Lecture Notes

Introduction to Strongly Correlated Electron Systems

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Introduction to strongly correlated electron systems

I. Introduction

Brief summary of electrons in solids, origin of strong electron correlations

II. Classes of strongly correlated electron systems

(a) Transition metal compounds: 3d-electrons

- Hubbard model, Mott insulator, metal-insulator transition
- Spin, charge, and orbital degrees of freedom and ordering phenomena, selected materials
- Pressure effect on the ground state properties of transition metal compounds

(b) Heavy fermion systems: 4f (5f) – electrons

- Landau Fermi-liquid model, Kondo effect, heavy fermion systems, non-Fermi liquid, quantum phase transitions, selected materials
- Pressure effect on the ground state properties of heavy fermion compounds

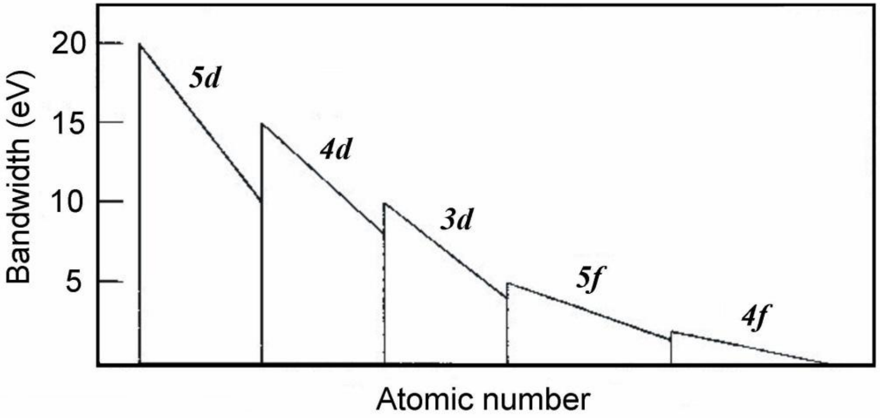
(c) Nanoscale structures:

- Quantum confinement, unusual properties for potential applications

III. Summary and open discussion

Some applications to the emergence of unusual ground states under high pressure

Local versus Itinerant magnetic moments

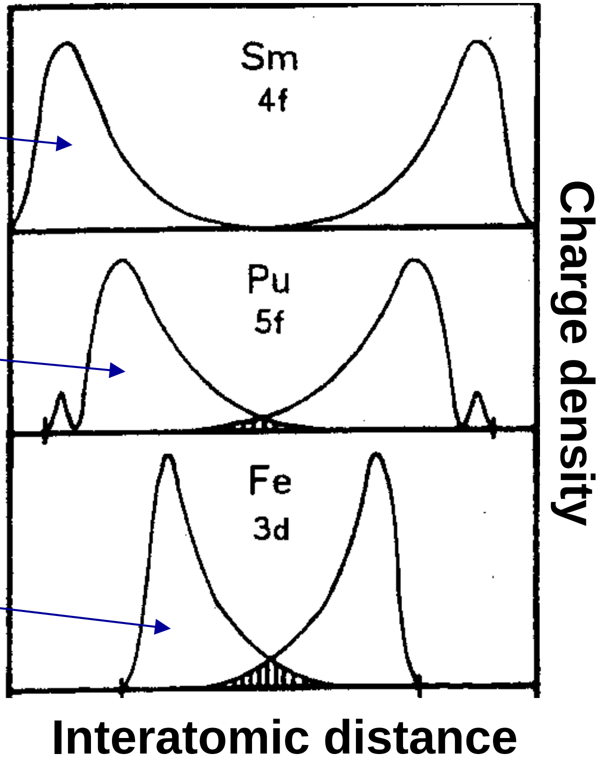


Bandwidth (W) of the metallic state

$W(Fe) \approx 4$ eV

$W(Pu) \approx 2$ eV

$W(Sm) \leq 1$ eV



local moment magnetism

localized / itinerant

itinerant electron magnetism

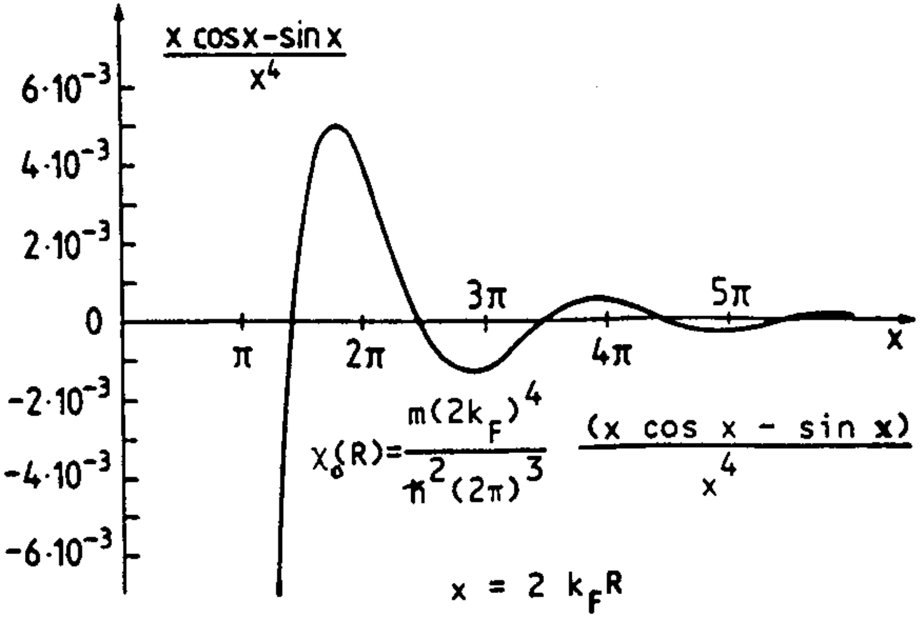
4f states are highly localized

No direct interaction possible!

RKKY interaction

Local moments (Spin S_i) in a sea of conduction electrons with itinerant spin s(r)

$$J(r) = 6\pi\, Z\, J\, D(E_F)\left[\frac{\sin(2k_F r)}{(2k_F r)^4} - \frac{\cos(2k_F r)}{(2k_F r)^3}\right]$$



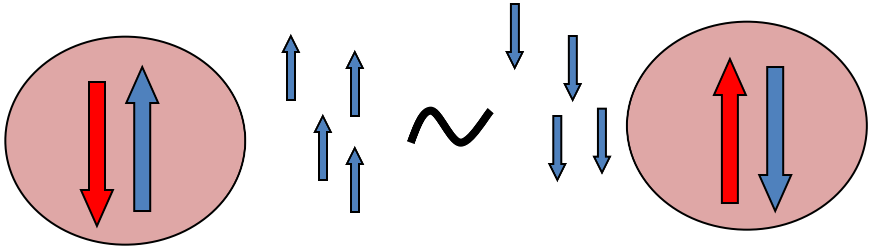
Z	number of electrons / atom
J	s-d (f) exchange interaction
$D(E_F)$	DOS at Fermi energy
k_F	Fermi momentum
r	distance between impurities

=> Oscillations of value and sign

P.H. Dederichs in: Magnetismus von Festkörpern und Grenzflächen, 24. IFF Ferienkurs, Jülich 1993

Theoretical description

Kondo-lattice-system: periodical arrangement of localized 4f- moments in a metallic matrix



Competition between:

Intrasite (on-site) interaction: Kondo-Effect

$E_K = k_B T_K$

$\Rightarrow$ screening of the magnetic moments

$\Rightarrow$ **nonmagnetic ground state**

$T_K \sim \exp(-1/N(E_F)J)$

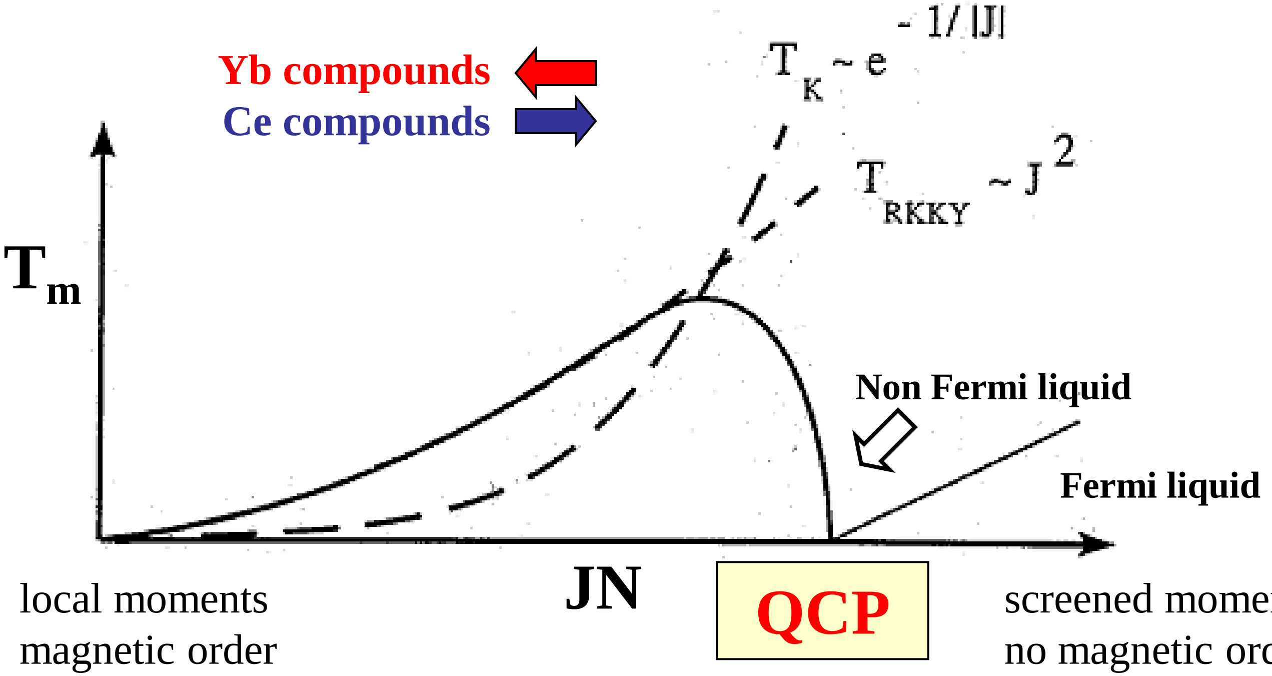
Intersite interaction: RKKY $E_{RKKY} = k_B T_{RKKY}$

$\Rightarrow$ **long range magnetic order**

$T_{RKKY} \sim N(E_F)\, J^2$

J: interaction between f- and conduction electrons

Doniach model



local moments
magnetic order

screened moments
no magnetic order
⇒ **Heavy Fermions**

$T_m \to 0$

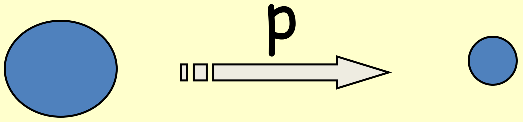
QCP: Quantum-Critical-Point

- **Non-Fermi-Liquid (NFL):**
  $\Delta\rho \propto T^{\varepsilon}$ $\varepsilon = 1 - 1.5$
  $\Delta C/T \propto -\ln T$
- **Superconductivity possible**

(e.g. $CeCu_2Si_2$, $CeRh_2Si_2$)

$Ce^{3+} \to 4f^1$ (J=5/2)
magnetic

$Ce^{4+} \to 4f^0$ (J=0)
nonmagnetic



$Yb^{2+} \to 4f^{14}$ (J=0)
nonmagnetic

$Yb^{3+} \to 4f^{13}$ (J=7/2)
magnetic

Yb heavy fermion compounds

Further motivation

analogy between Yb3+(4f13) and Ce3+(4f1):

- nature of heavy fermion state?

- pressure effect is opposite ! → Same theoretical description ??

(4f-radius: 0.25Å (Yb) < 0.37Å (Ce)

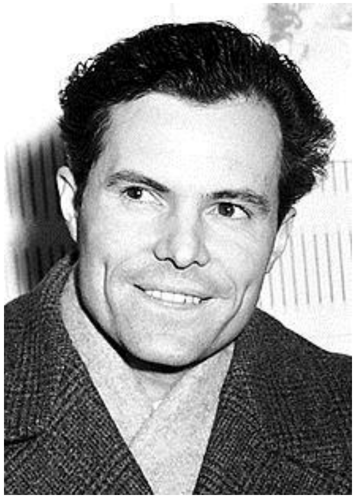
^{170}Yb is a Mössbauer isotope !

microscopic information on magnetic and electronic ground state properties

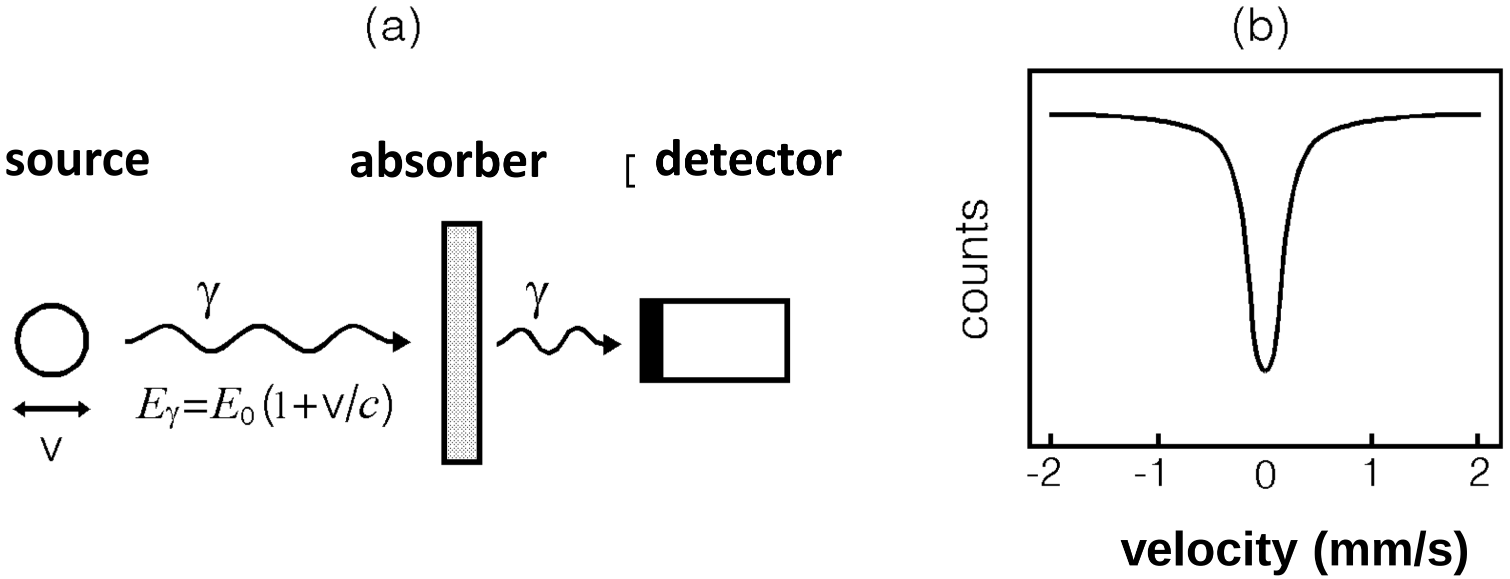
Mössbauer effect

Rudolf Mößbauer (1929-2011)

Discovery 1957, Nobel Prize 1961



Mössbuer Spectroscopy



- **recoilfree emission and absorption of γ-quanta of nuclei bounded in solids**
- **Doppler effect: $E = E_\gamma (1 + v/c)$**

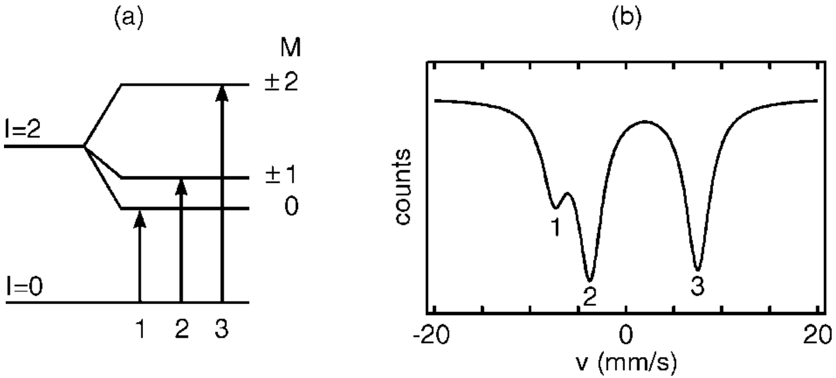
Mössbauer effect

Hyperfine interactions between nucleus and electrons in solid

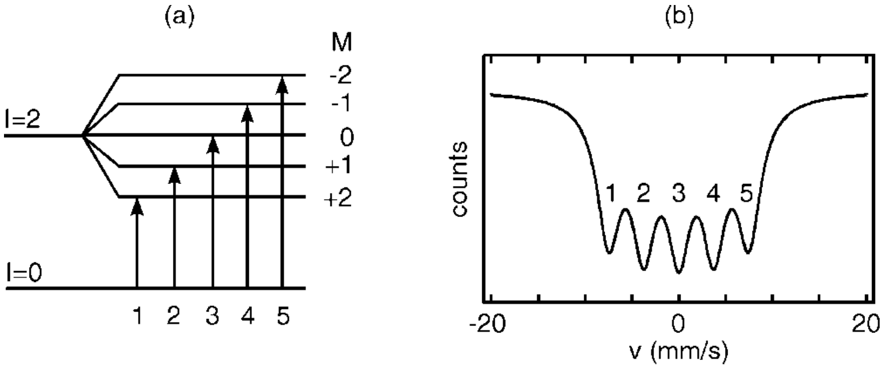
shift and splitting of nuclear energy levels

^{170}Yb :

electric quadrupole splitting



magnetic hyperfine splitting



- **E_γ = 84.25 keV**
- **natural abundance of ^{170}Yb only 3%**

⇒ very small effect ⇒ very long measuring time

Pressure effect on Mössbauer parameters

paramagnetic state

only quadrupole splitting

Yb^{3+}, $4f^{13}$ $\Rightarrow$ max. $eQV_{zz} \approx 47$ mm/s

Yb^{2+}, $4f^{14}$ $\Rightarrow$ $eQV_{zz} = 0$ mm/s

$\Rightarrow$ Possible change of the Yb valence state with p

magnetically ordered state

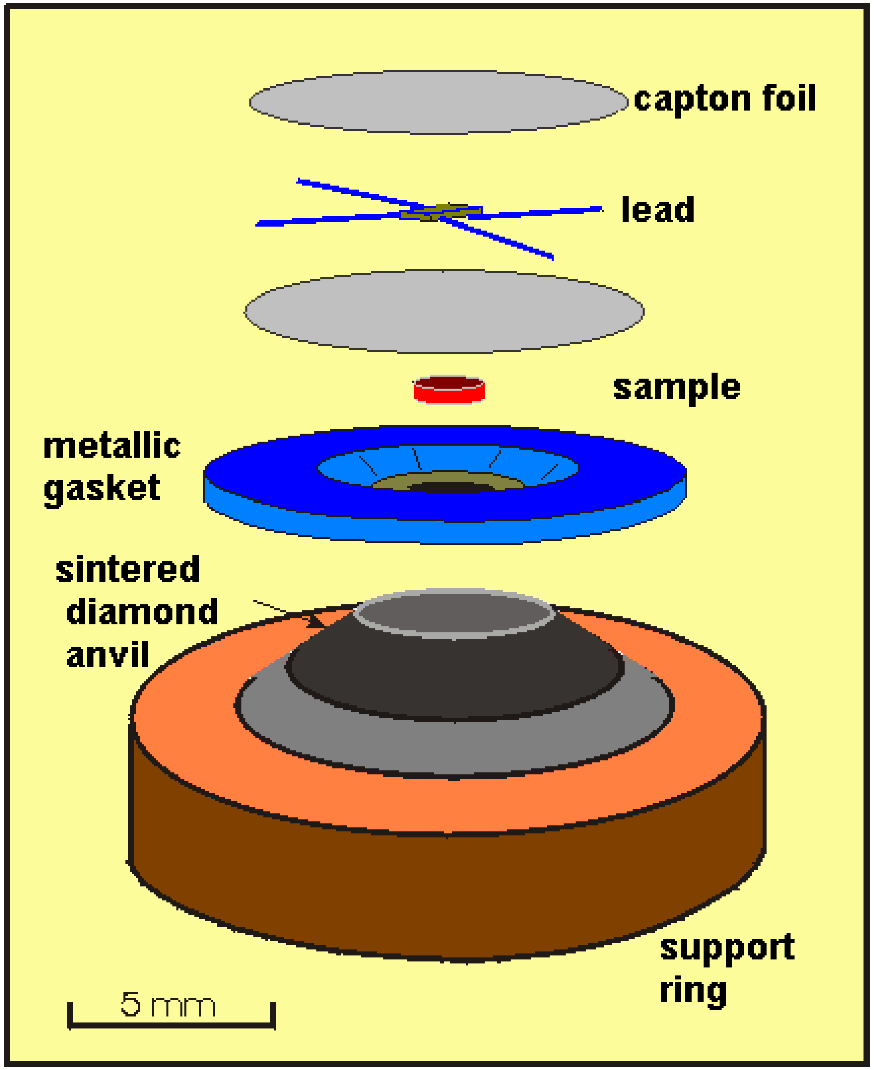
magnetic hyperfine splitting

contribution of the 4f moments is dominating

$$B_{eff} = (102\ T / \mu_B)\ \mu_{Yb}$$

$\Rightarrow$ information on **$\mu_B(p)$, $T_m(p)$, change of spin structure with p**

High pressure cell for ^{170}Yb-Mössbauer-spectroscopy



Requirements:

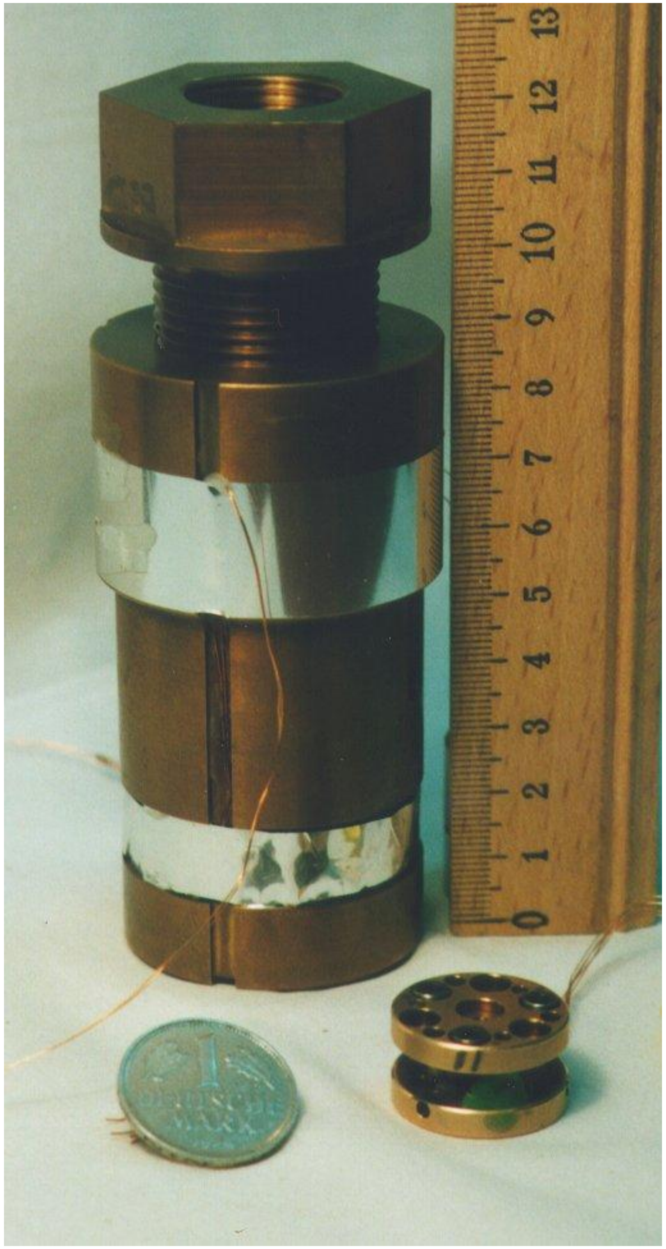
- large amount of sample – large sample volume necessary
  d = 2.5 mm , h = 0.5 mm

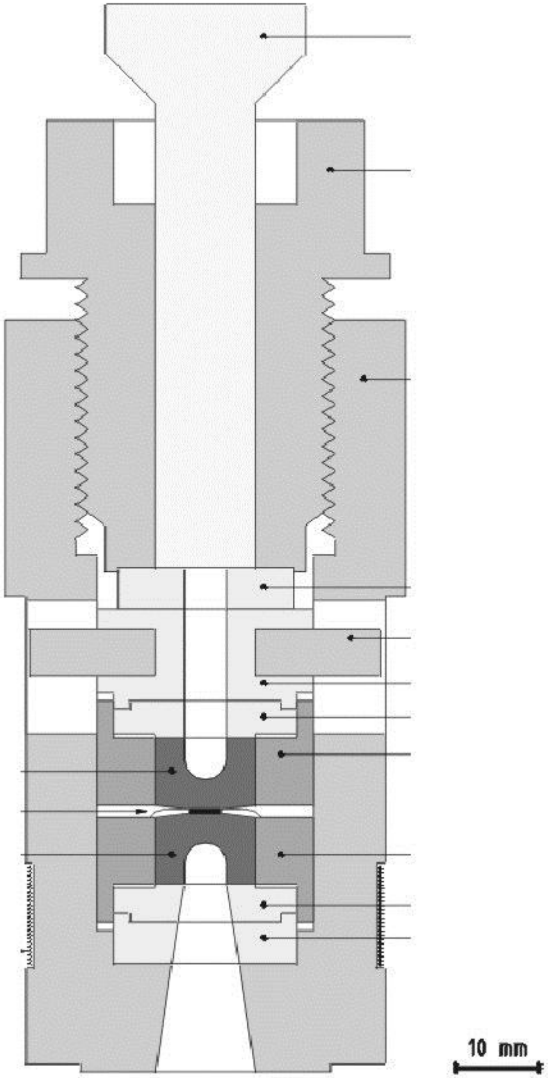
- higher pressure is needed
  $p \leq 20$ GPa (so far: $p < 9$ GPa)

