Charge Aspects of Composite Pair Superconductivity

Rebecca Flint (Iowa State)

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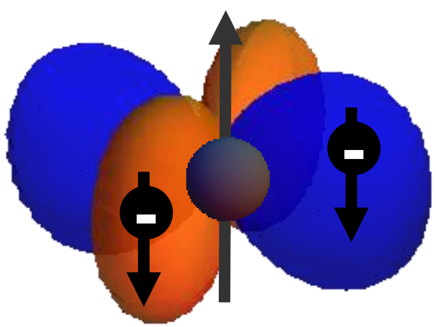
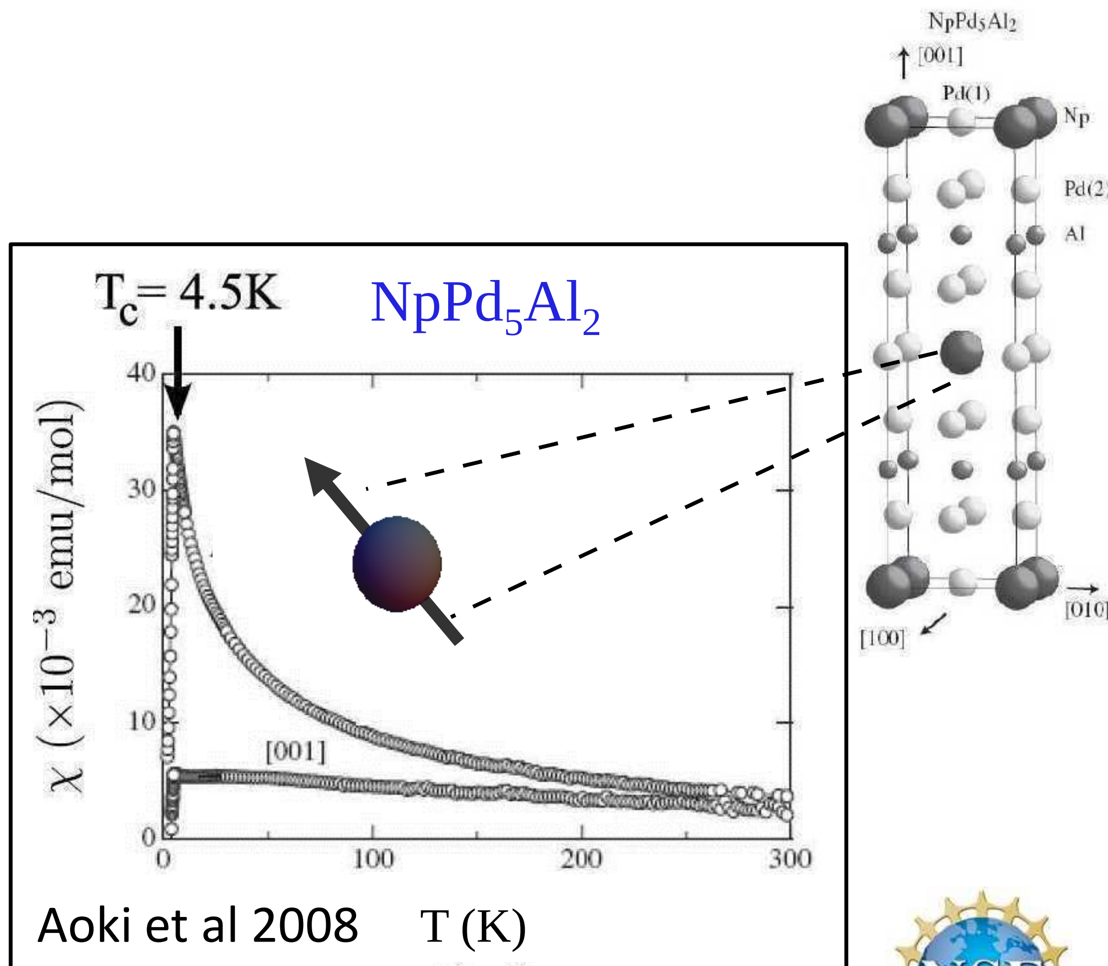


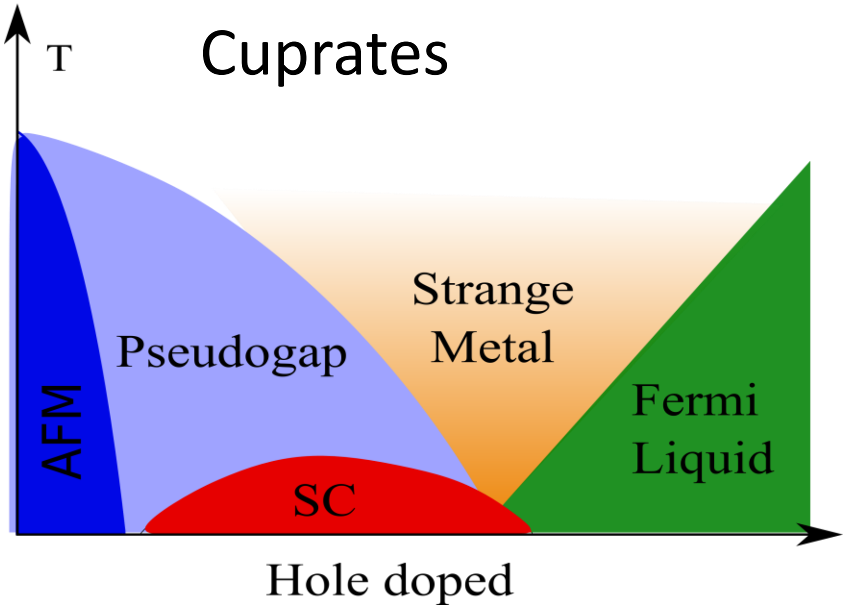


Aoki et al 2008

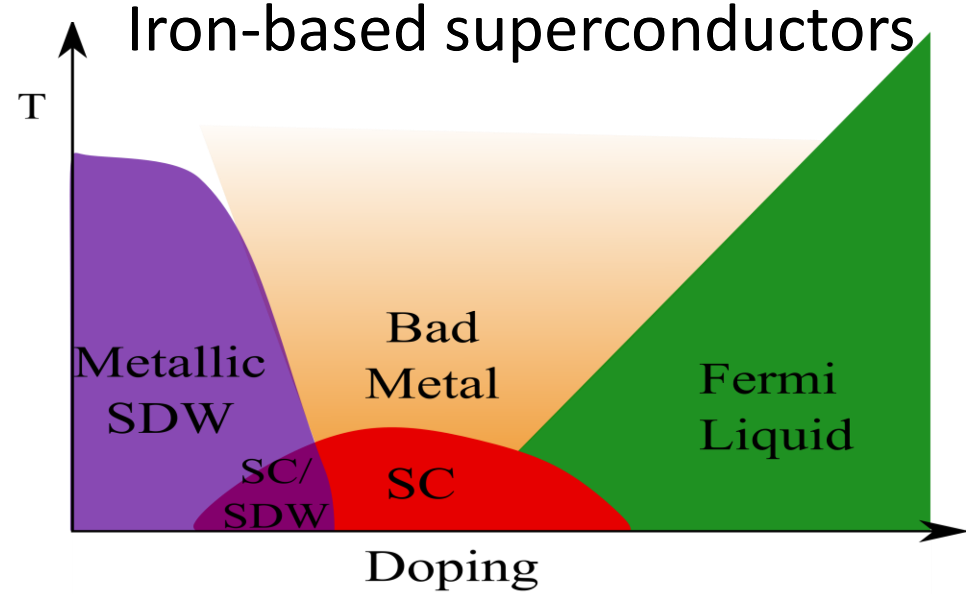
R. Flint, M. Dzero and P. Coleman, Nature Physics 4, 643(2008)
R. Flint, A.H. Nevidomskyy and P. Coleman, Phys. Rev. B 84, 064514 (2011)

Magnetic pairing appears ubiquitous

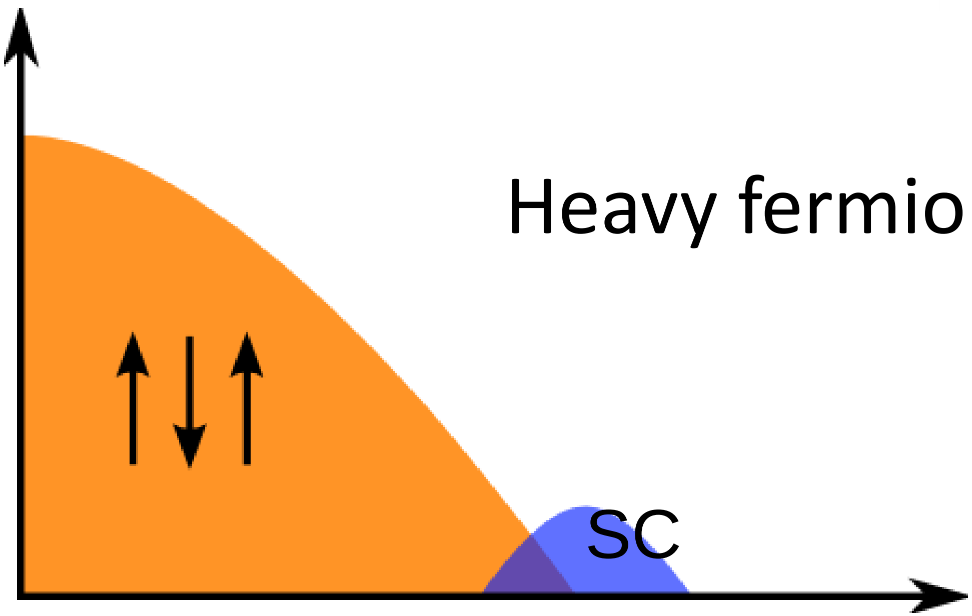
Cuprates

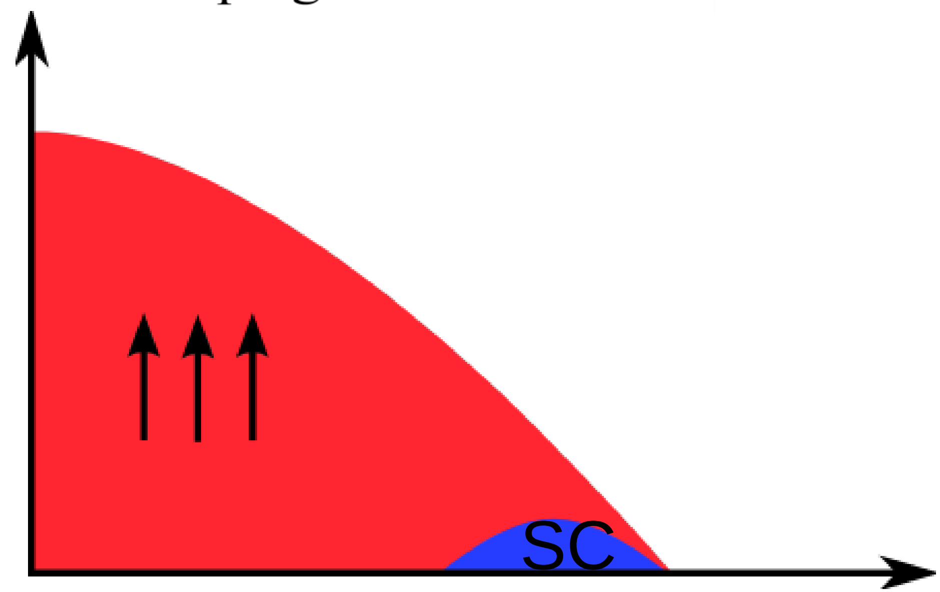


Iron-based superconductors



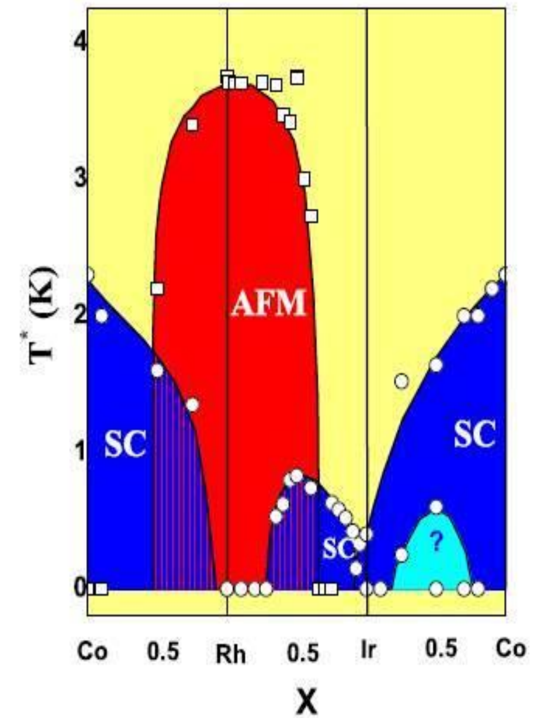
Heavy fermions





Magnetic pairing appears ubiquitous

Sarrao and Thompson, JPSJ (2007)



