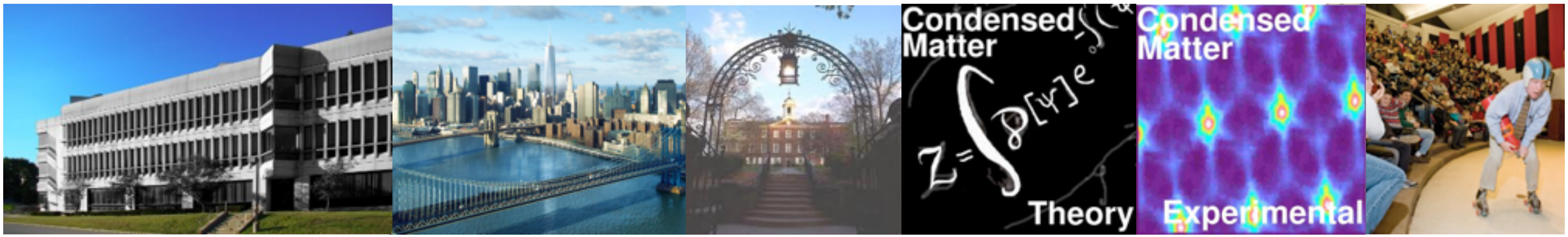
Some Topics of Great Current Interest In Heavy Fermion Physics

Zhejiang U, Hangzhou 13 April, 2015

Piers Coleman: Rutgers Center for Materials Theory, USA



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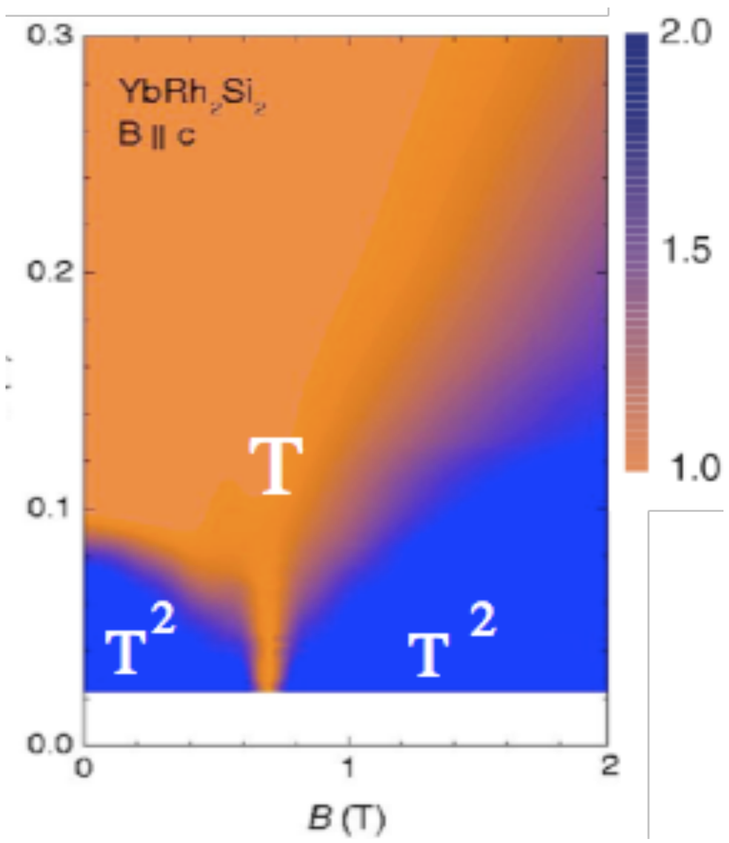
Quantum Criticality & Strange Metals



Royal Holloway University of London

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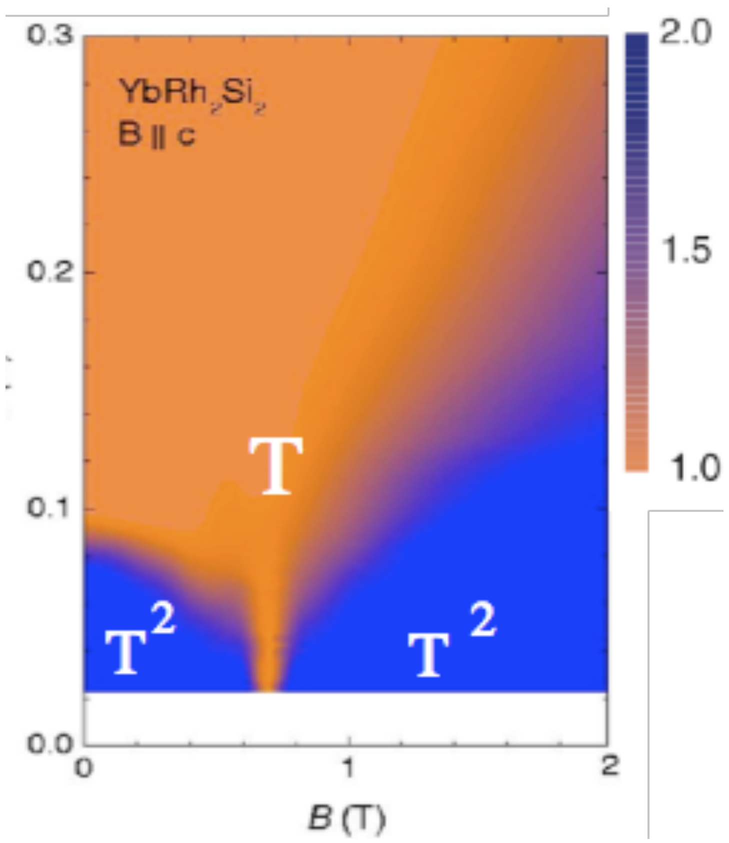

Heavy Fermion Superconductivity

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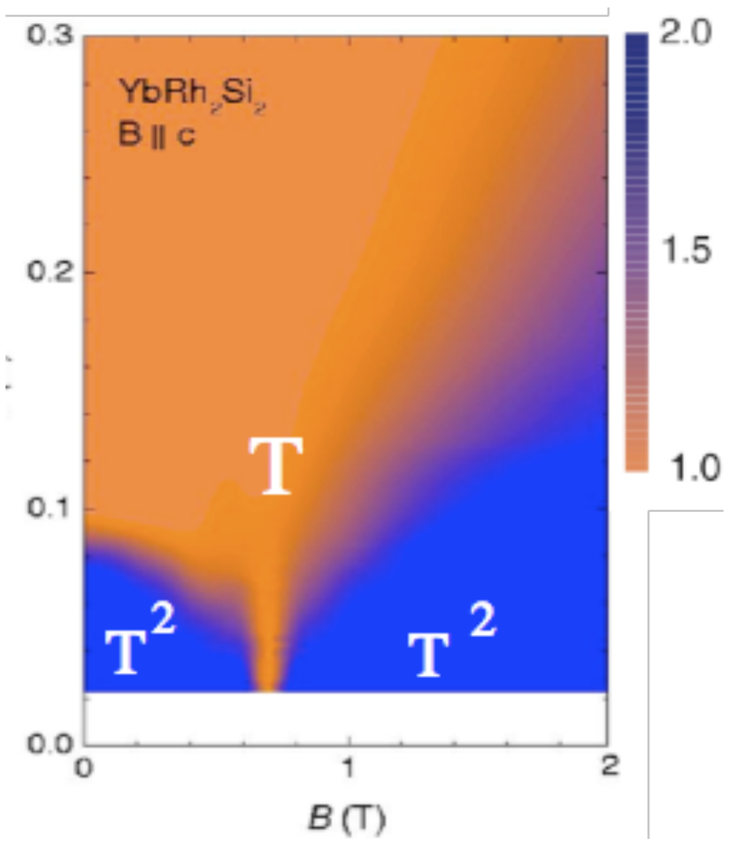
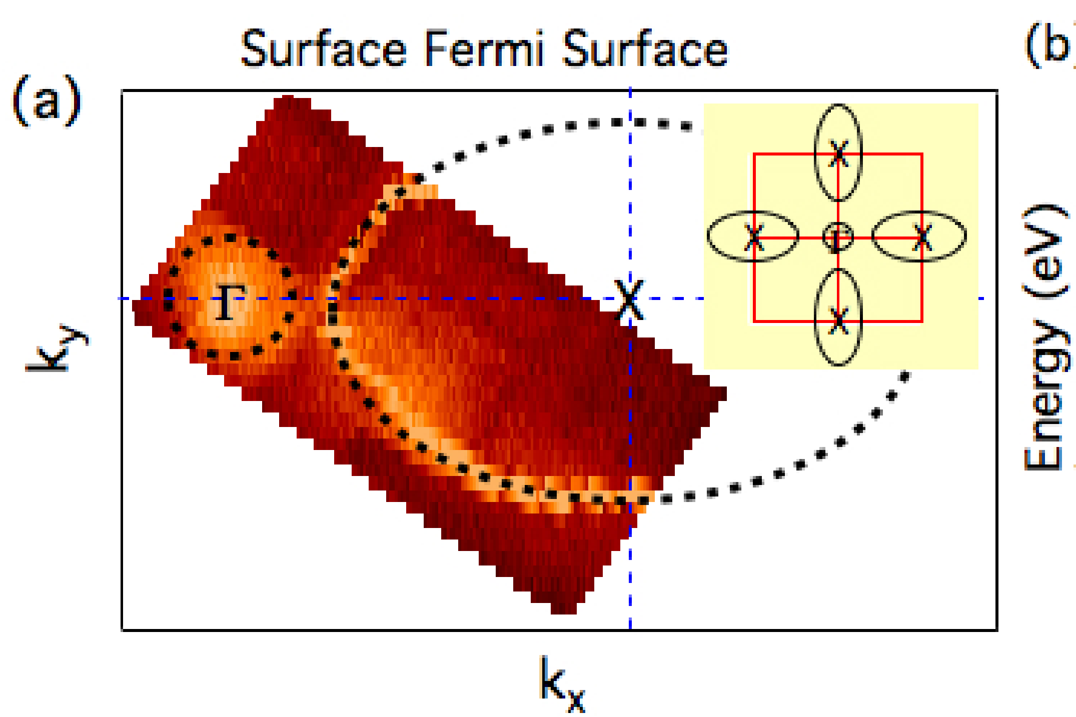


Heavy Fermion Superconductivity

Topological Kondo Insulators



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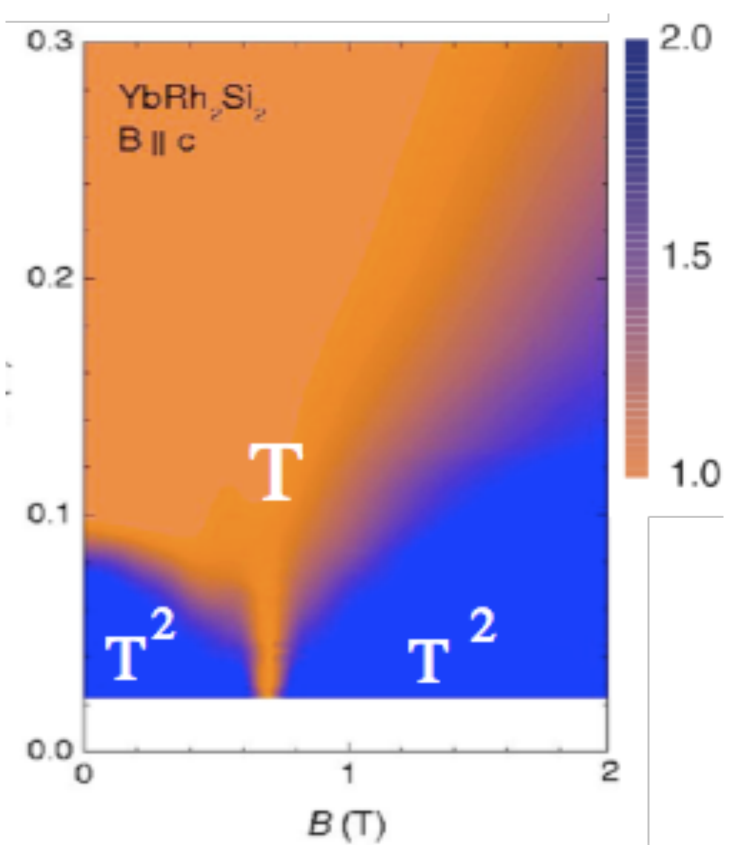

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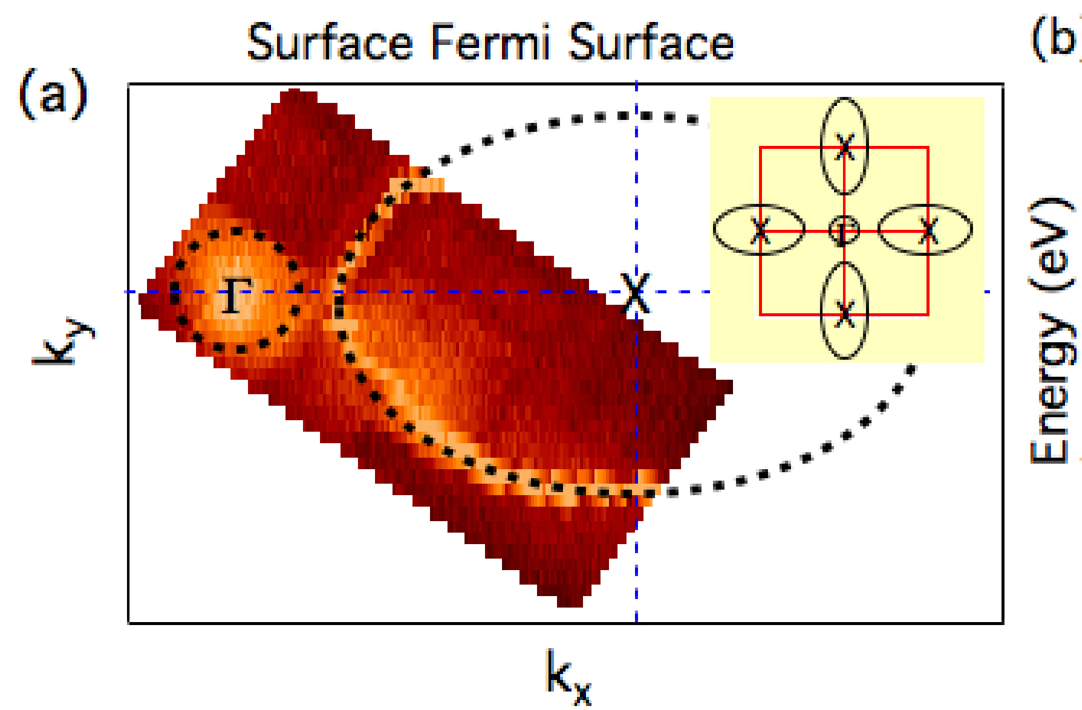
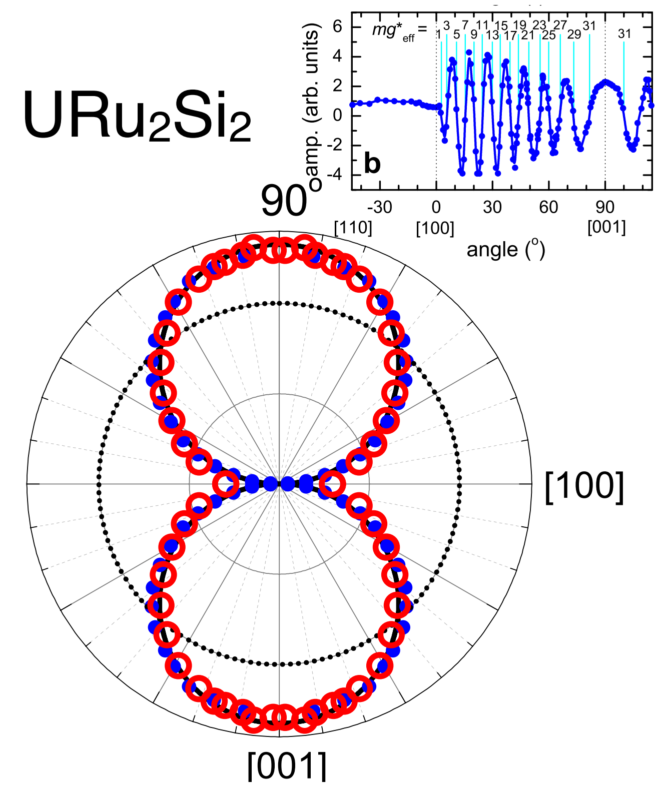


Hidden Order

URu2Si2



Royal Holloway University of London

Outline of the Topics

1. Introduction: Heavy Fermions and the Kondo Lattice.
2. Quantum Criticality and Strange Metals.
3. Heavy Fermion Superconductivity
4. Topological Kondo Insulators
5. Hidden Electron Order

Rutgers
Center for Materials Theory

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Please ask questions!

Collaborators.

Q. Si	Rice
R. Ramazashvili	Toulouse
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Aline Ramires	Rutgers
Rebecca Flint	Iowa State
Premi Chandra	Rutgers
Andriy Nevidomskyy	Rice
Alexei Tsvelik	Brookhaven NL
Hai Young Kee	U. Toronto
Natan Andrei	Rutgers
Onur Erten	Rutgers
Maxim Dzero	Kent State
Victor Galitski	U. Maryland
Kai Sun	U. Michigan

Experimentalists:

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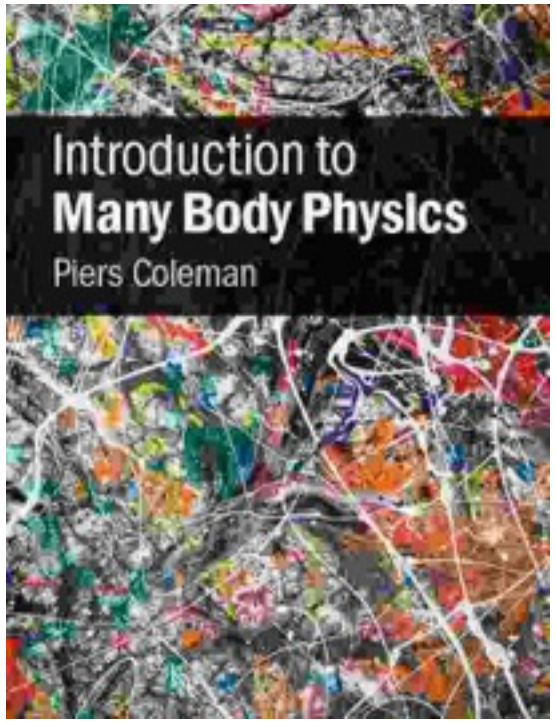
G. Aeppli	ETH, Zurich
A. Schröder	Kent State
S. Nakatsuji	ISSP
G. Lonzarich	Cambridge
S. Paschen	Vienna
J. Thompson	Los Alamos
J. Allen	U. Michigan
Z. Fisk	UC Irvine
F Steglich	Dresden/Zhejiang

Notes:

"Introduction to Many Body Physics", Ch 8,15-16", PC, CUP to be published (2015).



"Heavy Fermions: electrons at the edge of magnetism." Wiley encyclopedia of magnetism. PC. cond-mat/0612006.

"I2CAM-FAPERJ Lectures on Heavy Fermion Physics", (X=I, II, III)

http://physics.rutgers.edu/~coleman/talks/RIO13_X.pdf

General reading:

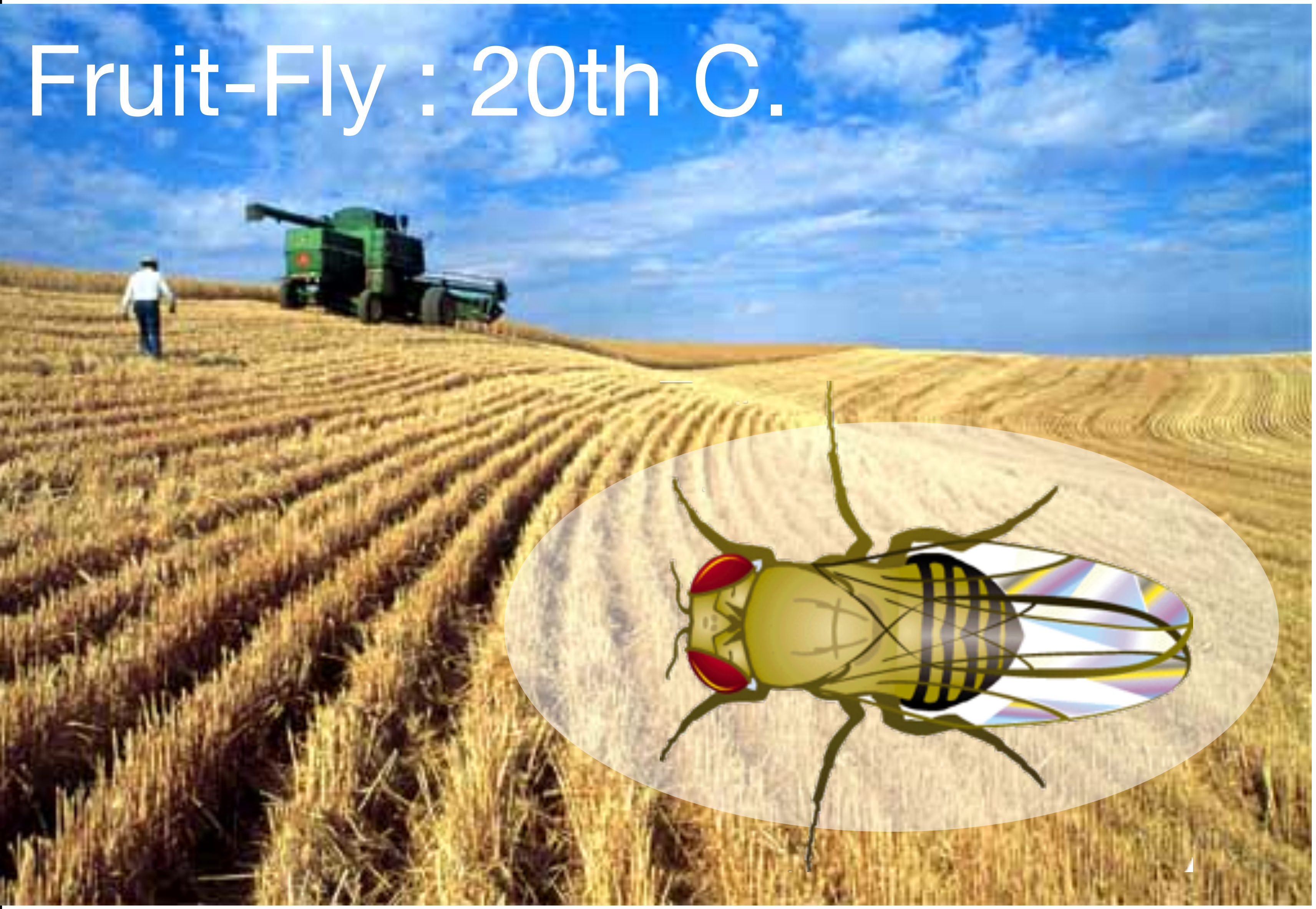
A. Hewson, "Kondo effect to heavy fermions", CUP, (1993).

"The Theory of Quantum Liquids", Nozieres and Pines (Perseus 1999).

Lecture 1 Introduction to Heavy Fermions and the Kondo Lattice.

1. Fruit Fly of the 21st Century.
2. Electrons on the Brink of Localization.
3. Cartoon introduction to Heavy Fermions.
4. Anderson & Kondo models
5. Doniach Hypothesis.

Fruit-Fly : 20th C.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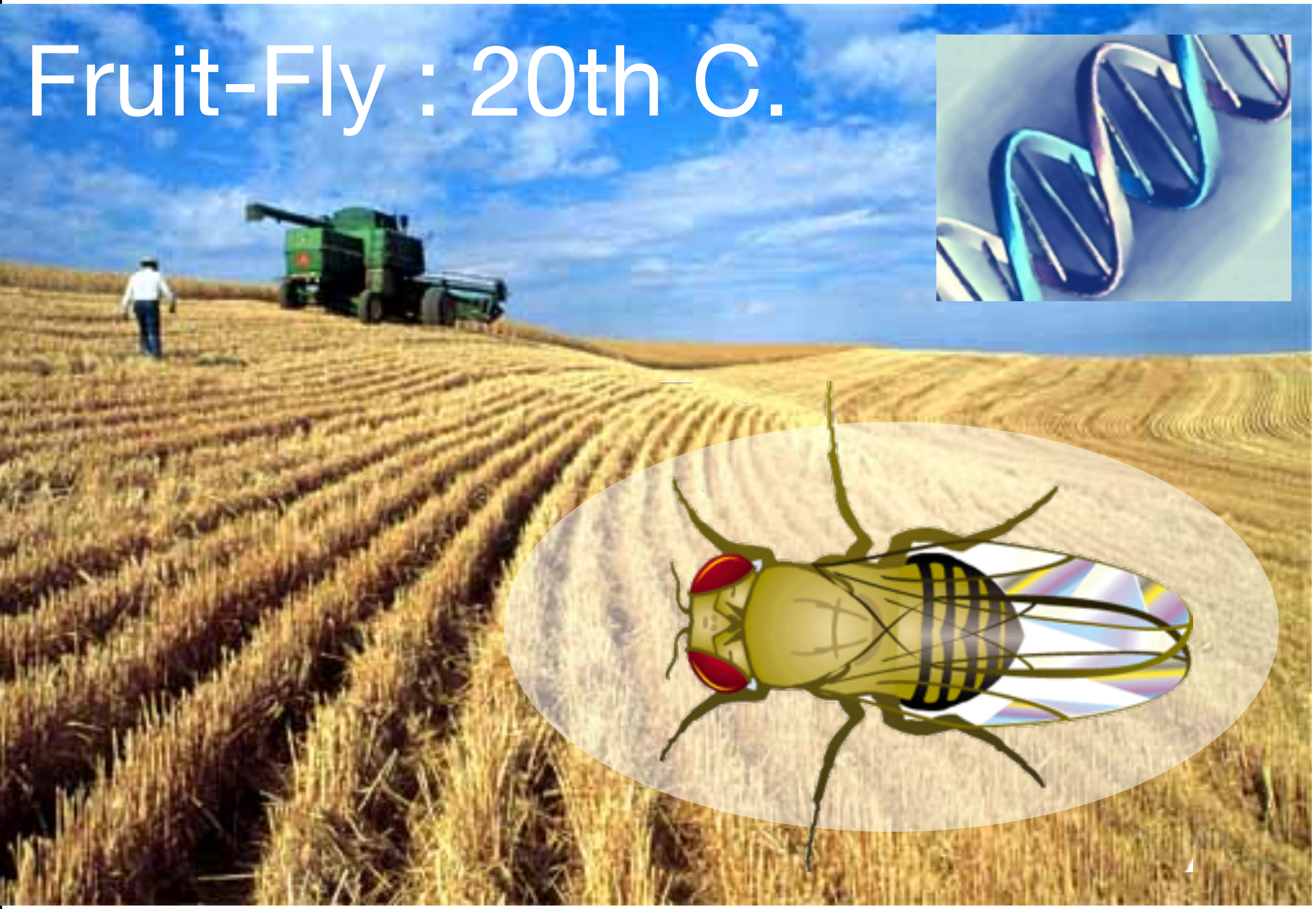
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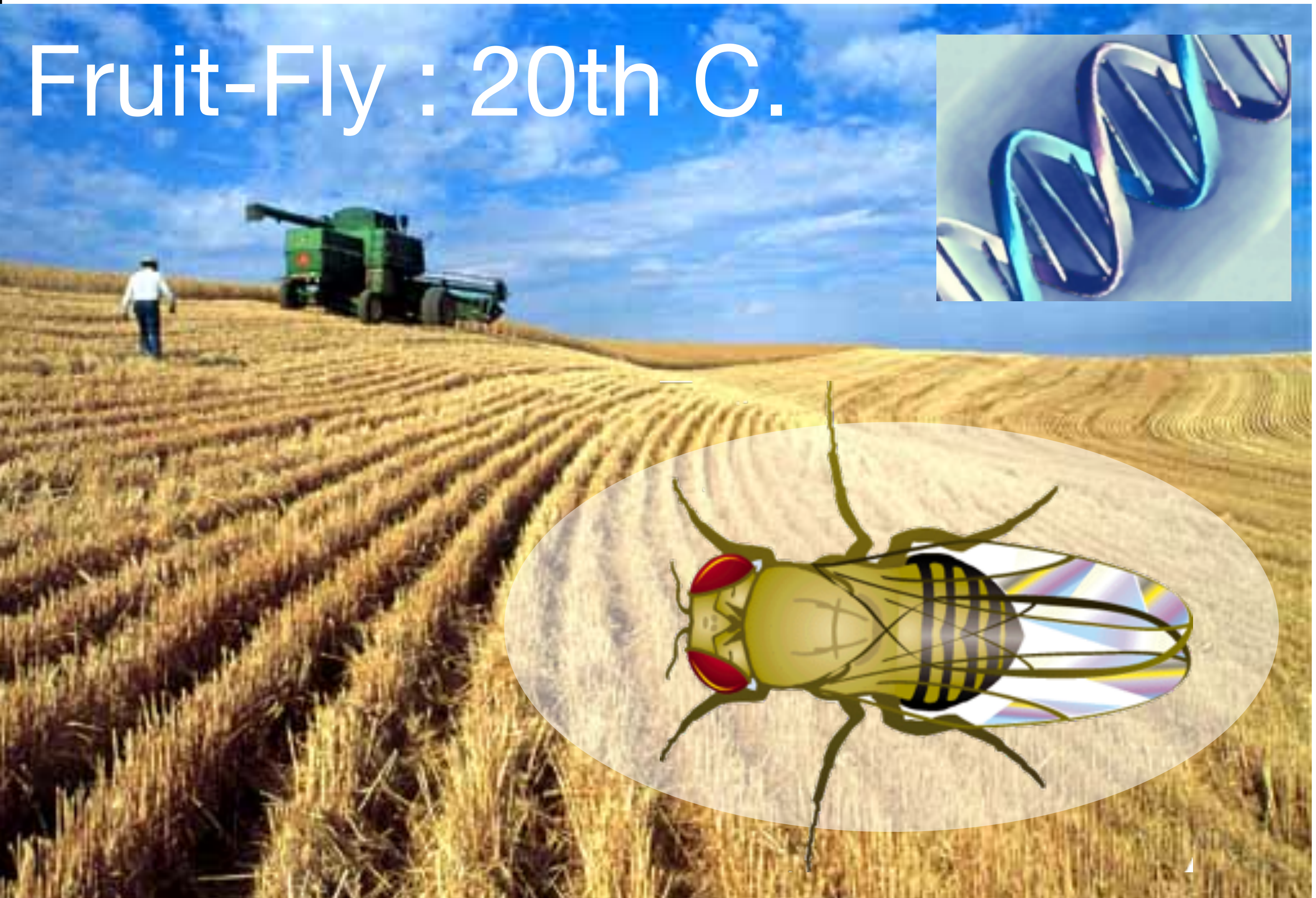
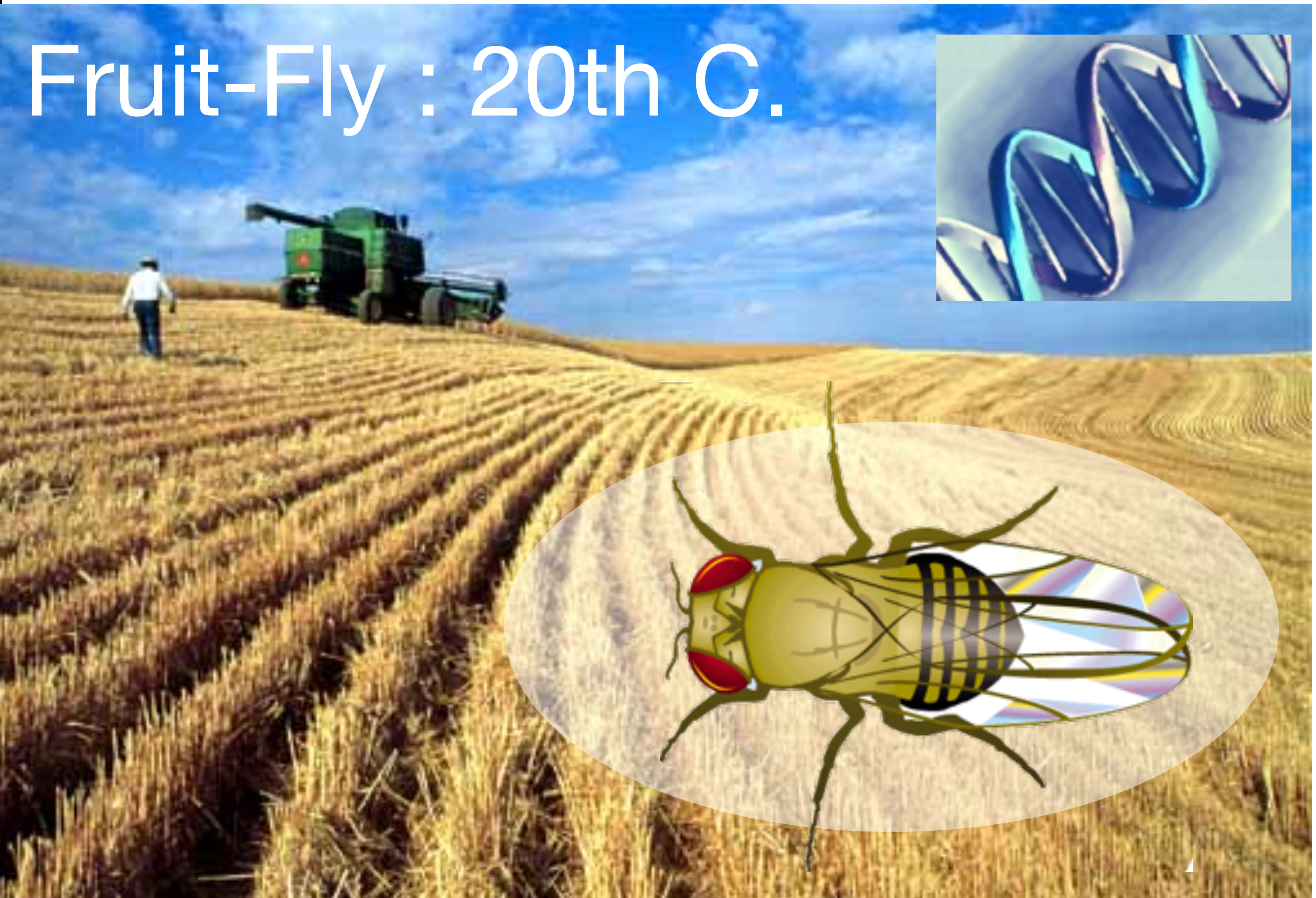
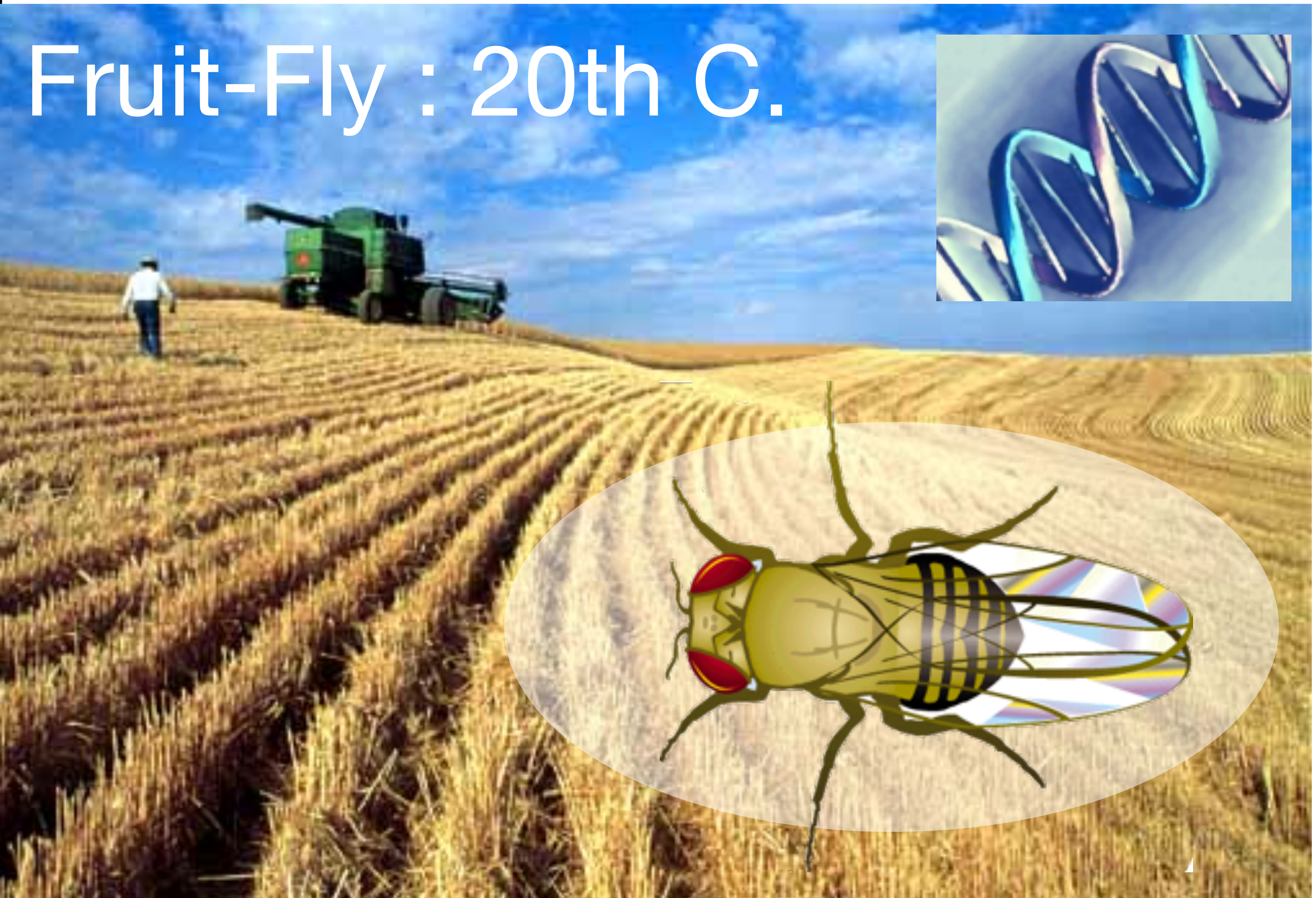

Fruit-Fly : 20th C.

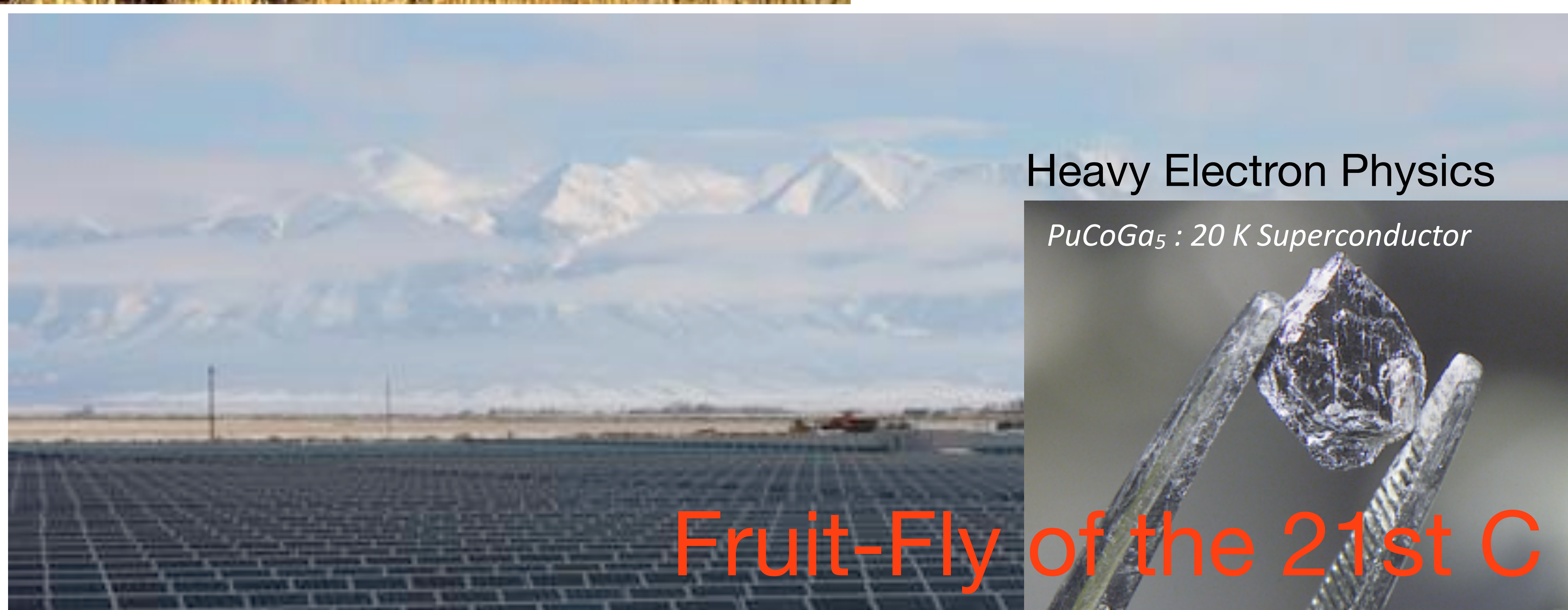

Fruit-Fly of the 21st C

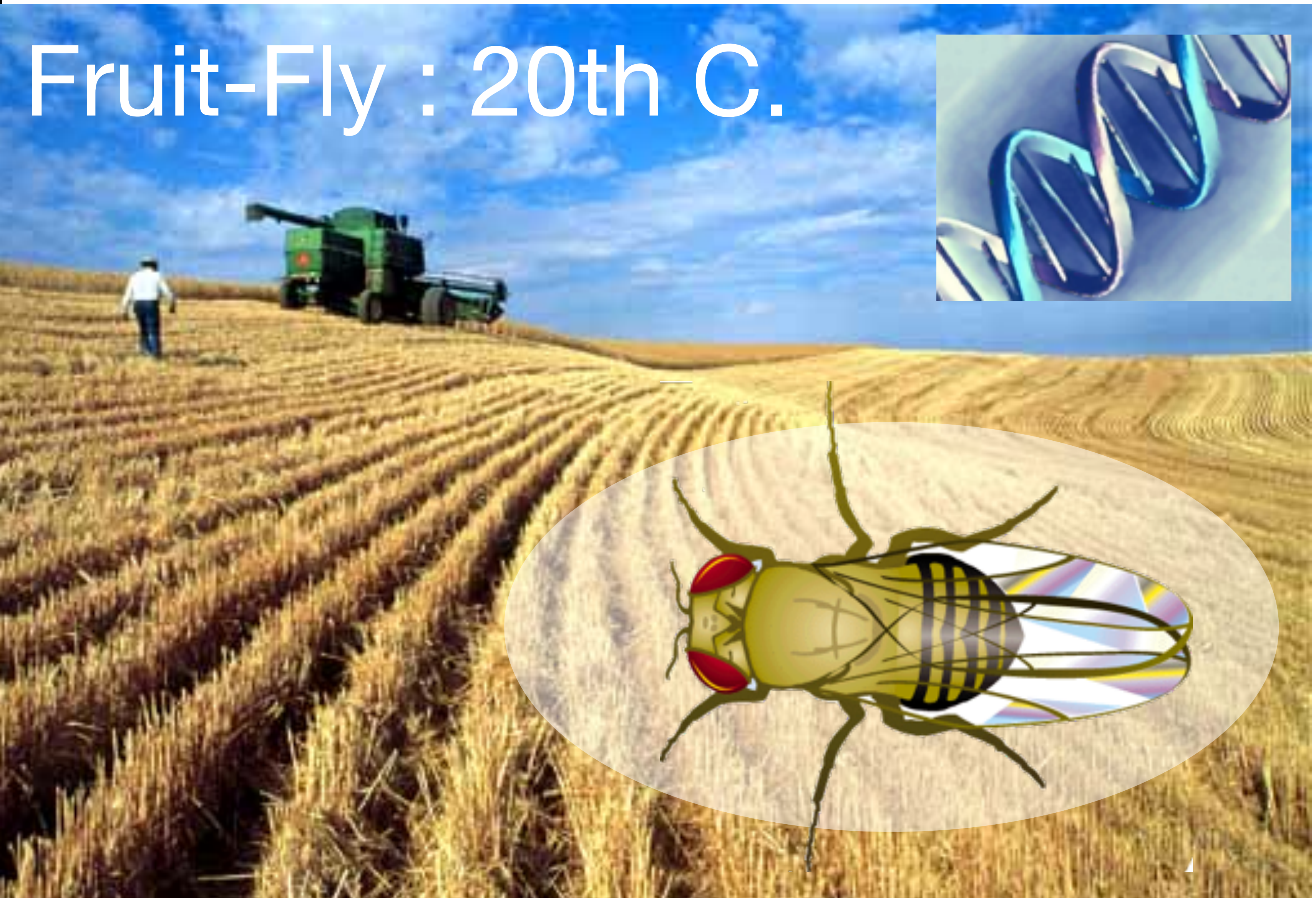

Fruit-Fly : 20th C.


Heavy Electron Physics
PuCoGa5 : 20 K Superconductor
Fruit-Fly of the 21st C


Fruit-Fly : 20th C.

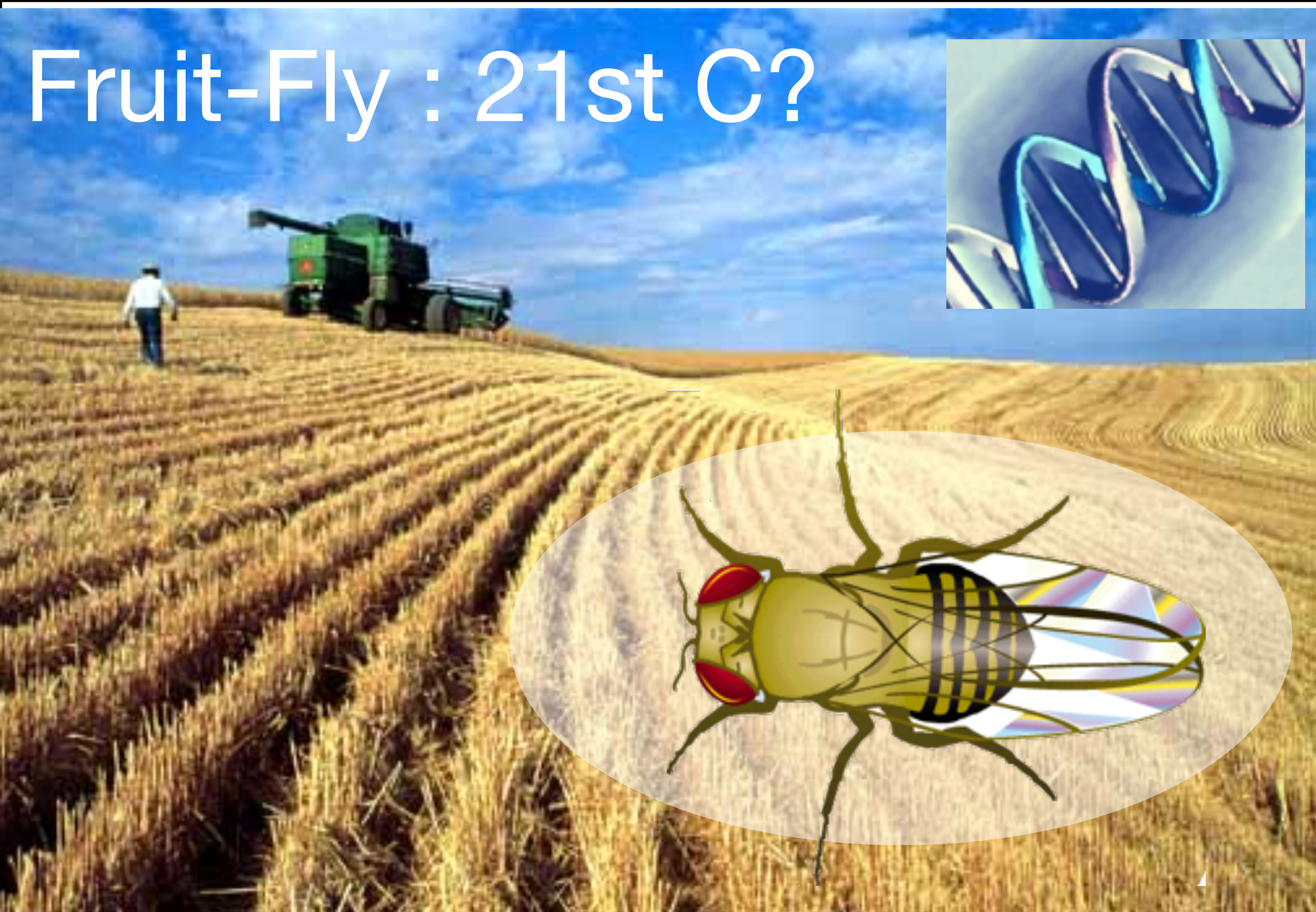
nm μm


Heavy Electron Physics
$PuCoGa_5$: 20 K Superconductor
Fruit-Fly of the 21st C



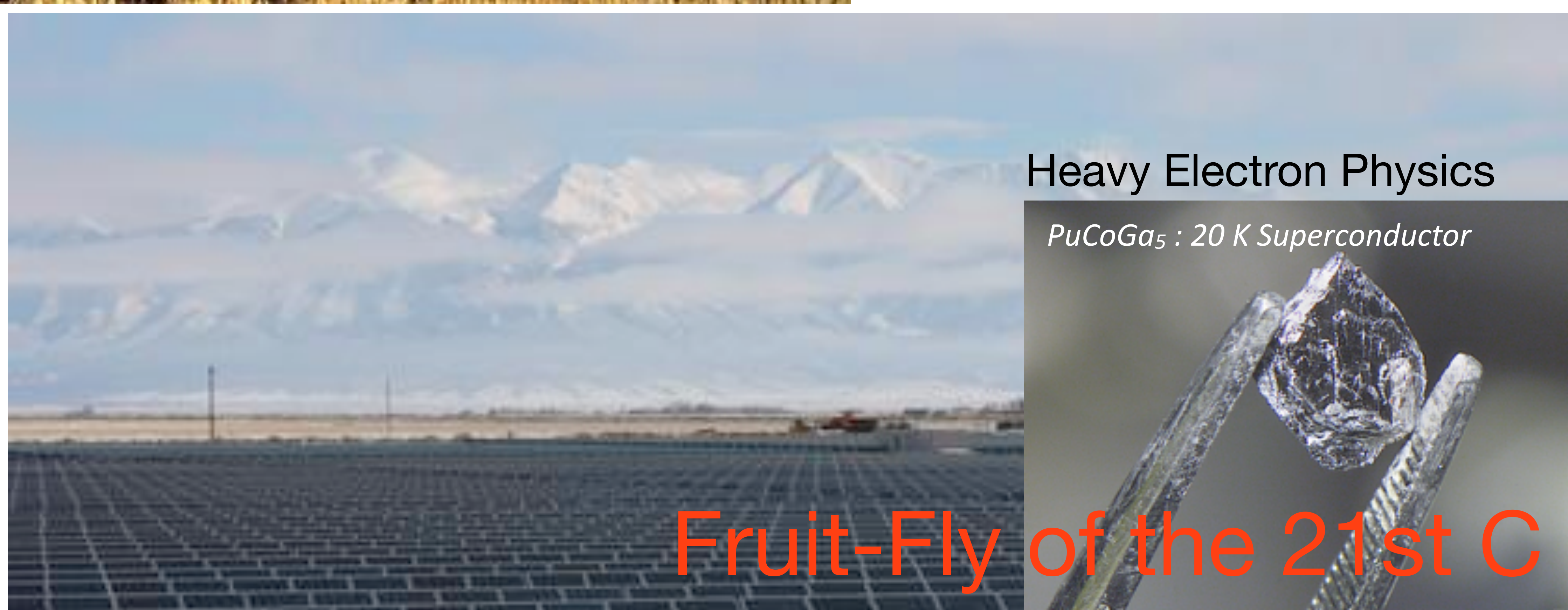
nm QUANTUM EMERGENCE μm

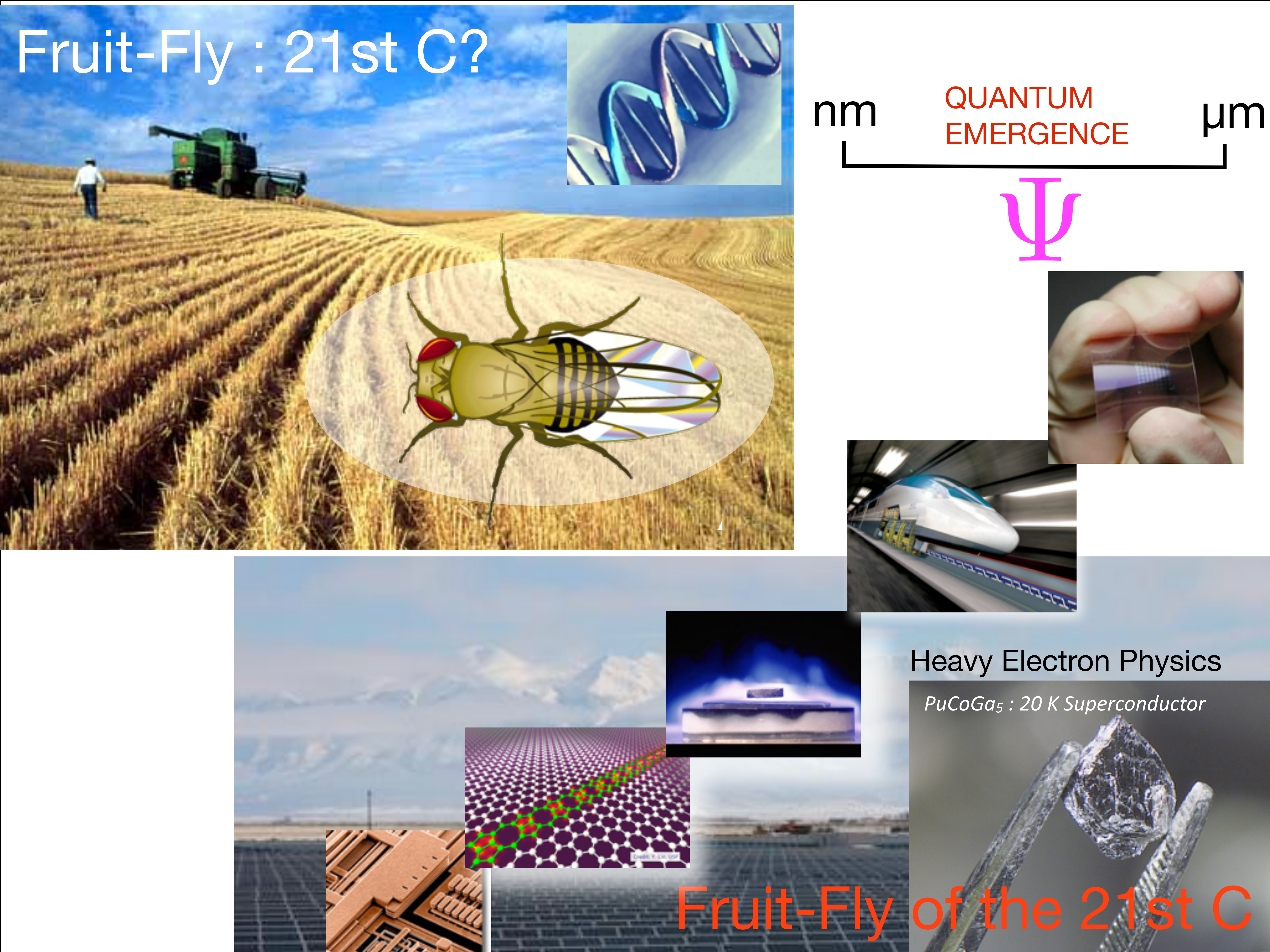
Ψ



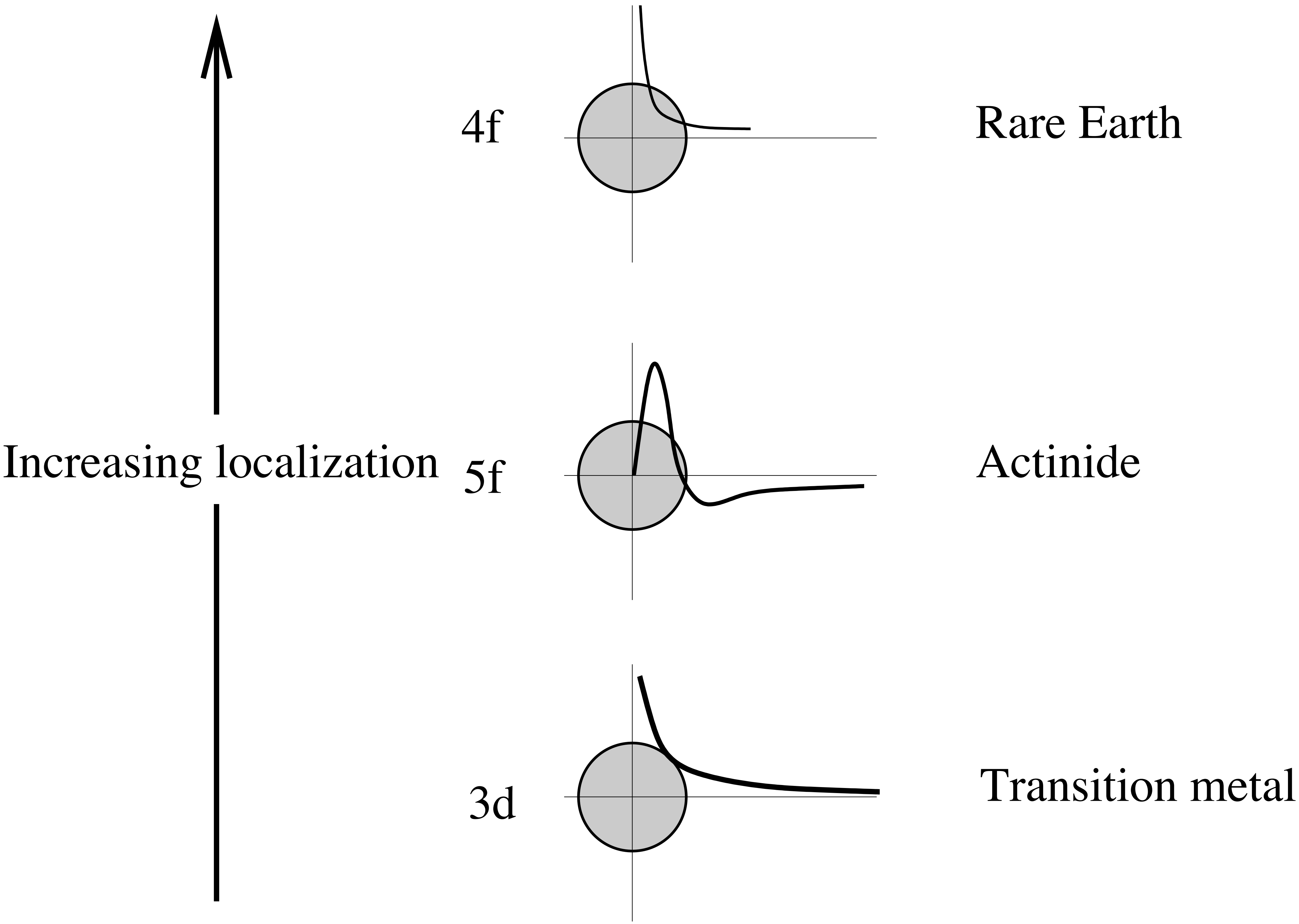
nm QUANTUM EMERGENCE μm

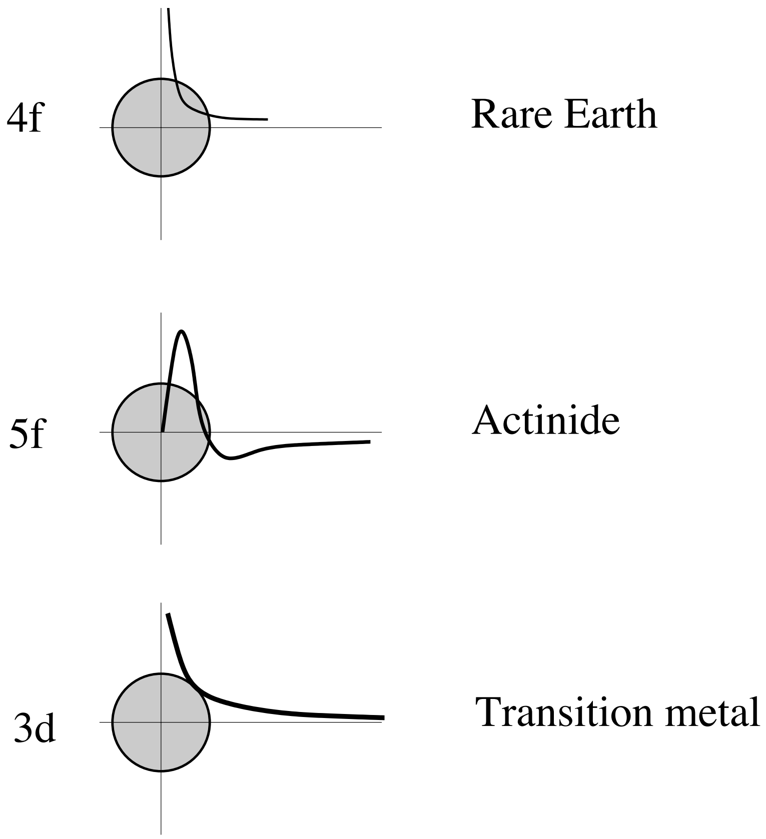
Ψ

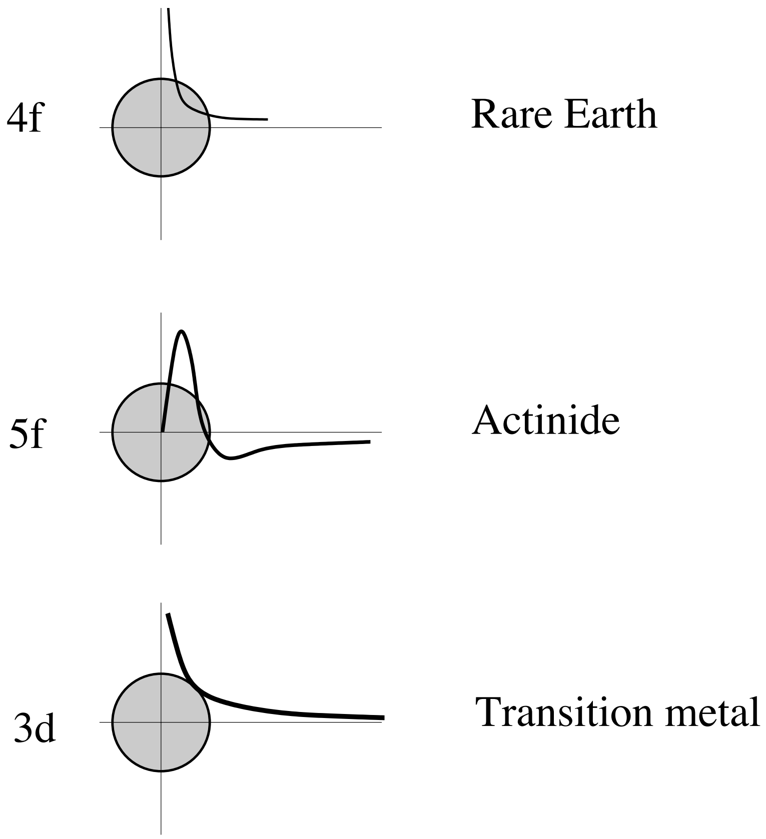


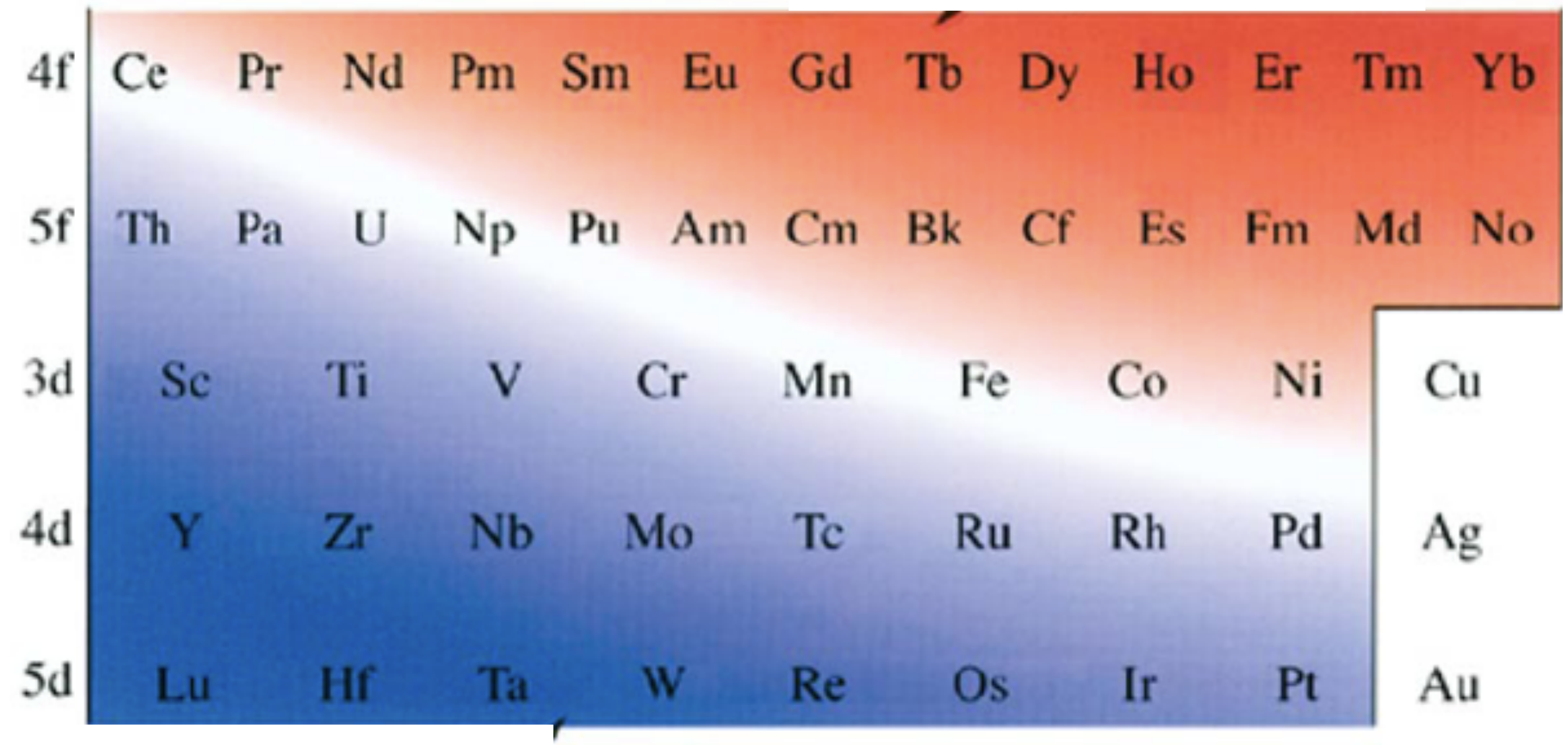

Fruit-Fly : 21st C?
nm
QUANTUM
EMERGENCE
μm
Ψ
Heavy Electron Physics
PuCoGa5 : 20 K Superconductor
Fruit-Fly of the 21st C

Electrons on the brink of localization

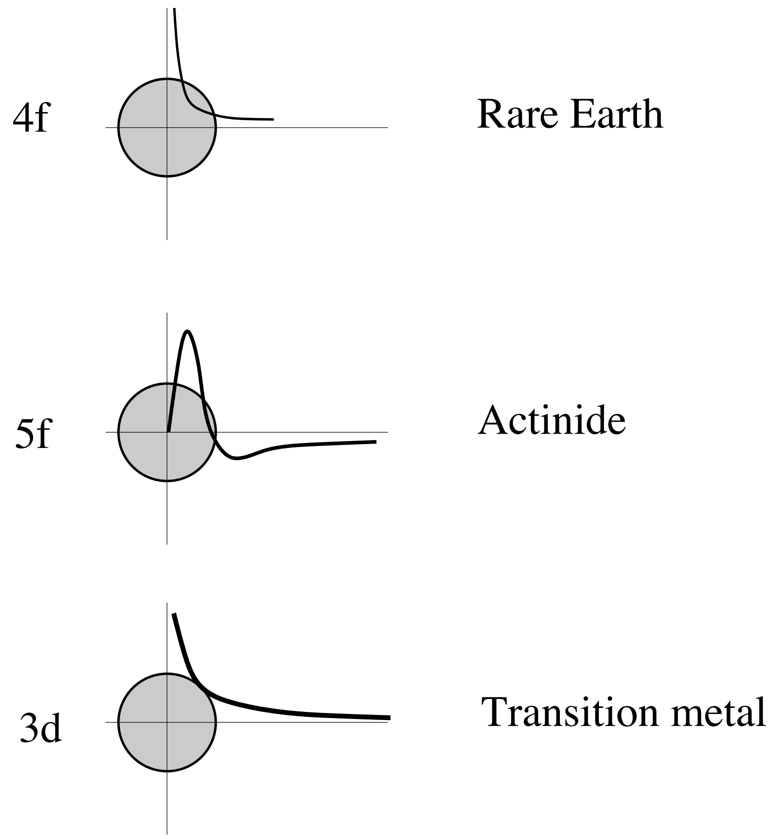

Increasing localization
4f
Rare Earth
5f
Actinide
3d
Transition metal

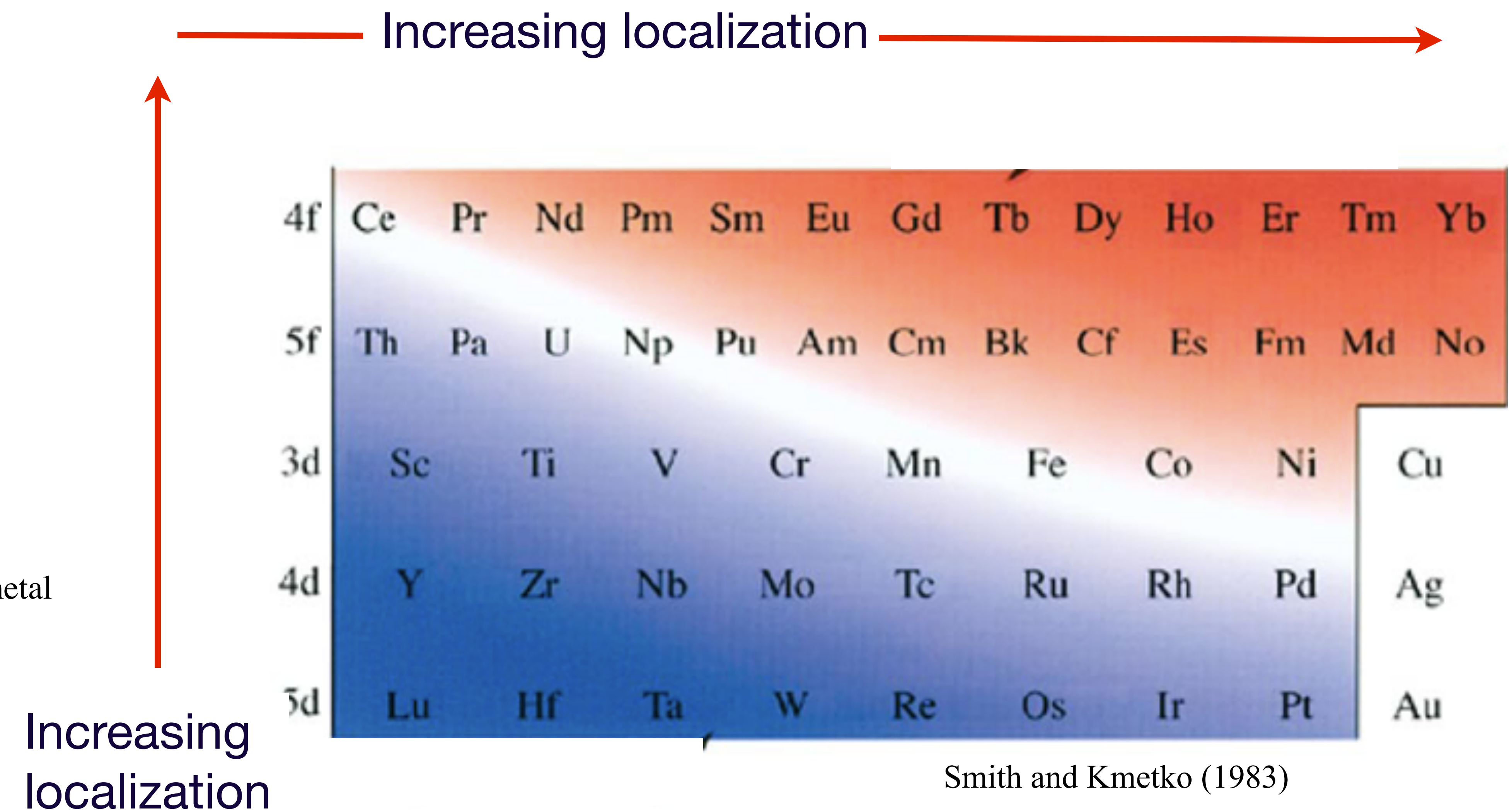

4f
Rare Earth
5f
Actinide
3d
Transition metal



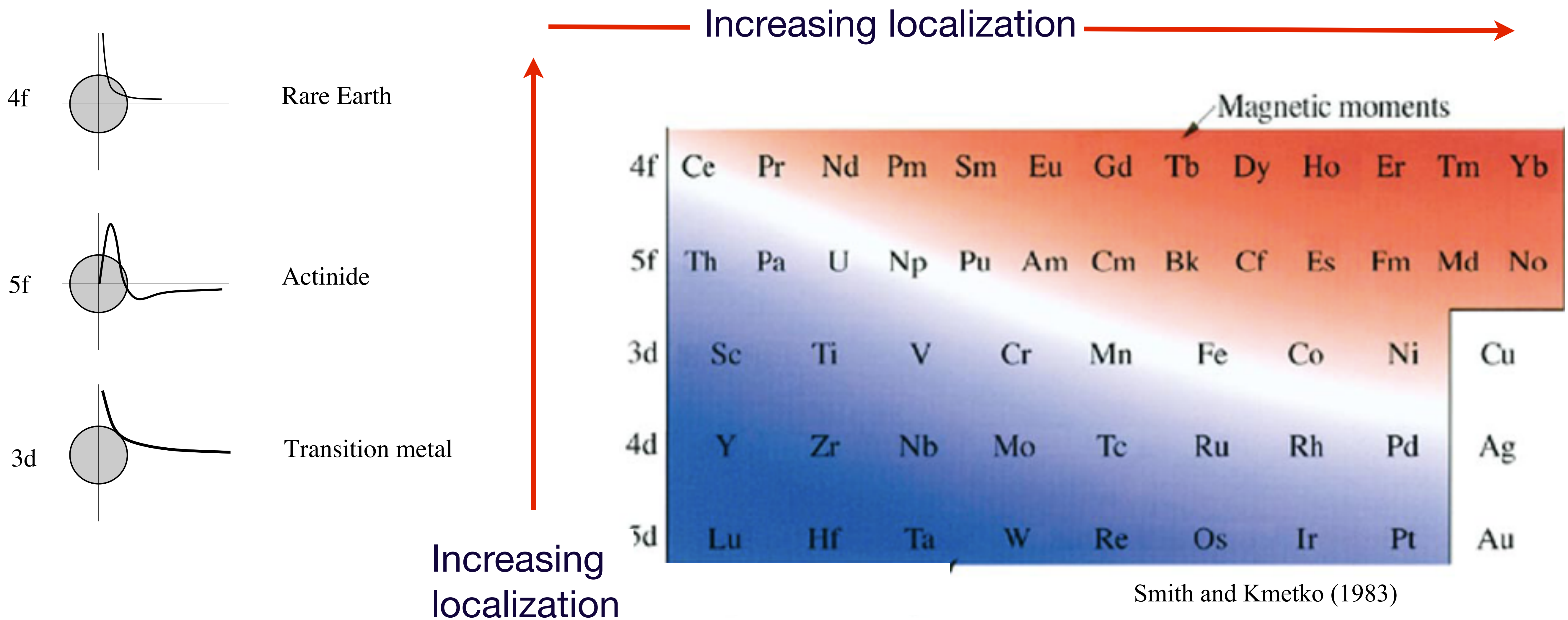


Smith and Kmetko (1983)





Smith and Kmetko (1983)



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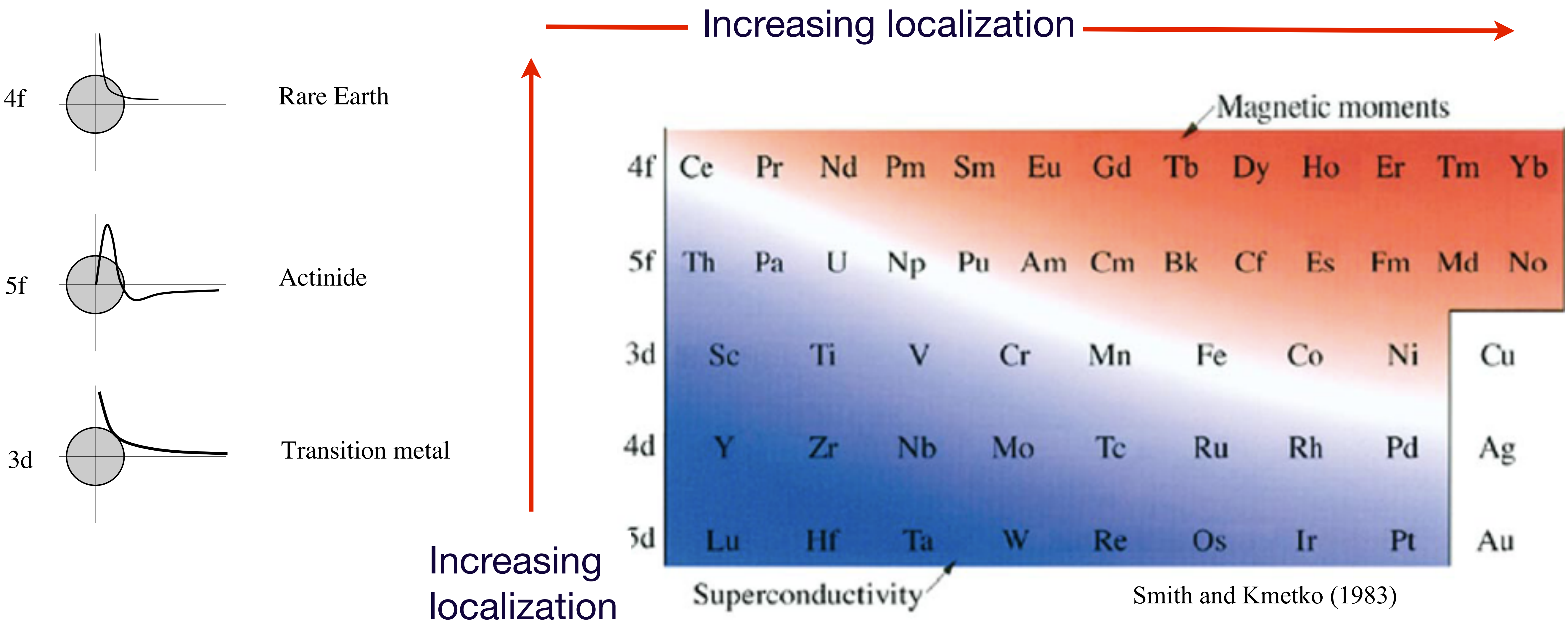
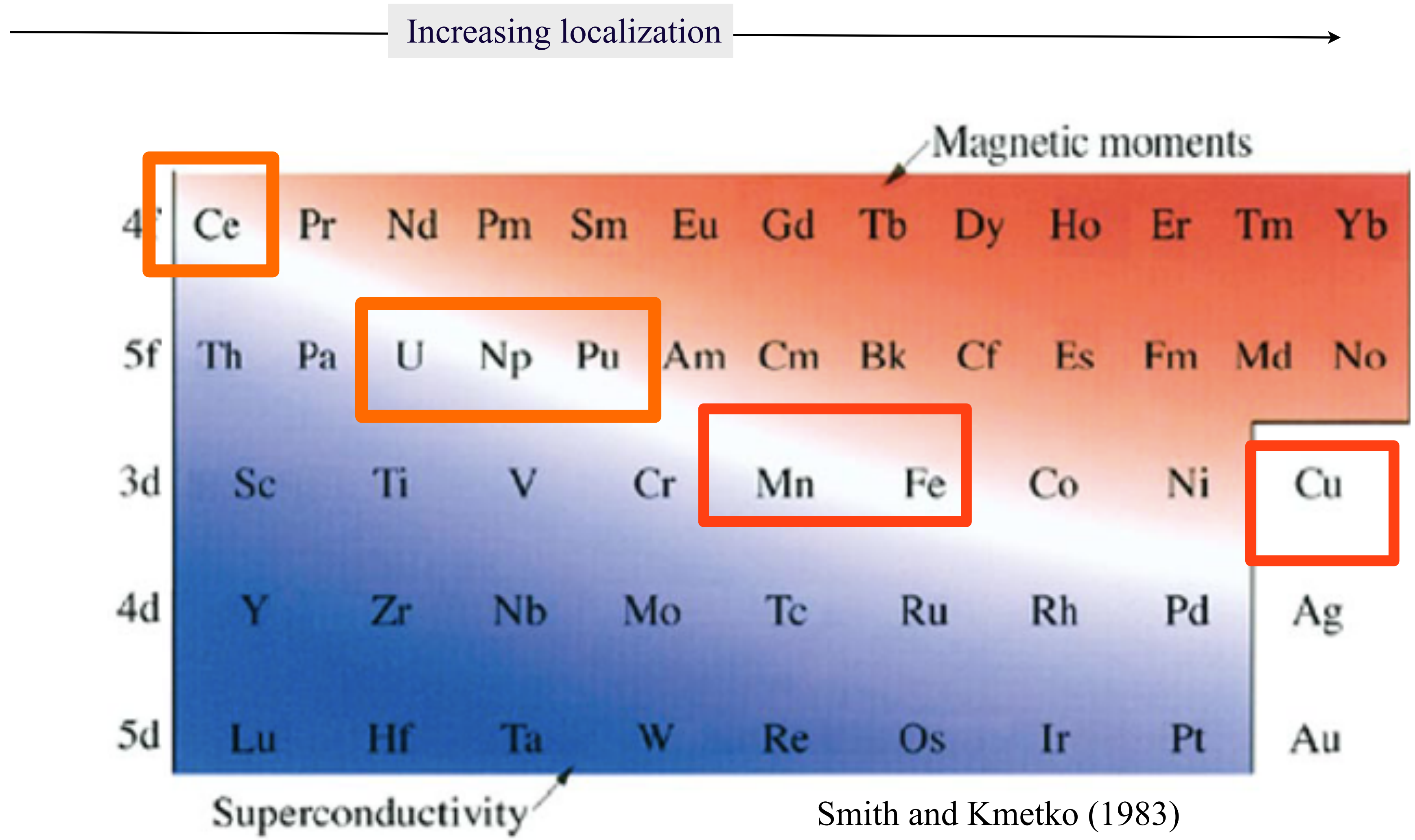
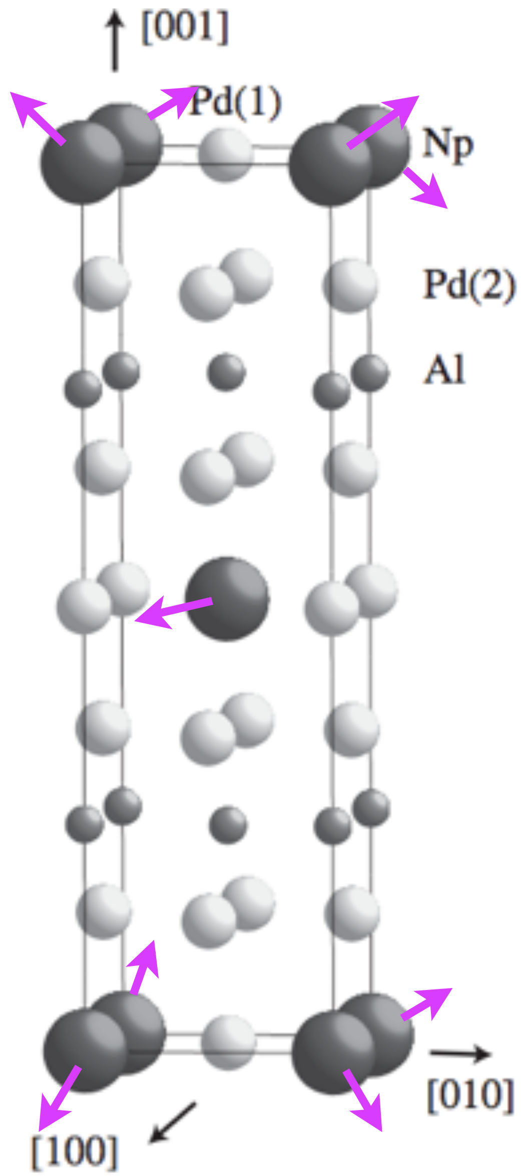


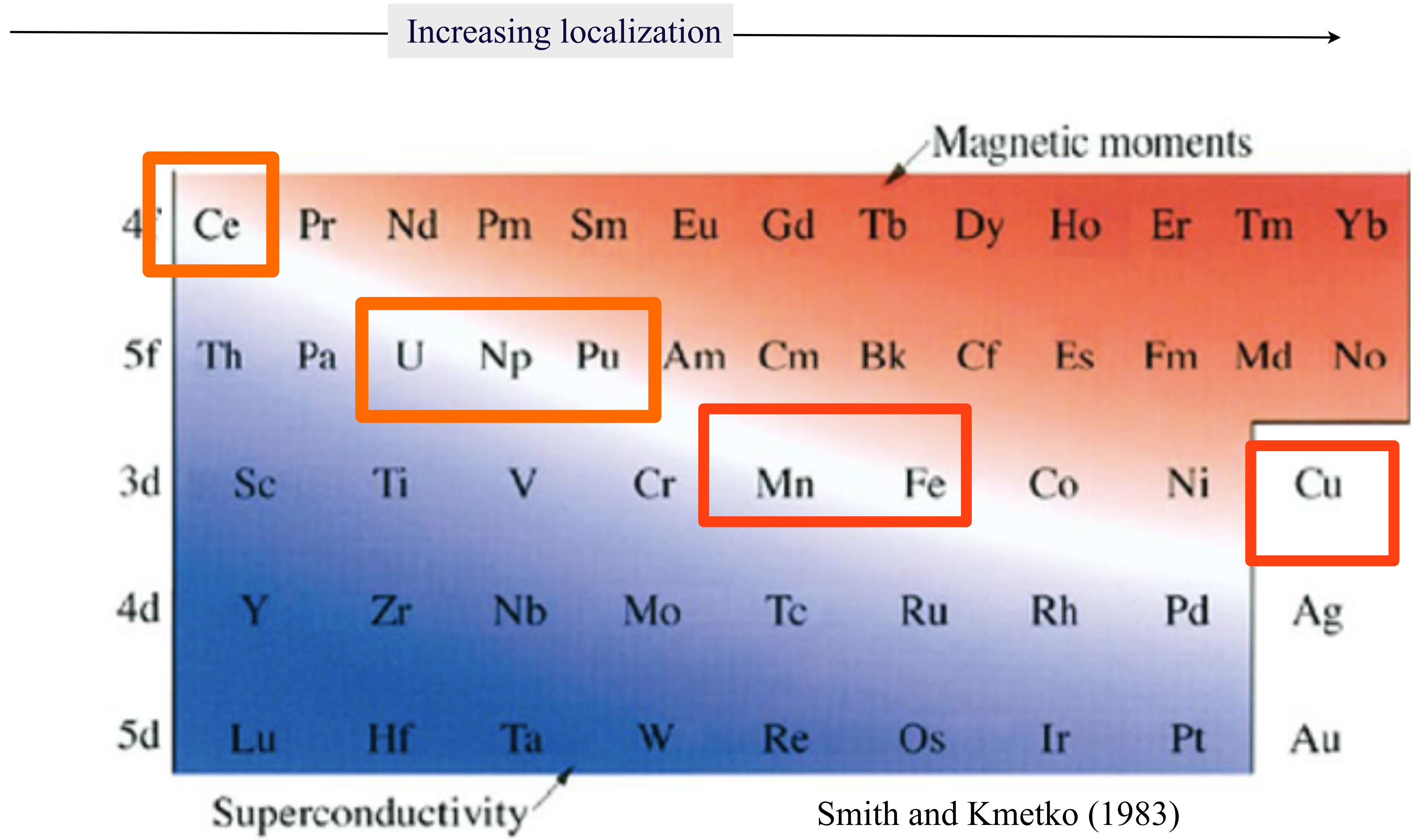
Increasing localization
4f
Rare Earth
5f
Actinide
3d
Transition metal
Increasing localization
Magnetic moments
4f Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb
5f Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No
3d Sc Ti V Cr Mn Fe Co Ni Cu
4d Y Zr Nb Mo Tc Ru Rh Pd Ag
5d Lu Hf Ta W Re Os Ir Pt Au
Superconductivity
Smith and Kmetko (1983)



Diversity of new ground-states on the brink of localization.



$NpAl_2Pd_5$

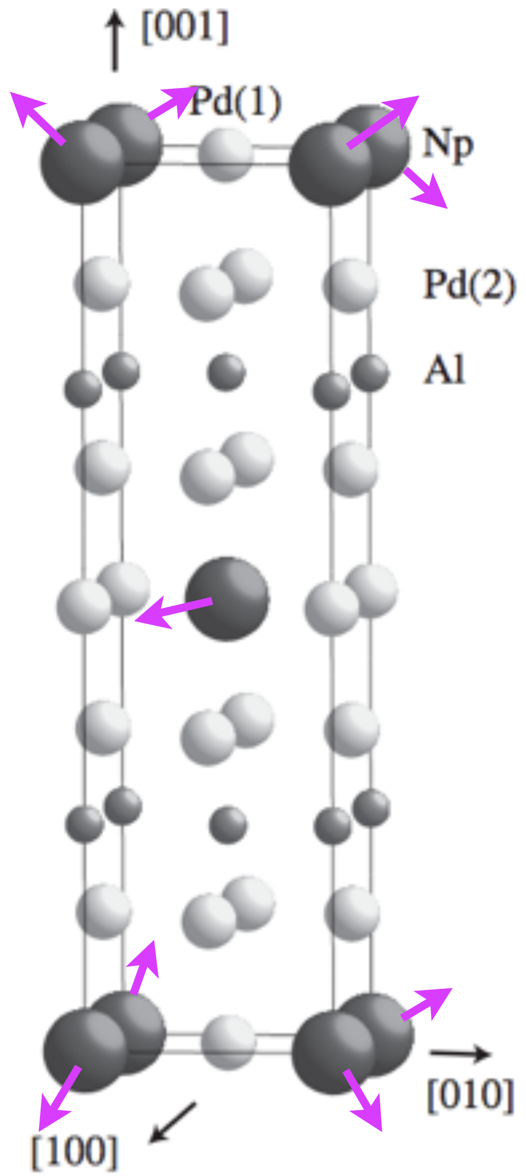


Smith and Kmetko (1983)

HF 115s
Tc=0.2 -18.5 K

Diversity of new ground-states on the brink of localization.

f-electron systems: 4f Ce, Yb systems 5f U, Np, Pu systems.



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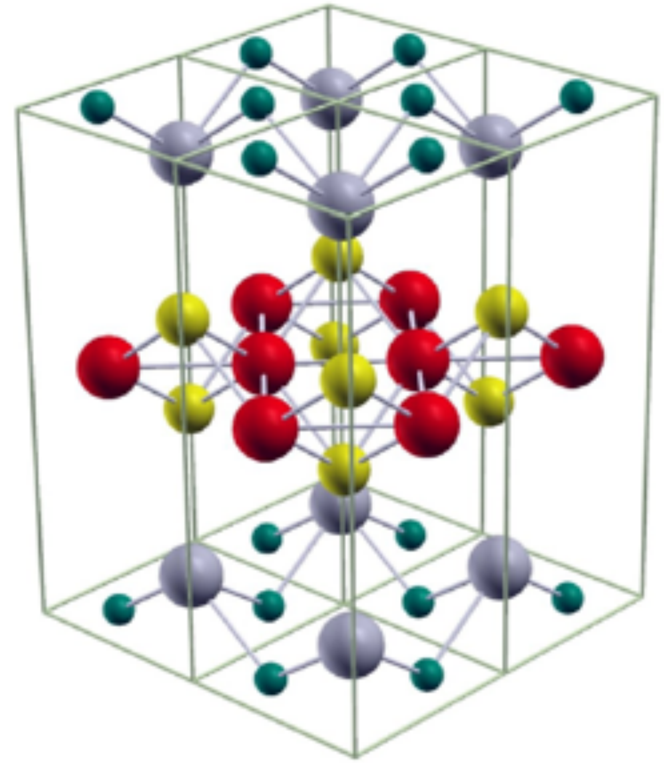
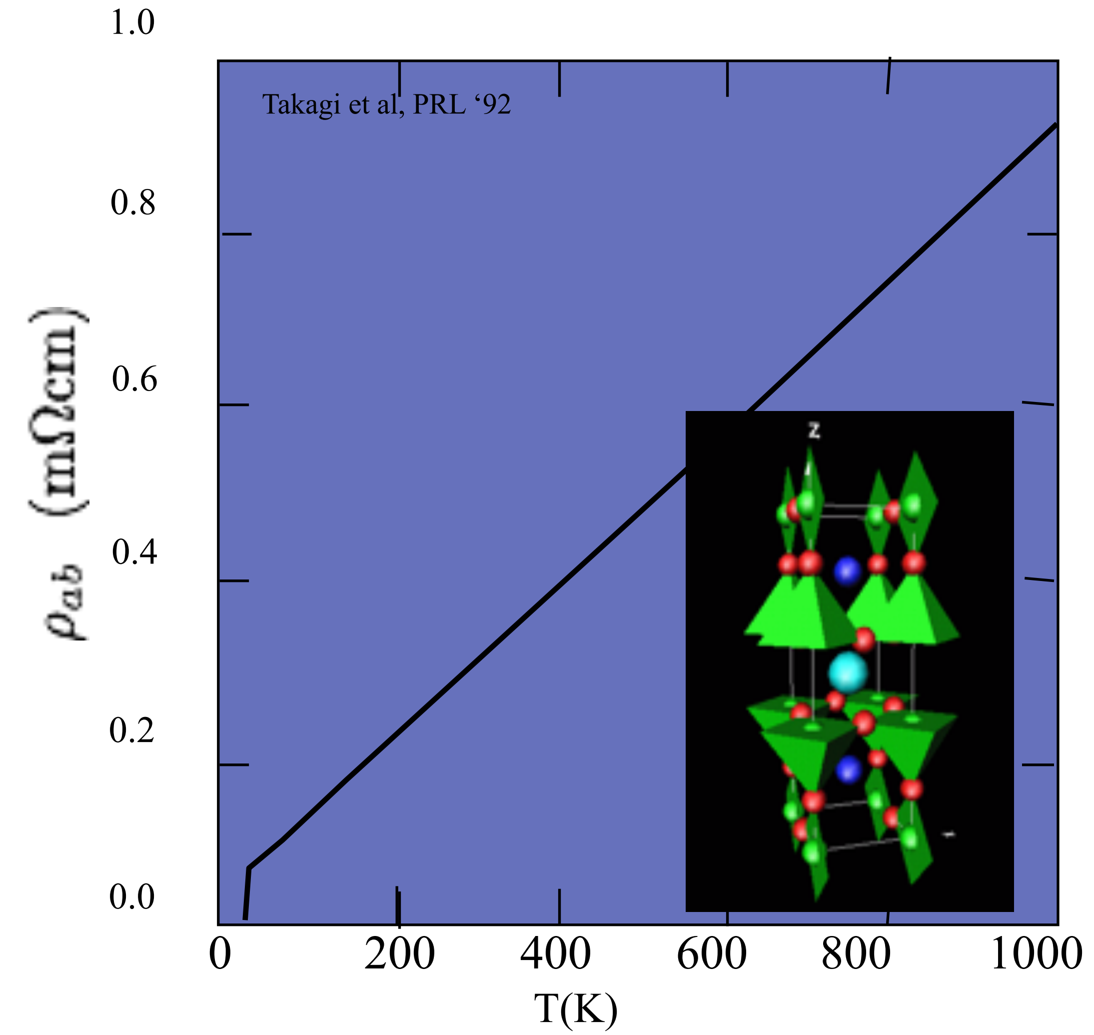


$PrF_xO_{1-x}FeAs$
Z.A. Ren et.al, Beijing, (08)



HF 115s
T_c=0.2 -18.5 K

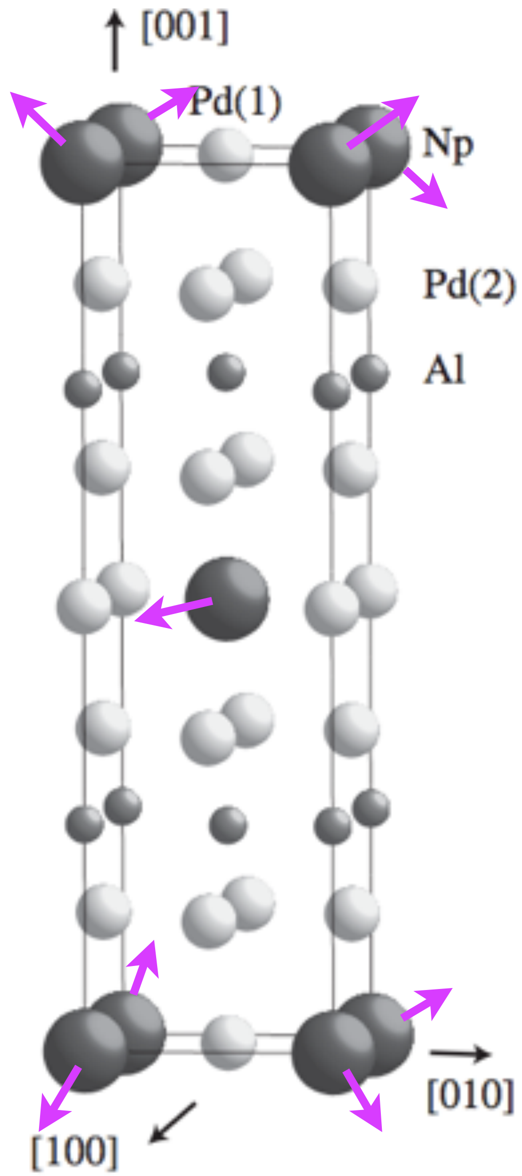
Iron based sc
T_c= 6 - 53 ++ ? K

Cuprates T_c=11-92K

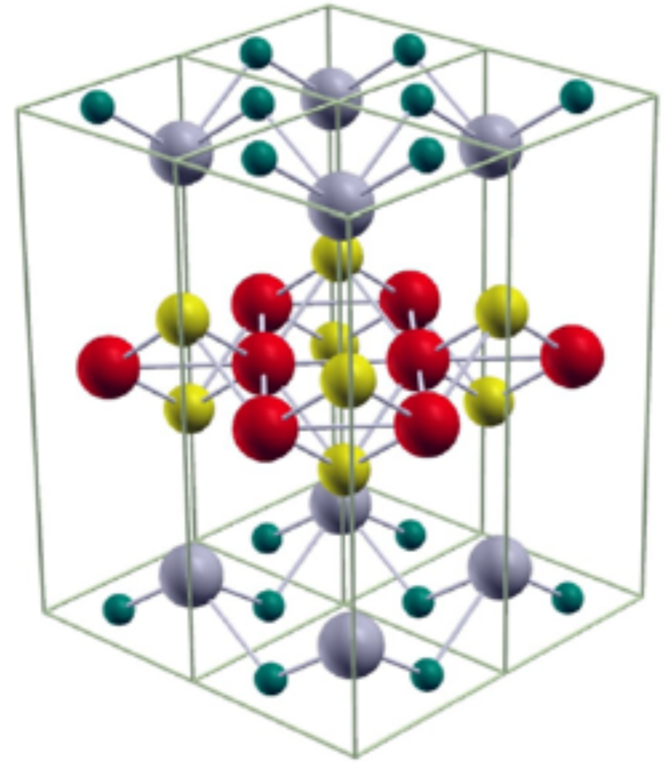
Diversity of new ground-states on the brink of localization.

f-electron systems: 4f Ce, Yb systems 5f U, Np, Pu systems.

d-electron systems: e.g Pnictides, Cuprate SC.



$NpAl_2Pd_5$



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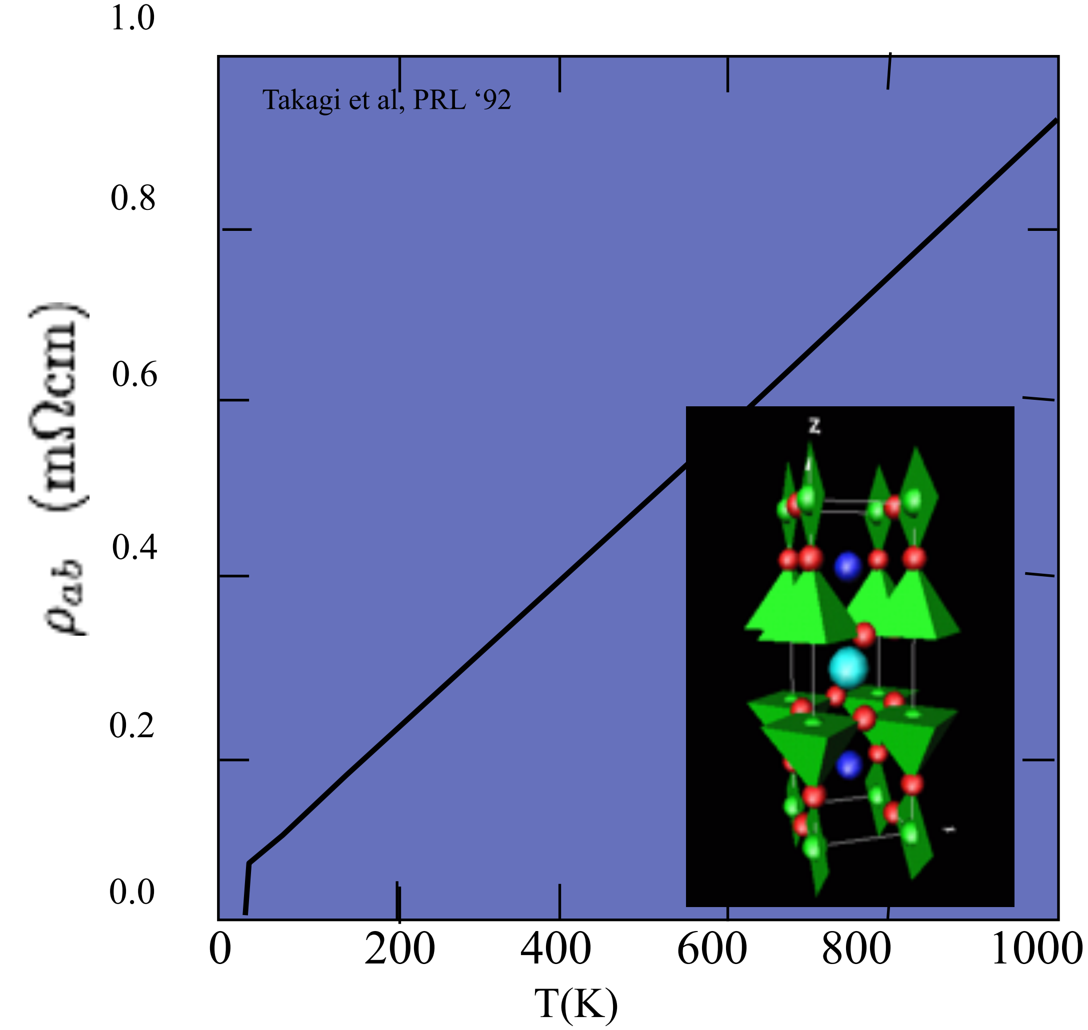

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T_c=0.2 -18.5 K

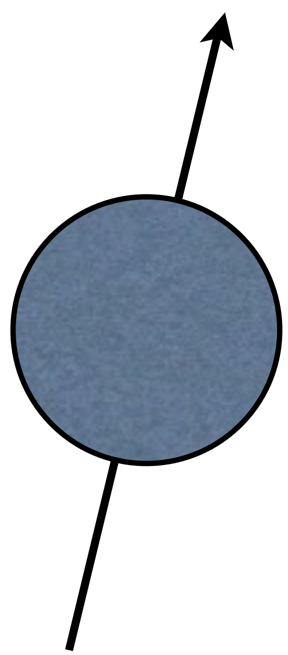
Iron based sc
T_c= 6 - 53 ++ ? K

Cuprates T_c=11-92K

A new era of mysteries

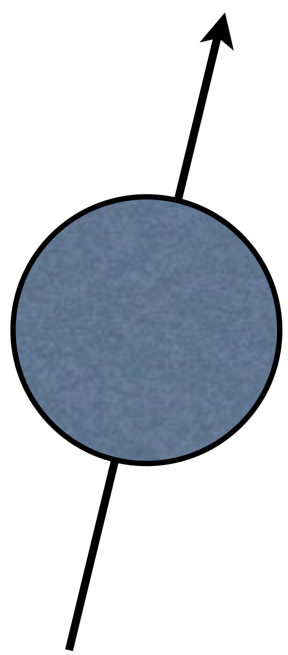
Cartoon Introduction to Heavy Fermions

Heavy Fermions + Kondo



Spin (4f,5f): basic
fabric of heavy
electron physics.

Heavy Fermions + Kondo



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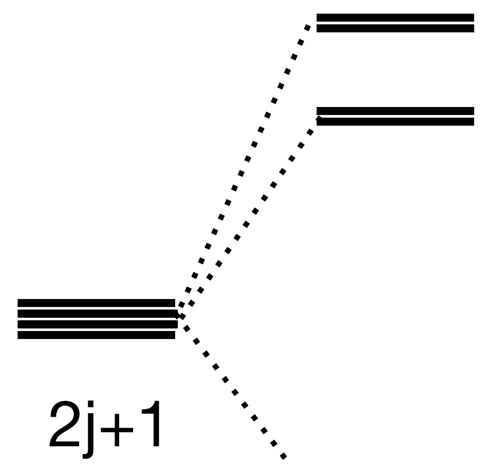

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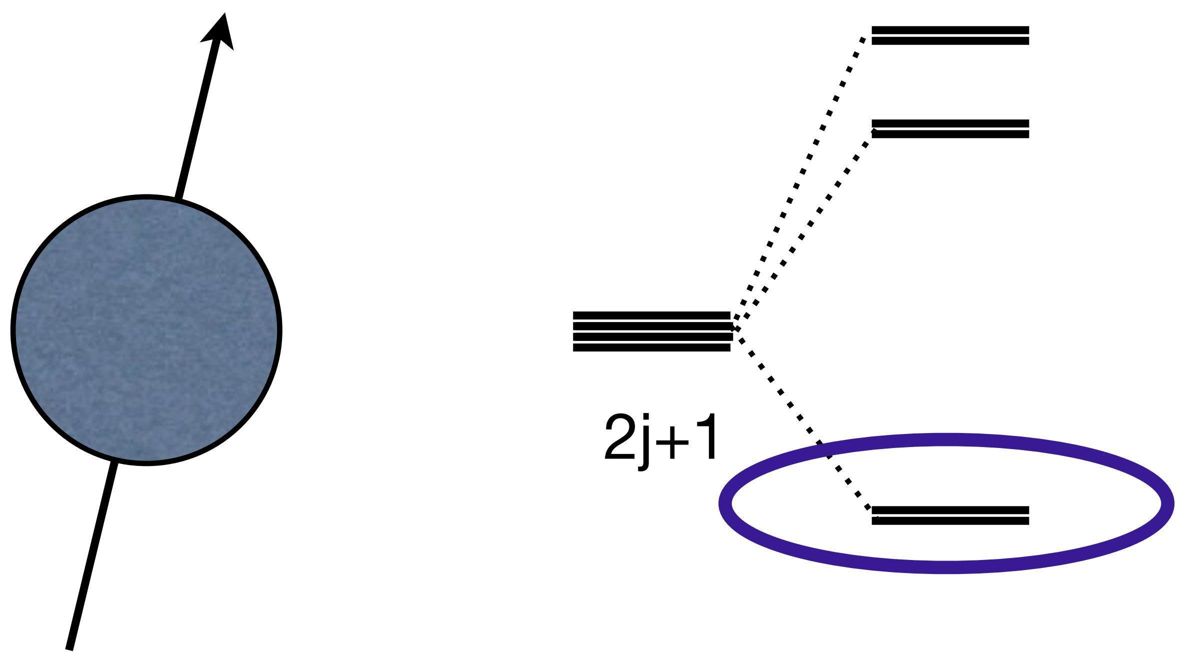

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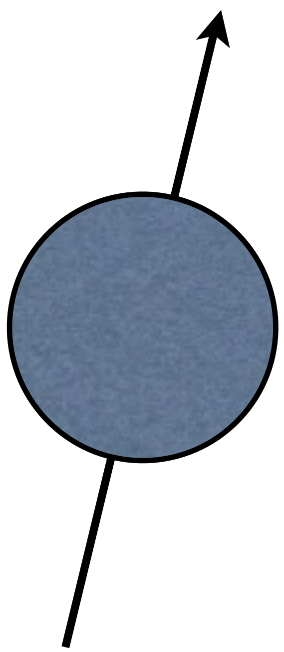

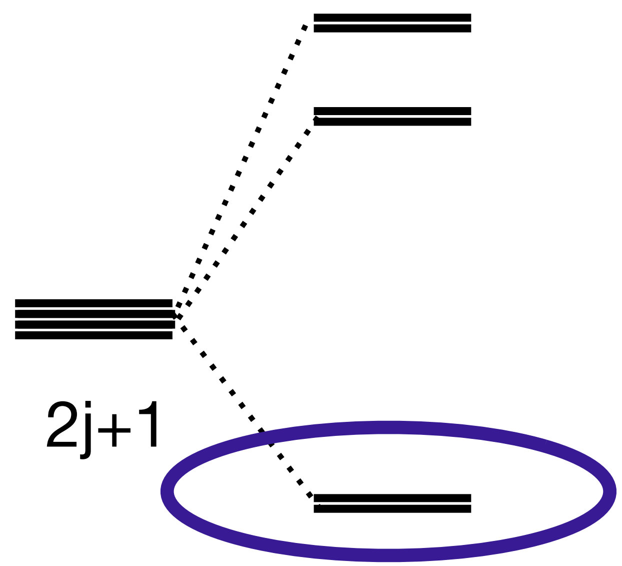

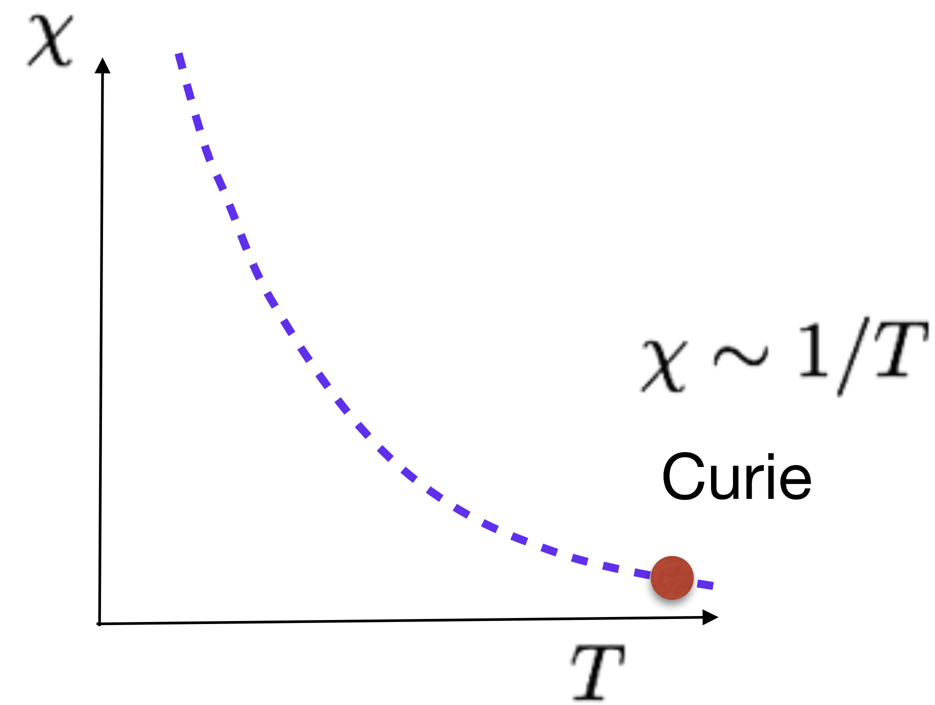

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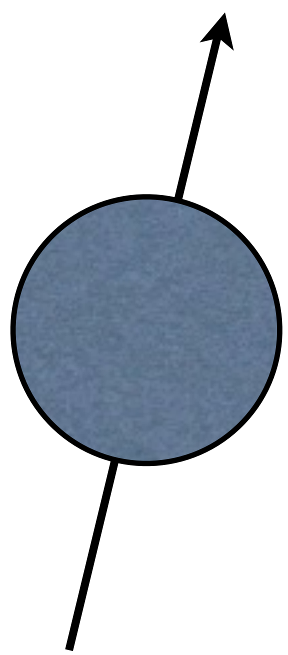
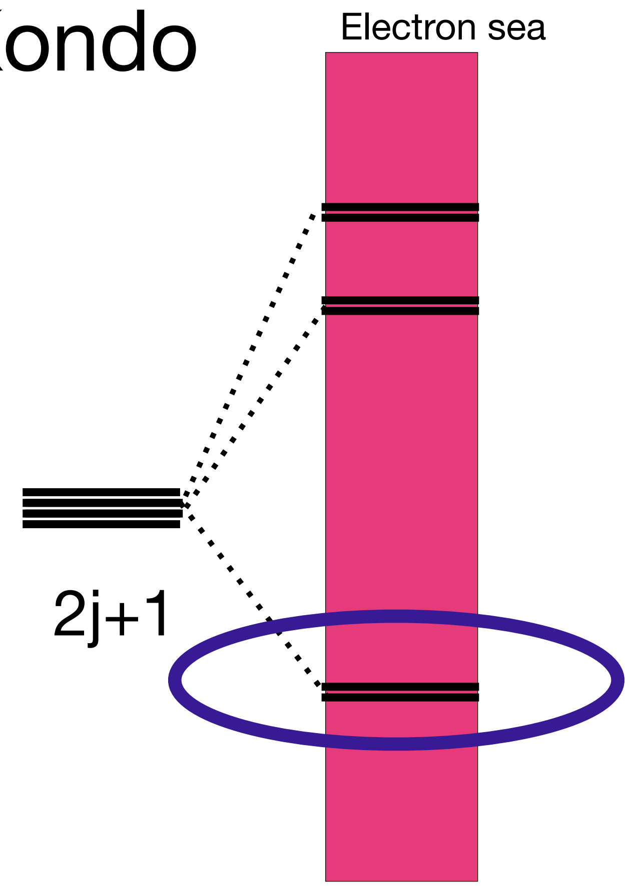
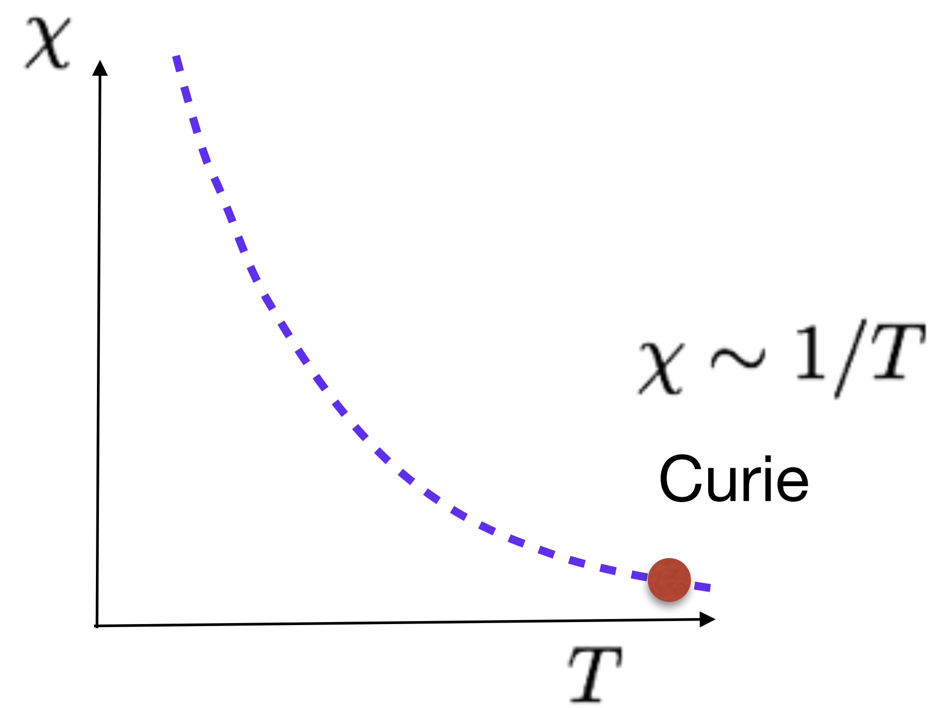






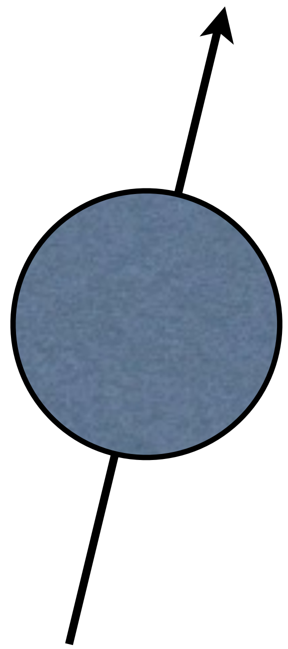
Spin (4f,5f): basic fabric of heavy electron physics.

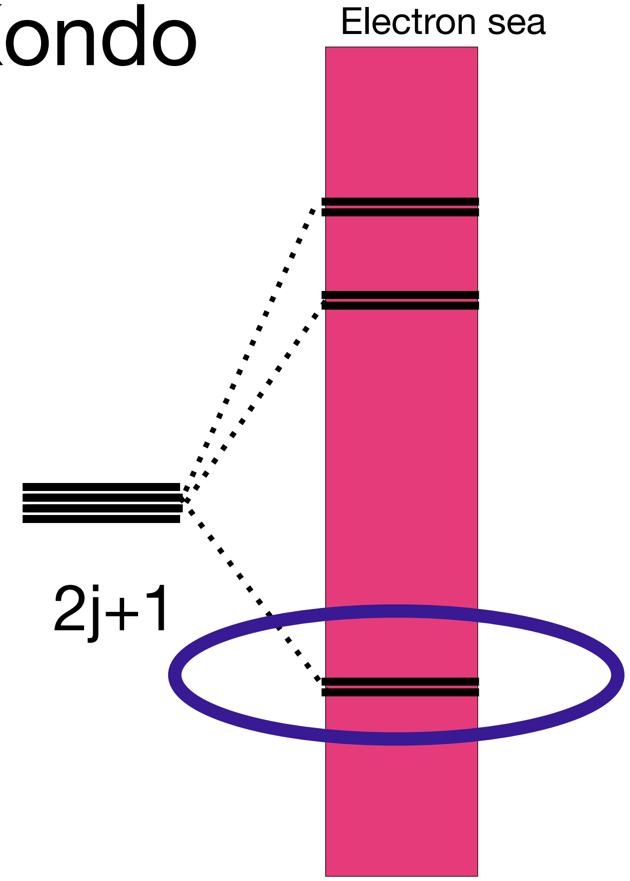
Scales to
Strong Coupling

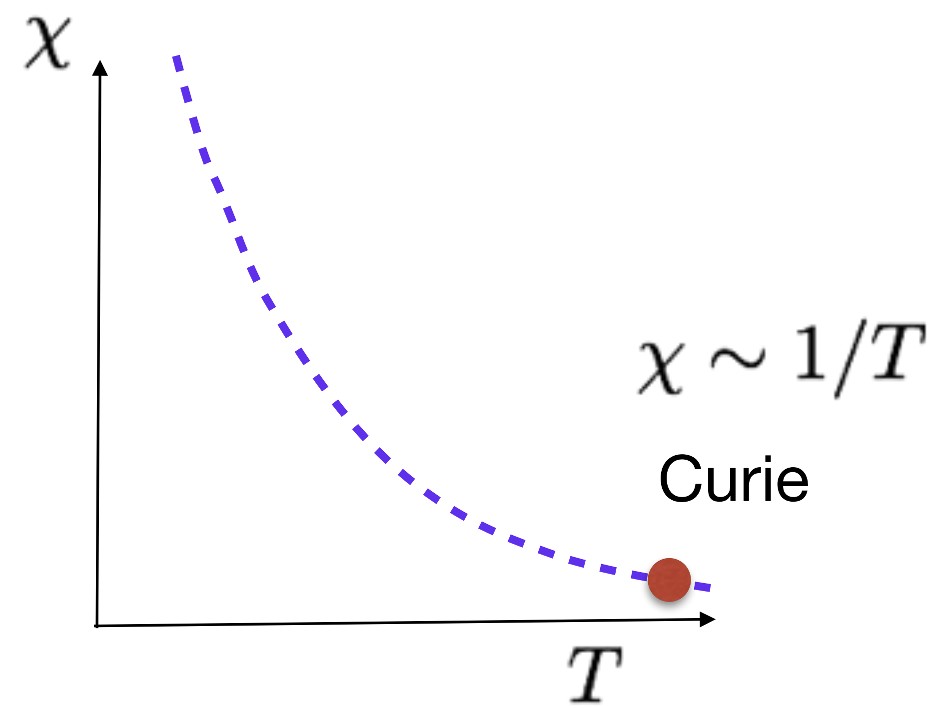
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \vec{S} \cdot \vec{\sigma}(0)$$

J. Kondo, 1962

Heavy Fermions + Kondo







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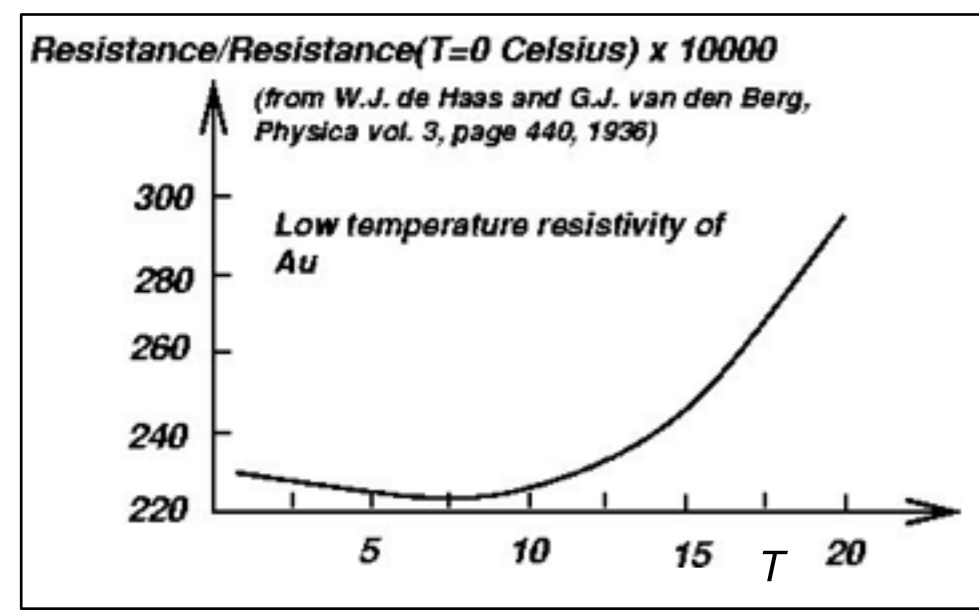

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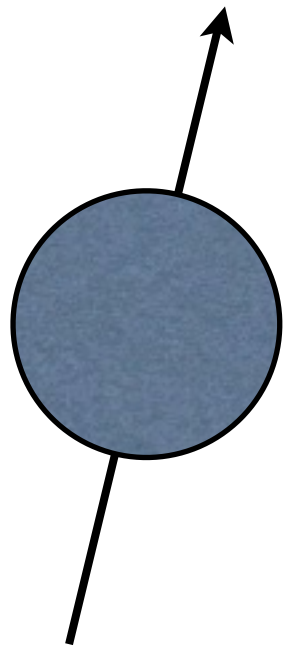
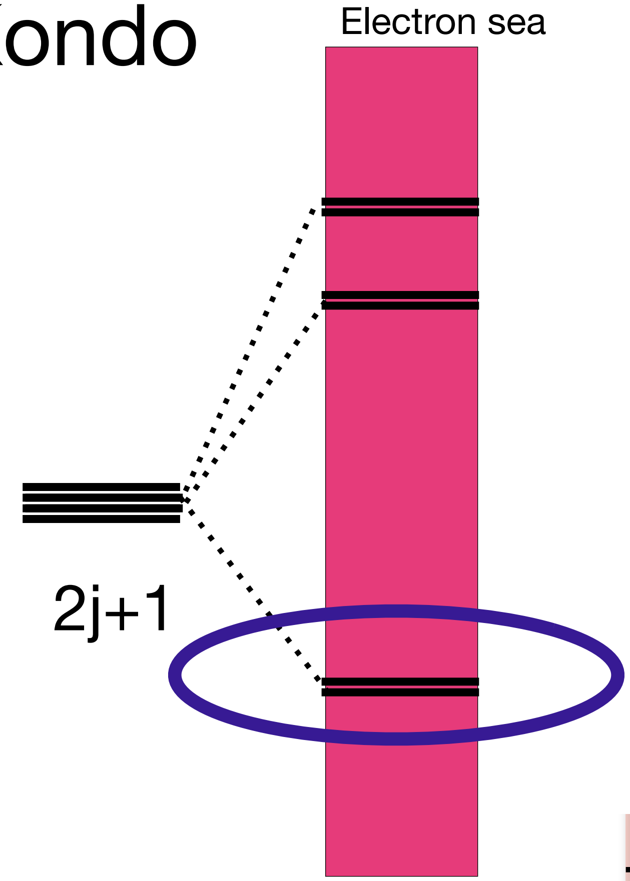
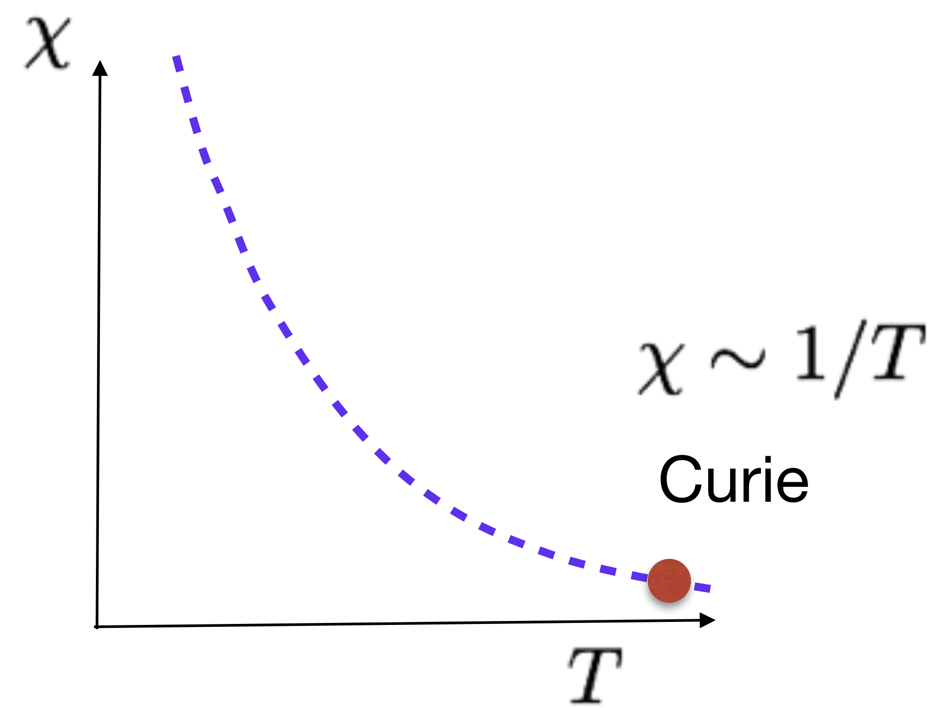
J. Kondo, 1962

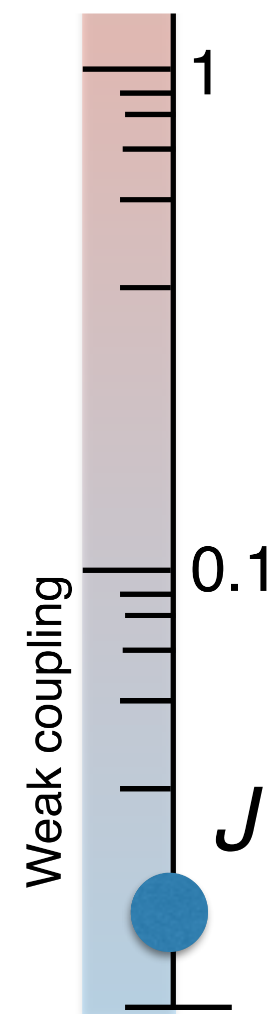
Heavy Fermions + Kondo

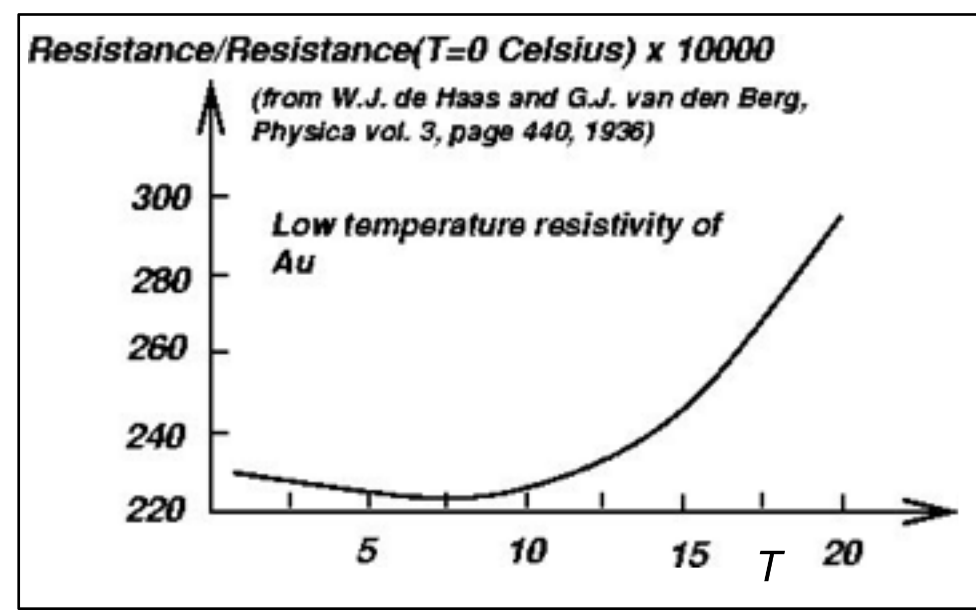






Spin (4f,5f): basic fabric of heavy electron physics.





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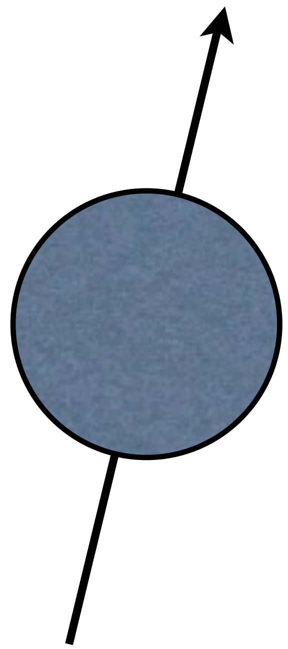
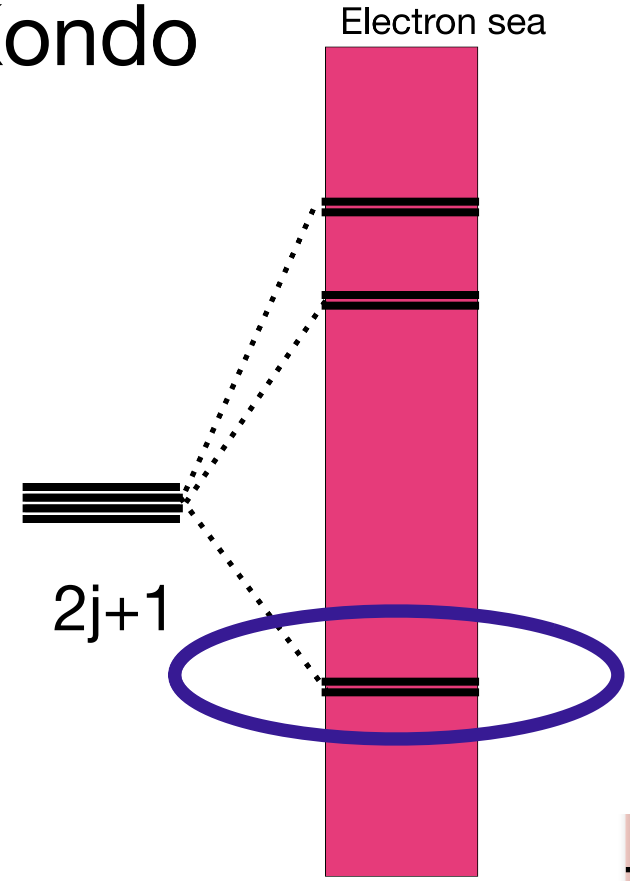
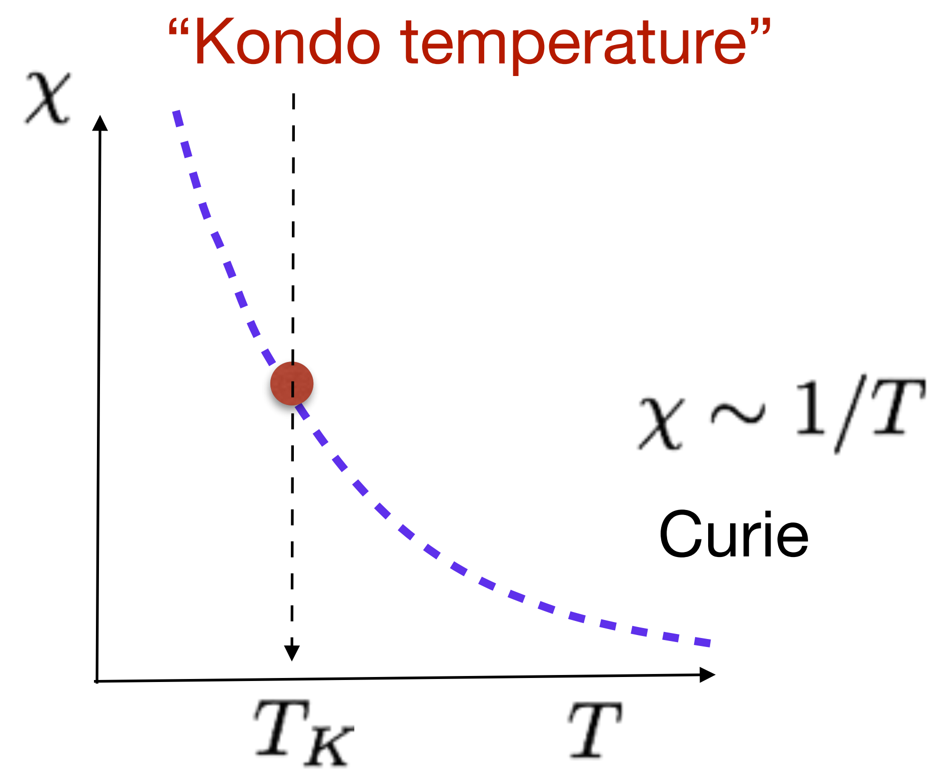
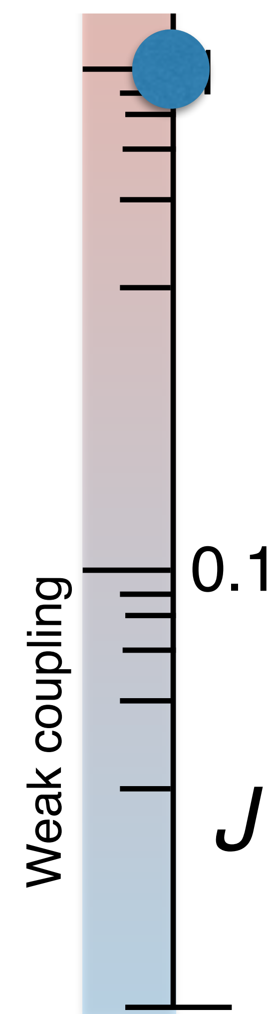
Heavy Fermions + Kondo



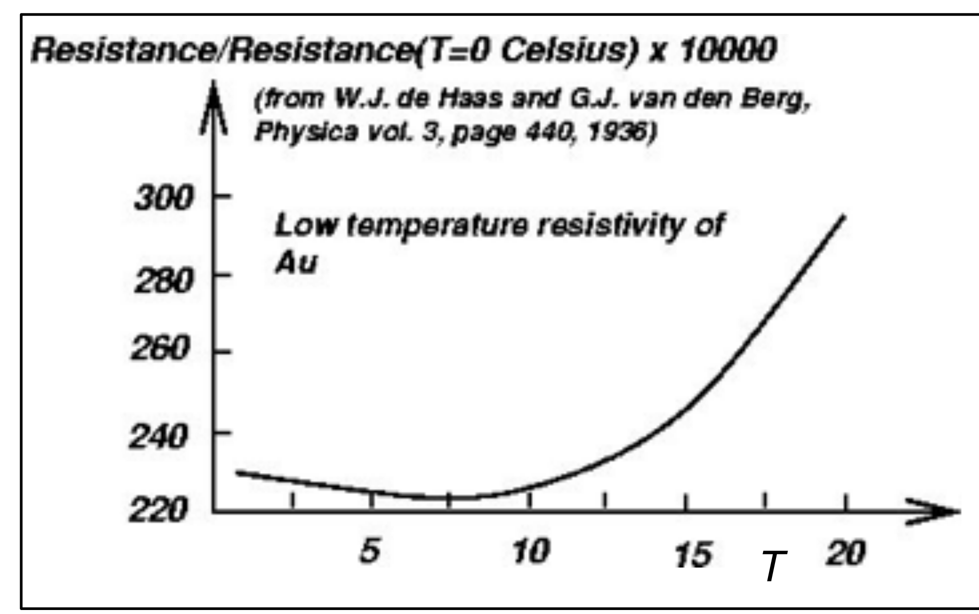




Spin (4f,5f): basic fabric of heavy electron physics.



$$T_K = W\sqrt{J\rho}\,e^{-\frac{1}{2J\rho}}$$

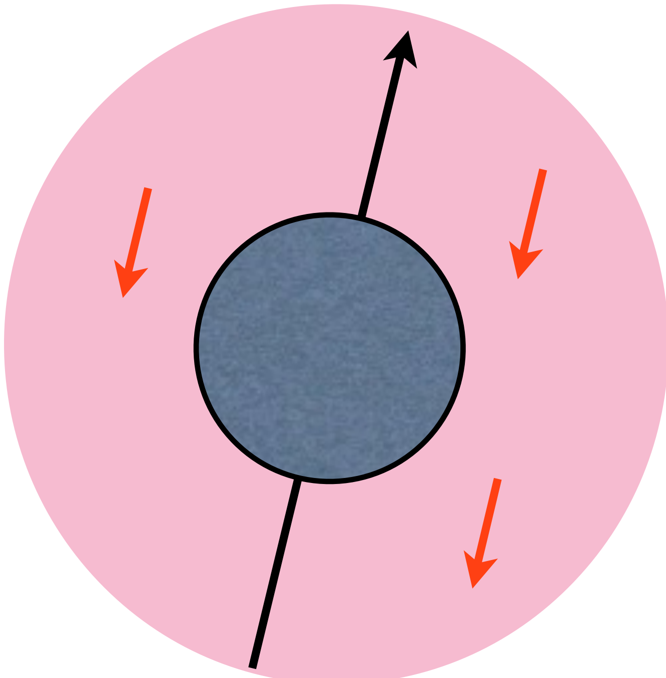


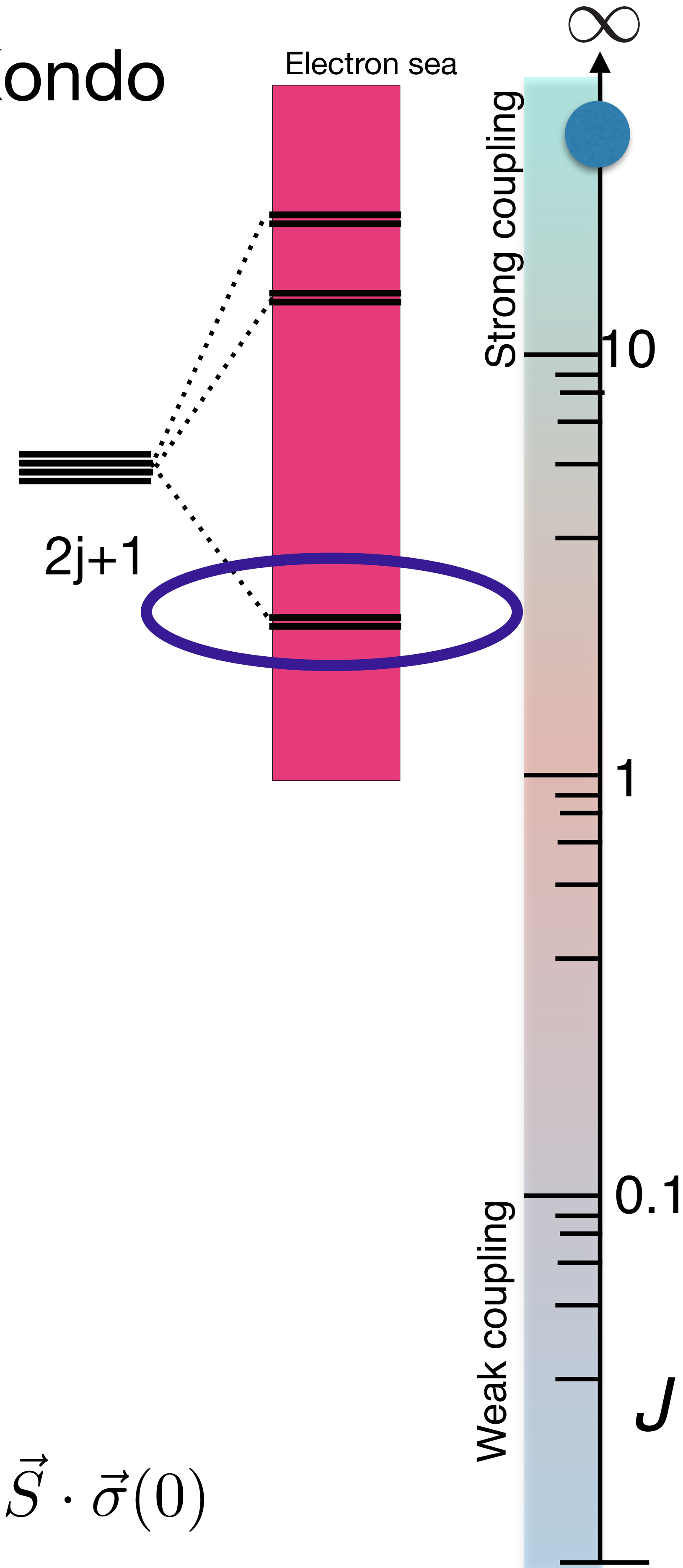
Scales to
Strong Coupling

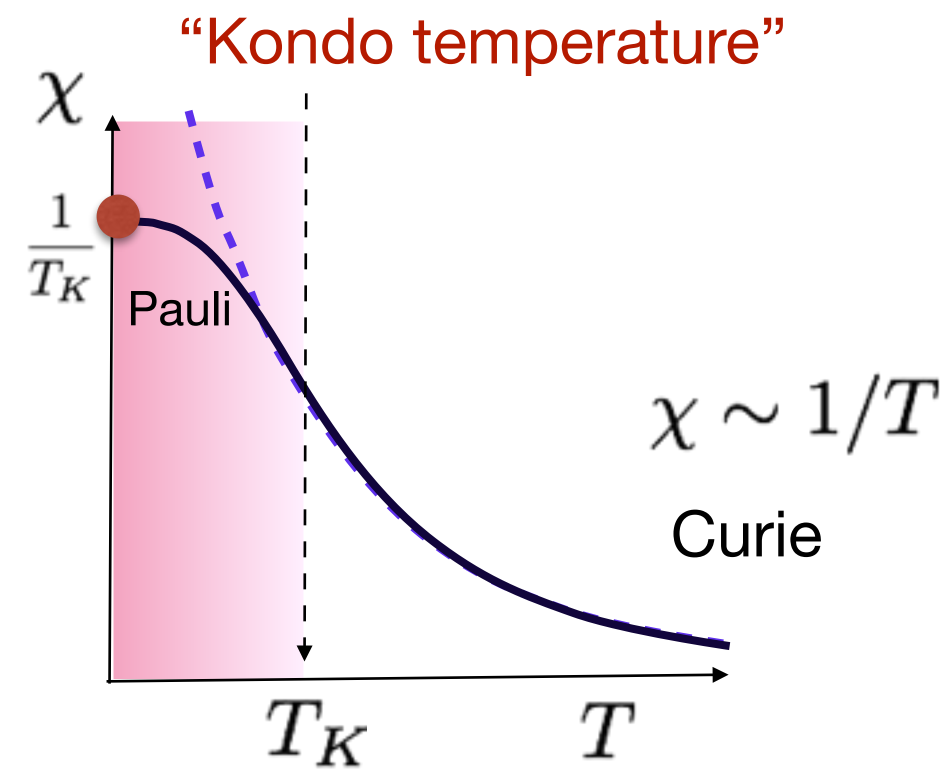
$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J\, \vec{S}\cdot\vec{\sigma}(0)$$

J. Kondo, 1962

Heavy Fermions + Kondo







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Spin screened by conduction electrons: entangled

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

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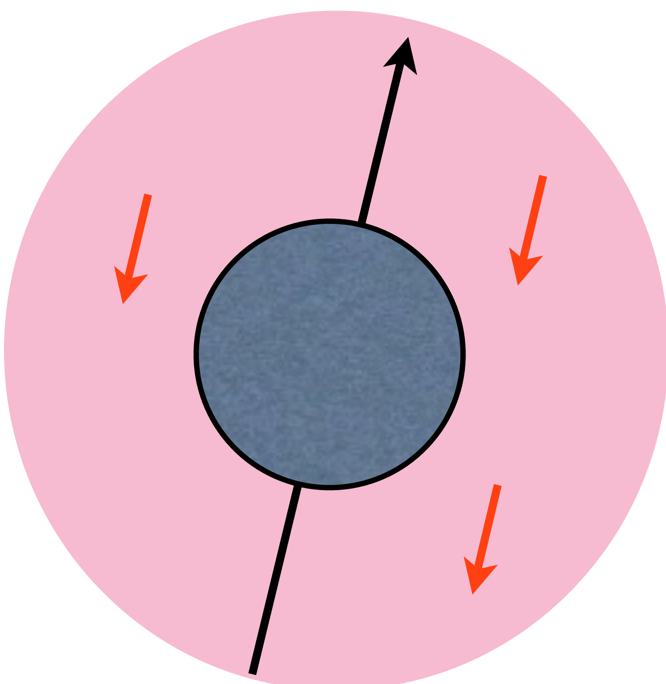

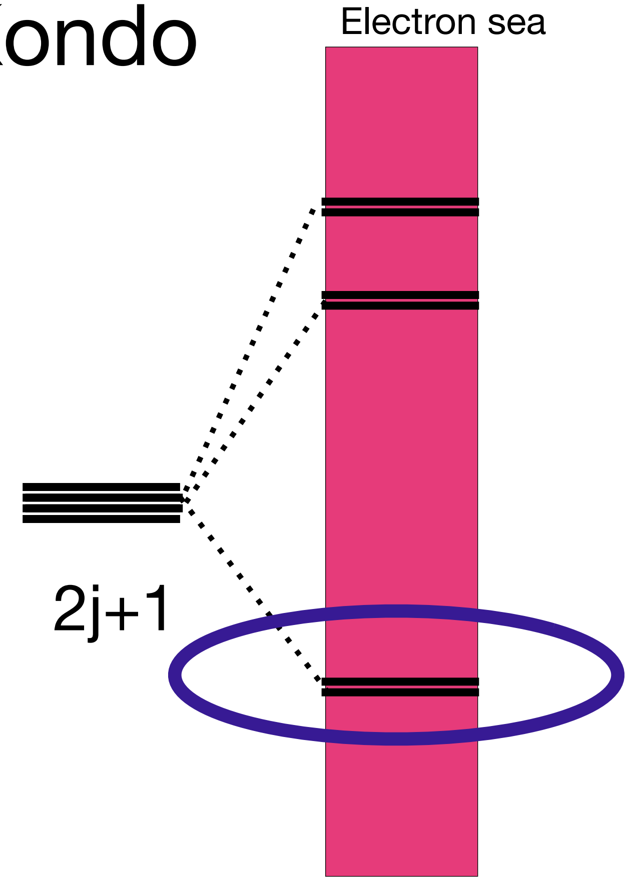

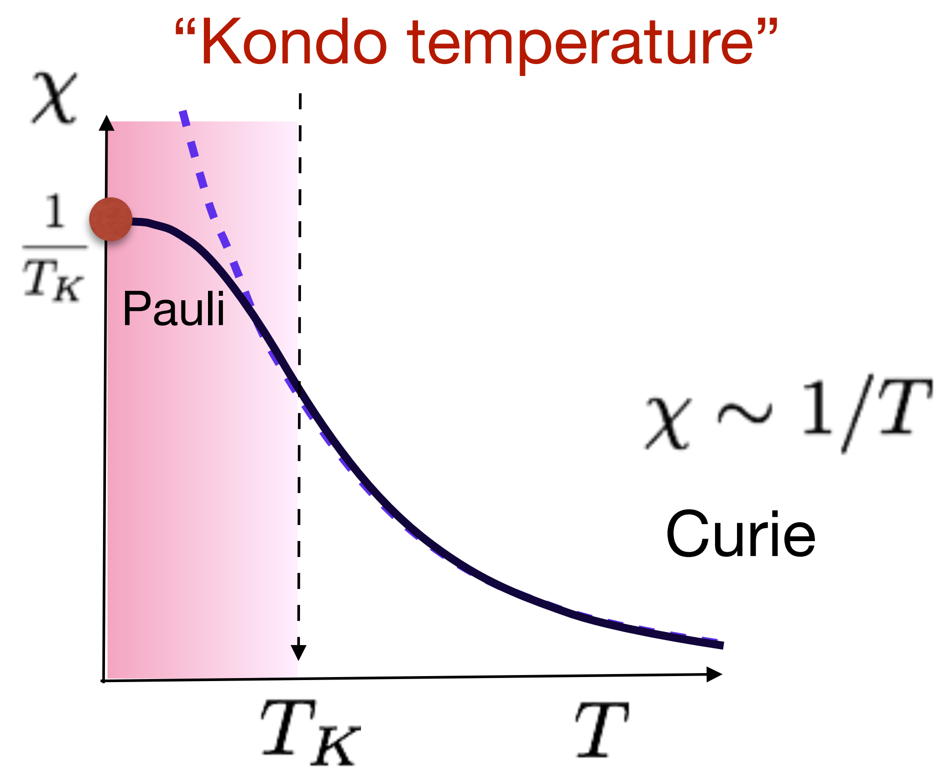

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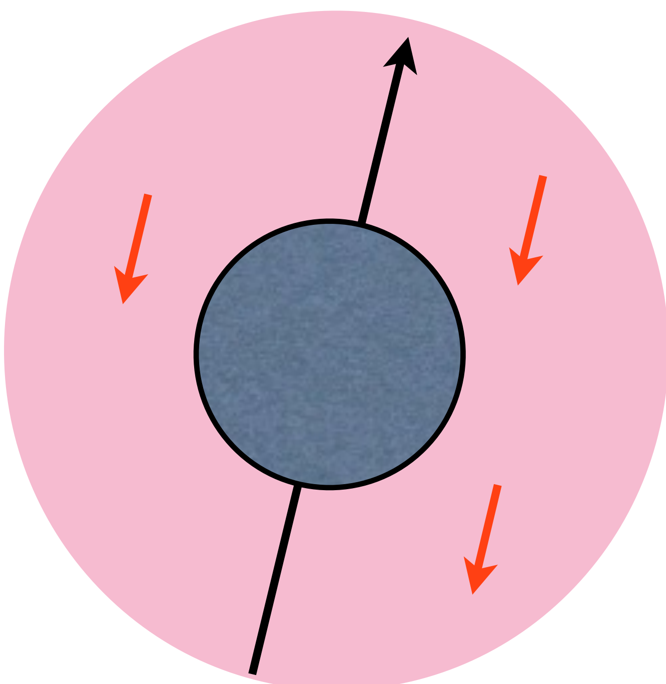

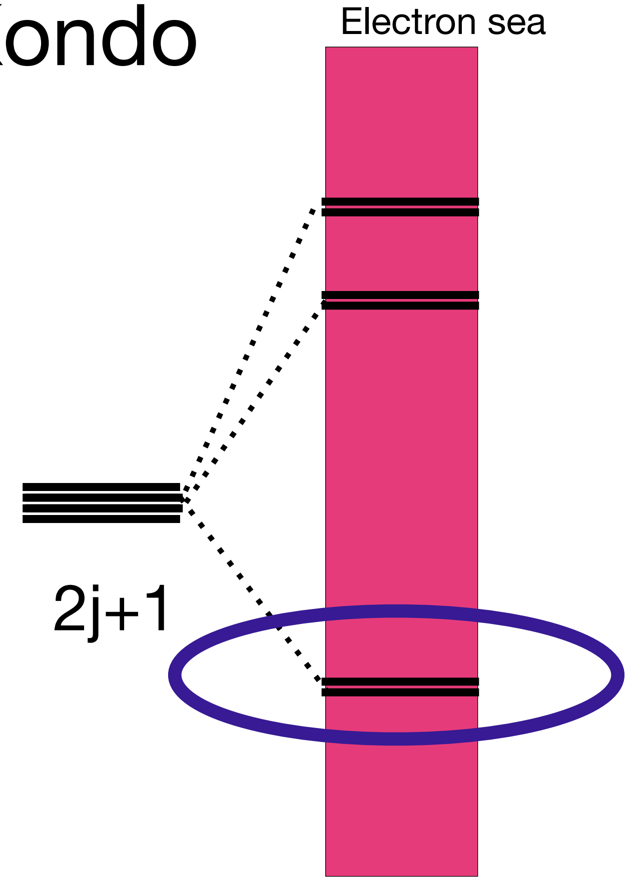

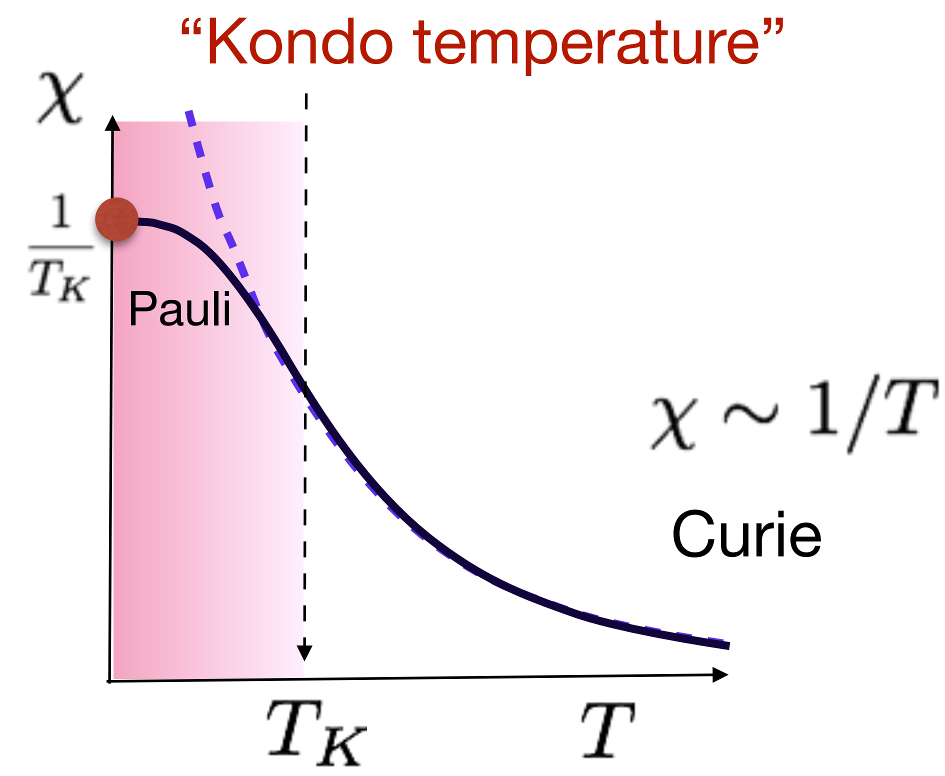

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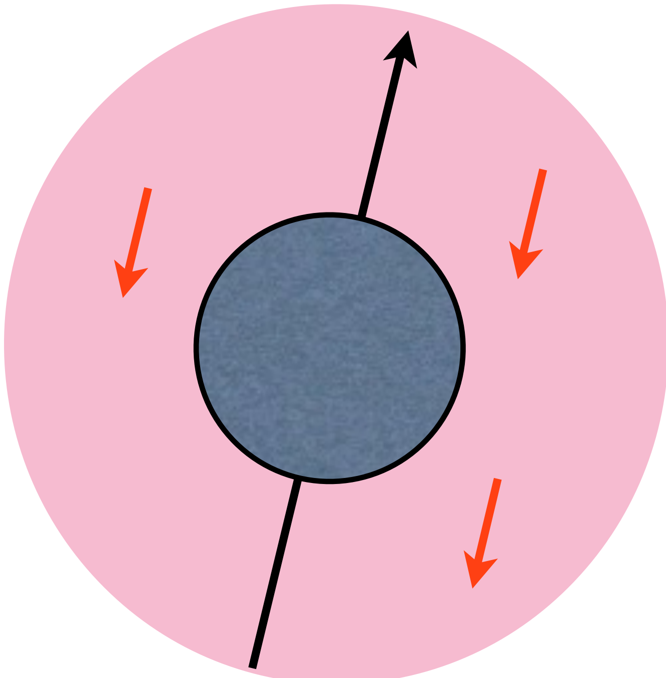
Spin screened by conduction electrons: <u>entangled</u>

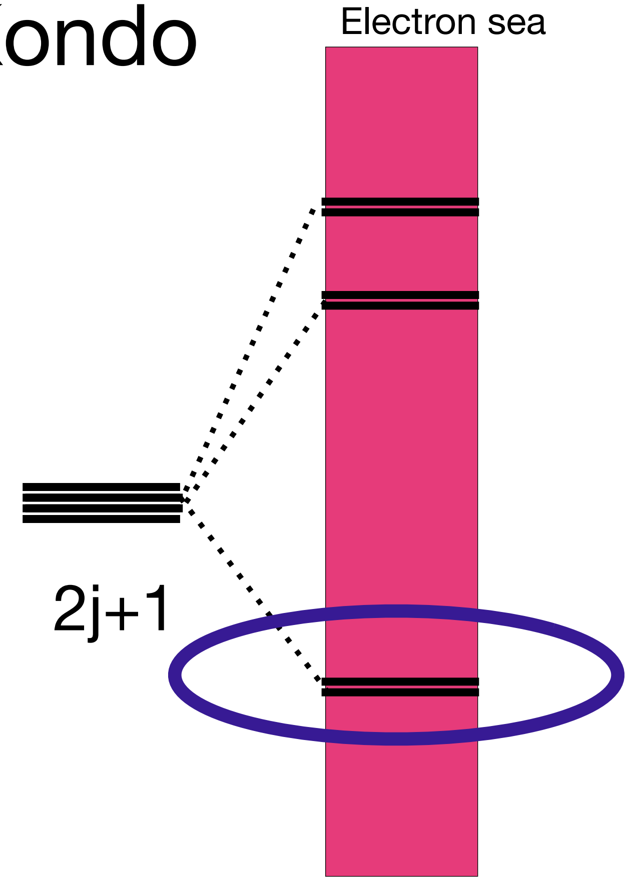
$\uparrow\downarrow - \downarrow\uparrow$

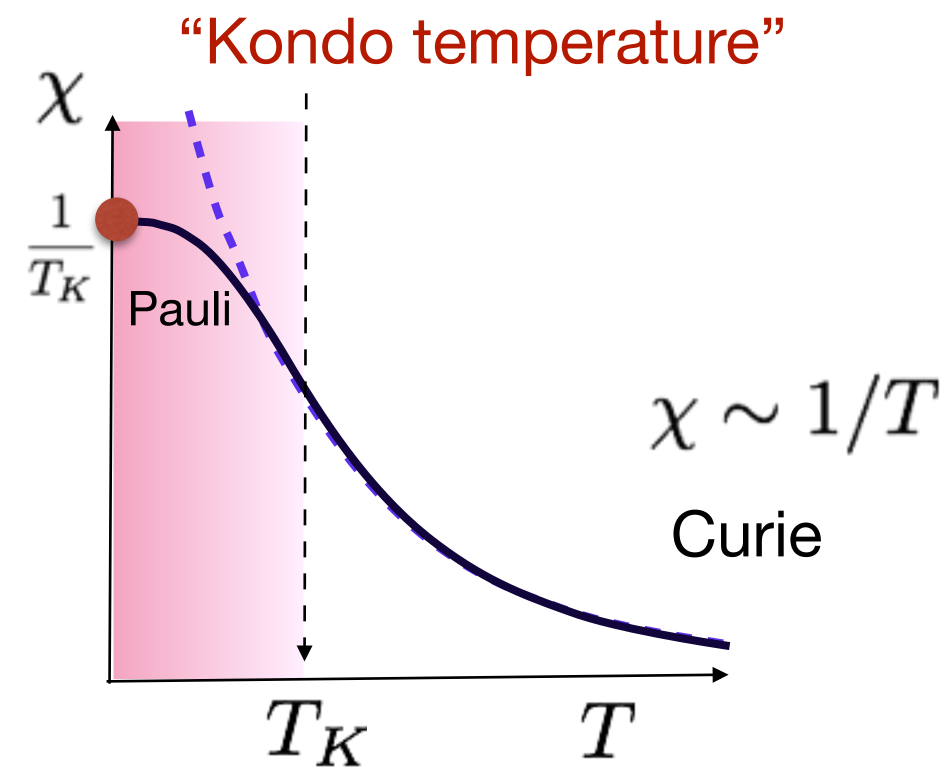
$$S(T) = \int_0^T \frac{C_V}{T'}dT'$$

Spin entanglement entropy

Heavy Fermions + Kondo







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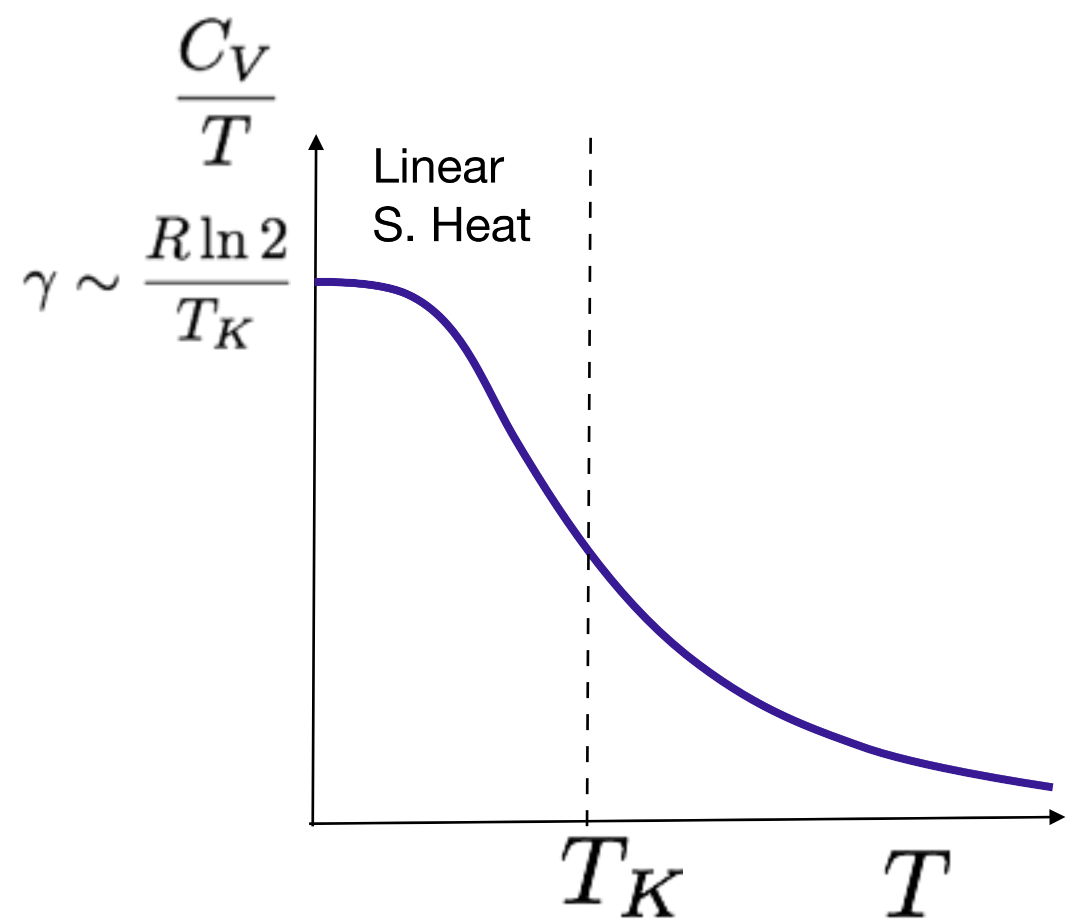

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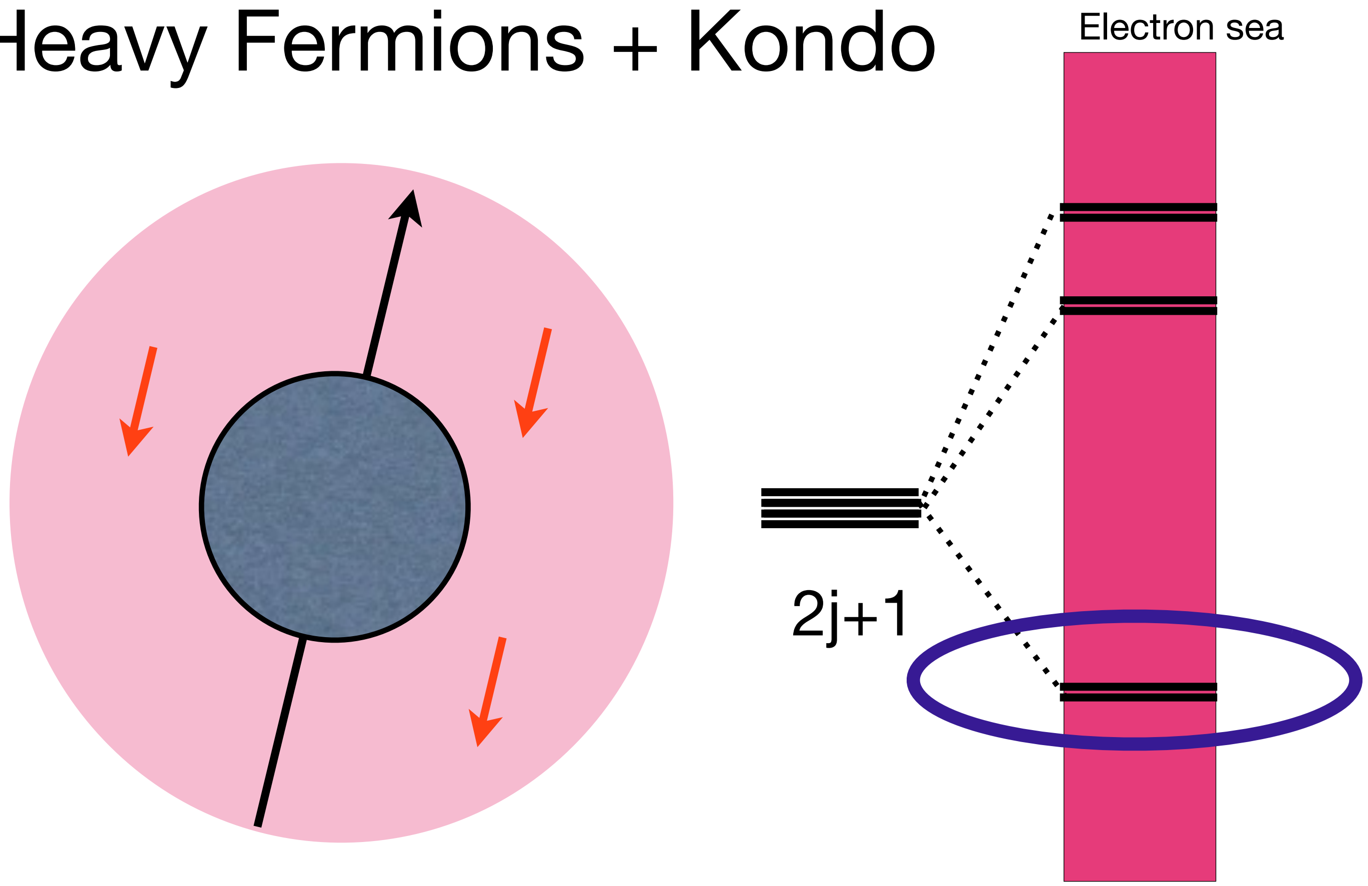

Spin screened by conduction electrons: <u>entangled</u>

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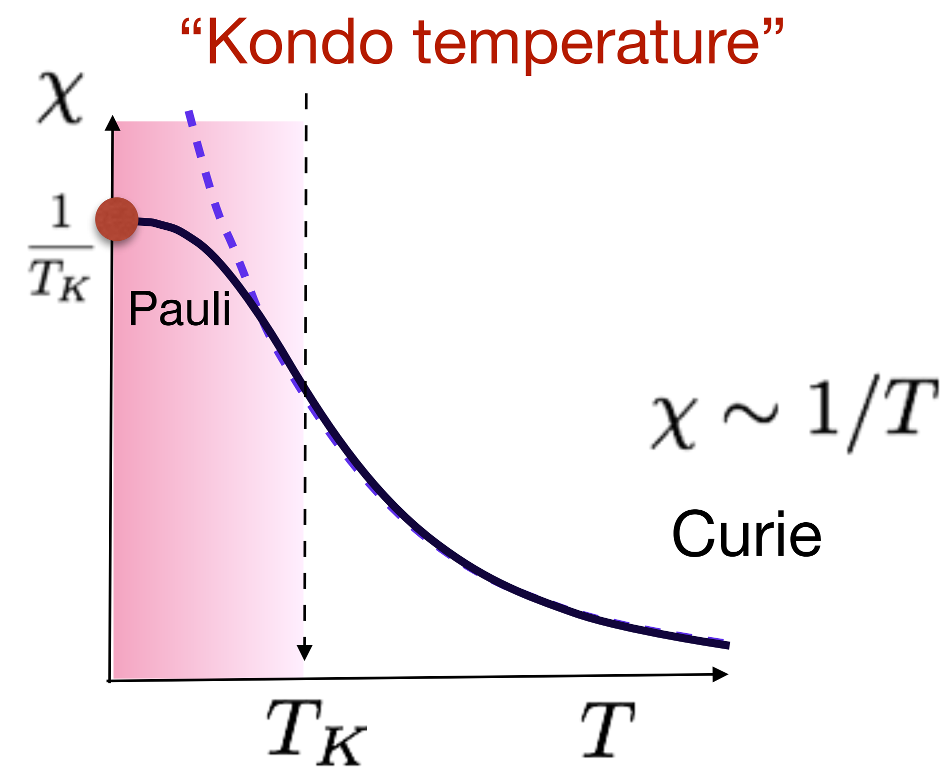

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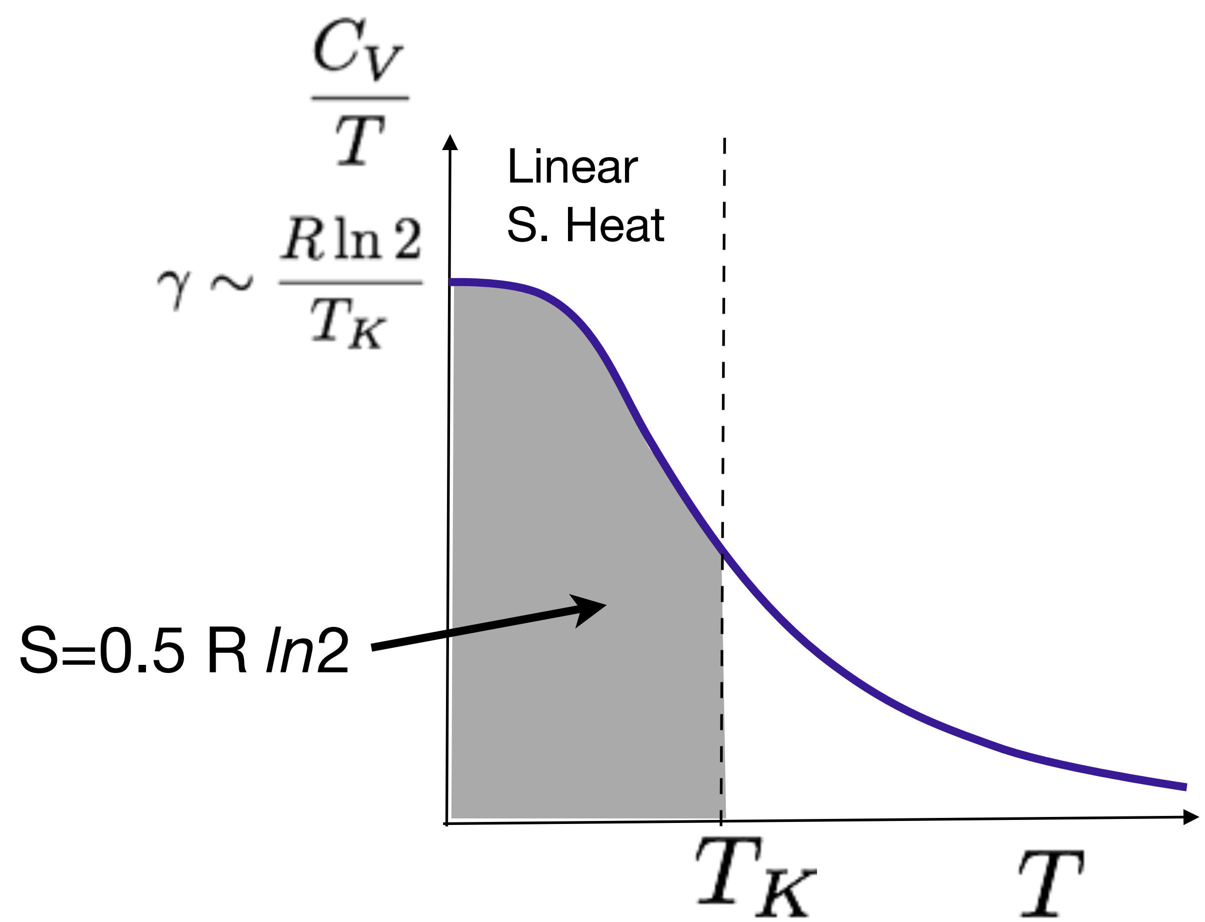

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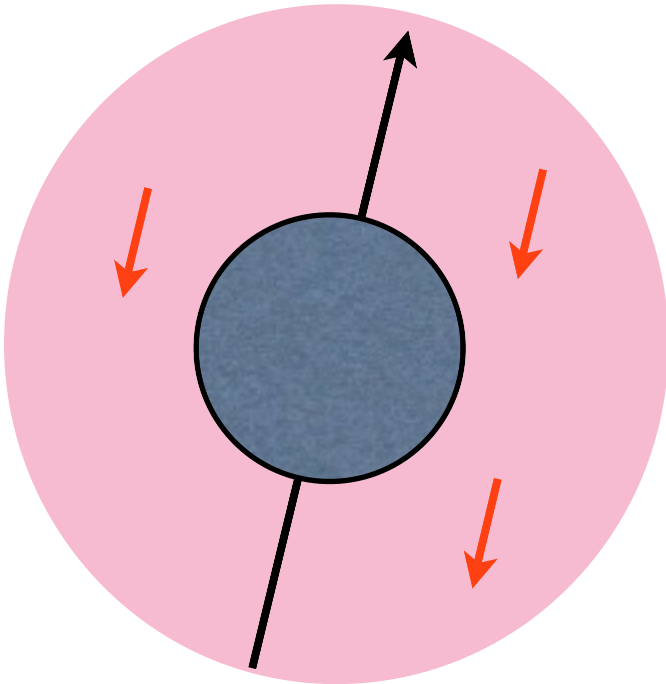
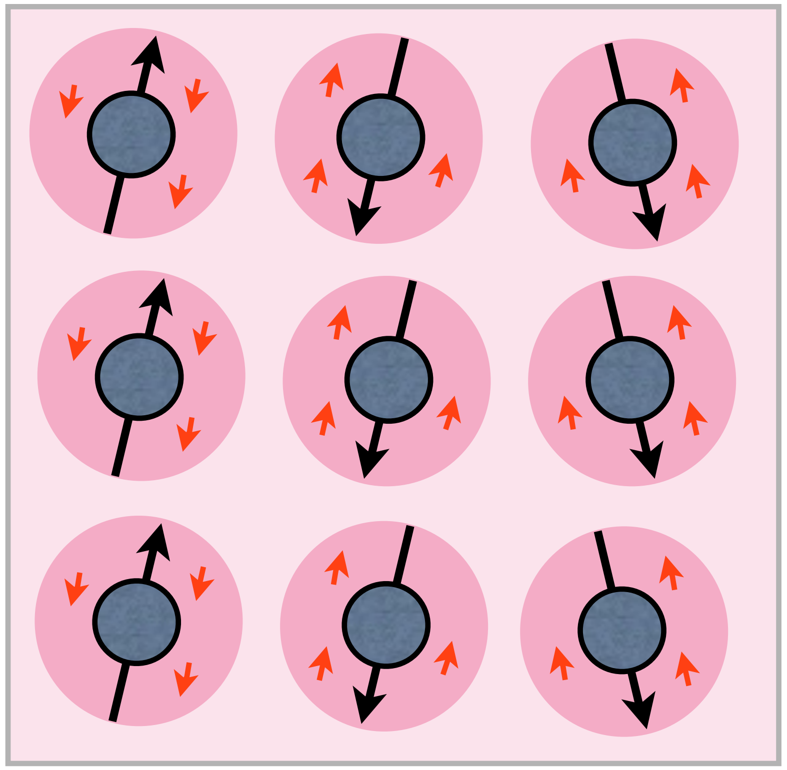
Spin entanglement entropy

Heavy Fermion Primer



$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + J \sum_{j} \vec{S}_j \cdot \vec{\sigma}(j)$$



"Kondo Lattice"

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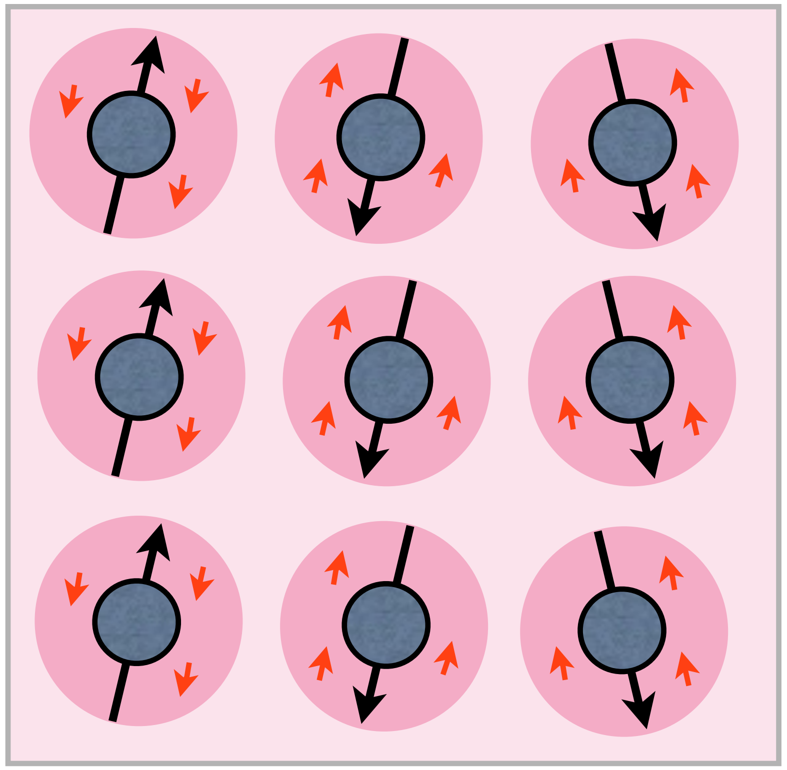

“Kondo Lattice”

Entangled spins and electrons
→ **Heavy Fermion Metals**

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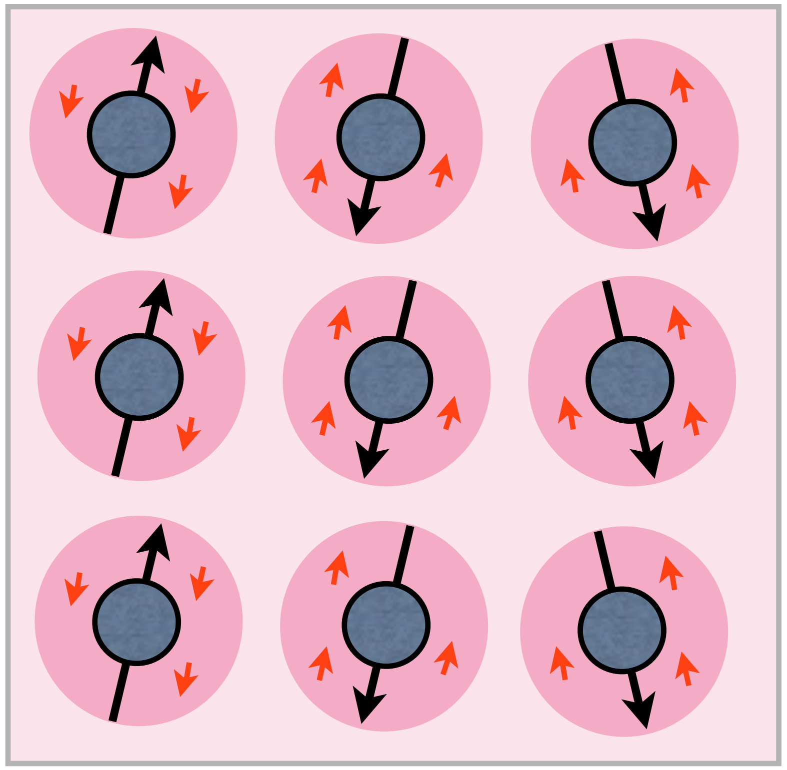

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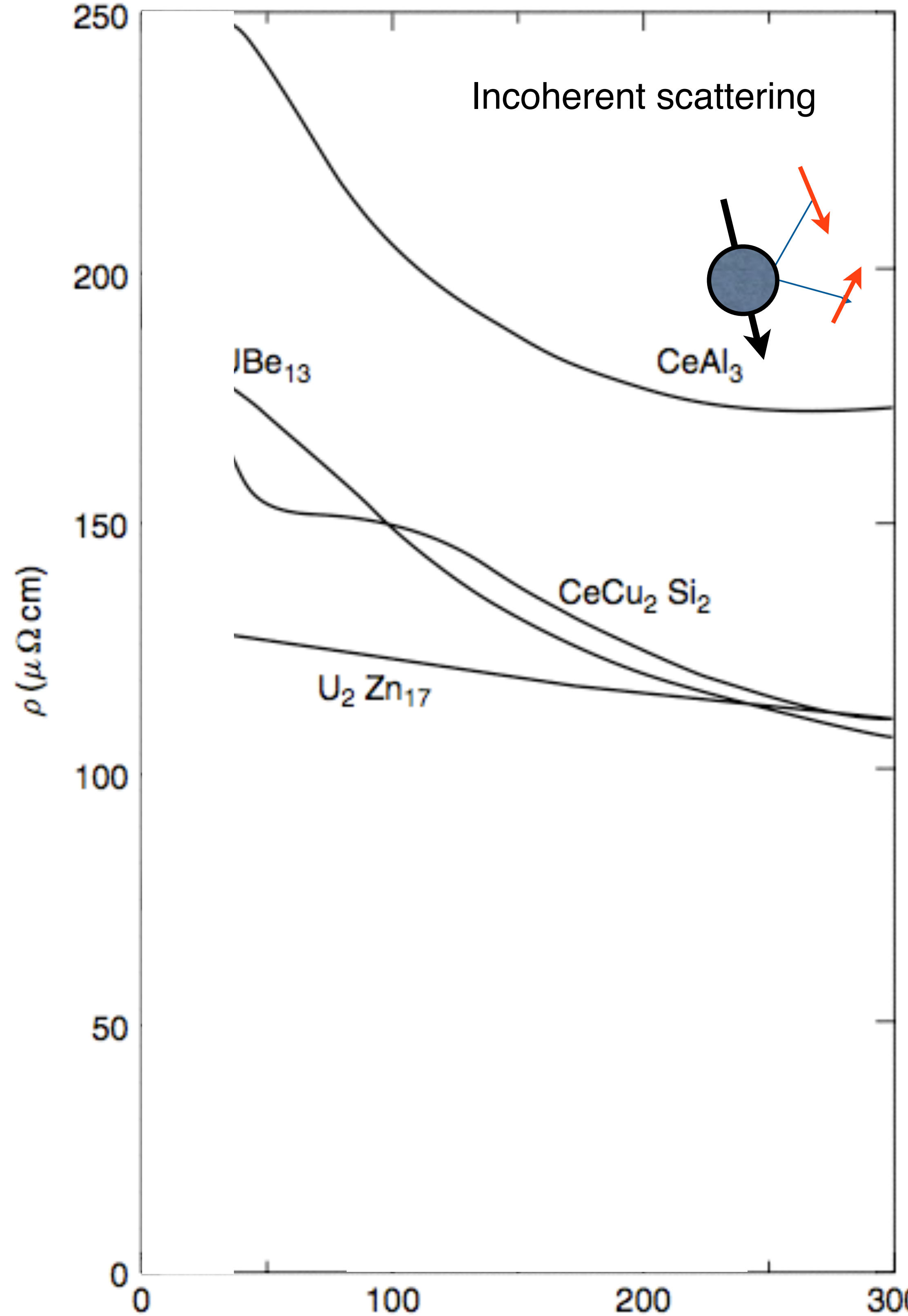

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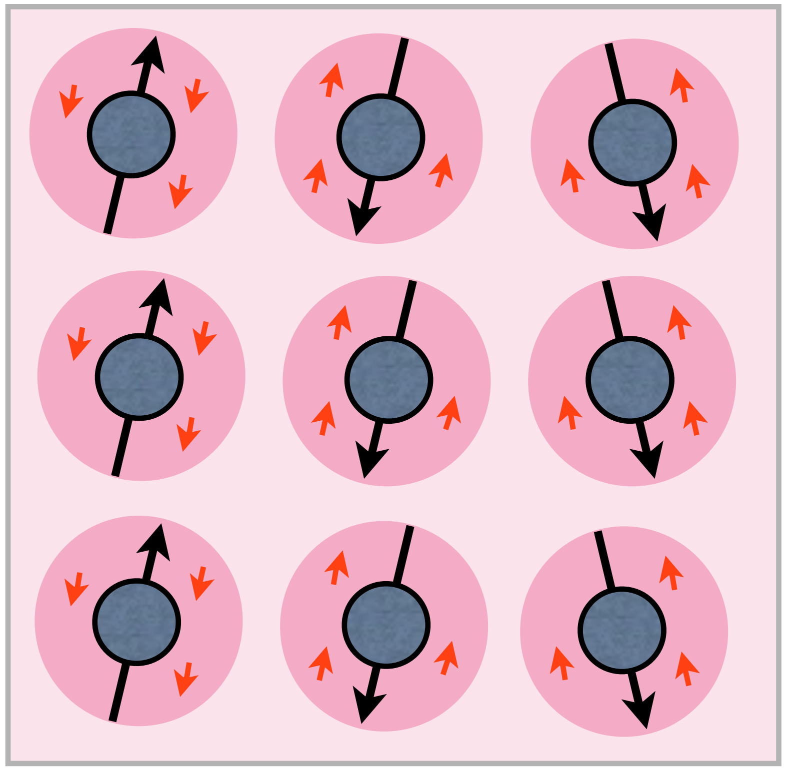

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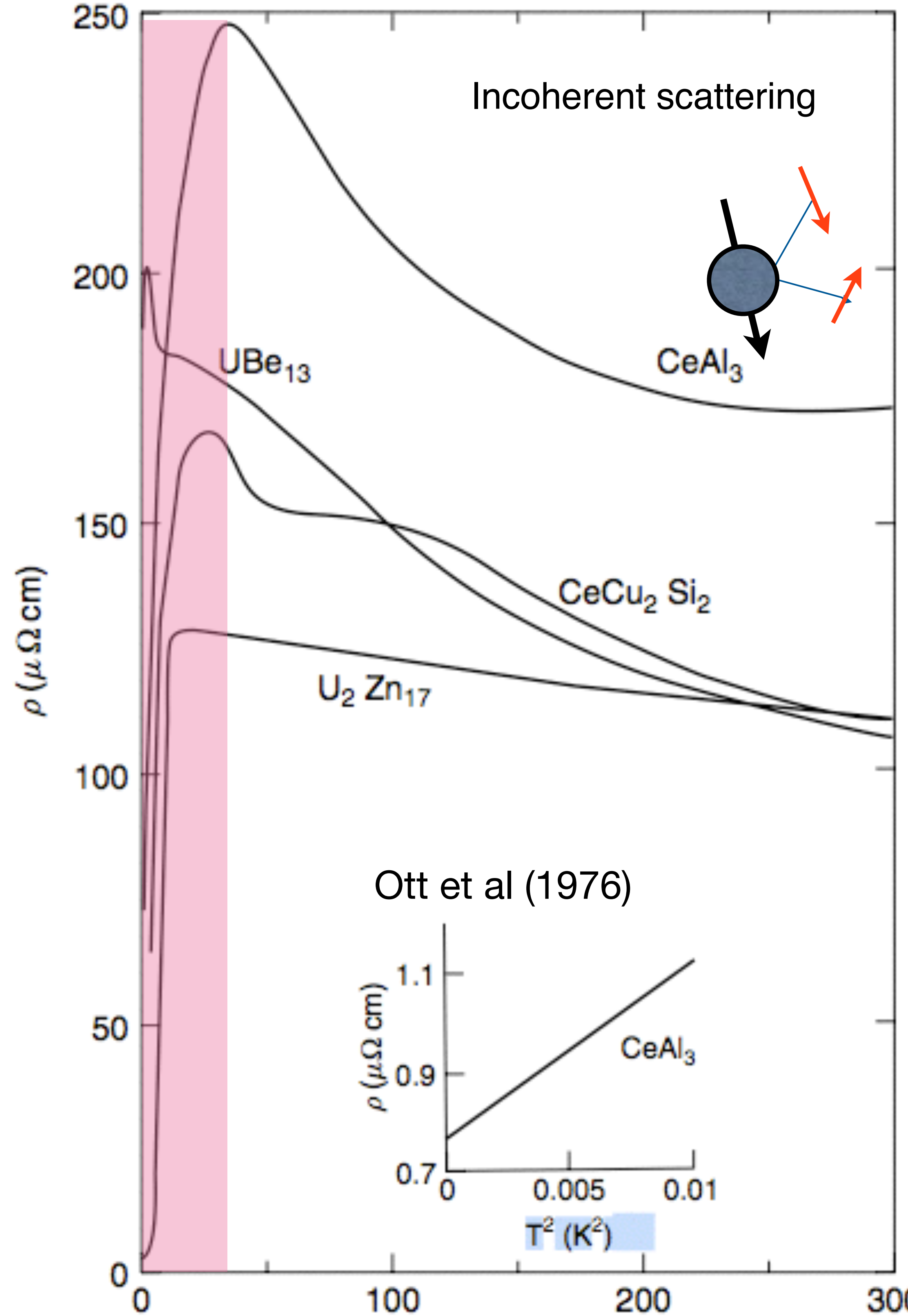

$$\rho(T) = \rho_0 + AT^2$$

Coherent Heavy Fermions

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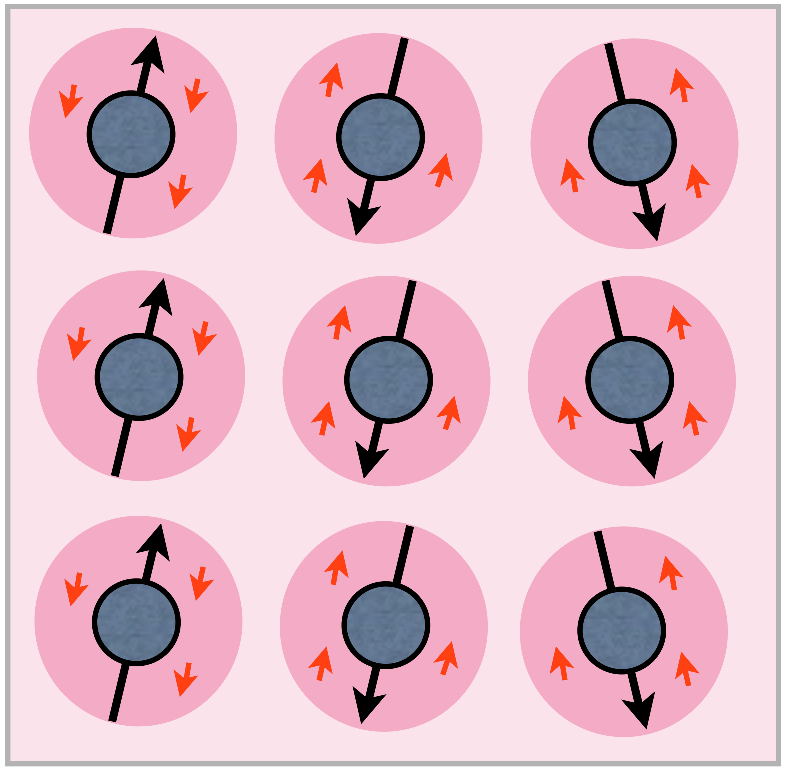
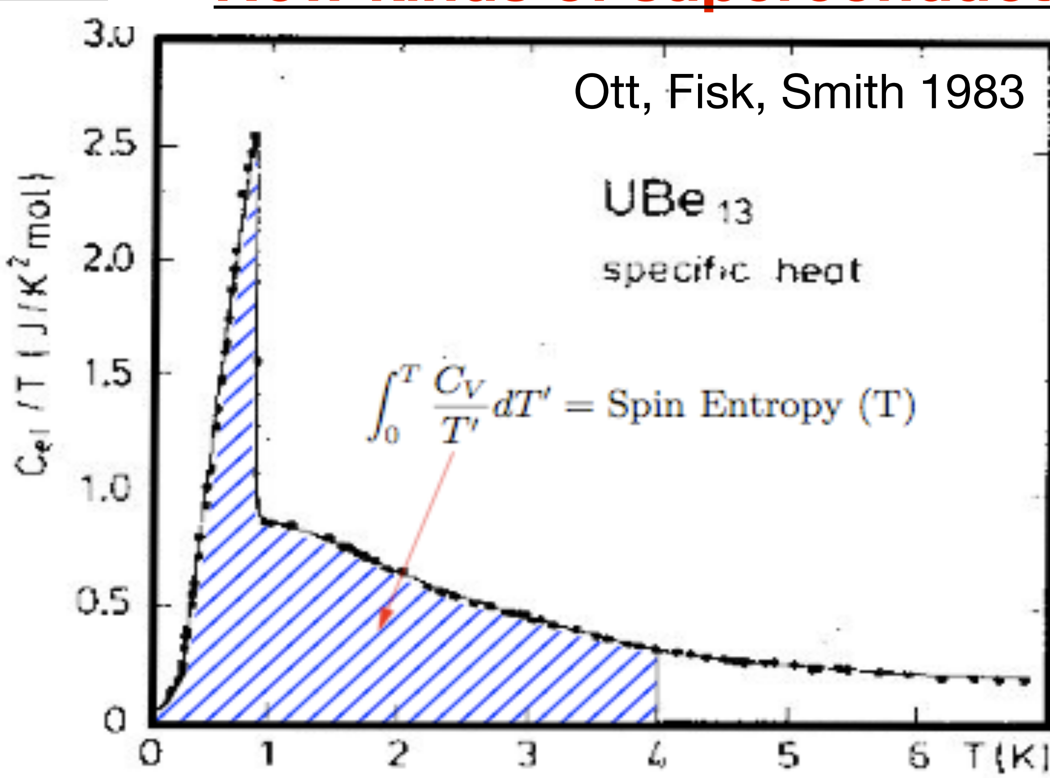
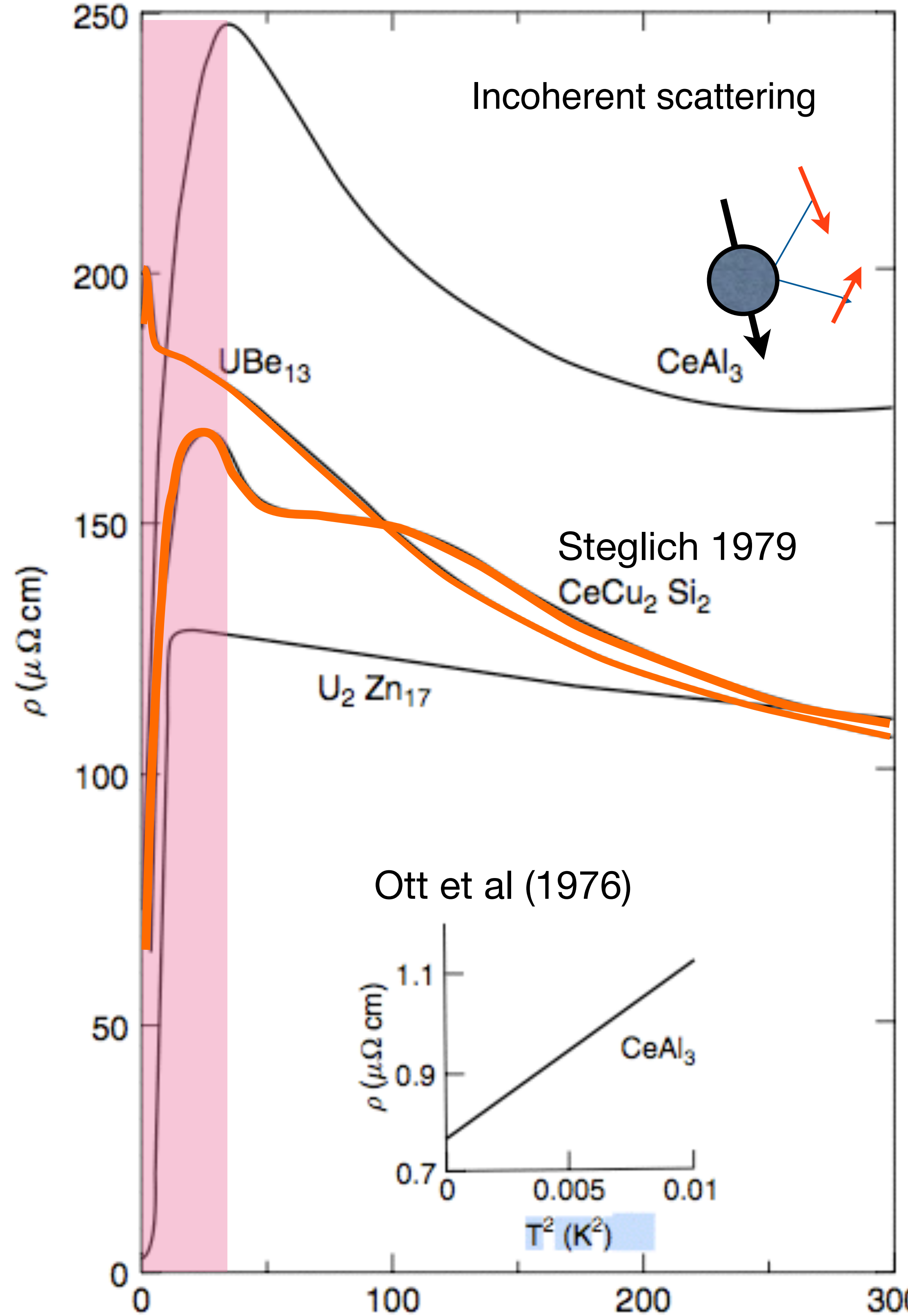


"Kondo Lattice"

Entangled spins and electrons

→ **New kinds of superconductor**





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Coherent Heavy Fermions

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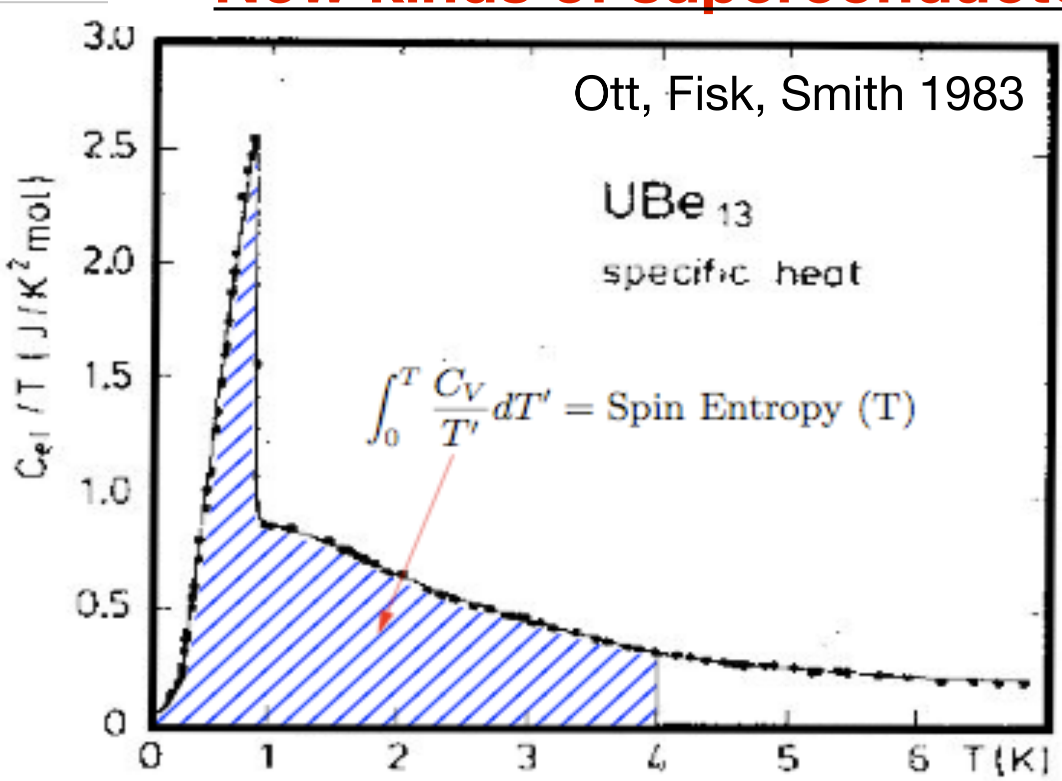
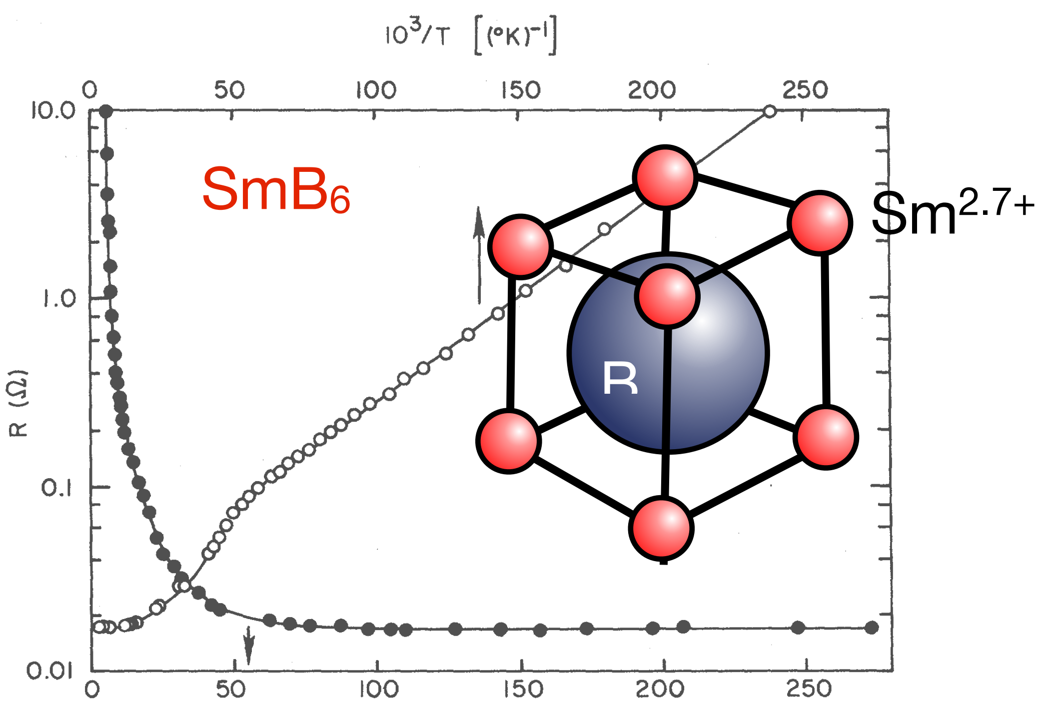


→ **New kinds of insulator**

Kondo Insulators



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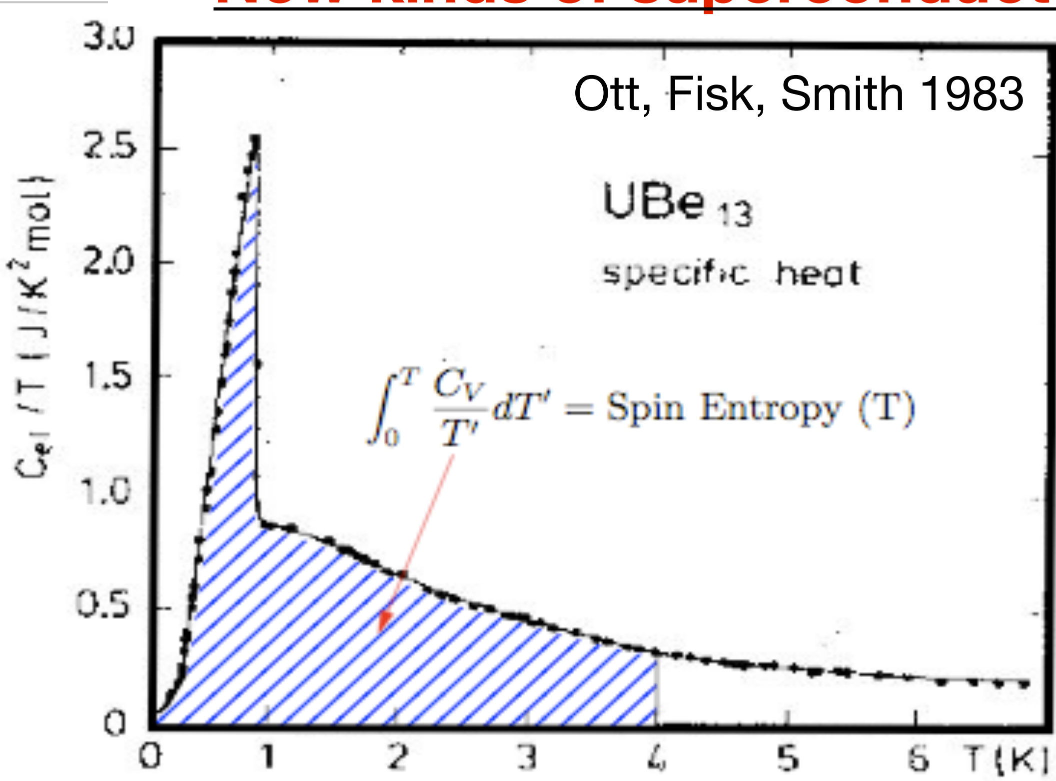
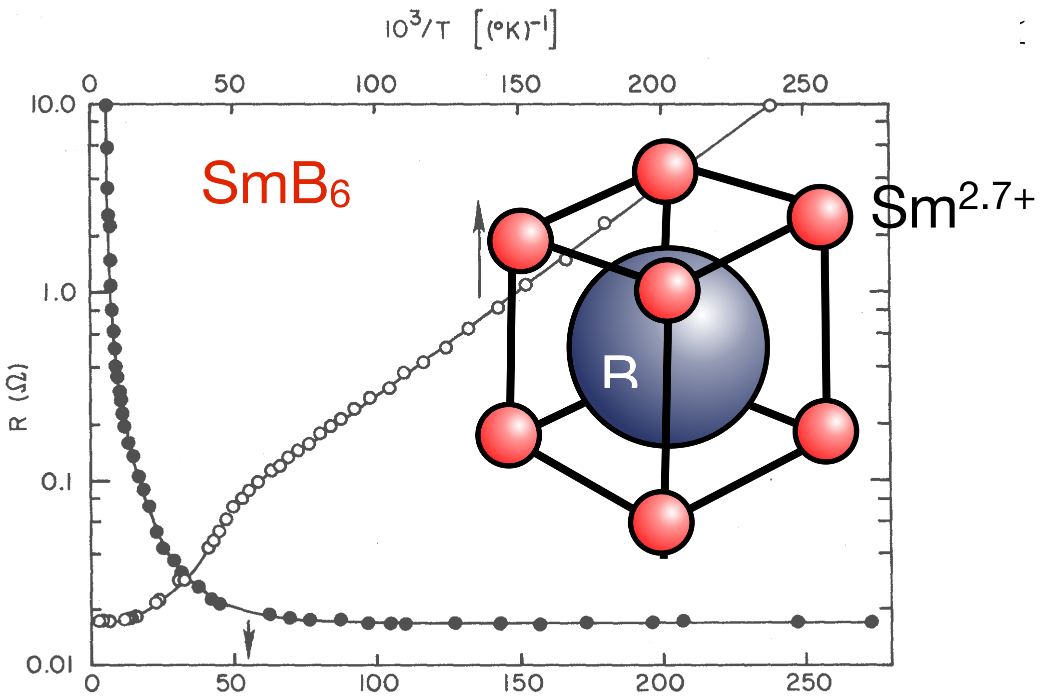
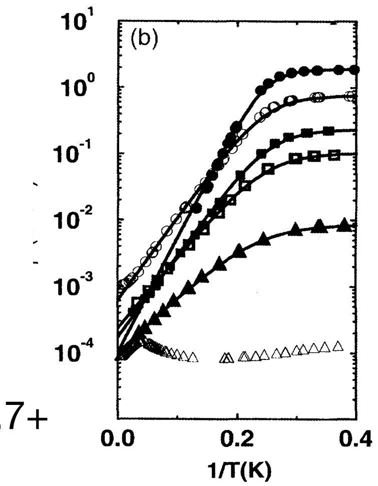


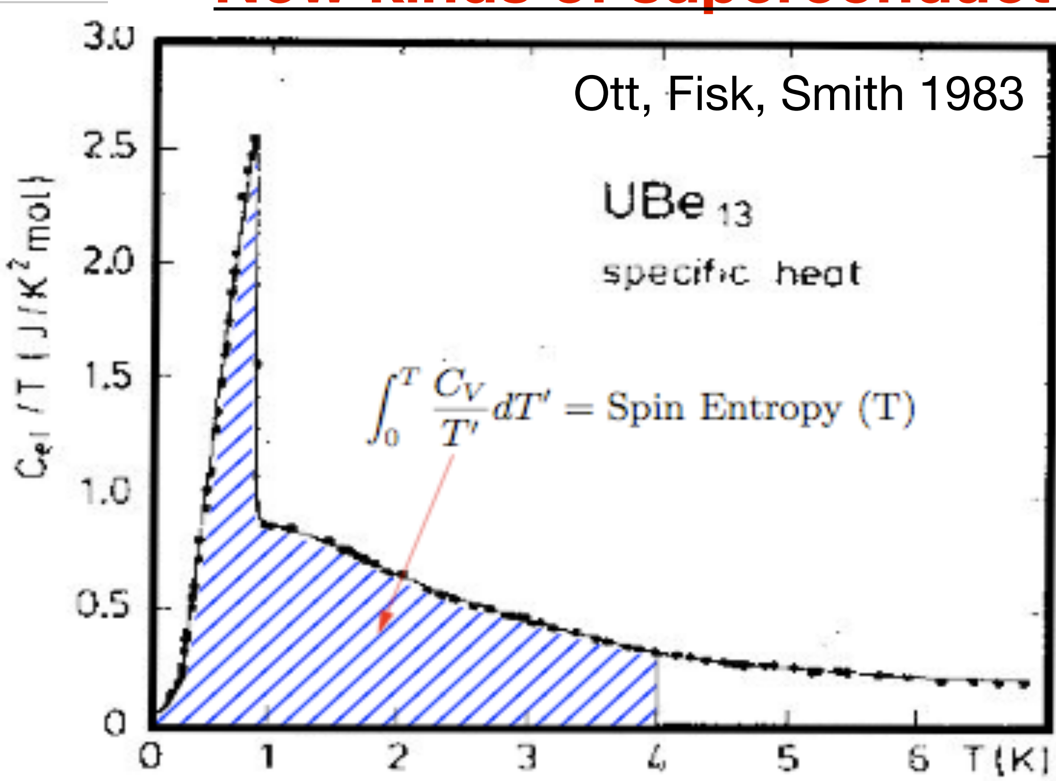
→ New kinds of insulator

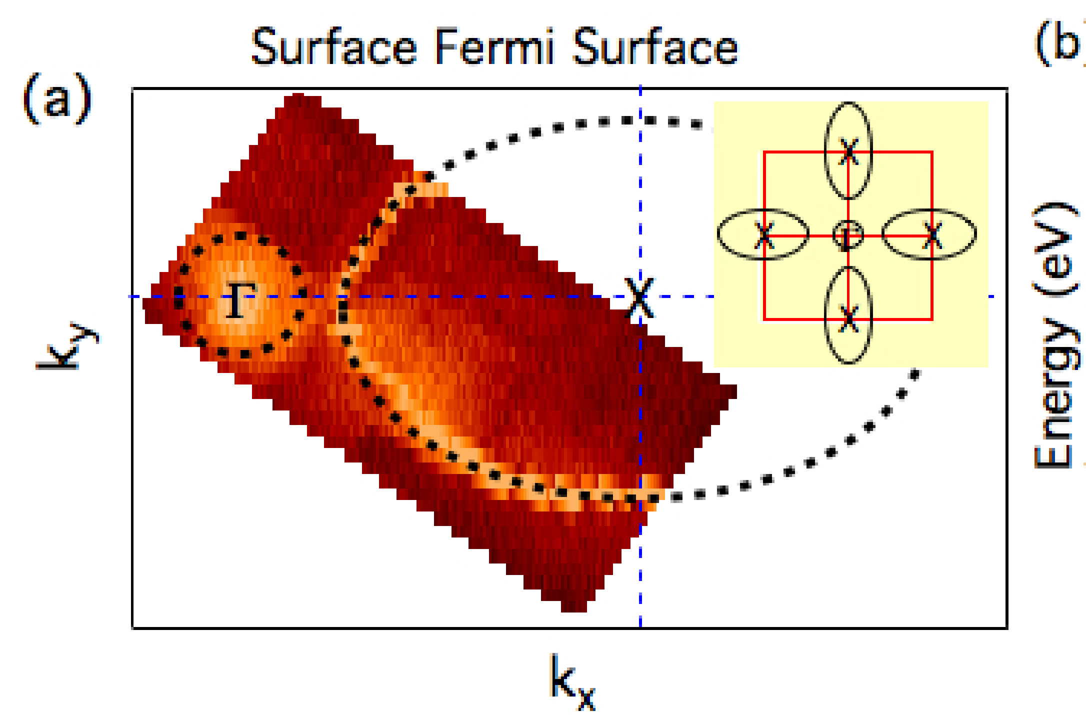
Topological Kondo Insulators





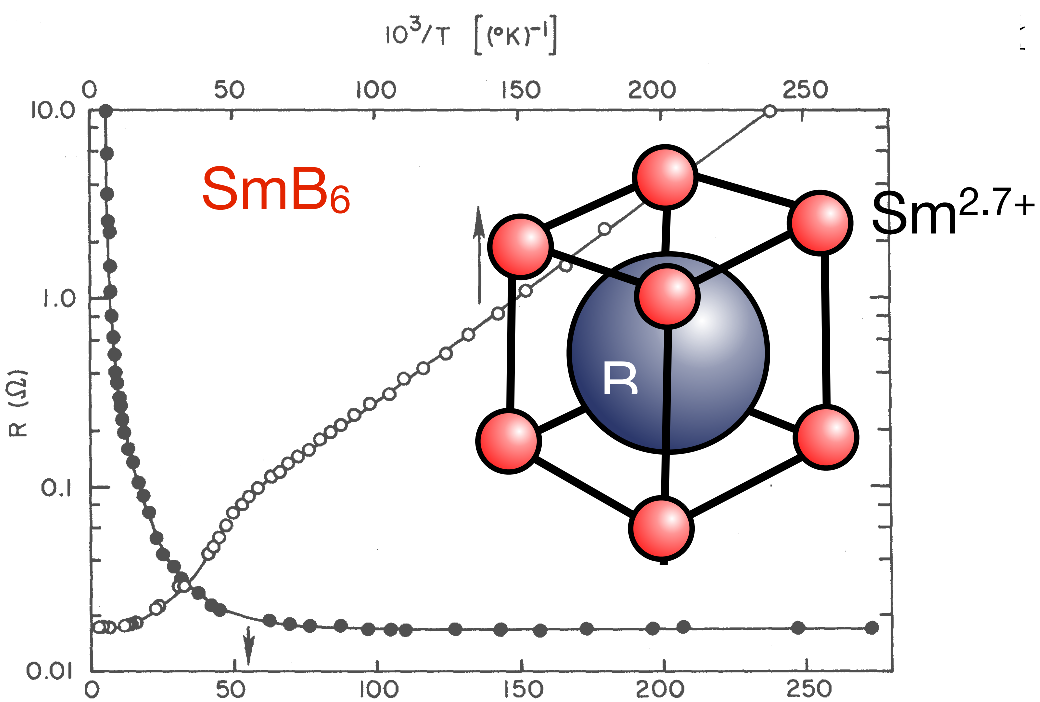
→ New kinds of superconductor

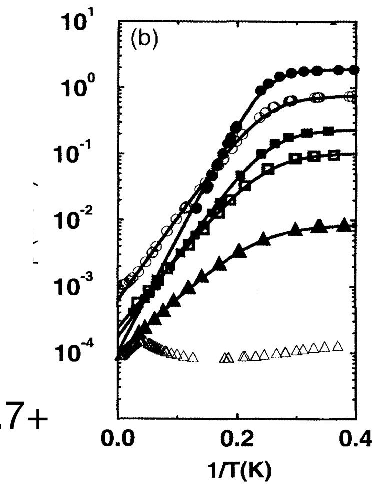




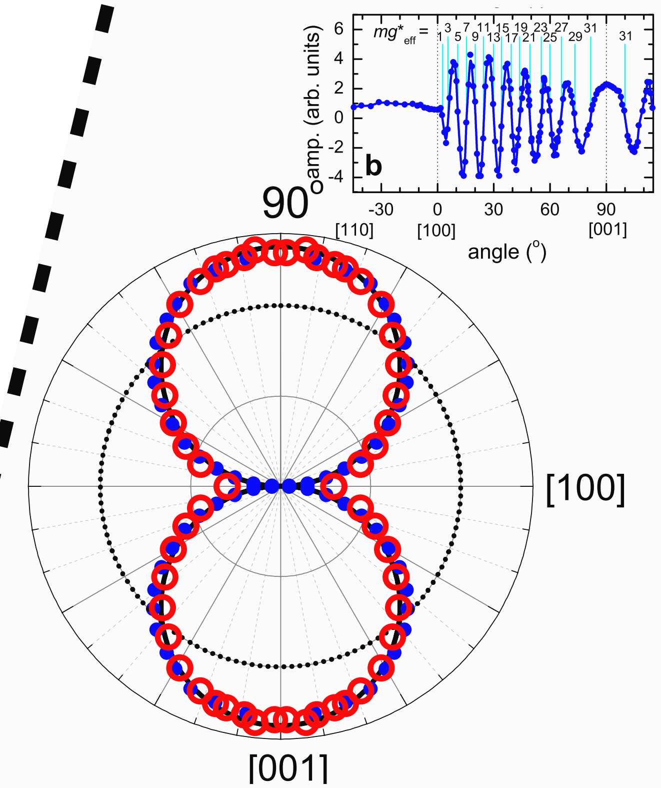
→ New kinds of insulator

Topological Kondo Insulators



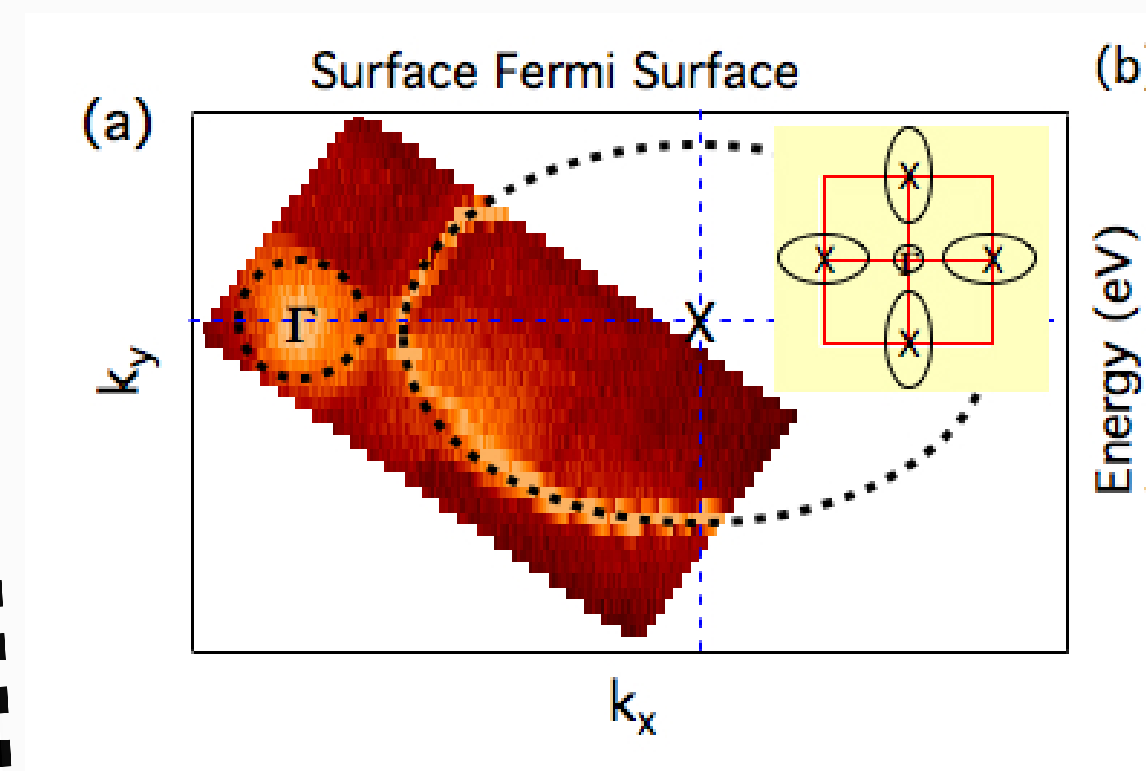


Altarawneh et al., (2012)



URu_2Si_2

→ New kinds of Electron Order



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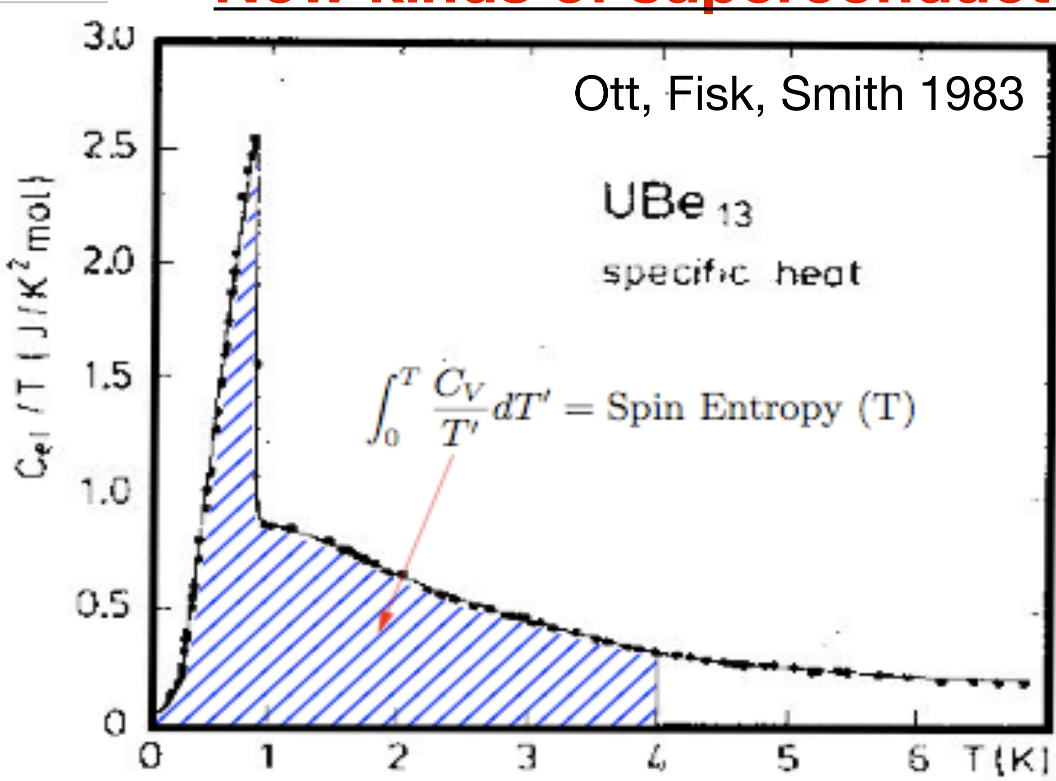

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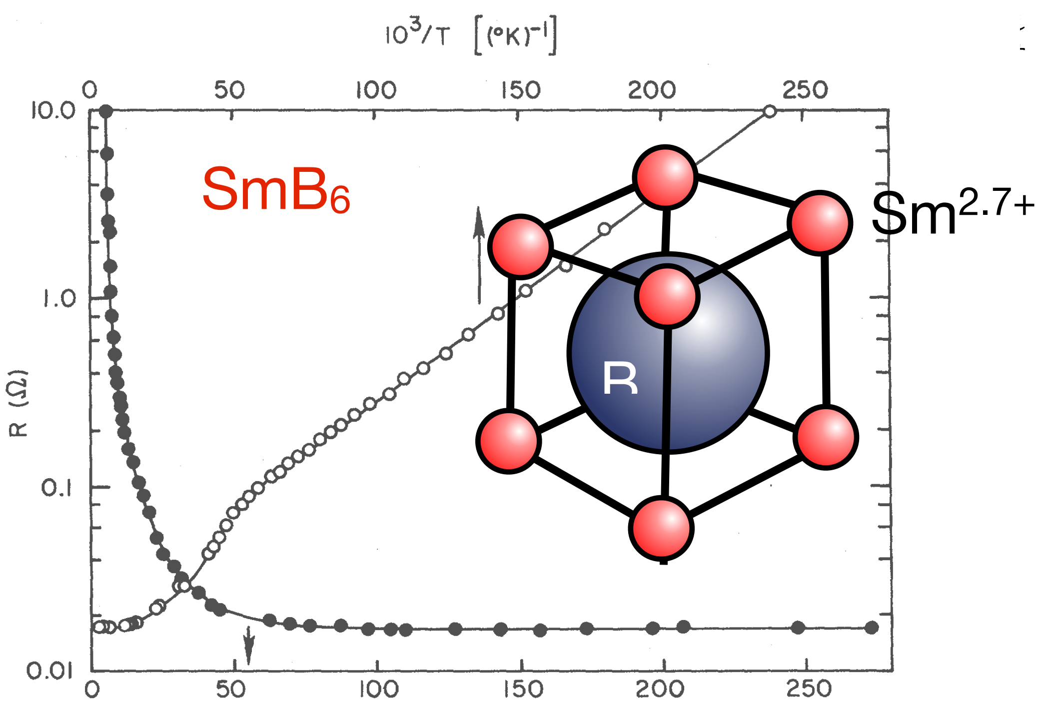

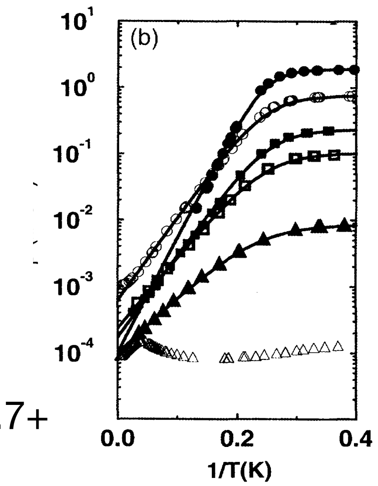

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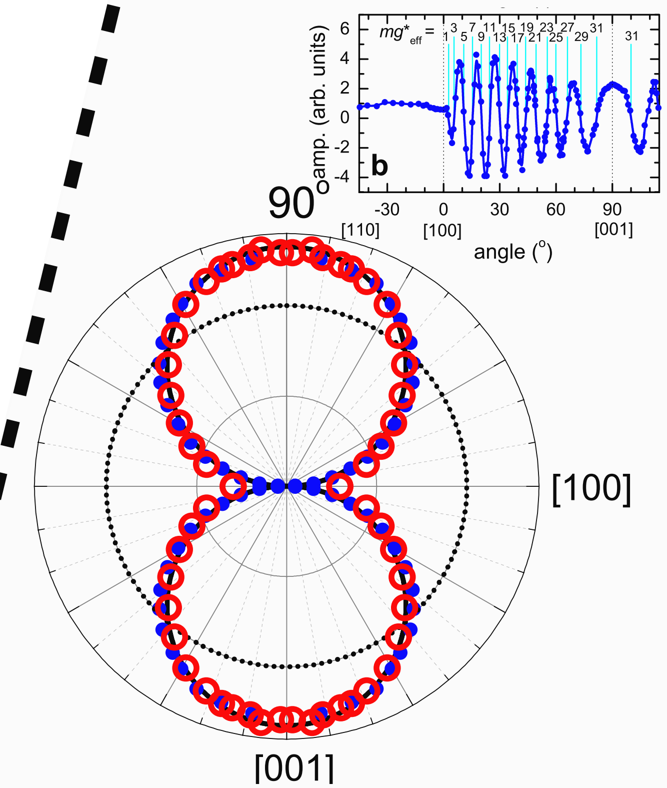
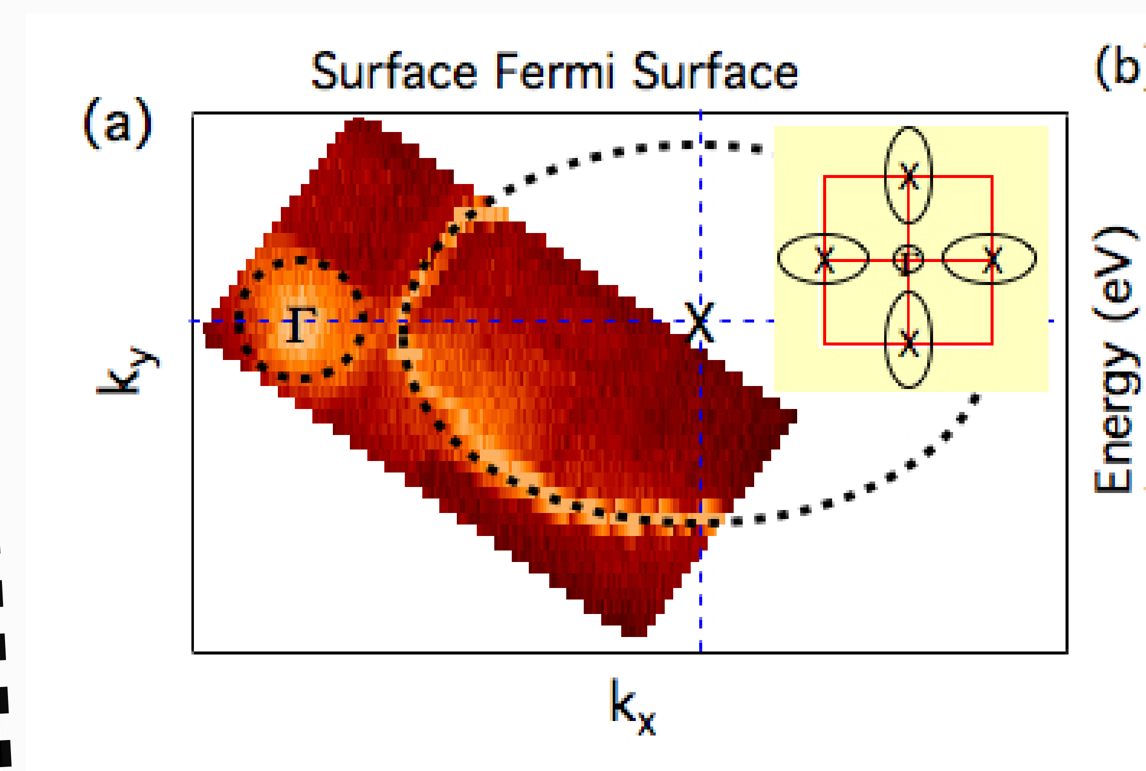


URu_2Si_2

$$\Psi = \begin{pmatrix} \langle \Psi_\uparrow \rangle \\ \langle \Psi_\downarrow \rangle \end{pmatrix}$$

Ising Electrons: *Hastatic order ?*

→ New kinds of Electron Order



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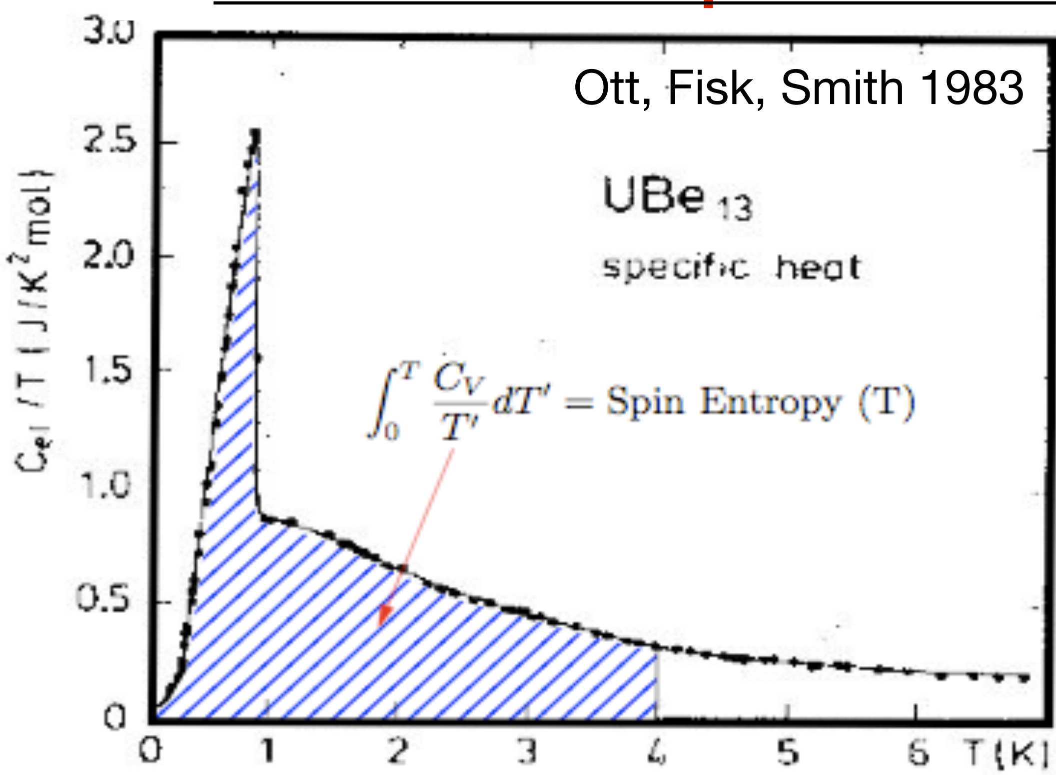

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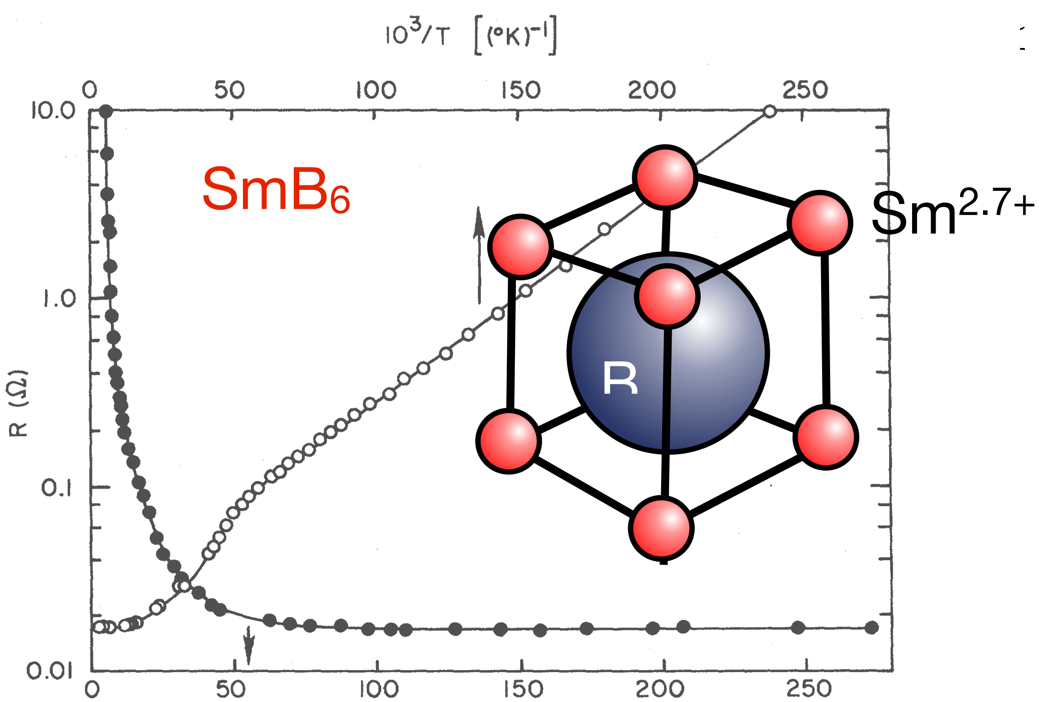
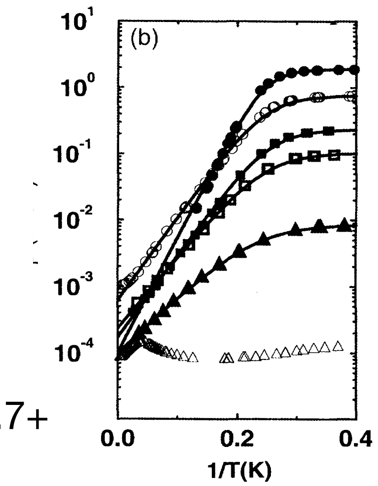
Topological Kondo Insulators





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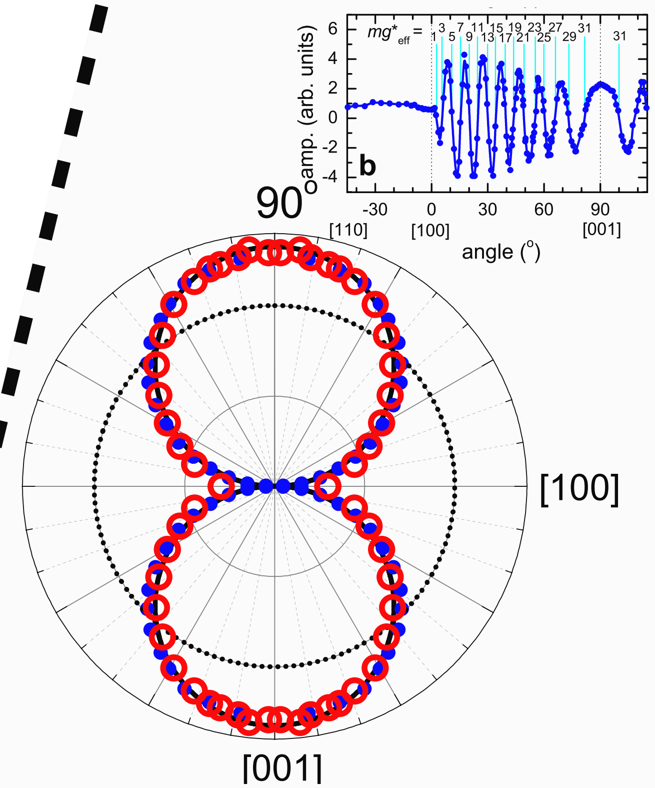

