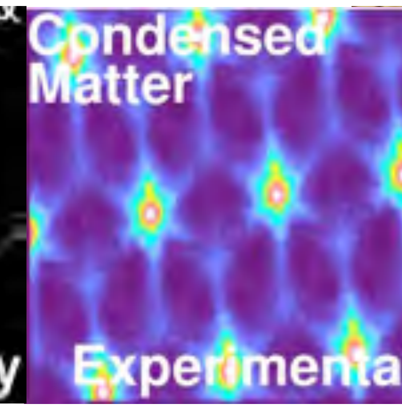
The Physics of Heavy Fermion Superconductivity

Lecture III. Glue vs Fabric? Good, Bad and Ugly Heavy Fermion Superconductors.



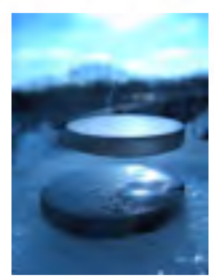
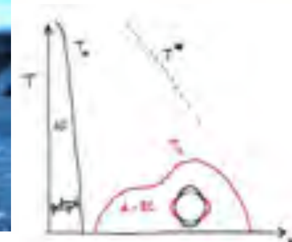



Piers Coleman

Center for Materials Theory, Rutgers.

Boulder School 2014: Modern Aspects of Superconductivity

June 30-July 25, 2014

14-17 July 2014

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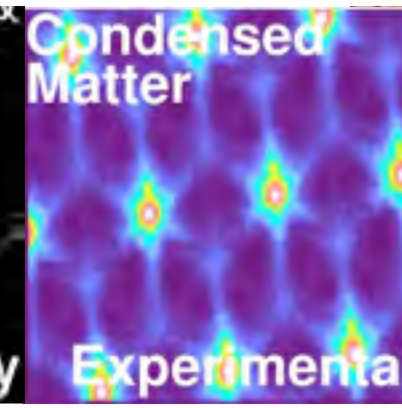

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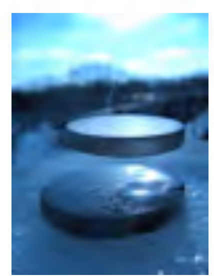


14-17 July 2014

NSF

Royal Holloway University of London

Collaborators

Rebecca Flint	Iowa State
Maxim Dzero	Kent State
Andriy Nevidomskyy	Rice
Alexei Tsvelik	Brookhaven NL
Hai Young Kee	U. Toronto
Natan Andrei	Rutgers


Rebecca


Maxim


Andriy


Alexei

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PRB 84, 064514 (2011).

PRL, 108, 107201, (2012).

ICAM-I2CAM Institute for Complex Adaptive Matter

Rutgers Center for Materials Theory

The Physics of Heavy Fermion Superconductivity

1. Introduction: Heavy Fermions and the Kondo Lattice.
2. BCS meets Kondo: mean-field approach to the Kondo Lattice.
3. Glue vs Fabric: Good, Bad and Ugly Heavy Fermion Superconductors.
4. Composite vs AFM induced pairing. Hastatic Order.

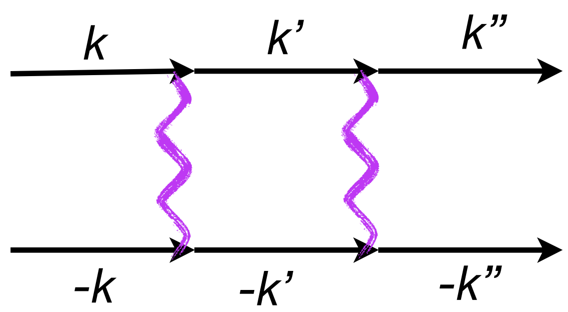
Rutgers
Center for Materials Theory

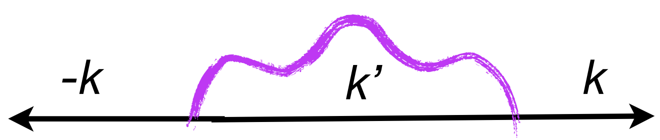
Fabric vs Glue?

Glue vs Fabric.

Glue vs Fabric.

Glue Spin fluctuations = pairing bosons





Eliashberg Approach (cf B. Keimer et al)

Glue vs Fabric.

Glue

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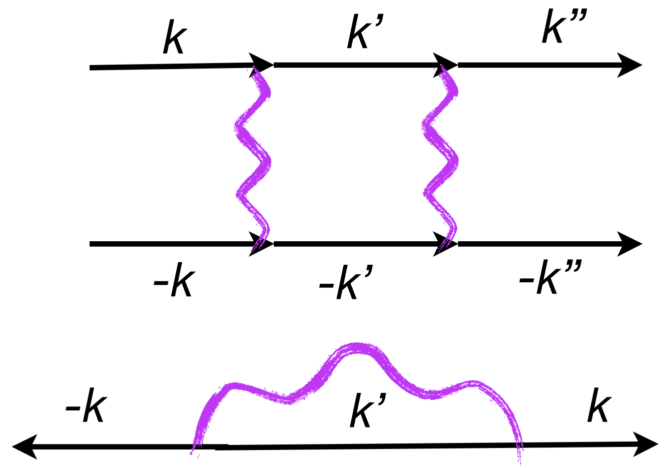

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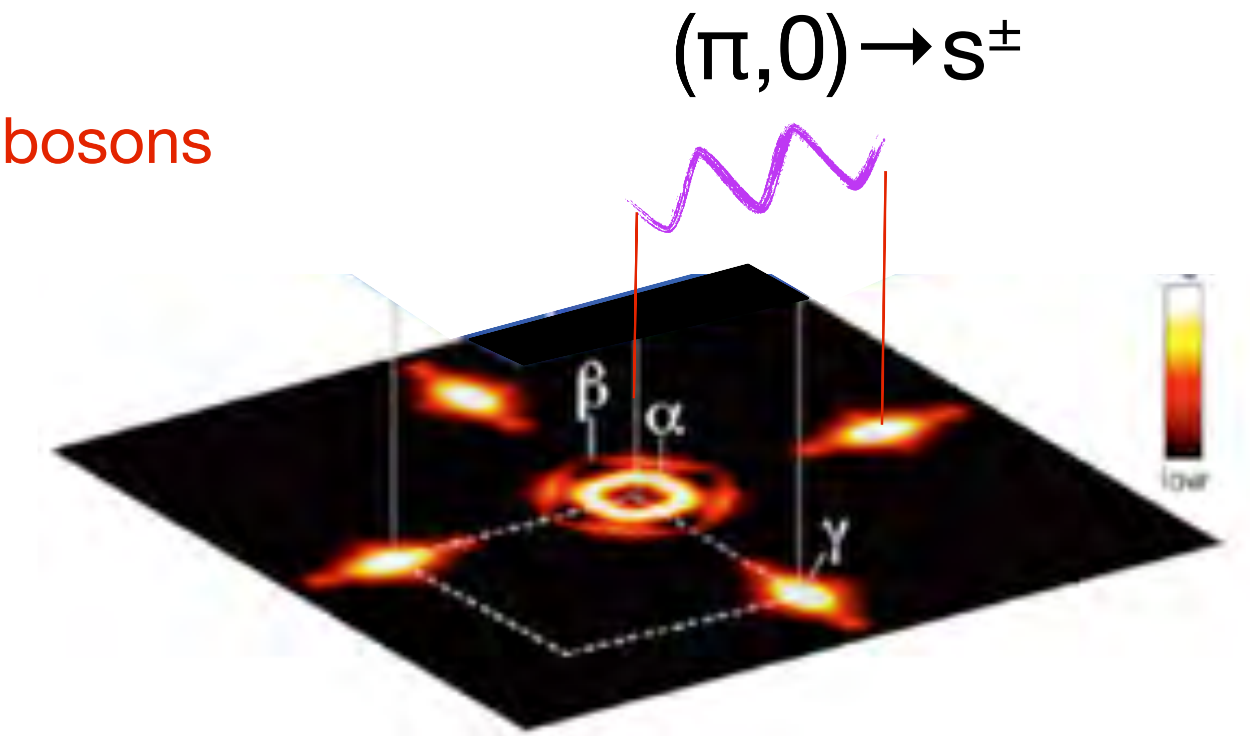

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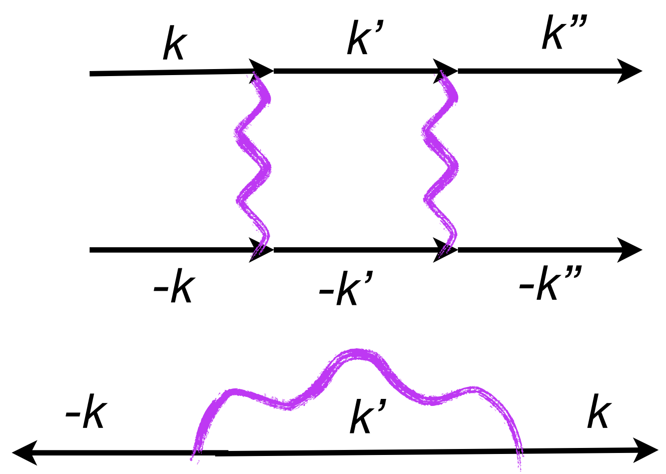

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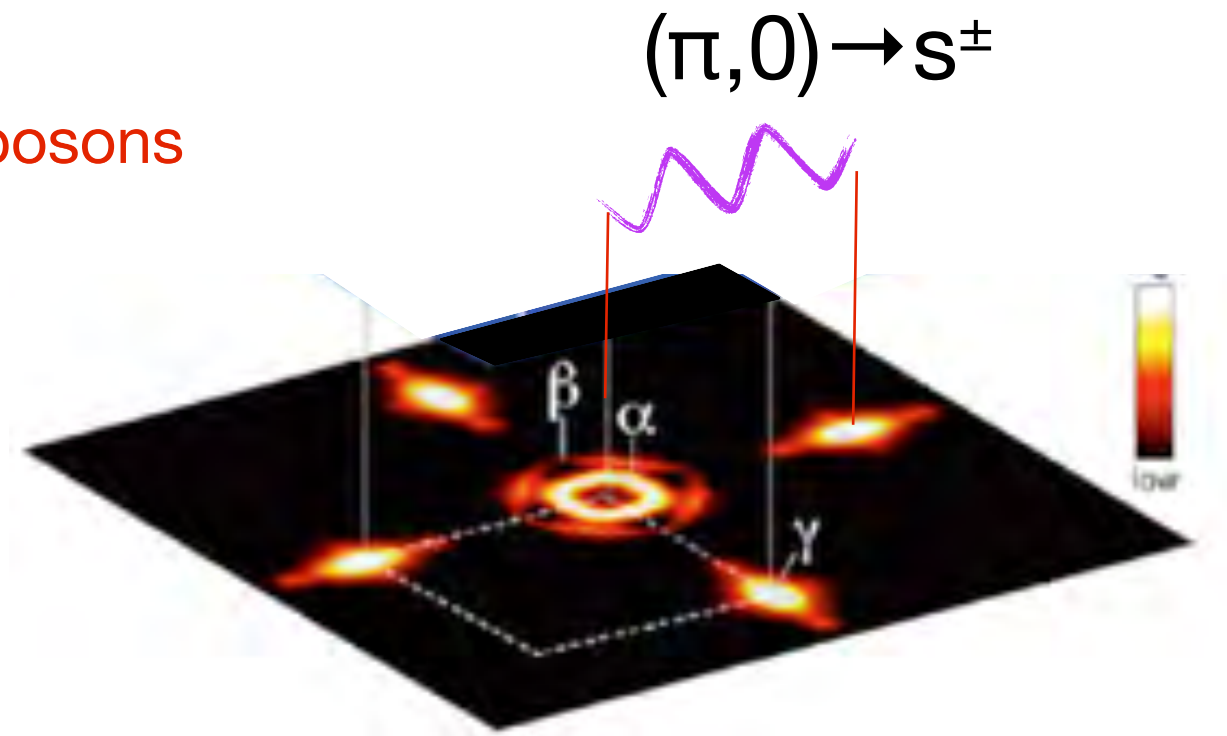

Fabric: spins *make* the pairs

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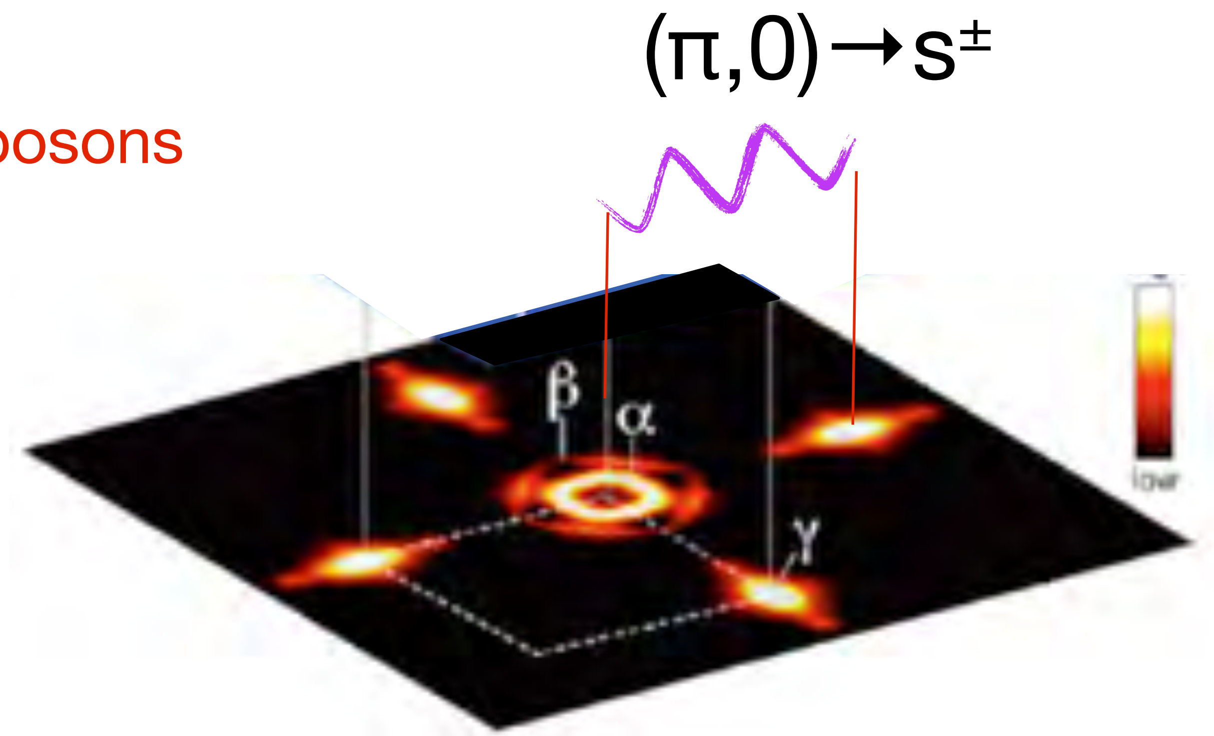

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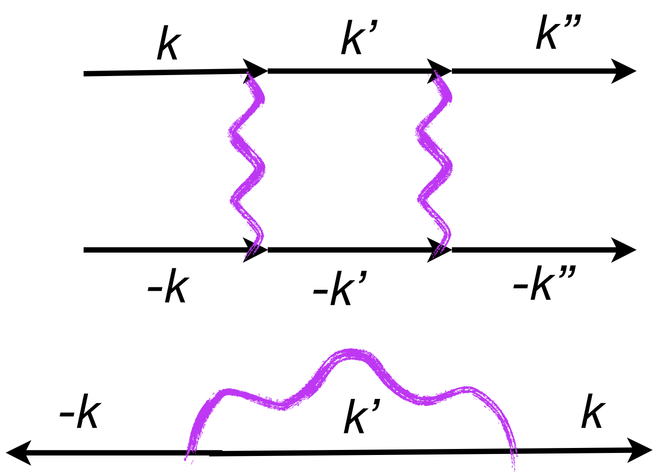

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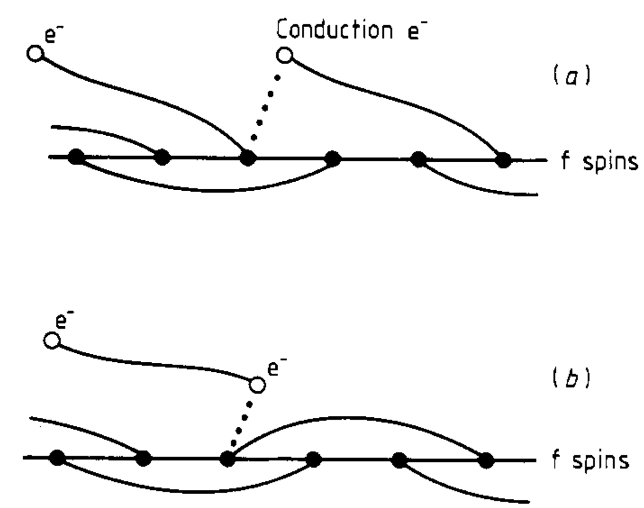

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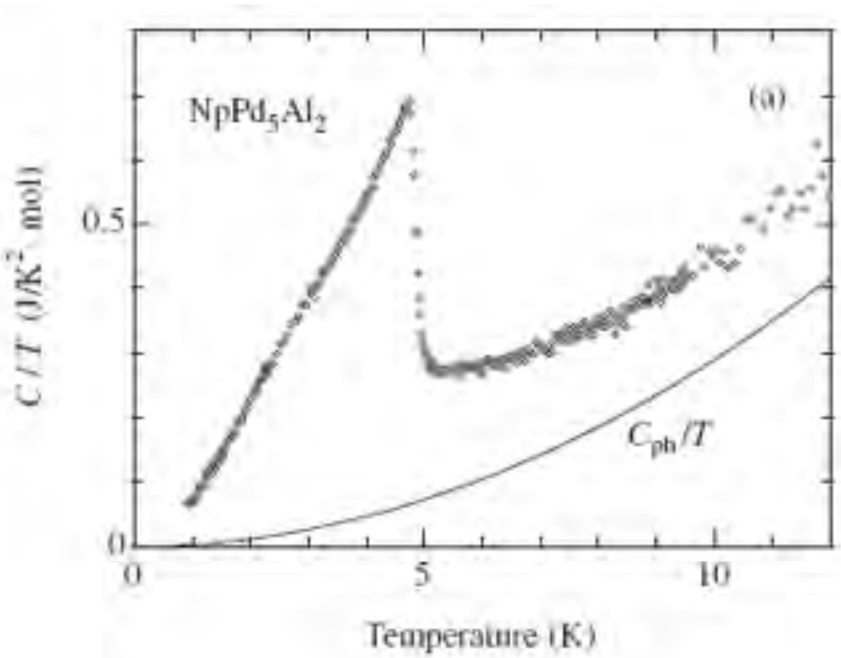

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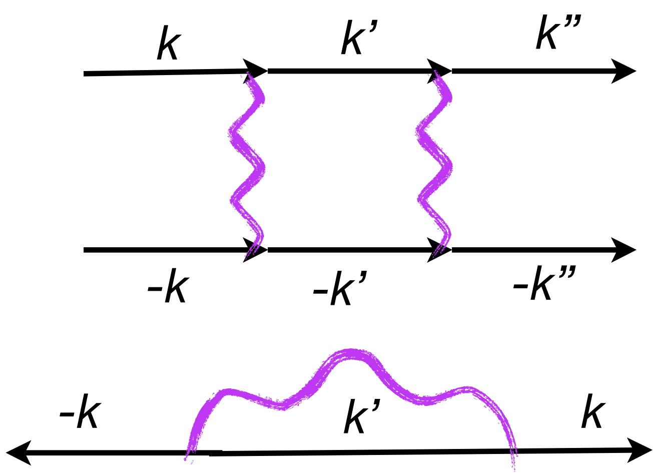

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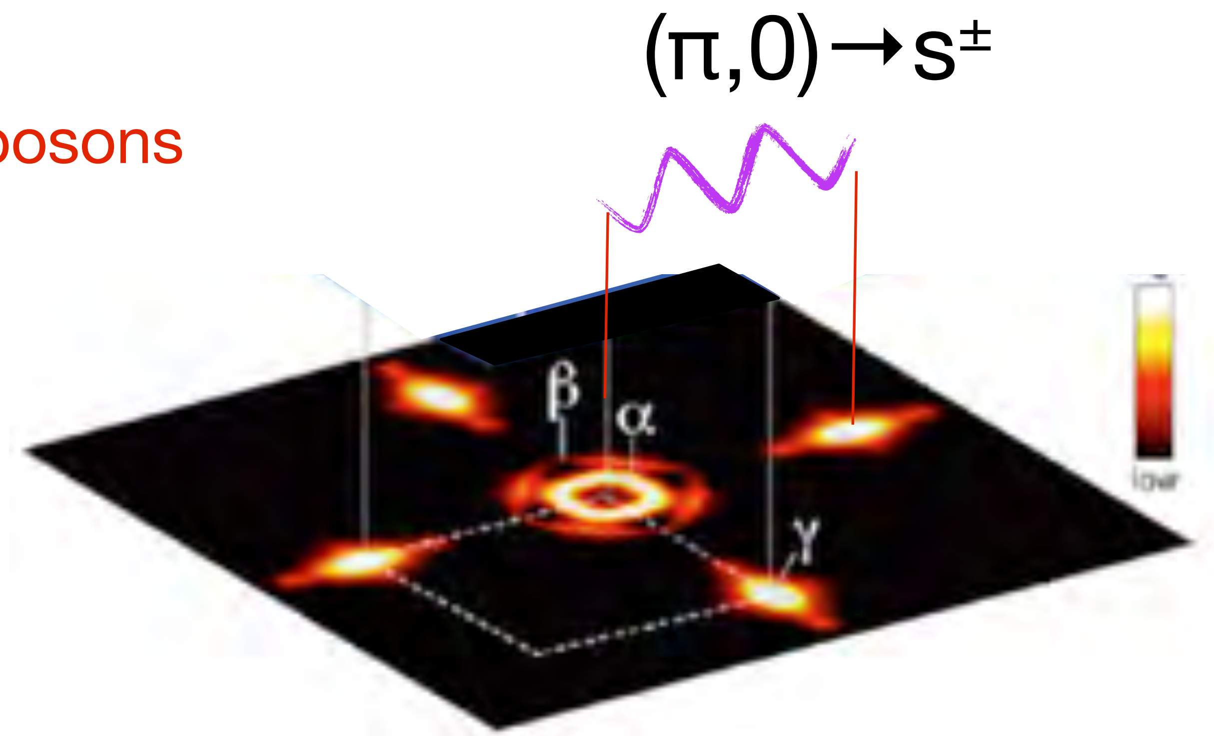

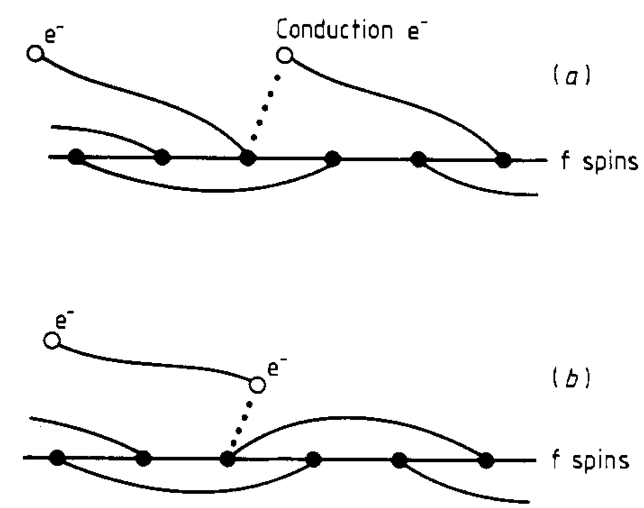

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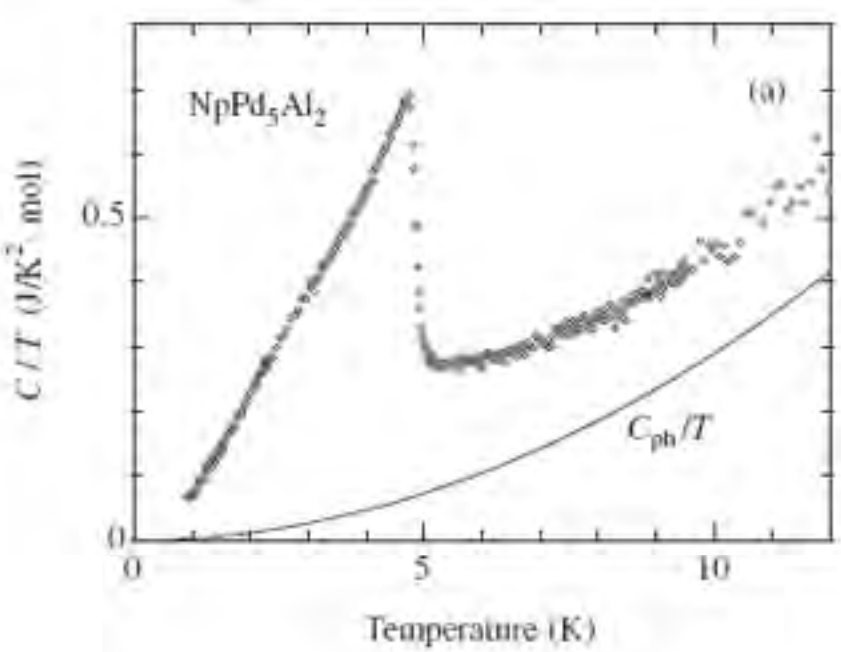


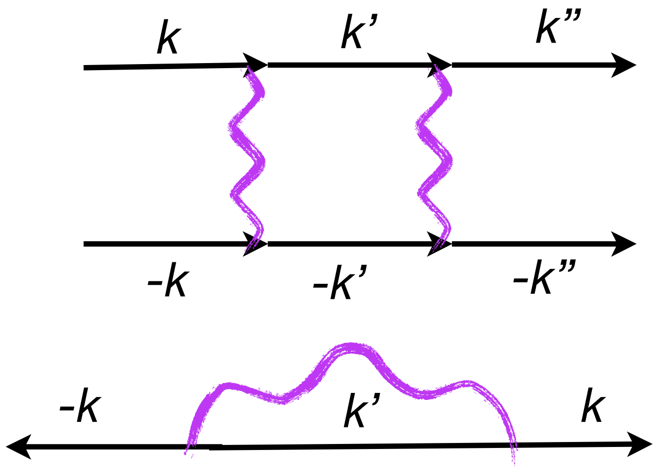
$$R \ln W = \int_0^T dT' \frac{C'}{T'}$$

"Hilbert Space Spectroscopy"

Glue vs Fabric.

Glue

Spin fluctuations = pairing bosons



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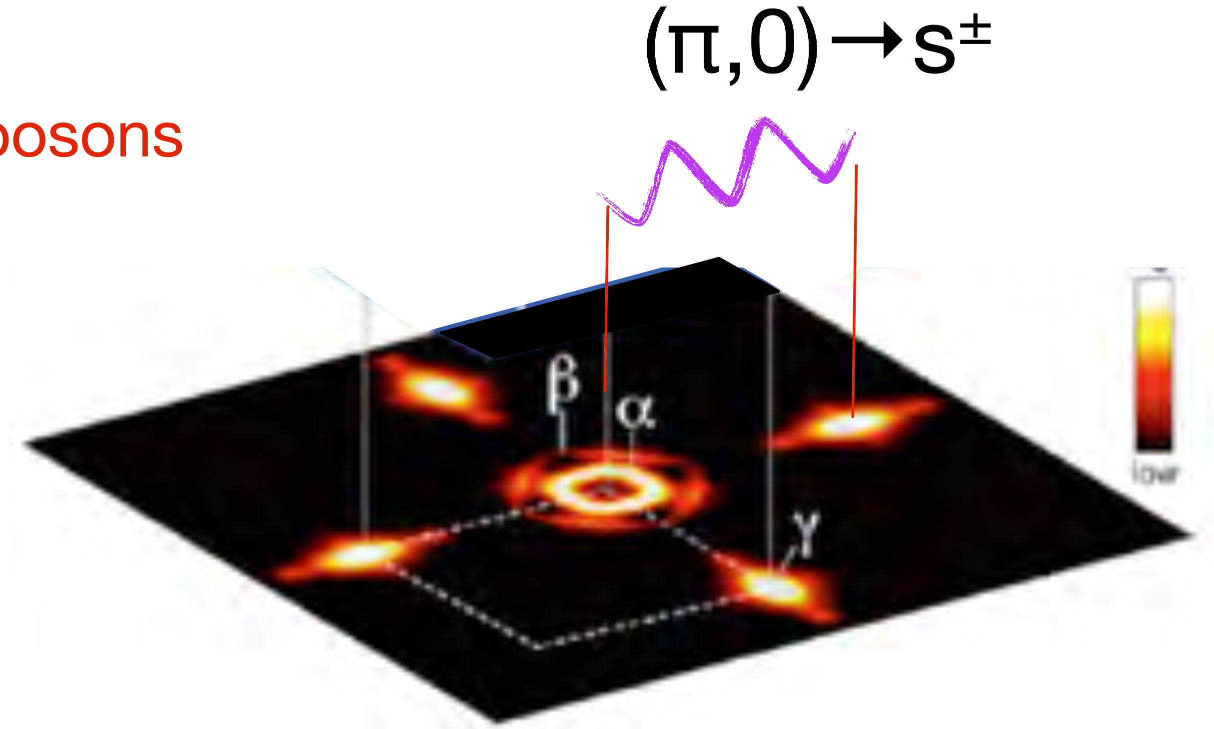

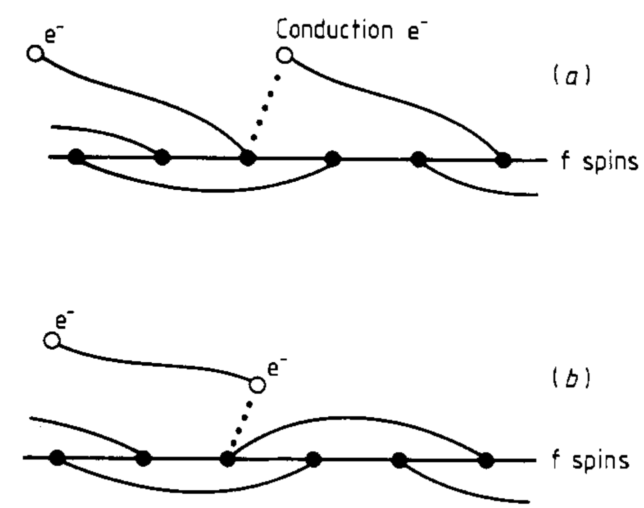

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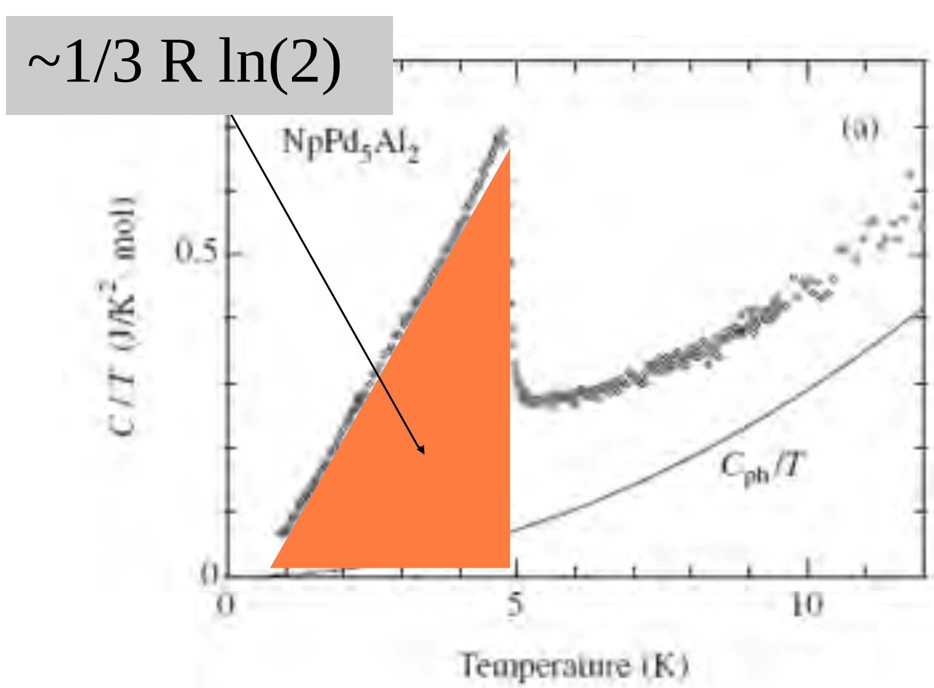

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Glue vs Fabric.

$(\pi,0) \rightarrow s^{\pm}$

Glue

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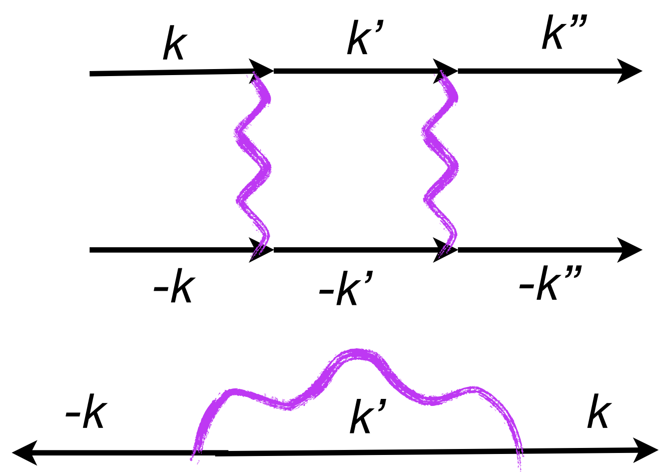

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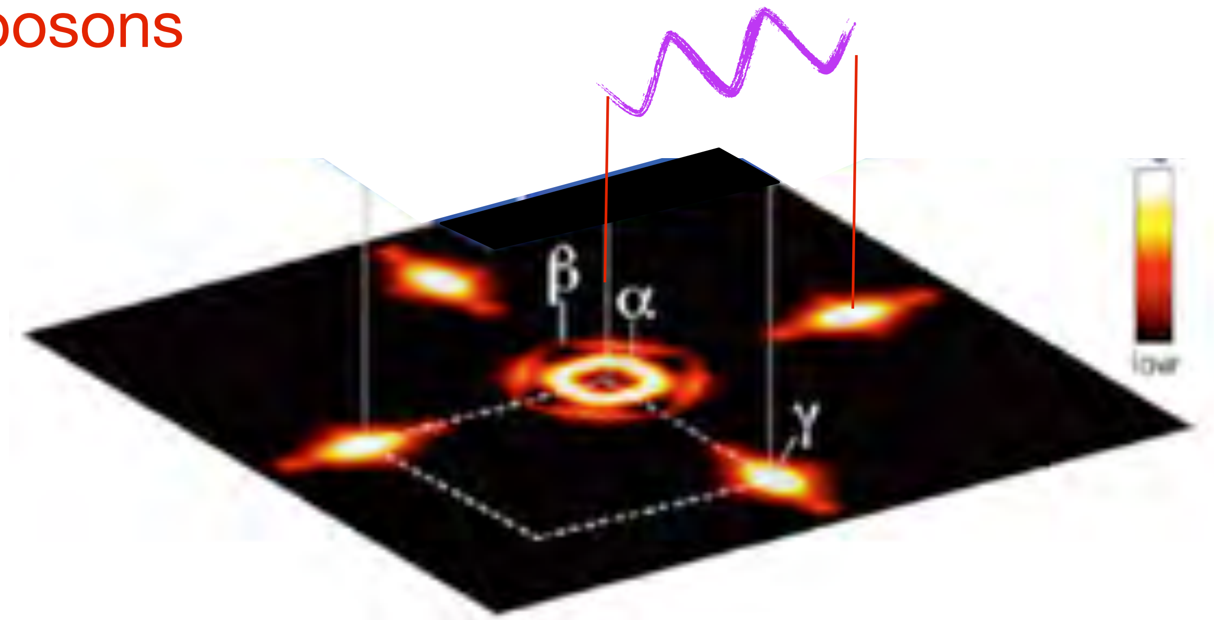

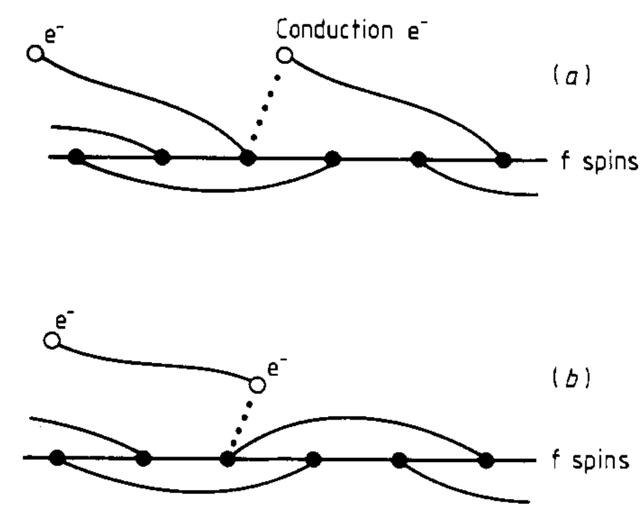

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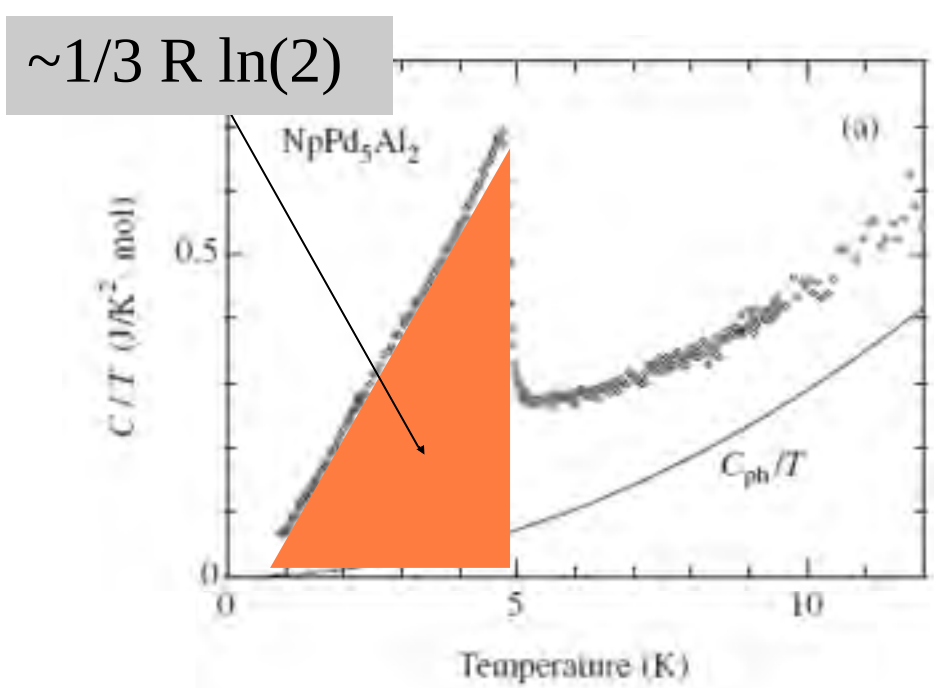

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SPIN Hilbert space BUILDS the pairs.

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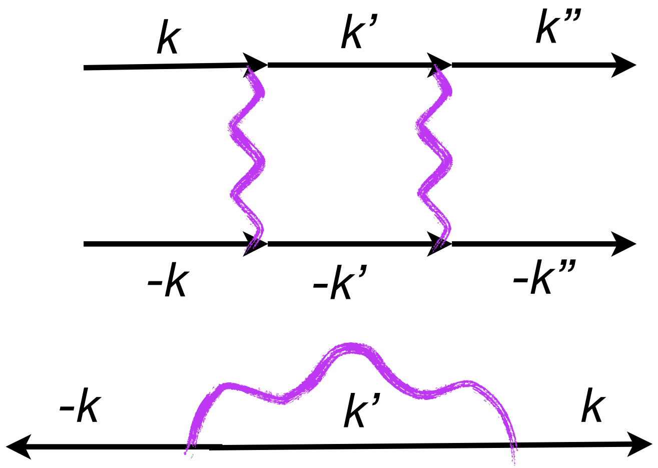

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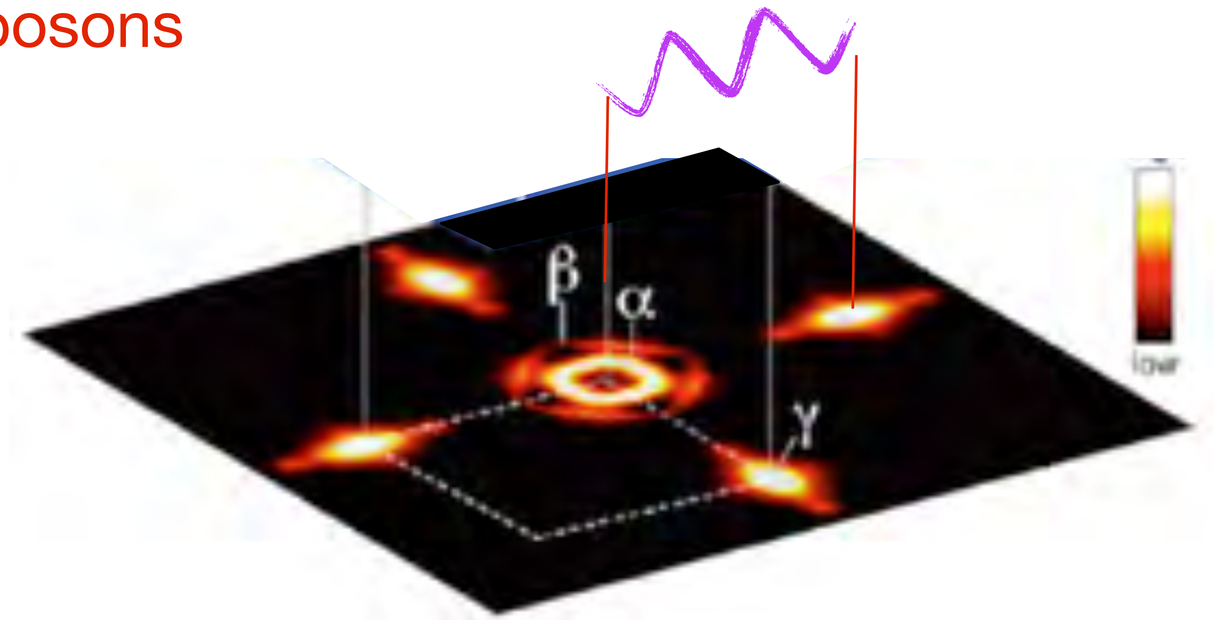

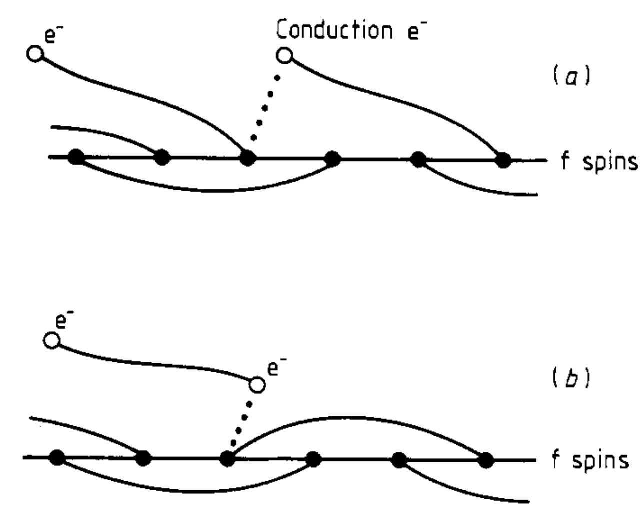

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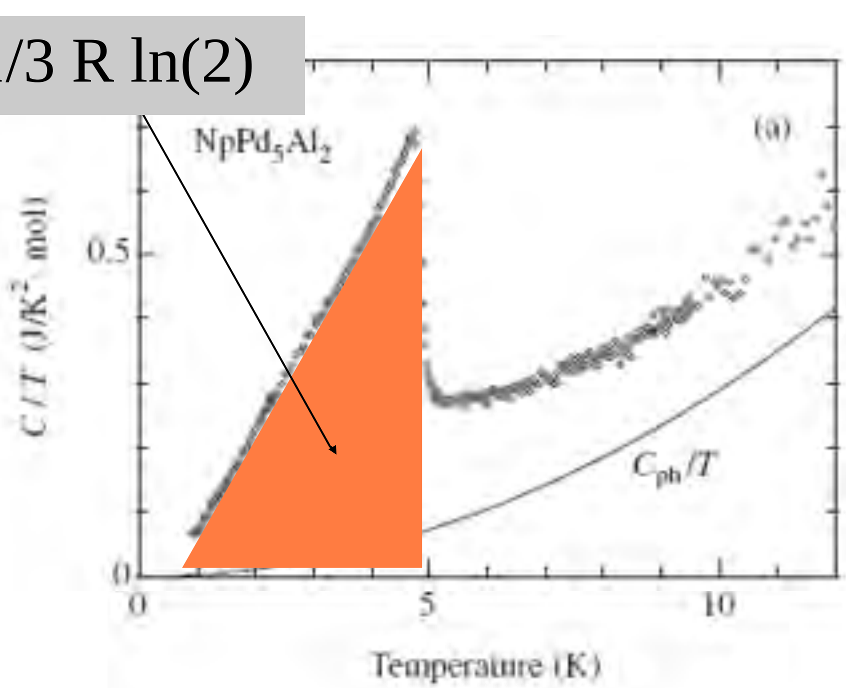

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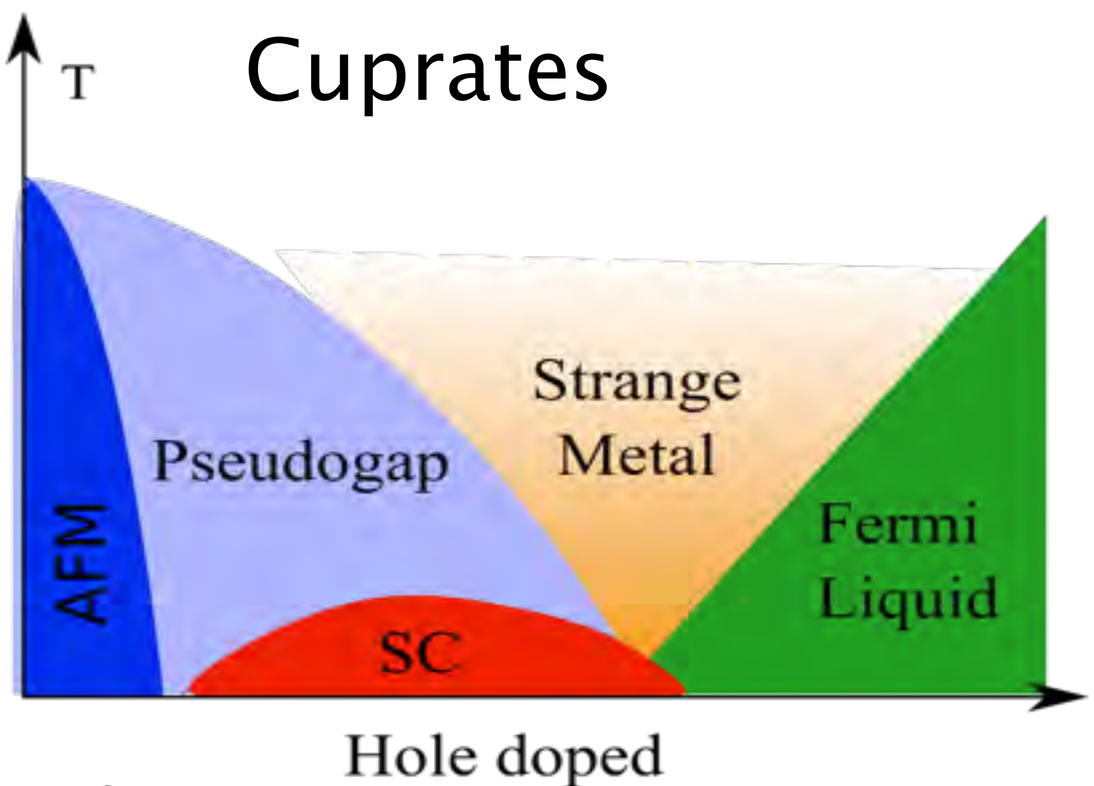
“Hilbert Space Spectroscopy”

SPIN Hilbert space BUILDS the pairs.

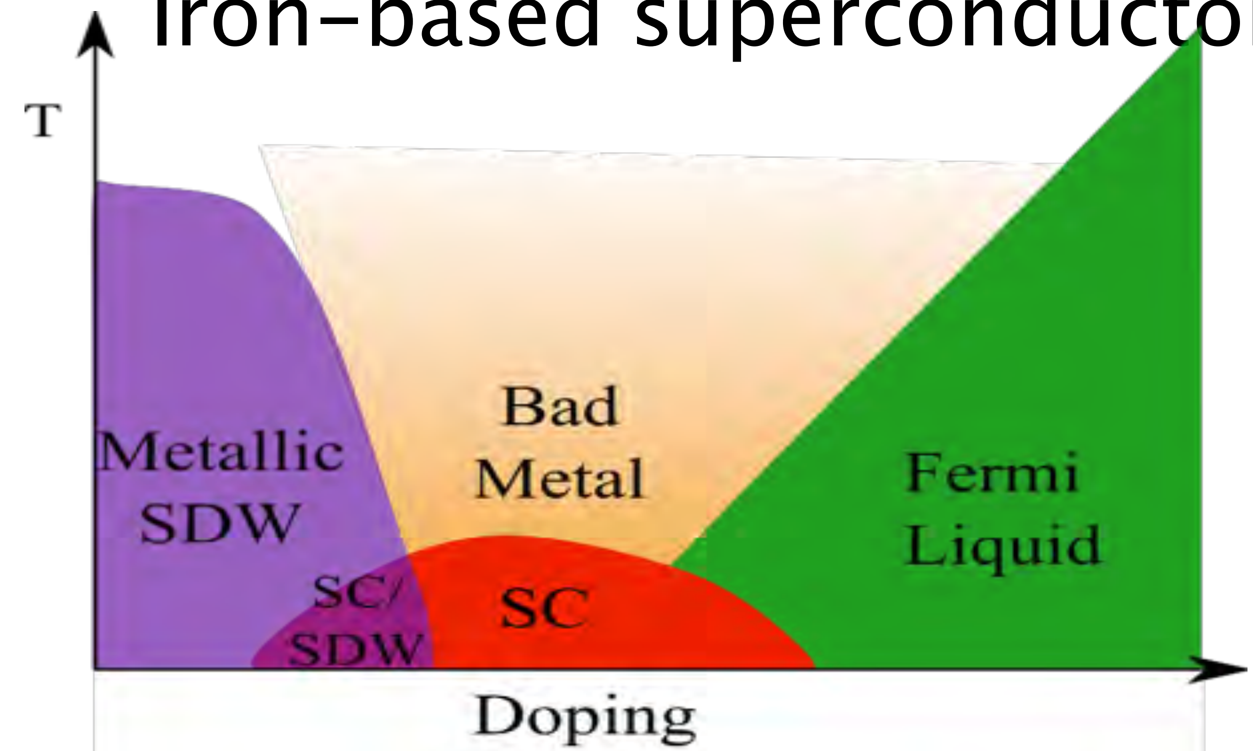
How?

Magnetic pairing appears ubiquitous

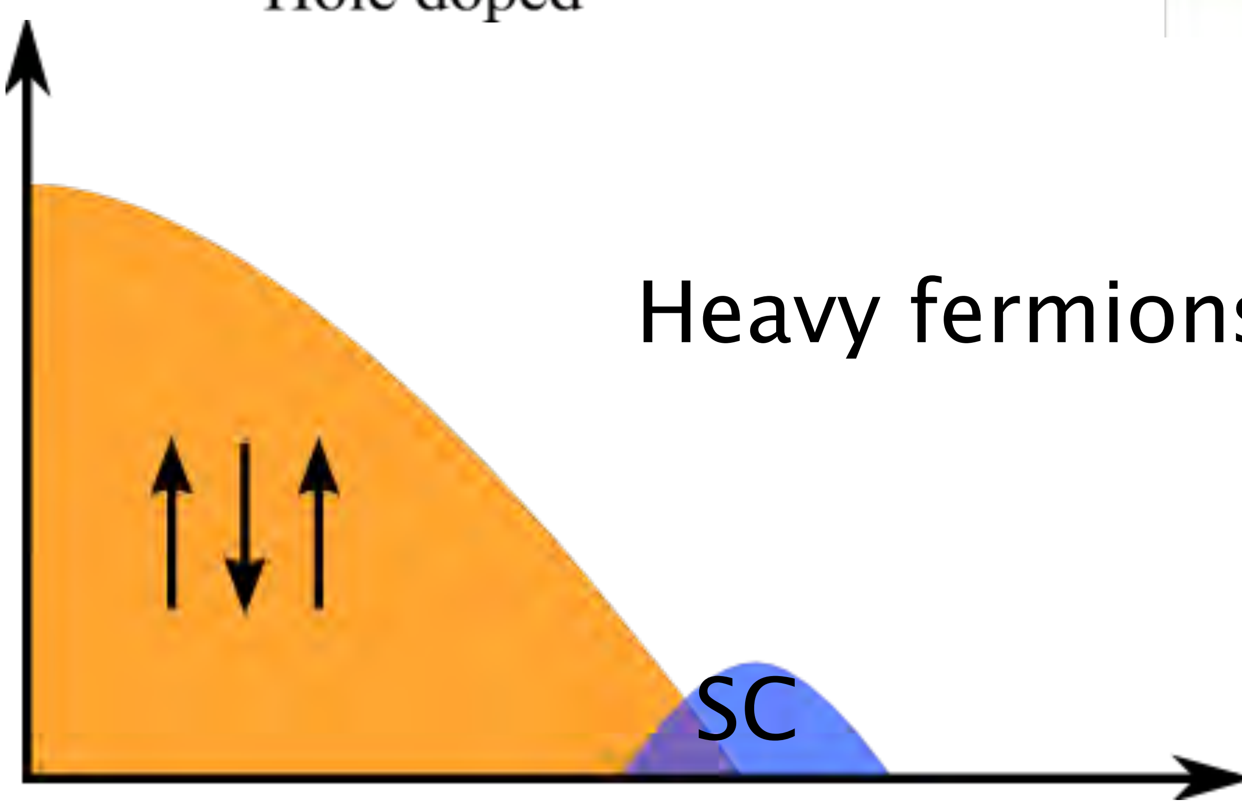
Cuprates

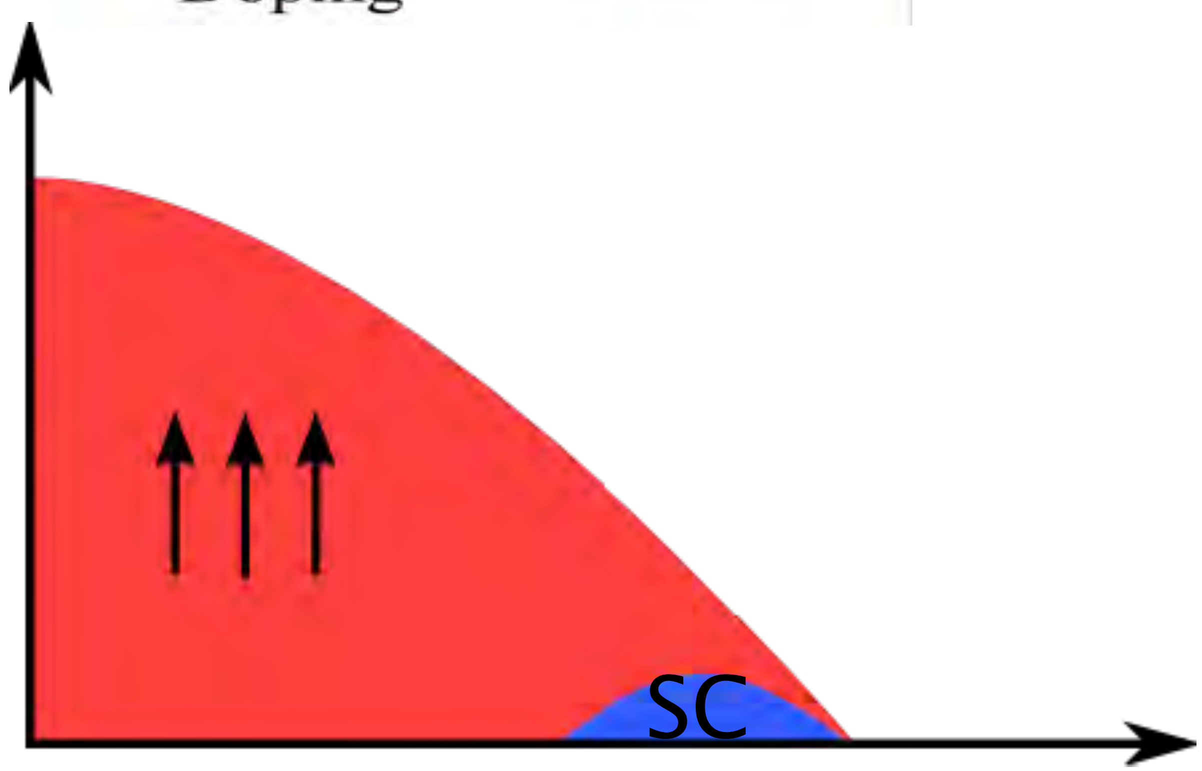


Iron-based superconductors



Heavy fermions





“FM”:	UIr, UGe2,URhGe, UCoGe
“AFM”:	CeCu2Si2, UPt3, CeIn3, CePd2Si2, CeRhIn5, CeCoIn5,CeRhIn5,UPd2Al3
Strange:	UBe13, PuCoGa5,NpPd5Al2, URu2Si2
Non centrosymmetric:	CePtSi, CeIrSi3, CeRhSi3
“Quadrupolar”:	PrOs4Sb2

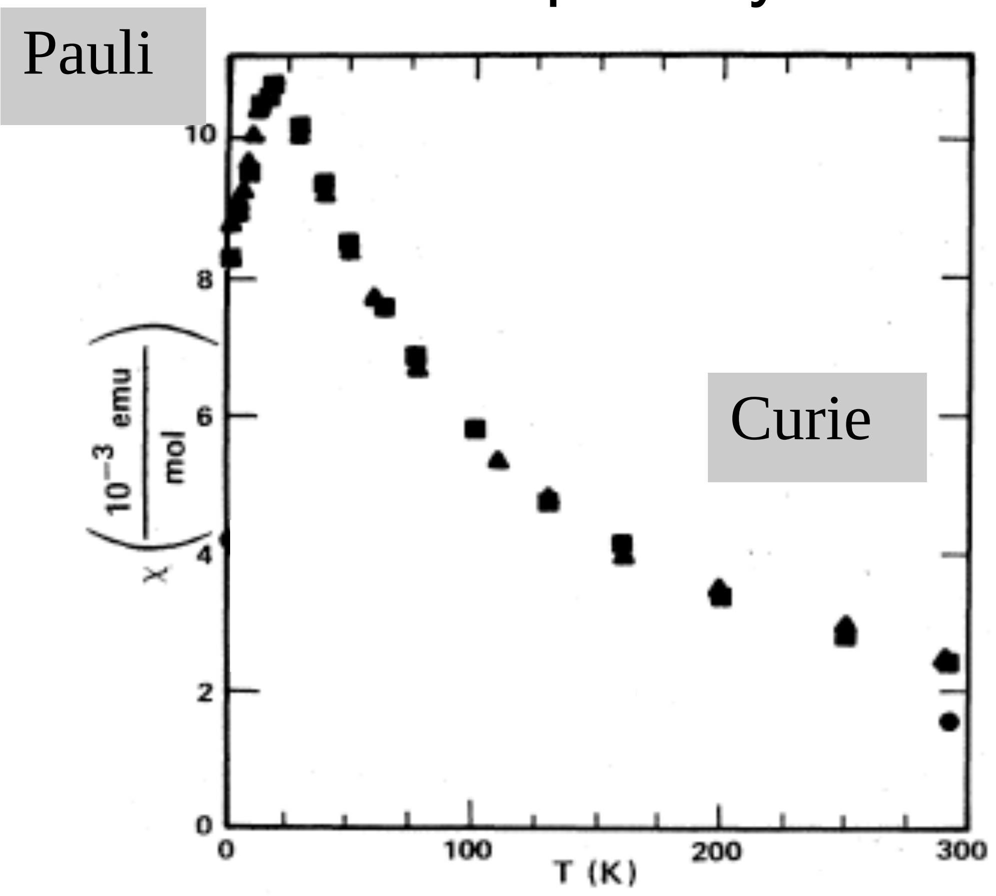
Heavy Fermion SC: The Good.

