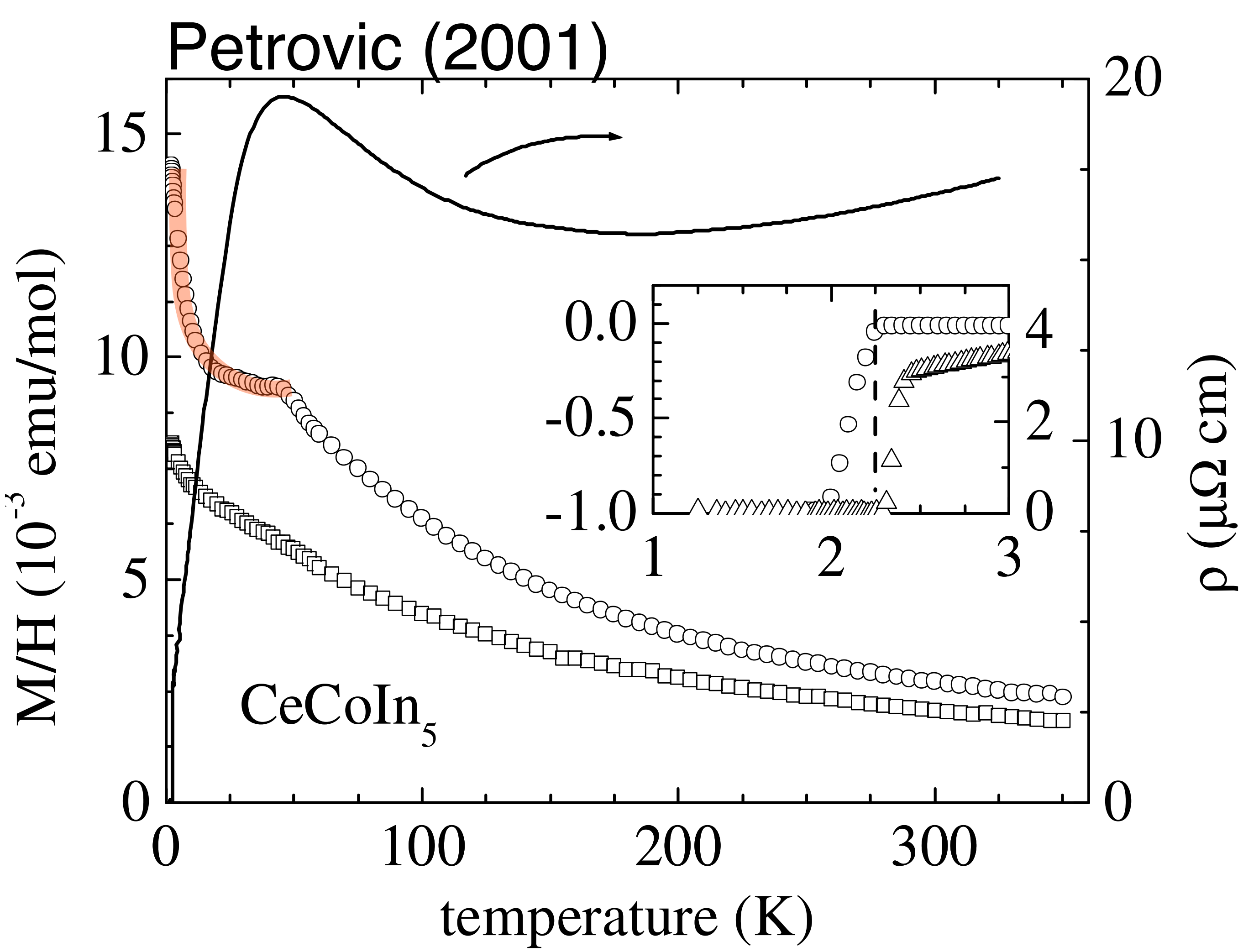
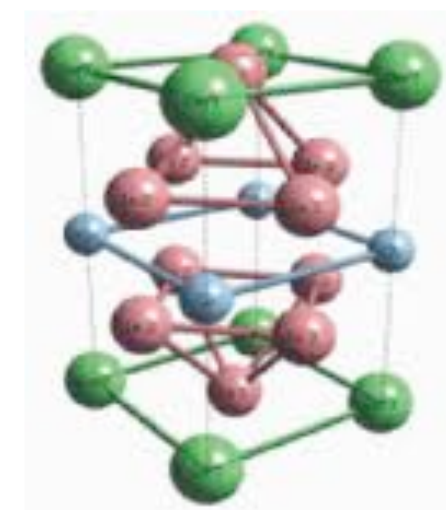
Composite vs *Spin Fluctuation* Pairing in
Heavy Fermion Superconductors
The Remarkable Case of Yb doped $CeCoIn_5$

Piers Coleman,
CMT, Rutgers University, NJ, USA
HTC, Royal Holloway, University of London, UK.

ICTP Trieste
Aug 17-21, 2015





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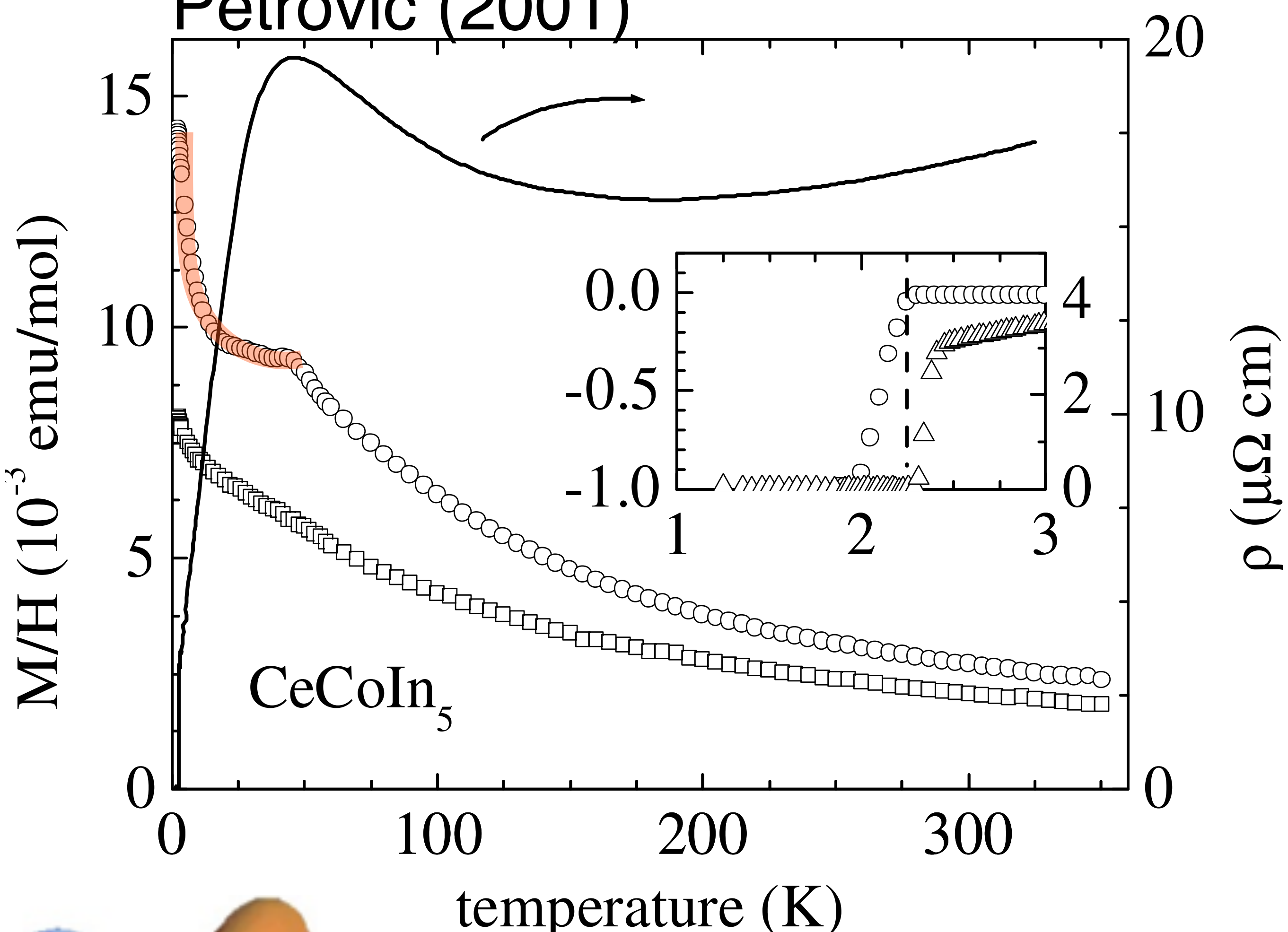
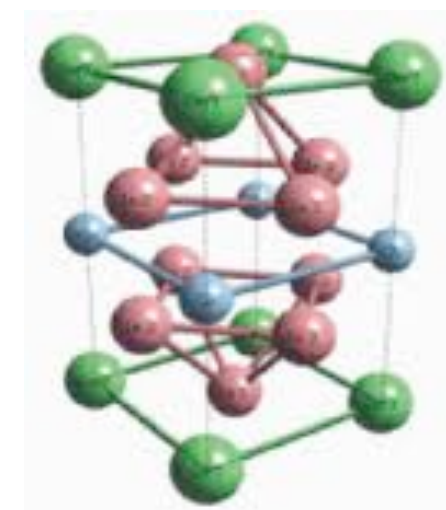
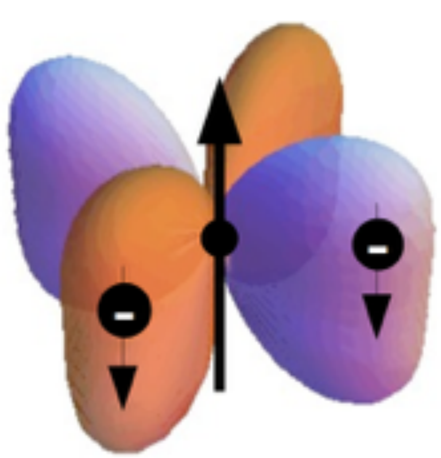
Petrovic (2001)







Composite pairing ?

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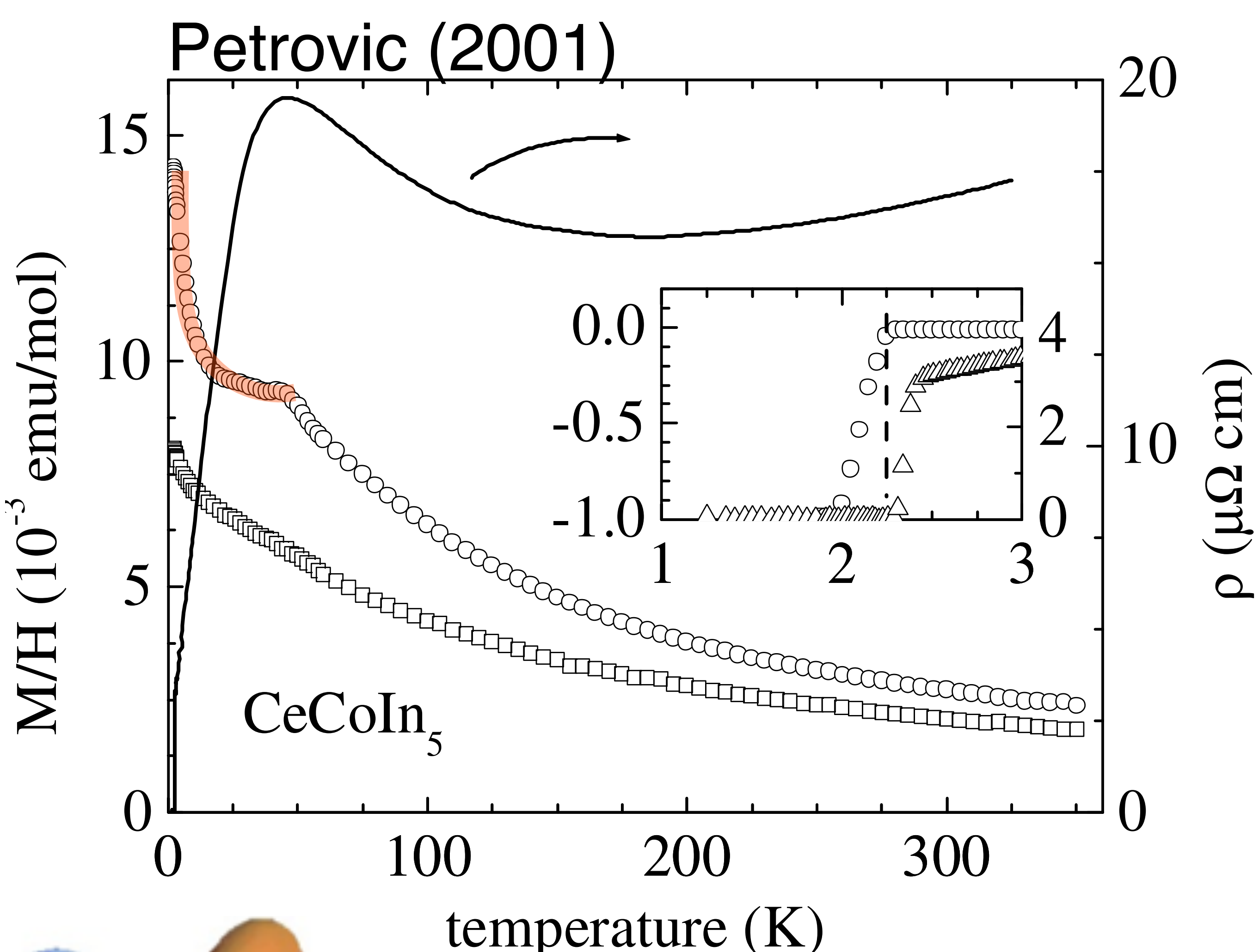

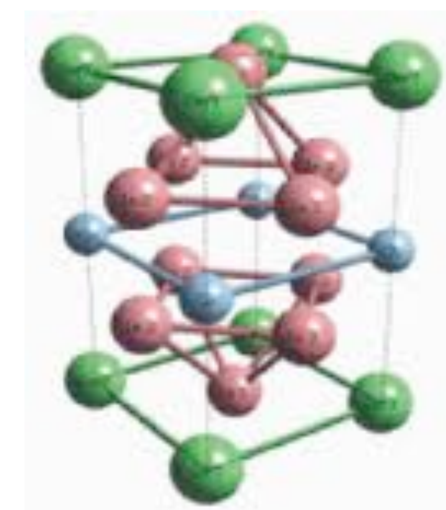

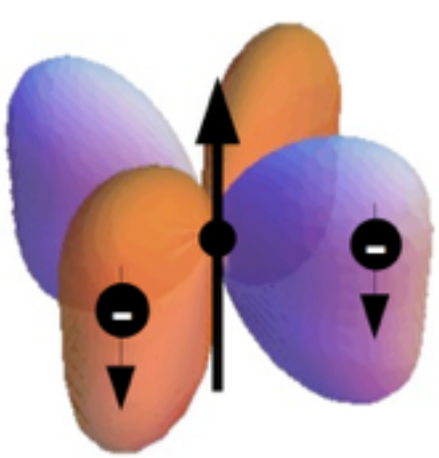

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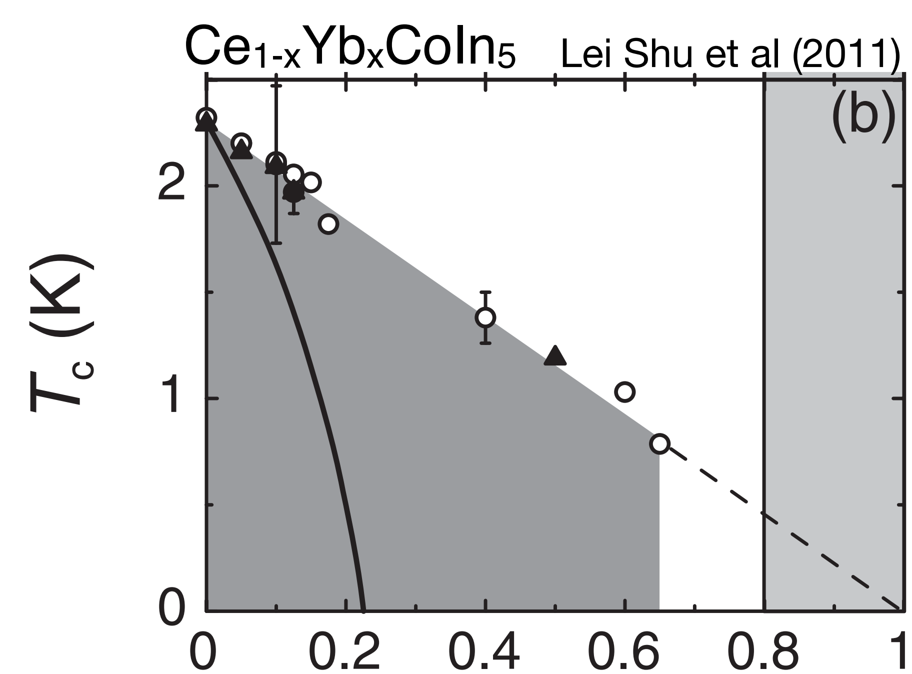

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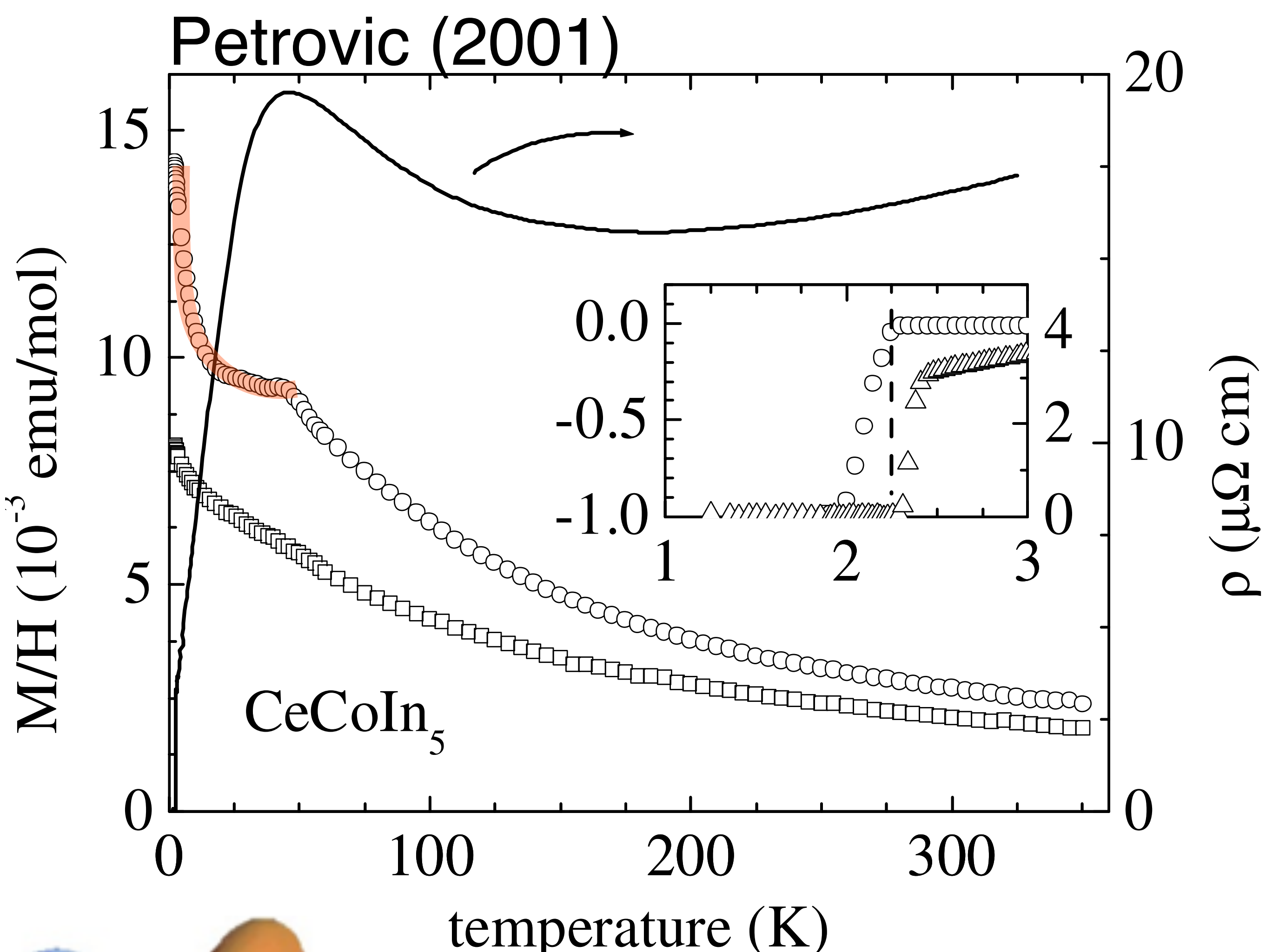

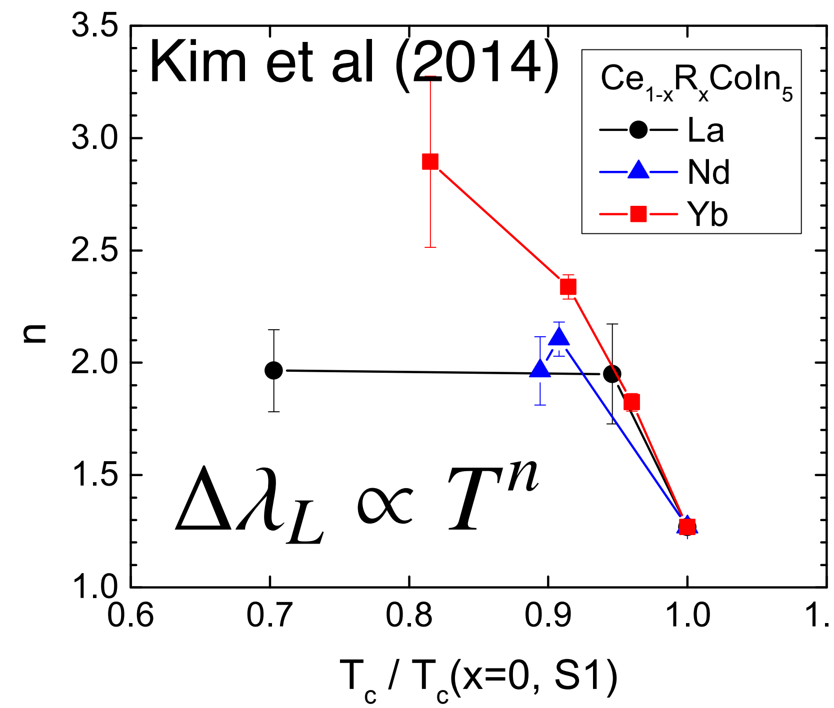

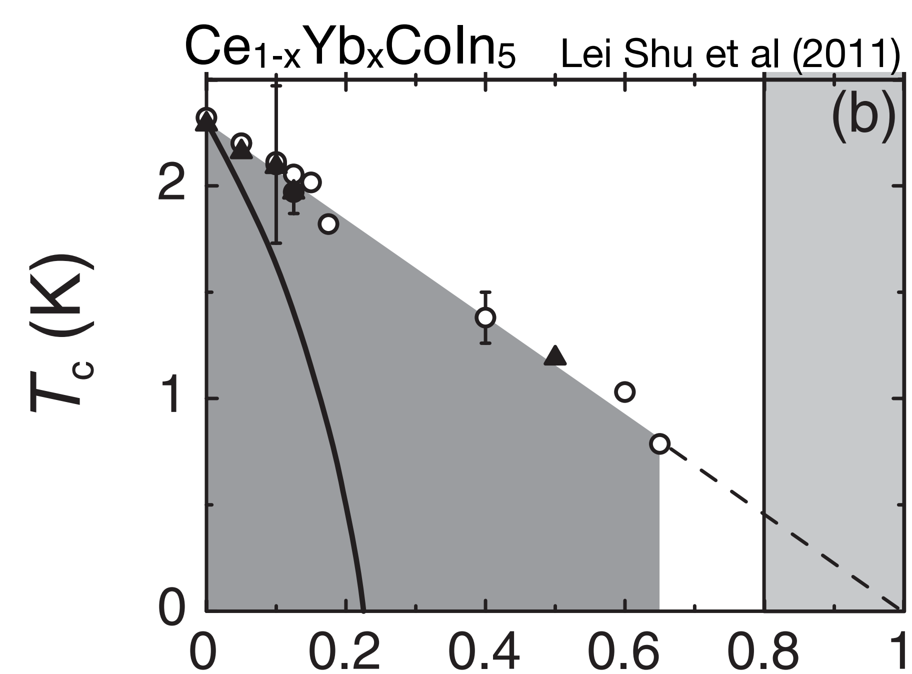

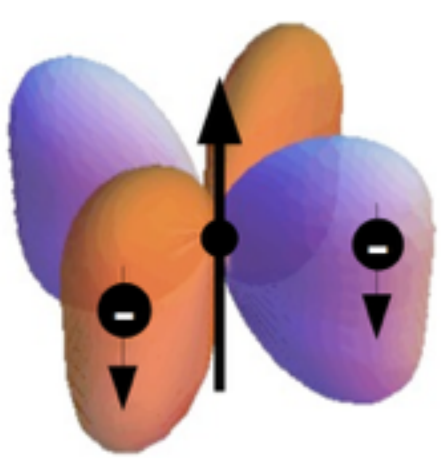

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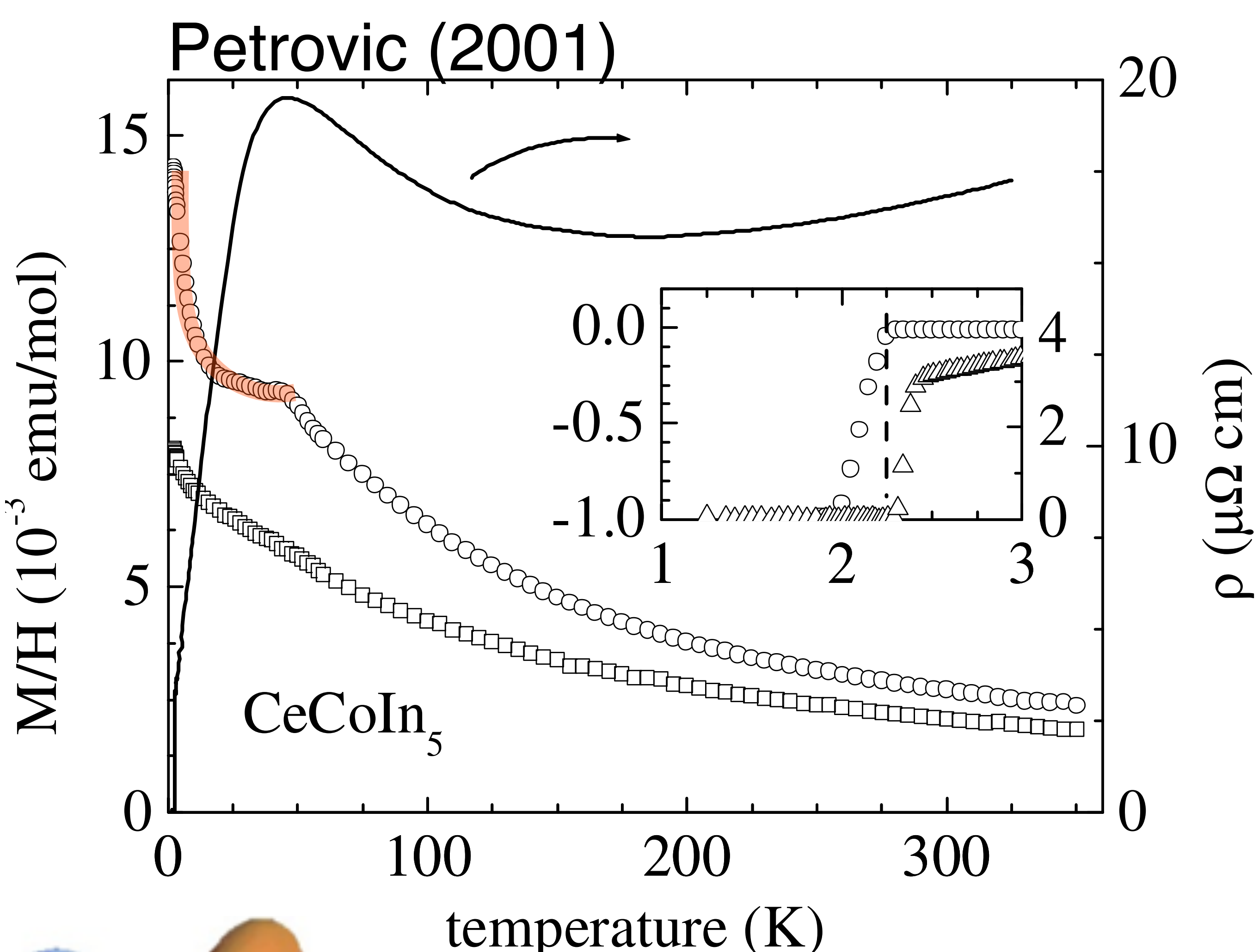
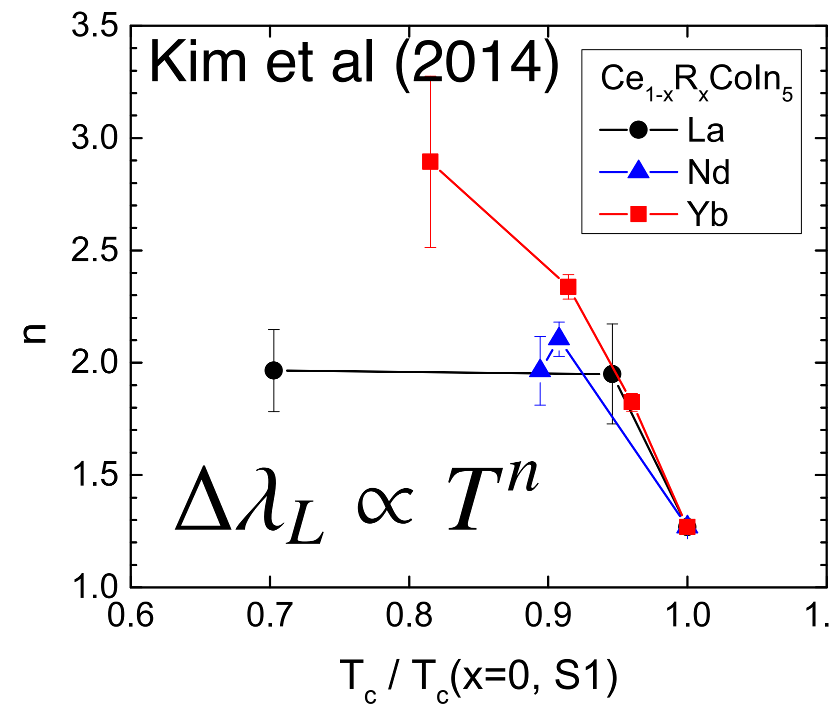
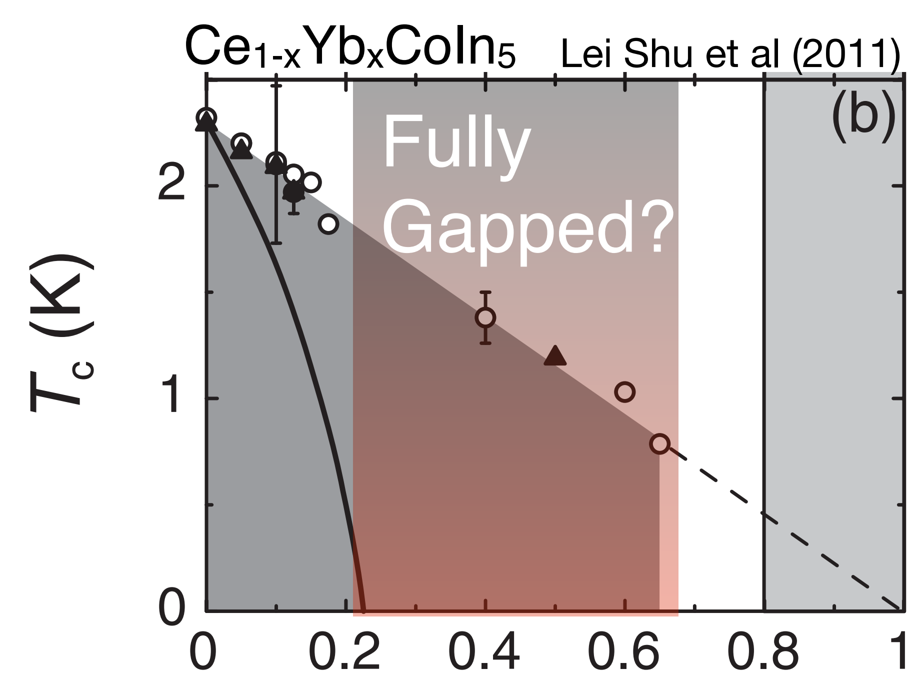
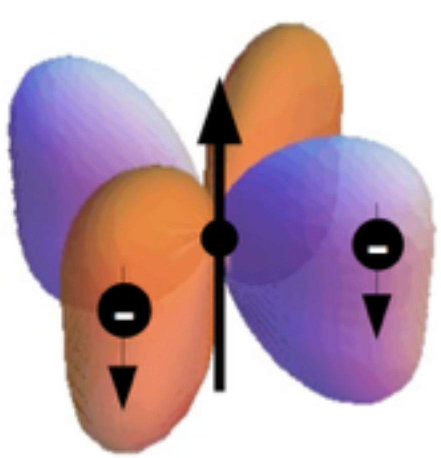








Composite pairing ?

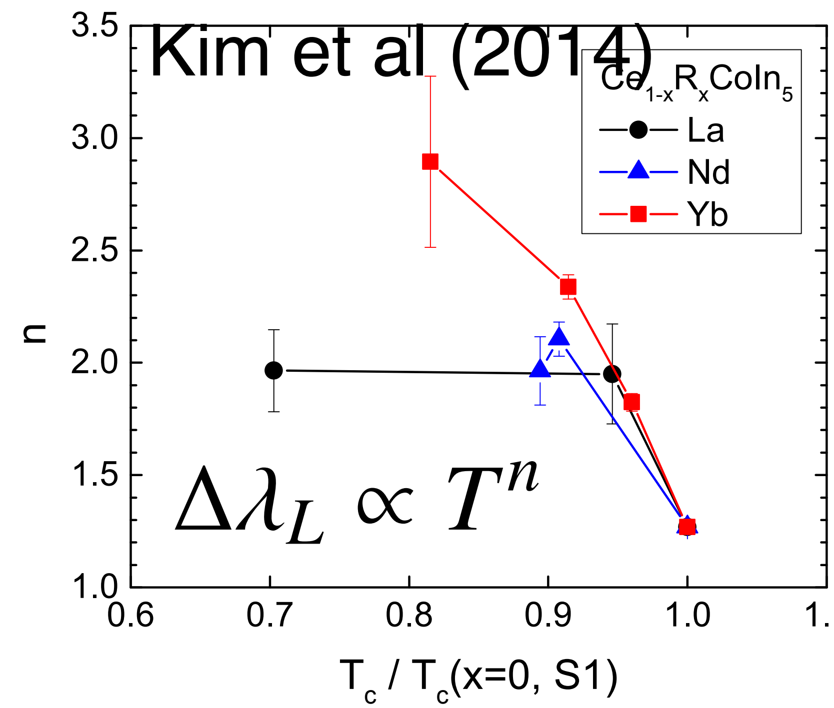
Composite vs Spin Fluctuation Pairing in **Heavy Fermion Superconductors**

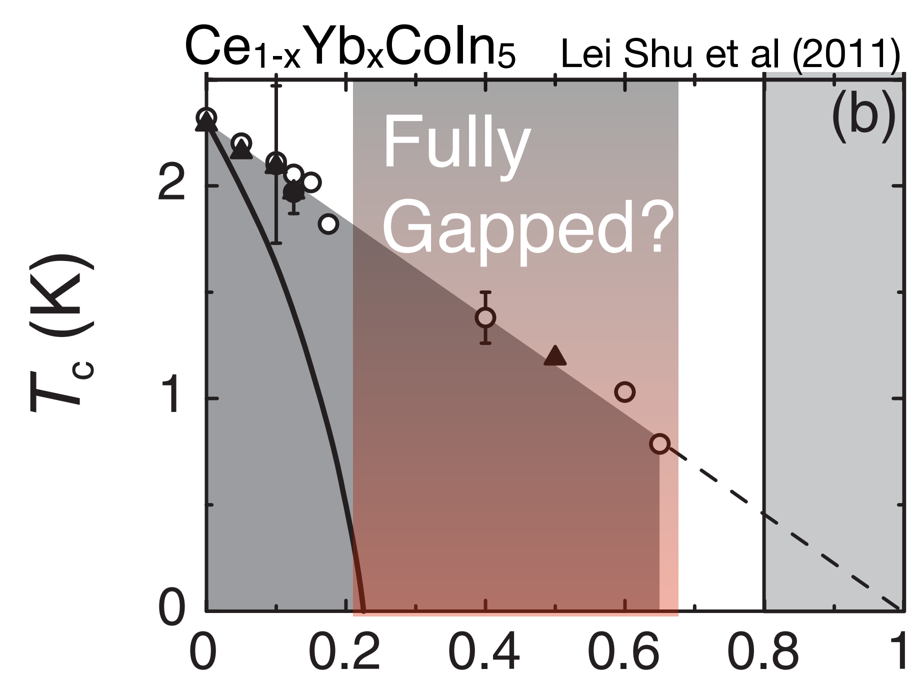
The Remarkable Case of Yb doped $CeCoIn_5$

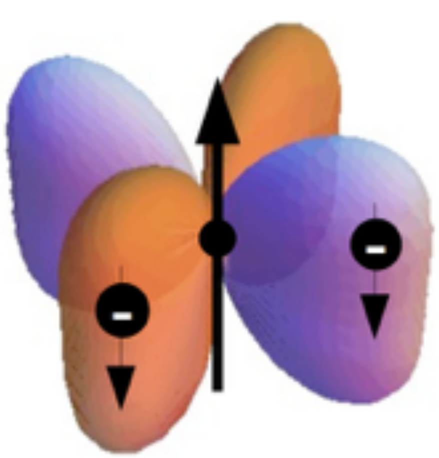
GRC Superconductivity
Hong Kong, May 24-29, 2015

Piers Coleman,
CMT, Rutgers University, NJ, USA
HTC, Royal Holloway, University of London, UK.

- Heavy Fermions
- Composite vs spin fluctuation pairing
- Yb doped $CeCoIn_5$.

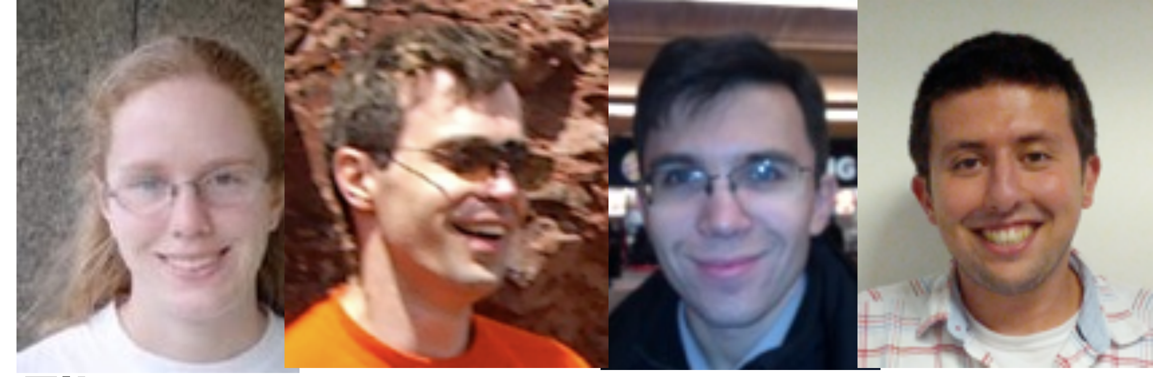






Composite pairing ?

Collaborators



Flint Dzero Nevidomskyy Erten

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

Composite pairs

R. Flint, PC, Comtes Rendu,15, 557-562 (2014).

Kim et al, PRL 026898, (2014).

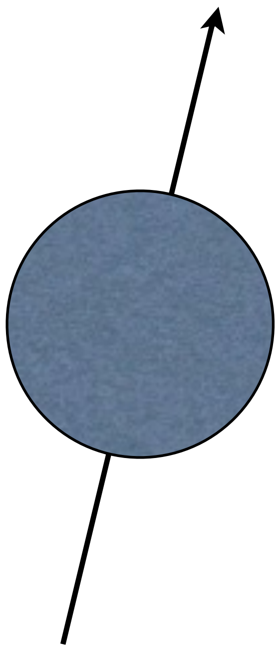
O. Erten, R. Flint, PC, PRL 114, 027002 (2014).

ICAM-I2CAM Institute for Complex Adaptive Matter

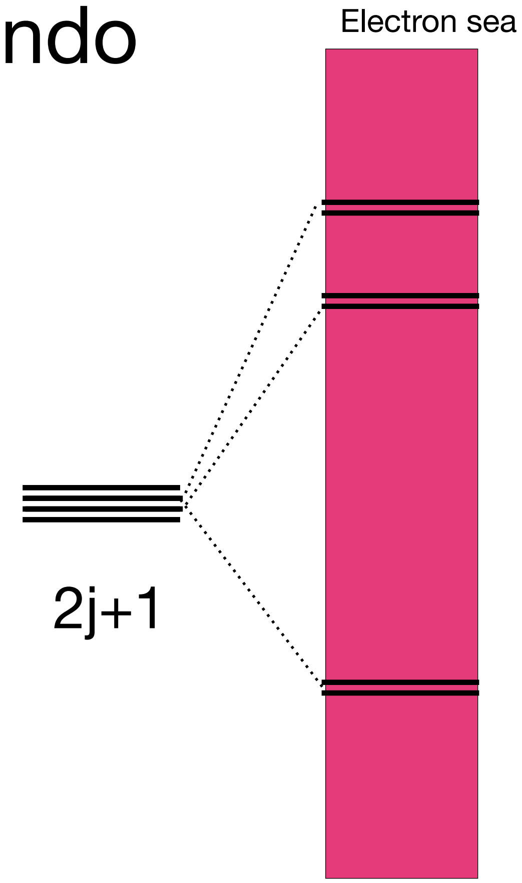
NSF

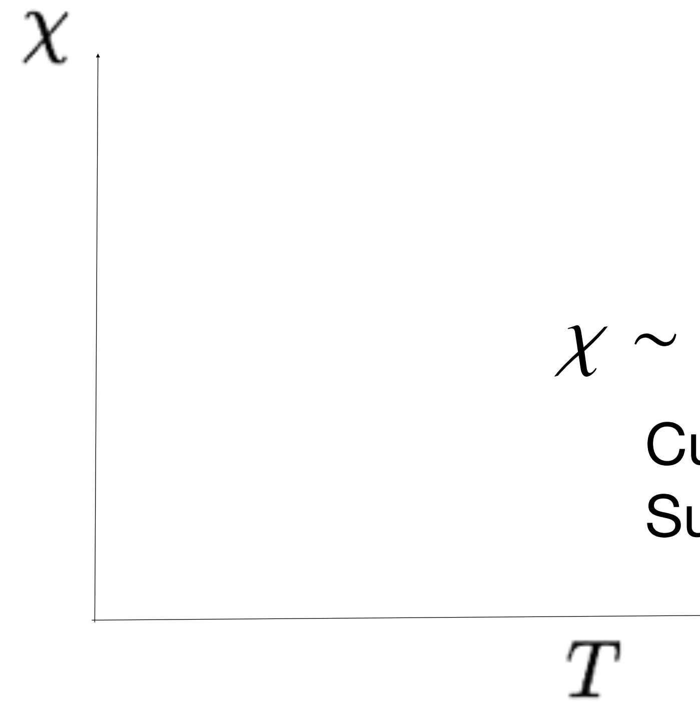
Rutgers Center for Materials Theory

Heavy Fermions + Kondo



Spin (4f,5f)

