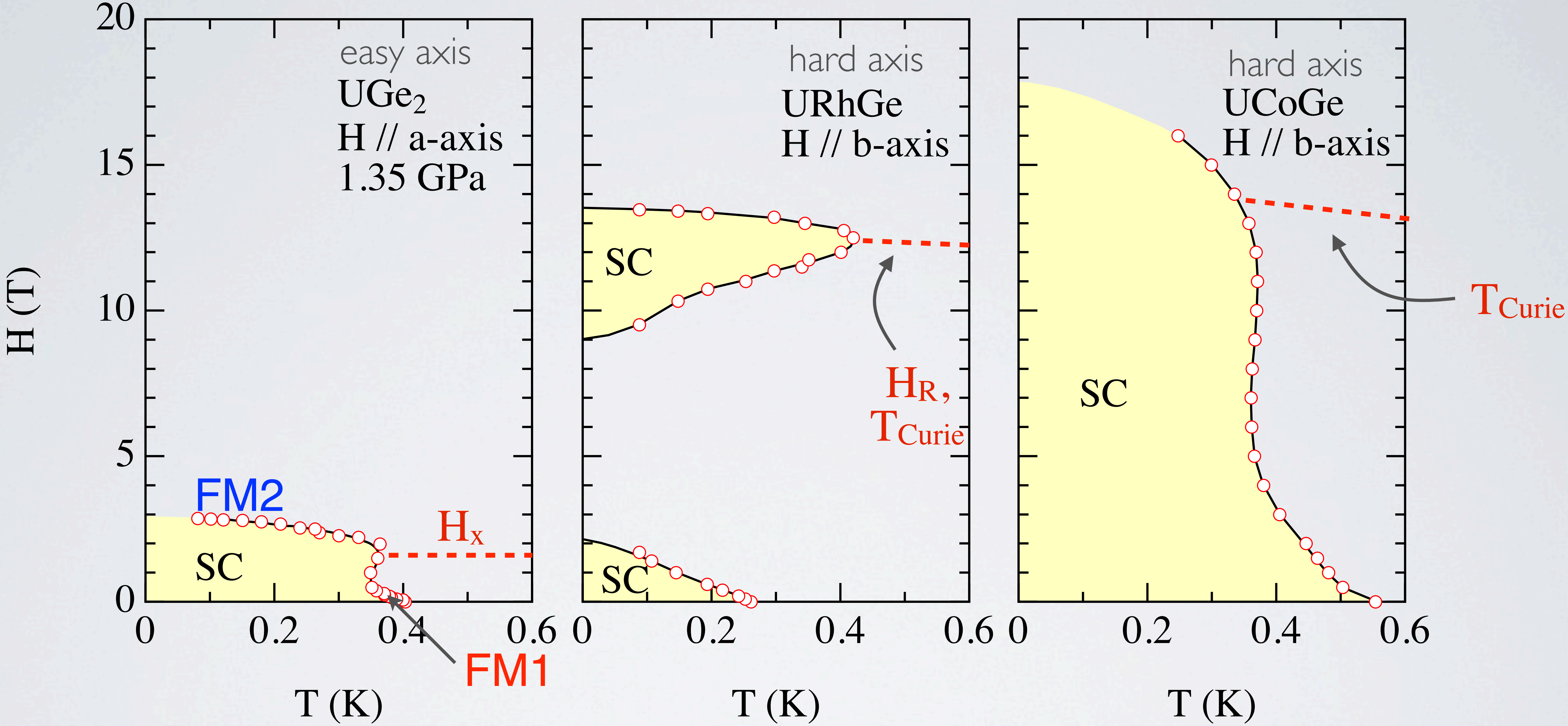


T_{sc} ~ 0.6 K

$H_{c2} \gg$ Pauli limit (~1T)

D. Aoki, et al.: JPSJ 78 (2009) 113709

“Re-entrant” SC in ferromagnetic superconductors, UGe_2, UCoGe, URhGe



I. Sheikin et al: PRB(2001)
V. Taufour: PhD thesis (2011)

F. Levy et al. Science (2005)
A. Miyake et al.: JPSJ (2008)

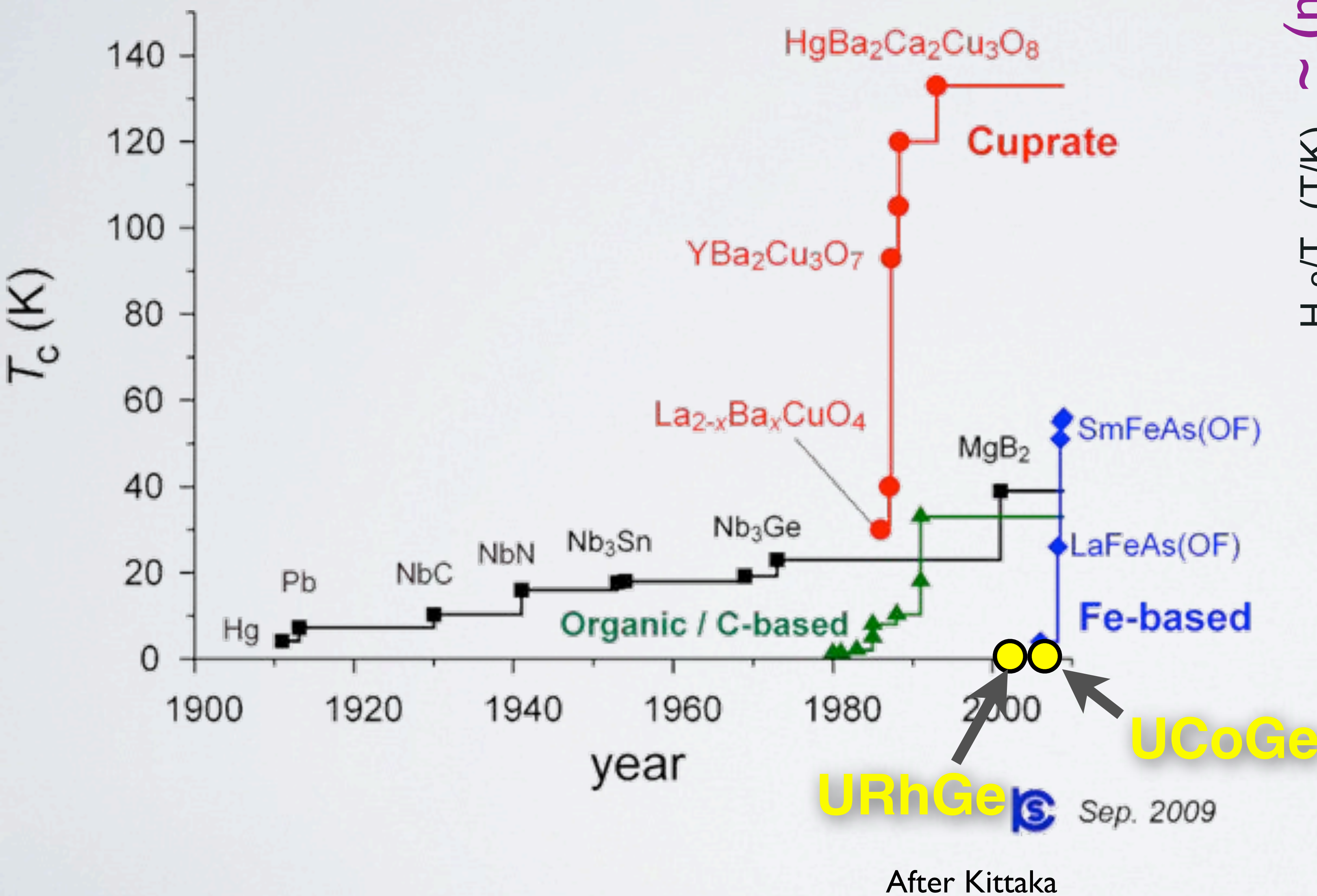
D. Aoki et al.: JPSJ (2009)

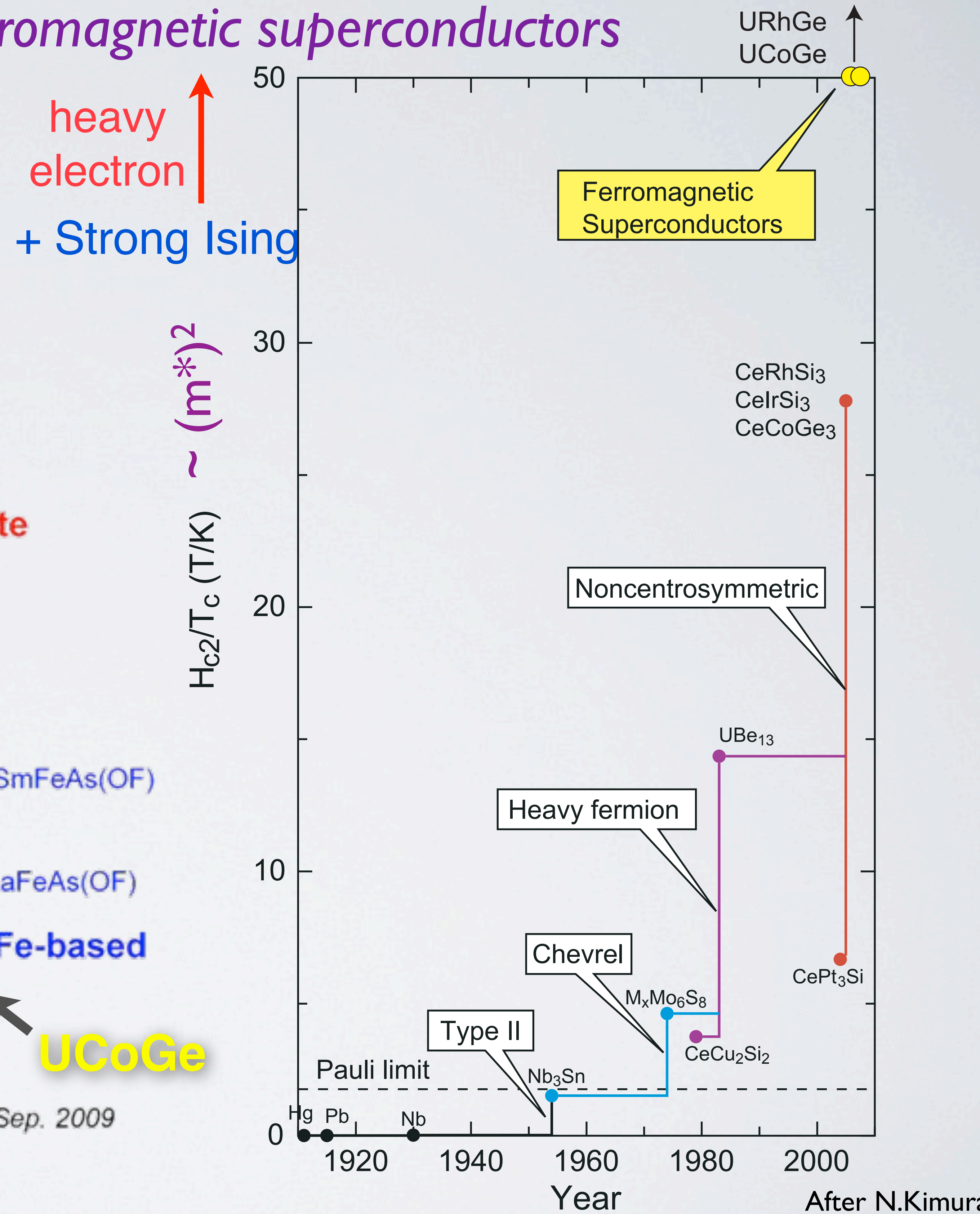
SC is reinforced by ferromagnetic instabilities

Spin-triplet state with equal spin pairing (↑↑ or ↓↓)