↓

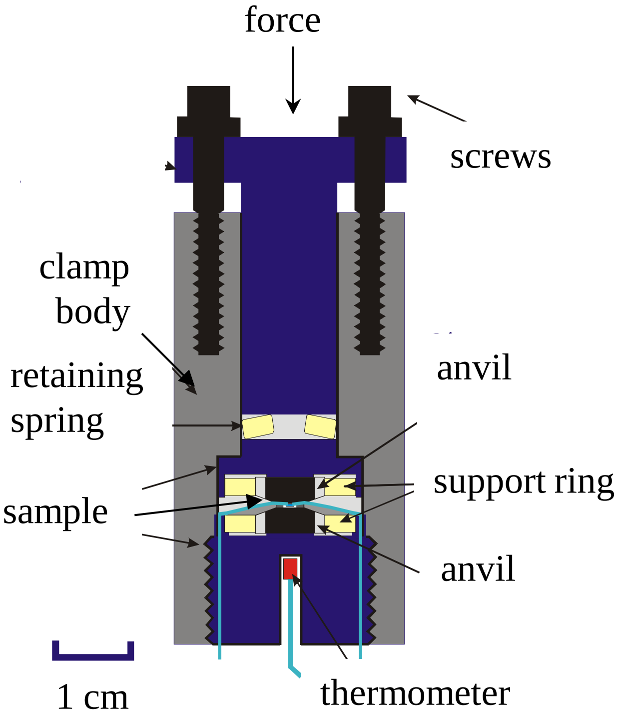
material must be
extremely hard

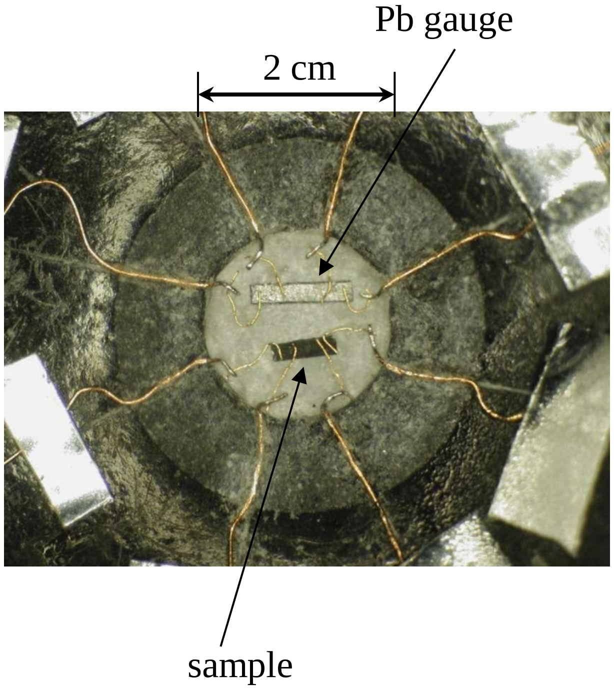
anvils made of
sintered diamonds
+
Re gasket




10 mm

High pressure technique: large-volume clamp





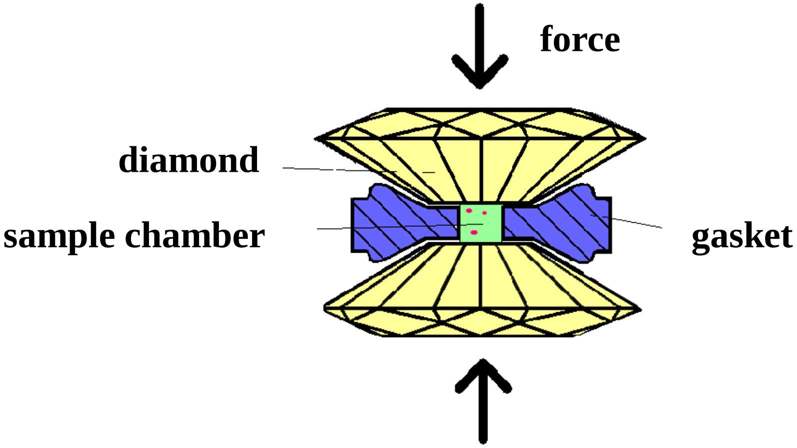
anvil culet: ~ 2 – 8 mm;
sample chamber: ~ 1 – 4 mm;
p_{max} ~ 40 GPa, quasihydrostatic

Benefits:

- large volume, large samples
- single crystals
- direction dependent electric transport

Experimental setup: Diamond Anvil Cell

i) x-ray diffraction



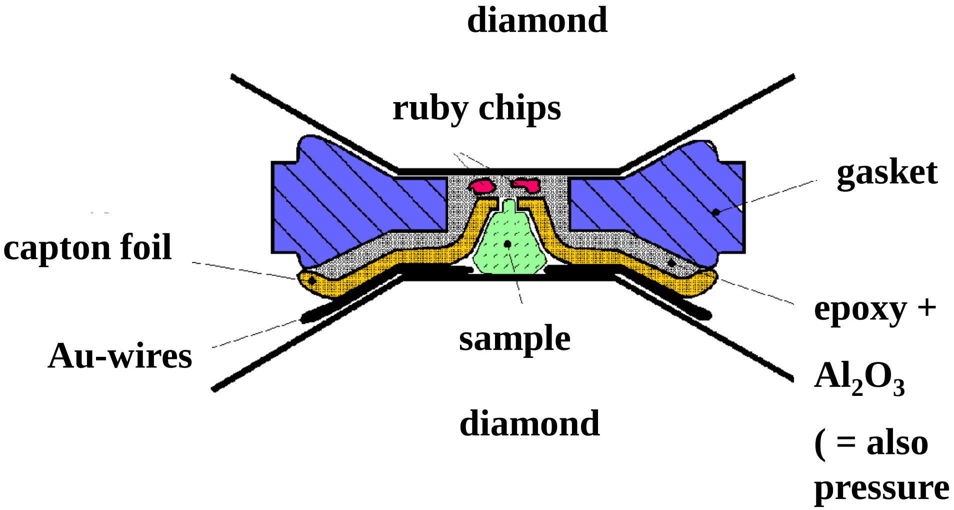
sample chamber: Ø = 100 - 300µm;

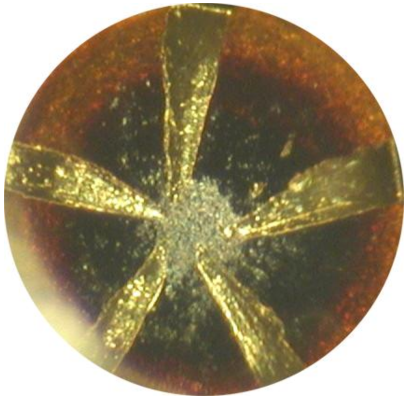
height: 25-50 µm

$p_{max} \approx 100$ GPa (= 1 Mbar)

Pressure media: e.g. liquid Nitrogen, liquid Argon, liq. Helium, Oil, Epoxy, etc.

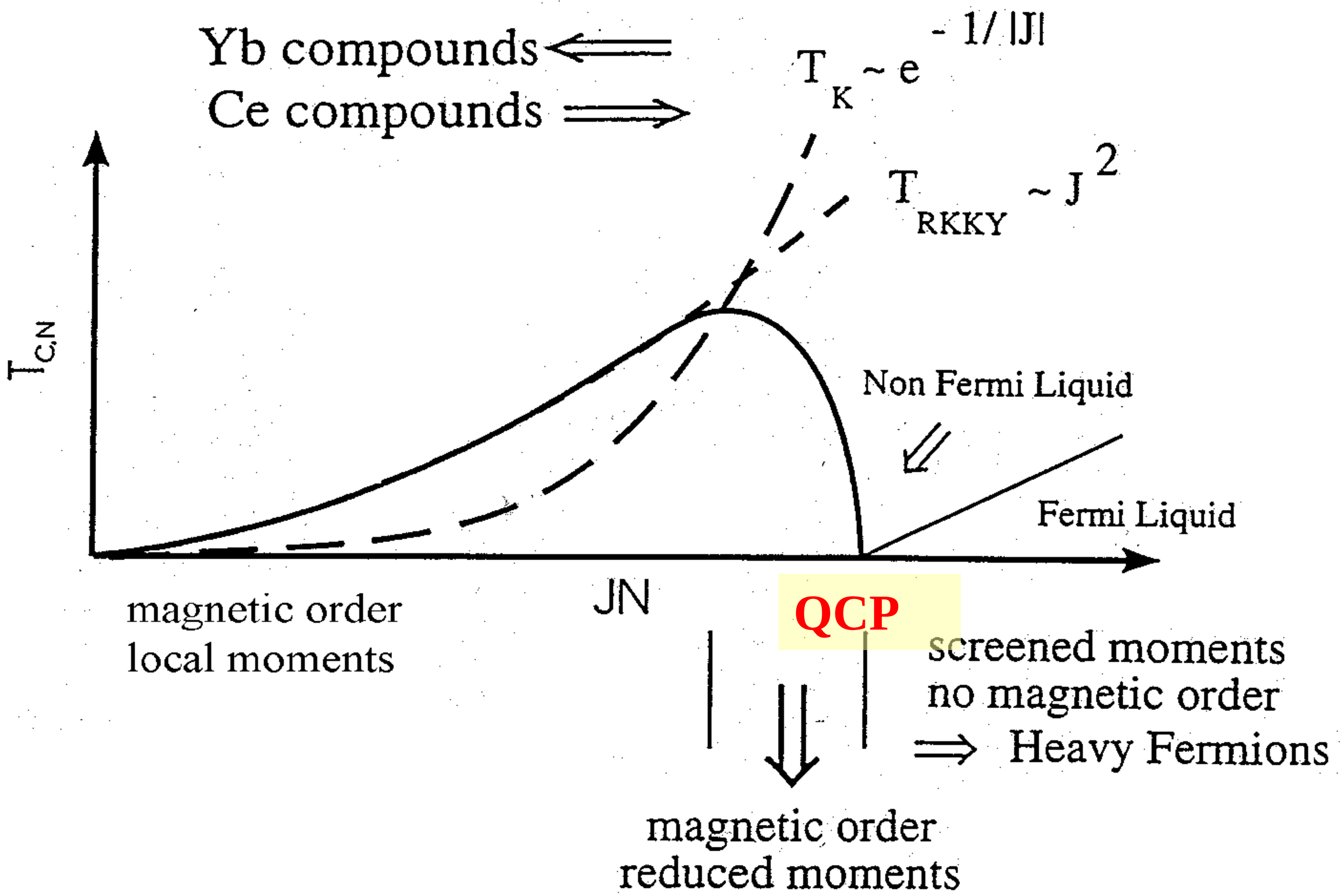
ii) resistivity measurements



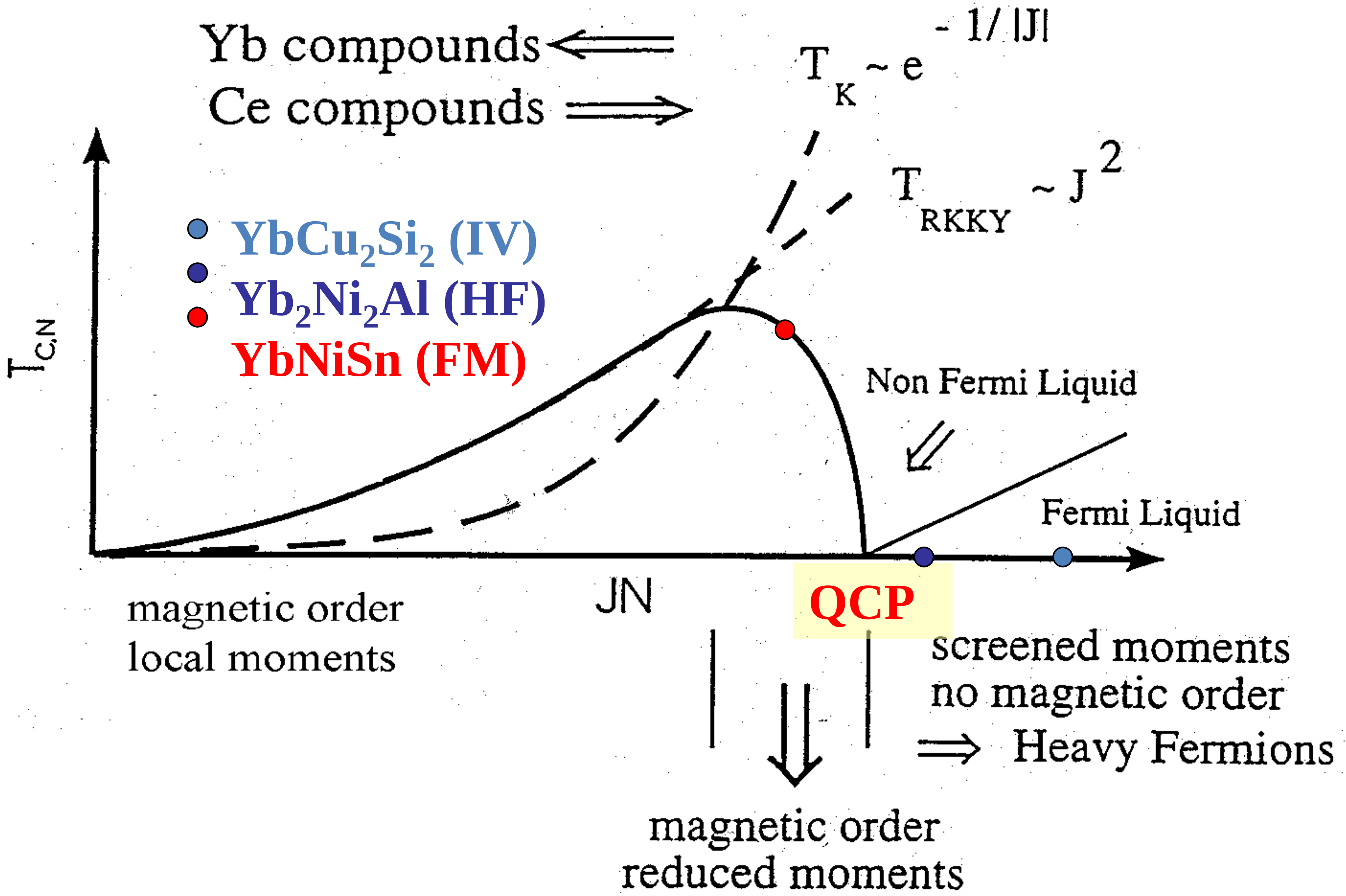


sample chamber Ø ≈ 100 µm

Some examples



Some examples



- ● **YbCu$_2$Si$_2$ (IV)**
- ● **Yb$_2$Ni$_2$Al (HF)**
- ● **YbNiSn (FM)**

QCP

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Competing Anisotropies in the Ferromagnetic Kondo-Lattice Compound YbNiSn: Observation of a Complex Magnetic Ground State under High Pressure

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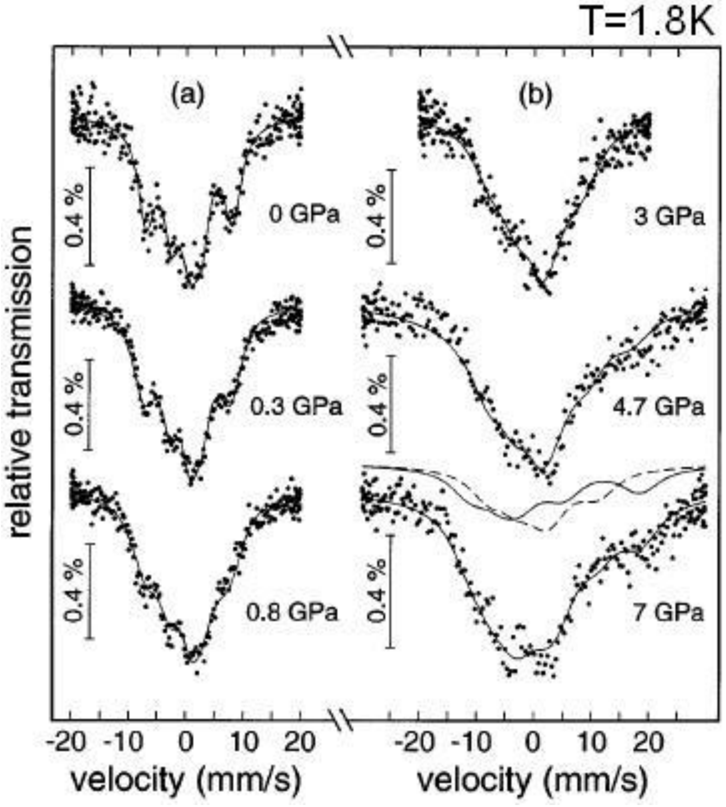
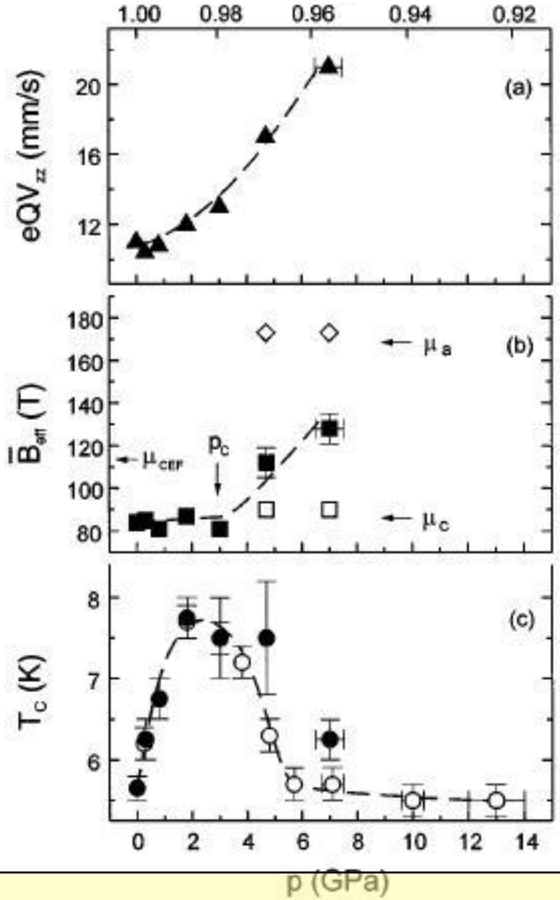
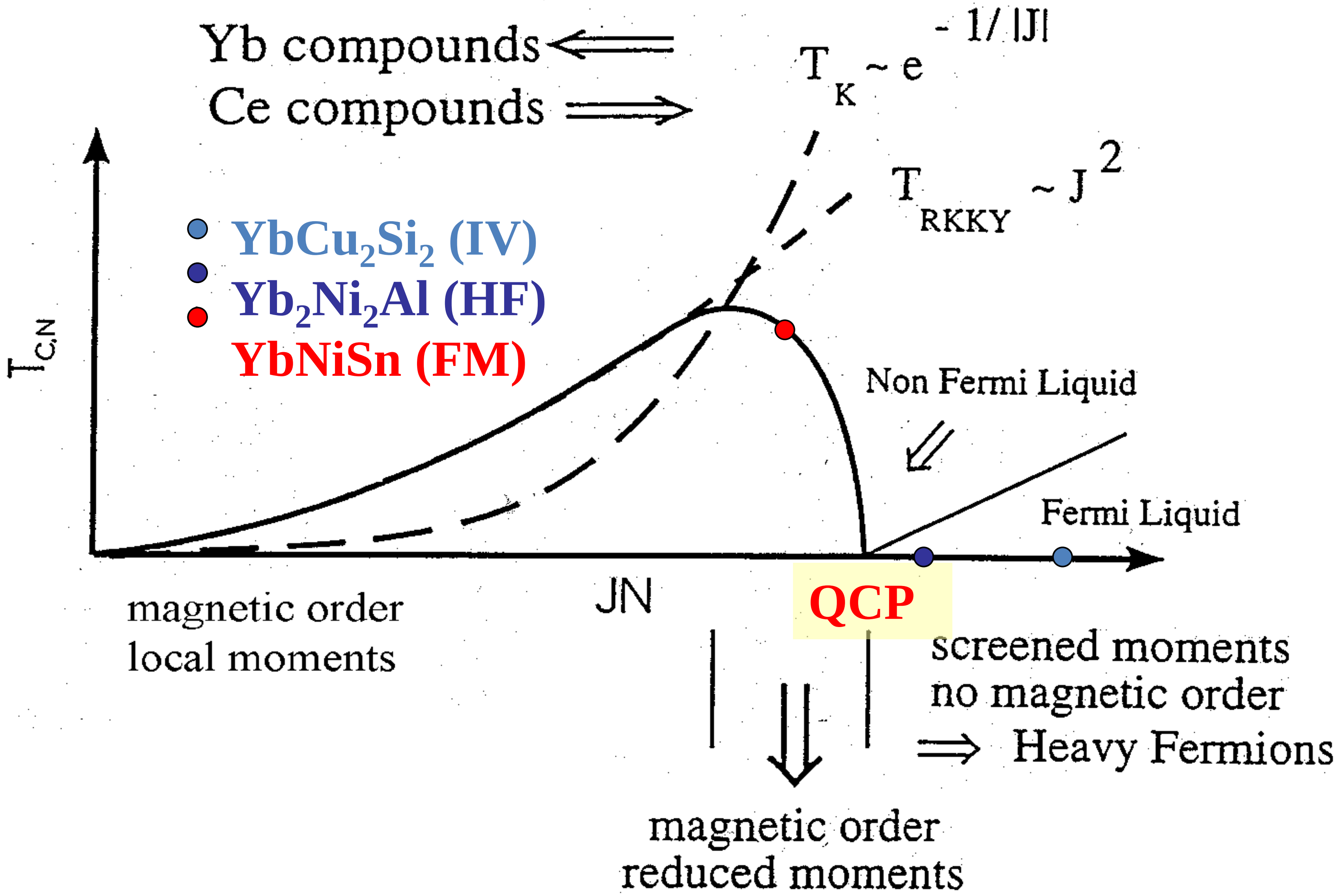
(Received 3 July 1996)





Stable moment up to 3 GPa ⇒ no Kondo screening !
Pressure-induced complex magnetic state

Some examples



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Pressure-Induced Local Moment Magnetism in the Nonmagnetic Heavy Fermion Compound Yb_2Ni_2Al