But…

- Two domes in Ce*M*In_5 (*M = Co,Rh,Ir)*
- Superconductivity without magnetism
  - $NpPd_5Al_2$, $PuCoGa_5$
- Robust to disorder *on the f-site*
  - 5% Sn on In kills T_c , 25% La on Ce required
- Nodeless superconductivity in $Ce_{1-x}Yb_xCoIn_5$
- Many Ce superconductors, few Yb ($T_c^{Ce} >> T_c^{Yb}$)
  - Magnetism should not discriminate

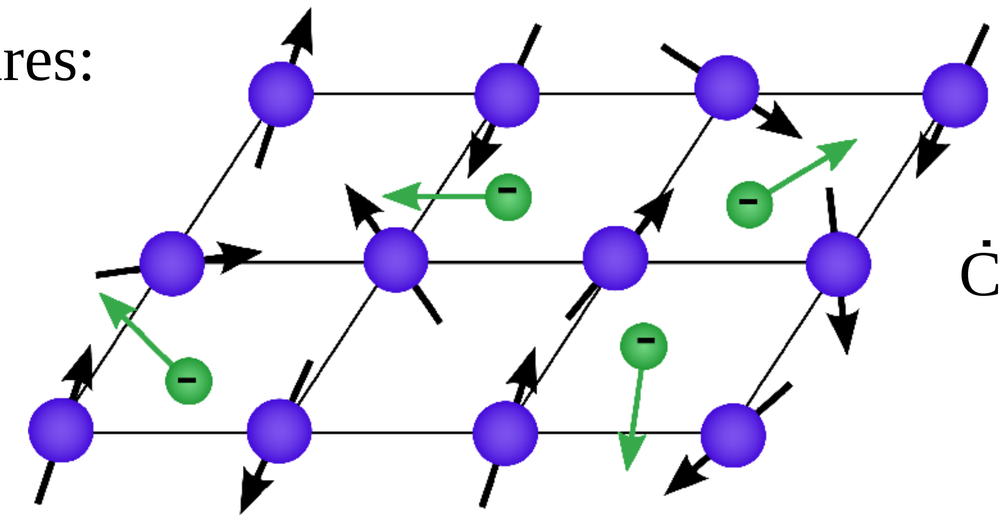
Are there other possible mechanisms?

Yes! Composite pairing

How can we tell?

“Conventional” heavy fermion superconductivity

At high temperatures:



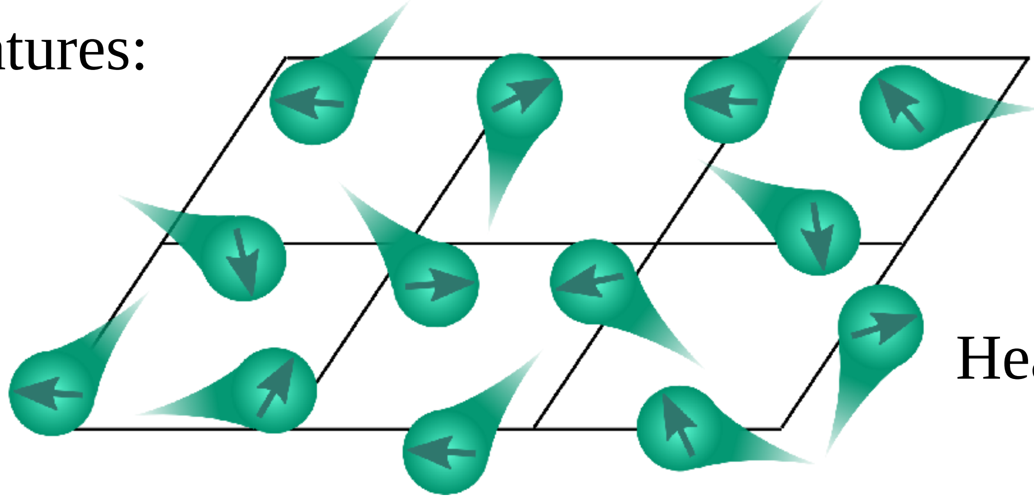
How do we get from here to heavy Cooper pairs?

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

“Conventional” heavy fermion superconductivity

At lower temperatures:

$$T < T^*$$



Heavy quasiparticles

How do we get from here to heavy Cooper pairs?

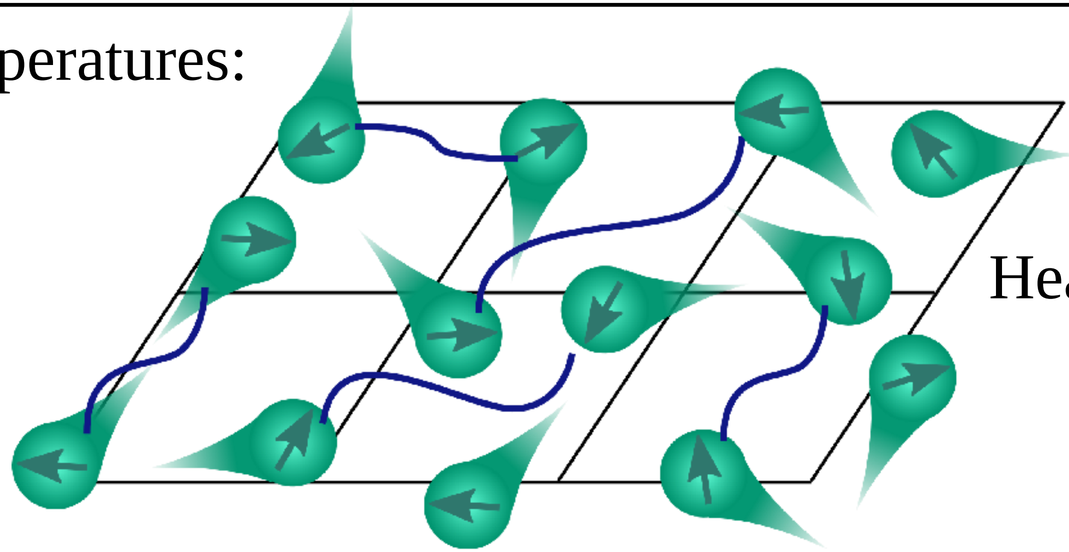
1. The local moments quench [via the Kondo effect], forming heavy quasiparticles

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

“Conventional” heavy fermion superconductivity

At very low temperatures:

$$T < T_C$$



How do we get from here to heavy Cooper pairs?

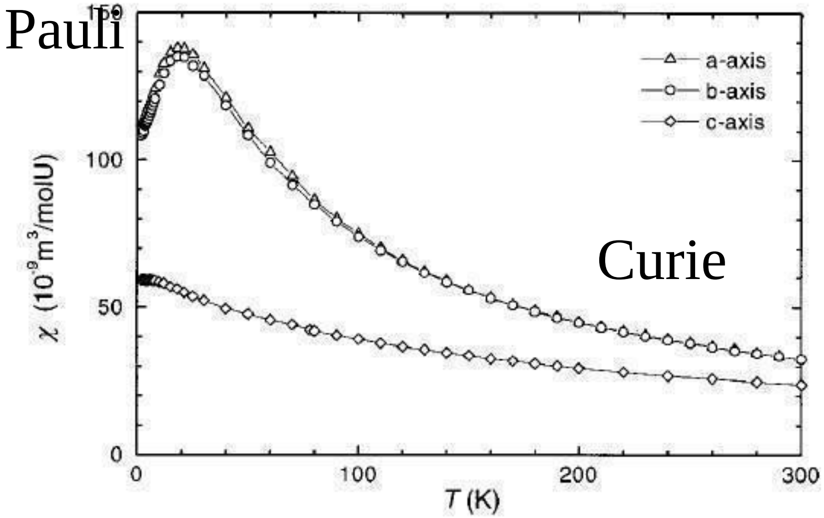
1. The local moments quench [via the Kondo effect], forming heavy quasiparticles

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

These two stages are well separated.

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

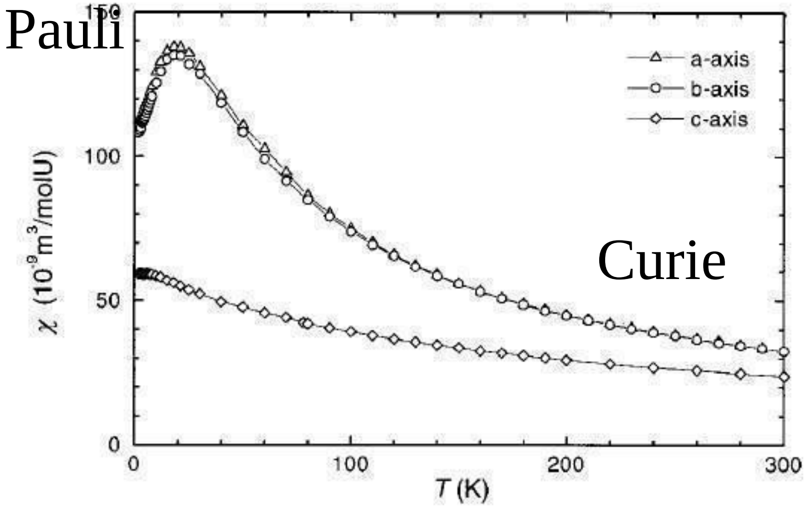
UPt3



Pauli paramagnetic by 30K

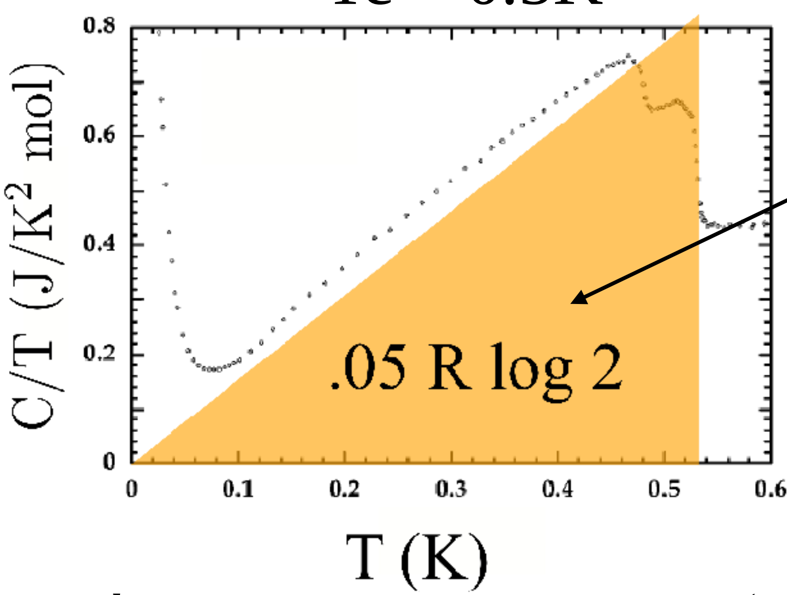
Frings *et al.* J. Magn. Magn. Mater. **31**, 240(1983)
Brison *et al.* J. Low Temp. Phys. **95**, 145*(*1994)

UPt3



Pauli paramagnetic by 30K

Tc = 0.5K



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

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

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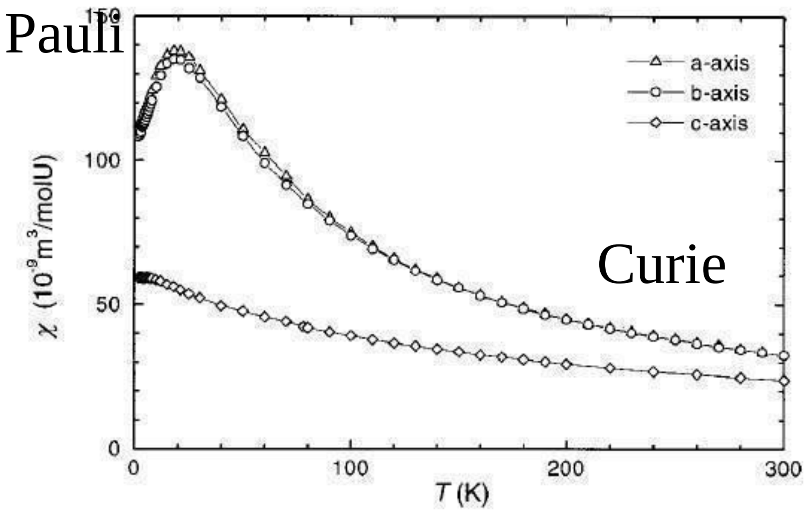
UPt3



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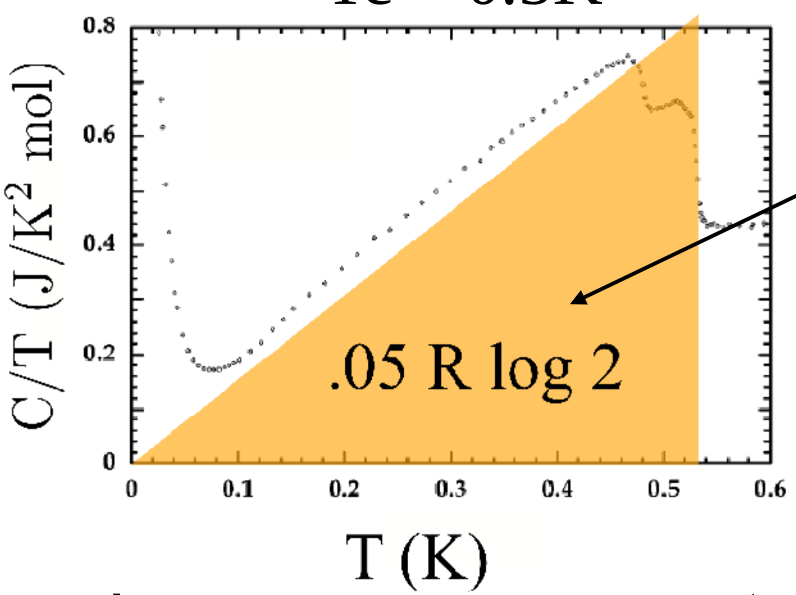