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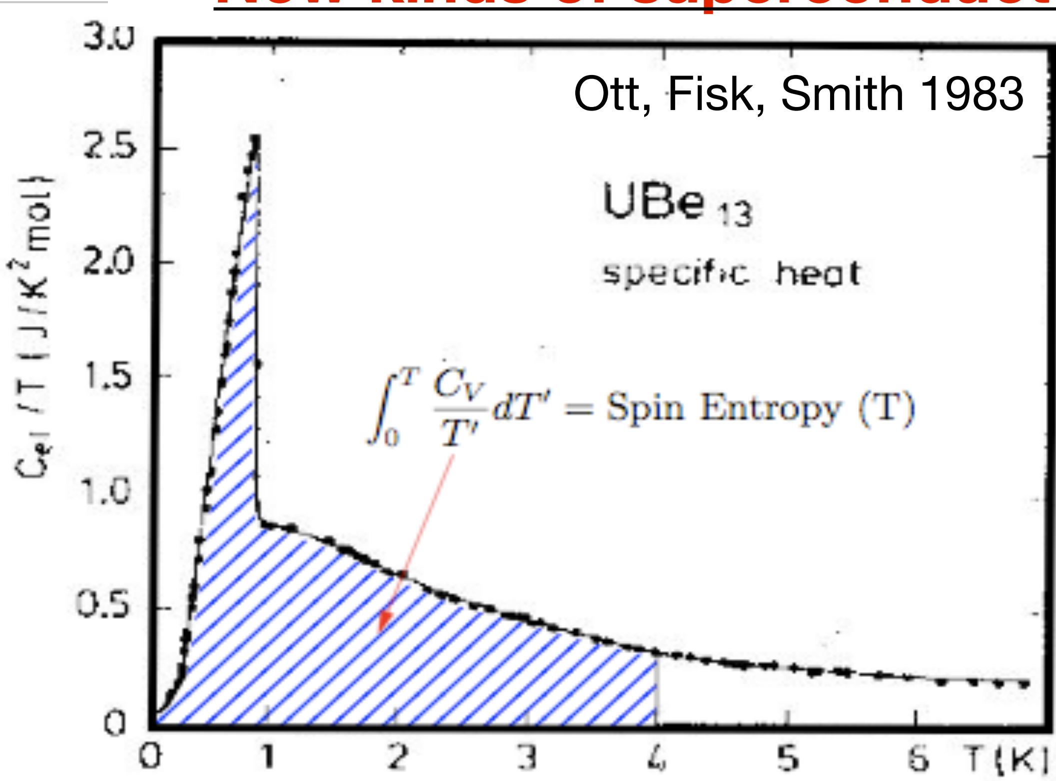
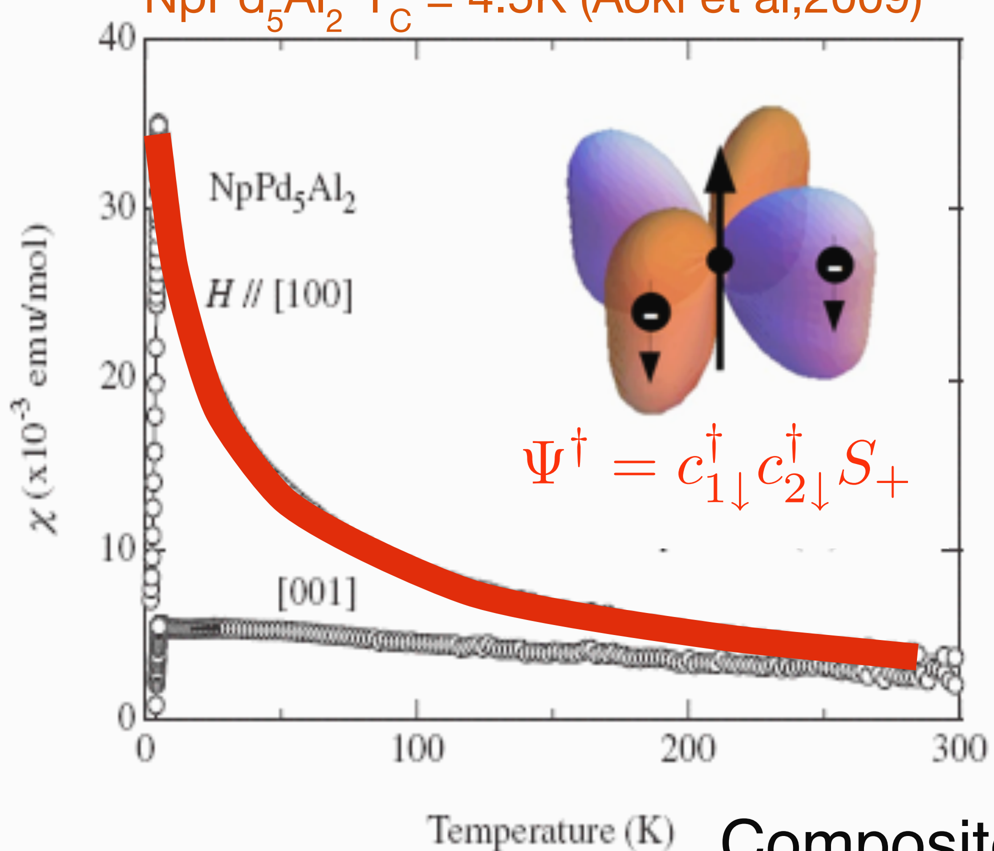


→ New kinds of Electron Order

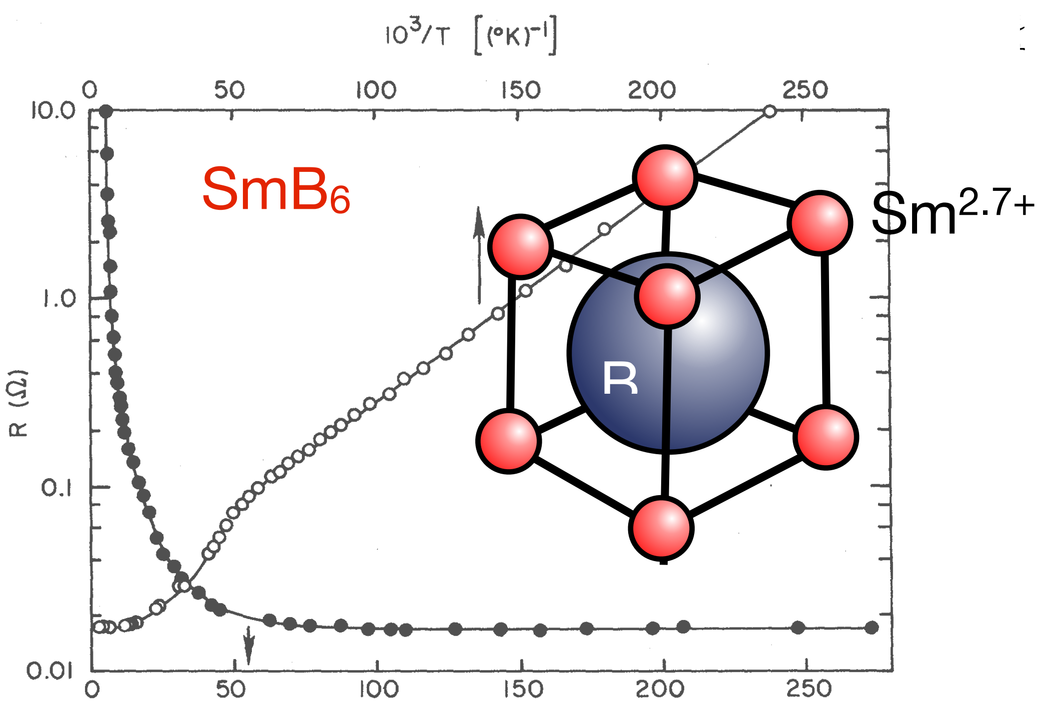
NpPd$_5$Al$_2$ T_C = 4.5K (Aoki et al,2009)

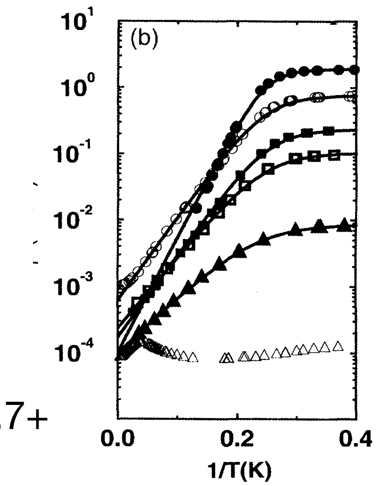


Composite Pairing

→ New kinds of insulator

Topological Kondo Insulators





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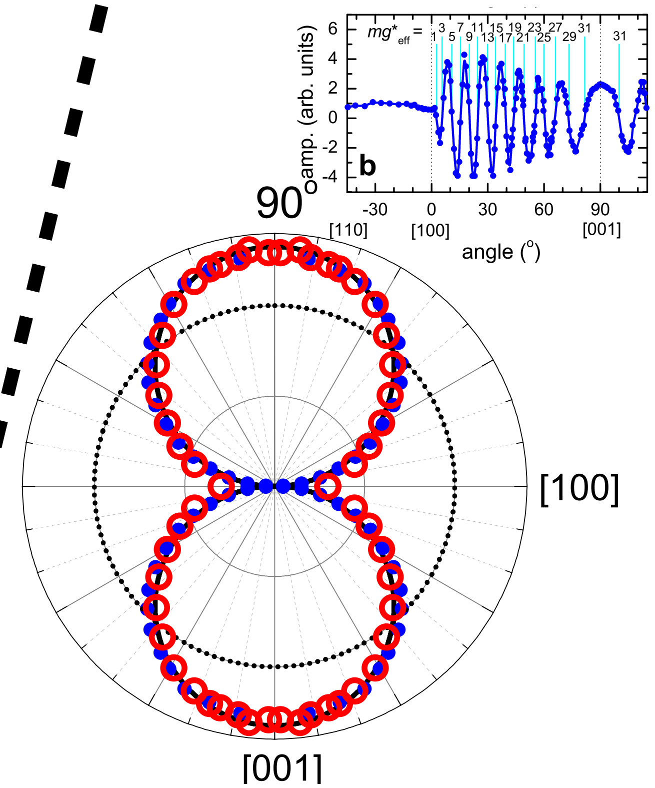

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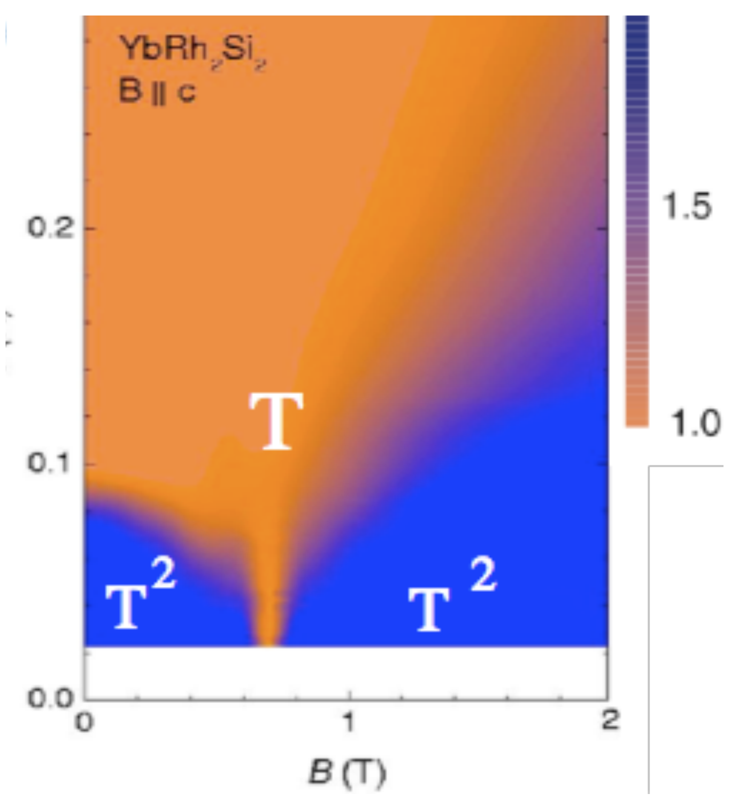
Ising Electrons: *Hastatic order*

→ New kinds of Phase Transition



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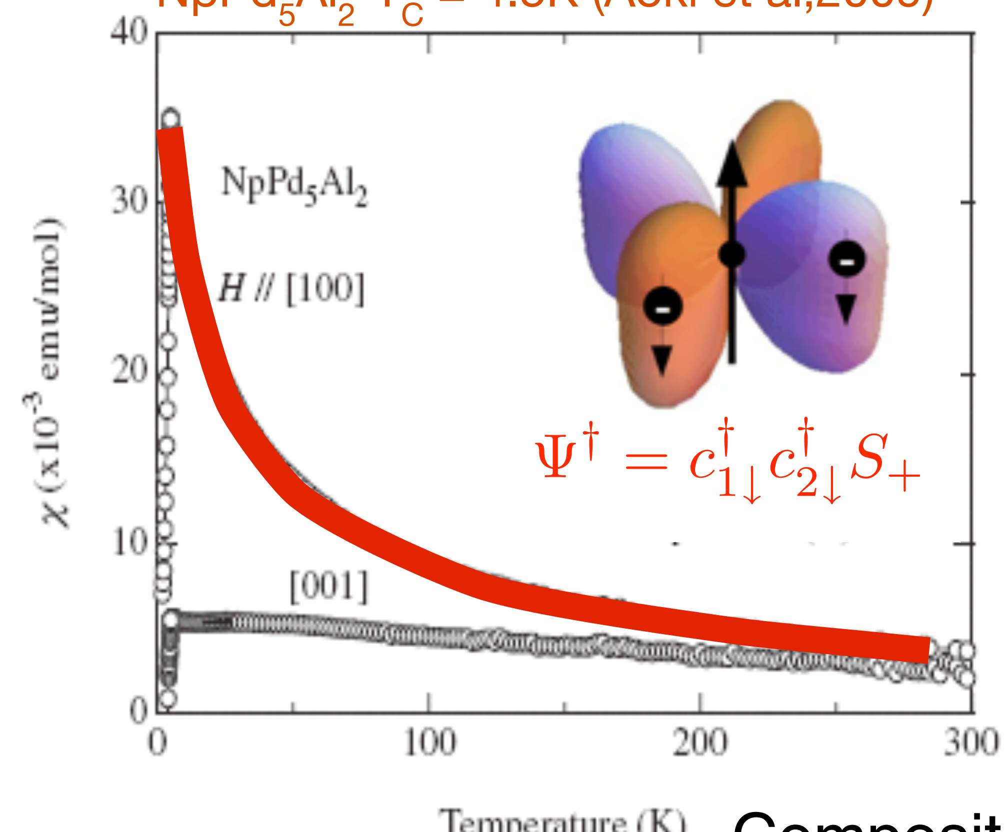
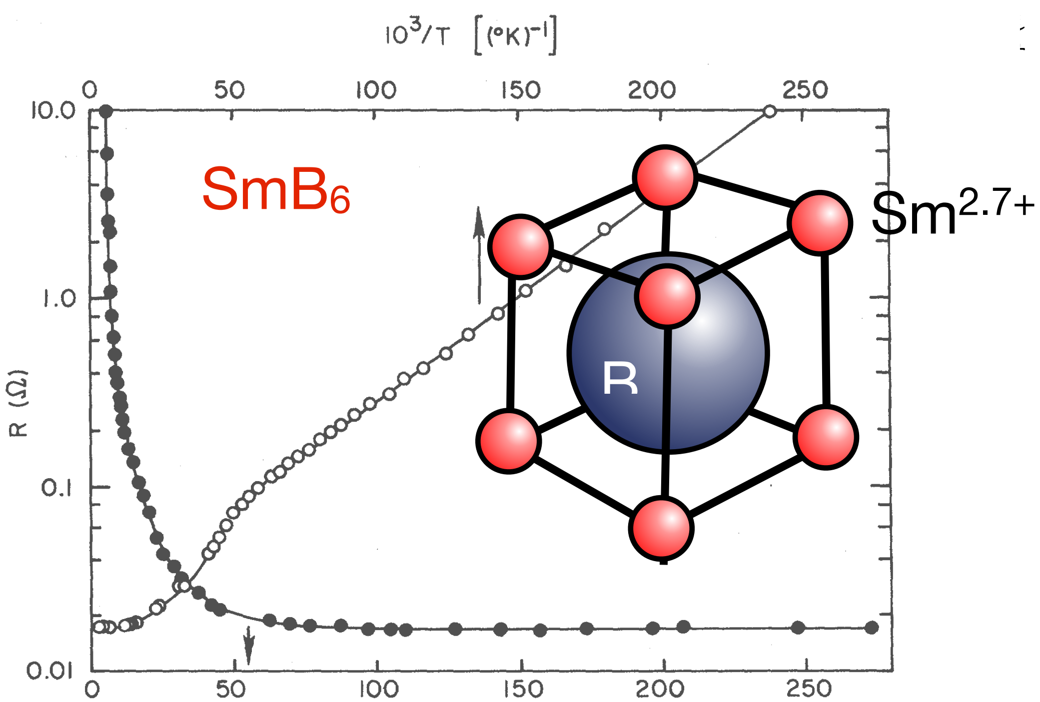
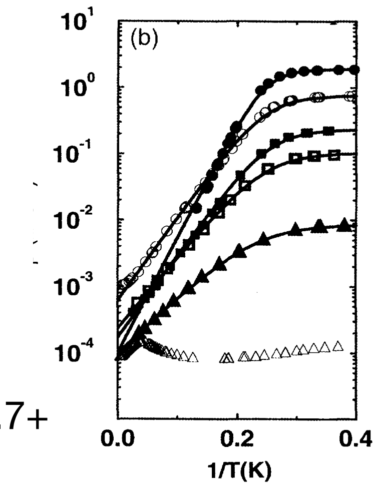


Composite Pairing

→ New kinds of insulator

Topological Kondo Insulators





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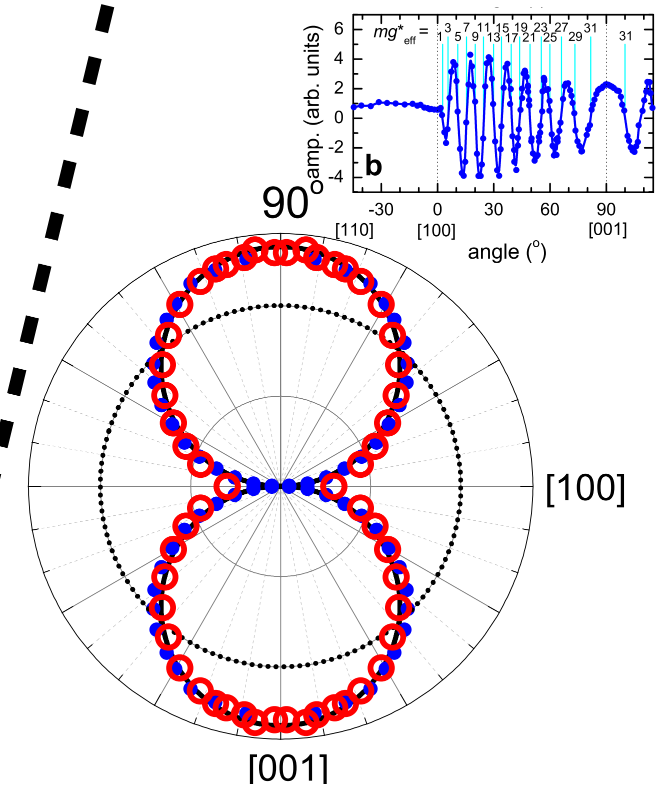

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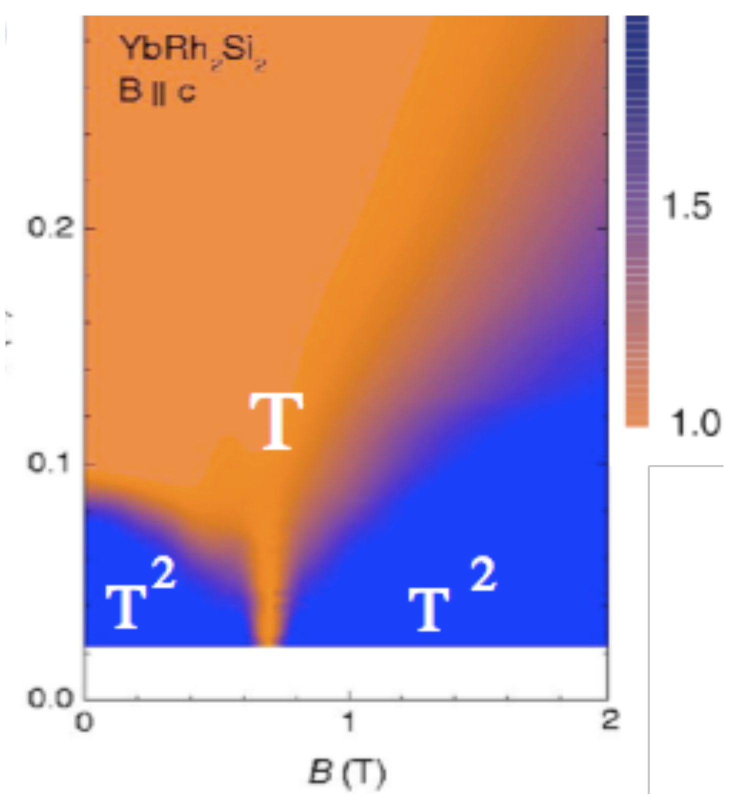
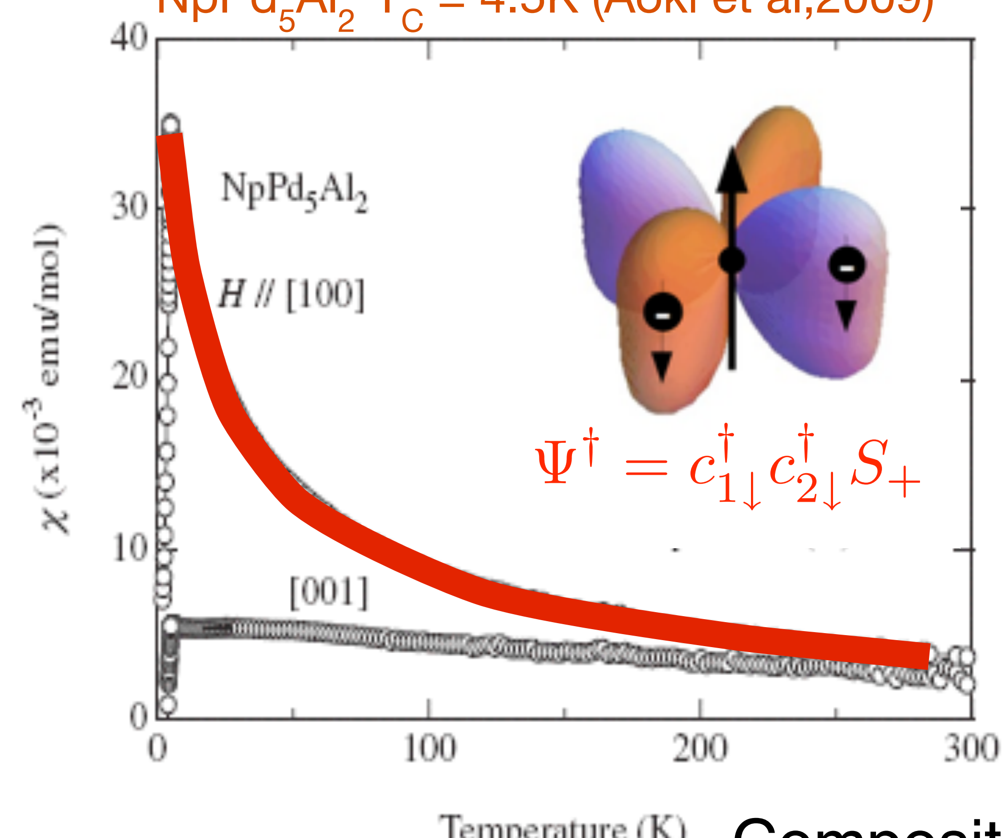


→ Quantum Criticality

→ New kinds of Electron Order

$NpPd_5Al_2$ T_C = 4.5K (Aoki et al,2009)

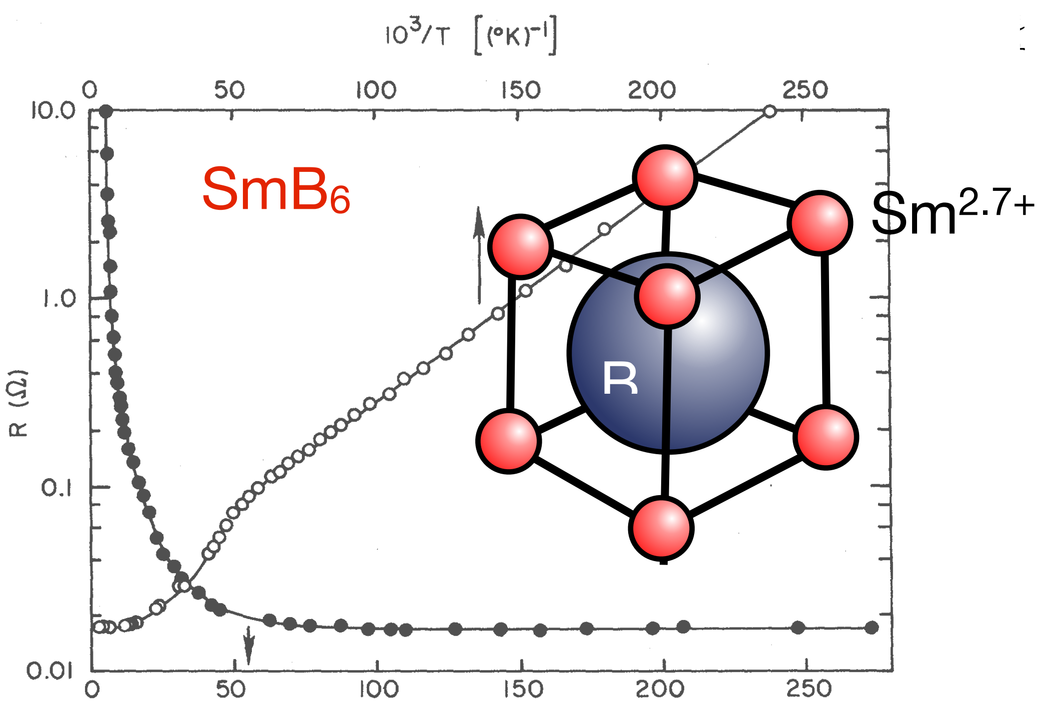


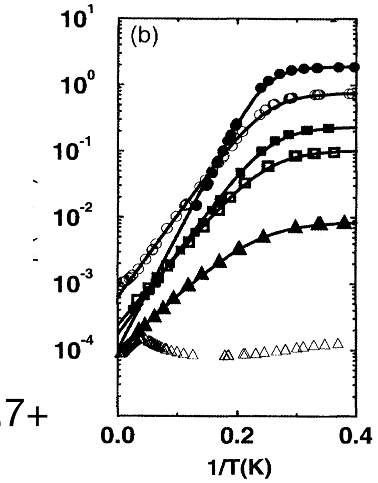
$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

Composite Pairing

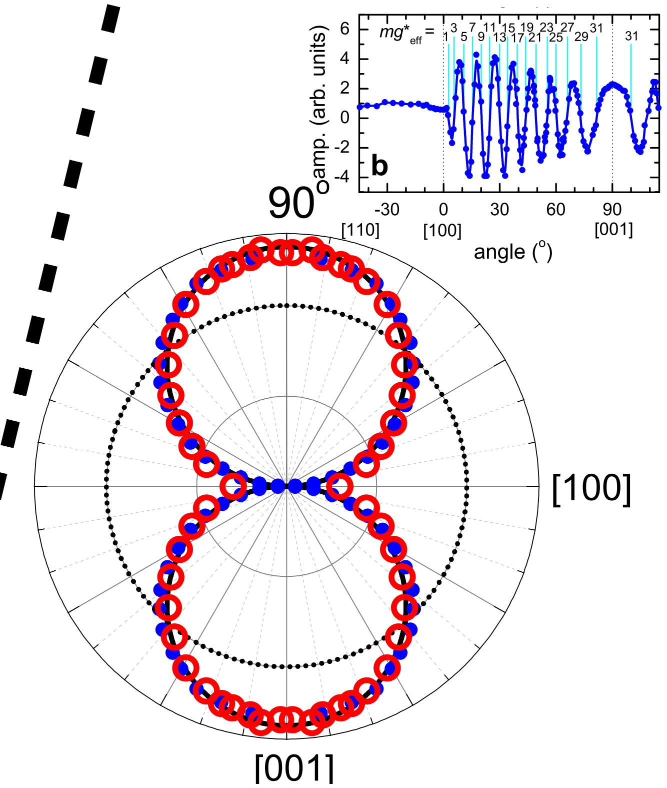
→ New kinds of insulator

Topological Kondo Insulators





Altarawneh et al., (2012)



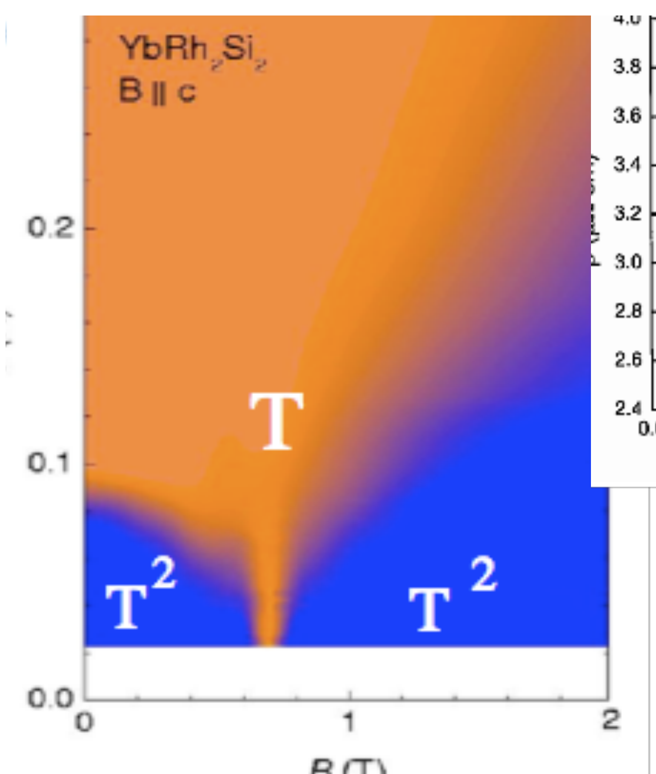
URu_2Si_2

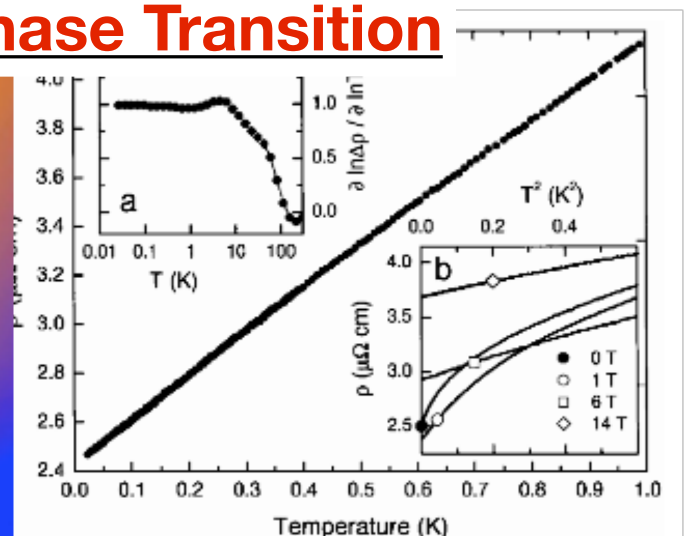
$$\Psi = \begin{pmatrix} \langle \Psi_\uparrow \rangle \\ \langle \Psi_\downarrow \rangle \end{pmatrix}$$

Ising Electrons: *Hastatic order*

→ New kinds of Electron Order

→ New kinds of Phase Transition





→ Strange Metals

→ Quantum Criticality

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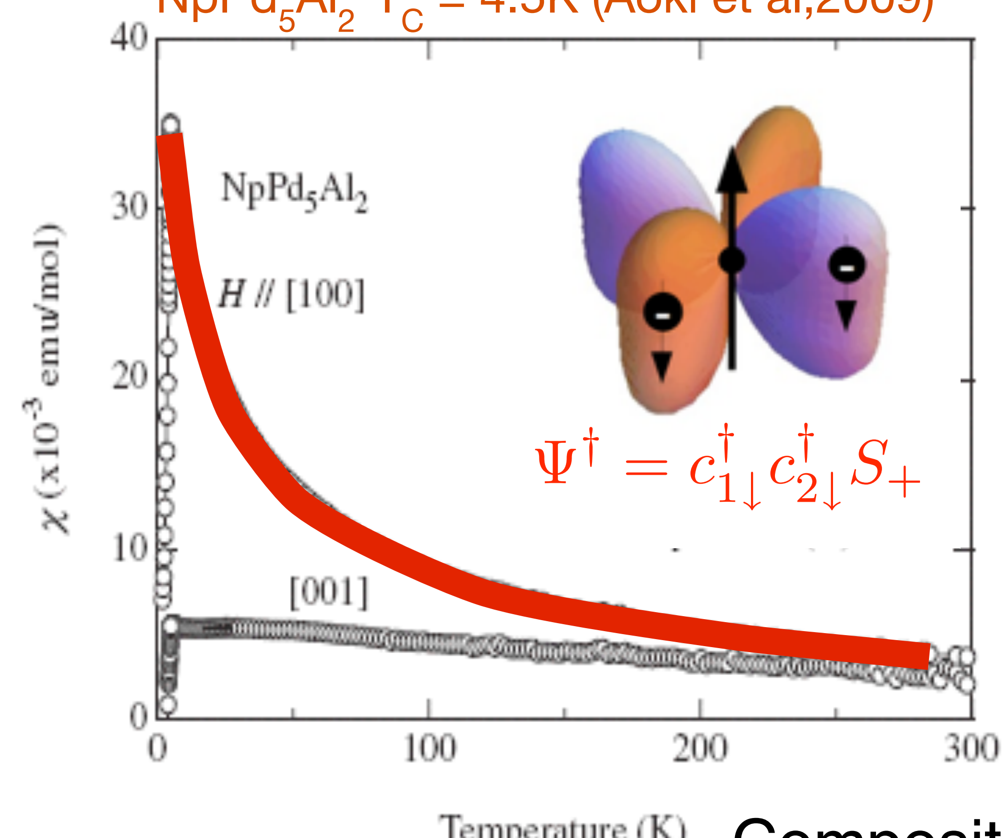

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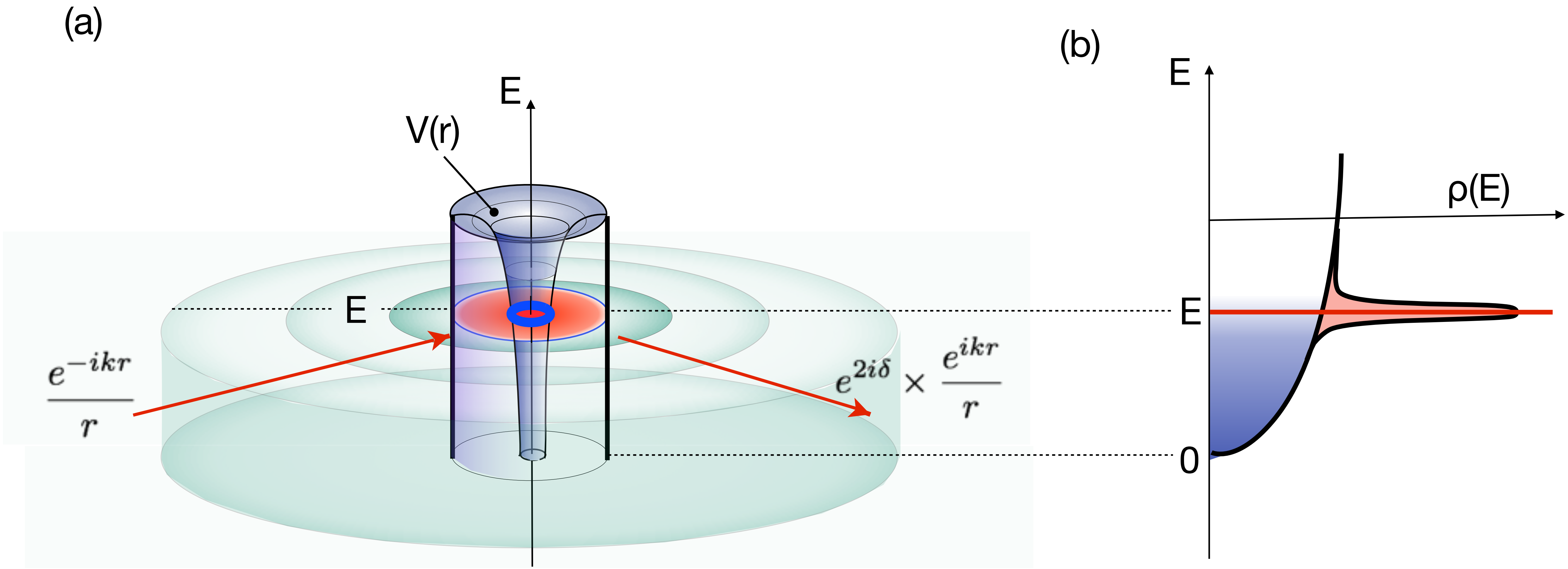
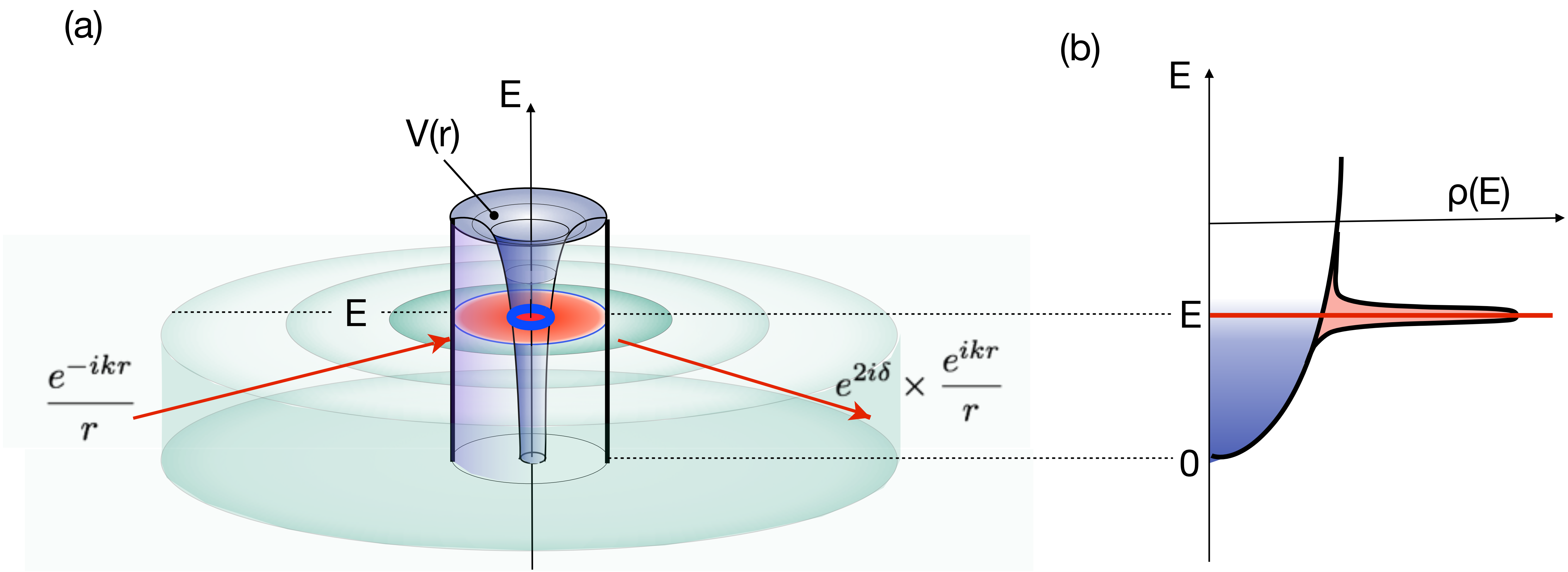
Composite Pairing

The Anderson and Kondo Models

The Anderson Model.

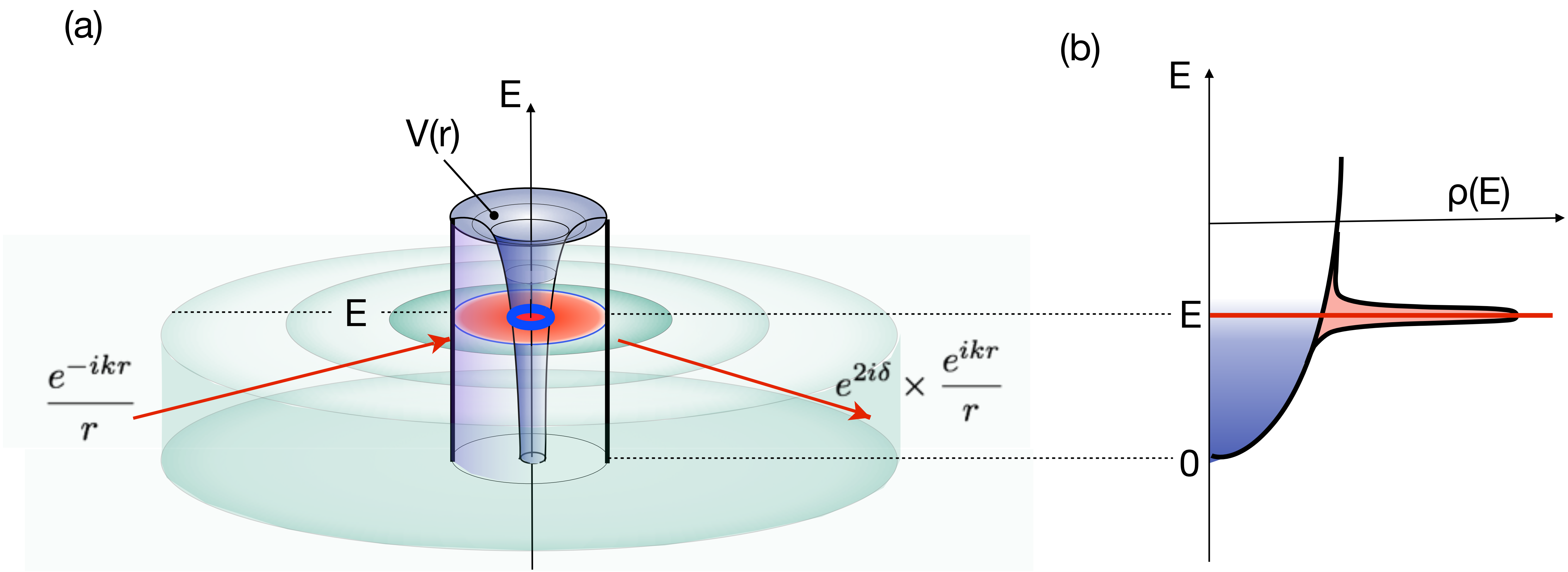


The Anderson Model.



$$H = \overbrace{\sum_{\mathbf{k},\sigma} \epsilon_{\mathbf{k}} n_{\mathbf{k}\sigma} + \sum_{\mathbf{k},\sigma} \left[V(\mathbf{k}) c^{\dagger}_{\mathbf{k}\sigma} f_{\sigma} + V^{*}(\mathbf{k}) f^{\dagger}_{\sigma} c_{\mathbf{k}\sigma} \right]}^{H_{resonance}} + \underbrace{E_f n_f + U n_{f\uparrow} n_{f\downarrow}}_{H_{atomic}},$$

The Anderson Model.



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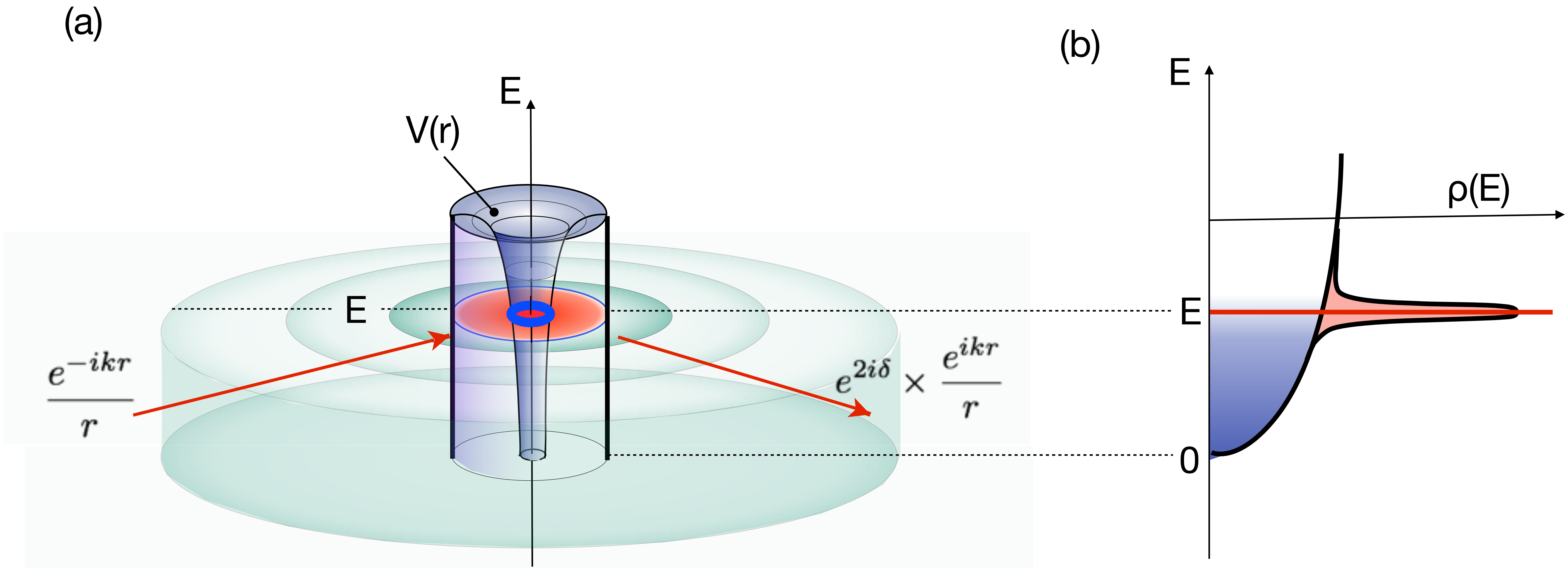

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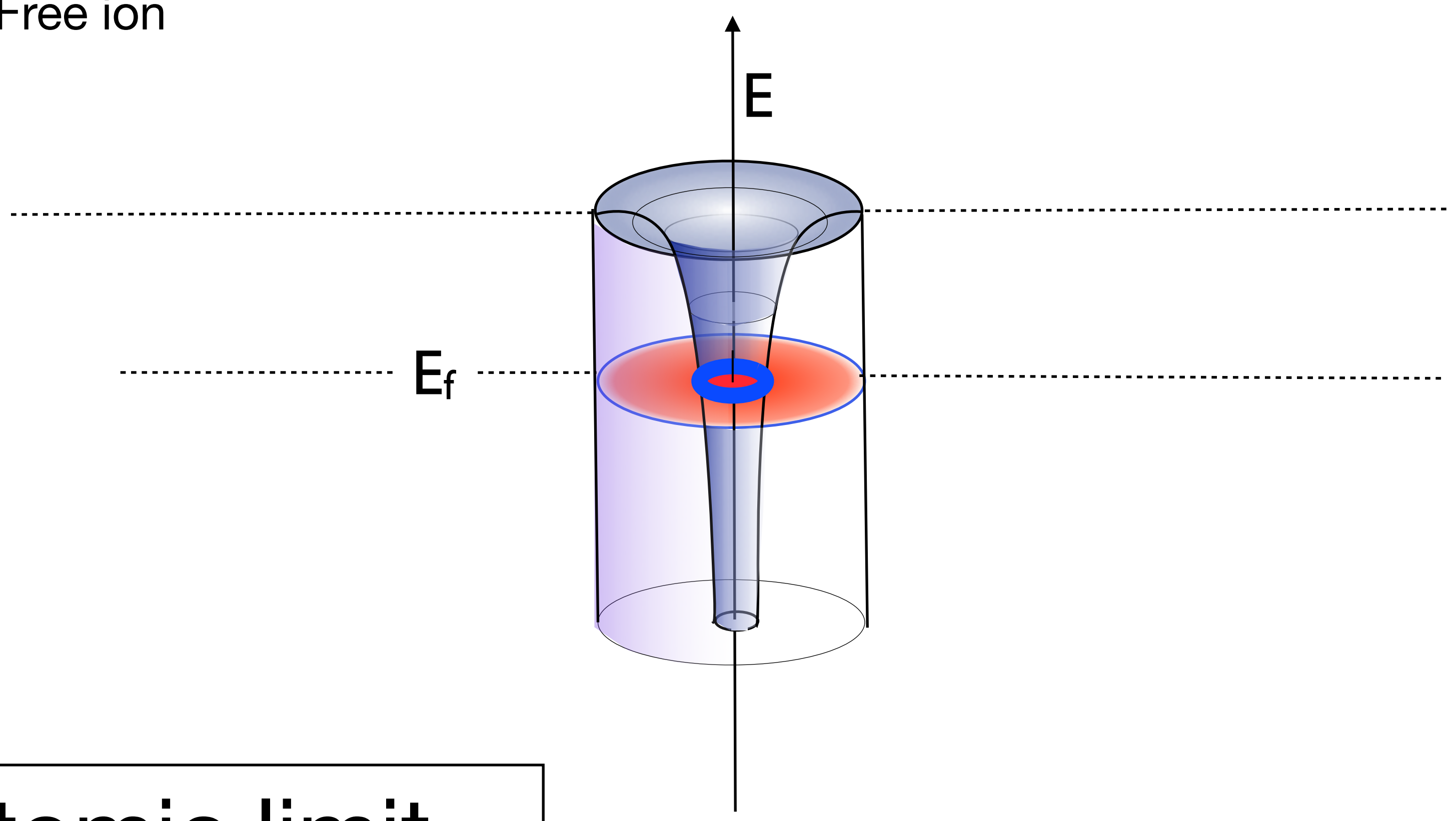
$$f^{\dagger}{}_{\sigma} = \int_{\mathbf{r}} \Psi_f(\mathbf{r}) \hat{\psi}^{\dagger}{}_{\sigma}(r), \qquad U = \frac{e^2}{4\pi\epsilon_0} \int_{\mathbf{r},\mathbf{r}'} \frac{1}{|\mathbf{r} - \mathbf{r}'|} \rho_f(\mathbf{r}) \rho_f(\mathbf{r}')$$

Atomic limit
($V=0$)

$$\left[-\nabla^2 + \hat{V}_{ion}\right]|f\rangle = E_f^{ion}|f\rangle,$$

$$H_{atomic} = E_f n_f + U n_{f\uparrow} n_{f\downarrow}.$$

Free ion



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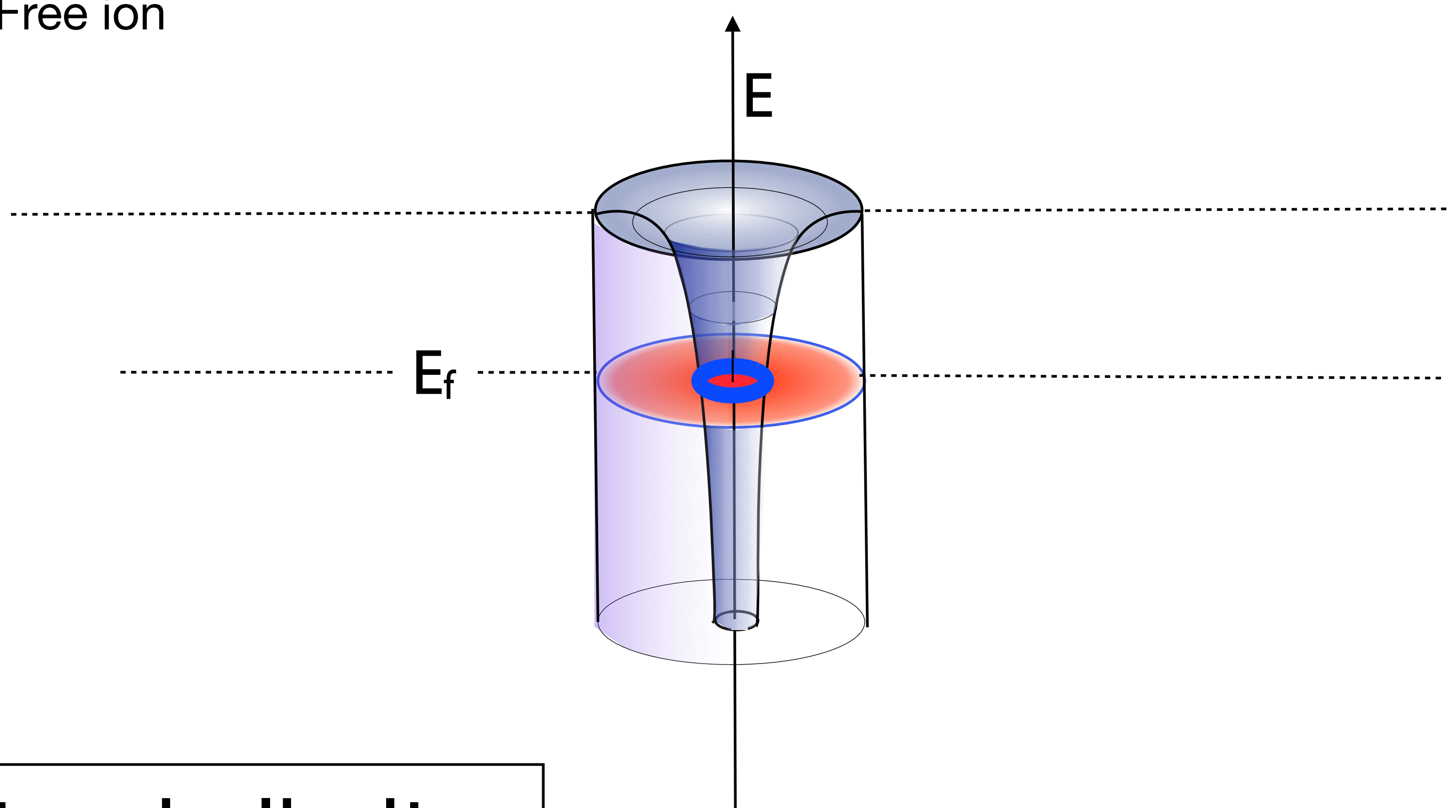

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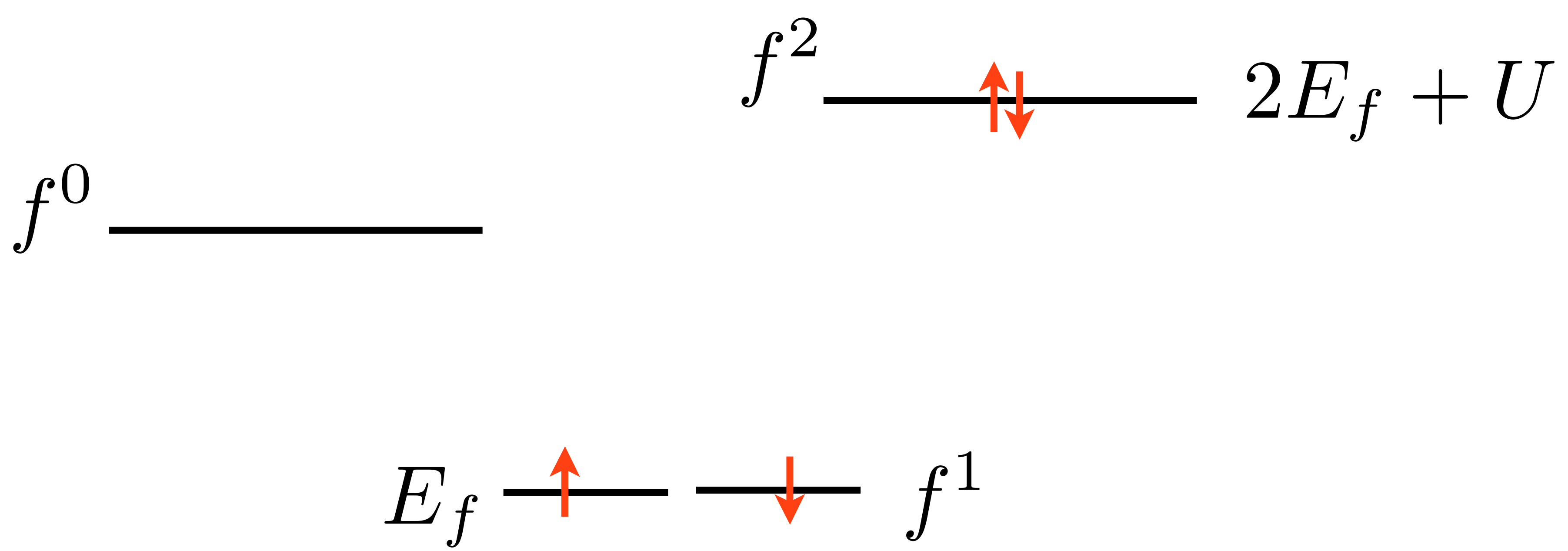

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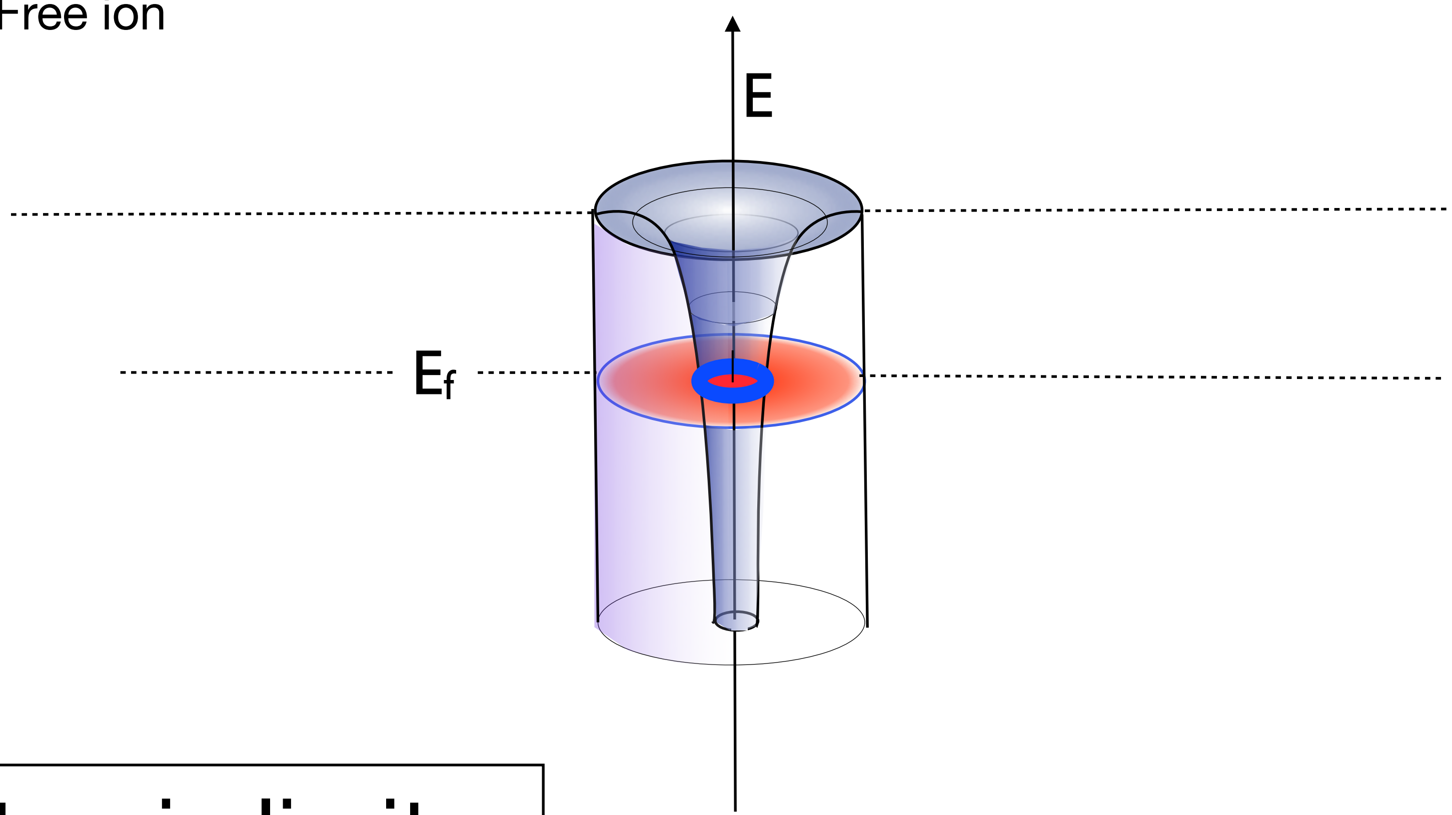

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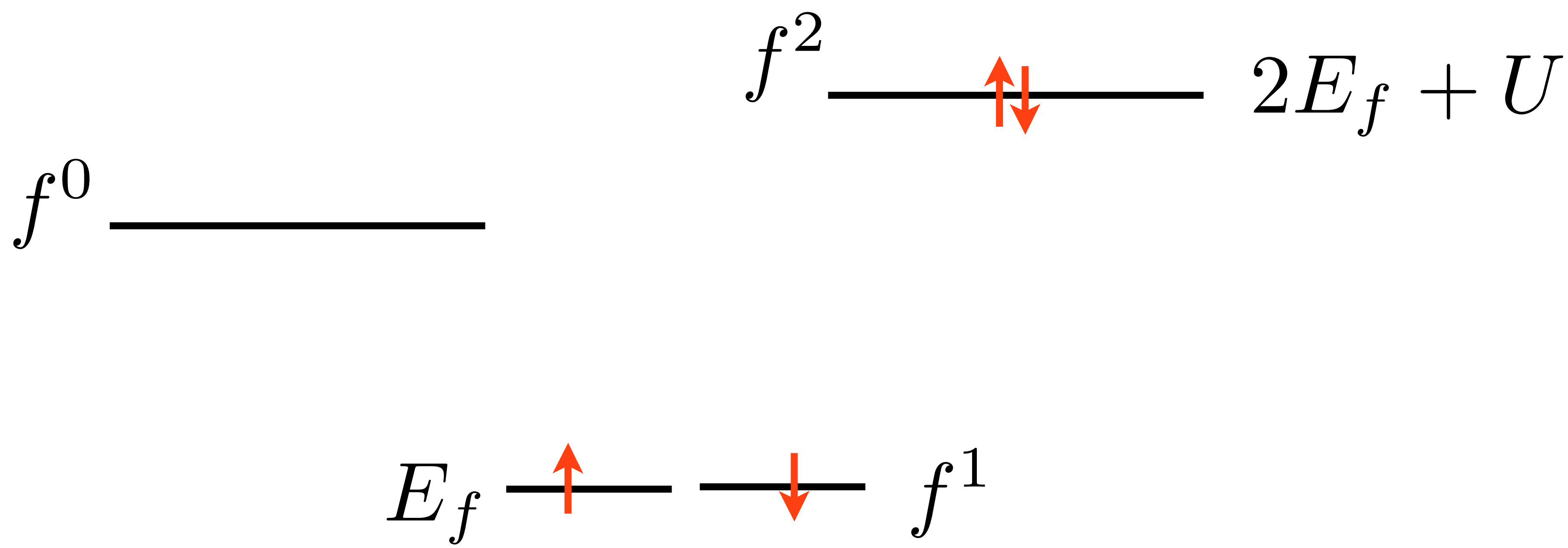

$$\left.\begin{array}{rcl} E_f & < & 0 \\ U + E_f & > & 0 \end{array}\right\}$$

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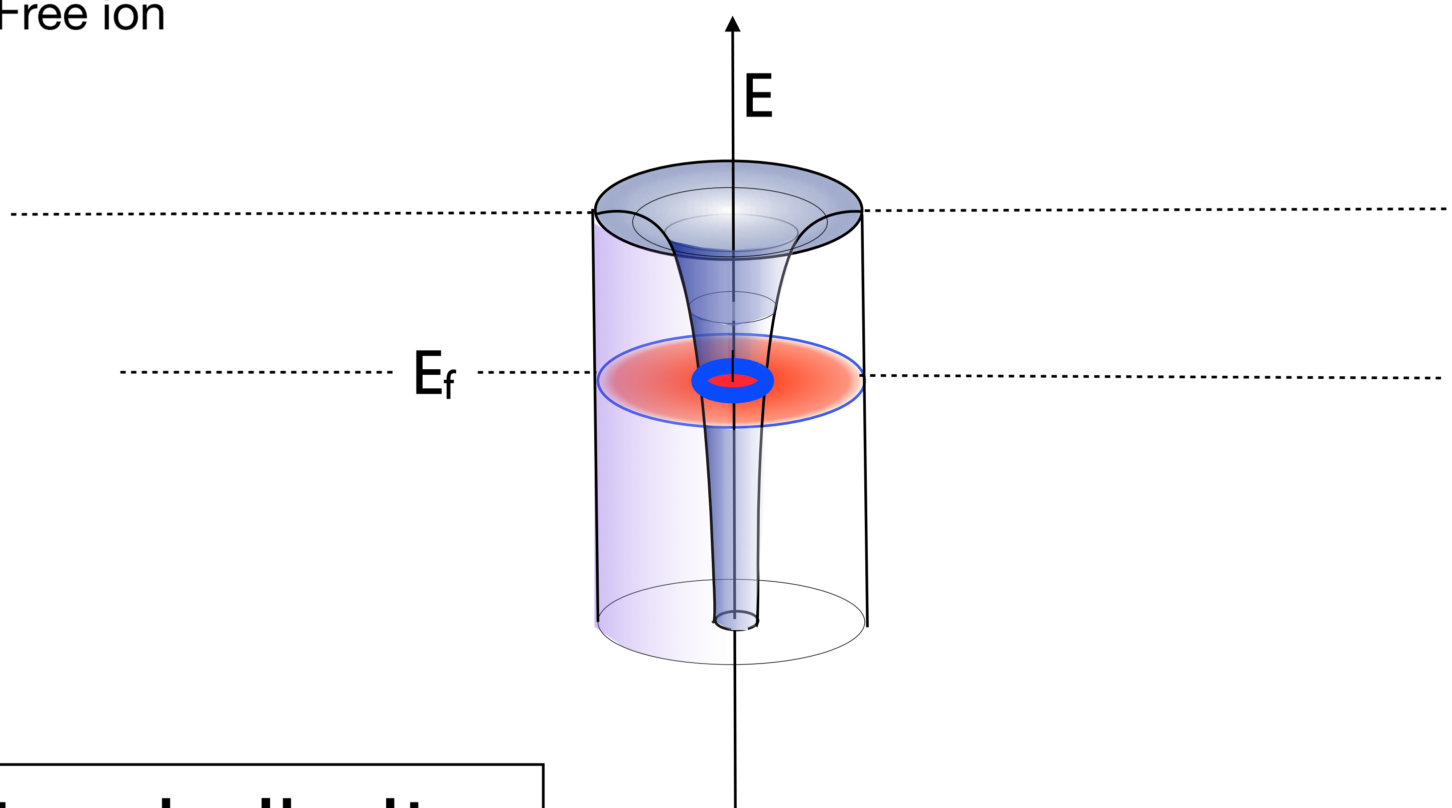
Free ion



Atomic limit (V=0)

f^2 —— $2E_f + U$

f^0 ——

E_f —— —— f^1

$$\left.\begin{array}{rcl} E_f & < & 0 \\ U + E_f & > & 0 \end{array}\right\} \Rightarrow \left\{\begin{array}{rcl} E_f + U/2 & < & U/2 \\ U/2 & > & -(E_f + U/2) \end{array}\right.$$

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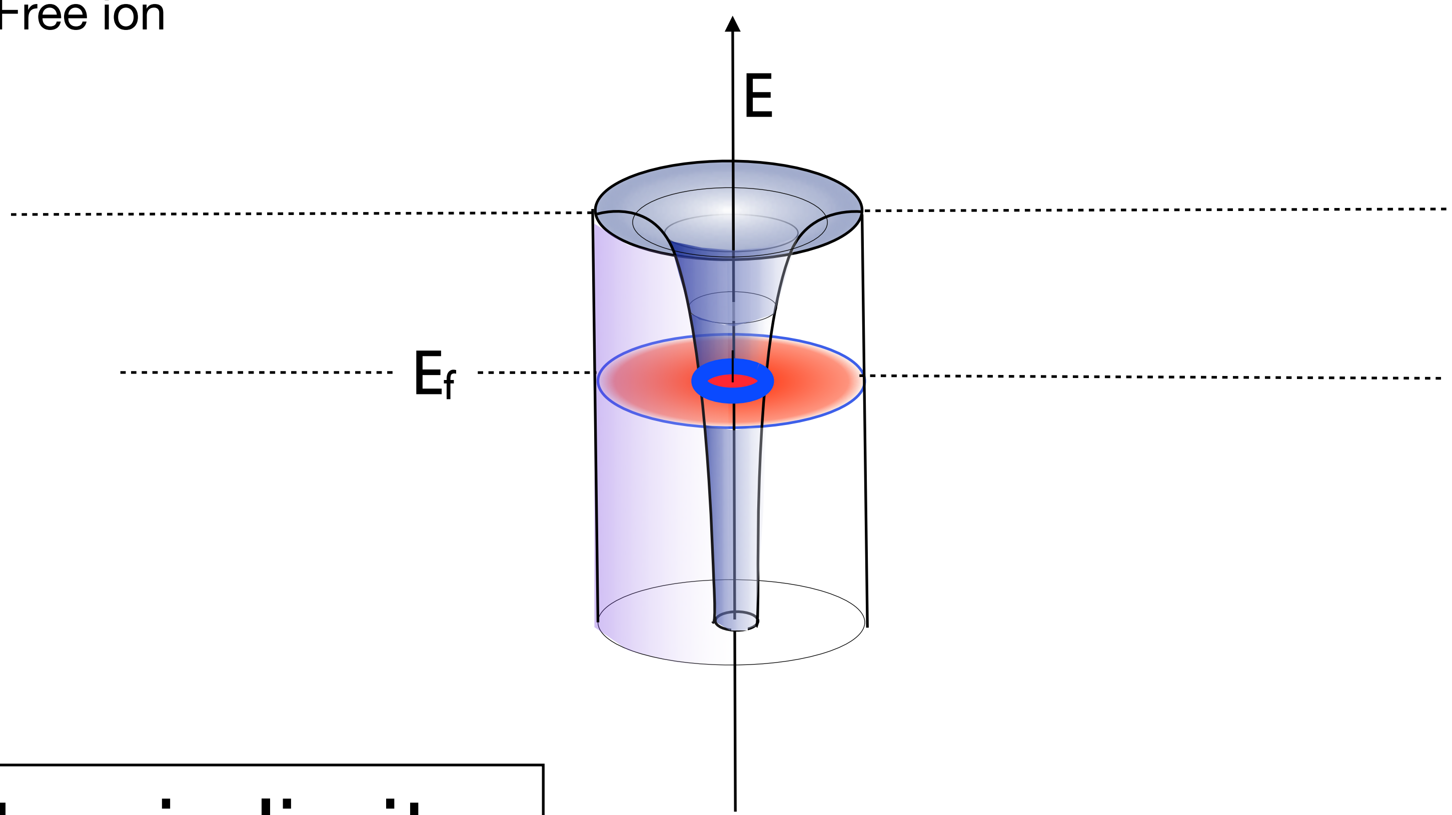

Atomic limit
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f^0

E_f f^1

$U/2 > |E_f + U/2|$

Magnetic GS

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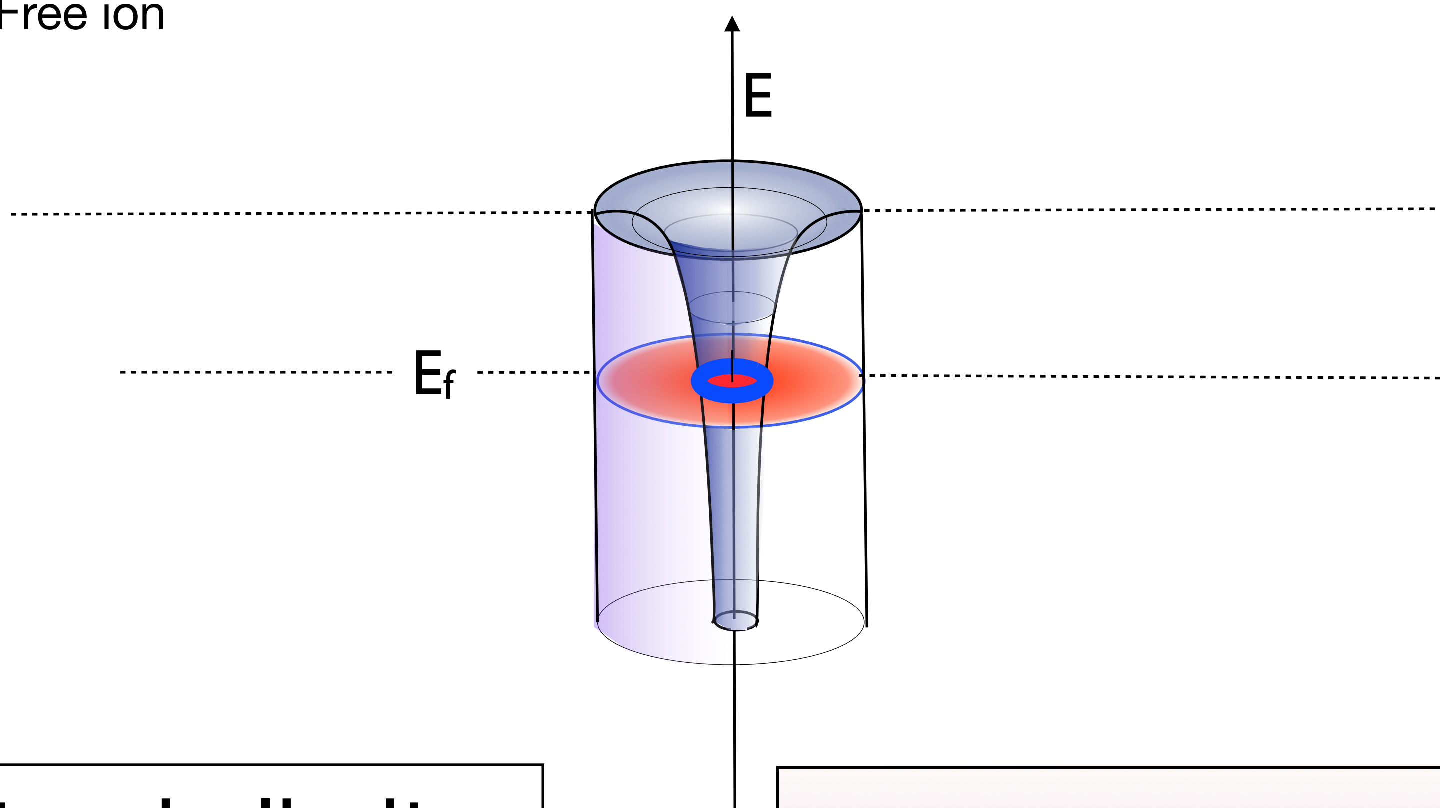
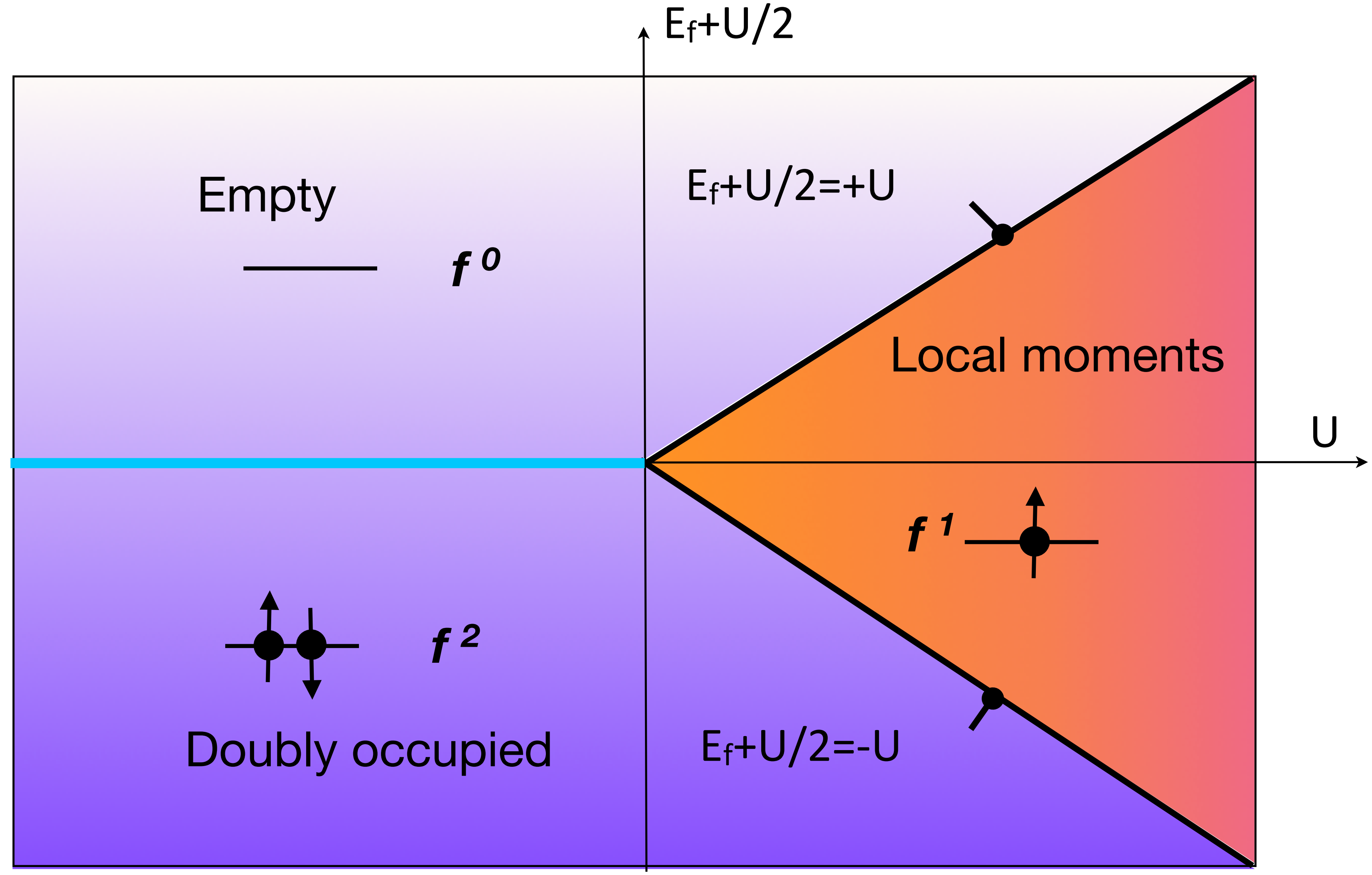
Free ion



Atomic limit (V=0)



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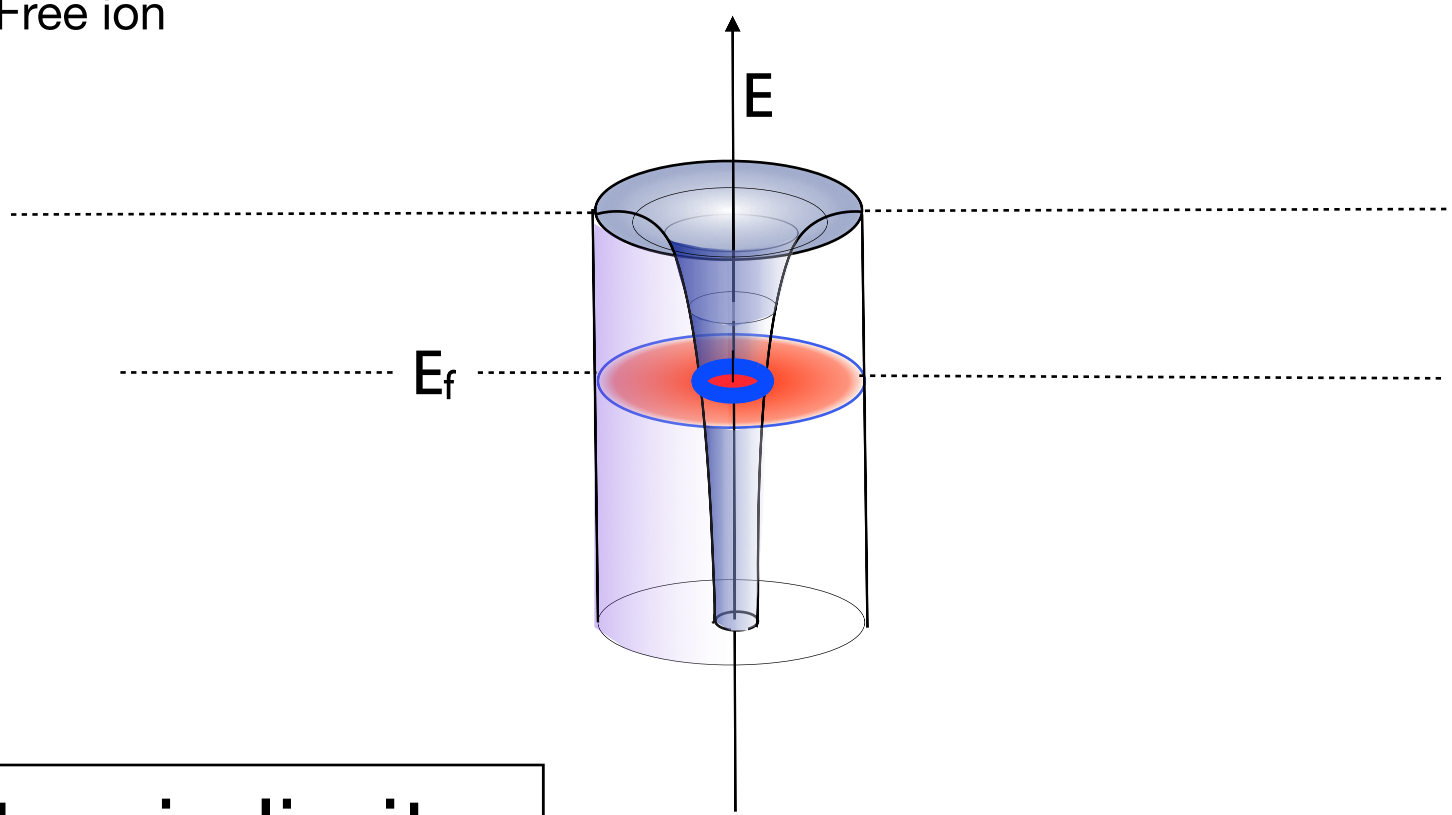

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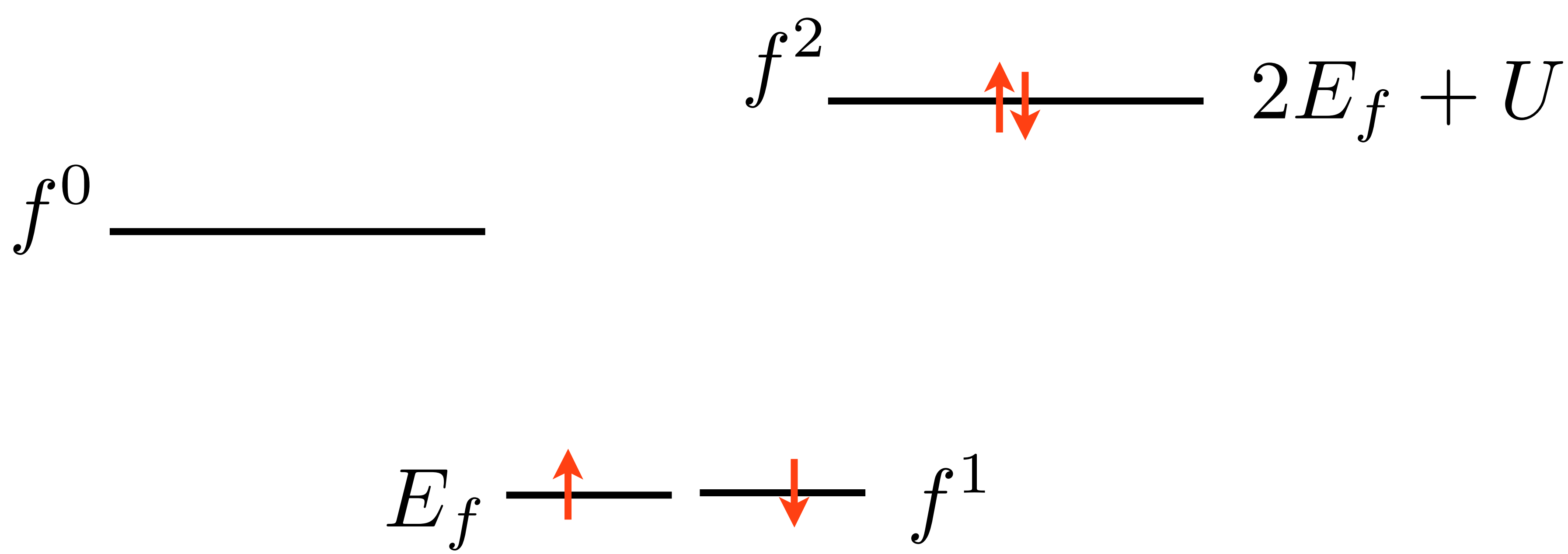

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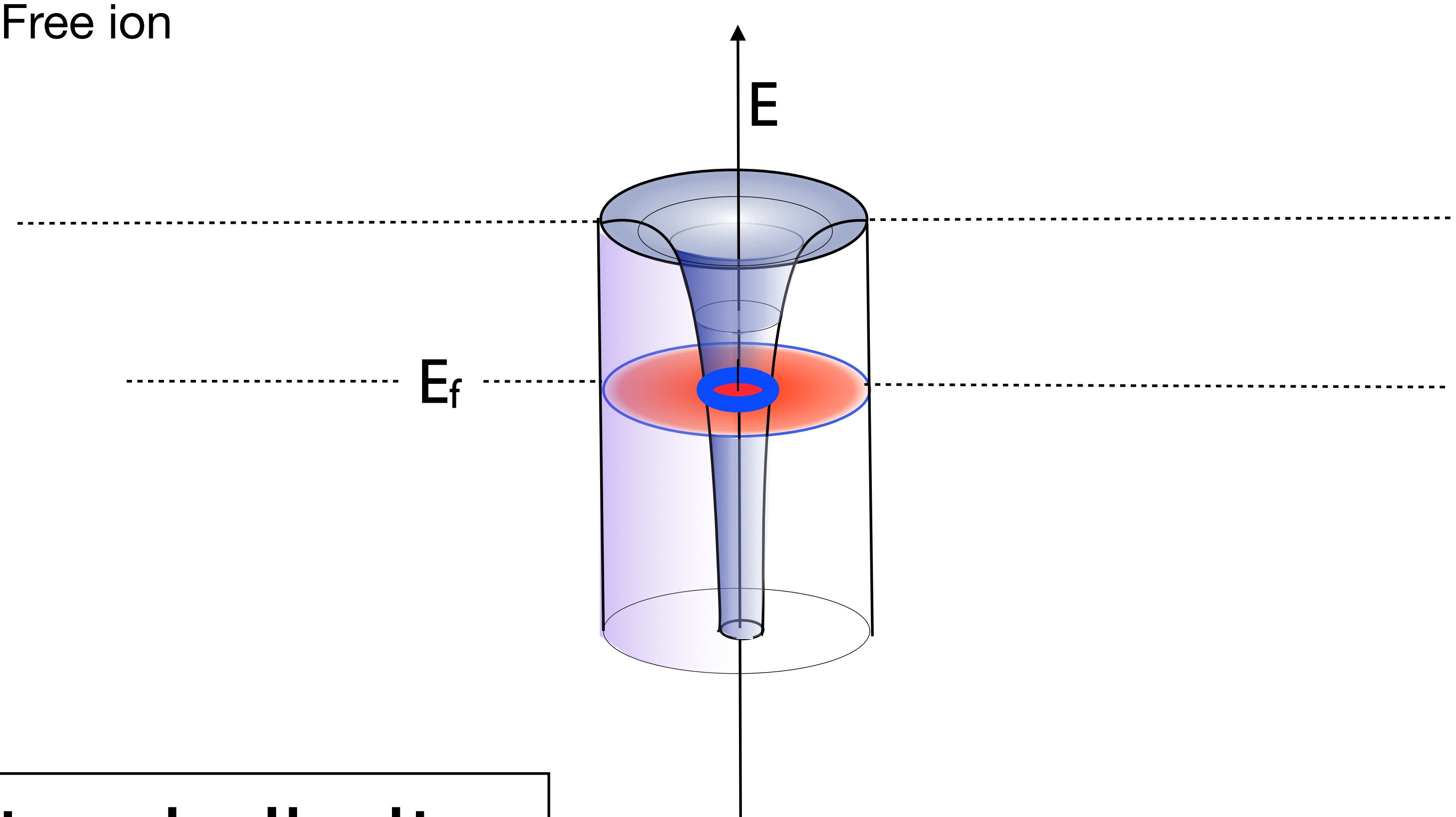

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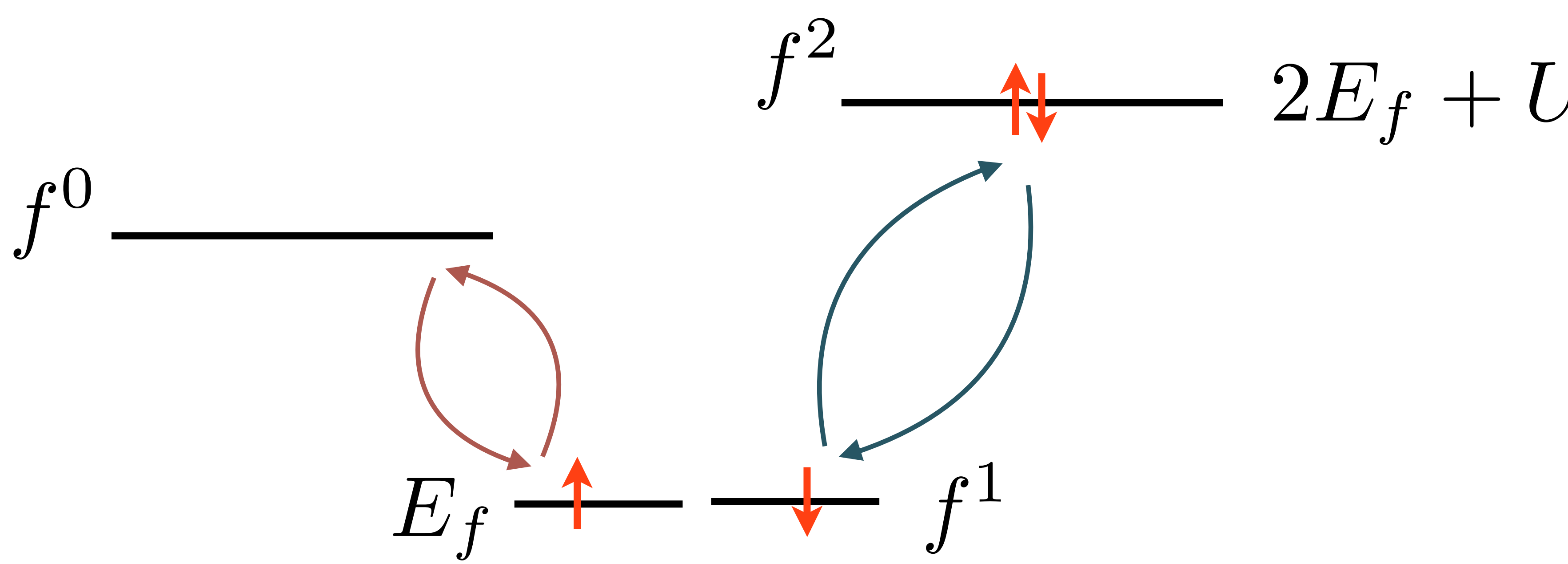
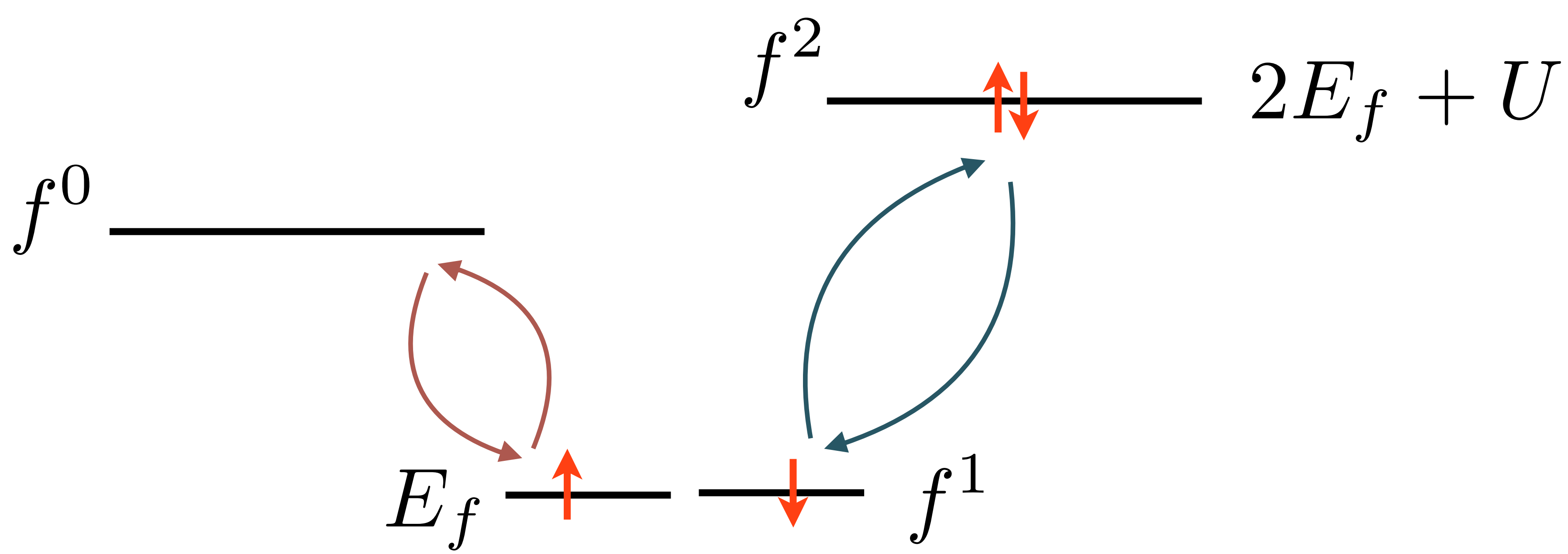


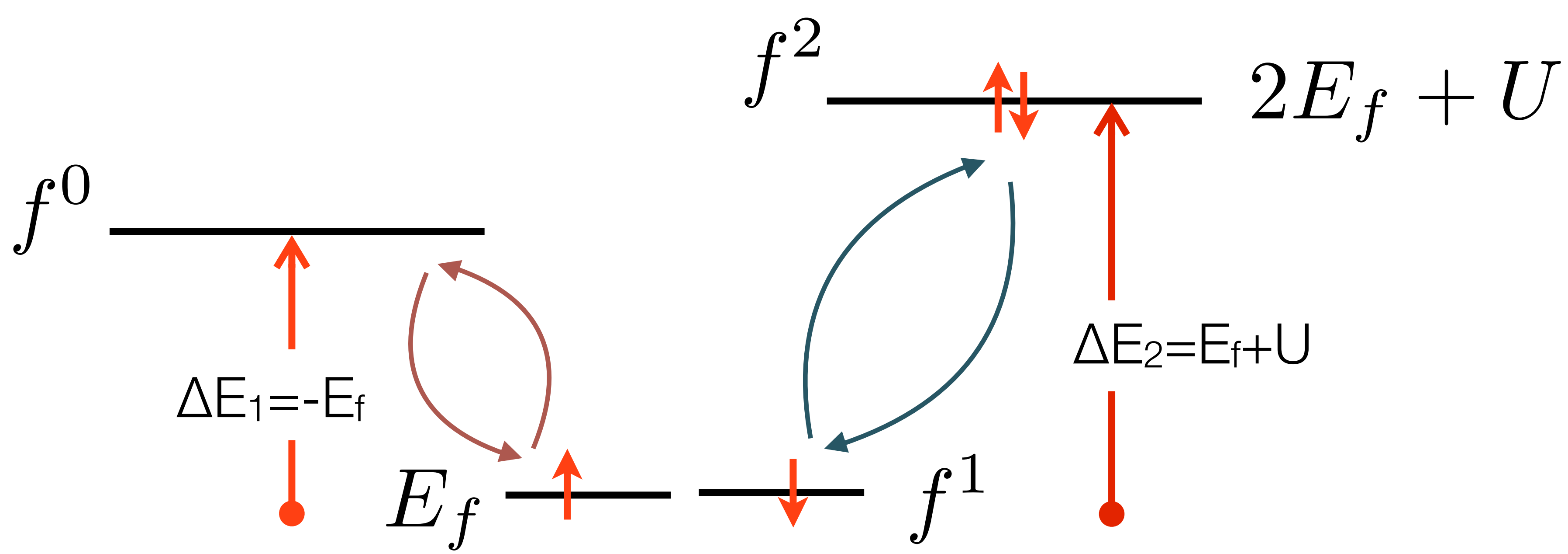
Valence Fluctuations

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.



Virtual Valence Fluctuations

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

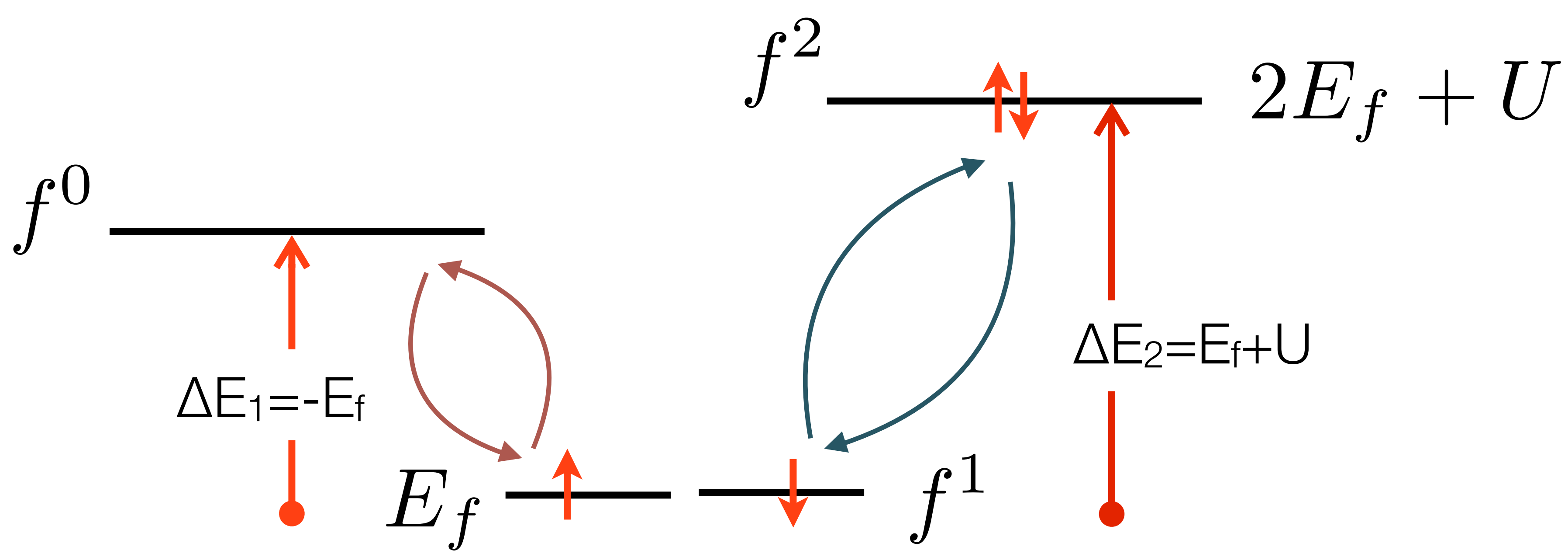


Virtual Valence Fluctuations

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

Virtual Valence fluctuations in the singlet channel, induced by hybridization

$$e^-_\uparrow + f^1_\downarrow \leftrightarrow f^2 \leftrightarrow e^-_\downarrow + f^1_\uparrow \qquad \Delta E_I \sim U + E_f$$
$$h^+_\uparrow + f^1_\downarrow \leftrightarrow f^0 \leftrightarrow h^+_\downarrow + f^1_\uparrow \qquad \Delta E_{II} \sim -E_f$$



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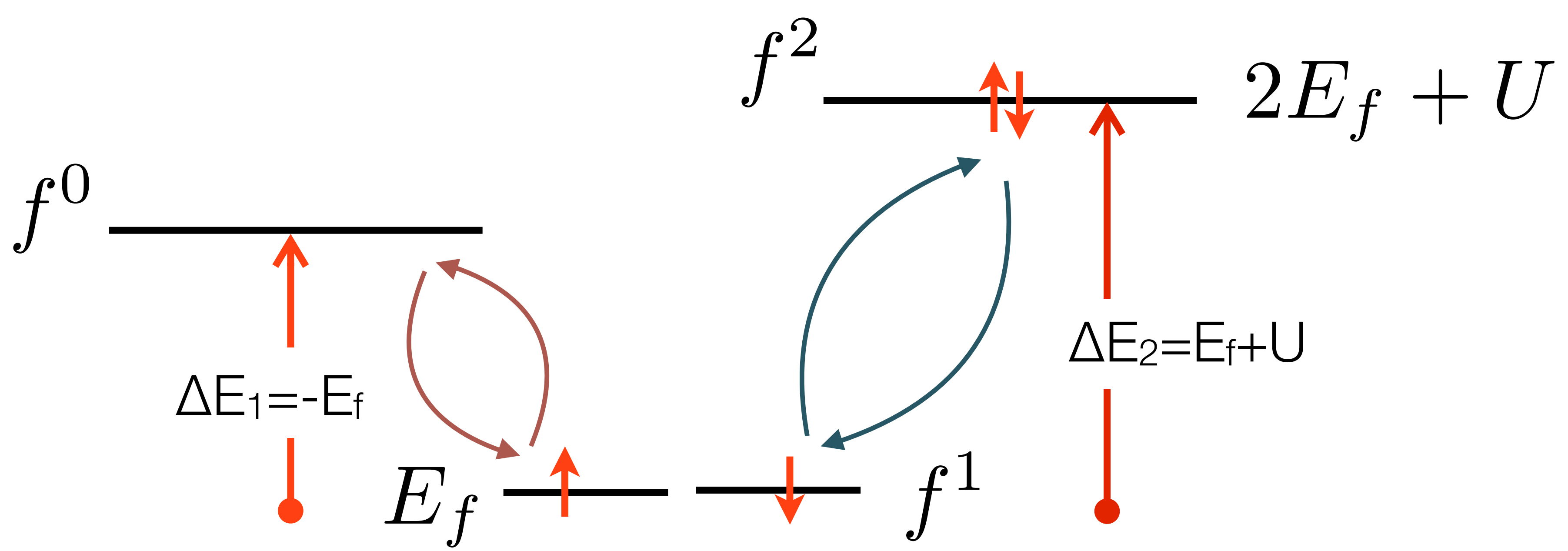
\end{array}
$$

From second order perturbation theory, the energy of c-f singlets reduces by an amount 2J, where

$$
J = V^2 \left[\frac{1}{\Delta E_1} + \frac{1}{\Delta E_2} \right]
$$



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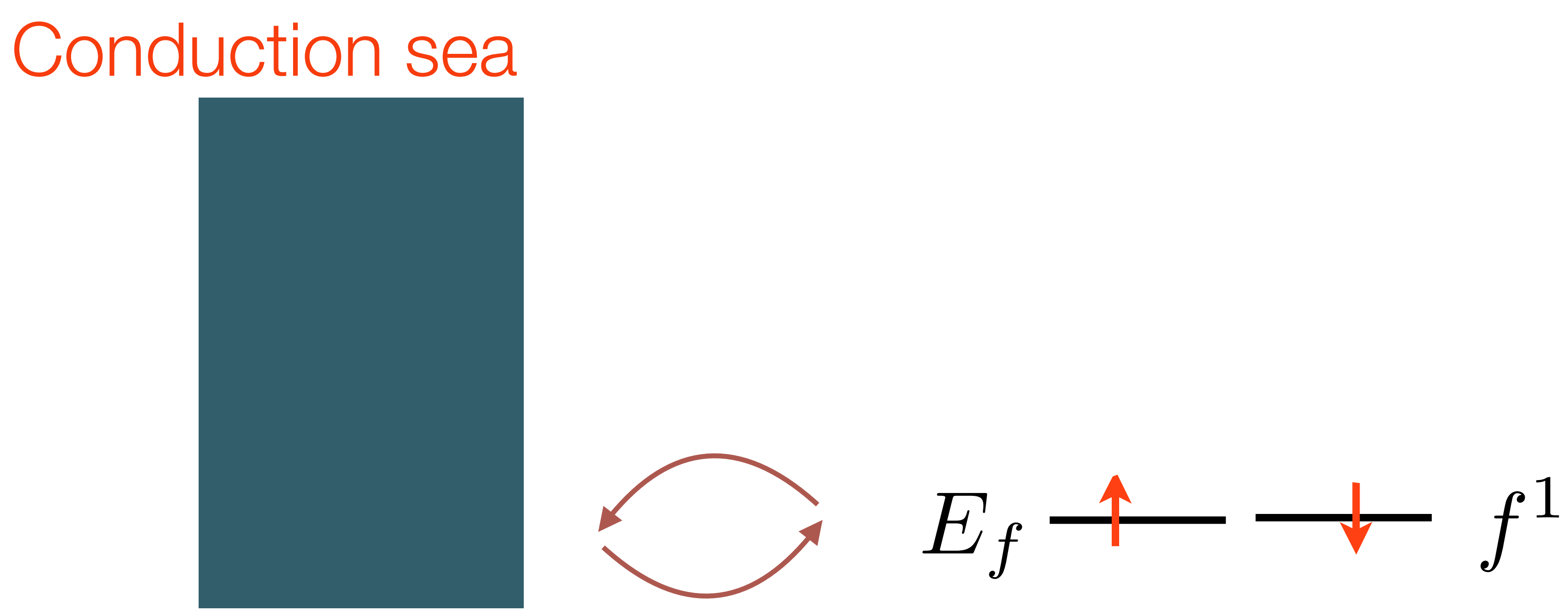
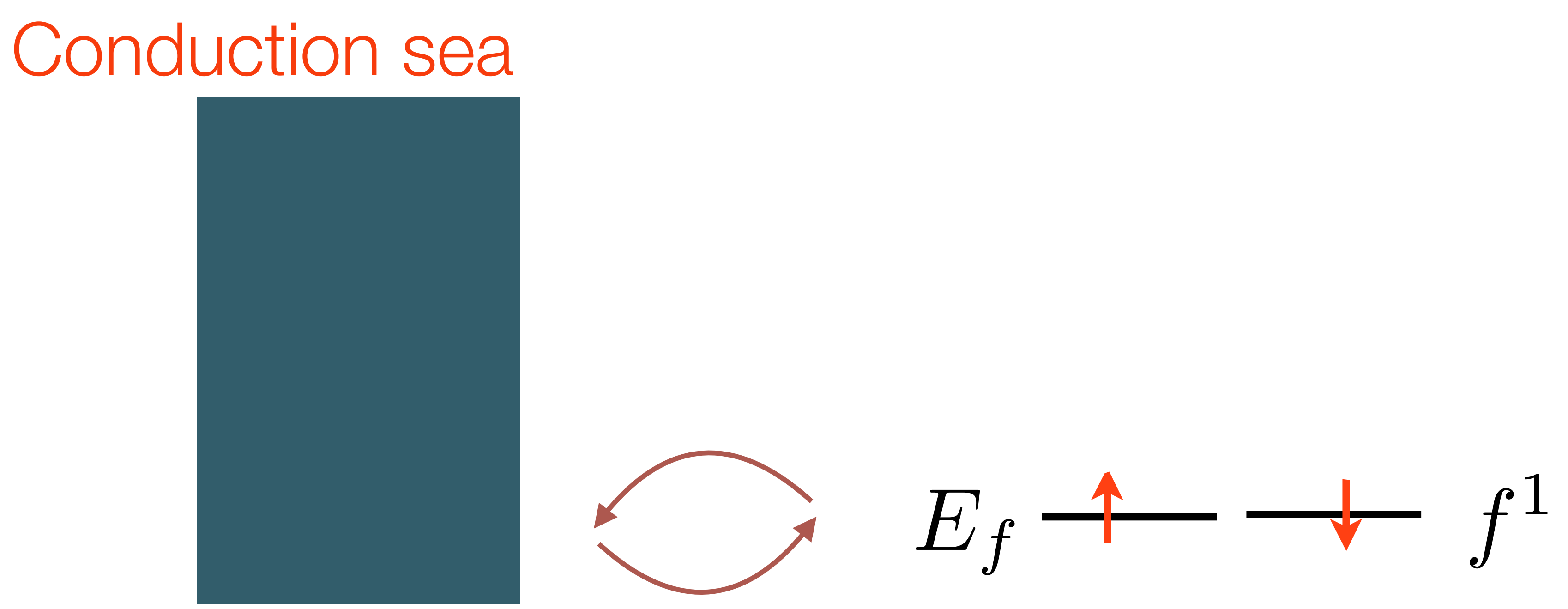


$$H_K = -2J P_{S=0} = -2J \left[\frac{1}{4} - \frac{1}{2} \vec{\sigma}_c(0) \cdot \vec{S}_f \right] \rightarrow J \vec{\sigma}_c(0) \cdot \vec{S}_f$$

Antiferromagnetic Kondo interaction

Schrieffer Wolff Transformation: integrate out high frequency valence fluctuations.

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{\mathcal{N}} \sum_{j} \vec{S}_j \cdot c^{\dagger}_{\mathbf{k}\alpha} \vec{\sigma}_{\alpha\beta} c_{\mathbf{k}'\beta} e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{R}_j}$$



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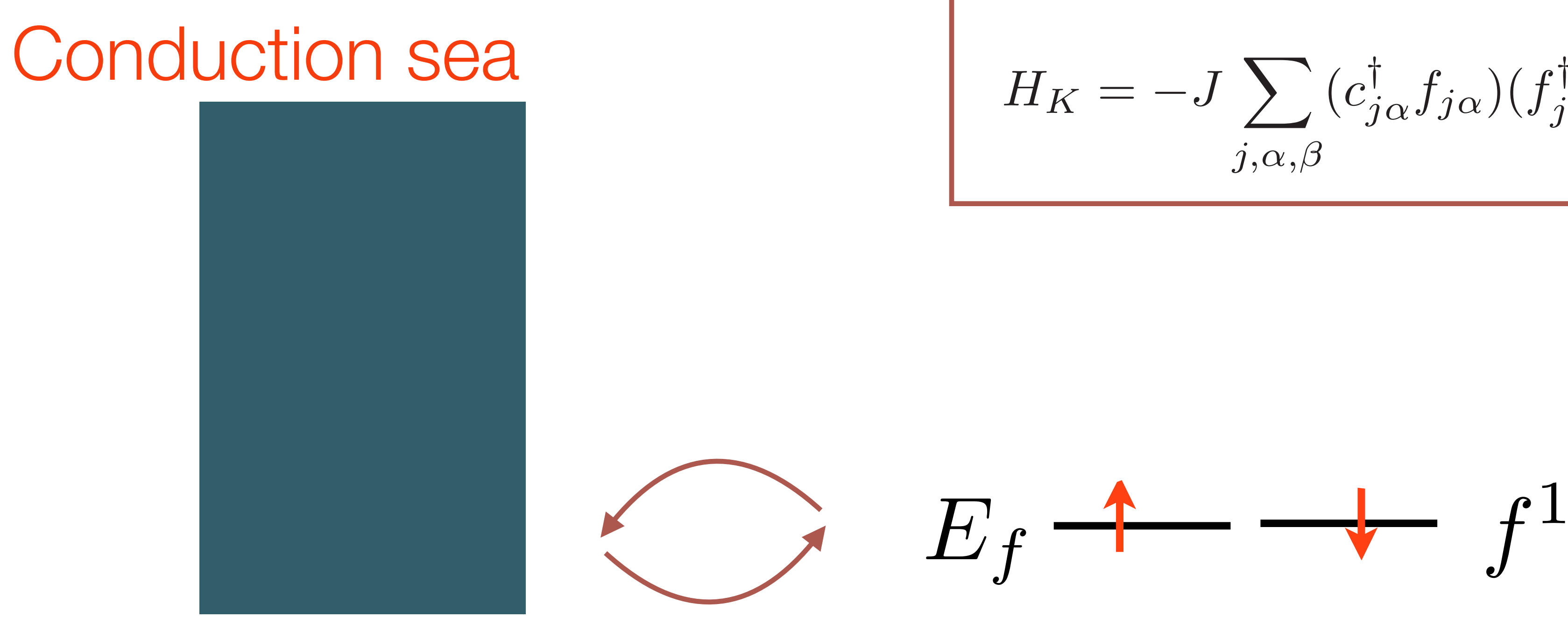
Note: can also write Kondo interaction in the "Coqblin Schrieffer" form

$$H_K = -J \sum_{j,\alpha,\beta} (c^{\dagger}_{j\alpha} f_{j\alpha})(f^{\dagger}_{j\beta} c_{j\beta})$$



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Antiferromagnetic Kondo interaction

Doniach Hypothesis

DONIACH'S Hypothesis.

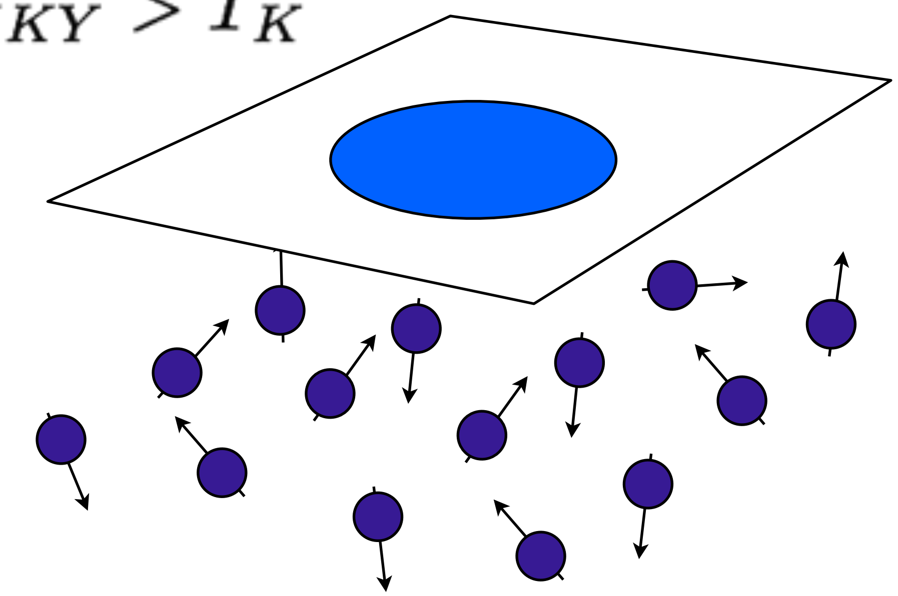
Doniach (1977)

$$H = \sum \varepsilon_k c_{k\sigma}{}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}{}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

Kondo Lattice Model
(Kasuya, 1951)

DONIACH'S
Hypothesis.
Doniach (1977)

$T_{RKKY} > T_K$



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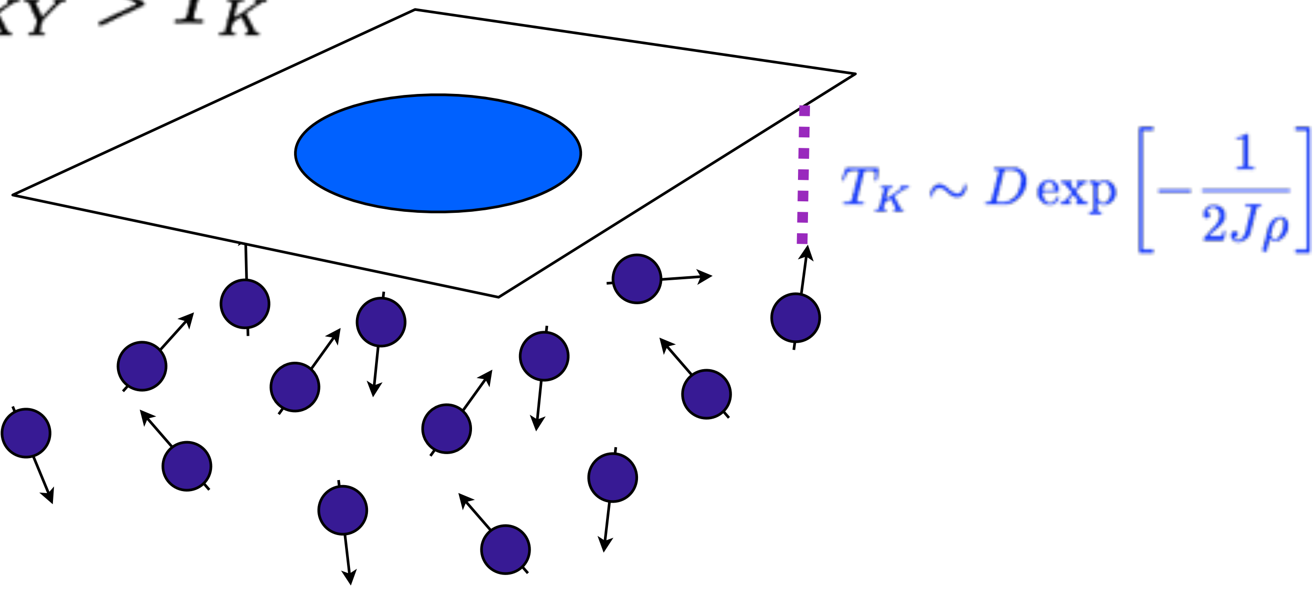

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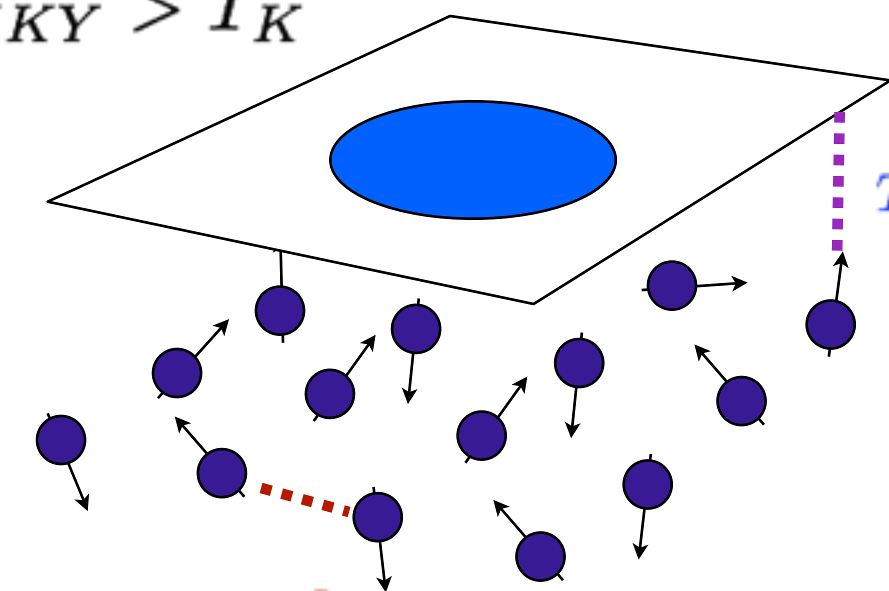

$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$

$T_{RKKY} \sim J^2 \rho$

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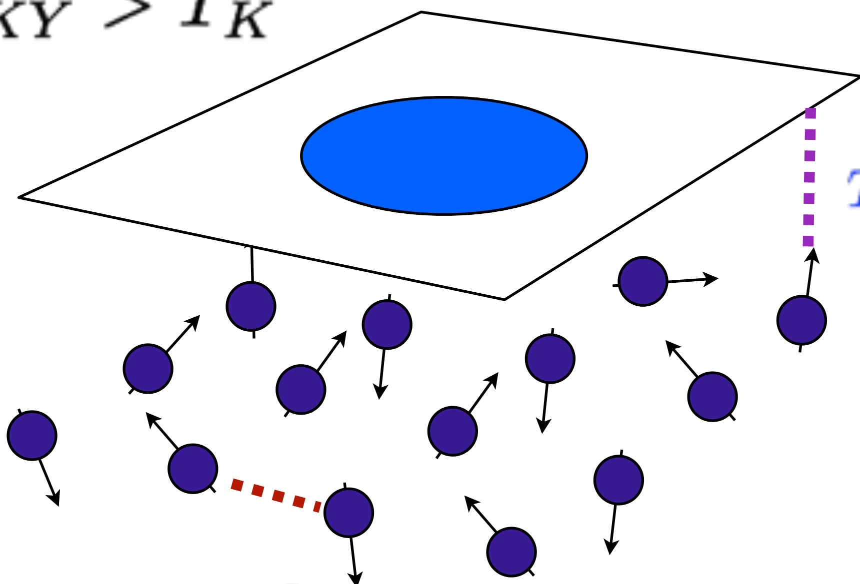

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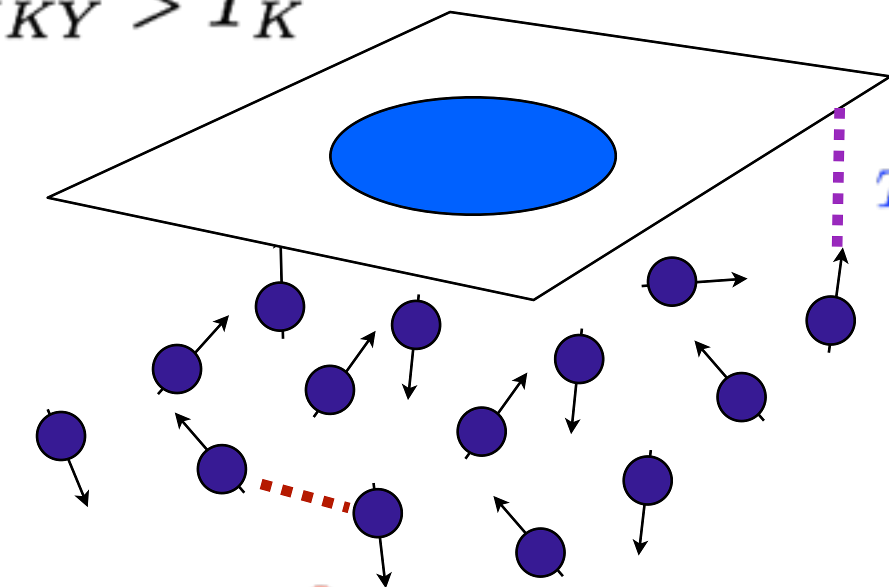

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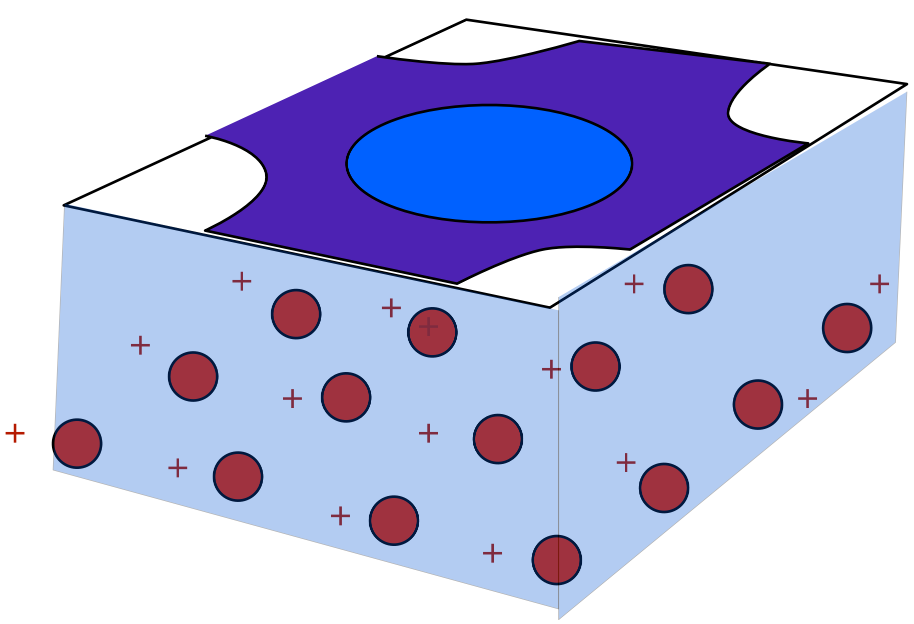
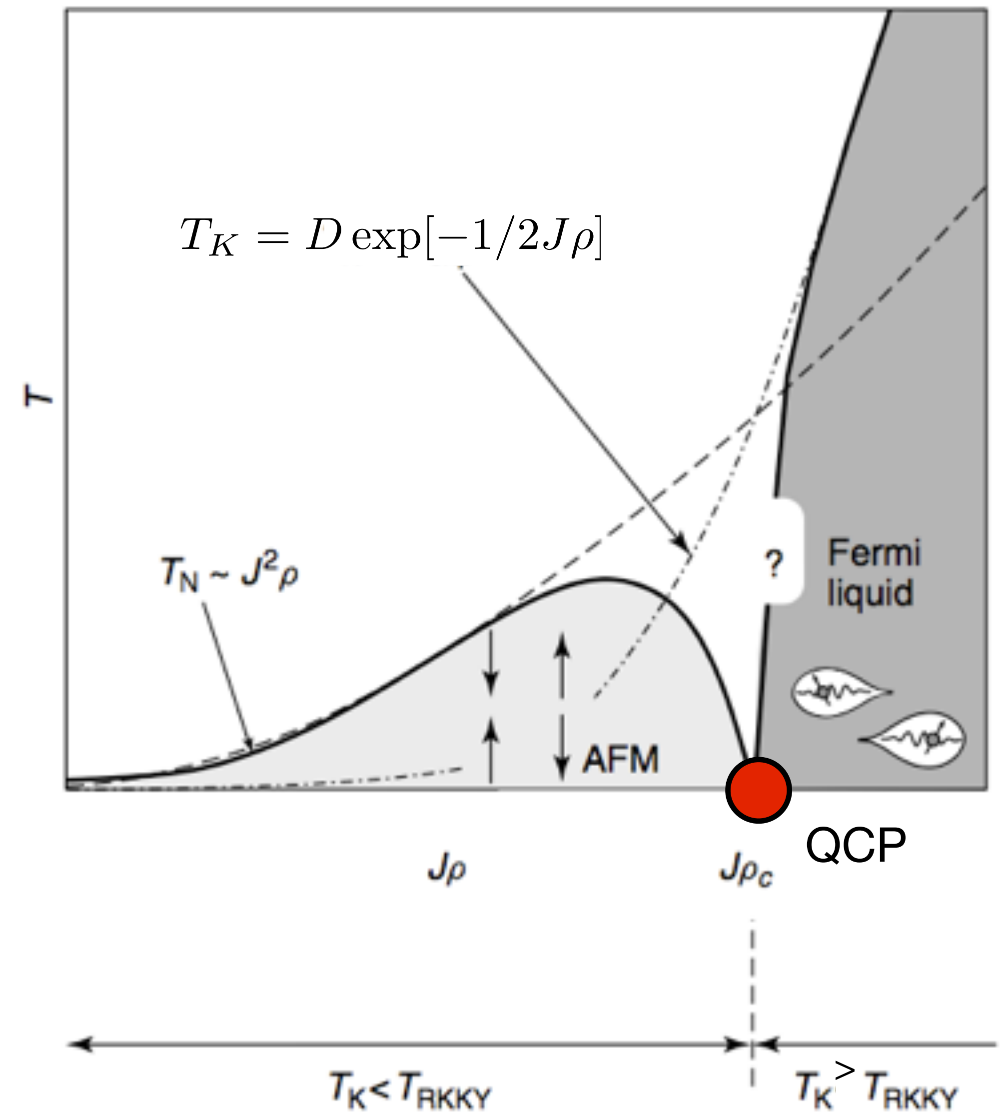
Large Fermi surface of composite Fermions





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The main result ... is that there should be a second-order transition at zero temperature, as the exchange is varied, between an antiferromagnetic ground state for weak J and a Kondo-like state in which the local moments are quenched.

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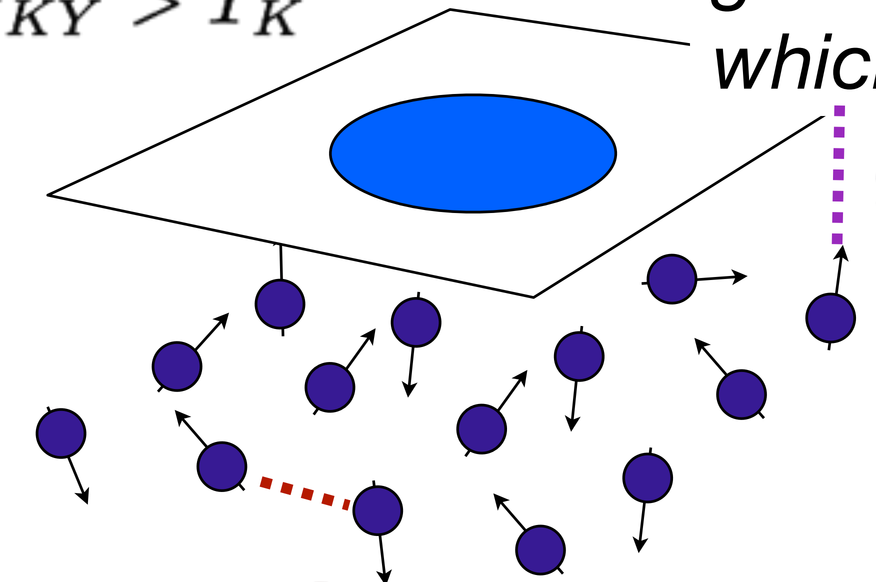

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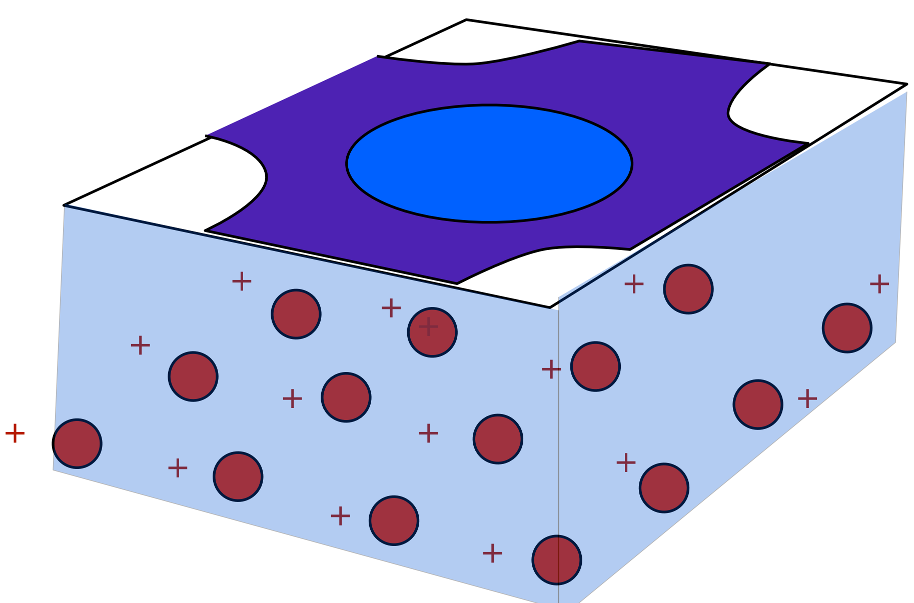

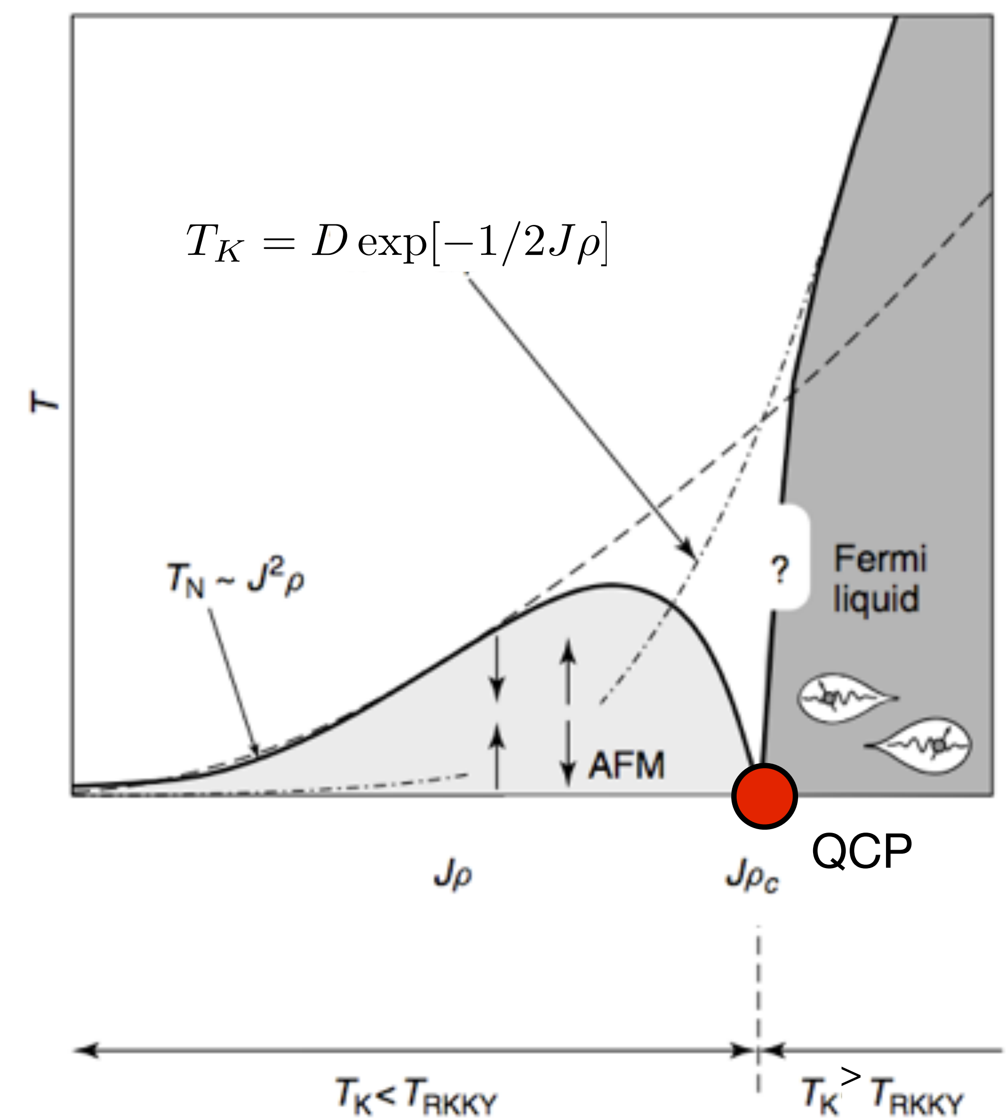

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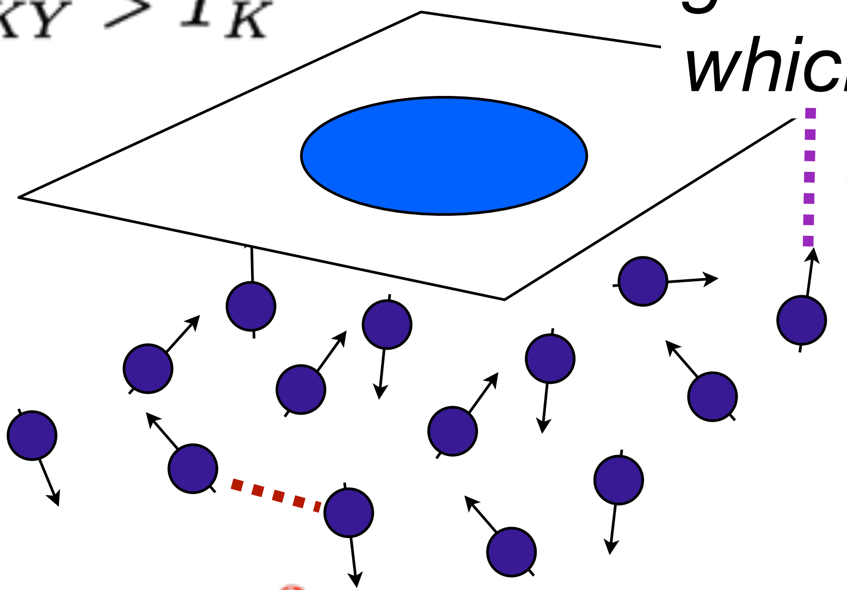
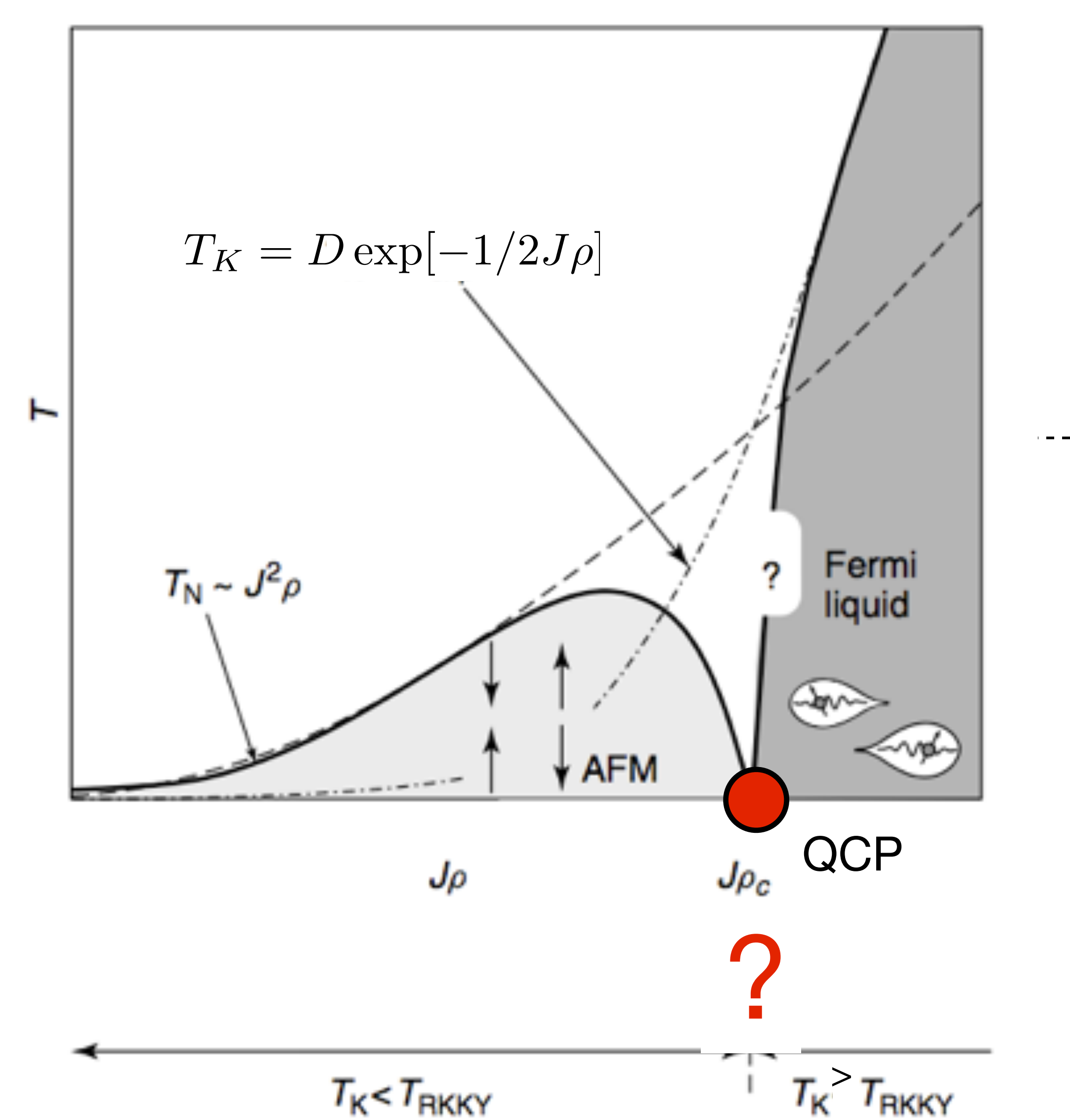
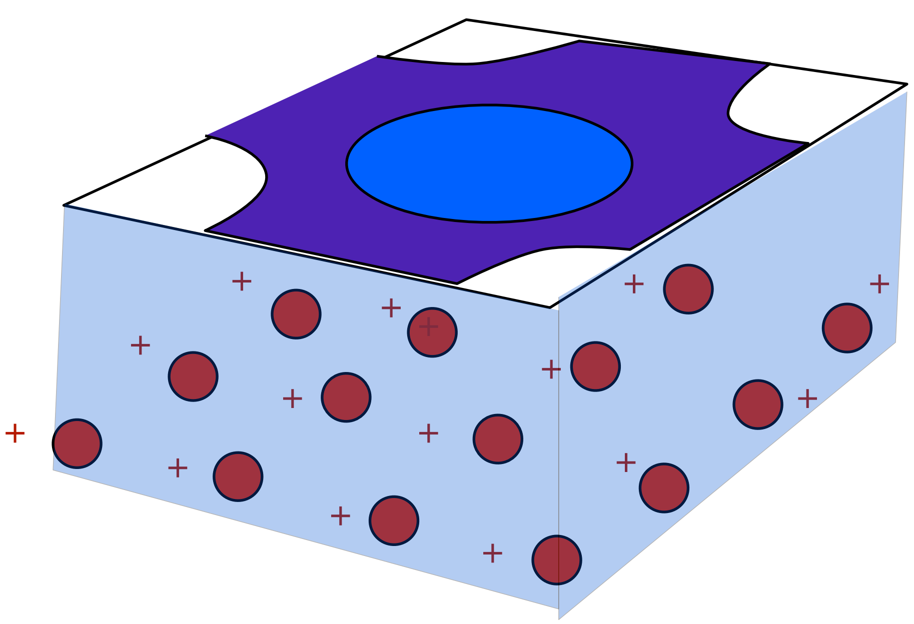


$$T_{RKKY} \sim J^2 \rho$$



$$T_{RKKY} < T_K$$

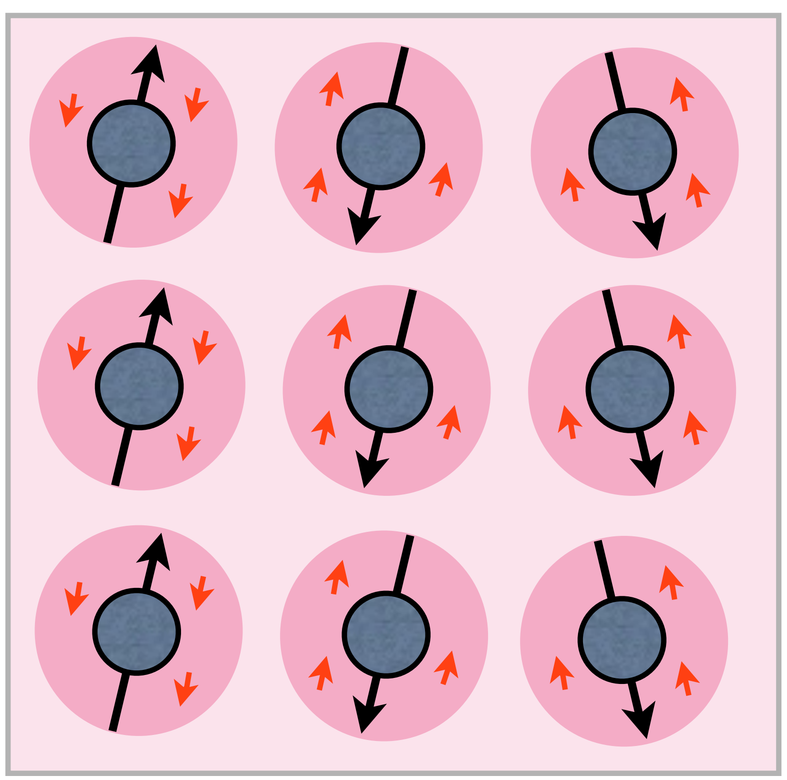
Large Fermi surface of composite Fermions



THE KONDO LATTICE

$$H = \sum_{\mathbf{k}\sigma} \epsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + \frac{J}{\mathcal{N}} \sum_{j} \vec{S}_j \cdot c^{\dagger}_{\mathbf{k}\alpha} \vec{\sigma}_{\alpha\beta} c_{\mathbf{k}'\beta} e^{i(\mathbf{k}'-\mathbf{k})\cdot\mathbf{R}_j}$$

T. Kasuya (1951)



“Kondo Lattice”

Strong coupling Kondo Lattice $J >> t$

$$H = J \sum \vec{\sigma}(j) \cdot \vec{S}_j - t \sum_{(i,j)} (c^\dagger_{i\sigma} c_{j\sigma} + \mathrm{H.c})$$

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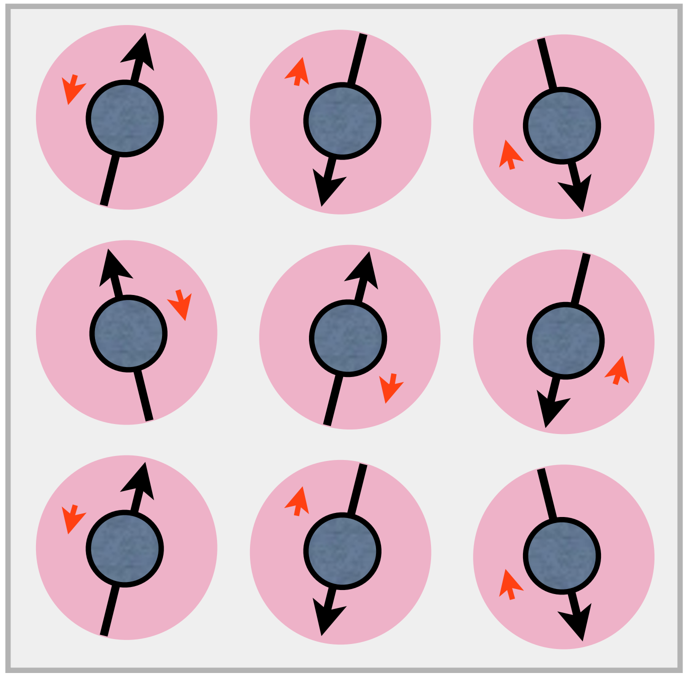

$$n_e = n_{\mathrm{spins}}$$

Kondo insulator

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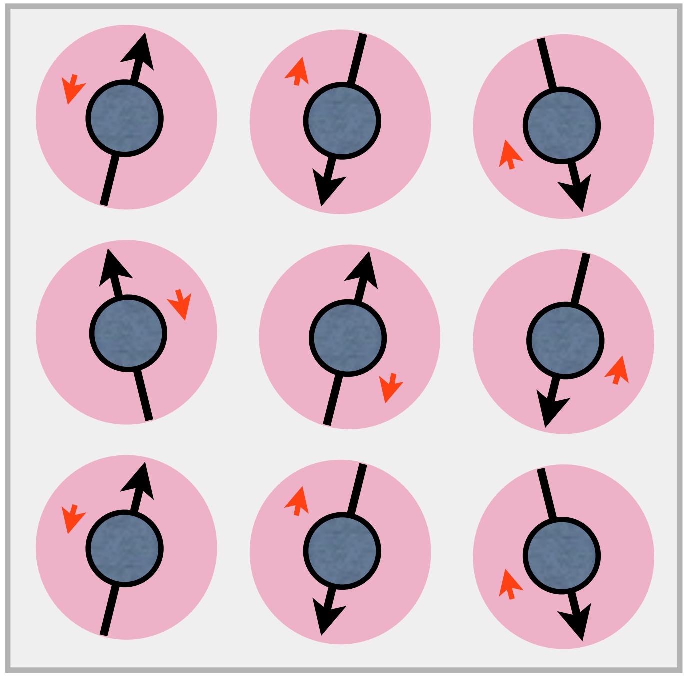

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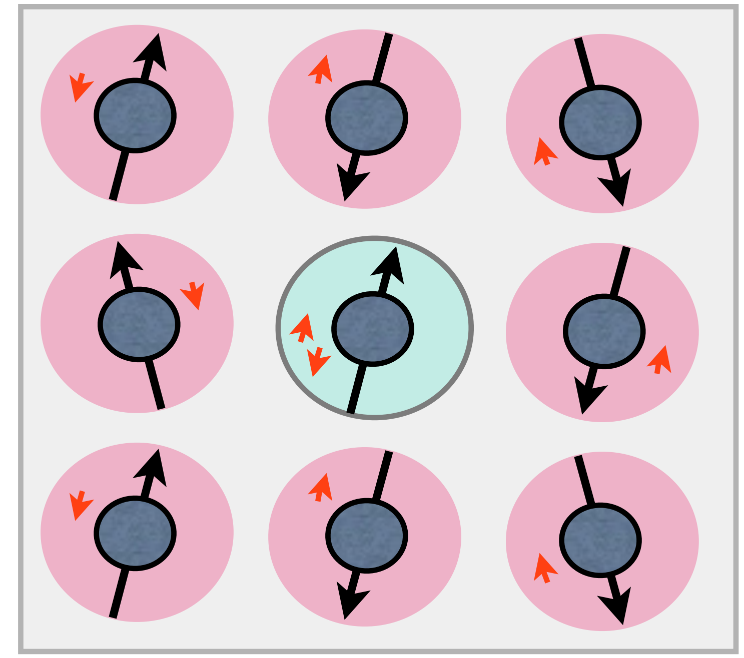

Electron doping

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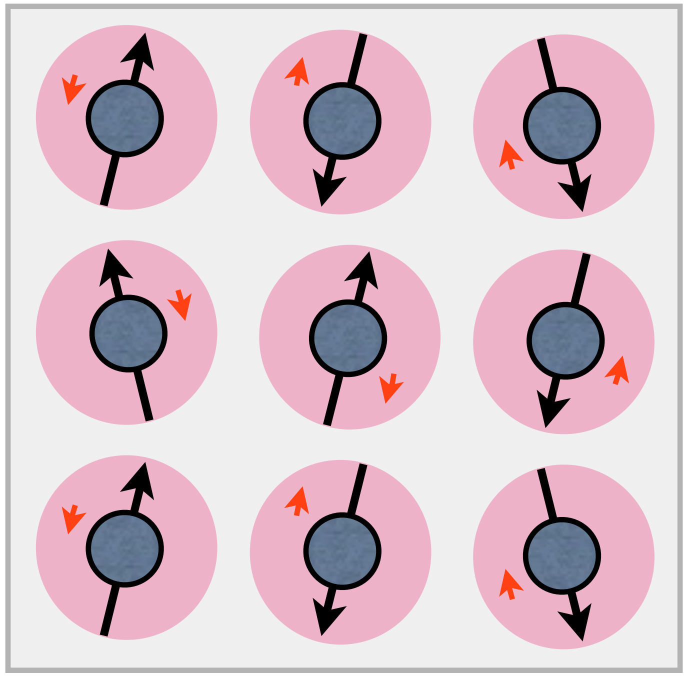

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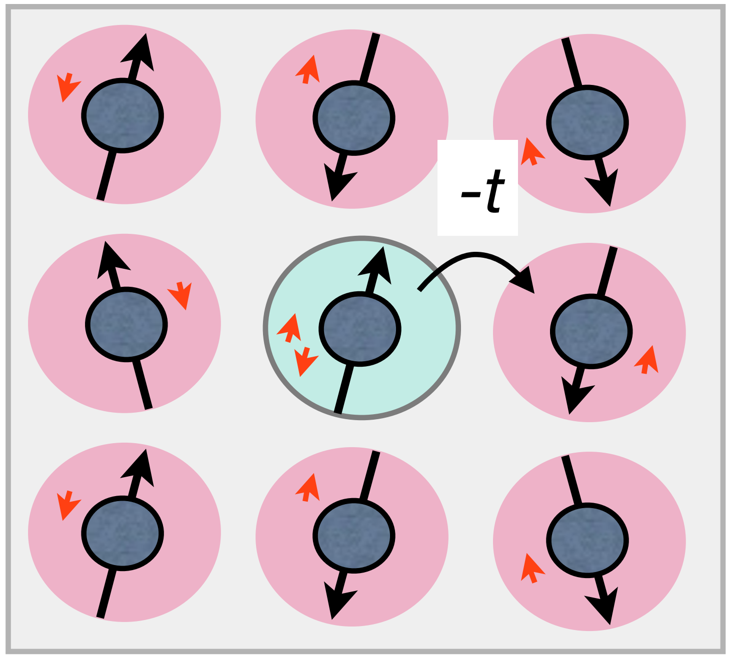

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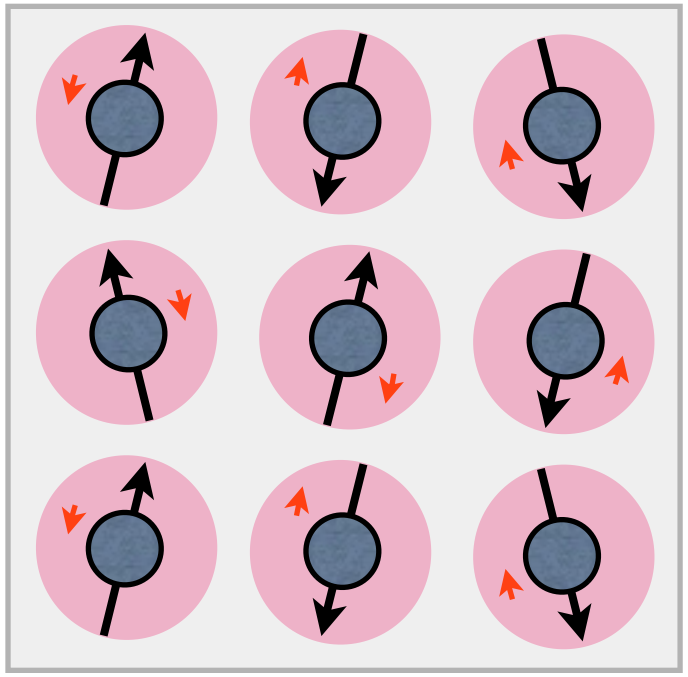

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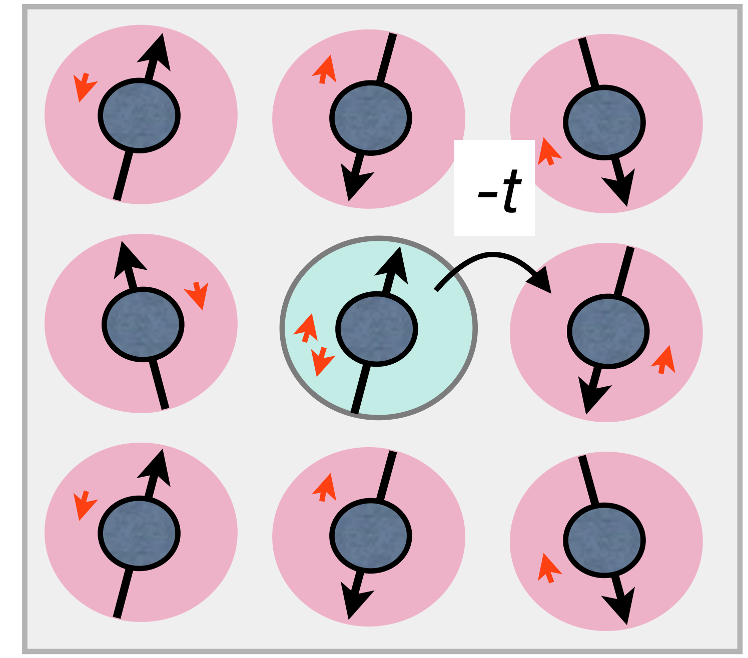

Electron doping
Mobile
“Heavy Electrons”

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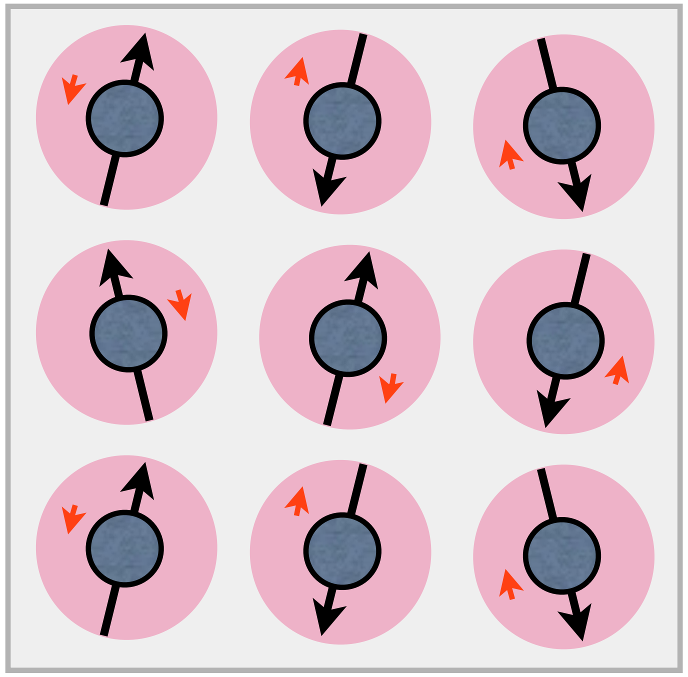

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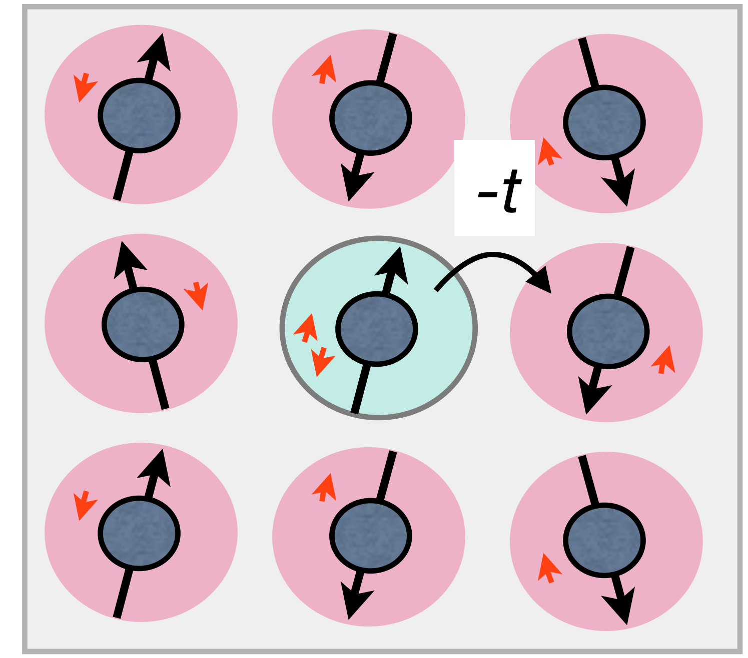

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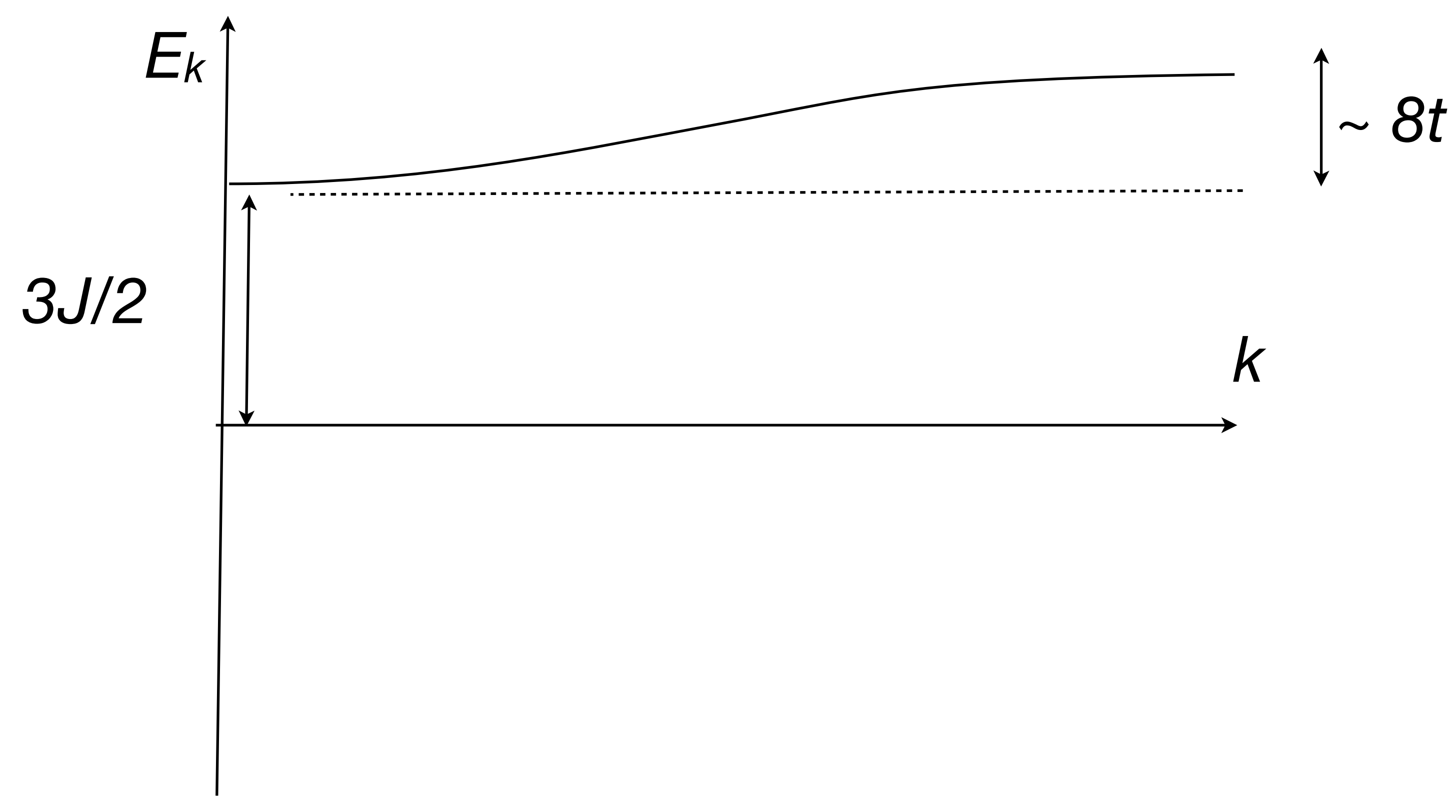

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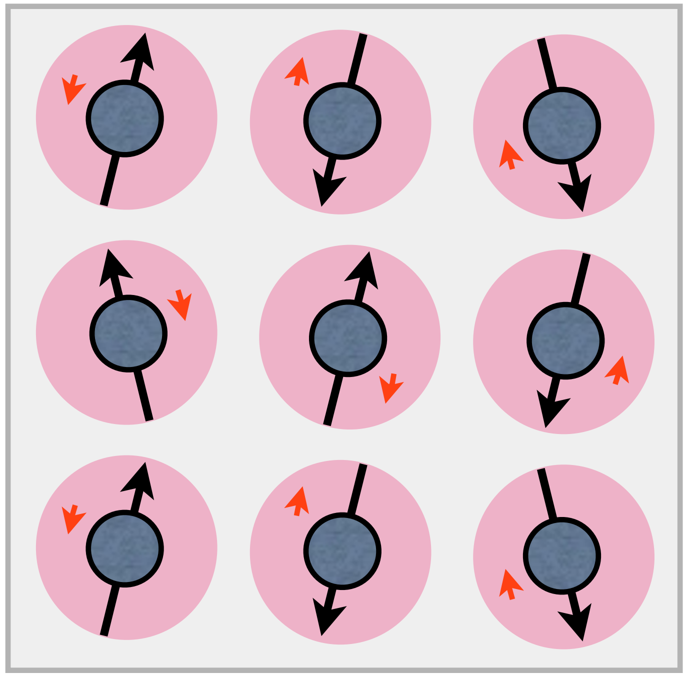

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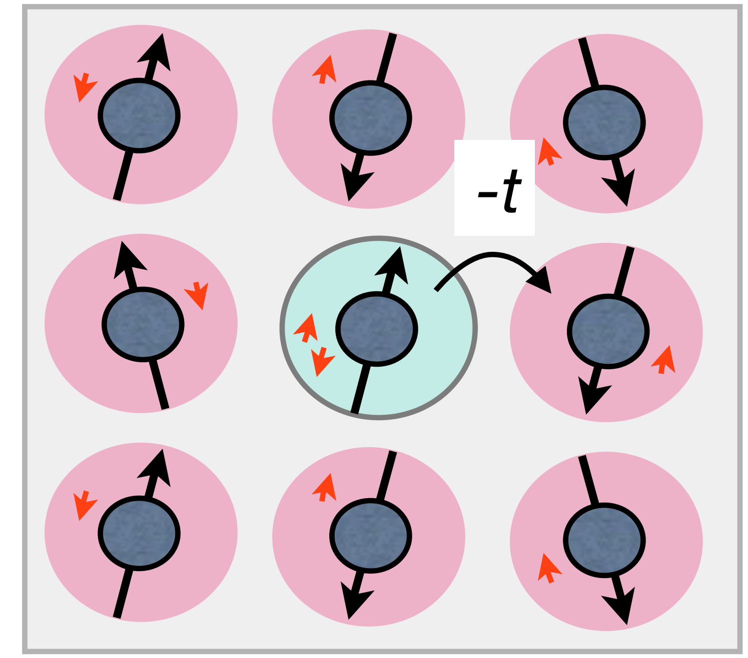

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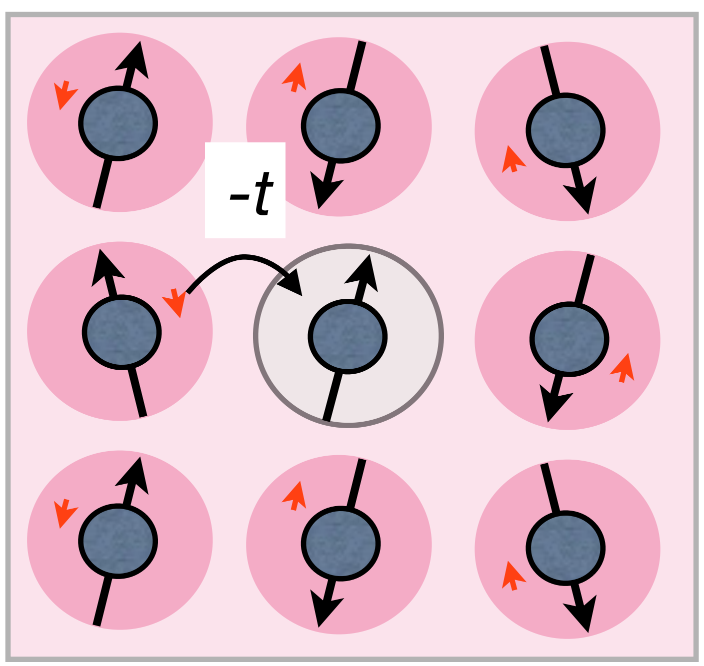
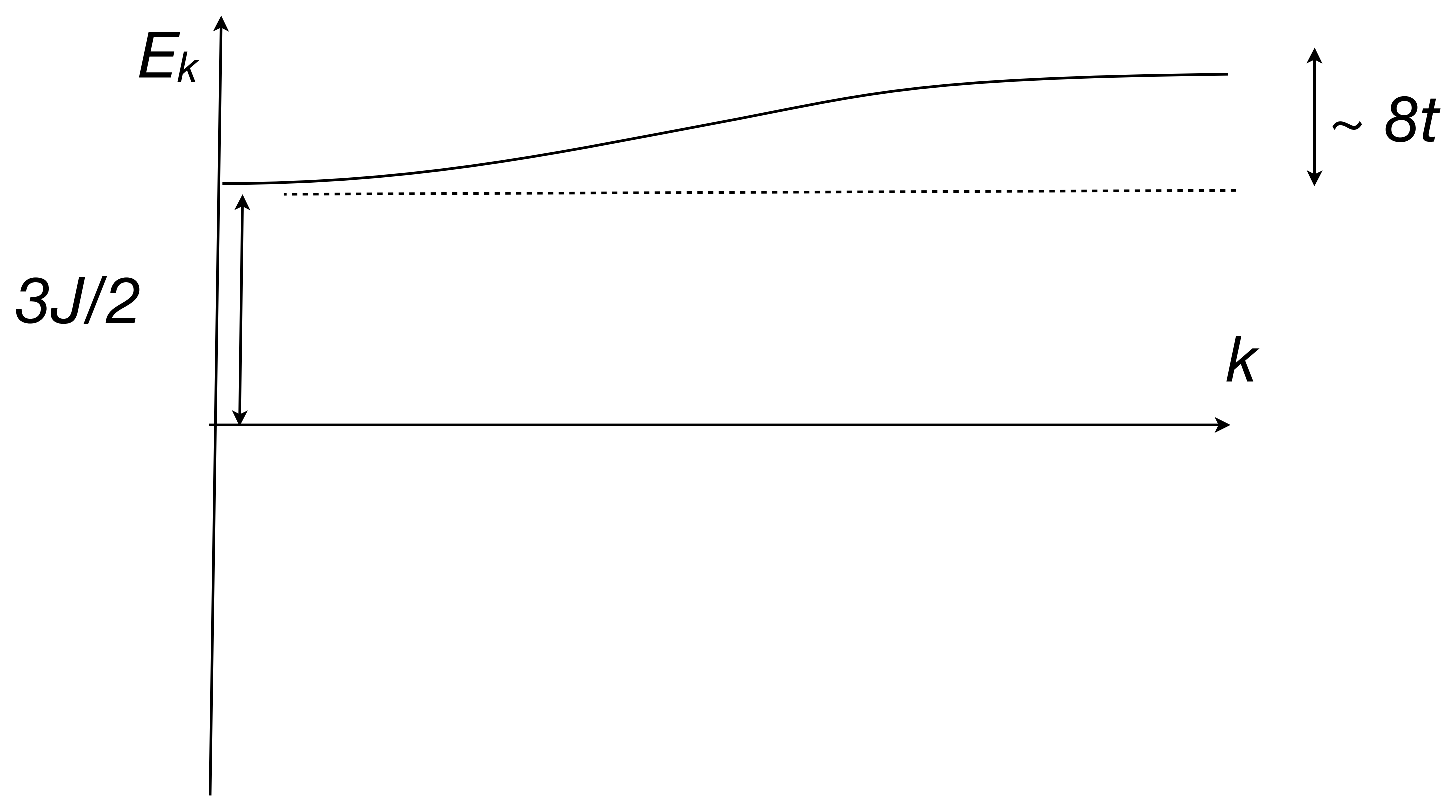


Hole doping: mobile heavy holes $n_e = n_{\mathrm{spins}} - \delta$



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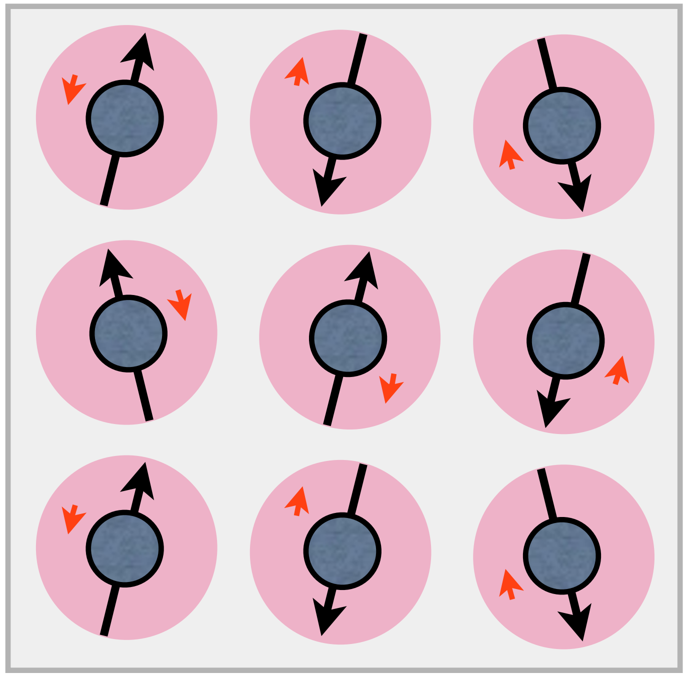

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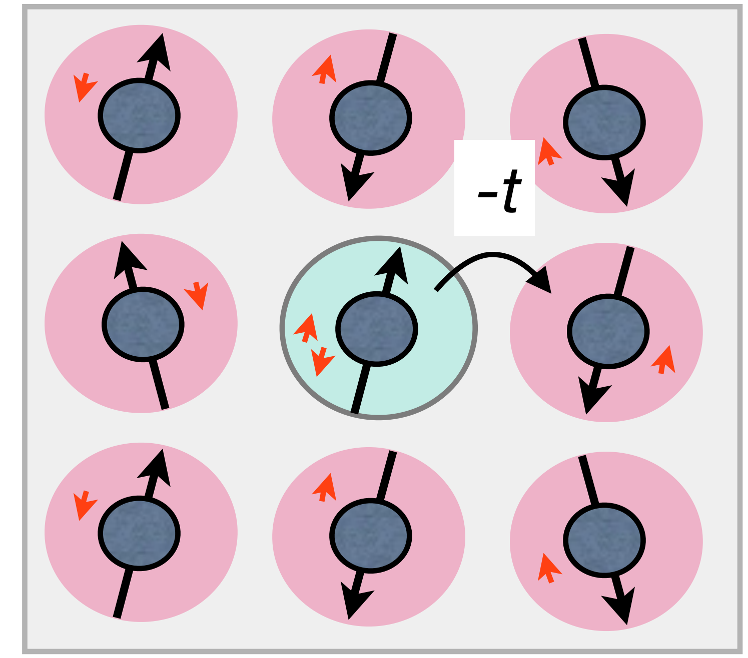
Kondo insulator



Electron doping
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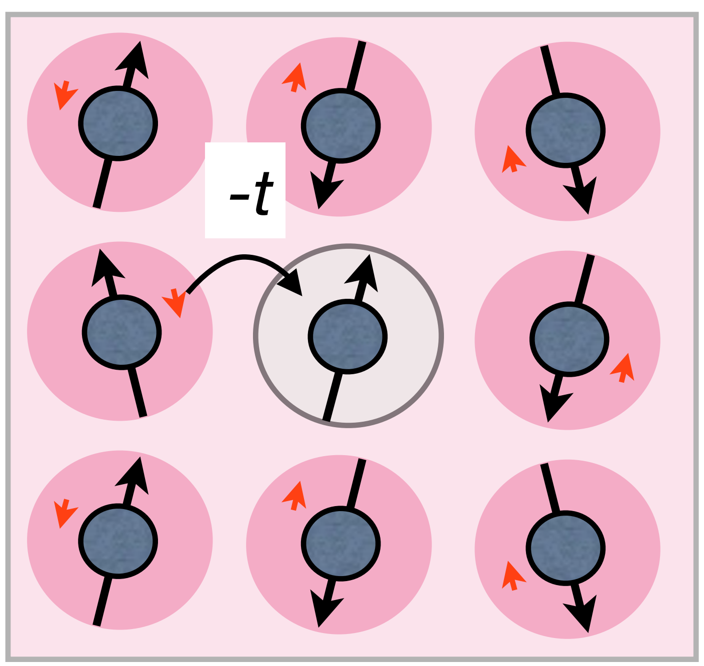

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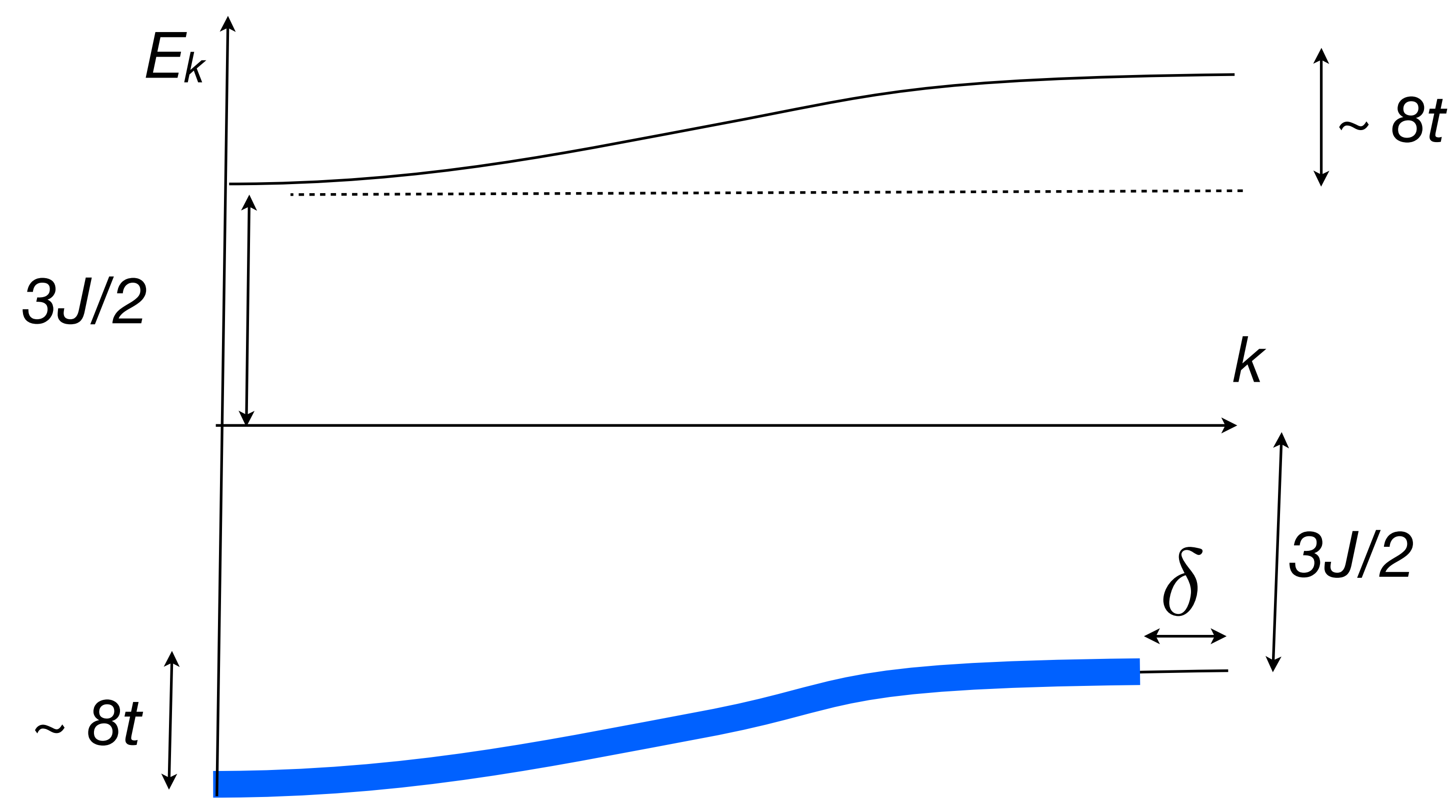

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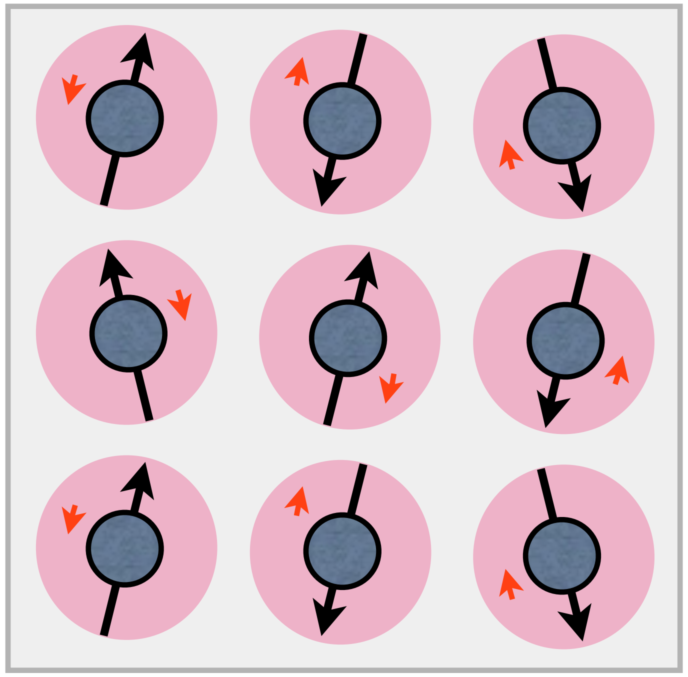

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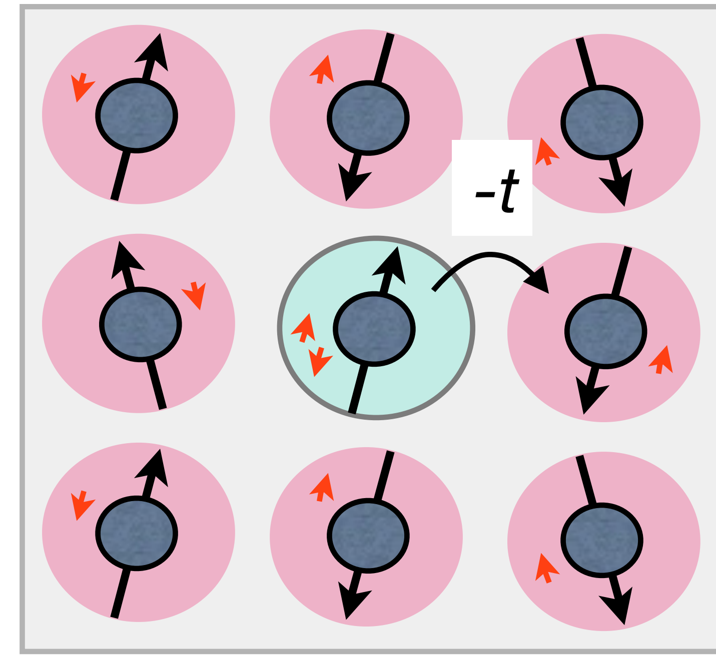
Kondo insulator



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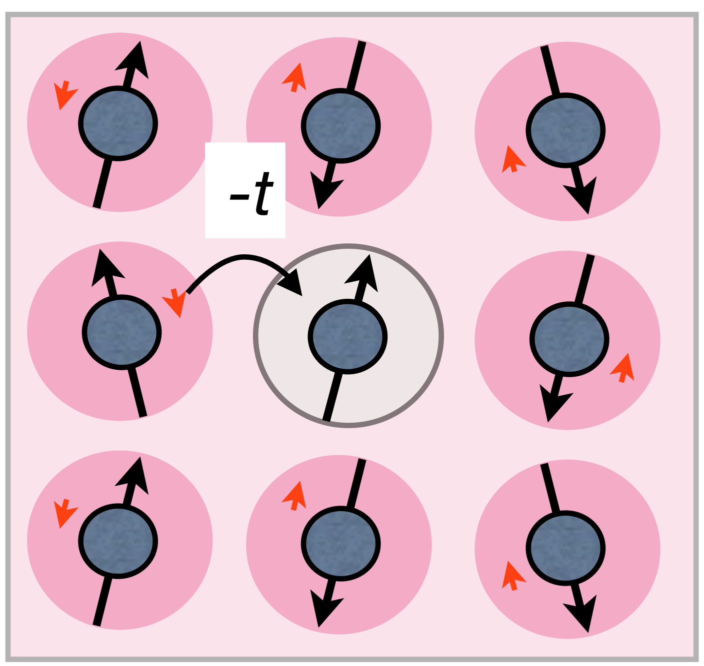

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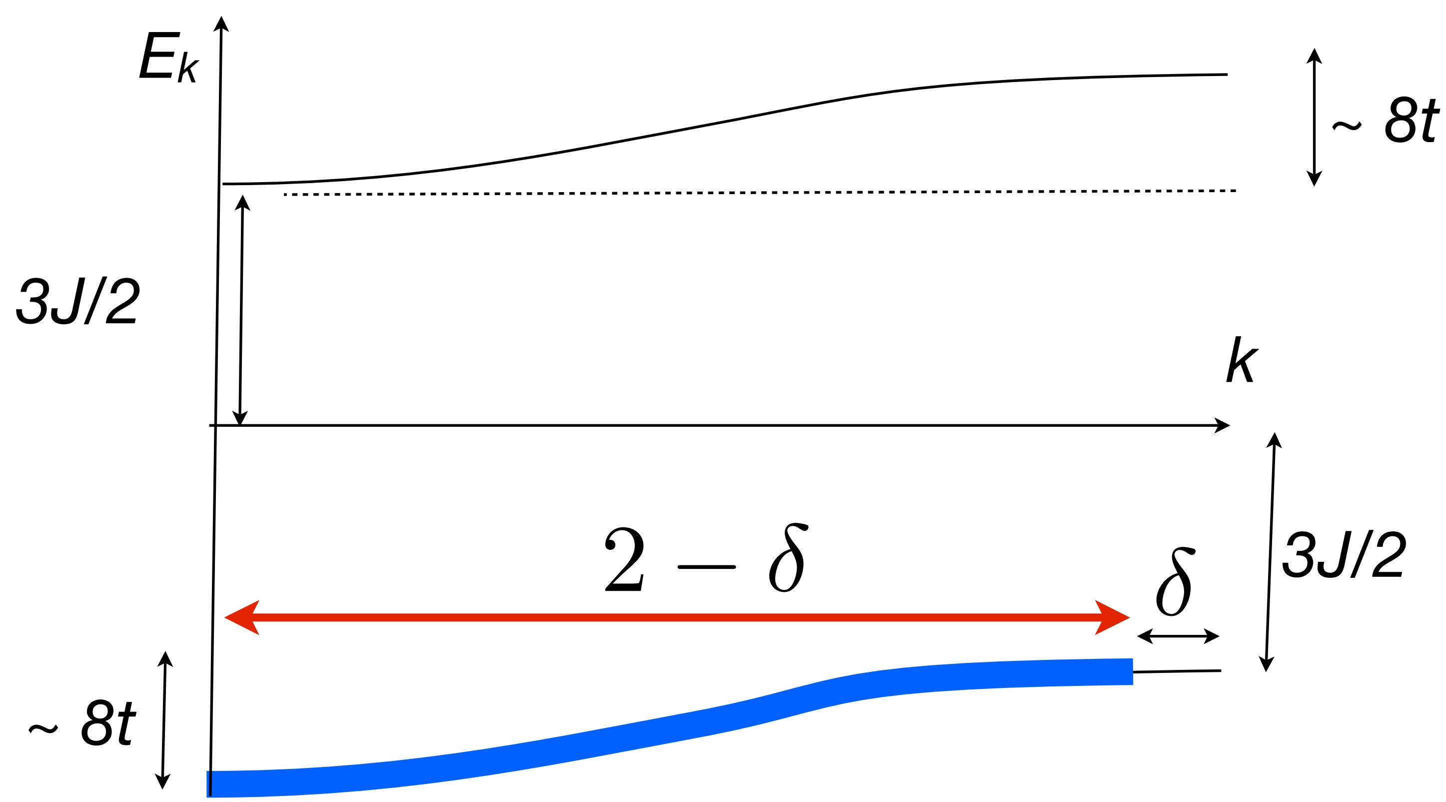

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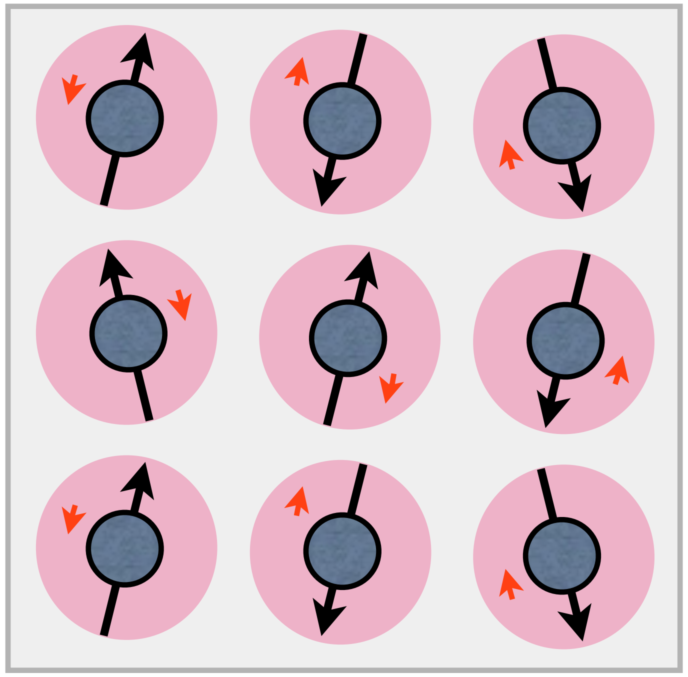
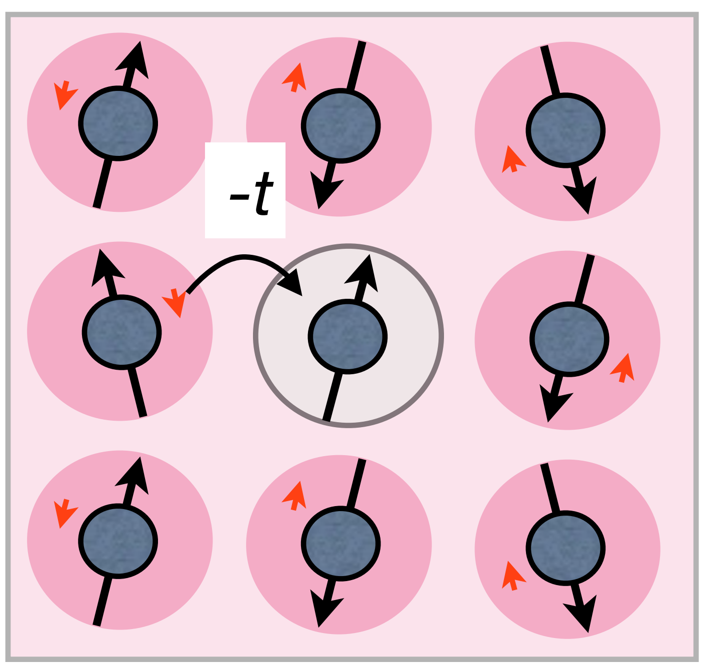


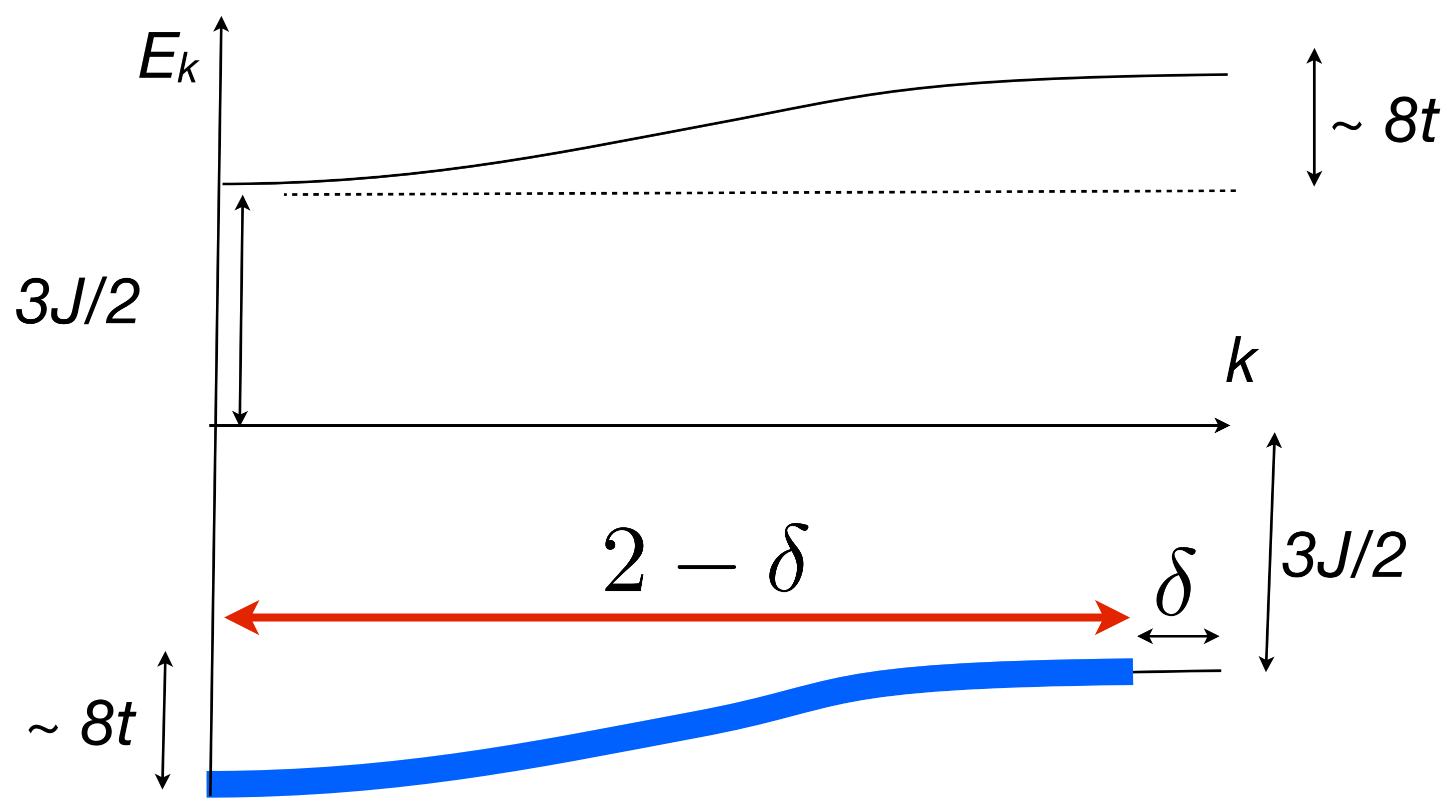
$n_e = n_{\text{spins}}$

Kondo insulator

$$2\left(\frac{v_{\text{FS}}}{(2\pi)^D}\right) = 2 - \delta = n_{\text{spins}} + n_e$$

FS sum rule counts spins as charged qp.





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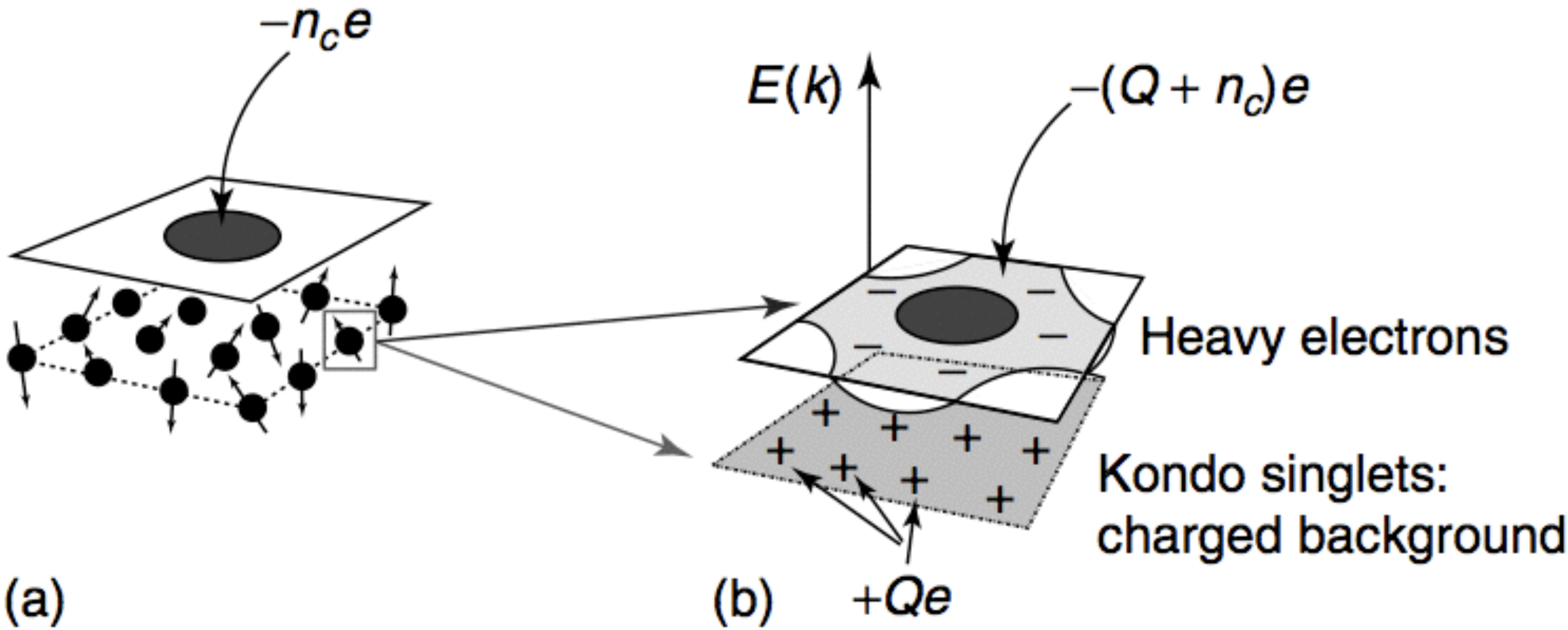
Large Fermi surface and the charge of the f-electron



Summary of Part 1.

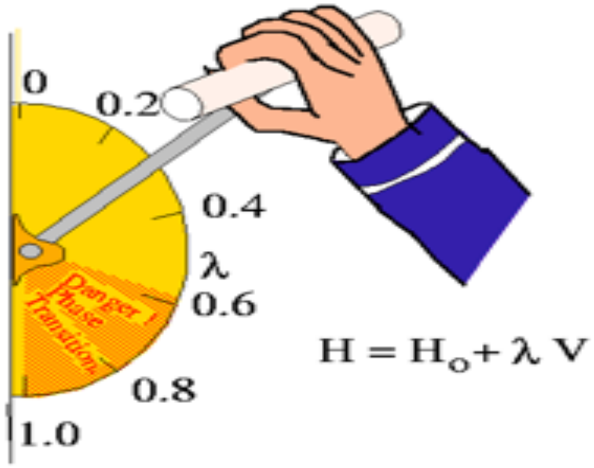
- Heavy Fermions: “Fruit fly” of condensed matter physics.
- Interesting physics at the border of magnetism.
- Local moments can entangle with electrons to produce new states of matter - emergent physics that we have only just begun to explore and understand.

Lecture 2 Quantum Criticality and Strange Metals

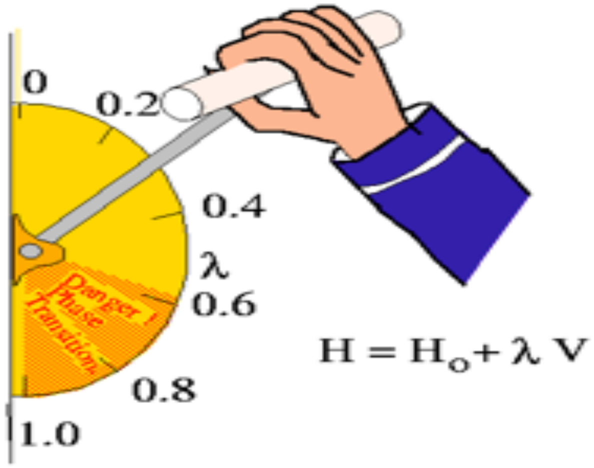
1. Lev Landau meets Ken Wilson
2. Quantum criticality as a driver of new states of matter.
3. Quantum critical heavy fermion systems
4. Frustration and Strange Metals

Lev Landau vs Ken Wilson:

Criticality as a driver of new States of Matter

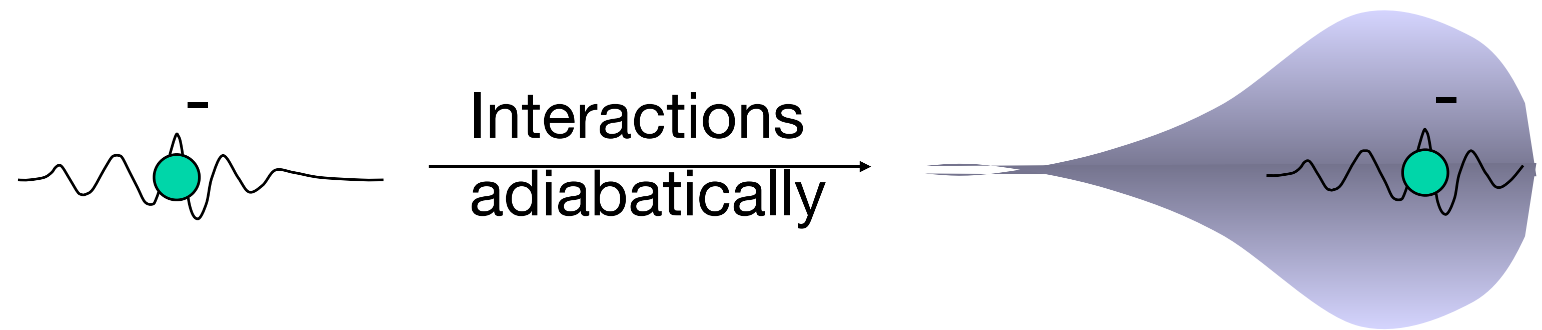


Landau: interactions can be turned on adiabatically, preserving the excitation spectrum.

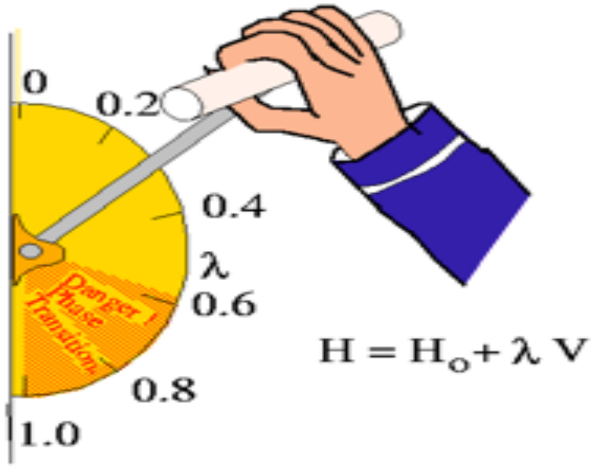


Landau: interactions can be turned on <u>adiabatically</u>, preserving the excitation spectrum.

"Quasiparticle"



$\left| e^{-} \right\rangle$ $\qquad\qquad$ $\left| qp^{-} \right\rangle$



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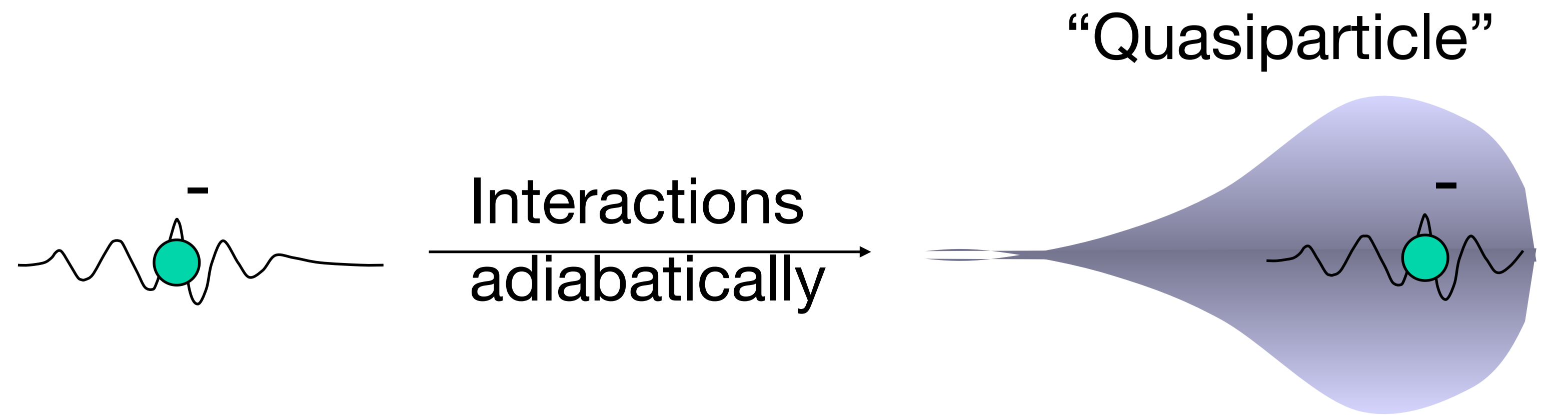
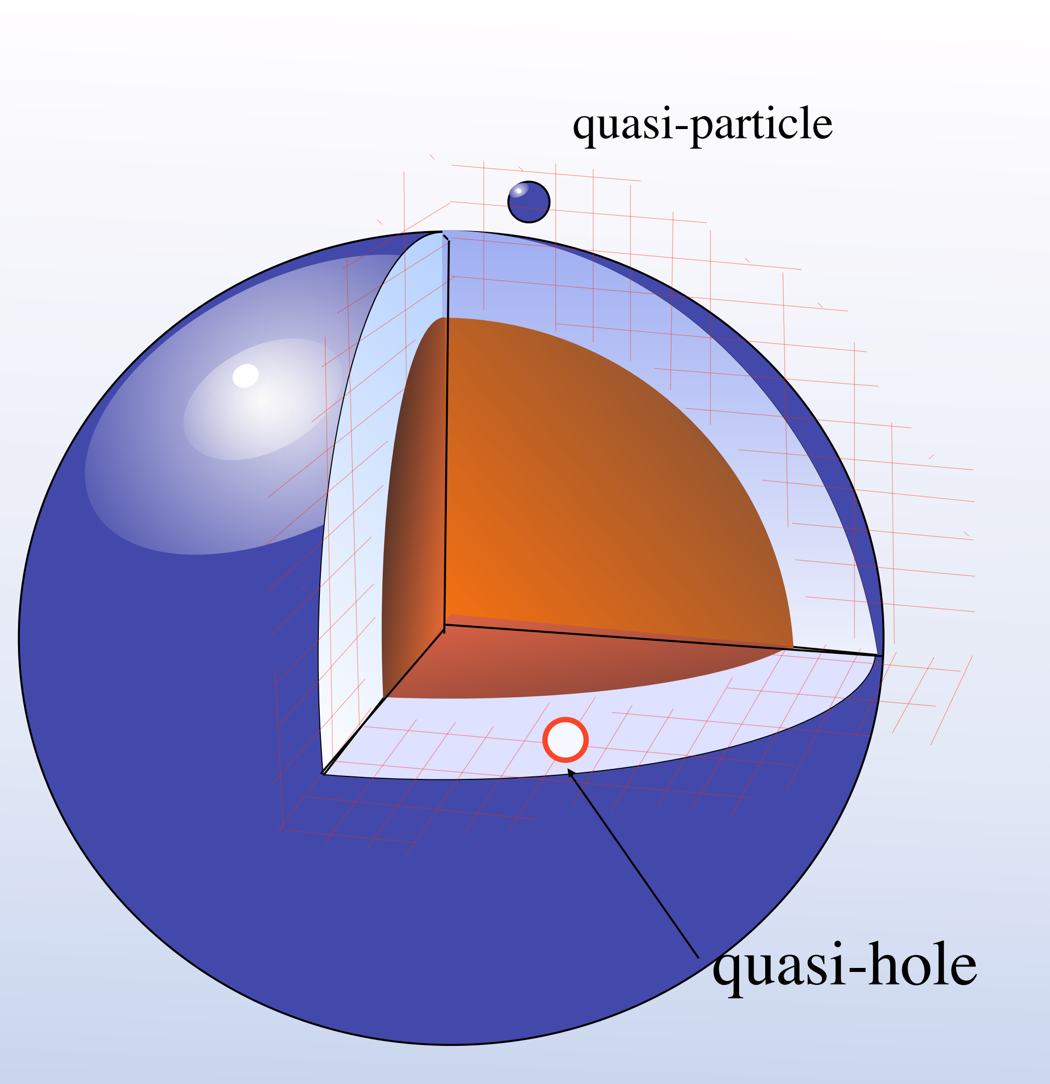
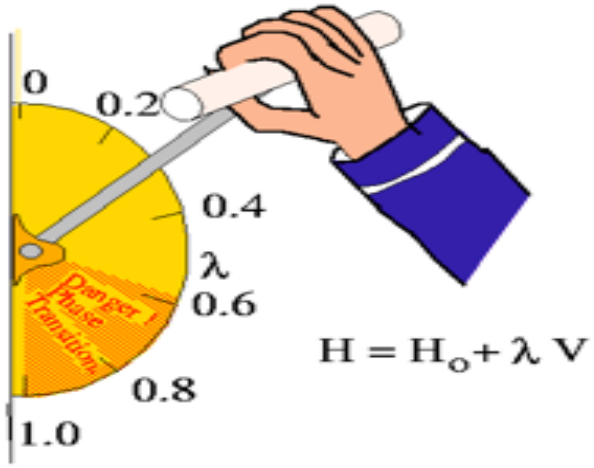


$$\left| e^- \right\rangle \qquad\qquad \left| qp^- \right\rangle$$





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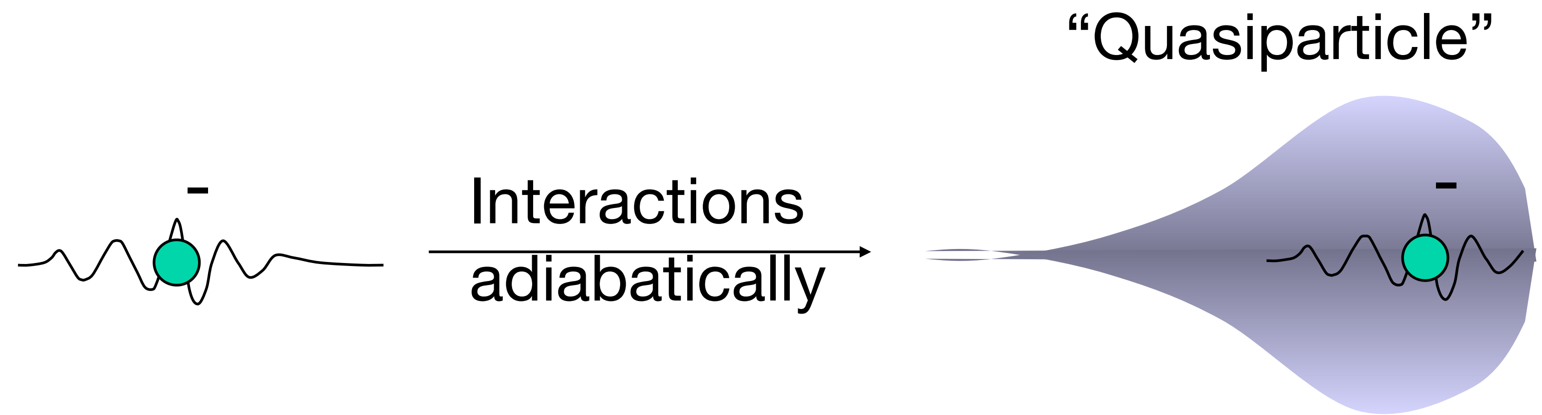
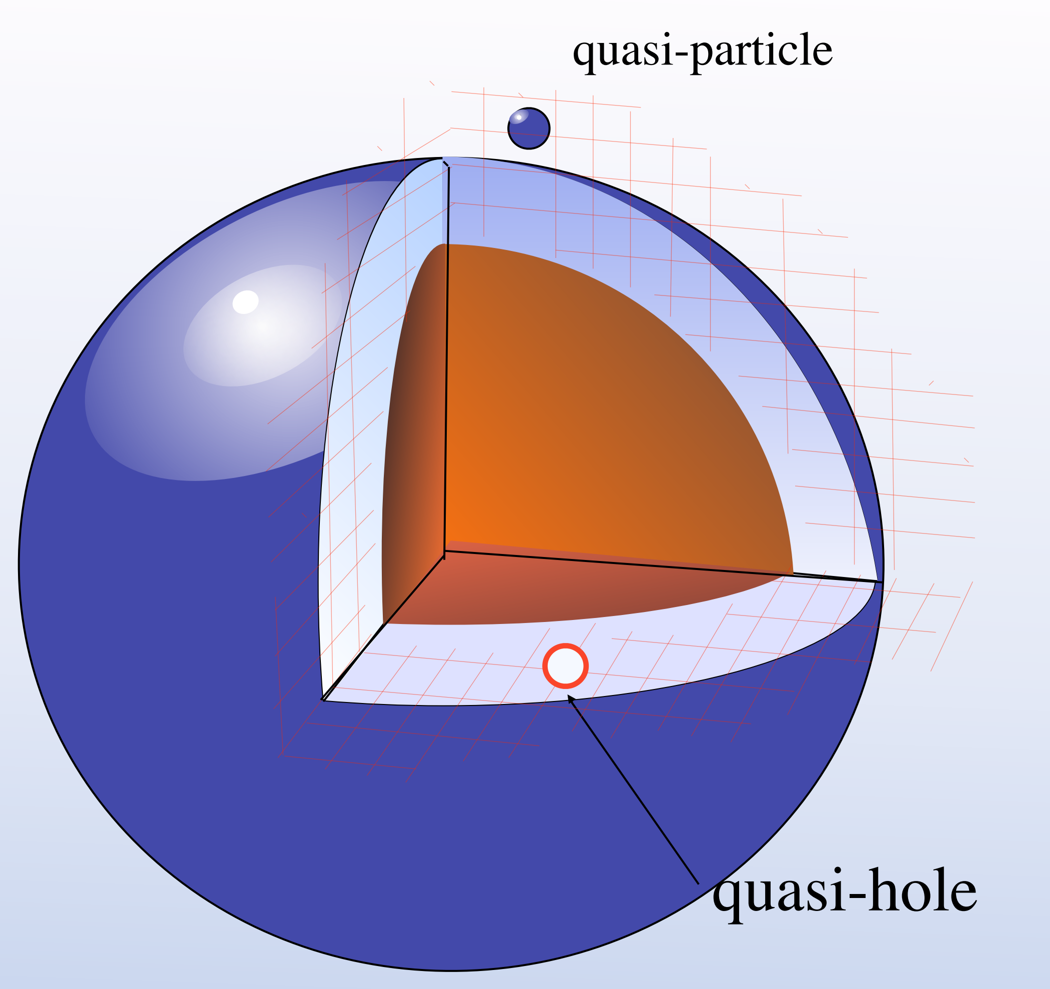


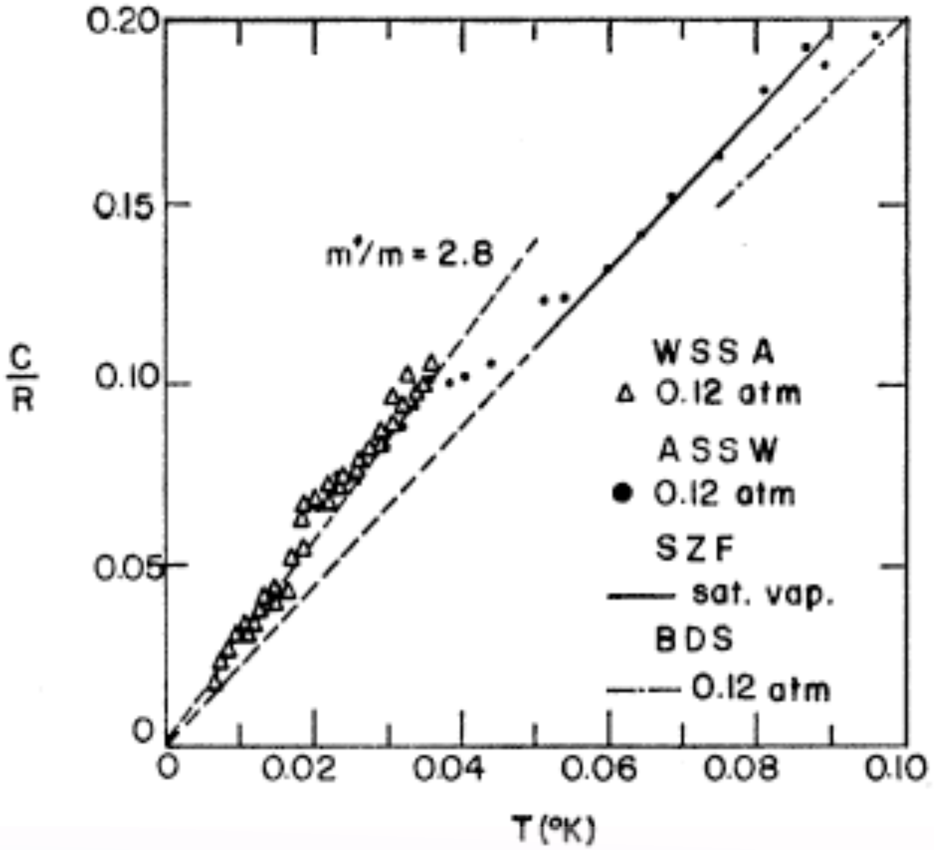
$$|e^-\rangle \qquad\qquad |qp^-\rangle$$

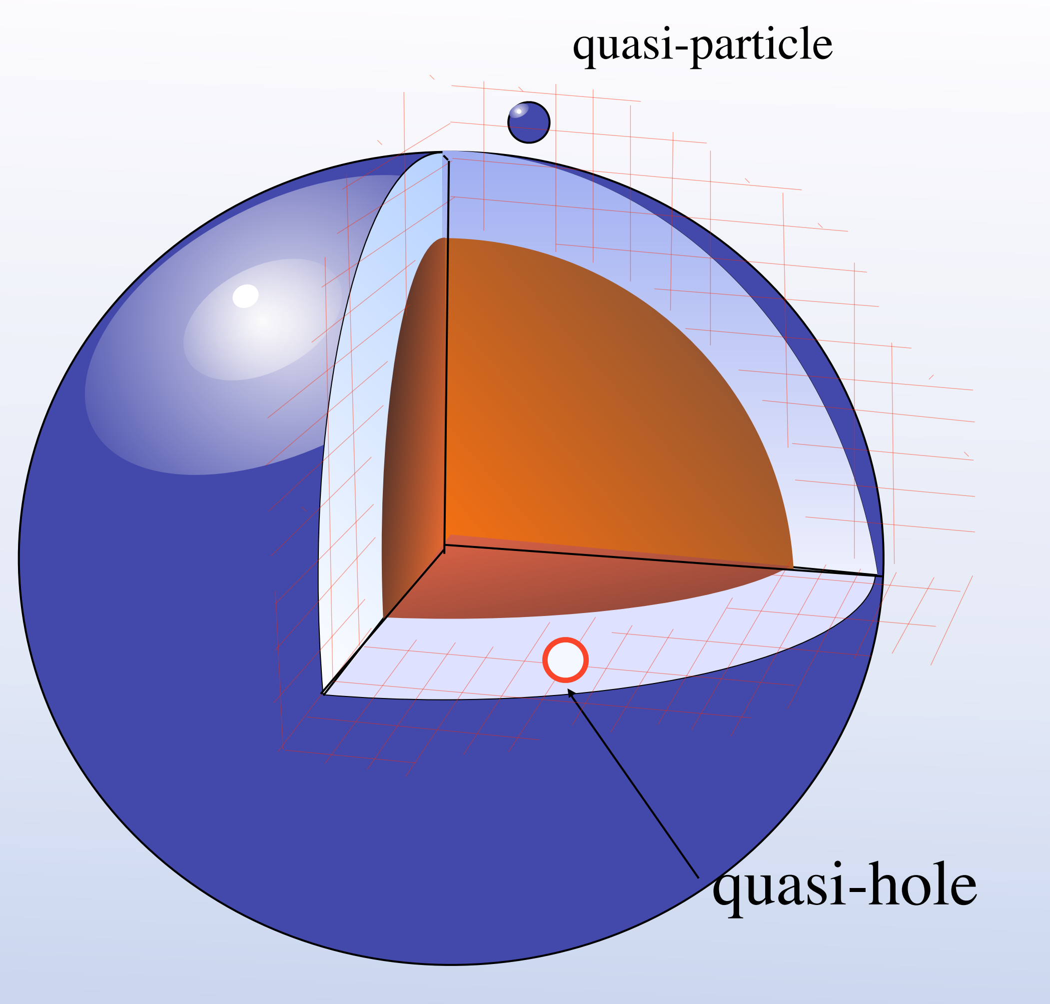


$$\frac{m^*}{m} = \frac{N(0)^*}{N(0)} = 1 + \frac{F_1^s}{3}$$

Landau, JETP 3, 920 (1957)

He-3 (1950/60s)
(Fairbanks, many others)





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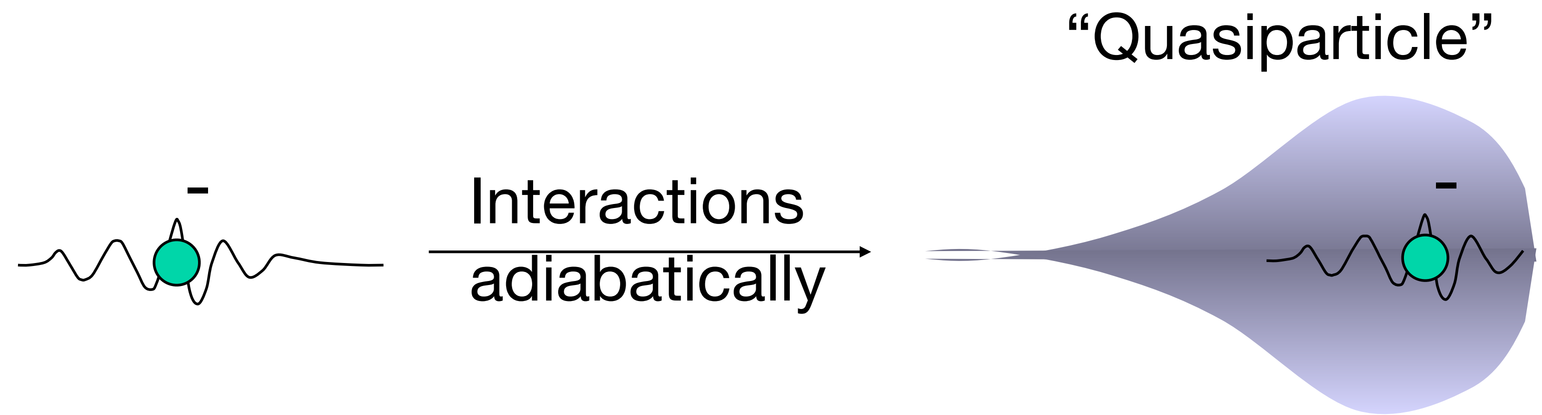

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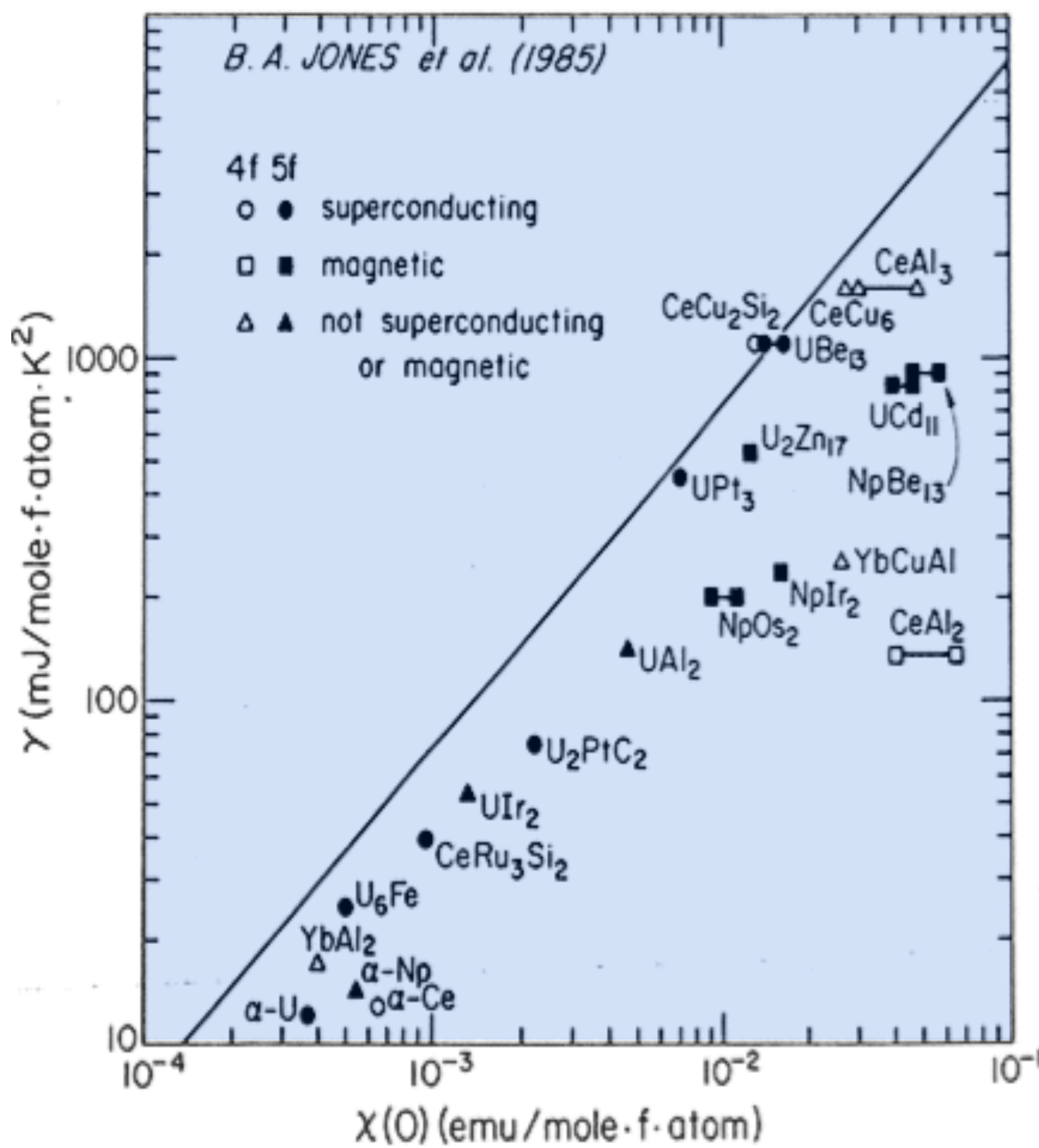
Landau, JETP 3, 920 (1957)

Heavy Fermions: magnetically polarizable Landau Fermi liquids.

$$E_{\mathbf{p}} = \frac{p^2}{2m^*}, \qquad N^*(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$



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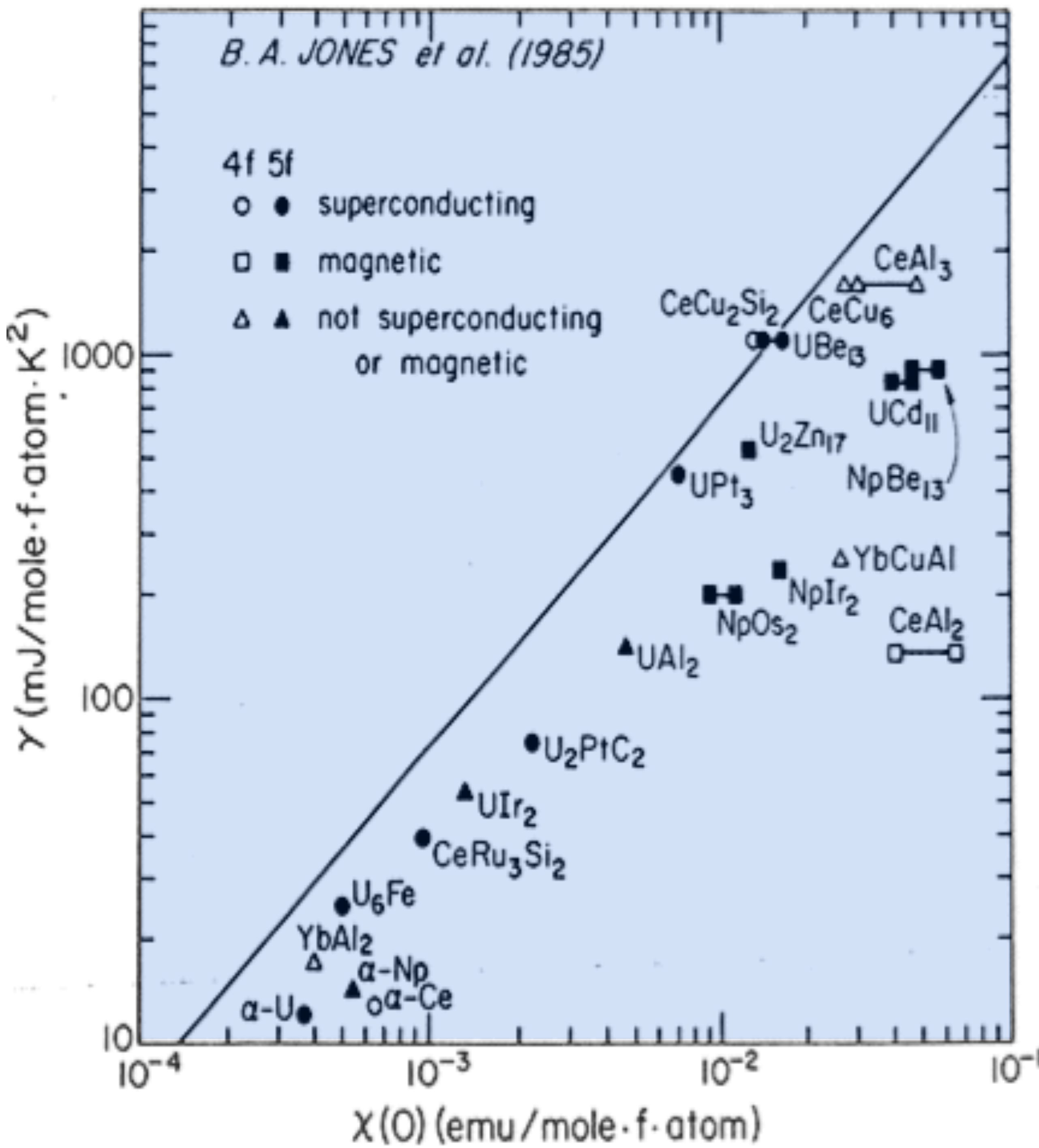

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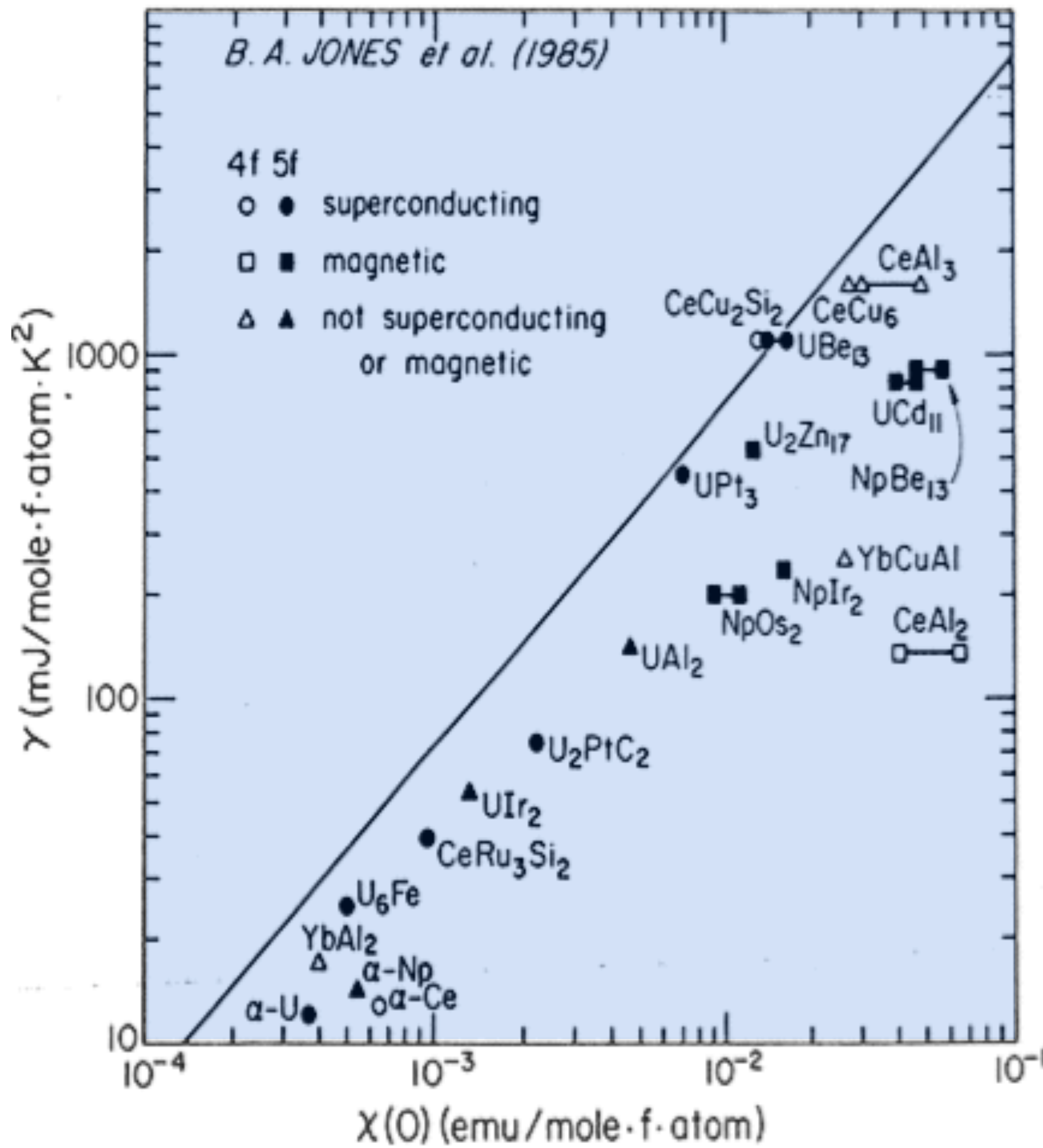

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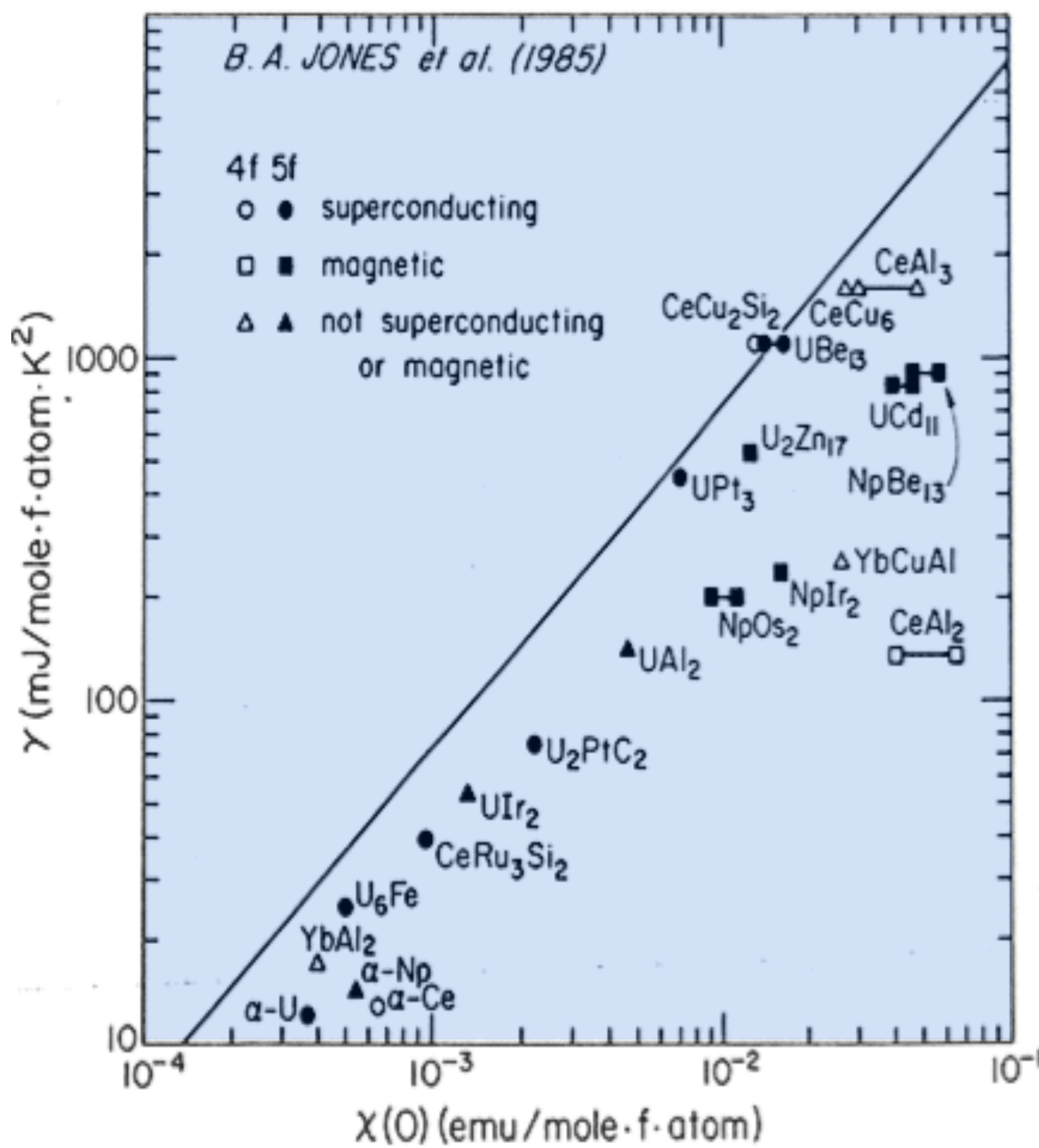
$$W = \frac{\chi}{\gamma} = 3\left(\frac{\mu_\mathrm{B}}{2\pi k_B}\right)^2 \frac{1}{1+F_0^a}$$

"Wilson" or "Sommerfeld" ratio.