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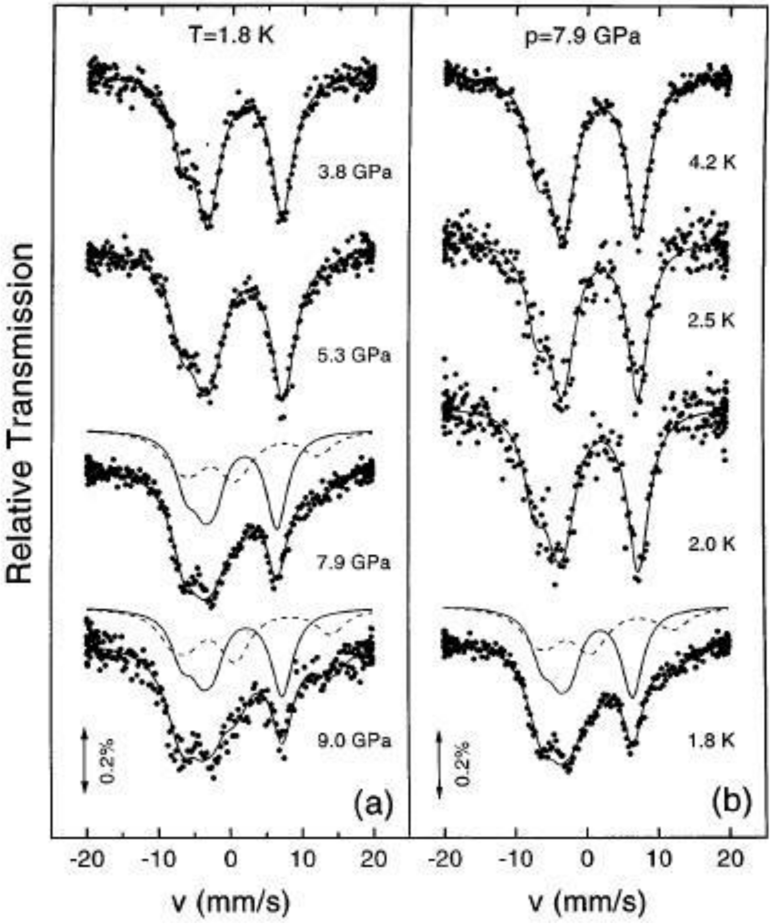
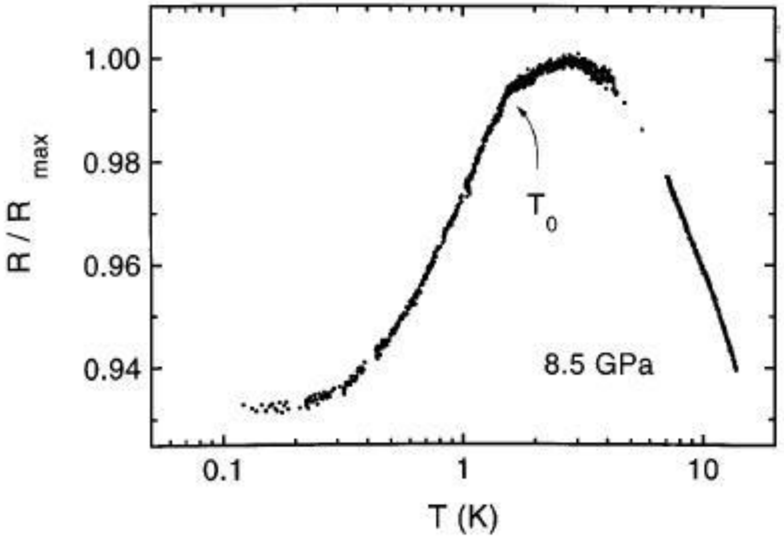
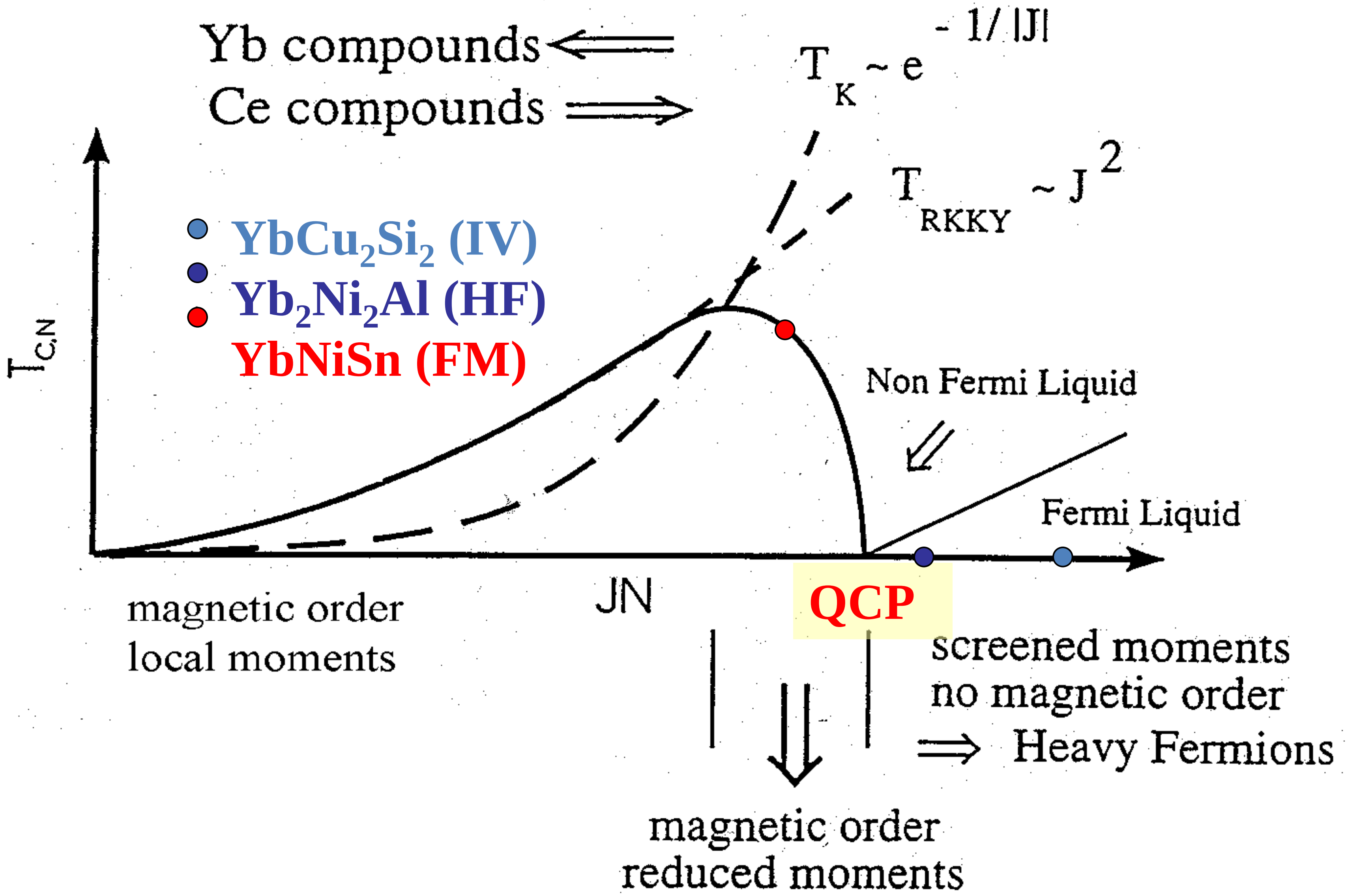
(Received 12 May 1998)





Pressure-induced first-order magnetic phase transition

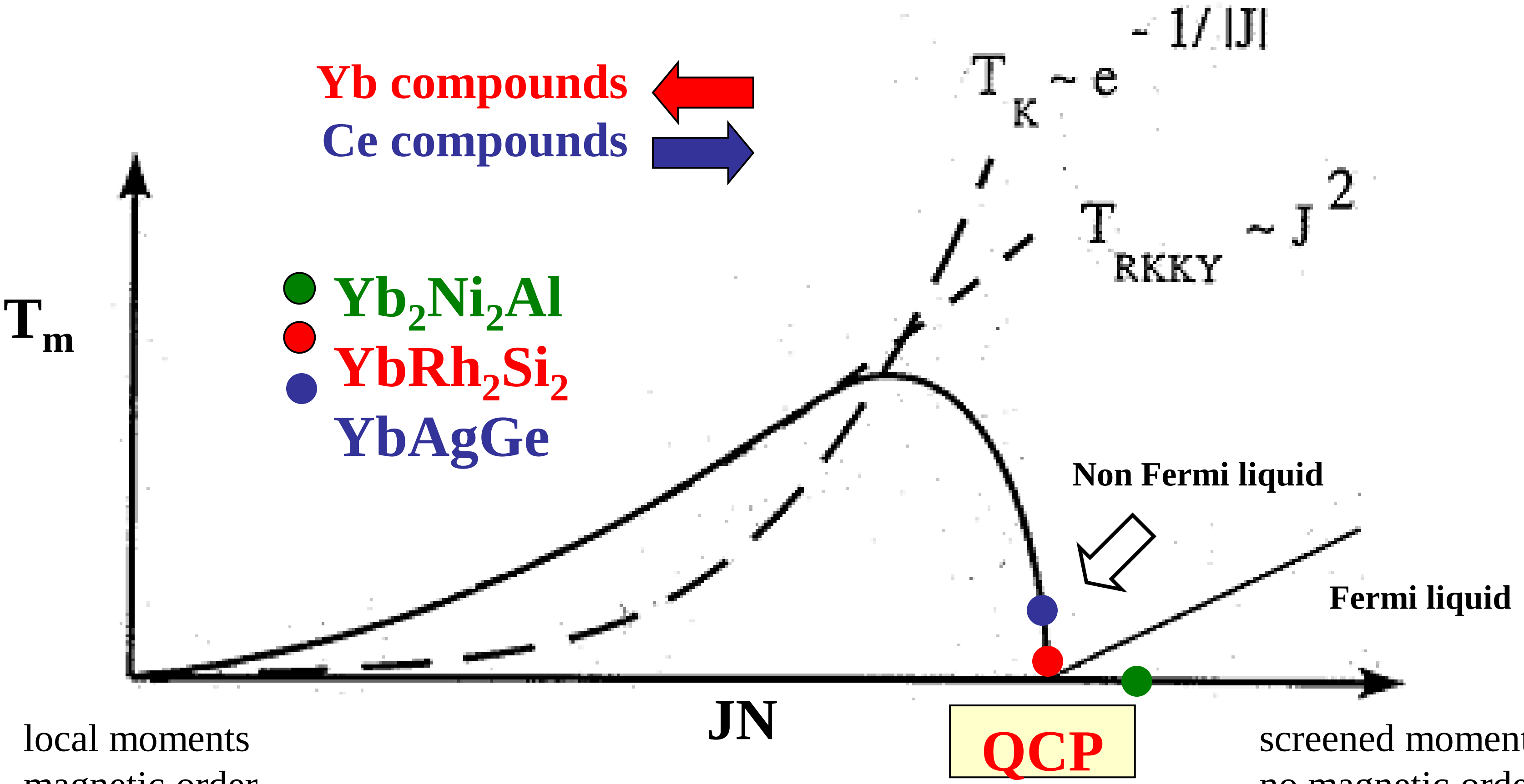
Some examples



● $YbCu_2Si_2$ (IV)
● Yb_2Ni_2Al (HF)
● YbNiSn (FM)

QCP

Some examples



Yb compounds ←
Ce compounds →

- ● **Yb_2Ni_2Al**
- ● **$YbRh_2Si_2$**
- ● **YbAgGe**

local moments
magnetic order

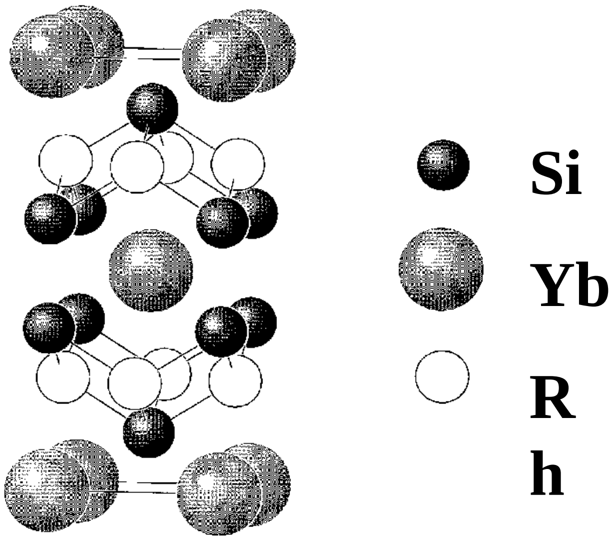
screened moments
no magnetic order
⇒ **Heavy Fermions**

$YbRh_2Si_2$ - non Fermi liquid system near a QCP

tetragonal $ThCr_2Si_2$-type structure (I4/mmm)

High quality single crystals (MPI Dresden)

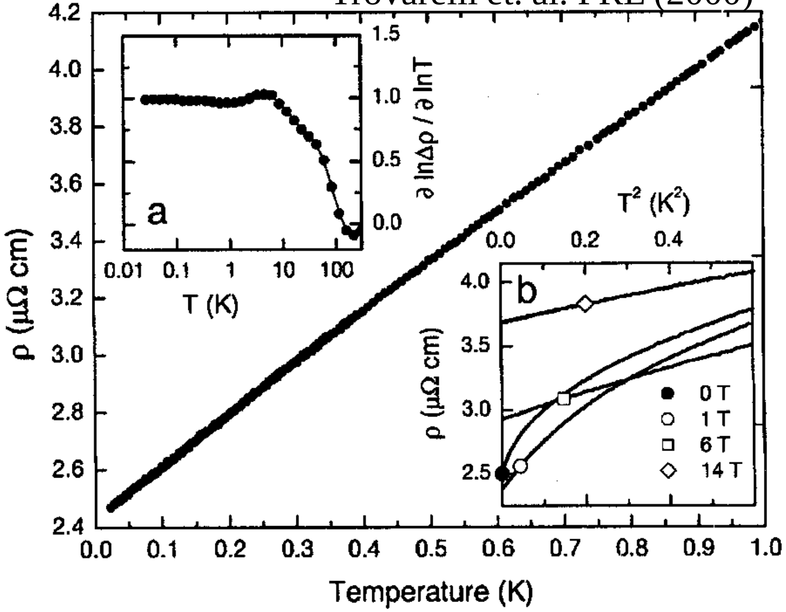
O. Trovarelli; C. Geibel

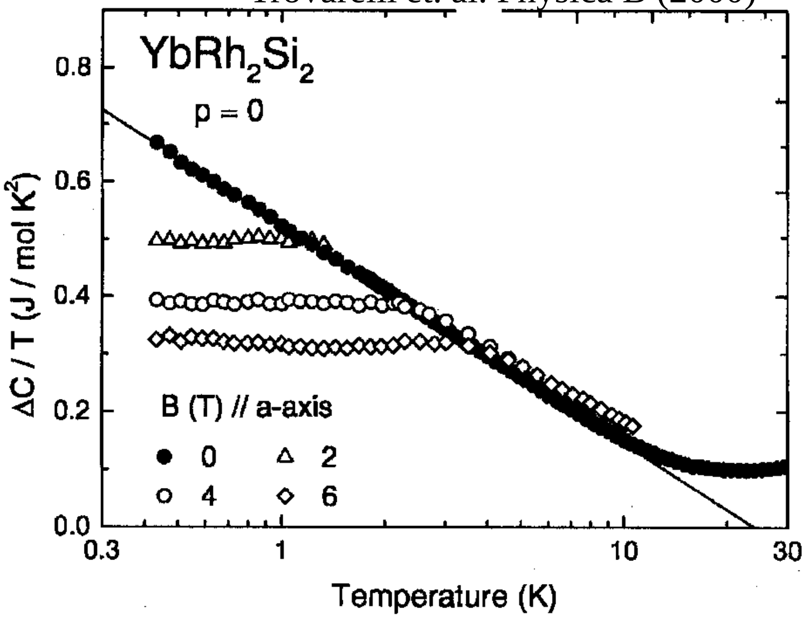


Model system for the observation of the evolution of the long range magnetic order out of the NFL state

Comparison with Ce-compounds possible

$YbRh_2Si_2$ - properties:
a) pronounced NFL-behaviour at low temperatures


Trovarelli et. al. PRL (2000)


Trovarelli et. al. Physica B (2000)

NFL

$\Delta \rho \propto T$

$\Delta C/T \propto -\ln T$

FL

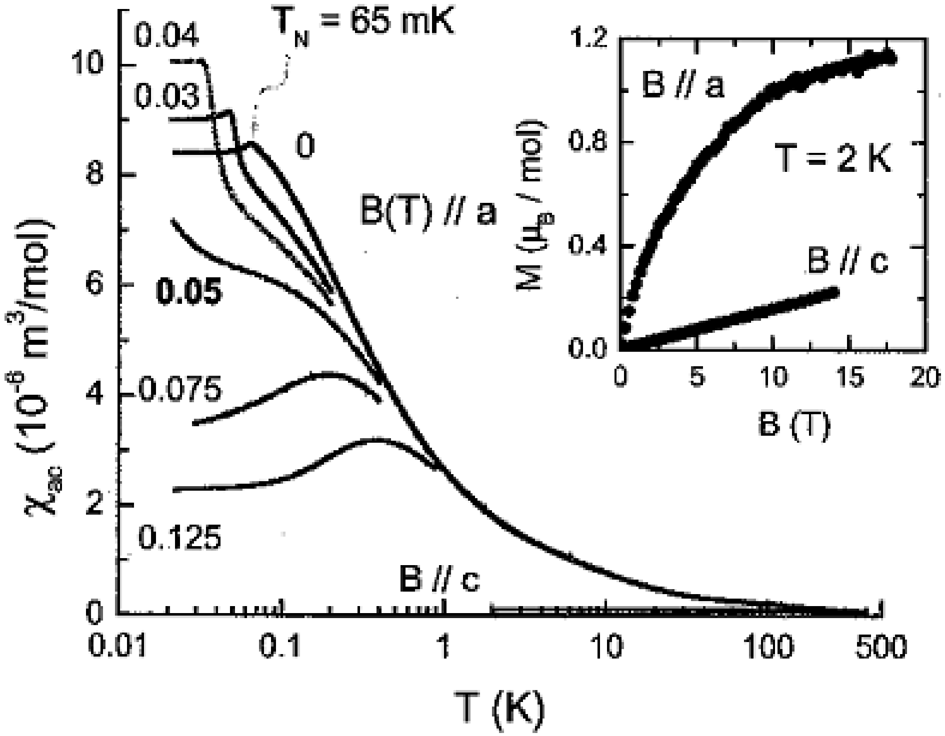
$\Delta \rho \propto T^2$

$\Delta C/T = \text{const.}$

B_{ext} suppresses NFL-behavior

NFL → FL

b) weak magnetic order at very low temperatures

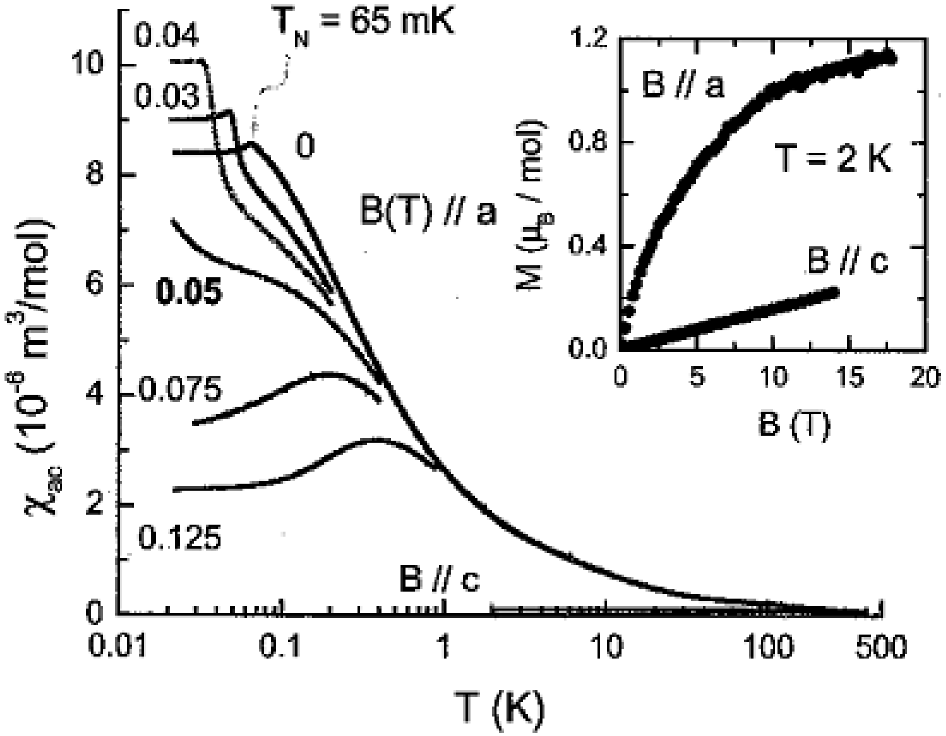

Trovarelli et al. PRL (2000)

- **$T_m \approx 65$ mK**
- **very weak magnetic order**
- **B_{ext} suppresses magn. order**

$T_m < 20$ mK for $B_{ext} = 45$ mT

b) weak magnetic order at very low temperatures

Trovarelli et al. PRL (2000)



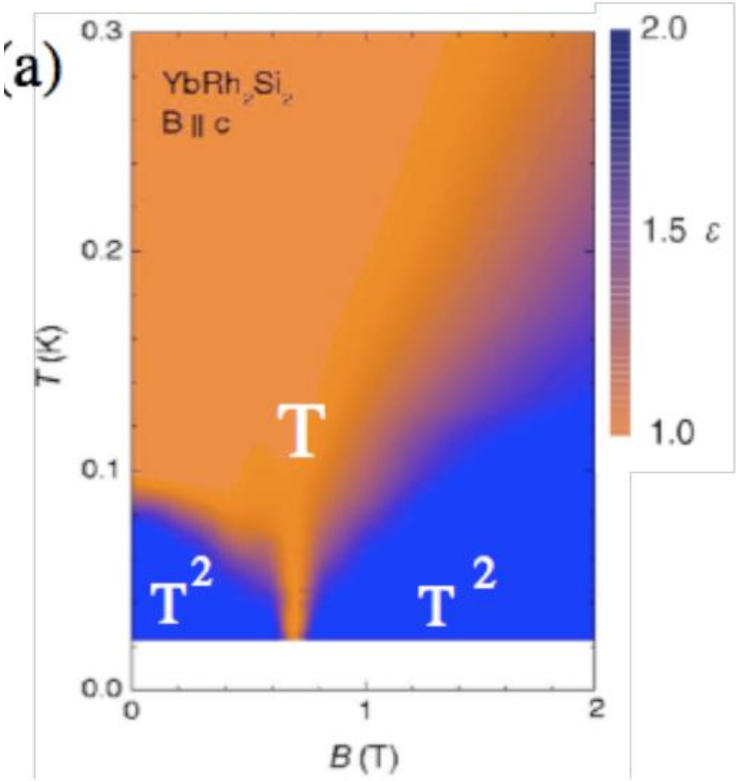
- **$T_m \approx 65$ mK**
- **very weak magnetic order**
- **B_{ext} suppresses mag. order**

$T_m < 20$ mK for B_{ext} = 45 mT

Proximity of $YbRh_2Si_2$ to a QCP !

YbRh2Si2:

Field-induced quantum critical point



Custers et al; (2003)

c) effect of pressure and Ge-doping

Pressure

- T_m increases!
- $T_m \approx$ 1K at p = 2.7 GPa

Ge-doping ⇔ volume-expansion

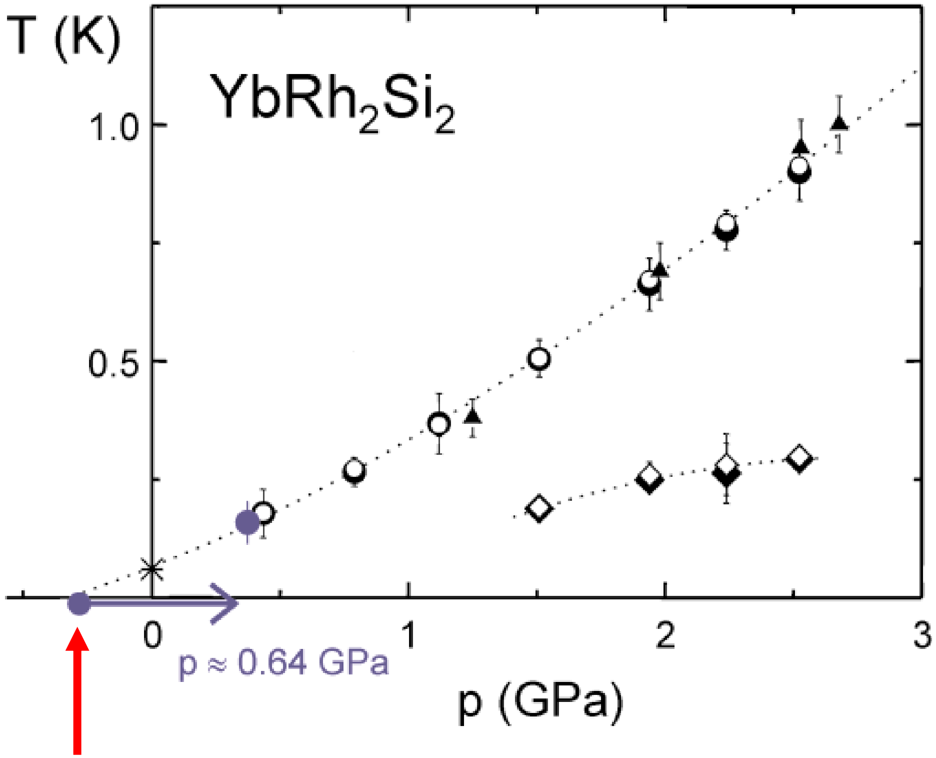
5 % Ge (T_m< 10mK)

- mag. order suppressed

$YbRh_2Si_2$ can be tuned to QCP

QCP: p ≈ - 0.3 GPa ≅ ~ 4% Ge

O. Trovarelli et al (2000)



QCP

$YbRh_2Si_2$ - magnetic ground state

P. Gegenwart et al. PRL (2002)

- **weak antiferromagnetic order below $T_N = 70$ mK**
- **paramagnetic moment $T_N < T < 0.6$ K; $\mu_{Yb} = 1.4\ \mu_B$**
- **ordered antiferromagnetic moment $\mu_{Yb} < 0.1\ \mu_B$**

→ **antiferromagnetic fluctuations** (NMR, K.Ishida et al., PRL (2002);

μSR, K. Ishida et al. Physica B (2003))

Low moment (LM) dynamic magnetic state at ambient pressure

Open questions

nature of the ground state near the QCP

- **change of the magnetic moment μ_{Yb} and T_m with pressure?**
- **pressure-induced magnetic phase transition?**

⇒ pressure-temperature magnetic phase diagram

?

