Heavy fermion phase diagram

Different ground states : PM / AF / FM / HO / Sc / M-I

One impurity Kondo effect

Kondo lattice

Phase diagram

- **URu_2Si_2 : Search for HO**
- **$CeRhIn_5$: AF-SC phase diagram**
- **FM uranium superconductors**

CEA Grenoble : D Aoki, F Bourdarot, E Hassinger, G Knebel, G Lapertot , A Miyake, S Raymond, A Villaume

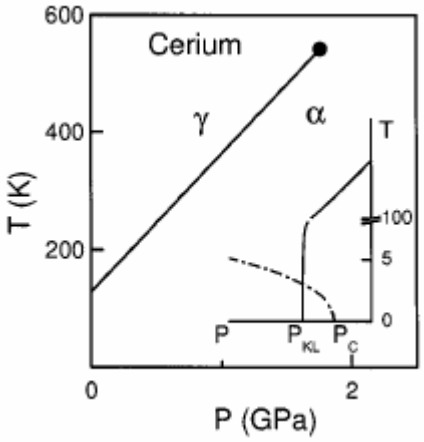
CNRS : K Behnia , JP Brison , P Lejay

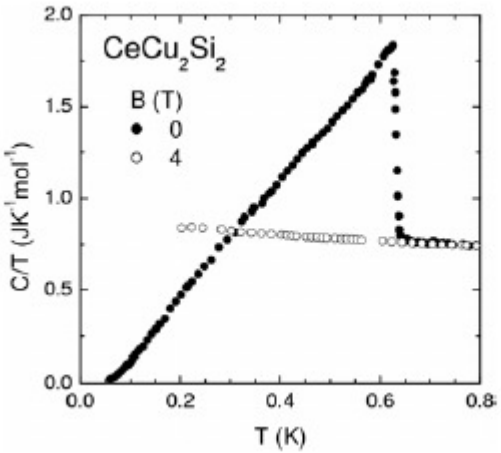
Theory: K Miyake, I Fomin , V Mineev, A Buzdin,H Harima

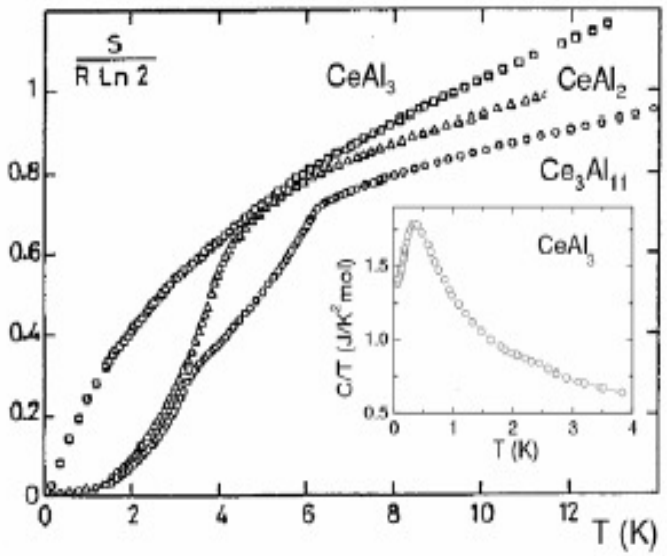
Valence transition (n_f) , phase diagram of Ce-metal

n_f near one : AF or PM ($CeAl_3$ versus $CeAl_2$)

SC : AF or PM …..QCP ($CeCu_2Si_2$)



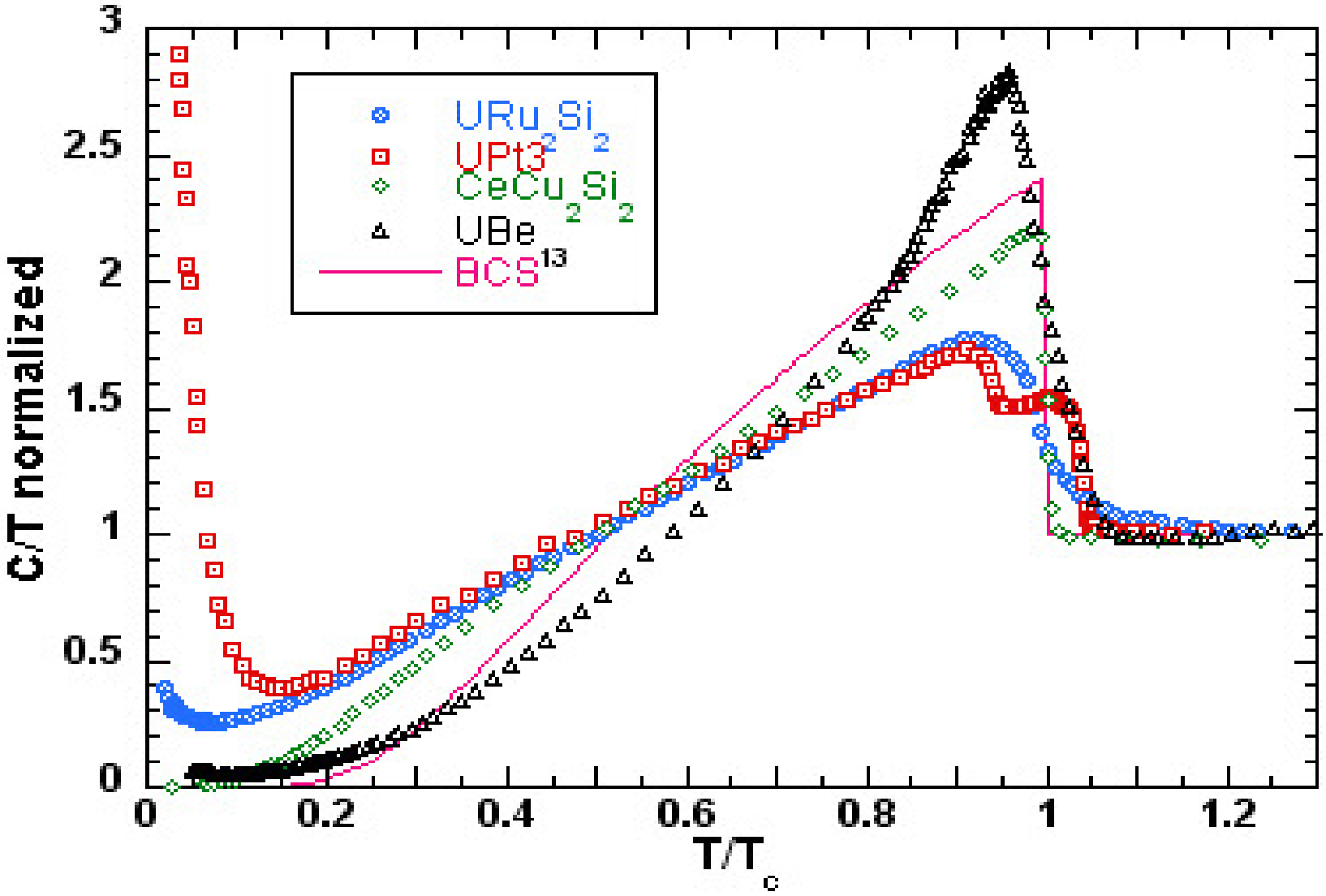




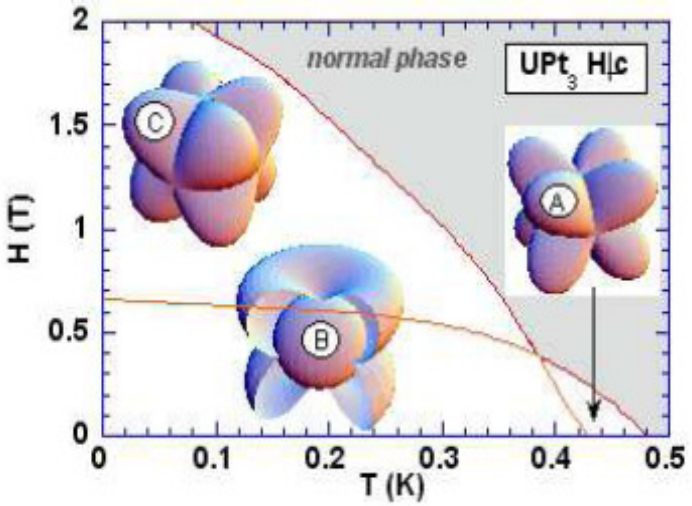
Ce : Bridgman before 1940

$CeAl_3$: Andres et al 1975

$CeCu_2Si_2$: Steglich et al 1979



UBe_{13} Ott et al 1983, UPt_3 Stewart et al 1984 , Schablitz et al 1986



Fisher et al 1989 , Hasselbach et al 1989

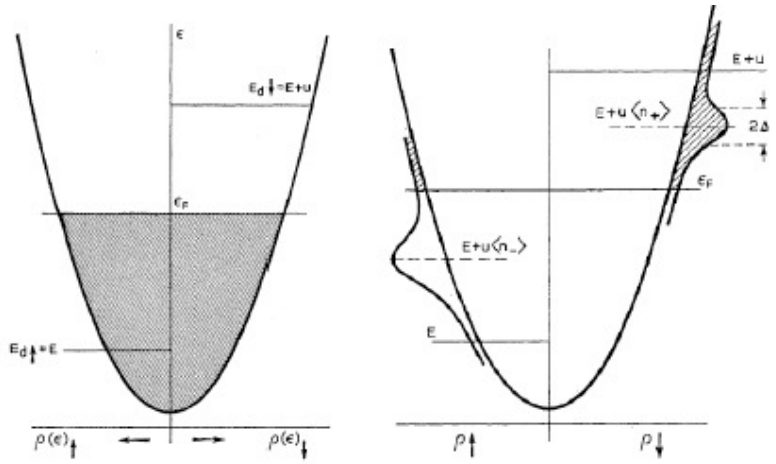
Power law dependence of $1/T_1T$, C , K : point of Zero, line of Zero.

Differences and analogies with ^3He

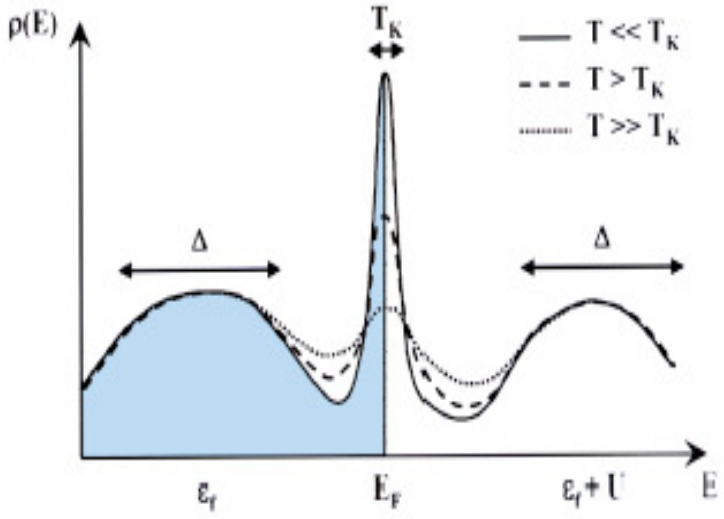
Unitary limit for the impurity : Pines , Miyake

Strong H dependence of the excitations : doppler shift- Volovik

One impurity Kondo effect : source of local fluctuation



Friedel and Anderson



Kondo,Wilson, Nozières …..

Limit n_f near one :Ce $^{3+}$

$$H = -\Gamma \vec{S}.\vec{s}$$

T_K is related to Γ and to the density of states of the light electrons $N(E_F)$ at the Fermi level

$$T_K = \frac{1}{N(E_F)} \exp -\frac{1}{\Gamma N(E_F)}.$$

Hugue

⇨ huge Gruneisen parameter

Grunneise

The negative value of Γ is related to the position E_0 of the virtual f level relatively to the Fermi level and its width Δ_0 according to the relation :

$\Gamma N(E_F) = \frac{\Delta_0}{E_0}$ when the on site Coulomb potential goes to infinity.

$$k_B T_K = \frac{1-n_f}{n_f} \Delta_0 N_f$$

$$\Delta_0 = \Pi V_{df}^2 N(E_F)$$

$$\gamma = \frac{C}{T} = \frac{1}{T_K}$$

$$\chi \approx \frac{1}{T_K}$$

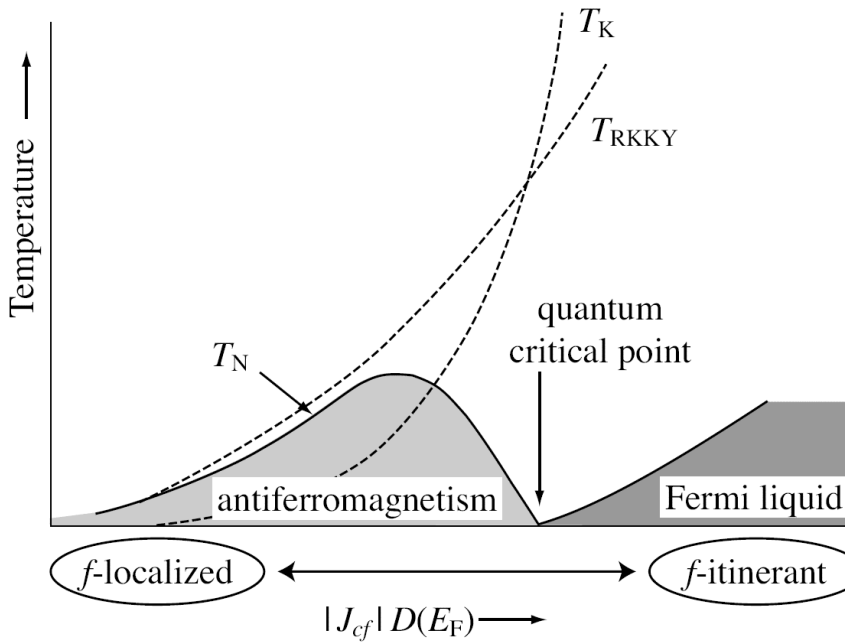
$$\rho = \rho_0 \left(1 - a\left(\frac{T}{T_K}\right)^2\right)$$

N (E_F) : density of state of light electron
V_{df}: hybridization

N_f occupation number of the trivalent configuration

Competition between Kondo effect and magnetic fluctuations

Doniach :



No systematic studies of Yb compounds

Electron hole analogy between
Ce and Yb compounds

Ce : $4f^1$	Yb : $4f^{13}$
S = 1/2, L = 3	S = 1/2, L=3
J = |S-L| = 5/2	J = |S+L| = 7/2
r_{4f} (Ce) = 0.37 Å	r_{4f} (Yb) = 0.25 Å

$$\langle \psi_{4f}^{\mathrm{Yb}} | \psi_{\mathrm{lig}} \rangle < \langle \psi_{4f}^{\mathrm{Ce}} | \psi_{\mathrm{lig}} \rangle$$

Ce^{3+} ($4f^1$) magnetic → Ce^{4+} ($4f^0$) non-magnetic

Increasing of pressure:

Yb^{2+} ($4f^{14}$) non-magnetic → Yb^{3+} ($4f^{13}$) magnetic

- Rich variety of case :

4f: Ce (1e^-, Kramers ions); Pr (2e^- , CF singlet), Tm (12 e^-),Yb (13 e^-)

- Hierarchy between T_K and C_{CF}
- Role of number of carrier
- Large high quality crystals
- Continuous discovery of new material:

(1,1,5) Ce compounds

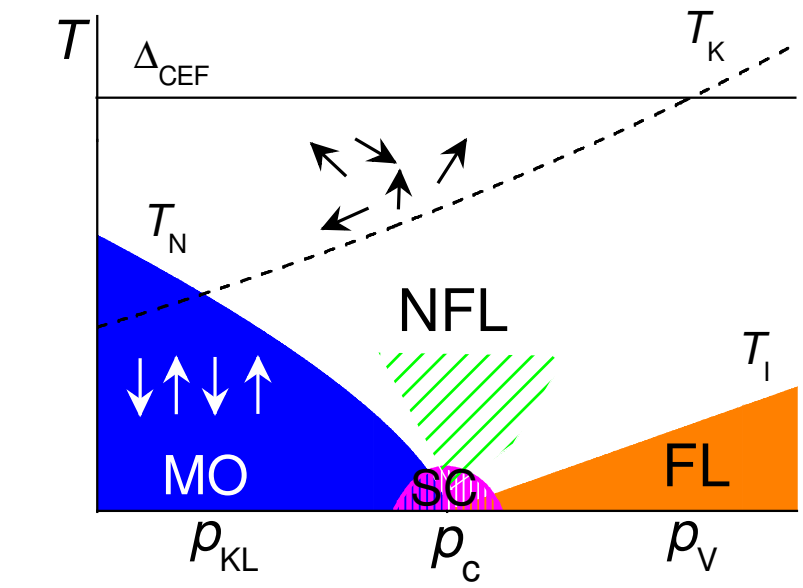
Pu, Np superconductors

U based ferromagnetic superconductors

superconductivity in non-centrosymetric crystals, $CePt_3Si$

Quantum criticality : Itinerant versus local scenario

Hertz, Millis, Moriya, Lonzarich, Continentino, …

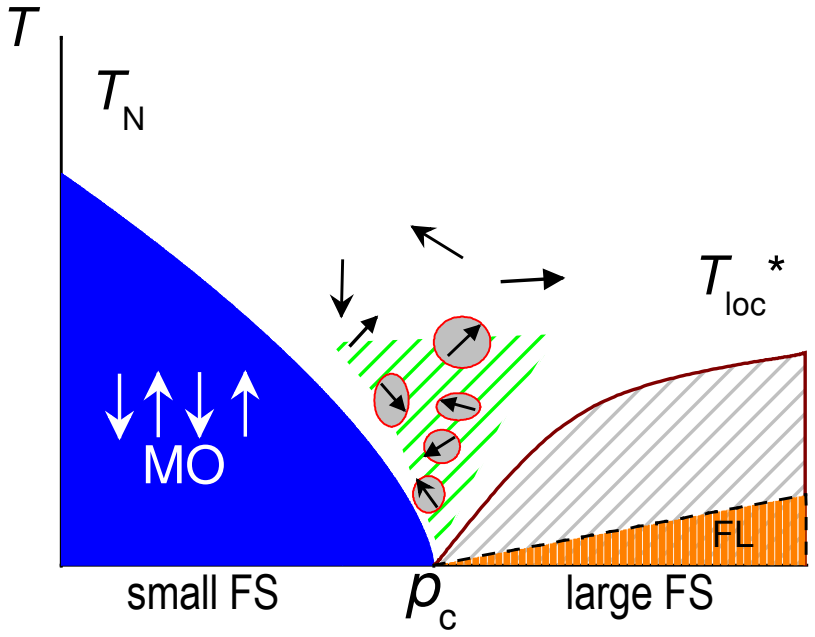


- local moments screened below T_K
- heavy QP considered to be itinerant above p_{KL}
- large Fermi surface, continous
- scattering of heavy QP by critical SF

e.g. **$CeNi_2Ge_2$**, $YbNi_2Ge_2$, $CeRu_2Si_2$

conventional

Coleman, Pépin, Si, …



- $T_{loc}^* \rightarrow 0$ at QCP
- Kondo resonance not fully developped at QCP
- reconstruction of FS at the QCP
- anomalous E/T, H/T scaling laws