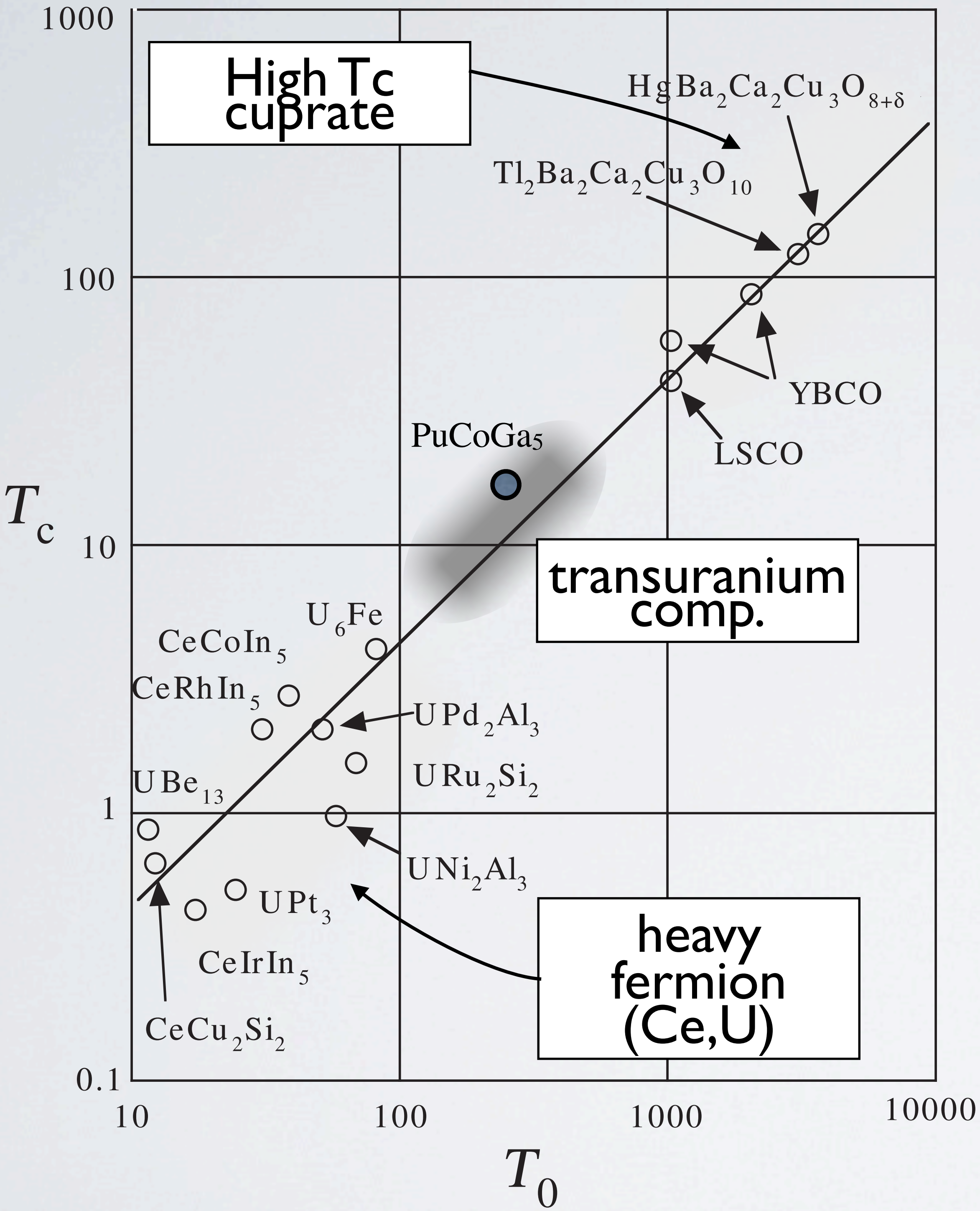
History of T_c and H_{c2}

Extremely huge H_{c2} of ferromagnetic superconductors

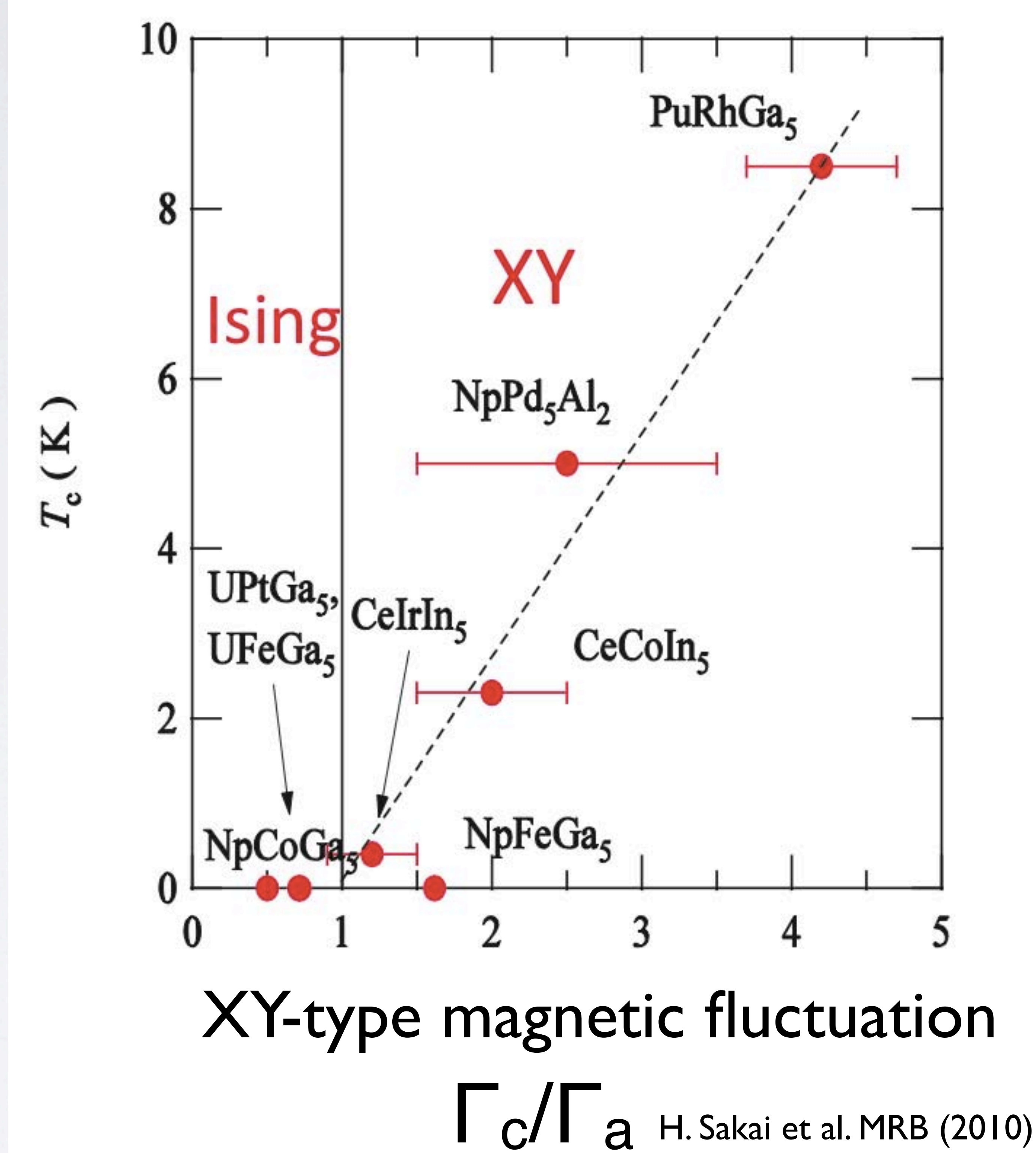




For high Tc



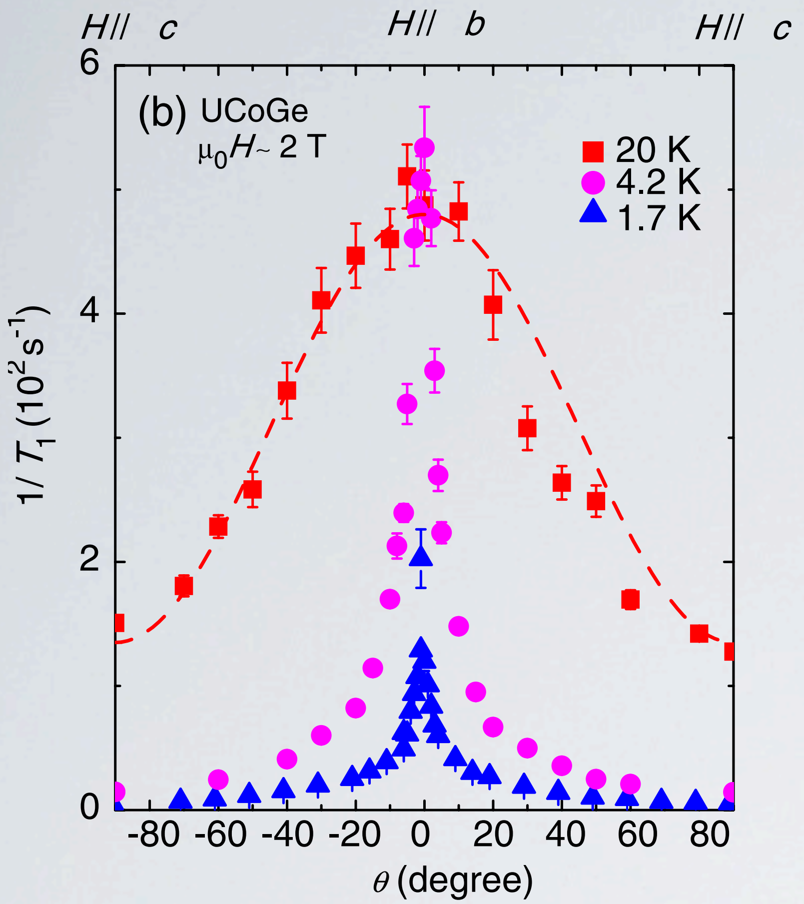
Moriya & Ueda: Rep. Prog. Phys (2003)



H. Sakai et al. MRB (2010)

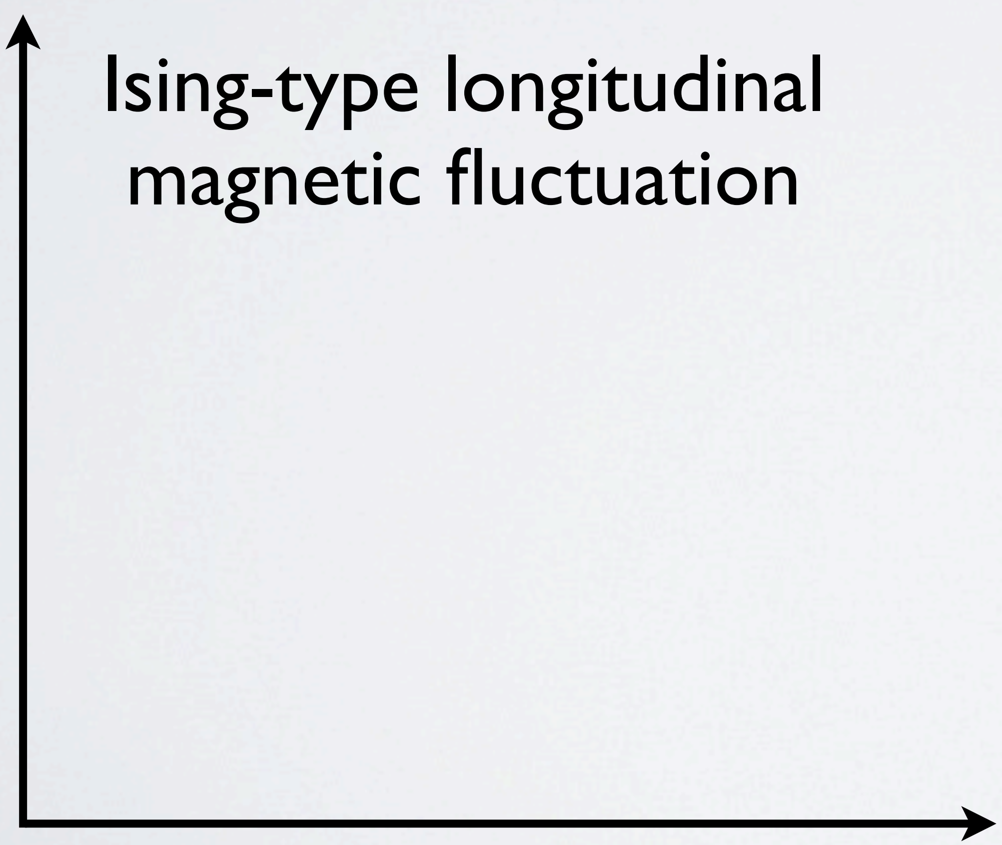
longitudinal and transverse magnetic fluctuation for H_{c2} and T_c

NMR view



Hattori et al. PRL (2012)

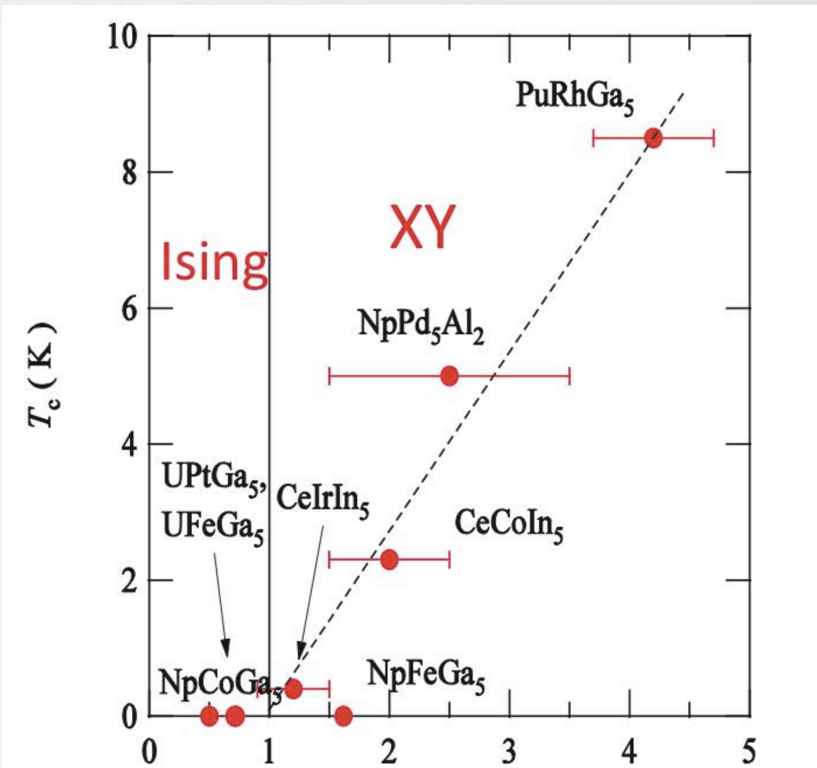
Hc2



Ising-type longitudinal magnetic fluctuation

Tc

XY-type transverse magnetic fluctuation



XY-type magnetic fluctuation

Γ_c/Γ_a H. Sakai et al. MRB (2010)

Field-induced superconductivity in other materials

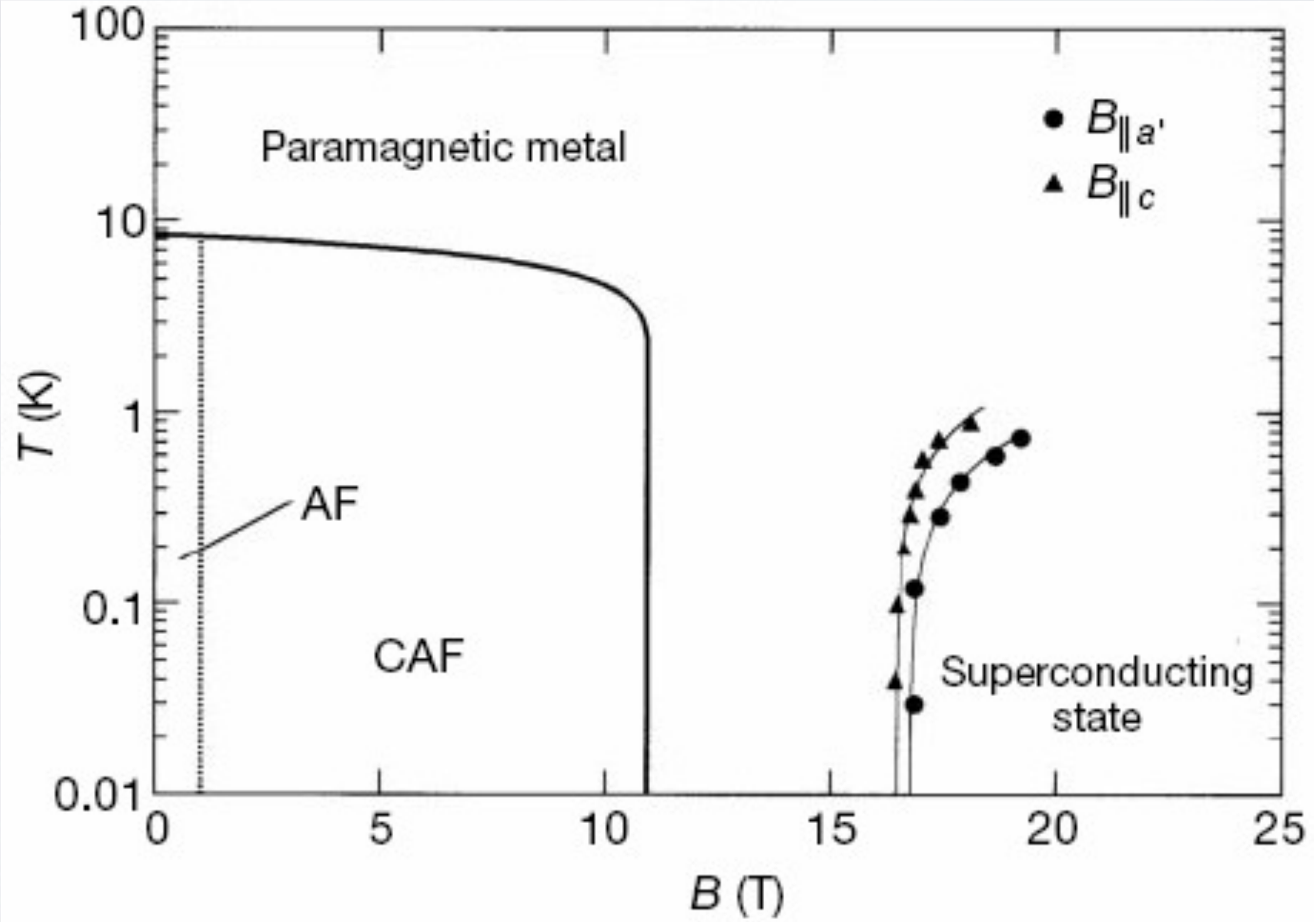
Chevrel phase compound

$Sn_{0.25}Mo_6S_{7.2}Se_{0.8}$: SC **4–23 T**

H.W. Meul et. al., PRL 53, 497 (1984)