Conventional Heavy Fermion Superconductivity

Example: UPt_3

$T^* \sim 100K, T_C = .56K$

Susceptibility



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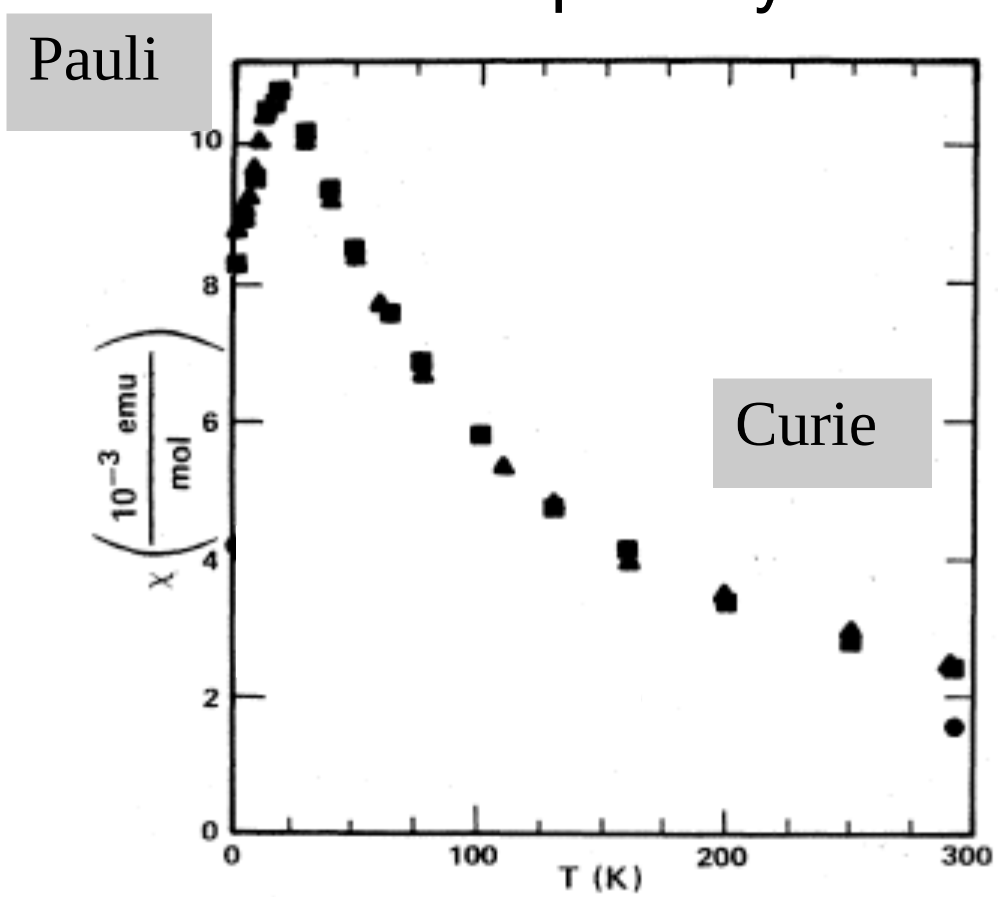

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Stage one: QP formation

Pauli paramagnetism fully developed by 30K~50 T_C

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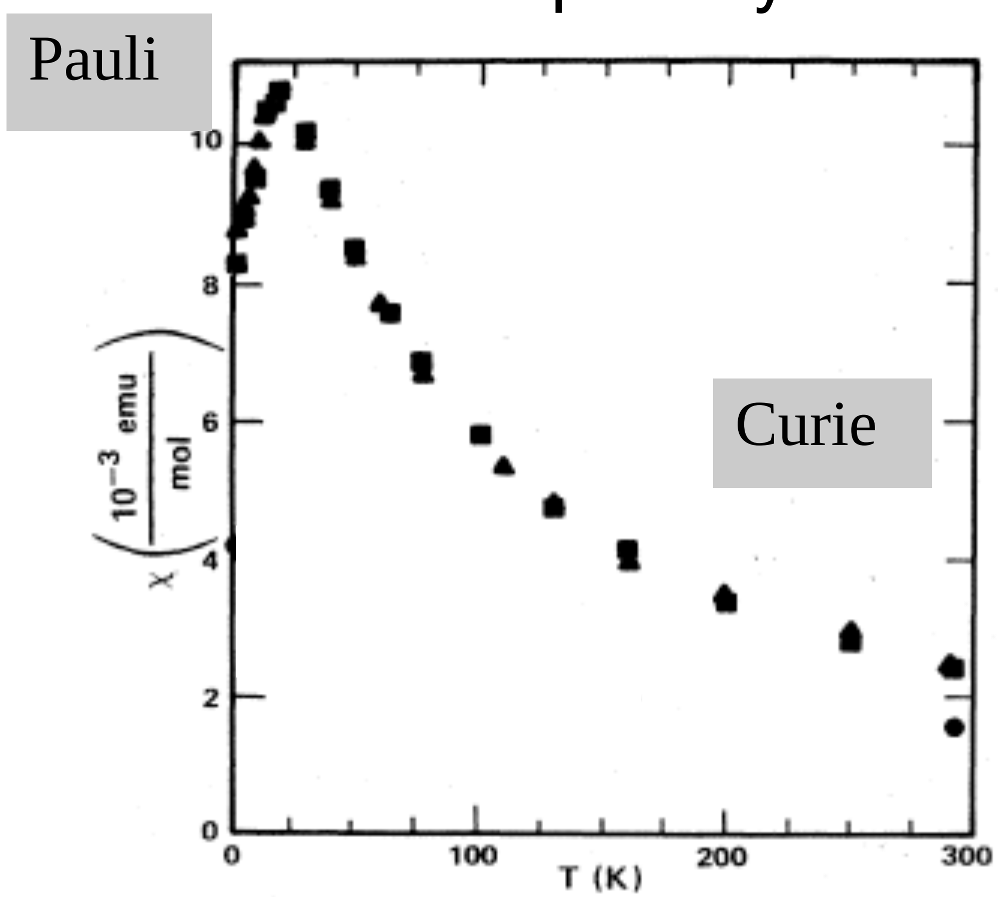

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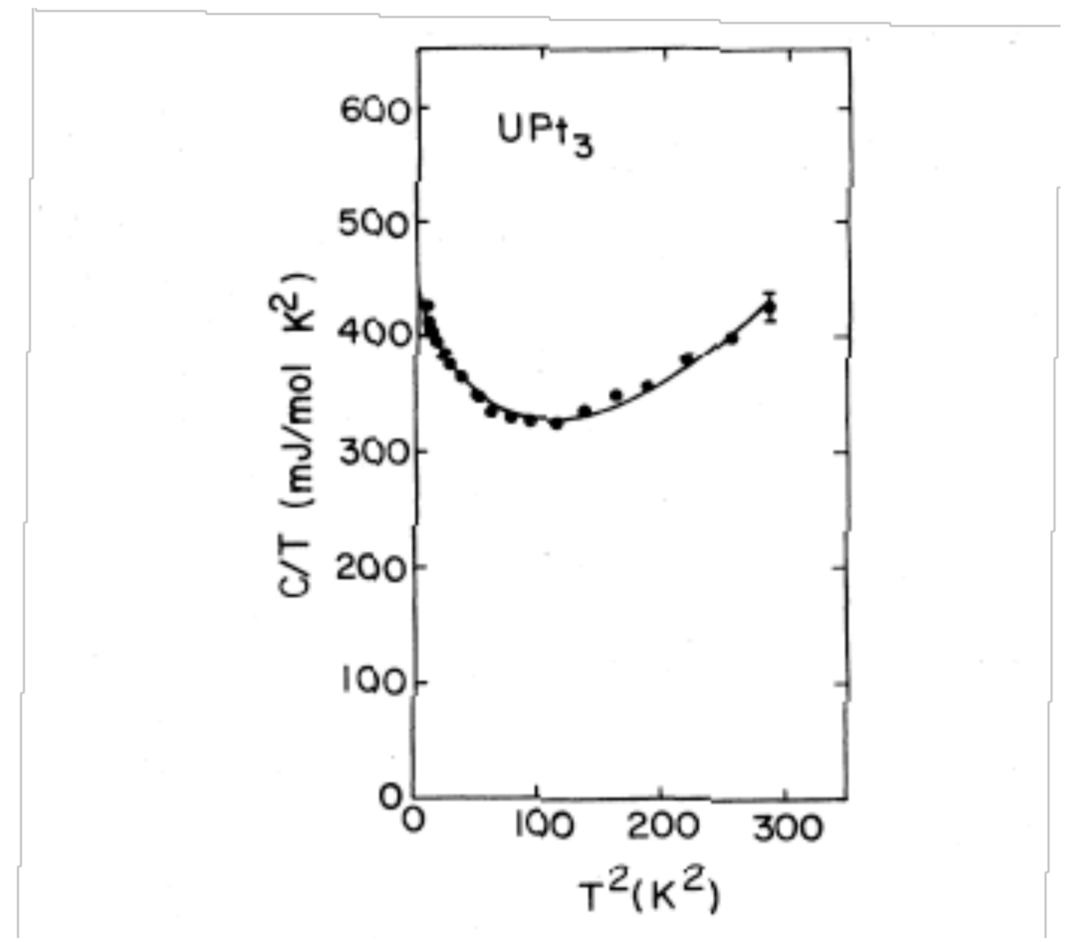

$$C/T = \gamma + \beta T^2 + \delta T^2 \log T$$

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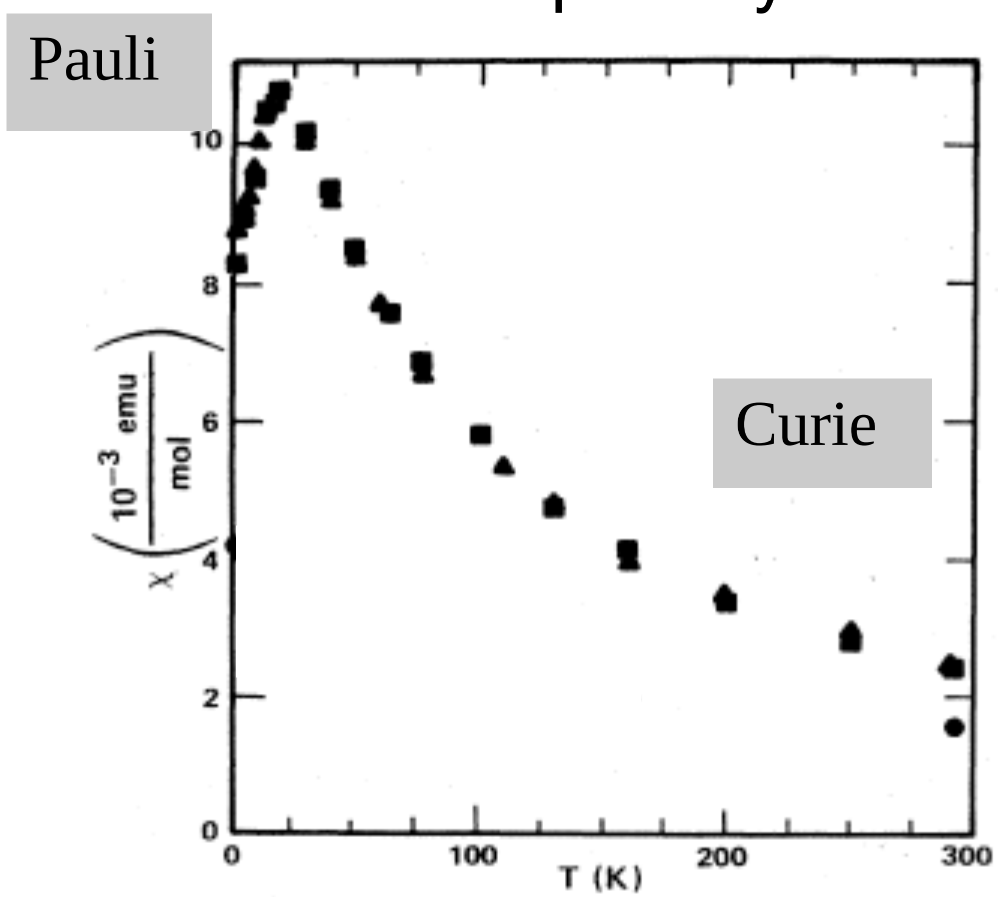

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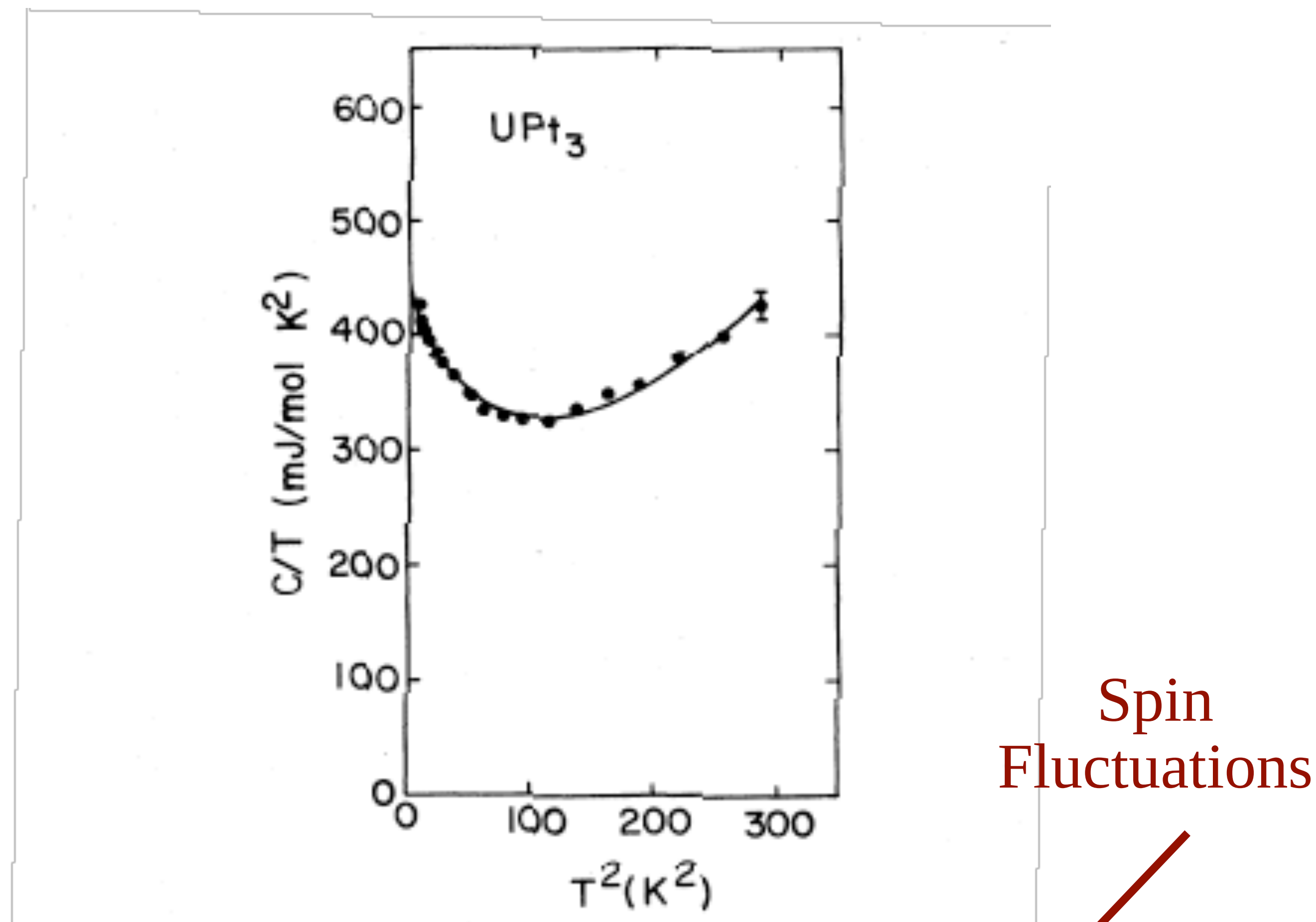

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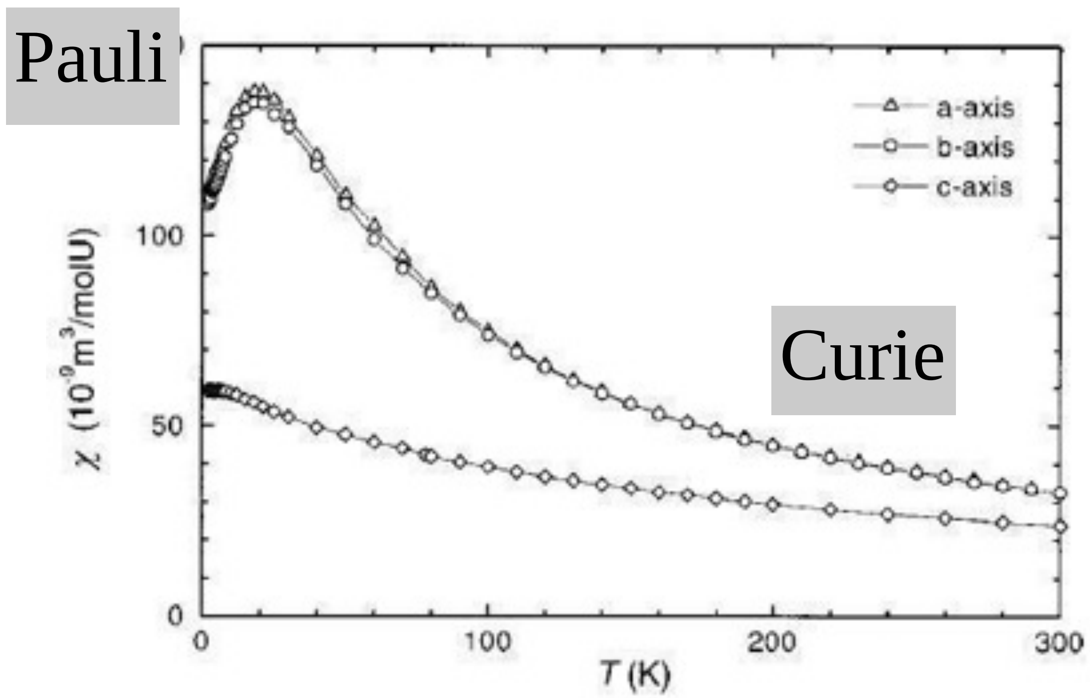
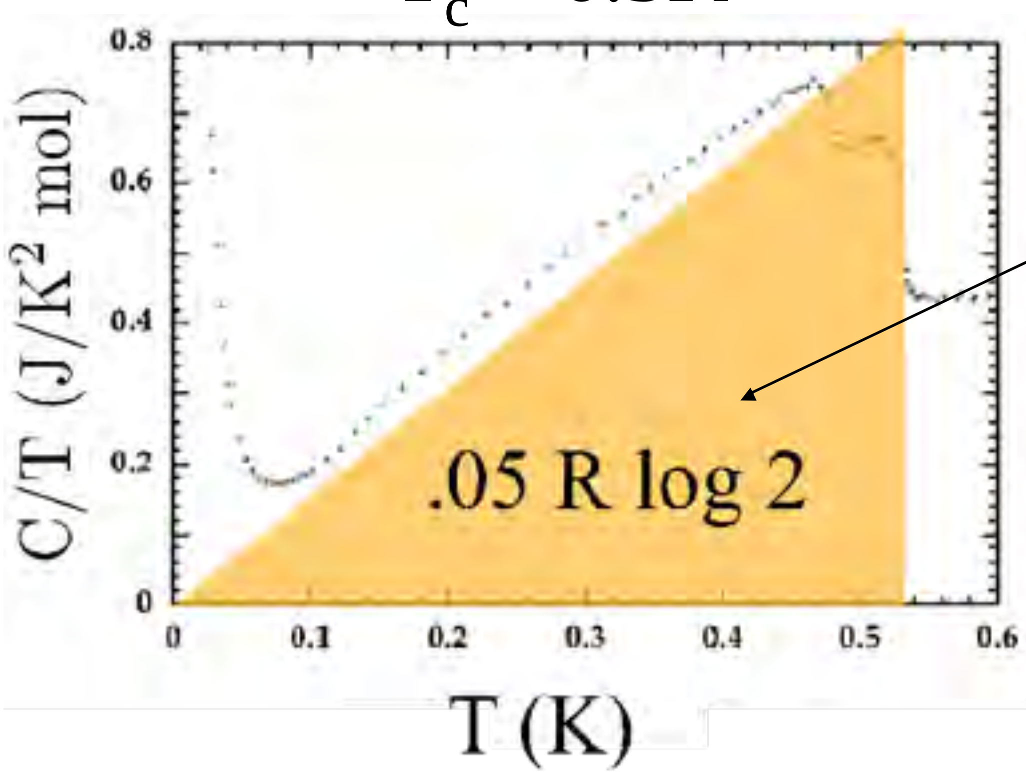


Pauli paramagnetic by 30K

T_c = 0.5K



$$S = \int_0^T \frac{C(T')}{T'} dT'$$

Frings *et al.* J. Magn. Magn. Mater. **31**, 240(1983)
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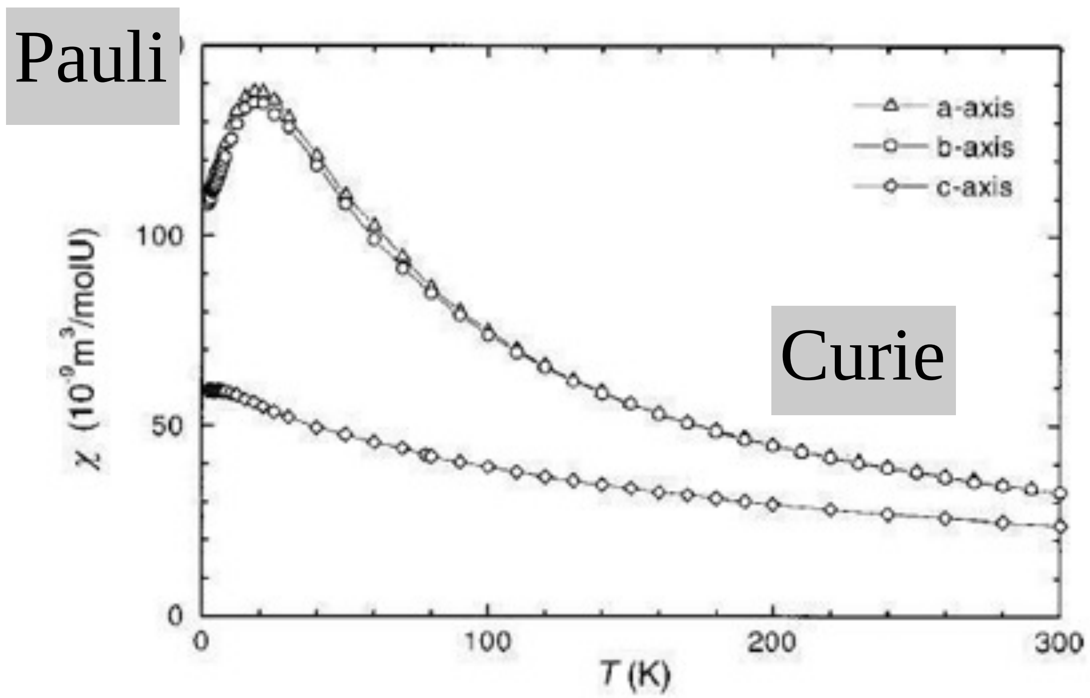

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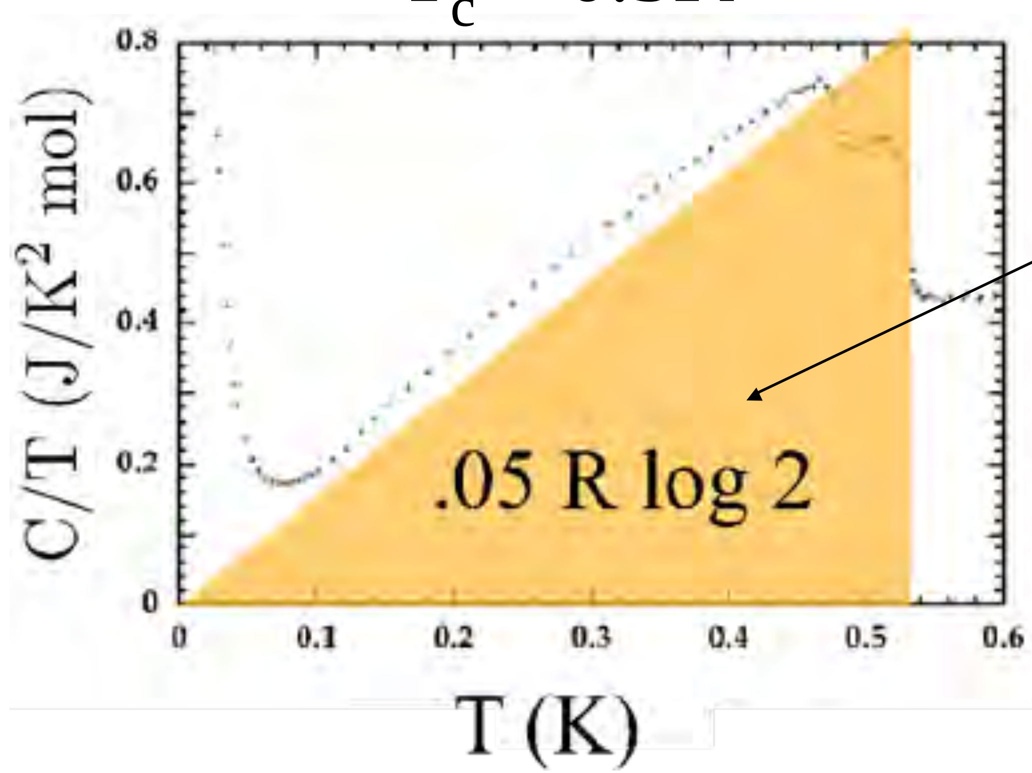

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Small condensation entropy
Spins are quenched
Two stages are well separated

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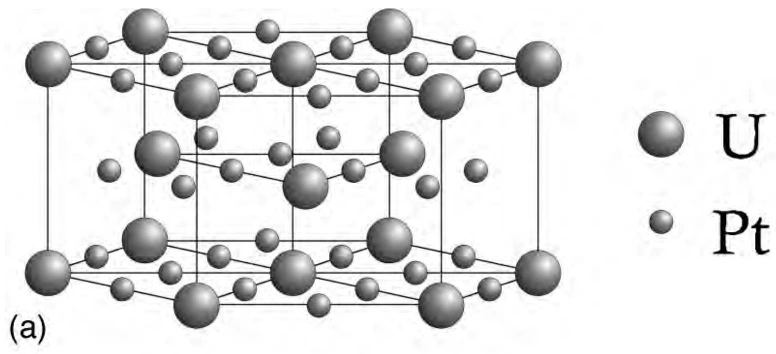
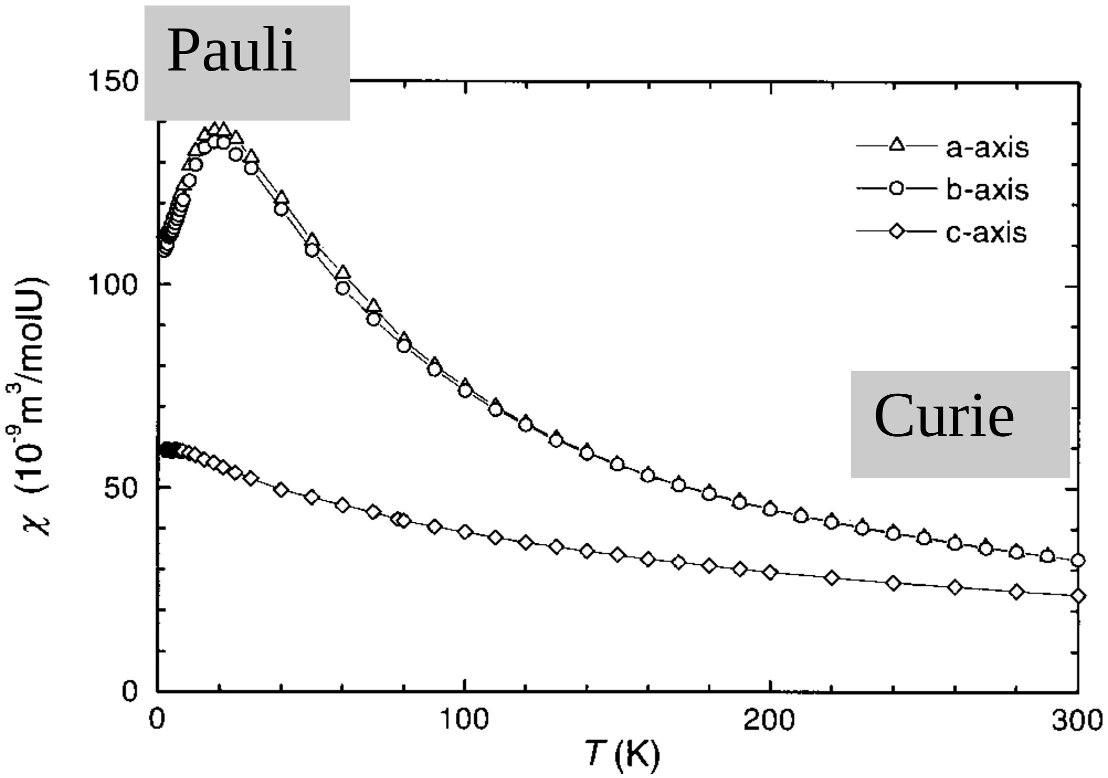
UPt$_3$: Classic HFSC



Joynt and Taillefer, RMP 2002.



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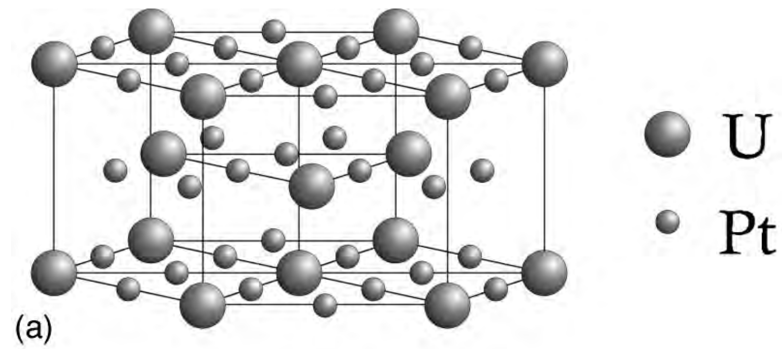

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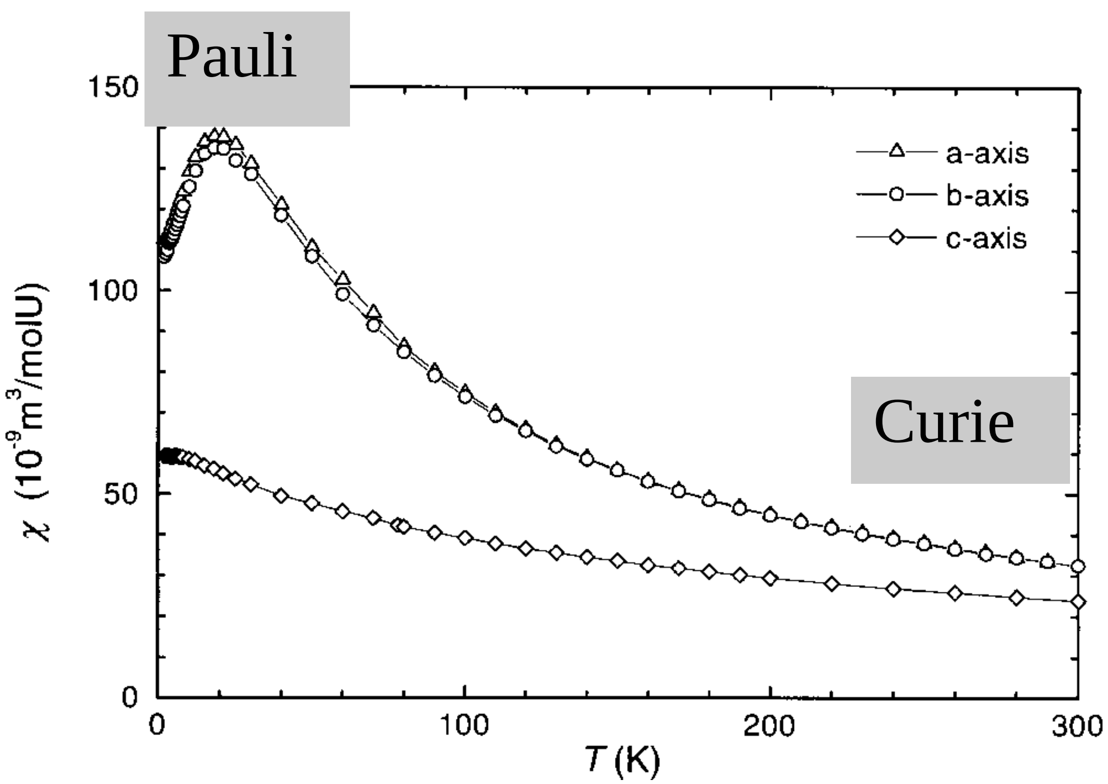
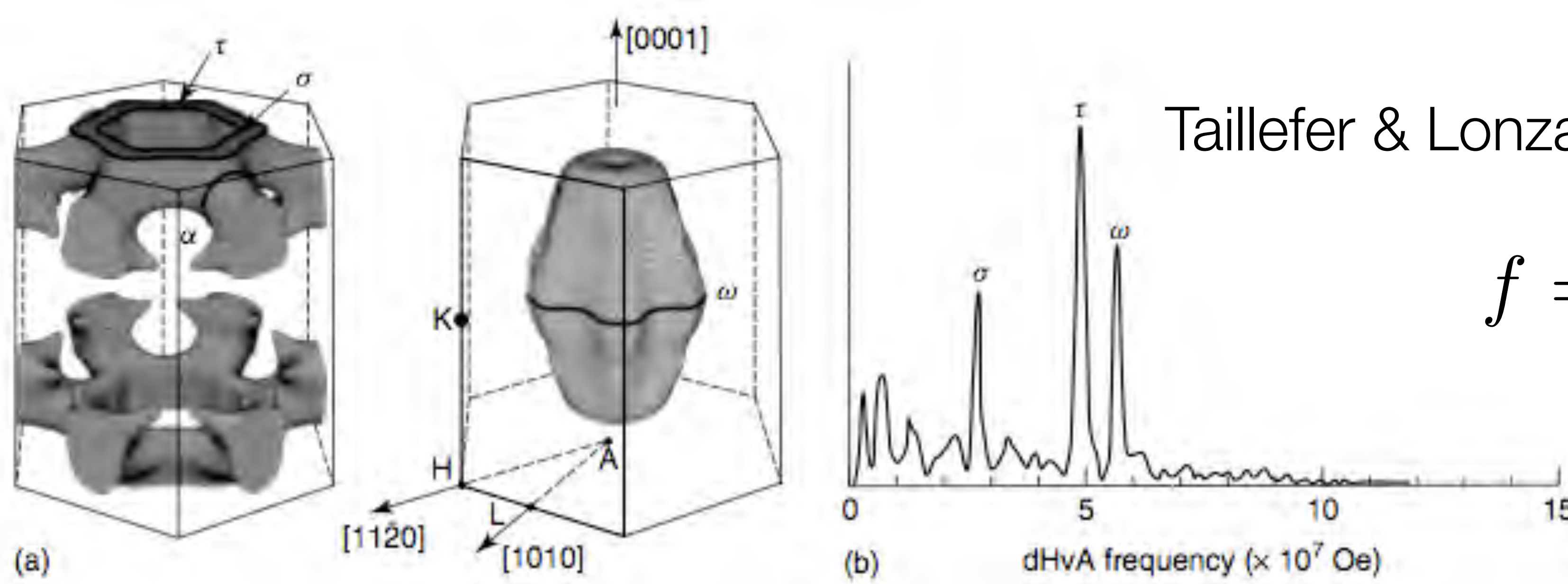
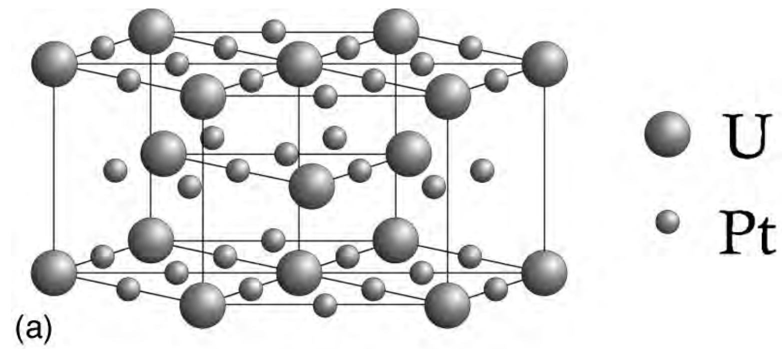


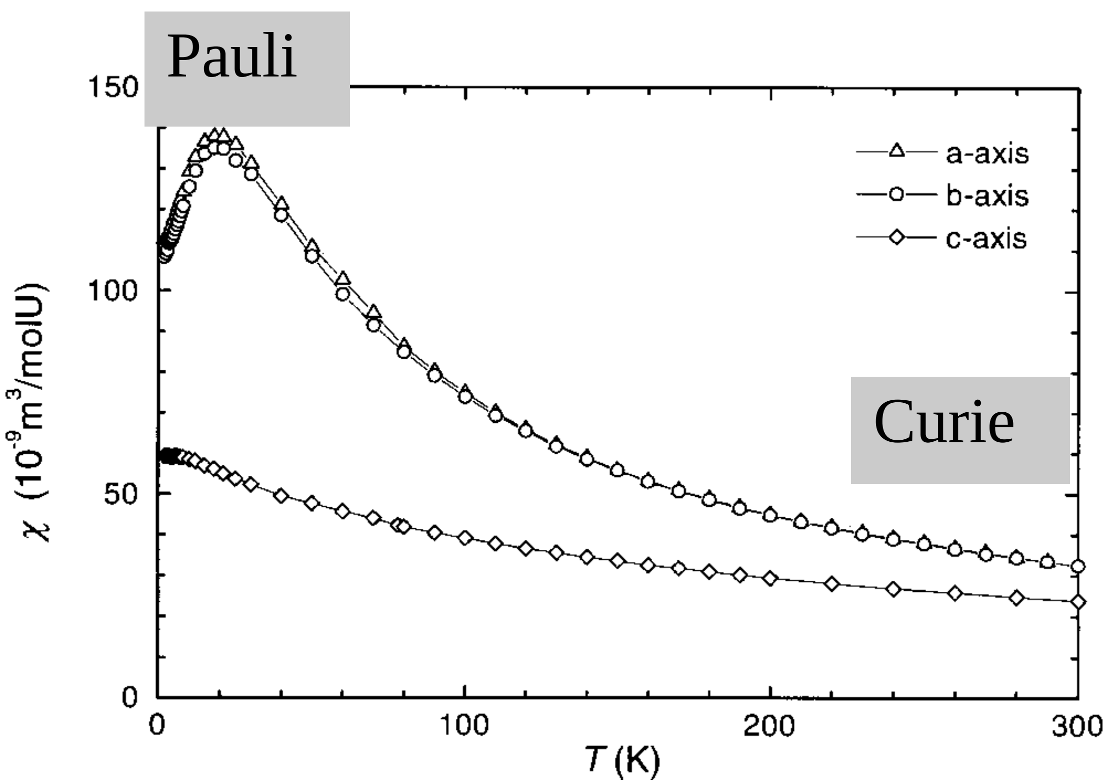


Taillefer & Lonzarich UPt_3 (1985)

$$f = A\left(\frac{\hbar^2}{2\pi e}\right)$$

UPt$_3$: Classic HFSC





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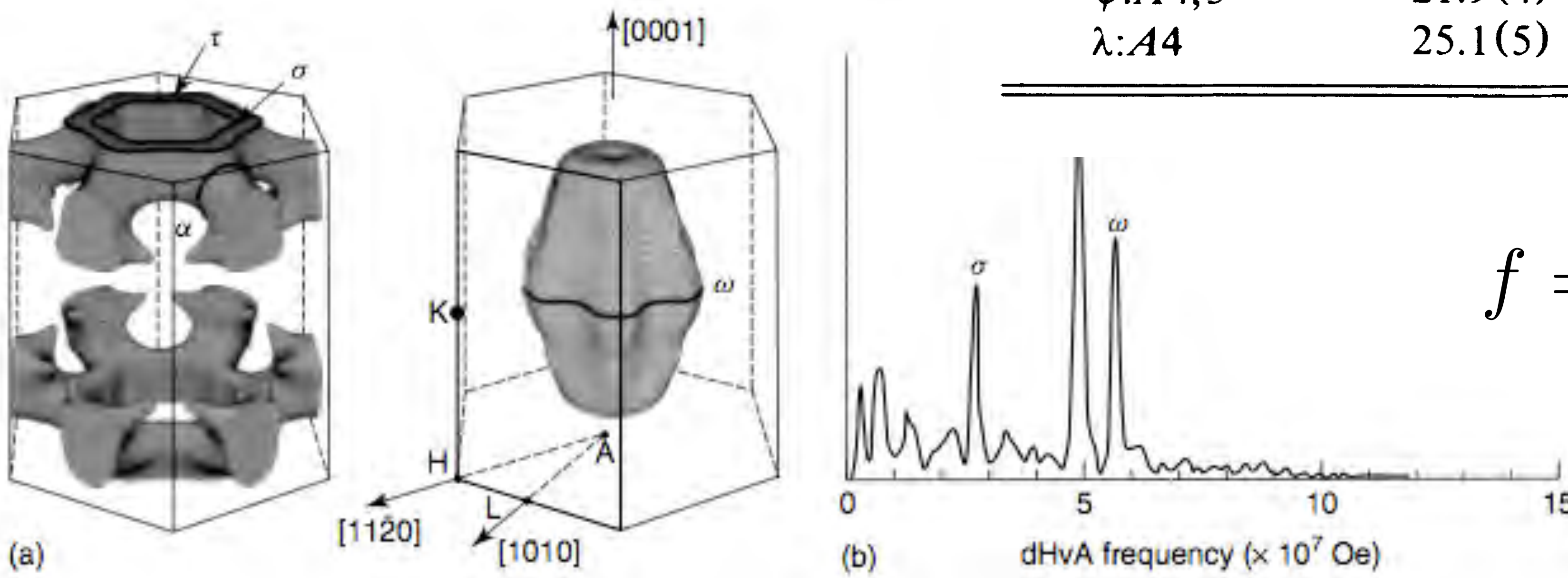
Branch:*FS* orbit	F (MG) Expt.	F (MG) Calc.	m^*/m_e Expt.	m^*/m_e Calc.
		a axis (ΓK)		
α:$ML4$	5.4(3)	10.4	25(3)	2.2
β:$L4$	6.0(4)	5.2	···	1.0
γ:$\Gamma 1$	7.3(3)	8.2	40(7)	2.0
δ:$A5$	14.0(3)	9.1	50(8)	1.9
ϵ:$\Gamma 2$	21.0(3)	24.0	60(8)	4.6
ω:$\Gamma 3$	58.5(5)	52.8	90(15)	5.3
		b axis (ΓM)		
α:$ML4$	4.1(2)		15(5)	
δ:$A5$	12.3(2)		30(3)	
θ:$A4,5$	15.5(2)		35(7)	
ϕ:$A4,5$	18.7(3)		40(8)	
ψ:$A4,5$	21.9(4)		···	
λ:$A4$	25.1(5)		(50)	



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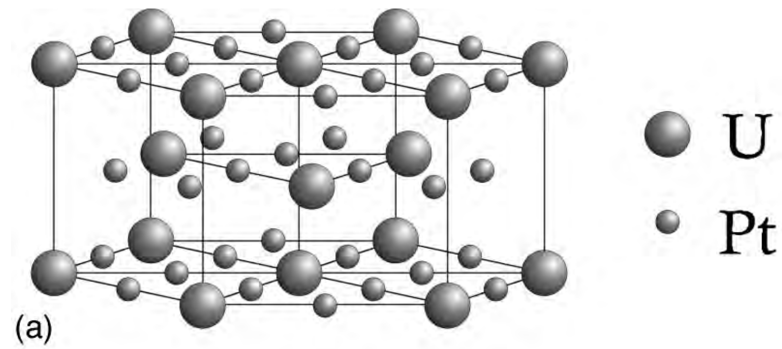
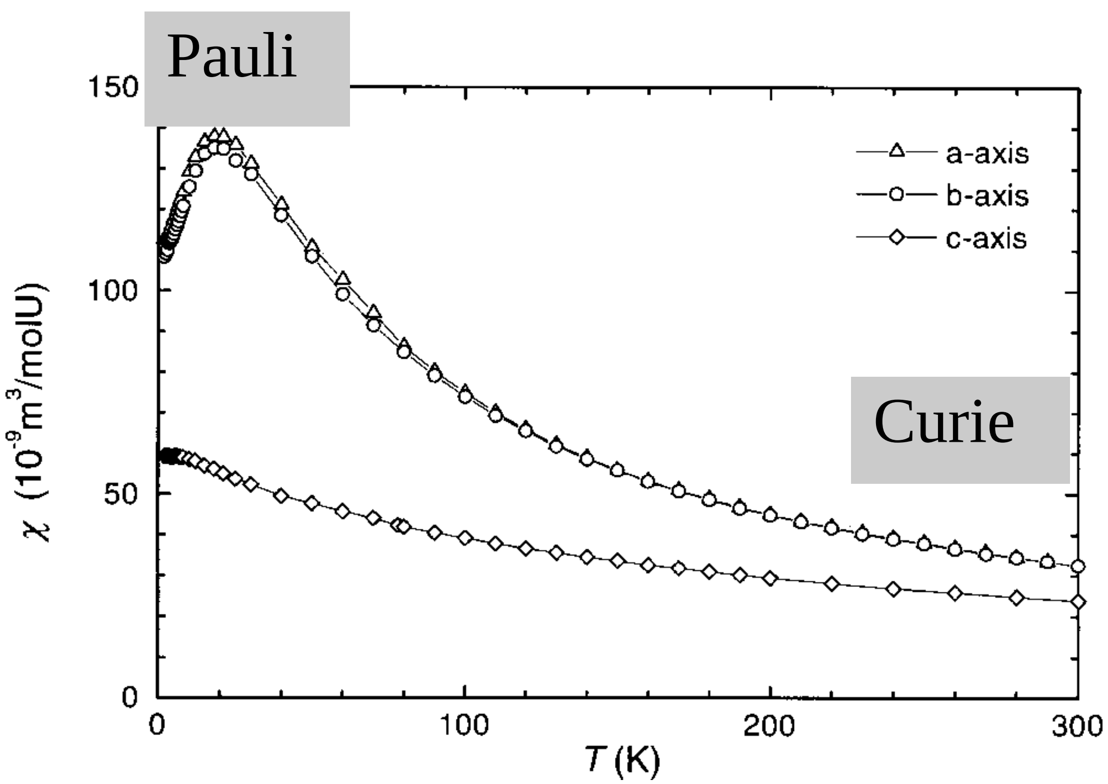
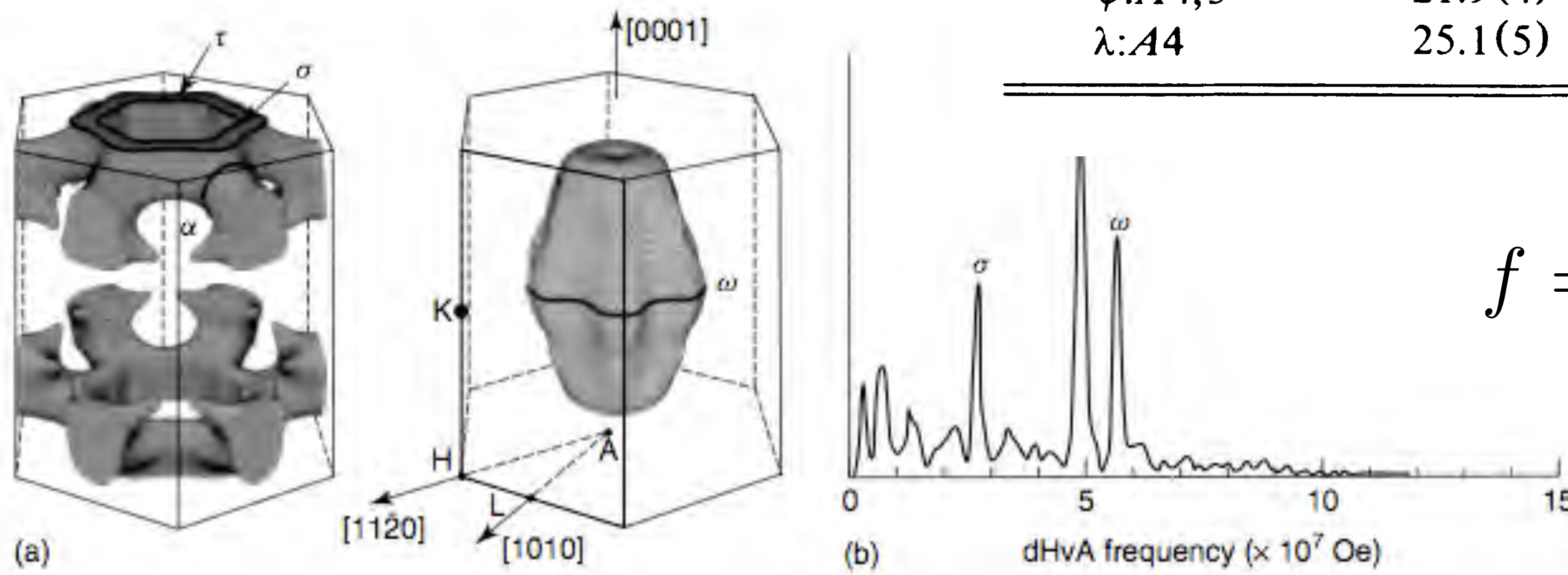




Joynt and Taillefer, RMP 2002.

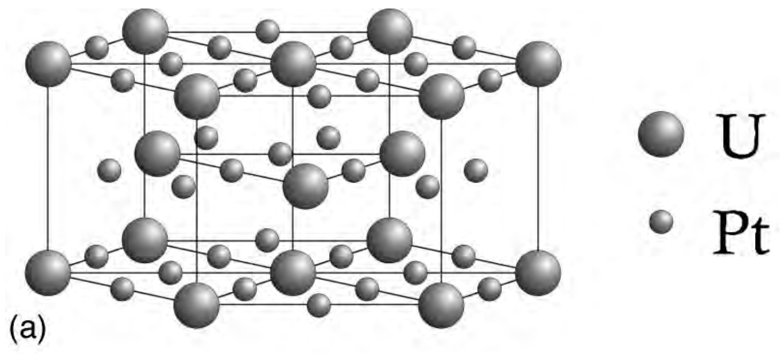
Branch:*FS* orbit	F (MG) Expt.	Calc.	m^*/m_e Expt.	Calc.
	a axis (Γ*K*)			
α:*ML*4	5.4(3)	10.4	25(3)	2.2
β:*L*4	6.0(4)	5.2	···	1.0
γ:Γ1	7.3(3)	8.2	40(7)	2.0
δ:*A*5	14.0(3)	9.1	50(8)	1.9
ε:Γ2	21.0(3)	24.0	60(8)	4.6
ω:Γ3	58.5(5)	52.8	90(15)	5.3
	b axis (Γ*M*)			
α:*ML*4	4.1(2)		15(5)	
δ:*A*5	12.3(2)		30(3)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

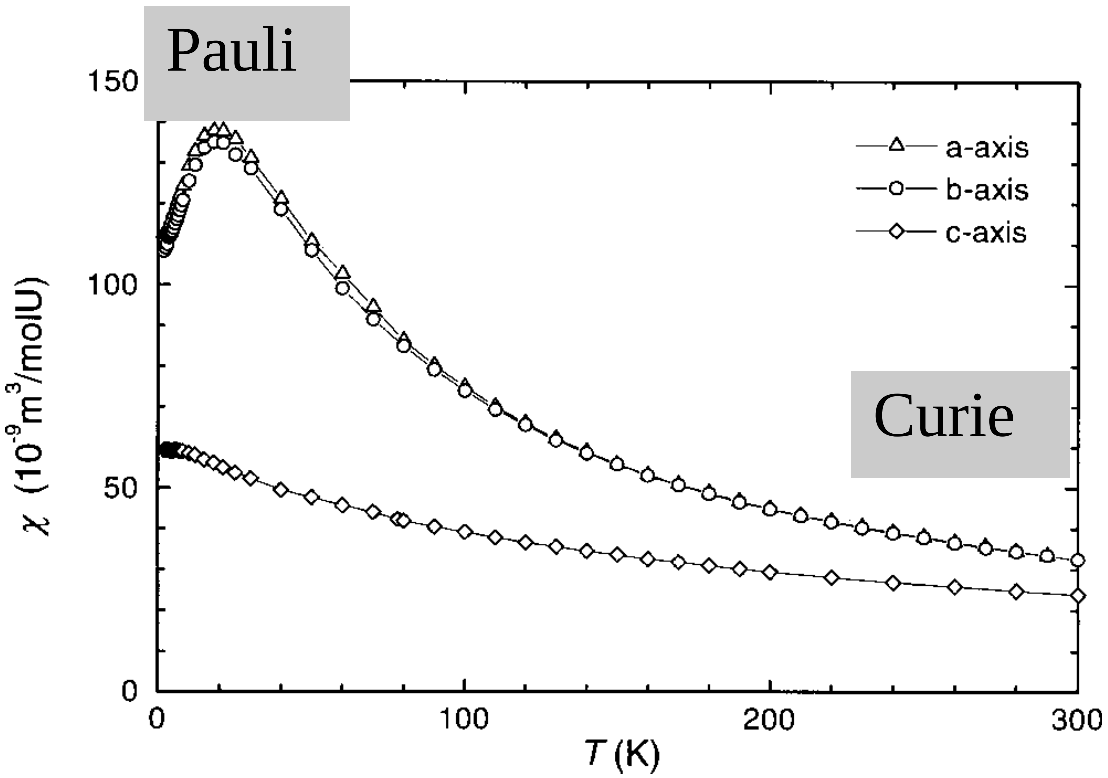


$$f = A\left(\frac{\hbar^2}{2\pi e}\right)$$

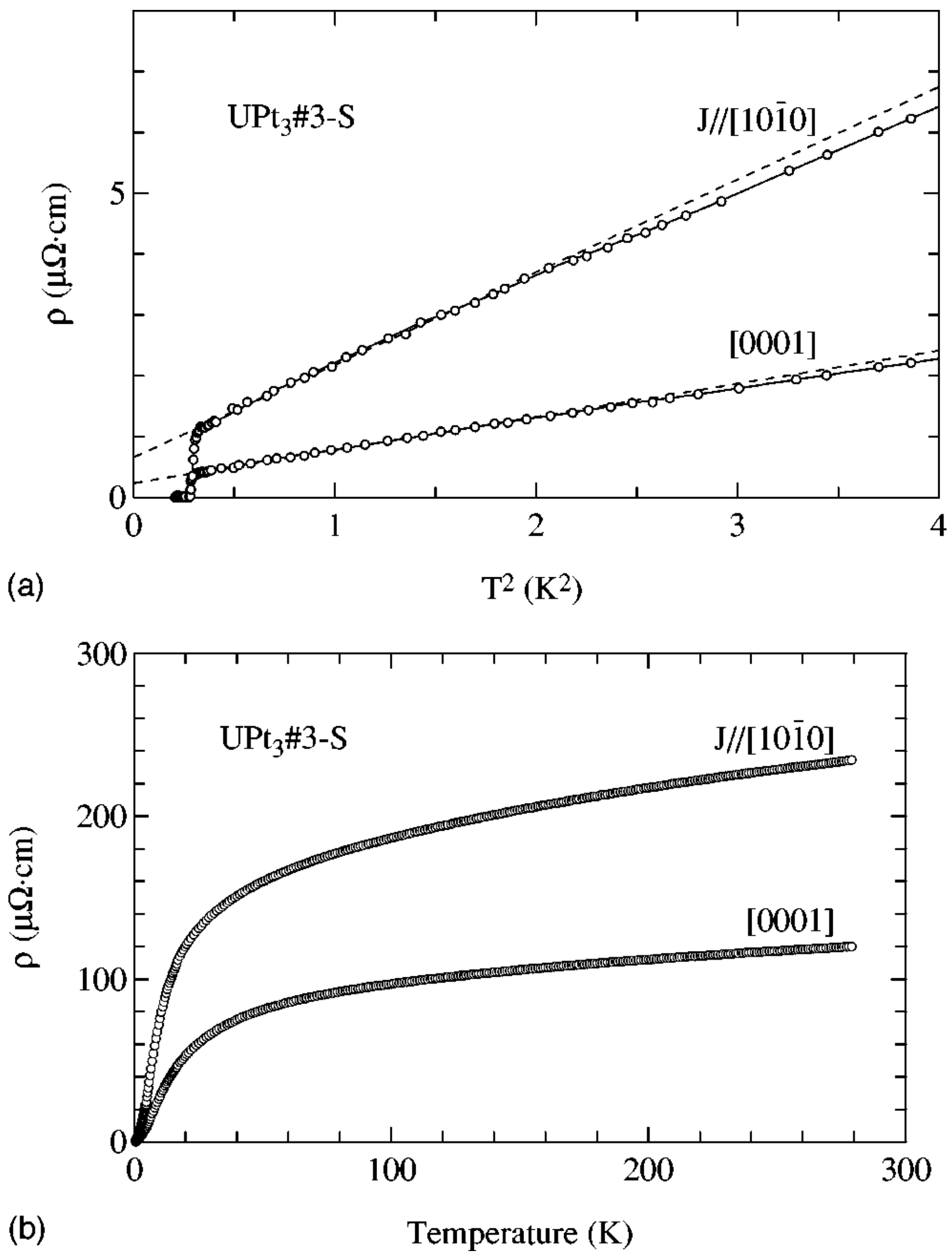
1

UPt$_3$: Classic HFSC

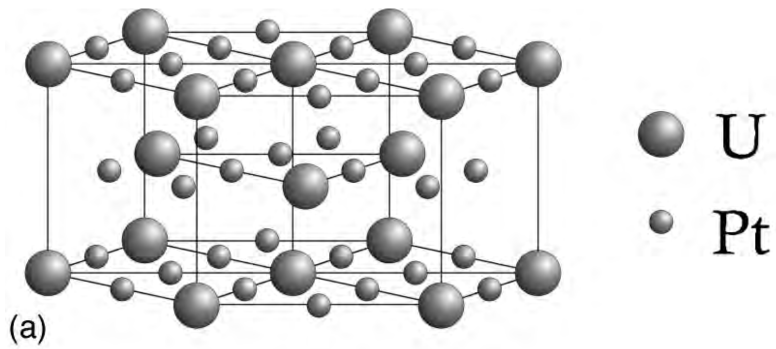


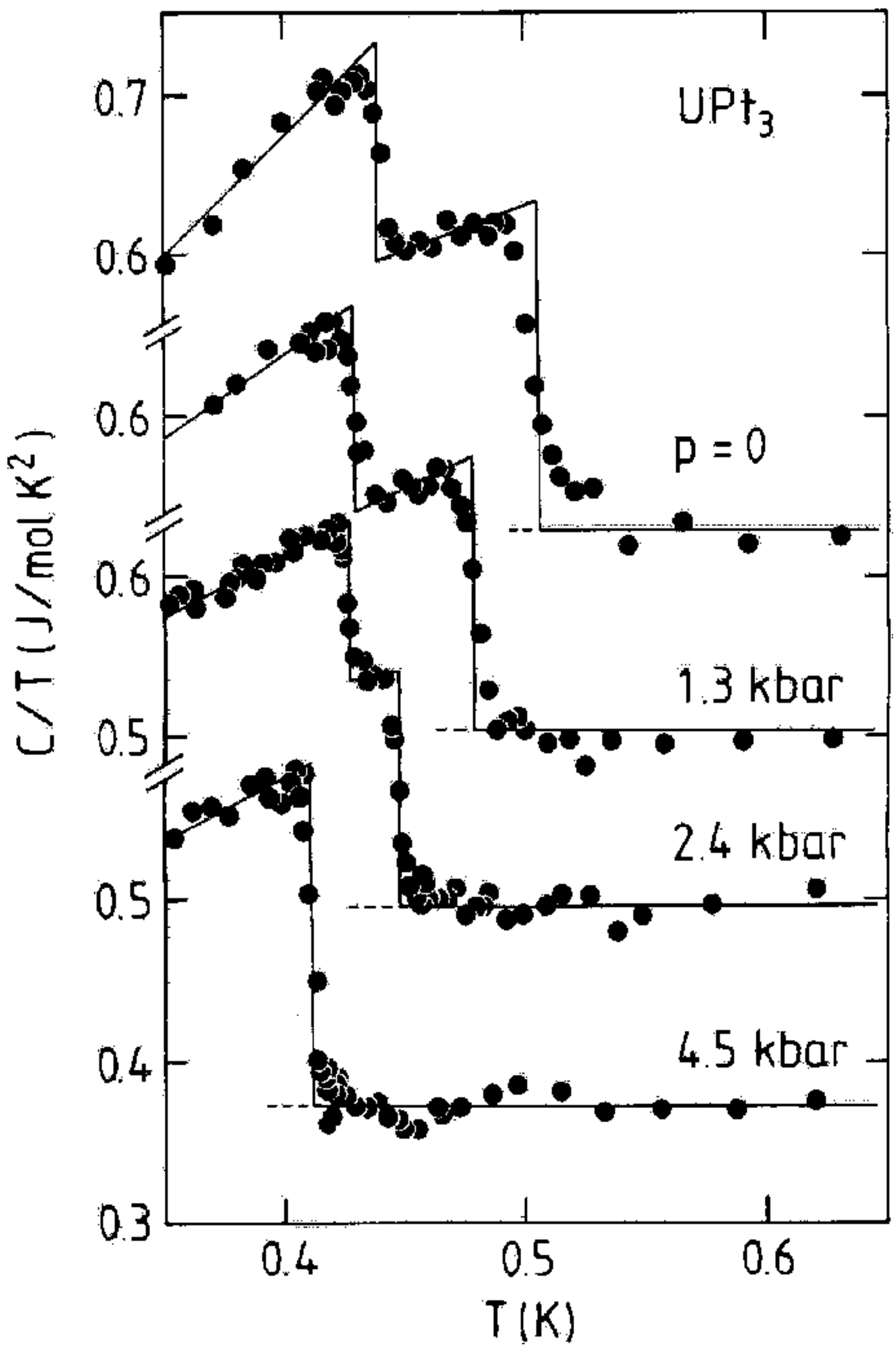


Joynt and Taillefer, RMP 2002.