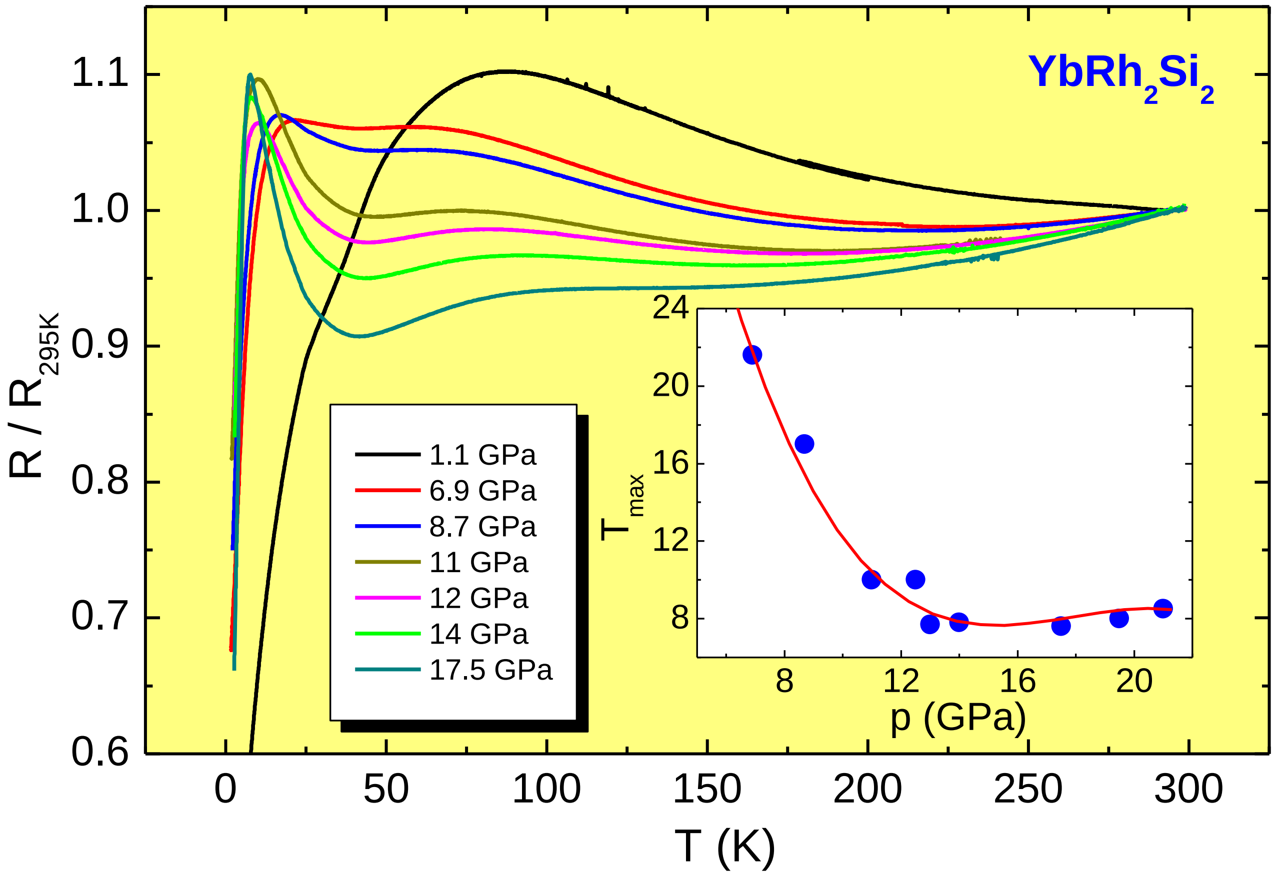
experiment ⟷ theory ?

⬇

experimental approach

- **^{170}Yb-Mössbauer spectroscopy $p \leq 20$ GPa , $T \geq 1.3$ K**
- **electrical resistance R(p,T,B) $p \leq 25$ GPa , $T \geq 1.7$ K and mK-range**
- **x-ray diffraction $p \leq 25$ GPa , $T = 300$ K**

$YbRh_2Si_2$ - electrical resistance under high pressure



Hints for magnetic order at $p \geq 11$ GPa !

$YbRh_2Si_2$ - ^{170}Yb-Mössbauer spectroscopy

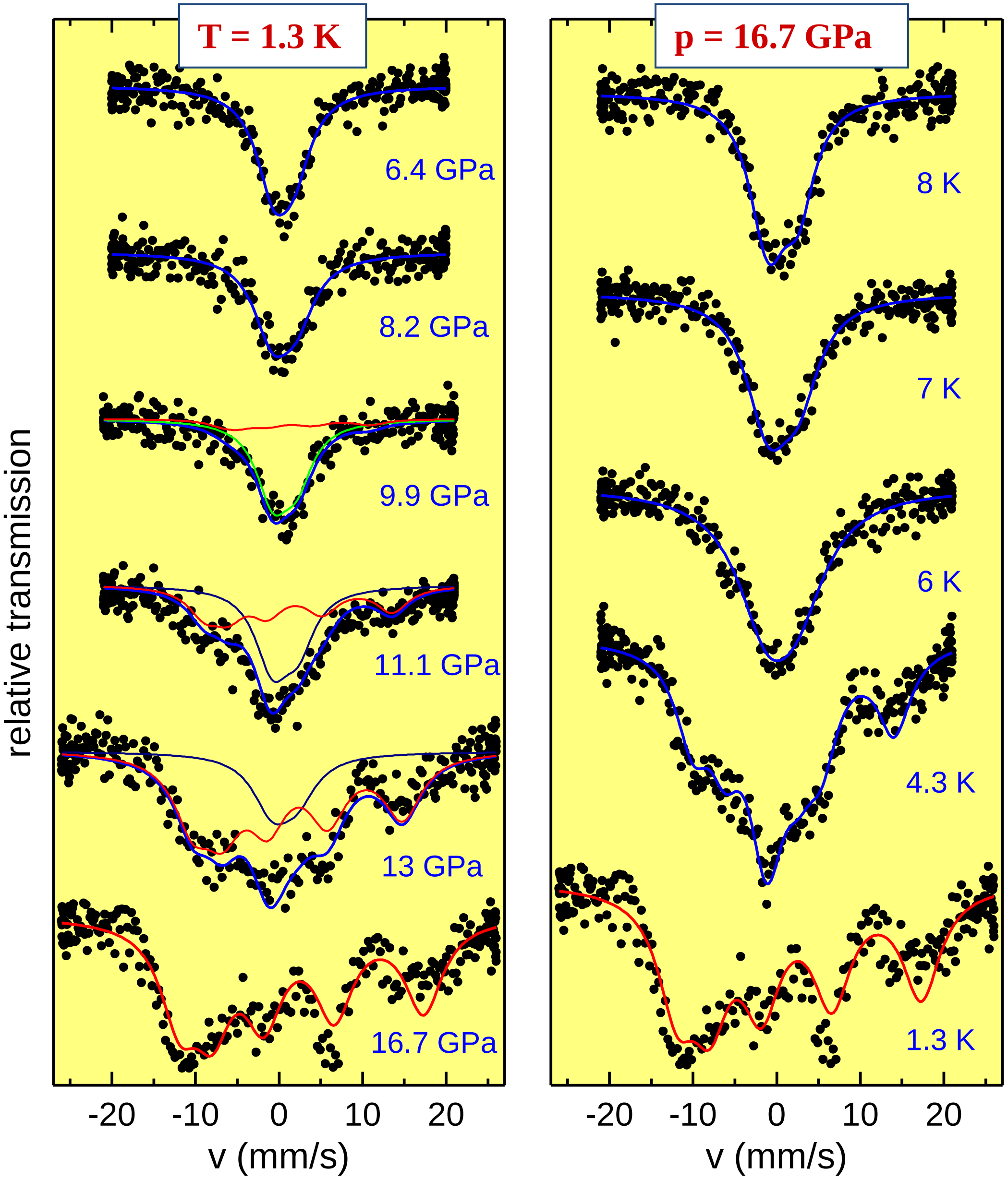
- observation of long range magnetic order for **p > 10 GPa** and **T < 1.5 K**
- for p ≥ 15 Gpa:

$T_{mag} \geq 7$ K

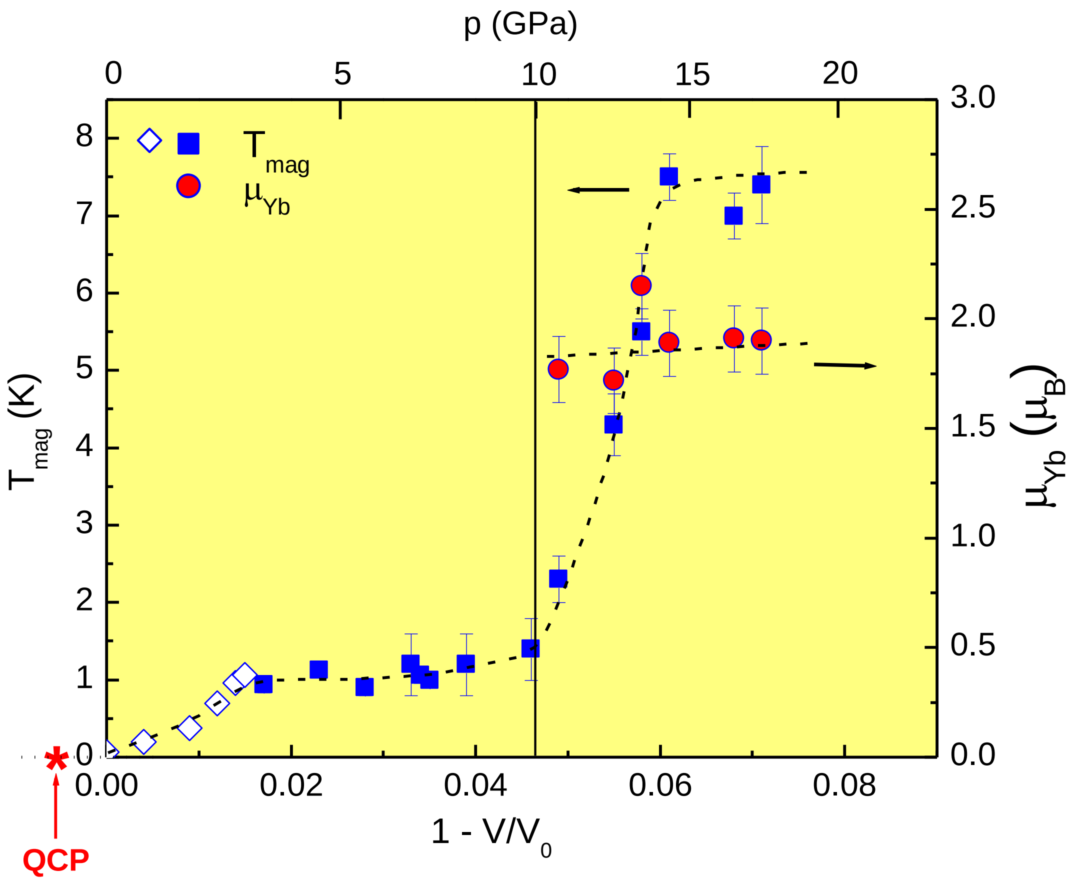
$\mu_{Yb} \sim 1.9\ \mu_B \parallel$ c-axis

(low moment ⊥ c-axis)

first-order magnetic phase transition (Low moment → High moment)



$YbRh_2Si_2$ - pressure dependence of T_{mag} and μ_{Yb}



unusual pressure dependance of T_{mag}

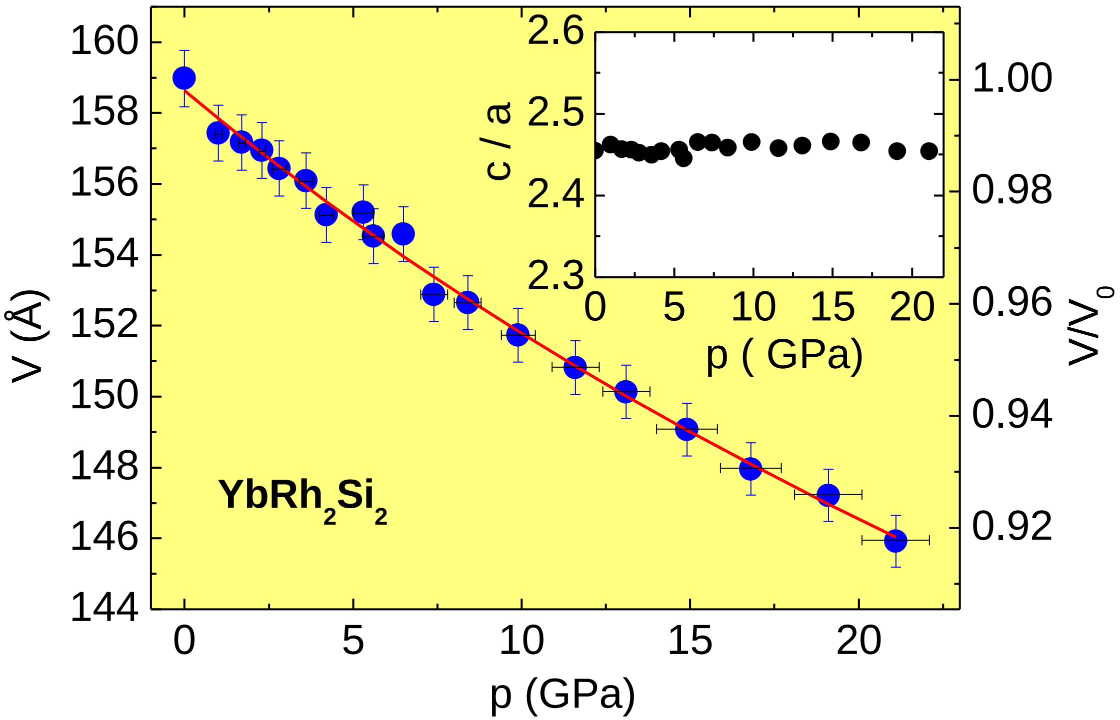
First order phase transition at p ≈ 10 GPa

structural phase transition?

$YbRh_2Si_2$ - x-ray diffraction under high pressure

crystal structure
stable for

$p \leq 21$ GPa !



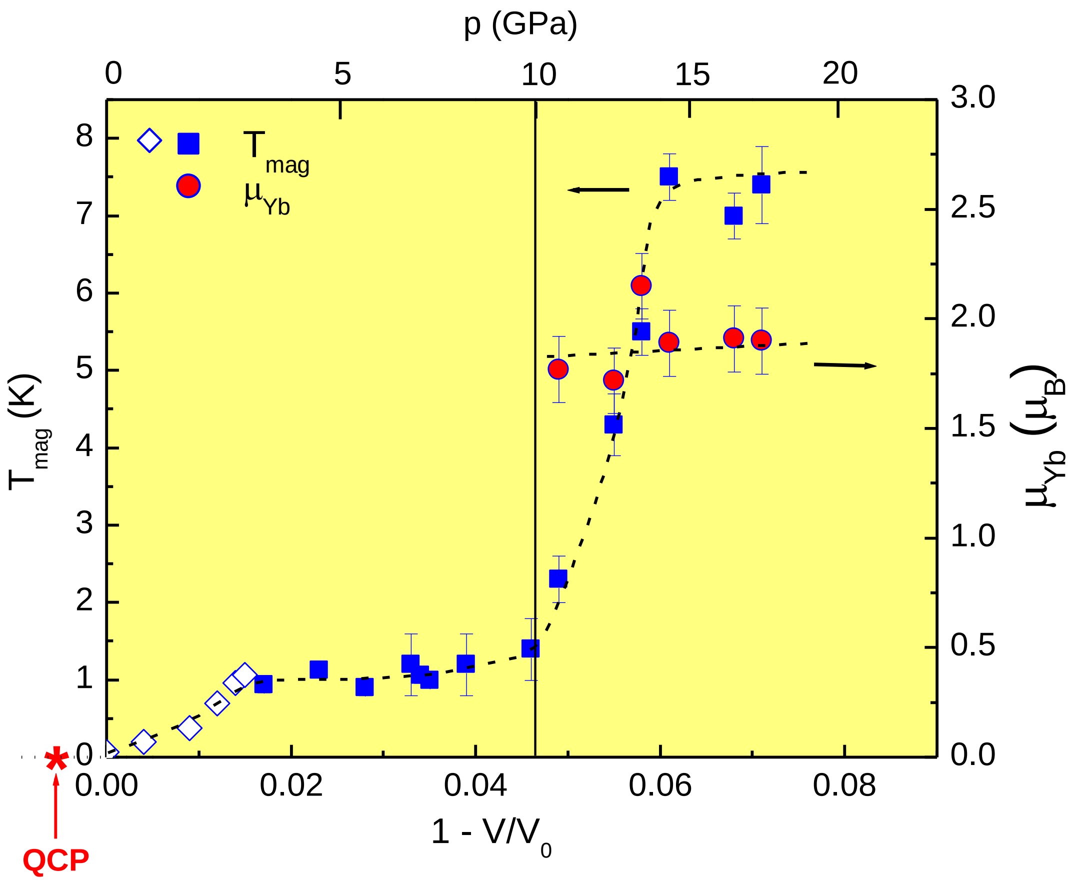
Bulk modulus: $B_0 = (198 \pm 15)$ GPa

comparison:

YbNiSn: $B_0 = (146 \pm 20)$ GPa

Yb_2Ni_2Al: $B_0 = (165 \pm 12)$ GPa

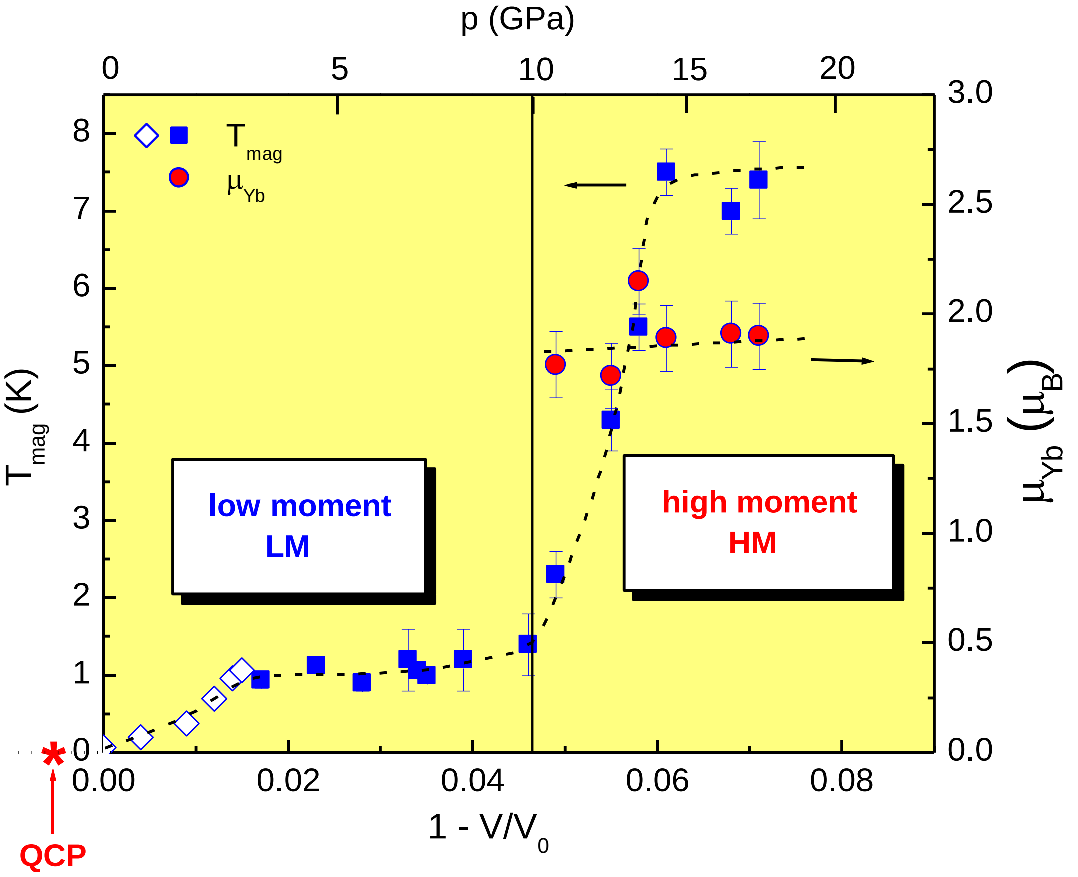
$YbRh_2Si_2$ - pressure dependence of T_{mag} and μ_{Yb}



unusual **pressure dependance of T_{mag}**

First order phase transition at p ≈ 10 GPa

$YbRh_2Si_2$ - pressure dependence of T_{mag} and μ_{Yb}



p < 10 GPa : LM state

dynamic fluctuations

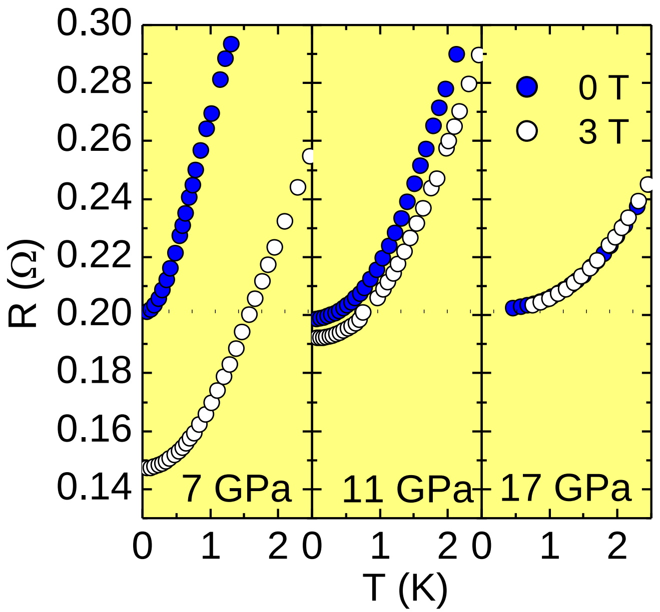
p > 10 GPa : HM state

- $\mu_{Yb} \approx 1.9\ \mu_B$
- static magnetic order

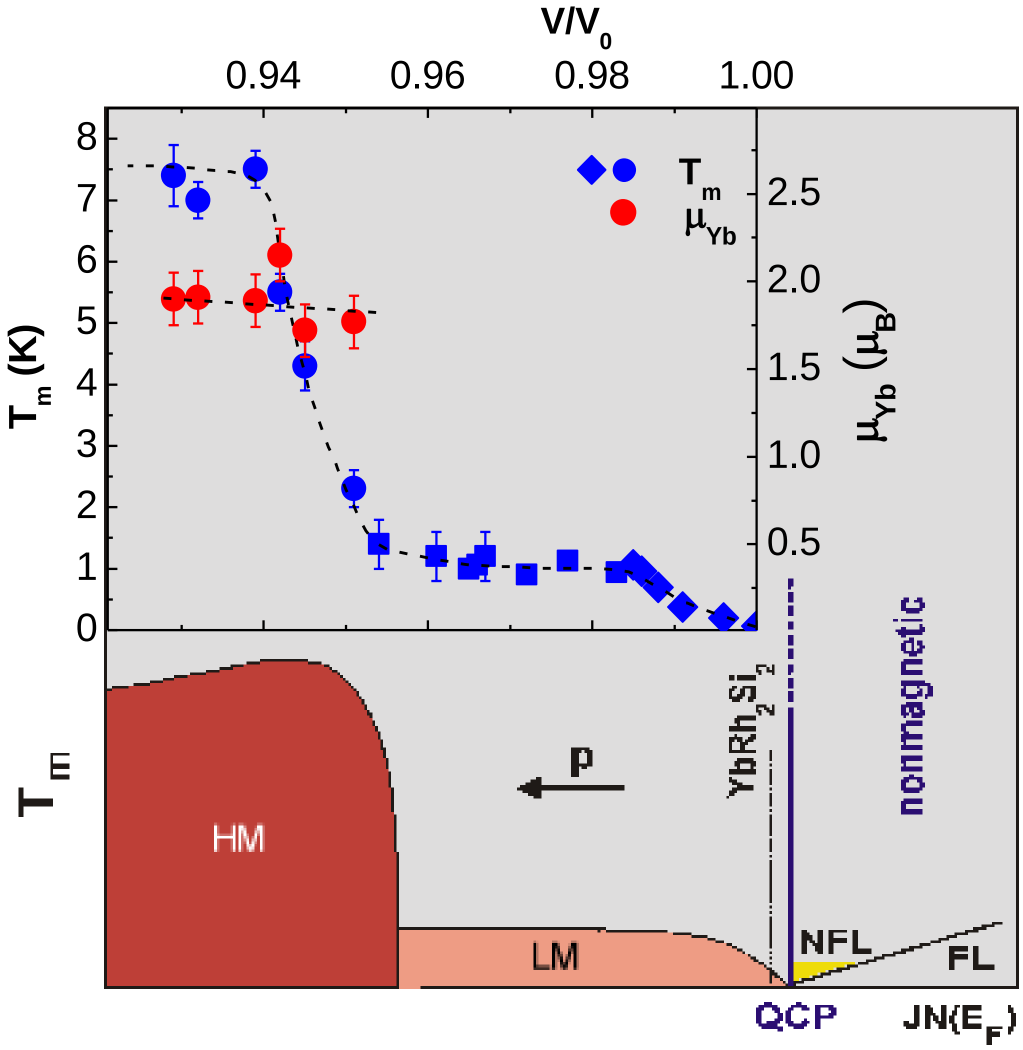
R(p,T) in external magnetic field for T → 0 K

negative magneto resistance in LM-state

→ evidence for spin fluctuations



Magnetic phase diagram - $YbRh_2Si_2$



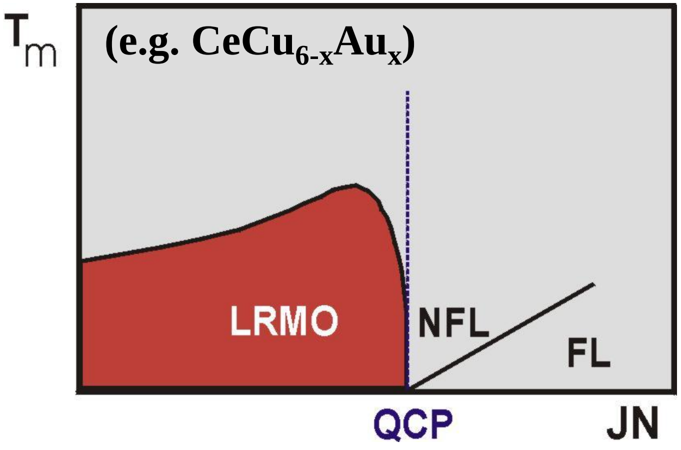
LM: low moment

HM: high moment

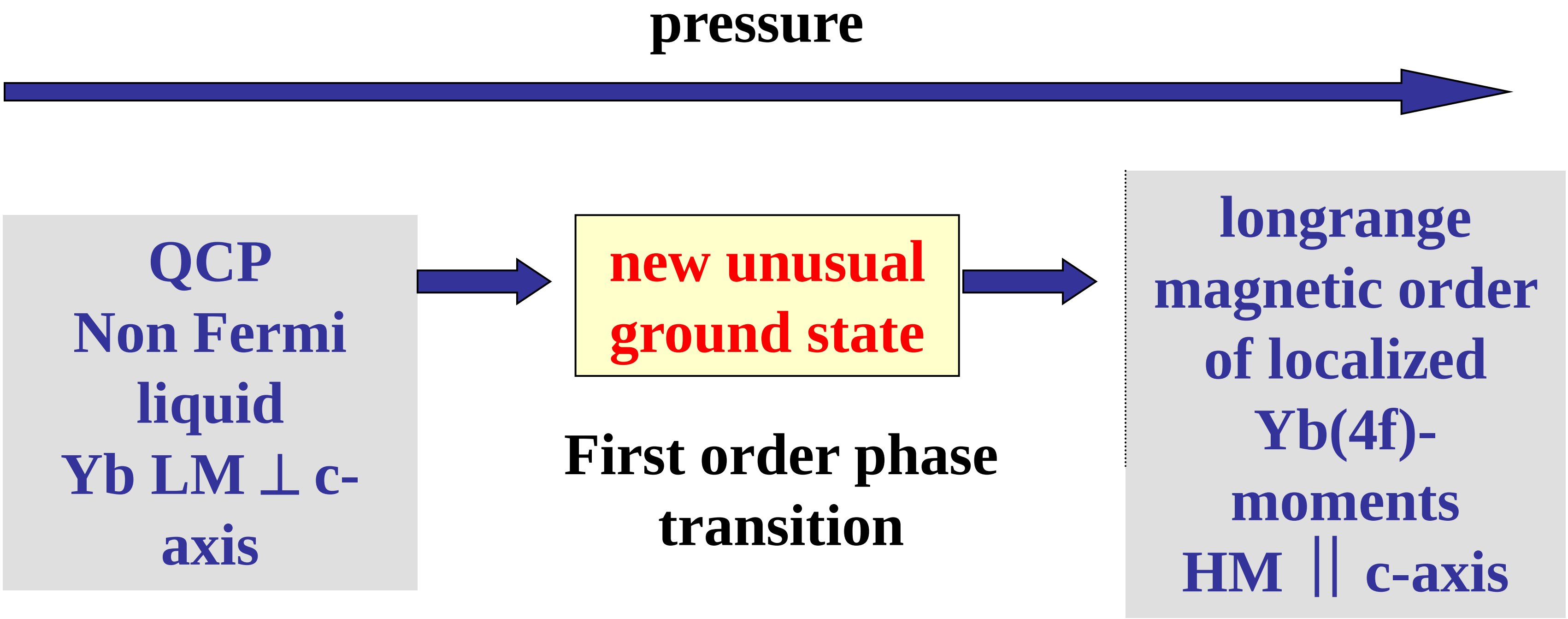
Description within the Doniach model not possible!

new unusual ground state in $YbRh_2Si_2$

stable up to $\Delta V/V_0 \approx 5$ % !!