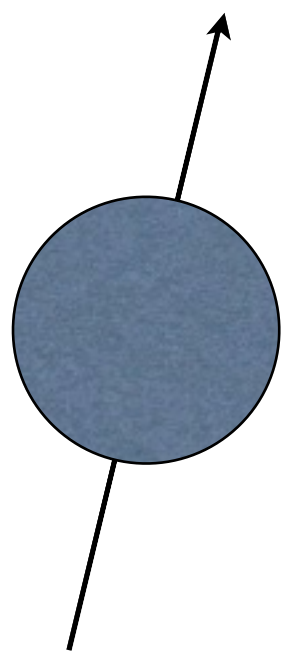


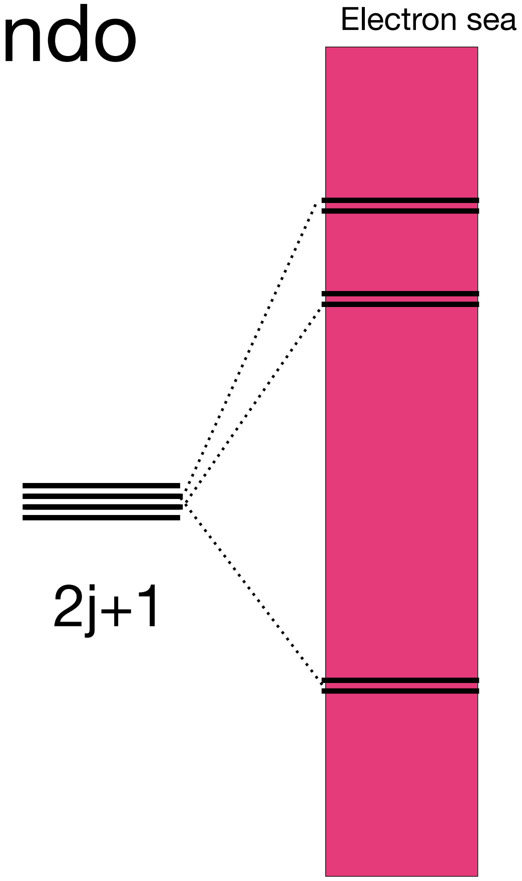


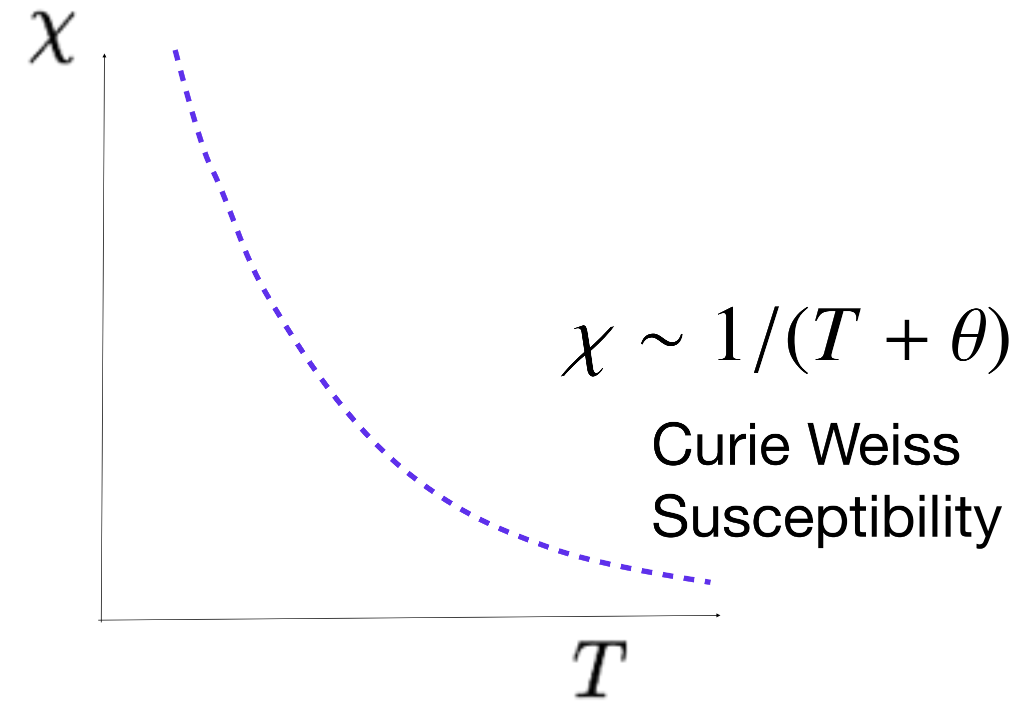
$$\chi \sim 1/(T+\theta)$$

Curie Weiss Susceptibility

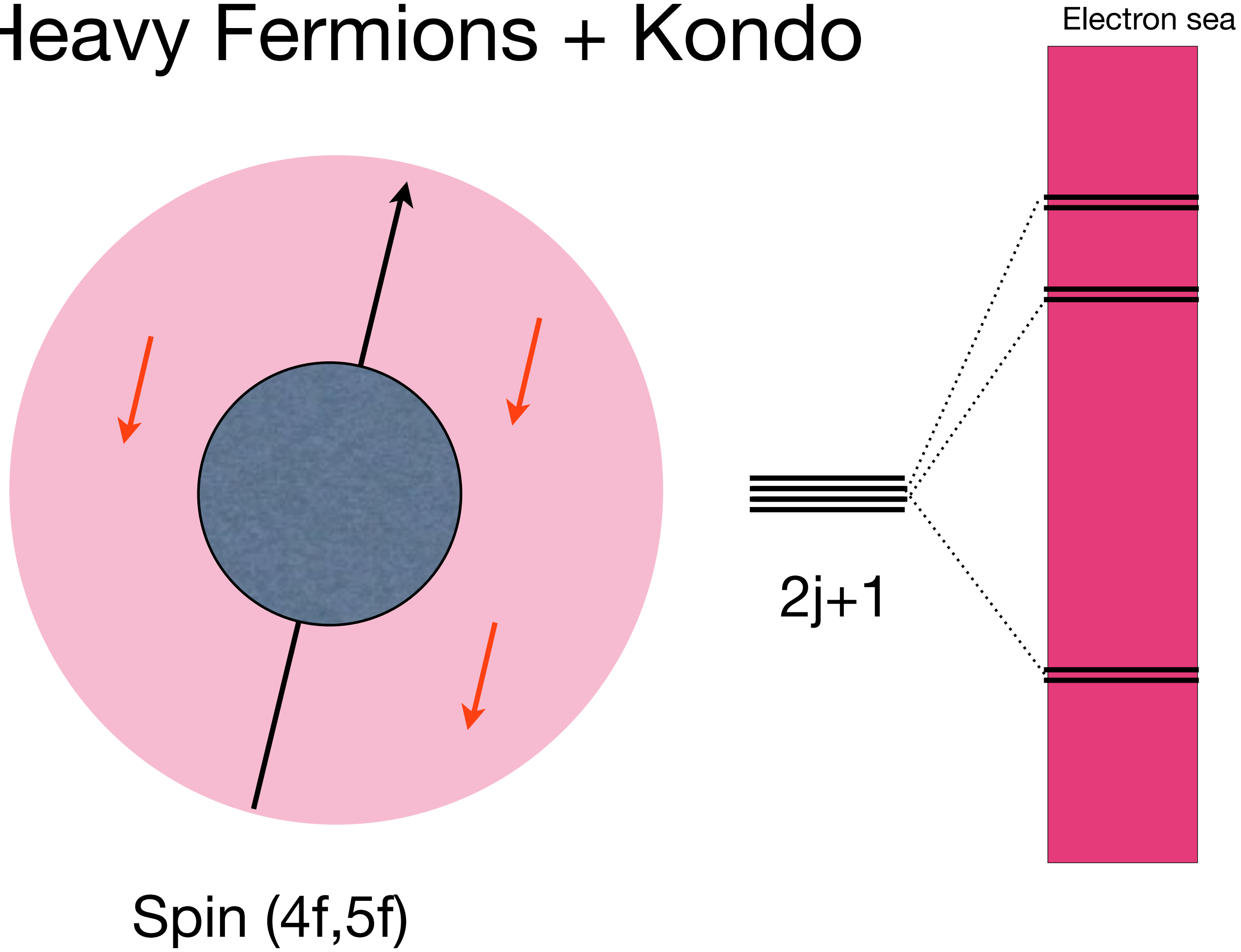
Heavy Fermions + Kondo

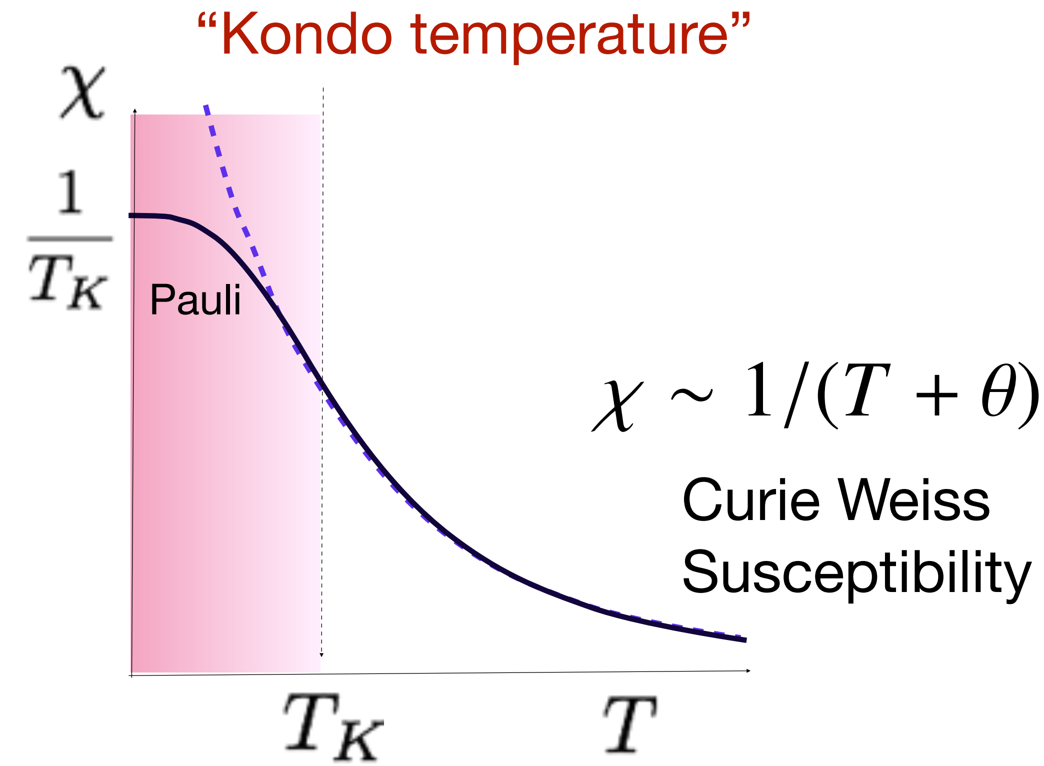






Heavy Fermions + Kondo

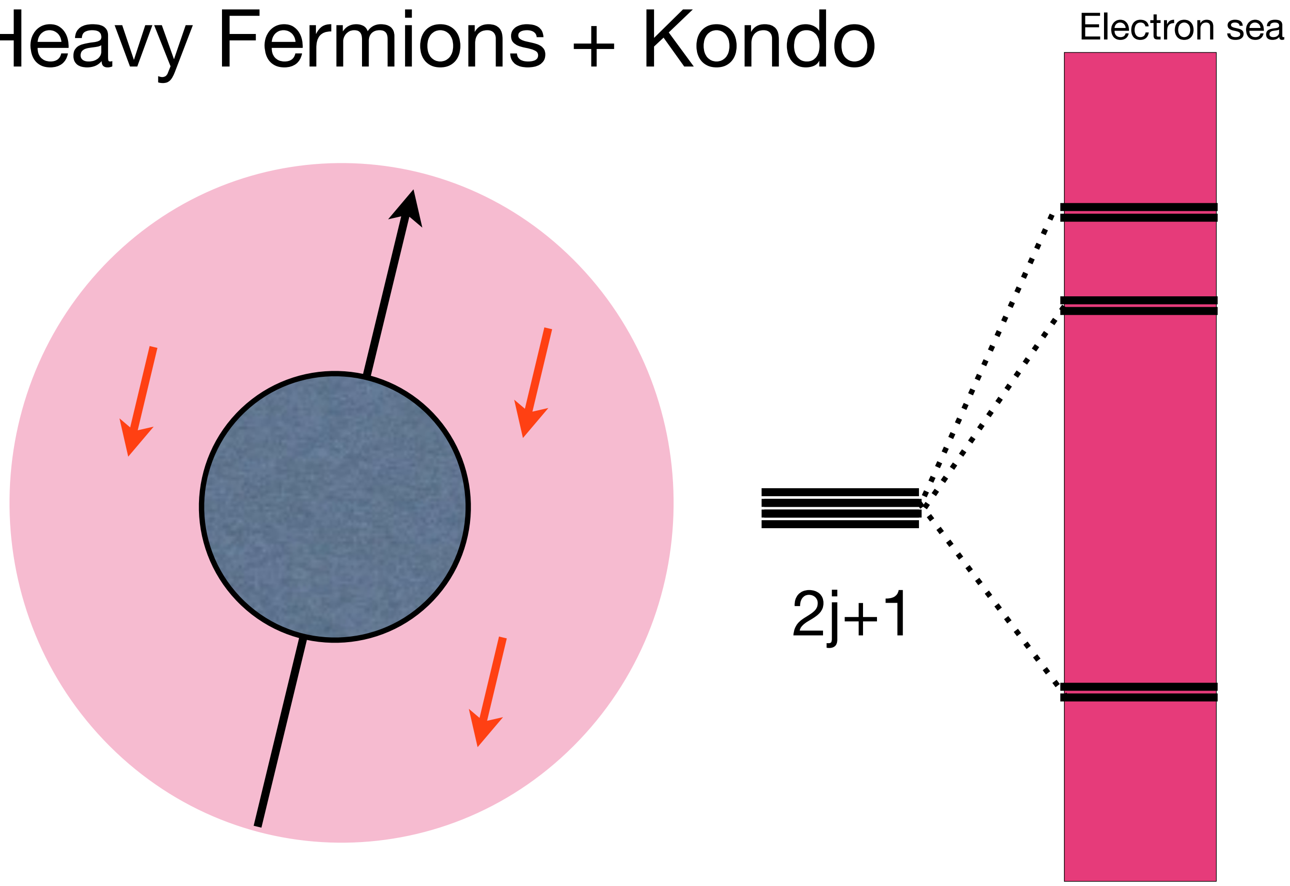




<u>Kondo Effect:</u> Spin screened by conduction electrons: <u>entangled</u>

$$\uparrow\downarrow - \downarrow\uparrow$$

Heavy Fermions + Kondo



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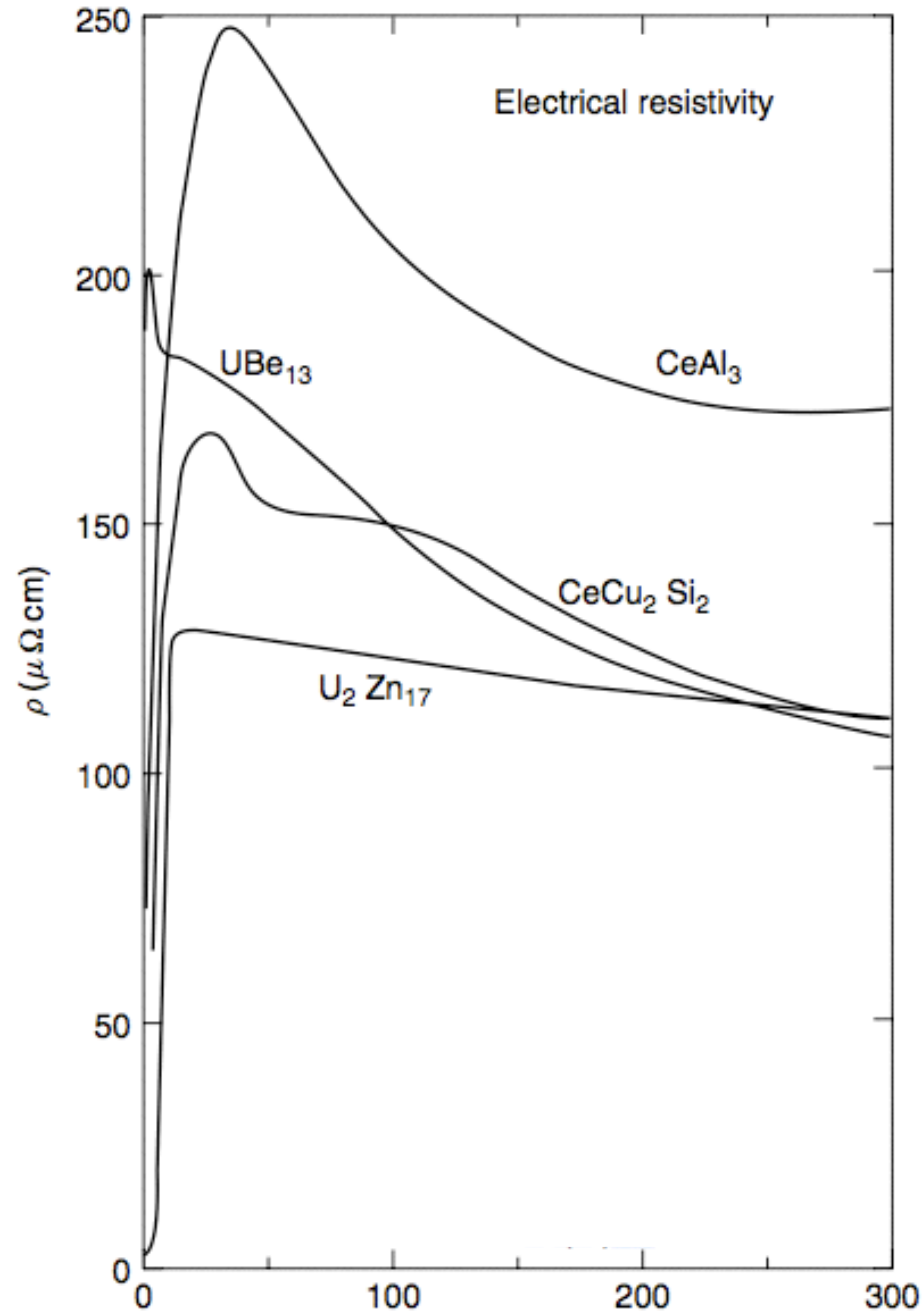
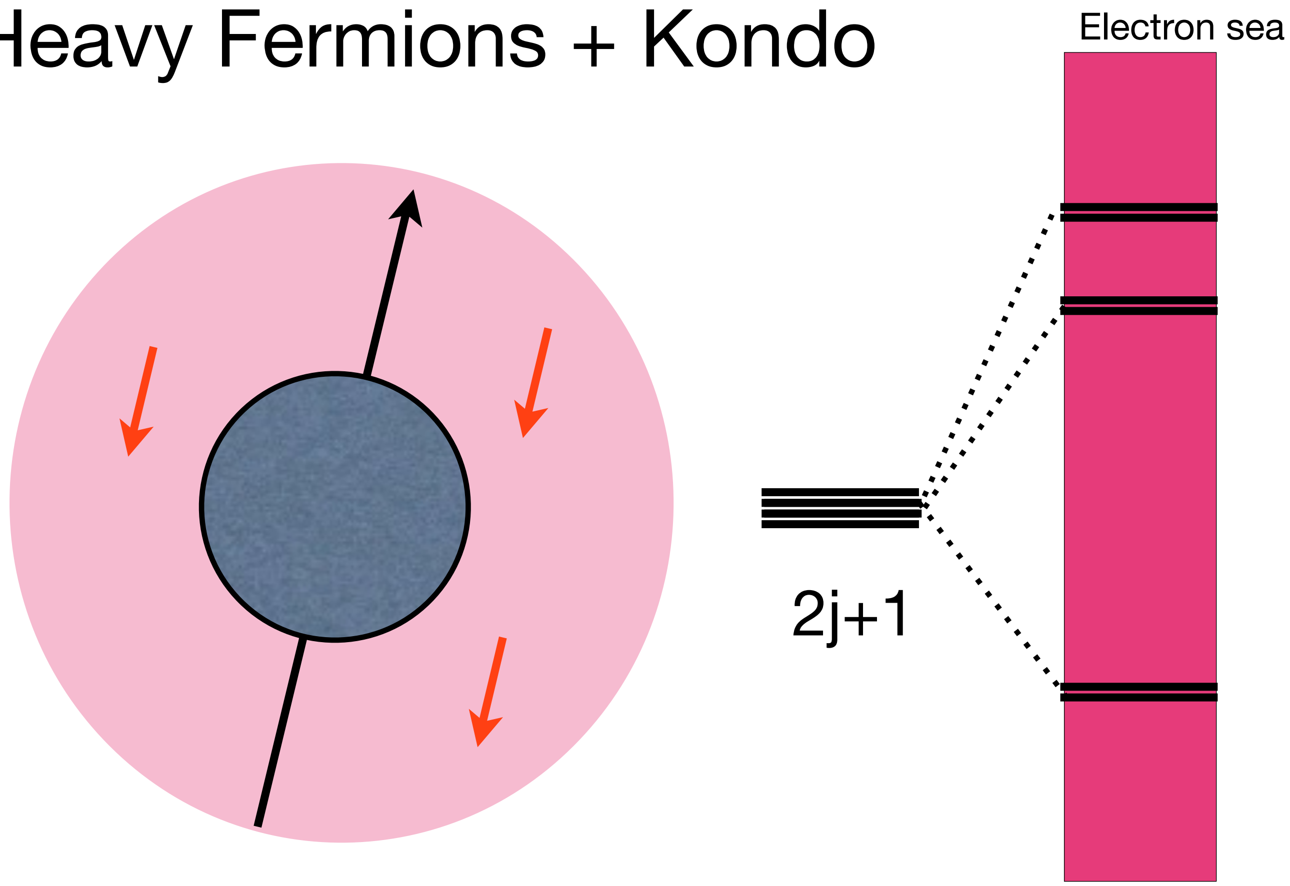
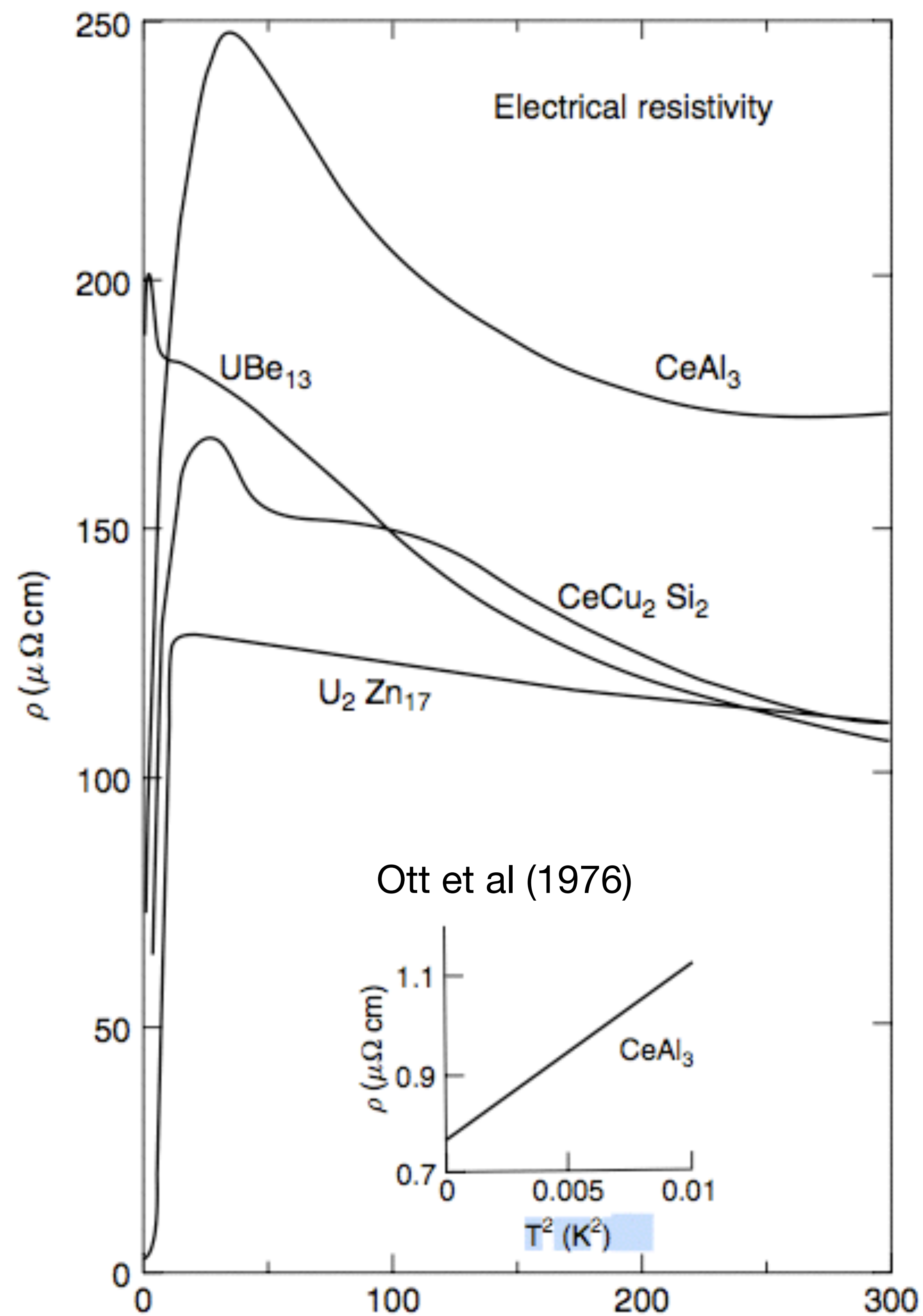


Heavy Fermions + Kondo





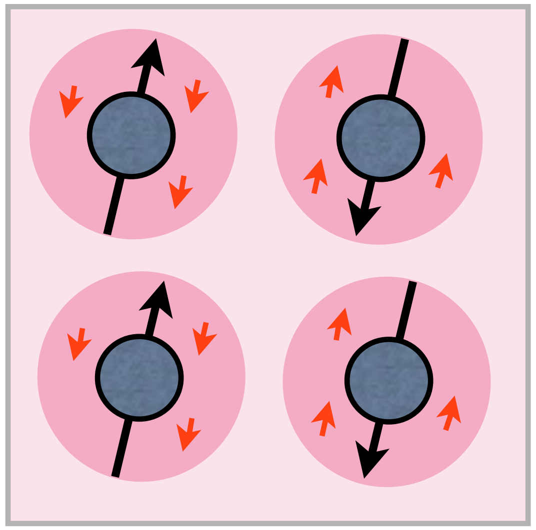
Kondo Effect: Spin screened by conduction electrons: entangled

$$\uparrow\downarrow - \downarrow\uparrow$$

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

Coherent Heavy Fermions

Heavy Fermions + Kondo



“Kondo Lattice”
(Doniach ’79)

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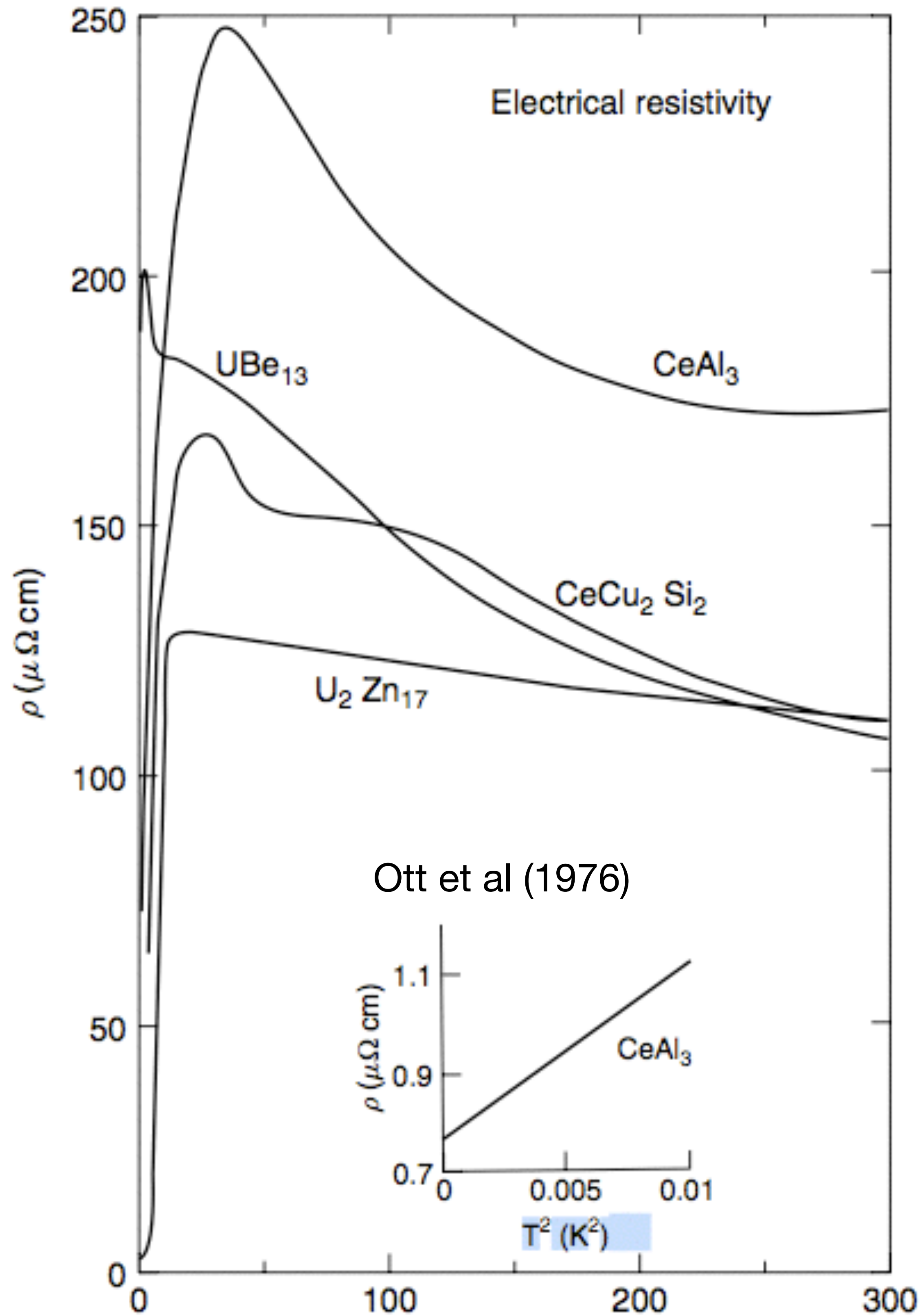
$\uparrow\downarrow - \downarrow\uparrow$



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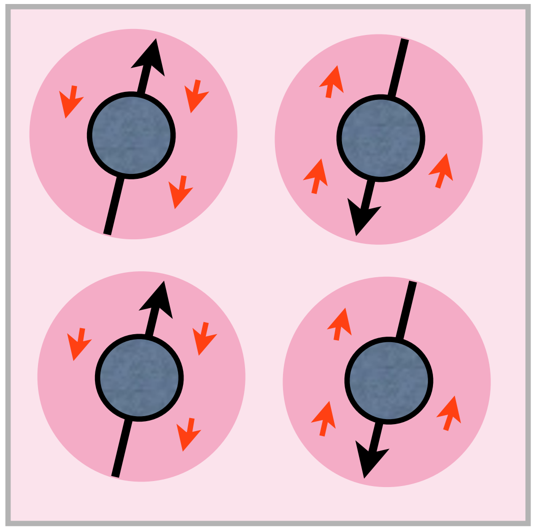
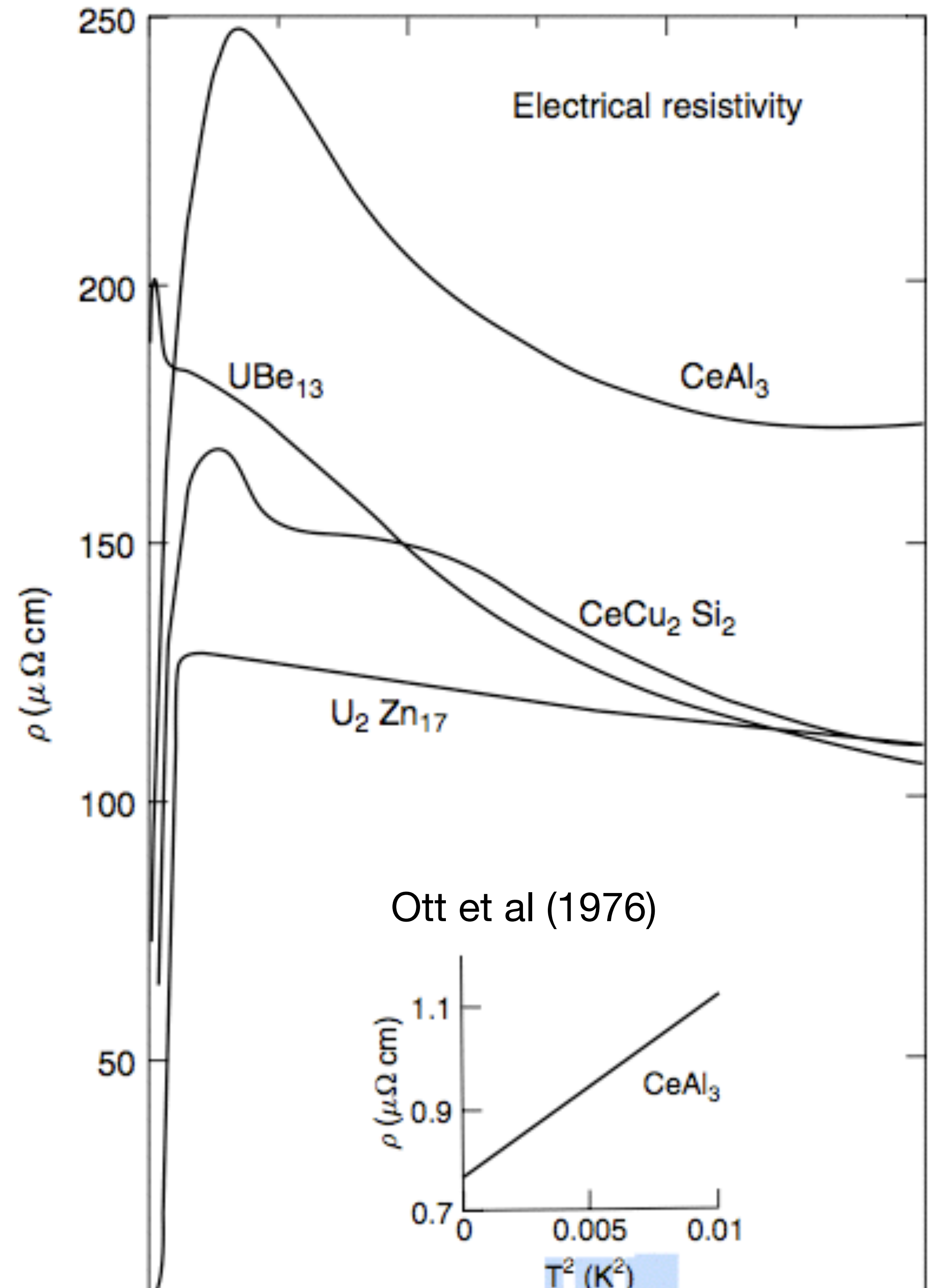


"Kondo Lattice"
(Doniach '79)

<u>Kondo Effect:</u> Spin screened by conduction electrons: <u>entangled</u>

$\uparrow \downarrow - \downarrow \uparrow$

Can this entanglement lead to
New ordered states? To Superconductivity?



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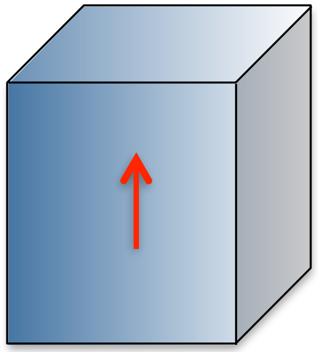
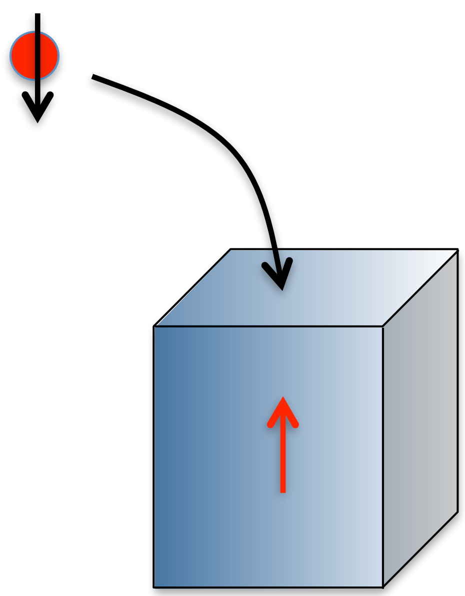
Coherent Heavy Fermions

Coherence and composite fermions



Coherence and composite fermions



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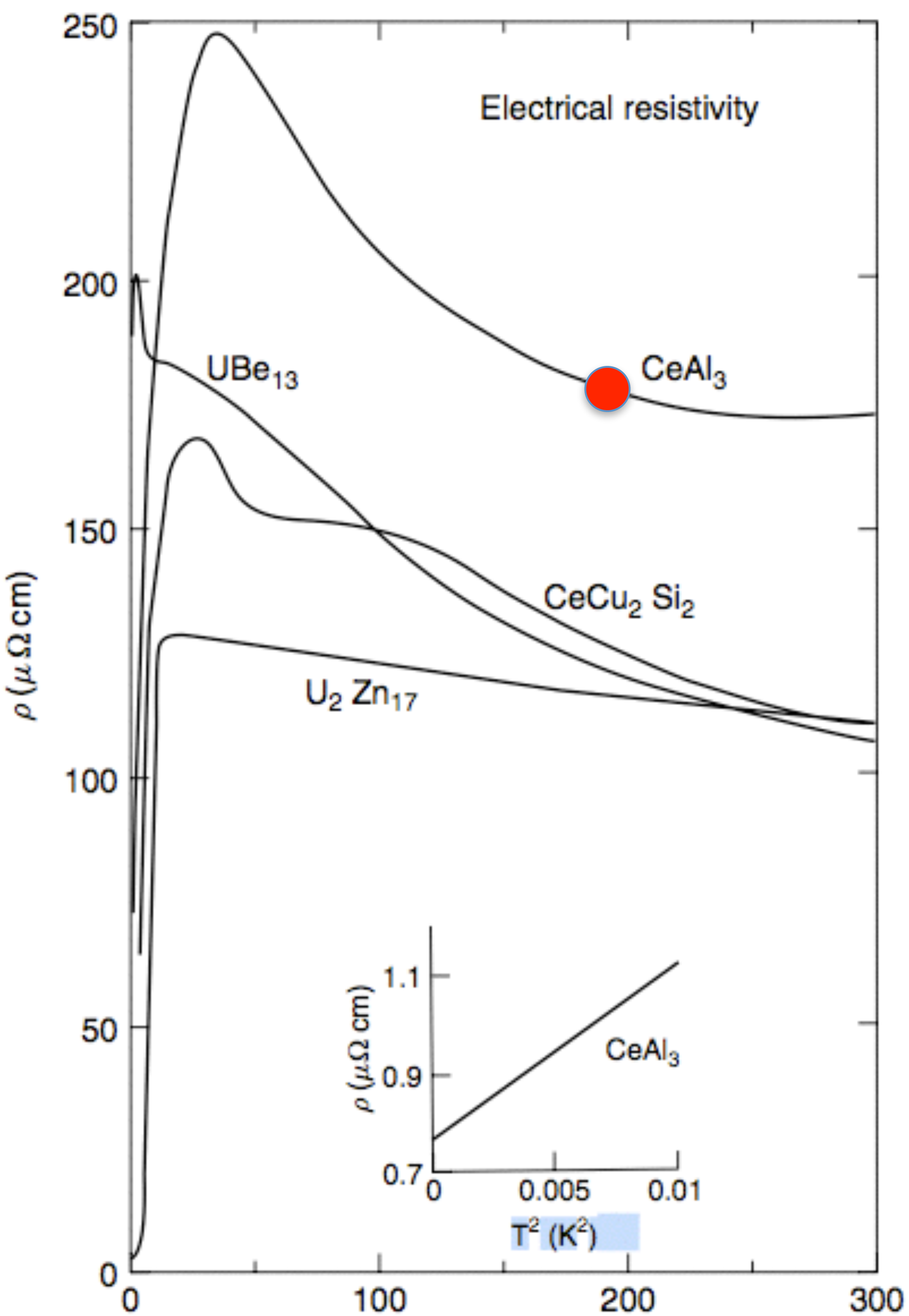

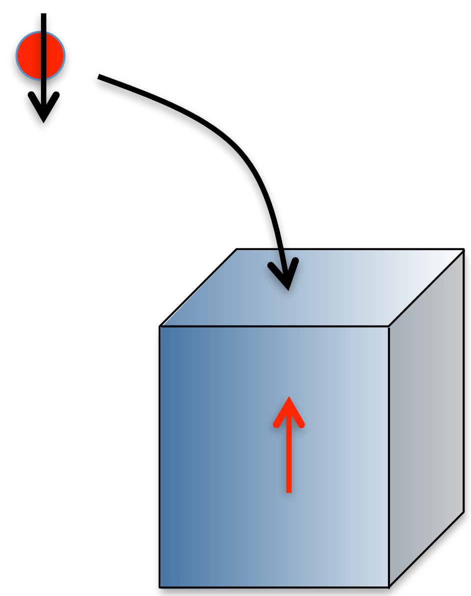

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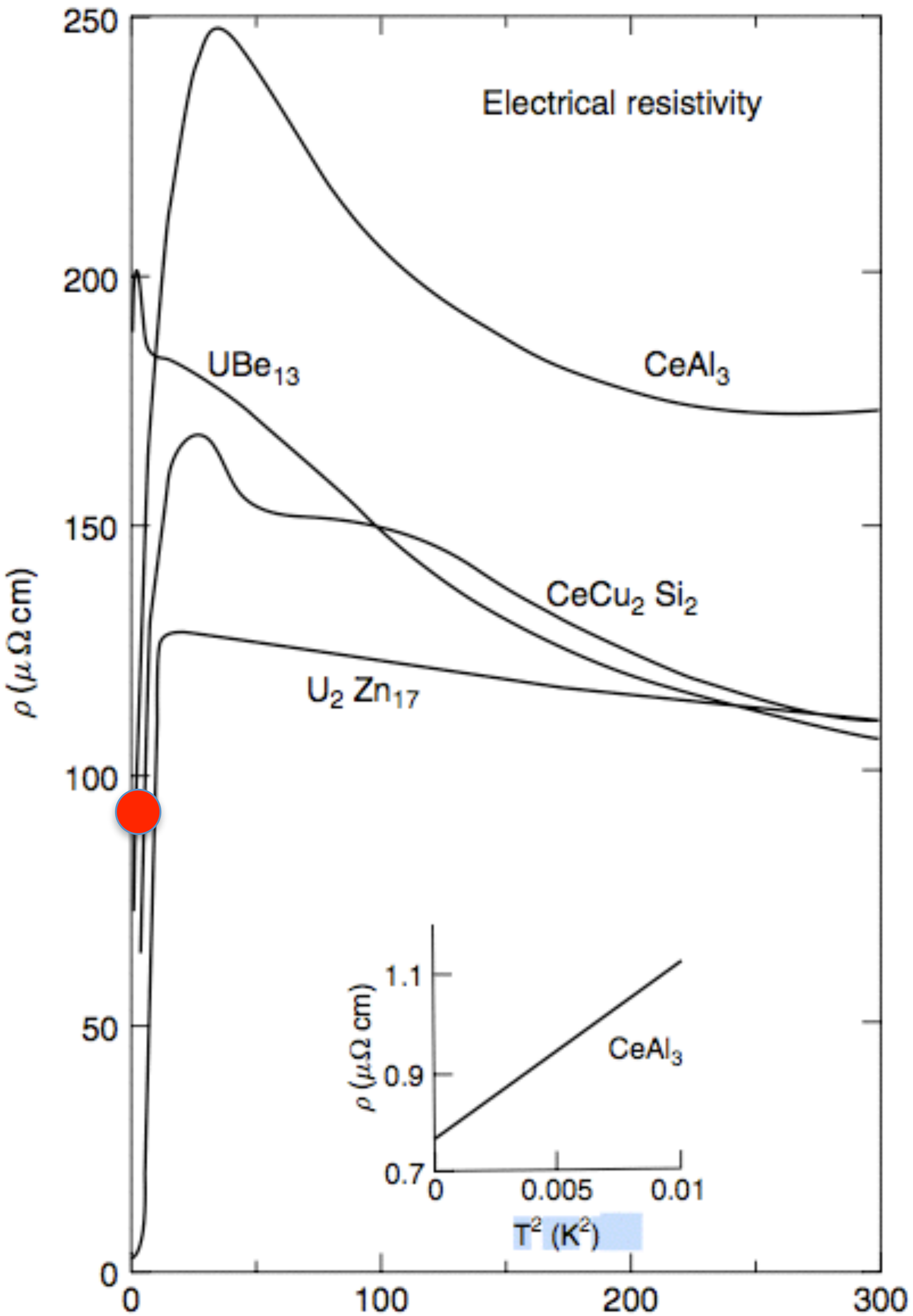
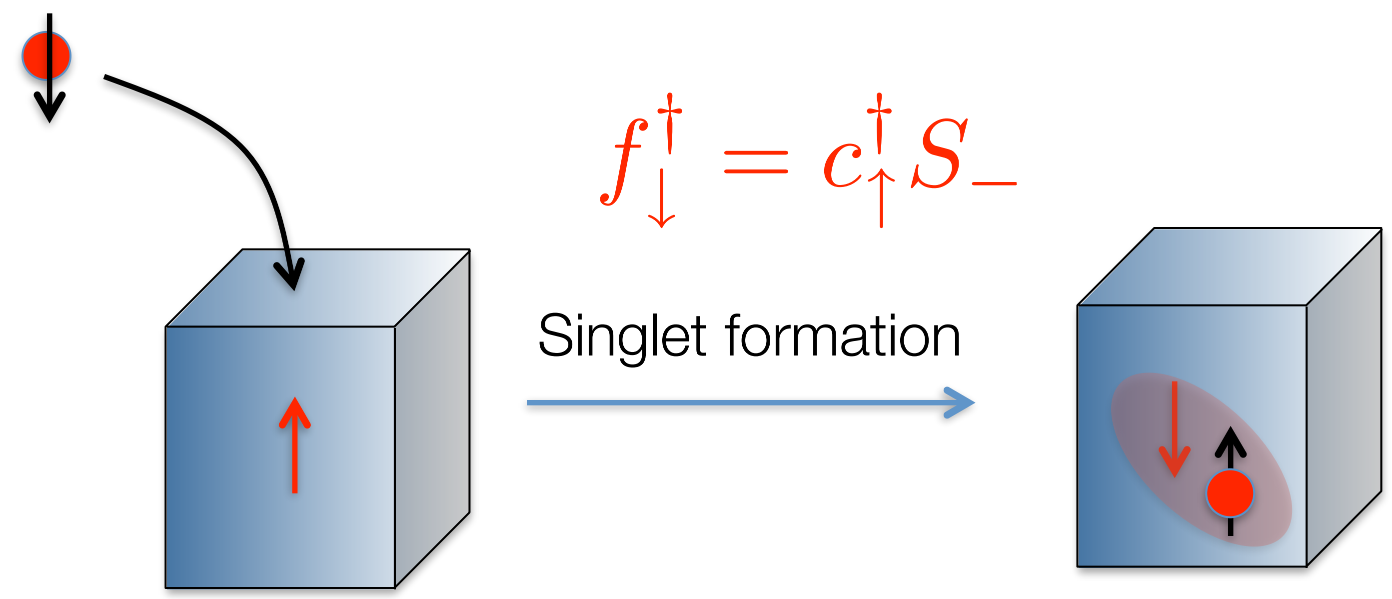
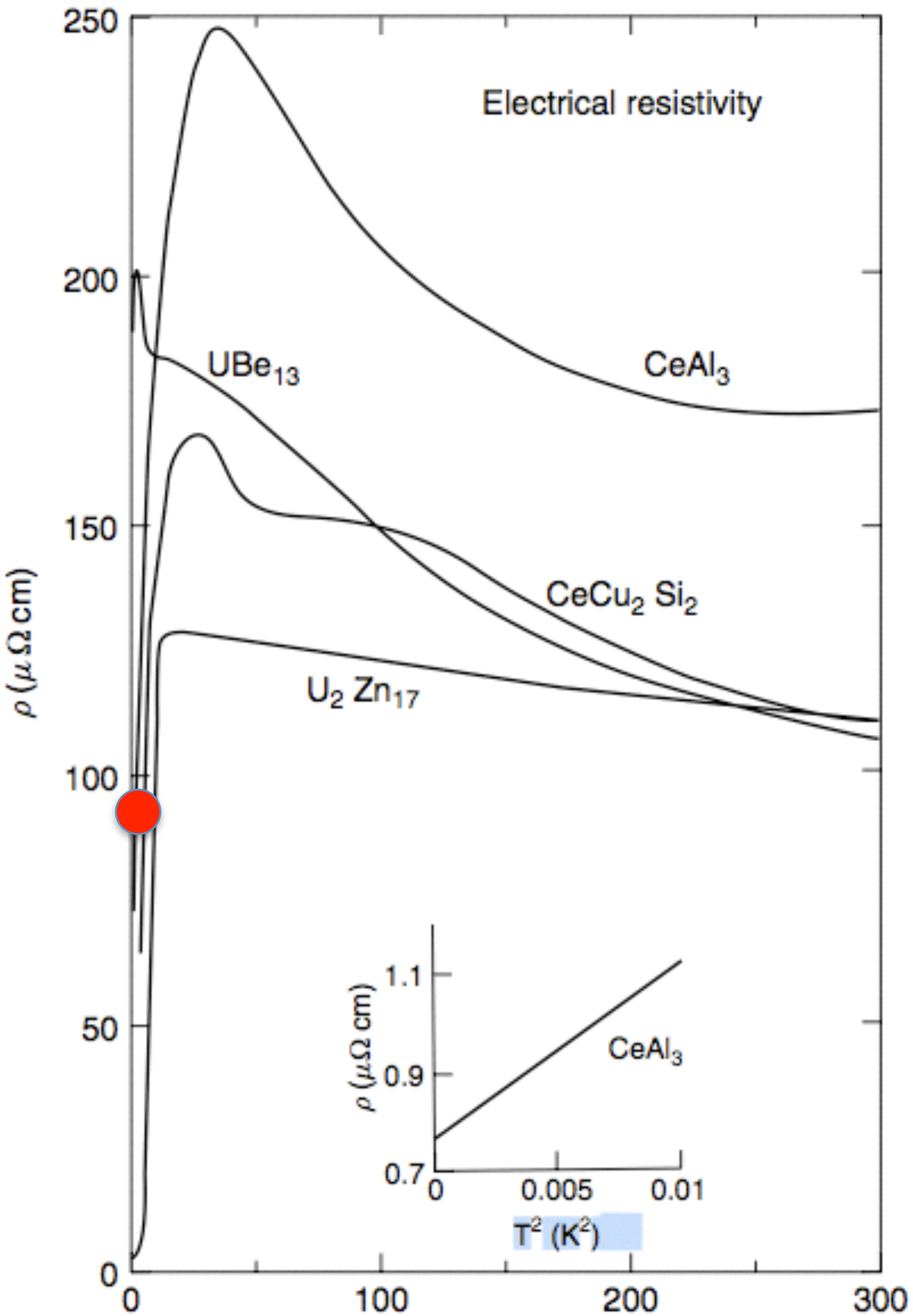
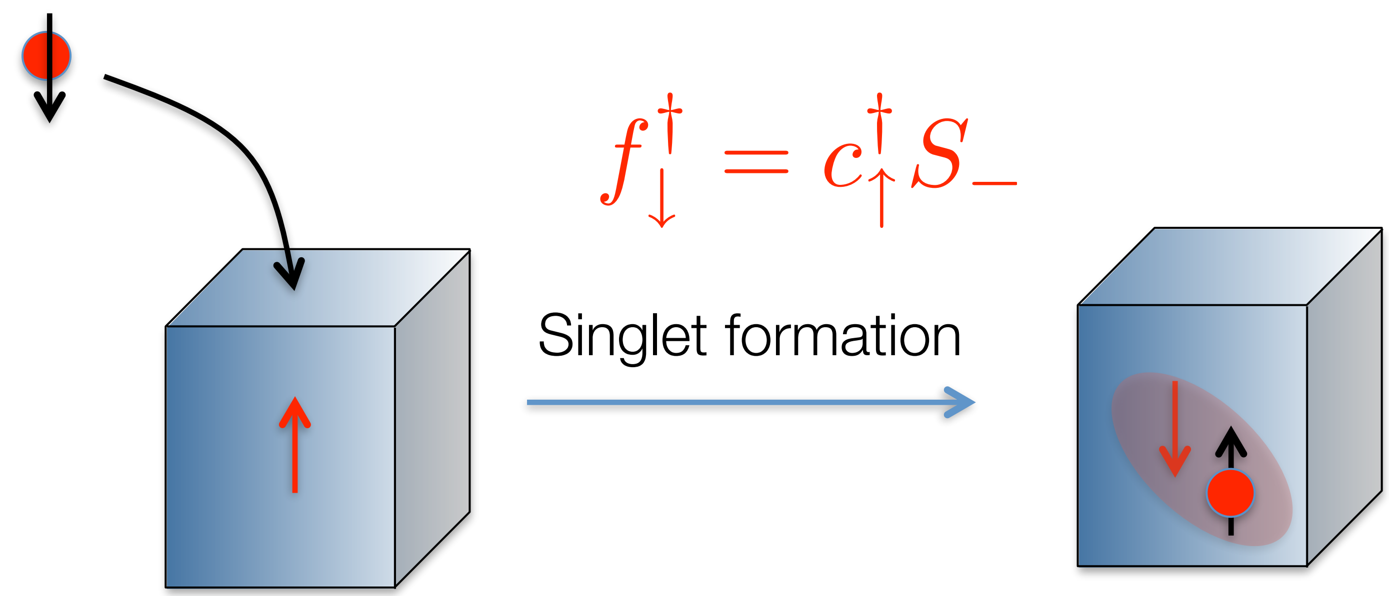




$$f^\dagger_\downarrow = c^\dagger_\uparrow S_-$$

Coherence and composite fermions

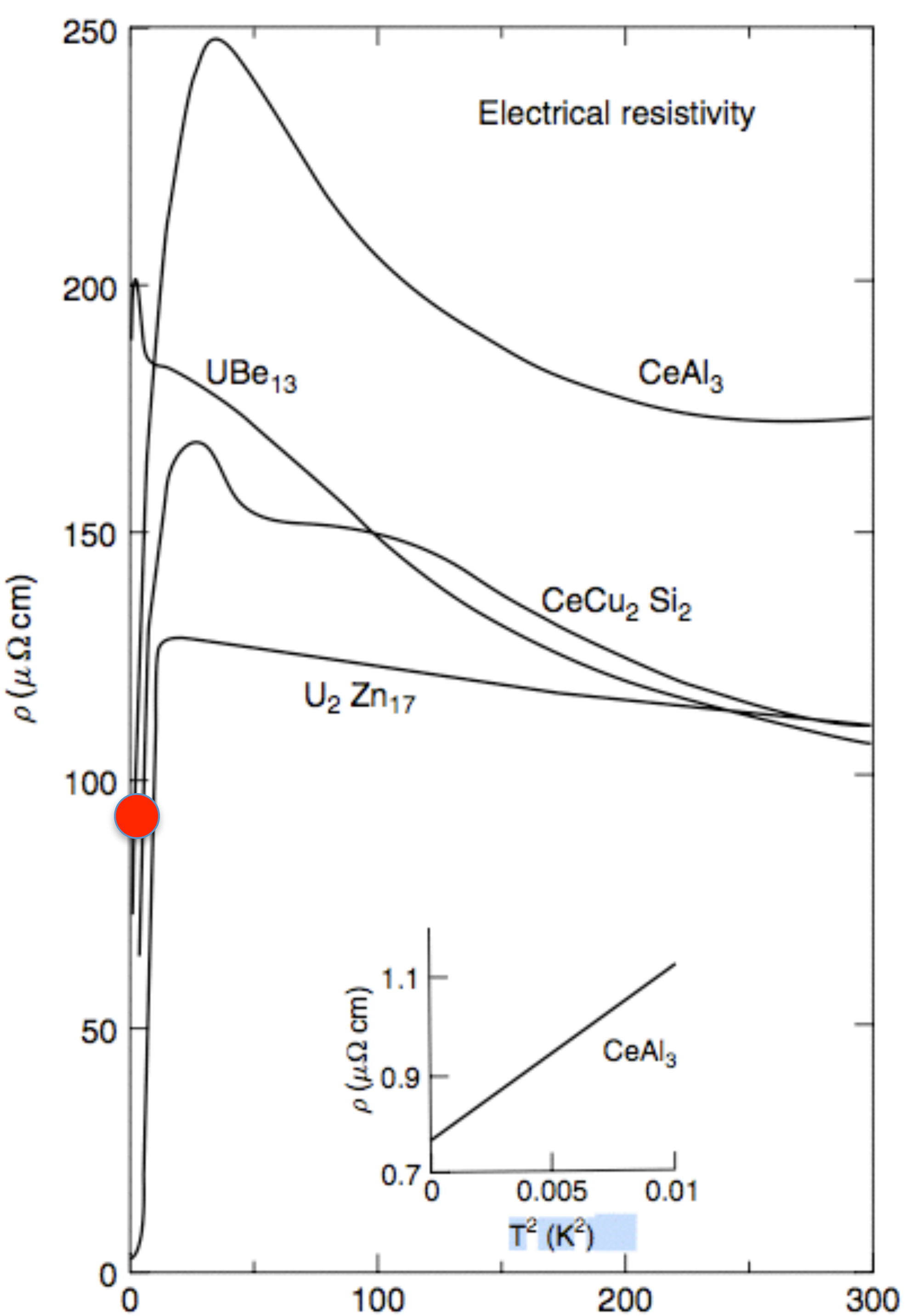


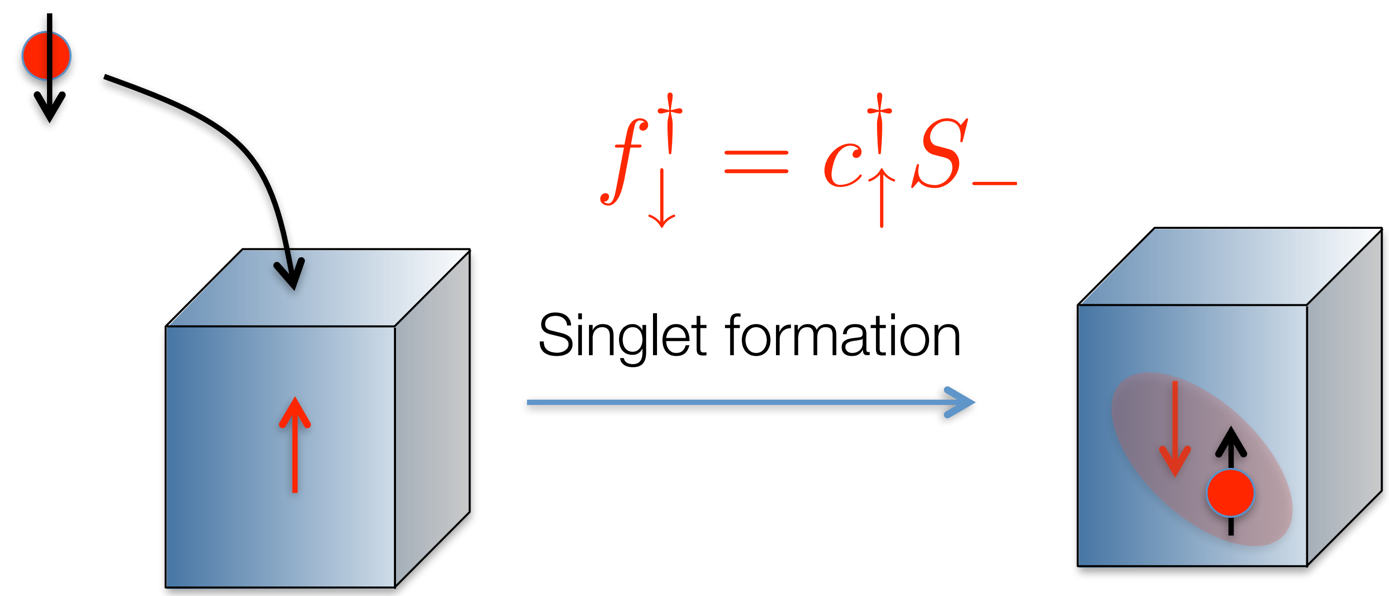


Heavy electron = (electron x spinflip)

Composite Fermion

Coherence and composite fermions





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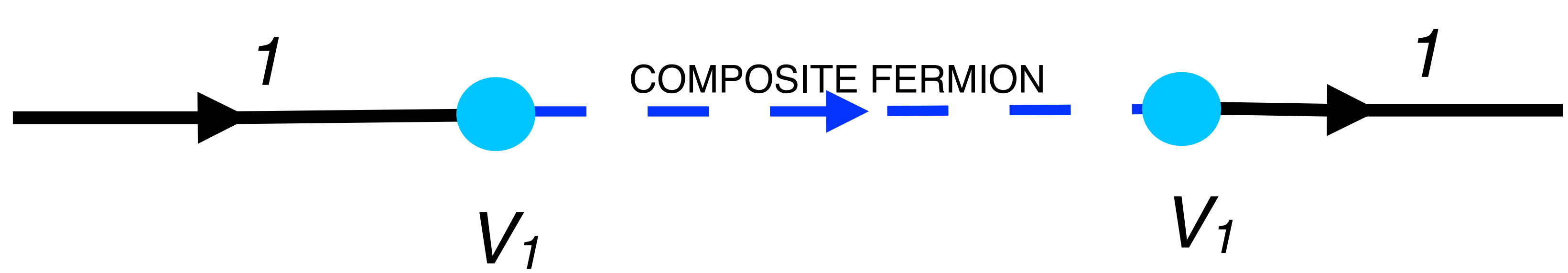
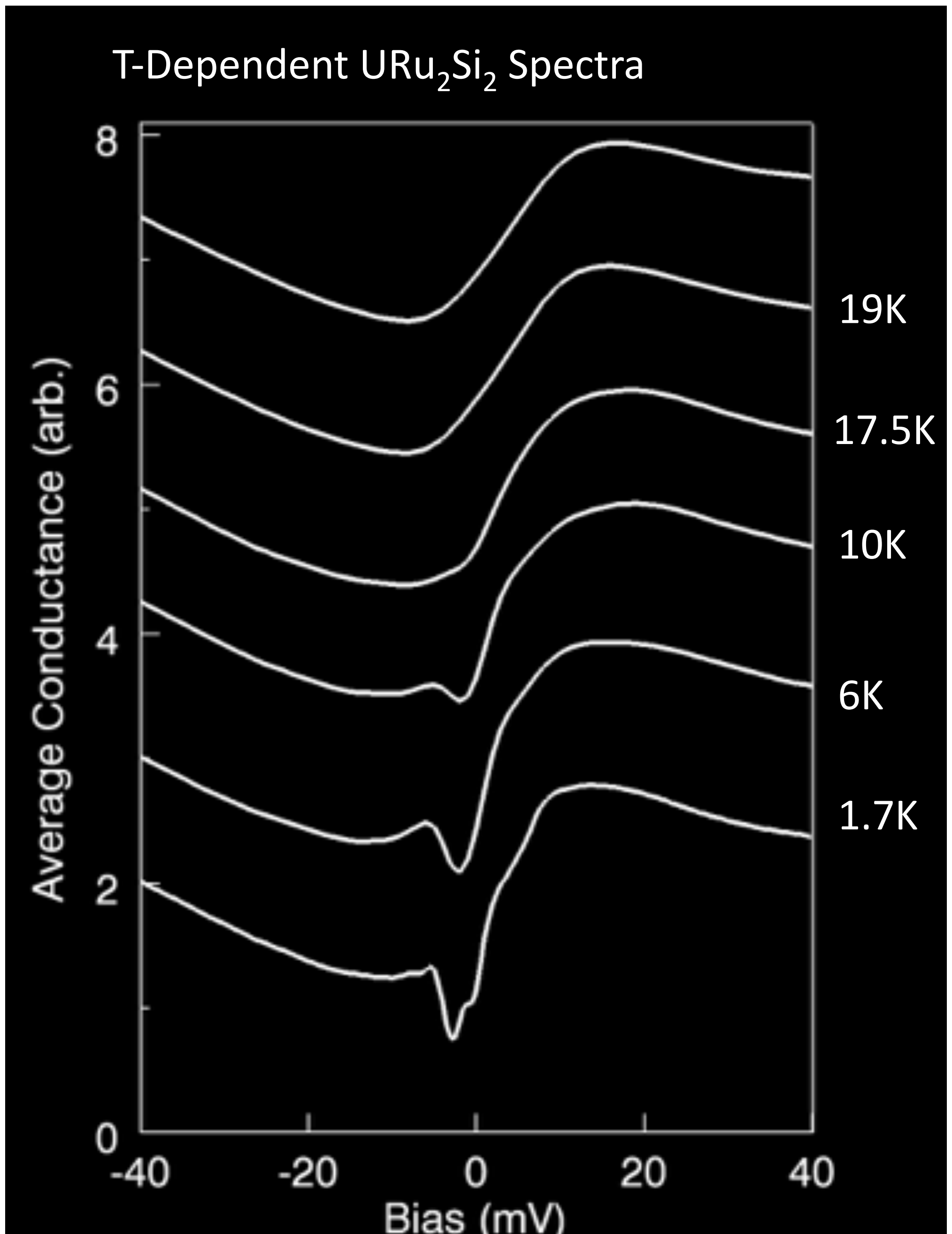
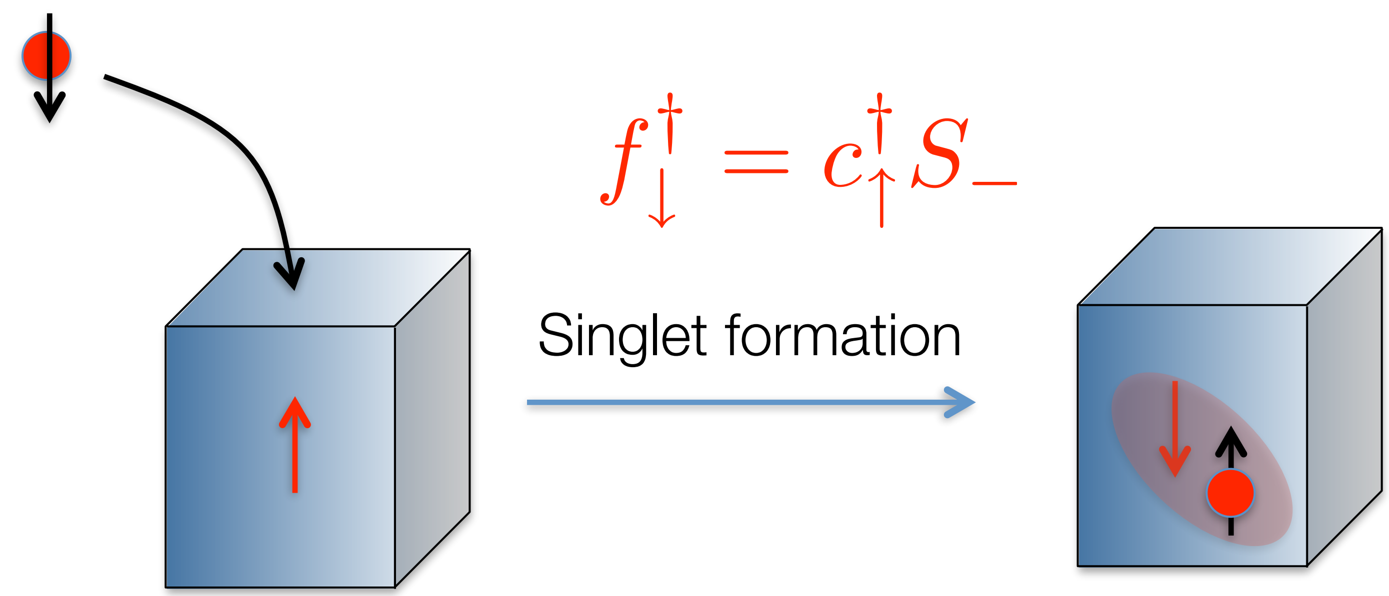