κ-$(BETS)_2FeBr_4$: SC **10–16 T**

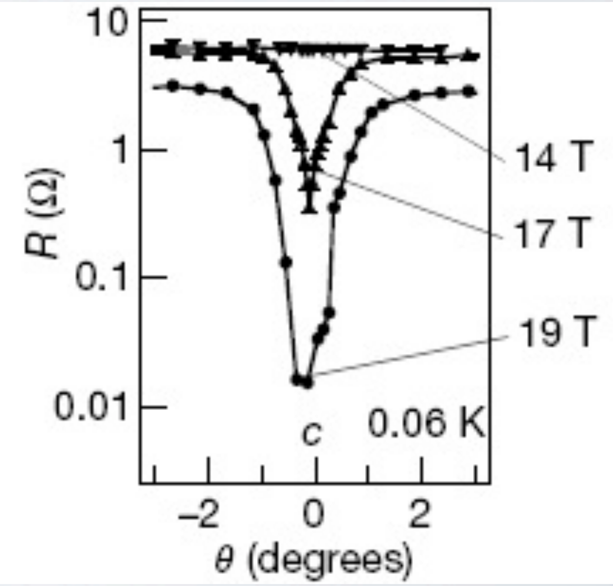
T. Konoike et al., PRB 70, 94514 (2004)



λ-$(BETS)_2FeCl_4$: SC **18 T < *H***

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

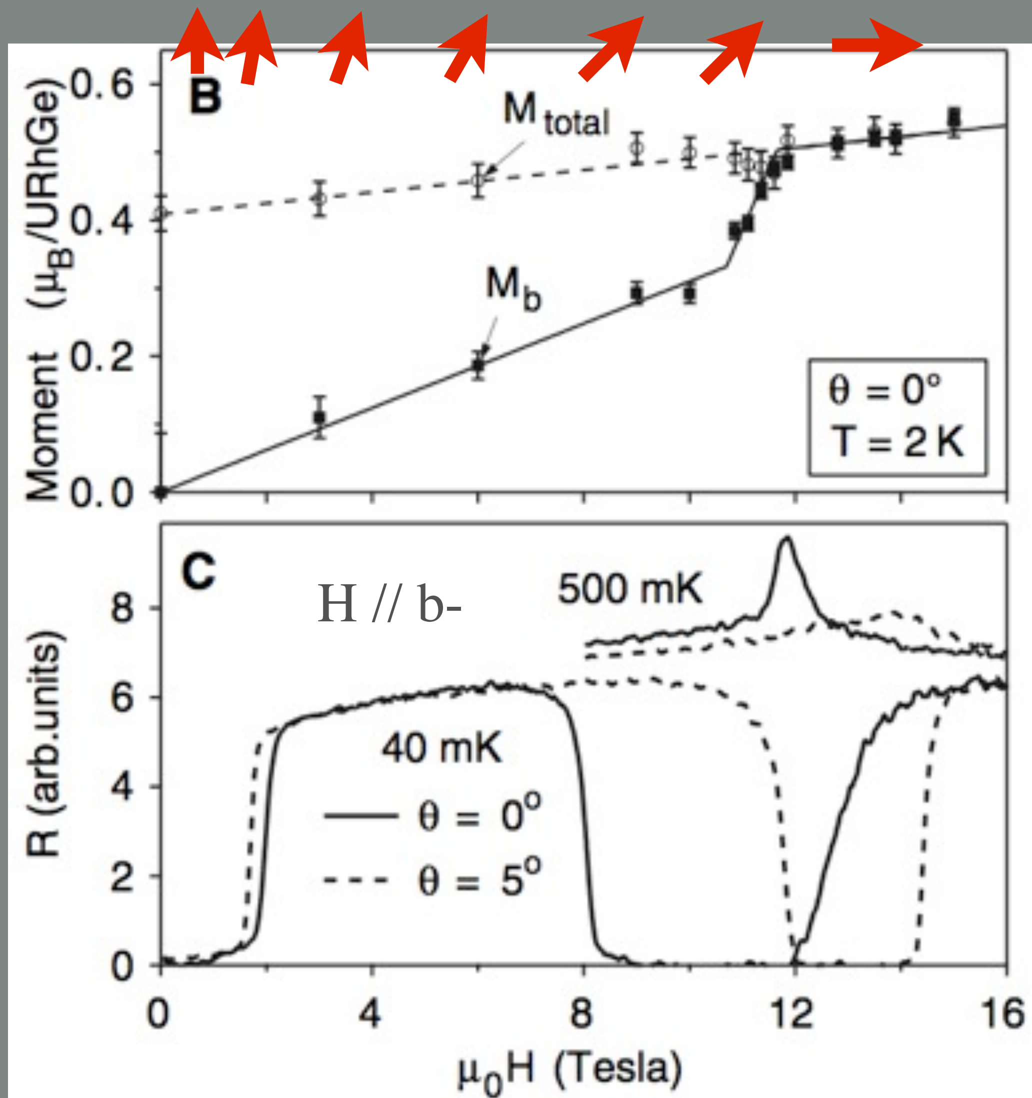
Field-induced superconductivity is due to the **Jaccarino-Peter effect** (compensation of the external field by internal exchange field).

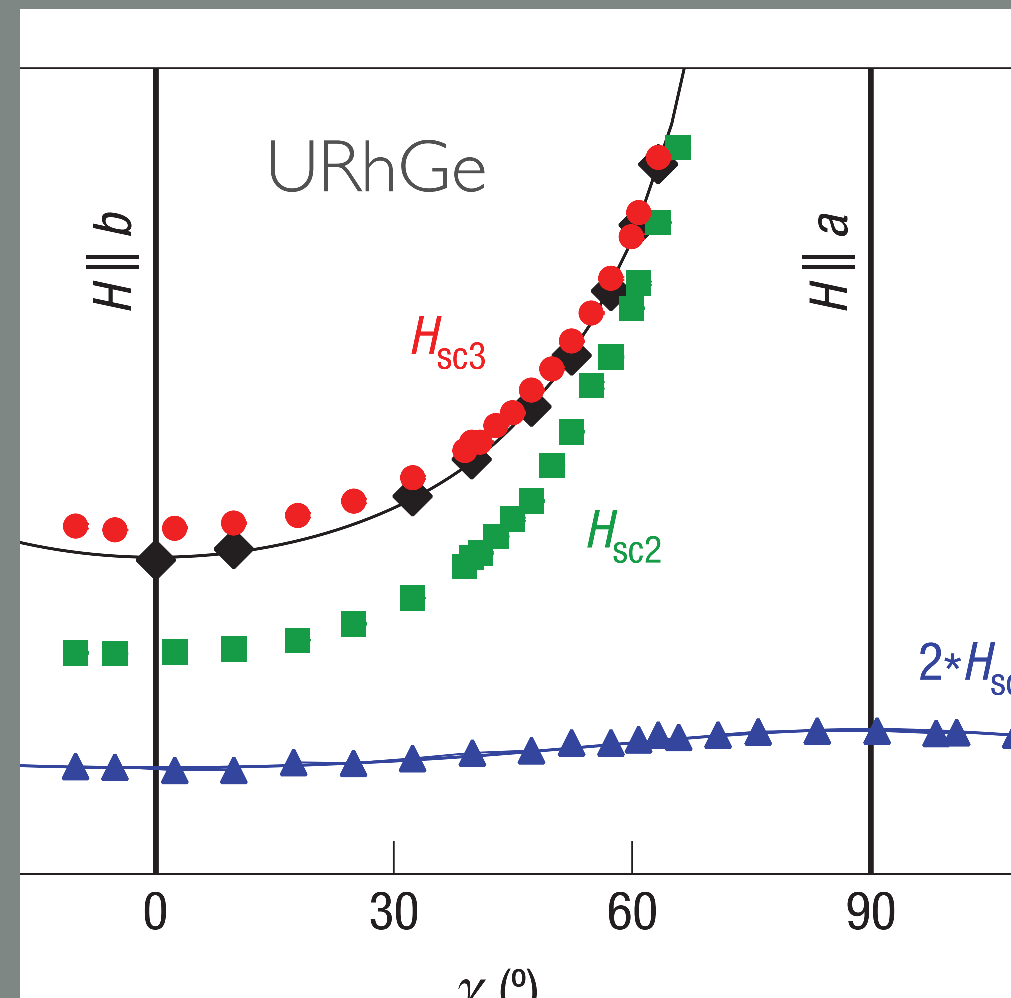


Re-entrant superconductivity appears only when *B* is applied in plane (no orbital limit)

Field-induced superconductivity in other materials

Chevrel phase compound





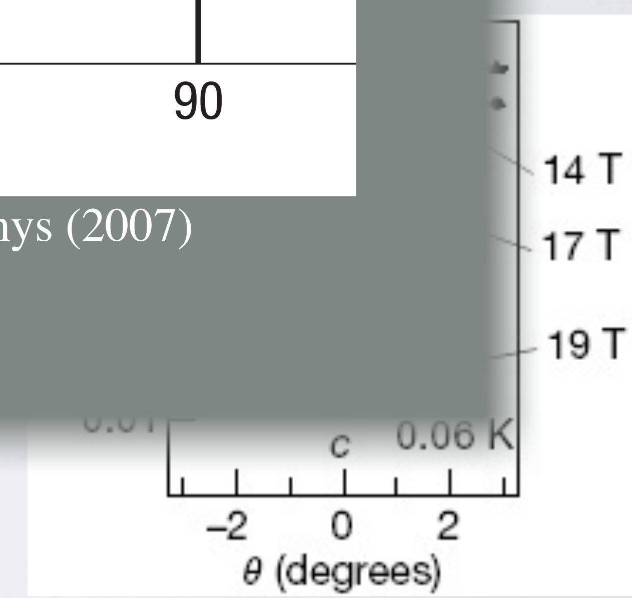
F. Levy et al. Nature Phys (2007)