Summary



pressure

QCP
Non Fermi liquid
Yb LM ⊥ c-axis

new unusual ground state

First order phase transition

longrange magnetic order of localized Yb(4f)-moments
HM || c-axis

- spin fluctuations along the pressure axis up to 10 GPa

- quite different behaviour than Ce heavy fermion systems

high pressure studies using Synchrotron Radiation

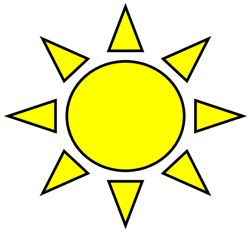
Mössbauer Spectroscopy with Synchrotron Radiation

Nuclear Forward Scattering of SR and some Applications

Why NFS?

Mössbauer Spectroscopy

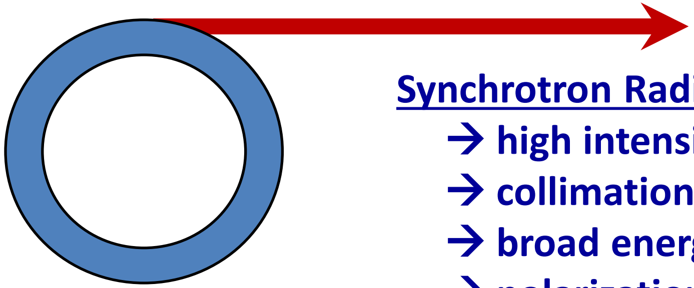
1958 Mössbauer



Radioactive source
→ 4 p emission

Nuclear Resonant Scattering of Synchrotron Radiation

1974 Ruby (proposition)
1986 Gerdau (first experiment)



Synchrotron Radiation:
- → high intensity
- → collimation
- → broad energy range
- → polarization
- → time structure

Information about hyperfine interactions between nucleus and surrounding environment

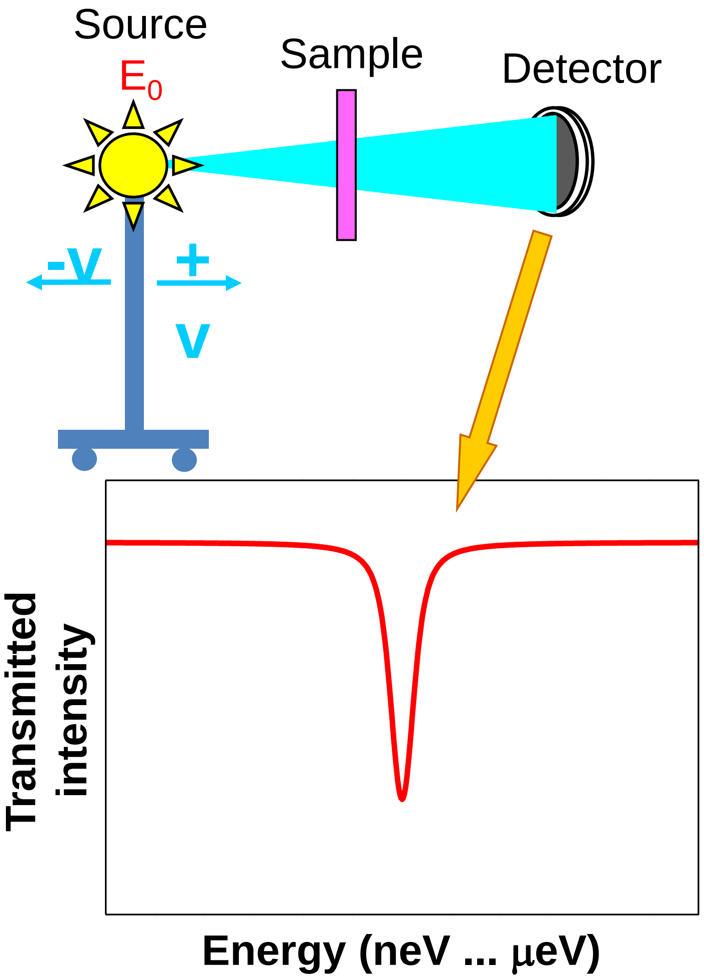
Magnetic and electronic properties

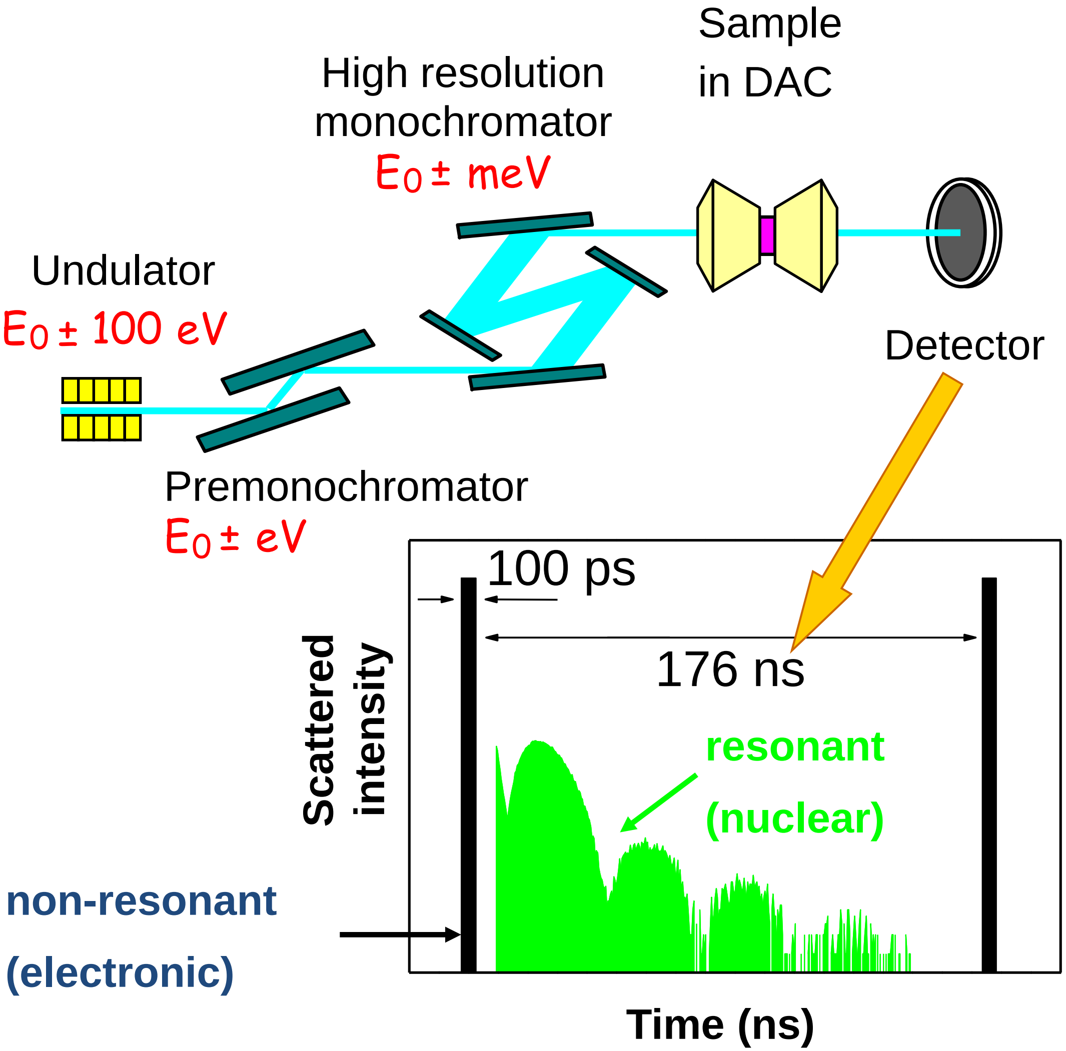
Well adapted to measurements under very high pressure and in external magnetic field!!

Mössbauer Spectroscopy and Nuclear Resonance Scattering

techniques based on the ⇨ **Nuclear Resonance Scattering (NRS)**

Mössbauer Spectroscopy

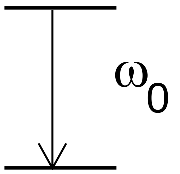


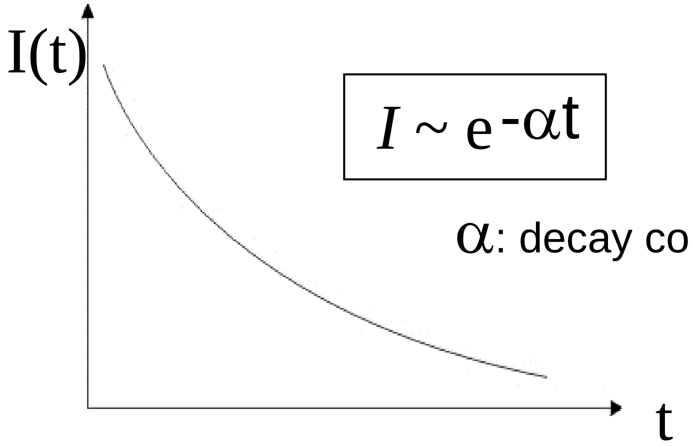


(a)

excited state

ground state





$I \sim e^{-\alpha t}$

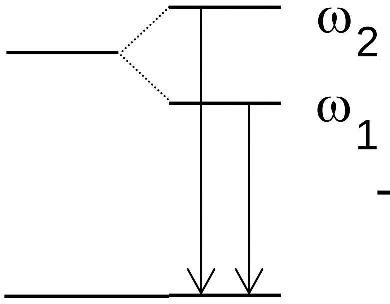
α: decay constant

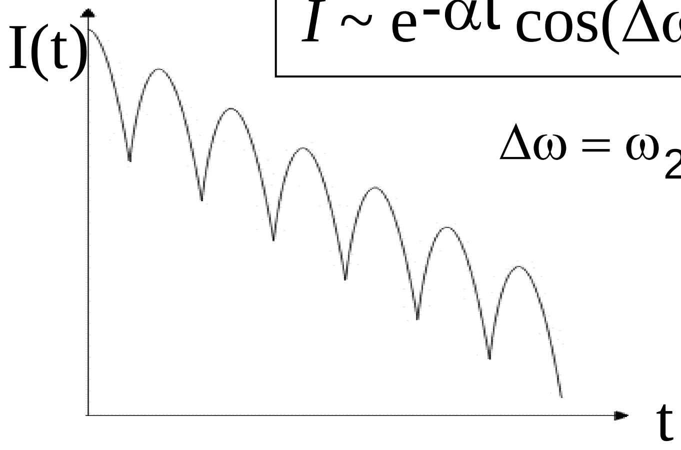
no hyperfine interactions → **radiative decay**

(b)

excited state

ground state



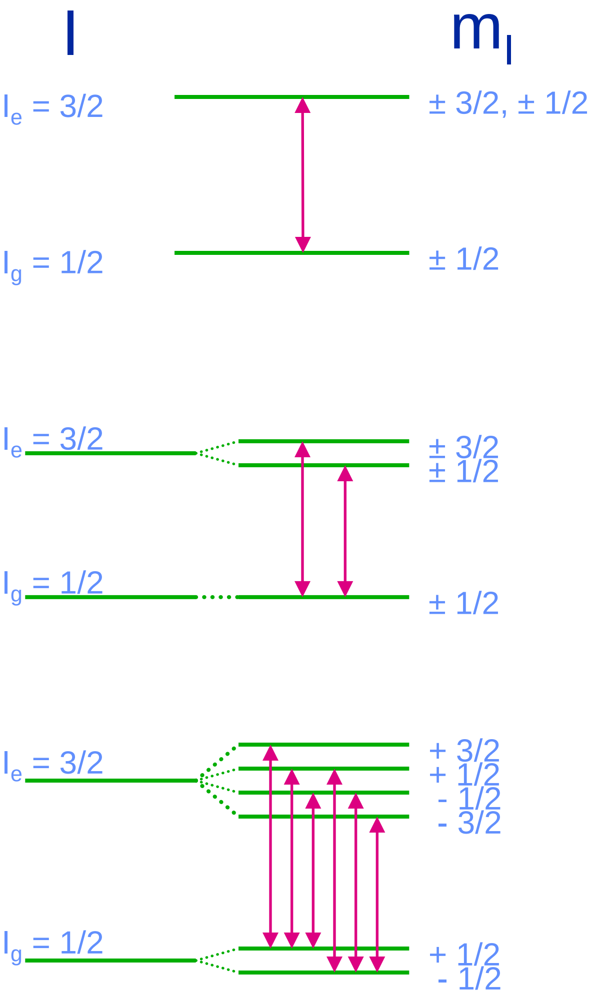


$I \sim e^{-\alpha t} \cos(\Delta\omega t)$

$\Delta\omega = \omega_2 - \omega_1$

hyperfine interactions → **quantum beats**

Comparison between Mössbauer spectroscopy and NFS for ^{119}Sn



I

m_I

$I_e = 3/2$ ± 3/2, ± 1/2

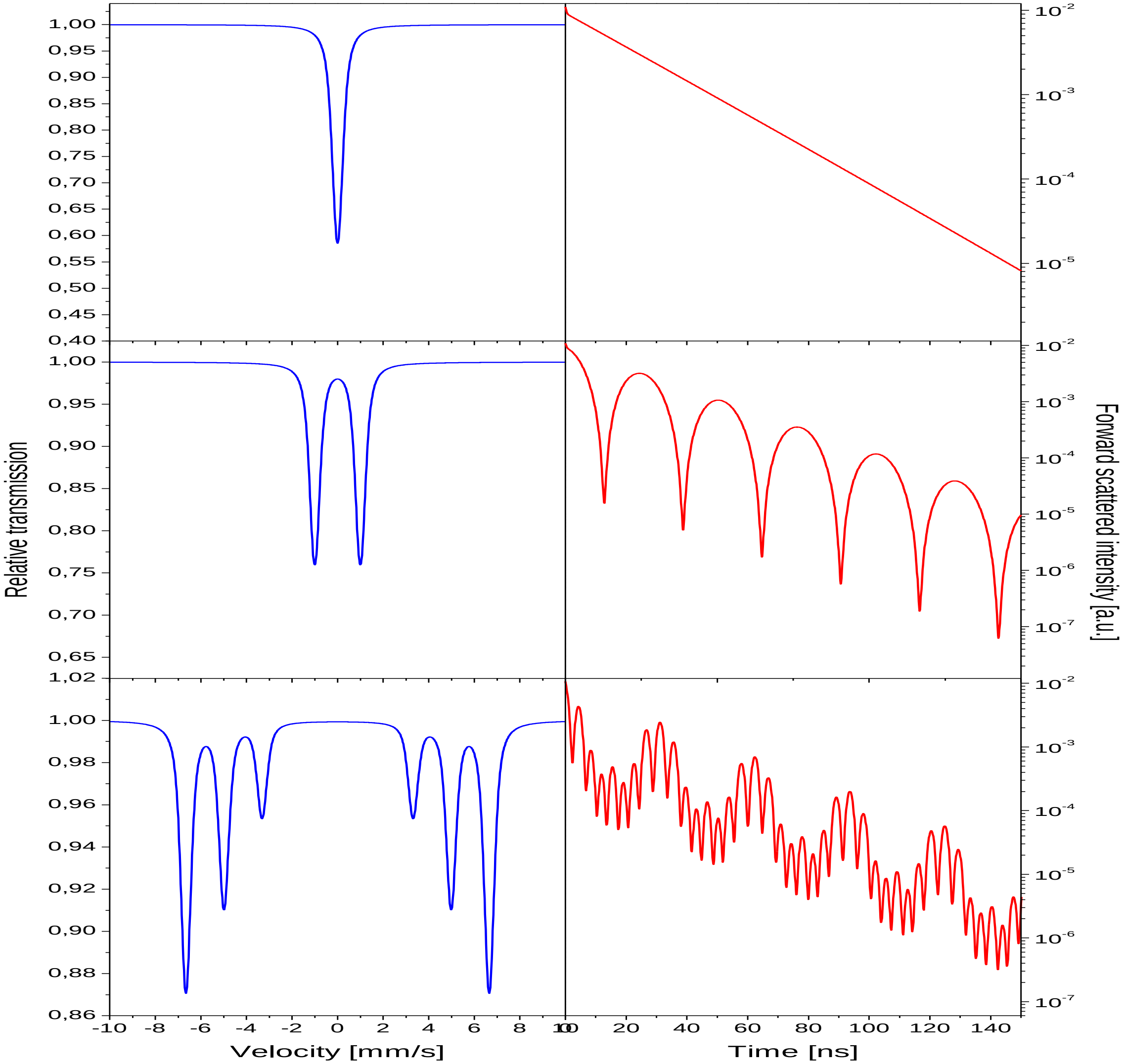
$I_g = 1/2$ ± 1/2

$I_e = 3/2$ ± 3/2
± 1/2

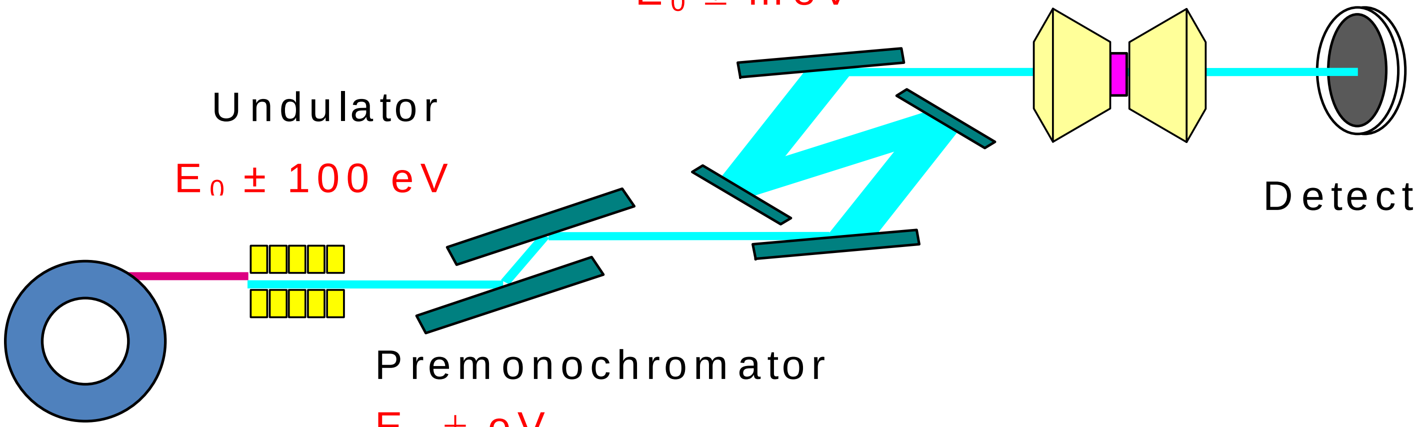
$I_g = 1/2$ ± 1/2

$I_e = 3/2$ + 3/2
+ 1/2
- 1/2
- 3/2

$I_g = 1/2$ + 1/2
- 1/2



Experimental setup for Nuclear Forward Scattering



High resolution monochromator

E$_0$ ± meV

Sample in DAC (200 µm)

Undulator

E$_0$ ± 100 eV

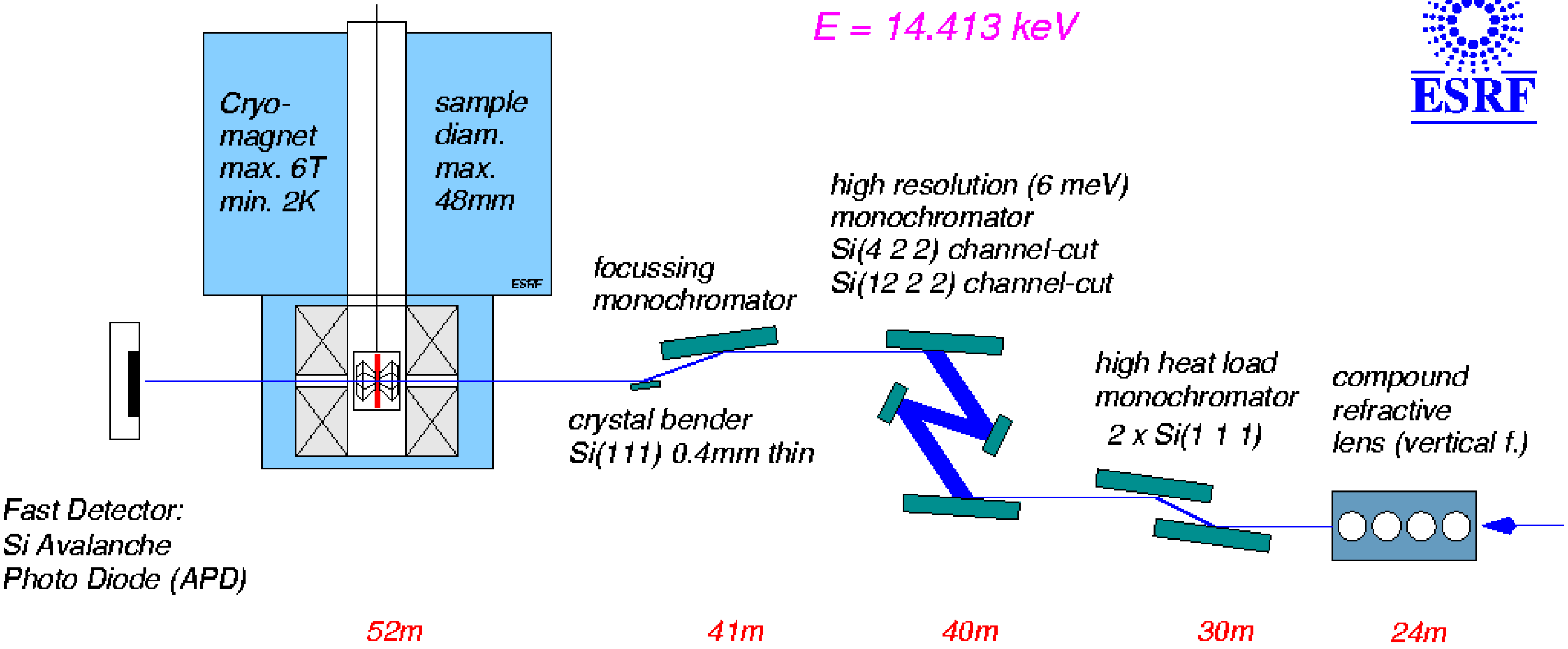
Detector

Premonochromator

E$_0$ ± eV

Storage ring

Experimental Setup for Nuclear Forward Scattering at ID18



$E = 14.413$ keV

Cryo-
magnet
max. 6T
min. 2K

sample
diam.
max.
48mm

focussing
monochromator

high resolution (6 meV)
monochromator
Si(4 2 2) channel-cut
Si(12 2 2) channel-cut

high heat load
monochromator
2 x Si(1 1 1)

compound
refractive
lens (vertical f.)