Coherence and composite fermions



Courtesy: M. Hamidian and J. C. Seamus Davis



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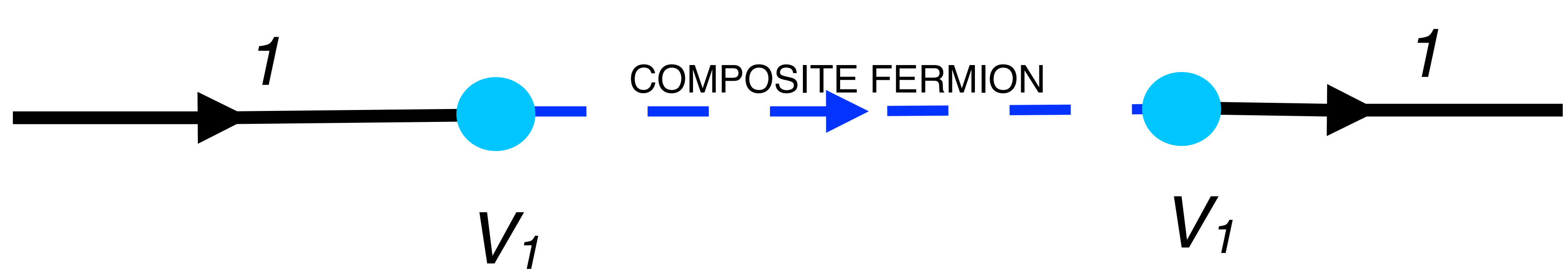
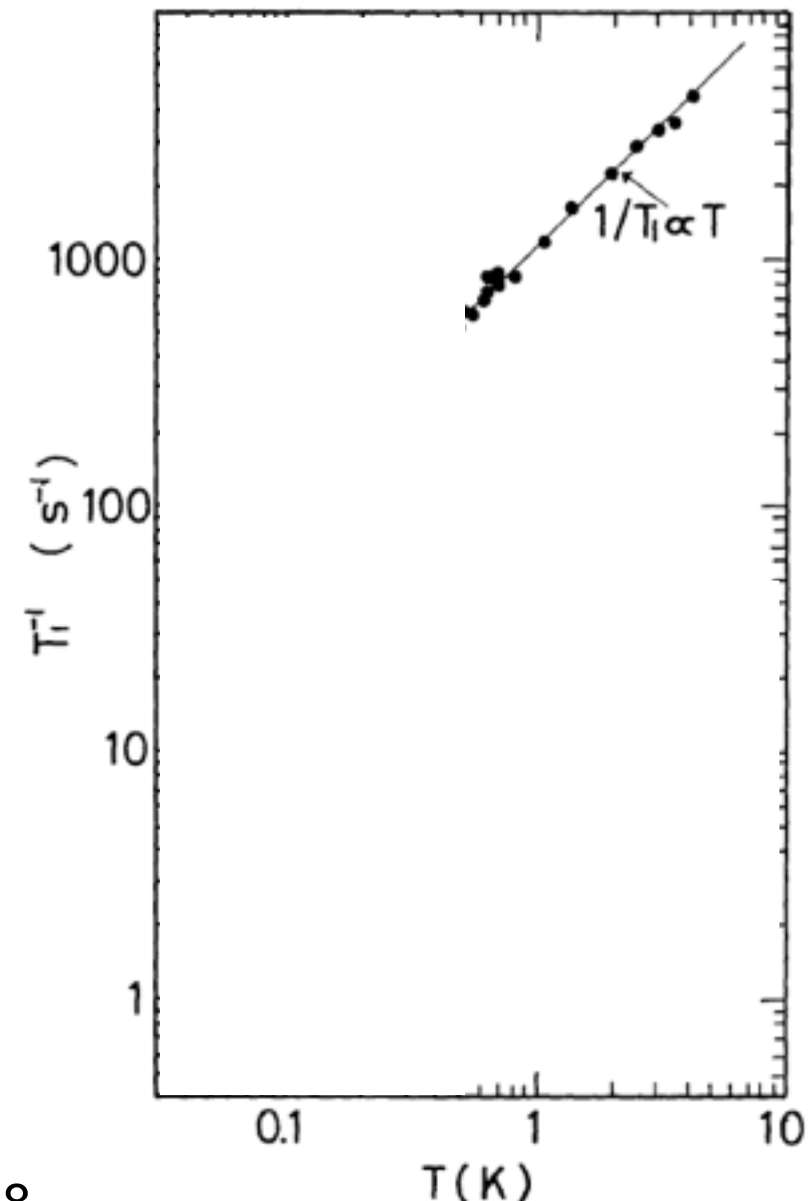


Spin Fluctuation Pairing in Heavy Fermion Superconductivity

Conventional Heavy Fermion Superconductivity

Example: UPt_3

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



Kohori 1988

Stage one: QP formation

Pauli paramagnetism fully developed by 30K~50 T_C

Conventional Heavy Fermion Superconductivity

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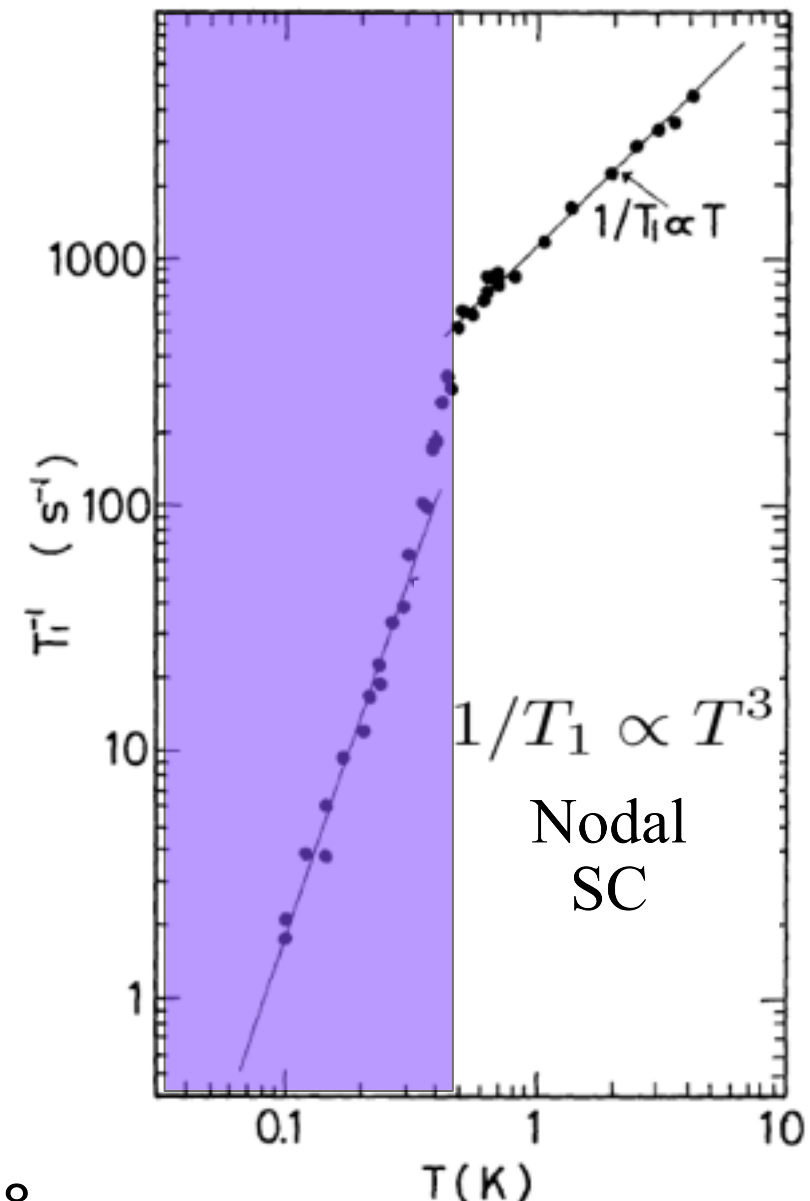
$T^* \sim 100K$, $T_C = .56K$



Kohori 1988

Stage one: QP formation

Pauli paramagnetism fully developed by 30K~50 T_C

Stage two

Unconventional superconductivity mediated by spin fluctuations

Conventional Heavy Fermion Superconductivity

Example: UPt_3

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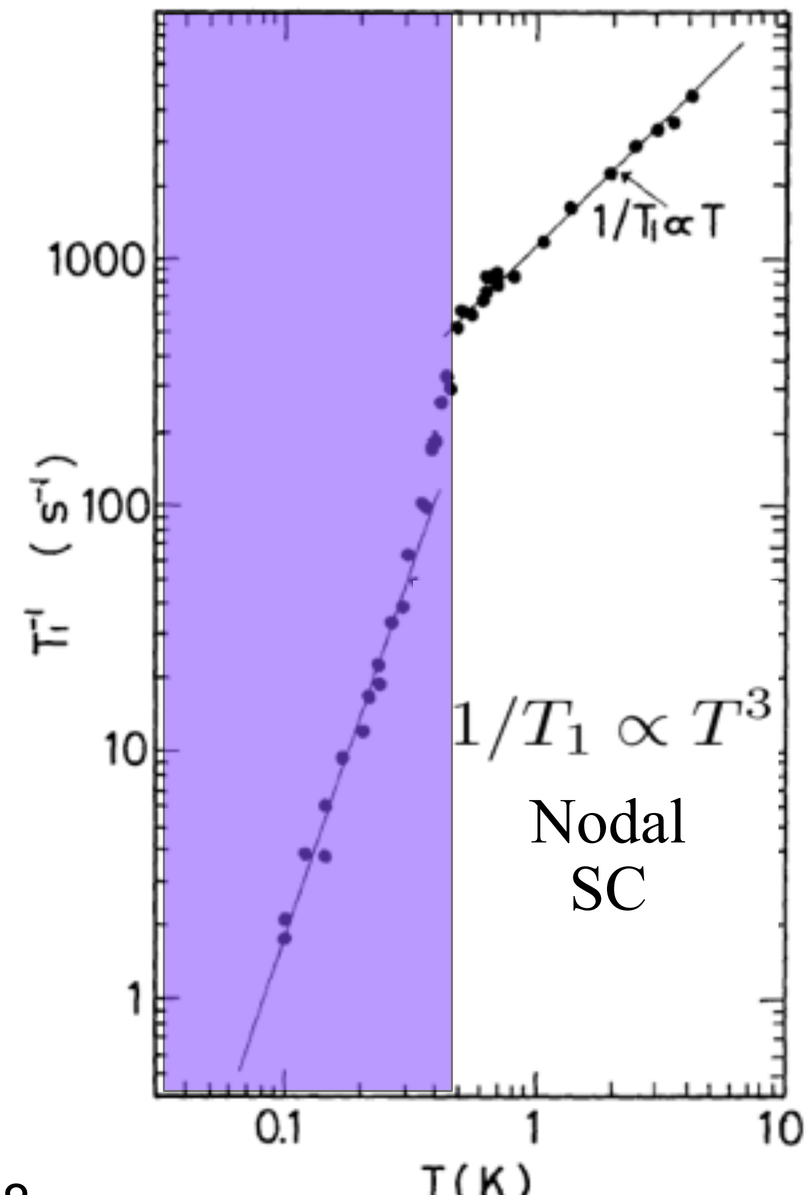


Kohori 1988

Stage one: QP formation

Pauli paramagnetism fully developed by 30K~50 T_C

Stage two

Unconventional superconductivity mediated by spin fluctuations

Led to proposal that AFM spin fluctuations drive d-wave pairing

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

Magnetically mediated superconductivity in heavy fermion compounds

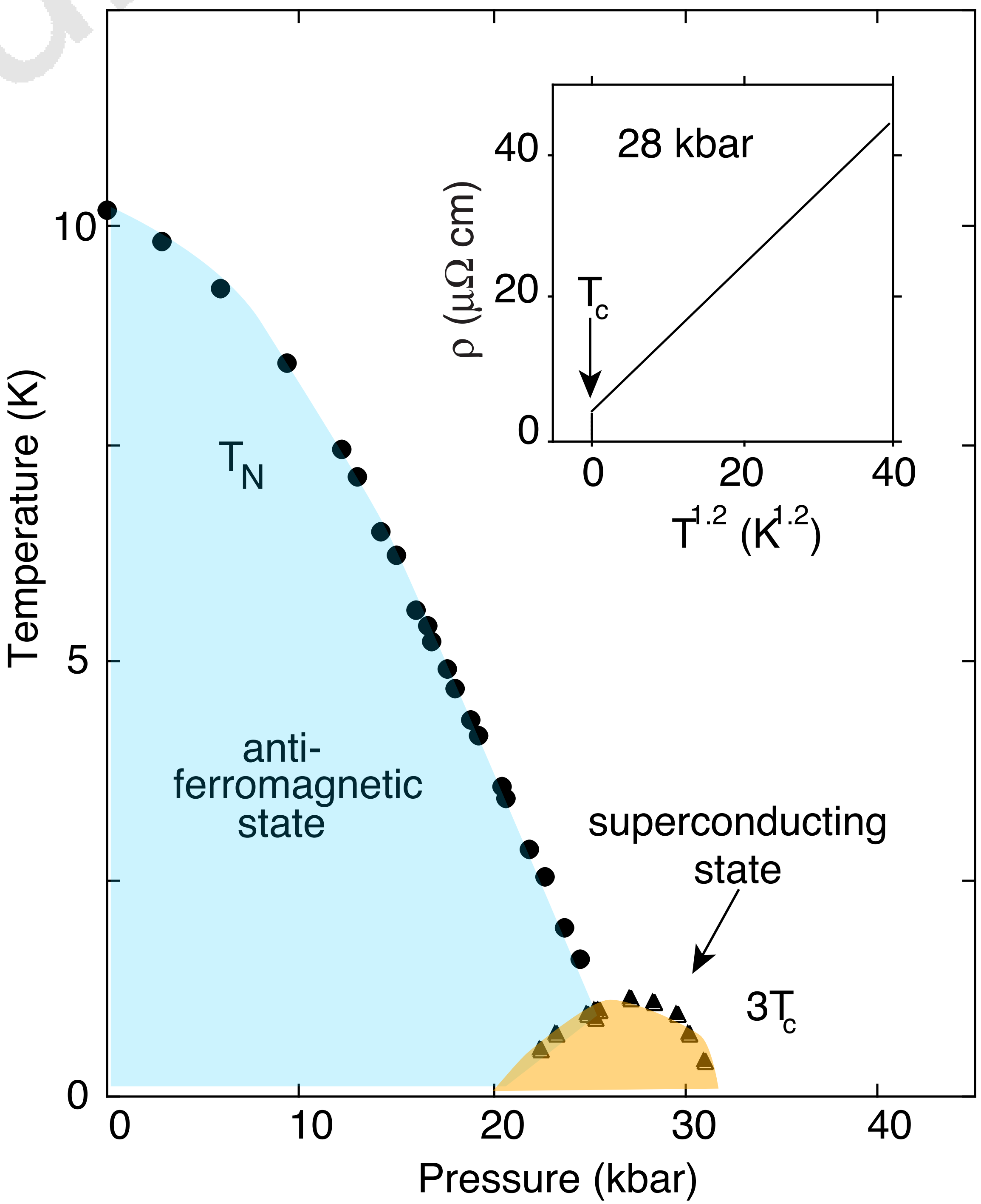
N. D. Mathur*, F. M. Grosche*, S. R. Julian, I. R. Walker, D. M. Freye, R. K. W. Haselwimmer & G. G. Lonzarich

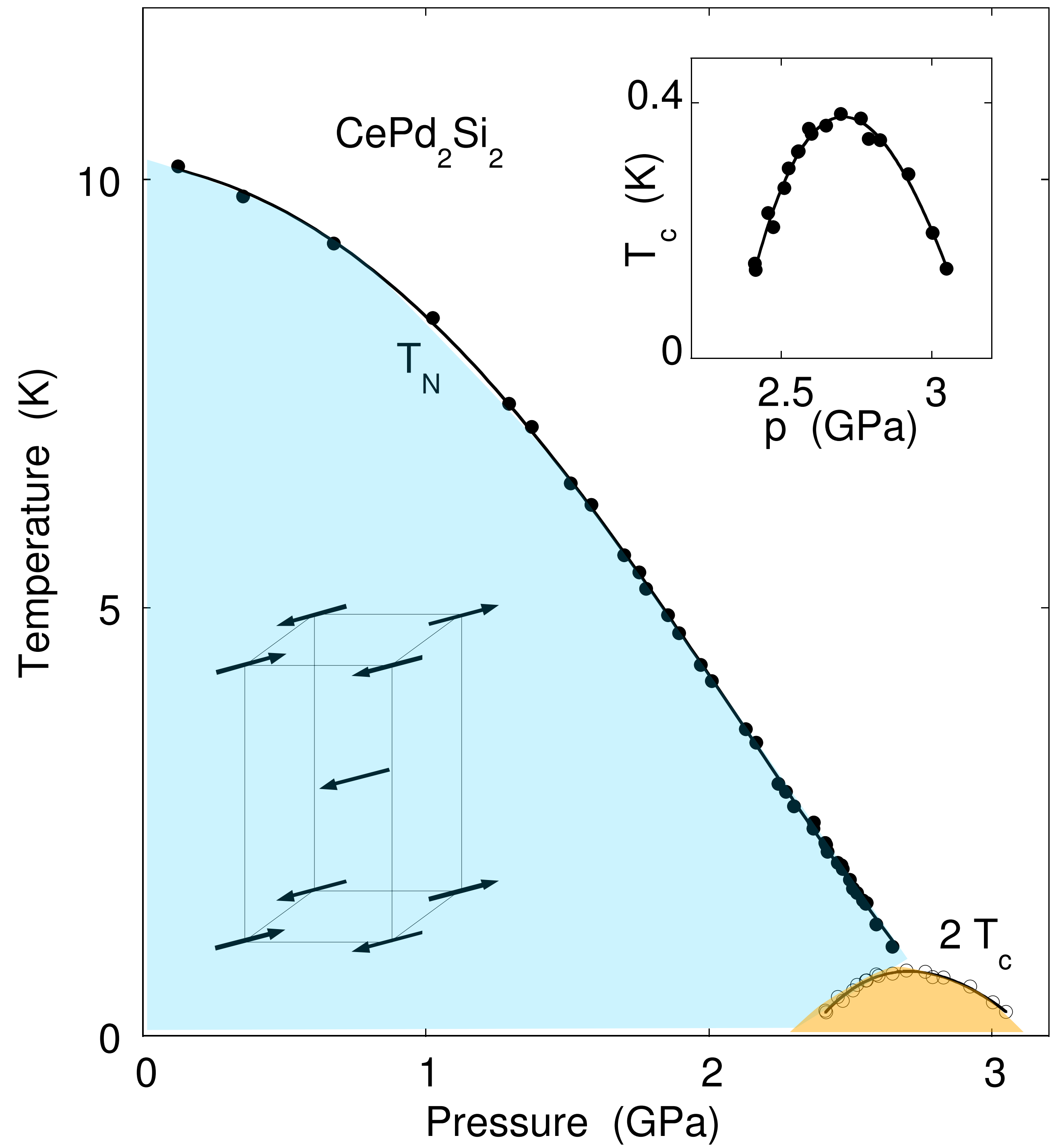
Cavendish Laboratory and the Interdisciplinary Research Centre for Superconductivity, University of Cambridge, Cambridge CB3 0HE, UK

NATURE | VOL 394 | 2 JULY 1998

Lonzarich, 1998

F. M. Grosche, I. R. Walker, S. R. Julian, N. D. Mathur, D. M. Freye, M. J. Steiner, and G. G. Lonzarich, J. Phys.: Condens. Matter 13 (2001) 2845.

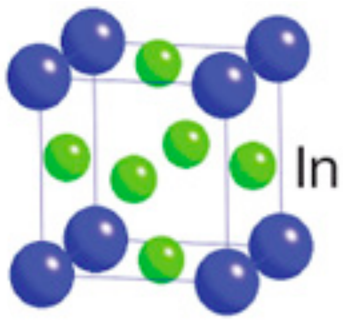


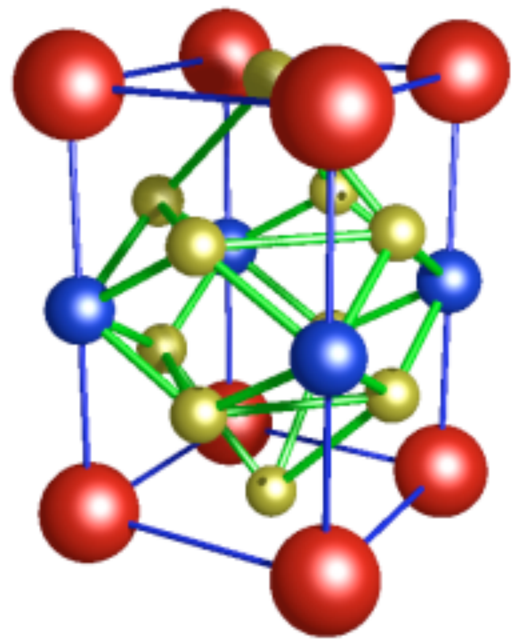


115 Superconductors

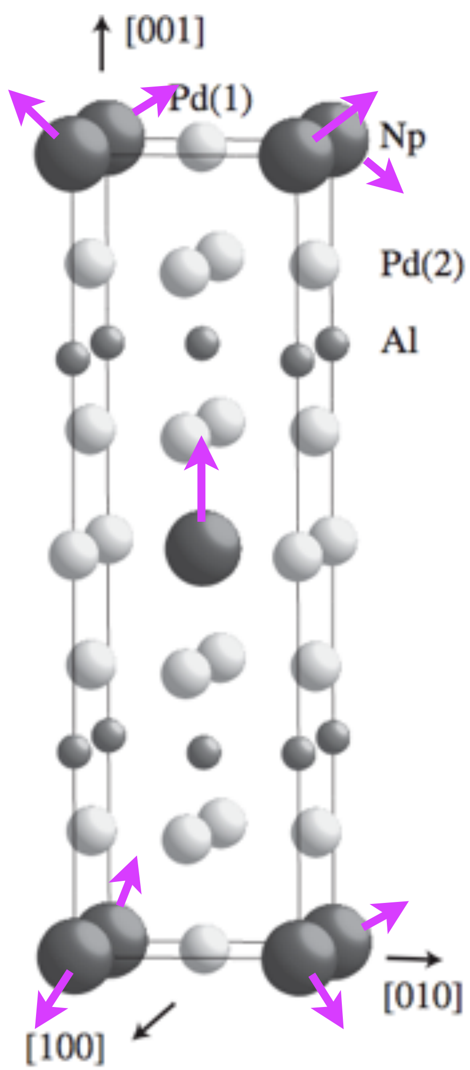
'115' Family

$CeIn_3$





$PuCoGa_5$
$CeCoIn_5$
$CeRhIn_5$
$CeIrIn_5$



$NpPd_5Al_2$

Oxides

?

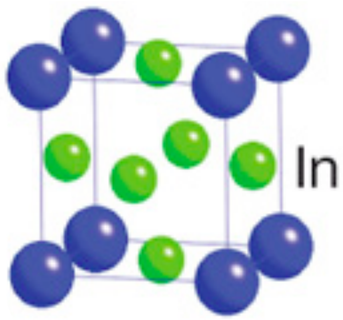
T_c

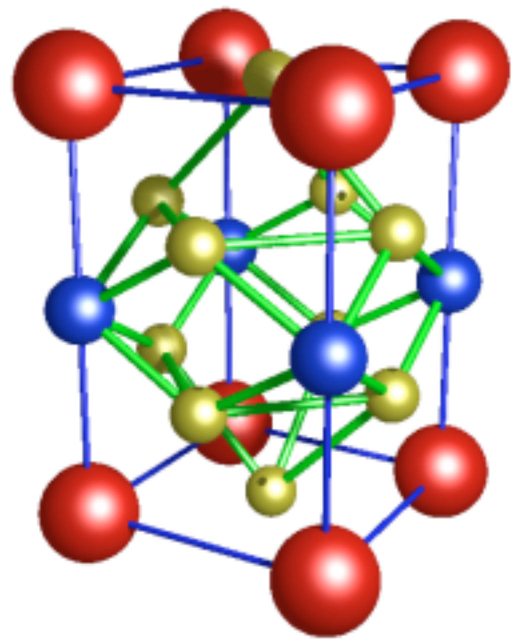
$YBa_2Cu_3O_7$ 92K

Ba2201 12K

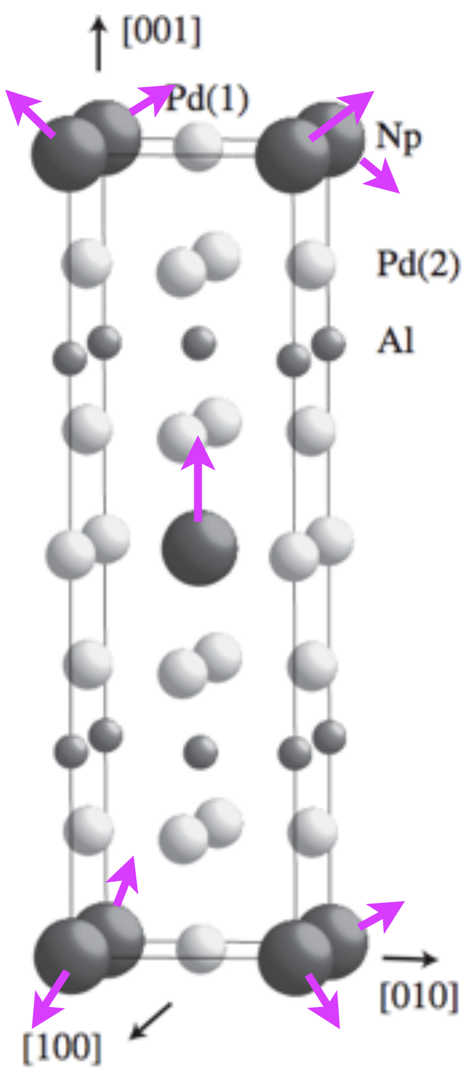
‘115’ Family

$CeIn_3$





$PuCoGa_5$
$CeCoIn_5$
$CeRhIn_5$
$CeIrIn_5$



$NpPd_5Al_2$

Oxides

?

T_c

$YBa_2Cu_3O_7$ 92K

Ba2201 12K

115 Intermetallics

T_c

18.5K $PuCoGa_5$

4.5K $NpAl_2Pd_5$

2K $CeCoIn_5$

0.2K $CeIn_3$

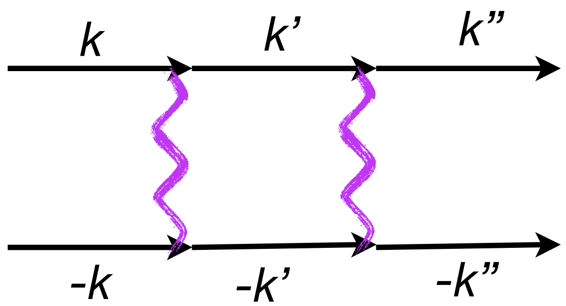
Glue vs Fabric.

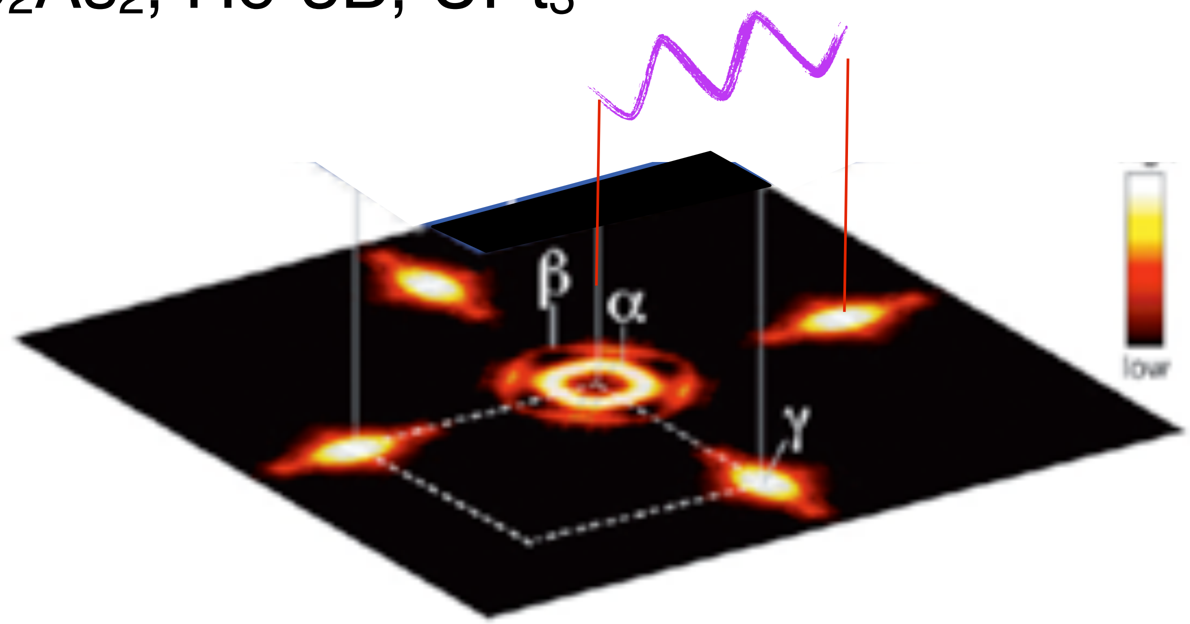
Glue vs Fabric.

Spin fluctuations = pairing glue.
eg $(Ba,K)Fe_2As_2$, He-3B, UPt_3

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

Glue





Glue vs Fabric.

Spin fluctuations = pairing glue.
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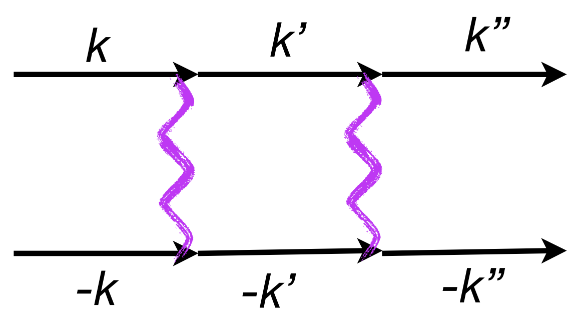
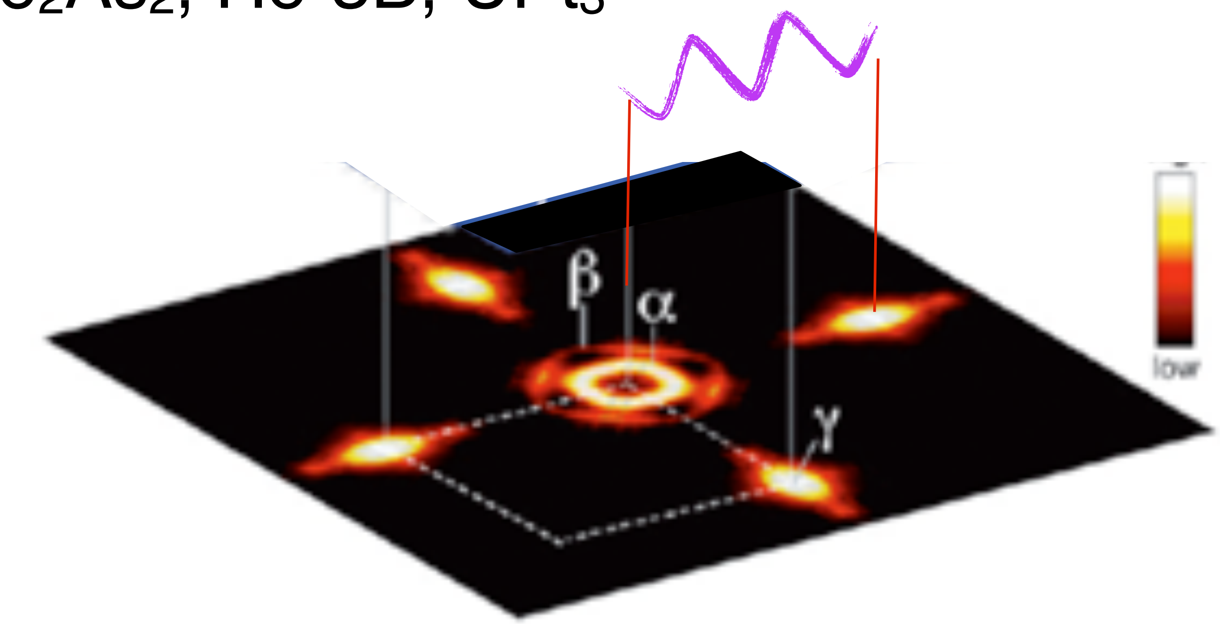
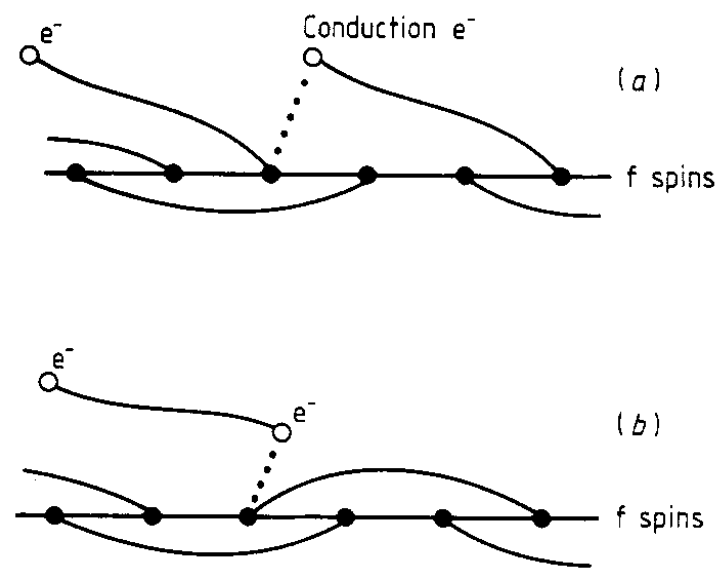
Glue

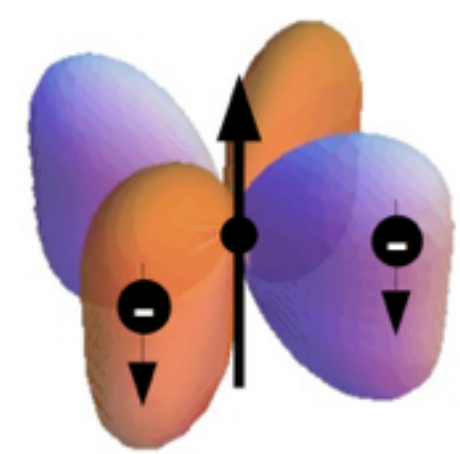




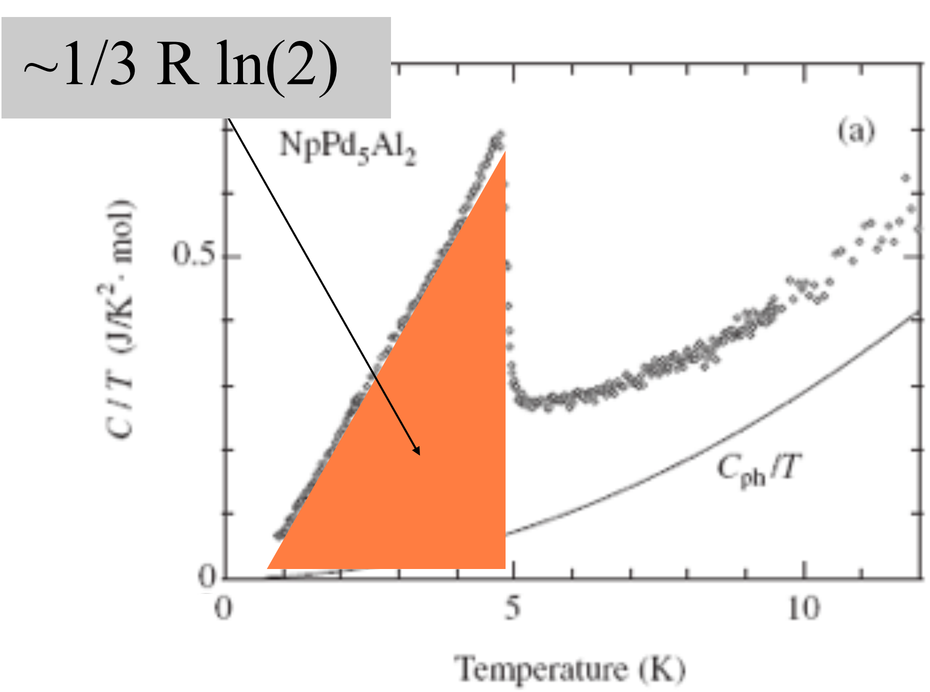
Fabric: spins *build* the pairs

HiTc: Anderson: RVB (1987)
Heavy Fermions: Andrei, PC (1989)





Composite pairs

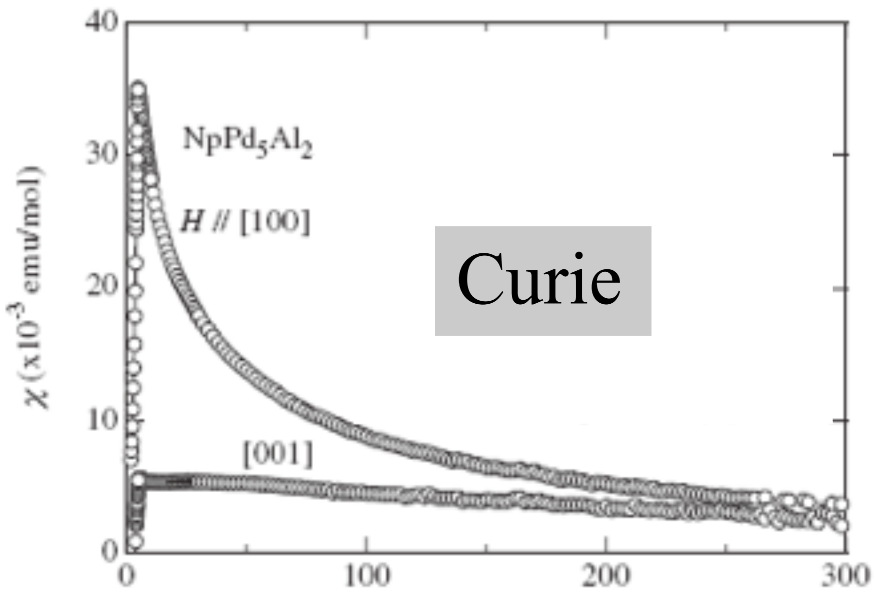


$$R \ln W = \int_0^T dT' \frac{C'}{T'}$$

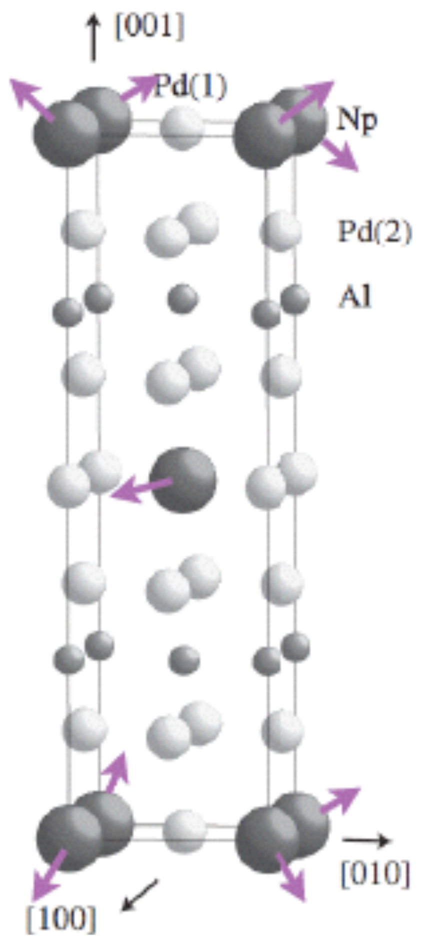
SPIN Hilbert space BUILDS the pairs.

The 115s: local moments at T_C

$NpPd_5Al_2$ $T_C = 4.5K$

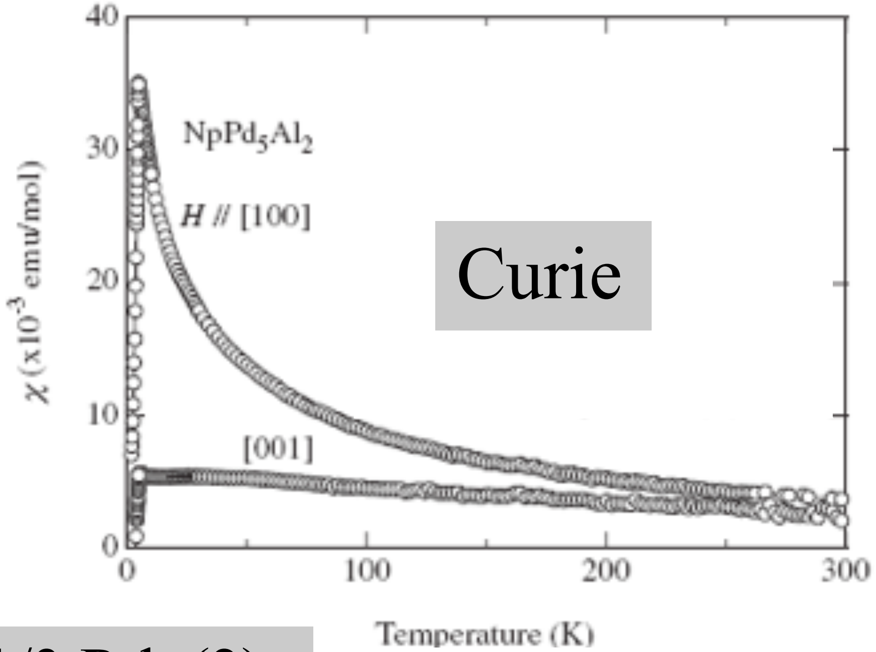


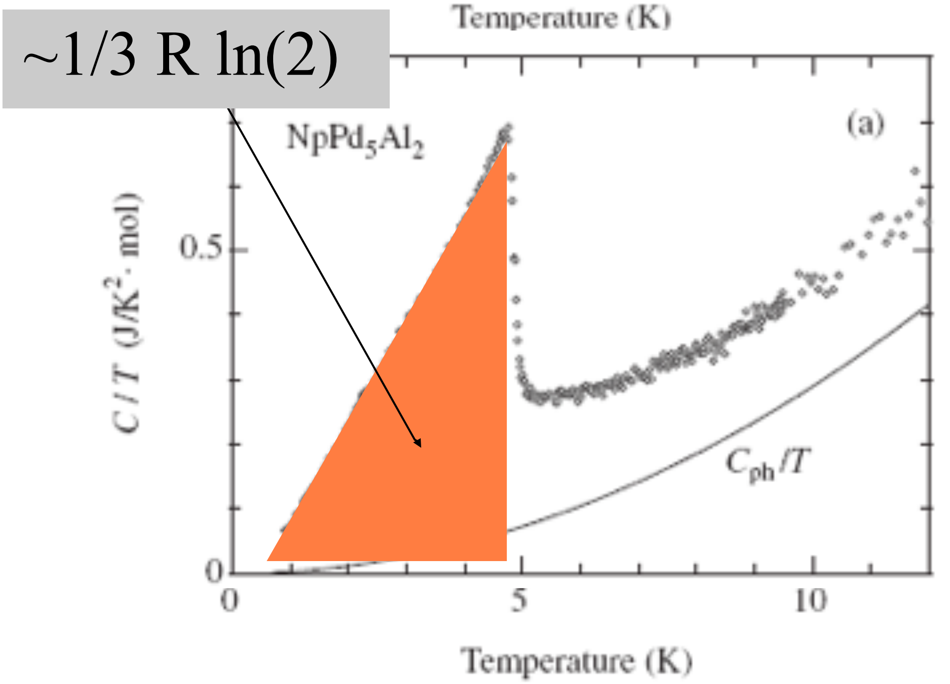
No Pauli paramagnetism



The 115s: local moments at T_C

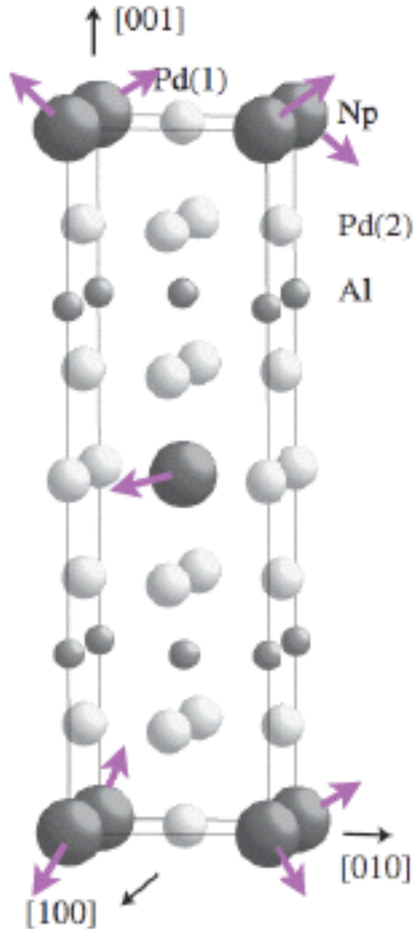
$NpPd_5Al_2$ $T_C = 4.5K$





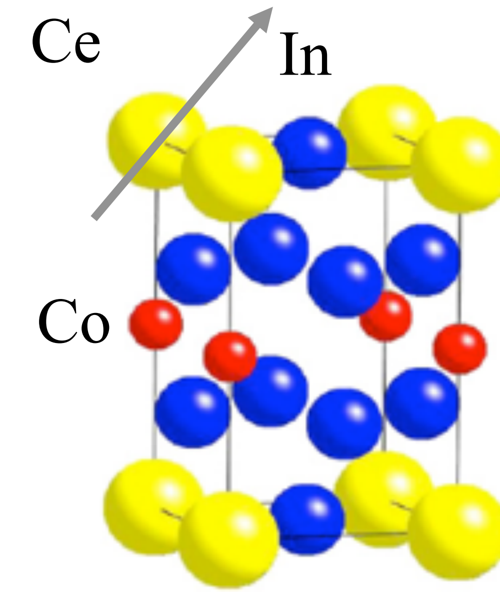
No Pauli paramagnetism

Large condensation entropy

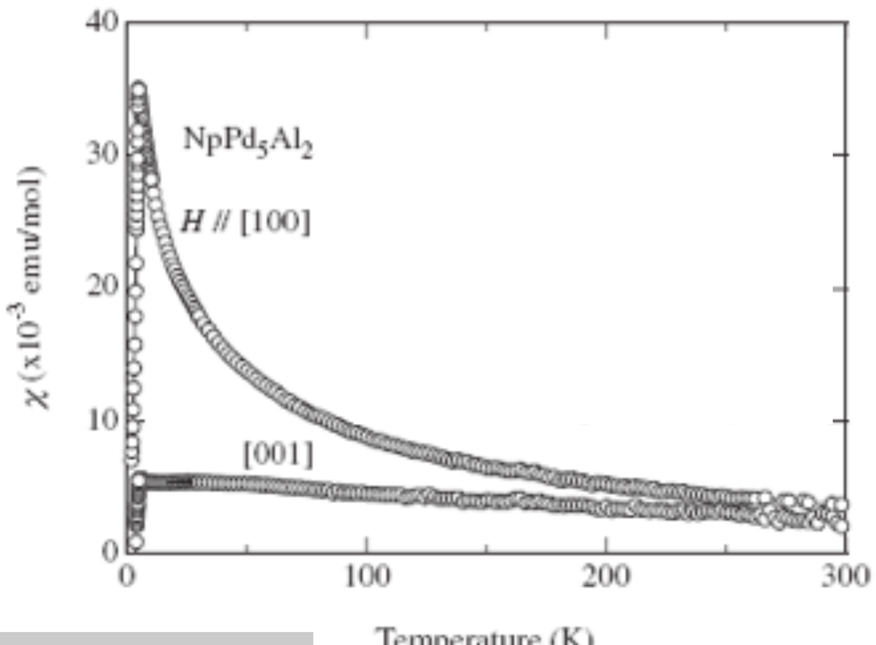


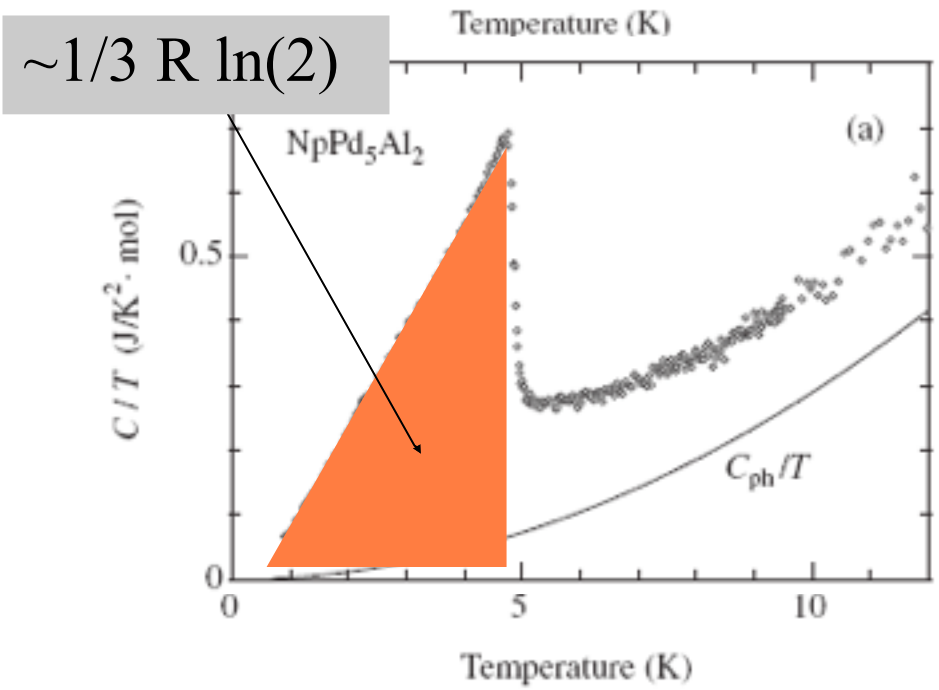
Aoki et al 2007

The 115s: local moments at T_C



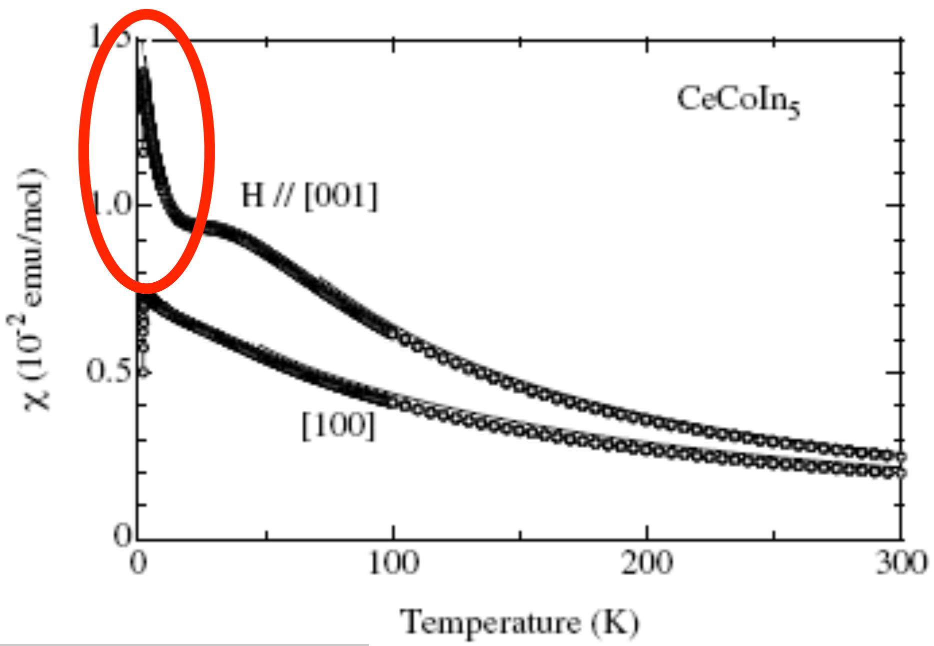
$NpPd_5Al_2$ $T_C = 4.5K$

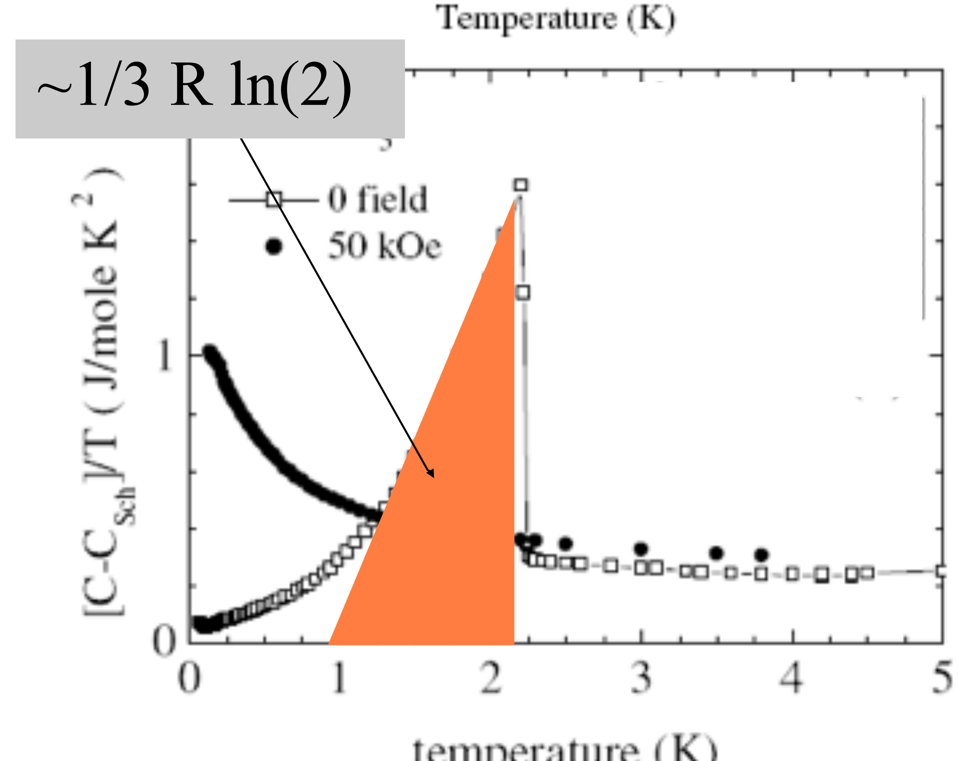




Aoki et al 2007

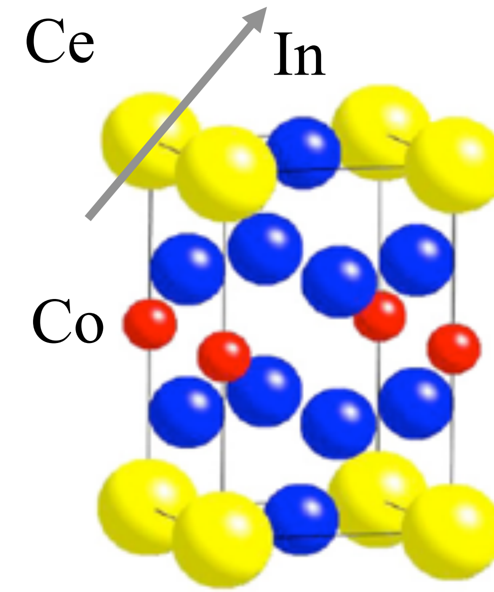
$CeCoIn_5$ $T_C = 2.3K$



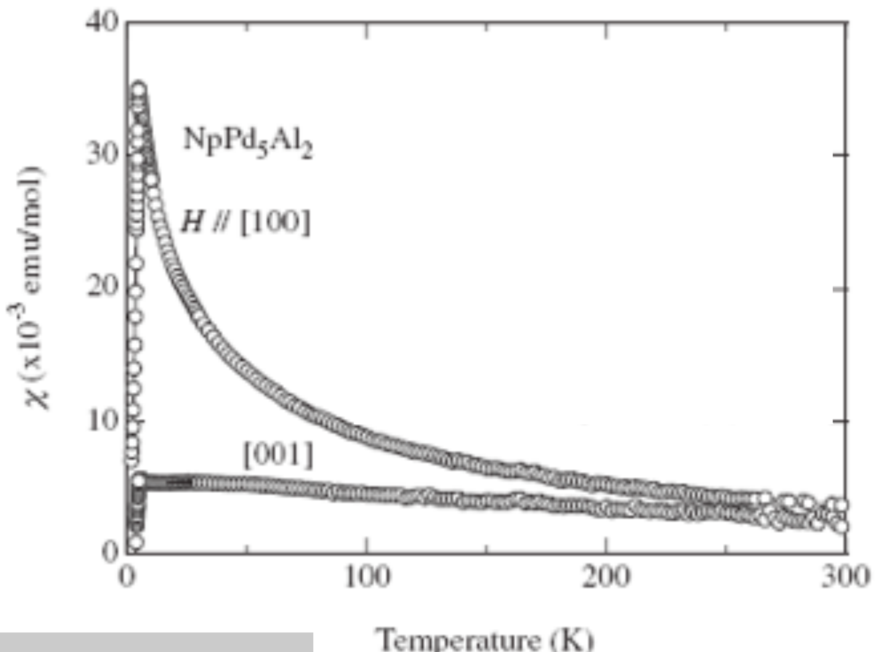


Petrovic et al 2001

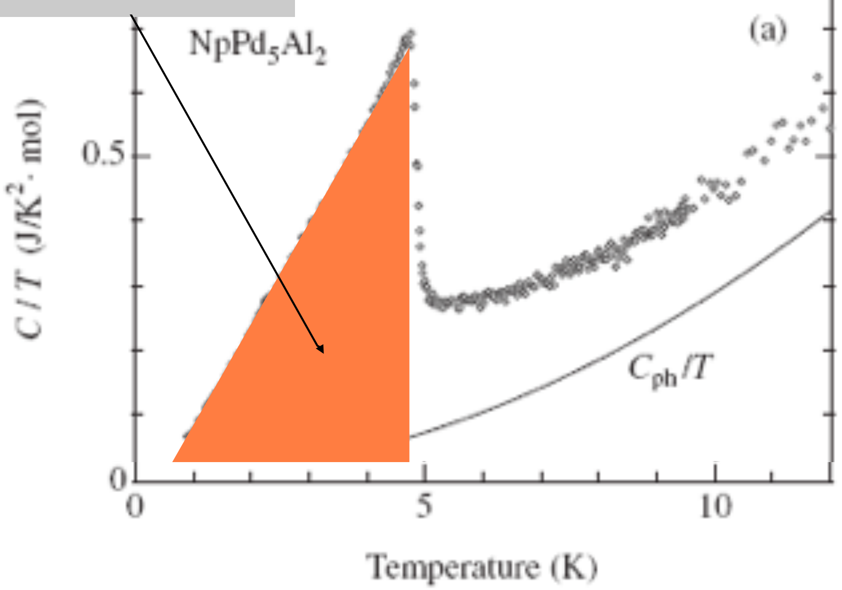
The 115s: local moments at T_C



$NpPd_5Al_2$ $T_C = 4.5K$



~1/3 R ln(2)