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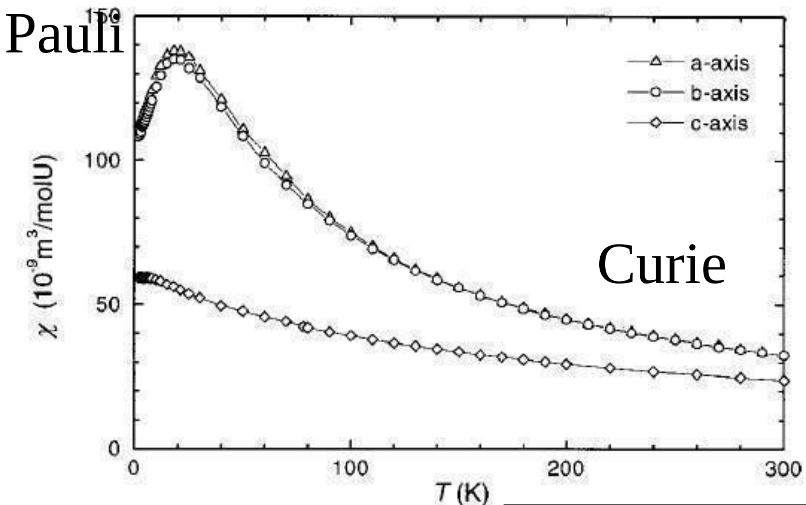
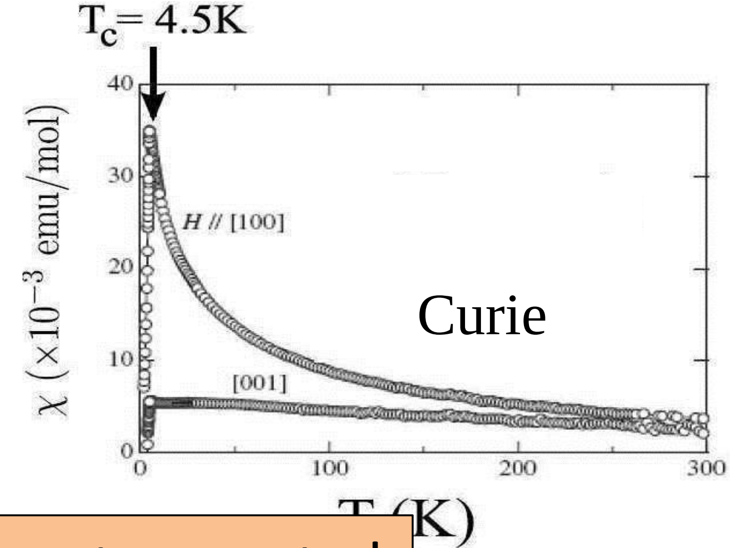
Small condensation entropy

Spins are quenched

Two stages are well separated

UPt_3 | $NpPd_5Al_2$





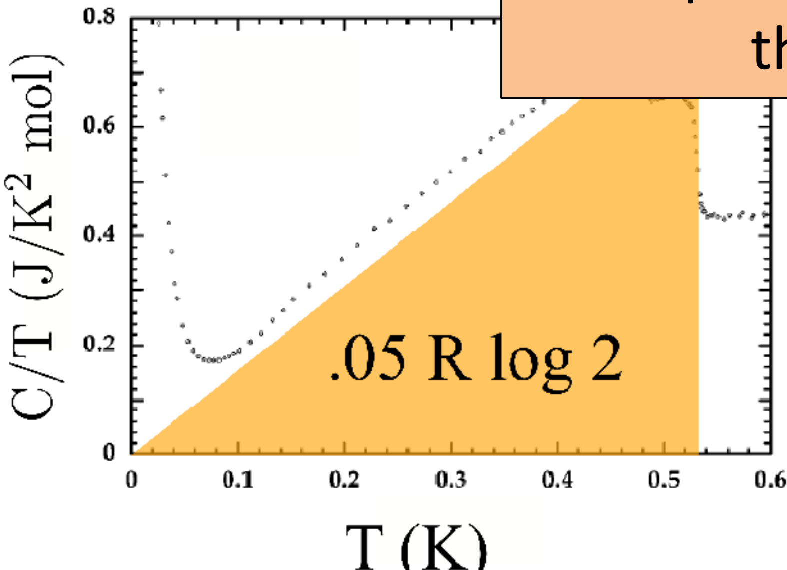
Pauli paramagn

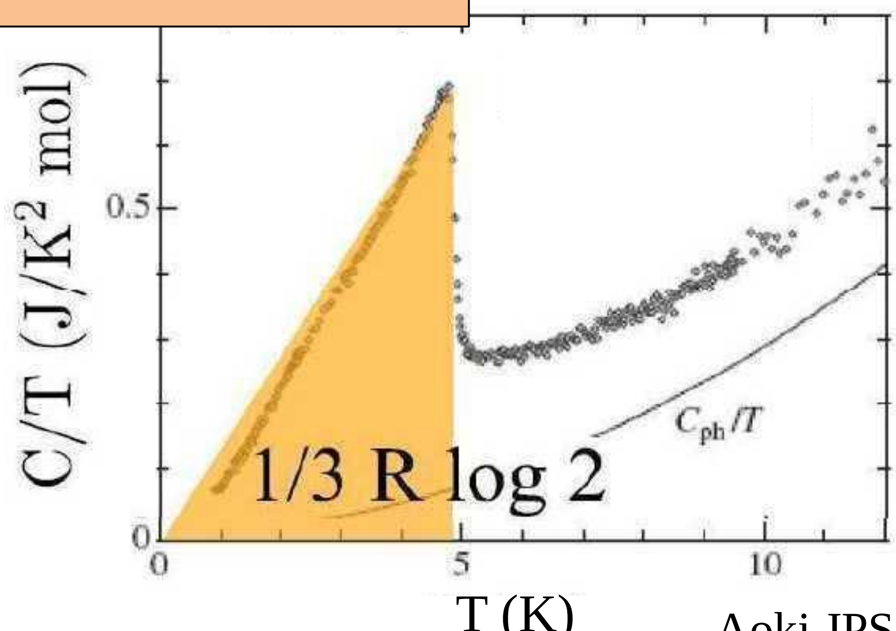
Tc = 0

The two stages are *not* separated
The spins condense *directly* into the condensate!

aramagnetism

= 4.5K





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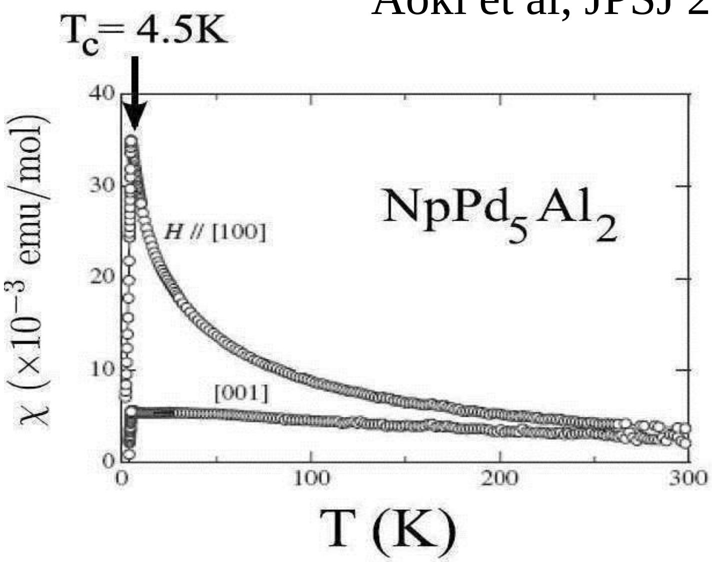
Aoki JPSJ 2008

Local moment superconductivity

Aoki et al, JPSJ 2007



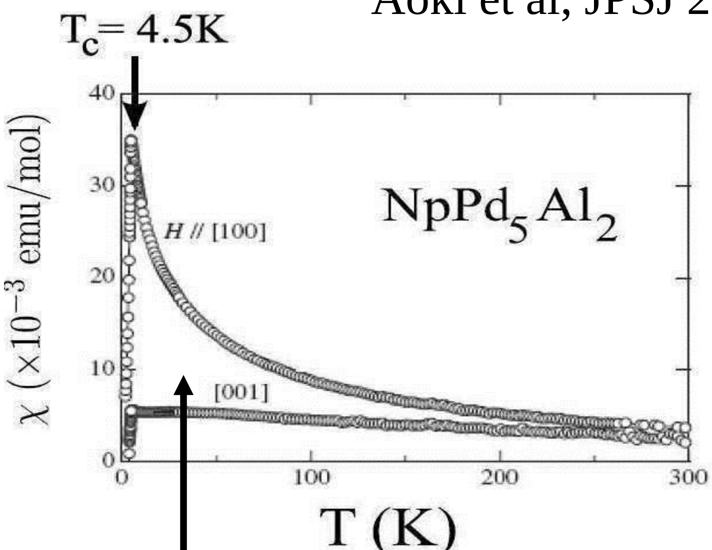
- Large condensation entropy (~ 1/3 R log 2)
  - Free local moments above T_C

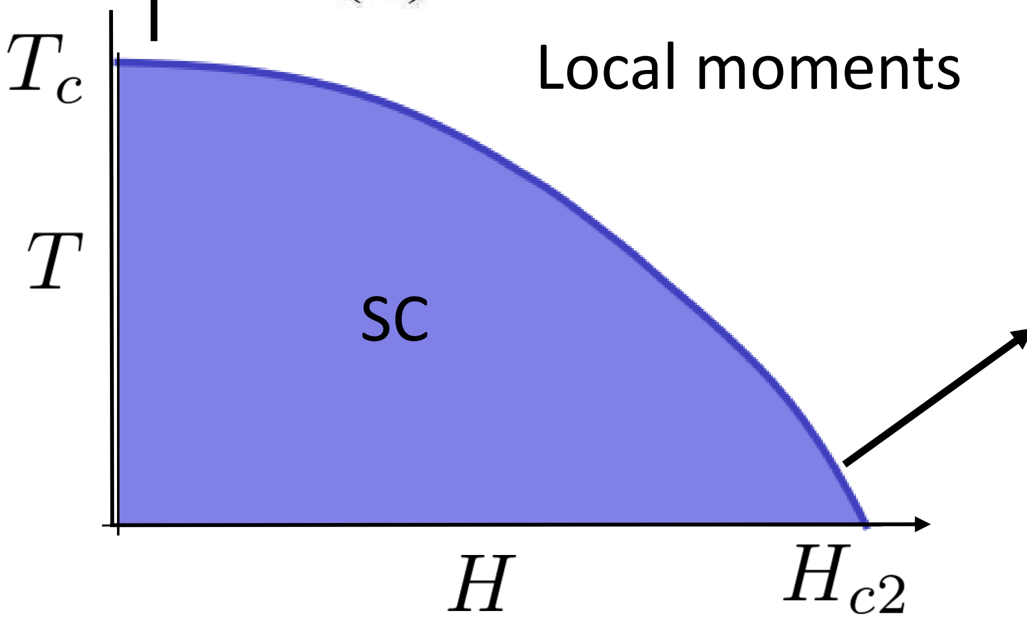
Local moment superconductivity

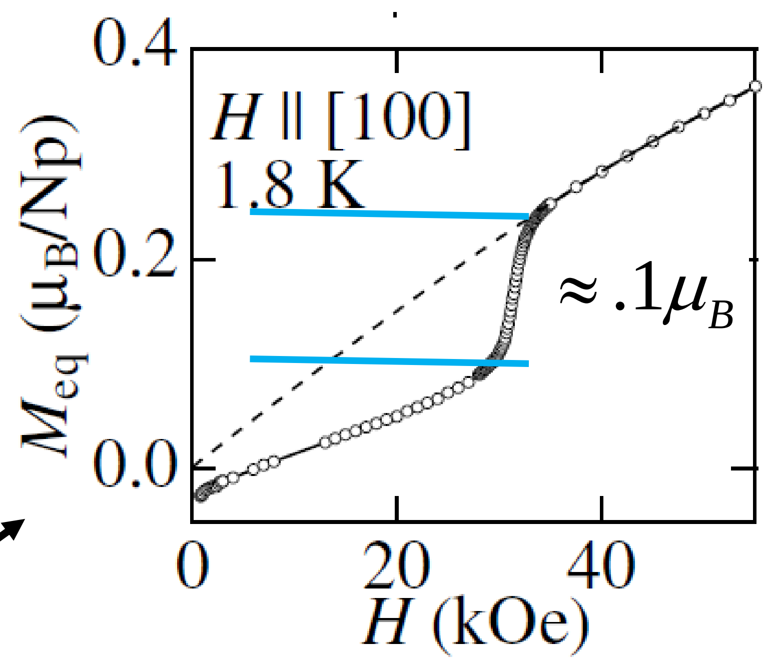
- Large condensation entropy (~ 1/3 R log 2)
  - Free local moments above T_C, H_{C2}
- Spins quench directly into the condensate!