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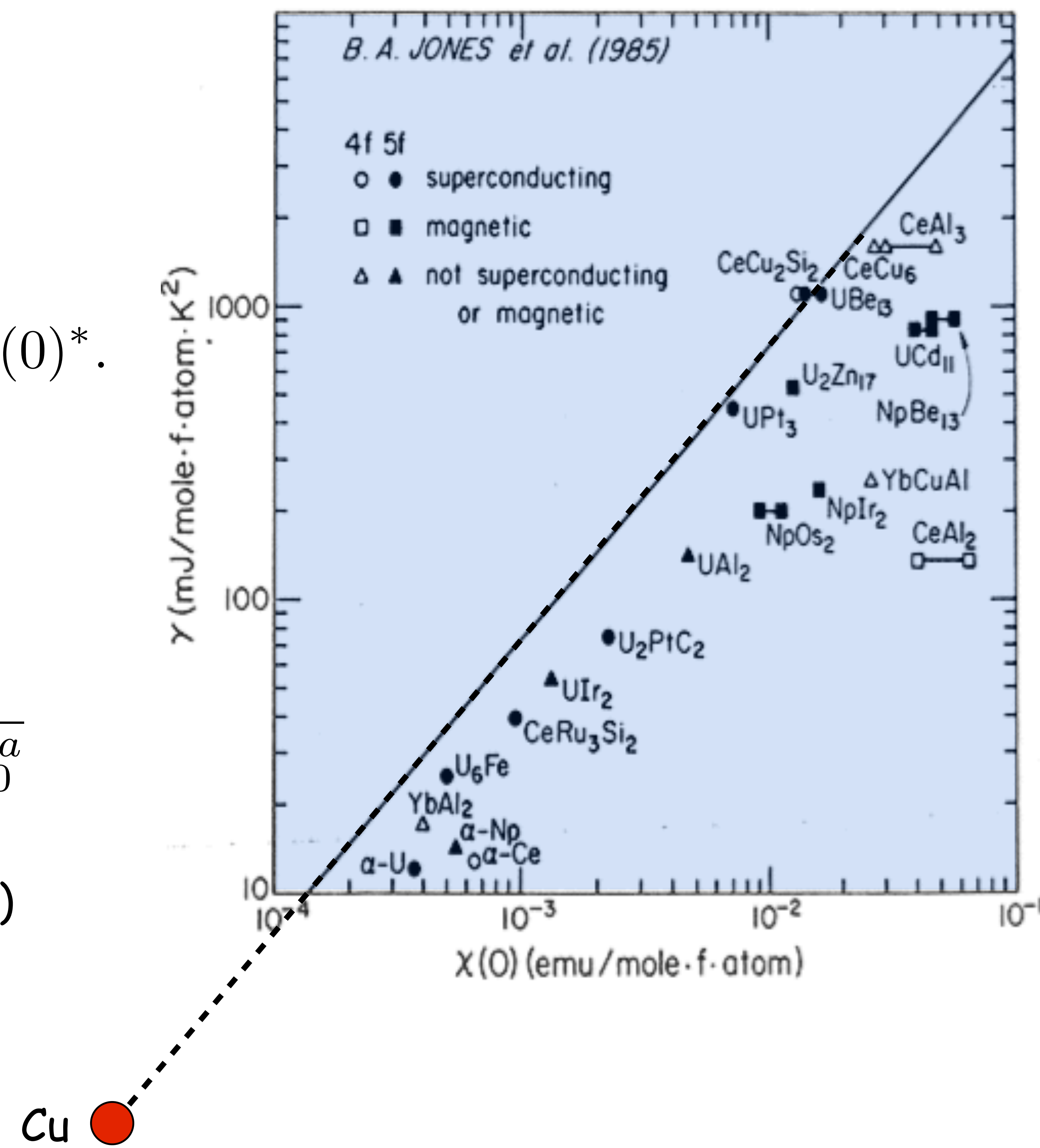
"Wilson" or "Sommerfeld" ratio.

eg Cu vs $CeCu_6$ (copper, spin doped)

γCu ~ 1 mJ/mol/K^2,



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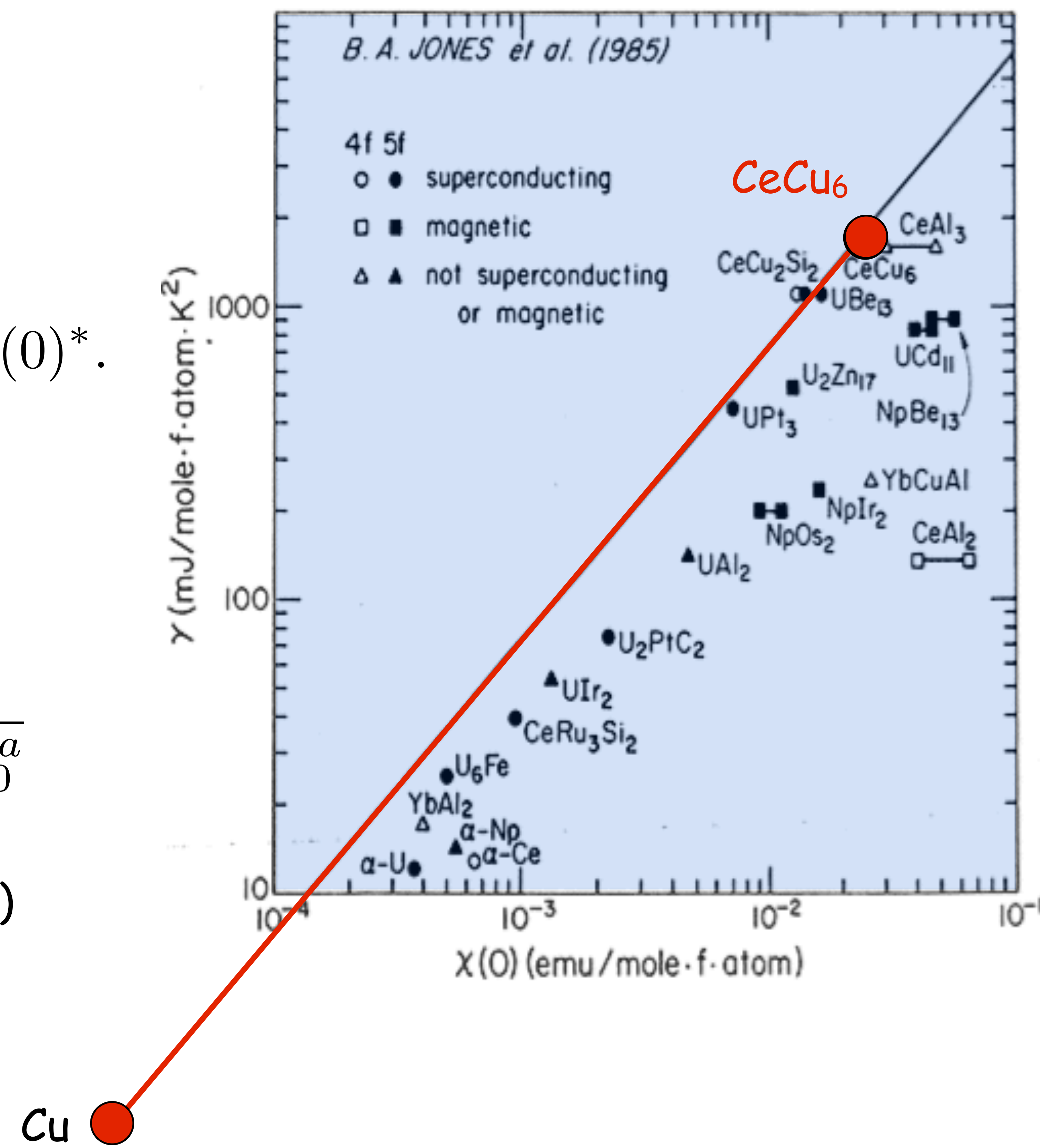
eg Cu vs $CeCu_6$ (copper, spin doped)

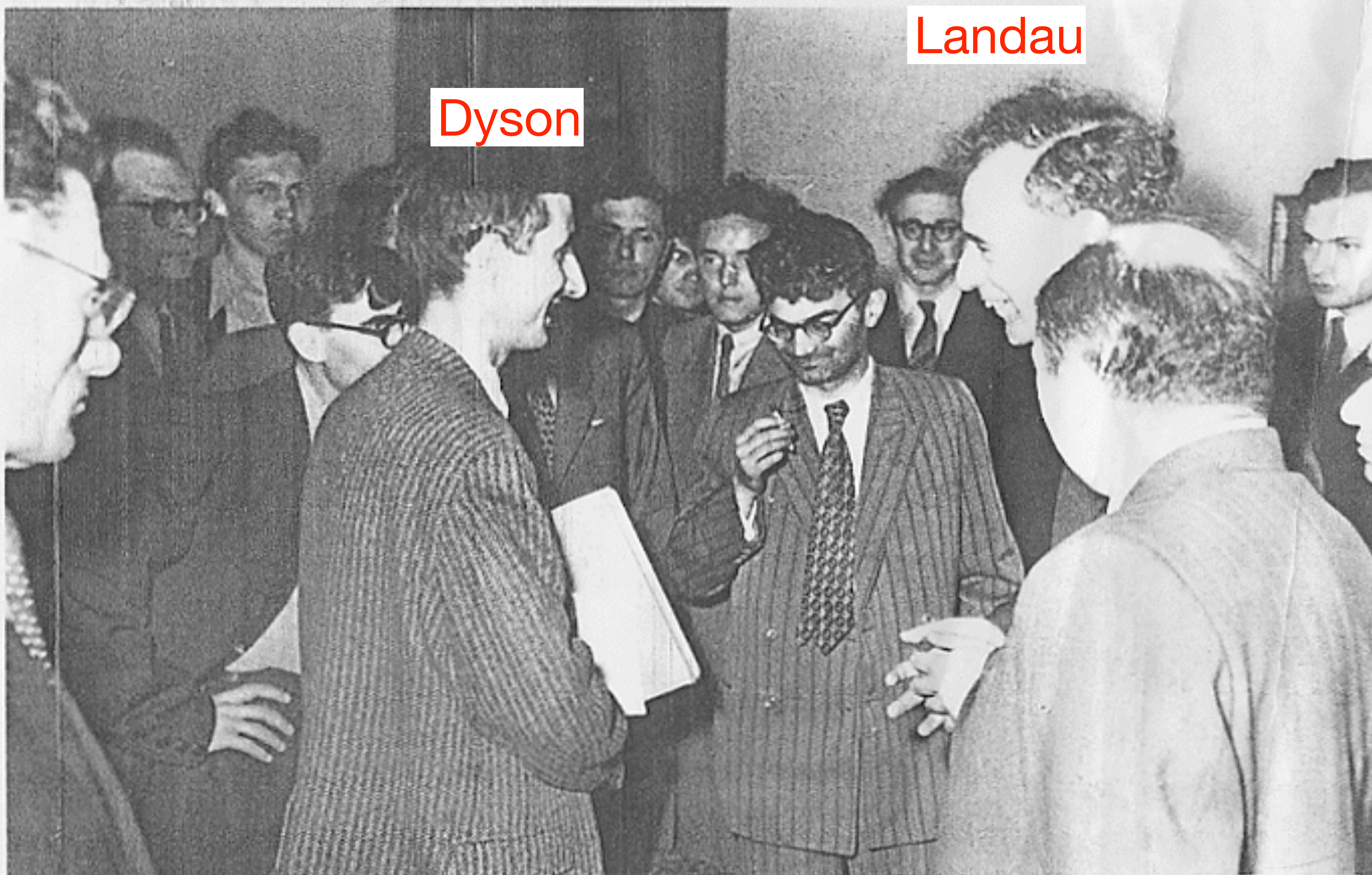
$\gamma Cu \sim 1$ mJ/mol/K^2,

$\gamma[CeCu_6] \sim 1000$ mJ/mol/K^2,

$m^*/m_e \sim 1000$



20. Moscow, 1956. Freeman Dyson (front, left), talking with I. Pomeranchuk and Lev Landau.



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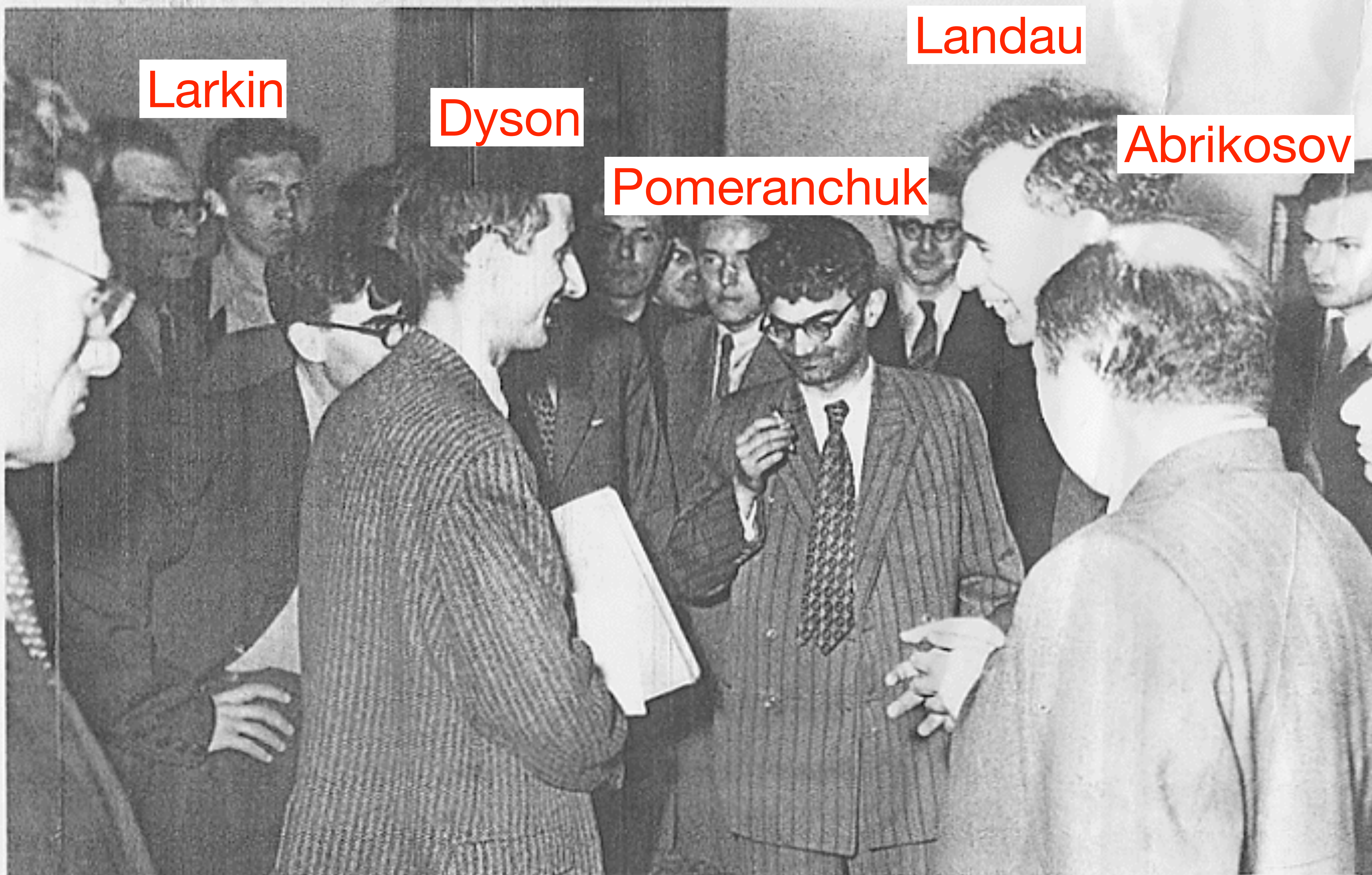

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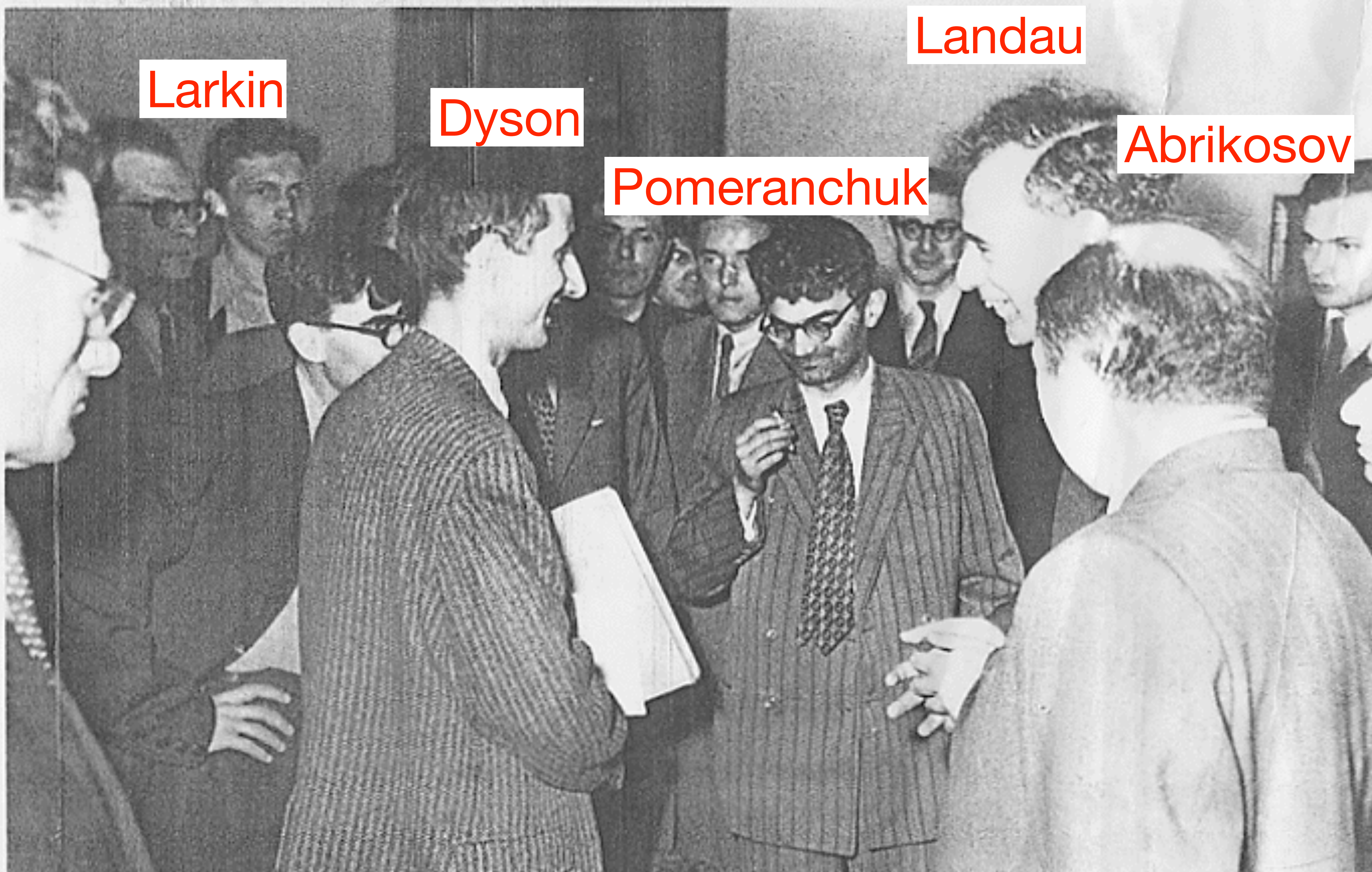
0 Fermi Liquid — Adiabaticity — Landau Fermi Liquid $X \sim U/t$



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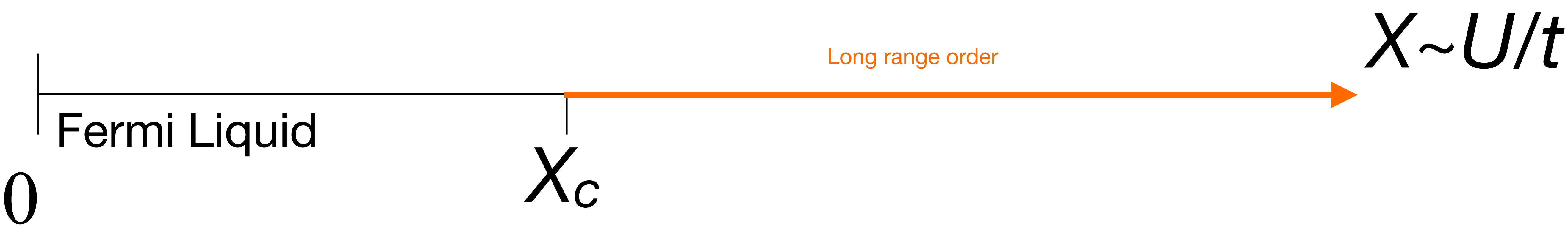
Fermi Liquid

0



What happens when the interaction becomes too large?

Wigner/ Landau 1934/36

“Electrons order”

What happens when
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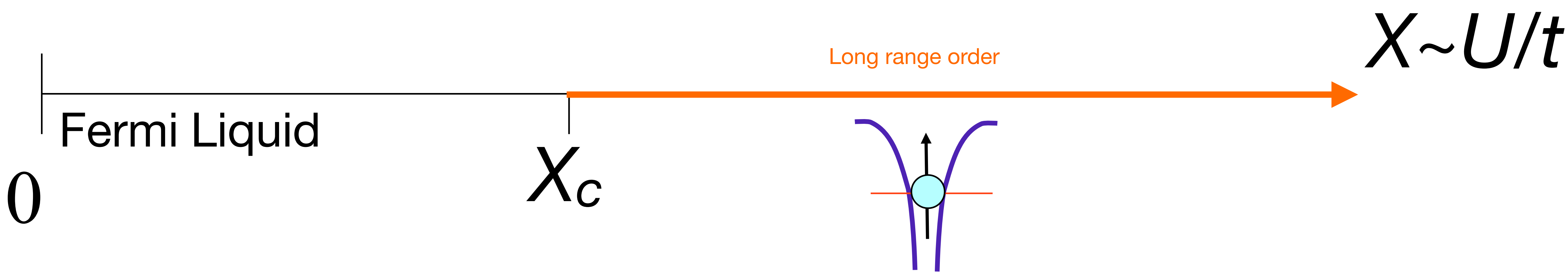

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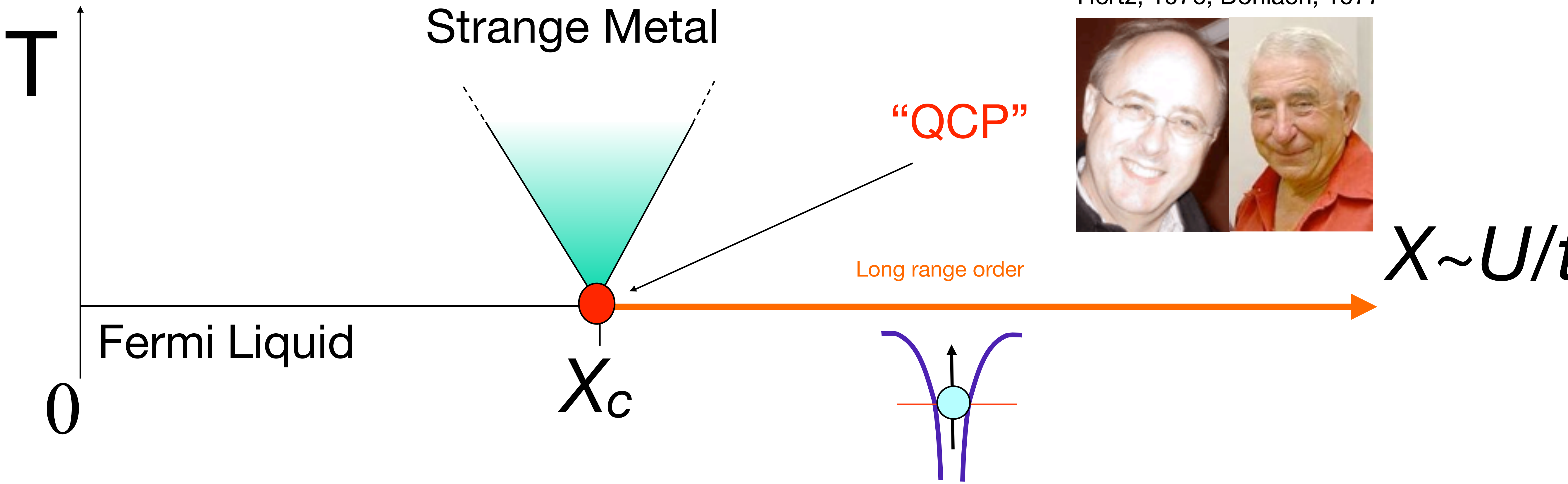
Hertz, 1976, Doniach, 1977



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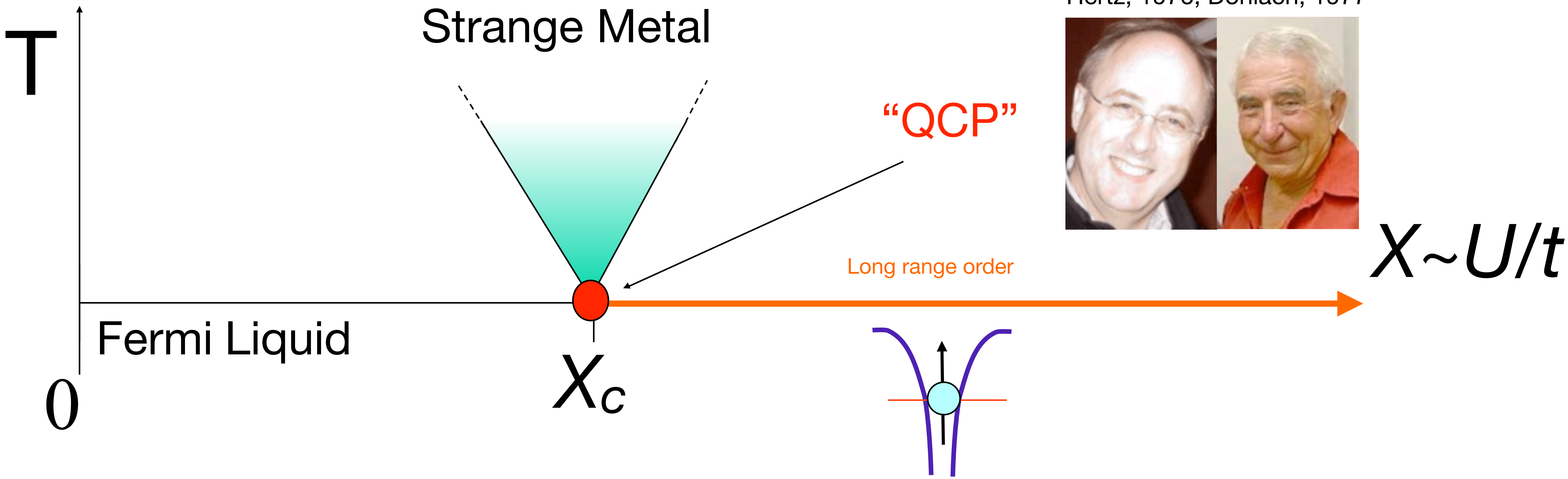

What happens when
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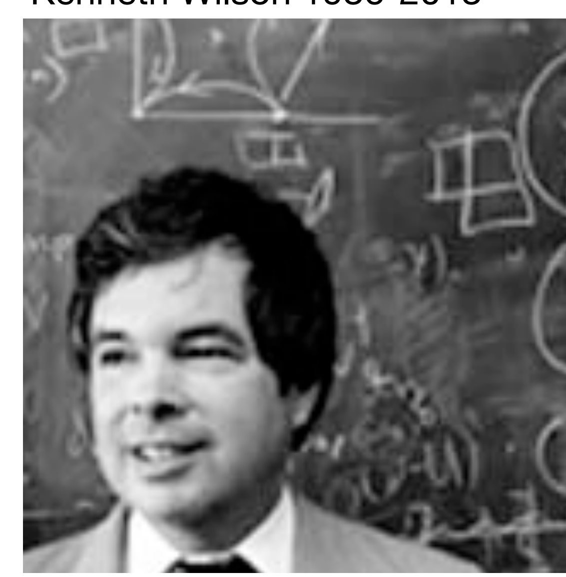
Kenneth Wilson 1936-2013



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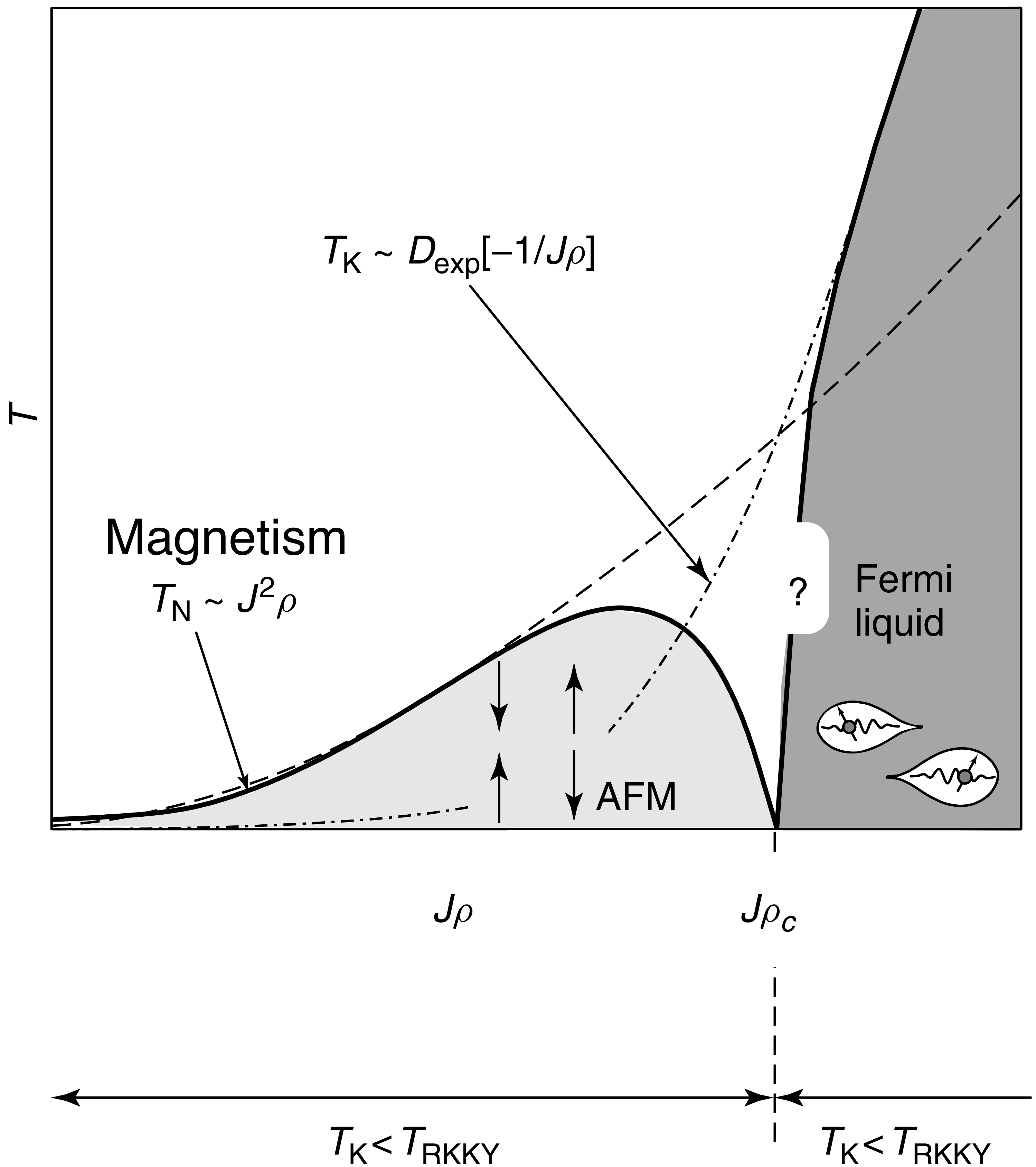
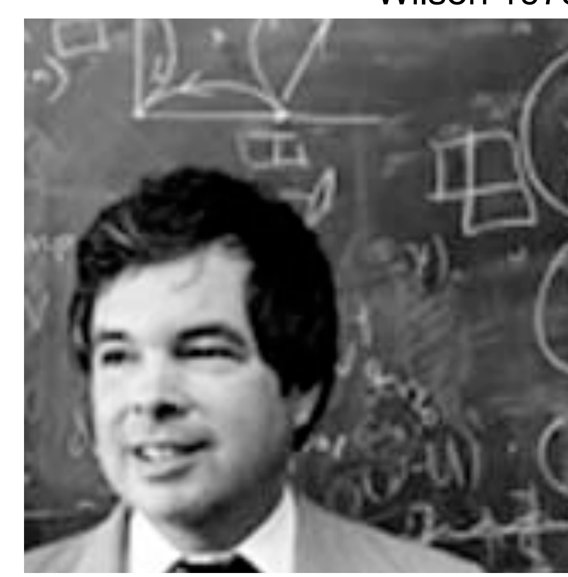
New Fixed Points

Mott, 1973
Doniach 1976



Wilson 1975



New Fixed Points

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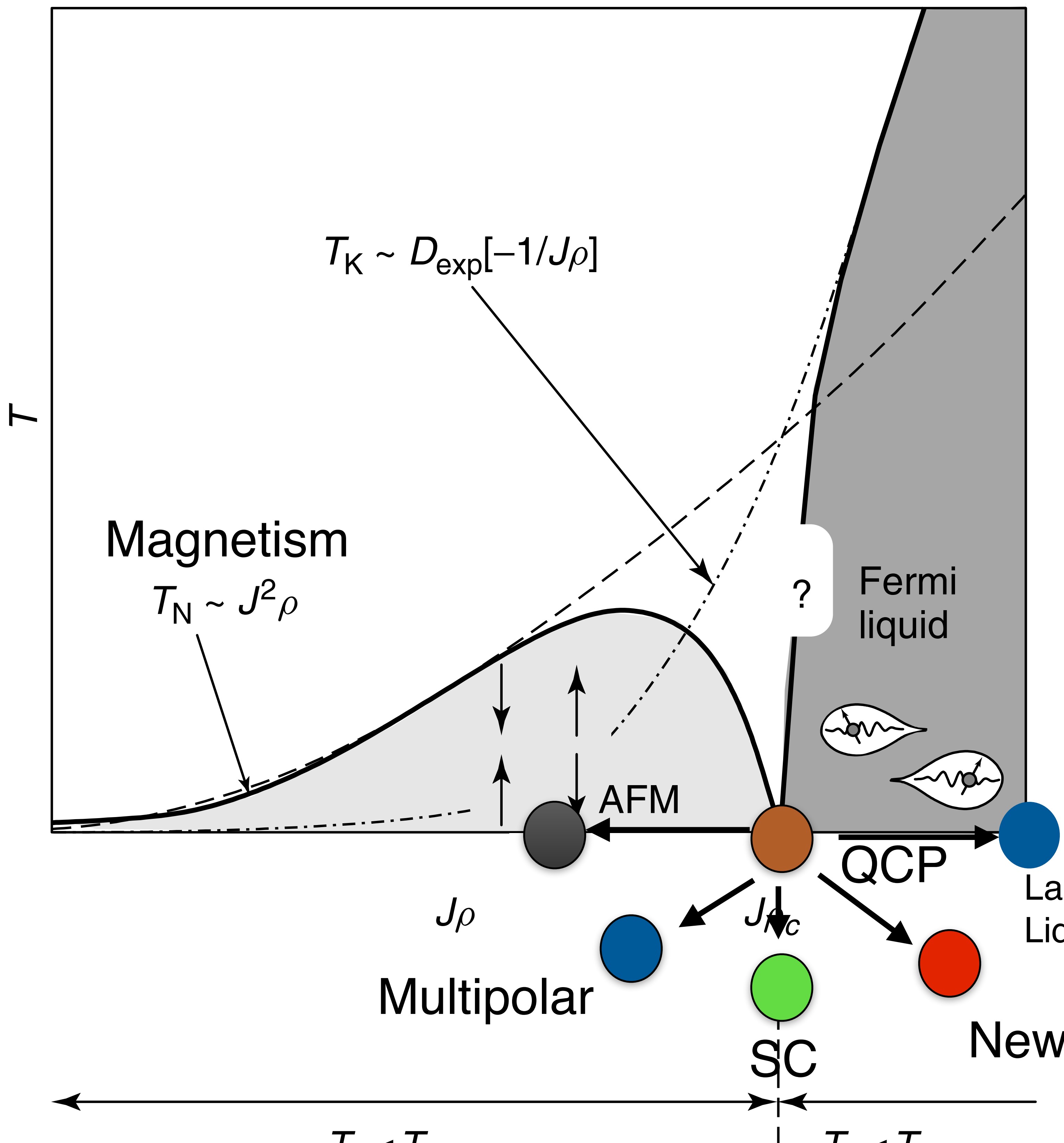
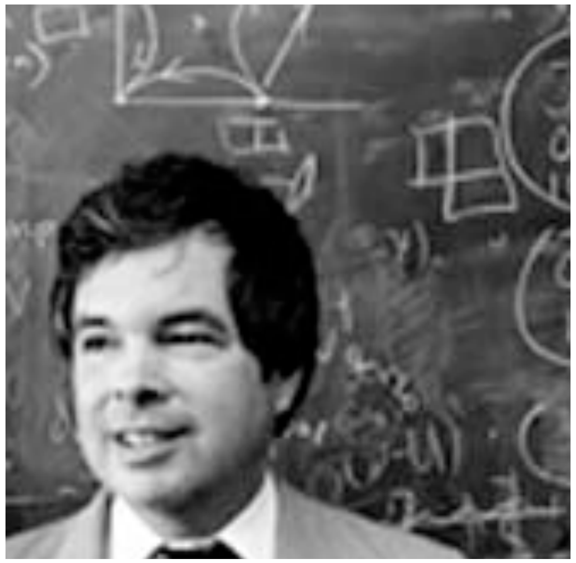


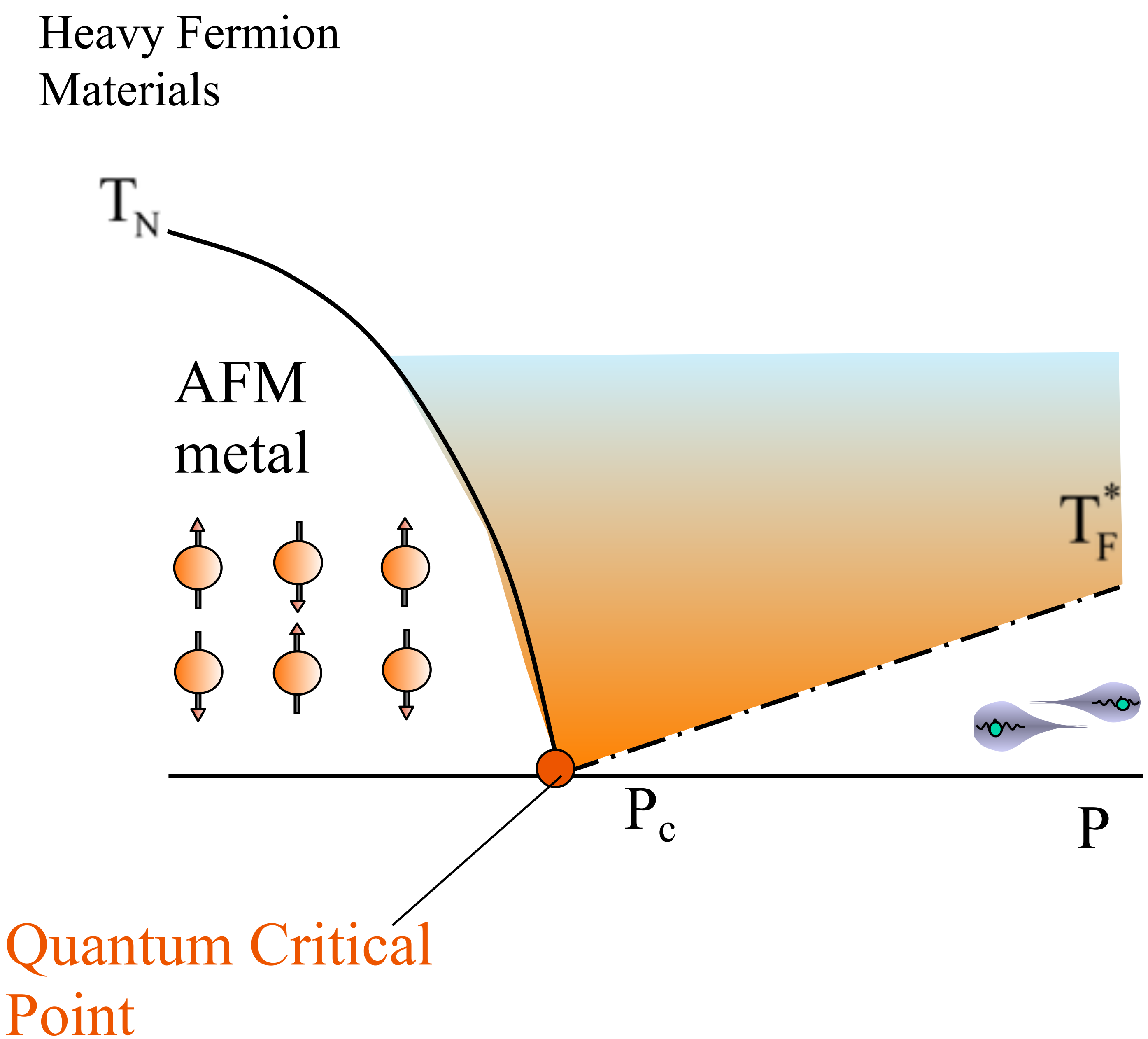
Wilson 1975



New Fixed Points

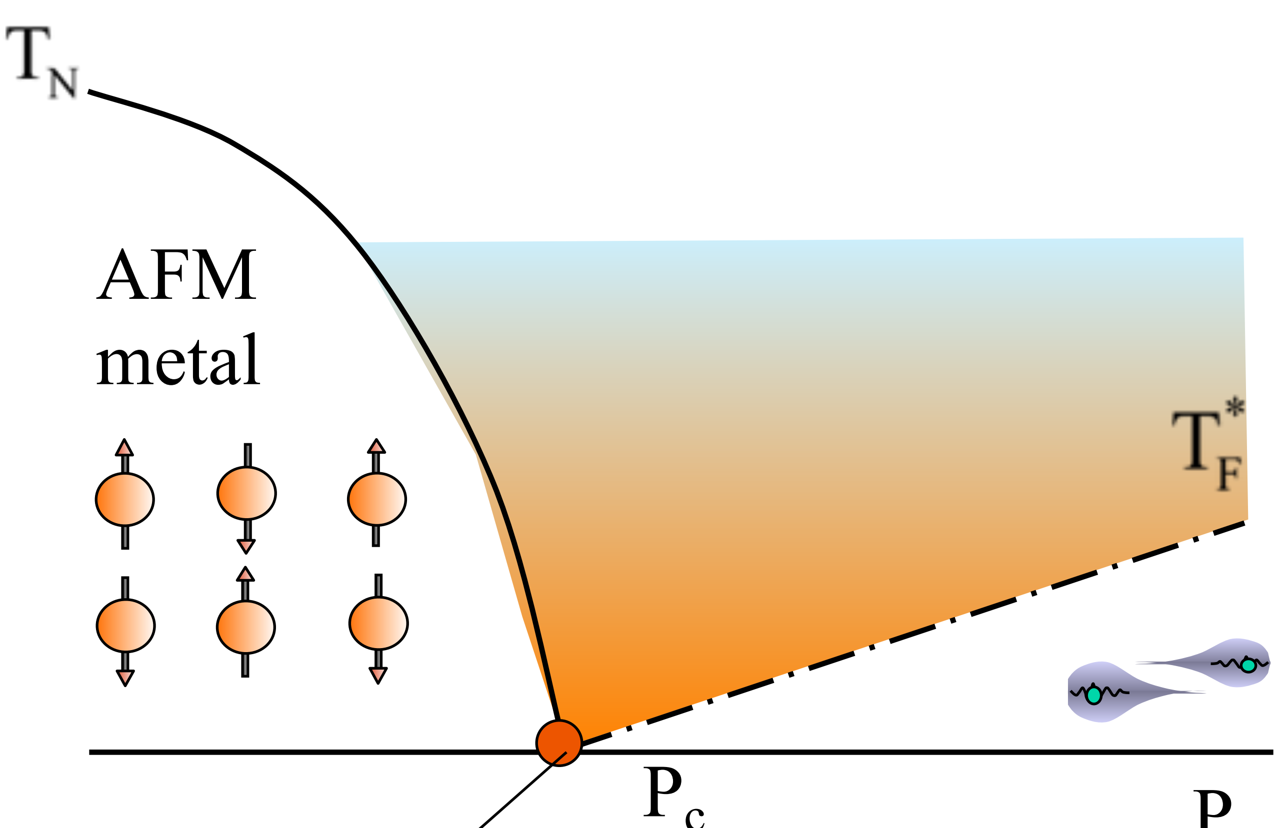
Quantum Criticality

Quantum Criticality:
divergent specific heat capacity



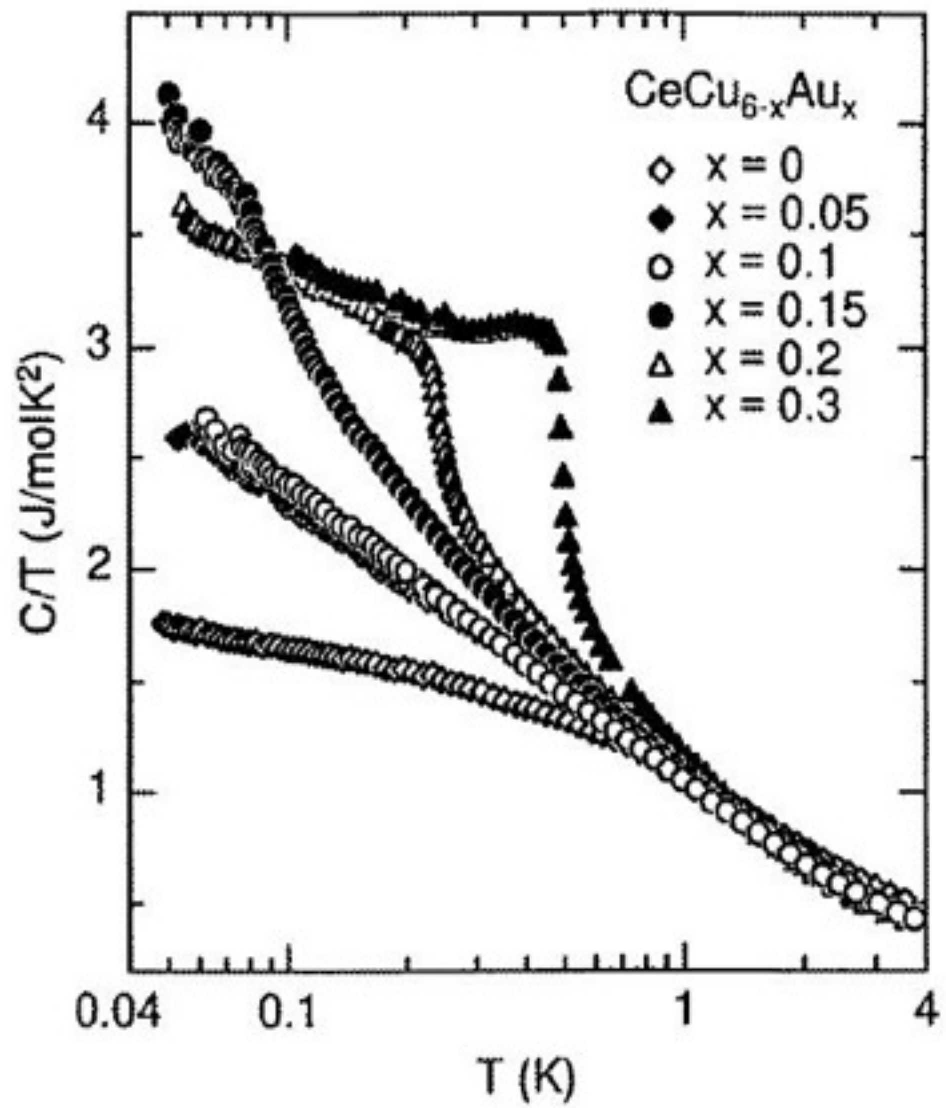
Quantum Criticality:
divergent specific heat capacity

Heavy Fermion Materials



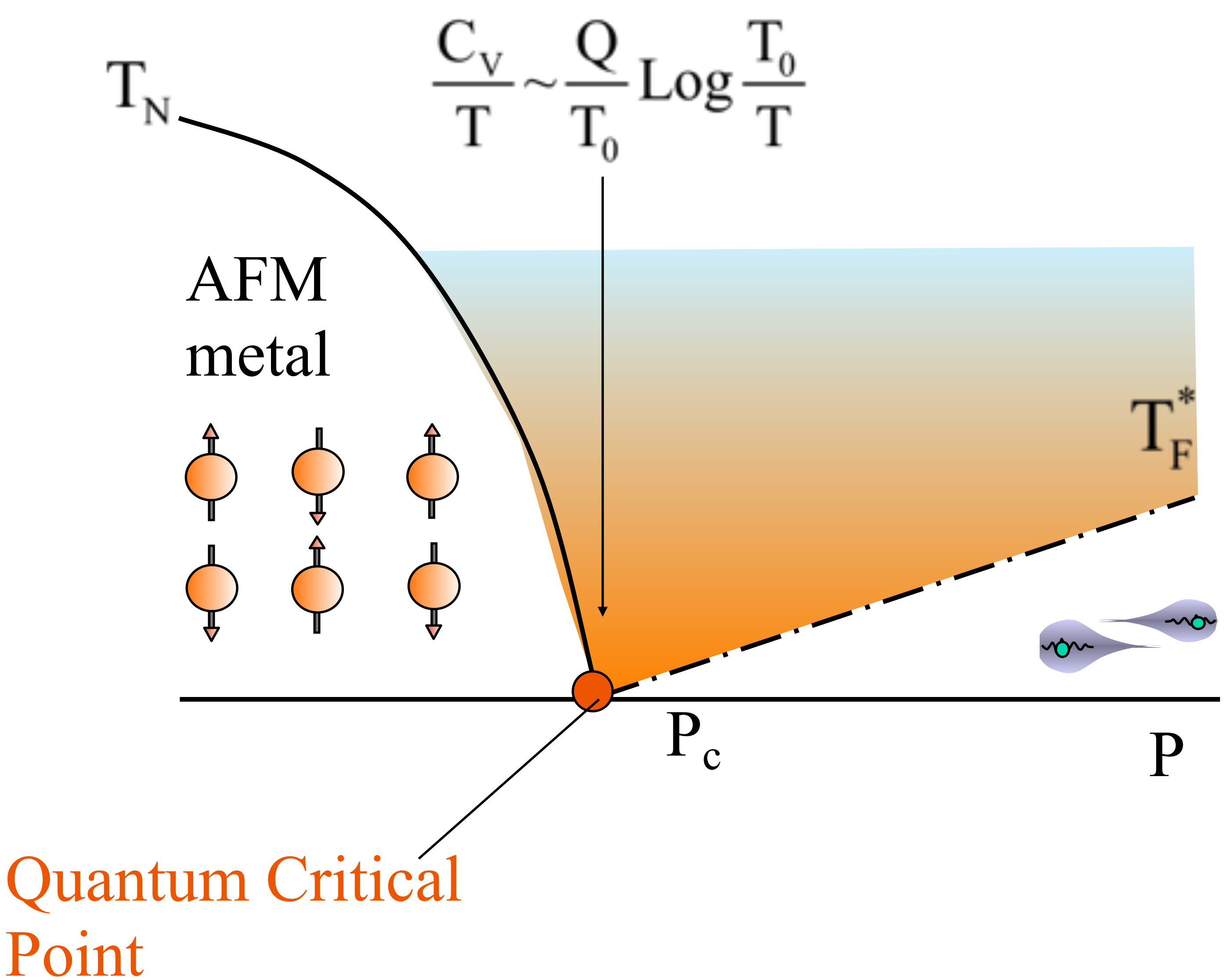
Quantum Critical Point

H. Von Lohneyson (1996)



Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



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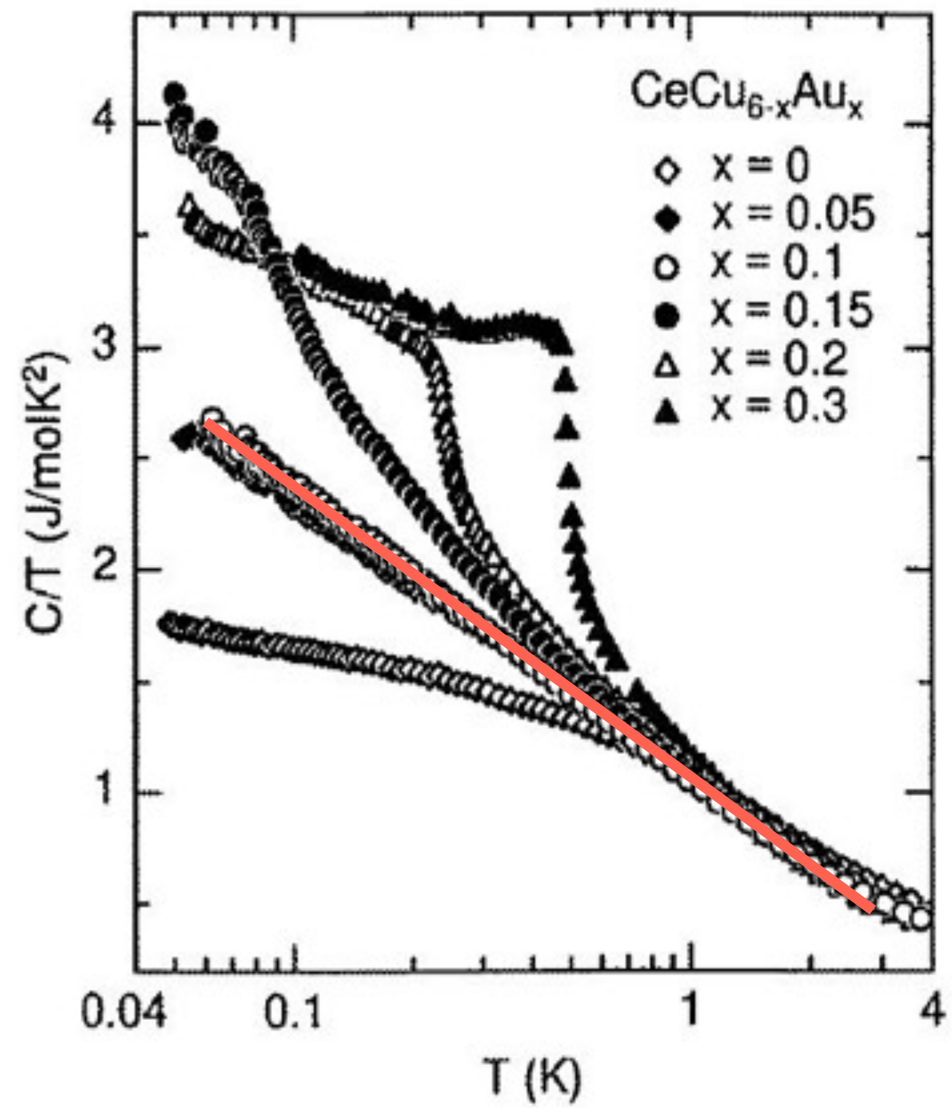

Quantum Criticality:
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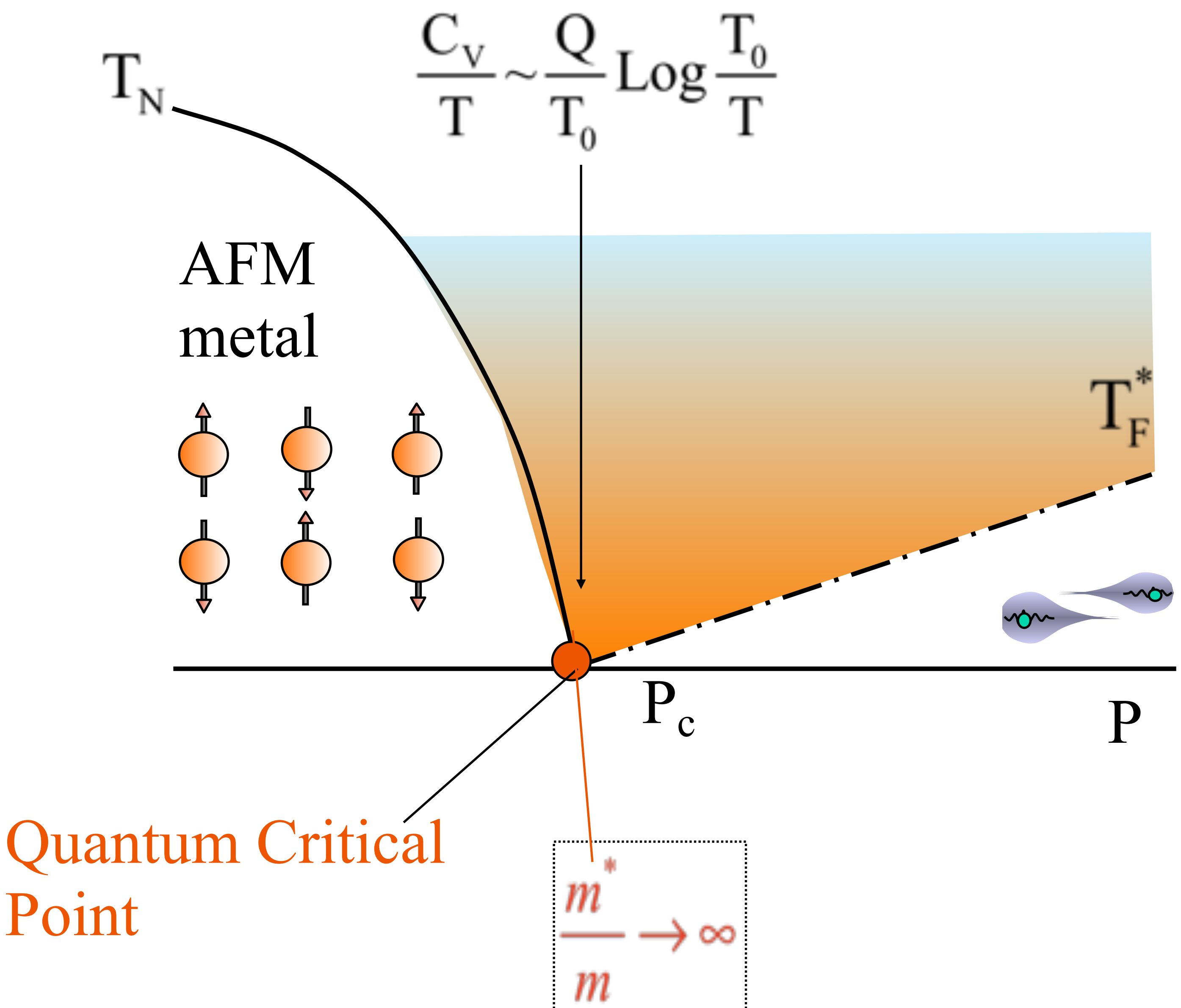
Heavy Fermion
Materials



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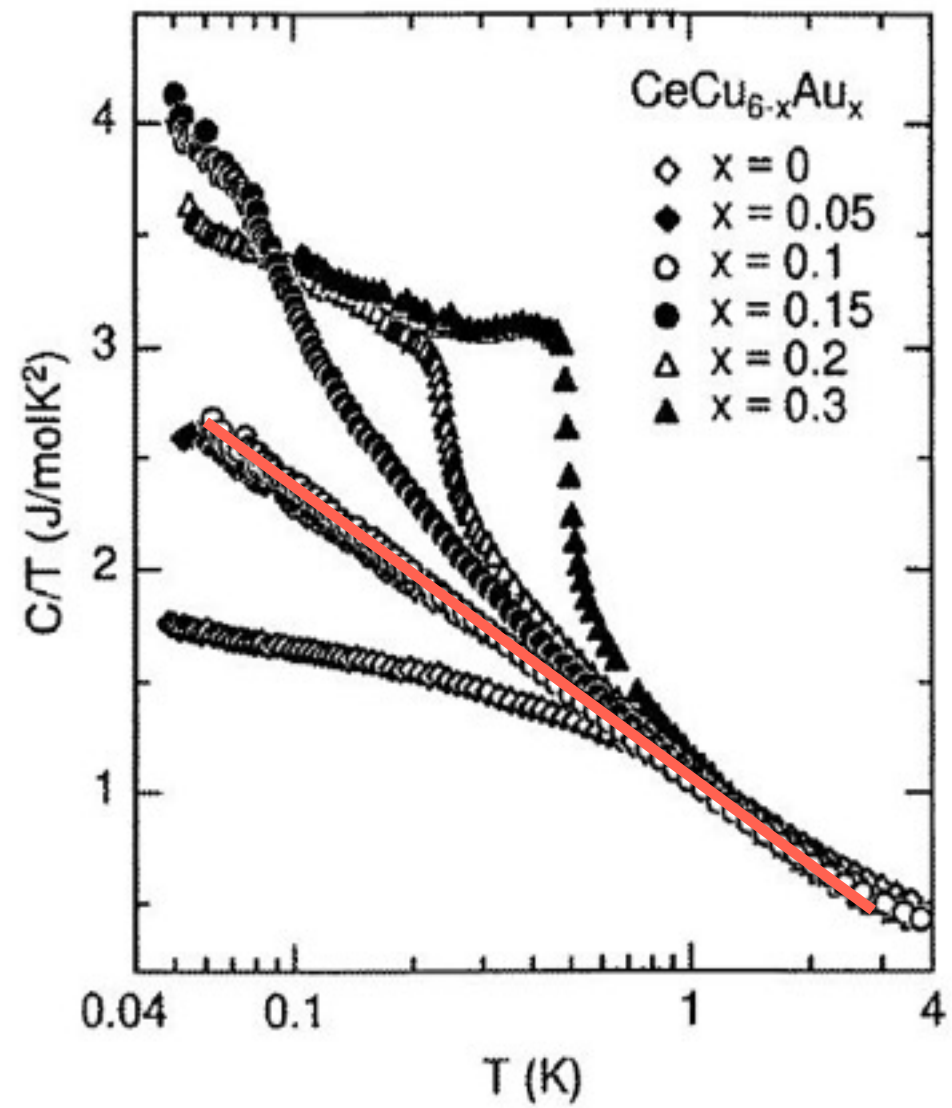
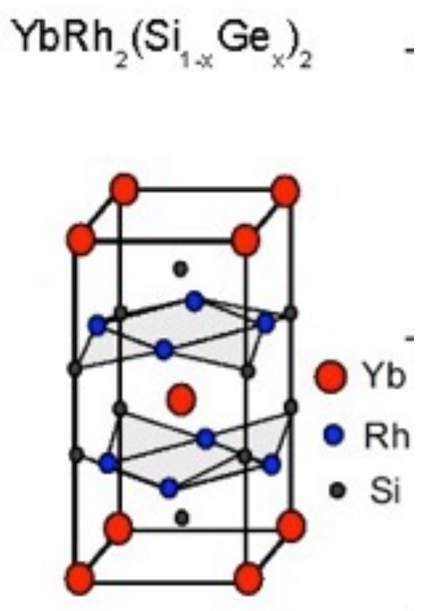
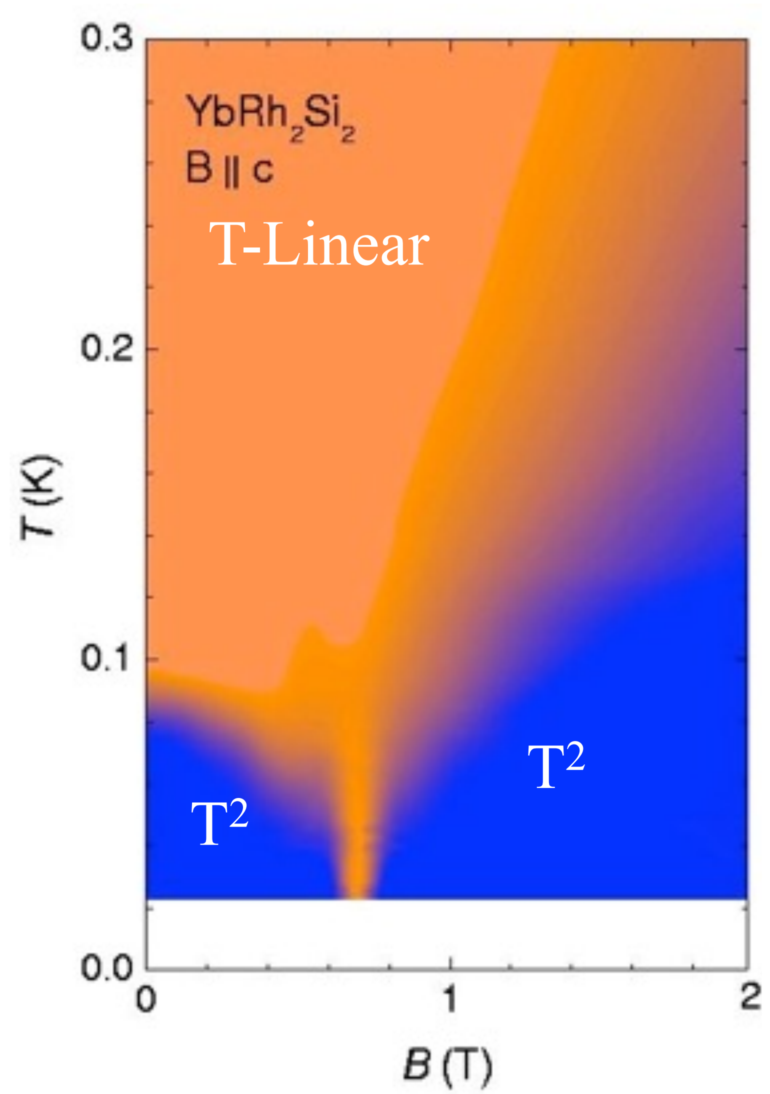


Divergence of Interaction and Effective Mass

Gegenwart et al (2002)





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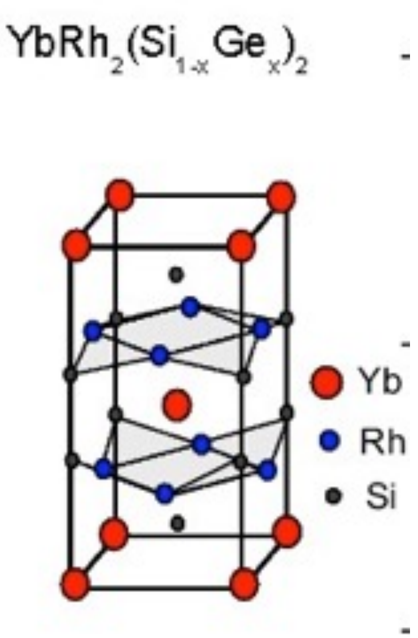

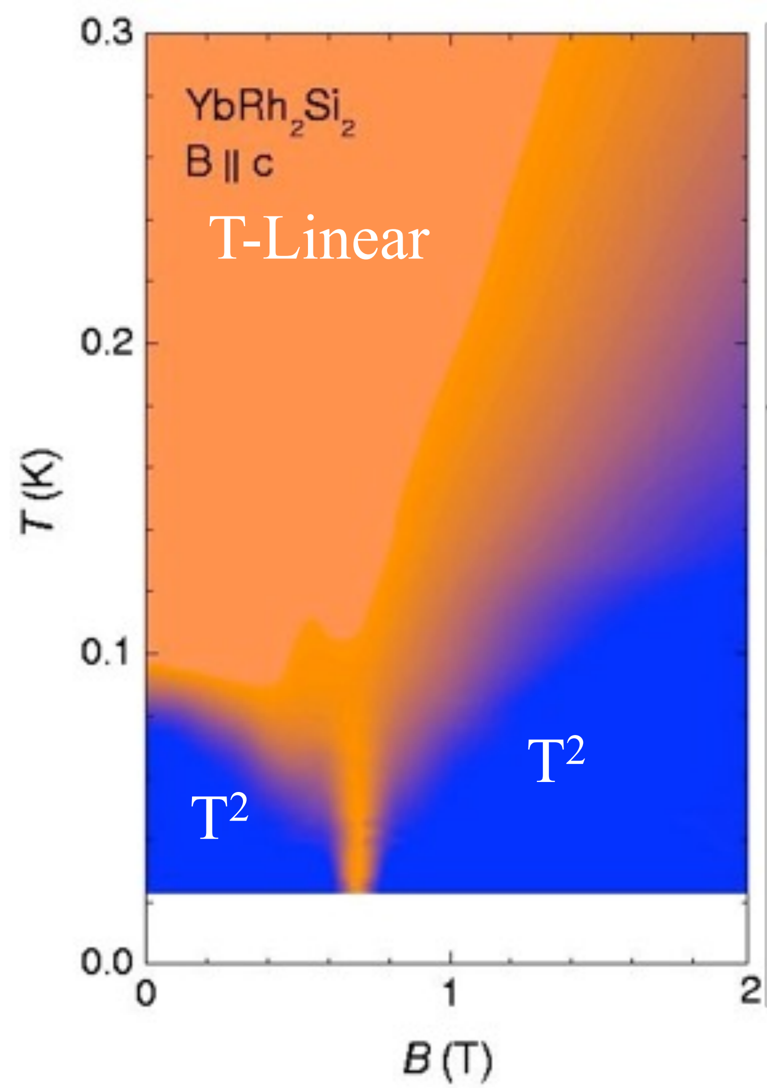

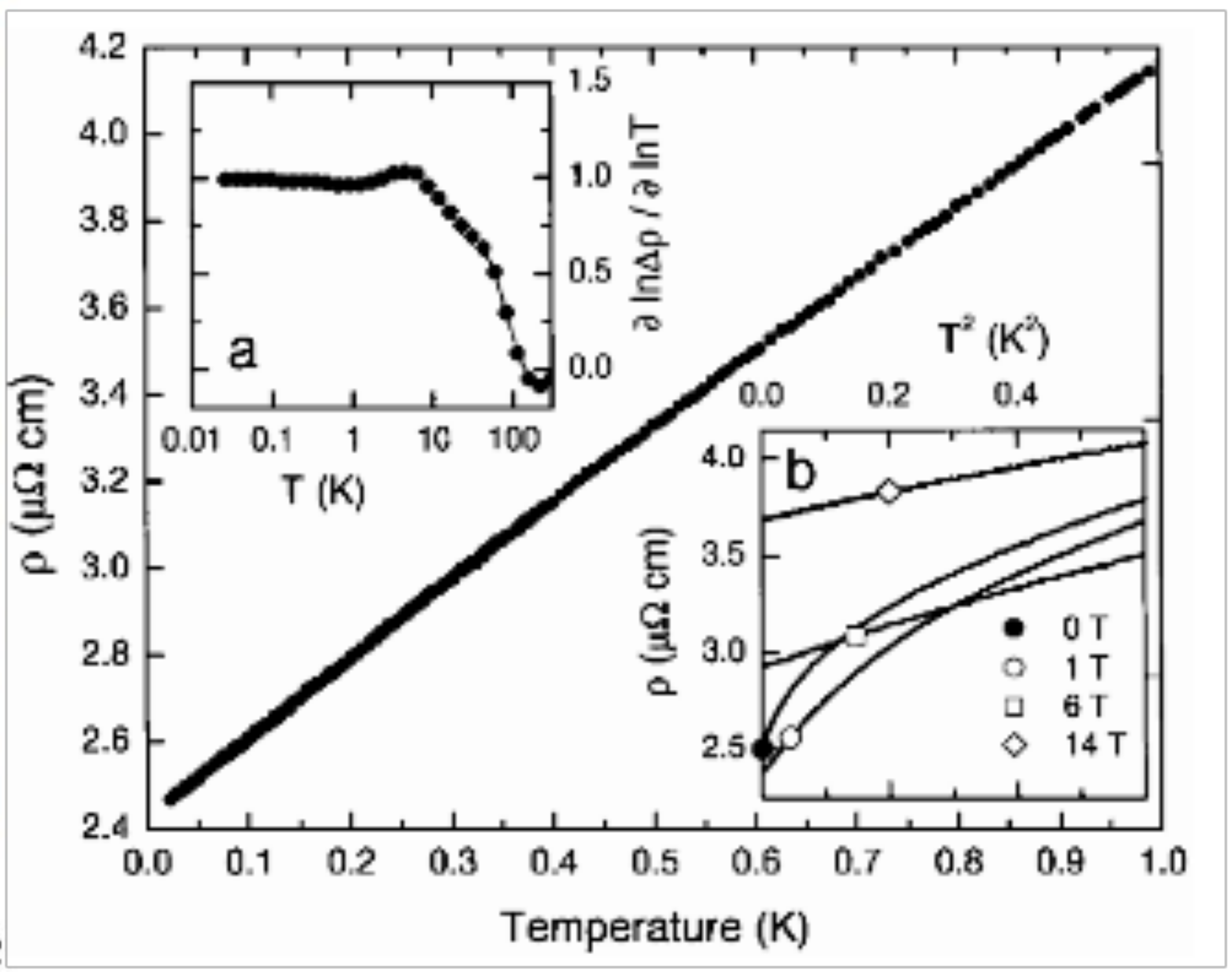

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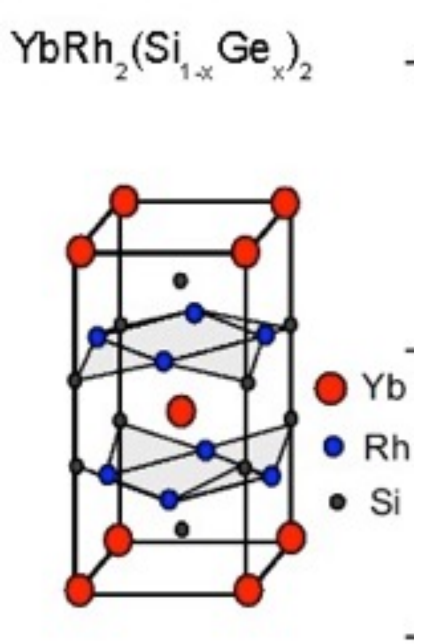

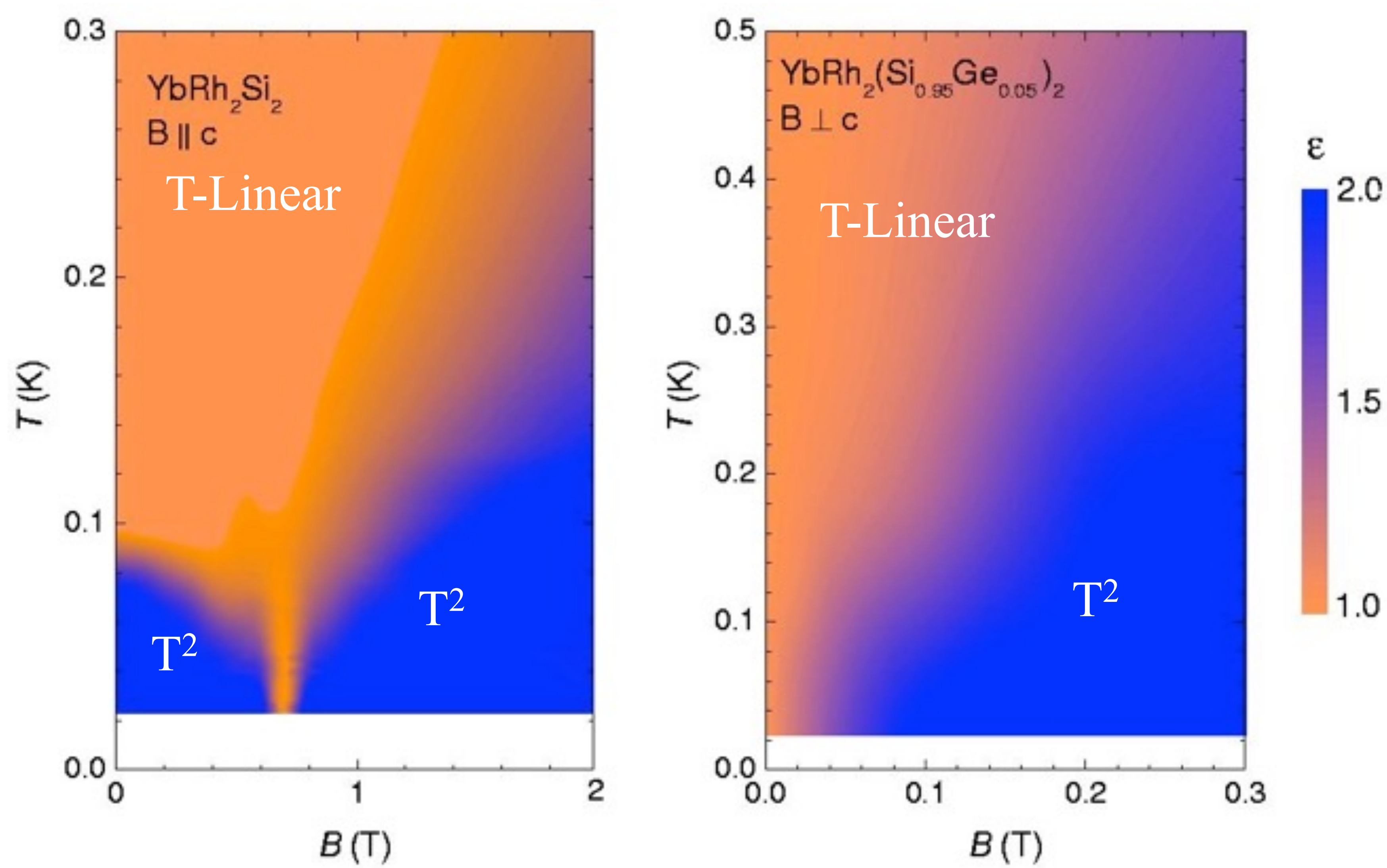

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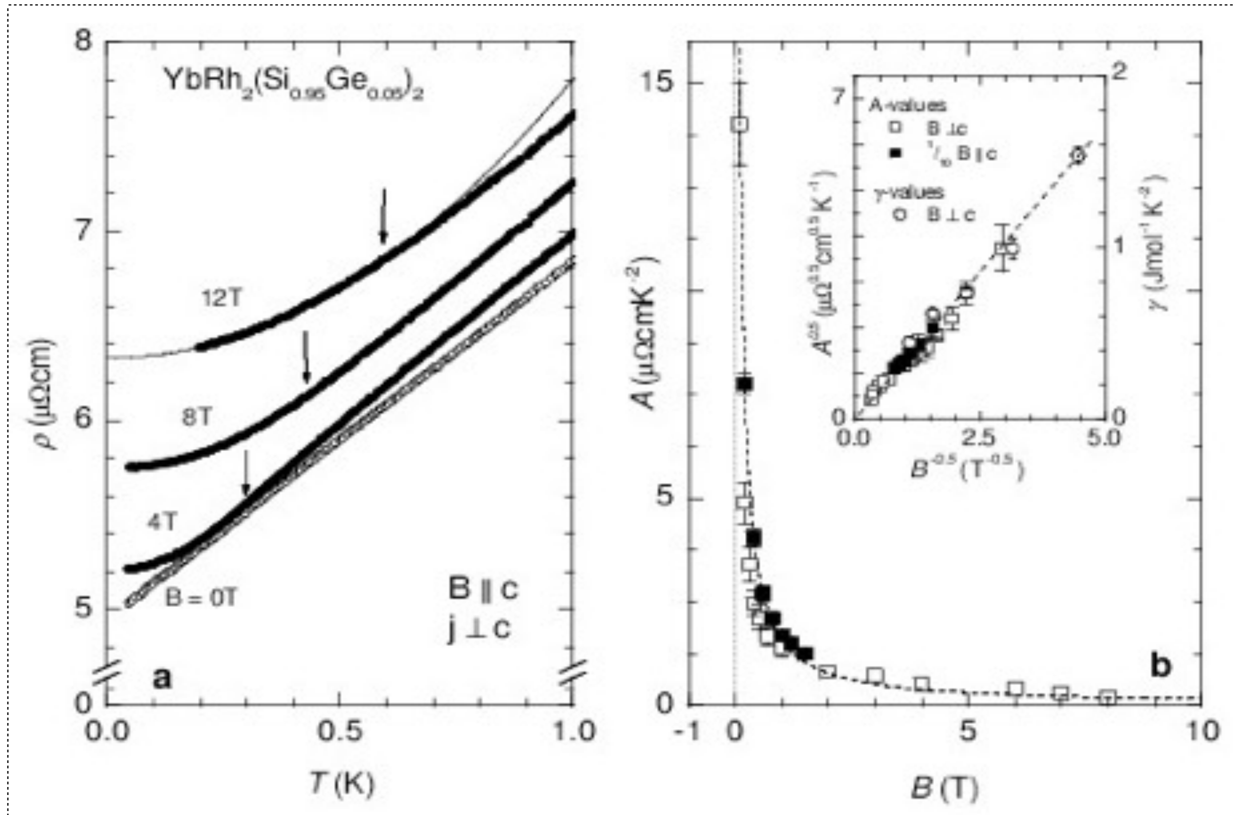
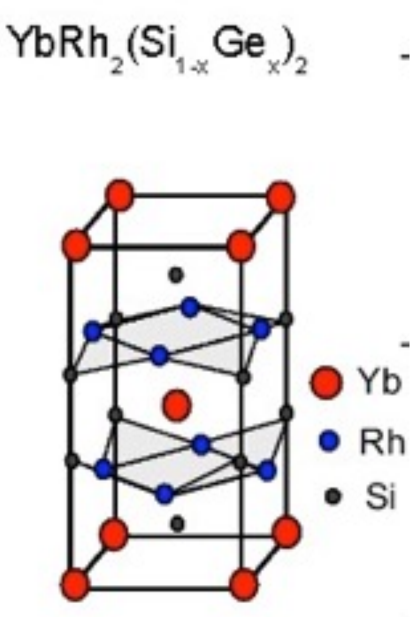
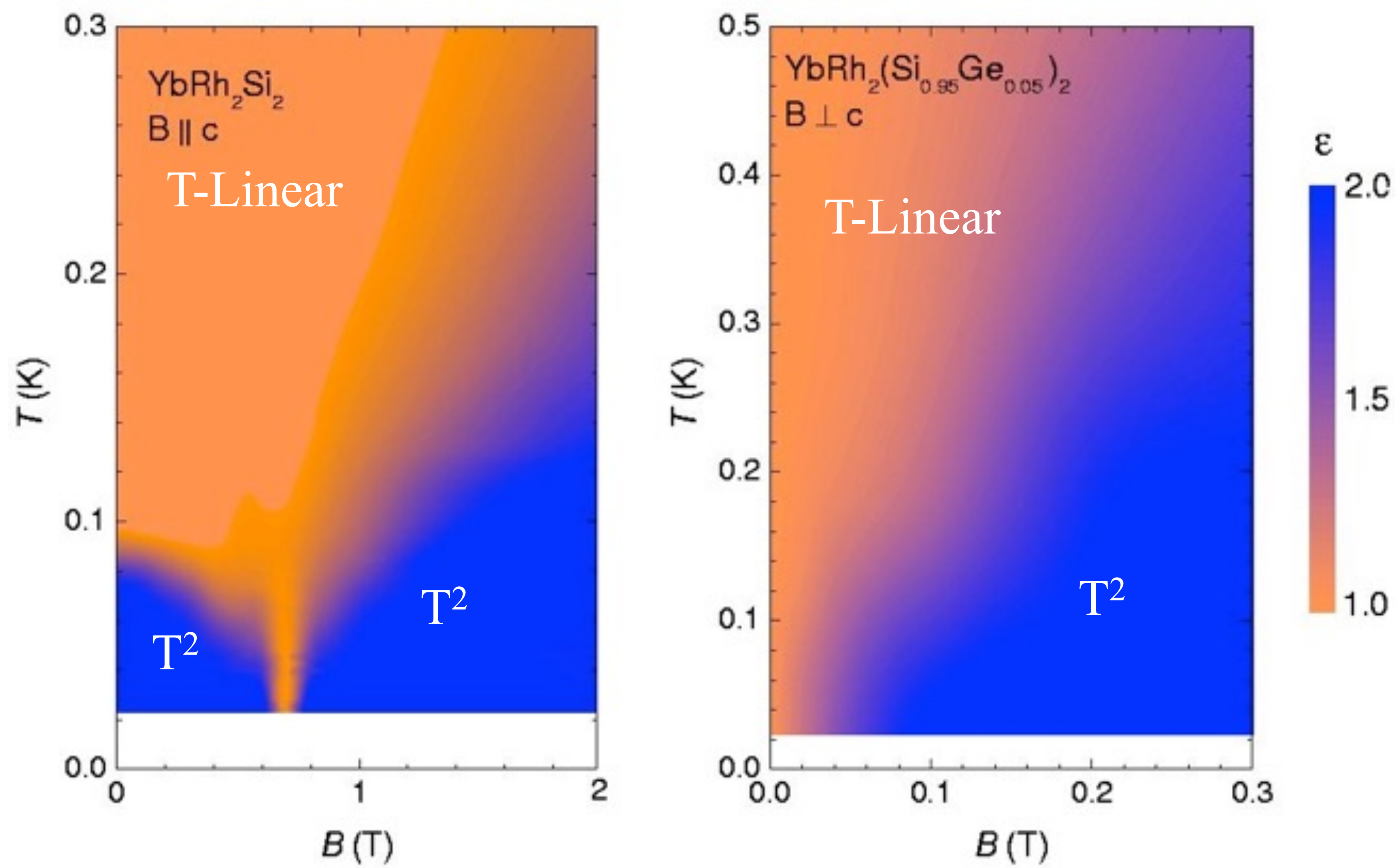


$$\rho = AT^2 + \rho_0$$

$$A \propto \frac{1}{T_F{}^2} \propto \frac{1}{B - B_c}$$

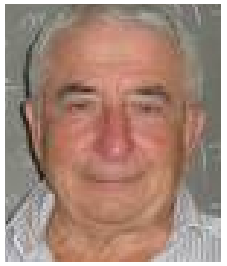
Gegenwart et al (2002)





Standard Model: Quantum SDW?

Moriya



Doniach

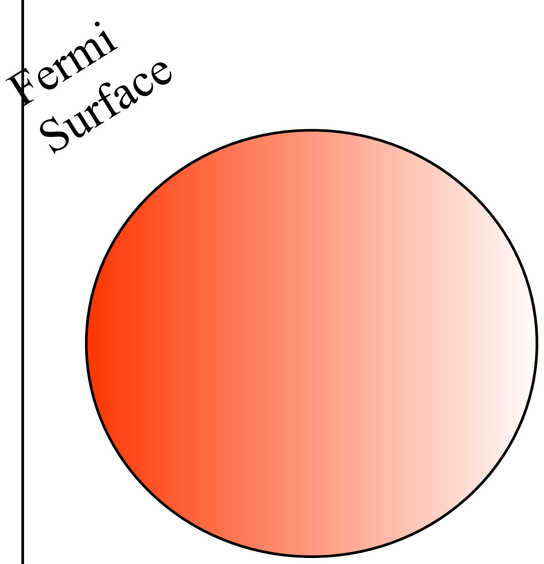
Schrieffer

Hertz

Millis

- Moriya, Doniach, Schrieffer (60s)
- Hertz (76)
- Millis (93)

$$d_{eff} = d + z$$



$$\chi_0^{-1} = -J(Q)$$

F.S. instability

Standard Model: Quantum SDW?

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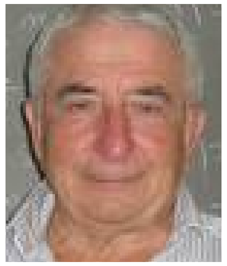

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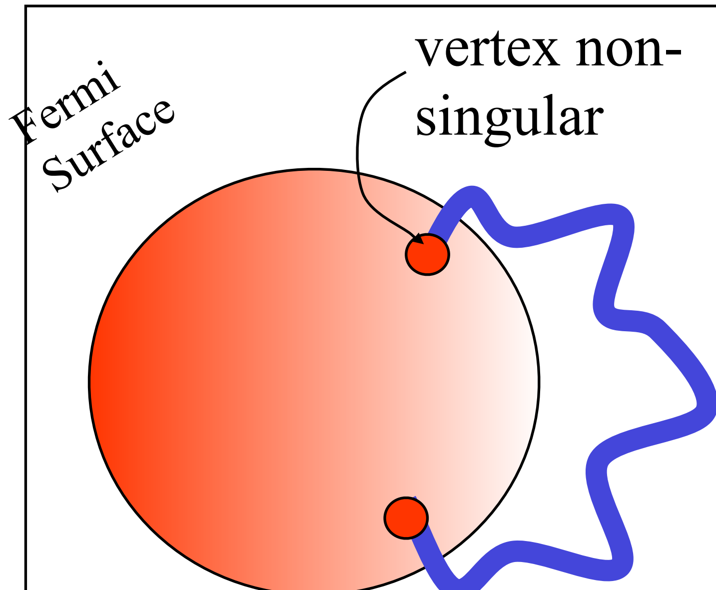

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$$\chi^{-1}(q,\omega) \propto (\xi^{-2} + (q-Q)^2 - i\omega/\Gamma)$$

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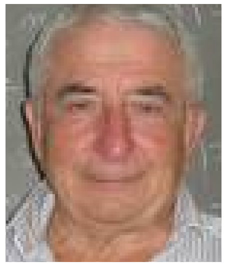
Center for Materials Theory

Standard Model: Quantum SDW?


Moriya

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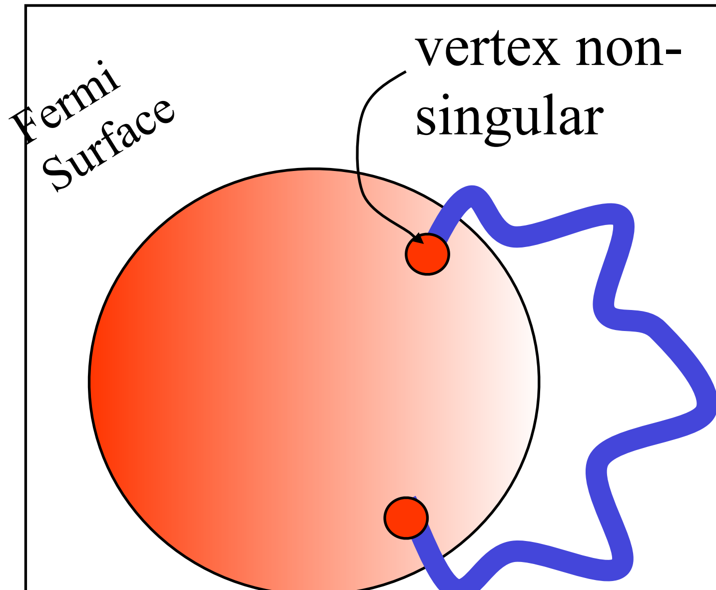

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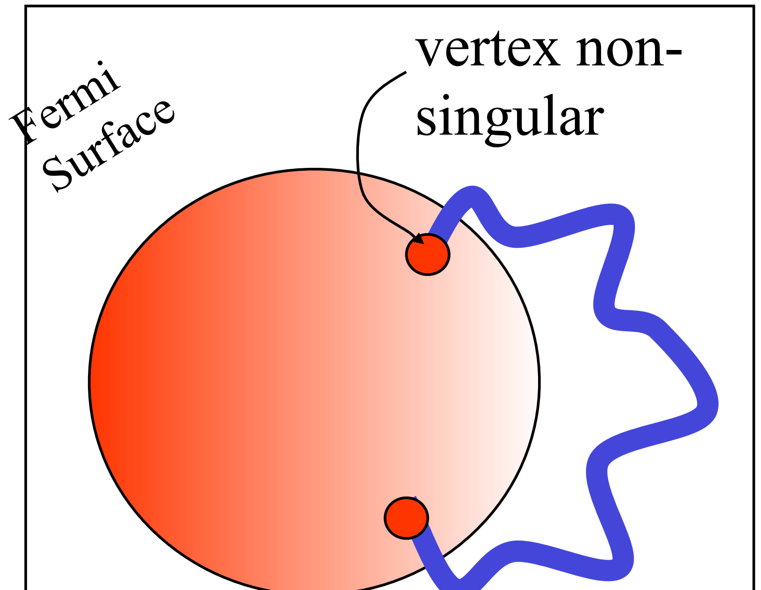

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<u>Time counts as z =2 scaling dimensions</u>

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Standard Model: Quantum SDW?

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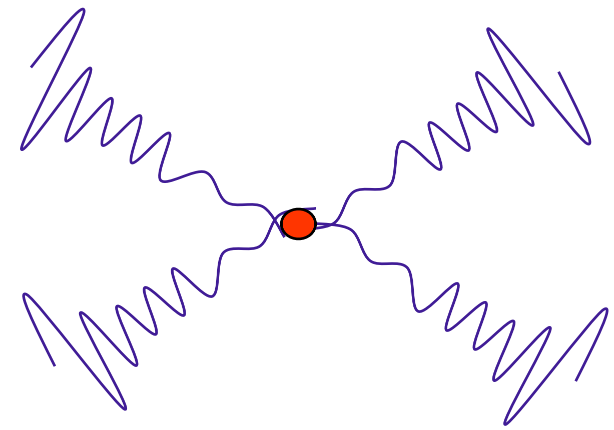

- Moriya, Doniach, Schrieffer (60s)
- Hertz (76)
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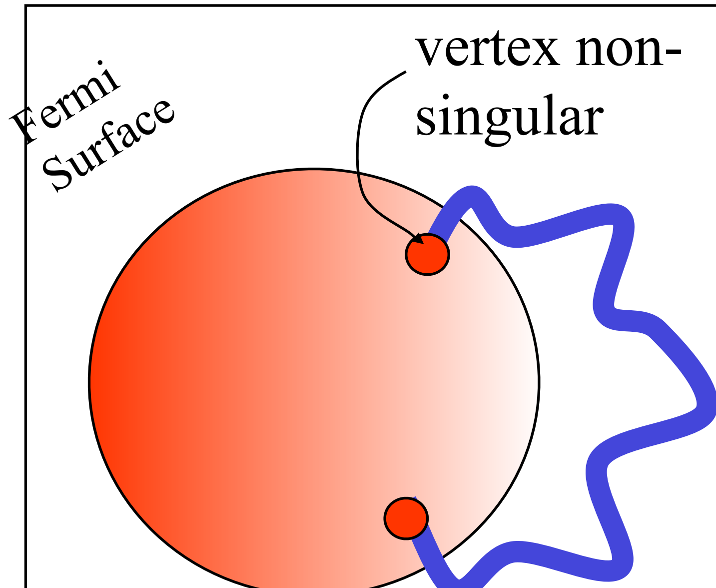
$$d_{eff} = d + z$$

If $d + z = d + 2 > 4$:
ϕ^4 terms "irrelevent"
Critical modes are <u>Gaussian</u>.
T is not the only energy scale.



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<u>Time counts as z =2 scaling dimensions</u>

$$V_{eff}(\vec{q},\omega) = g^2 \frac{\chi_o}{(\vec{q}-\vec{Q})^2 - i\omega/\Gamma_Q}$$

$$V_{eff}(\vec{r},\omega=0) \propto \frac{1}{r} e^{i\vec{Q}.\vec{r}}$$

Singular potential is rapidly modulated:
only affects electrons along hot-lines.

$$\varepsilon_{k_F} = \varepsilon_{k_F+Q}$$

Predicts:

Landau's Fermi Liquid Should
Survive at a Quantum Critical Point.

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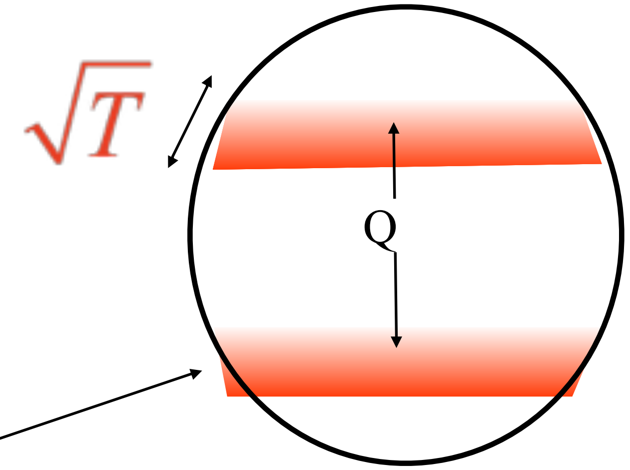

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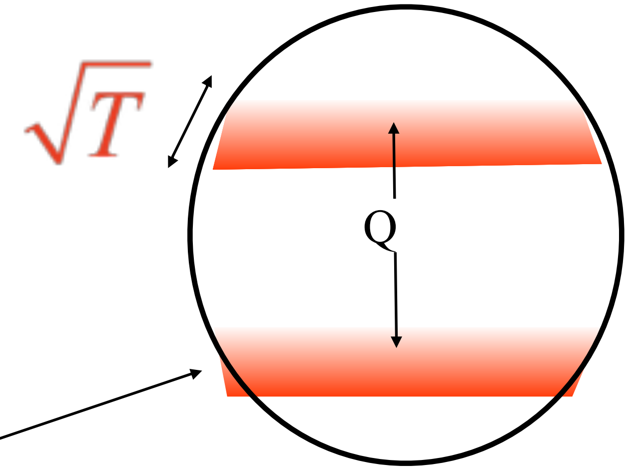
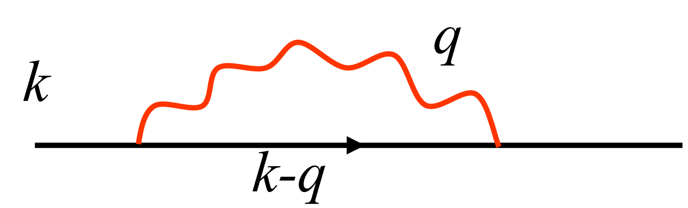


$$\Sigma(k,\omega) = -T\sum_{q,\nu} g^2 \chi_o(q,\nu) G(k-q,\omega-\nu)$$



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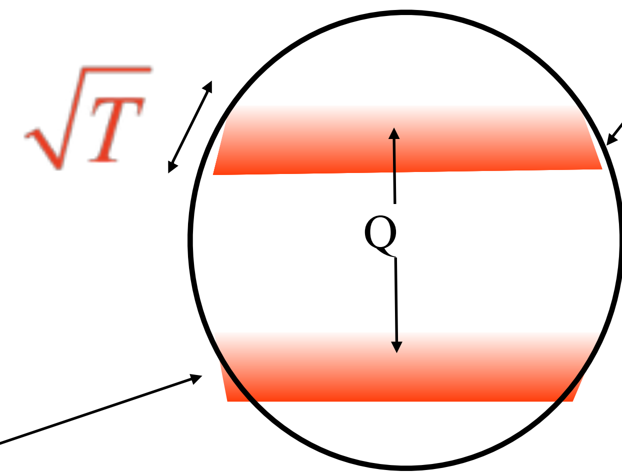
$$\frac{m^*}{m} \sim 1 - \frac{\partial \Sigma}{\partial \omega} \sim \ln(\Gamma/T)$$

divergent



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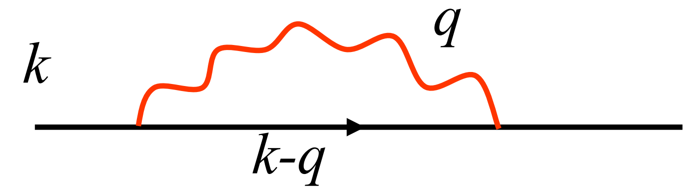

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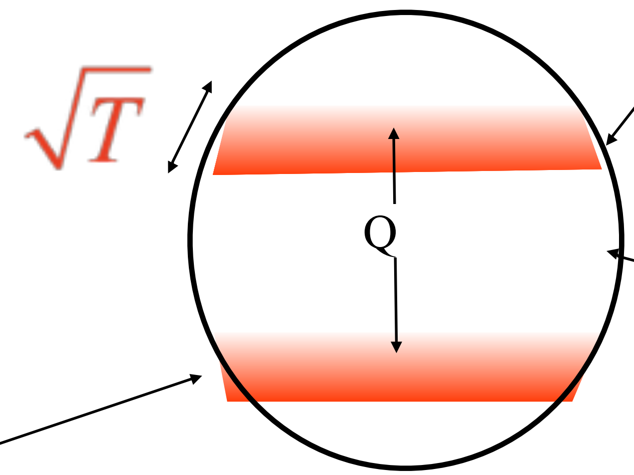
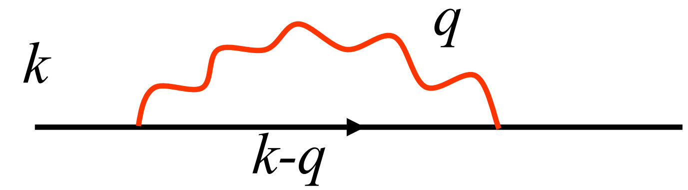


$\frac{m^*}{m}$ finite

$$\Sigma(k,\omega) = -T\sum_{q,\nu} g^2\chi_o(q,\nu)G(k-q,\omega-\nu)$$



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Singular potential is rapidly modulated:
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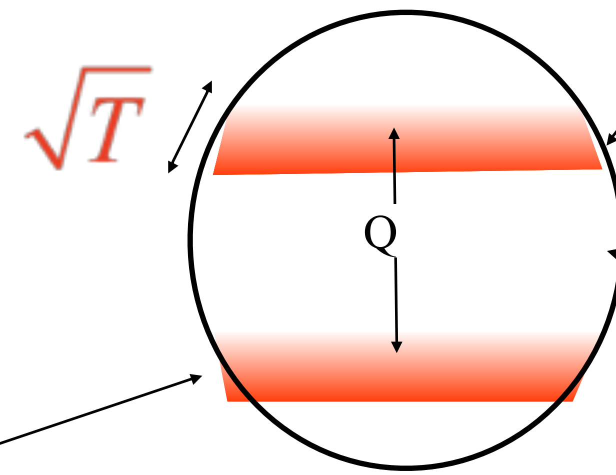
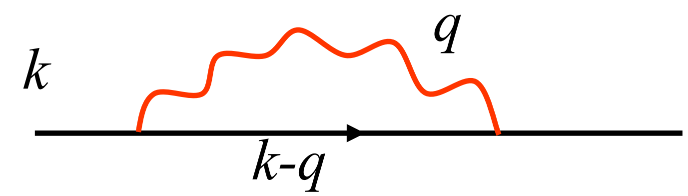
$$\varepsilon_{k_F} = \varepsilon_{k_F+Q}$$

$$\frac{m^*}{m} \sim 1 - \frac{\partial \Sigma}{\partial \omega} \sim \ln(\Gamma/T)$$ divergent



$\frac{m^*}{m}$ finite

$$\Sigma(k,\omega) = -T\sum_{q,\nu} g^2 \chi_o(q,\nu) G(k-q,\omega-\nu)$$



$$F_{Singular} \sim T\sum \int d^3q \log[\chi^{-1}(q,\omega)]$$
$$\sim T(T^{3/z}) \sim T^{5/2}$$

$$\boxed{\frac{C_V}{T} \sim \gamma_o - A\sqrt{T}}$$

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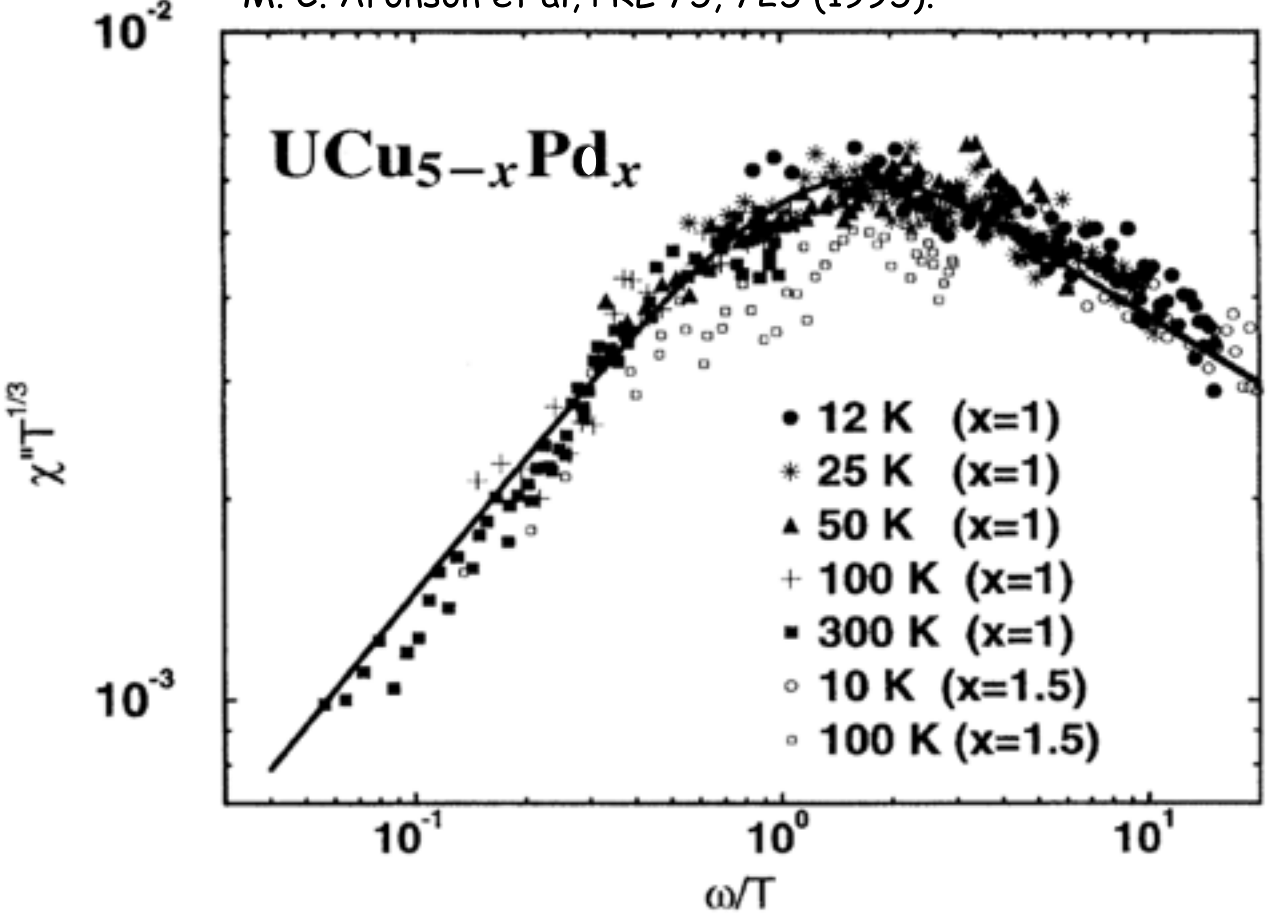
E/T Scaling:

Meigan Aronson

M. C. Aronson et al, PRL 75, 725 (1995).



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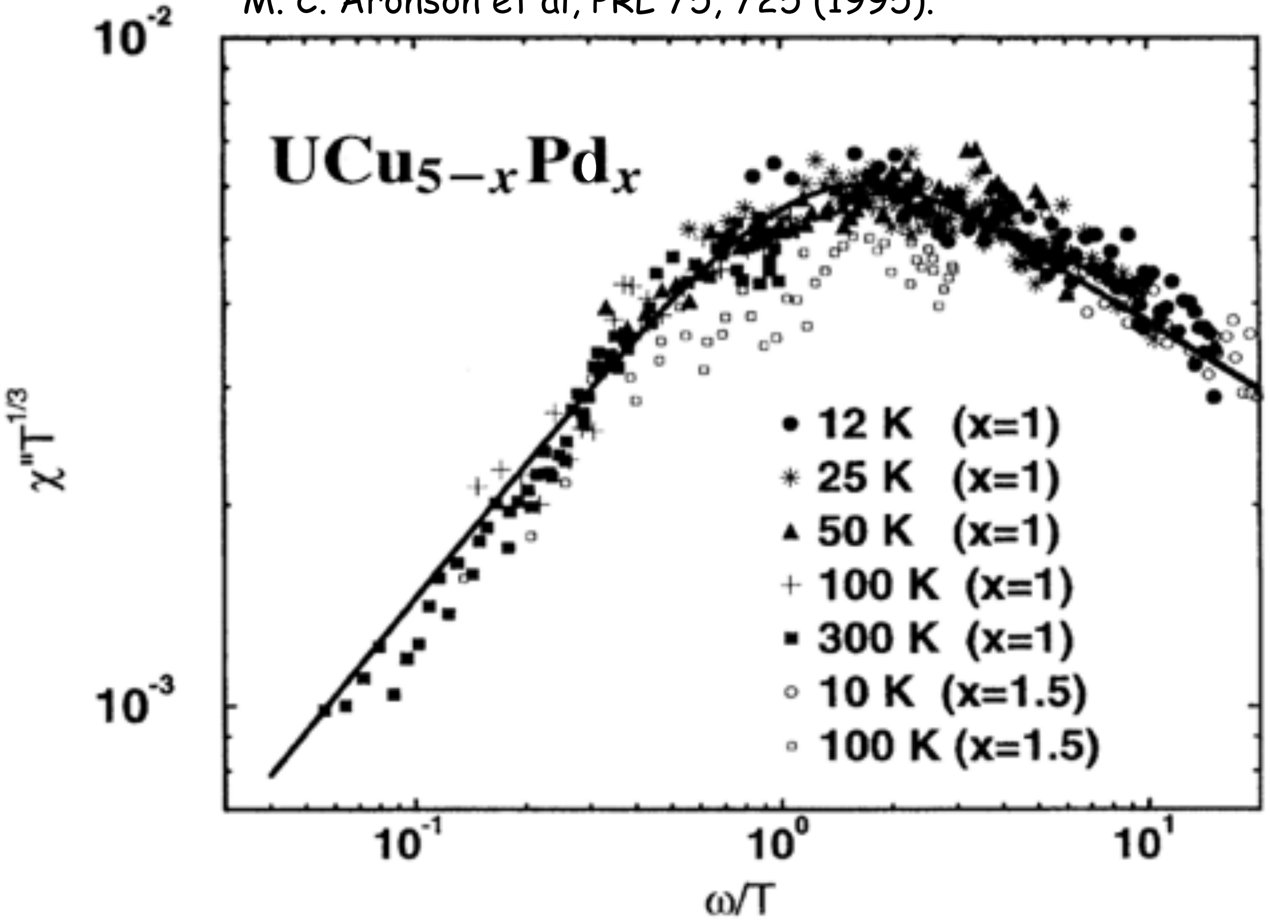

$$\chi''(E) = \frac{1}{E^{1-\alpha}} G\left(\frac{E}{T}\right)$$

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Center for Materials Theory

E/T Scaling:

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Almut Schroeder

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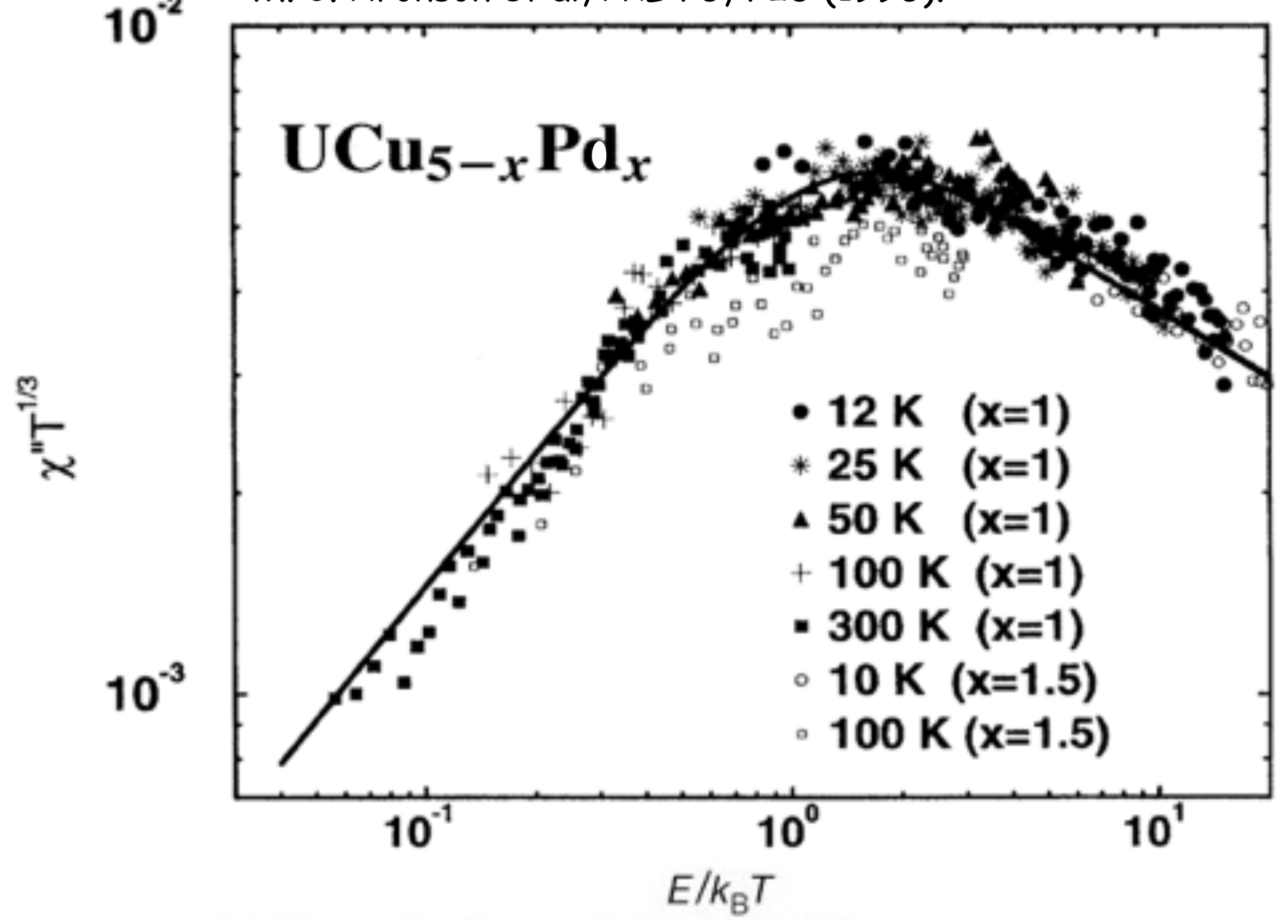
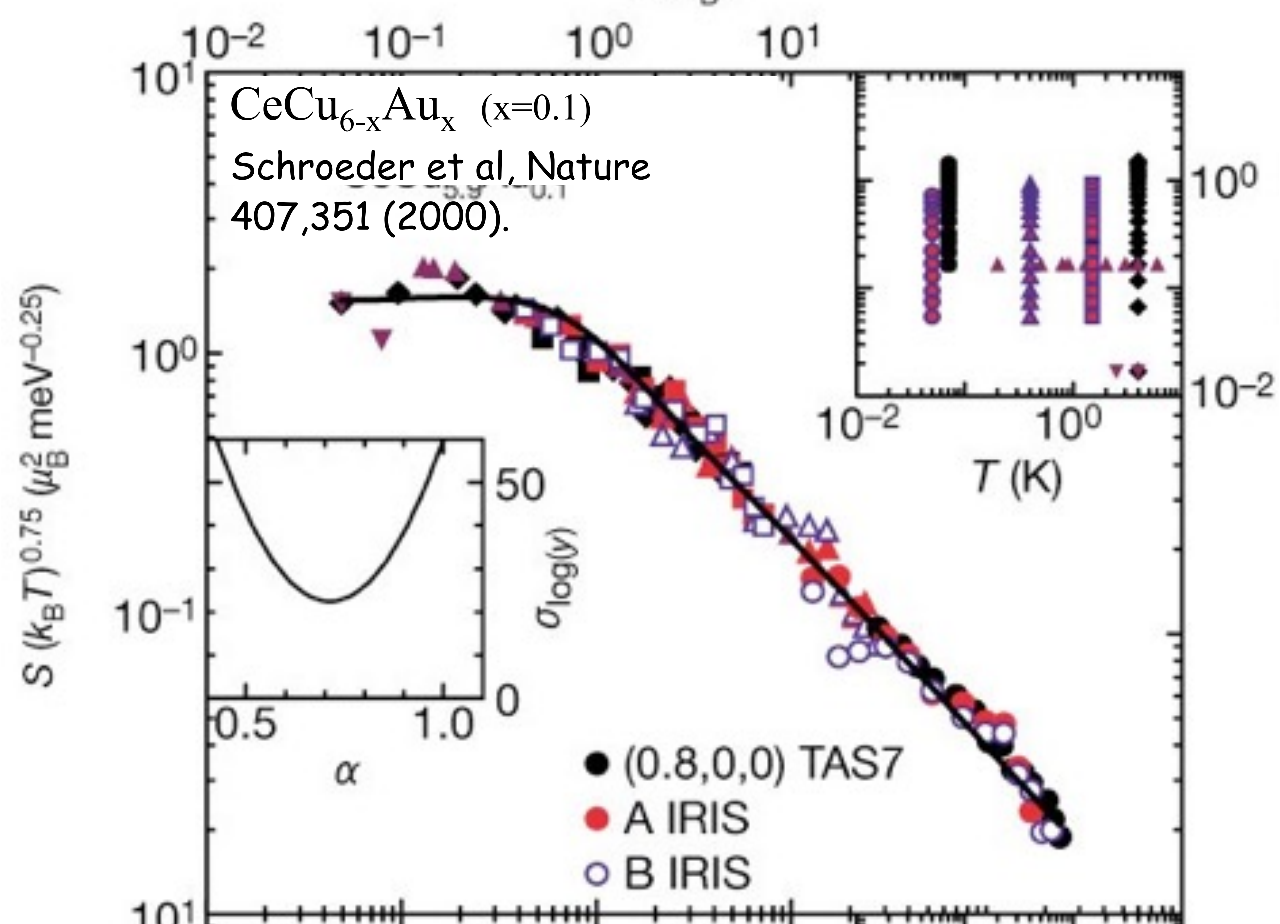




$CeCu_{6-x}Au_x$ (x=0.1)

Schroeder et al, Nature 407,351 (2000).

Rutgers
Center for Materials Theory

E/T Scaling:

Meigan Aronson

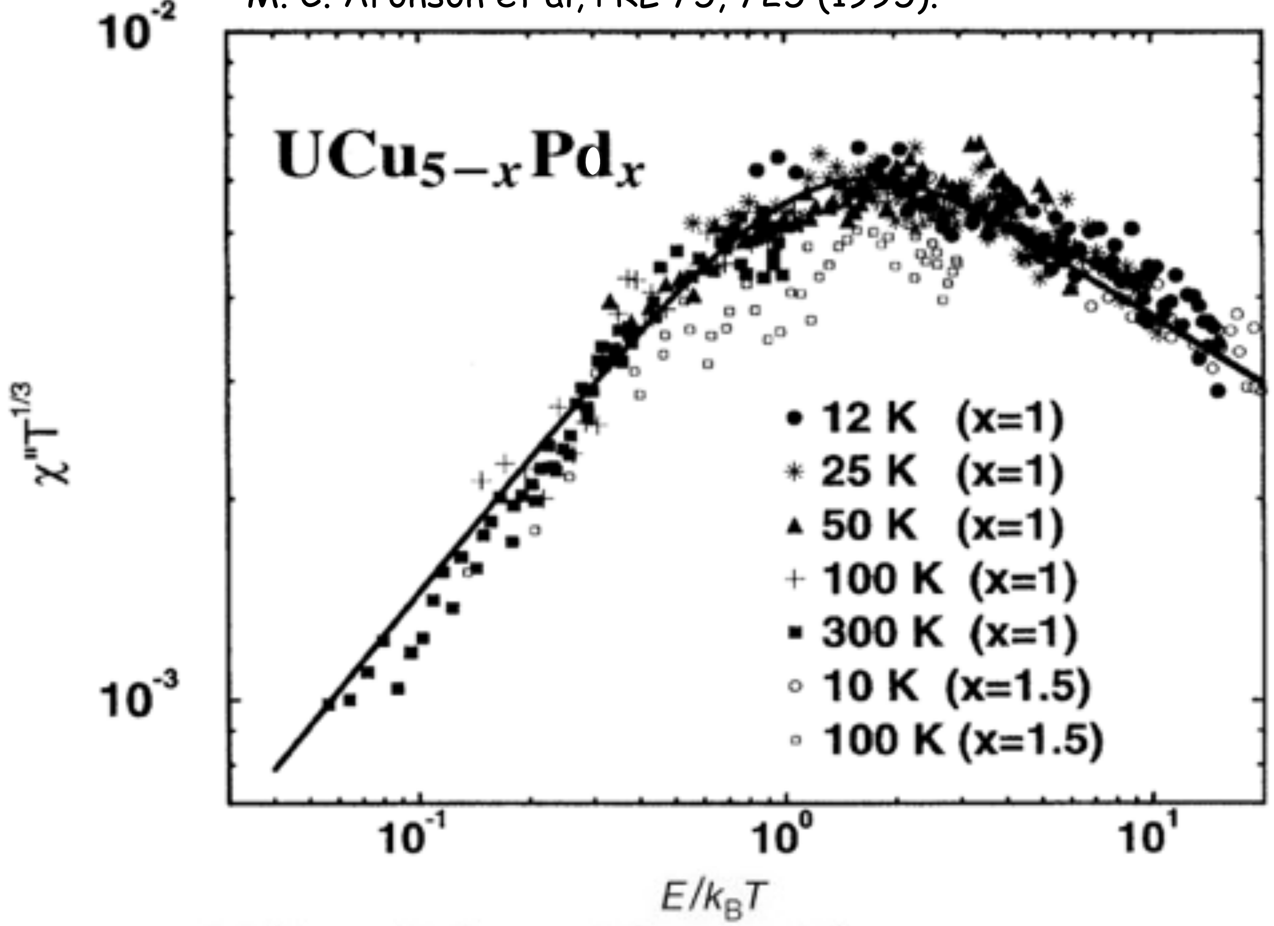
Almut Schroeder

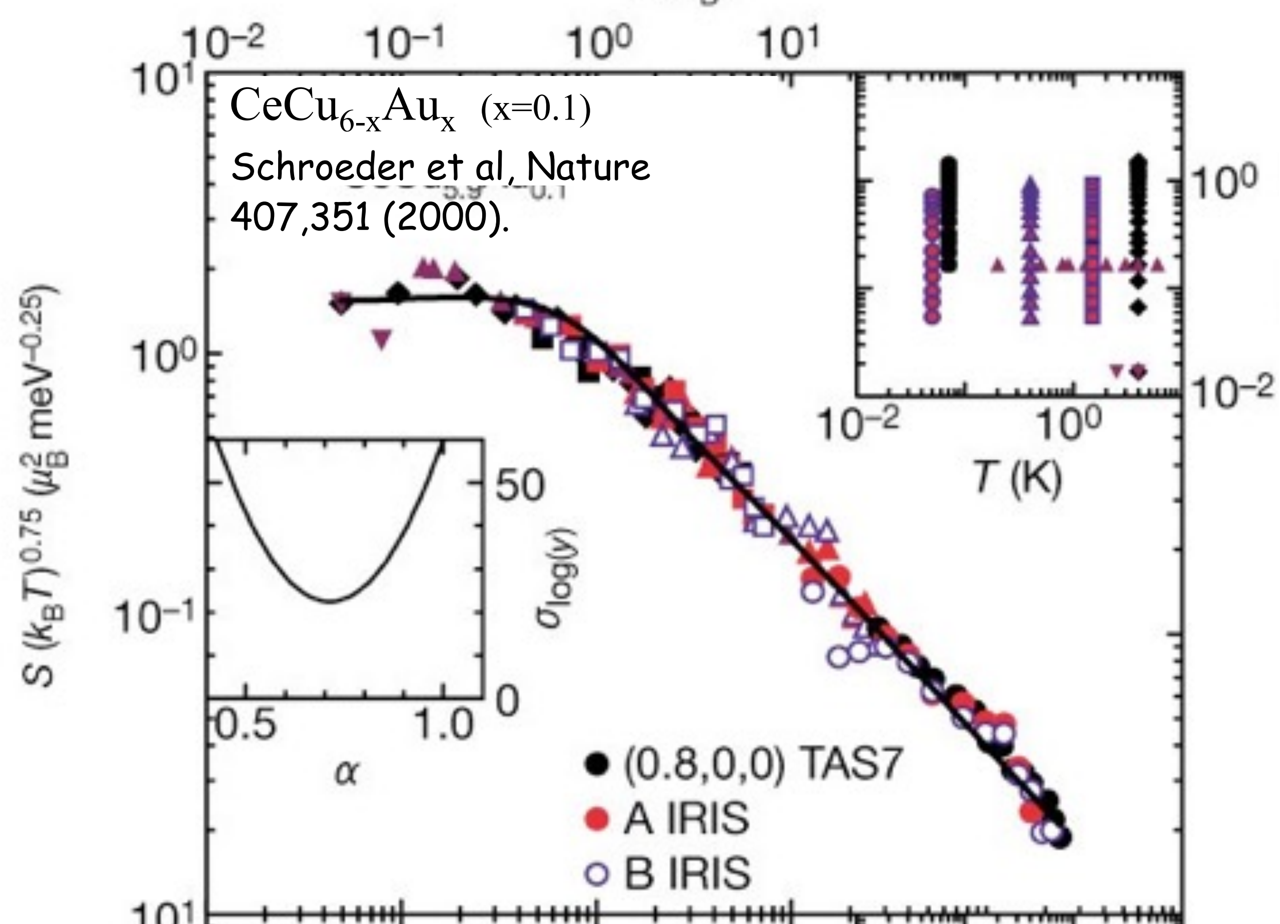
$$\chi''(E) = \frac{1}{E^{1-\alpha}} G\left(\frac{E}{T}\right)$$

Physics Below the upper
Critical Dimension.

Rutgers
Center for Materials Theory

M. C. Aronson et al, PRL 75, 725 (1995).

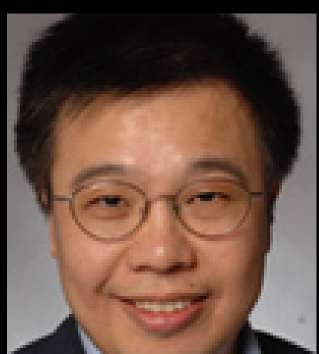


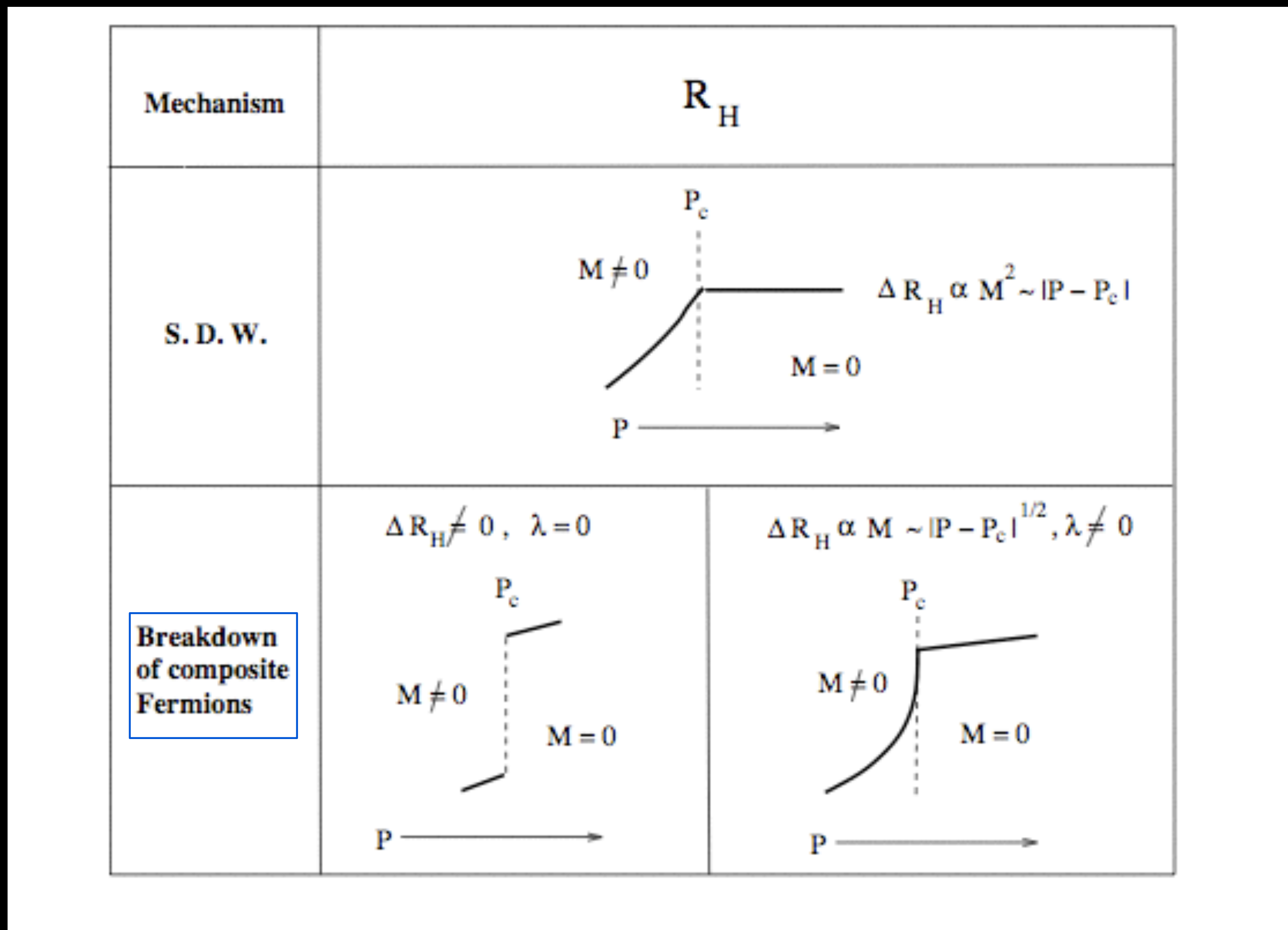


$CeCu_{6-x}Au_x$ (x=0.1)
Schroeder et al, Nature
407,351 (2000).

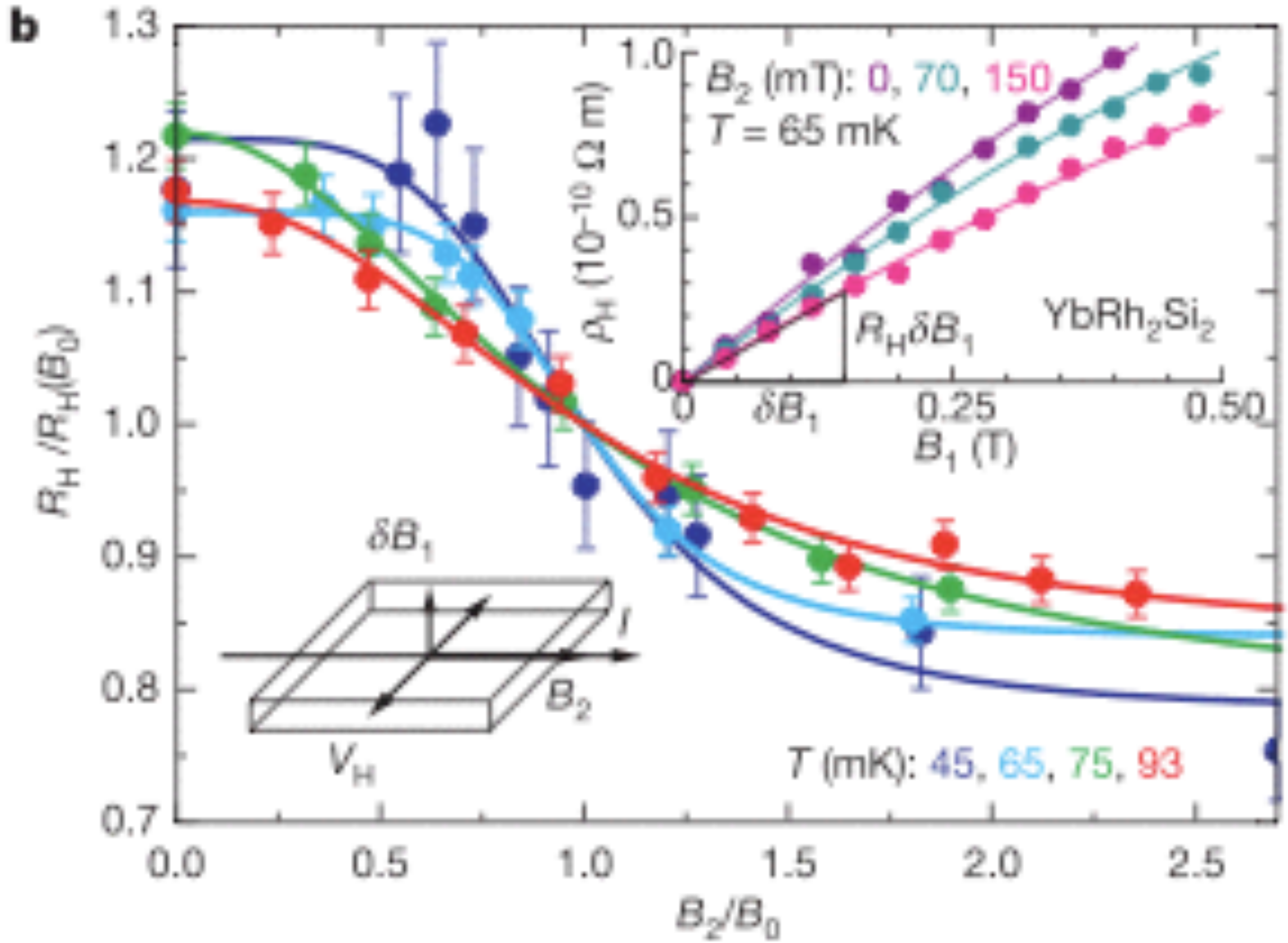
"How do fermions get heavy and die?" PC, Pepin, Si and Ramazashvili, J. Cond Matt. , 13}, R723 (2001).

anticipated an abrupt change in FS when a composite heavy electron undergoes a Kondo "breakdown".





S. Paschen et al, Nature 432, 881 (2004)



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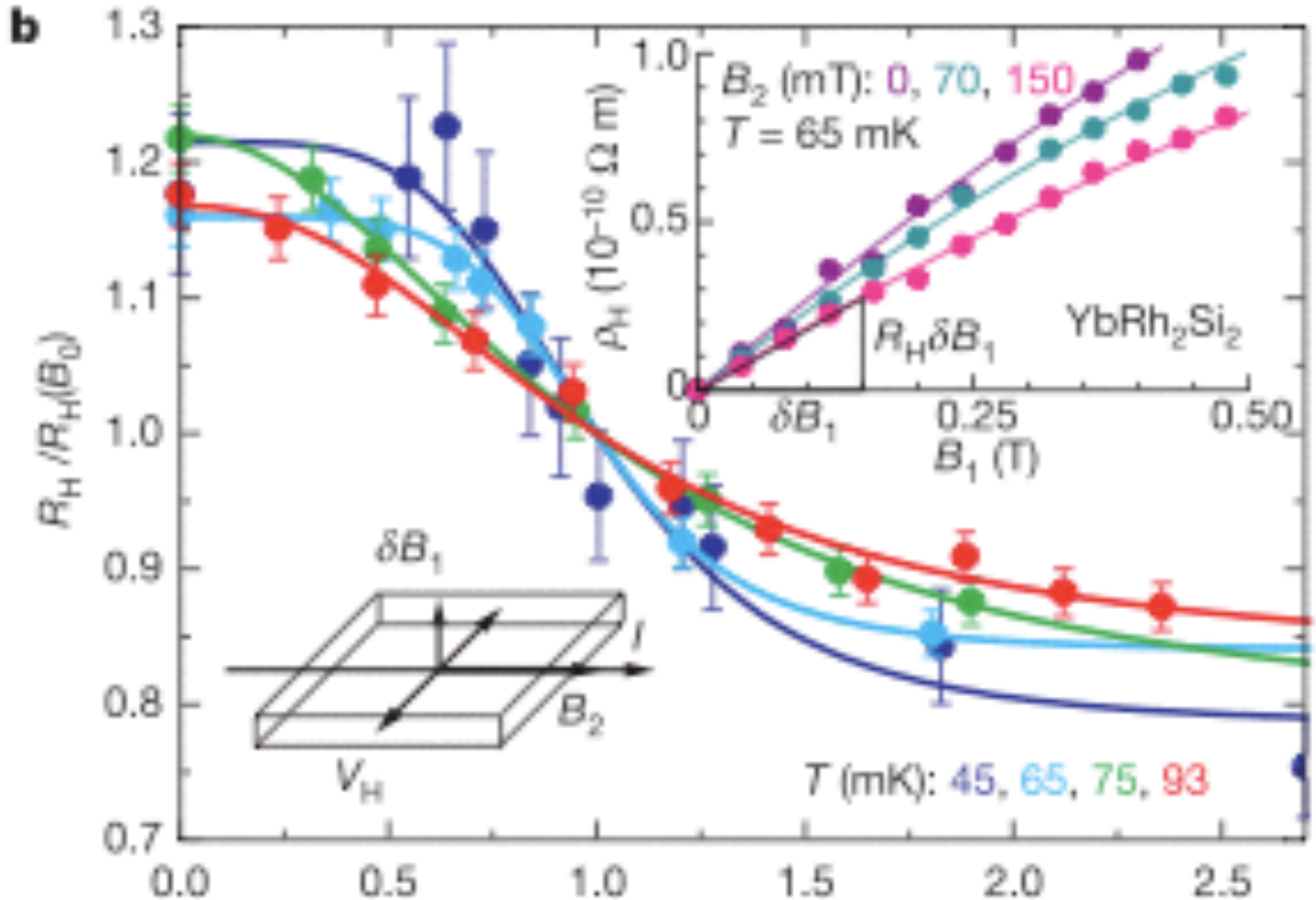
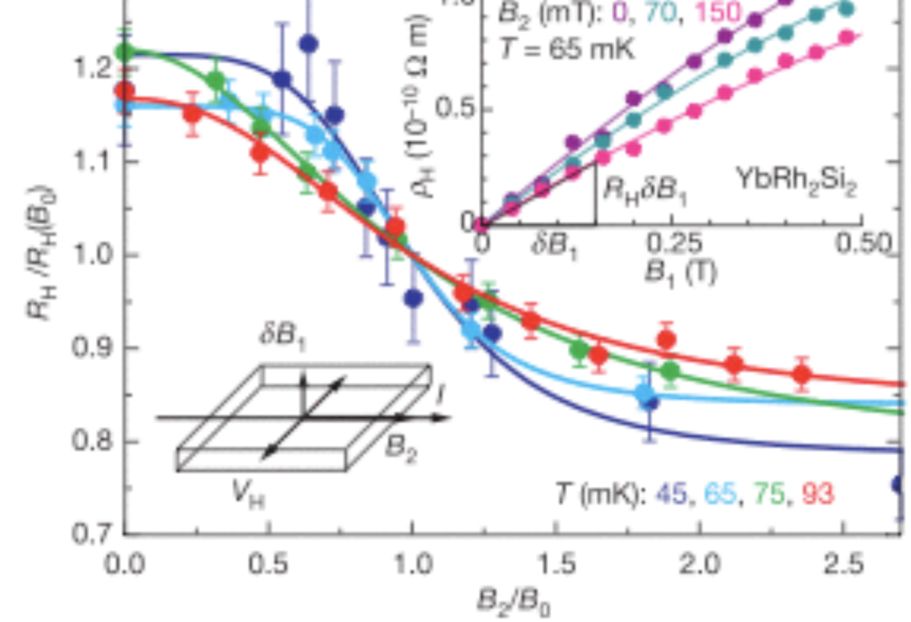
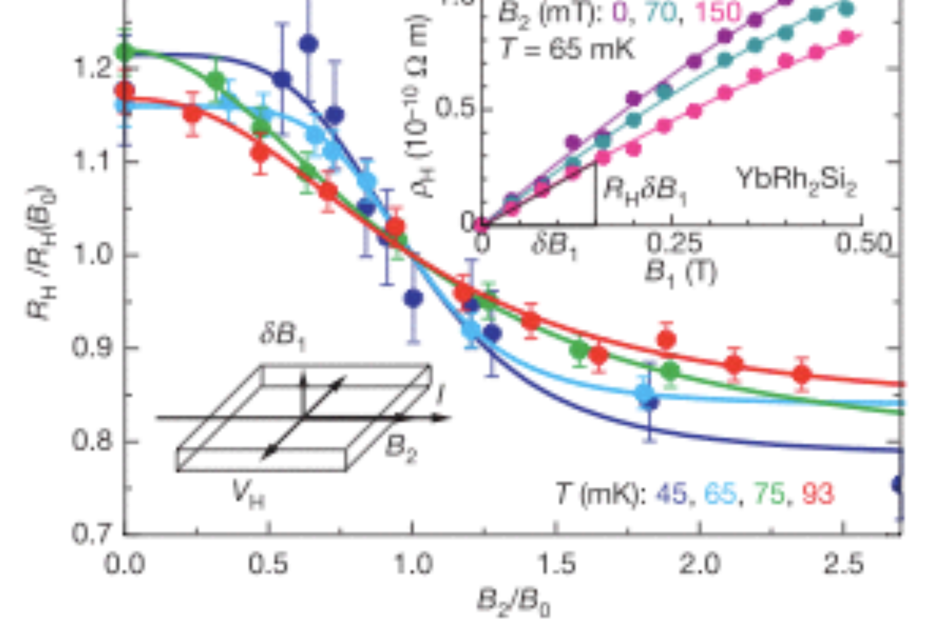


Jump in the Hall constant at a field tuned QCP.

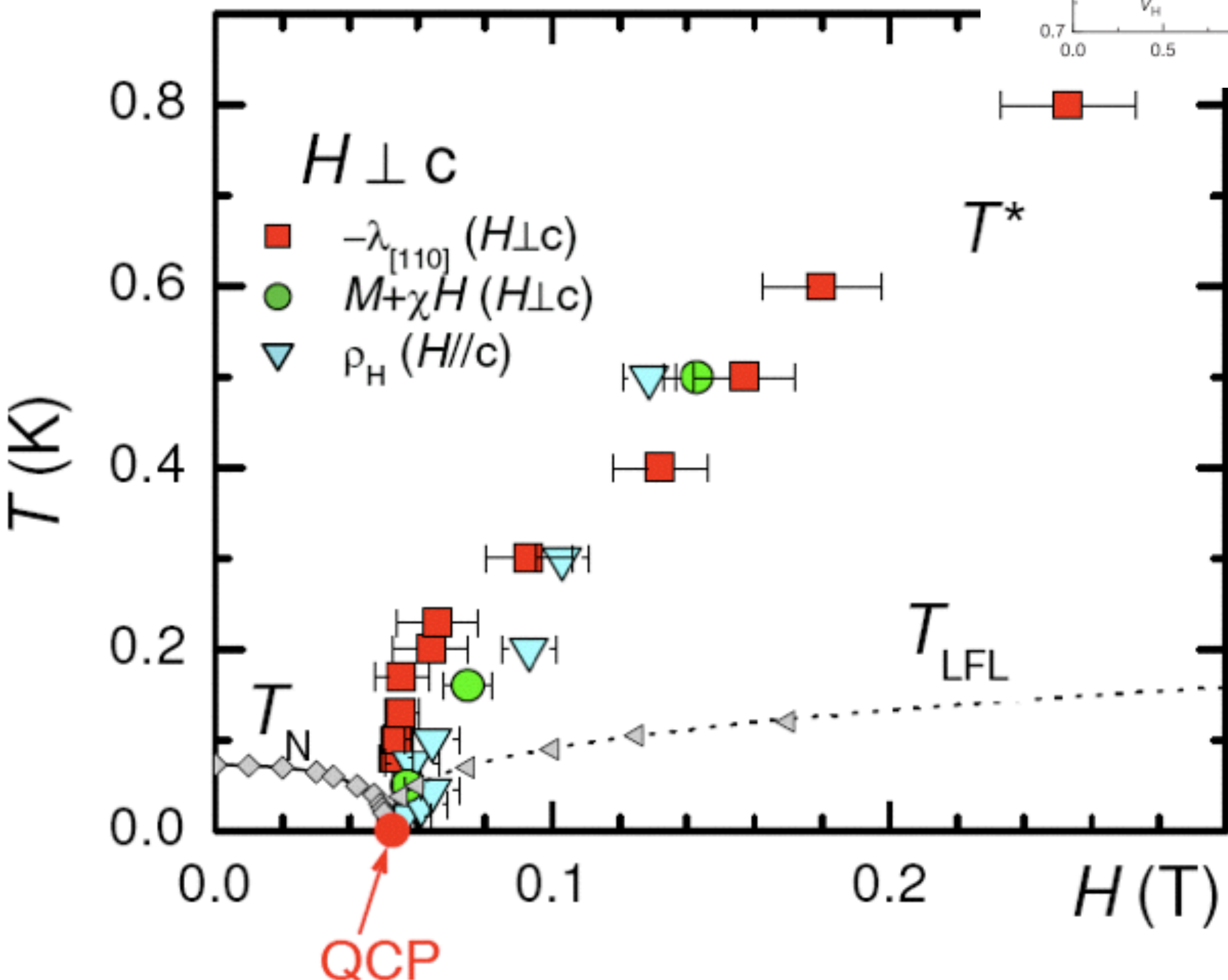


B2 (mT): 0, 70, 150
T = 65 mK
ρH (10−10 Ω m)
RHδB1
YbRh2Si2
δB1
B1 (T)
RH /RH(B0)
δB1
I
B2
VH
T (mK): 45, 65, 75, 93
B2/B0

P. Gegenwart, T. Westerkamp et al., Science 315, 5814 (2007)



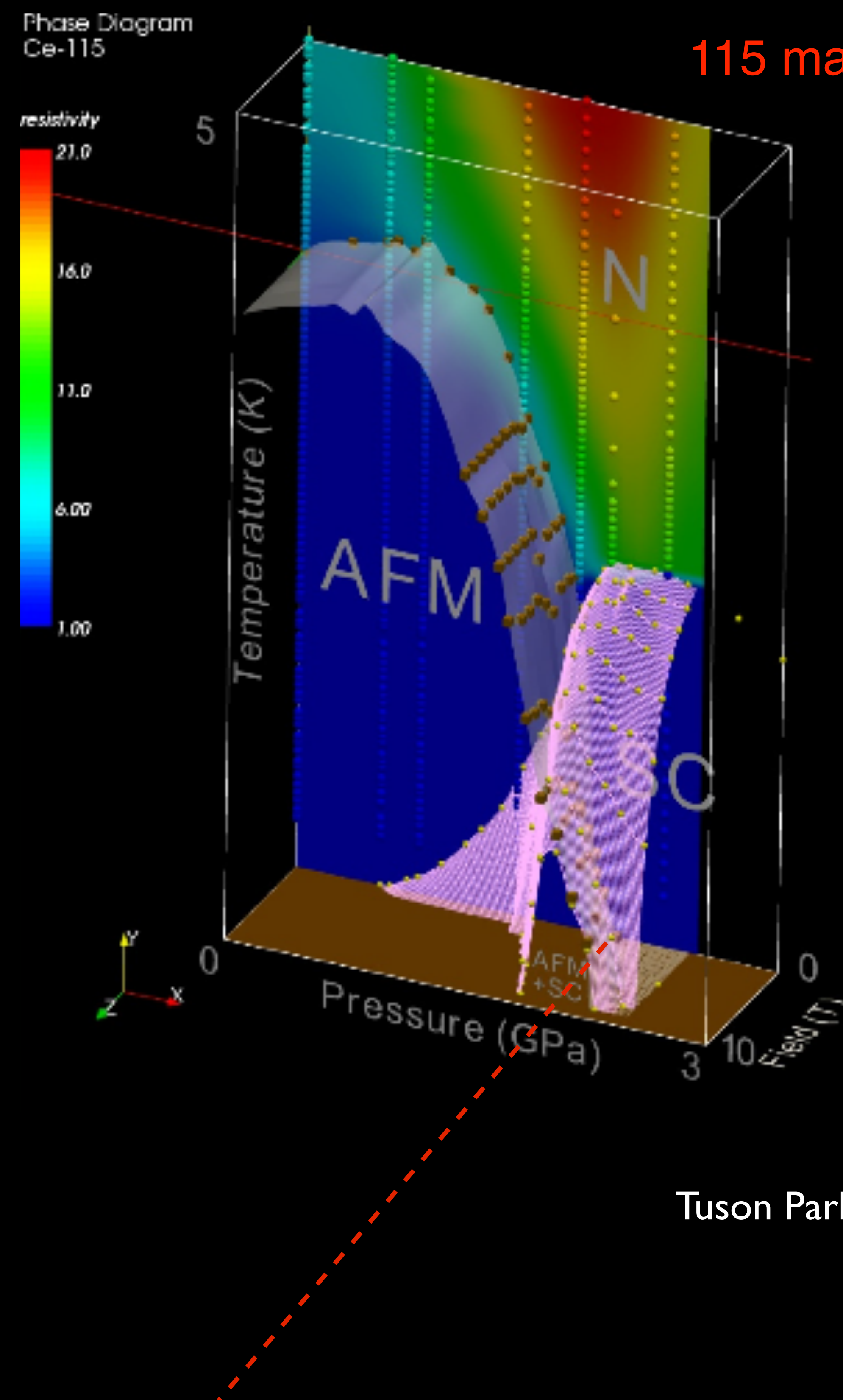
T_{Hall} represents a new energy scale (T^*)



Reconstruction of the Fermi Surface and mass divergence

$CeRhIn_5$

115 material



Tuson Park, (2007).

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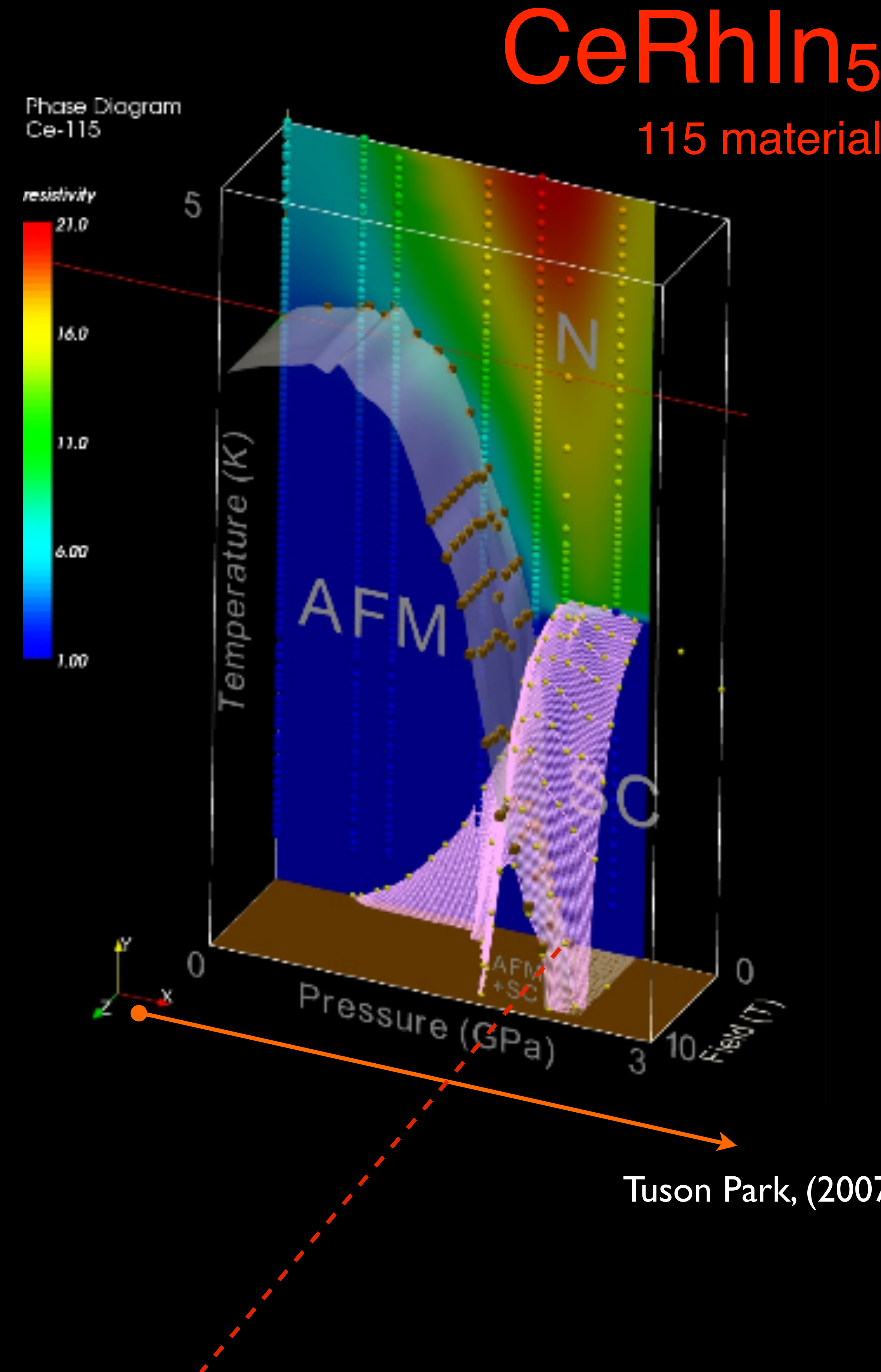

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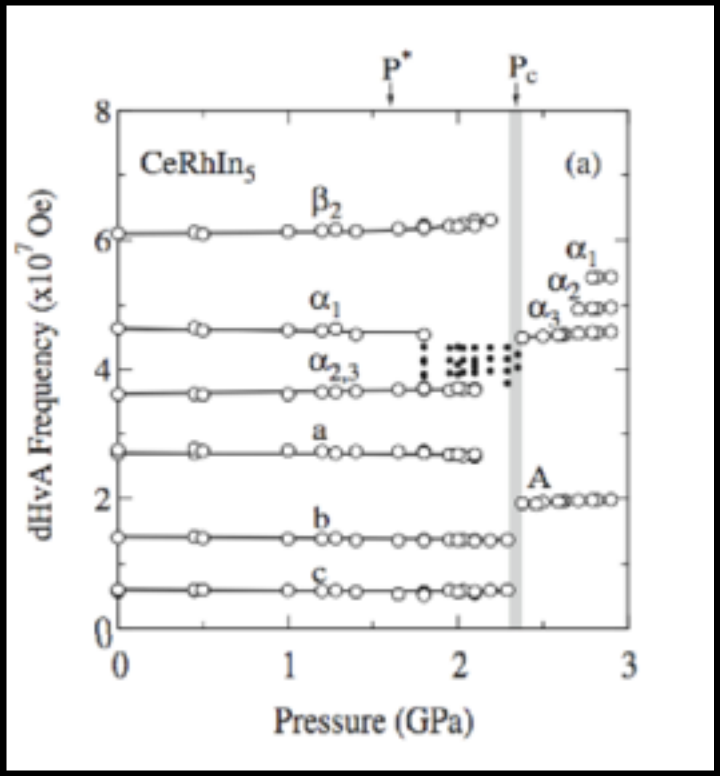
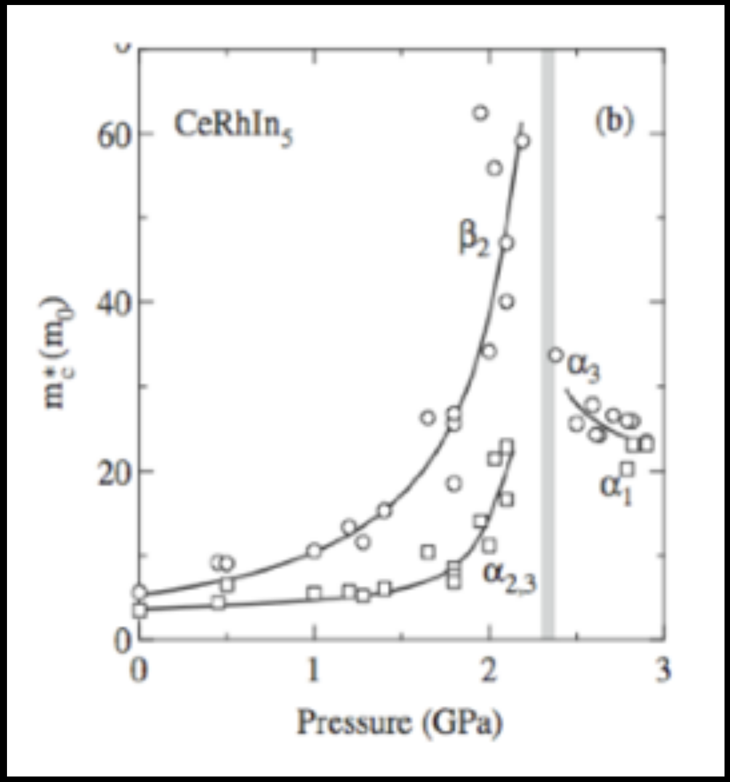
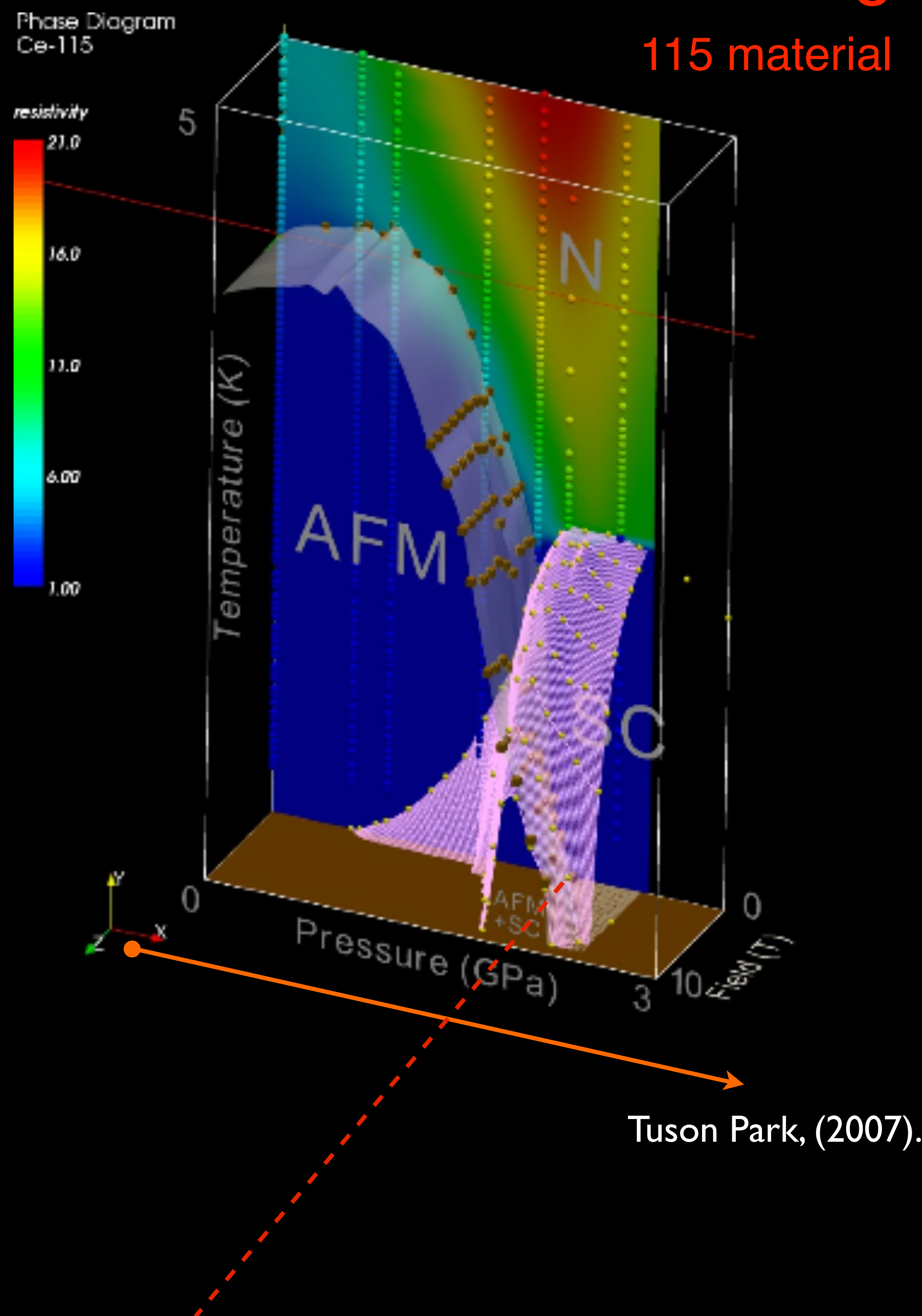




Shimuzu et al (2006)



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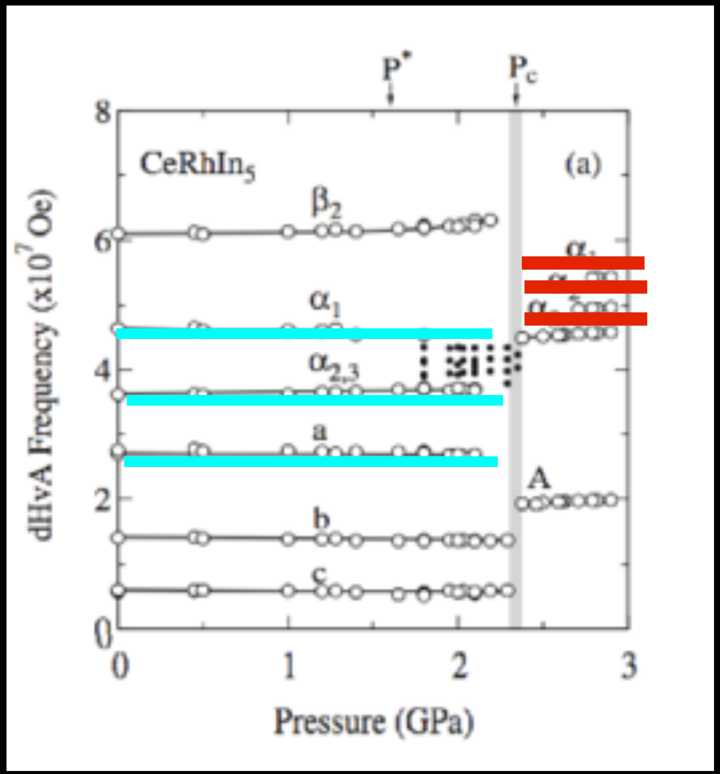

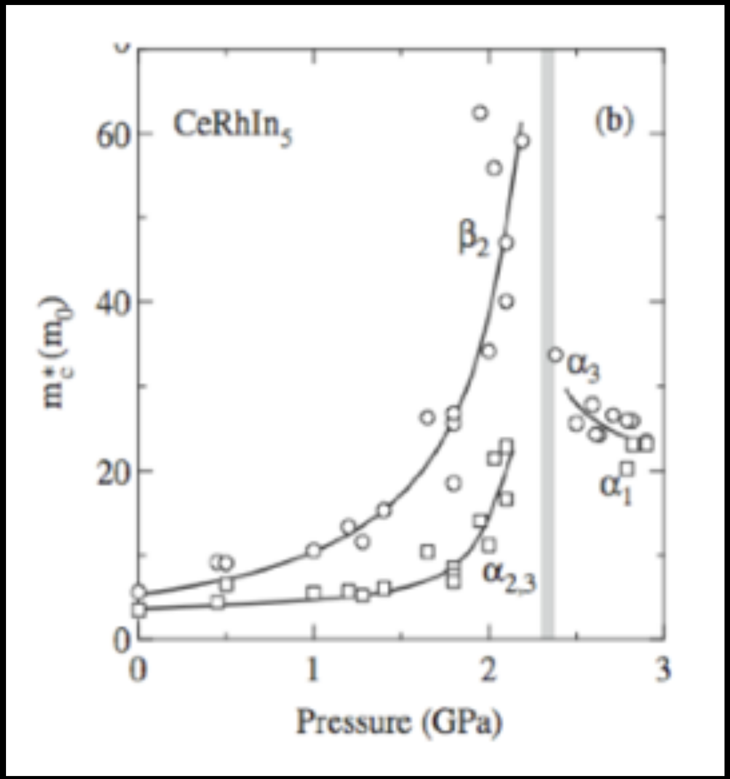

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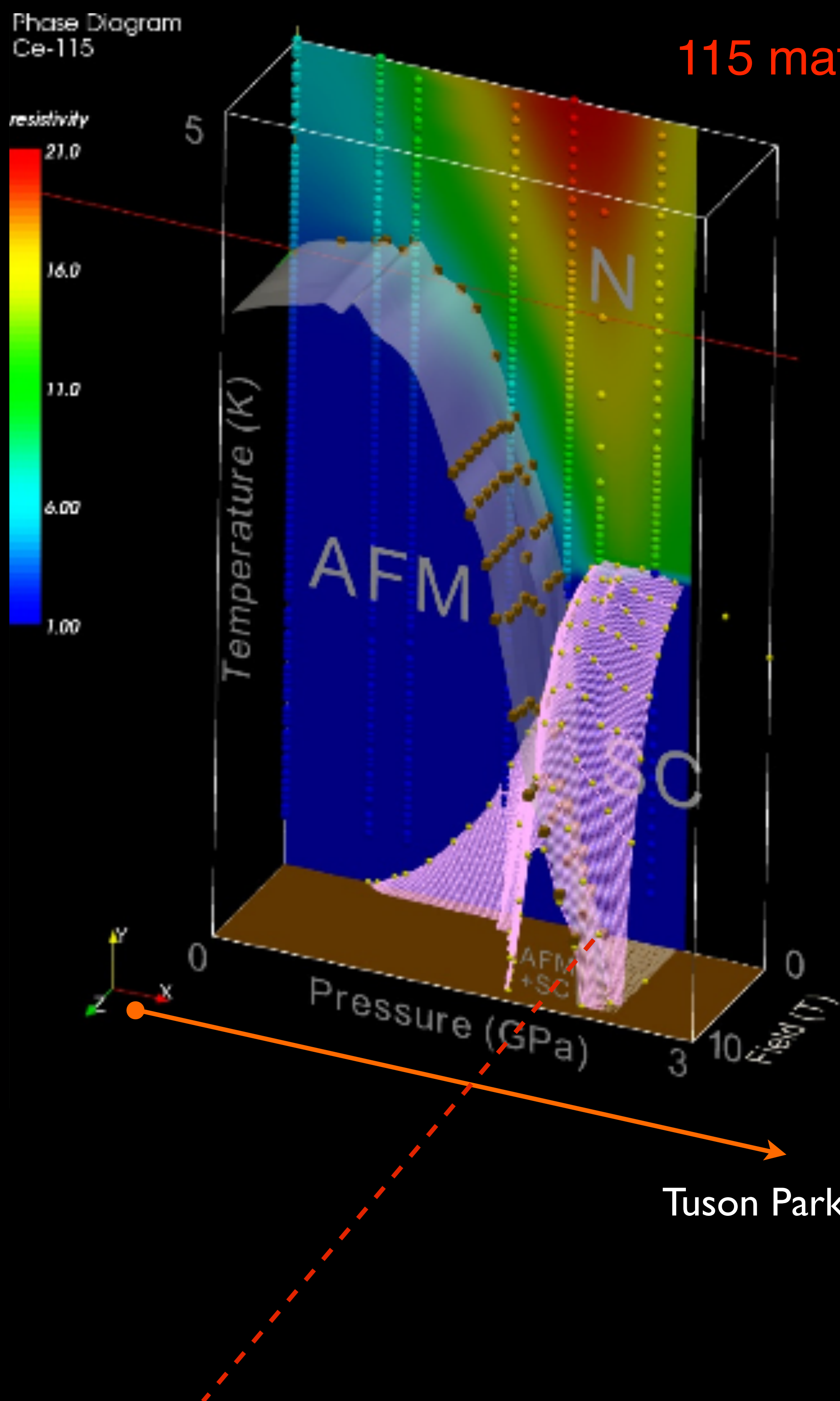

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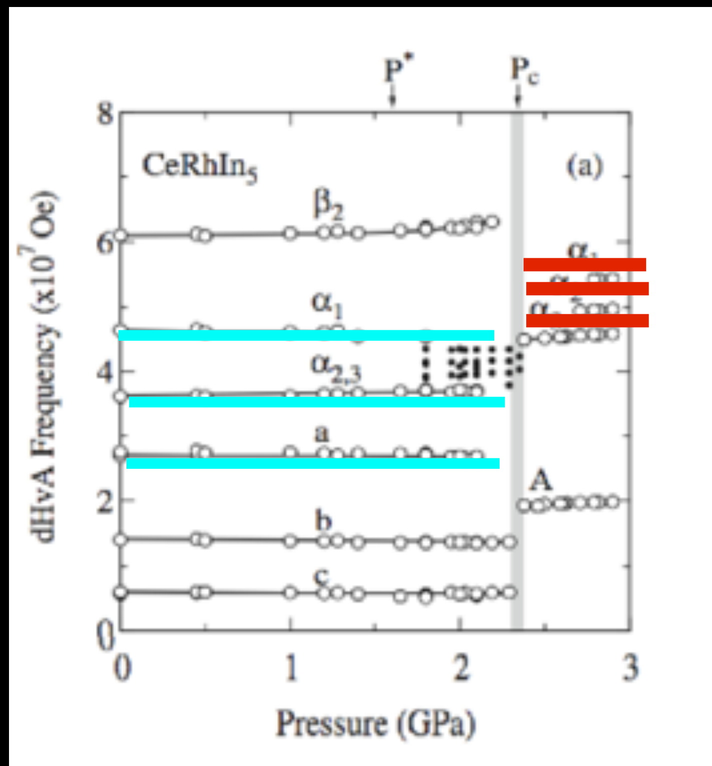

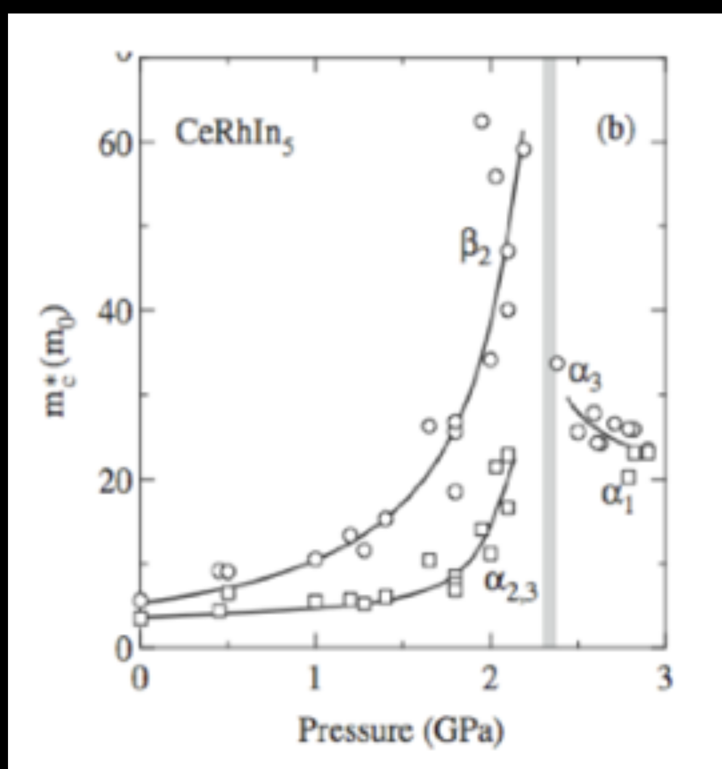

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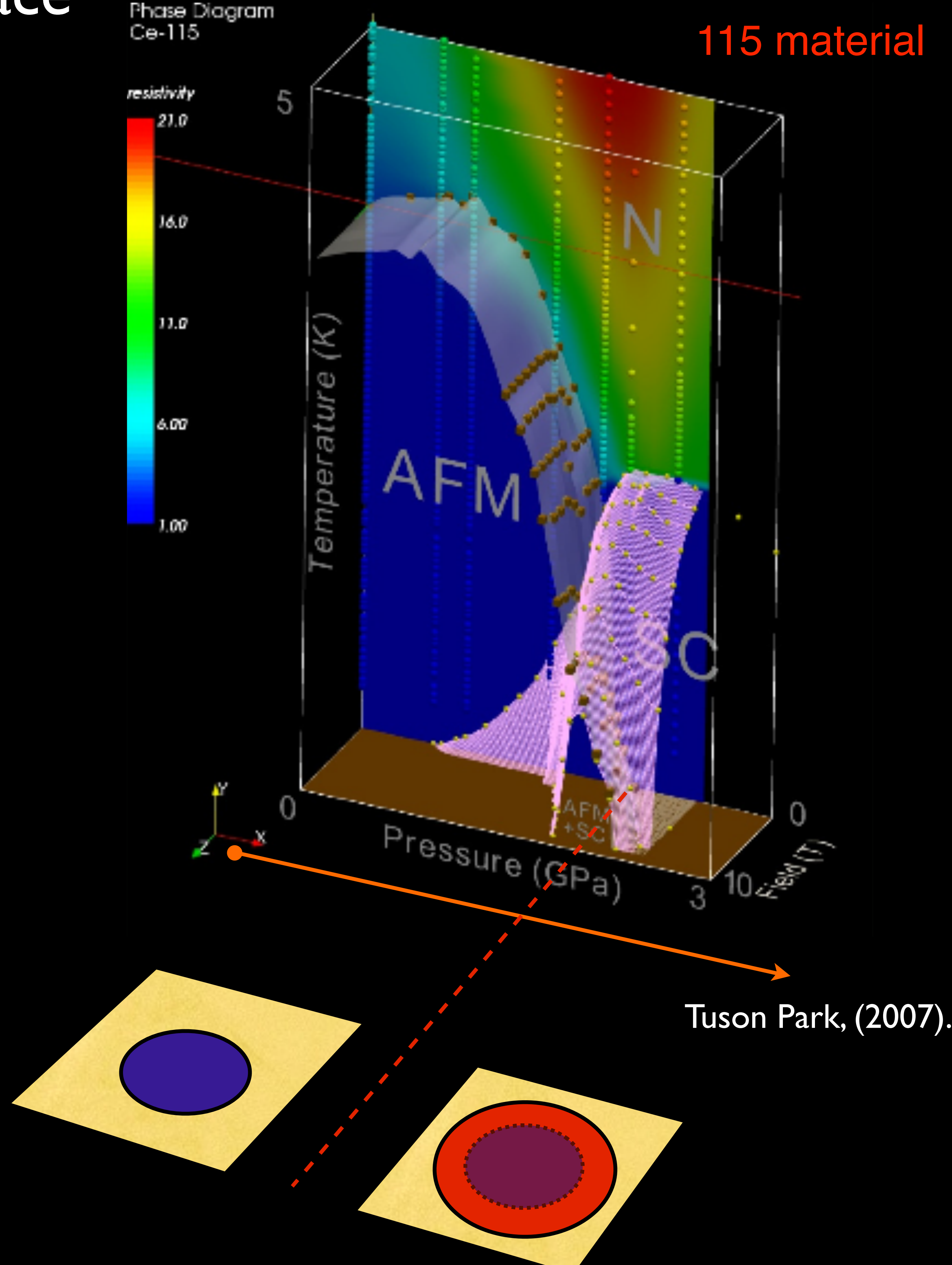

Tuson Park, (2007).

The Quantum Criticality Debate.

Alternative Ideas

Alternative Ideas

- **Local quantum criticality**

(Si, Ingersent, Smith, Rabello, Nature 2001):
Spin is the critical mode,
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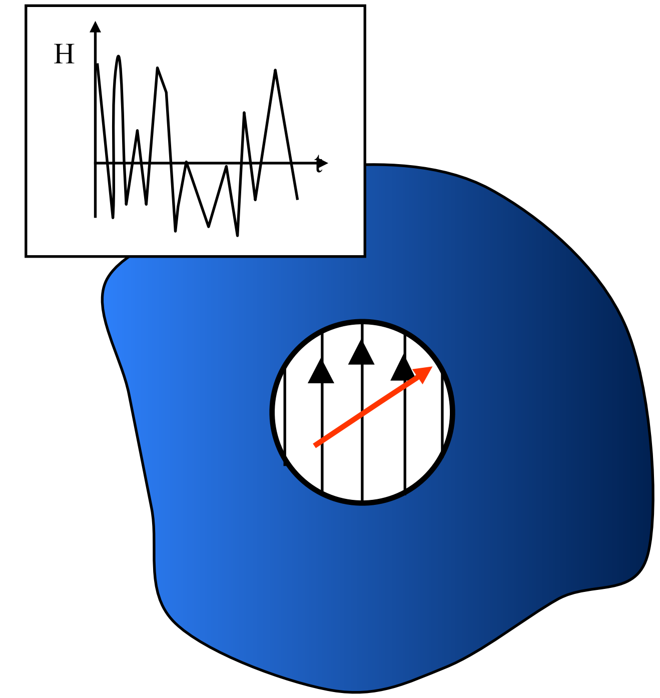
Requires a two dimensional spin fluid

Si, Ingersent

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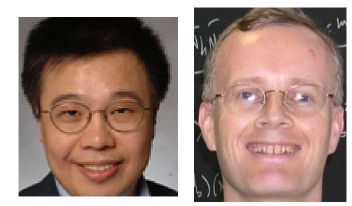

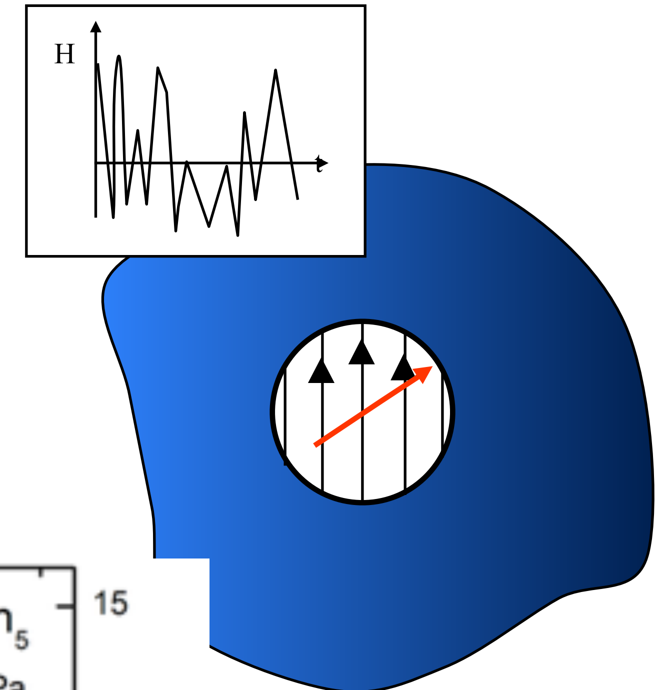

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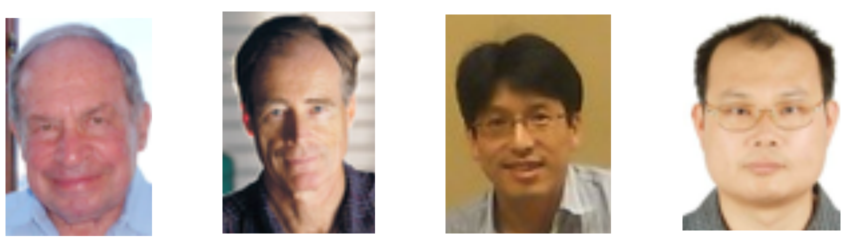
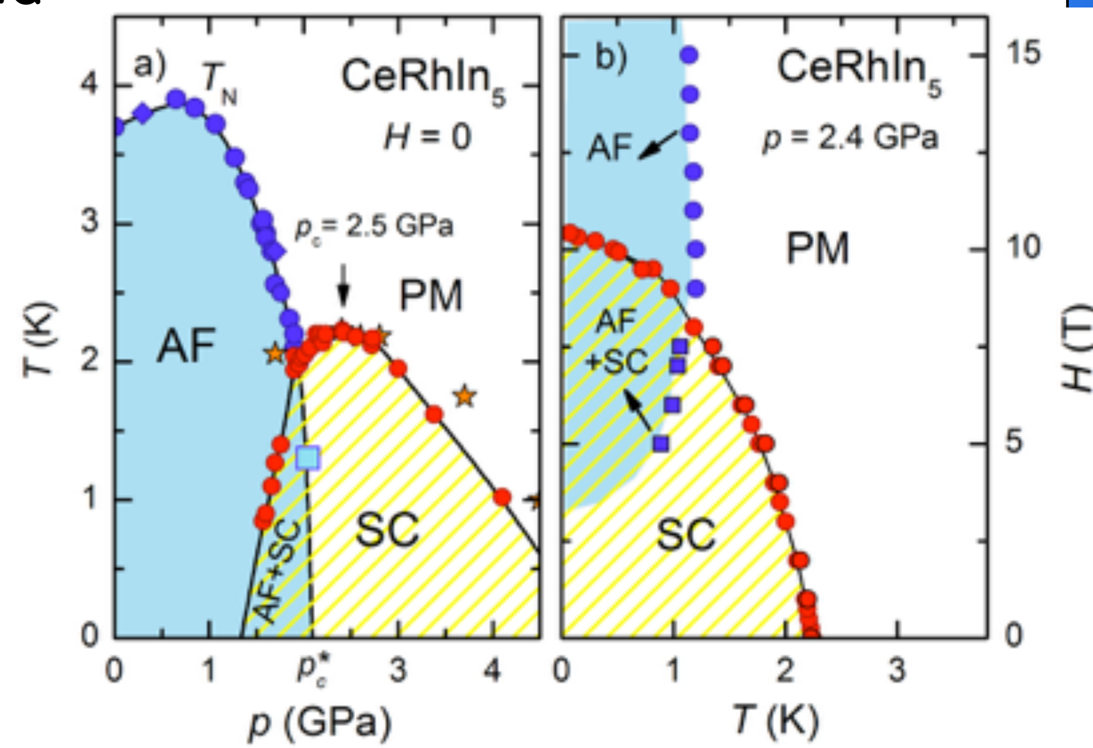


D. Pines Z. Fisk S. Nakatsuji Y. Yang

Nature (2008), PRL (2004)



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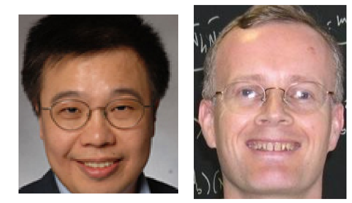

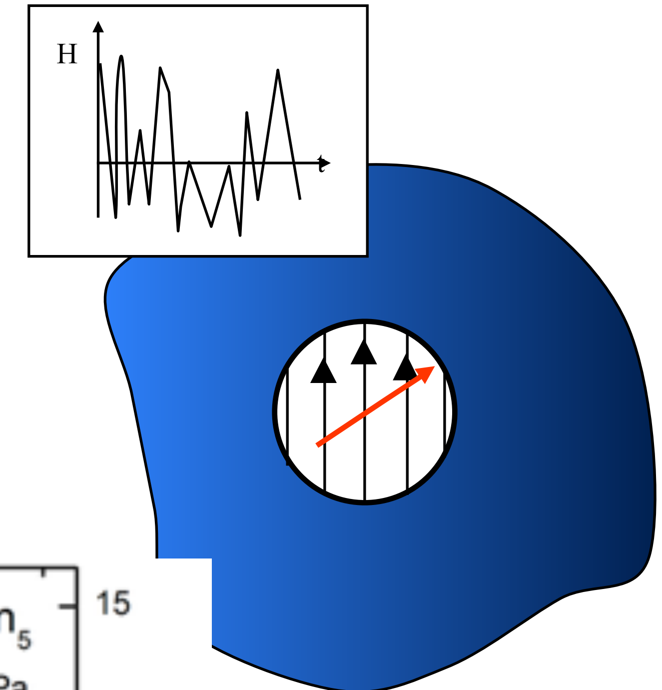

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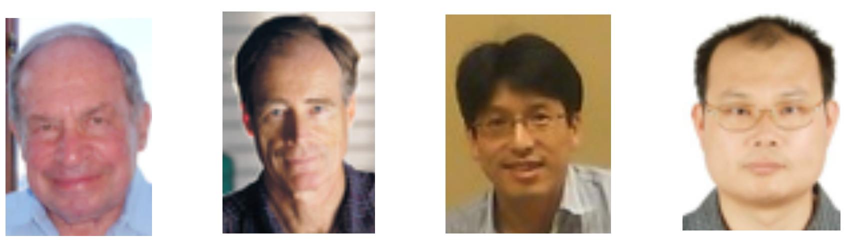

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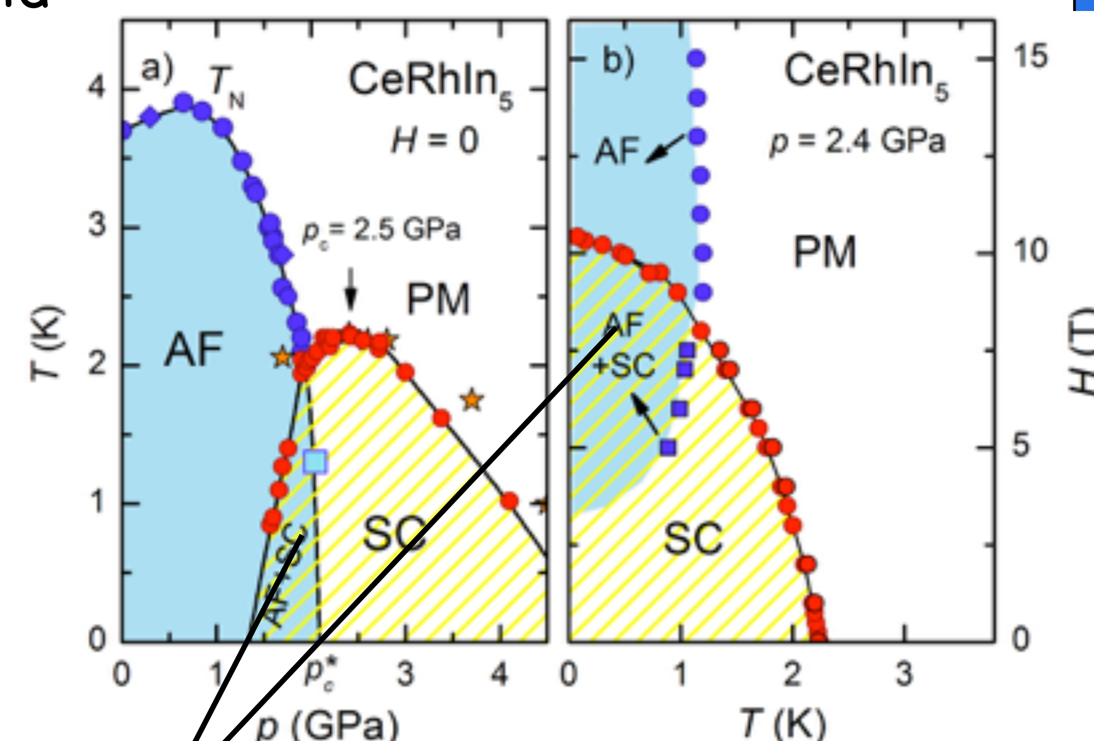

Magnetism LM + Kondo Pure Kondo

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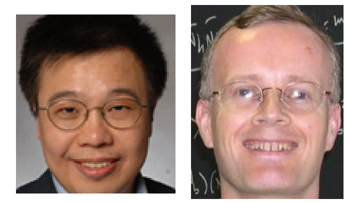

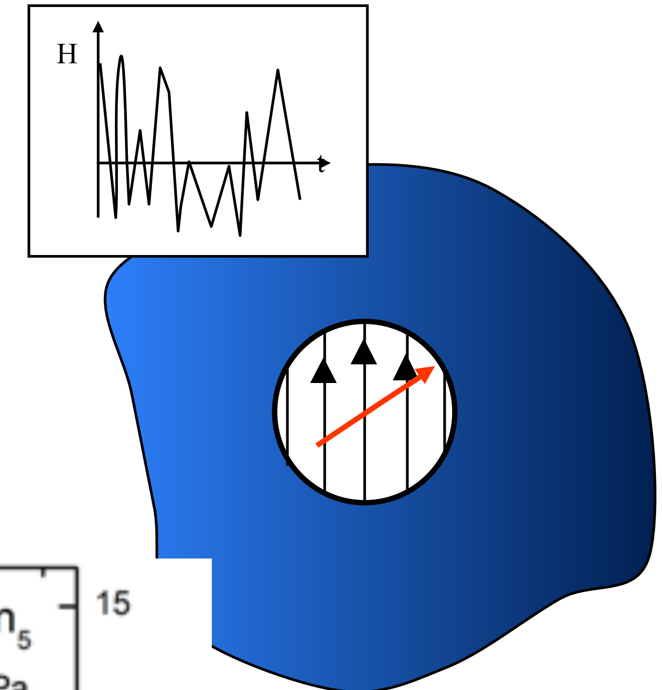

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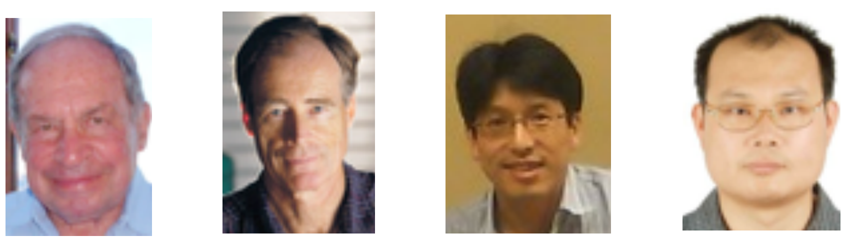

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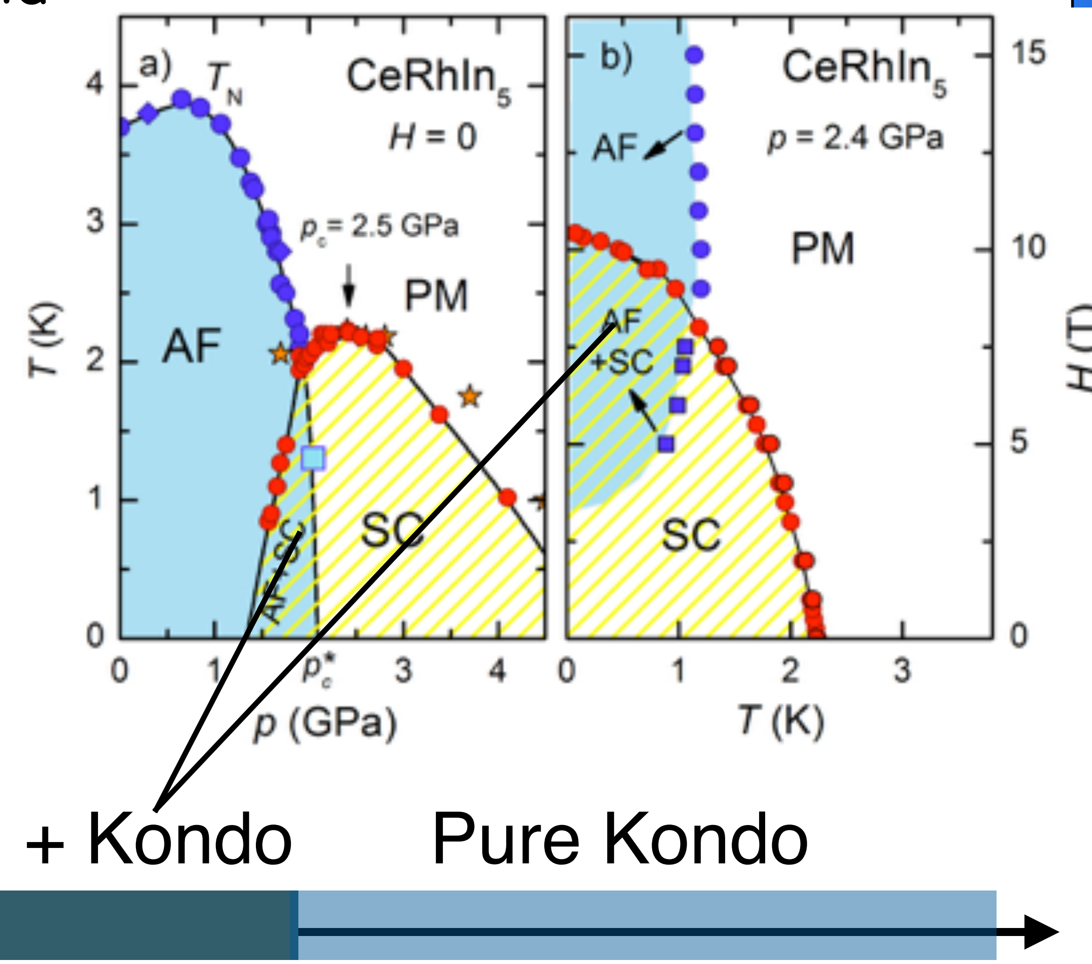

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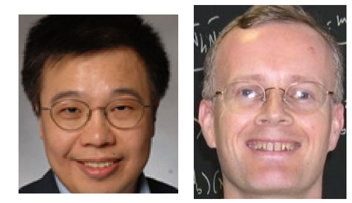

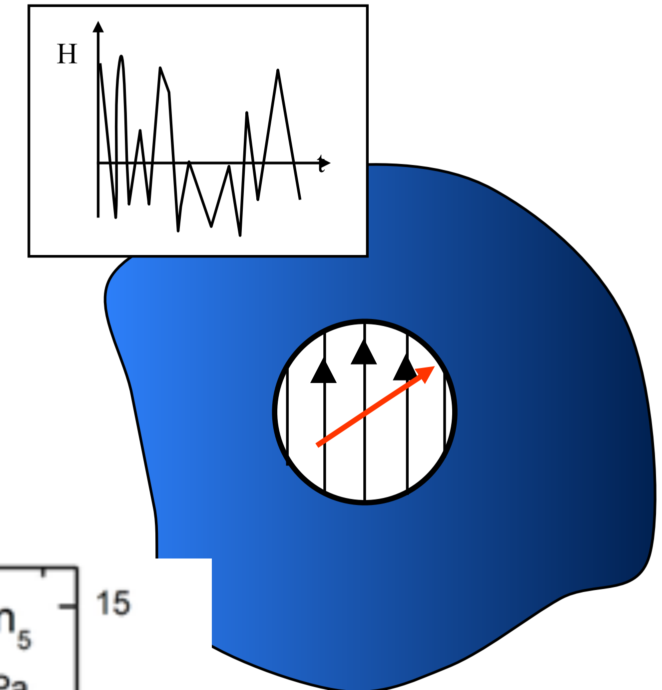

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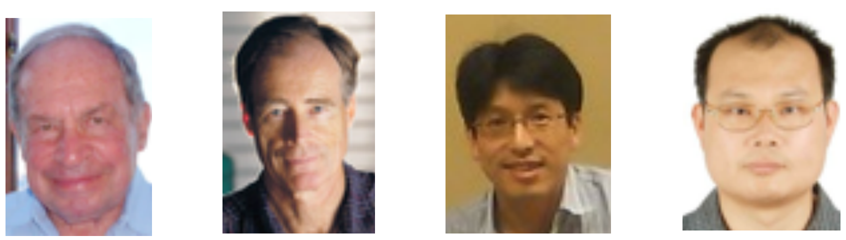

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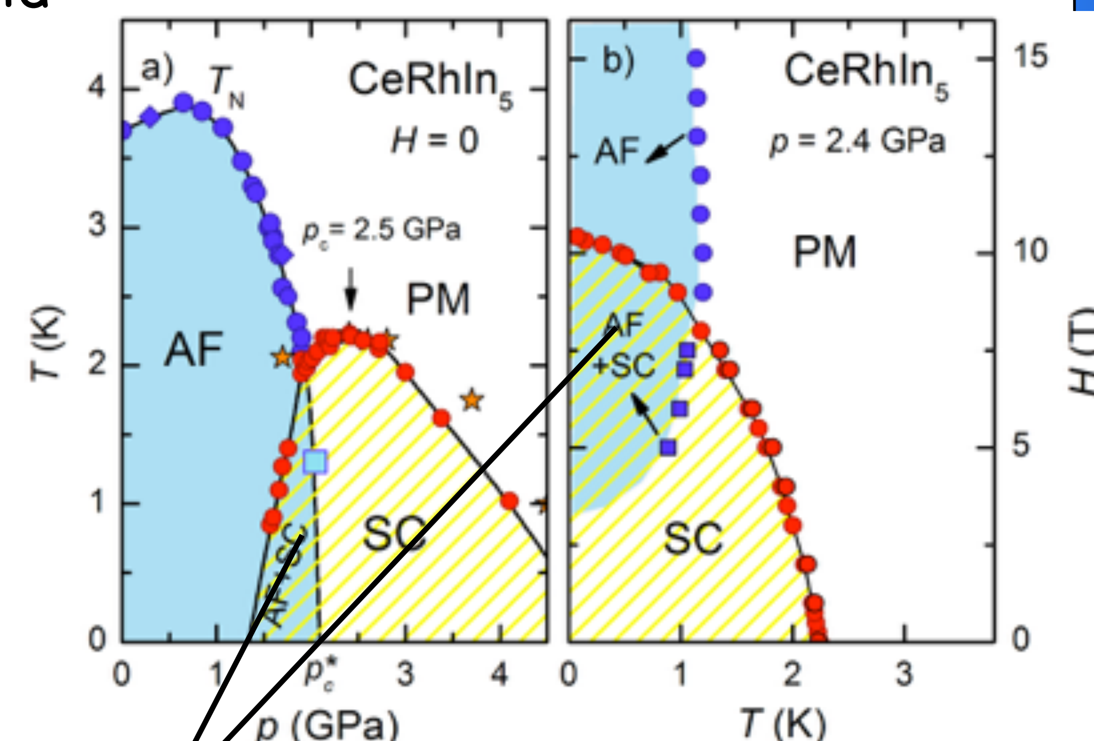

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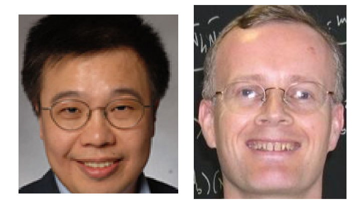

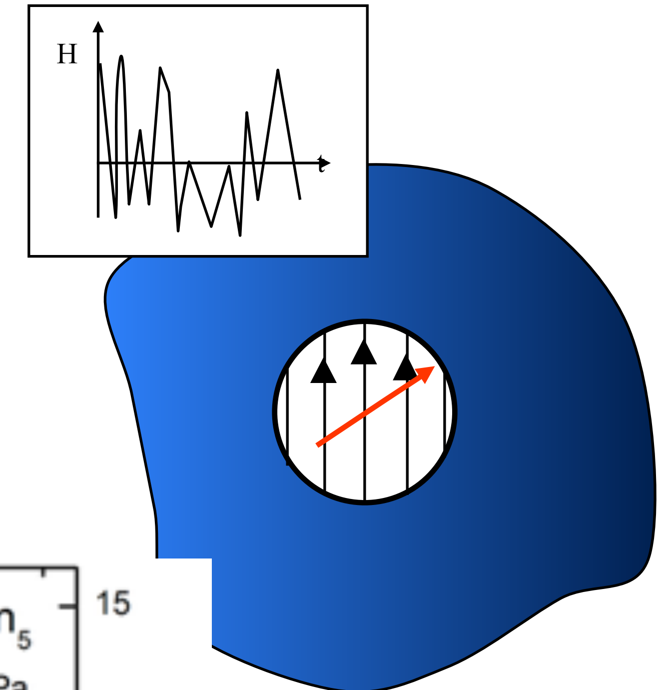

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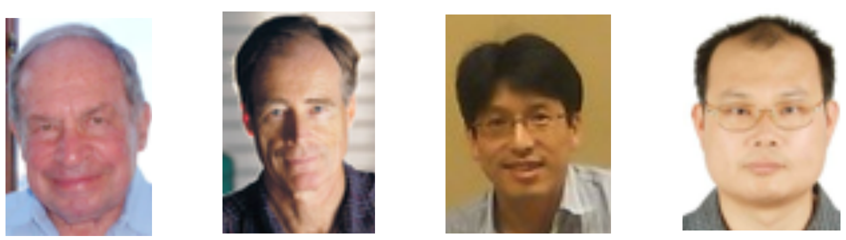

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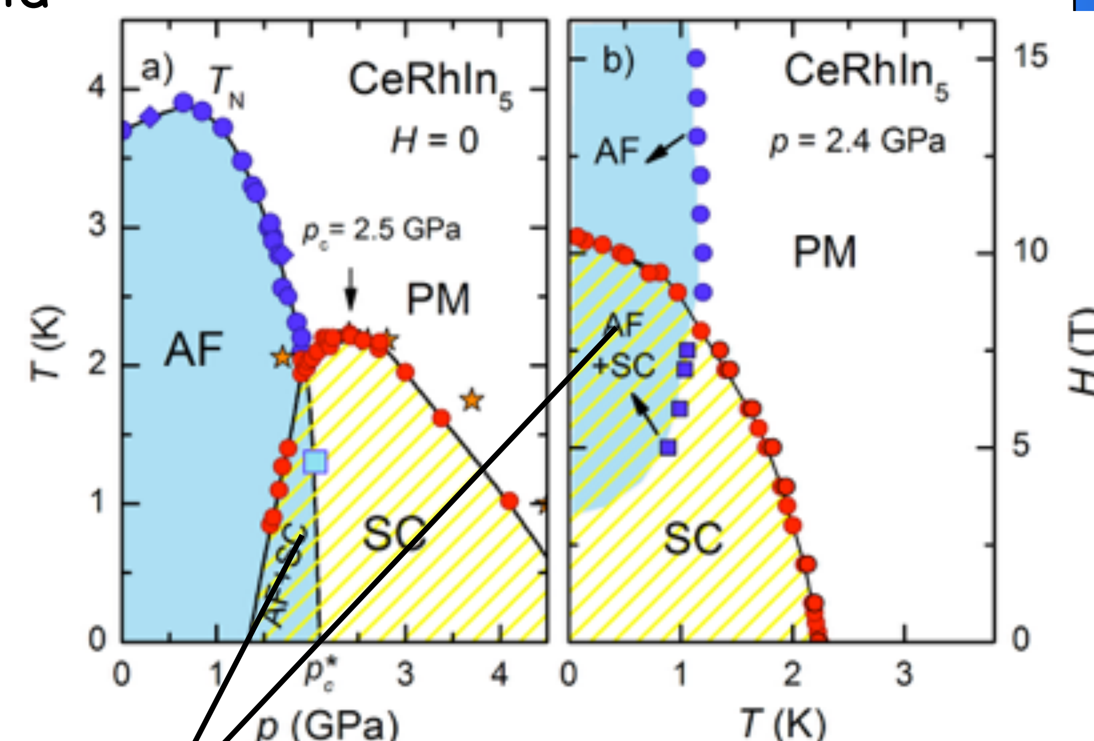

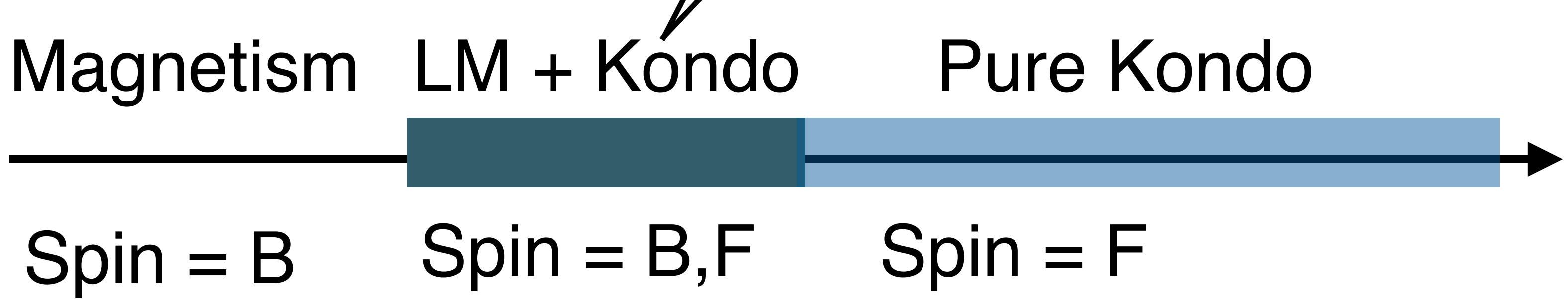

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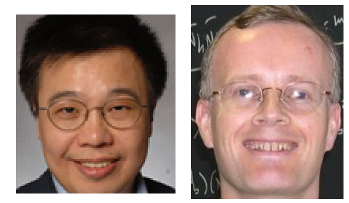

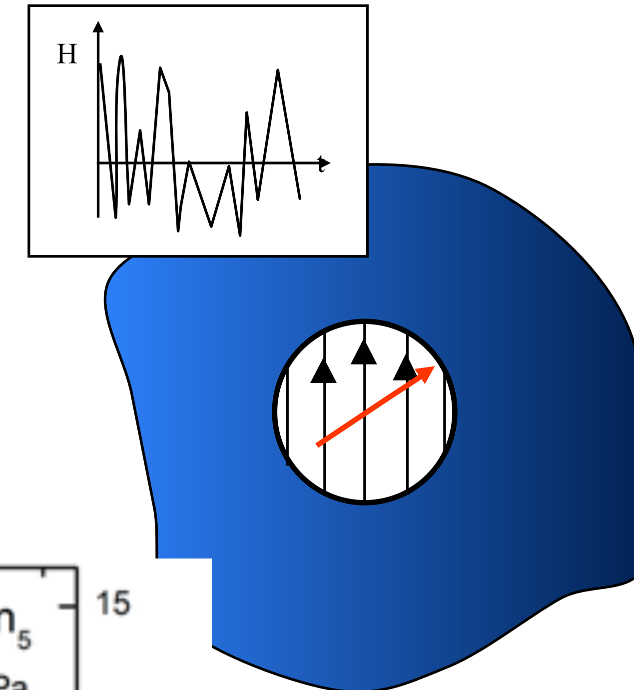

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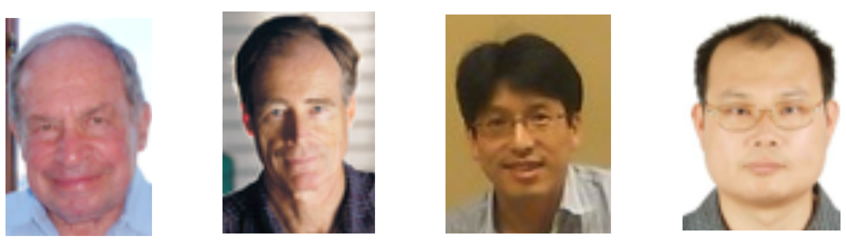

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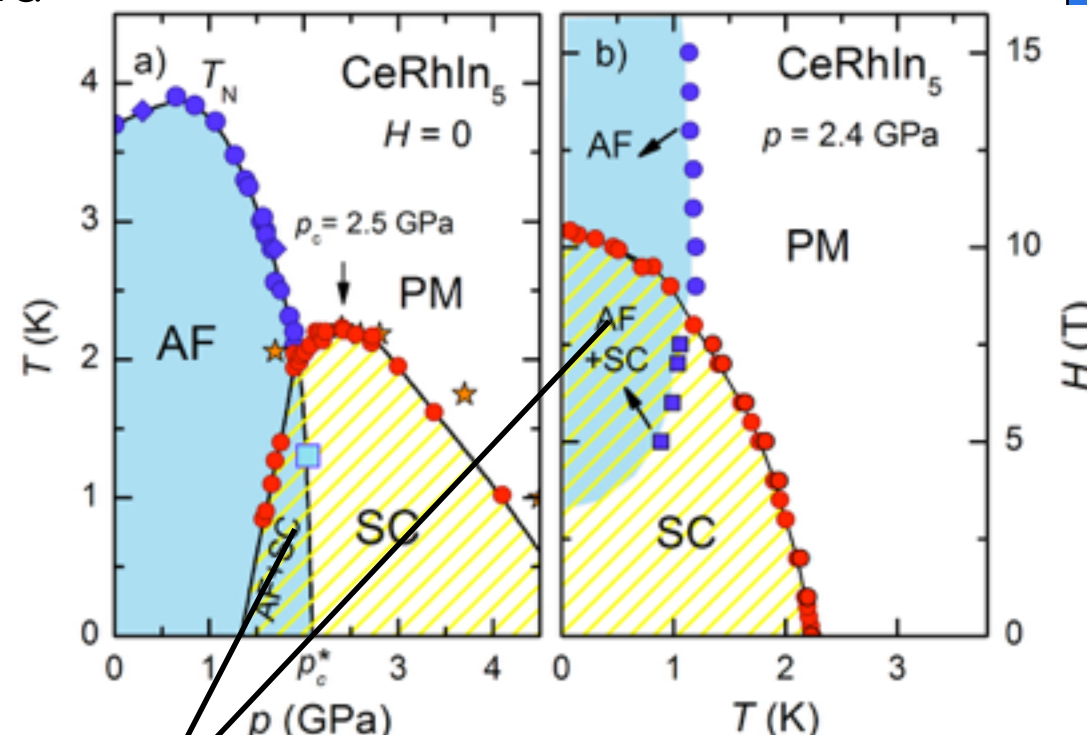

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Strange Metal = Unbroken Susy?

Frustration and strange metals.

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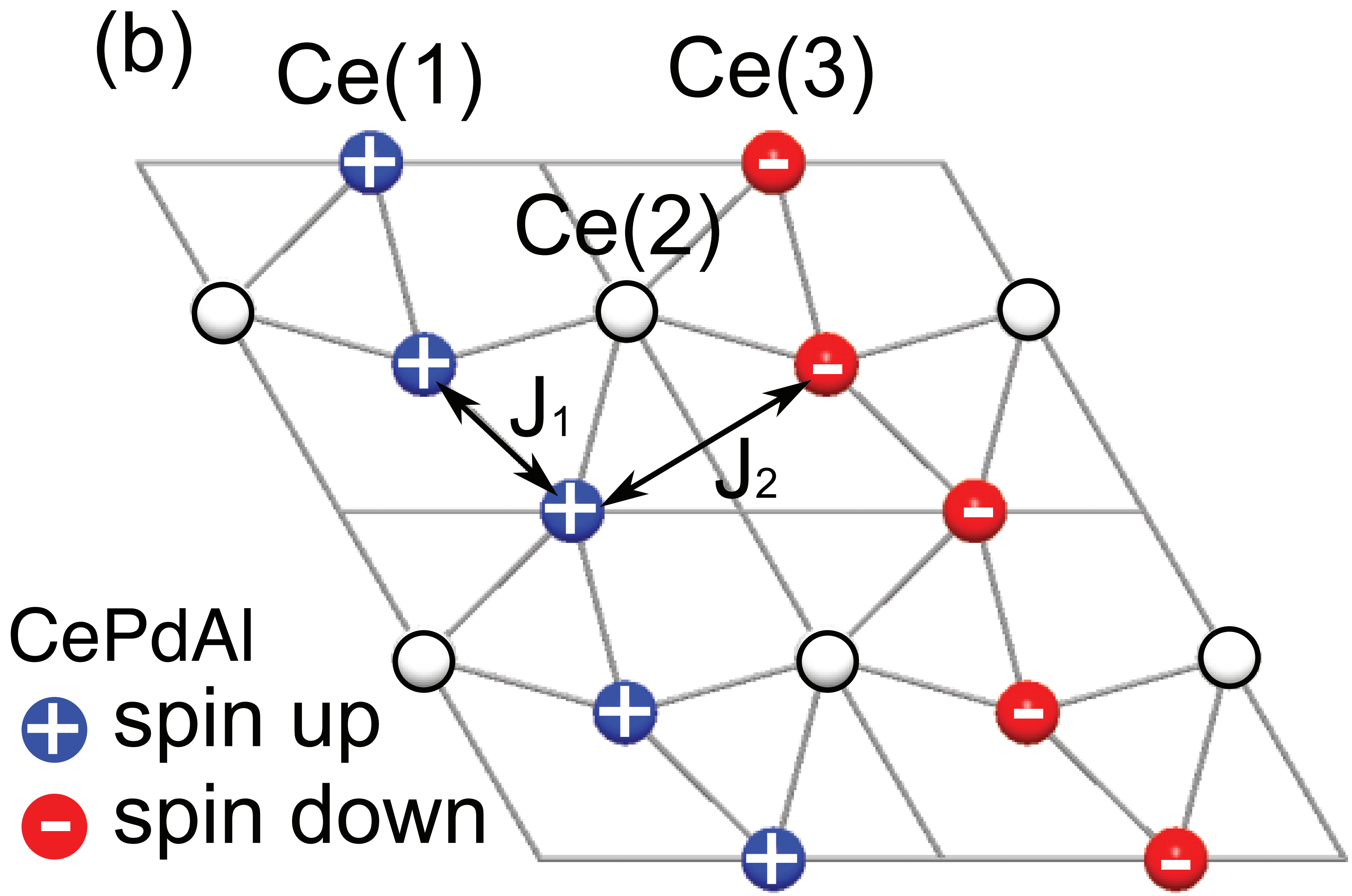
M. D. Nunez-Regueiro, C. Lacroix, and B. Canals, Physica C **282**, 1885 (1997).

V. Fritsch et al, PRB **89**, 054416 (2014)



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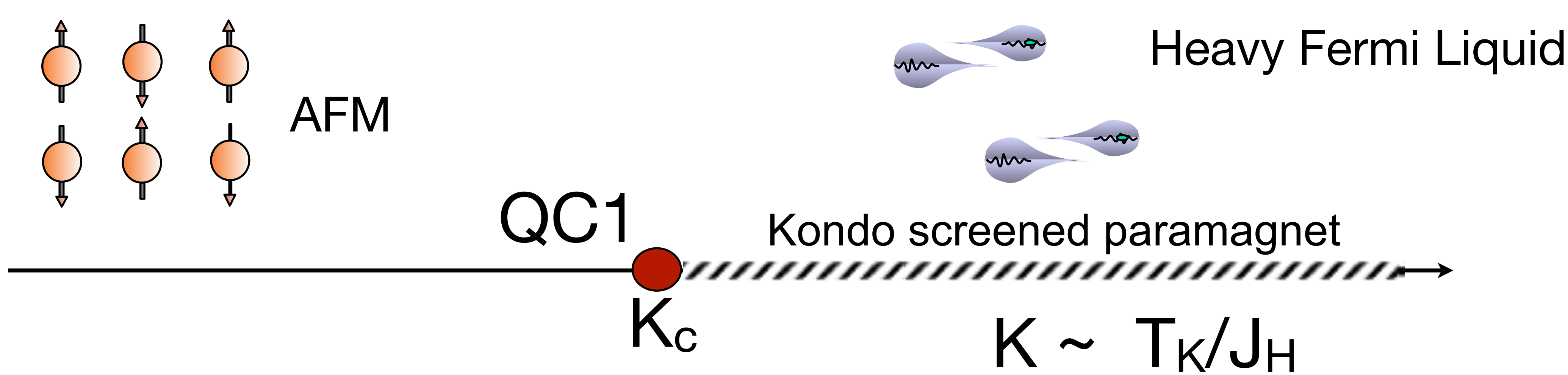

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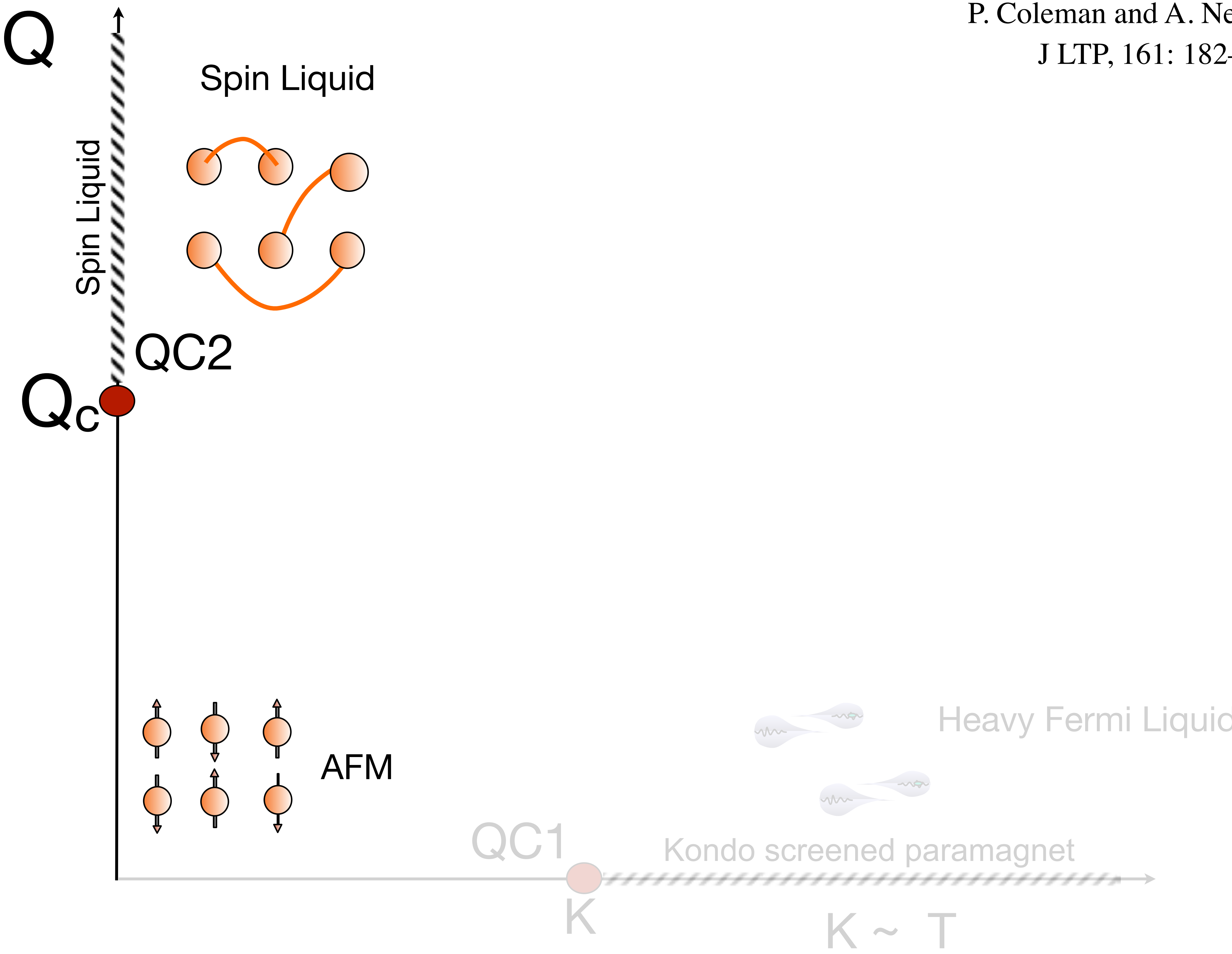

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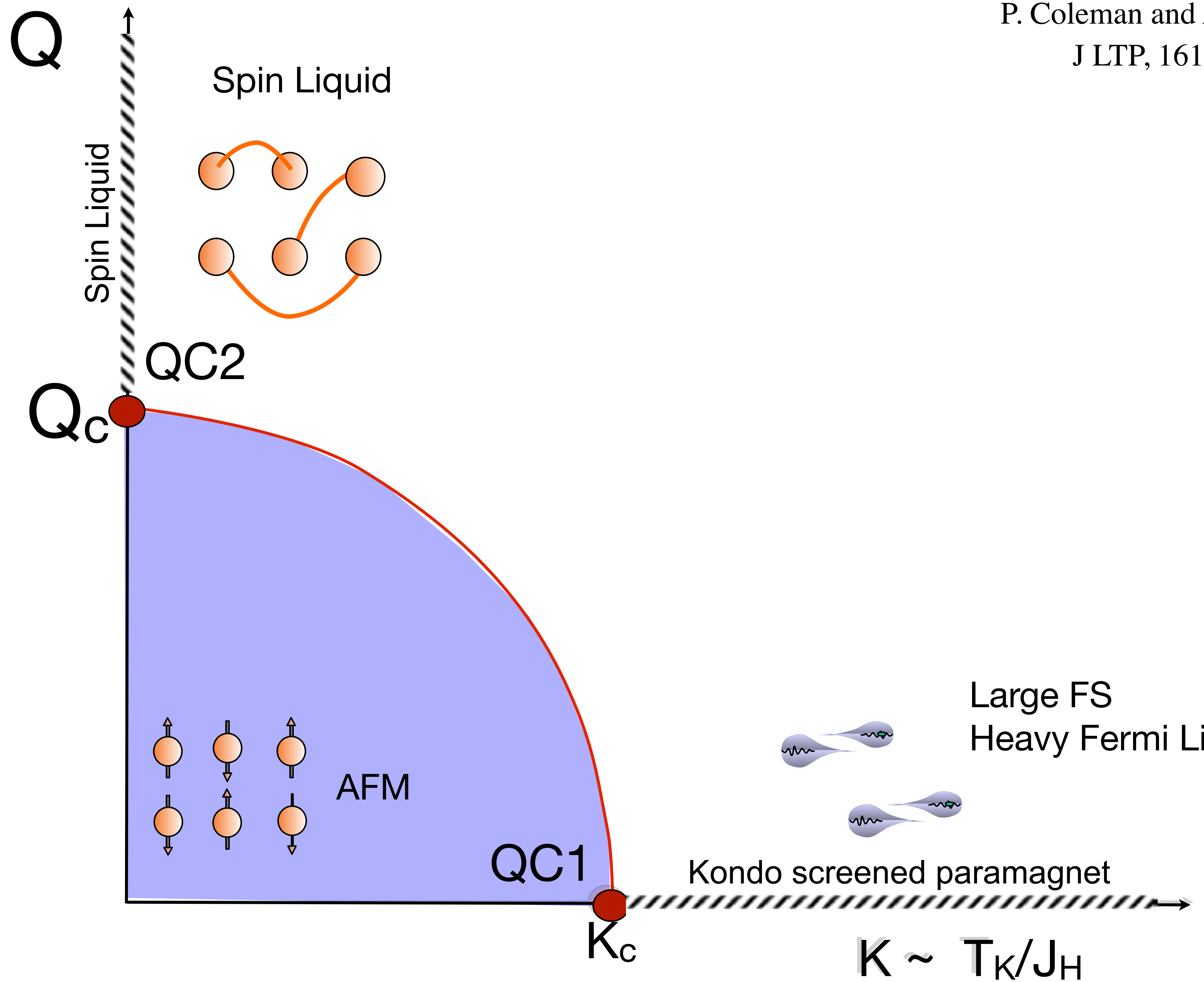

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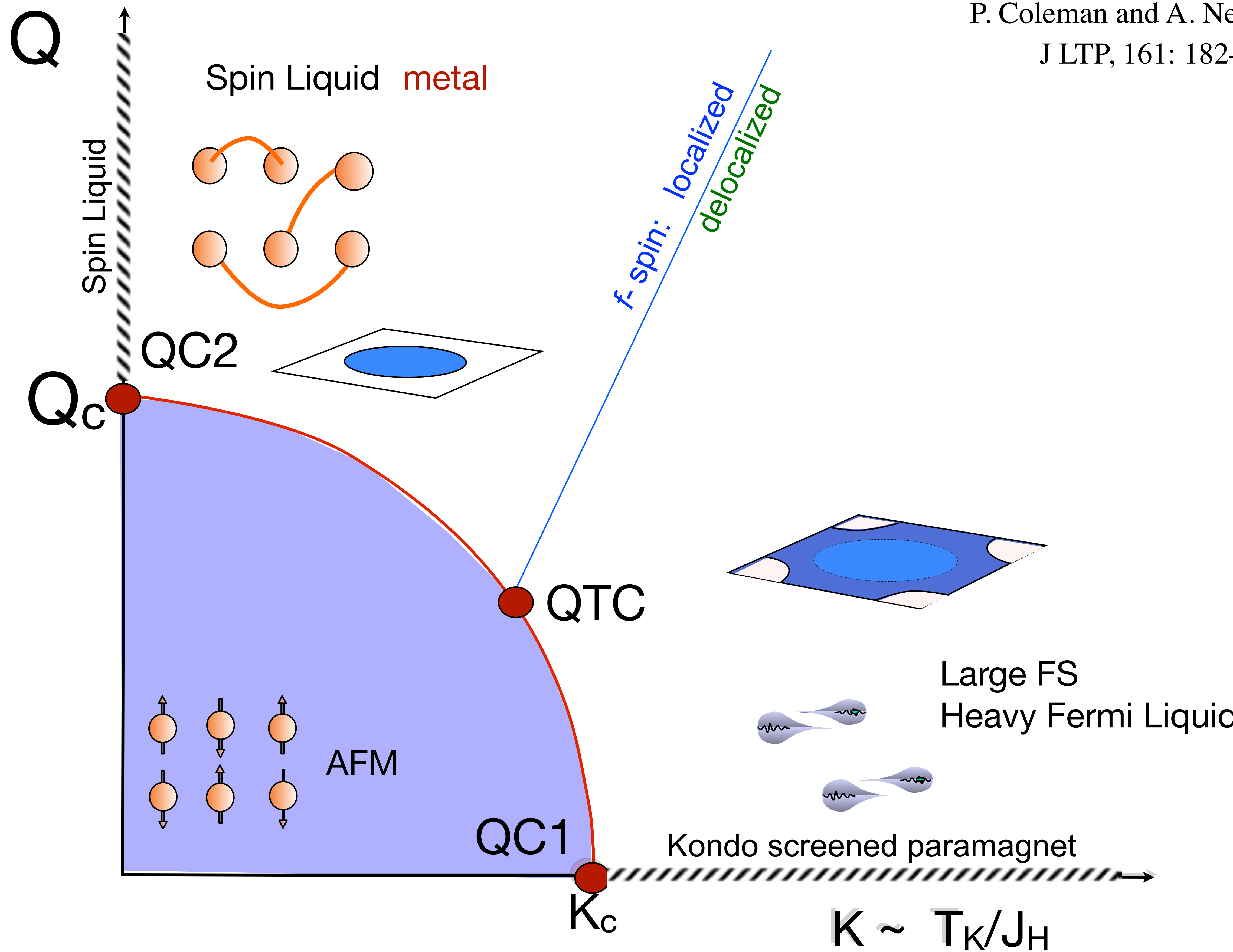

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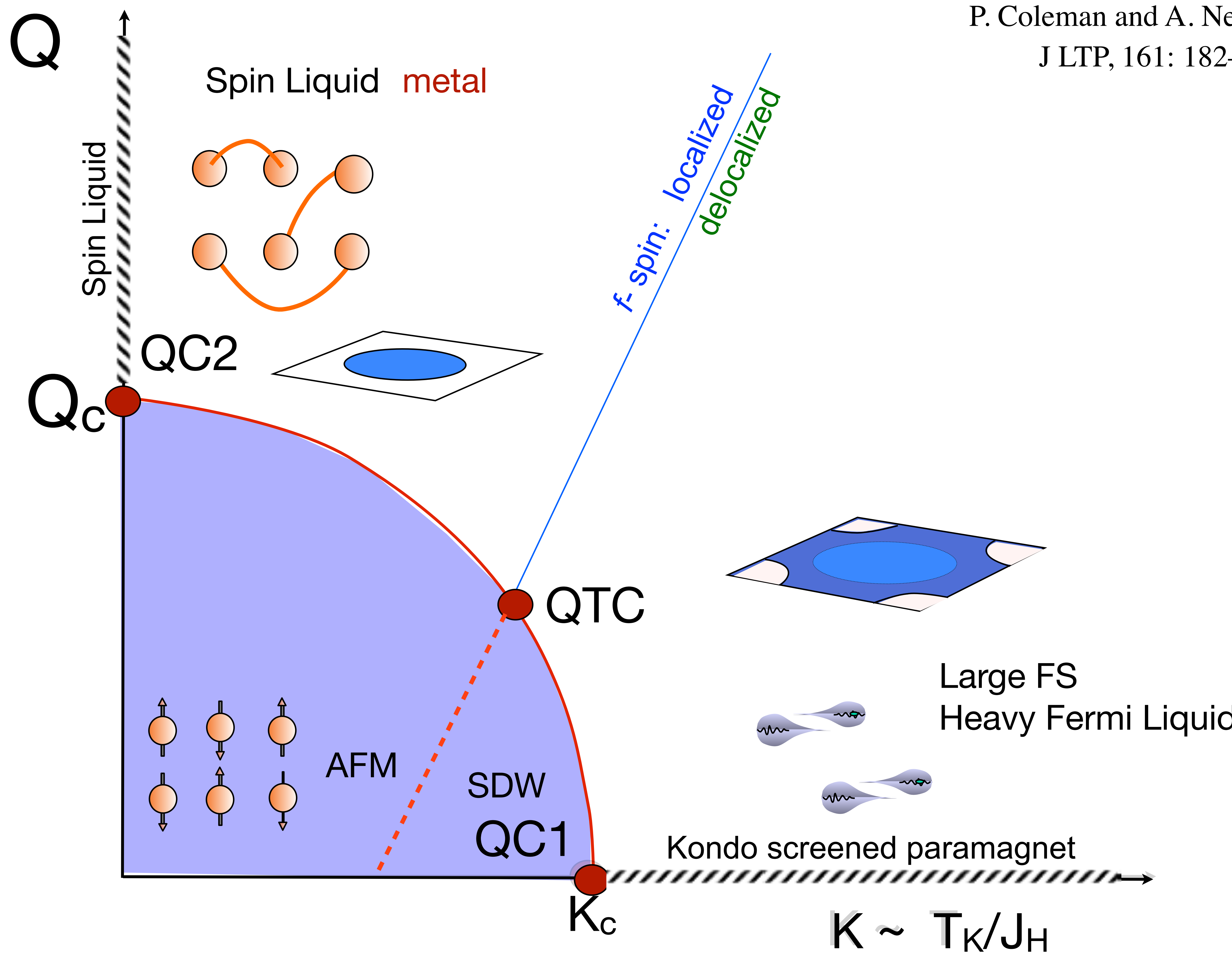

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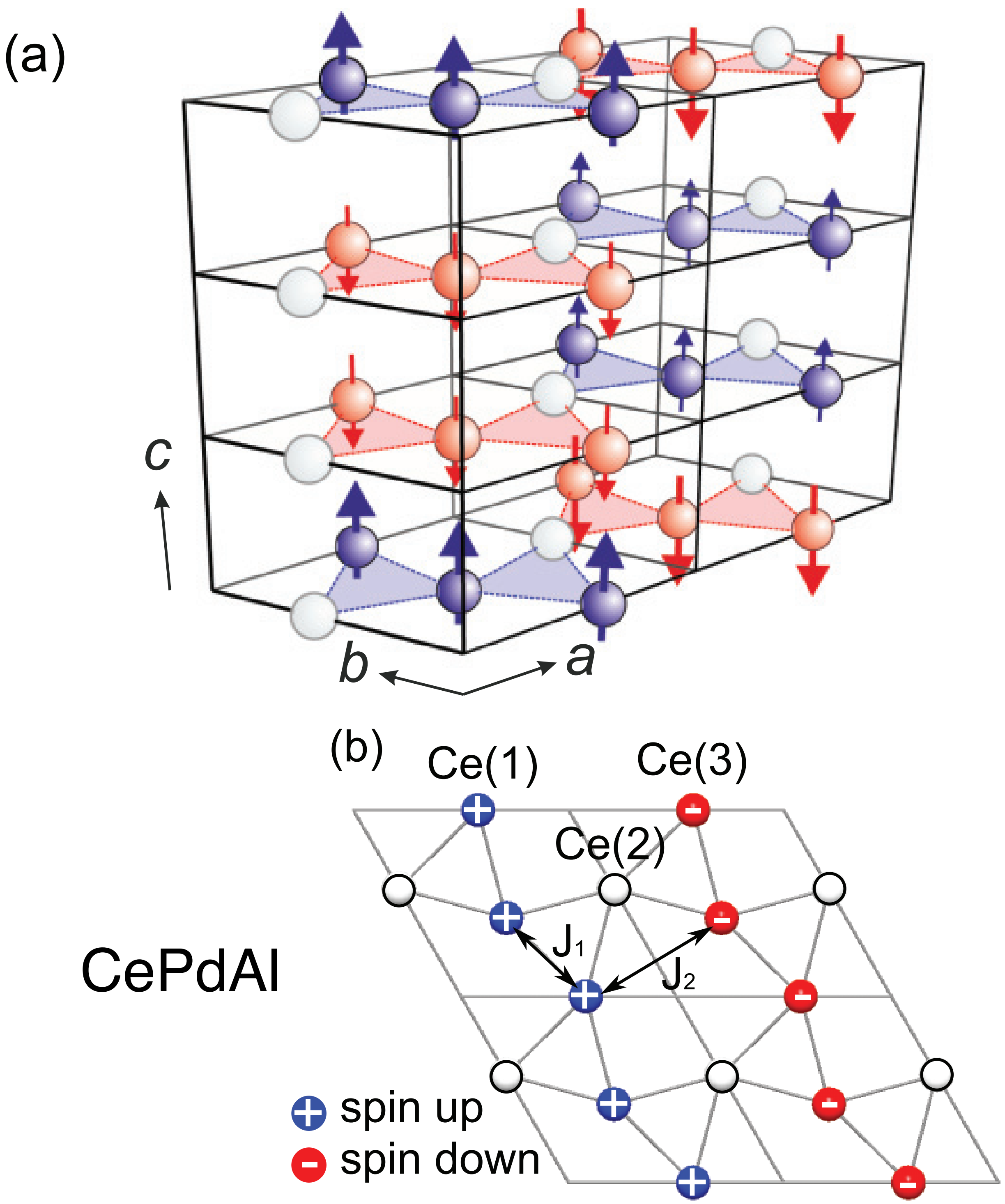

CePdAl

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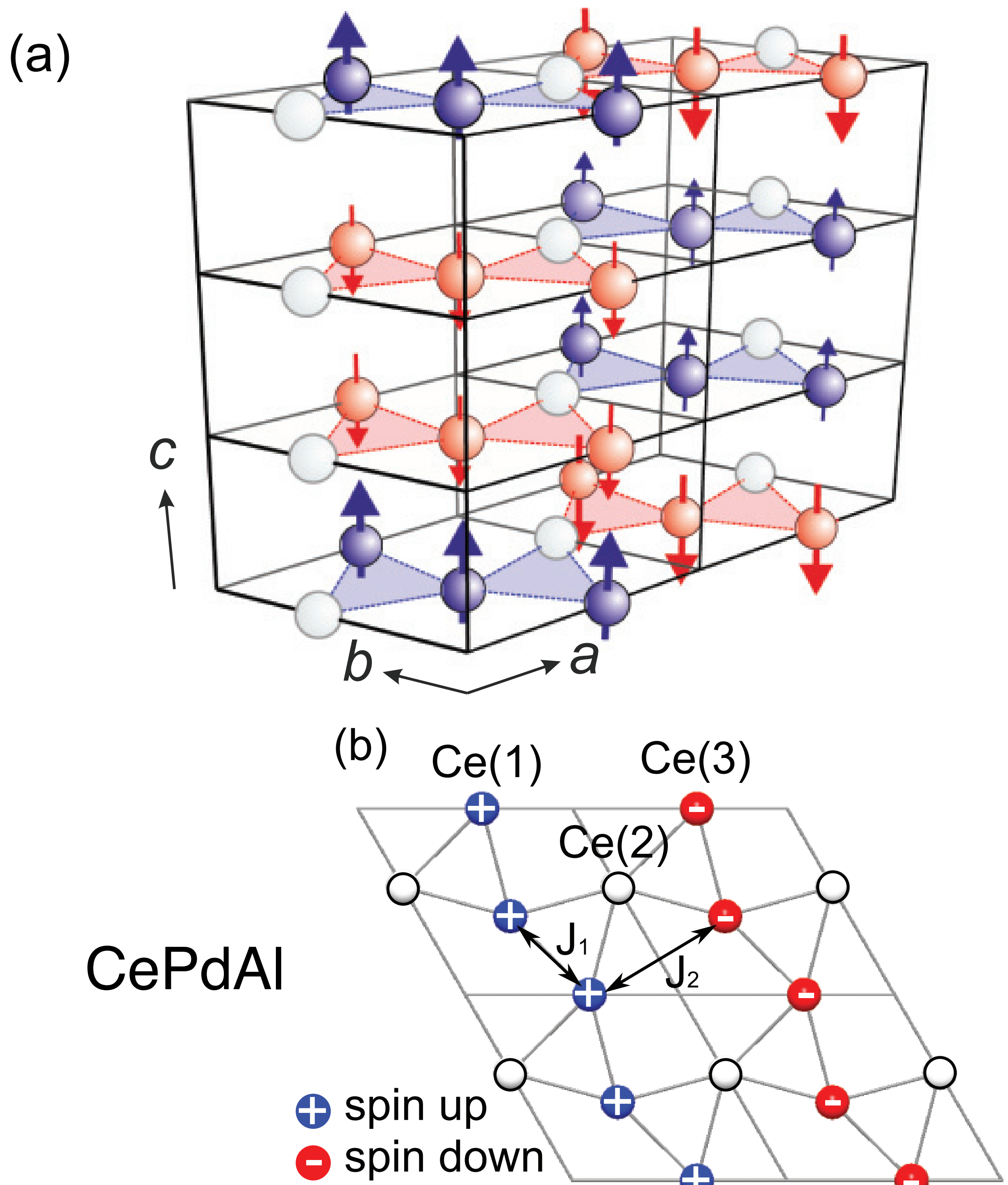

Kagome Frustration drives formation of magnetic sheets breaking equivalence between Ce sites.

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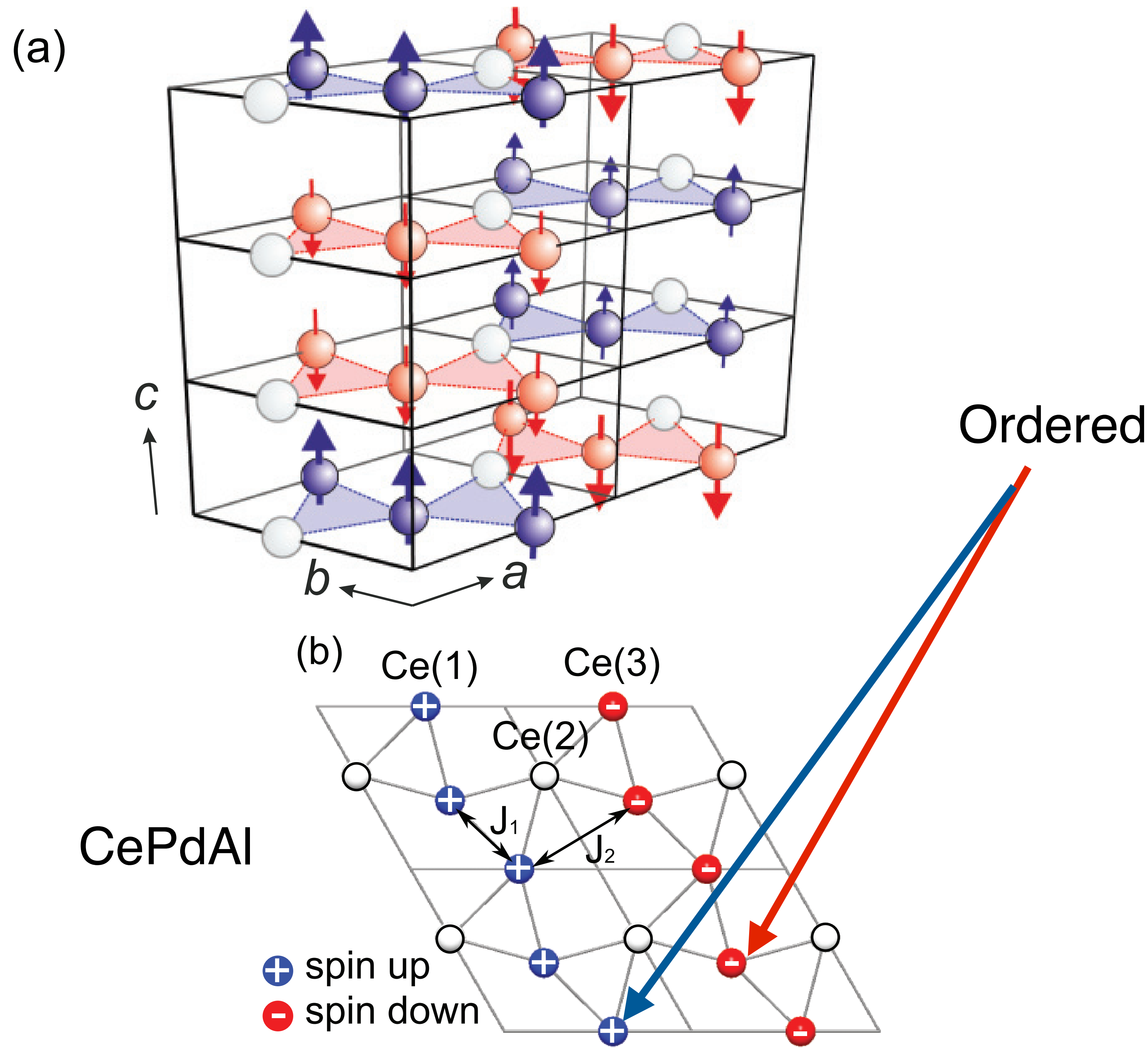

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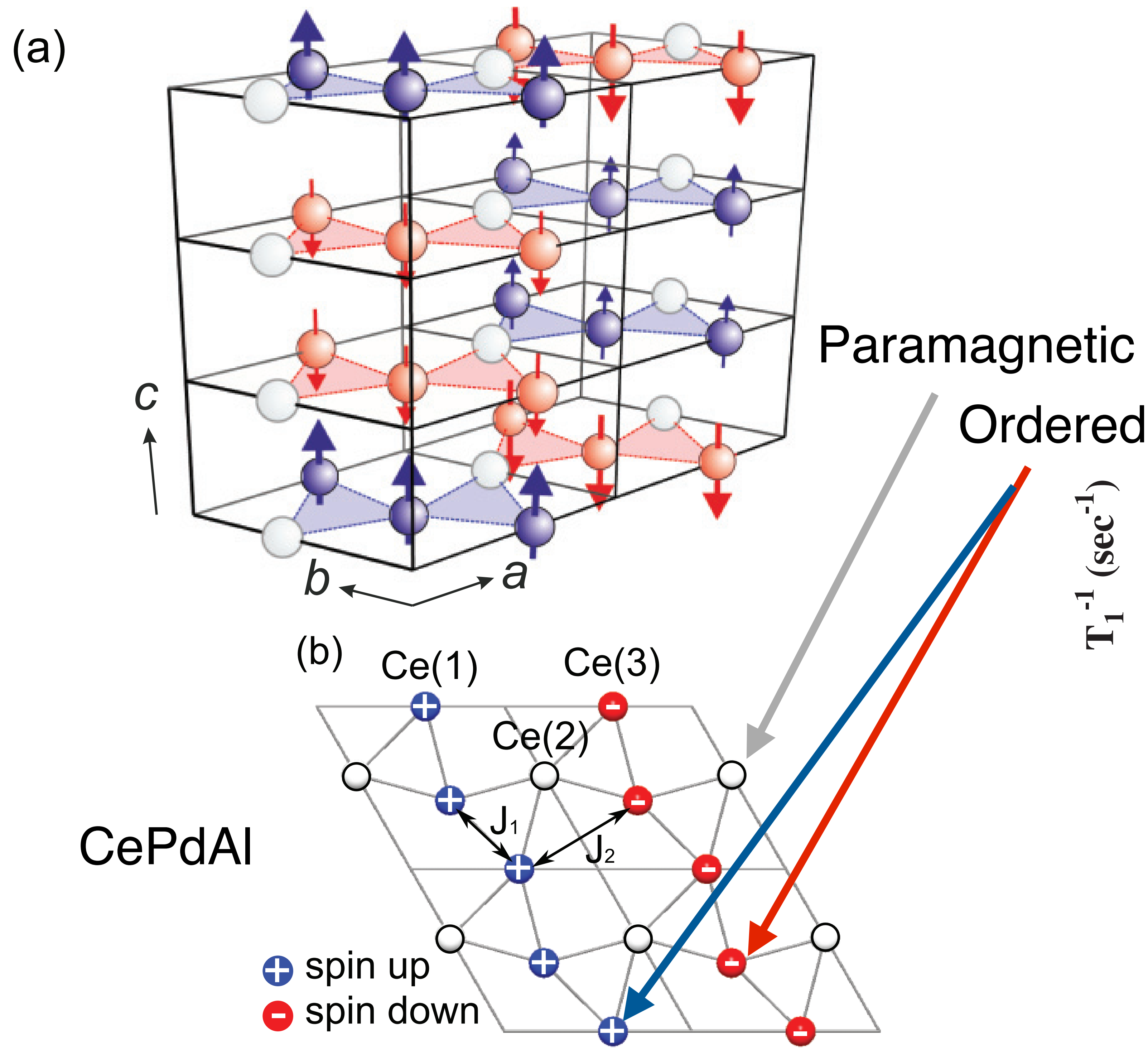
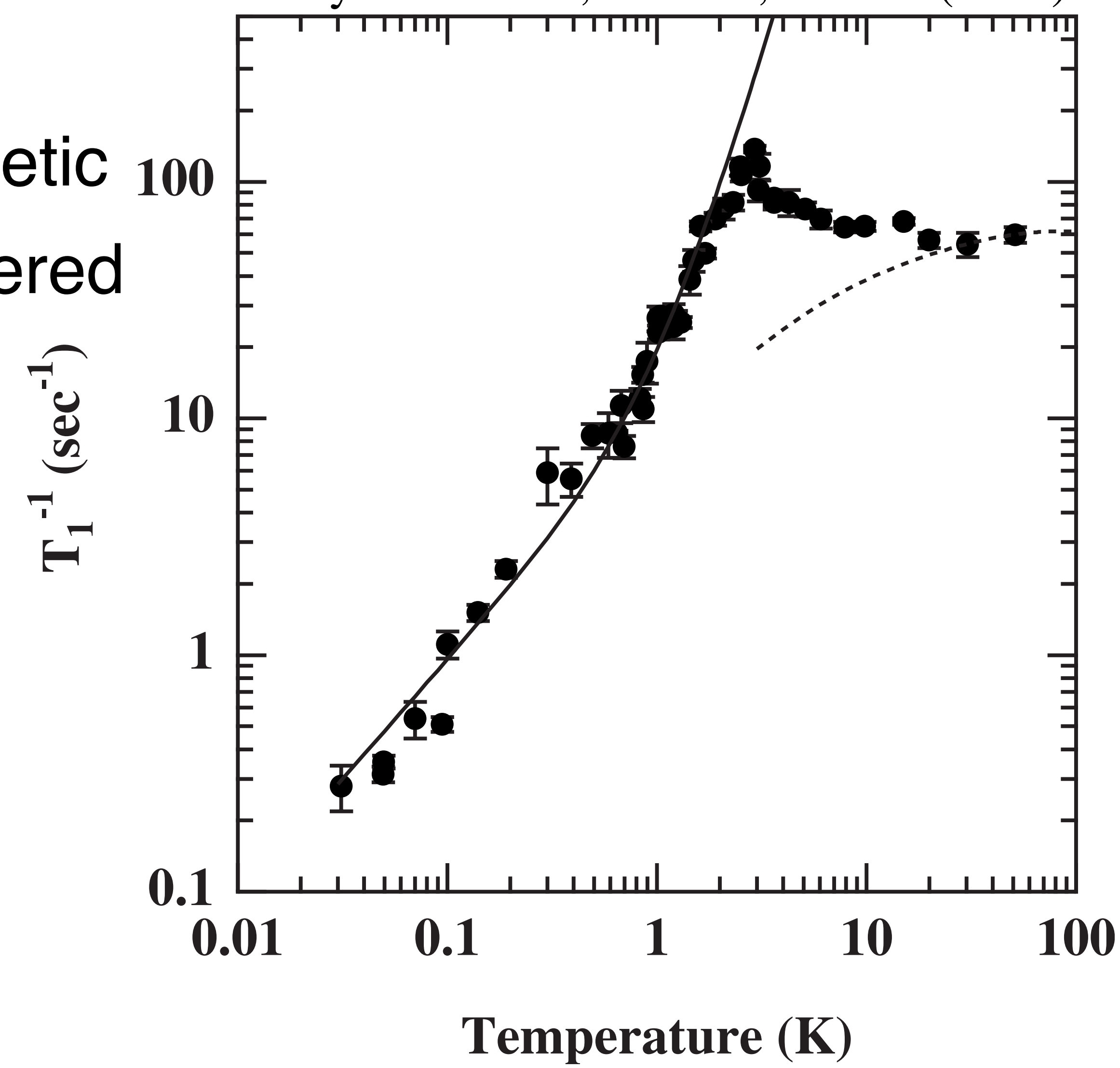


Oyamada et al, PRB **77**, 064432 (2008)



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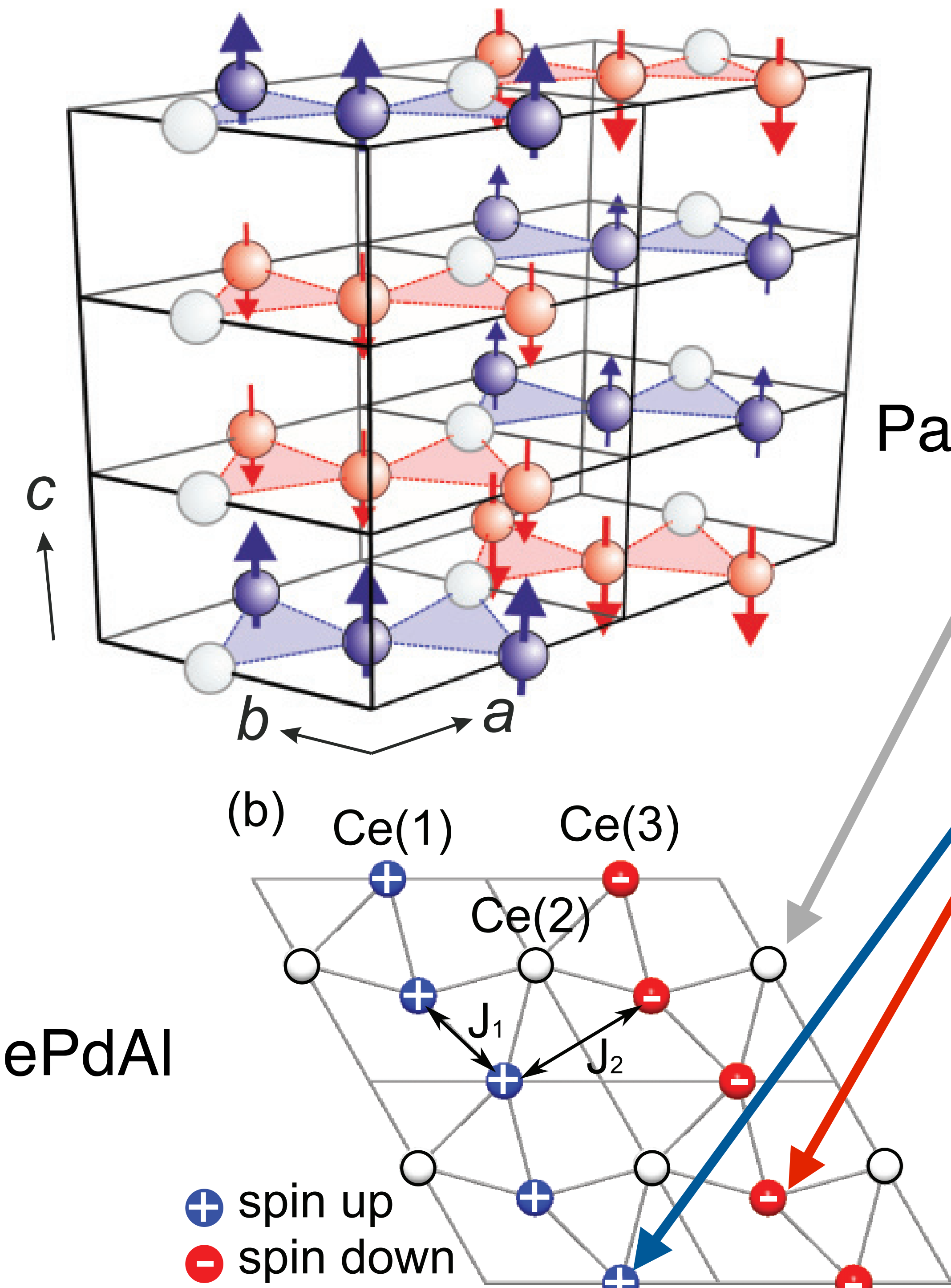
Co-existence of magnetic and delocalized f-electrons?