Aoki et al 2007

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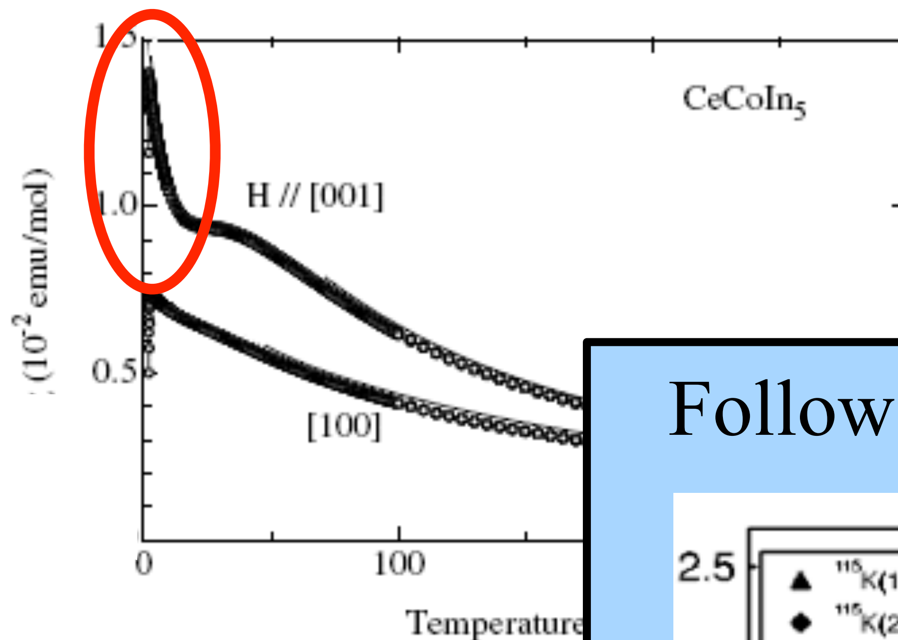
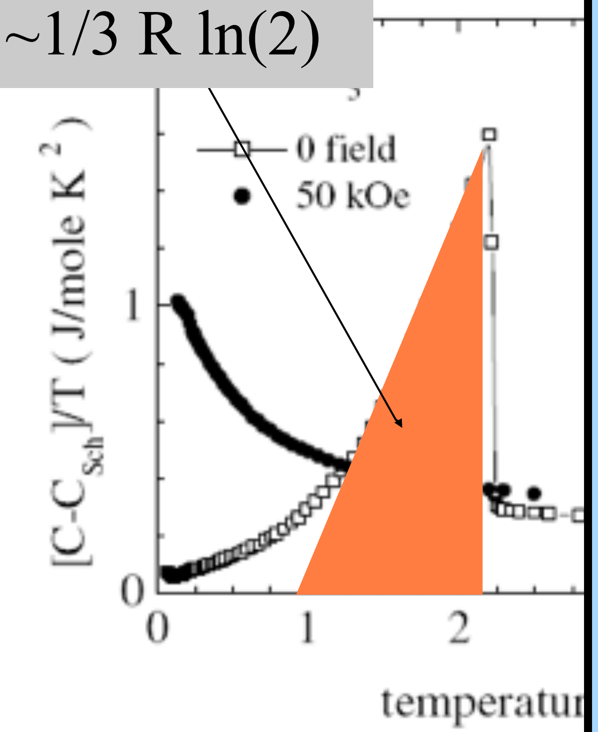
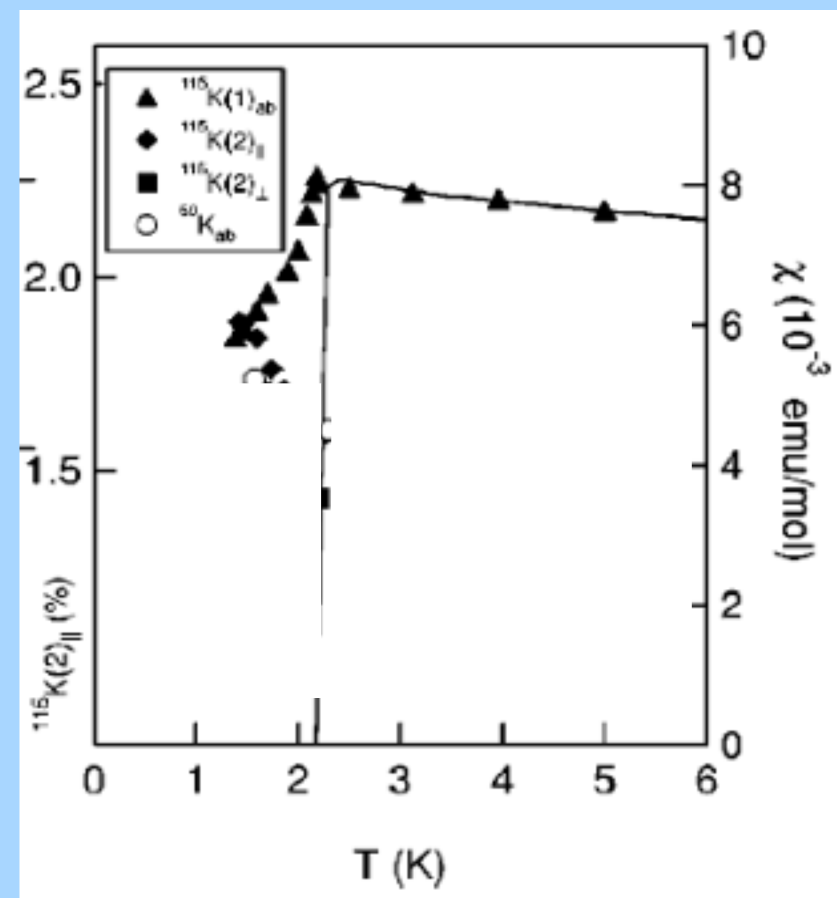


~1/3 R ln(2)



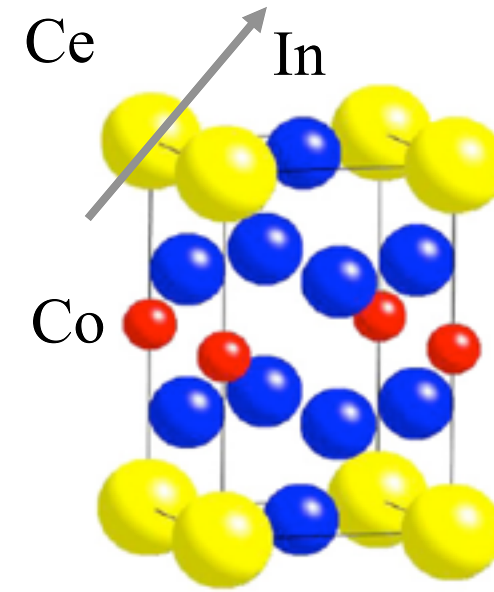
Petrovic et al 2001

Follow spins below T_C

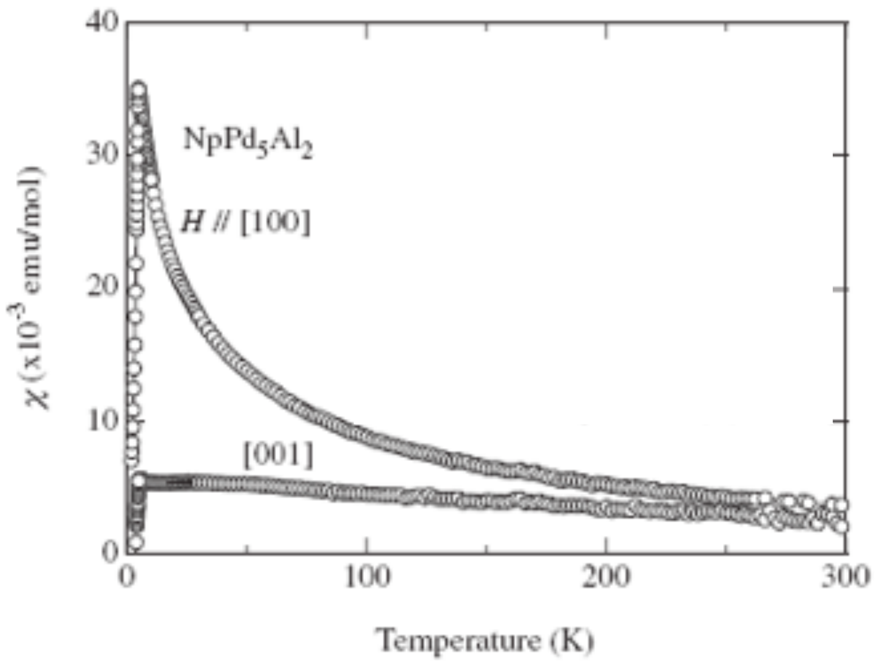


Curro et al 2001

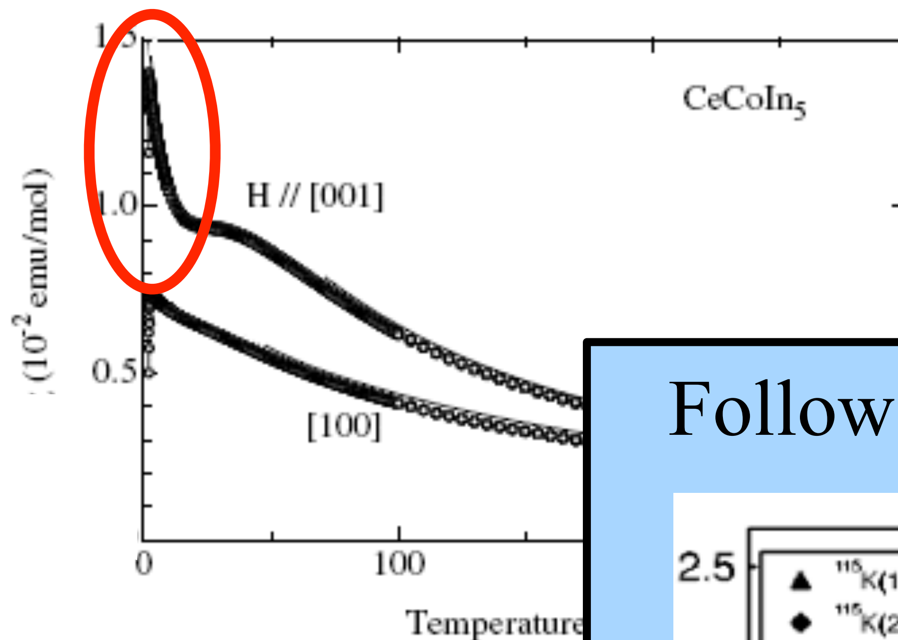
The 115s: local moments at T_C



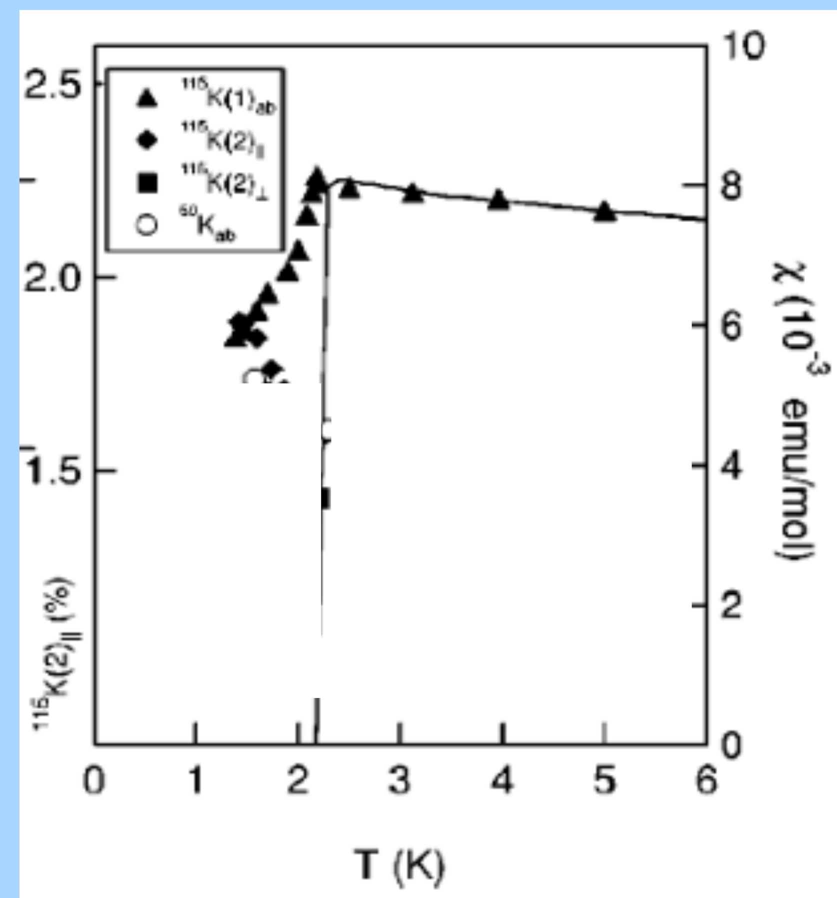
$NpPd_5Al_2$ $T_C = 4.5K$



$CeCoIn_5$ $T_C = 2.3K$



Follow spins below T_C



Curro et al 2001

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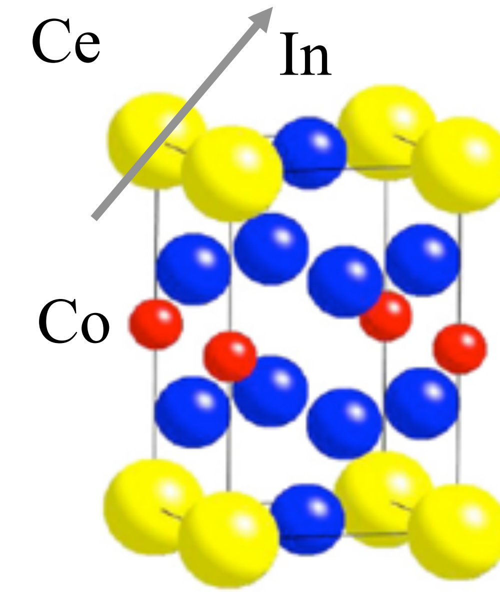
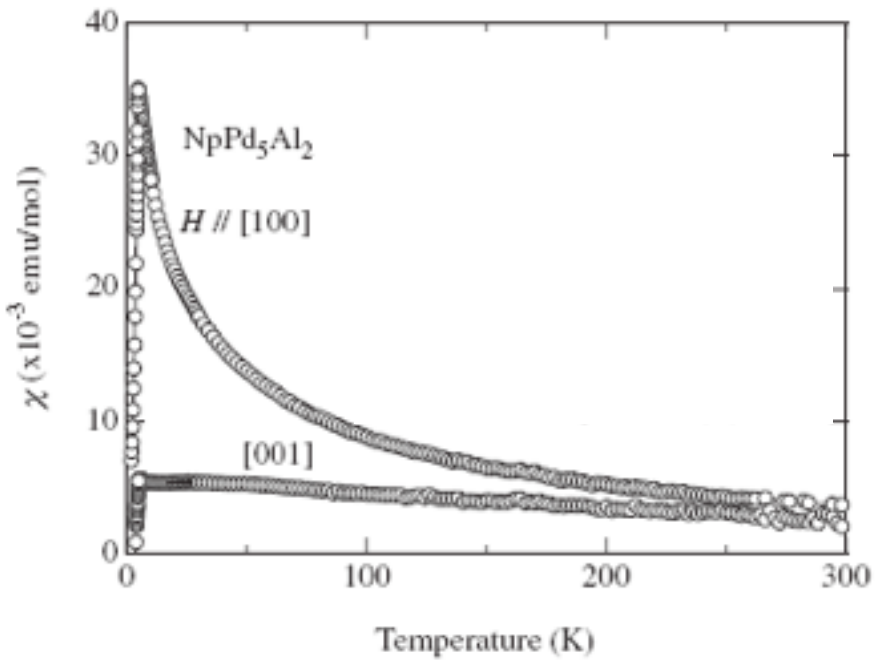


$NpPd_5Al_2$ $T_C = 4.5K$



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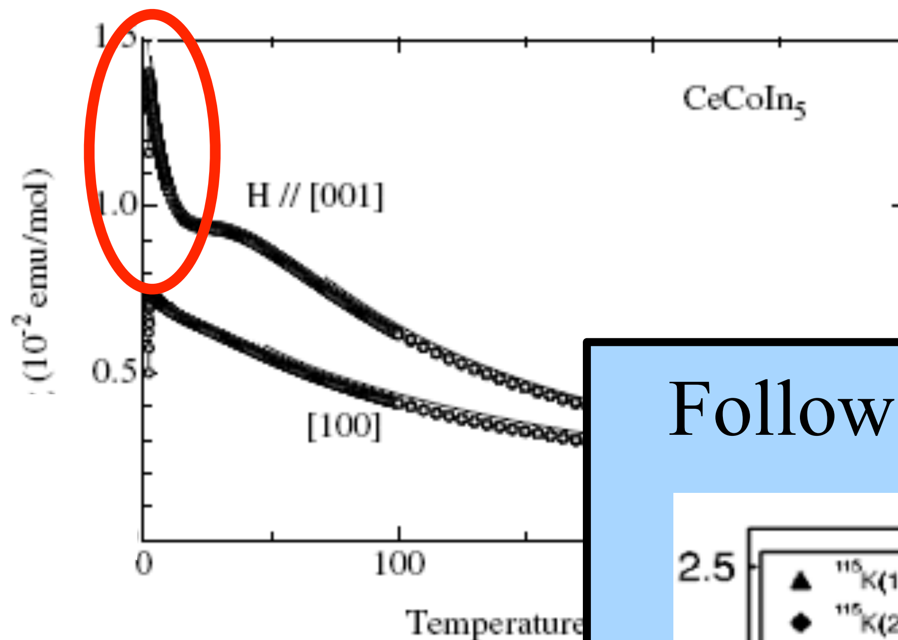
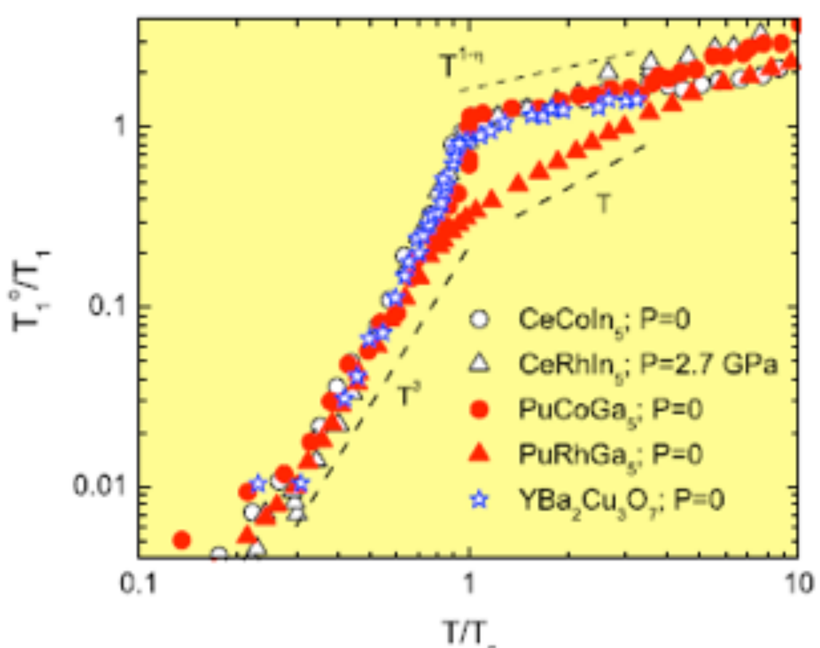
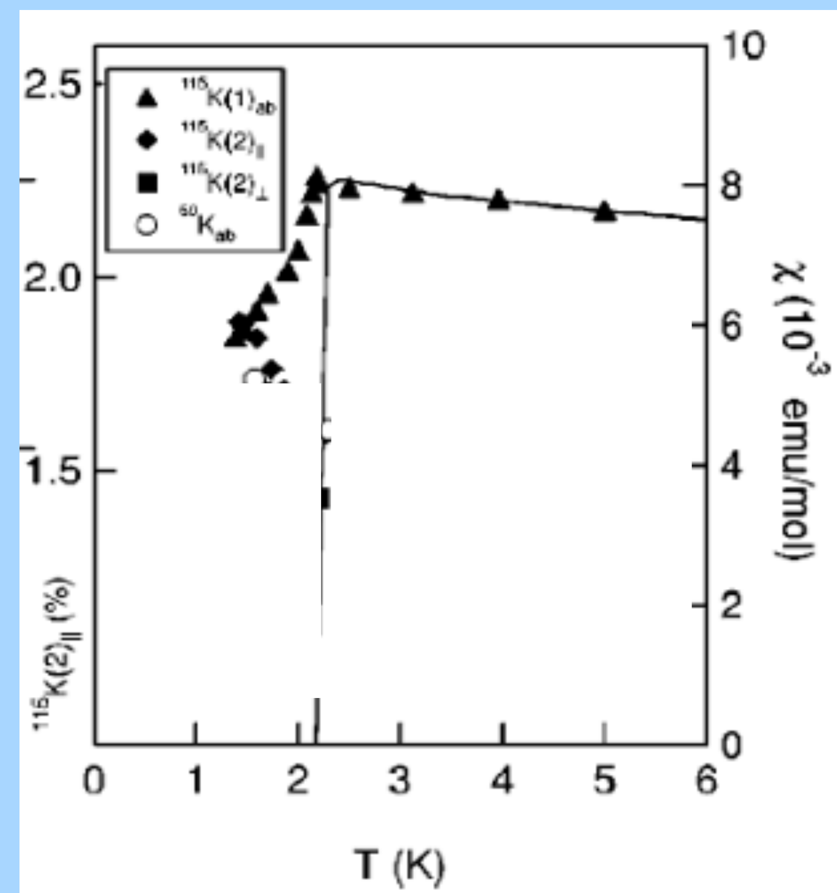




Sarrao and Thompson

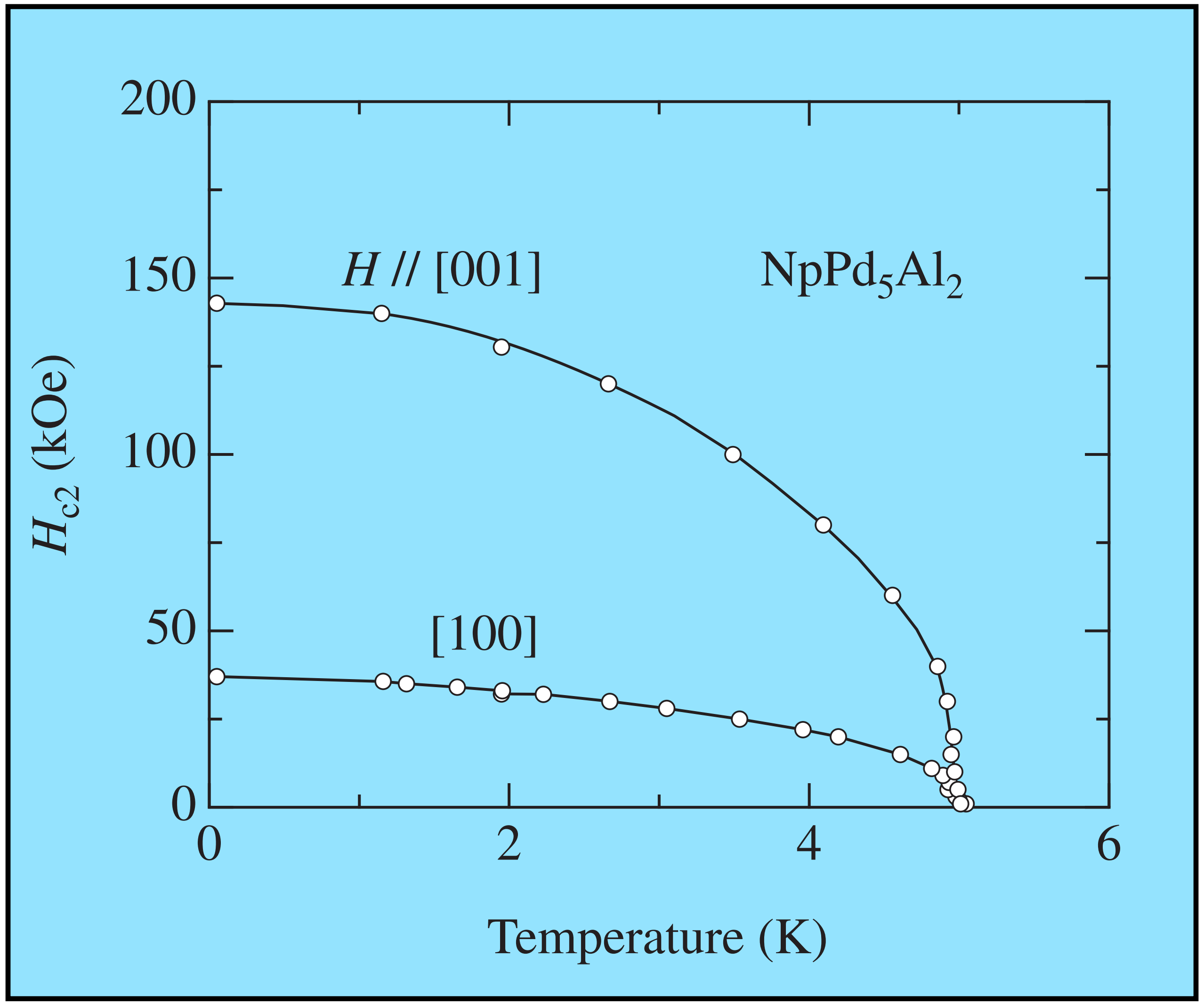
Spin singlet, nodal SC

Follow spins below T_C

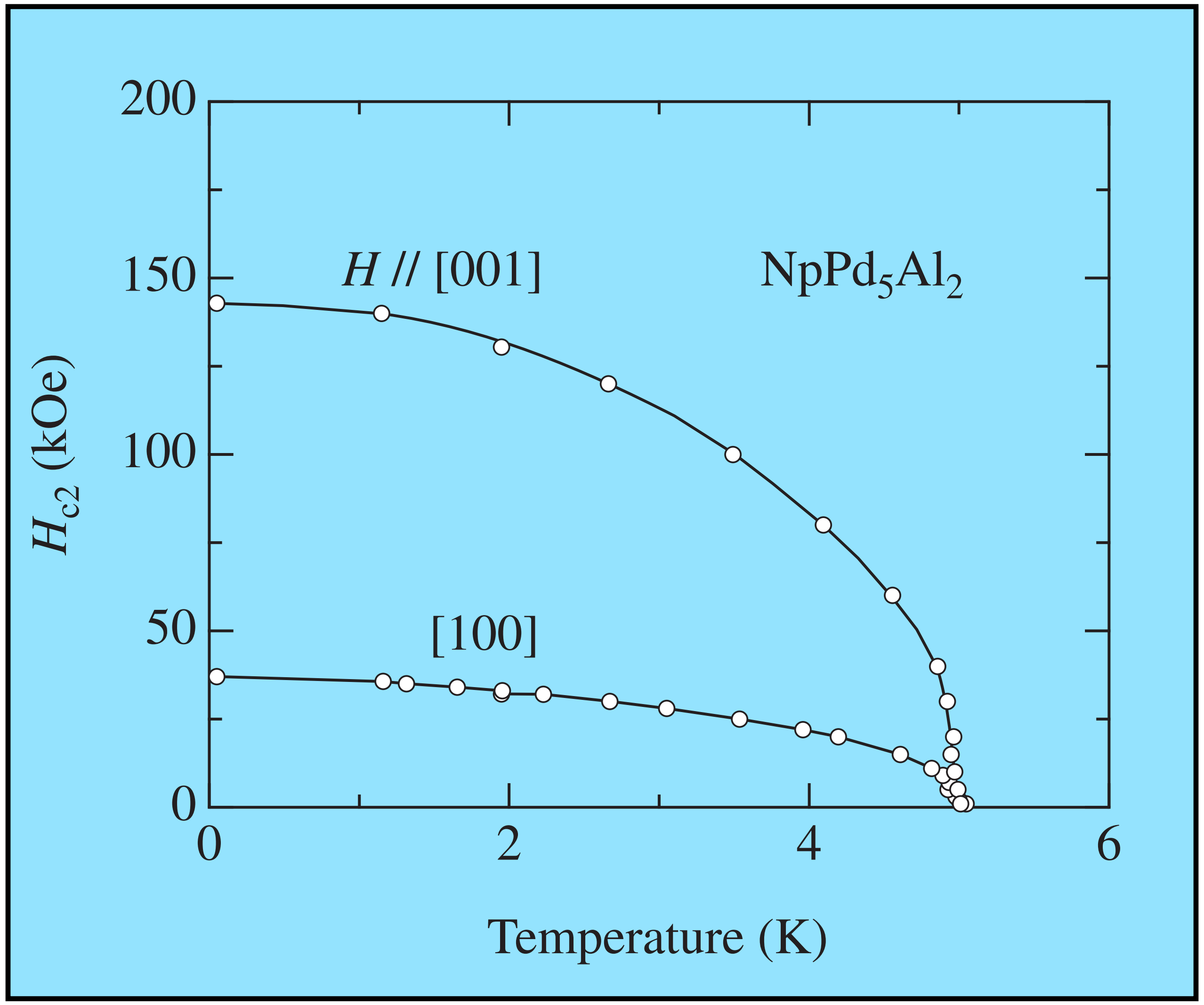


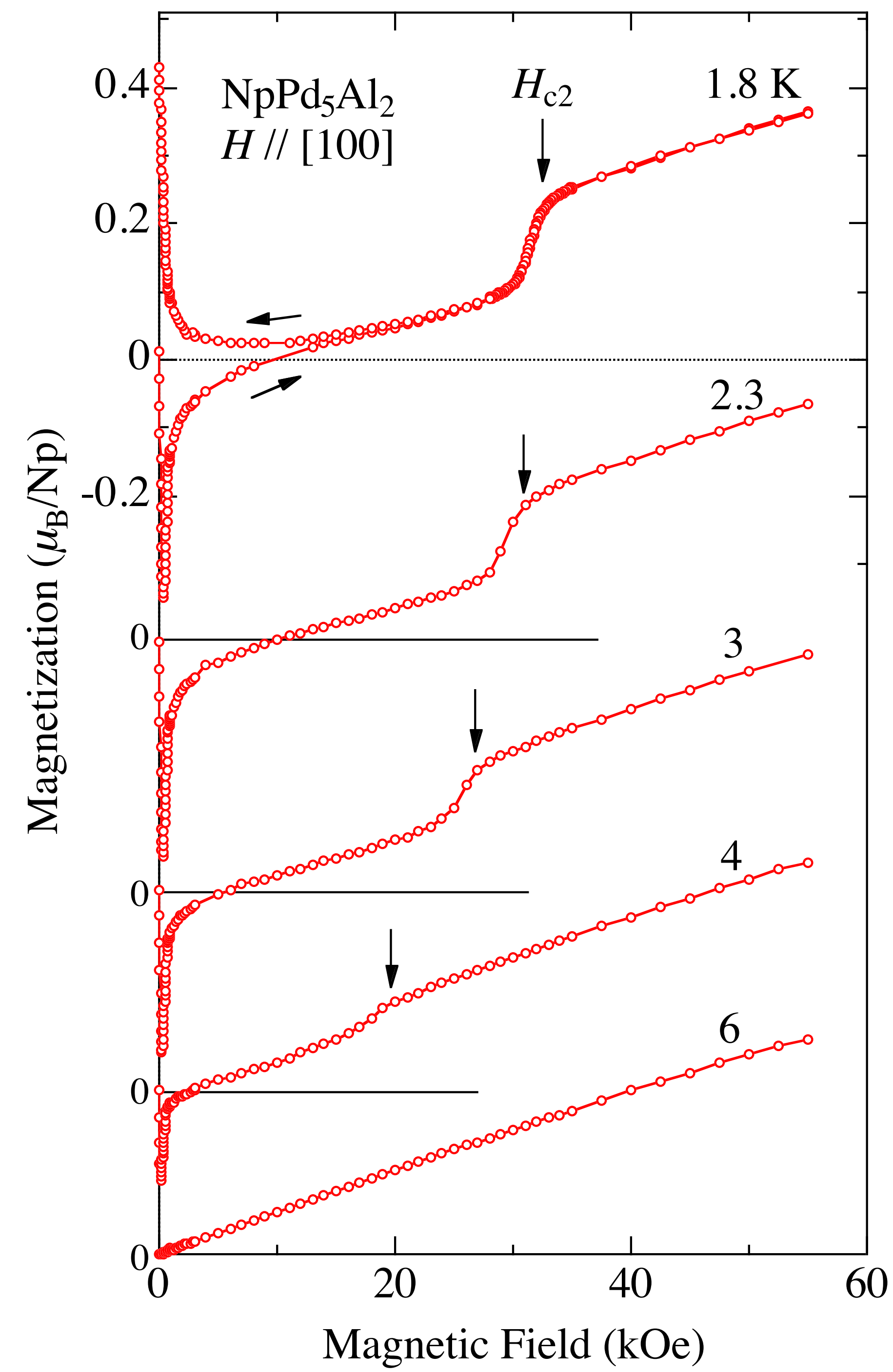
Curro et al 2001

Re-emergence of spins at H_{c2}.



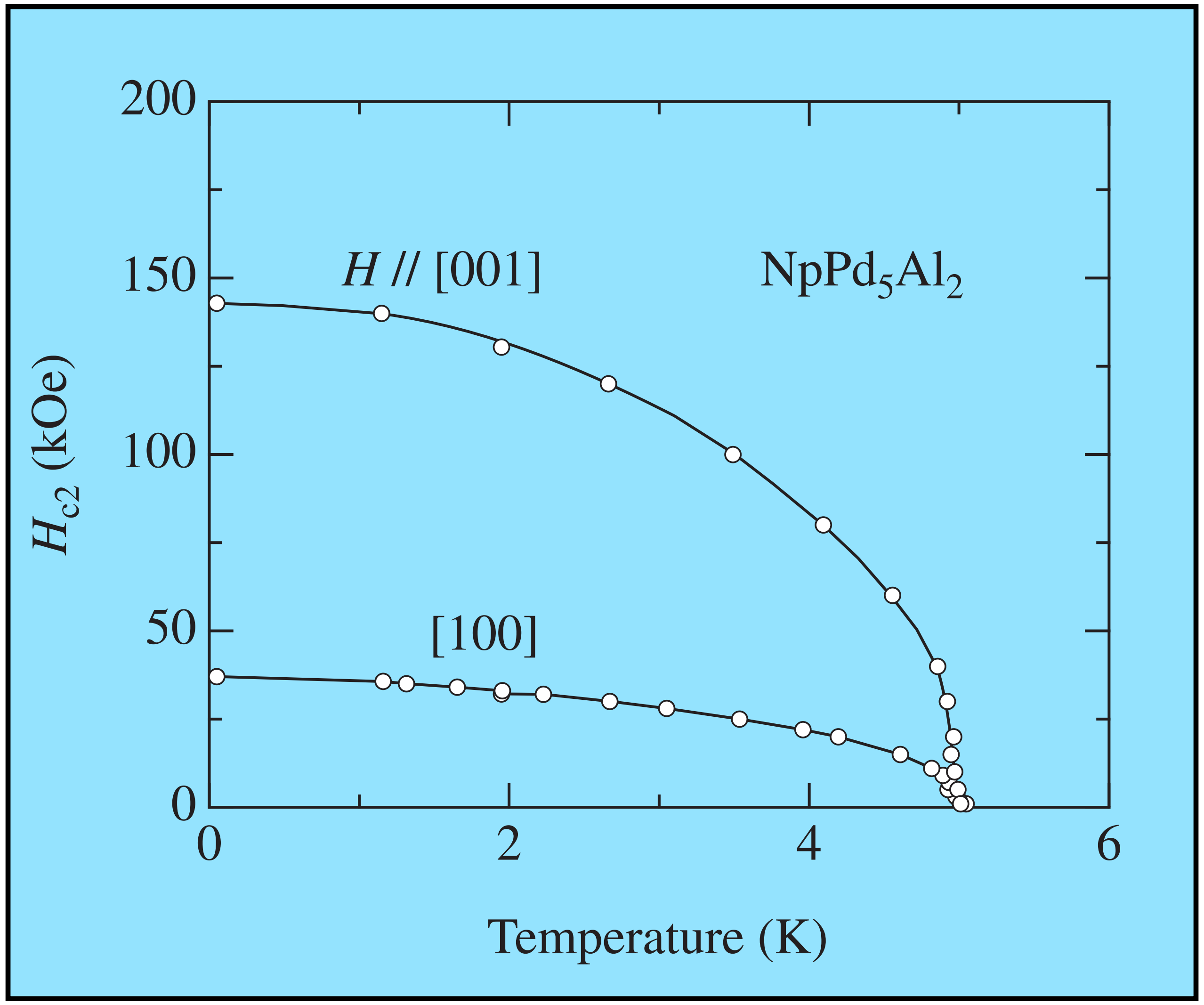
Re-emergence of spins at H_{c2}.

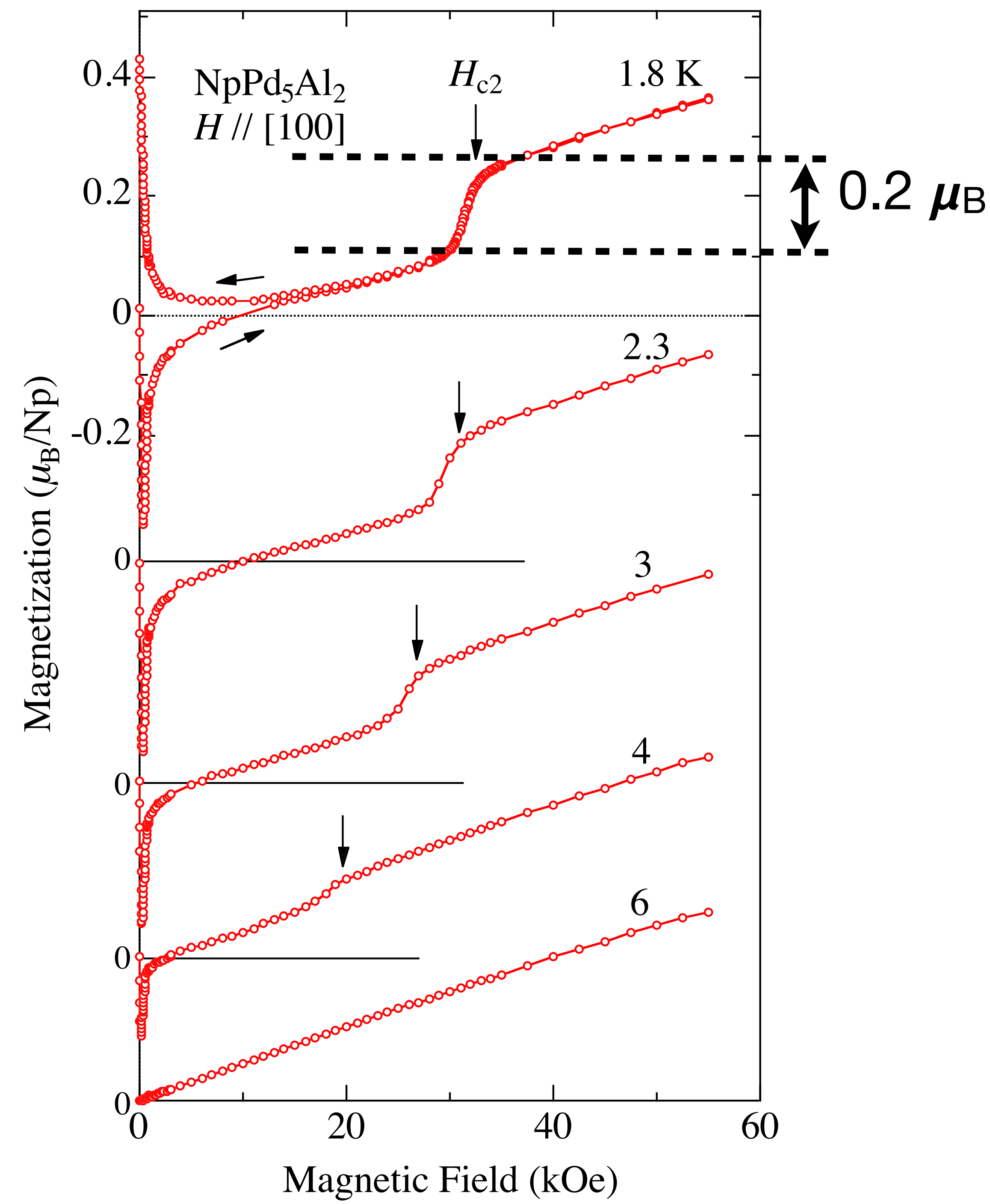




D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

Re-emergence of spins at H_{c2}.