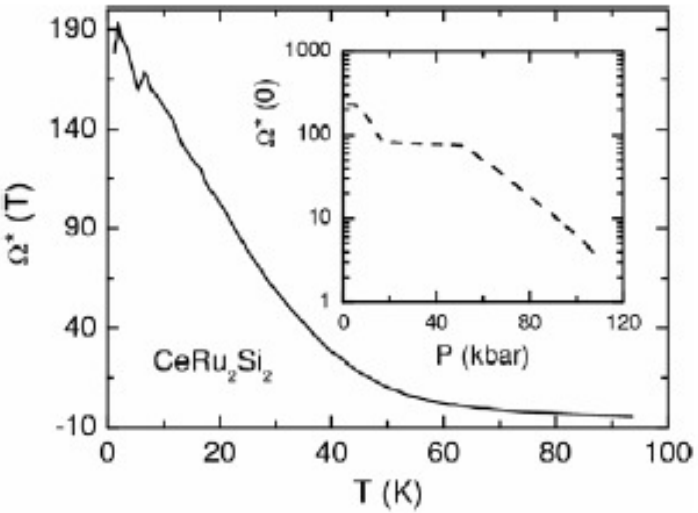
e.g. $Ce(Cu,Ag)_6$, **$YbRh_2Si_2$**

unconventional

Grüneisen coefficient : reaches its huge value only at very low temperature

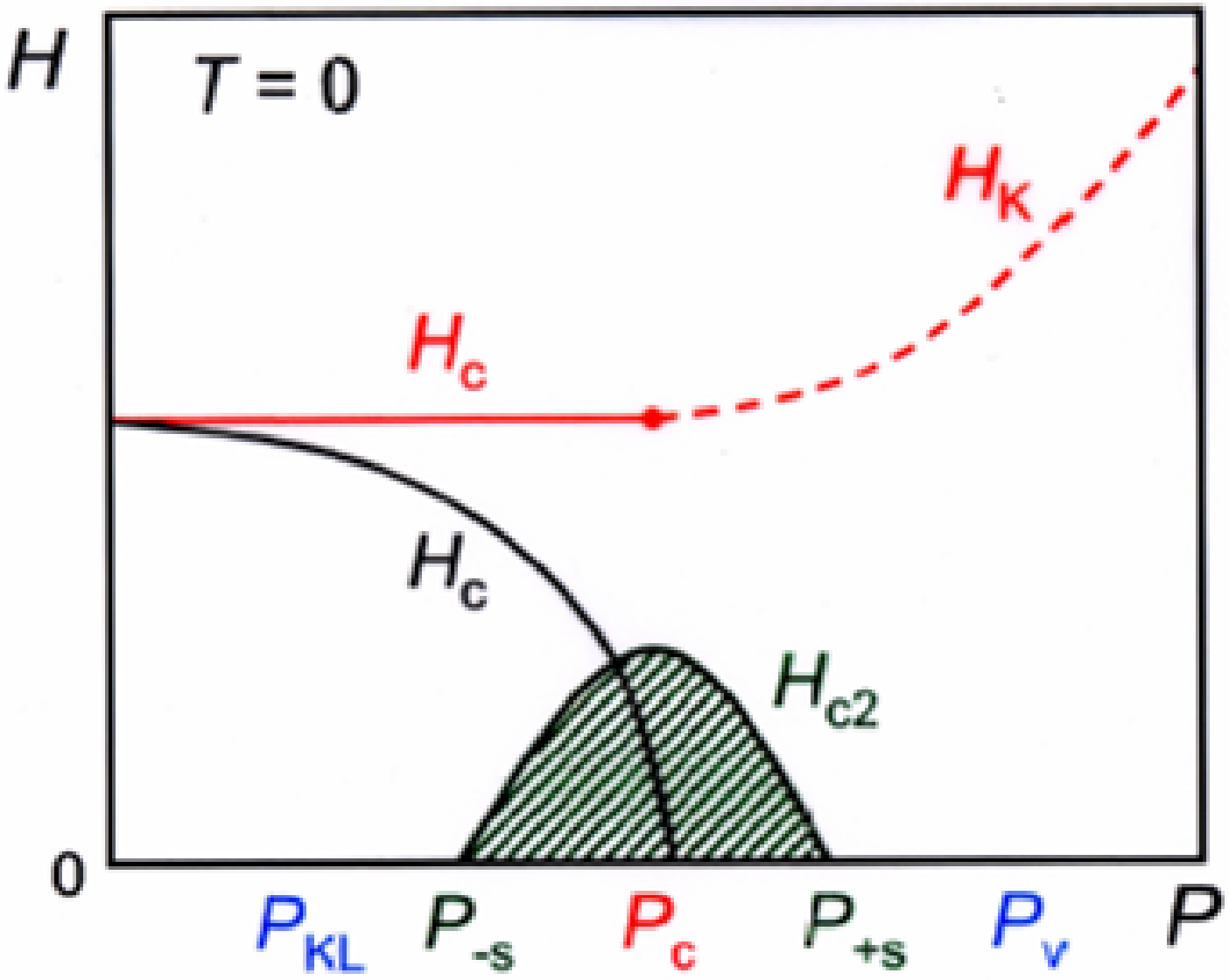
$$\Omega^\star(T) = \frac{\alpha}{C}\frac{V_0}{\kappa}$$

$$F(T) = T\Phi(\frac{T}{T^\star}) \quad \text{with} \quad \Omega^\star(0) = -\frac{\partial \log \mathrm{T}^\star}{\partial \log \mathrm{V}}$$



$\Omega_{T_K} = 50$, independent of T

Pressure or magnetic field are very efficient variables !


H
T = 0
H_K
H_c
H_c
H_c2
0
P_KL
P_-s
P_c
P_+s
P_v
P

Interplay of Different Phase Diagrams

- HO/AF/PM URu_2Si_2 $PrFe_4P_{12}$ ……
- SC/AF QCP (P,H) $CeRhIn_5$ / $CeCoIn_5$ (FFLO ??)
- SC/FM/PM (P,H) UGe_2/URhGe/ UCoGe
- QCP/ First order transition ΔV versus Ω

Non Fermi liquid properties

Hidden order versus AF and PM ground states, SC ?

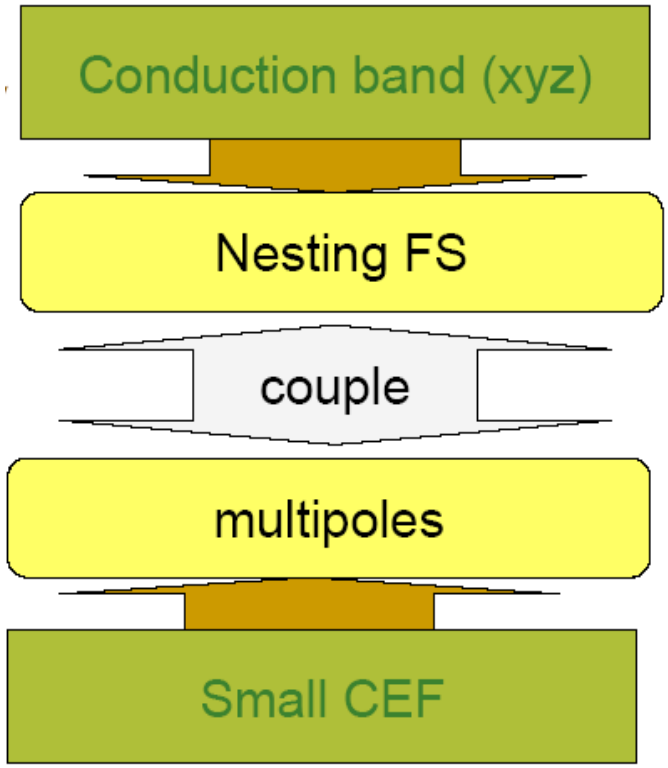
Phase Diagram of URu_2Si_2

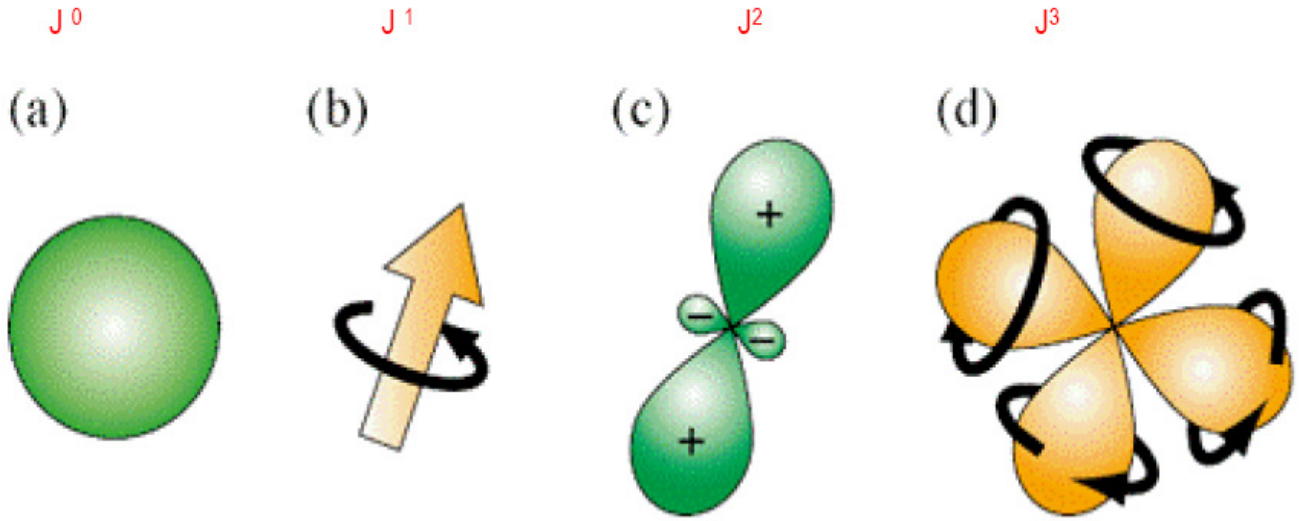
HO hidden order : multipoles

U^{4+} ($5f^2$) similar Pr^{3+} ($4f^2$)

Duality between localized and itinerant

Other studies Pr skutterudites: $PrFe_4P_{12}$ / $PrOs_4Sb_{12}$





2^0 Monopole **2^1 Dipole** **2^2 Quadrupole** **2^3 Octopole**

CeB6/ PrPb3

CeLaB6

J 4

2^4 Hexadecapole

PrFe4P12

J 5

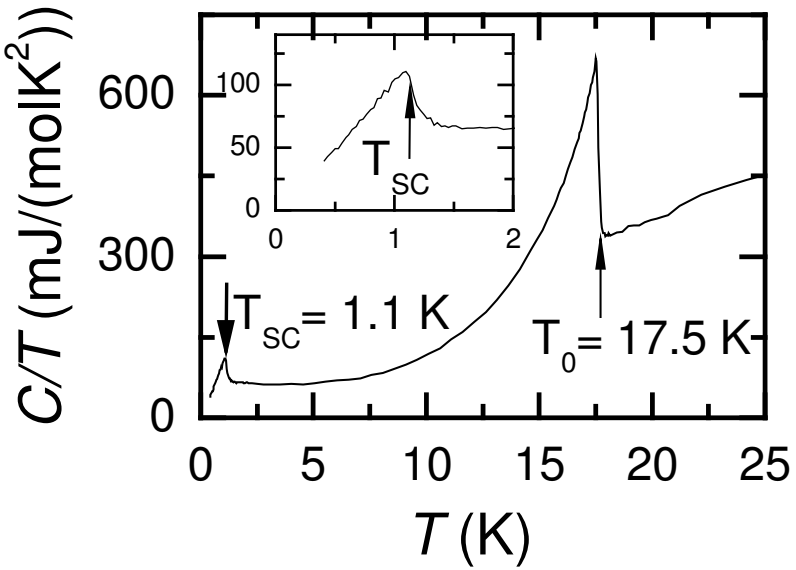
2^5 Triakontadipoles

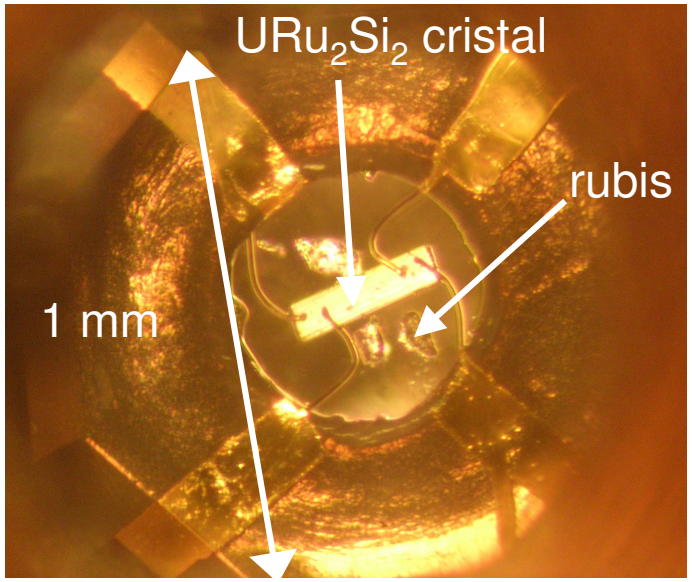
NpO2

Kusunose JPSJ 2007

Combined microcalorimetry and resistivity in H /P

Crystal made by P. Lejay, CNRS





Diamond anvil pressure cell

Dimensions:

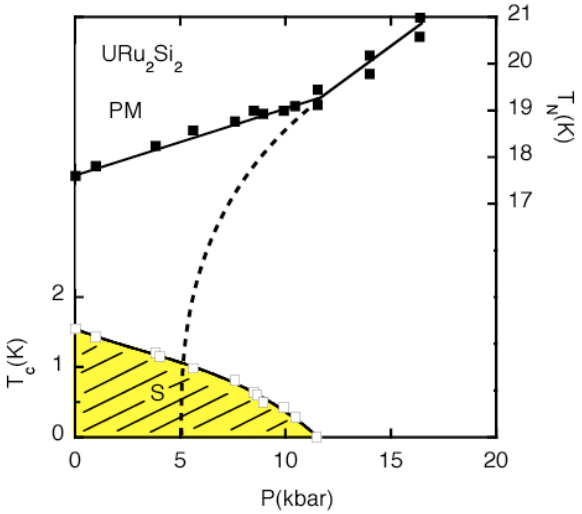
50 x 60 x 280 μm³

(cut by circular saw)

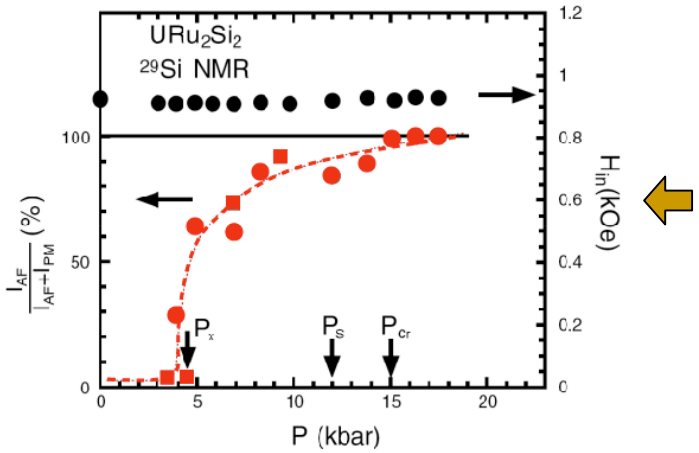
E.Hassinger (2007)
Diplomarbeit Grenoble/
Heidelberg

URu_2Si_2 : Introduction

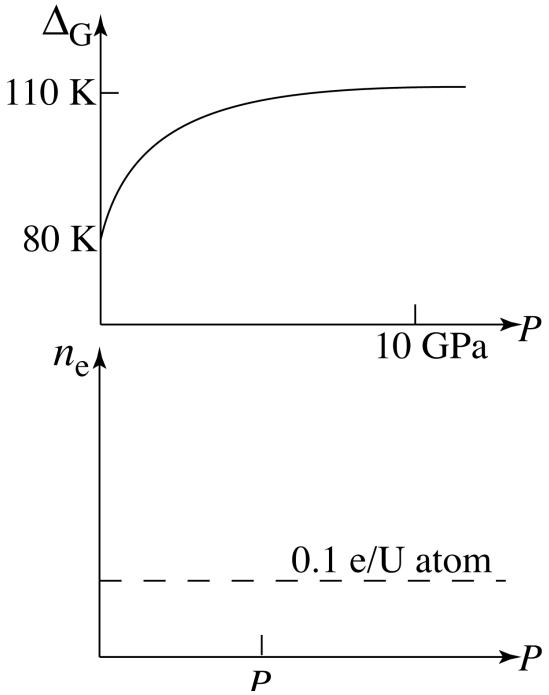
$P = 0: M_0 = 3\times10^{-2}\ \mu_B$ $P < P_x$: $M_0 < 0.3\ \mu_B$ $P > P_x$: $M_0 \sim 0.33\ \mu_B$