M. D. Nunez-Regueiro, C. Lacroix, and B. Canals, Physica C **282**, 1885 (1997).

V. Fritsch et al, PRB **89**, 054416 (2014)



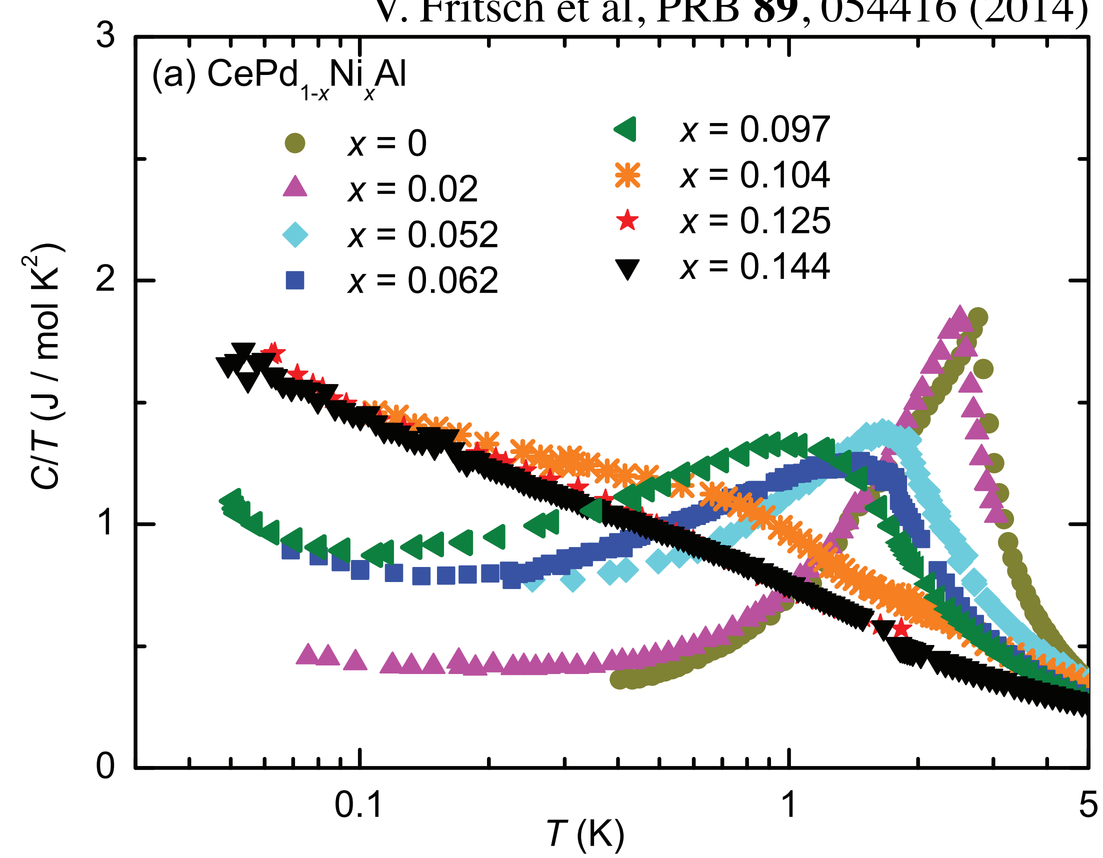
CePdAl

Paramagnetic

Ordered

-ve Pressure leads to AFM QCP

V. Fritsch et al, PRB **89**, 054416 (2014)



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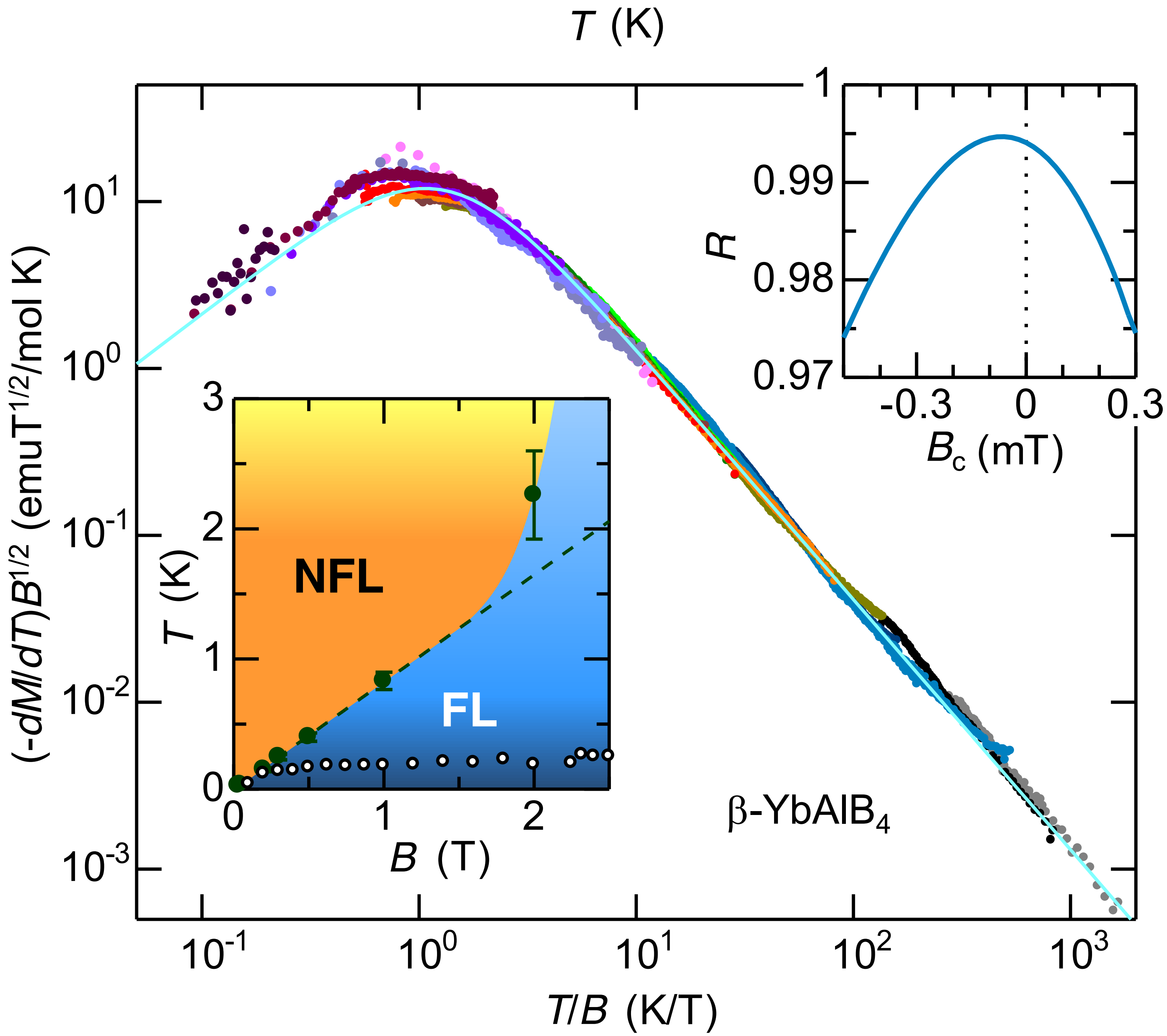
2. Intrinsically Quantum Critical. β-$YbAlB_4$



Yosuke Matsumoto, S. Nakatsuji et al (2010).

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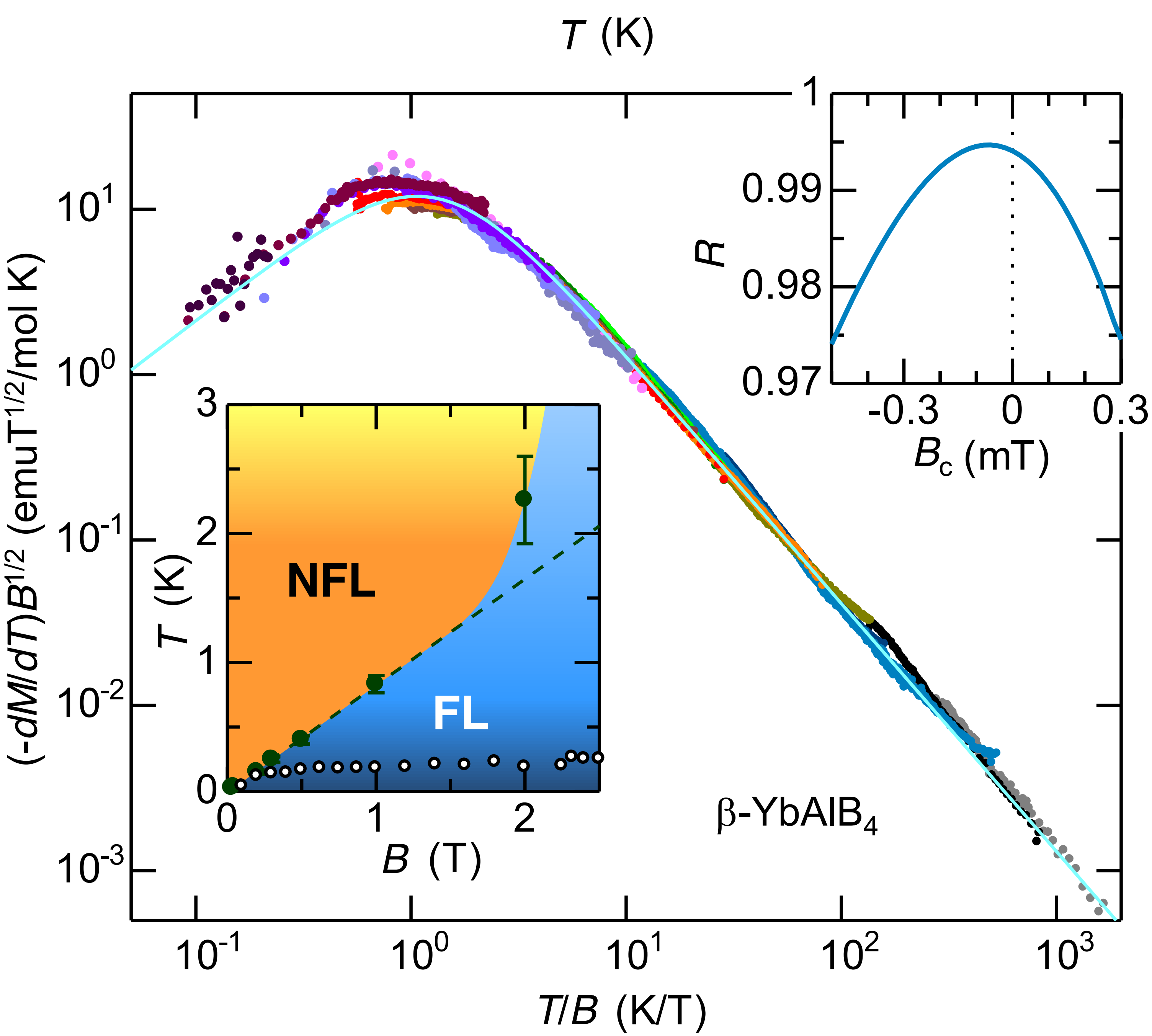

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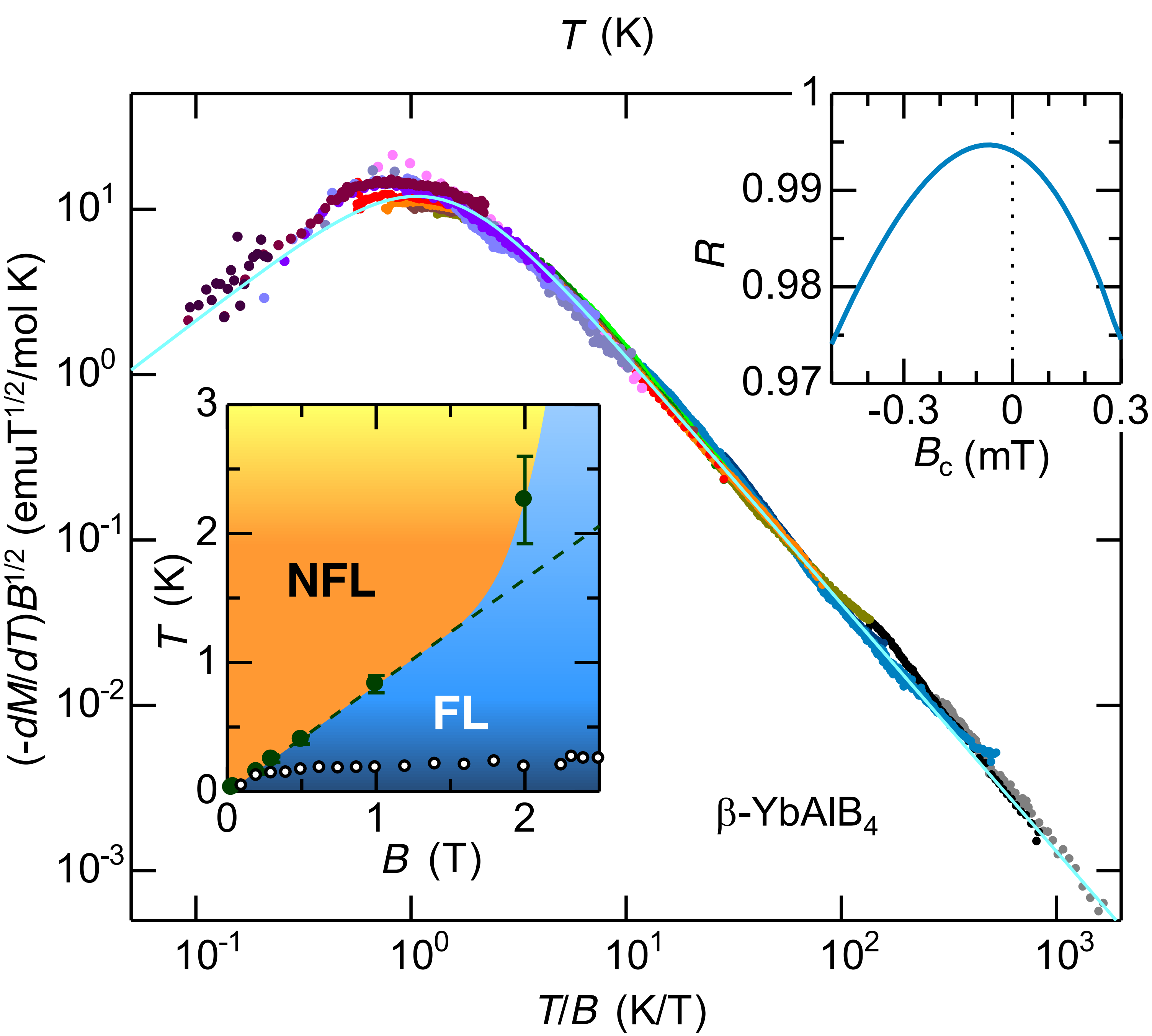

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$$B_c = -0.1 \pm 0.1\text{mT}$$

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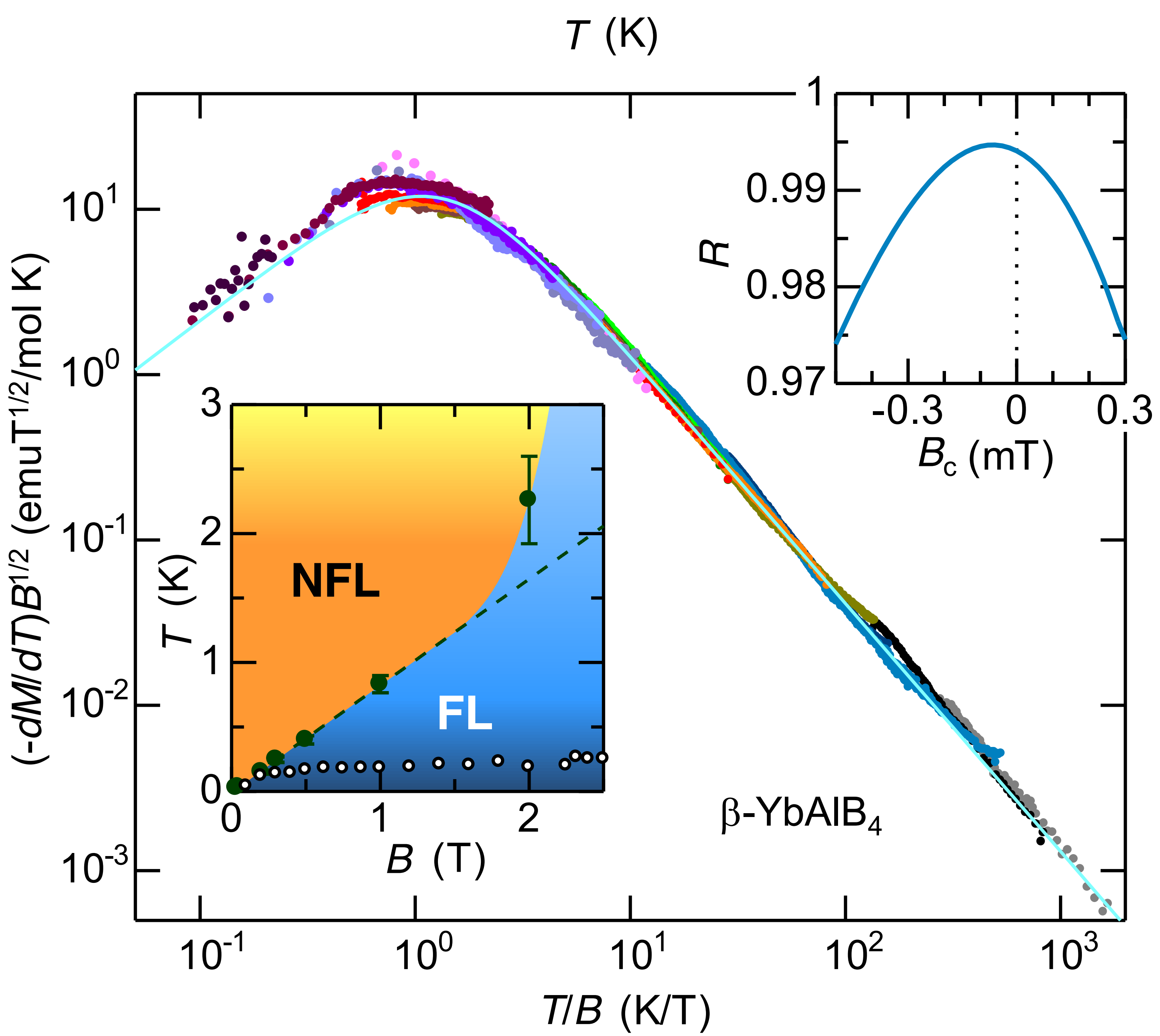

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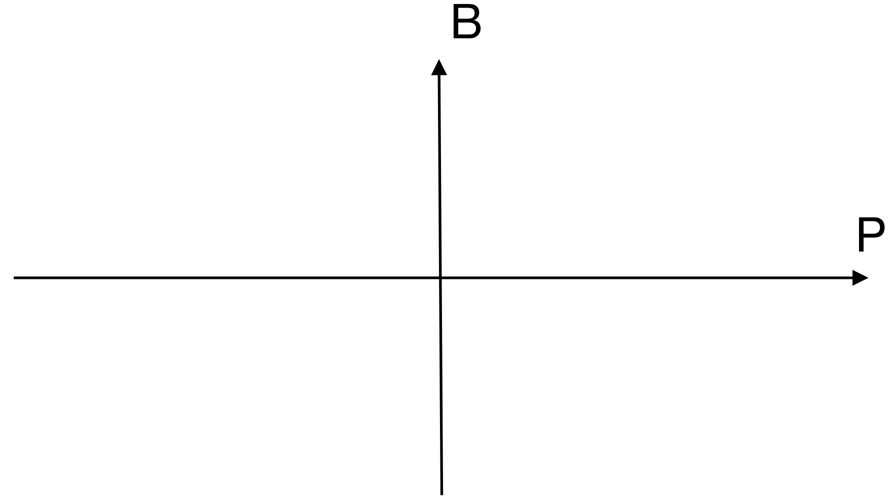

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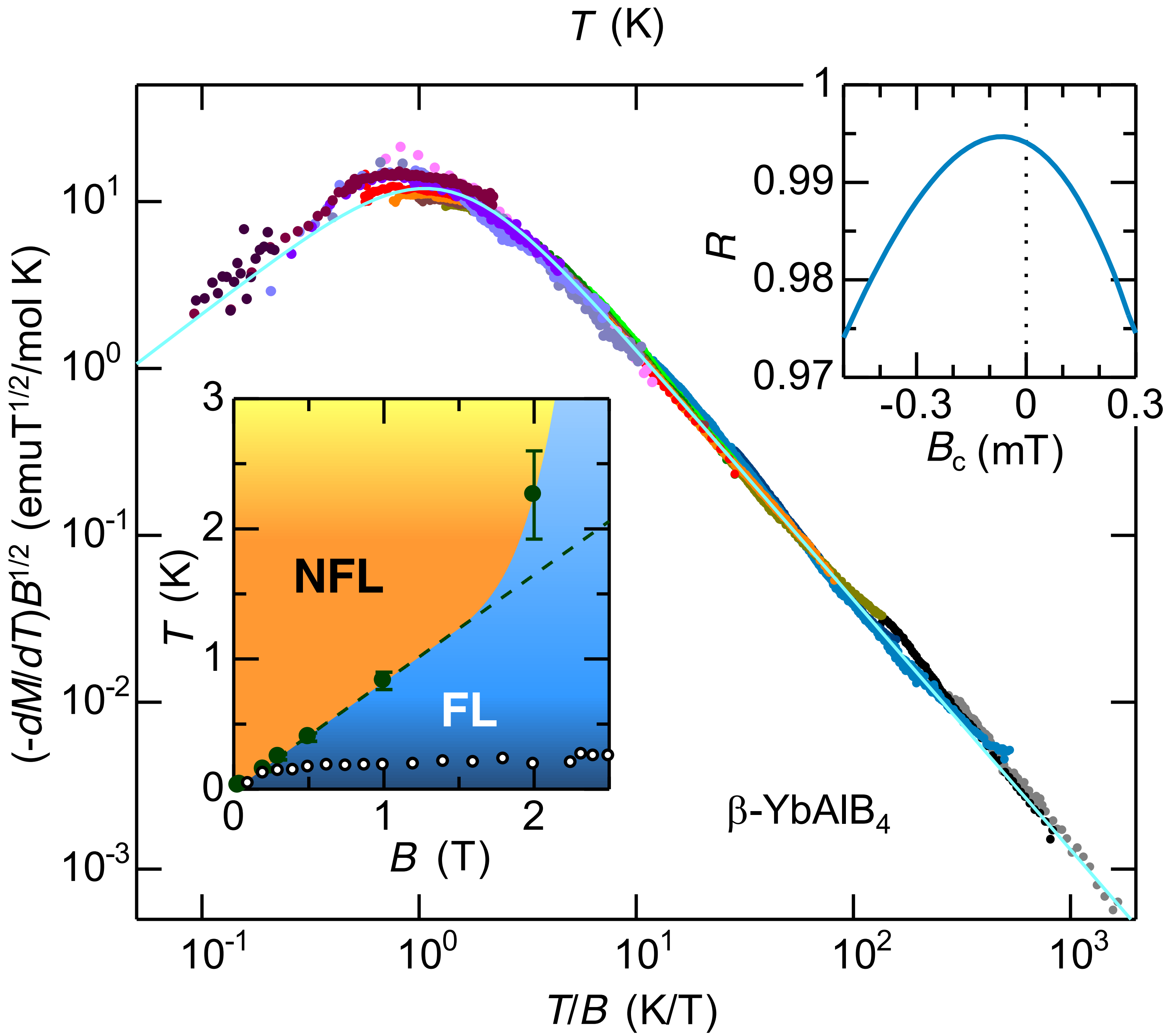

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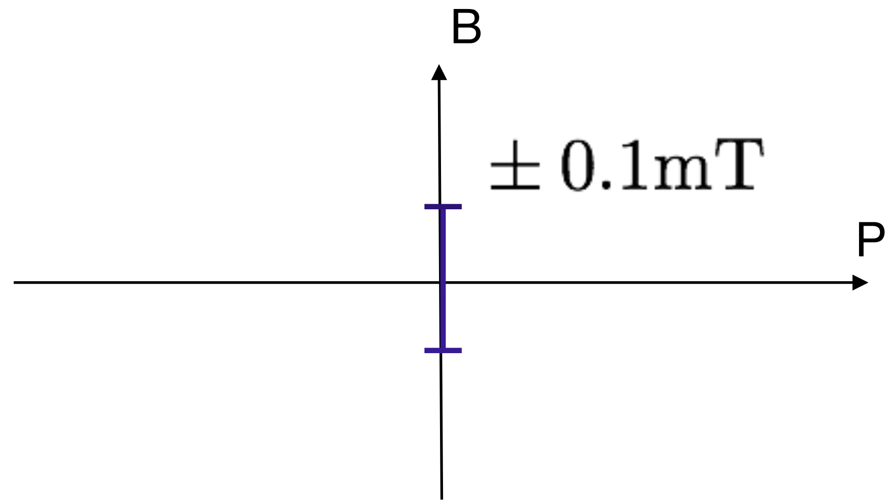

$\pm 0.1\mathrm{mT}$

Yosuke Matsumoto, S. Nakatsuji et al (2010).

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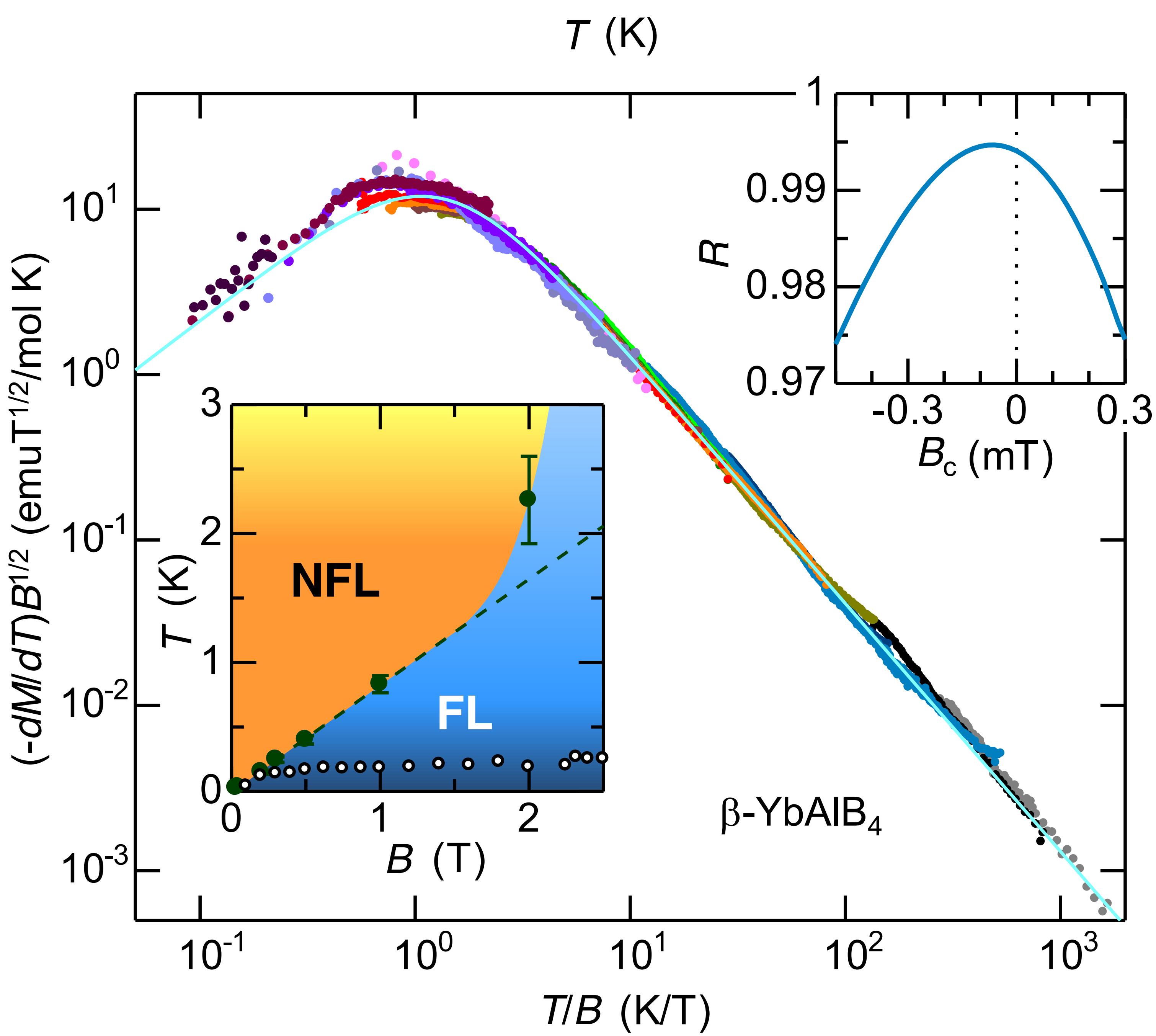

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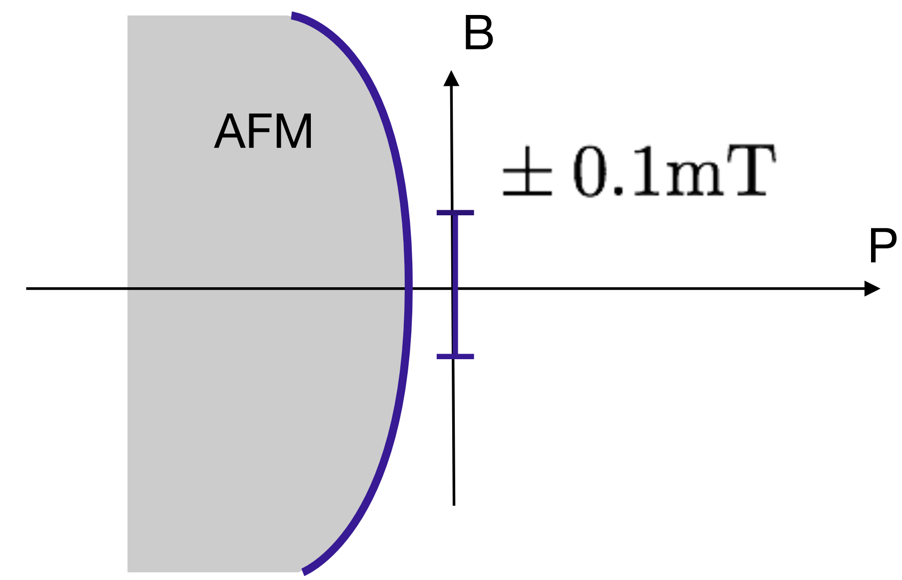

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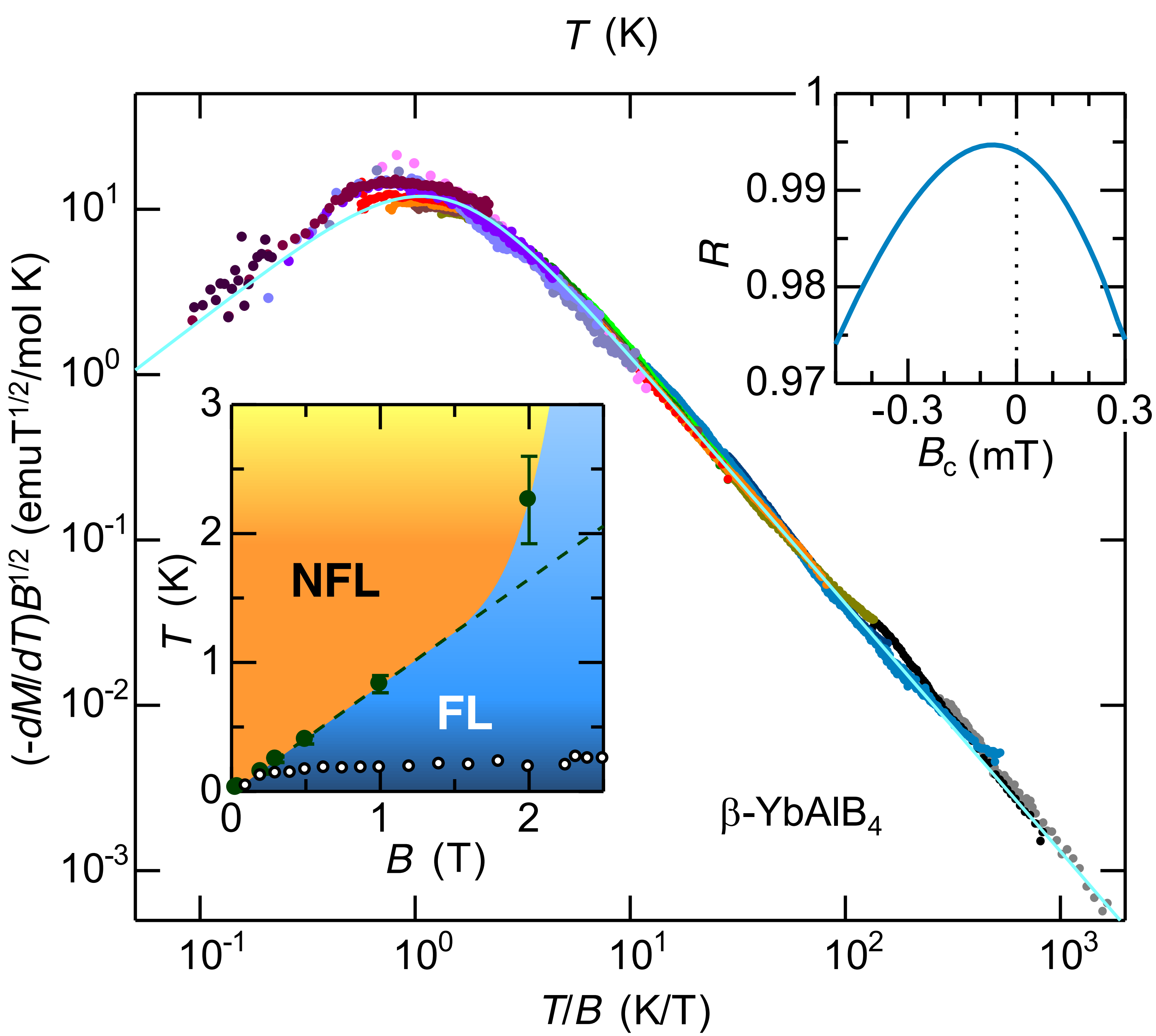

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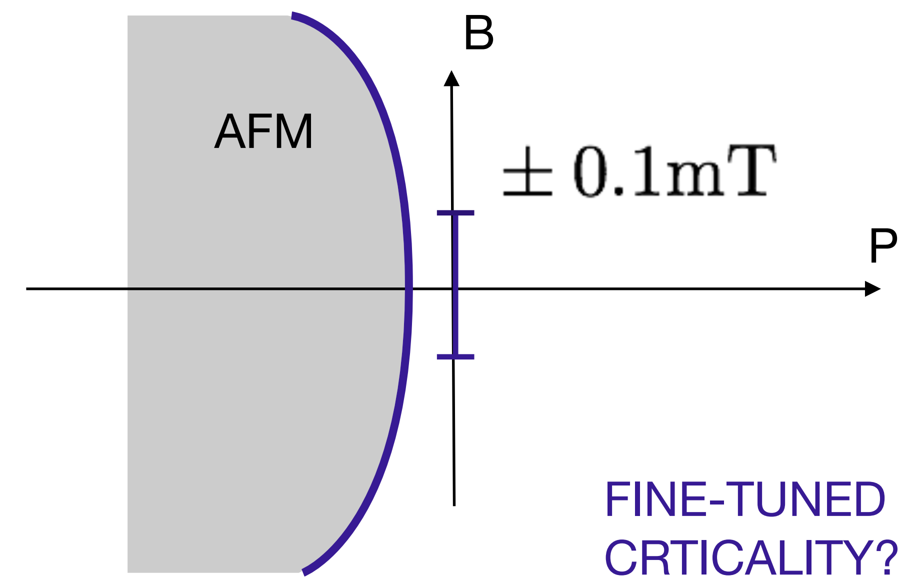

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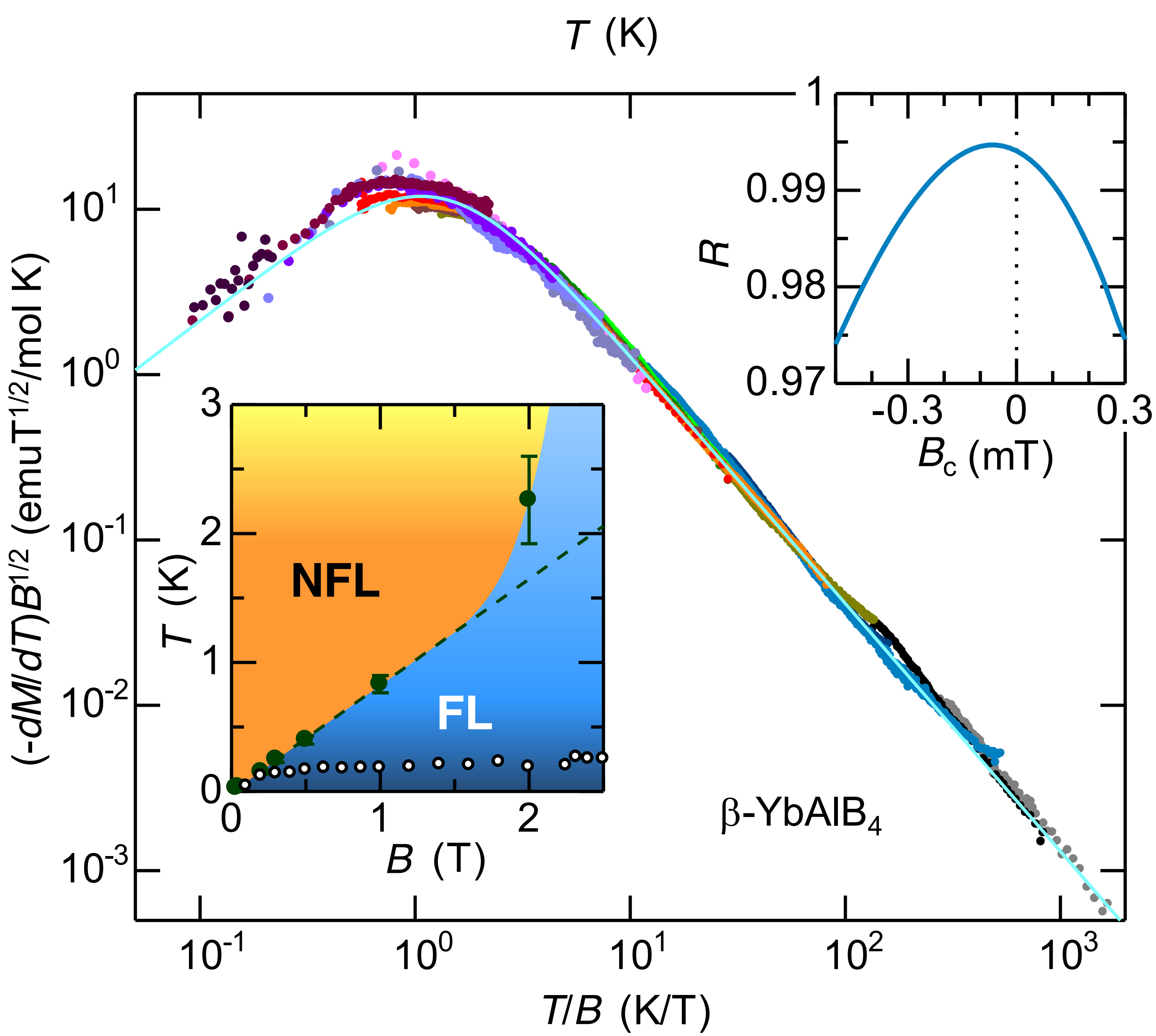

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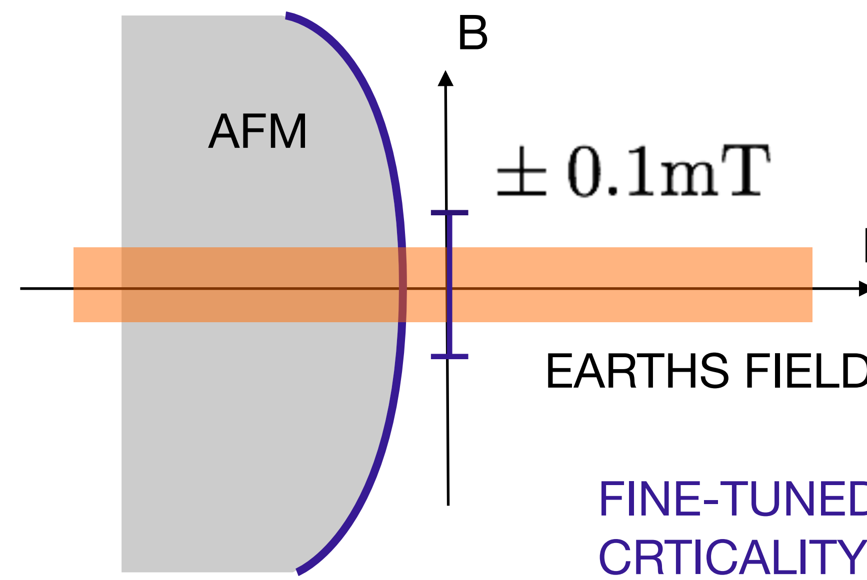

FINE-TUNED
CRTICALITY?

Yosuke Matsumoto, S. Nakatsuji et al (2010).

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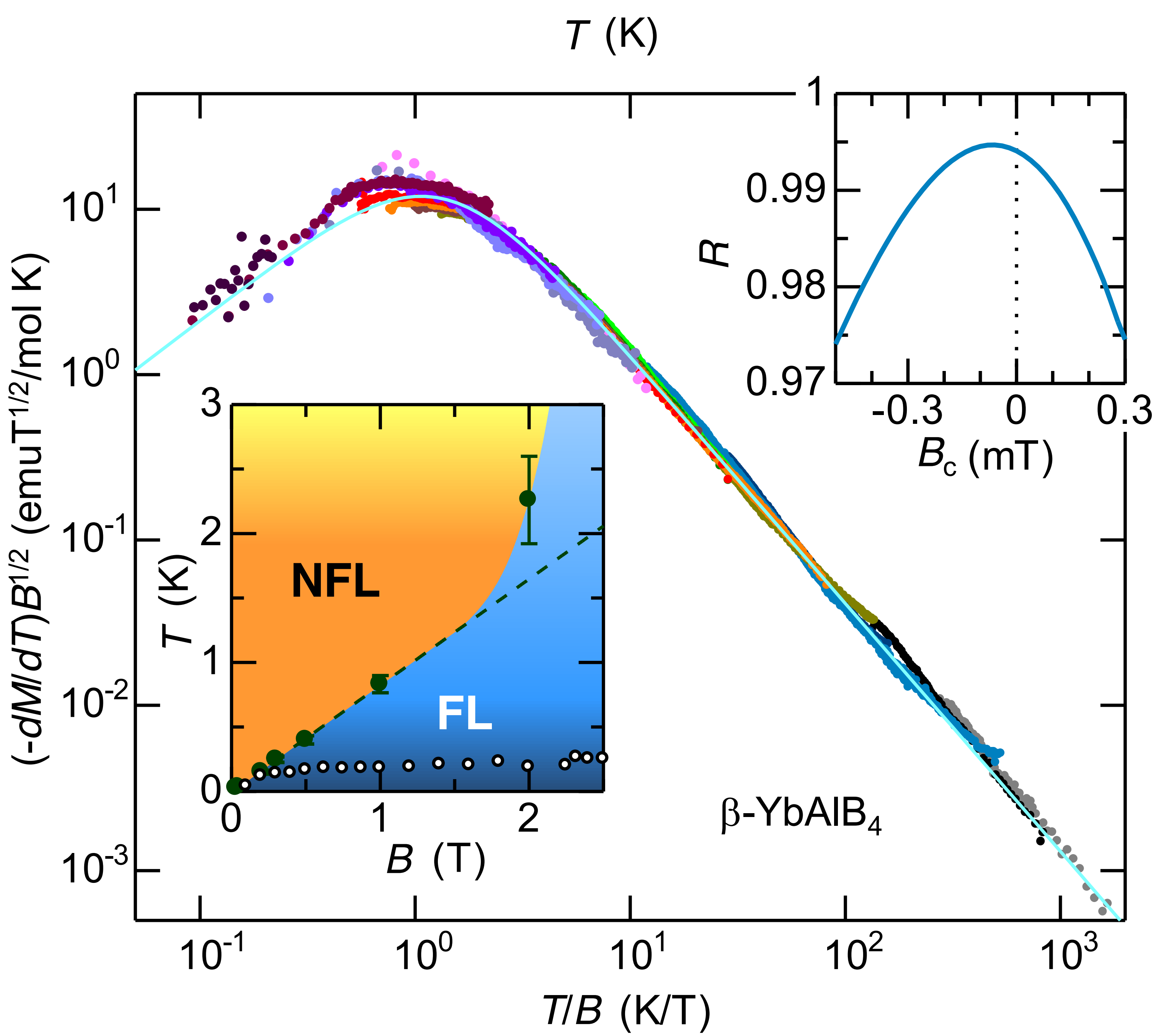

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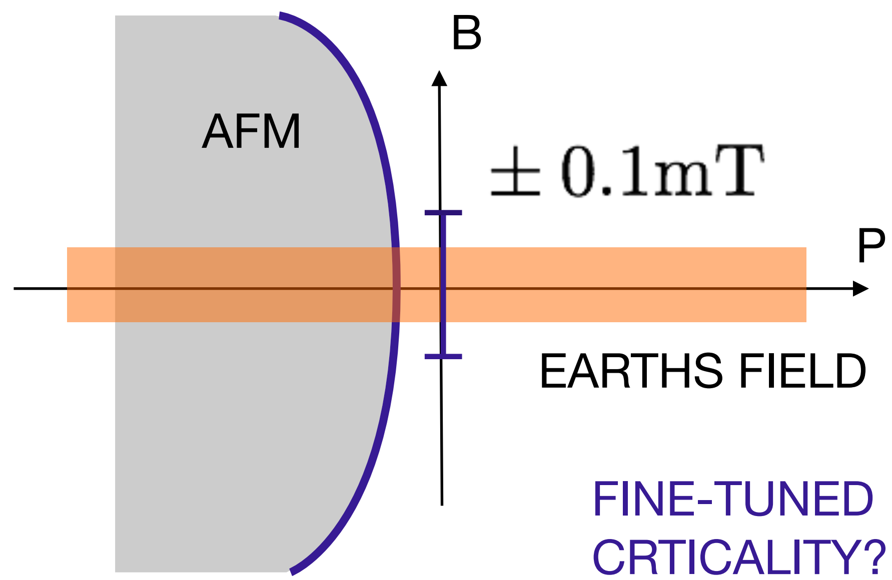

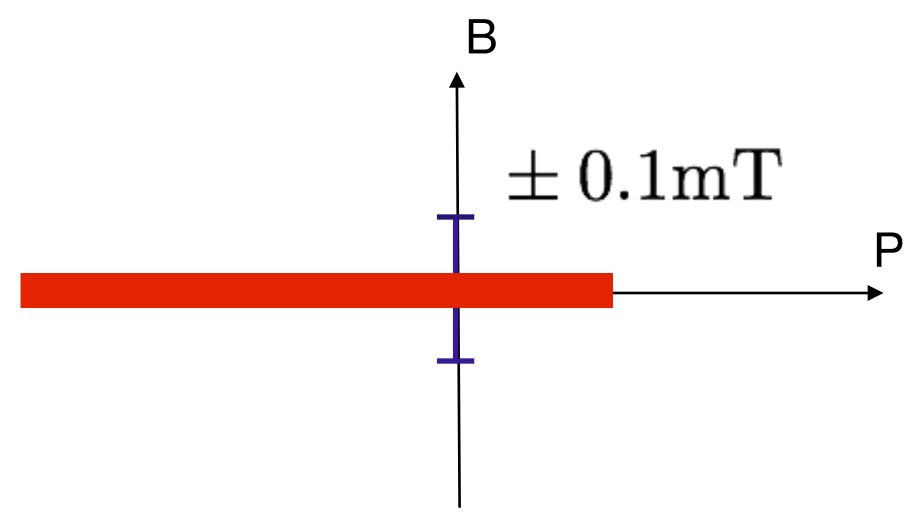

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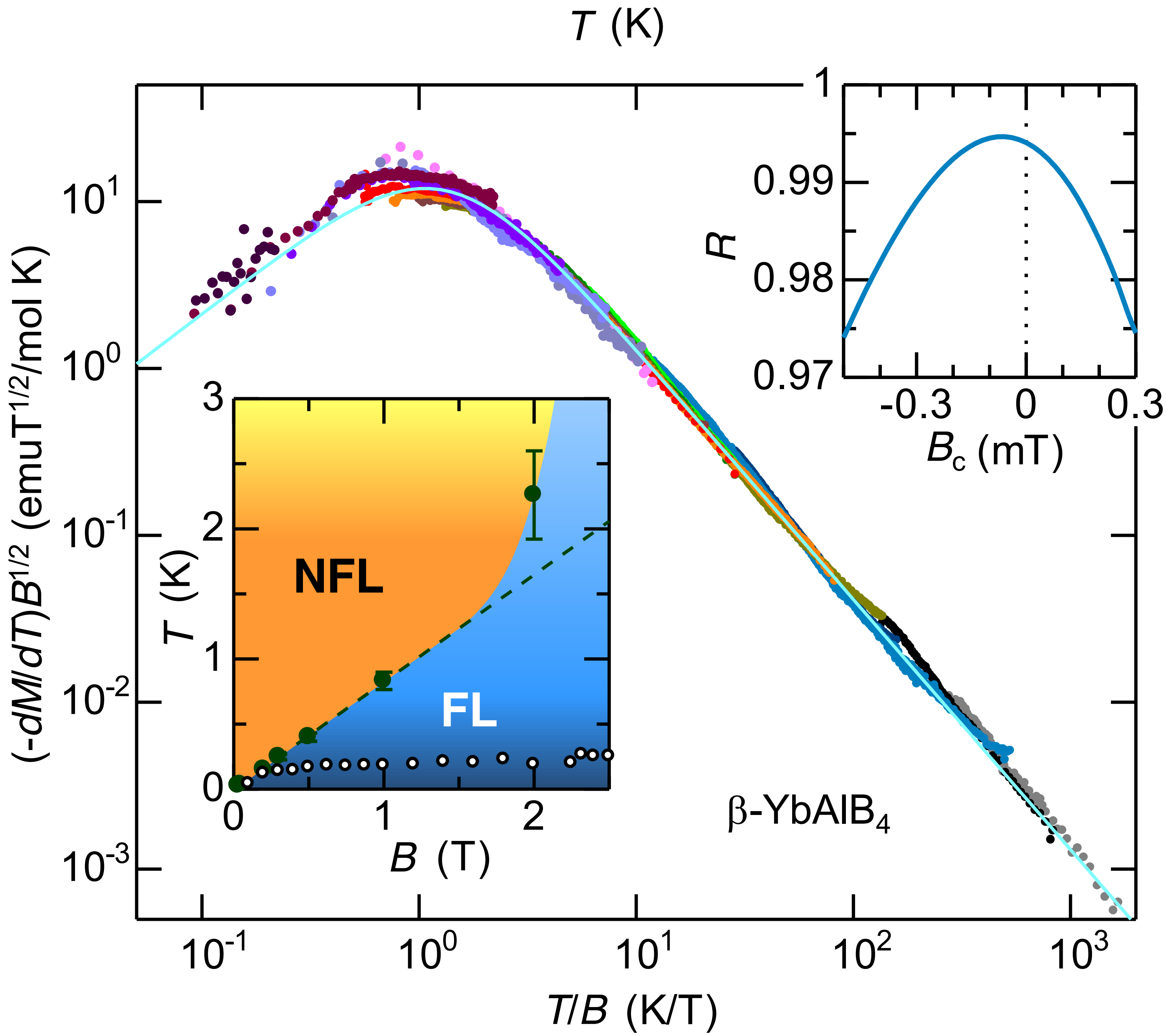

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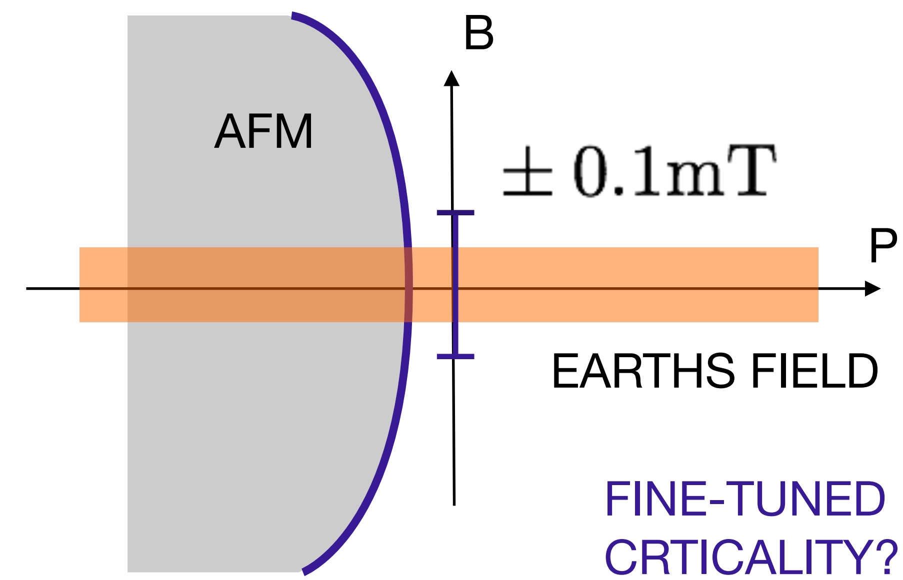

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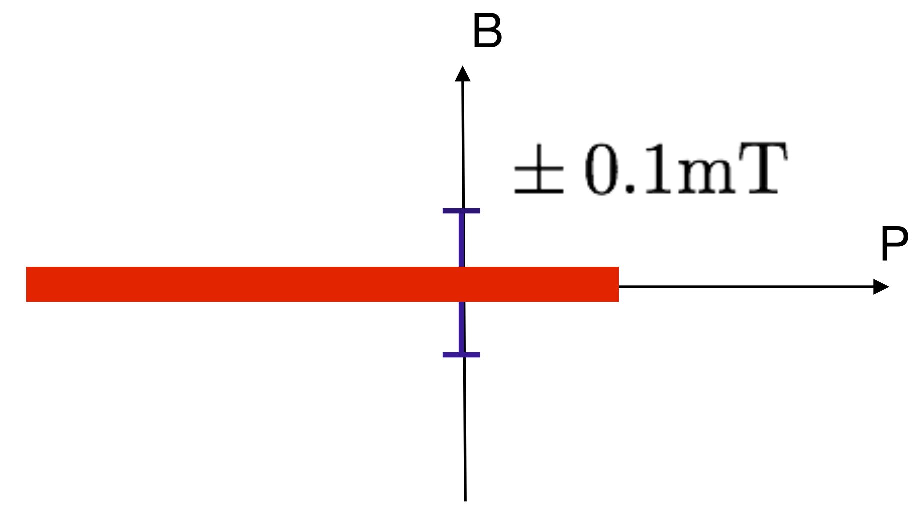

LINE OF FIXED POINTS?

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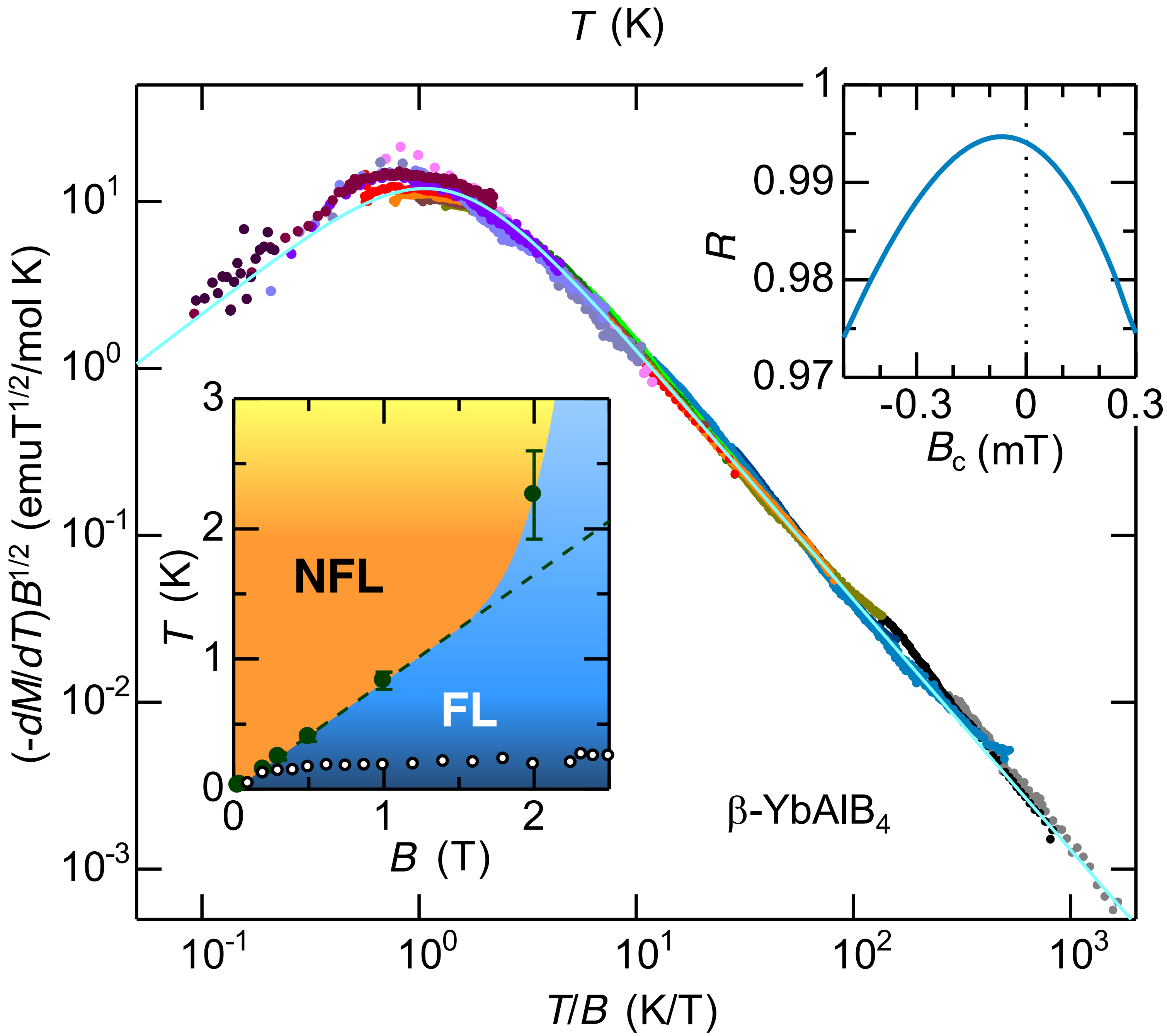

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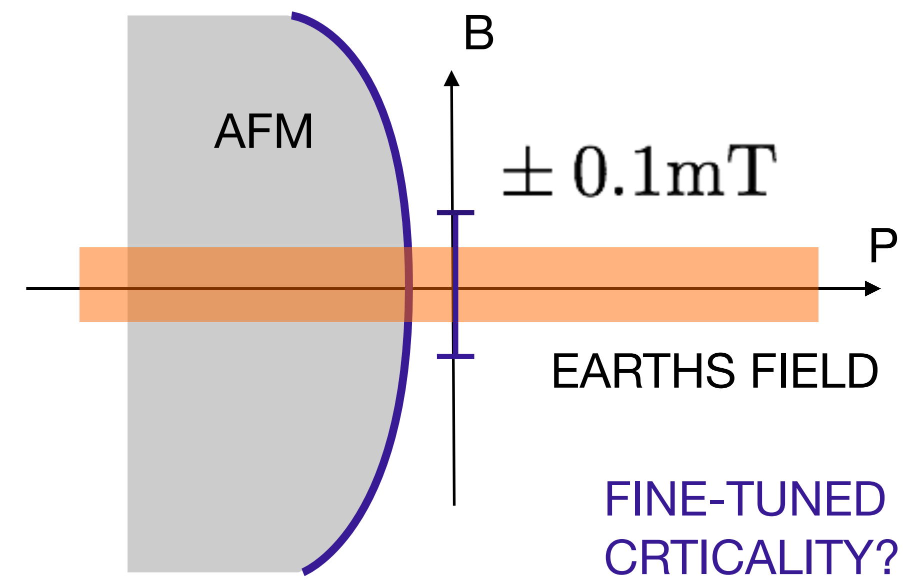

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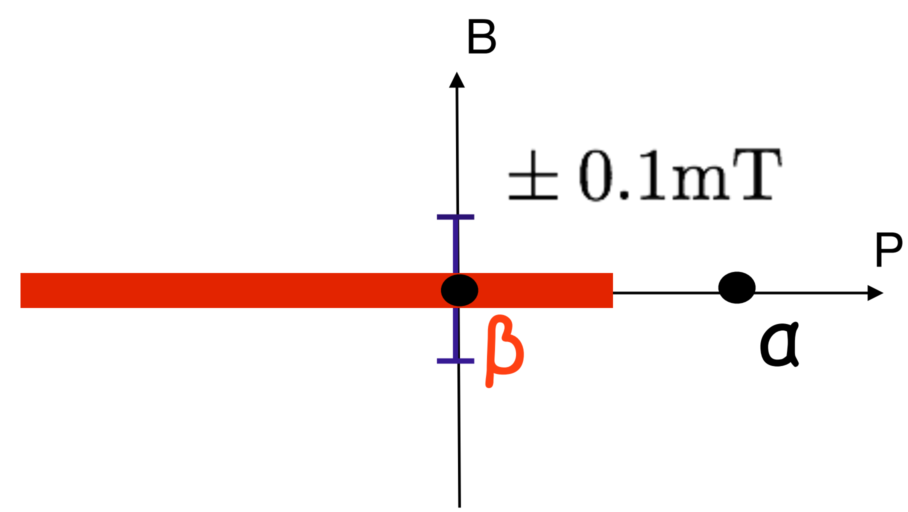

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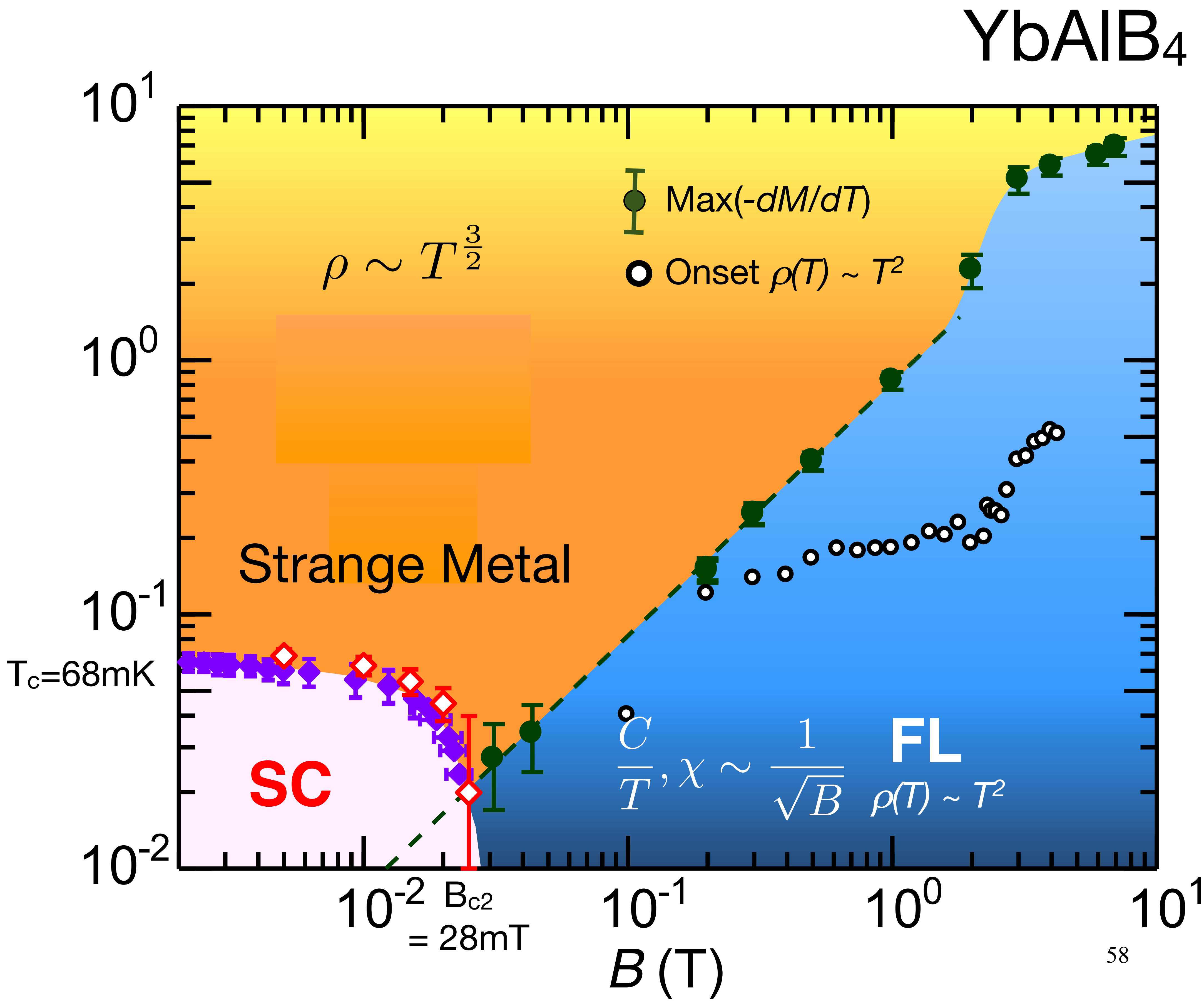


YbAlB$_4$
Max(-dM/dT)
Onset $\rho(T) \sim T^2$
$\rho \sim T^{\frac{3}{2}}$
Strange Metal
SC
FL
$\frac{C}{T}, \chi \sim \frac{1}{\sqrt{B}}$
$\rho(T) \sim T^2$
T$_c$=68mK
B$_{c2}$ = 28mT
B (T)
10^{-2}
10^{-1}
10^{0}
10^{1}

Open Challenges.

- Heavy Fermion QCPs: a new kind of quantum criticality demands a new kind of understanding.
- Needed: Explanation of universality of

$C/T \sim \mathrm{Log}(T_0/T)$, $\rho \sim T^{1+\alpha}$

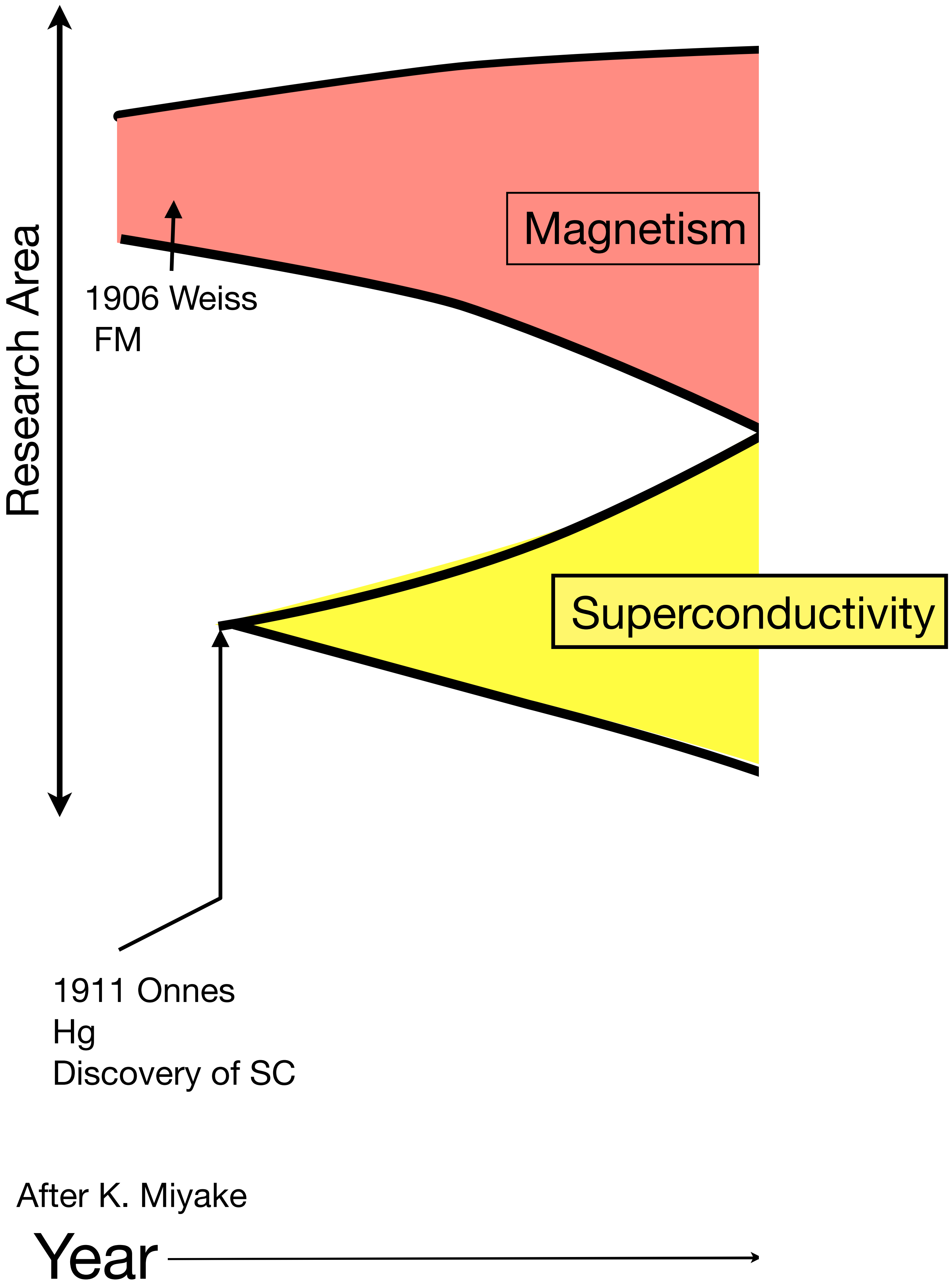
- Co-existence heavy fermions & LM AFM = Two fluid behavior?
- Role of Frustration?

The Physics of Heavy Fermion Superconductivity

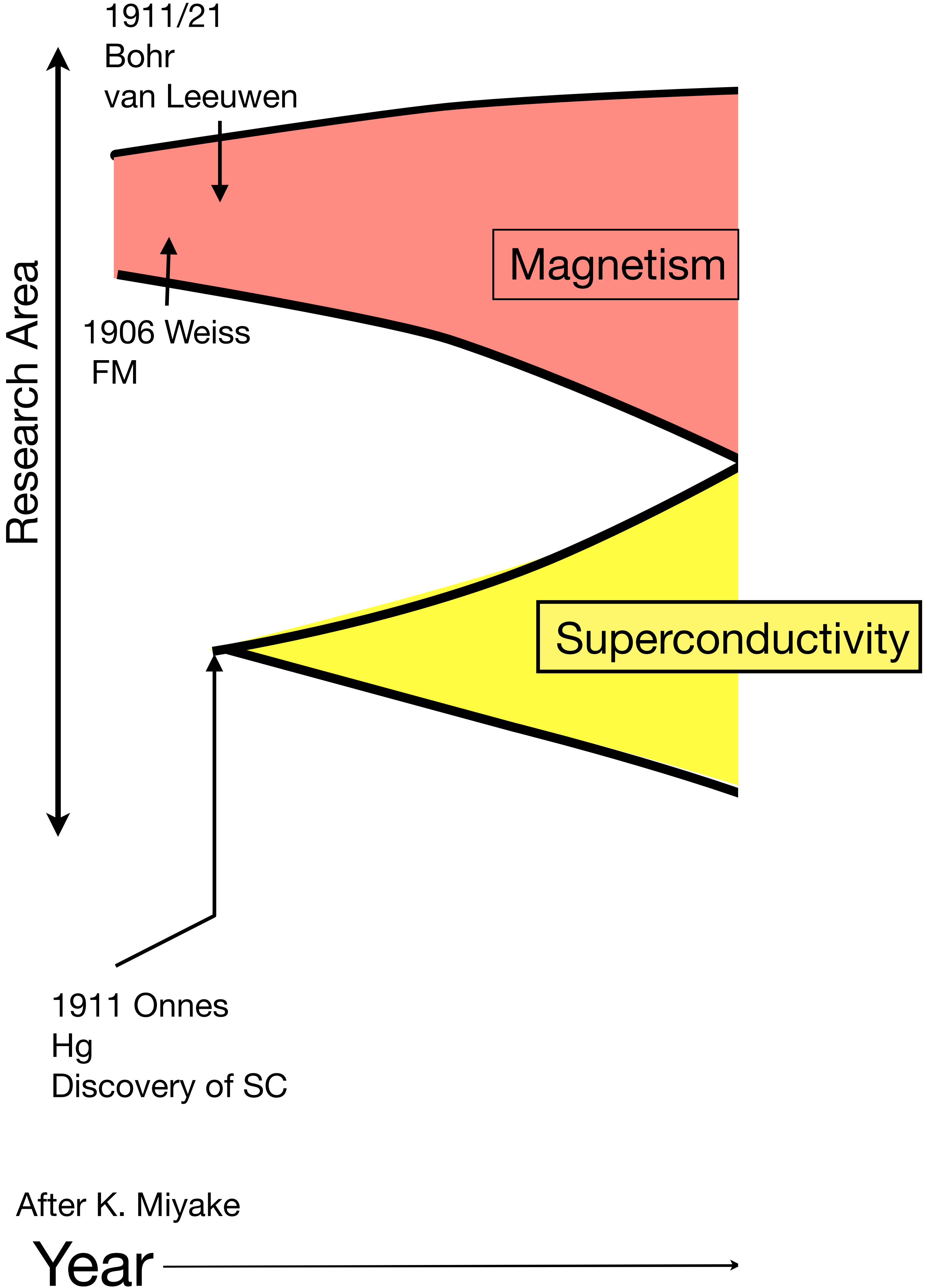
1. Magnetism and Superconductivity: a remarkable convergence.
2. Glue vs Fabric: Good, Bad and Ugly Heavy Fermion Superconductors.
3. The 115 paradox.
4. Composite pairing hypothesis.

Magnetism and Superconductivity:
A remarkable convergence

Magnetism and Superconductivity

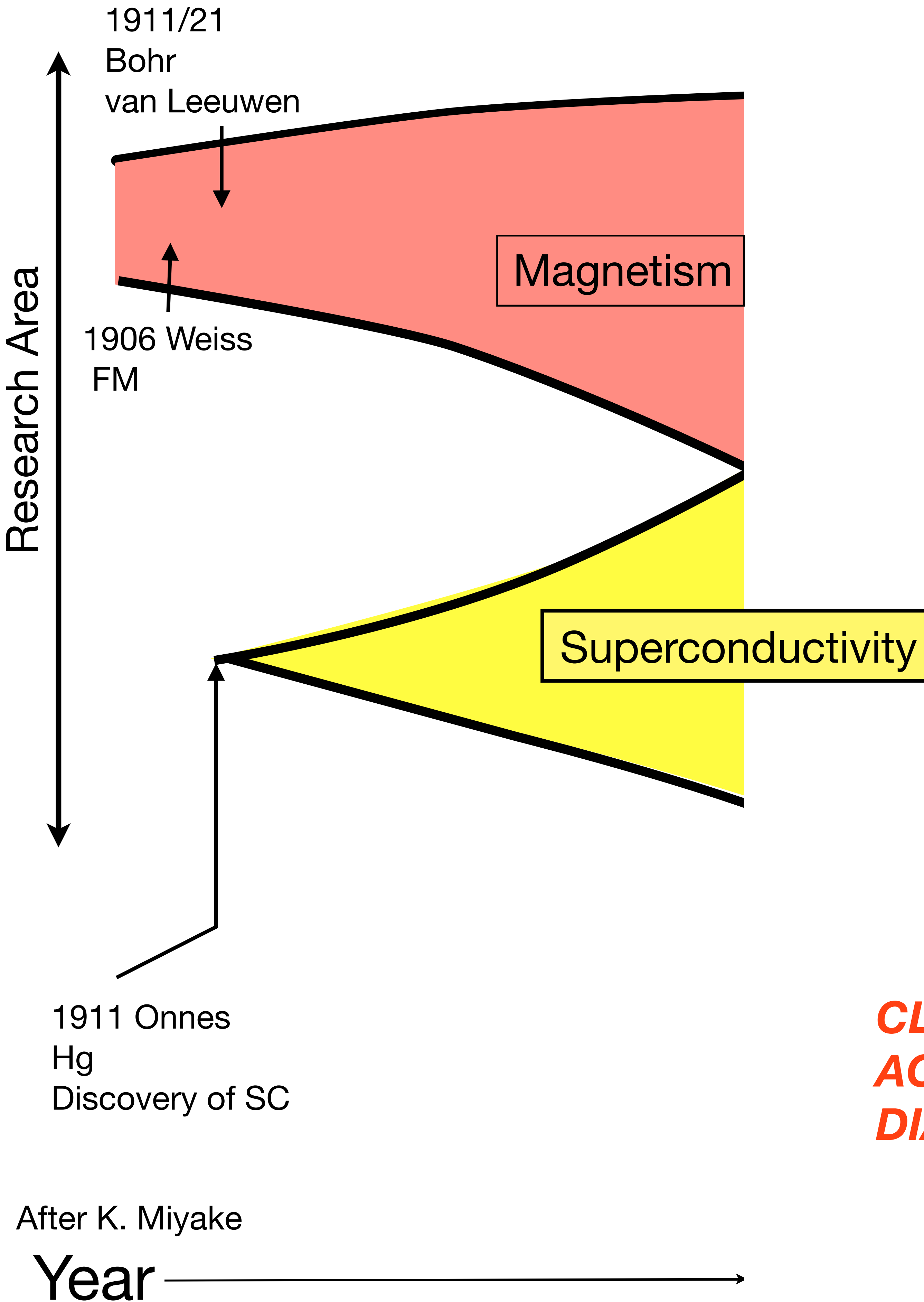


Magnetism and Superconductivity



Bohr-van Leeuwen Theorem (1911,1921)

Magnetism and Superconductivity



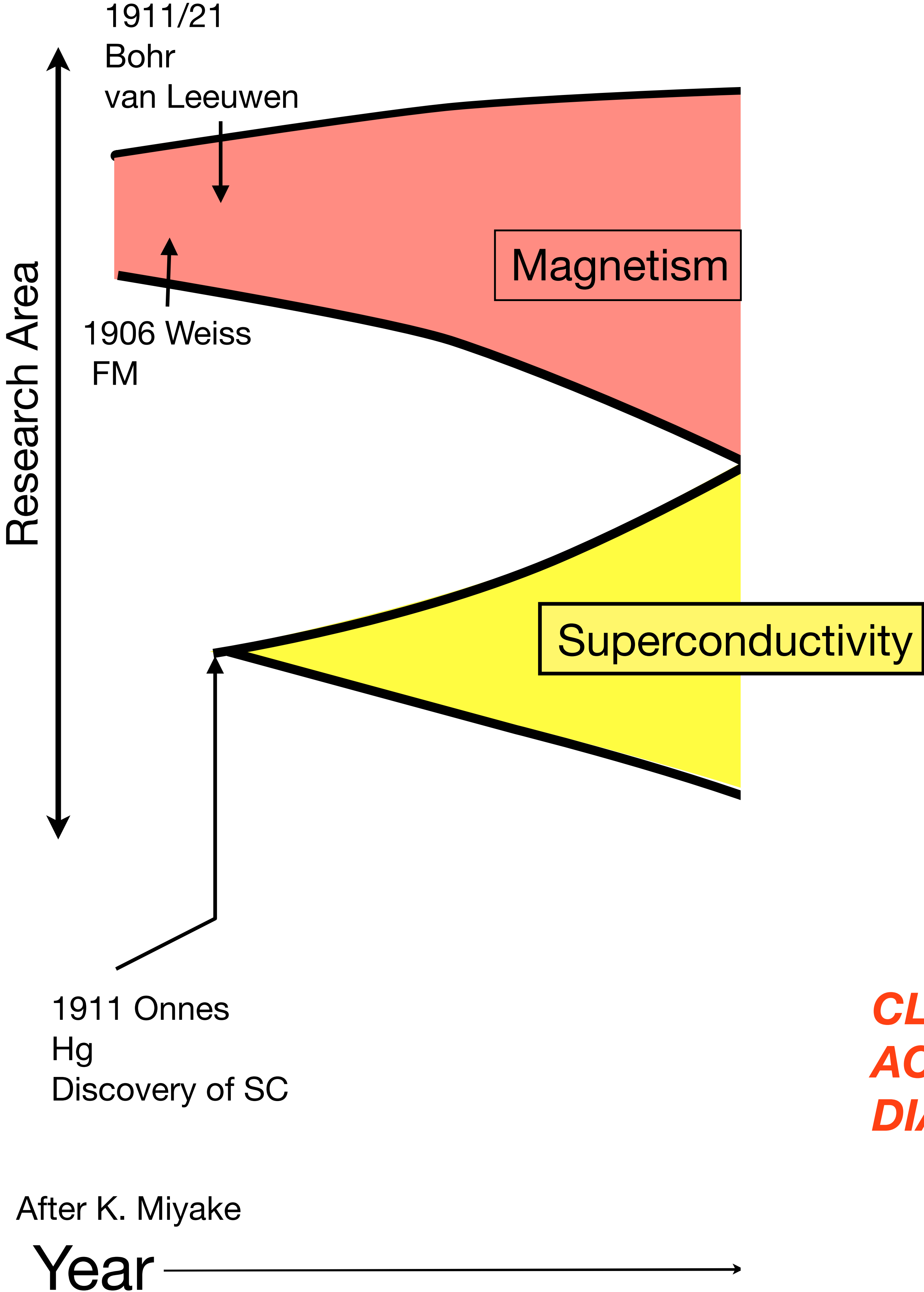
Bohr-van Leeuwen Theorem (1911,1921)

$$p' = p - eA$$

$$H[p, A] = H[p', A = 0]$$

CLASSICAL PHYSICS IS UNABLE TO ACCOUNT FOR ANY FORM OF MAGNETISM DIA- FERRO- OR PARA- MAGNETISM.

Magnetism and Superconductivity



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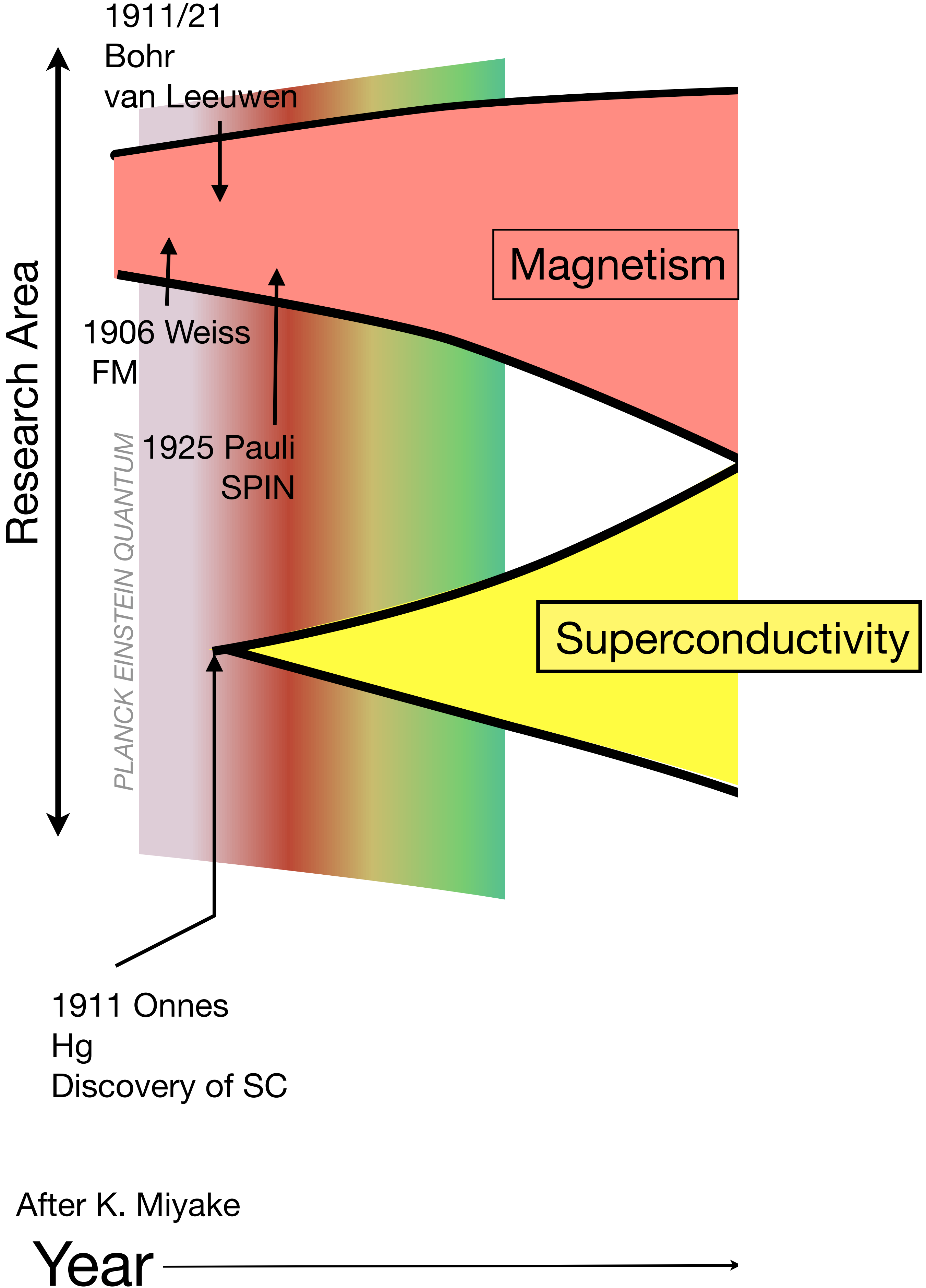
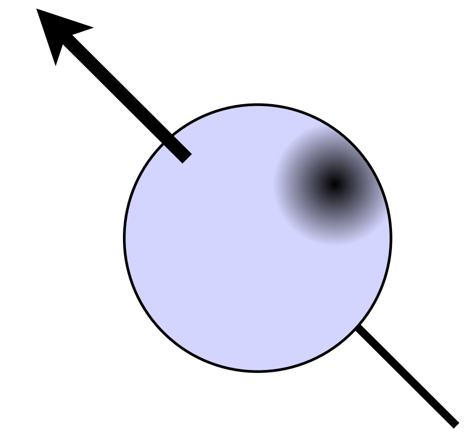
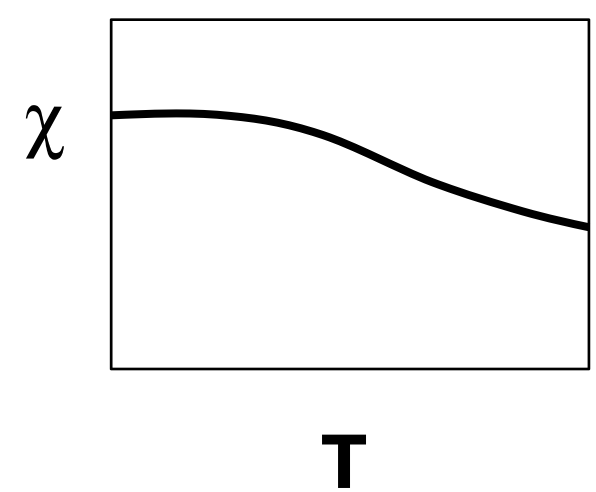


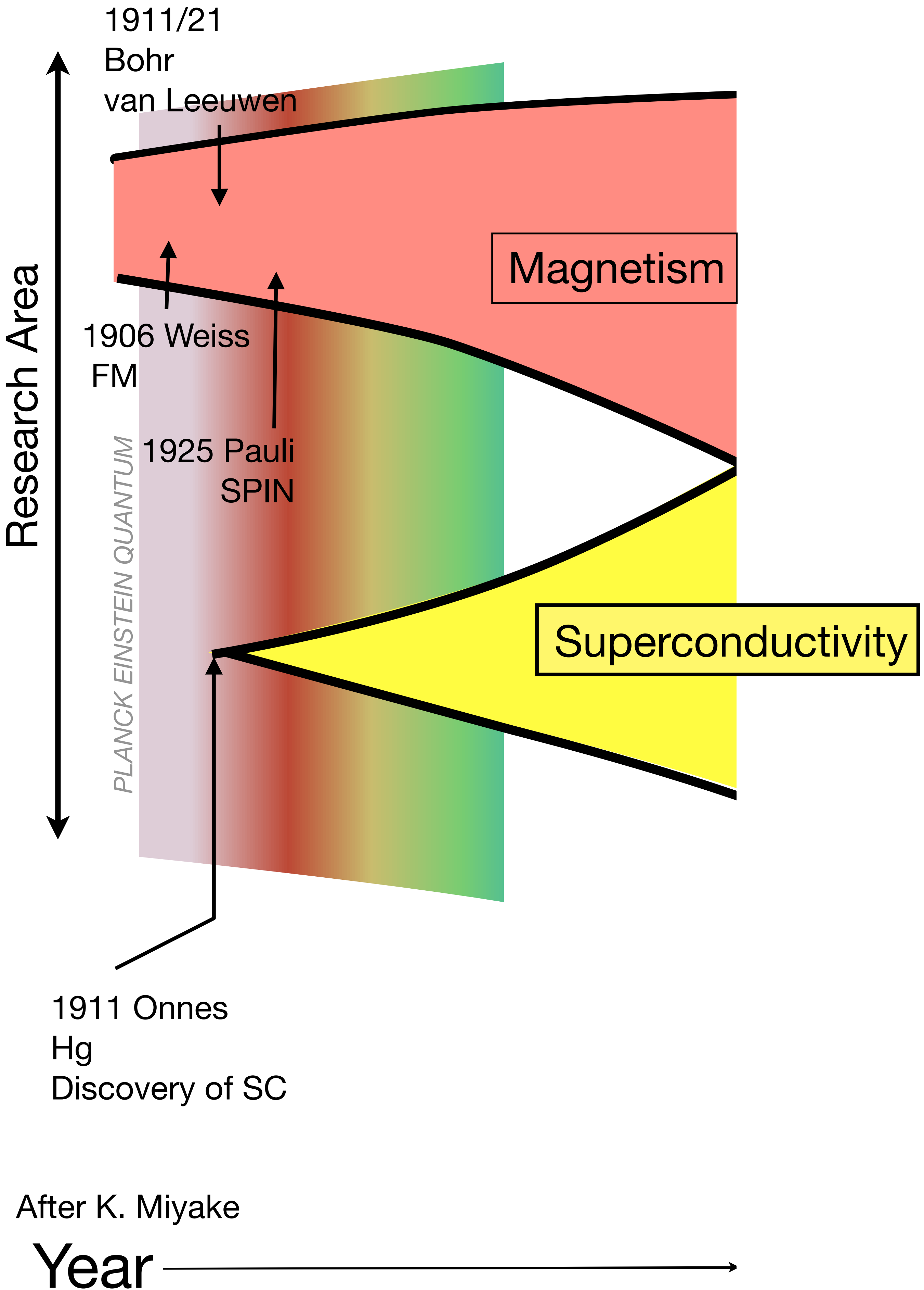
Pauli



spin



Magnetism and Superconductivity



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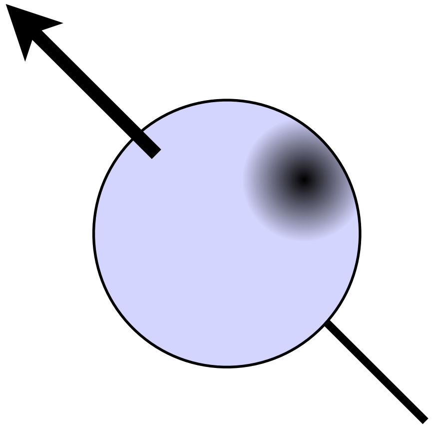

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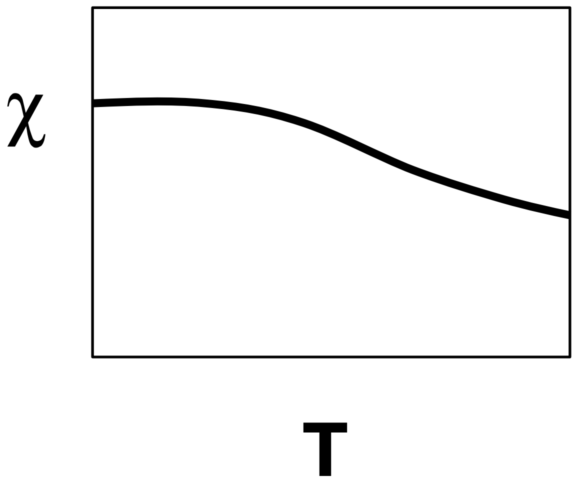

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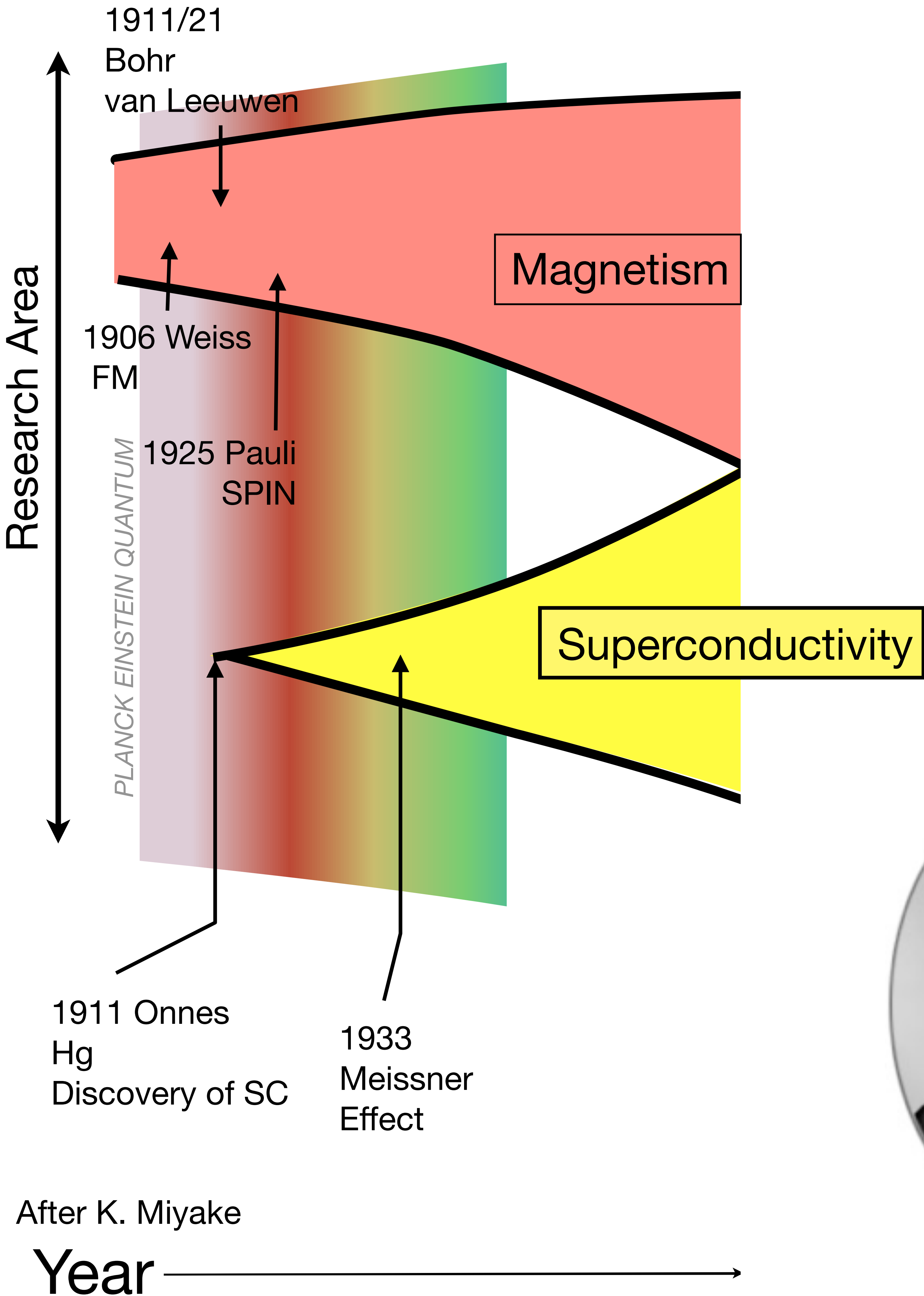

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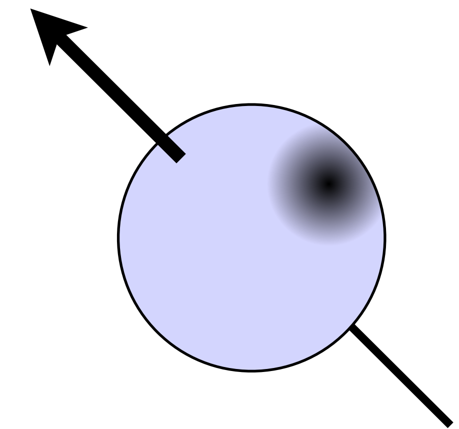

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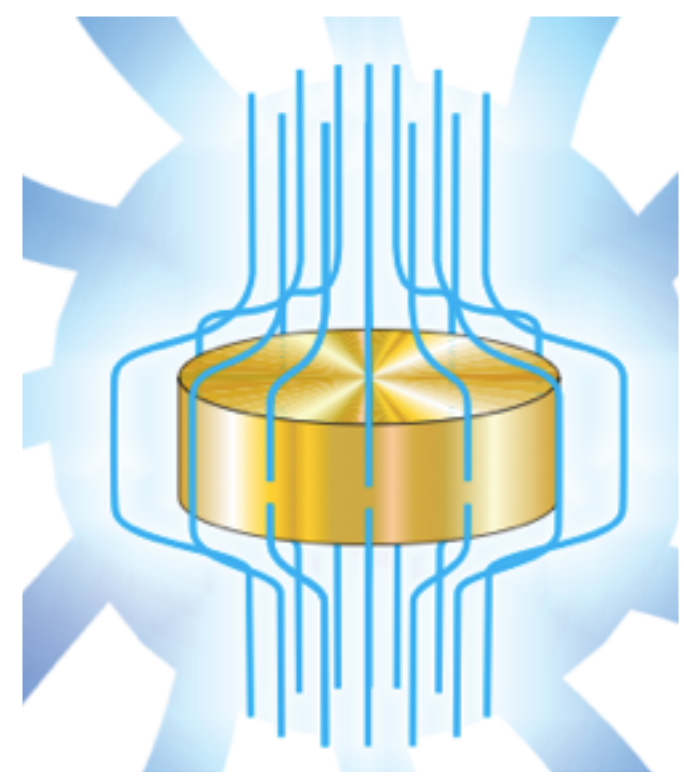

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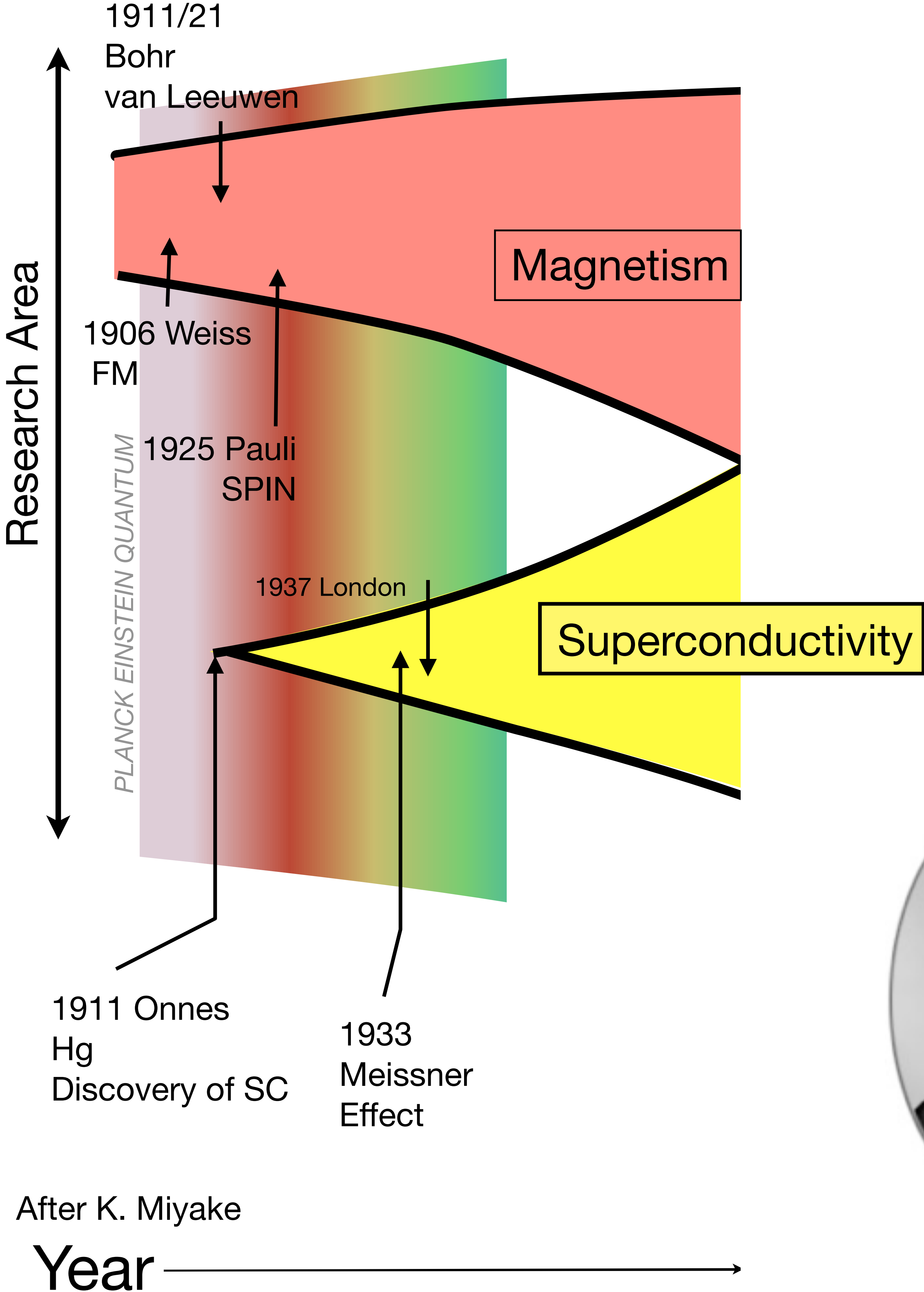
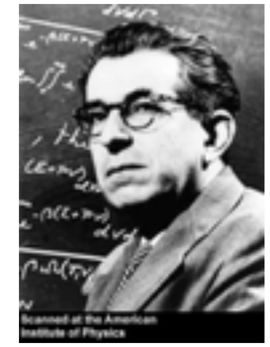
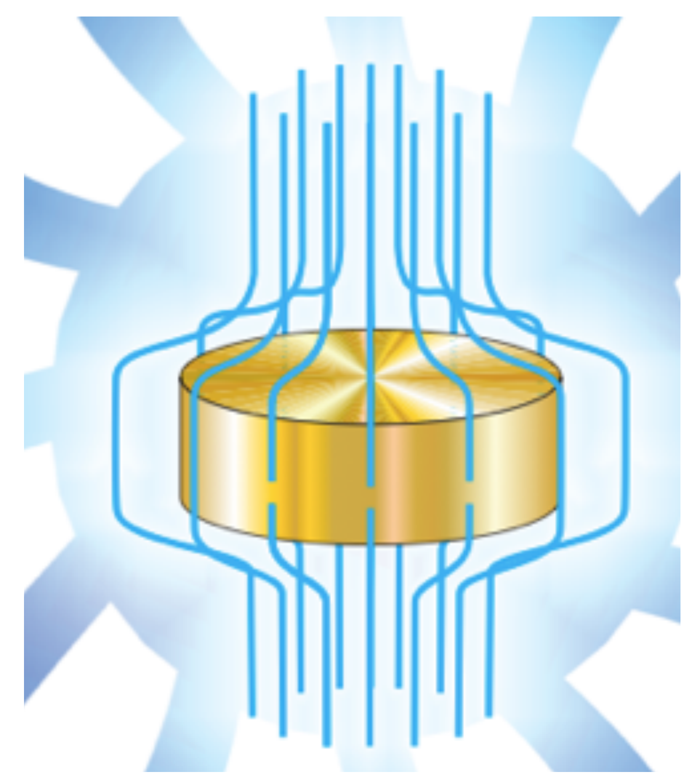




London 1937

Rigidity of wavefunction
-> DIAMAGNETISM

Walther Meissner
(1882-1974)



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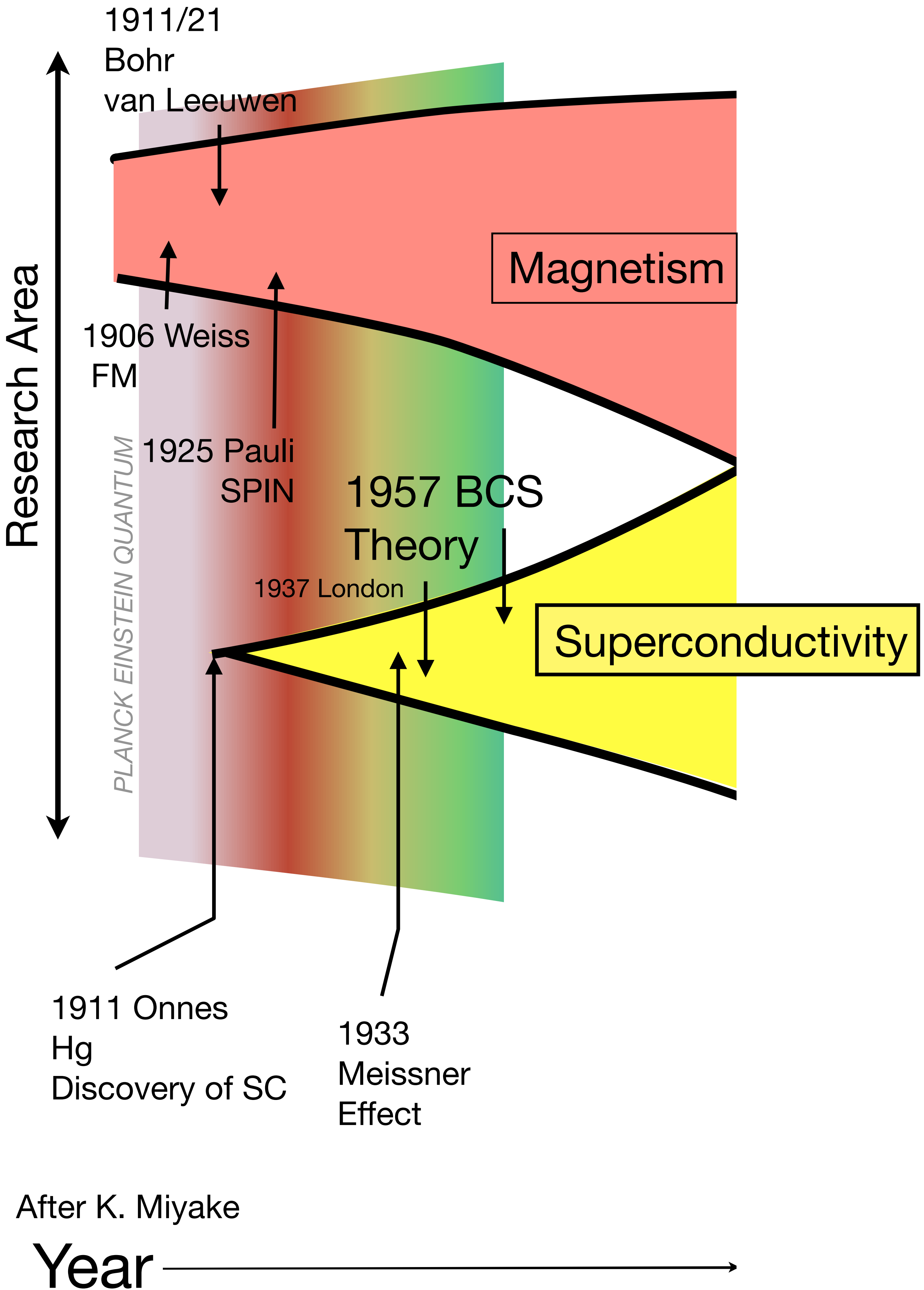

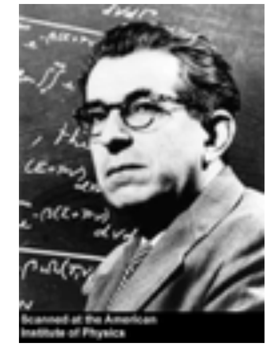

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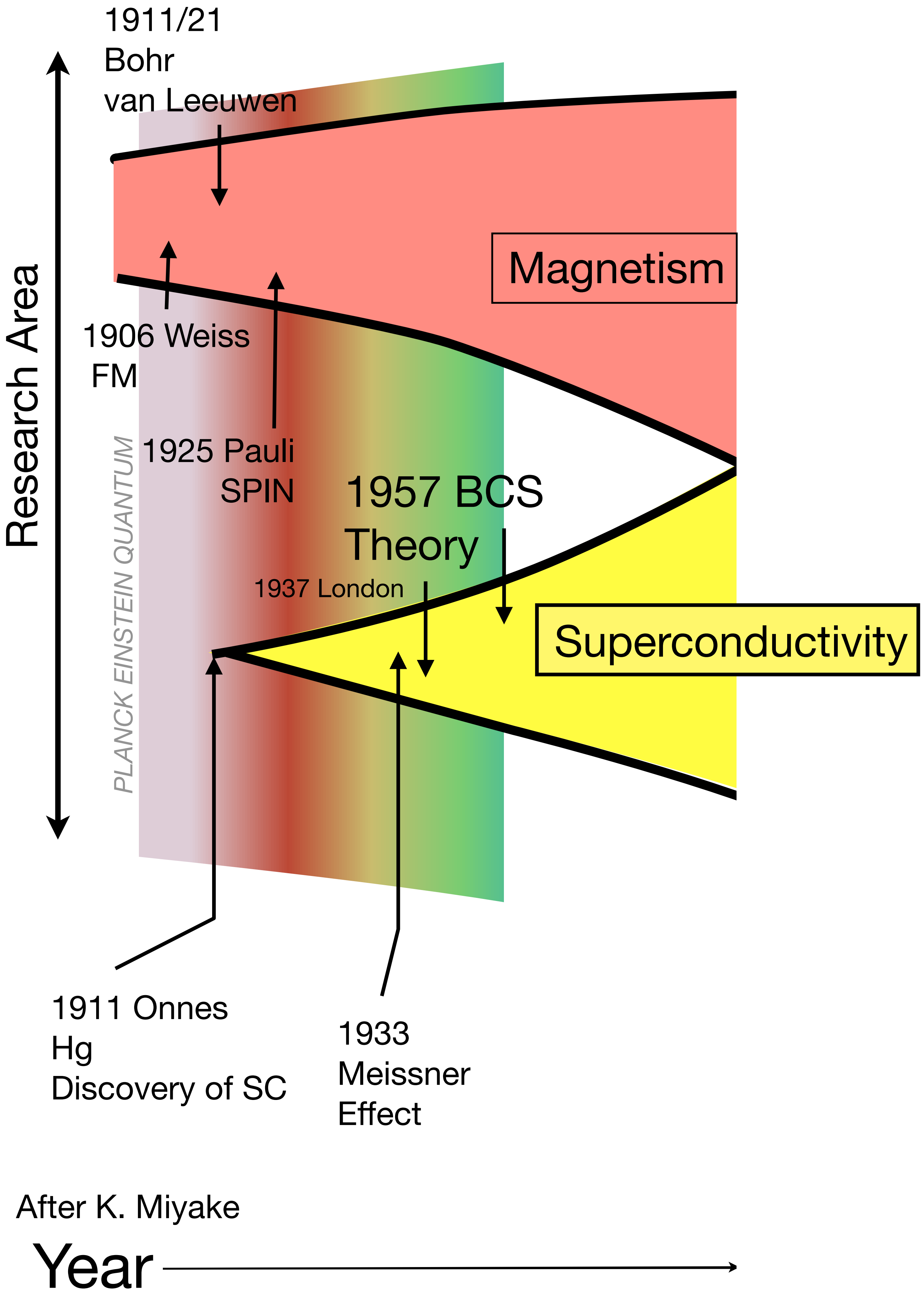
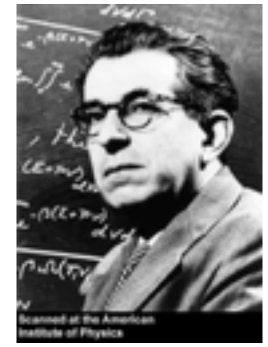
$$|\Psi\rangle = \prod_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}} c^\dagger_{-\mathbf{k}\downarrow} c^\dagger_{\mathbf{k}\uparrow})|0\rangle$$

Magnetism and Superconductivity





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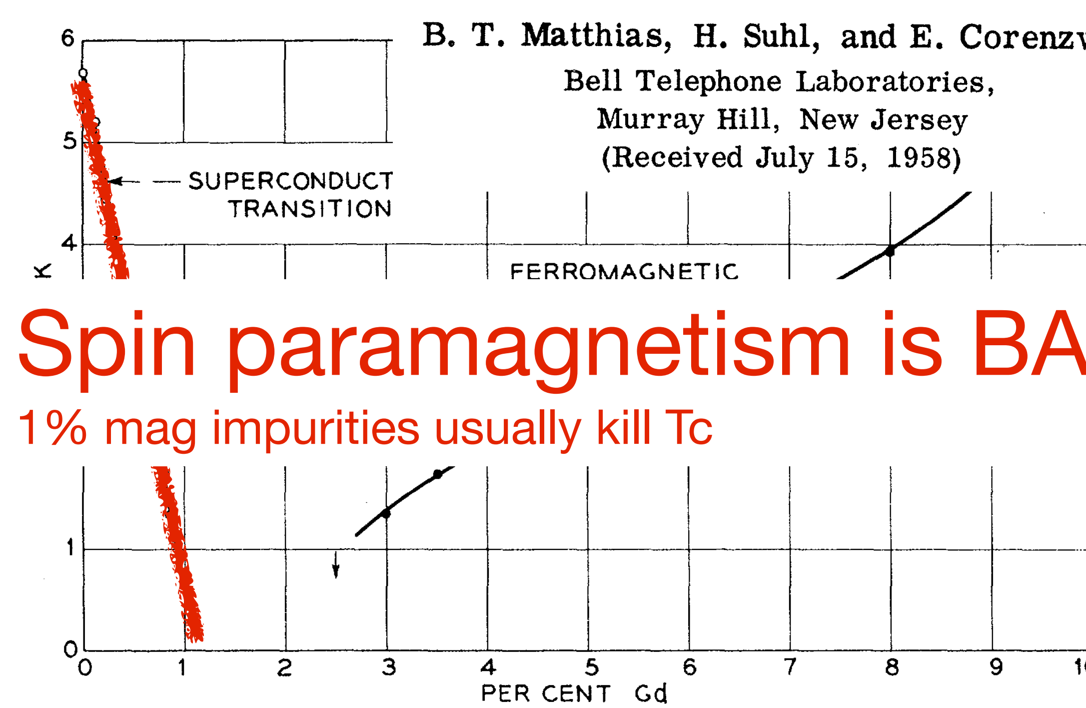
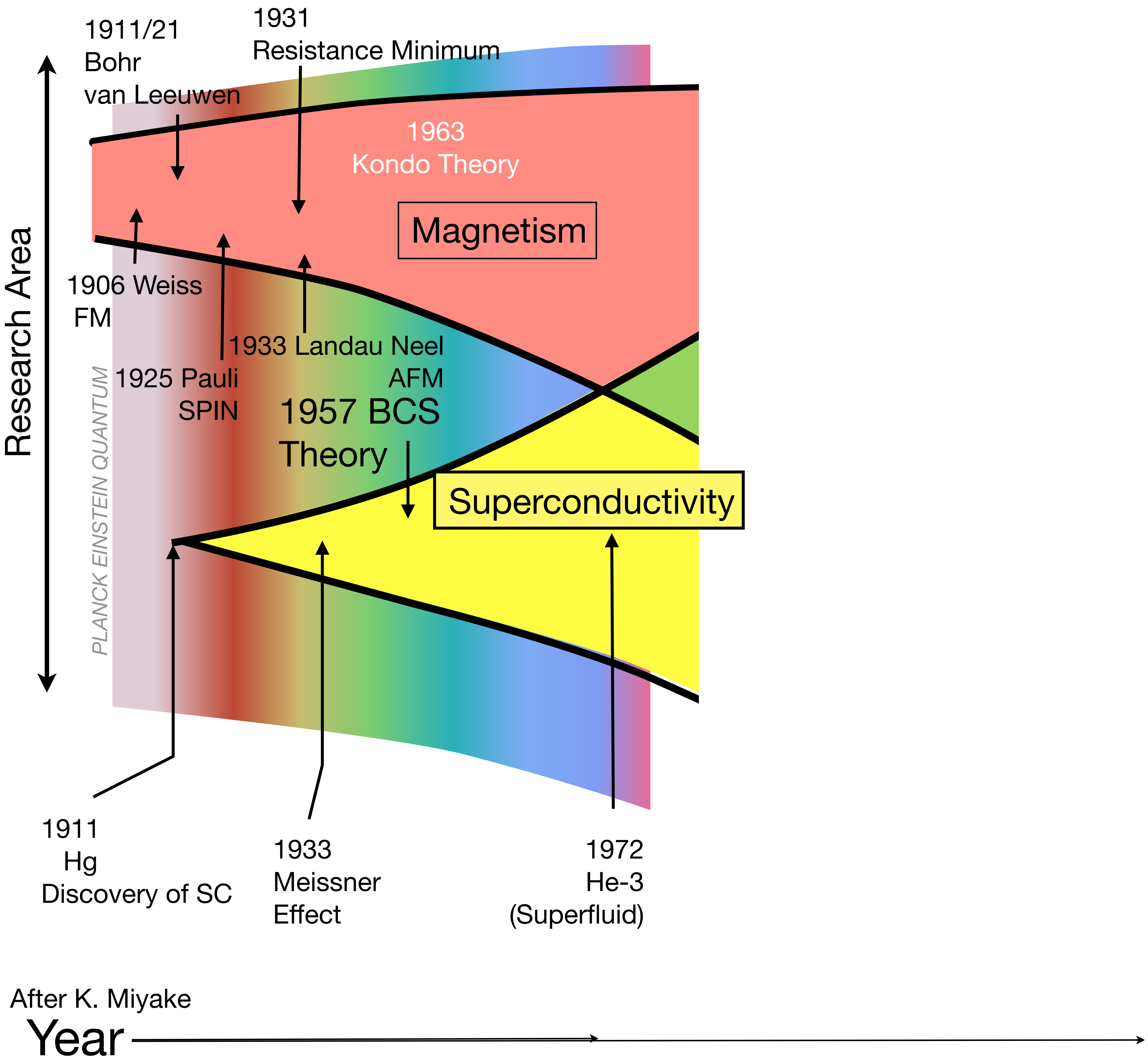


Spin paramagnetism is BAD!

1% mag impurities usually kill Tc

FIG. 3. Ferromagnetic and superconducting transition temperatures of solid solutions of gadolinium in lanthanum.

Magnetism and Superconductivity



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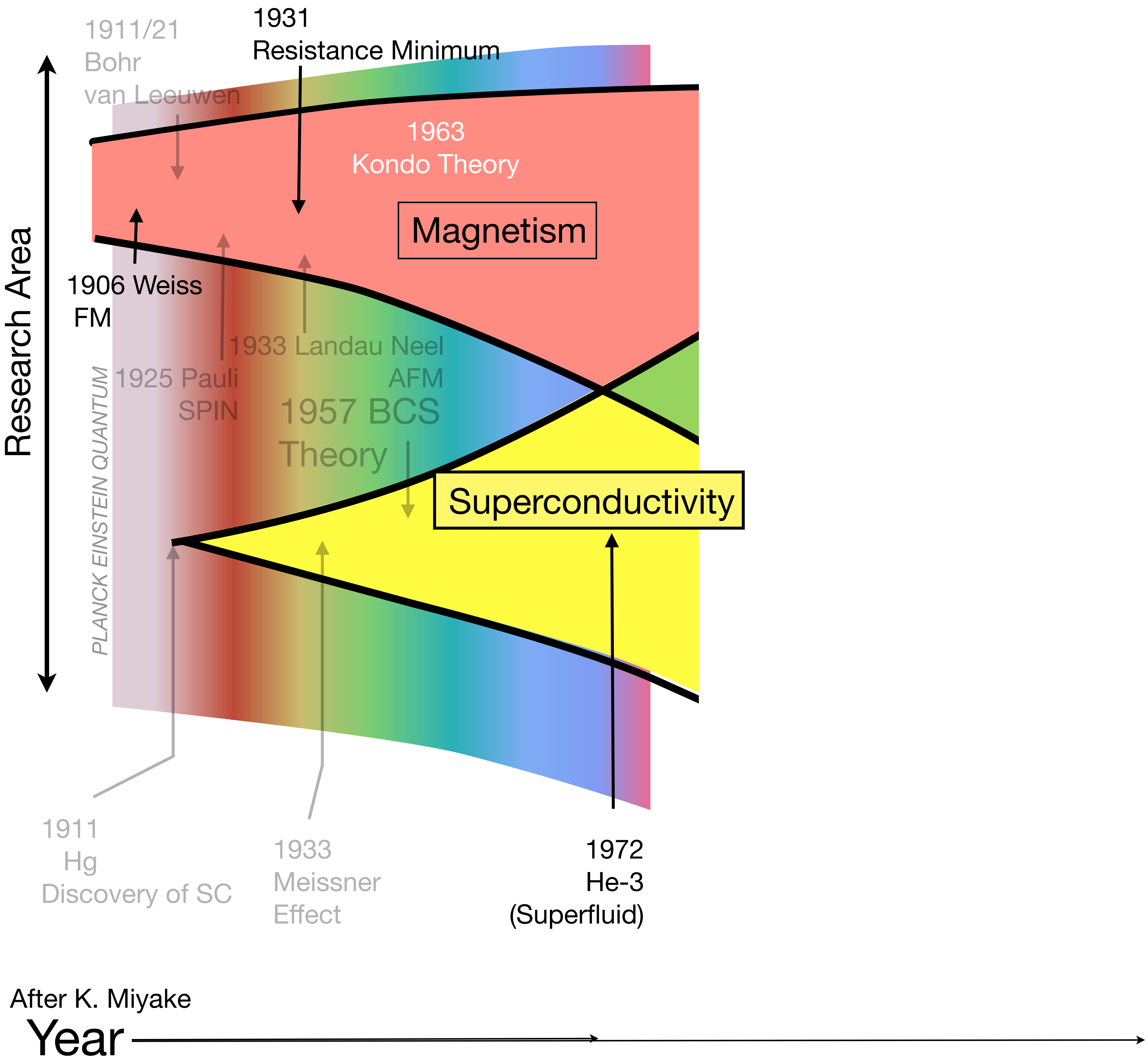

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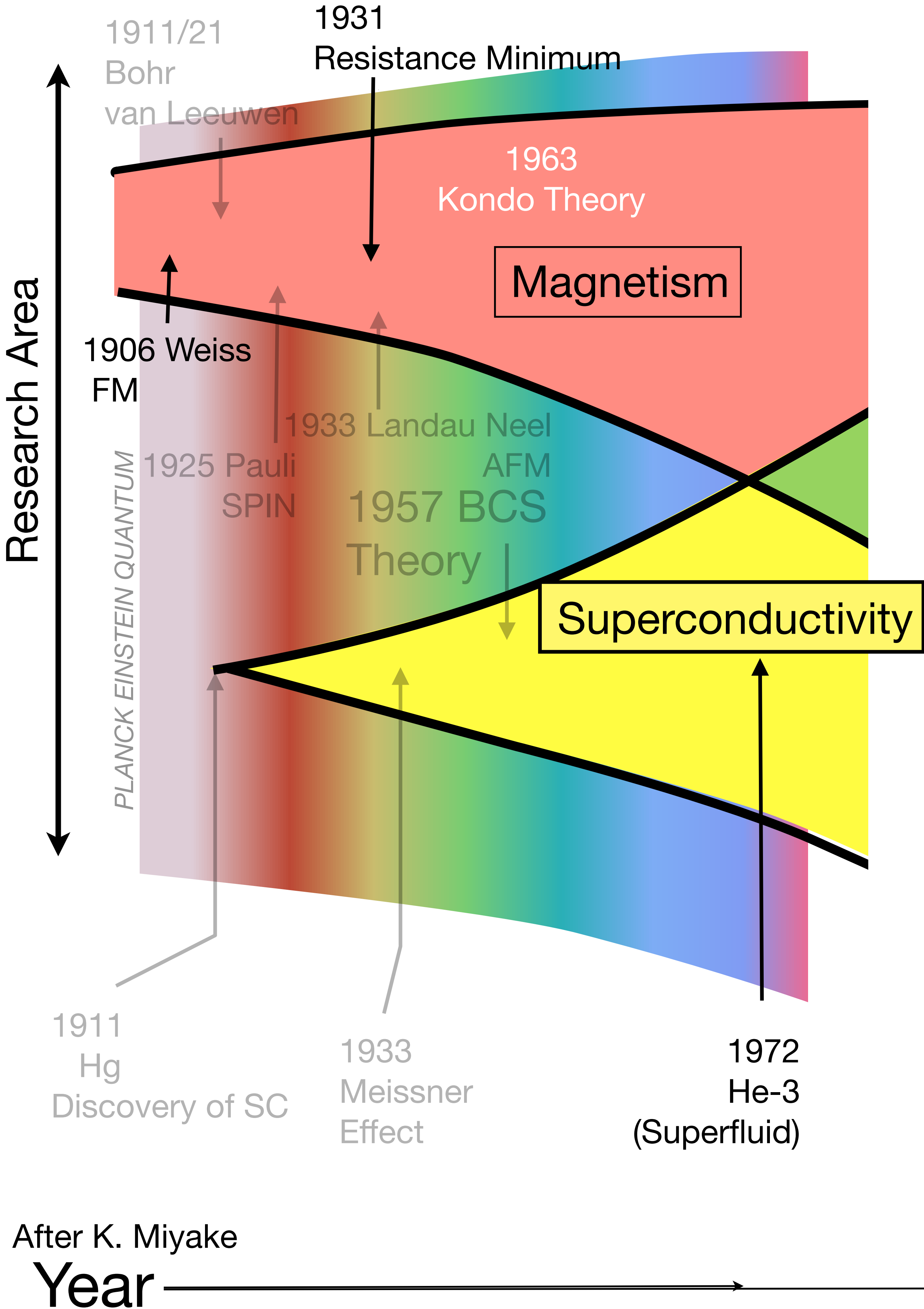
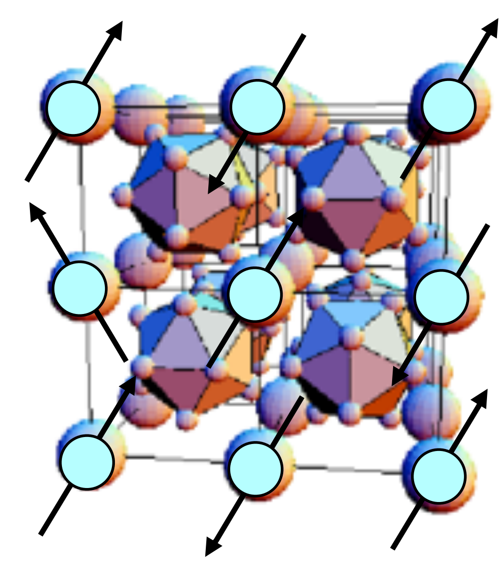


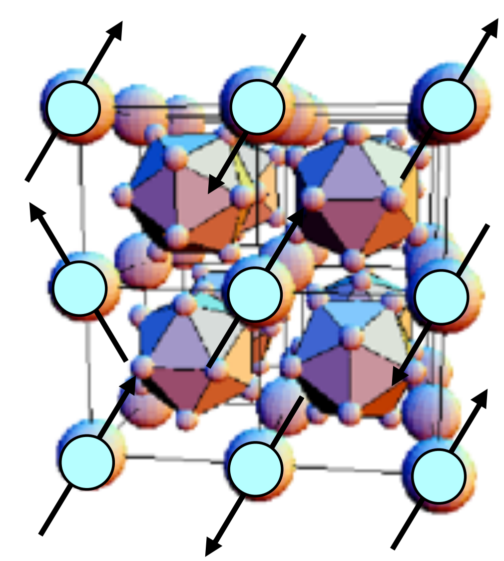


UBe_{13}

After K. Miyake

We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe.

Bell Labs, NJ 1973



UBe_{13}

PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

Electronic properties of beryllides of the rare earth and some actinides

E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 14 March 1974)

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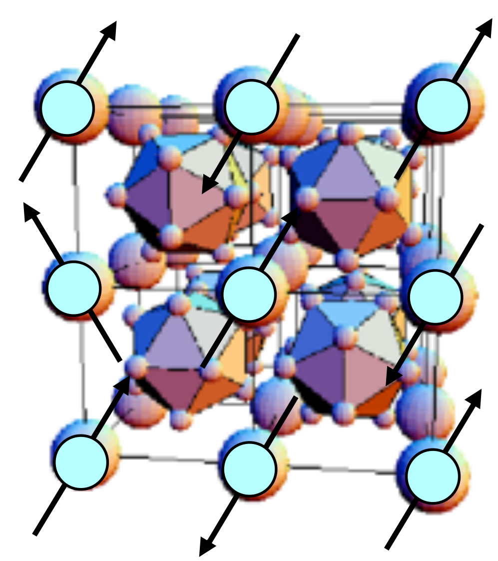

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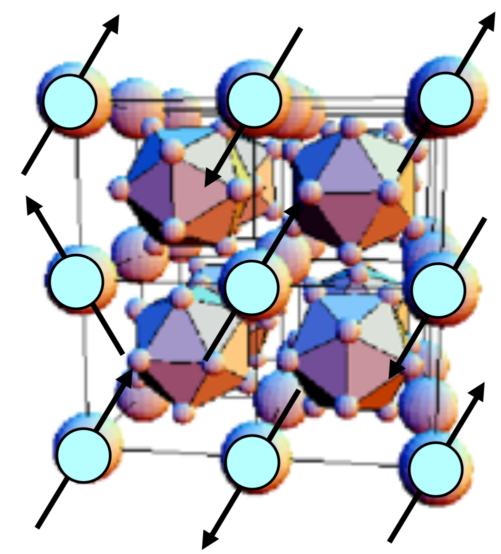
Steglich
1979



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VOLUME 43, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1979

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

and

J. Aarts, C. D. Bredl, W. Lieke, D. Meschede, and W. Franz
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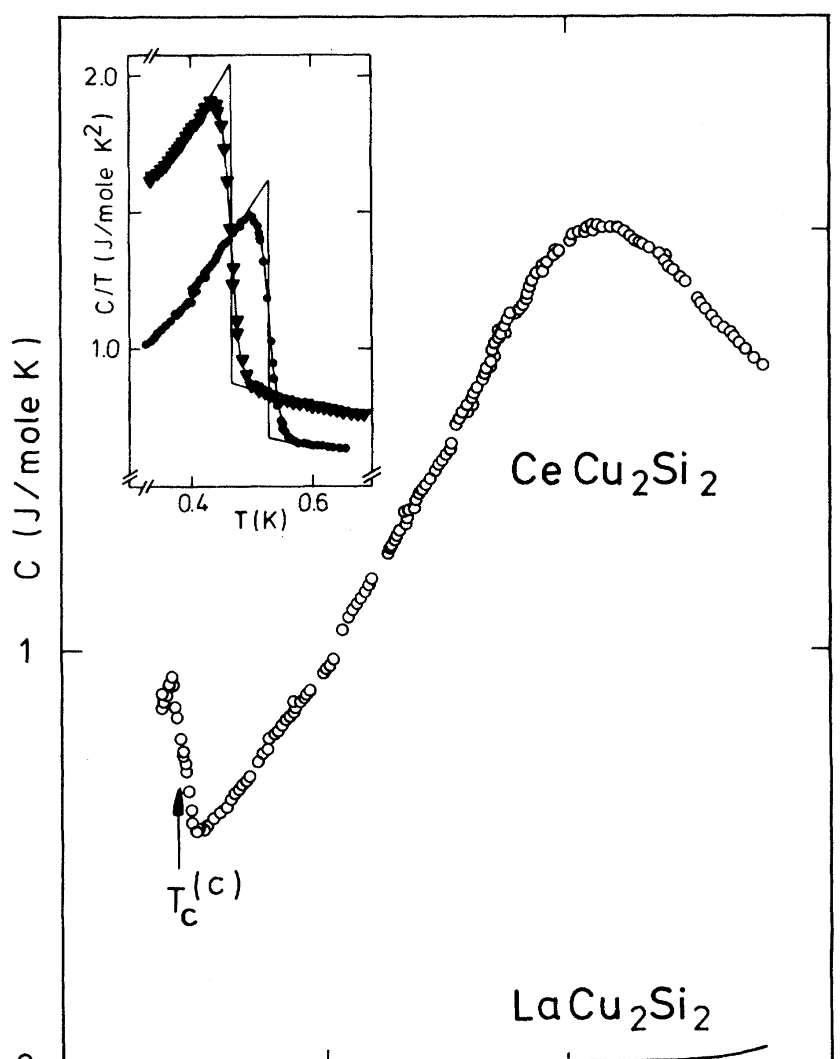
and

H. Schäfer
Eduard-Zintl-Institut, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany
(Received 10 August 1979; revised manuscript received 7 November 1979)

Steglich
1979



VOLUME 43, NUMBER 25 PHYSICAL REVIEW LETTERS 17 DECEMBER 1979

Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

F. Steglich
Institut für Festkörperphysik, Technische Hochschule Darmstadt, D-6100 Darmstadt, West Germany

and

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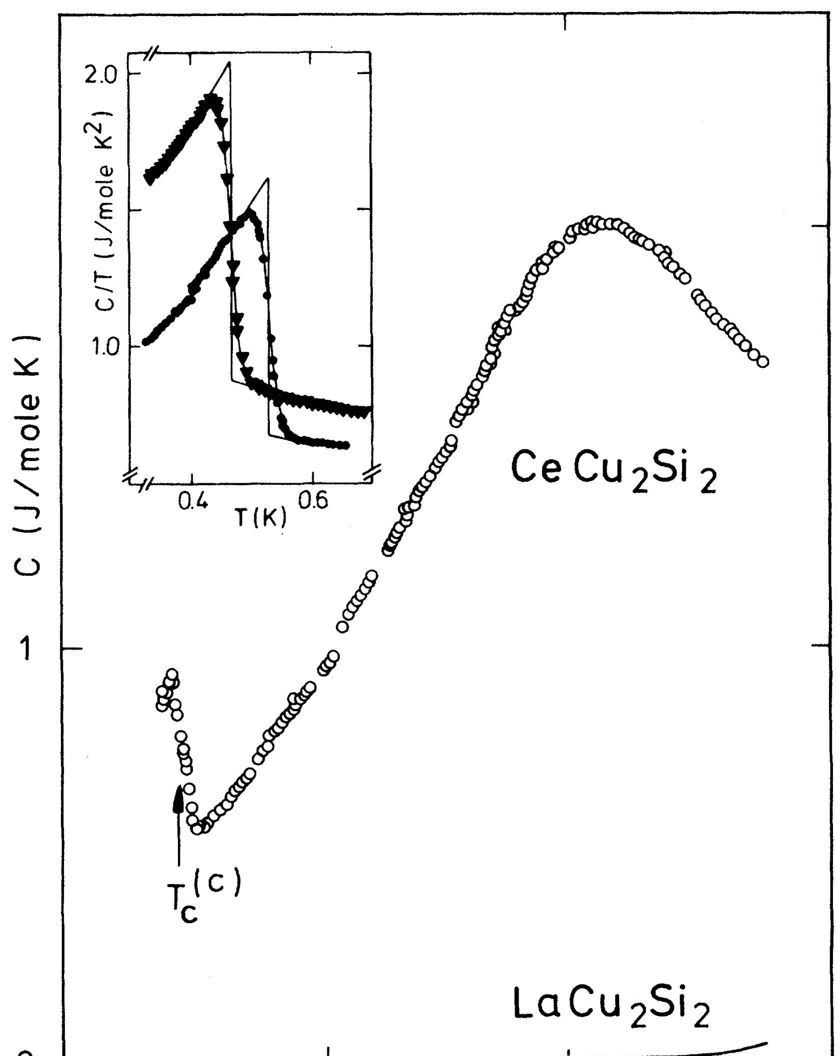
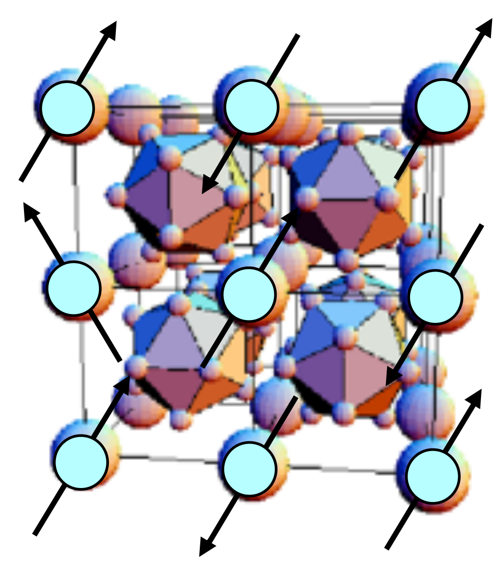


Since the Debye temperature, Θ, is of the order of 200 K,[5] we find $T_c < T_F < \Theta$ with $T_c/T_F \simeq T_F/\Theta \simeq 0.05$. This suggests that $CeCu_2Si$ (i) behaves as a "high-temperature superconductor" and (ii) cannot be described by conventional theory of superconductivity which assumes a typical phonon frequency $k_B\Theta/h \ll k_BT_F/h$, the characteristic frequency of the fermions.

We tried to detect any possible magnetic ordering below 1K. Instead we found a sharp superconducting transition at 0.97K, which was reduced by about 0.3K only in a field of 60kOe. This suggests that the superconductivity is not an intrinsic property of UBe13. Bell Labs, NJ 1973



UBe_{13}

PHYSICAL REVIEW B VOLUME 11, NUMBER 1 1 JANUARY 1975

Electronic properties of beryllides of the rare earth and some actinides

E. Bucher,* J. P. Maita, G. W. Hull, R. C. Fulton, and A. S. Cooper
Bell Laboratories, Murray Hill, New Jersey 07974

(Received 14 March 1974)

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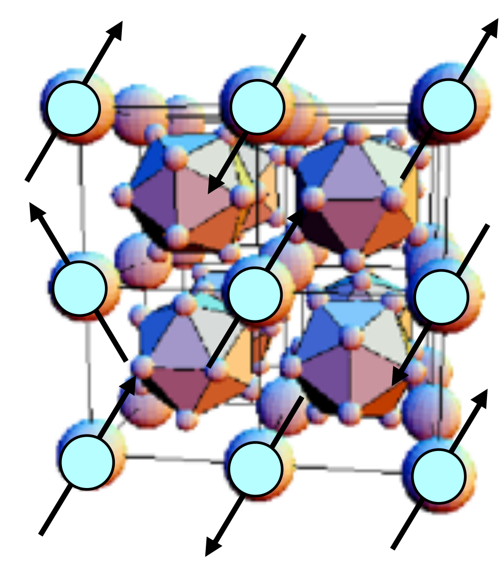

UBe_{13}

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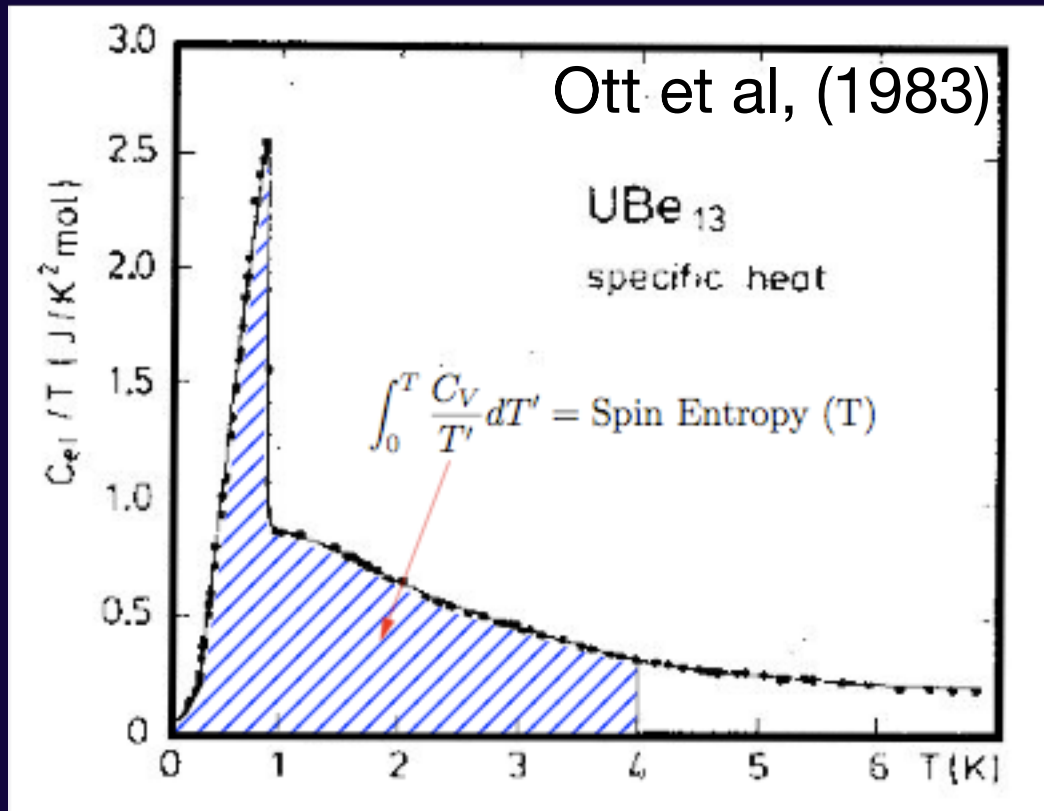

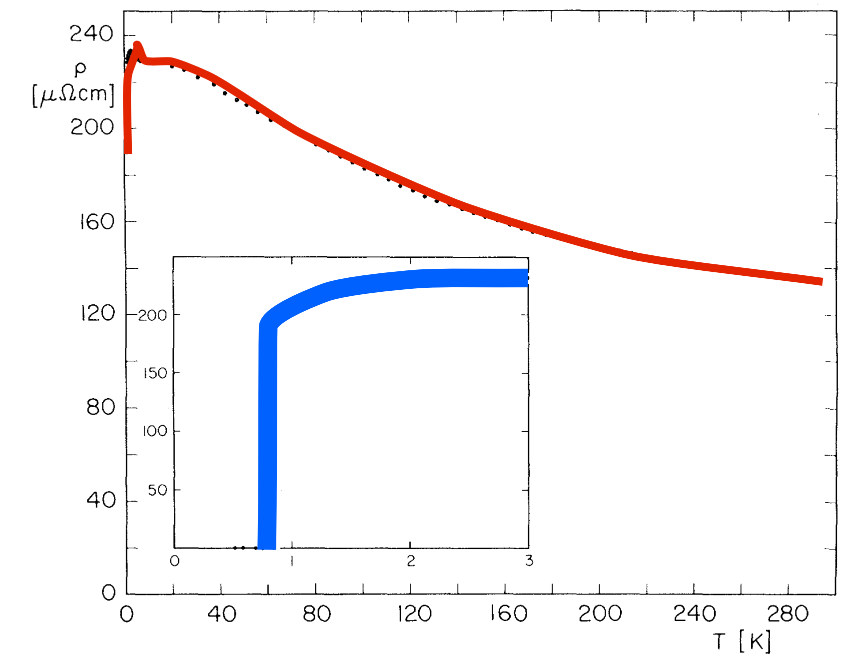

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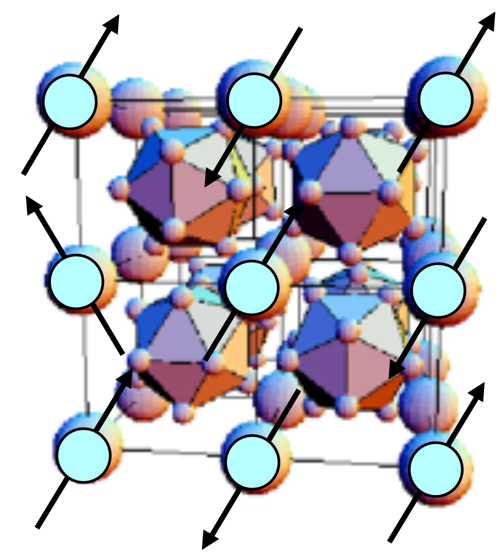

UBe_{13}

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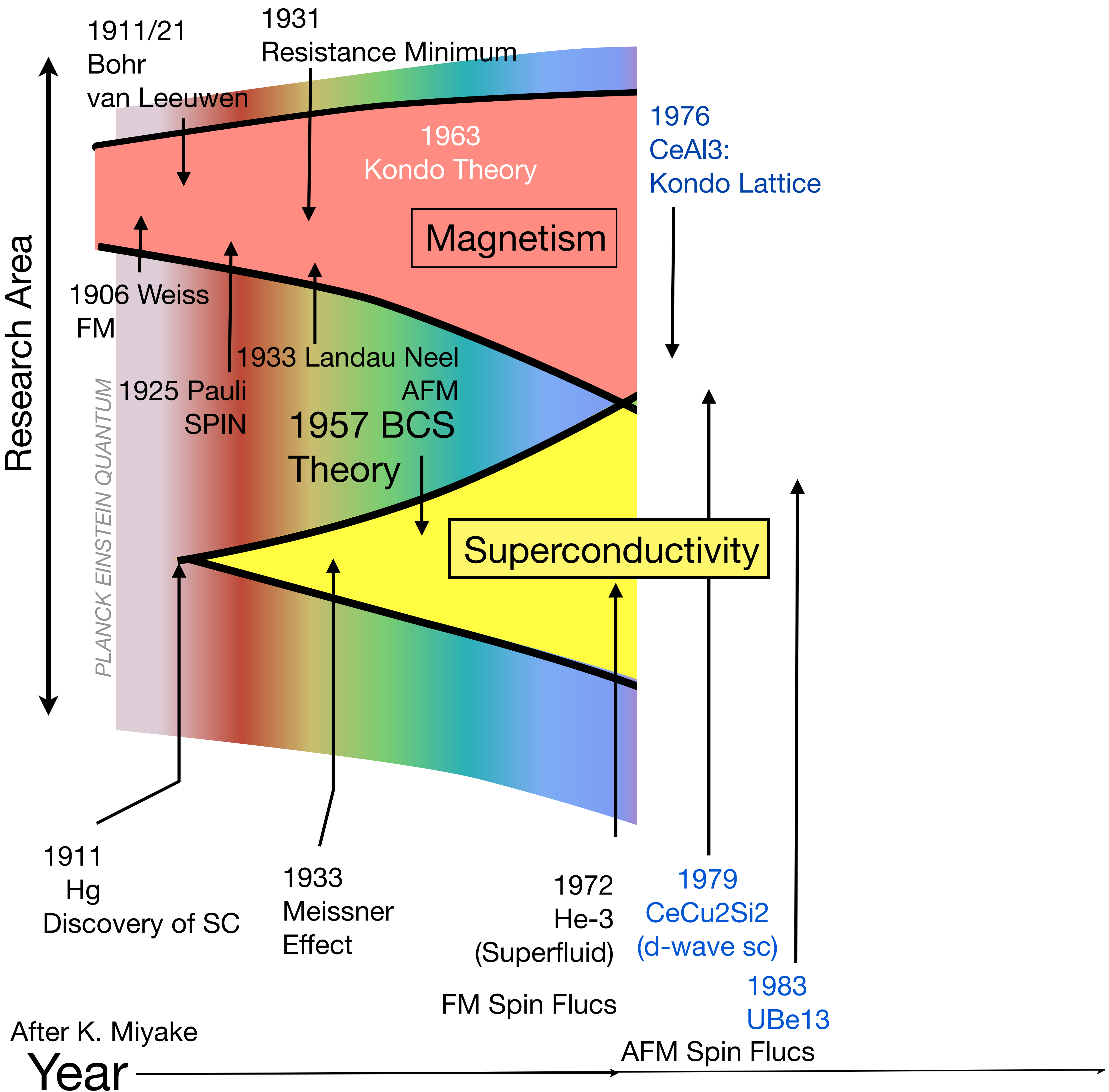
Magnetism and Supercond



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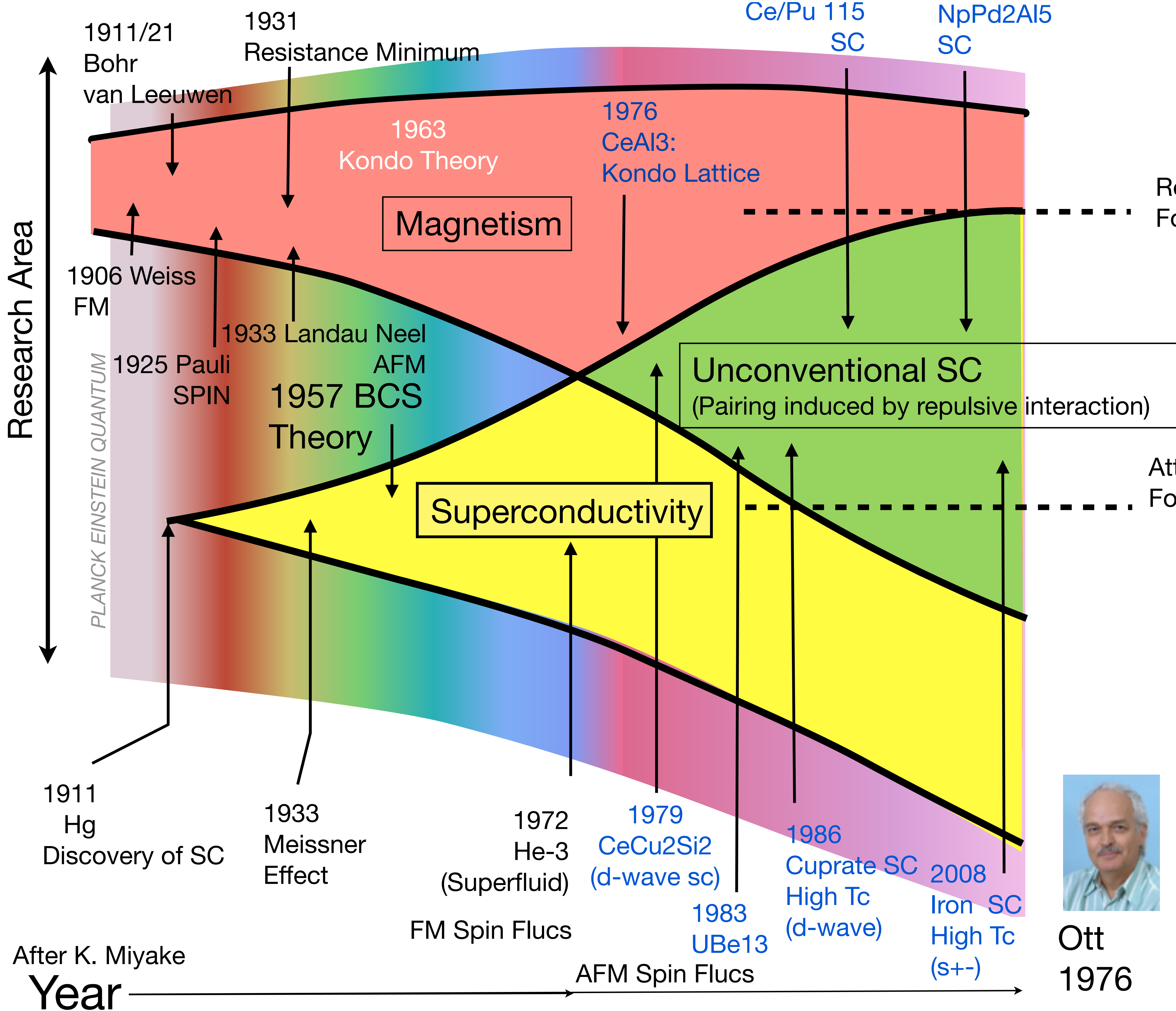
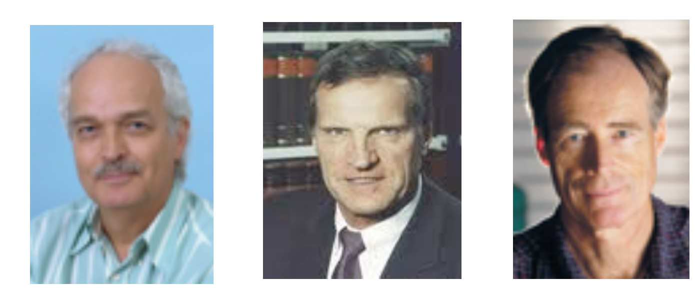
A remarkable convergence of two fields.





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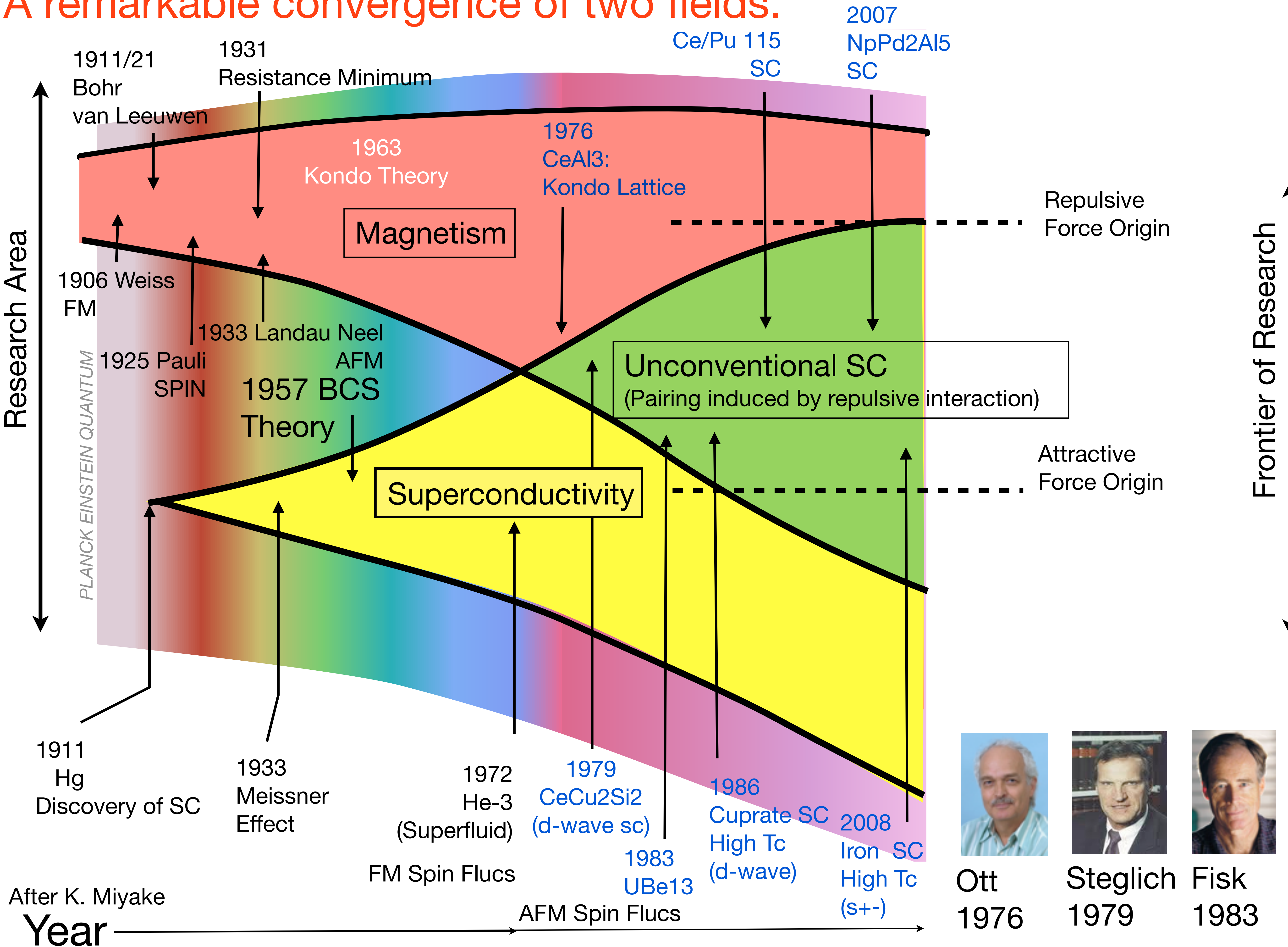
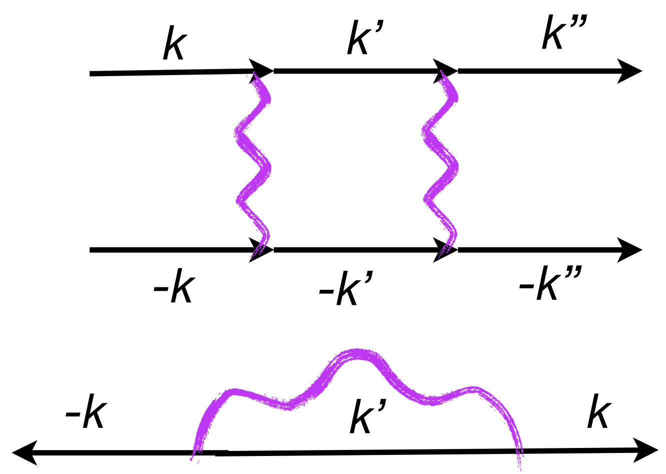


Fabric vs Glue?

Glue vs Fabric.

Glue vs Fabric.

Glue Spin fluctuations = pairing bosons



Eliashberg Approach (cf B. Keimer et al)

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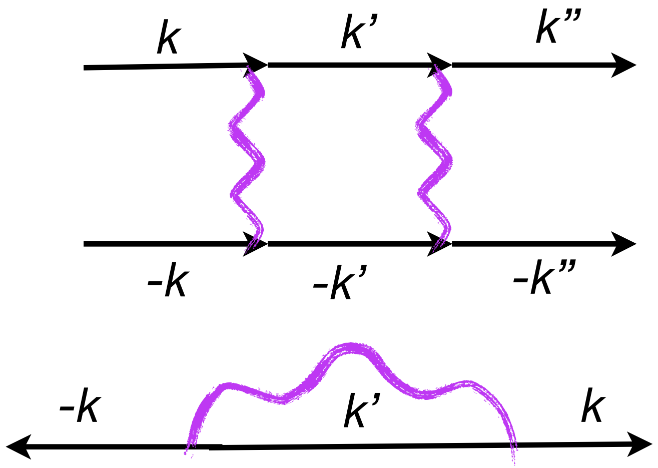

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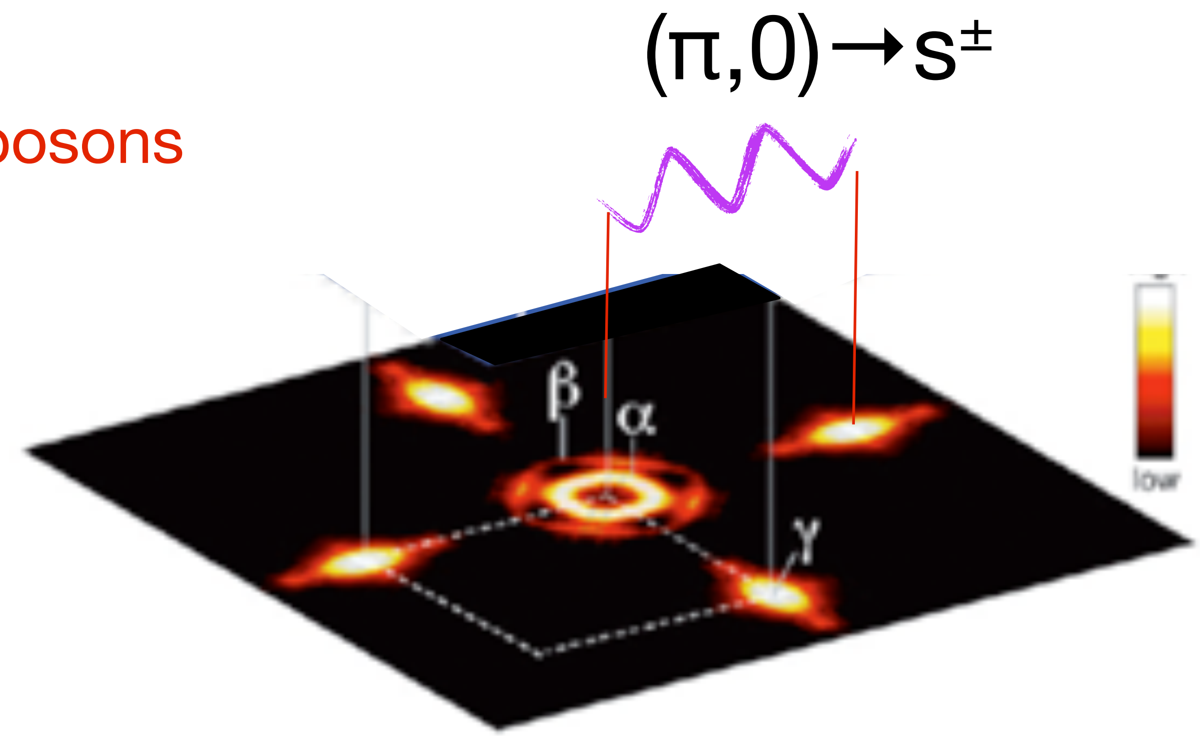

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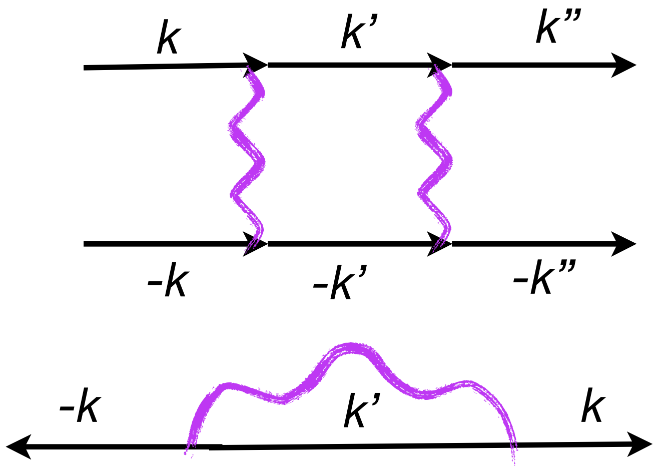

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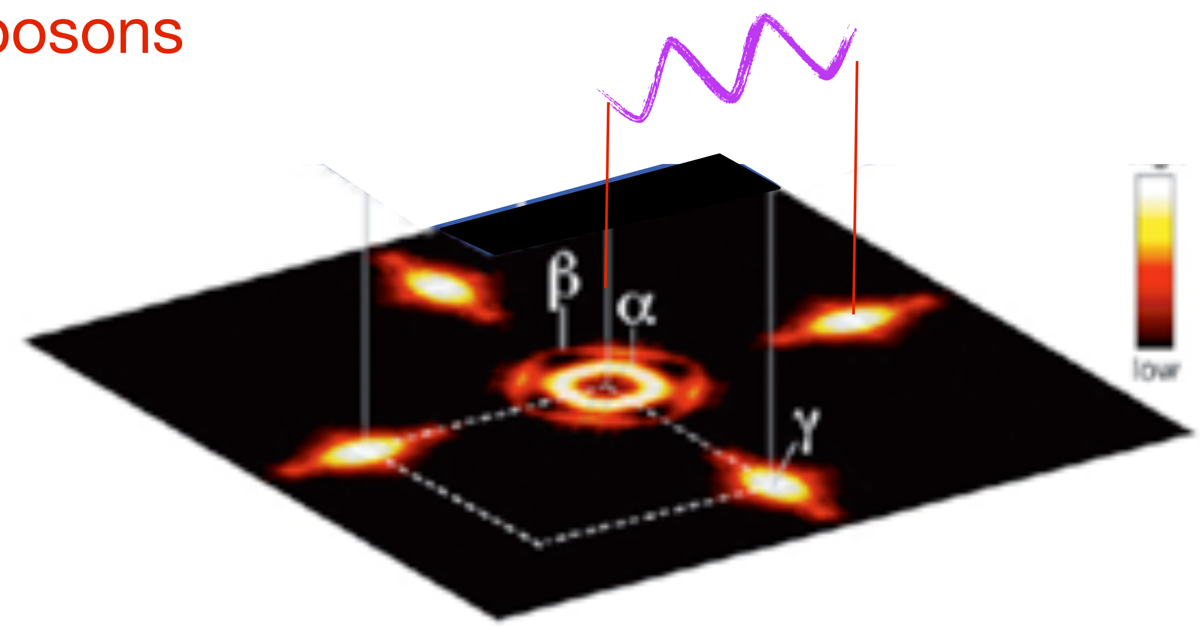
$(\pi,0) \rightarrow s^{\pm}$



Fabric: spins *make* the pairs

Glue vs Fabric.

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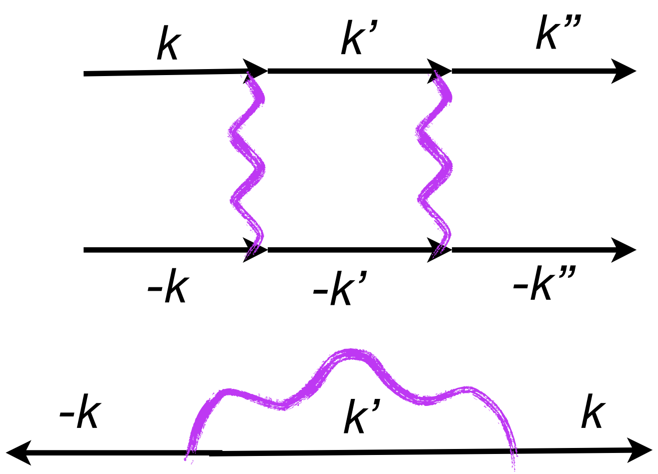

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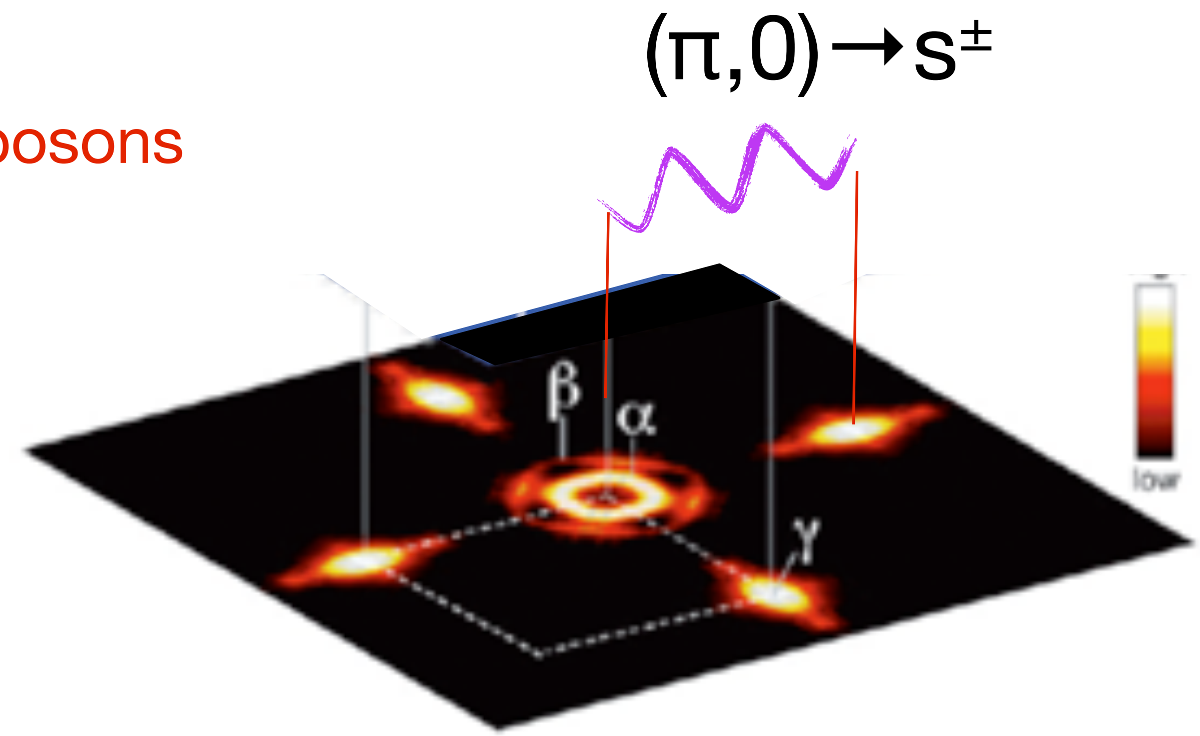

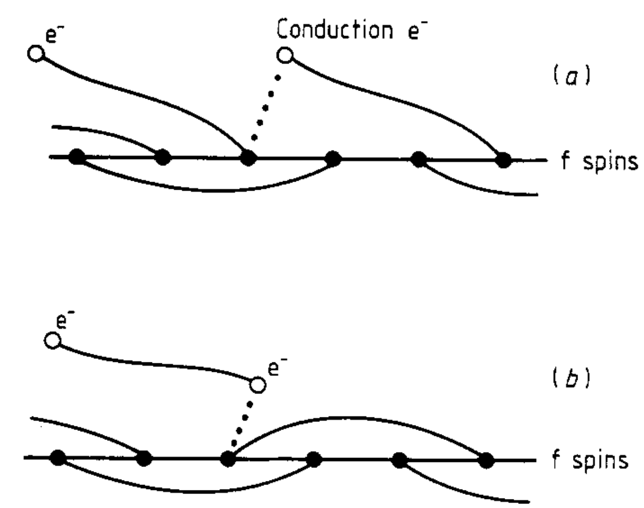

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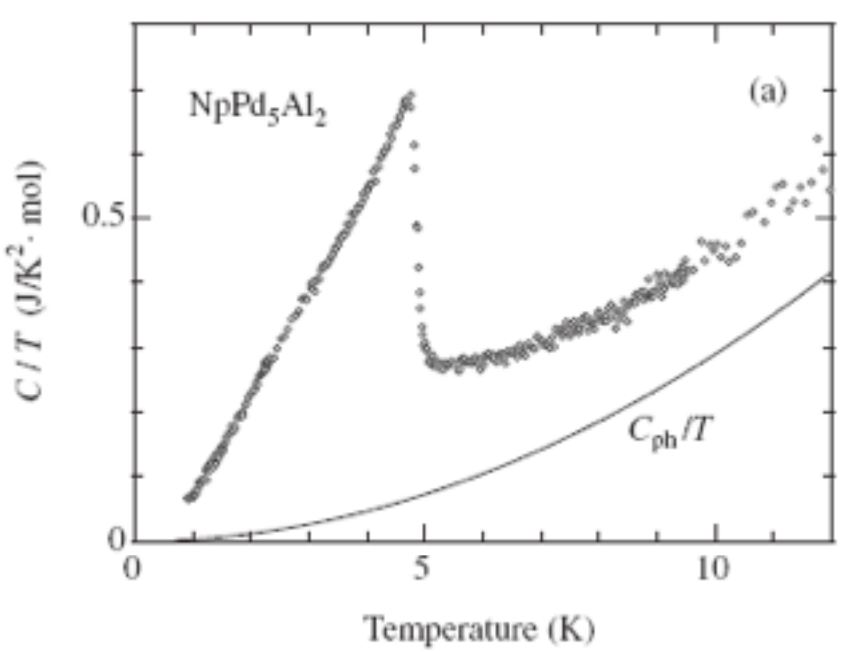

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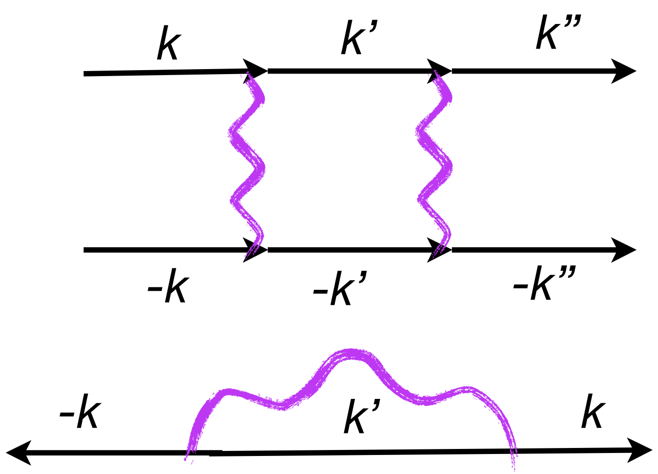

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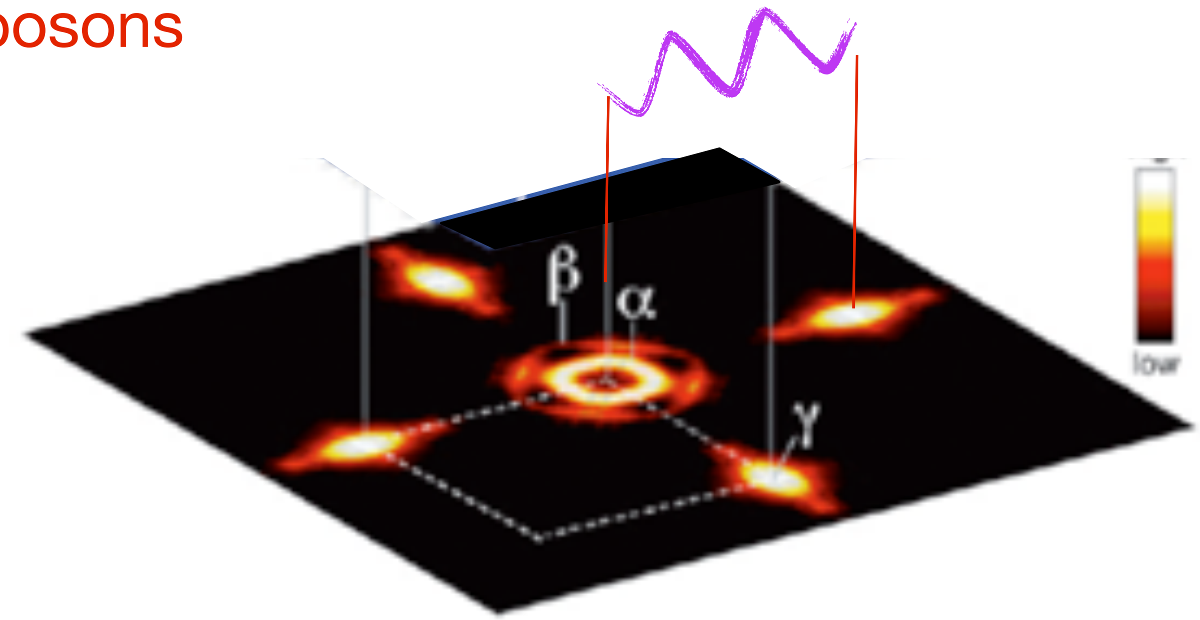

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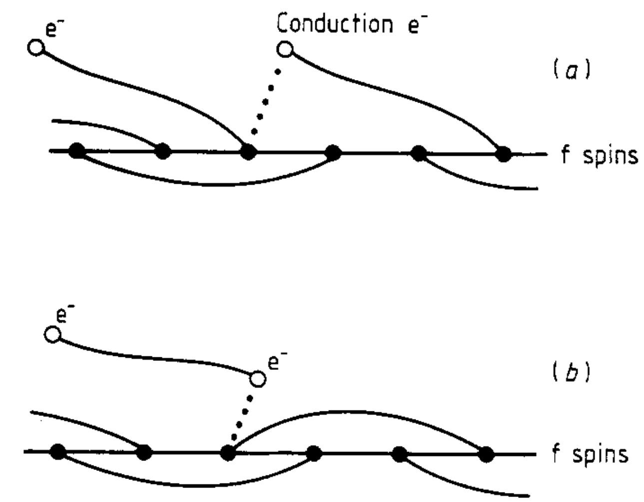
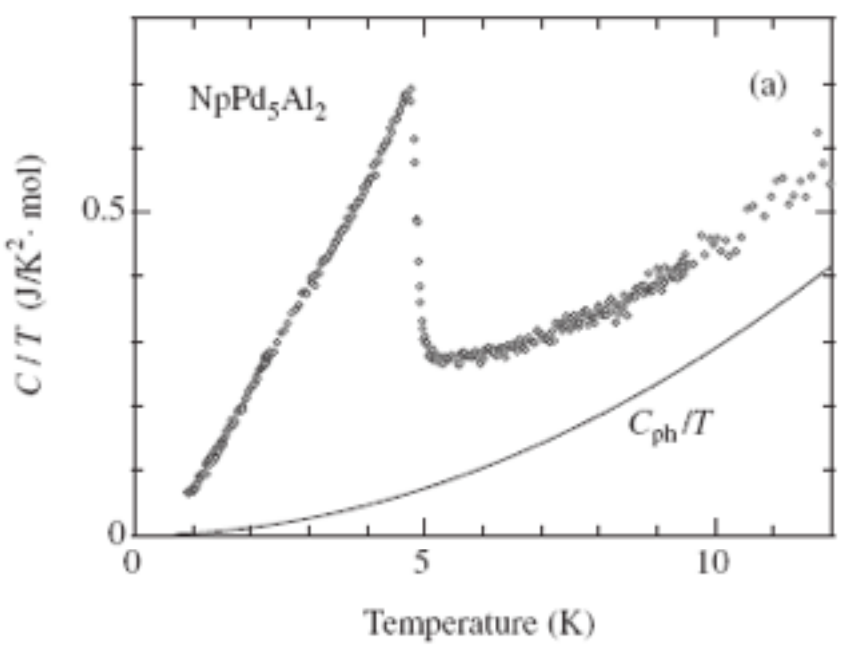




$$R \ln W = \int_0^T dT' \frac{C'}{T'}$$

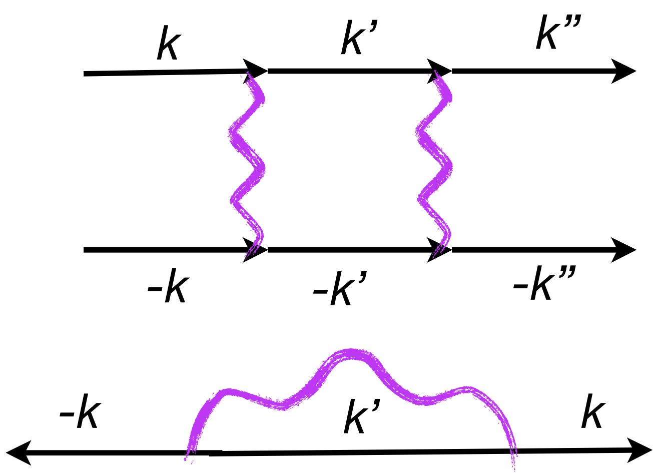
"Hilbert Space Spectroscopy"

Glue vs Fabric.

(π,0)→s$^{\pm}$

Glue

Spin fluctuations = pairing bosons



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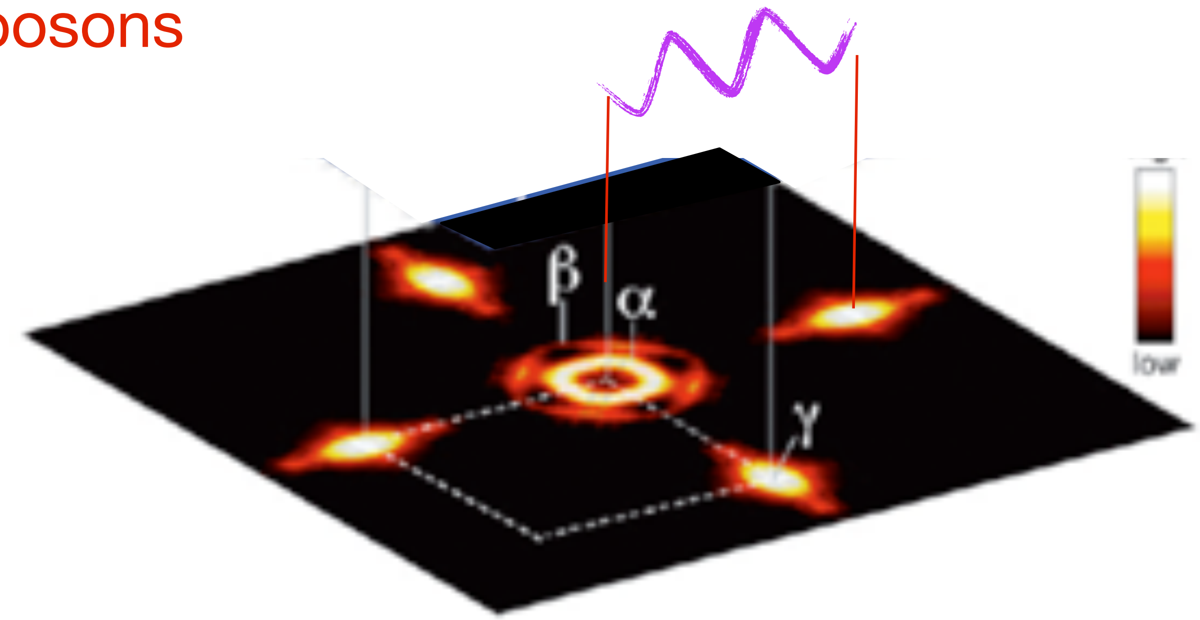

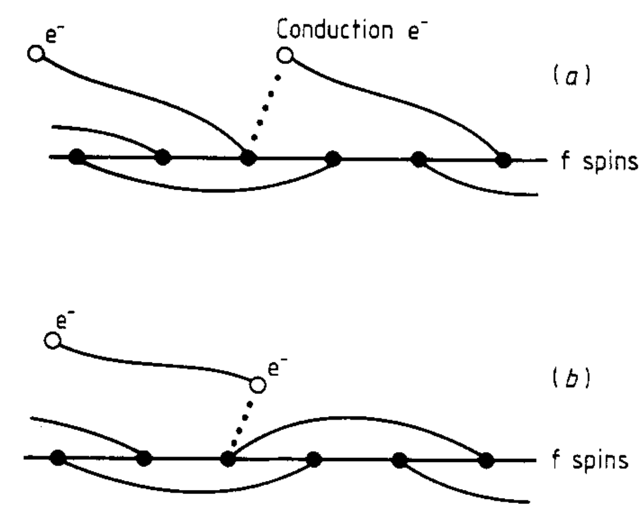

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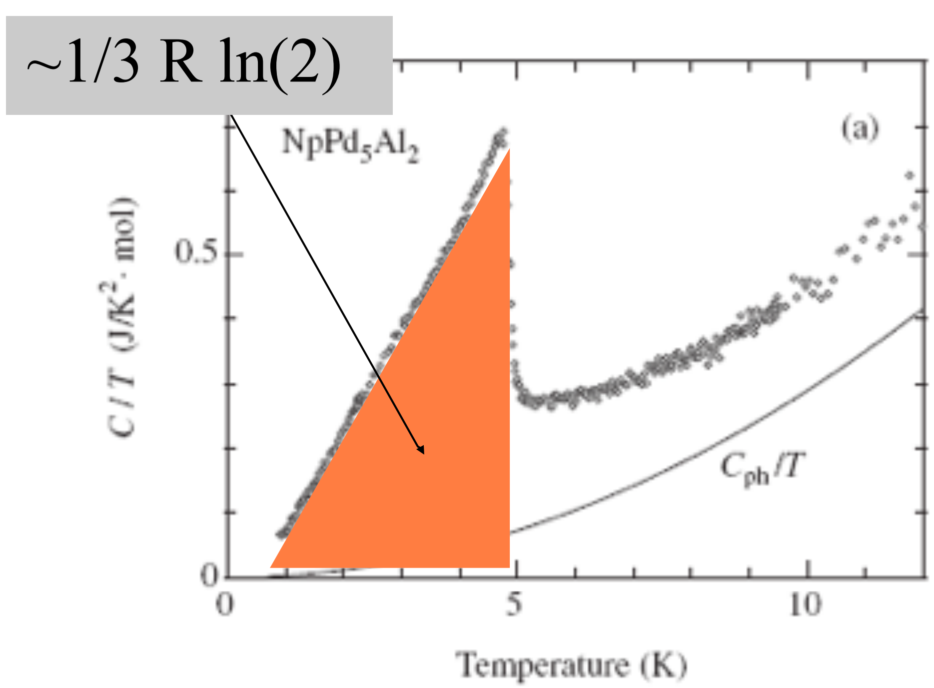

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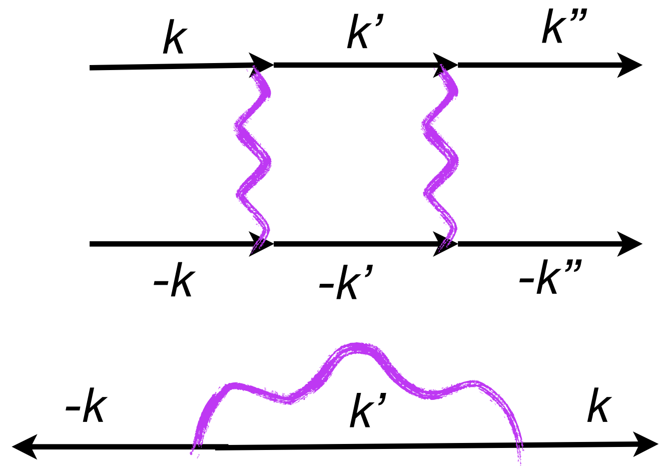

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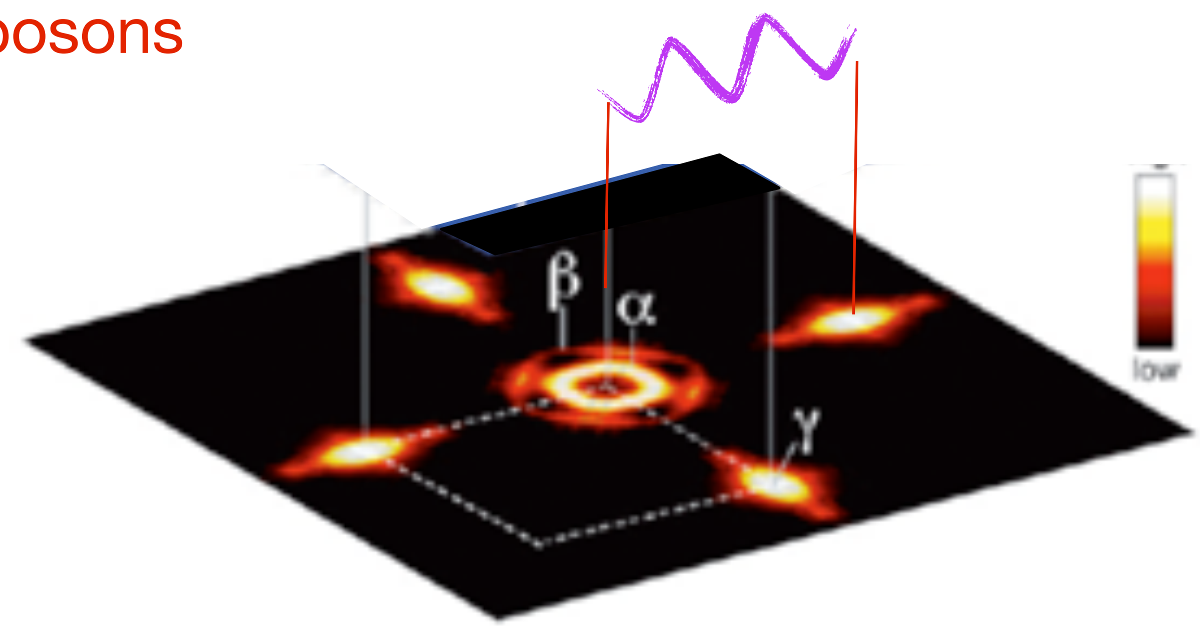

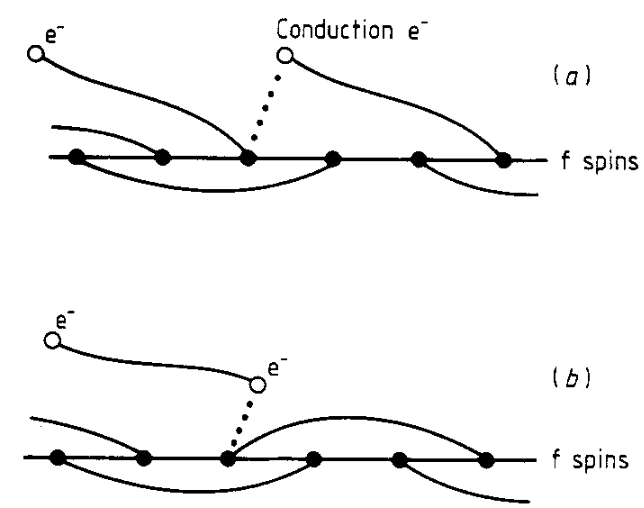

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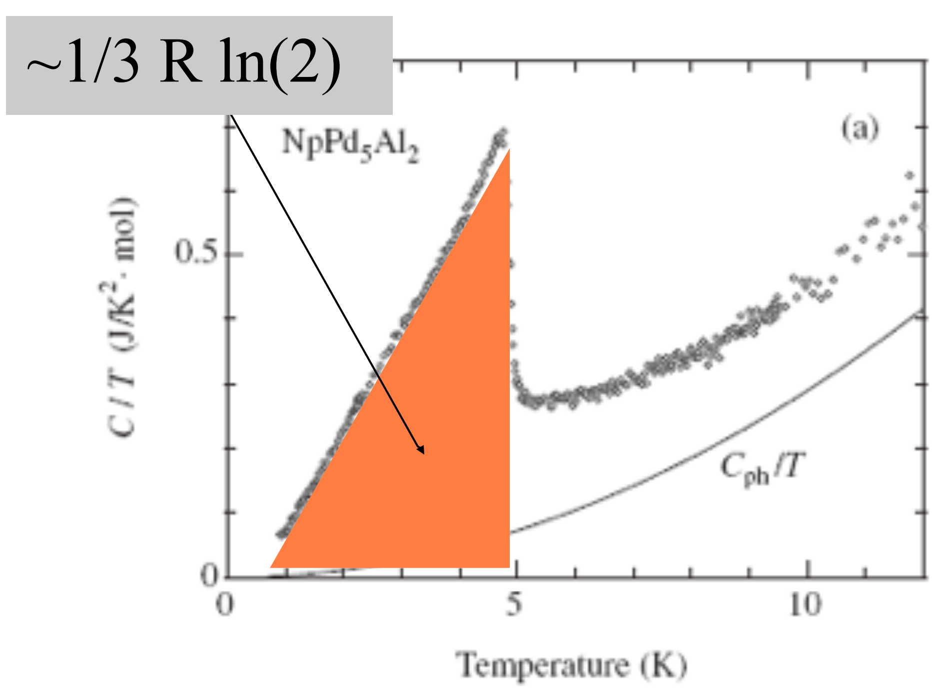

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“Hilbert Space Spectroscopy”

SPIN Hilbert space BUILDS the pairs.

Glue vs Fabric.

(π,0)→s±

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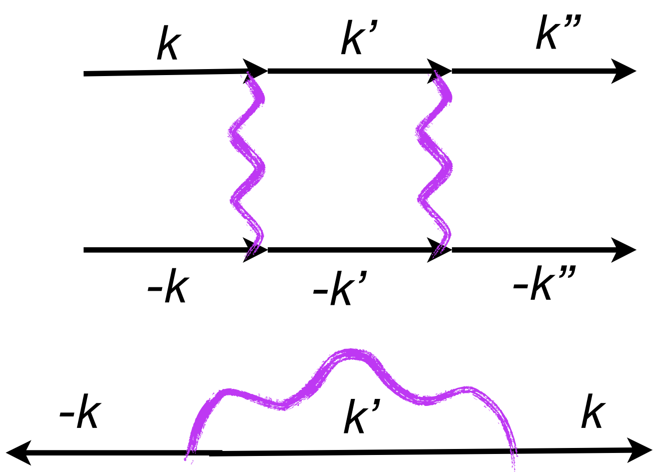

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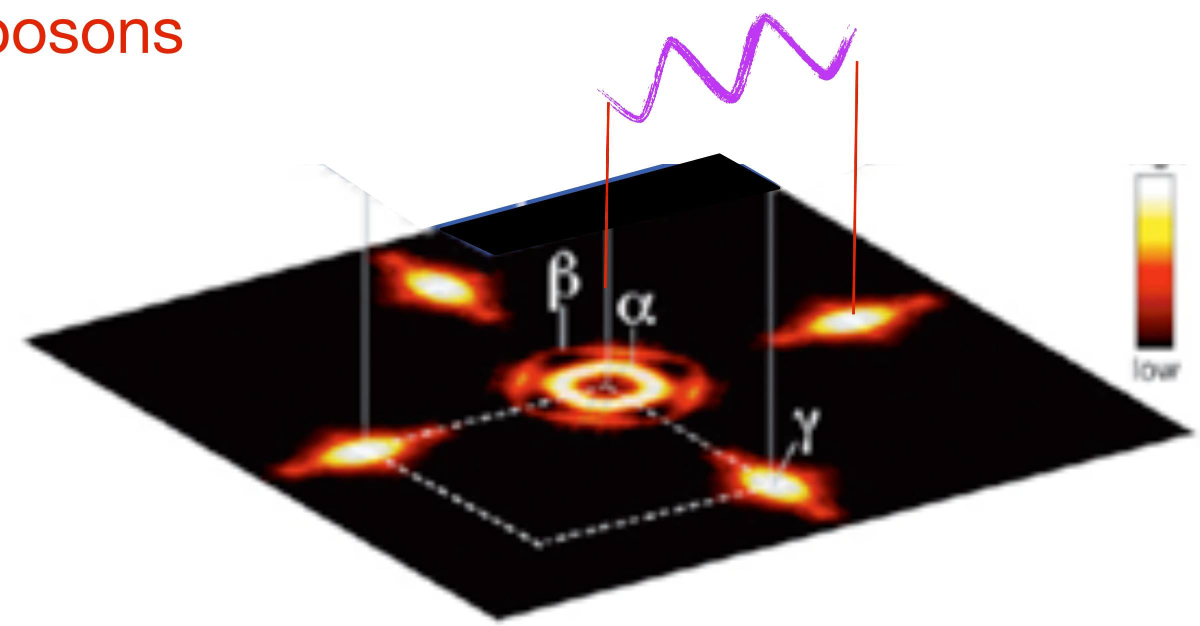

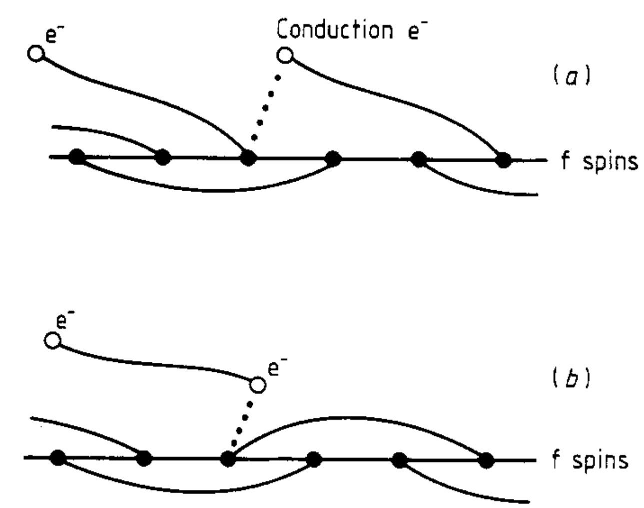

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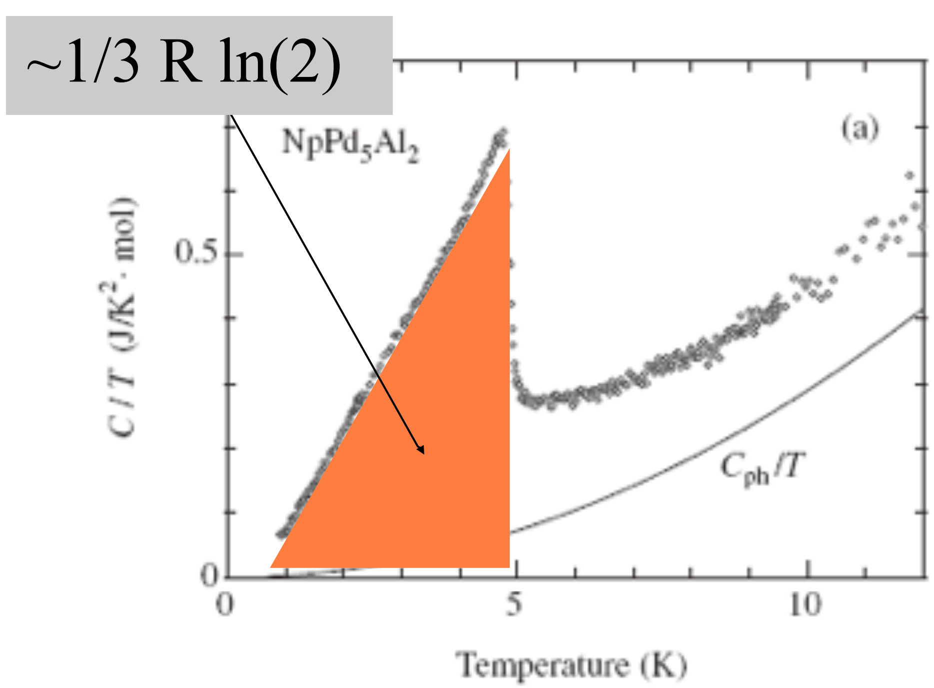

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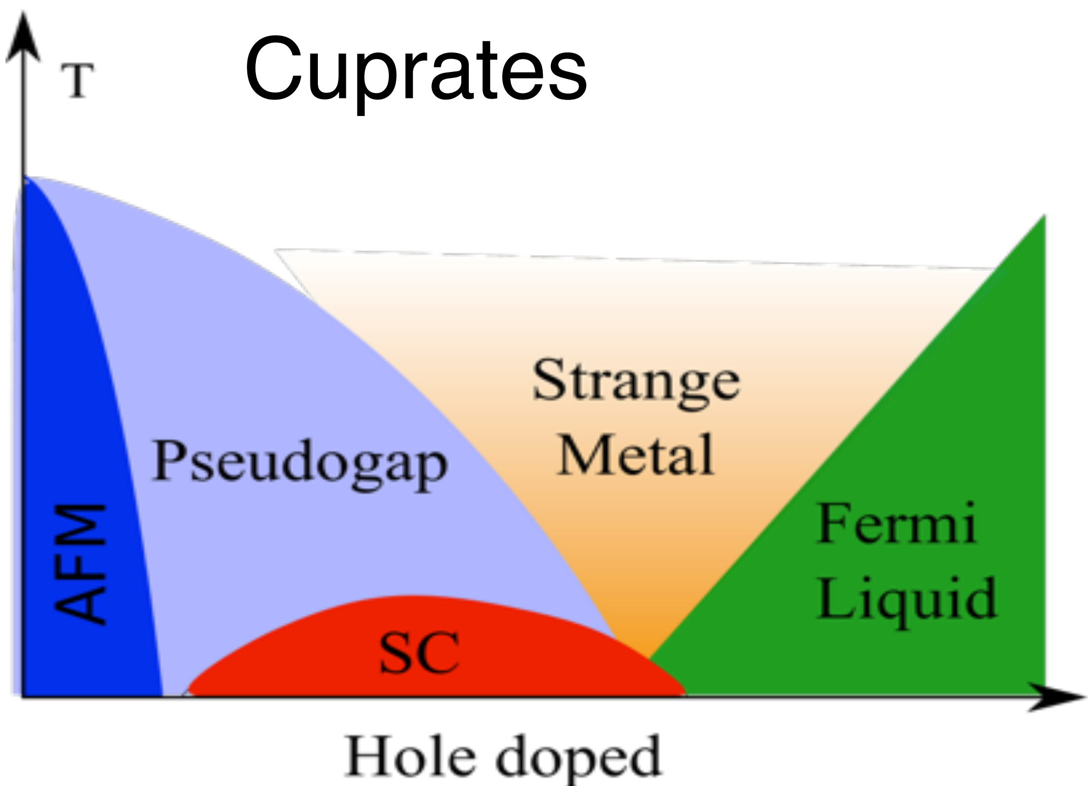
"Hilbert Space Spectroscopy"

SPIN Hilbert space BUILDS the pairs.

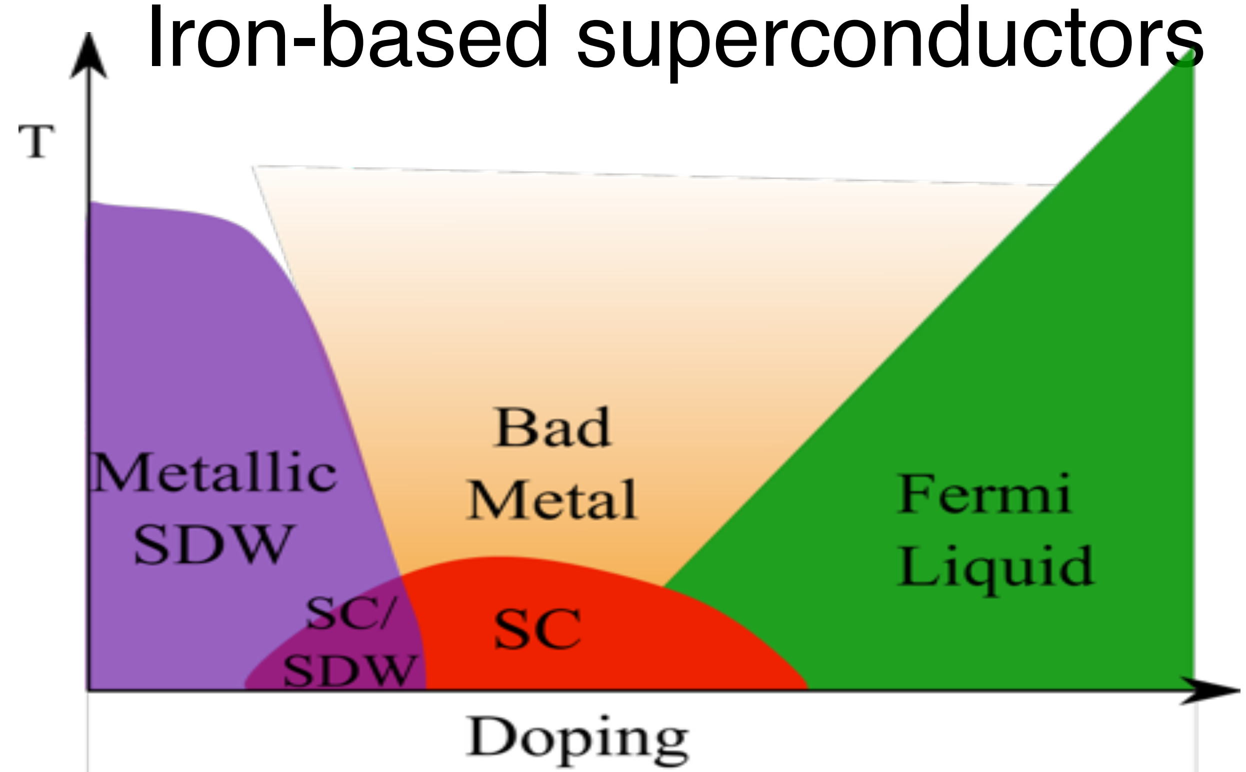
How?

Magnetic pairing appears ubiquitous

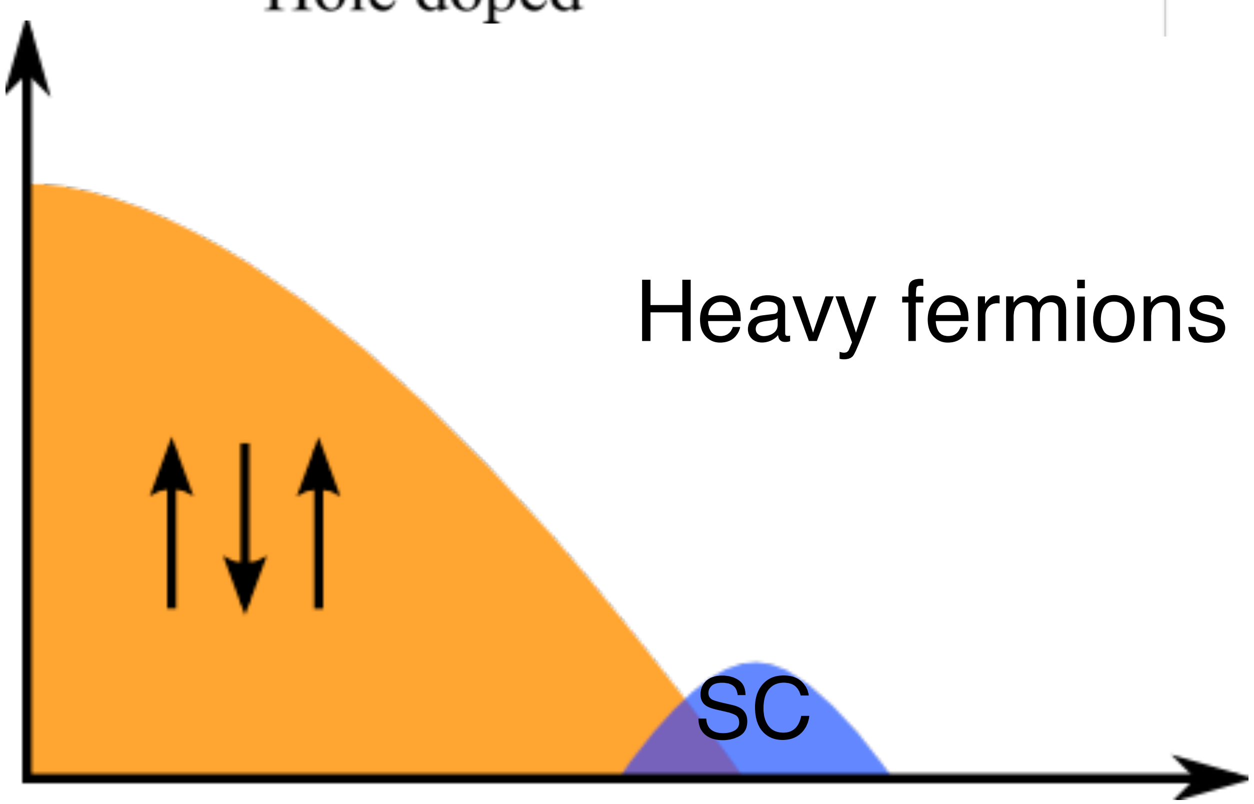
Cuprates

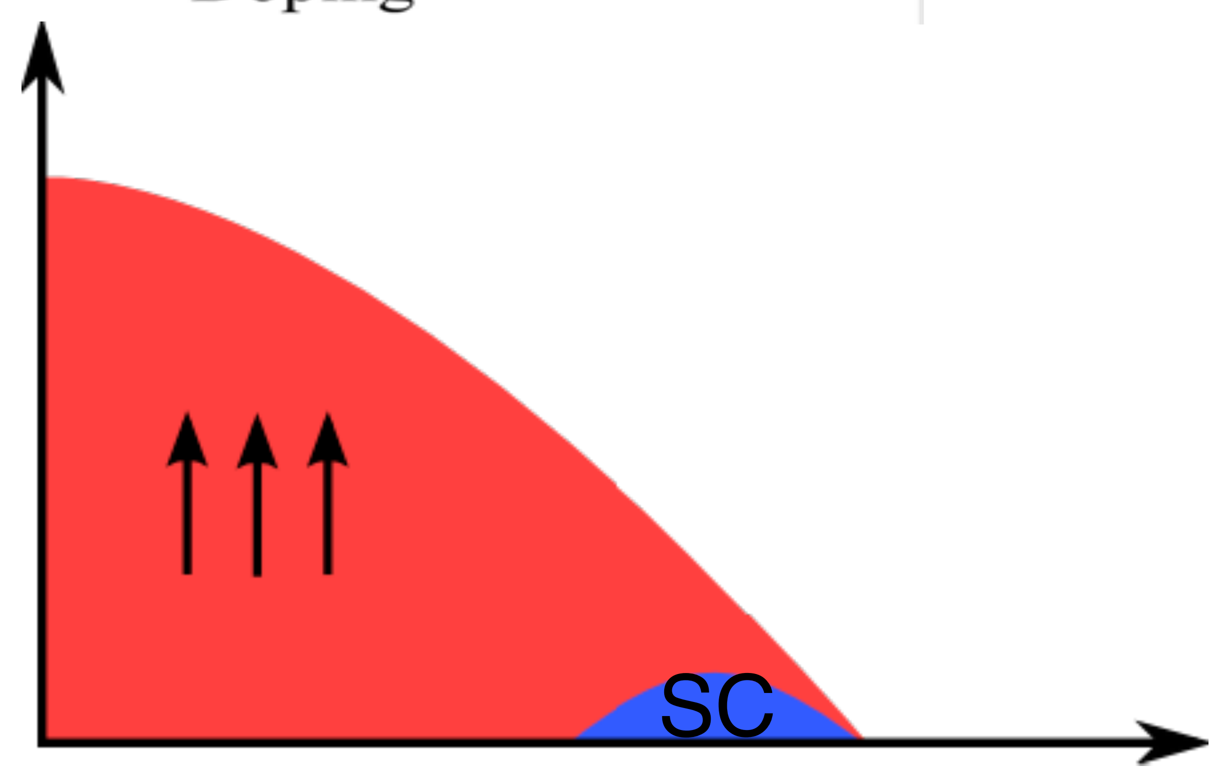


Iron-based superconductors



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

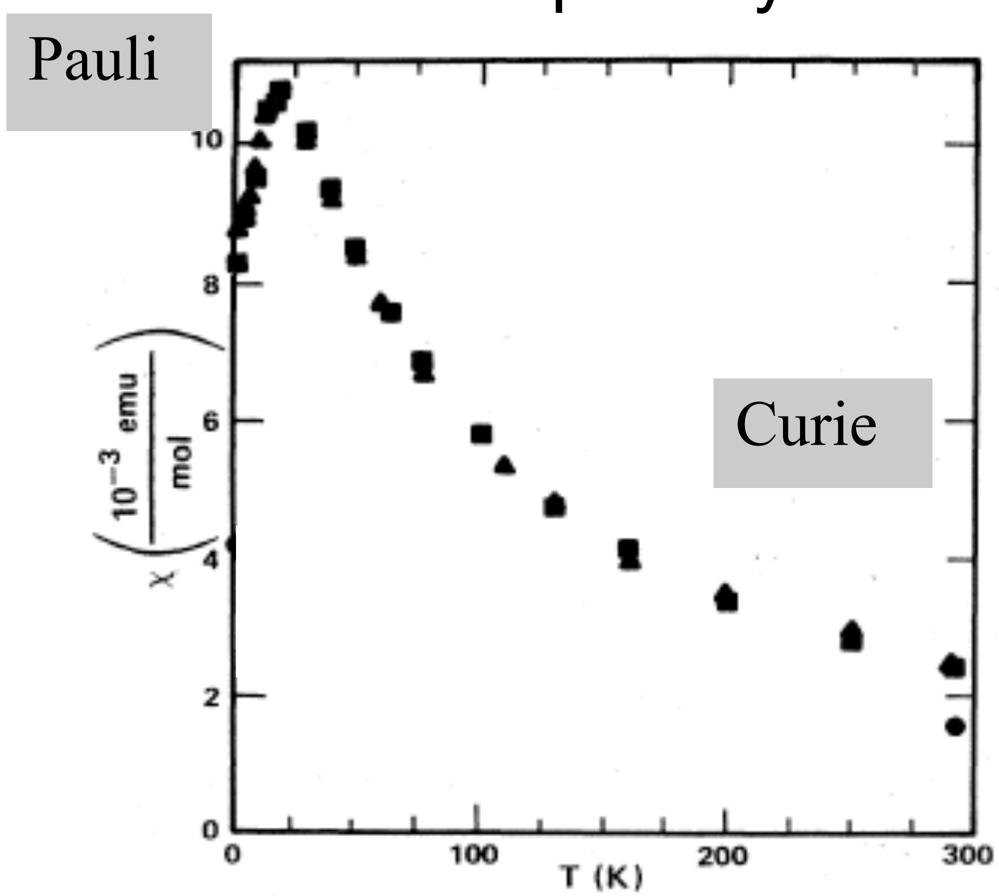
Heavy Fermion SC: The Good.

Conventional Heavy Fermion Superconductivity

Example: UPt_3

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

Susceptibility



Stewart, Fisk, Willis and Smith,

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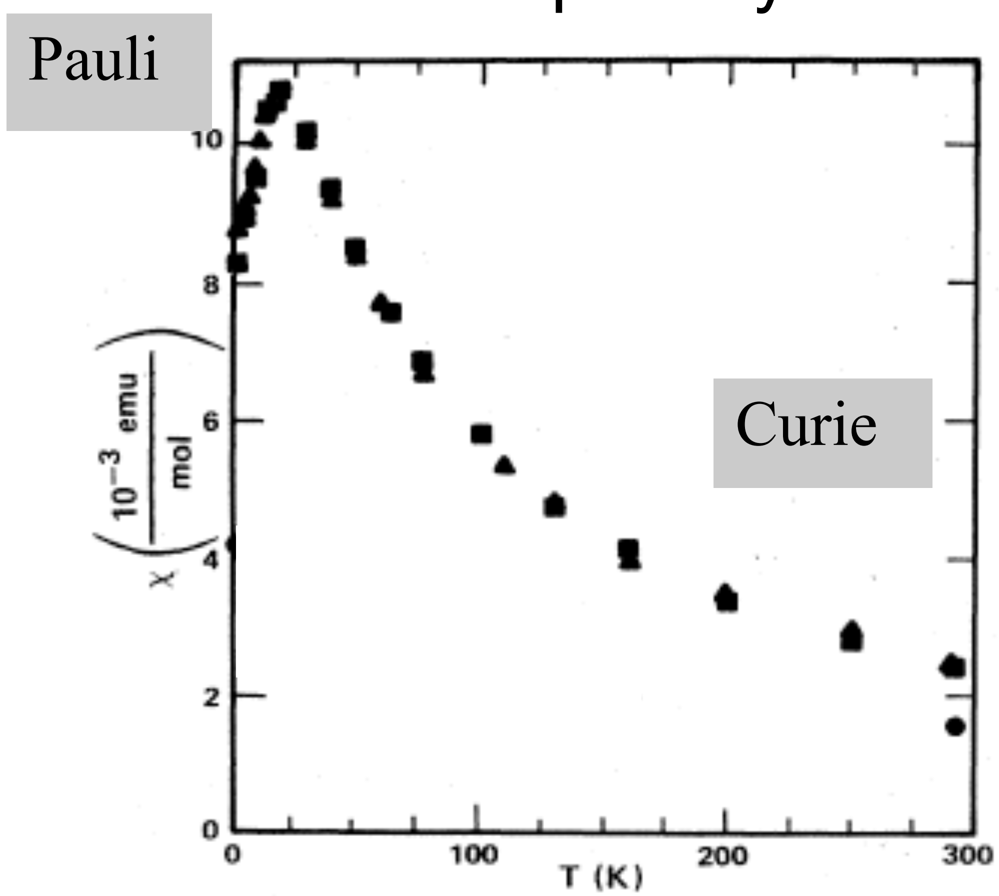

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Stage one: QP formation

Pauli paramagnetism fully developed by 30K~50 T_C

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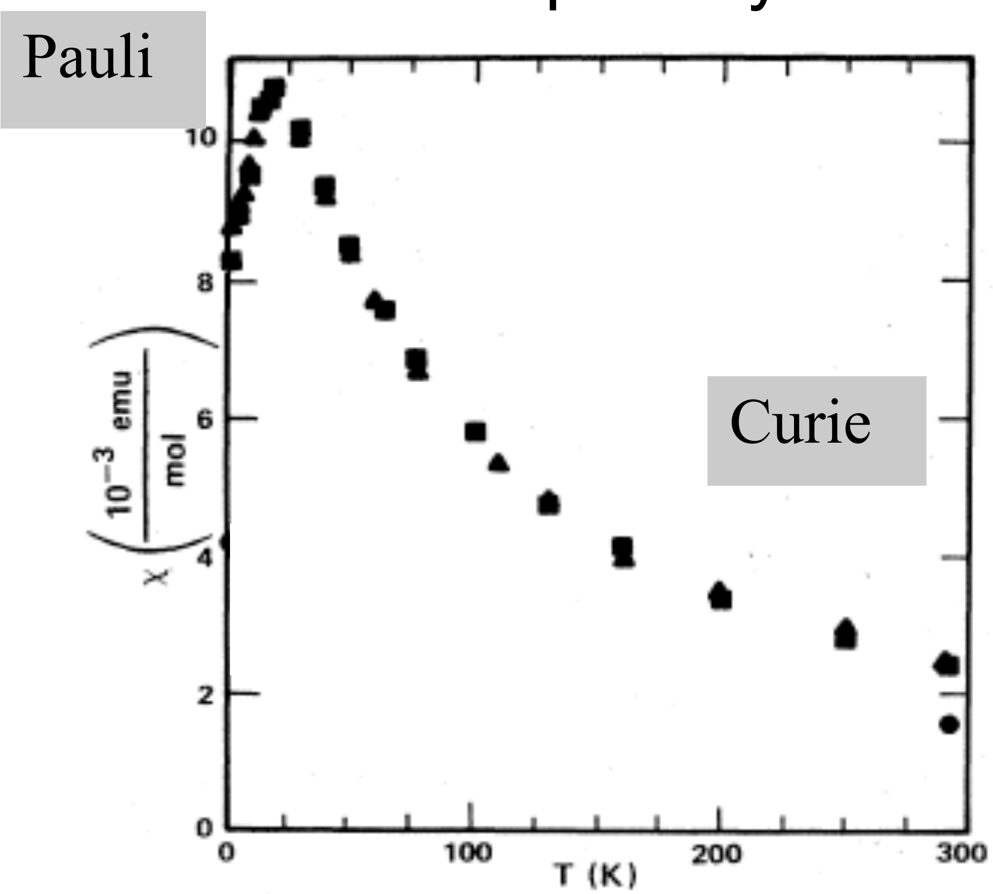

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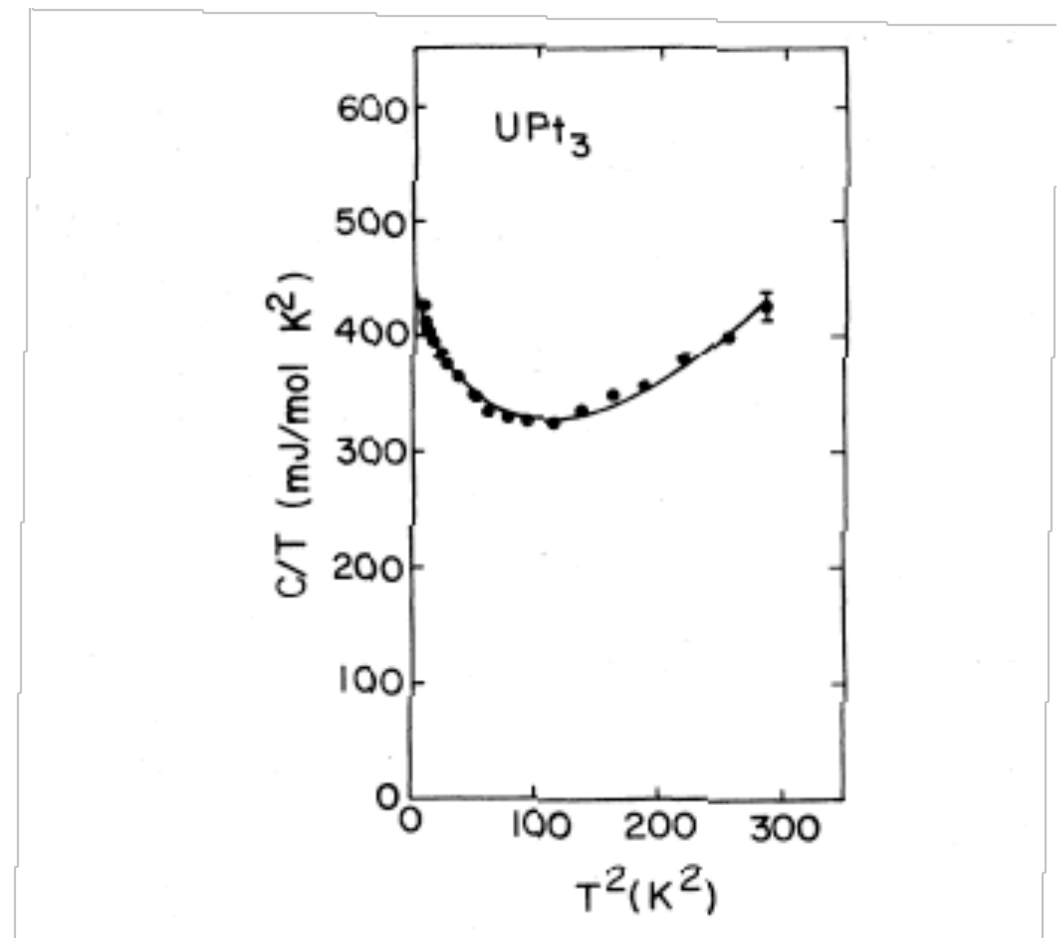
Stage one: QP formation

Pauli paramagnetism fully developed by $30K \sim 50\,T_C$



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

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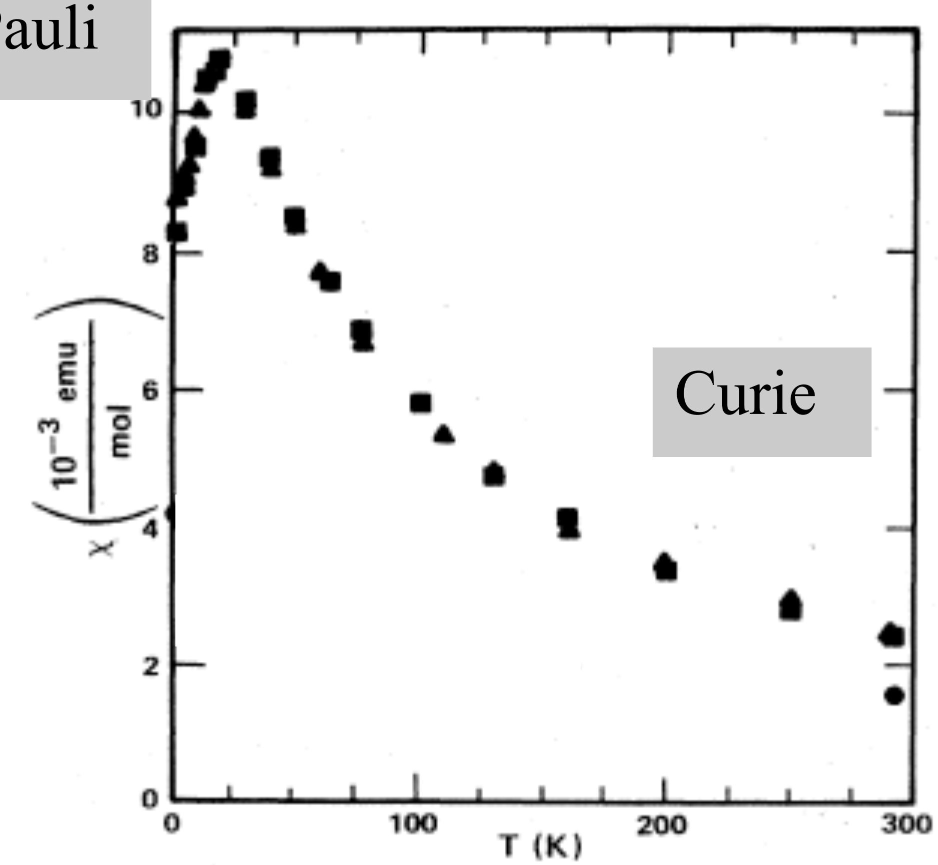
Susceptibility



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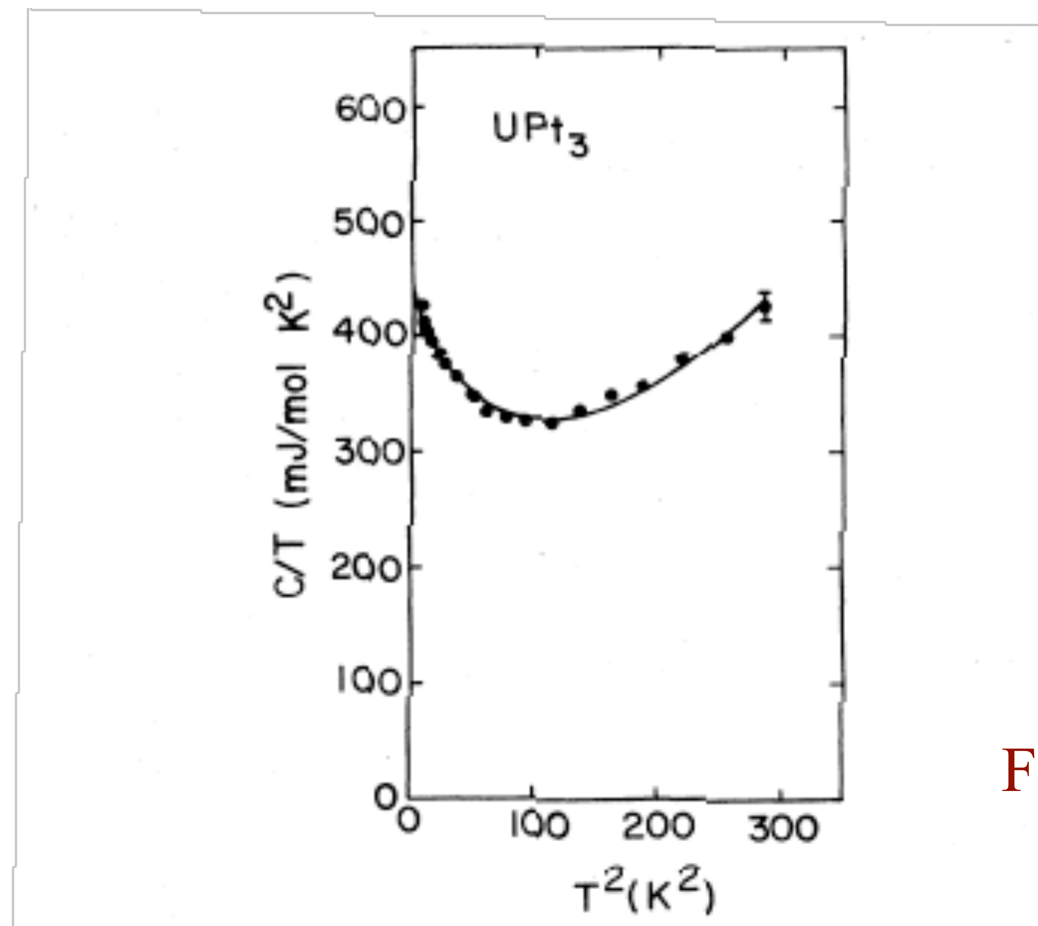

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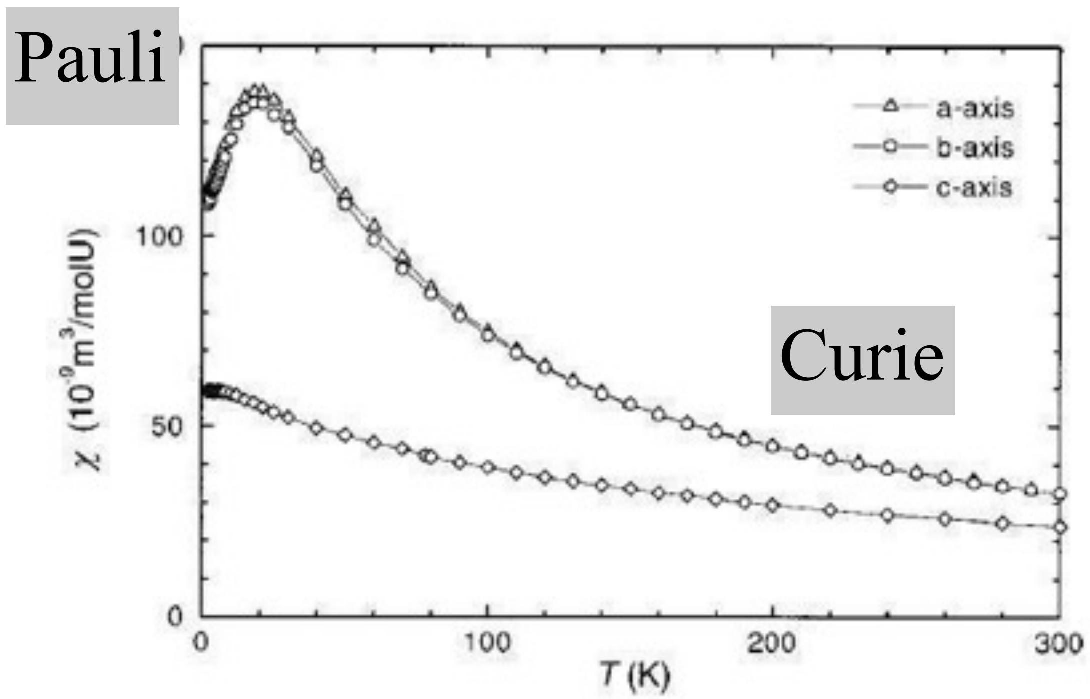
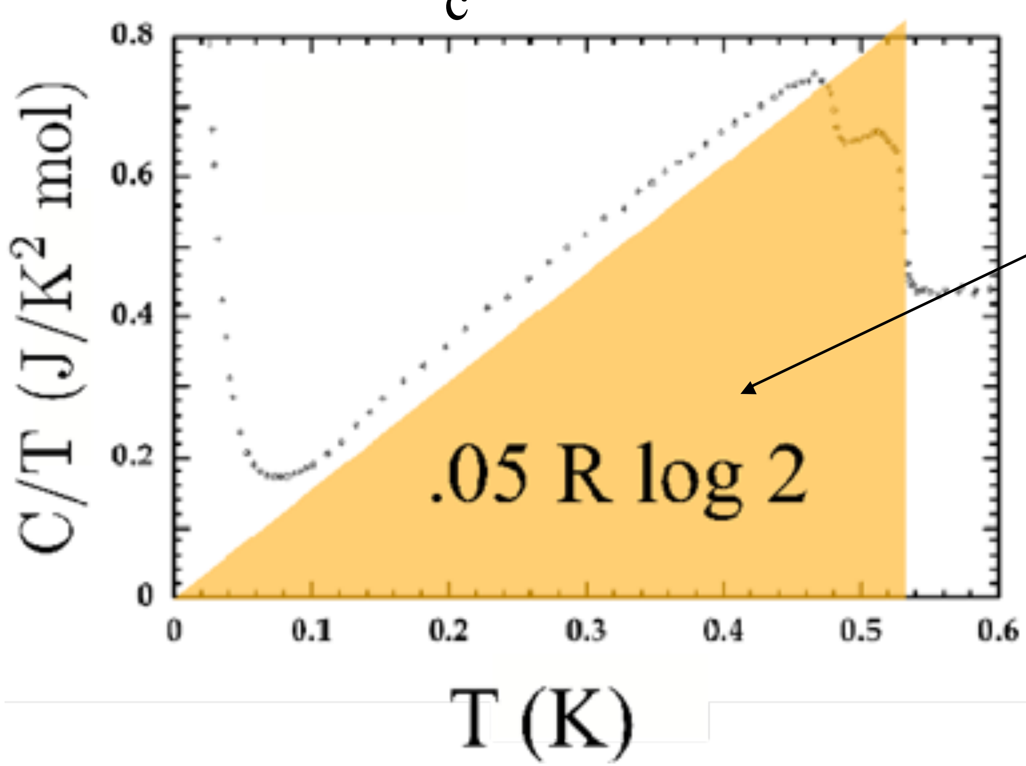
Spin Fluctuations

UPt_3



Pauli paramagnetic by 30K

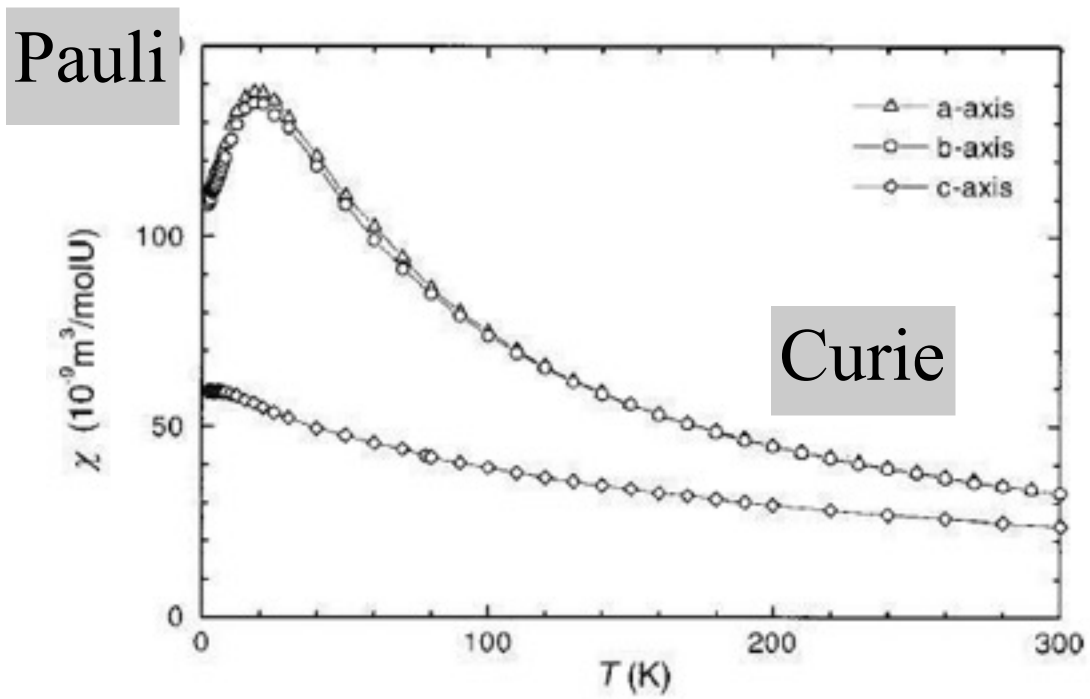
$T_c = 0.5K$



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

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

UPt_3



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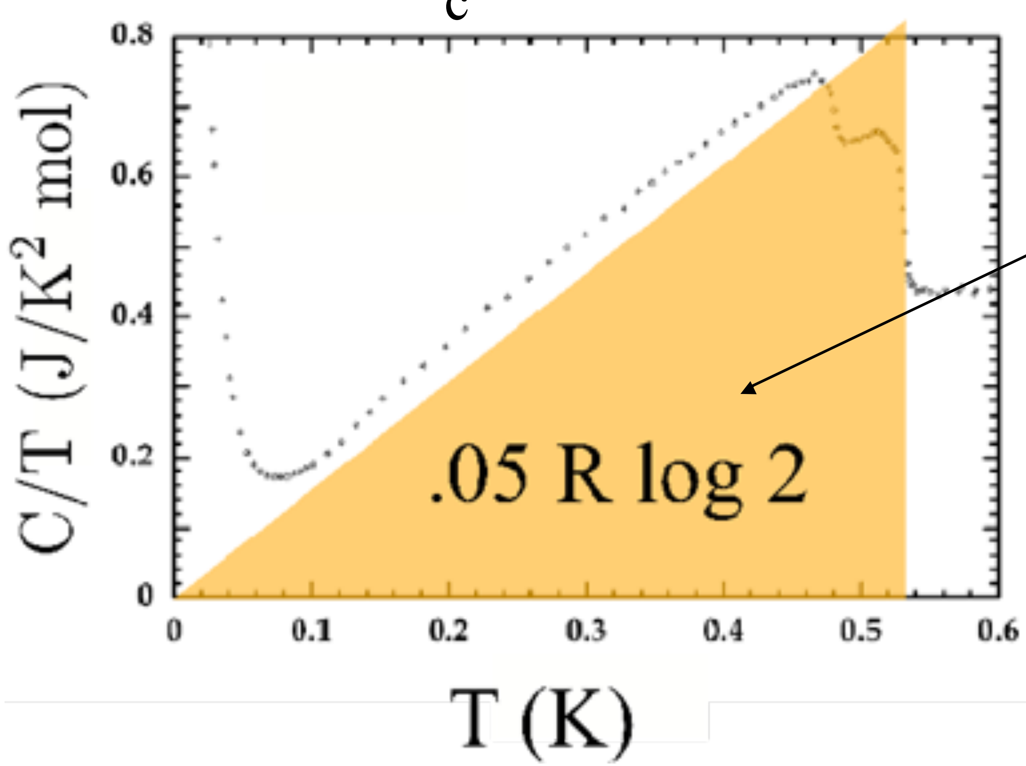

$$S = \int_0^T \frac{C(T')}{T'} dT'$$

Small condensation entropy
Spins are quenched
Two stages are well separated

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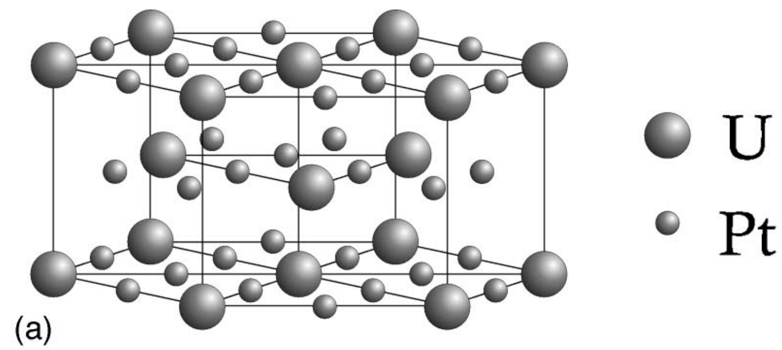
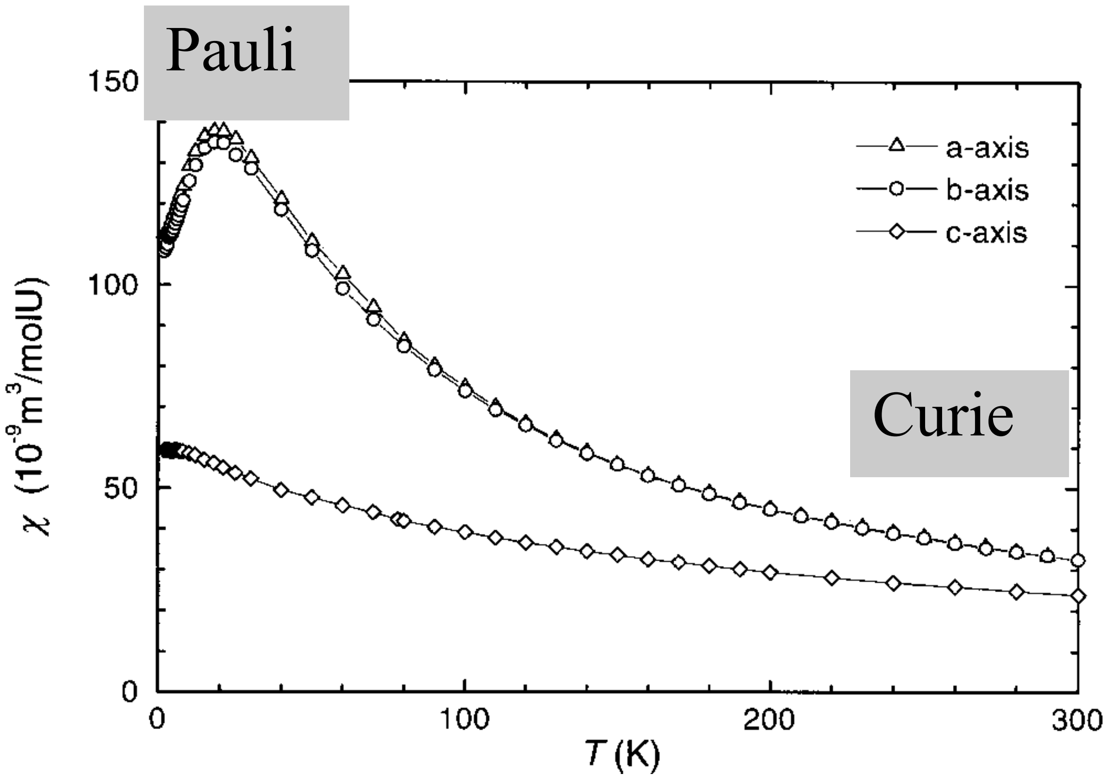
UPt$_3$: Classic HFSC



Joynt and Taillefer, RMP 2002.