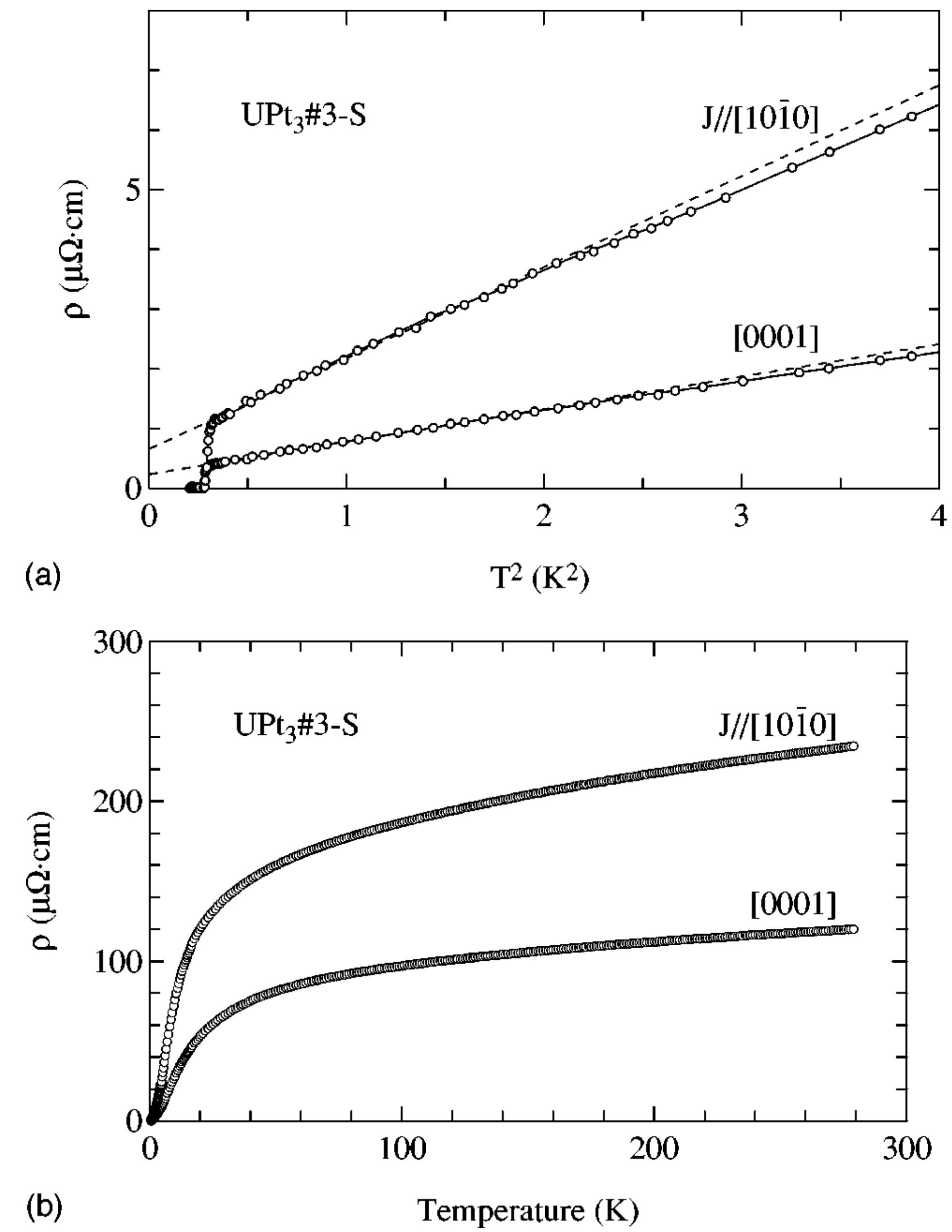


UPt_3: Classic HFSC



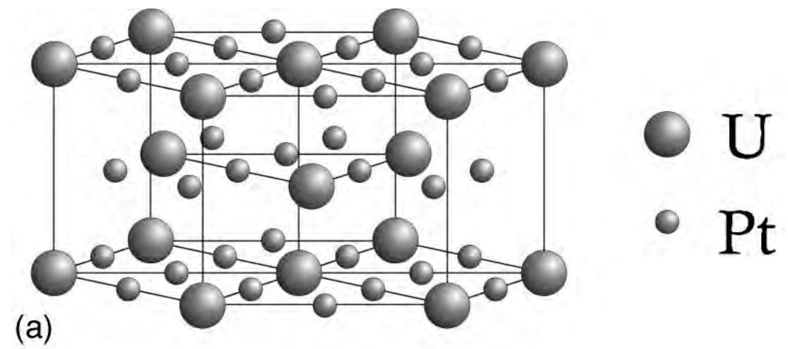


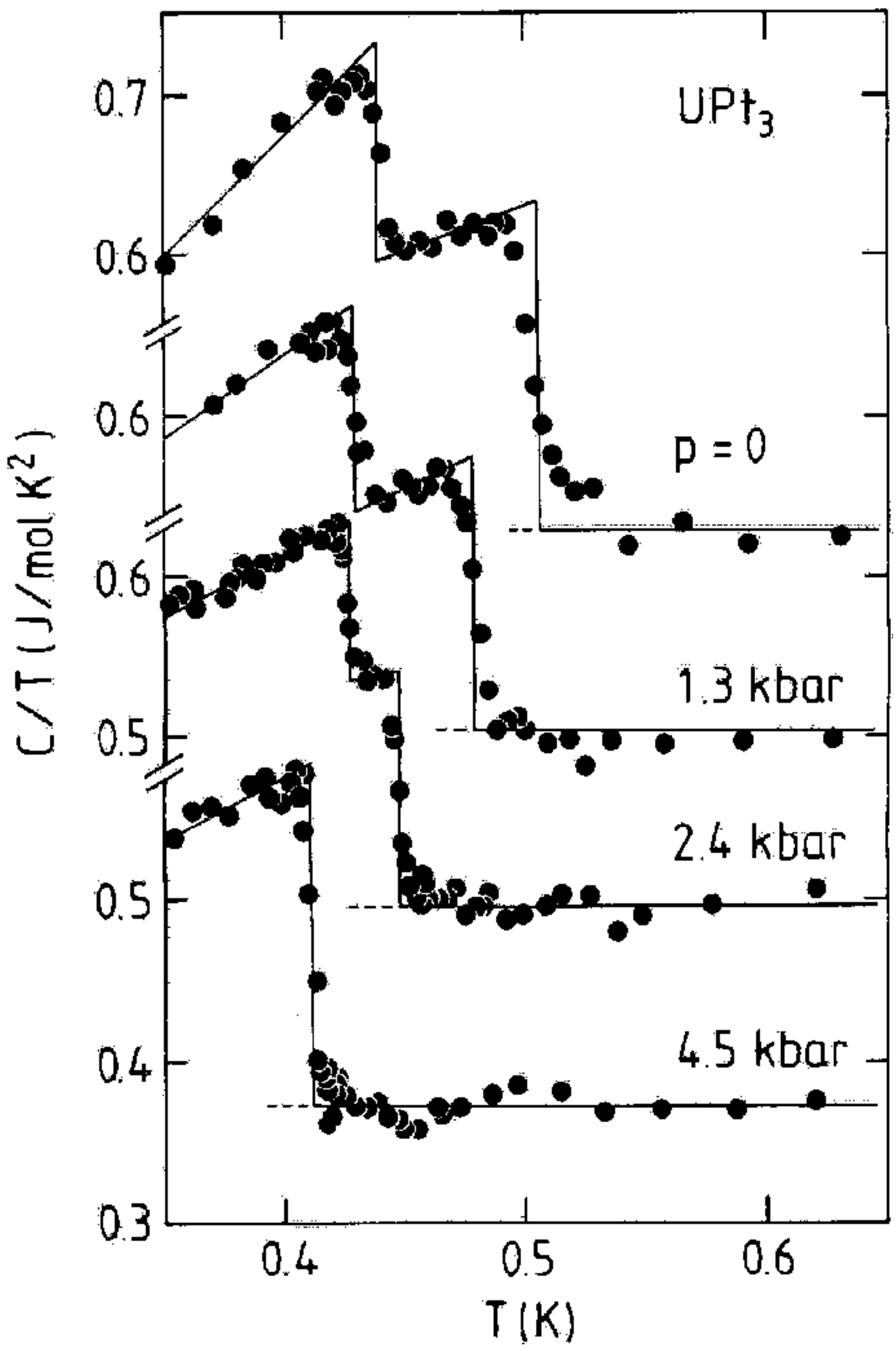
Joynt and Taillefer, RMP 2002.

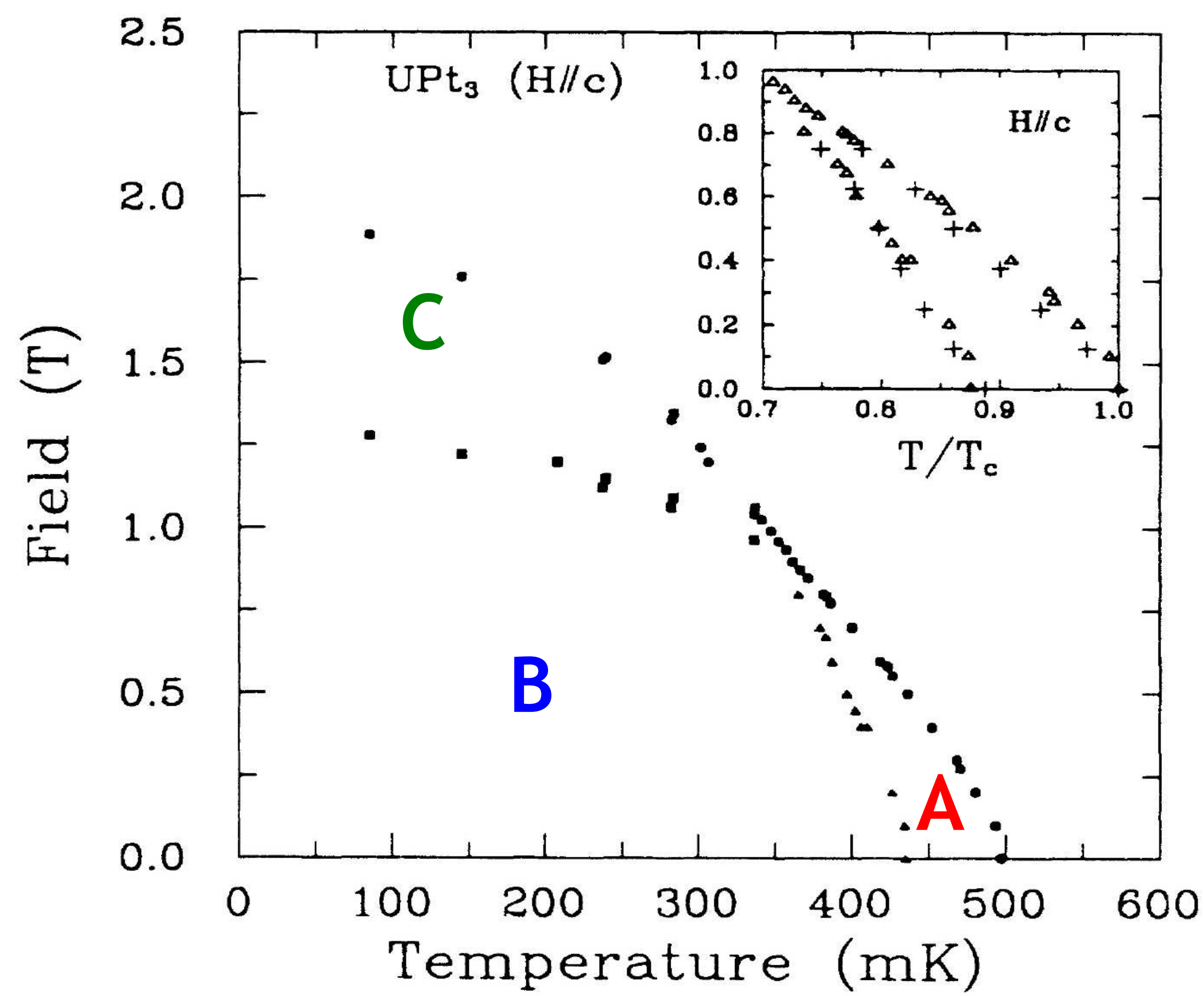


UPt_3: Classic HFSC

Joynt and Taillefer,
RMP 2002.







Magnetic Order and Fluctuations in Superconducting UPt_3

G. Aeppli and E. Bucher
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

C. Broholm and J. K. Kjems
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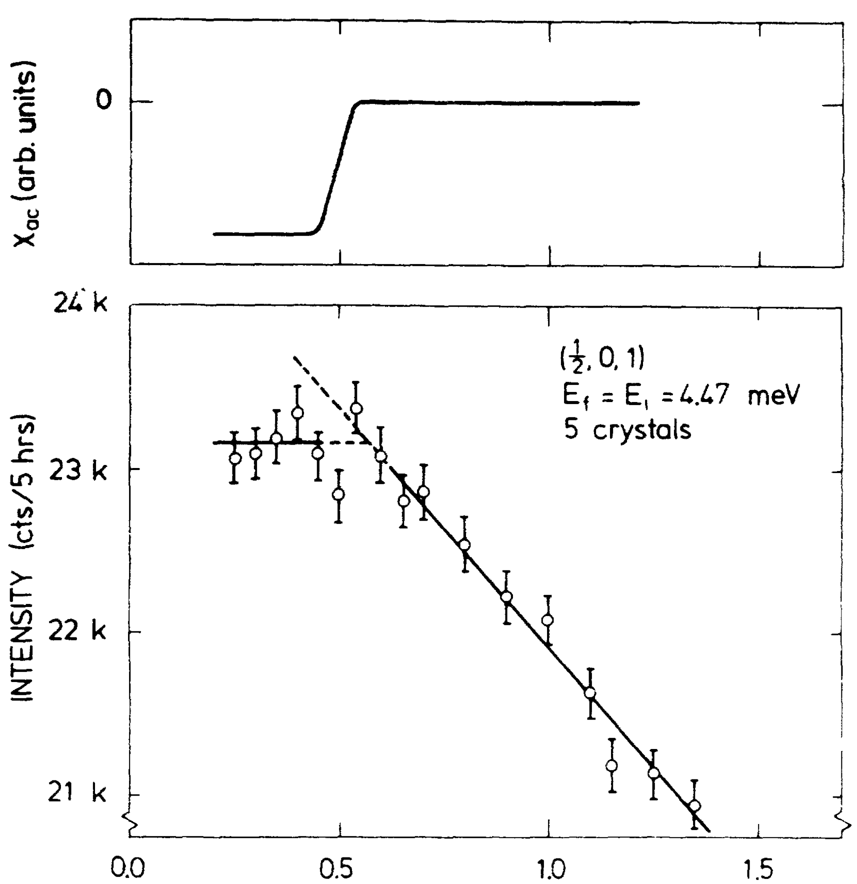
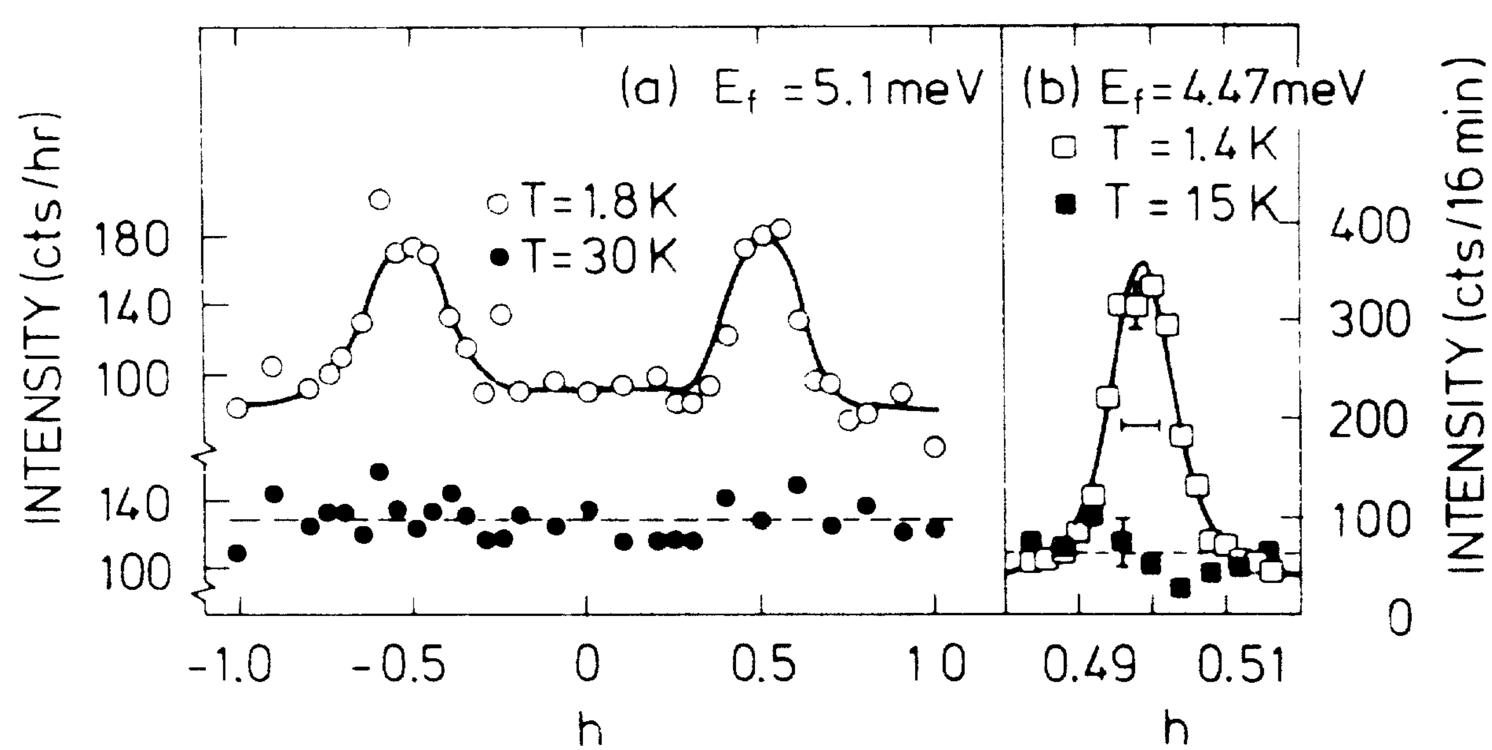
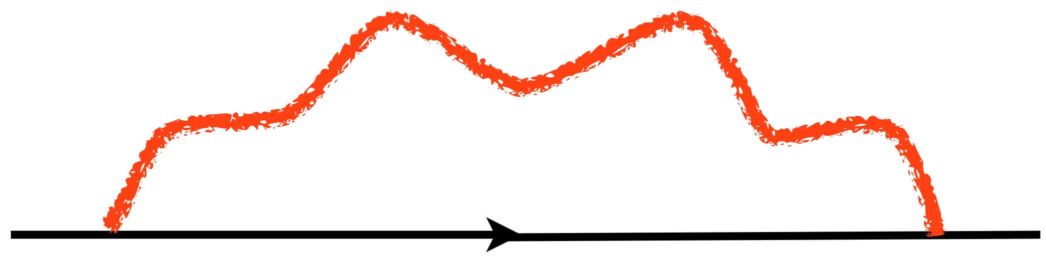
and

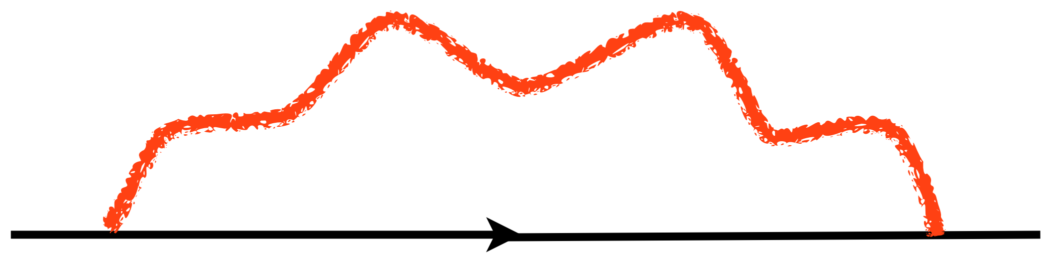
J. Baumann and J. Hufnagl
University of Konstanz, D-7750 Konstanz, Federal Republic of Germany
(Received 24 September 1987)



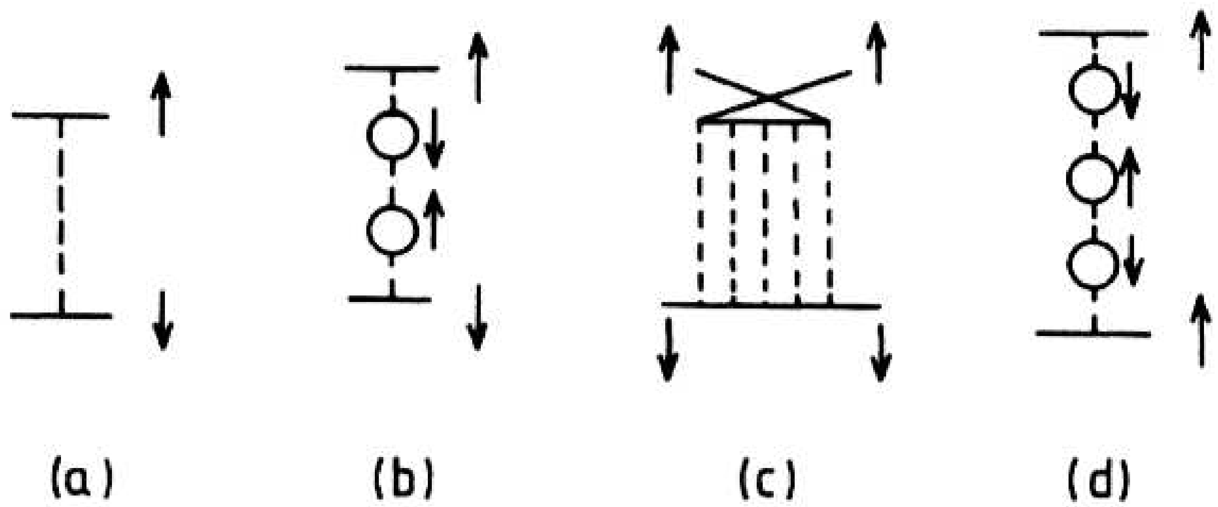




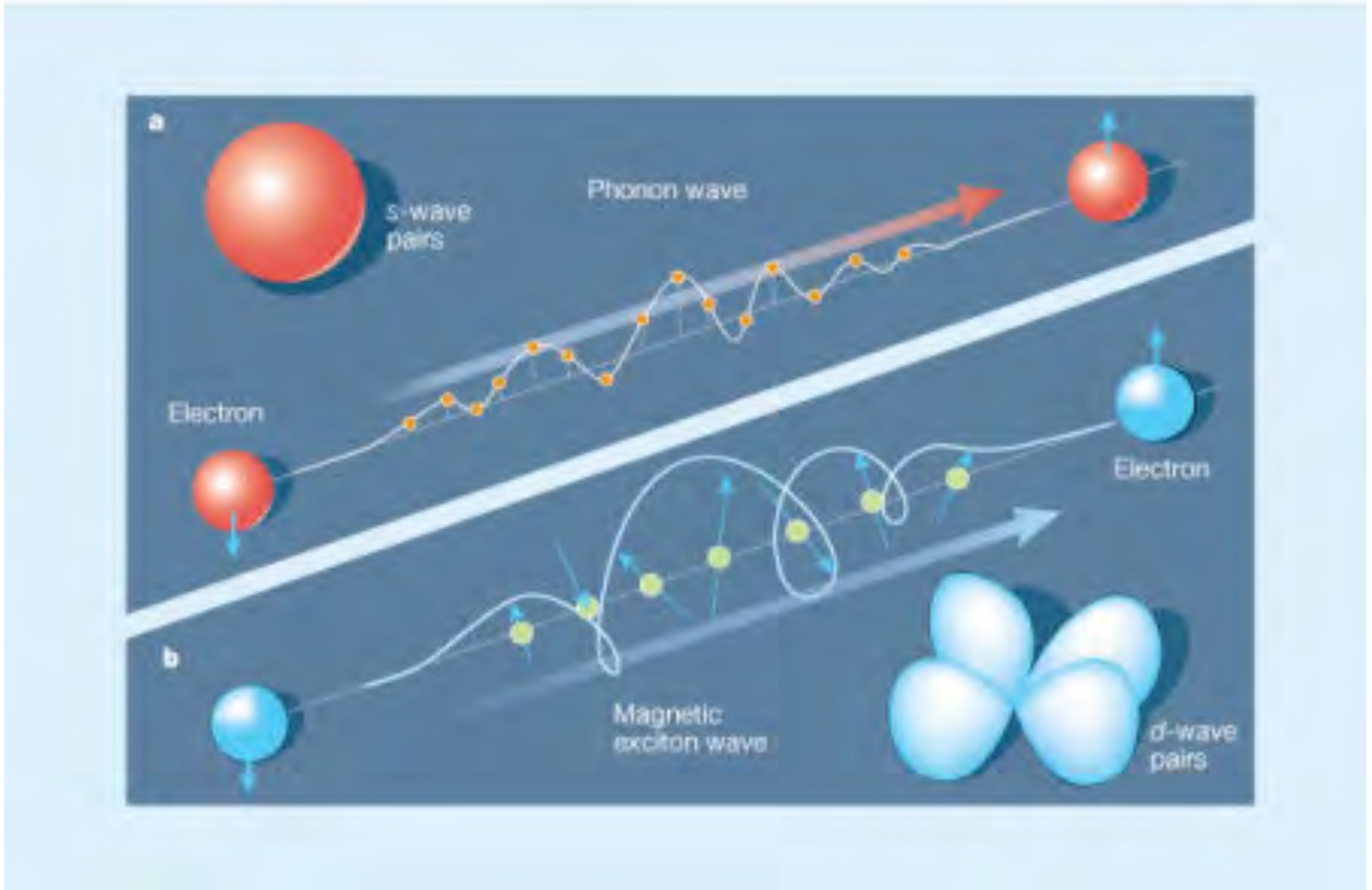
AFM -> d-wave pairing.



AFM -> d-wave pairing.



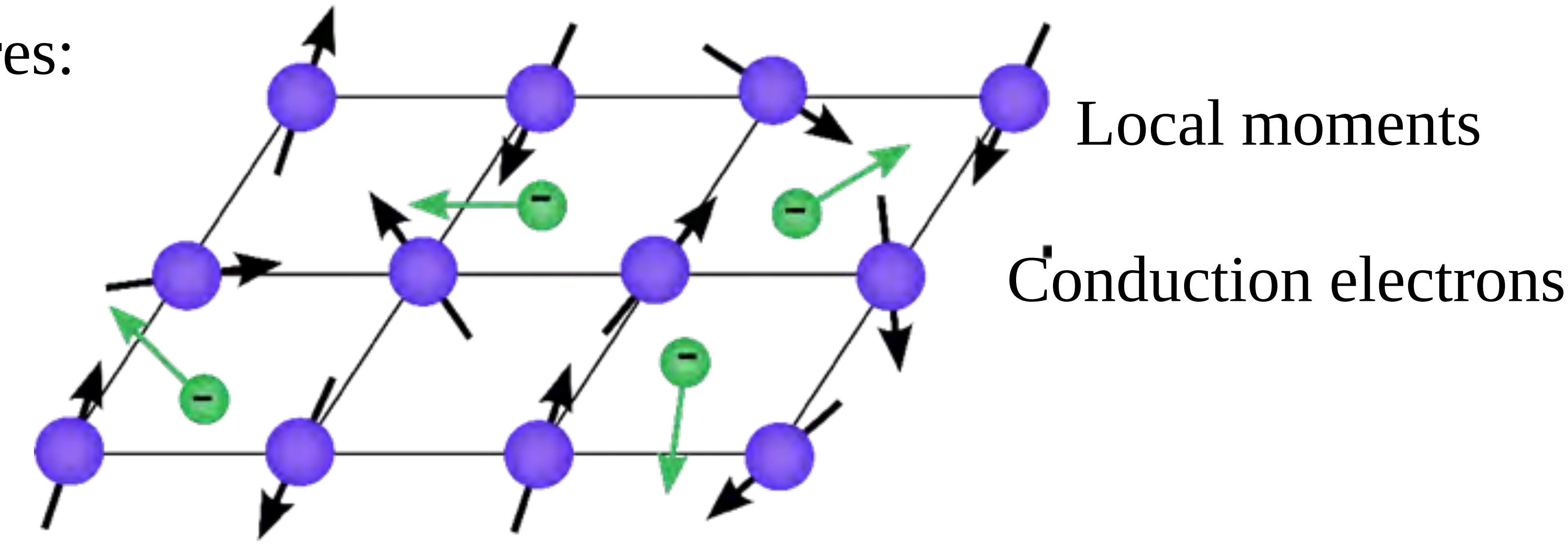
Beal-Monod, Bourbonnais and Emery (1986)
Scalapino, Loh and Hirsch (1986)
Miyake, Schmitt-Rink and Varma (1986)



Conventional
Heavy Fermion SC:

"Conventional" heavy fermion superconductivity

At high temperatures:



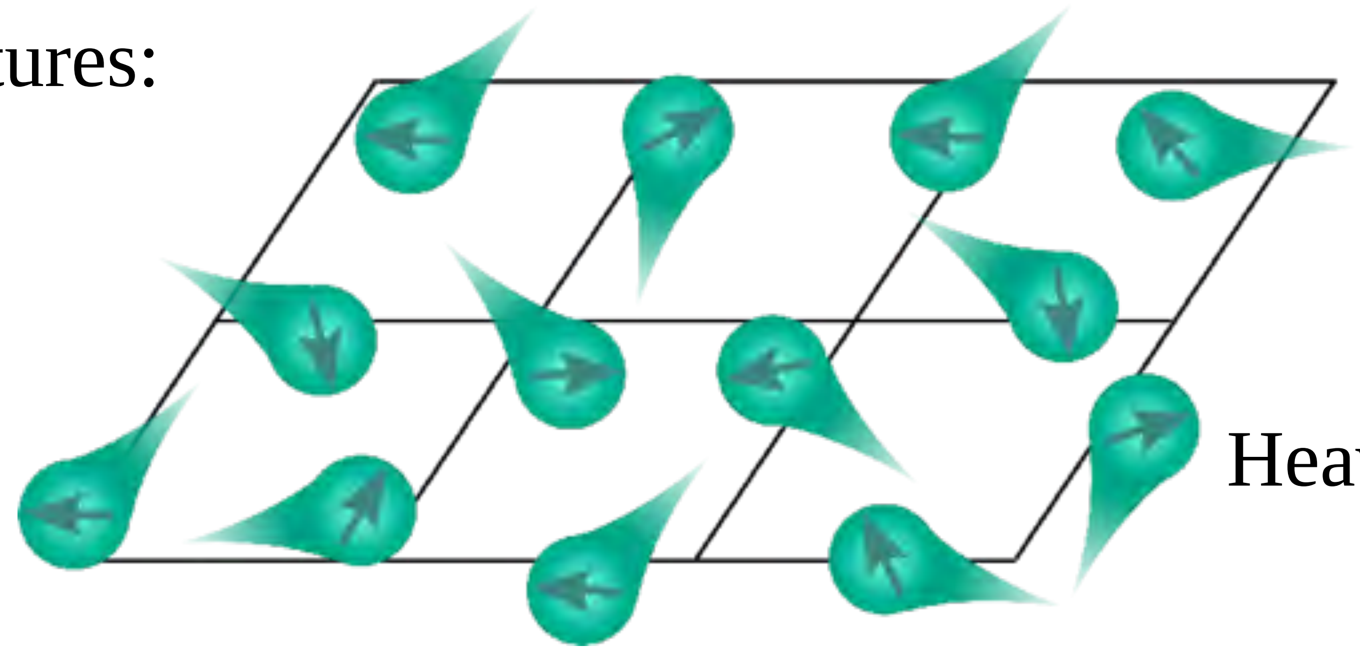
How do we get from here to heavy Cooper pairs?

Beal-Monod, Bourbonnais and Emery (1986)
Scalapino, Loh and Hirsch (1986)
Miyake, Schmitt-Rink and Varma (1986)

“Conventional” heavy fermion superconductivity

At lower temperatures:

$T < T^*$



Heavy quasiparticles

How do we get from here to heavy Cooper pairs?

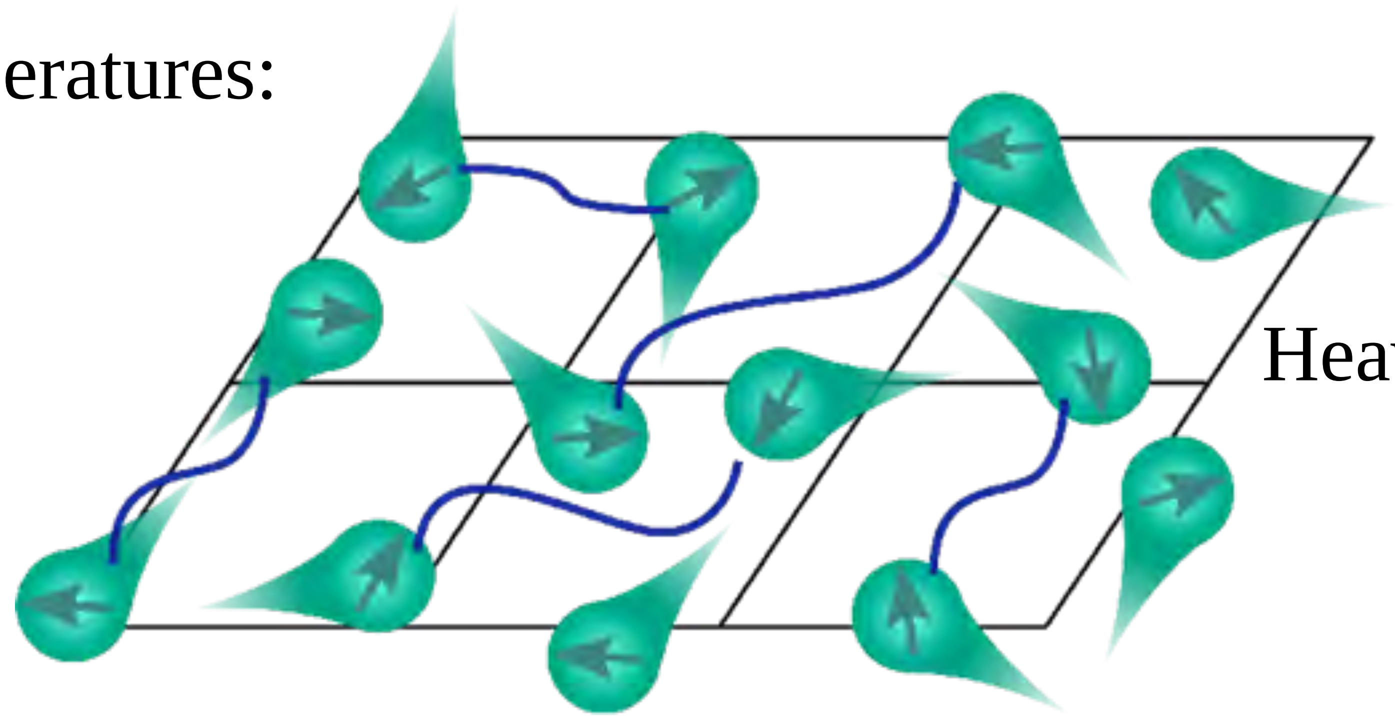
1. The local moments quench [via the Kondo effect], forming heavy quasiparticles

Beal-Monod, Bourbonnais and Emery (1986)
Scalapino, Loh and Hirsch (1986)
Miyake, Schmitt-Rink and Varma (1986)

“Conventional” heavy fermion superconductivity

At very low temperatures:

$T < T_C$



How do we get from here to heavy Cooper pairs?

1. The local moments quench [via the Kondo effect], forming heavy quasiparticles

2. The heavy quasiparticles pair [via residual spin fluctuations]

These two stages are well separated.

Beal-Monod, Bourbonnais and Emery (1986)
Scalapino, Loh and Hirsch (1986)
Miyake, Schmitt-Rink and Varma (1986)

SP(N)

But what about Superconductivity?

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Frustrated magnetism: pairing of spinons SP(N).

Read and Sachdev, PRL, 66, 1773 (1991)

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Rutgers NHETC.

PC: why don't you ever use the group SP(N)?

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SU(N): *Mesons* *Baryons*

$\bar{q}q$ $q_1 q_2 \cdots q_N$

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	$\bar{q}q$	$q_1 q_2 \cdots q_N$
		Cooper pairs
SP(N):	$\bar{q}q$	$q_a q_{-a}$

But what about Superconductivity?

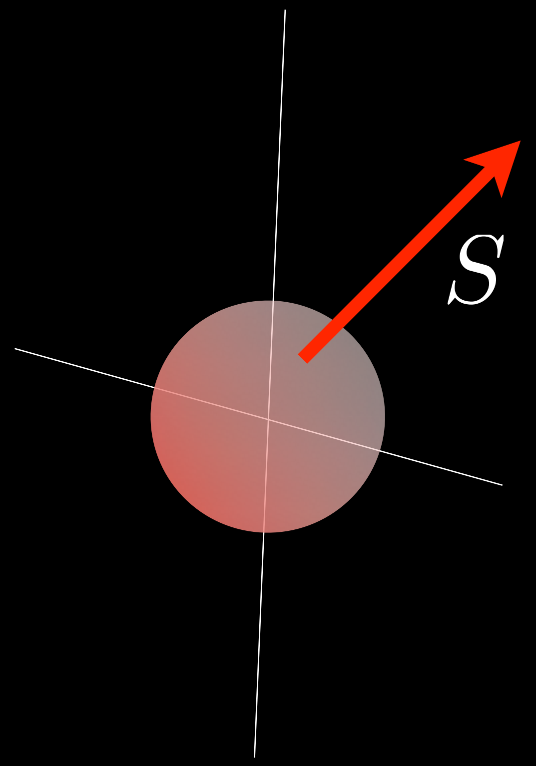
Frustrated magnetism: pairing of spinons SP(N).
Read and Sachdev, PRL, 66, 1773 (1991)

"Symplectic Large N" R. Flint and PC '08

$$S^{ba} = f_b^\dagger f_a - \text{sgn}(a)\text{sgn}(b) f^\dagger_{-b} f_{-a}$$

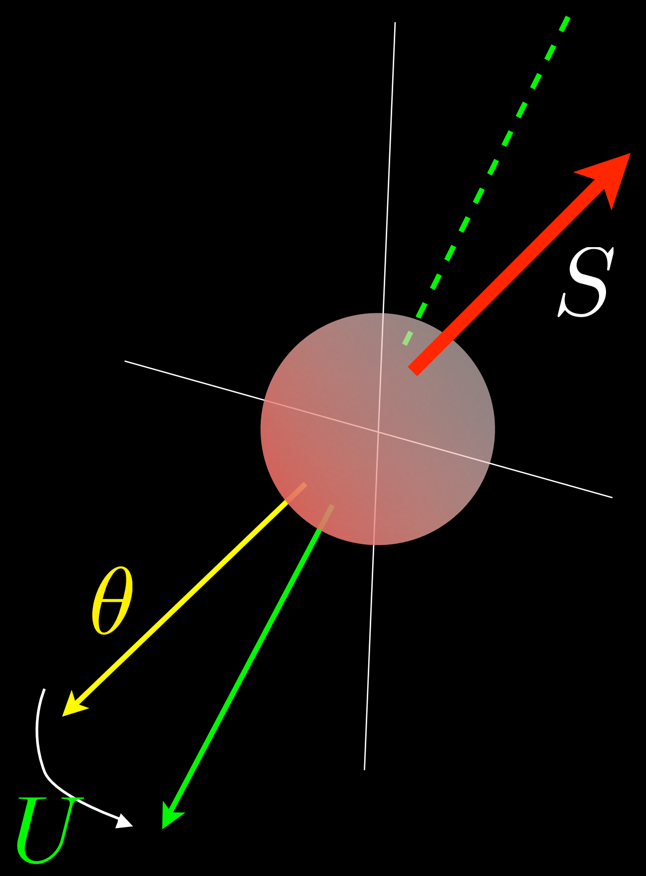
SU(N):	*Mesons*	*Baryons*
	$\bar{q}q$	$q_1 q_2 \cdots q_N$
		Cooper pairs
SP(N):	$\bar{q}q$	$q_a q_{-a}$

The Sympectic symmetry of spin



The Sympectic symmetry of spin

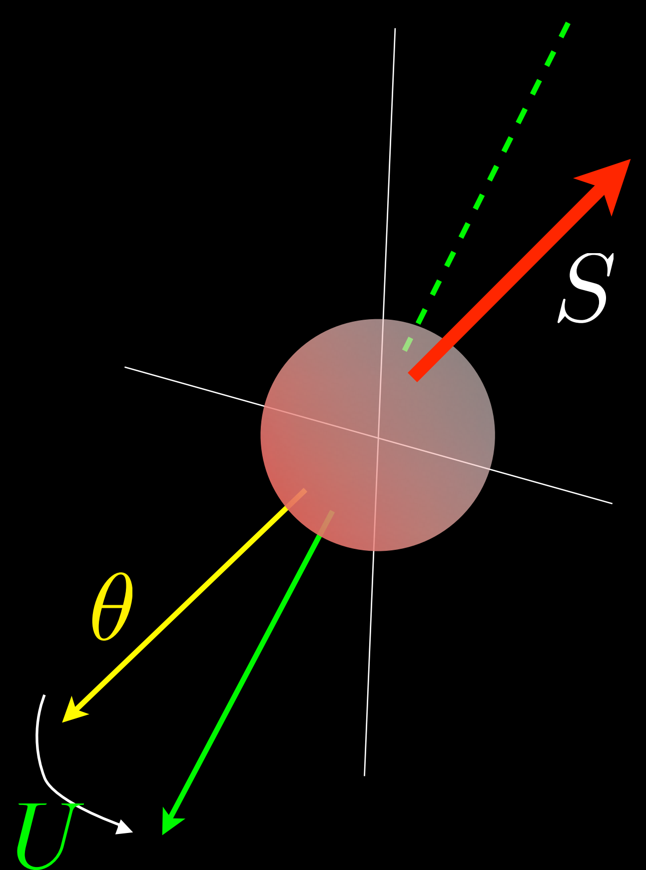
Rotation x time reversal



$$S \xrightarrow{U\theta} \underline{R}(-S)$$

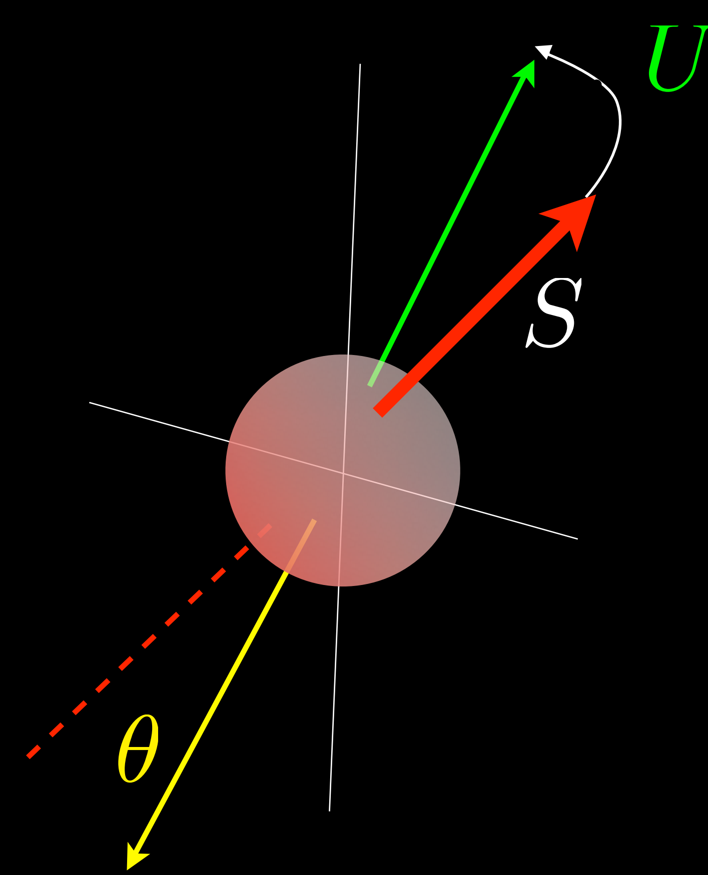
The Sympectic symmetry of spin

Rotation x time reversal



$$S \xrightarrow{U\theta} \underline{R}(-S)$$

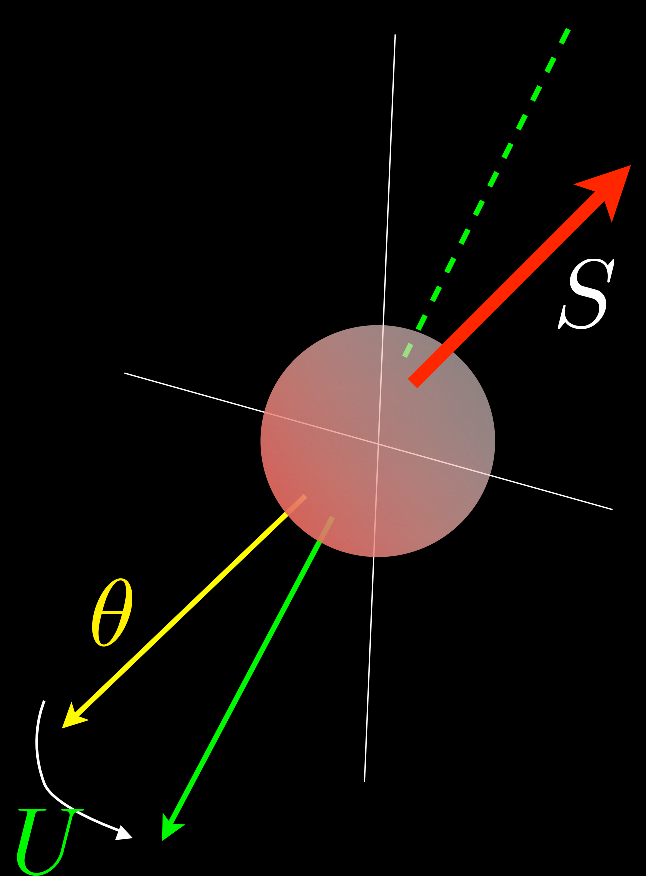
Time reversal x rotation



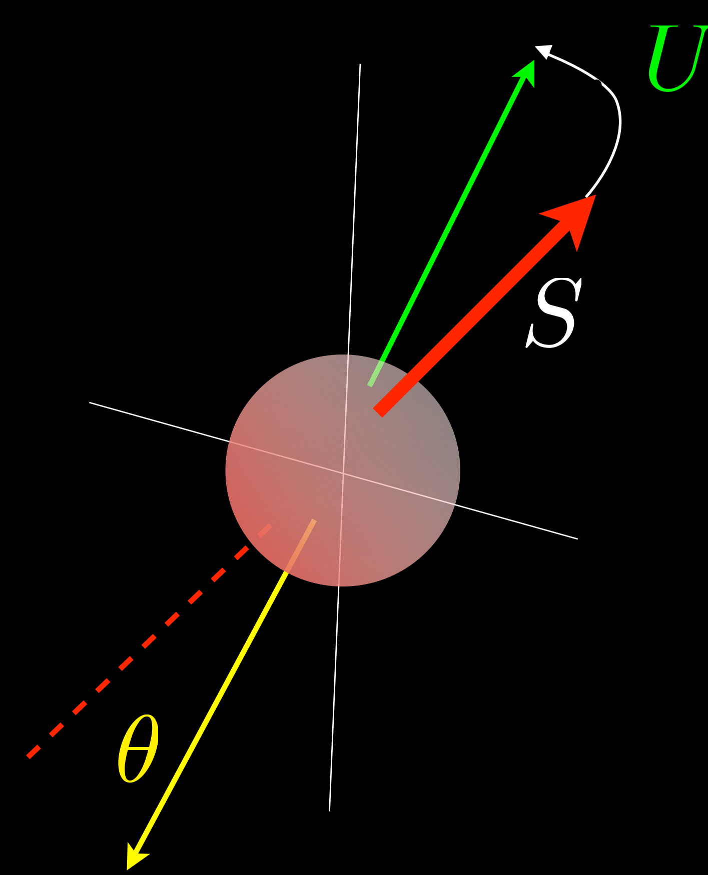
$$S \xrightarrow{\theta U} -(\underline{R}S)$$

The Sympectic symmetry of spin

Rotation x time reversal = Time reversal x rotation



$$S \xrightarrow{U\theta} \underline{R}(-S)$$

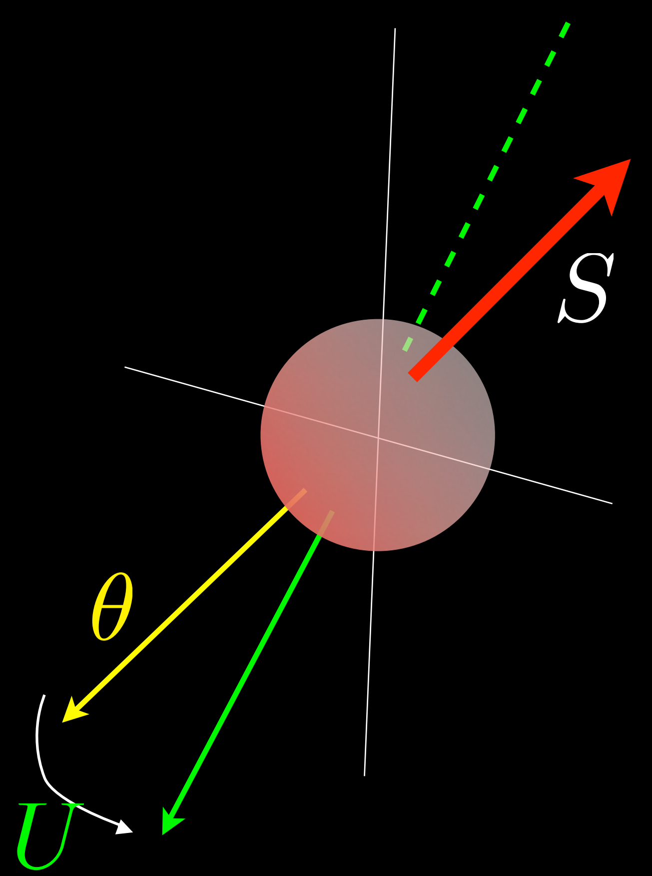


$$S \xrightarrow{\theta U} -(\underline{R}S)$$

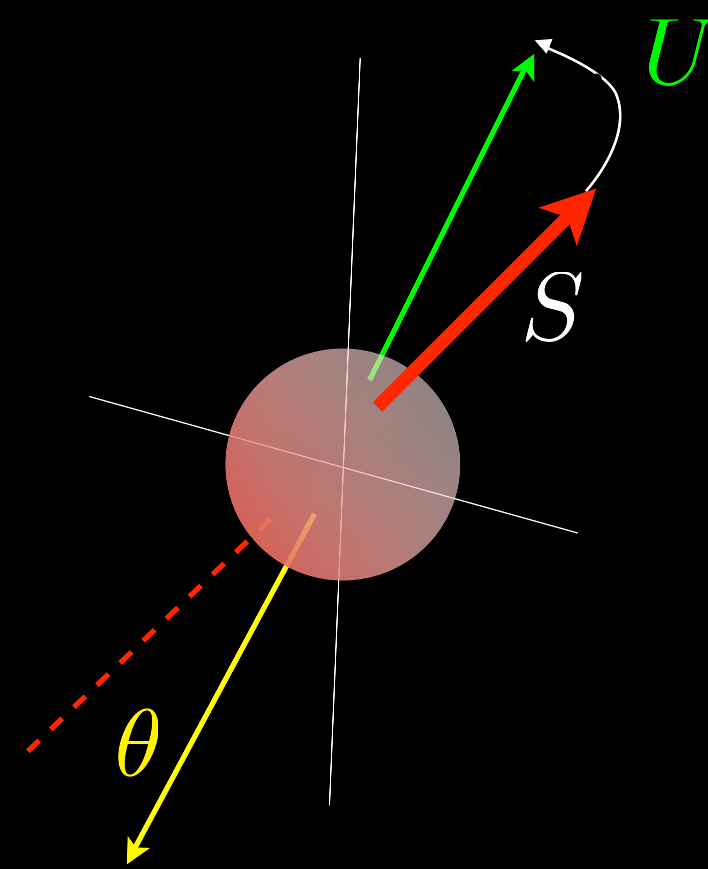
The Sympectic symmetry of spin

Rotation x time reversal = Time reversal x rotation

$$U\theta = \theta U$$



$$S \xrightarrow{U\theta} \underline{R}(-S)$$



$$S \xrightarrow{\theta U} -(\underline{R}S)$$

The Sympectic symmetry of spin

Rotation x time reversal = Time reversal x rotation

$$U\theta = \theta U$$

So that:

$$U\theta U^{\dagger} = \theta$$

The Sympectic symmetry of spin

Rotation x time reversal = Time reversal x rotation

$$U\theta = \theta U$$

So that:

$$U\theta U^\dagger = \theta$$

$$\theta = i\sigma_2 \times K$$

Antiunitary operator

The Sympectic symmetry of spin

Rotation x time reversal = Time reversal x rotation

$$U\theta = \theta U$$

So that:

$$U\theta U^\dagger = \theta$$

$$\theta = i\sigma_2 \times K$$

Antiunitary operator

$$U i\sigma_2 U^T = i\sigma_2$$

SYMPLECTIC CONDITION

N-component Symplectic spin operator: generator of SP(N)

$$S_{\alpha\beta} = f^\dagger_\alpha f_\beta - \tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha}$$

$n_f = N/2$

N-component Symplectic spin operator: generator of SP(N)

$$S_{\alpha\beta} = f^\dagger_\alpha f_\beta - \tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha}$$

$$n_f = N/2$$

$$[S, \tilde{\alpha} f_\alpha f_{-\alpha}] = 0$$

Singlet pair commutes with symplectic spin

N-component Symplectic spin operator: generator of SP(N)

$$S_{\alpha\beta} = f^\dagger_\alpha f_\beta - \tilde{\alpha}\tilde{\beta} f^\dagger_{-\beta} f_{-\alpha}$$

$$n_f = N/2$$

$$[S, \tilde{\alpha} f_\alpha f_{-\alpha}] = 0$$

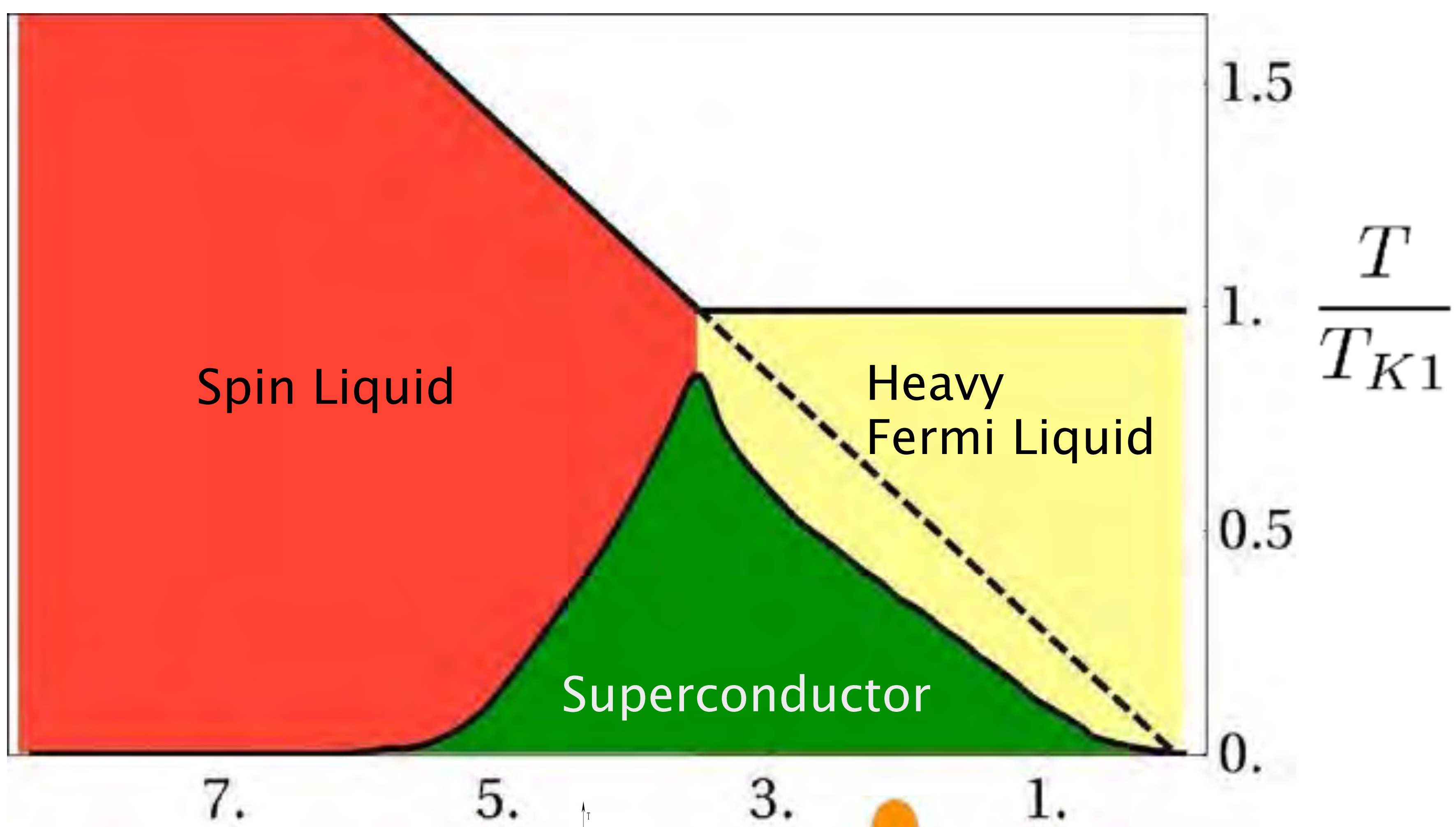
$$[\tilde{\alpha} f_\alpha f_{-\alpha}, S] = 0$$

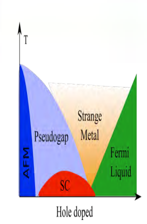
Singlet pair commutes with symplectic spin

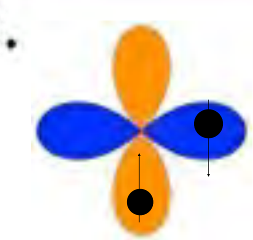
→ Local SU(2) gauge symmetry.