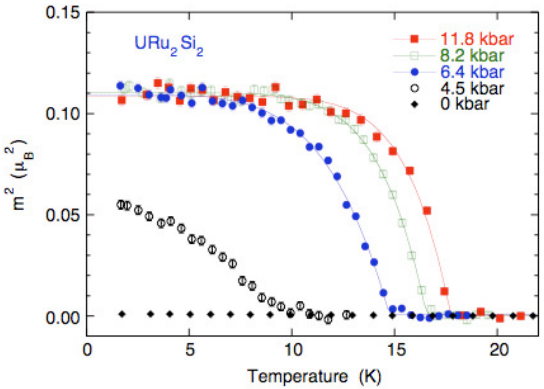


H.O. Δ_G, n_e | $\Delta_{1,0,0}$ $\Delta_{1.4,0,0}$ | M_0

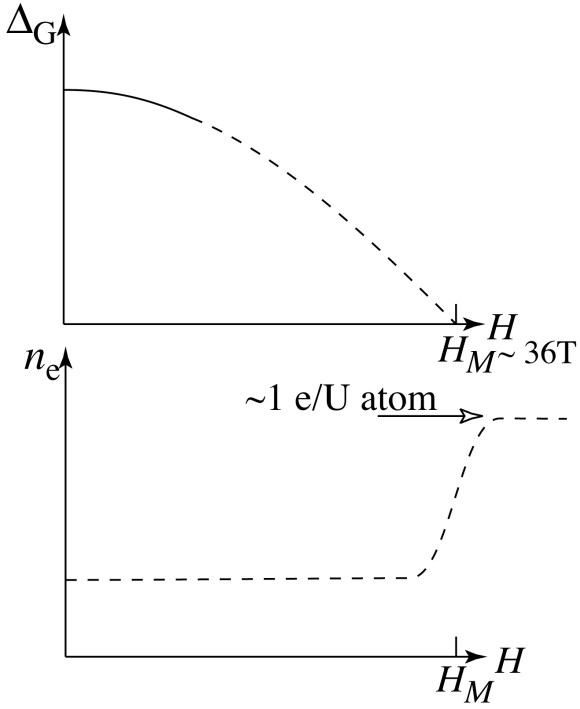


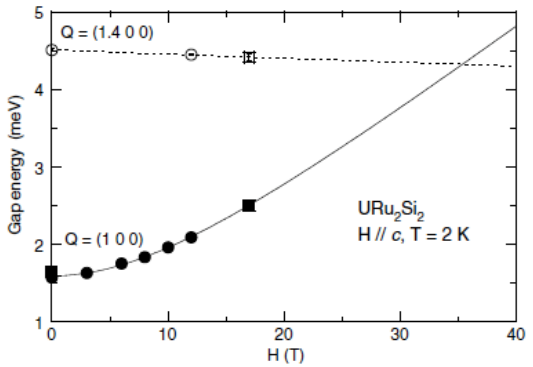
Homogeneity ??





F. Bourdarot *et al.*
Physica B **359-361**, 986 (2005).

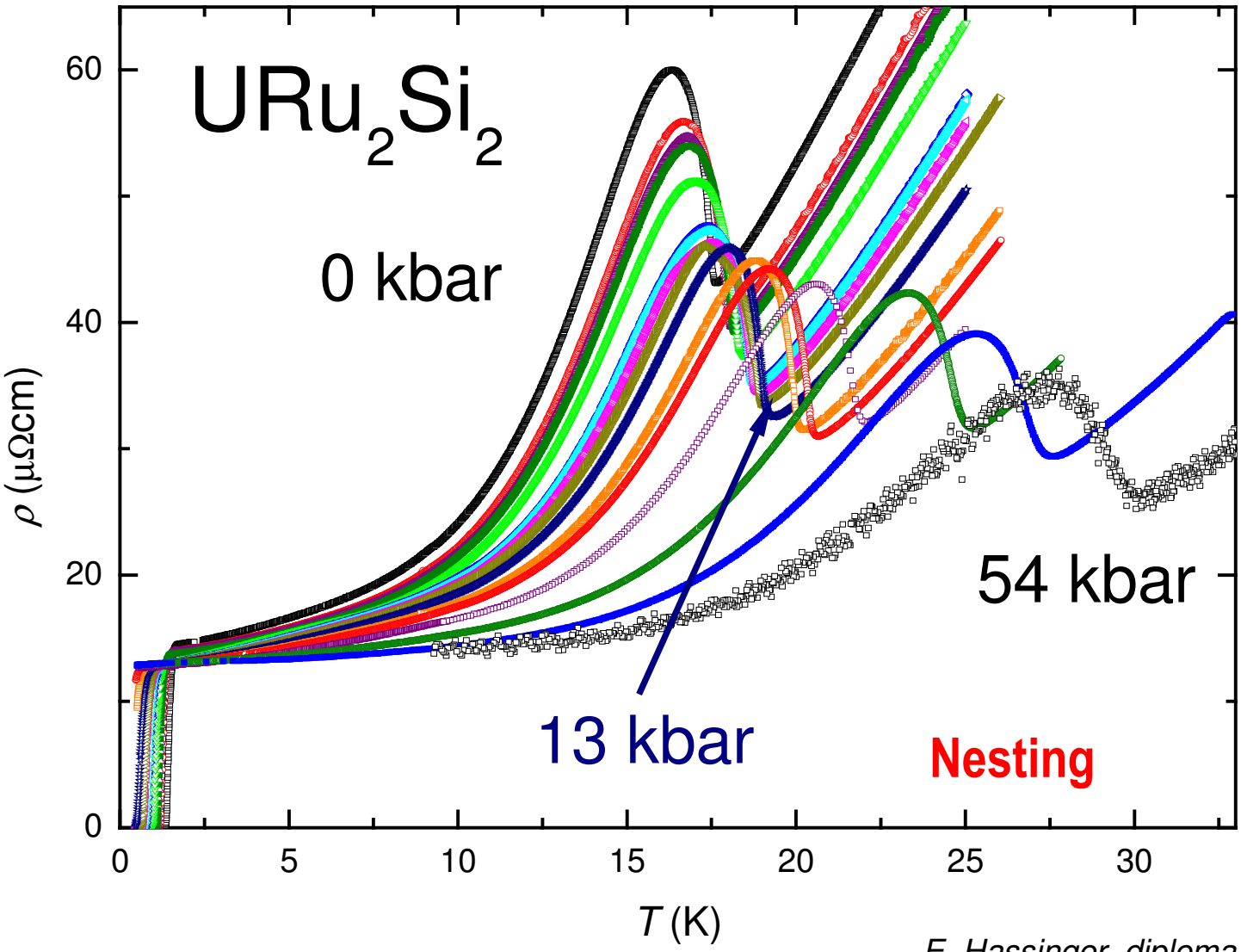




F. Bourdarot *et al.* Phys. Rev. Lett. **90**, 067203 (2003).

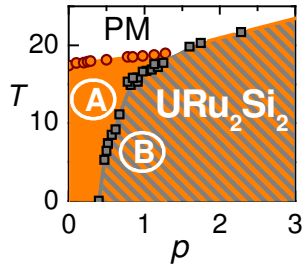
Localization in H

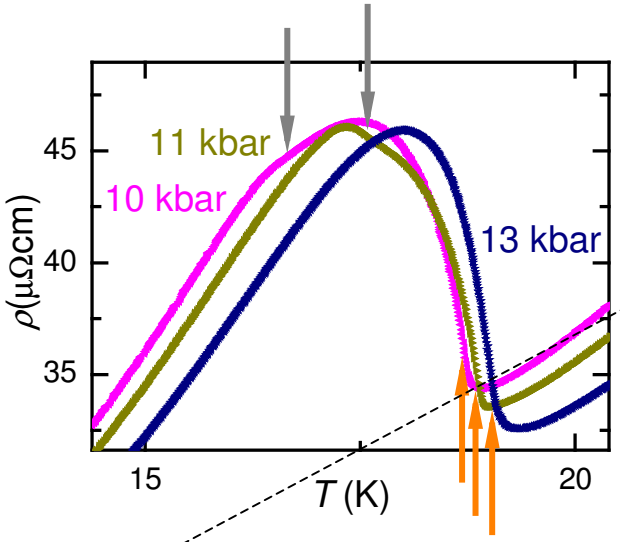
Resistivity measurements

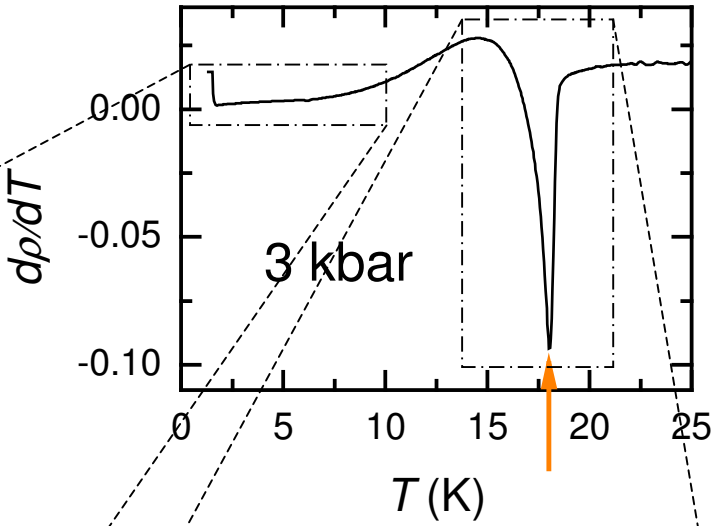


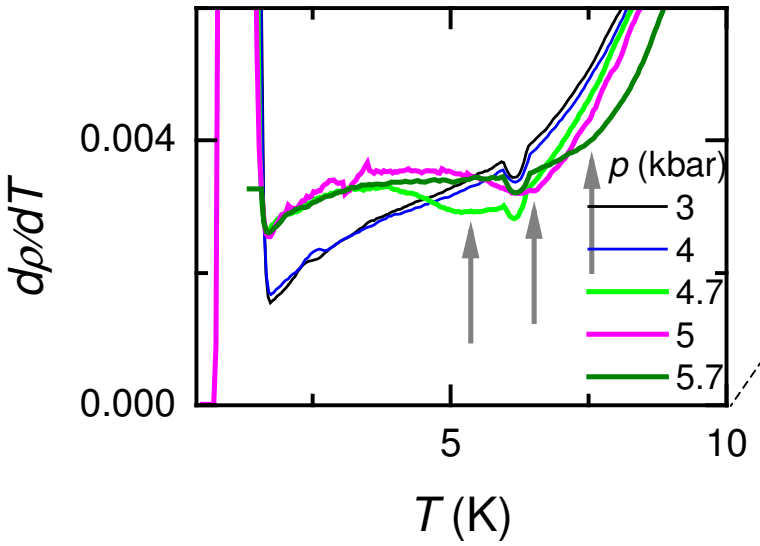
E. Hassinger, diploma thesis 2007

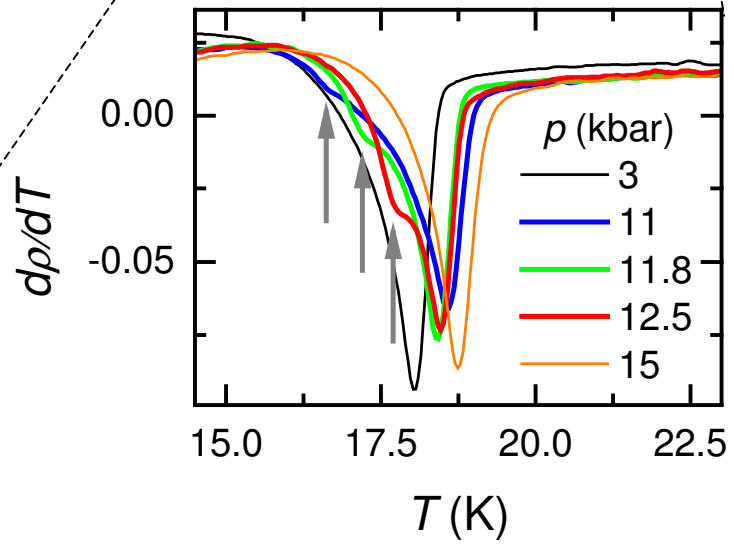
Transition to AF

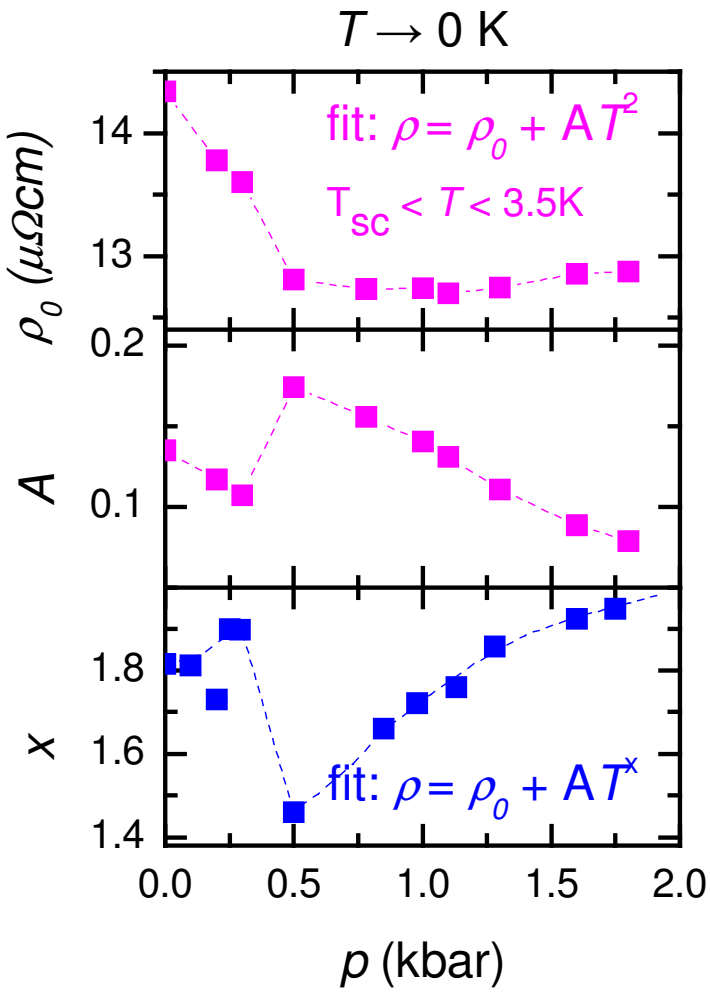


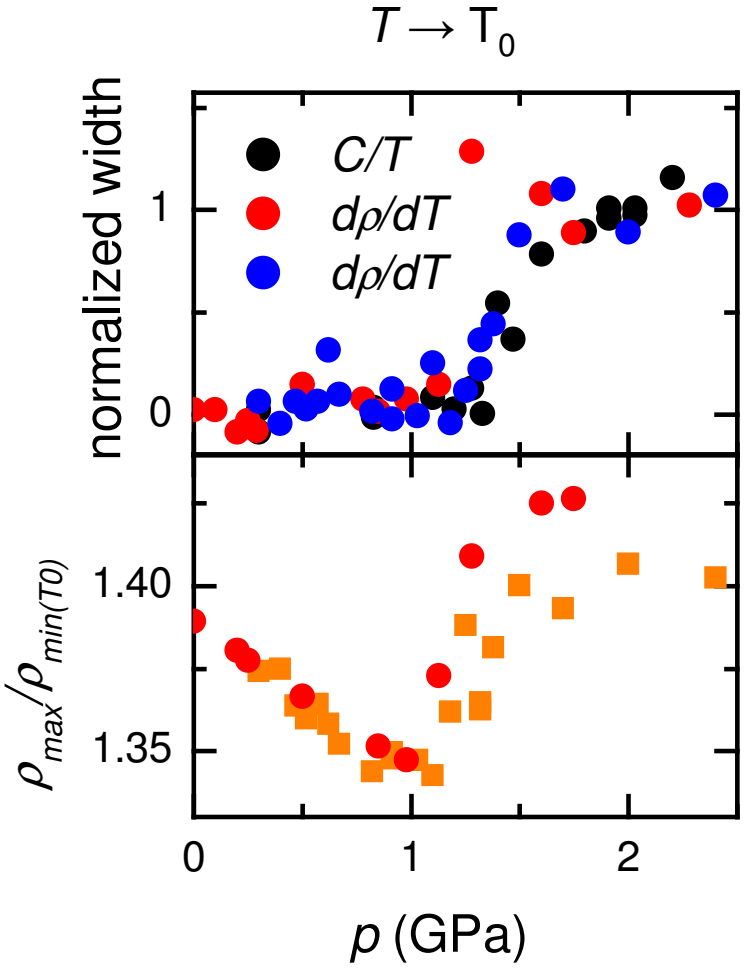








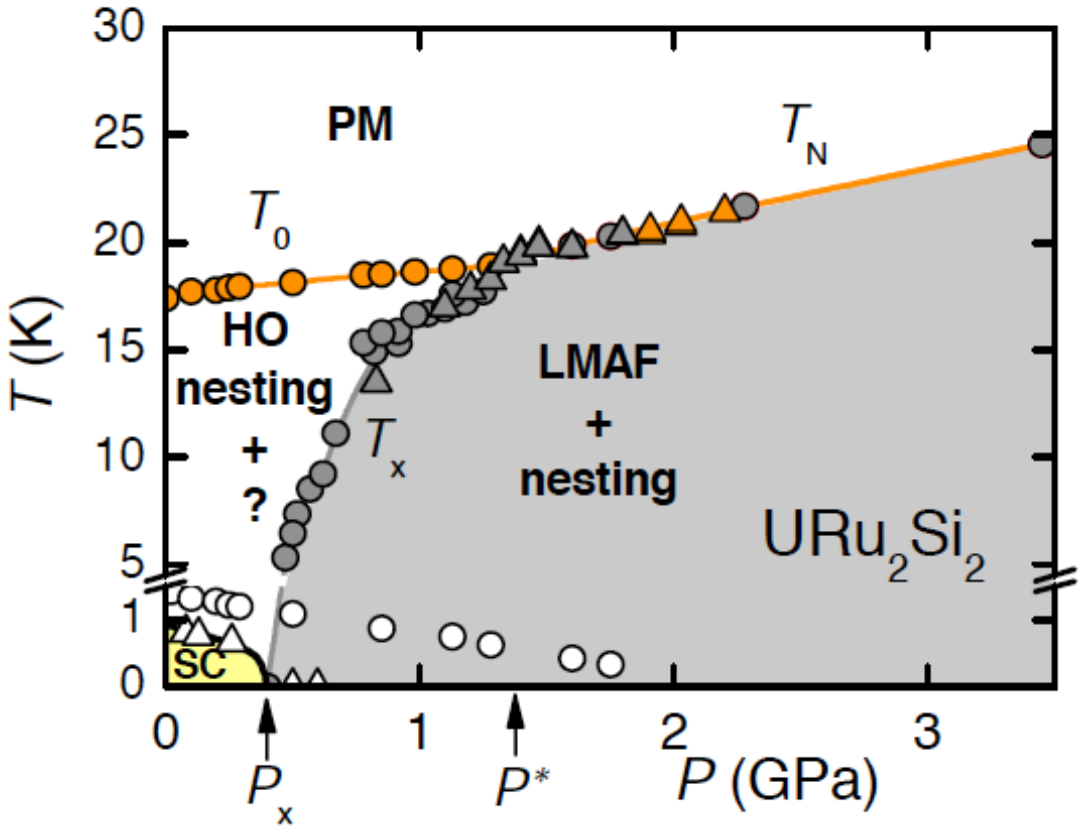




Looking carefully never T^2 term ?????

