High pressure for studies of correlated electron systems

Daniel Braithwaite

Université Grenoble Alpes and CEA Grenoble

Heavy fermion systems

What are they ?
Why are they interesting ?
How does high pressure help ?

School on High pressure techniques, June 20th 2019

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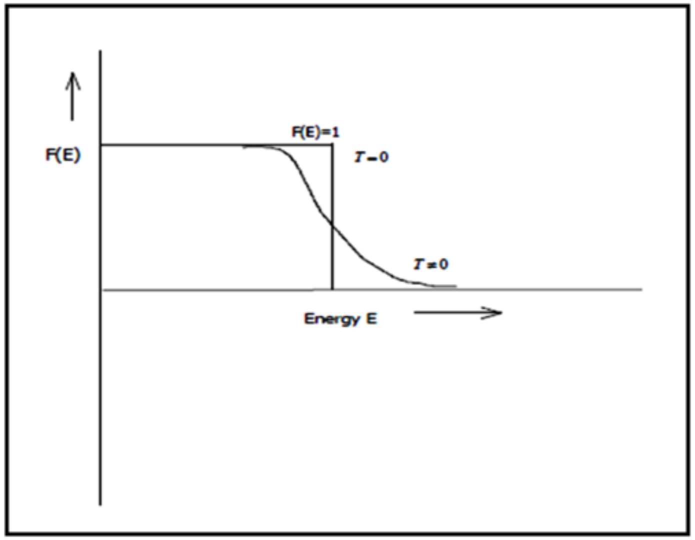
Heavy fermion systems

Some of the most exciting solid state physics today

Pressure experiments can be applied to many different materials

School on High pressure techniques, June 20th 2019

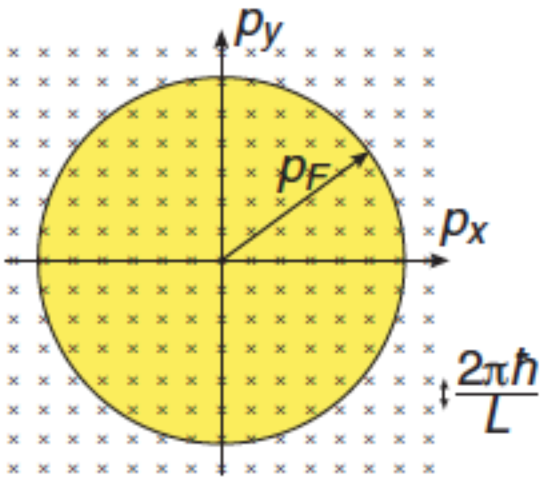
Fermi Gas



Drude-Sommerfeld model

$$c_{v,\mathrm{el}} = \frac{\partial u}{\partial T} = \frac{\pi^2}{3} g(\varepsilon_F) k_B^2 T = \frac{\pi^2}{2} n k_B \left(\frac{k_B T}{\varepsilon_F} \right) = \gamma T$$

Fermi Liquid or Landau-Fermi Liquid



$$\gamma^* = \frac{C}{T} = \frac{m^*}{m}\frac{3}{2}R\left(\frac{\pi^2 k_B}{3\varepsilon_F}\right) = \frac{m^*}{m}\gamma$$

$\rho = \rho_0 + AT^2$

Empirical relation : $A^2 \approx m^*$

C/T of copper 0.7 mJ/mol.K^2

$CeAl_3$: The 1st heavy fermion

Fermi liquid : $C=\gamma T$

$\rho=\rho_0+AT^2$

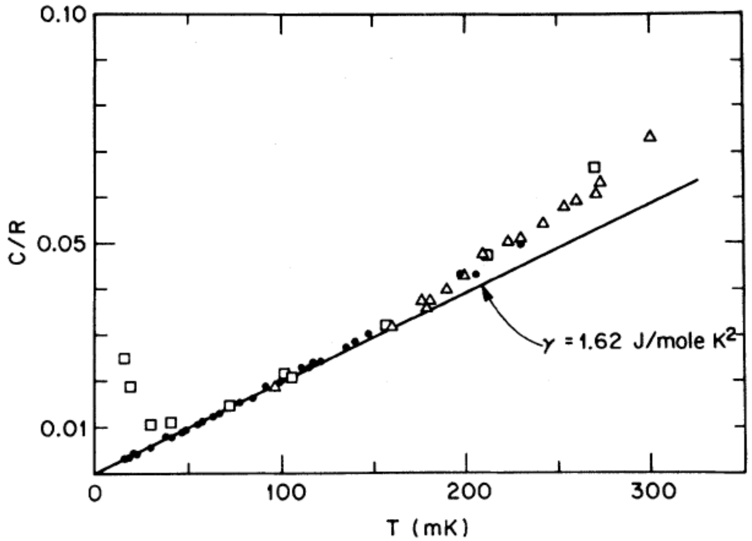


FIG. 1. Specific heat of $CeAl_3$ at very low temperatures in zero field (●, Δ) and in 10 kOe (□).

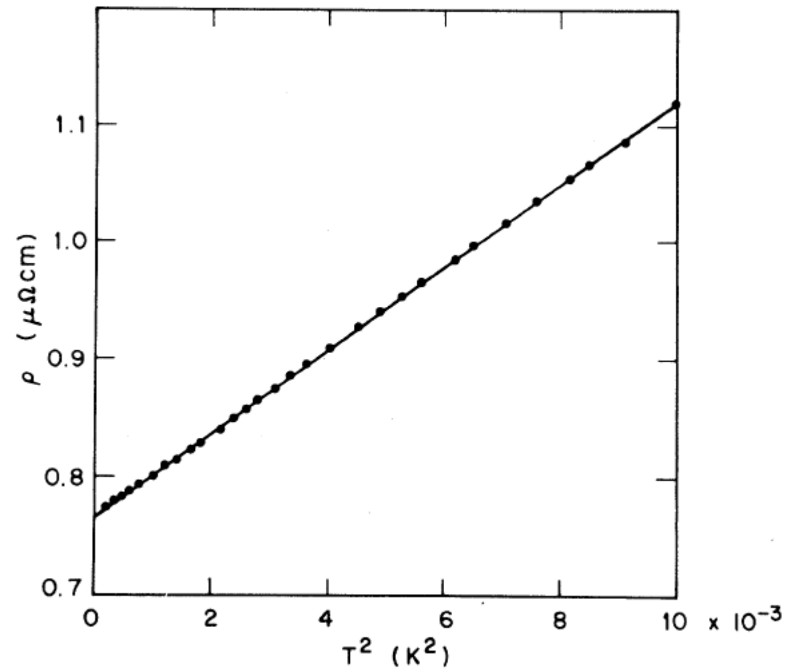
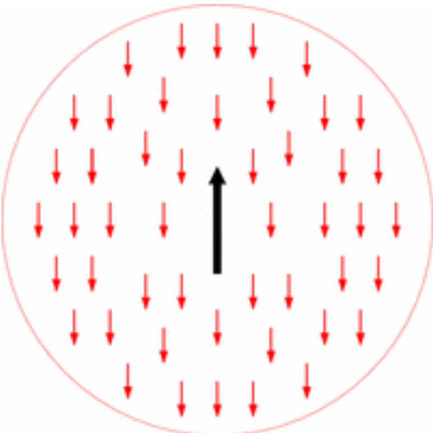


FIG. 3. Electrical resistivity of $CeAl_3$ below 100 mK, plotted against T^2.

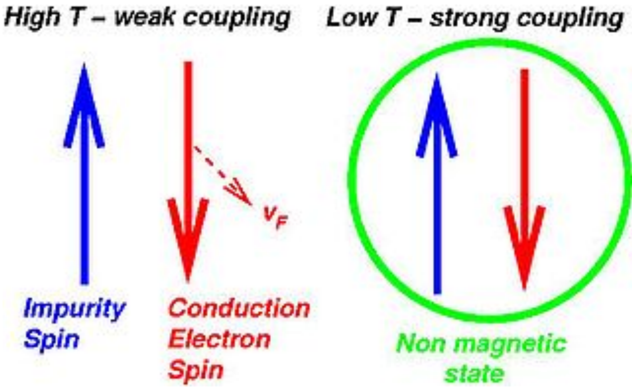
K. Andres et al. PRL 1975

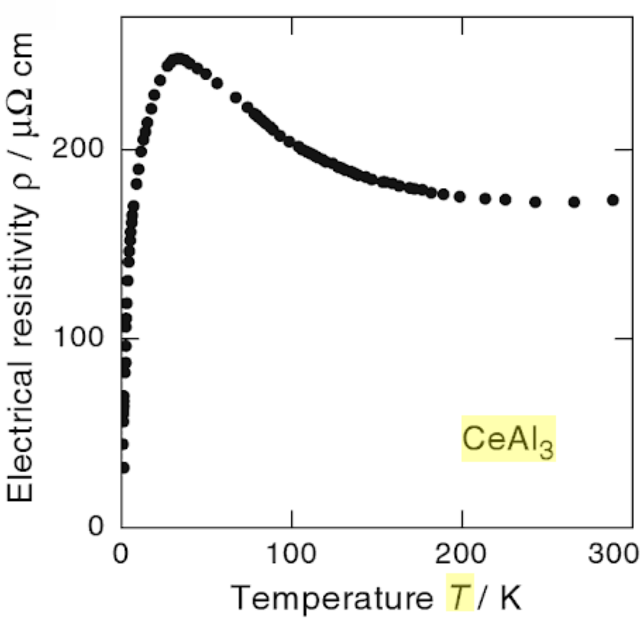
Heavy Fermions : Kondo Effect

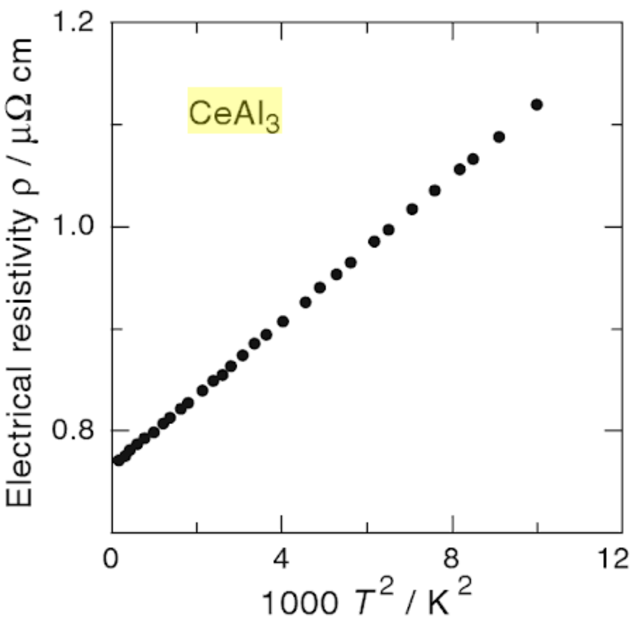
AF interaction between local spins and conduction electrons



Kondo impurety => singlet
Kondo Lattice :
exhaustion and coherence

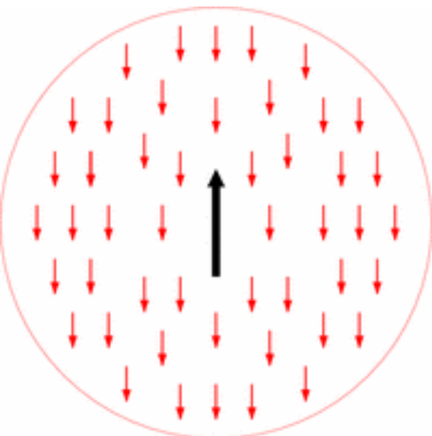






Heavy Fermions : Kondo Effect

AF interaction between local spins and conduction electrons



Kondo impurety => singlet
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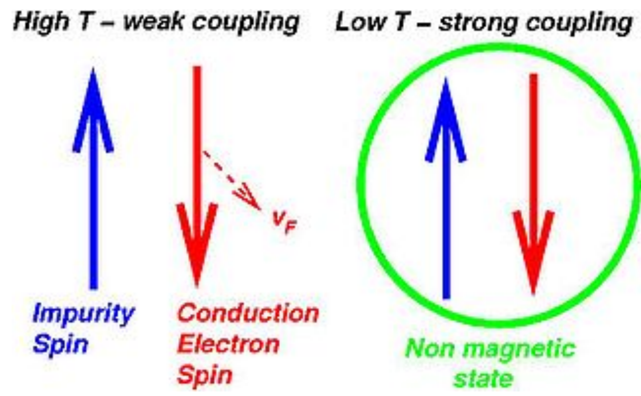
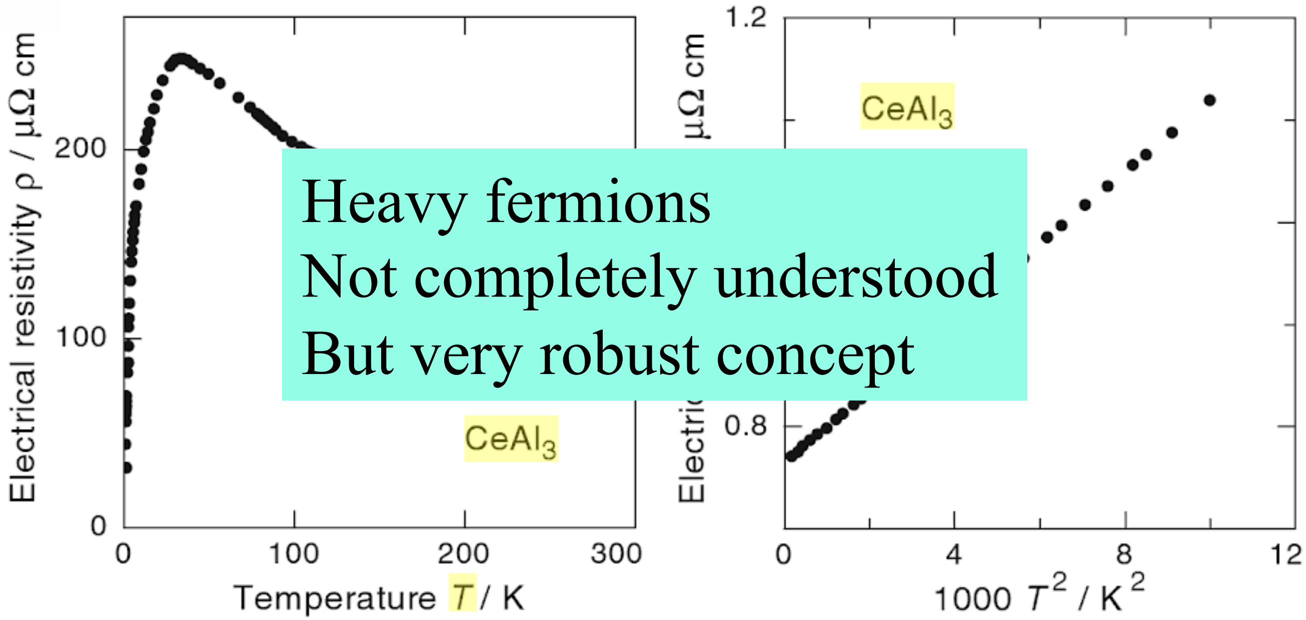
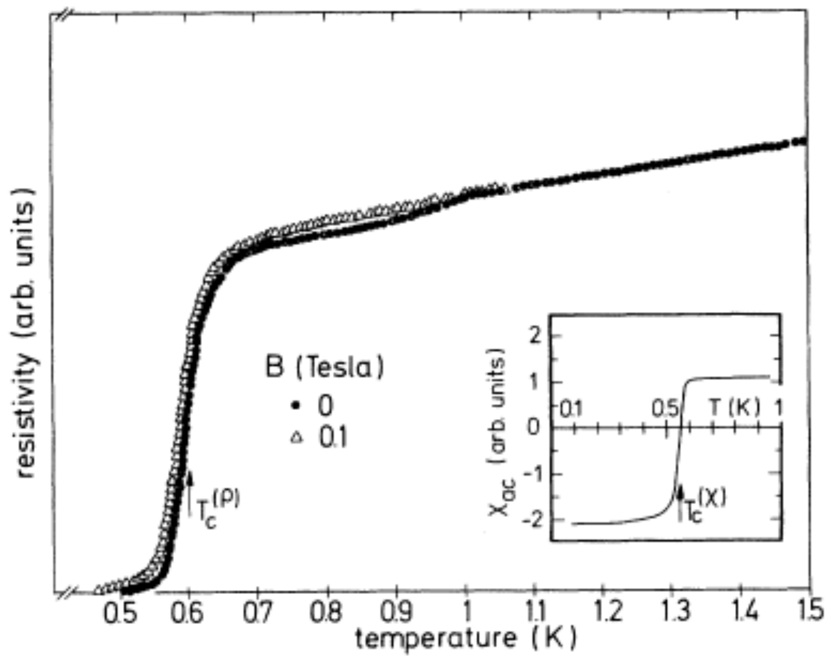
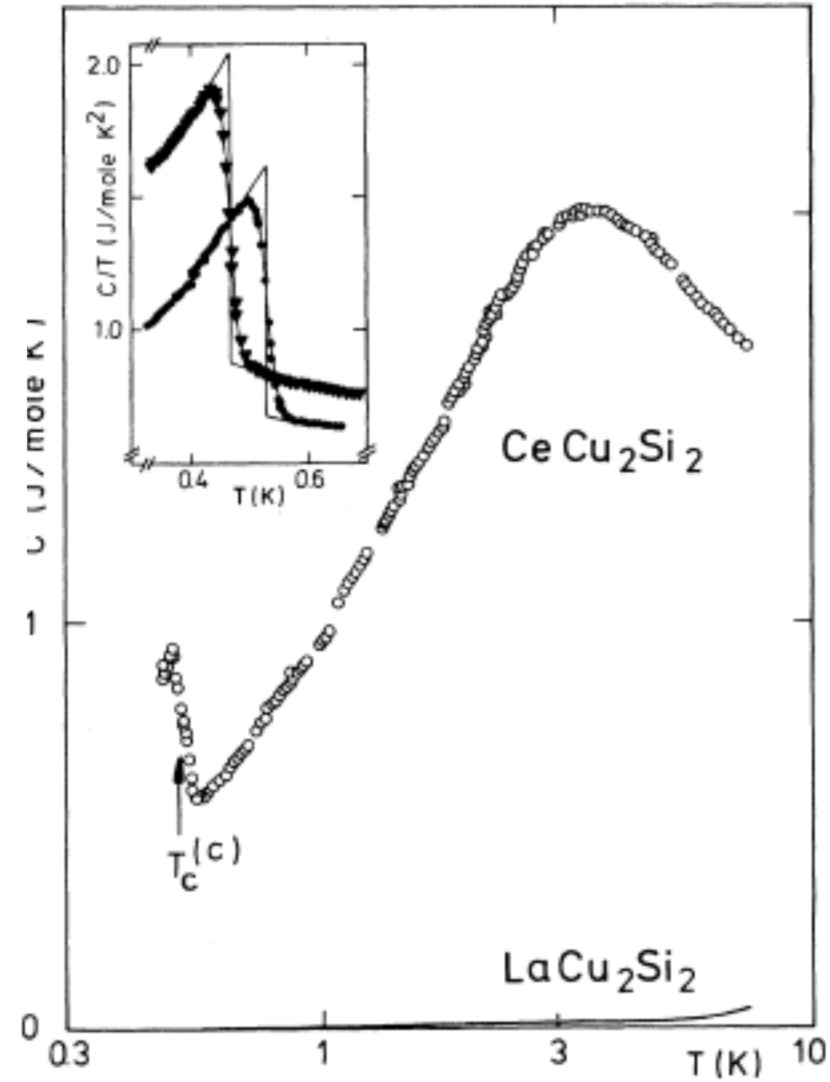




Heavy fermions
Not completely understood
But very robust concept

Unconventional superconductivity





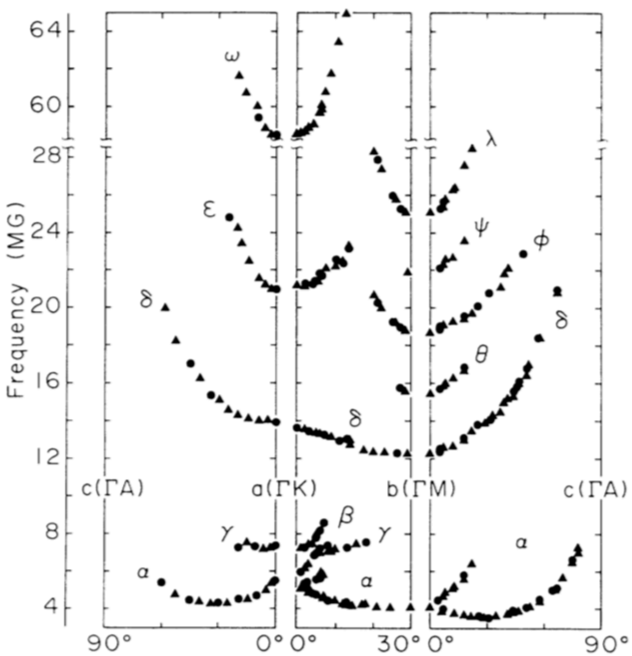
F. Steglich et al. PRL 43, 1892 (1979)