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

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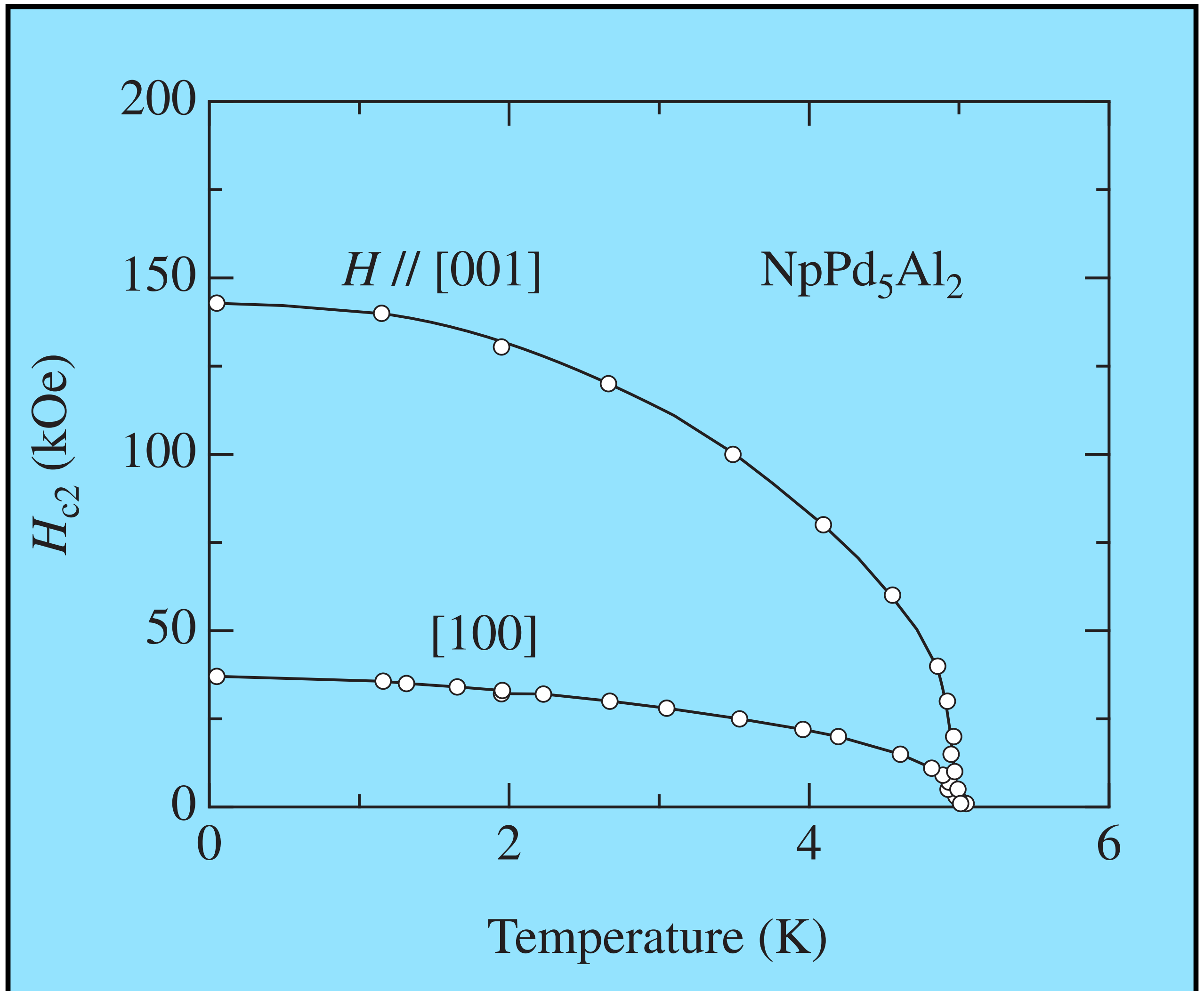
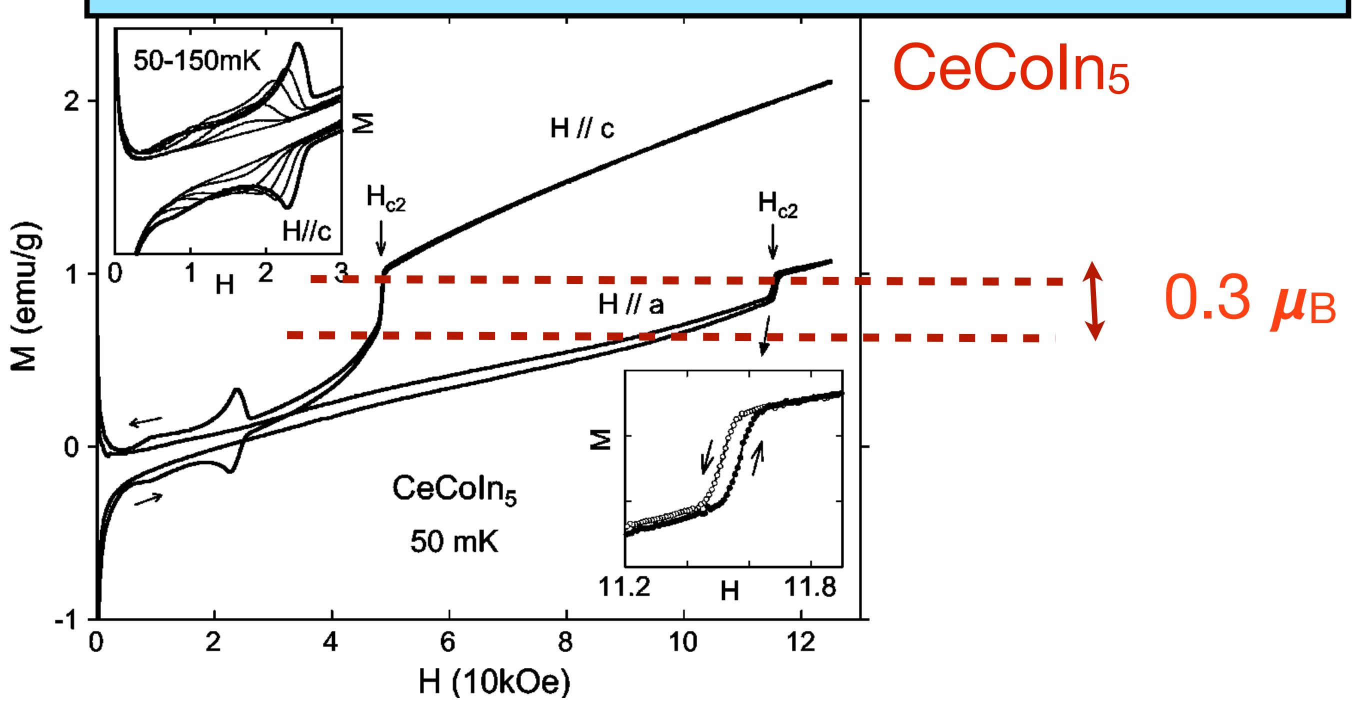
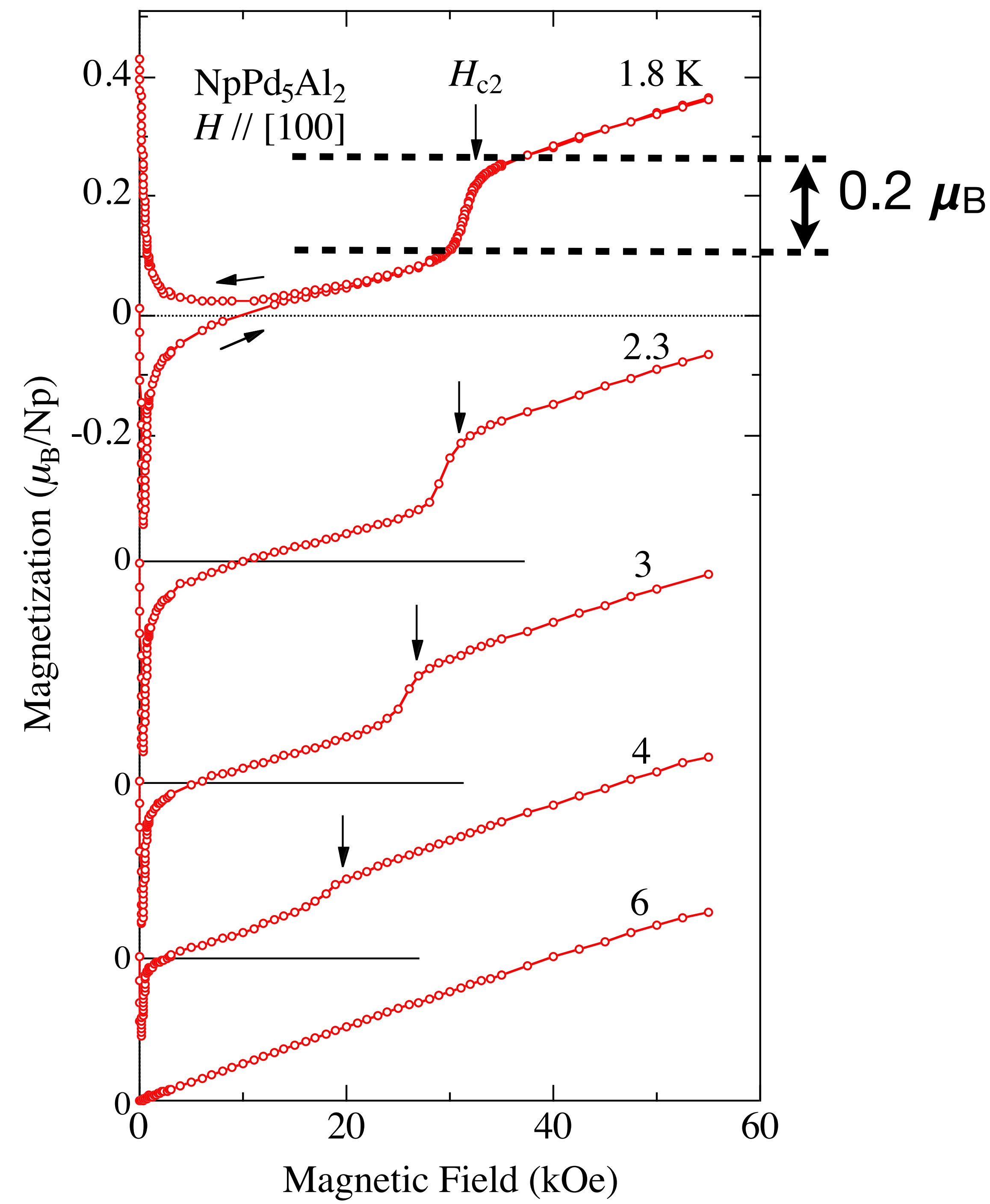




T. Tayama et al., RPB **65**, 180504R (2002)



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

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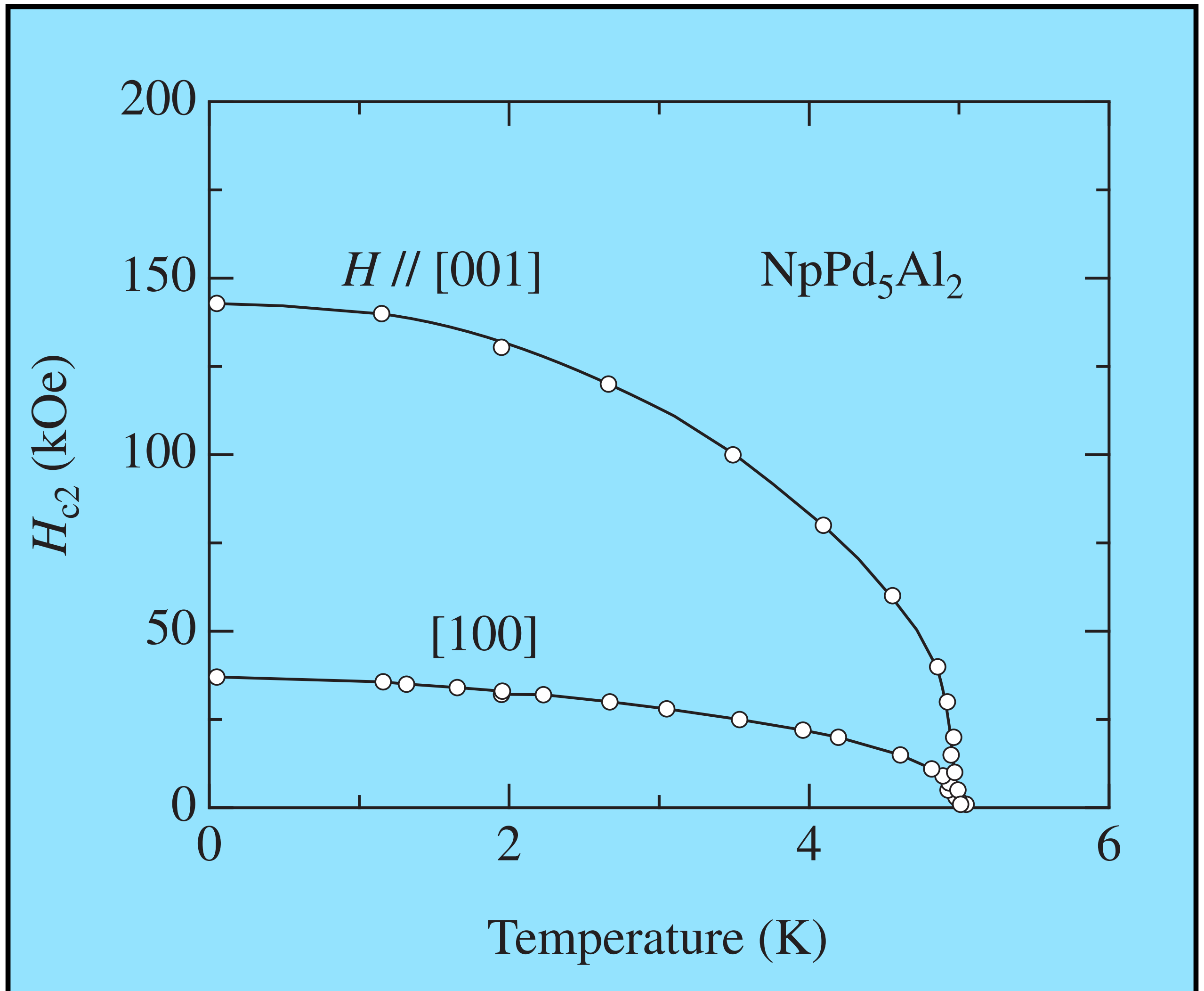
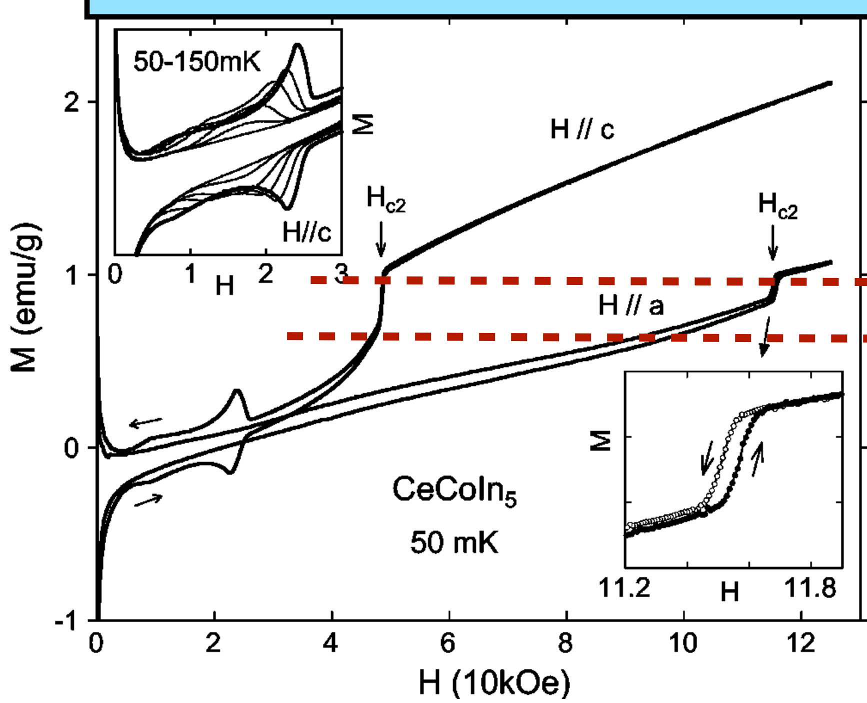


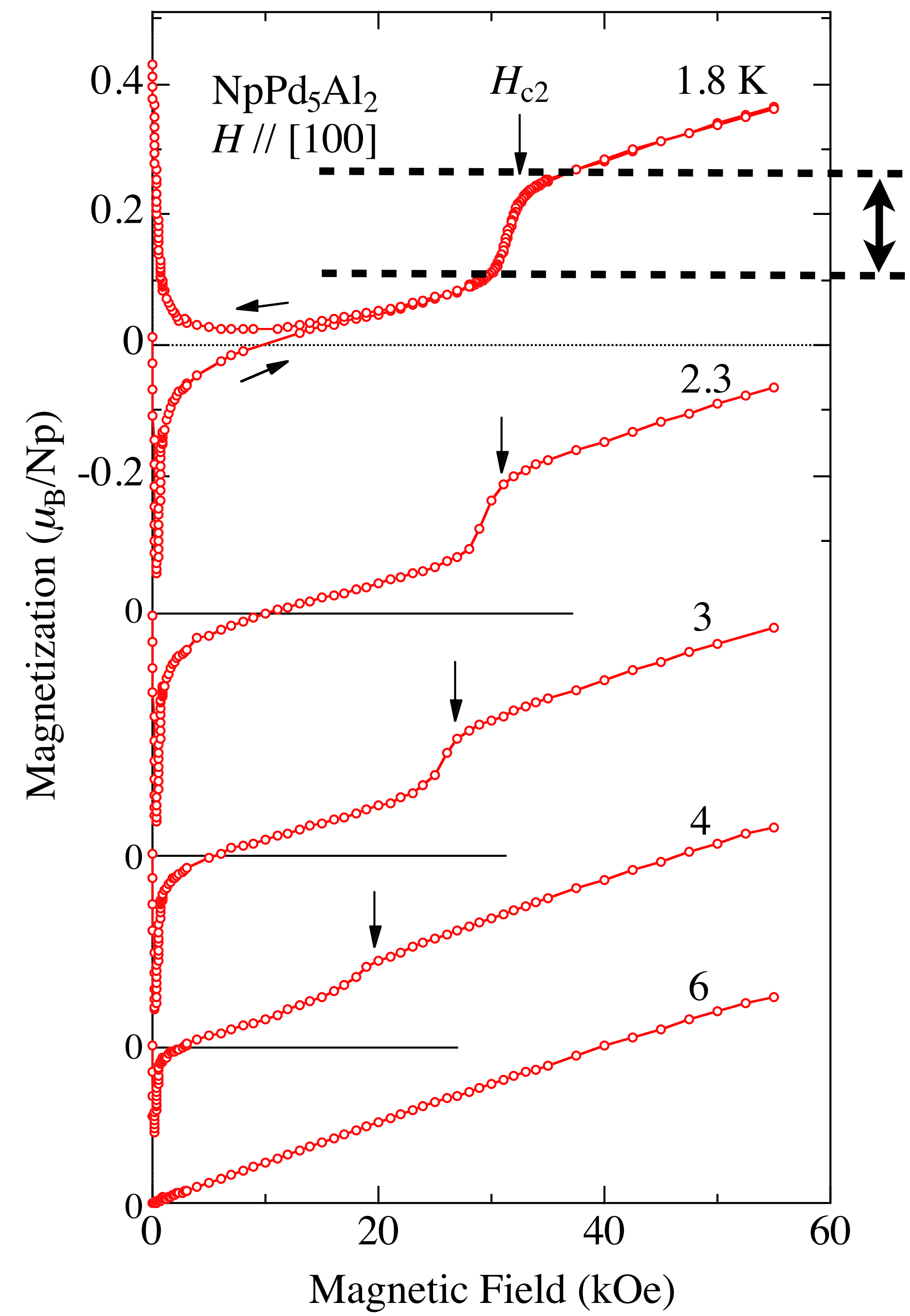
CeCoIn$_5$



0.3 μ_B

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

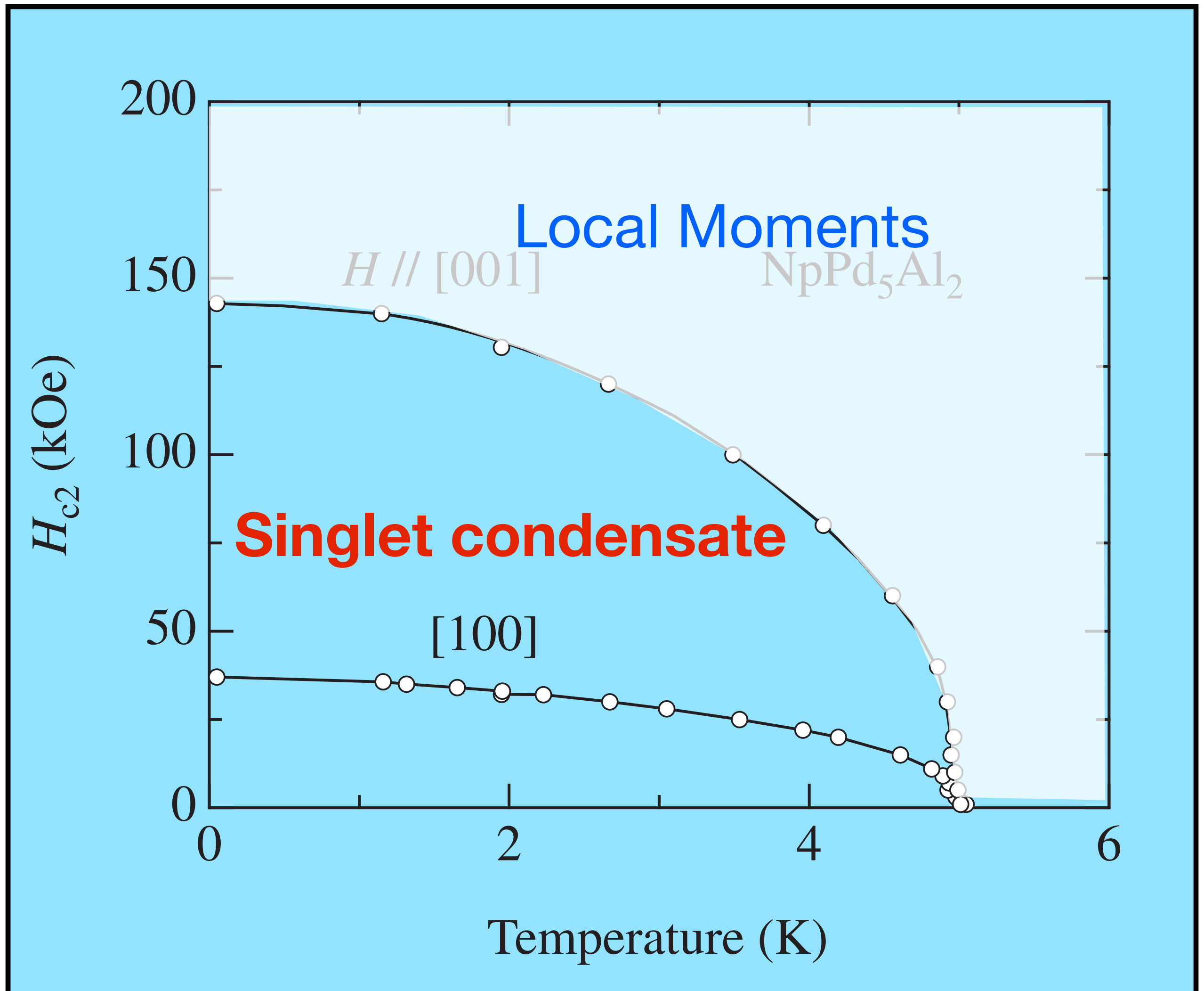
Release of the local moment from the condensate.

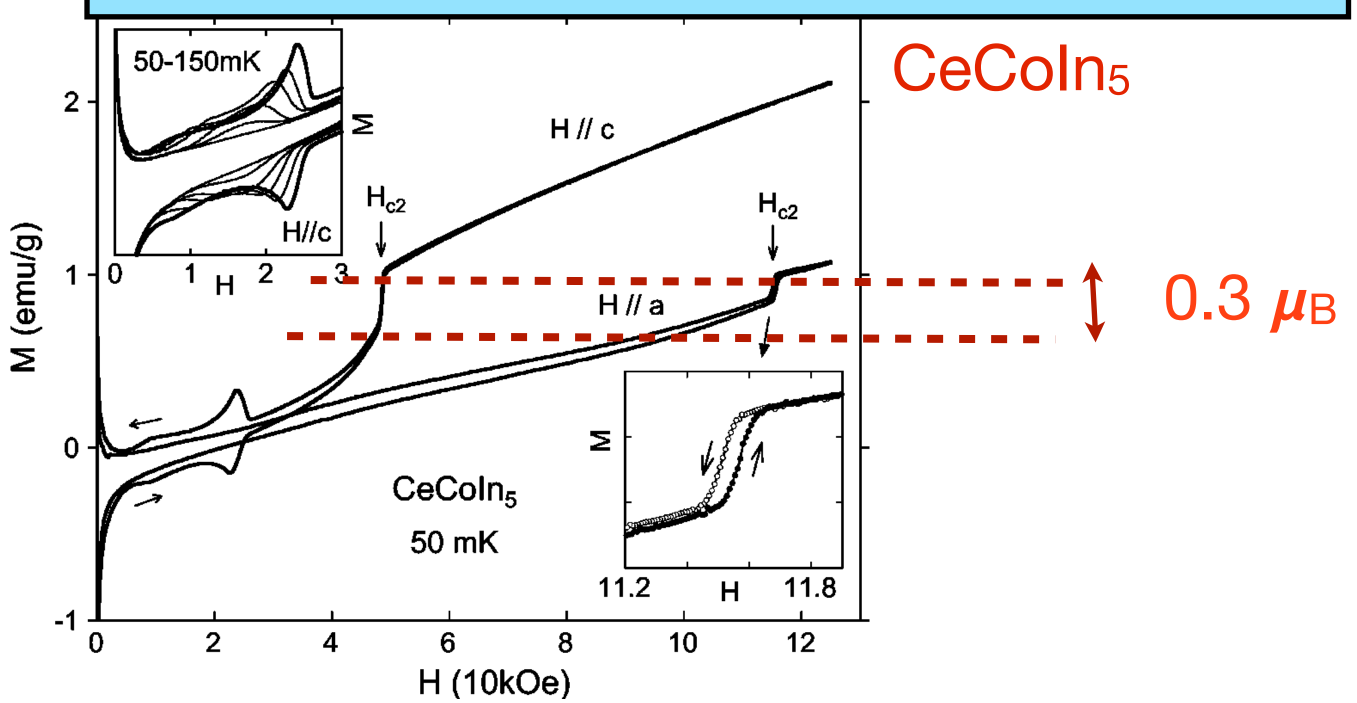


0.2 μ_B

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

Re-emergence of spins at H_{c2}.





CeCoIn$_5$

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

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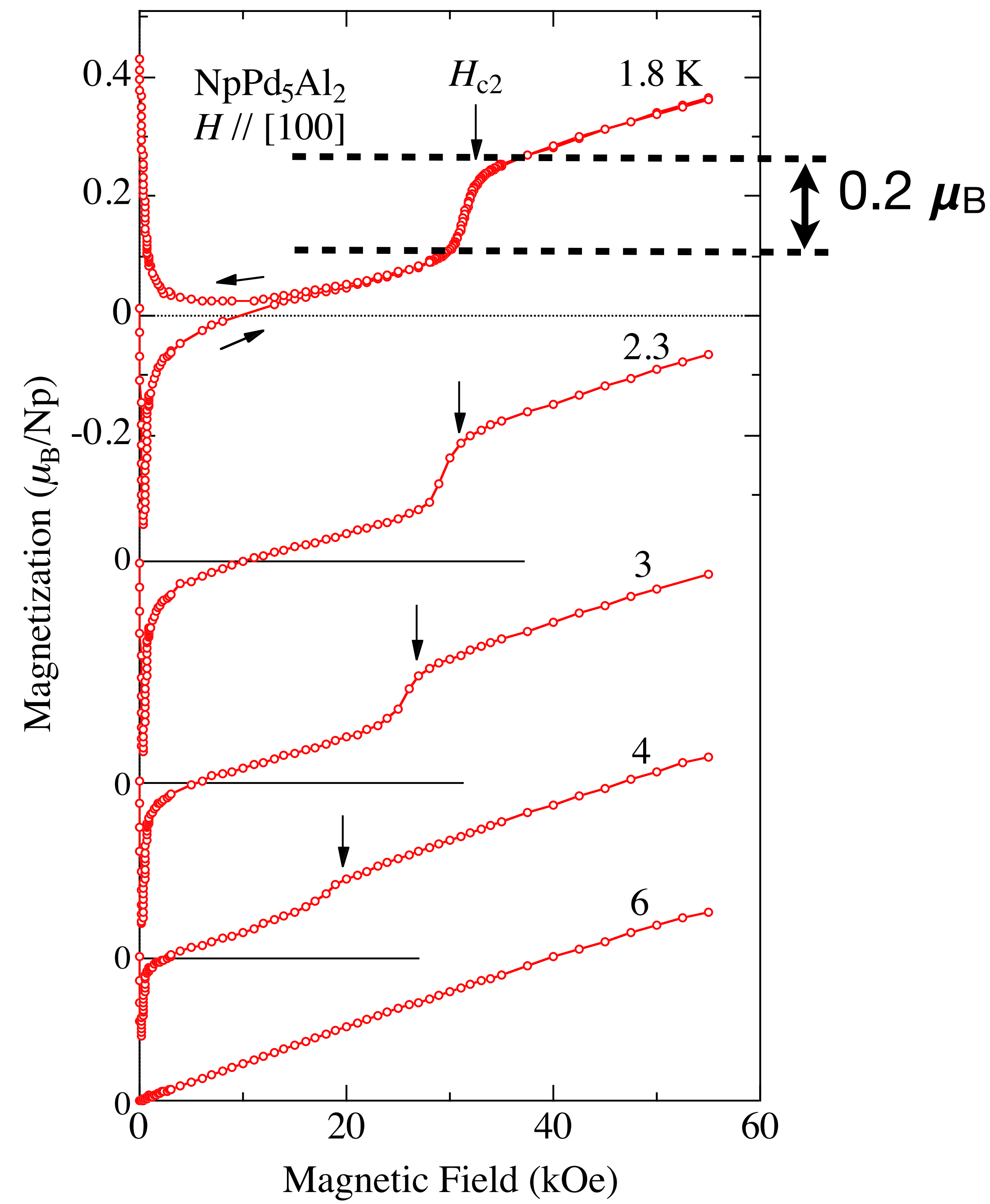
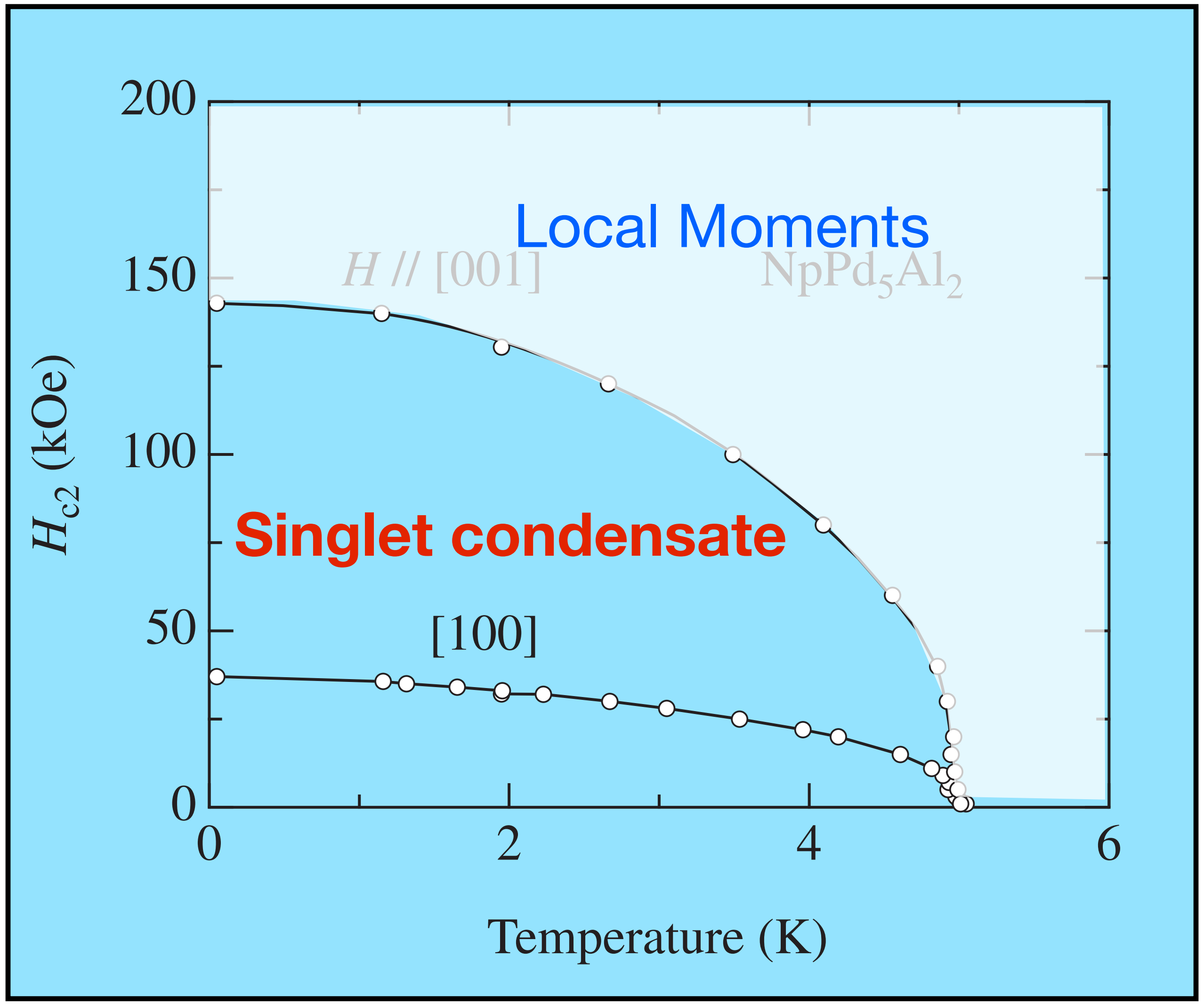
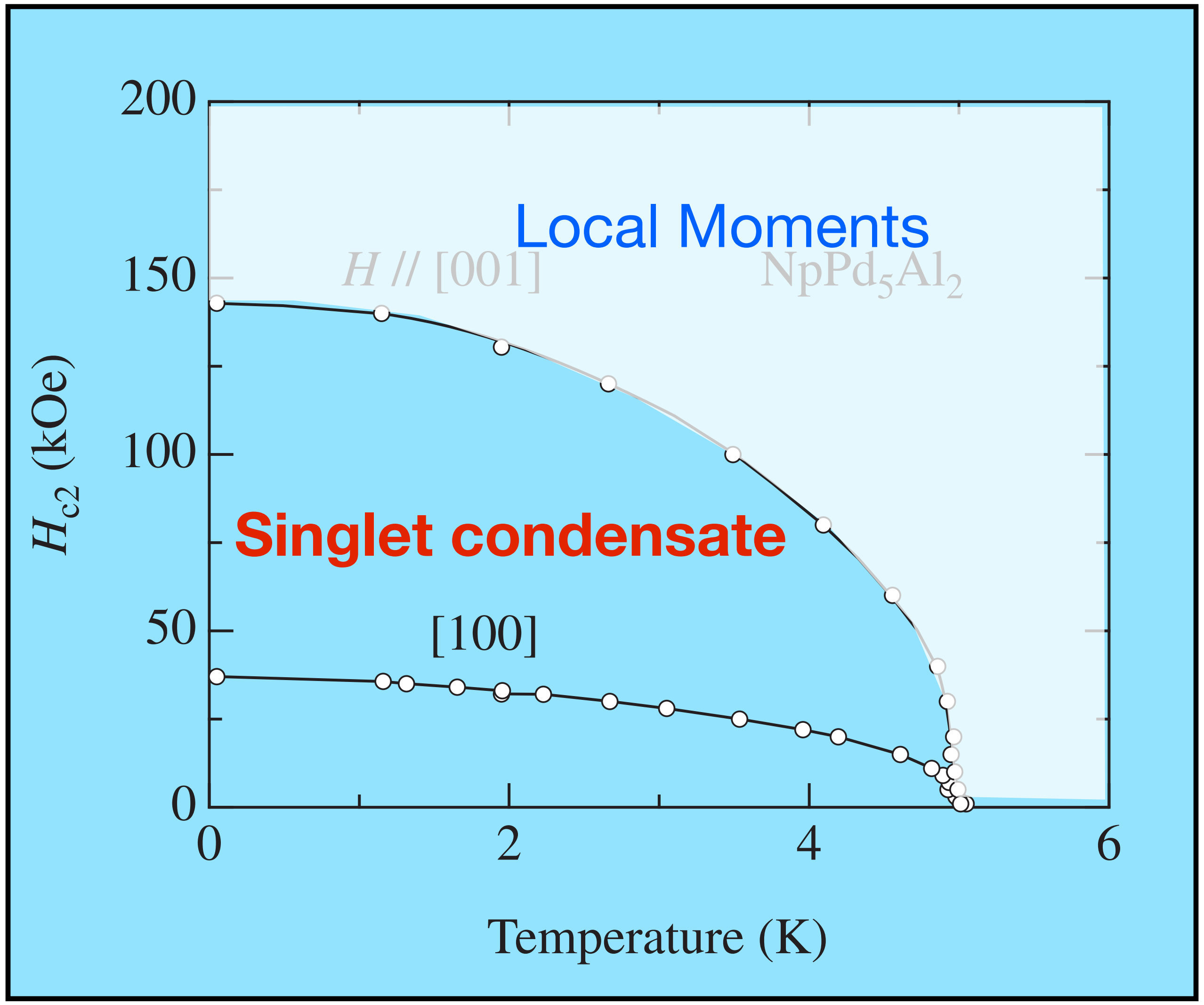


D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.



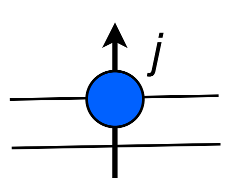
Paradox:

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



Paradox:

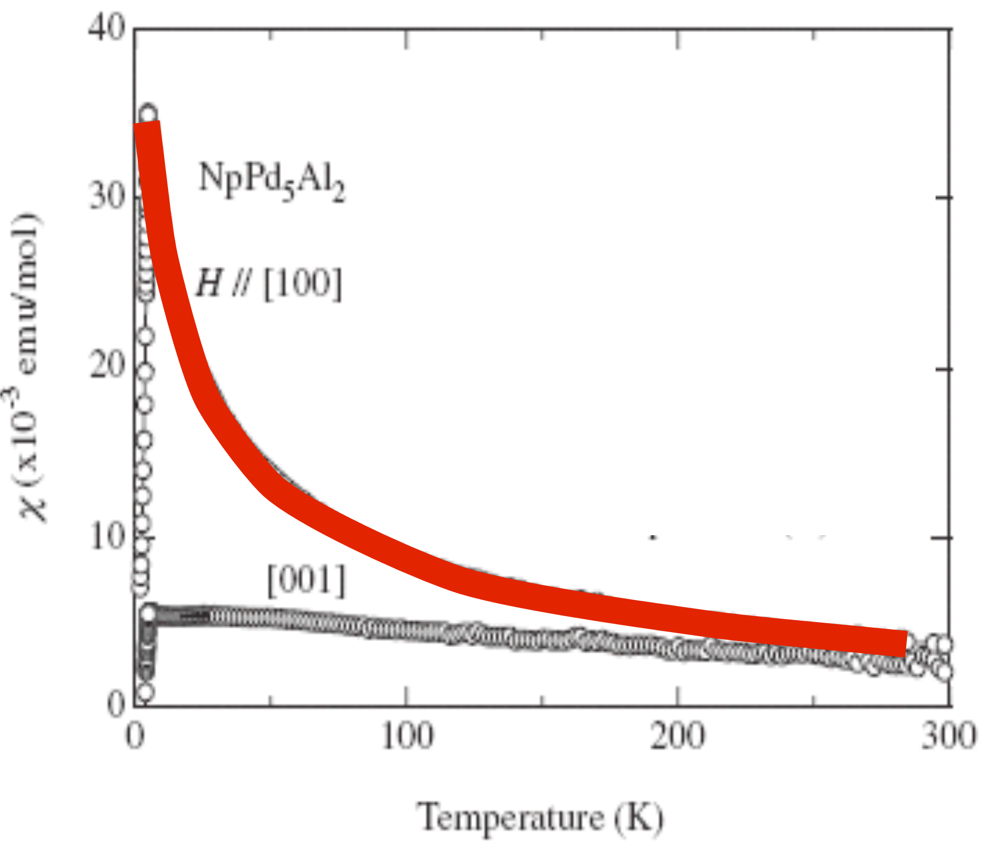
How can a neutral magnetic moments form a charged superconducting condensate?

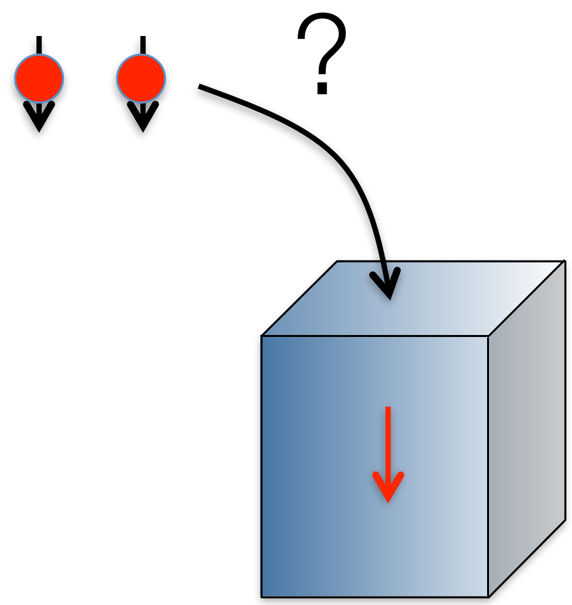
$\prod_{\otimes j} \{$  $\}$ $\otimes$ Charge = Condensate Hilbert Space

Composite pairing Hypothesis.

Composite pairing

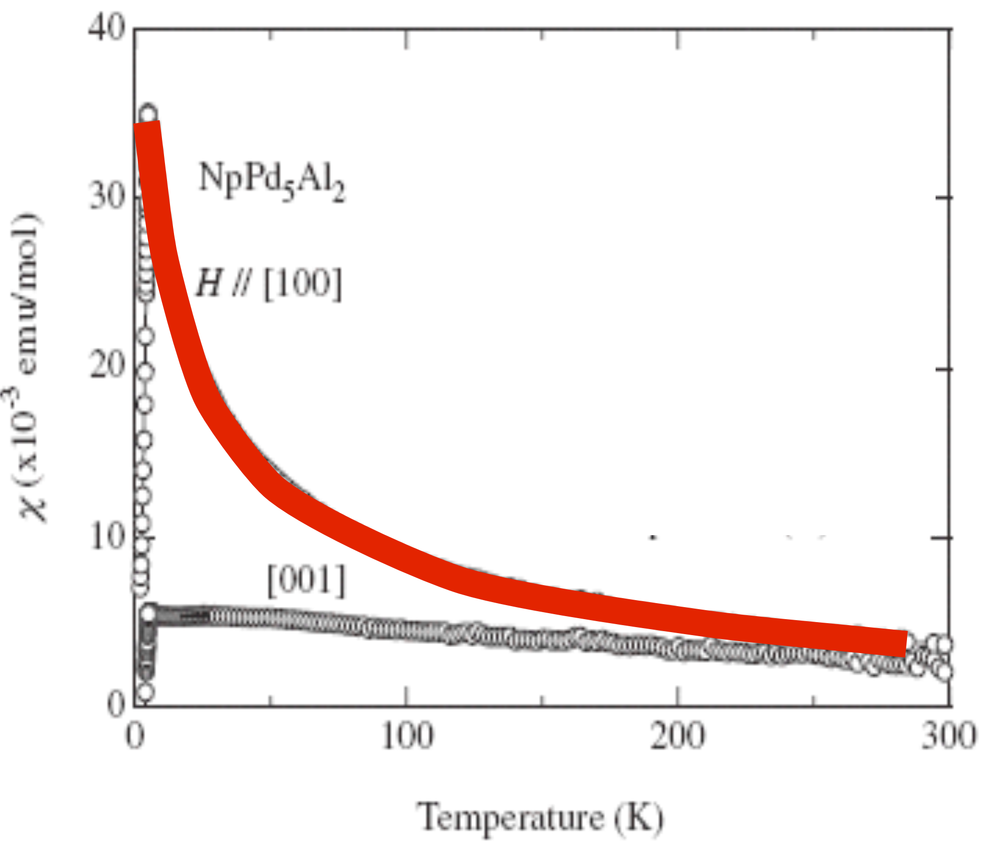
$NpPd_5Al_2$ $T_C = 4.5K$

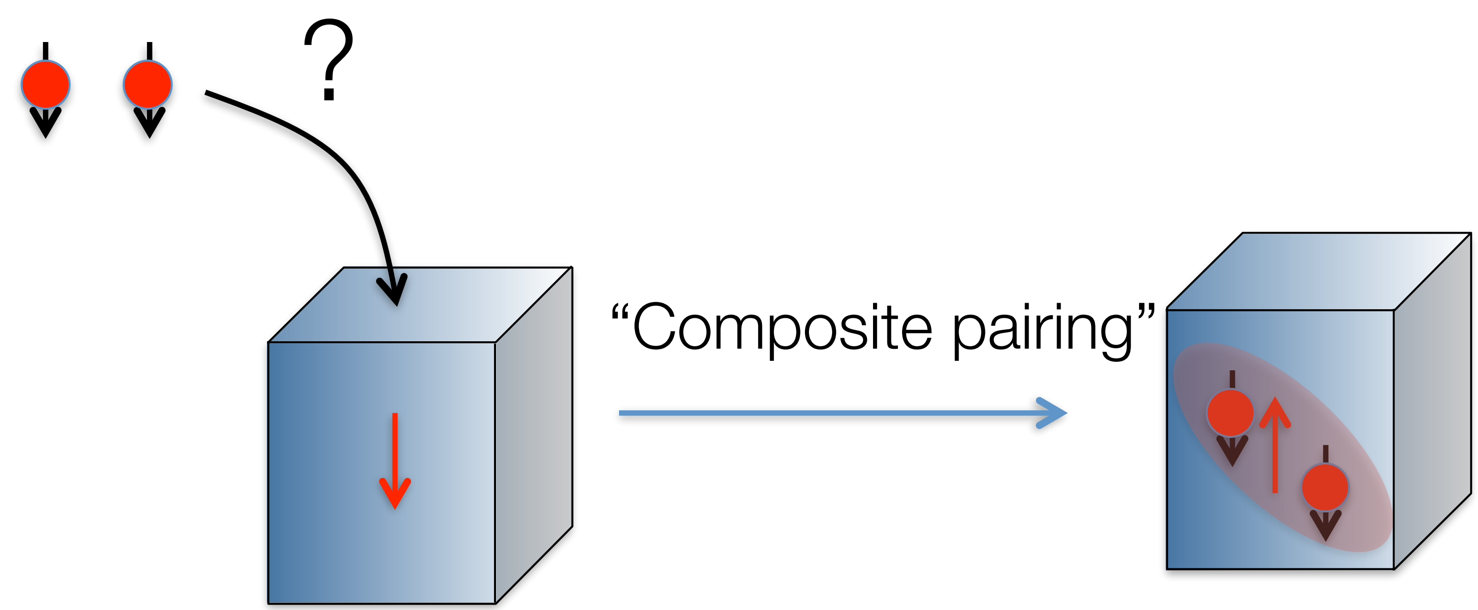




Composite pairing

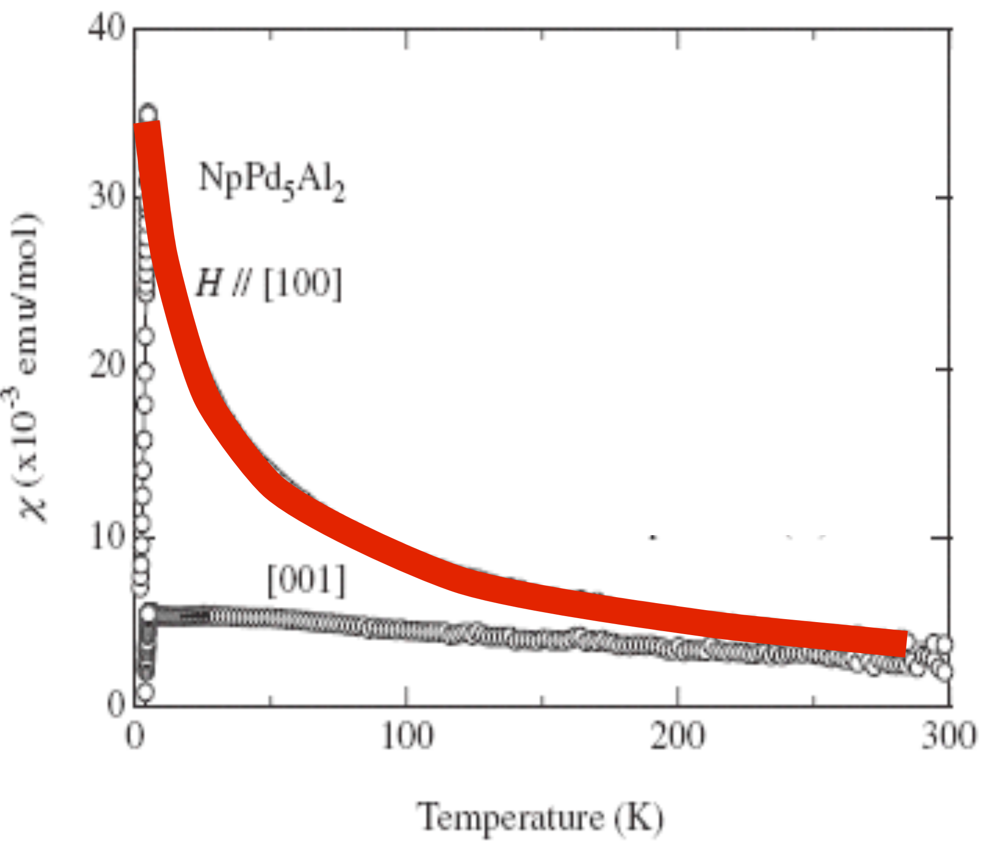
$NpPd_5Al_2$ T_C = 4.5K

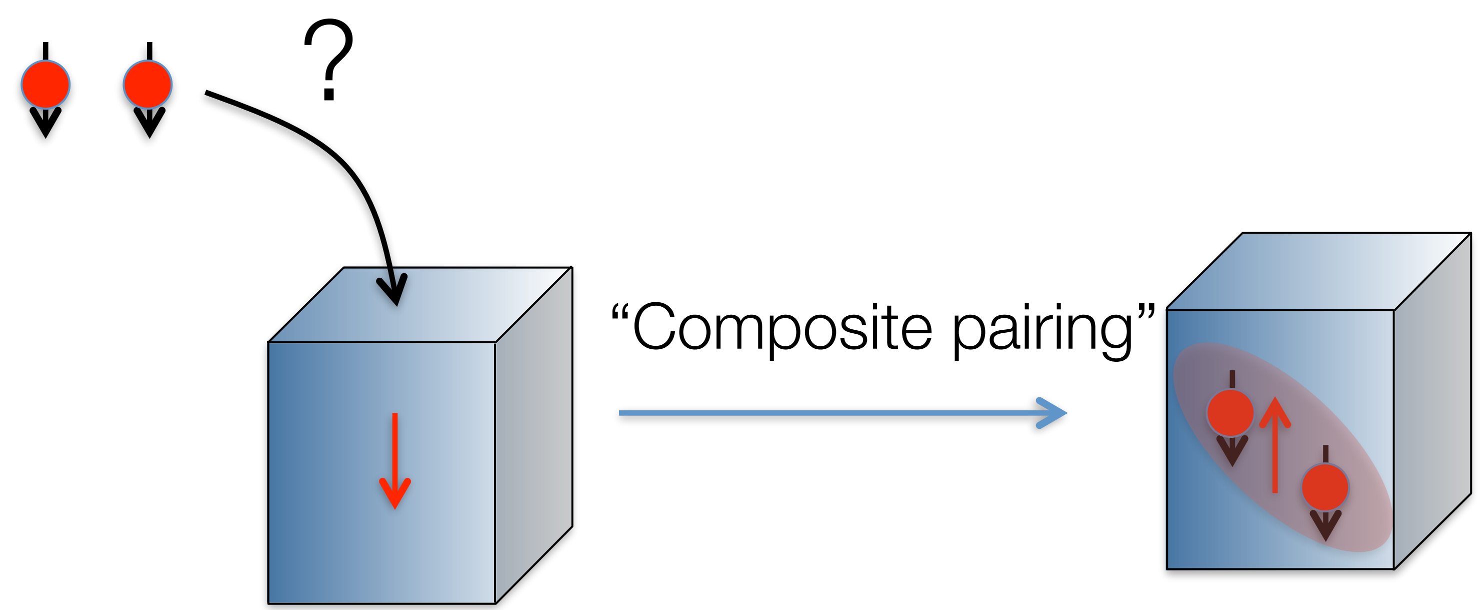




Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$

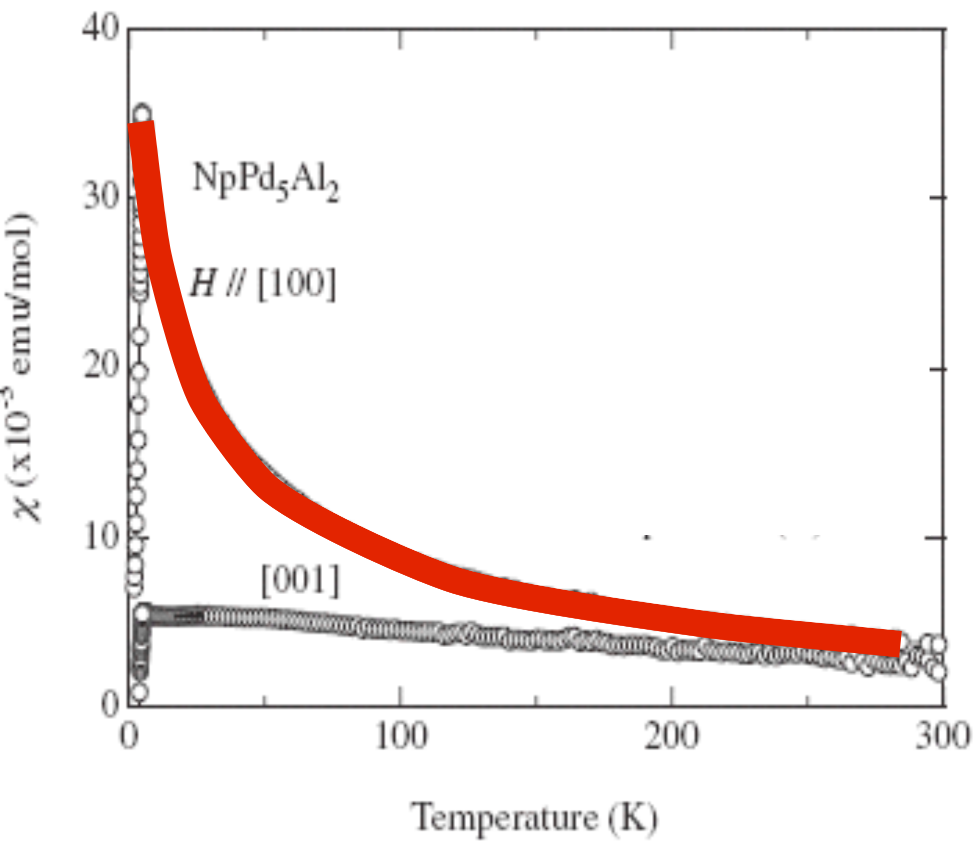


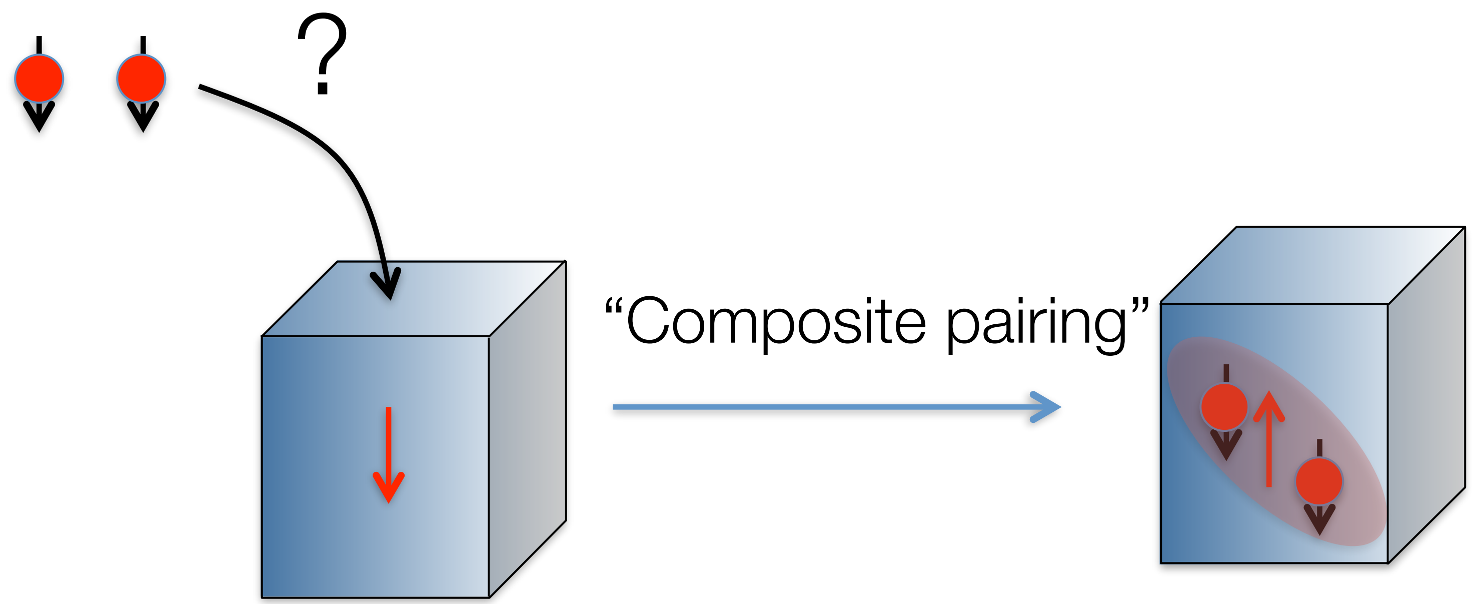


Heavy Cooper pair = (pair x spinflip)

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

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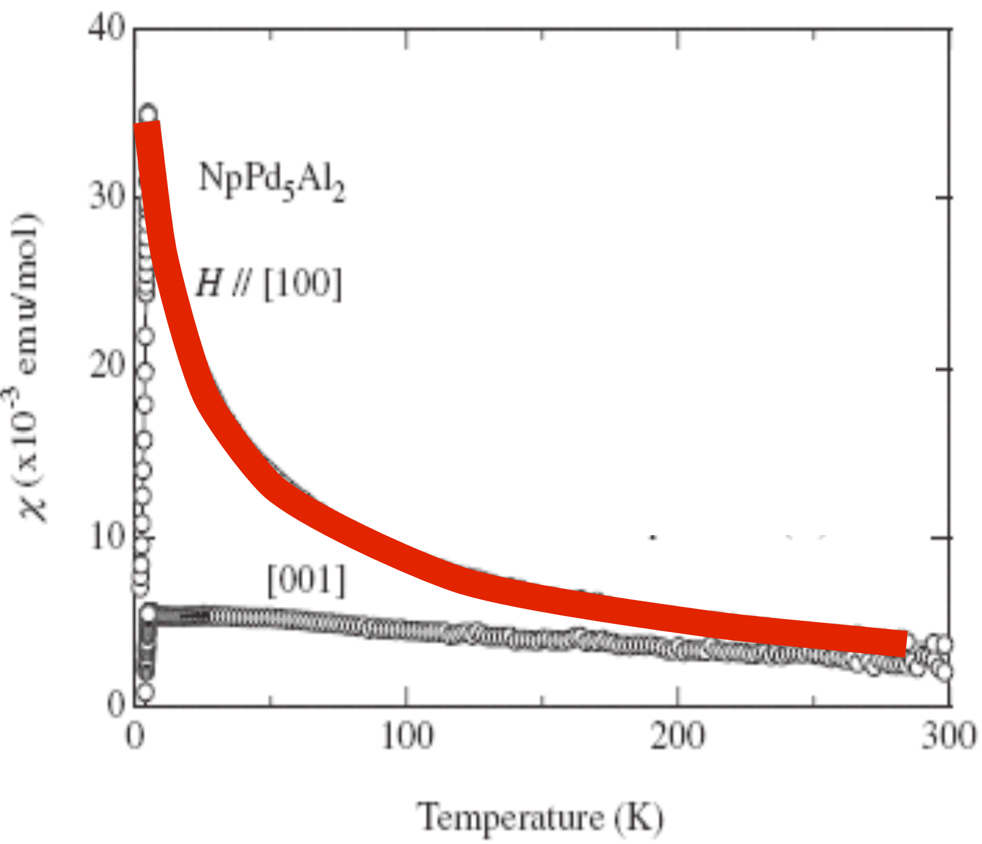

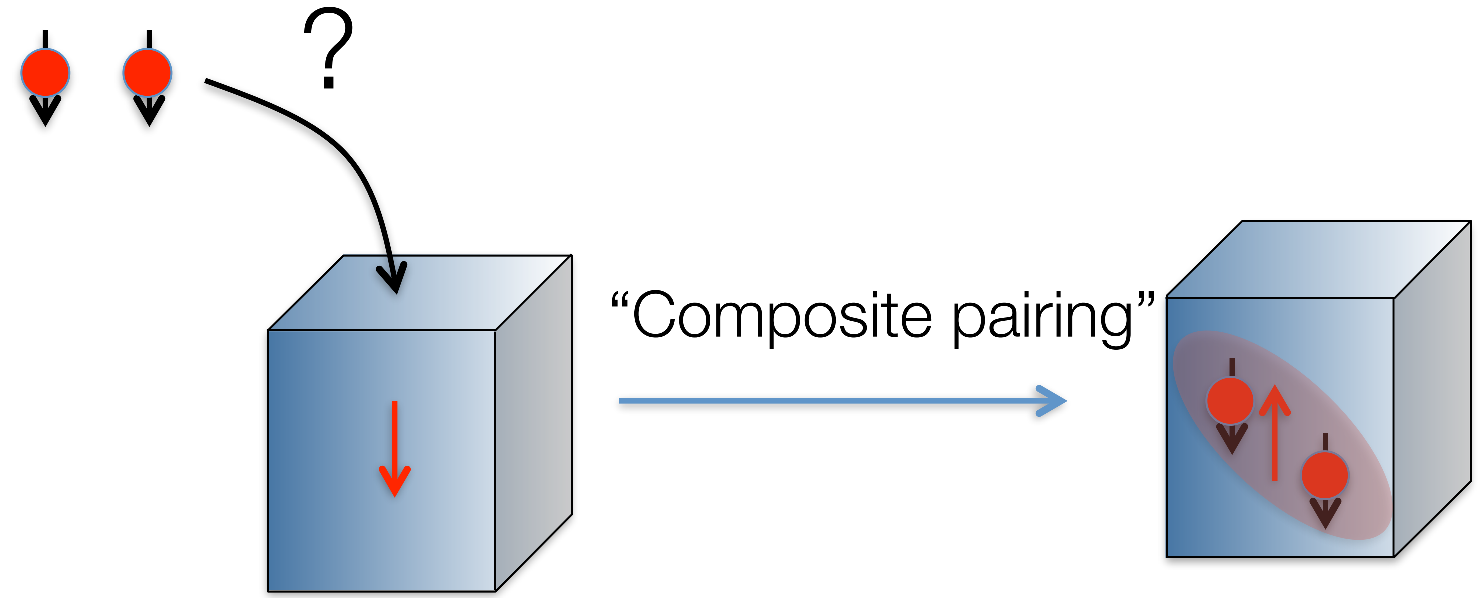

Heavy Cooper pair = (pair x spinflip)

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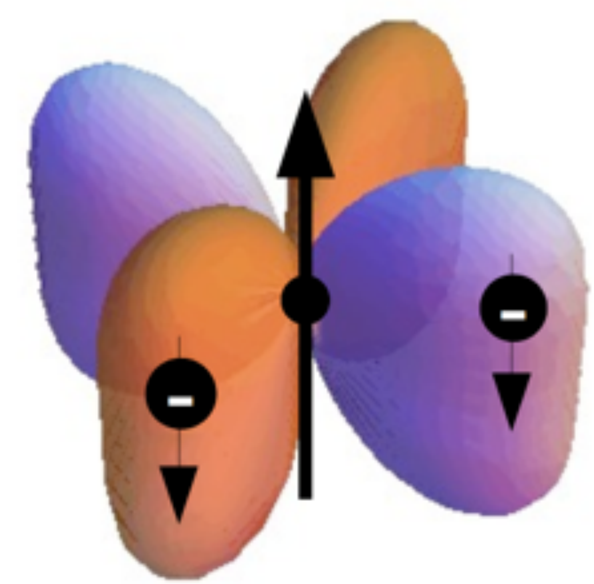


Emery and Kivelson, 1992; Abrahams, Balatsky, Scalapino, Schrieffer 1995

A solvable model of composite pairing.