How?

Aoki et al, JPSJ 2007



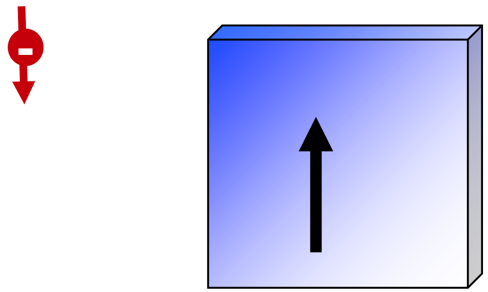




Y. Haga et al, Actinides 2009

Composite Fermions (Kondo effect)

Co-tunneling



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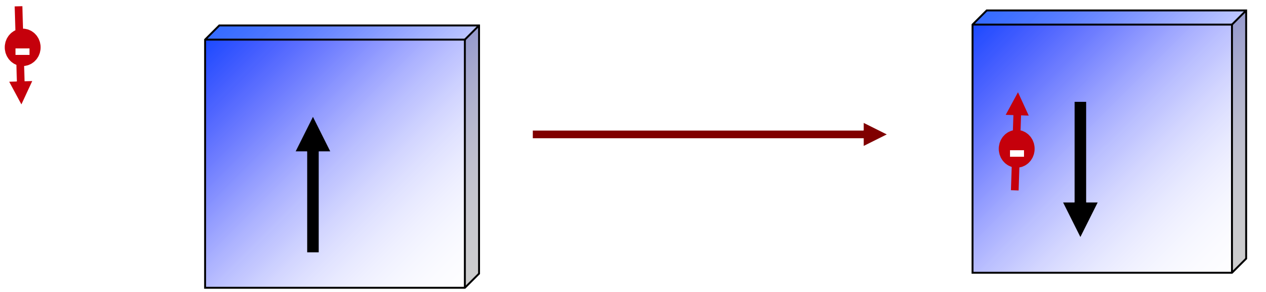


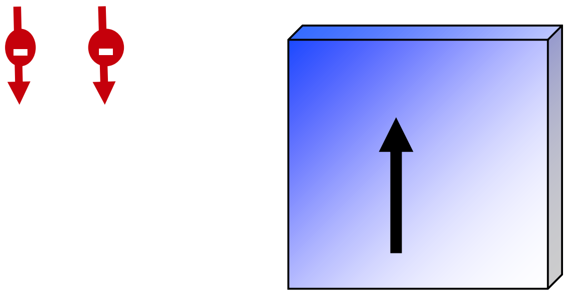
$c_{\uparrow}^{\dagger} S_{-}$

Composite fermion

The product of a conduction electron and a spin flip

Composite Pairing

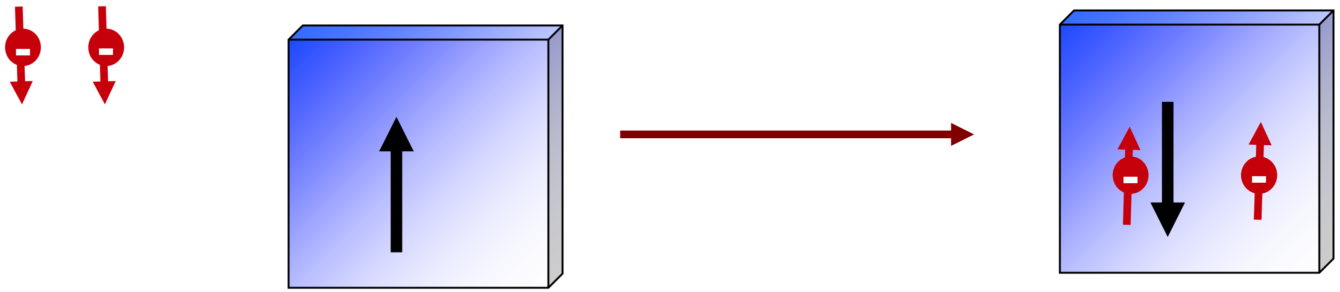
Copairing



Abrahams, Balatsky, Scalapino, Schrieffer 1995

Composite Pairing

Copairing



$$c^{\dagger}_{A\uparrow}c^{\dagger}_{B\uparrow}S_{-}$$

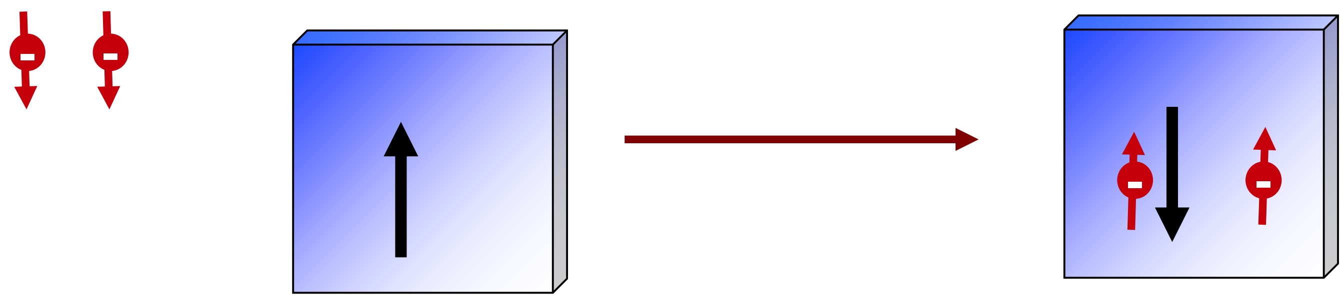
Composite **pair**

The product of a conduction electron **pair** and a spin flip

Abrahams, Balatsky, Scalapino, Schrieffer 1995

Composite Pairing (Two channel Kondo)

Copairing



$$c^\dagger_{A\uparrow} c^\dagger_{B\uparrow} S_-$$

Composite pair

The product of a conduction electron pair and a spin flip

The composite pair is a **singlet**

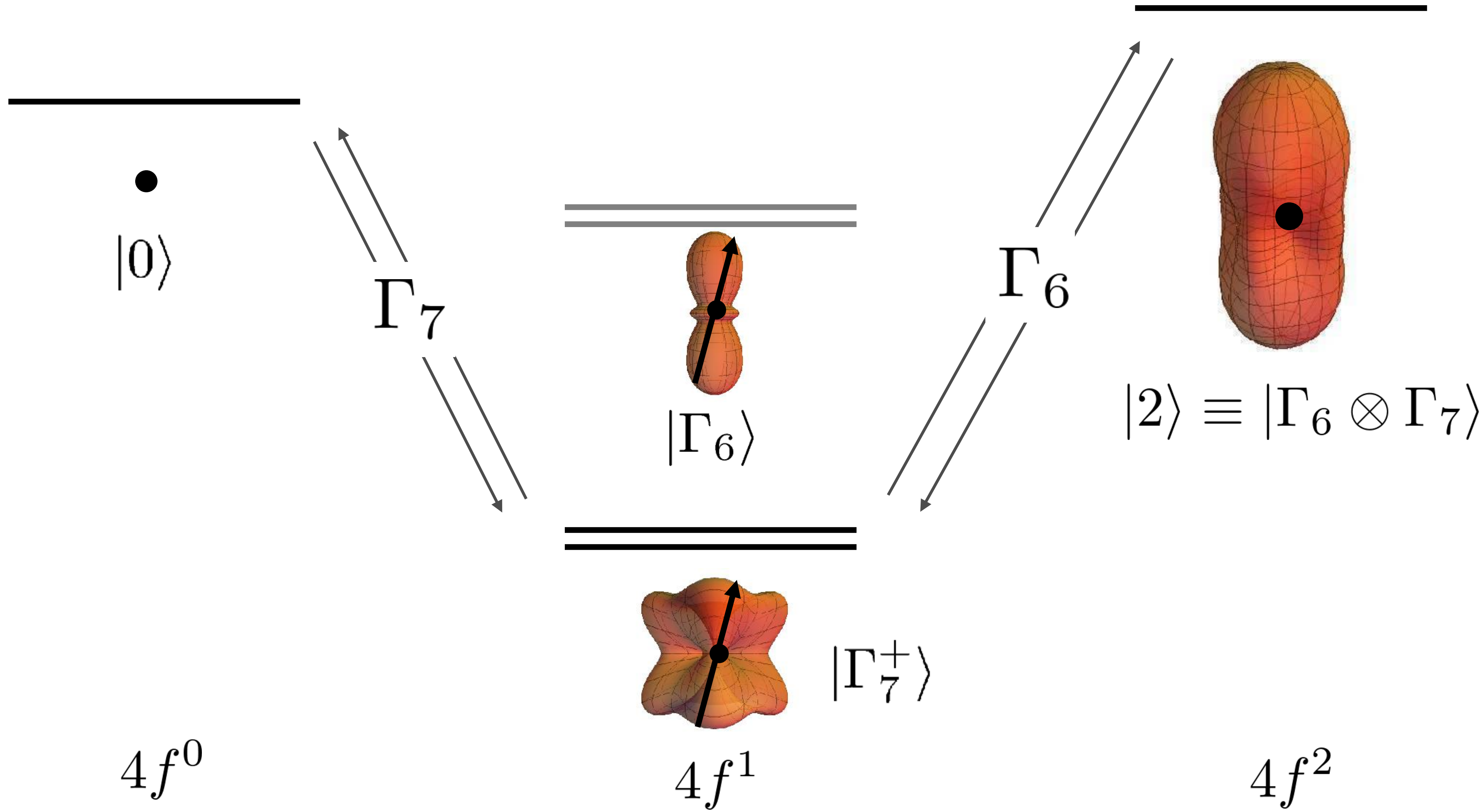
– requiring a **triplet** pair of conduction electrons

→ Antisymmetric spatially – two electrons, two orthogonal channels

Abrahams, Balatsky, Scalapino, Schrieffer 1995

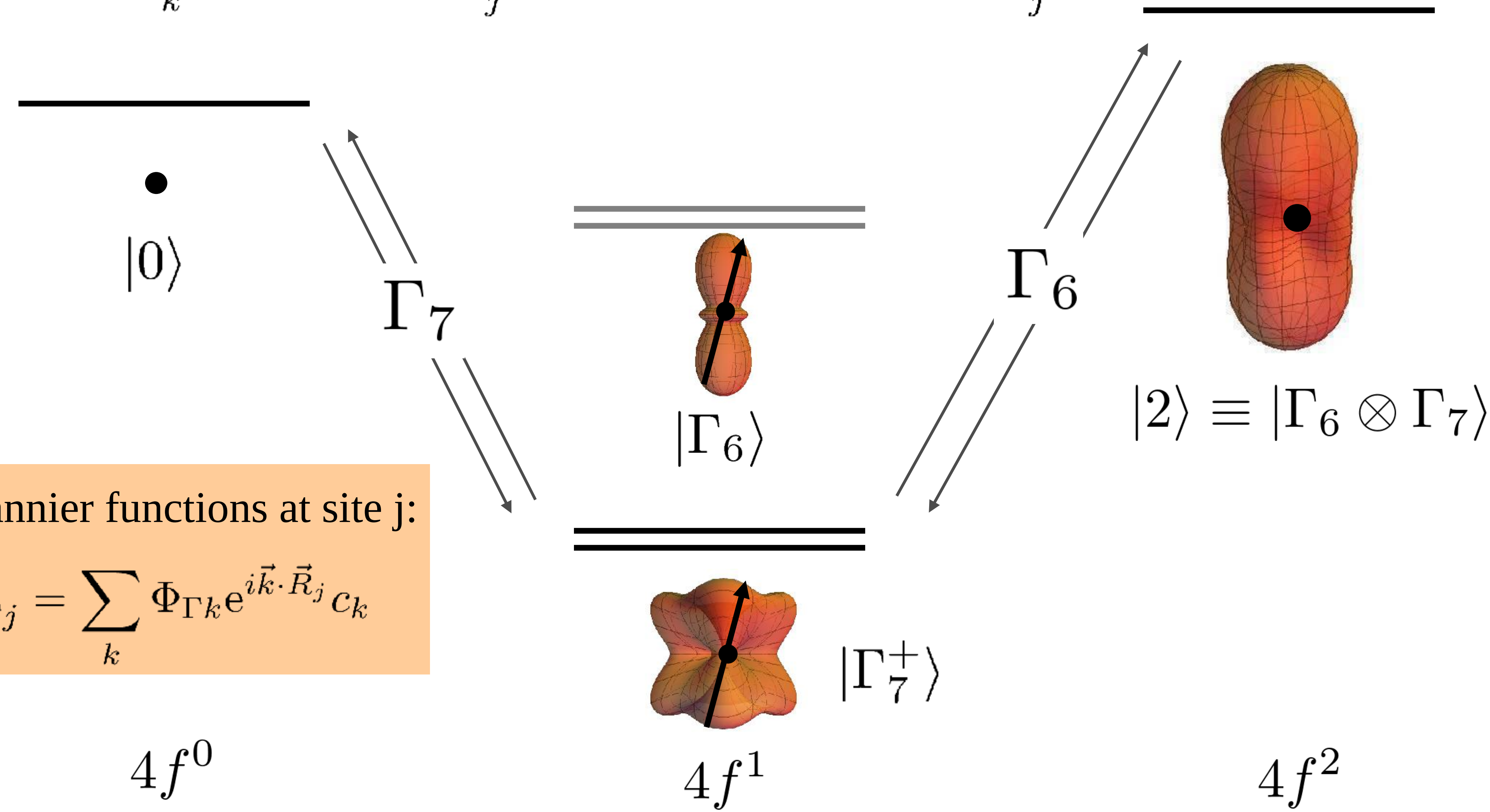
The origin of composite pairing

Requires two orthogonal Kondo channels



The origin of composite pairing

$$H = \sum_k \epsilon_k c_k^\dagger c_k + J_1 \sum_j \psi^\dagger_{1j\alpha} \vec{\sigma}_{\alpha\beta} \psi_{1k\beta} \cdot \vec{S}_j + J_2 \sum_j \psi^\dagger_{2j\alpha} \vec{\sigma}_{\alpha\beta} \psi_{2k\beta} \cdot \vec{S}_j$$