E Hassinger

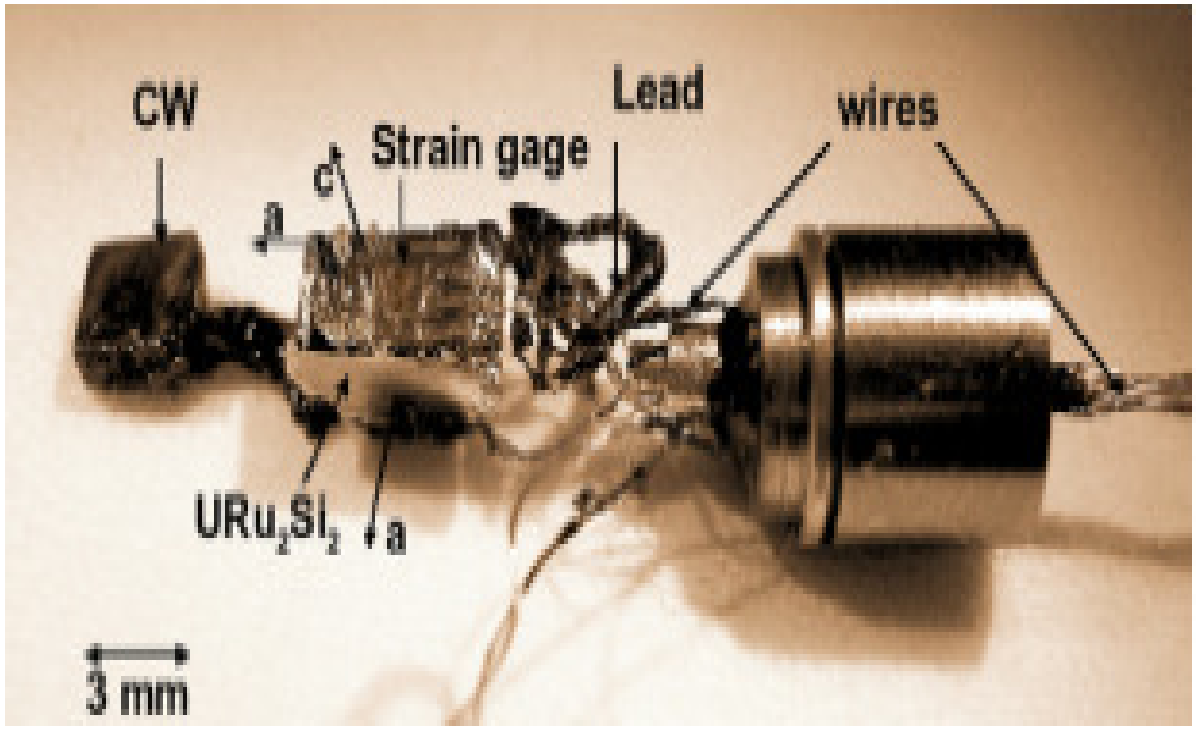
E Hassinger



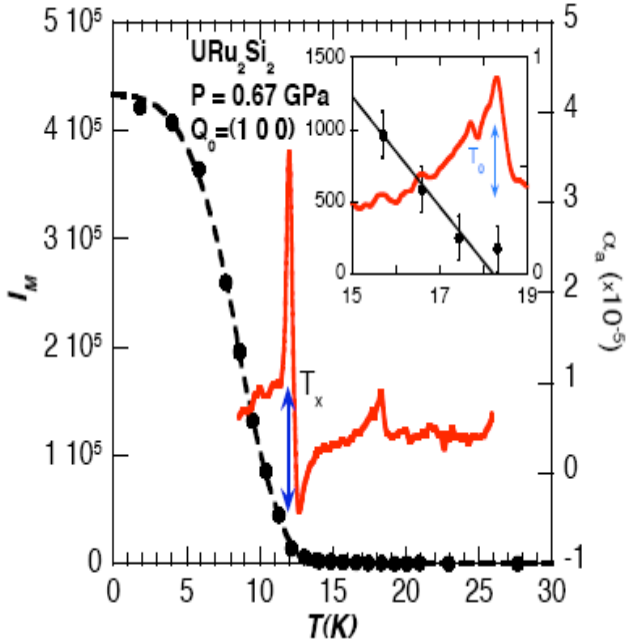
For SC Haga's nice crystal : the difficulty and nostalgy to be far from Japan ?

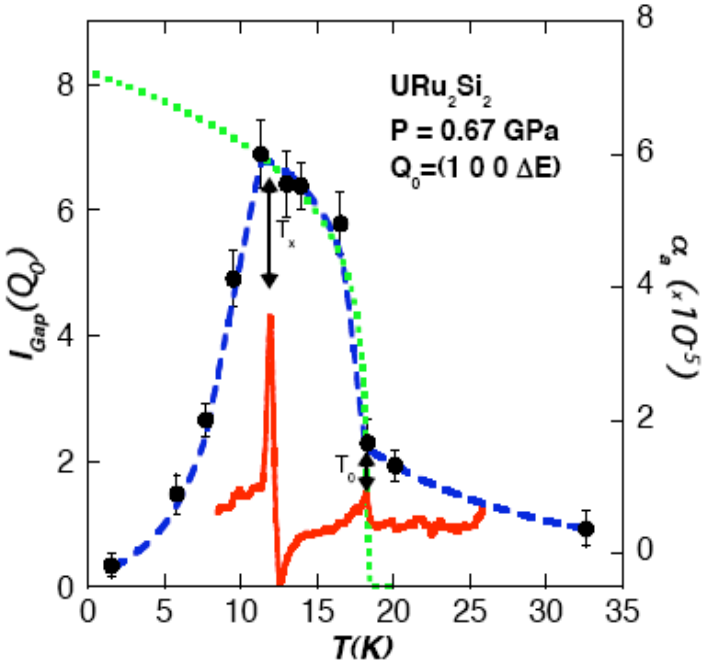
Definition of ther purity ?

Simultaneous elastic, inelastic and thermal expansion measurements (ILL IN12/ IN22)
A Villaume et al (Phys Rev 2008)



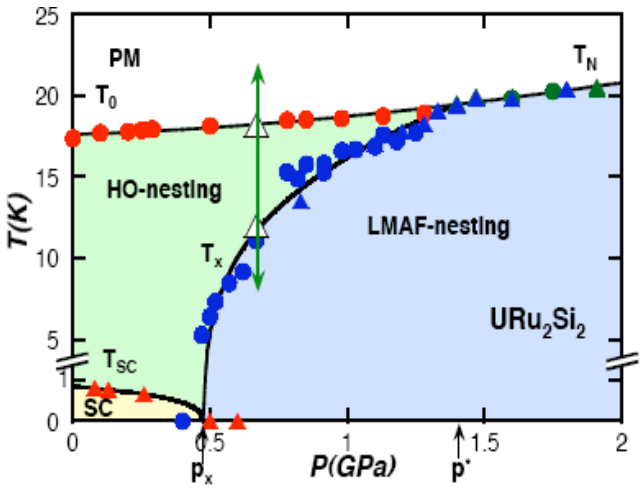
Inelastic neutron scattering IN12 CEA-CRG/ILL : F Bourdarot et al Dec 2007





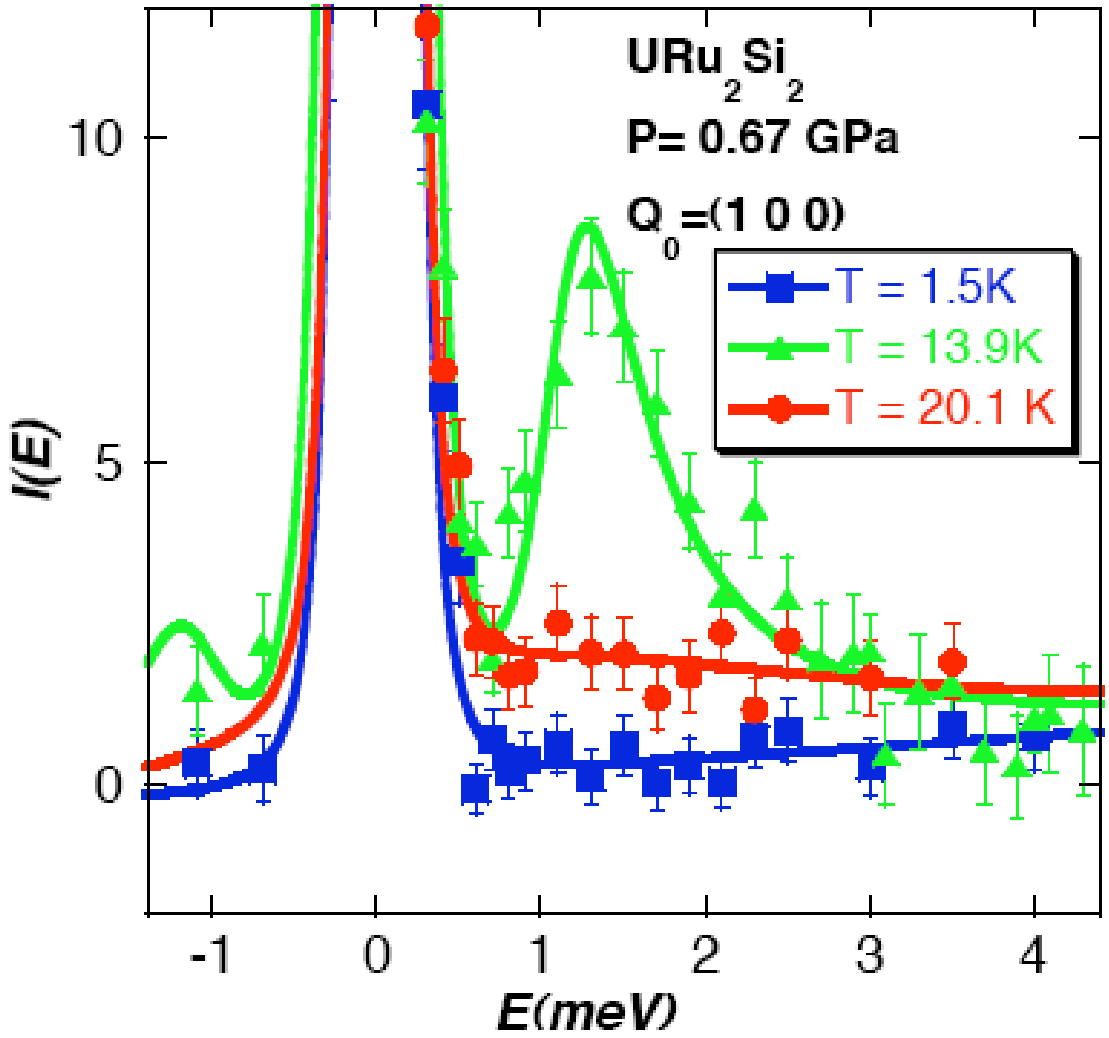
Simultaneous elastic and inelastic neutron scattering plus thermal expansion