Magnetic Pairing: the Kondo–Heisenberg model

$$H = \sum_k \epsilon_k c_k^\dagger c_k + J_1 \sum_j \psi_{1j\alpha}^\dagger \vec{\sigma}_{\alpha\beta} \psi_{1j\beta} \cdot \vec{S}_j + J_H \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

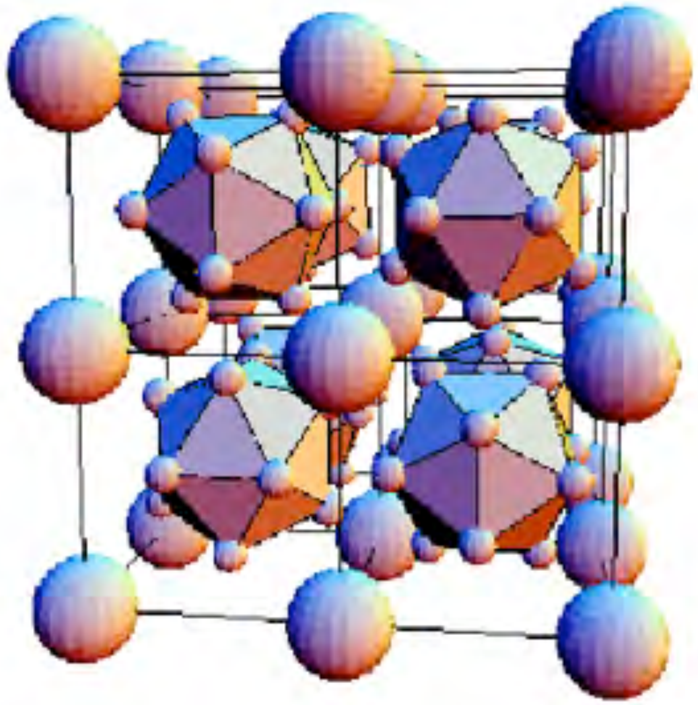




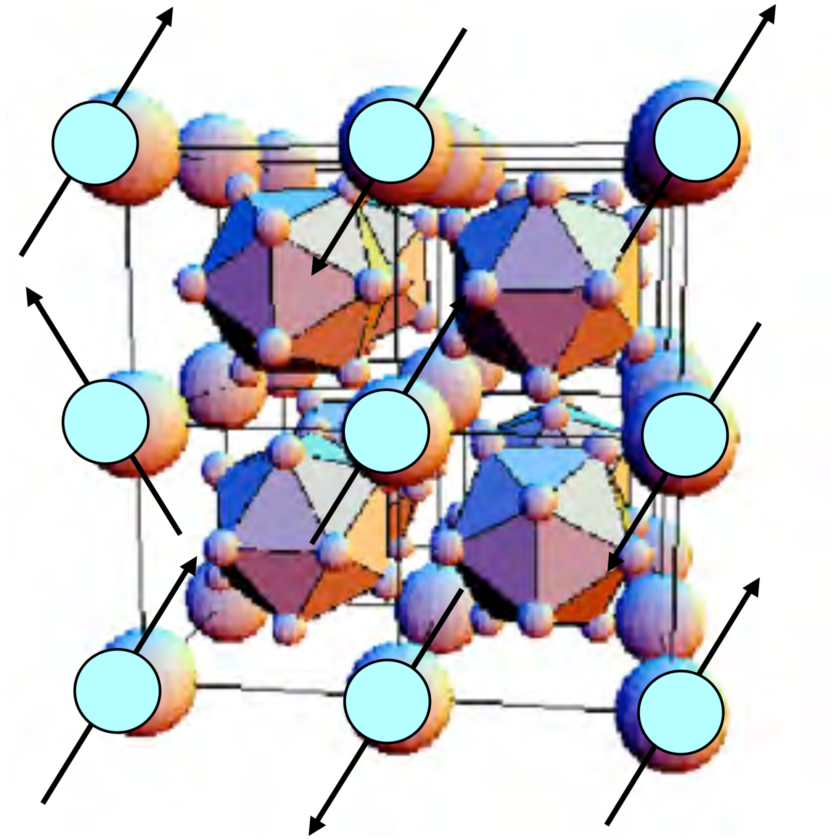


Andrei and Coleman 1989

Heavy Fermion SC: Bad and Ugly

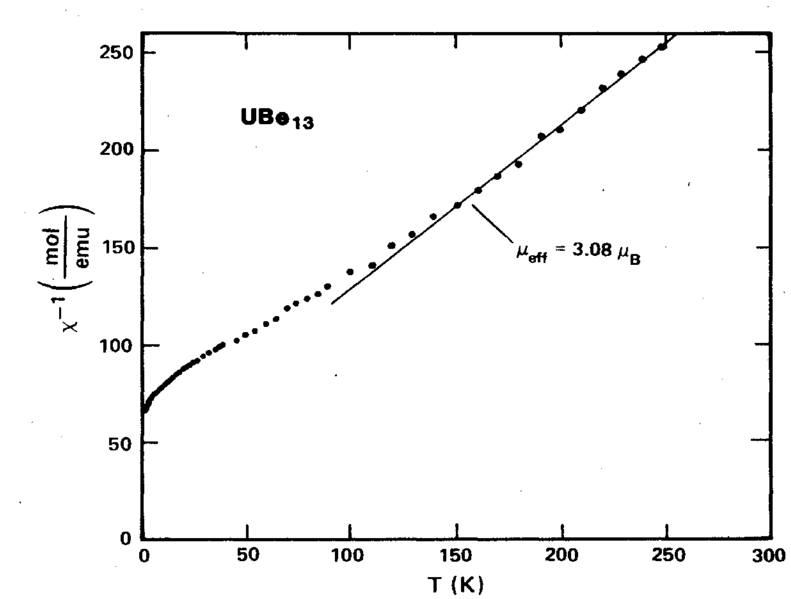


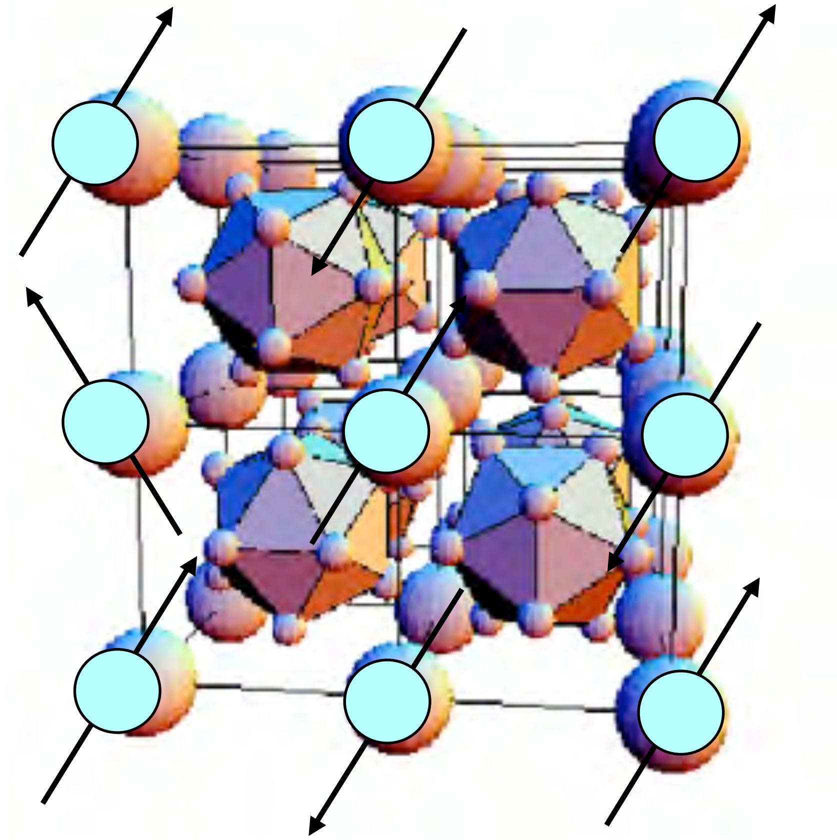
UBe_{13}



UBe_{13}

Local Moments

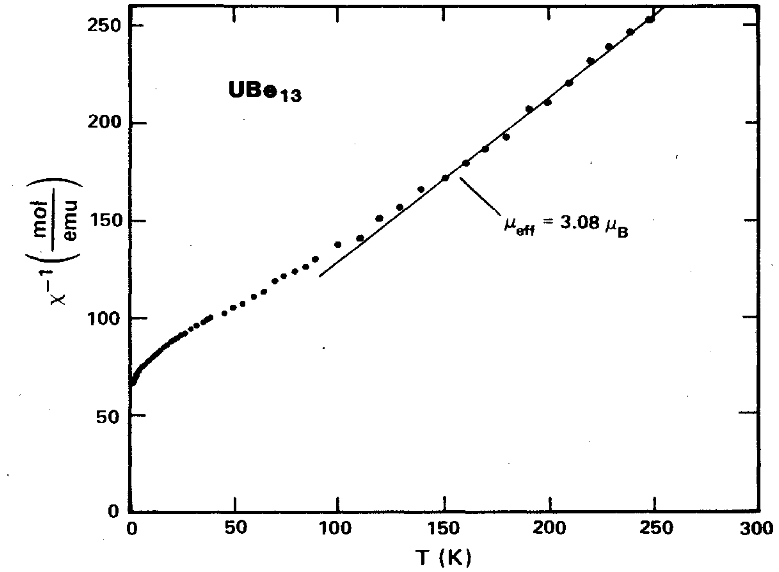


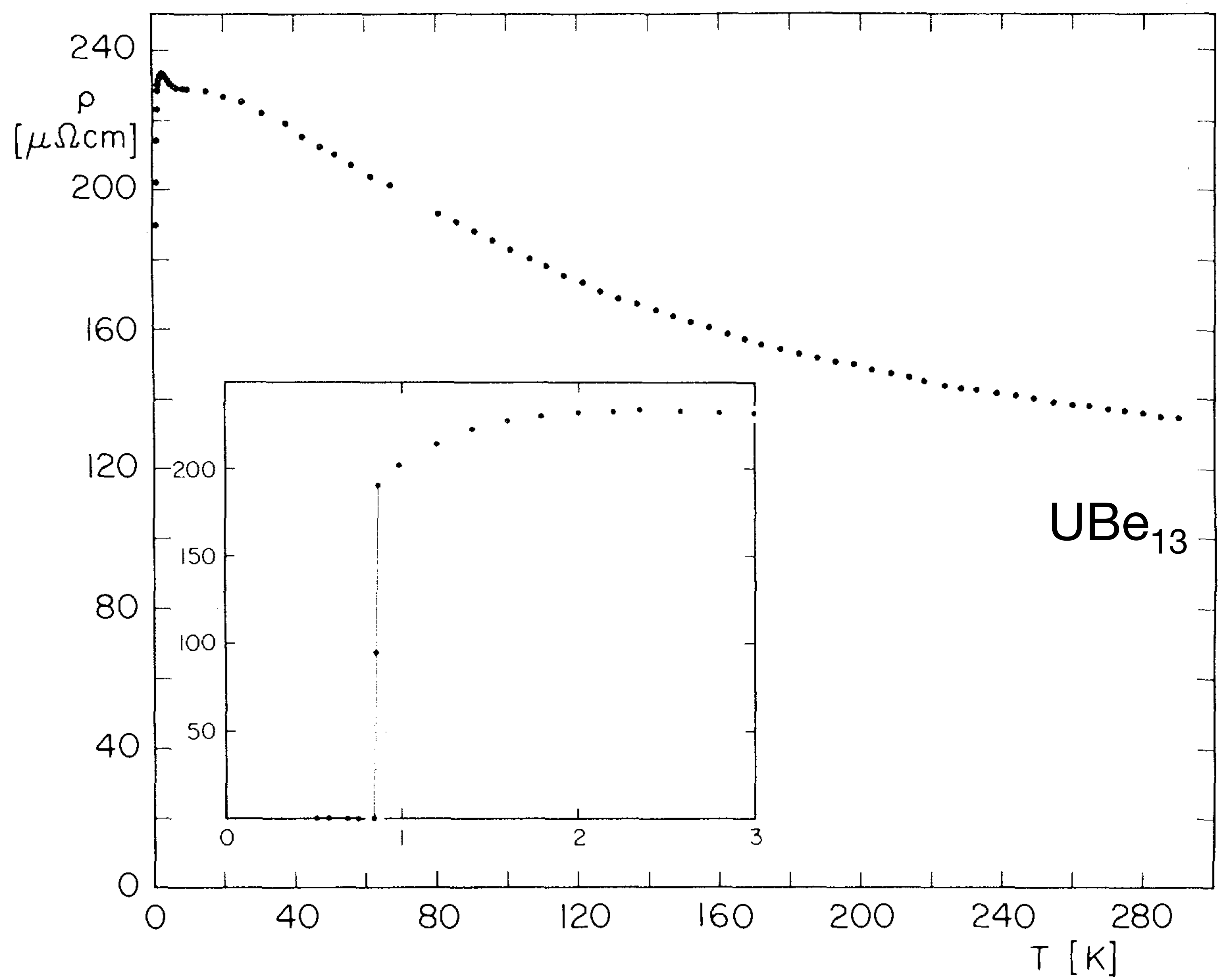


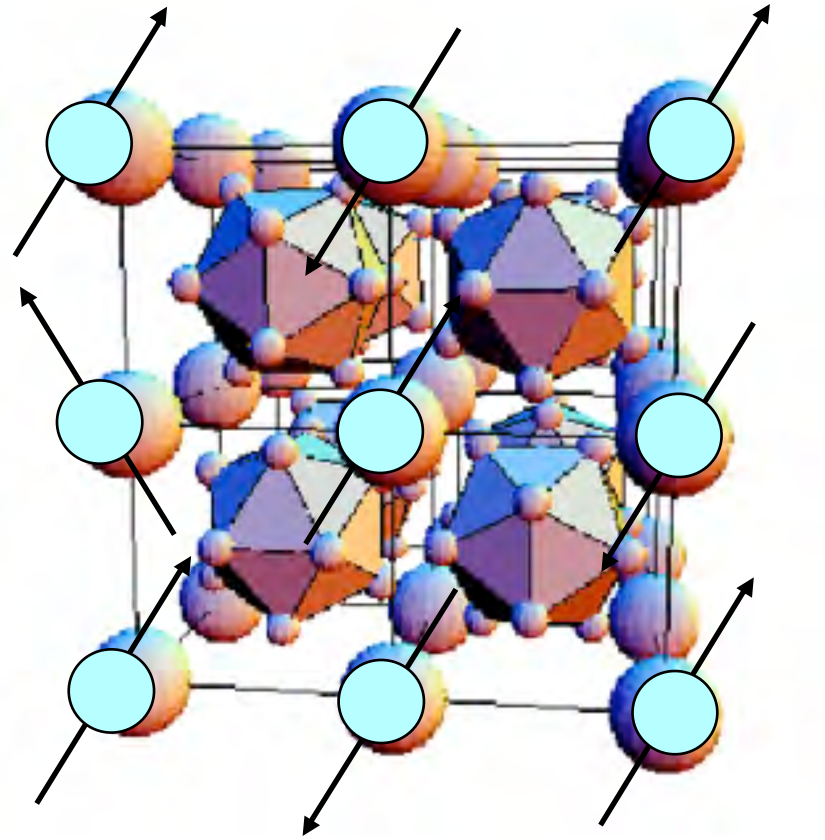
UBe$_{13}$

Local Moments

Ott, Fisk, Smith (198







UBe$_{13}$

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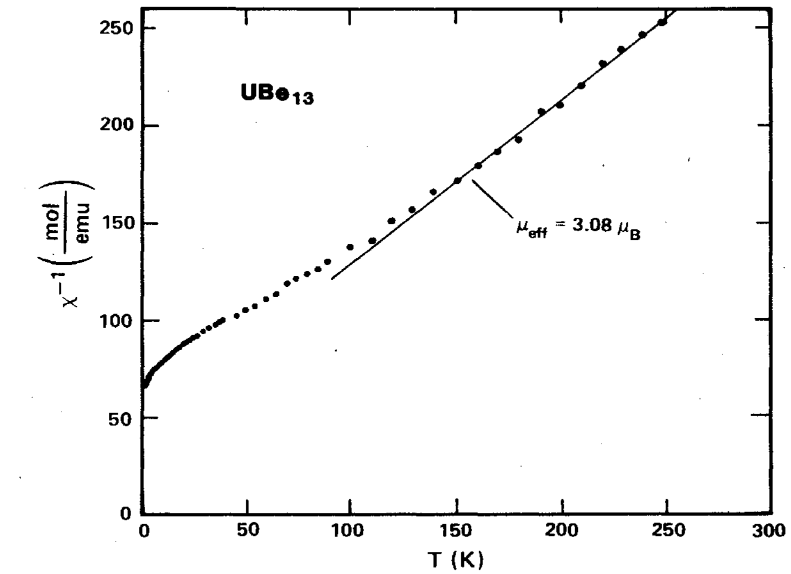

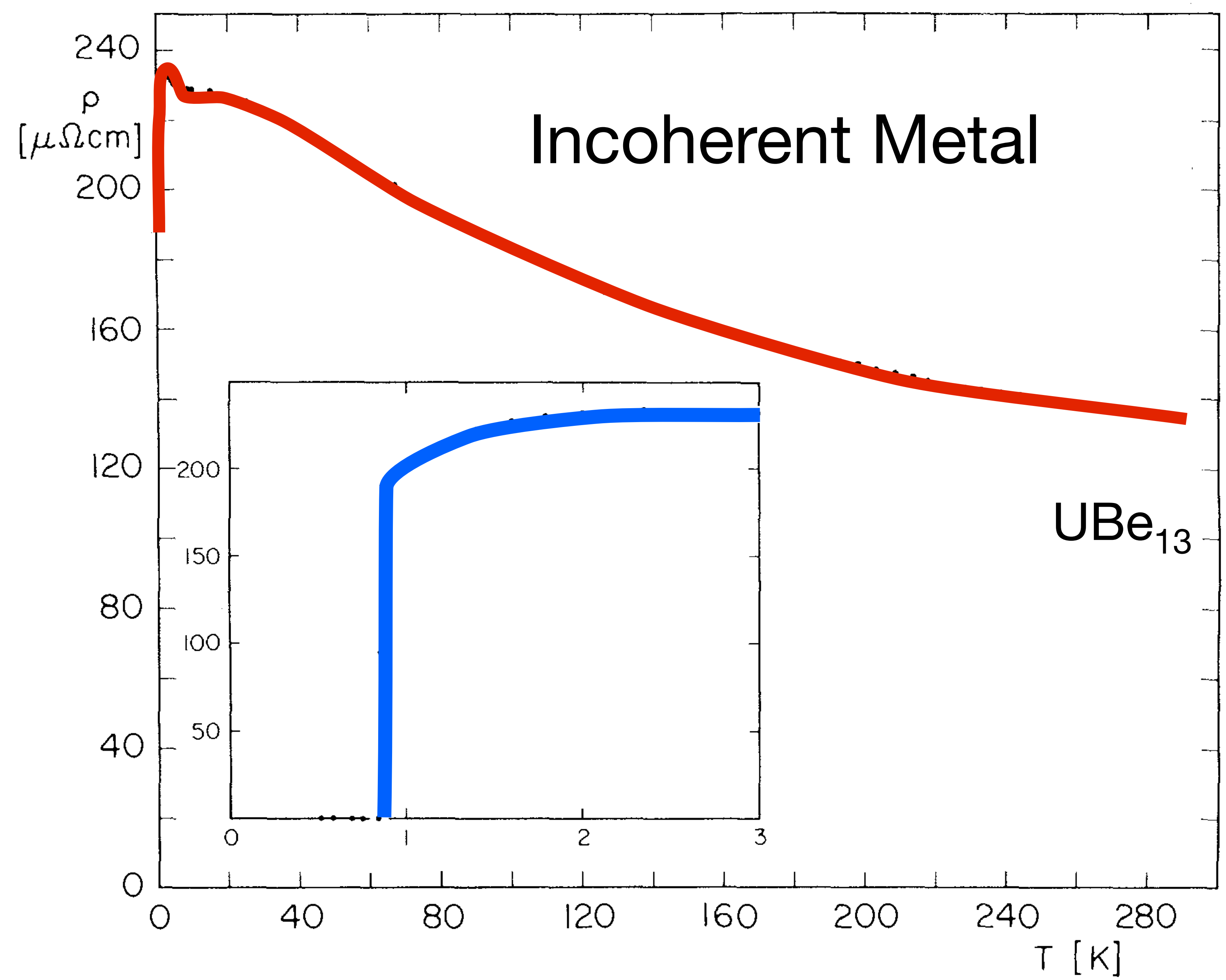

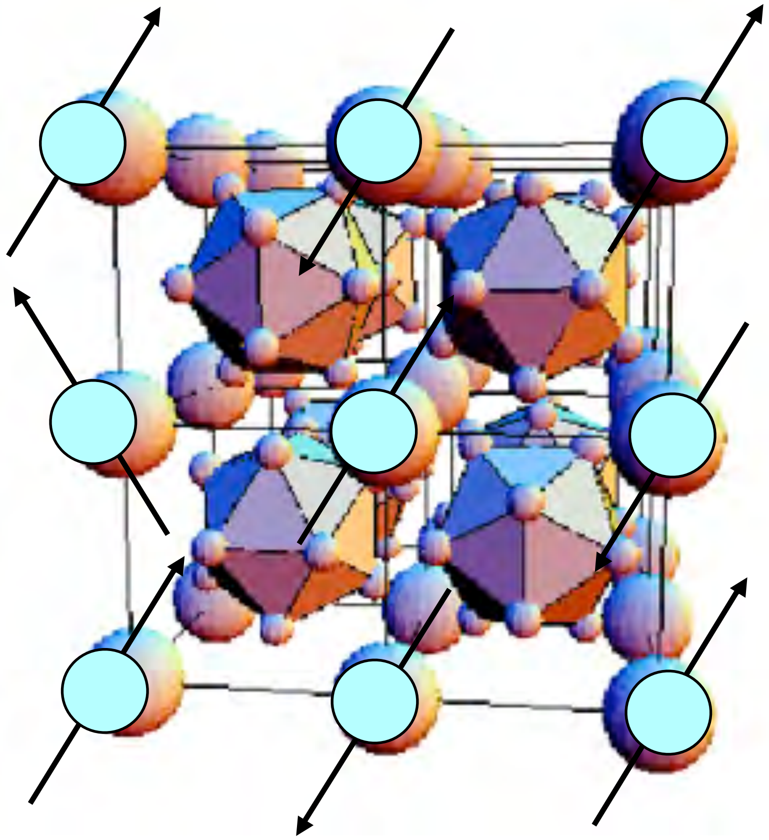

UBe_{13}

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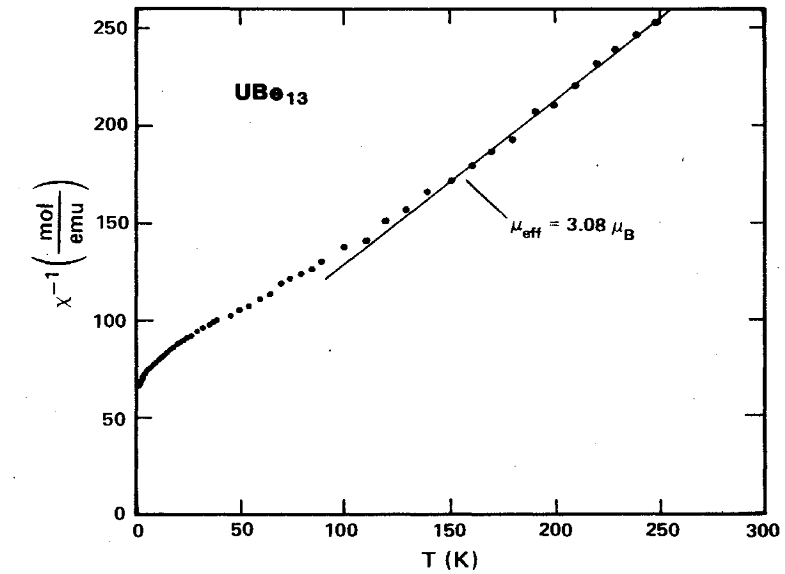
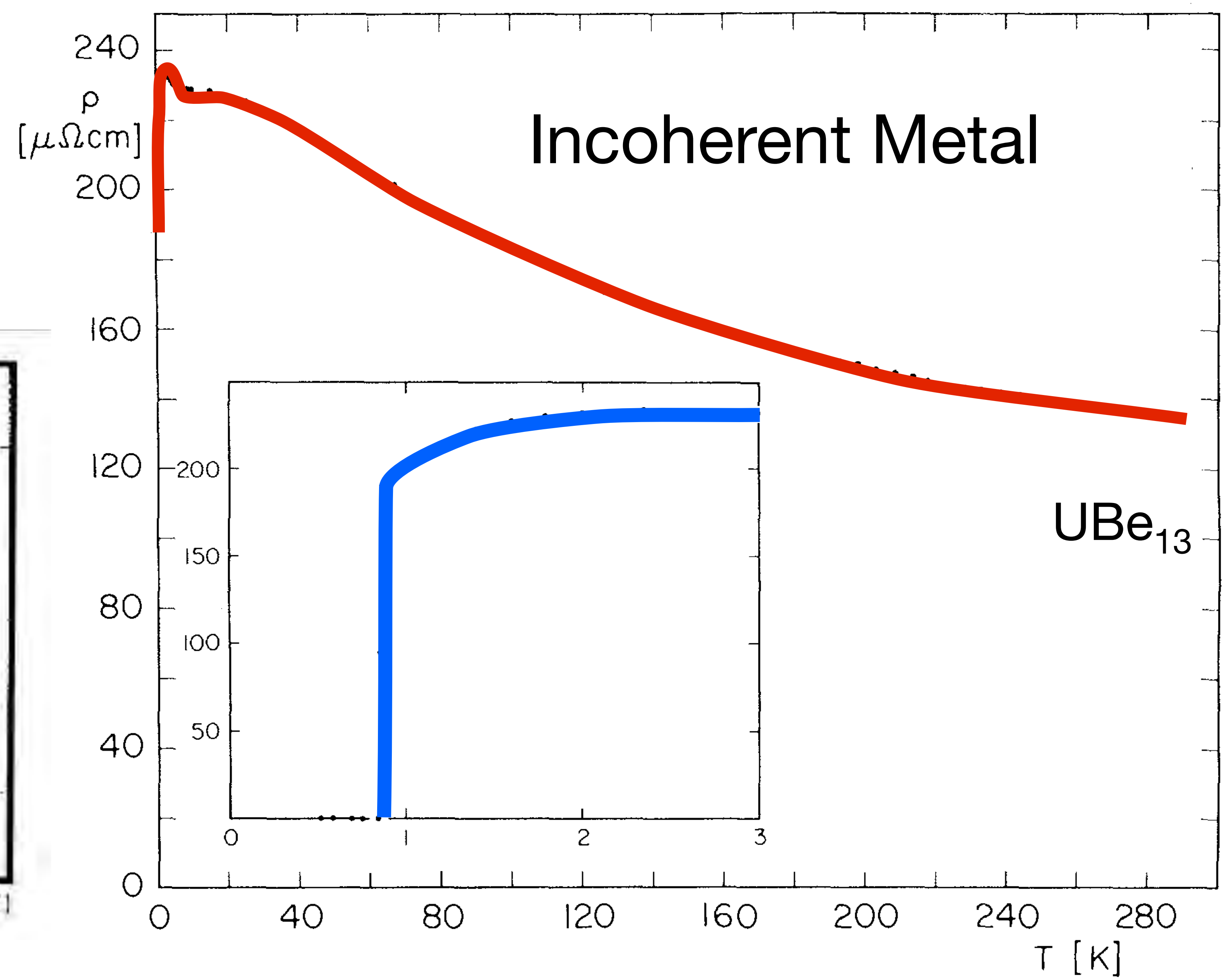
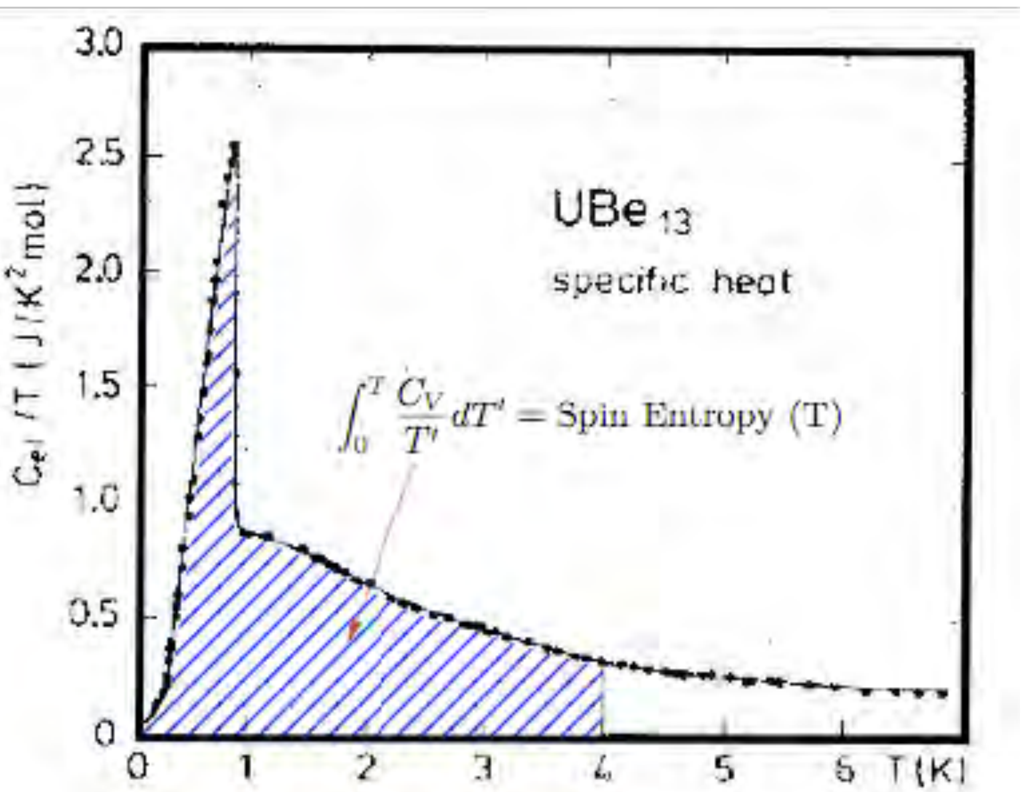




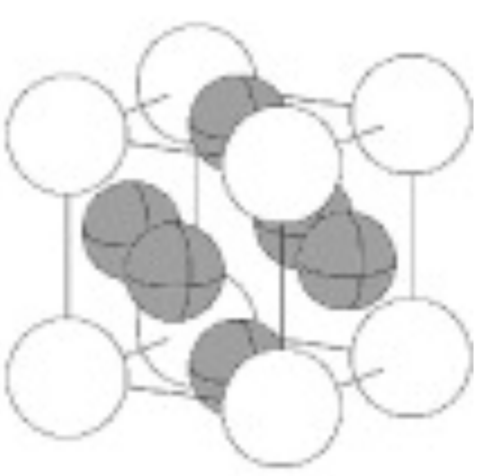


Ott et al, (1983)

“115” Family

1K

CeIn3



0.1K

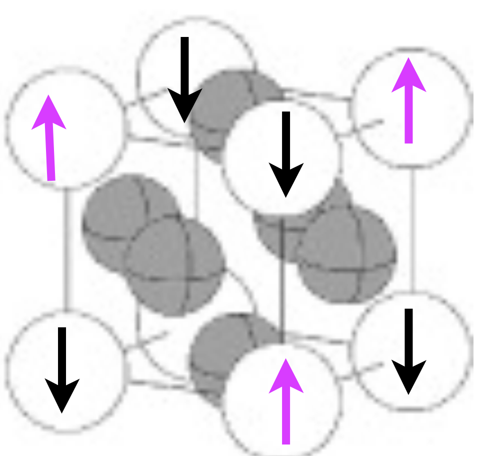
“115” Family

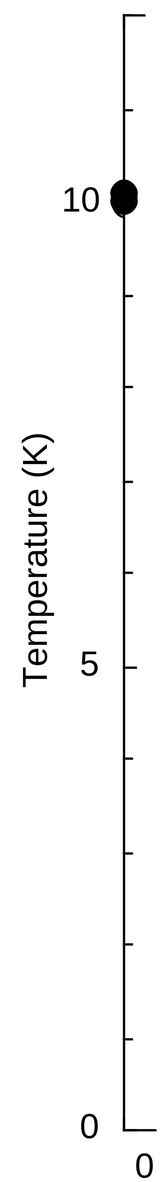
1K

0.1K

CeIn3

10K AFM

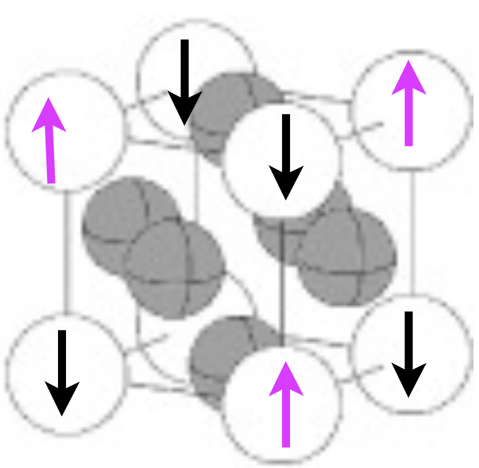


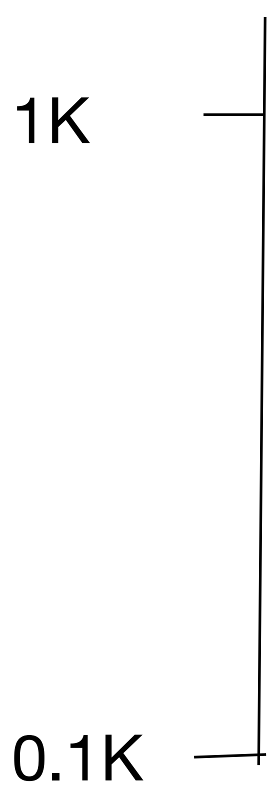


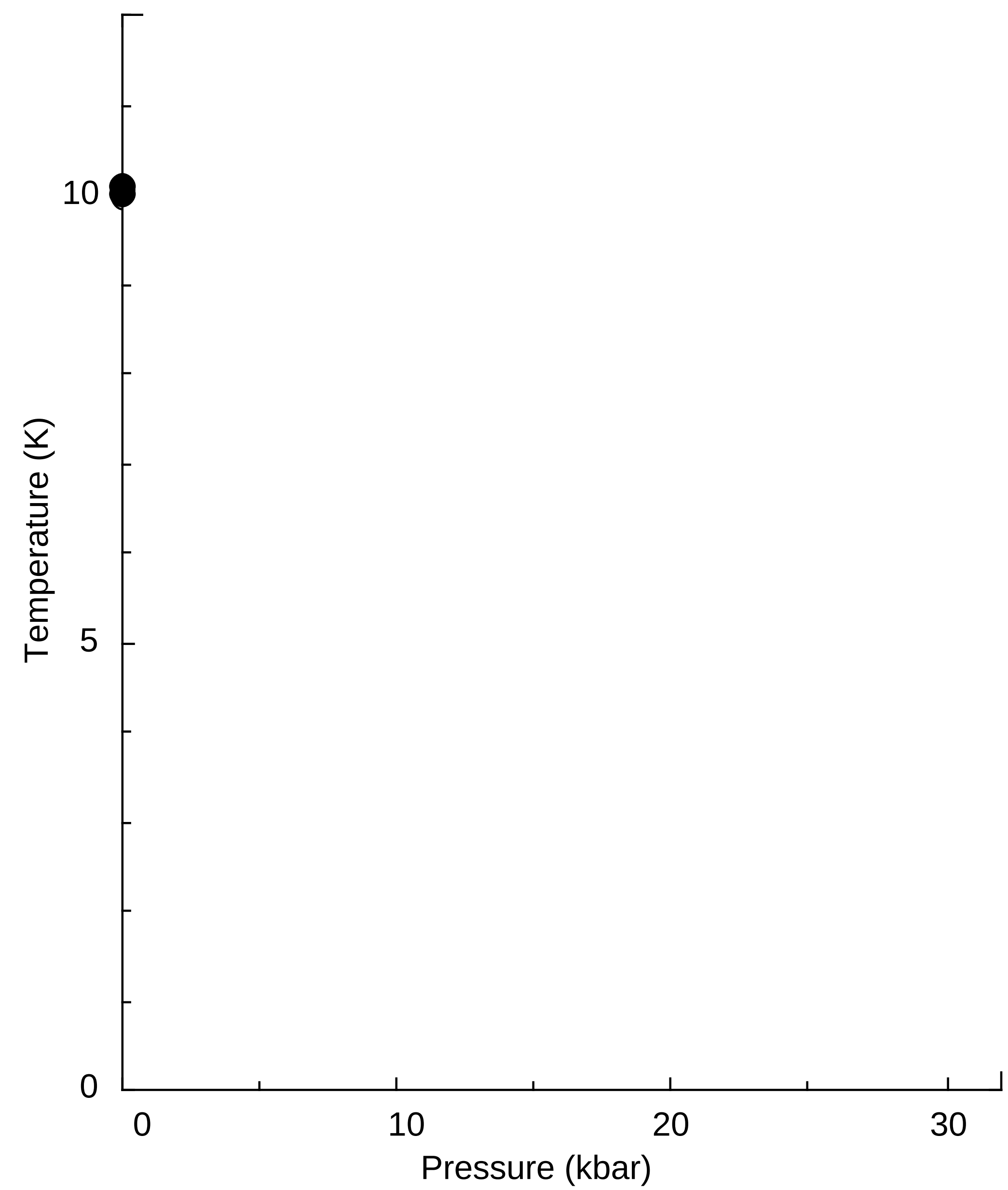
“115” Family

CeIn3

10K AFM







“115” Family

1K

CeIn3

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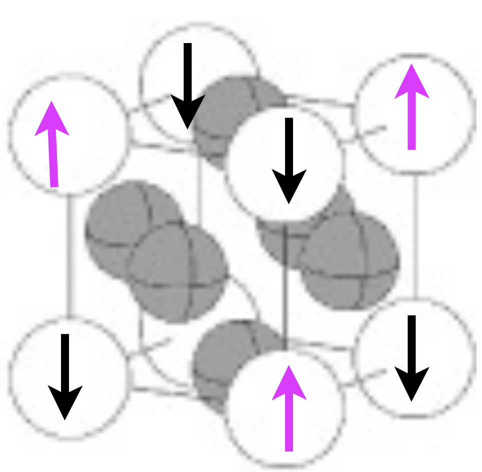
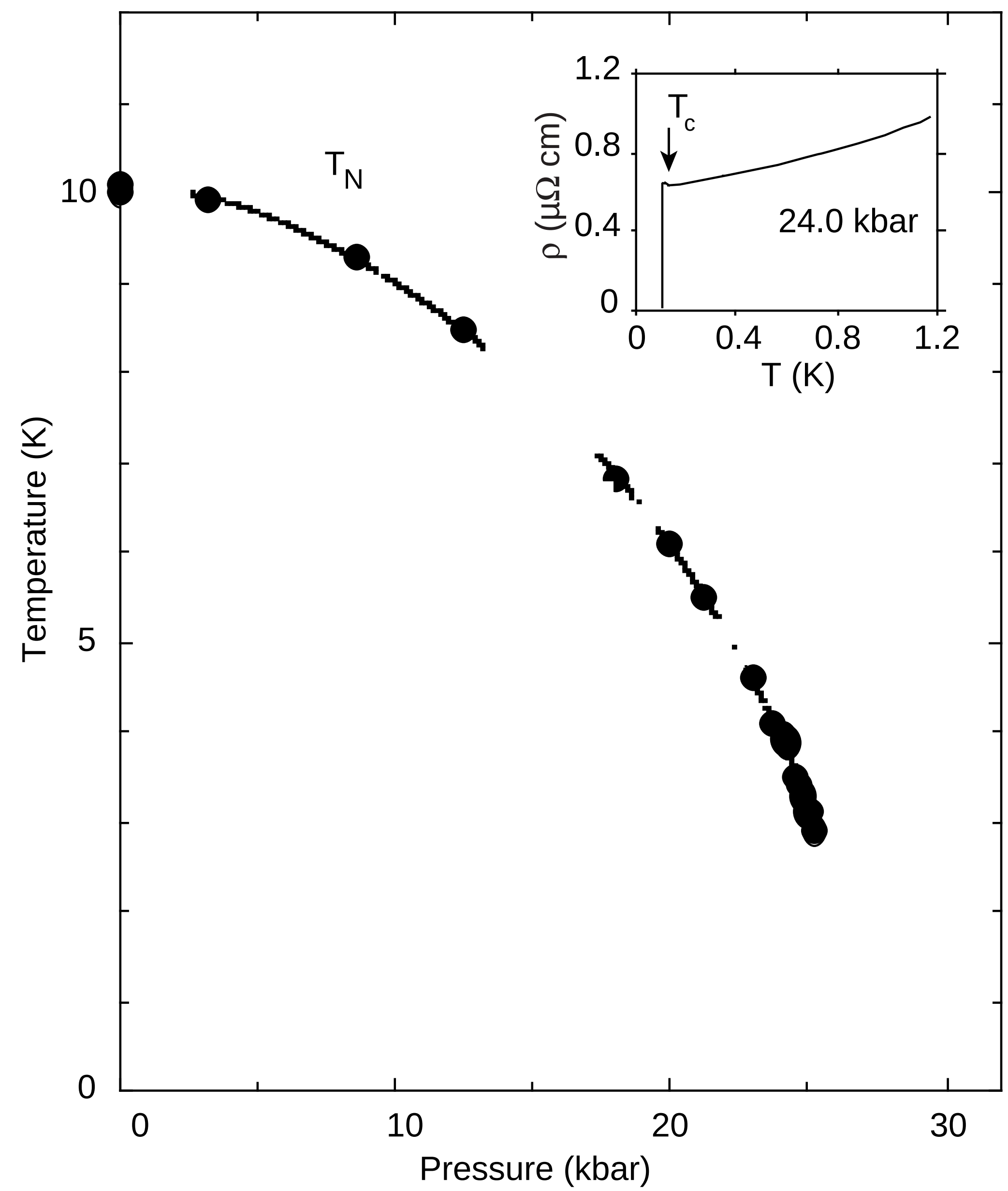


0.1K

Mathur, Lonzarich et al (1998)



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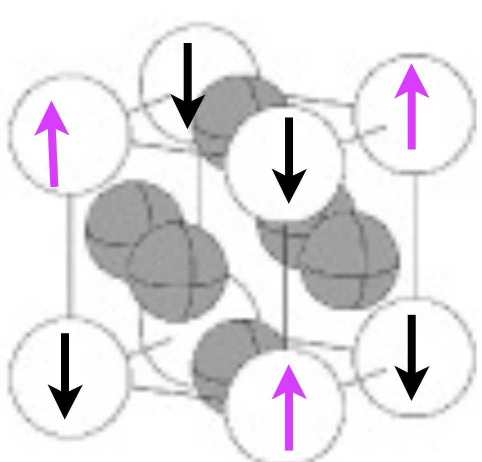
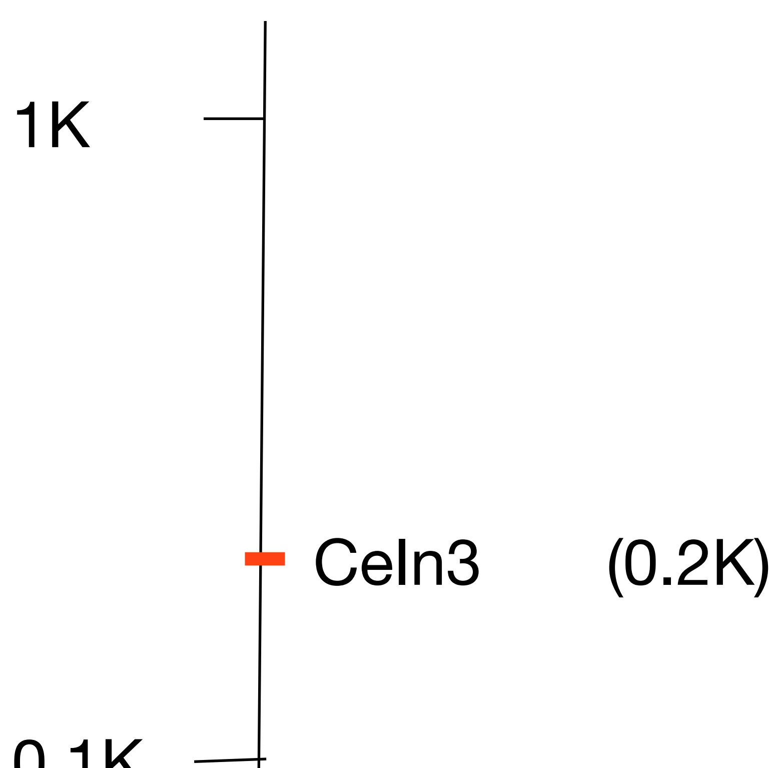
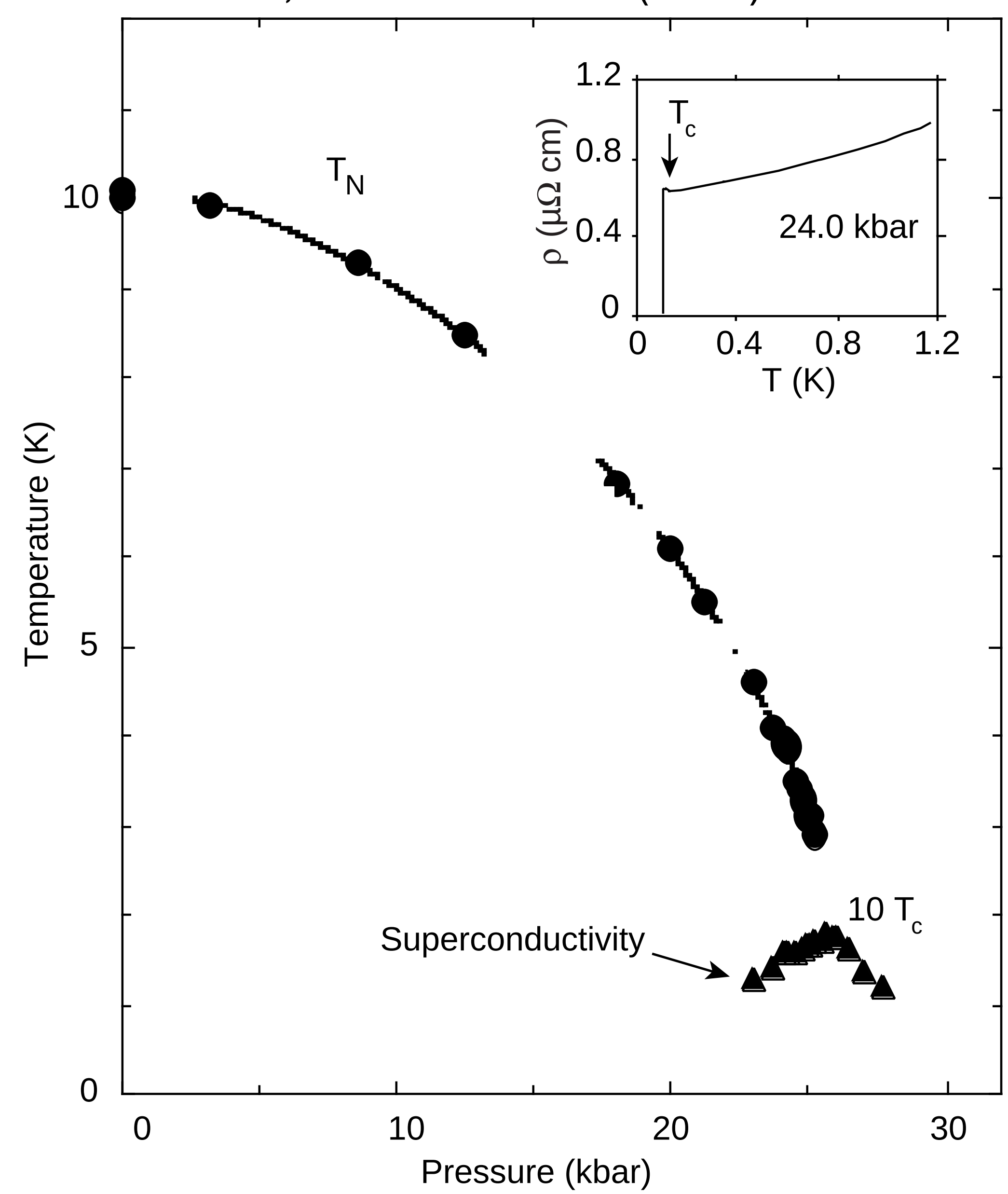
10K AFM





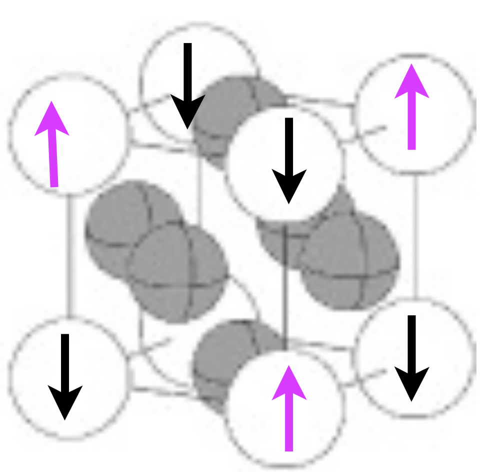
Mathur, Lonzarich et al (1998)

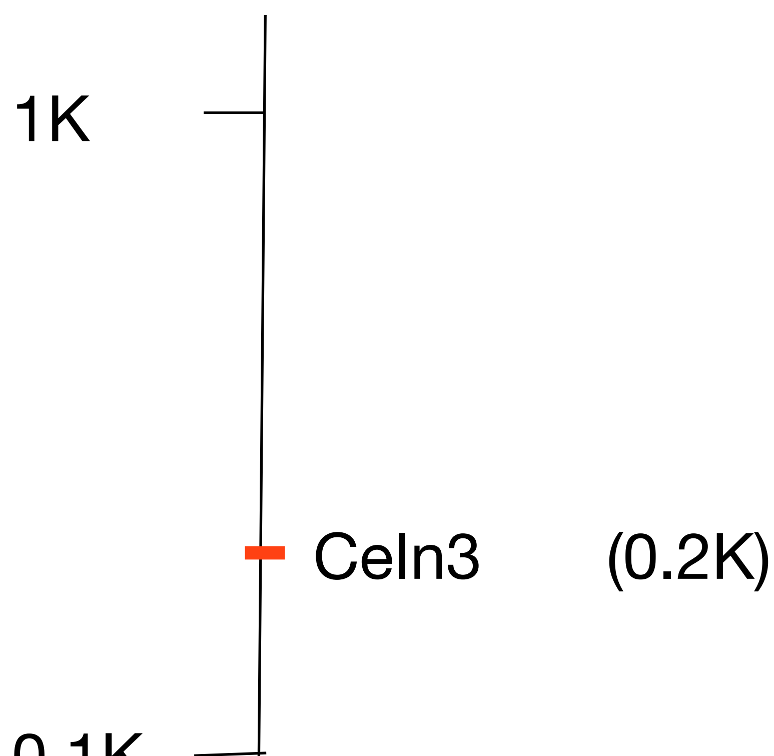


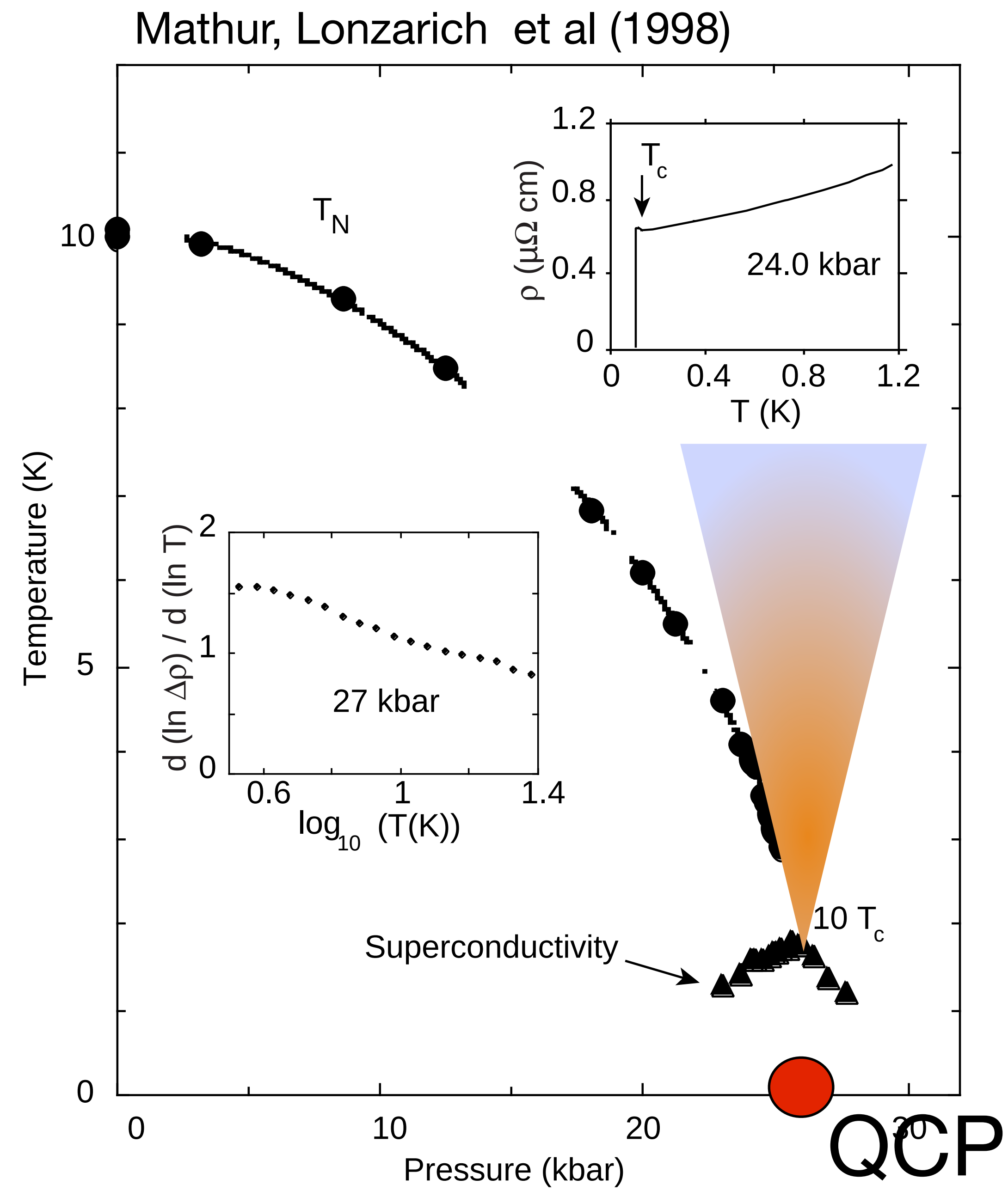
“115” Family

CeIn3

10K AFM



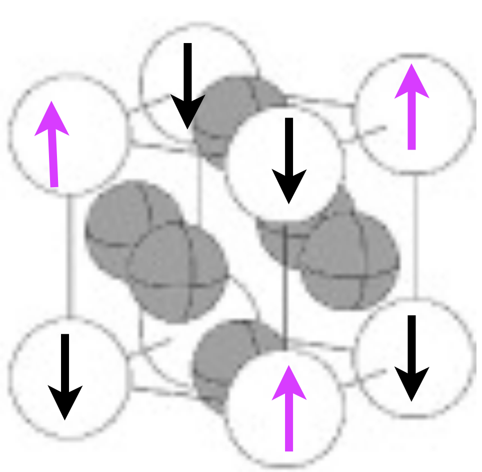


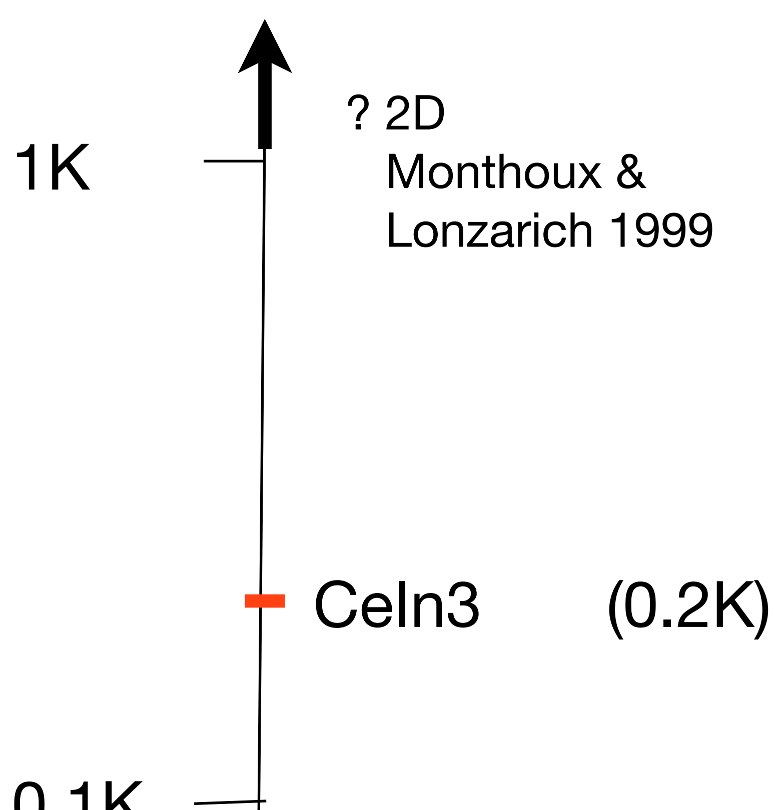


“115” Family

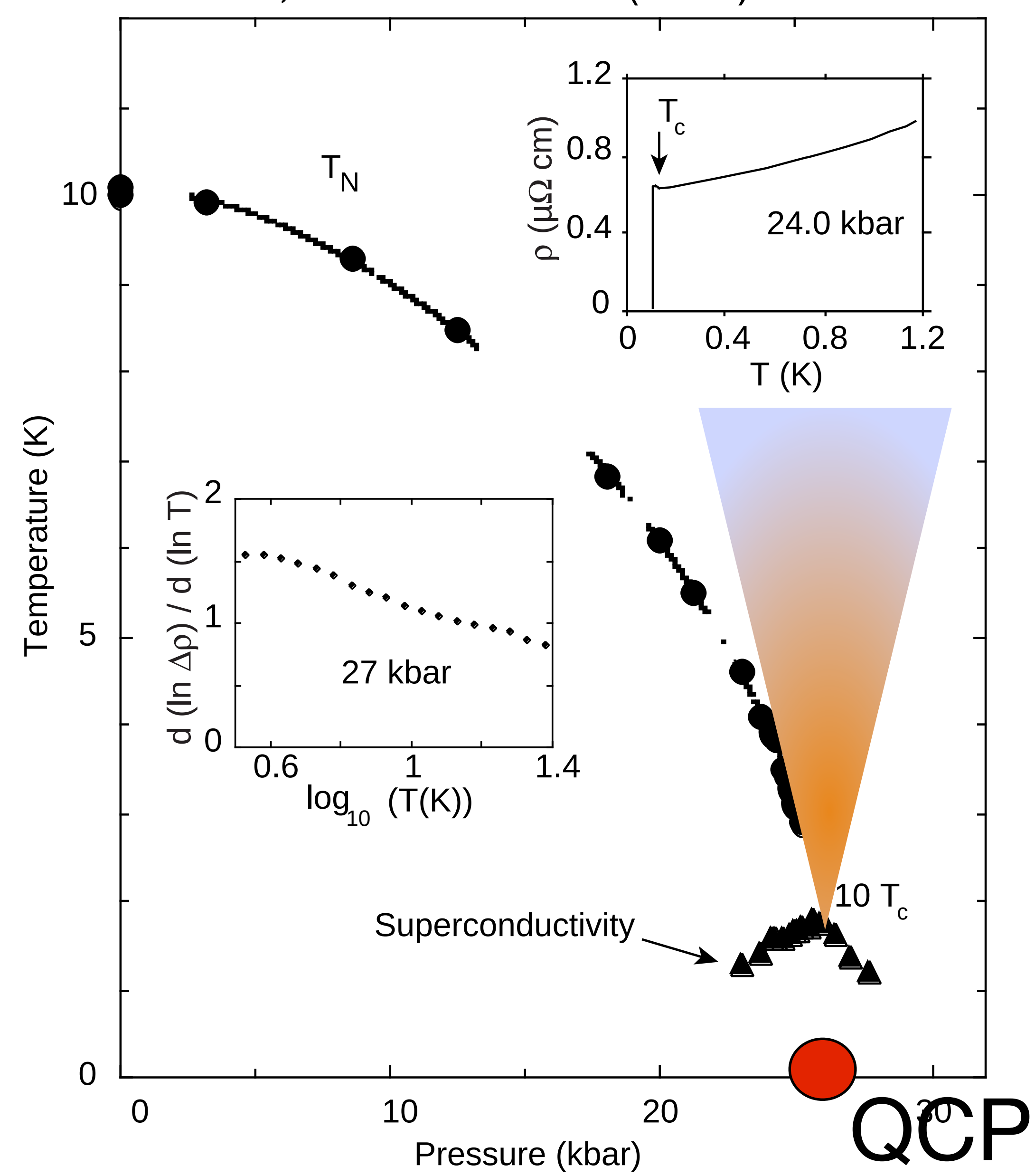
CeIn3

10K AFM



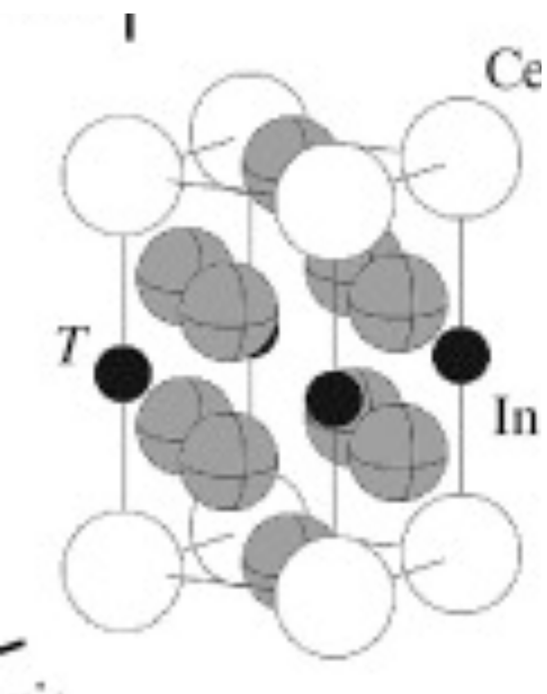


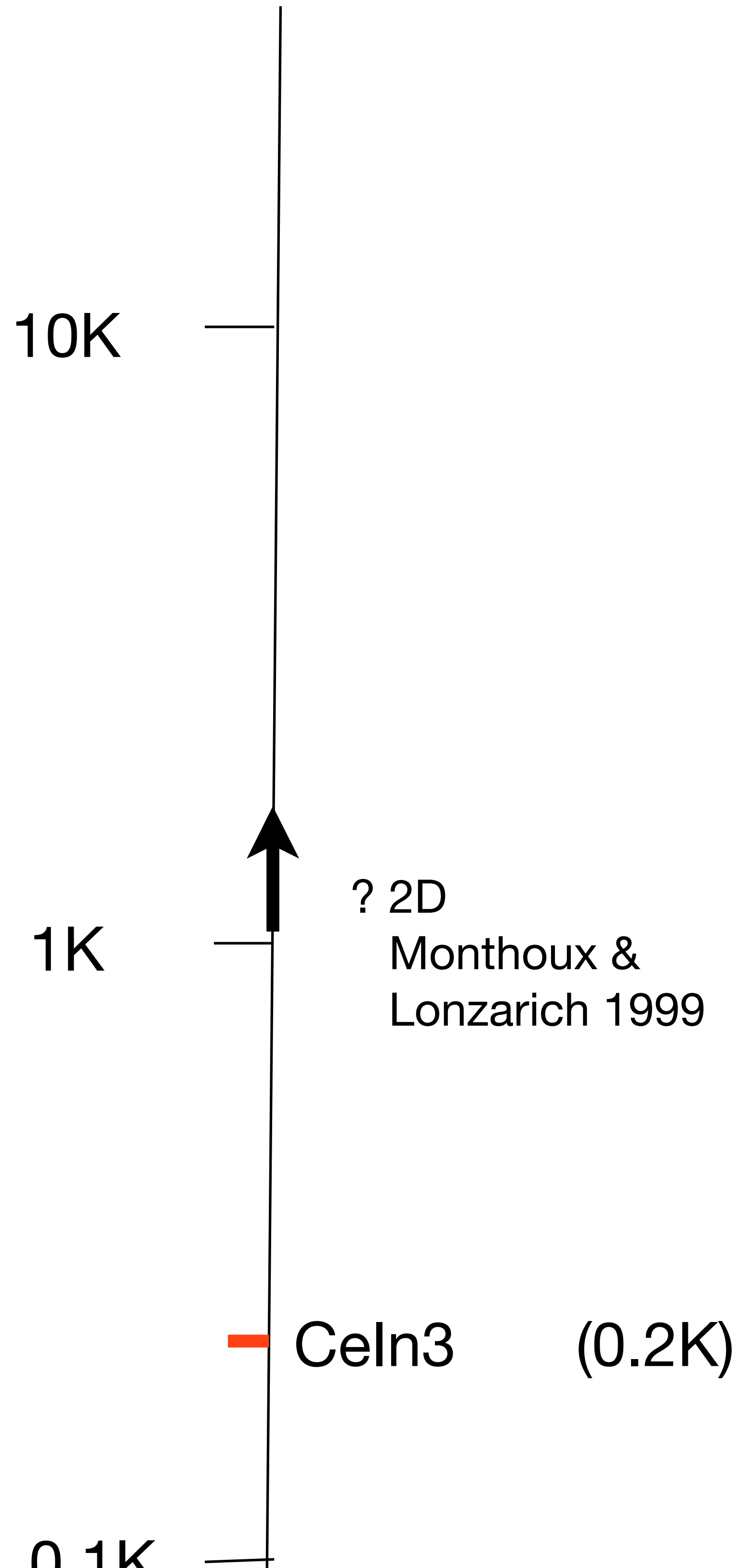
Mathur, Lonzarich et al (1998)