Wannier functions at site j:

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

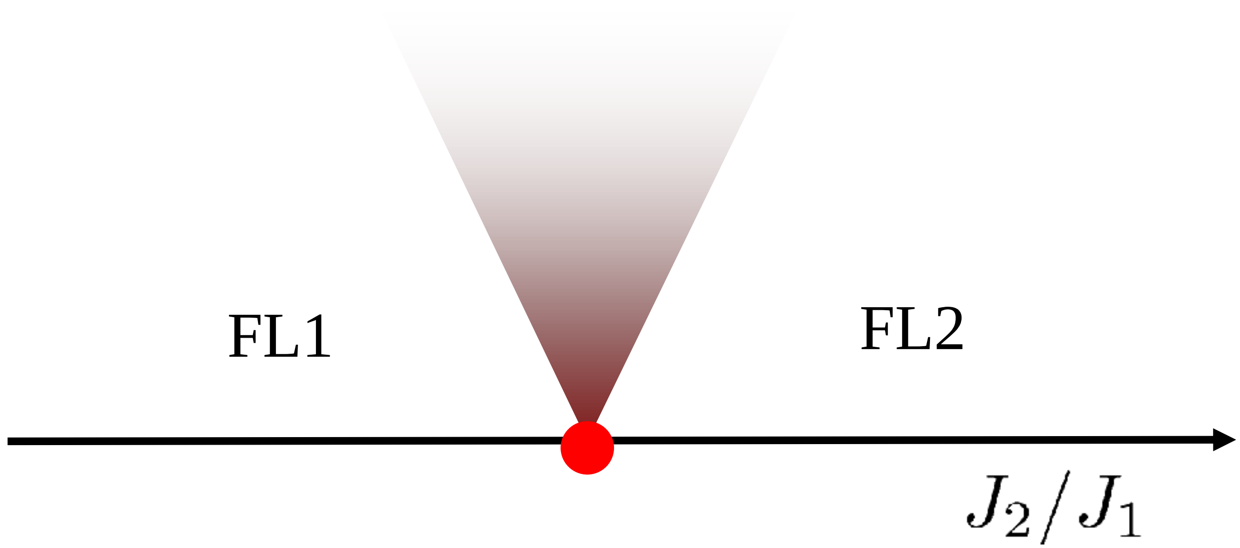
The two channel Kondo model: impurity

The impurity has a quantum critical point for $J_1 = J_2$

Zero point entropy ½ R log 2

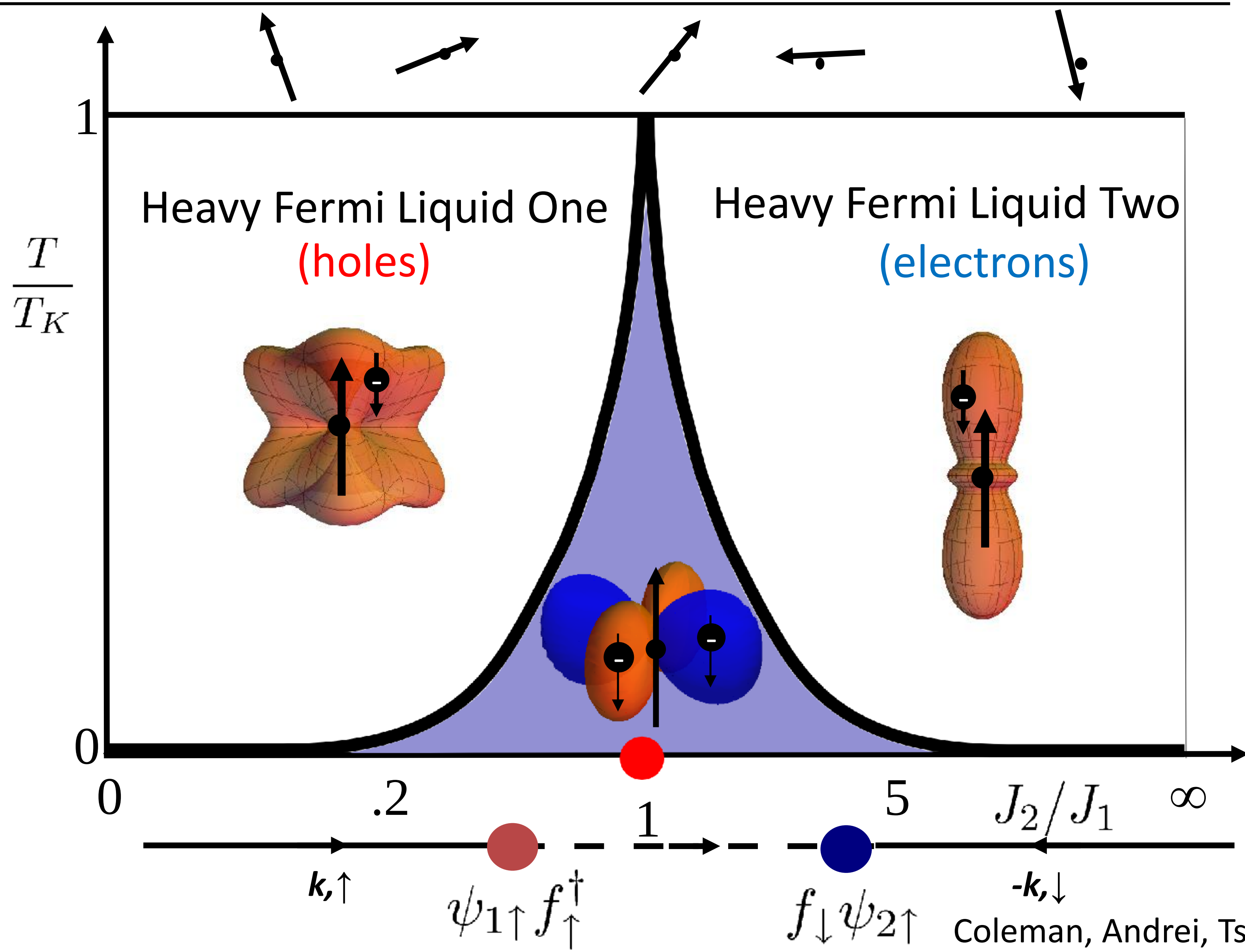
Singular composite pair fluctuations

– expect to be hidden in the lattice



Emery and Kivelson 1992

The two channel Kondo model: lattice



Coleman, Andrei, Tsvelik, Kee 1999

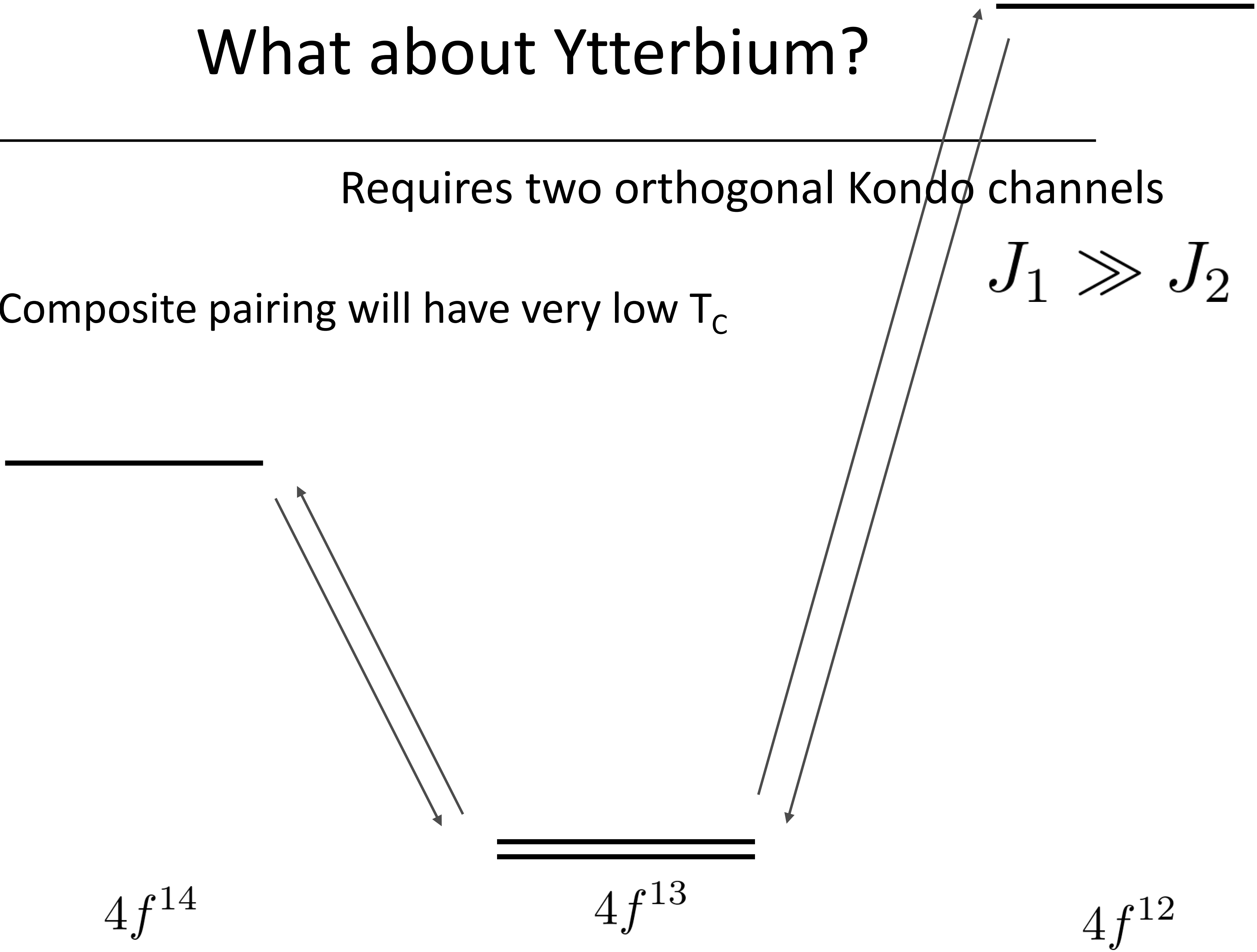
Flint, Dzero, Coleman 2008

What about Ytterbium?

Requires two orthogonal Kondo channels

$$J_1 \gg J_2$$

Composite pairing will have very low T_C



What is a composite pair?

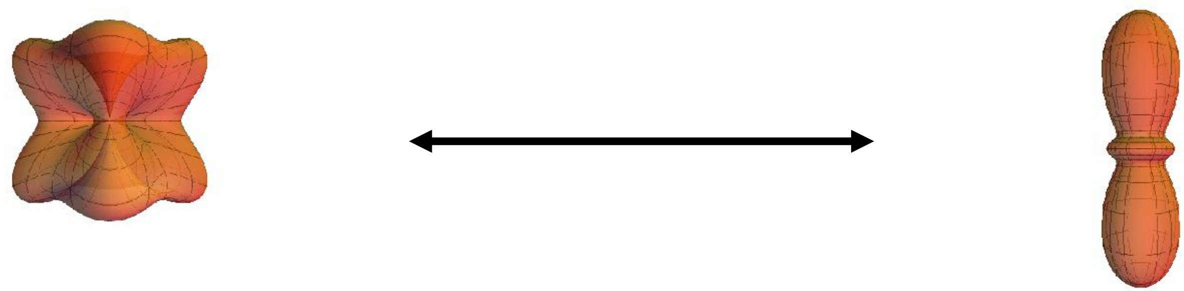
- Total spin singlet: $c^\dagger_{j1\downarrow} c^\dagger_{j2\downarrow} S_{j+}$

What is a composite pair?

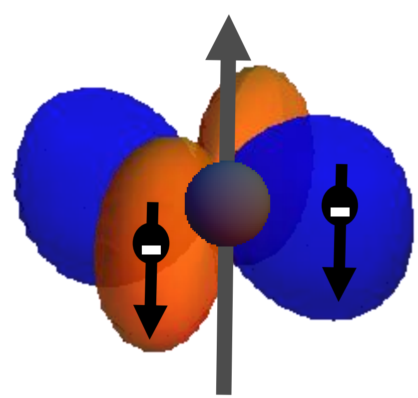
- Total spin singlet: $c^{\dagger}_{1j}\vec{\sigma}(i\sigma_2)c^{\dagger}_{2j} \cdot \vec{S}_j$

What is a composite pair?