Selection of P scan though PM – HO – AFM in temperature



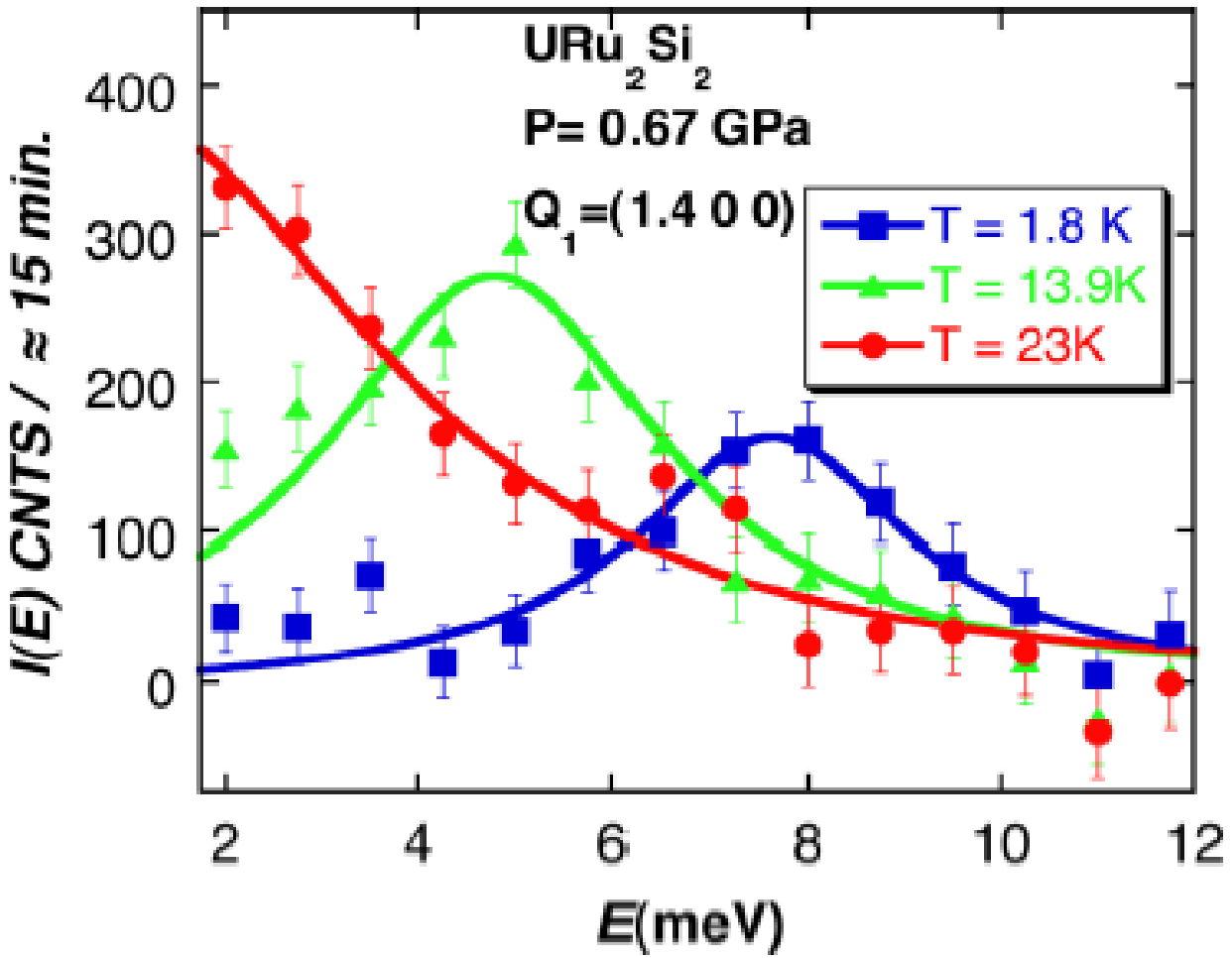
At Q_0 =1,0,0 **HO** I_{gap}

AF M_0

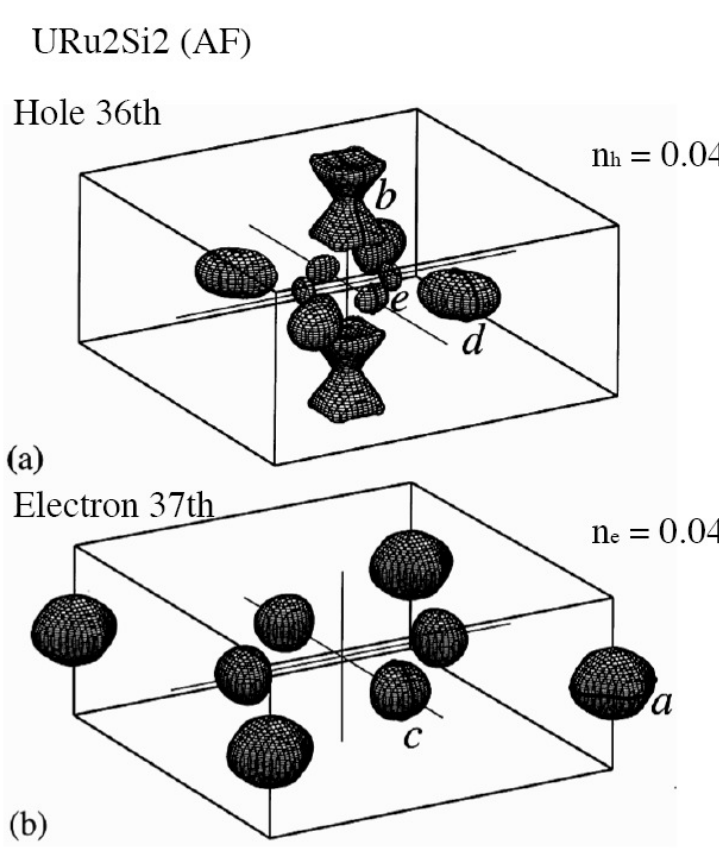


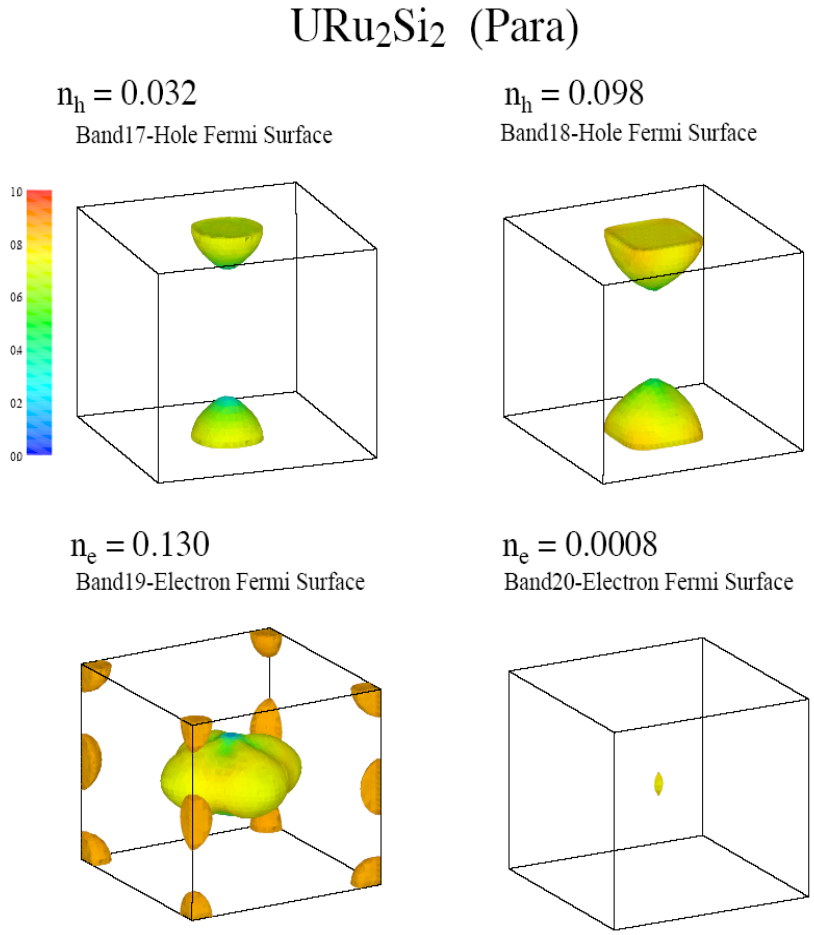
At Q_1 =(1.4, 0, 0)
Invariance necessity
of nesting

IN12 spectrometer at ILL


URu2Si2
P= 0.67 GPa
Q1=(1.4 0 0)
T = 1.8 K
T = 13.9K
T = 23K
I(E) CNTS / ≈ 15 min.
E(meV)
0
100
200
300
400
2
4
6
8
10
12

From Yamagami / Harima
Model 5f² itinerant or localized





Brillouin zone reconstruction drop carrier per U atom factor 3
Fermi instability C Varma…..

Status of URu_2Si_2. By comparison to $PrFe_4P_{12}$ Difficulty complexity of the band structure and wipe out of the CF

Under P

$P < P_x$ Nesting main phenomena n = 0.08 / U atom - fancy effects

P_x first order ΔV (Motoyama *et al*. Phys. Rev. Lett. **90** 166402.)

P_x, T_M line

tricritical point P*= 1,3GPa

Above $P \sim 1.3$ GPa at least up to 10 GPa

LMAF is stabilized but coupled with the same FS reconstruction.

SC and LMAF antagonist main effect change of the dynamic at Q_0

$T_c \rightarrow 0$ for P_x 100% LMAF phase.

Under H

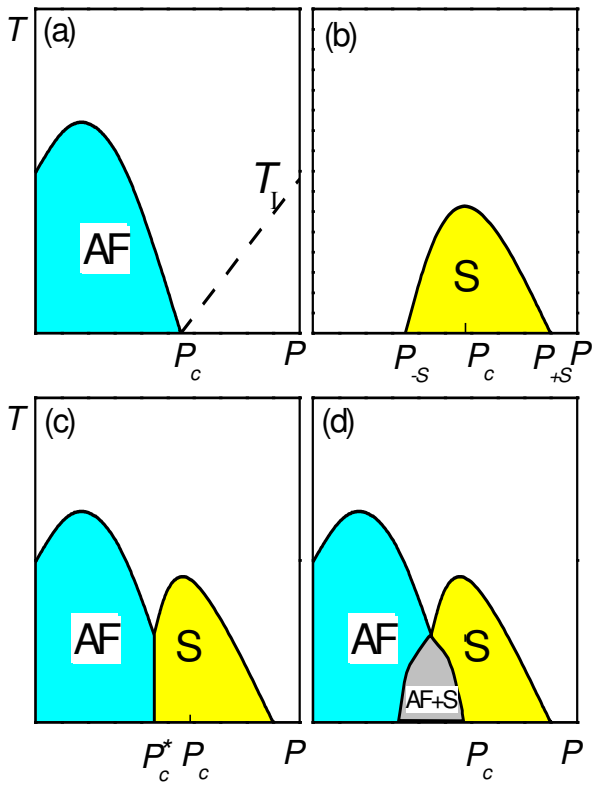
-H_M not very sensitive to P.

-$H \rightarrow H_M$, $n_e \rightarrow 1$.

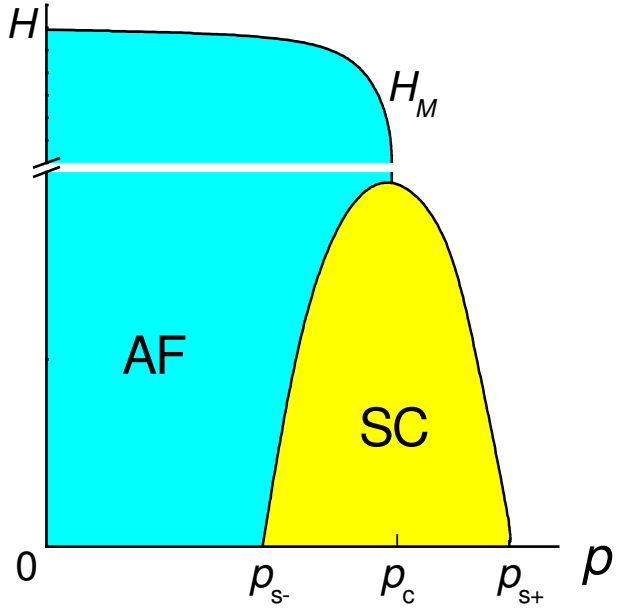
URu_2Si_2 looks like an ordinary heavy fermion AF with different AF phases and polarized paramagnetic (PP) phase similarity with CeRu2Si2

Competition antiferromagnetism - superconductivity

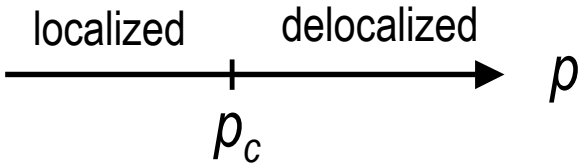
Pressure :

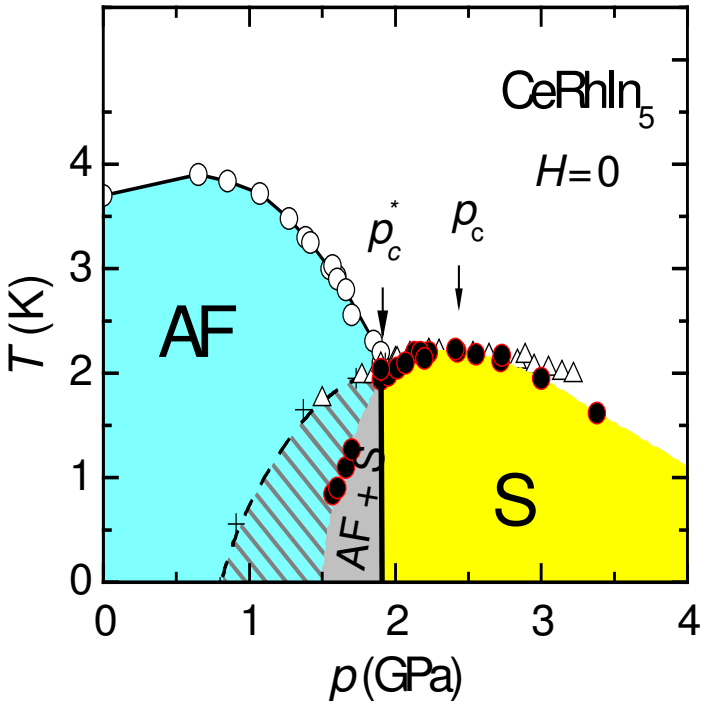


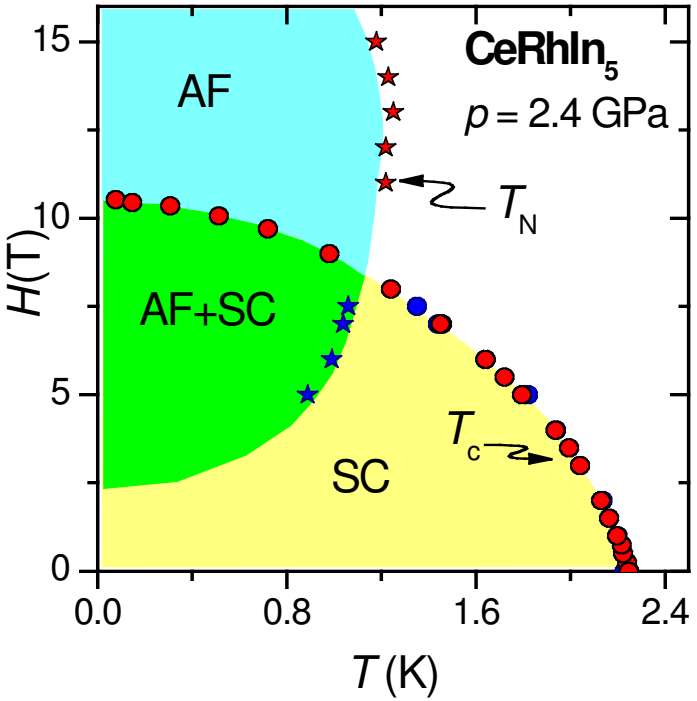
Magnetic field



Heavy fermion and Fermi surface







NMR Yashima incomm /comm

Tetracritical point

G Knebel and also T Parks

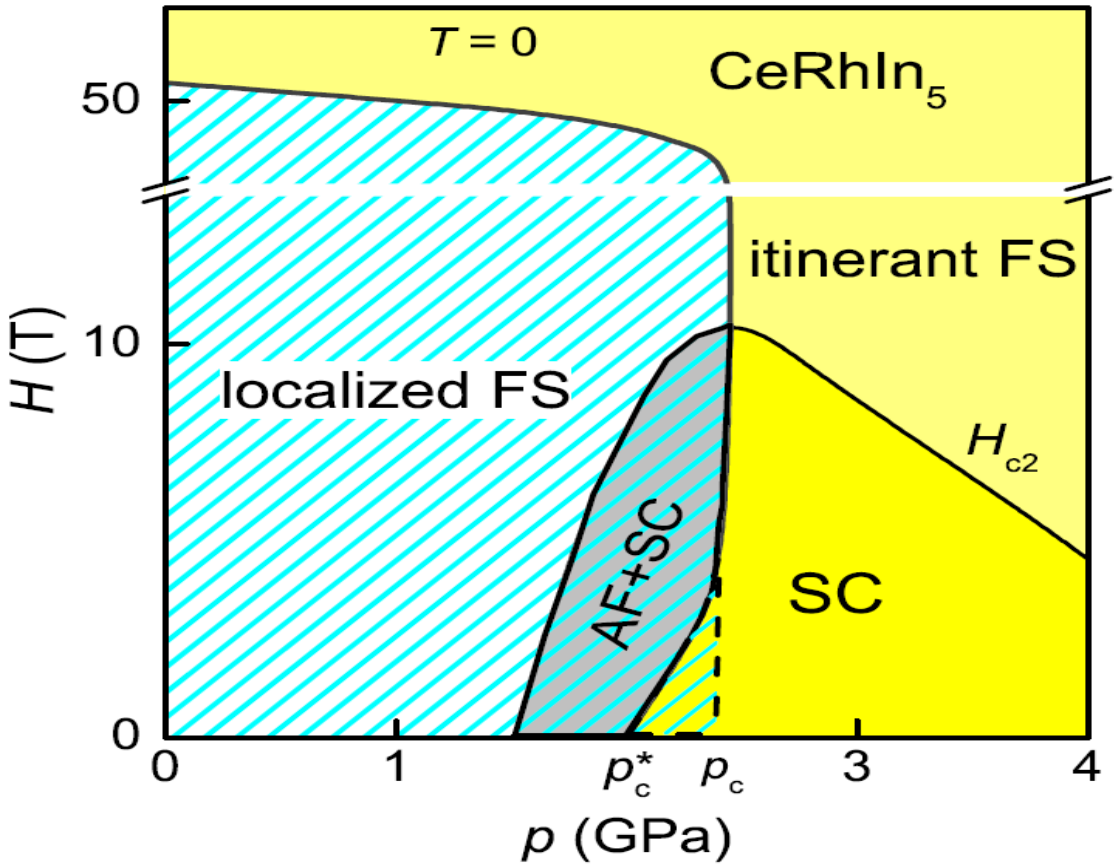
P^*_c , H^* story of gaps ?

$$
\begin{aligned}
T_N(p) &\sim T_N(p_c^\star)\frac{p_c - p}{p_c - p_c^\star} \\
T_c(p,H) &\sim T_c(p_c^\star)\frac{H_0 - H}{H_0} \\
T_N(p) &= T_c(p,H^*) = T_c(p_c^\star)\frac{H_0 - H^*}{H_0}
\end{aligned}
$$

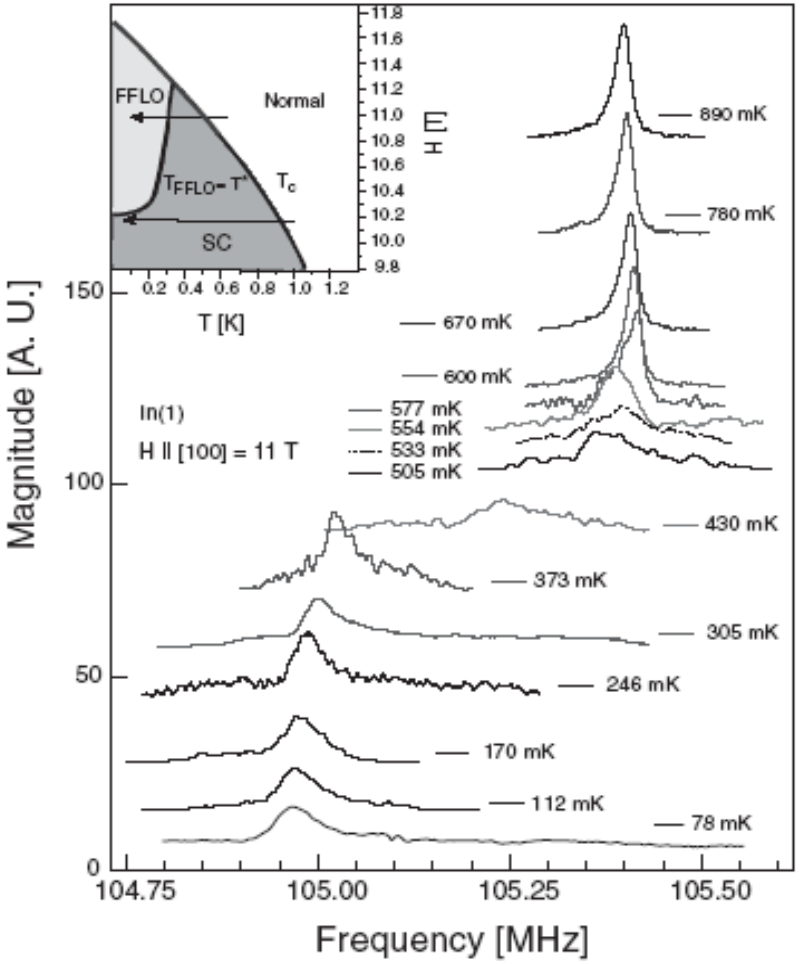
$$
\text{with} \quad T_N(p^\star) = T_c(p_c^\star) \quad \text{at} \quad H^* = H_0 - H_0\left(\frac{p_c - p}{p_c - p_c^\star}\right)
$$

Vortices ??