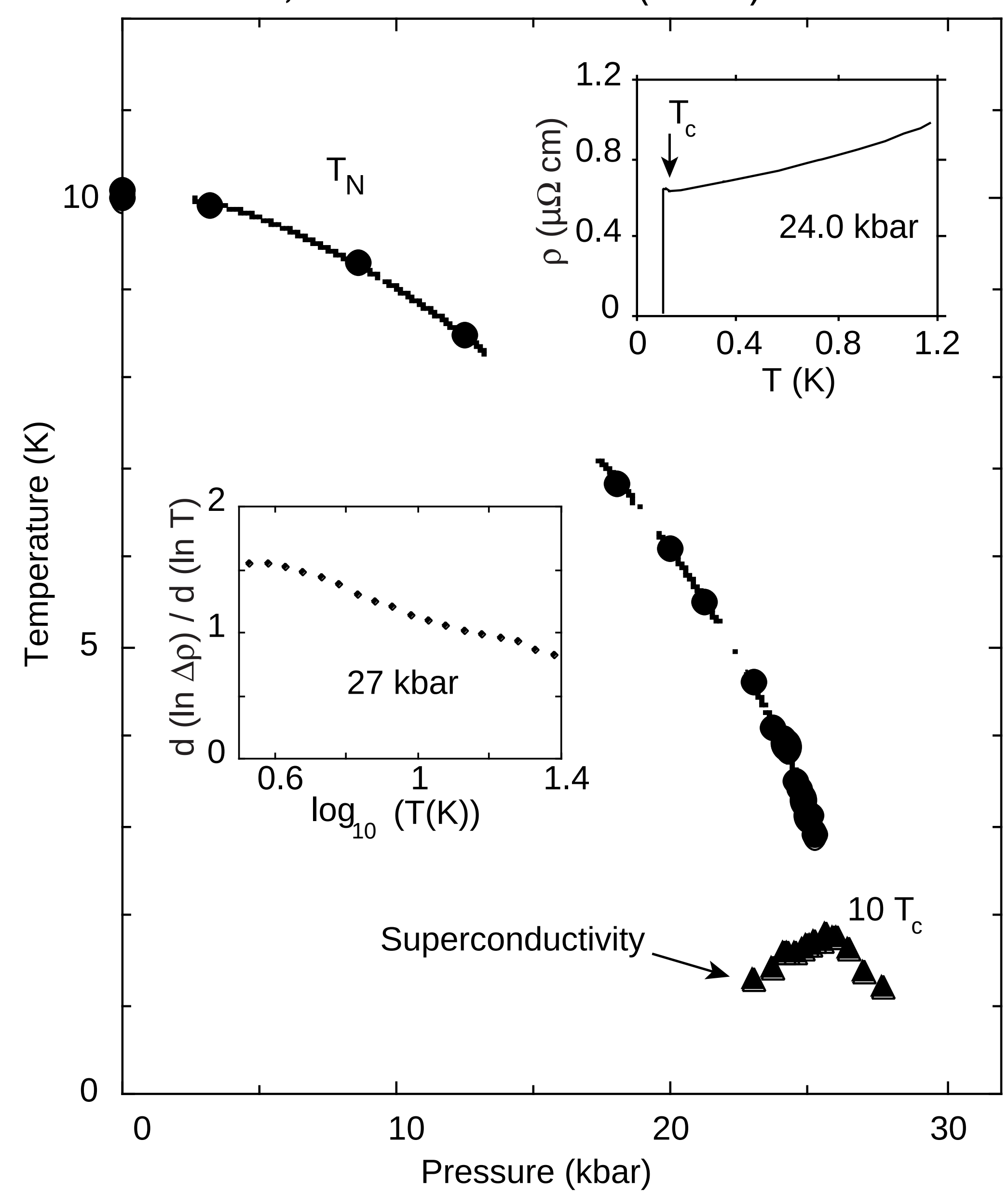
"115" Family

Petrovic et al 2001

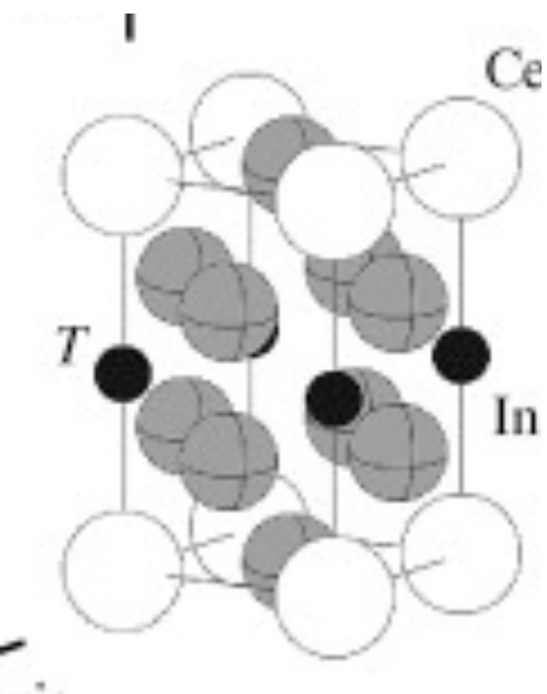


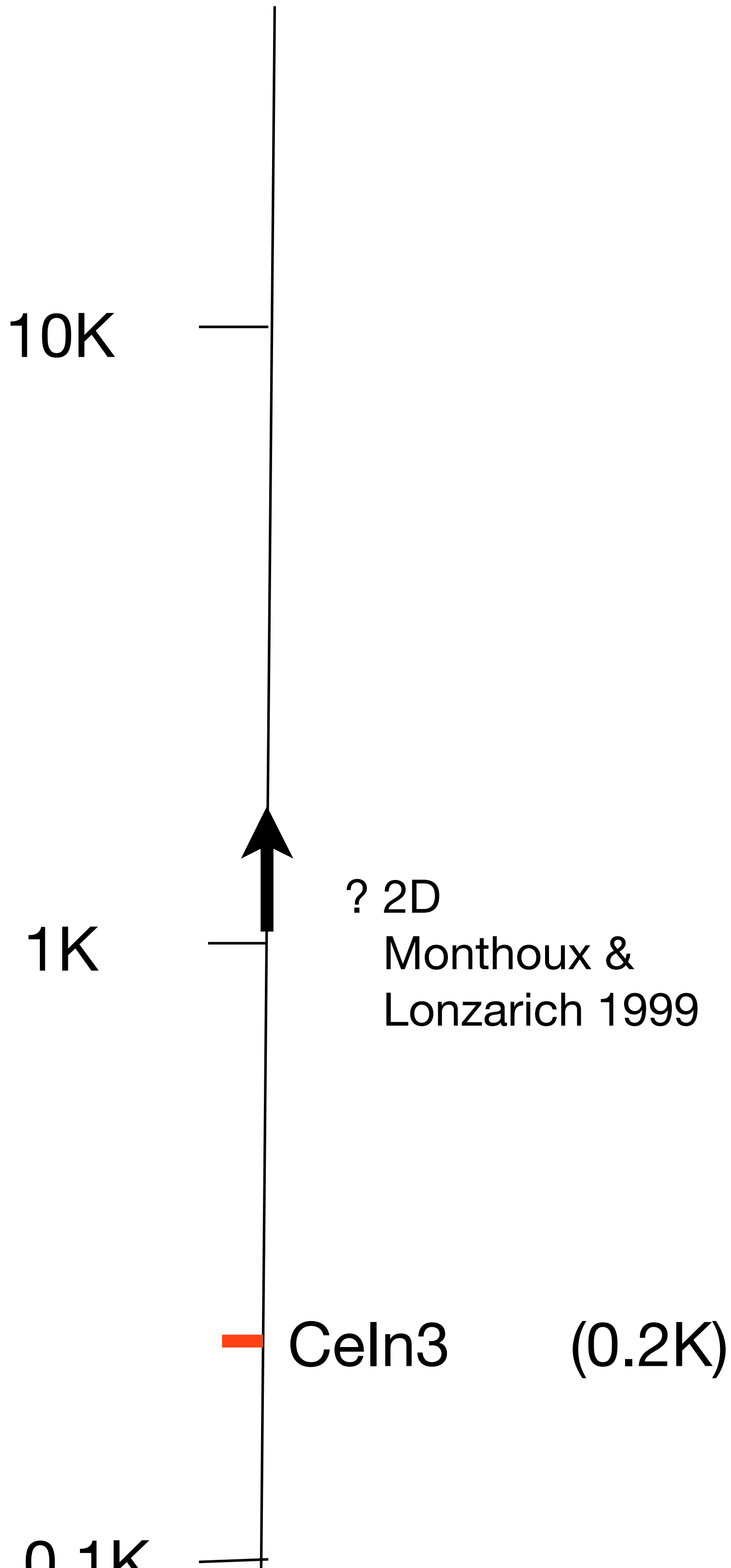


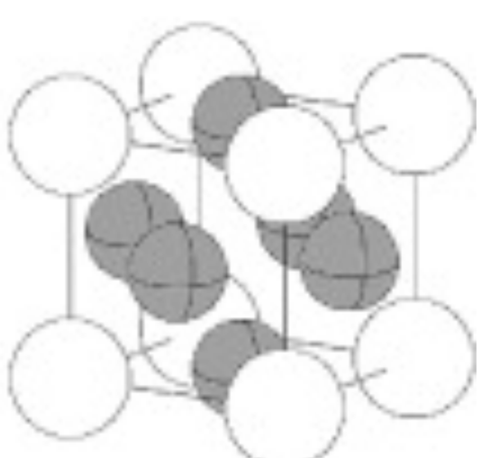
Mathur, Lonzarich et al (1998)

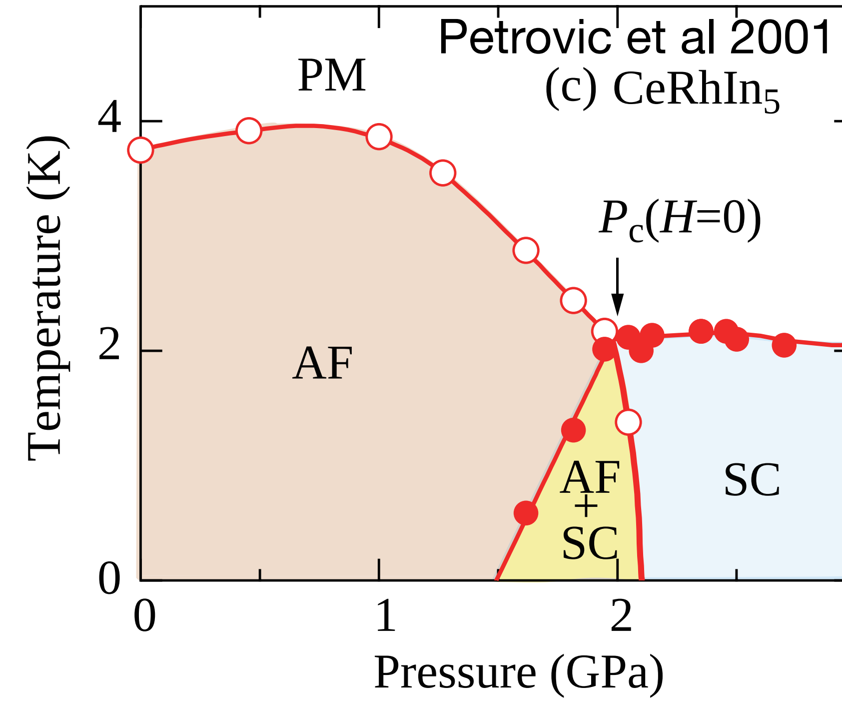


“115” Family

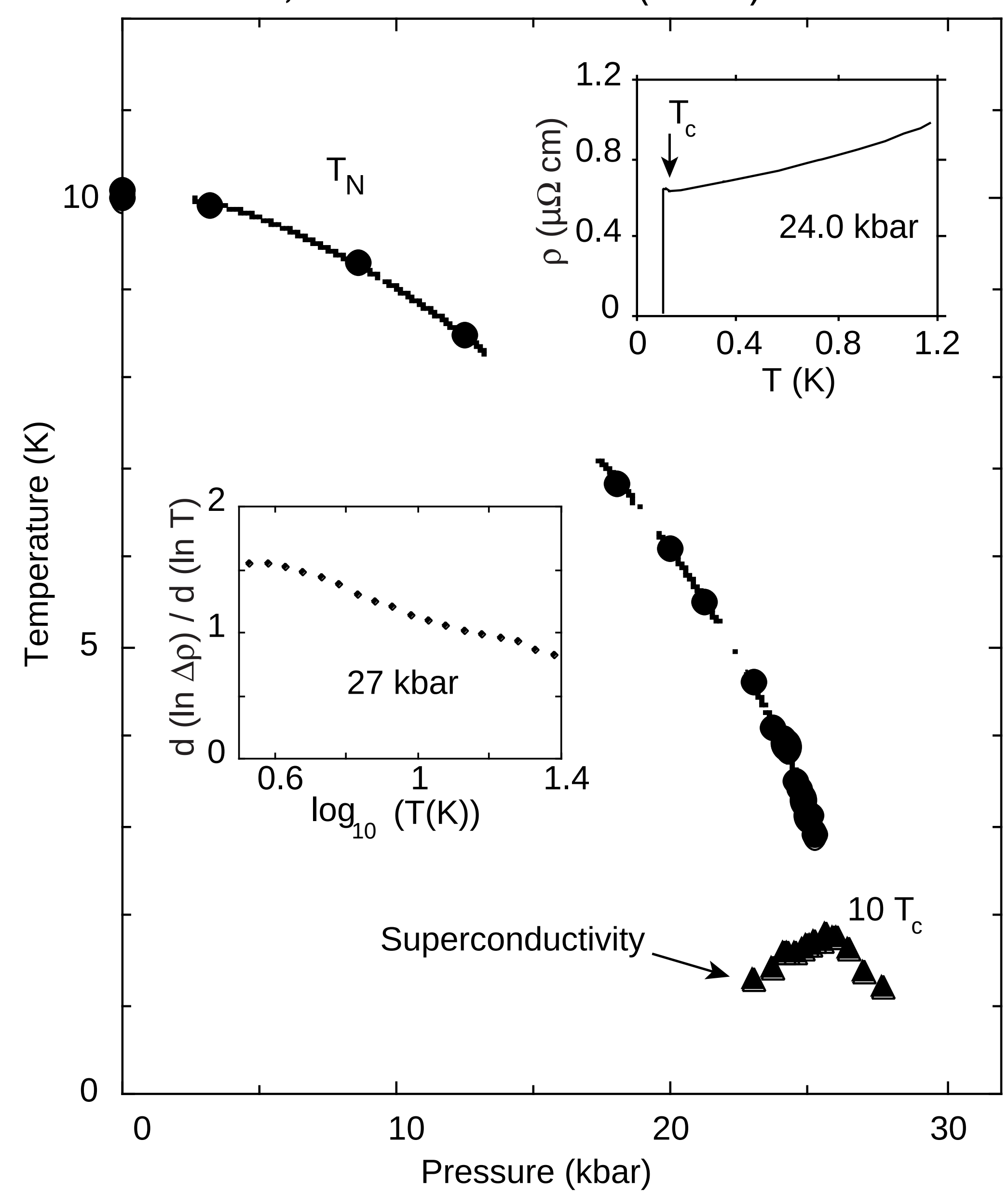




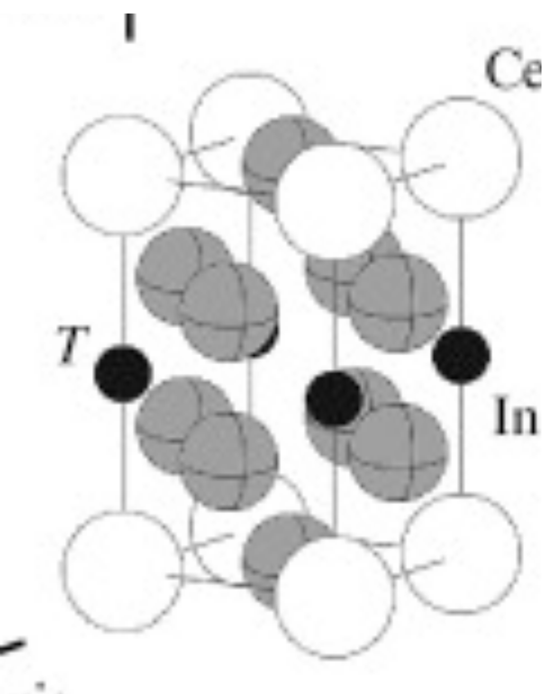


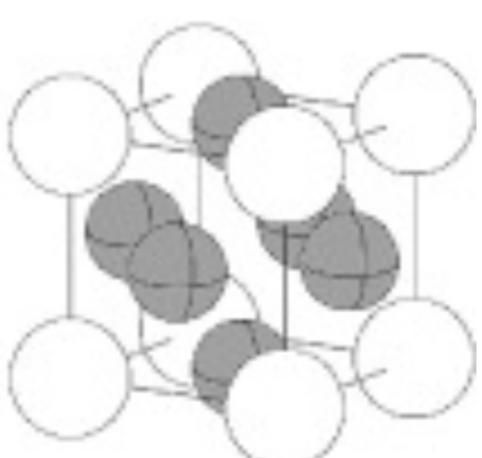


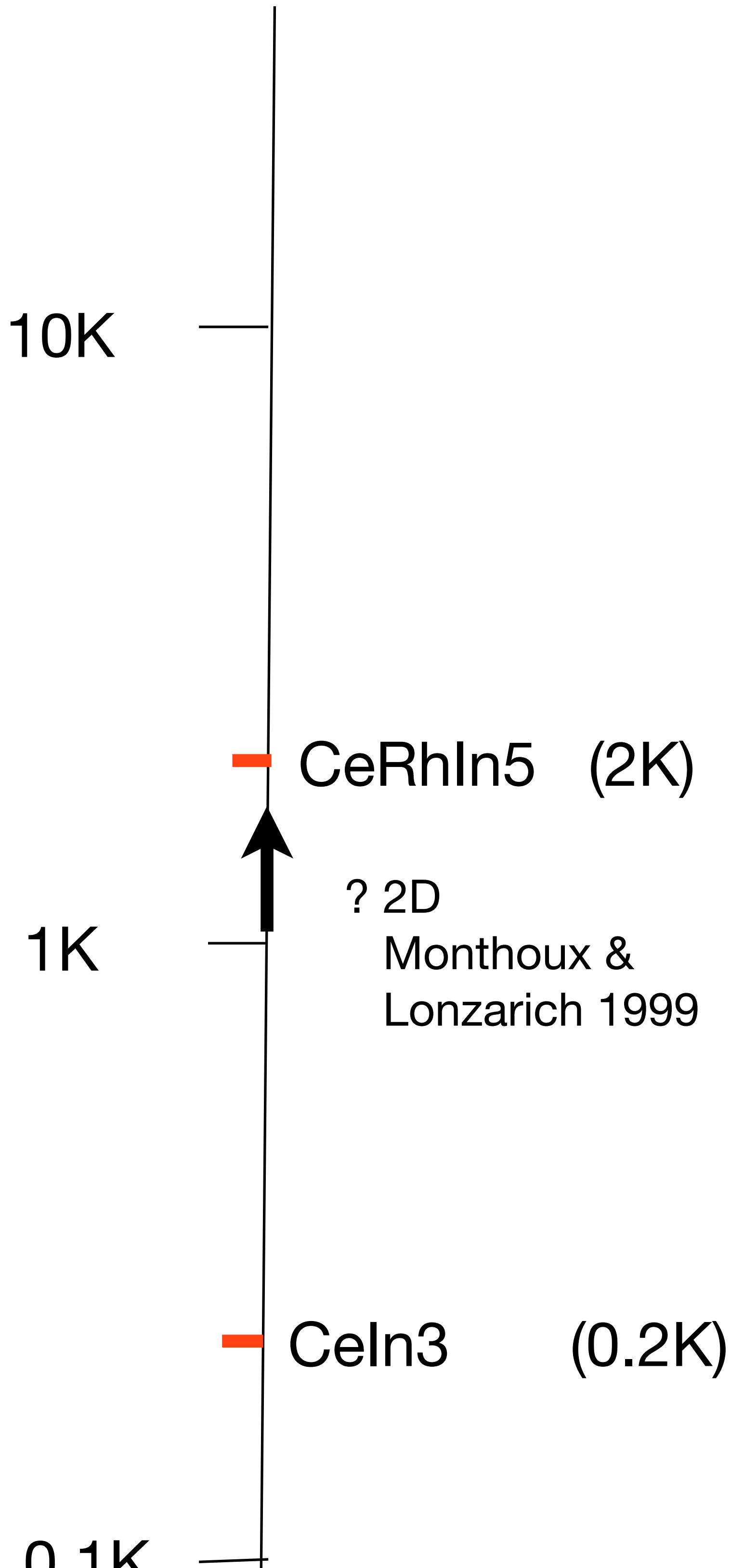
Mathur, Lonzarich et al (1998)

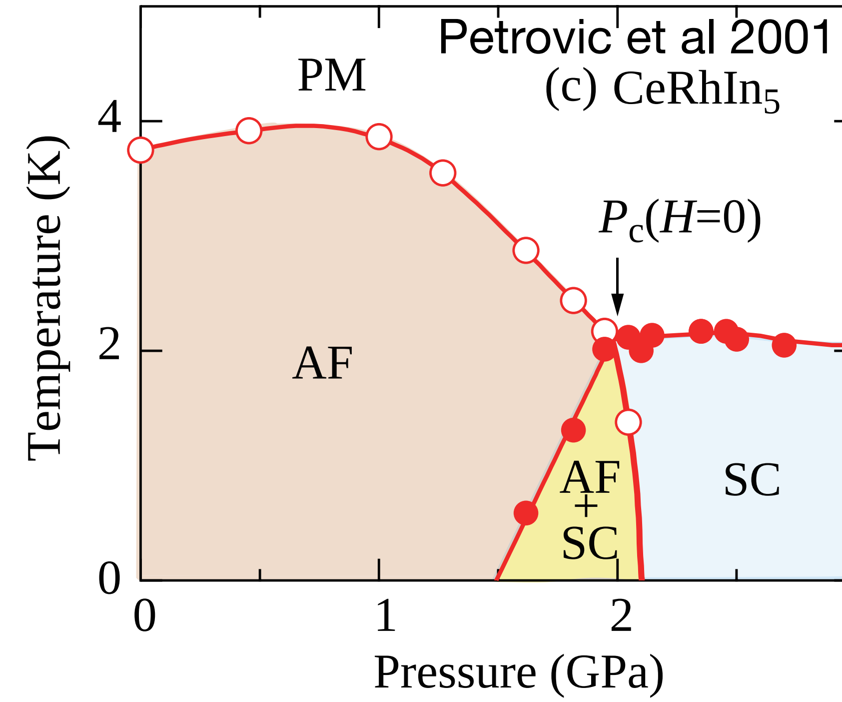


"115" Family

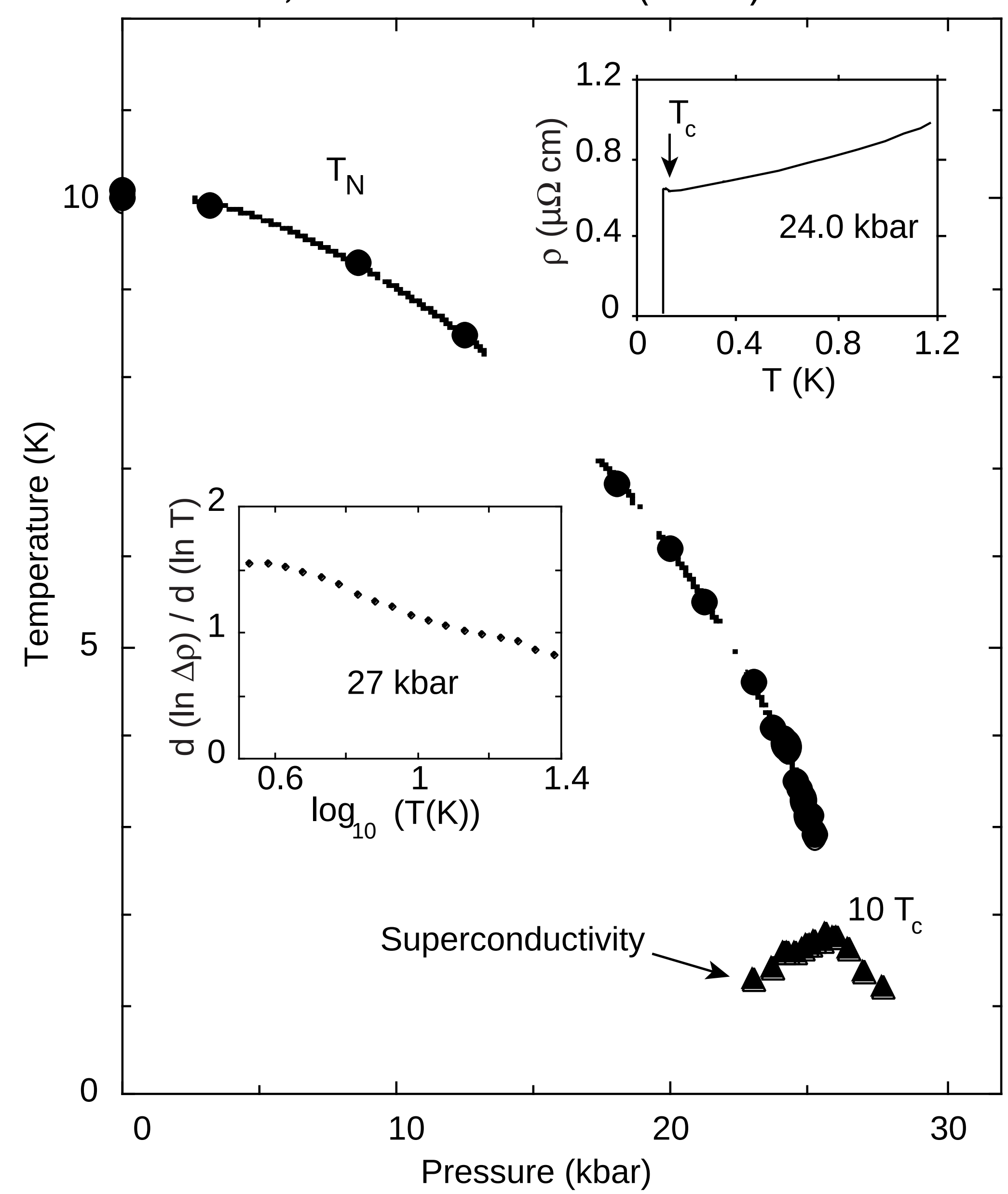




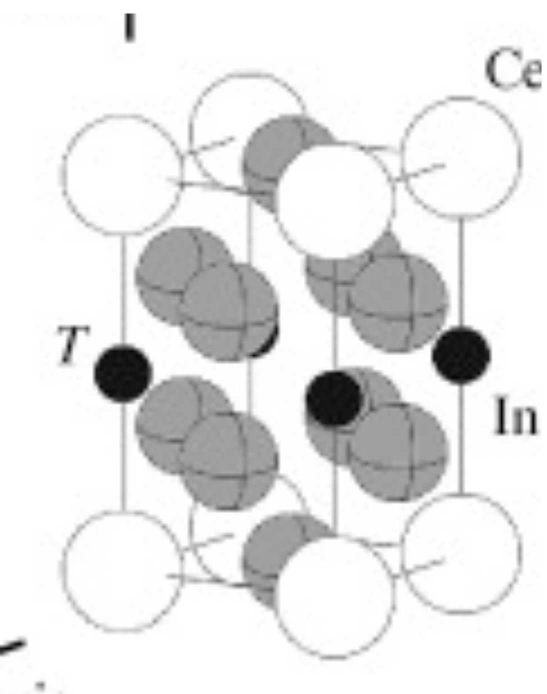




Mathur, Lonzarich et al (1998)



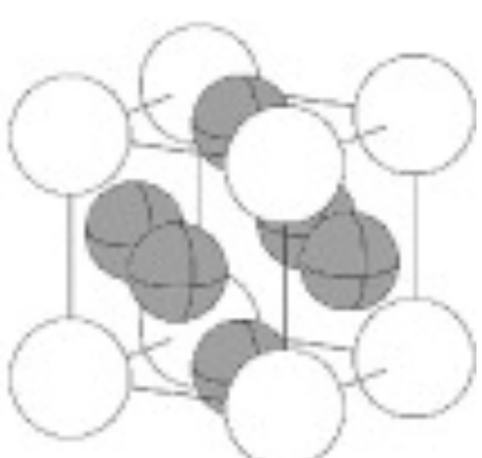
“115” Family



10K

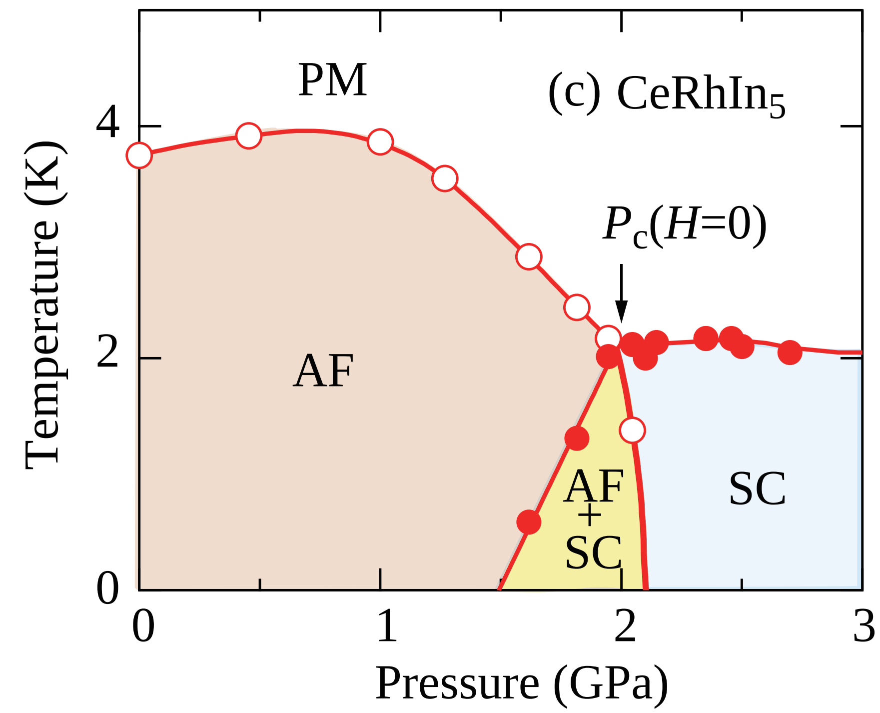
CeRhIn5 (2K)

1K

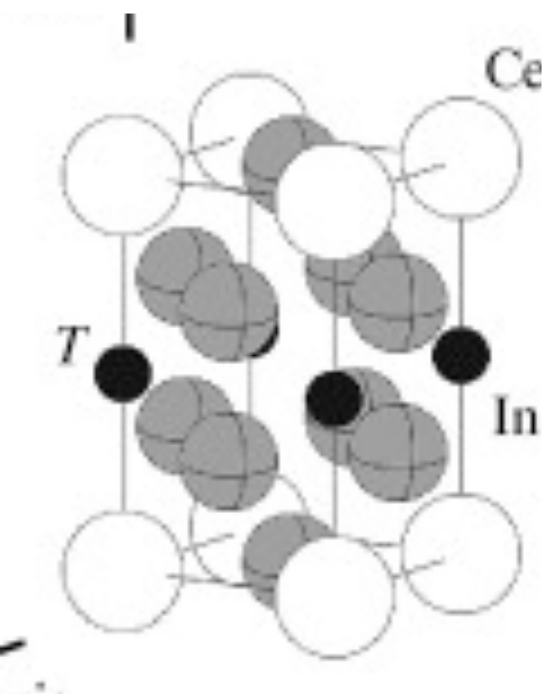


CeIn3 (0.2K)

0.1K



“115” Family



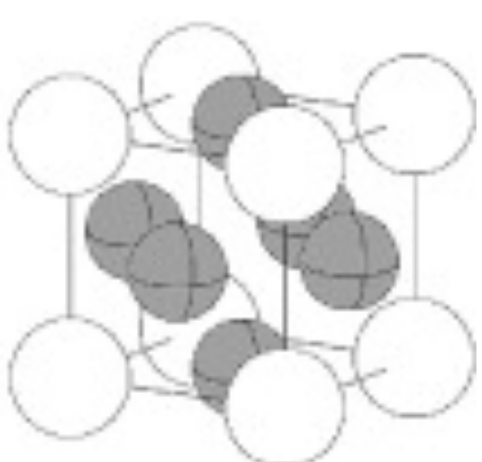
10K

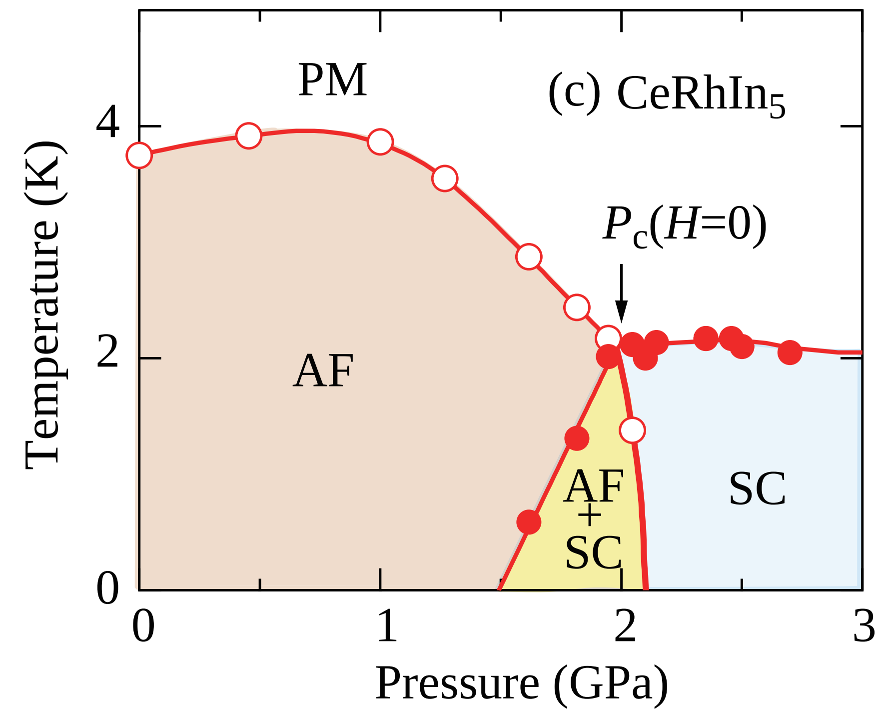
- PuCoGa5 (18.5K)
- PuRhGa5 (9K)
- NpAl2Pd5 (4.5K)
- CeCoIn5 (2.5K)
- CeRhIn5 (2K)

1K

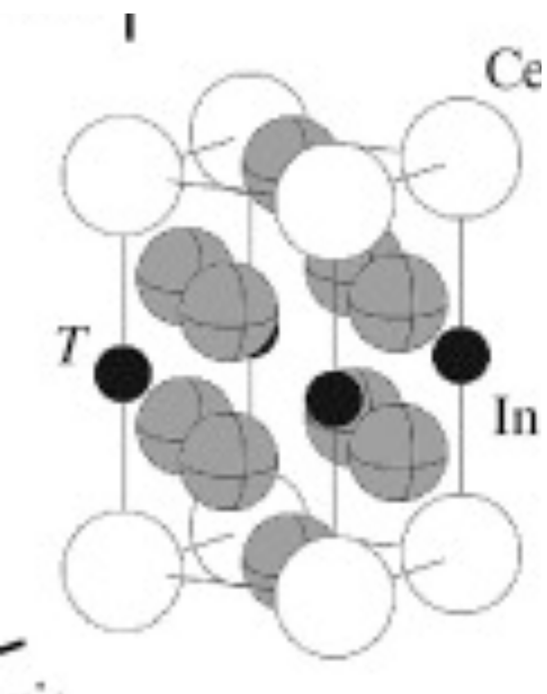
- CeIn3 (0.2K)

0.1K

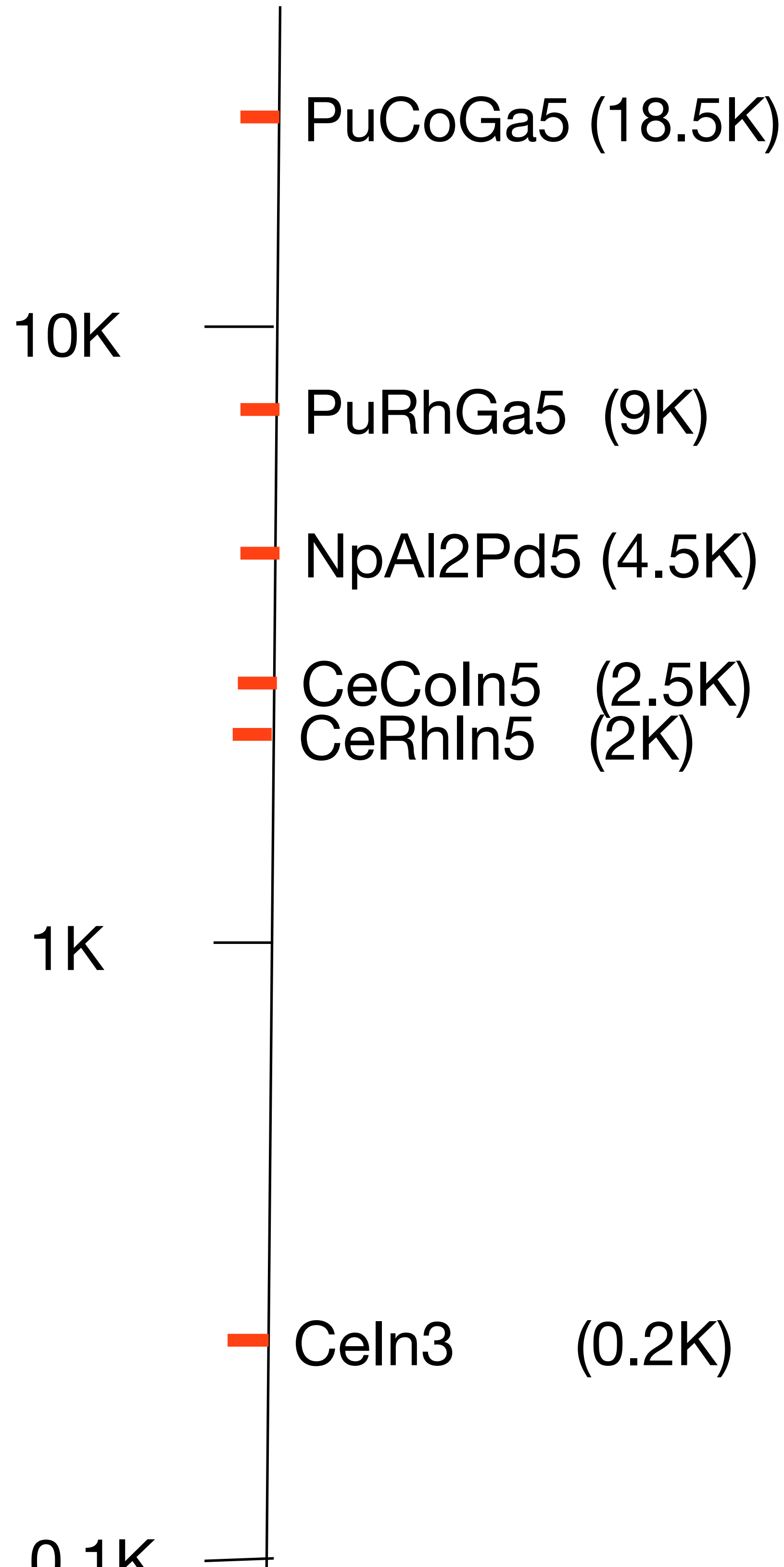




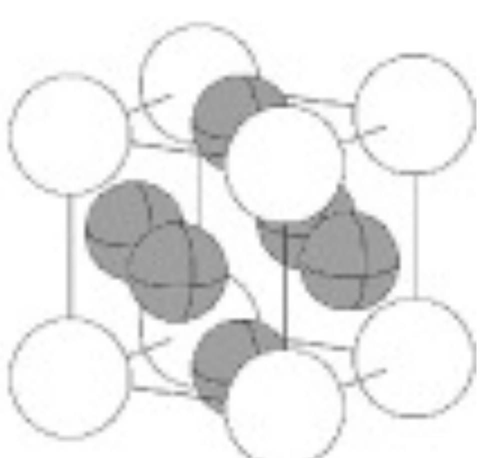
“115” Family

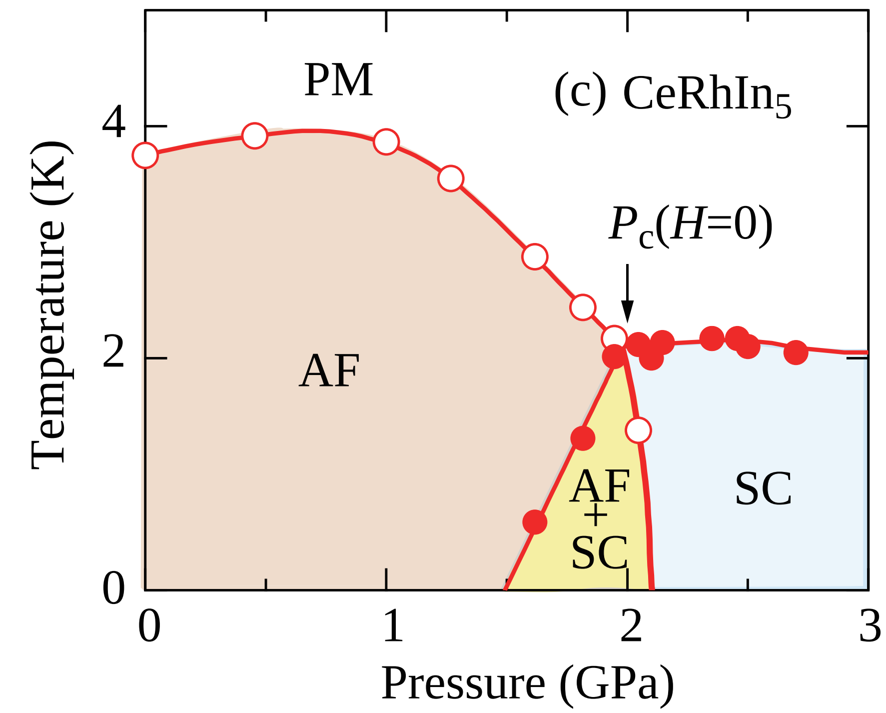


Ce
T
In

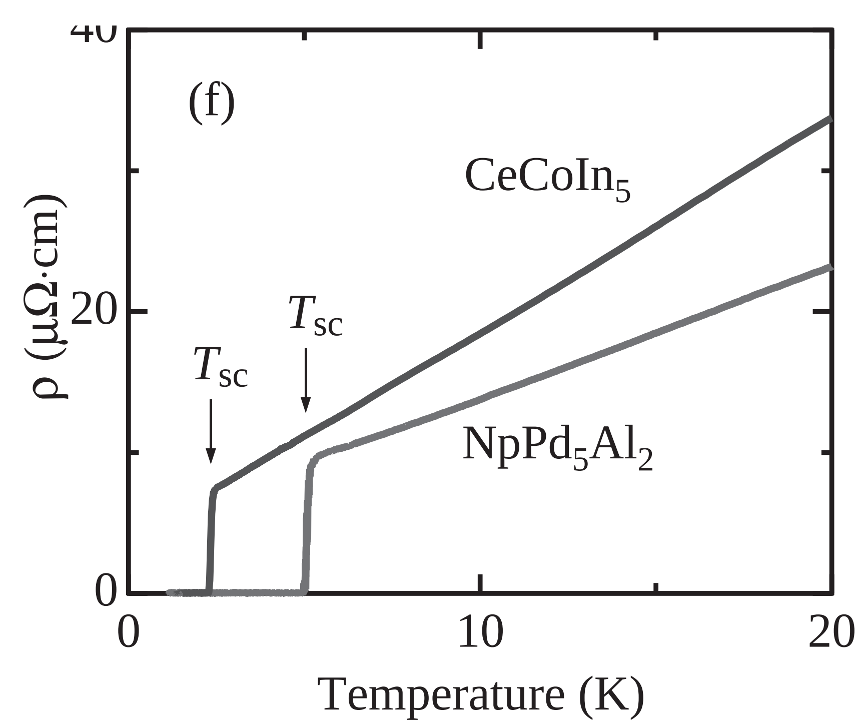


PuCoGa5 (18.5K)
10K
PuRhGa5 (9K)
NpAl2Pd5 (4.5K)
CeCoIn5 (2.5K)
CeRhIn5 (2K)
1K
CeIn3 (0.2K)
0.1K



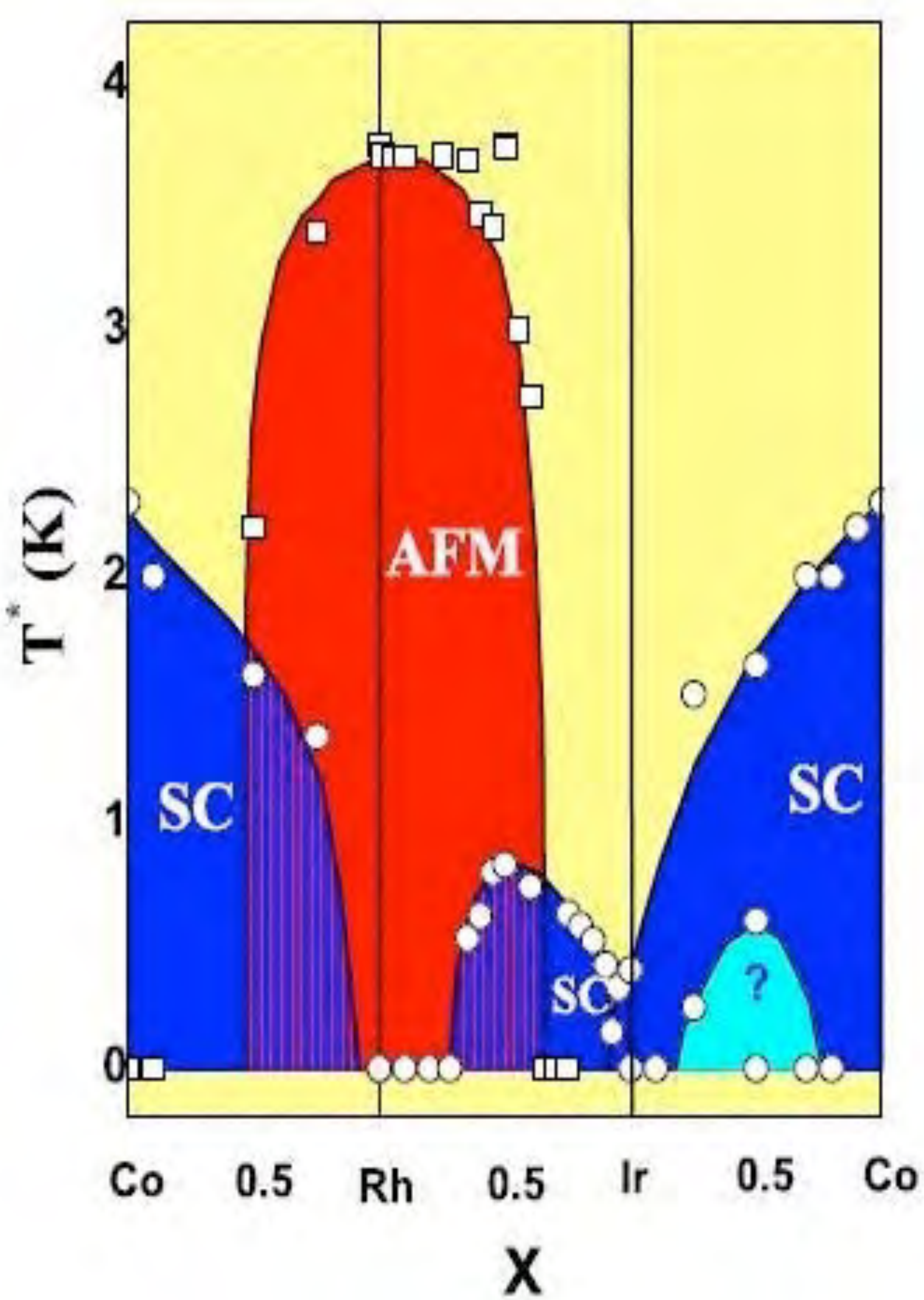


PM
(c) CeRhIn$_5$
$P_c(H=0)$
AF
AF + SC
SC
Temperature (K)
Pressure (GPa)
0
2
4
0
1
2
3



(f)
CeCoIn$_5$
T_{sc}
T_{sc}
NpPd$_5$Al$_2$
ρ (μΩ·cm)
Temperature (K)
0
20
40
0
10
20

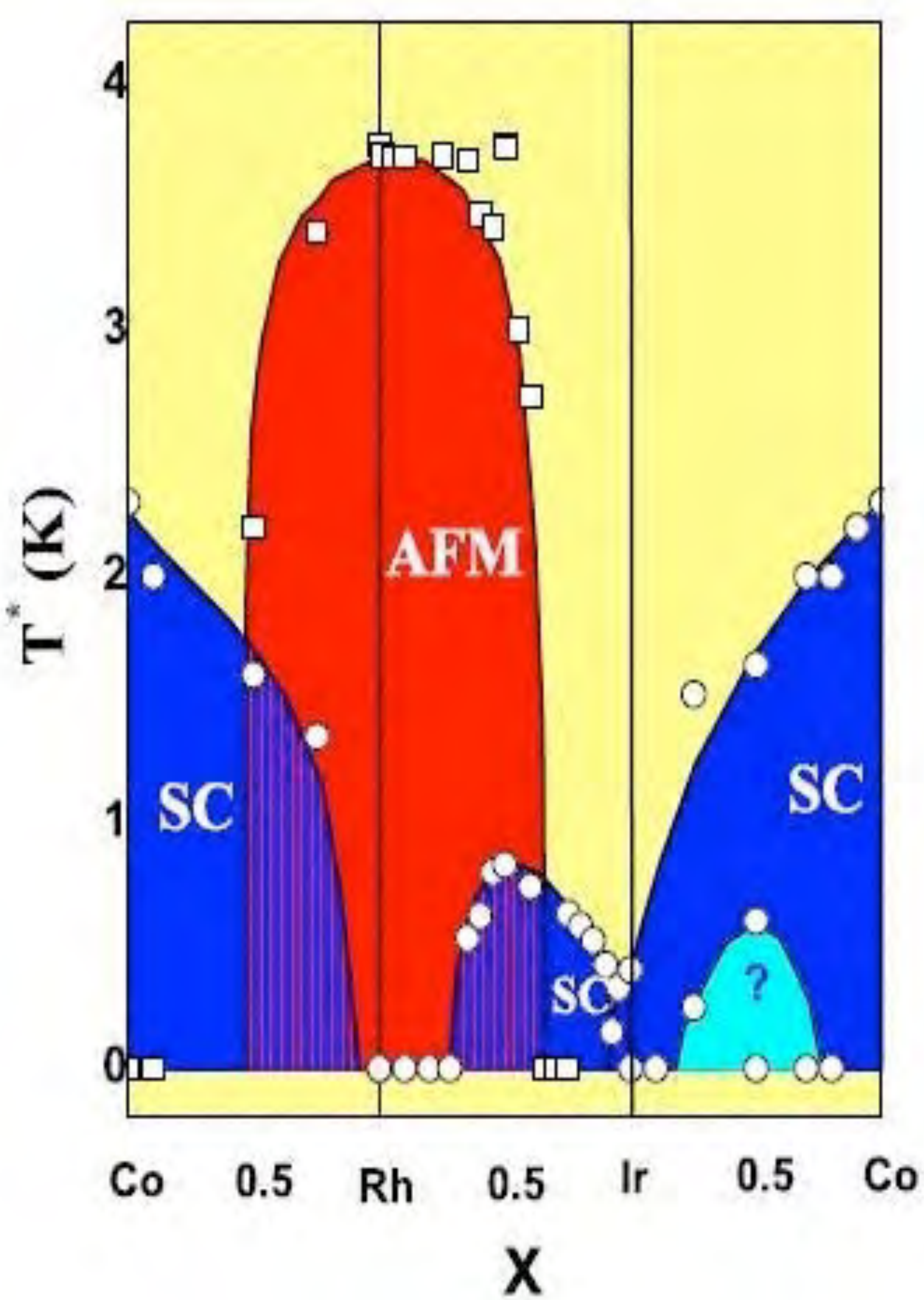
The 115 Family. Magnetism appears ubiquitous.



Sarrao and Thompson JPSJ (2007)

$CeXIn_5$

The 115 Family. Magnetism appears ubiquitous.



Sarrao and Thompson JPSJ (2007)

$CeXIn_5$

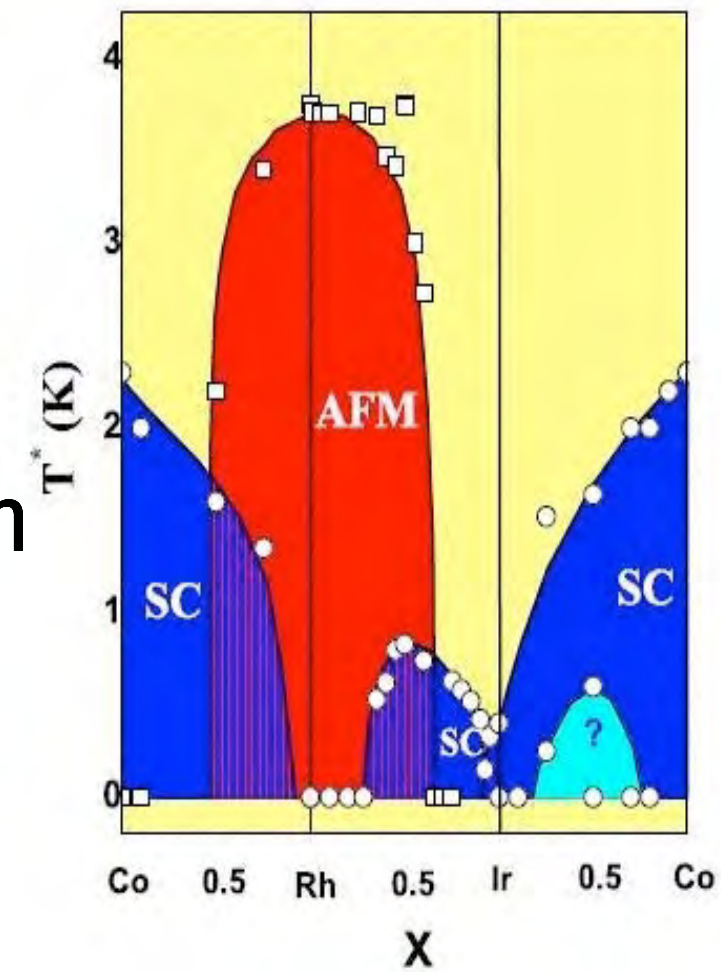
Yet…

Magnetic pairing appears ubiquitous

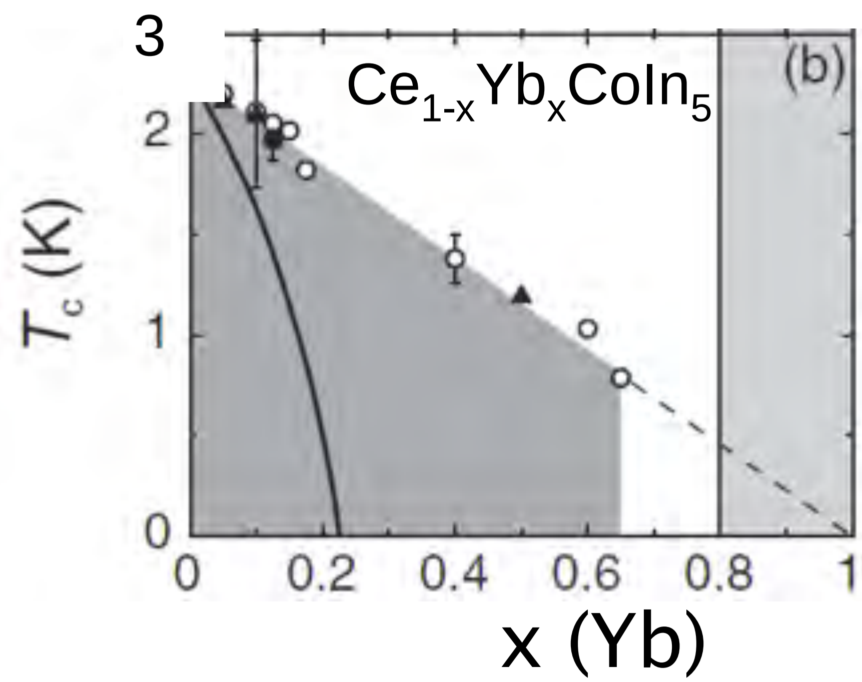
But...

- Two domes in $CeMIn_5$
- Superconductivity without magnetism ($PuMIn_5$, $PuMGa_5$, $NpPd_5Al_2$)
- Extreme robustness to disorder
- Many Ce superconductors, one (weak) Yb superconductor

Are there other possible mechanisms?