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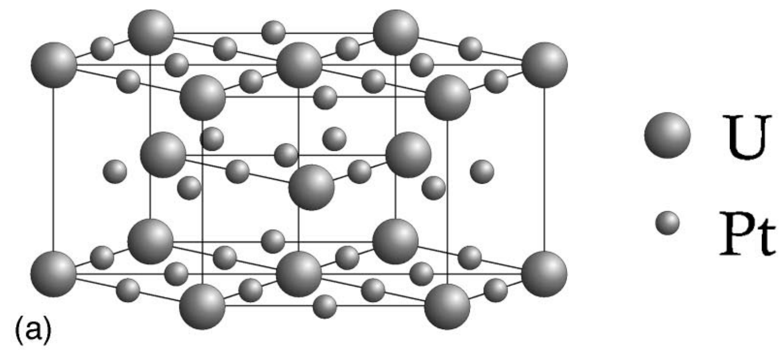

Joynt and Taillefer,
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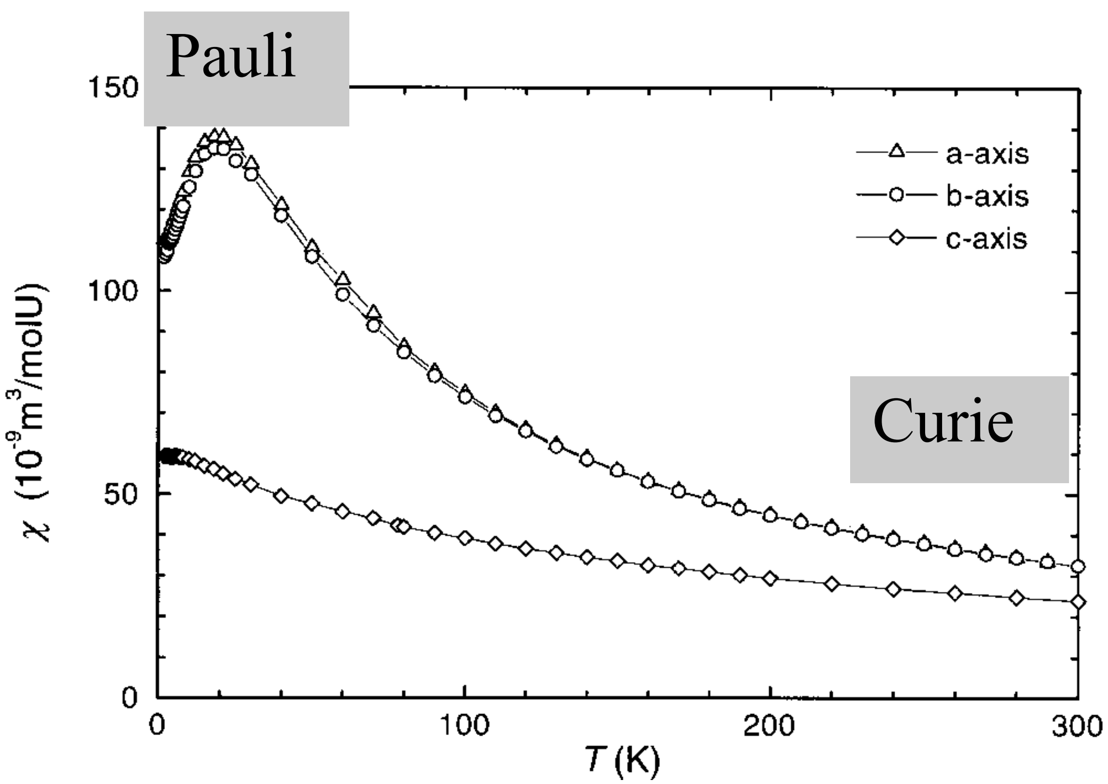
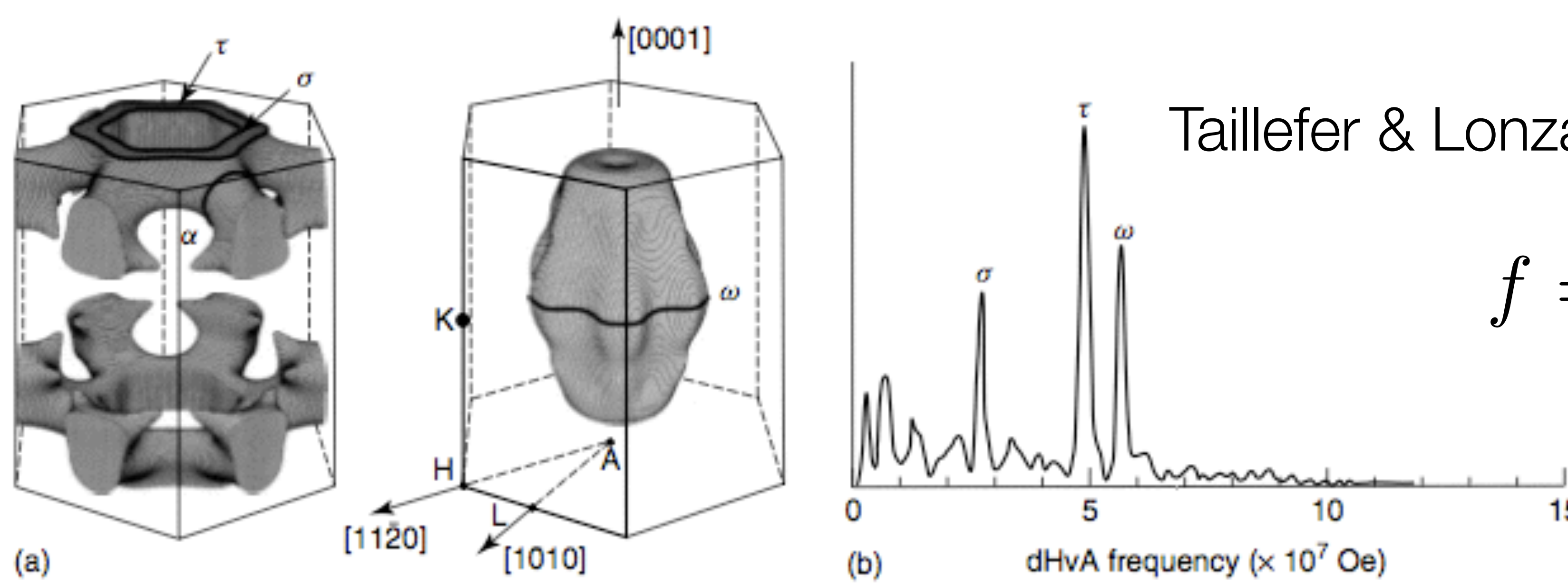
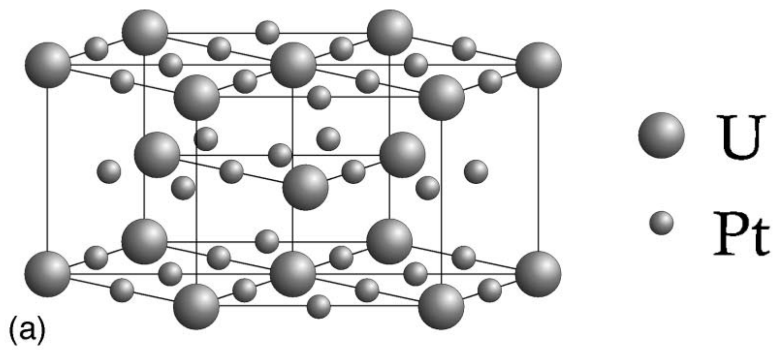


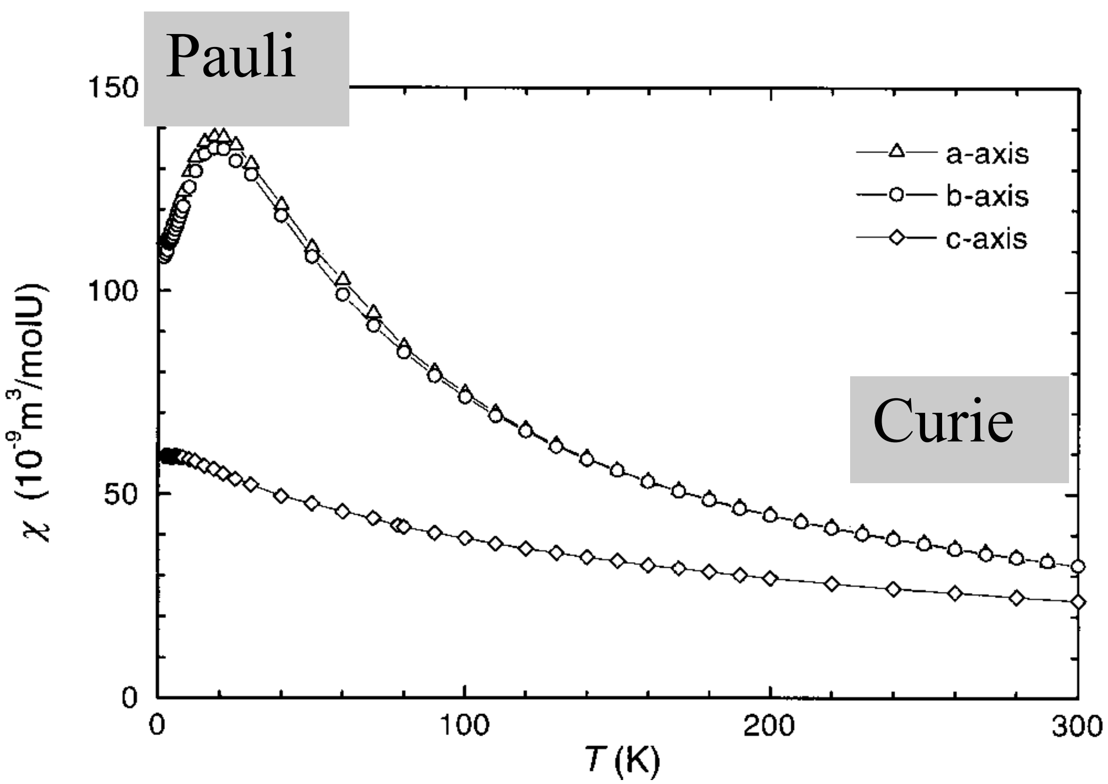


Taillefer & Lonzarich UPt$_3$ (1985)

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

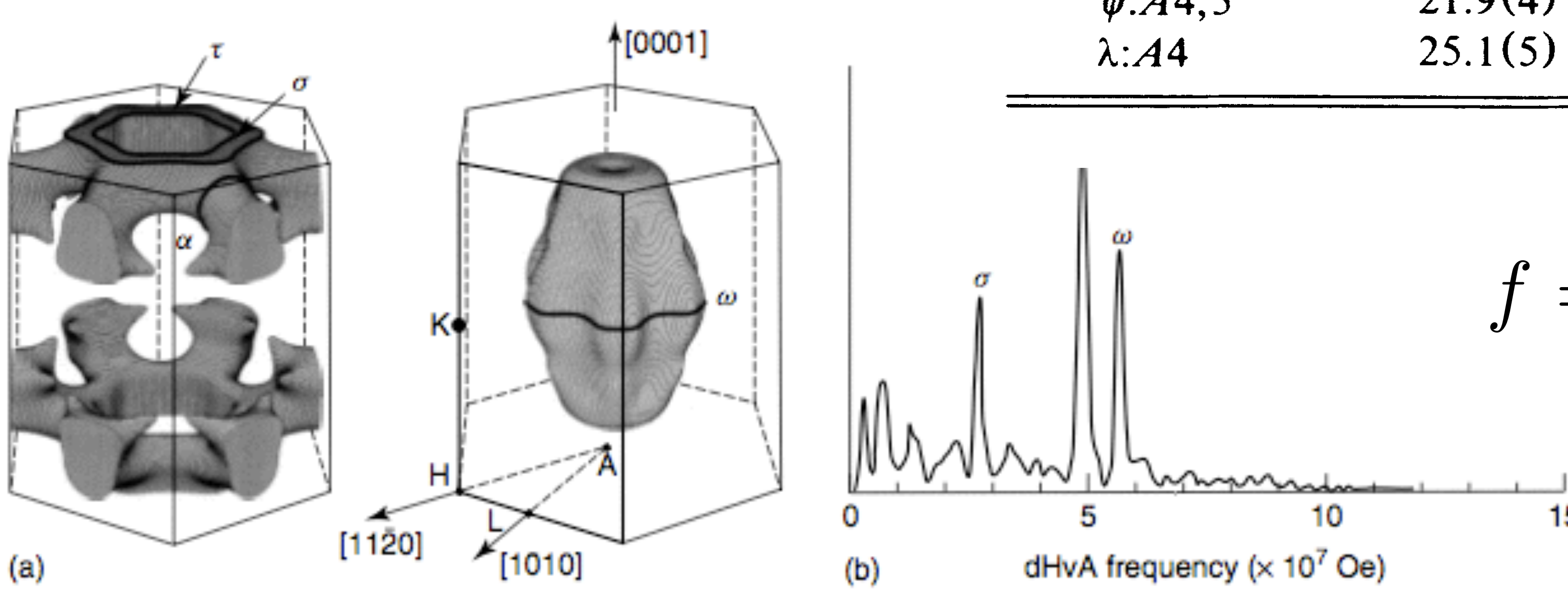
UPt_3: Classic HFSC





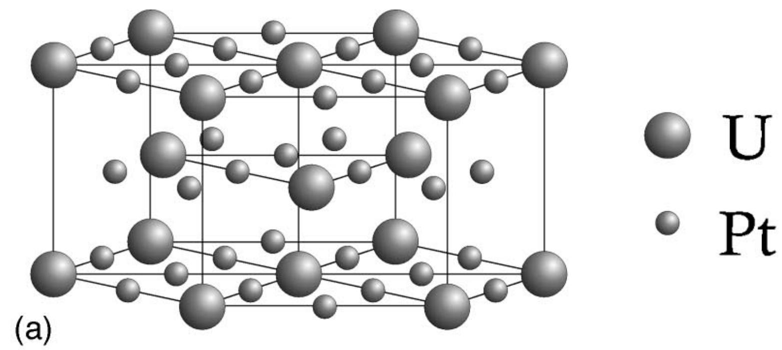
Joynt and Taillefer,
RMP 2002.

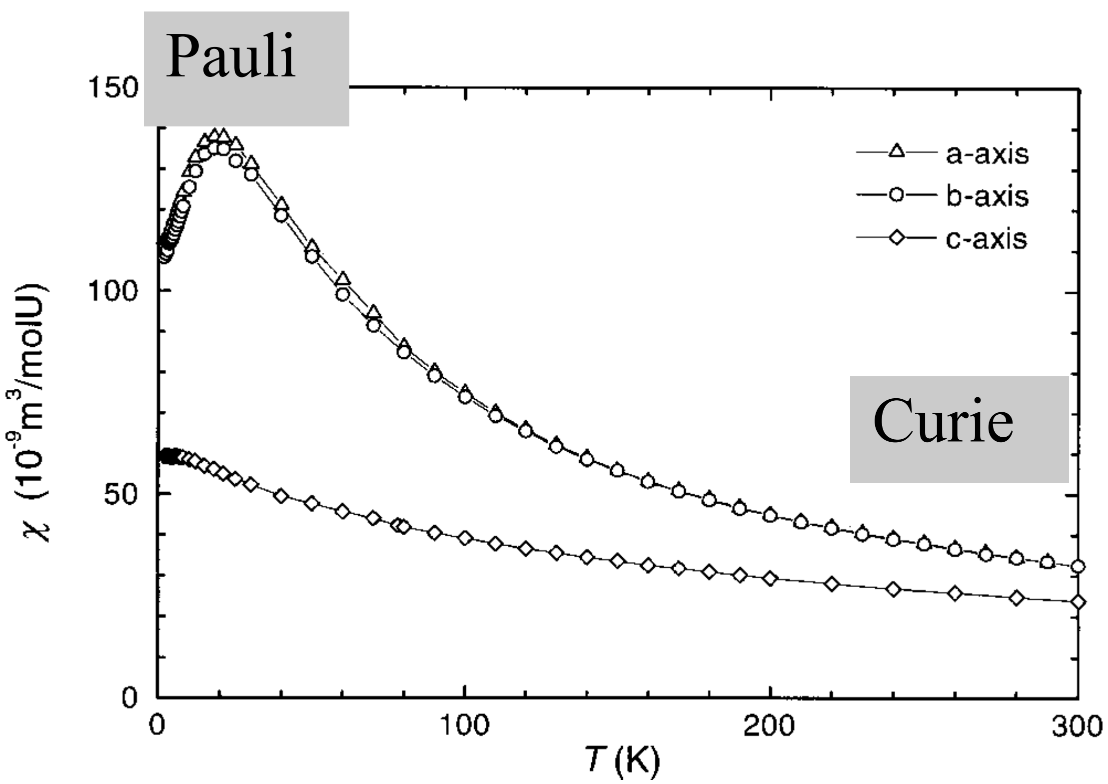
Branch:FS orbit	F (MG) Expt.	F (MG) Calc.	m^*/m_e Expt.	m^*/m_e Calc.
		a axis (ΓK)		
α:$ML4$	5.4(3)	10.4	25(3)	2.2
β:$L4$	6.0(4)	5.2	···	1.0
γ:$\Gamma 1$	7.3(3)	8.2	40(7)	2.0
δ:$A5$	14.0(3)	9.1	50(8)	1.9
ϵ:$\Gamma 2$	21.0(3)	24.0	60(8)	4.6
ω:$\Gamma 3$	58.5(5)	52.8	90(15)	5.3
		b axis (ΓM)		
α:$ML4$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



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

UPt3: Classic HFSC





Joynt and Taillefer, RMP 2002.

Branch:*FS* orbit	F (MG) Expt.	Calc.	m^*/m_e Expt.	Calc.
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α:$ML4$	4.1(2)		15(5)	
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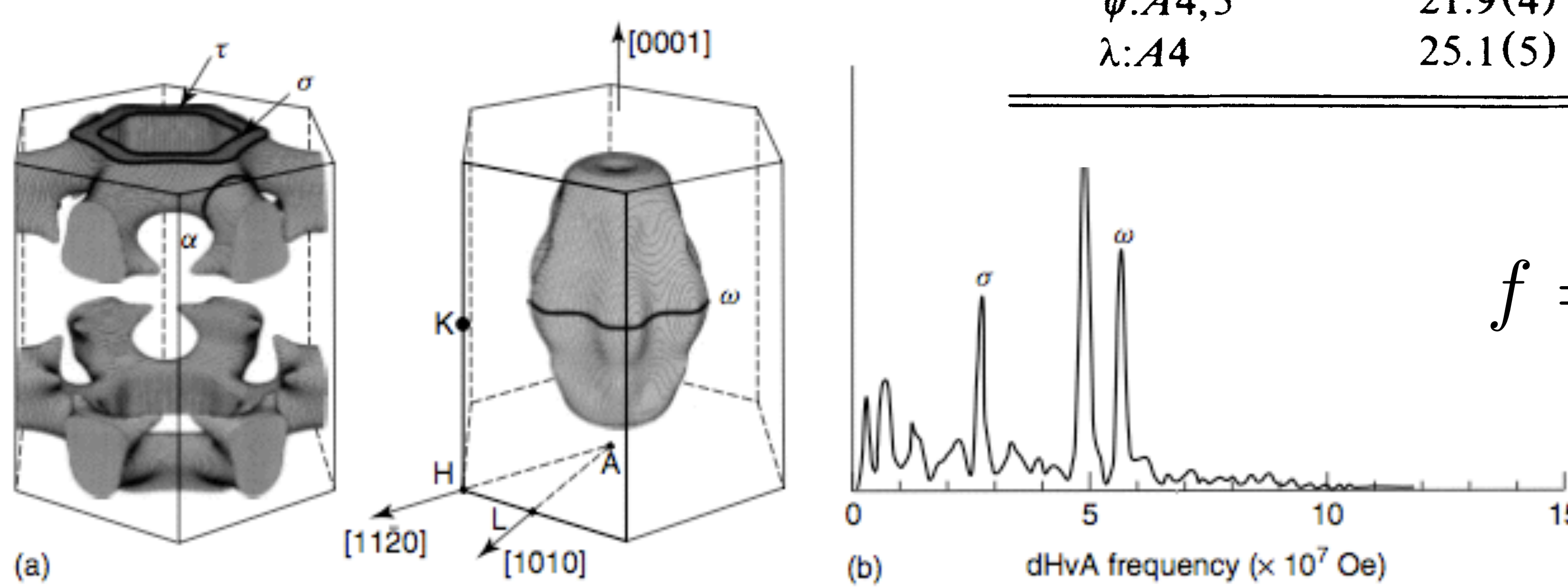
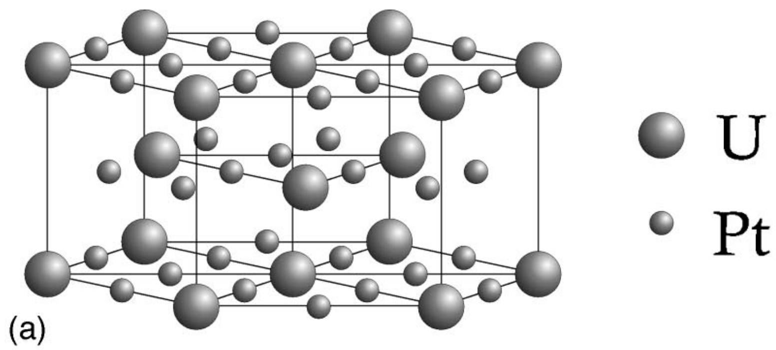
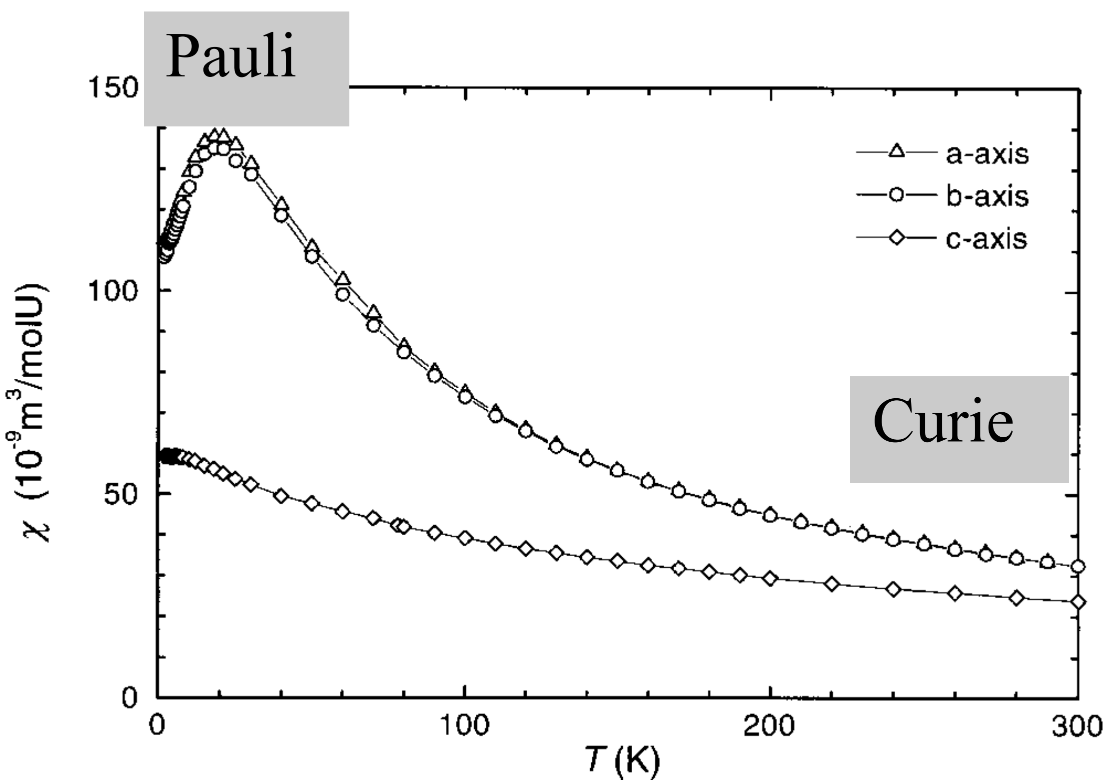


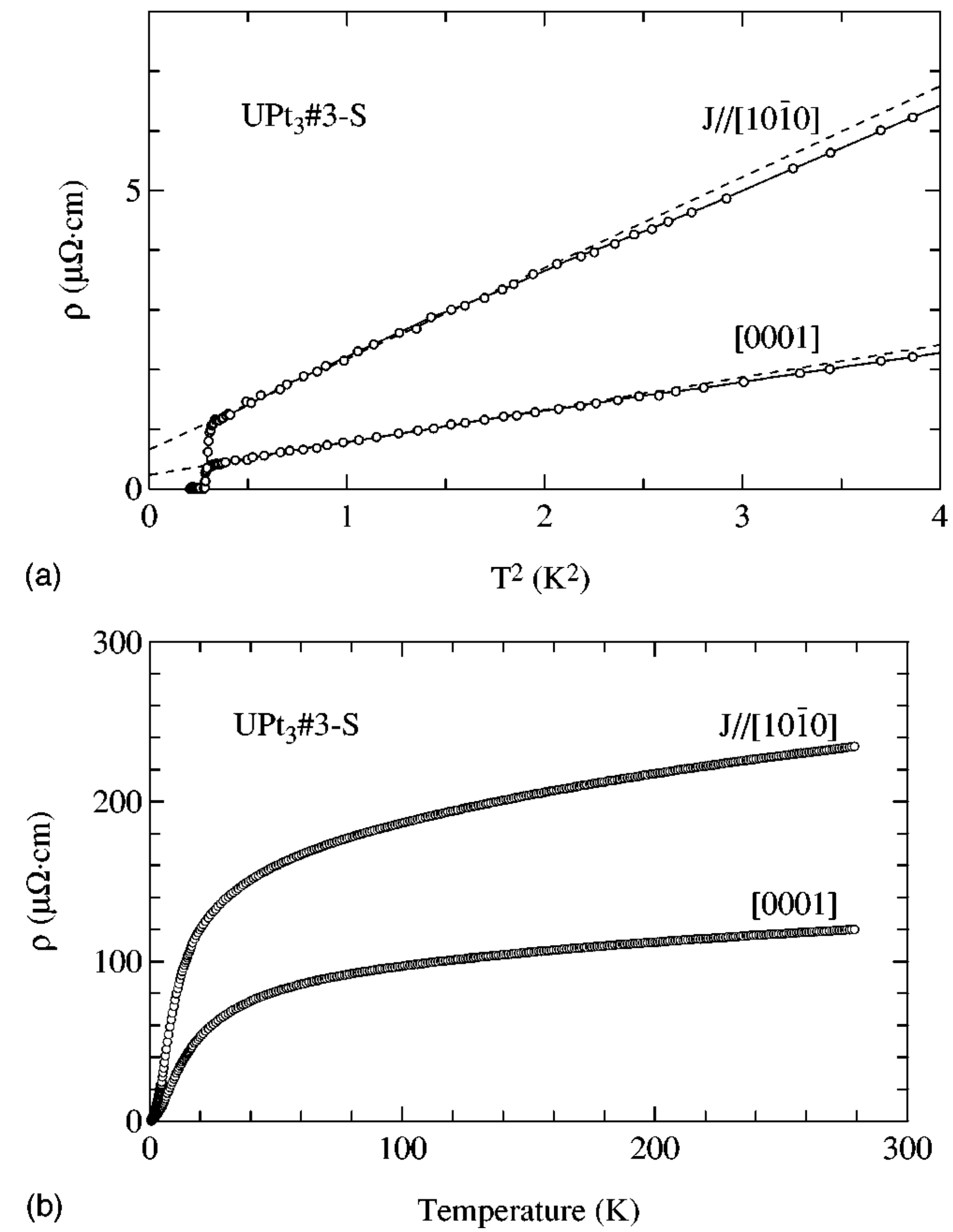
$$f = A\left(\frac{\hbar^2}{2\pi e}\right)$$

UPt$_3$: Classic HFSC

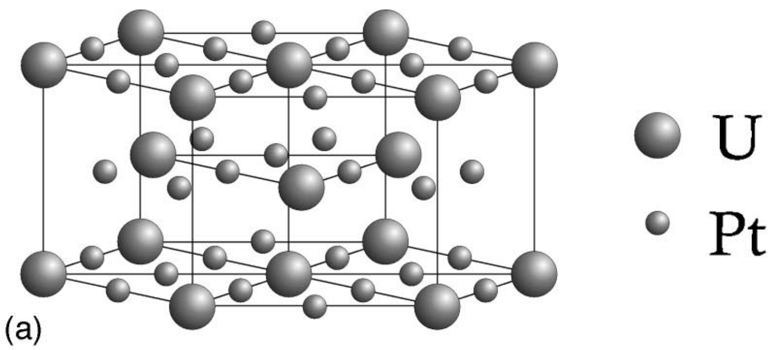
Joynt and Taillefer, RMP 2002.



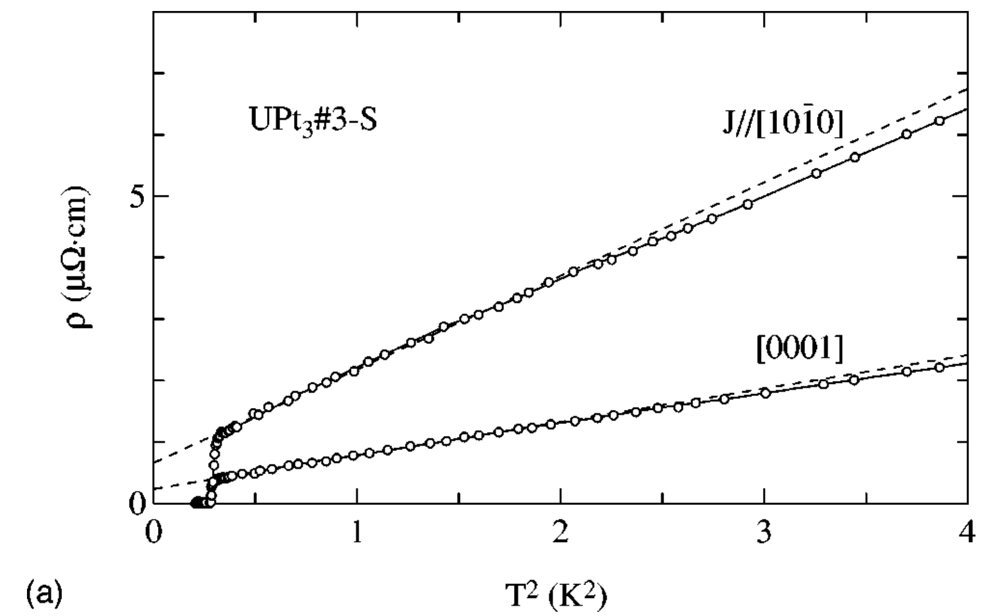


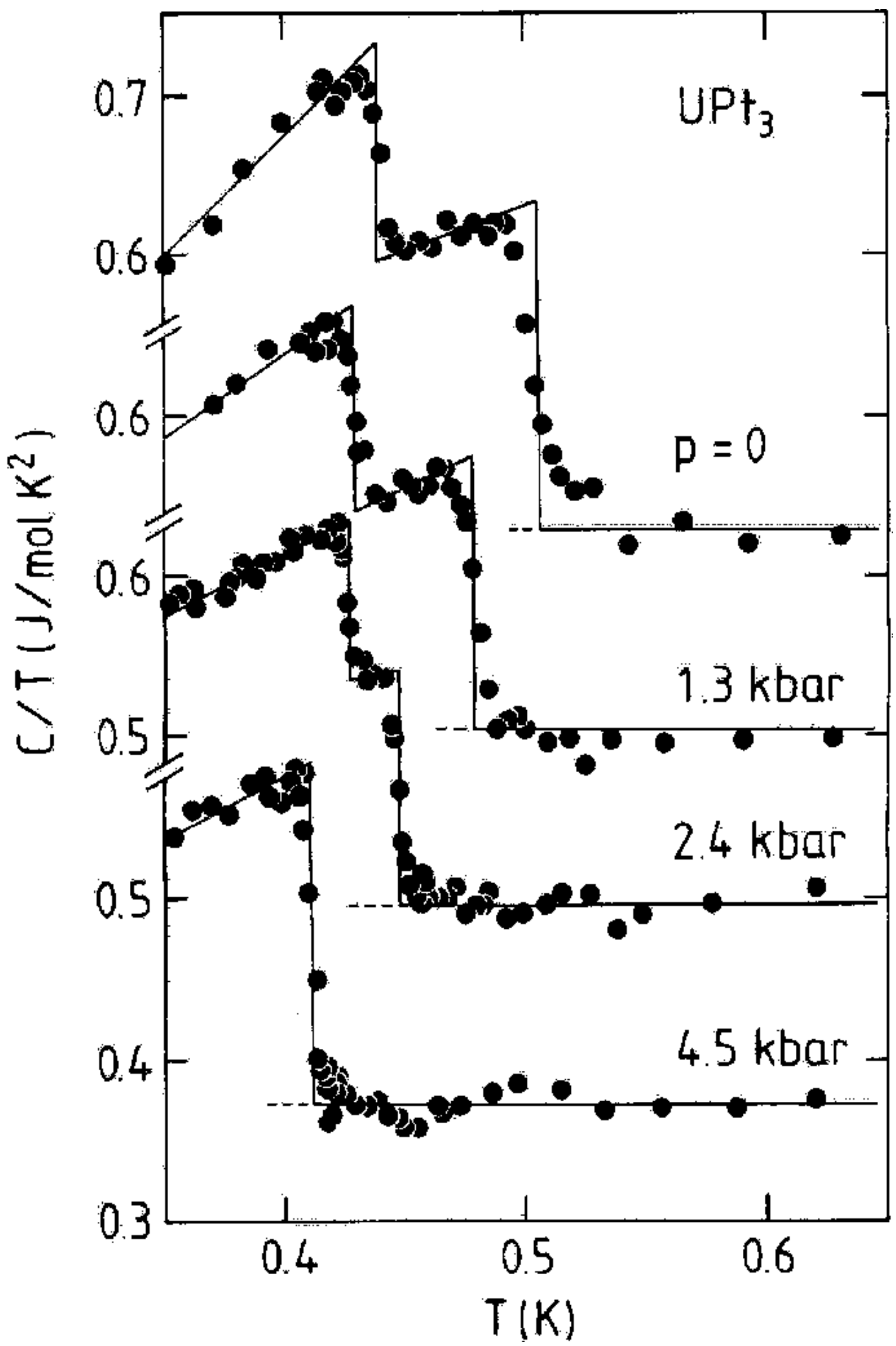


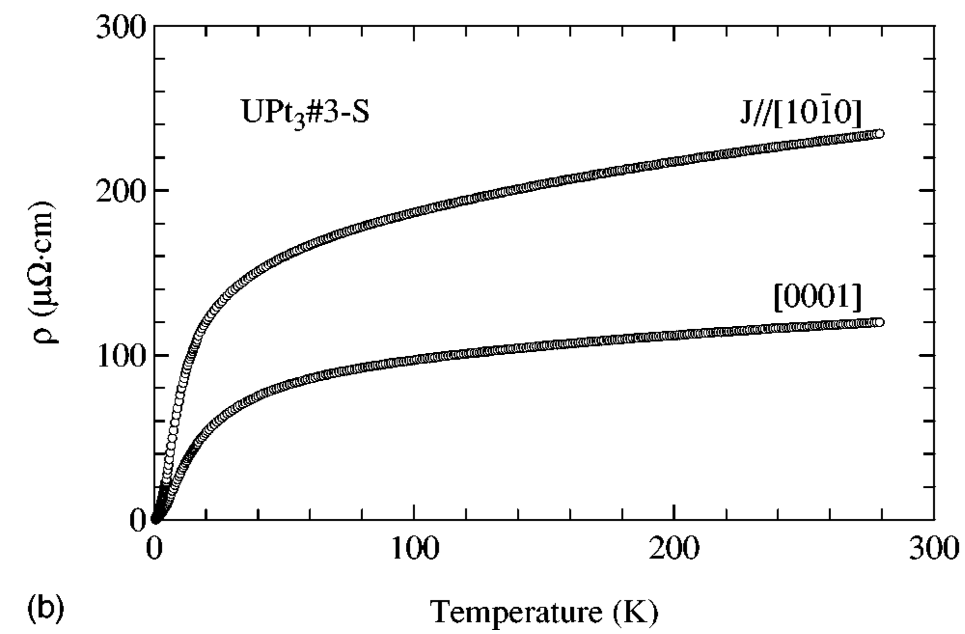
UPt$_3$: Classic HFSC



Joynt and Taillefer,
RMP 2002.

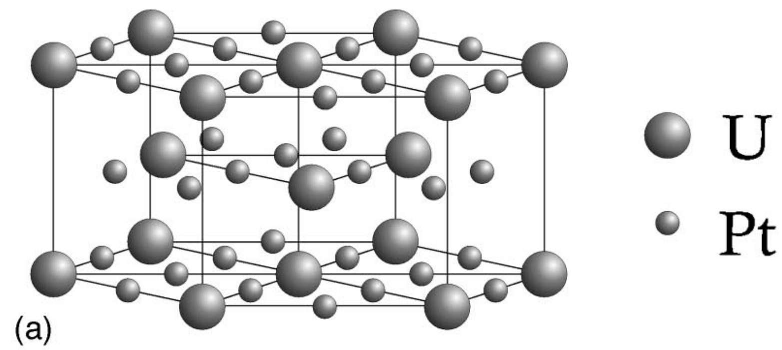


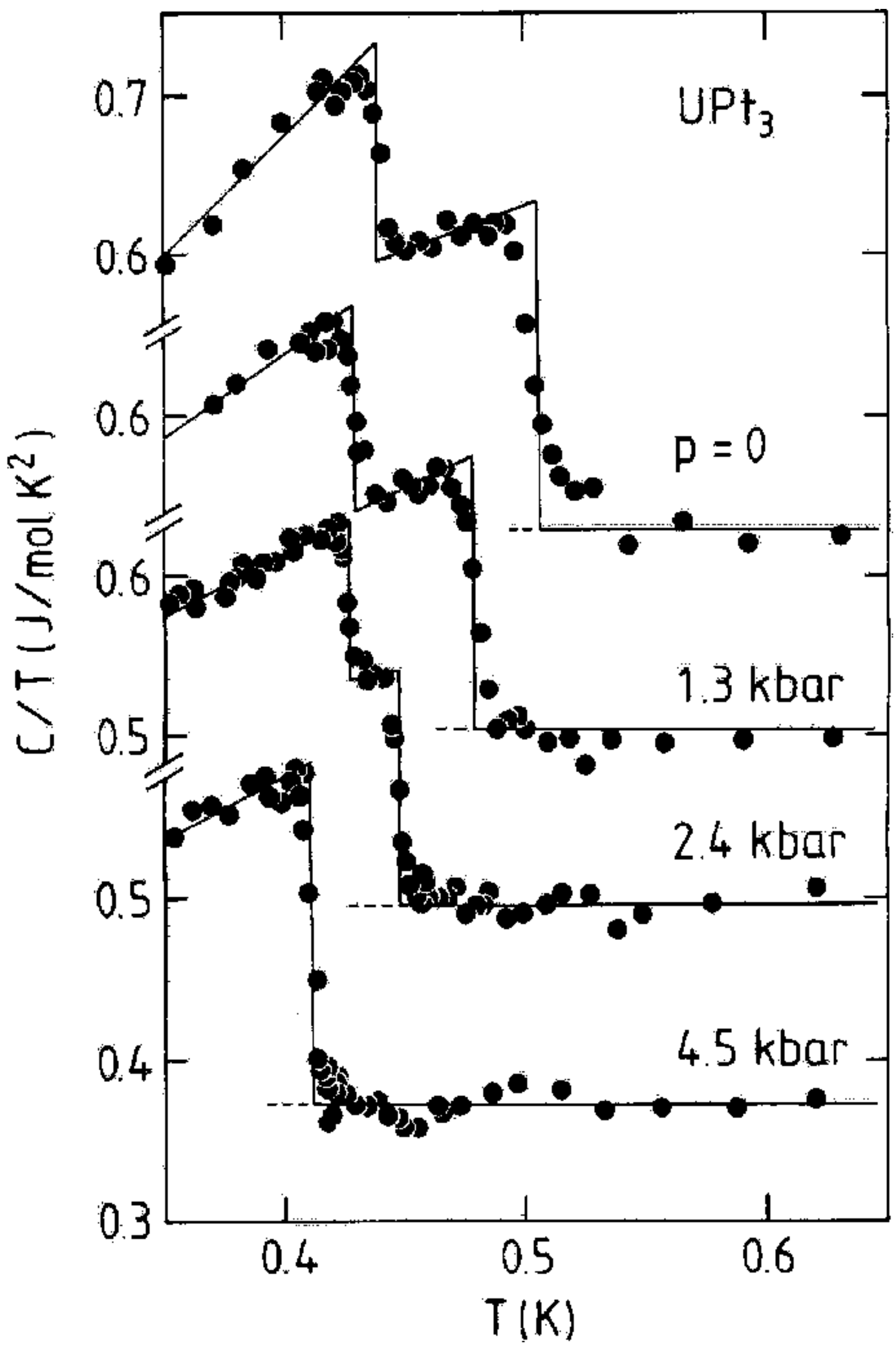


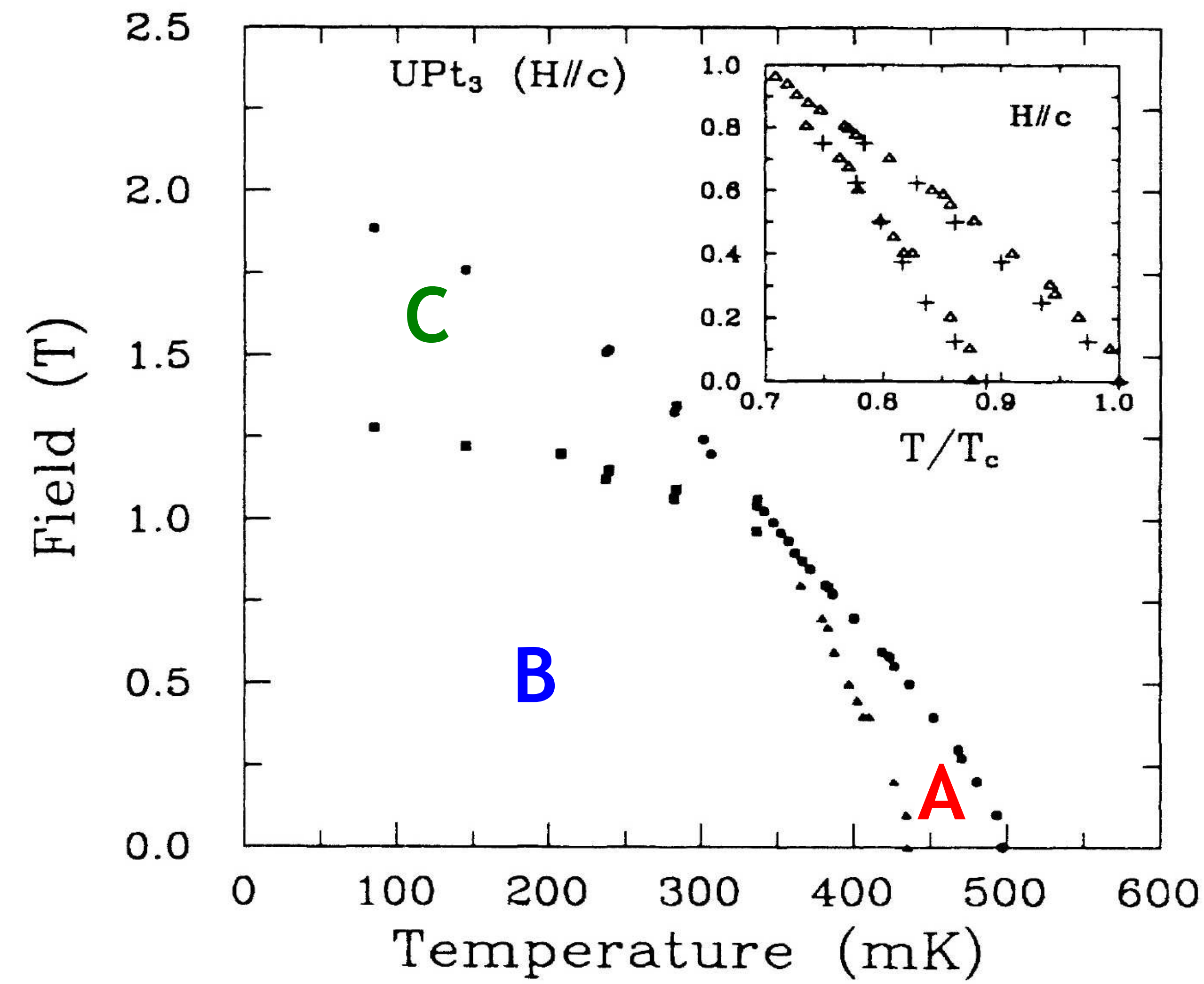


UPt$_3$: Classic HFSC

Joynt and Taillefer,
RMP 2002.







Magnetic Order and Fluctuations in Superconducting UPt_3

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C. Broholm and J. K. Kjems
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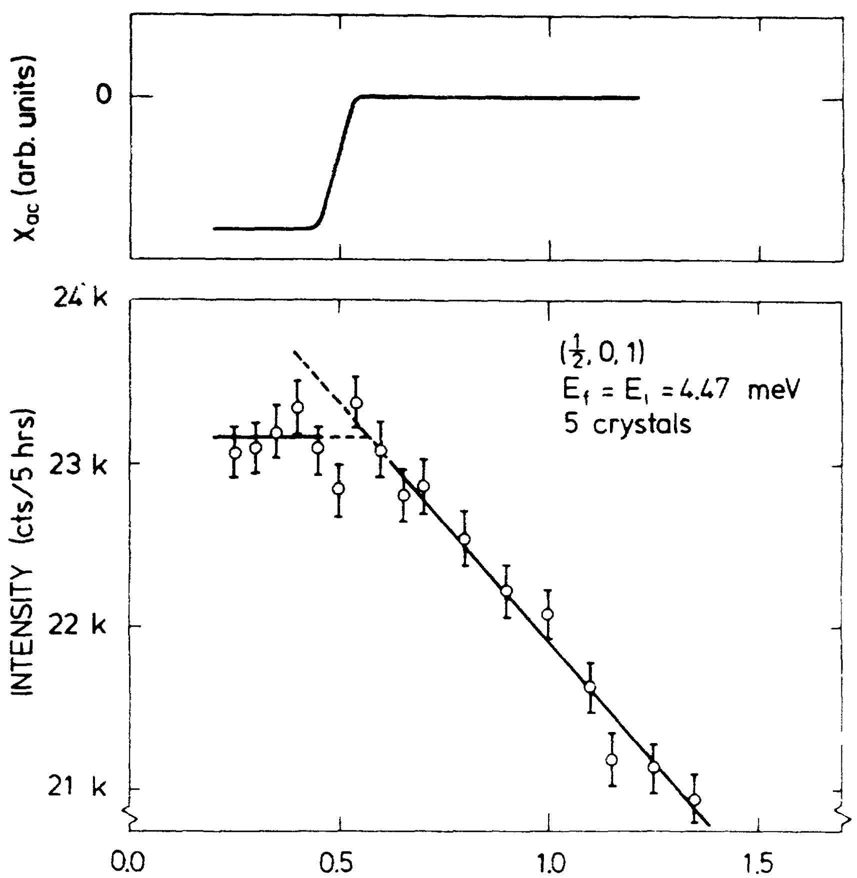
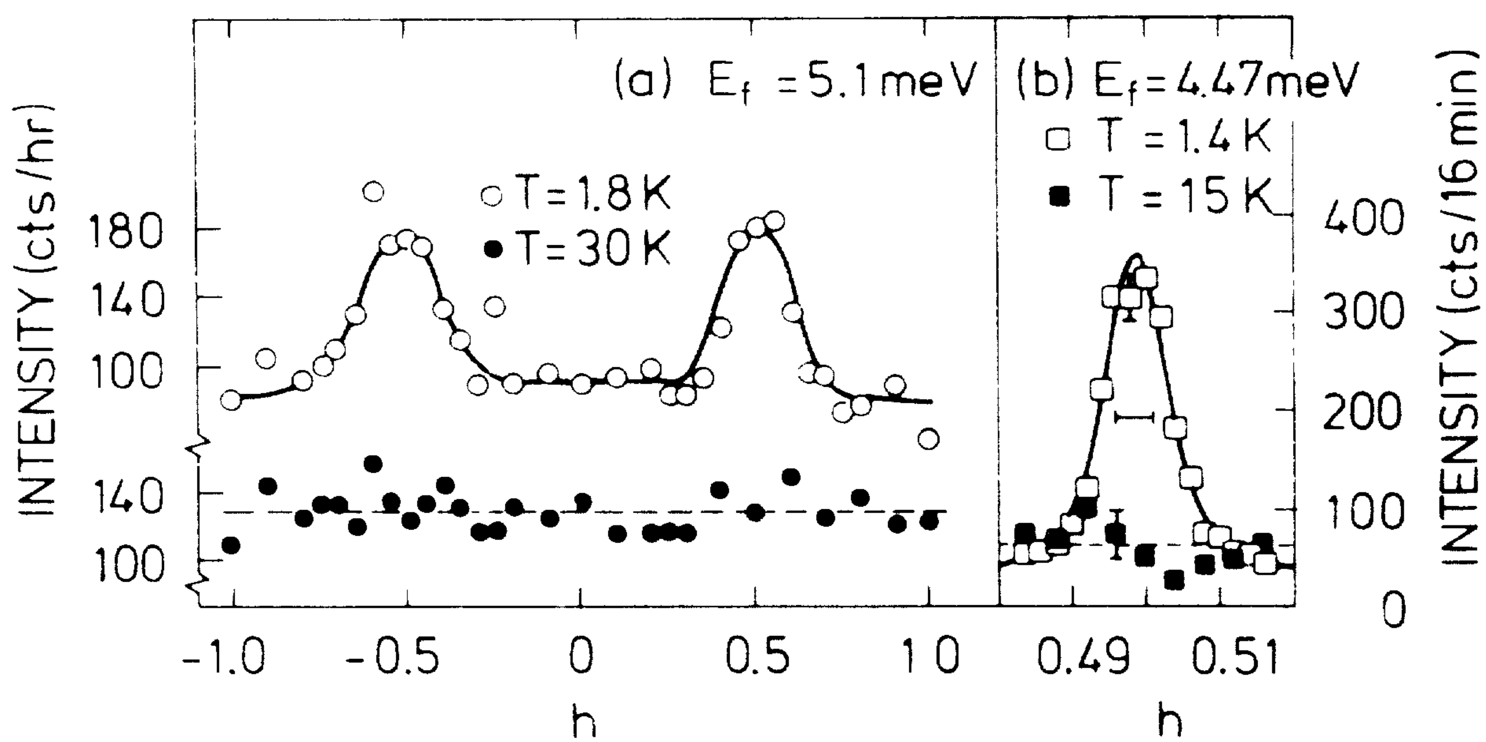
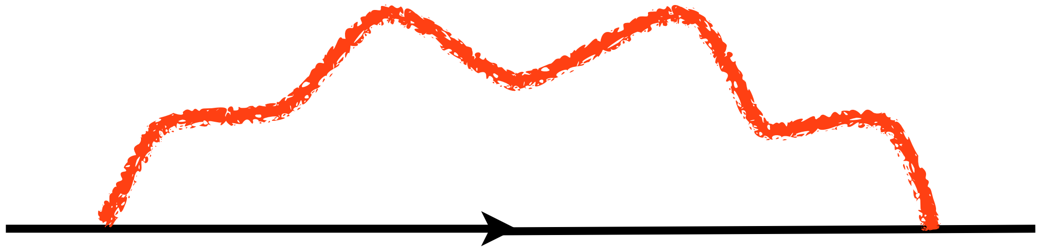
and

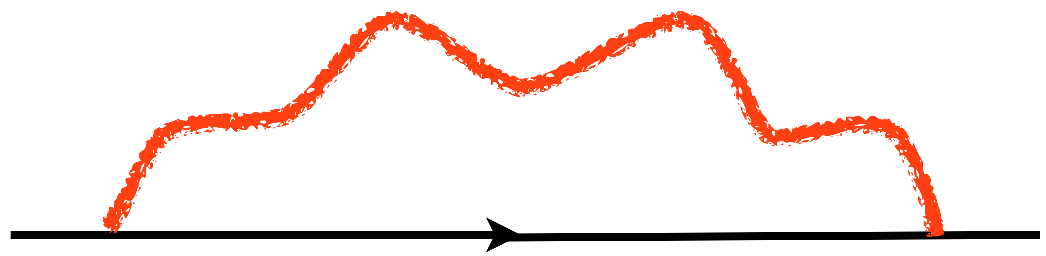
J. Baumann and J. Hufnagl
University of Konstanz, D-7750 Konstanz, Federal Republic of Germany
(Received 24 September 1987)



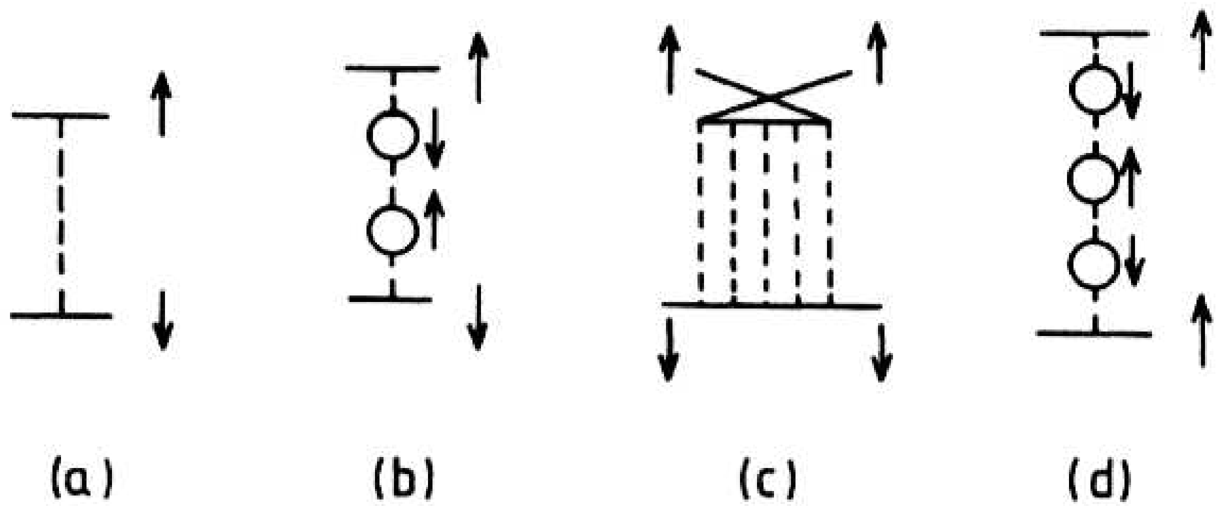




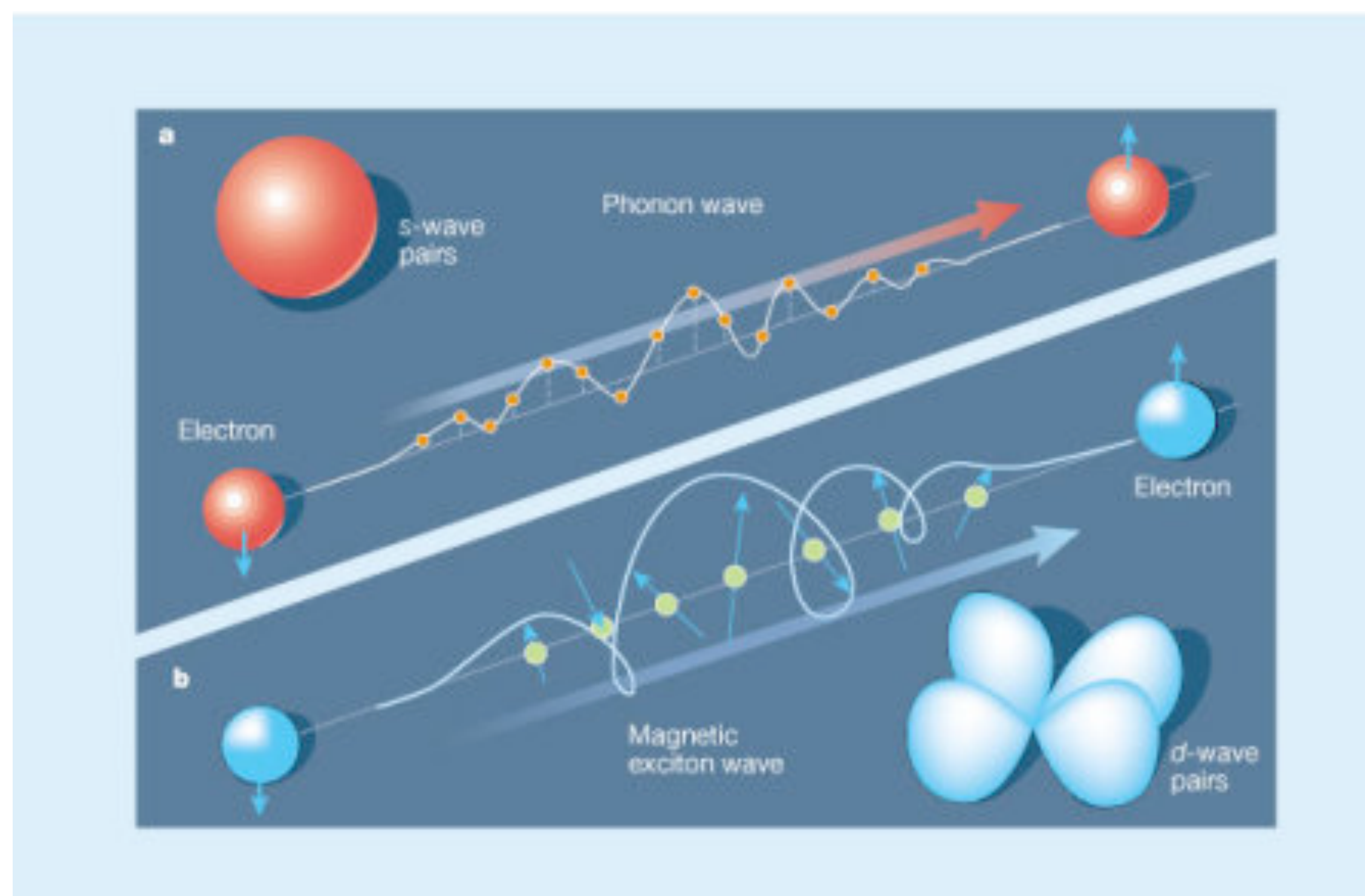
AFM -> d-wave pairing.



AFM -> d-wave pairing.



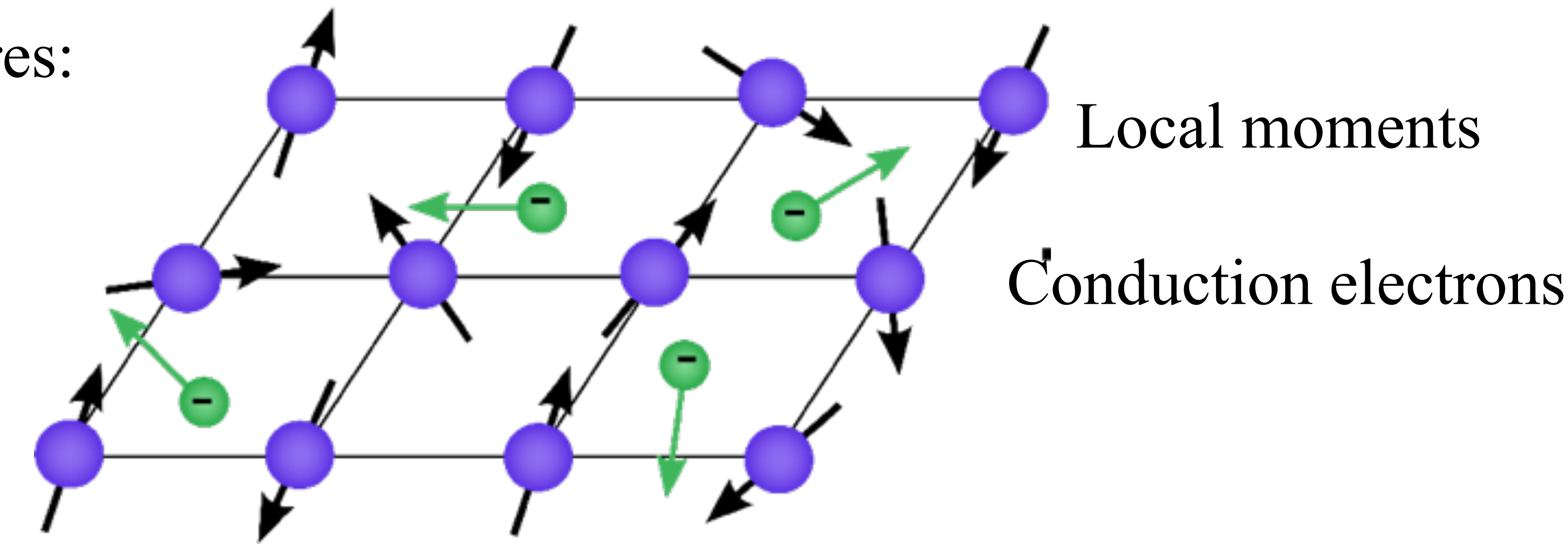
Beal-Monod, Bourbonnais and Emery (1986)
Scalapino, Loh and Hirsch (1986)
Miyake, Schmitt-Rink and Varma (1986)



Conventional
Heavy Fermion SC:

"Conventional" heavy fermion superconductivity

At high temperatures:



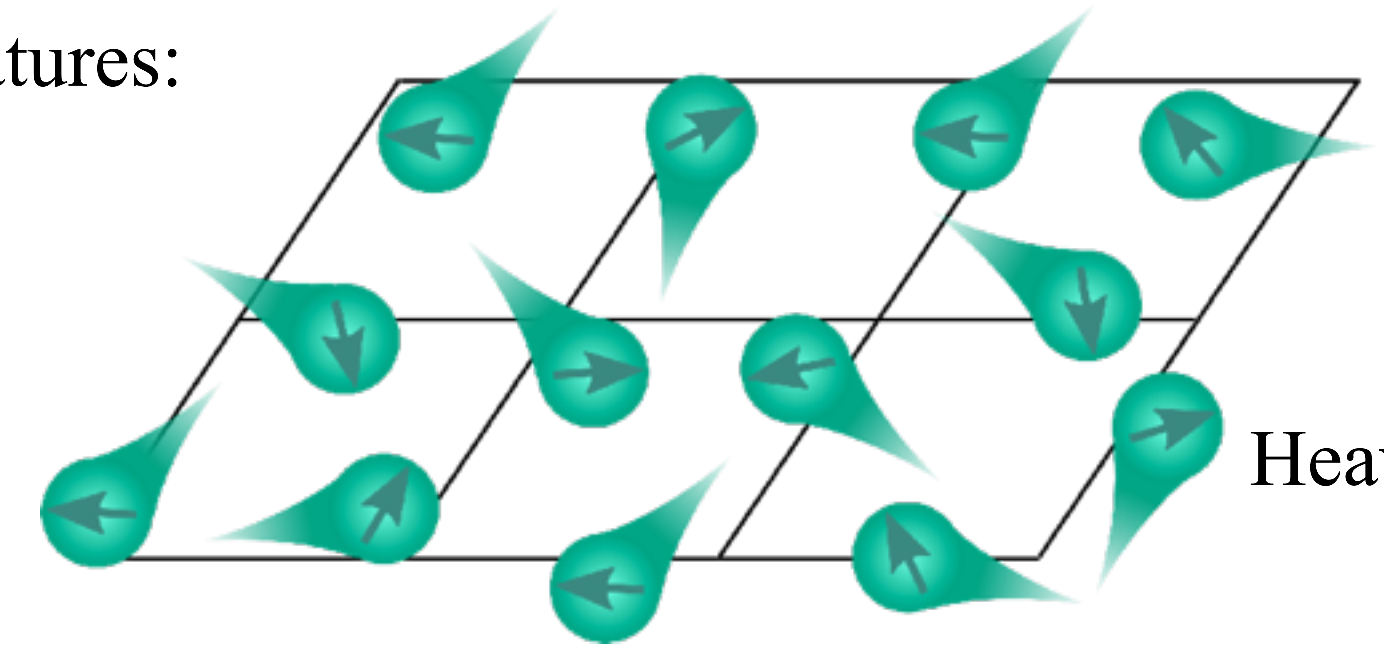
How do we get from here to heavy Cooper pairs?

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?

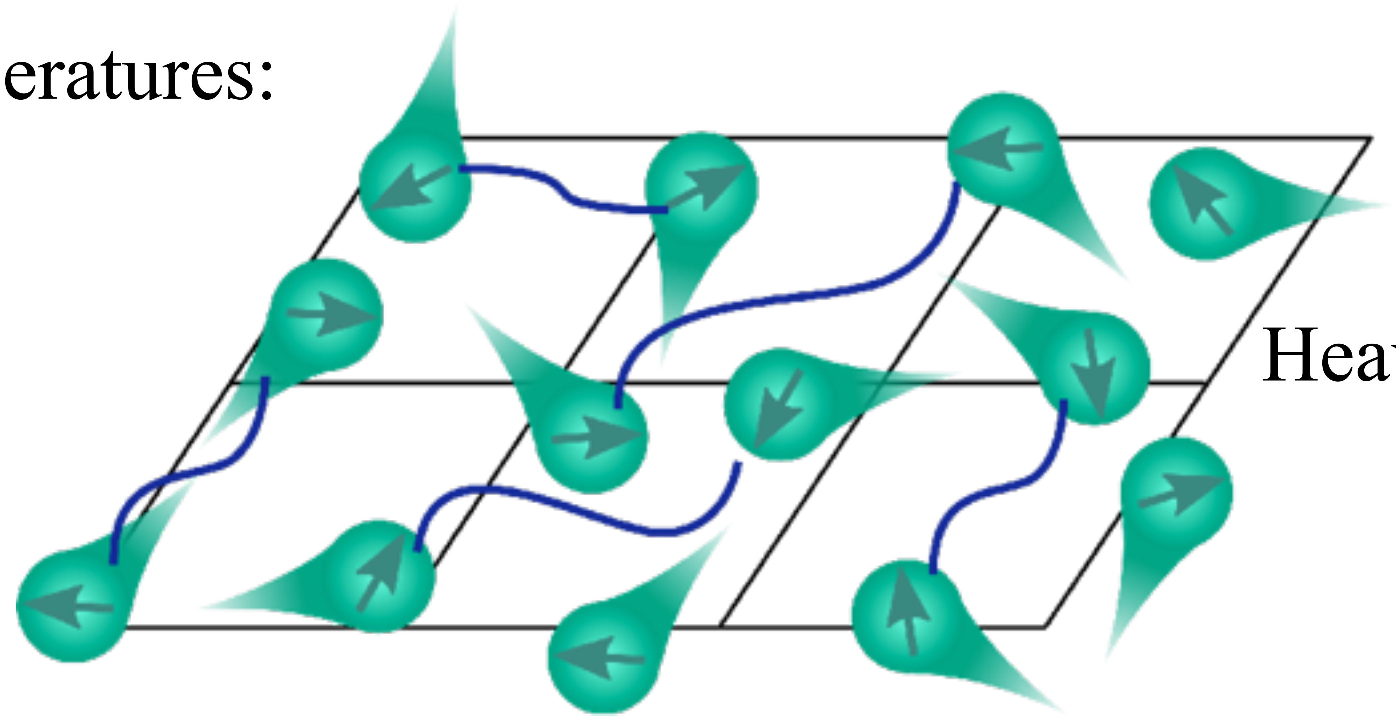
1. The local moments quench [via the Kondo effect], forming heavy quasiparticles

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:

$T < T_C$



Heavy Cooper Pairs

How do we get from here to heavy Cooper pairs?

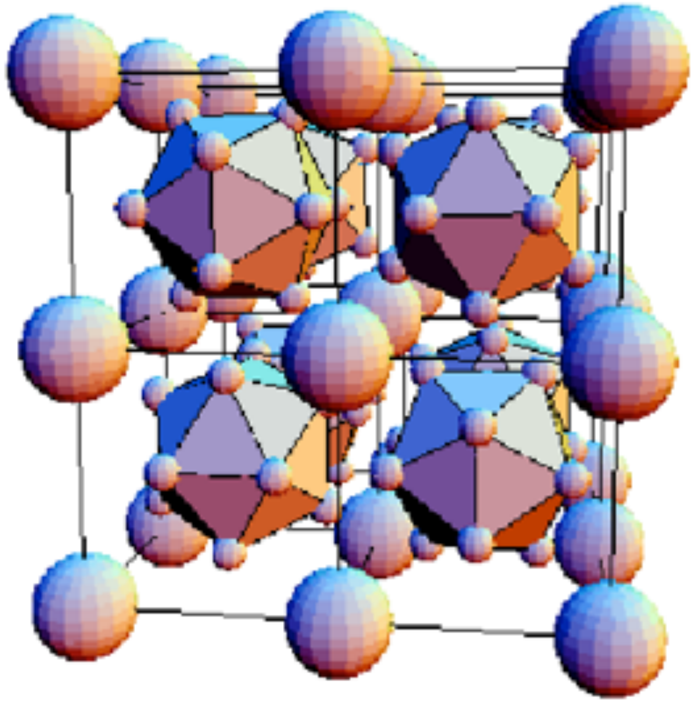
1. The local moments quench [via the Kondo effect], forming heavy quasiparticles

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

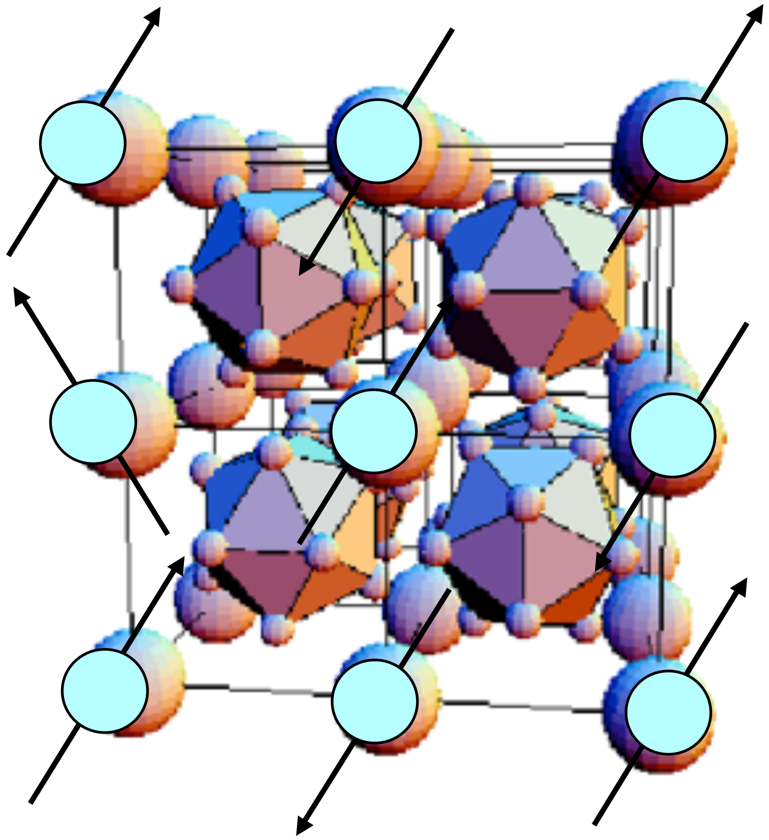
These two stages are well separated.

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

Heavy Fermion SC: Bad and Ugly

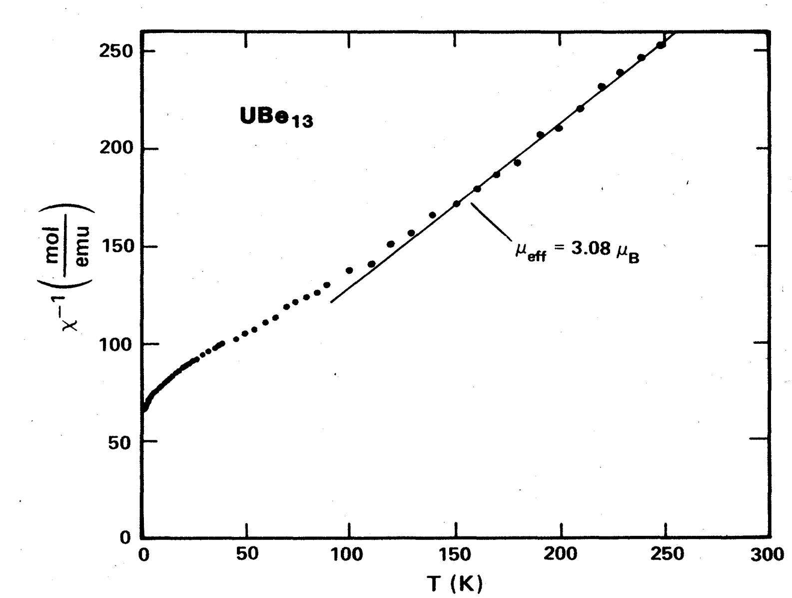


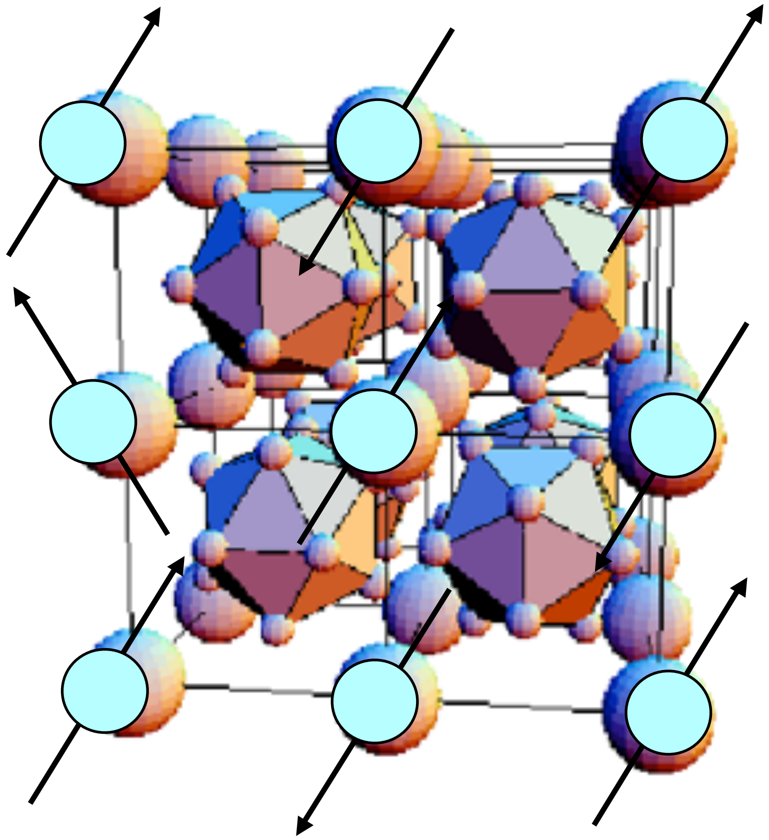
UBe_{13}



UBe_{13}

Local Moments

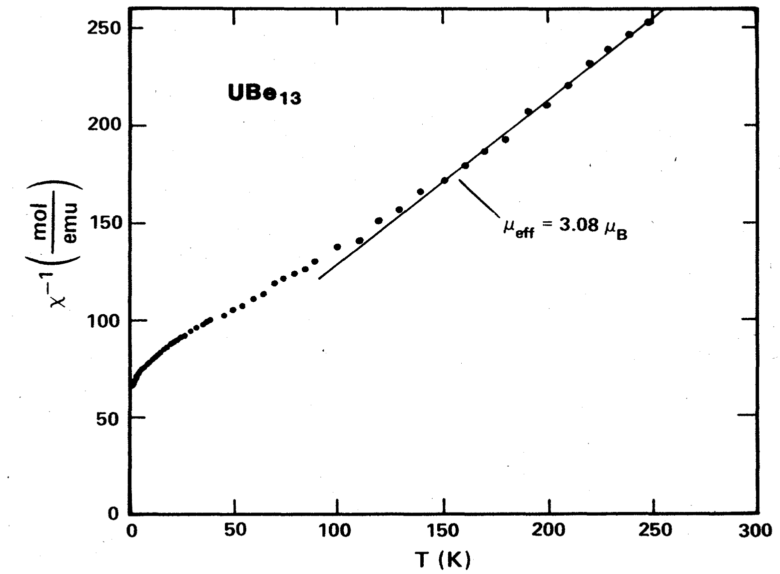


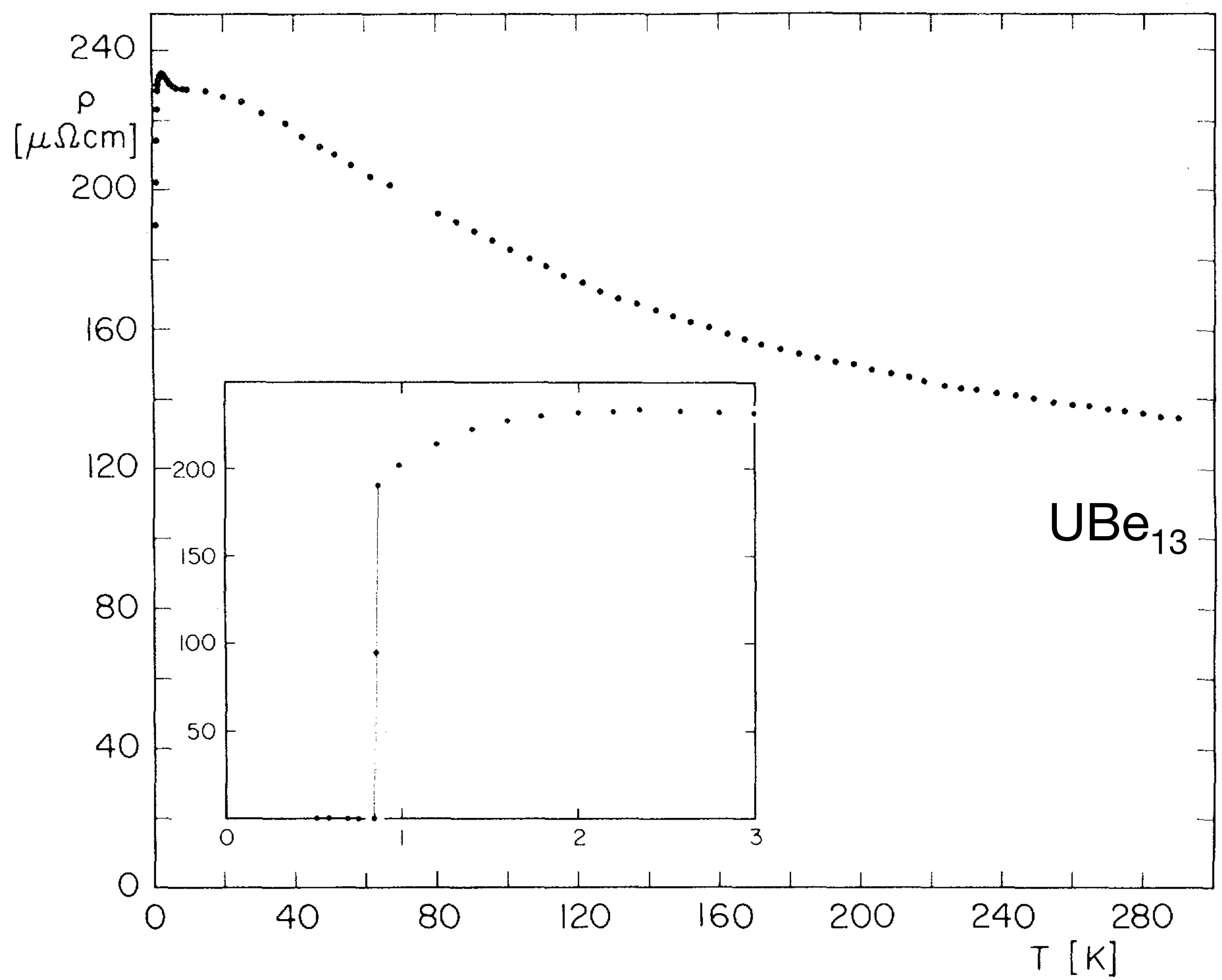


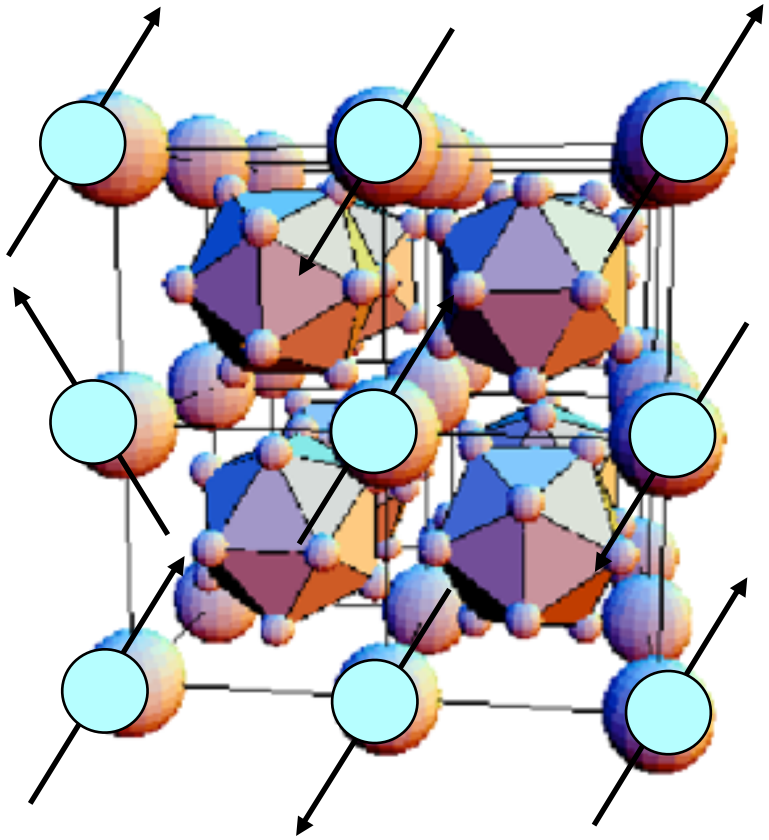
Local Moments

UBe$_{13}$

Ott, Fisk, Smith (198



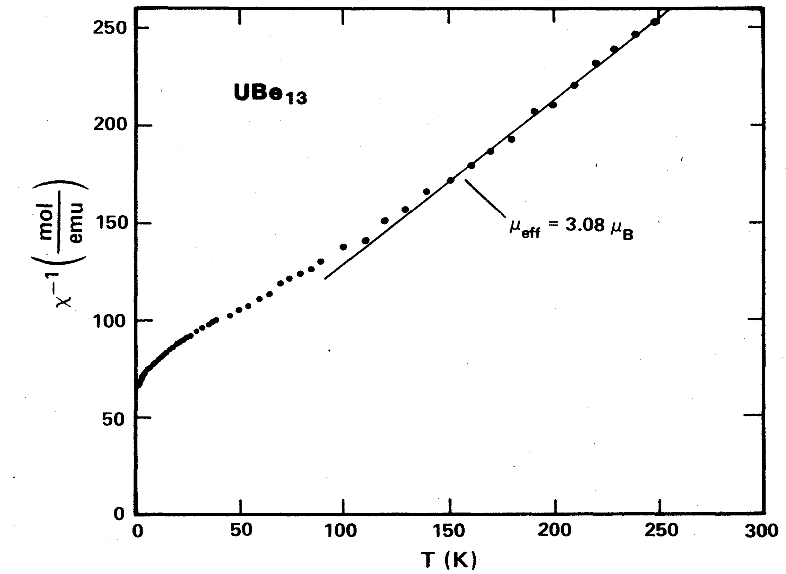


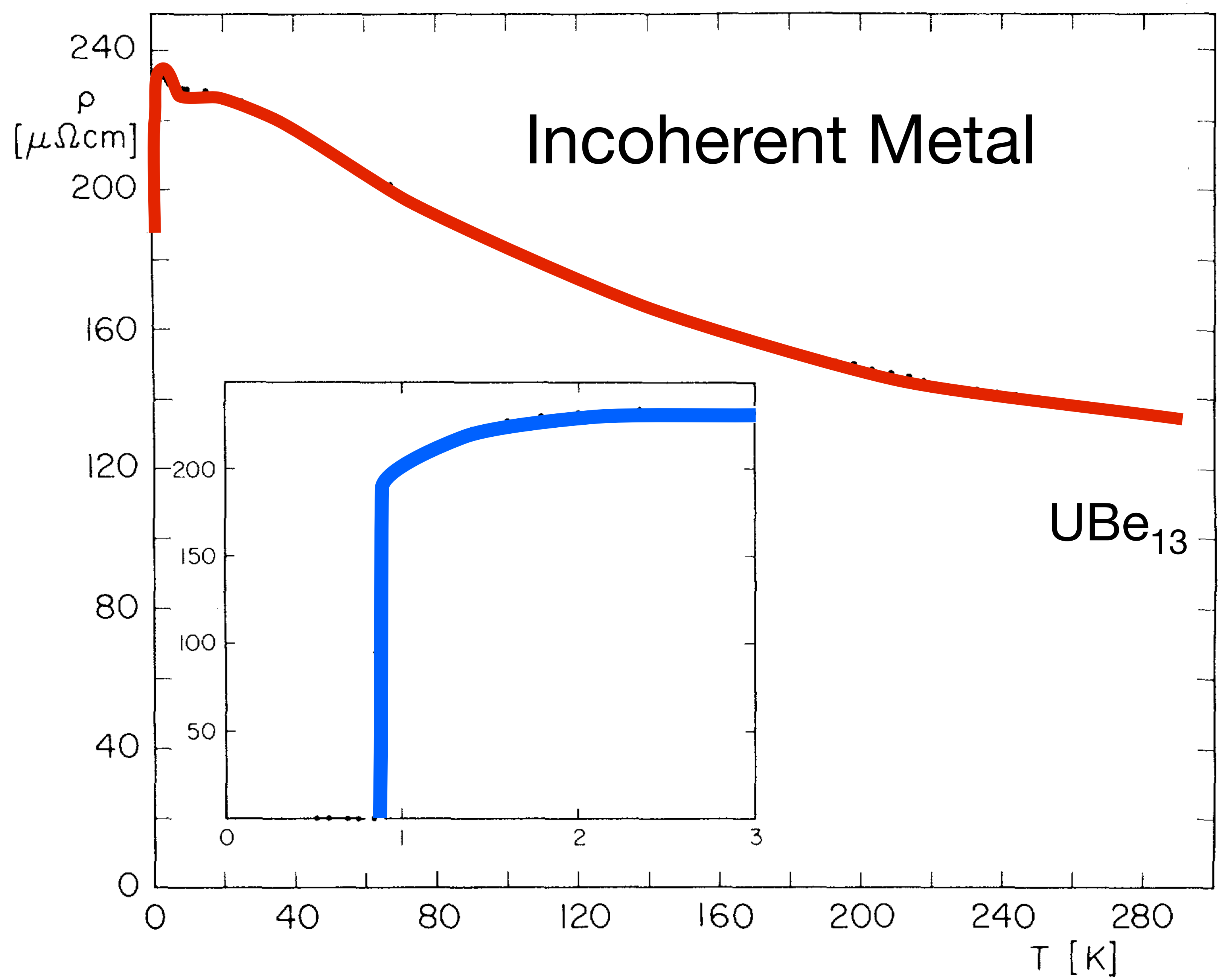


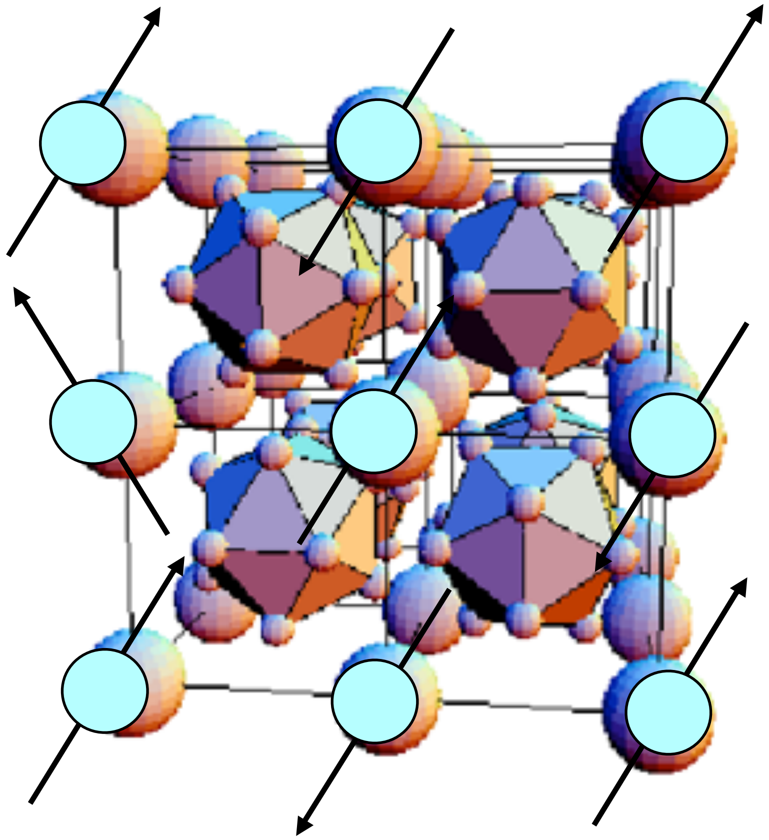
Local Moments

UBe_{13}

Ott, Fisk, Smith (198







UBe_{13}

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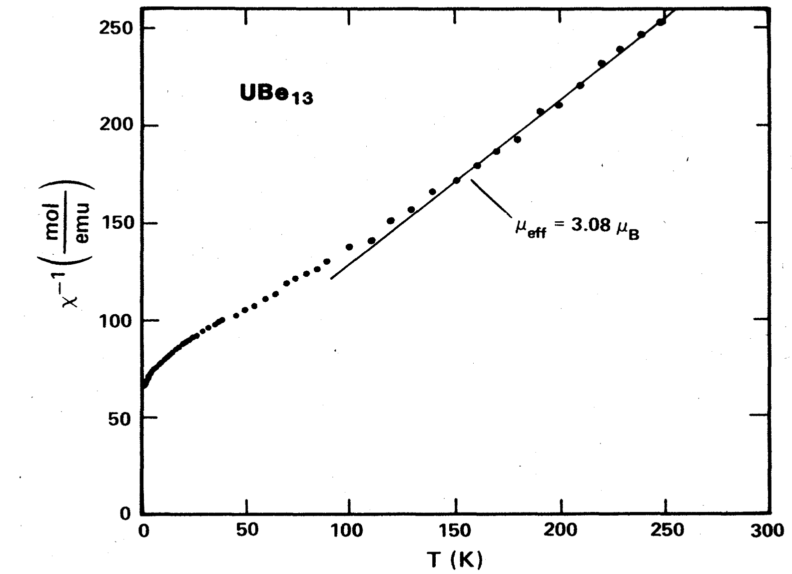
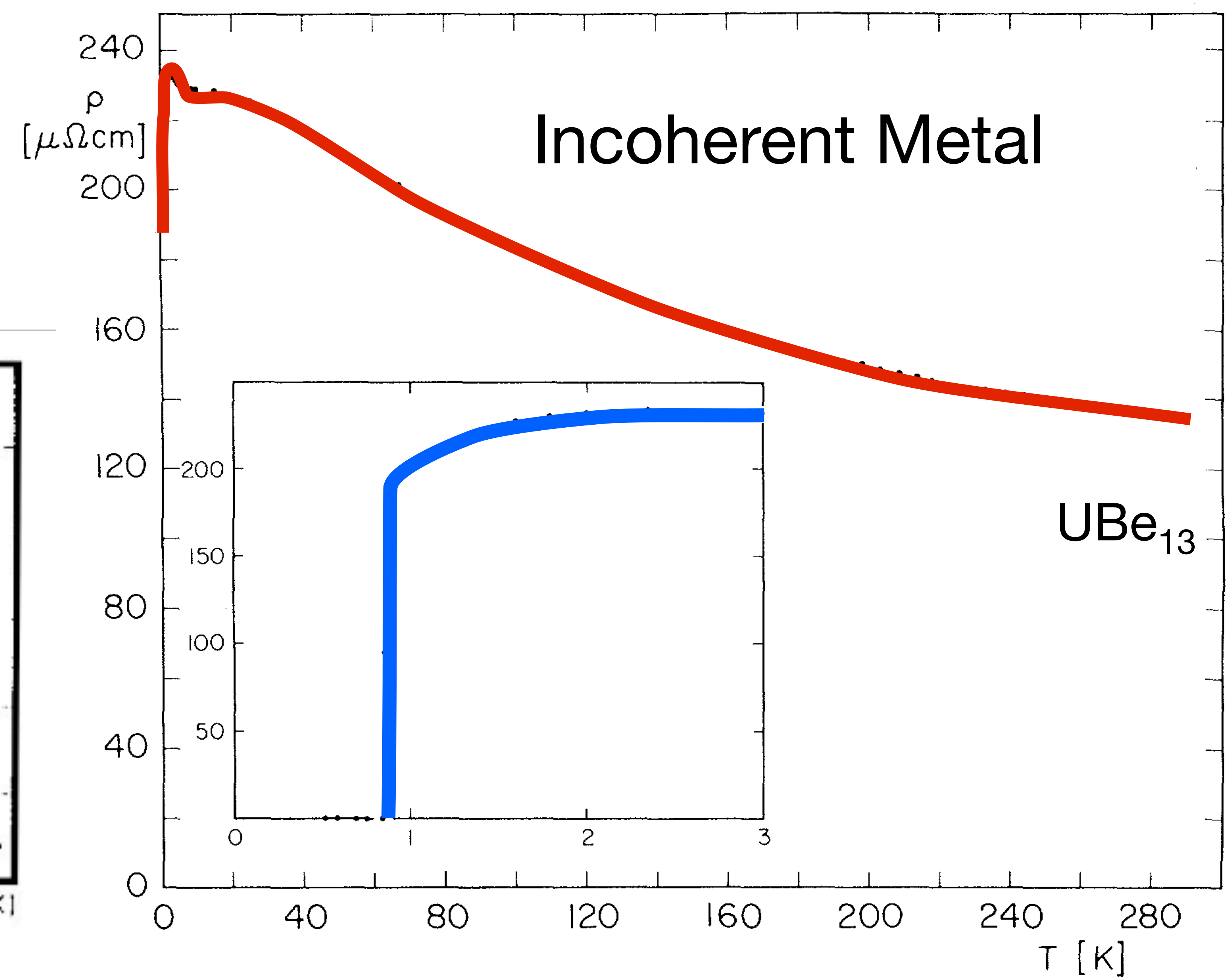
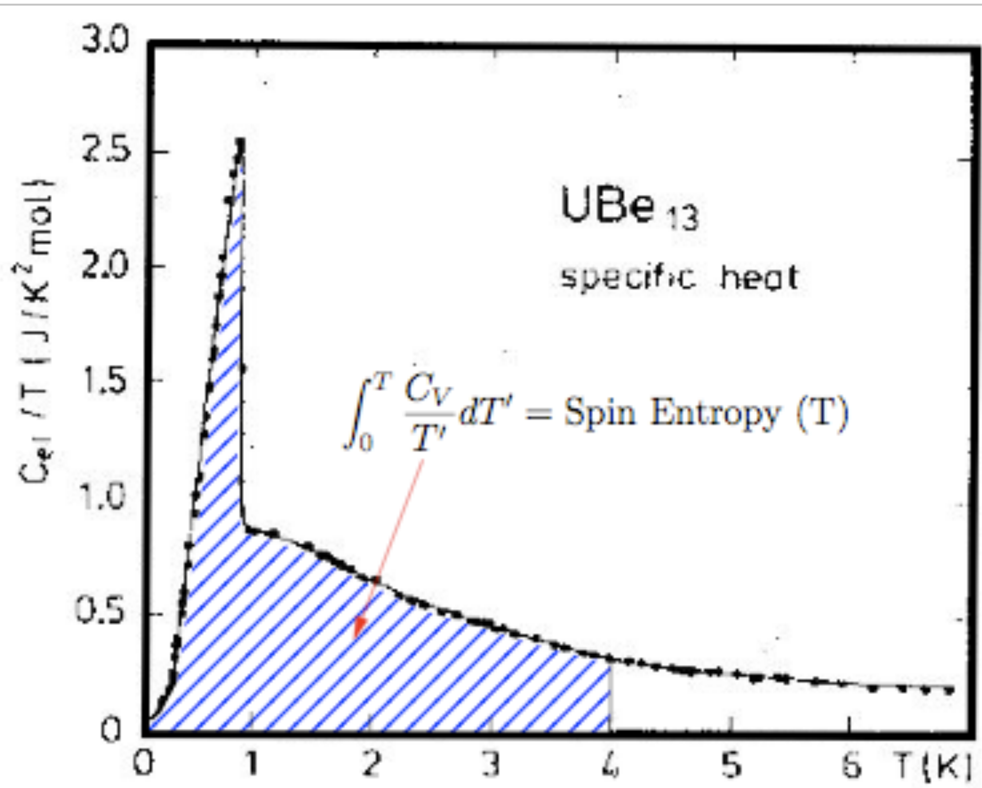
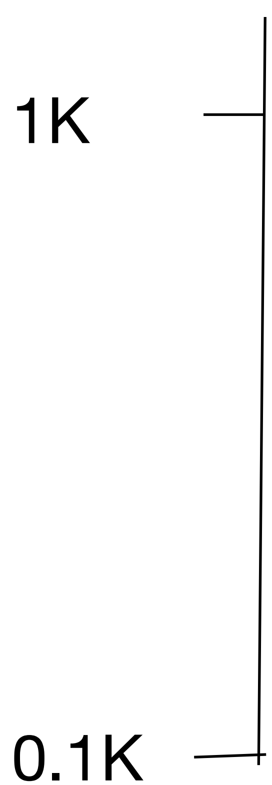




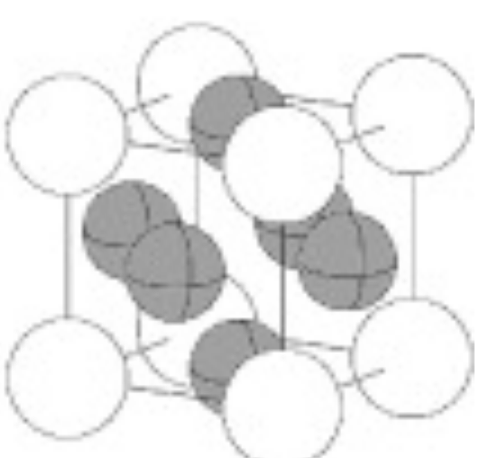


Ott et al, (1983)

“115” Family



CeIn3



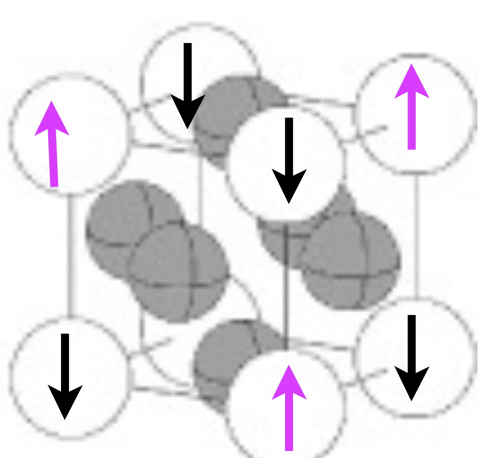
“115” Family

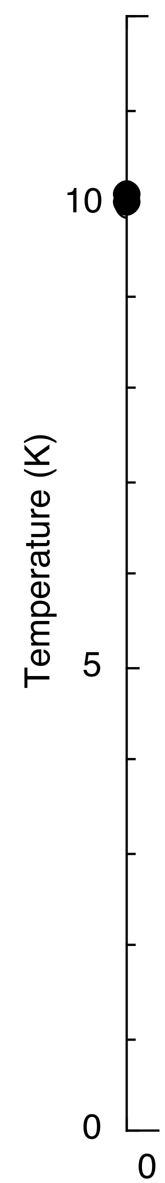
1K

0.1K

CeIn3

10K AFM

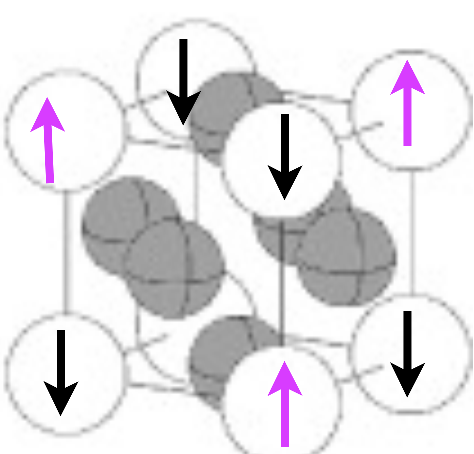


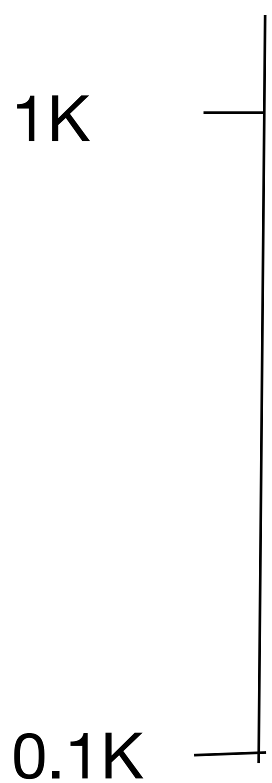


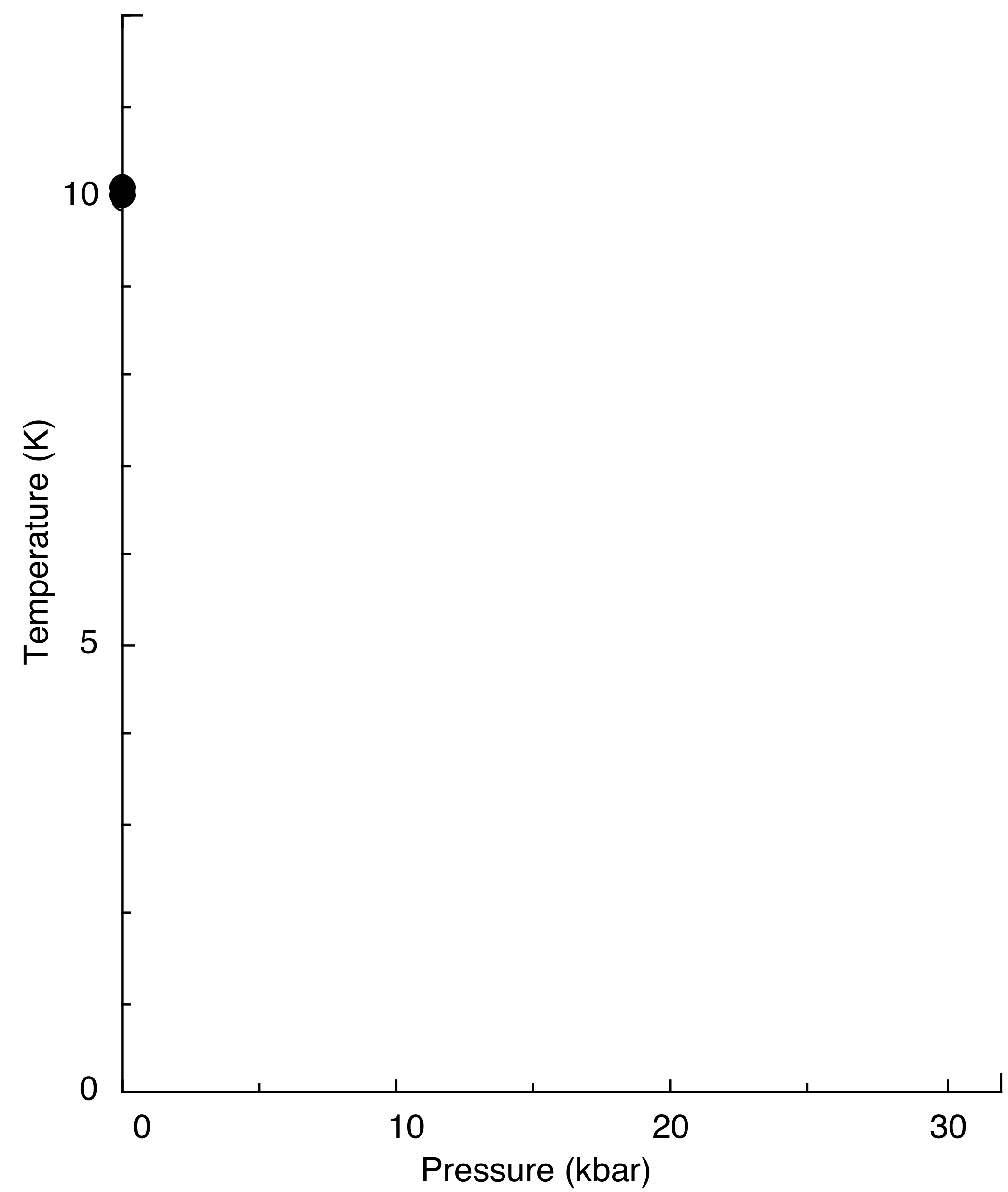
“115” Family

CeIn3

10K AFM



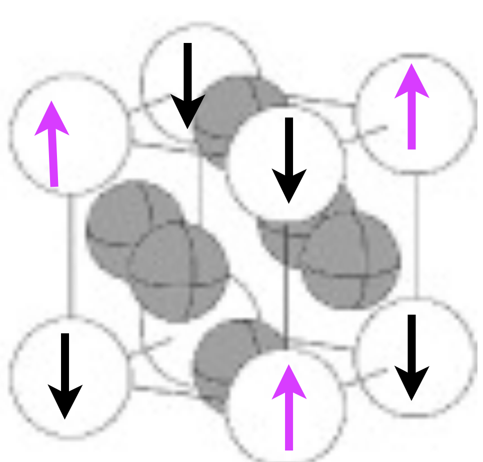


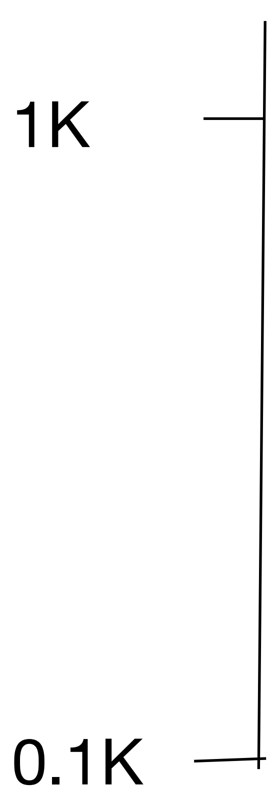


“115” Family

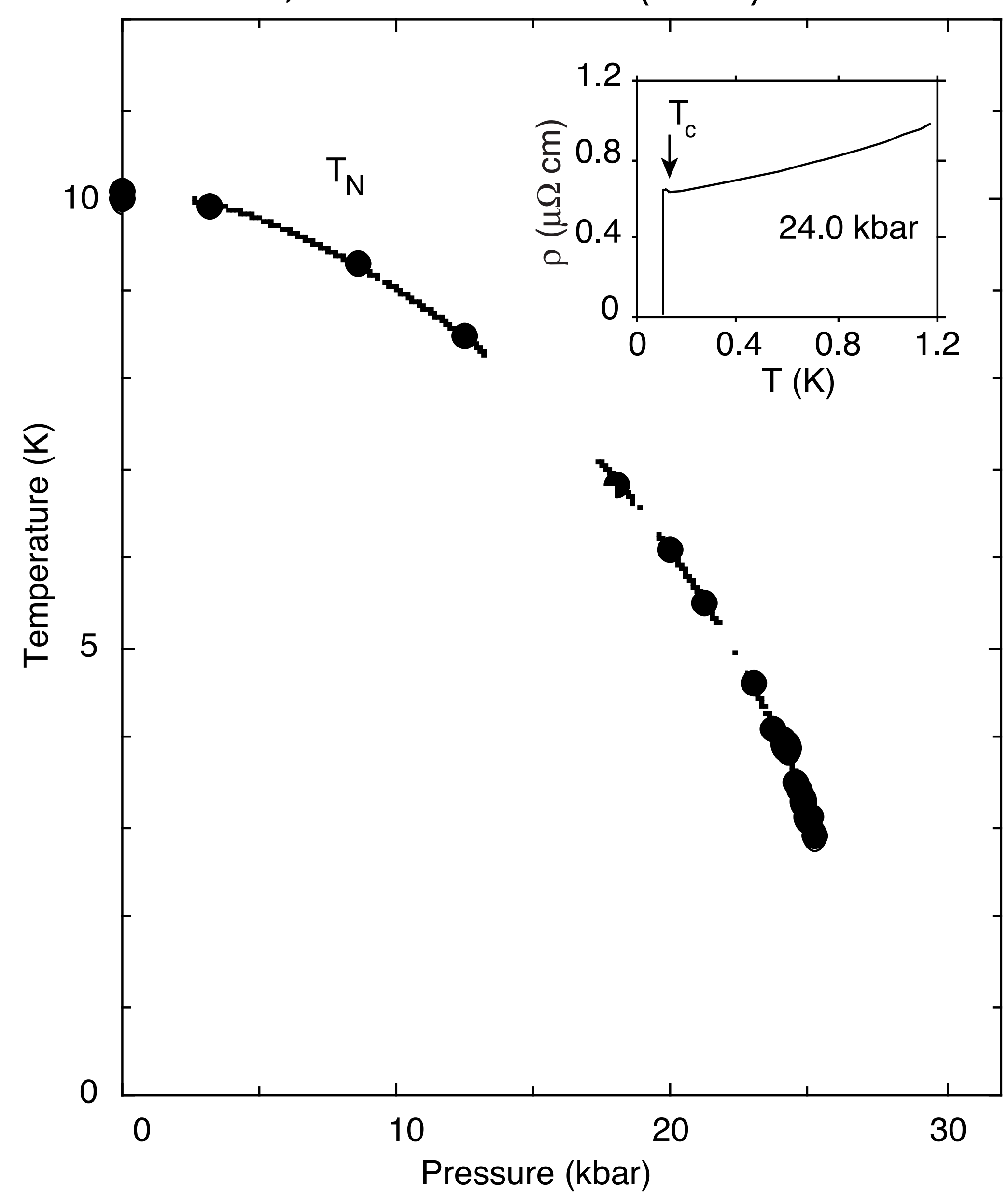
CeIn3

10K AFM

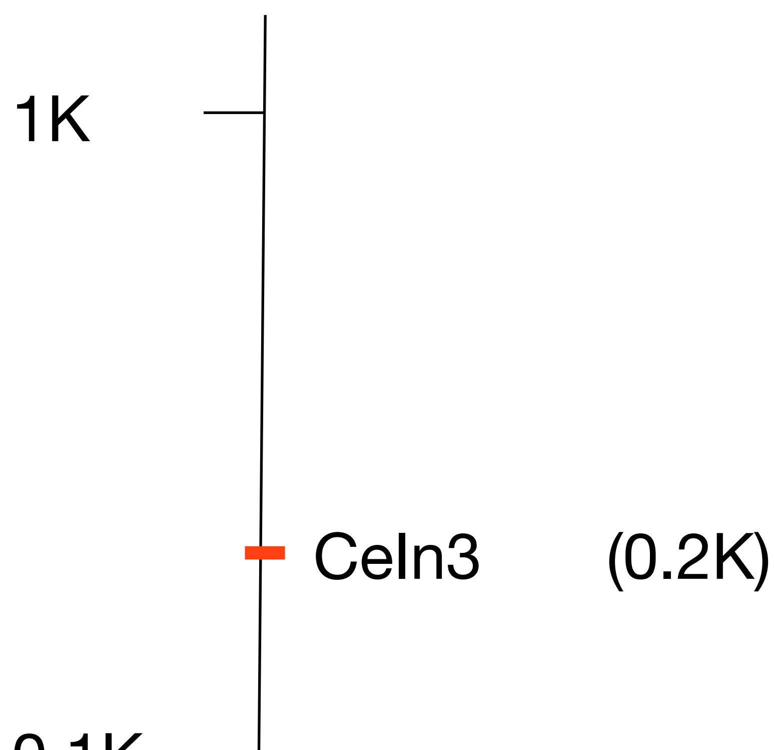




Mathur, Lonzarich et al (1998)

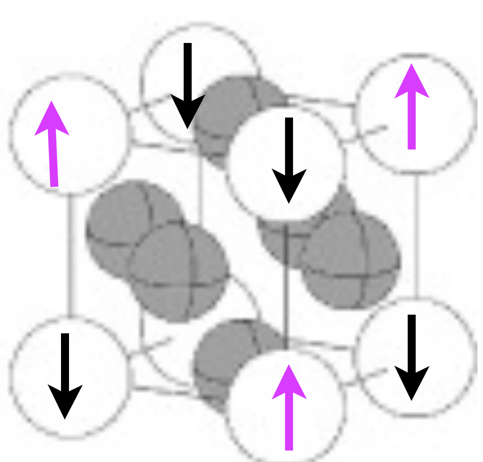


“115” Family

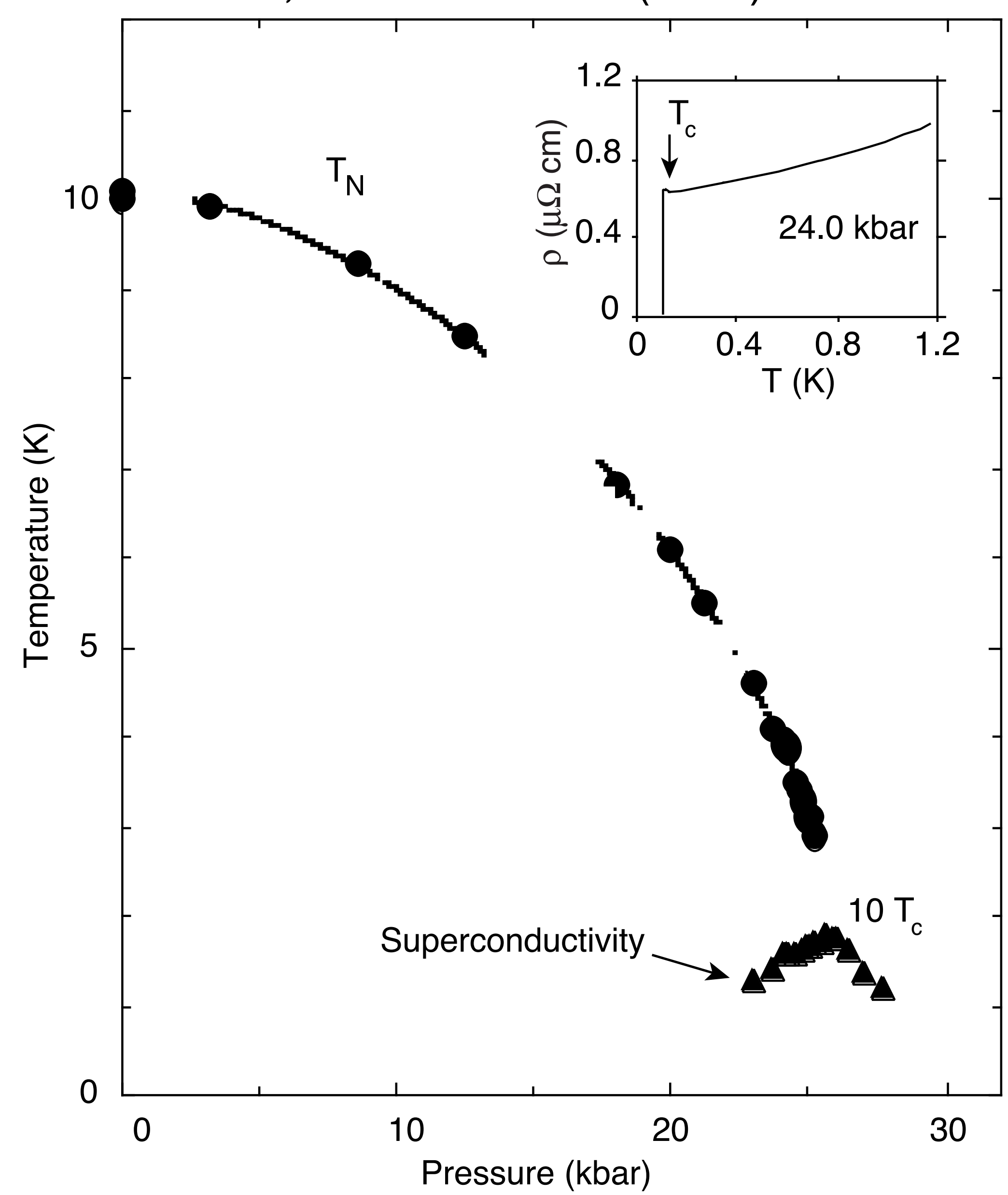


CeIn3

10K AFM



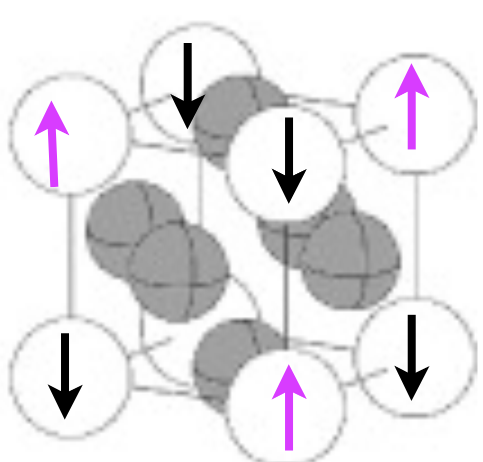
Mathur, Lonzarich et al (1998)

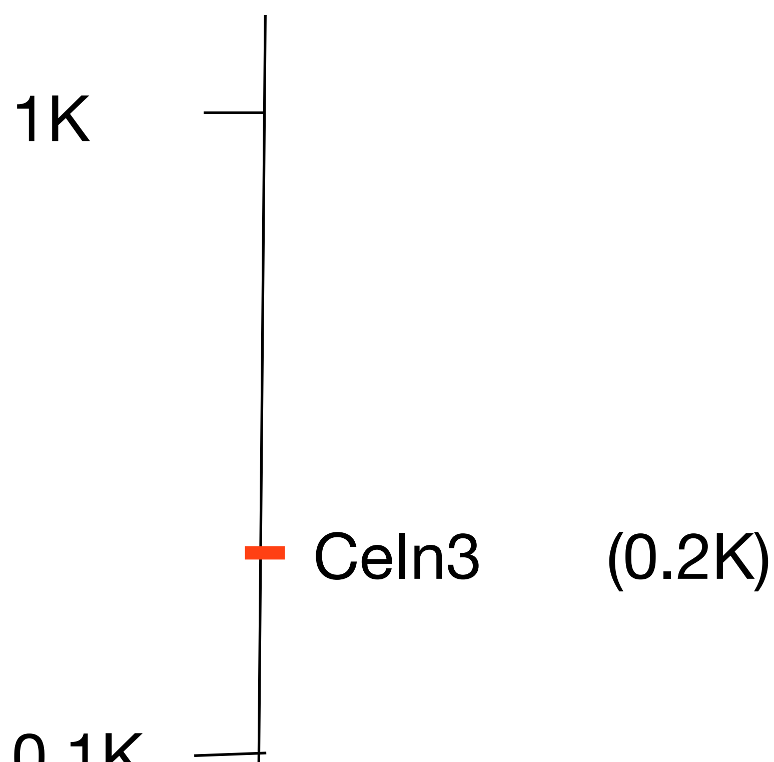


“115” Family

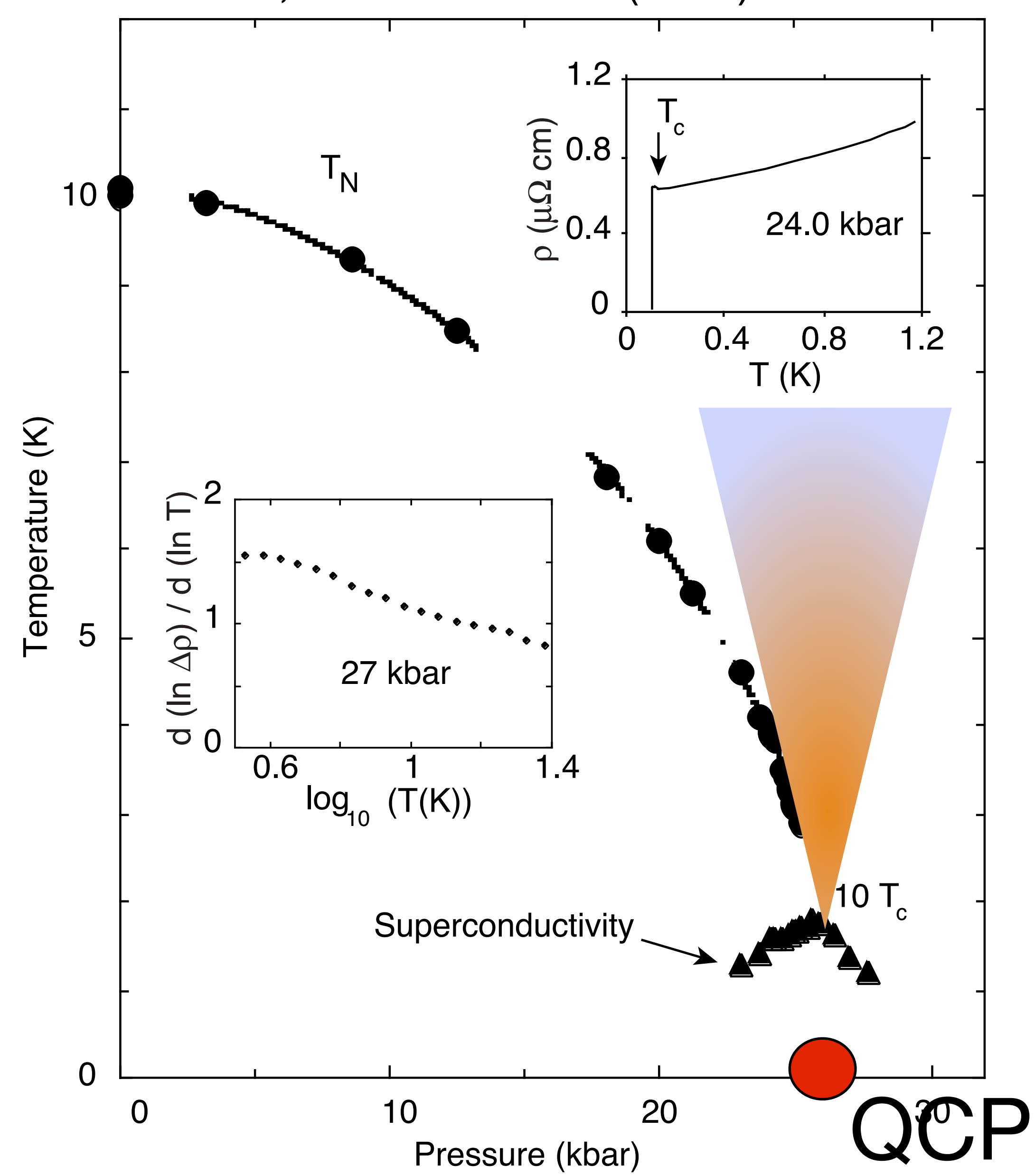
CeIn3

10K AFM





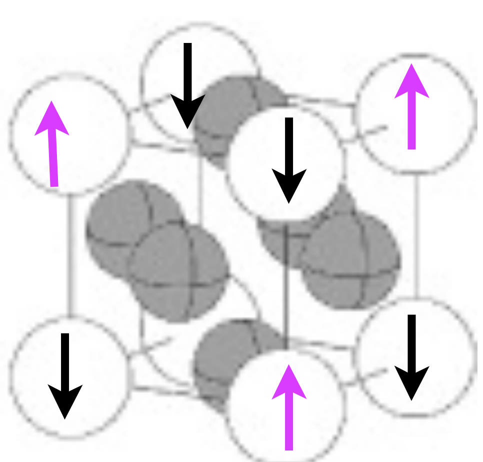
Mathur, Lonzarich et al (1998)

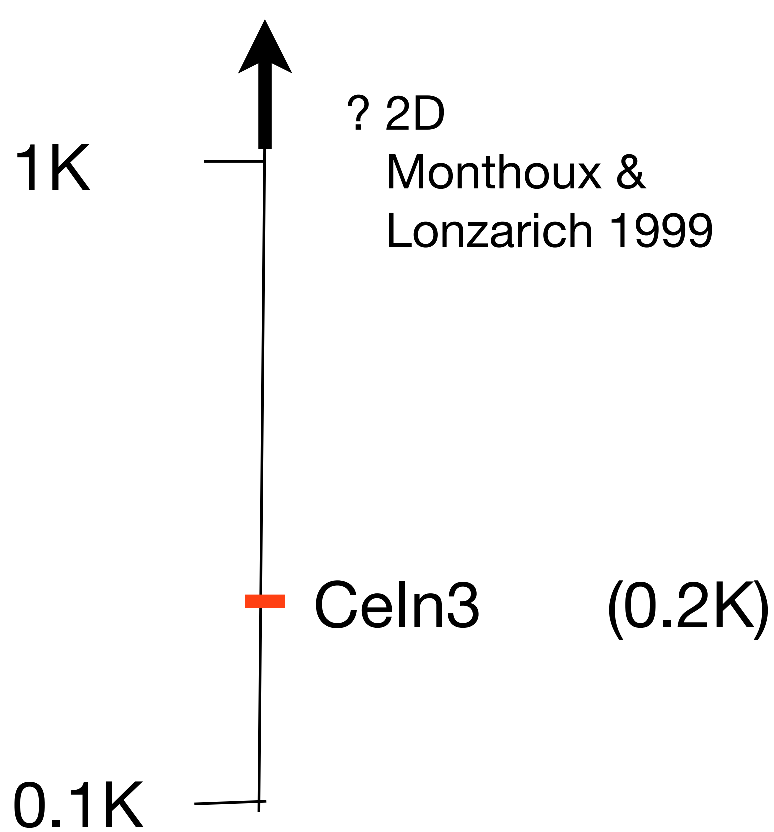


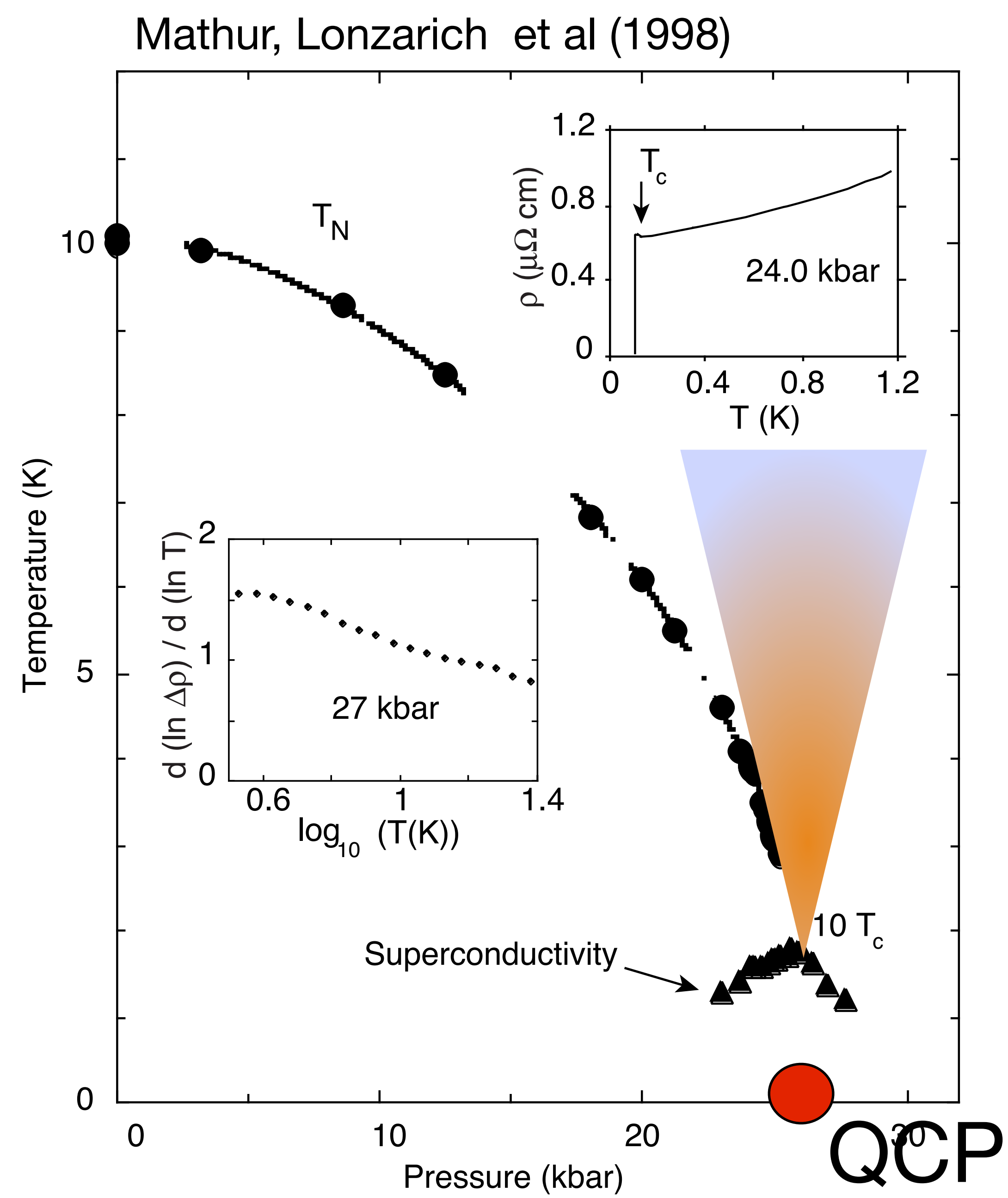
“115” Family

CeIn3

10K AFM

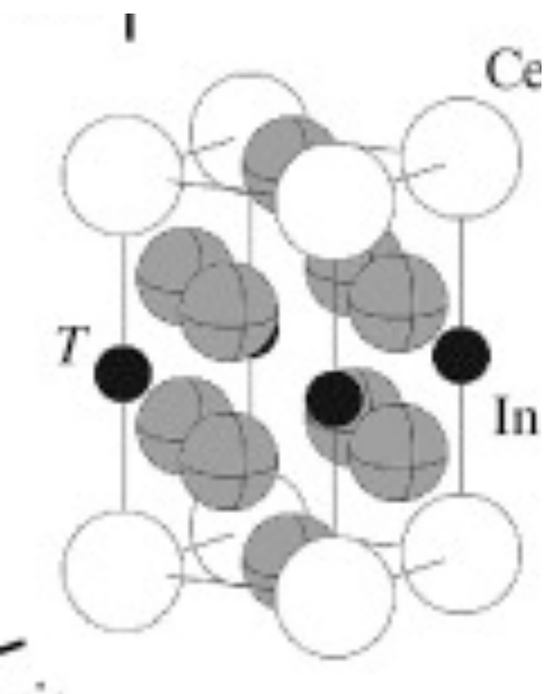


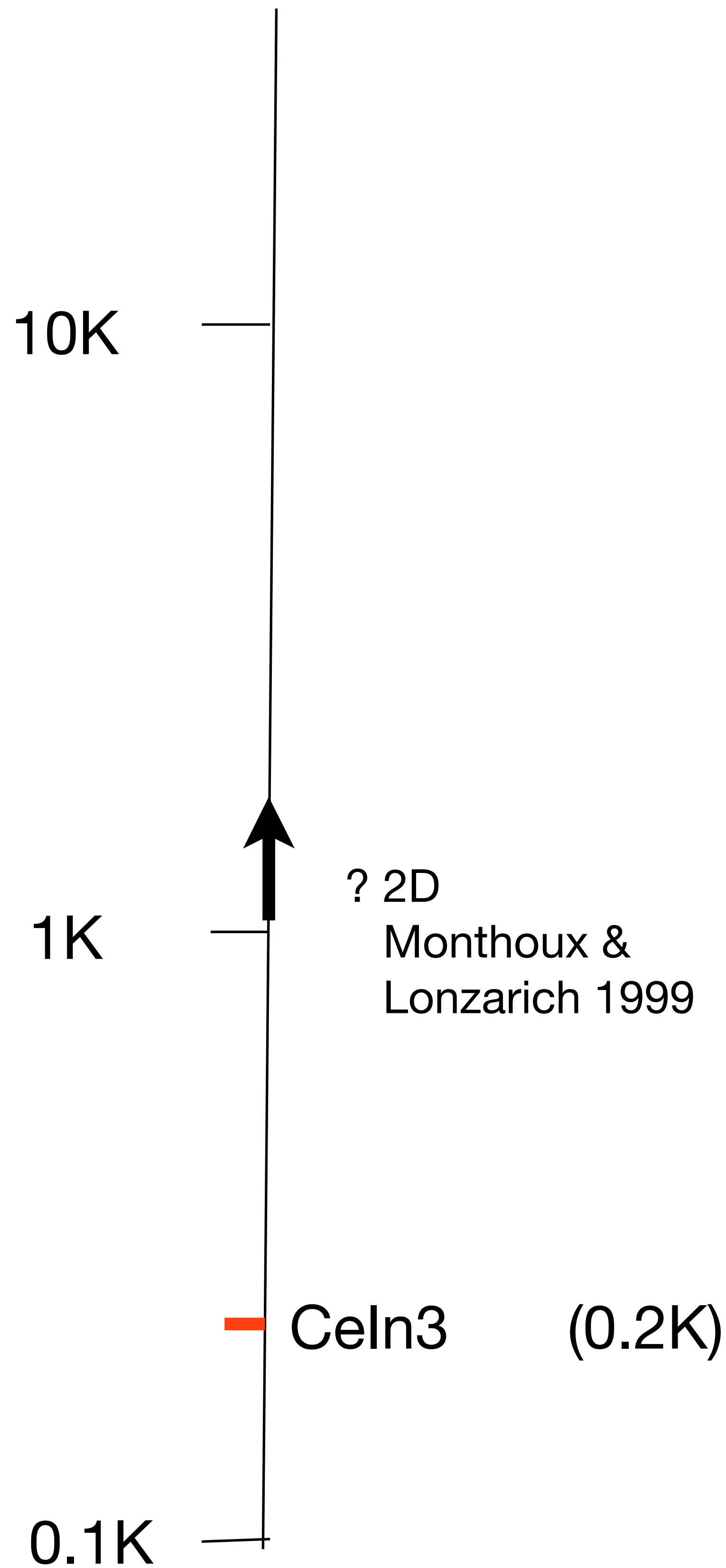




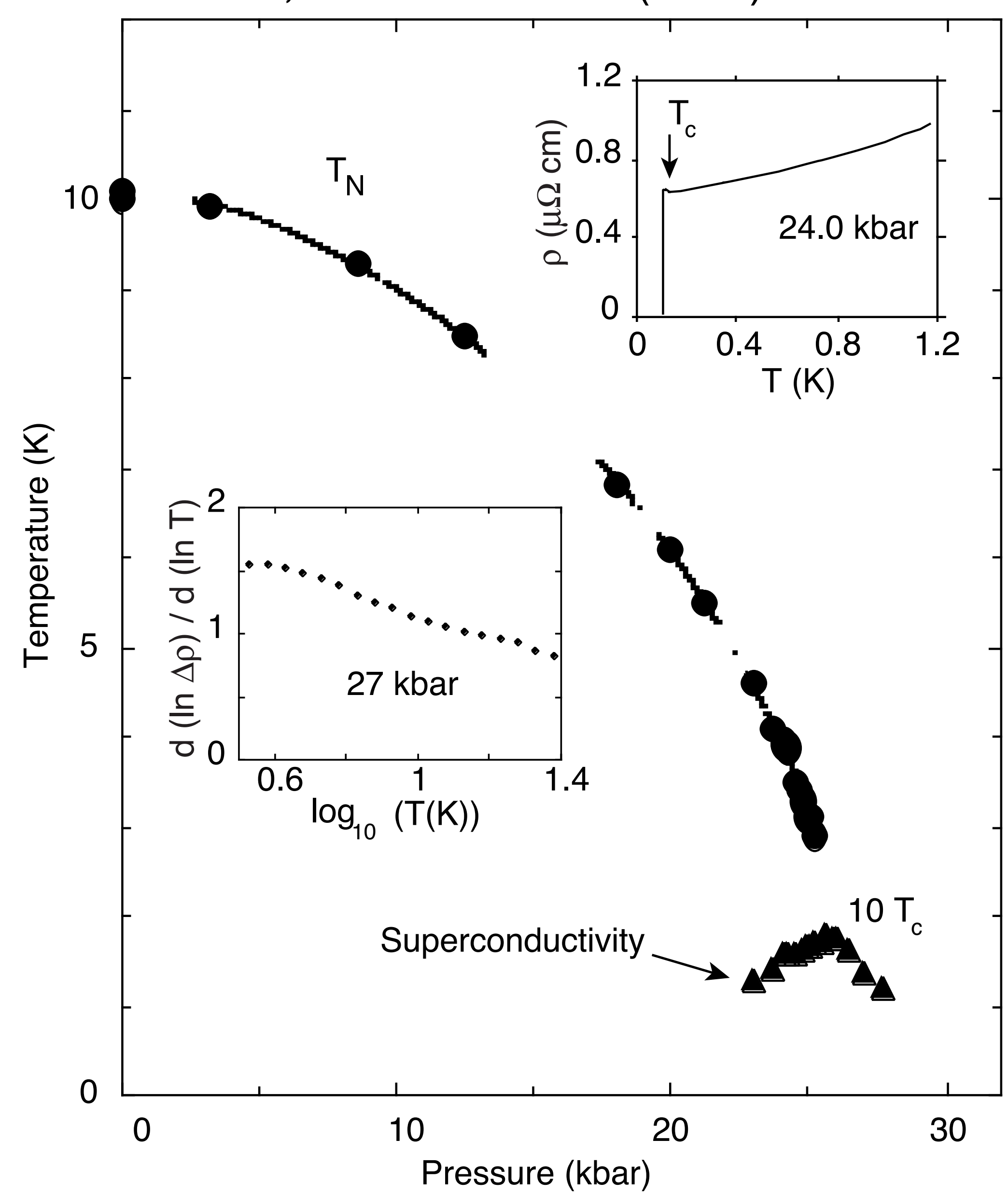
“115” Family

Petrovic et al 2001

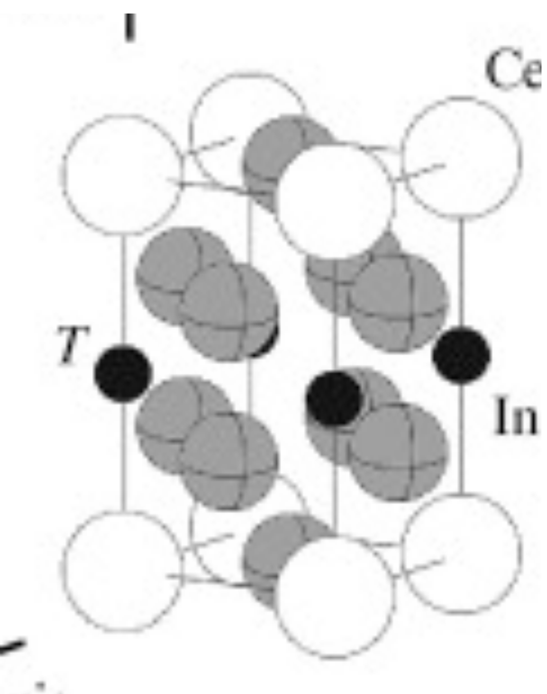


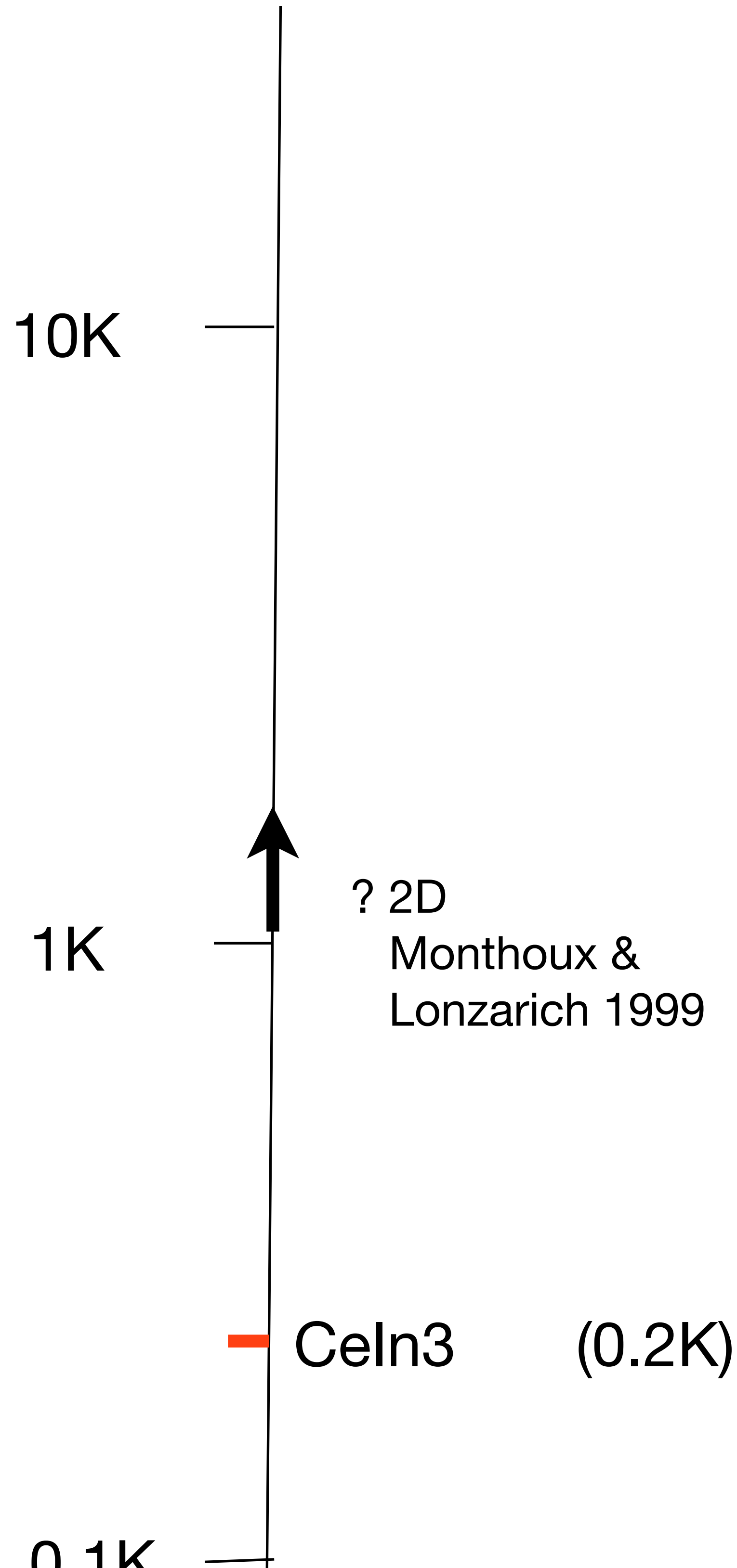


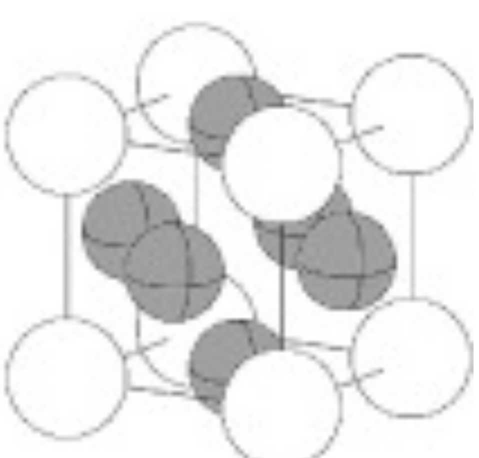
Mathur, Lonzarich et al (1998)

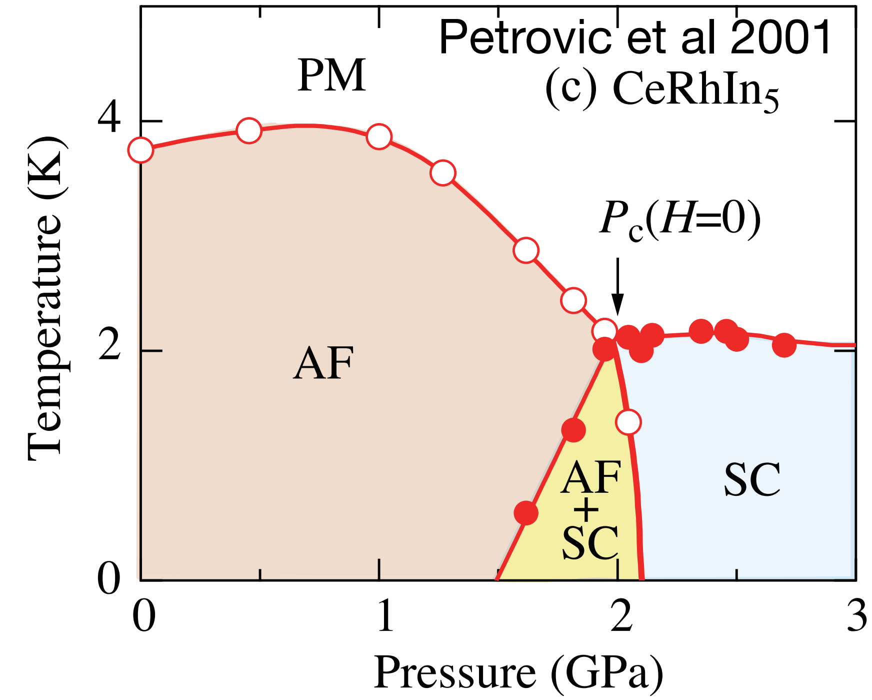


“115” Family

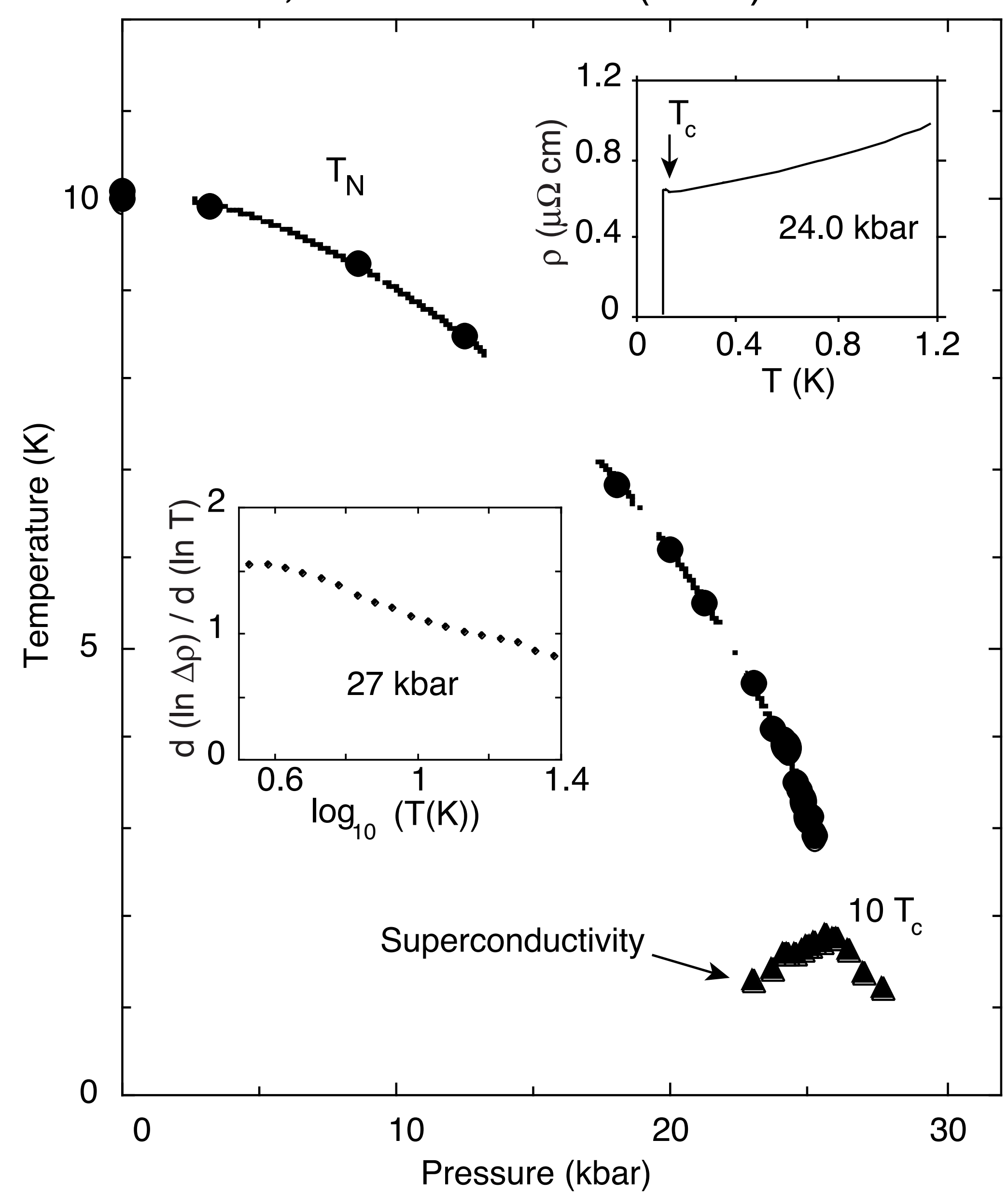




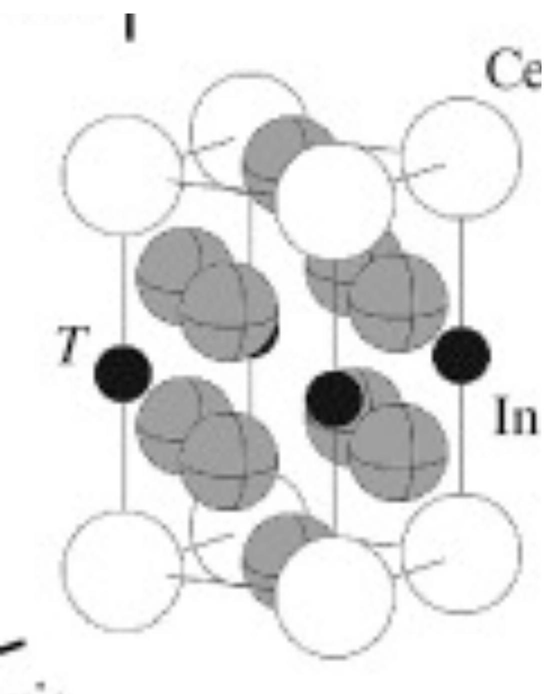


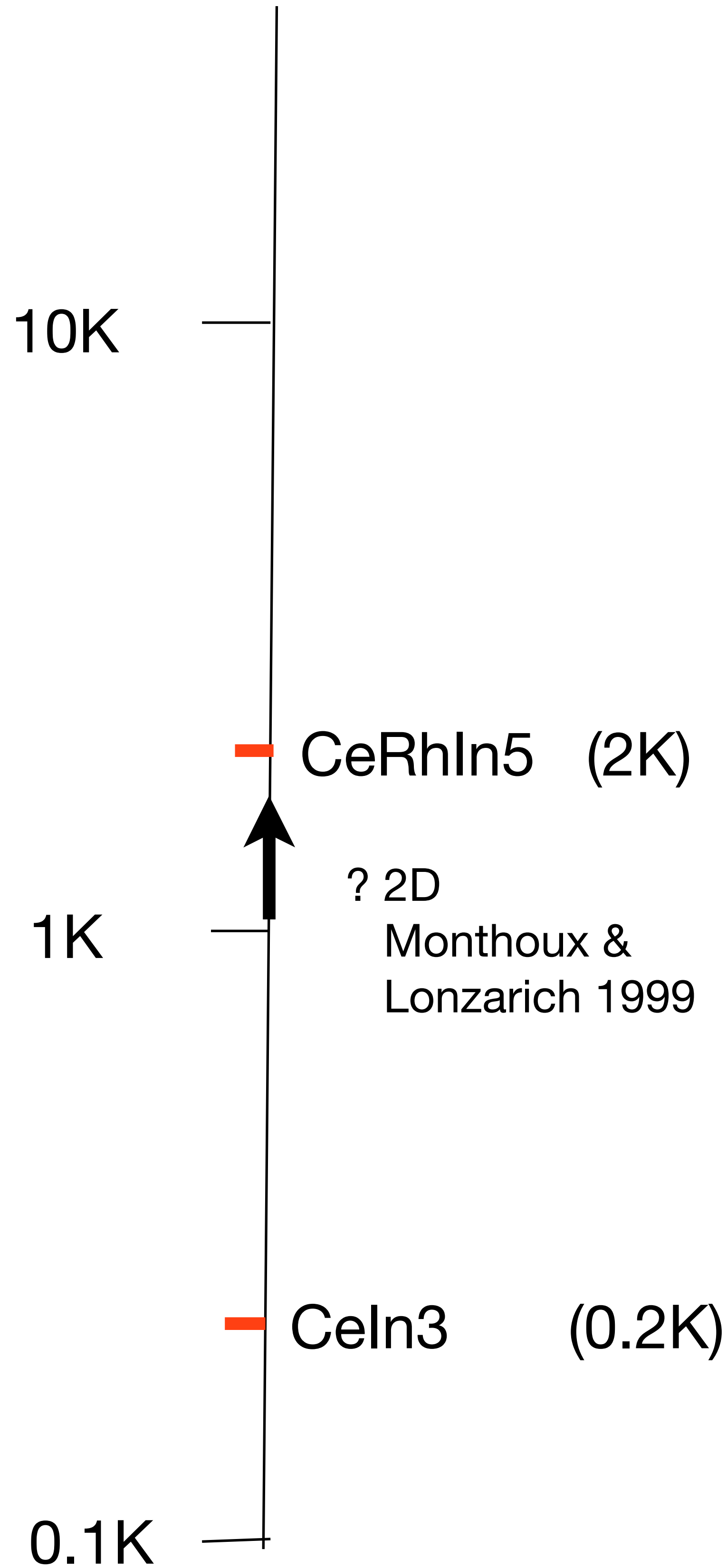


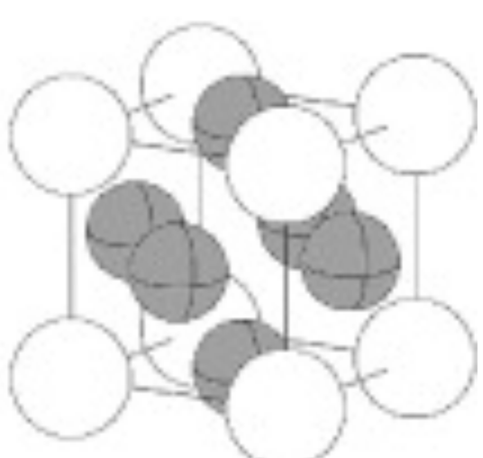
Mathur, Lonzarich et al (1998)

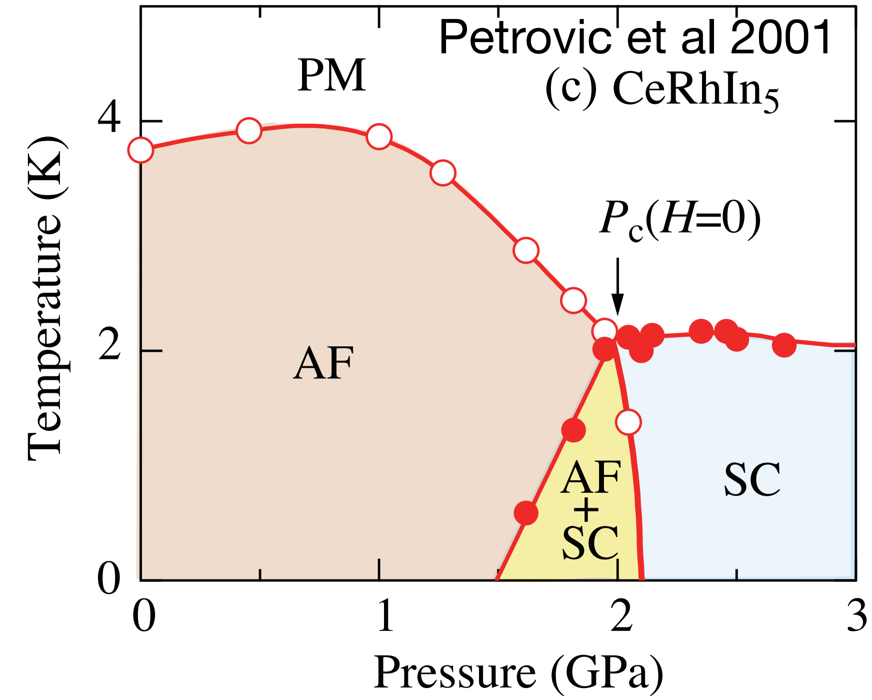


“115” Family

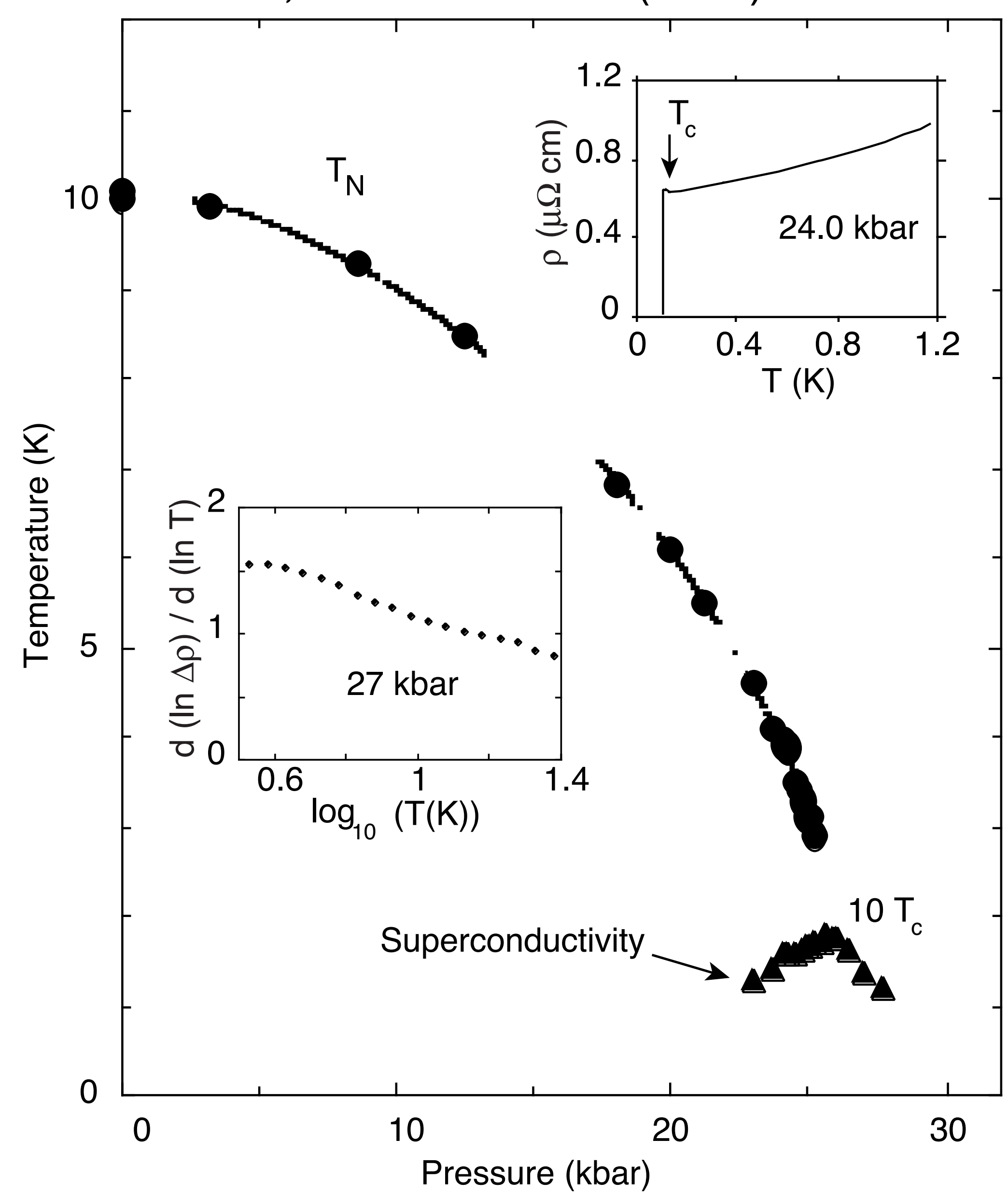




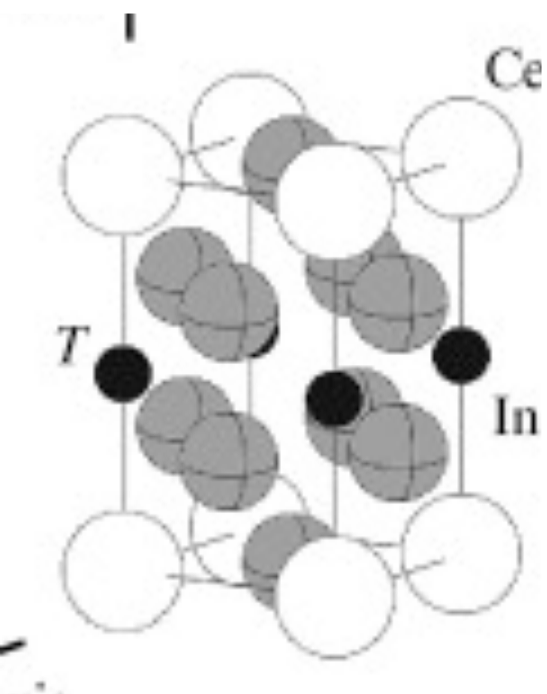




Mathur, Lonzarich et al (1998)



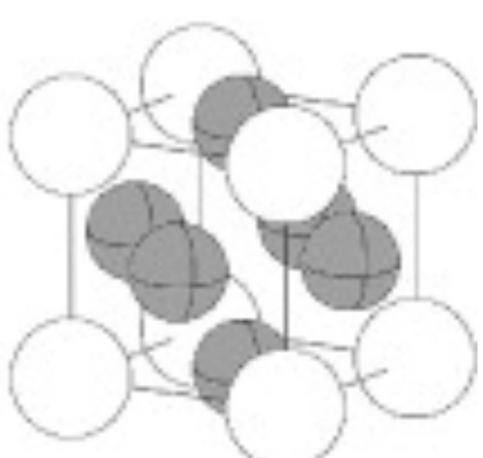
"115" Family



10K

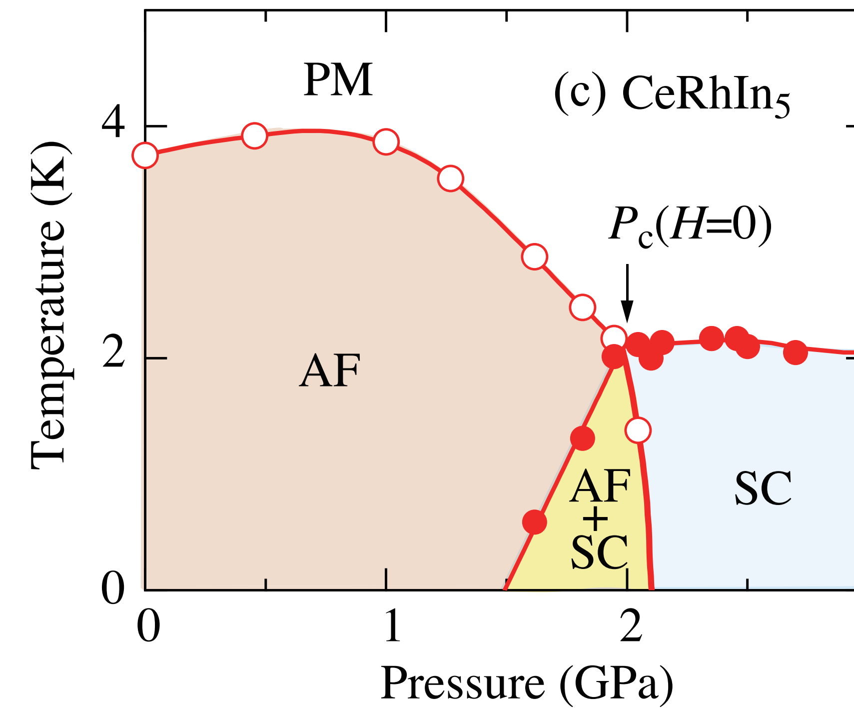
CeRhIn5 (2K)

1K

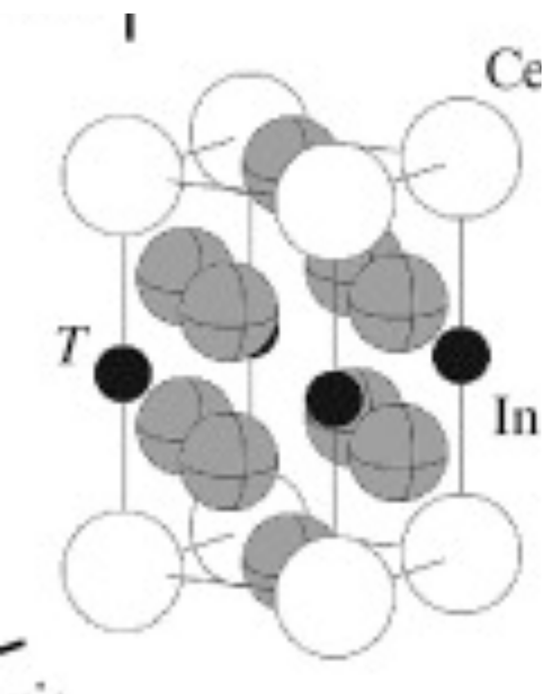


CeIn3 (0.2K)

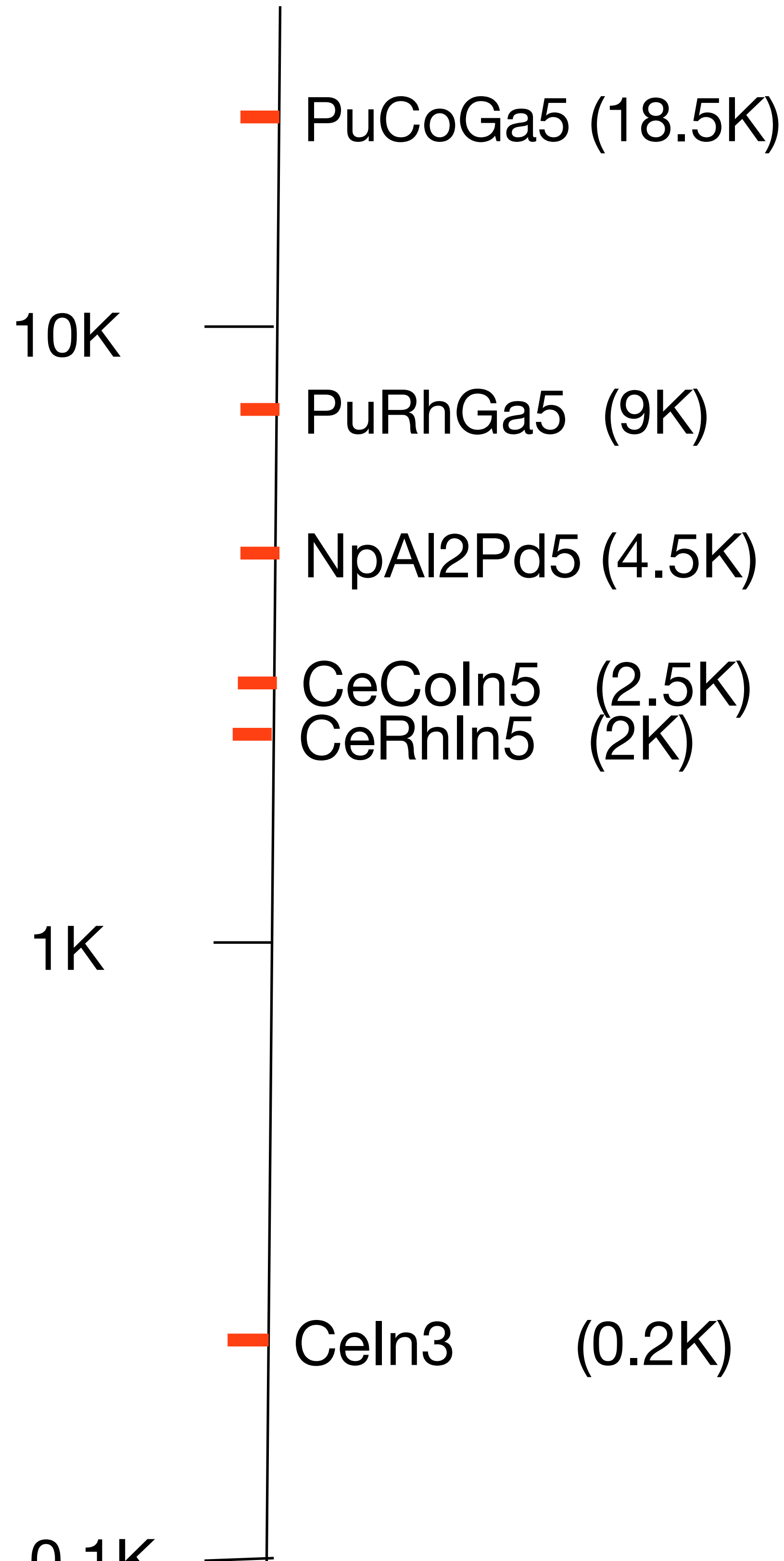
0.1K



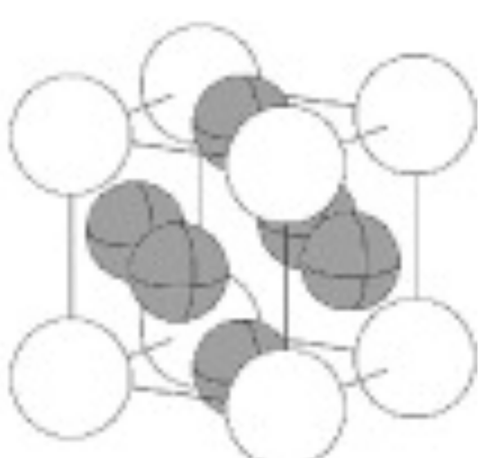
“115” Family

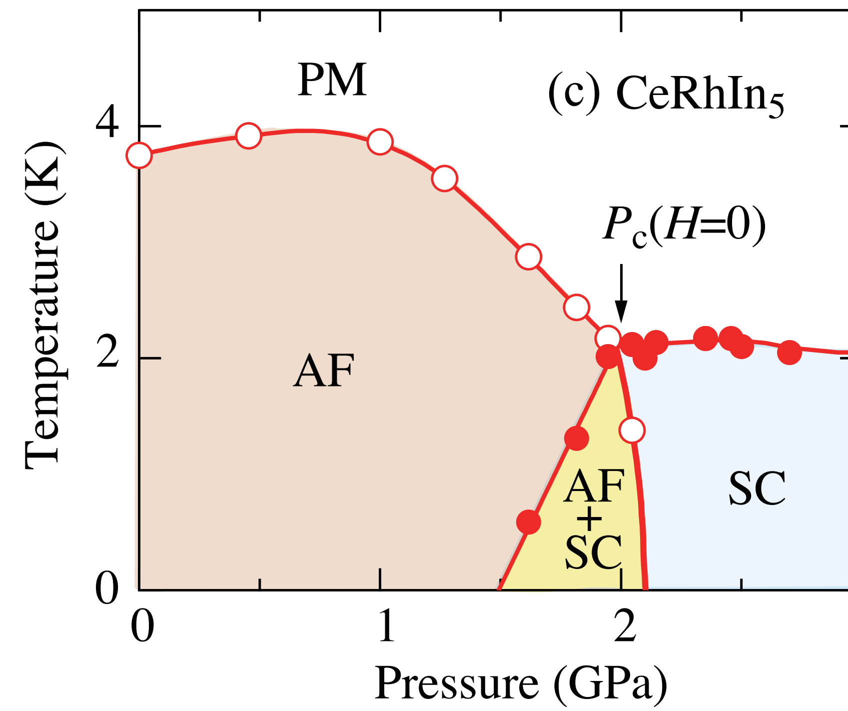


Ce
T
In



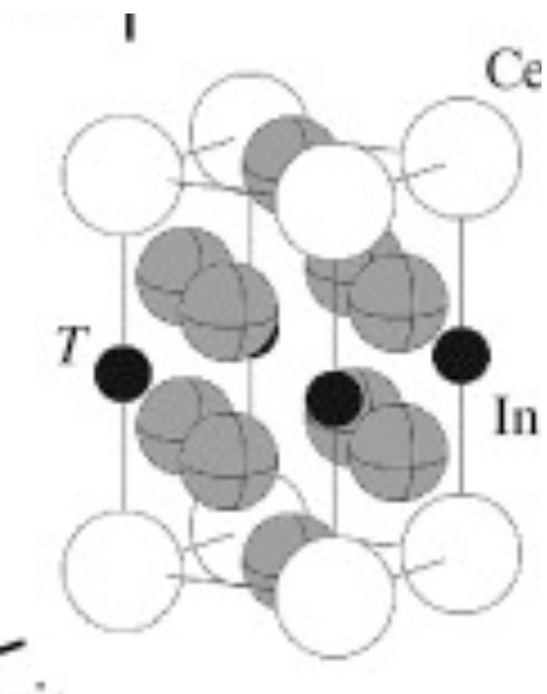
PuCoGa5 (18.5K)
10K
PuRhGa5 (9K)
NpAl2Pd5 (4.5K)
CeCoIn5 (2.5K)
CeRhIn5 (2K)
1K
CeIn3 (0.2K)
0.1K

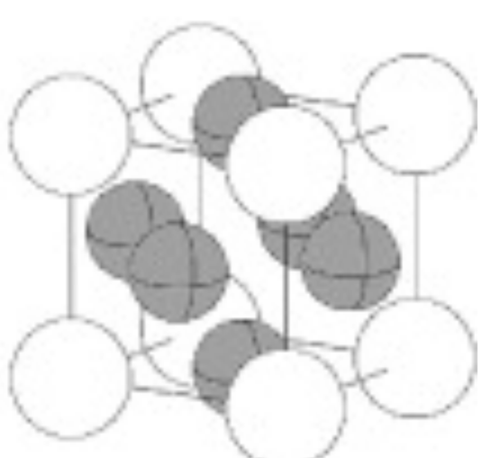


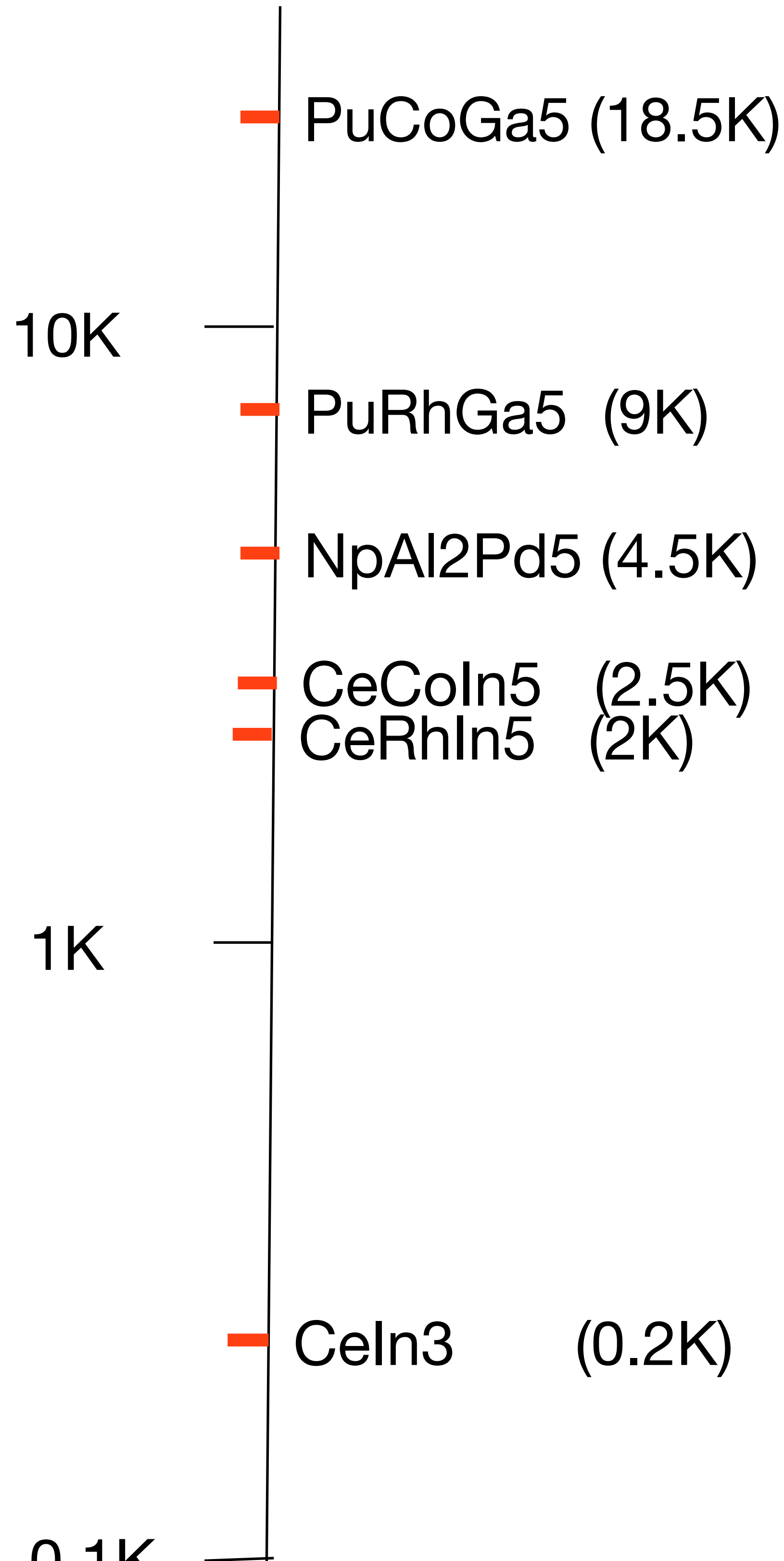


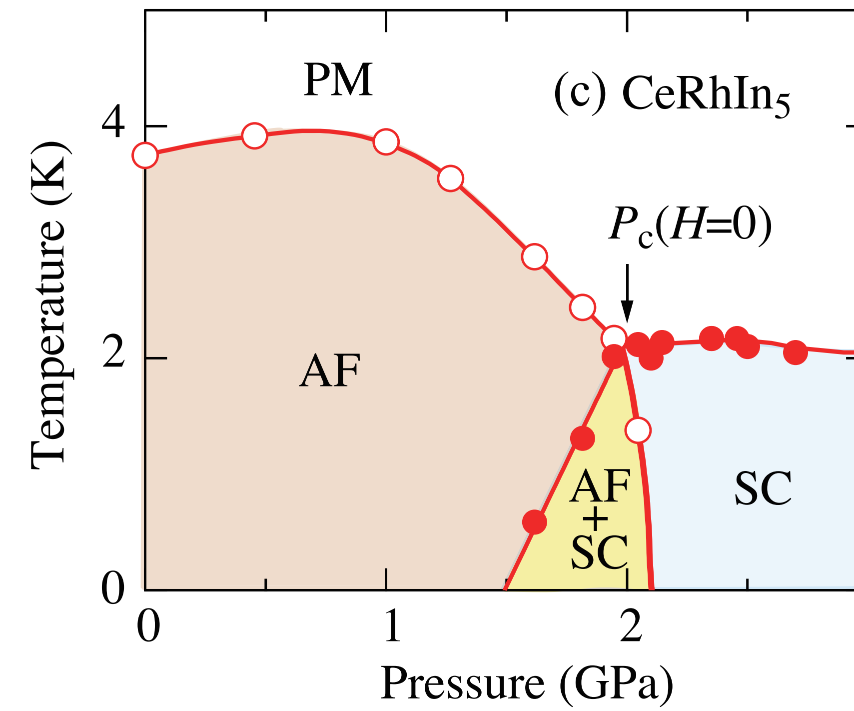
PM
(c) CeRhIn5
Pc(H=0)
AF
AF + SC
SC
Temperature (K)
Pressure (GPa)
0
1
2
3
4

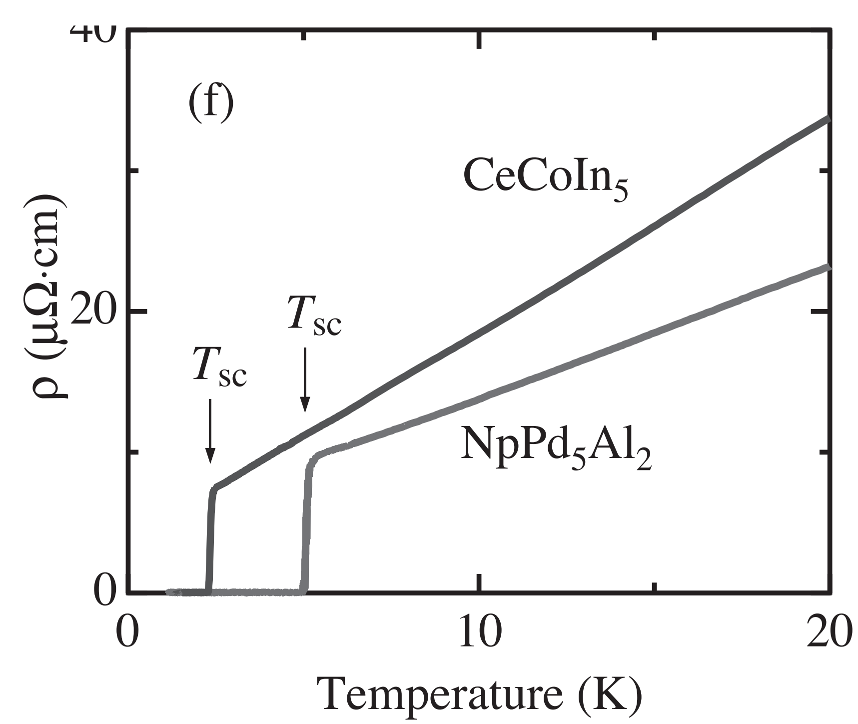
“115” Family


Ce
T
In

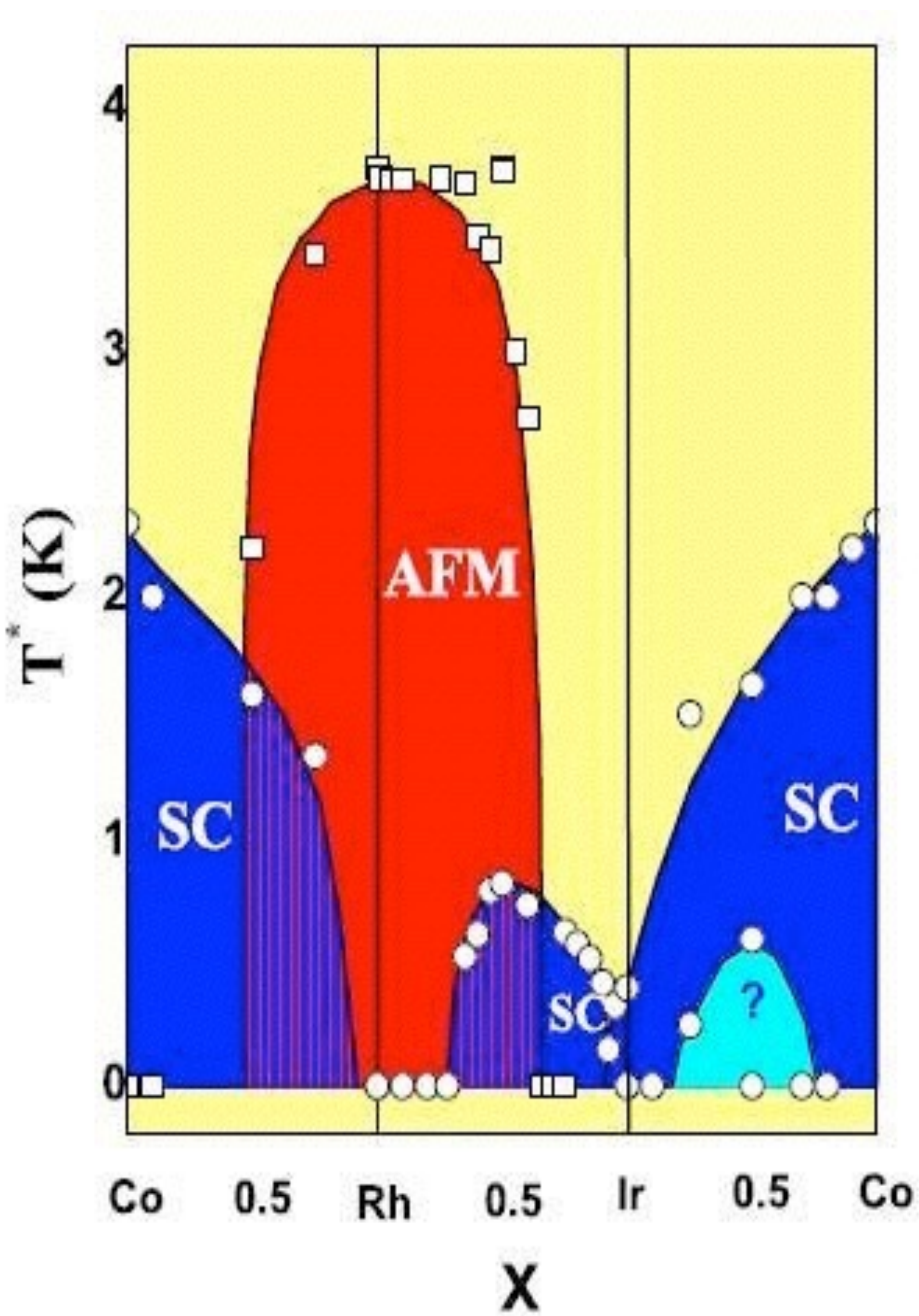



PuCoGa5 (18.5K)
10K
PuRhGa5 (9K)
NpAl2Pd5 (4.5K)
CeCoIn5 (2.5K)
CeRhIn5 (2K)
1K
CeIn3 (0.2K)
0.1K


(c) CeRhIn5
PM
AF
$P_c(H=0)$
AF + SC
SC
Temperature (K)
Pressure (GPa)
0
1
2
3
0
2
4


(f)
CeCoIn5
NpPd5Al2
T_{sc}
T_{sc}
ρ (μΩ·cm)
Temperature (K)
0
10
20
0
20

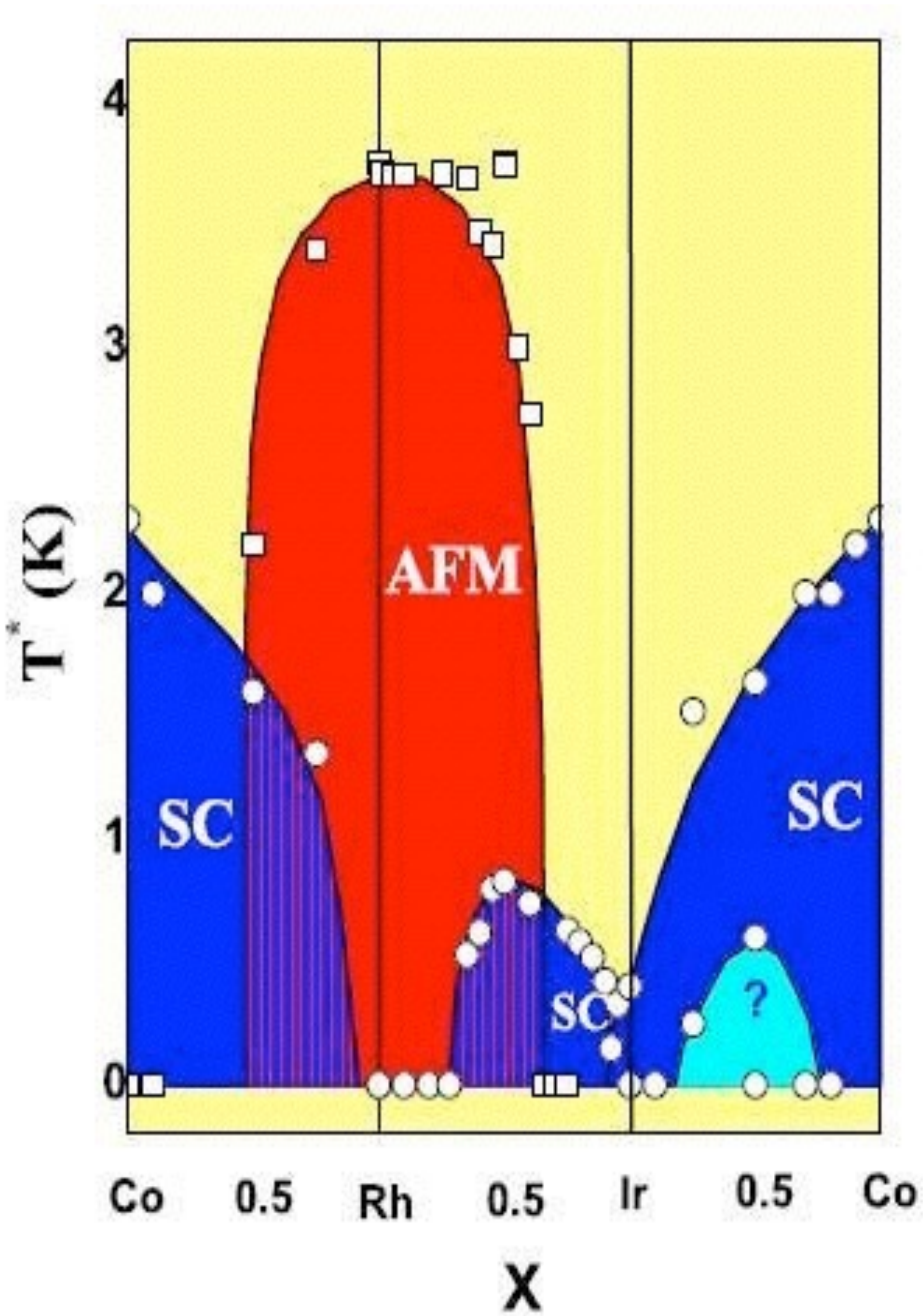
The 115 Family. Magnetism appears ubiquitous.



Sarrao and Thompson JPSJ (2007)

$CeXIn_5$

The 115 Family. Magnetism appears ubiquitous.



Sarrao and Thompson JPSJ (2007)

CeXIn$_5$

Yet…

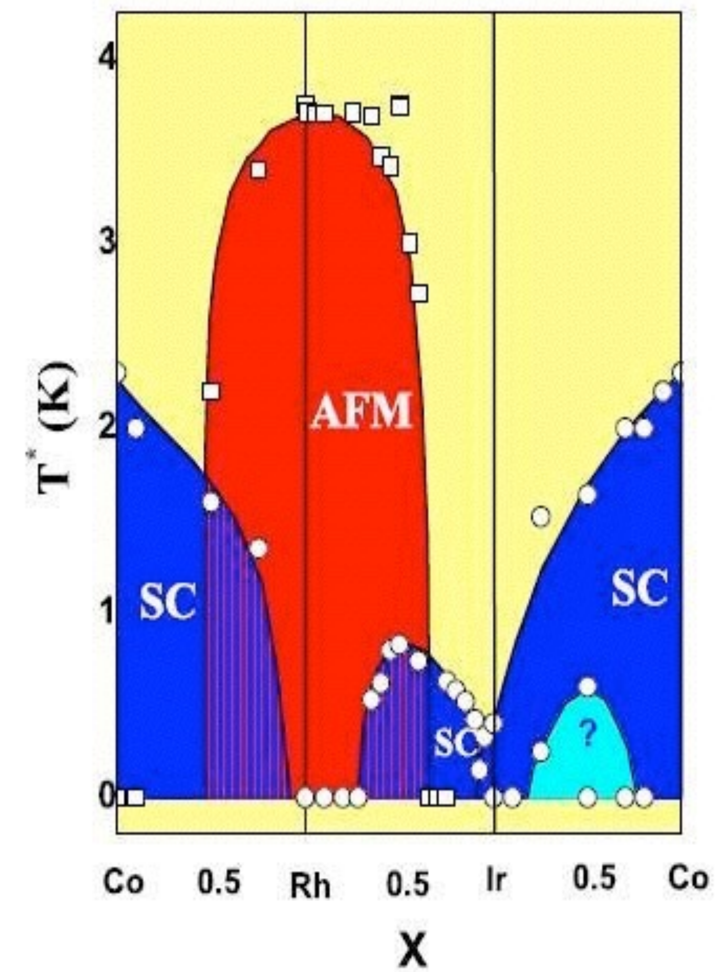
Magnetic pairing appears ubiquitous

But...

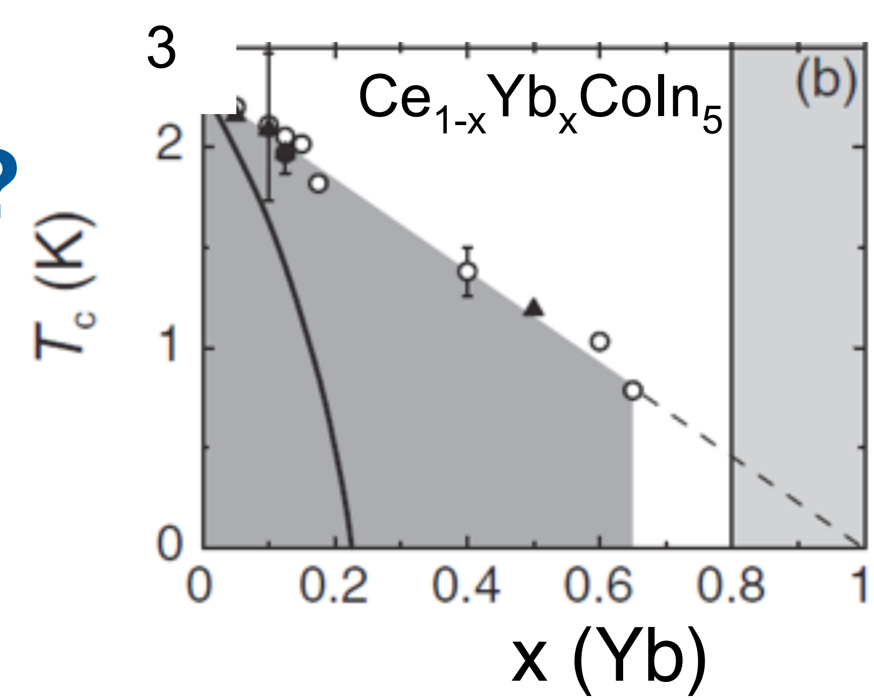
- Two domes in Ce*M*In_5
- Superconductivity without magnetism (Pu*M*In_5, Pu*M*Ga_5, $NpPd_5Al_2$)
- Extreme robustness to disorder

- Many Ce superconductors, one (weak) Yb superconductor

Are there other possible mechanisms?

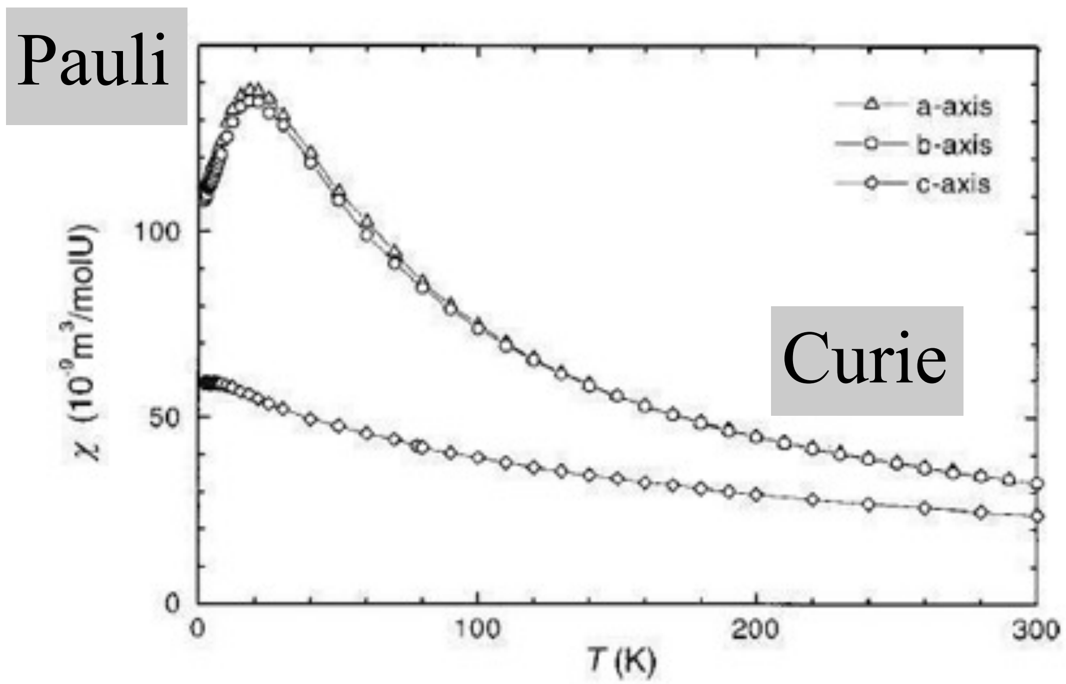


Sarrao and Thompson JPSJ (2007)



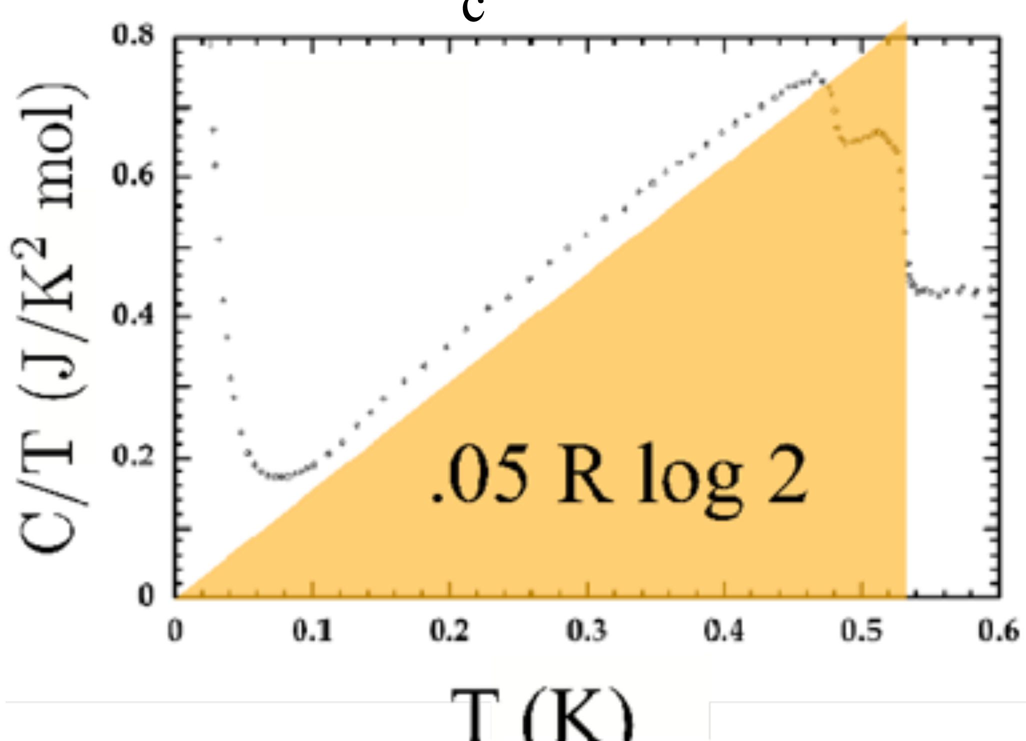
L. Shu et al PRL 2011

UPt_3



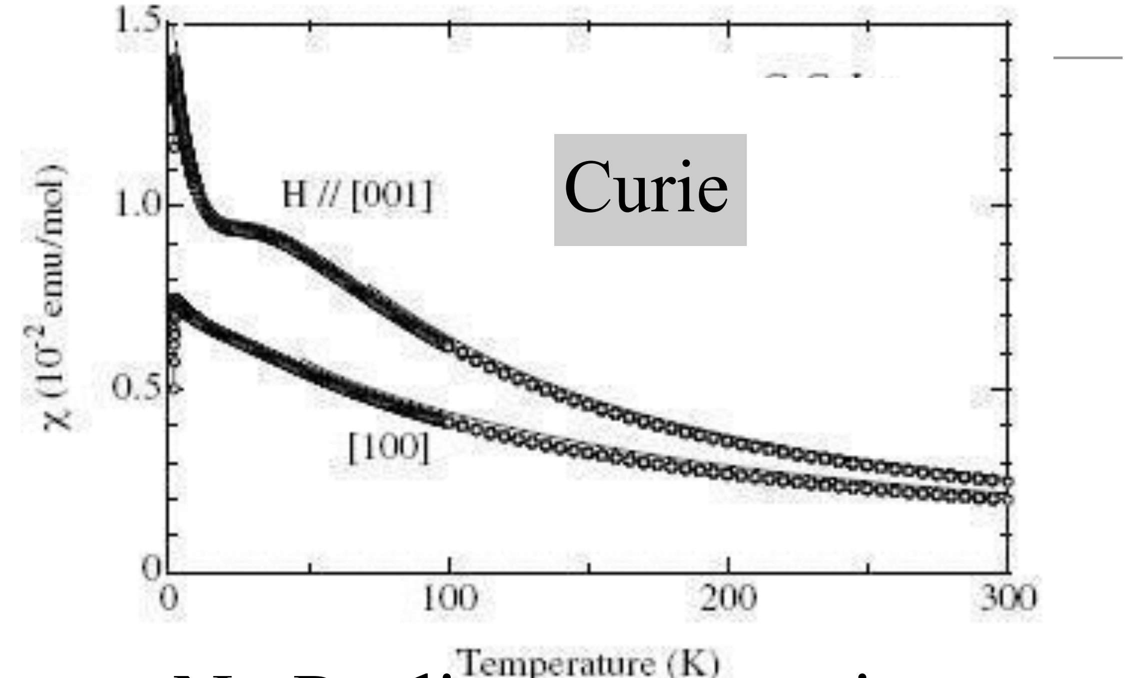
Pauli paramagnetic by 30K

$T_c = 0.5K$



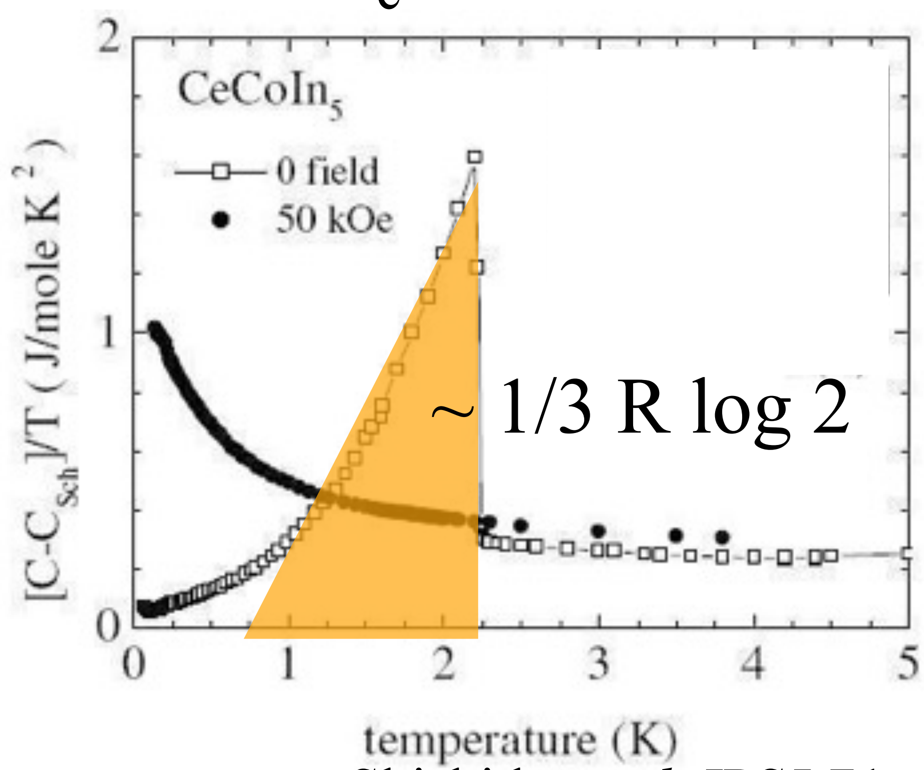
Frings *et al.* J. Magn. Magn. Mater. **31**, 240(1983)
Brison *et al.* J. Low Temp. Phys. **95**, 145(1994)

$CeCoIn_5$



No Pauli paramagnetism

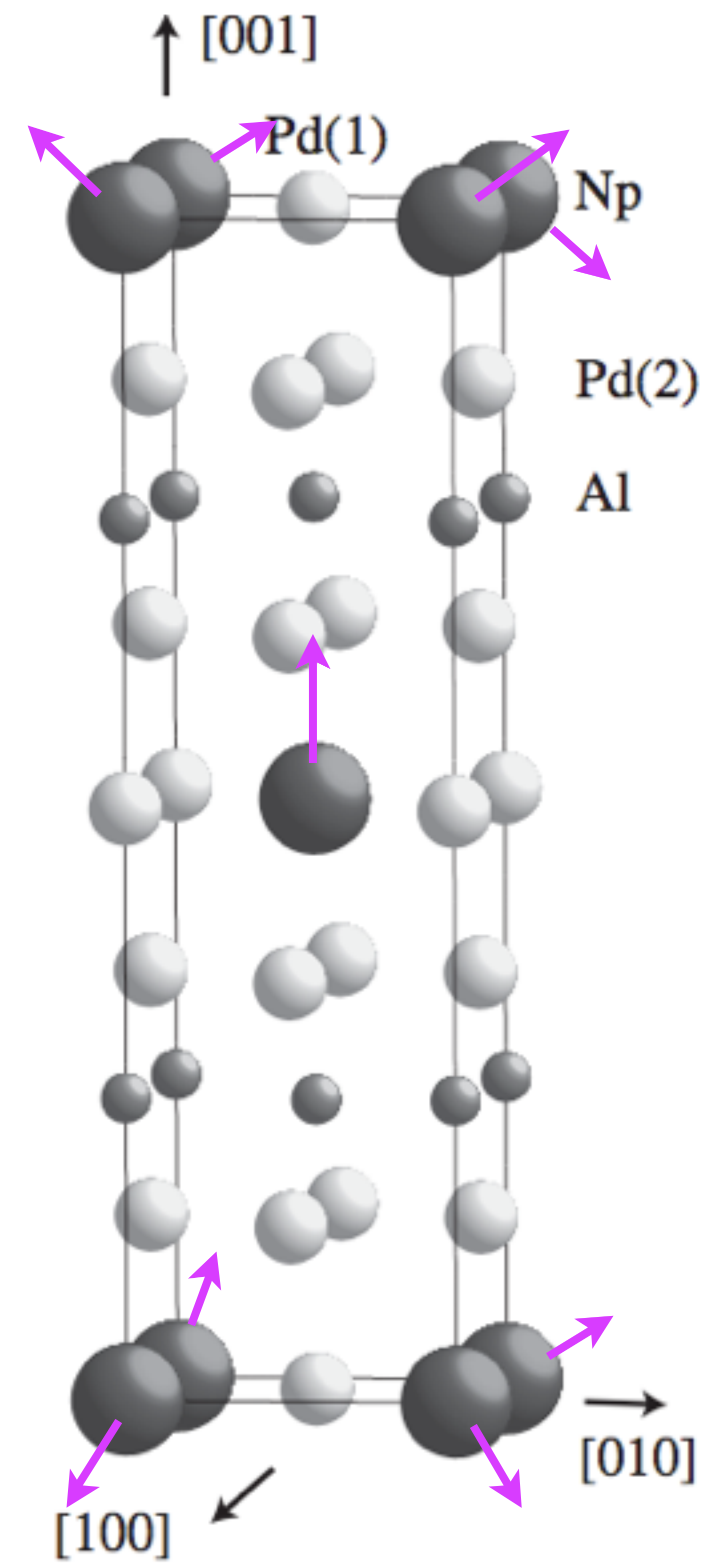
$T_c = 2.3K$



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

115 Mystery.

The Mystery of $NpPd_5Al_2$

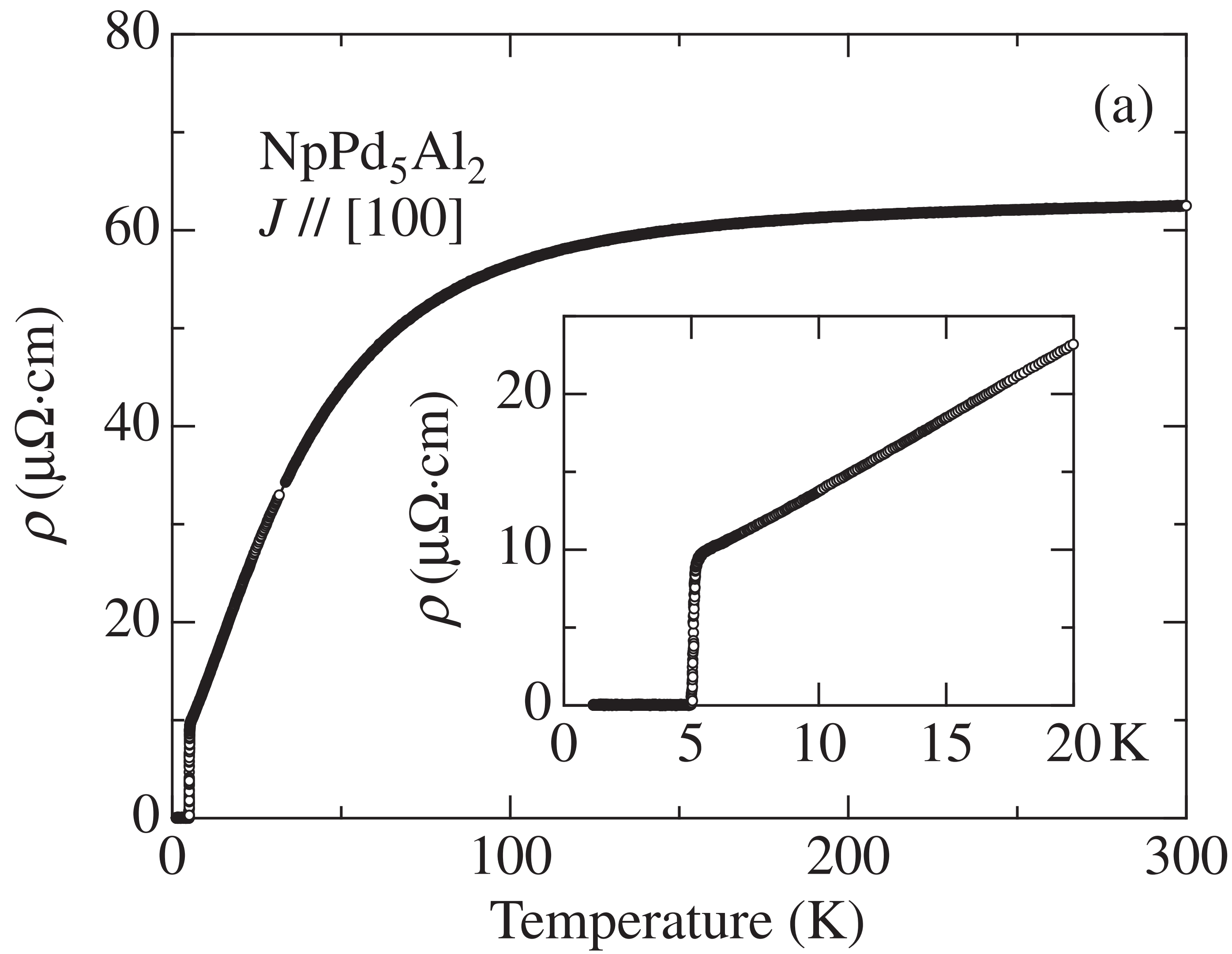


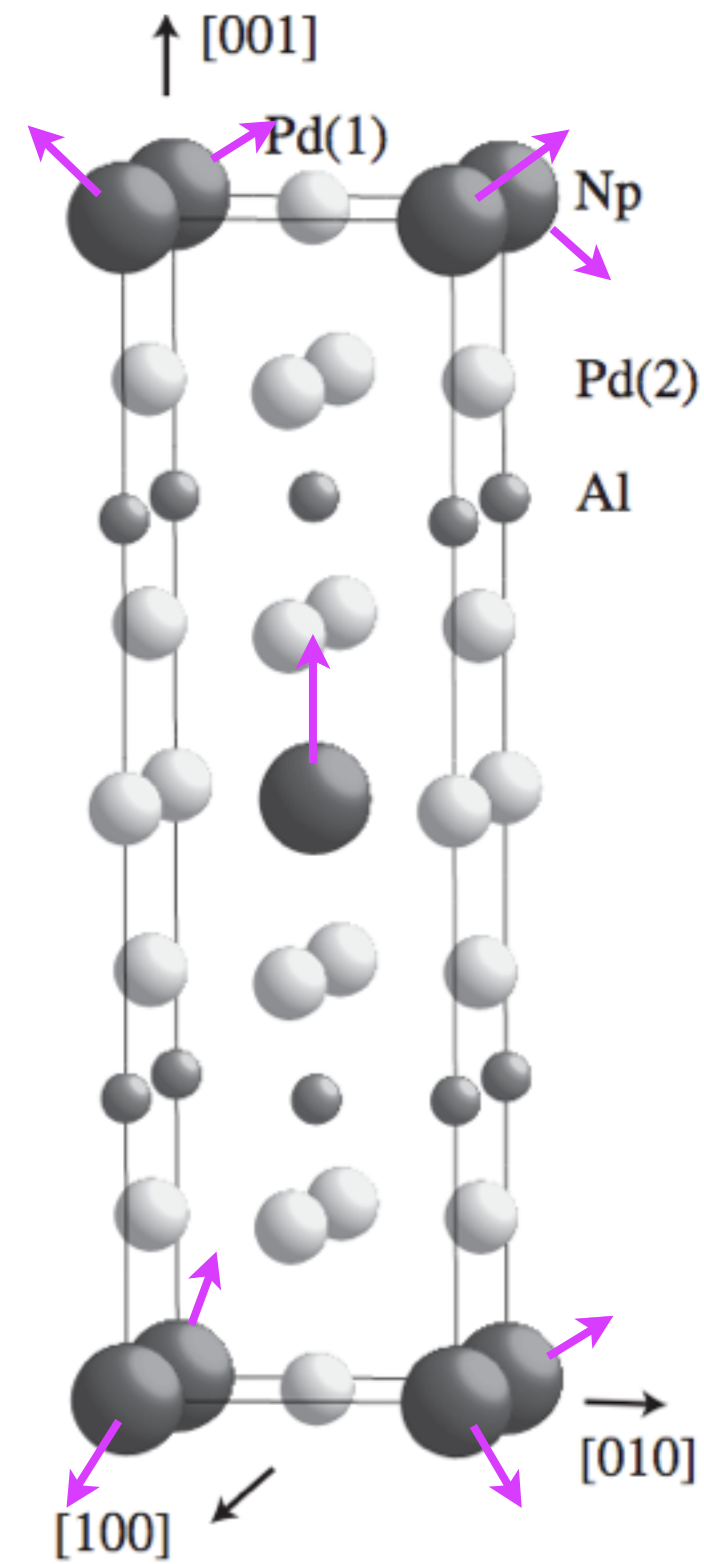
4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$



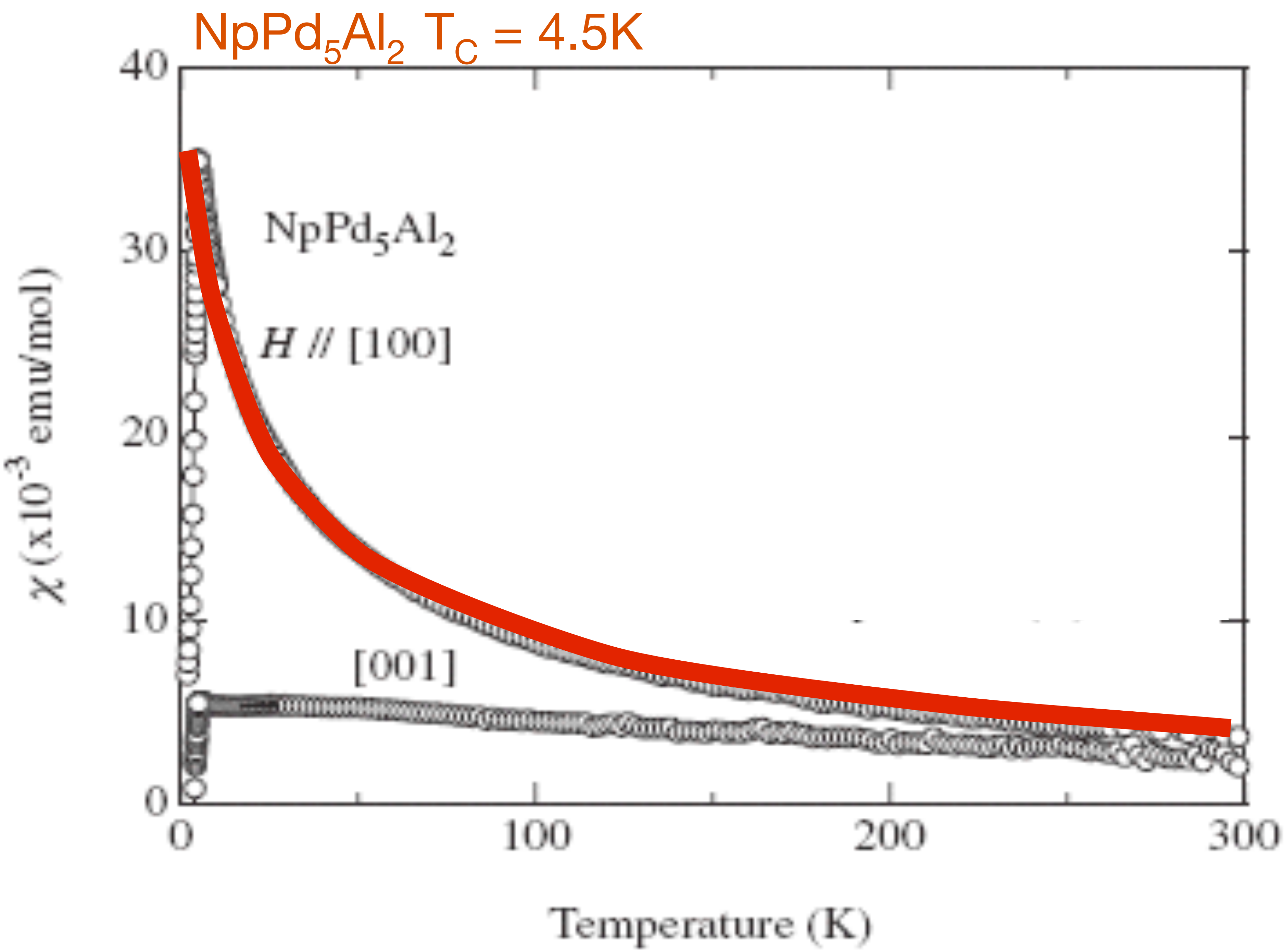


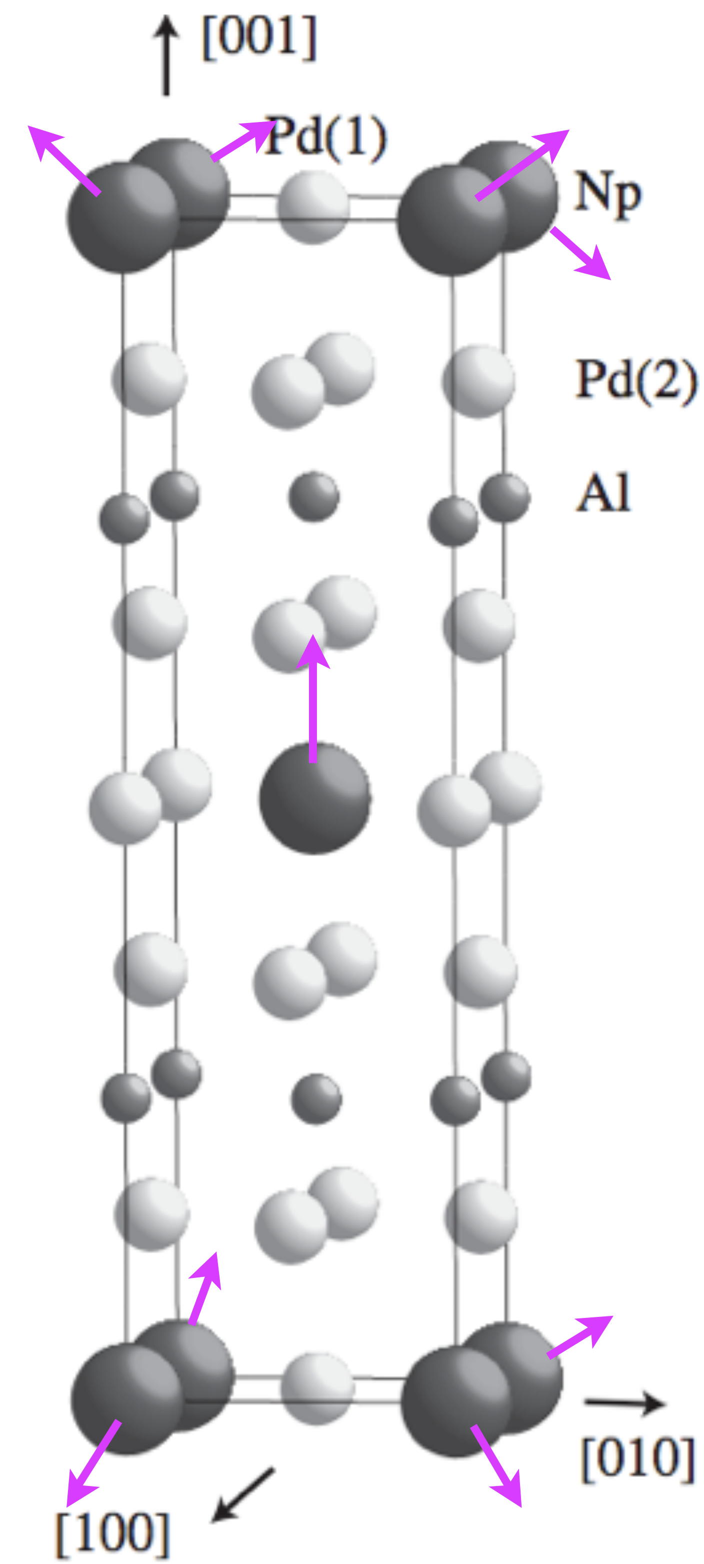
4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$





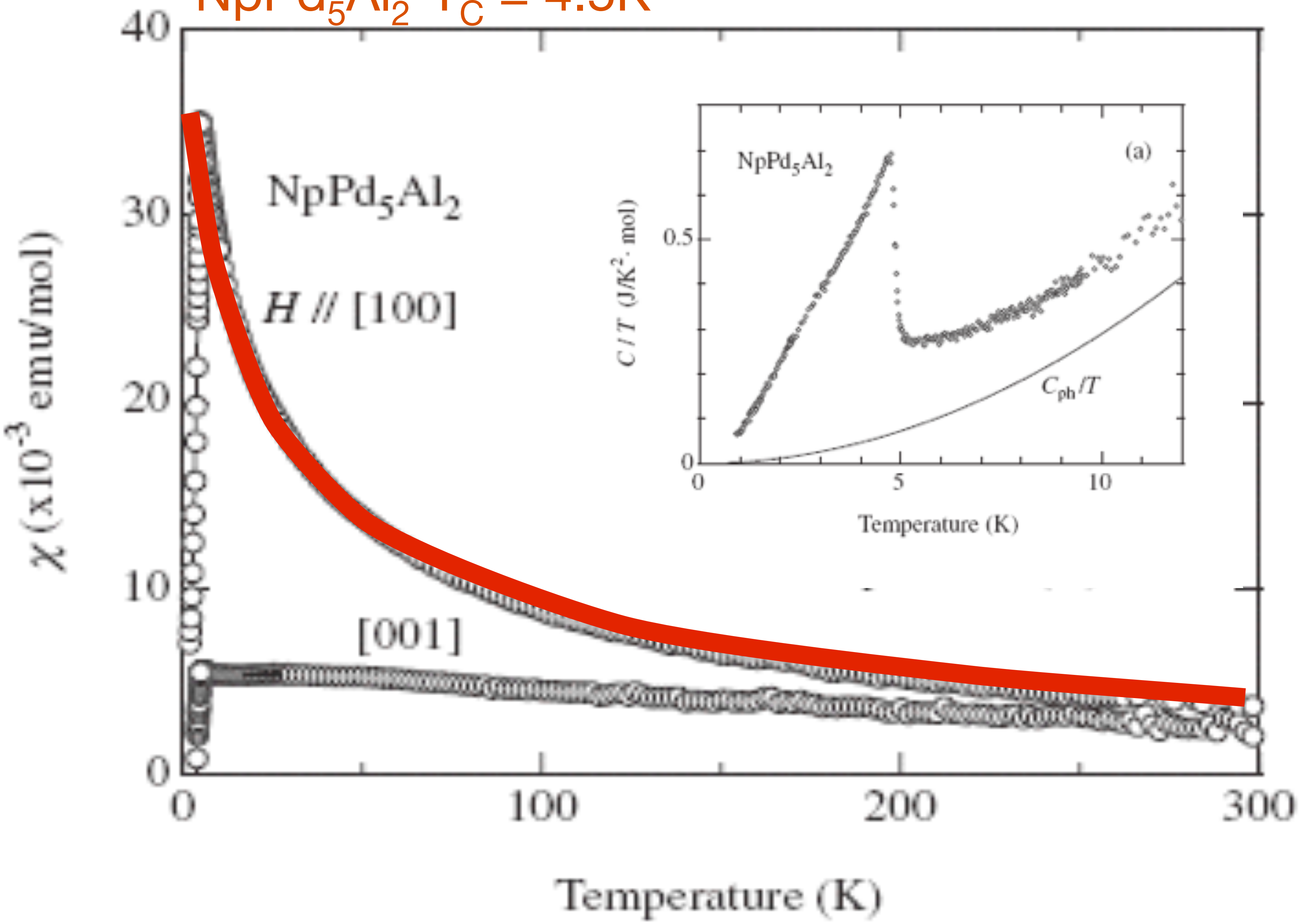
4.5K Heavy Fermion S.C

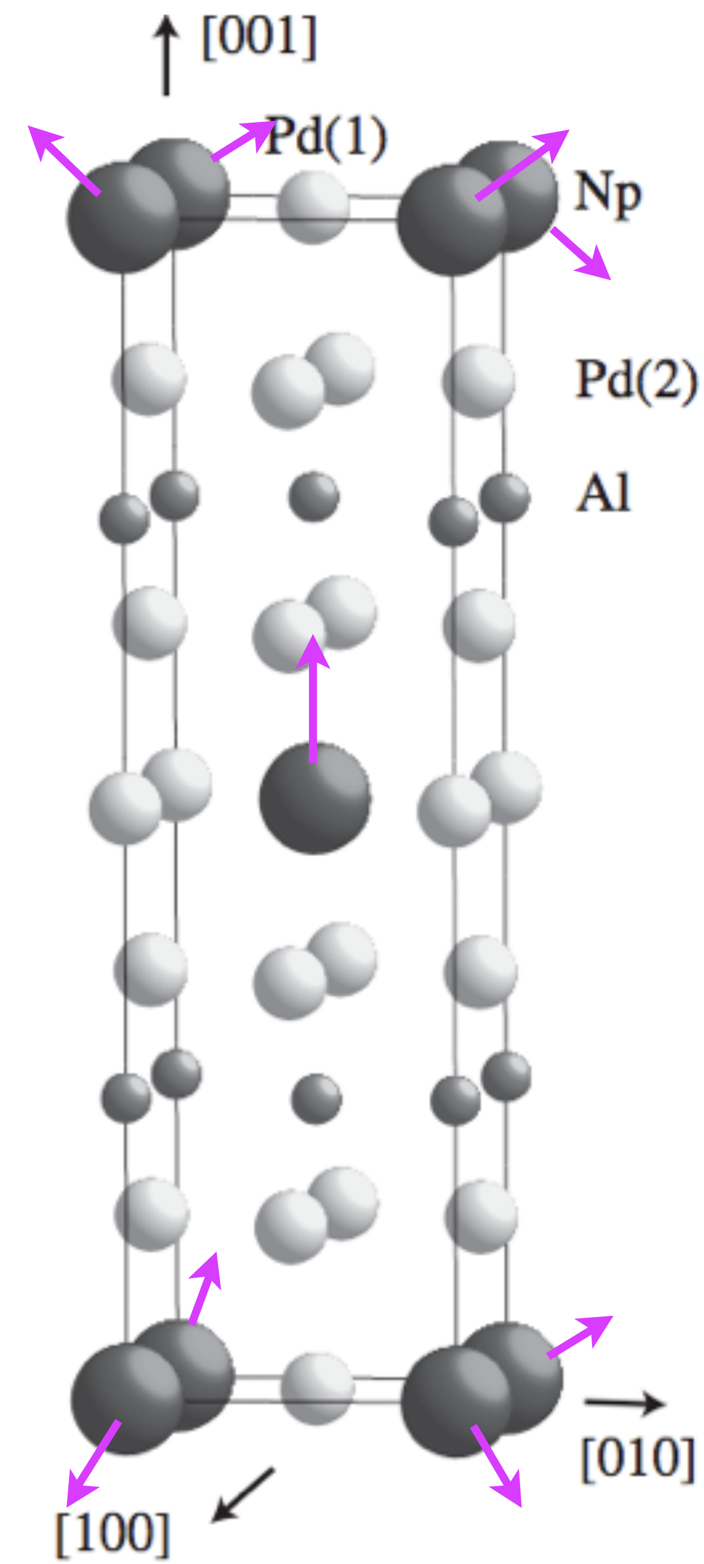
$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$

$NpPd_5Al_2$ $T_C = 4.5K$





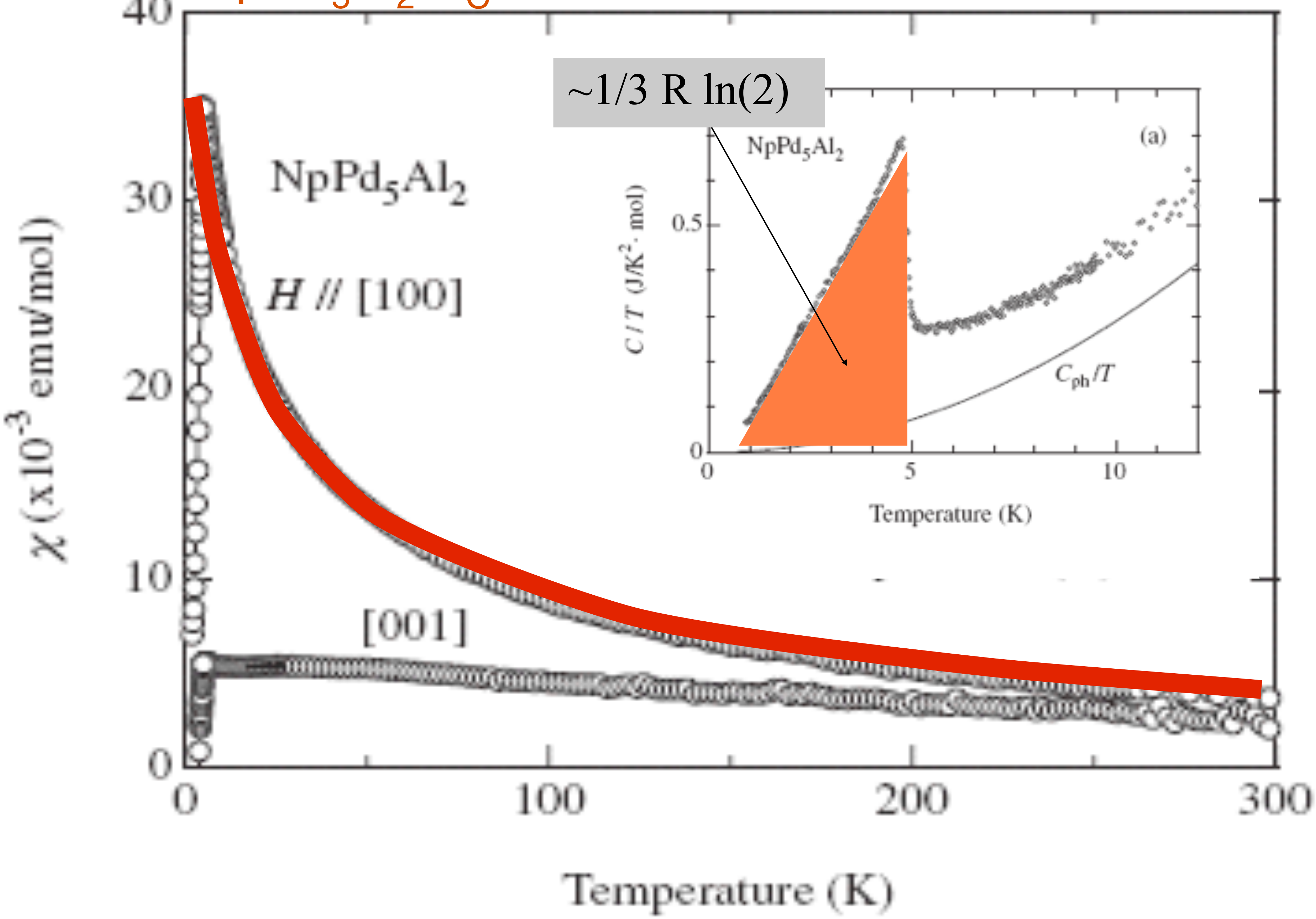
4.5K Heavy Fermion S.C

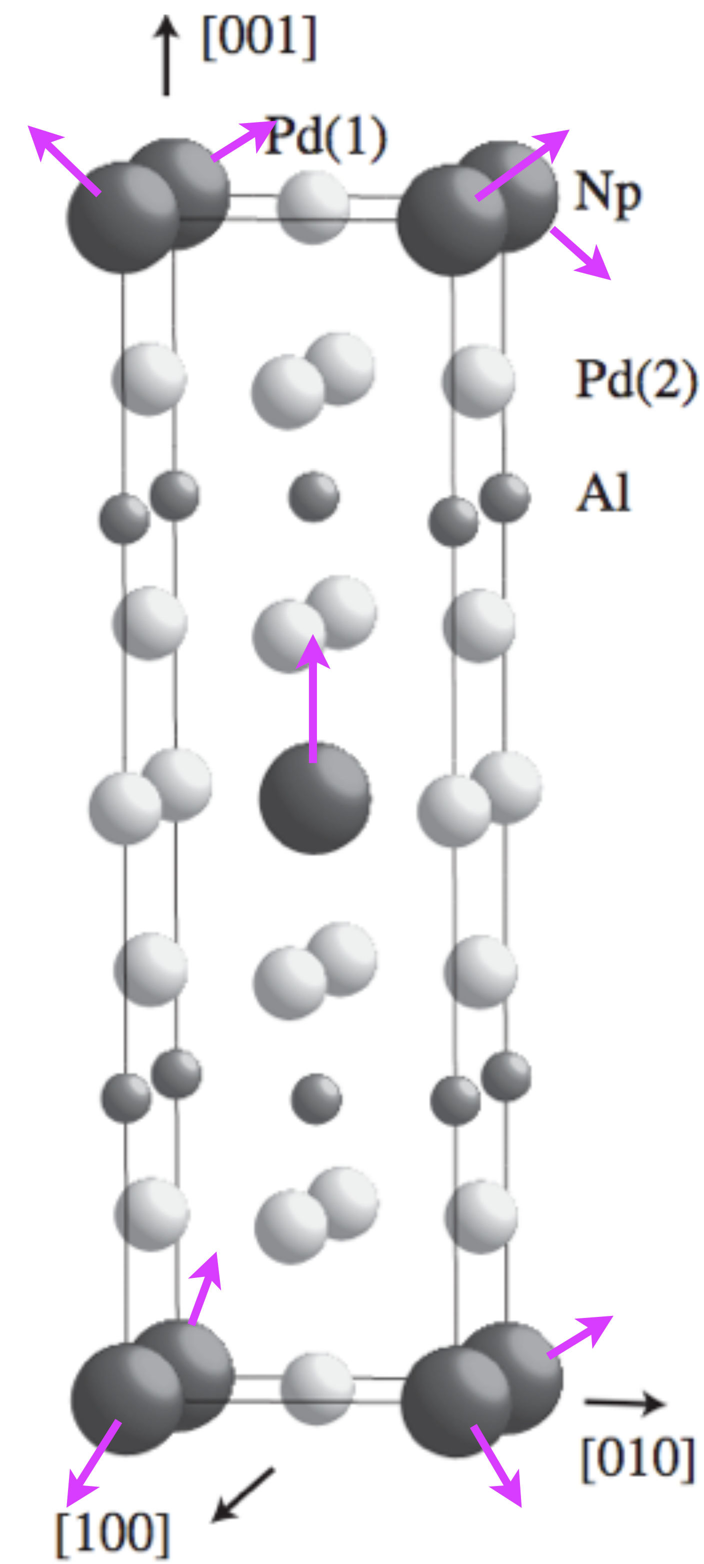
$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$

$NpPd_5Al_2$ $T_C = 4.5K$





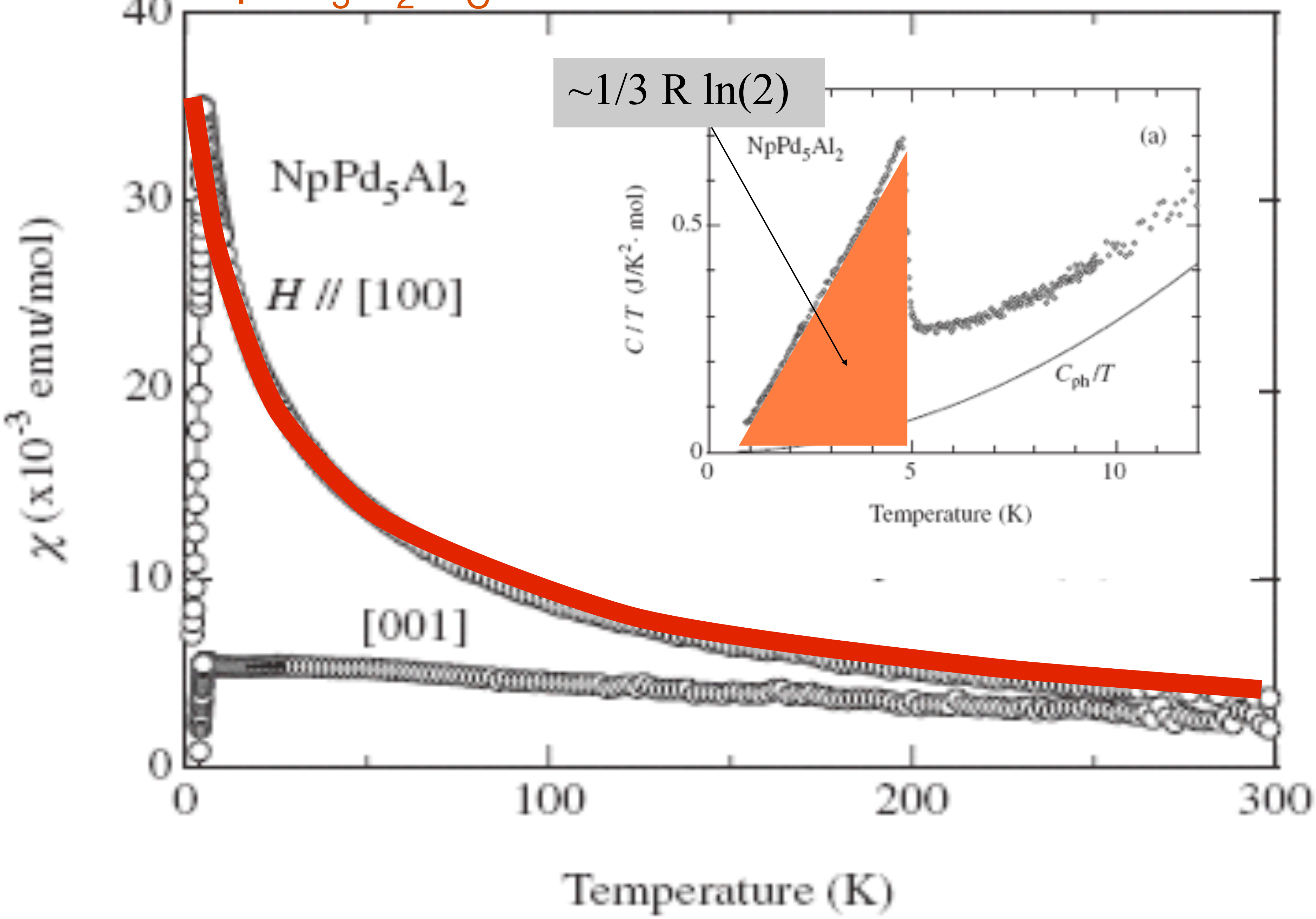
4.5K Heavy Fermion S.C

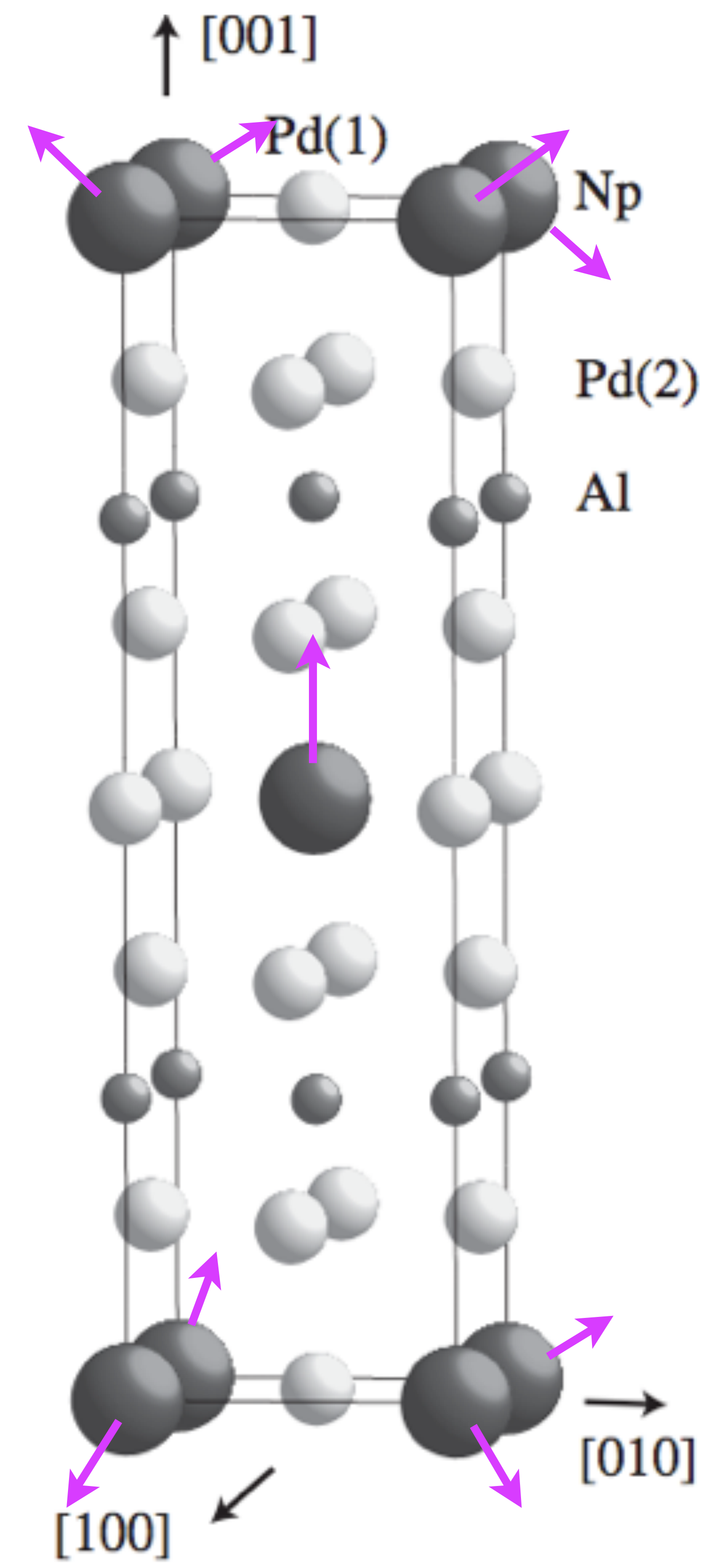
$NpAl_2Pd_5$

Aoki et al 2007

The Mystery of $NpPd_5Al_2$

$NpPd_5Al_2$ $T_C = 4.5K$



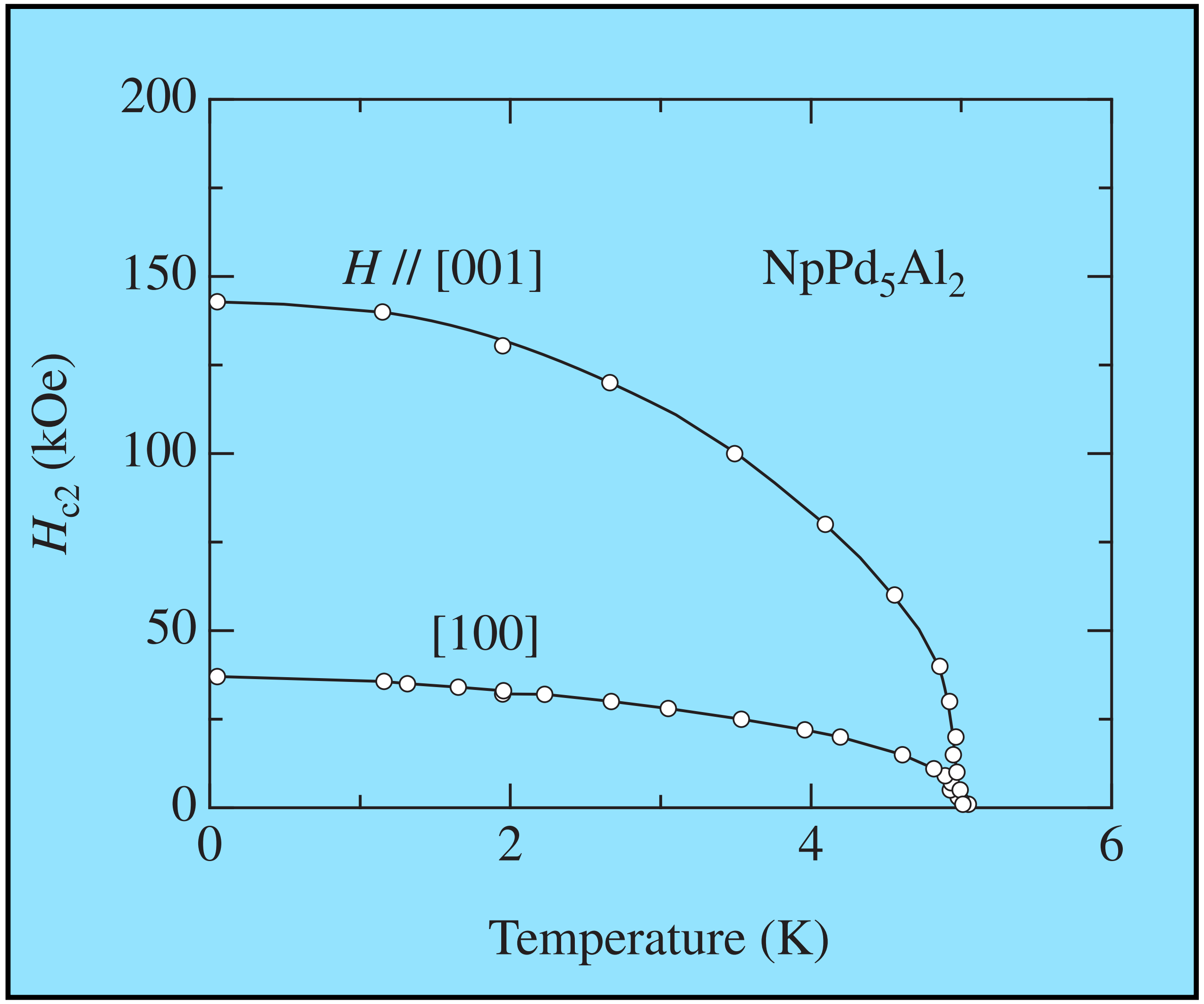


How does the spin form the condensate?