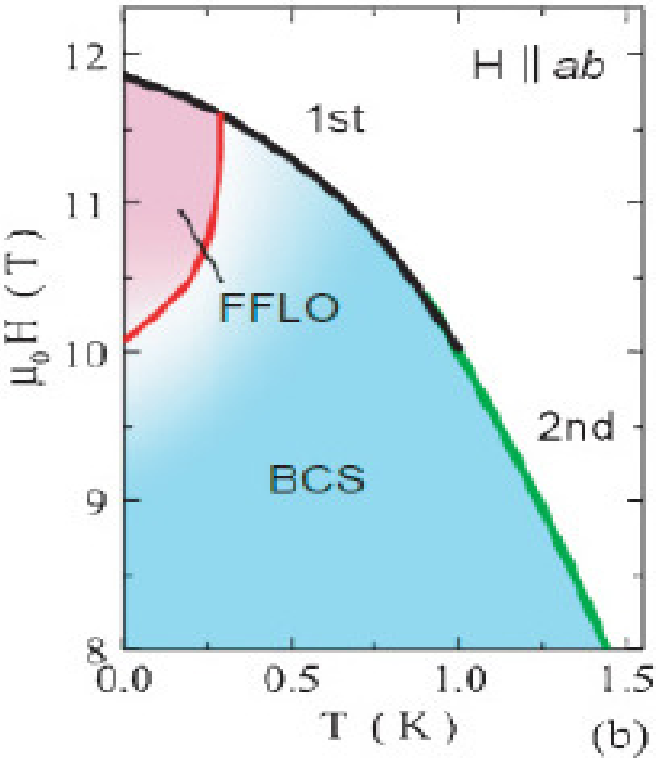
Fermi surface : QCP/ AF/SC Settai- Onuki



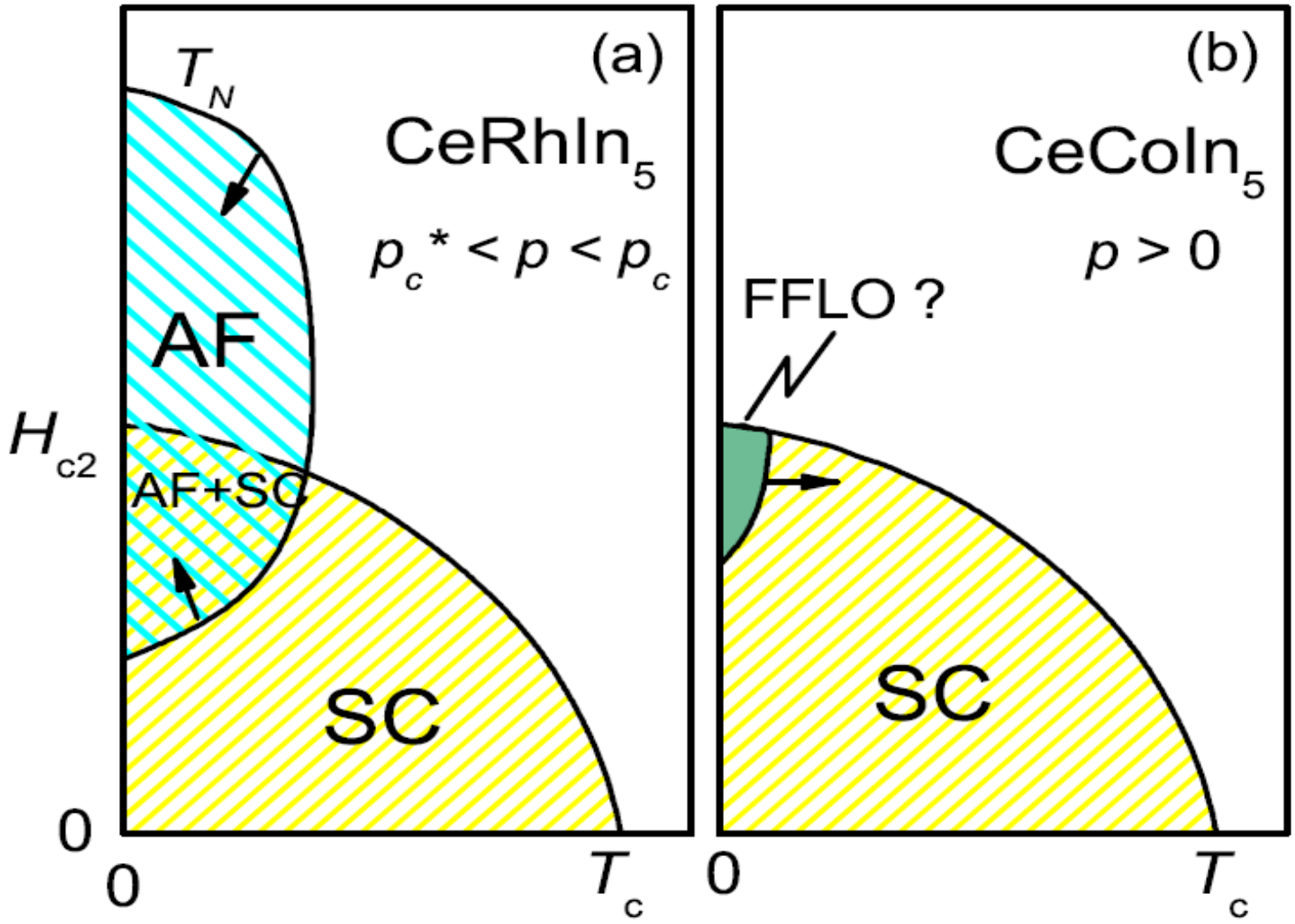
$CeCoIn_5$: low temperature – high magnetic field phase



Bianchi et al

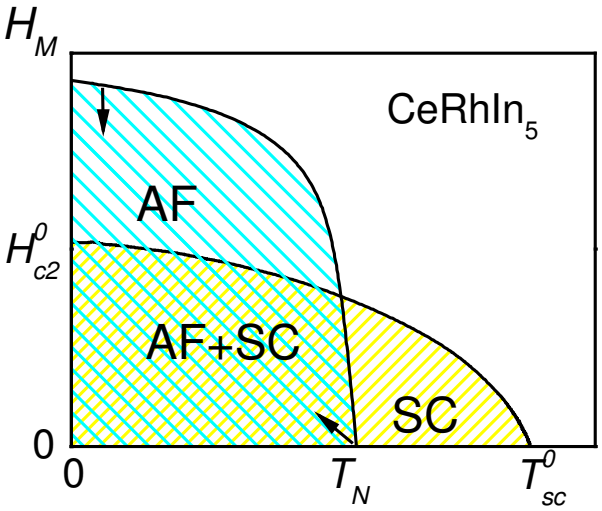


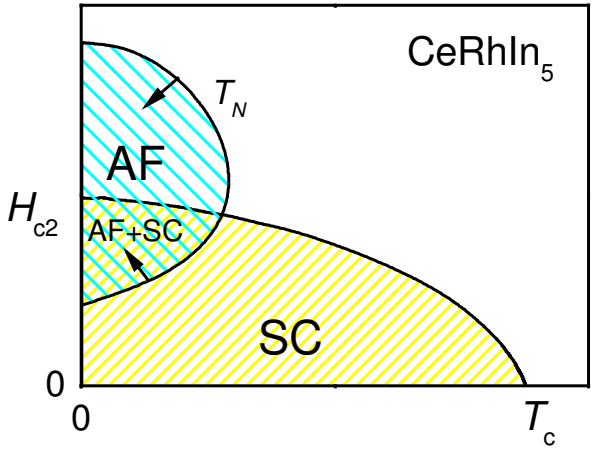
Mitrovic et al / Kumagai / Curro

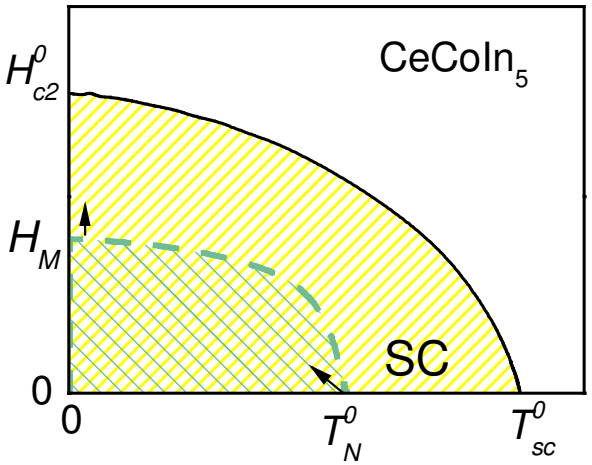

(a)
CeRhIn5
p_c* < p < p_c
T_N
AF
AF+SC
SC
H_c2
0
0
T_c
(b)
CeCoIn5
p > 0
FFLO ?
SC
0
T_c

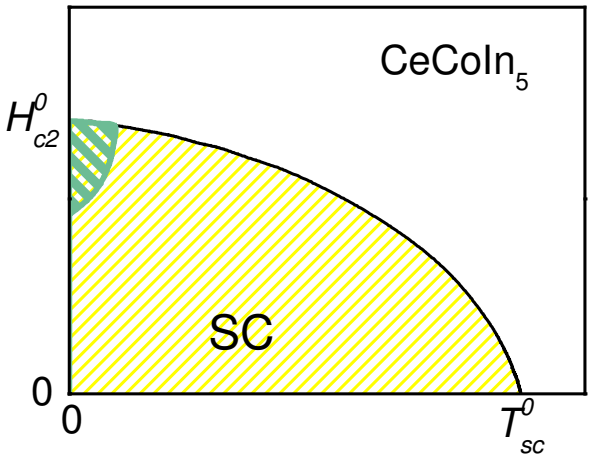
Comparison : $CeRhIn_5$ ⟷ $CeCoIn_5$ $\quad p_c^* < p < p_c$