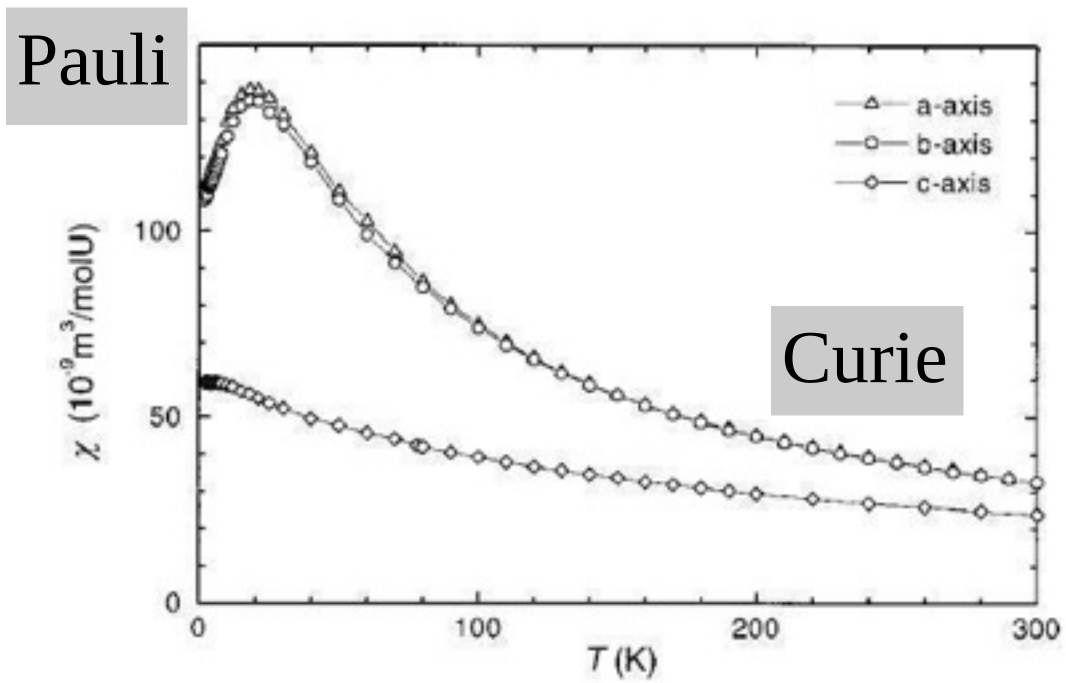


Sarrao and Thompson JPSJ (2007)

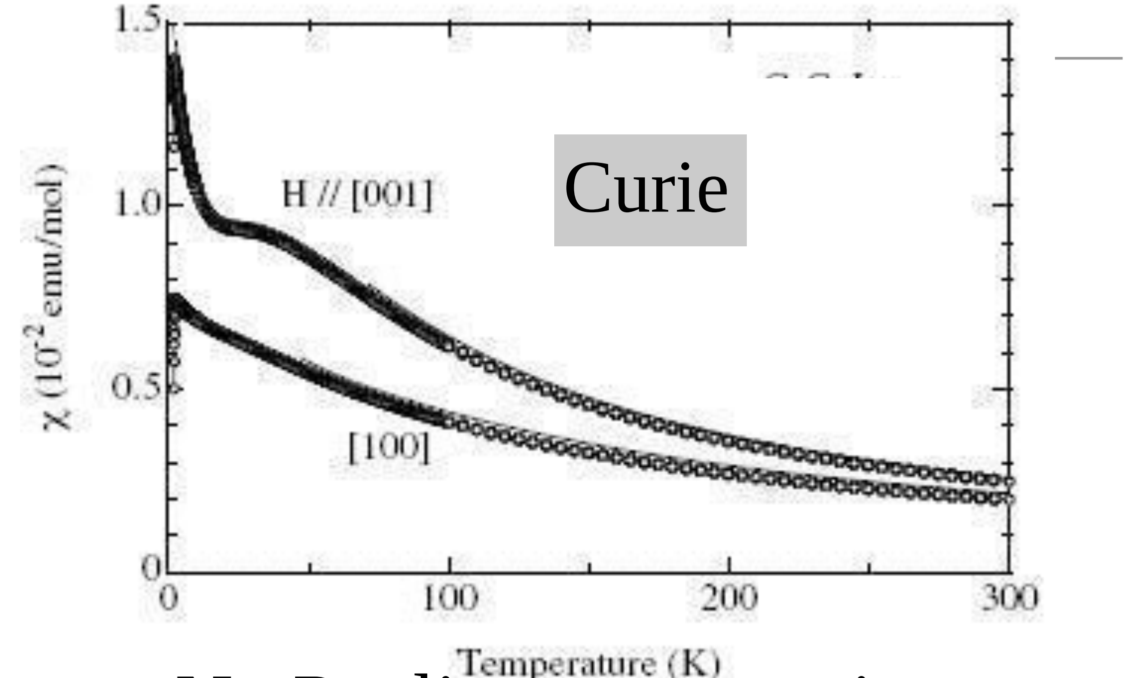


L. Shu et al PRL 2011

UPt_3 | $CeCoIn_5$

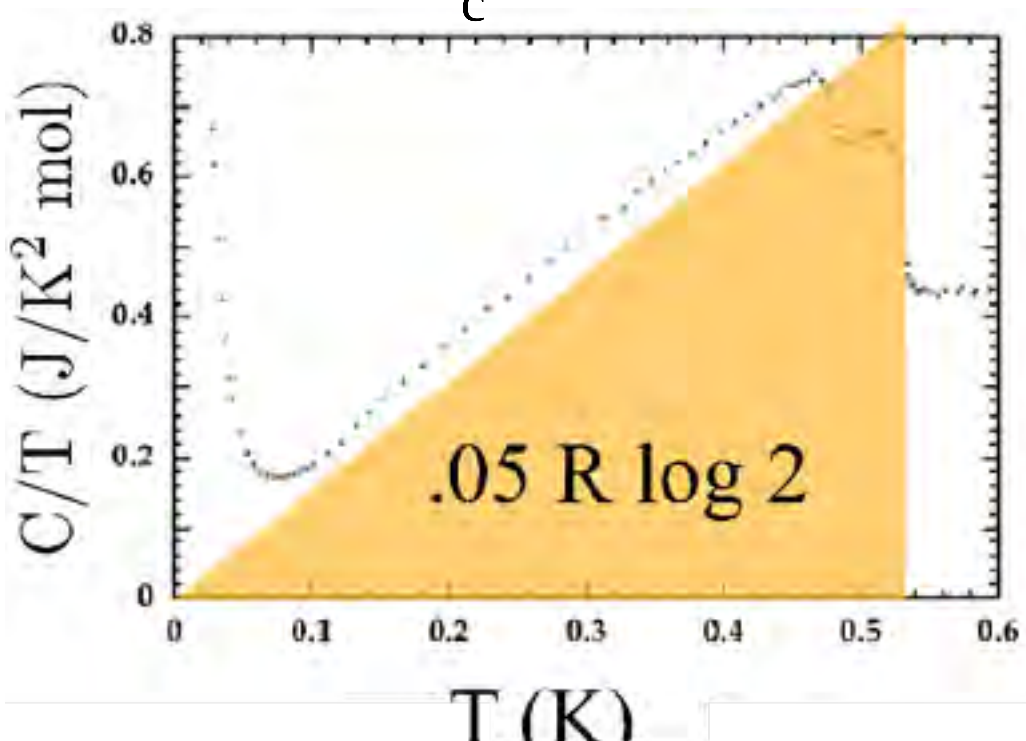


Pauli paramagnetic by 30K

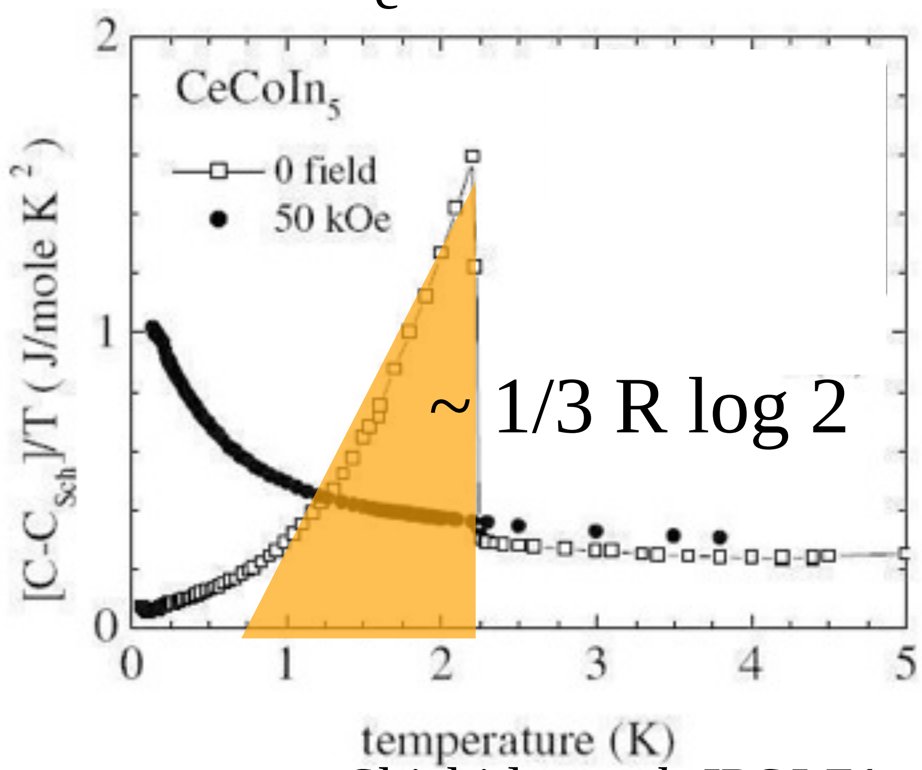


No Pauli paramagnetism

T_c = 0.5K



T_c = 2.3K

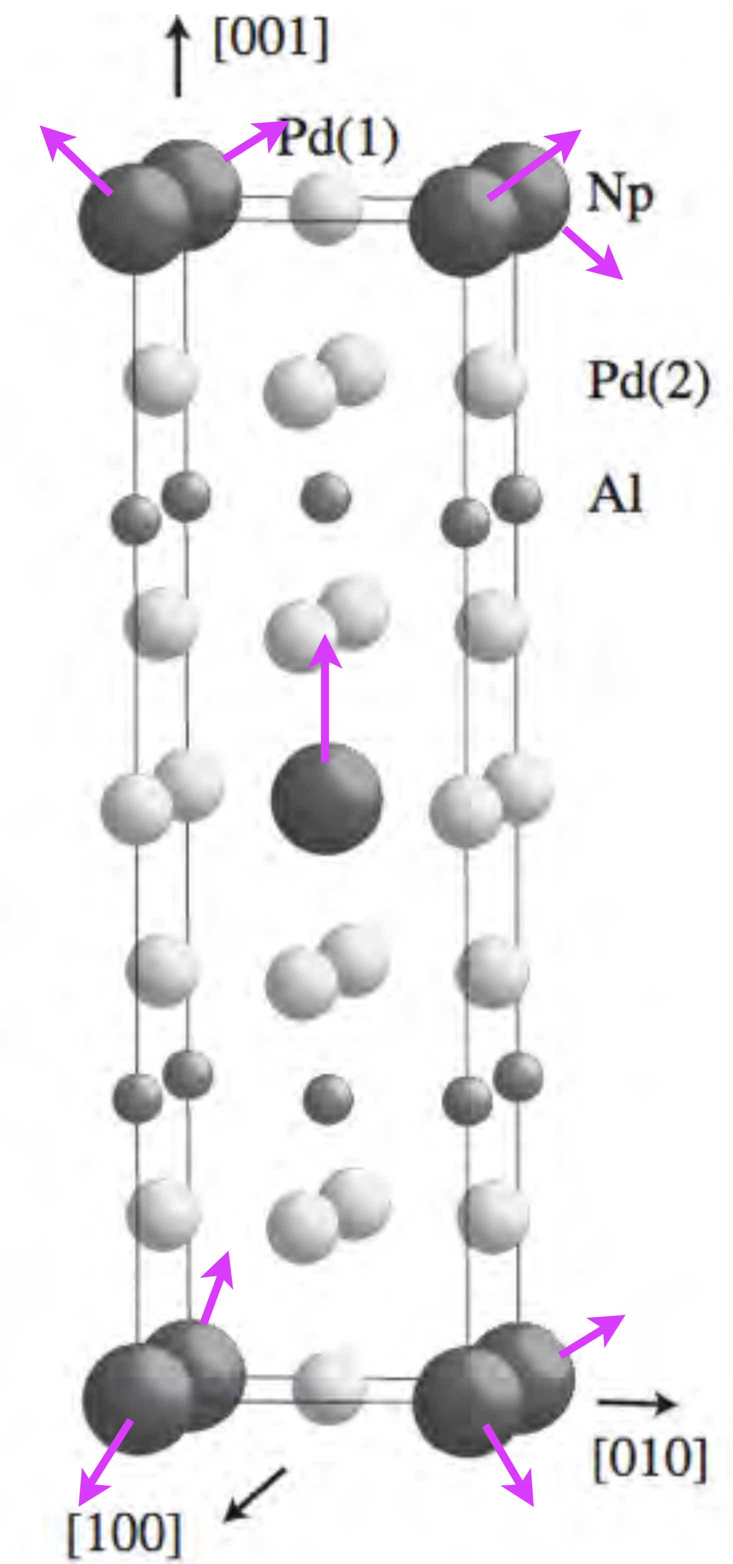


Frings *et al*. J. Magn. Magn. Mater. **31**, 240(1983)
Brison *et al*. J. Low Temp. Phys. **95**, 145(1994)

Shishido *et al*. JPSJ **71**, 162 (2002)
Petrovic *et al*. J.Phys Condens. Matter **13** 337 (2001)

115 Mystery.

The Mystery of $NpPd_5Al_2$

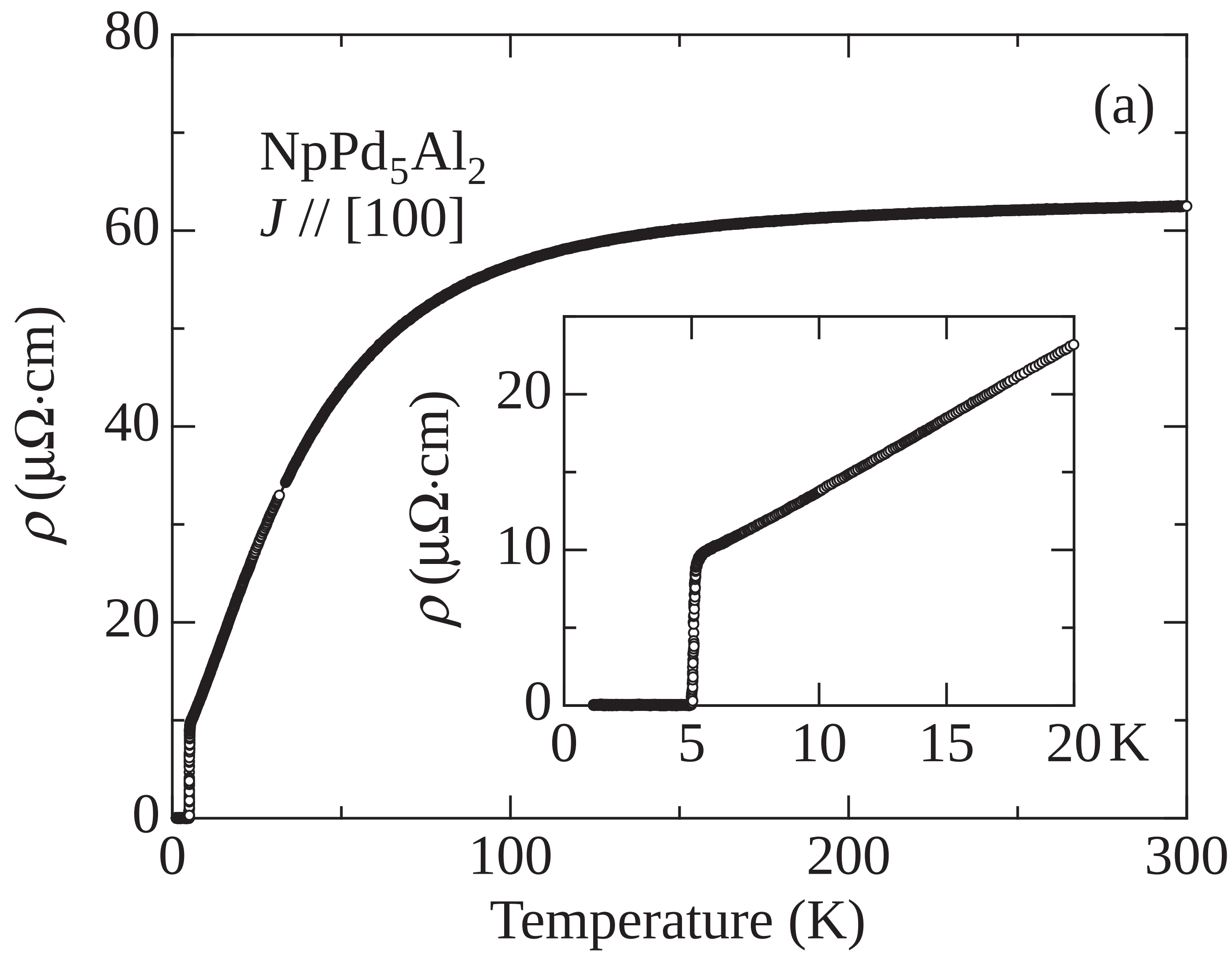


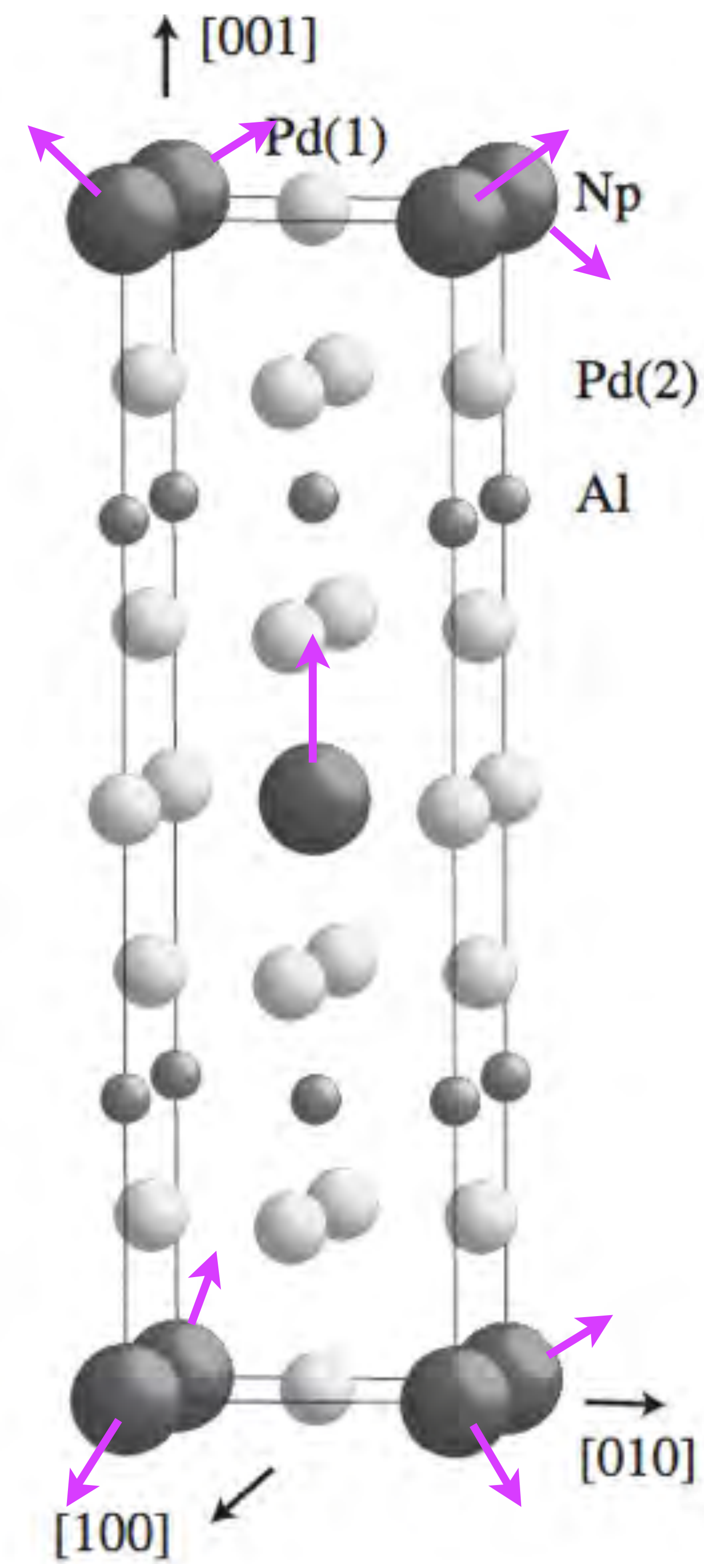
4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$



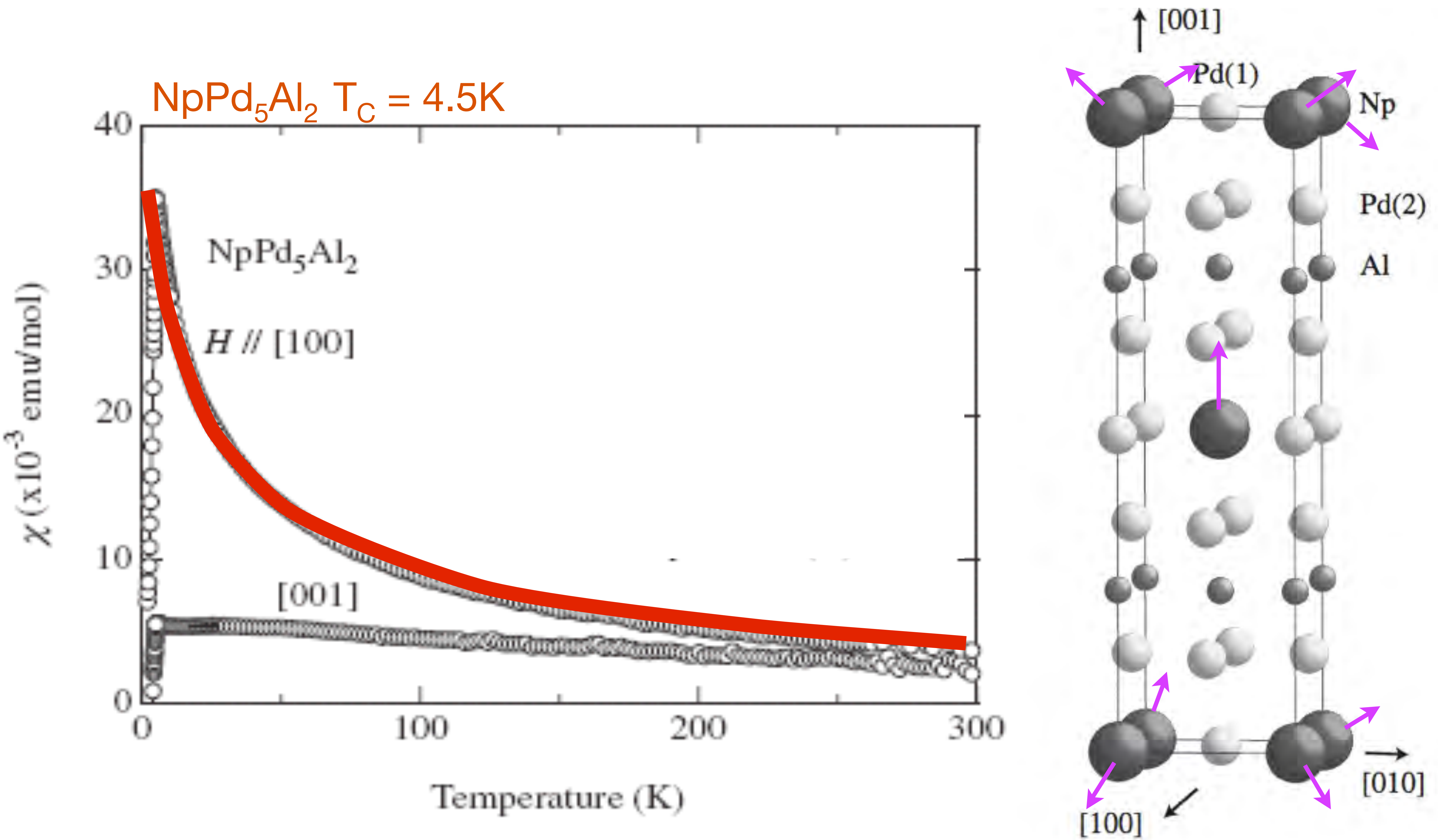


4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$

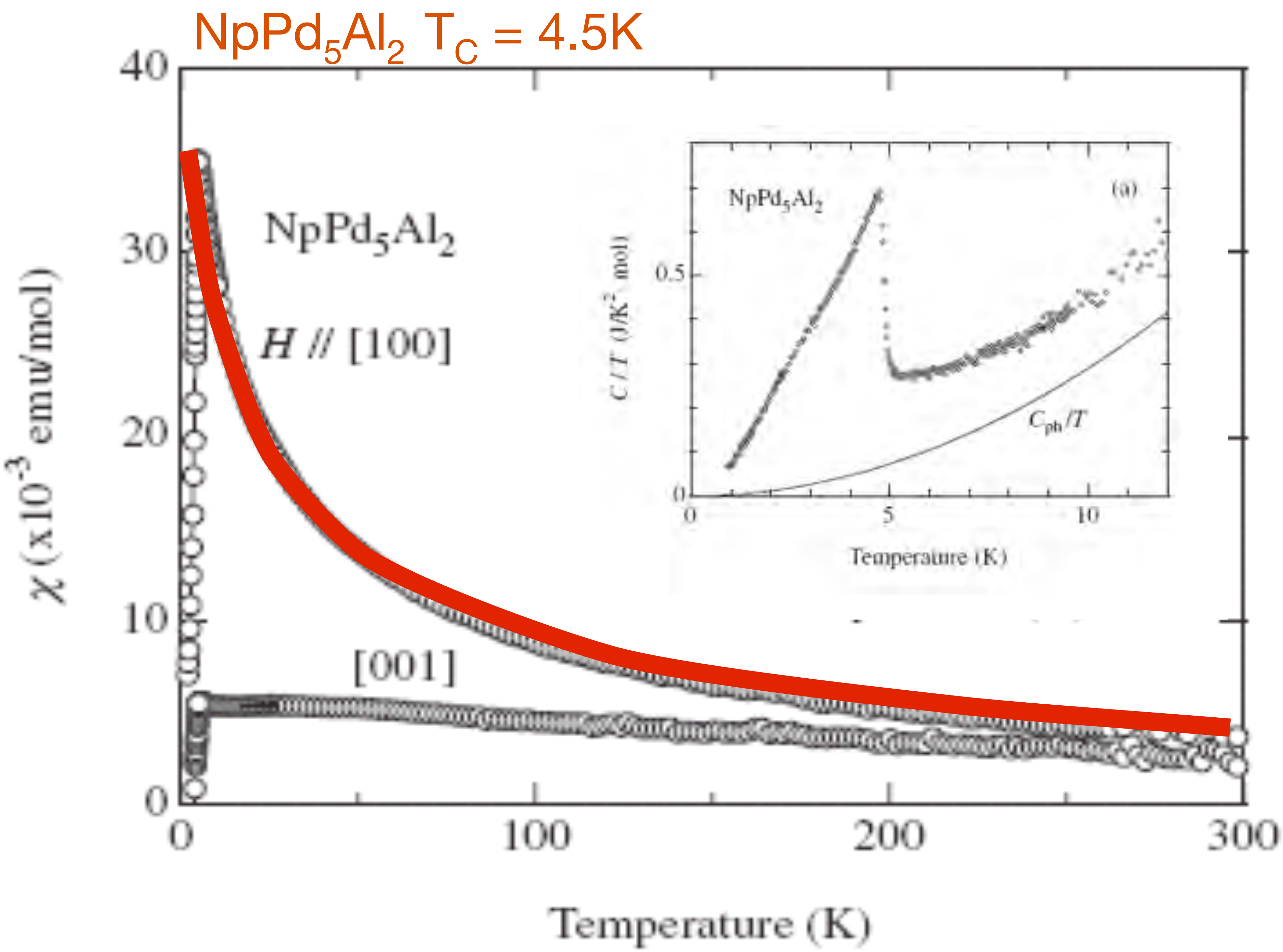


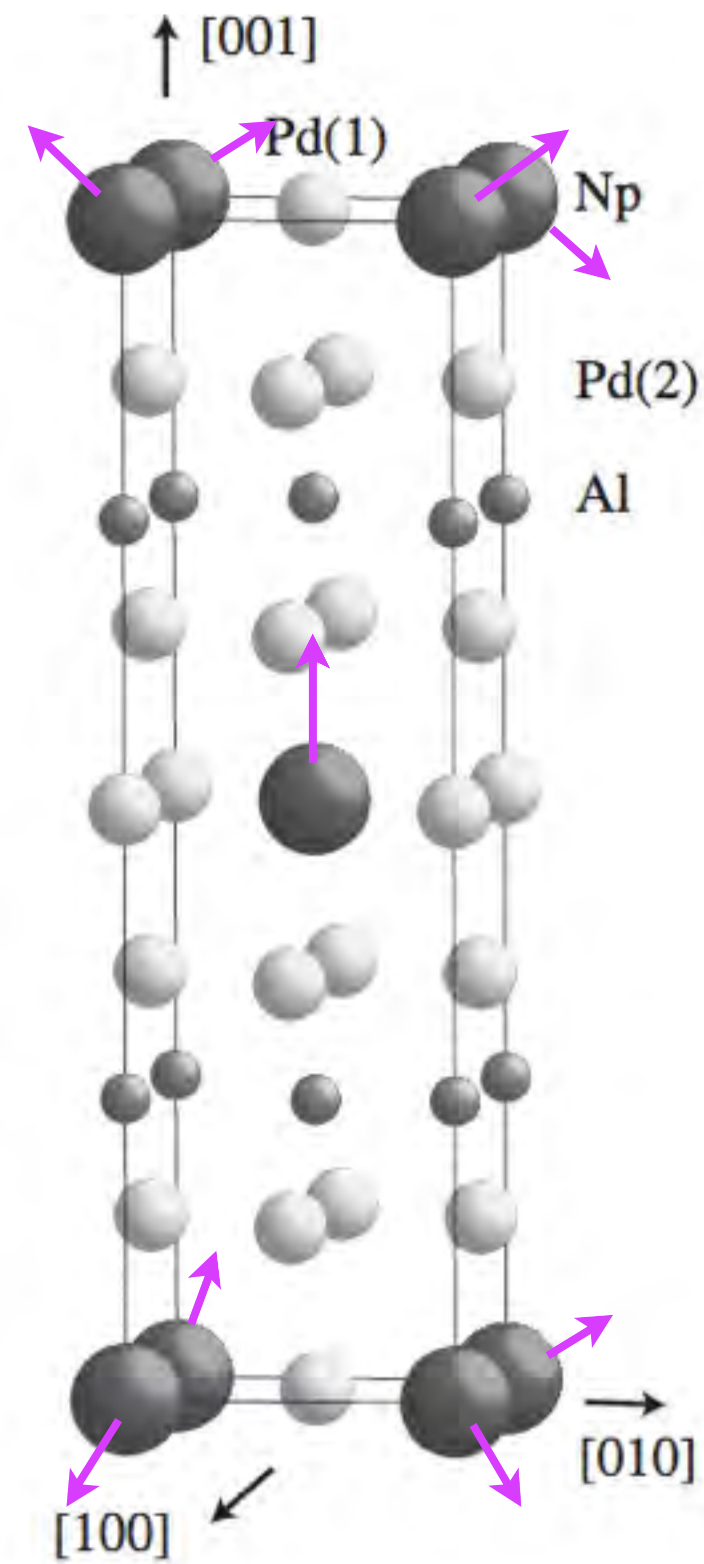
4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$



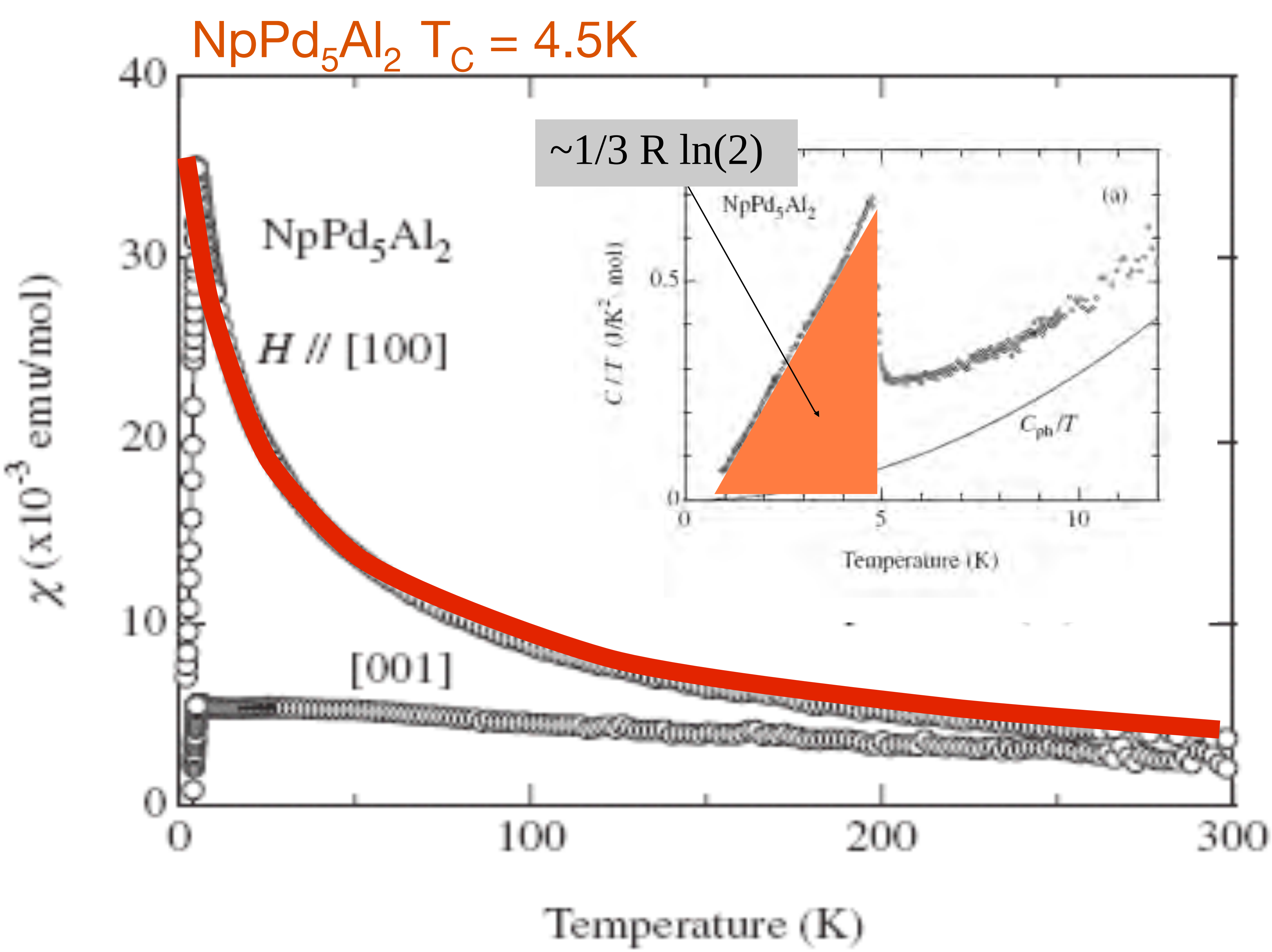


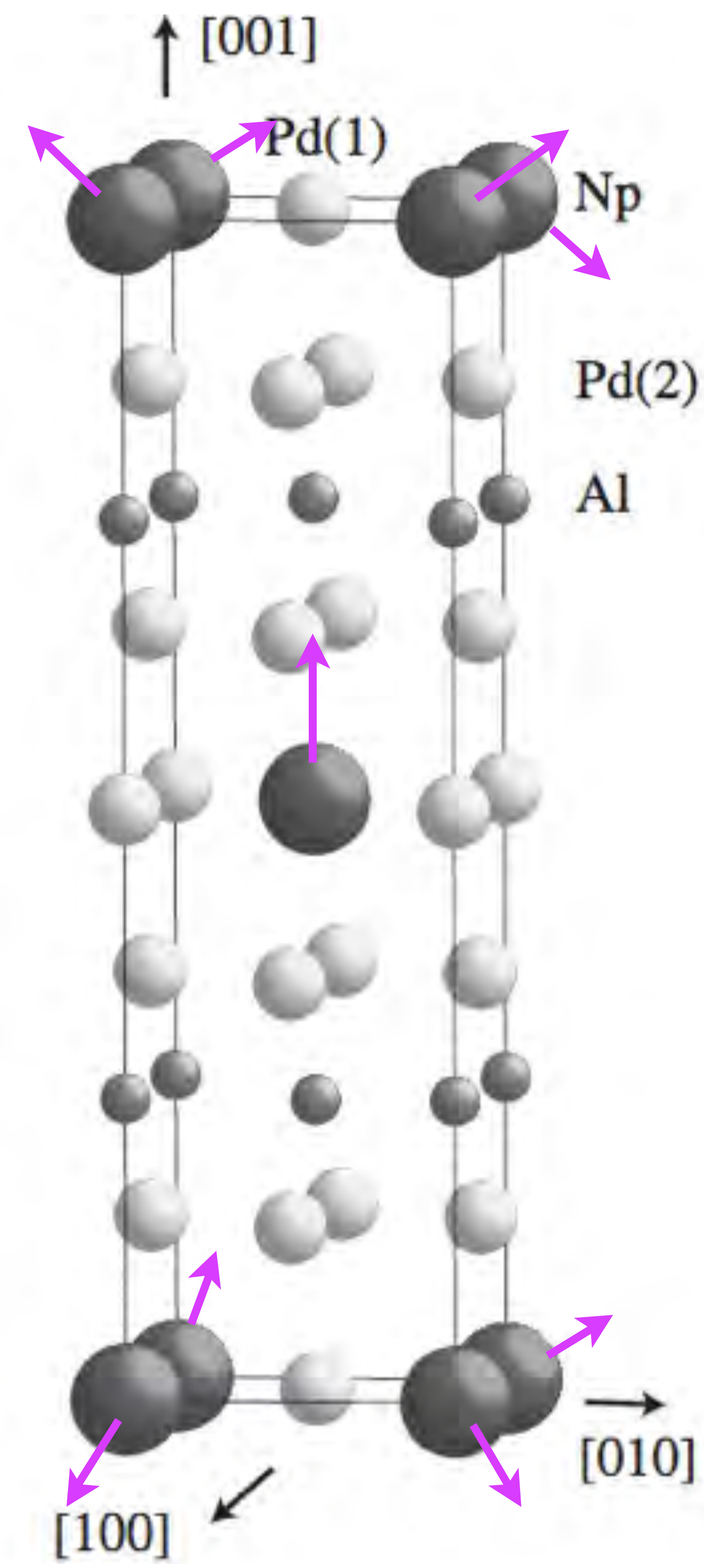
4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$



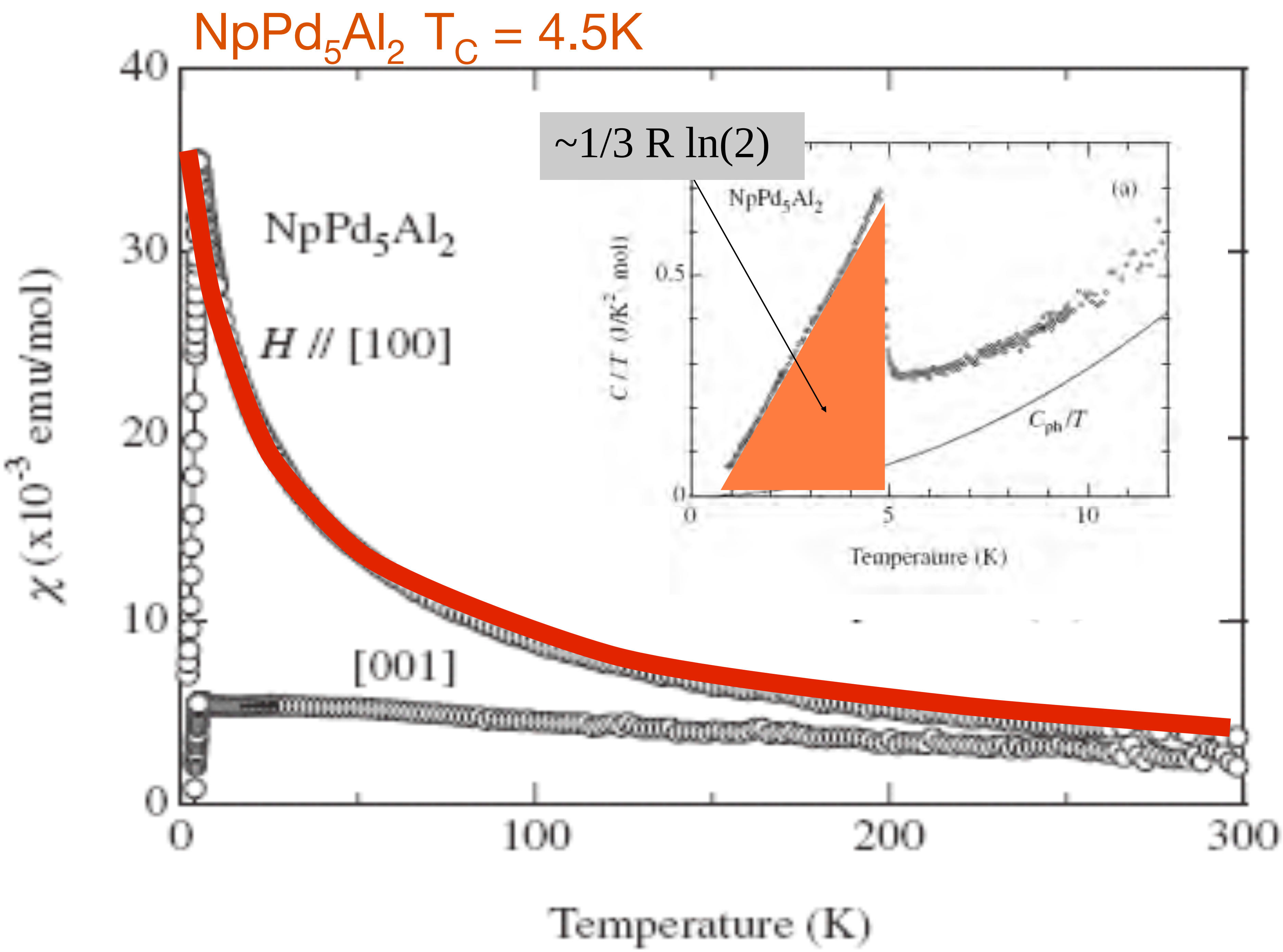


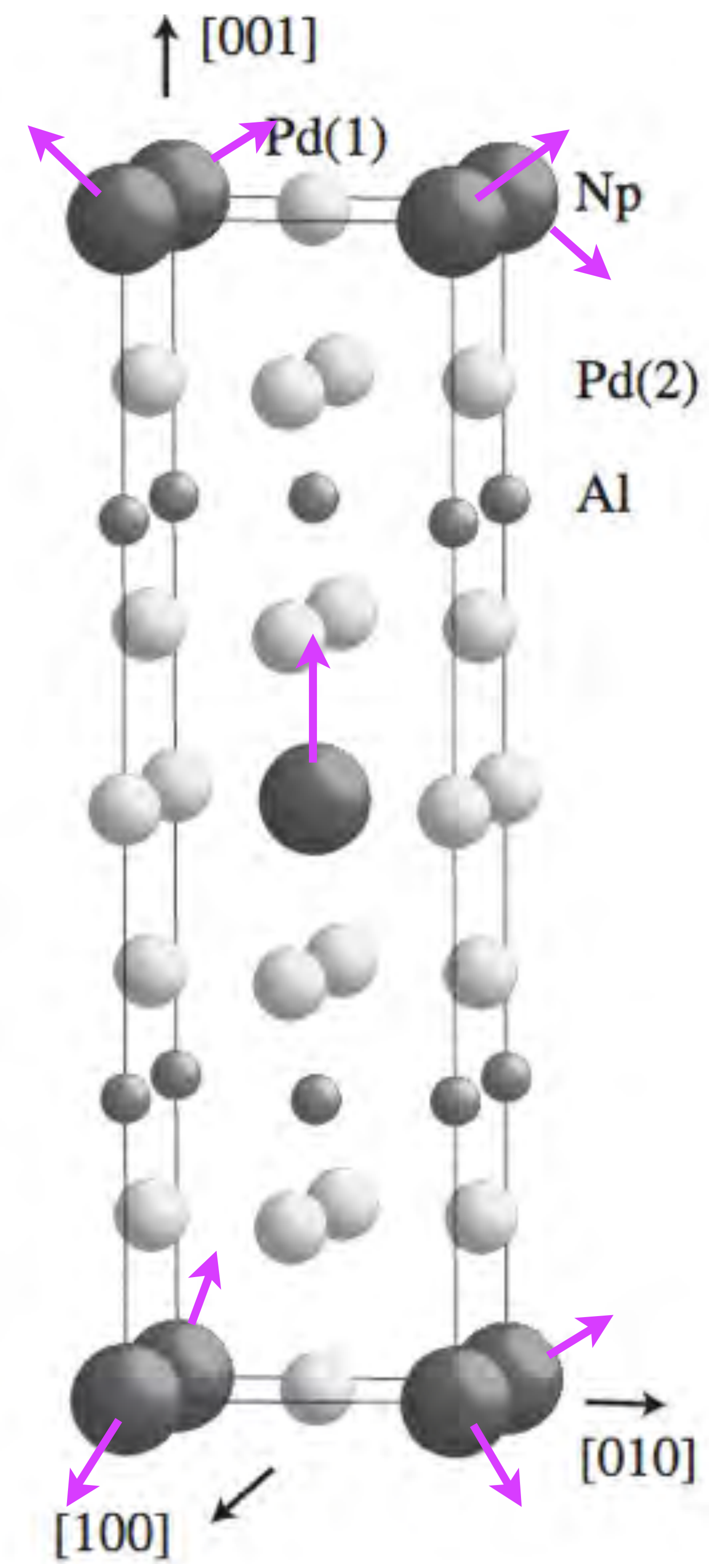
4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$



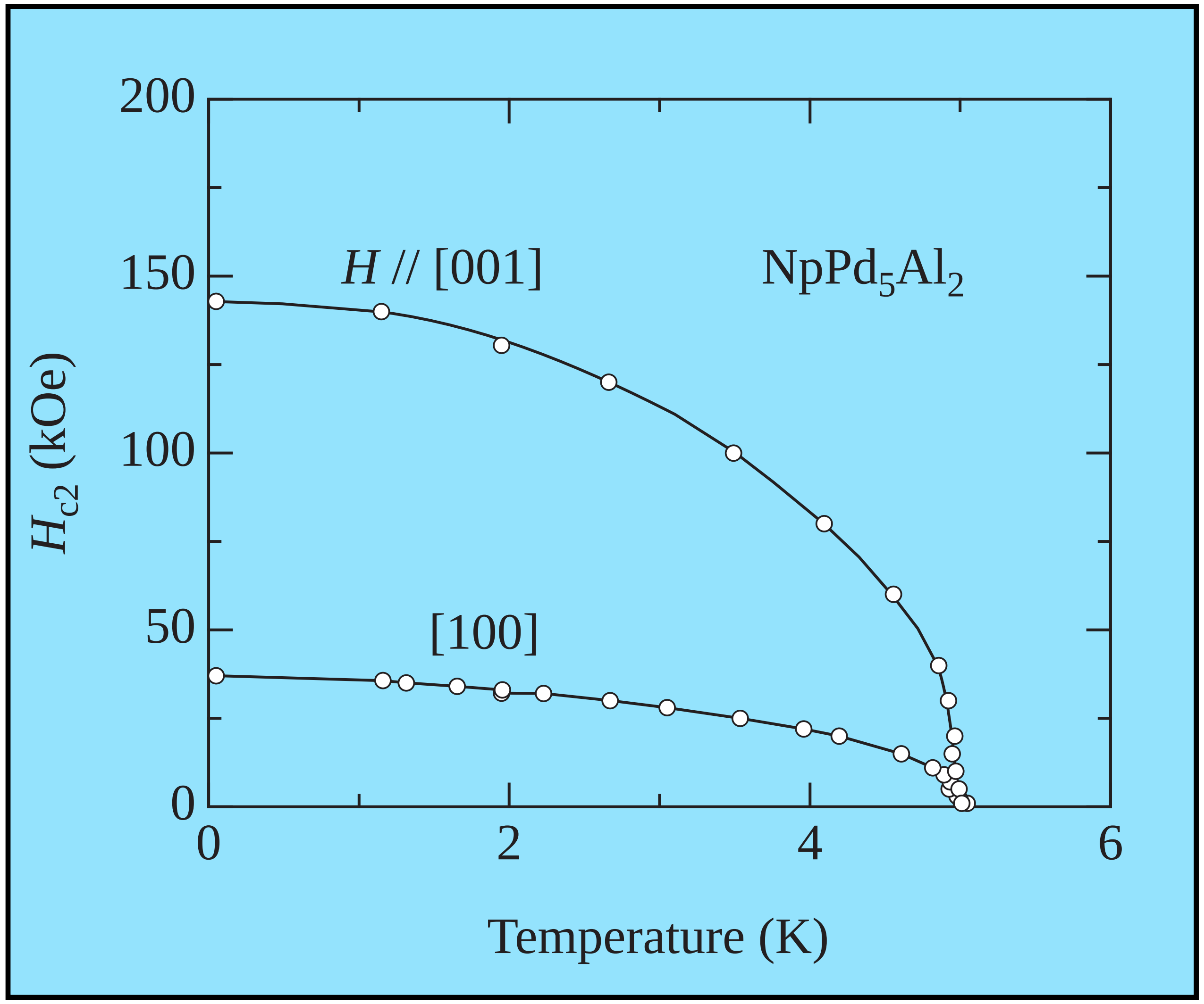


How does the spin form the condensate?

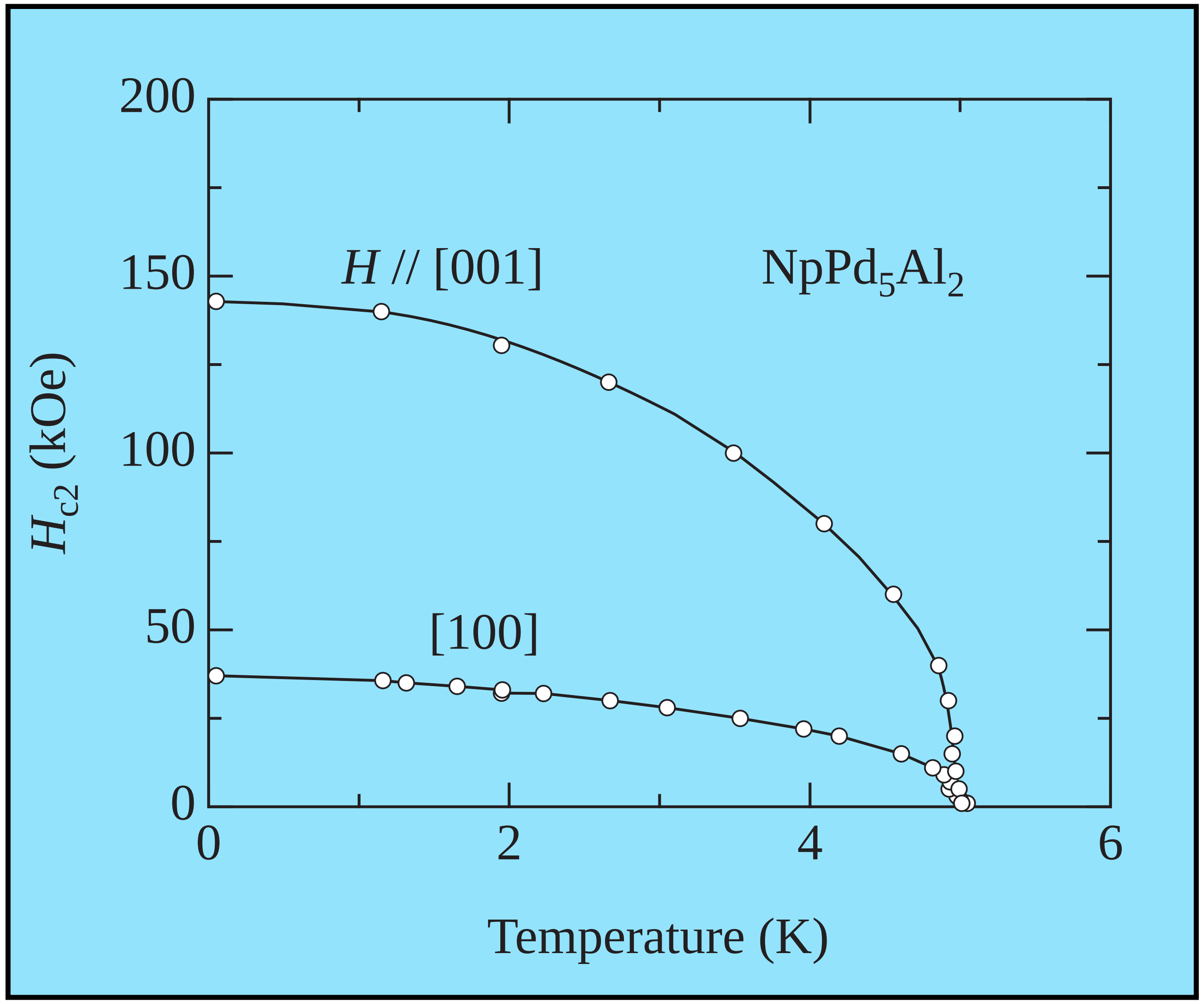
4.5K Heavy Fermion S.C

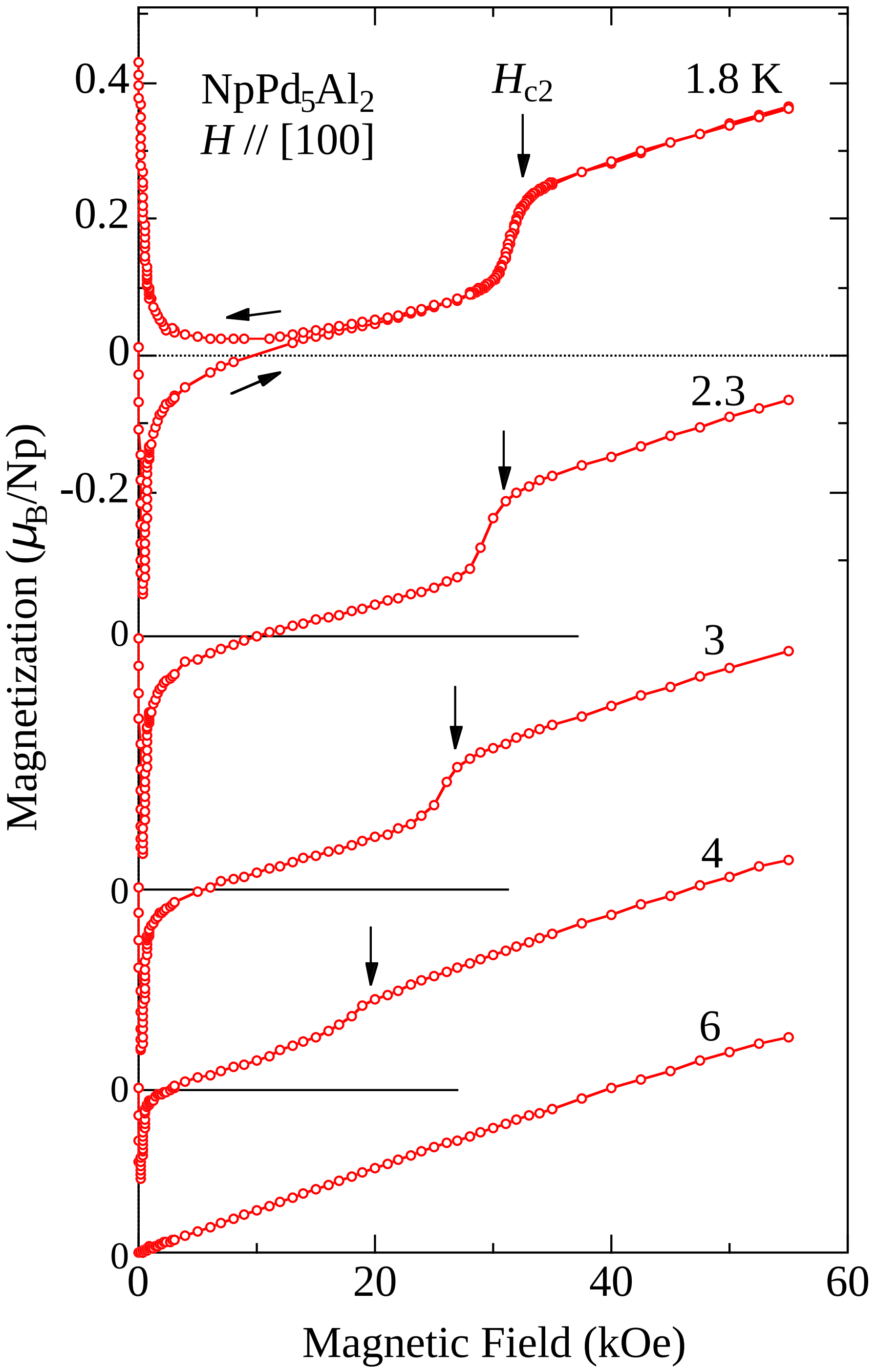
$NpAl_2Pd_5$

Aoki et al 2007

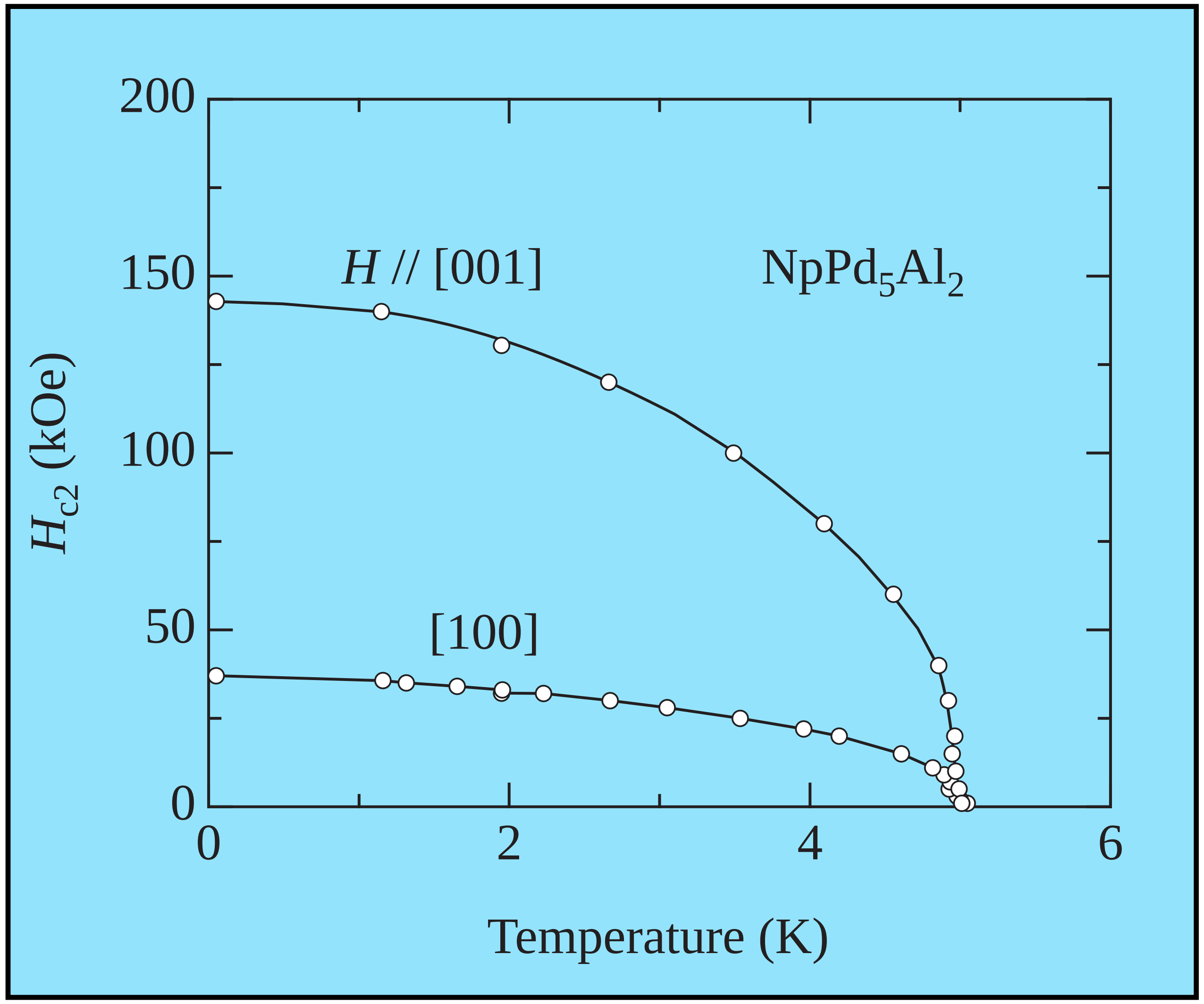


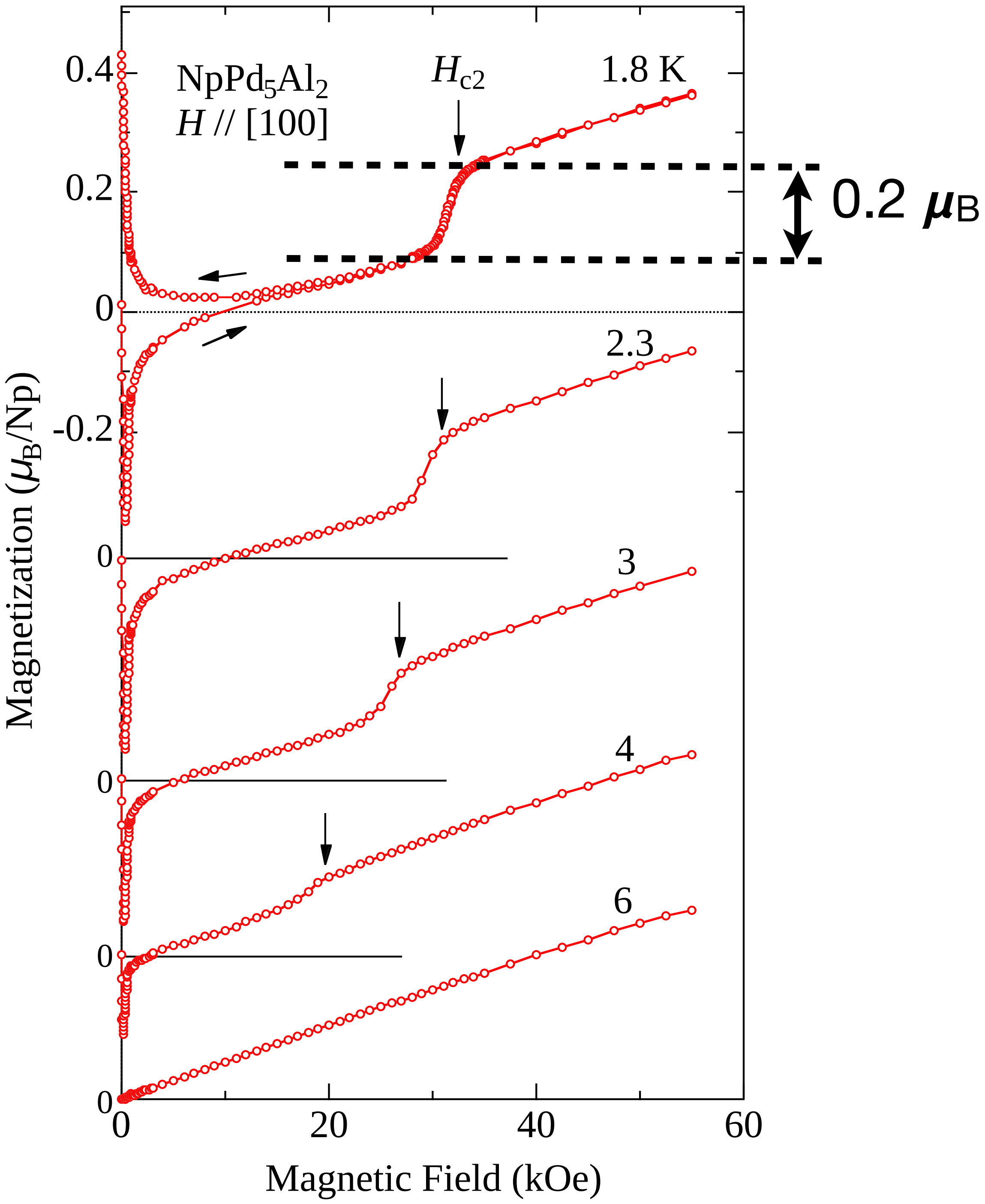
200
150
100
50
0
H_c2 (kOe)
H // [001]
NpPd5Al2
[100]
0
2
4
6
Temperature (K)