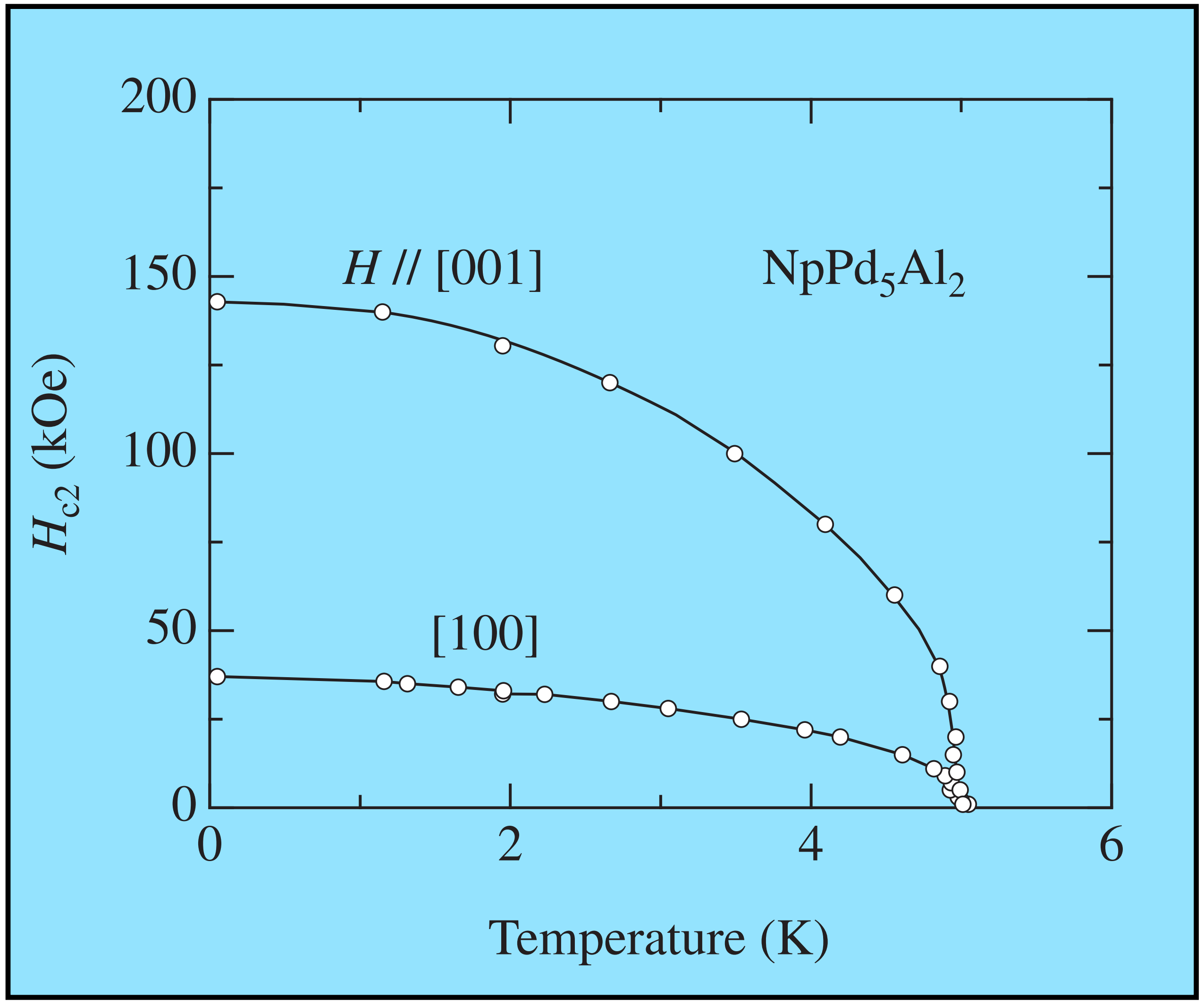
4.5K Heavy Fermion S.C

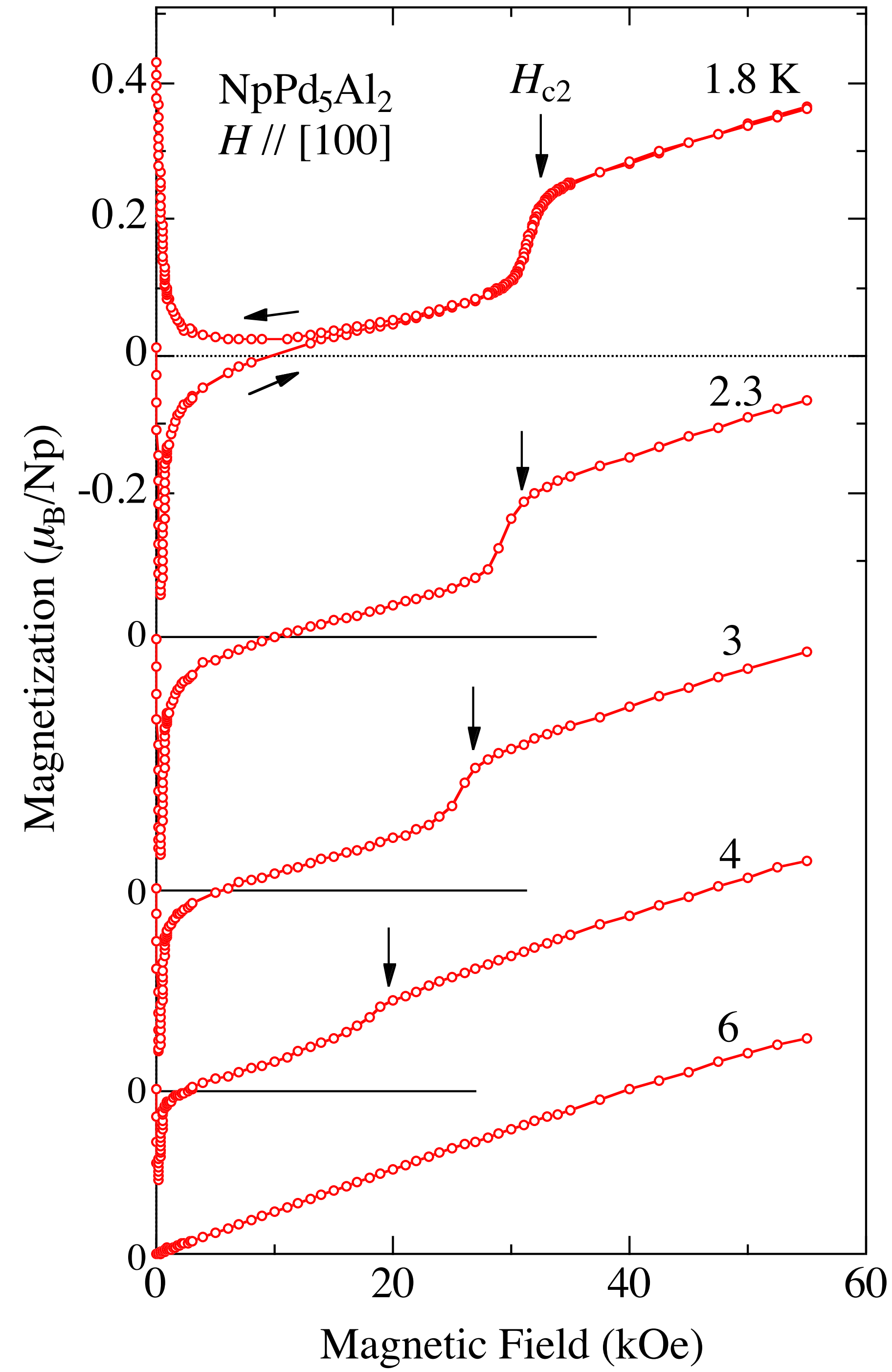
$NpAl_2Pd_5$

Aoki et al 2007

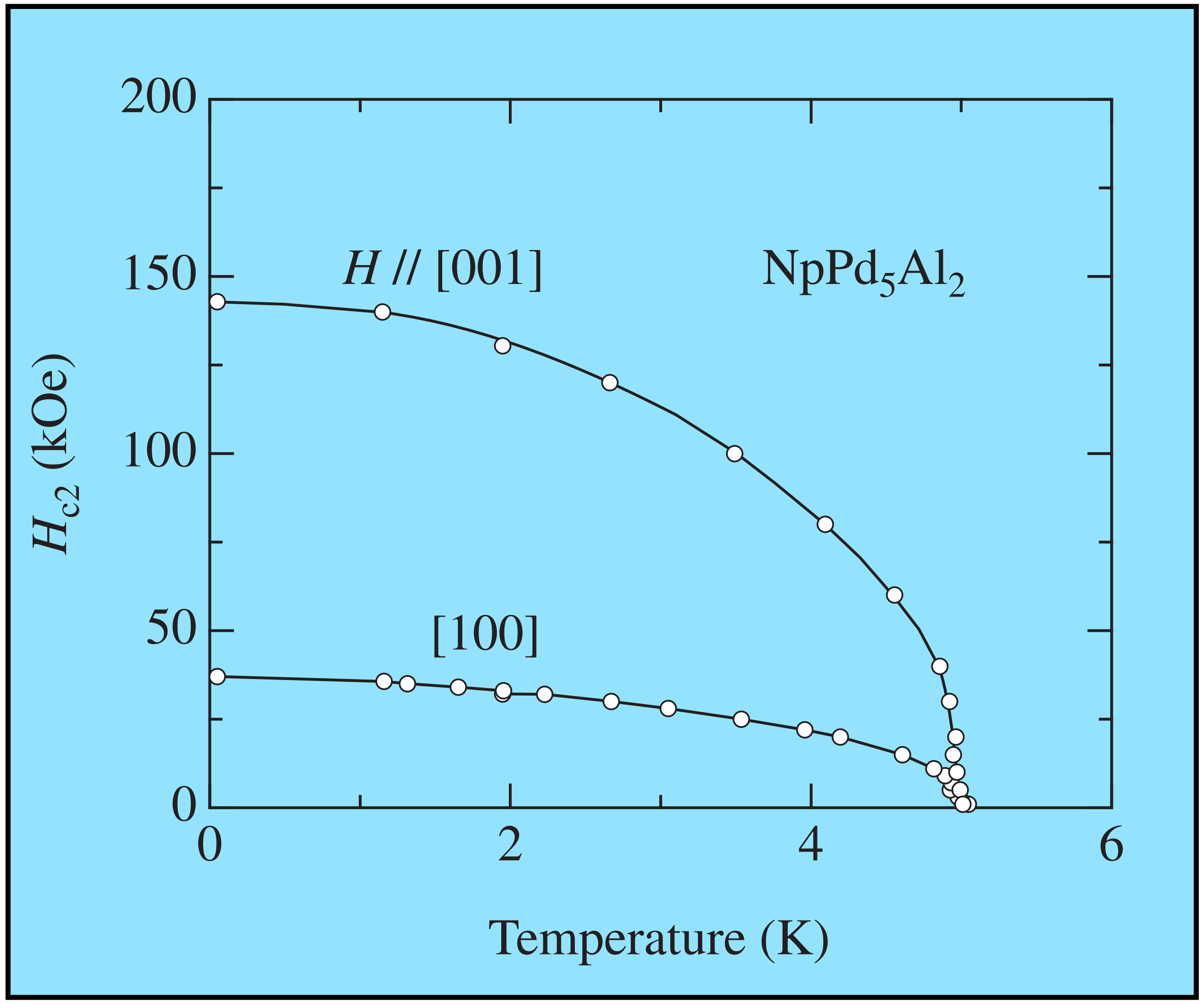


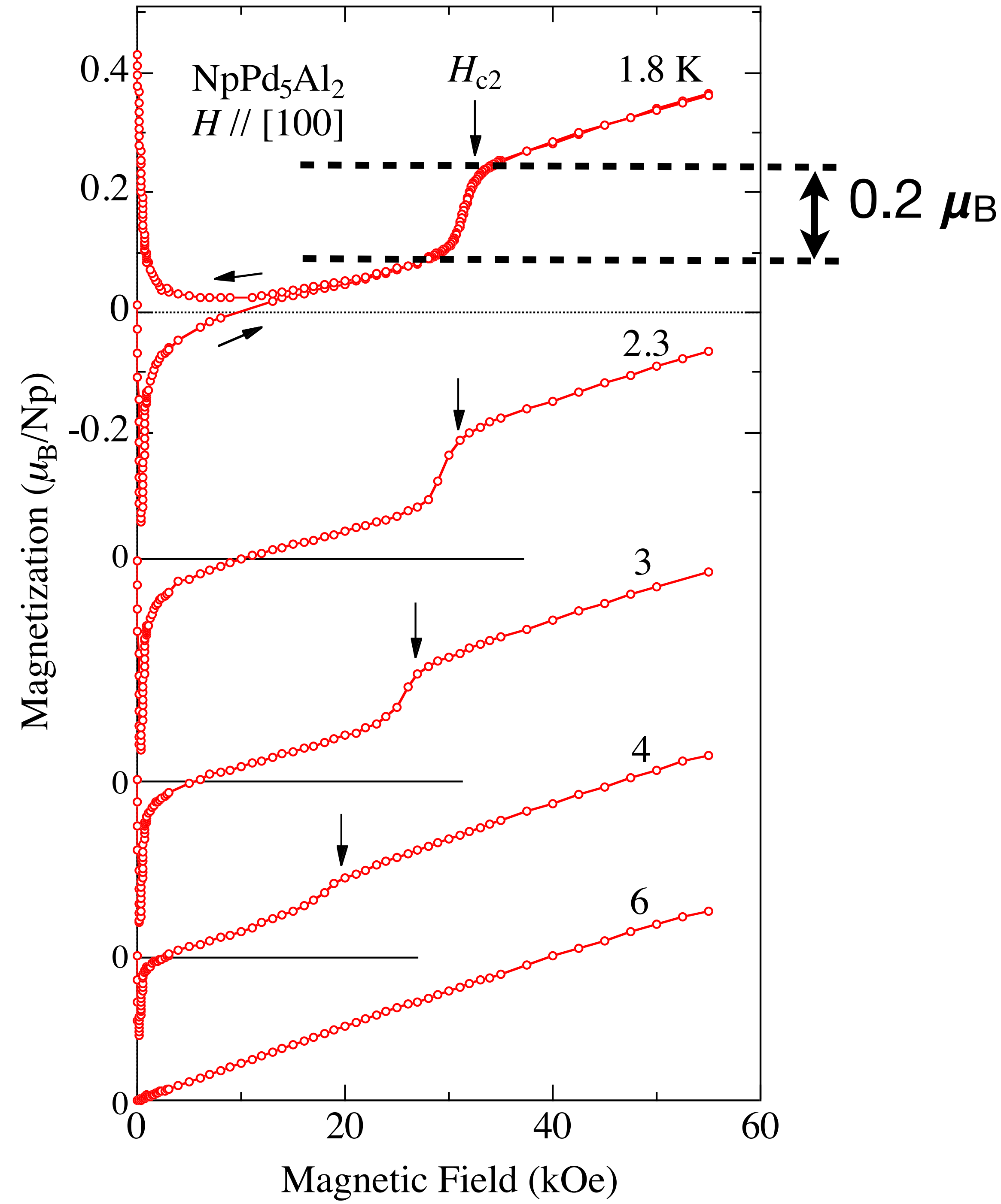
200
150
100
50
0
H_{c2} (kOe)
H // [001]
$NpPd_5Al_2$
[100]
0
2
4
6
Temperature (K)





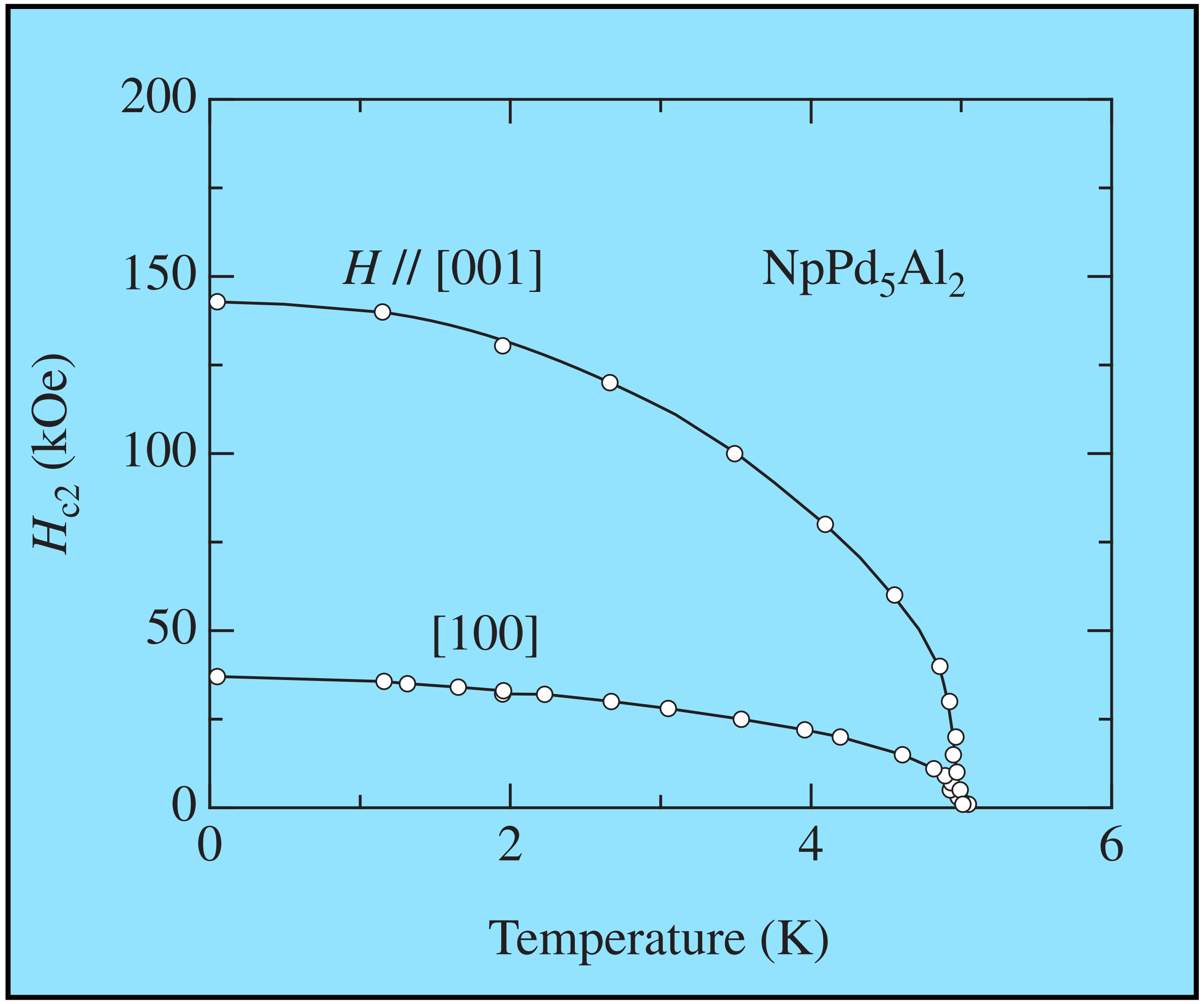
D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

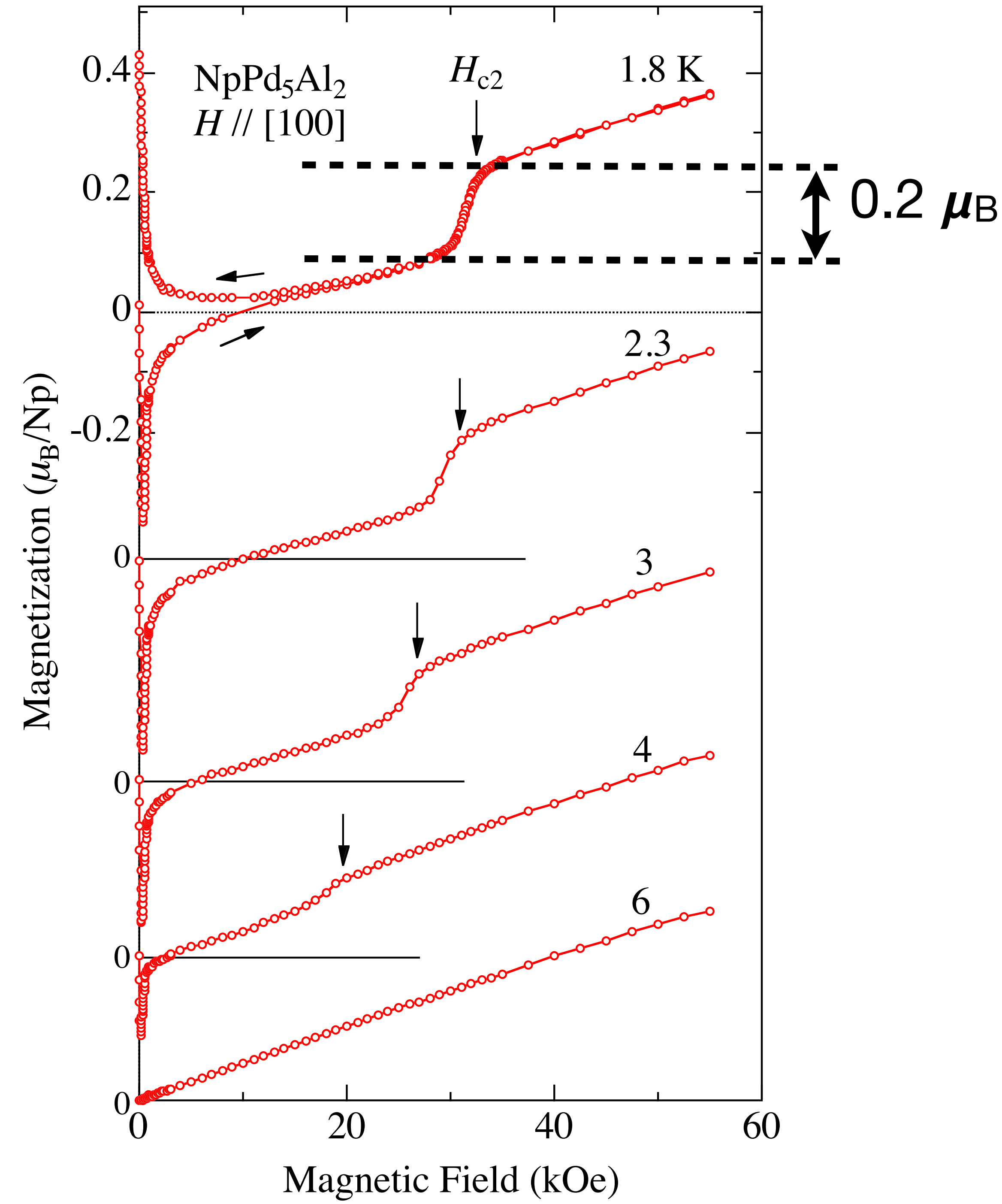




D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

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





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

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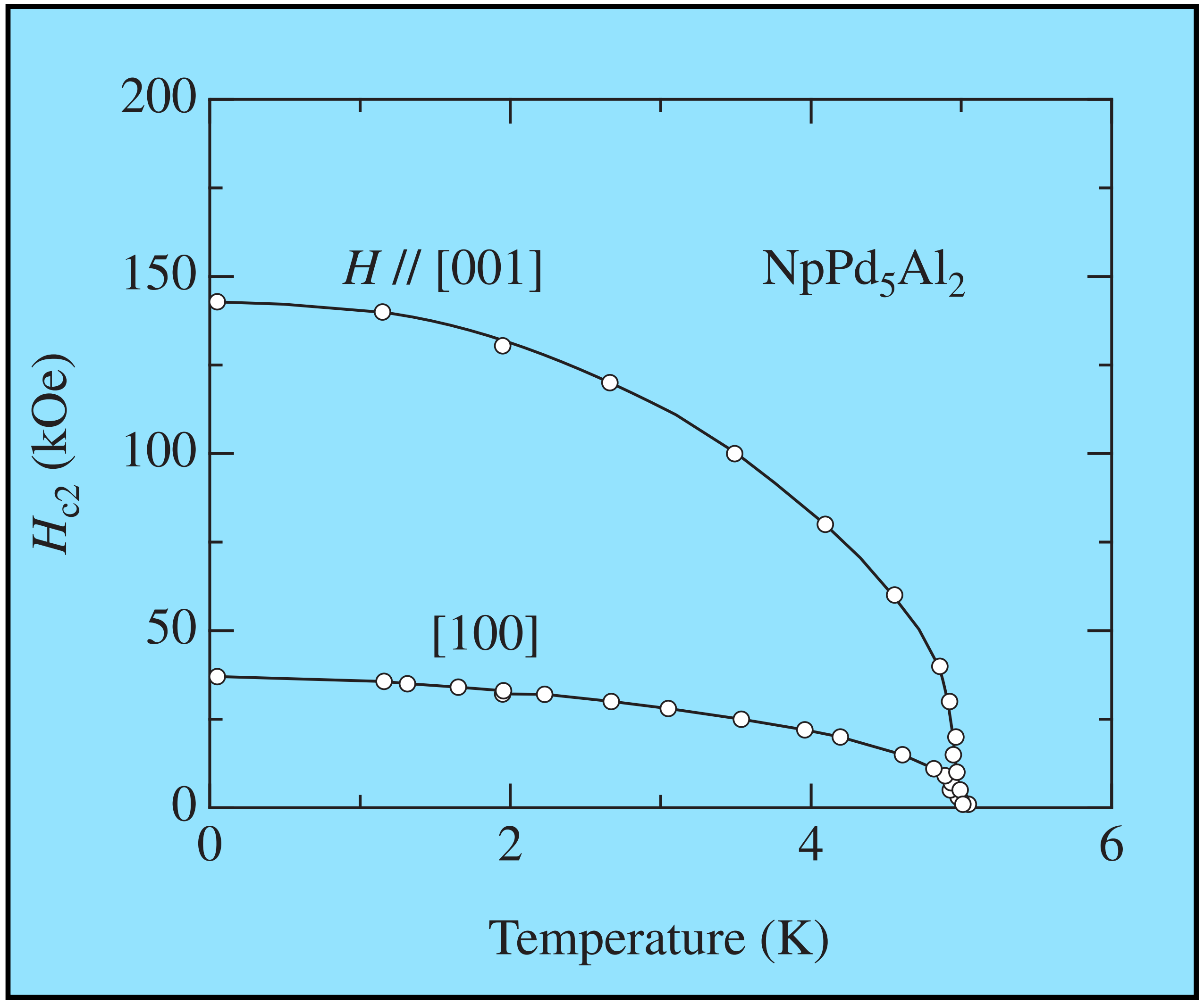
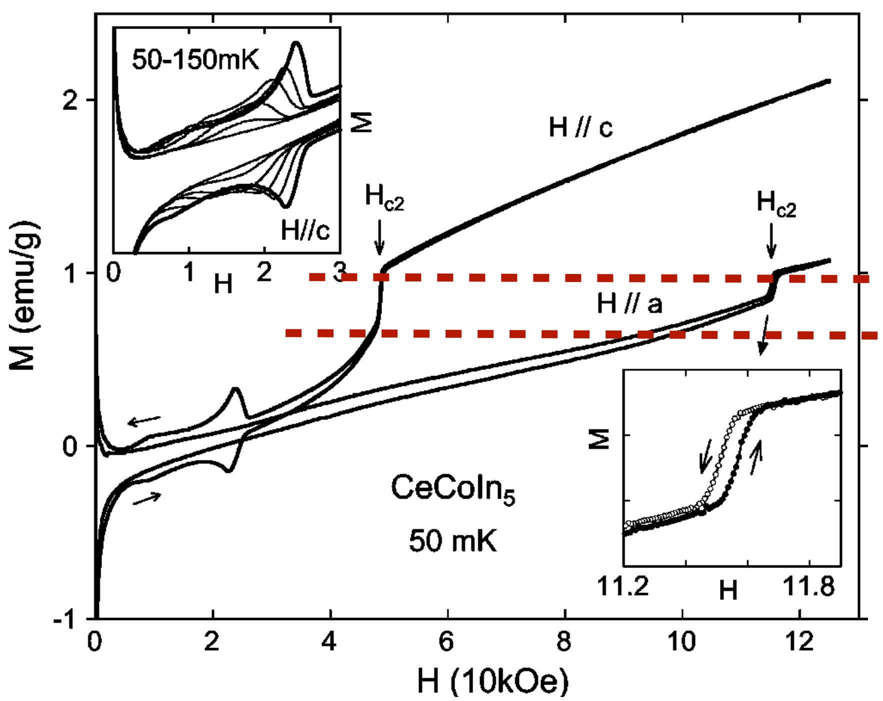
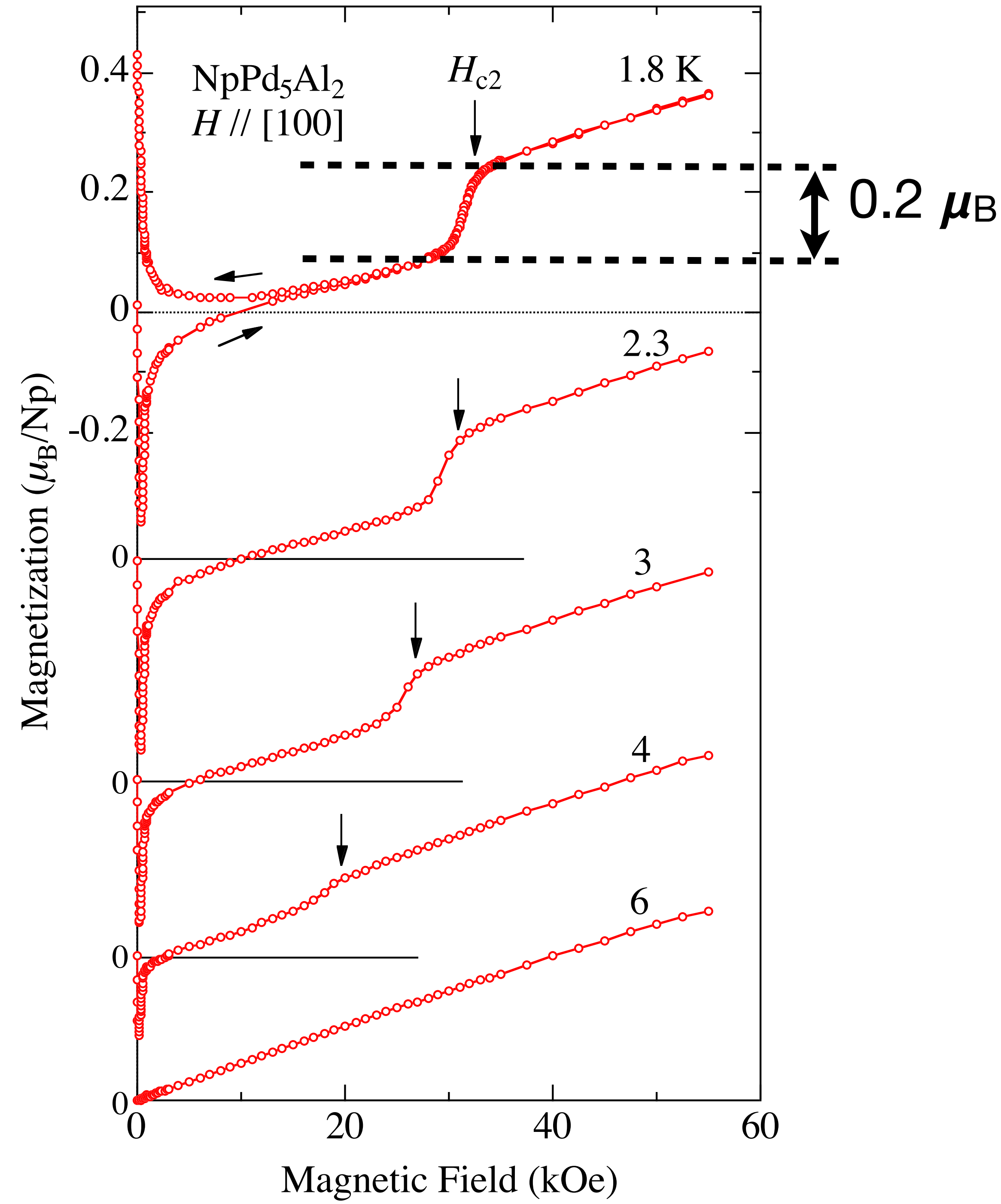




CeCoIn₅

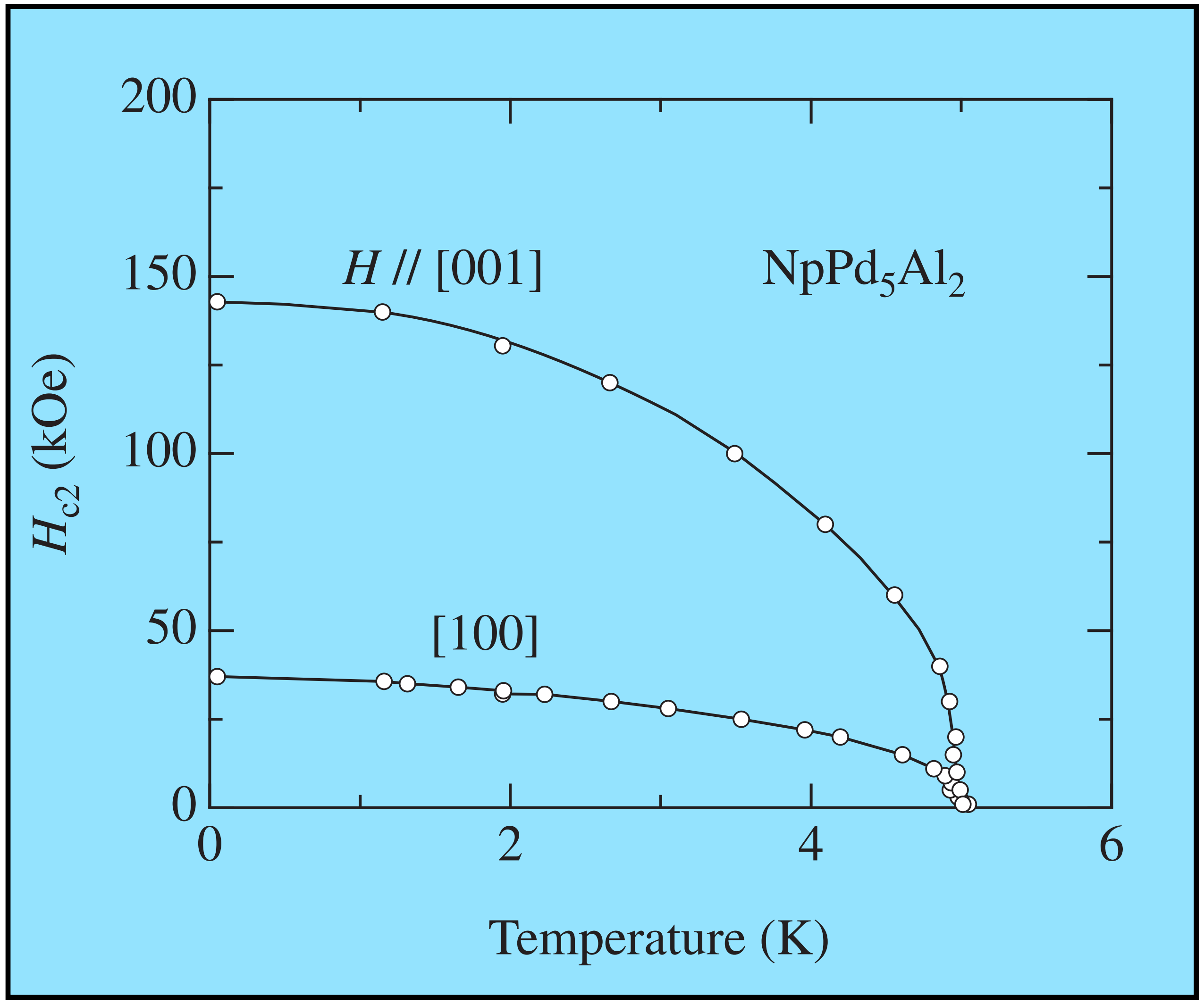
0.3 μ_B

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

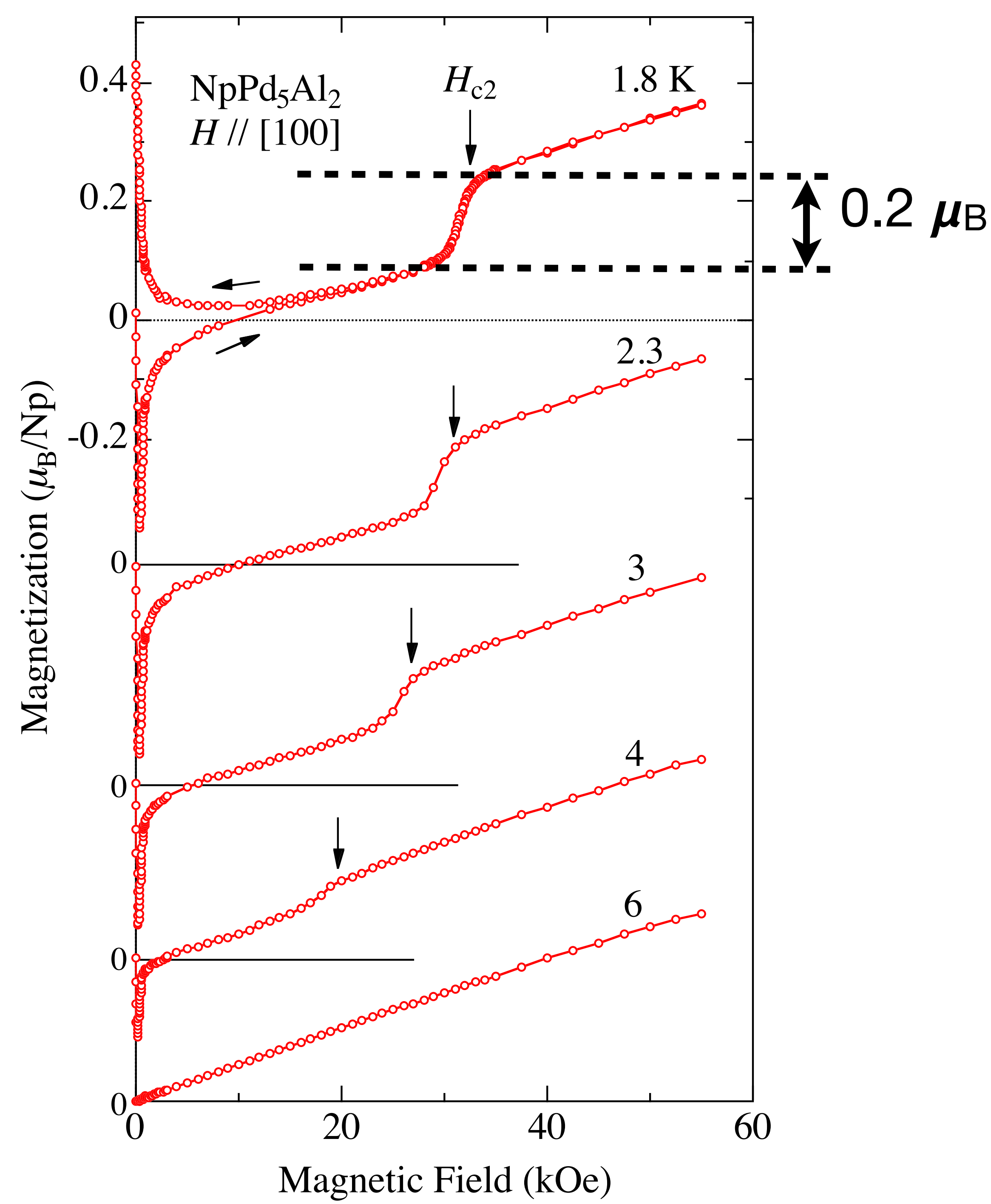


D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

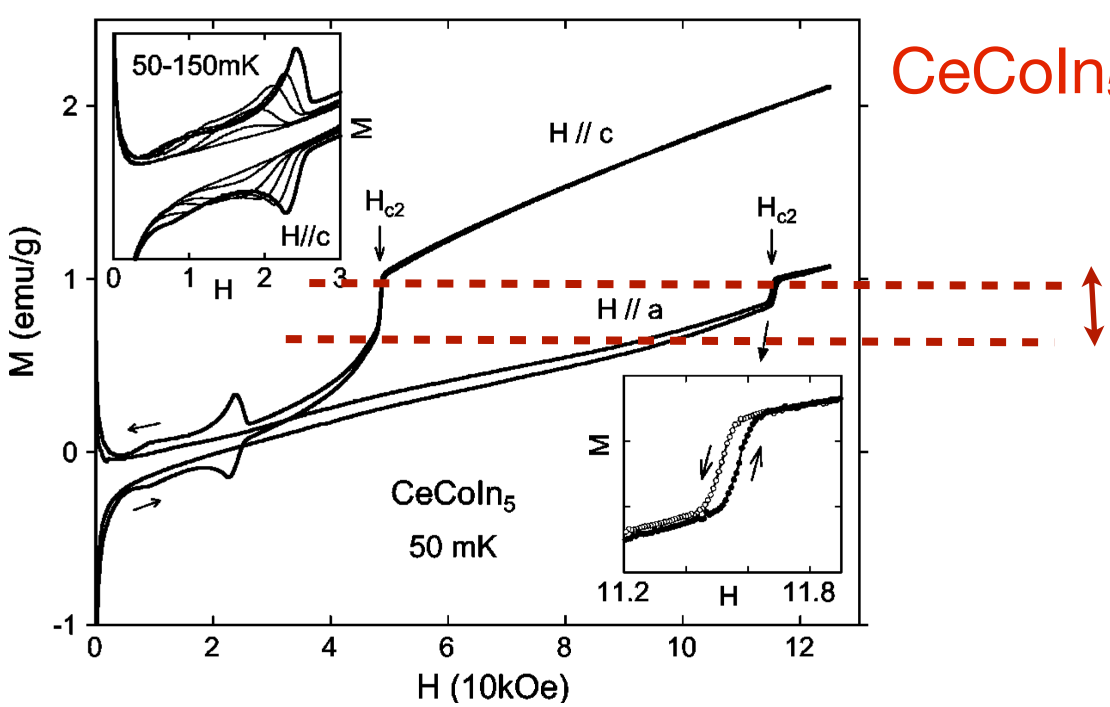
Large first order jump in magnetization at H_{c2}.



Signals a release of the local moment from the condensate.



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

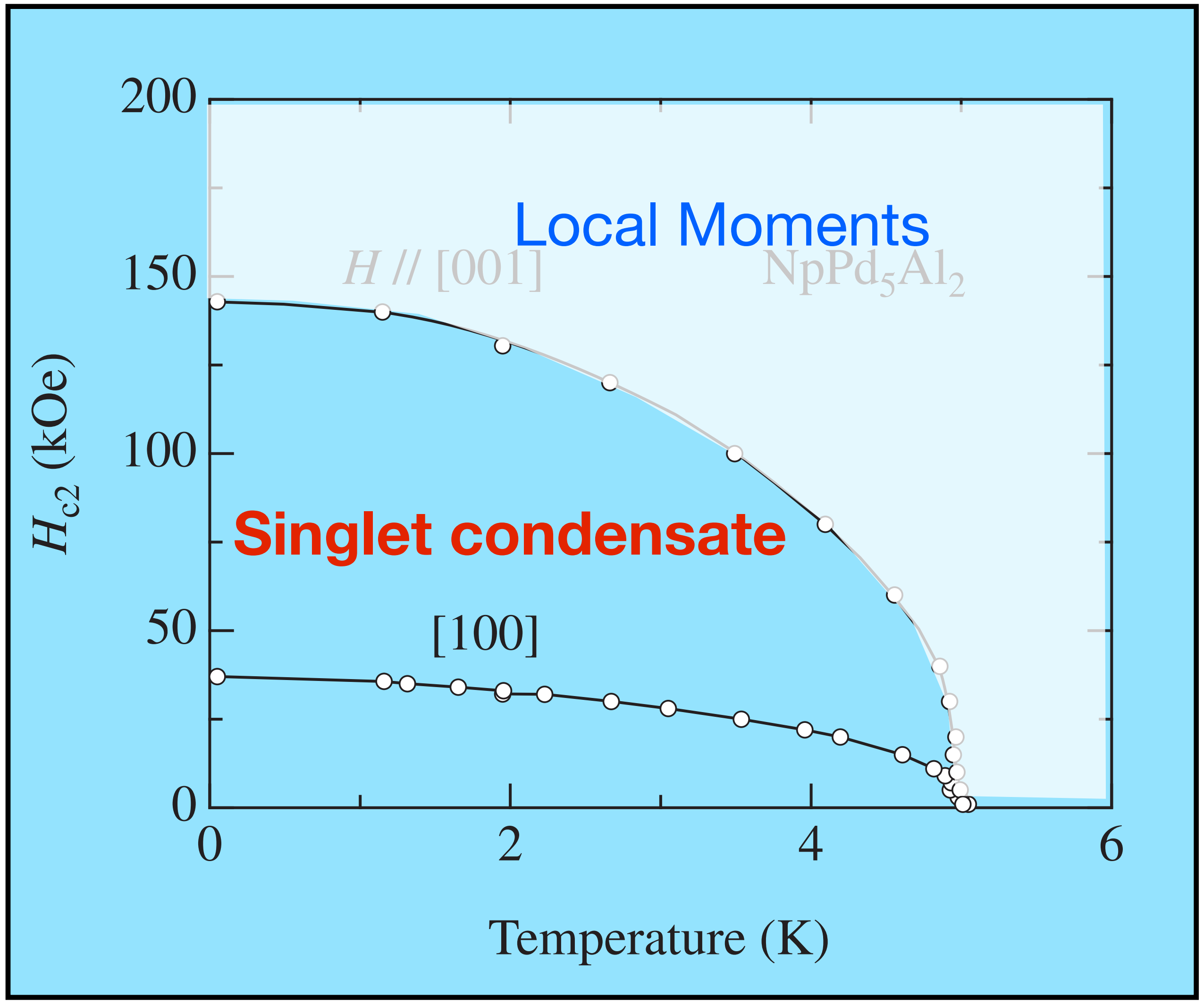


CeCoIn$_5$

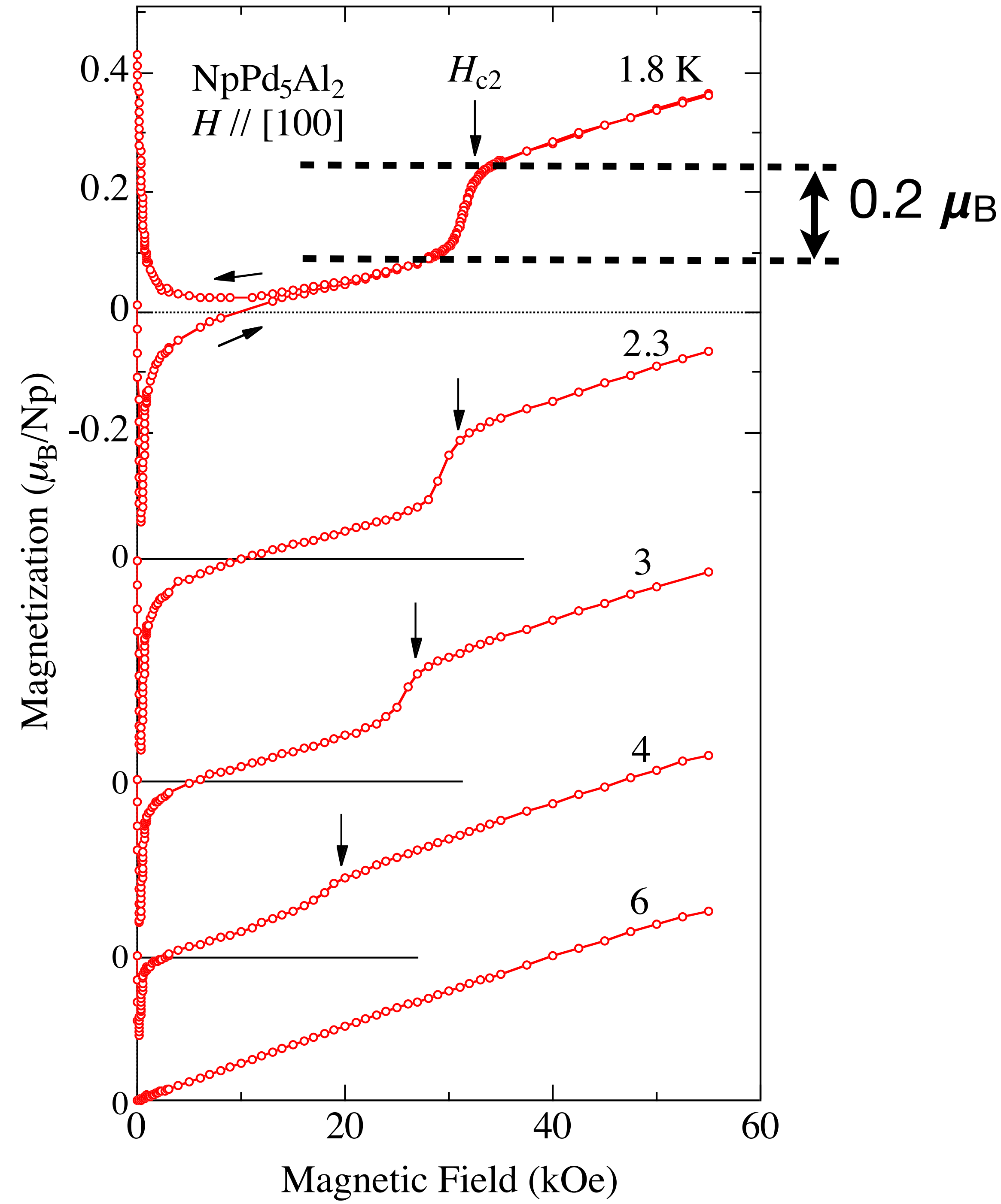
0.3 μ_B

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

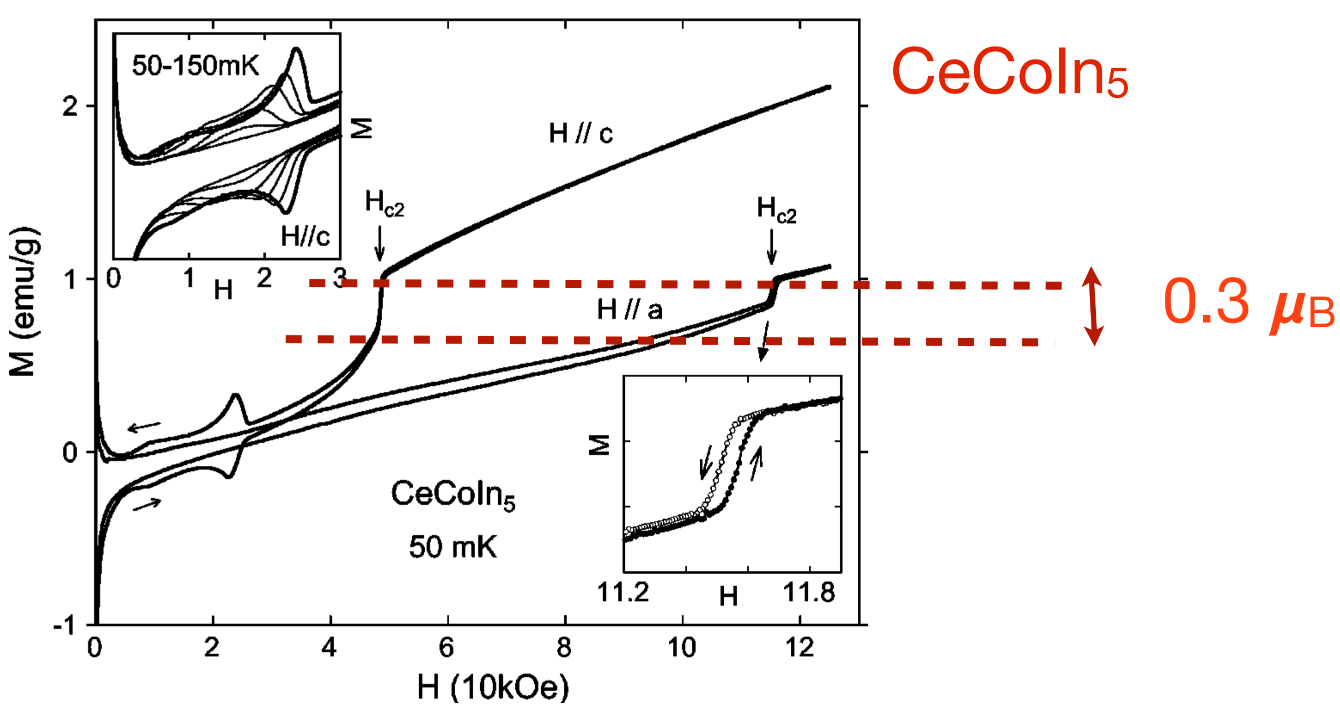
Large first order jump in magnetization at H_{c2}.



Signals a release of the local moment from the condensate.

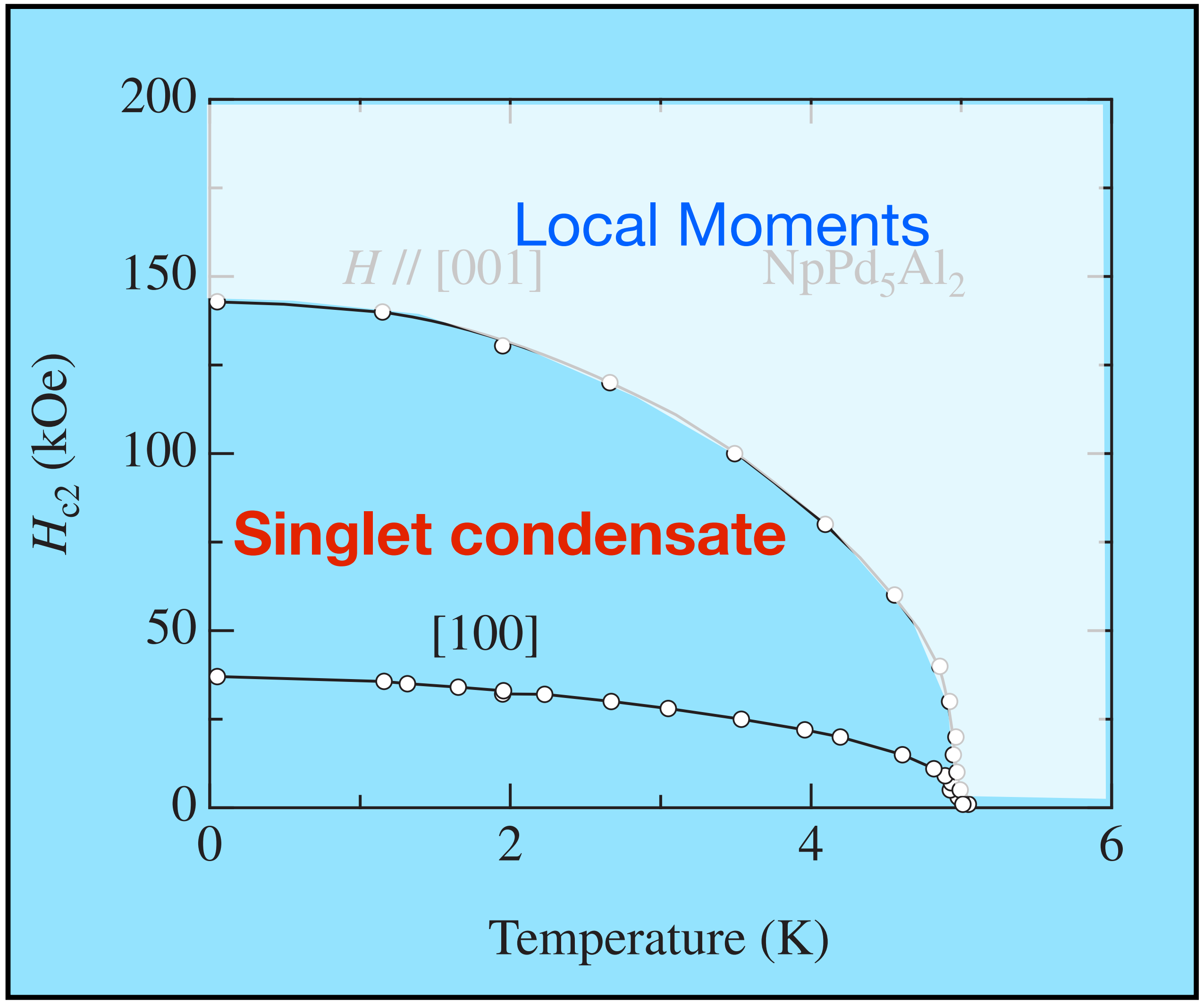


D. Aoki et al., J. Phys. Soc. Jpn. **76** (2007) 063701.

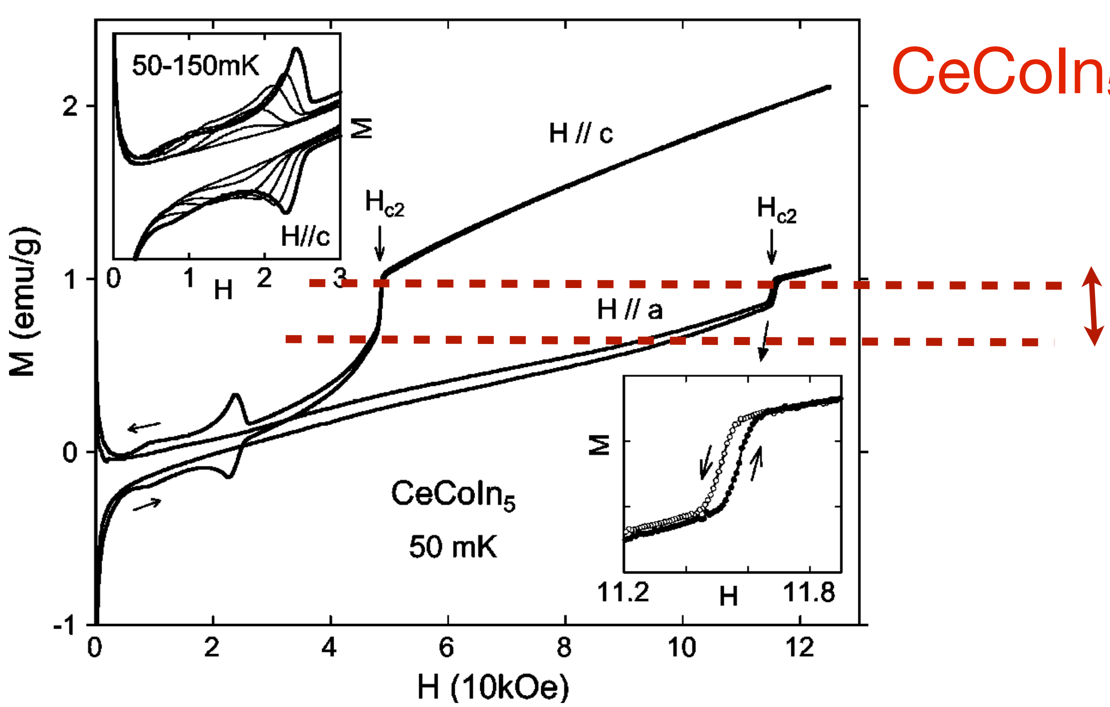


CeCoIn5

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

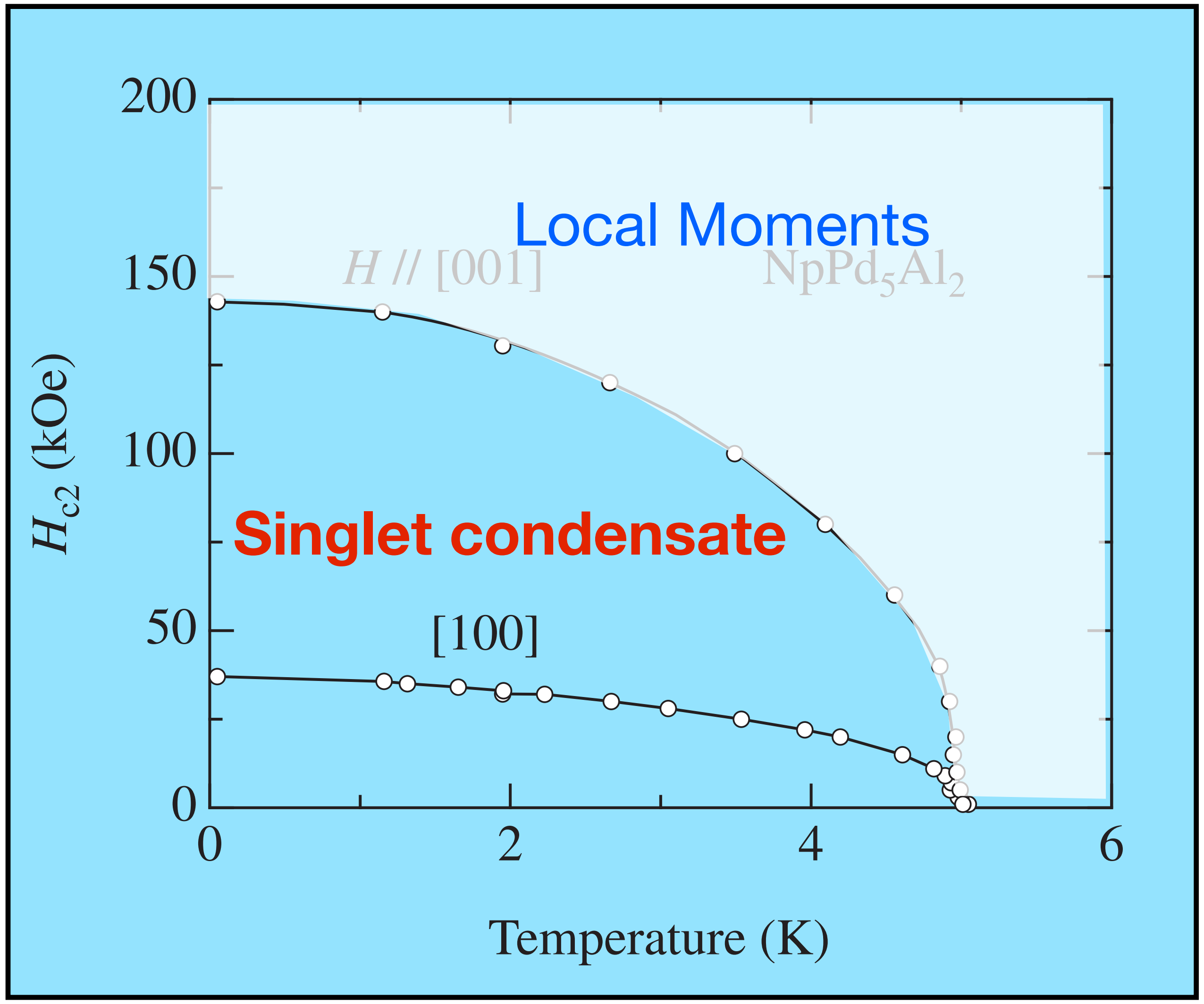


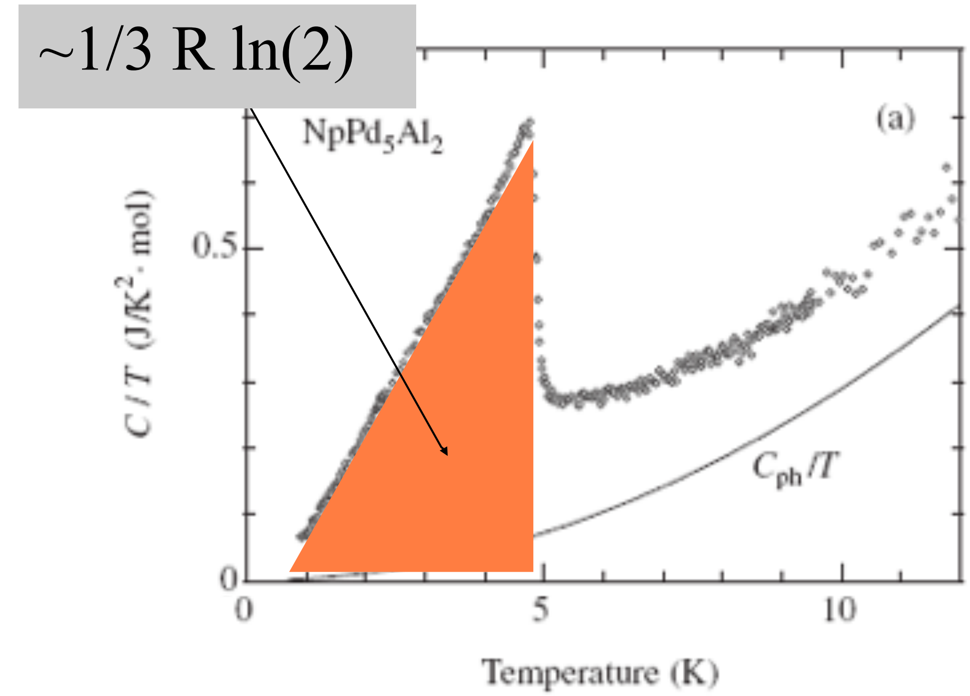
CeCoIn$_5$

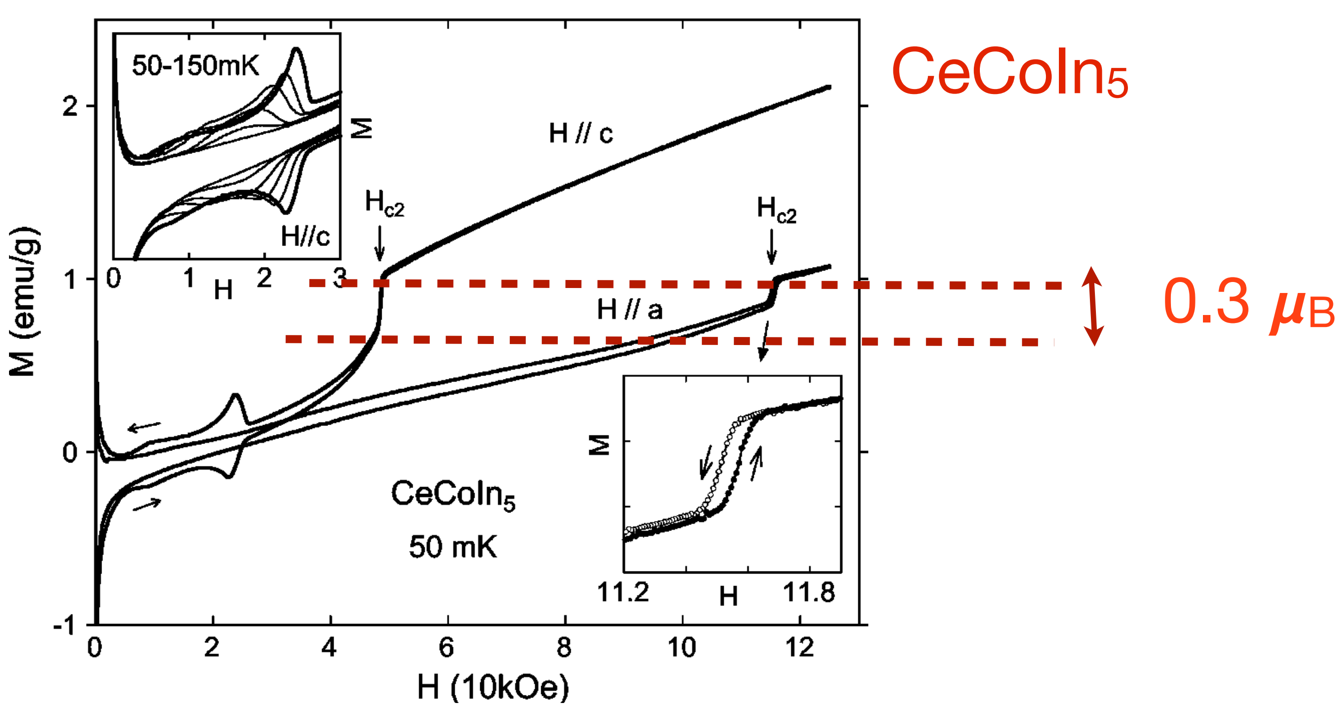


0.3 μ_B

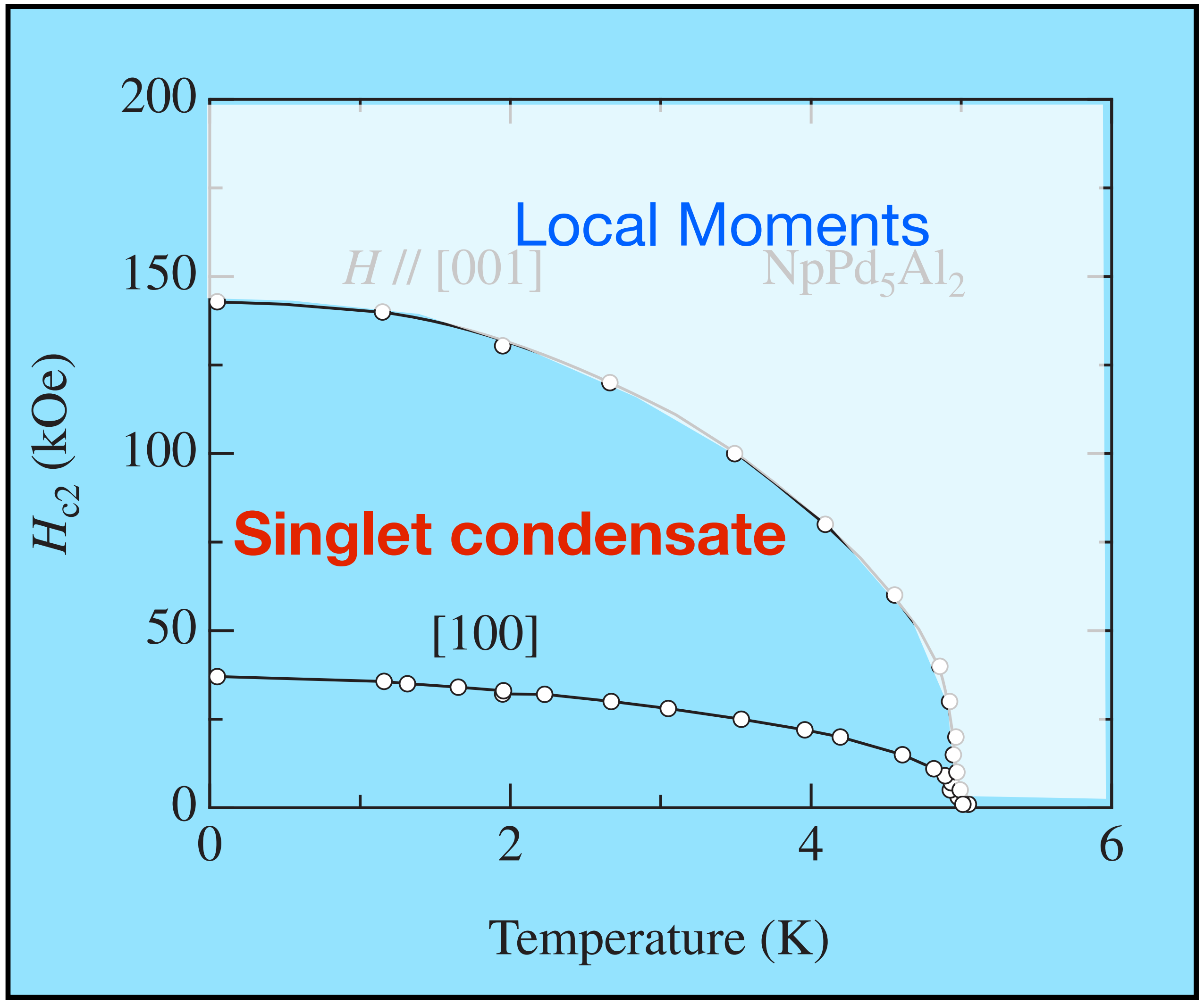
T. Tayama et al., RPB **65**, 180504R (2002)

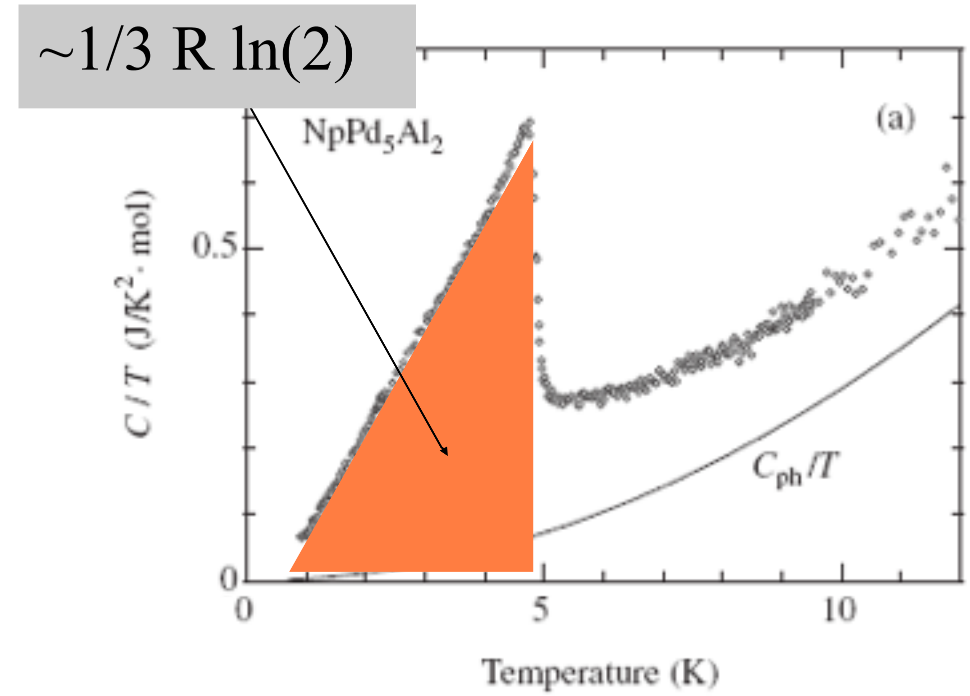


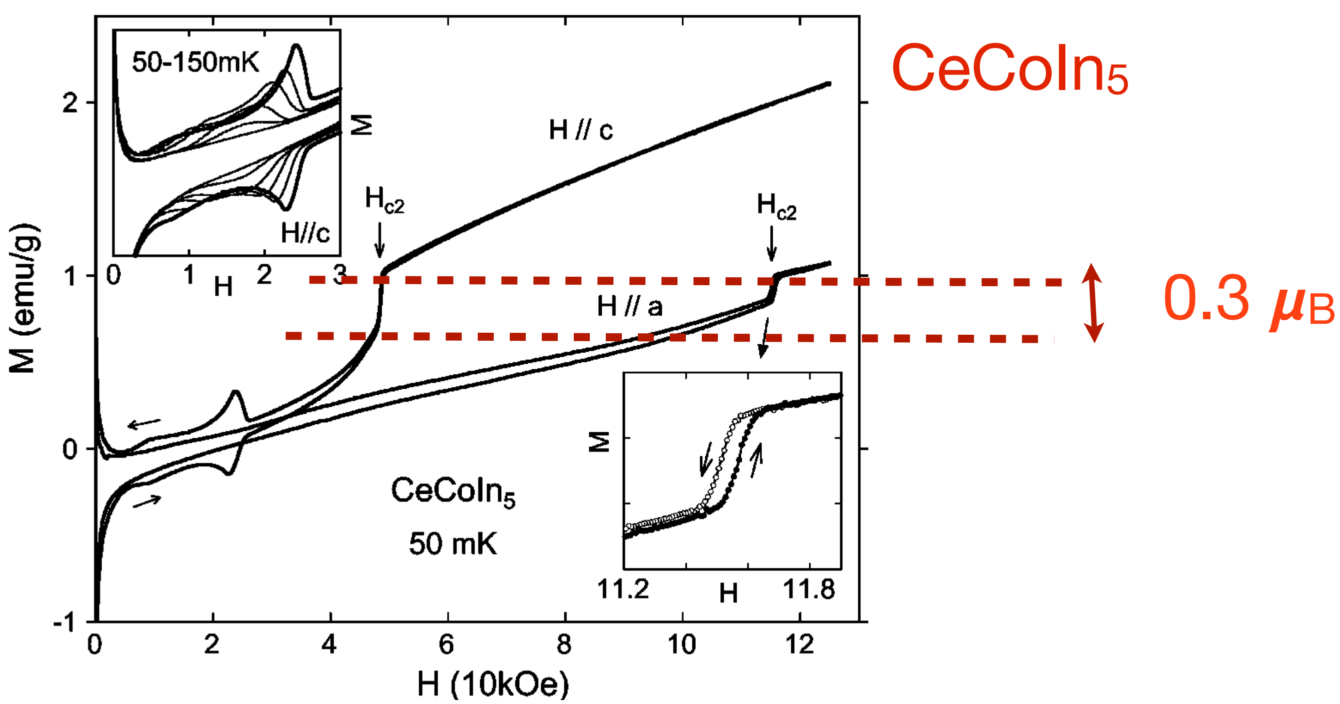




T. Tayama et al., RPB **65**, 180504R (2002)



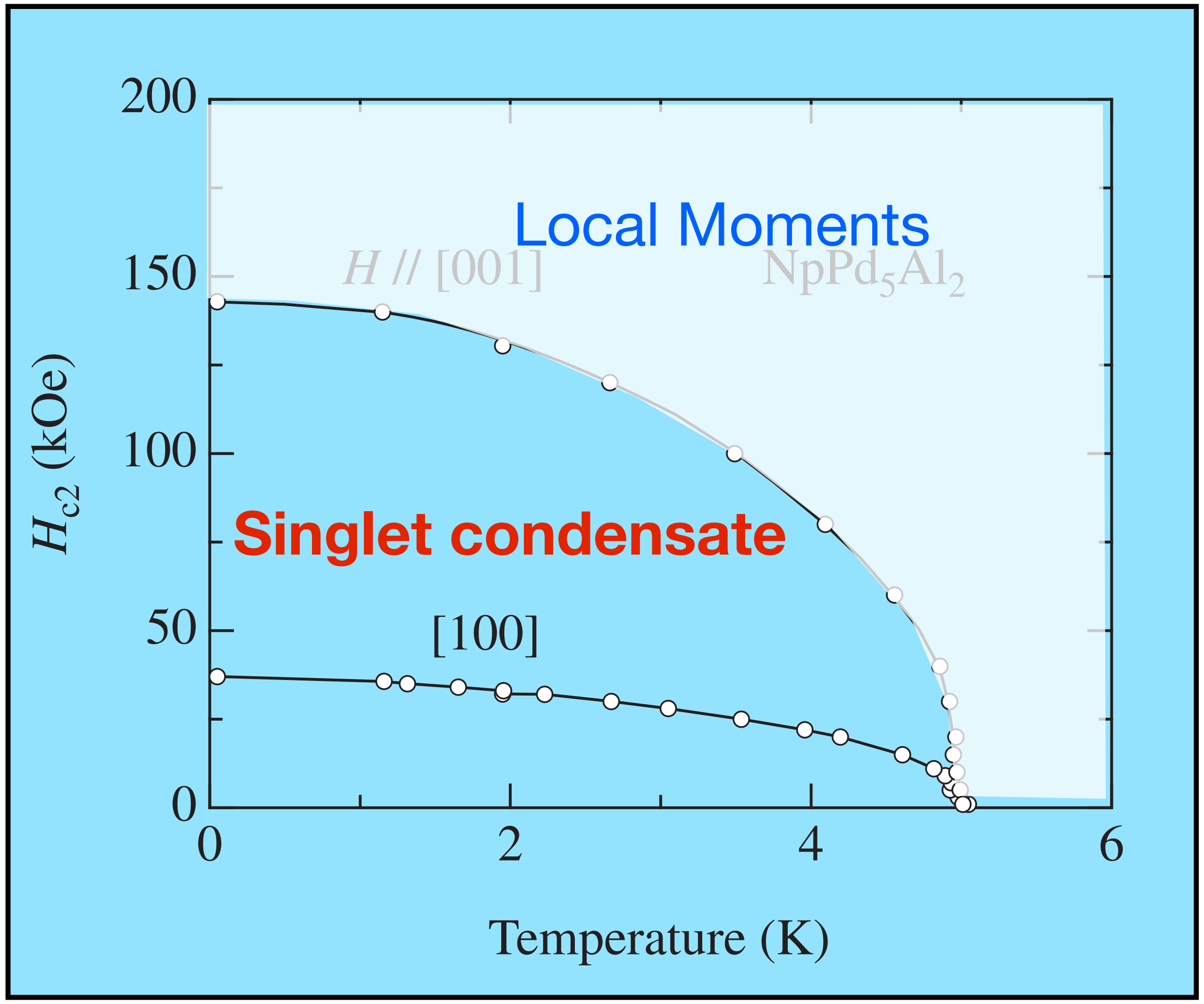


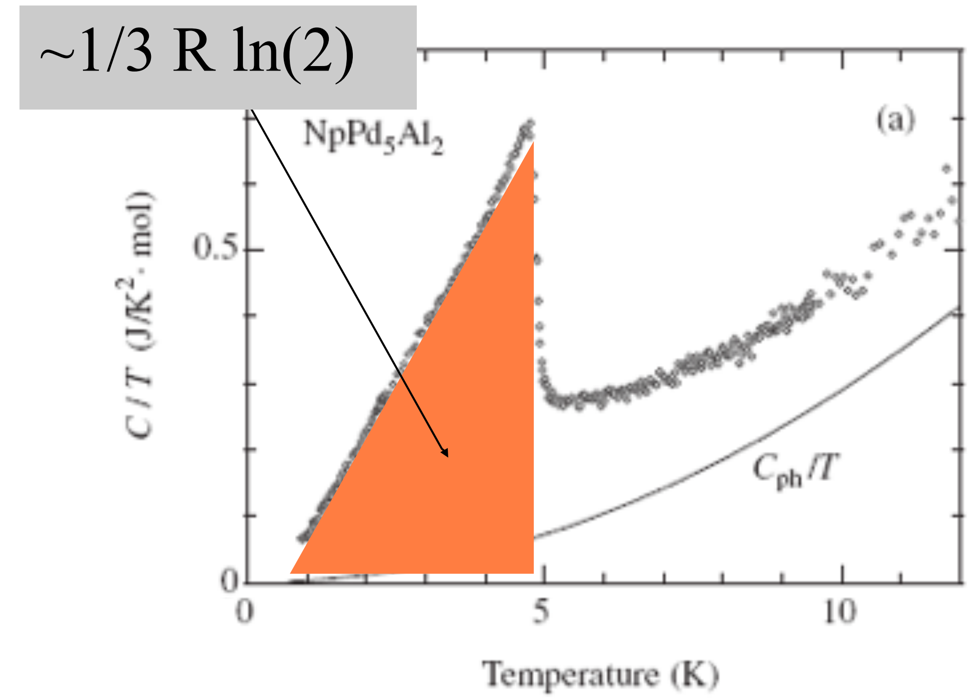


T. Tayama et al., RPB **65**, 180504R (2002)

Paradox:

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





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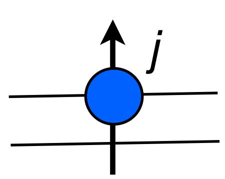
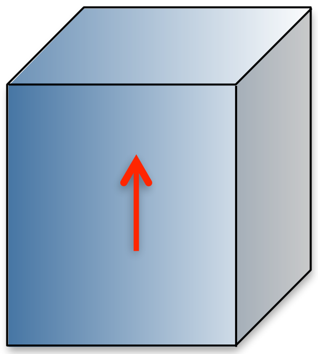
$$\prod_{\otimes j} \Big\{$$  $$\Big\} \otimes$$ Charge = Condensate Hilbert Space

Composite pairing Hypothesis.

Coherence and composite fermions



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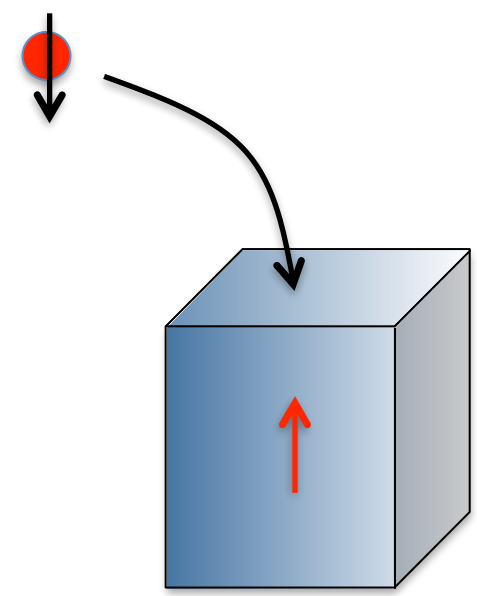

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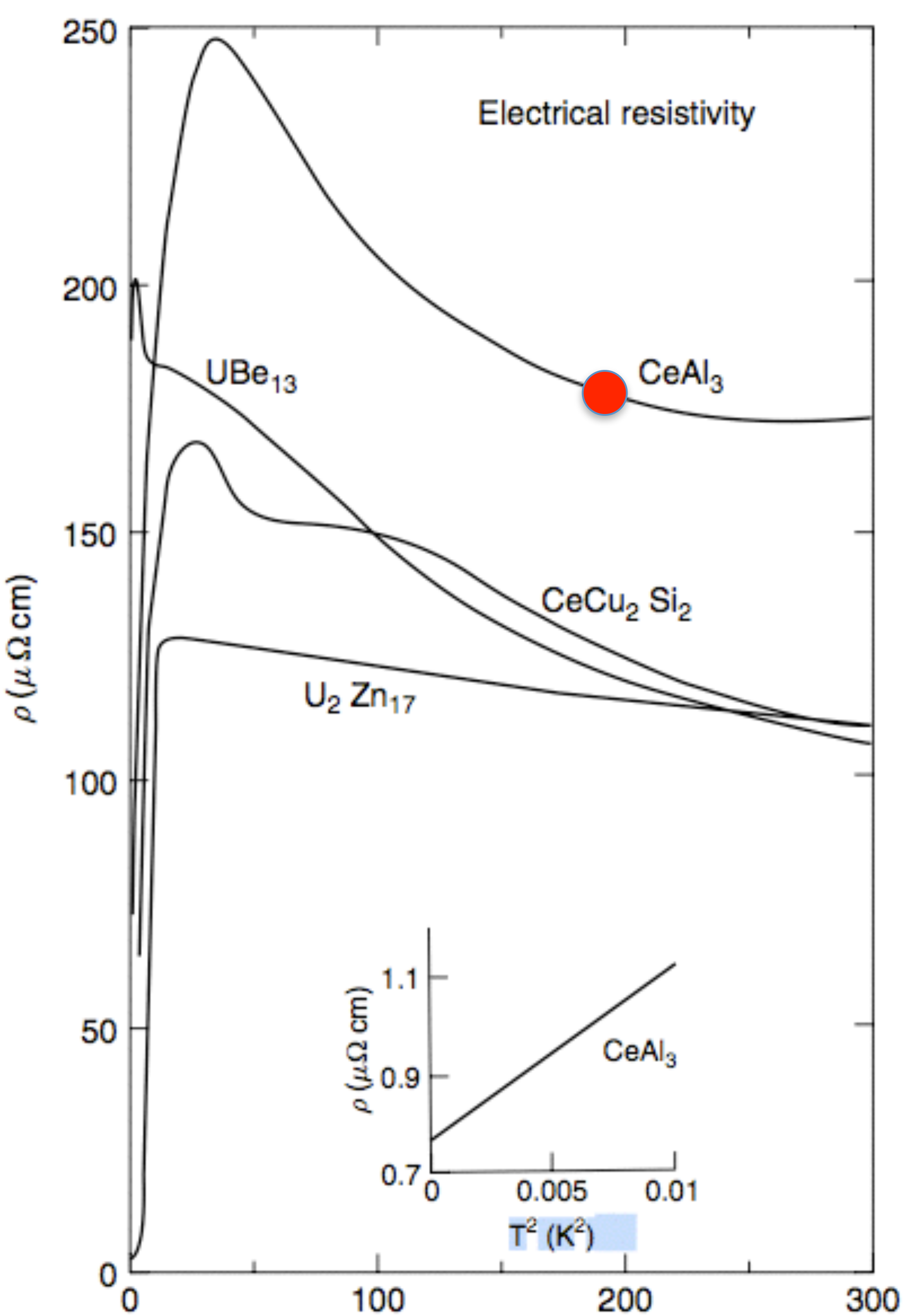

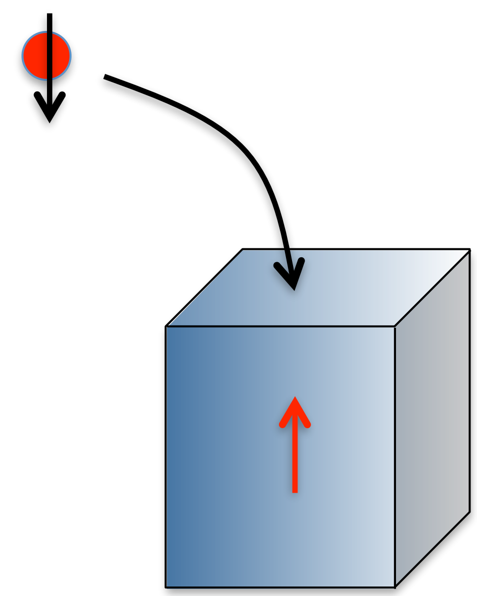

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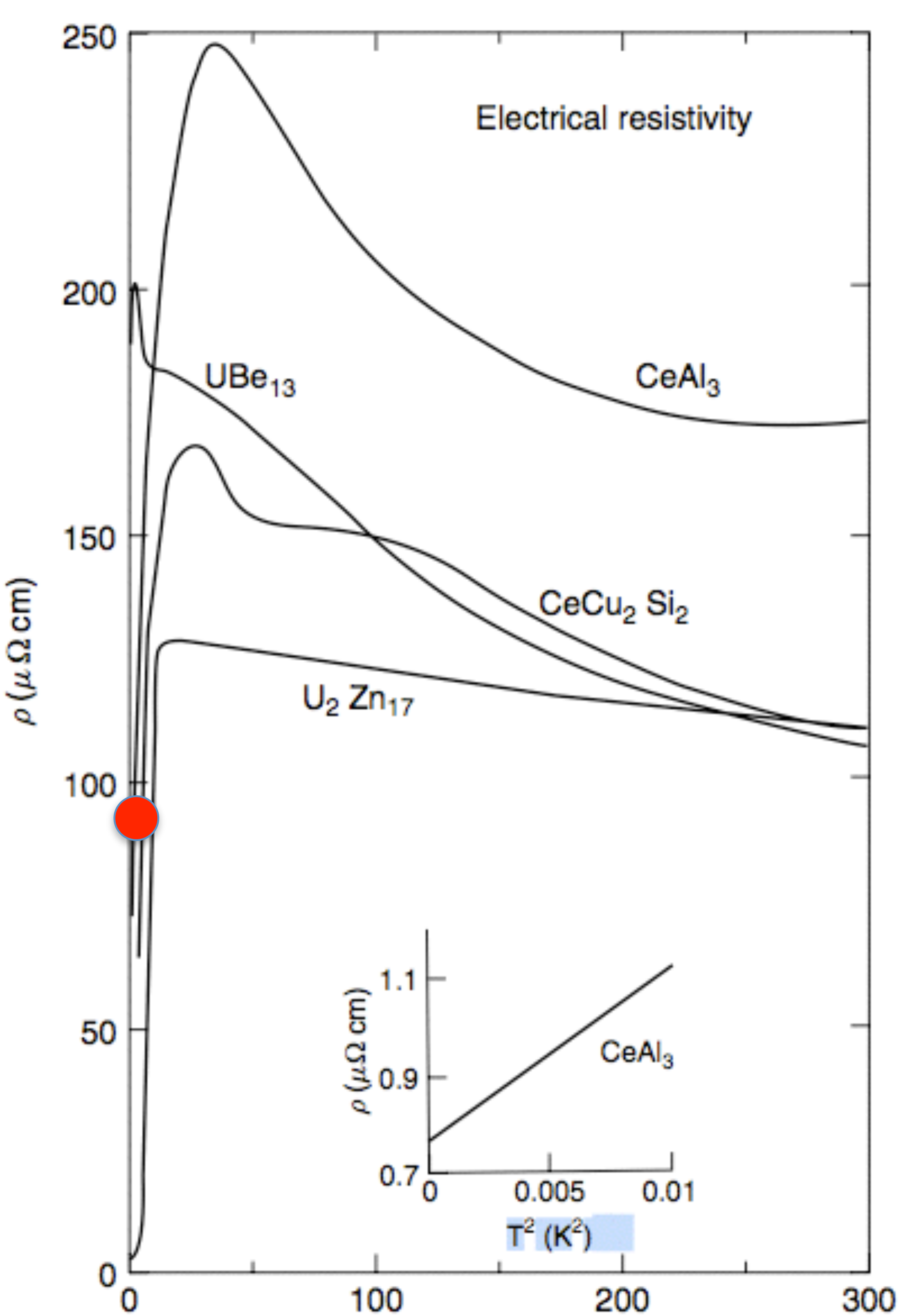

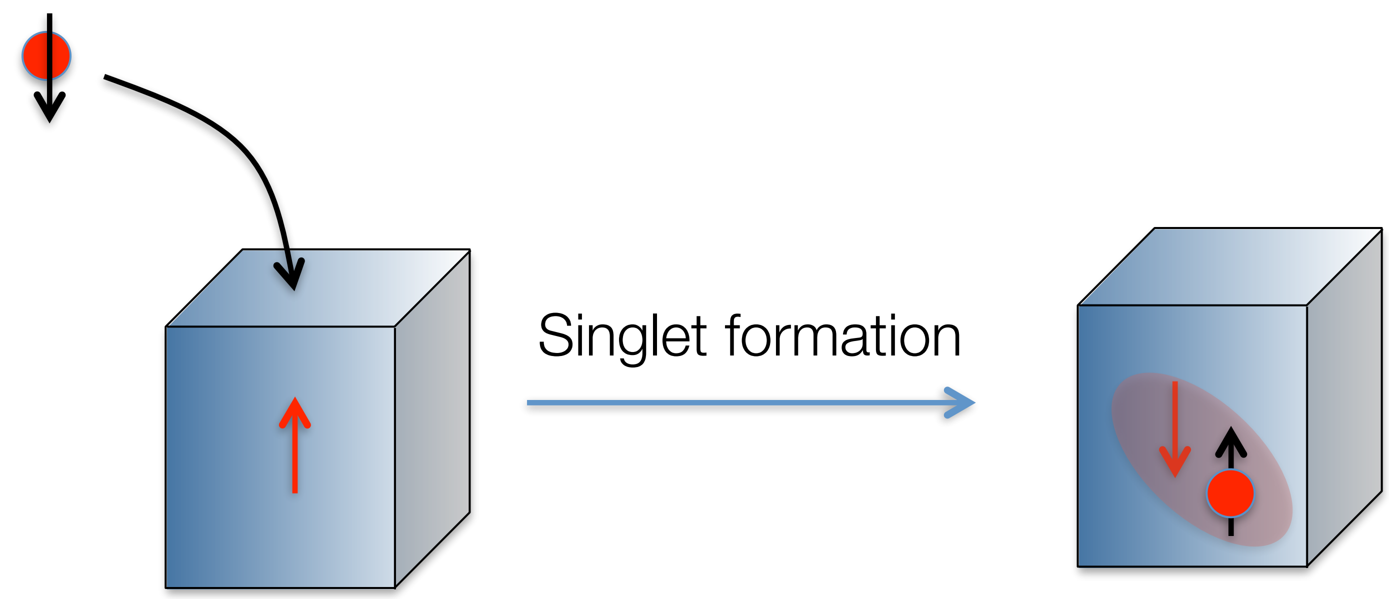

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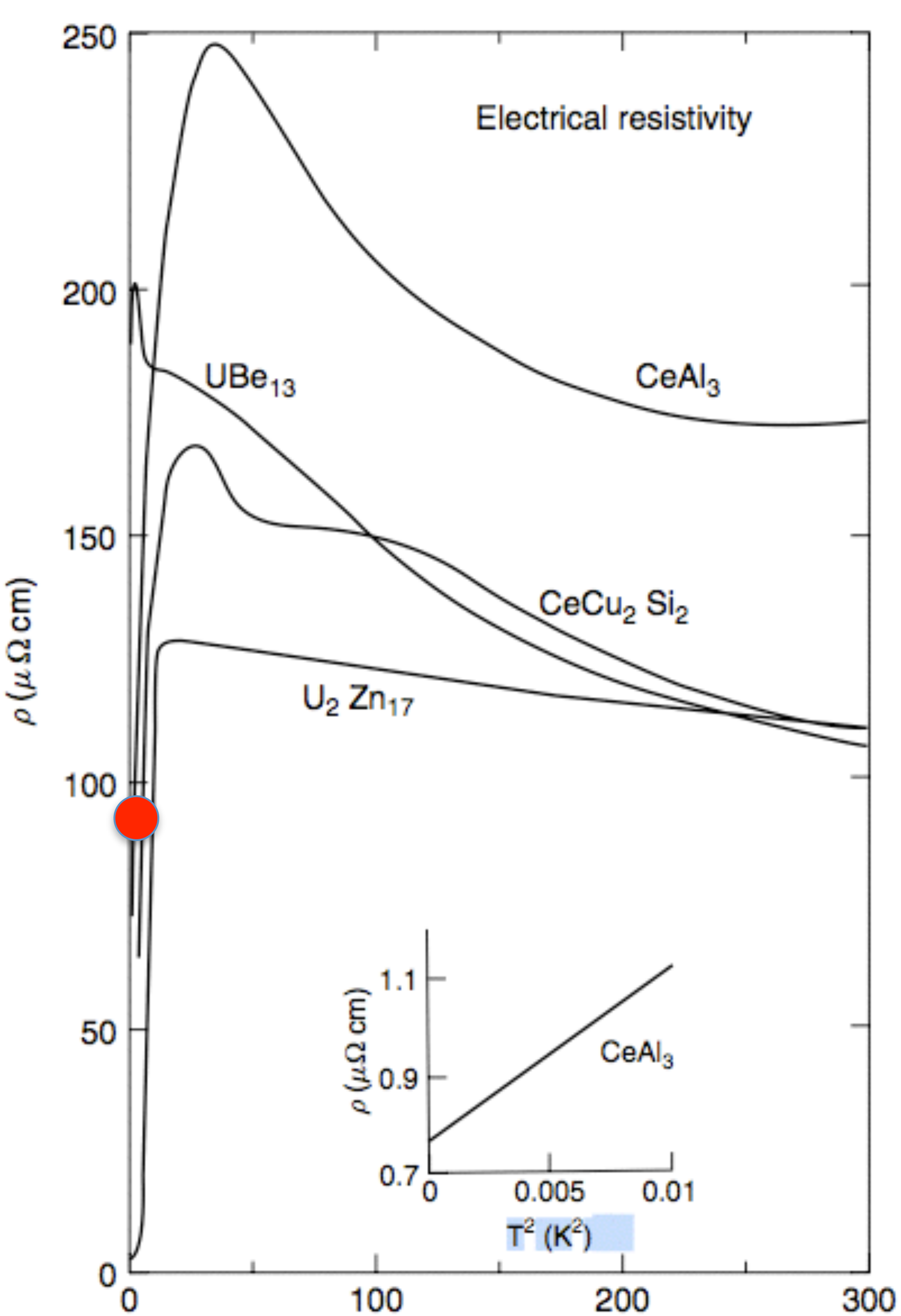
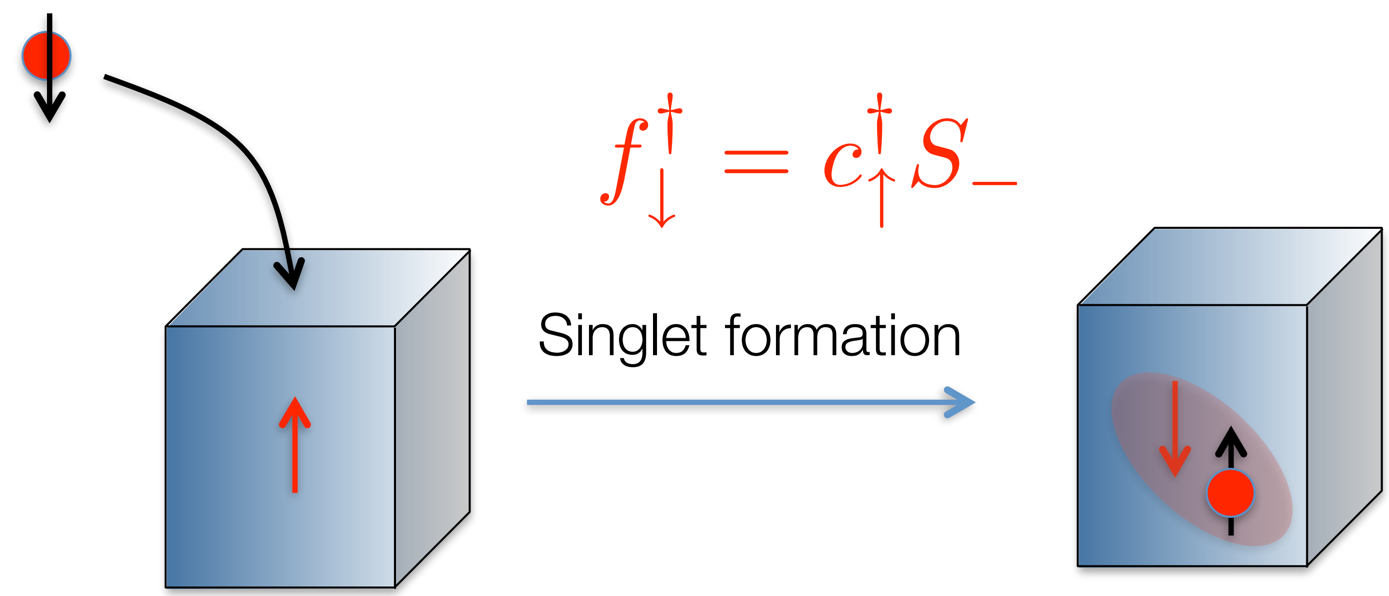
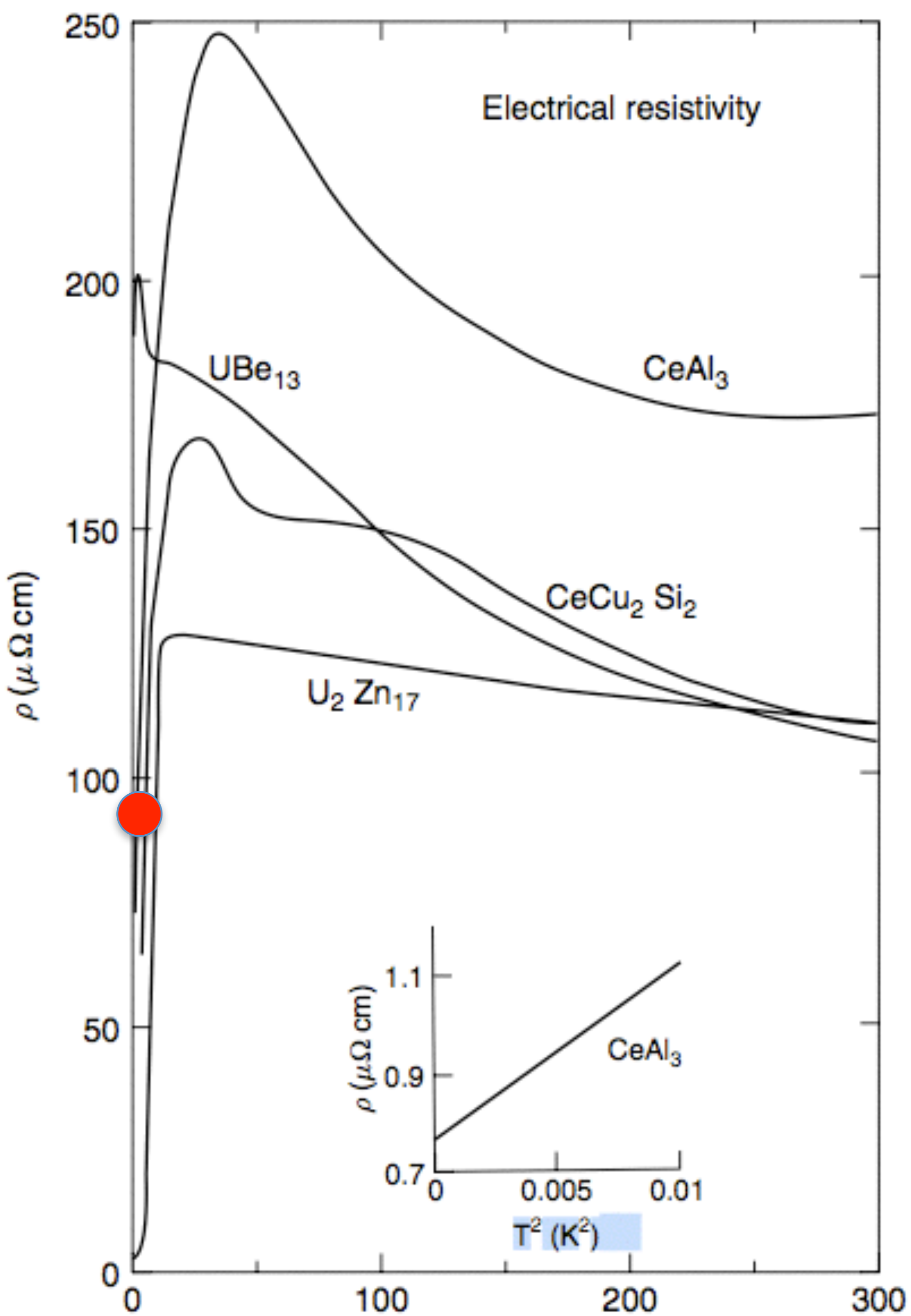


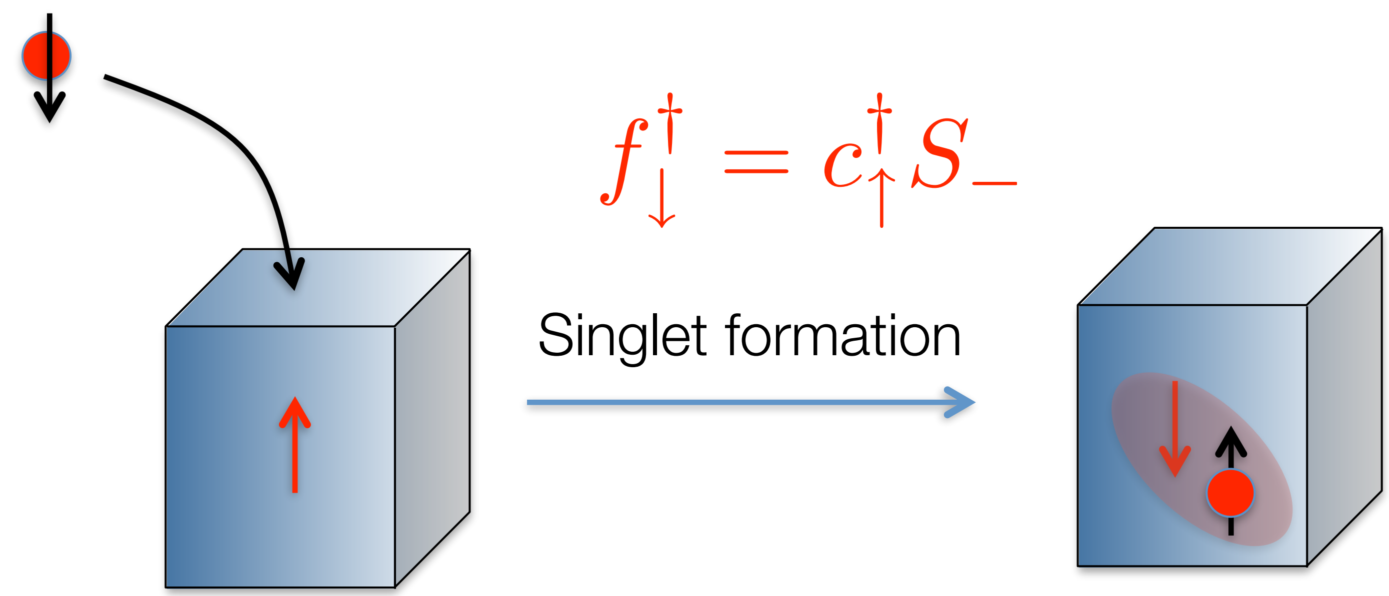
$$f^\dagger_\downarrow = c^\dagger_\uparrow S_-$$



Heavy electron = (electron x spinflip)

Coherence and composite fermions





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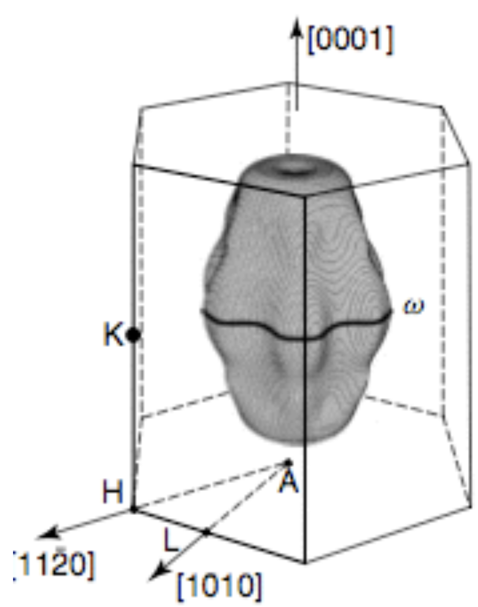
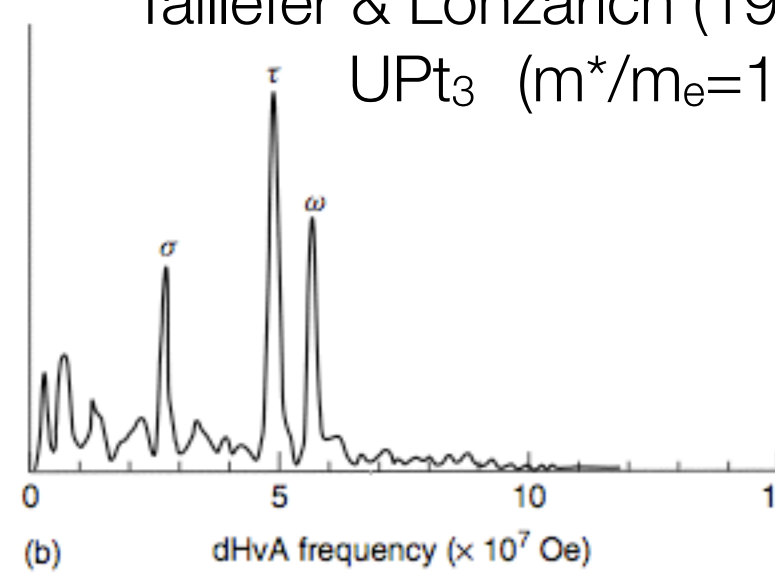
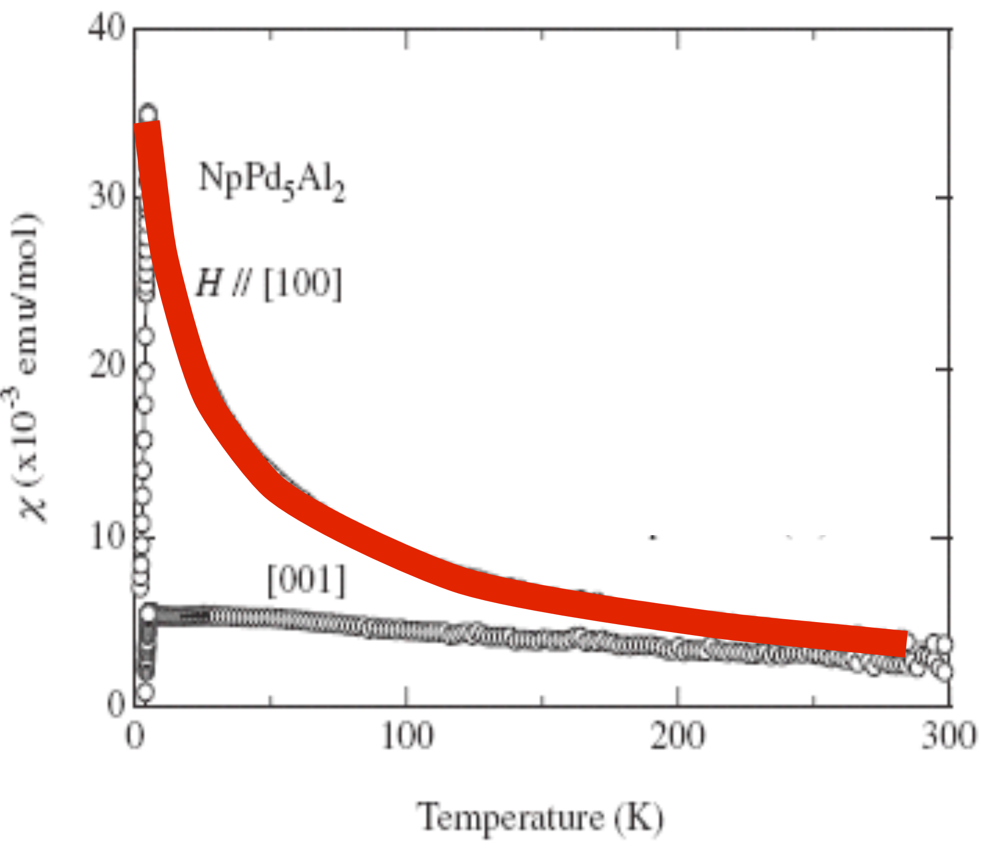


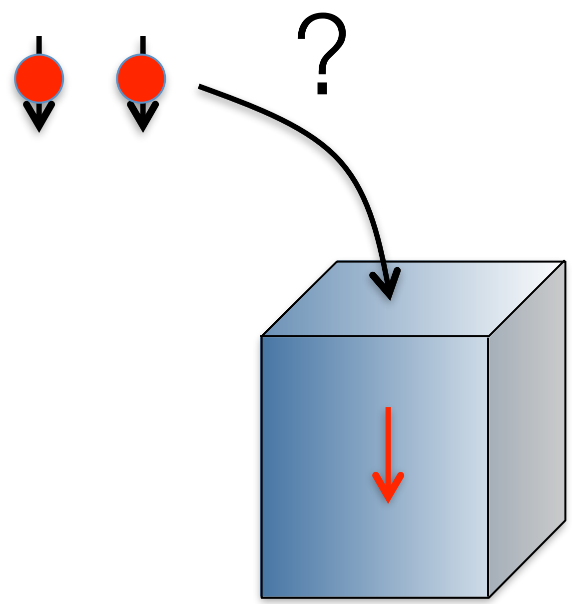
Taillefer & Lonzarich (1985)
UPt$_3$ (m^*/m_e=120)



Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$





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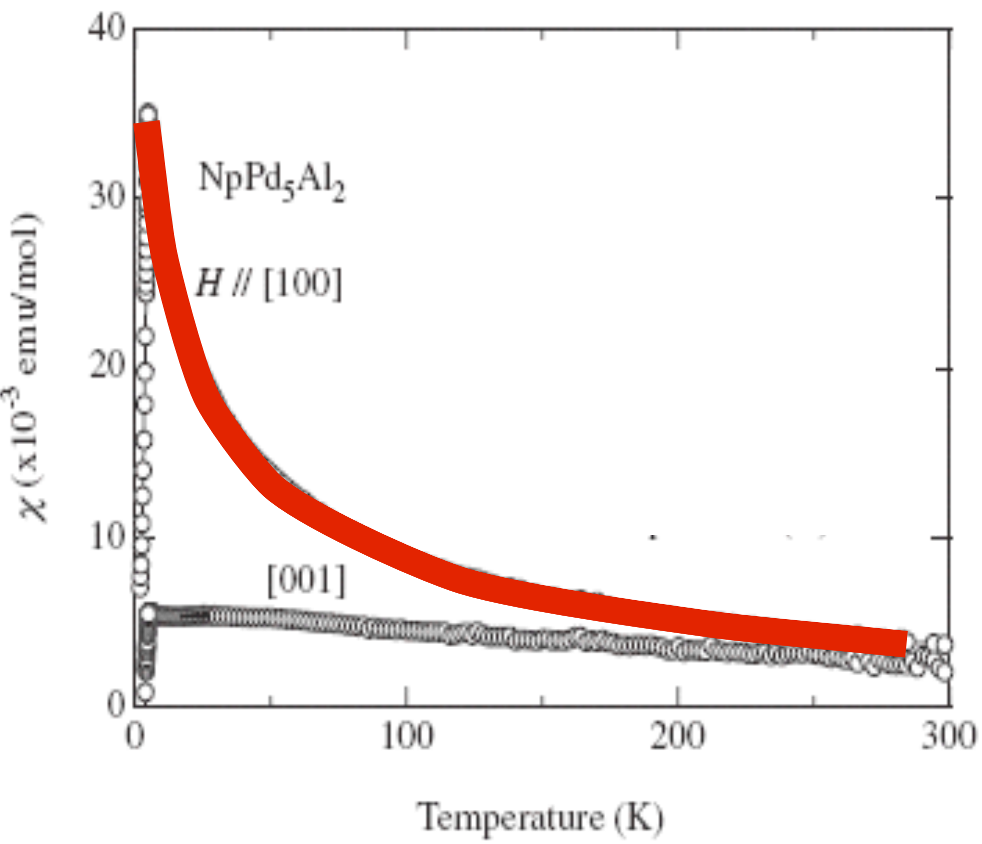

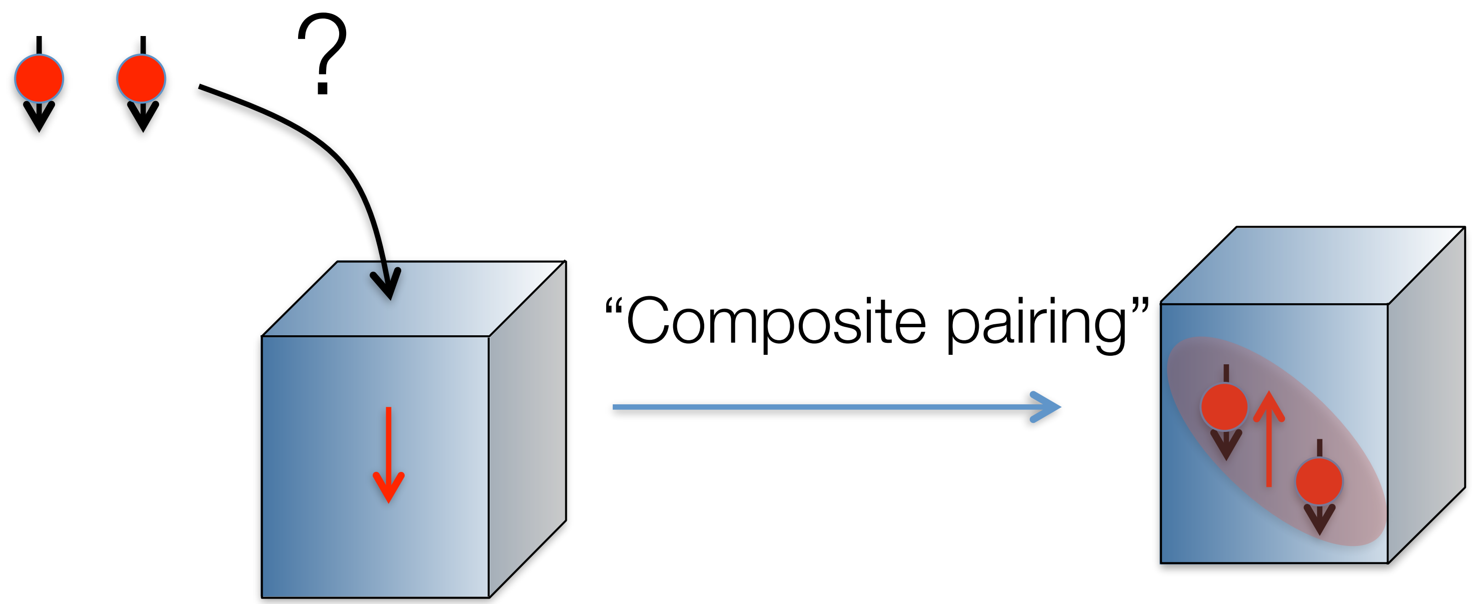

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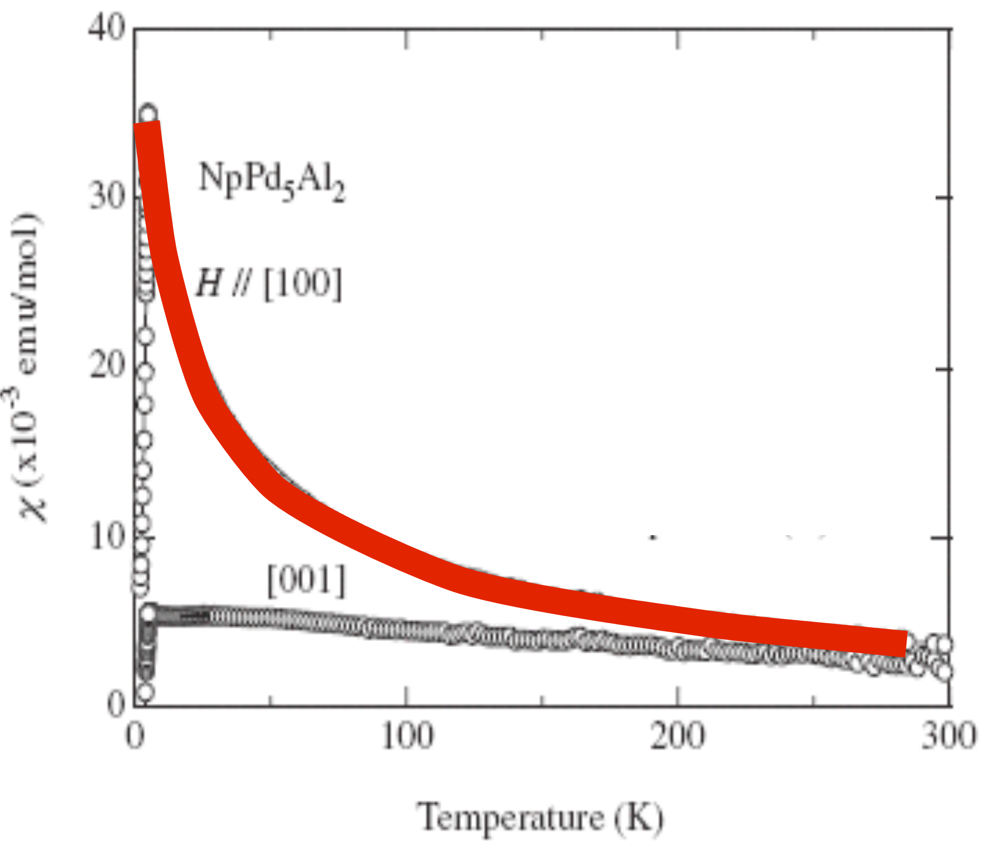

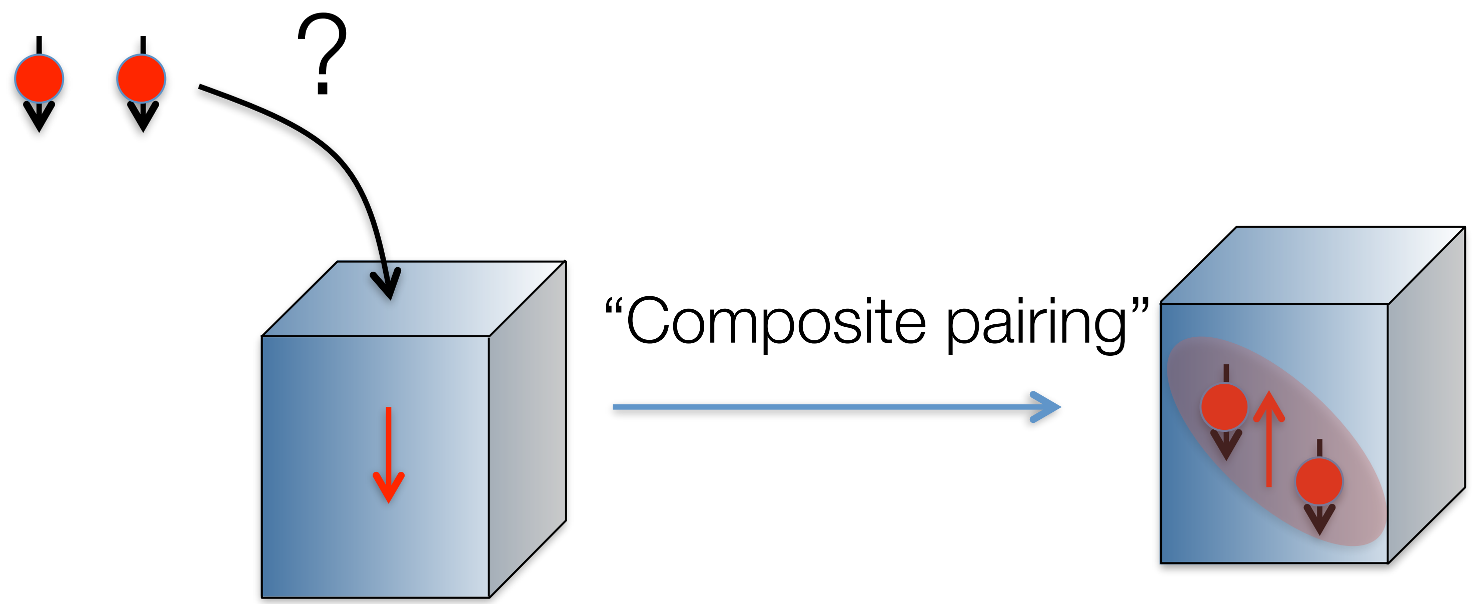

Heavy Cooper pair = (pair x spinflip)

Composite pairing

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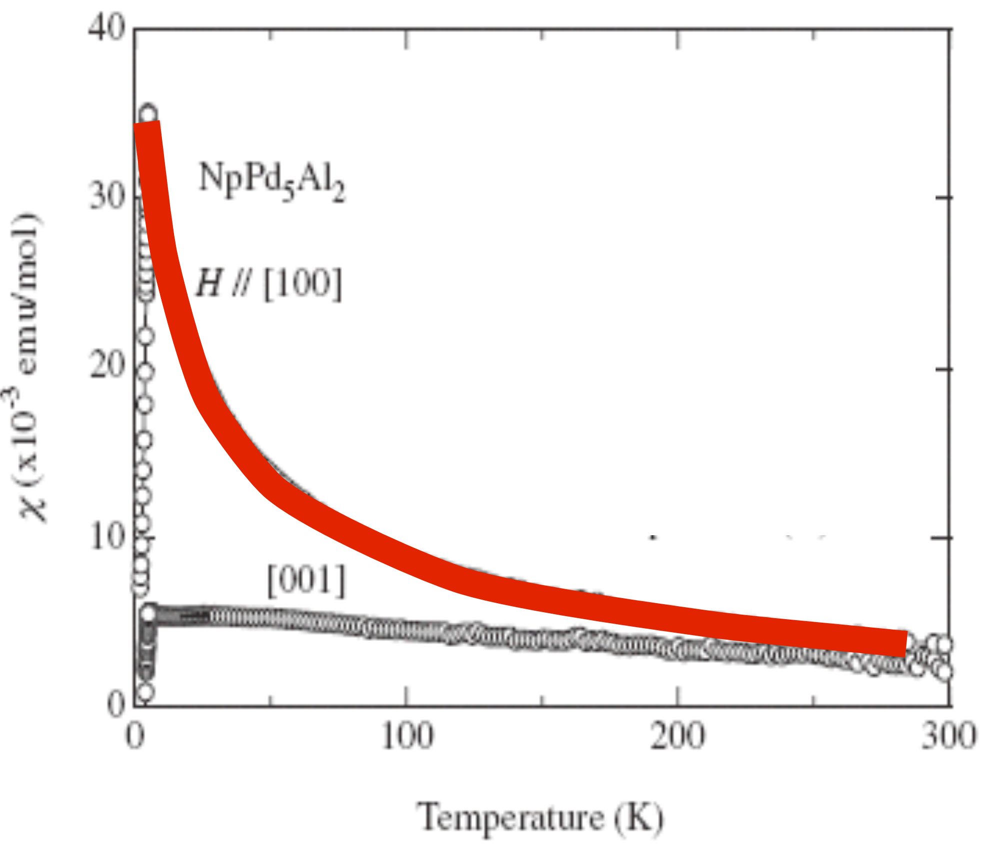

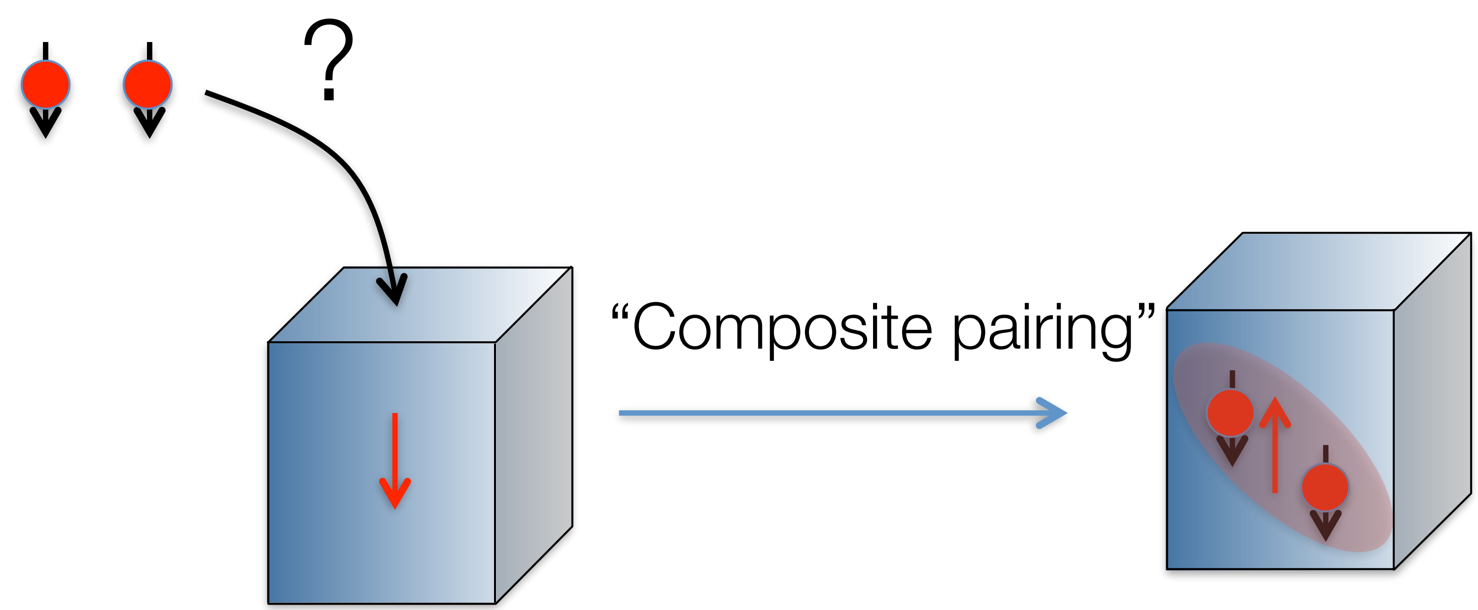

Heavy Cooper pair = (pair x spinflip)

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

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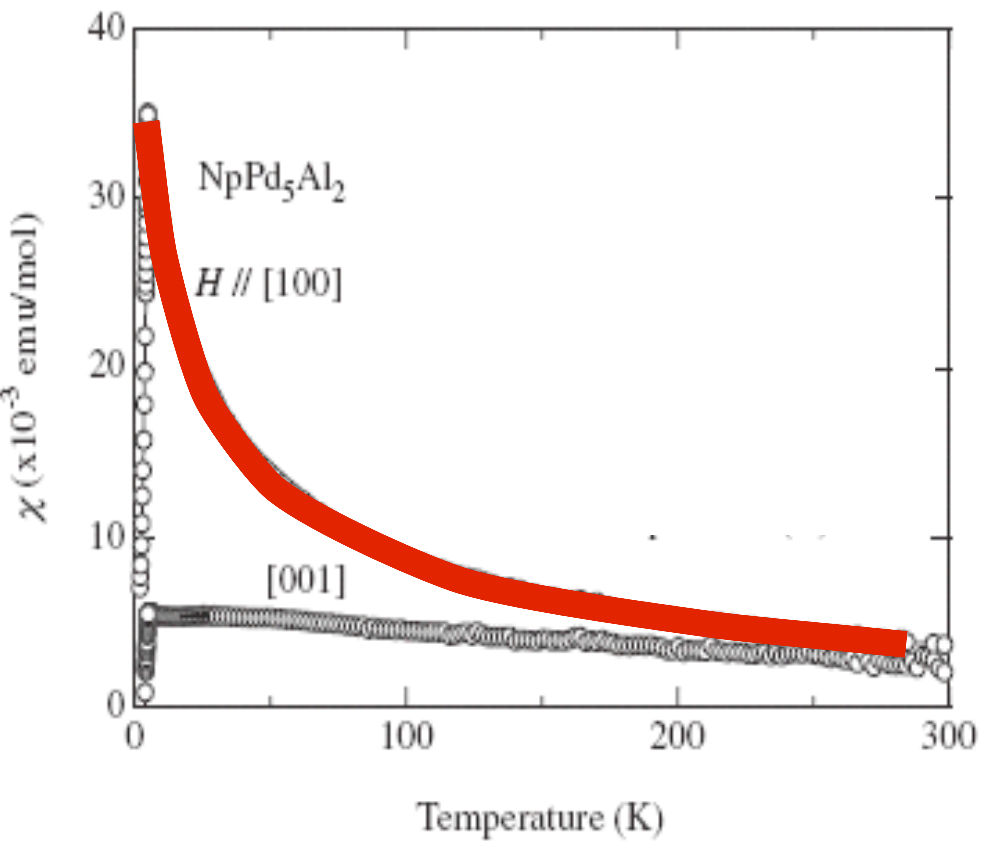

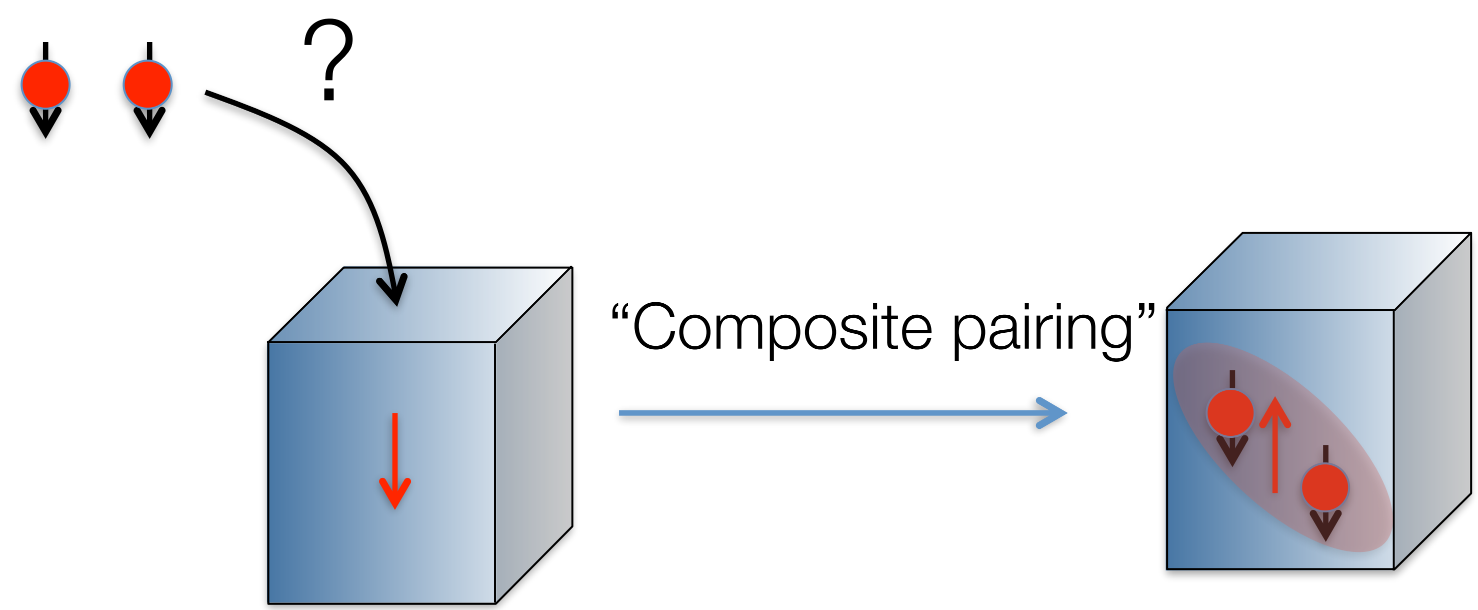

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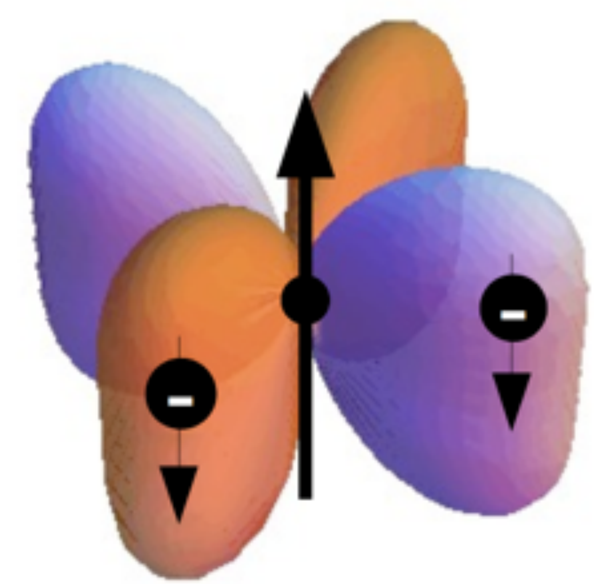


Abrahams, Balatsky, Scalapino, Schrieffer 1995

A solvable model of composite pairing.

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

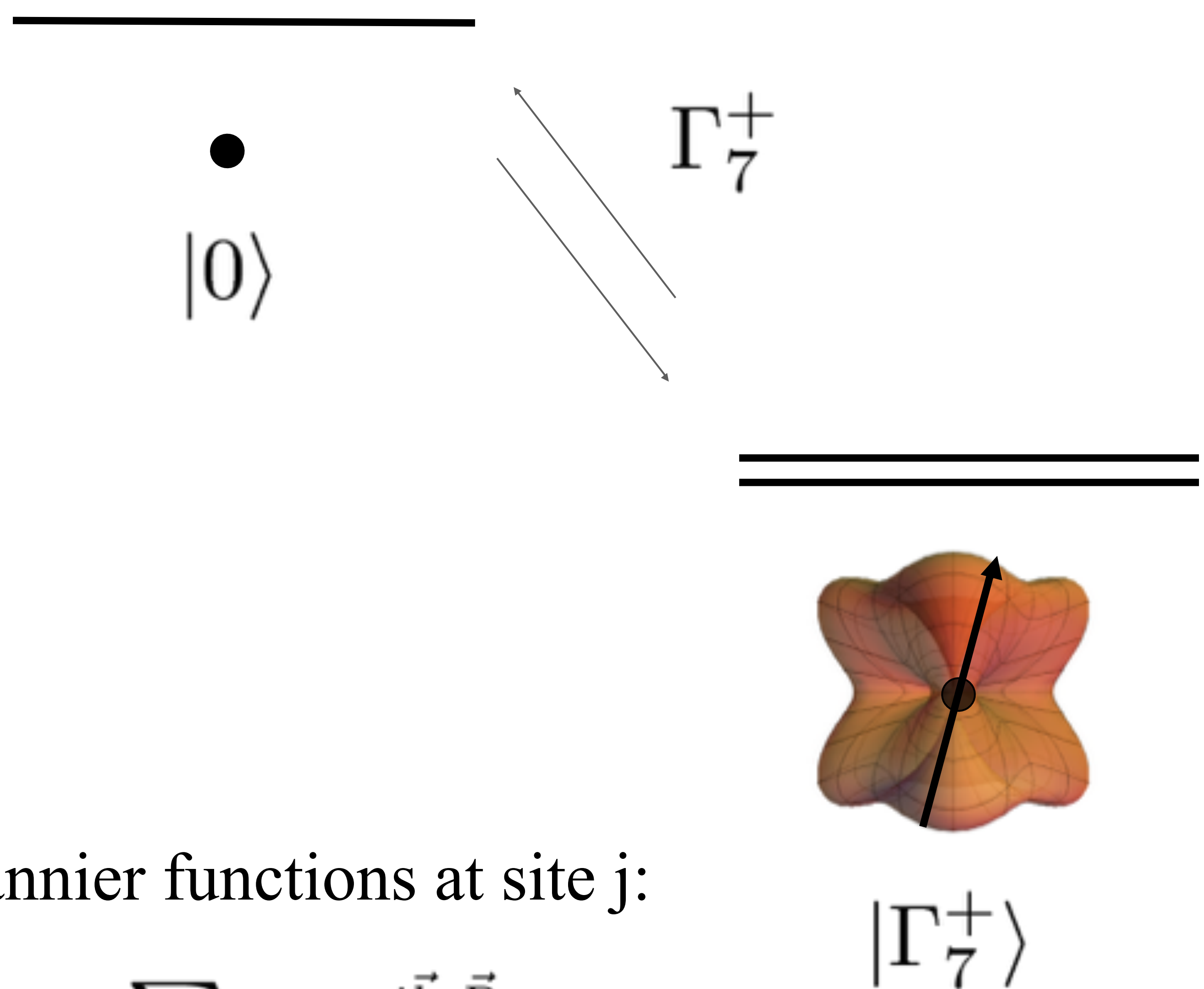
Flint, Dzero, PC, Nature Physics 4, 643 (2008).

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

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

The Two Channel Kondo Model

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



Wannier functions at site j:

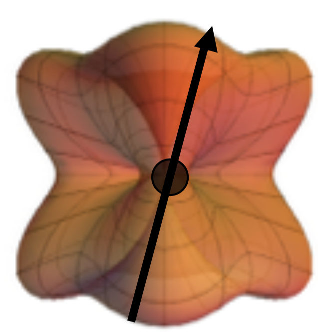
$$\psi^\dagger_{\Gamma j} = \sum_k \Phi_{\Gamma k} e^{i\vec{k}\cdot\vec{R}_j} c_k$$

The Two Channel Kondo Model

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

$|0\rangle$

Γ_7^+



$|\Gamma_7^+\rangle$

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- Both $\left\{ \begin{array}{l} f^0 + e^- \rightleftharpoons f^1 \\ f^1 \rightleftharpoons f^2 + h^+ \end{array} \right.$

The Two Channel Kondo Model

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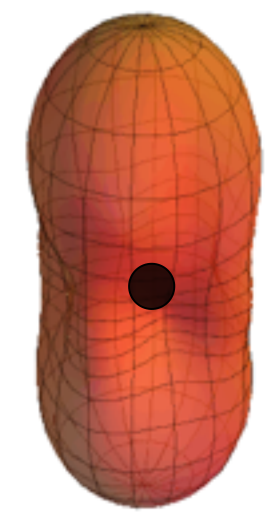
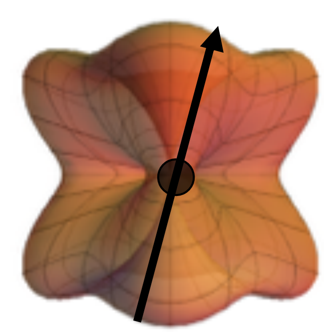
$|0\rangle$

Γ_7^+

Γ_6



$|\Gamma_7^+ \otimes \Gamma_6\rangle$



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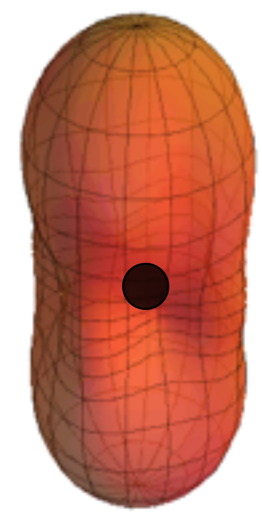
$|0\rangle$

Γ_7^+

Γ_6



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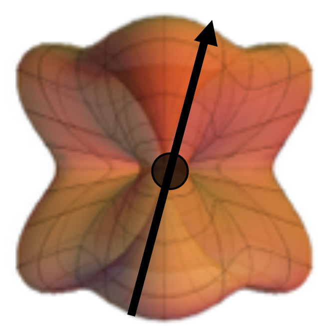

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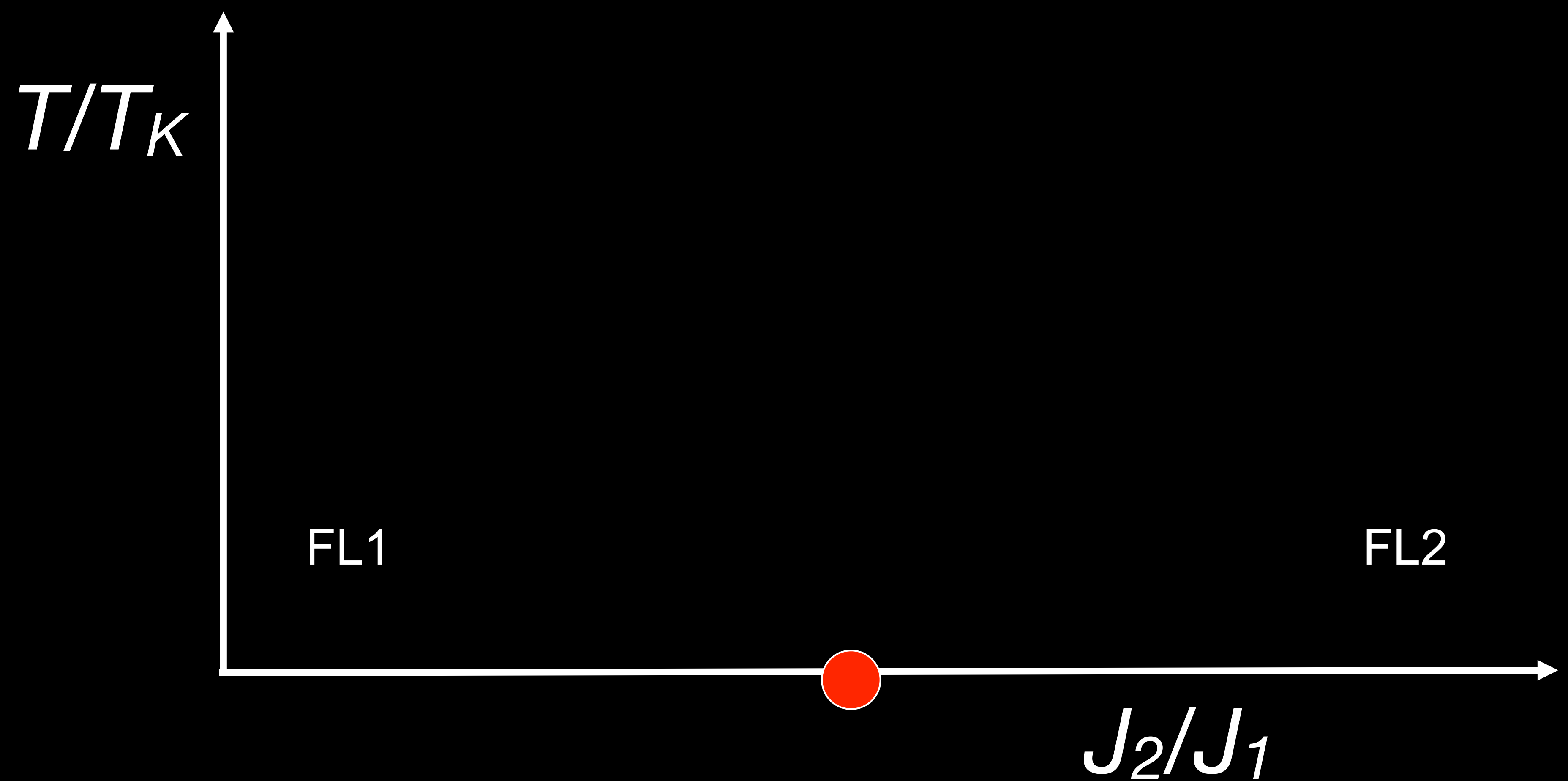
Single FS, two channels.

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

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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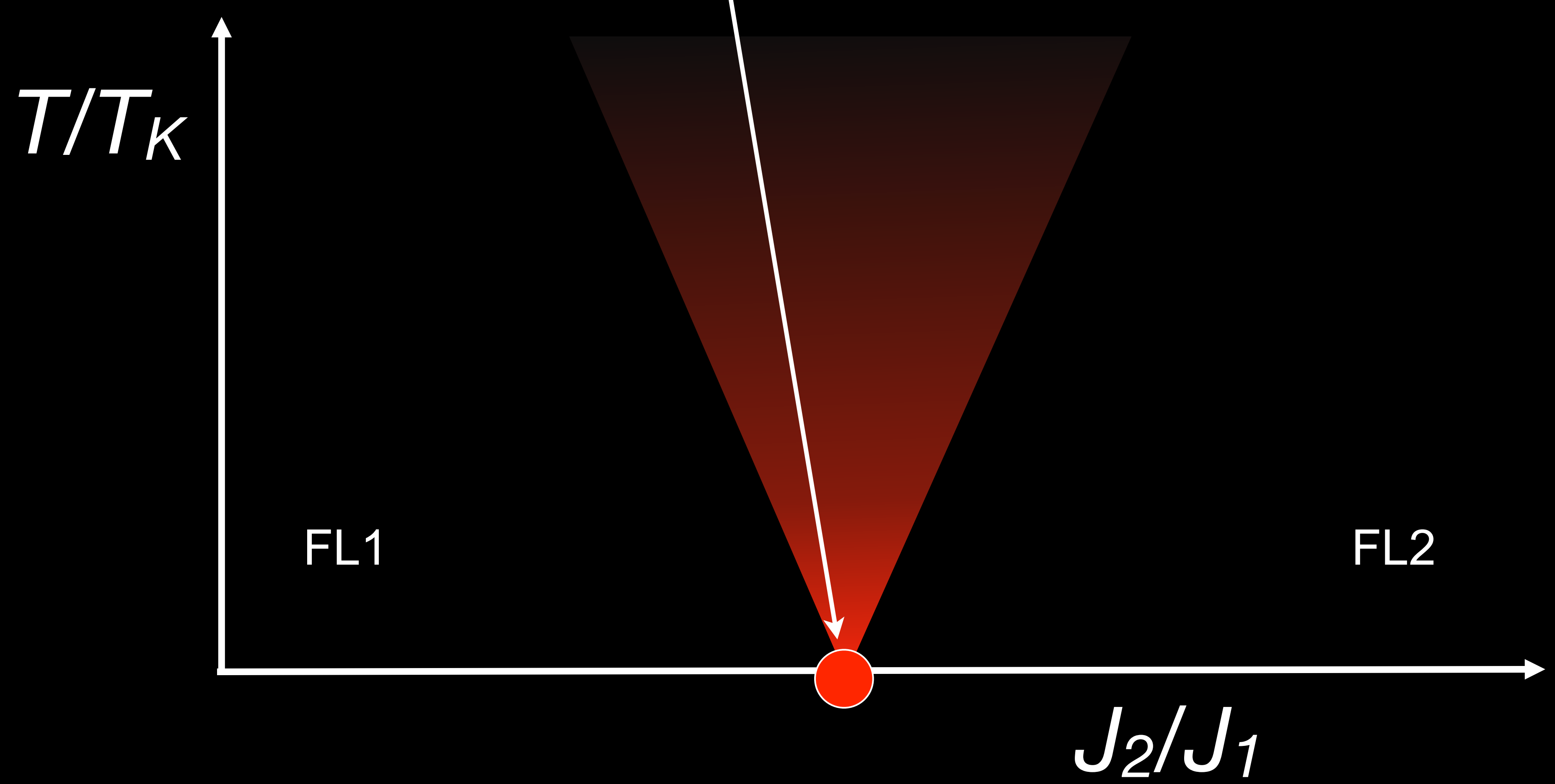
Singular composite pair fluctuations

Emery and Kivelson 1992



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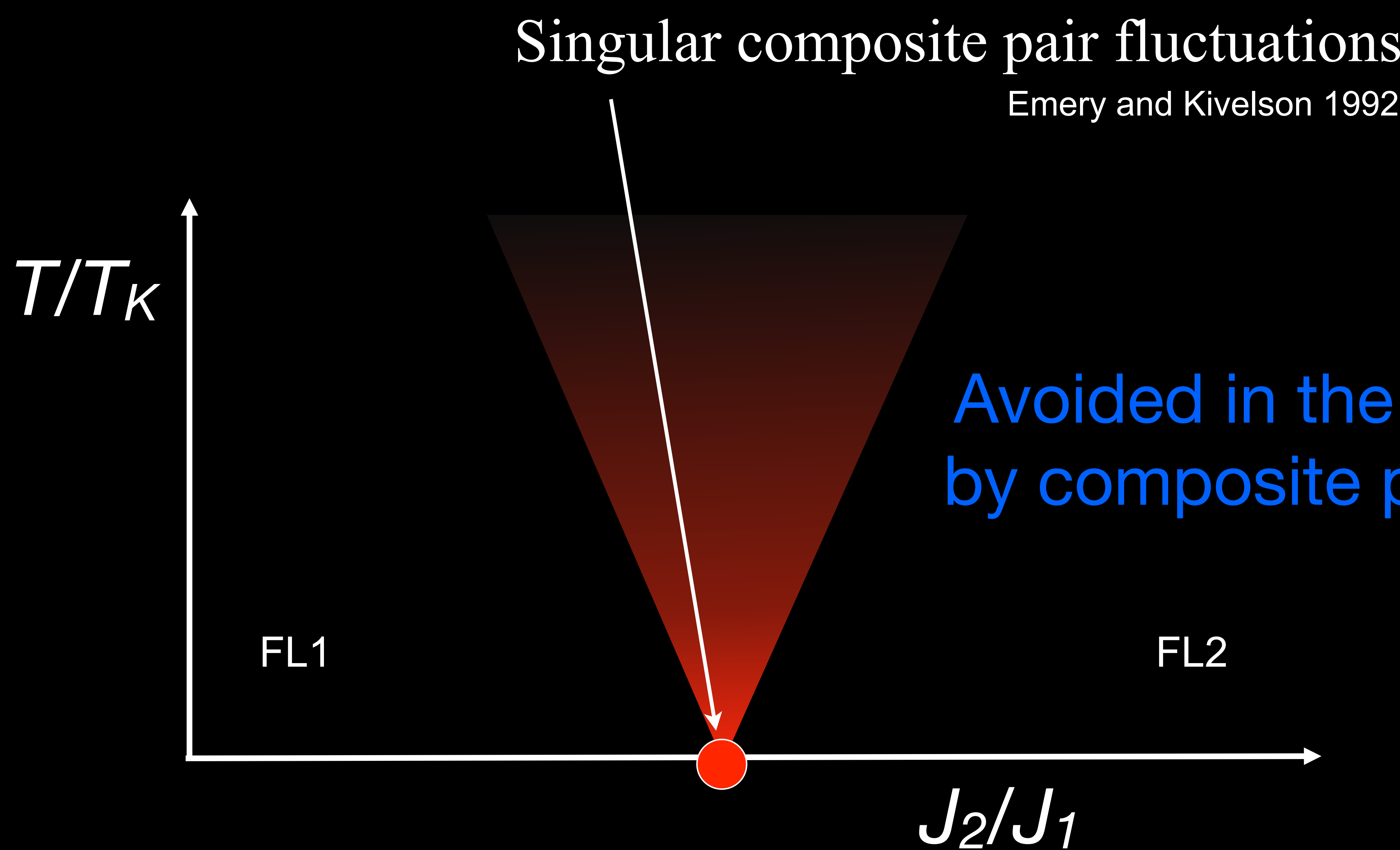

Avoided in the lattice by composite pairing.

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

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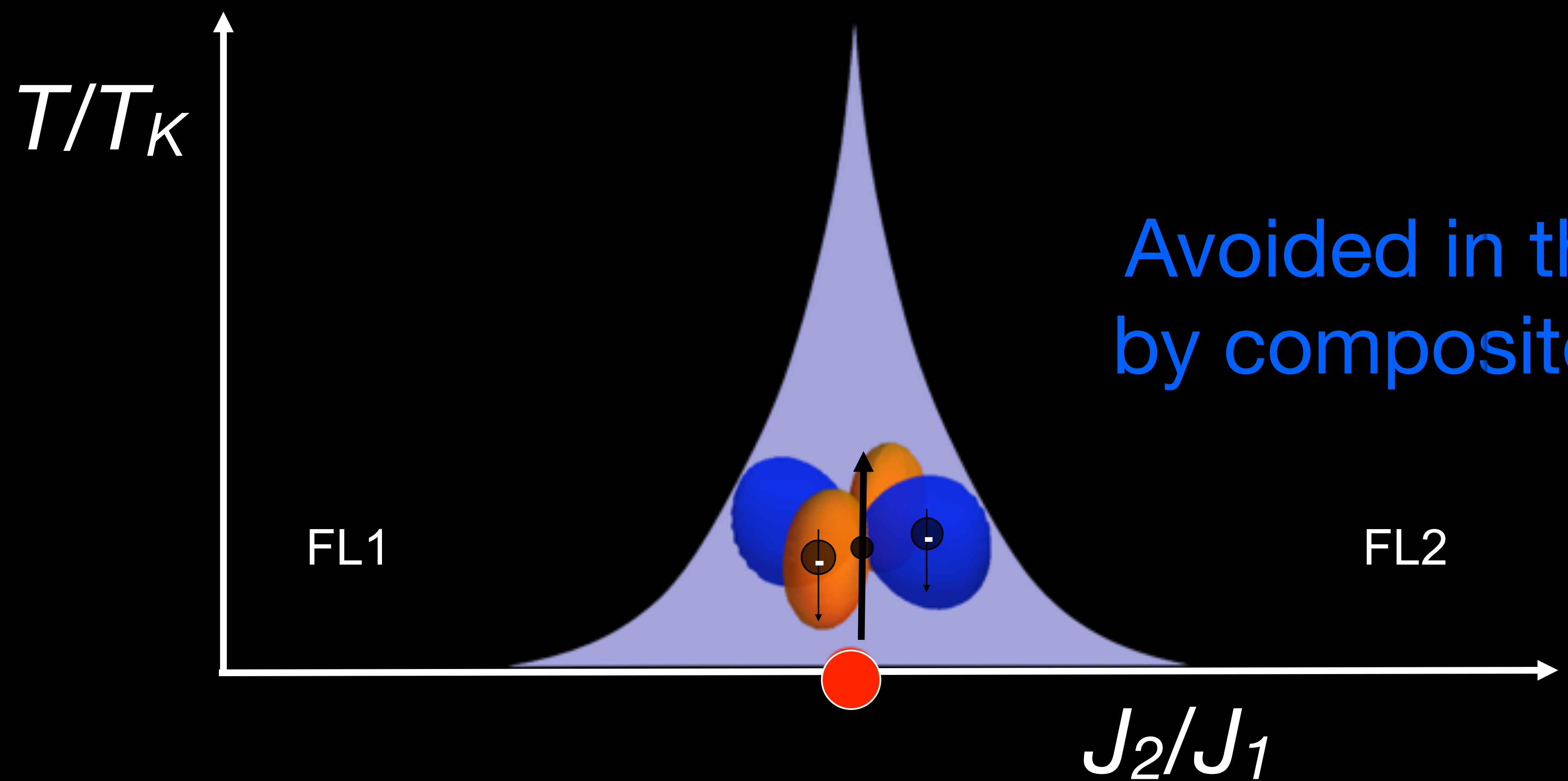

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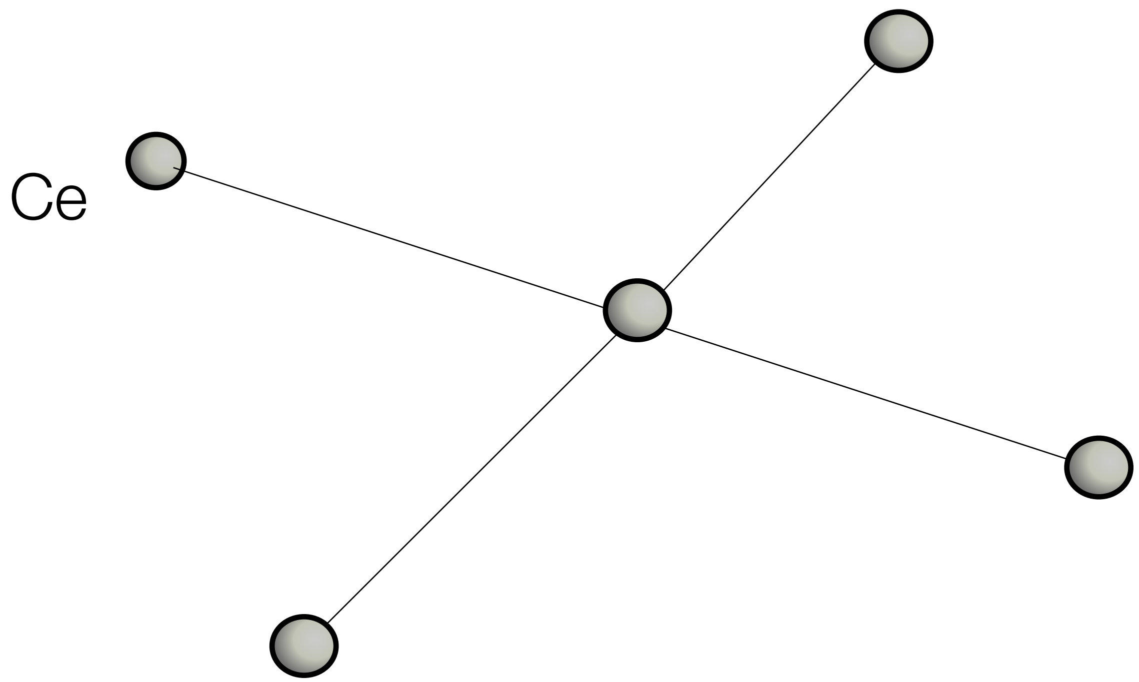
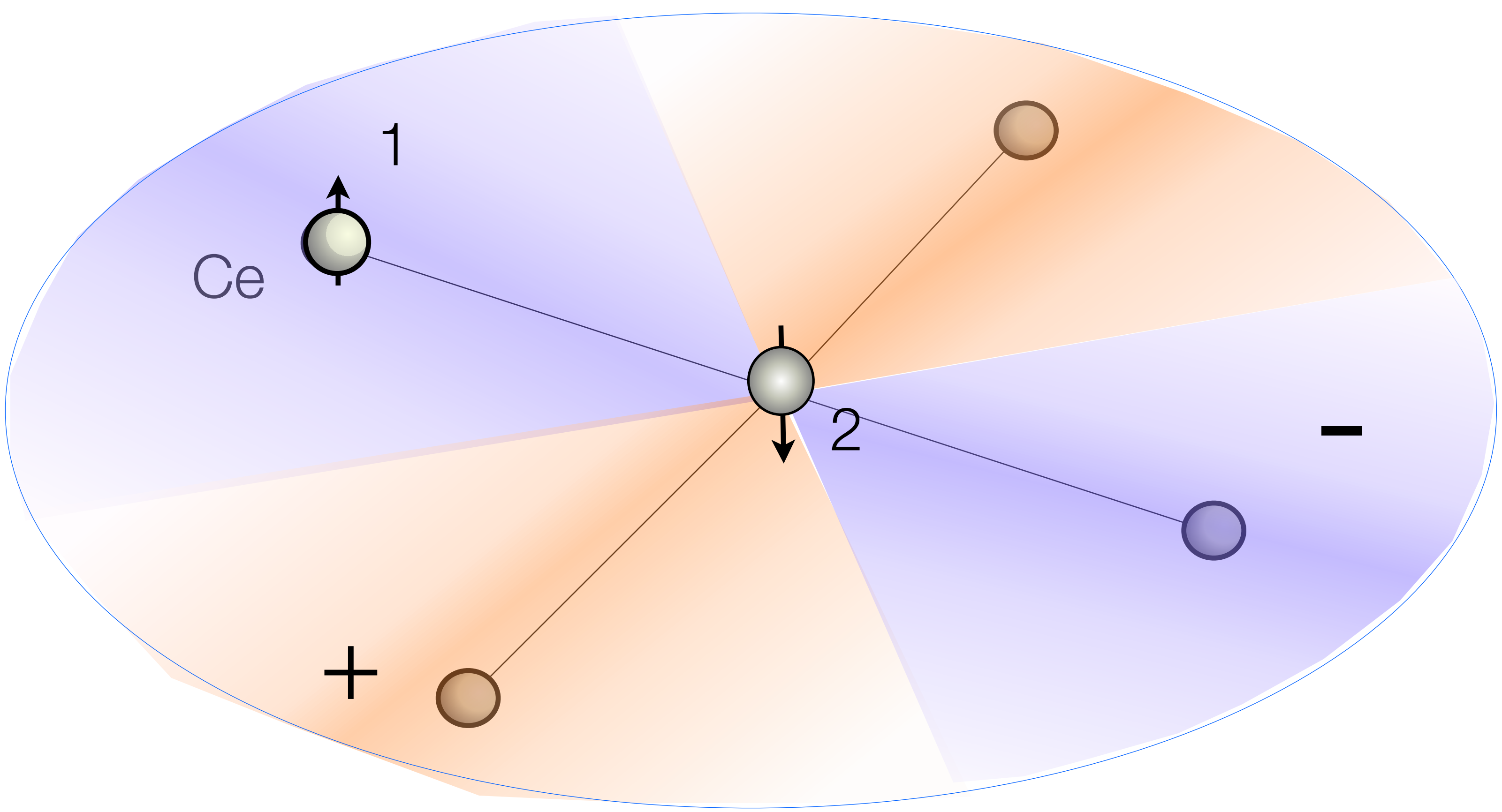
Real-space structure of pair



Real-space structure of pair

Magnetic pair: intercell

$$\Psi^{\dagger}_{M} = \Delta_d(1-2) f^{\dagger}_{\uparrow}(1) f^{\dagger}_{\downarrow}(2)$$



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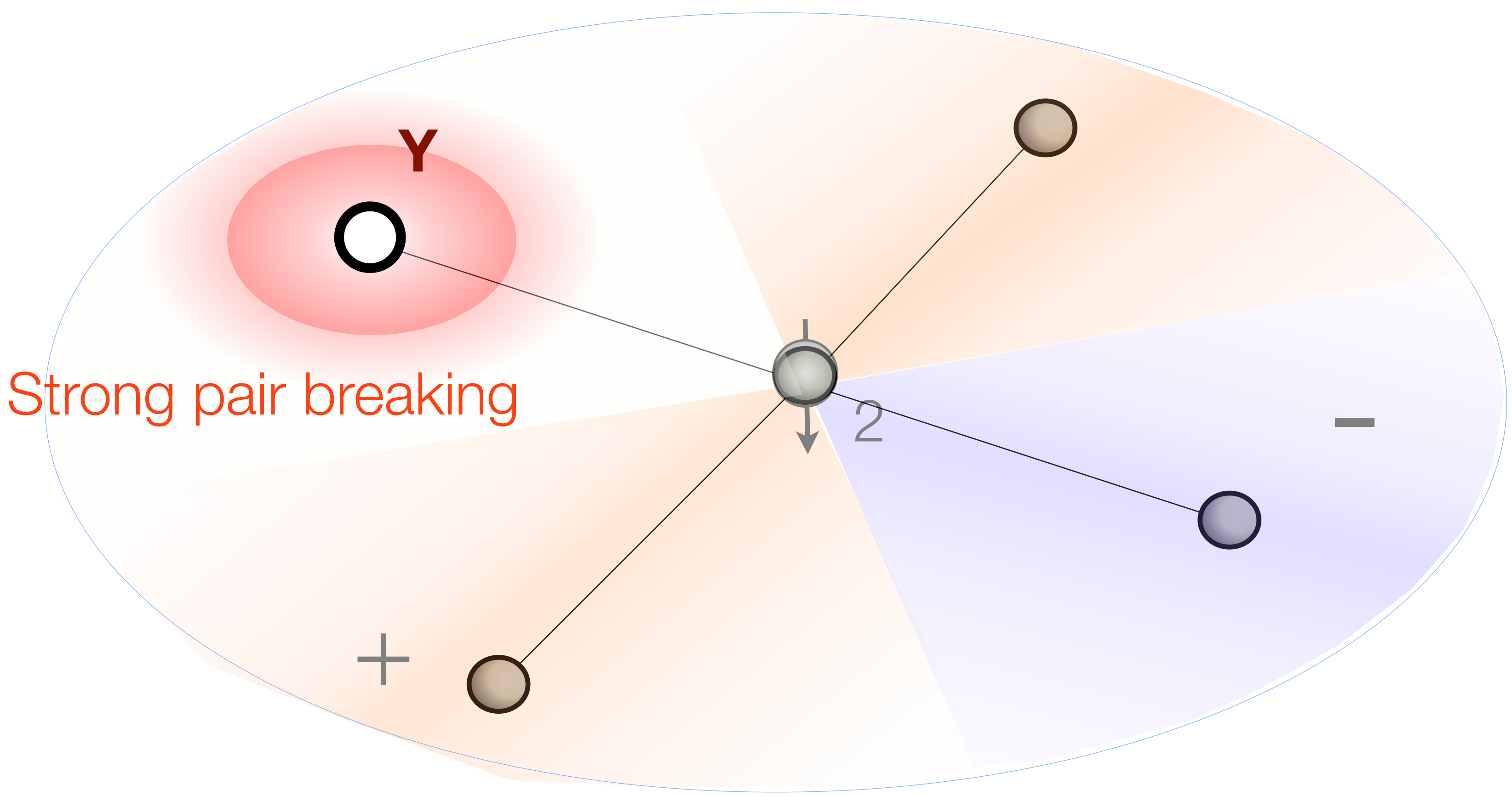

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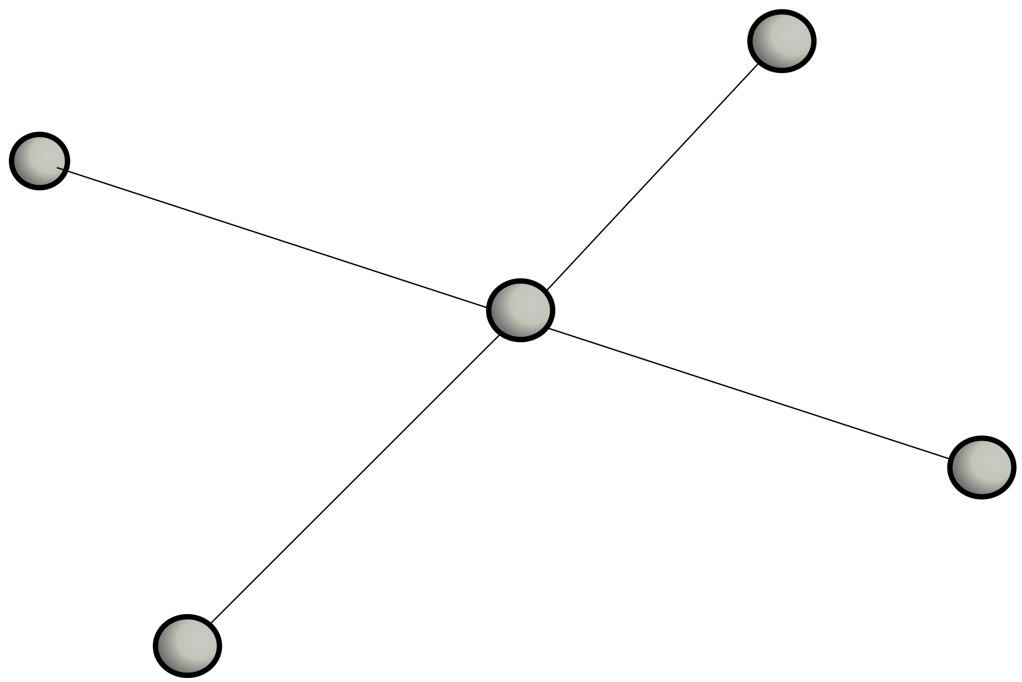

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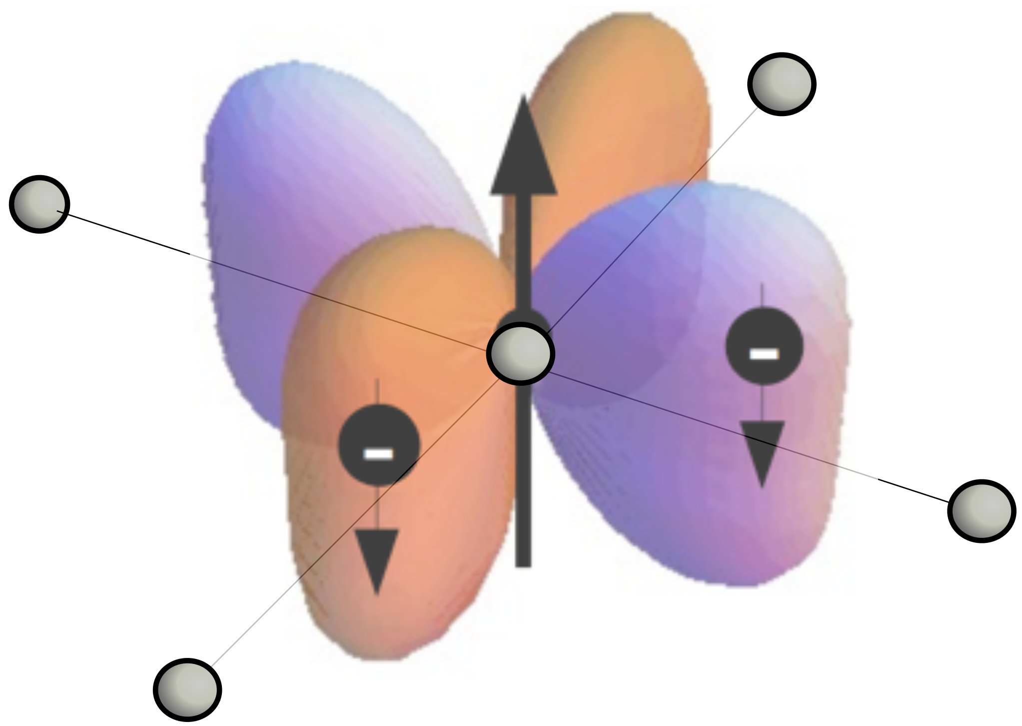

Composite pair

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

Abrahams, Balatsky, Scalapino, Schrieffer 1995

Andrei, Coleman, Kee & Tsvelik PRB (1998)
Flint, Dzero, Coleman , Nat. Phys, (2008)

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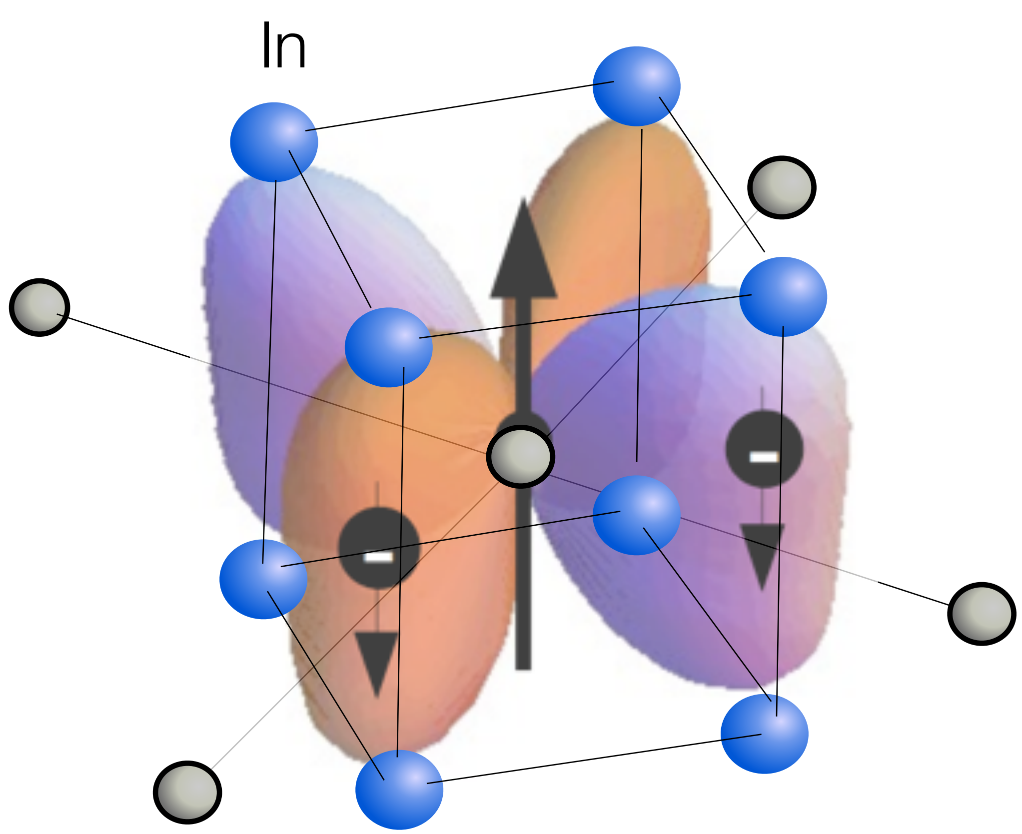

Composite pair**: intra-cell boson**

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

Abrahams, Balatsky, Scalapino, Schrieffer 1995

Andrei, Coleman, Kee & Tsvelik PRB (1998)
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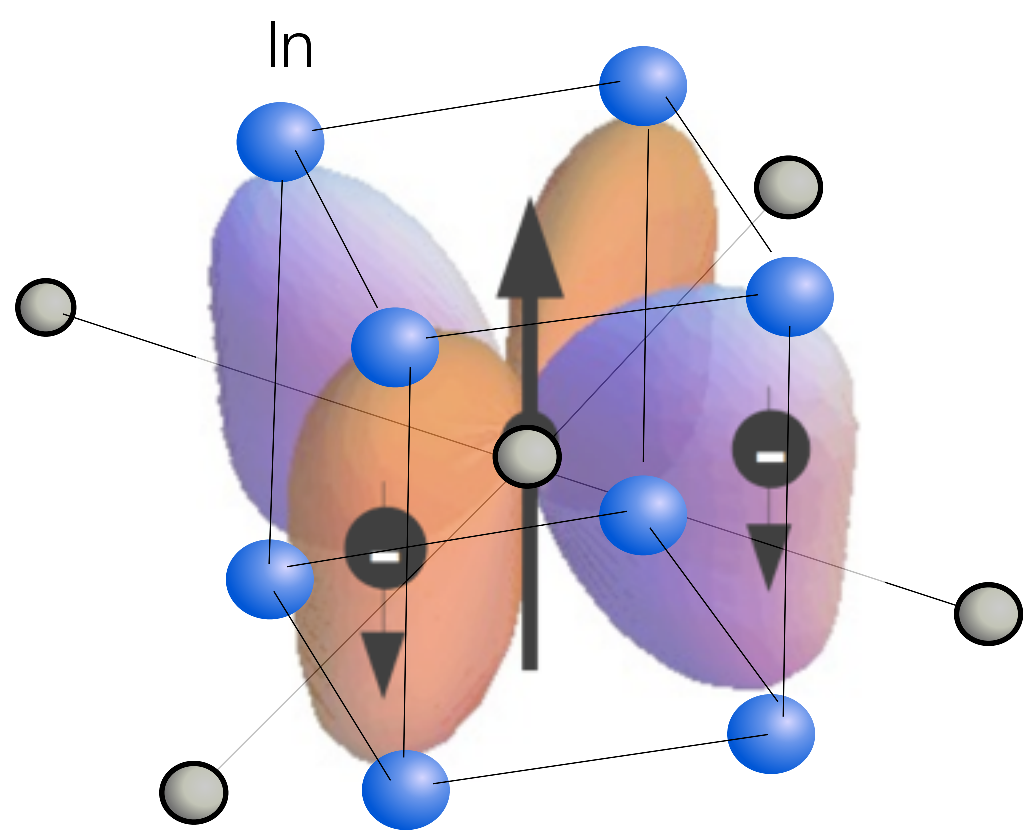
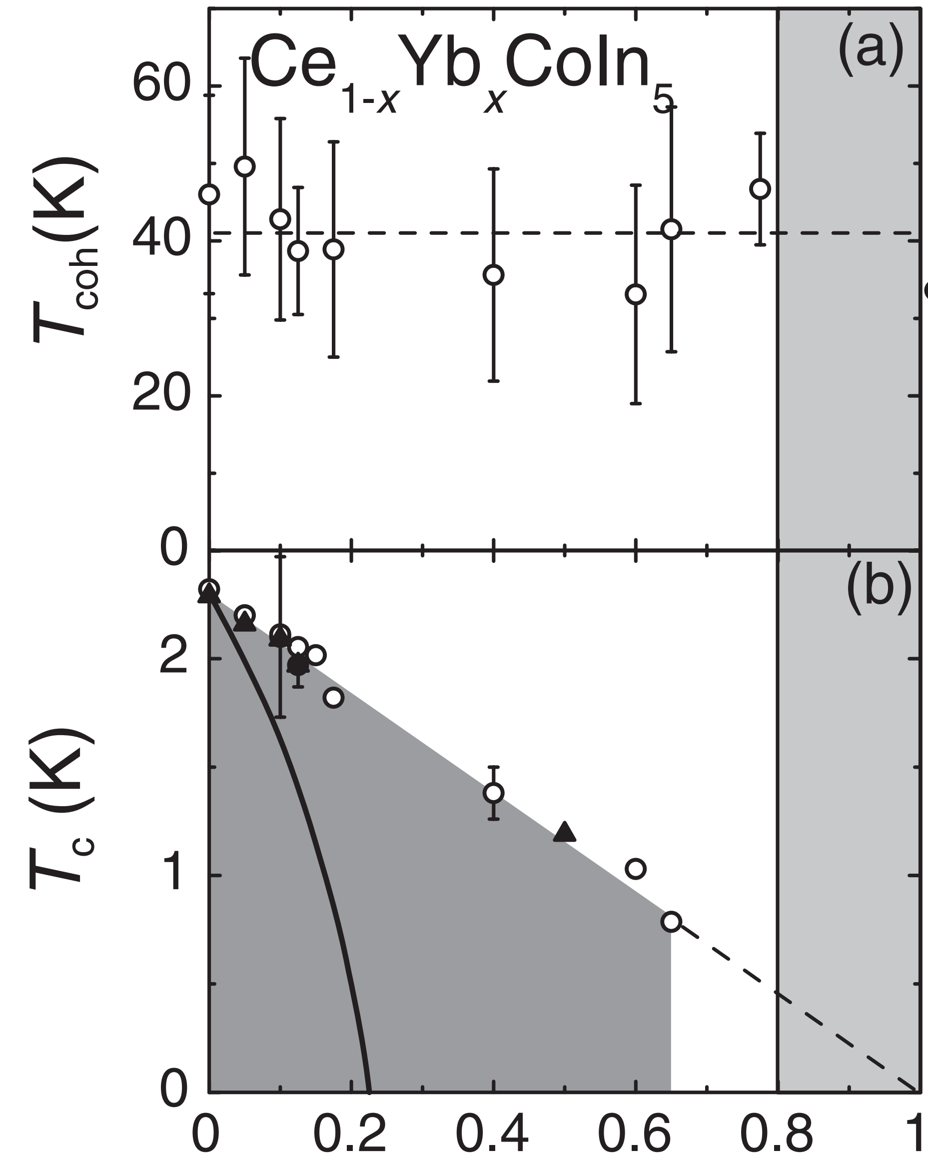
Real-space structure of pair

Extreme Resilience to doping on Ce site.

Magnetic pair: intercell

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





Lei Shu et al, PRL, (2011)

Composite pair**: intra-cell boson**

$$\Psi_C^\dagger = c_{1\downarrow}^\dagger c_{2\downarrow}^\dagger S_+$$

Abrahams, Balatsky, Scalapino, Schrieffer 1995

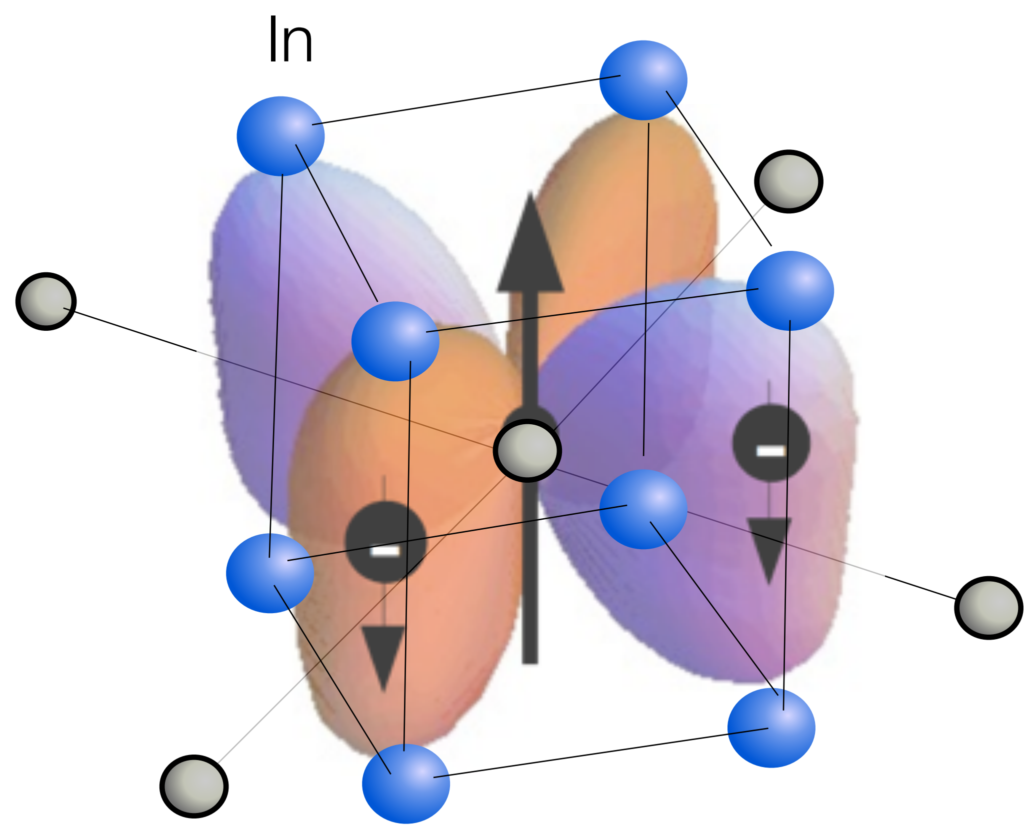
Andrei, Coleman, Kee & Tsvelik PRB (1998)
Flint, Dzero, Coleman , Nat. Phys, (2008)

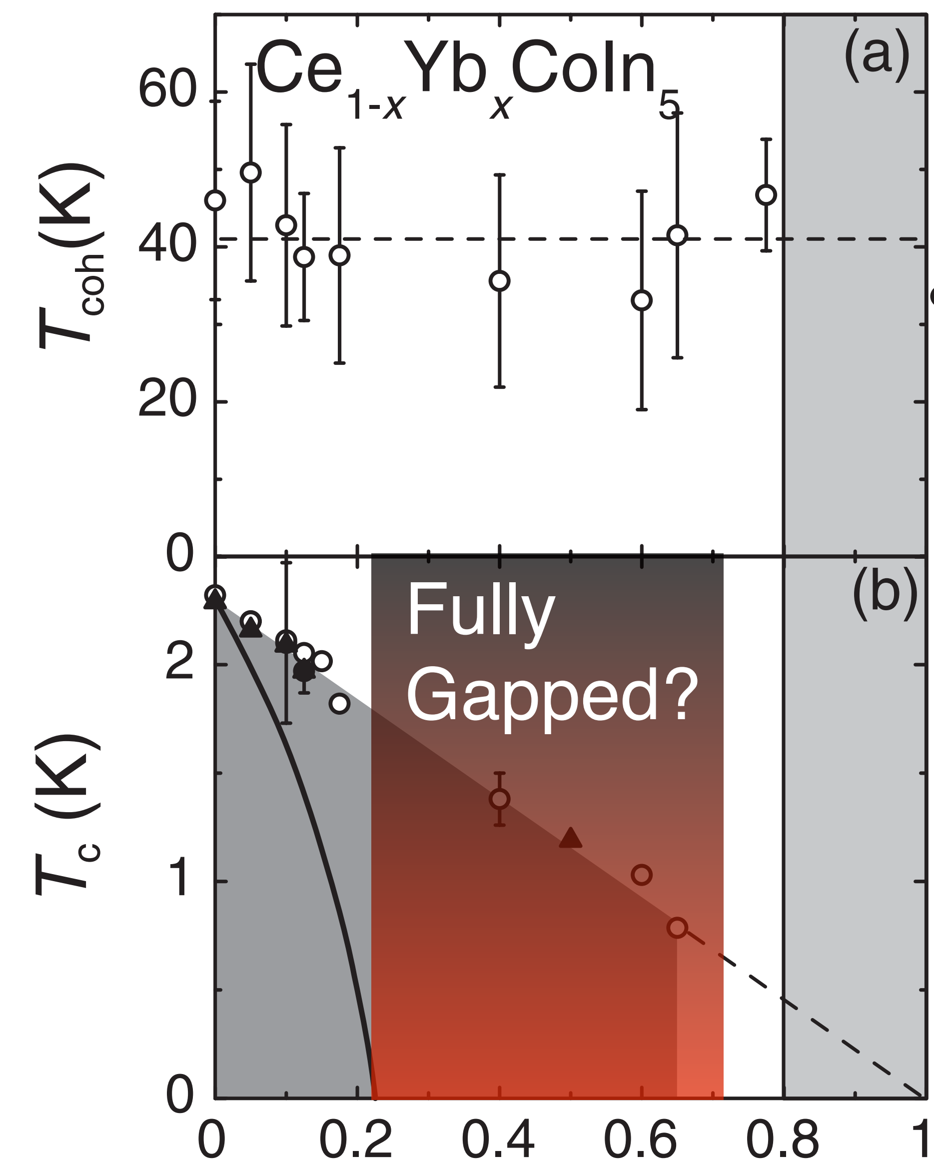
Real-space structure of pair

Extreme Resilience
to doping on Ce
site.

Magnetic pair: intercell

$$\Psi^\dagger_M = \Delta_d(1-2) f^\dagger_\uparrow(1) f^\dagger_\downarrow(2)$$





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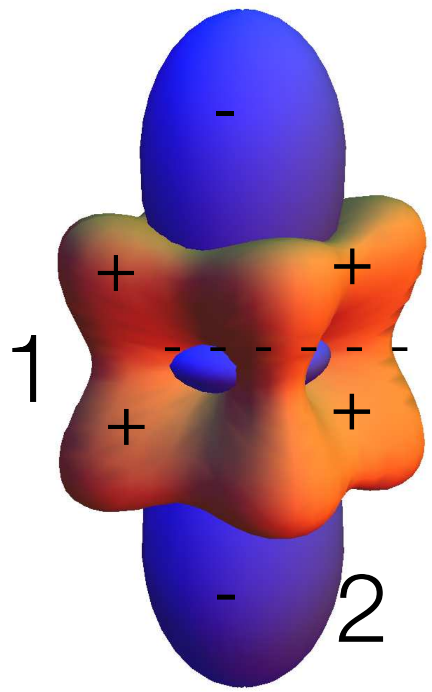
Lei Shu et al, PRL, (2011)

M. Tanatar et al (unpublished)
Erten and PC arXiv1402.7361

4f/5f superconductors



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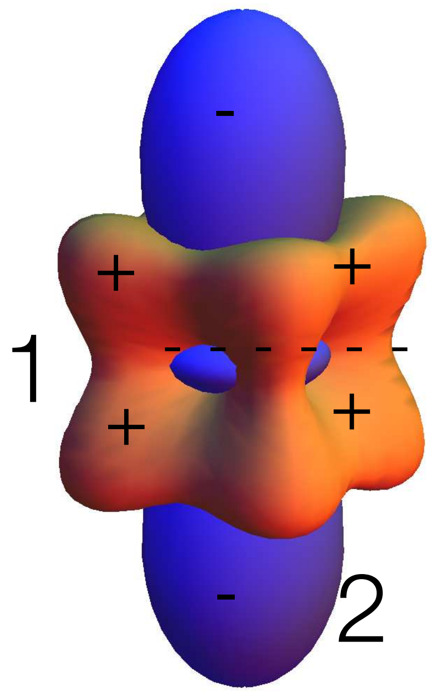
4f/5f superconductors



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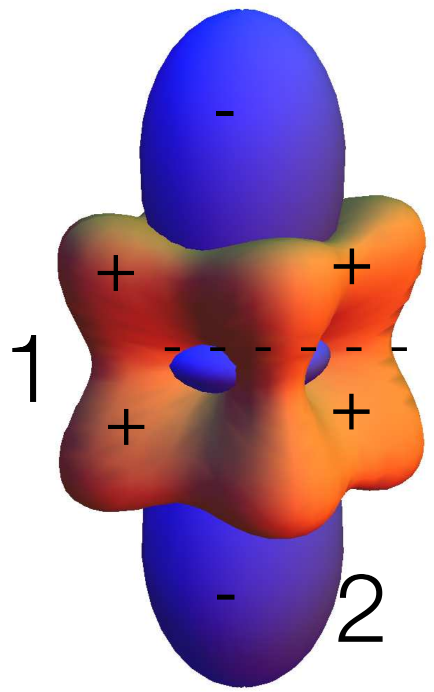
$$Q_{zz} \propto \Psi_C^2$$

4f/5f superconductors

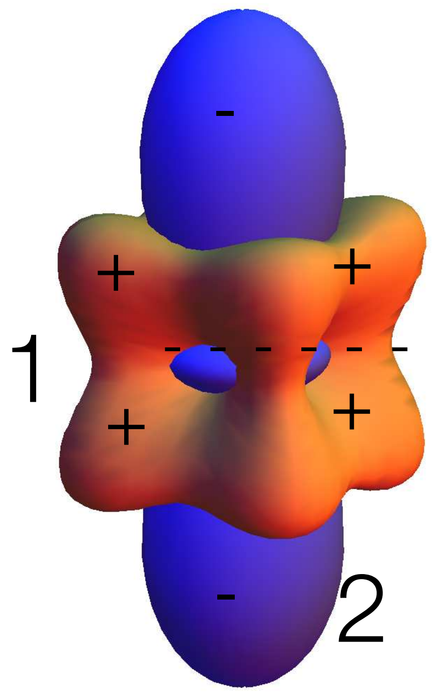


$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

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

$$\Delta F \propto -Q_{zz} u_{tet}$$

4f/5f superconductors



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

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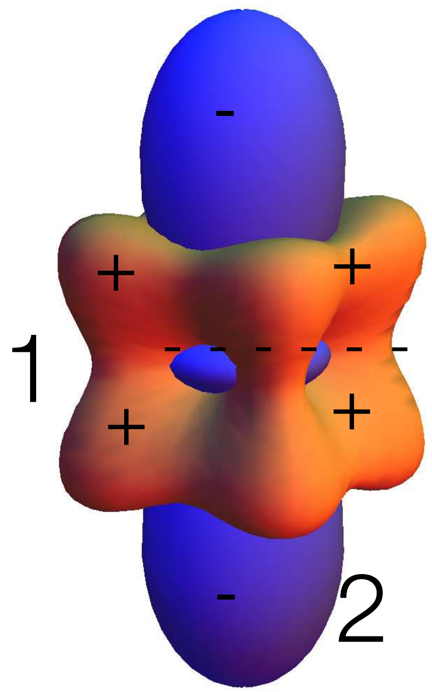
$$\alpha_2 [T - (T_{c2} + \lambda u_{tet})] \Psi_C^2$$

4f/5f superconductors



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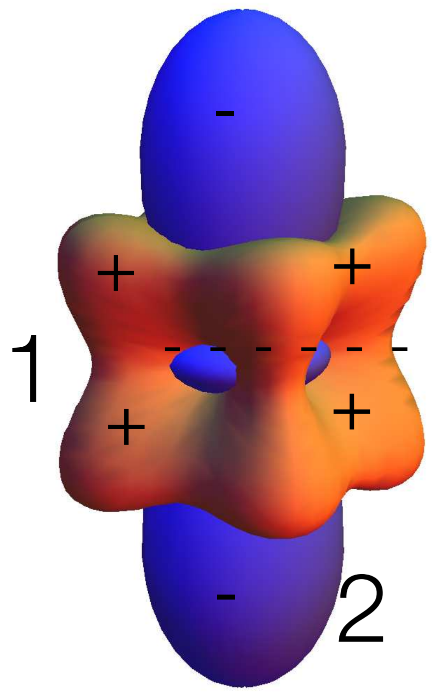
4f/5f superconductors



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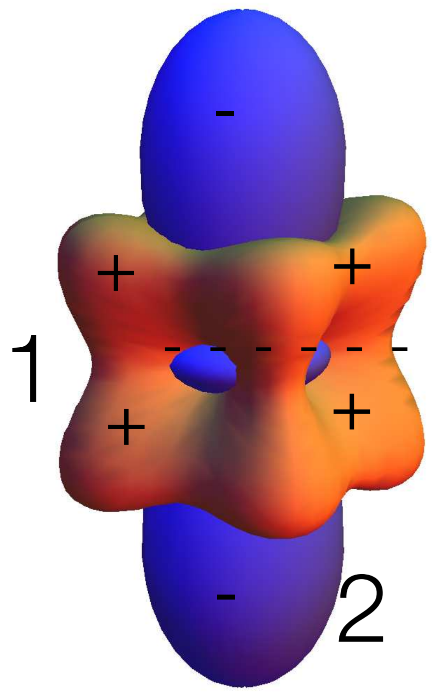
Strain expected to enhance Tc

4f/5f superconductors



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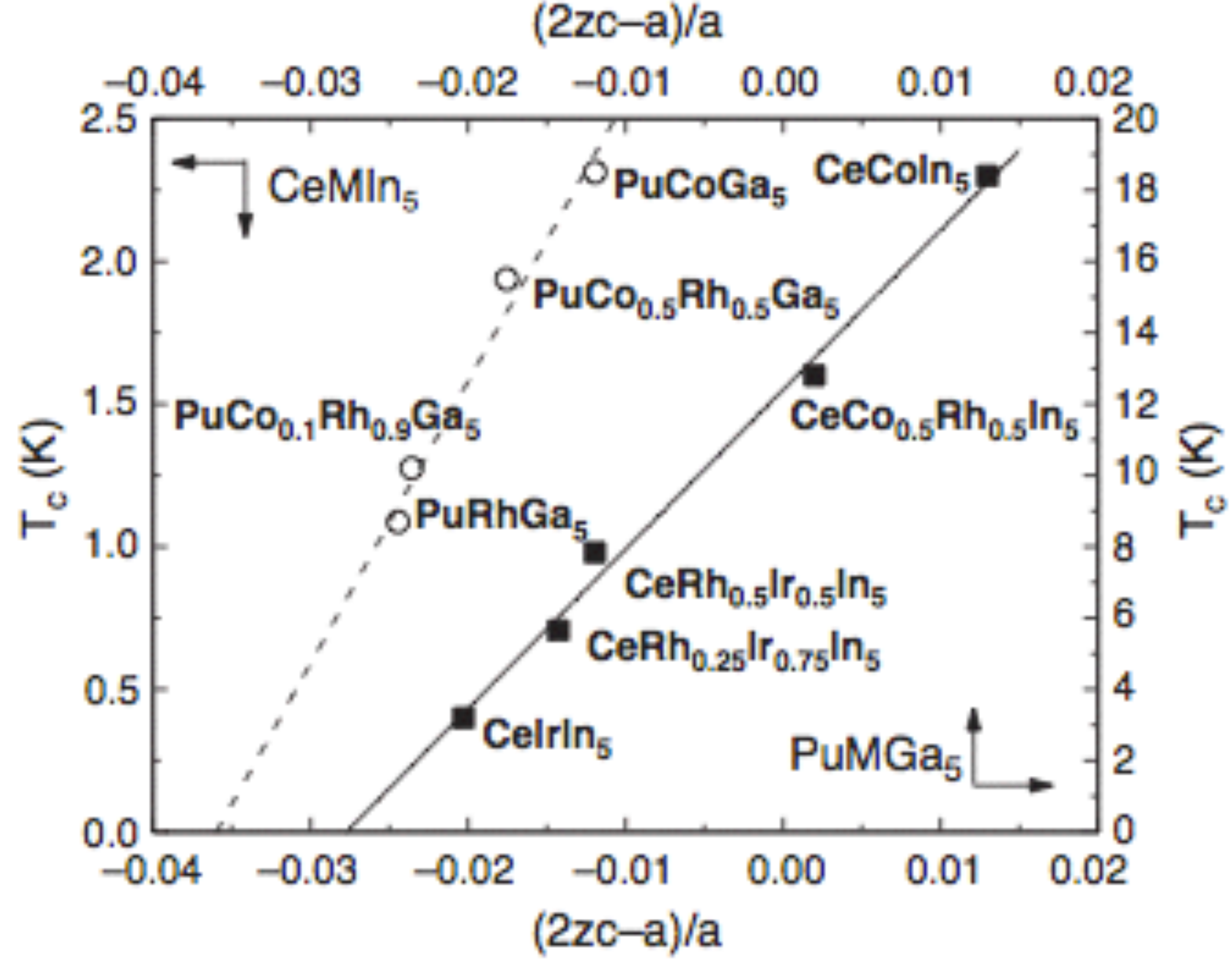

J.L. Sarrao et al. / Physica B 359– 361 (2005) 1144–1146

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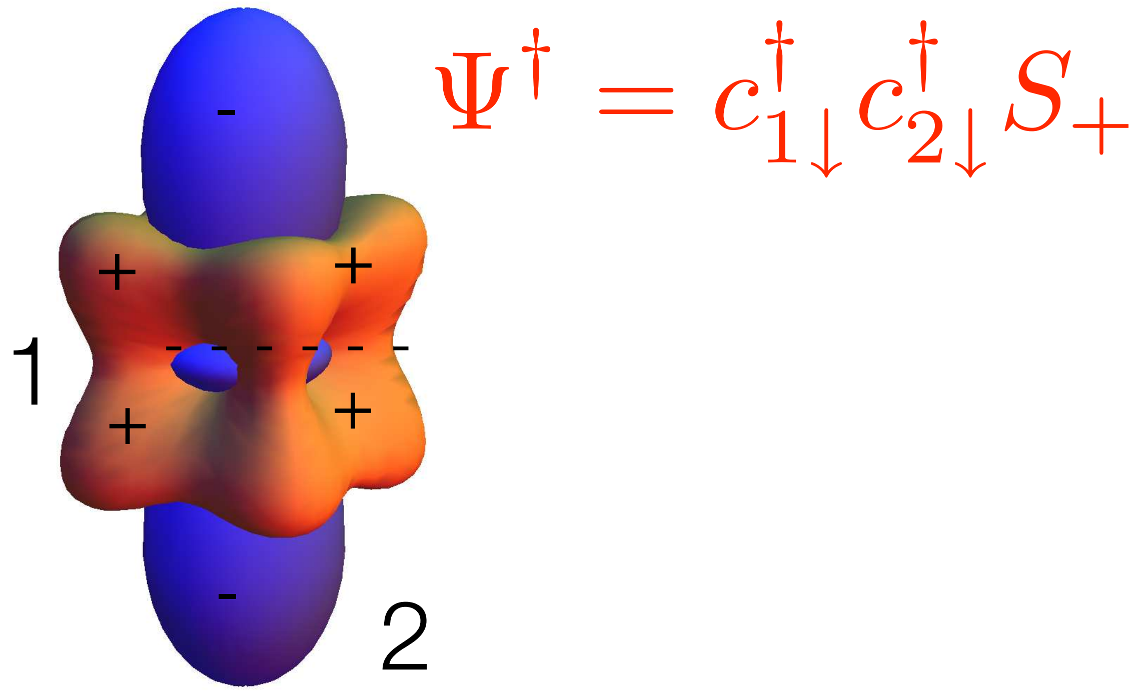
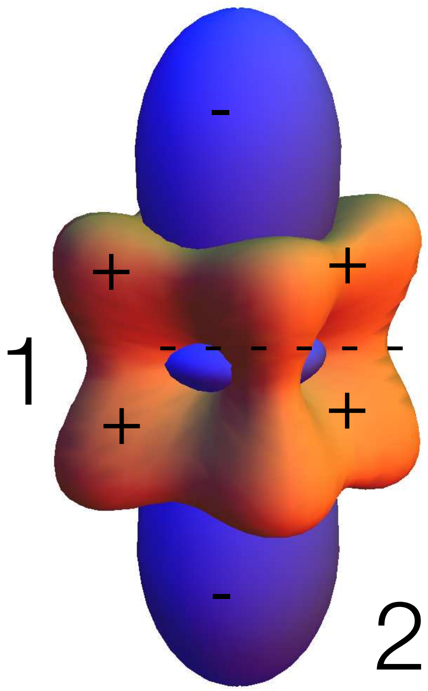
Strain expected to enhance Tc



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



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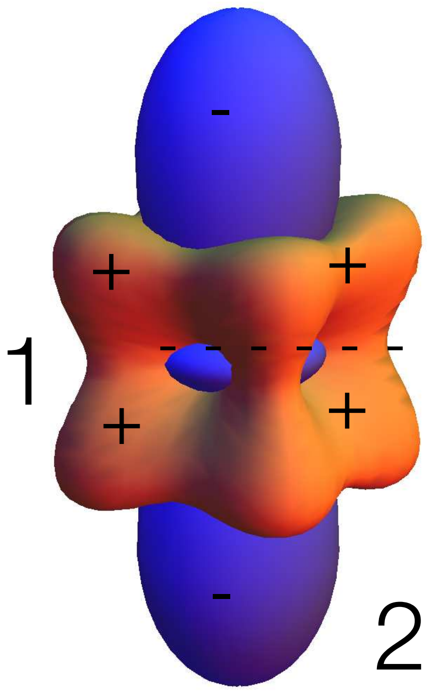

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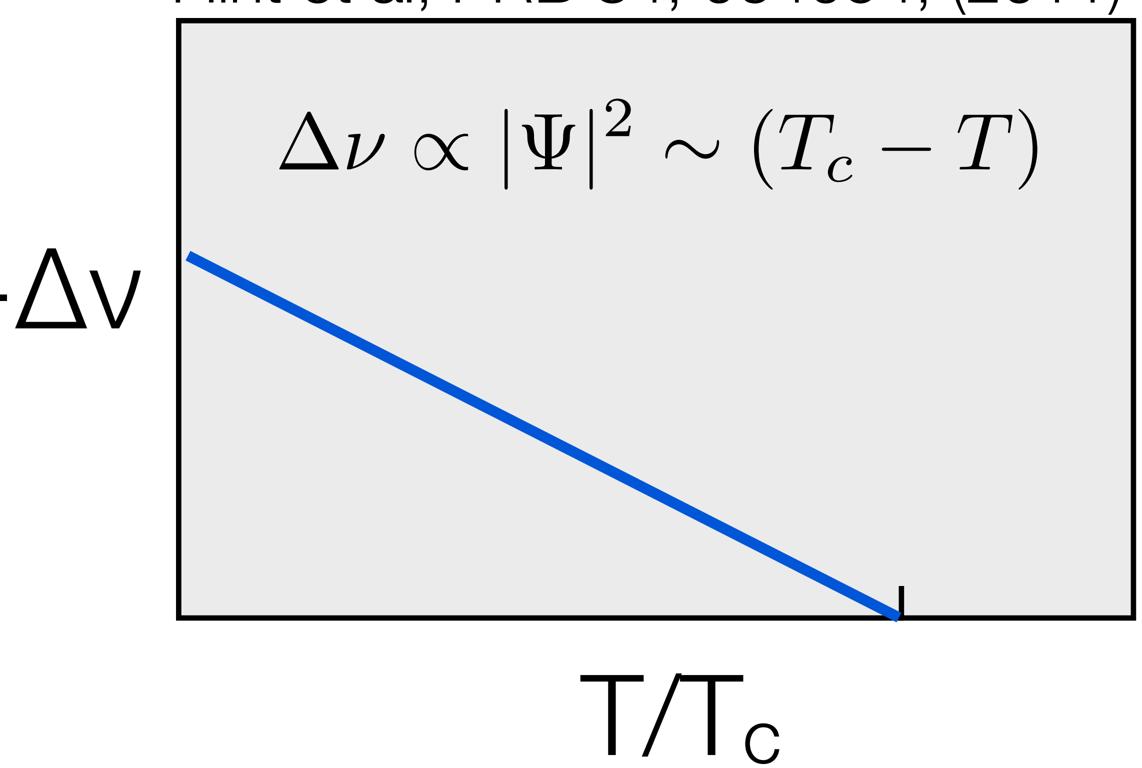
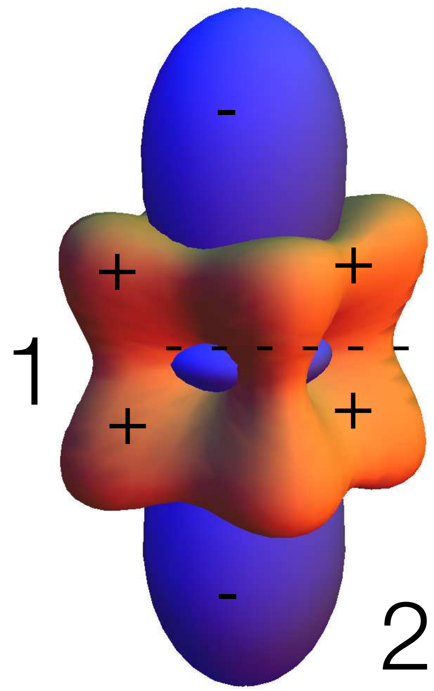
Flint et al, PRB 84, 064054, (2011)





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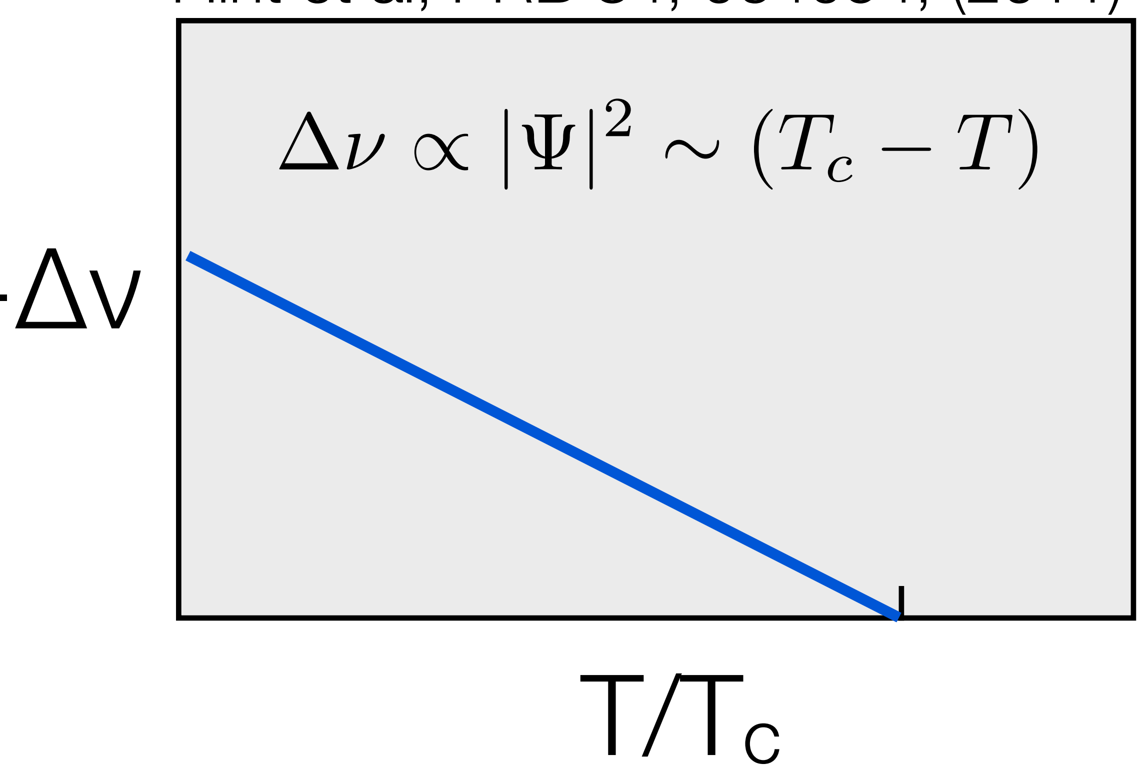
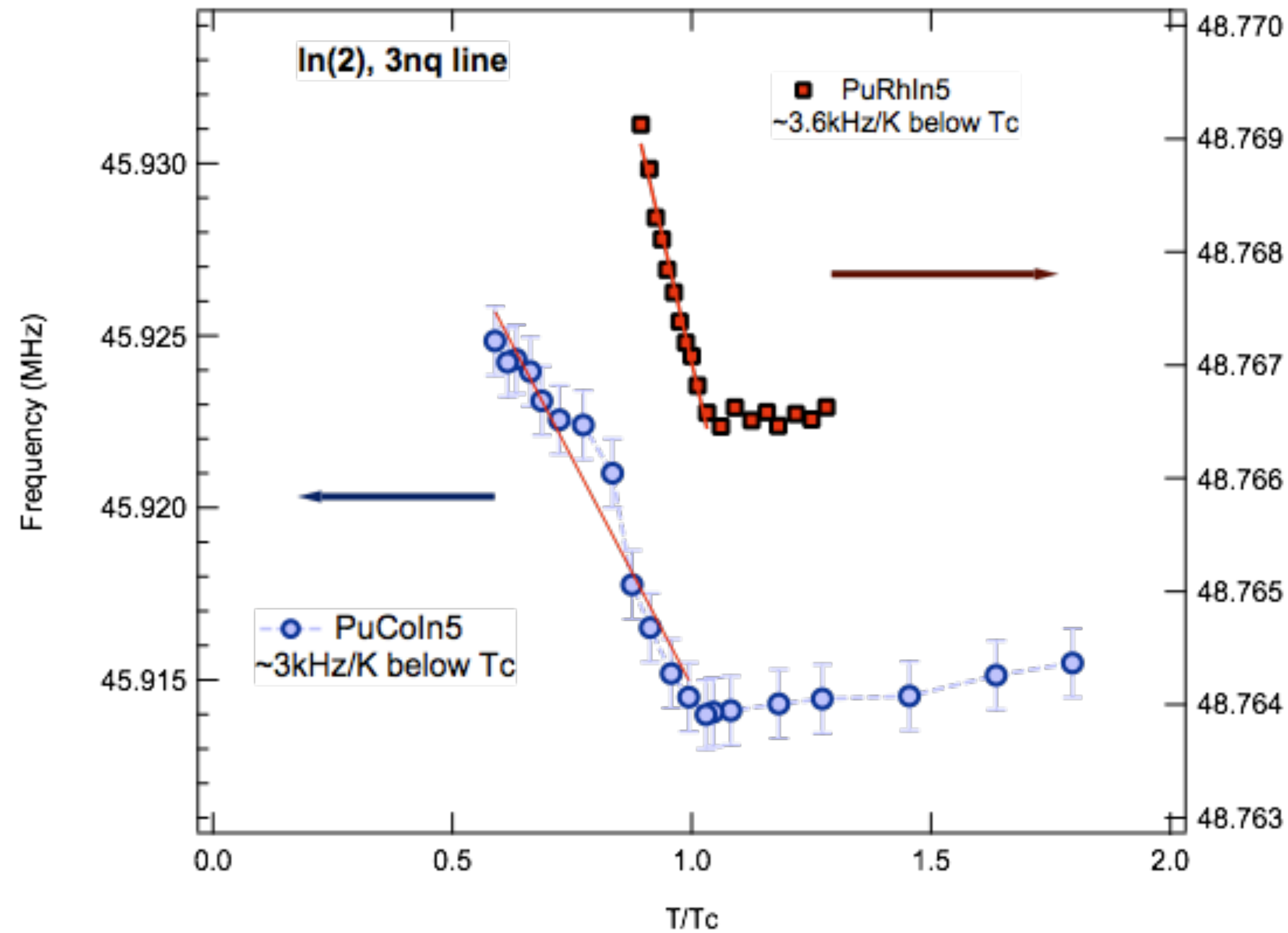
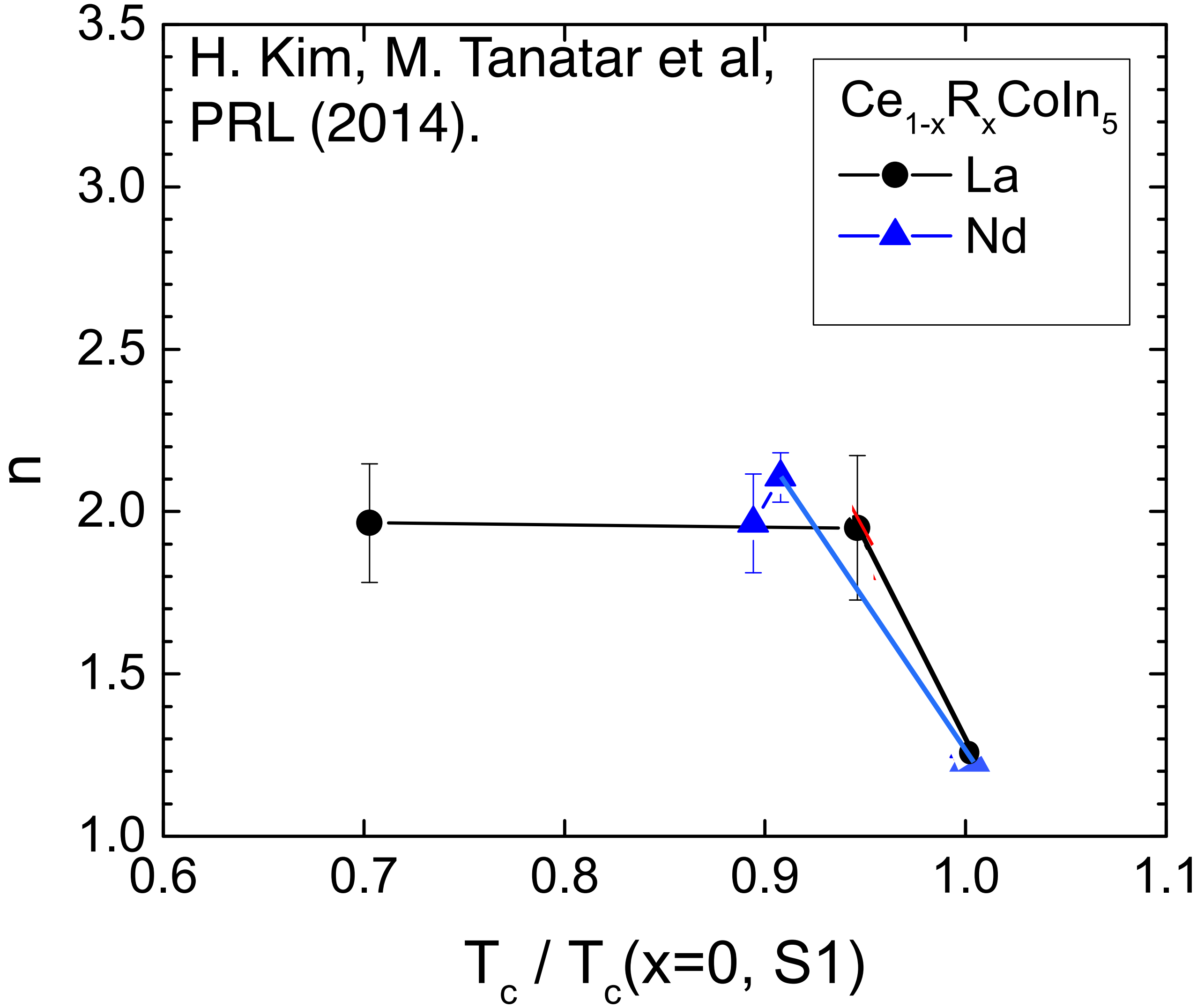
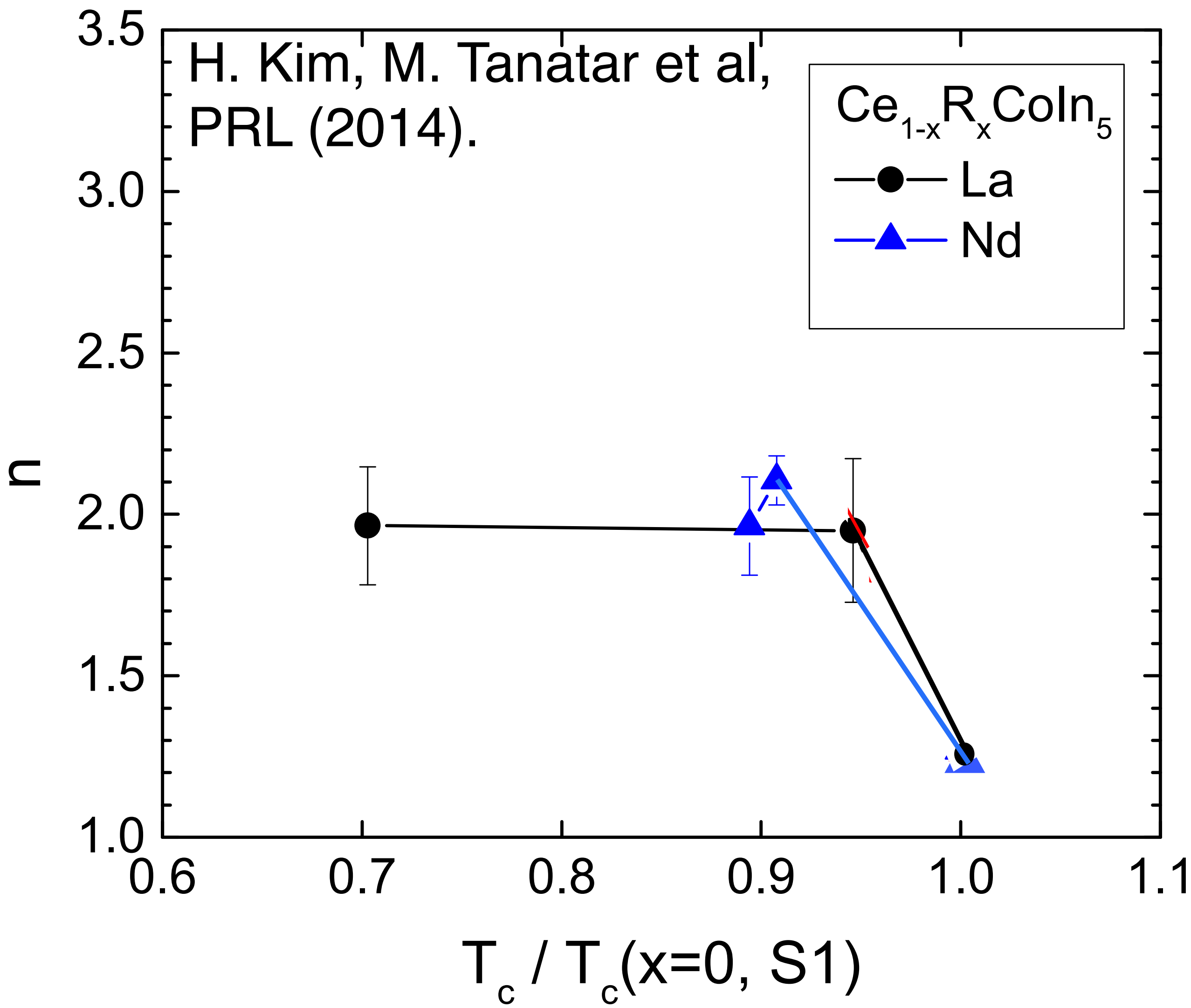


Bauer, G. Koutroulakis Yasuoko,(2014)

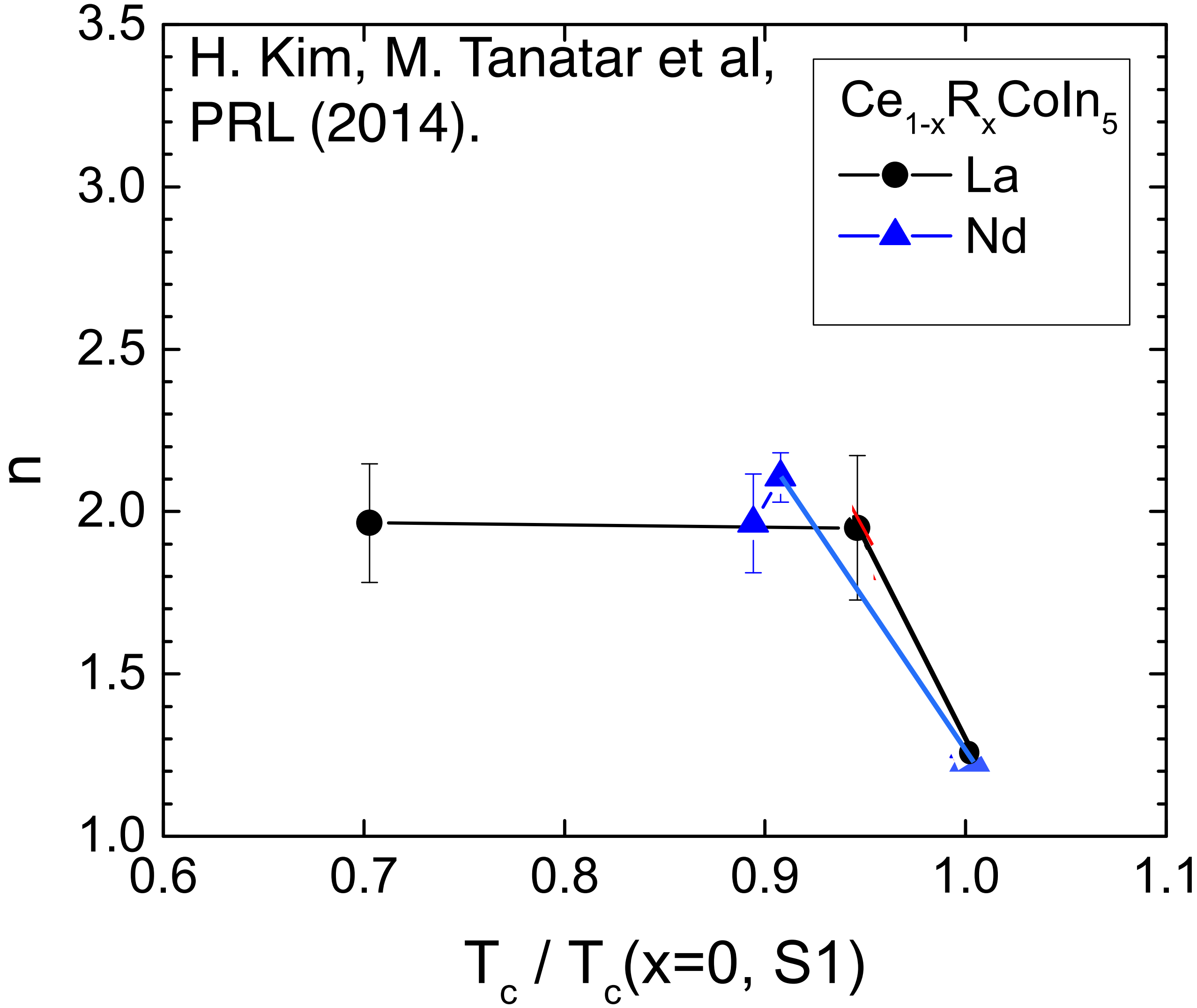


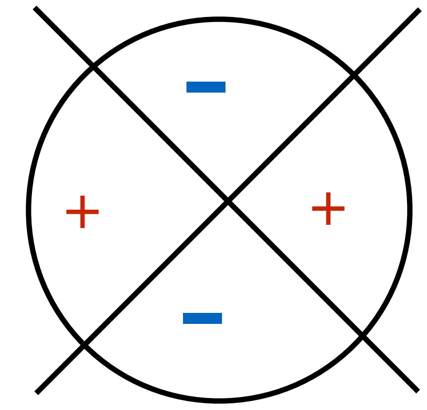

H. Kim, M. Tanatar et al,
PRL (2014).
$Ce_{1-x}R_xCoIn_5$
La
Nd
n
3.5
3.0
2.5
2.0
1.5
1.0
0.6
0.7
0.8
0.9
1.0
1.1
T_c / T_c(x=0, S1)



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

Penetration Depth





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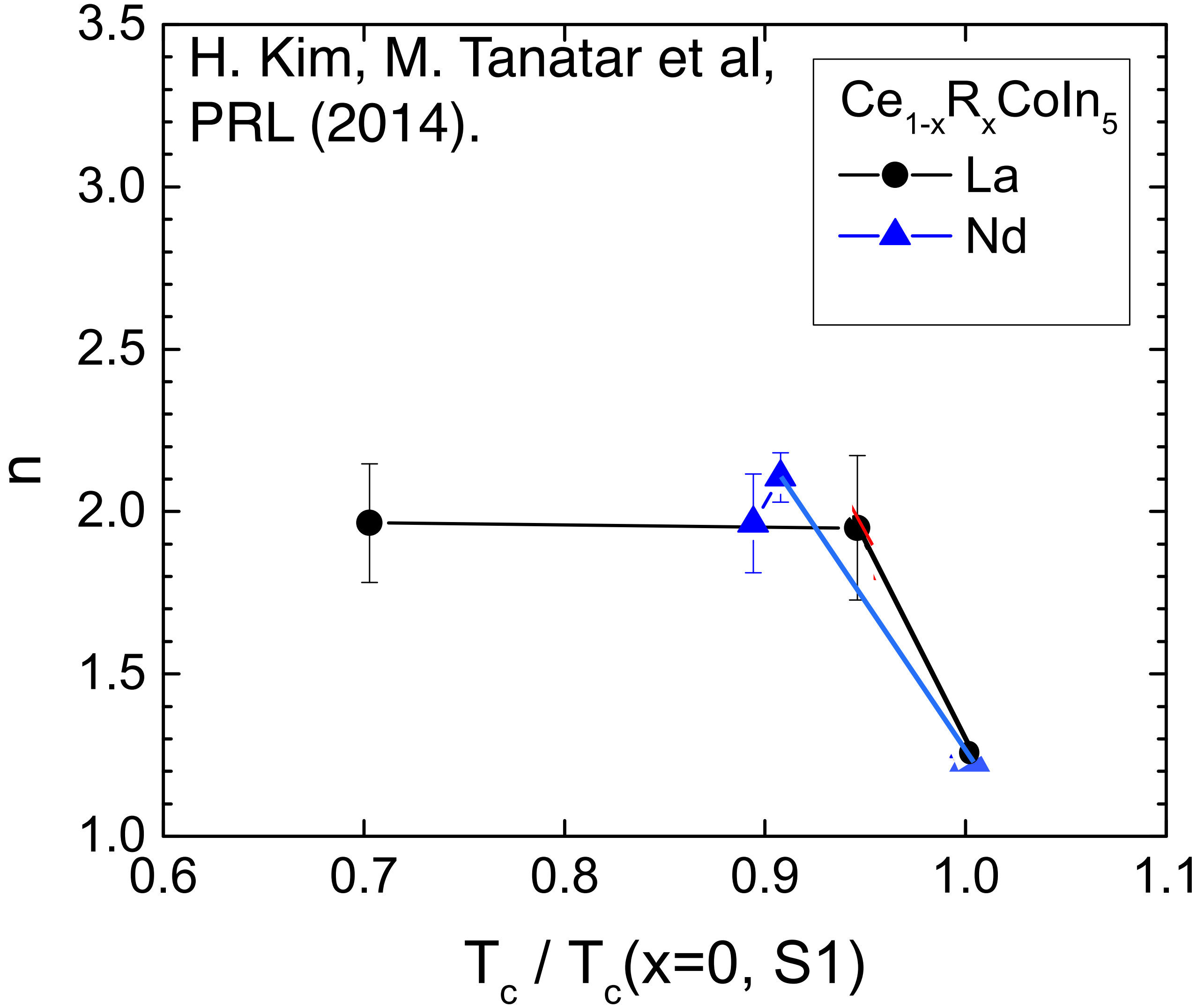

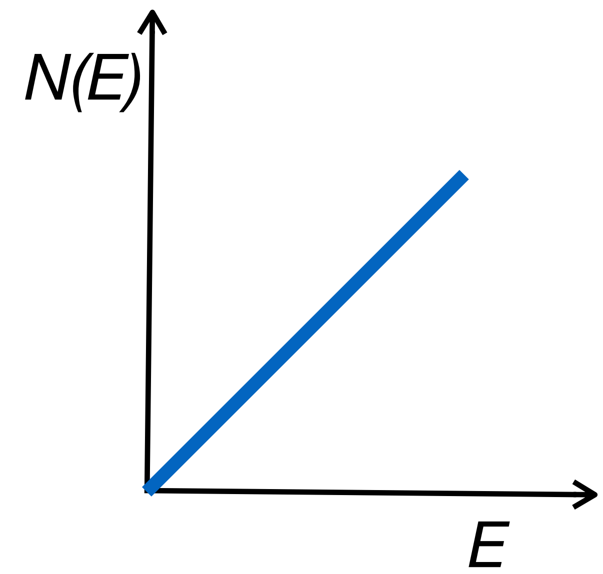

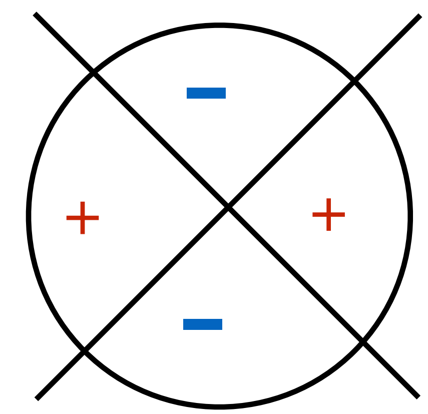

d-wave sc

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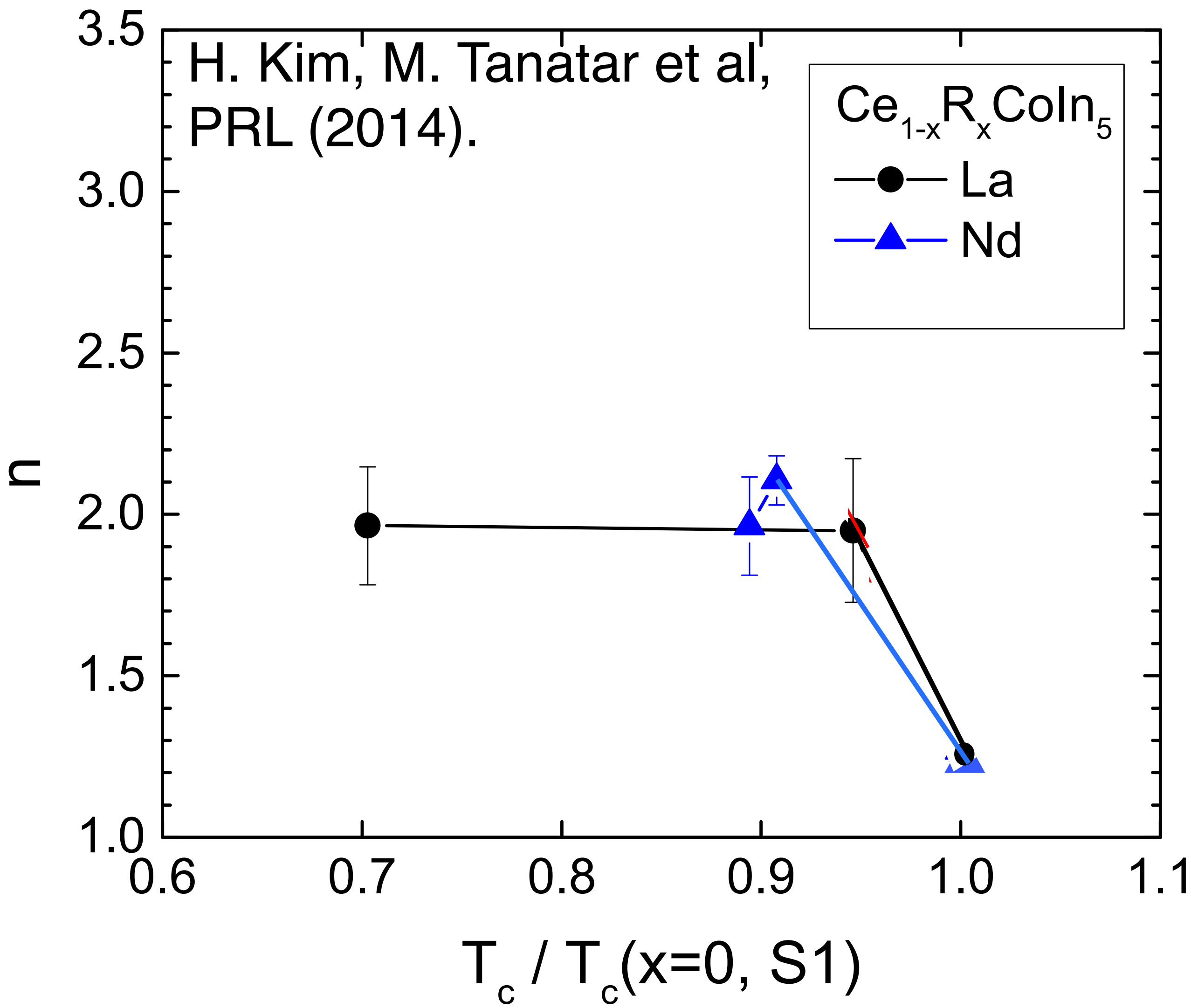
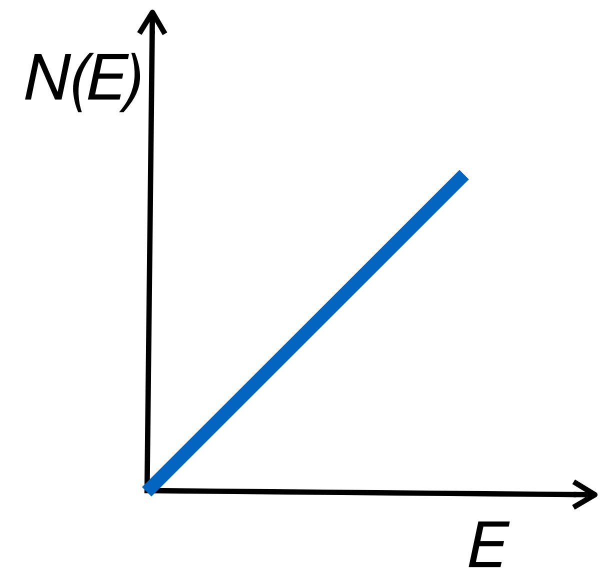
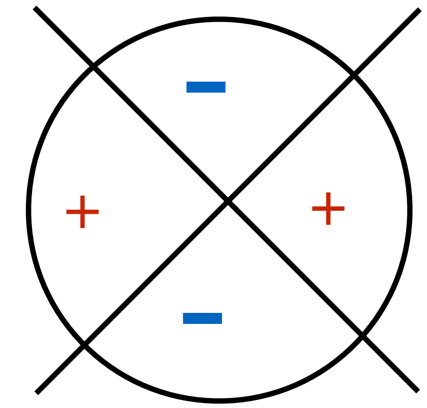
Penetration Depth