$T_N^0(p, H)$, $H_M^0(p, H)$, pseudogap
$T_N^0(p, H)$, $H_M^0(p, H)$, pseudgap









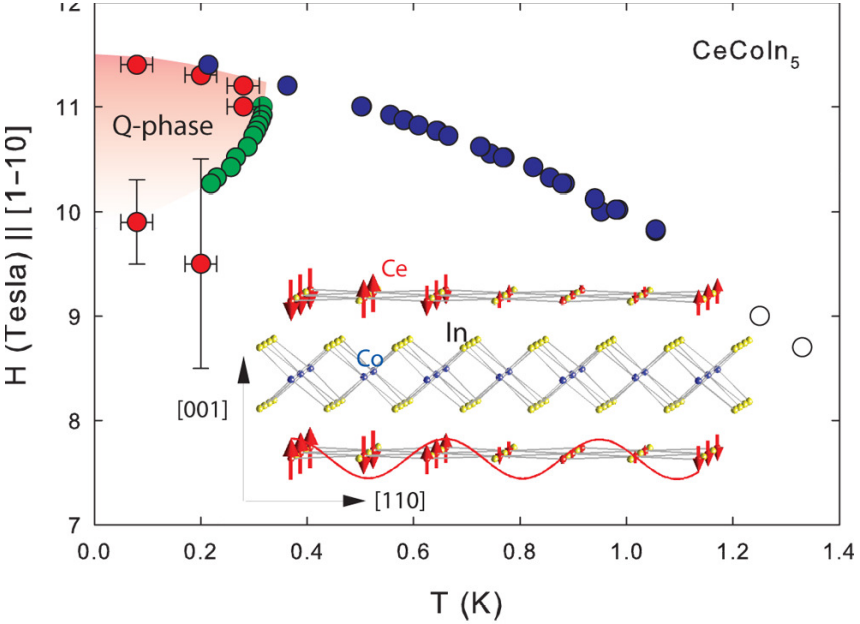
H_M sticked to H_{c2}

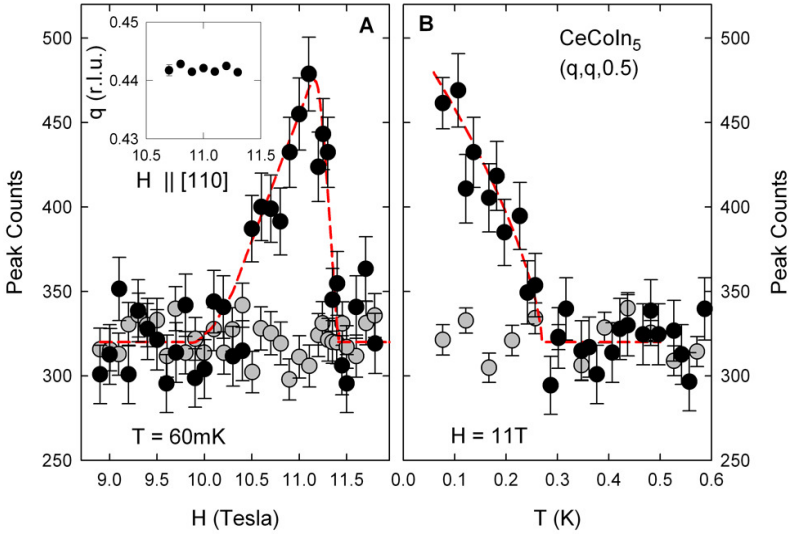
AF pseudogap

SC gap

Coupled superconductivity and magnetic order in $CeCoIn_5$

M Kenzelmann et al Science 21 august 2008



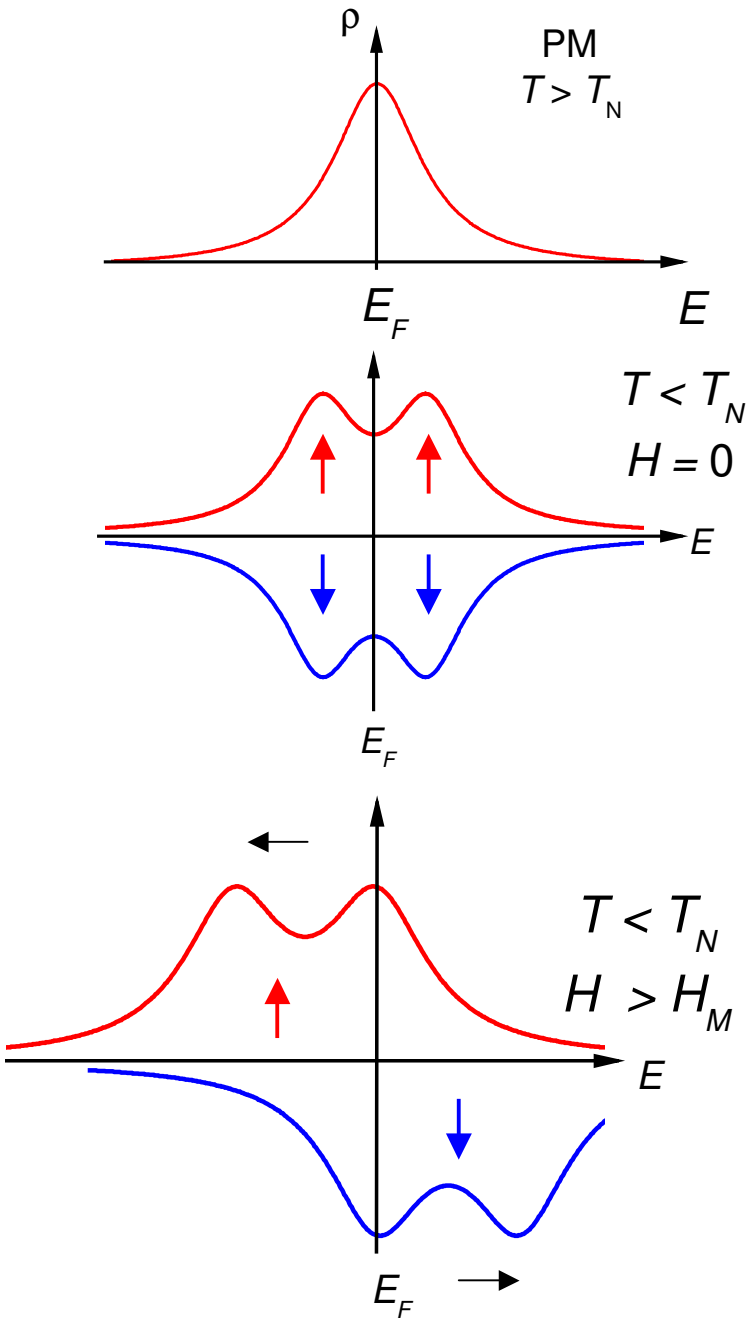


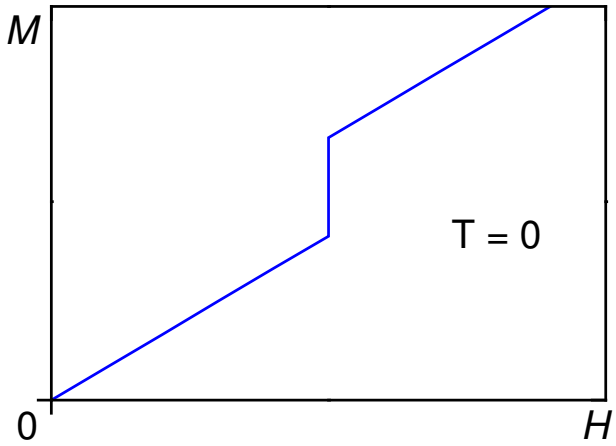
Model Yanase –Sigrist : IC versus C

Miyake : C + FFLO

Density of state and AF in HFC

CeAl2



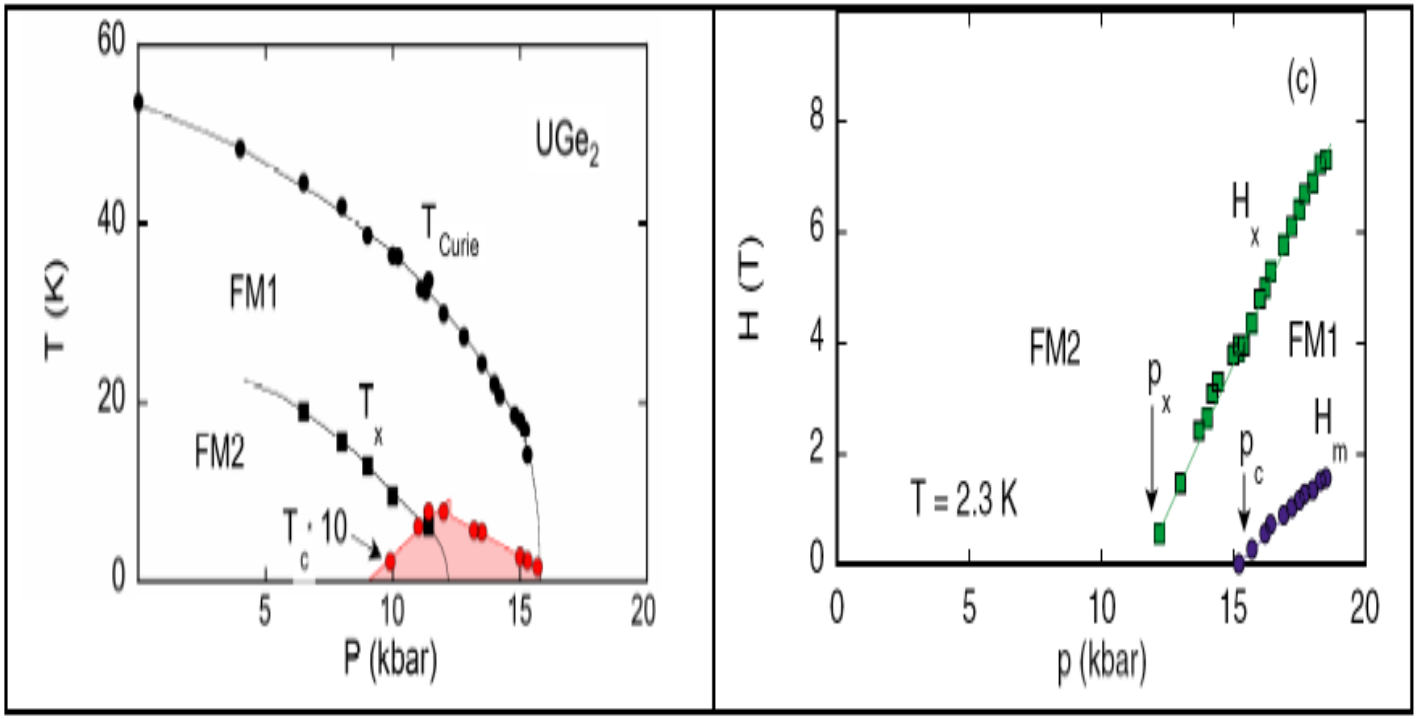


Ferromagnetic superconductor

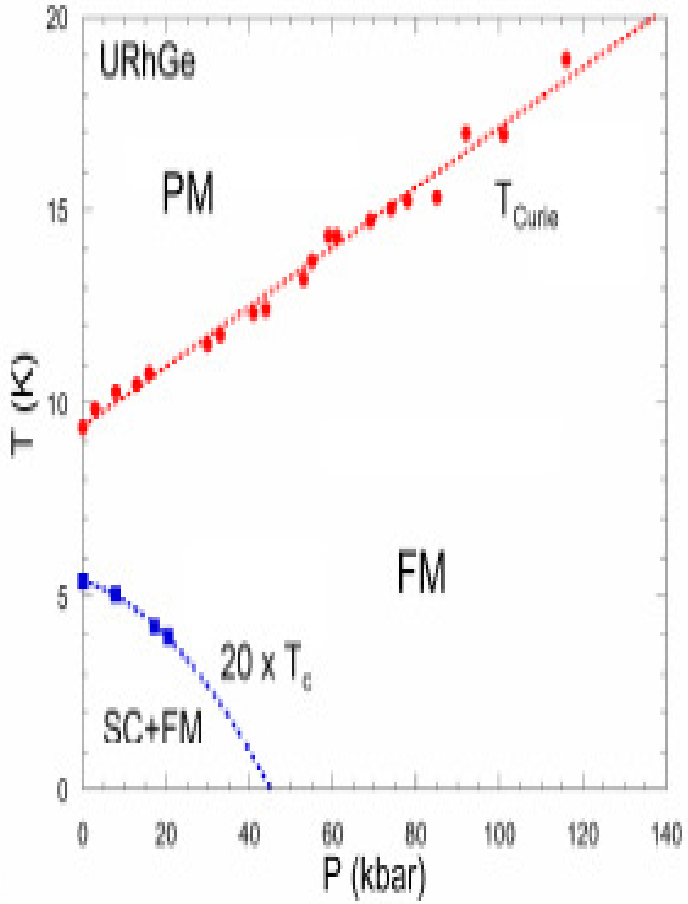
- UGe_2 : SC only in FM state
- URhGe : Reentrant SC
- UCoGe : Crosing the FM instability

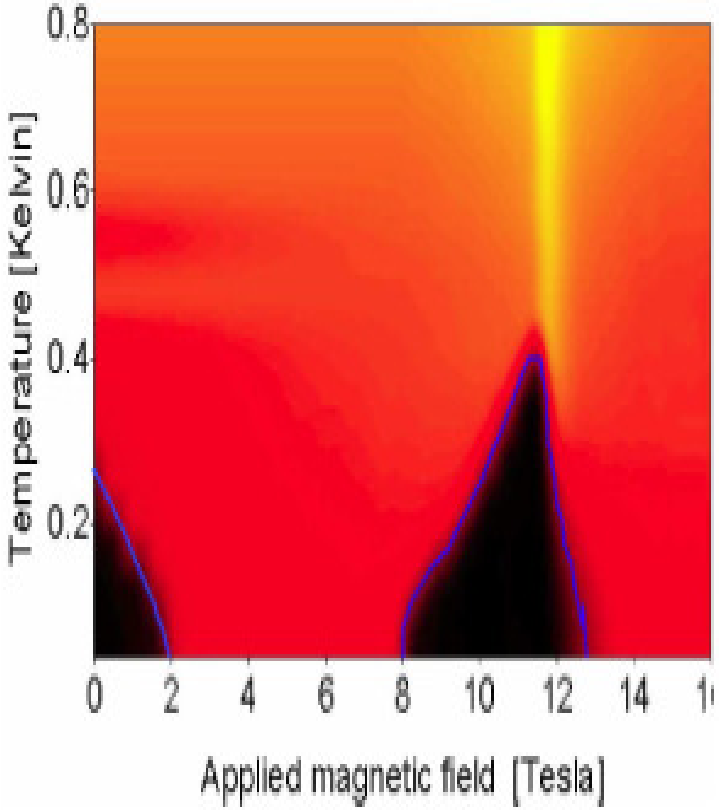
Ferromagnetism and SC : Discovery Saxena et al
N Sato (V) / Kitaoka (NMR) / Aso (neutron scattering)

First example : UGe_2

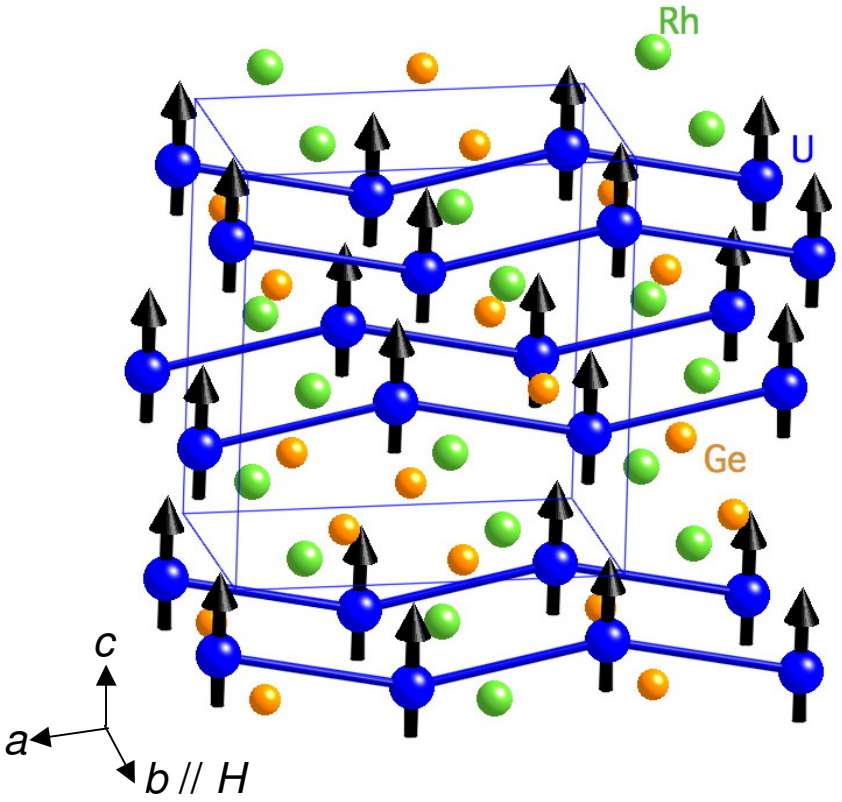


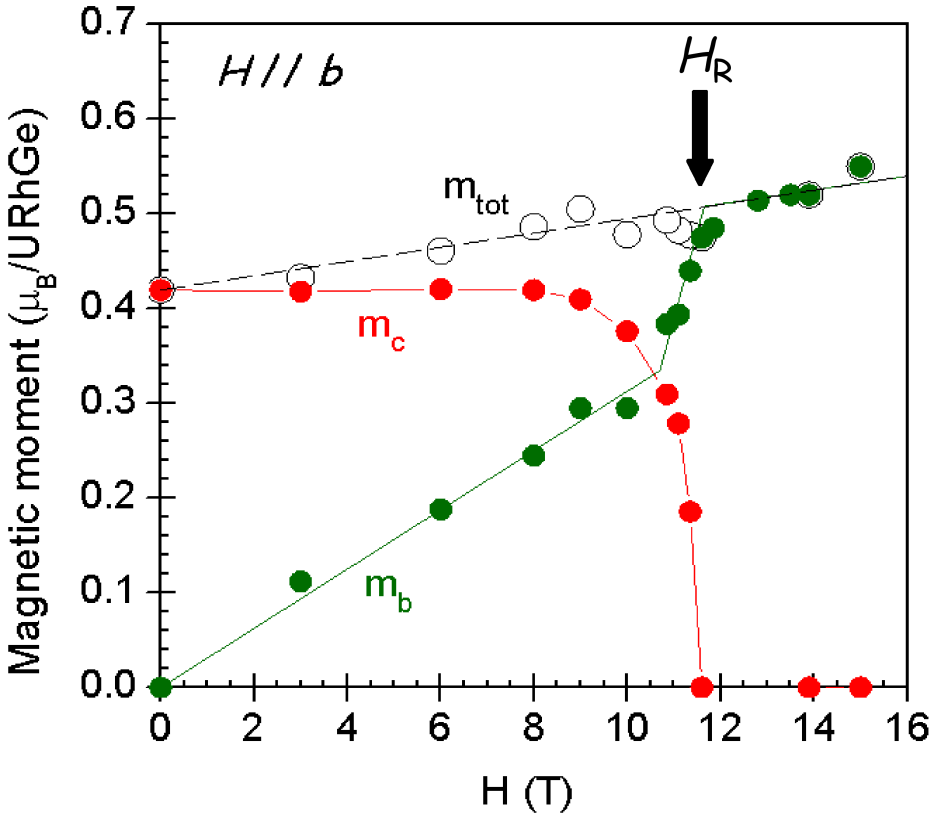
URhGe : ferromagnetic superconductor
Discovery H=0 Dai Aoki et al
H_R F Levy et al : spin reorientation





Spin reorientation in URhGe at H_R = 12 T



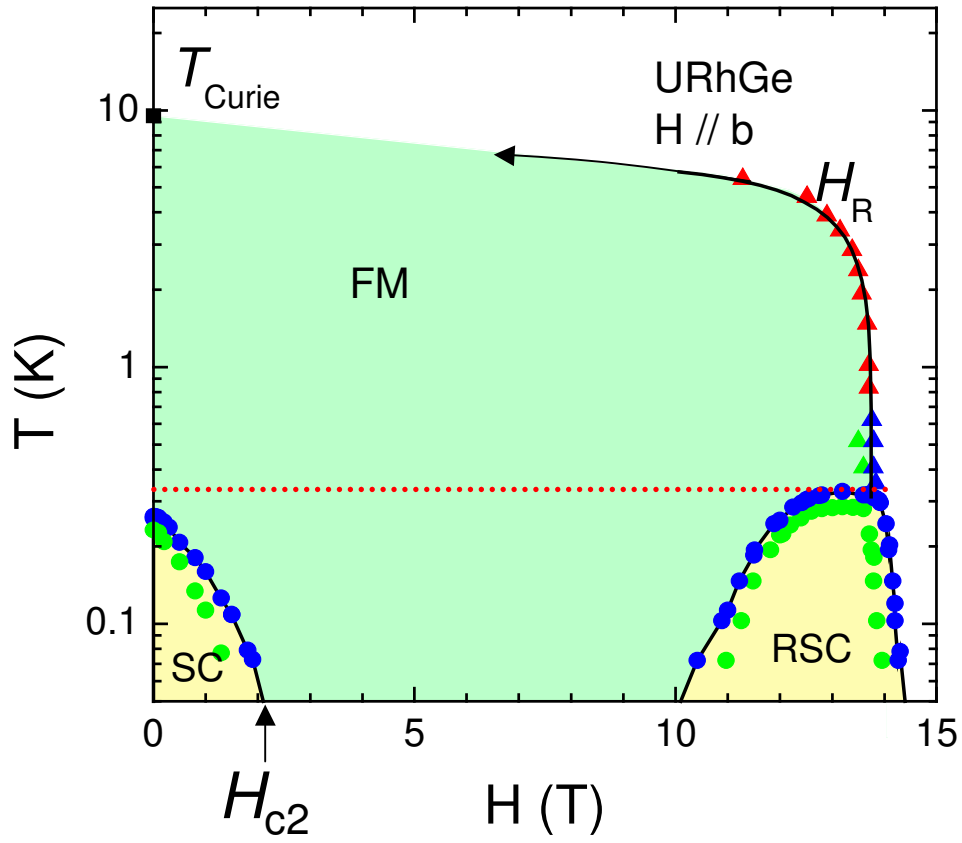


B Grenier et al

- Magnetization axis changes from *c*- to *b*-axis at H_R~12 T.

Fluctuation of spin reorientation is an important role for RSC

Phase diagram of URhGe

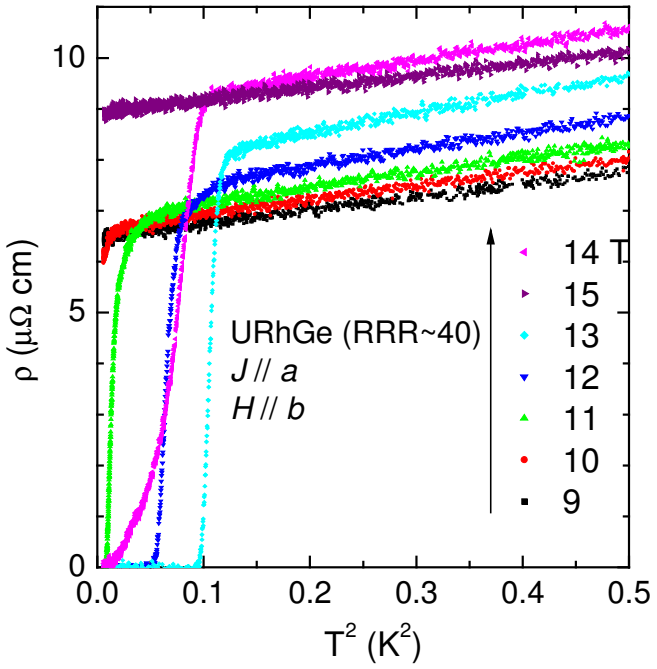


- $H_{c2}(0) > H_p = 0.46$ T.
- T_{sc} (13.7 T) > T_{sc} (0).
- RSC strongly sticks to H_R.
- H_R may connect T_{Curie}.