crystal bender
Si(111) 0.4mm thin

Fast Detector:
Si Avalanche
Photo Diode (APD)

52m

41m

40m

30m

24m

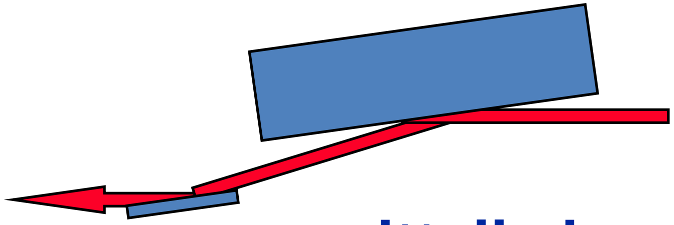
distance to ID18 U23, U32

$\Delta E = 6$meV

$\Delta E = 3$eV

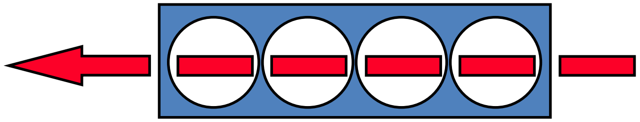
Optics for high pressure

HORIZONTAL FOCUSSING



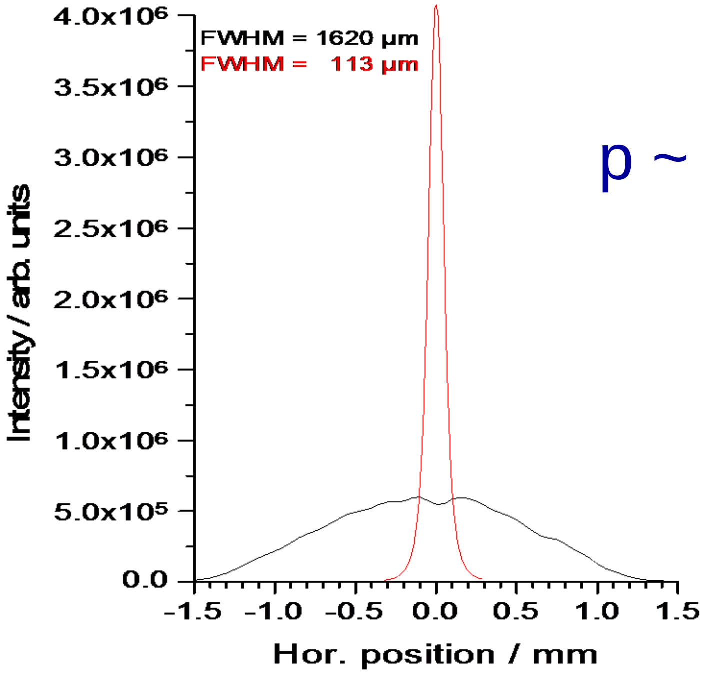
sagittally bent crystal

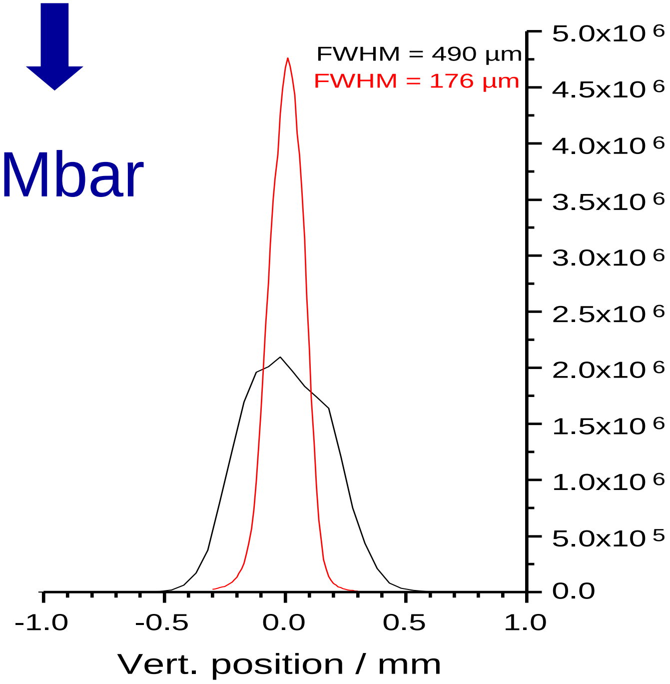
VERTICAL FOCUSSING



Be compound refractive lens

p ~ Mbar





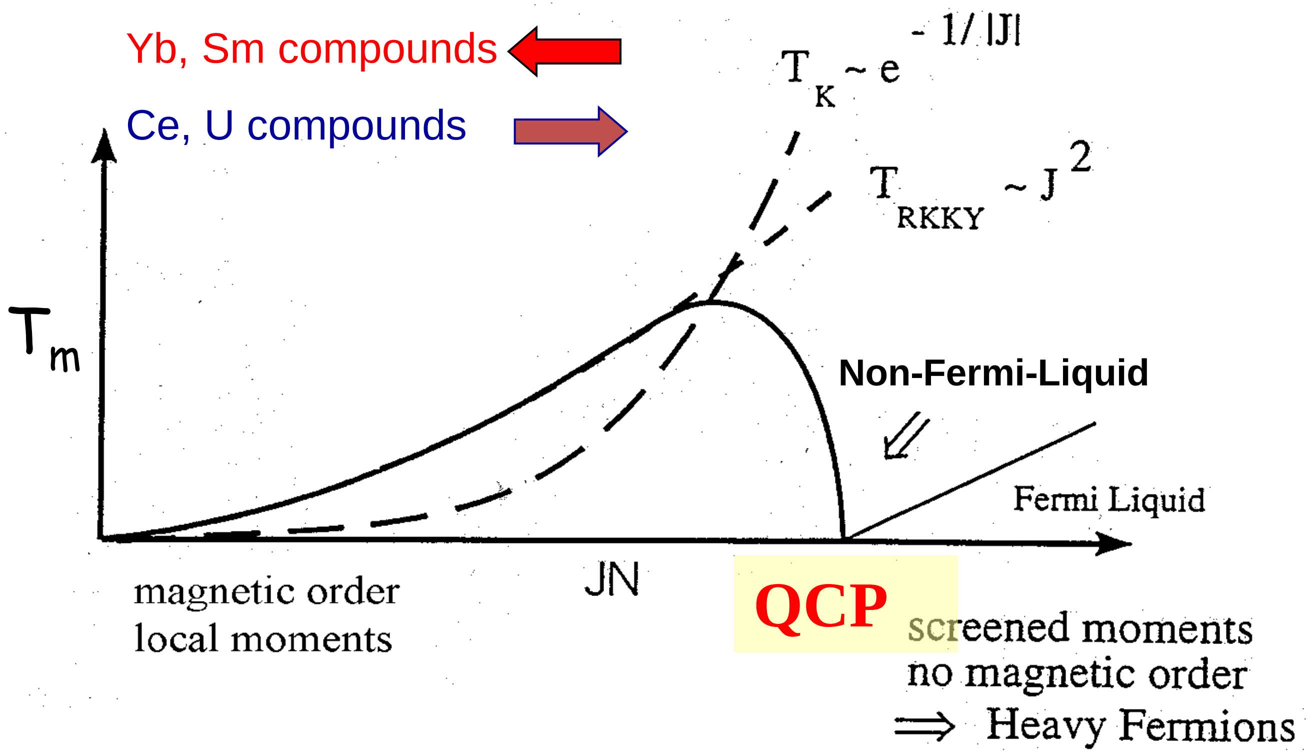
Some Application of NFS
High pressure studies

Application to magnetic properties of SmS under high pressure

Extended Doniach Model

Yb, Sm compounds ←

Ce, U compounds →



$T_m \rightarrow 0$

QCP: Quantum-Critical-Point

- **Non-Fermi-Liquid (NFL):**
  - $\Delta\rho \propto T^{\varepsilon}$ $\varepsilon = 1 - 1.5$
  - $\Delta C/T \propto -\ln T$
- **Superconductivity possible**

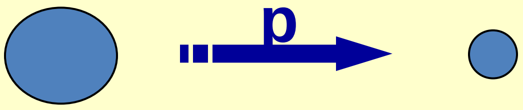
(e.g. $CeCu_2Si_2$, $CeRh_2Si_2$)

$Ce^{3+} \rightarrow 4f^1$ (J=5/2)

magnetic

$Ce^{4+} \rightarrow 4f^0$ (J=0)

nonmagnetic



$Yb^{2+} \rightarrow 4f^{14}$ (J=0)

$Sm^{2+} \rightarrow 4f^6$ (J=0)

nonmagnetic

$Yb^{3+} \rightarrow 4f^{13}$ (J=7/2)

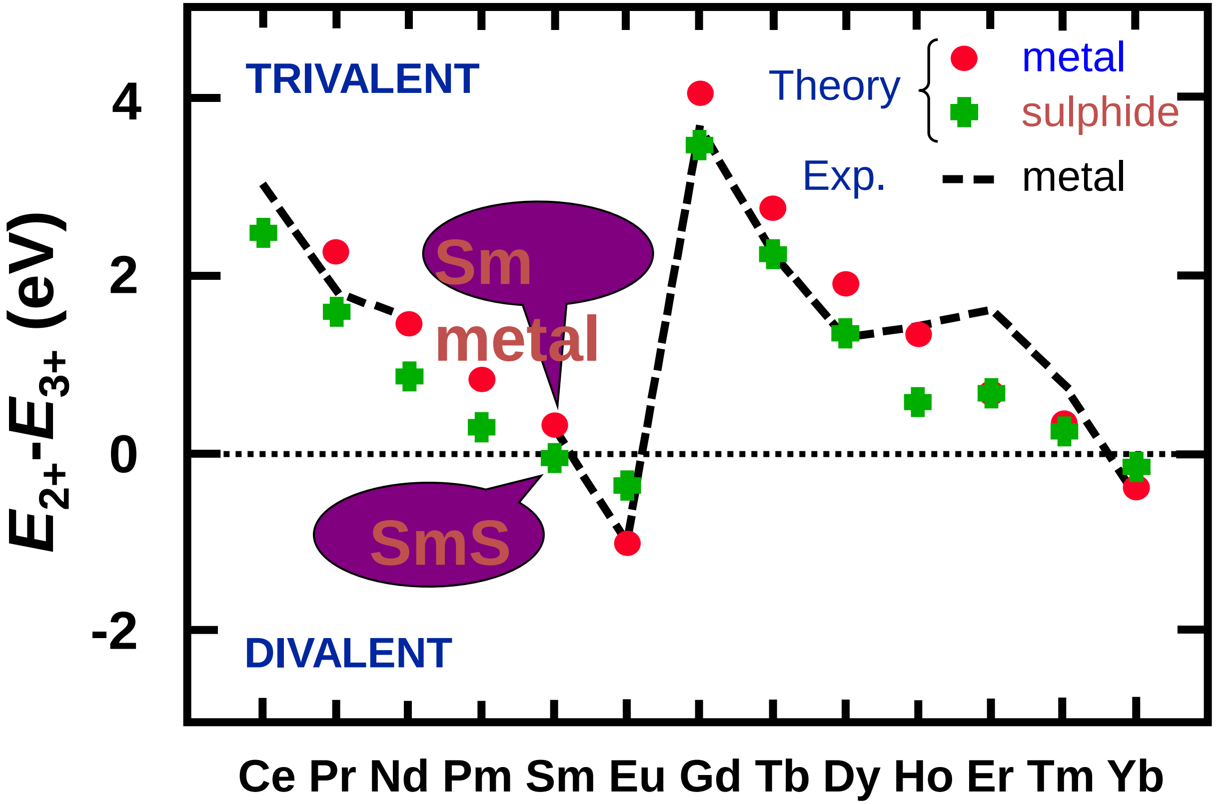
$Sm^{2+} \rightarrow 4f^5$ (J=5/2)

magnetic

SmS: Pressure-induced magnetic ordering in the vicinity of metal insulator transition

Why SmS?

Rare earth valence in elemental *R* and in the monosulphides *R*S



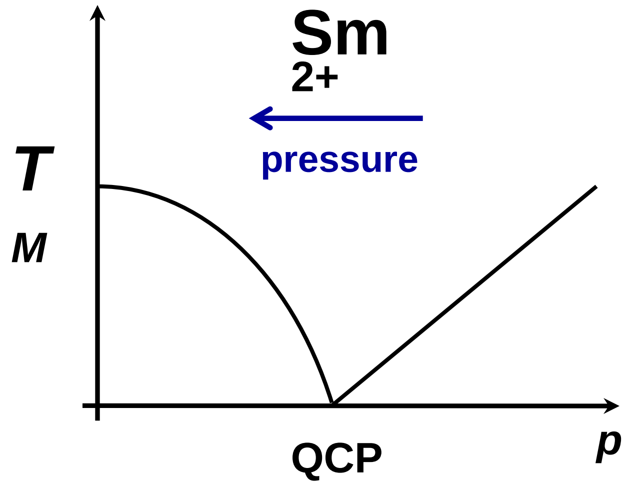
P. Strange et al., Nature 399, 756 (1999)

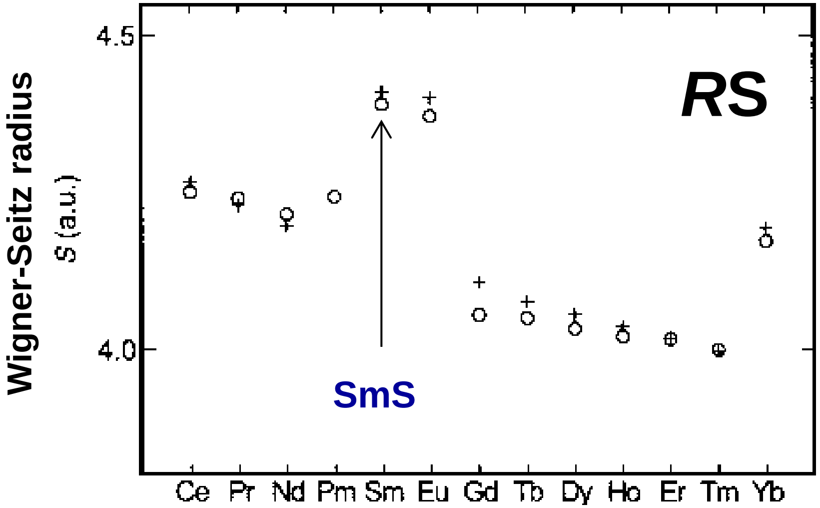
Sm metal → Sm^{3+}

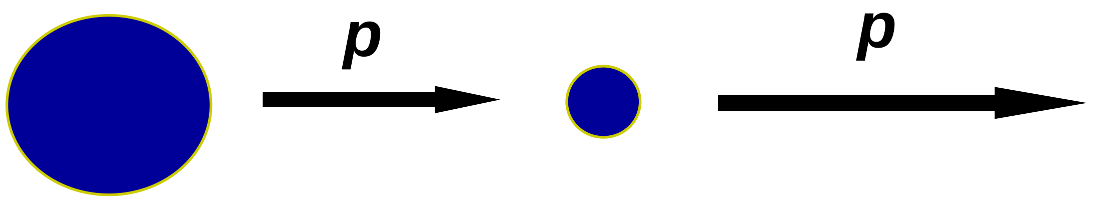
SmS → Sm^{2+} **close to a valence instability**

SmB_6 → $Sm^{2.6+}$ **intermediate valent**

Effect of pressure on Sm^{2+}- Systems







delocalization

Sm^{2+} : $4f^6$ ($J = 0$)

nonmagnetic

Sm^{3+} : $4f^5$ ($J = 5/2$)

magnetic

nonmagnetic

(?)

SmS

ambient pressure

- NaCl-type structure
- Nonmagnetic ground state (Sm^{2+}, $4f^6$:$^7F_0$)
- semiconductor (black phase)

At p = 0.65GPa (room temperature)

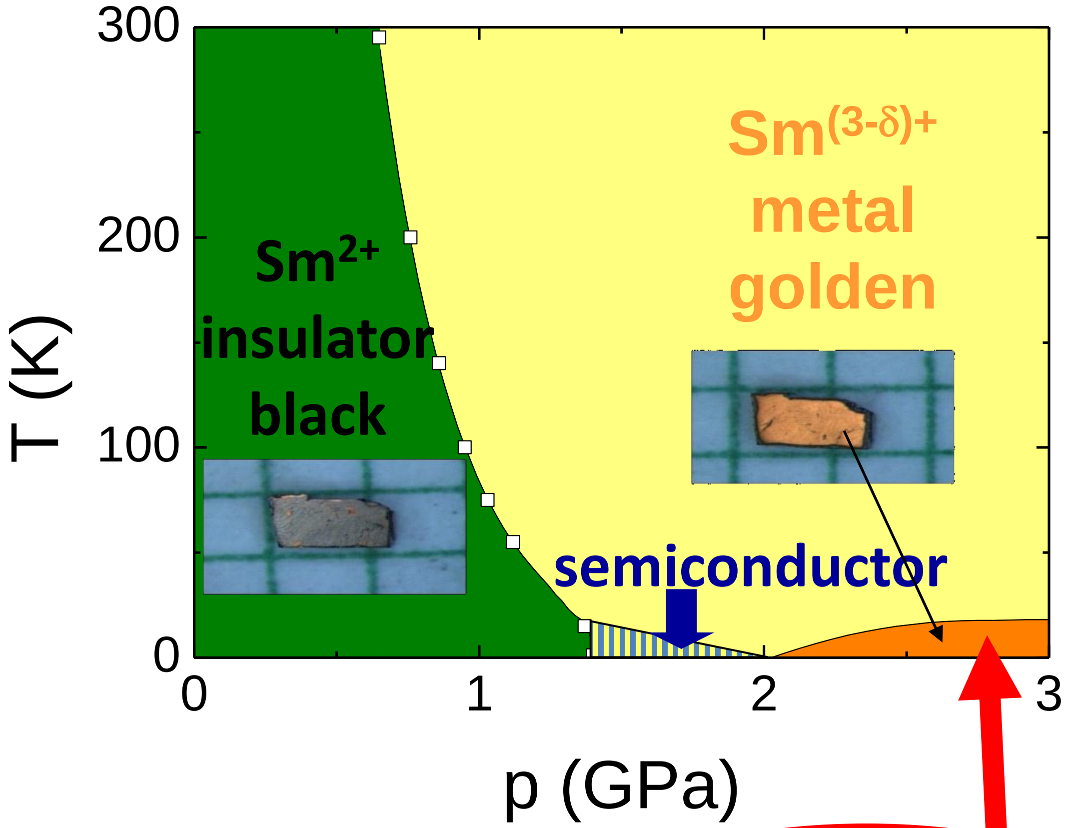
- first order isostructural phase transition
- metallic (golden phase)
- intermediate valence state (n ~ 2.7)

A. Jayaraman et al.,
PRL 25, 1430 (1970),

J.M. Coey et al., PRB 14,
3744 (1976)

- Metallic behavior down to low temperatures only above 2GPa

(T, p) phase diagram of SmS



NaCl-type structure

High pressure techniques:

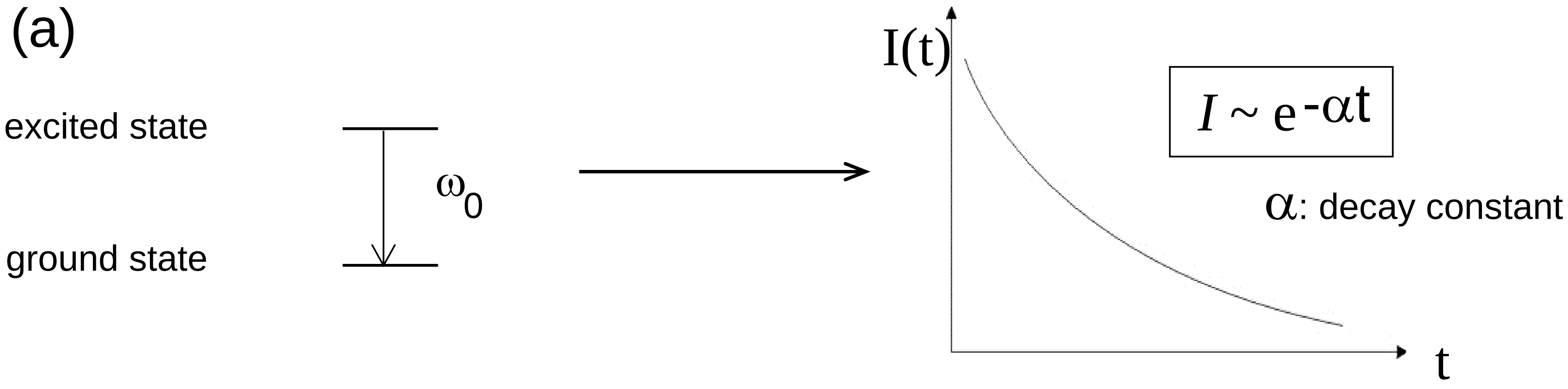
- ^{149}Sm Nuclear Forward Scattering
- Specific Heat

Sm^{3+}?

Magnetic order ?