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



d-wave sc

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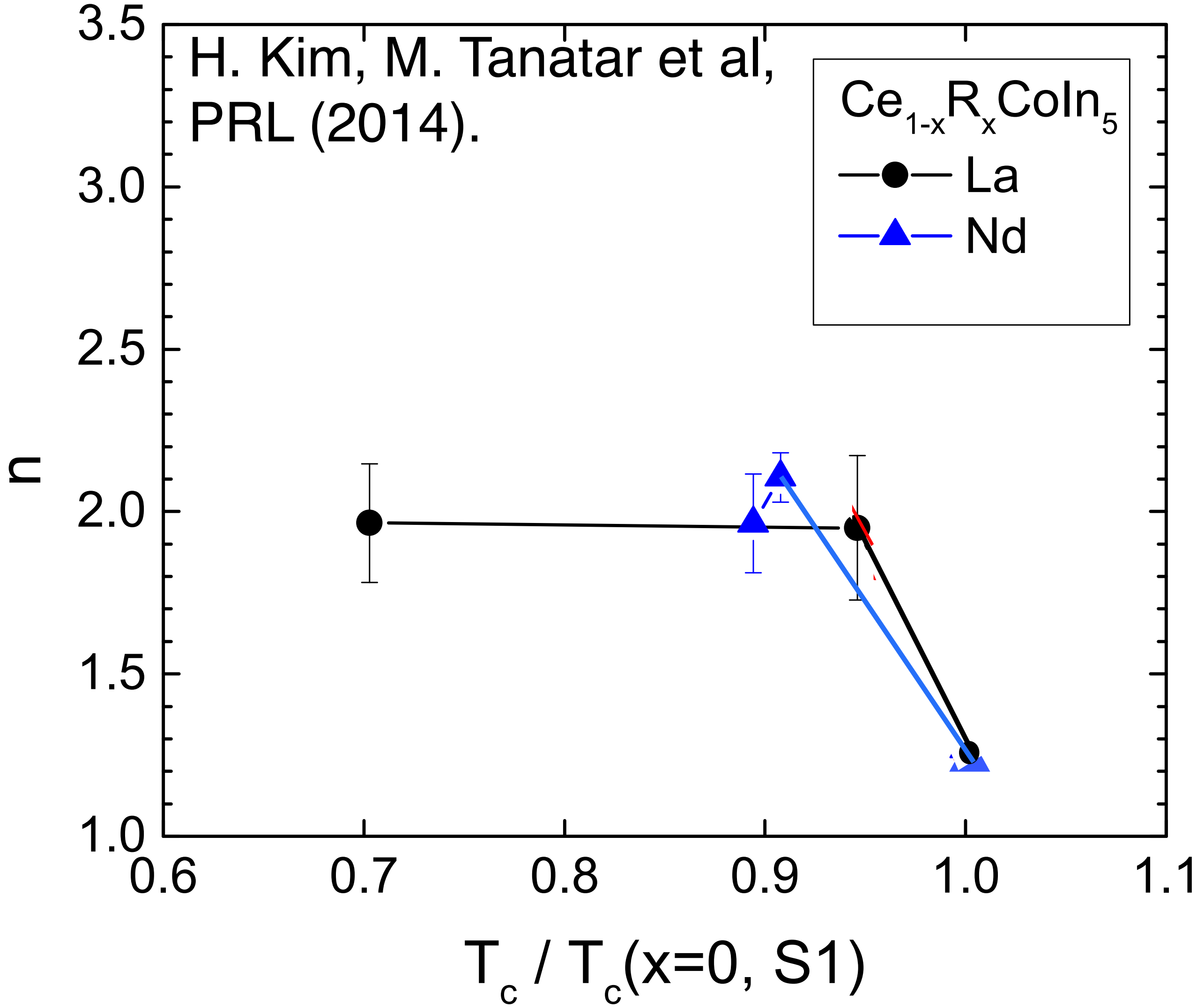
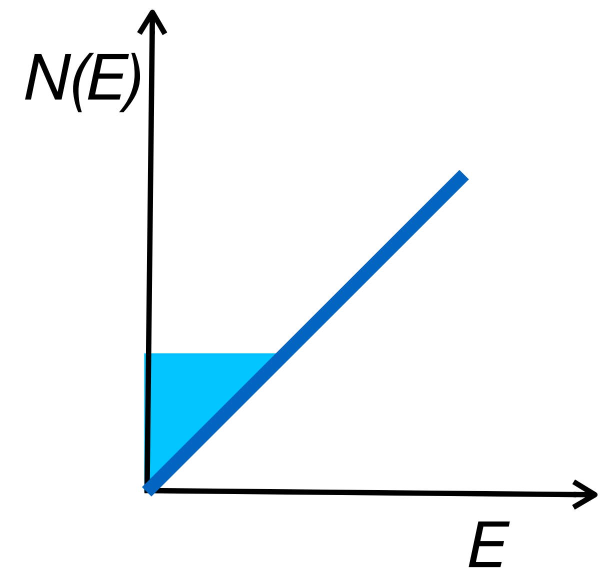
Penetration Depth





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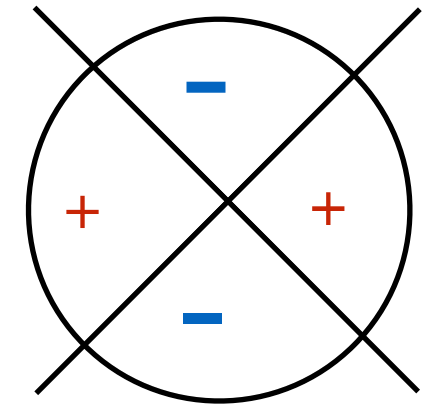

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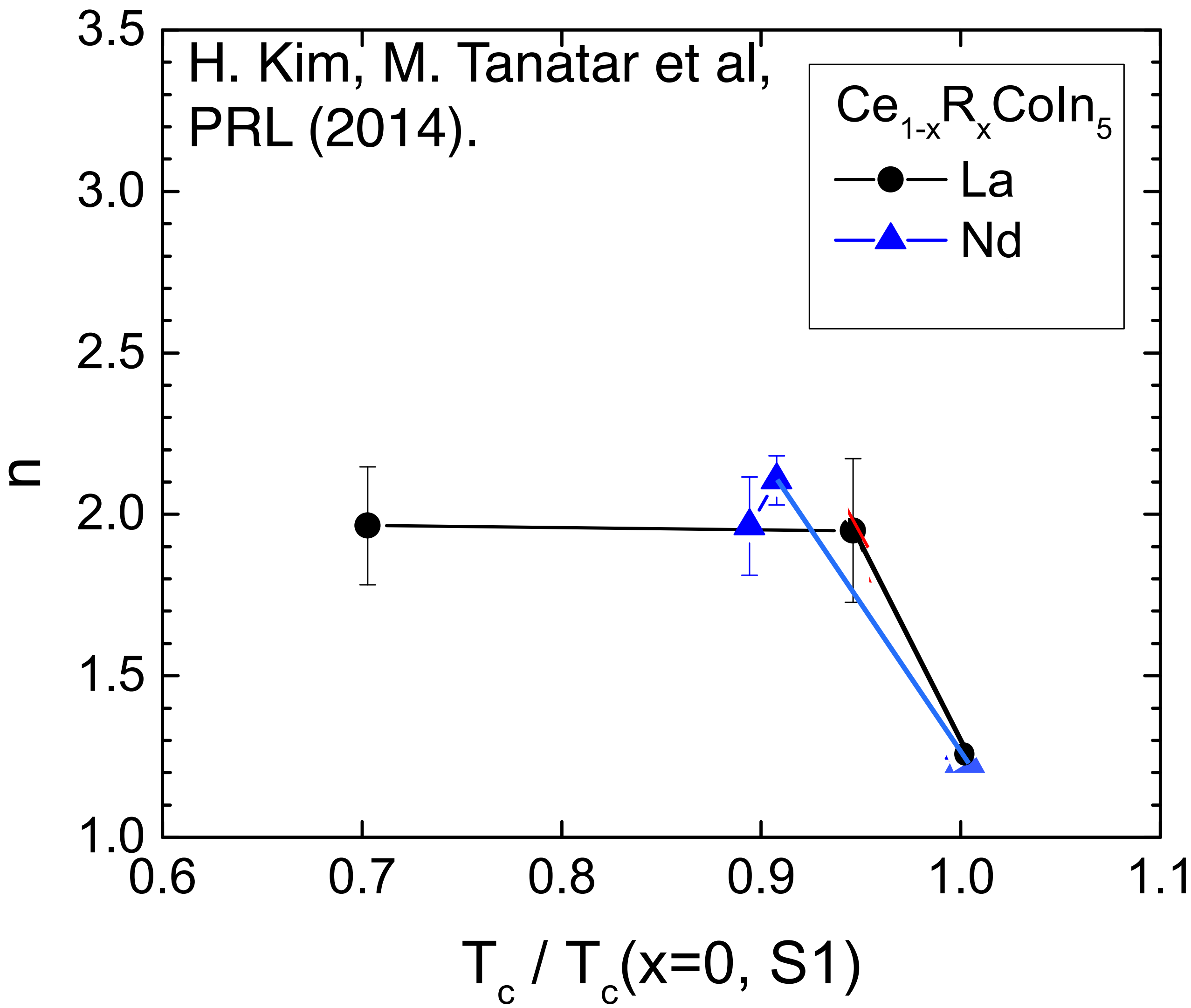
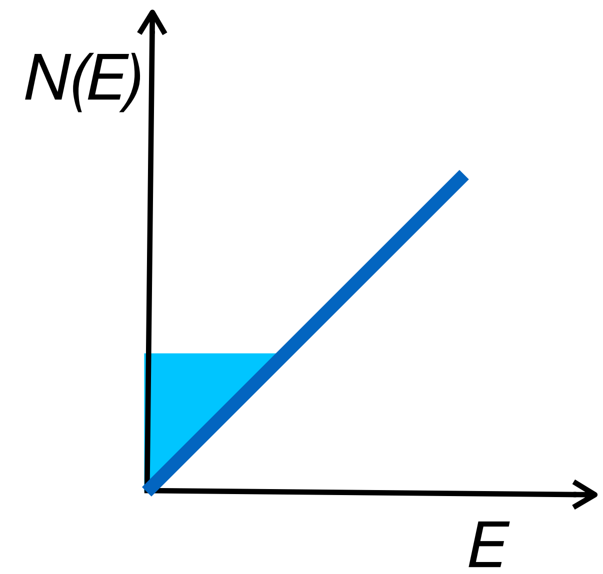
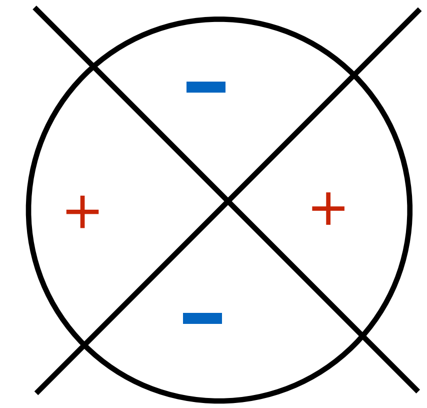




Clean $\overline{N(\epsilon)} \sim T$

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



d-wave sc

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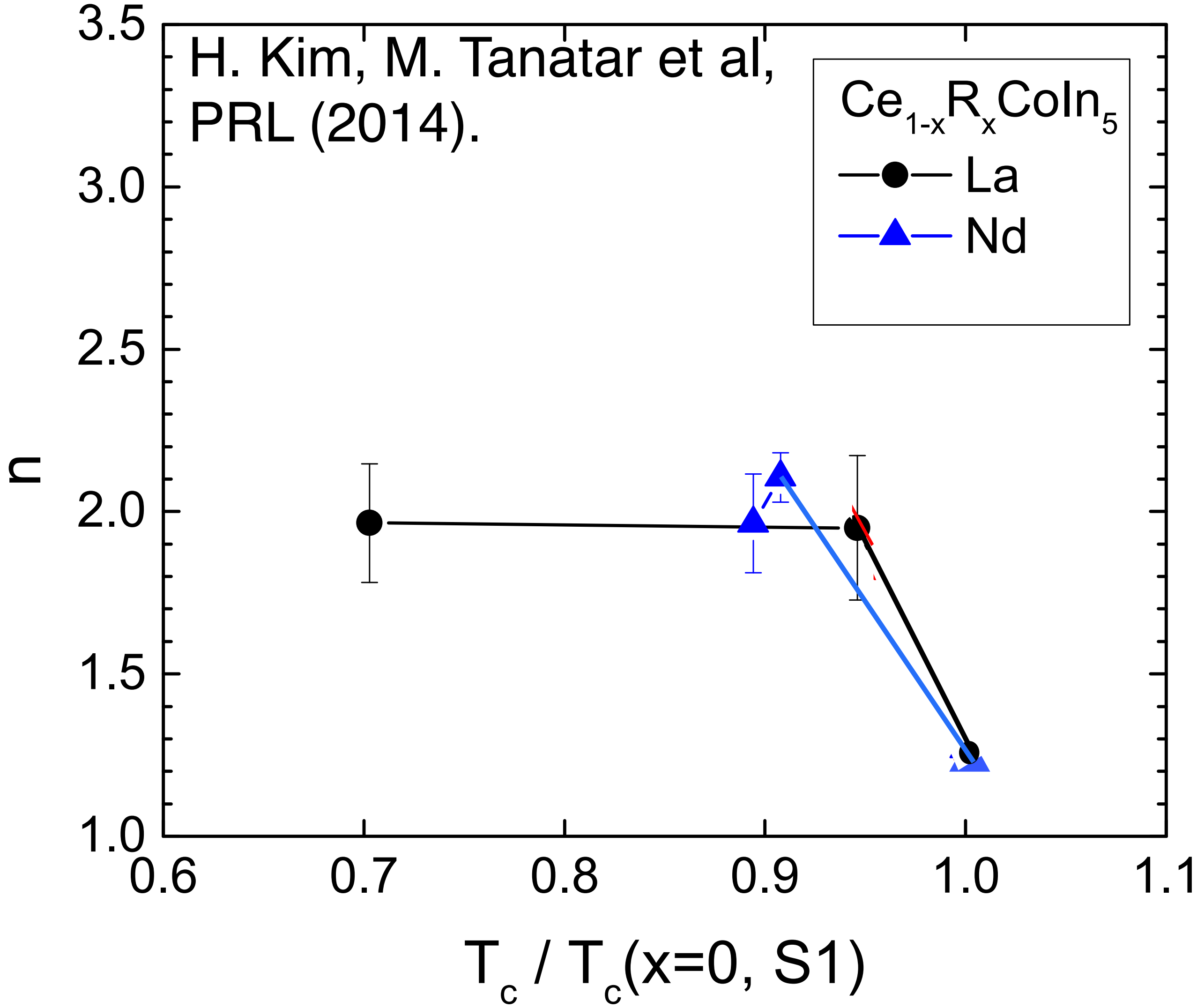
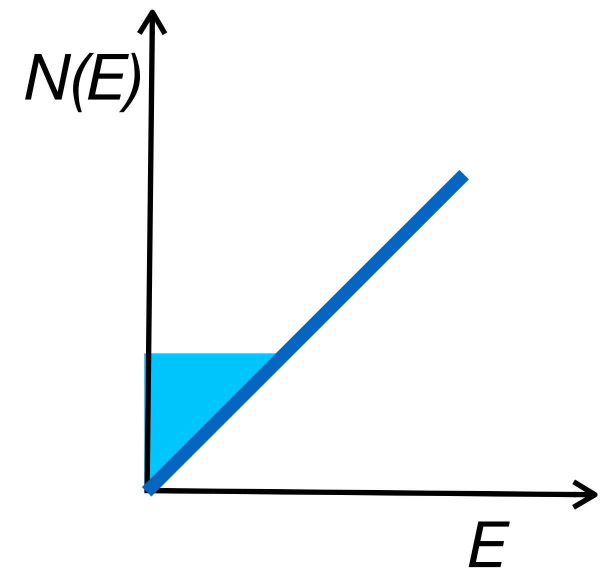
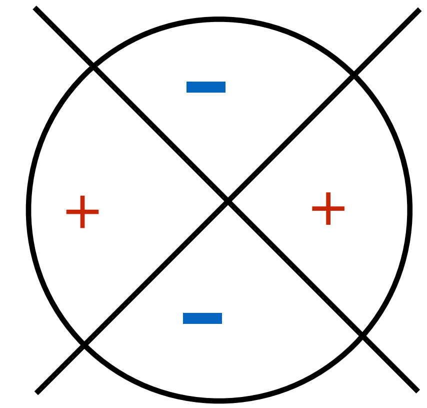
Penetration Depth







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d-wave sc

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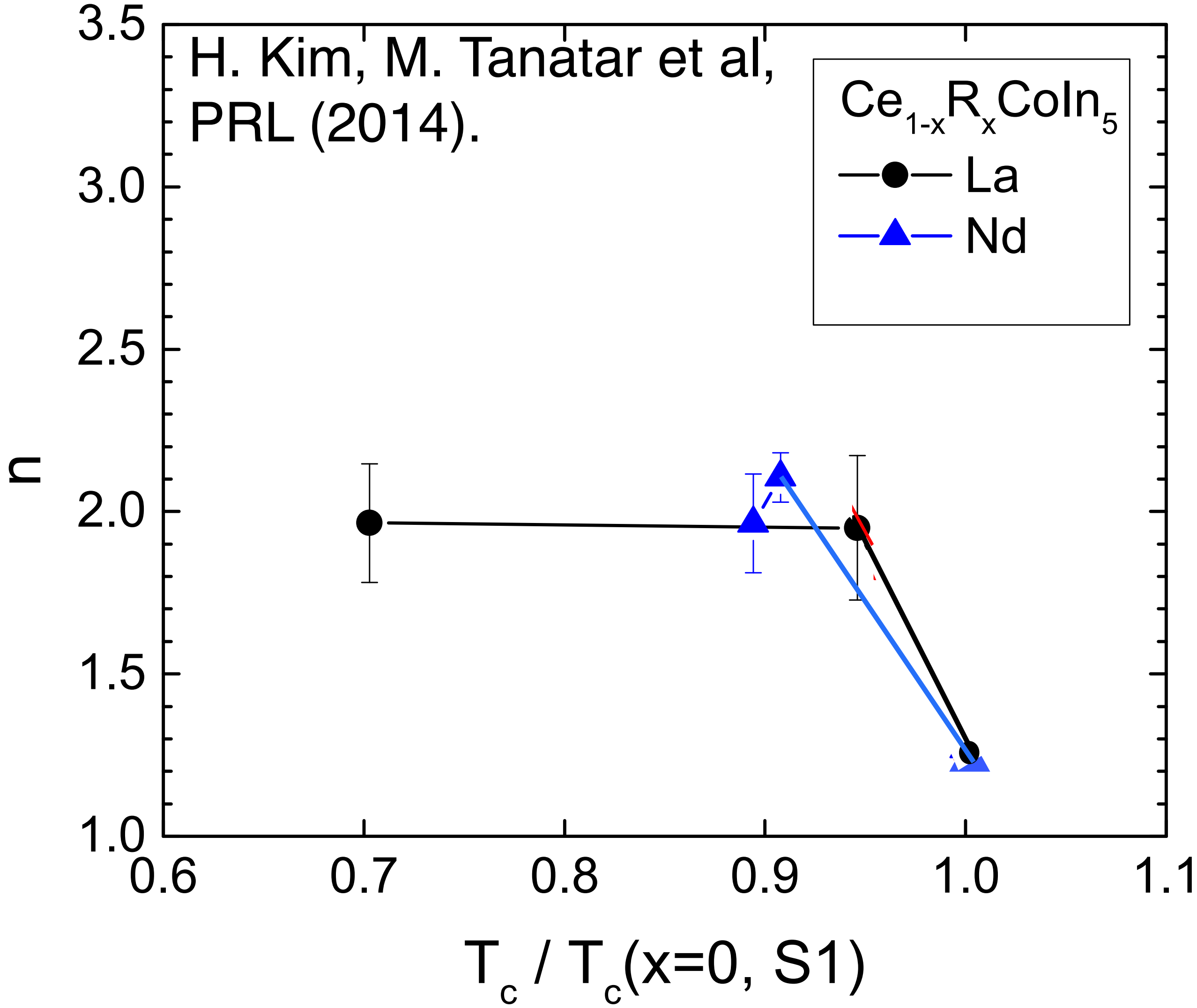

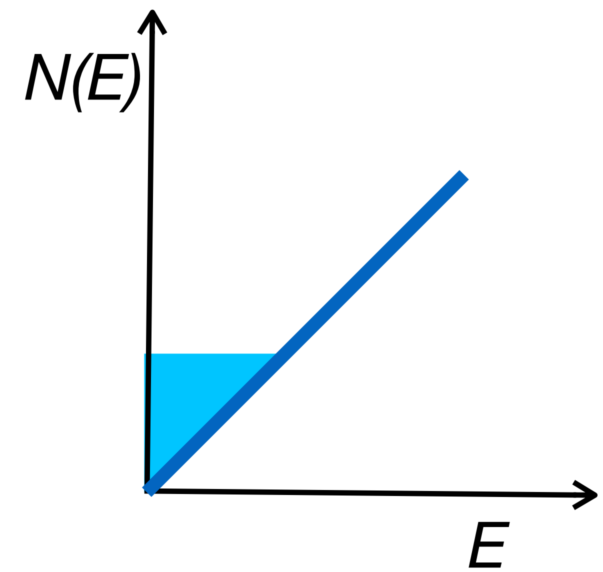

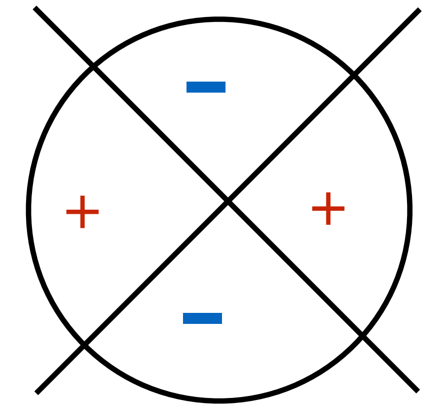

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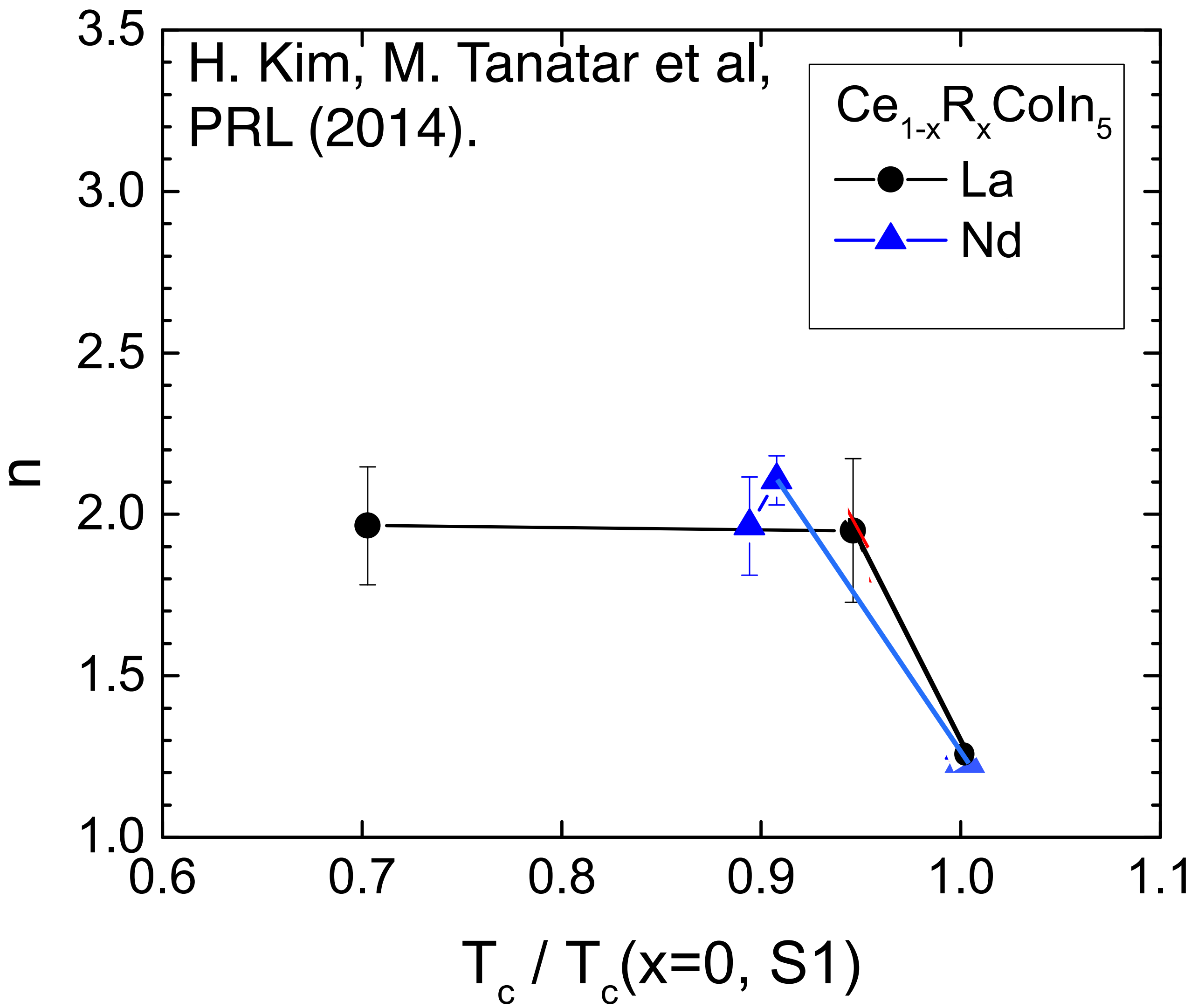

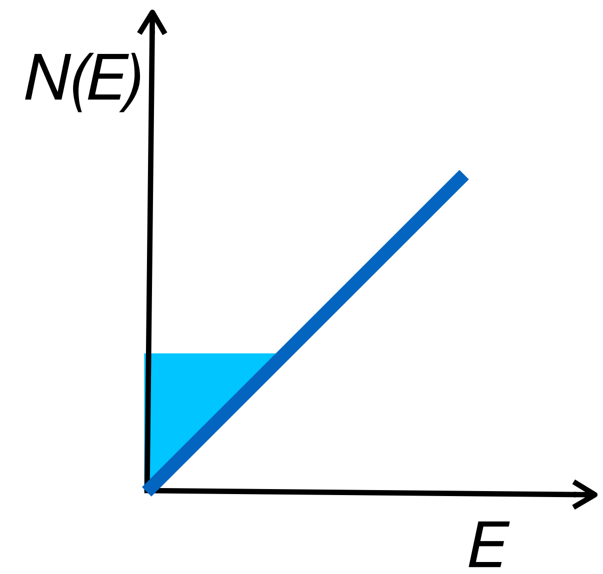

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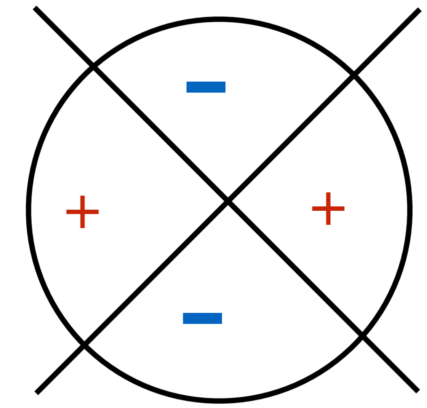
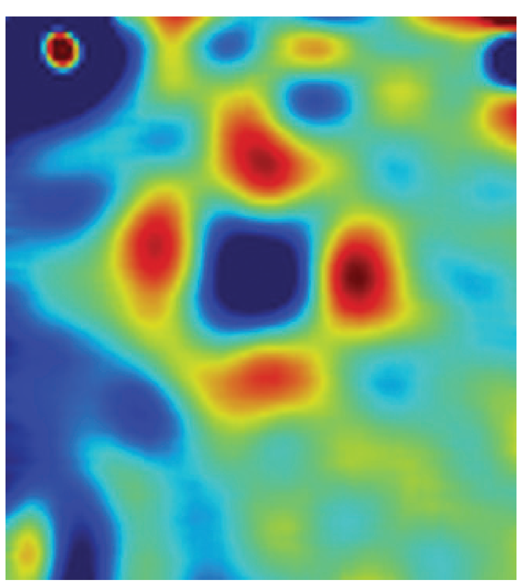
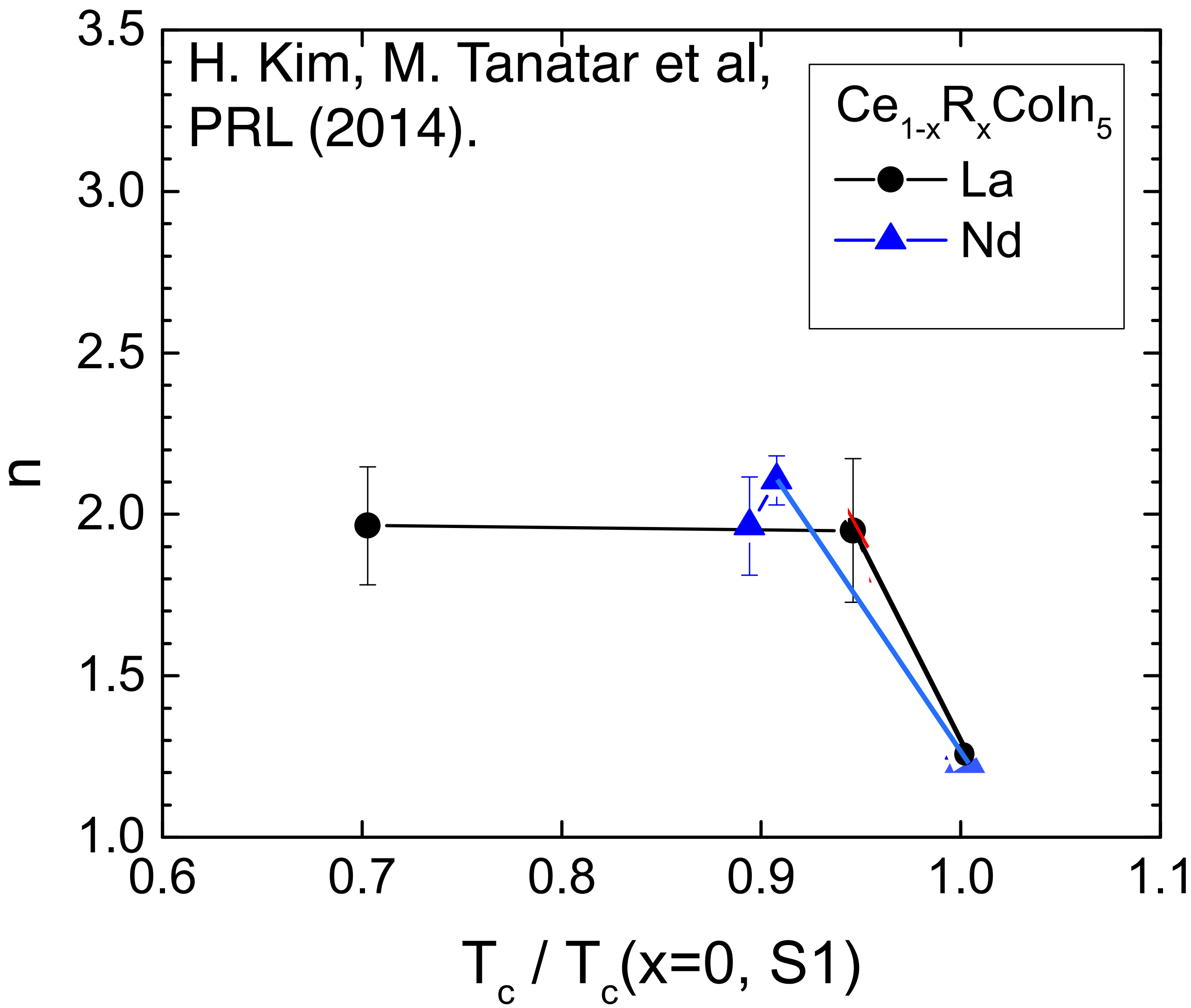
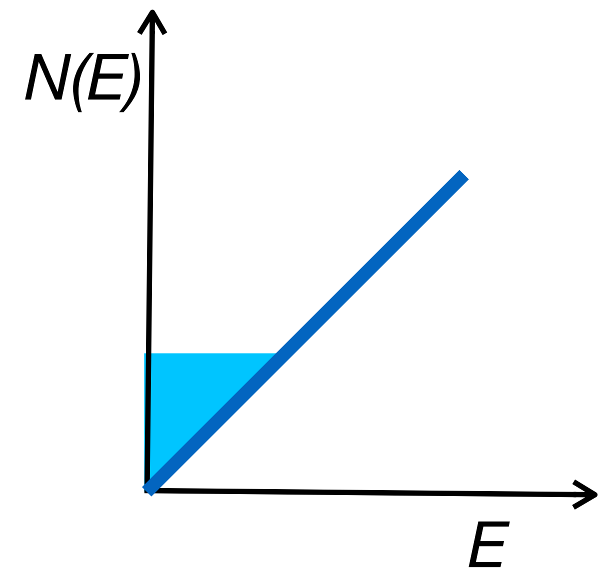


d-wave sc



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





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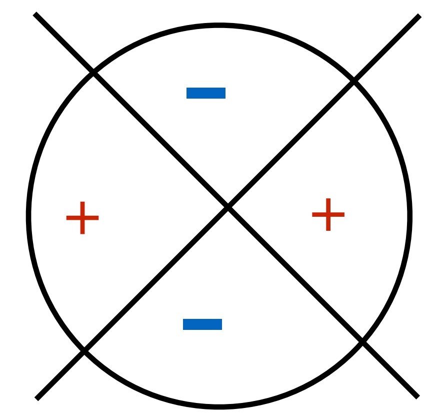

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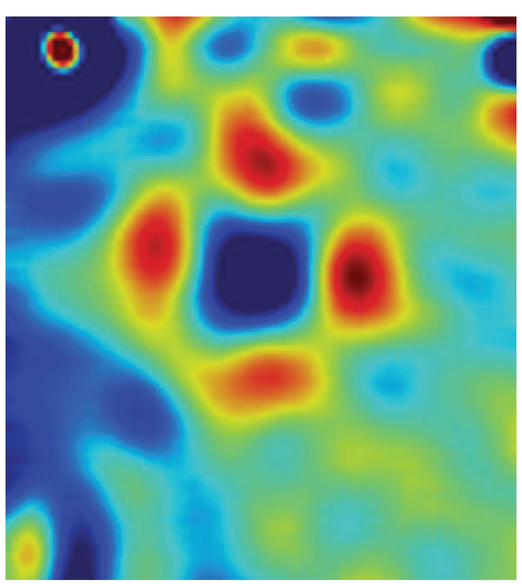

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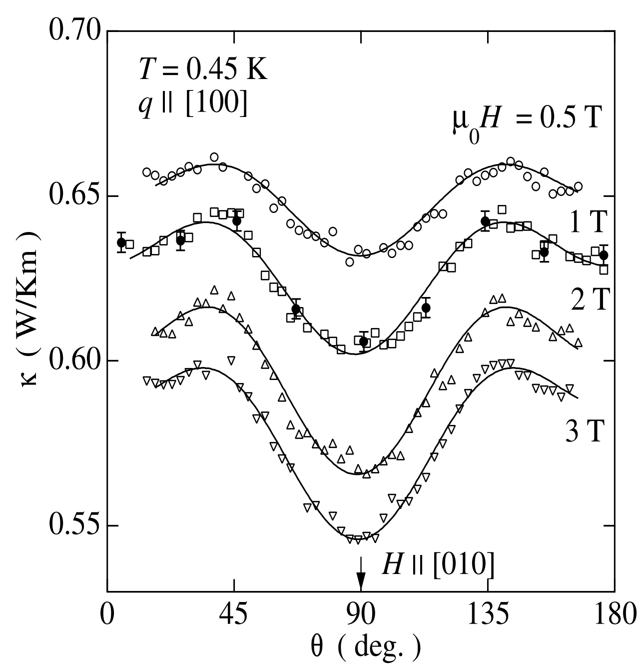
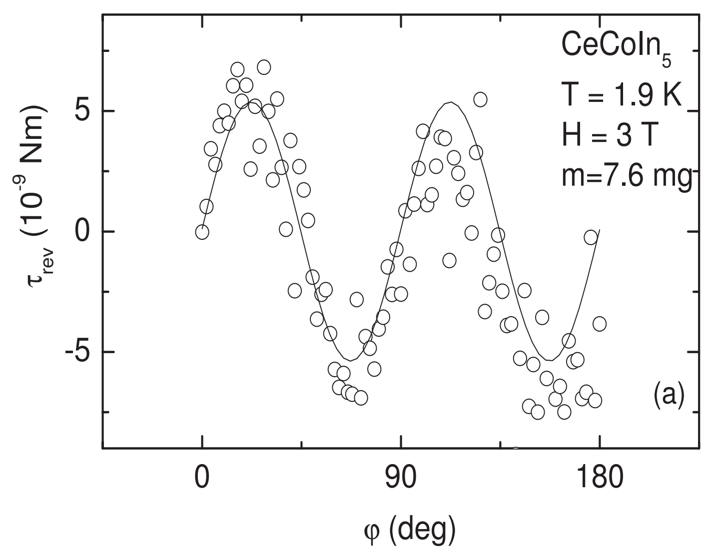
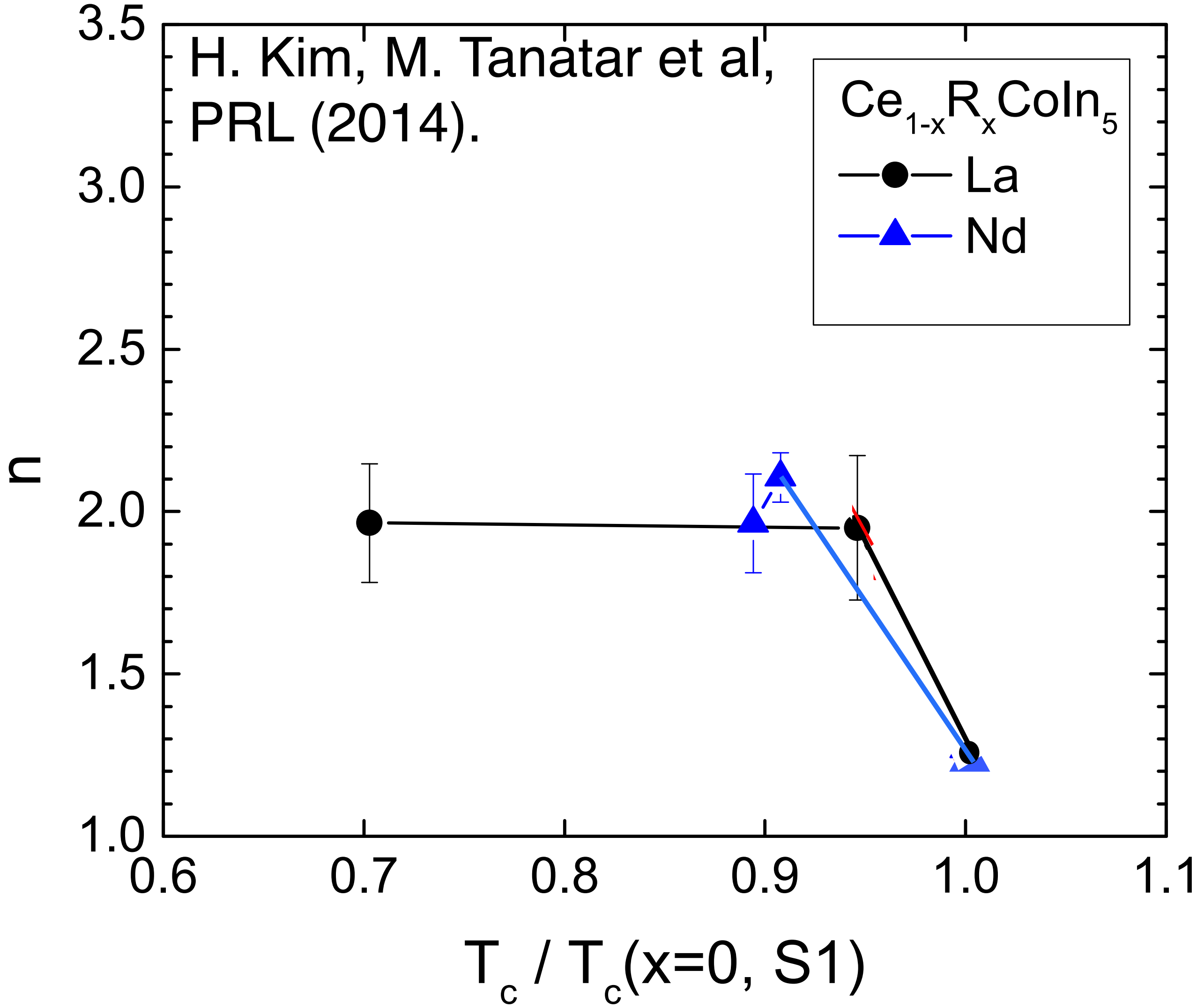
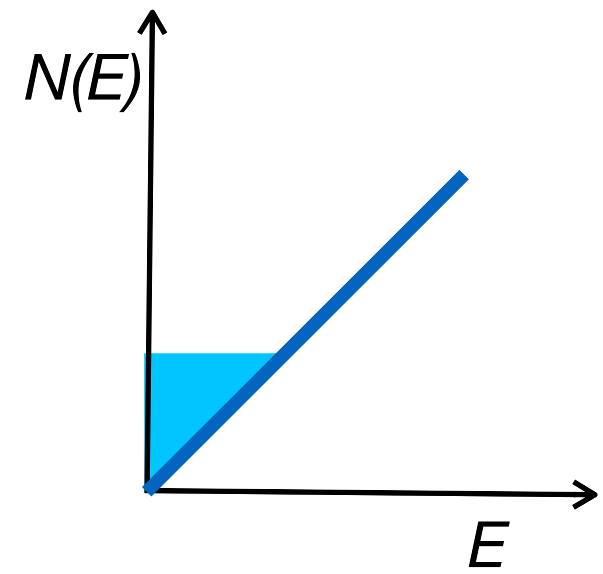


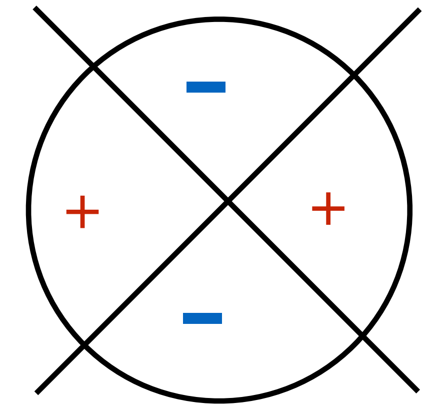
Thermal cond:
K. Izawa *et al.* PRL 87, 057002 (2001)



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







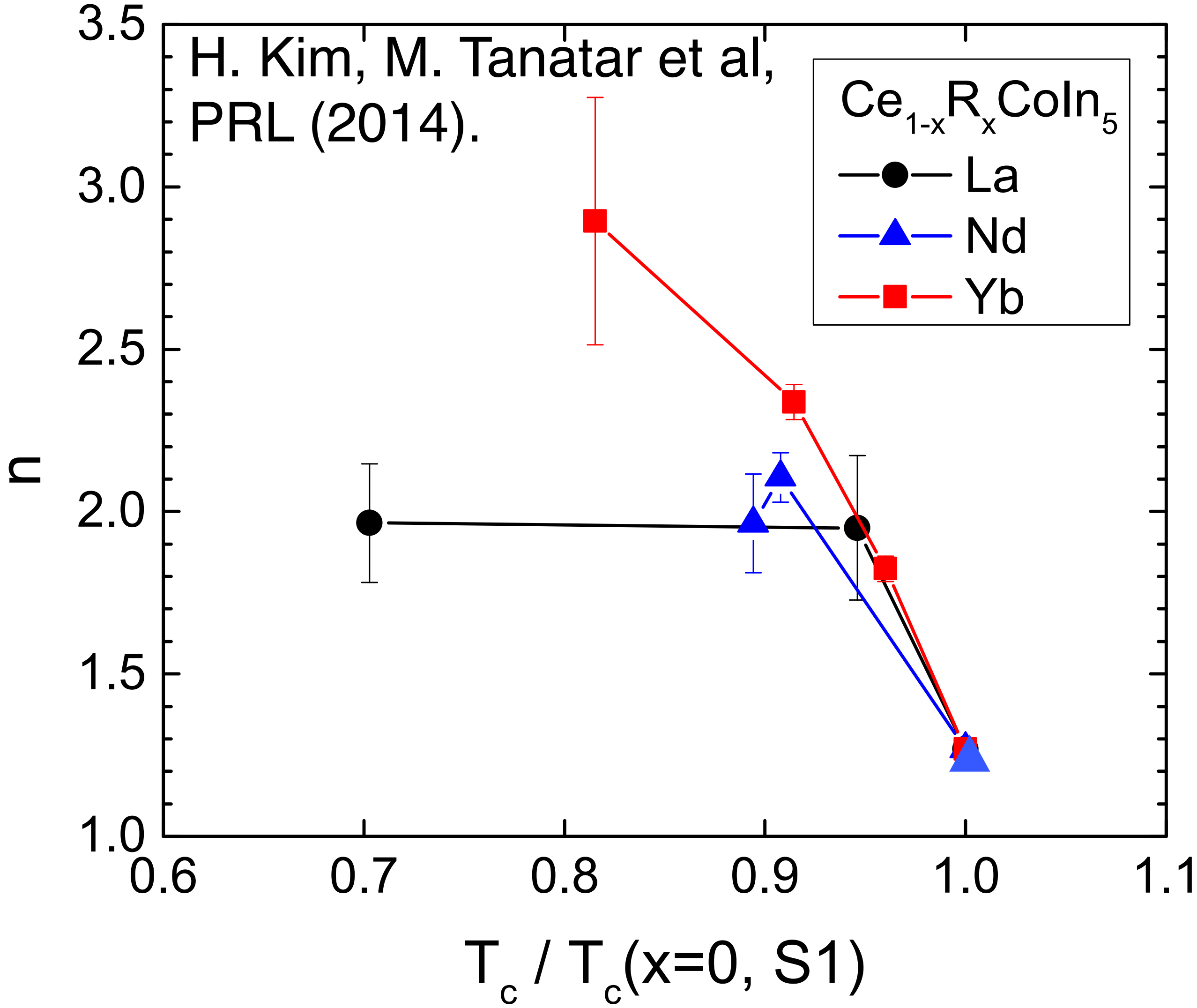
Clean $\overline{N(\epsilon)} \sim T$ ✓

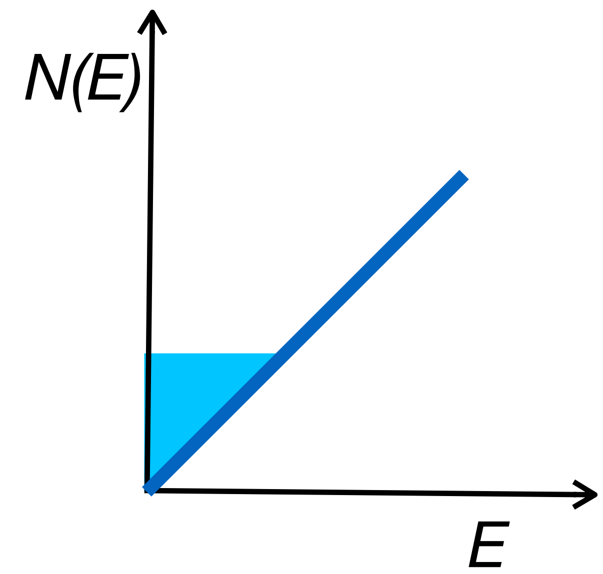
d-wave sc

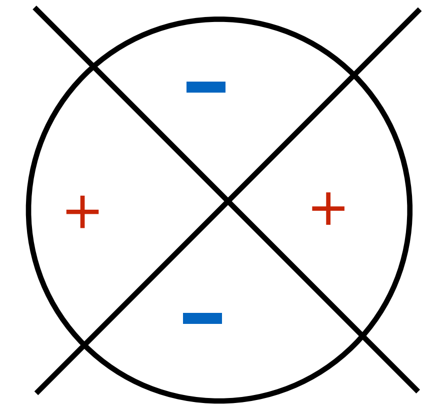
Dirty $\delta\overline{N(\epsilon)} \sim T^2$ ✓

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

Penetration Depth







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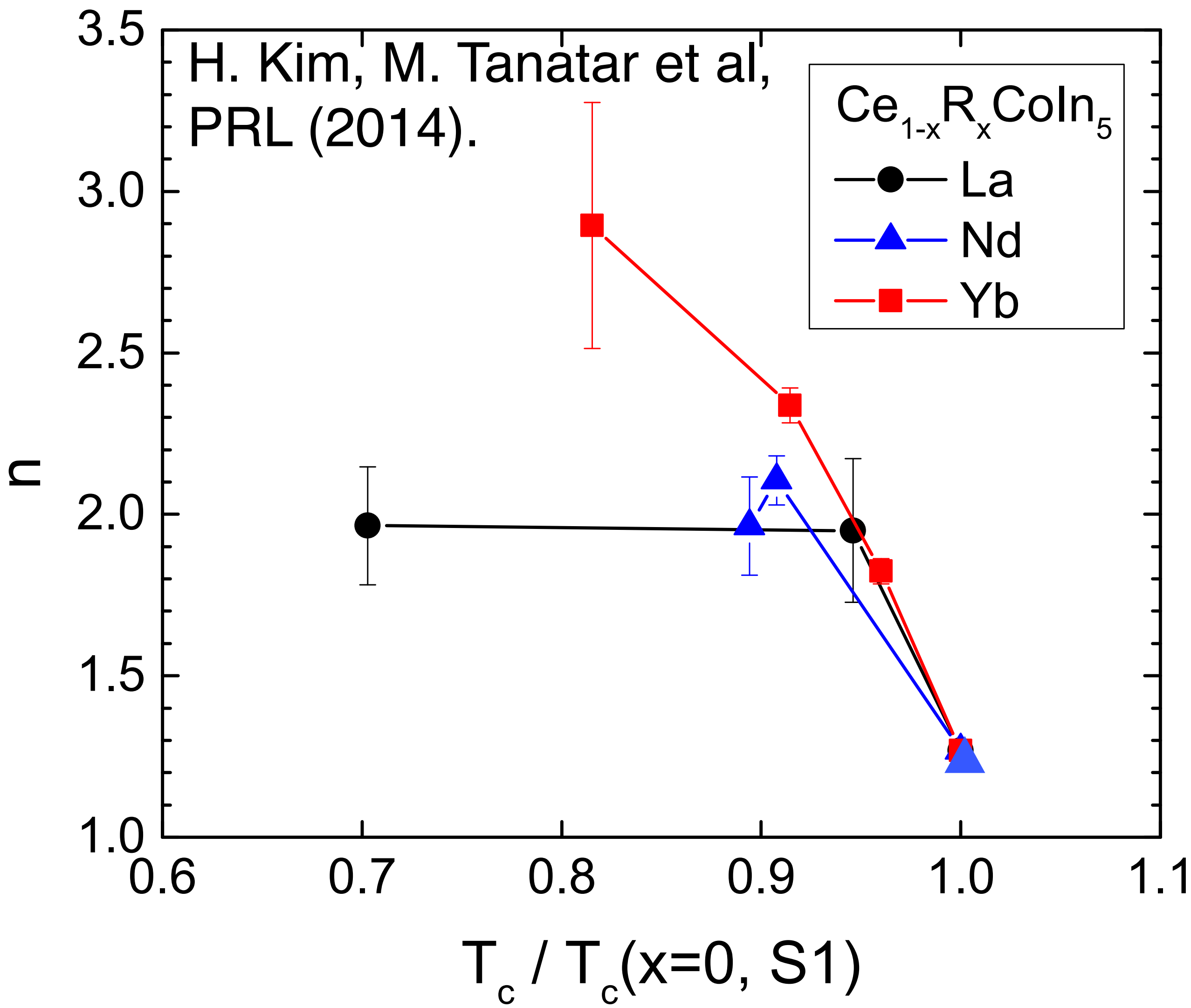
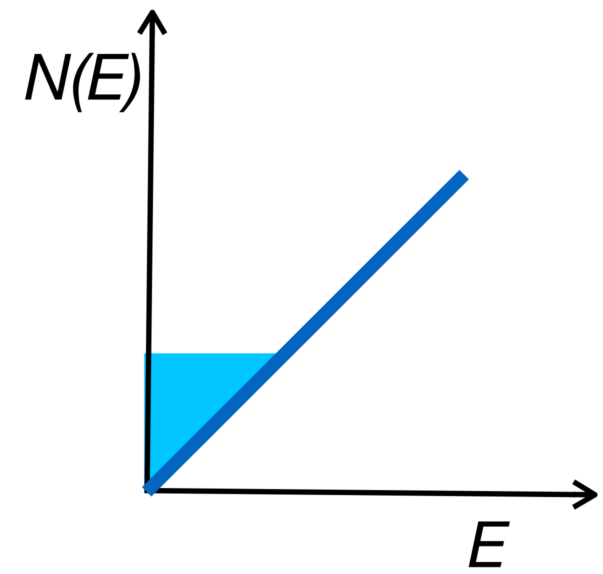
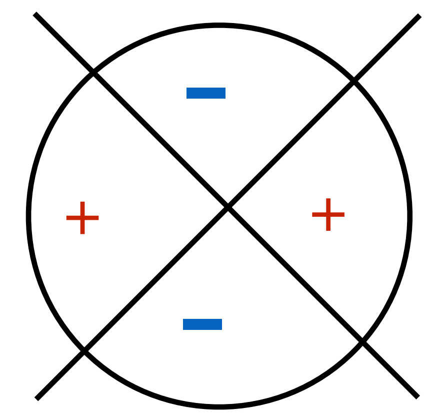
Penetration Depth



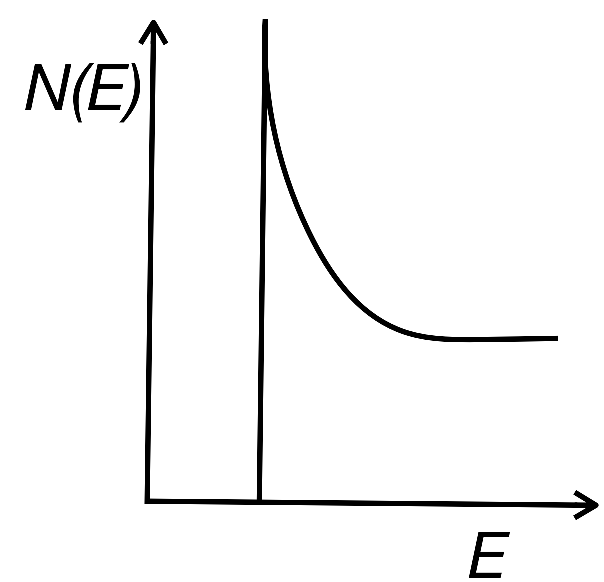


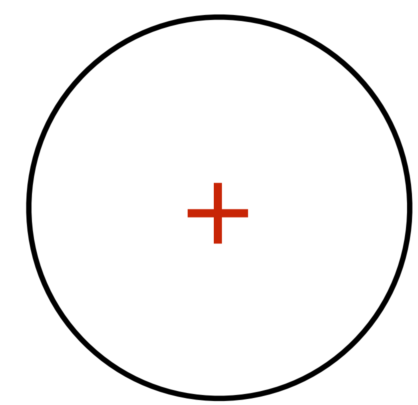


Clean $\overline{N(\epsilon)} \sim T$ ✓

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

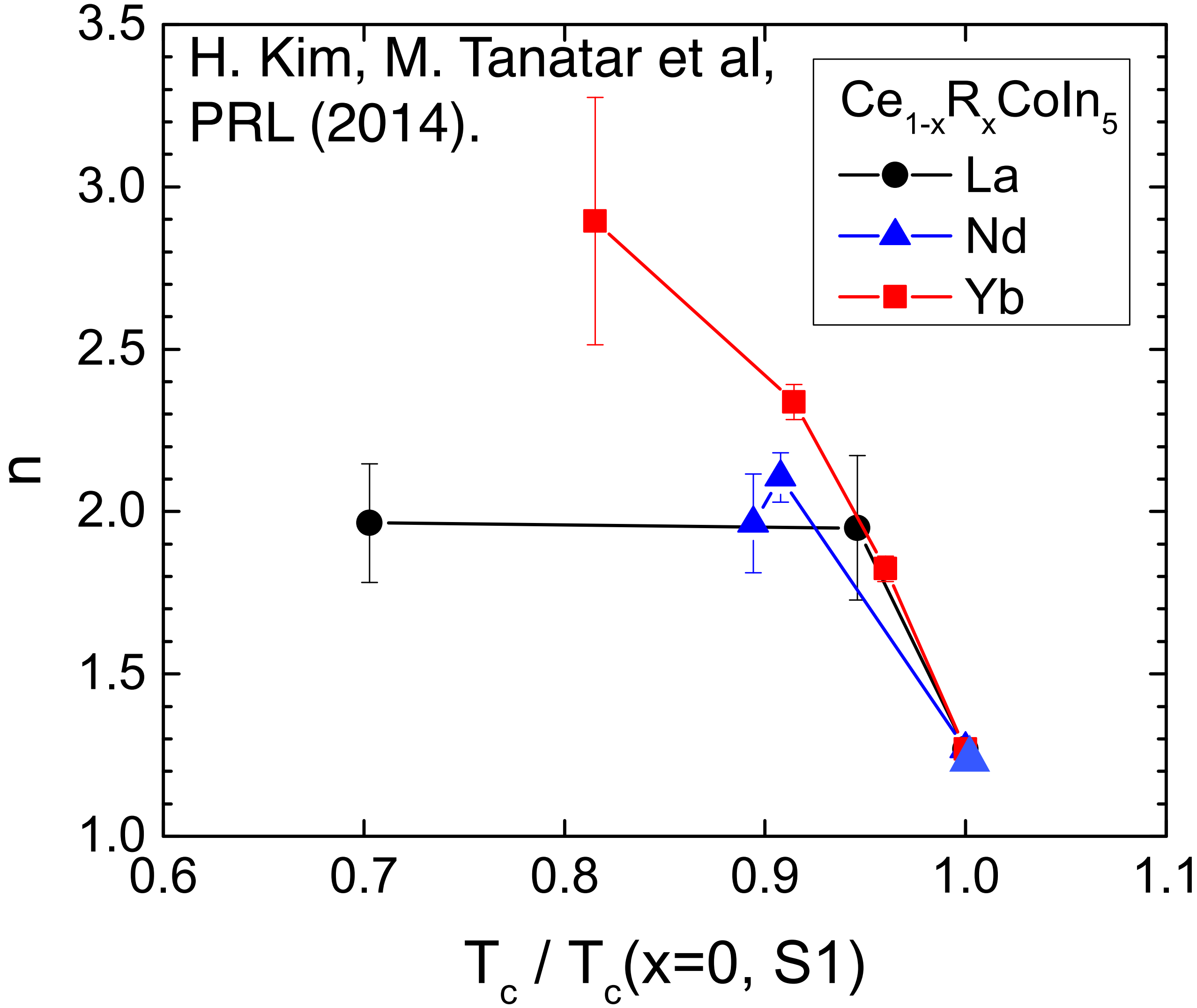
d-wave sc

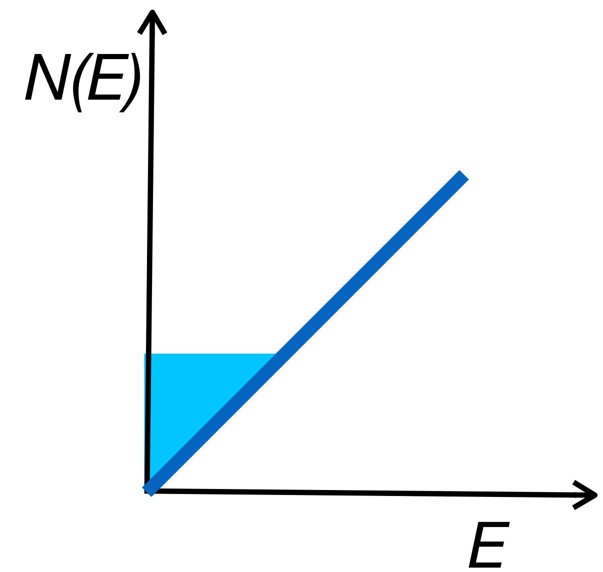


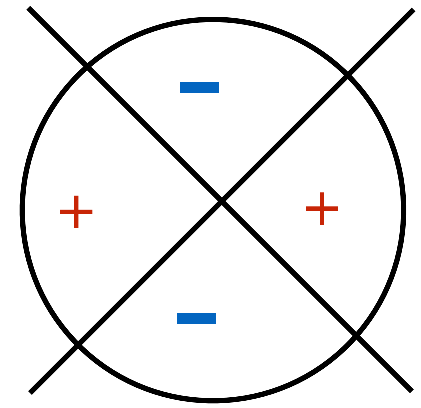


$$\frac{1}{\lambda_L^2(T)} = \frac{1}{\lambda_L^2(0)} - \overline{N(\epsilon)}$$

Penetration Depth







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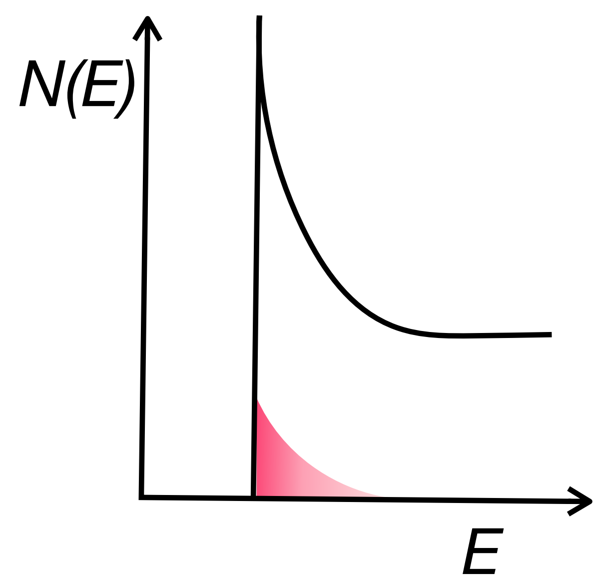

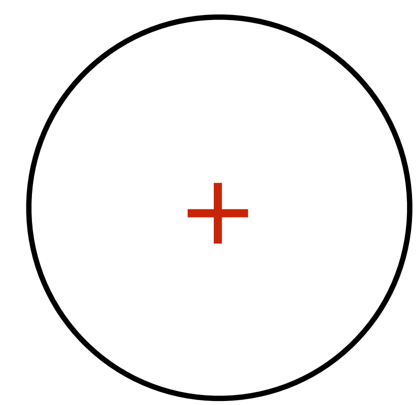

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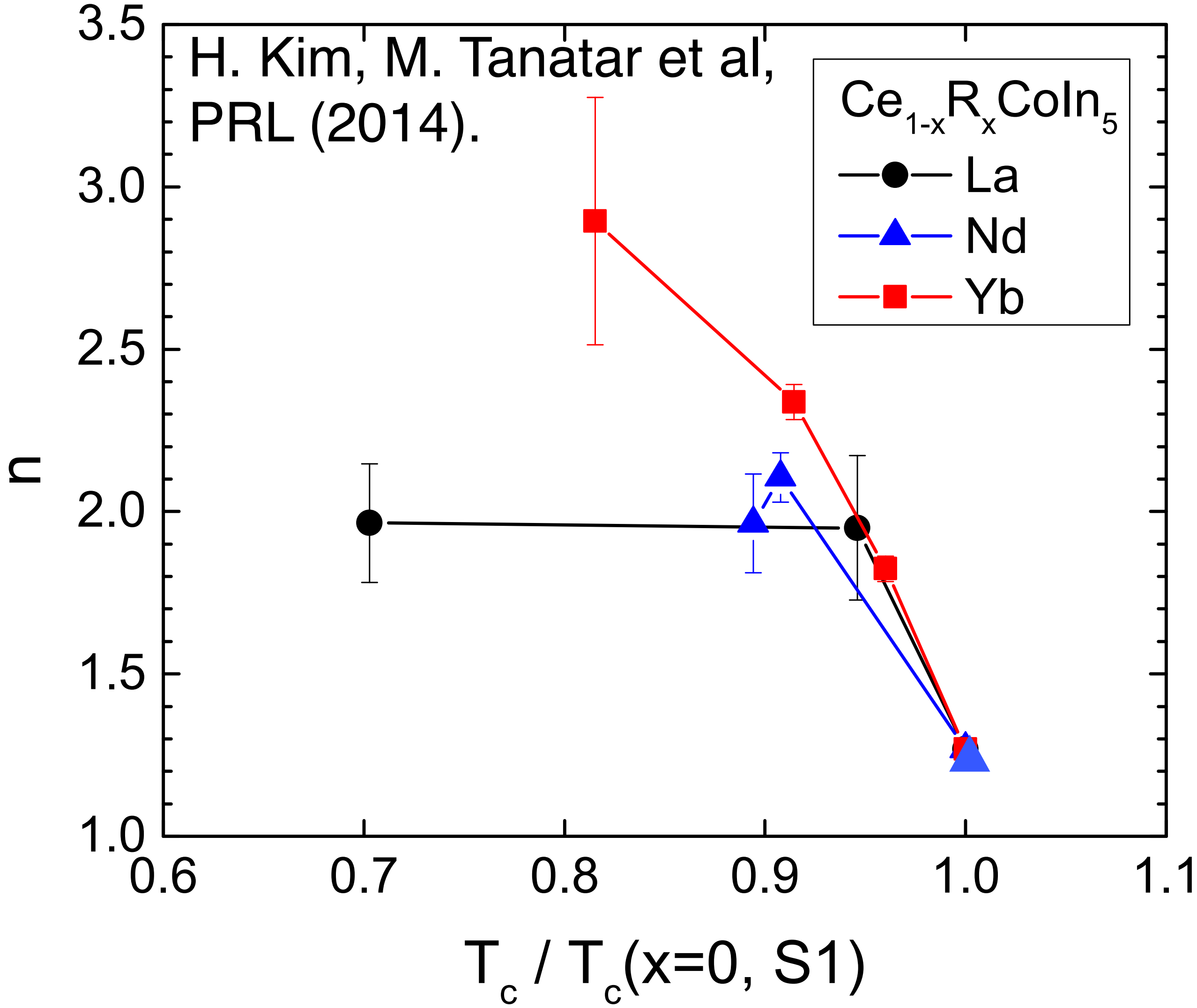

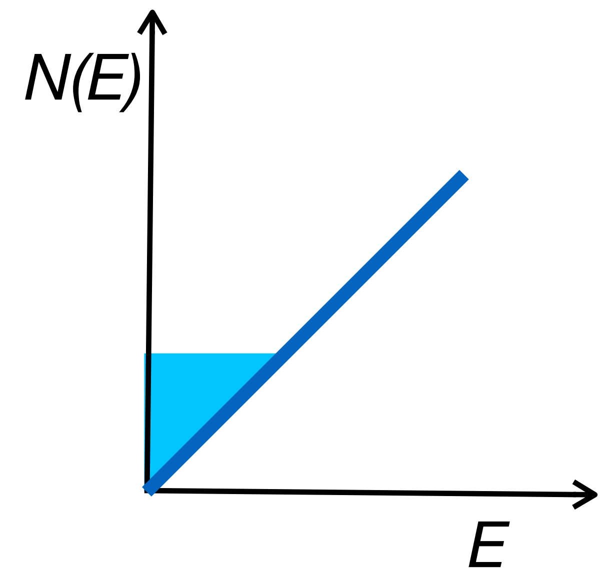

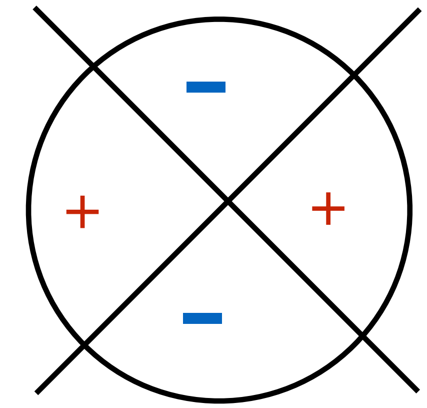

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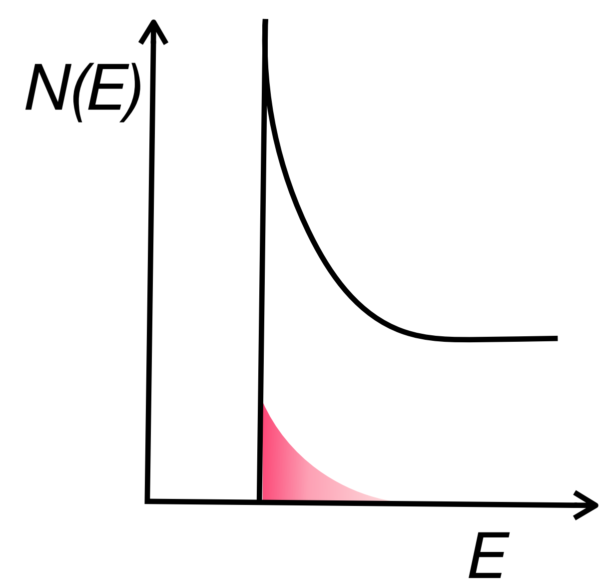
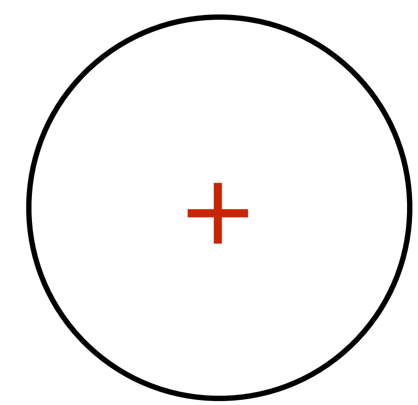
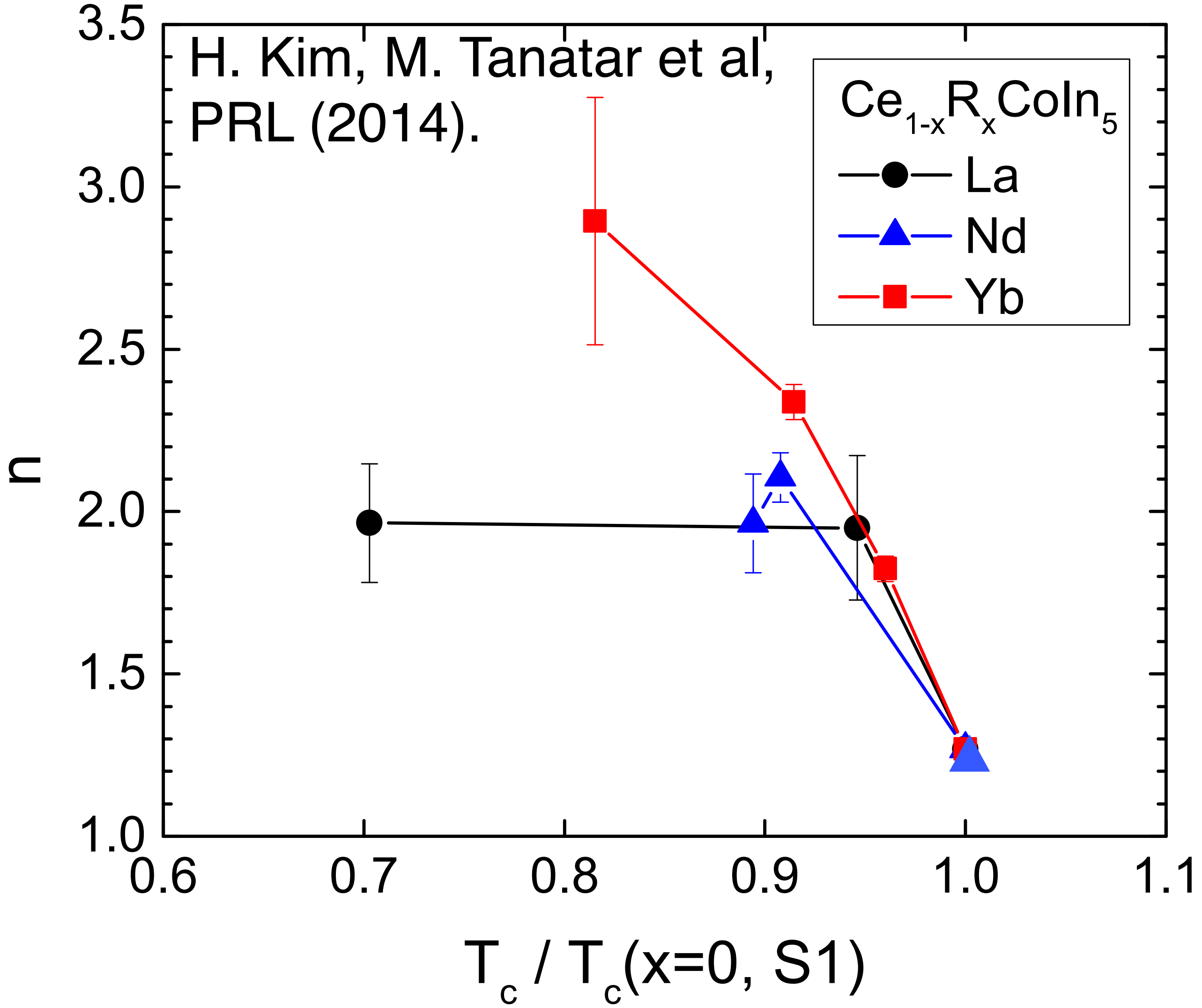
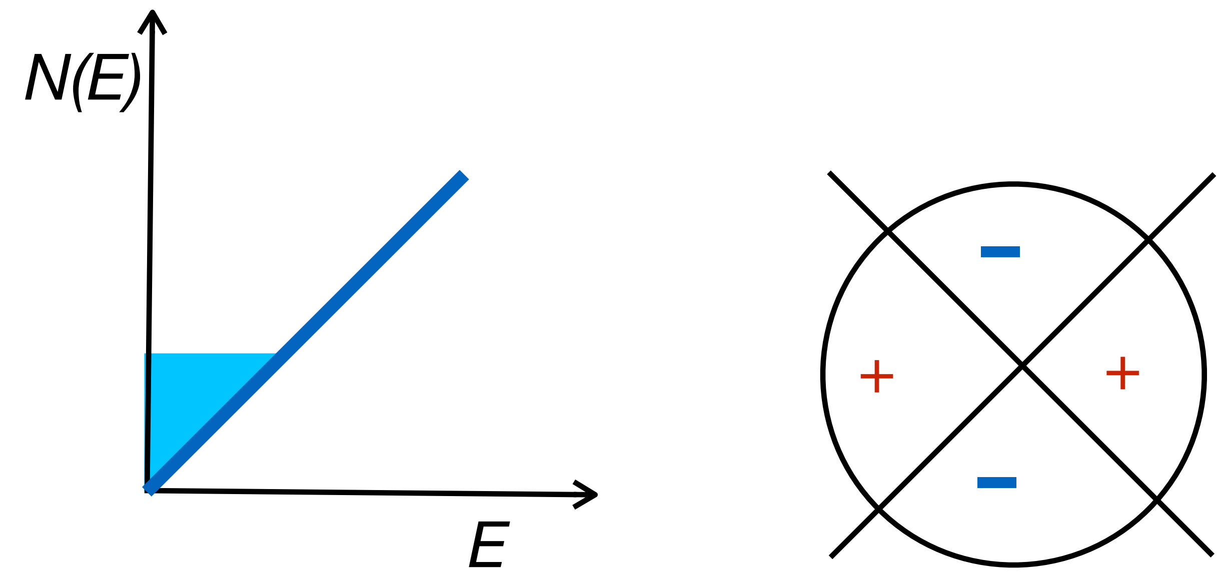




Gapped $\overline{N(\epsilon)} \sim e^{-\Delta/T} \sim T^{n>3}$





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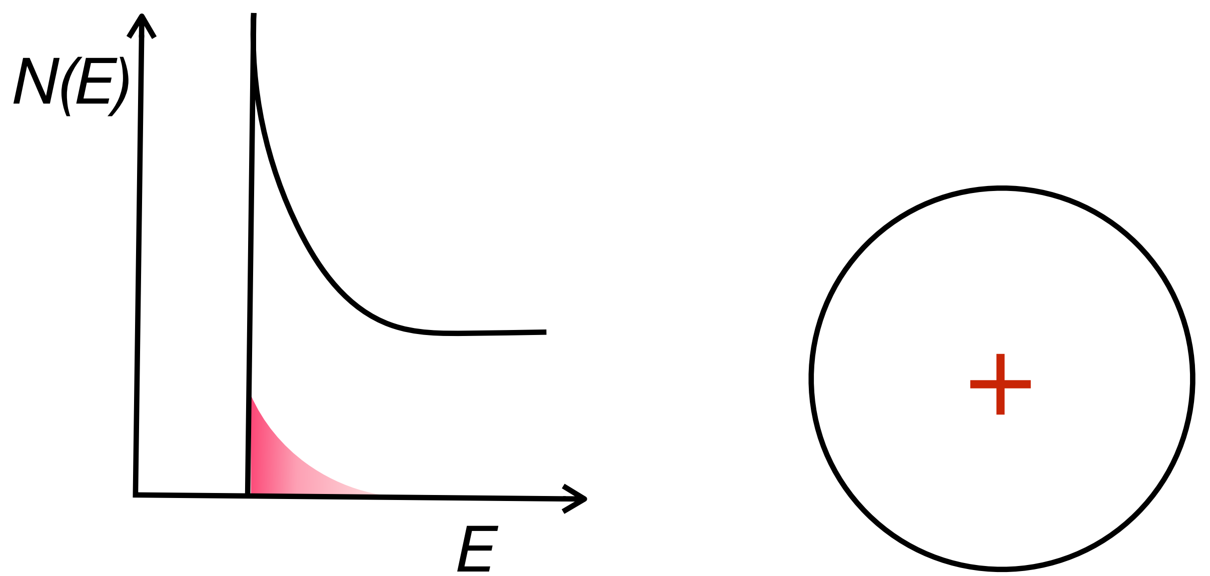

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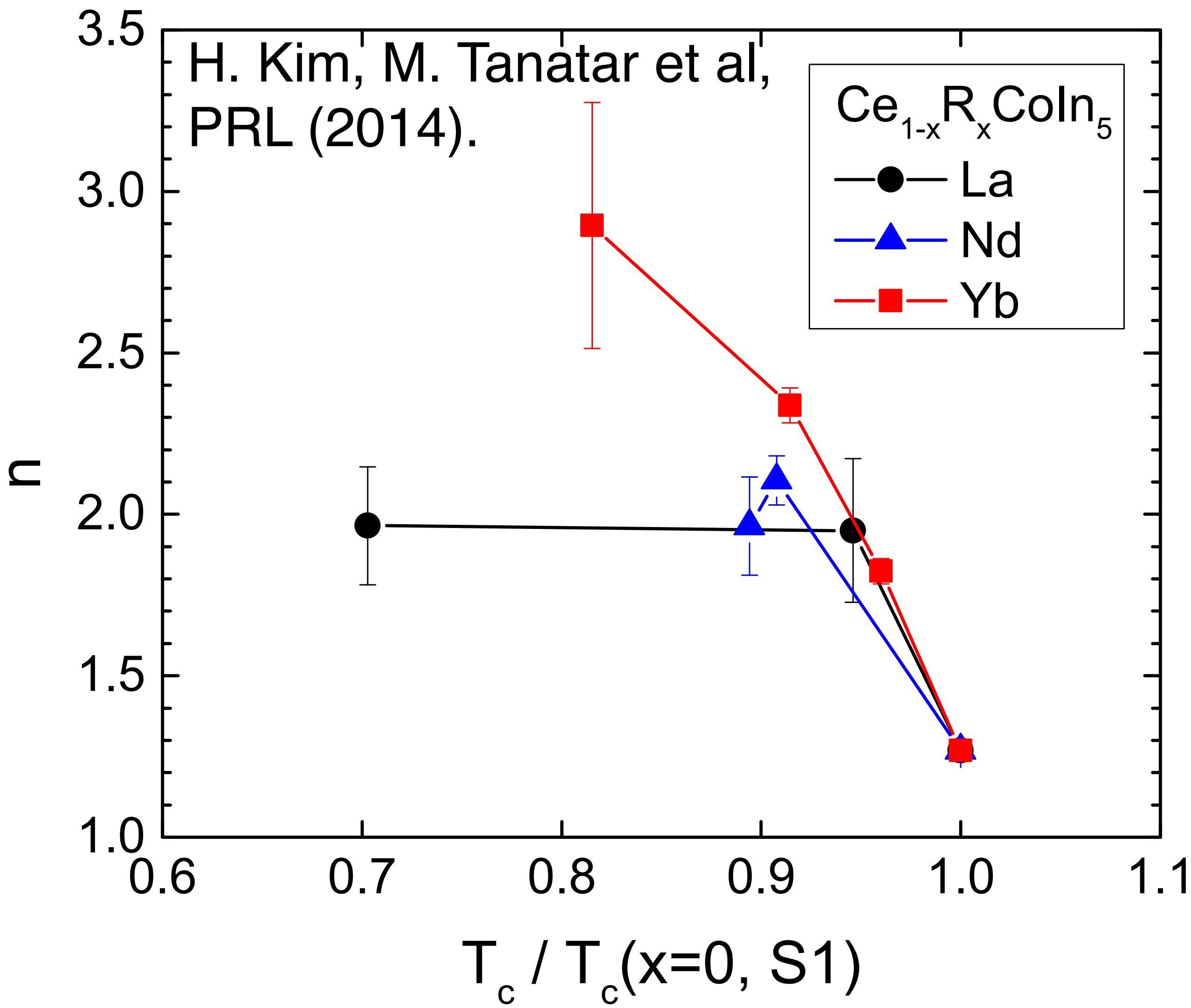
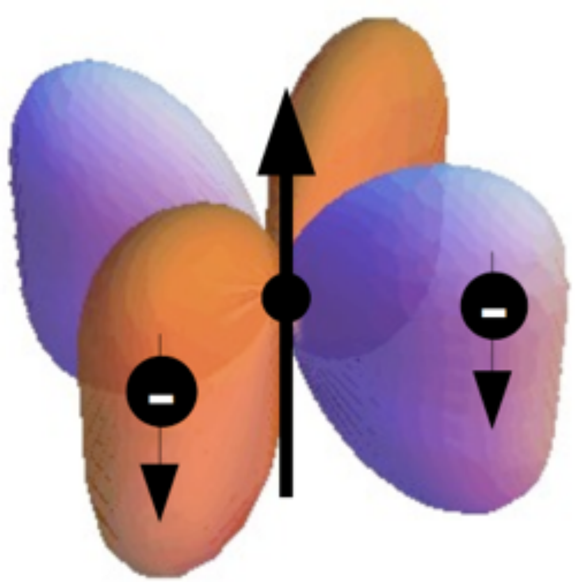
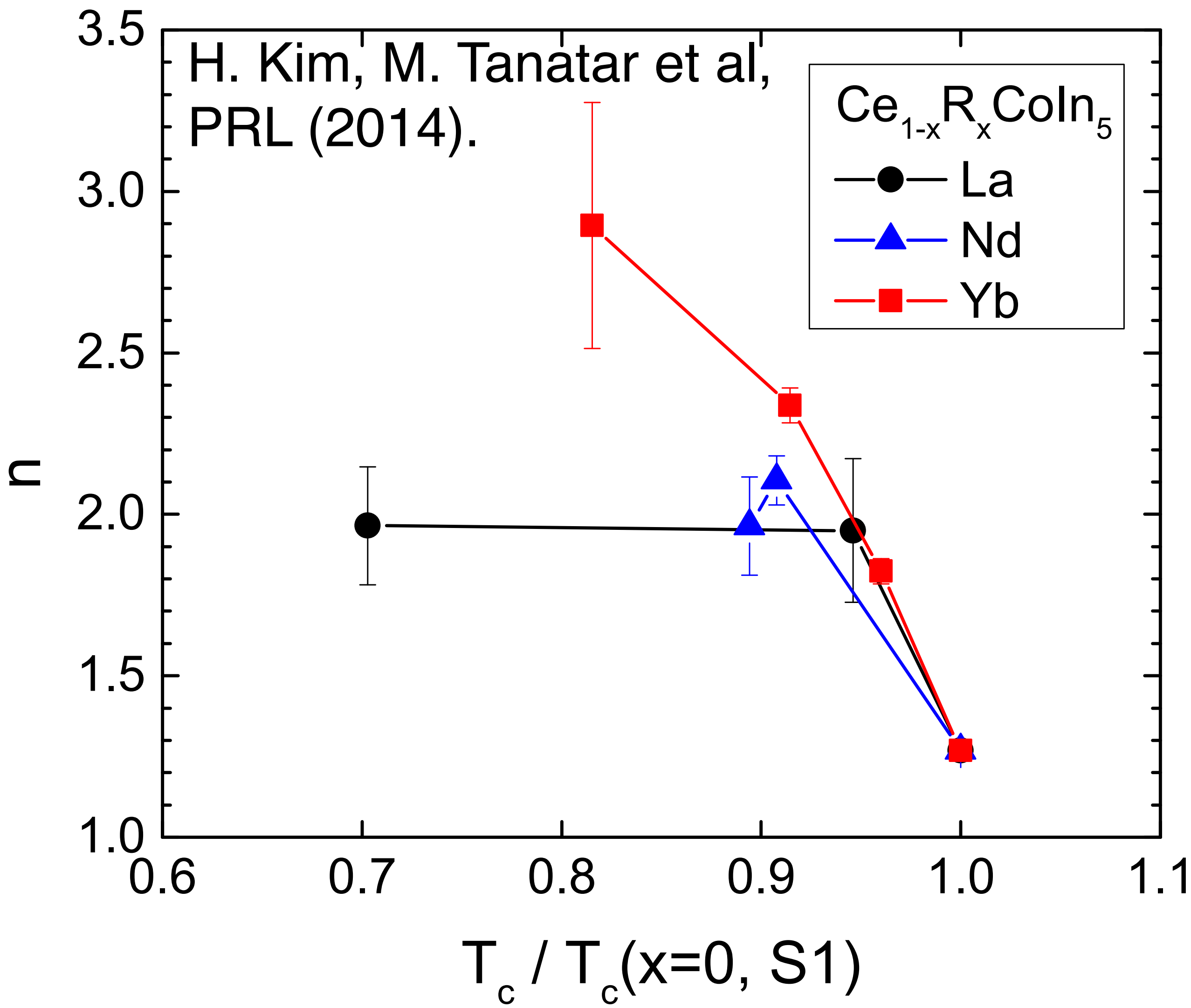
But Inconsistent with observed d-wave character??



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



Erten, Flint, PC, 2014



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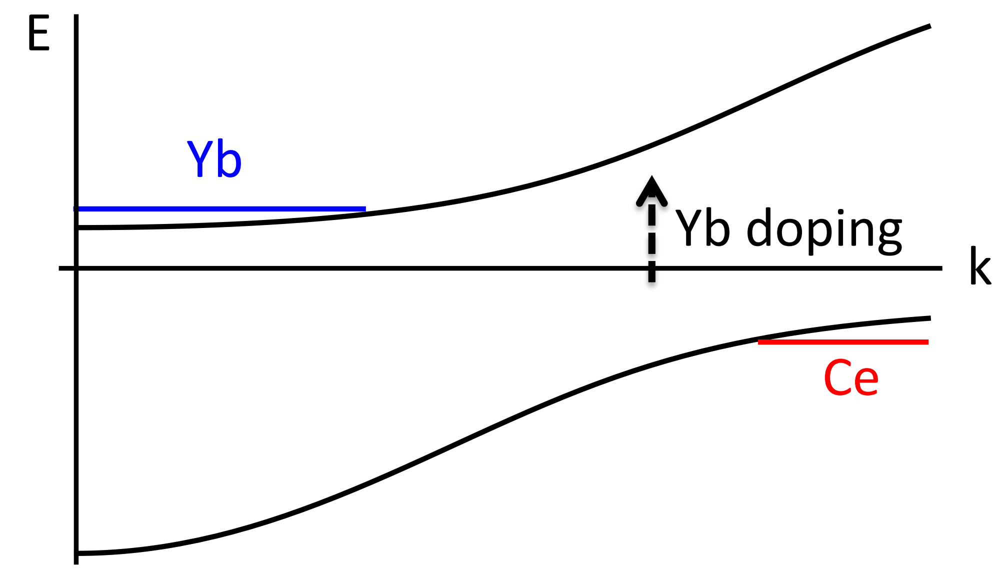

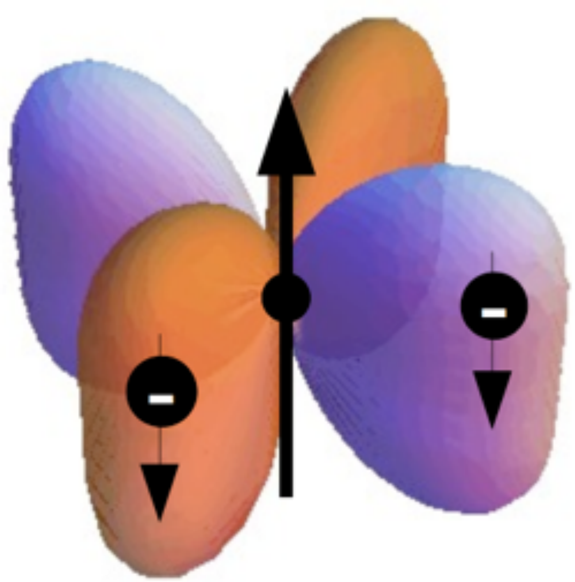

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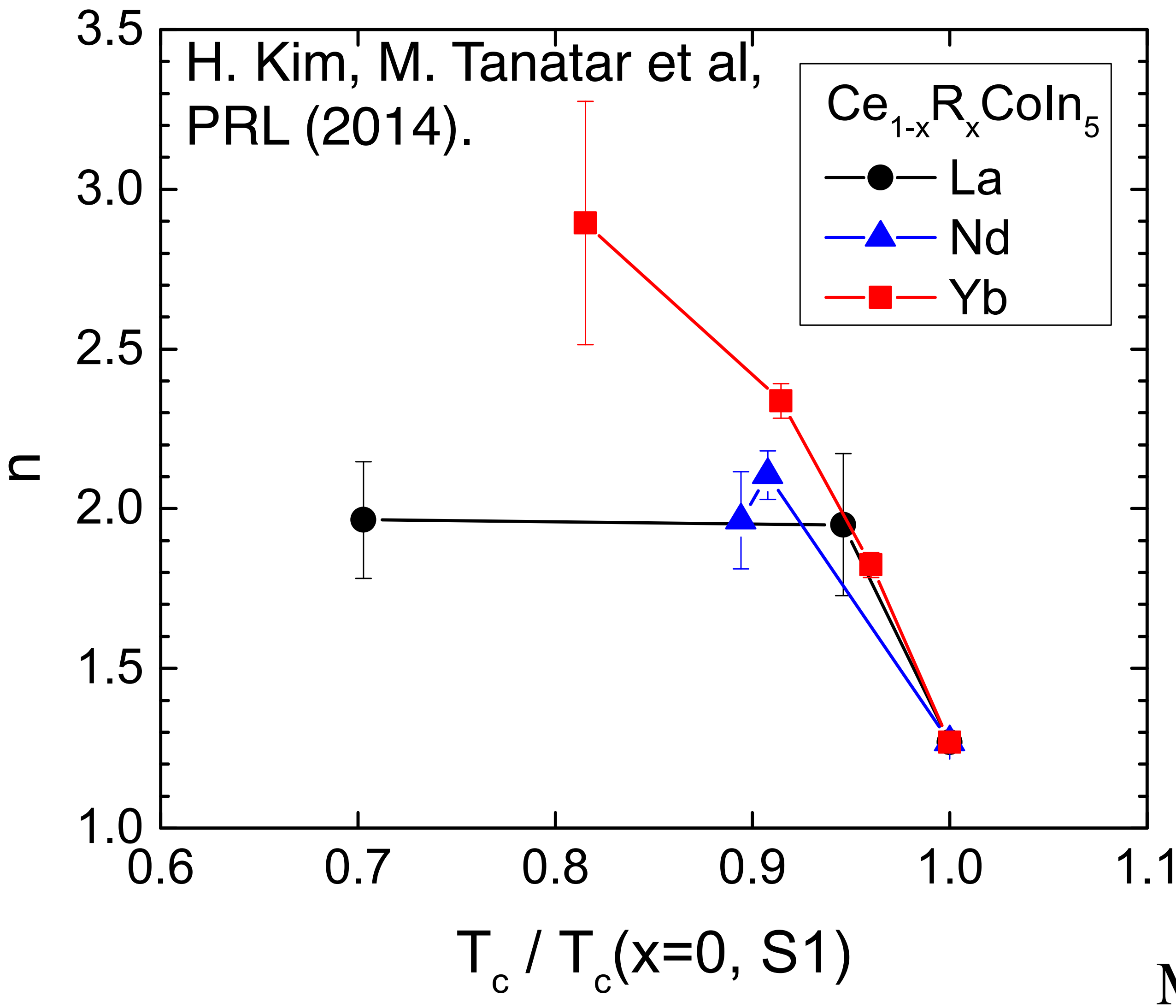

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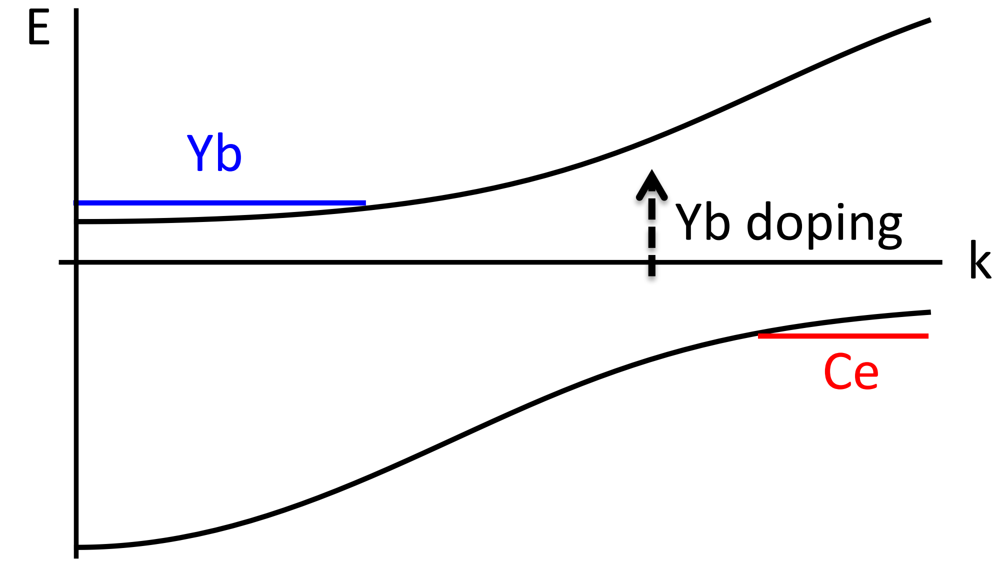

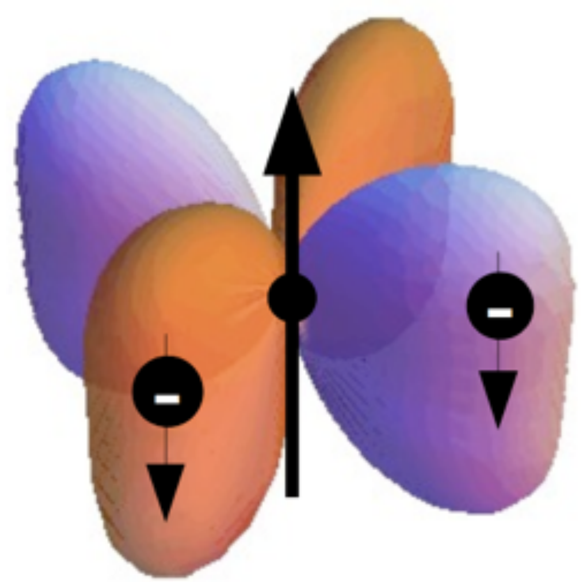

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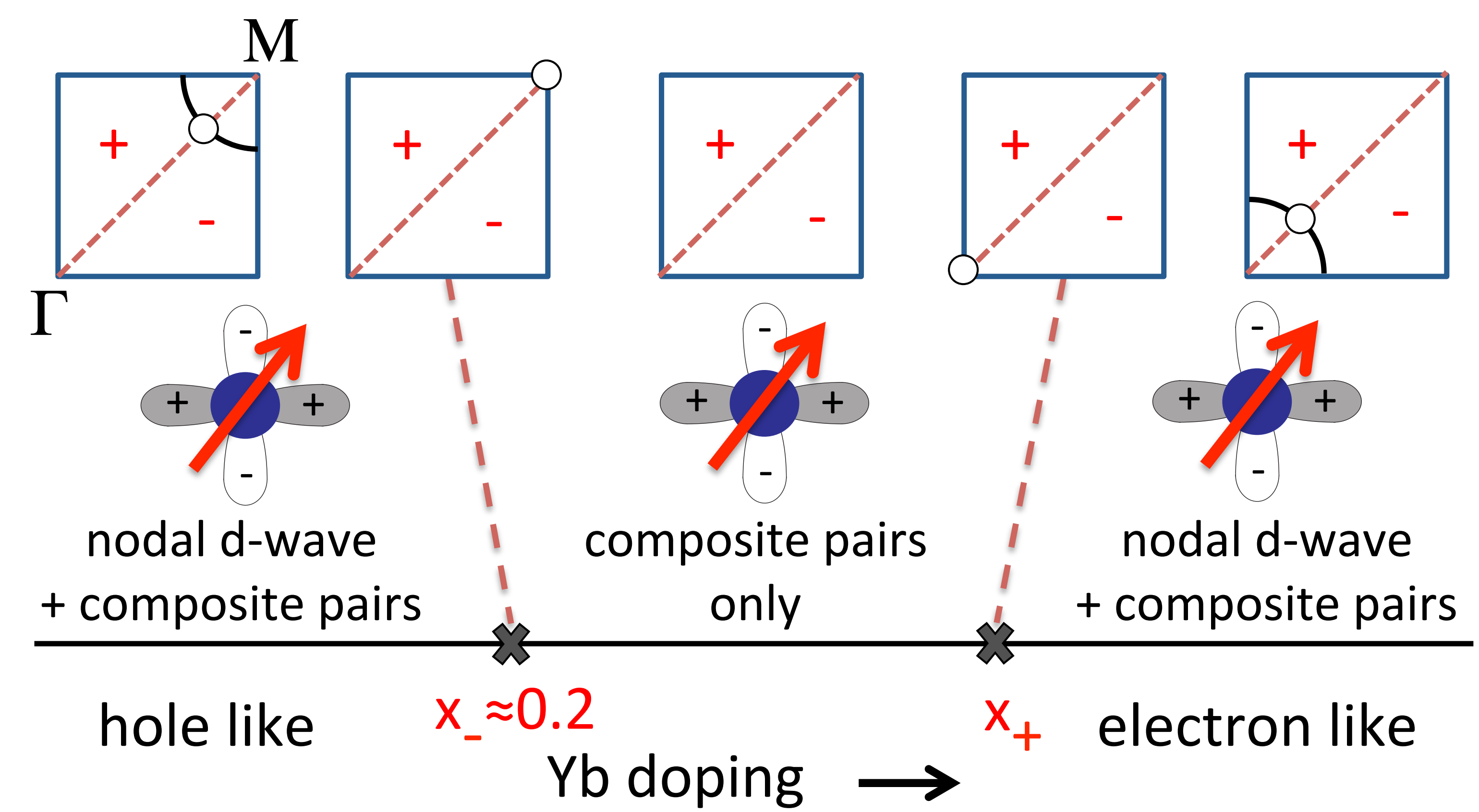


$$\rho_s = \rho_0 - \alpha T^{(1-2)} \quad \rho_s = \rho_0 - \beta T^{(3-4)} \quad \rho_s = \rho_0 - \alpha T^{(1-2)}$$

Open Challenges.

- Convergence of magnetism and superconductivity: require new concepts over and beyond spin fluctuation theory. POTENTIAL FOR DISCOVERY.
- HFSC: how is the spin incorporated into the condensate?
- 115 heavy fermion superconductors suggest a new kind of pairing: composite pairing, robust against disorder on magnetic site.
- Could the same phenomenon occur in d-electron materials, at much higher temperatures?

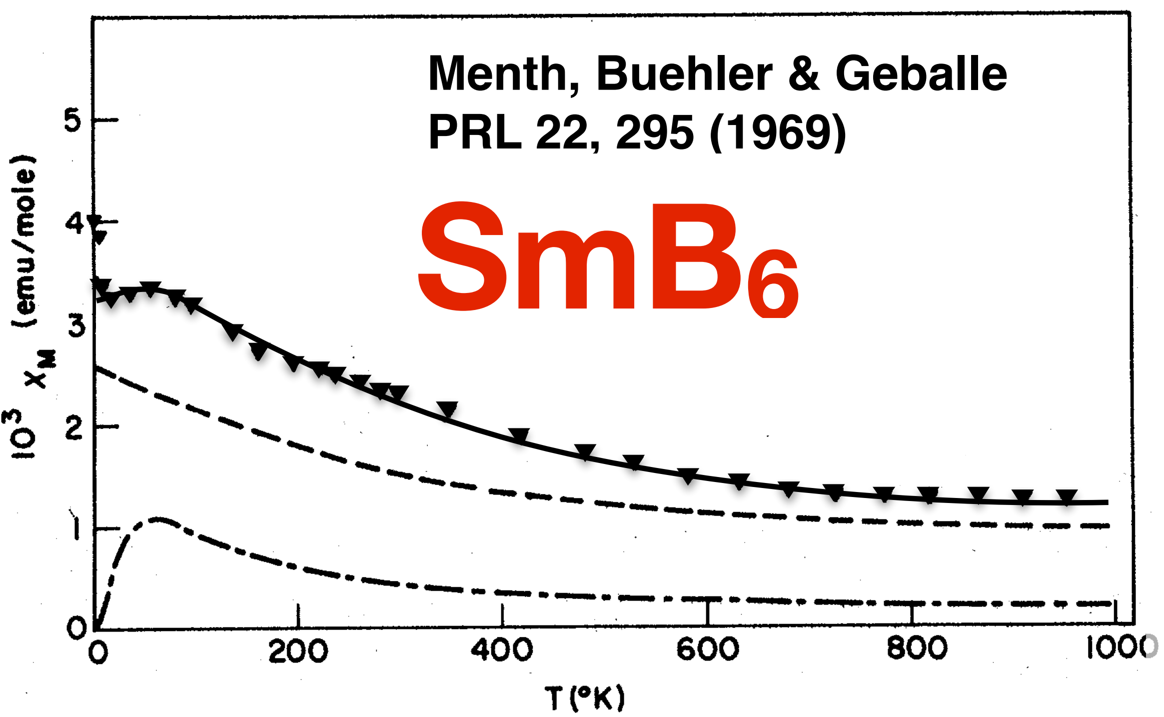
Topological Kondo insulators and other (hidden) forms of order.

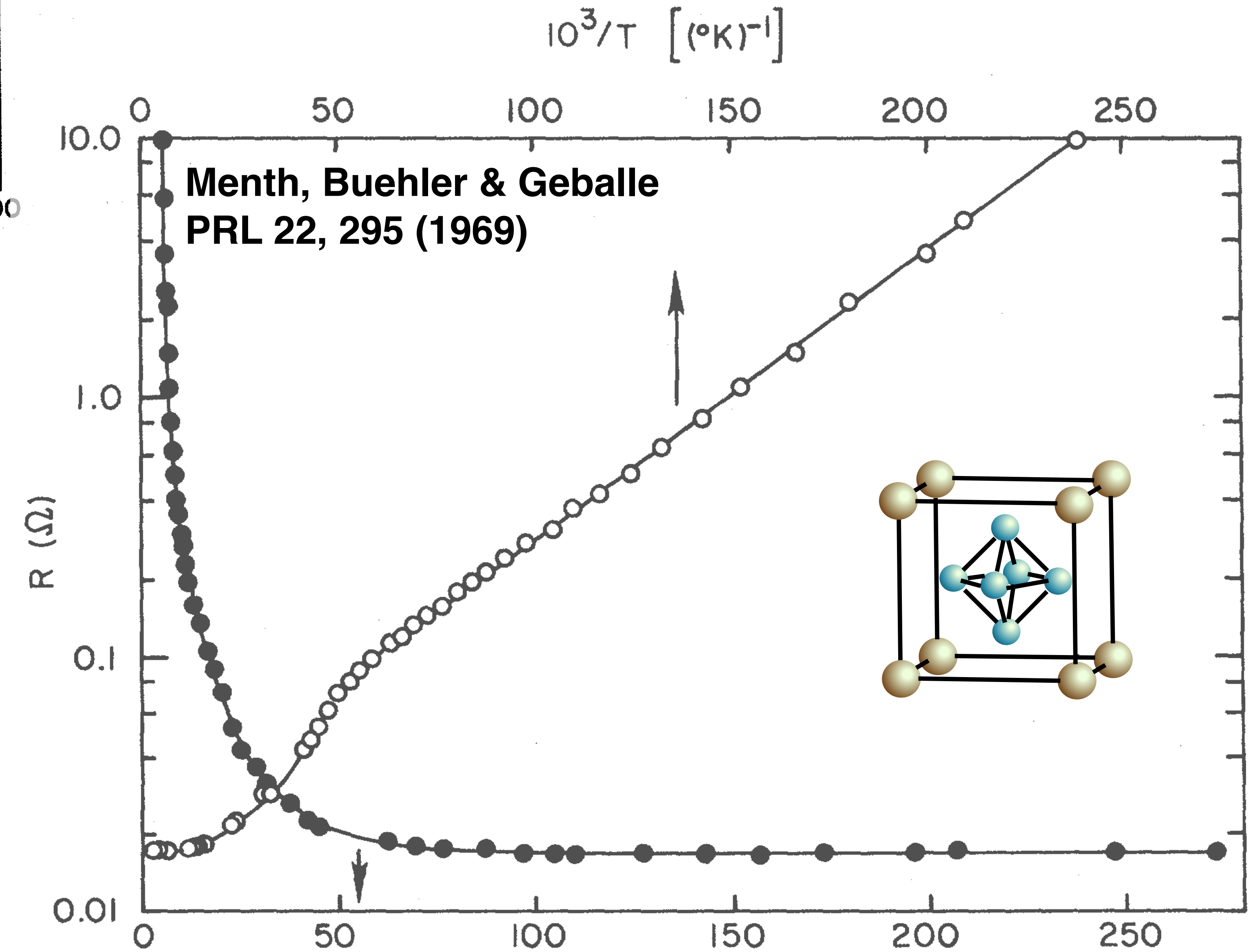
1. Heavy Fermions: The Rise of topology.
2. Is SmB6 topological?
3. Hidden electron Order.
4. Another long-lived puzzle: URu2Si2
5. Dipoles, multipoles, spinors?

Heavy Fermions

Piers Coleman,
Center for Materials Theory, Rutgers, NJ.
Royal Holloway, University of London, UK.

UBC Brainstorming
Session 14-16 May 2014





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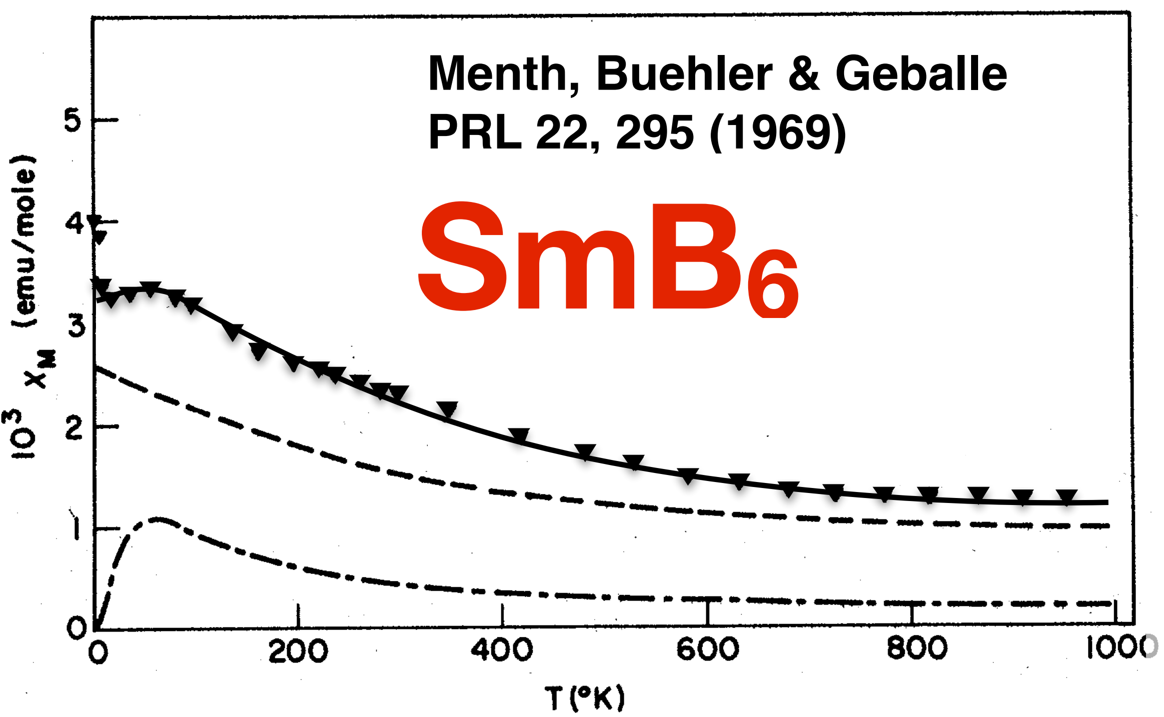

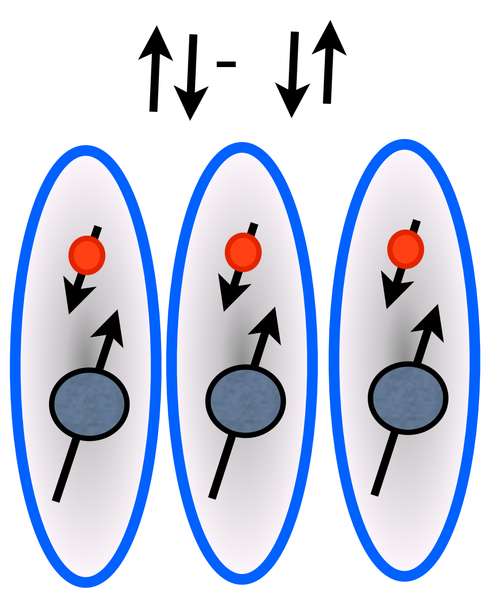

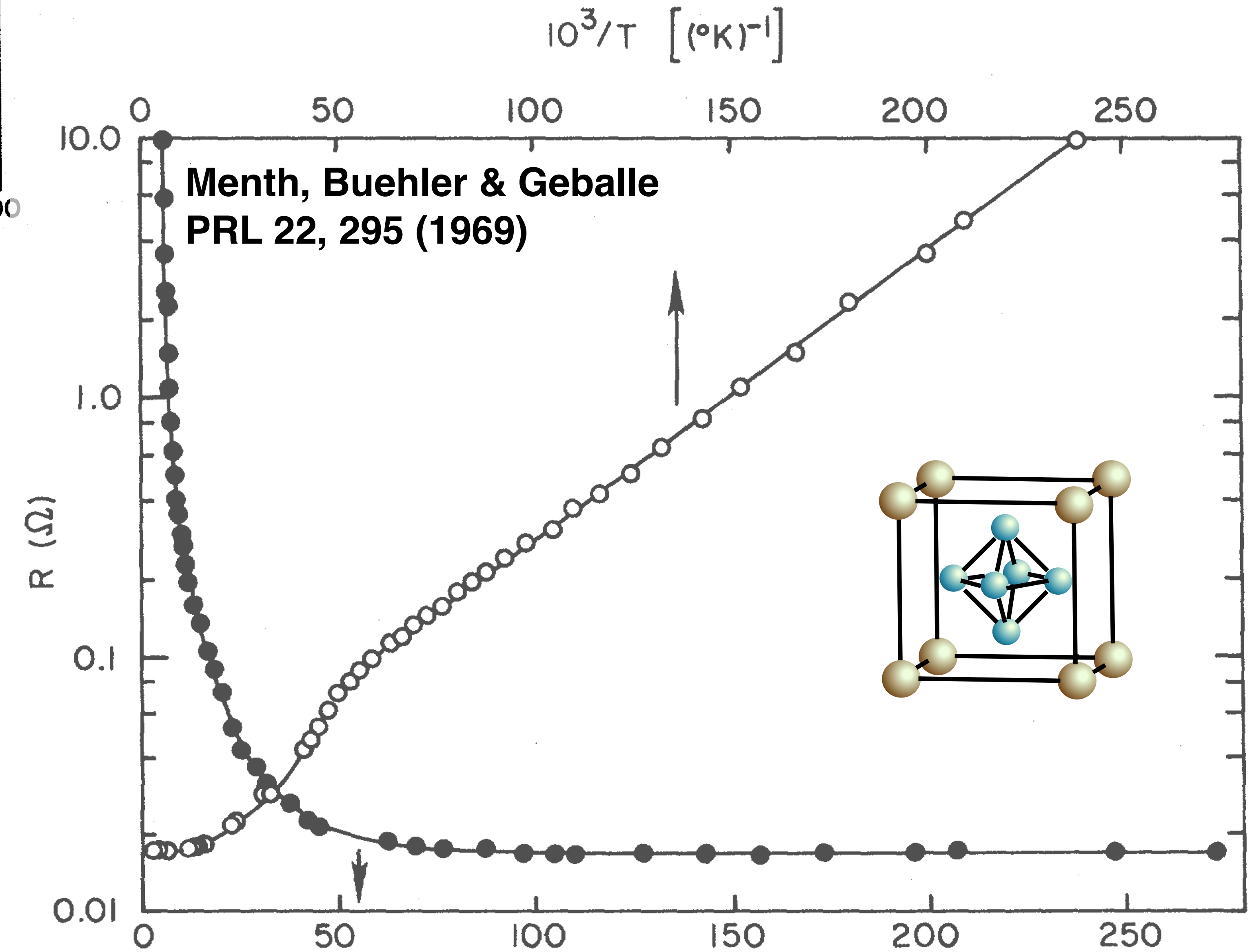

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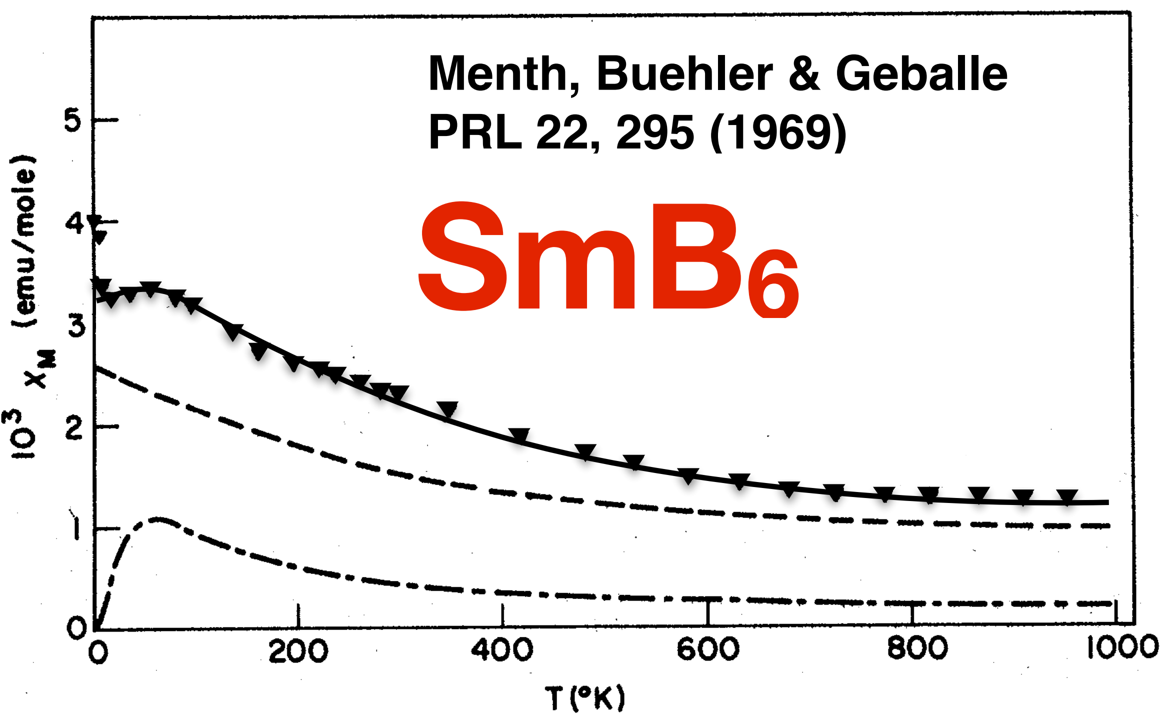
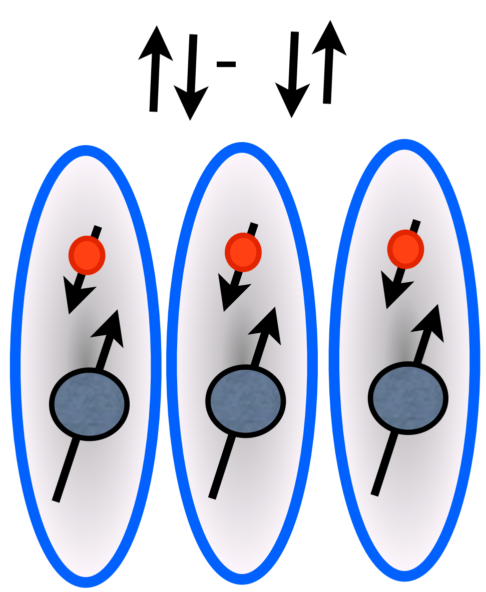
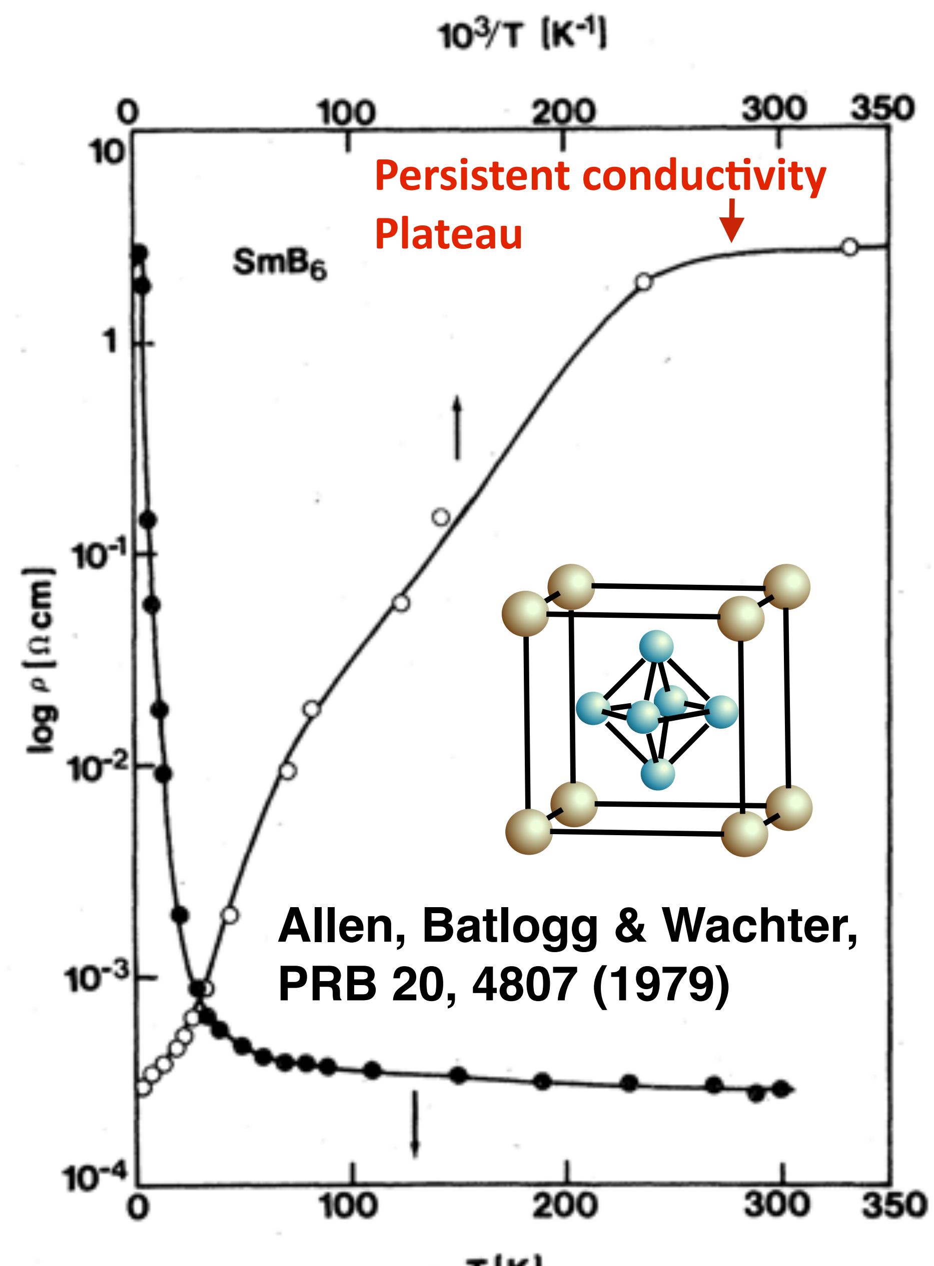




"Kondo Insulator"



Heavy Fermions *:The Rise of Topology.*

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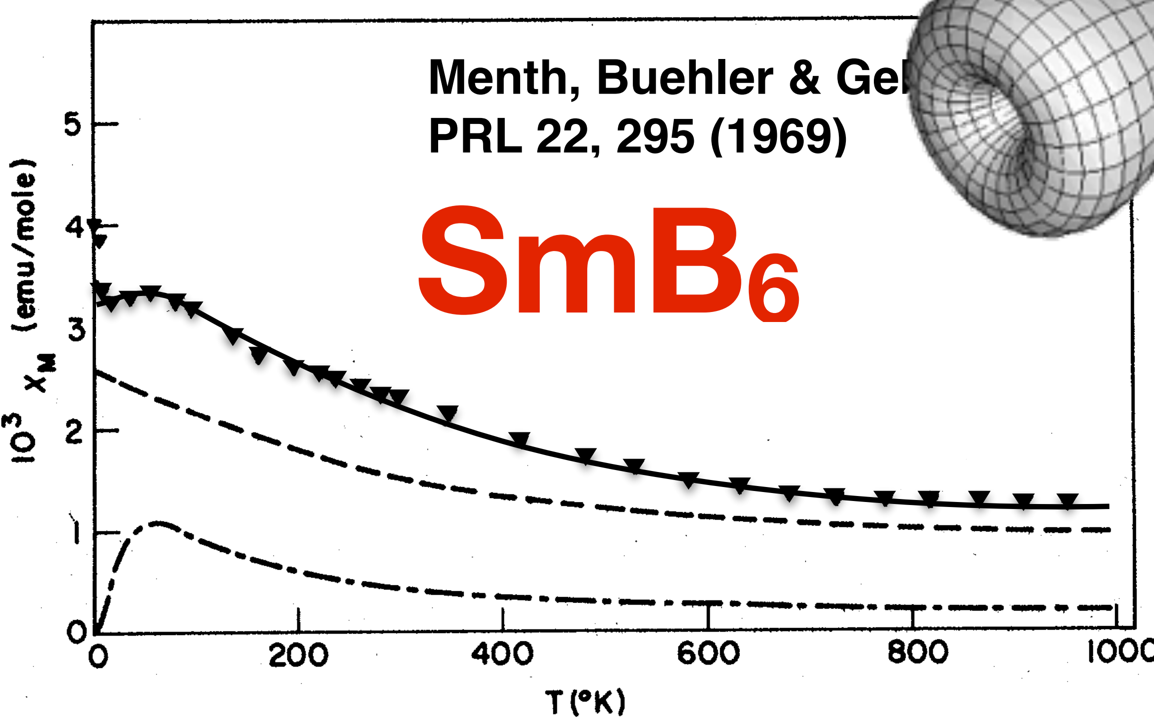

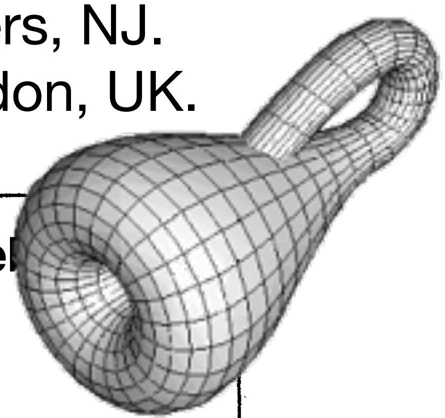

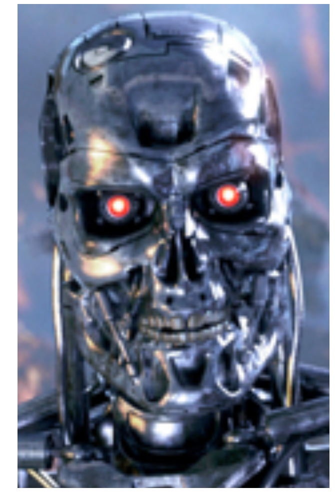

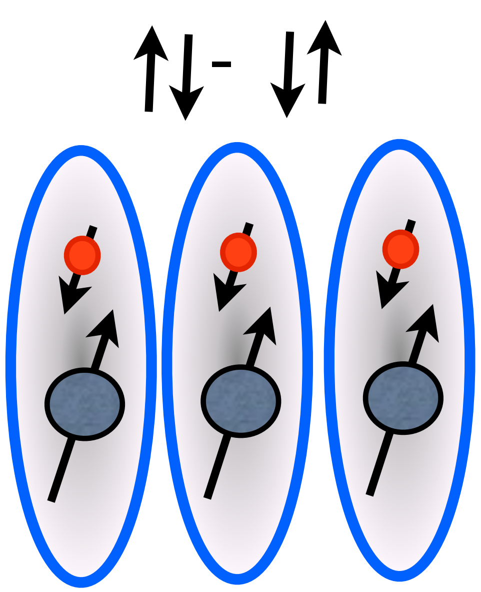

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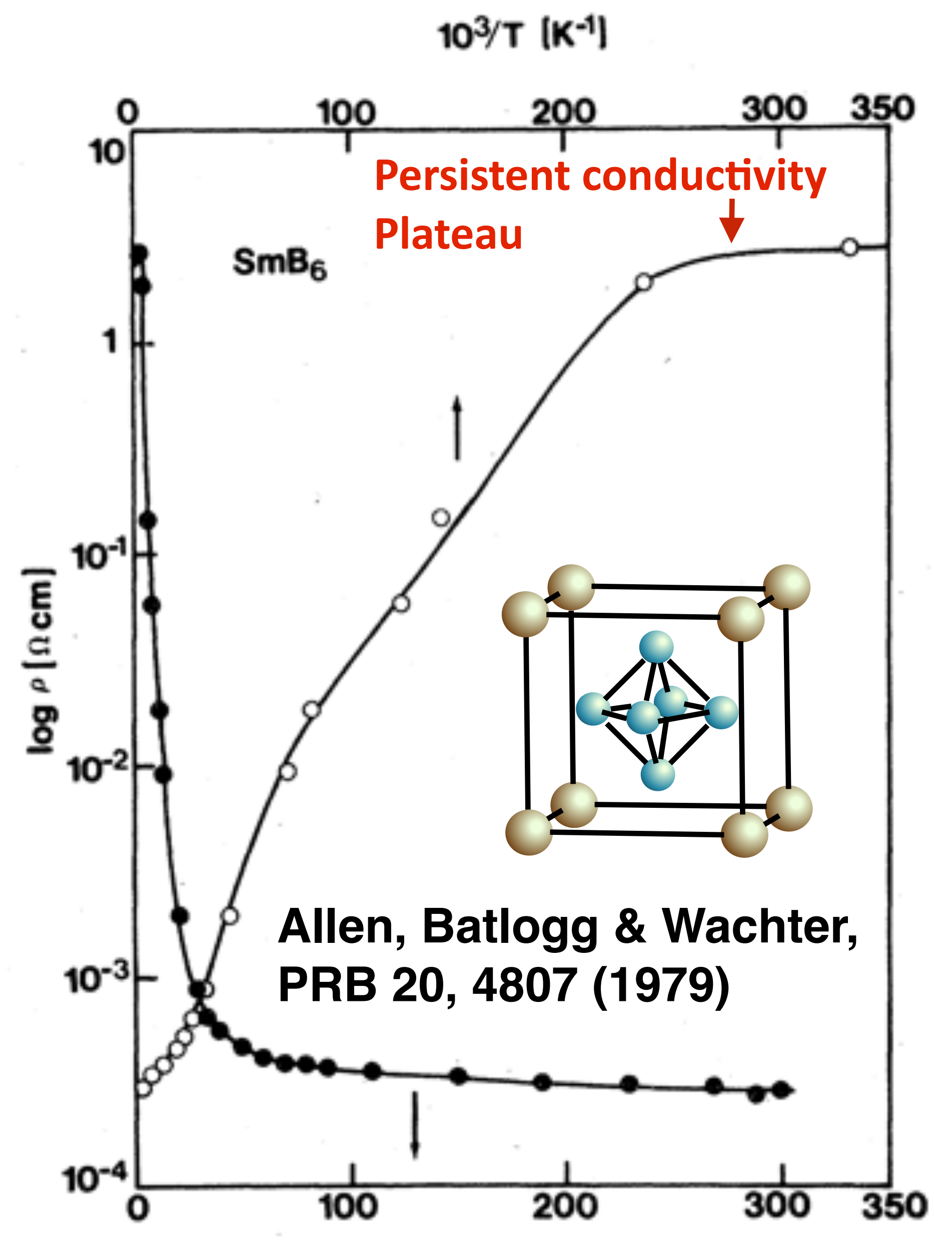

Kondo insulators:

Parent compound of Heavy Fermions

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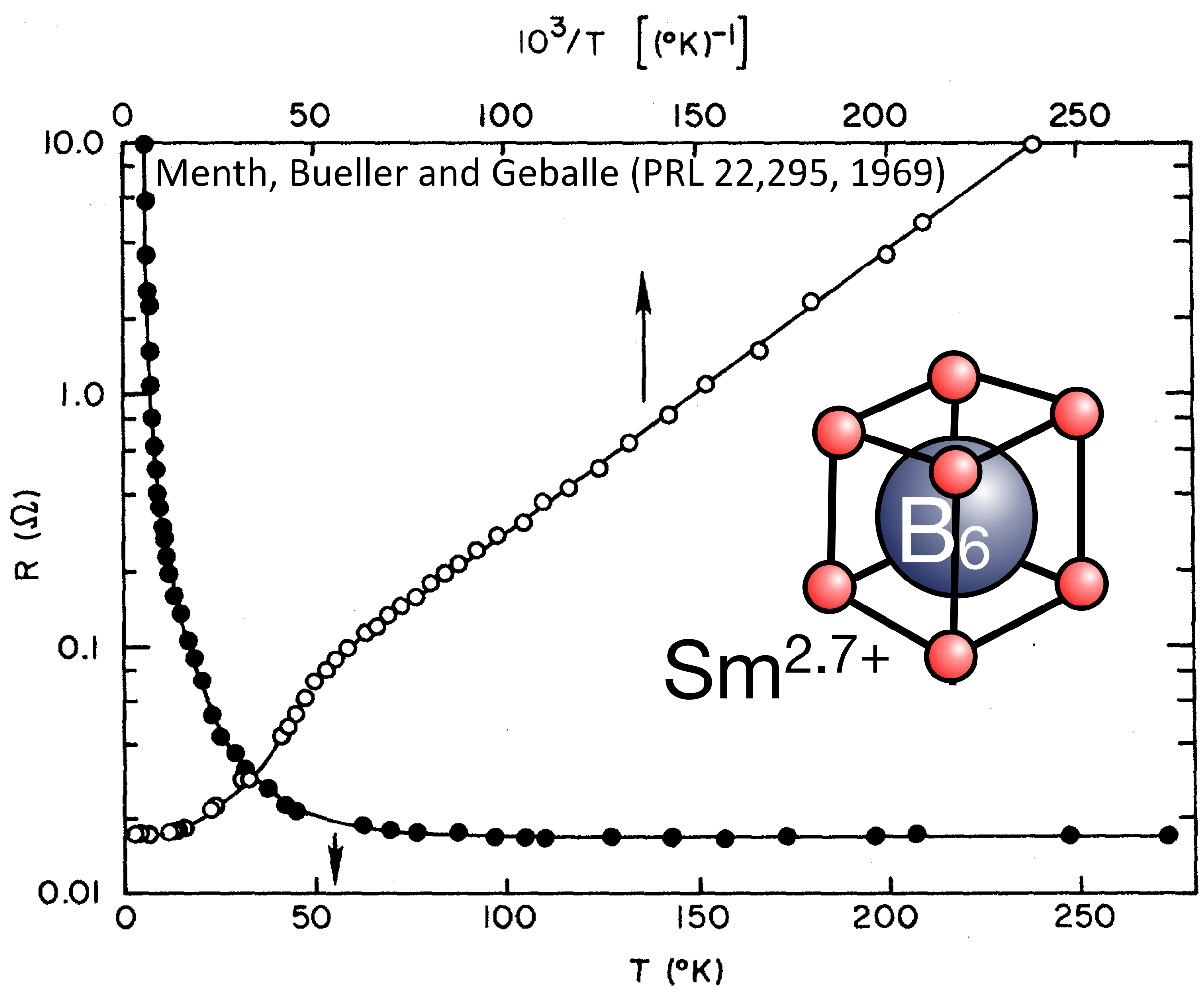

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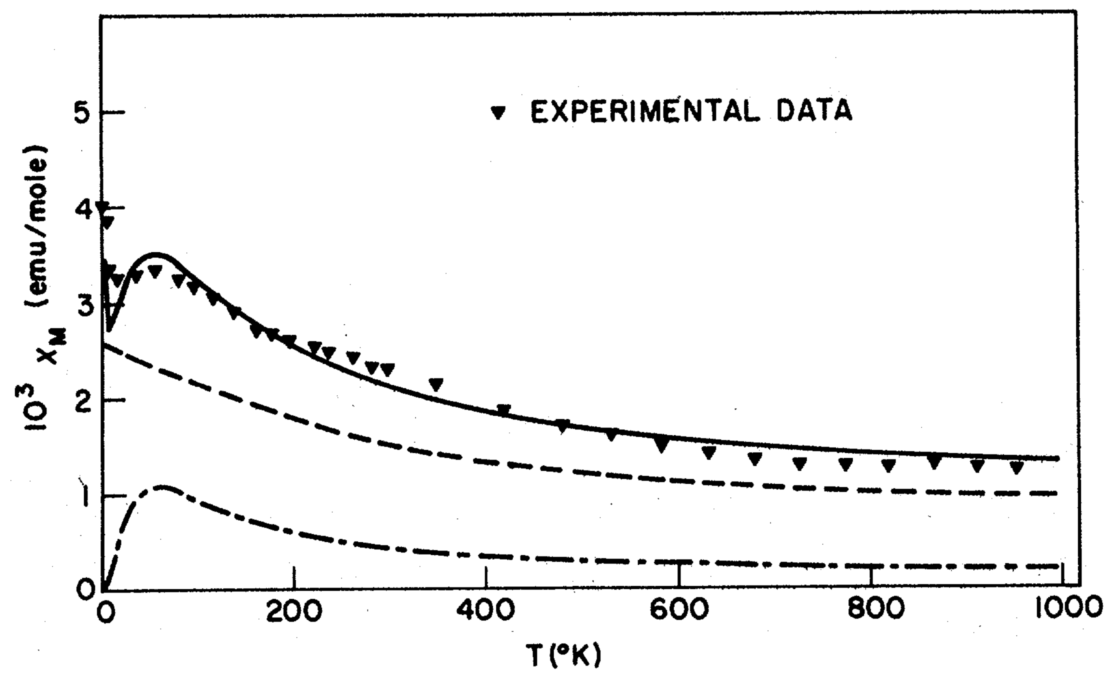

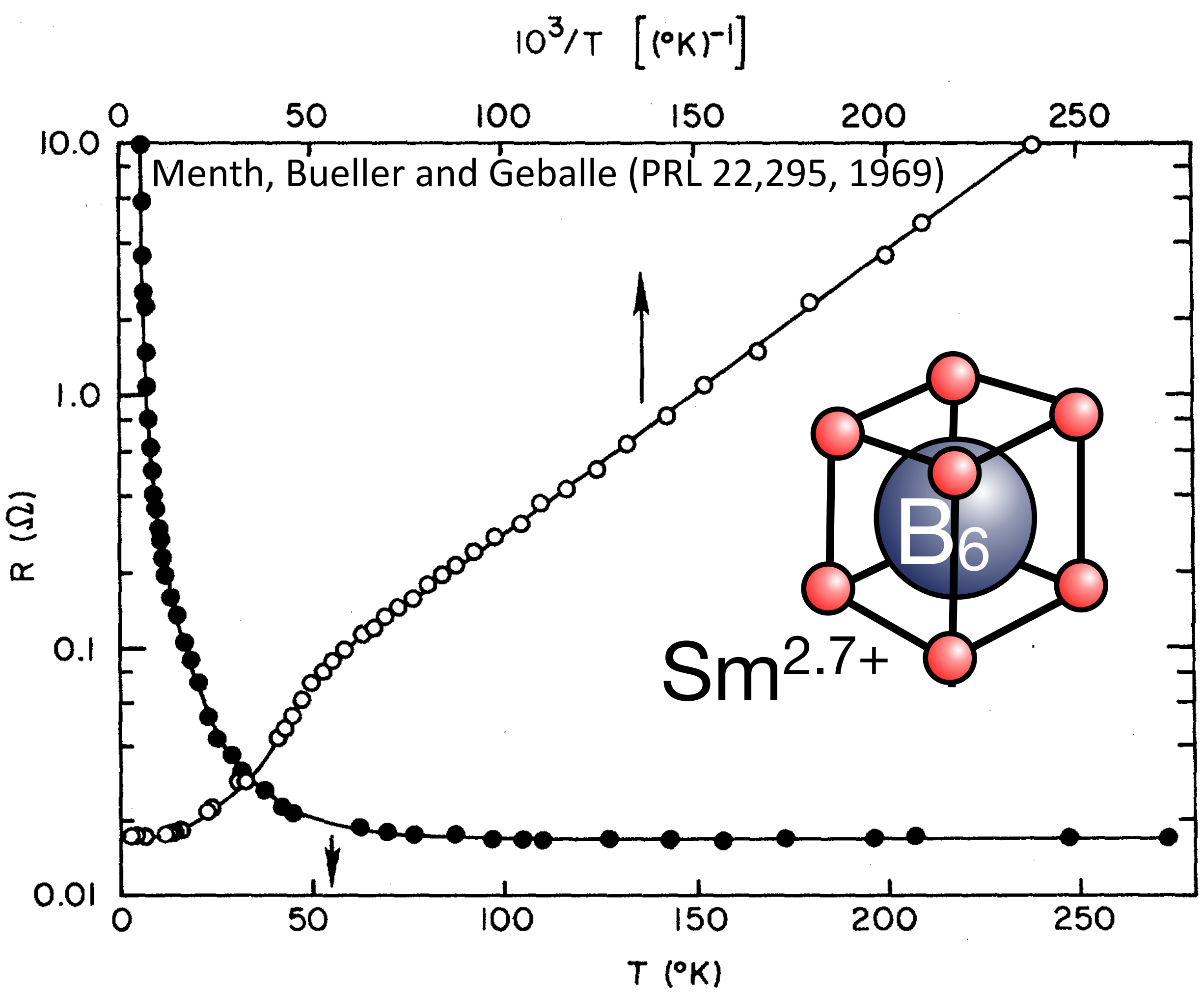

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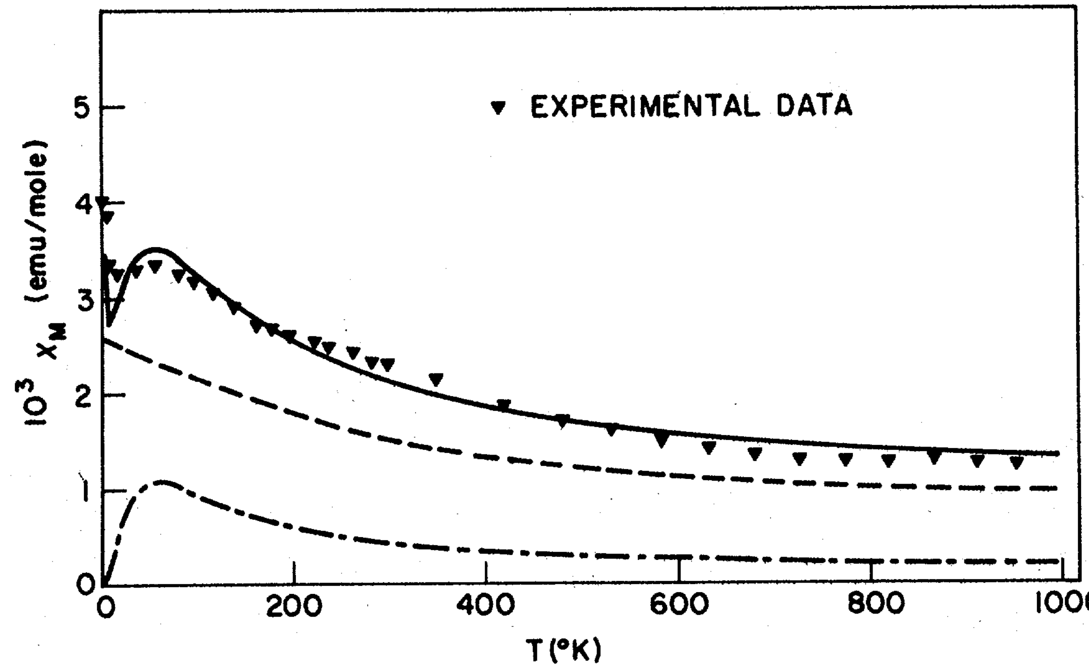
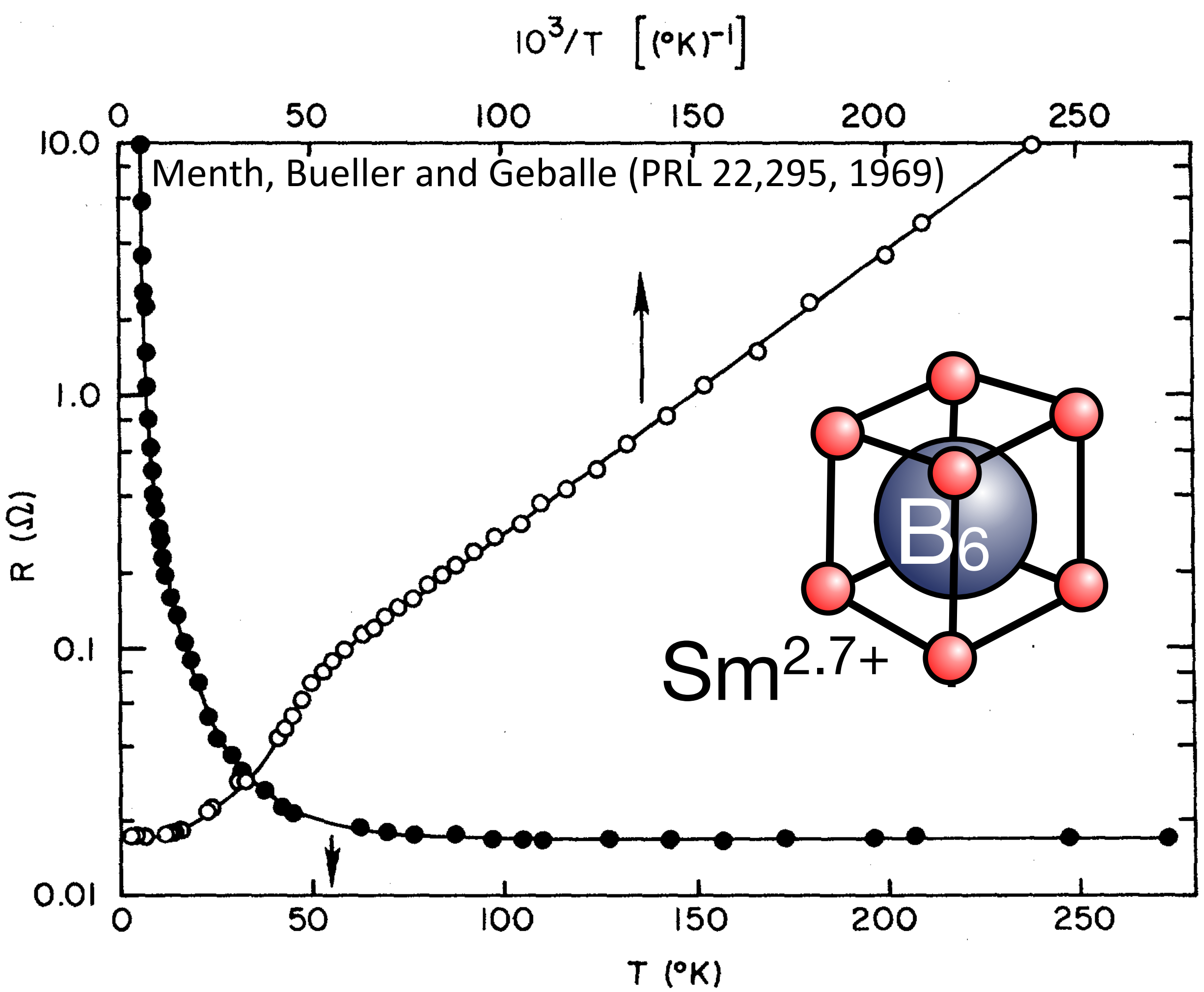
N. Mott Phil Mag 30,403,**1974**





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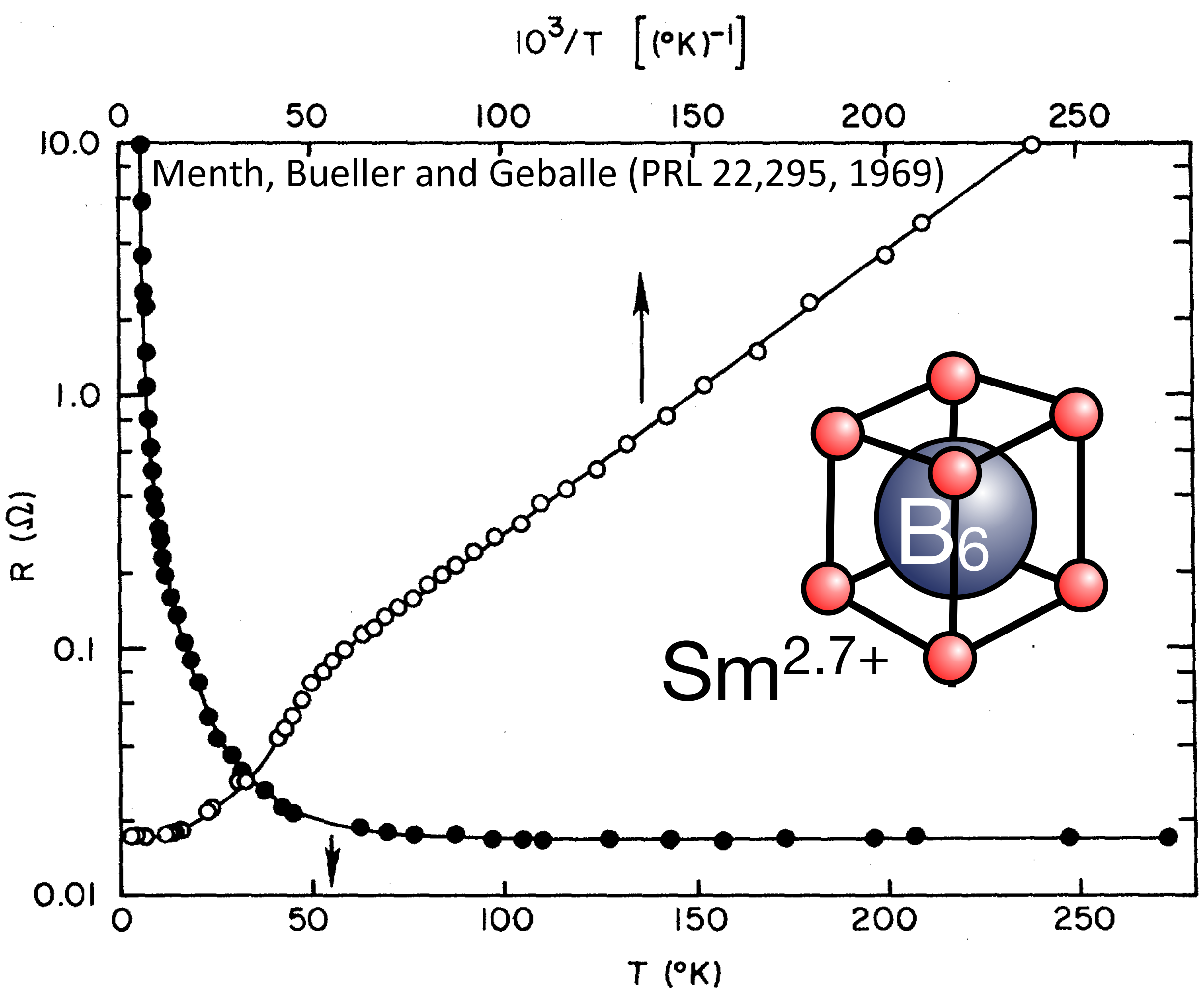

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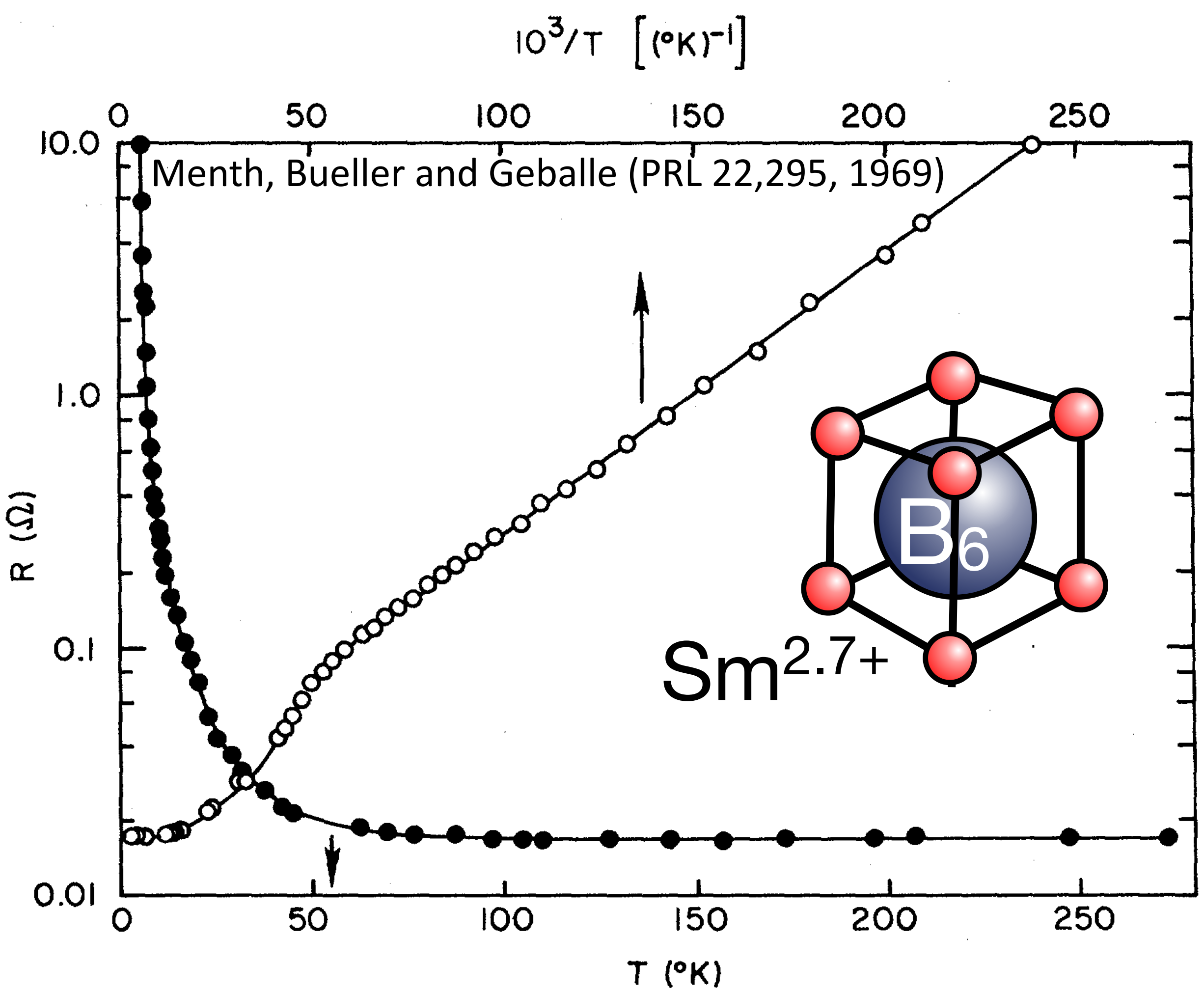

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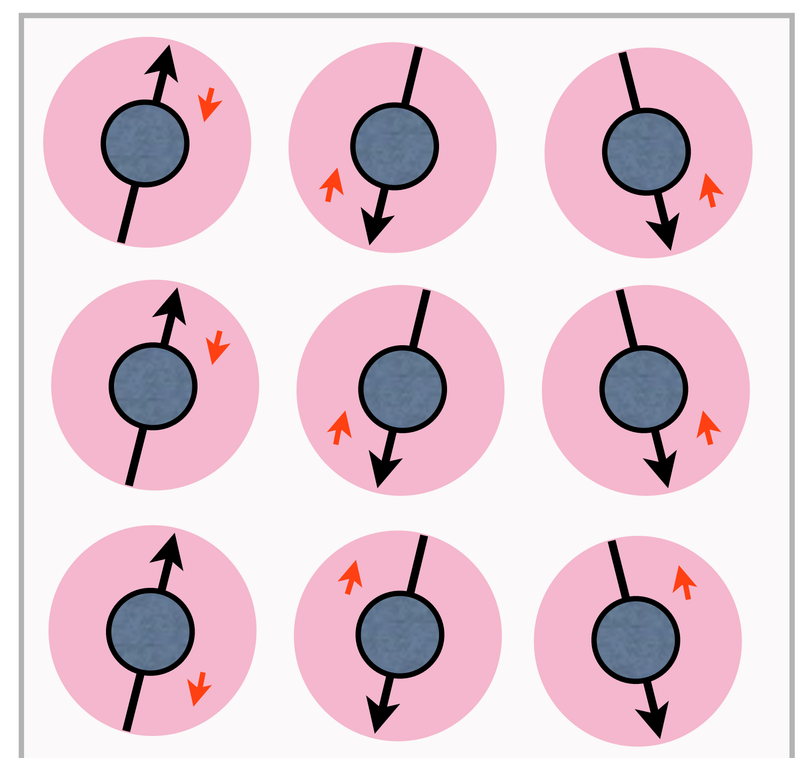

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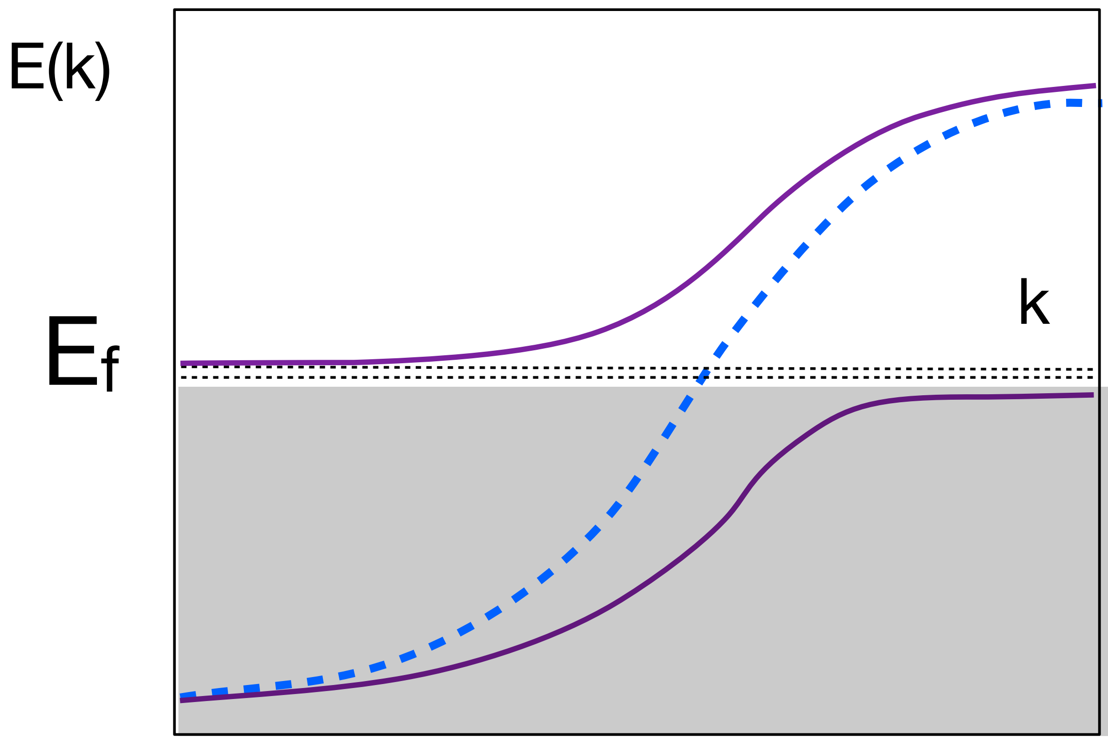
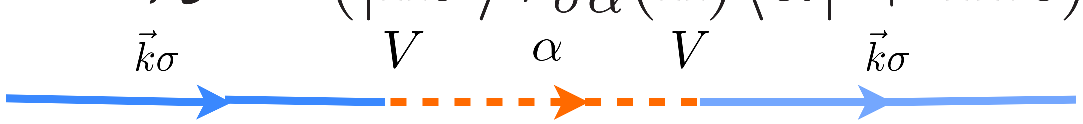


$$\mathcal{H} = (|\mathbf{k}\sigma\rangle V_{\sigma\alpha}(\mathbf{k})\langle\alpha| + \mathrm{H.c})$$



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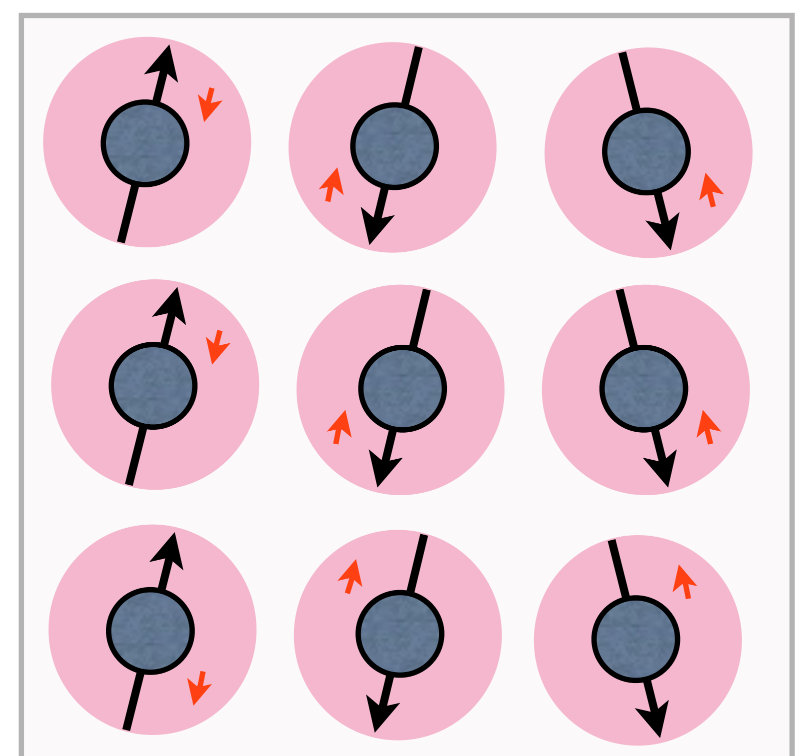

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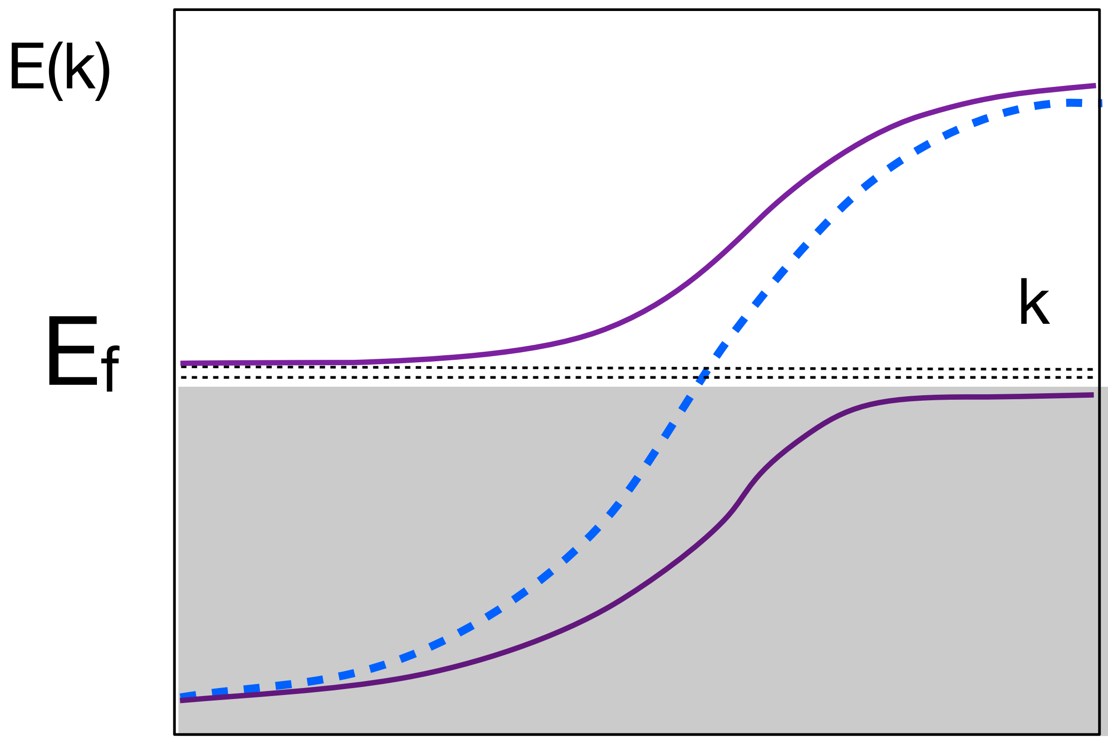

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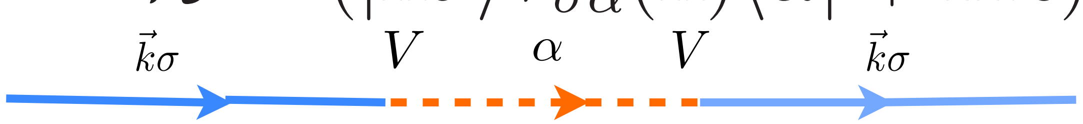

Martin and Allen(J. Appl Phys, 49,2078, 1979)

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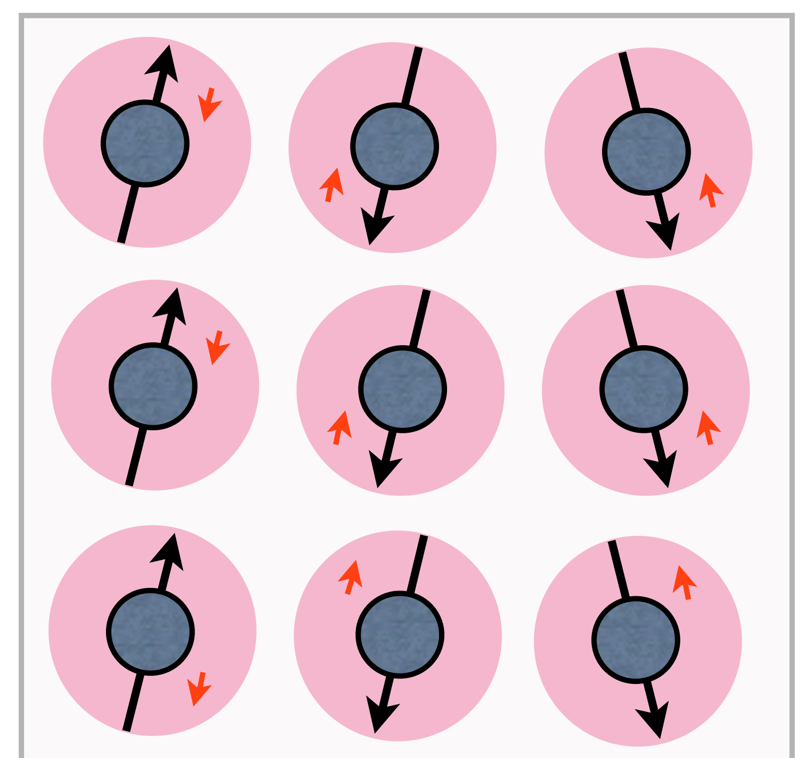

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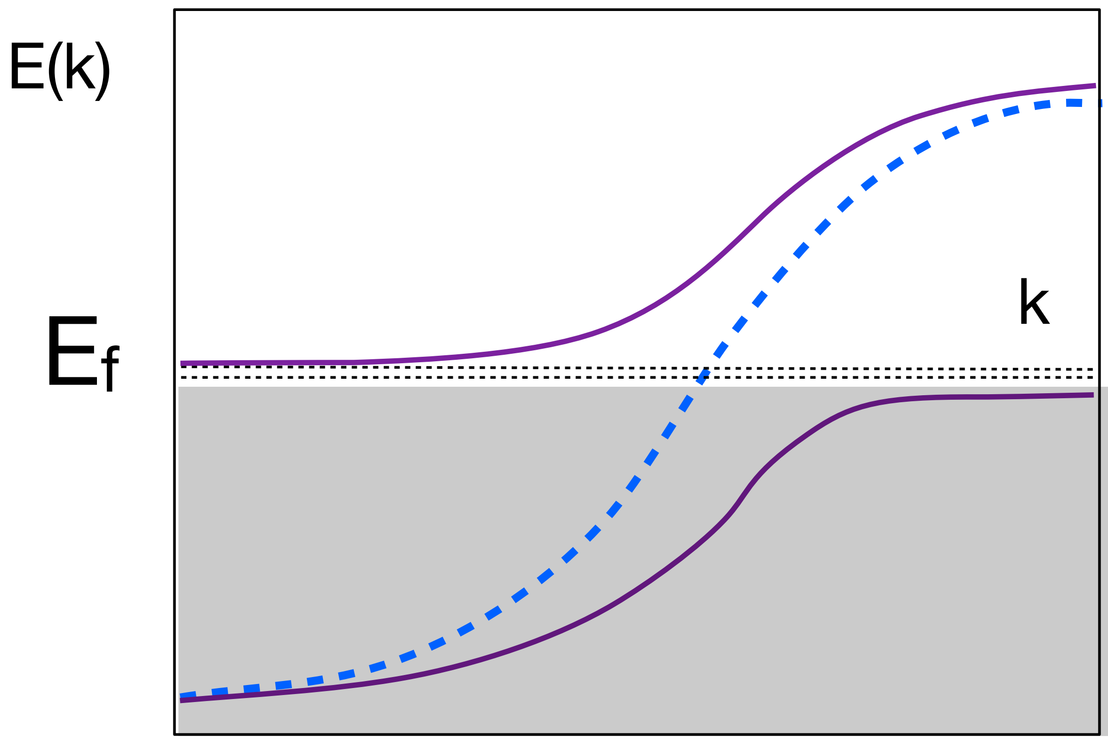

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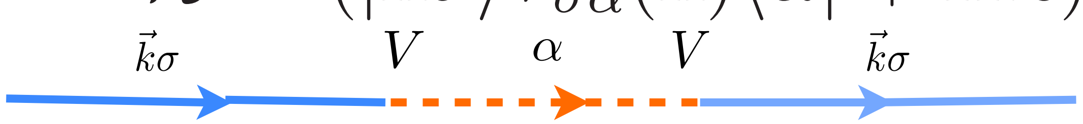

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Aeppli and Fisk (Comments CMP 16, 155, 1992)

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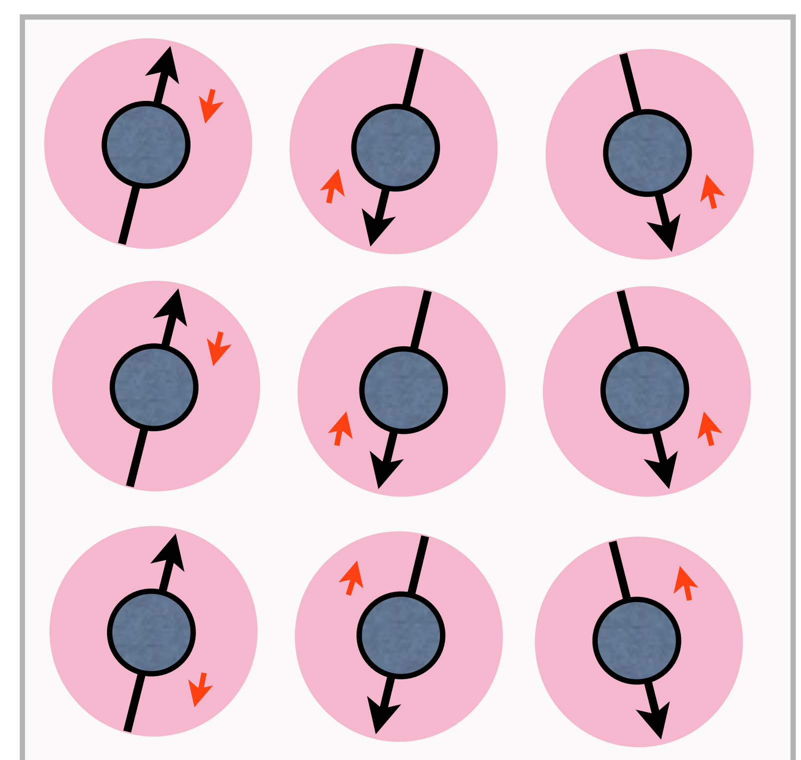

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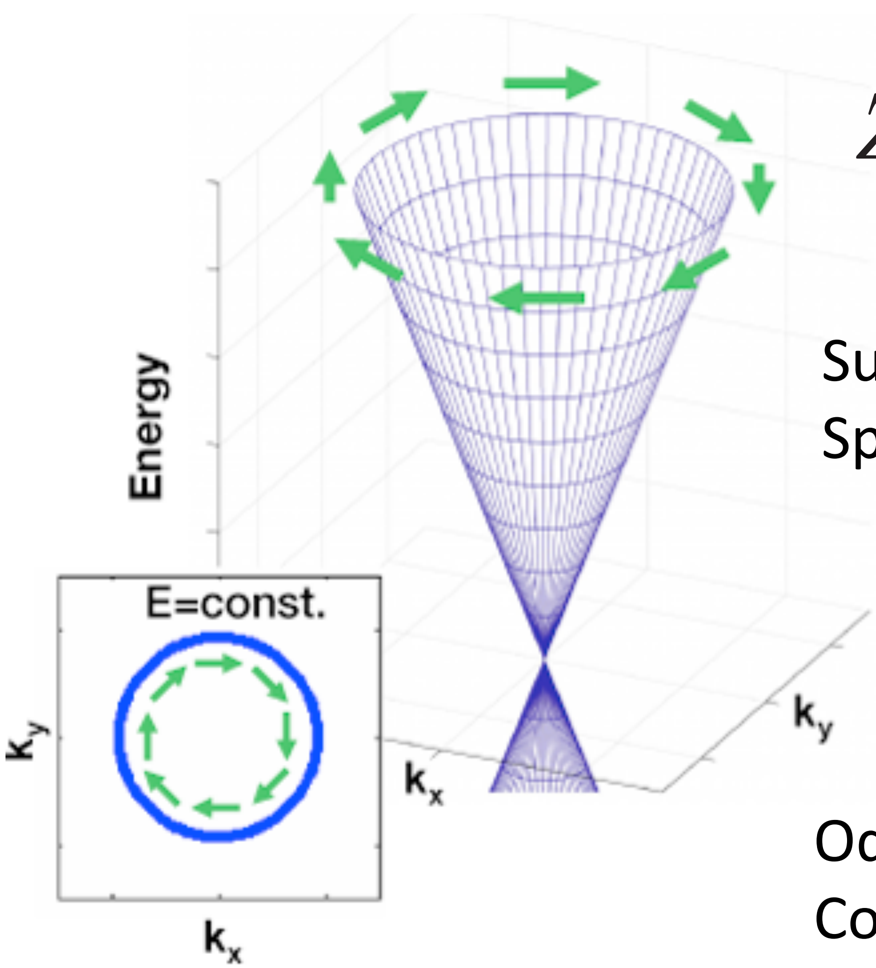
The Rise of Topology.

$$\vec{a}_{\mathbf{k}\mu\nu} = i\langle u_{\mu,\mathbf{k}}|\vec{\nabla}_{\mathbf{k}}|u_{\nu,\mathbf{k}}\rangle$$

Berry Connection ~ Field (texture) in momentum space

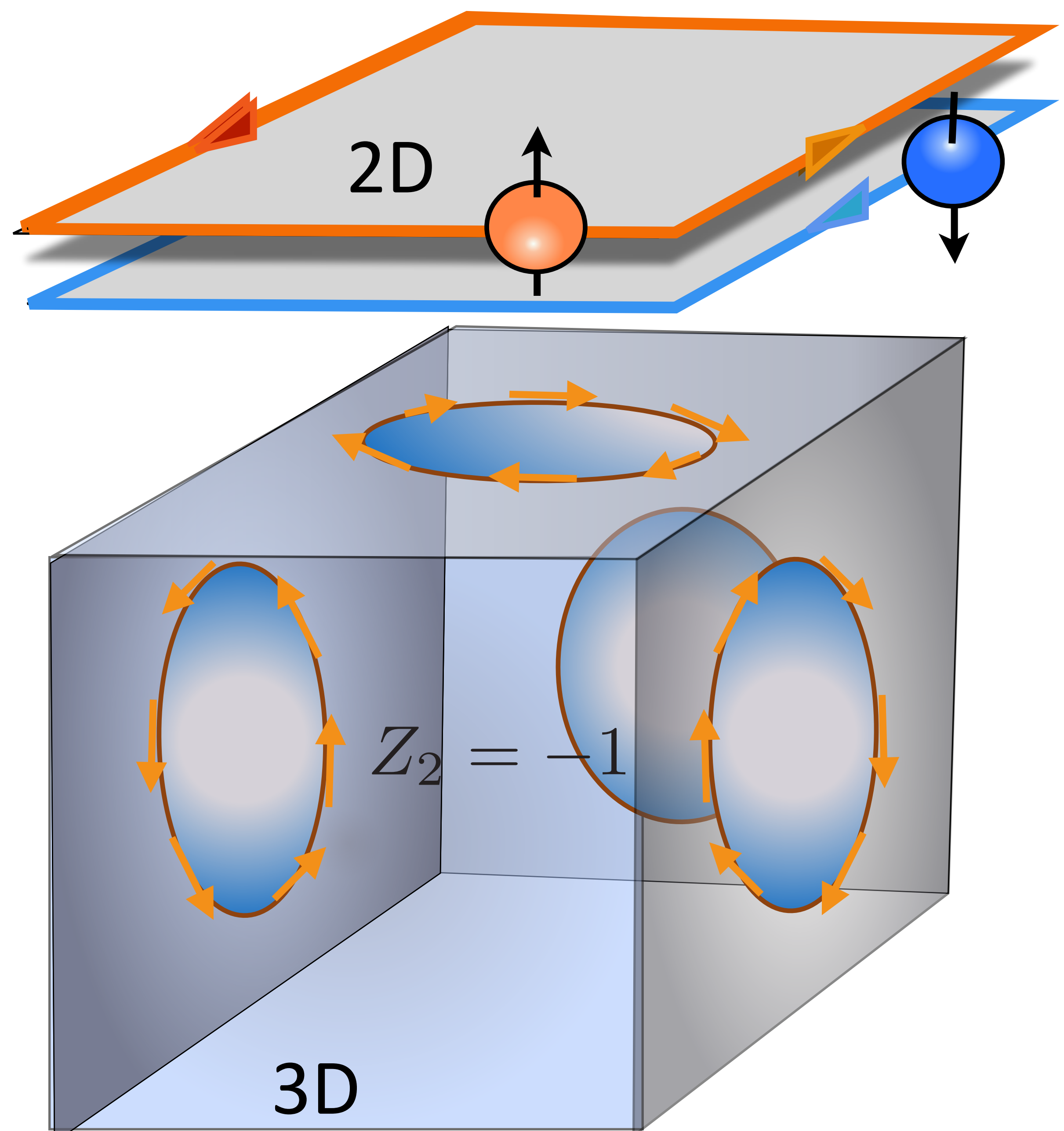
Thouless et al	(1982)	IQHE
Haldane	(1987)	NO NET FIELD REQD
Kane and Mele	(2005)	Spin orbit: Q. Spin Hall
Bernevig & Zhang	(2006)	Spin orbit: Q. Spin Hall
Fu and Kane	(2007)	3D Z_2 insulator



$$Z_2 = -1$$

Surface states are Spin Polarized.

Odd no of Dirac Cones per surface.



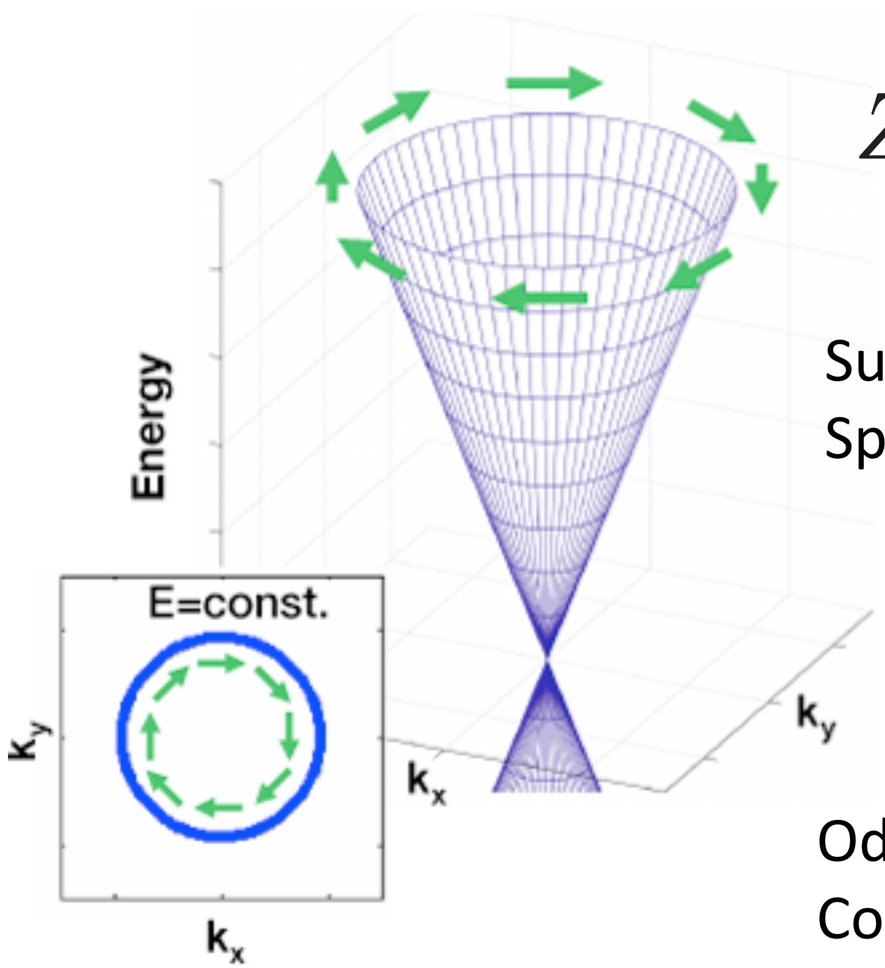
$$\vec{a}_{\mathbf{k}\mu\nu} = i\langle u_{\mu,\mathbf{k}}|\vec{\nabla}_{\mathbf{k}}|u_{\nu,\mathbf{k}}\rangle$$

Berry Connection ~ Field (texture) in momentum space

$$Z_2 = \prod_i \delta(\Gamma_i)$$

Fu and Kane (2008) :Parity equation.

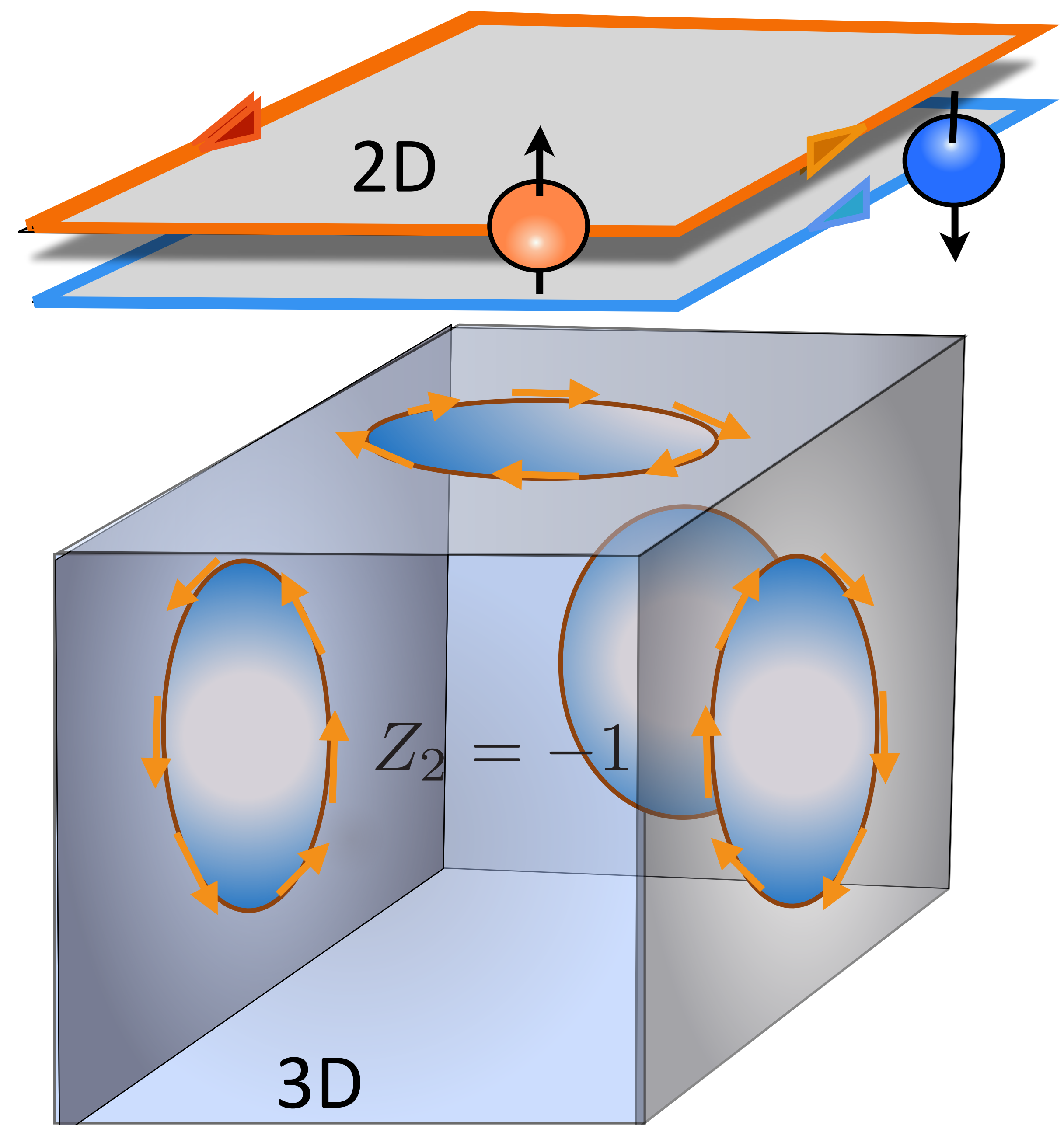
Thouless et al	(1982)	IQHE
Haldane	(1987)	NO NET FIELD REQD
Kane and Mele	(2005)	Spin orbit: Q. Spin Hall
Bernevig & Zhang	(2006)	Spin orbit: Q. Spin Hall
Fu and Kane	(2007)	3D Z_2 insulator



$$Z_2 = -1$$

Surface states are Spin Polarized.

Odd no of Dirac Cones per surface.



Are *Kondo* insulators topological?

Topological Kondo Insulators, Dzero, Sun, Galitski, PC   Phys. Rev. Lett. **104**, 106408 (**2010**)

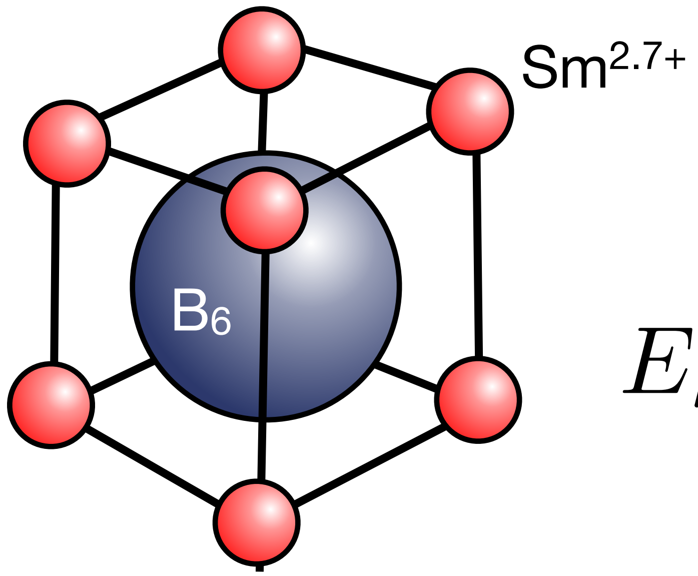
Maxim Dzero, Kai Sun, Piers Coleman and Victor Galitski, Phys. Rev. B 85 , 045130-045140 (2012).

Tight binding model for SmB_6: T. Takimoto, J. Phys. Soc. Jpn. 80, 123710 (2011).

Victor Alexandrov, Maxim Dzero and Piers Coleman Phys. Rev. Lett 111, 226403 (2013).

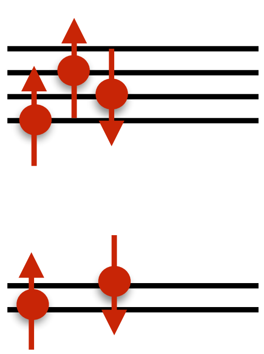
Gutzwiller + Band Theory F. Lu, J. Zhao, H. Weng, Z. Fang and X. Dai, Phys. Rev. Lett. 110, 096401 (2013).

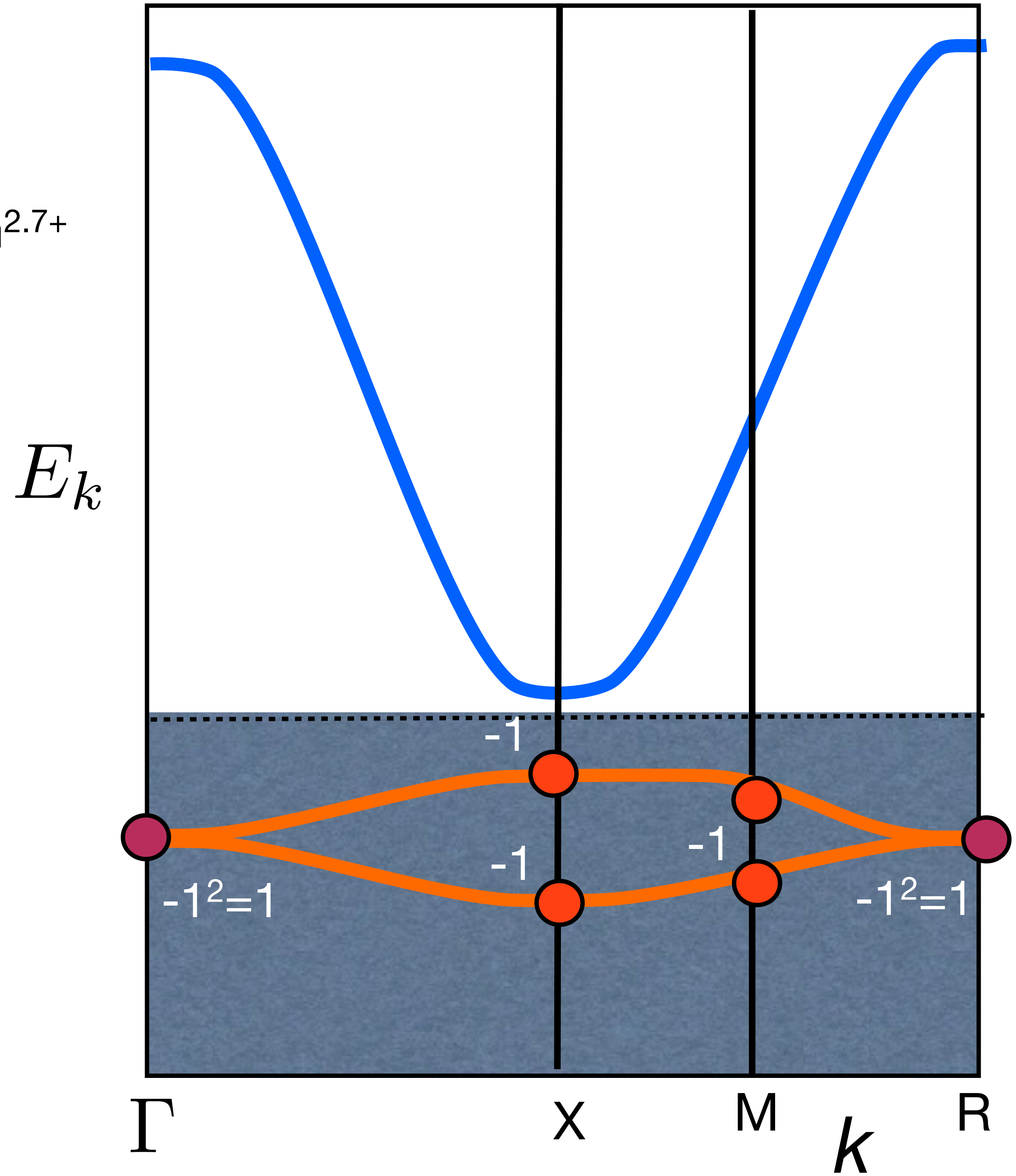
3D Cubic Kondo Insulator

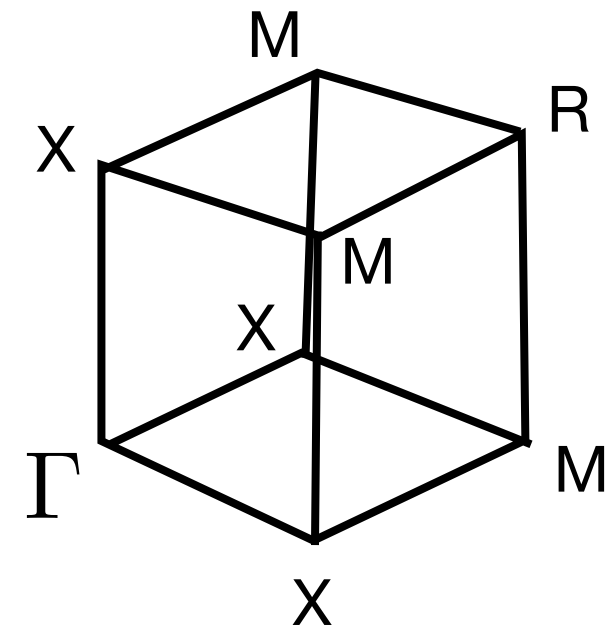


SmB6

Sm3+



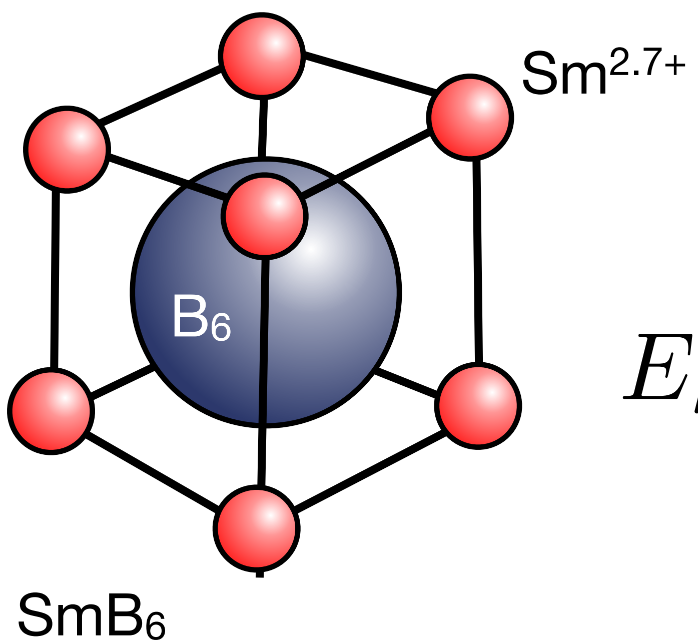


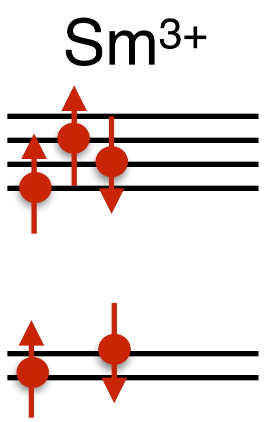


$d^0\, f^6$

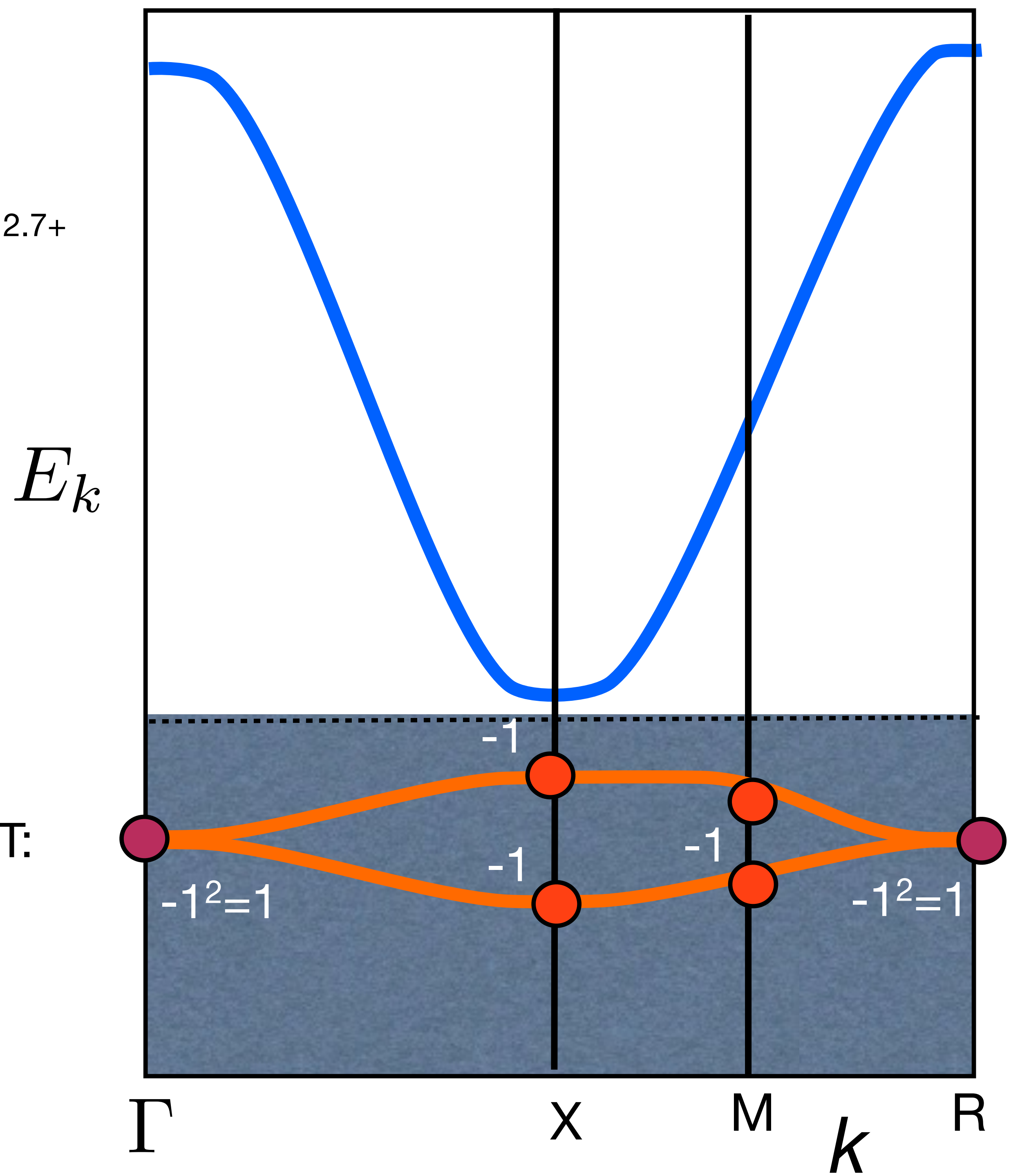
$\nu = +1$

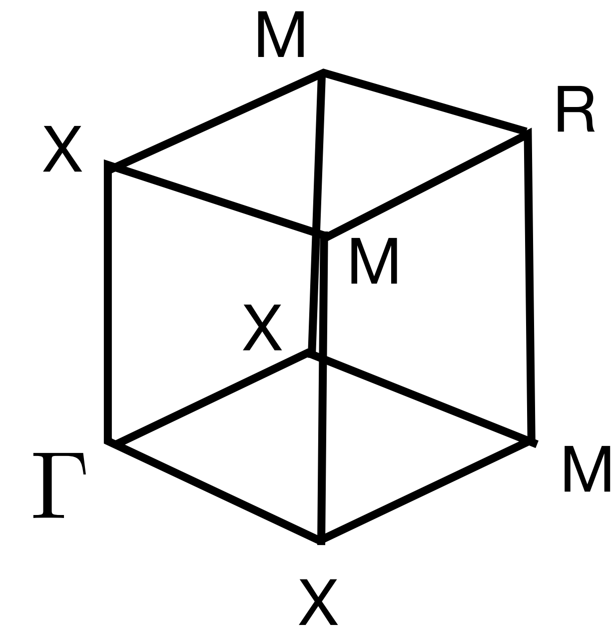
3D Cubic Kondo
Insulator





QUARTET:

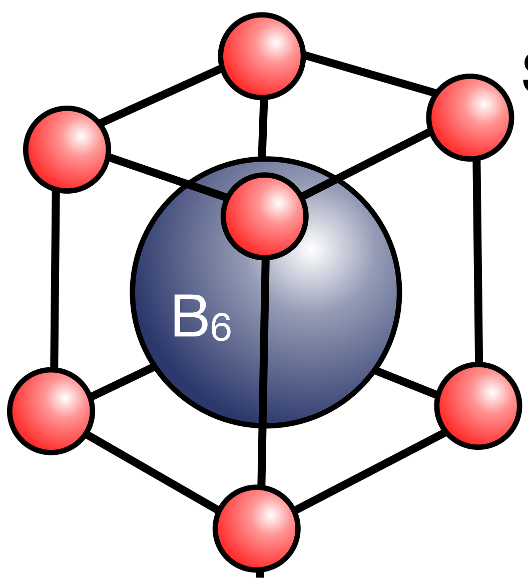




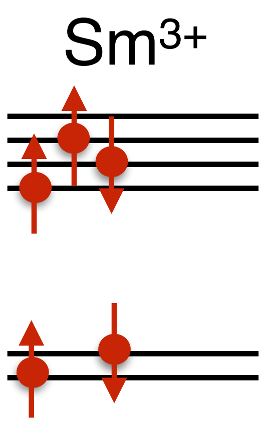
$d^0\, f^6$

$$\nu = +1$$

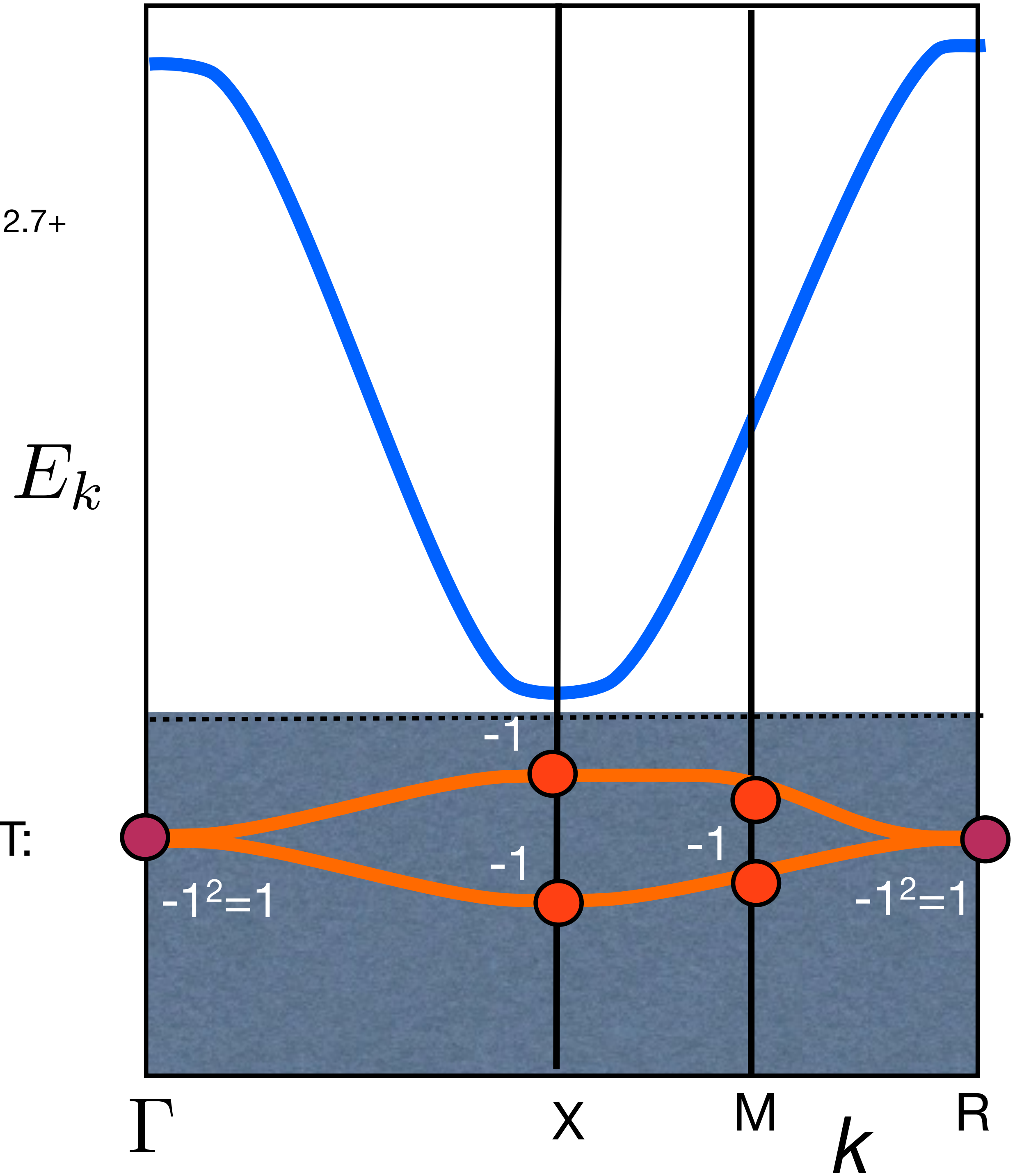
3D Cubic Kondo
Insulator

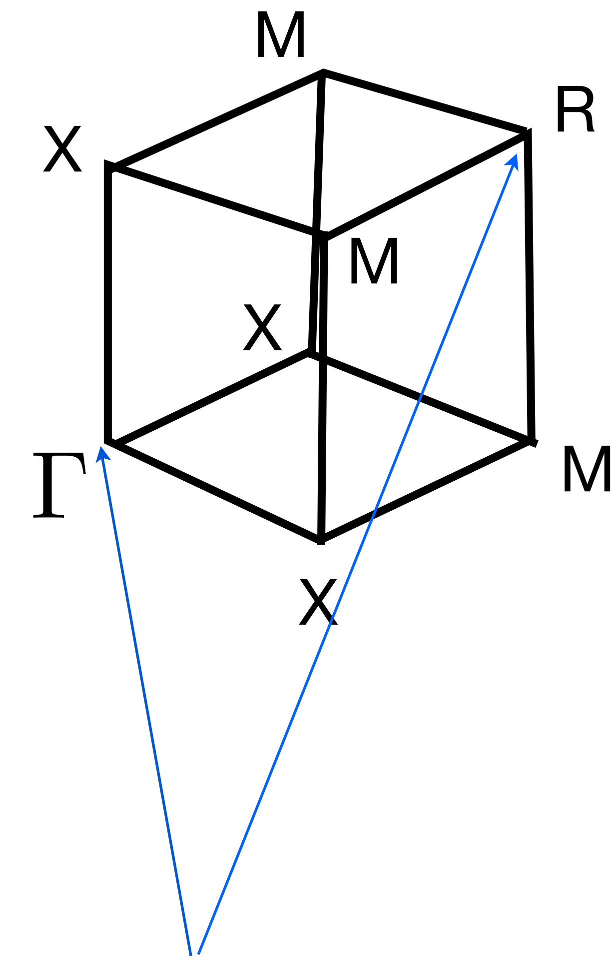


SmB6



QUARTET:

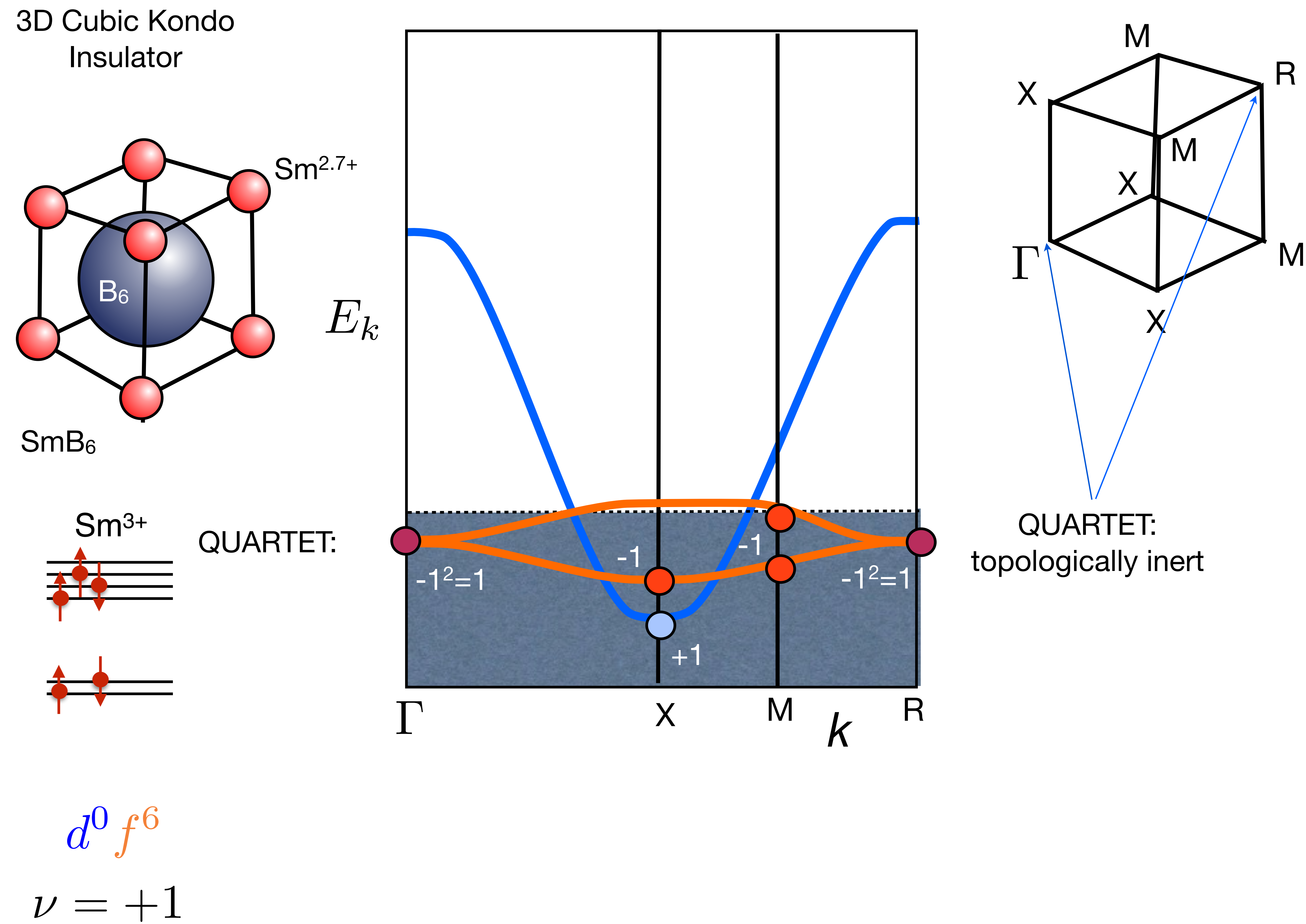


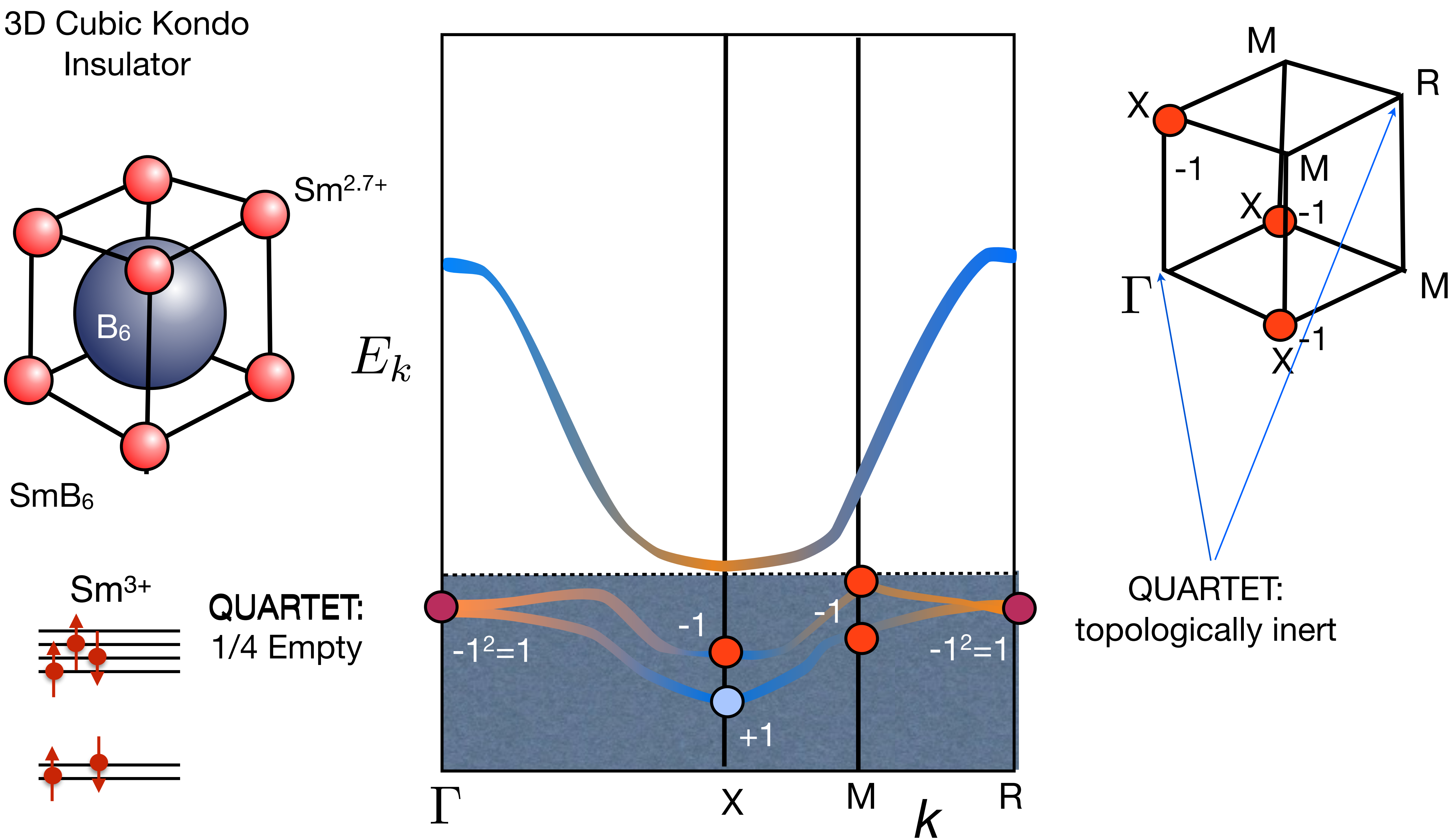


QUARTET:
topologically inert

$d^0\, f^6$

$\nu = +1$

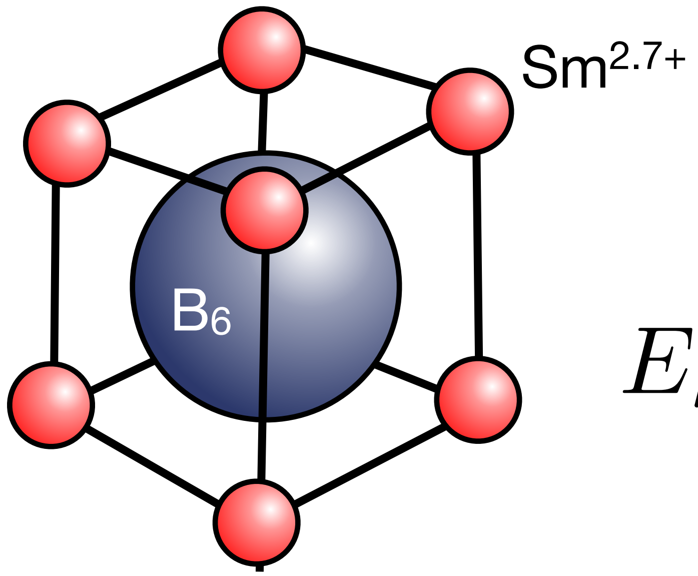

3D Cubic Kondo Insulator
Sm2.7+
B6
SmB6
Sm3+
QUARTET:
Ek
-1²=1
-1
-1
+1
-1²=1
Γ
X
M
k
R
M
R
X
M
X
Γ
M
X
QUARTET:
topologically inert
d0 f6
ν = +1



$$d^0 f^6 \longrightarrow d^1 f^5$$

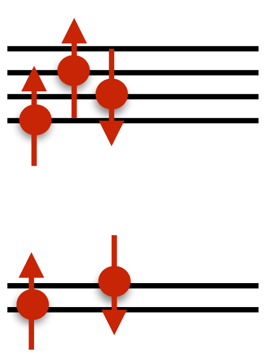
$$\nu = +1 \qquad \nu = -1$$

3D Cubic Kondo Insulator

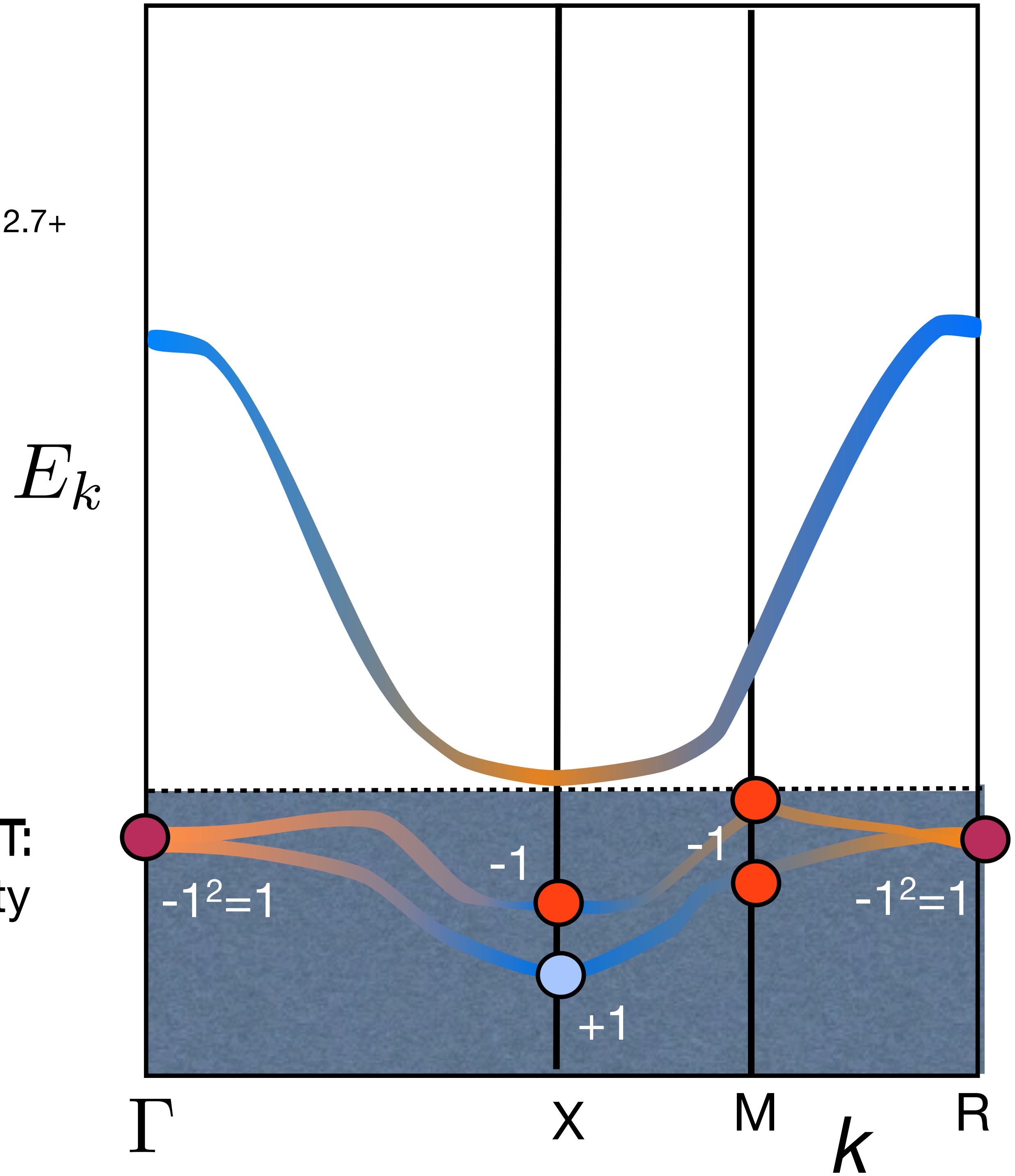


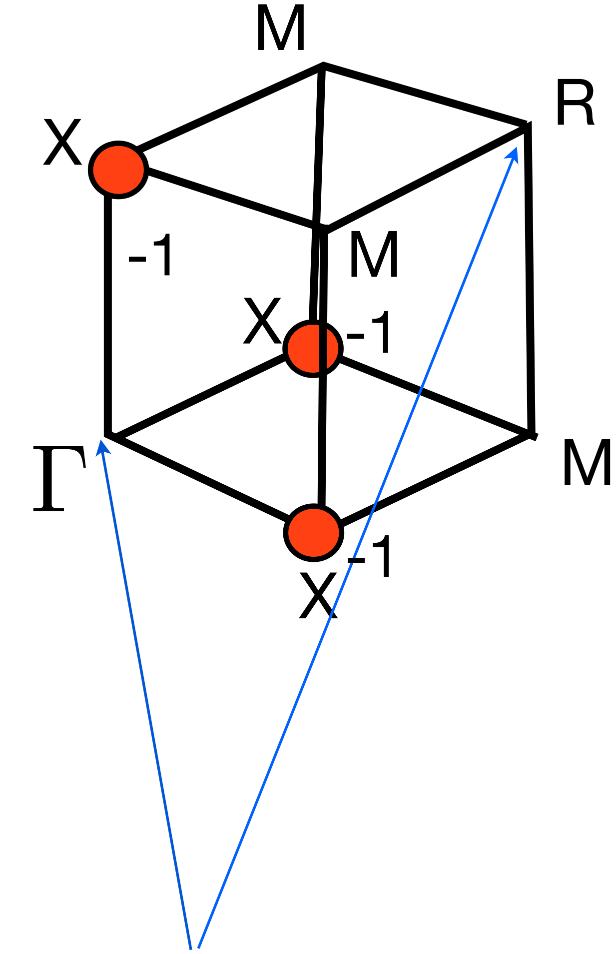
SmB_6

Sm^{3+}



QUARTET:
1/4 Empty





QUARTET:
topologically inert

$$\color{blue}{d^0}\,\color{orange}{f^6} \longrightarrow \color{blue}{d^1}\,\color{orange}{f^5}$$

$$\nu = +1 \qquad \nu = -1$$

THREE DIRAC CONES
ON SURFACE.

M. Tran et al (2012)

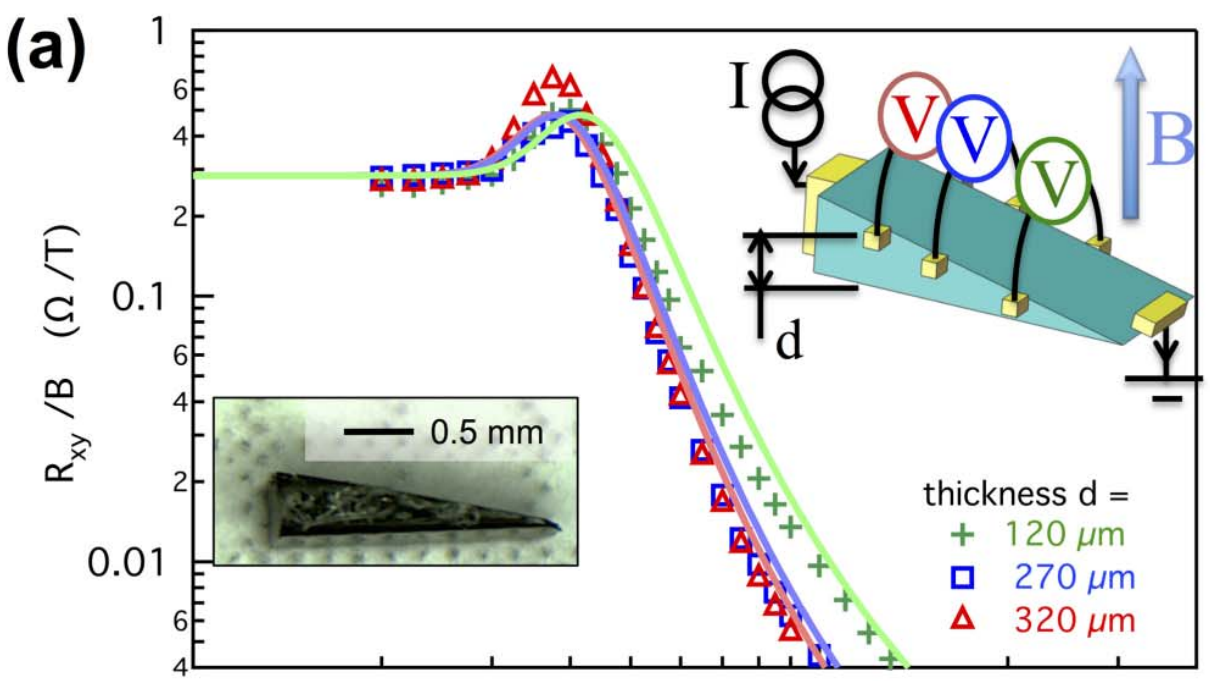
F. Lu et al (2013)

Alexandrov, Dzero and PC (2013)

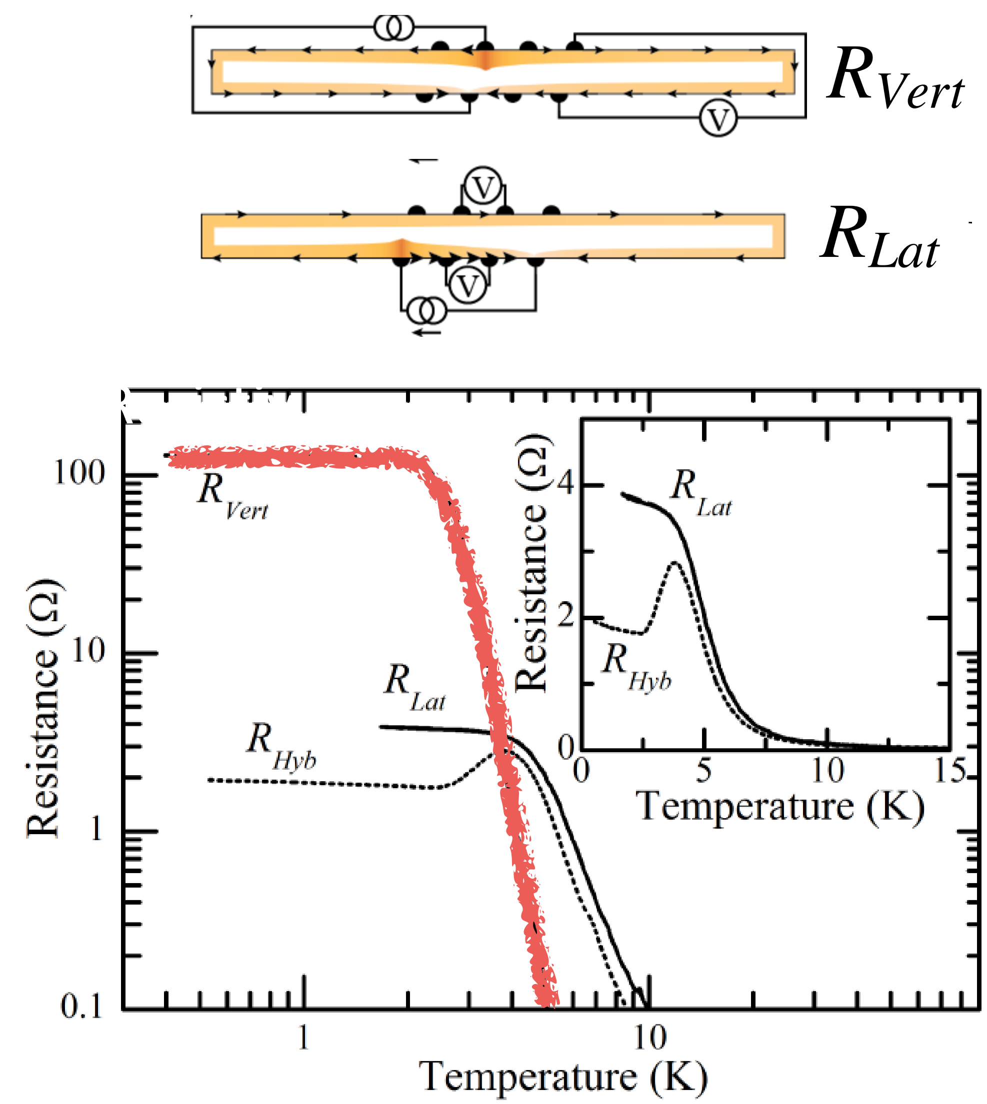
SmB6   TKI Check List.

- ☐ Bulk Insulator
- ☐ Surface Conductivity
- ☐ Robustness/Sensitivity to potential/magnetic scattering.

(D. J. Kim, Paglione)



D. J. Kim et al, Scientific Reports 3, 3150 (**2013**)



Wolgast et al, Phys Rev B, 88, 180405 (2013)

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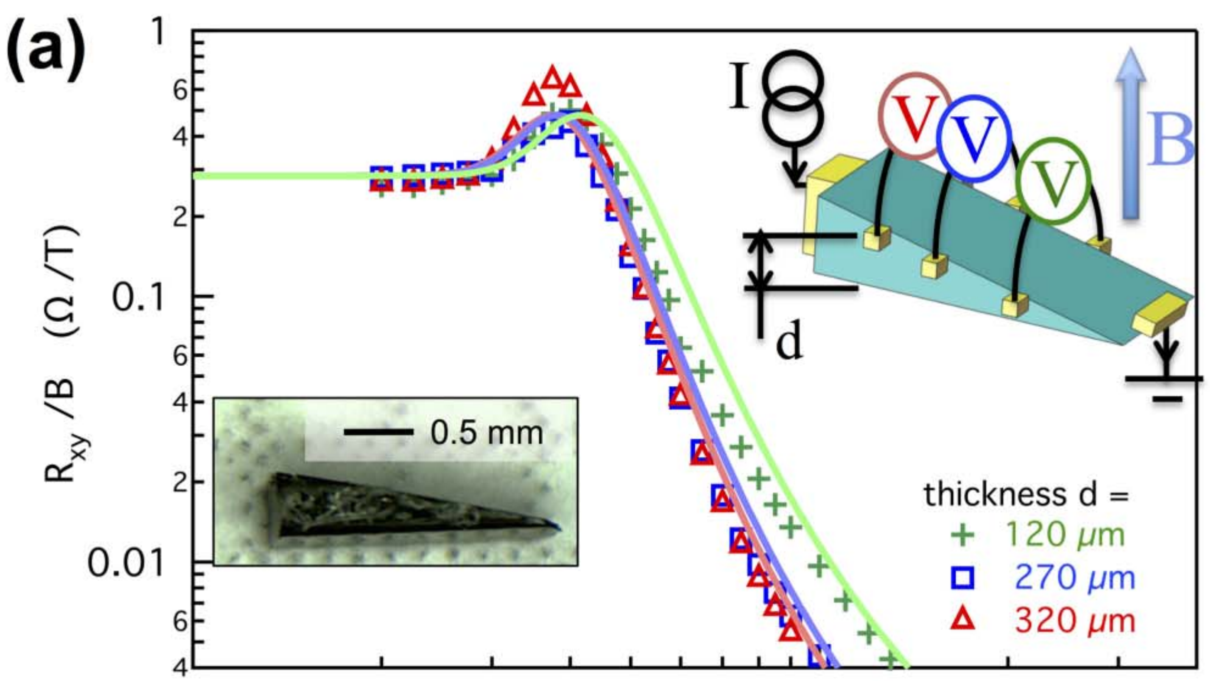

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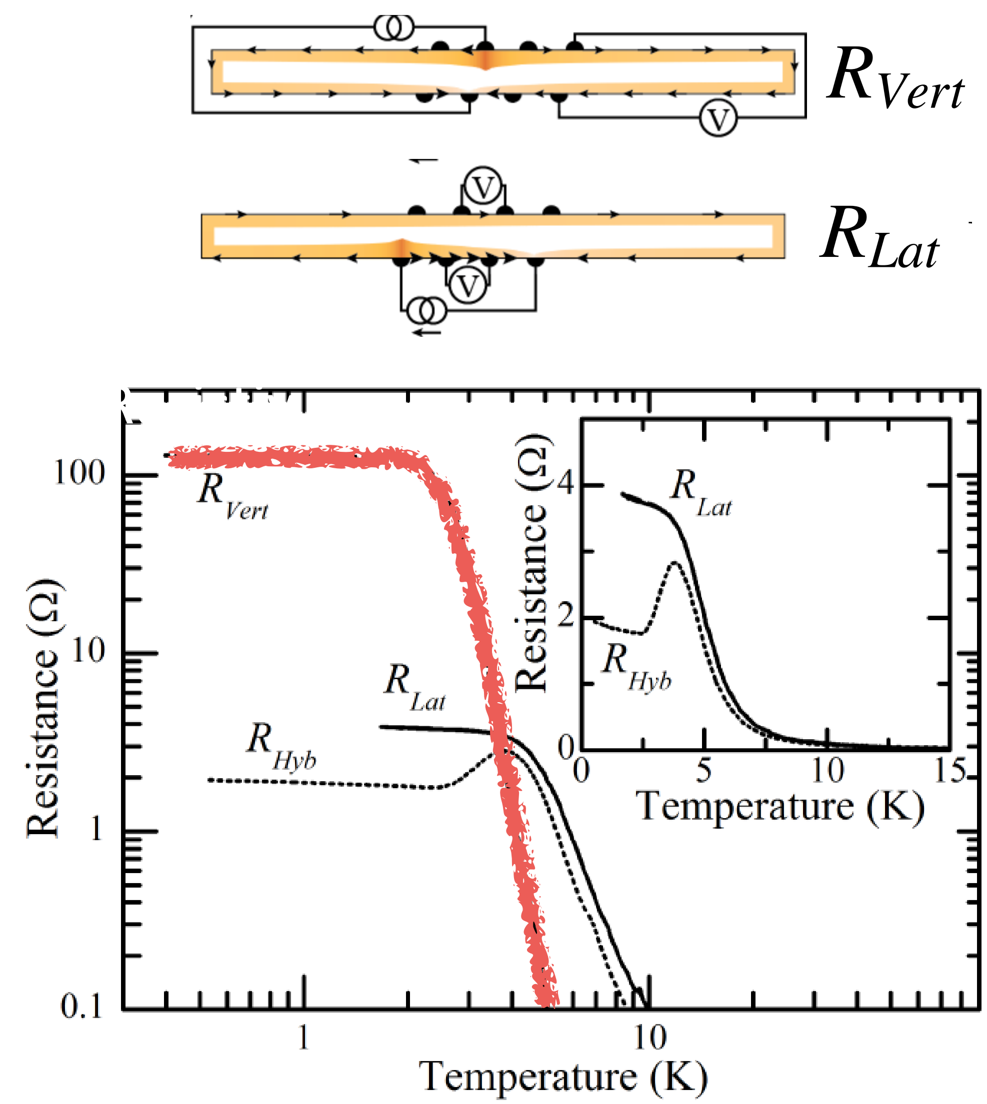
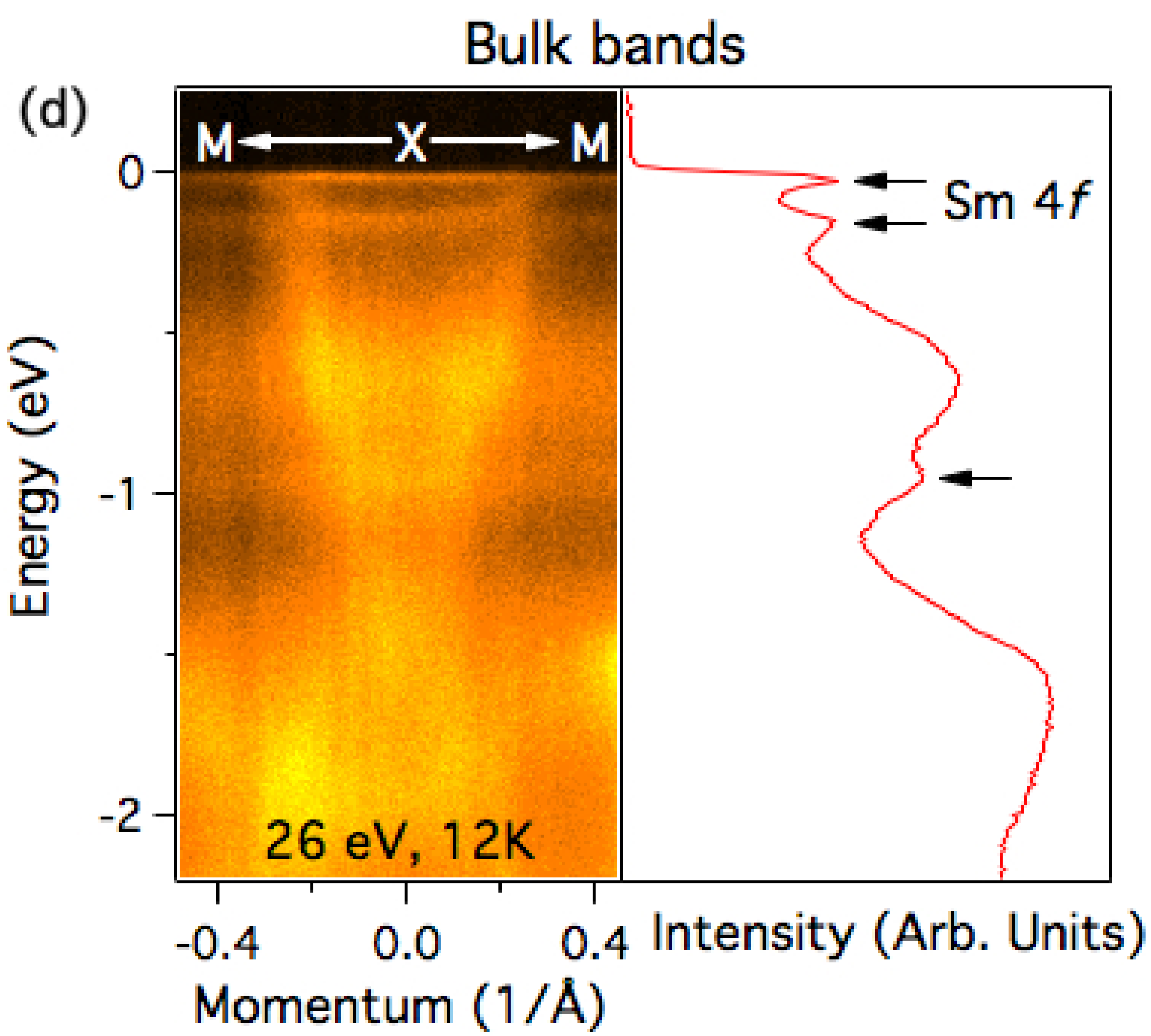


Wolgast et al, Phys Rev B, 88, 180405 (2013)

SmB6   TKI Check List.

- [ ] d-band crossing at X points (Zahid Hasan, Xi Dai)
- [ ] Odd number (3) of Surface FS (ARPES, dHVA, STM). (Zahid Hasan, Xi Dai)



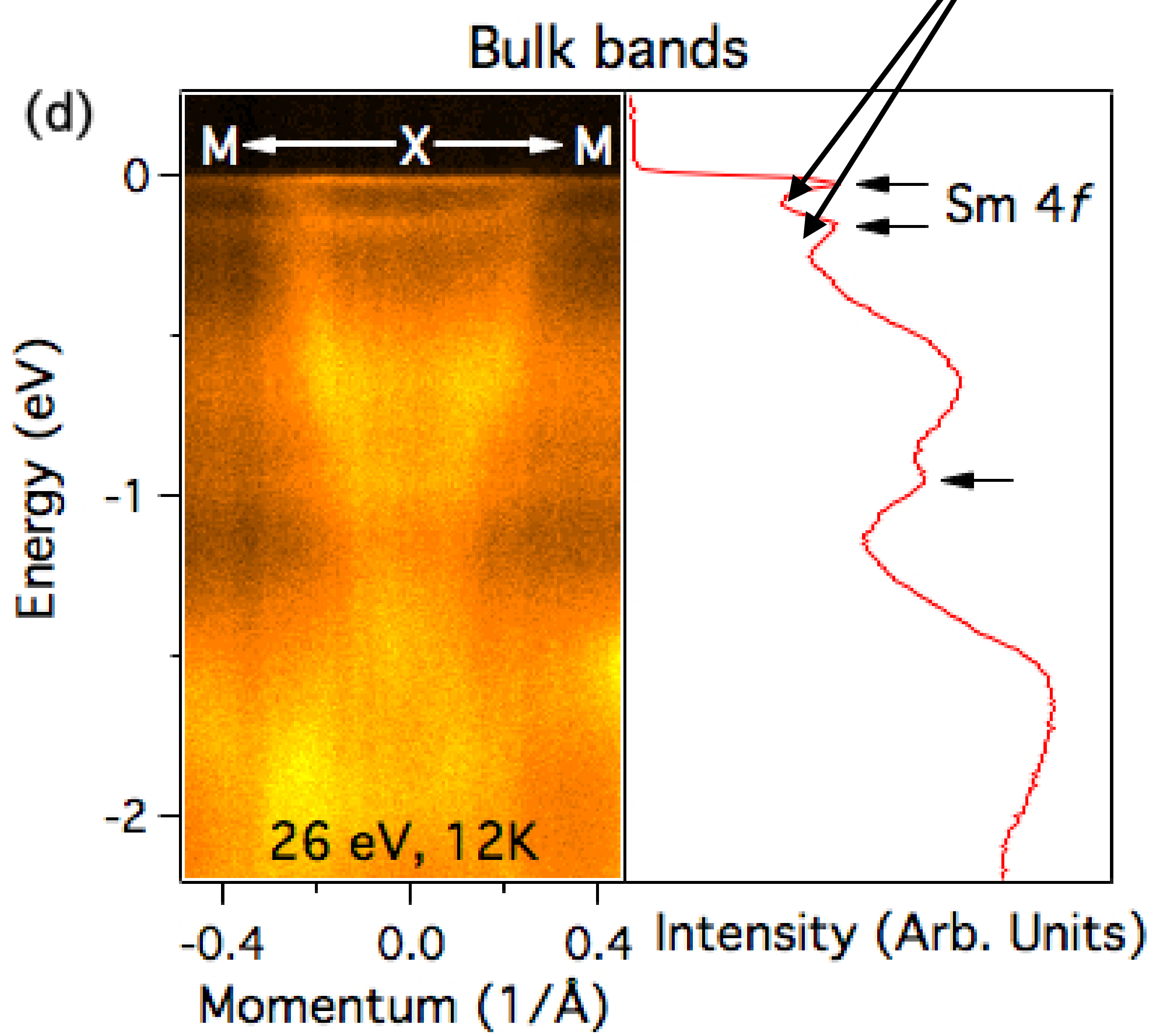
Neupane et al. arXiv: 1306.4634,
Nature Commnunications 4, (2013).