Heavy Quasiparticles seen by dHvA oscillations

VOLUME 60, NUMBER 15 PHYSICAL REVIEW LETTERS 11 APRIL 1988

Heavy-Fermion Quasiparticles in UPt_3

L. Taillefer and G. G. Lonzarich
Cavendish Laboratory, Cambridge CB3 0HE, United Kingdom
(Received 21 October 1987)



Branch:*FS* orbit	*F* (MG) Expt.	*F* (MG) Calc.	m^*/m_e Expt.	m^*/m_e Calc.
	a axis (Γ*K*)			
α:*ML*4	5.4(3)	10.4	25(3)	2.2
β:*L*4	6.0(4)	5.2	···	1.0
γ:Γ1	7.3(3)	8.2	40(7)	2.0
δ:*A*5	14.0(3)	9.1	50(8)	1.9
ϵ:Γ2	21.0(3)	24.0	60(8)	4.6
ω:Γ3	58.5(5)	52.8	90(15)	5.3
	b axis (Γ*M*)			
α:*ML*4	4.1(2)		15(5)	
δ:*A*5	12.3(2)		30(3)	
θ:*A*4,5	15.5(2)		35(7)	
φ:*A*4,5	18.7(3)		40(8)	
ψ:*A*4,5	21.9(4)		···	
λ:*A*4	25.1(5)		(50)	

Heavy Fermions are model systems for studies

Reduced energy scales

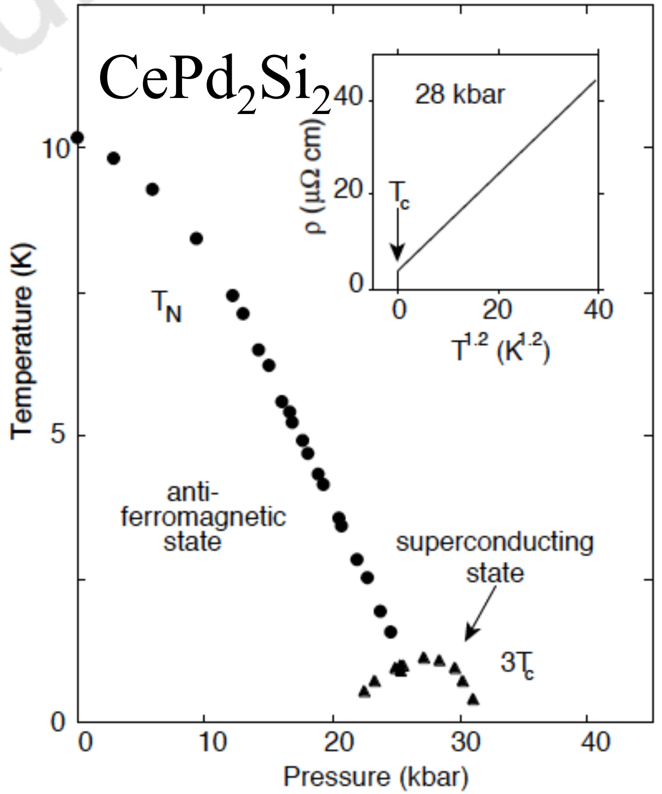
T_F 10^5 K => T_K 10K -100K

Easy to change ground state with external H, P

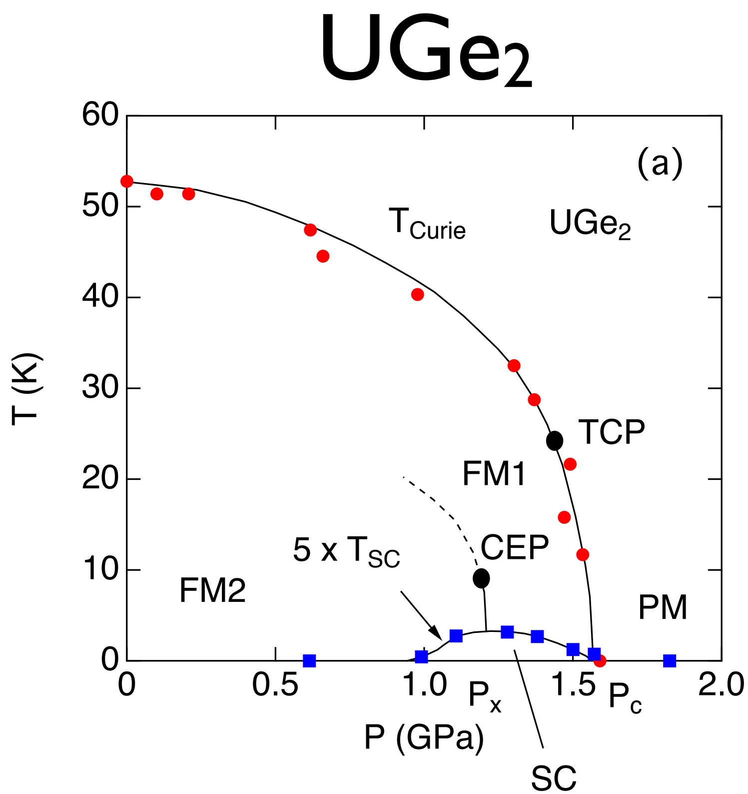
High pressure to probe strongly correlated systems

$dV/V = dP/B_0$ Typically 1 GPa => $dV/V = 1\%$ ($B_0 = 100$ GPa)

But low energy scales => relatively low pressures needed



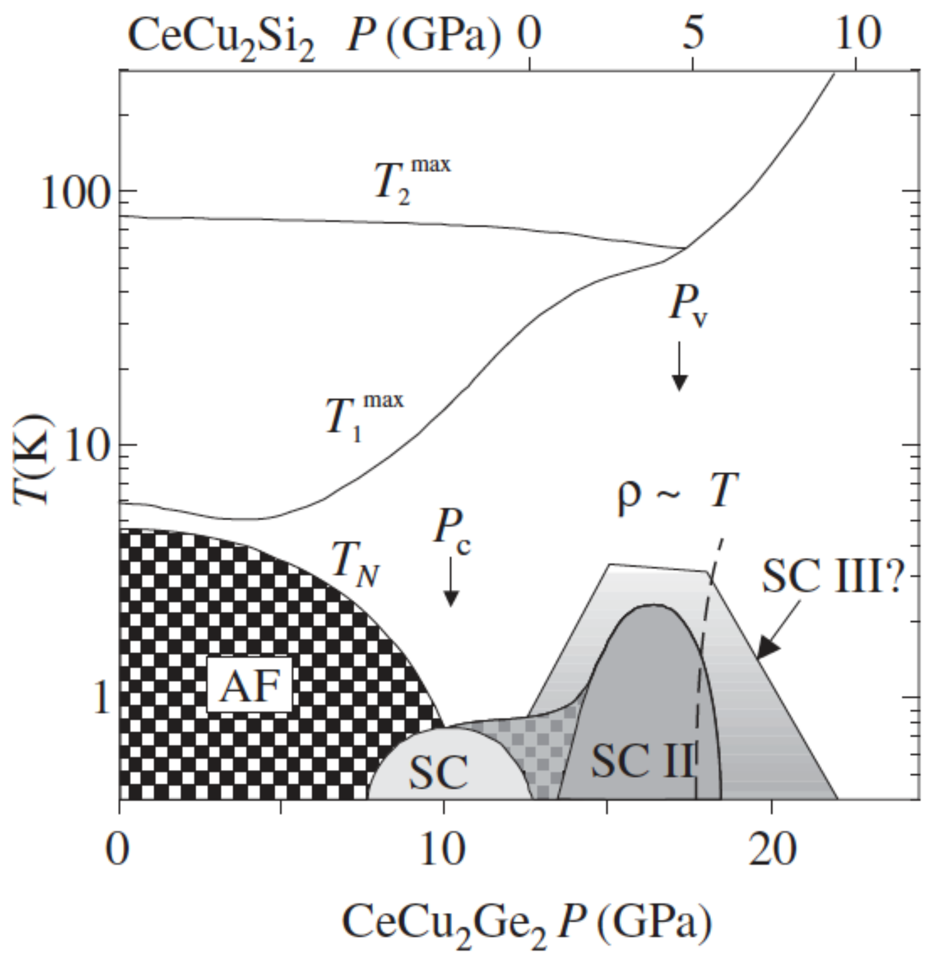
N. Mathur et al. NATURE |VOL 394 | 2 JULY 1998



Saxena et al. Nature 406 (2000) 587

Often 2-3 GPa is enough : Large volume piston cylinder cells

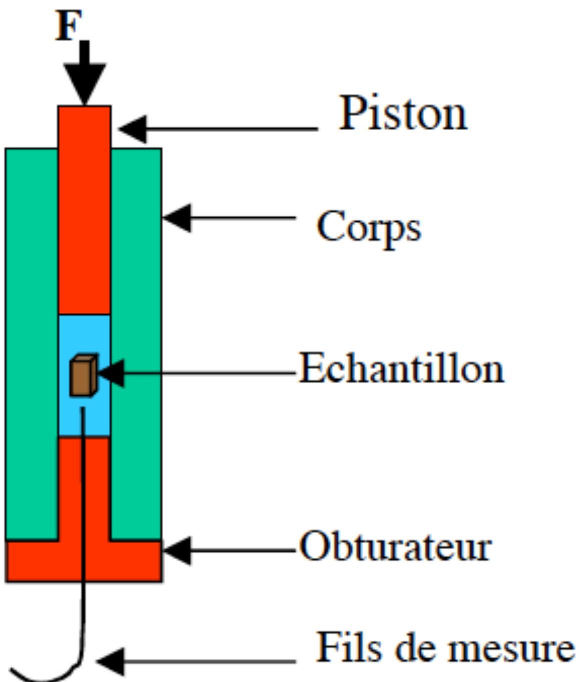
But not always…



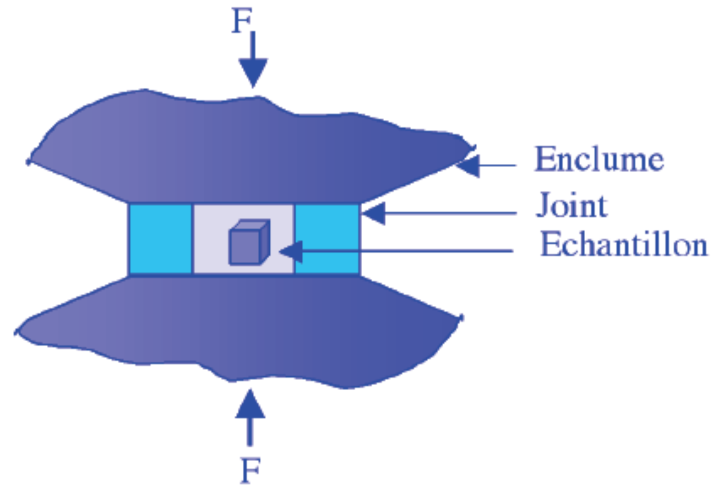
A. Holmes et al. J. Phys. Soc. Jpn., Vol. 76, No. 5

Pmax 10-20 GPa is desirable

High pressure generation

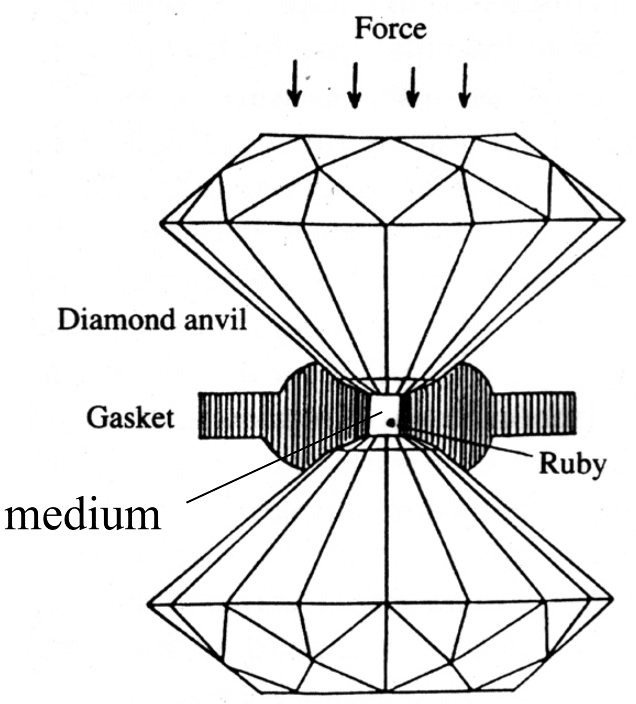


Piston/cylinder
3 GPa

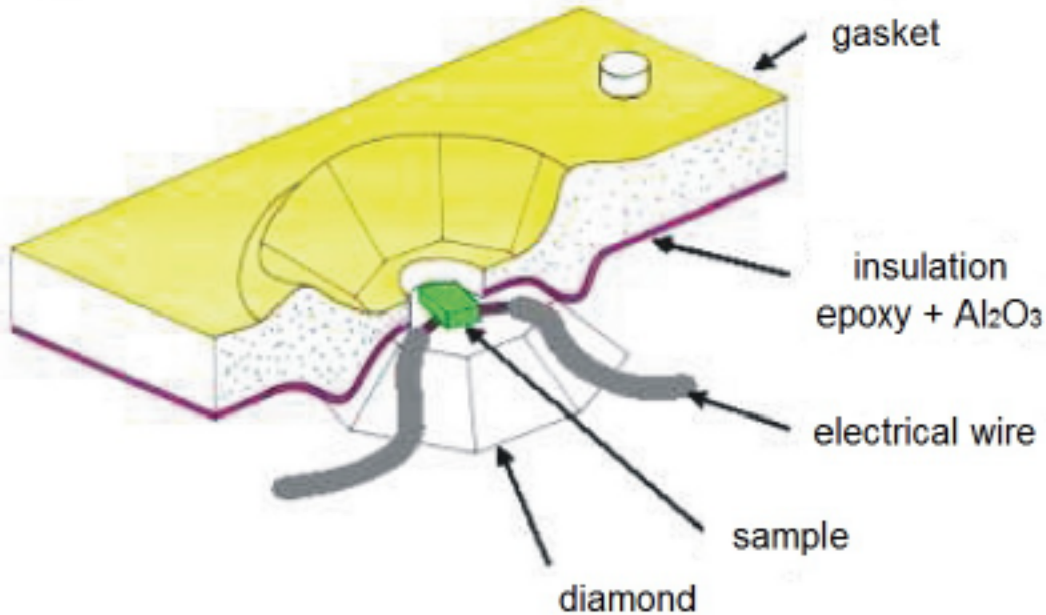


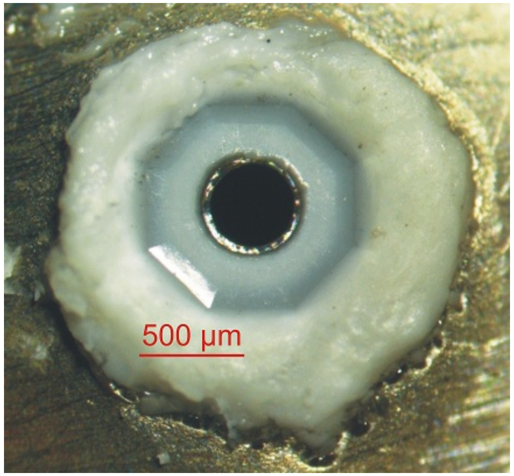
Anvil cell
30 GPa

Measurements in the DAC

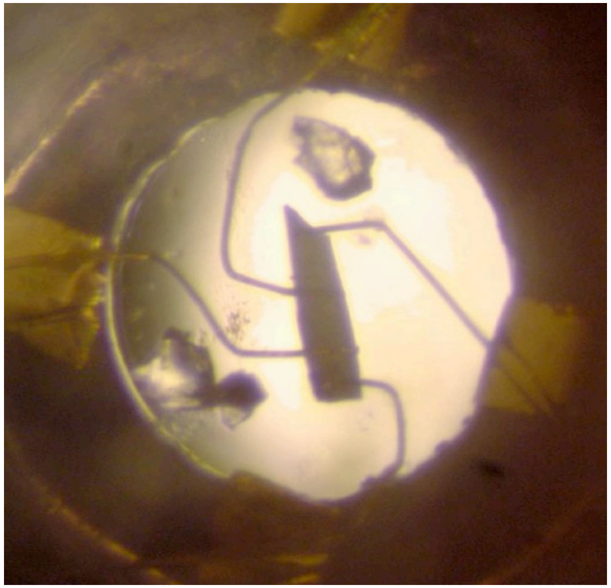


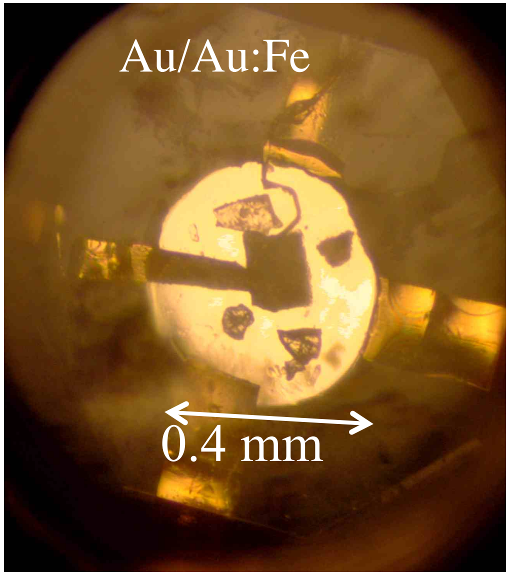
The principle of a DAC.

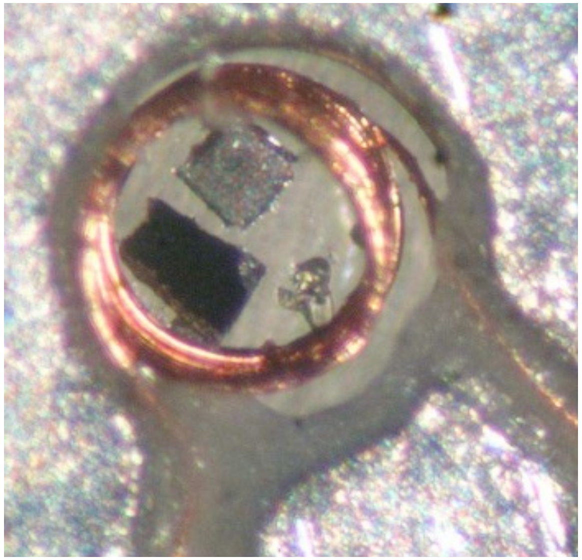


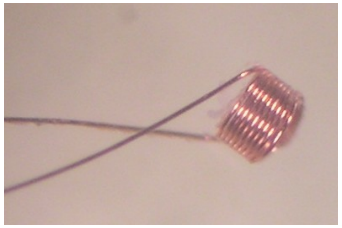


Measurements in the DAC



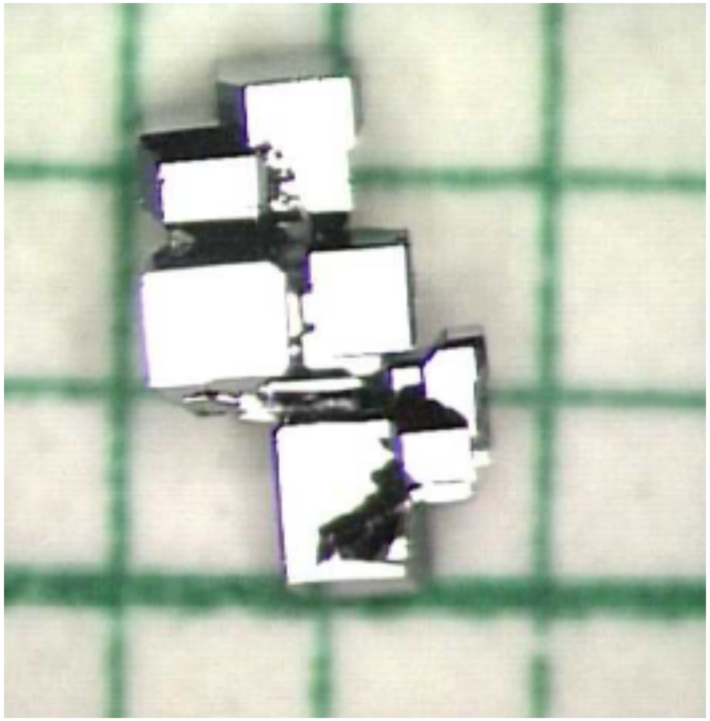


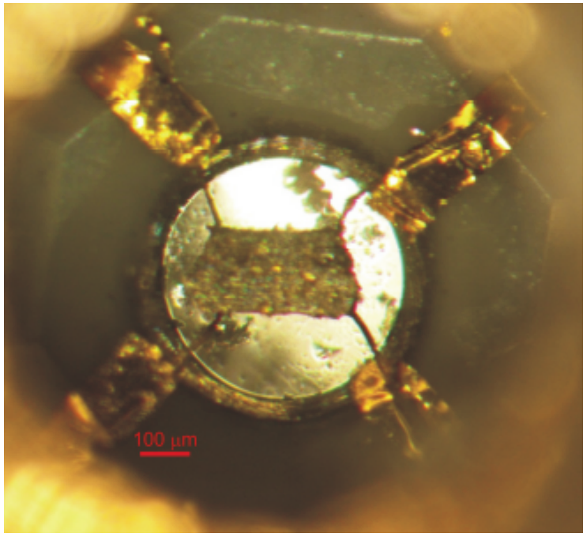




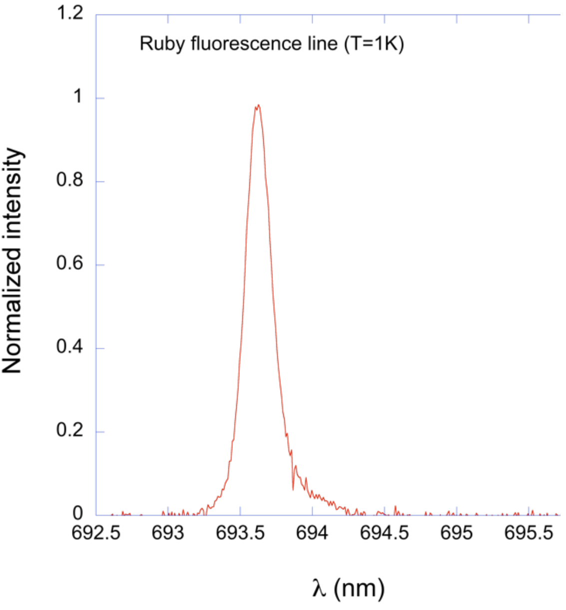
Resistivity, calorimetry, ac susceptibility
15 GPa, 50mK, 18T