- Total spin singlet: $c^{\dagger}_{1j}\vec{\sigma}(i\sigma_2)c^{\dagger}_{2j}\cdot\vec{S}_j$
- Nodal d-wave symmetry emerges naturally from crystal fields



$\sim|\pm\frac{5}{2}\rangle$ $\quad$ $\Delta l = 2$ $\quad$ $|\pm\frac{1}{2}\rangle$



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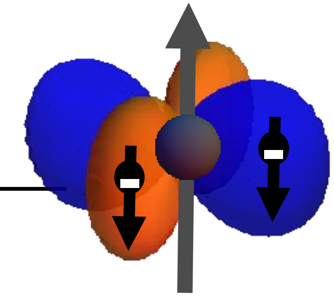

- Total spin singlet: $c^\dagger_{1j}\vec{\sigma}(i\sigma_2)c^\dagger_{2j}\cdot\vec{S}_j$
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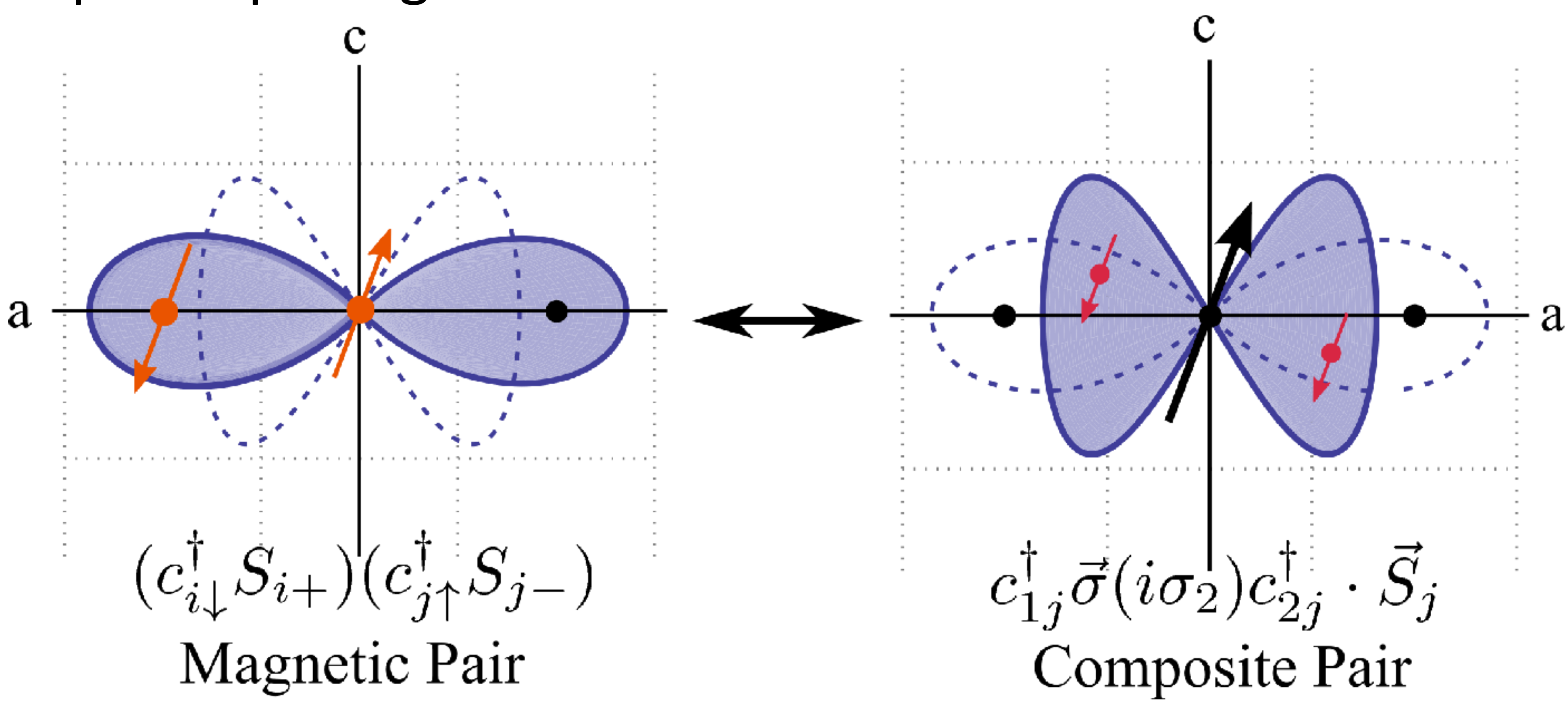
- These symmetries are shared with magnetic pairing, but composite pairing is ***local***



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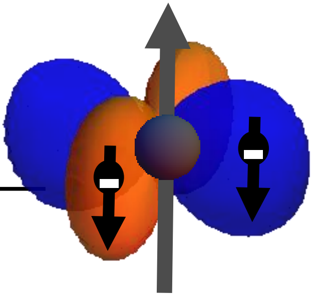

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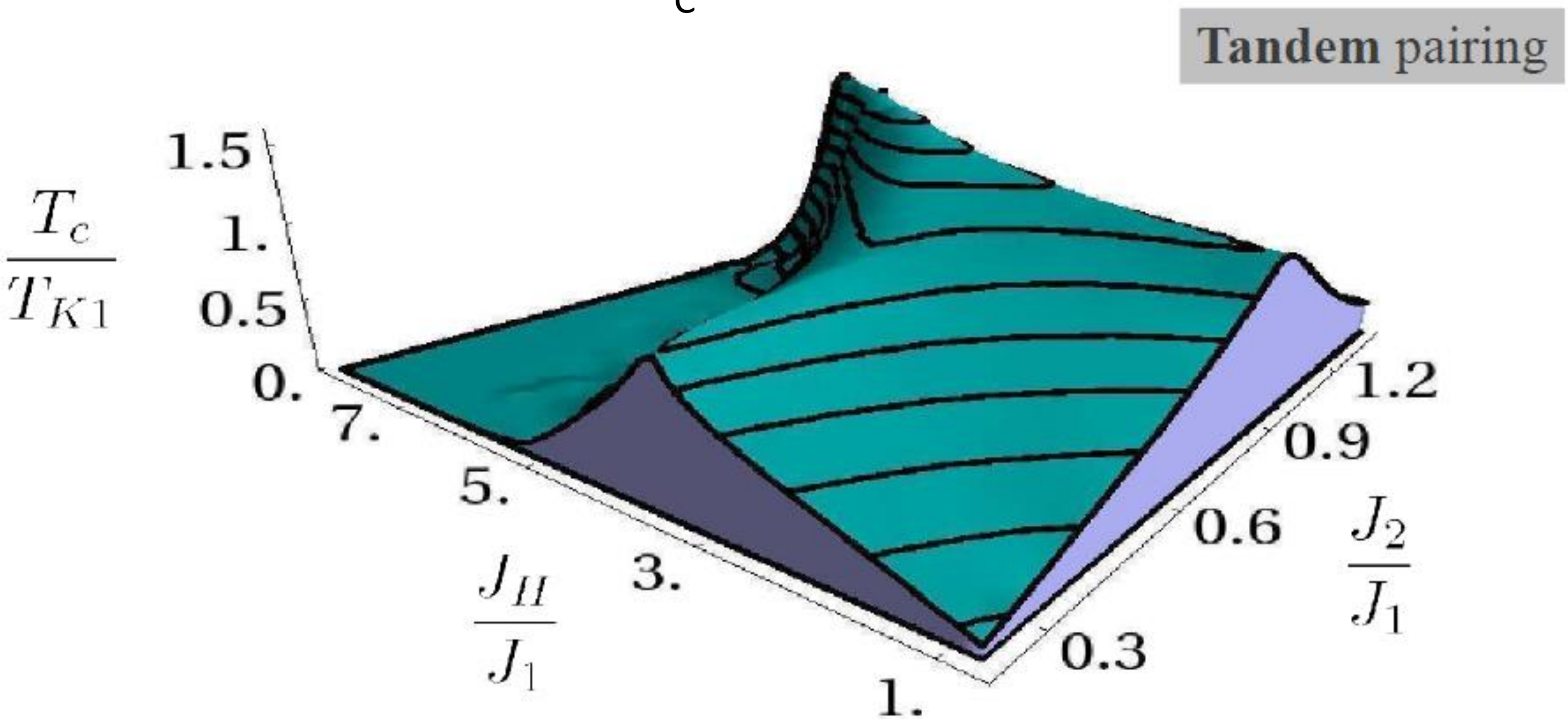
- Nodal d-wave symmetry emerges naturally from crystal fields
- These symmetries are shared with magnetic pairing, but composite pairing is ***local***
  - Can work *in tandem* to raise T_C



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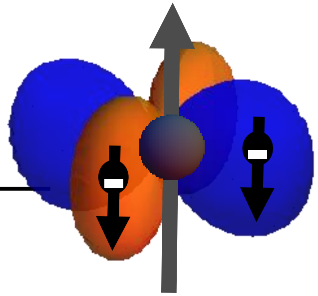
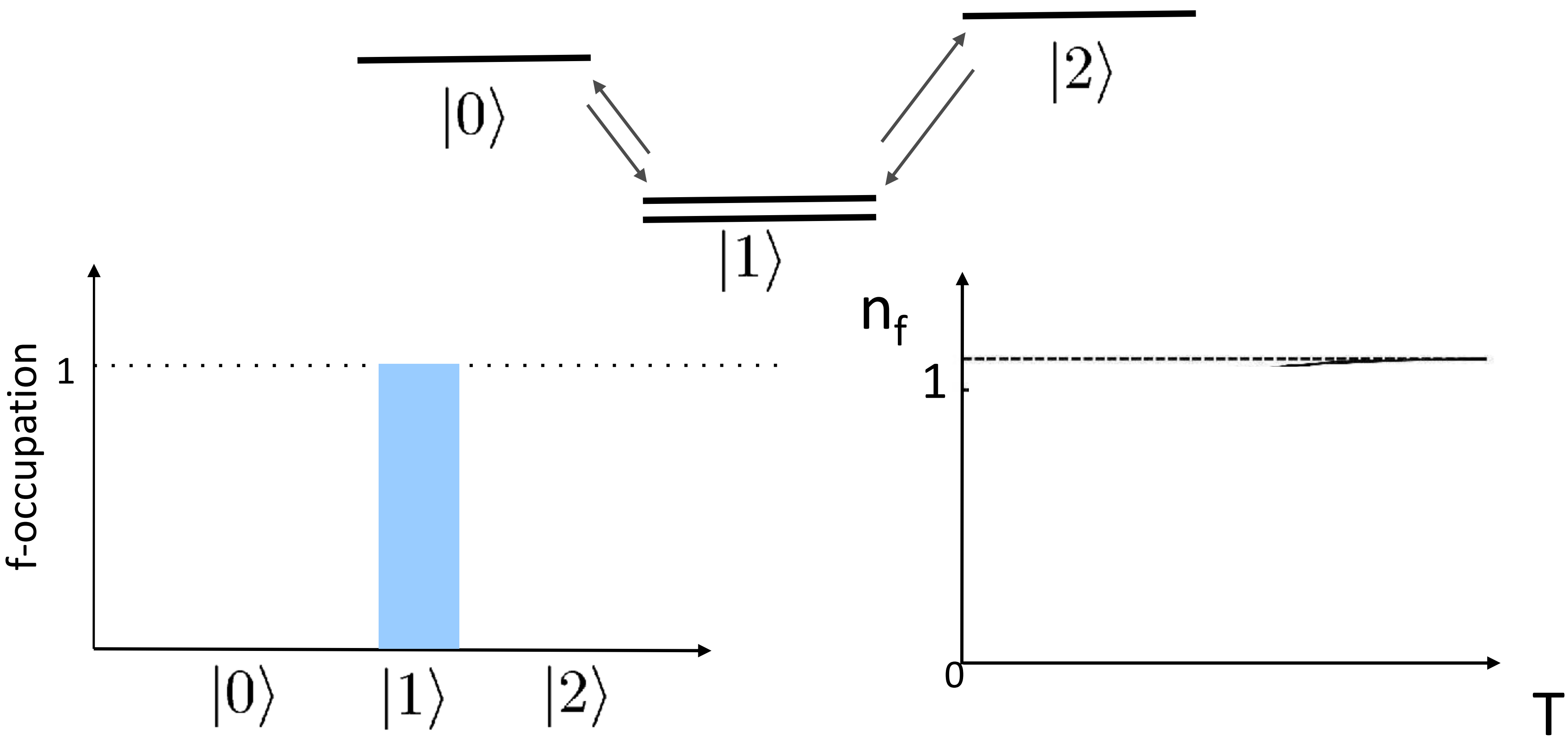


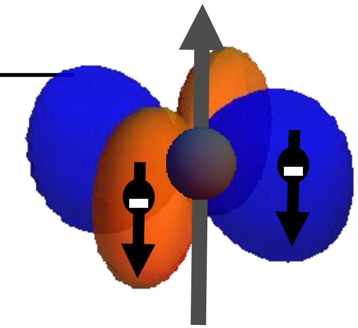
- Total spin singlet: $c^\dagger_{1j}\vec{\sigma}(i\sigma_2)c^\dagger_{2j}\cdot\vec{S}_j$
- Nodal d-wave symmetry emerges naturally from crystal fields
- Charge aspects: Kondo effect *adds and removes* electrons