SmB6   TKI Check List.

☐ d-band crossing at X points (Zahid Hasan, Xi Dai)

☐ Odd number (3) of Surface FS (ARPES, dHVA, STM). (Zahid Hasan, Xi Dai)

4f Crystal Fields
Doublet/Quartet.



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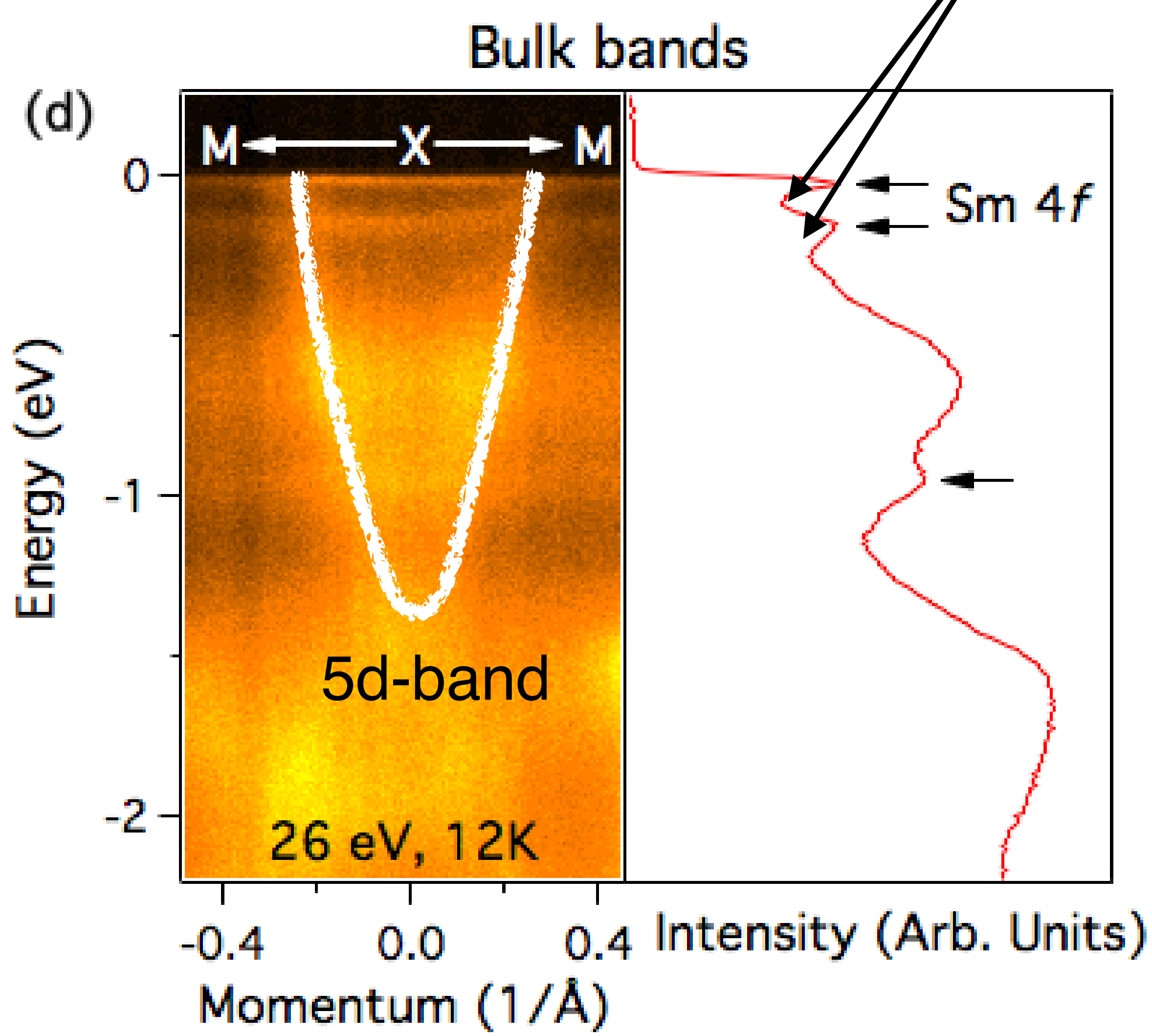
Doublet/Quartet.



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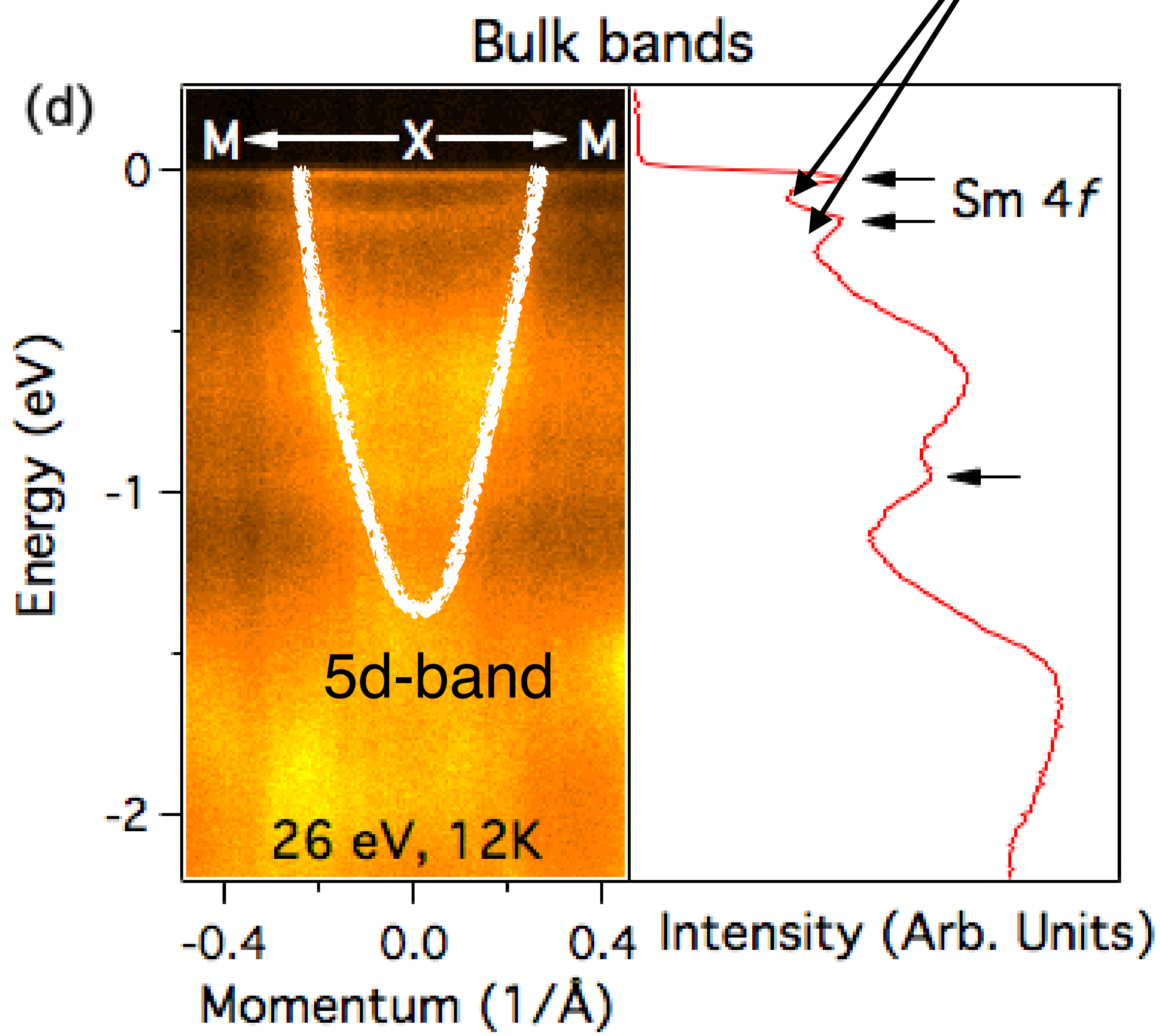

Neupane et al. arXiv: 1306.4634,
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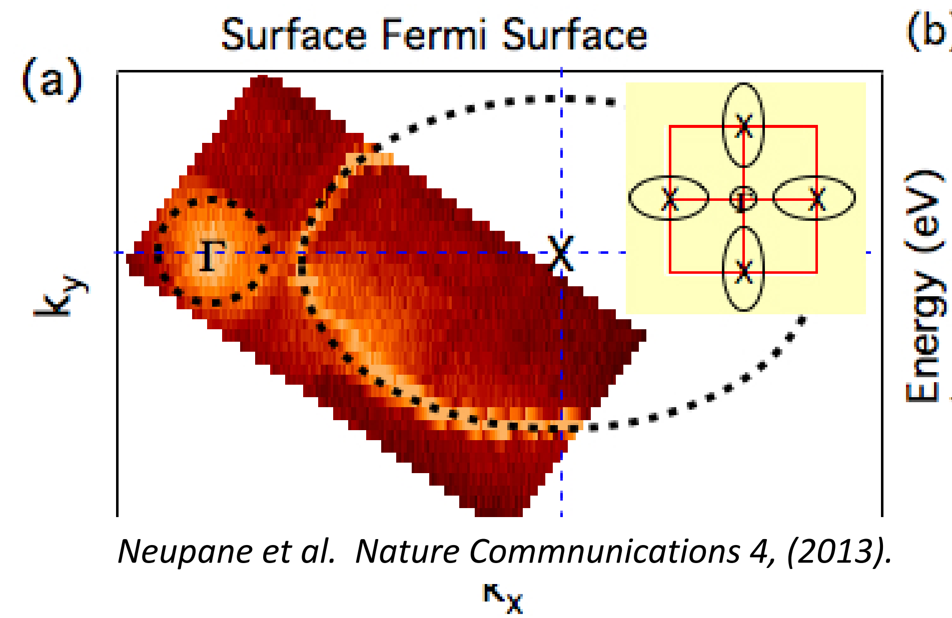
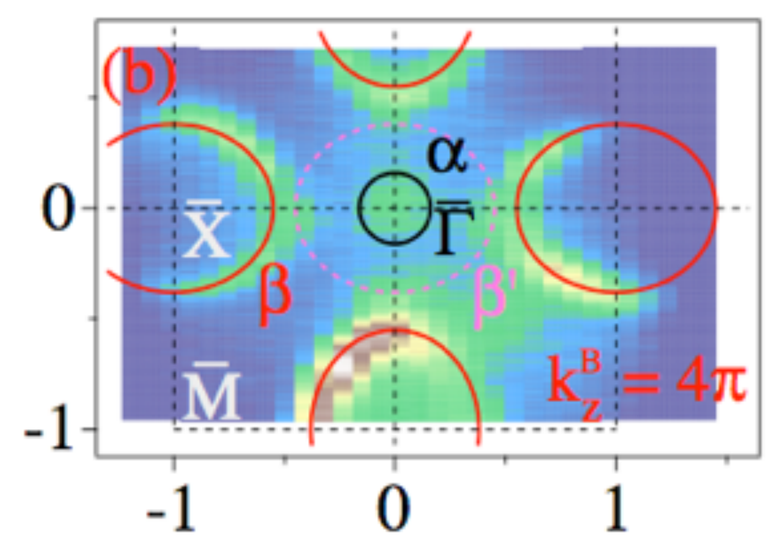


Neupane et al. Nature Commnunications 4, (2013).

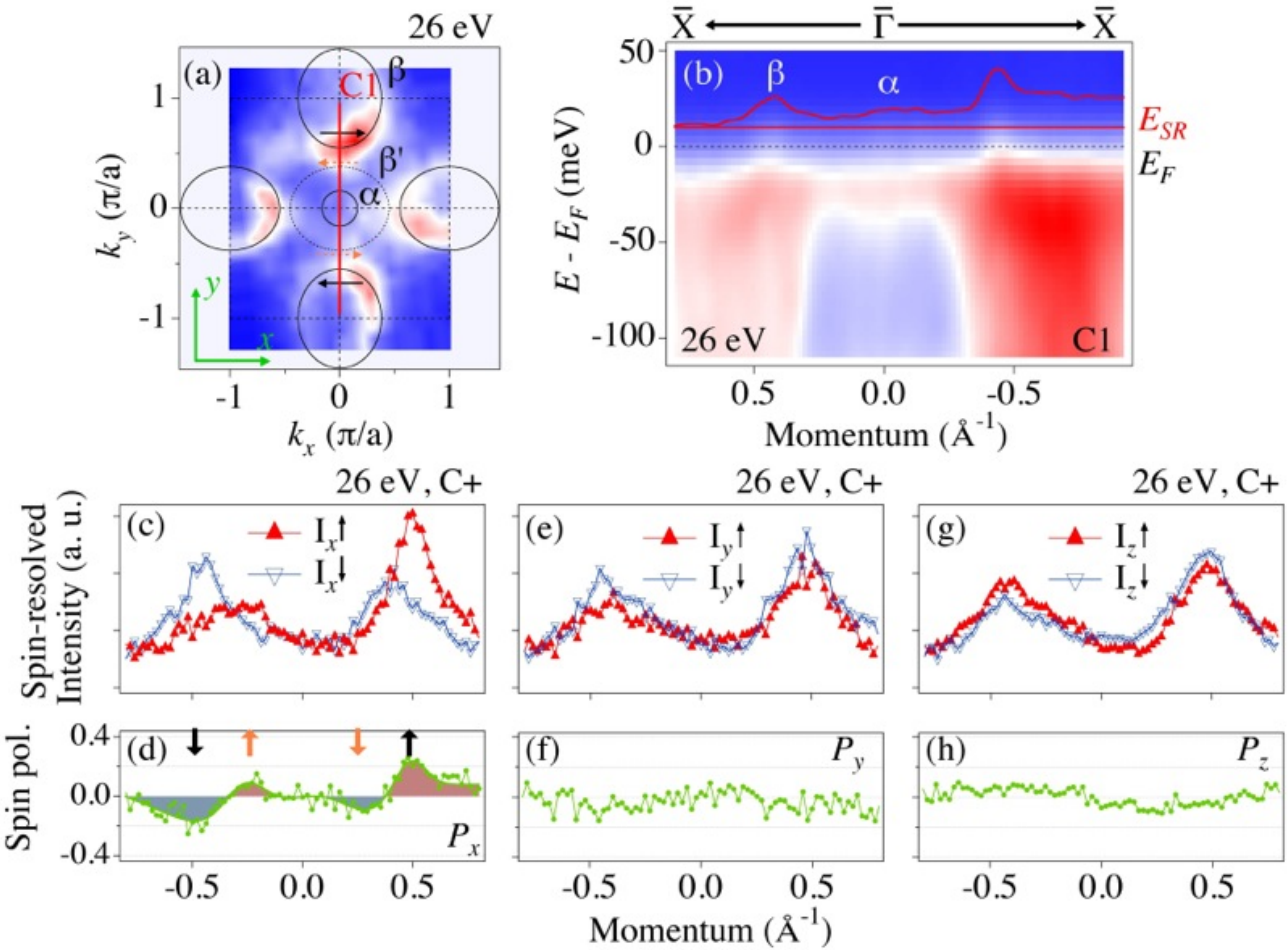


Xu, PRB 88, 121102 (2013)

D43.00001

Nan Xu , X. Shi , P. Biswas , C. Matt , R. Dhaka , Y. Huang , N. Plumb , M. Radovic ,
J. Dil , E. Pomjakushina , K. Conder , A. Amato , Z. Salman , D. Paul , J. Mesot , Hong Ding , Ming Shi

Spin Resolved ARPES (Courtesy, Hong Ding)



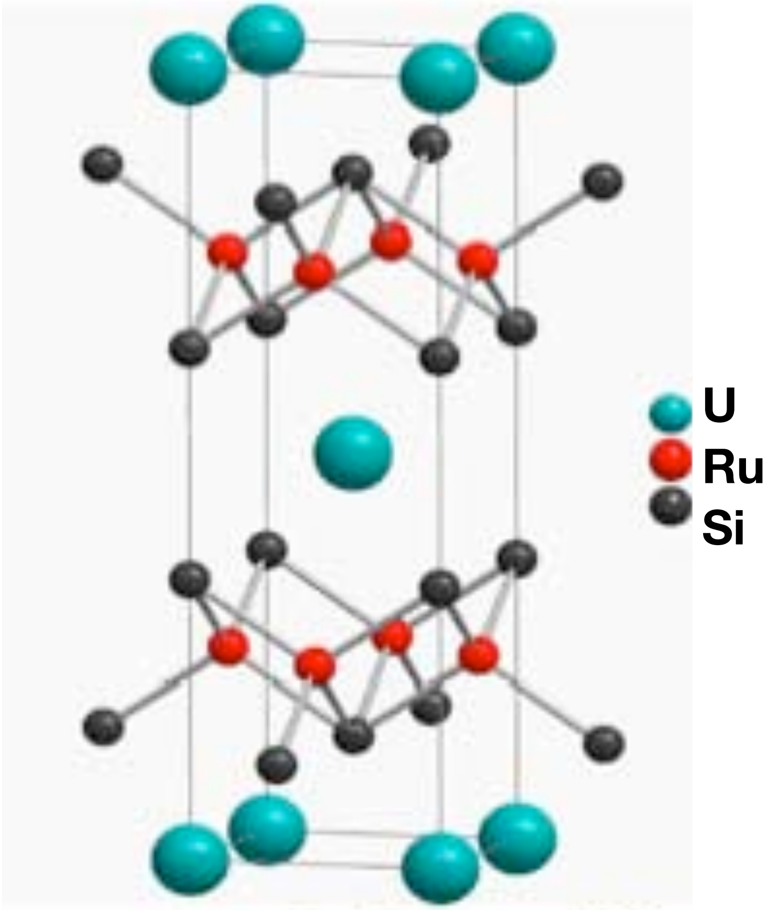
N. Xu *et al.*, Submitted (2013).

Open Challenges.

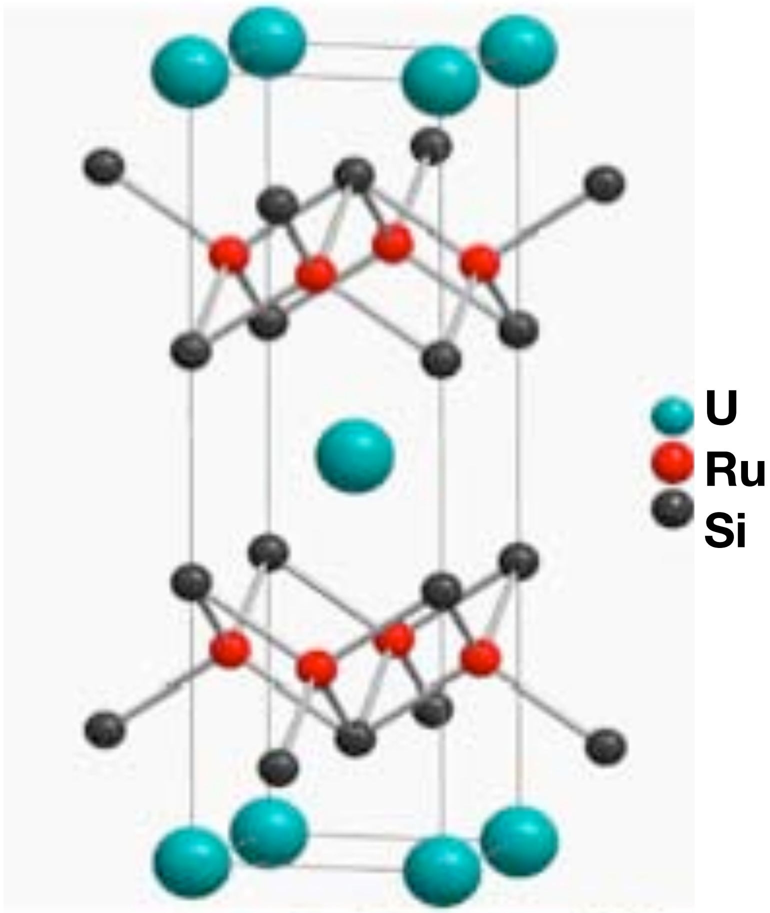
- Surface Kondo physics
- Why are the surface states so light?
- What aspects of KIs/TKIs are different to their weakly interacting counterparts?

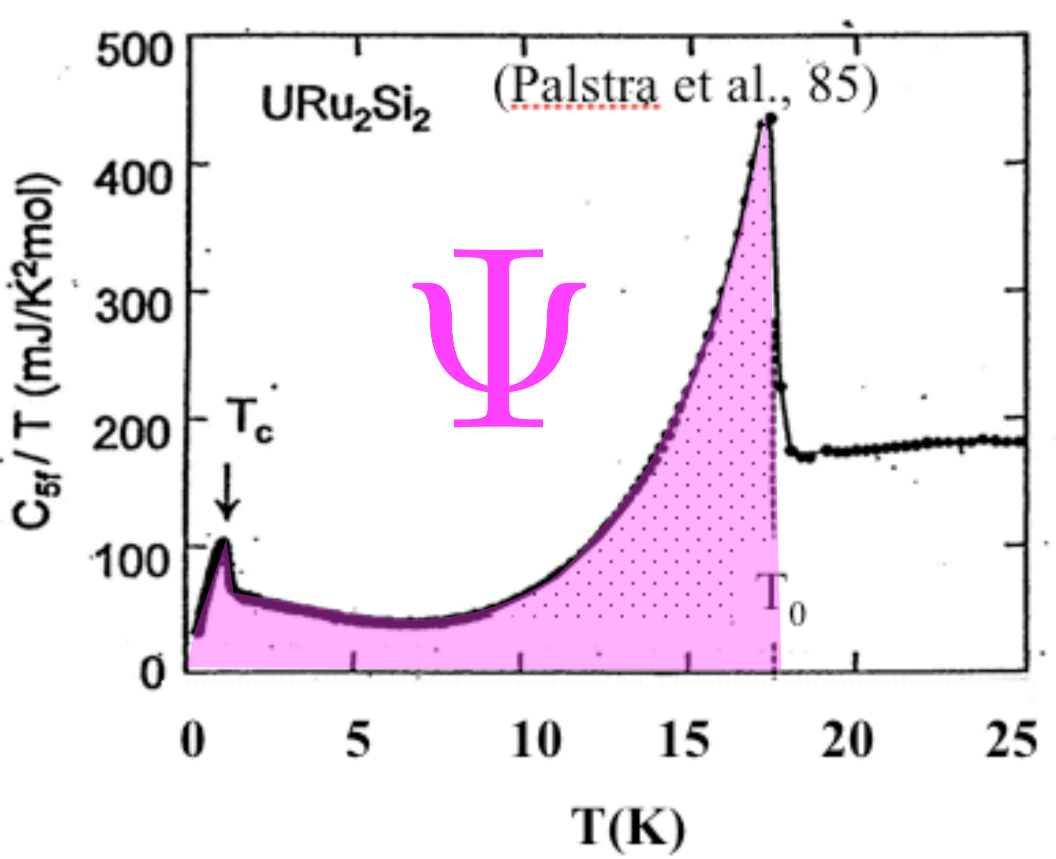
URu_2Si_2: The Hidden Order Mystery

Hidden Order in URu_2Si_2

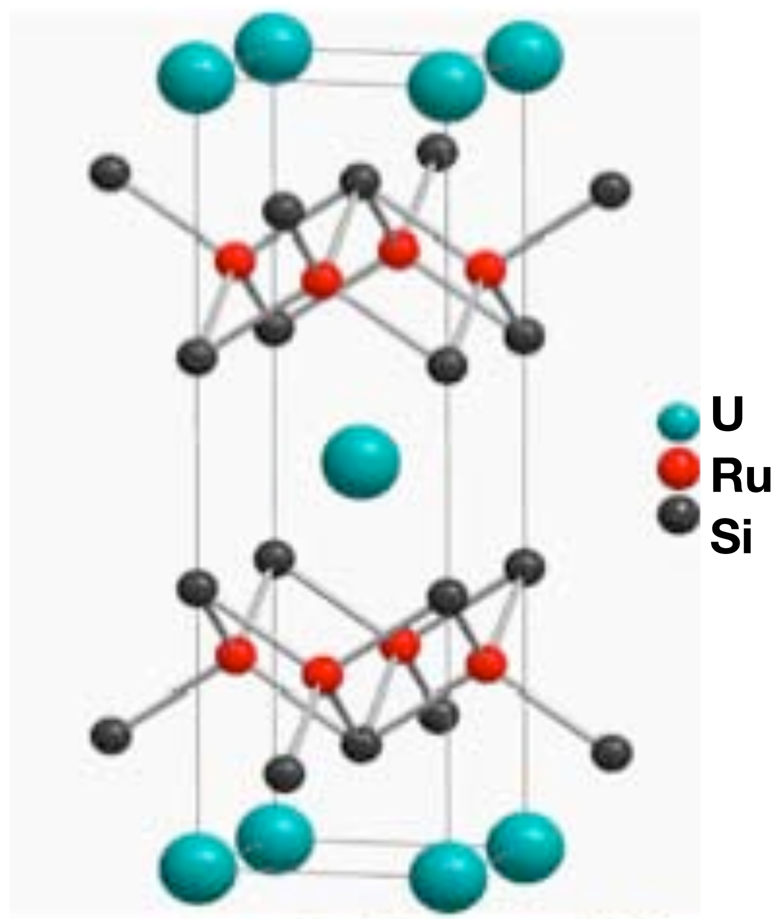


Hidden Order in URu_2Si_2

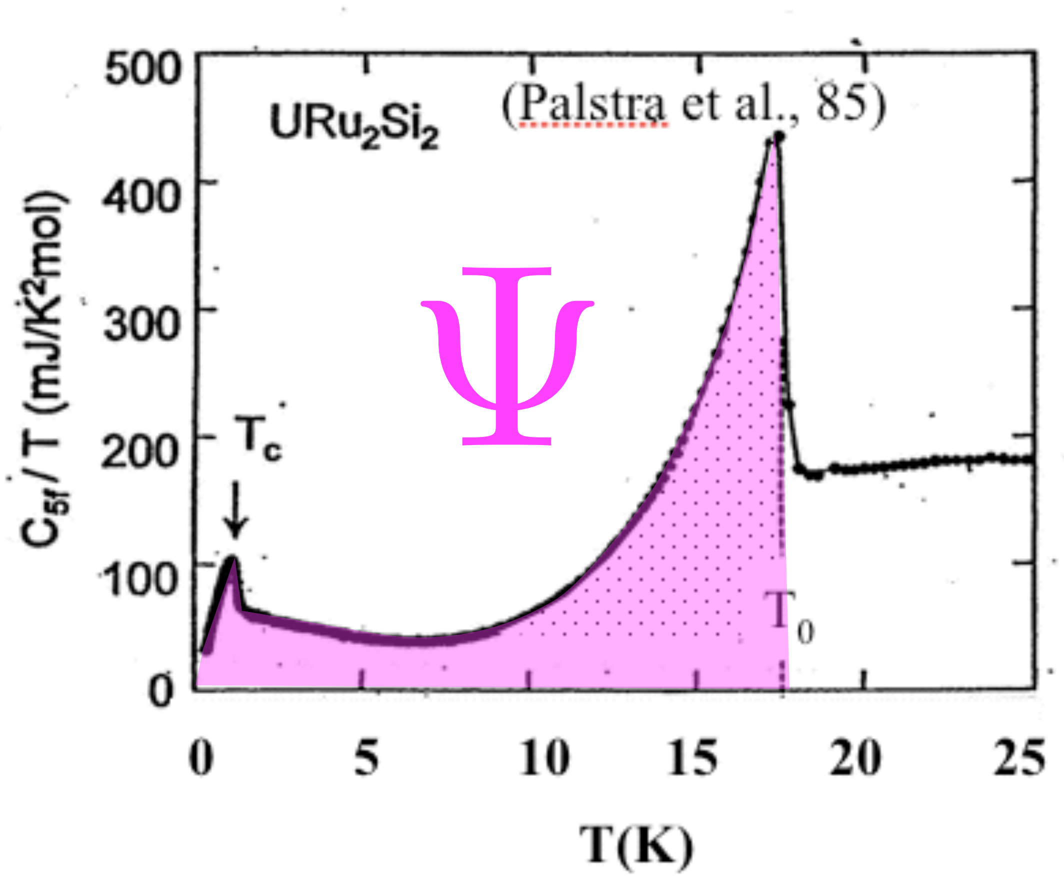




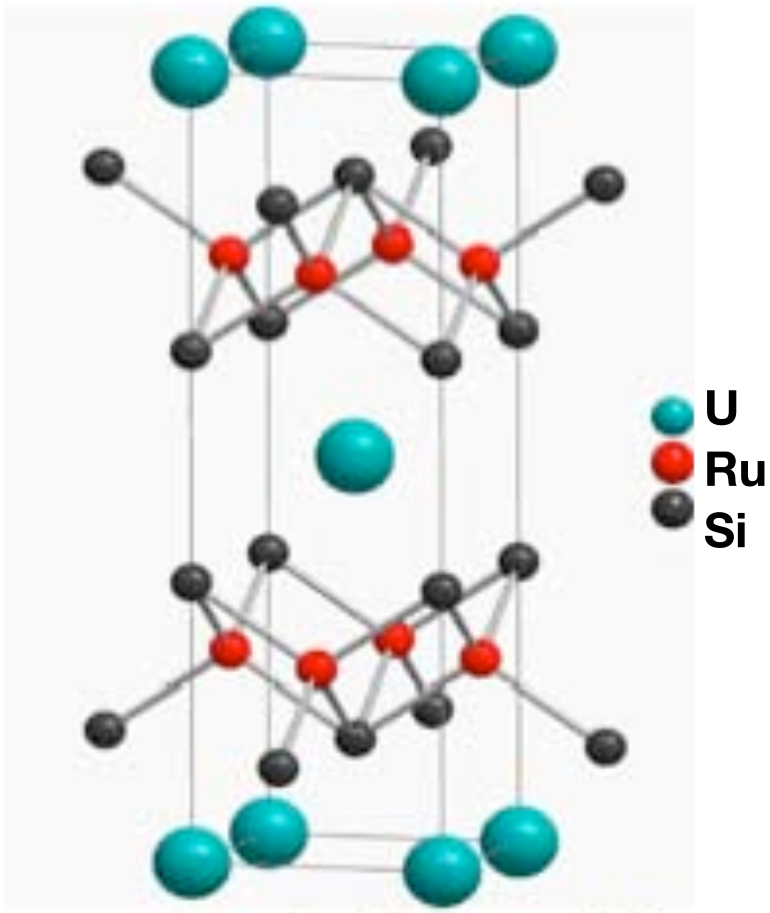
Hidden Order in URu_2Si_2



$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$



Hidden Order in URu_2Si_2



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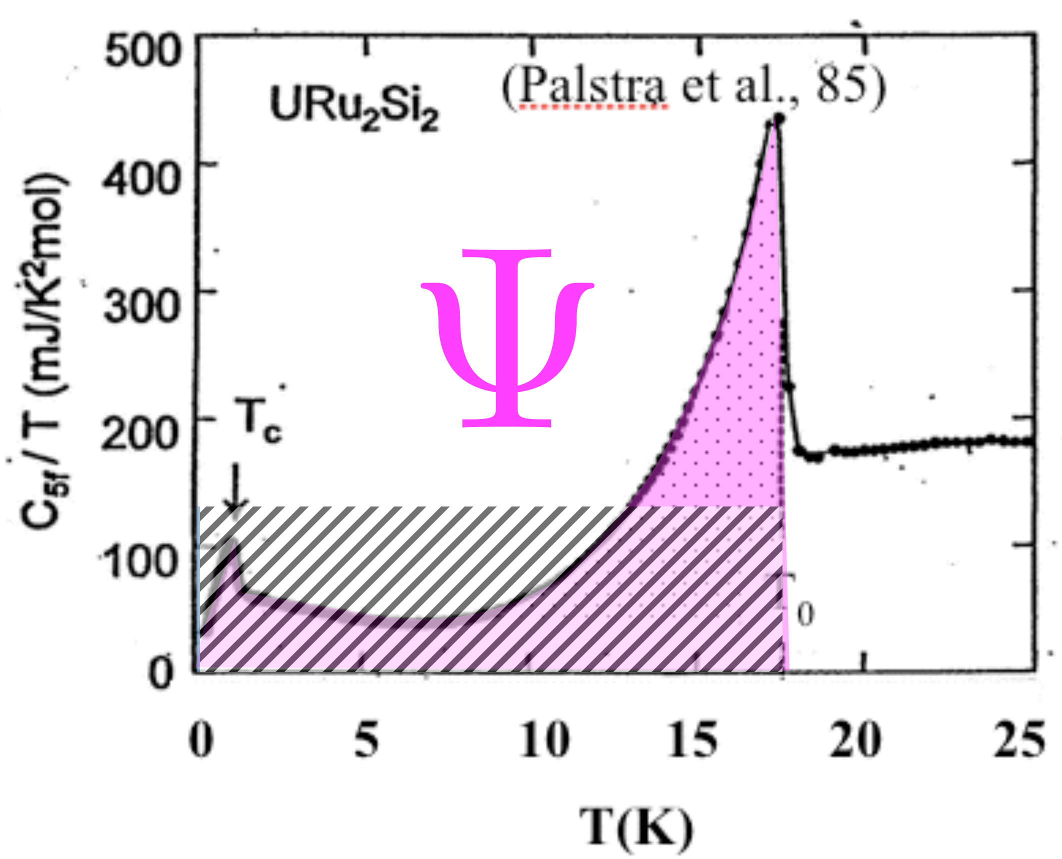

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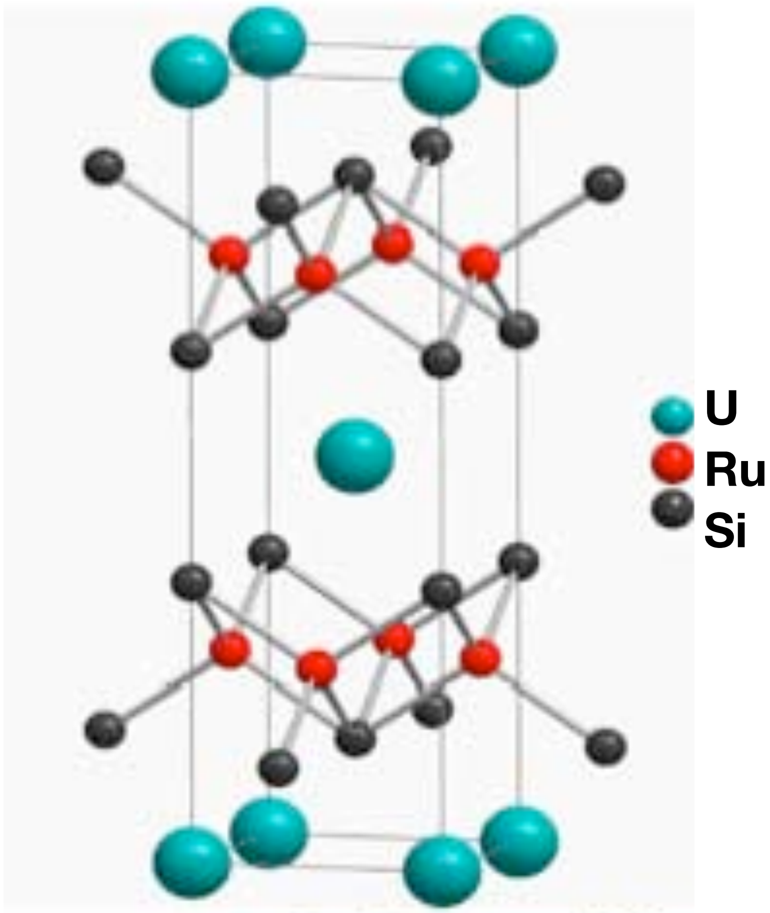
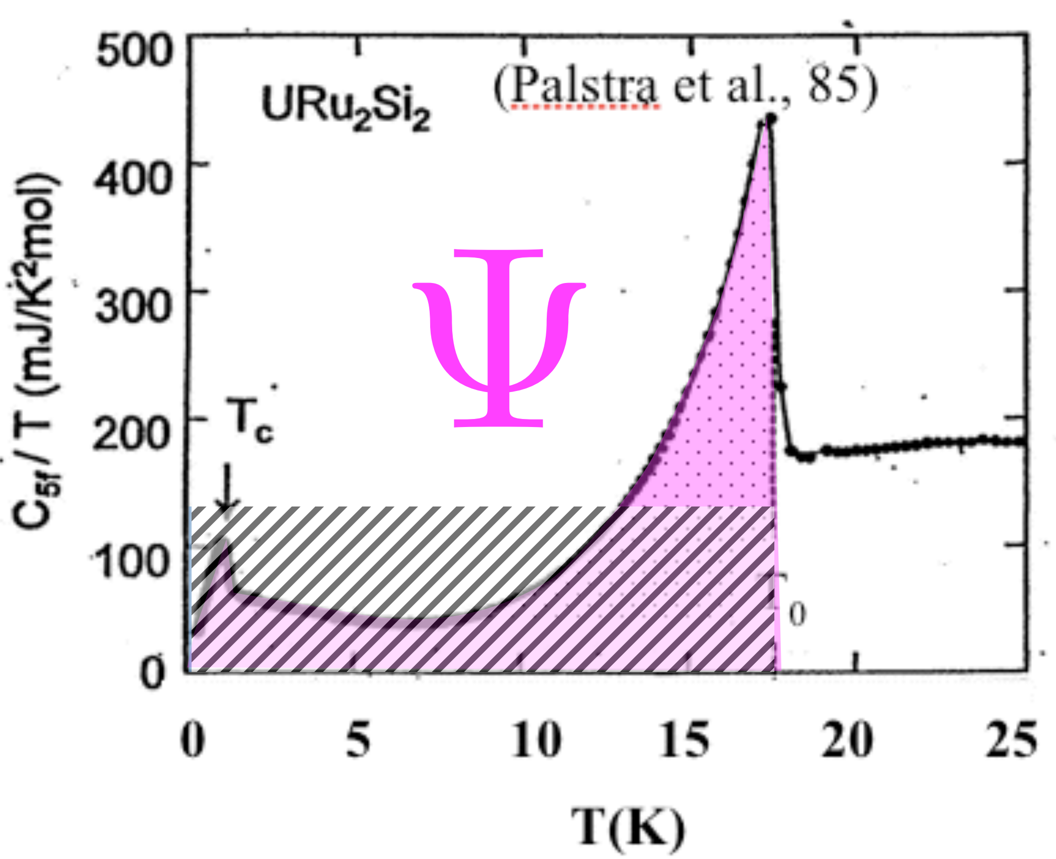


$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT$$

=0.14 x 17.5 K
=2.45 J/mol/K
=0.42 R ln 2



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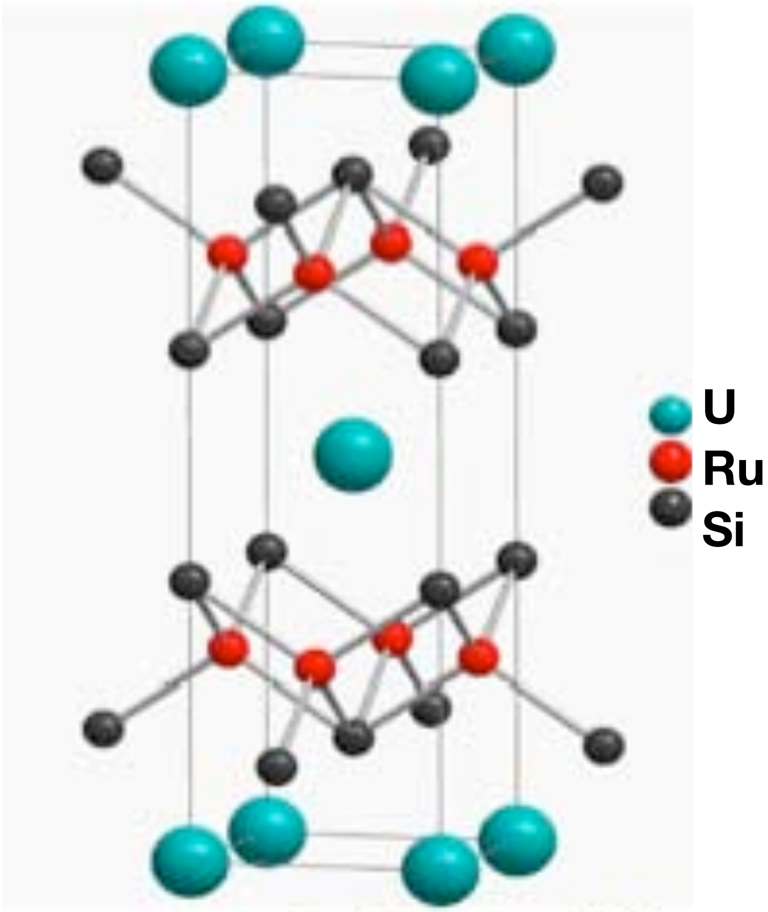

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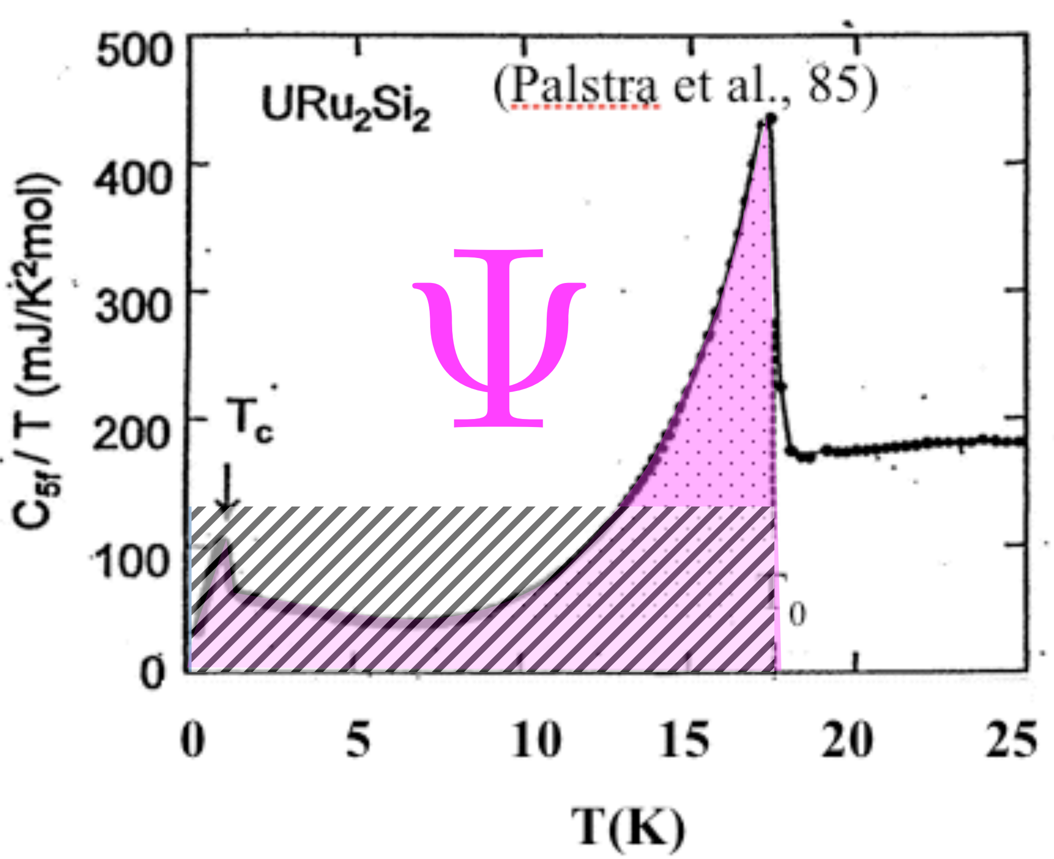
Large entanglement entropy.



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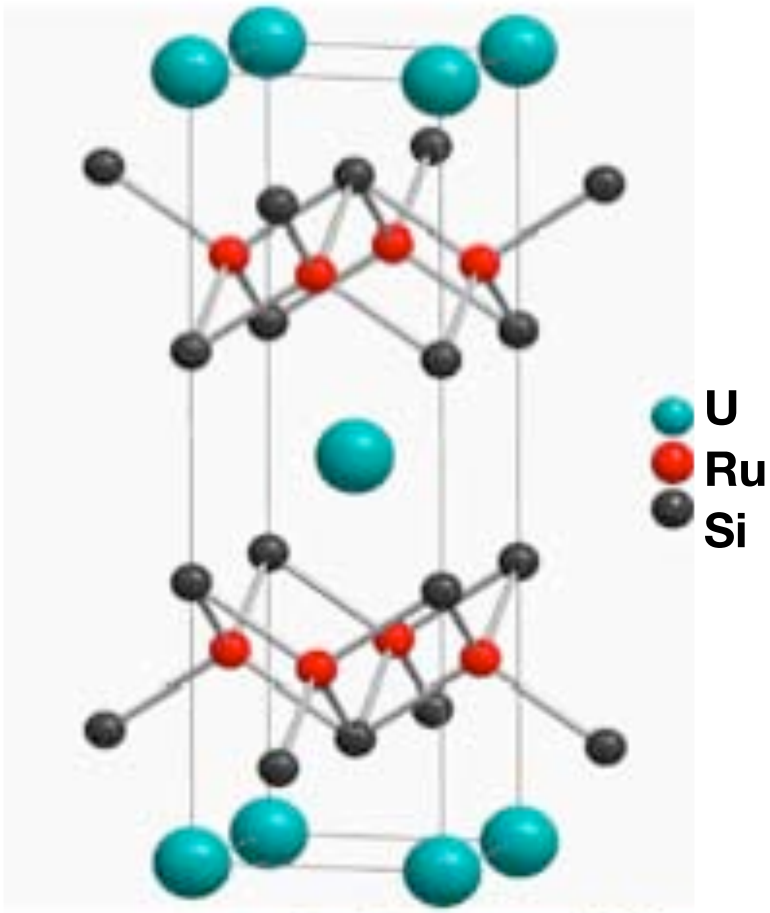

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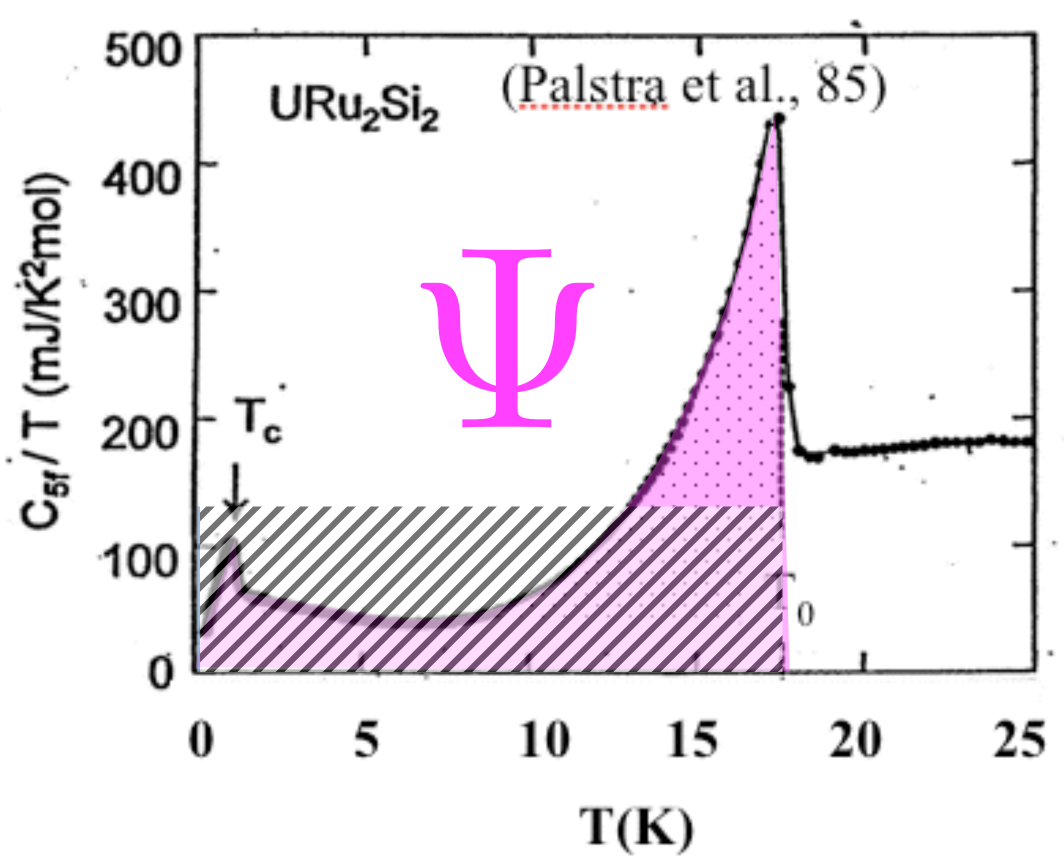
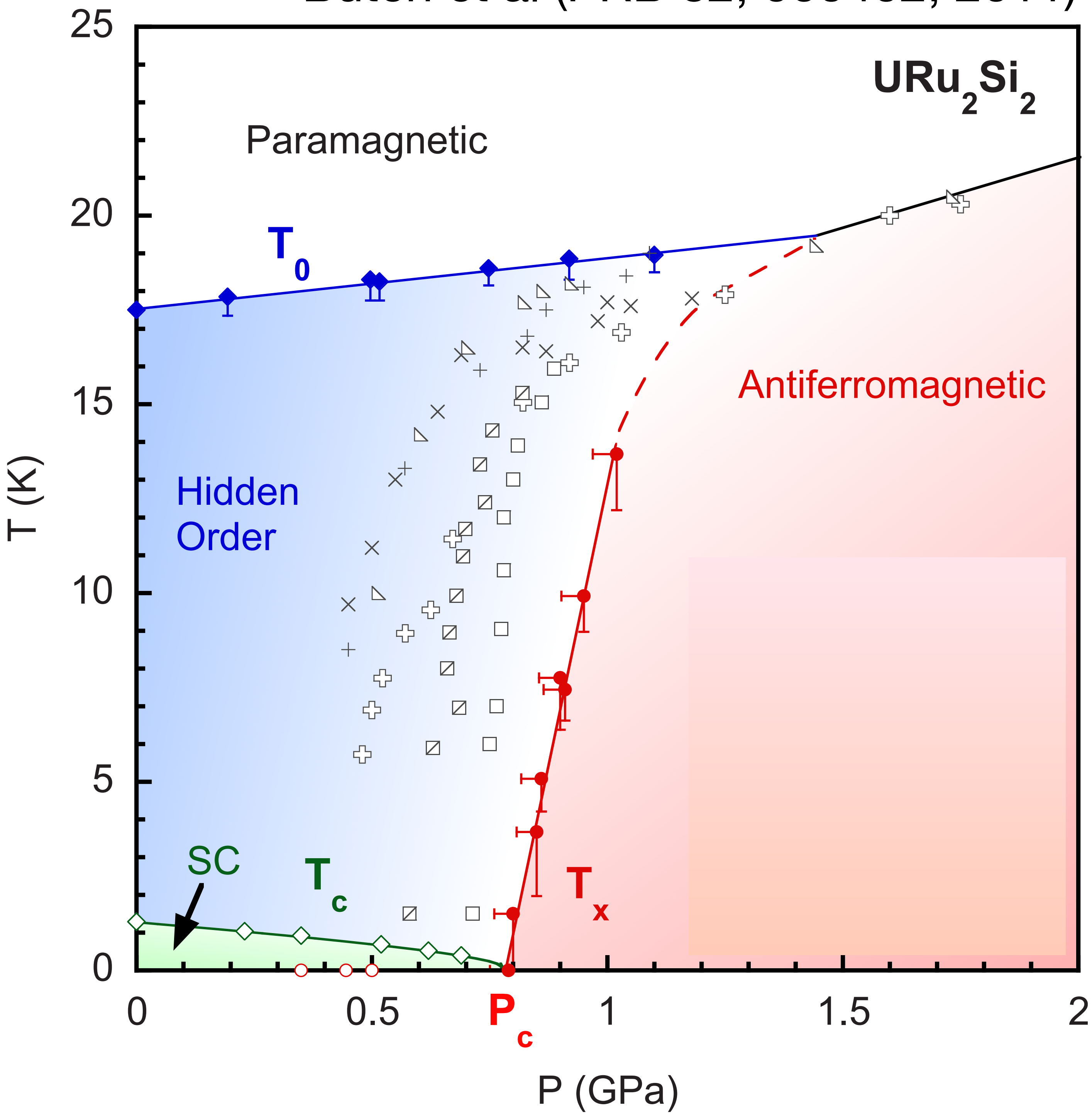


What is the nature of the hidden order?

High pressures, high fields

Butch et al (PRB 82, 060402, 2011)



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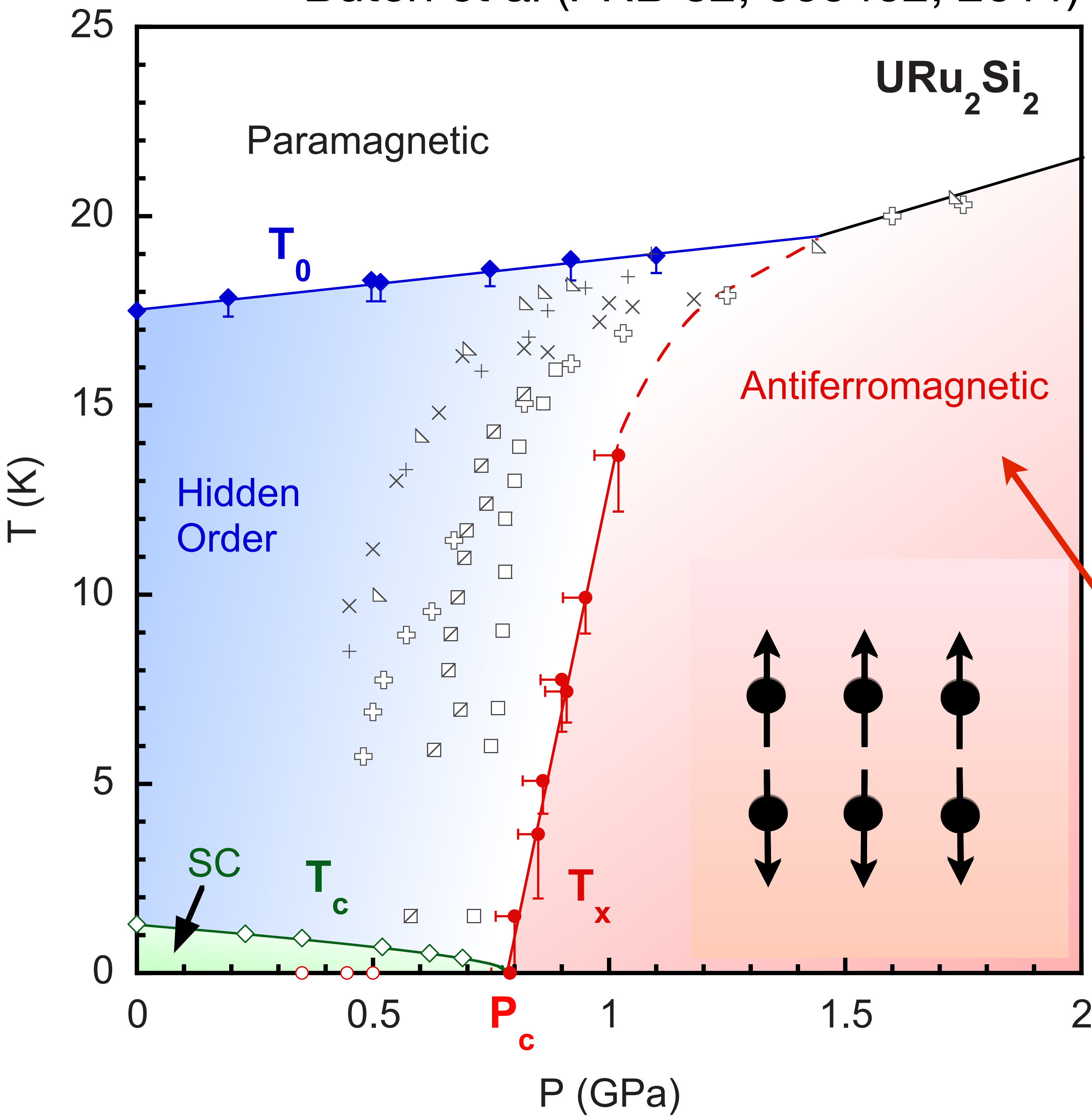
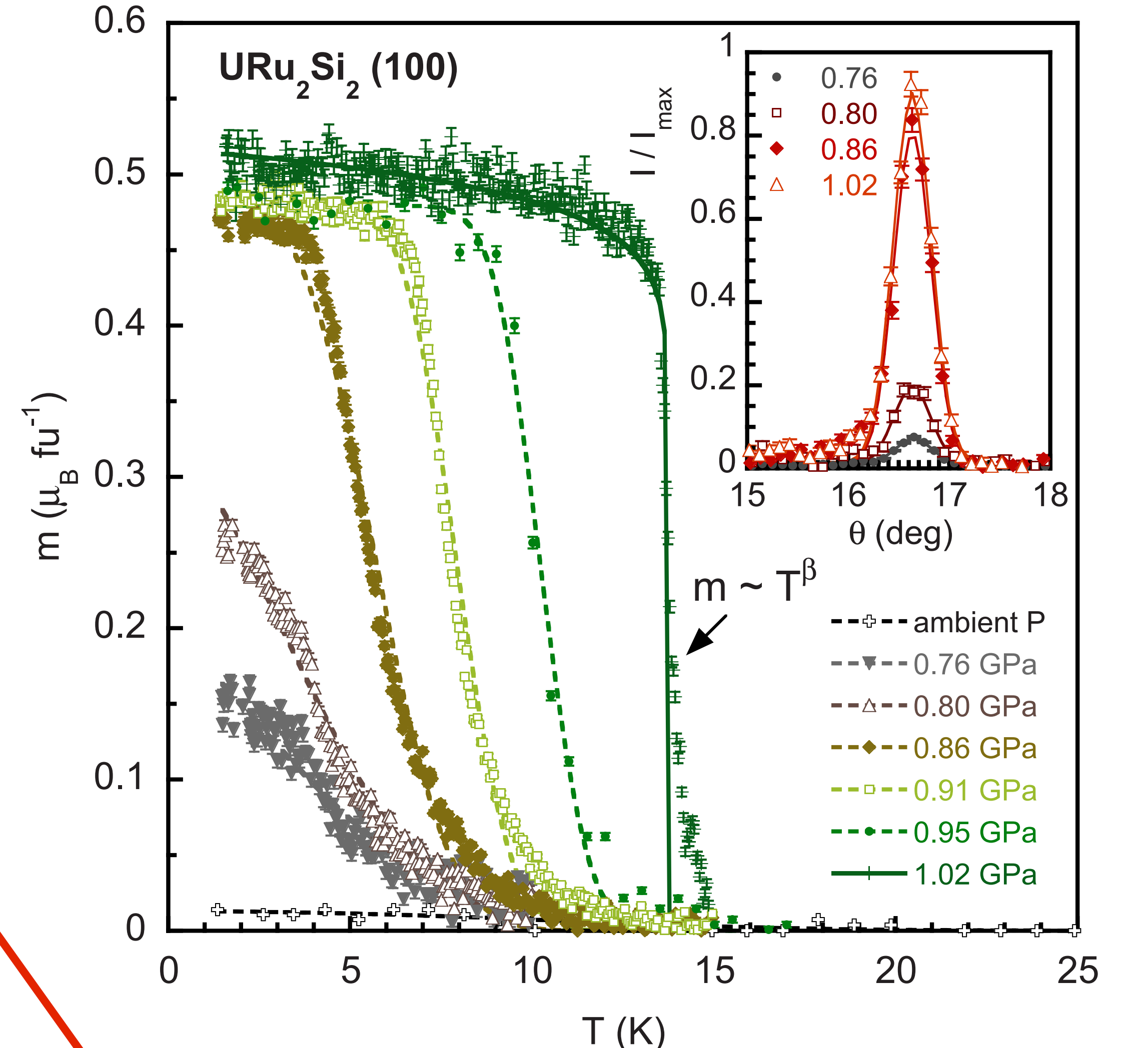


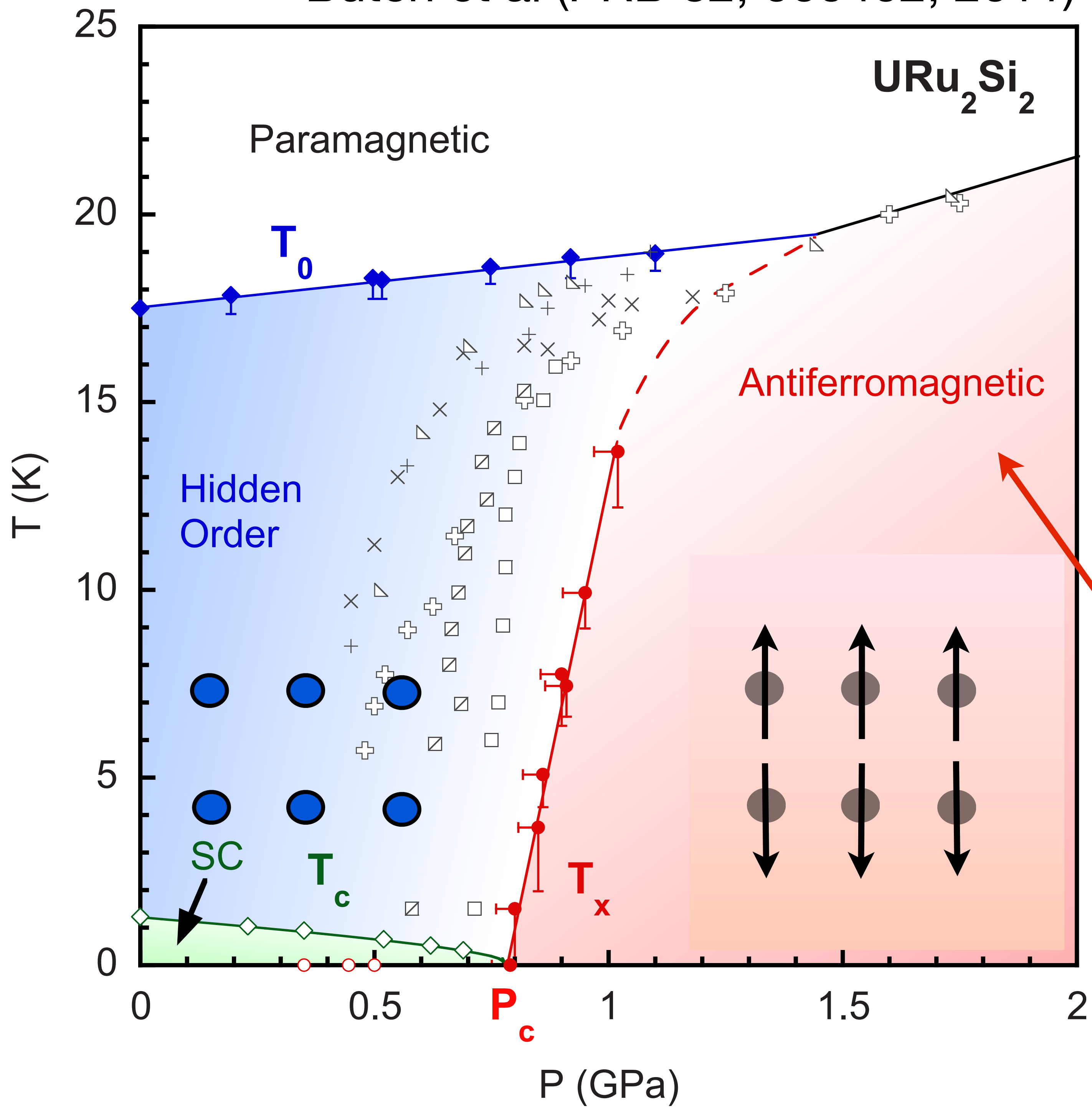


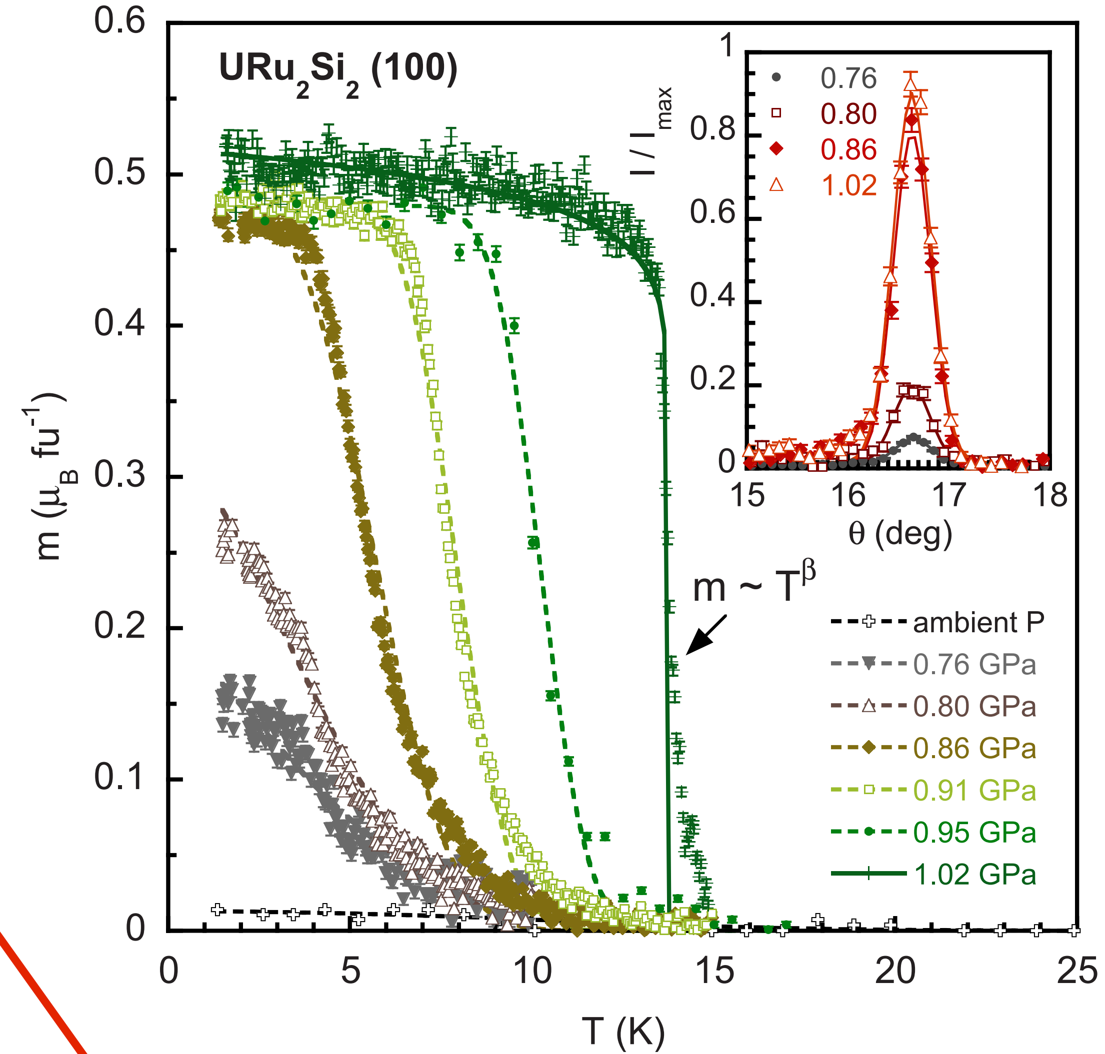
Ising order, present in LMAF,

High pressures, high fields

Rutgers Center for Materials Theory

Butch et al (PRB 82, 060402, 2011)

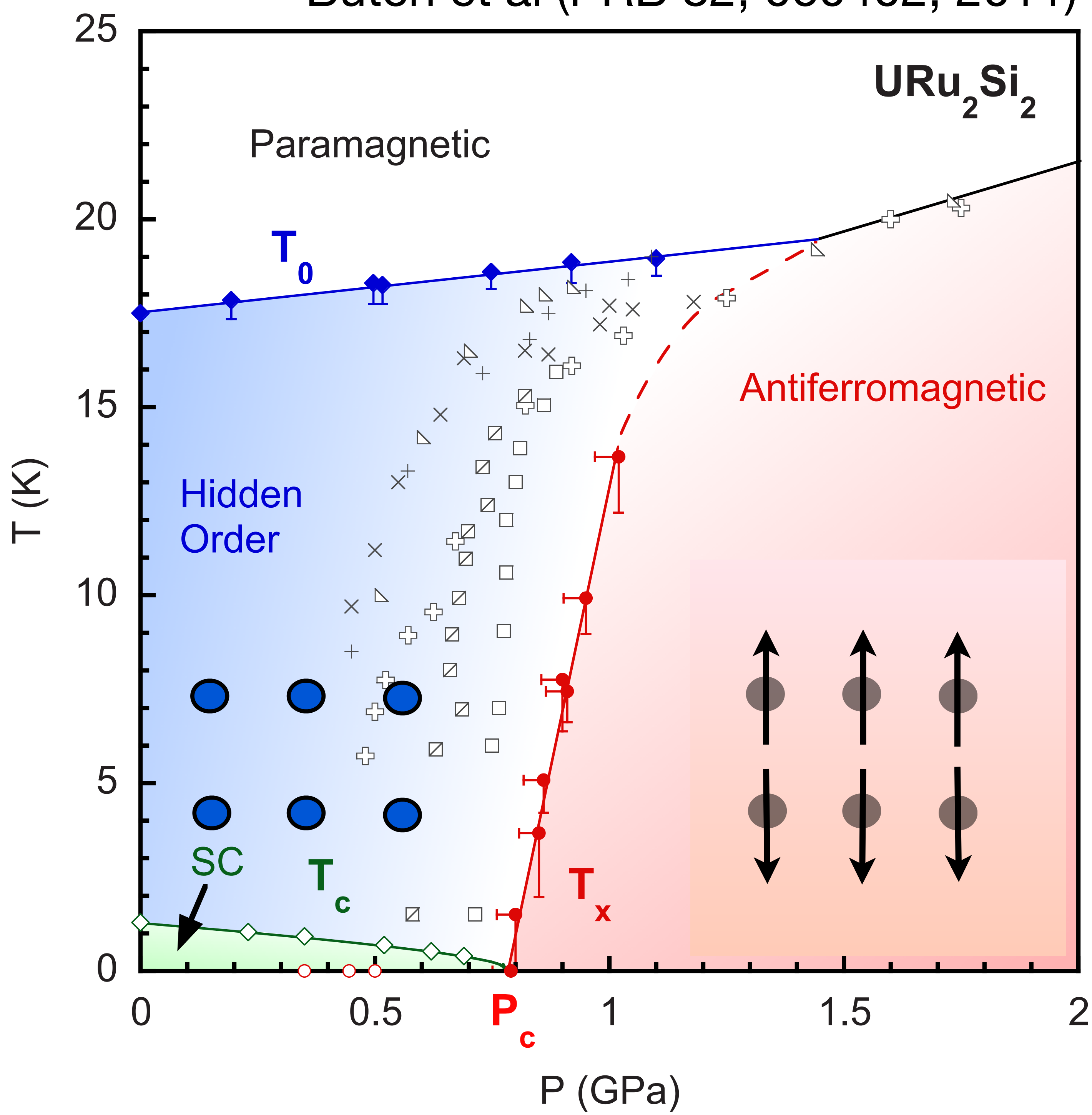




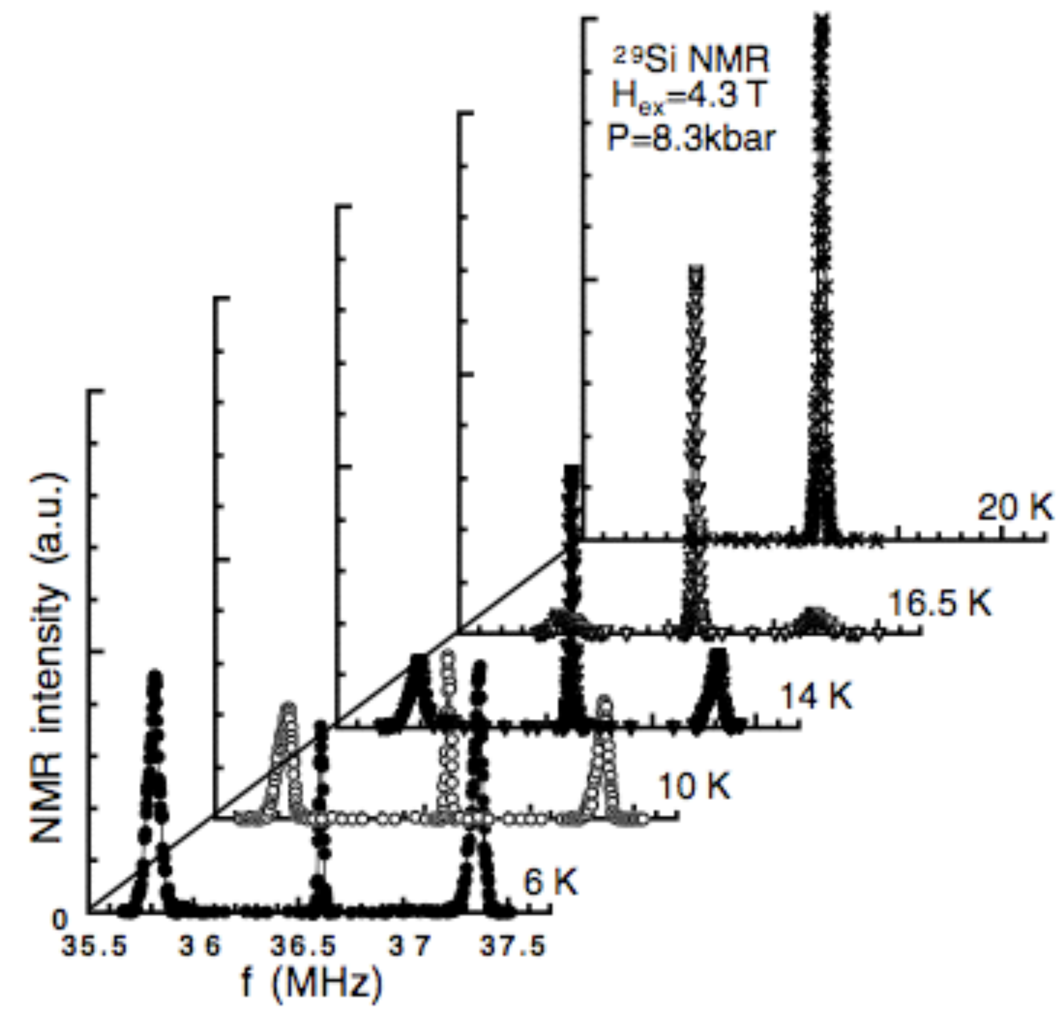
Ising order, present in LMAF, vanishes in the hidden order state. (NMR,MuSR).

High pressures, high fields

Butch et al (PRB 82, 060402, 2011)



McElfresh et al. (87), Fisher et al (90), Luke et al (94), Amitsuka et al. (99)



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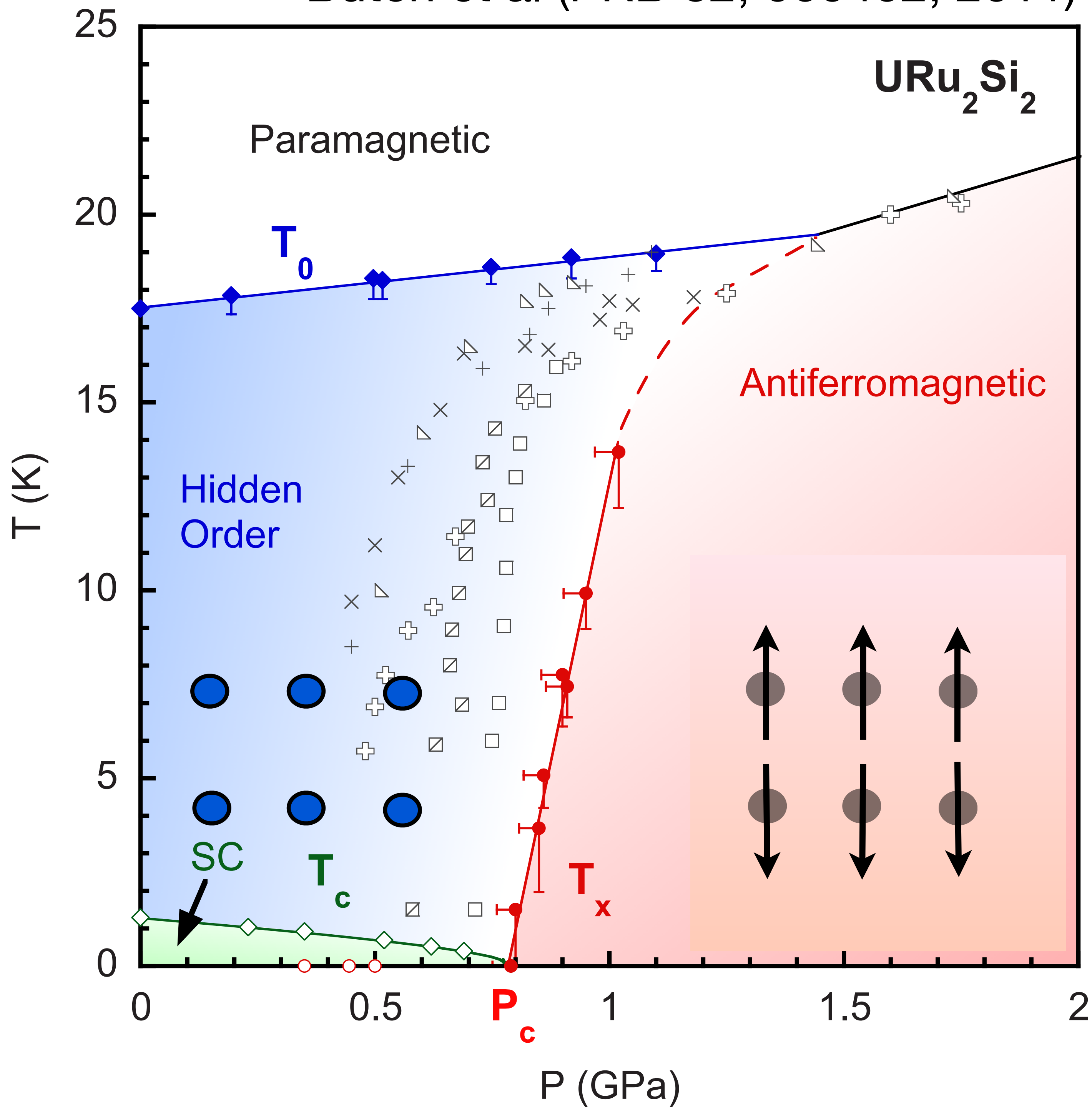

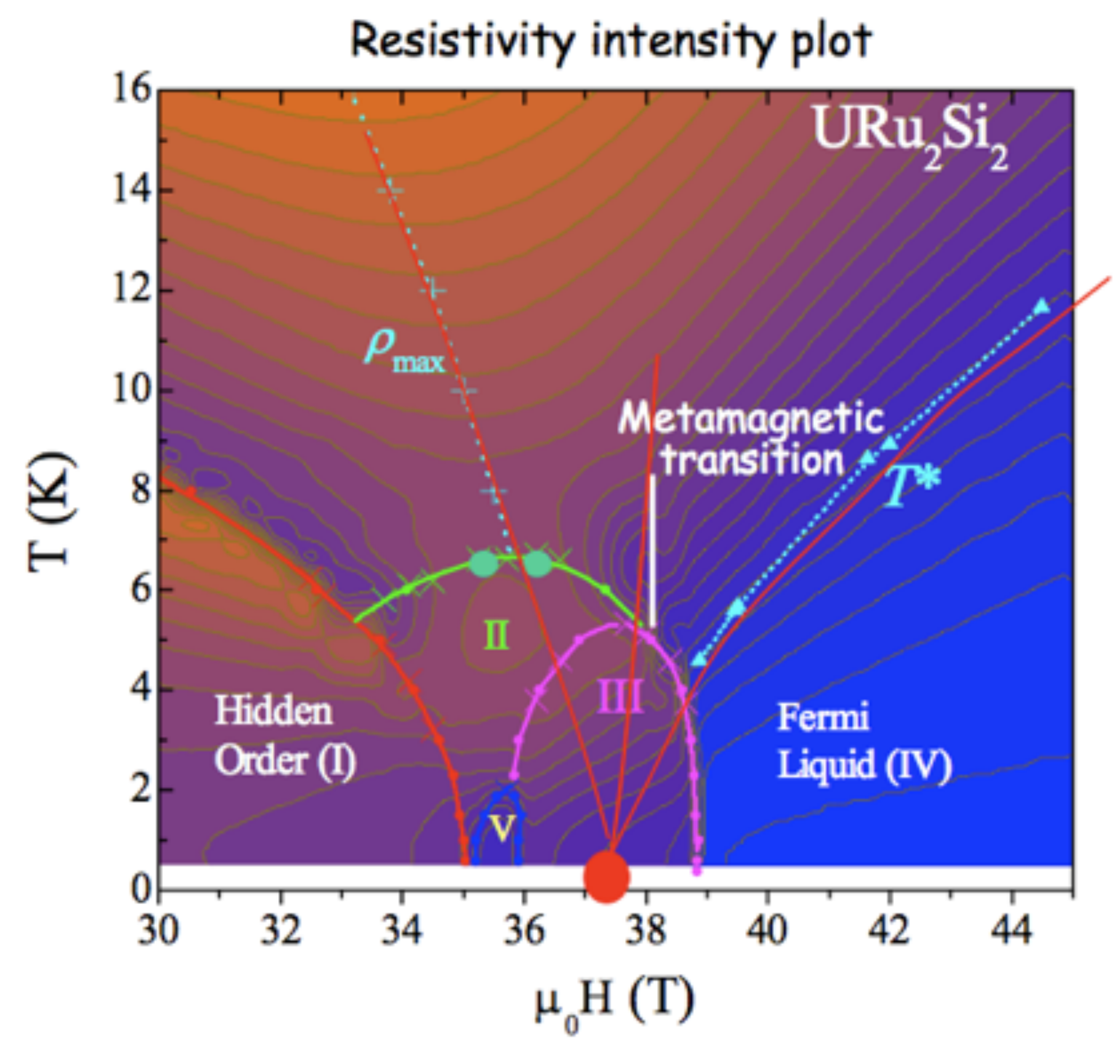

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What is the nature of the hidden order?

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25 Years of Theoretical Proposals

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25 Years of Theoretical Proposals

Landau Theory

Shah et al. ('00) "Hidden Order"

What is the nature of the hidden order?

25 Years of Theoretical Proposals

Landau Theory	Shah et al. ('00) "Hidden Order"
Itinerant	Ramirez et al, '92 (Quadrupolar SDW)
	Ikeda and Ohashi '98 (d-density wave)
	Okuno and Miyake '98 (composite)
	Tripathi, Chandra, PC and Mydosh, '02 (orbital afm)
	Dori and Maki, '03 (Unconventional SDW)
	Mineev and Zhitomirsky, '04 (SDW)
	Varma and Zhu, '05 (Spin-nematic)
	Ezgar et al '06 (Dynamic symmetry breaking)
	Fujimoto, '11 (Spin-nematic)
	Ikeda et al '12 (Rank 5 nematic)
	Rau and Kee '12 (Rank 5 pseudo-spin vector)
	Tanmoy Das '12 (Topological Spin-nematic)

What is the nature of the hidden order?

25 Years of Theoretical Proposals

Landau Theory	Shah et al. ('00) "Hidden Order"
Itinerant	Ramirez et al, '92 (Quadrupolar SDW)
	Ikeda and Ohashi '98 (d-density wave)
	Okuno and Miyake '98 (composite)
	Tripathi, Chandra, PC and Mydosh, '02 (orbital afm)
	Dori and Maki, '03 (Unconventional SDW)
	Mineev and Zhitomirsky, '04 (SDW)
	Varma and Zhu, '05 (Spin-nematic)
	Ezgar et al '06 (Dynamic symmetry breaking)
	Fujimoto, '11 (Spin-nematic)
	Ikeda et al '12 (Rank 5 nematic)
	Rau and Kee '12 (Rank 5 pseudo-spin vector)
	Tanmoy Das '12 (Topological Spin-nematic)
Local	Barzykin & Gorkov, '93 (three-spin correlation)
	Santini & Amoretti, '94, Santini ('98) (Quadrupole order)
	Amitsuka & Sakihabara (Γ_5, Quadrupolar doublet, '94)
	Kasuya, '97 (U dimerization)
	Kiss and Fazekas '04, (Rank 3 octupolar order)
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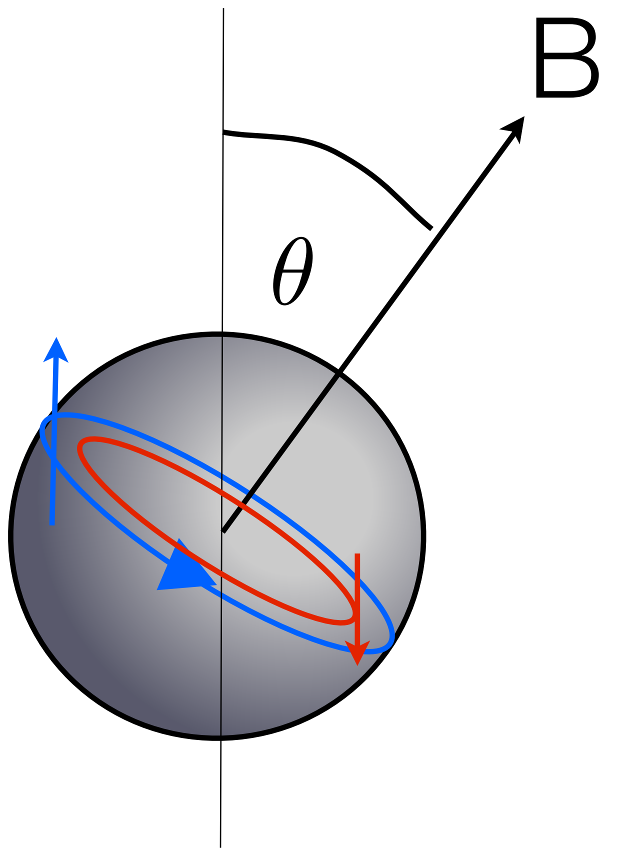
	Pepin et al '10 (Spin liquid/Kondo Lattice)
Kondo Lattice	Dubi and Balatsky, '10 (Hybridization density wave)

The Giant Ising Anisotropy.

Quantum Oscillations and Spin Zeros

Quantum Oscillations and Spin Zeros



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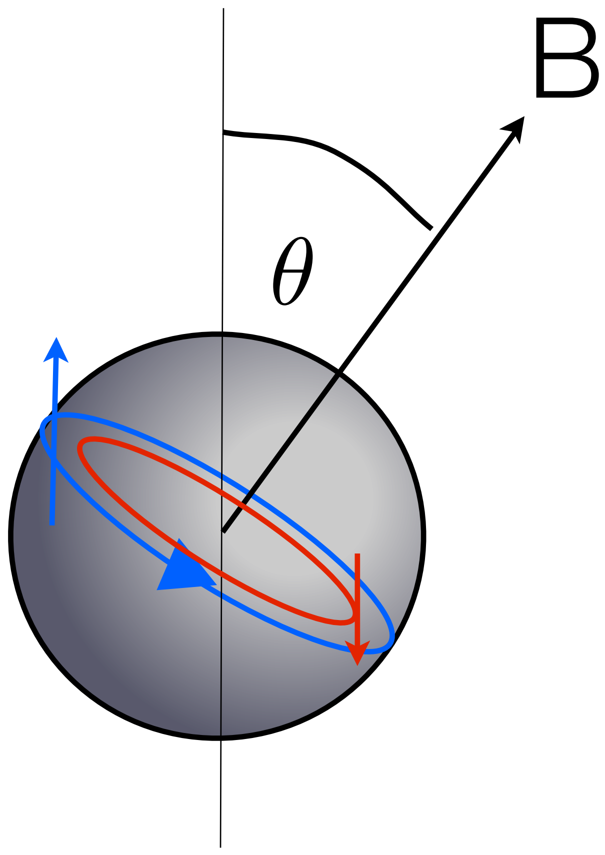
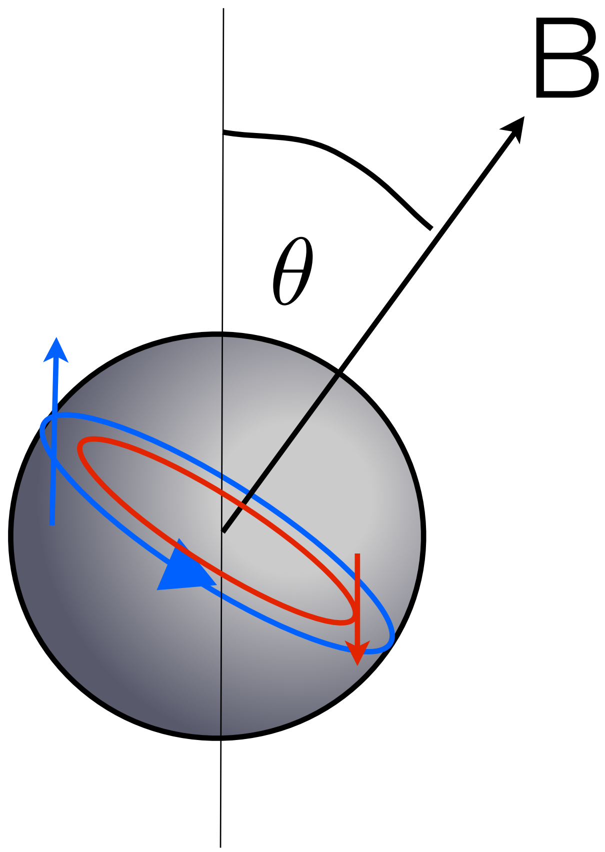


$$M \propto \cos\left[2\pi \frac{\text{Zeeman}}{\text{cyclotron}}\right]$$

Quantum Oscillations and Spin Zeros



$$\frac{g}{2}\,\frac{eB}{2m_e}$$

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$$\omega_c = \frac{eB}{m^*}$$

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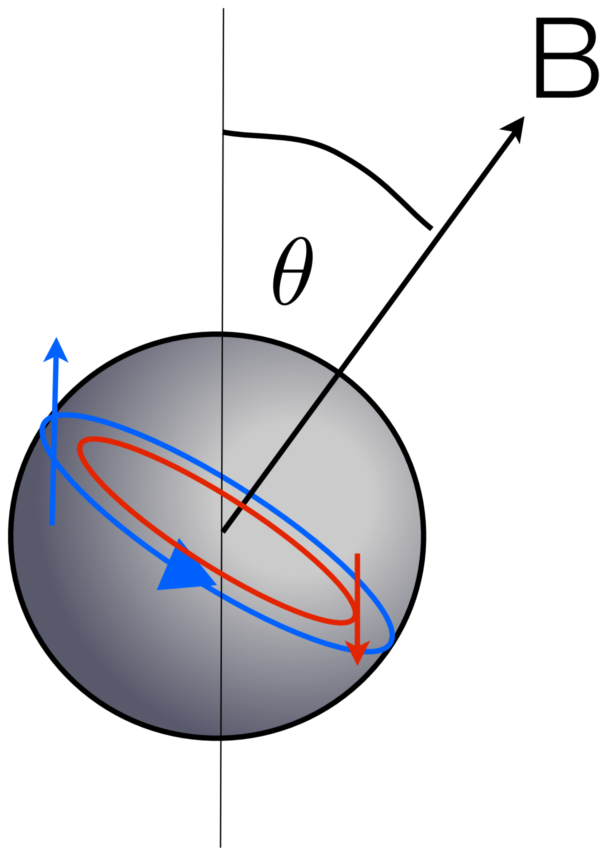

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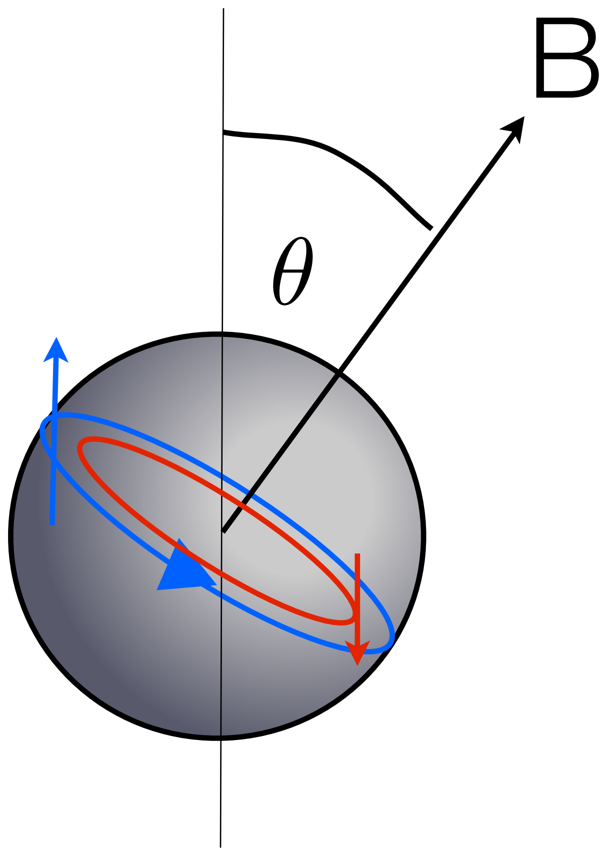

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Spin Zero condition

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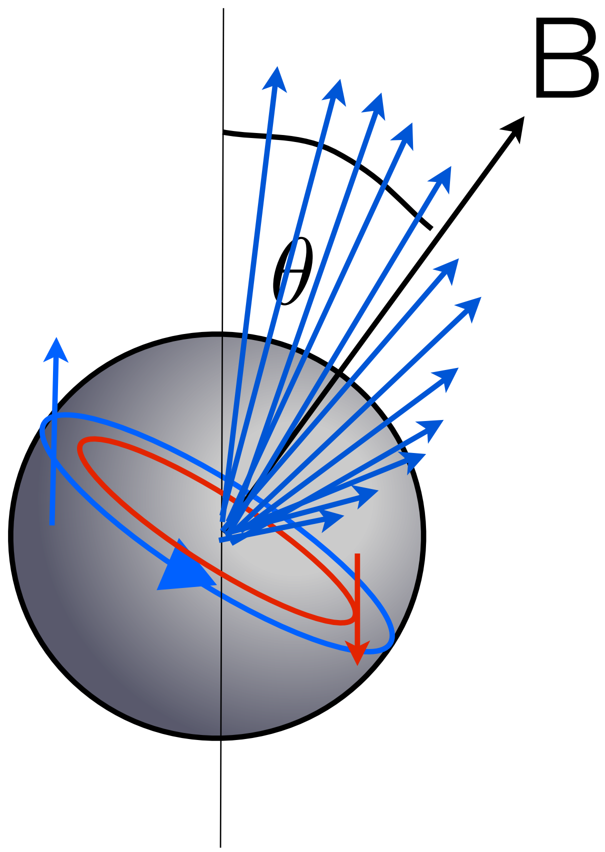

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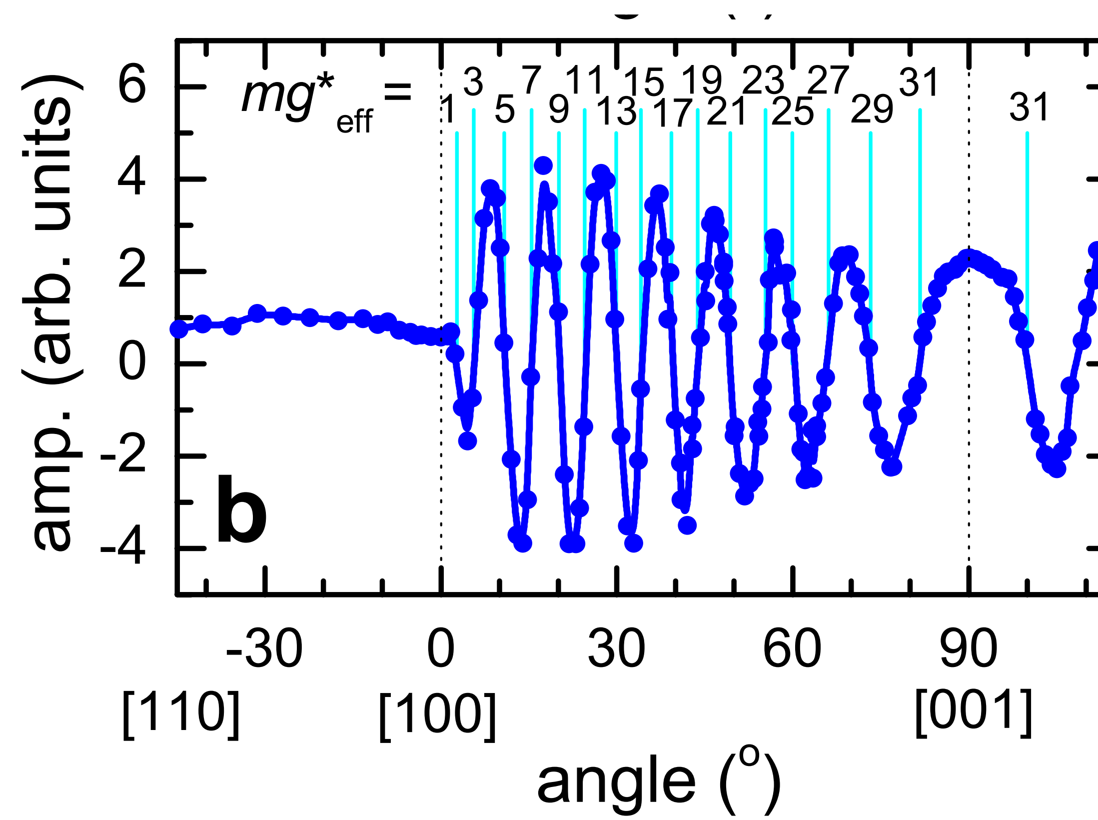

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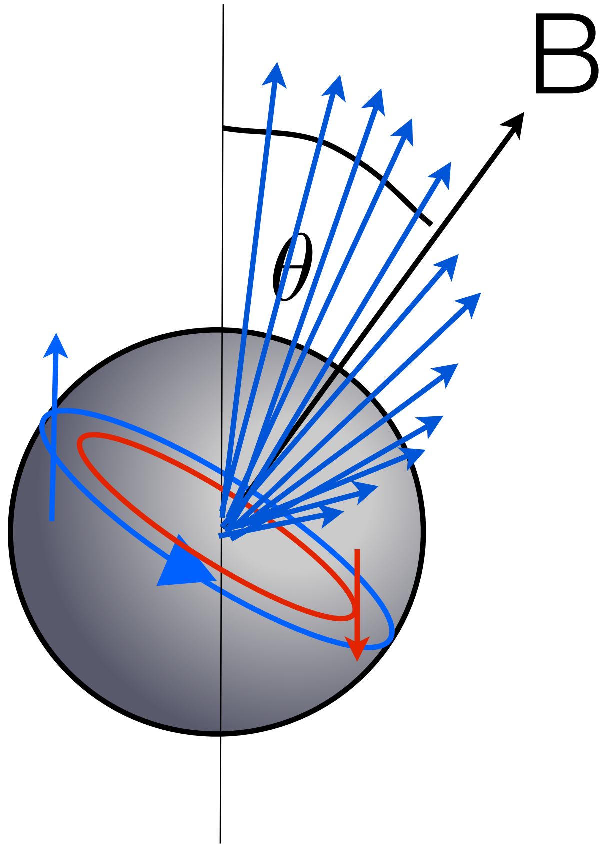
Quantum Oscillations and Spin Zeros



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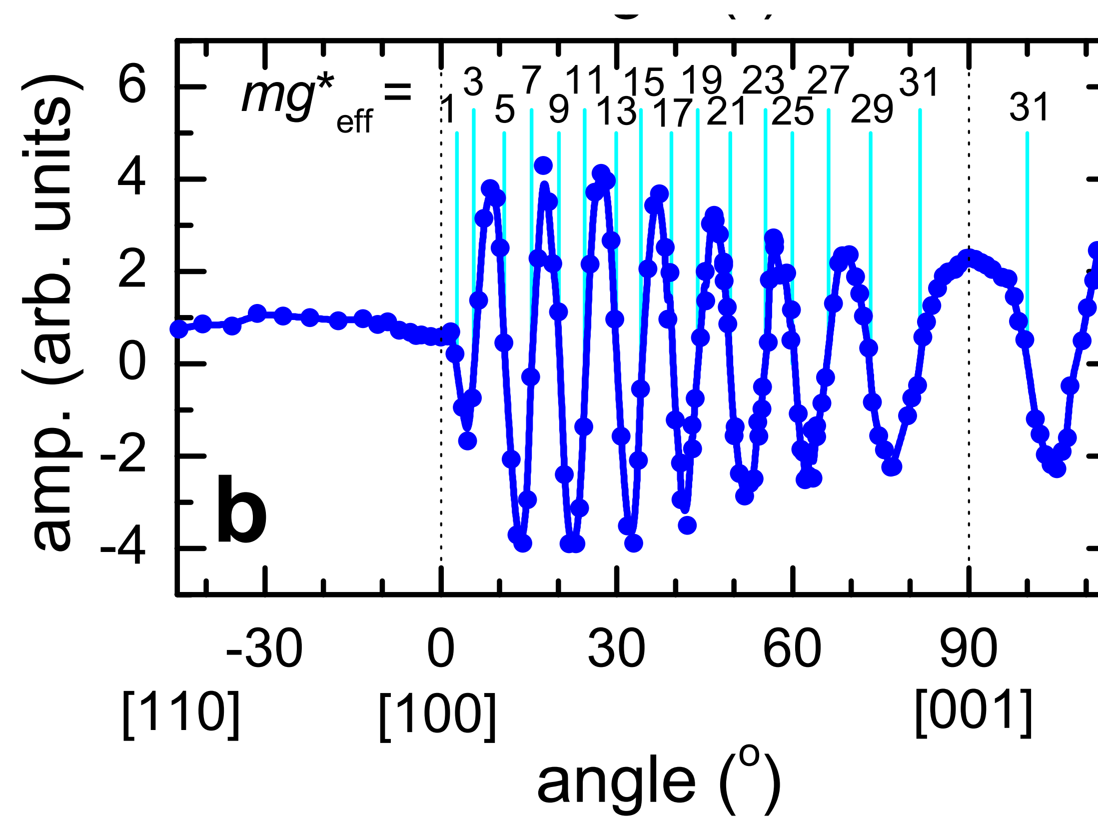

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16 spin zeros!

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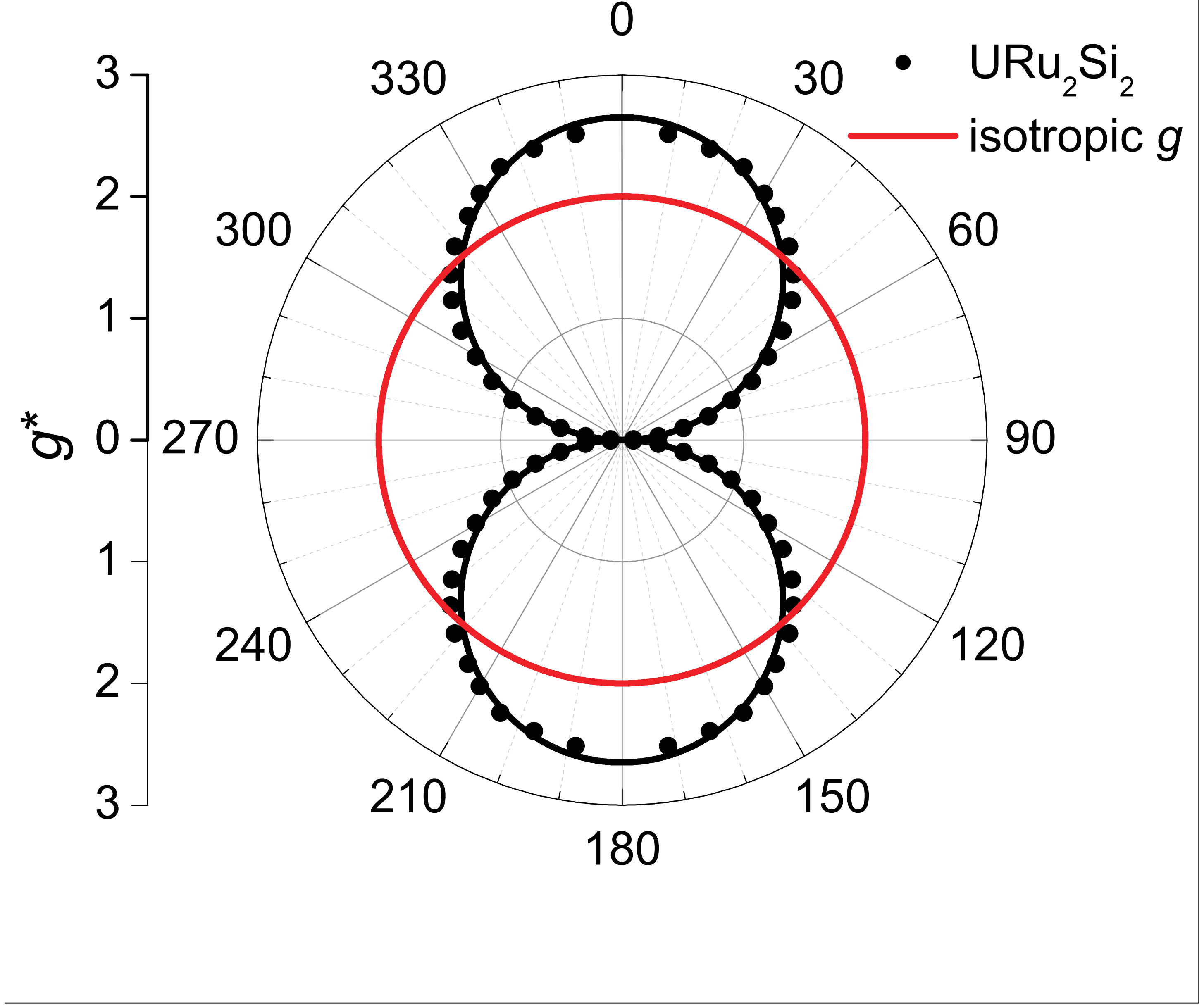

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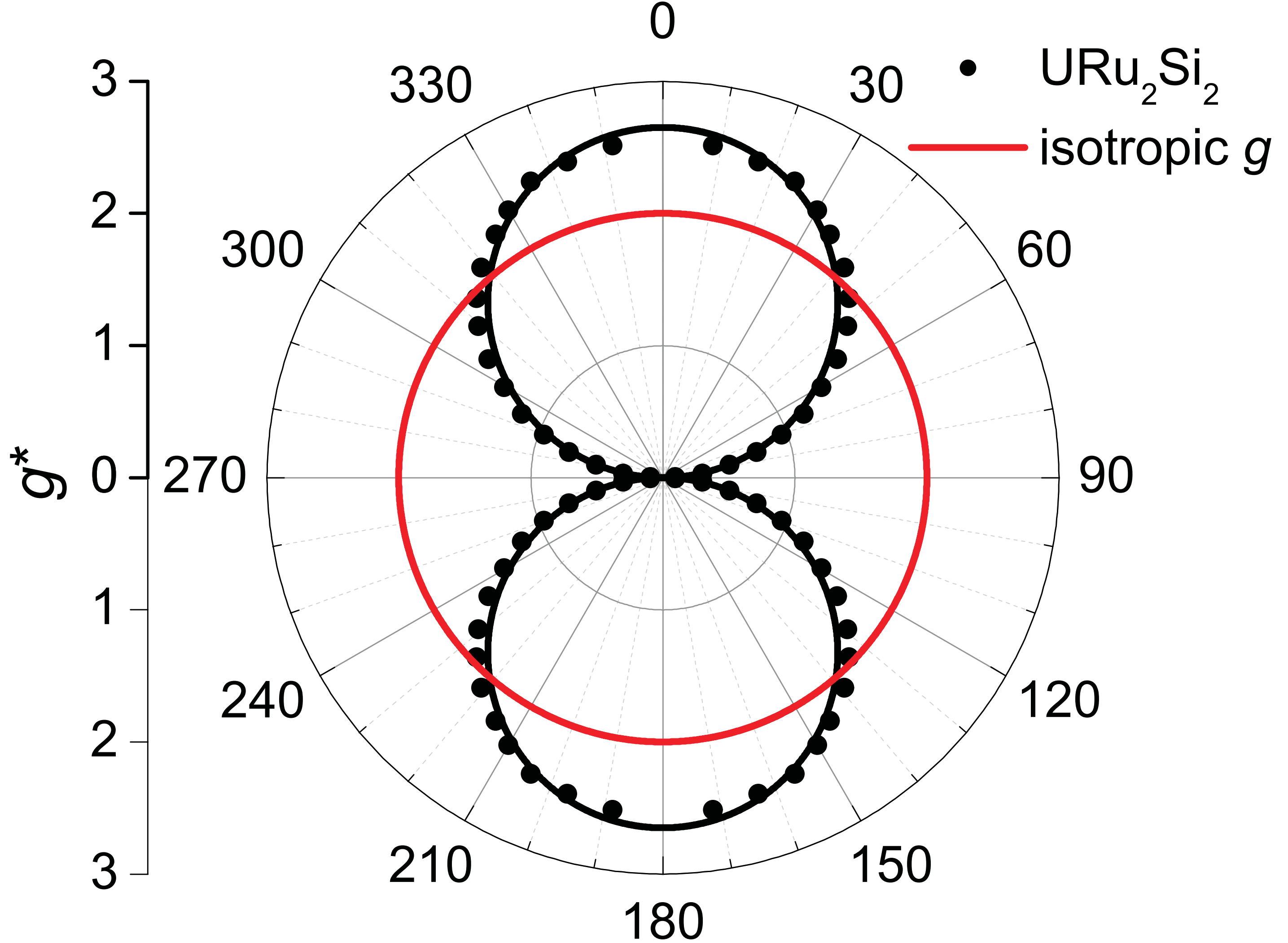

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Quasiparticle with giant Ising anisotropy > 30.
Pauli susceptibility anisotropy > 900

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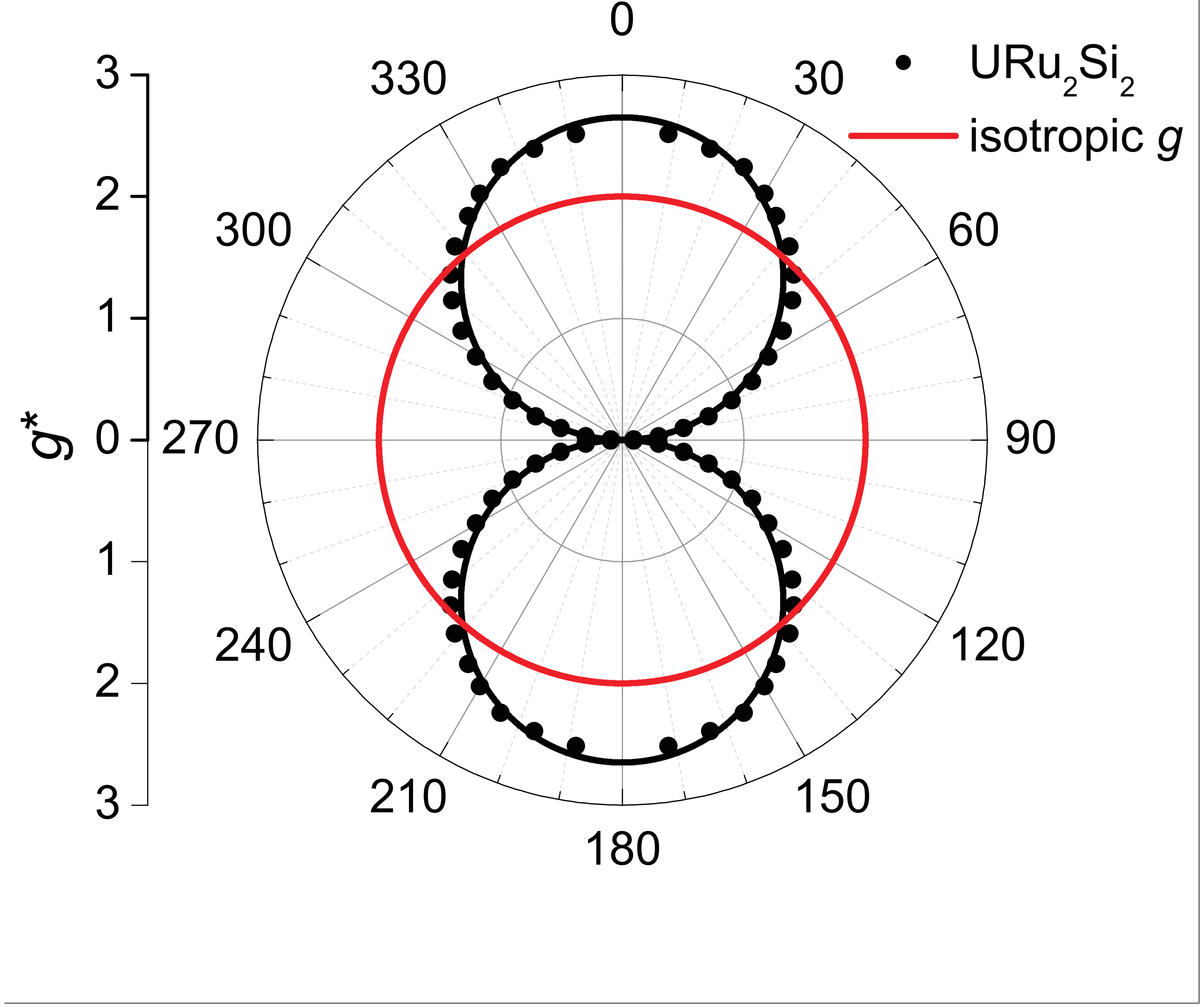

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Superconductivity: Giant Ising Anisotropy

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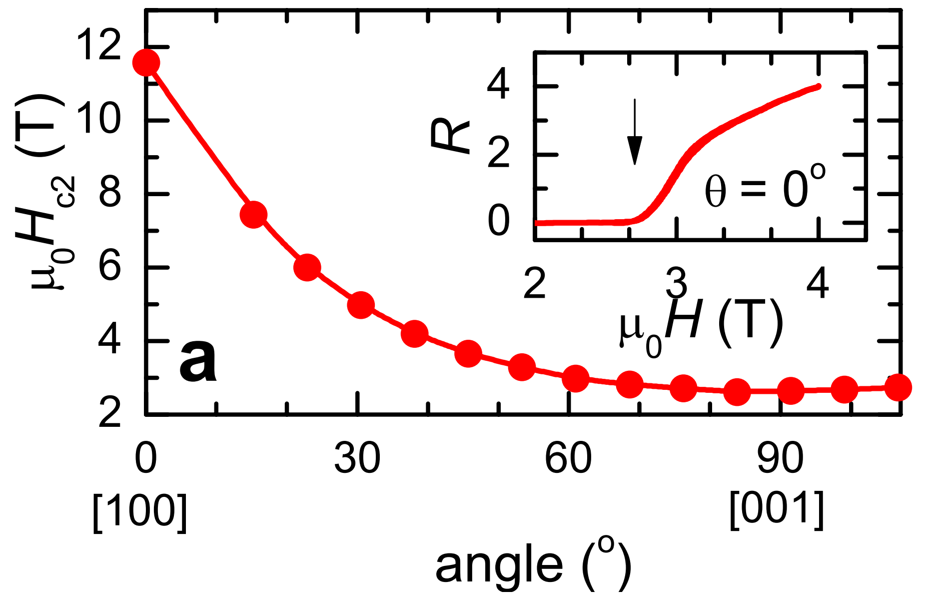
Altarawneh et al., PRL 108, 066407 (2012)



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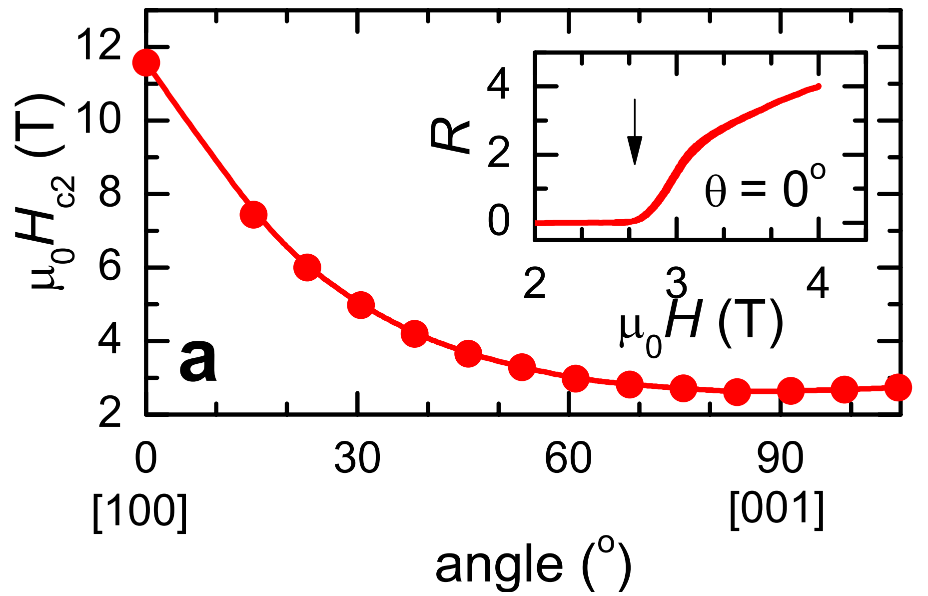

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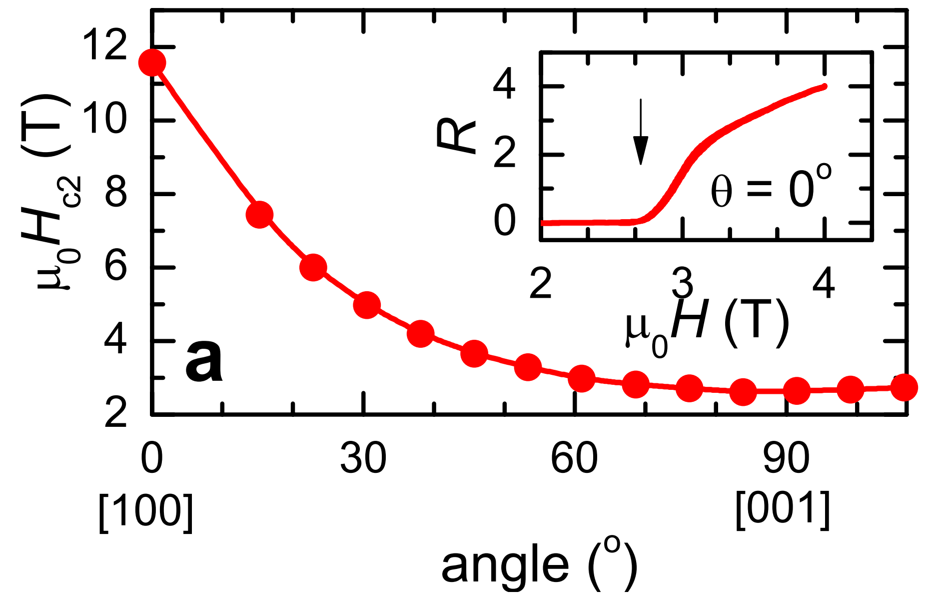

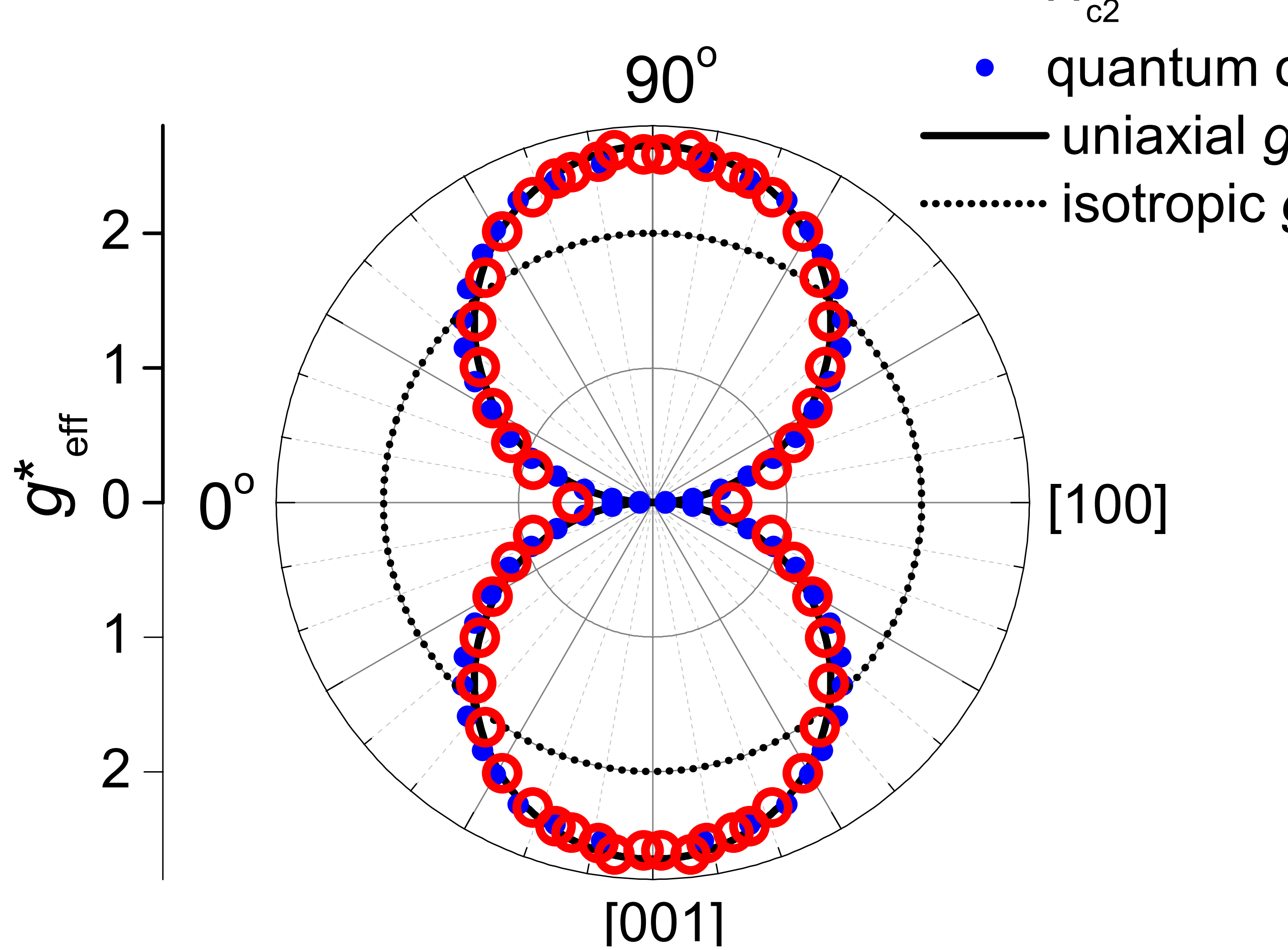

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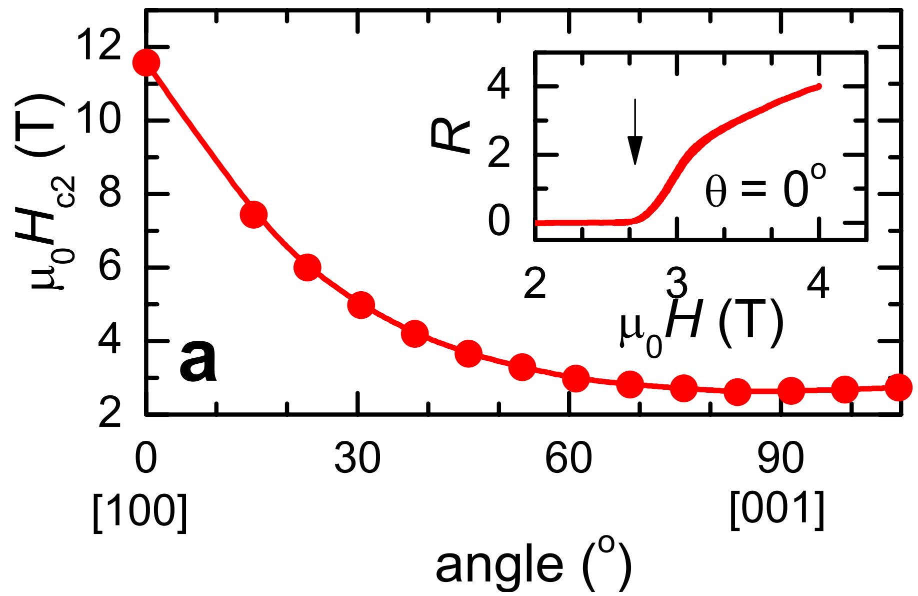

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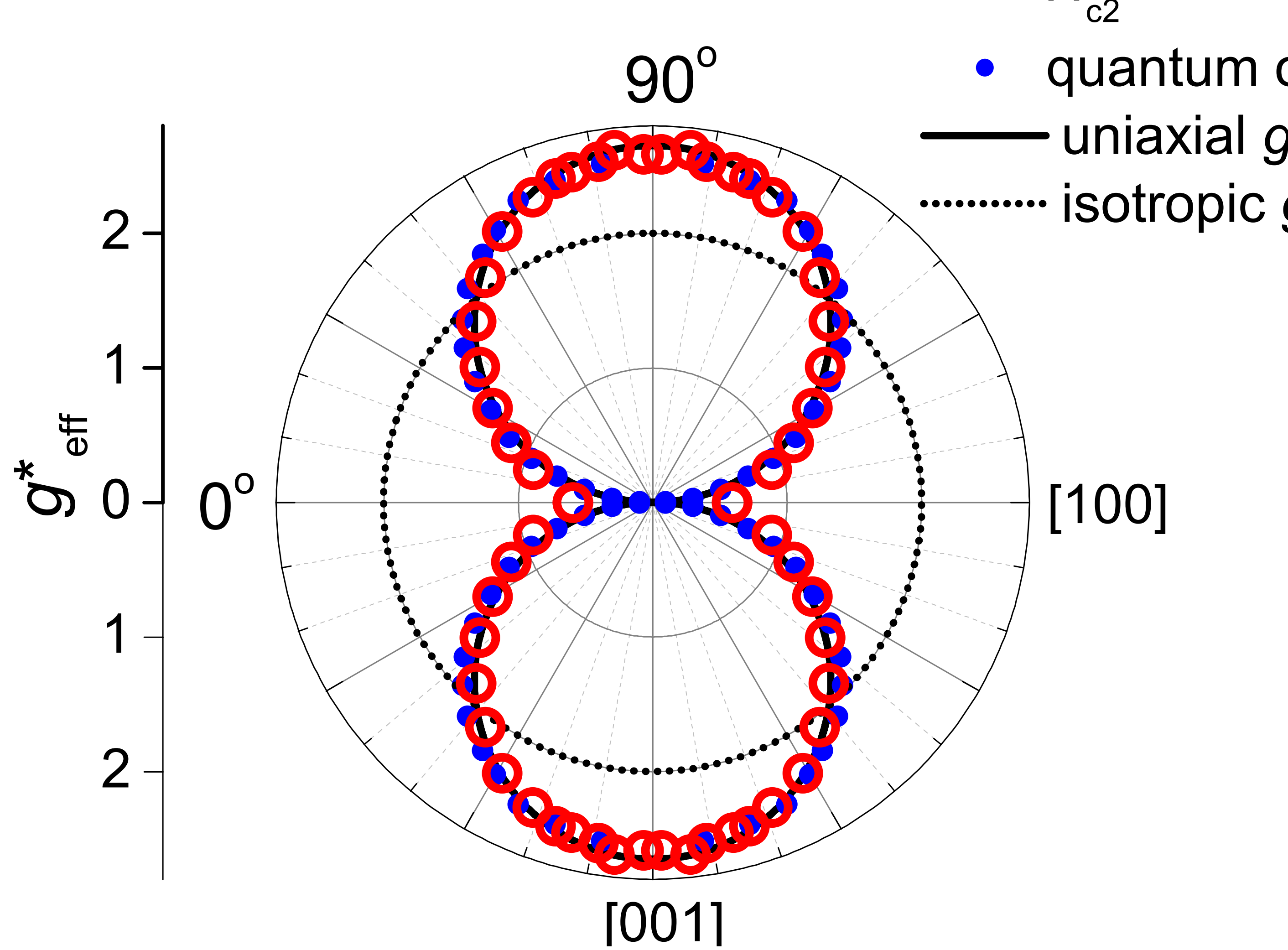

<u>Ising QP's pair condense.</u>

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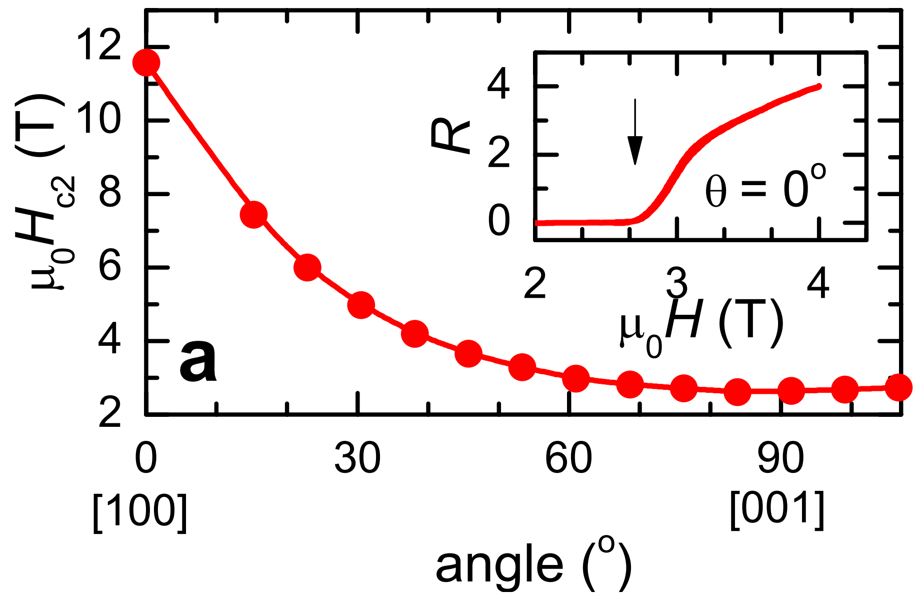

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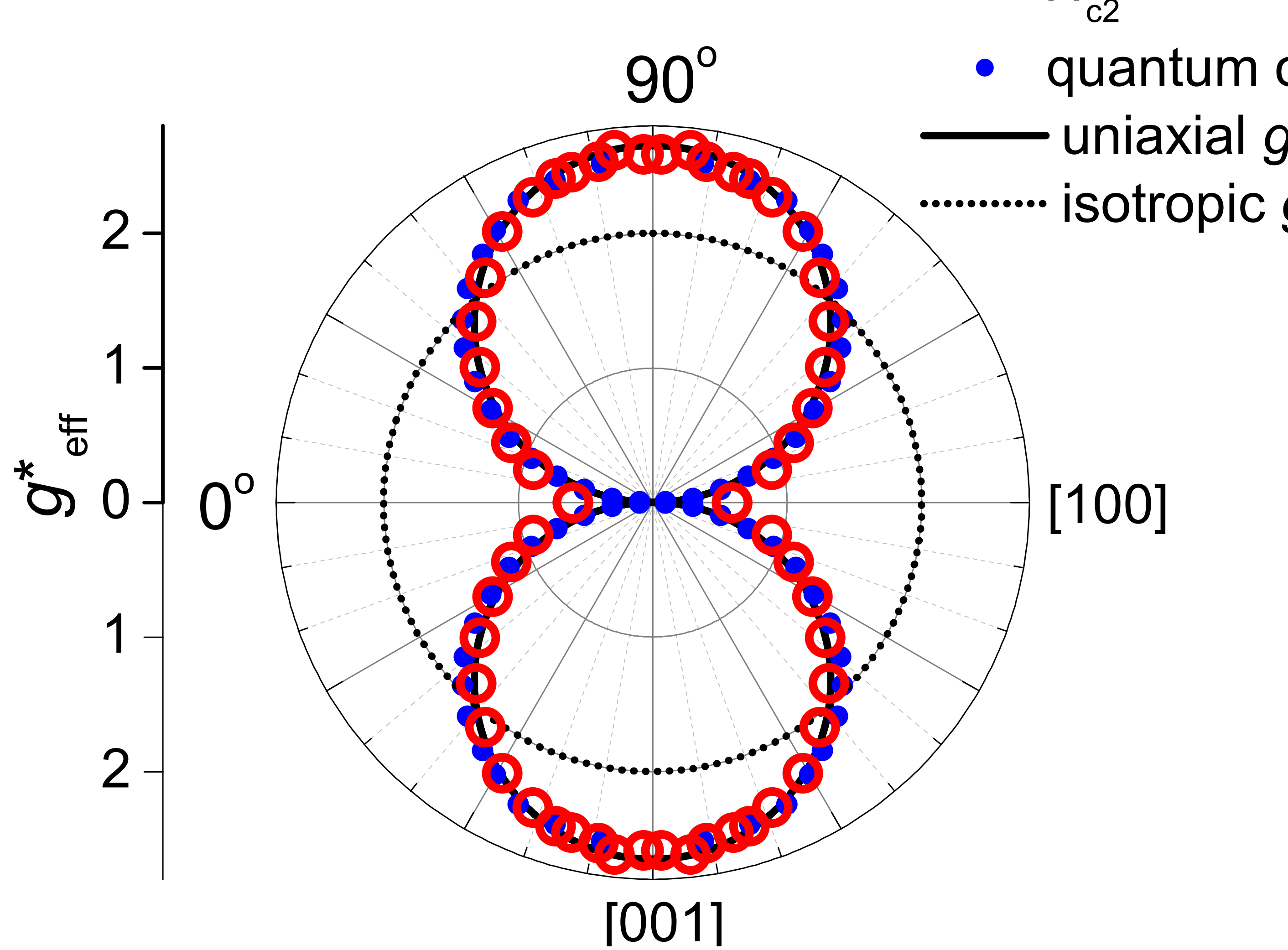

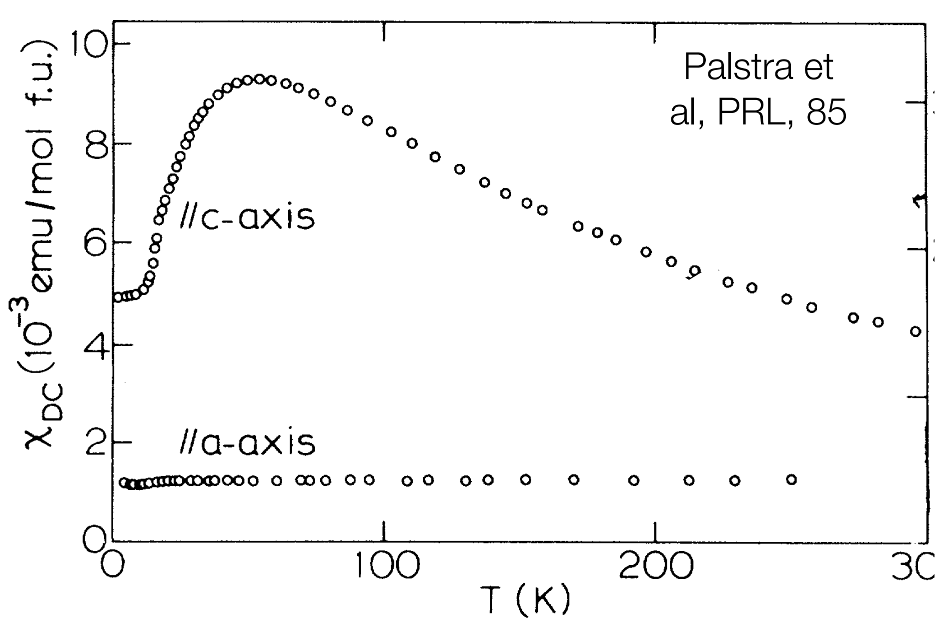

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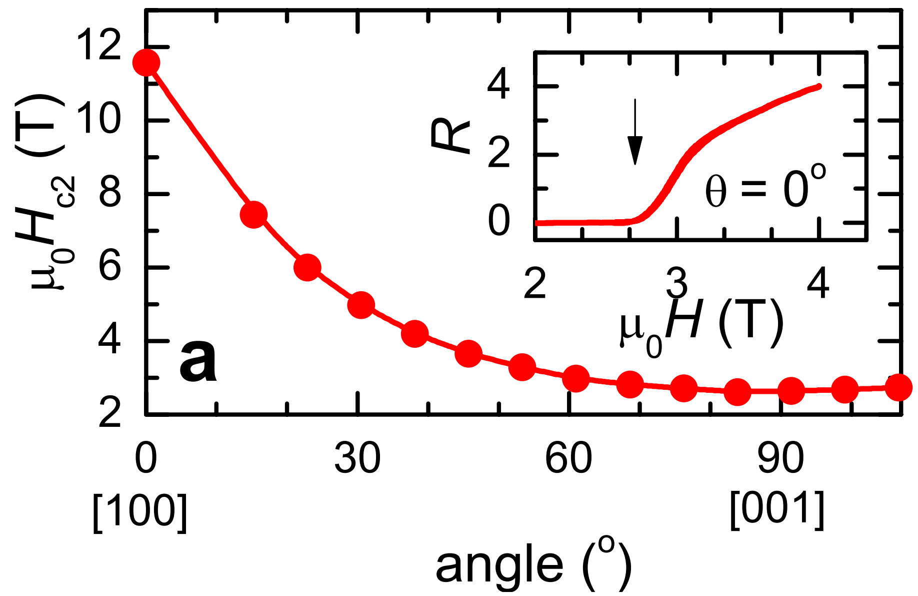

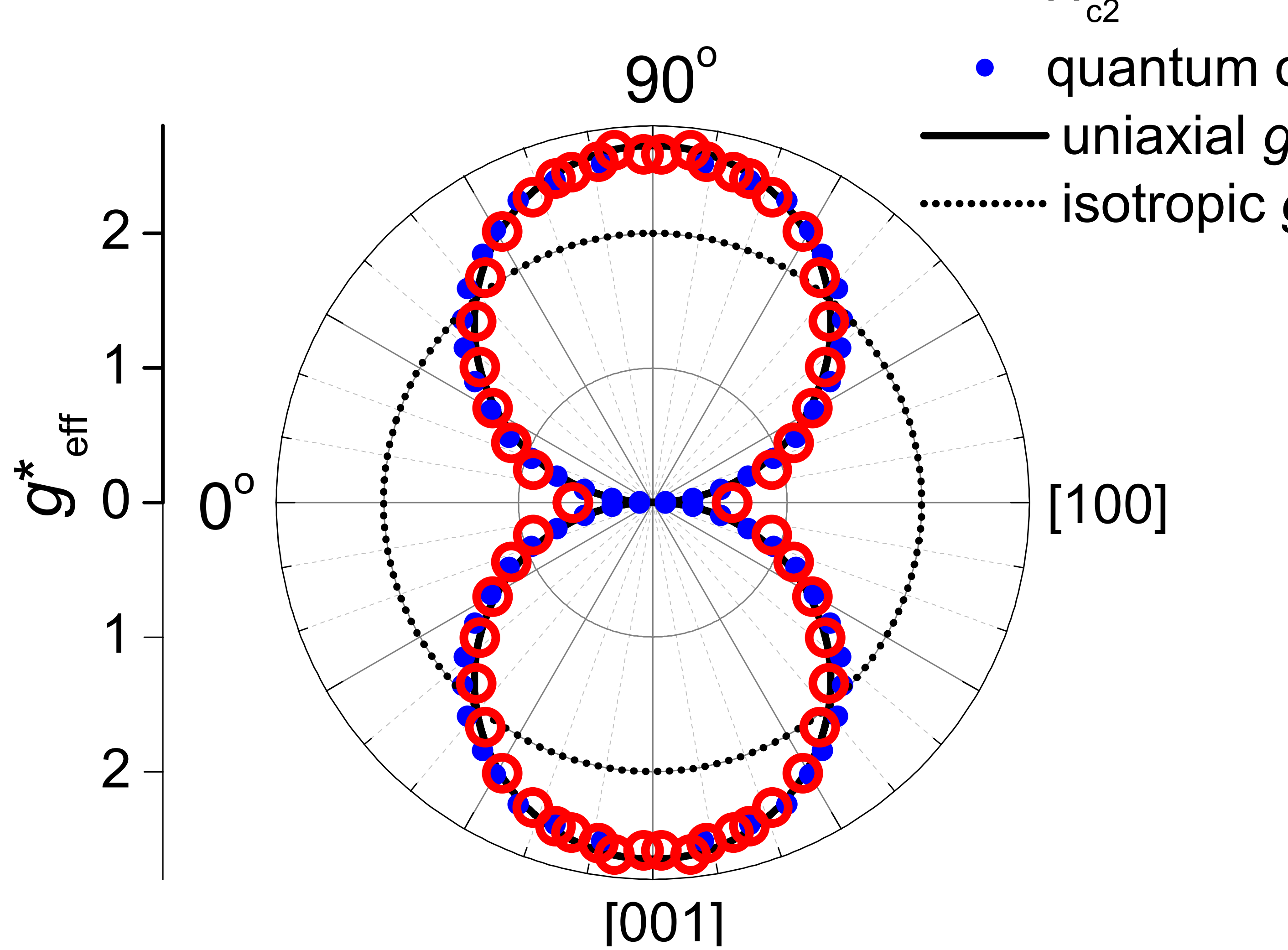

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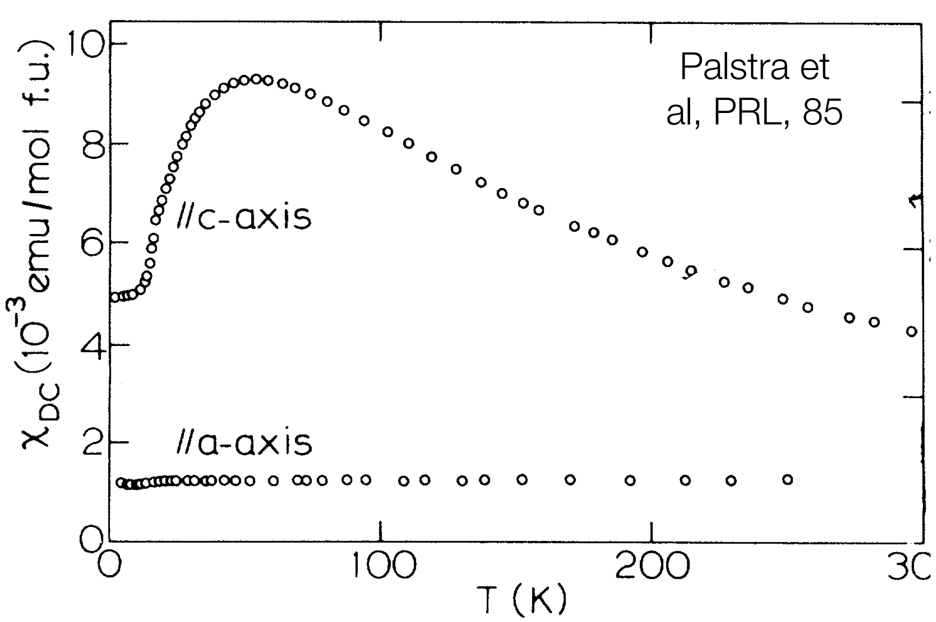

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Electrons hybridize with Ising 5f state to form Landau quasiparticles. $\langle \mathbf{k}\sigma | J_{\pm} | \mathbf{k}\sigma' \rangle = 0$

Hastatic Order in URu_2Si_2

Hasta: Spear (Latin). A new kind of spinor order.

Piers Coleman
Center for Materials Theory
Rutgers, USA

Royal Holloway
University of London

Rebecca Flint
(MIT)

Premi Chandra
(Rutgers)

P.Chandra, R. Flint and P.C
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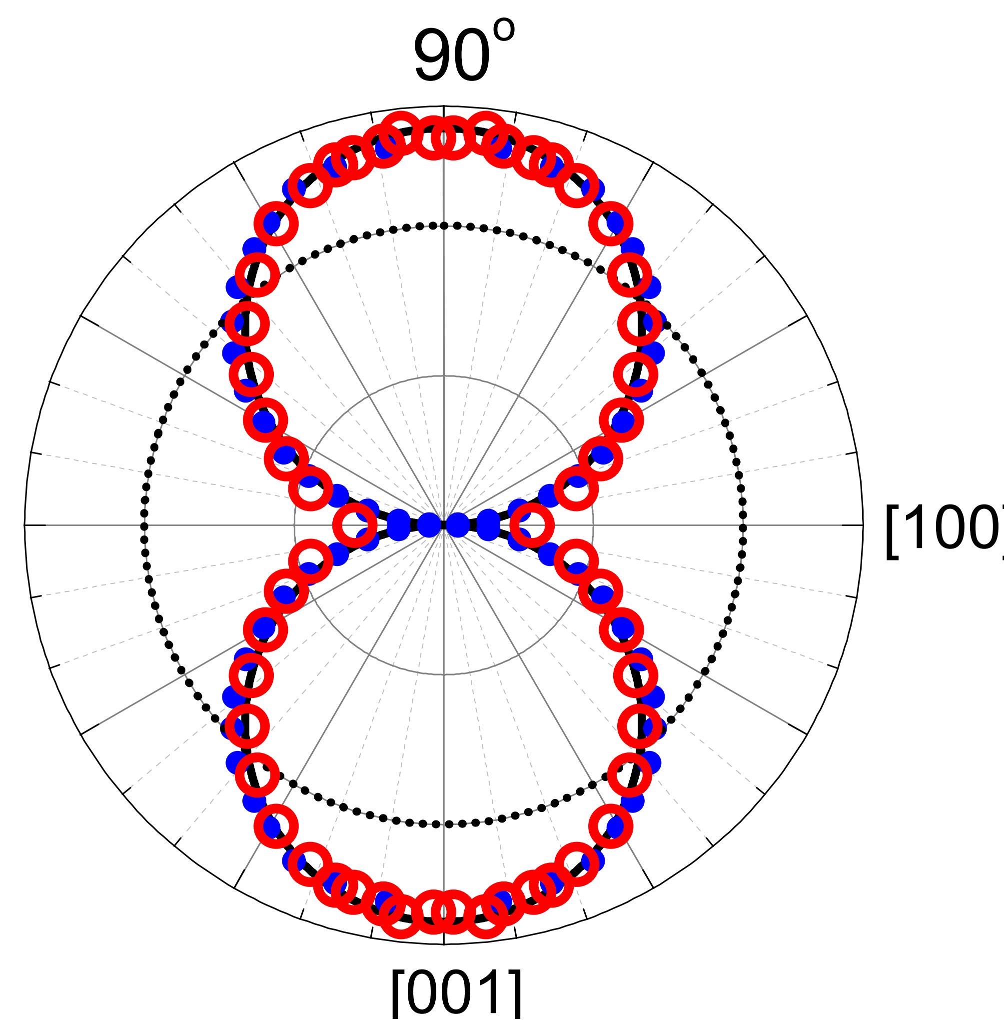
Wills Lab, Bristol U
19 Jun 2014



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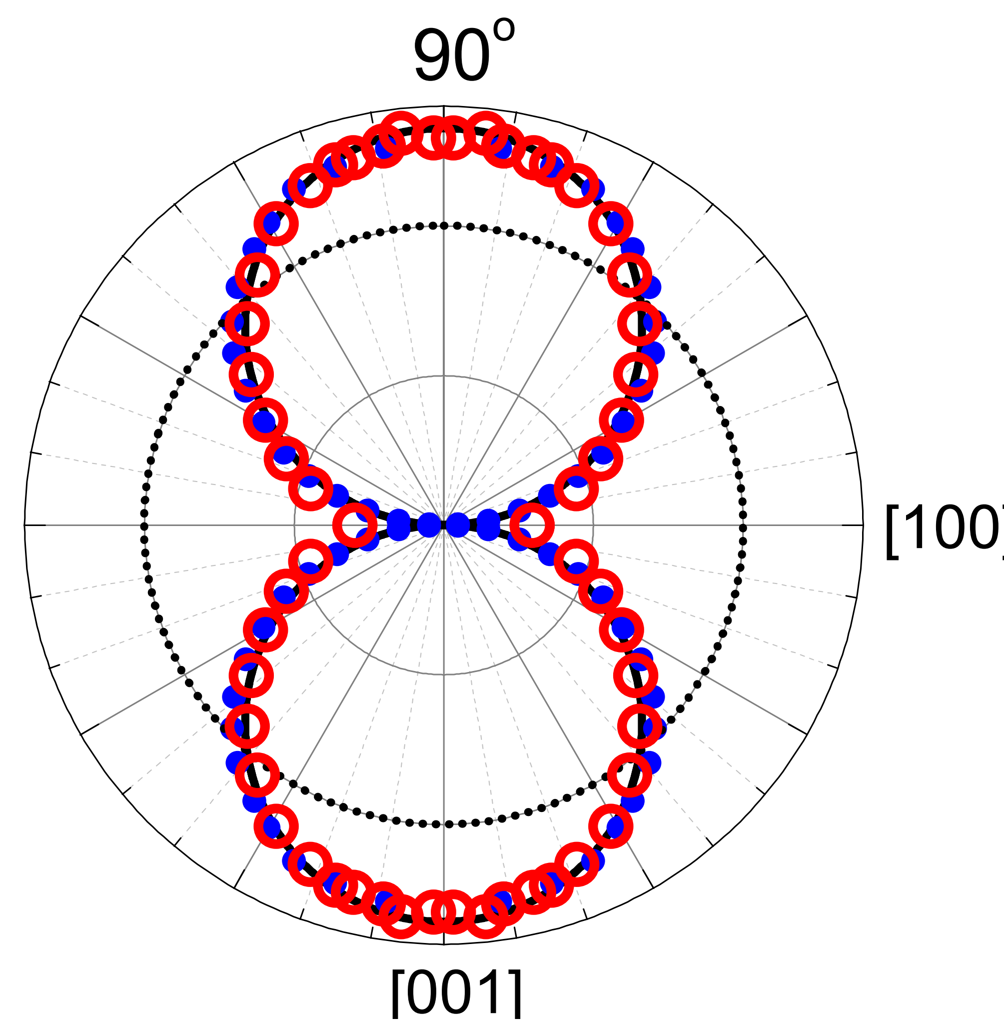
Take-home:
Observation of (Perfect) Ising Quasiparticles



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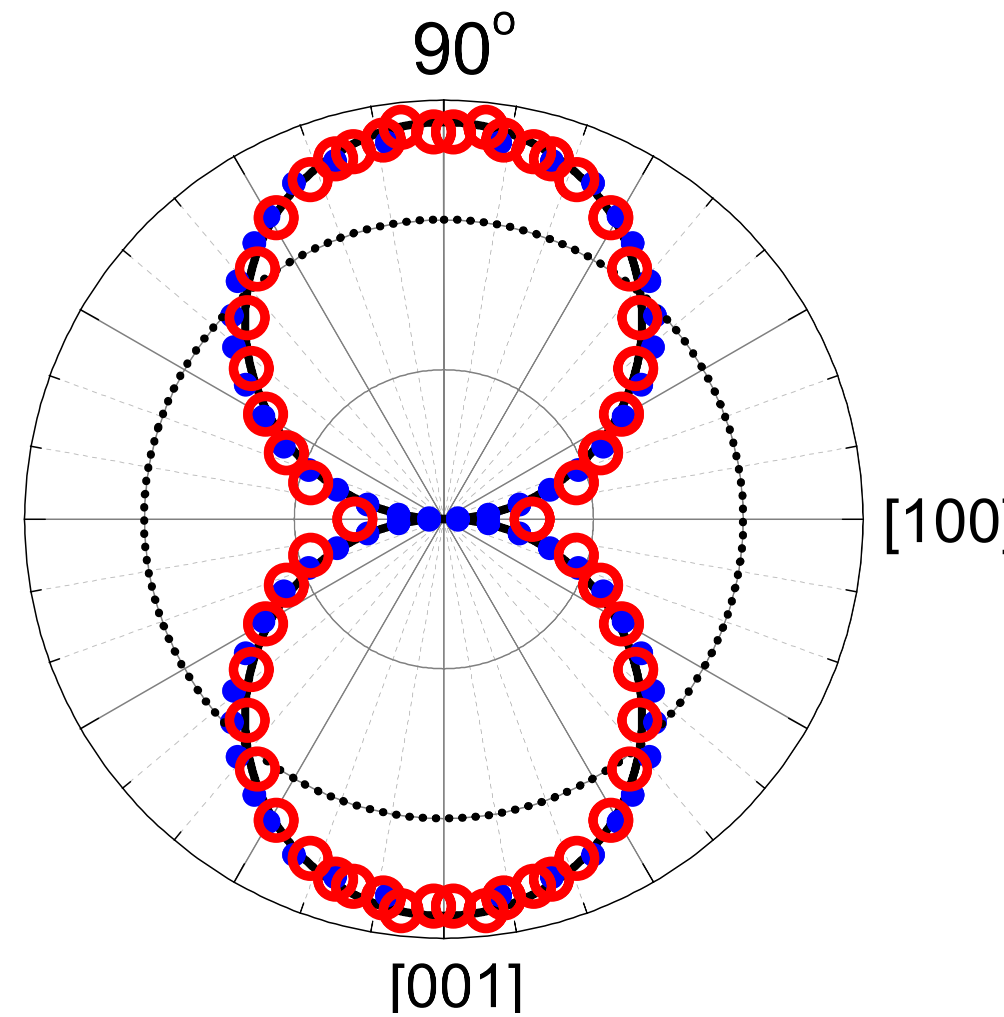
↓

Many body hybridization
Spin 1/2 e ⇌ <u>Integer spin</u> (J_z=±1) Doublets



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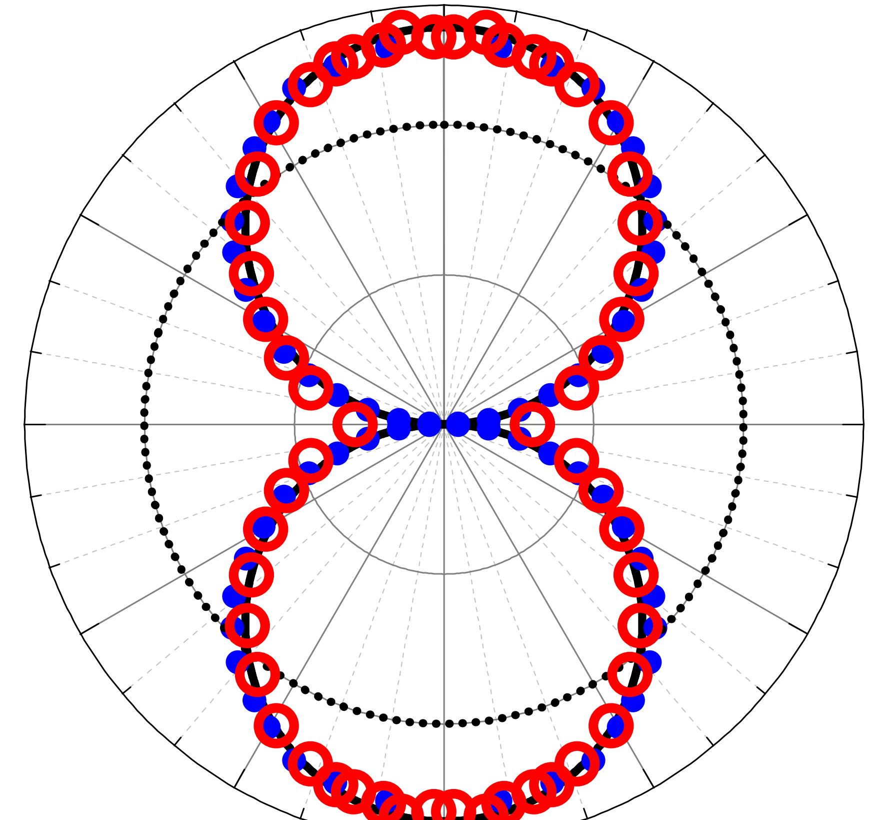
Proposal: Order parameter is a <u>spinor</u>



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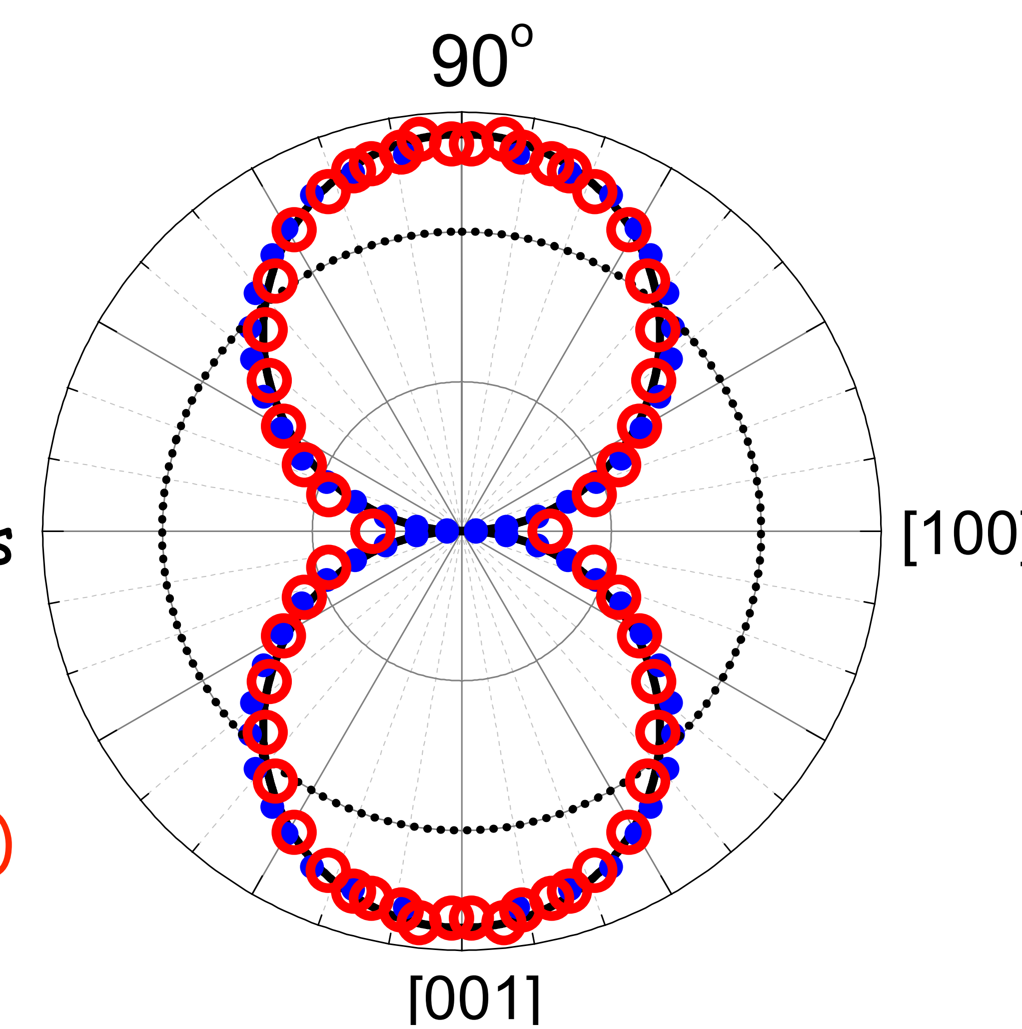
↓

Proposal: Order parameter is a <u>spinor</u>
(mixing J & J+1/2, breaking <u>double</u> time reversal)

$$\Theta^2 = (-1)^{2J}$$



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URu_2Si_2: Electronic Polaroid

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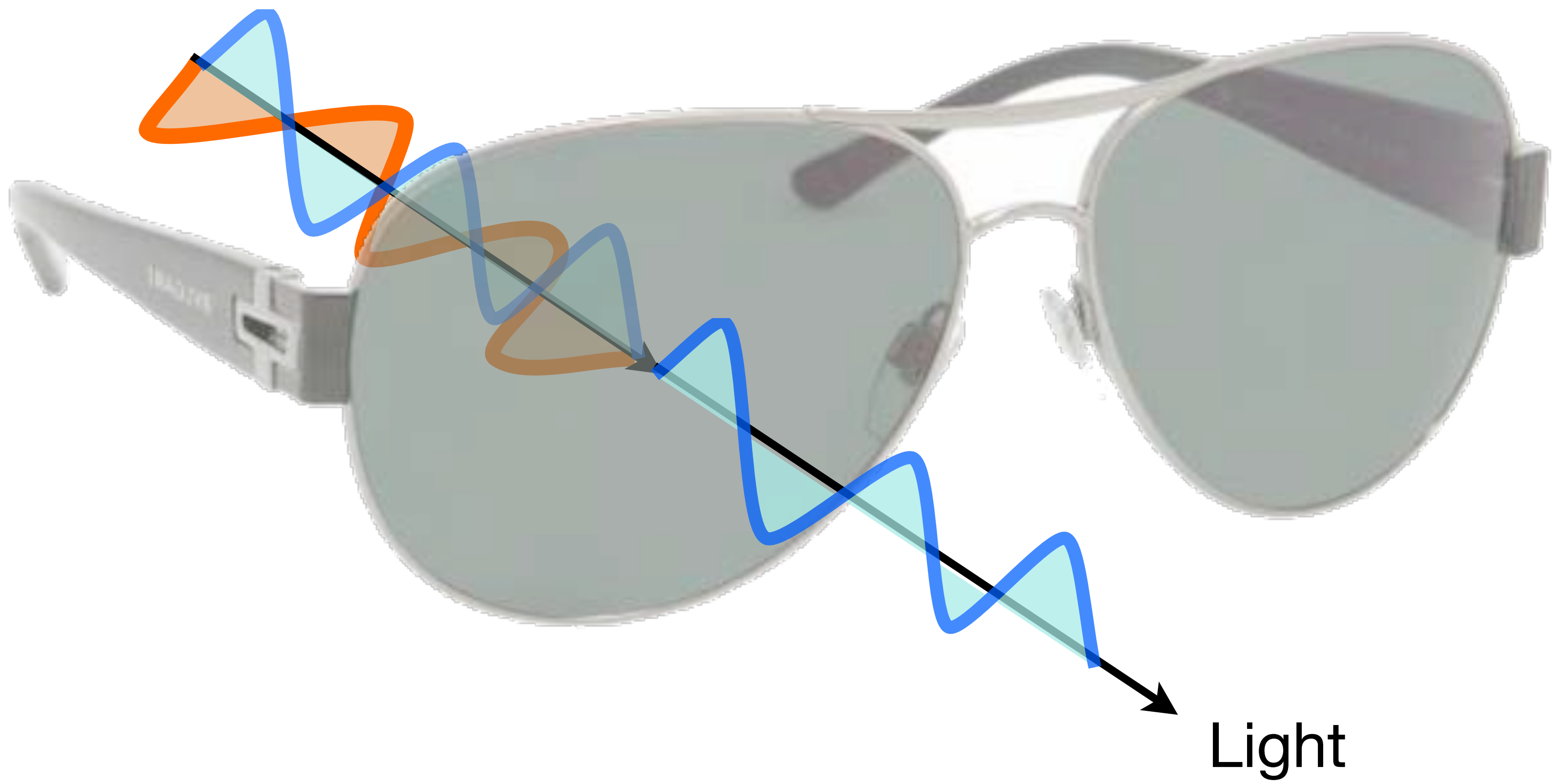

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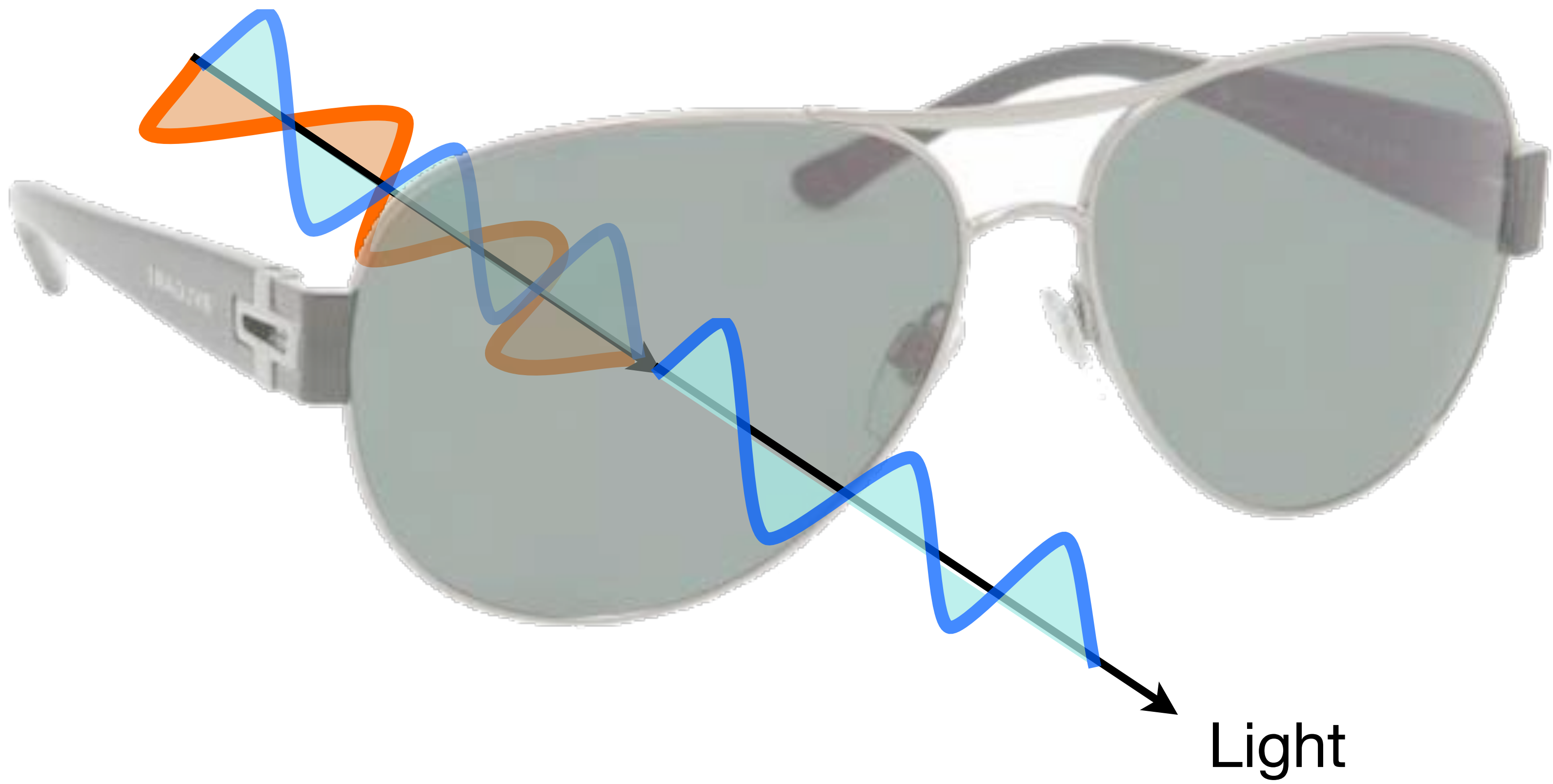

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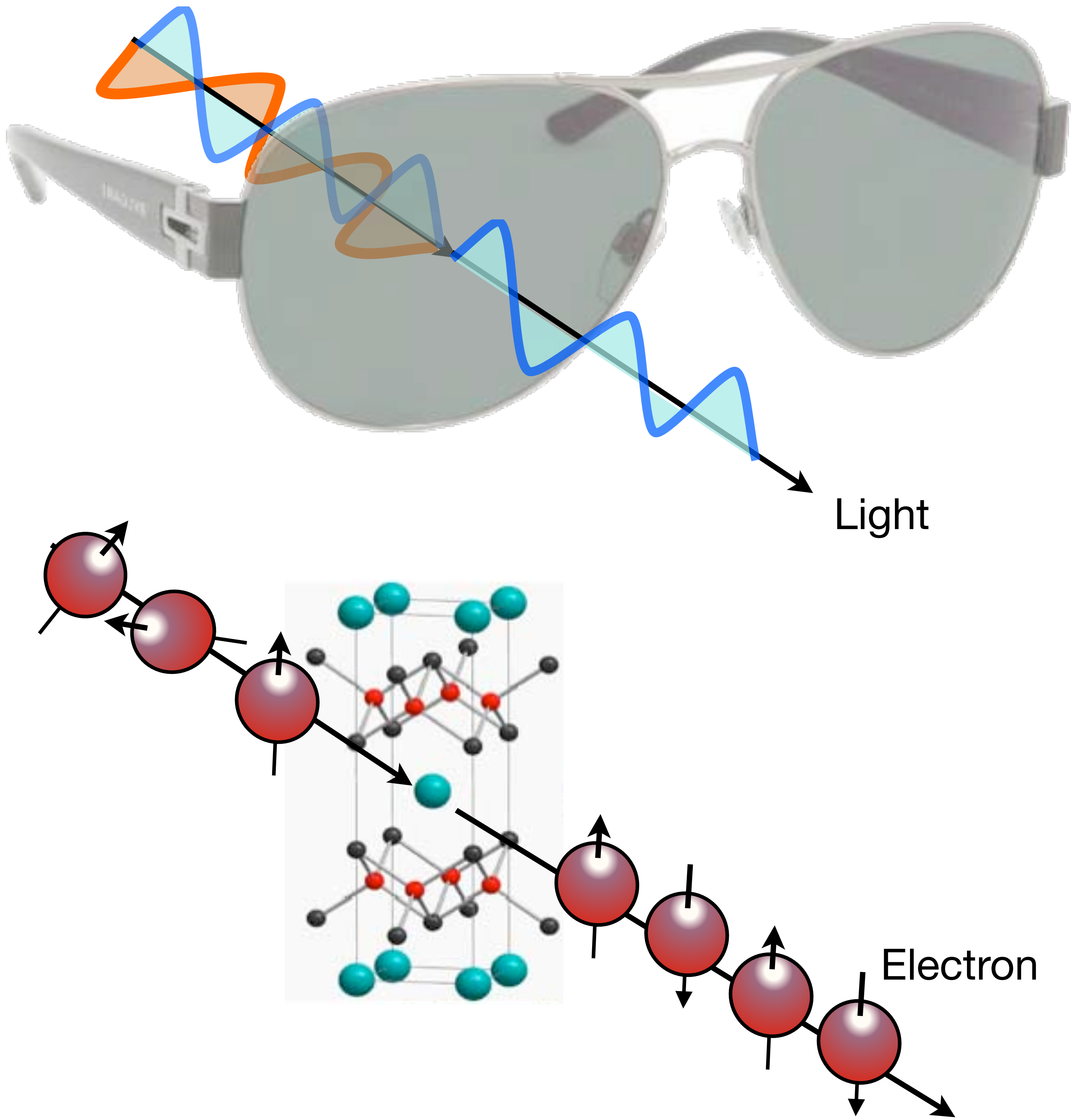

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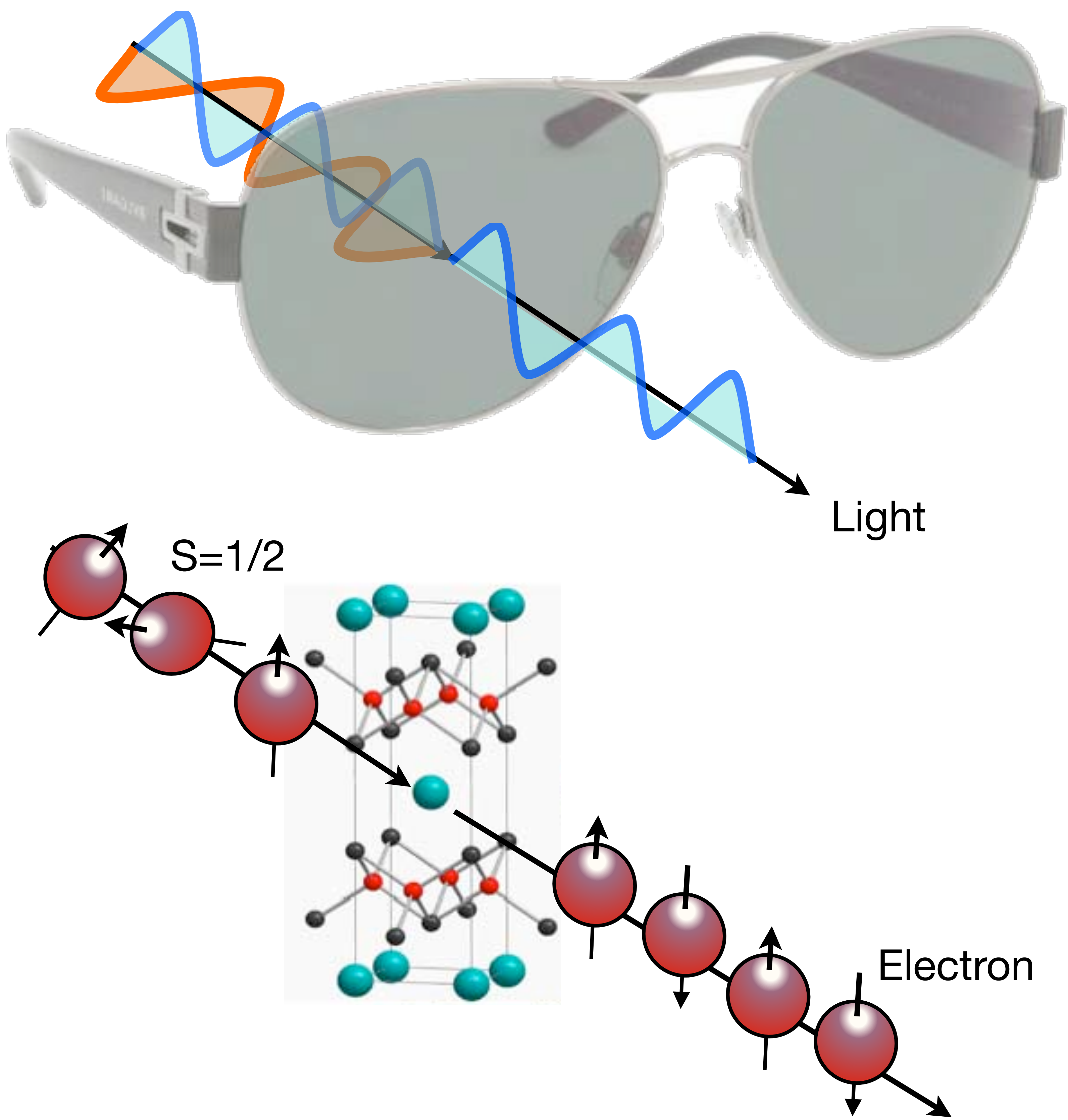

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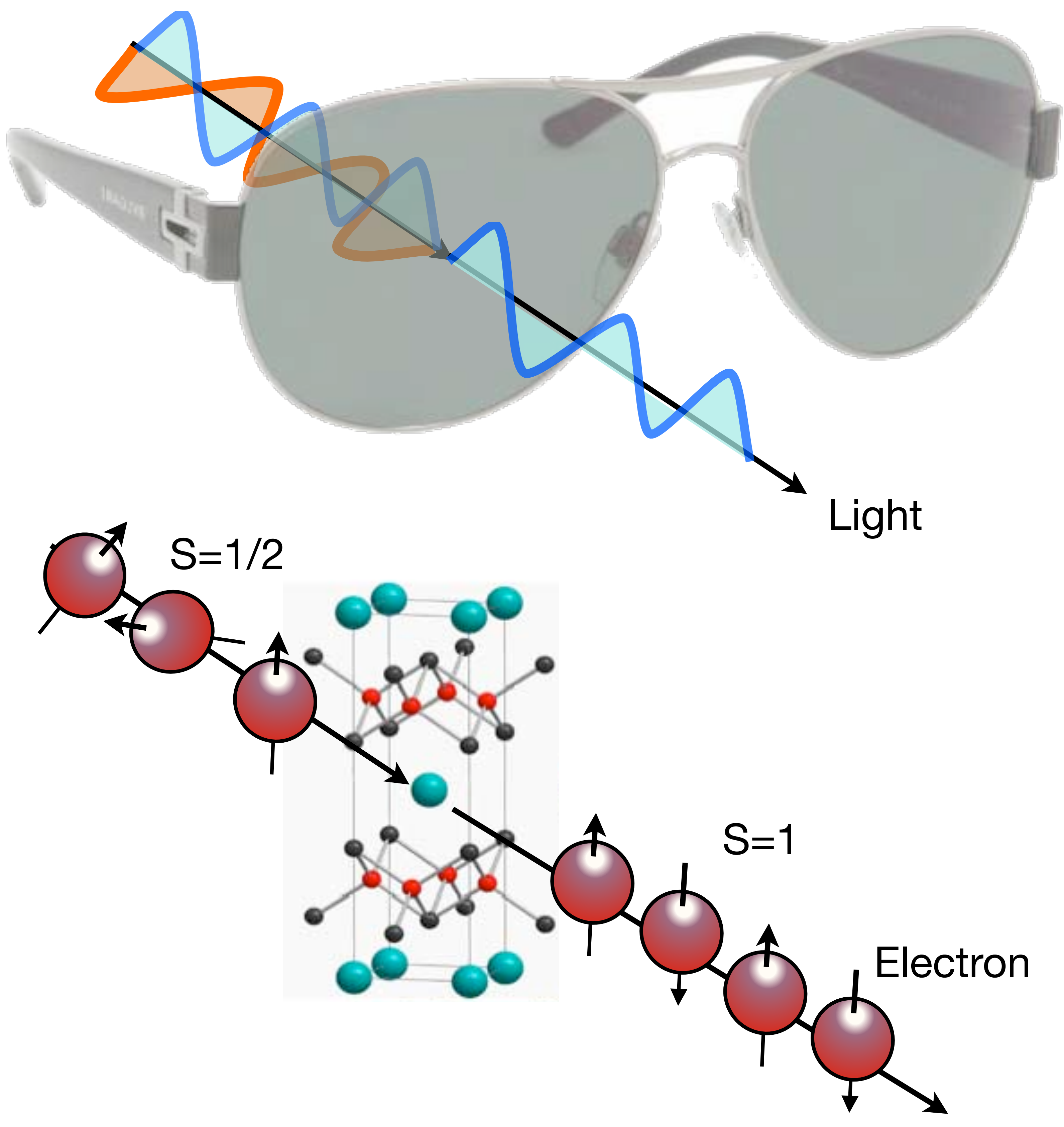

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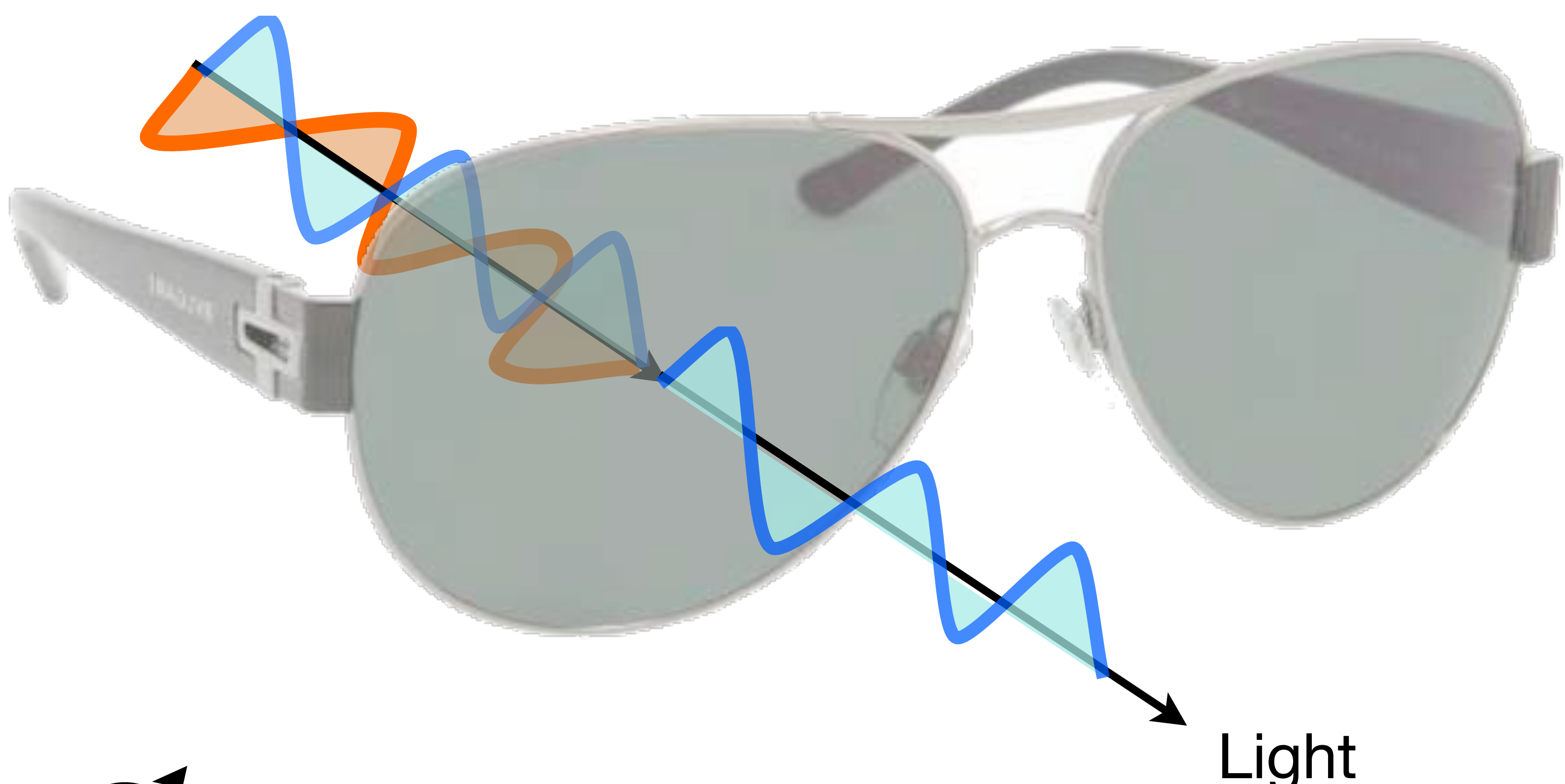
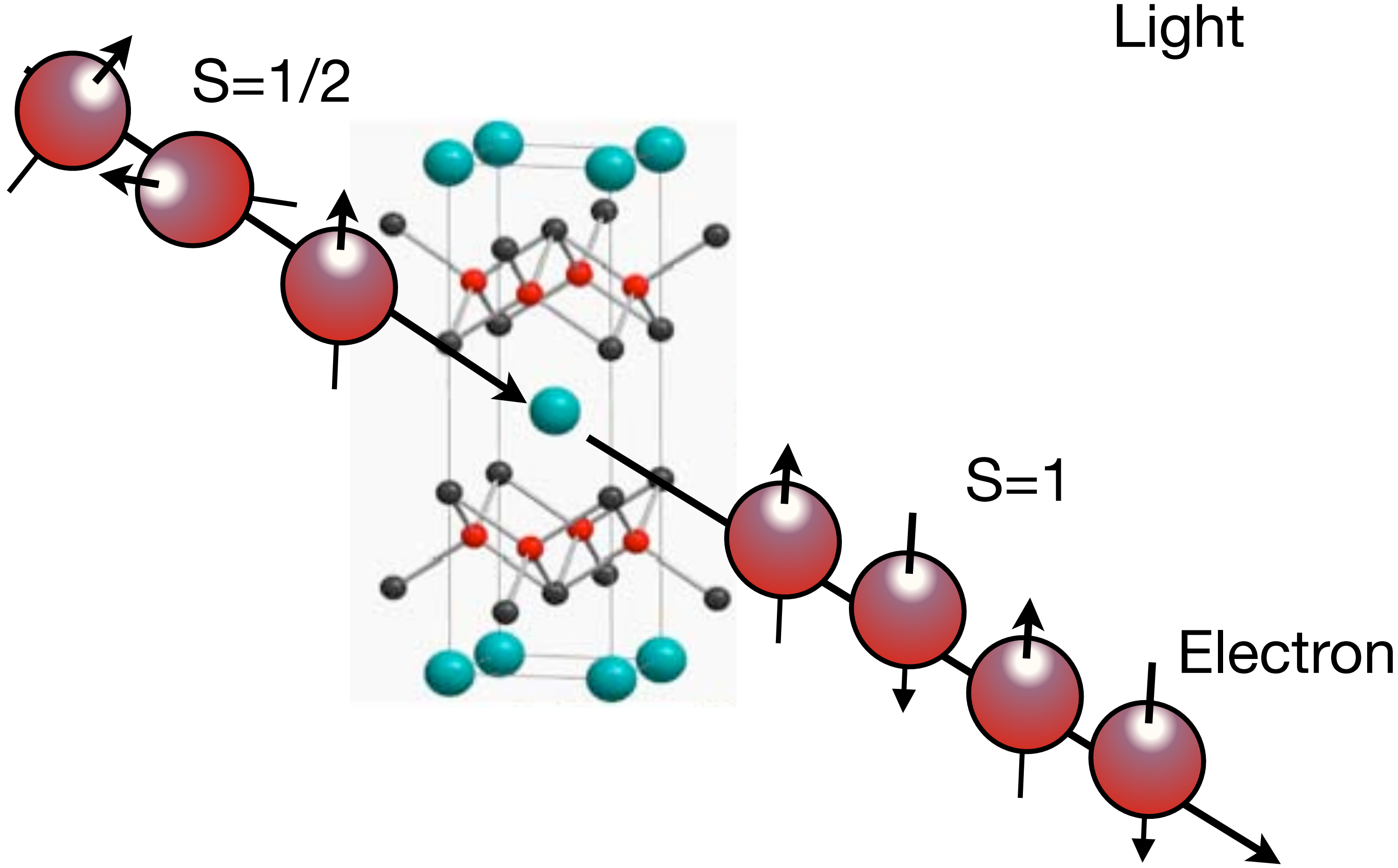


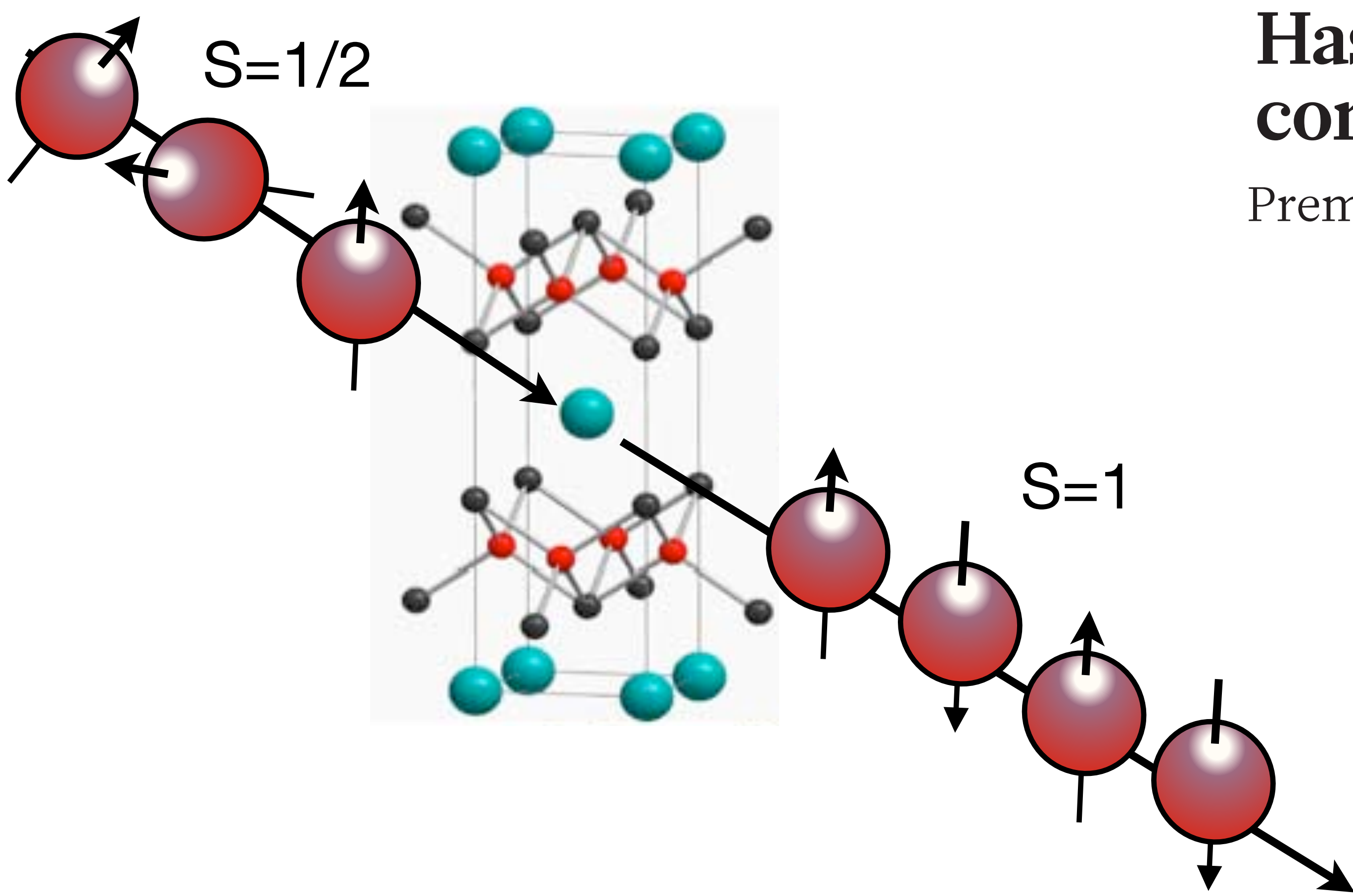


Ψ

Order parameter carries half-integer spin

“Spinor”

URu_2Si_2: Electronic Polaroid



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Hastatic order in the heavy-fermion compound URu_2Si_2

Premala Chandra[1], Piers Coleman[1,2] & Rebecca Flint[3]

$$\Psi$$

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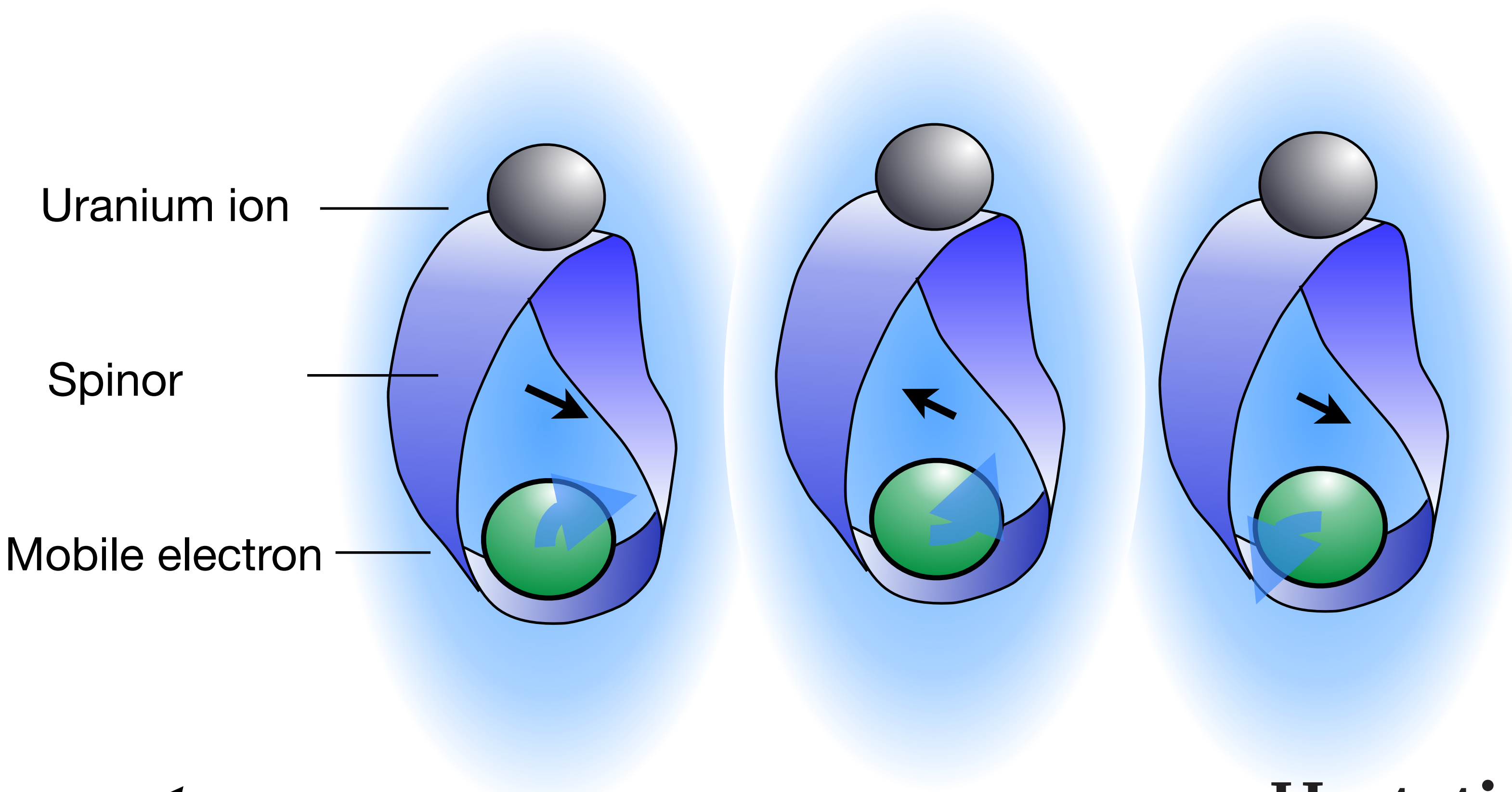

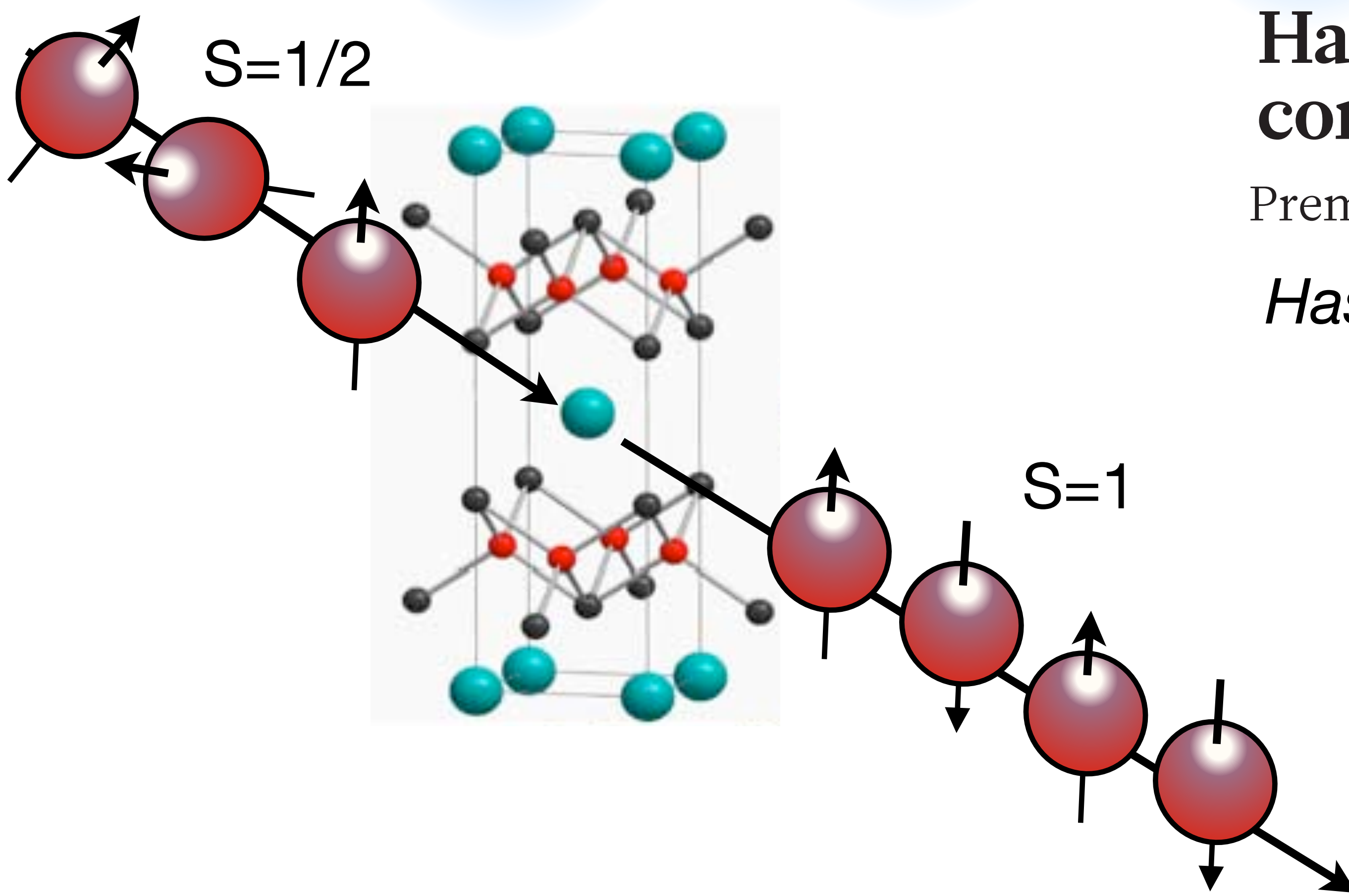

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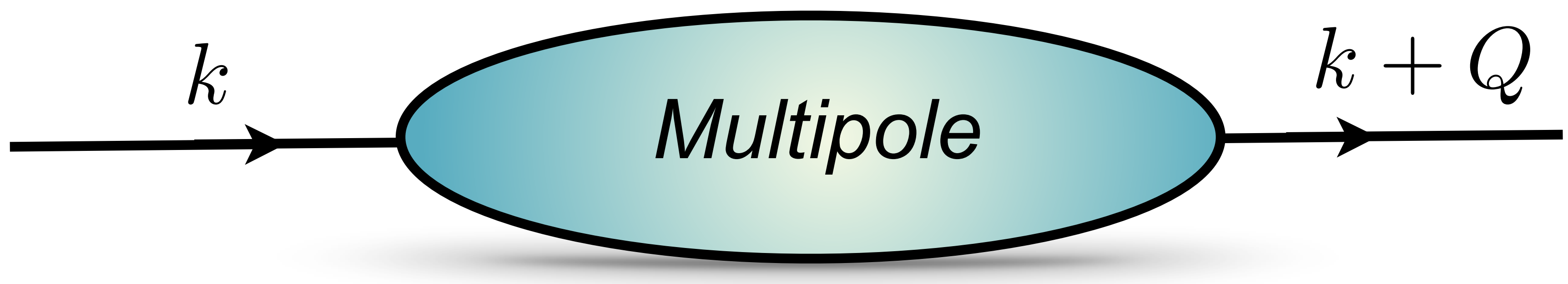
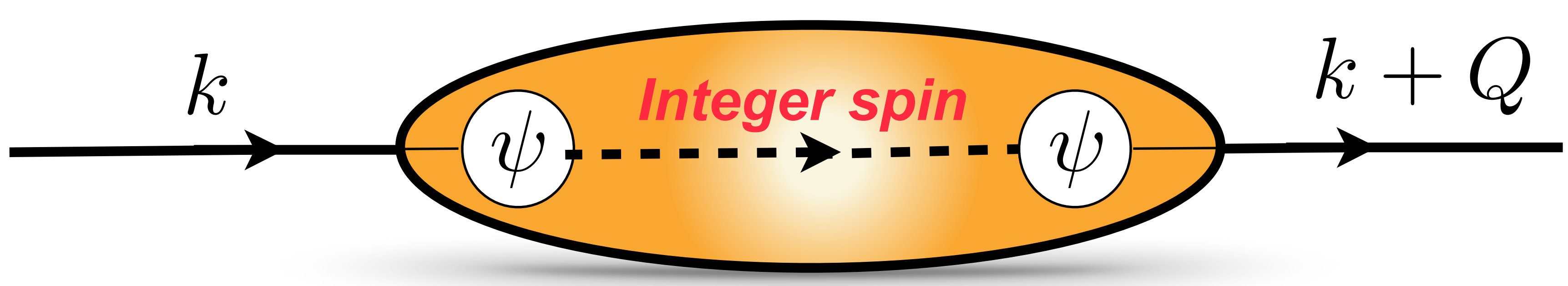


$$\langle c^{\dagger}_{\mathbf{k}+Q\alpha} c_{\mathbf{k}} \rangle = \Psi_{\alpha\beta}(\mathbf{k}) = \begin{cases} \psi_0(\mathbf{k}) & \text{CDW} \\ \vec{d}(\mathbf{k}) \cdot \vec{\sigma}_{\alpha\beta} & \text{SDW} \end{cases}$$

$$\Psi(R\mathbf{k}) = D(R)\Psi(\mathbf{k})$$

b)



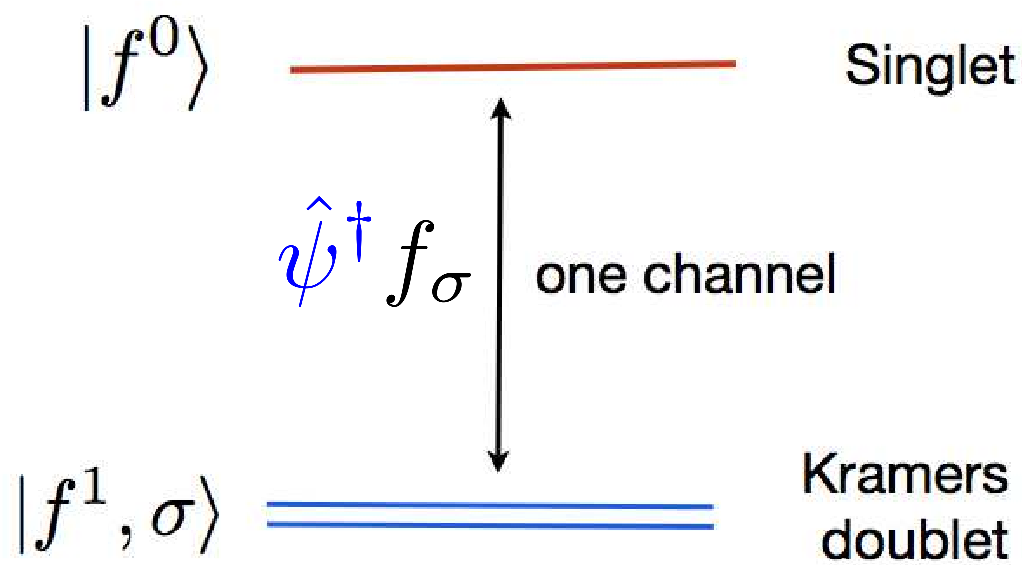
$$\psi = \sqrt{\text{Multipole}} = \text{Spinorial OP}$$

“Hastatic” order.

hasta: spear (latin)

"Hastatic" order.

In conventional heavy fermion materials a hybridization derives from virtual excitations between a Kramers doublet and an excited singlet.



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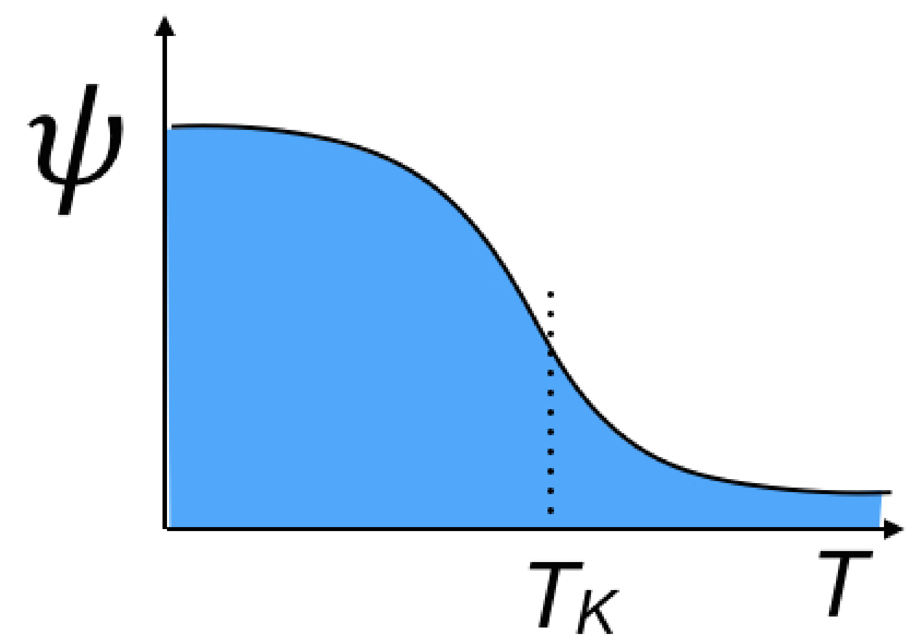
“Hastatic” order.

In conventional heavy fermion materials a hybridization derives from virtual excitations between a Kramers doublet and an excited singlet. A uniform hybridization breaks no symmetry and develops as a cross-over.



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"Hastatic" order.

H. Amitsuka and T. Sakakibara, *J. Phys. Soc. Japan* **63**, 736-47 (1994).

But if the ground-state is a non-Kramer's doublet, the Kondo effect occurs via an *excited Kramer's doublet*.

hasta: spear (latin)

non-Kramers (K=+1) Γ_5

$$|5f^2, \alpha\rangle = \hat{\chi}^\dagger_\alpha |0\rangle$$

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H. Amitsuka and T. Sakakibara, *J. Phys. Soc. Japan* **63**, 736-47 (1994).

But if the ground-state is a non-Kramer’s doublet, the Kondo effect occurs via an *excited Kramer’s doublet*.

Kramers (K=-1) Γ_7 $|5f^3, \sigma\rangle = \hat{\Psi}^\dagger_\sigma |0\rangle$

non-Kramers (K=+1) Γ_5 $|5f^2, \alpha\rangle = \hat{\chi}^\dagger_\alpha |0\rangle$

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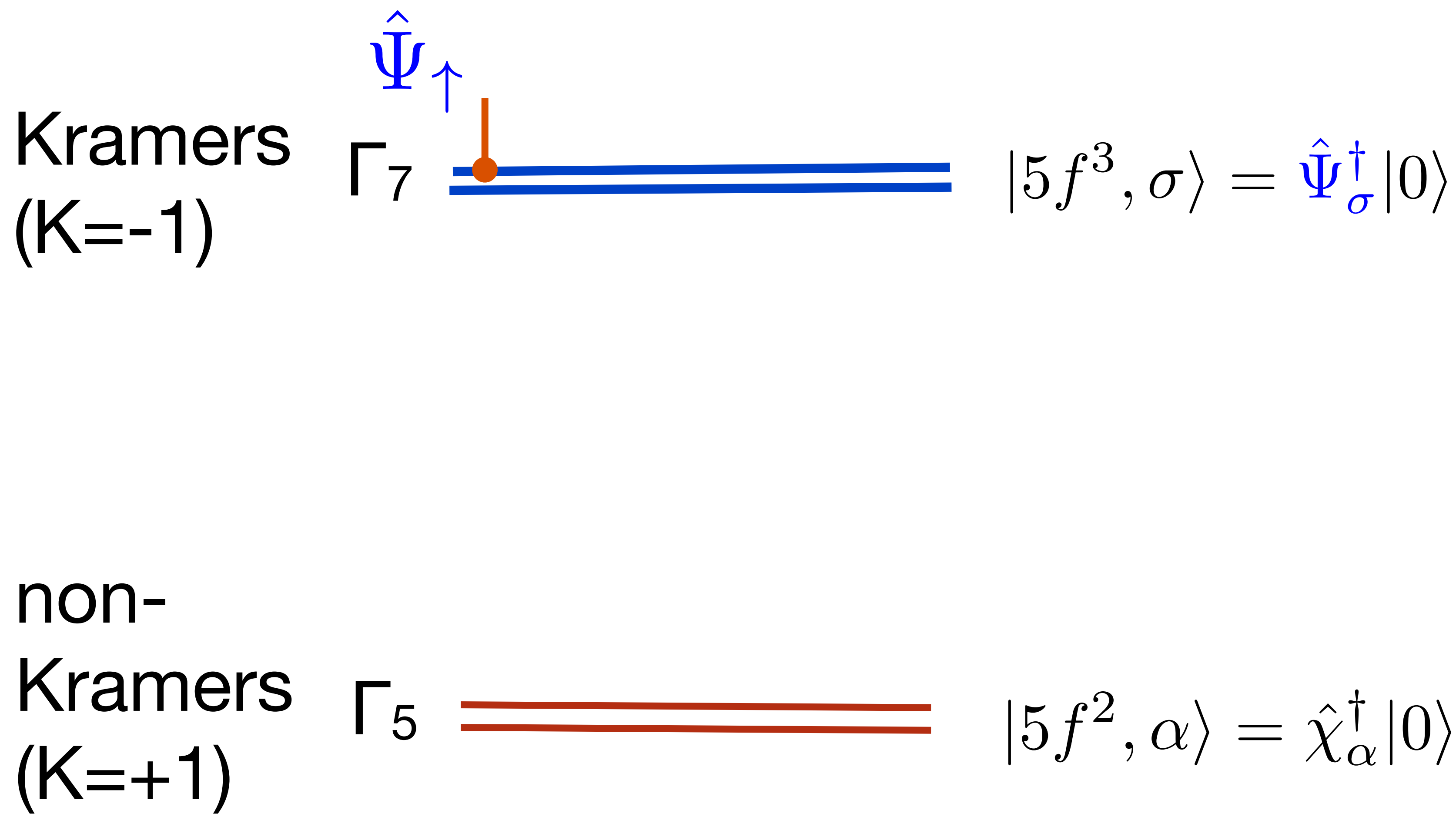

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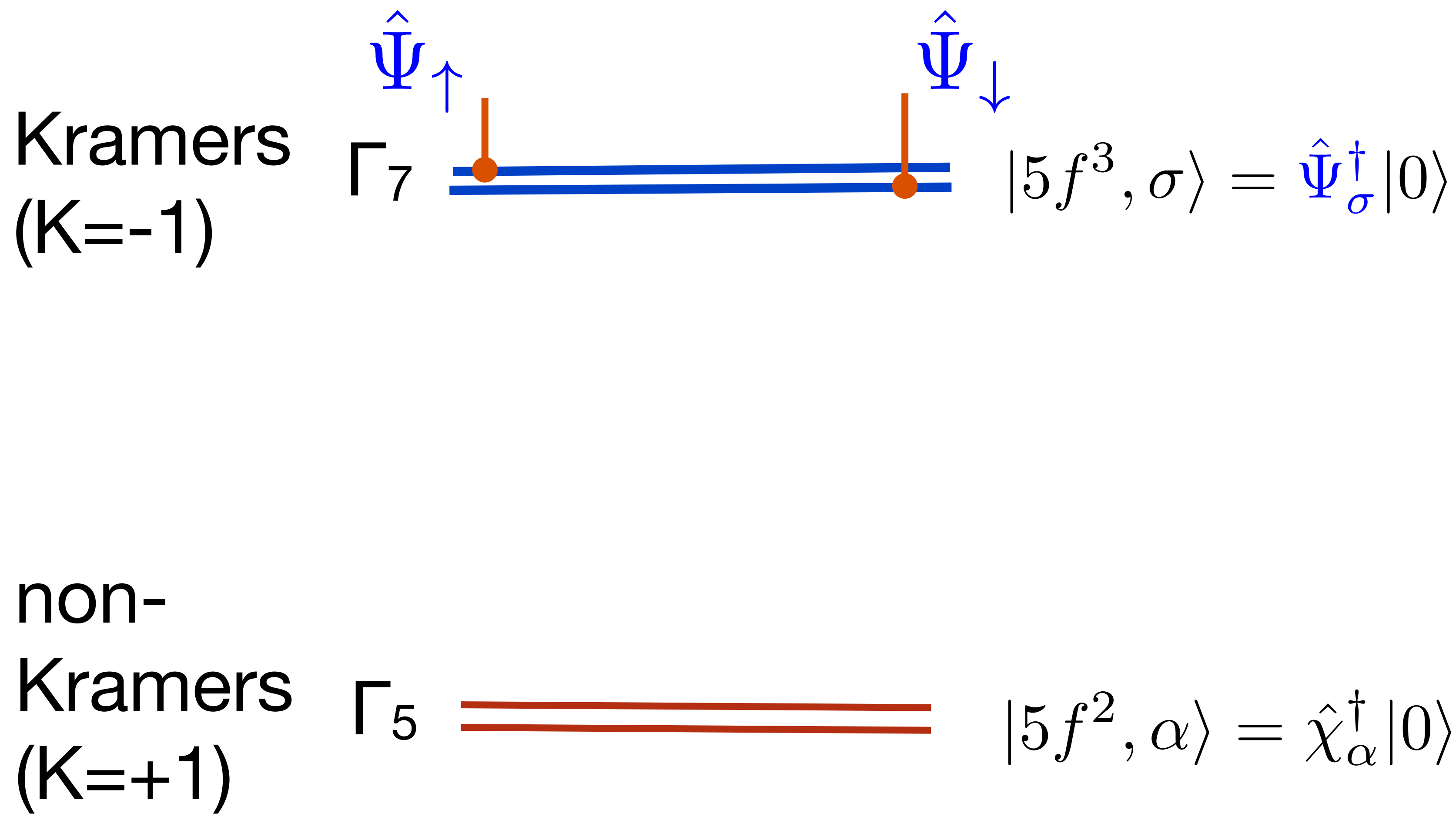

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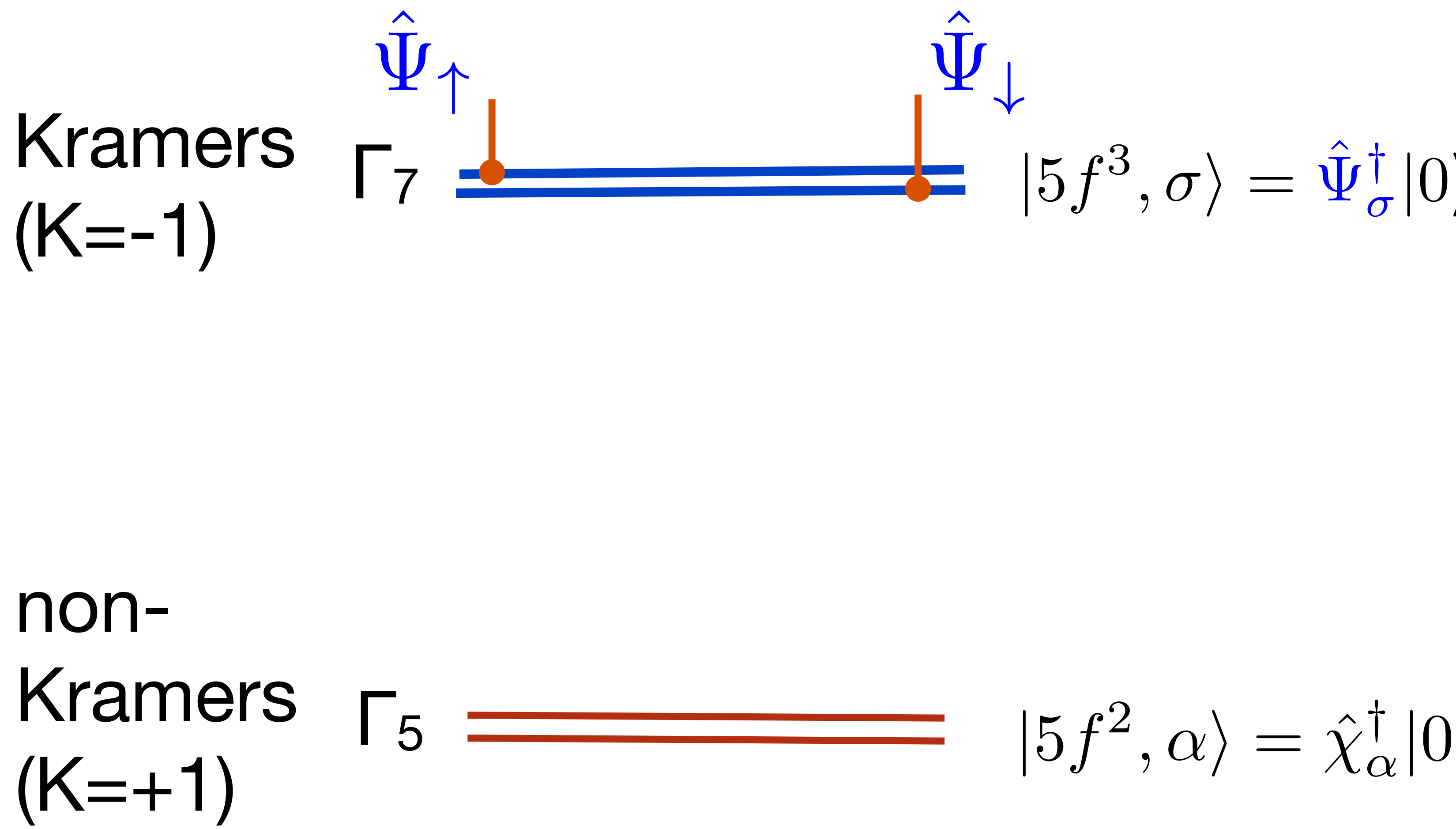

hasta: spear (latin)

$$|5f^3,\sigma\rangle\langle 5f^2,\alpha| = \hat{\Psi}^{\dagger}_{\sigma}\hat{\chi}_{\alpha}$$

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H. Amitsuka and T. Sakakibara, *J. Phys. Soc. Japan* **63**, 736-47 (1994).

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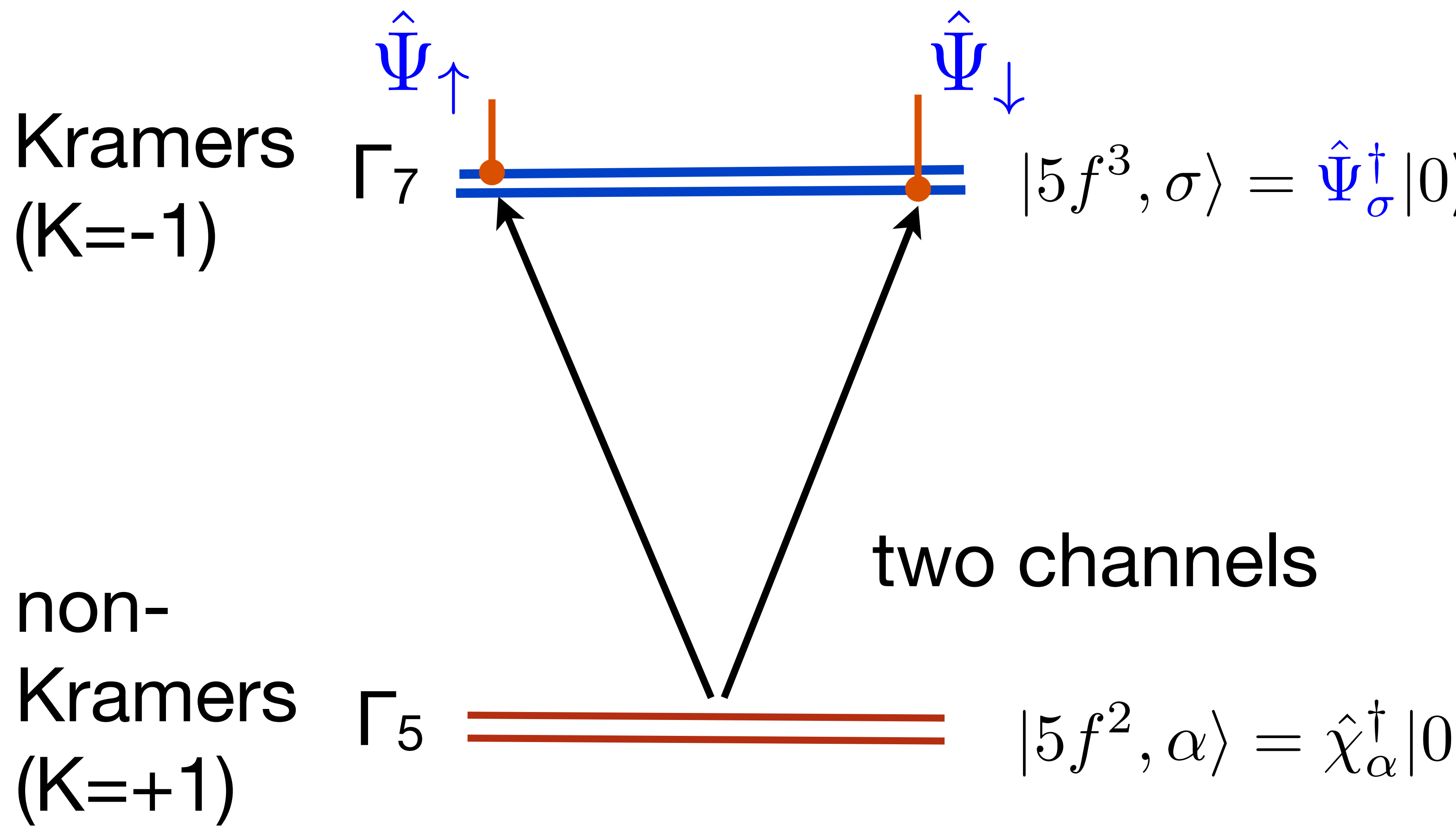

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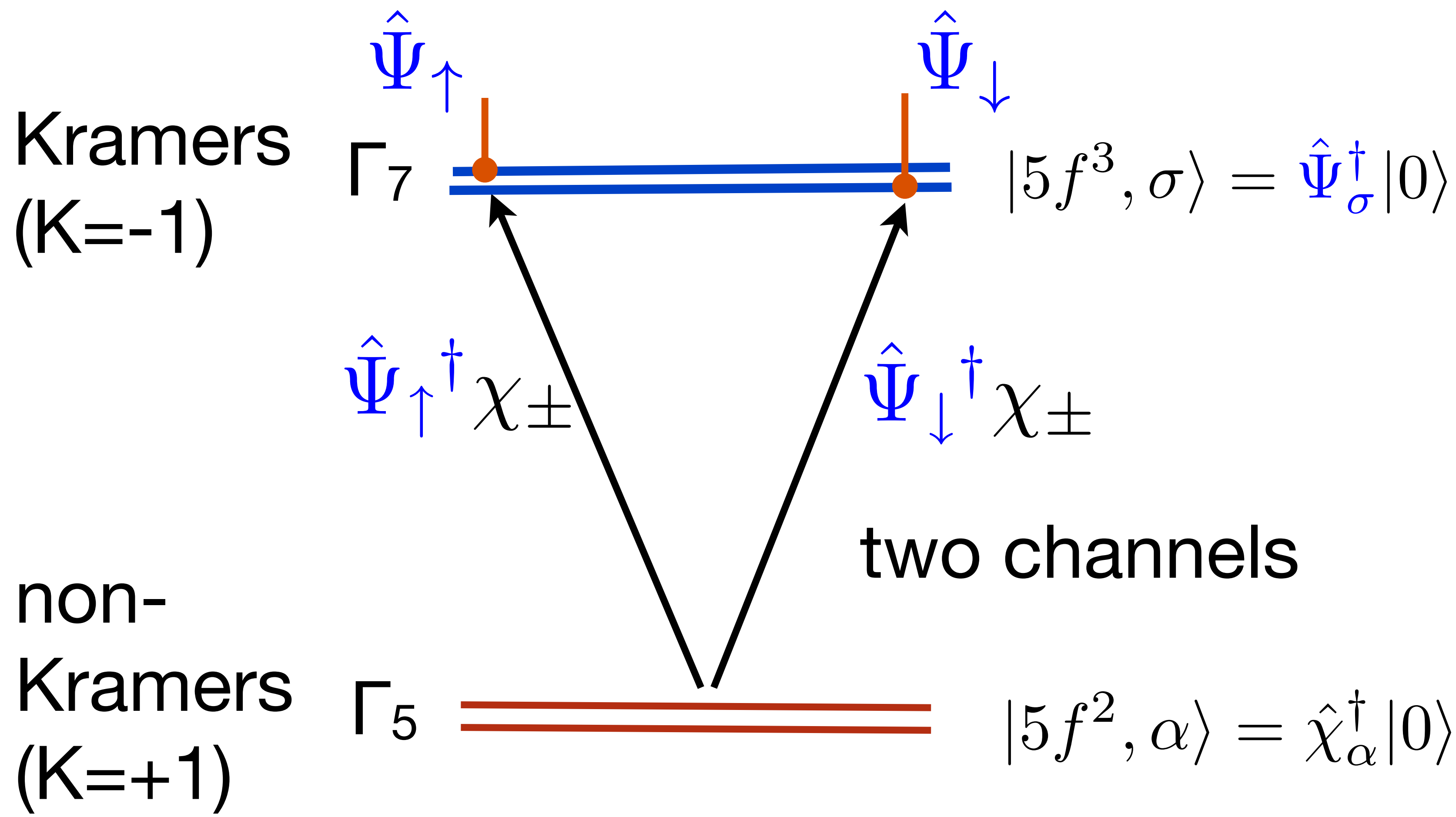

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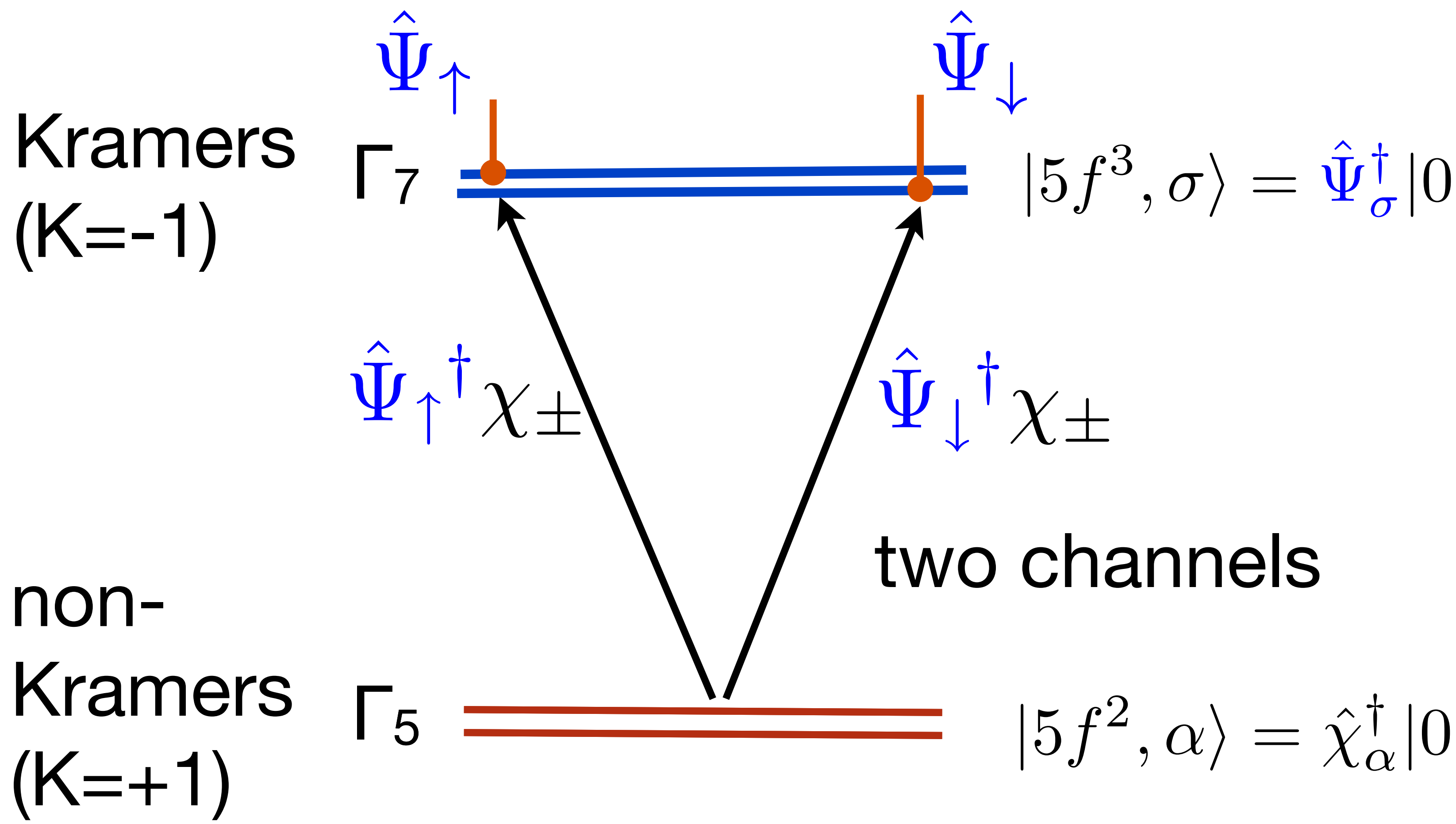
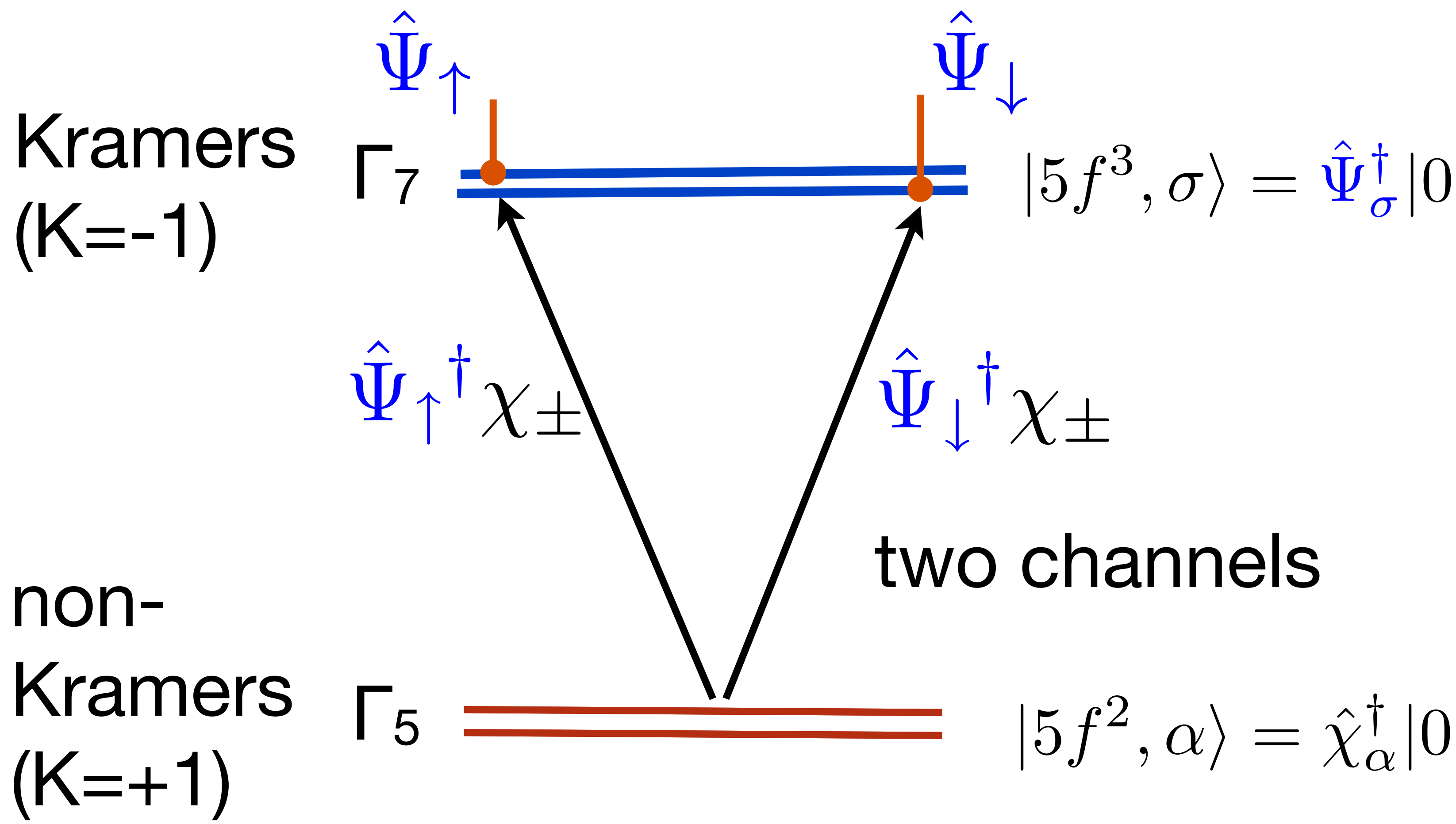


$$|5f^3, \sigma\rangle\langle 5f^2, \alpha| = \hat{\Psi}^\dagger_\sigma \hat{\chi}_\alpha$$

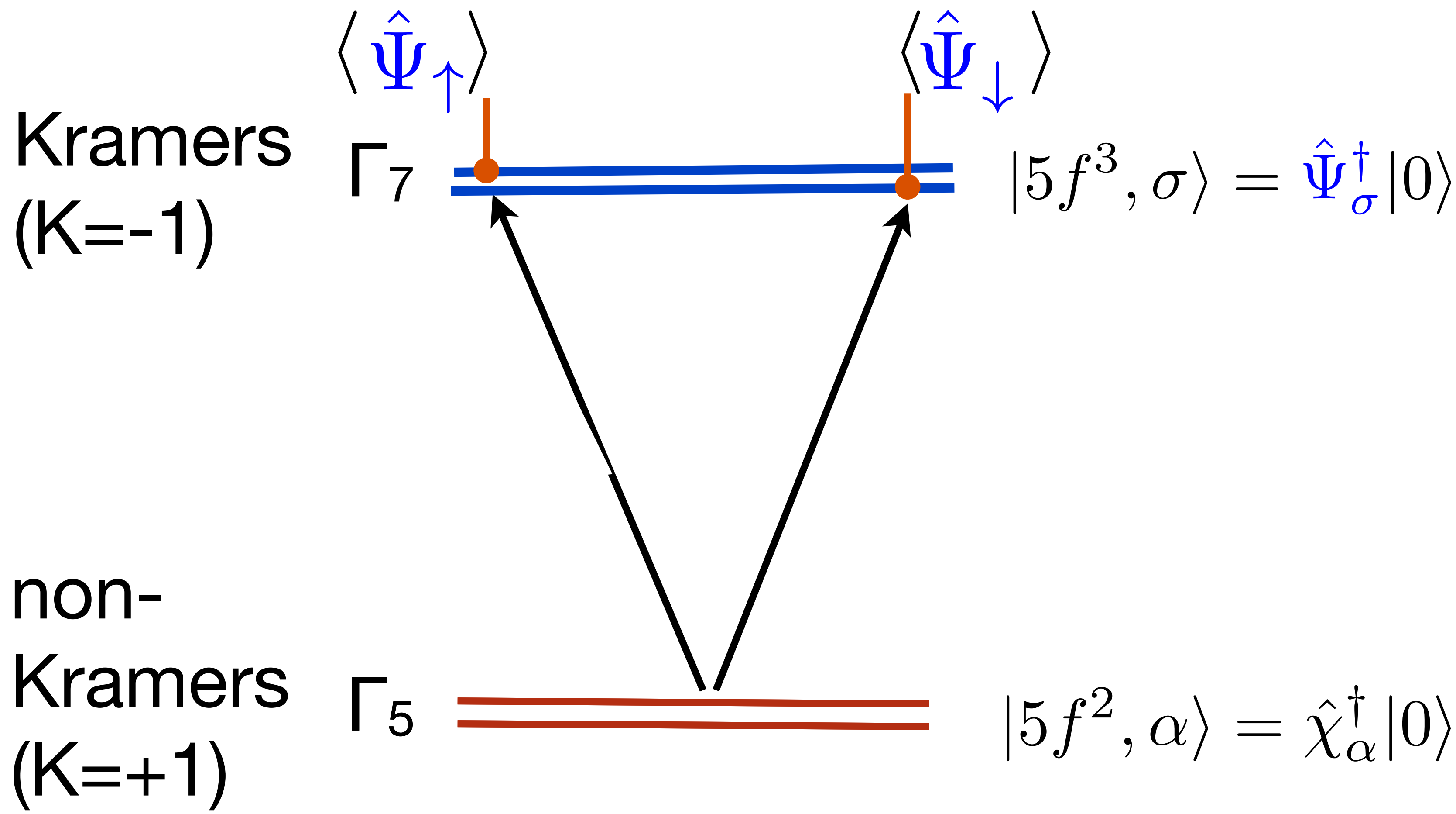
"Hastatic" order.



$$|5f^3,\sigma\rangle\langle 5f^2,\alpha| \longrightarrow \langle\hat{\Psi}^\dagger_\sigma\rangle\hat{\chi}_\alpha$$

hasta: spear (latin)

“Hastatic” order.

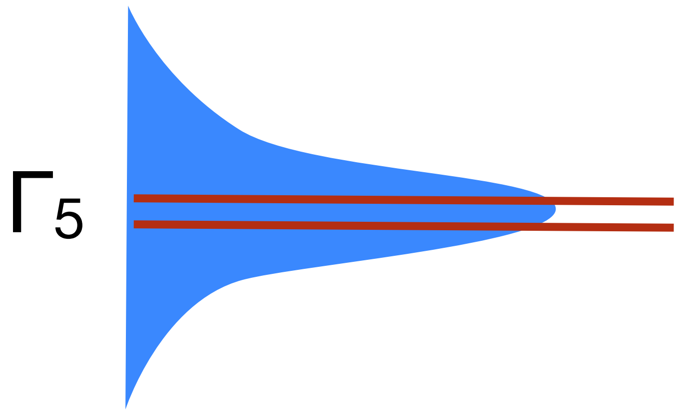


(“Magnetic Higgs Boson”)

$$\Psi = \begin{pmatrix} \langle \Psi_{\uparrow} \rangle \\ \langle \Psi_{\downarrow} \rangle \end{pmatrix}$$

$$|5f^3, \sigma\rangle\langle 5f^2, \alpha| \longrightarrow \langle \hat{\Psi}^{\dagger}_{\sigma} \rangle \hat{\chi}_{\alpha}$$

"Hastatic" order.



("Magnetic Higgs Boson")

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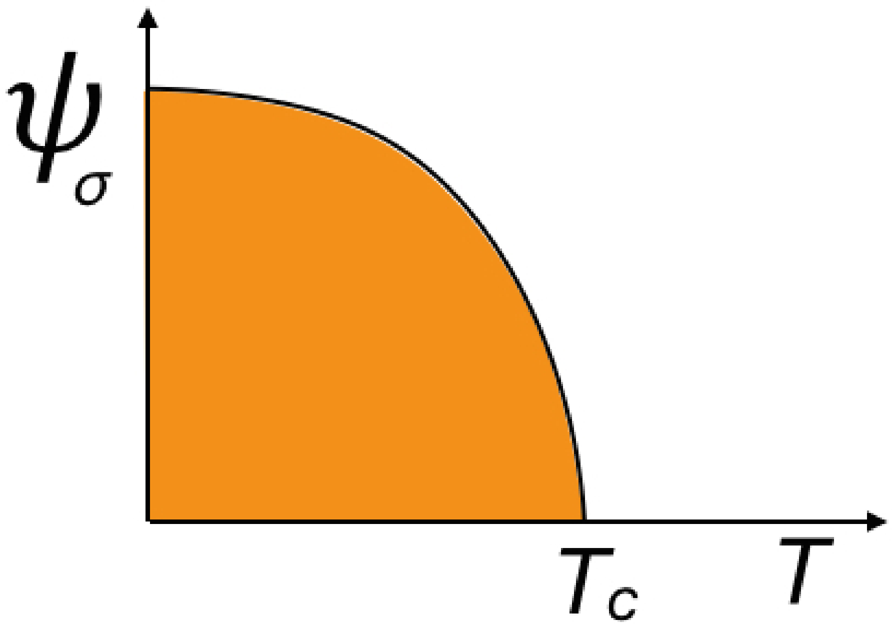
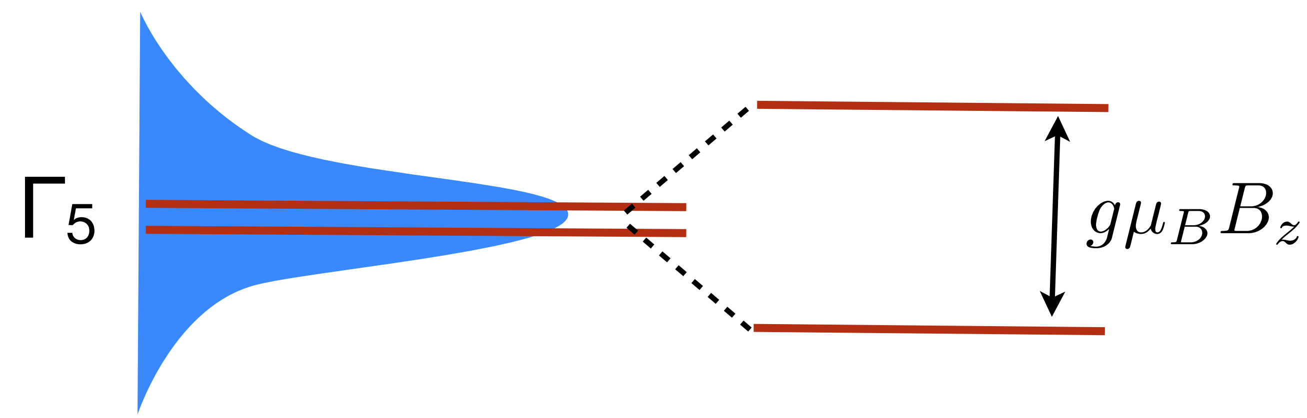
"Hastatic" order.

Quasiparticles acquire the Ising anisotropy of the non-Kramers doublet.





("Magnetic Higgs Boson")

$$\Psi = \begin{pmatrix} \langle \Psi_\uparrow \rangle \\ \langle \Psi_\downarrow \rangle \end{pmatrix}$$

$$|5f^3, \sigma\rangle\langle 5f^2, \alpha| \longrightarrow \langle \hat{\Psi}^\dagger_\sigma \rangle \hat{\chi}_\alpha$$

Open Challenges.

- QCPs: Origin of $C/T \sim \text{Log}(T_0/T)$? $\rho \sim T$?
- Co-existence heavy fermions & LM AFM = Two fluid behavior? [Supersymmetry? B/F]
- HFSC: how is the spin incorporated into the condensate? [Composite pairs?]
- Hidden order (HO). Origin of ISING qps? [1/2 integer spinor OP]
- HO: complex MDW (multipolar density wave) vs Fractional spinor order.

Thank You!