SmS

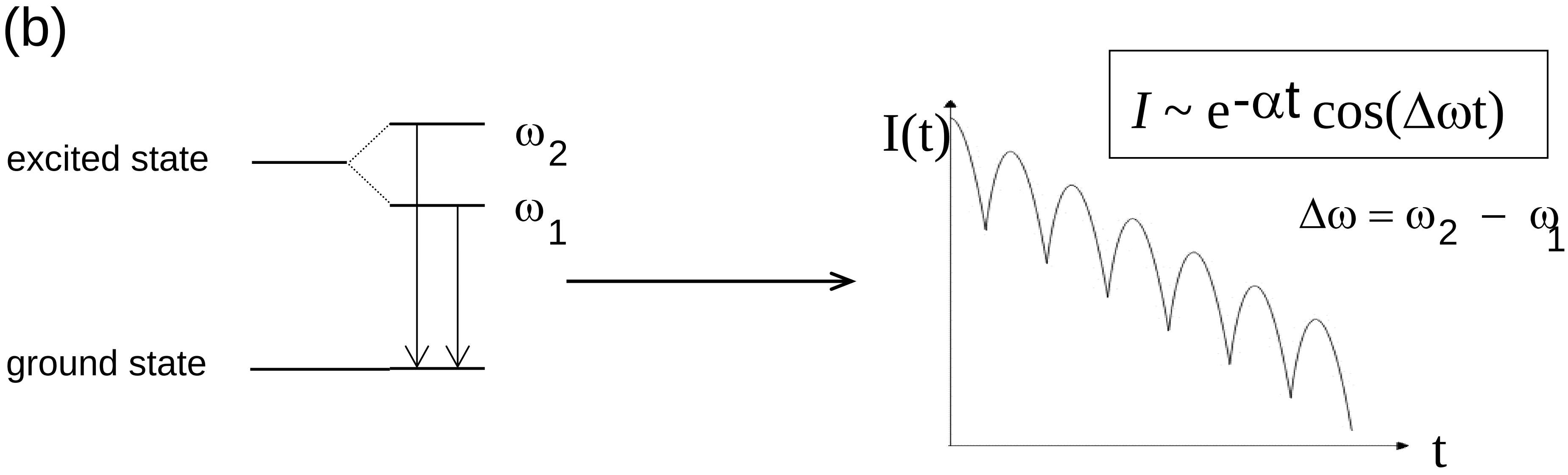
Experimental results



$I \sim e^{-\alpha t}$

α: decay constant

no hyperfine interactions → **radiative decay**



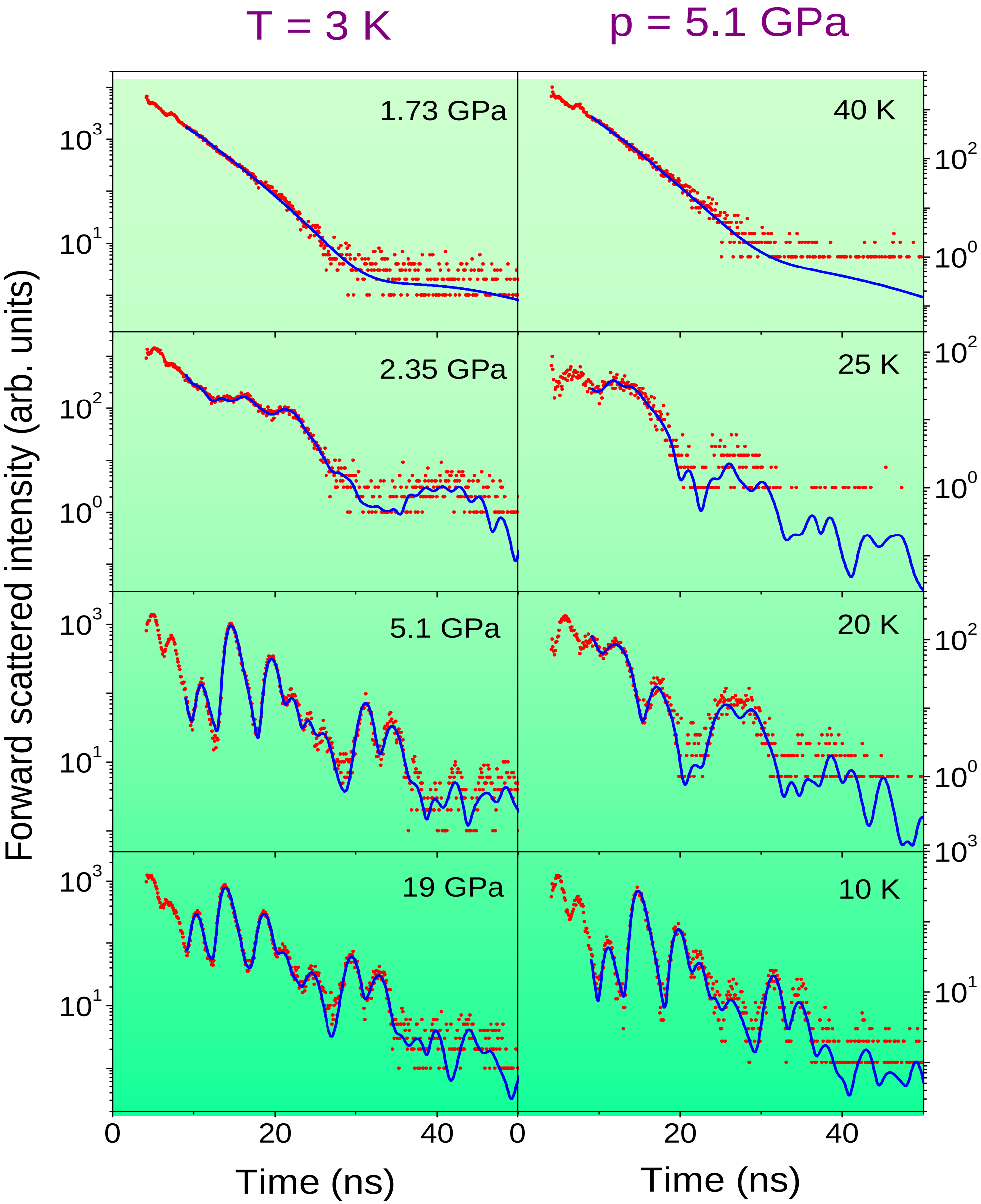
$I \sim e^{-\alpha t} \cos(\Delta\omega t)$

$\Delta\omega = \omega_2 - \omega_1$

hyperfine interactions → **quantum beats**

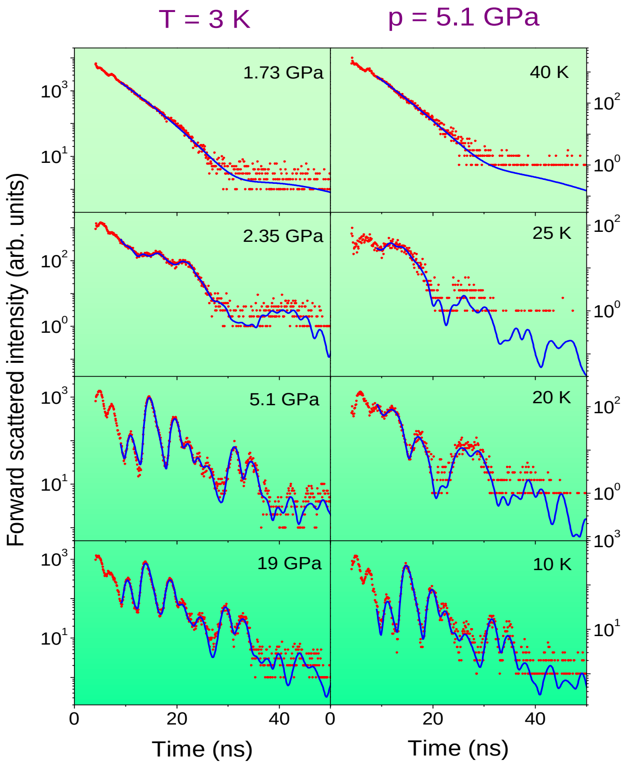
SmS - ^{149}Sm NFS

A. Barla et al., PRL (2004)



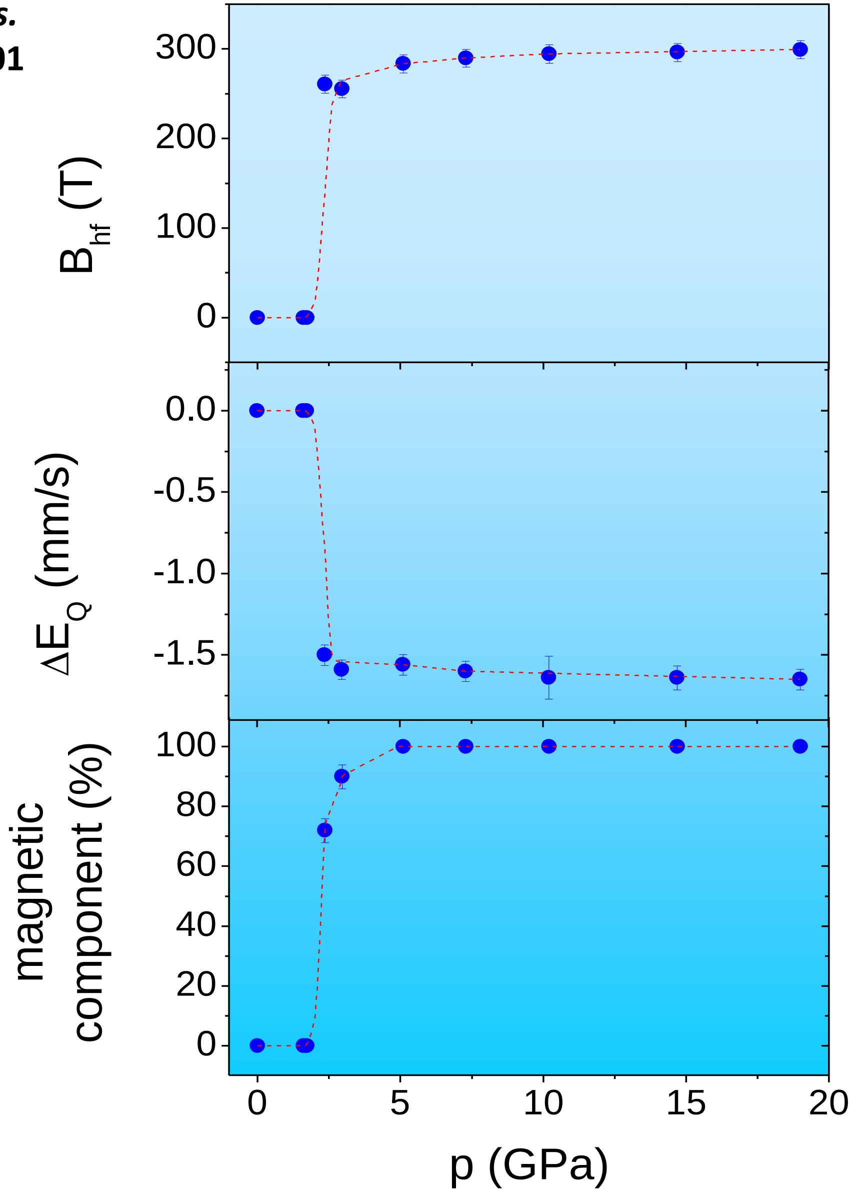
SmS - ^{149}Sm NFS

SmS @ 3 K



A. Barla et al., *Phys. Rev. Lett.* 92, 066401 (2004)

ESRF – ID22N

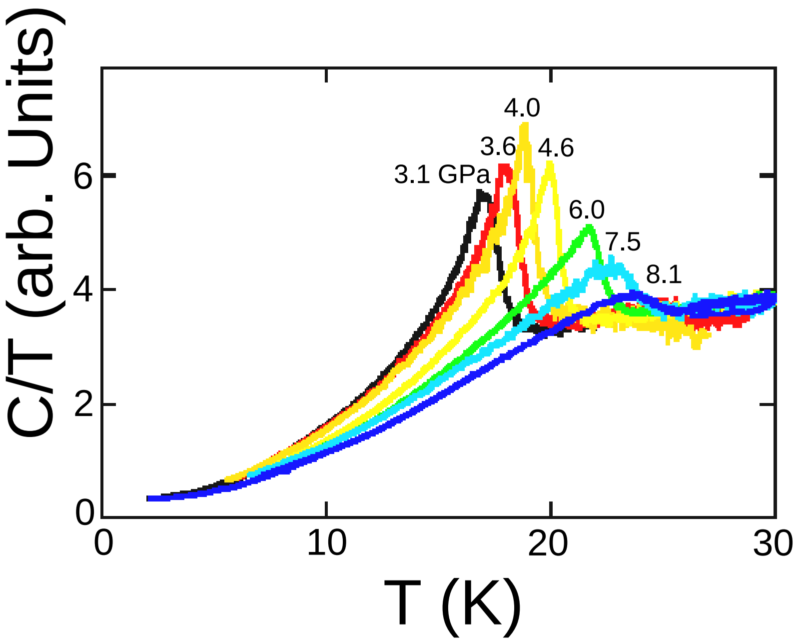


- **first order magnetic phase transition at *p* ~ 2 GPa**

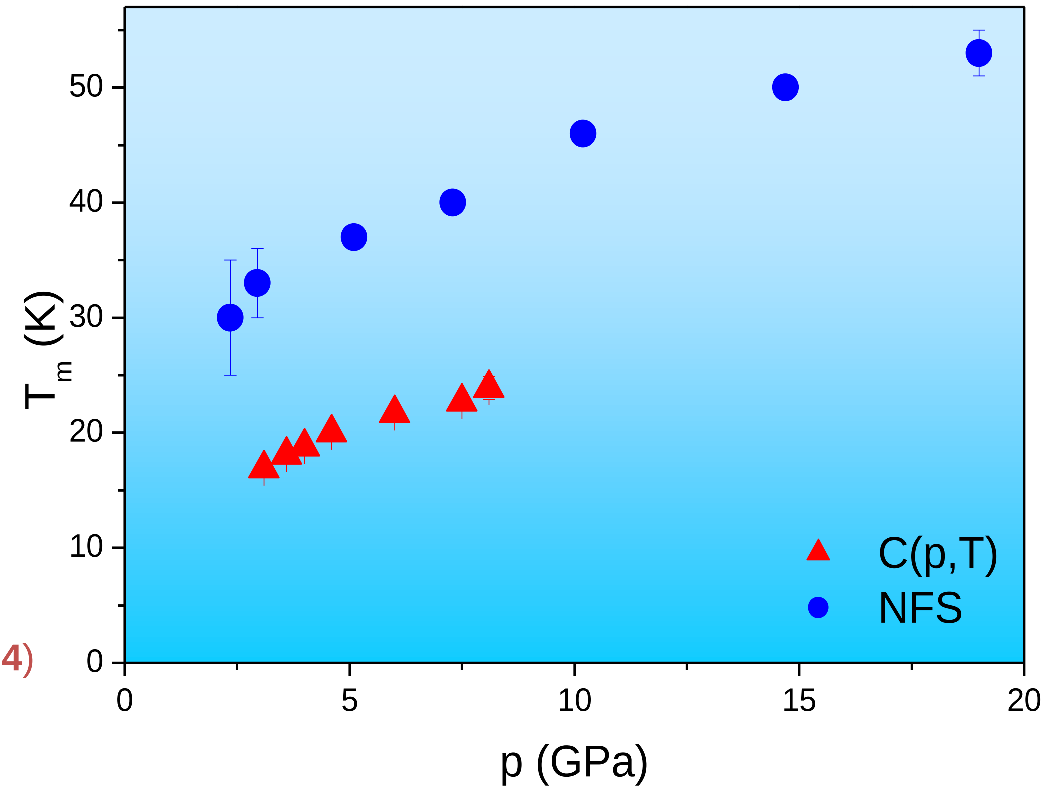
- **Γ_8 crystal field ground state (B_{hf} = 250 T, ΔE_Q = -1.7 mm/s)**

- **$\mu_{Sm} \approx 0.5\mu_B$ ($0.7\mu_B$ Sm^{3+} free ion)**

SmS – specific heat



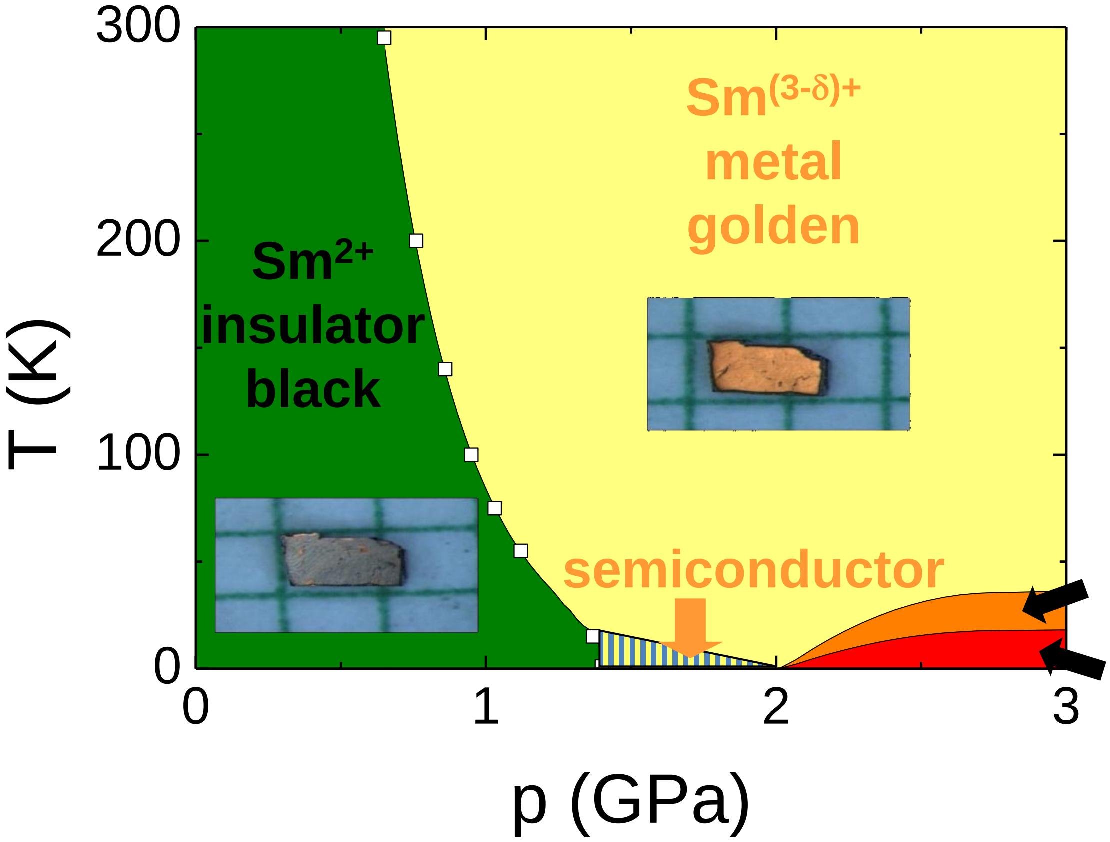
Y. Haga et al., *Phys. Rev. B* 70, 220406(R) (2004)



Specific heat anomaly → onset of long range magnetic order

Magnetic short range order above T_m deduced from $C(p,T)$

SmS



short range magnetic order

long range magnetic order

Sm^{2+}
insulator

pressure

intermediate valent

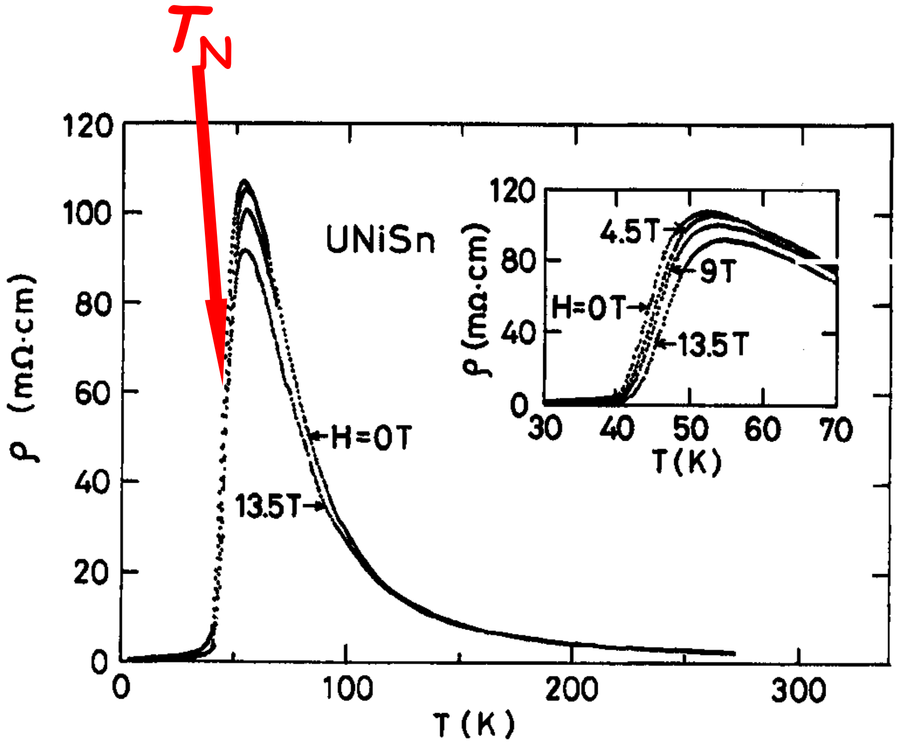
~ Sm $^{3+}$
metallic and magnetic

UNiSn: pressure-induced collapse of magnetism

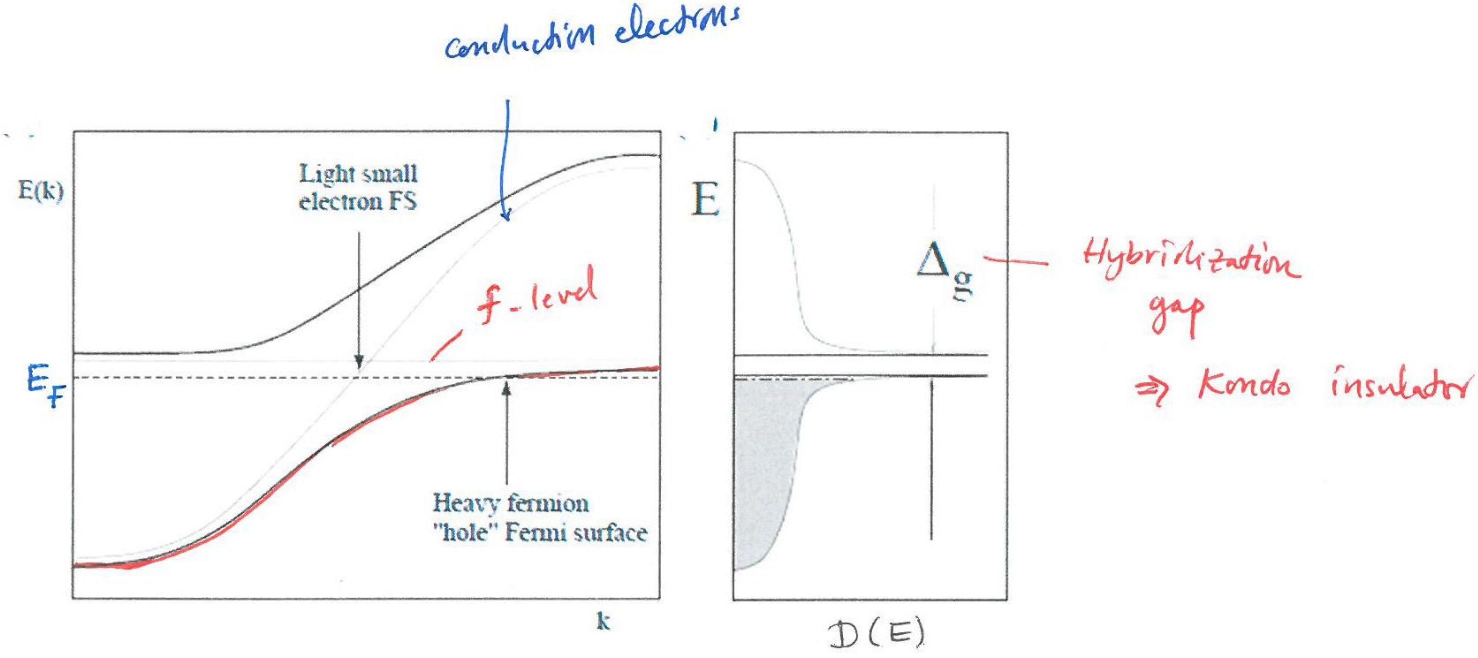
UNiSn: Why Interesting?

metal-insulator transition associated with the AF transition

→ Inverse Mott-Hubbard type metal-insulator transition



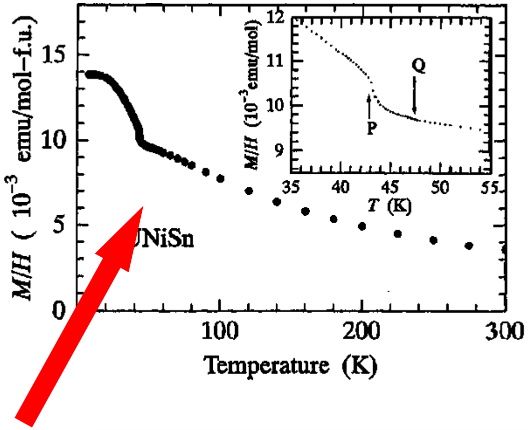
UNiSn belongs to the class of the so-called Kondo insulator or narrow gap semiconductor (like SmB_6, golden SmS……)



conduction electrons
E(k)
Light small
electron FS
f-level
E_F
Heavy fermion
"hole" Fermi surface
k
E
Δ_g
Hybridization
gap
⇒ Kondo insulator
D(E)

UNiSn: Properties at ambient pressure

MAGNETIC SUSCEPTIBILITY



T_N

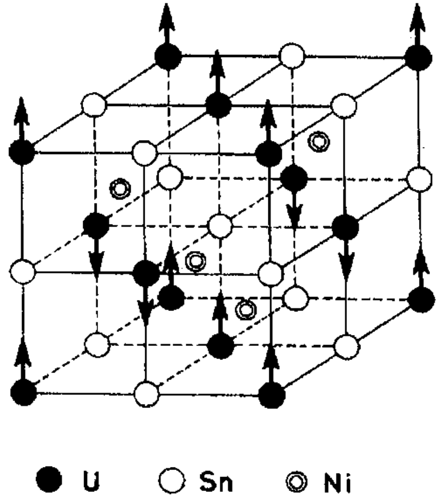
Curie-Weiss law

$\mu_{eff} = 3.08\ \mu_B$

$\theta_p = -\ 75$ K

$T_N \sim 43$ K

CRYSTALLOGRAPHIC AND MAGNETIC STRUCTURE



Cubic (MgAgAs-type)

d(U-U) = 4.53 Å

AF – type I

$\vec{m}$ // [001]

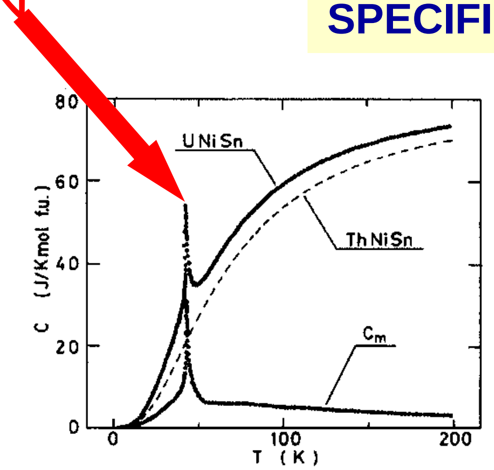
$T_N \sim 46$ K

$m = 1.55(10)\mu_B$

H. Fujii et al., *J. Phys. Soc. Jpn.* 58, 2495 (1989)
Y. Aoki et al., *Phys. Rev. B* 47, 15060 (1993)
H. Kawanaka et al., *J. Phys. Soc. Jpn.* 58, 3481 (1989)

SPECIFIC HEAT

T_N



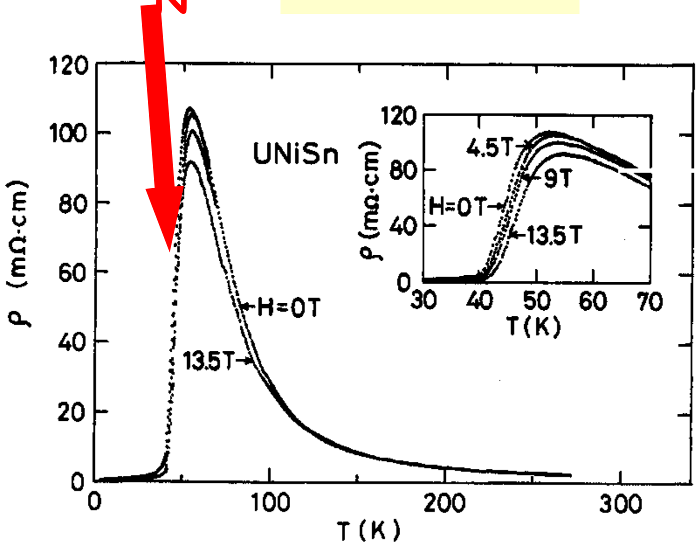
anomaly at 43 K

S_m (43K) ~ Rln2

γ = 18.2 mJ/(mol K^2)