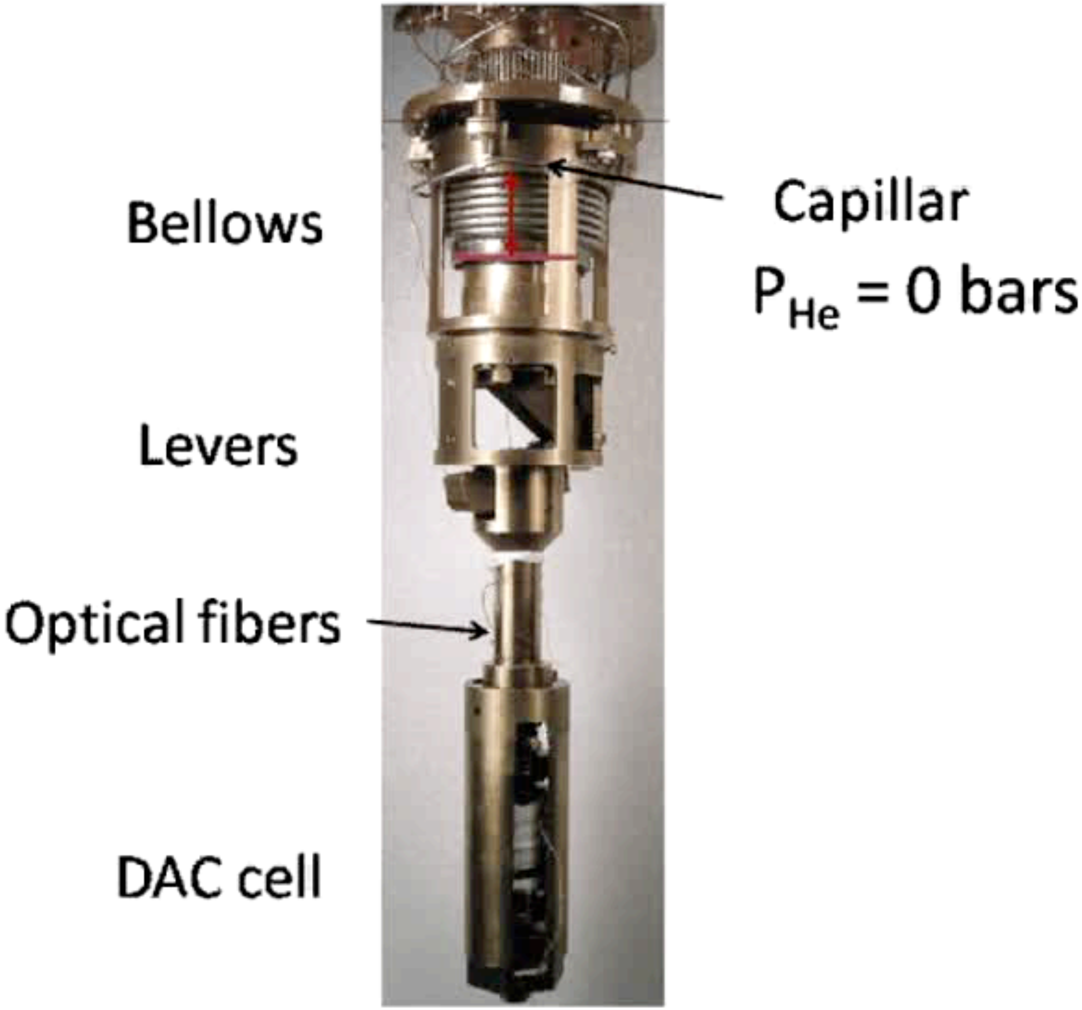
Material growth : single crystals





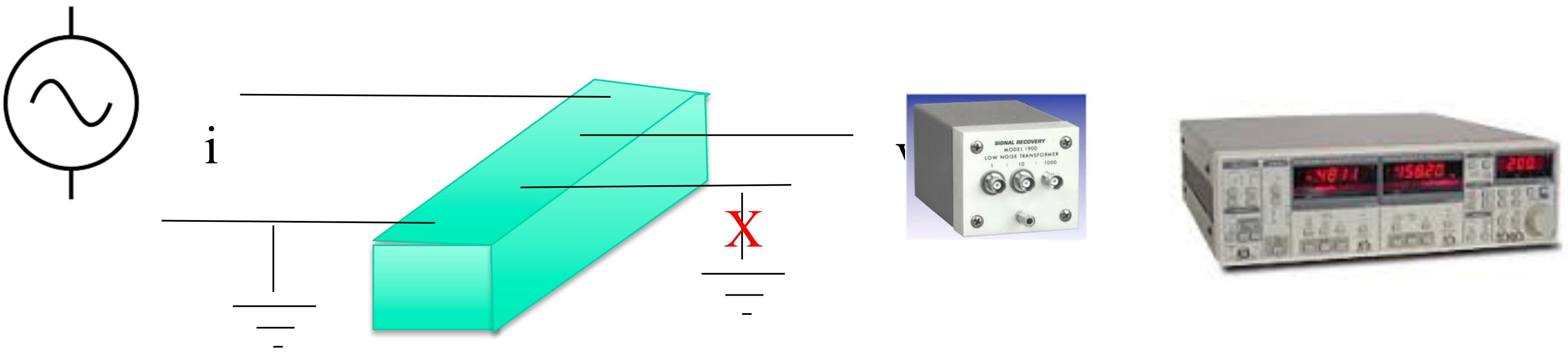
In-situ pressure tuning





Transport measurements

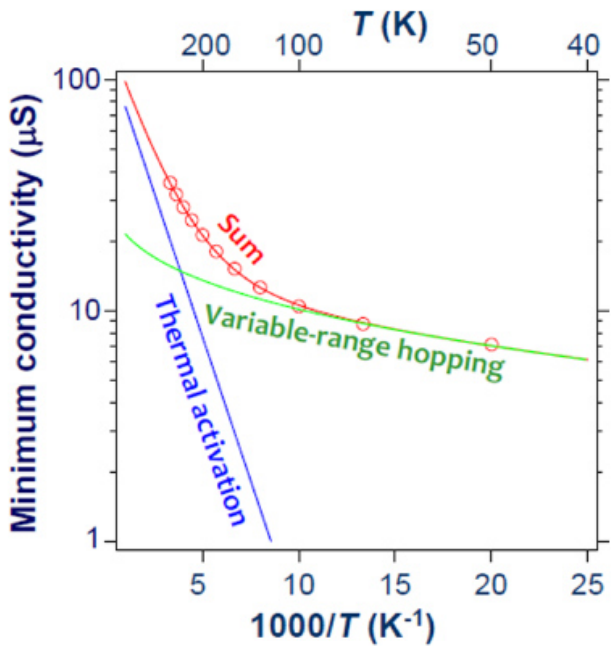
Resistivity



$$R=\rho L/S=\rho L/lxh$$

Semi-conductors

activation



Metals

Scattering

$\rho = \rho_{IMP} + \rho_{PH\,+} + \rho_{MAG} + \rho_{EL}$

ρ_{IMP} =Cte

ρ_{PH} = T^5 (LT) then T

ρ_{MAG} = complicated !

ρ_{EL} = AT^2 with A^2 proportional to m*

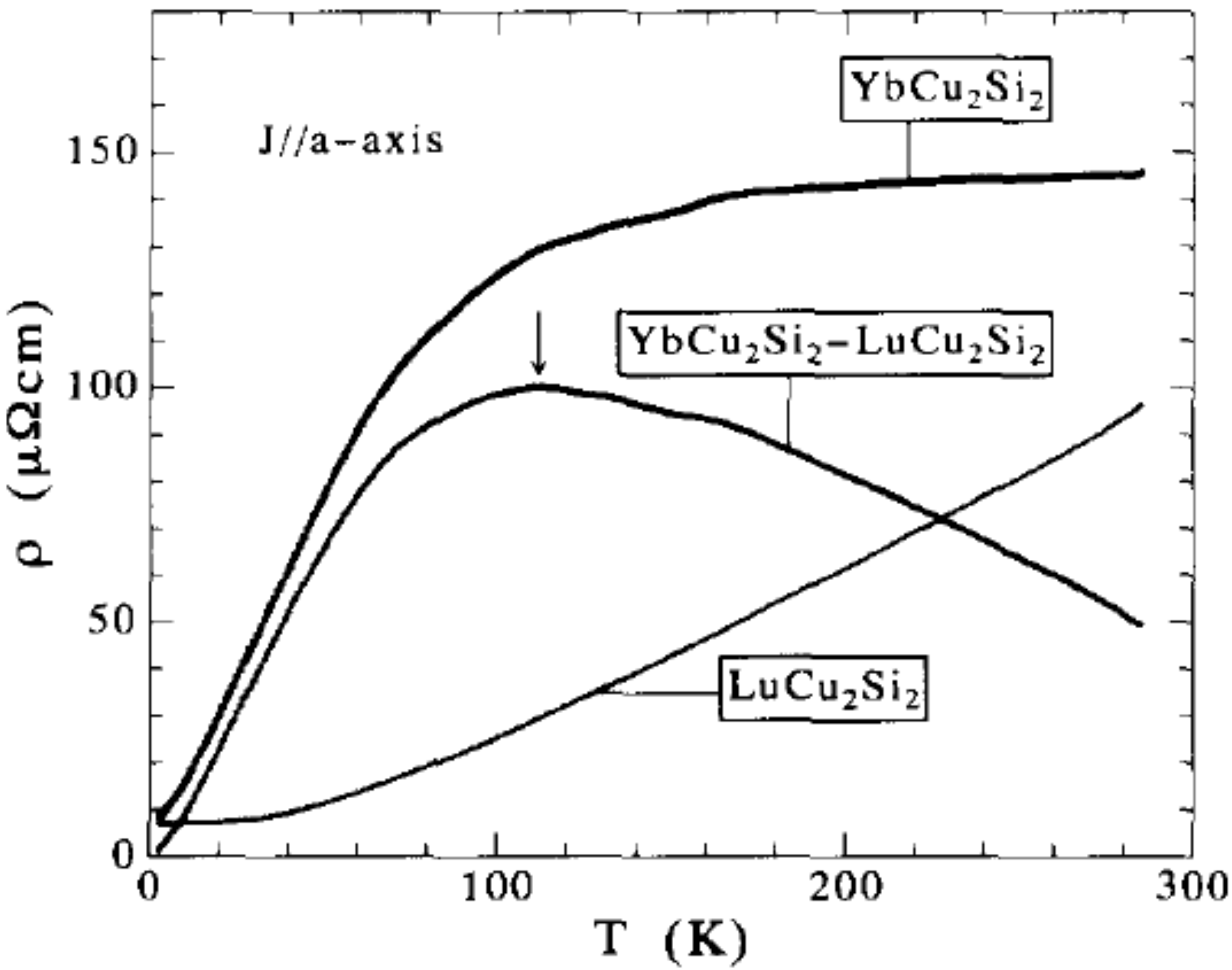
Superconductors

R=0

Electrical transport

Scattering

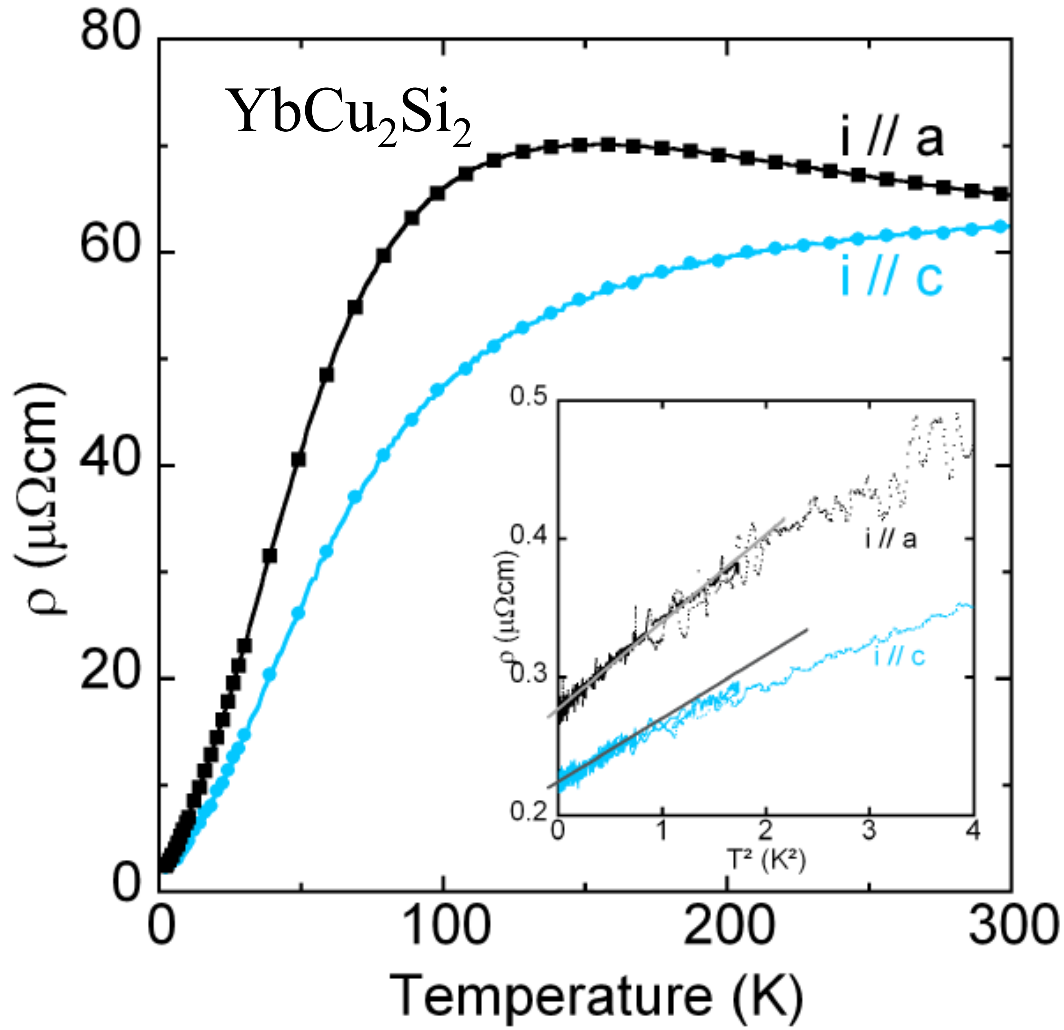
$\rho = \rho_{IMP} + \rho_{PH} + \rho_{MAG} + \rho_{EL}$