Fie

Jac

e

NOT Jaccarino-Peter effect

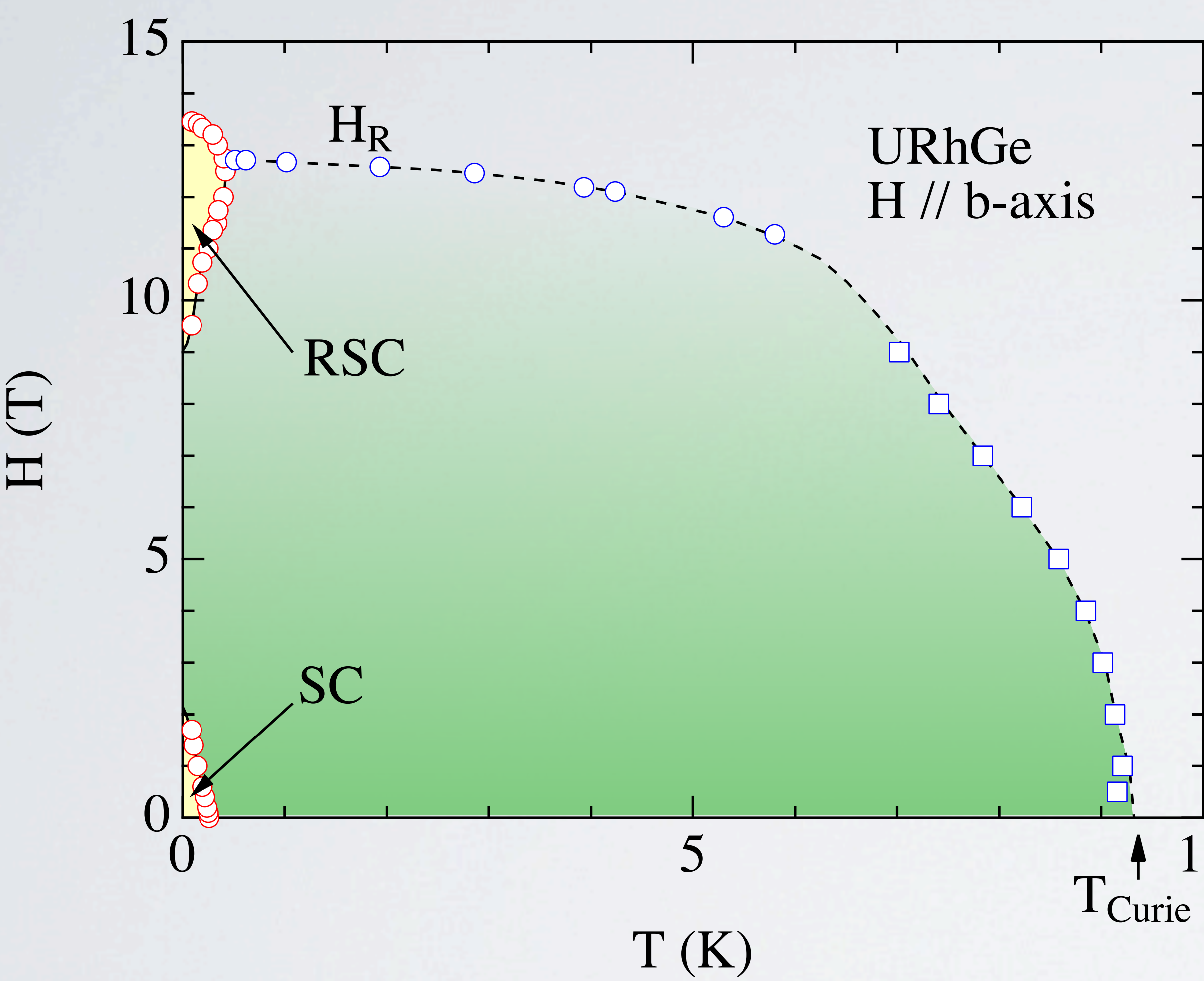


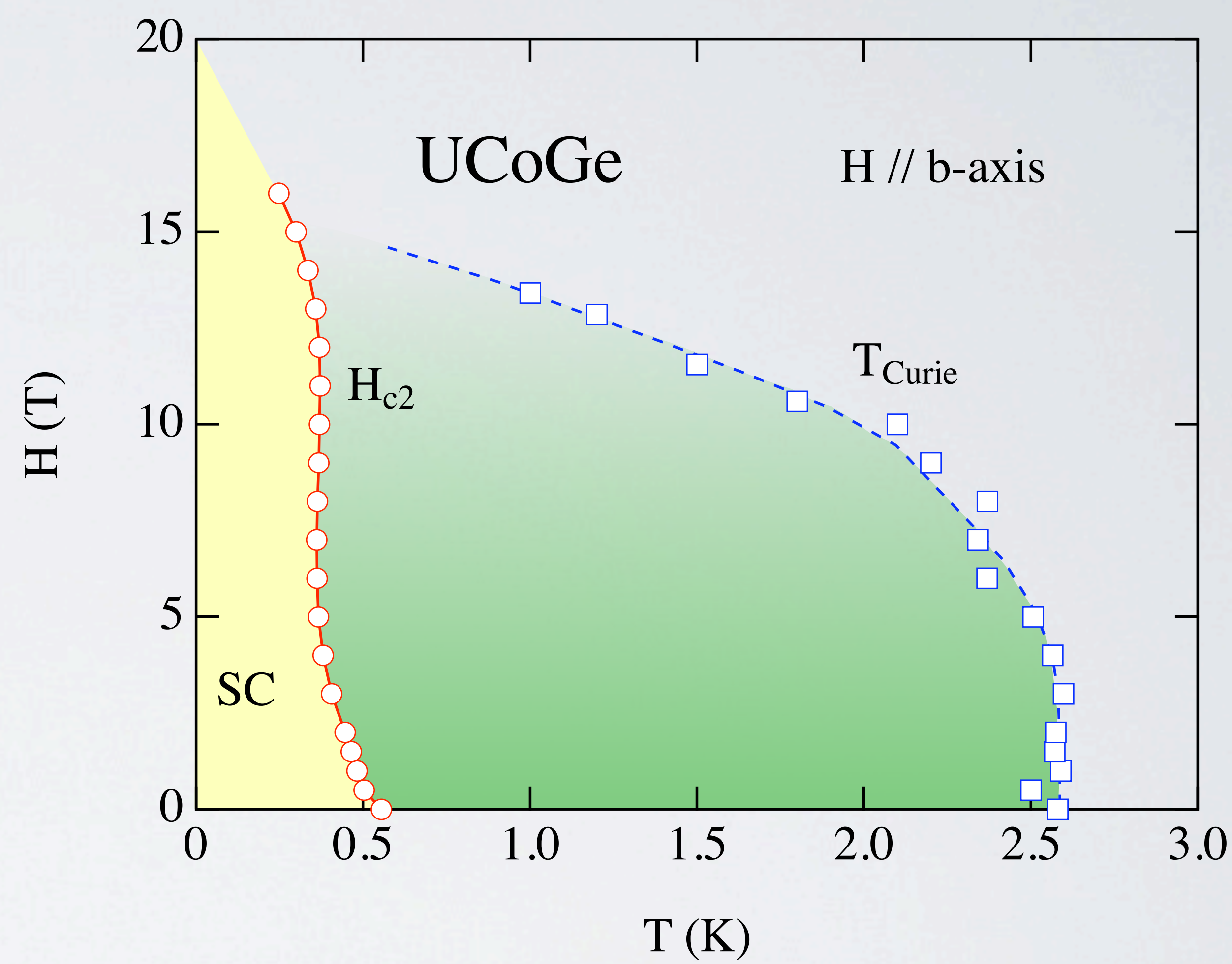
Re-entrant superconductivity appears only when *B* is applied in plane (no orbital limit)

Why field-reinforced SC appears?

For H // hard-mag. axis

$\Delta T_{\mathrm{Curie}} \propto H^2$ V. Mineev PRB (2011)

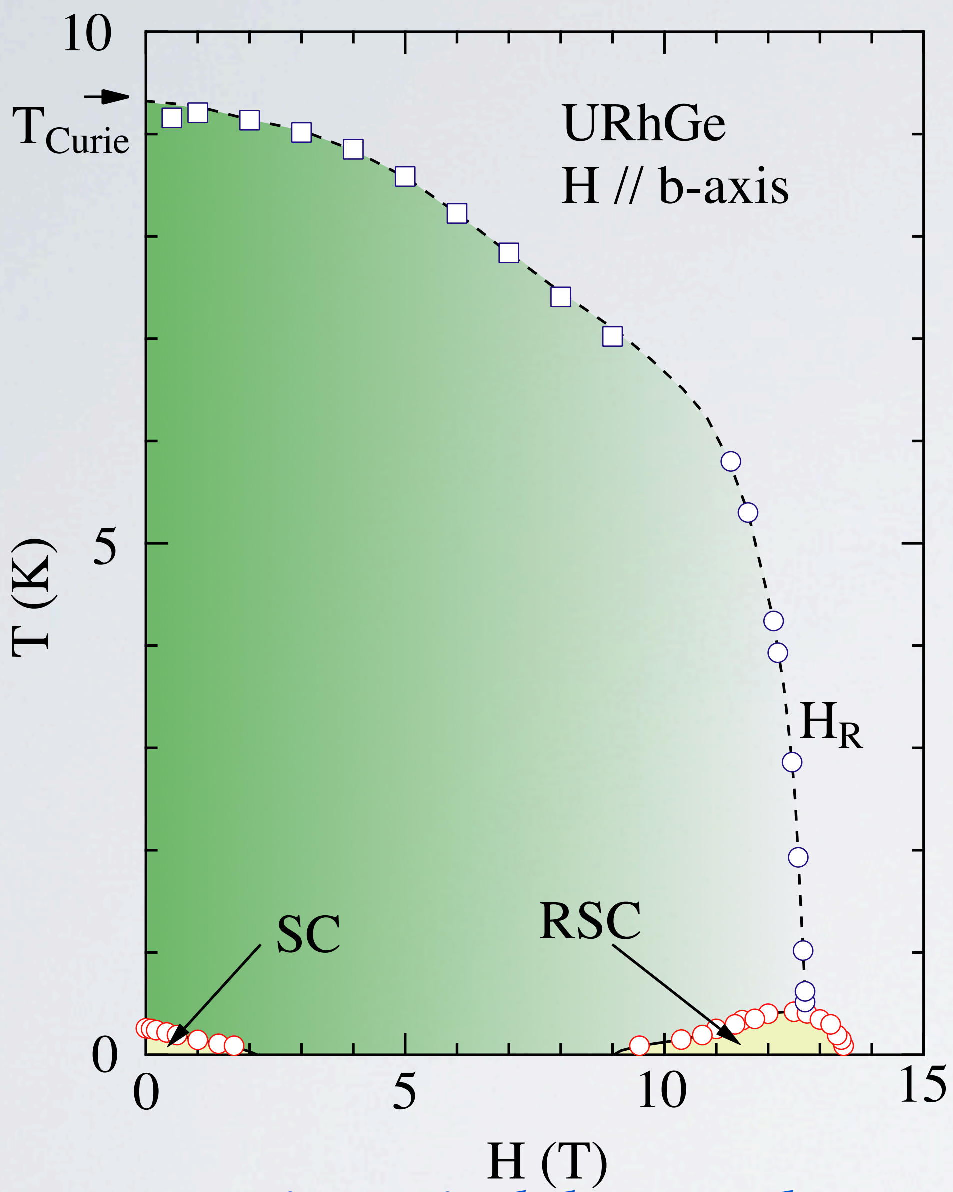




FM instability → enhancement of m* → Re-entrant (S-shaped) SC phase

F. Levy et al. Science (2005)
A. Miyake et al. JPSJ (2008)
D. Aoki et al. JPSJ (2009)

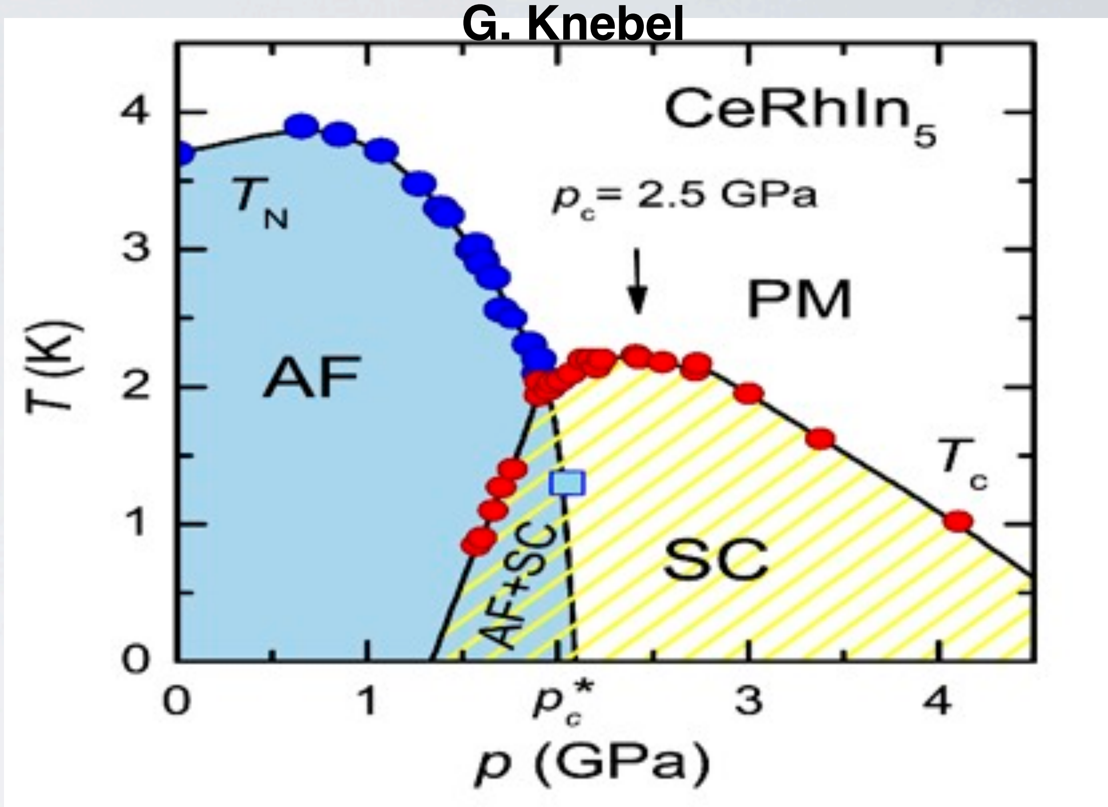
Similarity of the phase diagram



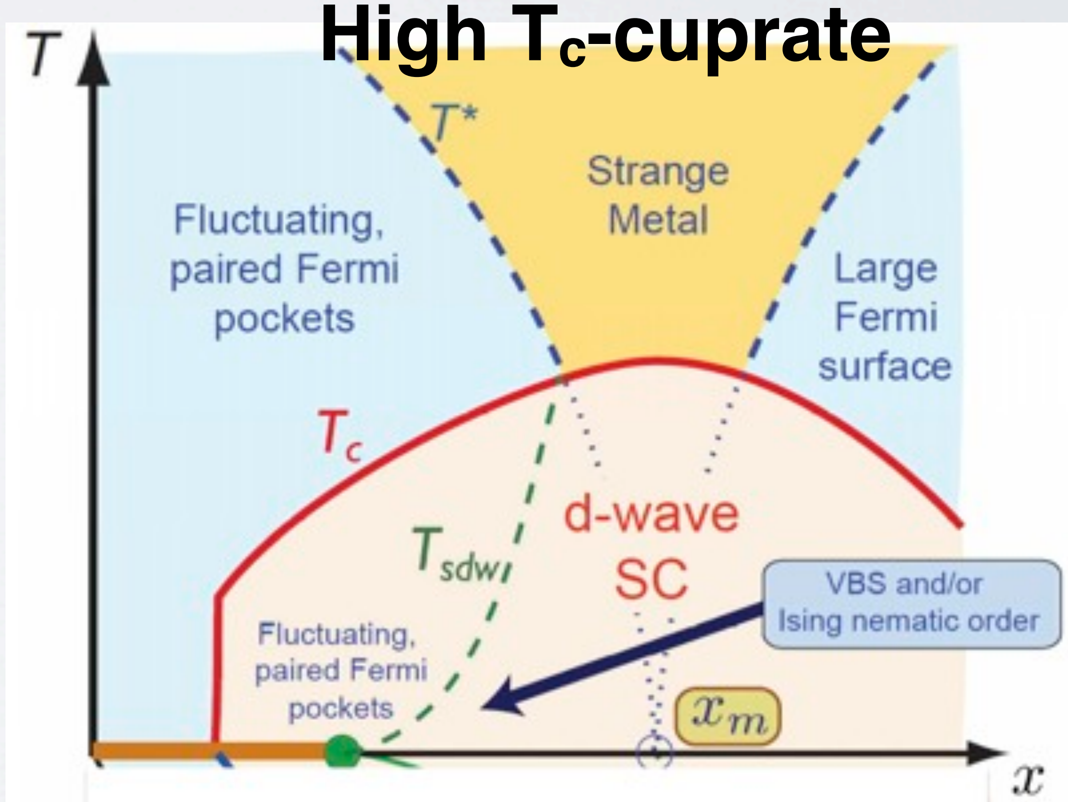
Magnetic Field can be a tuning parameter for quantum criticality (classically P, doping, ...)