Electrostatically active composite condensate

- Charge aspects
  - Hybridization *adds and removes* f-electrons



Electrostatically active composite condensate



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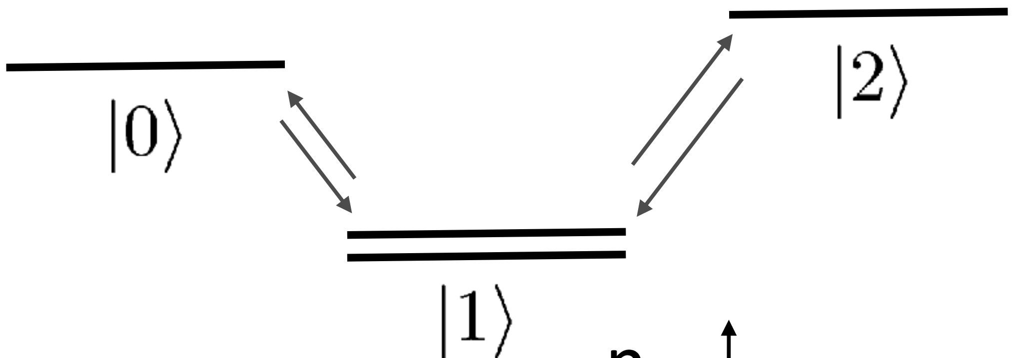
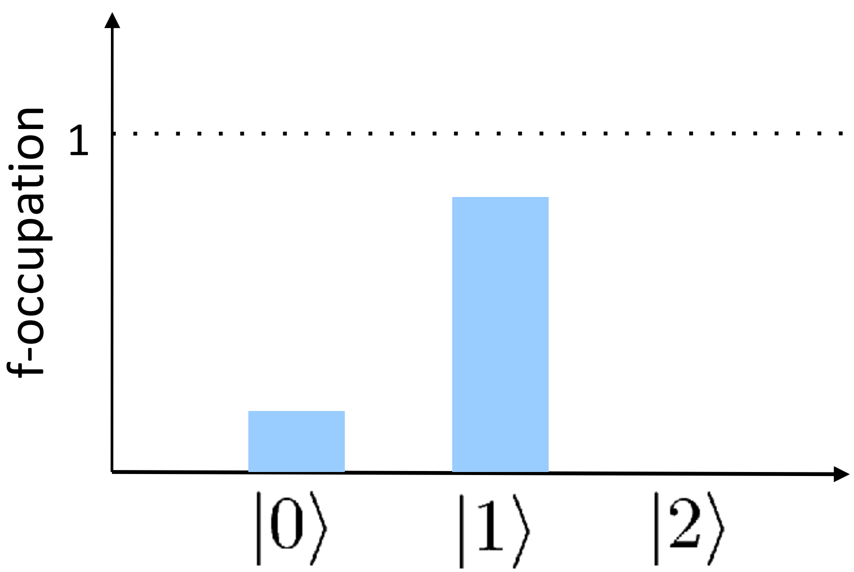
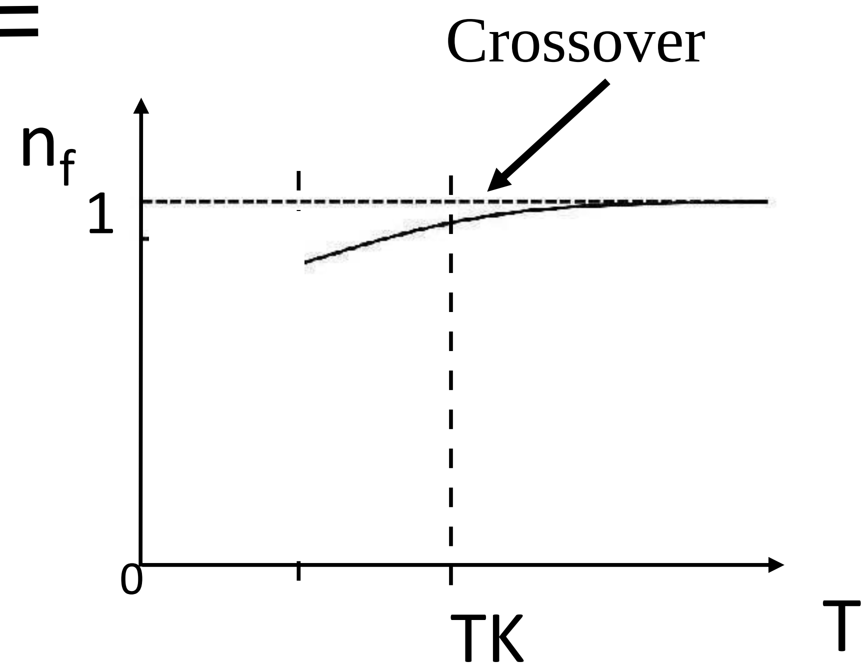
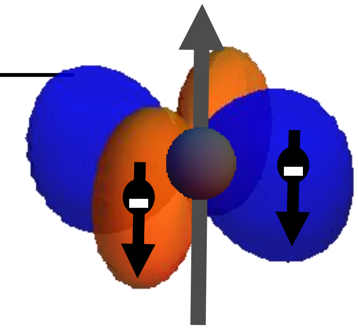






Electrostatically active composite condensate



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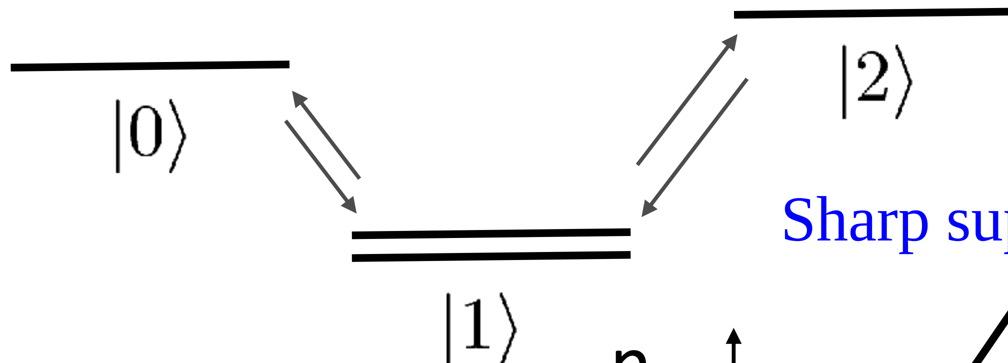
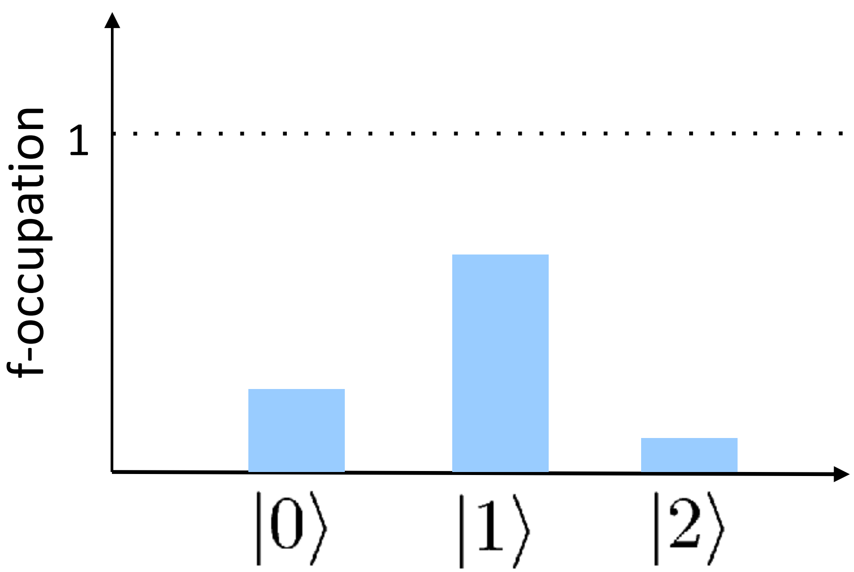
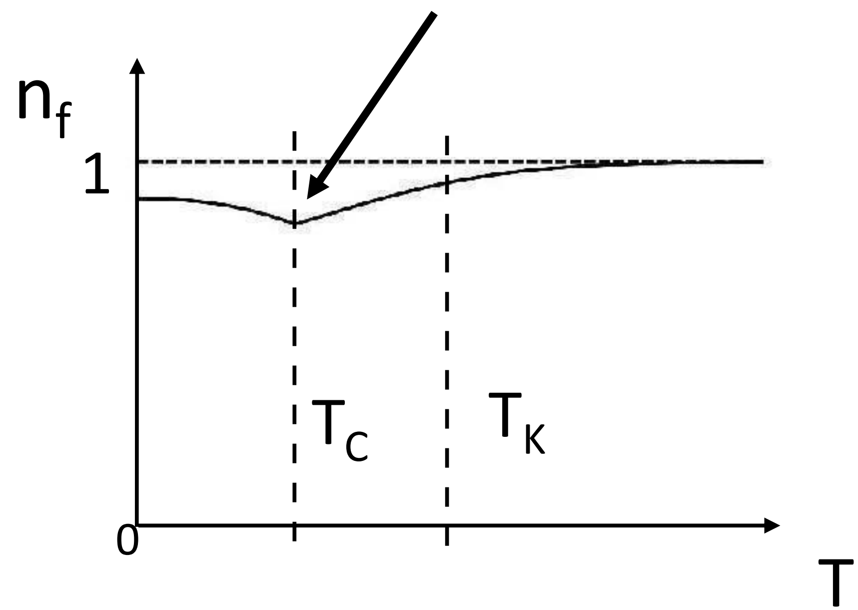


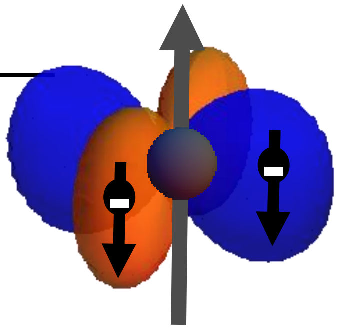


Sharp superconducting shift



$n_f(T)$ measured by core-level x-ray spectroscopy or Mossbauer isomer shift

Electrostatically active composite condensate



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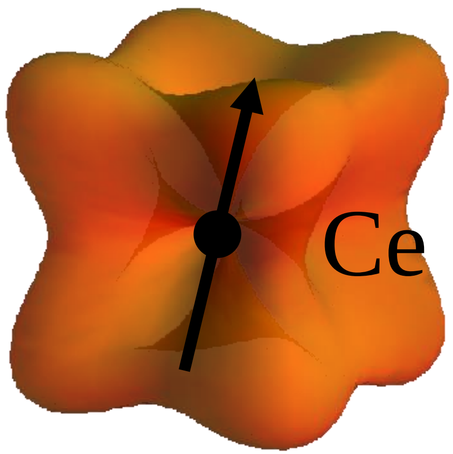
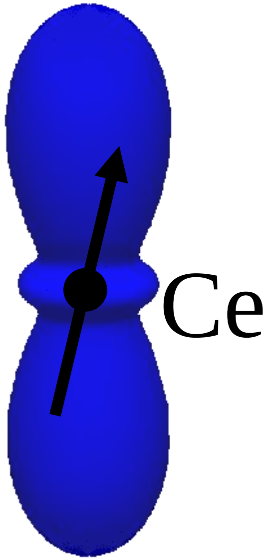
Hole Kondo effect