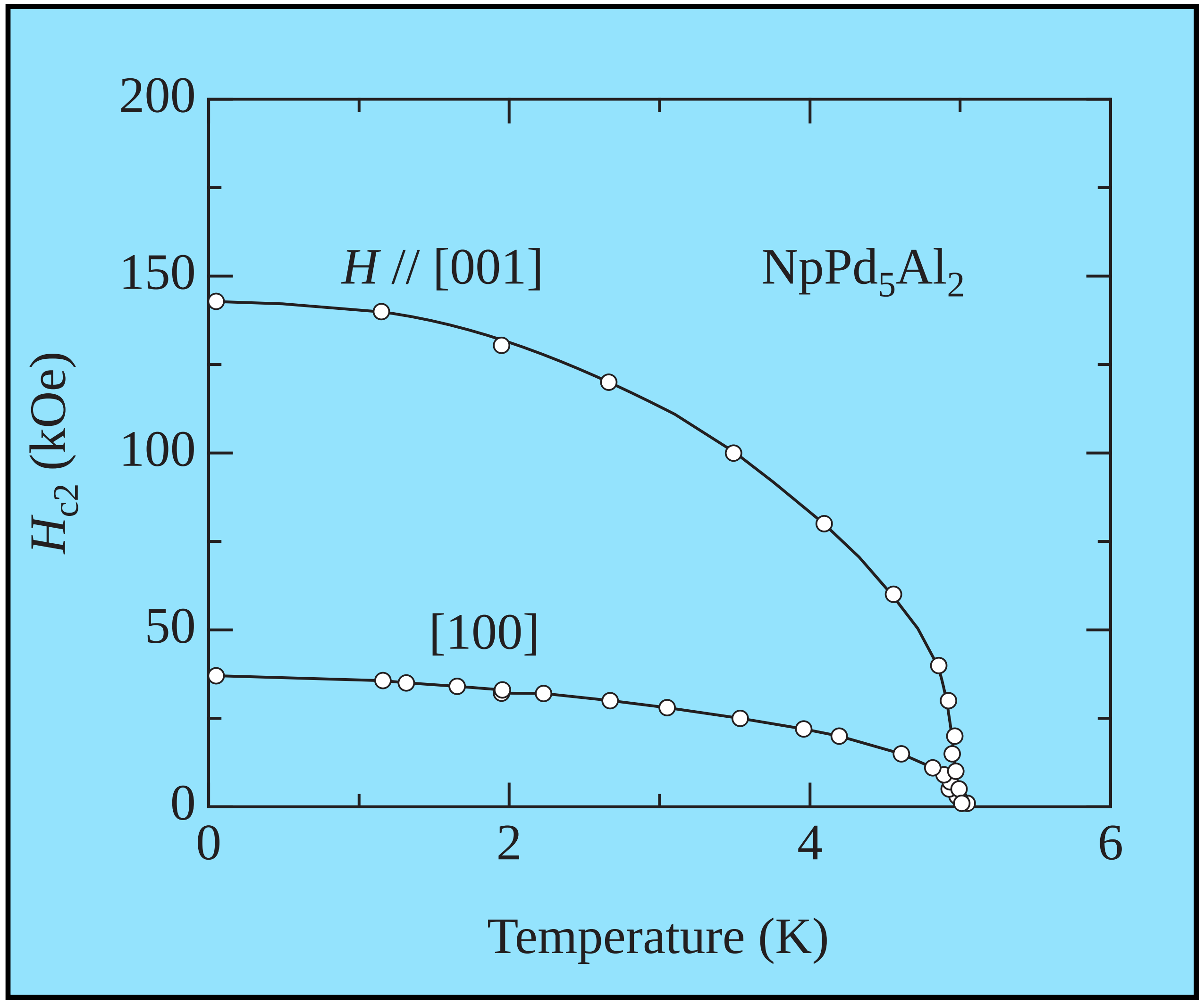
D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

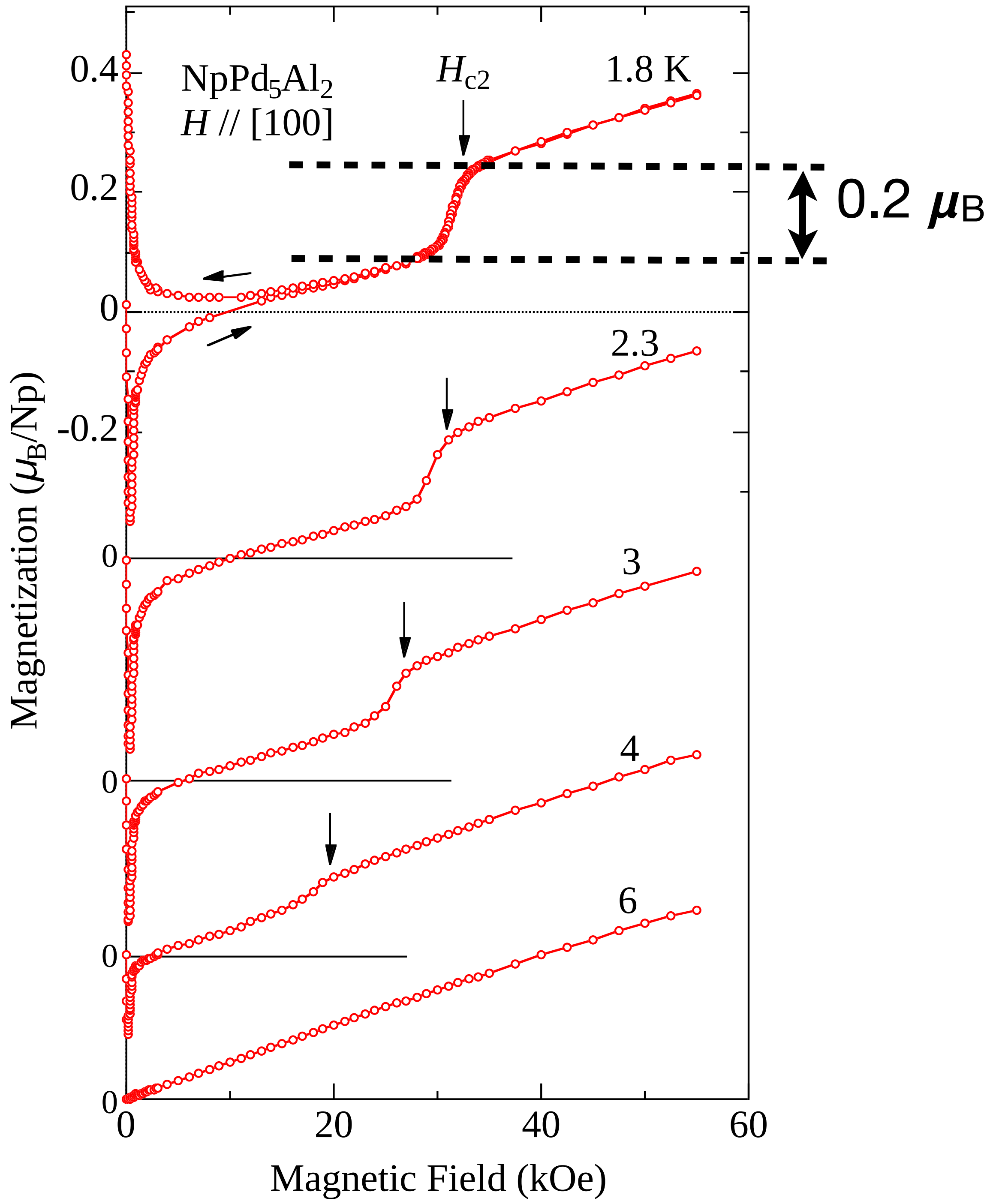




D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

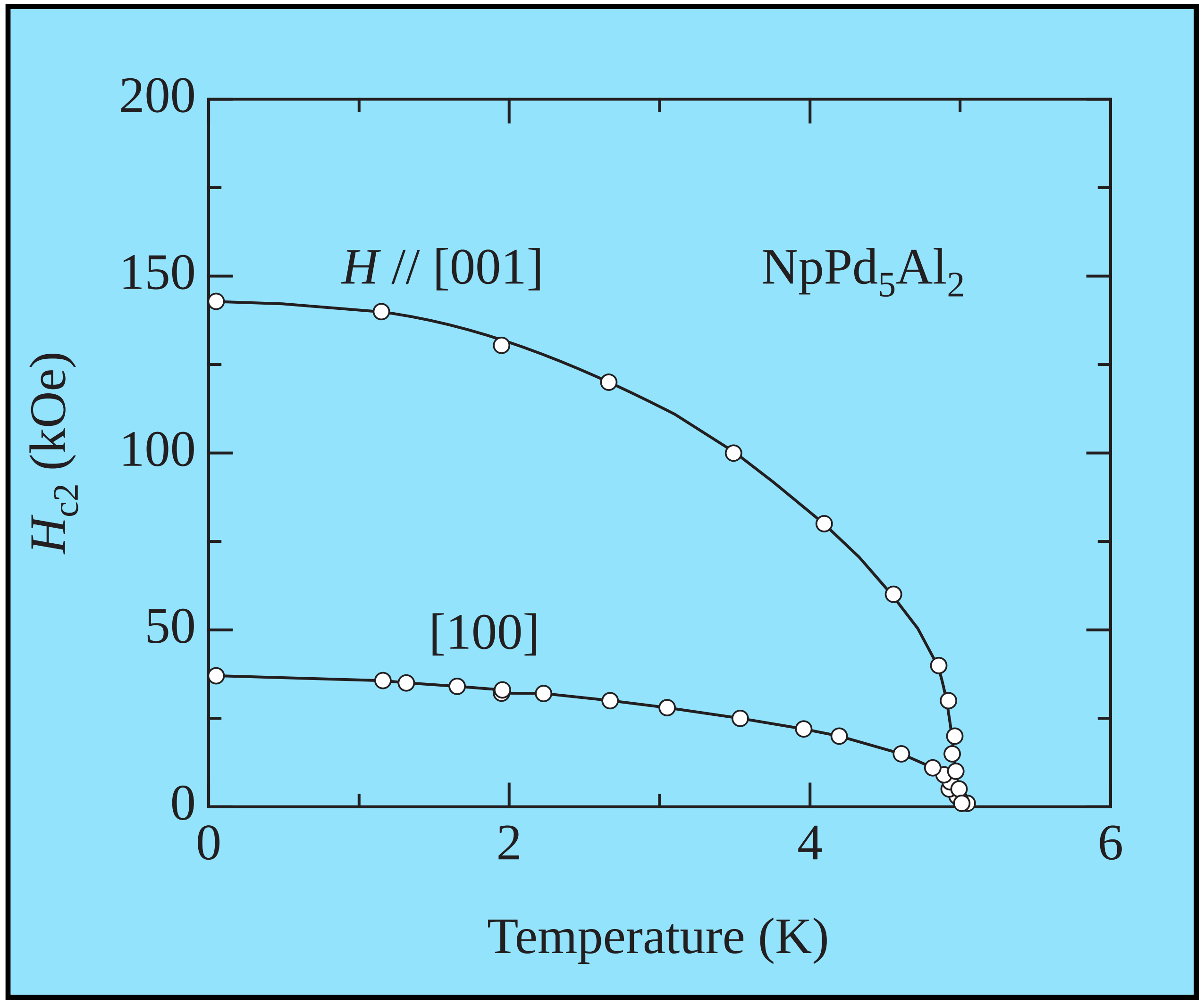
Large first order jump in magnetization at H_{c2}.

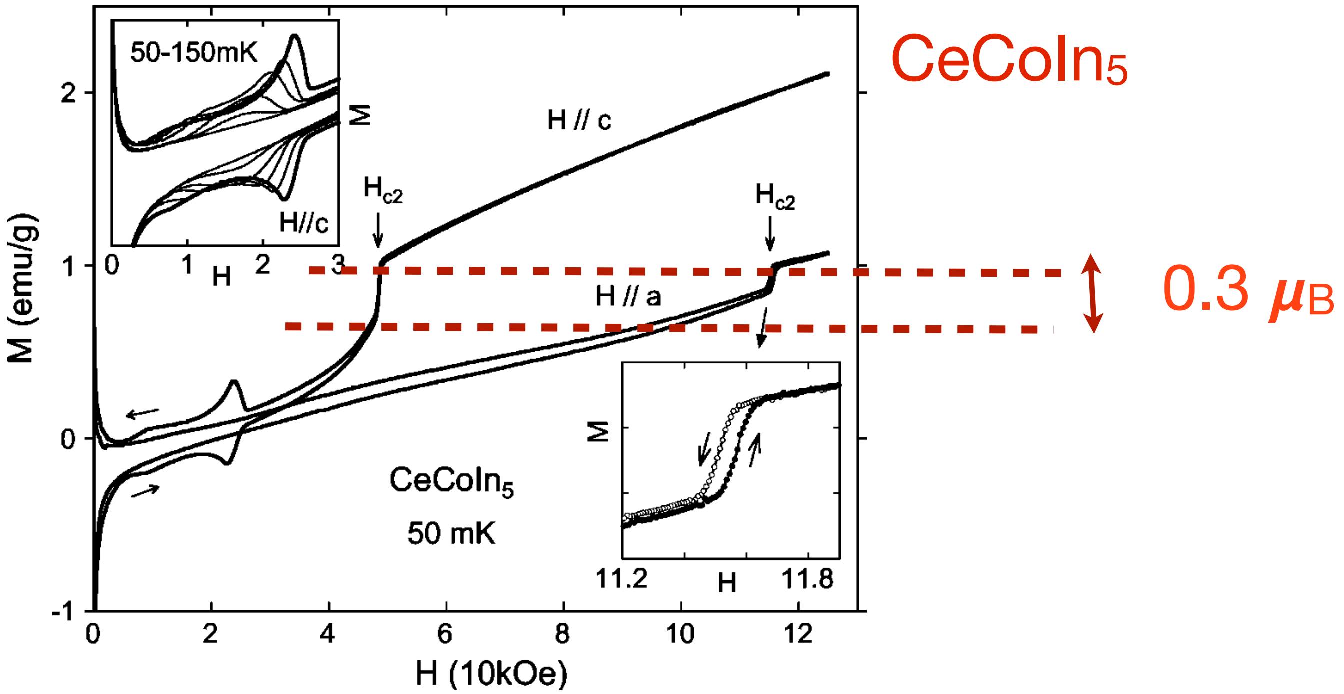




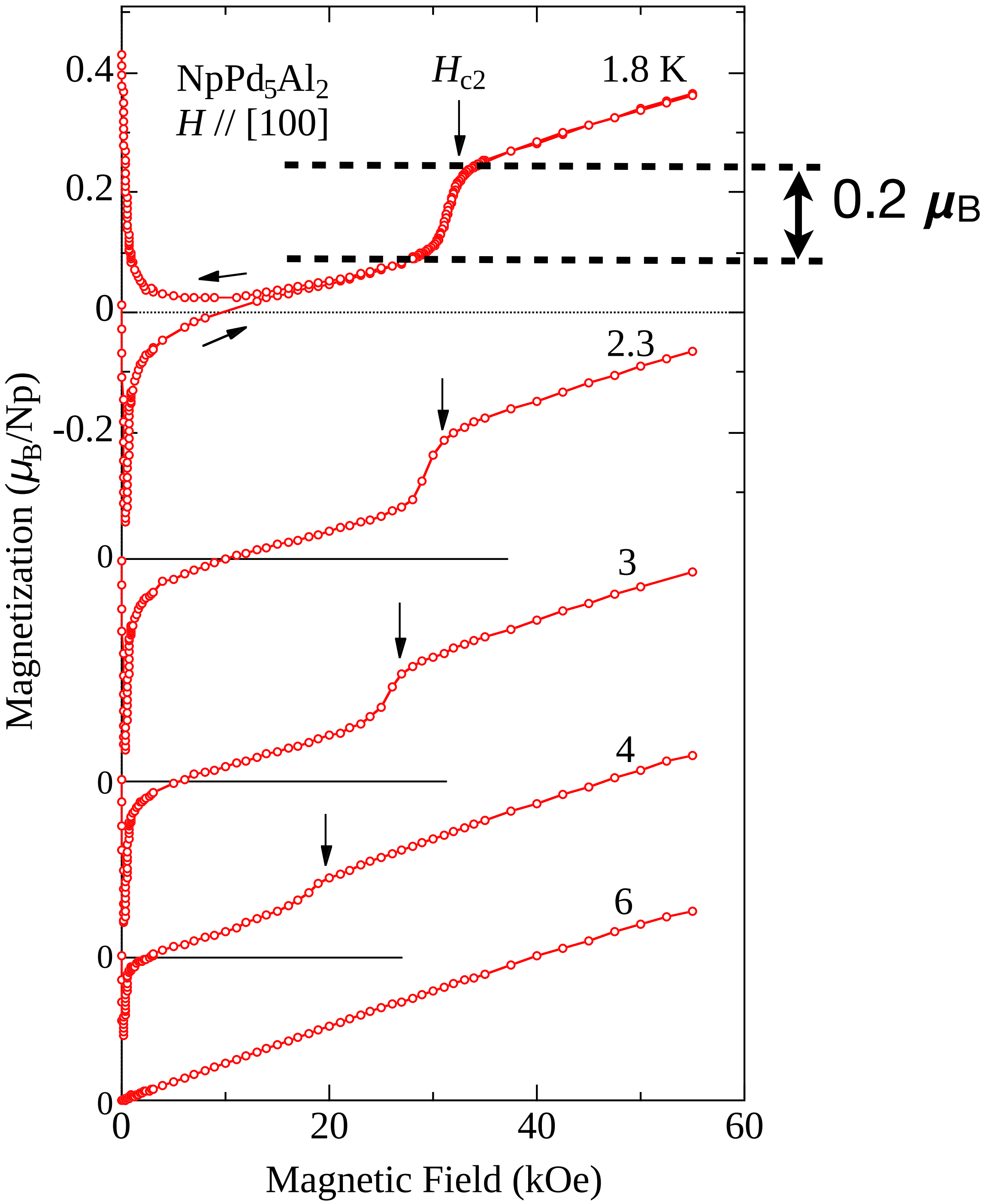
D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

Large first order jump in magnetization at H_{c2}.





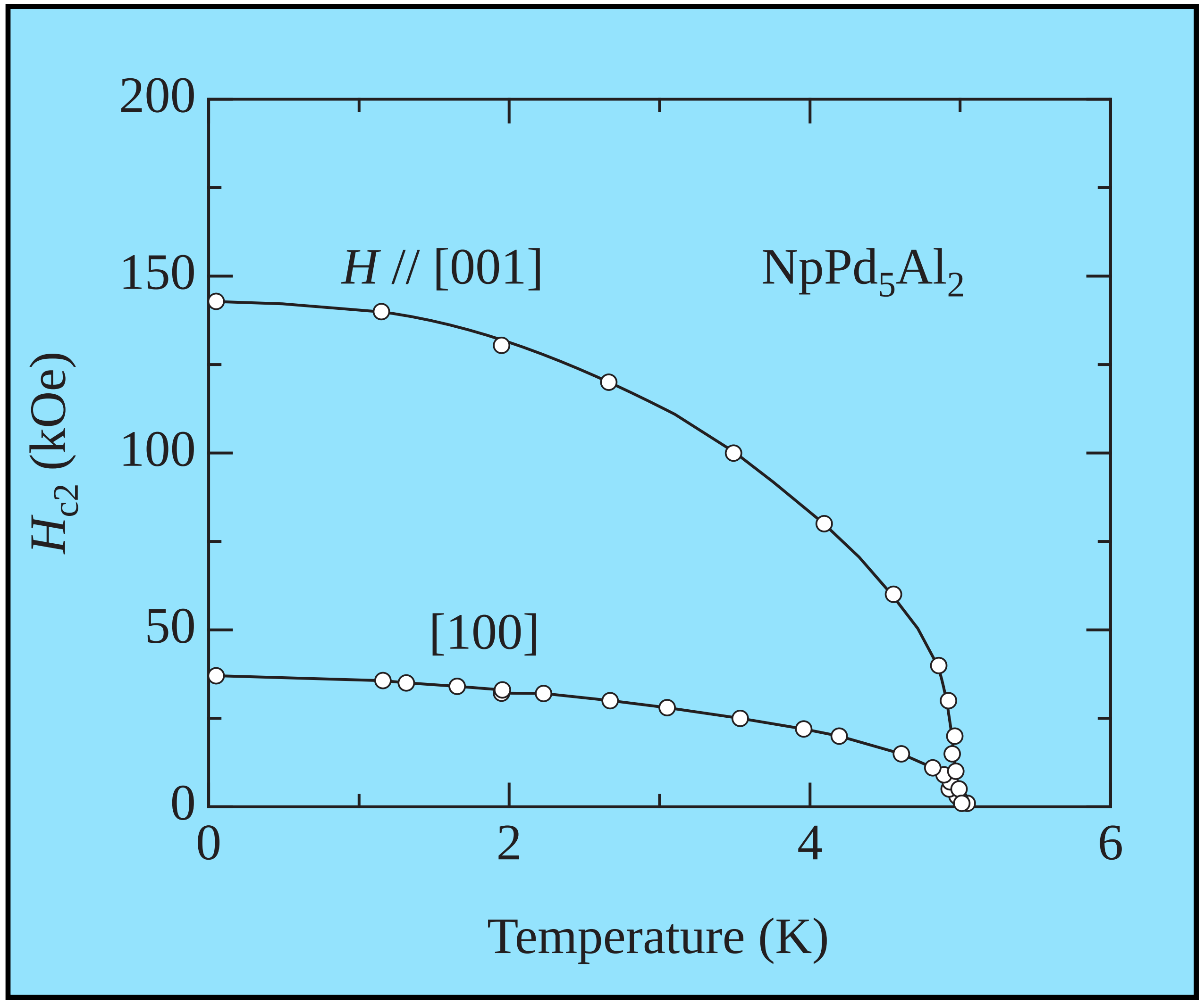
T. Tayama et al., RPB **65**, 180504R (2002)

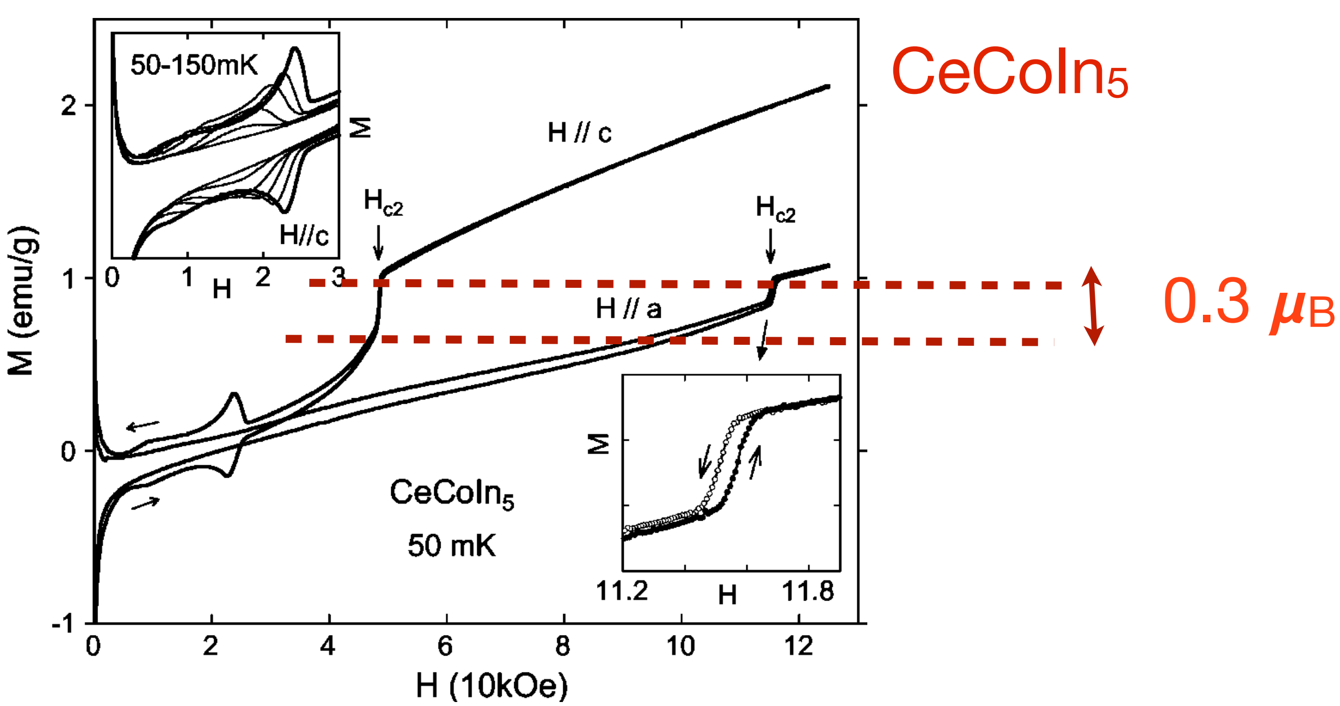


D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

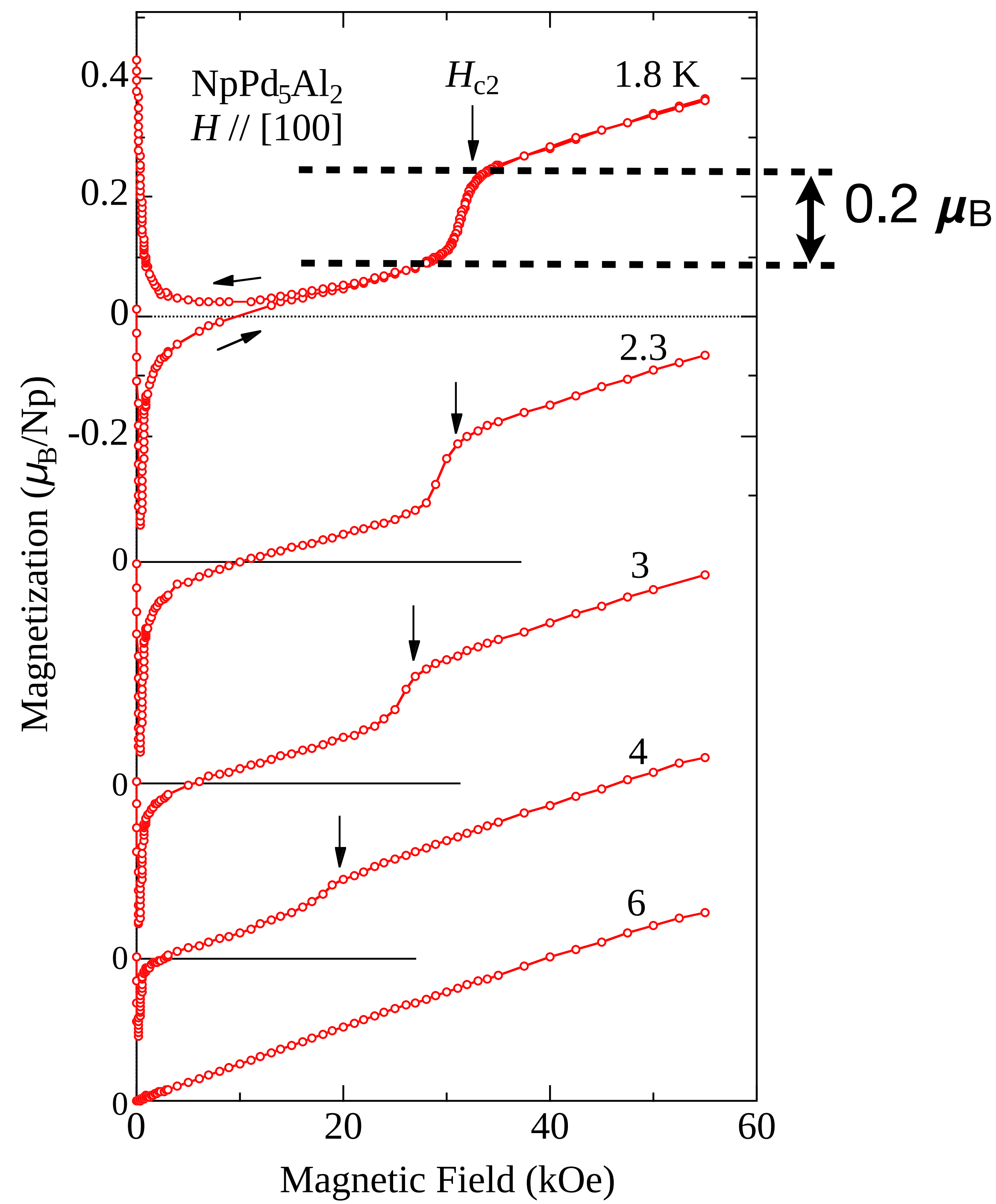
Large first order jump in magnetization at H_{c2}.

Signals a release of the local moment from the condensate.





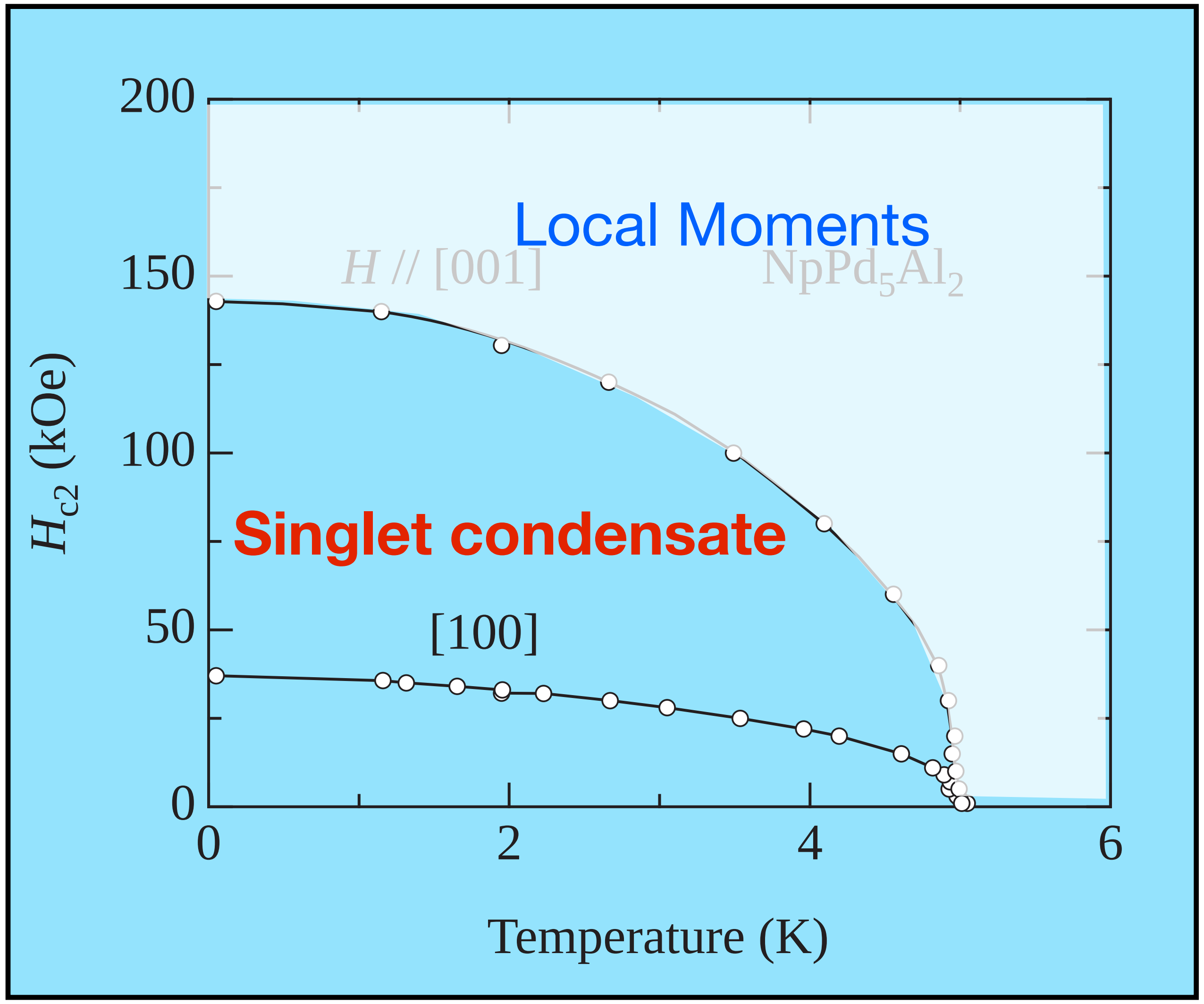
T. Tayama et al., RPB **65**, 180504R (2002)

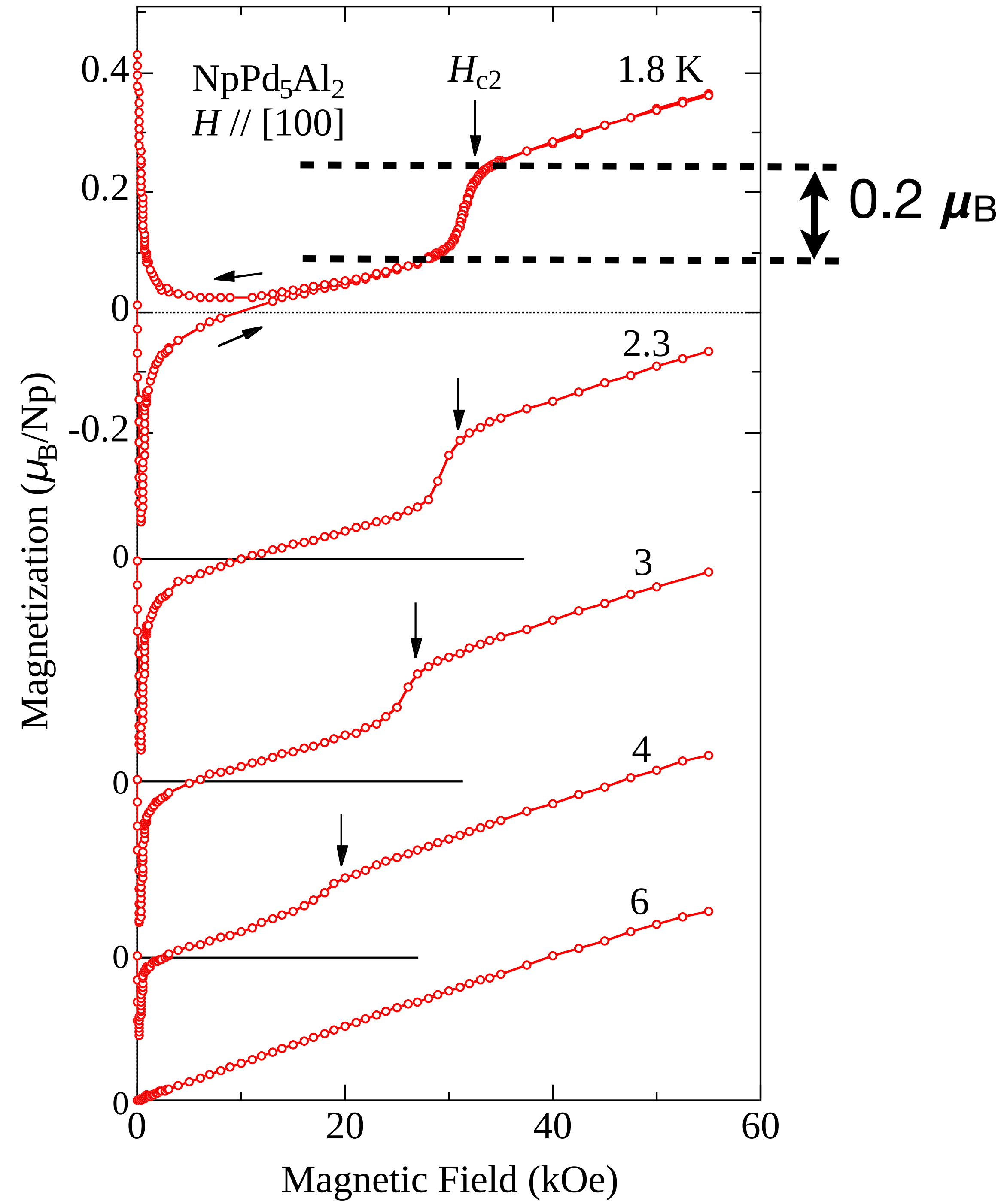


D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

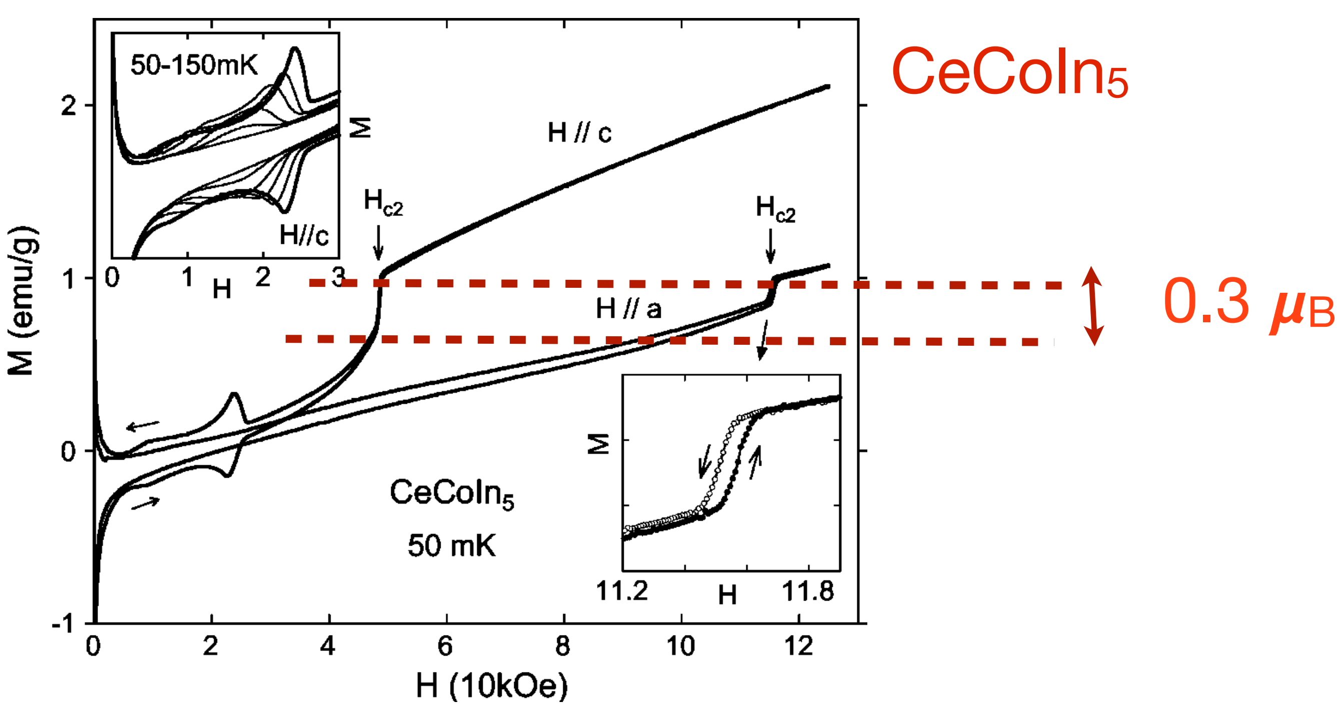
Large first order jump in magnetization at H_{c2}.

Signals a release of the local moment from the condensate.

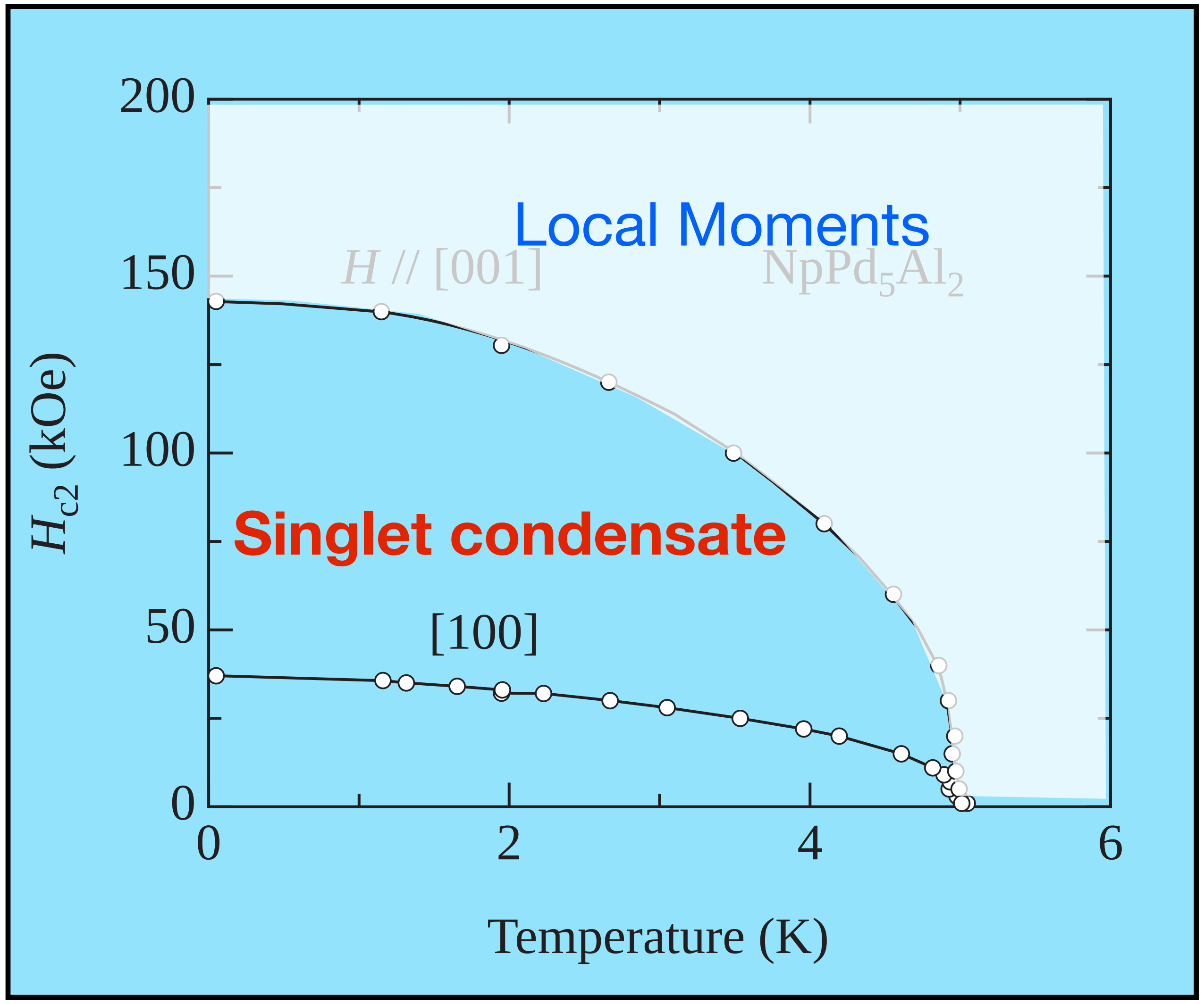


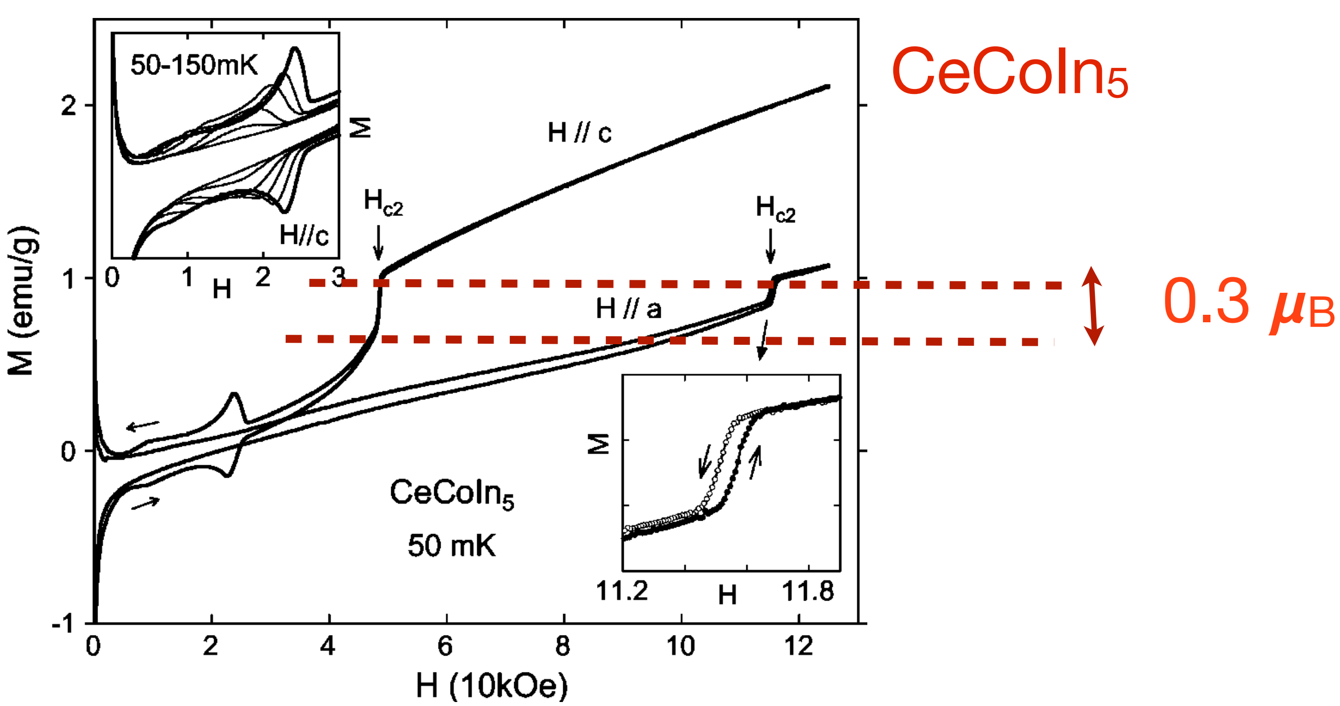


D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.



T. Tayama et al., RPB **65**, 180504R (2002)





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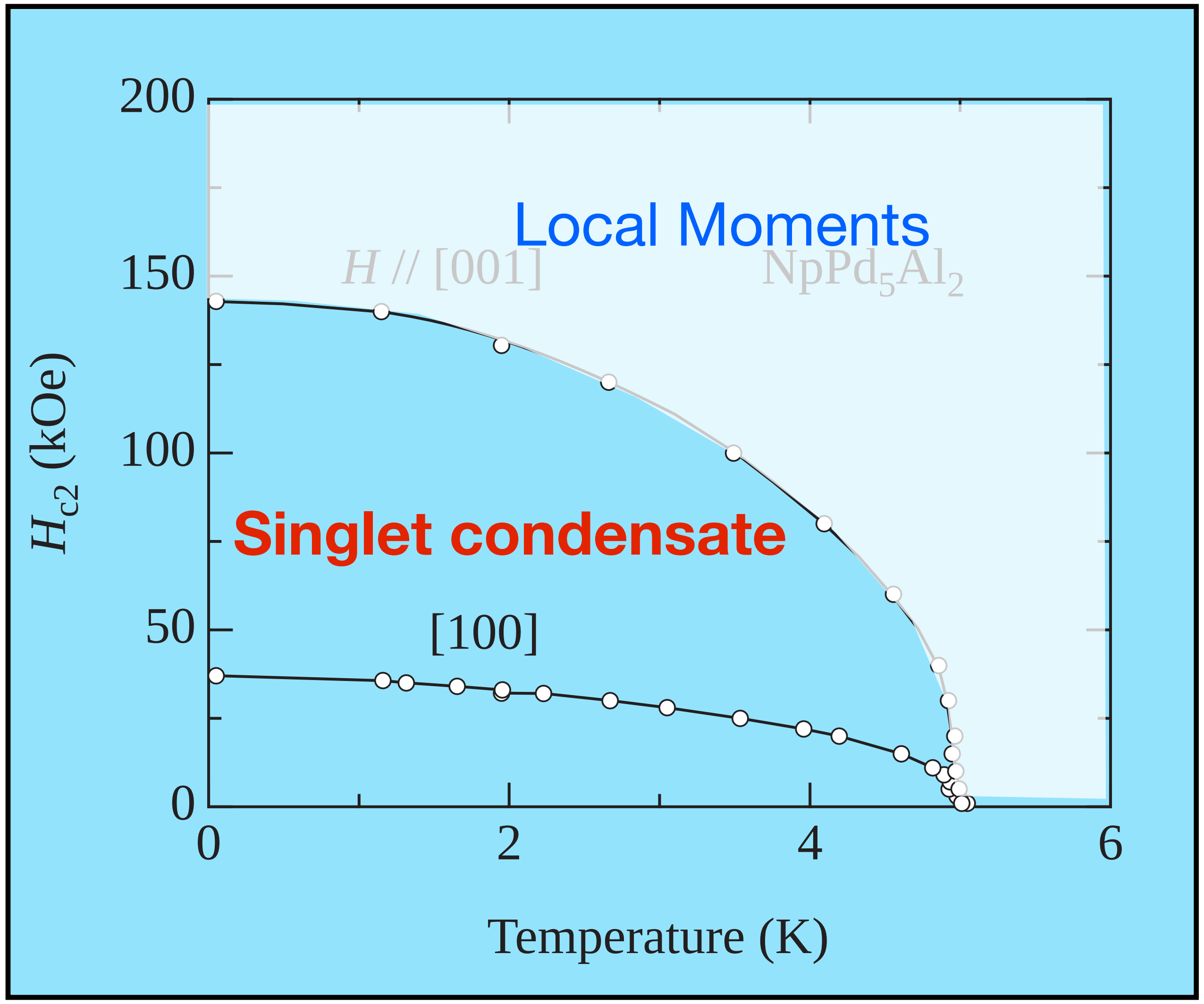
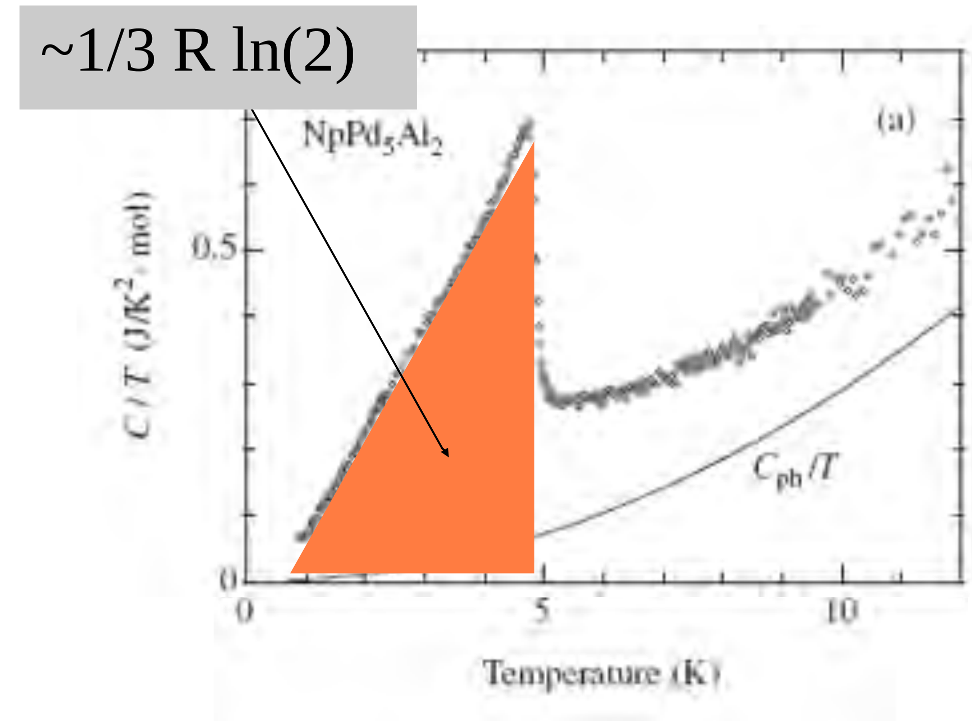
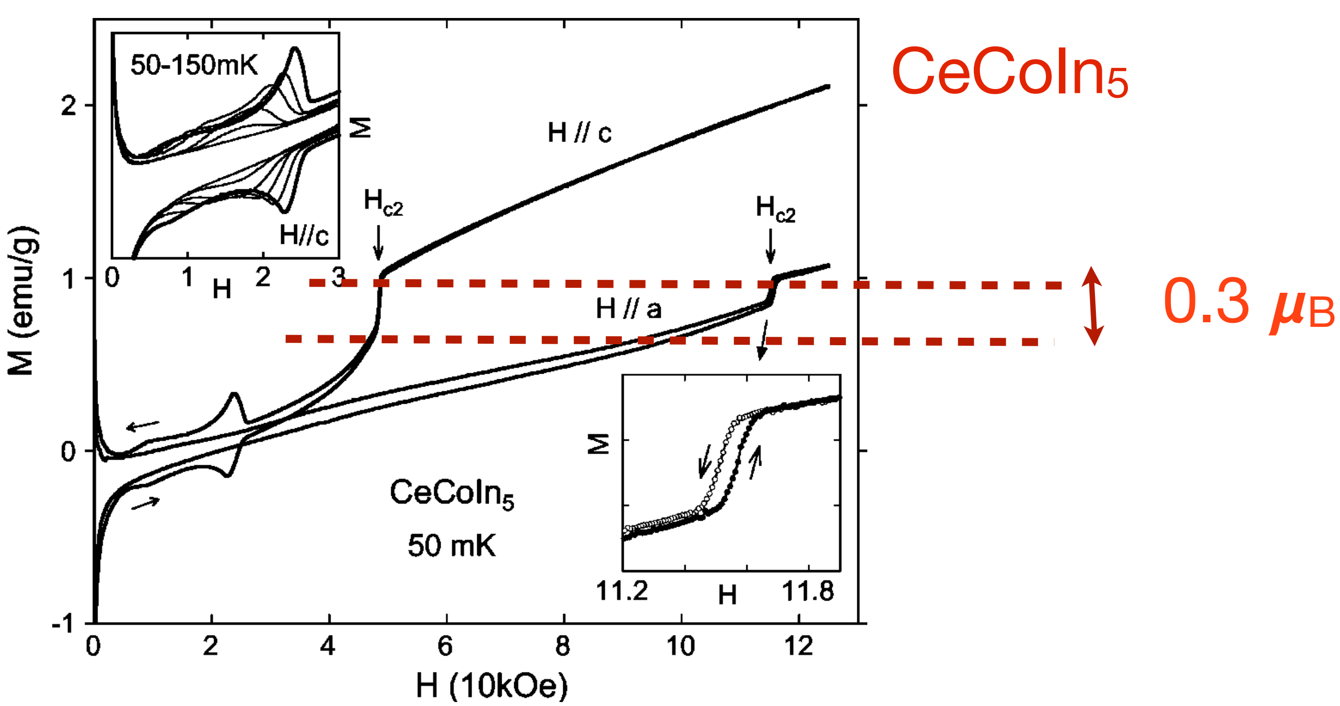
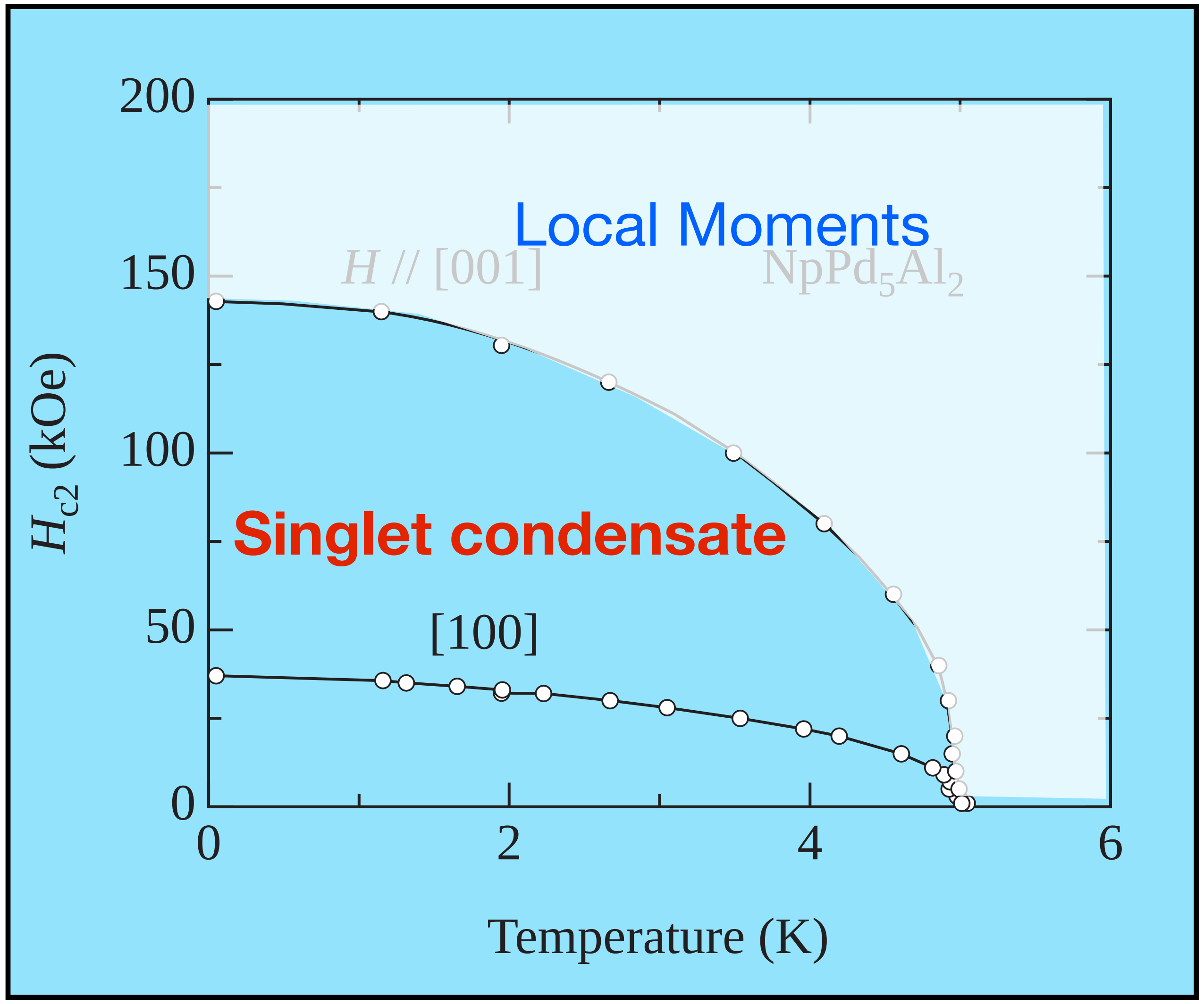
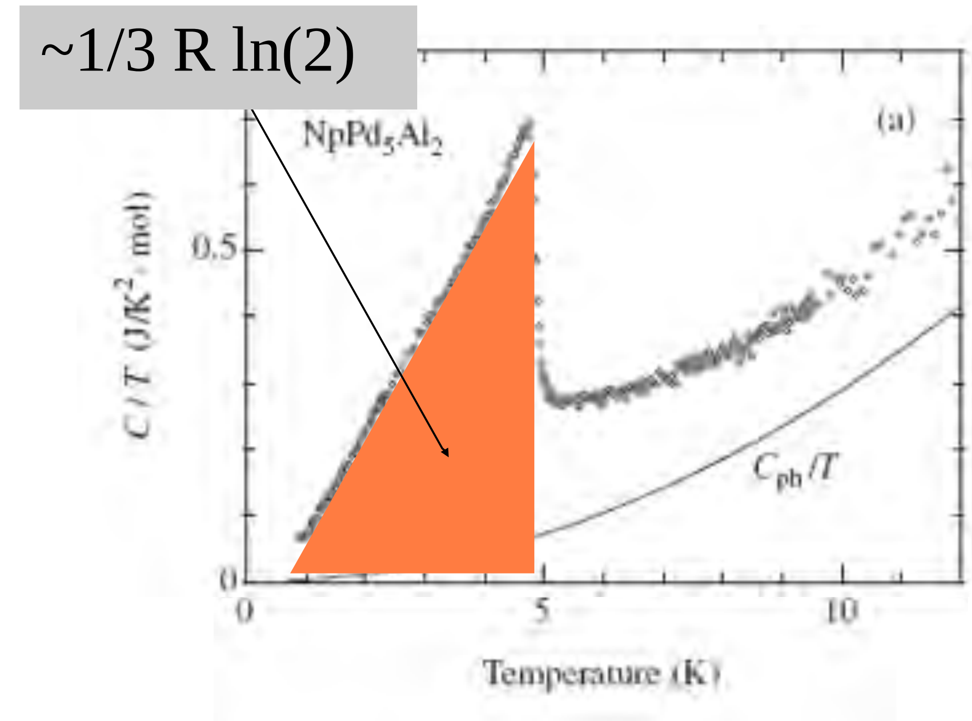






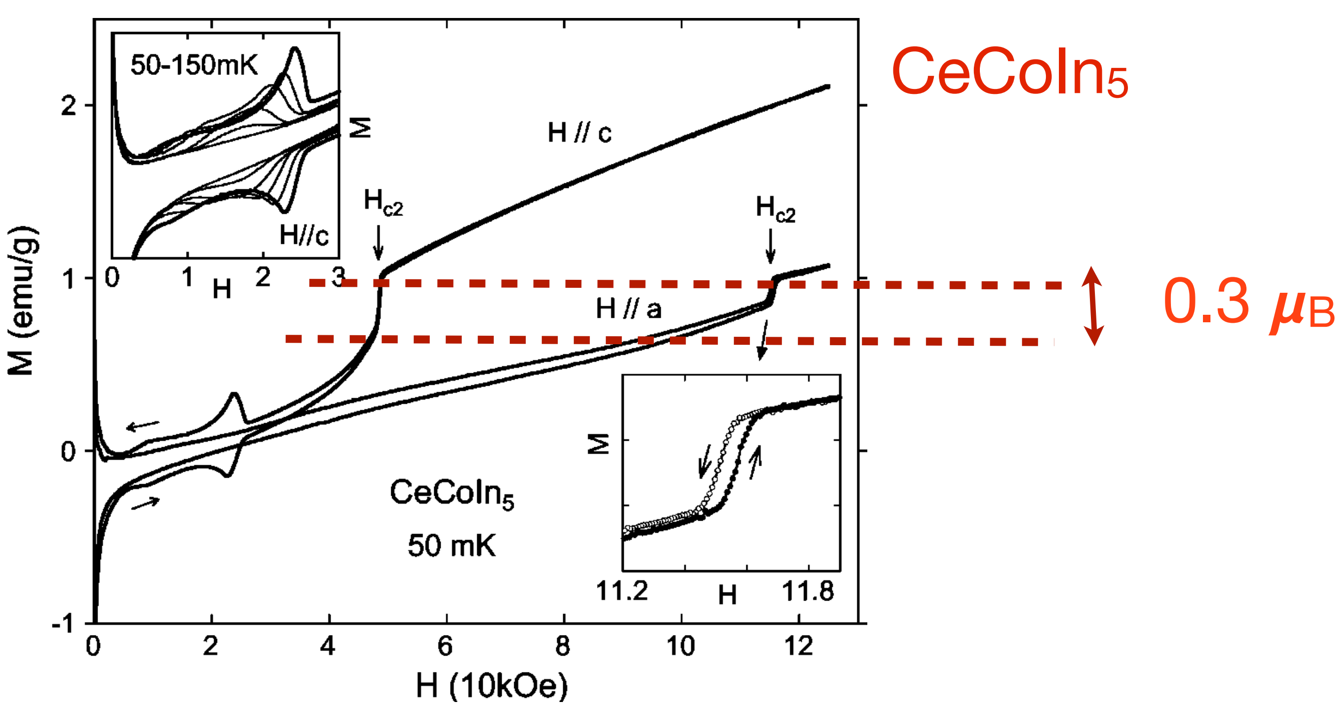
T. Tayama et al., RPB **65**, 180504R (2002)





Paradox:

How can a neutral magnetic moments form a charged superconducting condensate?