AF-Quantum Critical Point

G. Knebel

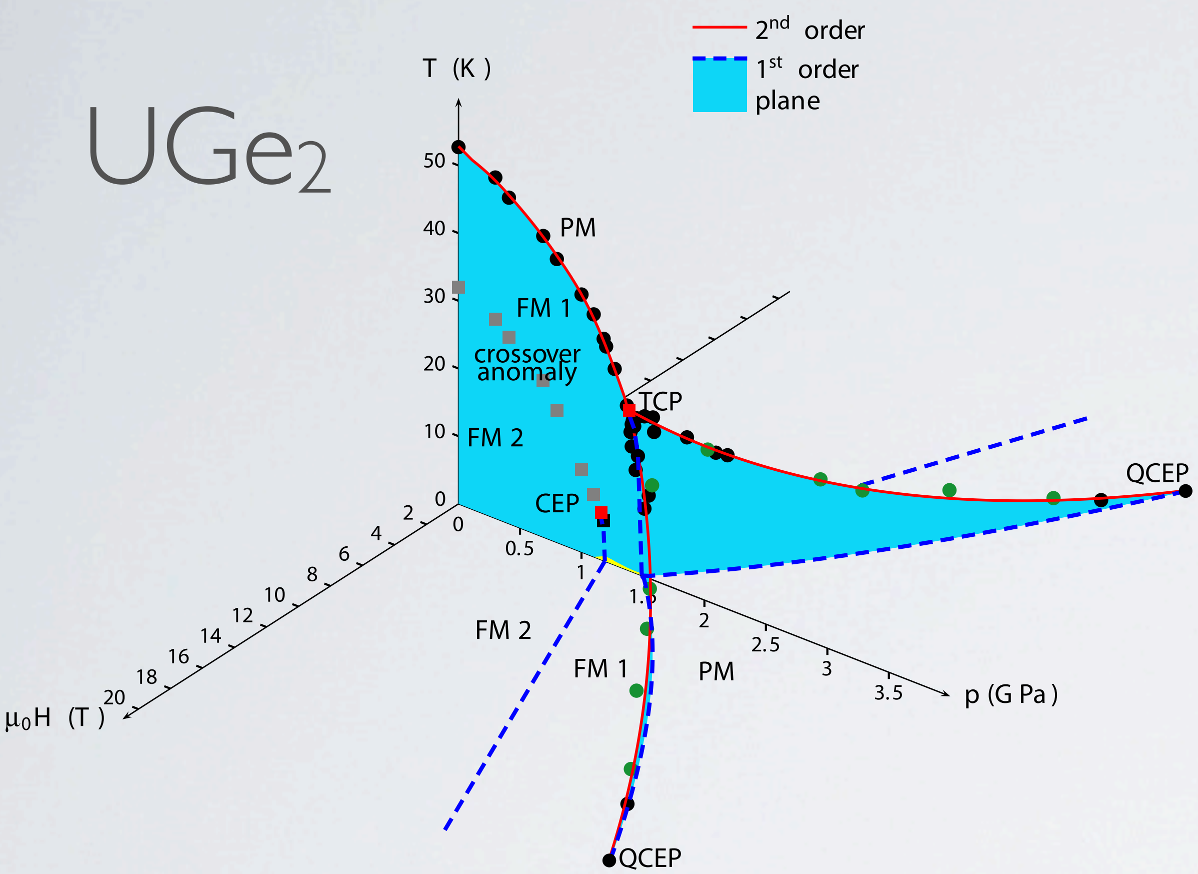


High T_c-cuprate

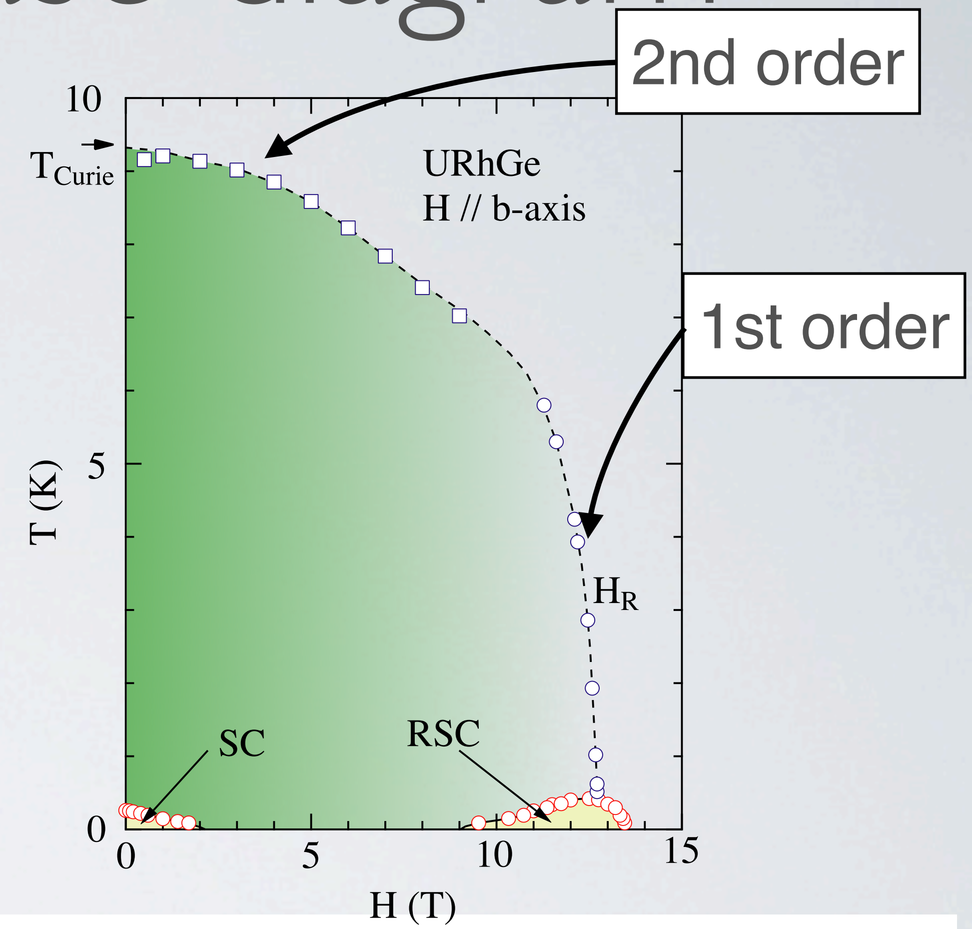


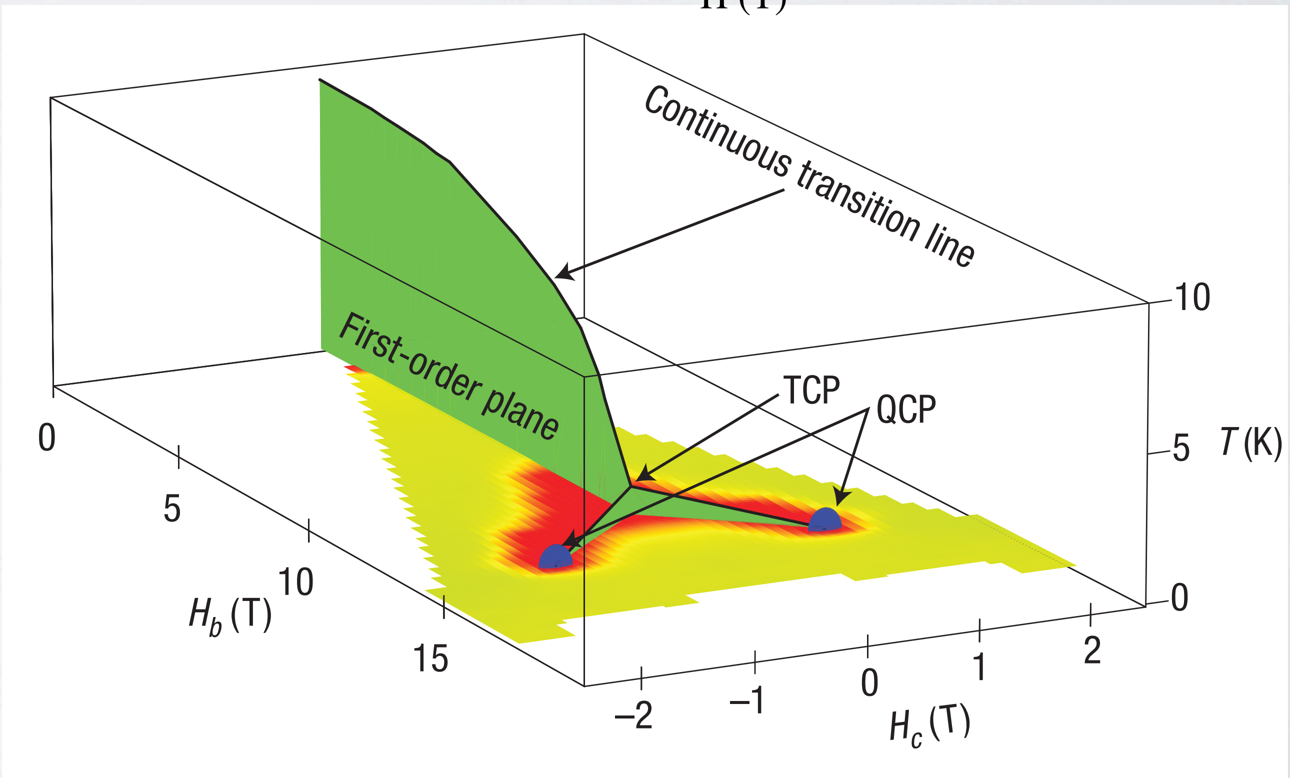
Similarity to (T,P,H) phase diagram

UGe2



URhGe

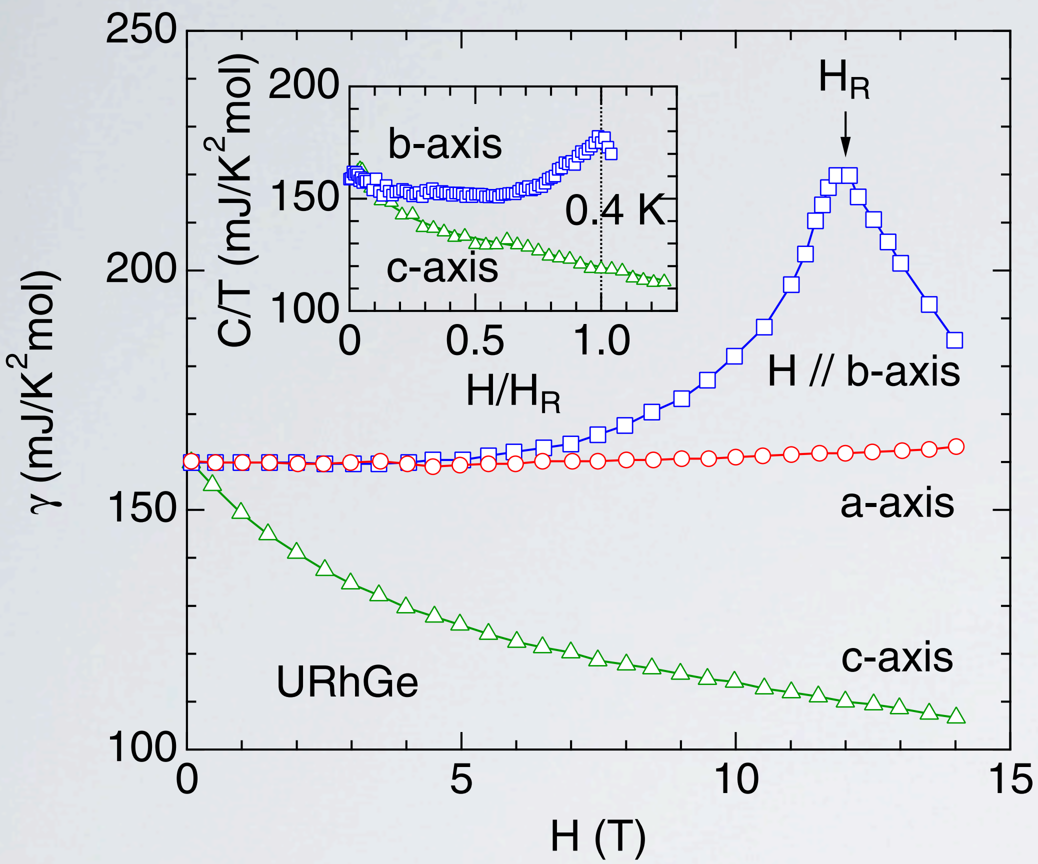


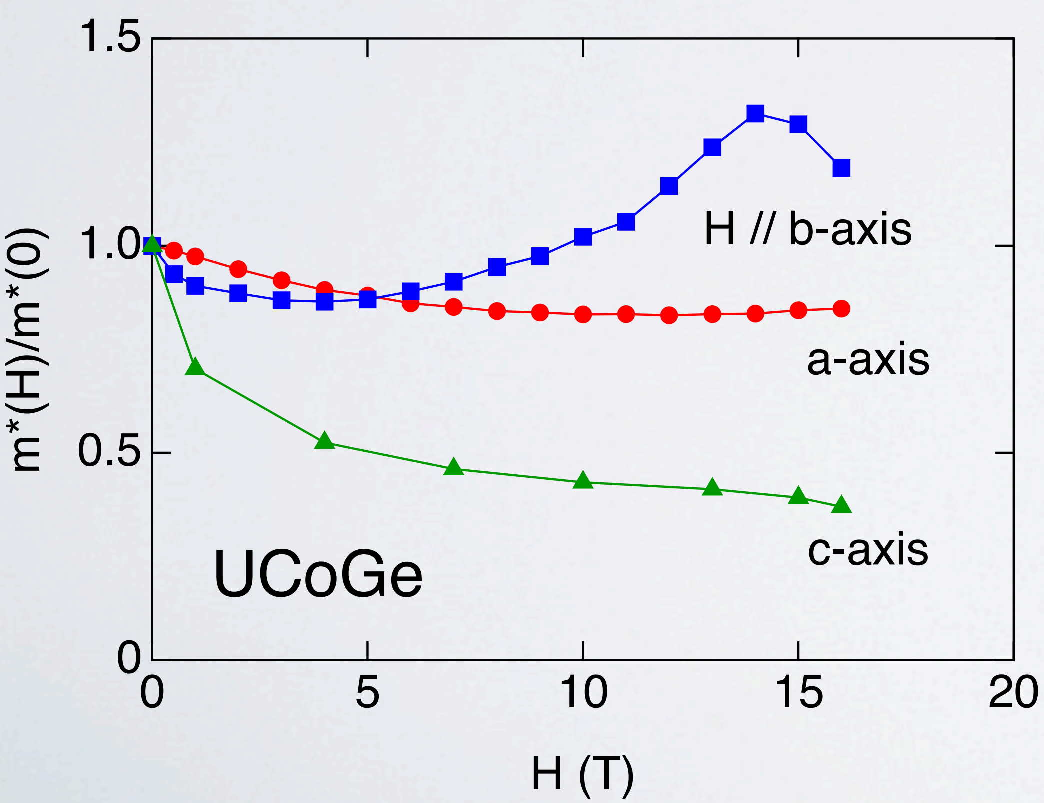


Field along b-axis can be a tuning parameter in URhGe

F. Levy et al.

Enhancement of m* stabilizes SC





$$T_{\rm sc} \propto \exp[-(\lambda+1)/\lambda]$$ McMillan-type

$$m^* = (1+\lambda)m_{\rm b}$$

FM-SC

Triplet pair(↑↑ or ↓↓)