PC, Tsvelik, Kee, Andrei PRB 60, 3605 (1999).

Flint, Dzero, PC, Nature Physics 4, 643 (2008).

Flint, PC, PRL, 105, 246404 (2010).

Flint, Nevidomskyy, PC, PRB 84, 064514 (2011).

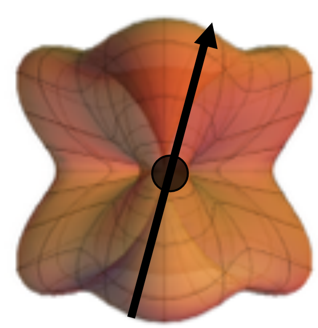
The Two Channel Kondo Model

$$H = \sum_k \epsilon_k c_k^\dagger c_k + J_1 \sum_j \psi^\dagger_{1j\alpha} \vec{\sigma}_{\alpha\beta} \psi_{1k\beta} \cdot \vec{S}_j$$

$\bullet$

$|0\rangle$

Γ_7^+



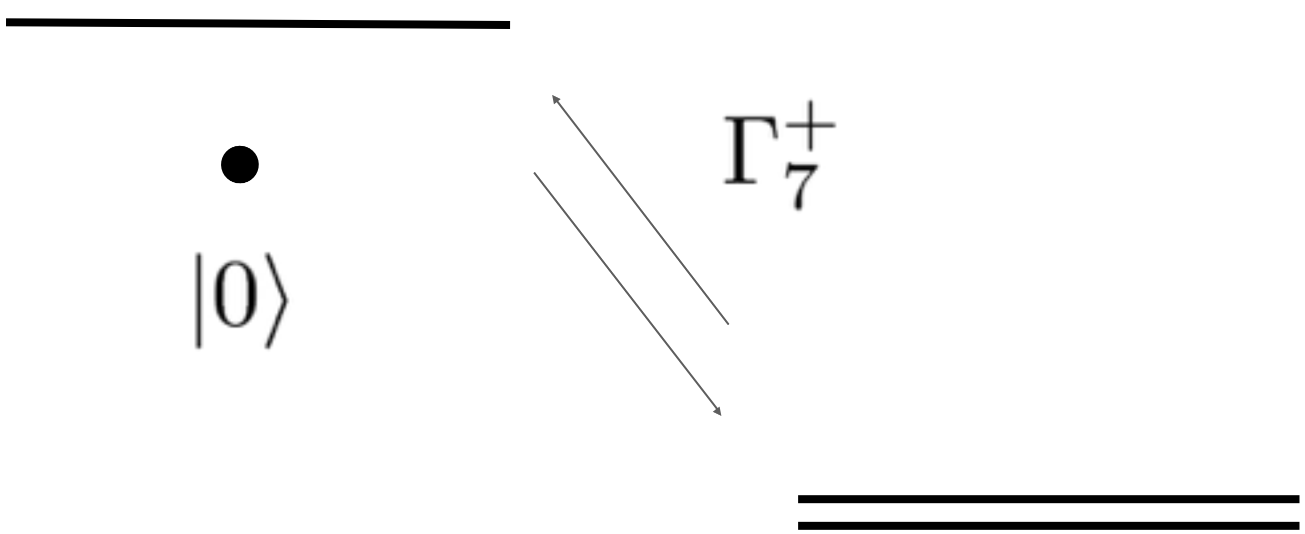
$|\Gamma_7^+\rangle$

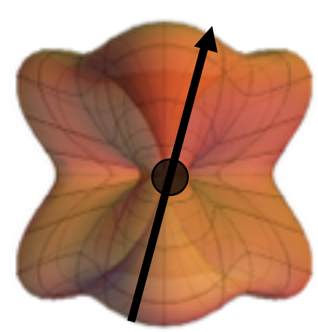
Wannier functions at site j:

$$\psi^\dagger_{\Gamma j} = \sum_k \Phi_{\Gamma k} e^{i\vec{k}\cdot\vec{R}_j} c_k$$

The Two Channel Kondo Model

$$H = \sum_k \epsilon_k c_k^\dagger c_k + J_1 \sum_j \psi_{1j\alpha}^\dagger \vec{\sigma}_{\alpha\beta} \psi_{1k\beta} \cdot \vec{S}_j$$





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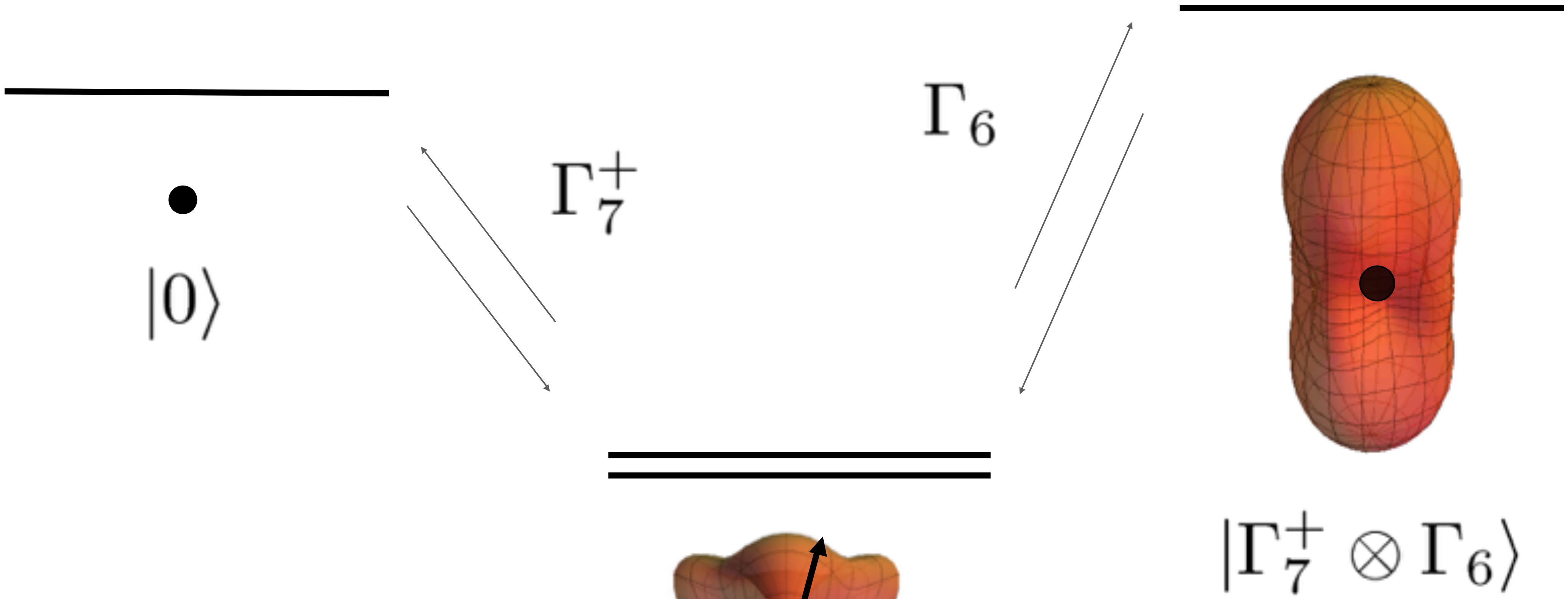

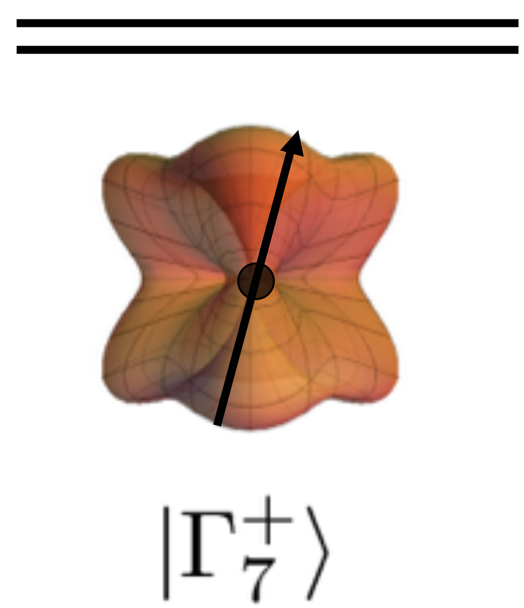

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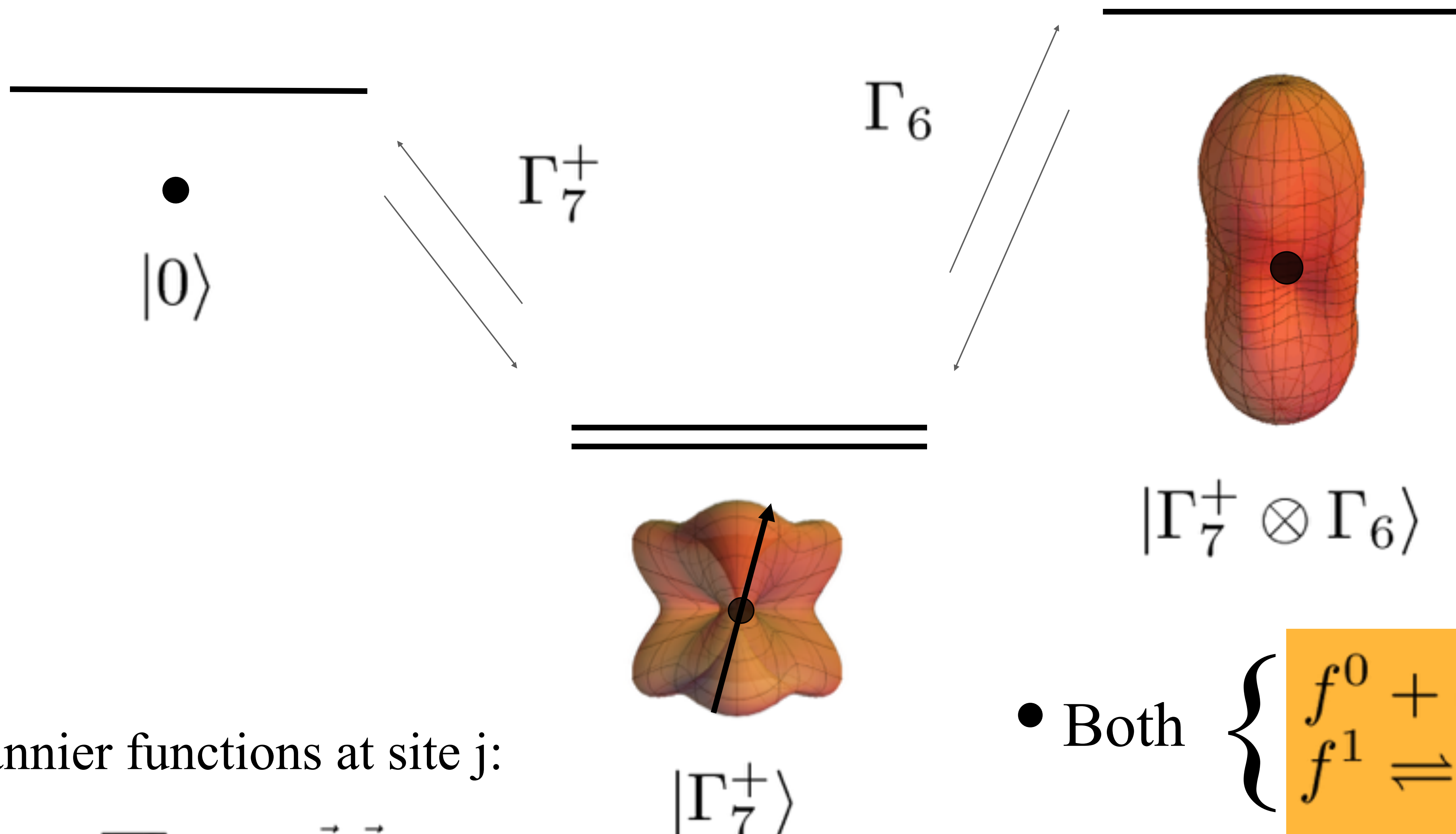

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Composite Fermions and Order.

R. Flint, PC, Comtes Rendu,15, 557-562 (2014).

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Symplectic *N*

$$H_I \to -J_1 \left[(\psi^\dagger f)(f^\dagger \psi) + (\psi^\dagger \sigma_2 f^\dagger)(f \sigma_2 \psi) \right]$$

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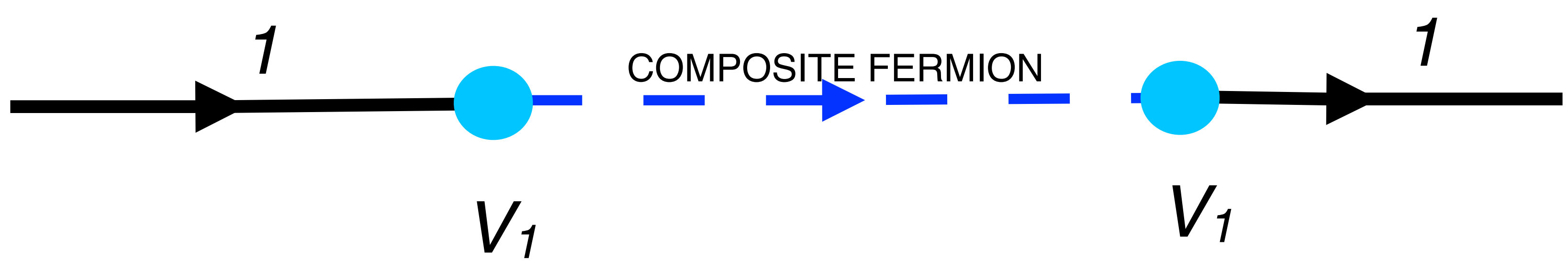

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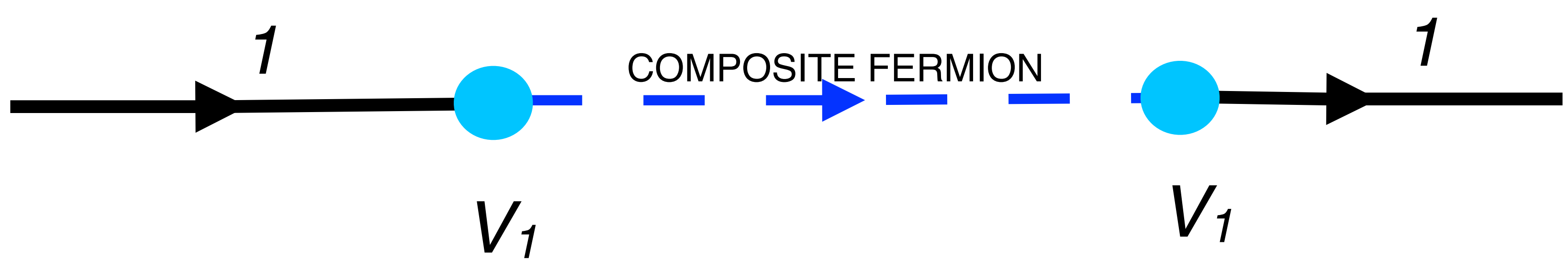

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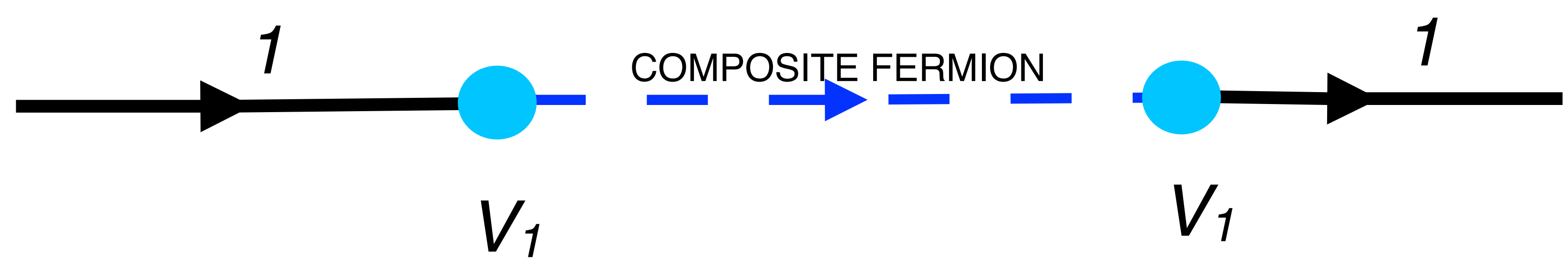
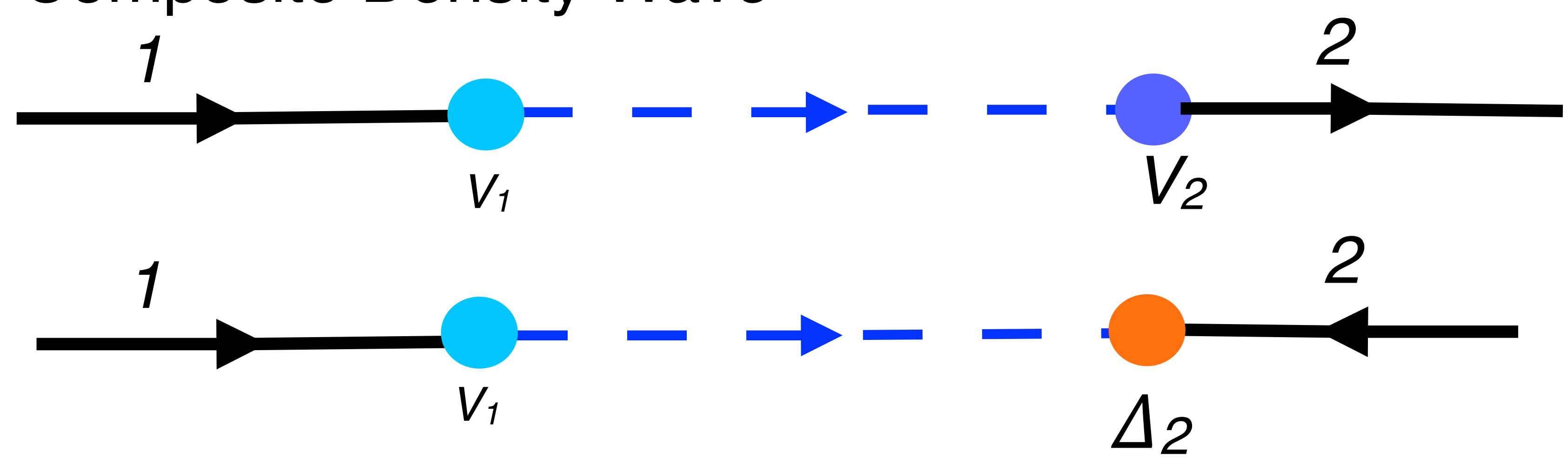


Composite Density Wave

Two channels



Composite Pairing

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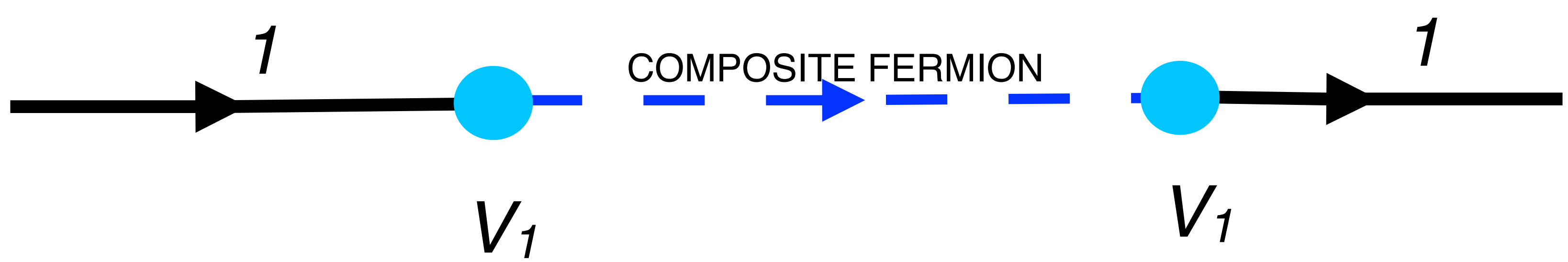

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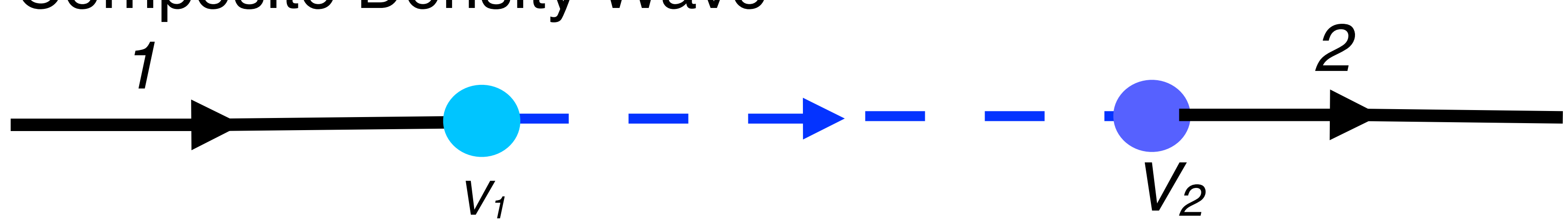
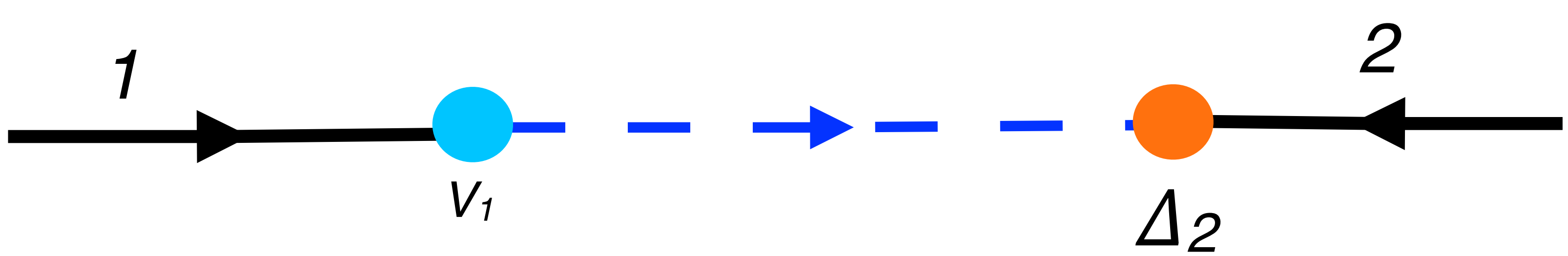


Two channels

$$\Psi = \begin{pmatrix} V_2 \\ \Delta_2 \end{pmatrix}$$



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$$H = \sum_{k} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{1}{N} \sum_{\mathbf{k},\mathbf{k}'} \left(J_1 \psi^{\dagger}_{1a}(j) \psi_{1b}(j) + J_2 \psi^{\dagger}_{2a}(j) \psi_{2b}(j) \right) S^{ba}(j)$$

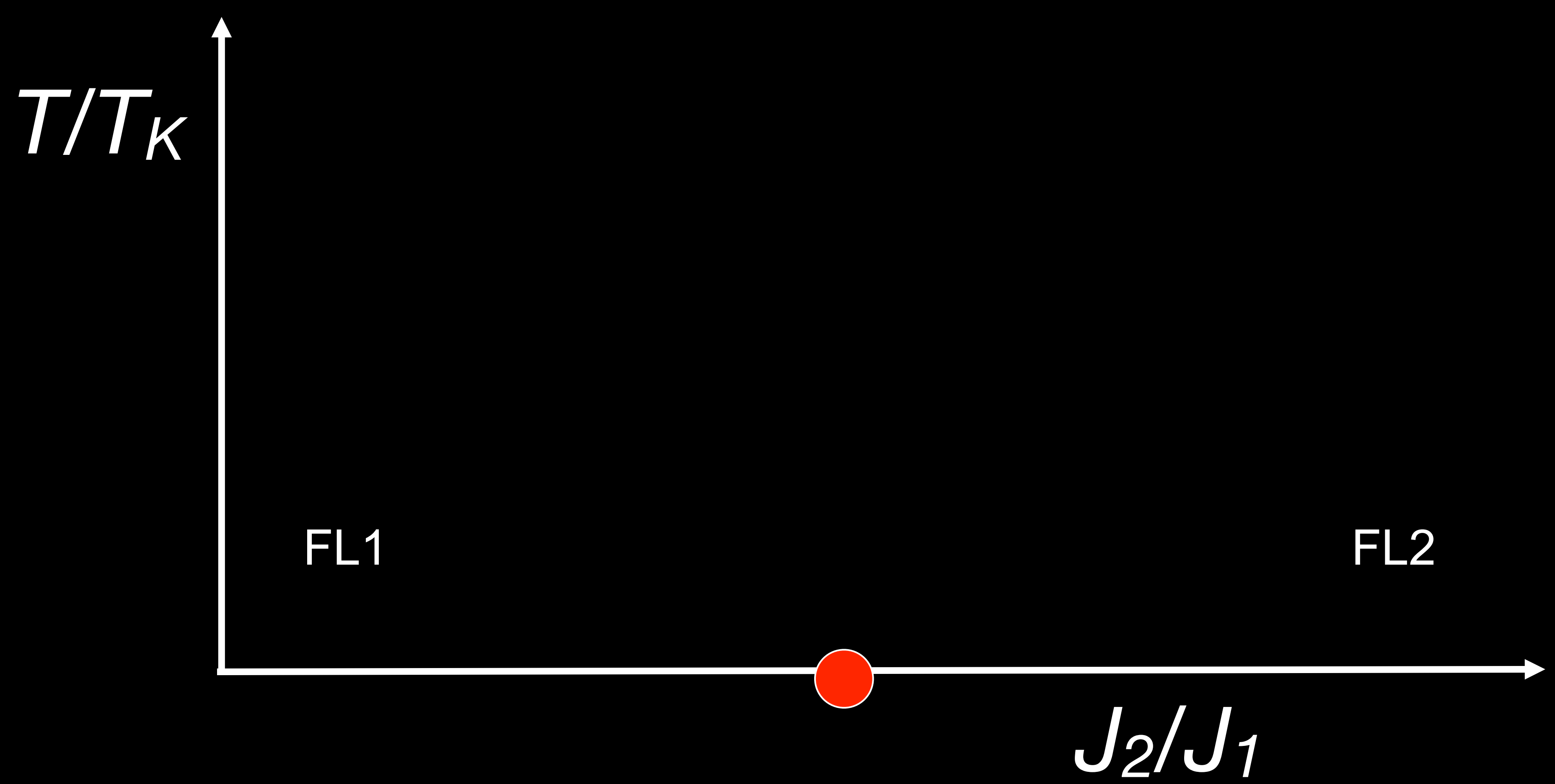
Single FS, two channels.

$$\psi_{\Gamma}(j) = \frac{1}{\sqrt{V}} \sum_{\mathbf{k}} \gamma_{\Gamma\mathbf{k}} \;\; c_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}_j}$$

cf Cox, Pang, Jarell (96)
PC, Kee, Andrei, Tsvelik (98)

Impurity: quantum critical point for $J_1 = J_2$

Nozieres and Blandin 1980



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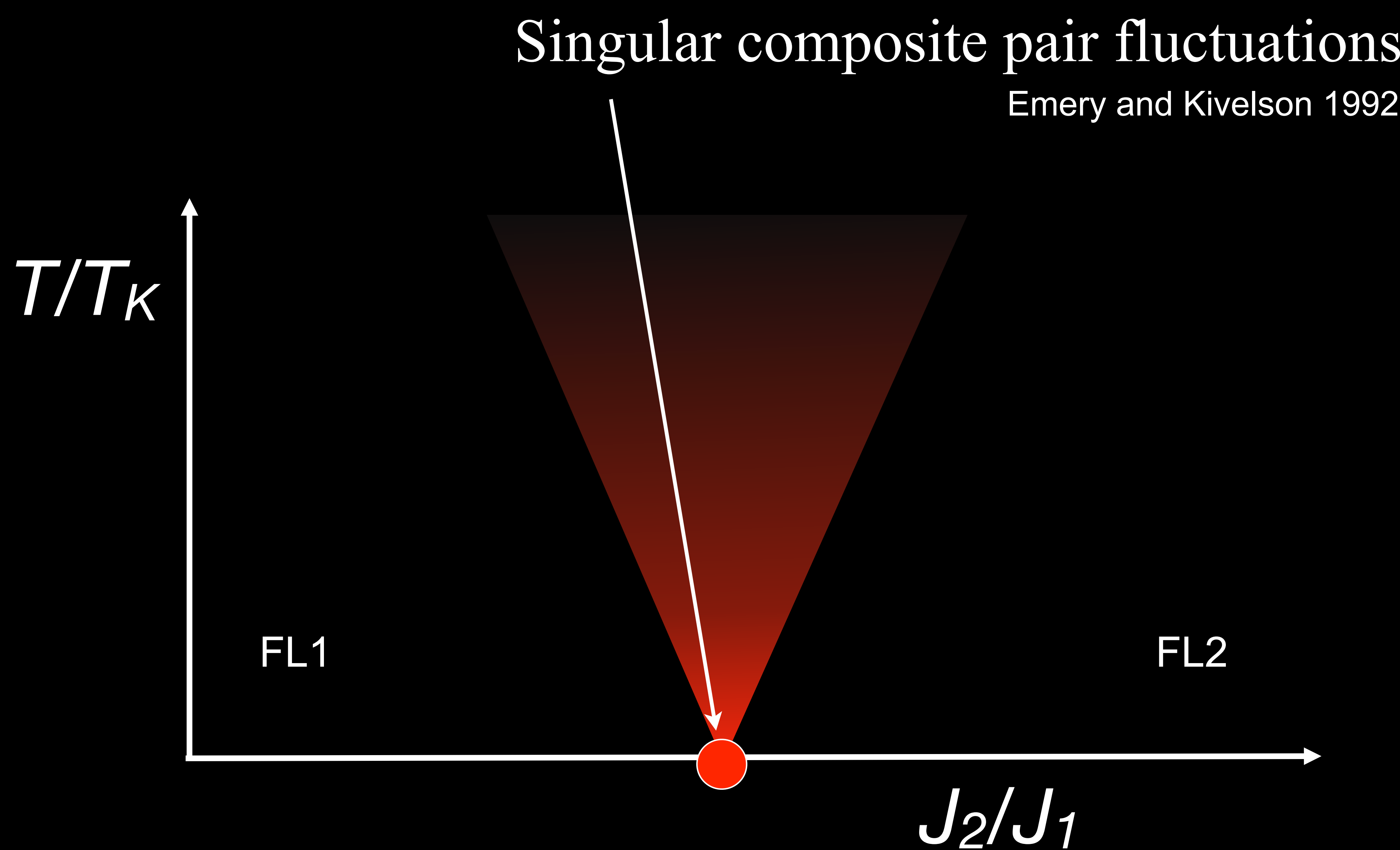

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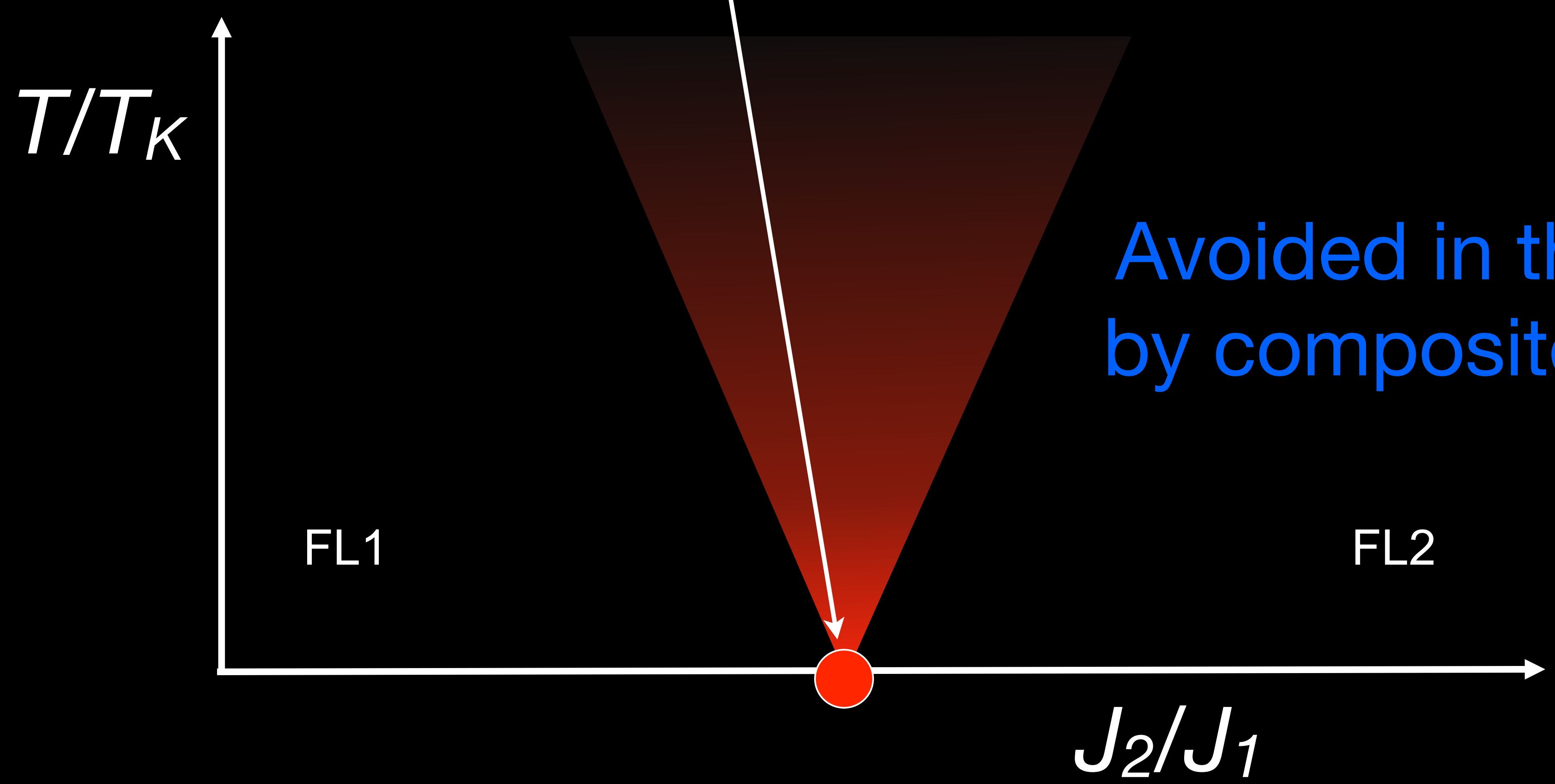
Singular composite pair fluctuations

Emery and Kivelson 1992



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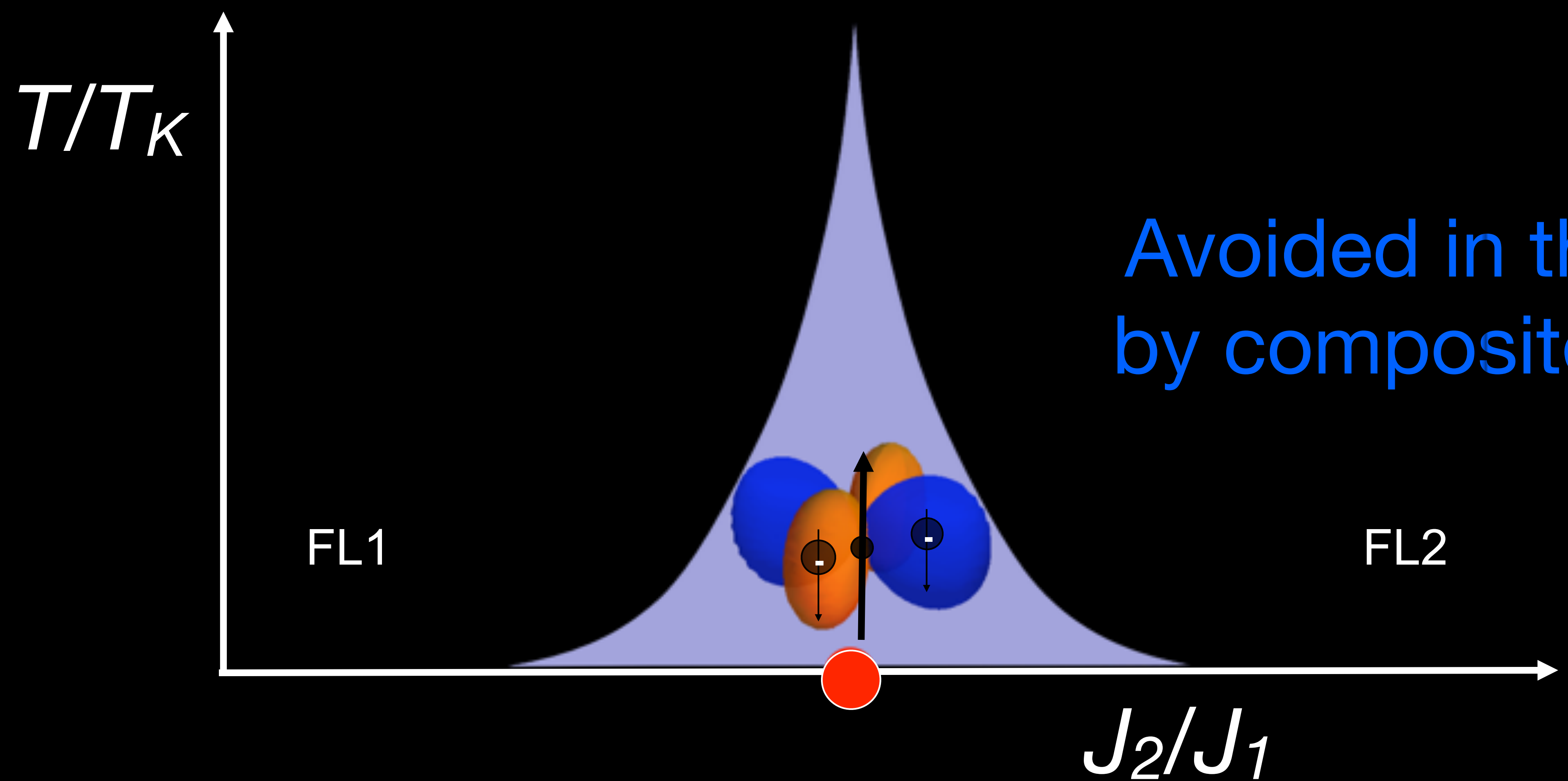

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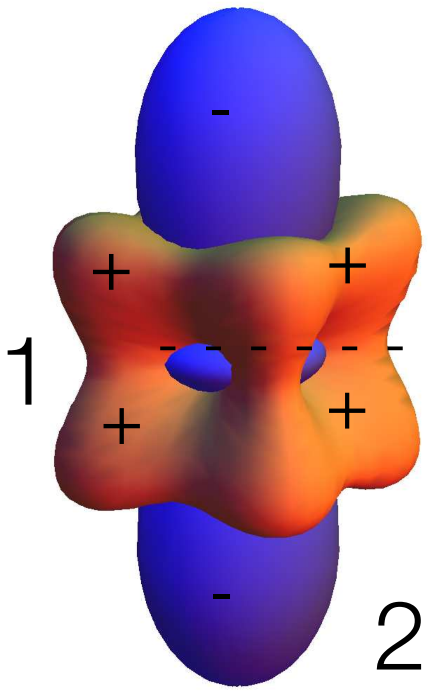

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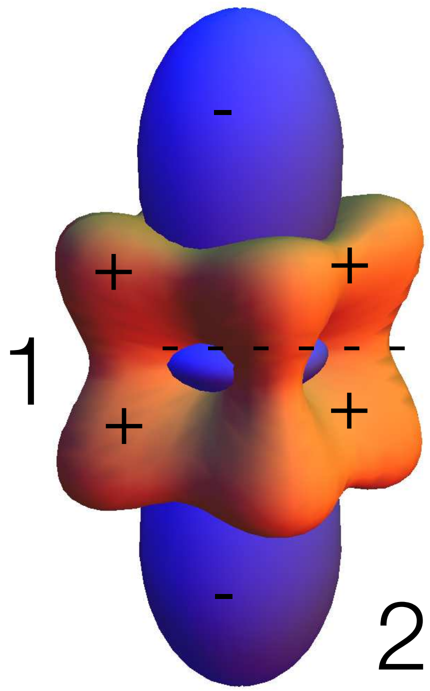

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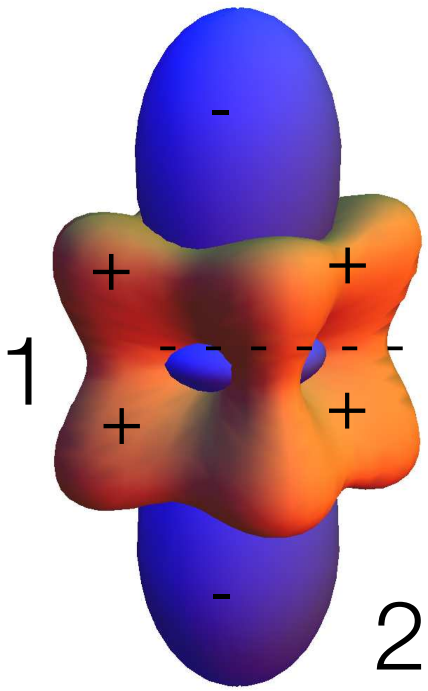
$$Q_{zz} \propto \Psi_C^2$$



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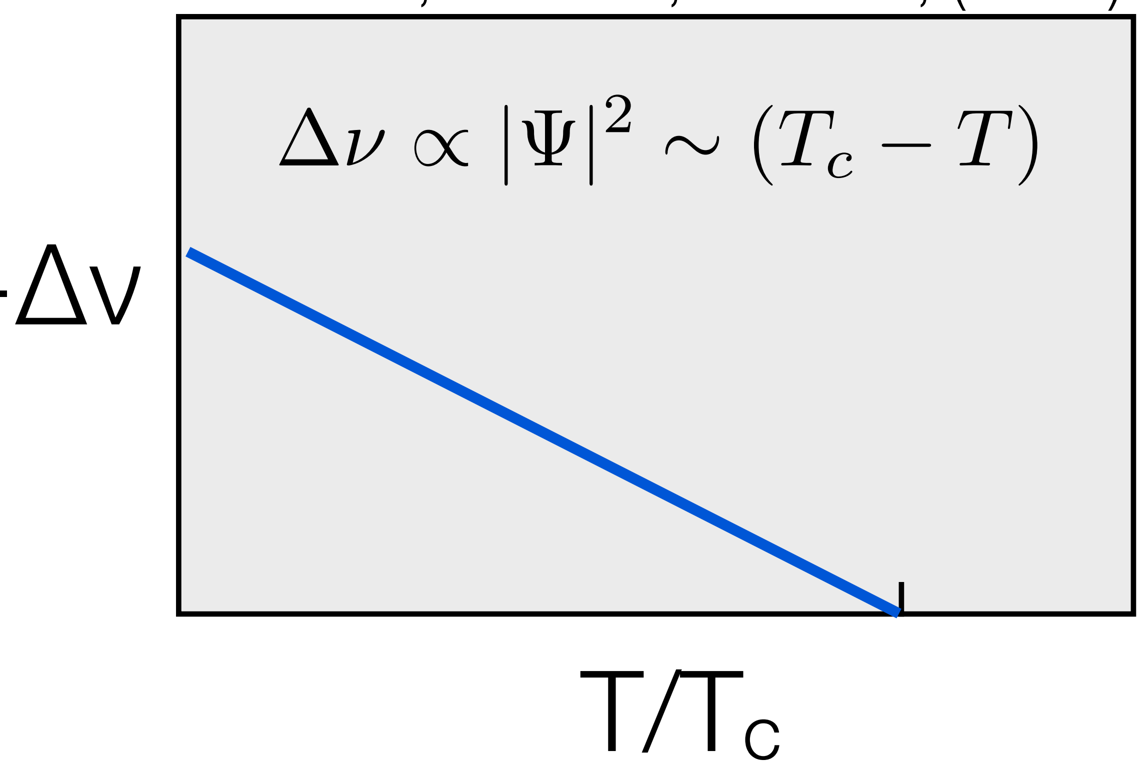

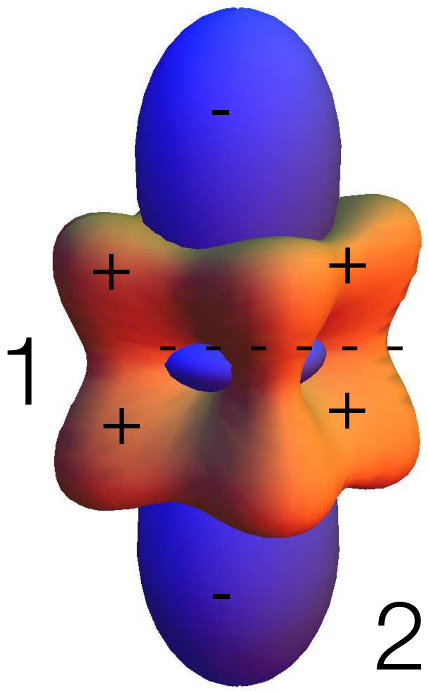

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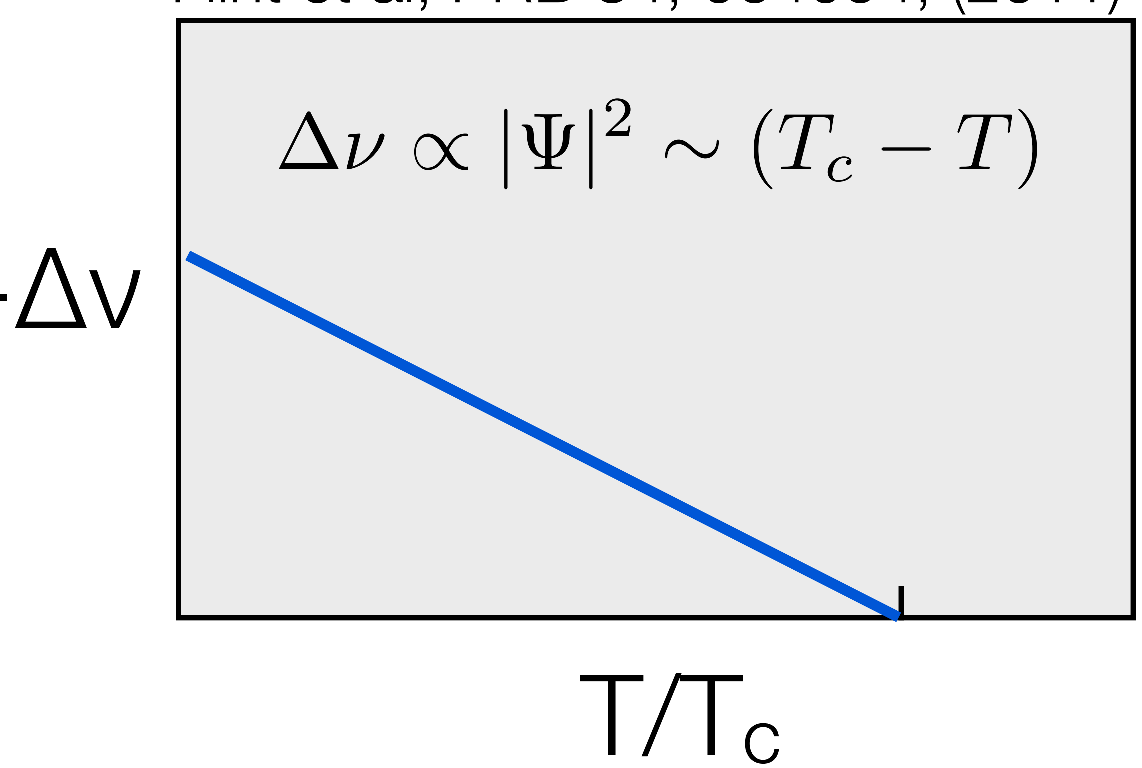
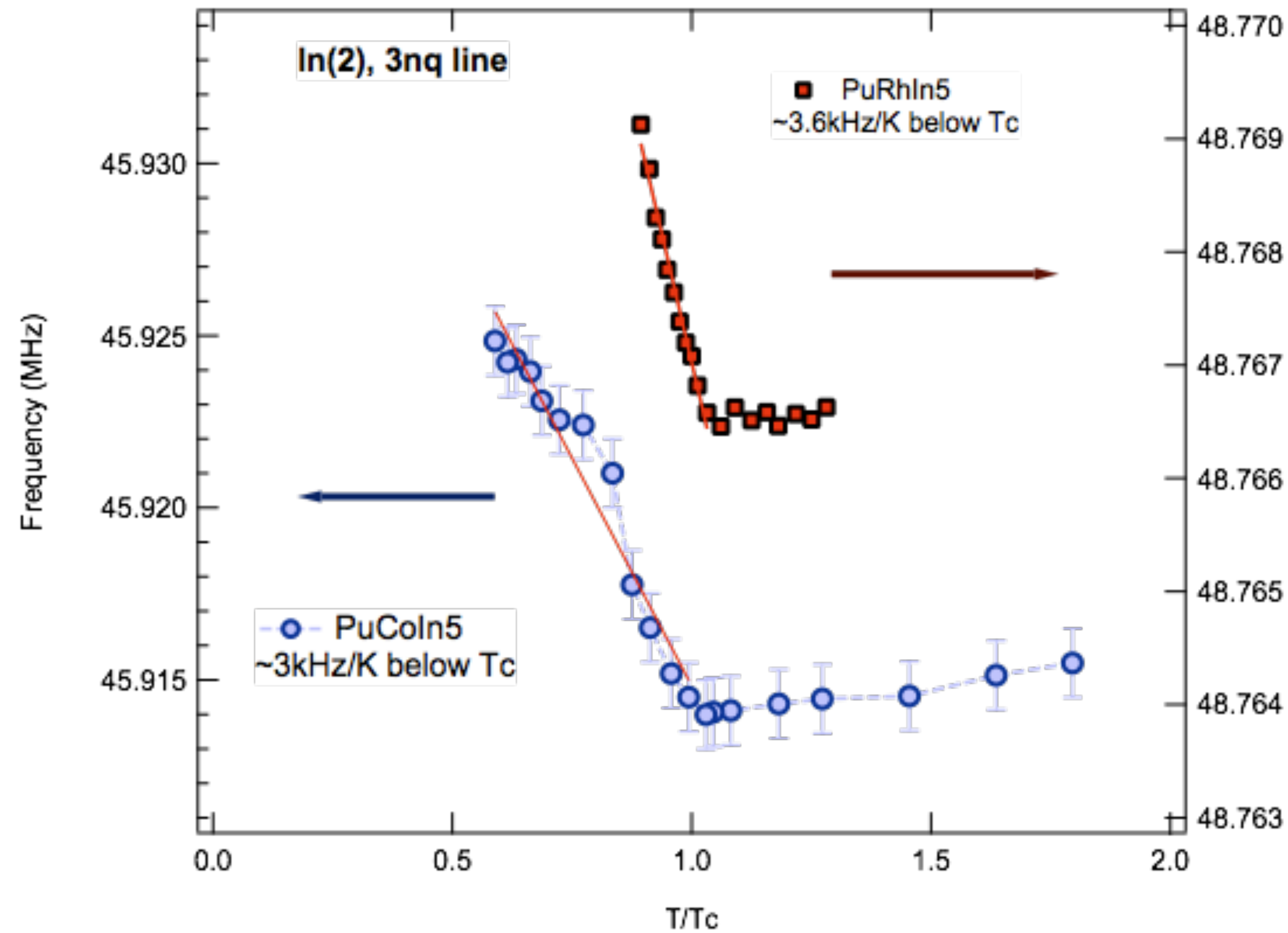
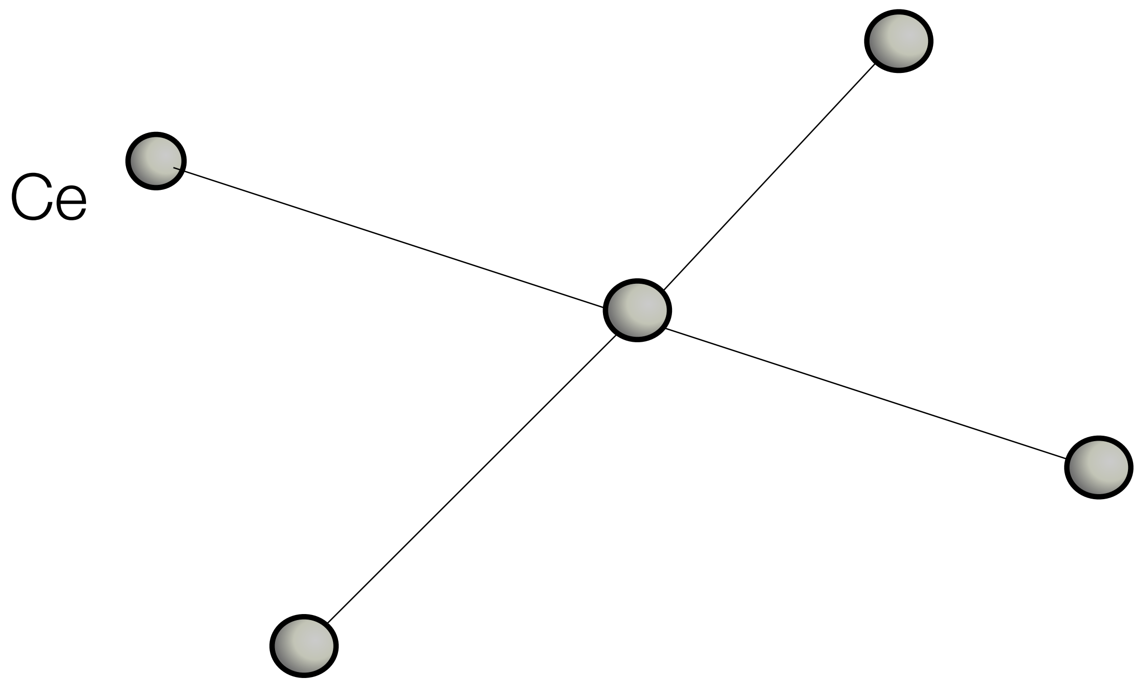