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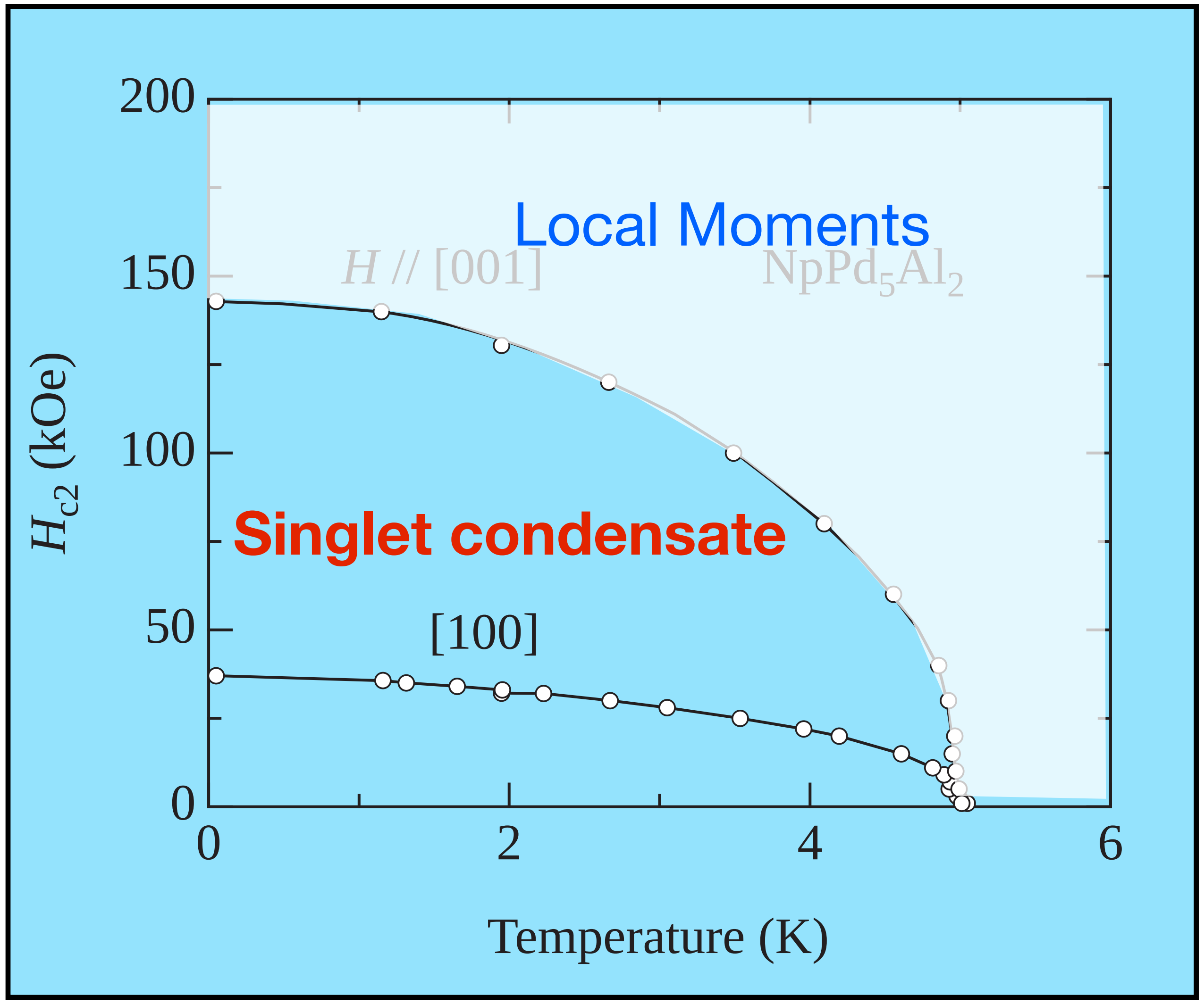

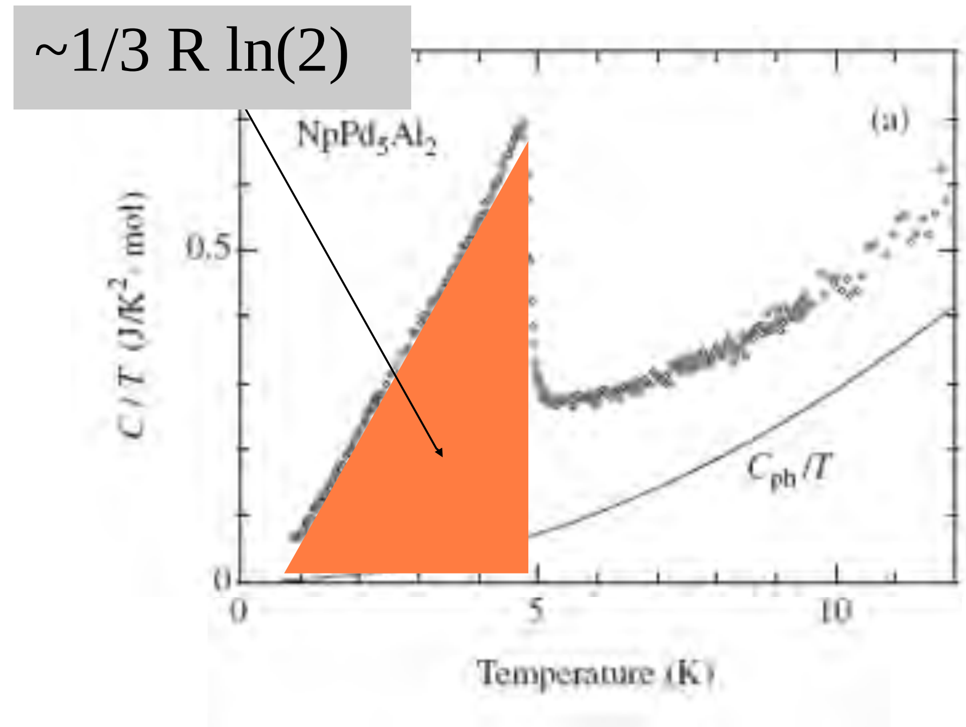

Paradox:

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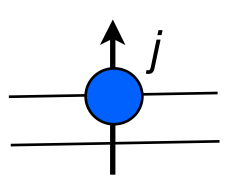
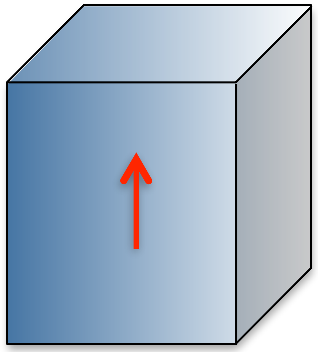
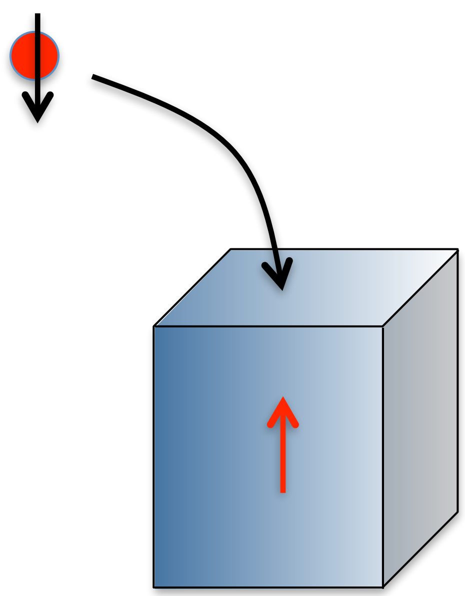
$\prod_{\otimes j}$ {  } $\otimes$ Charge = Condensate Hilbert Space

Composite pairing Hypothesis.

Coherence and composite fermions



Coherence and composite fermions



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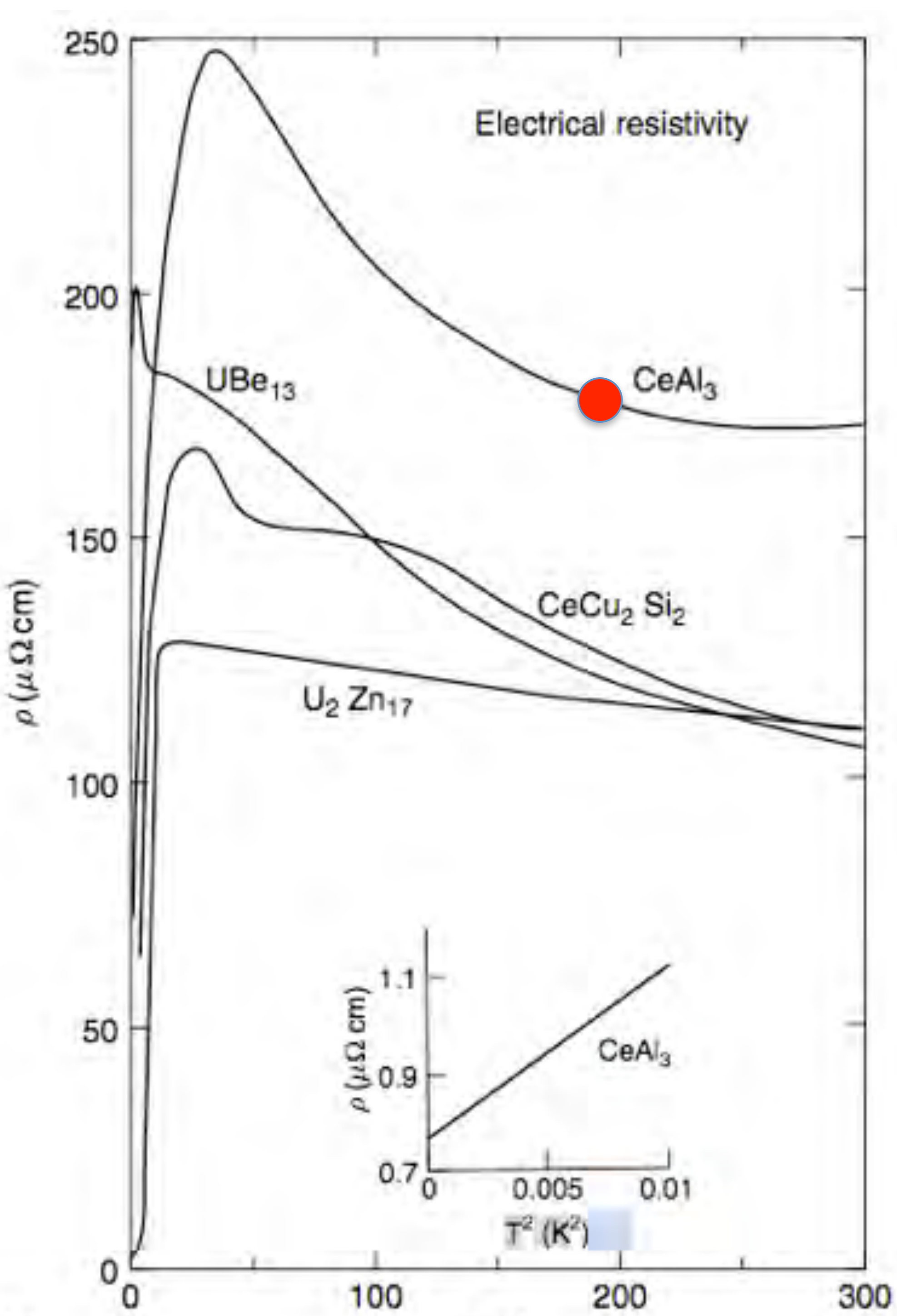
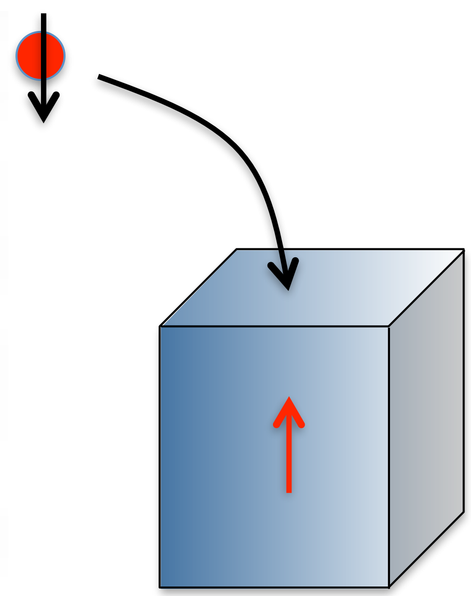
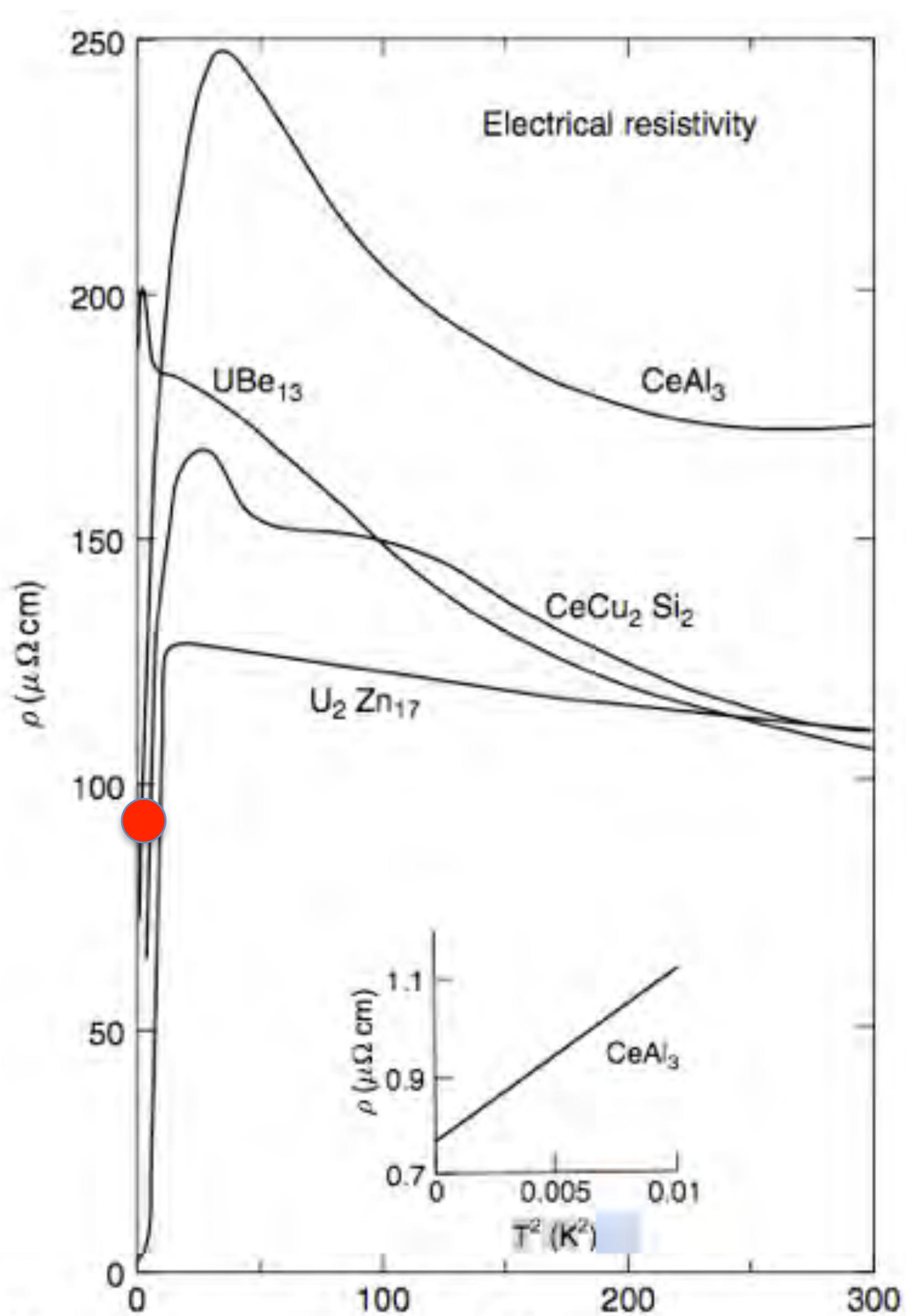
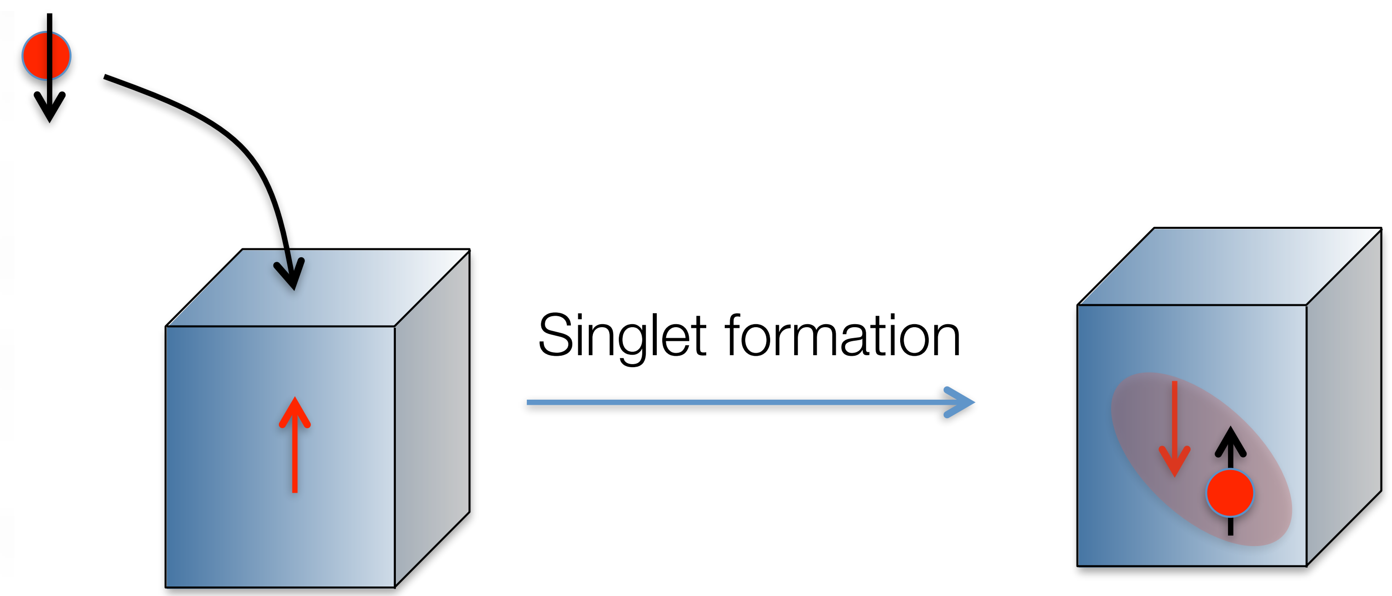


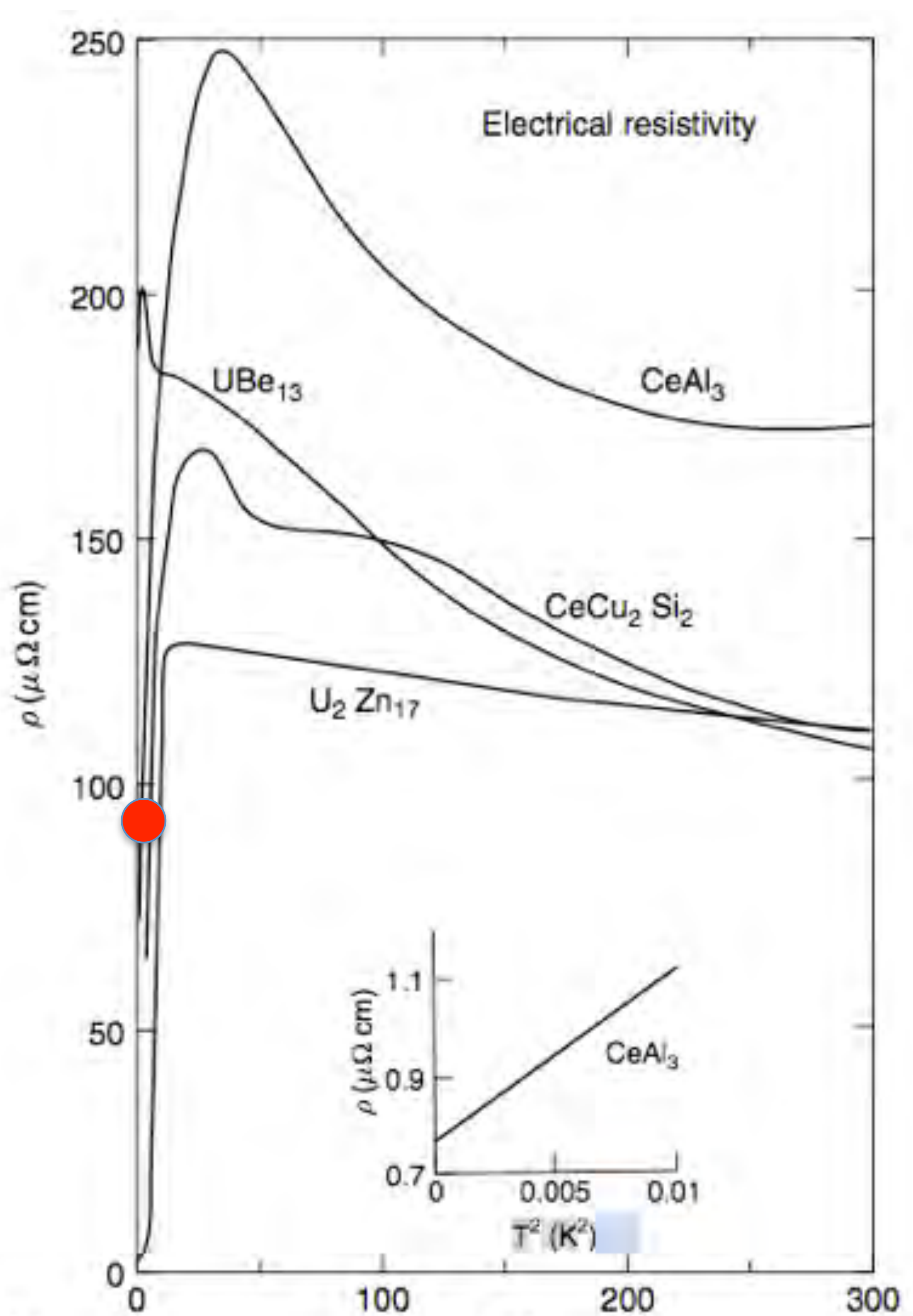


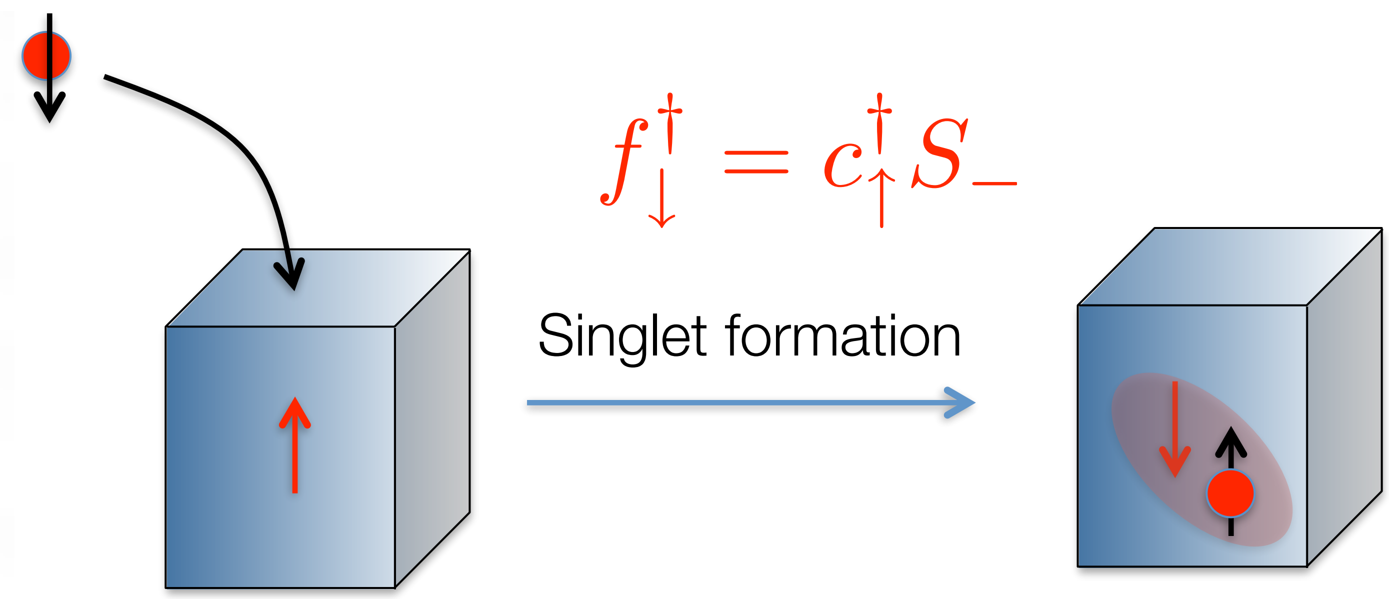
Coherence and composite fermions





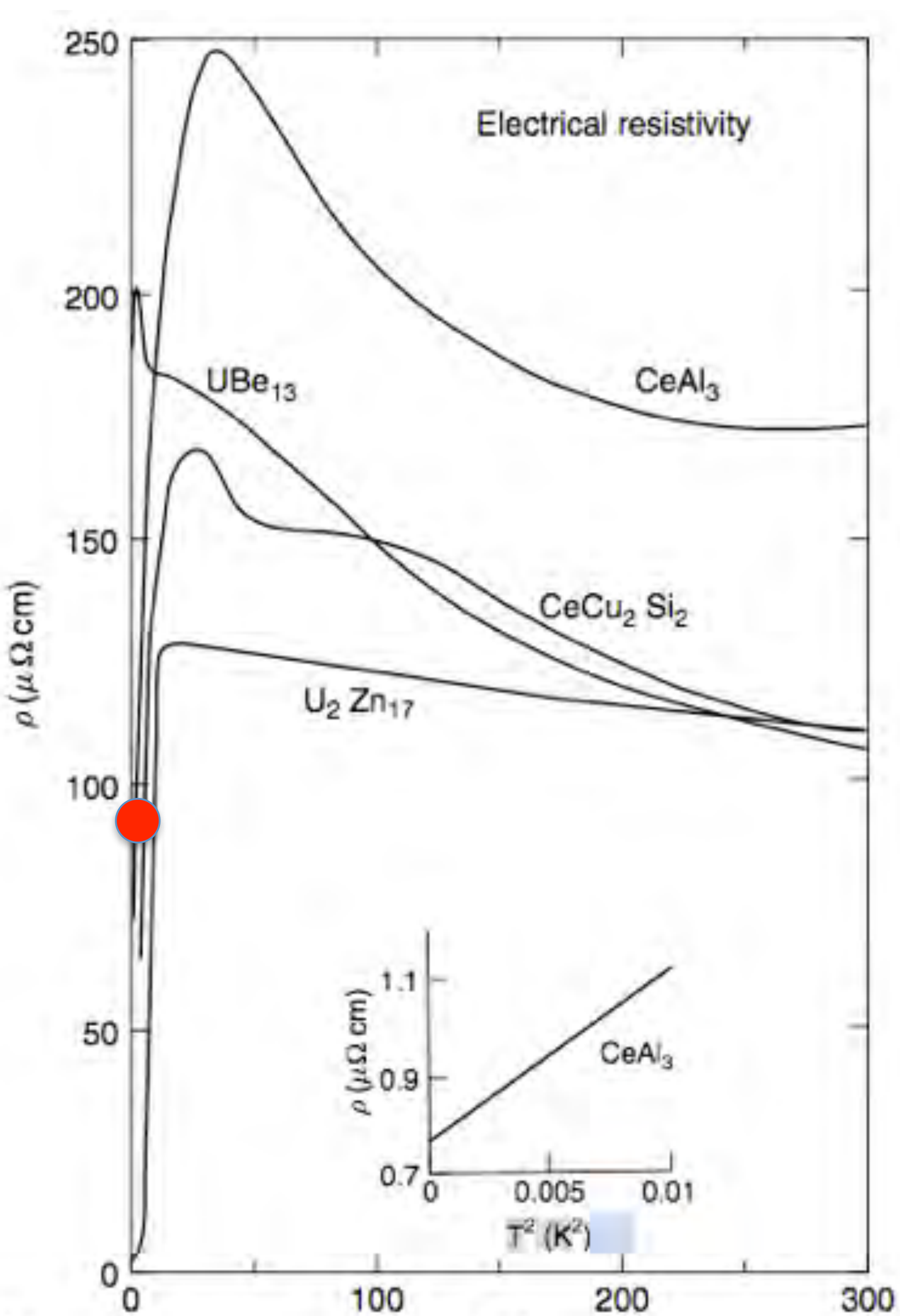
Coherence and composite fermions

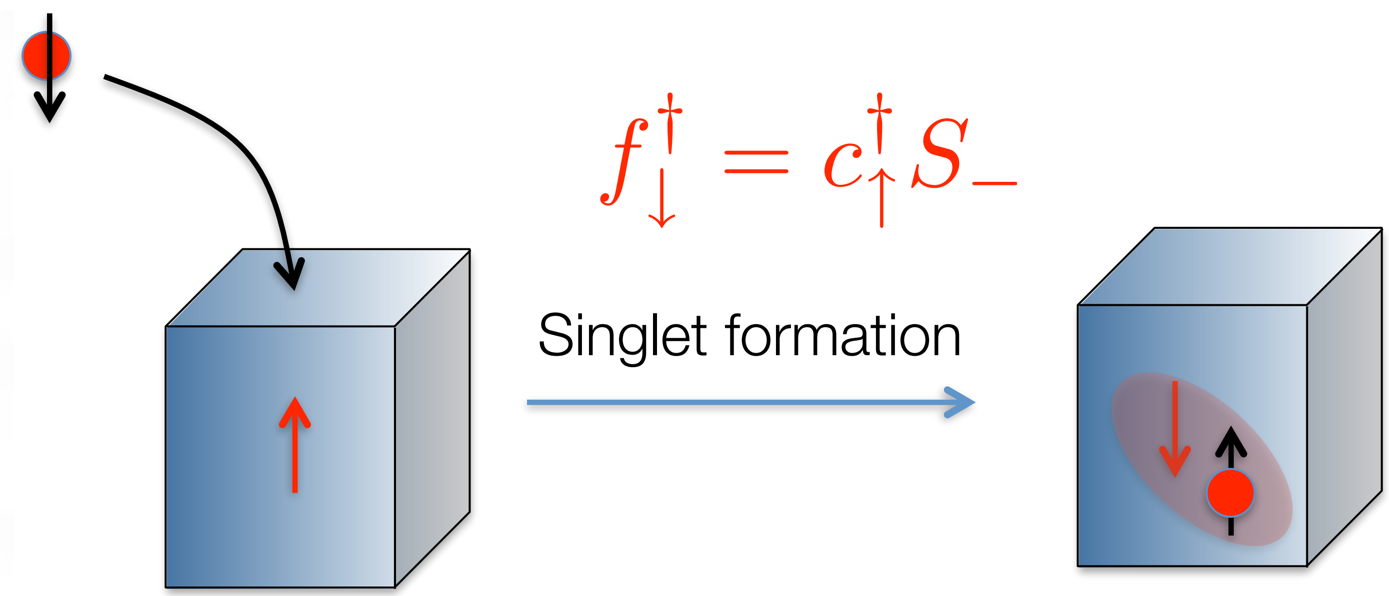




Heavy electron = (electron x spinflip)

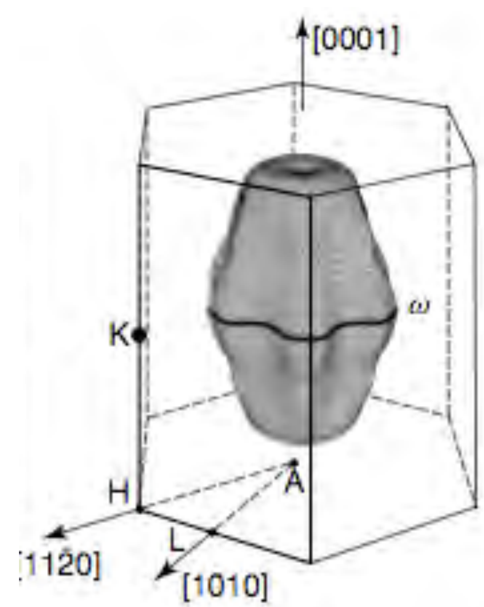
Coherence and composite fermions

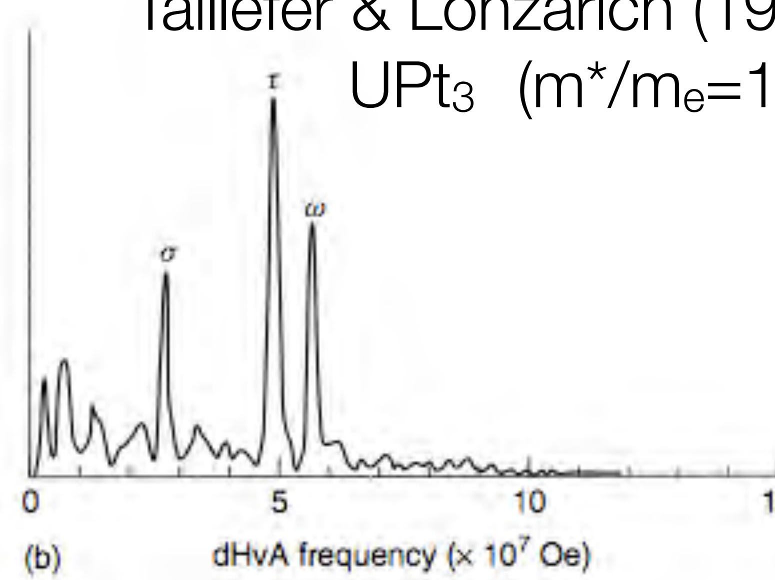




$$f^\dagger_\downarrow = c^\dagger_\uparrow S_-$$

Heavy electron = (electron x spinflip)

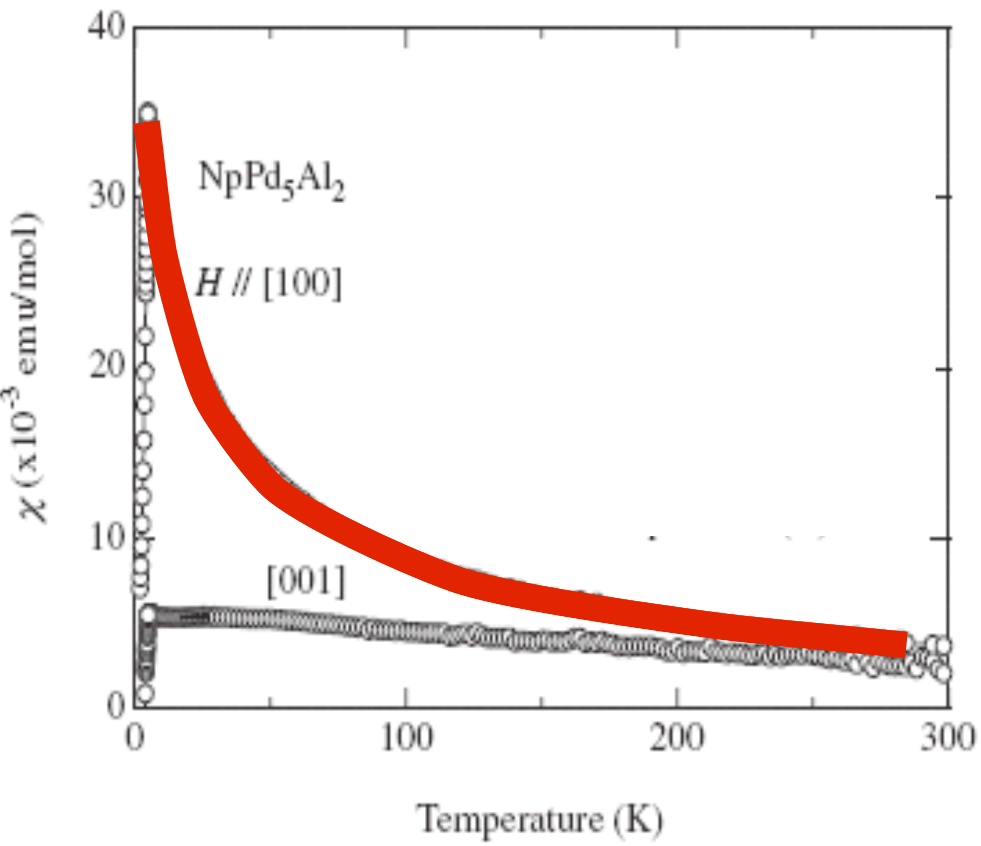


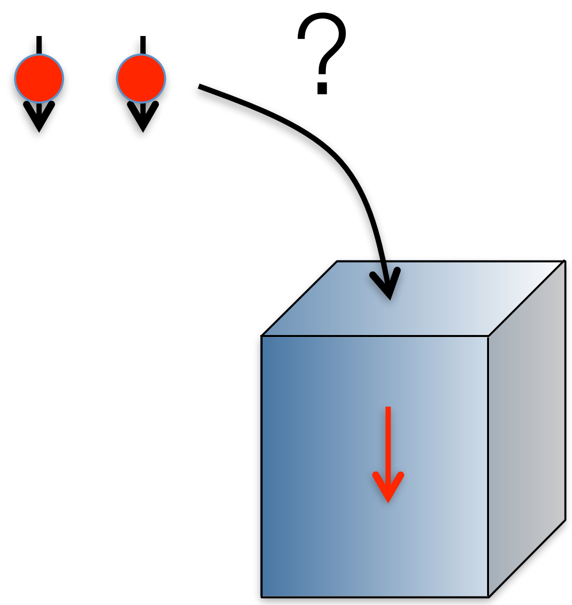


Taillefer & Lonzarich (1985)
UPt_3 (m^*/m_e=120)

Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$





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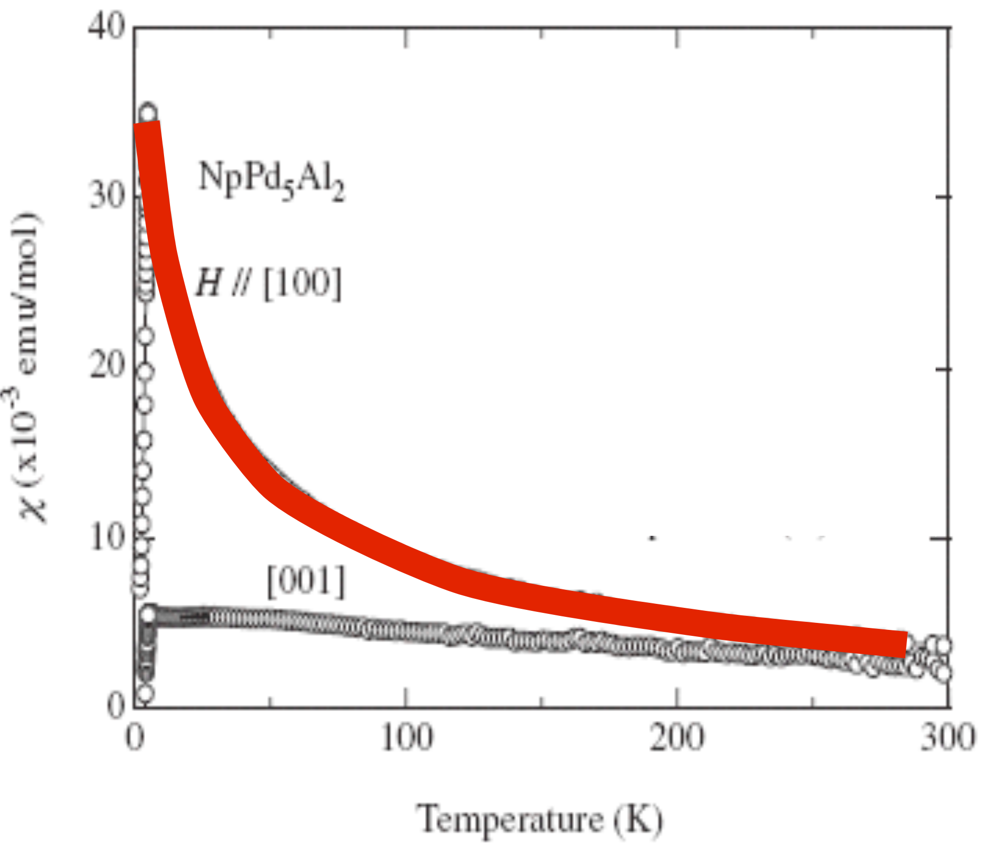

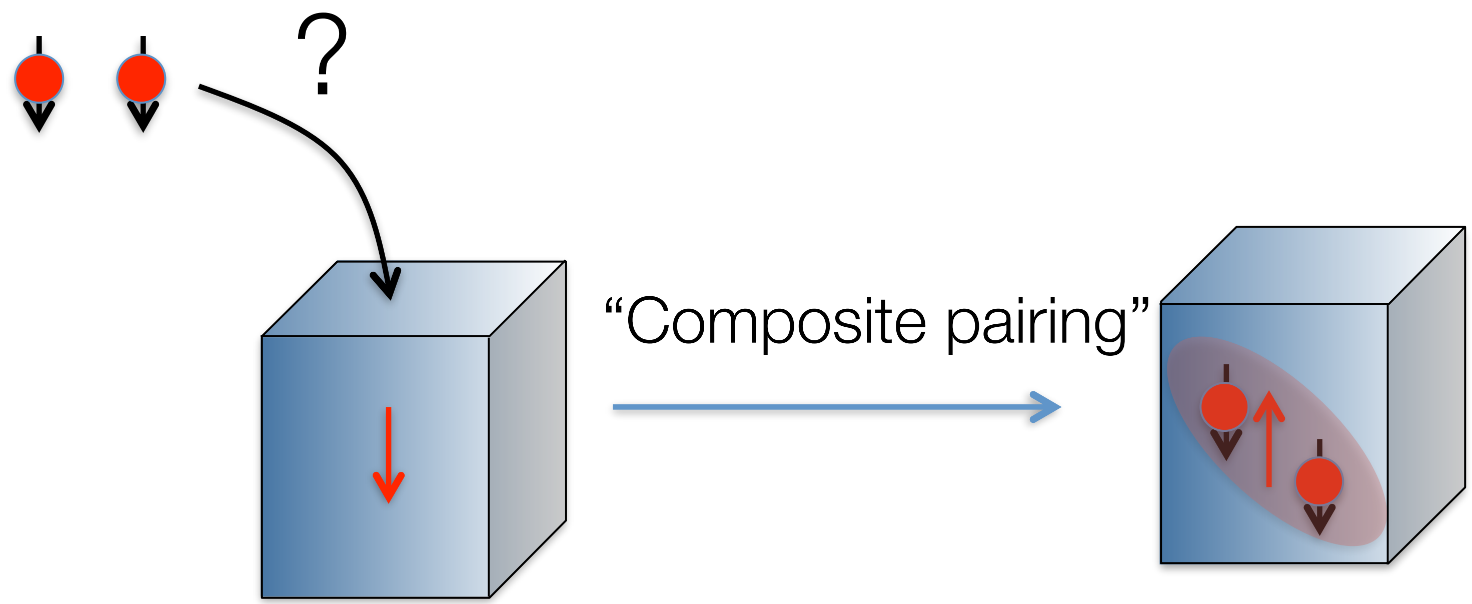

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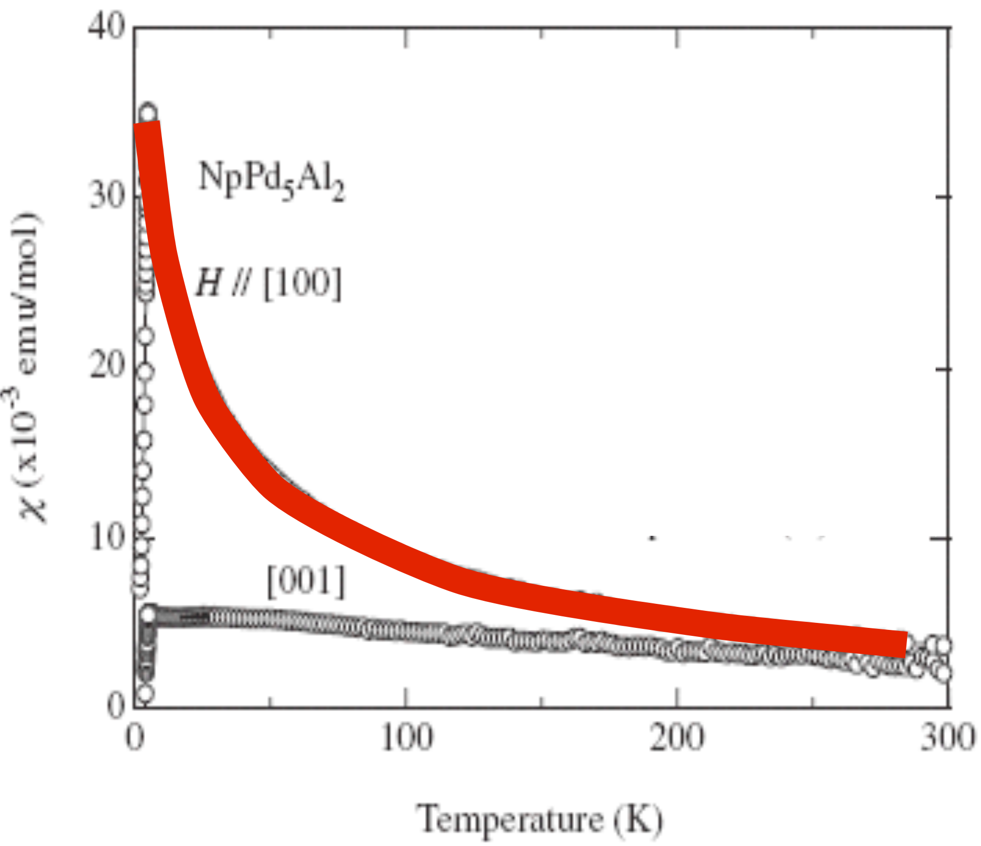
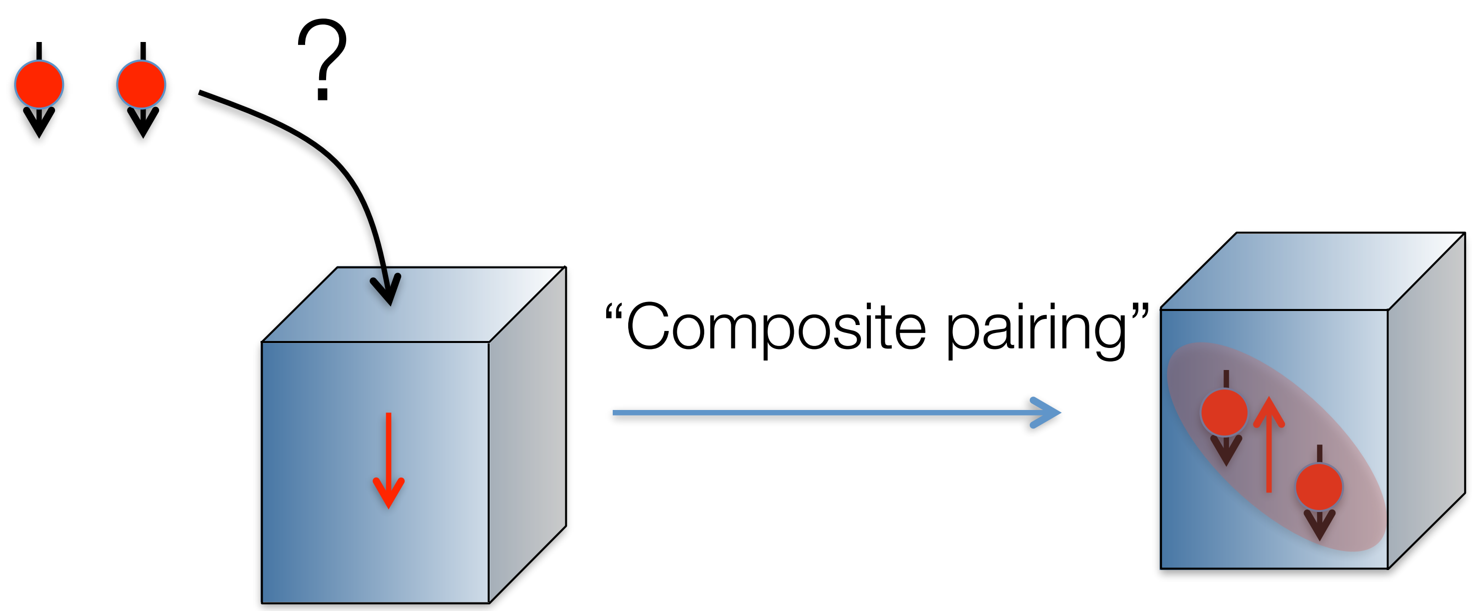
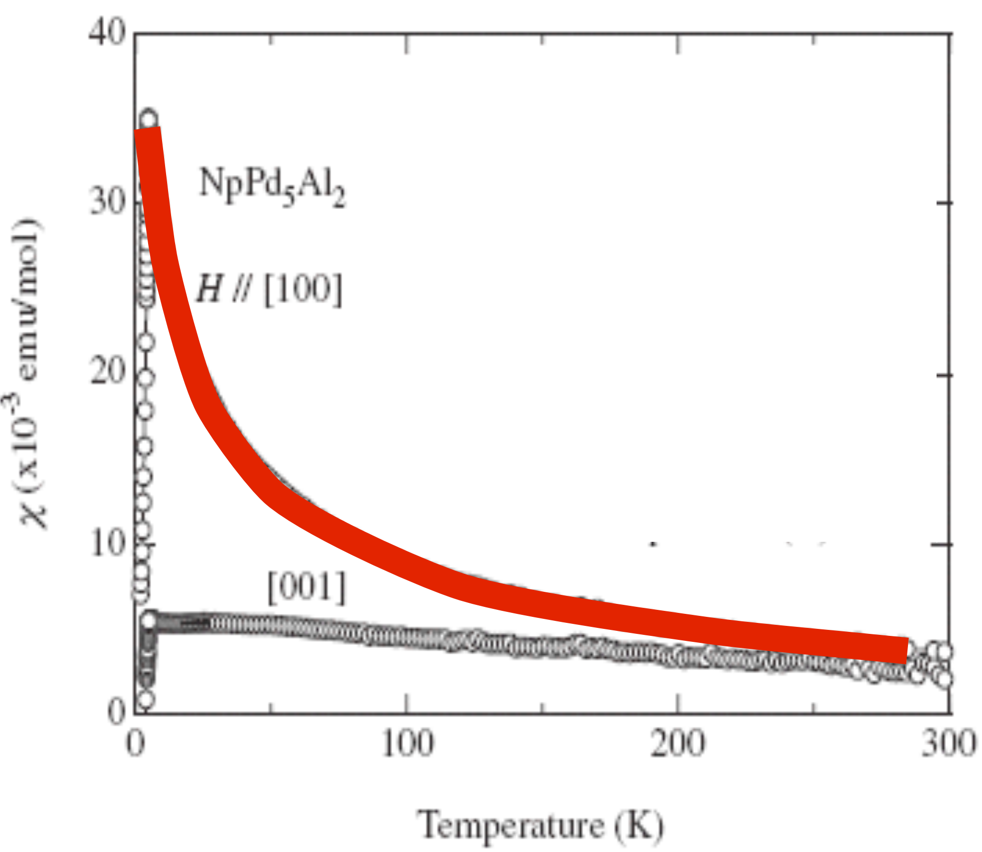


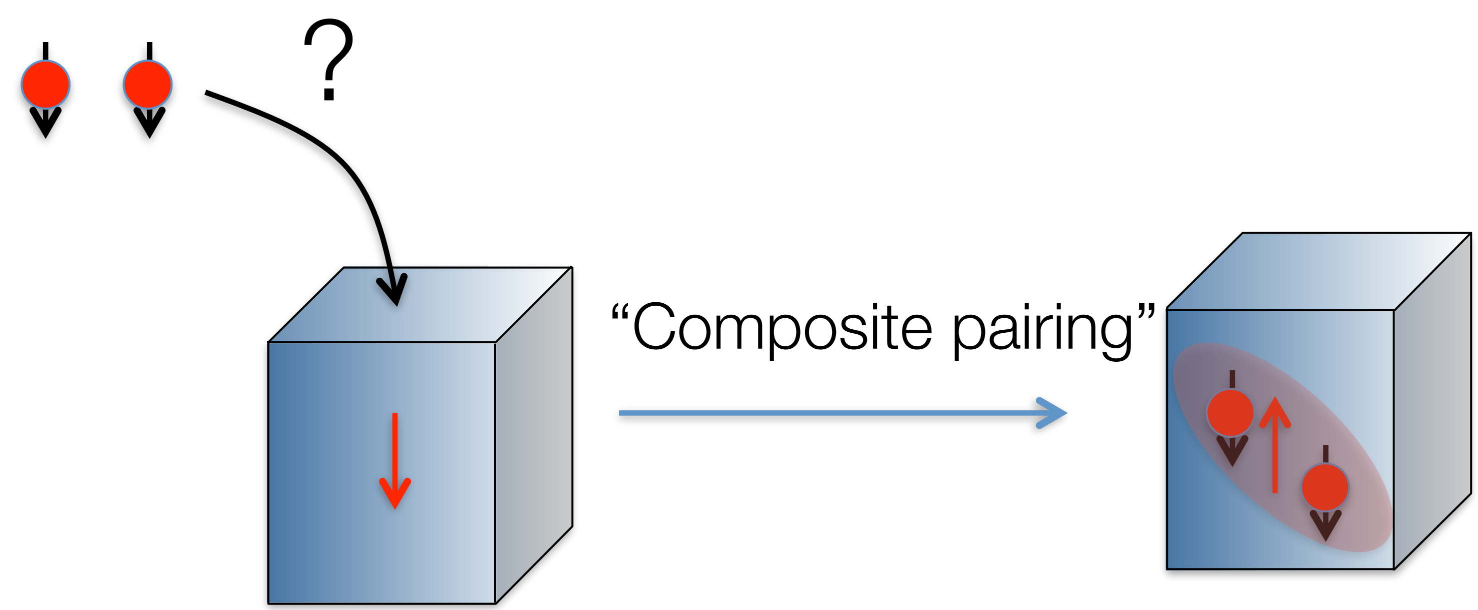


Heavy Cooper pair = (pair x spinflip)

Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$



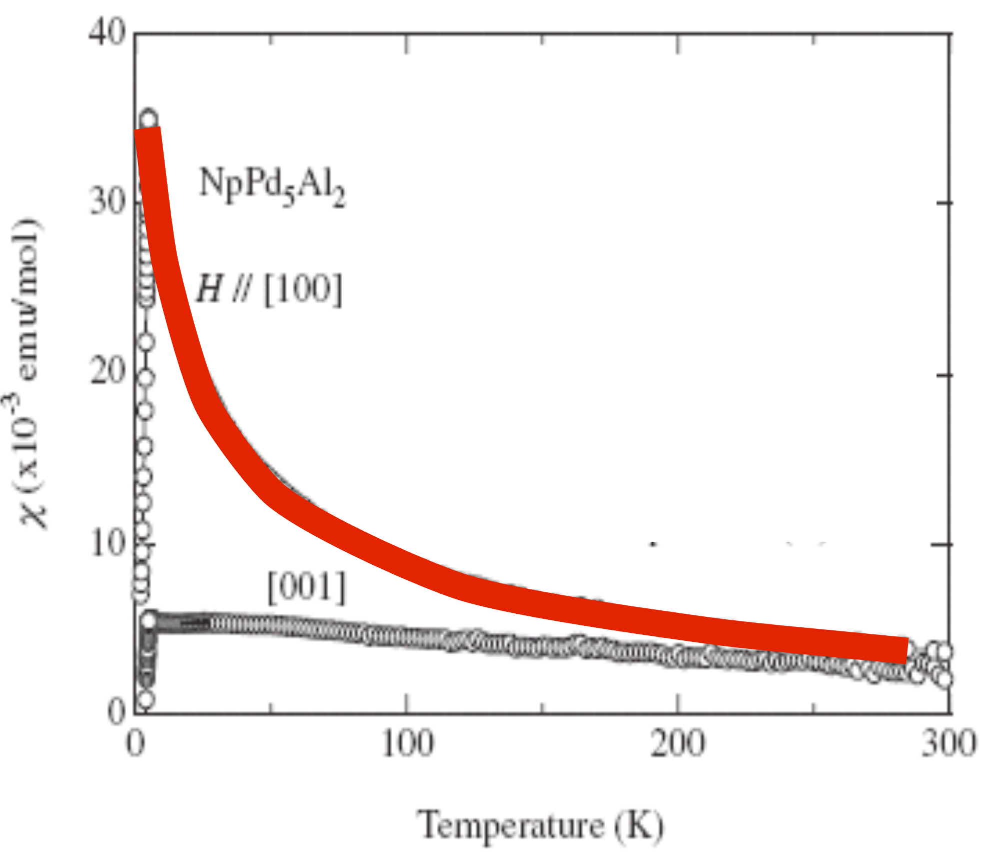


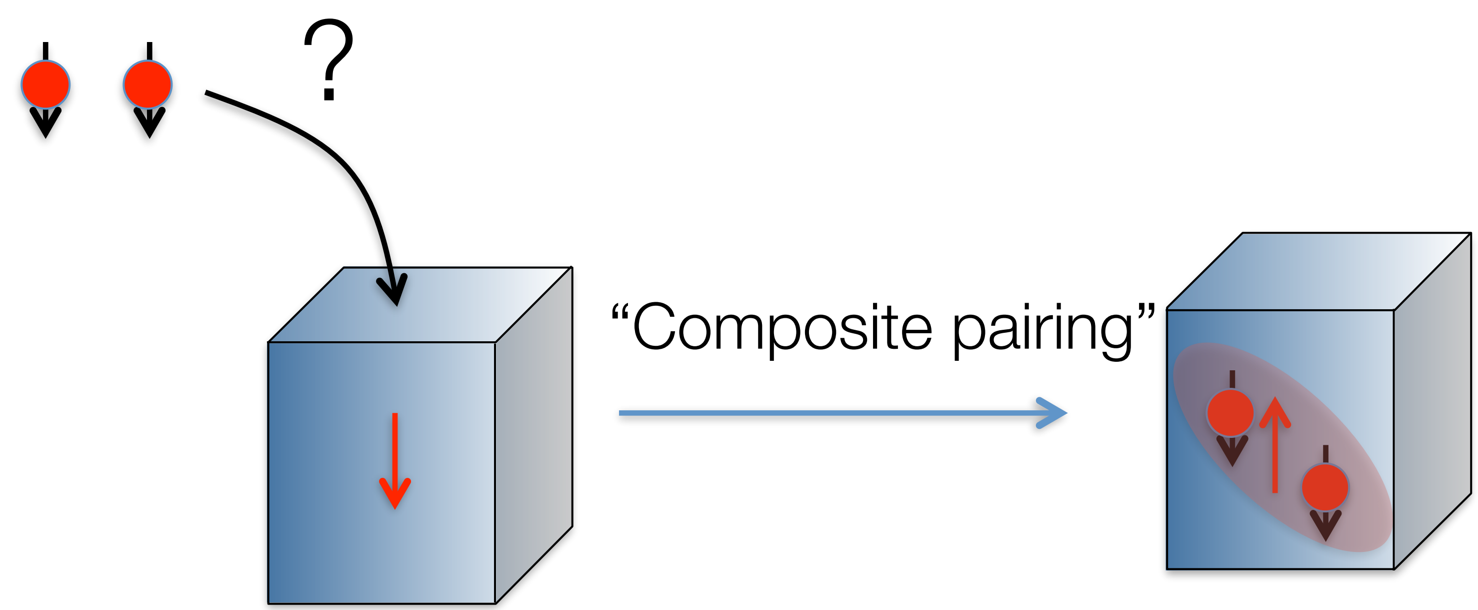
Heavy Cooper pair = (pair x spinflip)

$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$





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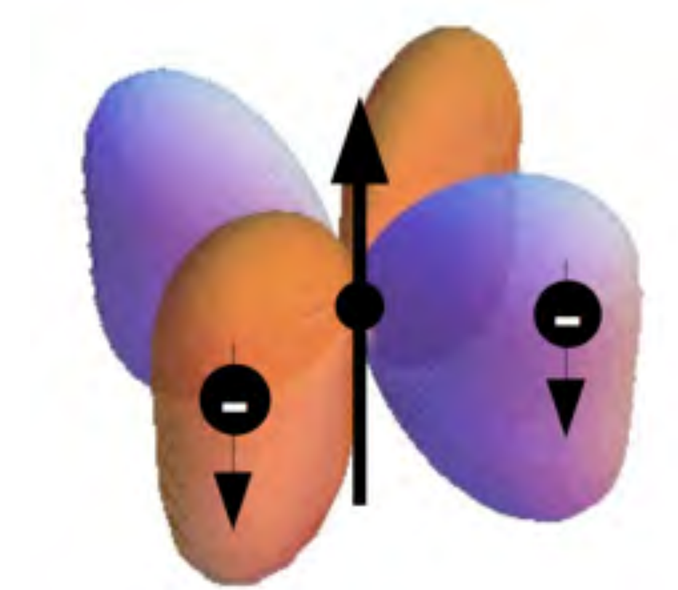

Abrahams, Balatsky, Scalapino, Schrieffer 1995