H_{c2}

- No Pauli limit (Zeeman)
- Orbital limit

$$\xi \sim \hbar v_{\rm F}/k_{\rm B}T_{\rm sc} \propto 1/m^*T_{\rm sc}$$

$$H_{c2} \sim (m^*T_{\rm sc})^2$$

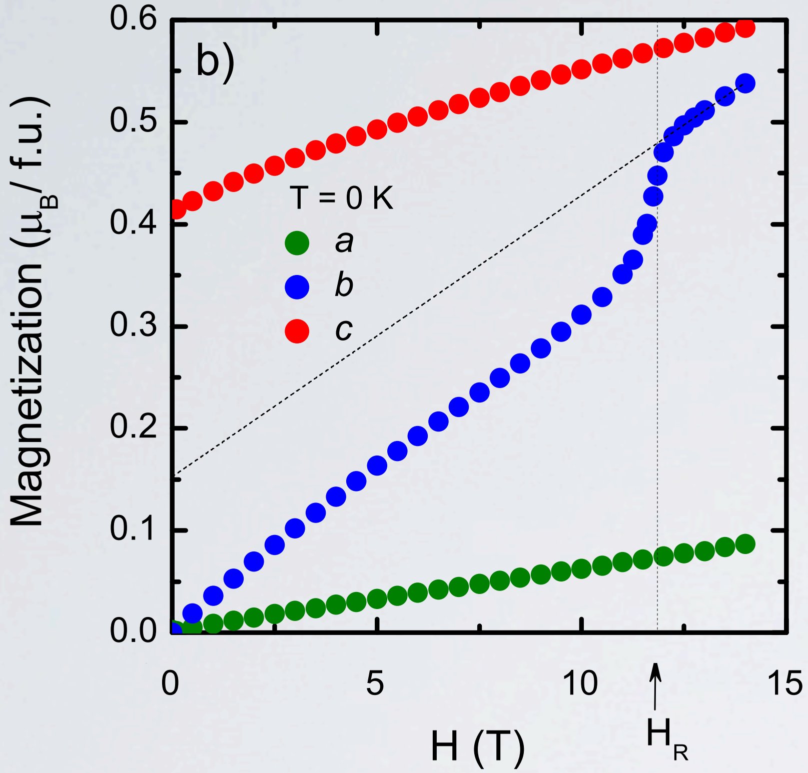
Theory

V. Mineev: PRB (2010)

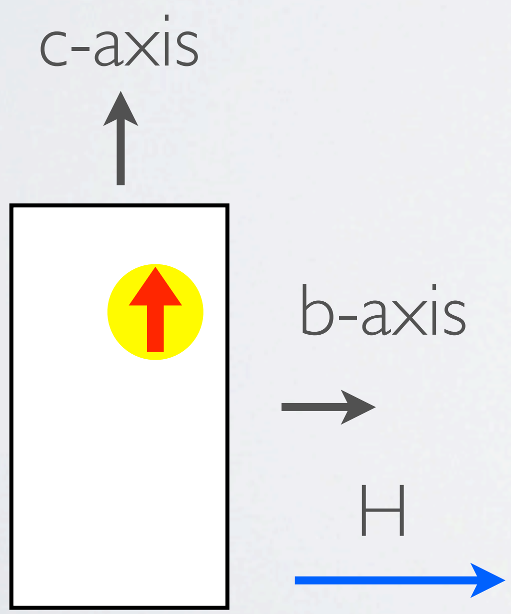
Y. Tada et al.: JPSJ (2010)

Differences

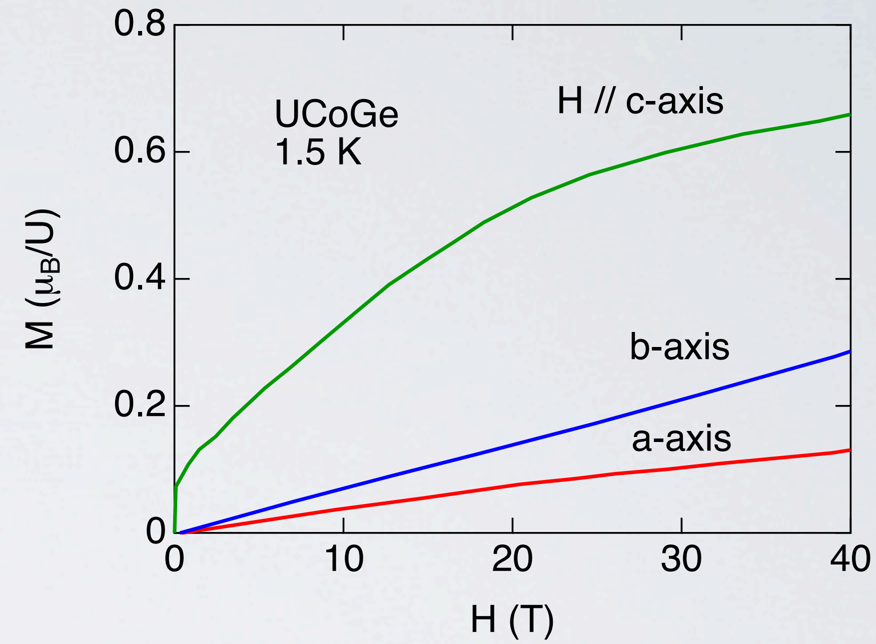
URhGe



Spin re-orientation

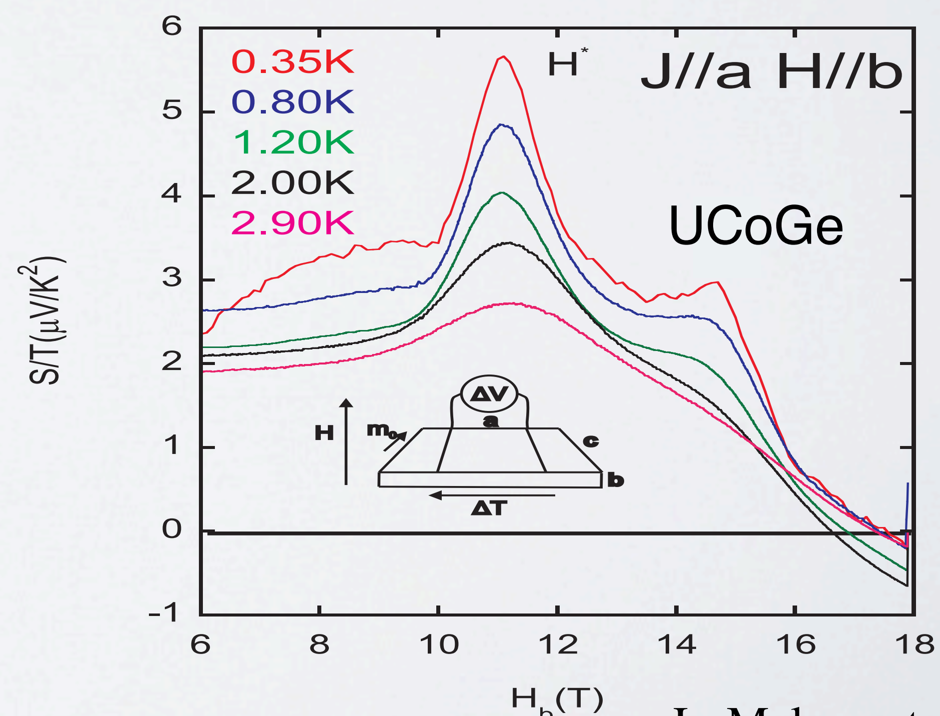


UCoGe



W. Knafo, et al. submitted, LNCMI-T

No anomaly, but...

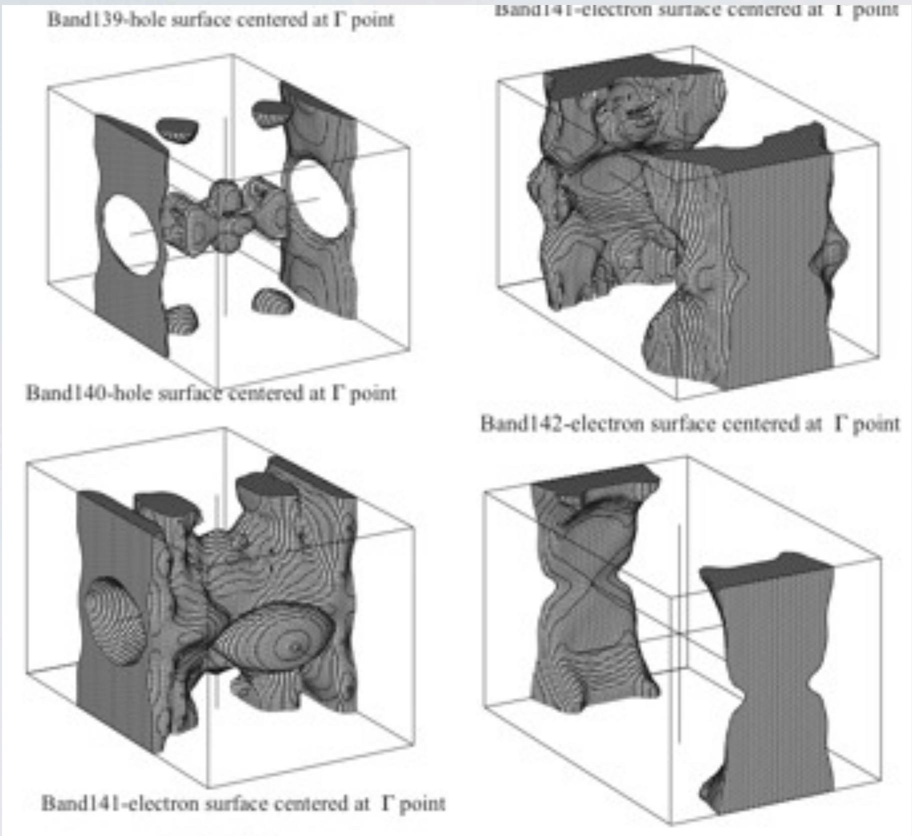


L. Malone et al. PRB (2012)

Differences

URhGe

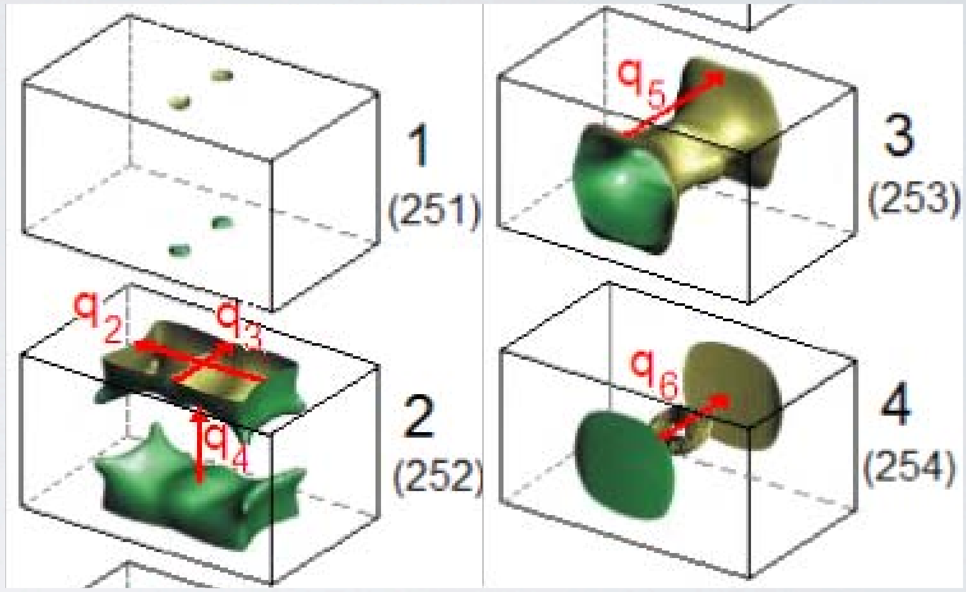
$m_0 = 0.4\ \mu_B$



H. Yamagami

UCoGe

$m_0 = 0.05\ \mu_B$



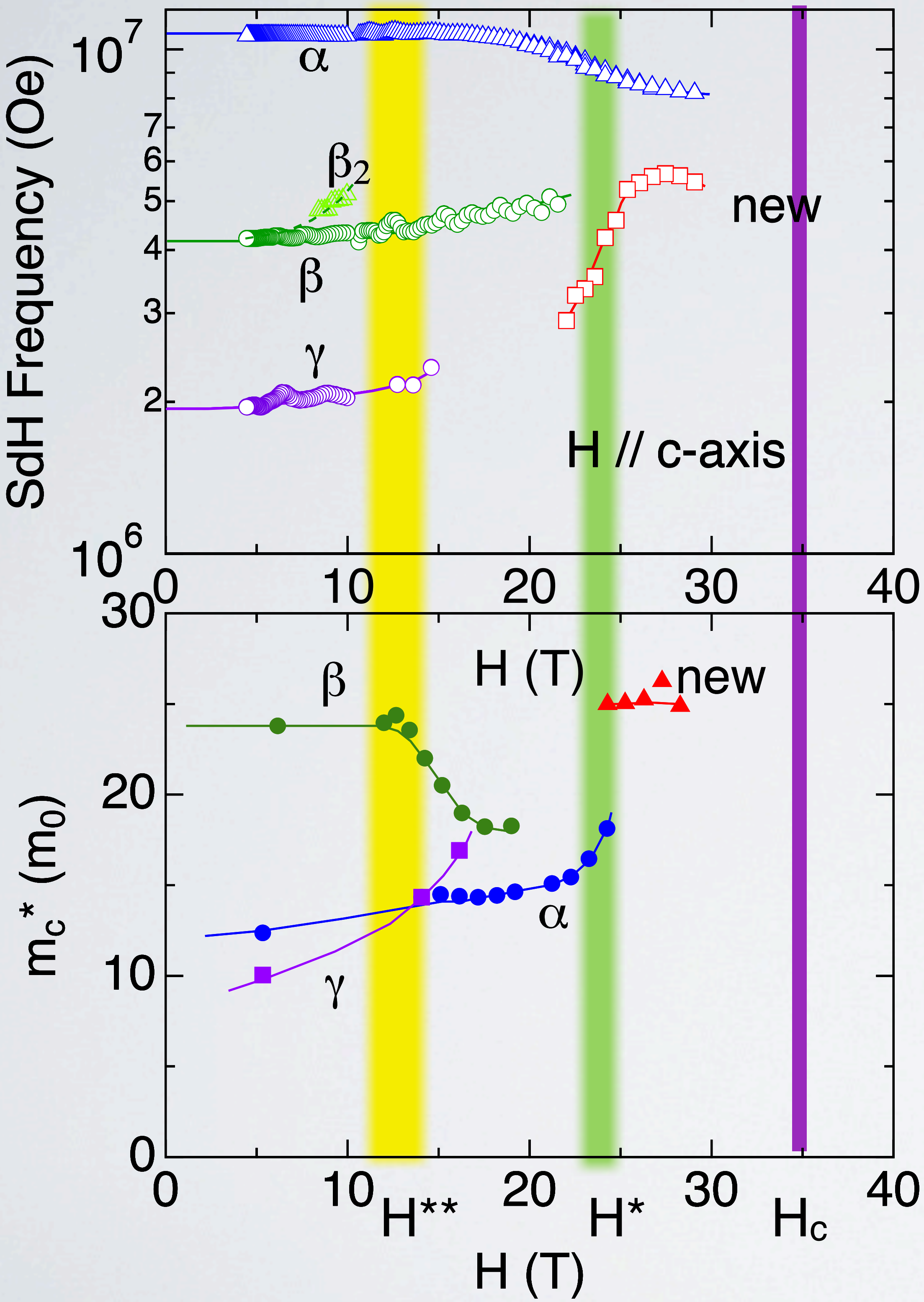
M. Samsel-Czekala et al. JPCM (2010)