A Miyake et al 2008

A-coefficient is enhanced around SC phases

T^2-dependence of resistivity

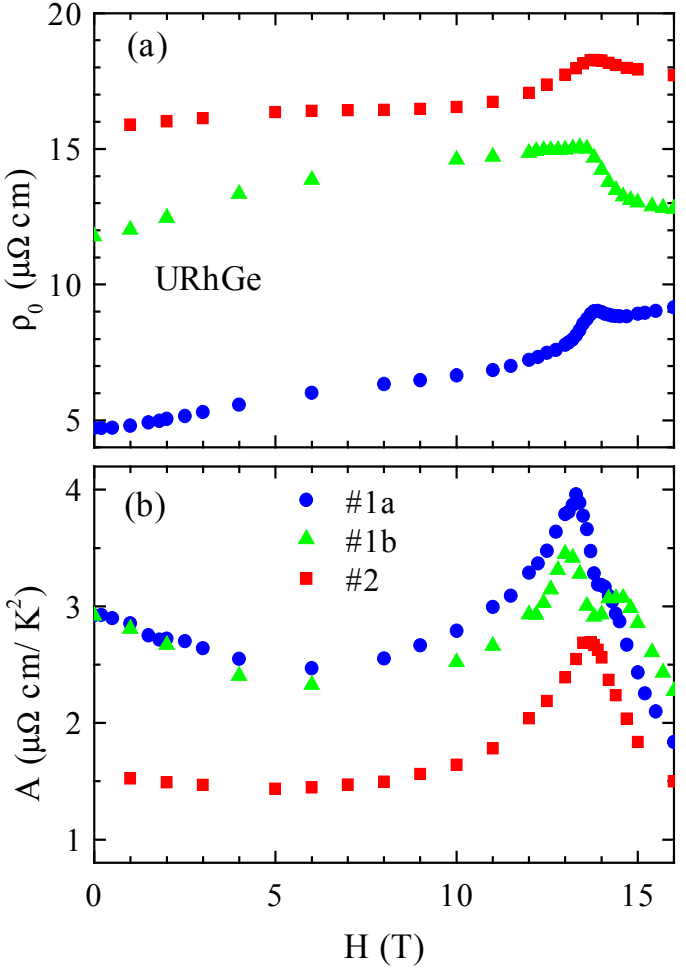


Fermi liquid law

$$\rho(T) = \rho_0 + AT^2$$

$$A \propto \gamma^2 \propto (m_H^*)^2$$

H-dependence of ρ_0 and *A*

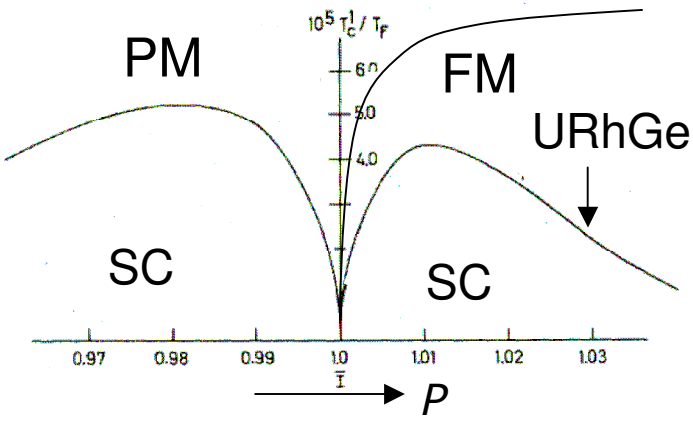


$\rho_0 \propto 1/l$

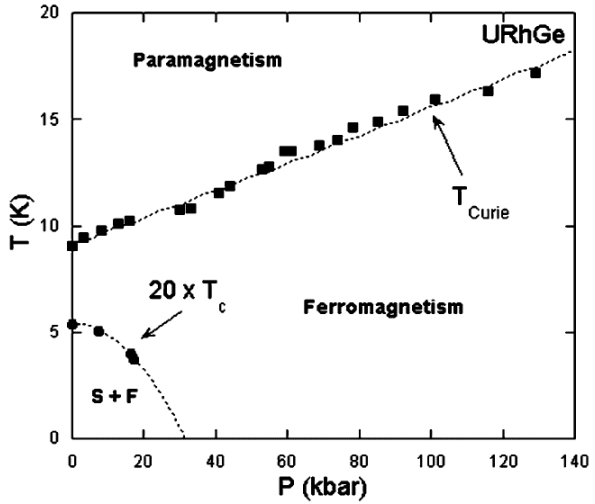
$\xi \propto 1/(m^* T_{sc})$

A Miyake et al 2008

Calculation of T_{sc} as a function of effective mass

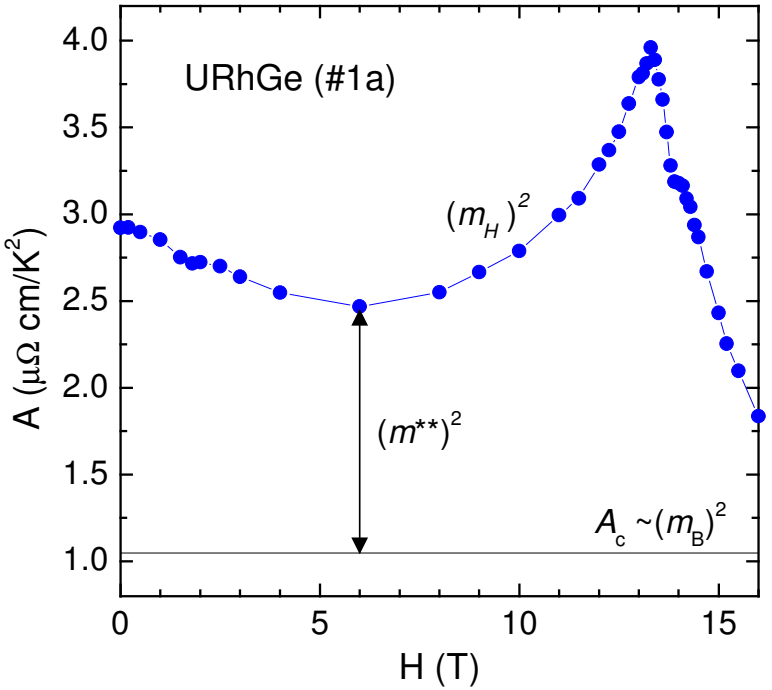


Fay and Appel., (1980)



Hardy *et al.*, (2005)

Non proximity to FM instability



$$m_H^* = \underbrace{m_B}_{\text{band}} + \underbrace{m^{**}}_{\text{correlation}}$$

McMillan-type formula at zero-field.

$$T_{sc}^0(m_H^*) = T_0 \exp\left(-\frac{m_H^*}{g m^{**}}\right)$$

T_{sc} depends on effective mass

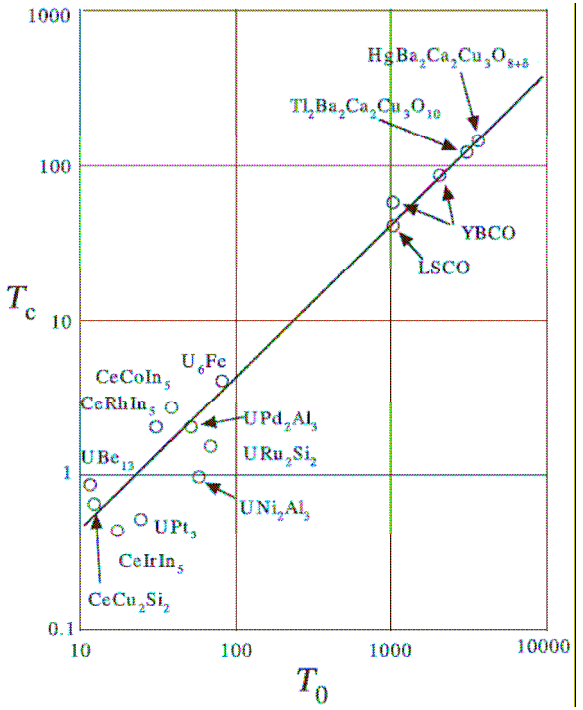
$$T_{\rm sc}(m_H^*) = T_0 \exp\left[-\left(\frac{m_{\rm B}}{m^{**}} + 1\right)\right]$$

Grüneisen parameter

$$\Omega_T = -d(\log T_{\rm eff})/d(\log V)$$

$$T_{\rm B} \sim 1/m_{\rm B},\ T^{**} \sim 1/m^{**}$$

$$\Omega_{T_{\rm sc}} = \frac{1}{\lambda}(\Omega_{T_{\rm B}} - \Omega_{T^{**}}) \qquad \lambda = m^{**}/m_{\rm B}$$



Moriya and Ueda (2003)

URhGe $\Omega_{T_{sc}}$ = -16

$\Omega_{T^{**}}$ = 14

Hardy (2004)

	UPt_3	URu_2Si_2	UBe_{13}
$\Omega_{T_{sc}}$	-65	-59	-21
$\Omega_{T^{**}}$	50	40	52

Flouquet *et al.*, (1991)

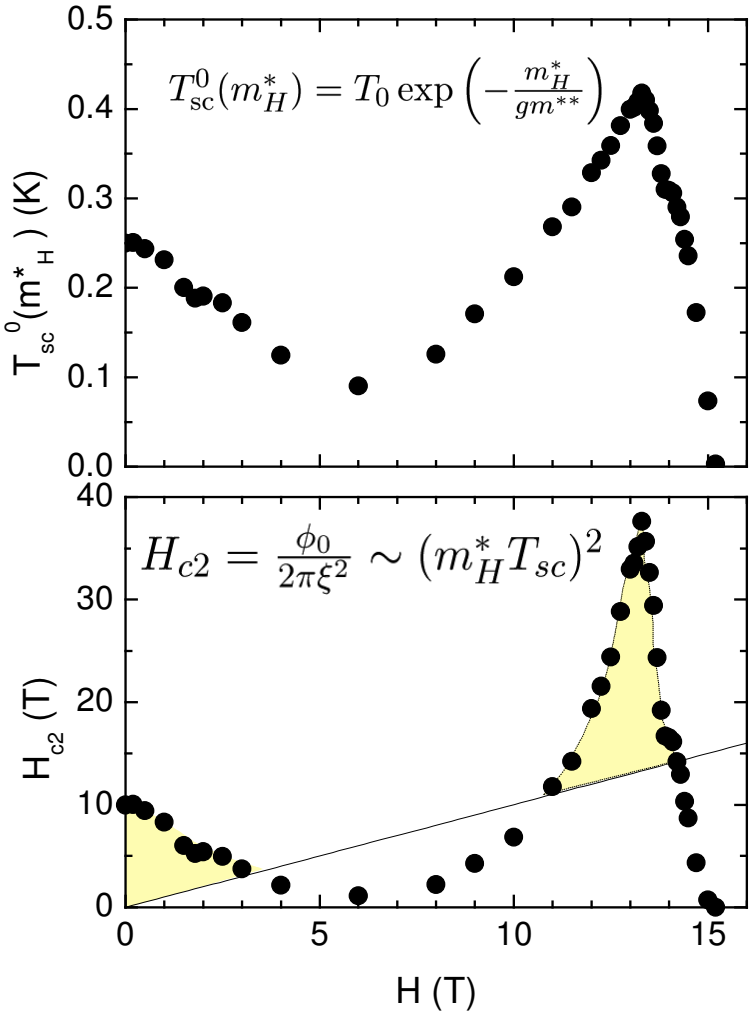
$T_{sc} \sim 1/\gamma \sim T_B$

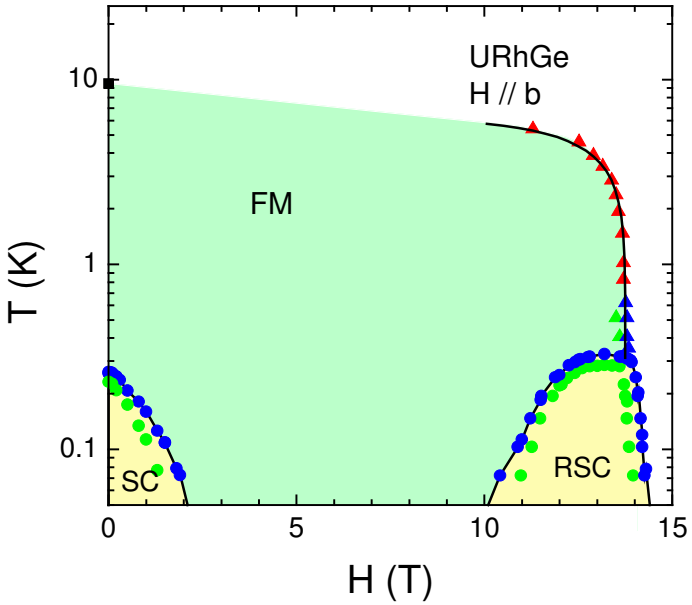
m_B ↗, T_{sc} ↘

m^{**} ↗, T_{sc} ↗

See Monthoux

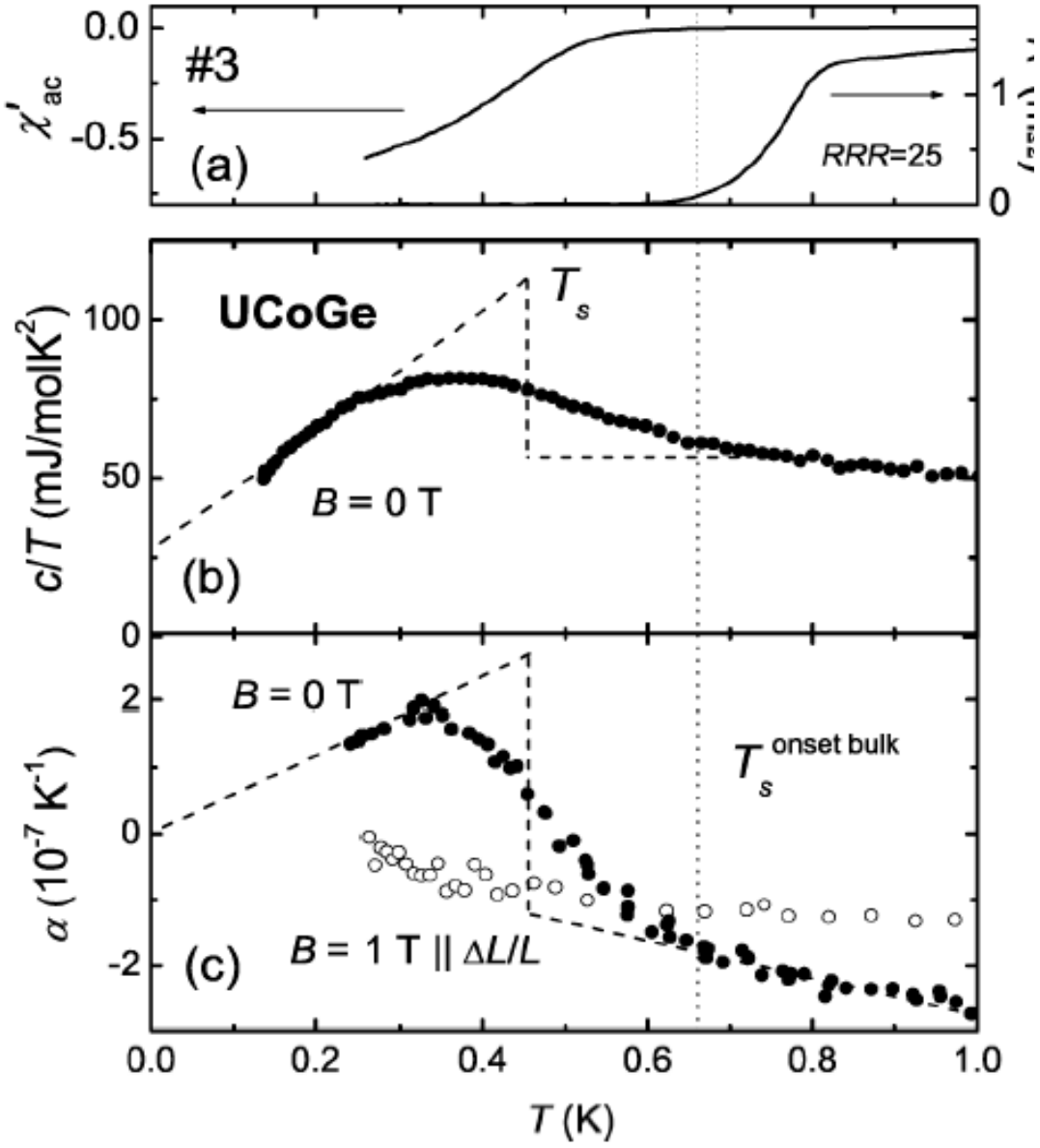
T_{sc}^0 and H_{c2} enhances around 0 T and H_R

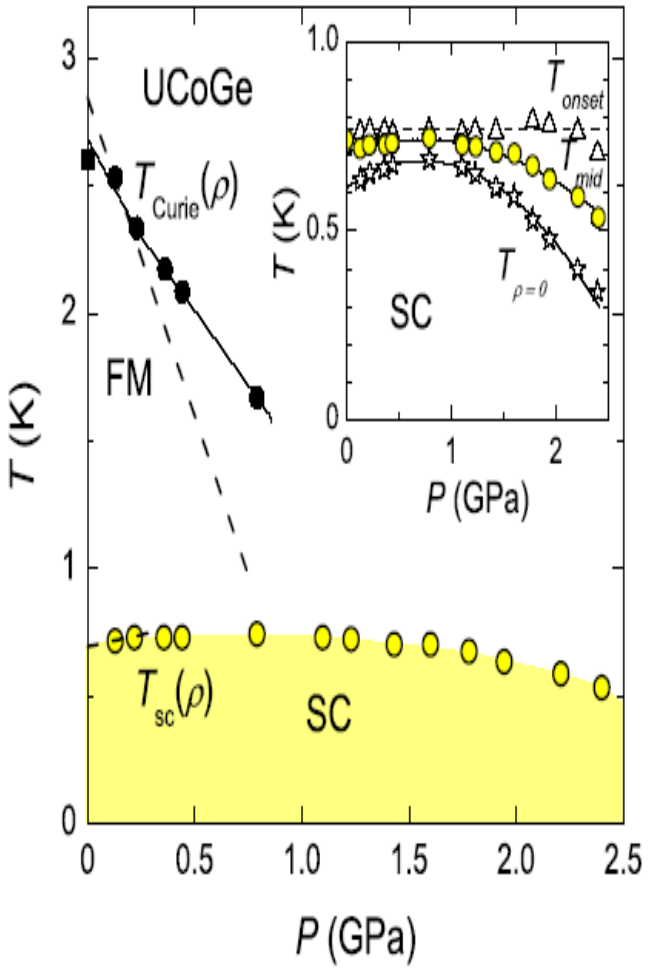




The calculation well reproduces the experimental results!

URhGe is a good example that the mass enhancement describes SC.





UCoGe (A deVisser) see also Ishida : **material improvement**