Bauer, G. Koutroulakis Yasuoko,(2014)



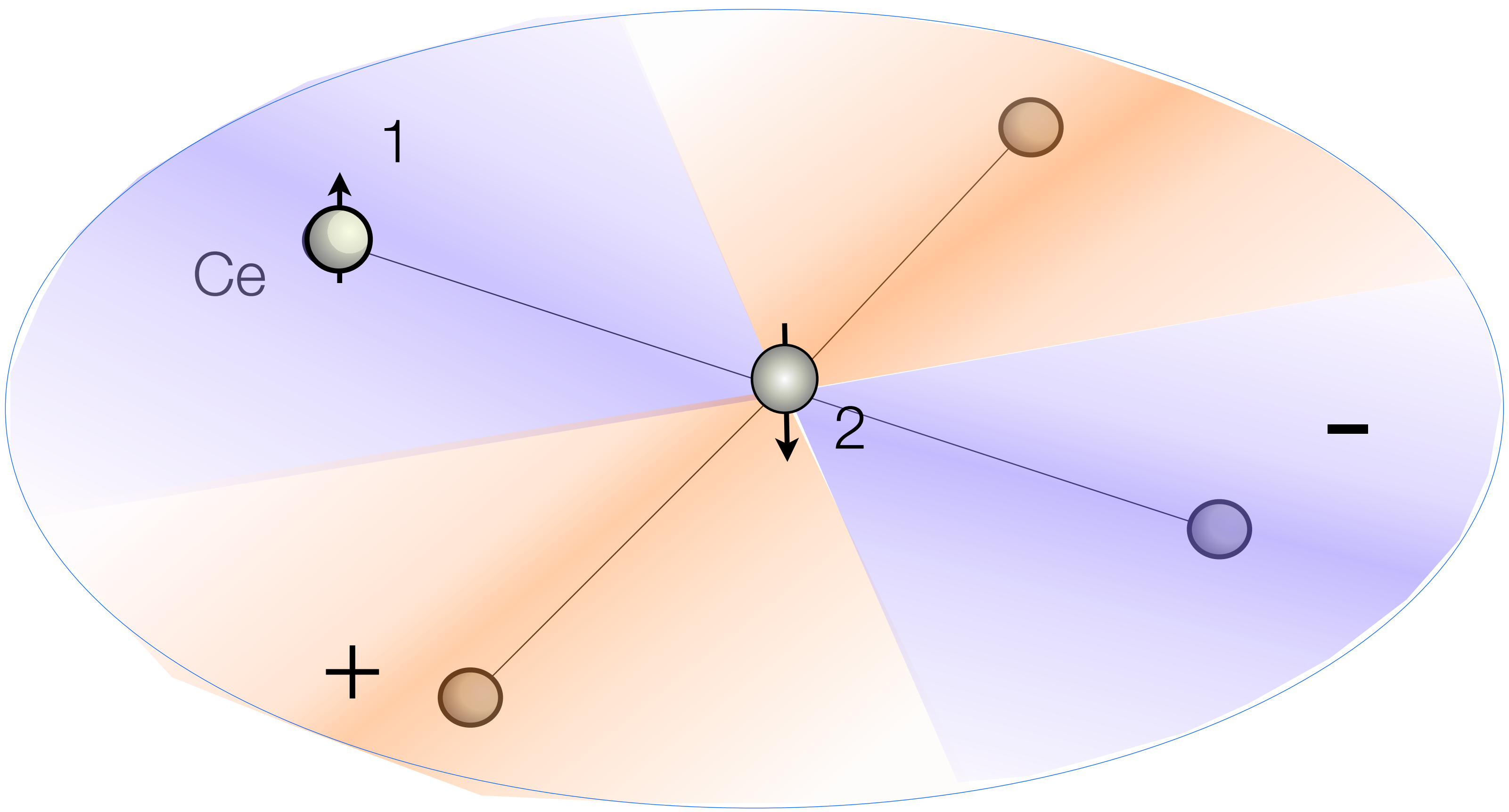
Pair breaking and Yb Doping



Pair breaking and Yb Doping

Magnetic pair: intercell: doping strongly pair breaking.

$$\Psi_M^\dagger = \Delta_d(1-2) f_\uparrow^\dagger(1) f_\downarrow^\dagger(2)$$



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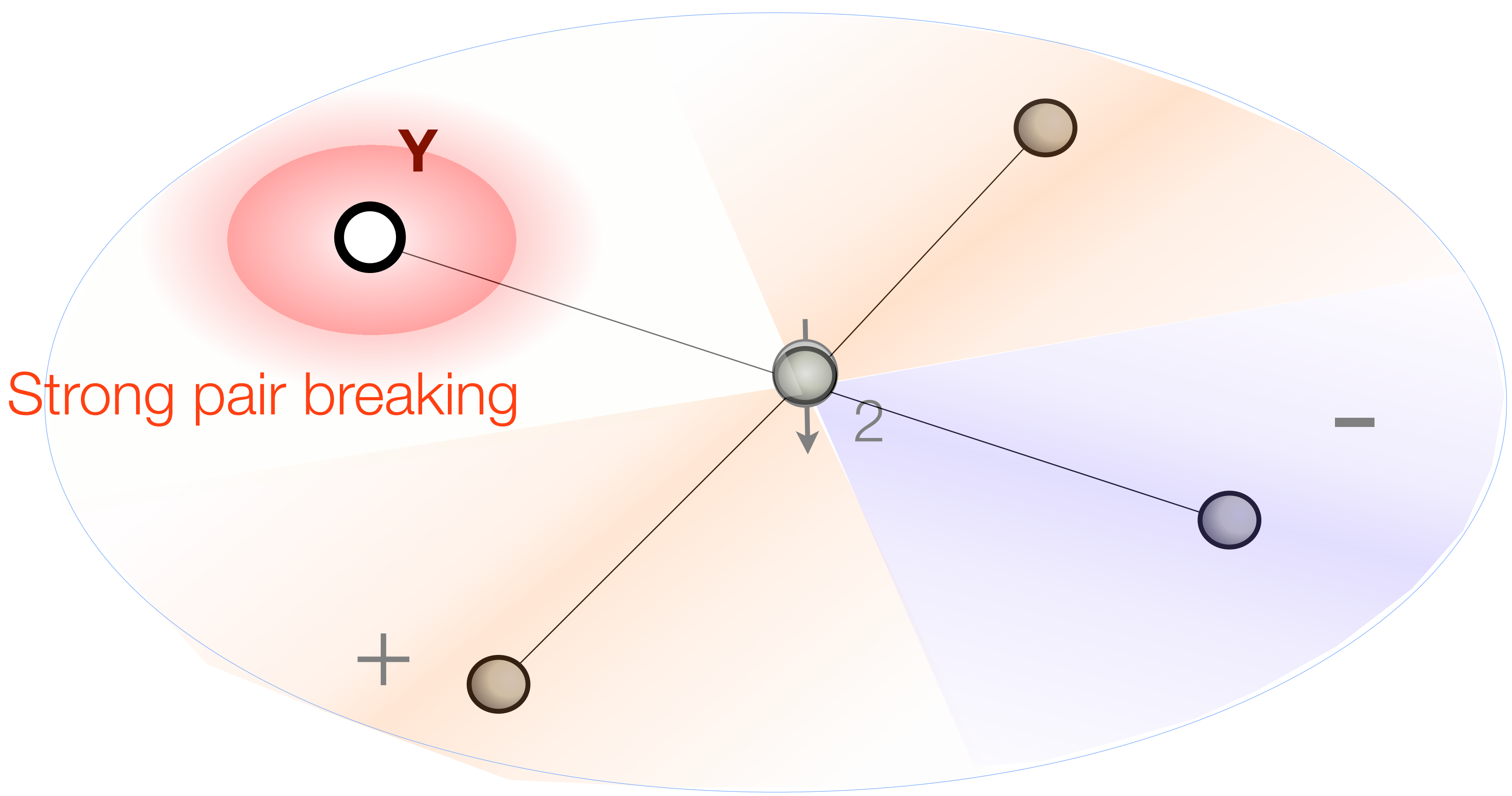

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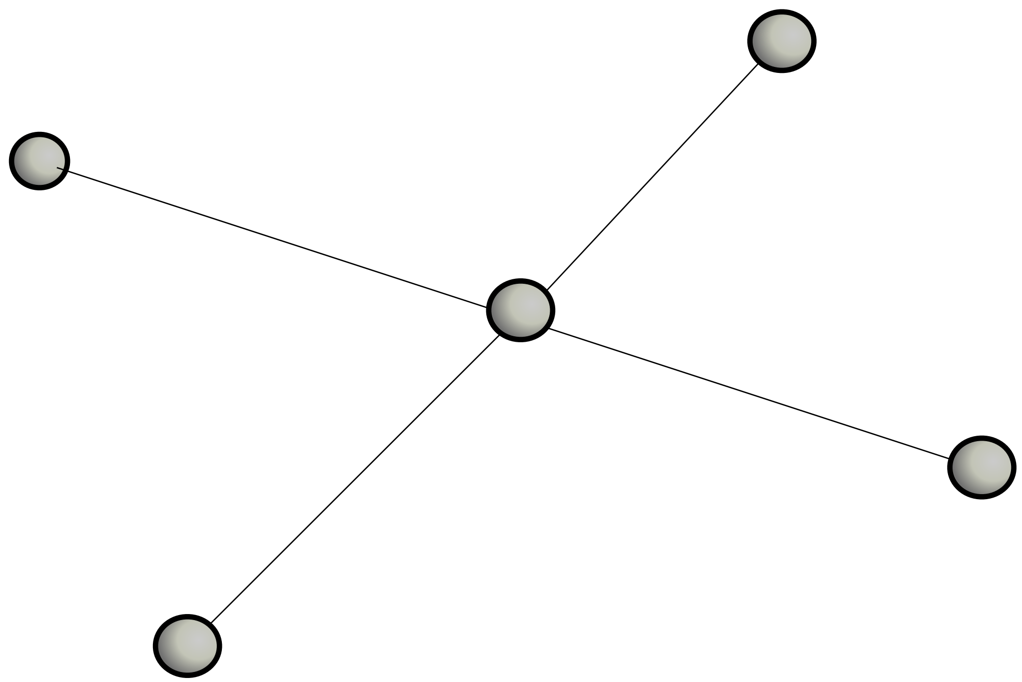

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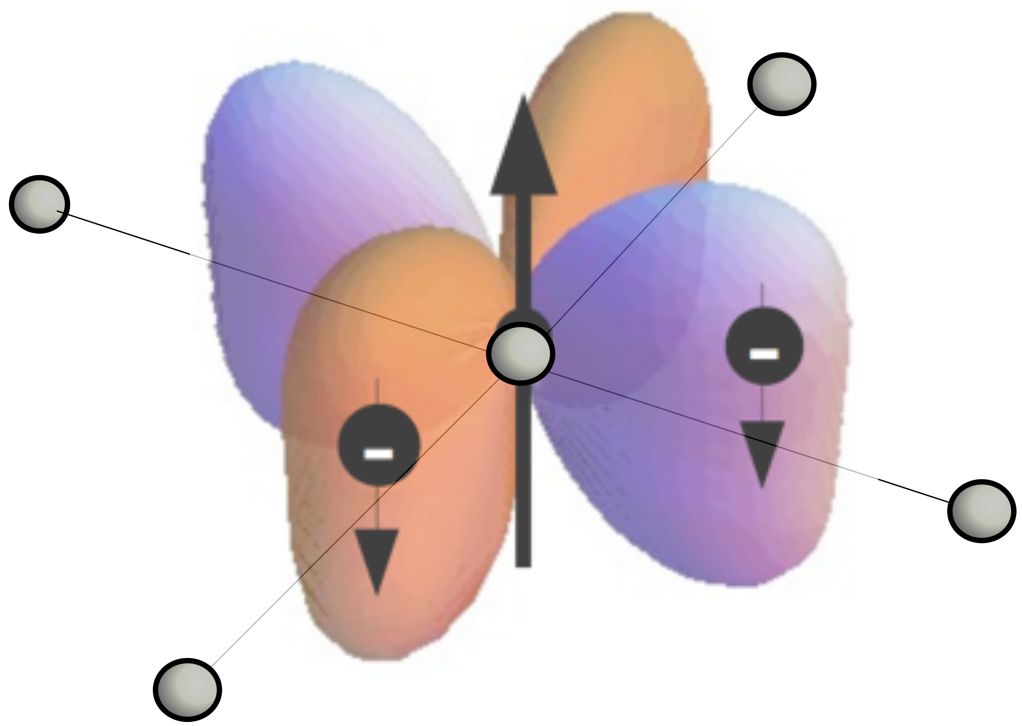

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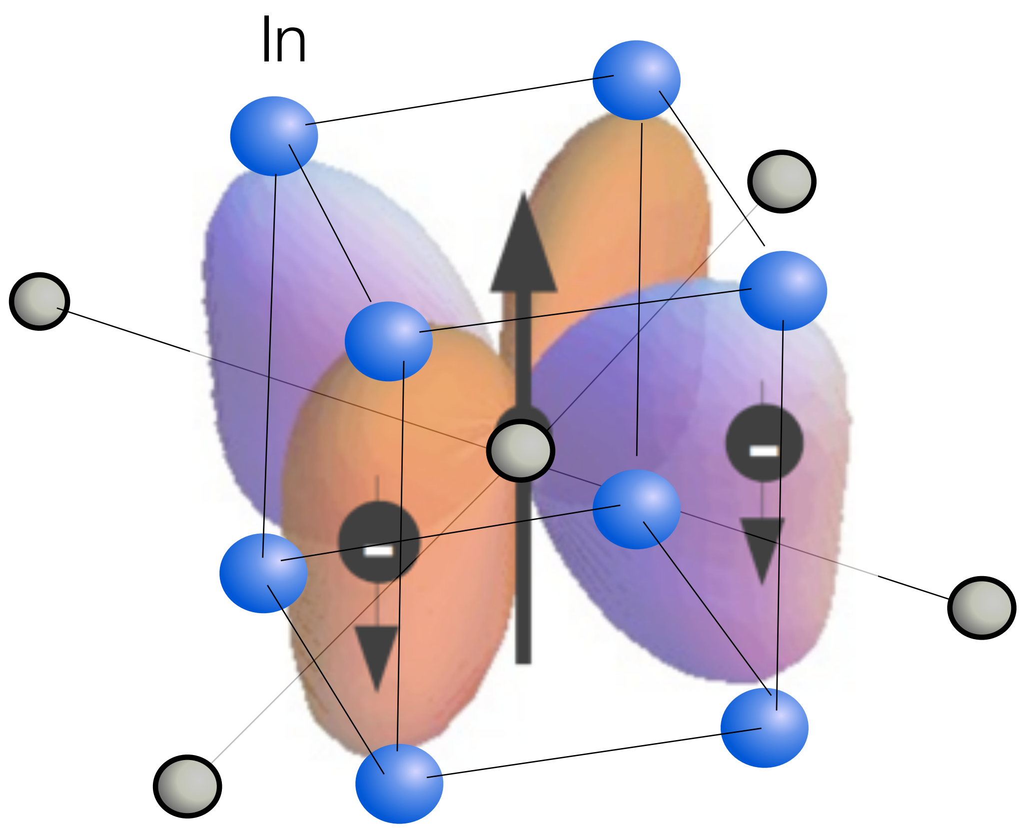

Composite pair**: intra-cell boson**

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Extreme Resilience to doping on Ce site.

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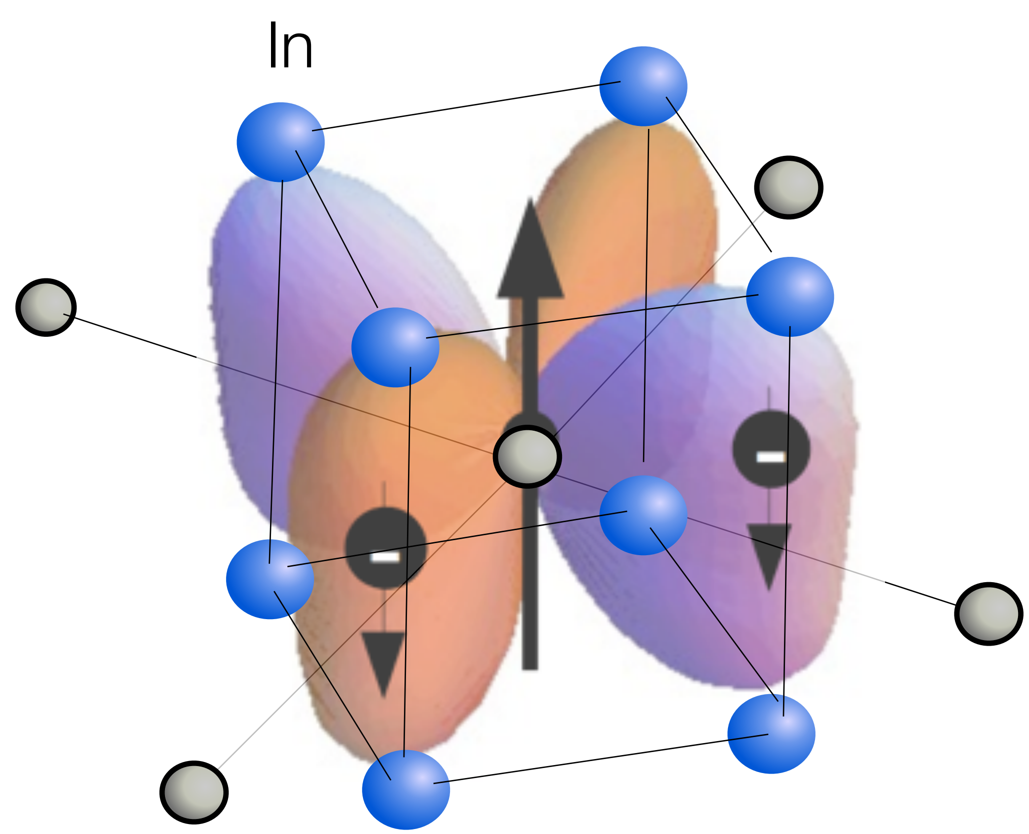

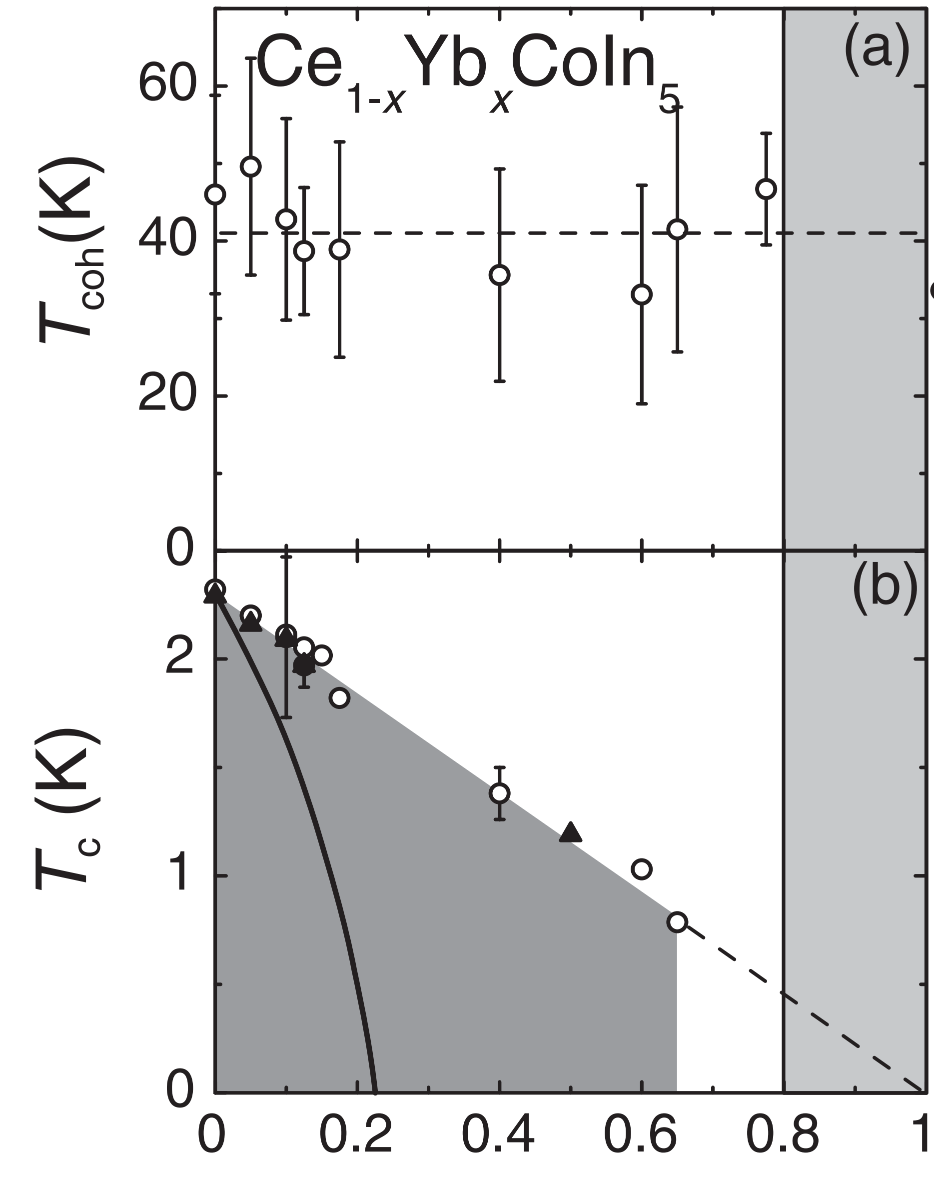

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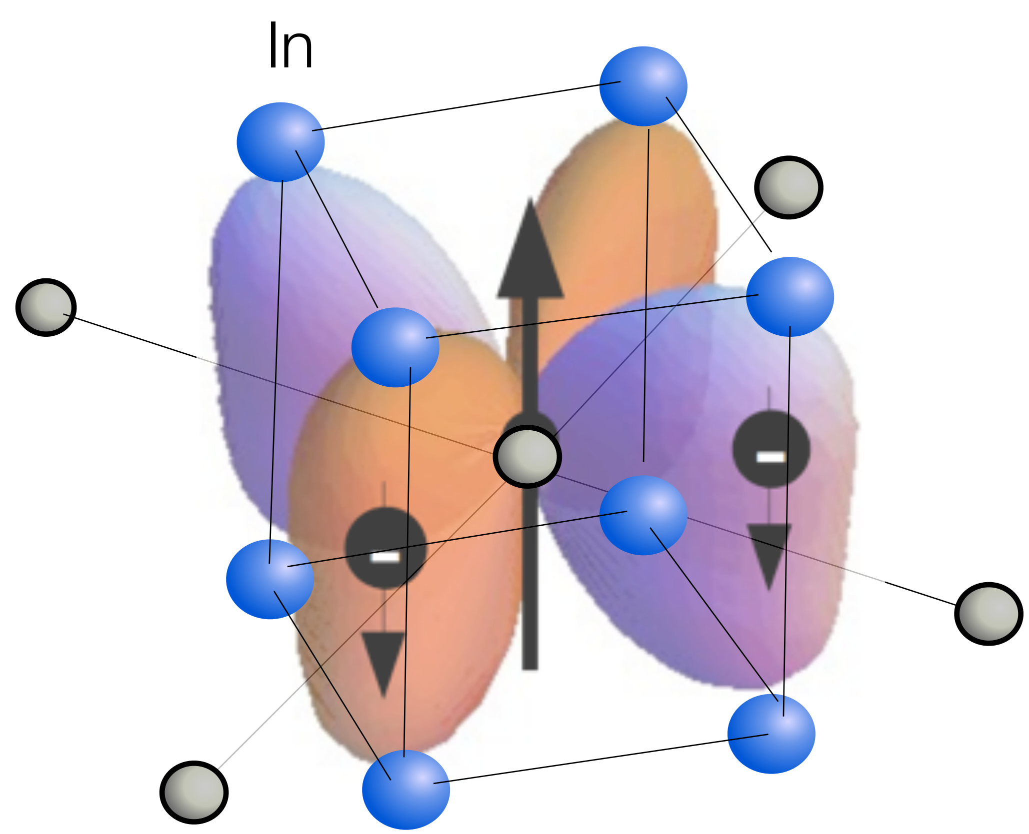

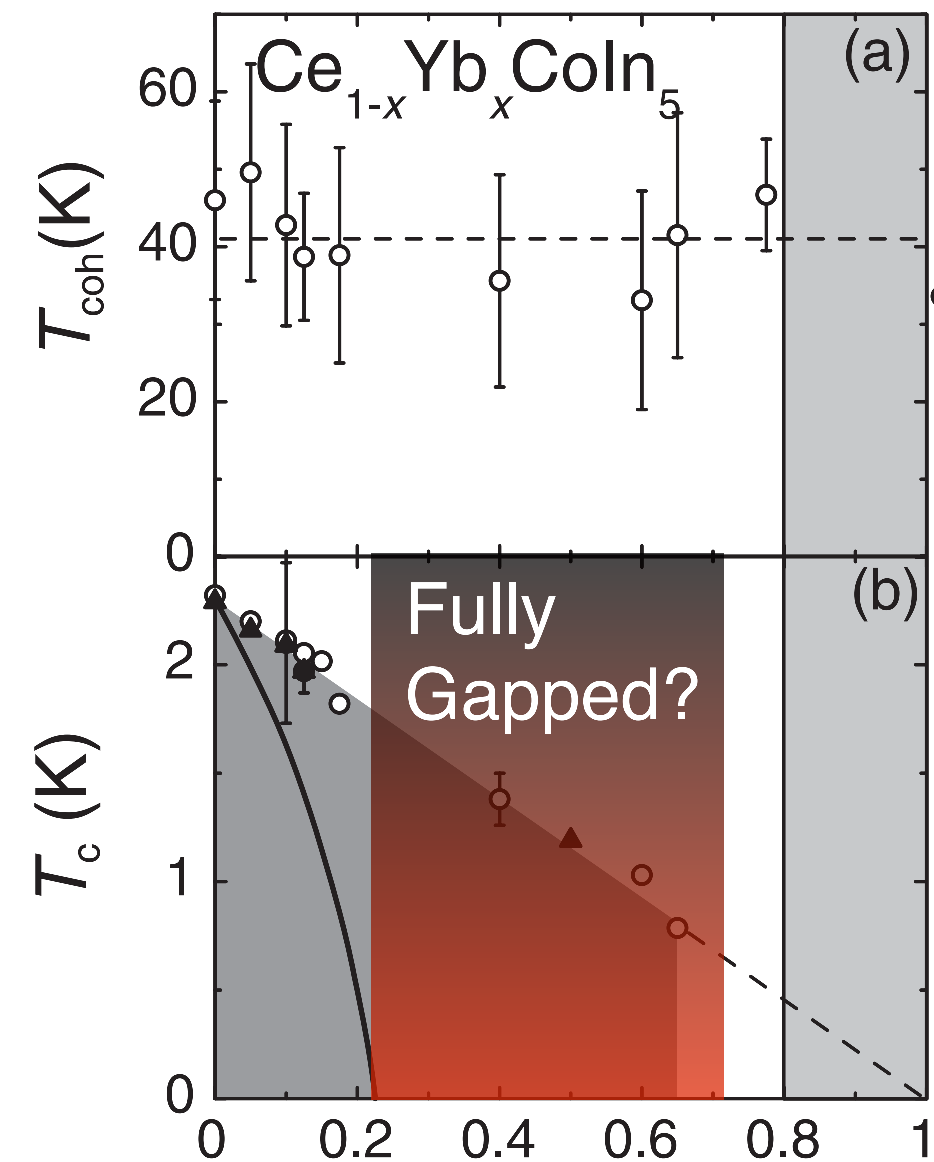

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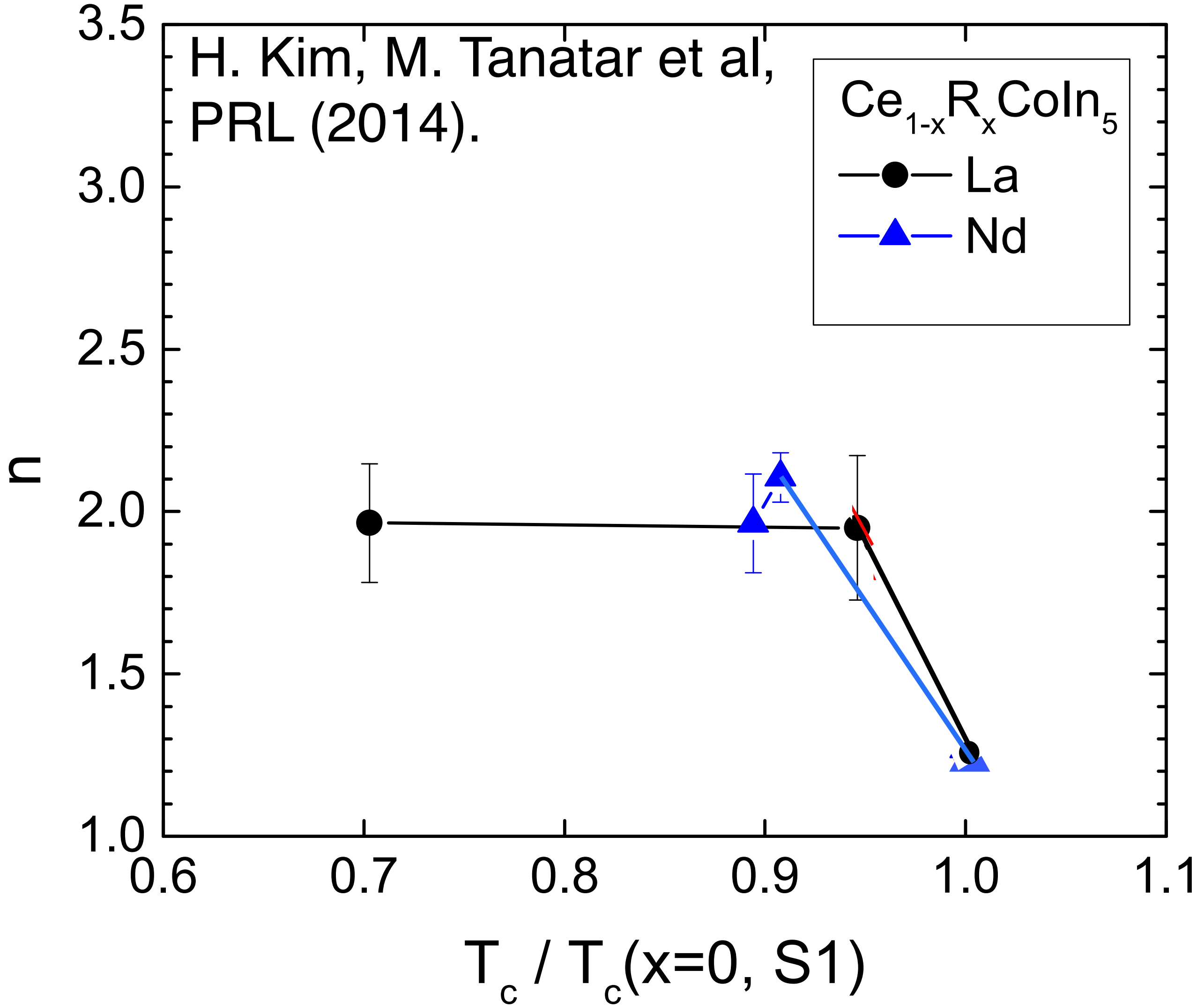
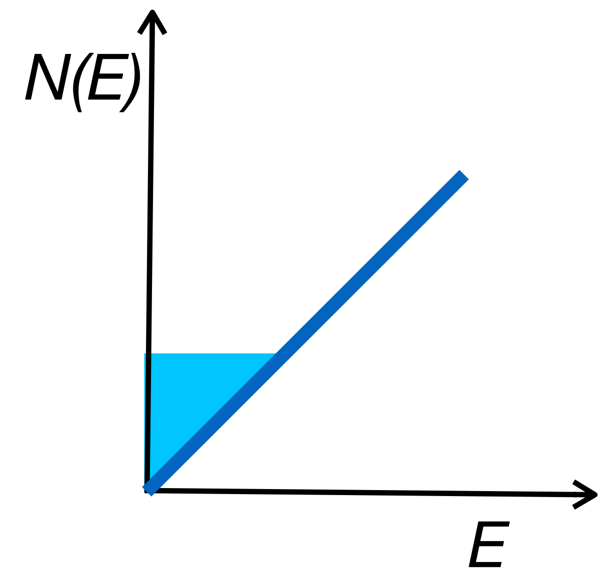
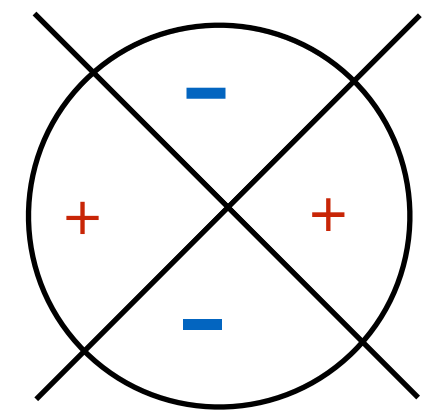






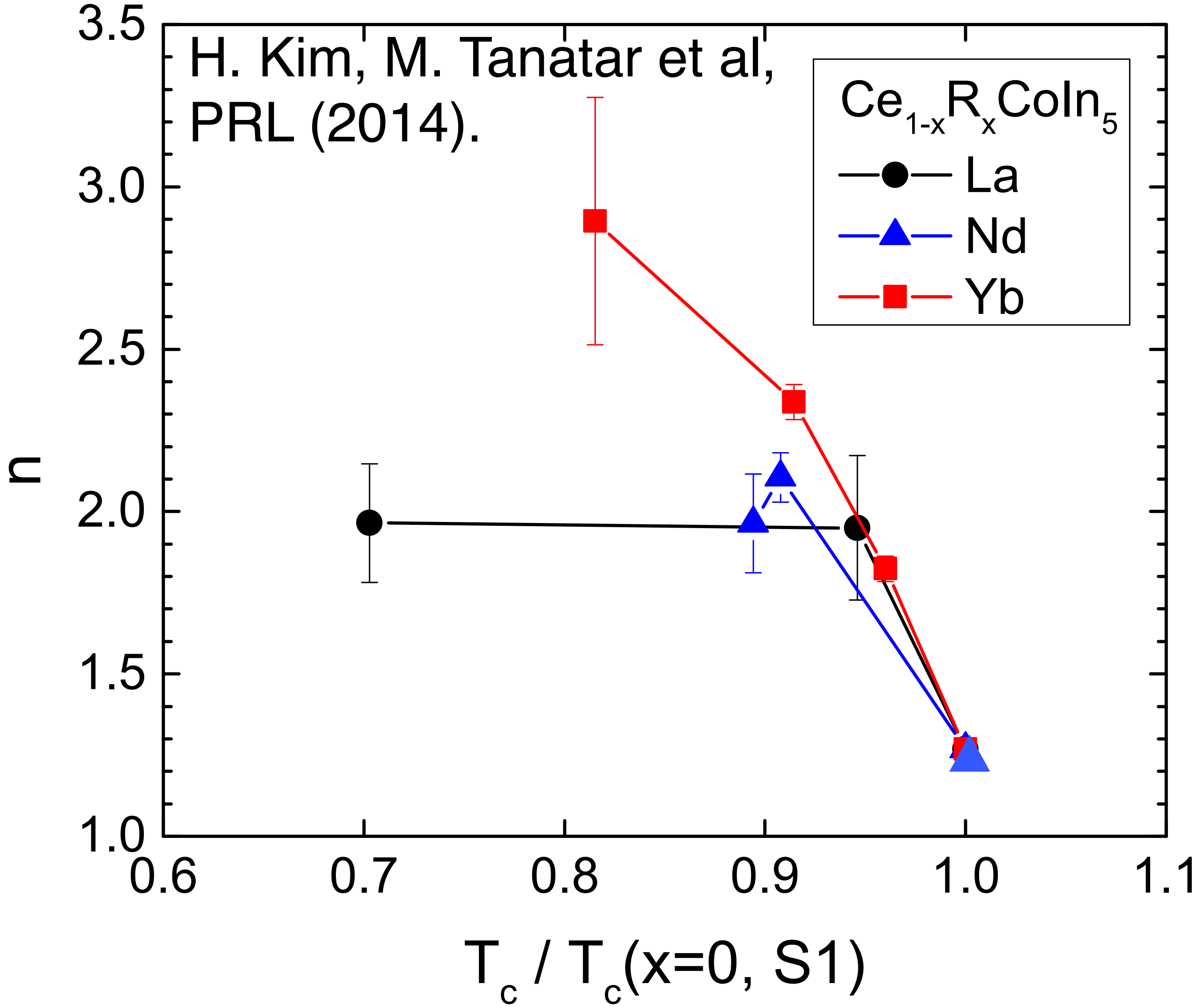
Clean $\overline{N(\epsilon)} \sim T$ ✓

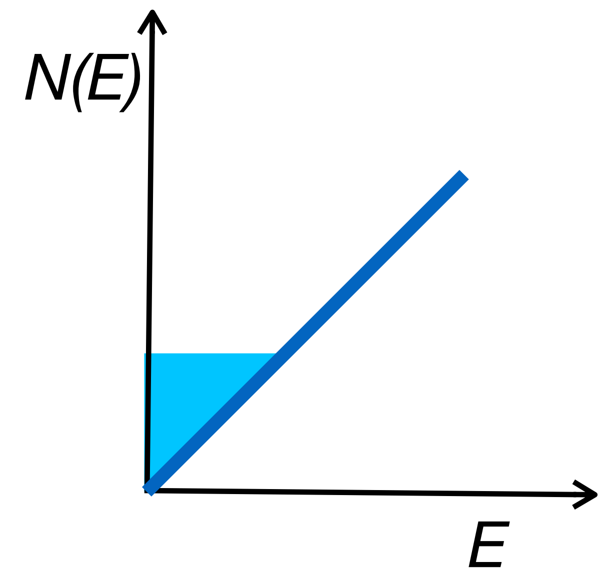
d-wave sc

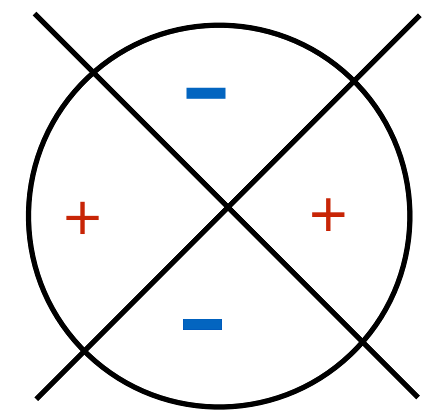
Dirty $\delta\overline{N(\epsilon)} \sim T^2$ ✓

$$\frac{1}{\lambda_L^2(T)} = \frac{1}{\lambda_L^2(0)} - \overline{N(\epsilon)}$$

Penetration Depth







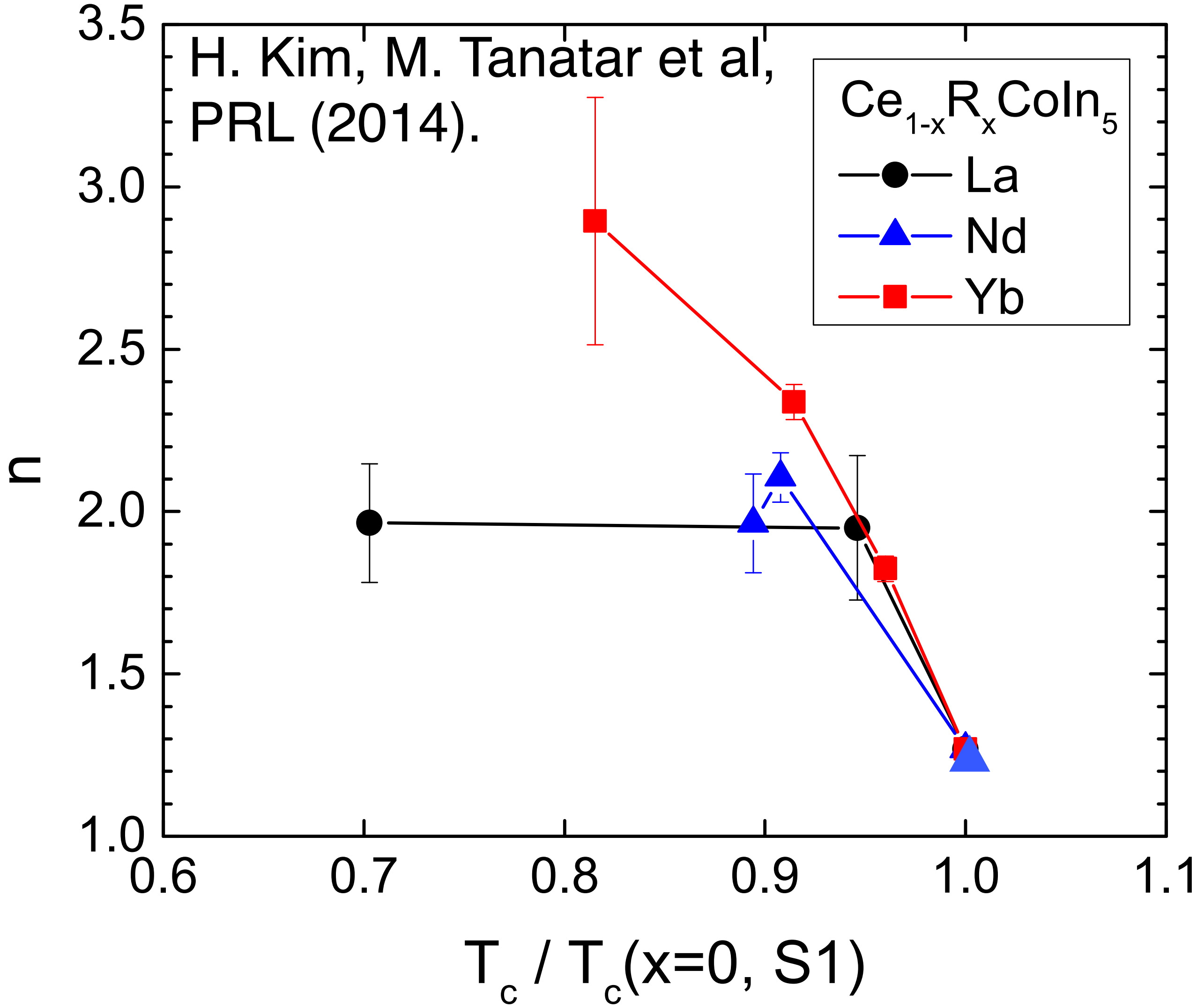
Clean $\overline{N(\epsilon)} \sim T$ ✓

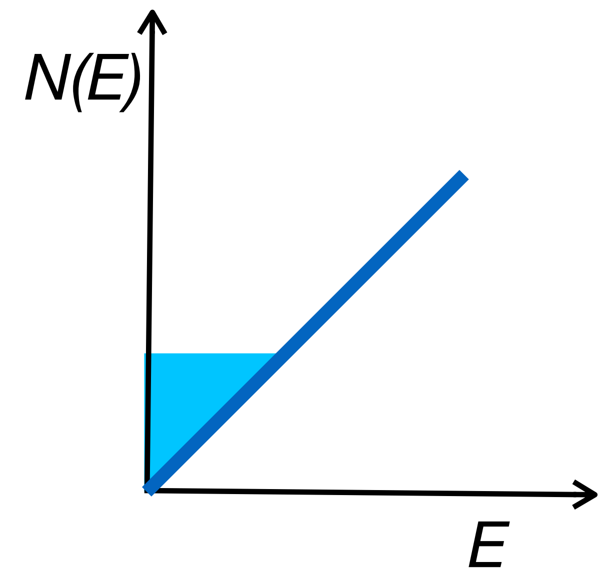
Dirty $\delta\overline{N(\epsilon)} \sim T^2$ ✓

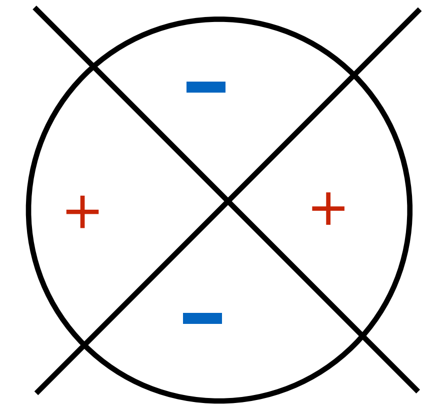
d-wave sc

$$\frac{1}{\lambda_L^2(T)} = \frac{1}{\lambda_L^2(0)} - \overline{N(\epsilon)}$$

Penetration Depth







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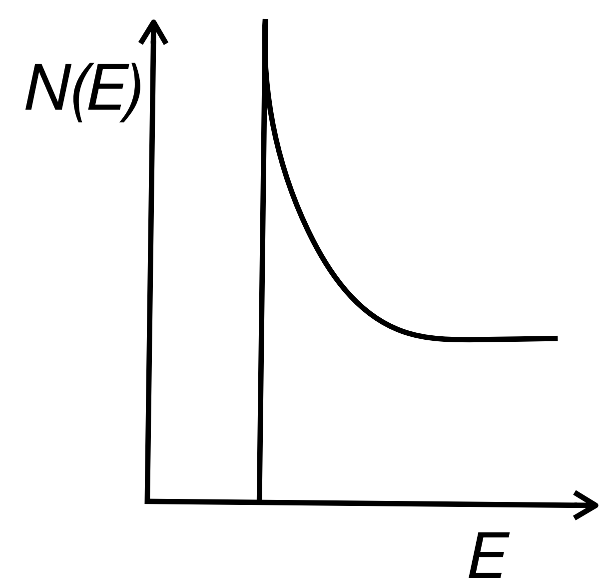

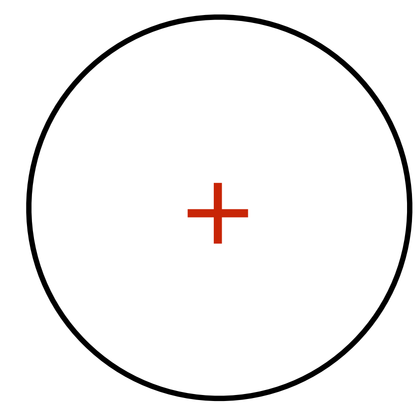

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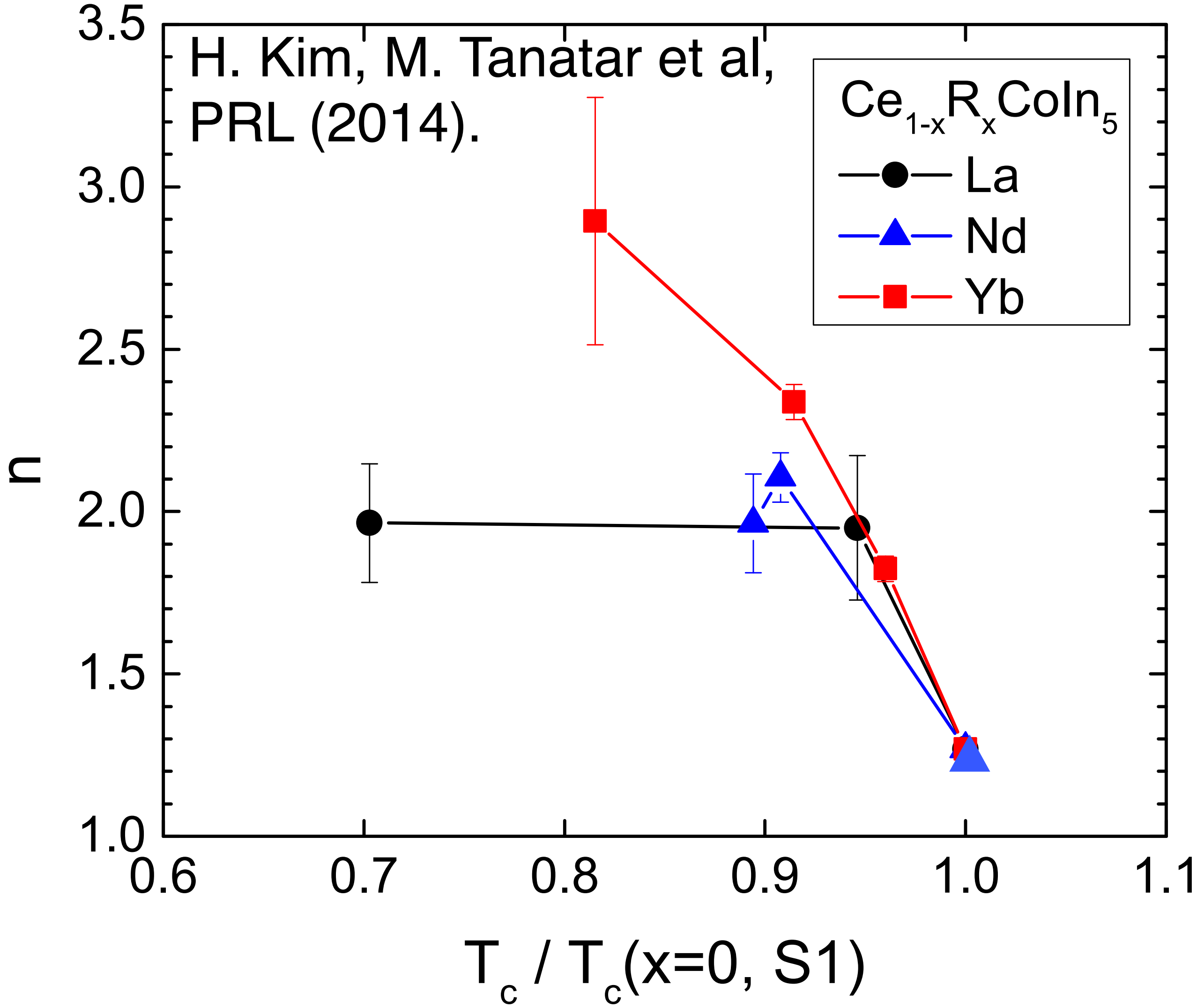
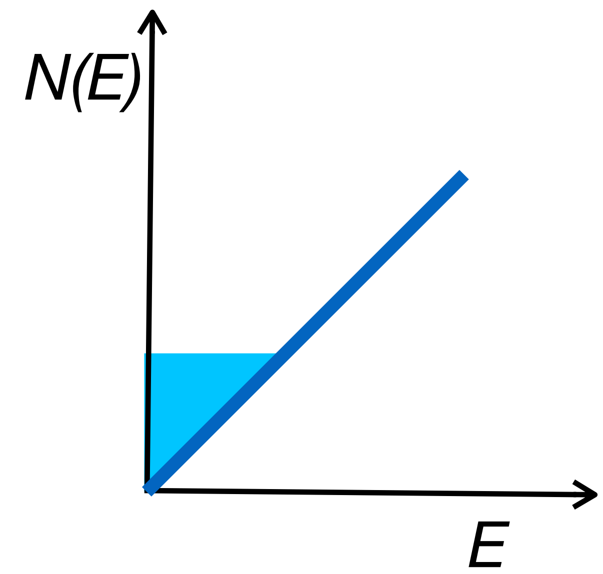
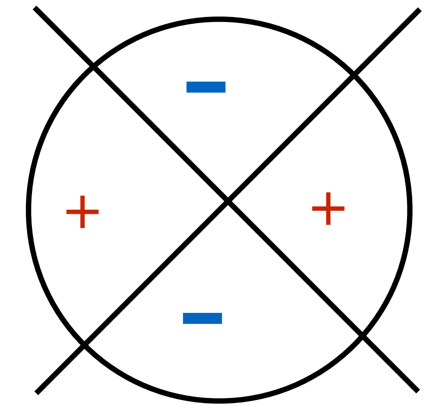
Penetration Depth