heavy, but low carrier numbers

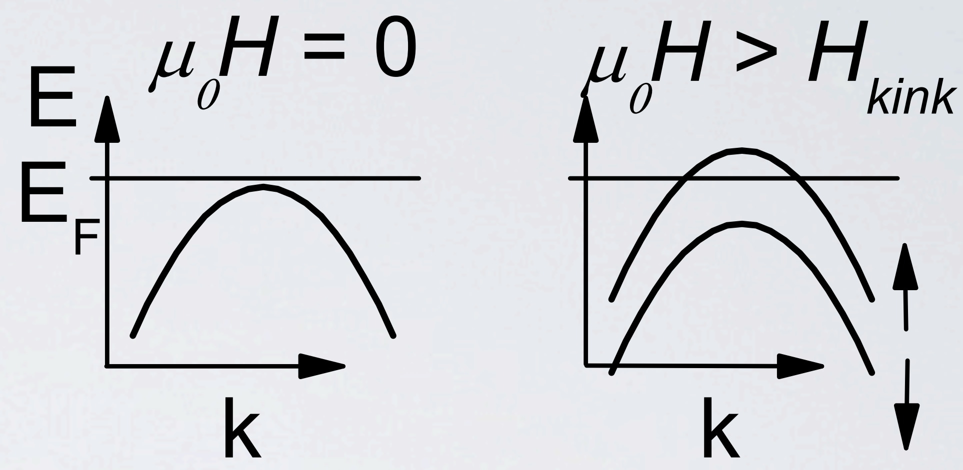
Similar to URu_2Si_2, maybe...

$\varepsilon_{\mathrm{F}} \sim \dfrac{\hbar e F}{m^*}$ and Zeeman energy $g\mu_{\mathrm{B}}\sigma B$

Fermi surface reconstruction in URu_2Si_2



D. Aoki et al. JPSJ 81 (2012) 074715

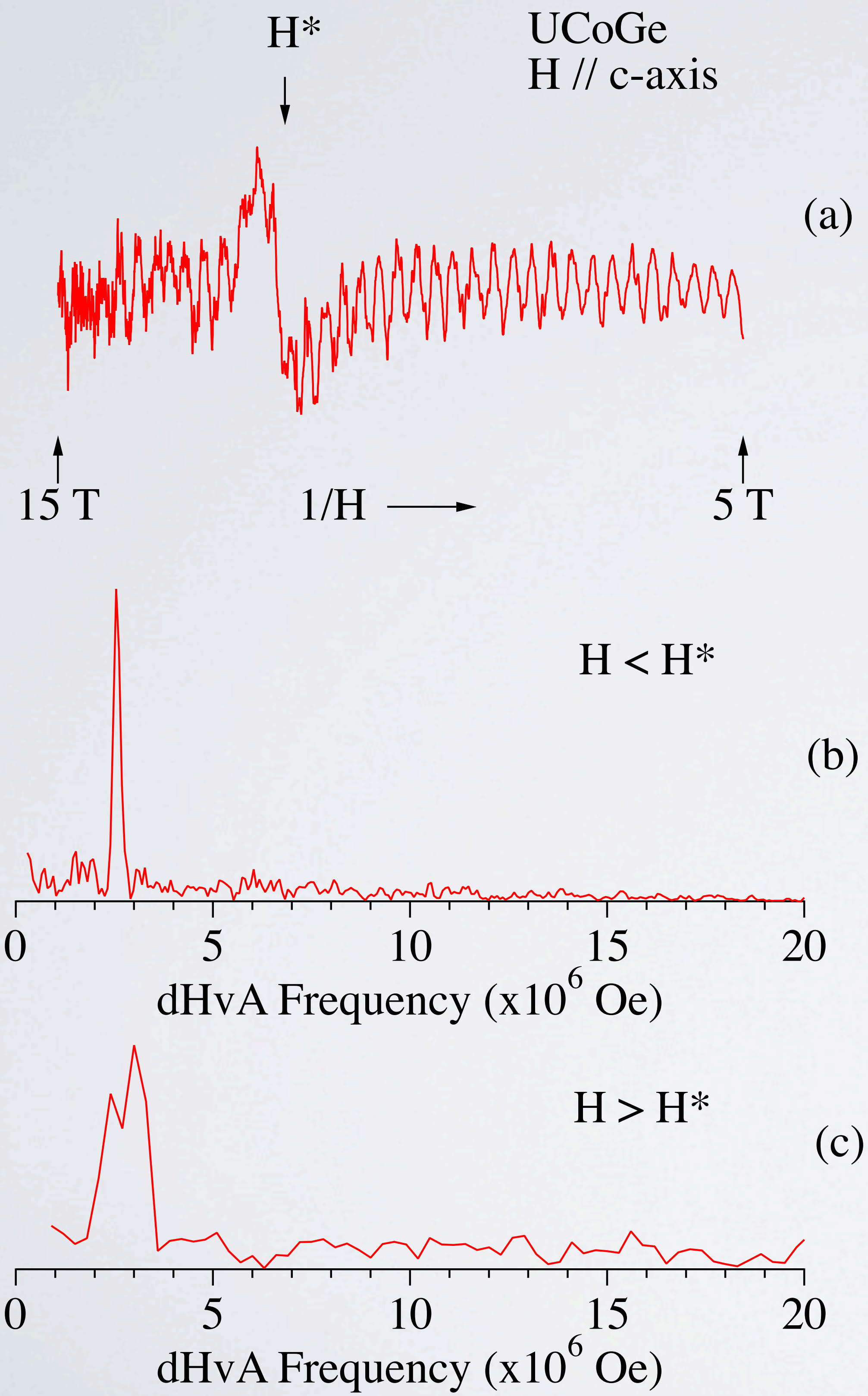


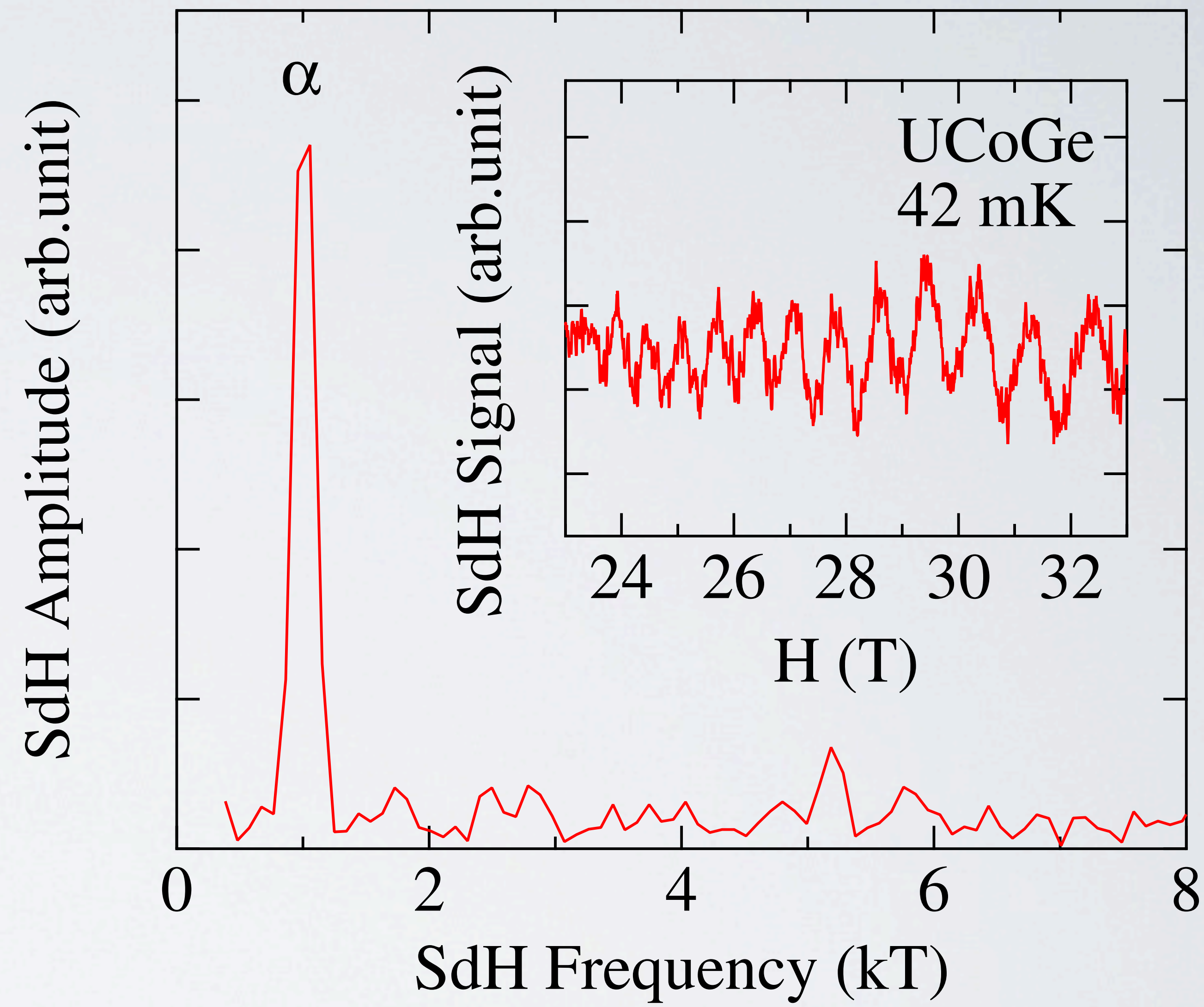
E. Hassinger et al. PRL 2010
L. Malone et al. PRB 2011
M. M. Altarawneh et al. PRL 2011

Low carrier system
Fermi surface reconstruction by spin polarization
Lifshitz transition

LNCMI-G

Quantum oscillations in UCoGe





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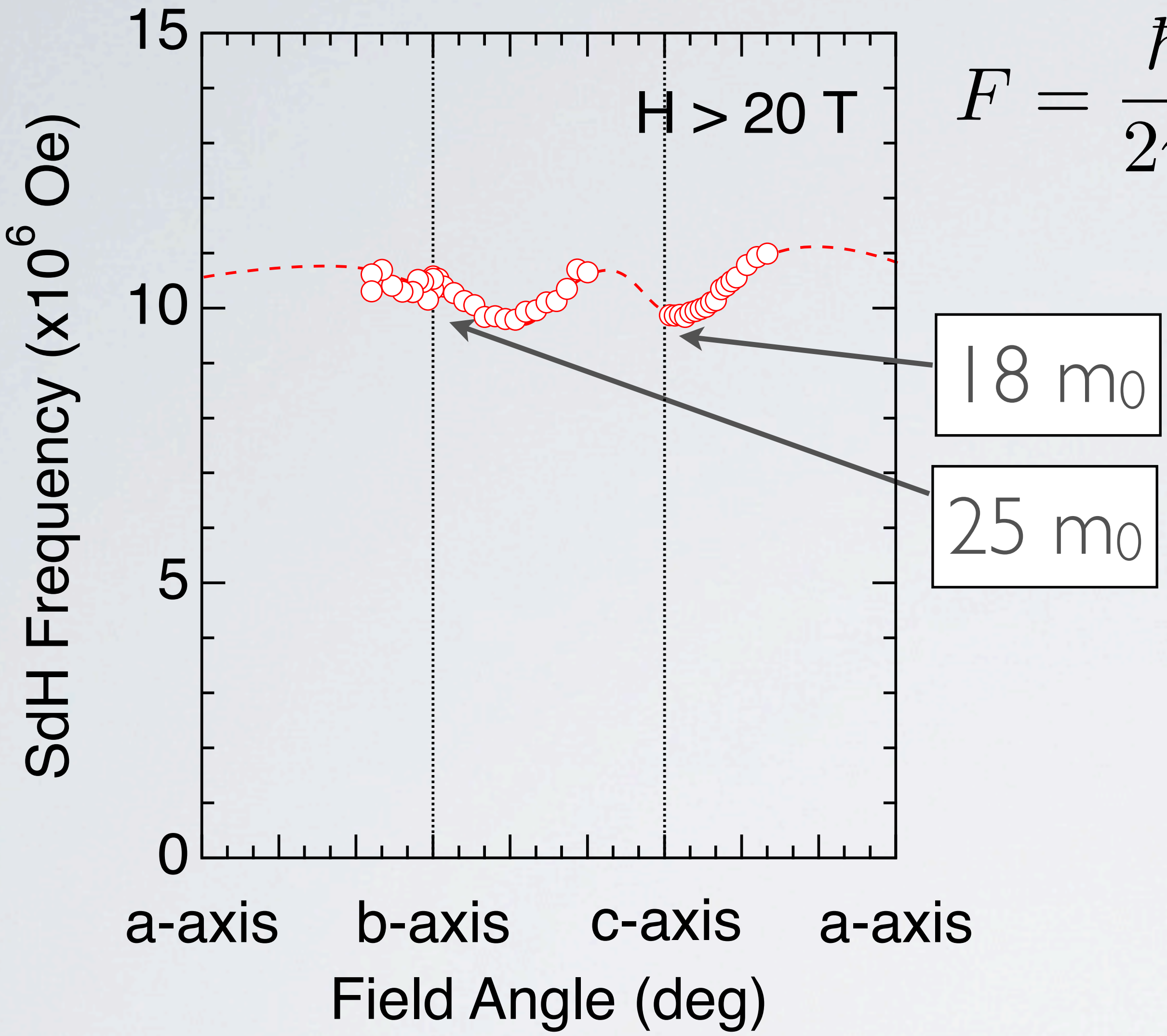
SdH experiments at high field in UCoGe



$$F = \frac{\hbar c}{2\pi e} S_F$$

small volume (2%) in BZ, but
γ ~ 7 mJ/K^{2}mol (13%)

Cp (total): γ = 55 mJ/K^{2}mol

D. Aoki et al. JPSJ 80 (2011) 013705

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small pocket Fermi surface with heavy mass