Anisotropy => need single crystals

Scattering

$\rho = \rho_{IMP} + \rho_{PH+} + \rho_{MAG} + \rho_{EL}$

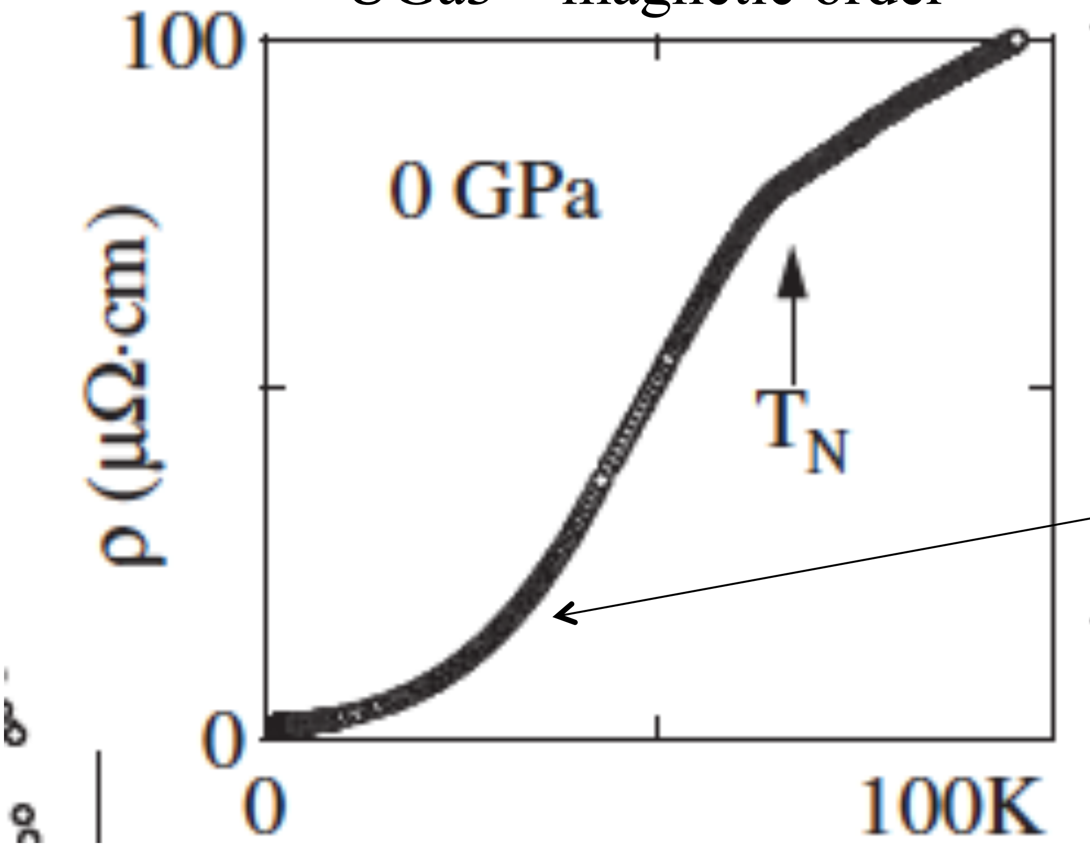


Electrical transport

Scattering

$\rho = \rho_{IMP} + \rho_{PH+} + \rho_{MAG} + \rho_{EL}$

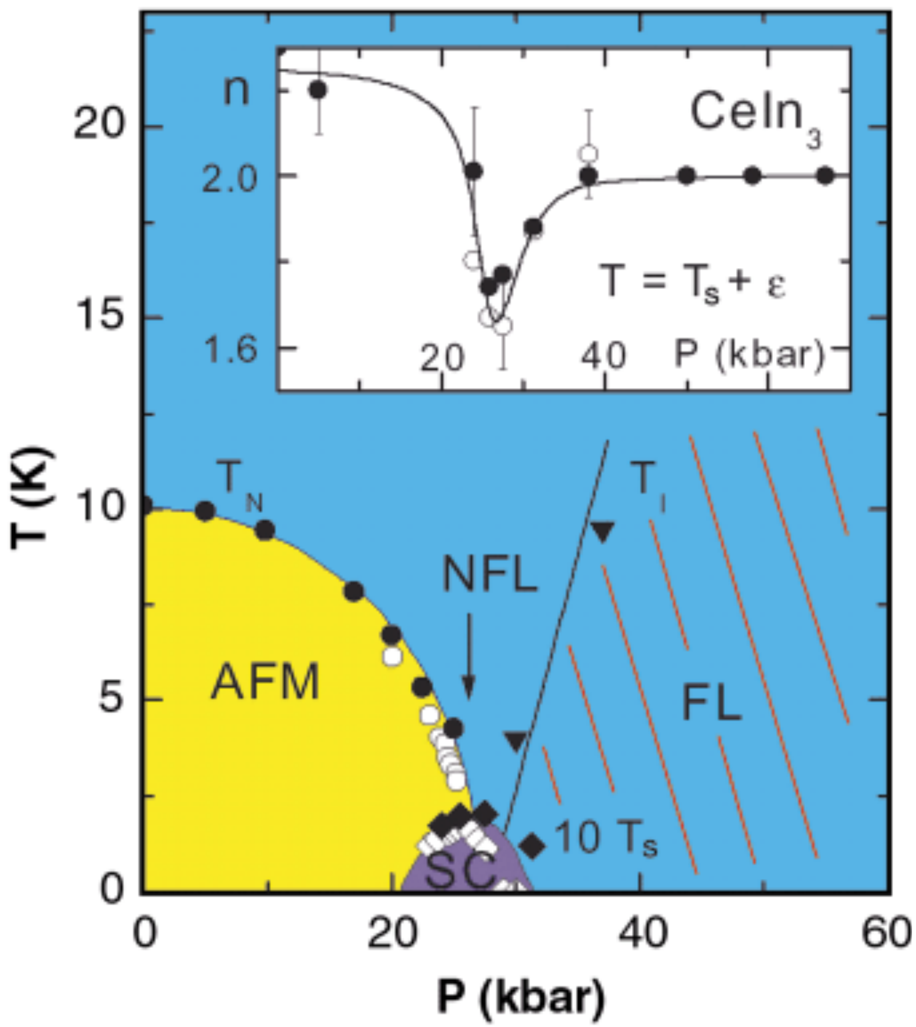
UGa3 – magnetic order



Magnons

T^n with n>2

Magnetically mediated superconductivity at a QCP



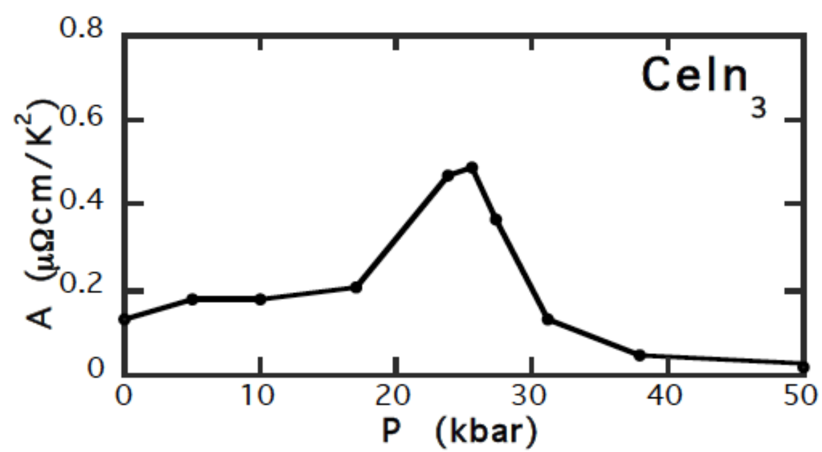
Quantum critical point

Fluctuations diverge even at 0K

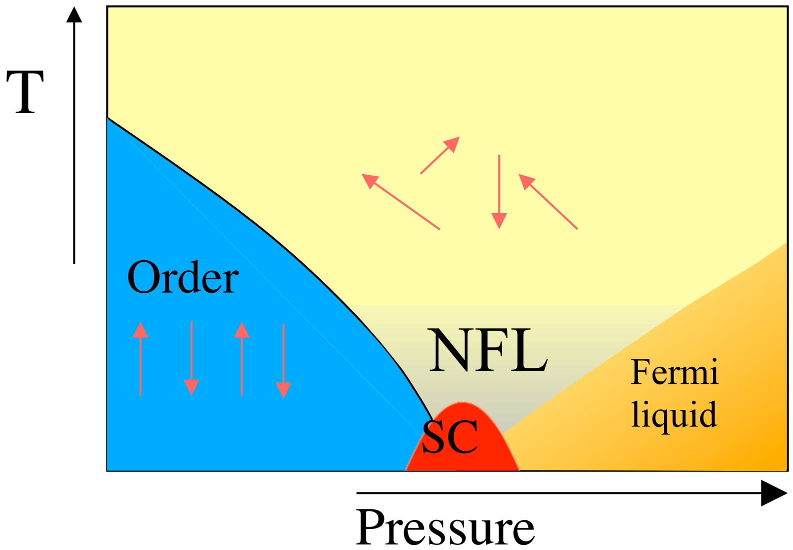
Non-Fermi Liquid effect

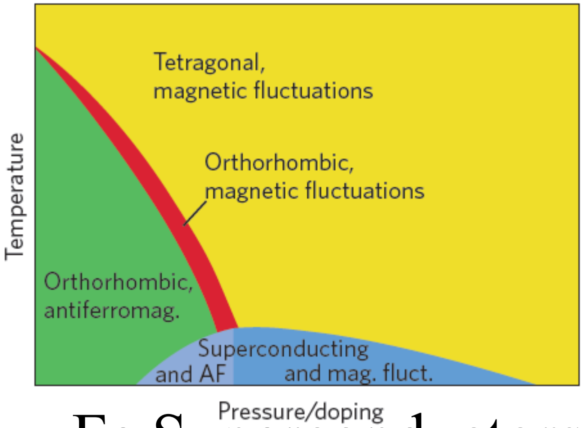
Increase of effective mass

Superconductivity

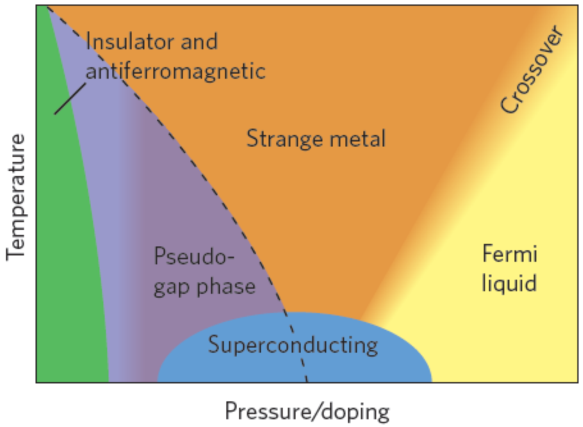


Heavy Fermions : model systems for Quantum Criticality





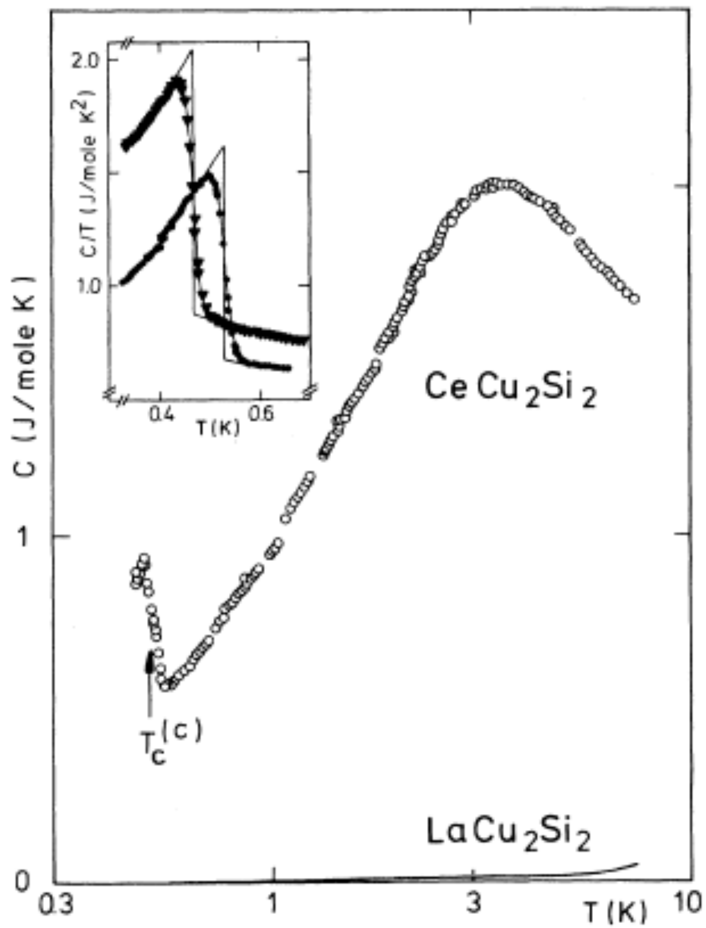
Fe Superconductors



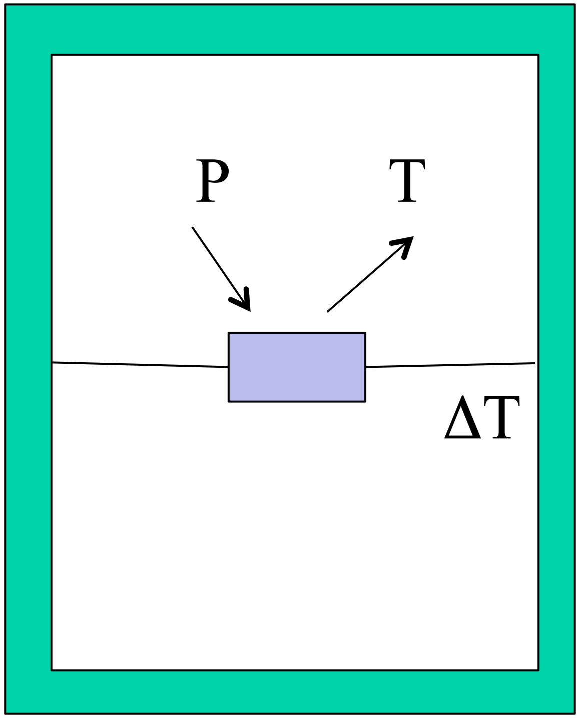
High T_C Superconductors

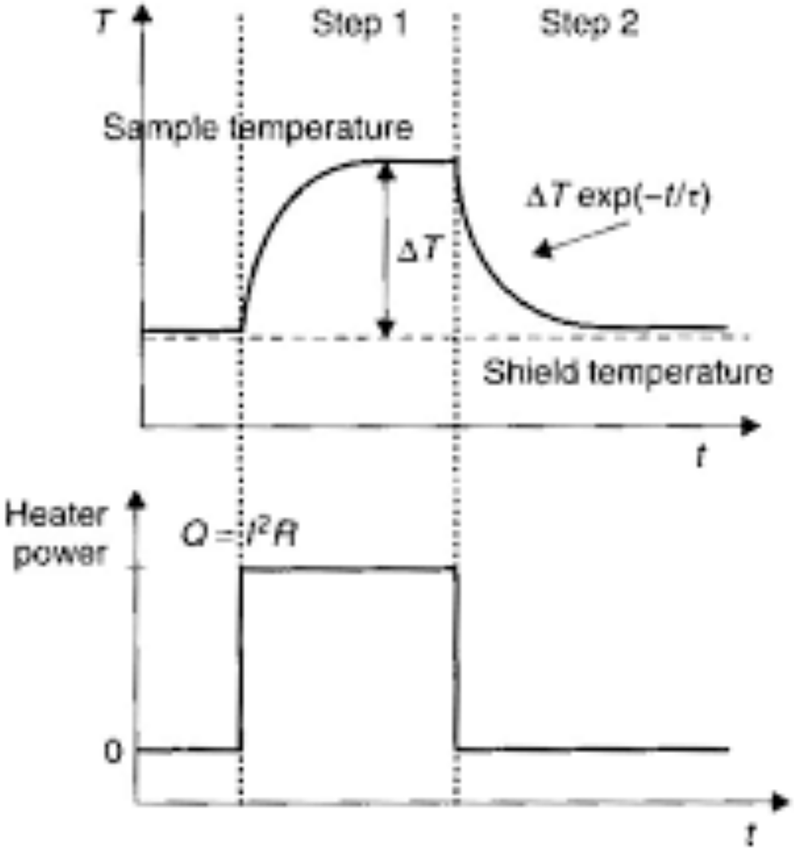
Specific Heat

Thermodynamic quantity



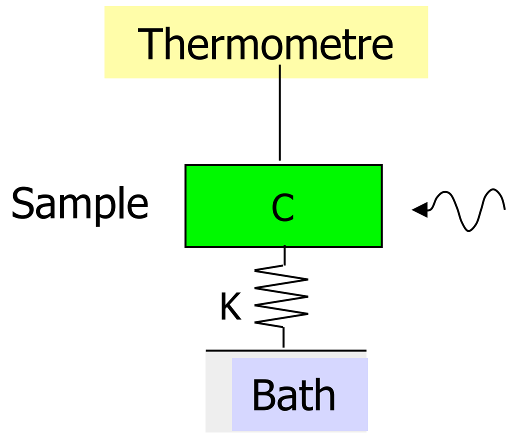
Non-adiabatic relaxation method





(b)

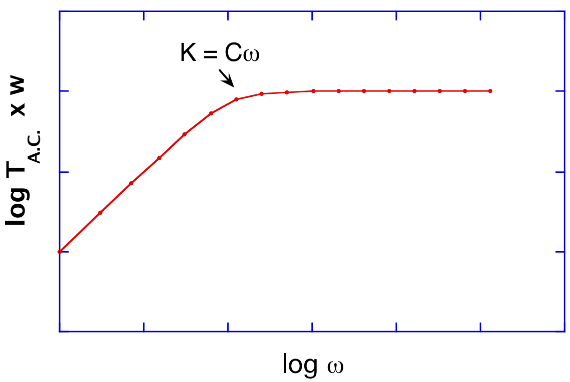
A.C. Specific heat measurement



$$T_{ac} = \frac{P_0}{K + jC\omega}$$

$$P = P_0(1+\cos\omega t)$$

C is contained in the signal *amplitude* and *Phase*

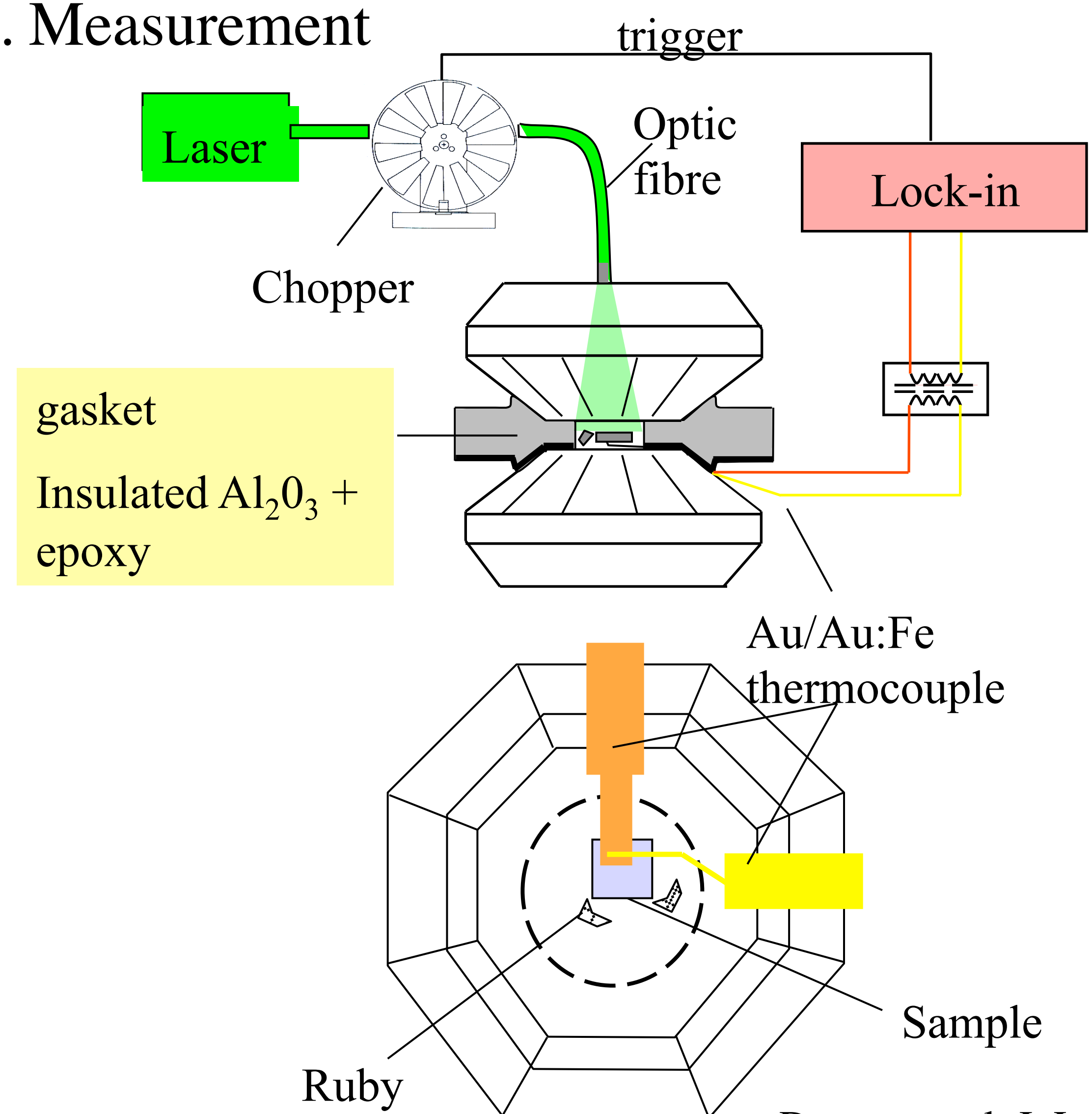


High frequency - C

Low frequency - K

In the diamond anvil cell

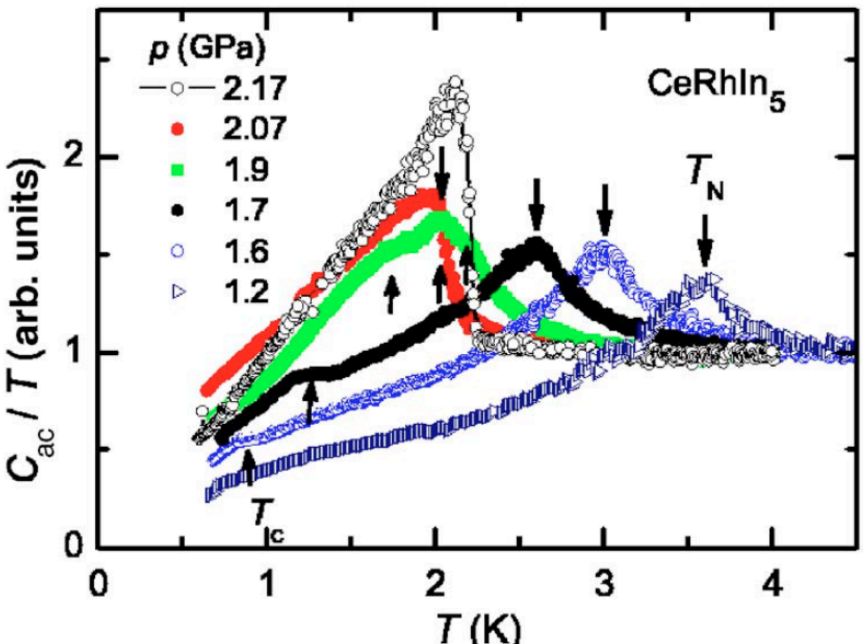
A.C. Measurement

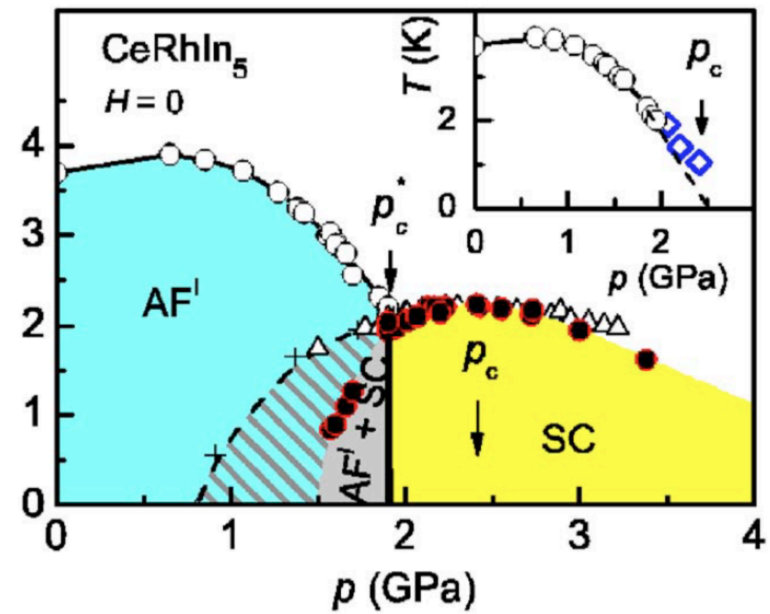


Demuer et al. J. Low Temp. Phys. (2000)

AC specific heat under pressure

Not quantitative *but* bulk measurement

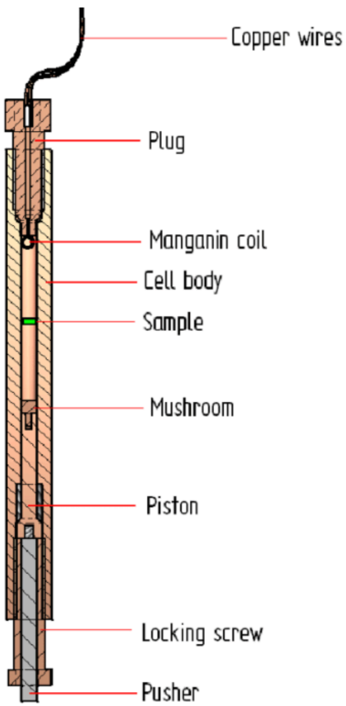


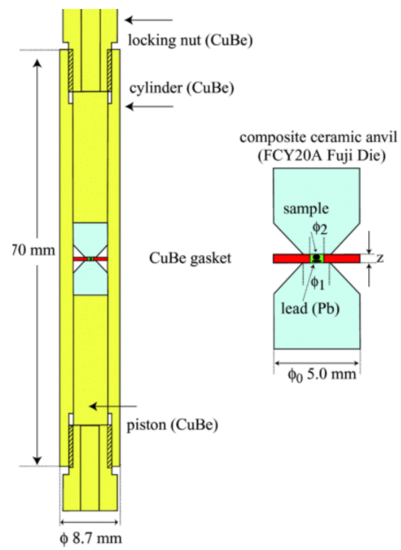


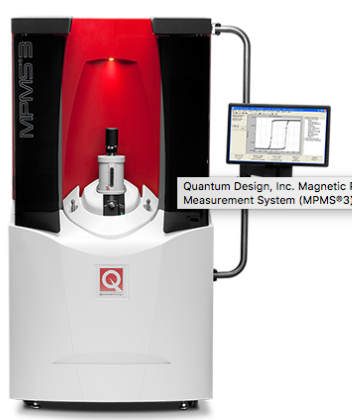
G. Knebel et al. PHYSICAL REVIEW B **74**, 020501R 2006