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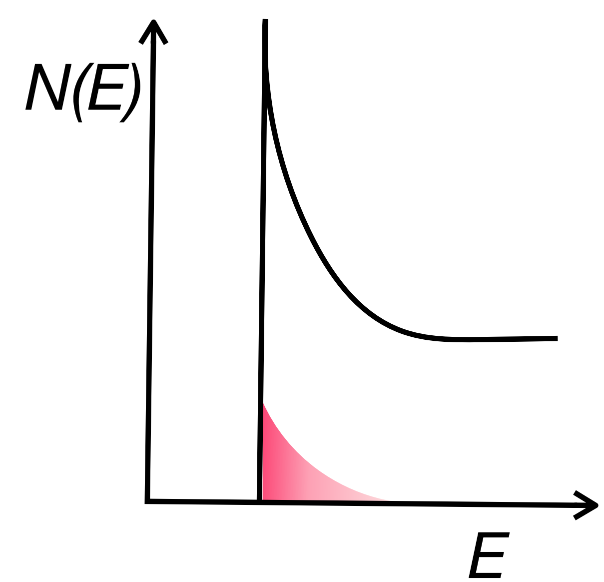

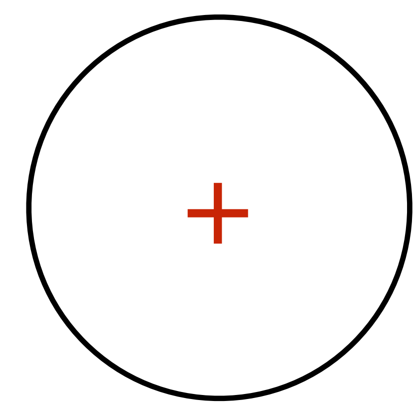

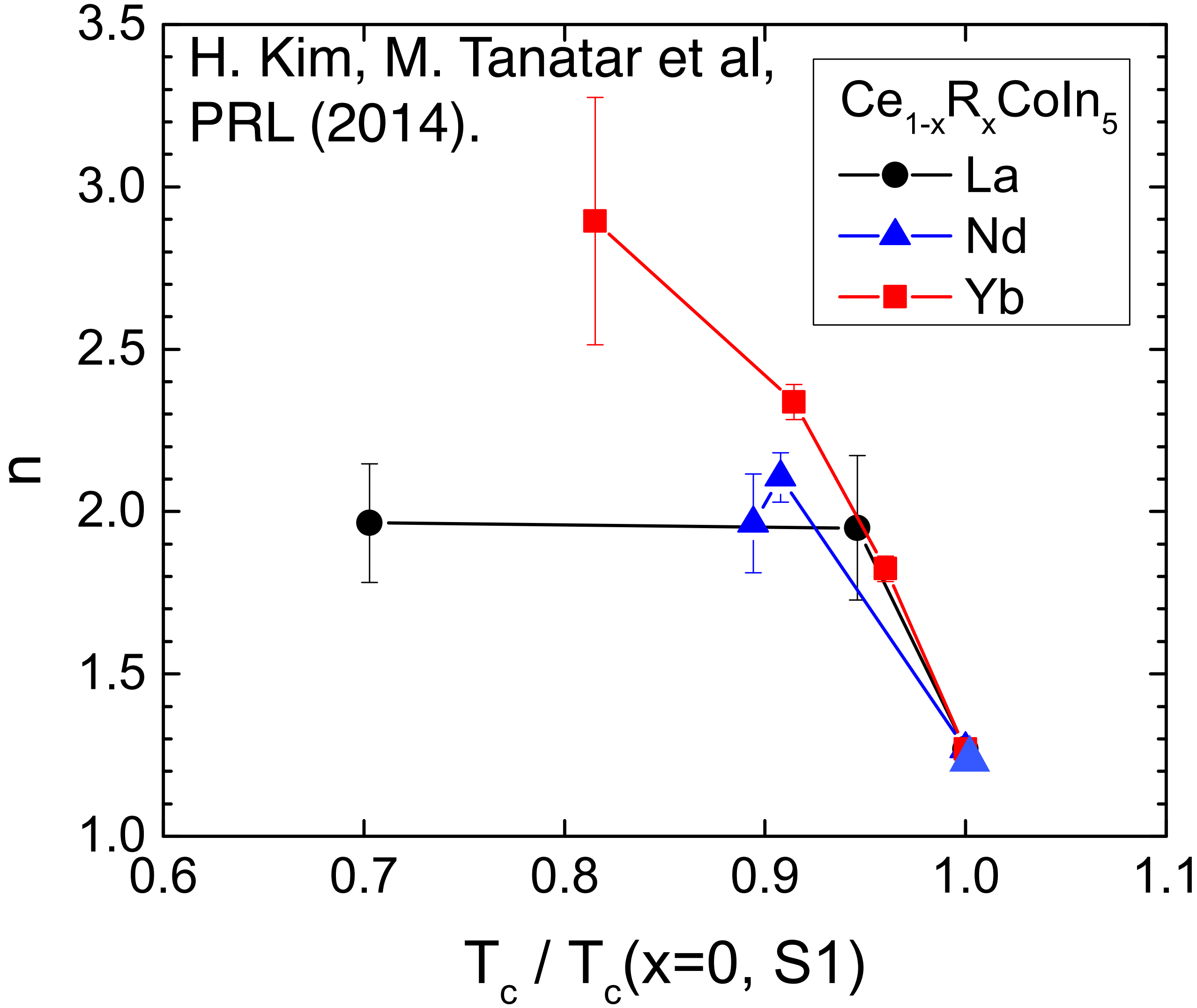

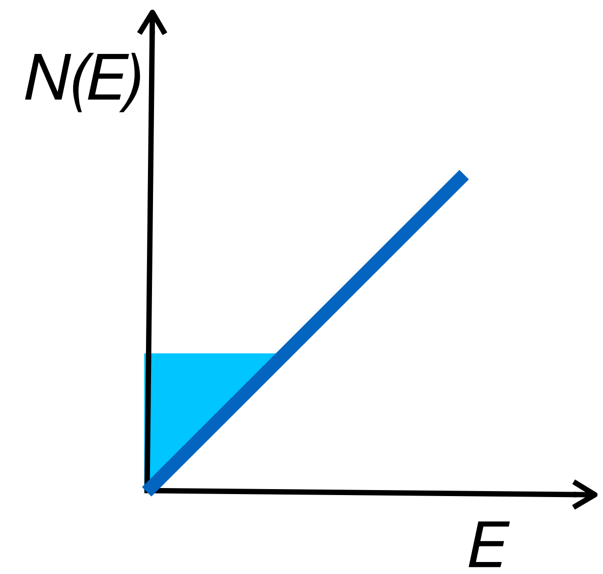

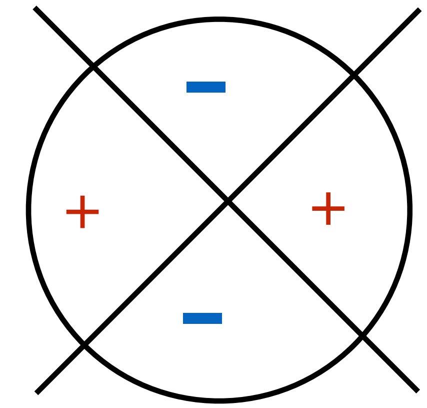

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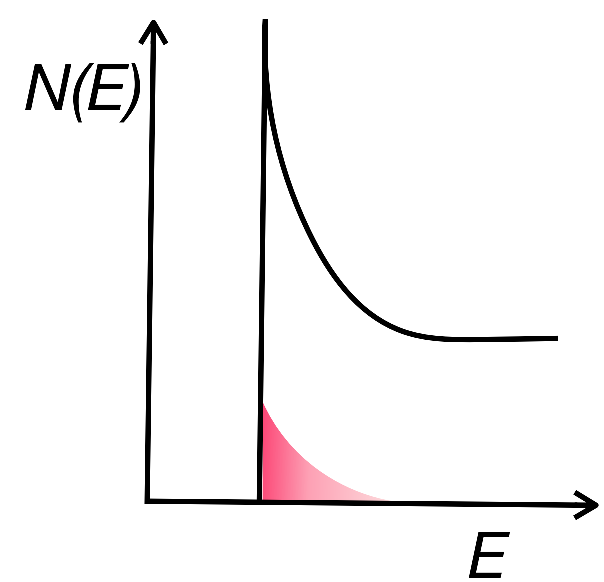
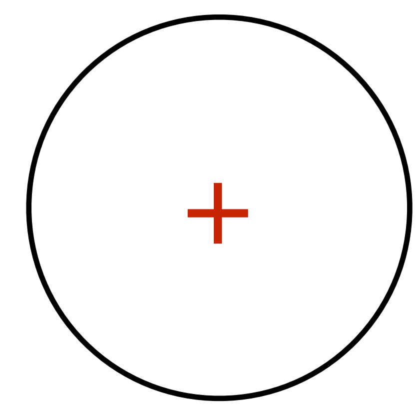
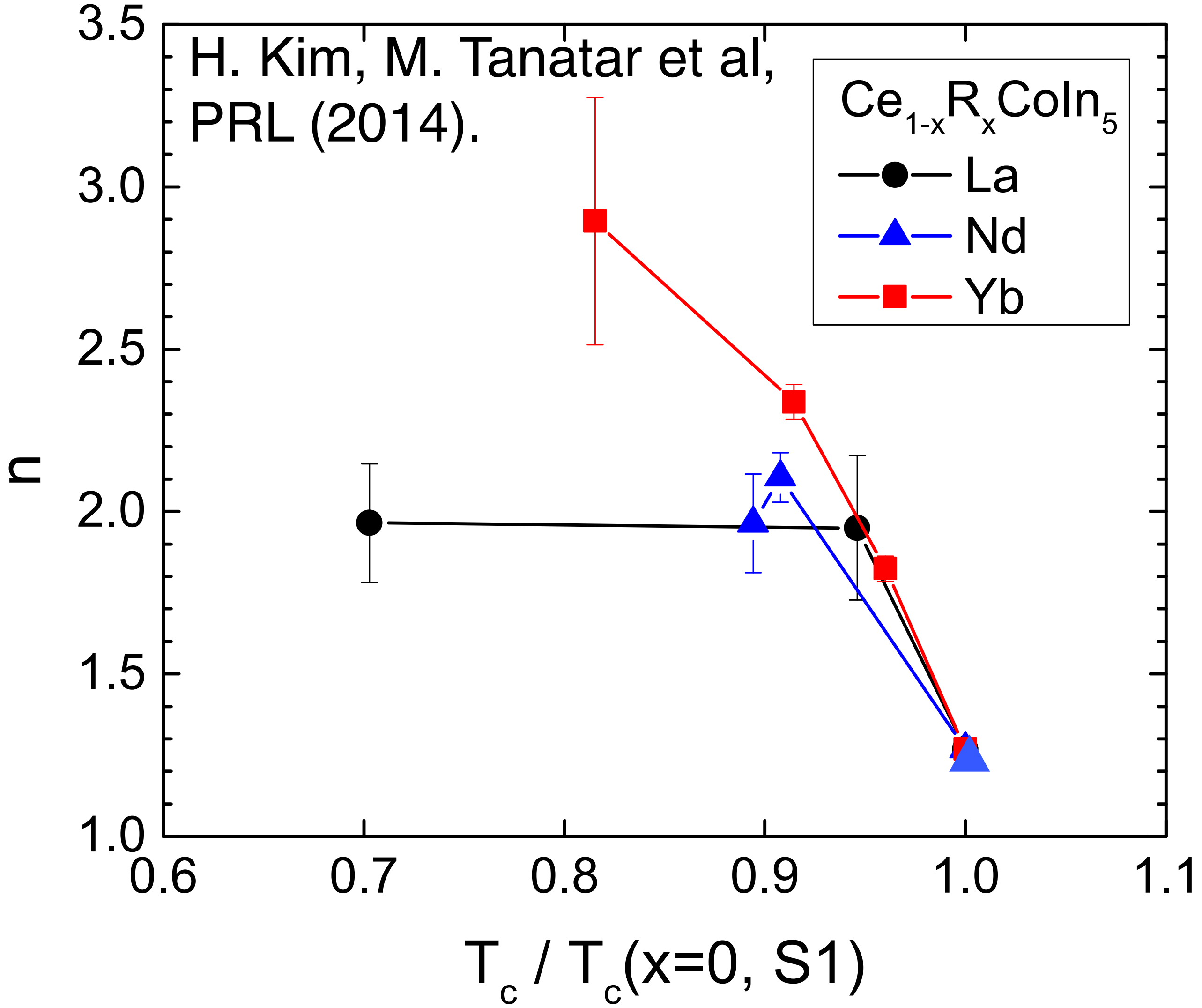
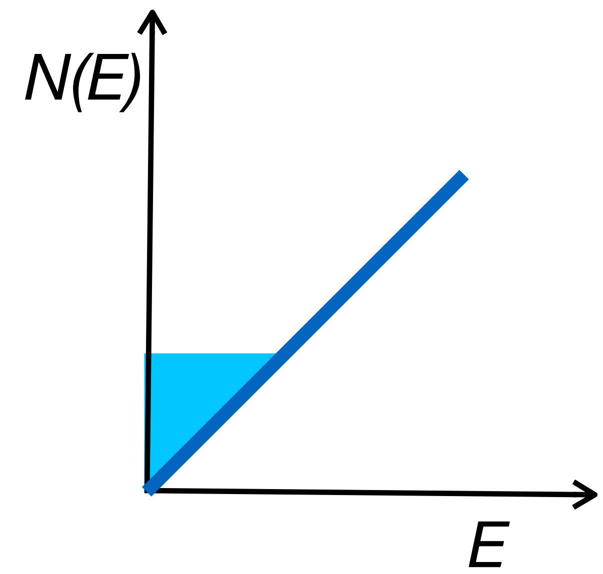
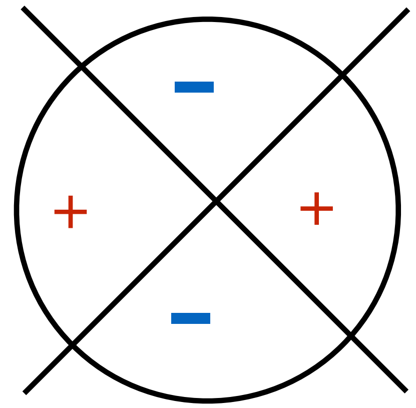




Gapped $\overline{N(\epsilon)} \sim e^{-\Delta/T} \sim T^{n>3}$







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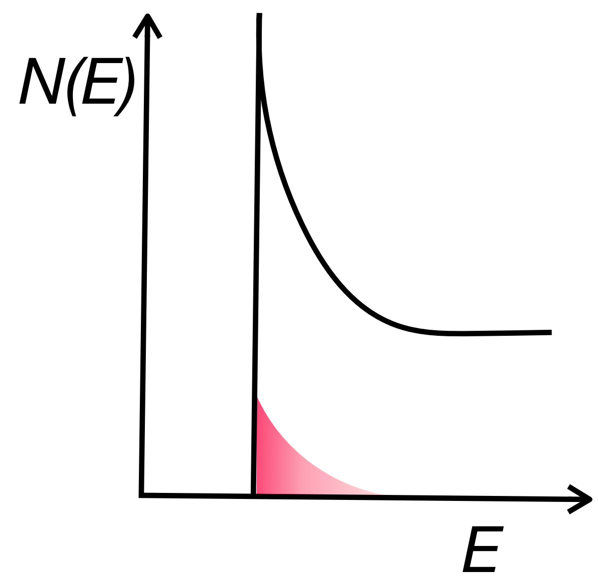

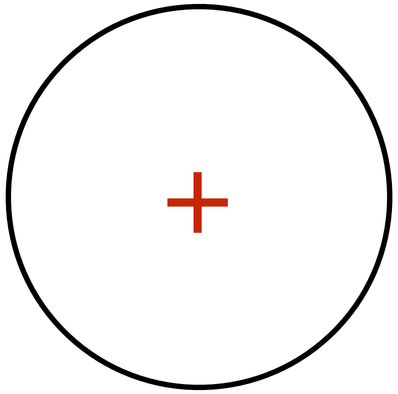

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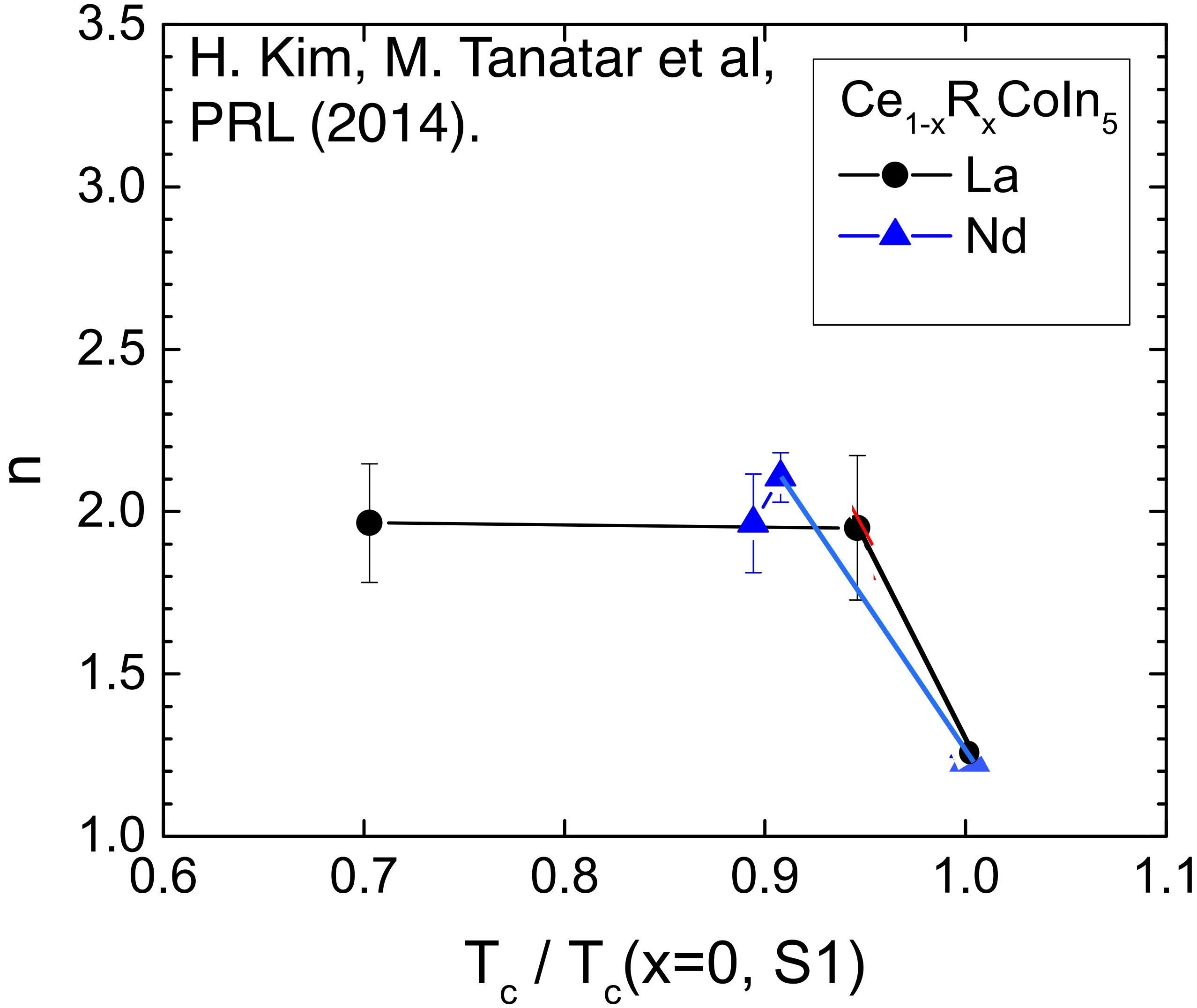
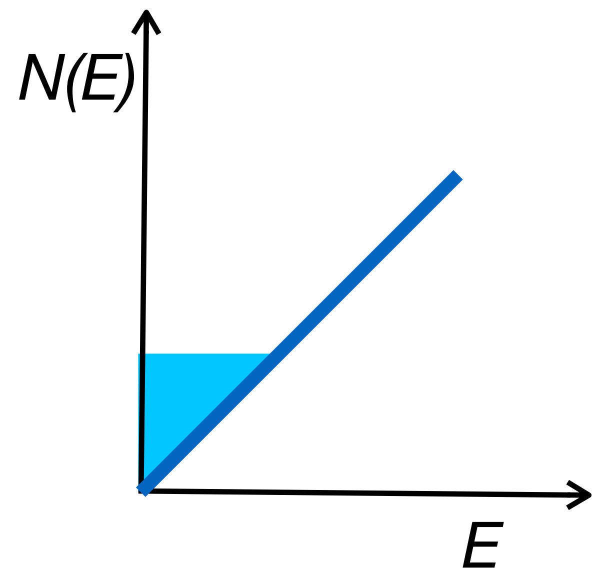
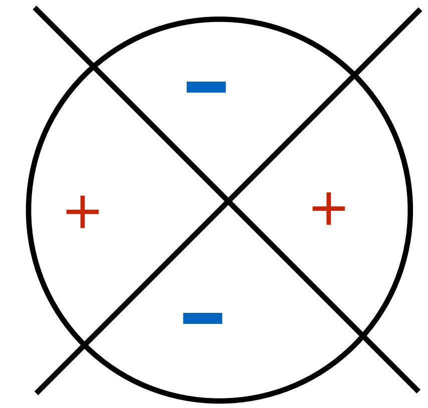
Penetration Depth

Gapped $\overline{N(\epsilon)} \sim e^{-\Delta/T} \sim T^{n>3}$

But Inconsistent with observed d-wave character??







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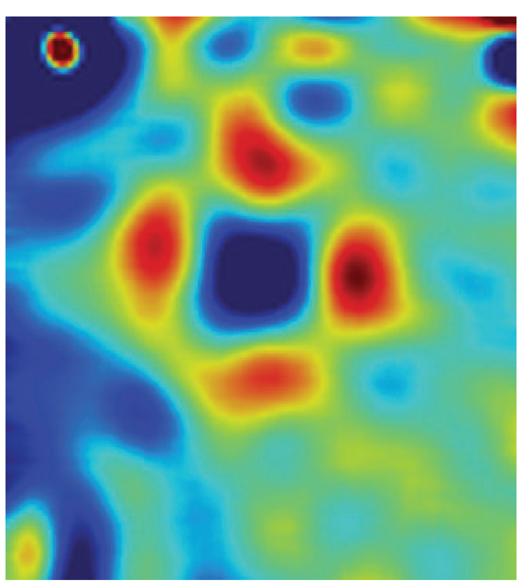
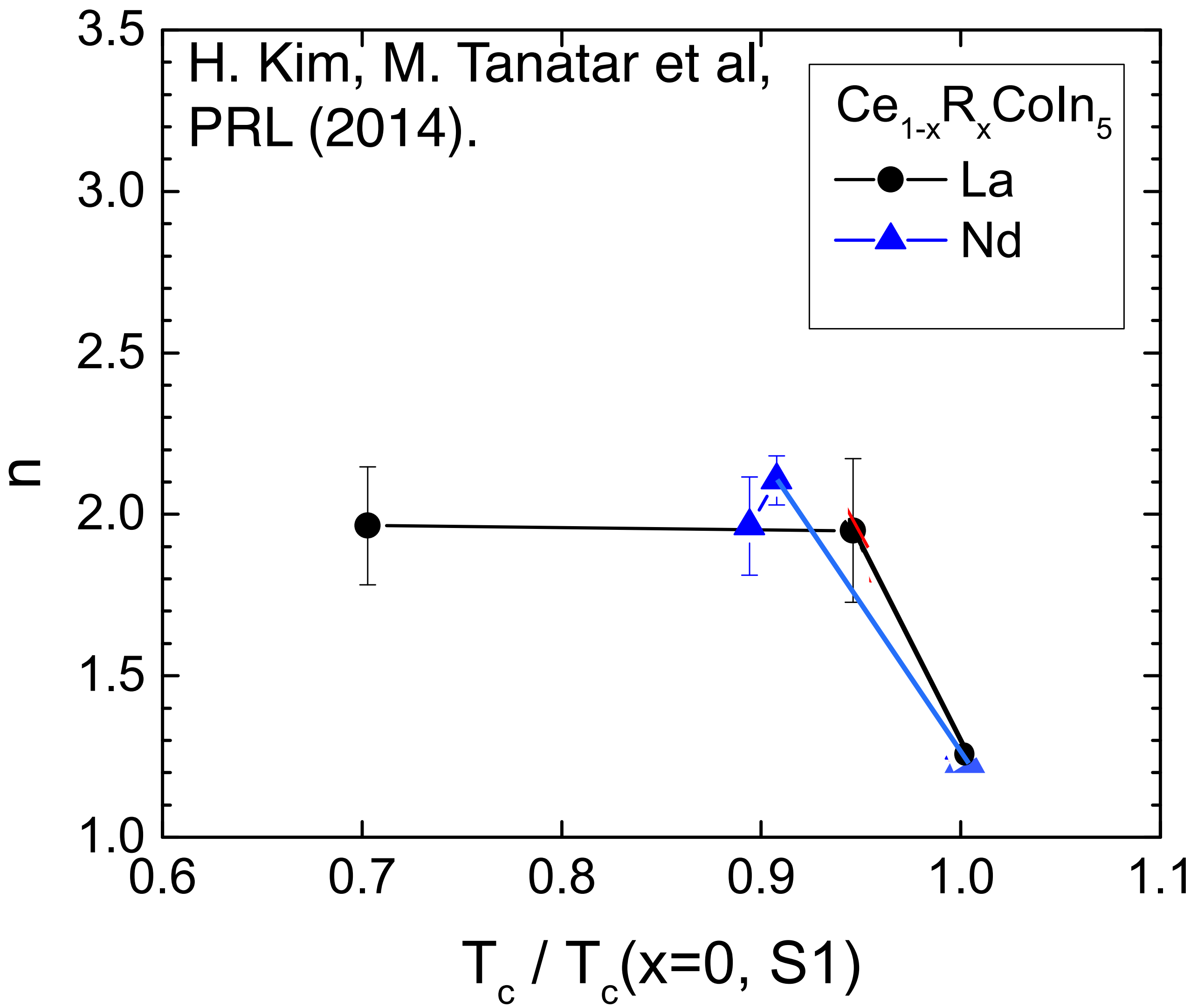
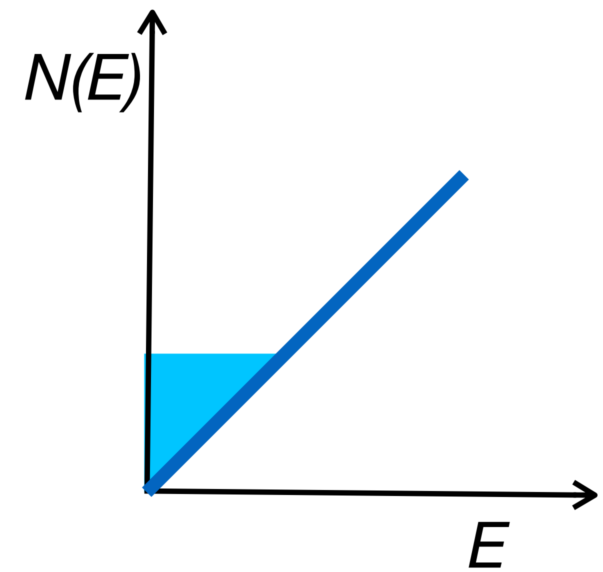
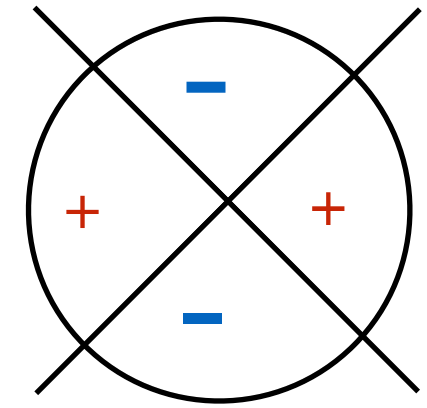


STM: B. Zhou *et al.*
Nature Phys. 9, 474 (2013)







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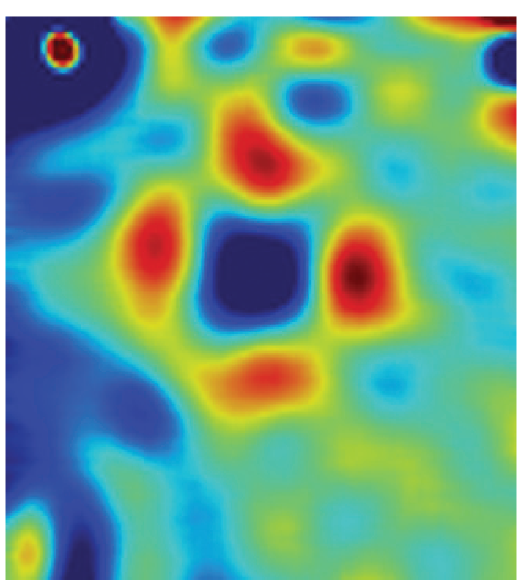

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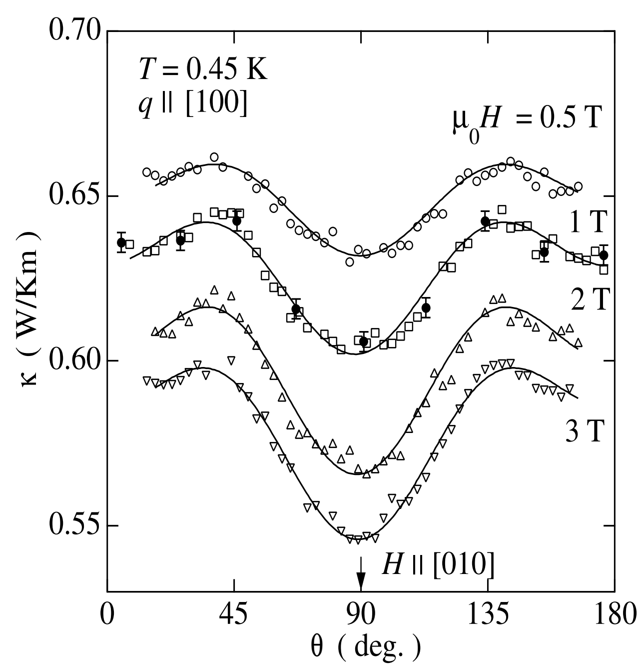
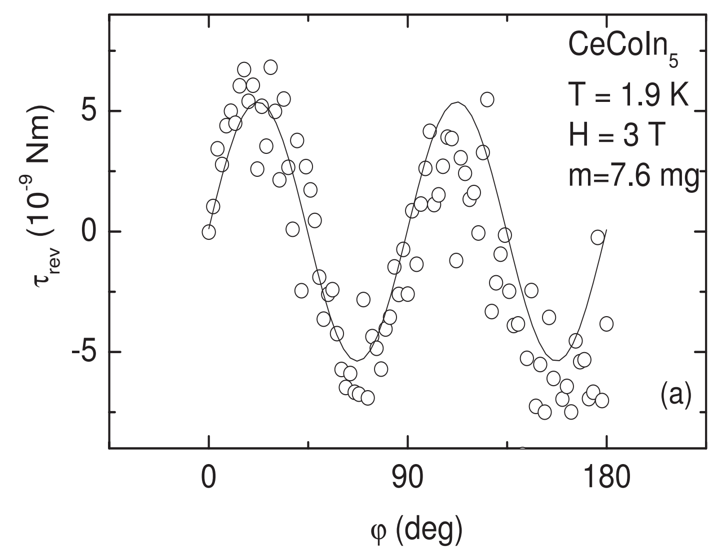
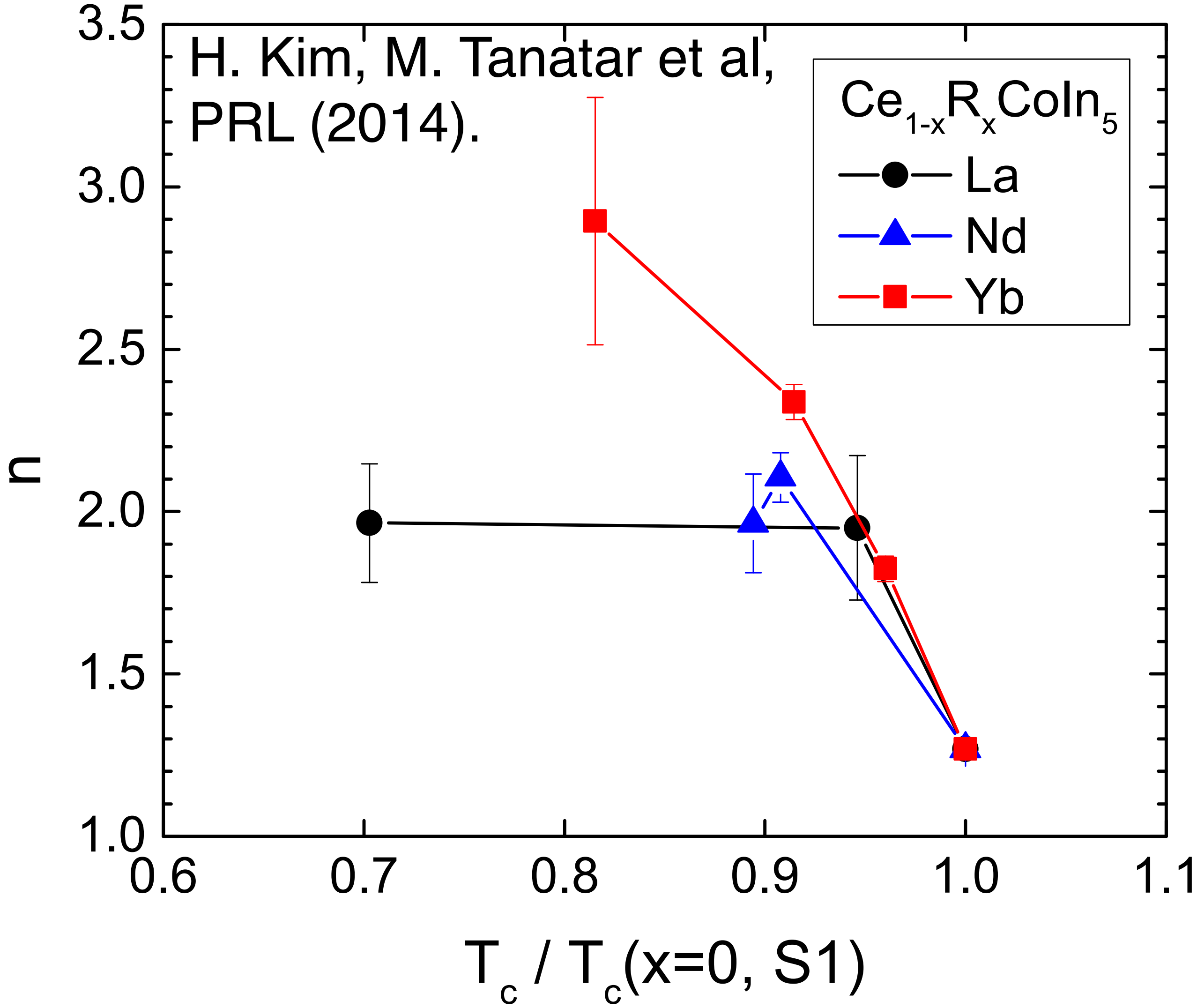


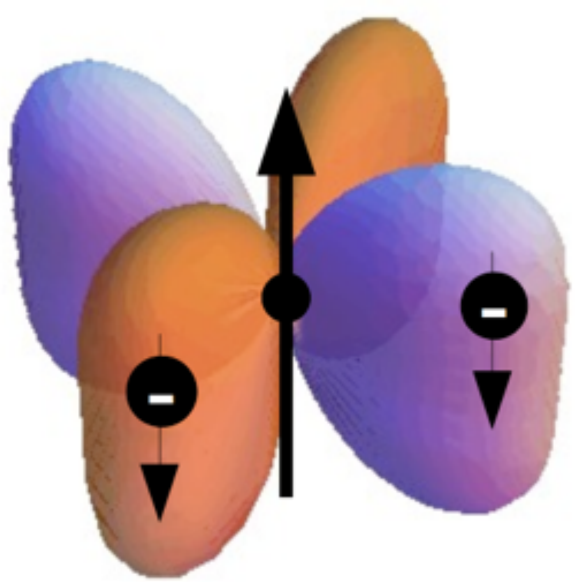
Thermal cond:
K. Izawa *et al.* PRL 87,
057002 (2001)



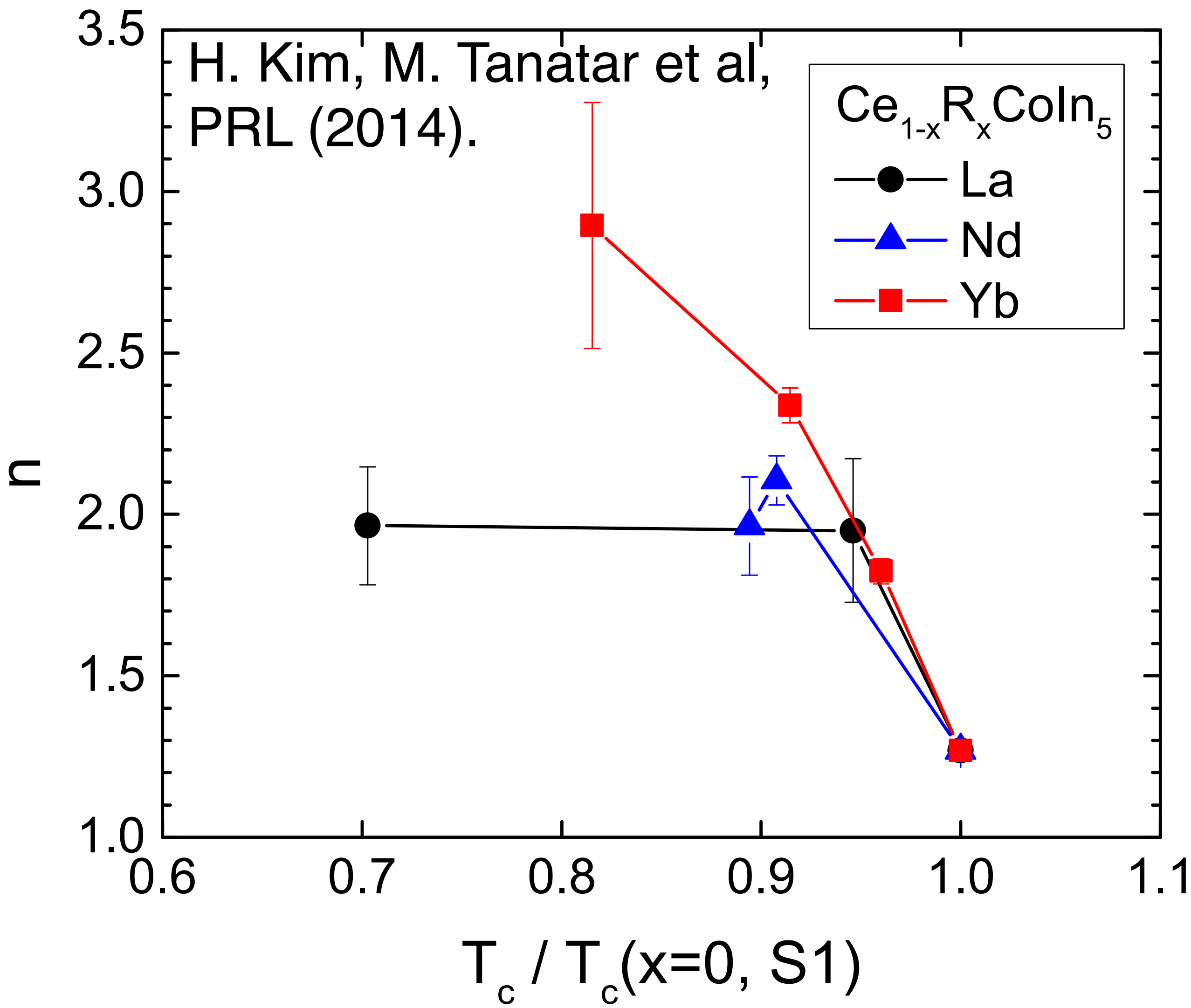
Torque magnetometry:
H. Xiao *et al.* PRB 78,
014510 (2008)



$$\lambda_L(T) = \lambda_L(0) + aT^n$$



Erten, Flint, PC, 2014



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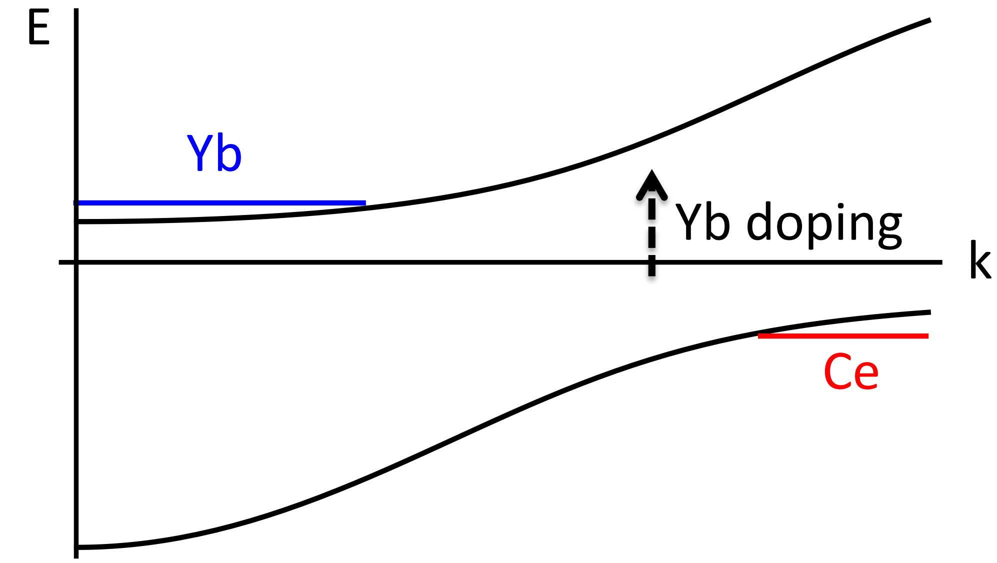
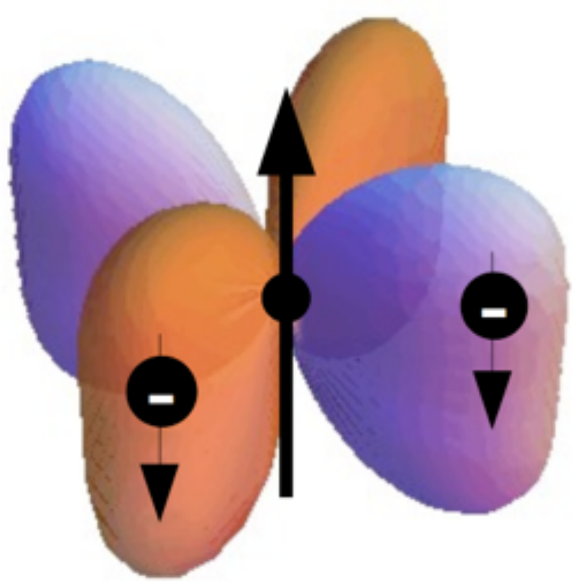
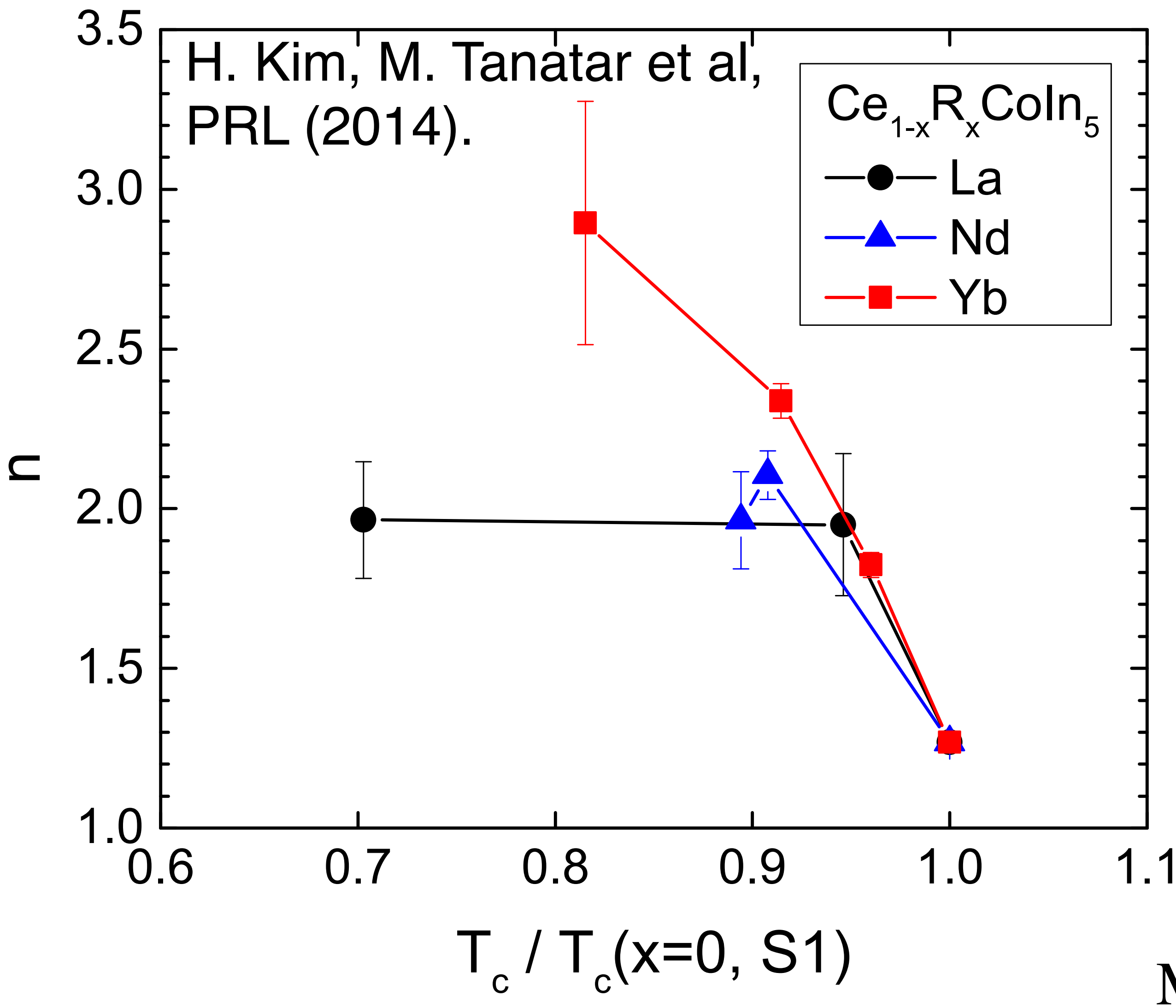




Erten, Flint, PC, 2014



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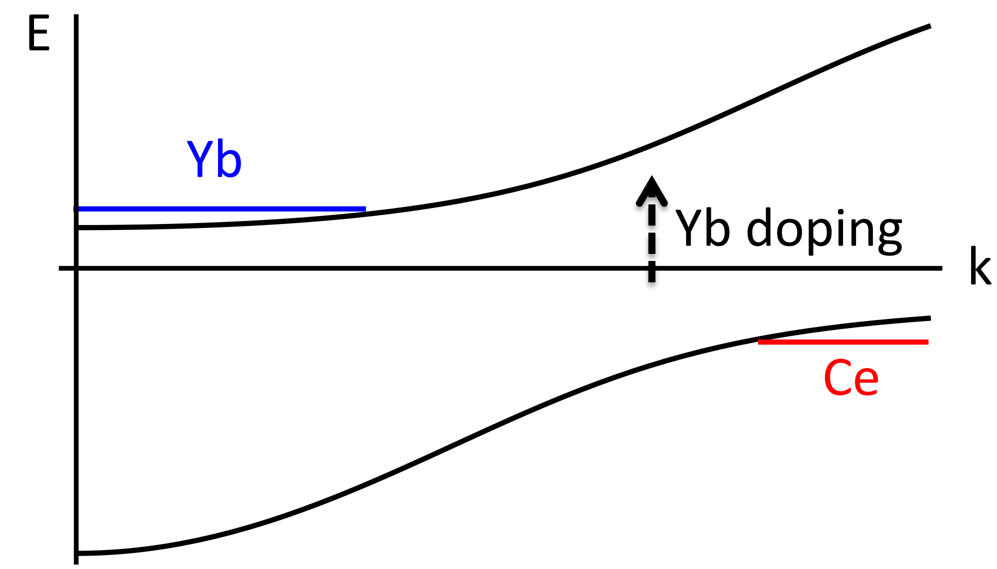

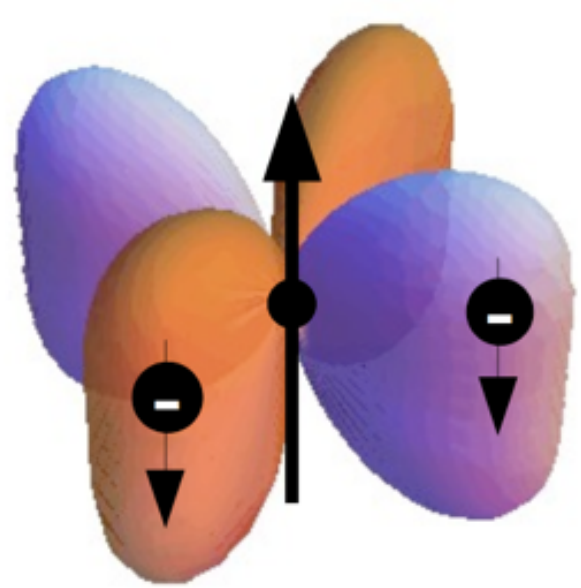

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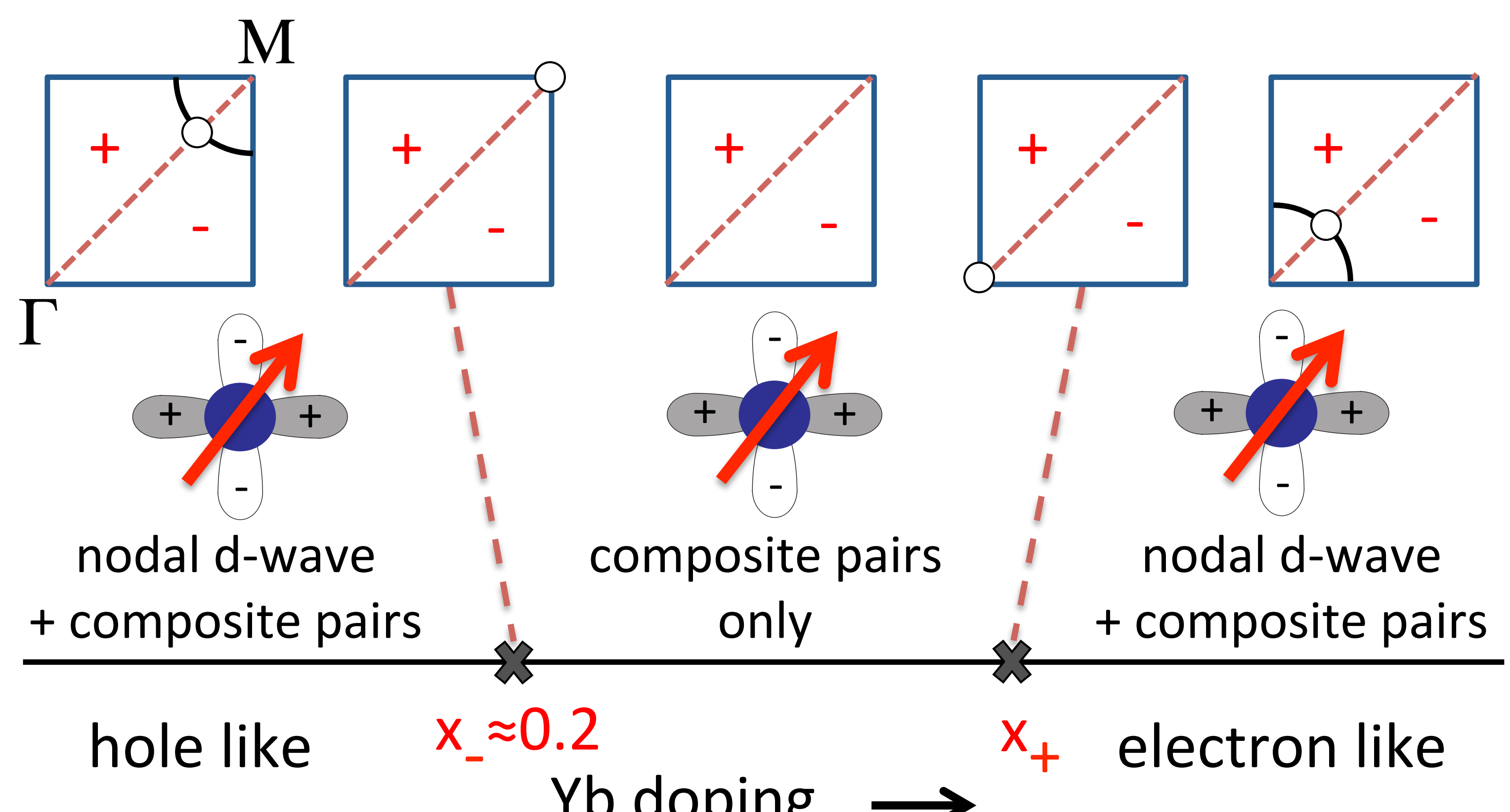

$\rho_s = \rho_0 - \alpha T^{(1-2)}$ $\rho_s = \rho_0 - \beta T^{(3-4)}$ $\rho_s = \rho_0 - \alpha T^{(1-2)}$

Conclusions.

- 115 Materials, with direct Curie to superconductor transition may involve composite pairing.

- Composite pairing may be regarded as a kind of resonant pairing.

- Composite pairing leads to a charge distribution. Observed in NQR measurements.

- Appearance of fully gapped region in Yb doped $CeCoIn_5$ consistent with condensate of pure composite bosons.

- Could this kind of order occur at higher temperatures, in d-electron systems?

Thank you!