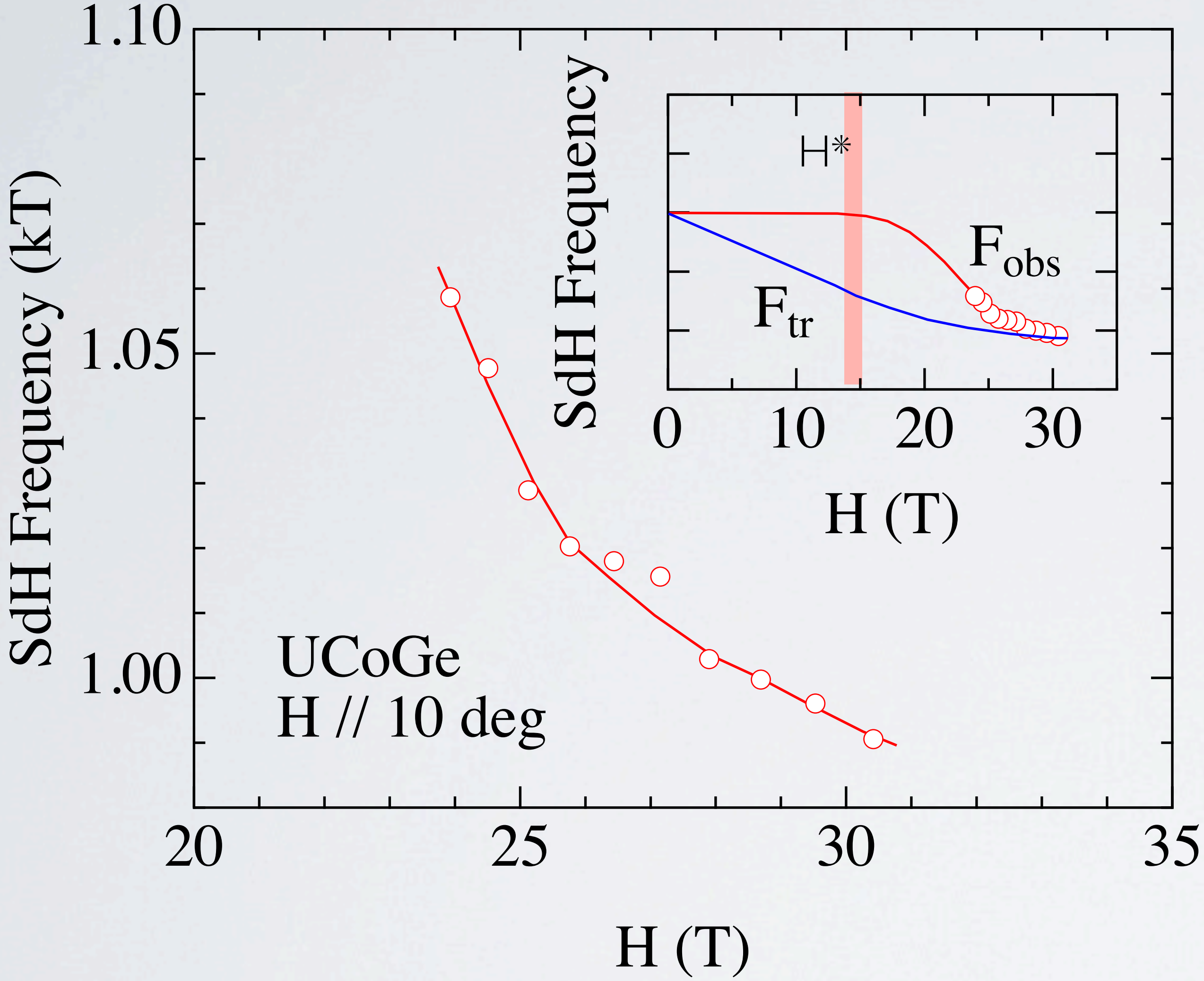
low carrier & heavy mass

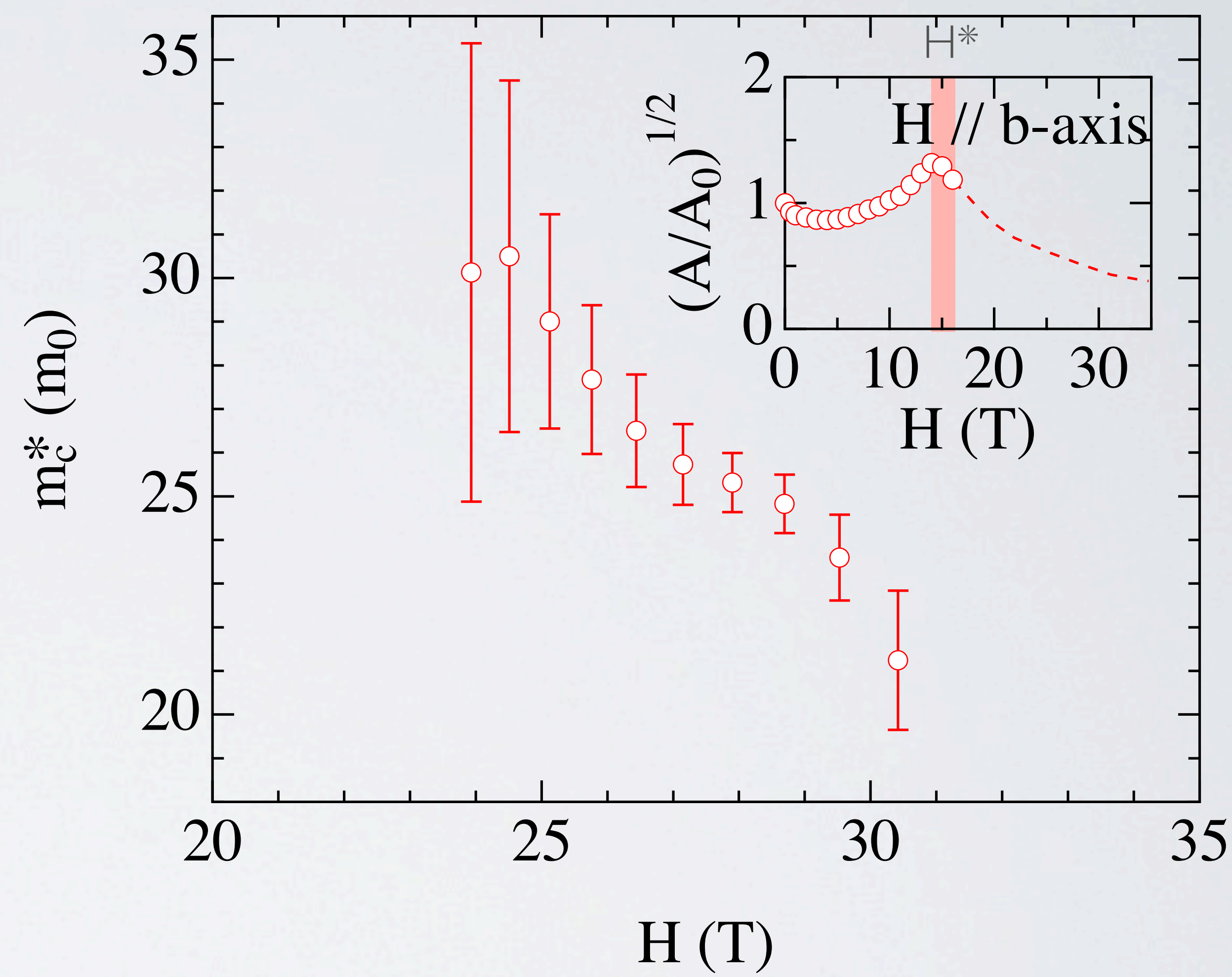
→ Fermi surface is easily affected by H

similar to URu_2Si_2

$$\varepsilon_F \sim \frac{\hbar e F}{m^*}$$ and Zeeman energy $$g \mu_B \sigma B$$

Field dependence of Freq. and m*





Shrinkage of minority Fermi surface
with non-linear response

Decrease of m*

→ consistent with resistivity A coefficient and H_{c2} curve

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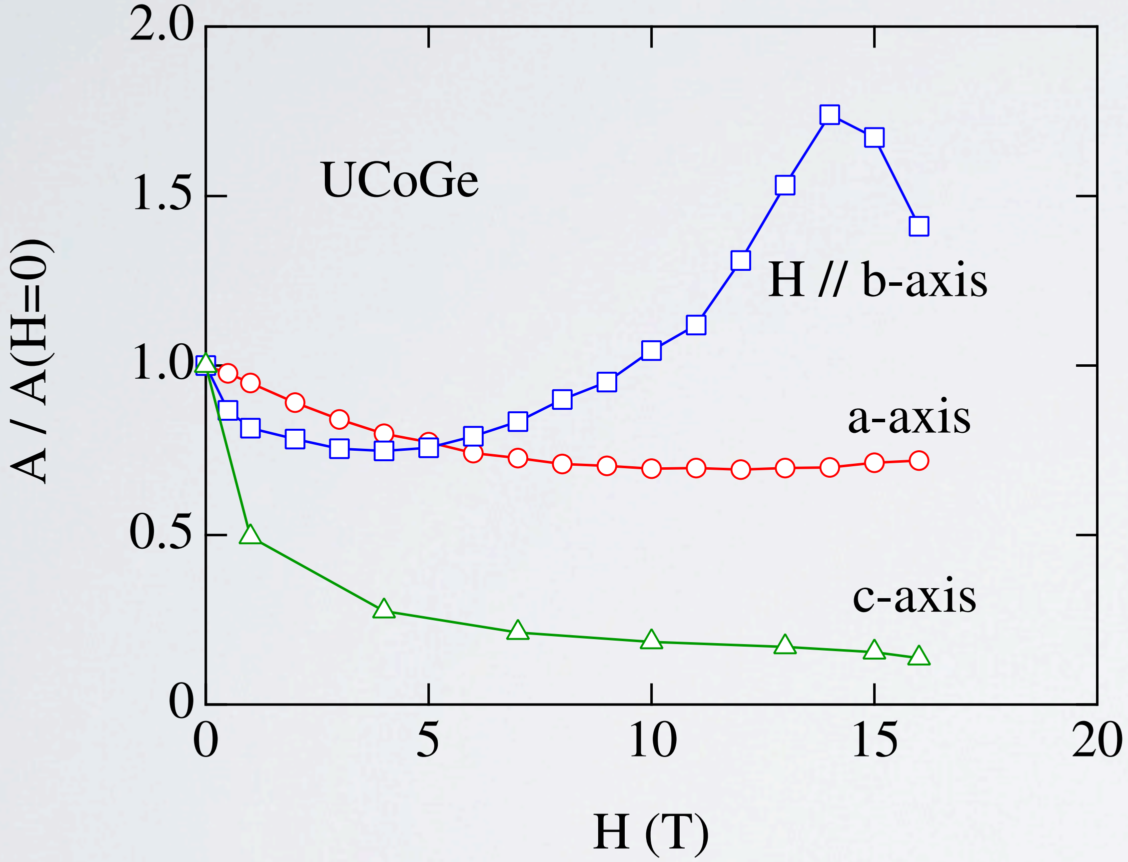
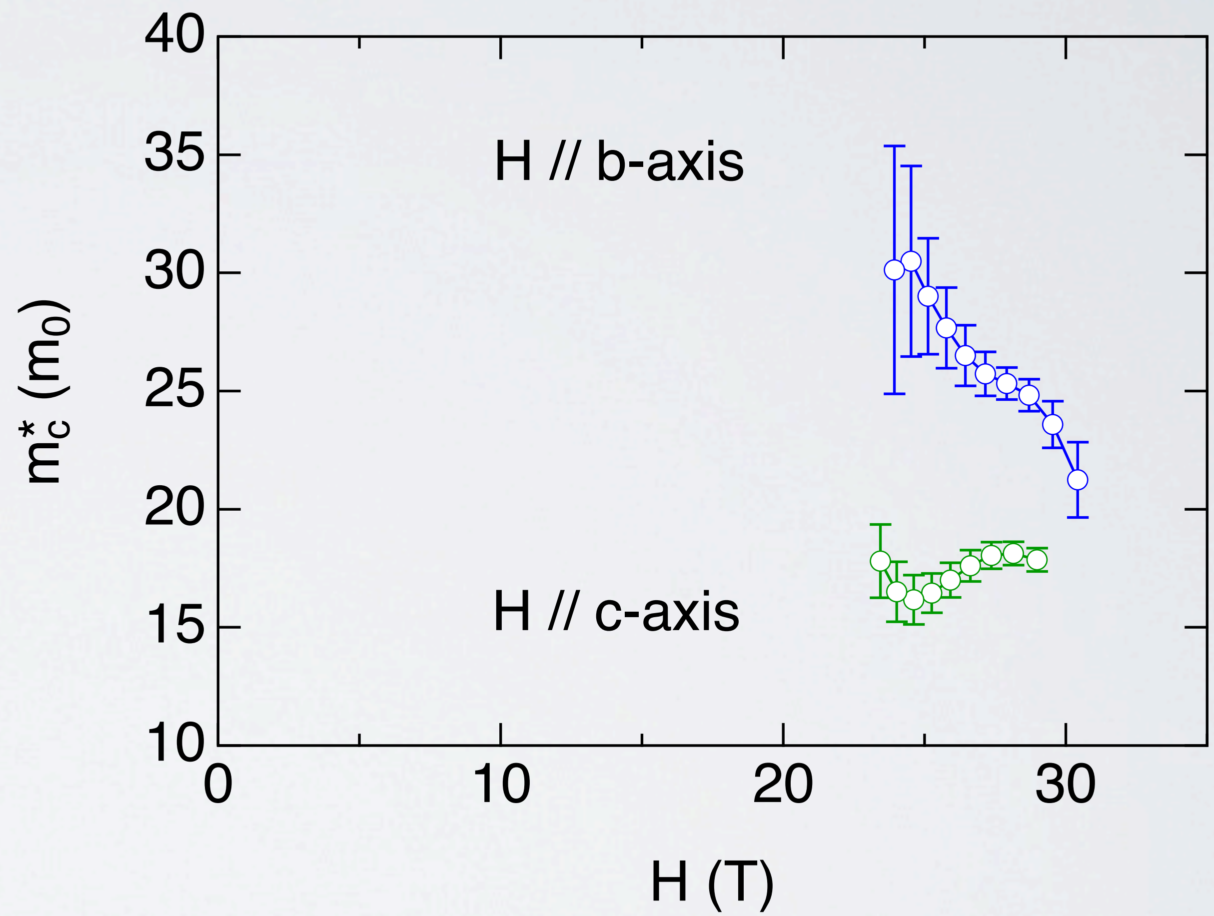
Anisotropic field dependence of m*





D. Aoki et al. JPSJ 80 (2011) 013705
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SUMMARY

- FM-QCEP in UGe_2
- Field reinforced SC for H // hard-mag axis (URhGe, UCoGe)
- Suppression of huge H_{c2} with P in UCoGe
- FM fluctuations → feedback to Fermi surface instabilities in UCoGe