In general AF order and SC are in competition, even though AF fluctuations are probably the mechanism behind SC

DC Magnetization measurements



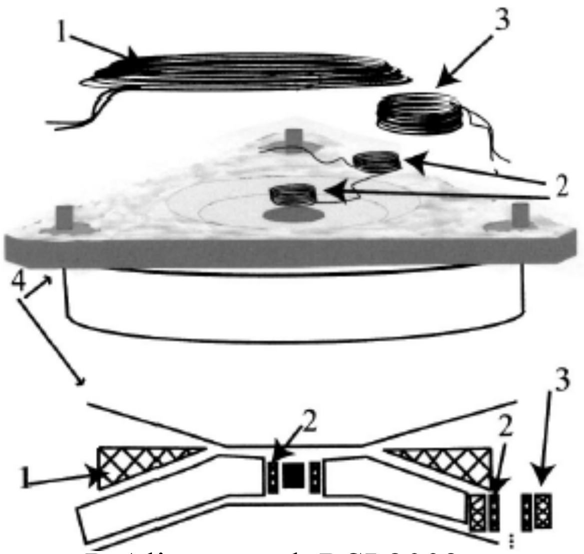




NV centres

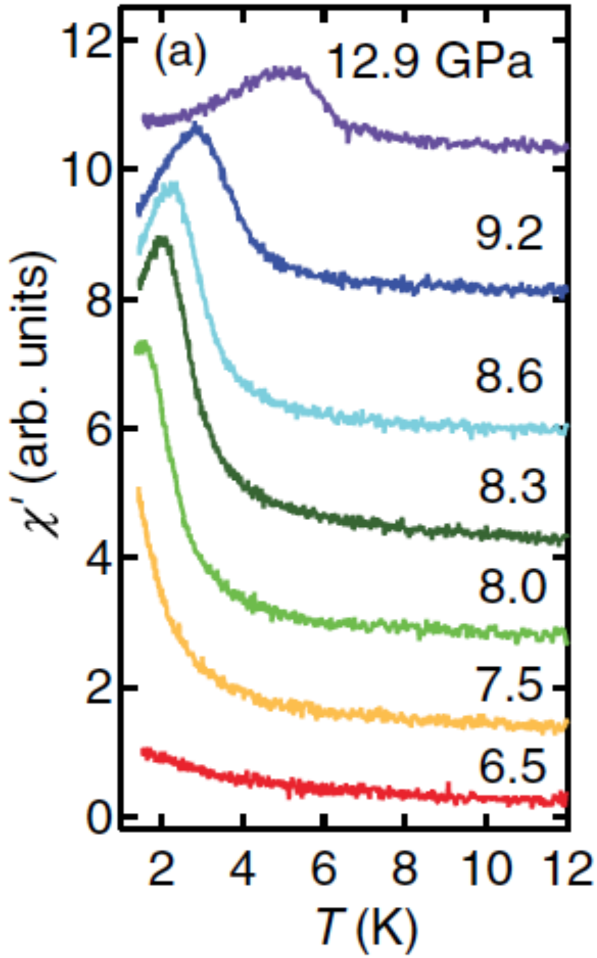
XMCD

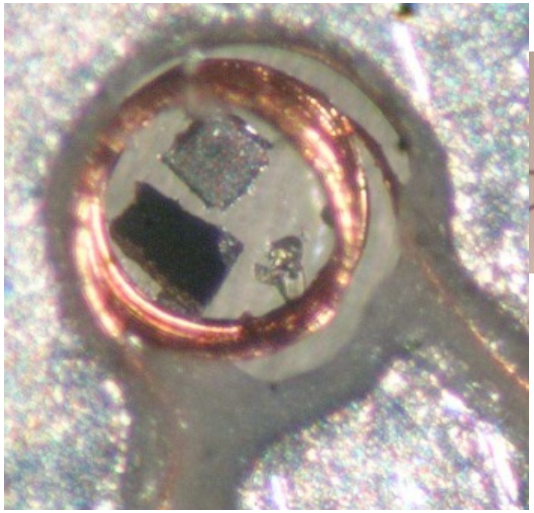
AC Magnetization measurements

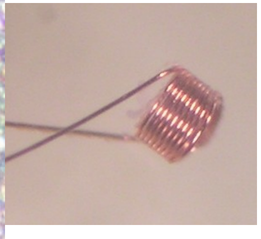


P. Alireza et al. RSI 2003

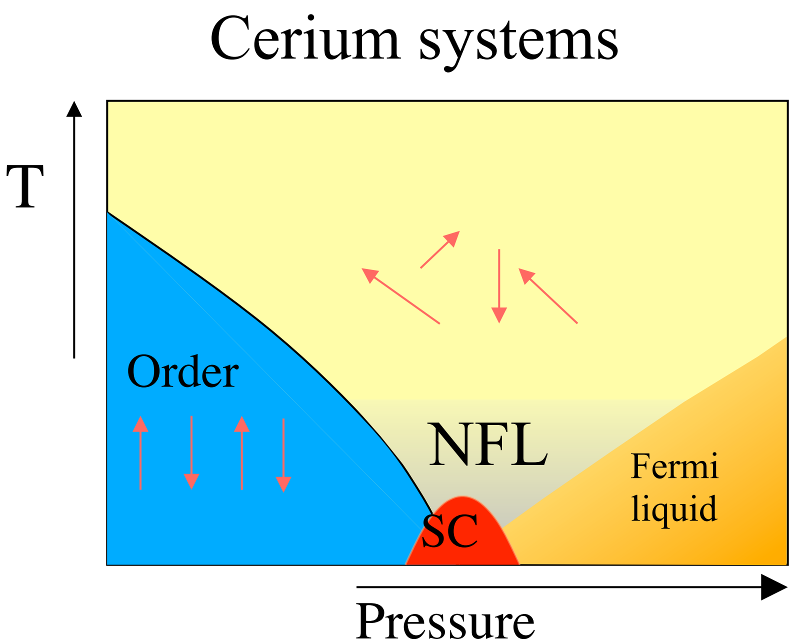
YbCu$_2$Si$_2$

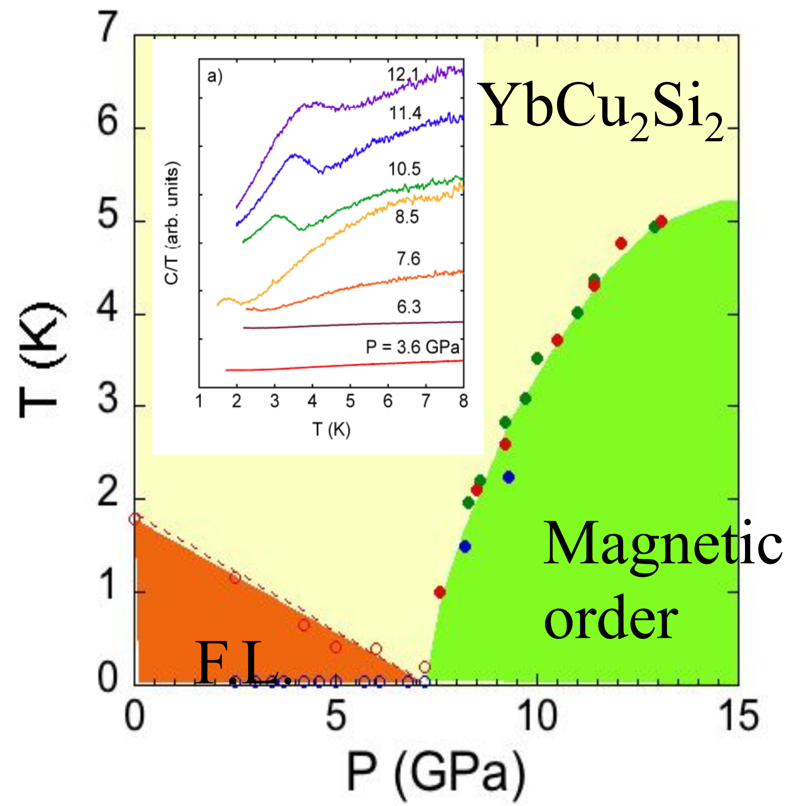






Quantum critical point in $YbCu_2Si_2$



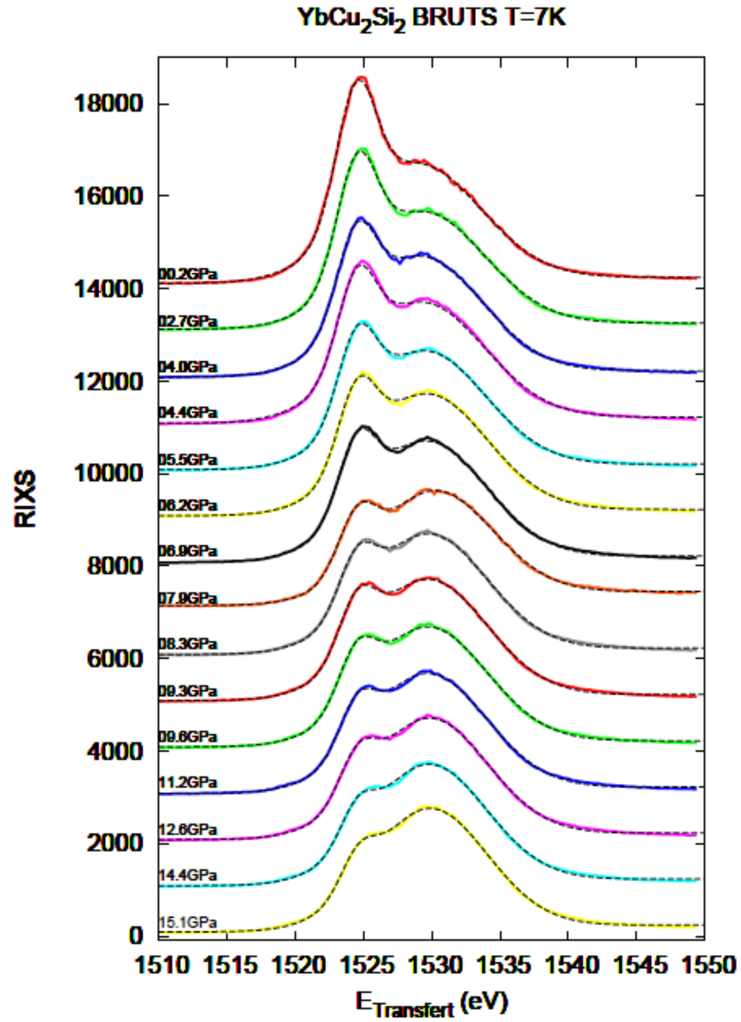


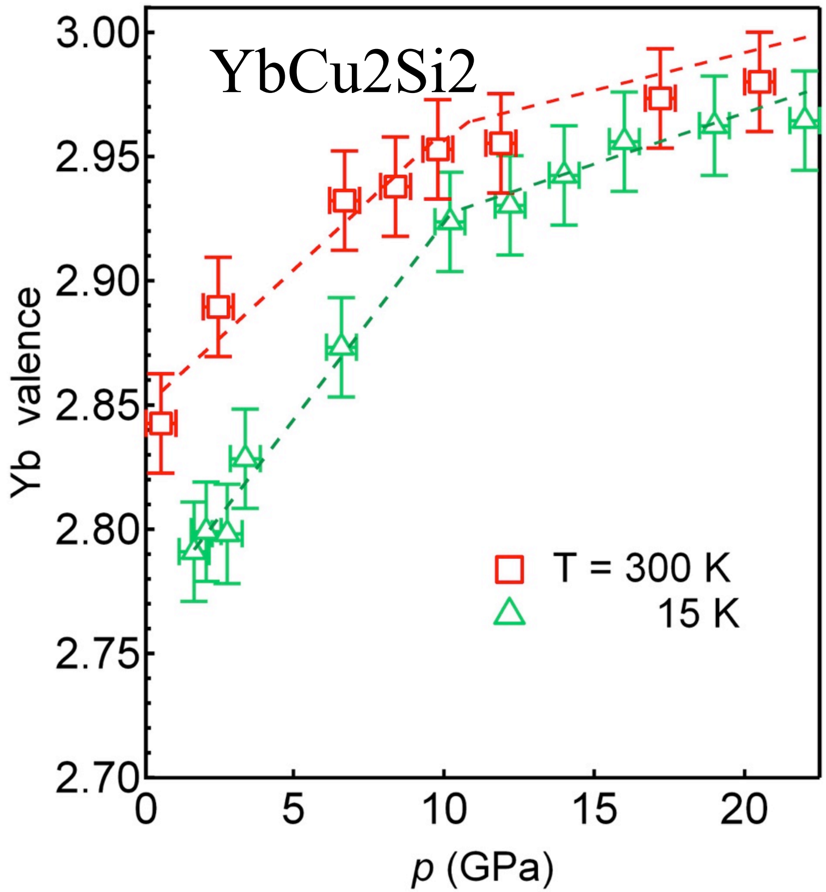
Ce^{3+} ($4f^1$) magnetic → Ce^{4+} ($4f^0$) non-magnetic

Increasing of pressure:

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

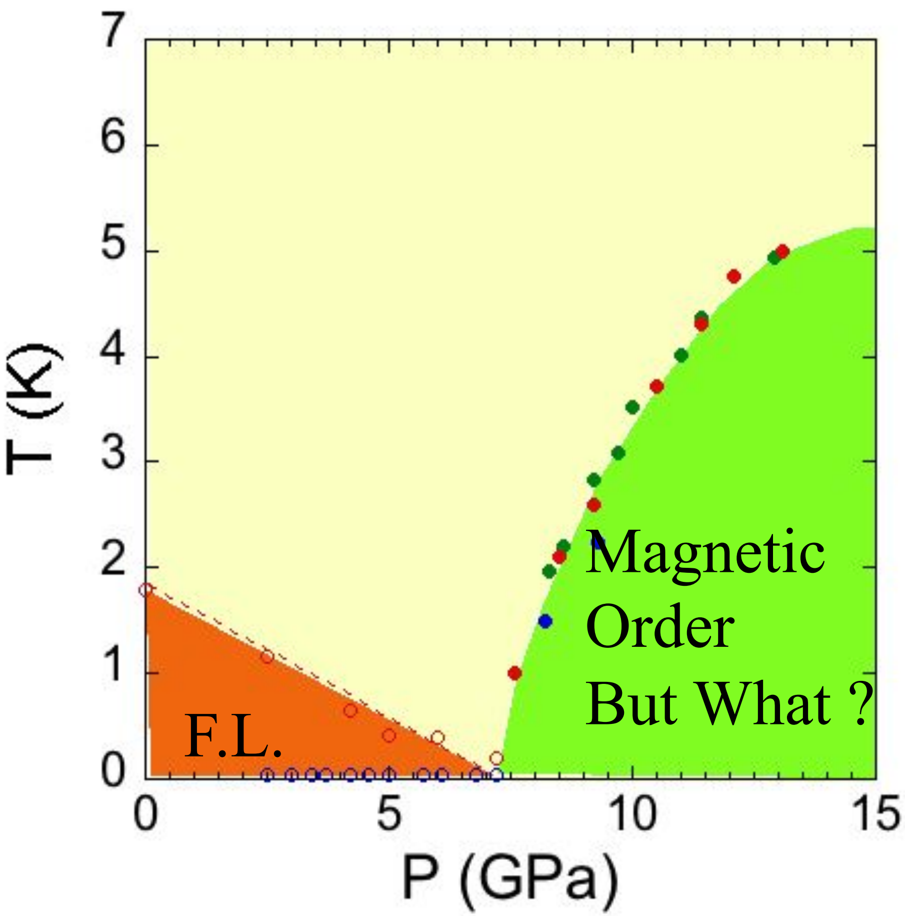
RE valence measured by RIXS

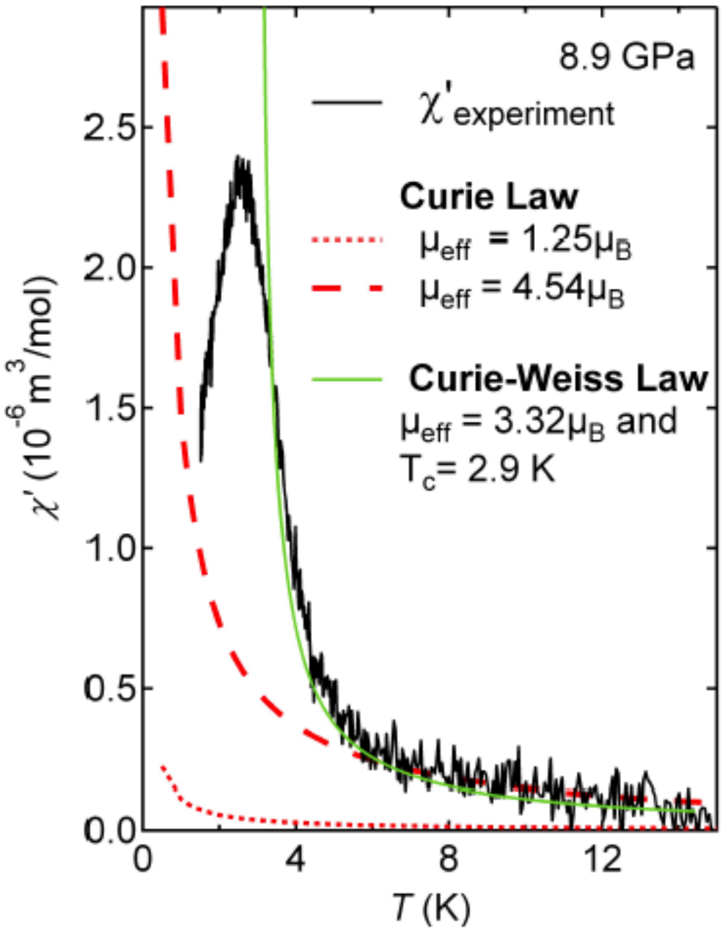




A. Fernandez-Pañella et al PRB 2012

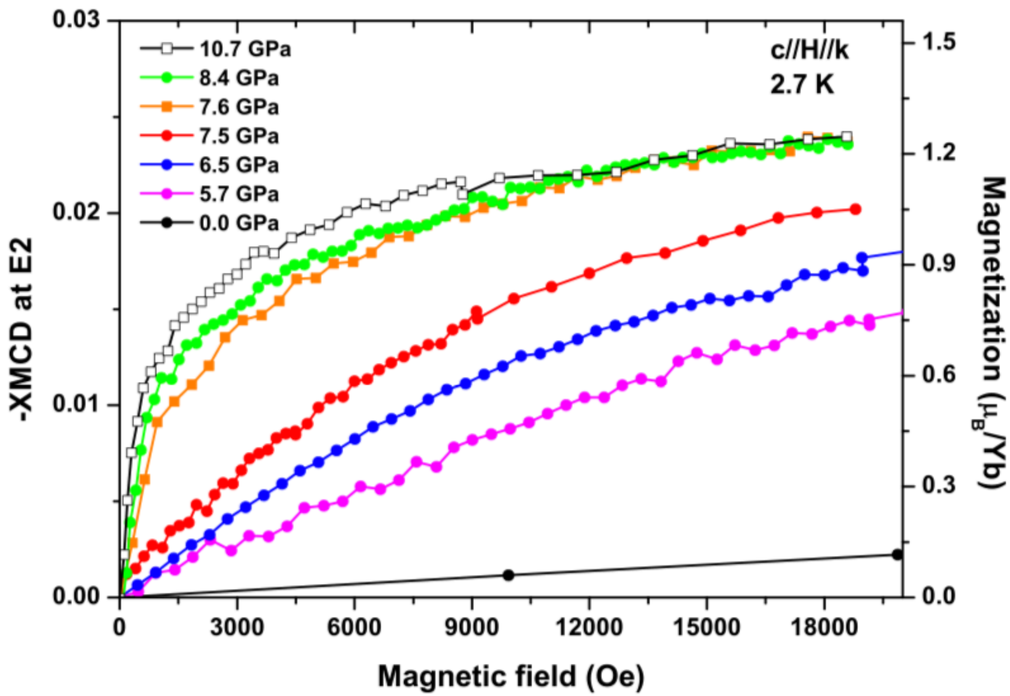
Ferromagnetic order in $YbCu_2Si_2$



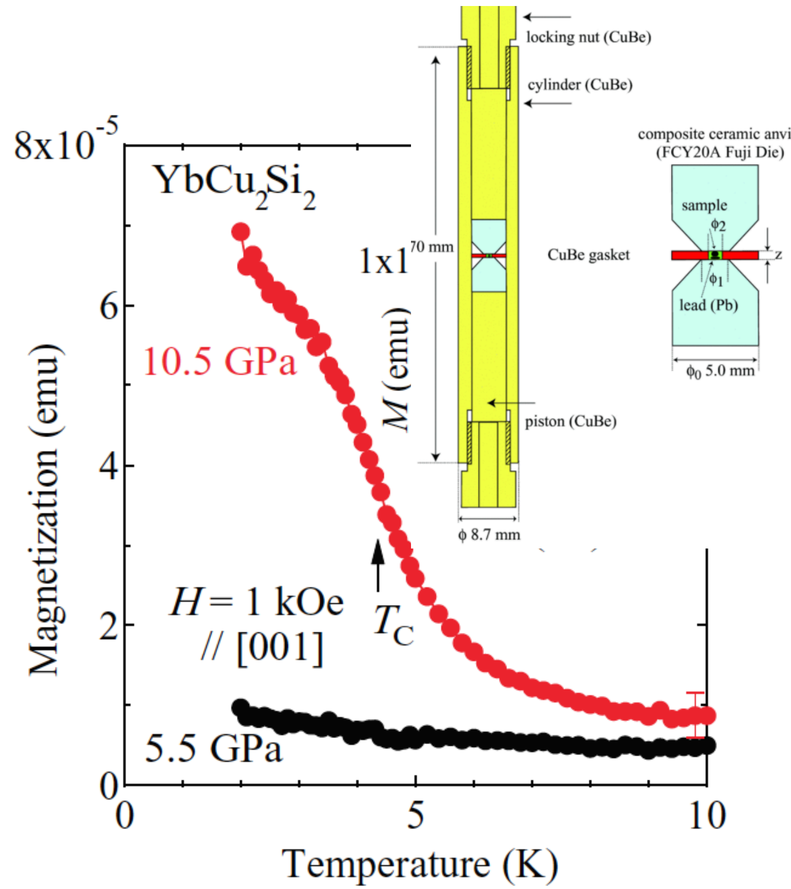


Fernandez-Panella et al. PRB **84**, 134416 (2011)