RESISTIVITY

T_N

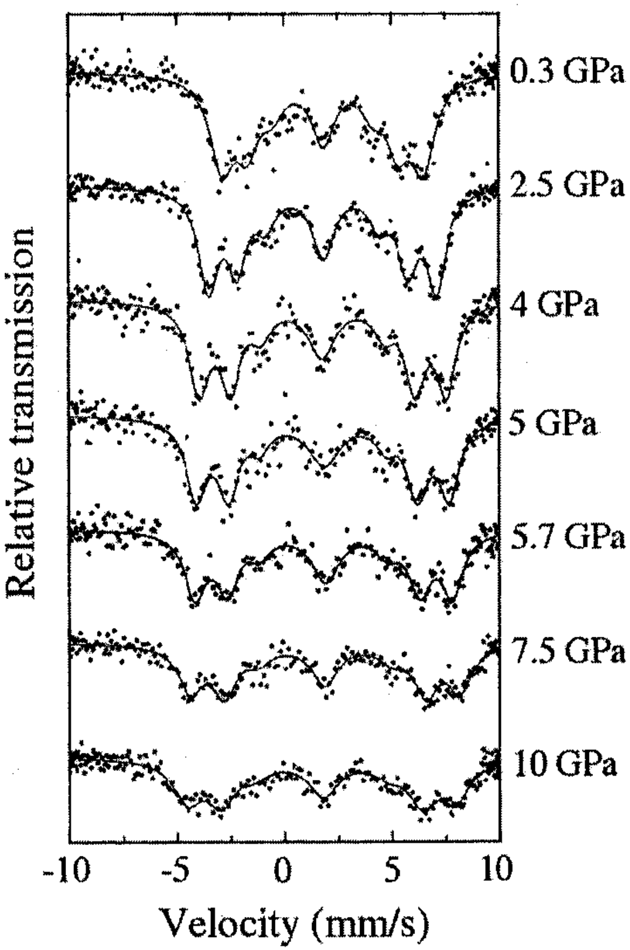


High pressure results:

- **x-ray diffraction**
- **Mössbauer and NFS of synchrotron radiation**
- **Electrical resistance**

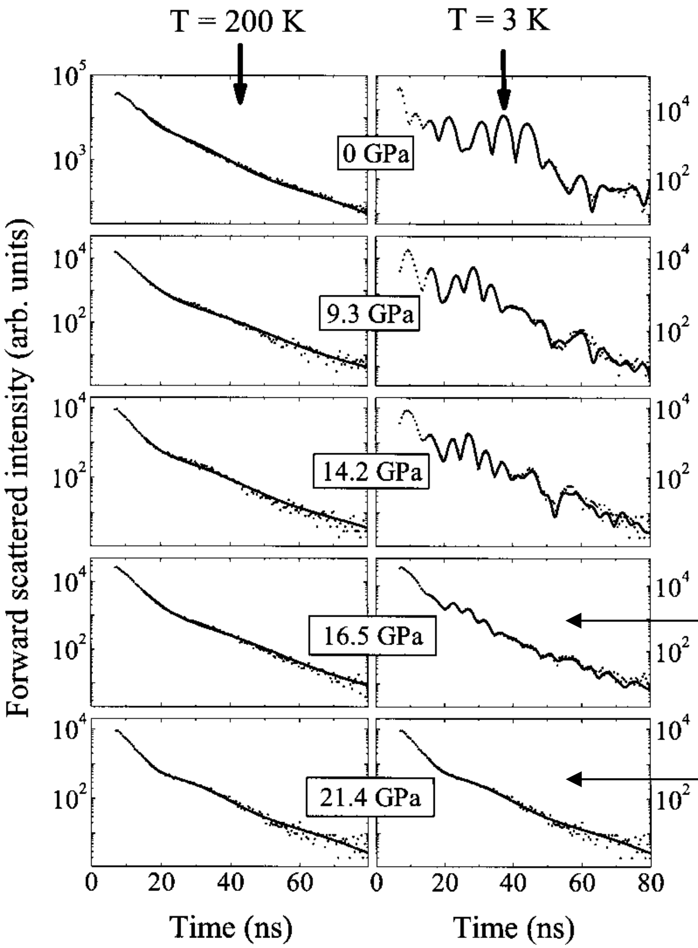
UNiSn : High pressure ^{119}Sn Mössbauer and NFS

- **^{119}Sn Mössbauer spectroscopy at 4.2 K**



B_{thf} = 7.15T at p = 0

- **^{119}Sn NFS of synchrotron radiation**

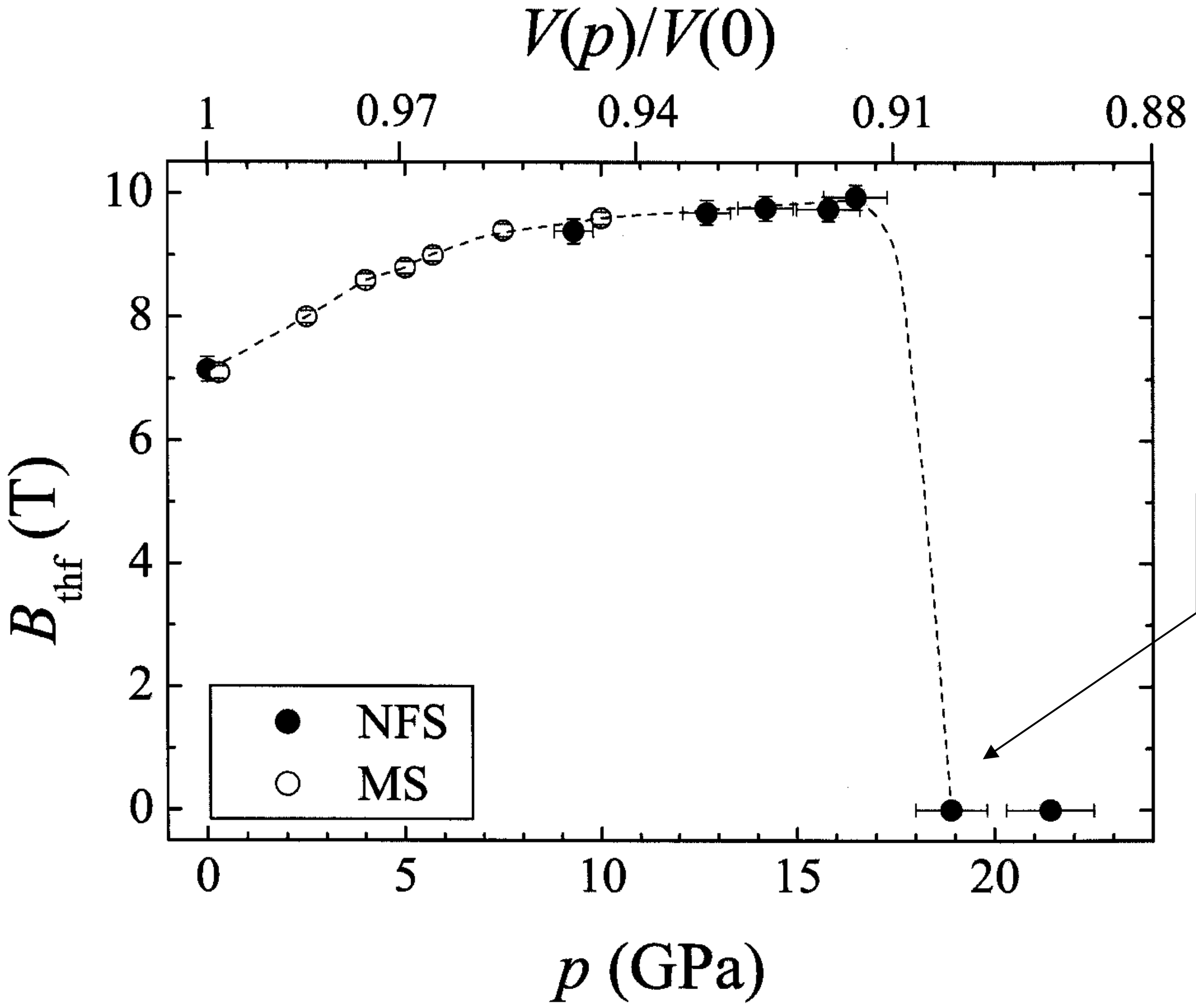


magnetic

nonmagnetic

A. Barla et al., PRB 71, 20402R (2005)

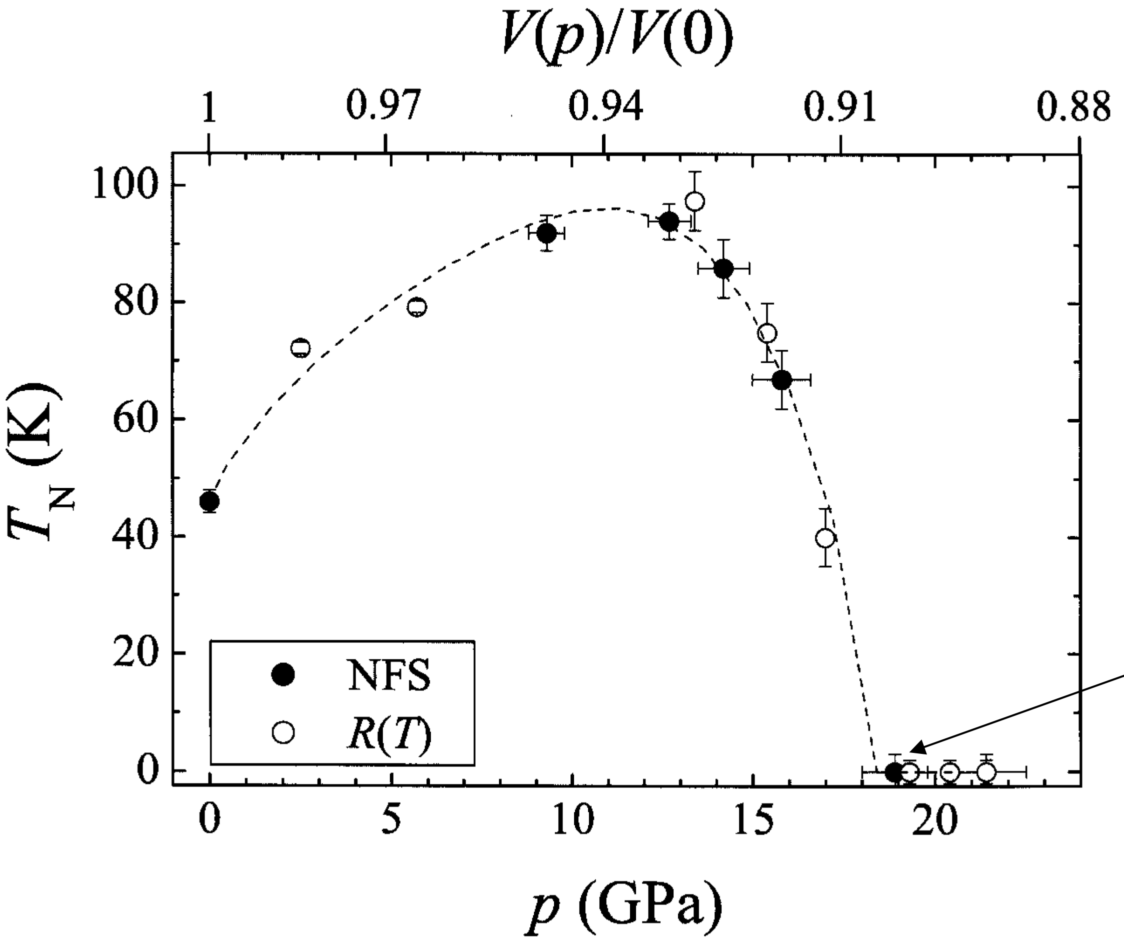
UNiSn : pressure dependence of B_{thf}



B_{thf} disappears for T ≤ 1.8K

A. Barla et al., PRB 71, 20402R (2005)

UNiSn : pressure dependence of T_N



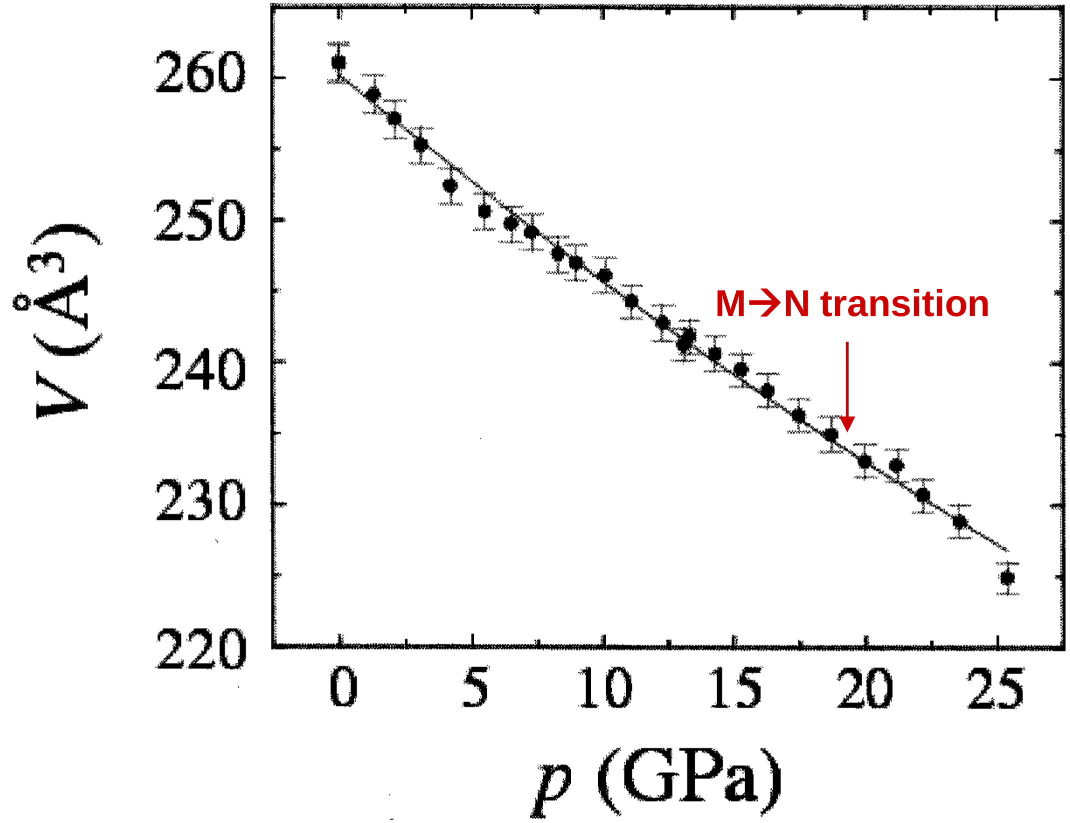
$T_N \rightarrow 0$ for p ~ 19 GPa

→ No magnetic ordering down to 1.8K !

A. Barla et al., PRB 71, 20402R (2005)

UNiSn : High pressure x-ray diffraction

- **Energy dispersive method at RT**



- **Fit with Murnaghan's EOS**

B_0 = 168(10)GPa

B_0' ~ 1.4

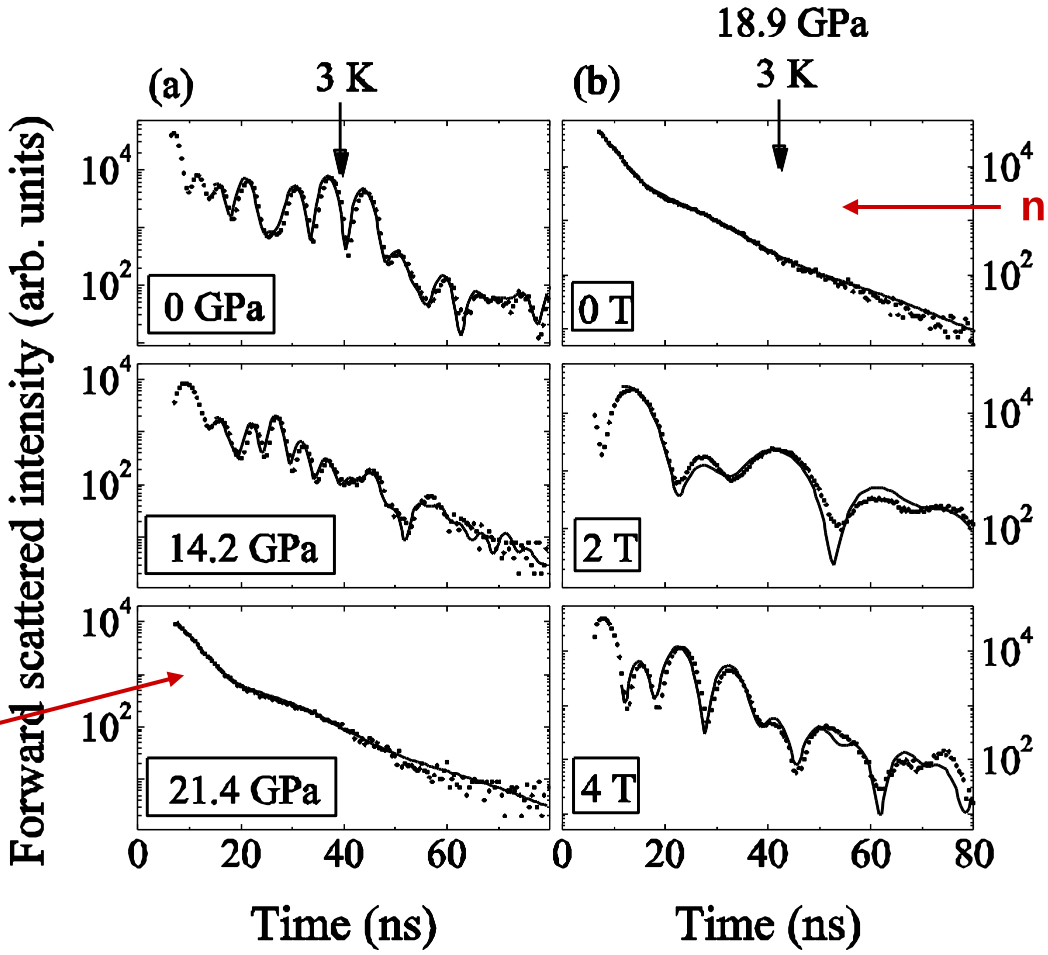
Comparable to RNiSn compounds

Structure remains stable (cubic) up to 25 GPa !!

Pressure-induced magnetic → nonmagnetic transition is not connected with structural phase transition

Nature of the high-pressure nonmagnetic state

A.) NFS spectra in external magnetic field



nonmagnetic state

$B_{induced}$ = 0.4(2)T

$B_{induced}$ = 0.6(2)T

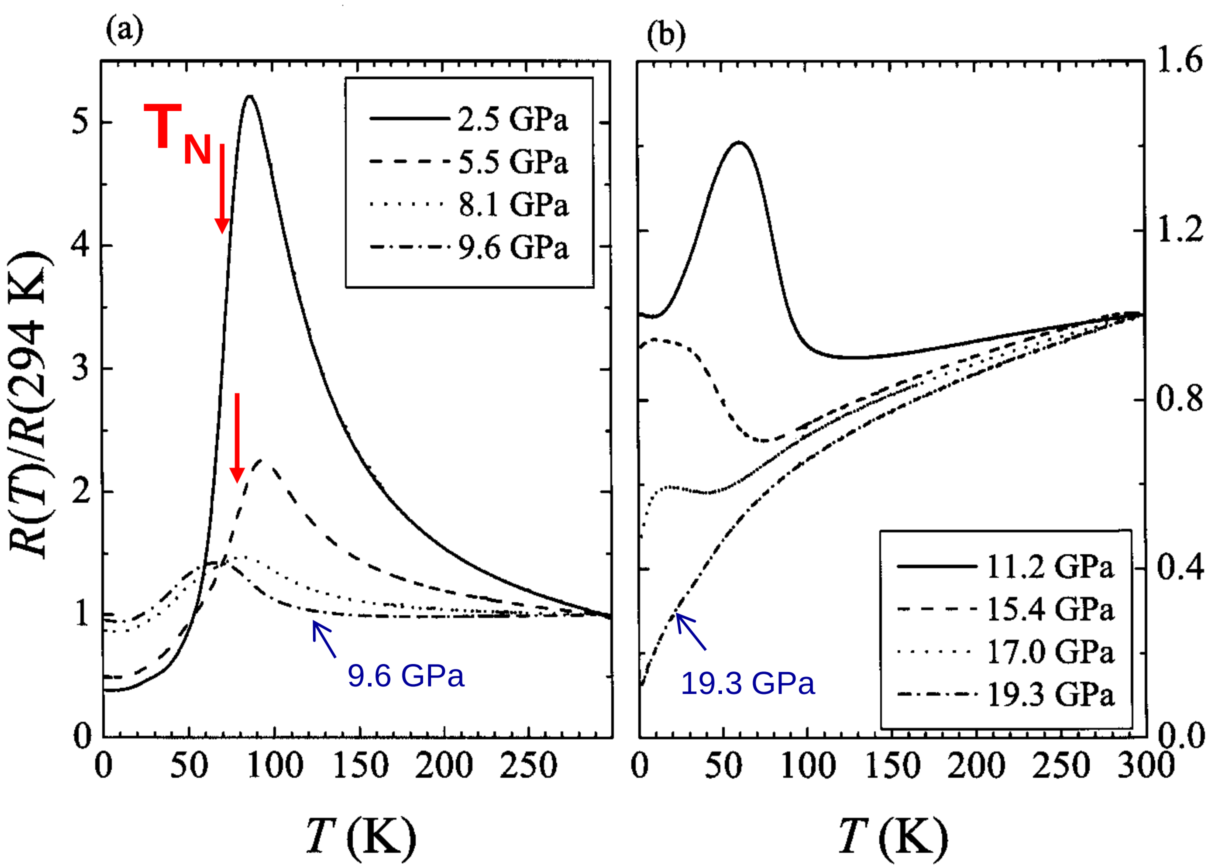
nonmagnetic state

Evidence for rapidly fluctuating U 5f moments in the nonmagnetic state

B.) pressure dependence of the resistance at low temperatures

Semiconducting gap decreases with pressure

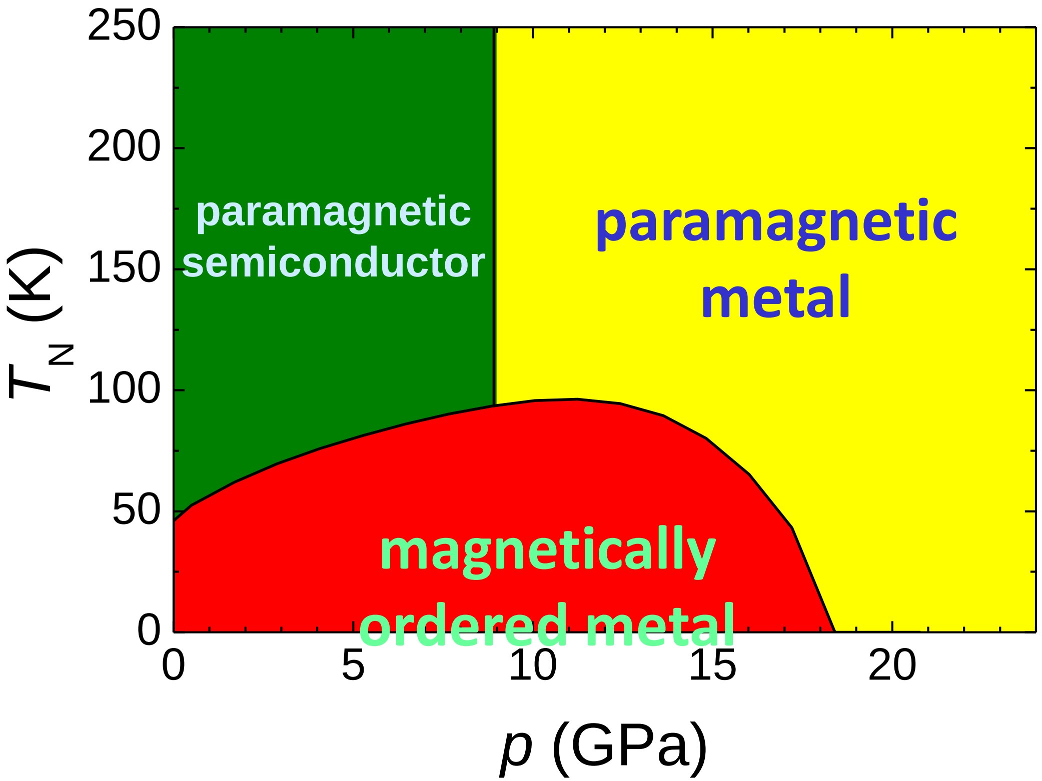
metallic state at p ~ 9GPa



nonmagnetic state at p > 19GPa:

- **R(T) at 19.3 GPa typical for nonmagnetic materials close to a magnetic instability**
- **No evidence for superconductivity down to ~ 60mK.**

Conclusions



- Metallic behavior above p ~ 9GPa

- Interplay between RKKY interaction and U(5f)-Sn(5sp) hybridization
  - crossover localized → itinerant at p ~ 12GPa
  - collapse of magnetism → QPT at p ~ 19 Gpa
  - no superconductivity in the proximity of QCP