Direct microscopic proof of ferromagnetism : XMCD



F. Wilhelm et al. PHYSICAL REVIEW B **99**, 180409(R) (2019)

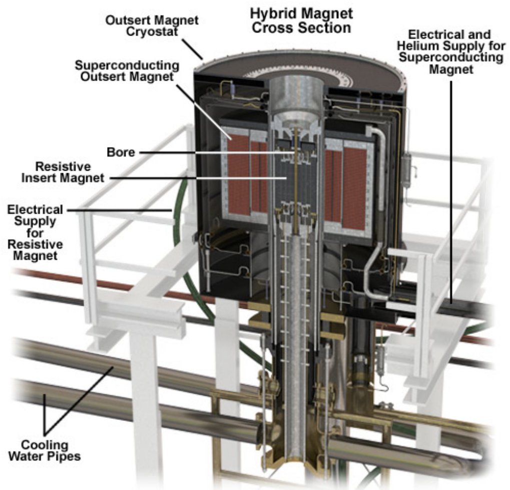


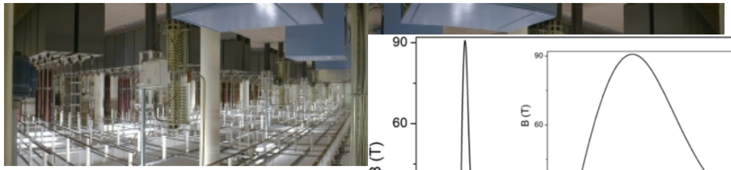
Tateiwa et al. RSI 2012

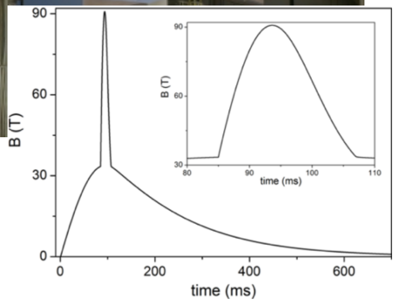
Extreme conditions : High magnetic field and pressure

Superconducting magnets 20T
Hope from HTSC => 30T

Resistive magnets 35T
Hybrid 45T



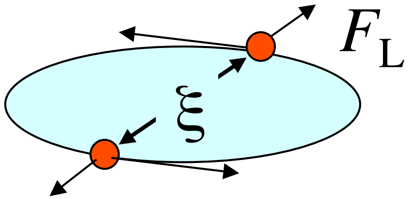




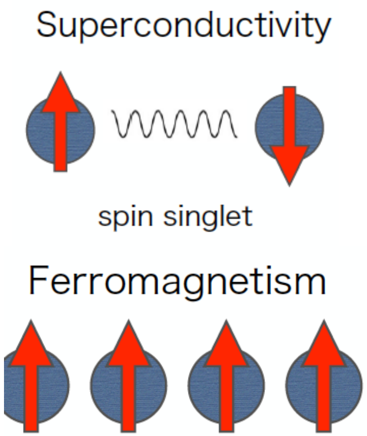
Pulsed field 100T

Ferromagnetic superconductor ?

Normally antagonistic states

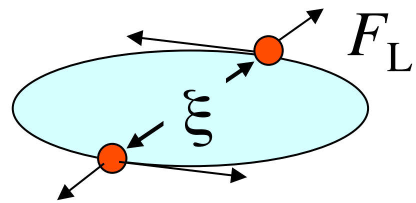


$$H_{C2} \times 2\pi\xi^2 = \Phi_0$$



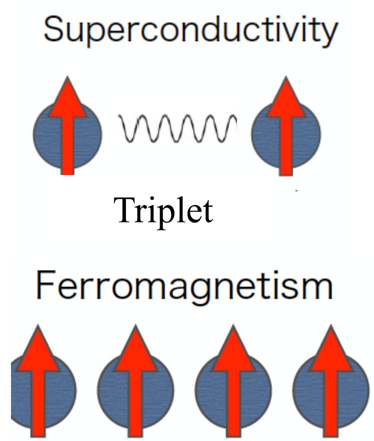
$$H_P = \frac{\sqrt{2}\Delta}{g\mu_B} \approx 1.85\, T_C$$

Ferromagnetic superconductor ?



$$H_{C2} \times 2\pi\xi^2 = \Phi_0$$

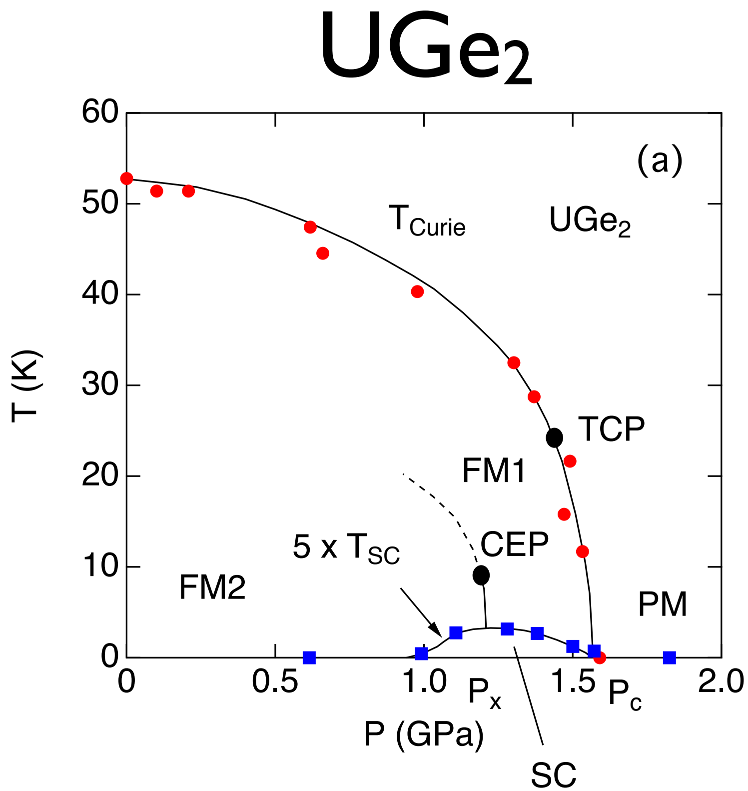
Normally antagonistic states



Implies triplet SC order parameter

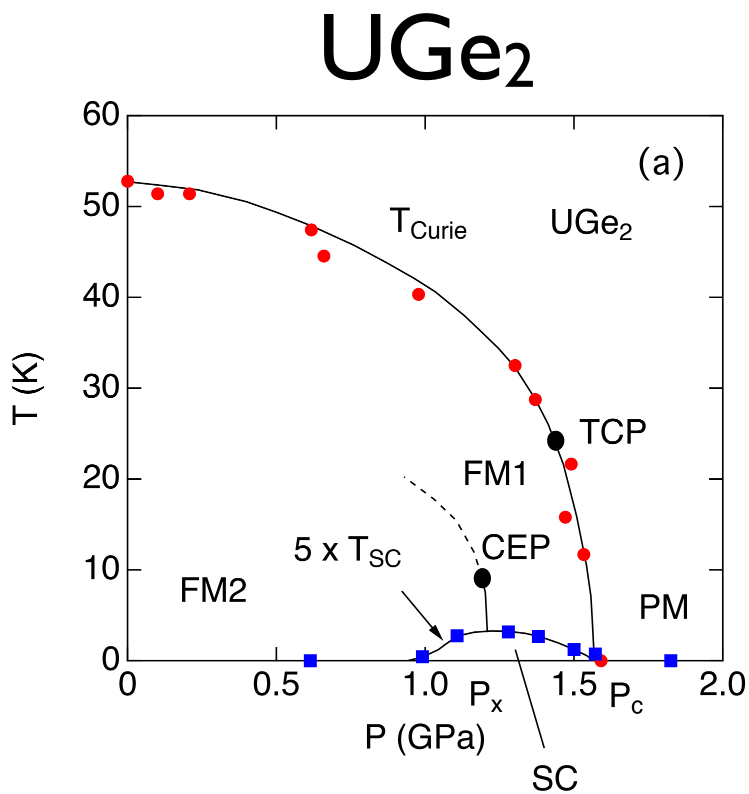
$$H_P = \frac{\sqrt{2}\Delta}{g\mu_B} \approx 1.85\, T_C$$

UGe_2 : First ferromagnetic superconductor

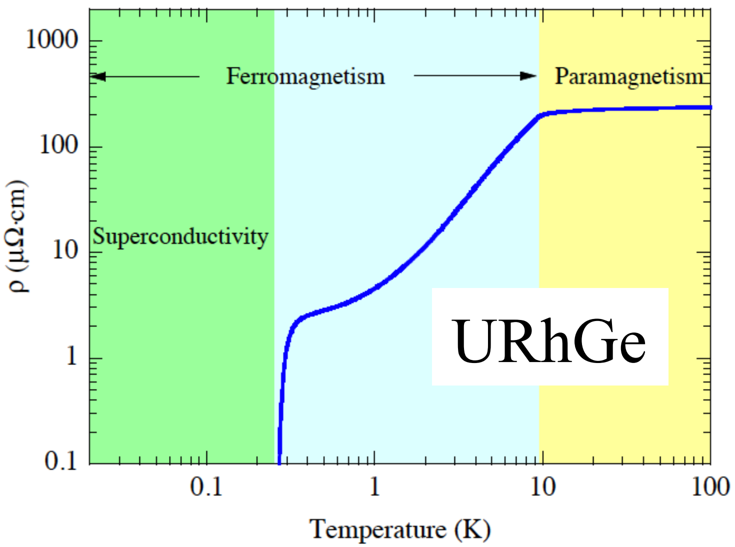


Saxena et al. Nature 406 (2000) 587

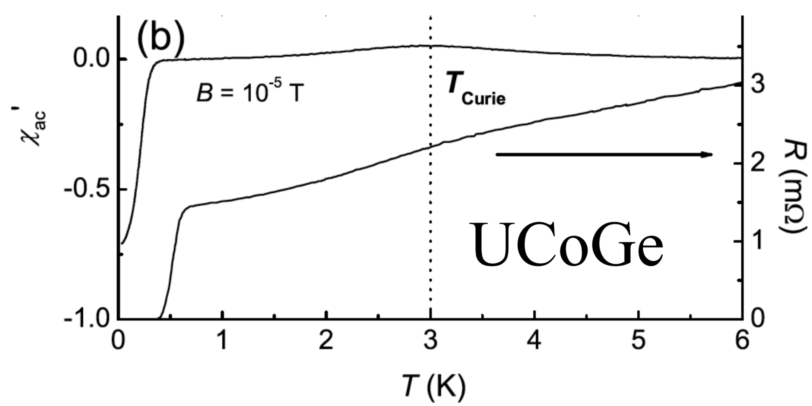
3 ferromagetic superconductors



Saxena et al. Nature 406 (2000) 587



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



N.T. Huy et al.: PRL 99 (2007) 067006

FM fluctuations are the « glue » for the pairing mechanism

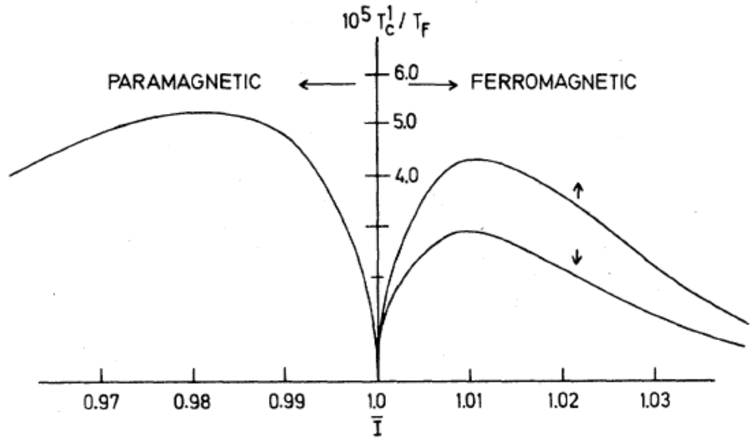
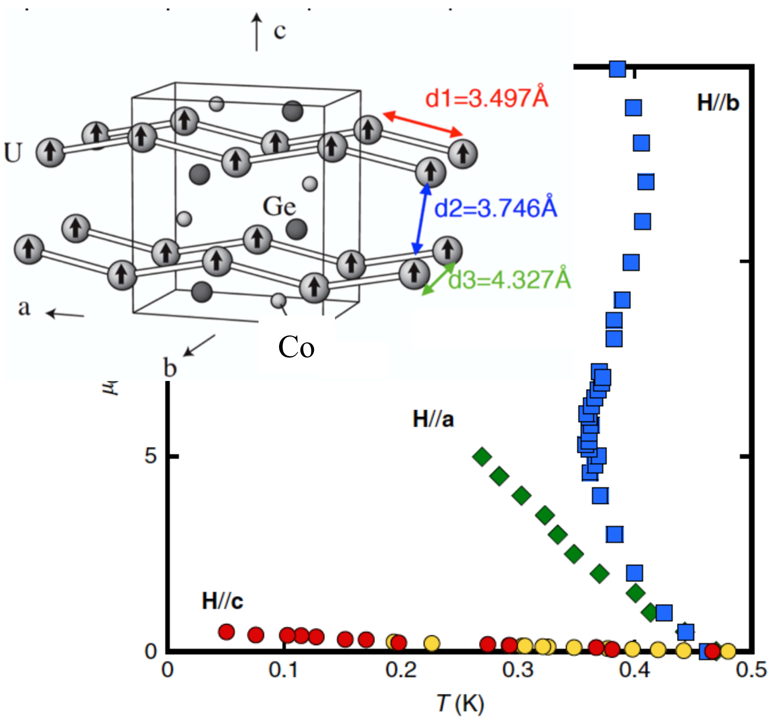


FIG. 2. The p-state superconducting transition temperature as a function of the exchange interaction parameter $\bar{I}$ with range $b = 0.5 k_F^{-1}$.



Magnetic (FM) fluctuations can be the glue for Cooper pairs

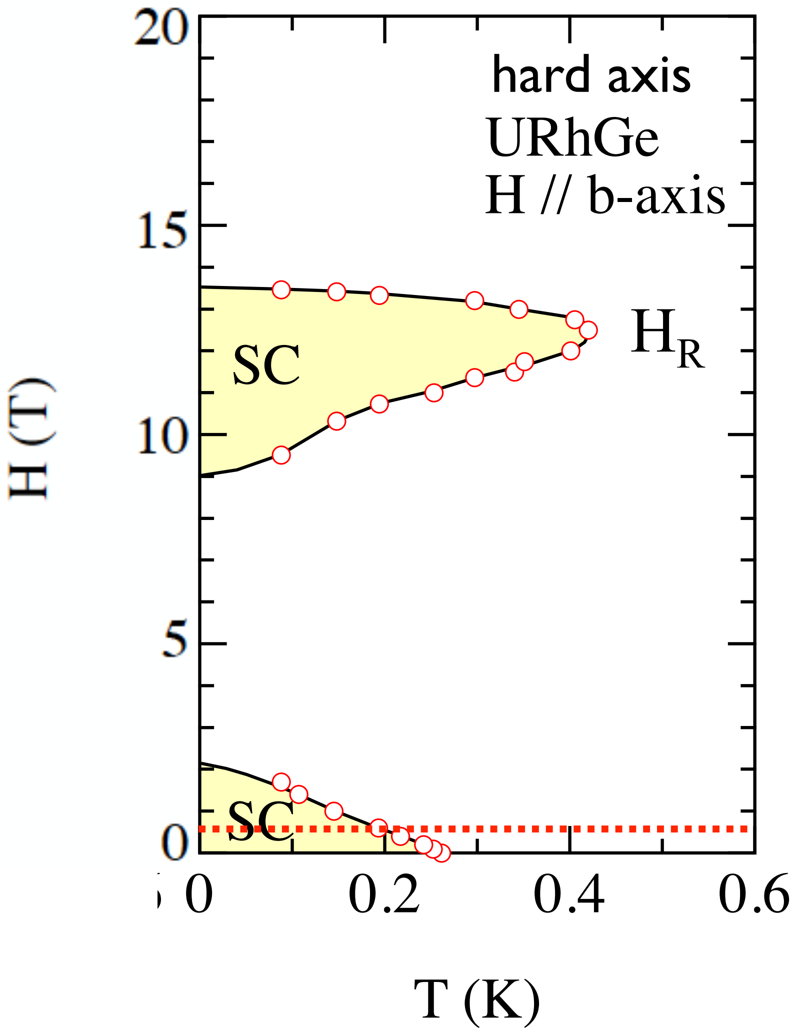
D. Fay and J. Appel, Phys. Rev. B 22, 3173 1980.

B. Wu et al., Nature Communications, 14480 (2017)

Magnetic field can also tune the pairing interaction

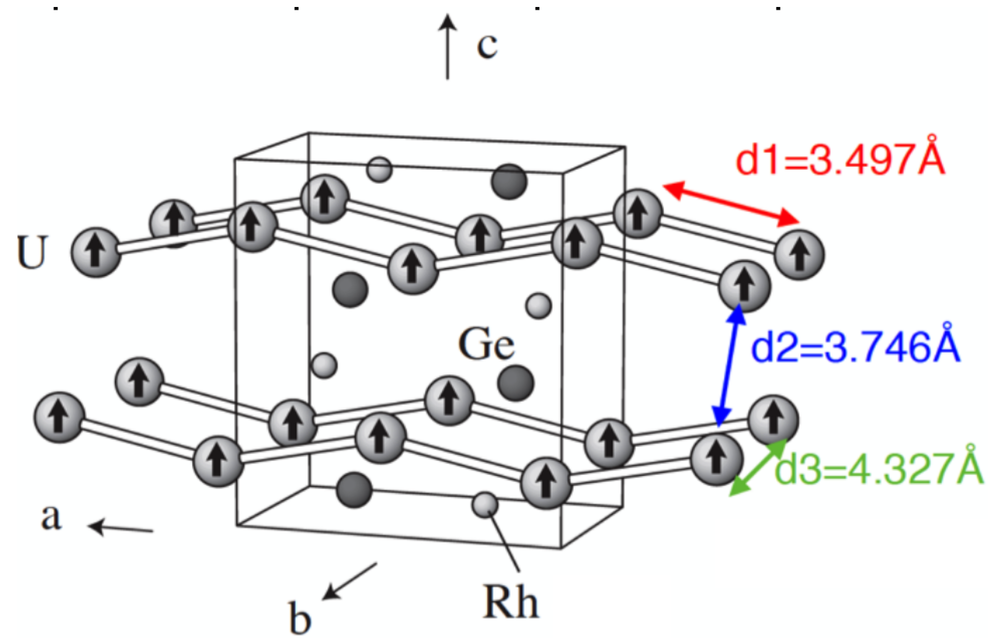
Proof of the role of FM fluctuations

Re-entrant superconductivity in URhGe

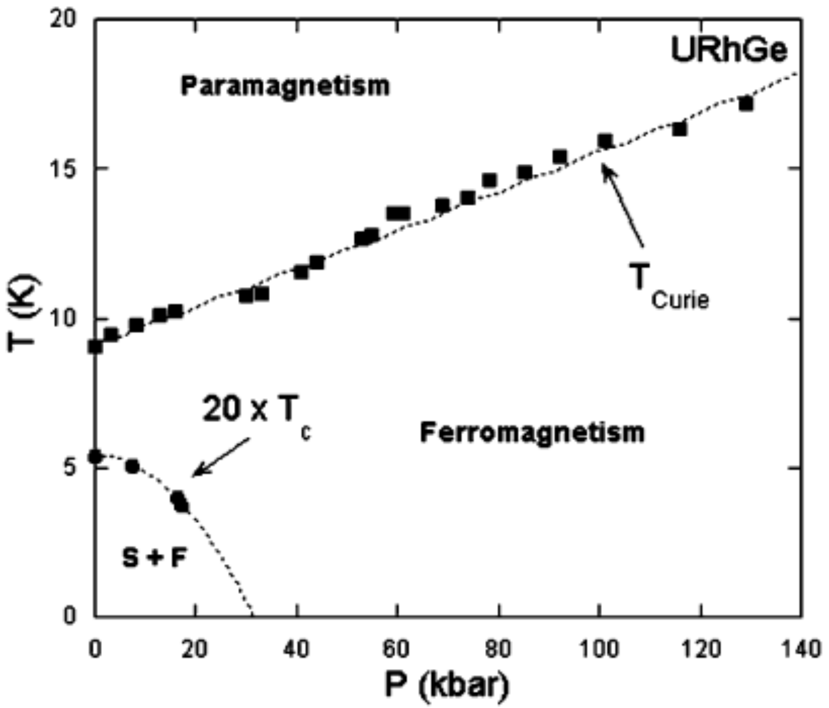


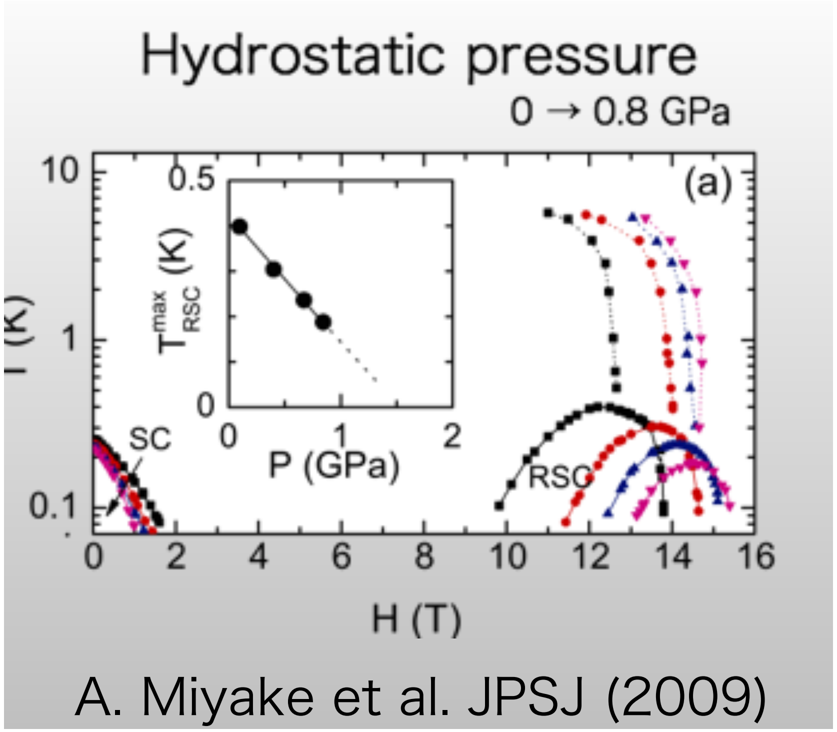
F. Levy et al. Science (2005)
A. Miyake et al.: JPSJ (2008)

Orthorhombic
Ising FM with easy c-axis



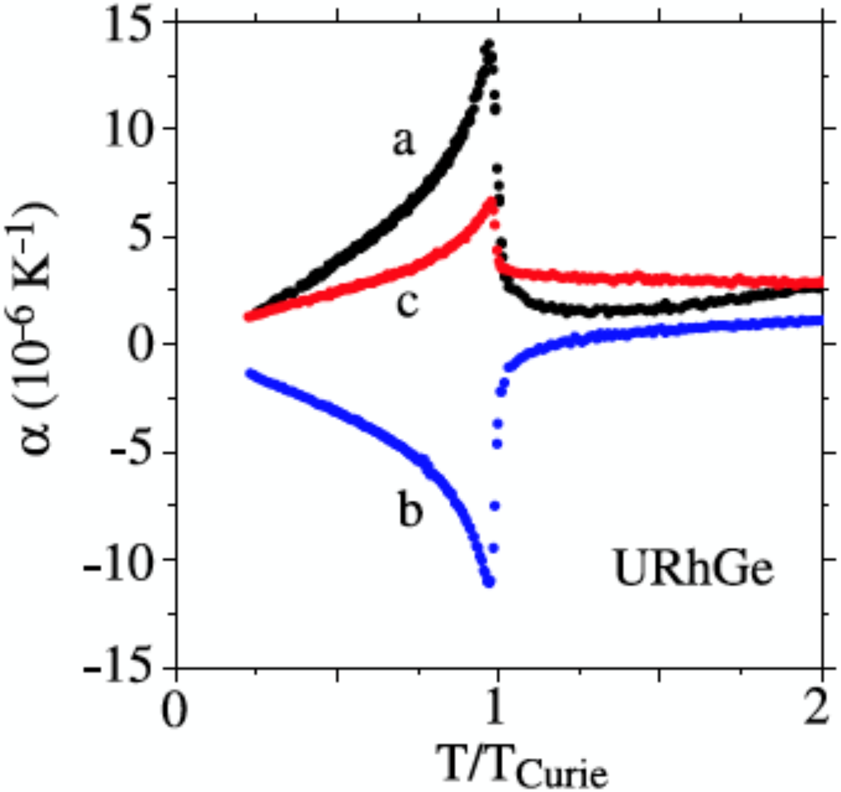
URhGe under hydrostatic pressure





pressure drives URhGe the wrong way !

Negative pressure : Uniaxial stress ?

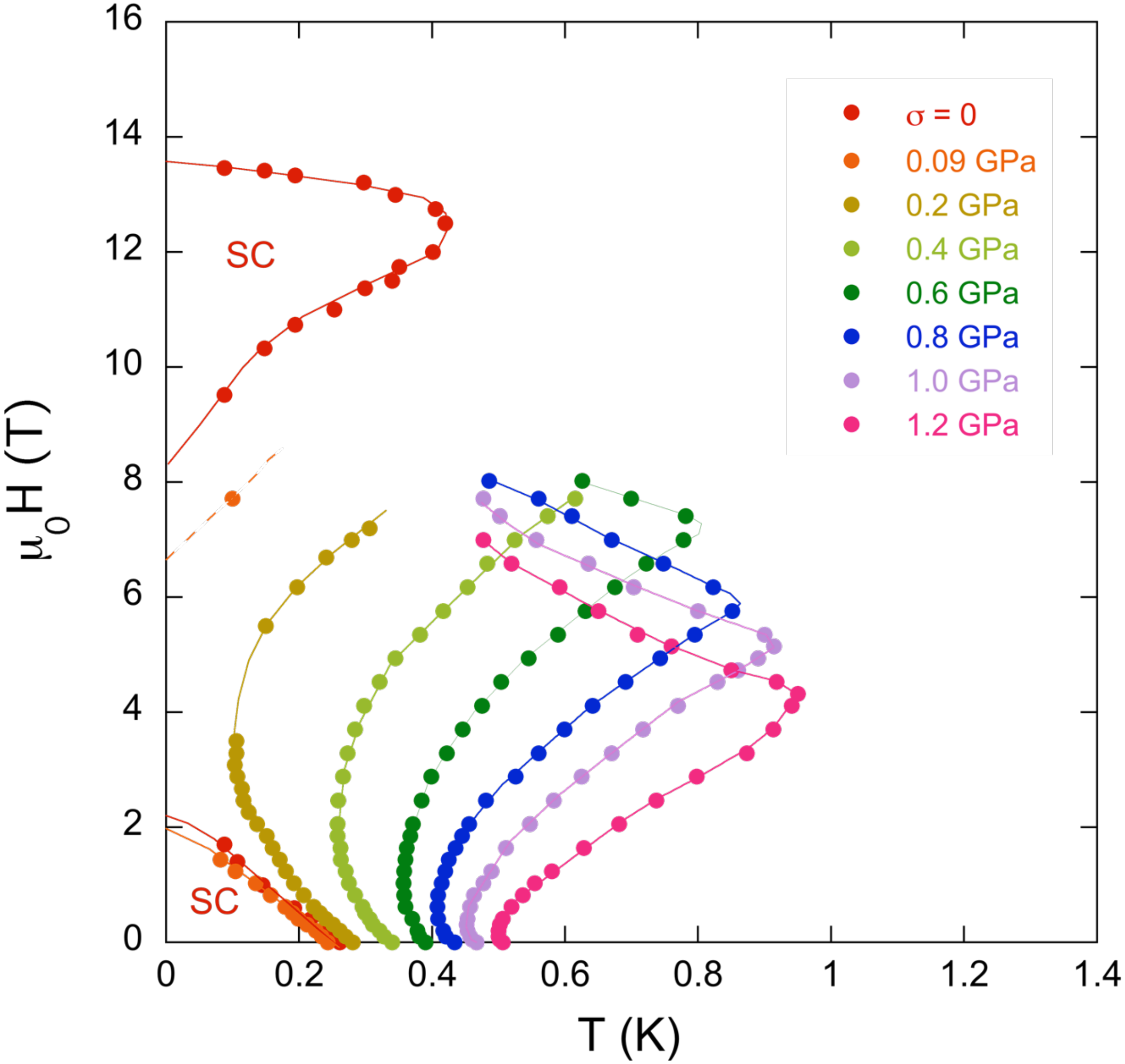


Measurement F. Hardy.
D. Aoki et al. Comptes Rendus Physique (2011).

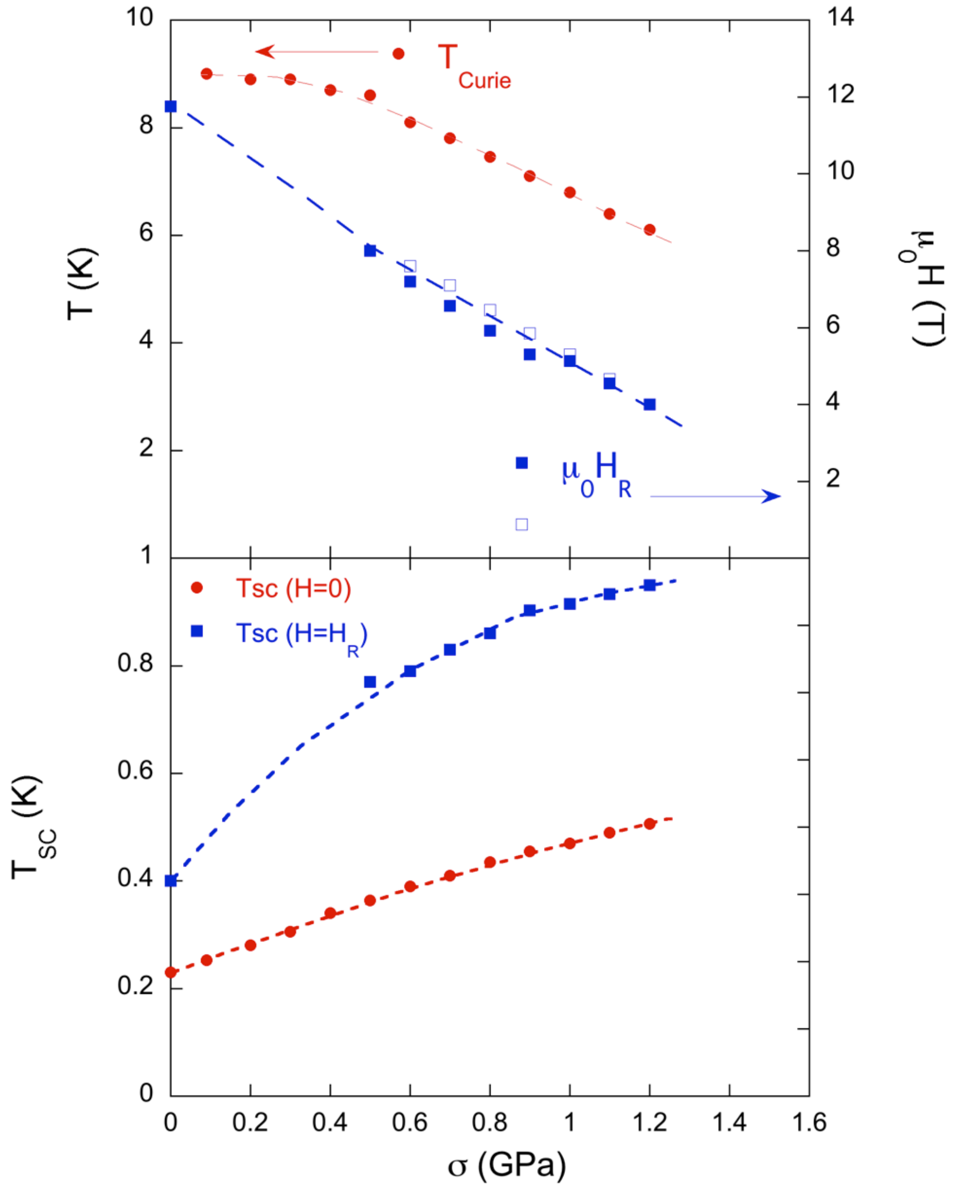
Ehrenfest : $dT_{Curie}/dP = -1.6$ K/GPa

URhGe : superconducting phase diagram with stress

- H_R decreases
- T_{SC} increases



URhGe : Stress dependence of parameters



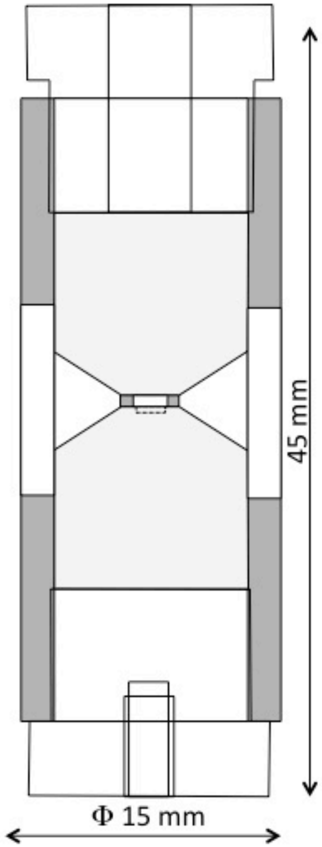
H_R extremely sensitive to stress, more than T_{Curie}

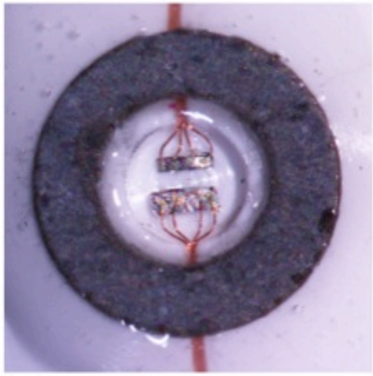
Superconductivity strongly enhanced

T_{SC} seems correlated to H_R and not to T_{curie}

Braithwaite et al. *PRL 120, 037001 (2018)*

Combining Pressure and Pulsed Magnetic Field



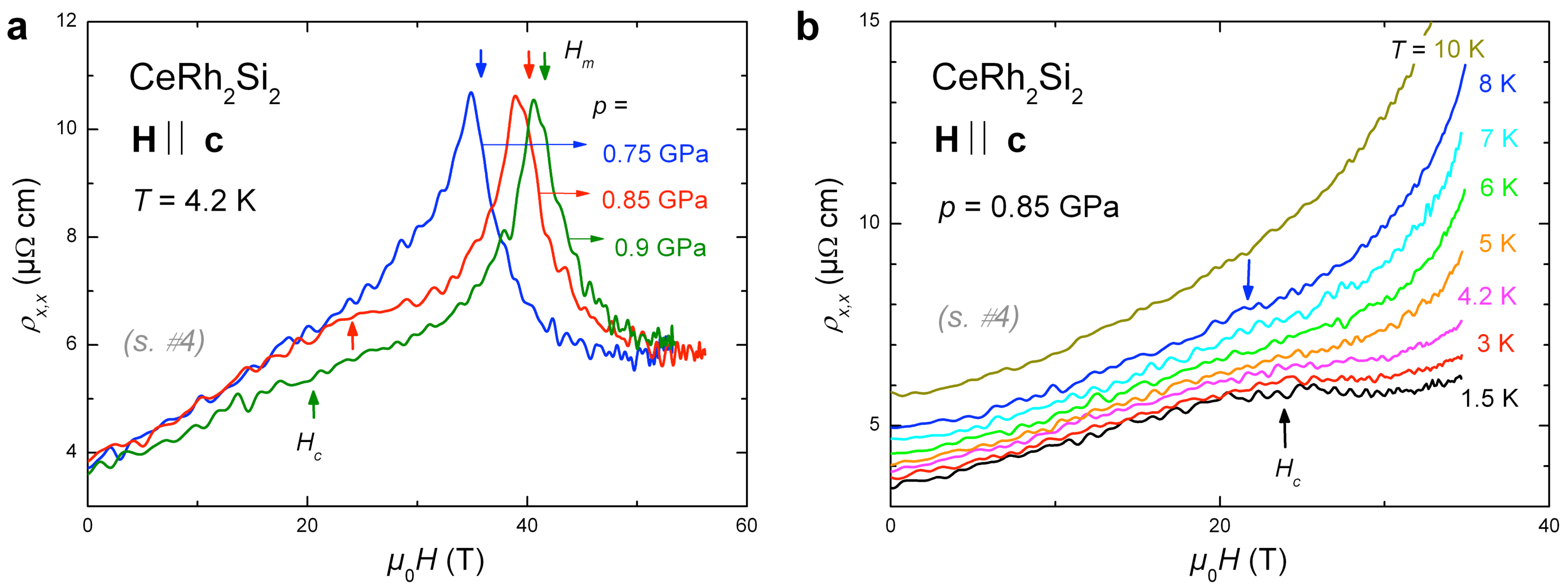


60T field pulse

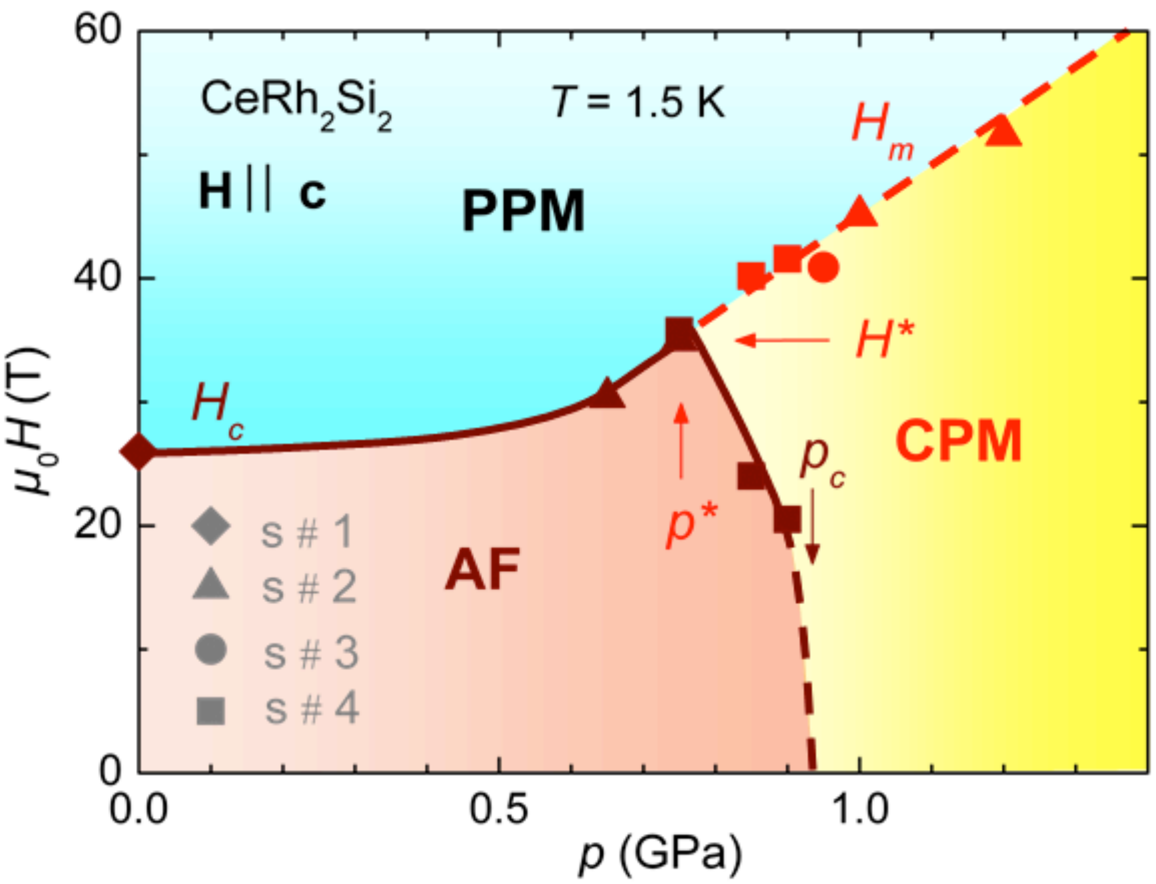
T_{MIN} 1.5K

Heating = 0.1K

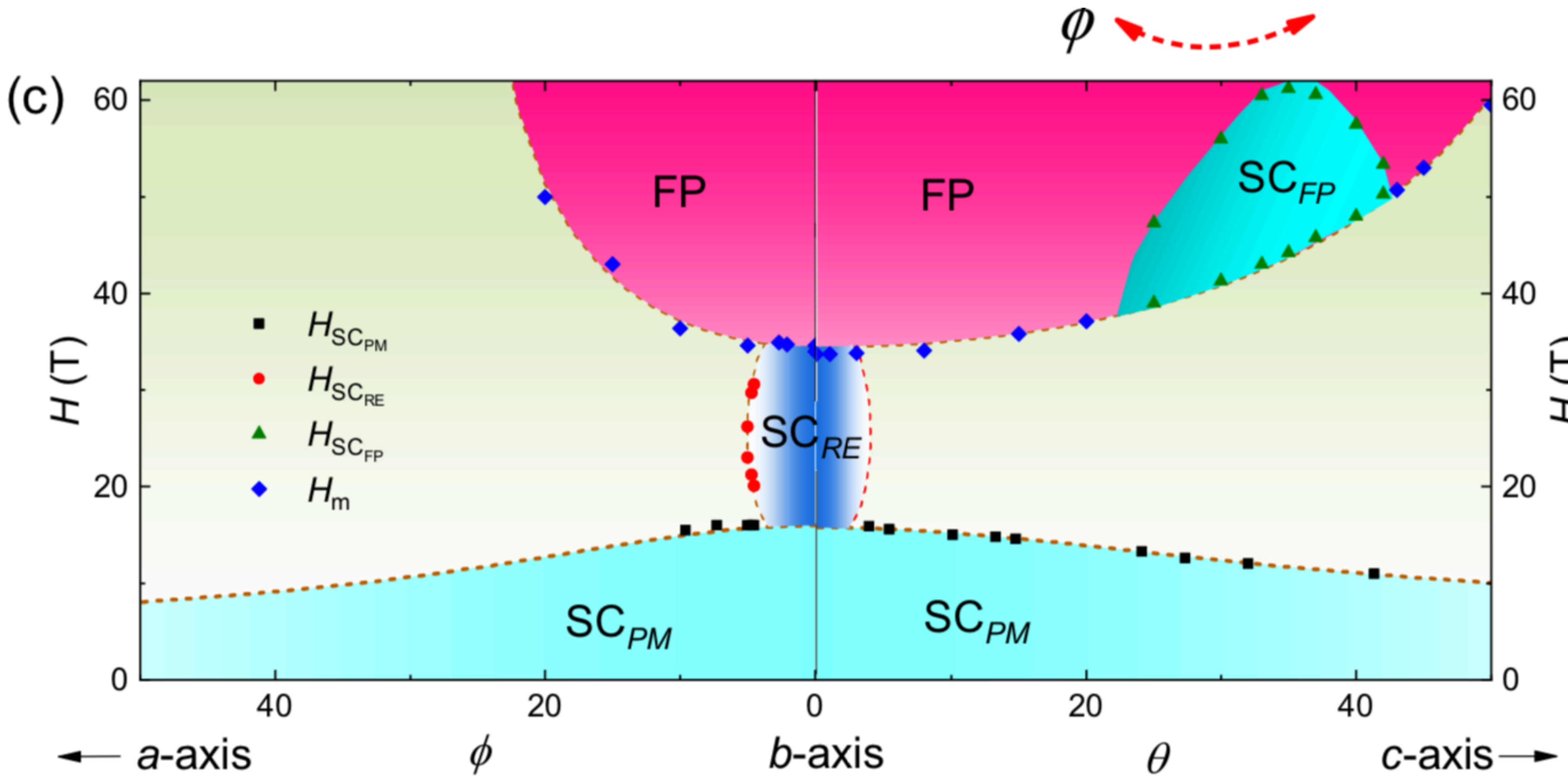
$CeRh_2Si_2$ - Low temperature phase diagram



$CeRh_2Si_2$ - Low temperature phase diagram



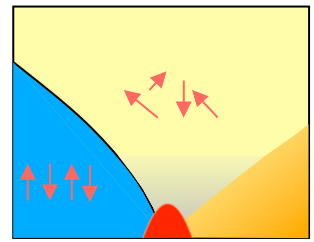
Re-entrant superconductivity in UTe2



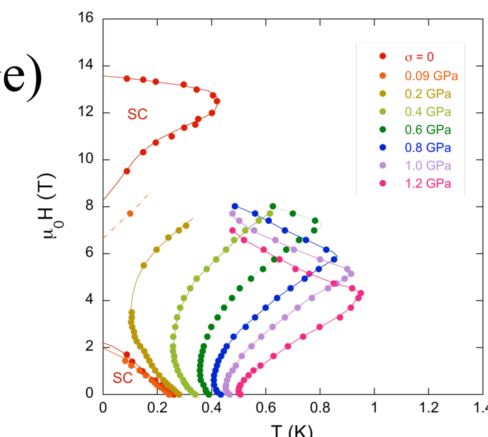
Ran et al. arxiv.org/abs/1905.04343

Summary for heavy fermion superconductivity/ High pressure

AF Quantum critical point : magnetically mediated superconductivity



Ferromagnetic superconductors (UGe2, URhGe, UCoGe)



- Triplet p-wave superconductivity

- Superconductivity reinforced by magnetic field

- Information on the microscopic mechanism of superconductivity

In general we are much closer to a full understanding of superconductivity in heavy fermion systems than in other unconventional superconductors

Perspectives for SCES with the EBS

Extreme conditions

- Lower T. Close to, though not necessarily in, the SC state

- Higher Fields

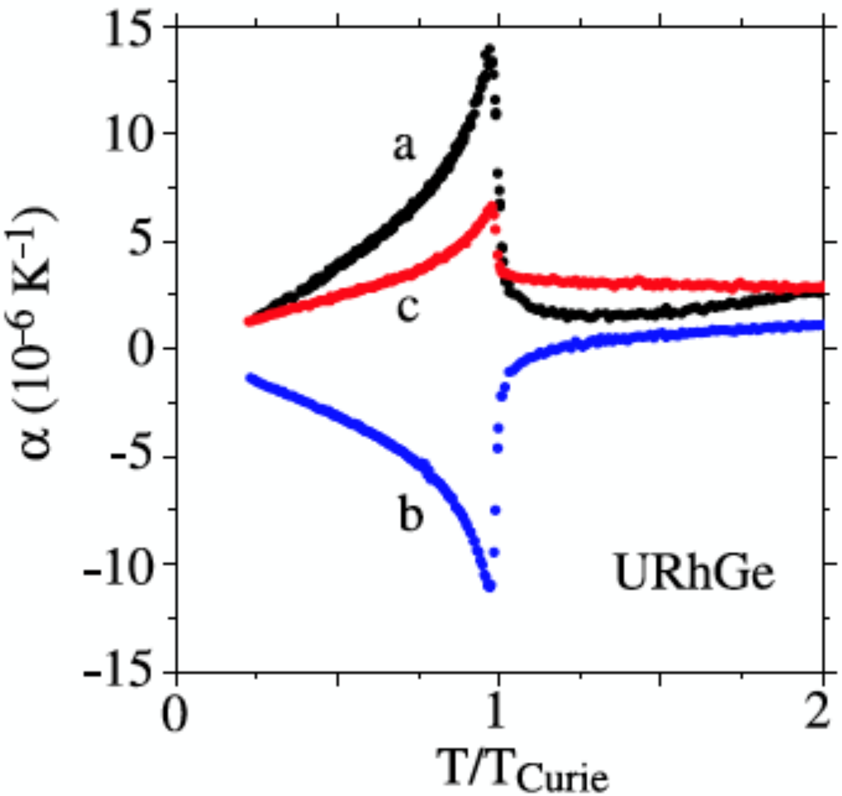
To study :
- Structure
- Valence
- Magnetism

Diffraction : structural parameters

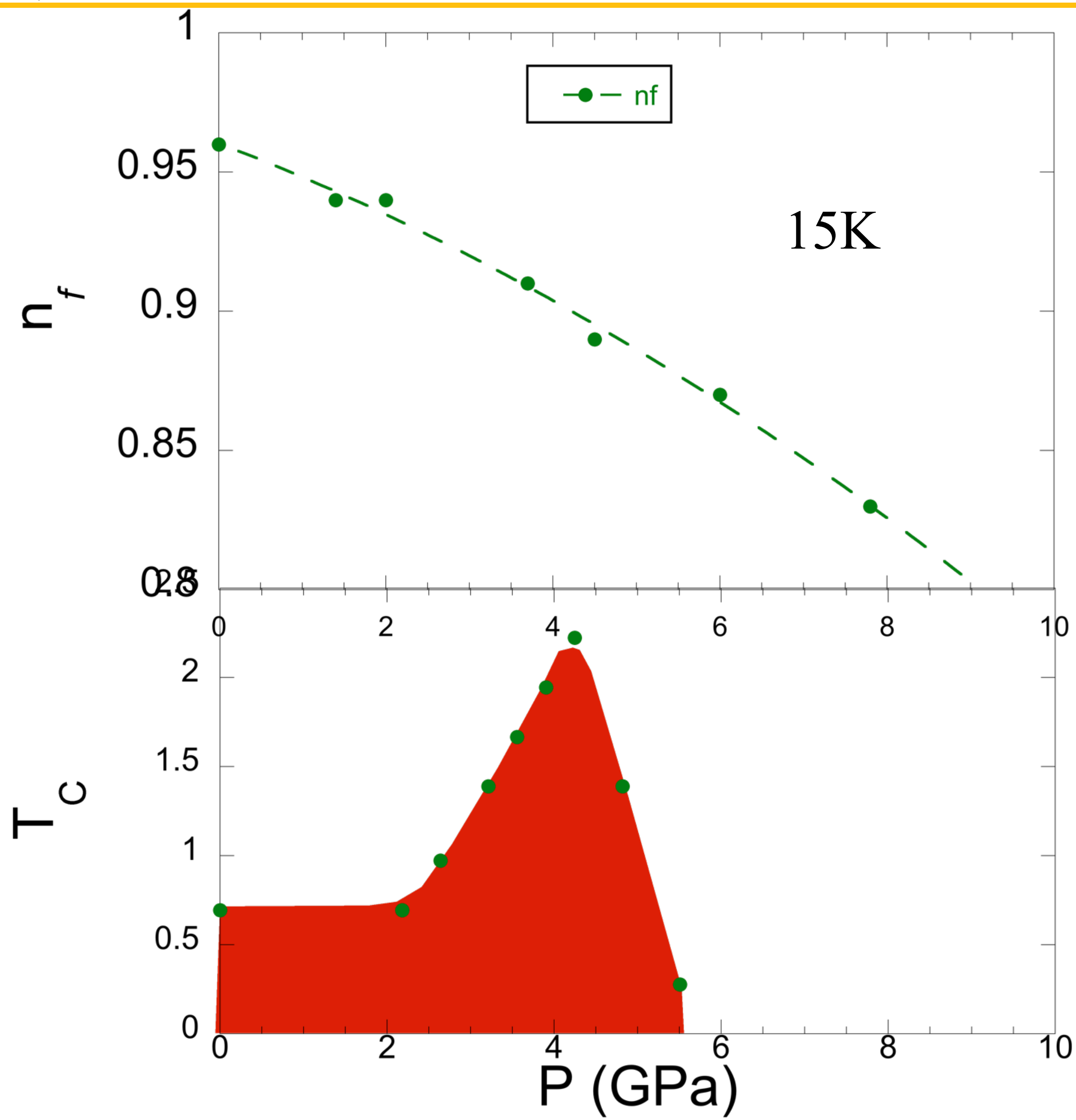
Compressibility, structural phase transitions

At low T, high field

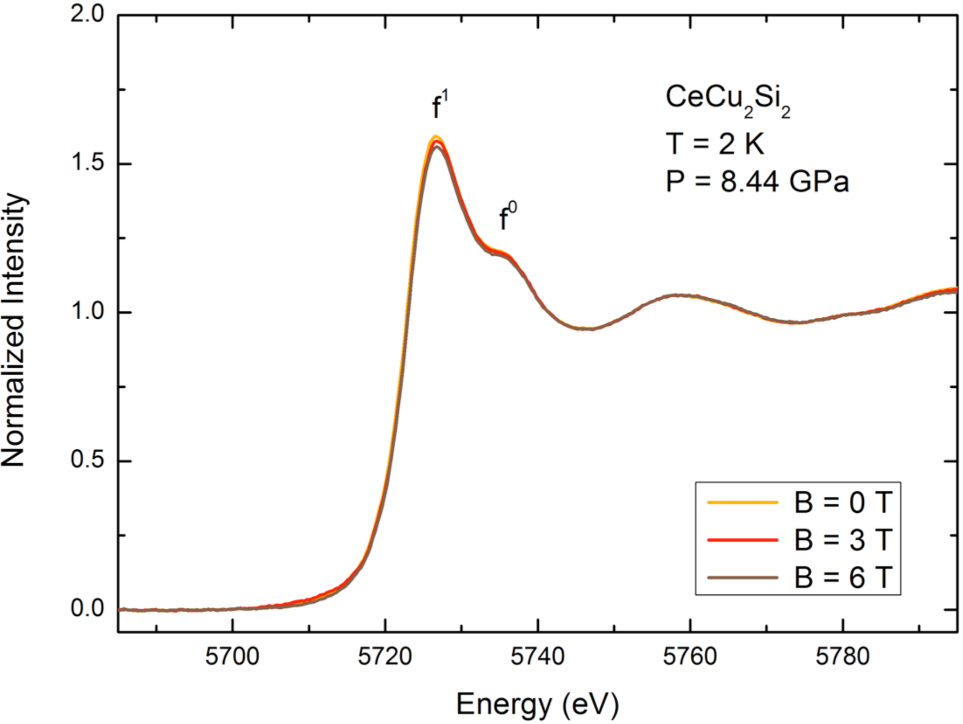
Thermal expansion?

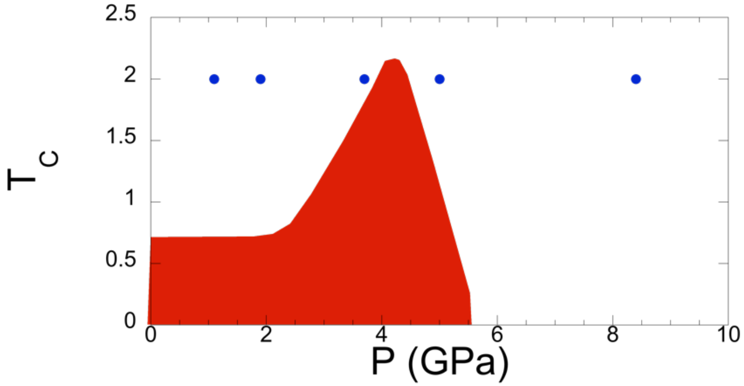


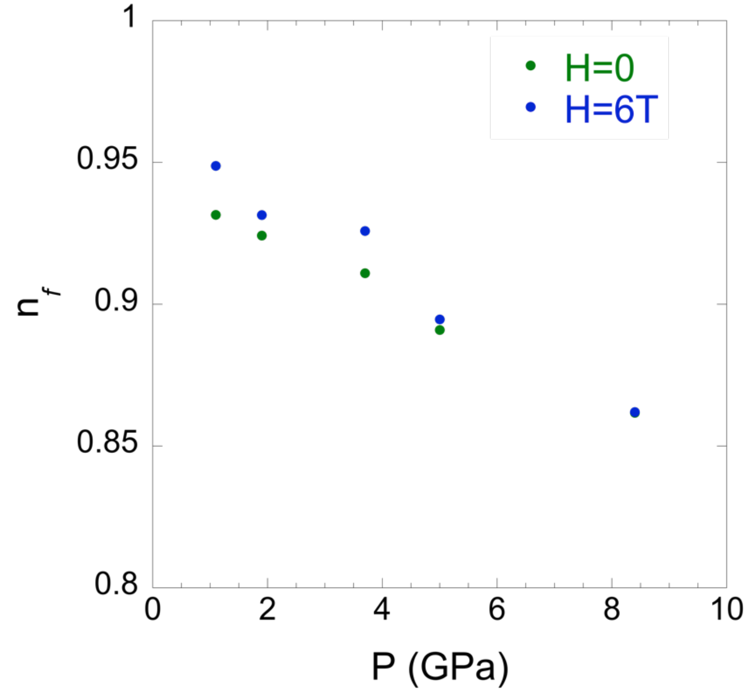
Absorption: valence state of the Rare Earth



Magnetic field control of valence ?



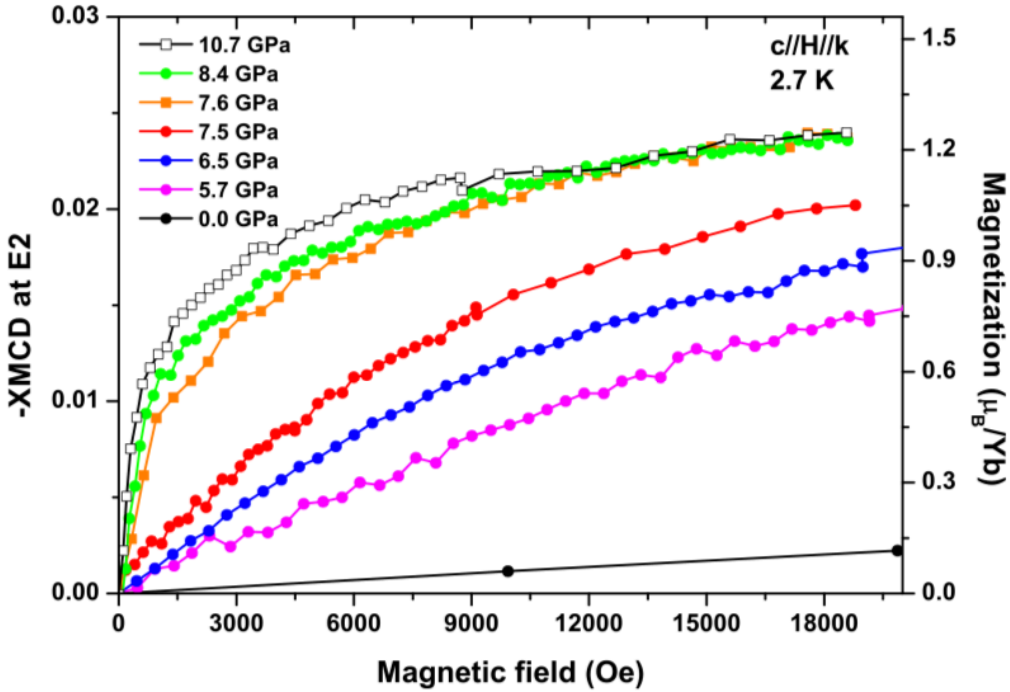




ID12 experiment

Magnetism

XMCD : already the most precise magnetization measurment for FM under pressure



Probing the pressure dependence of the orbital to spin moment ratio in the ferromagnetic superconductor UGe2

F. Wilhelm et al, to be published

Magnetic diffraction under pressure ?

Measurement in ID20 $Ce(Fe,Co)_2$ in 2005

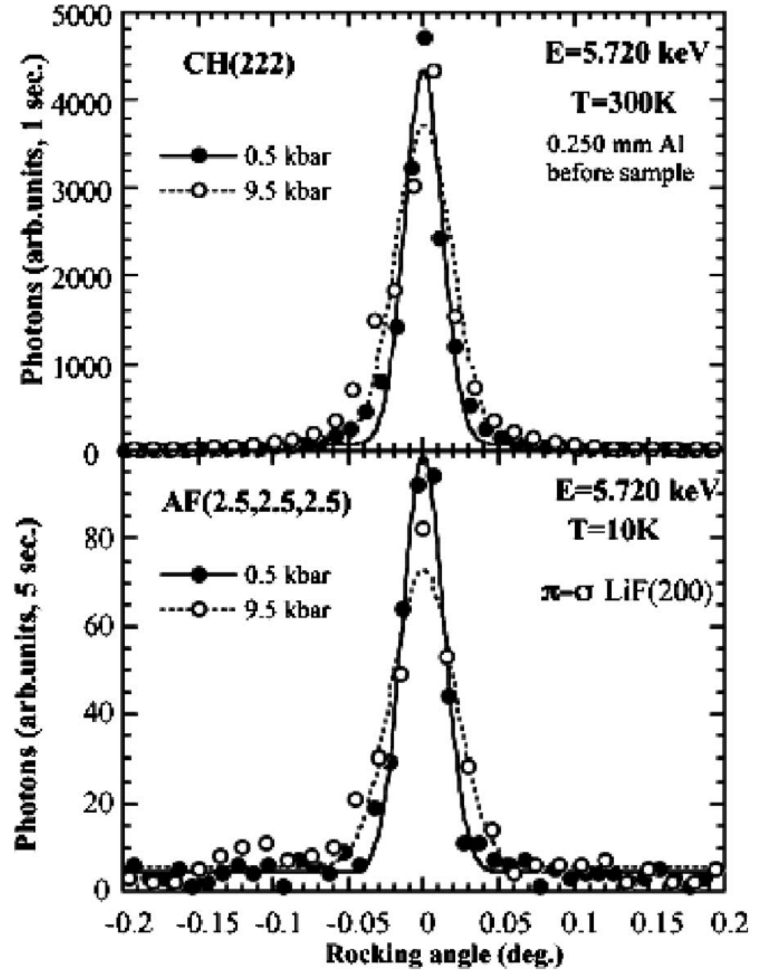
REVIEW OF SCIENTIFIC INSTRUMENTS **76**, 083909 (2005)

Pressure device for resonant magnetic x-ray scattering

Nolwenn Kernavanois,[a] Pascale P. Deen, and Luigi Paolasini
European Synchrotron Radiation Facility, BP 220, 38043 Grenoble, France

Daniel Braithwaite
Département de Recherche Fondamentale sur la Matière Condensée, SPSMS-LCP, CEA-Grenoble, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France

(Received 31 January 2005; accepted 25 April 2005; published online 4 August 2005)



I. Povedano et al (Diamond), talk in EHPRG Prague sept 2019

Predictions are difficult

In general advances in Strongly Correlated Electrons have been due to the discovery of new materials

Macroscopic measurements have been predominant in SCES studies under pressure

This balance is probably going to change