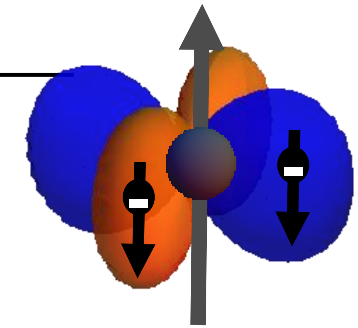
Γ_7^+

Electron Kondo effect



Γ_6

Electrostatically active composite condensate



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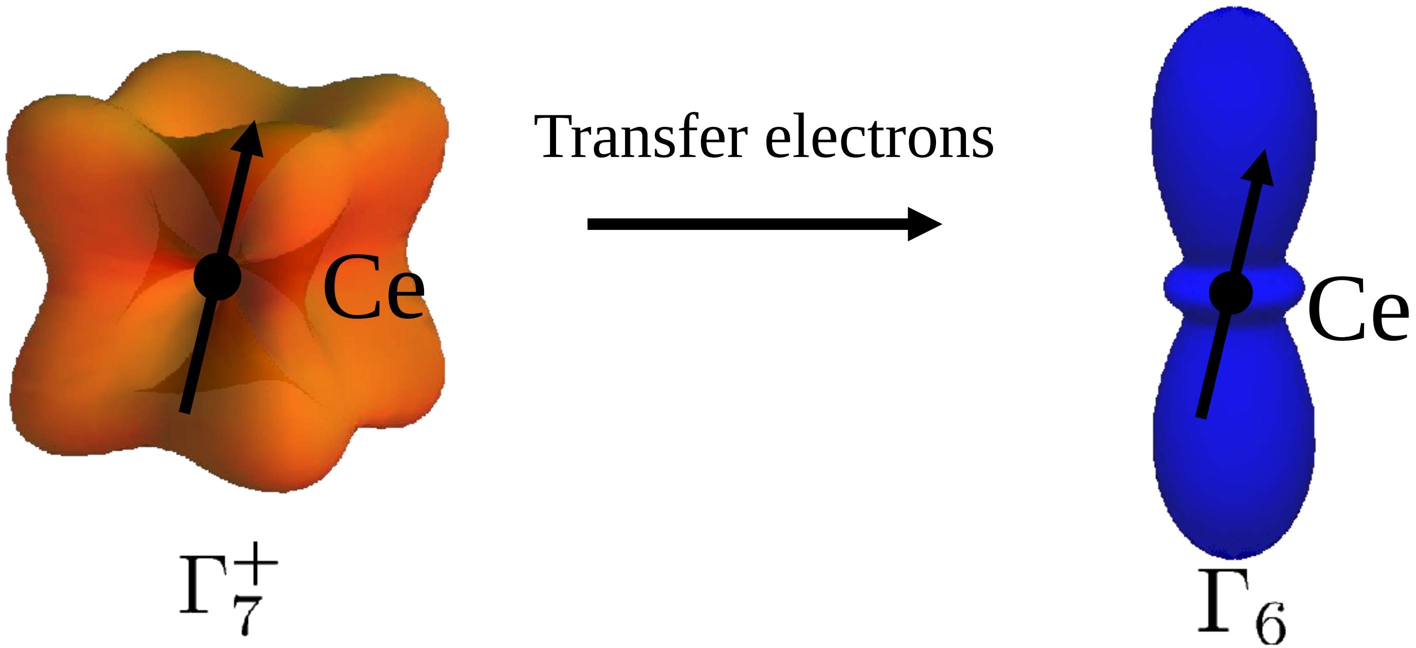
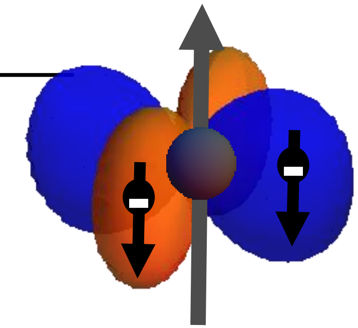
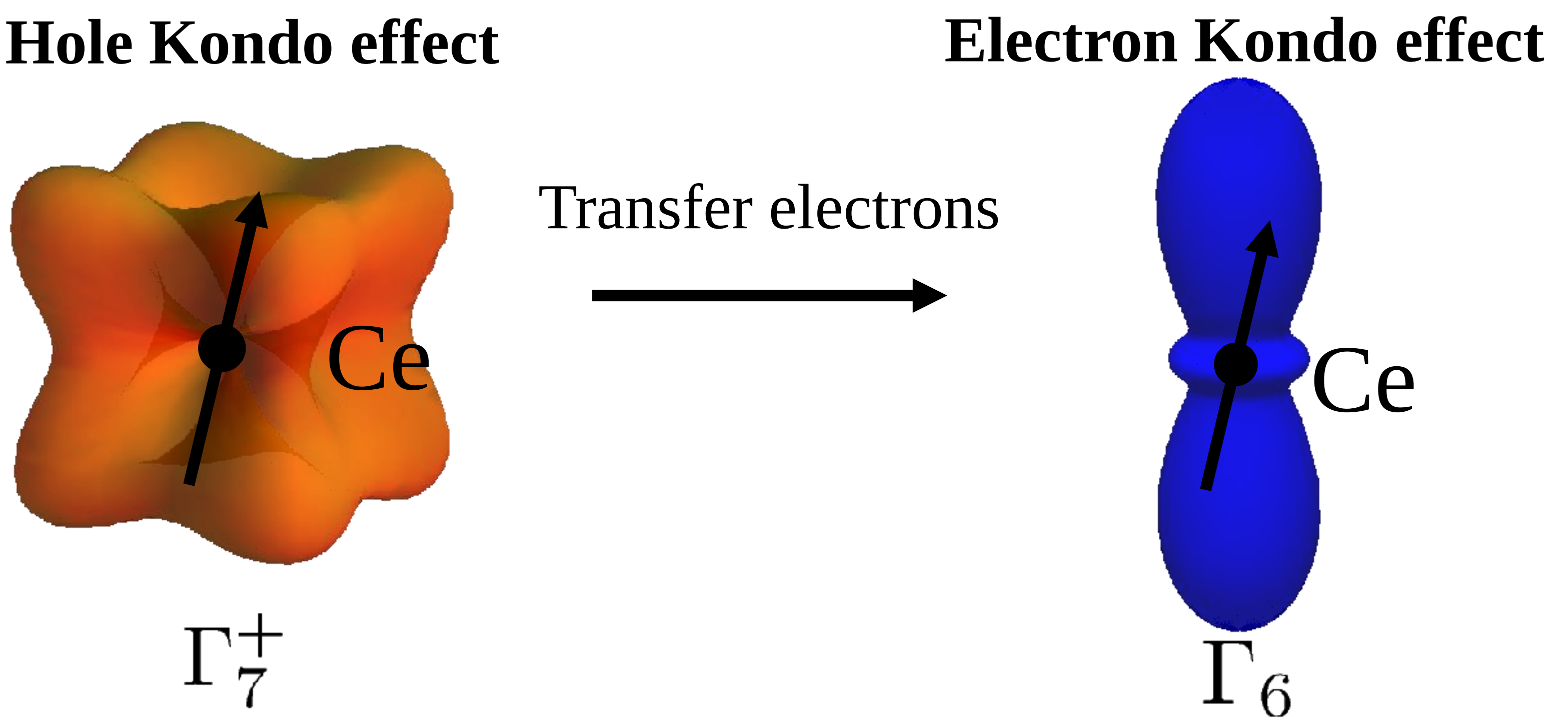
Hole Kondo effect **Electron Kondo effect**



Electrostatically active composite condensate



- Charge aspects
  - Hybridization *adds and removes* f-electrons

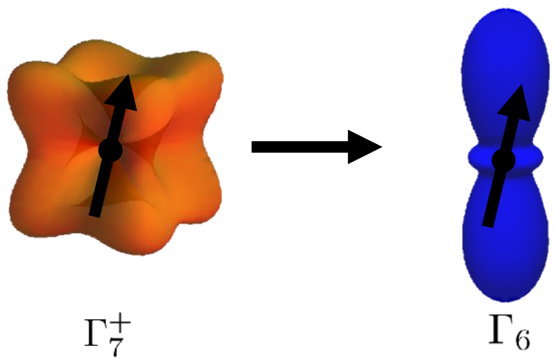


- Composite pair condensate acquires a quadrupole moment

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

Electrostatically active composite condensate

- Charge aspects
  - Composite condensate acquires a quadrupole moment

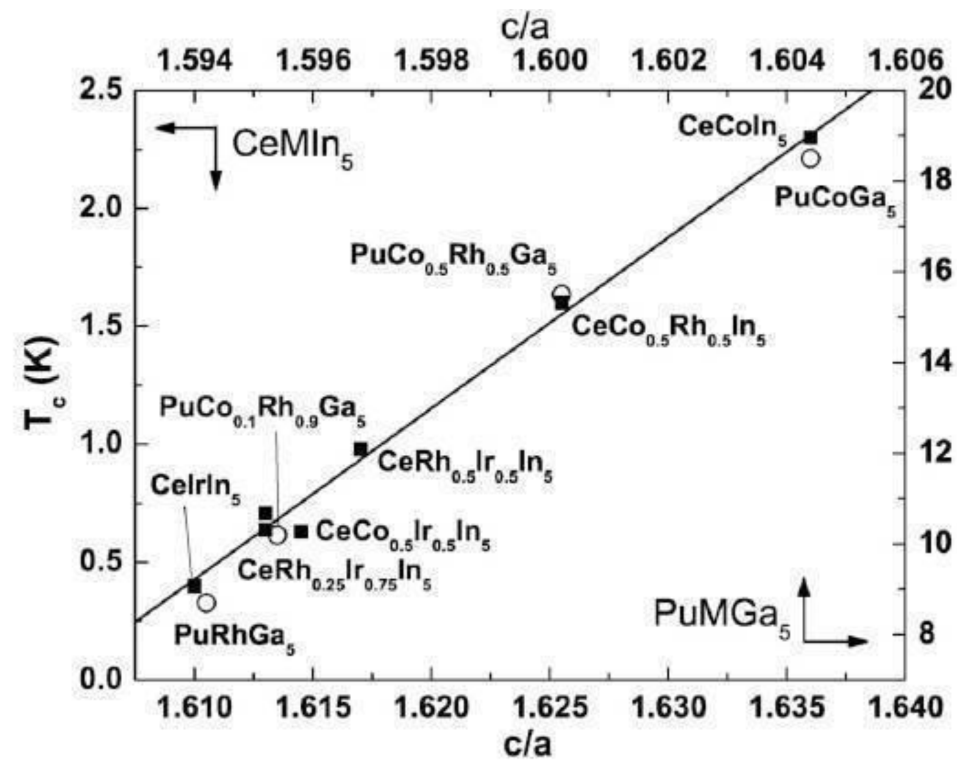


$$Q_{zz} \propto \Psi_C^2$$

The quadrupole moment couples to tetragonal strain ~ c/a

$$\Delta F \propto -Q_{zz}\frac{c}{a}$$

$$F = \alpha_2\left[T - (T_c + \lambda\frac{c}{a})\right]\Psi_C^2$$

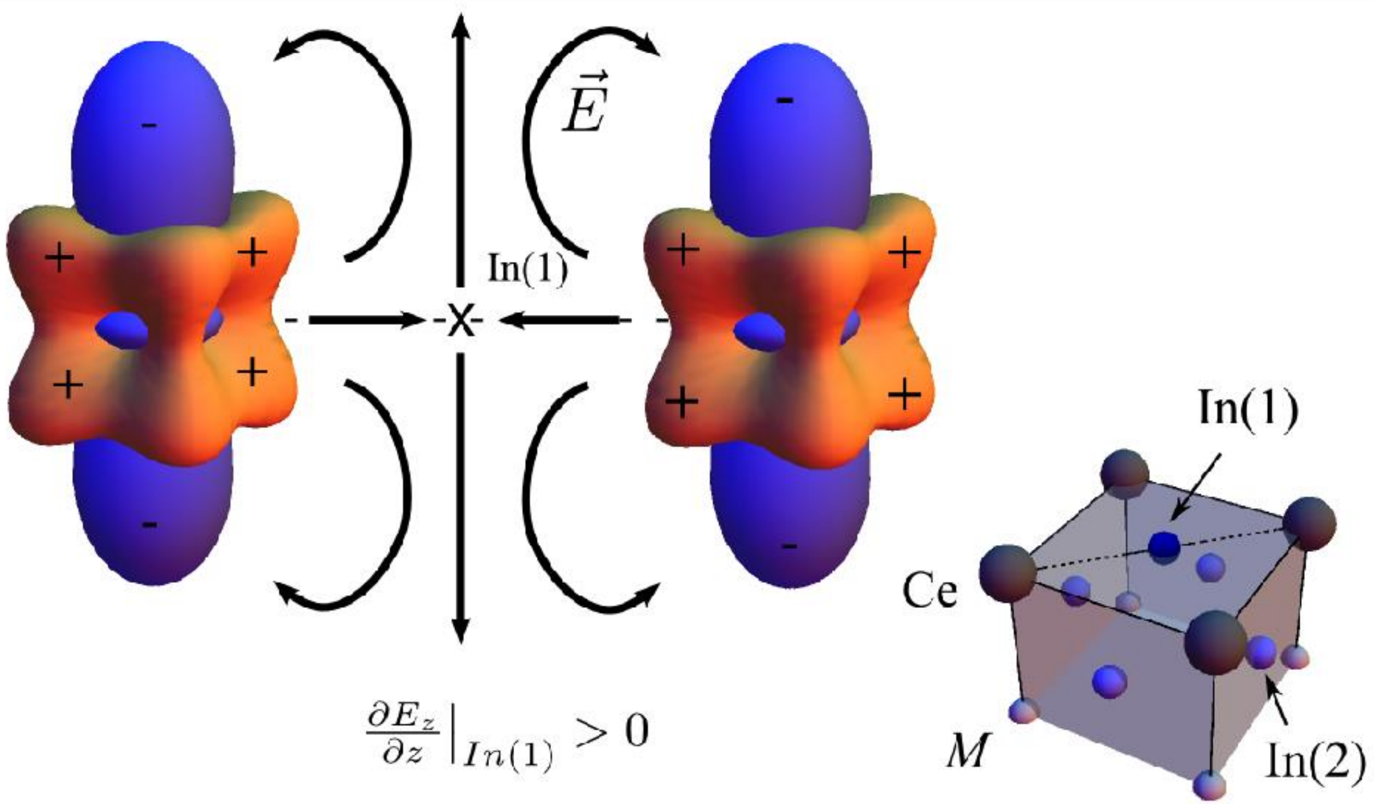


T_c increases linearly with c/a

Bauer *et al.* PRL **93**, 147005 (2004)

Electrostatically active composite condensate

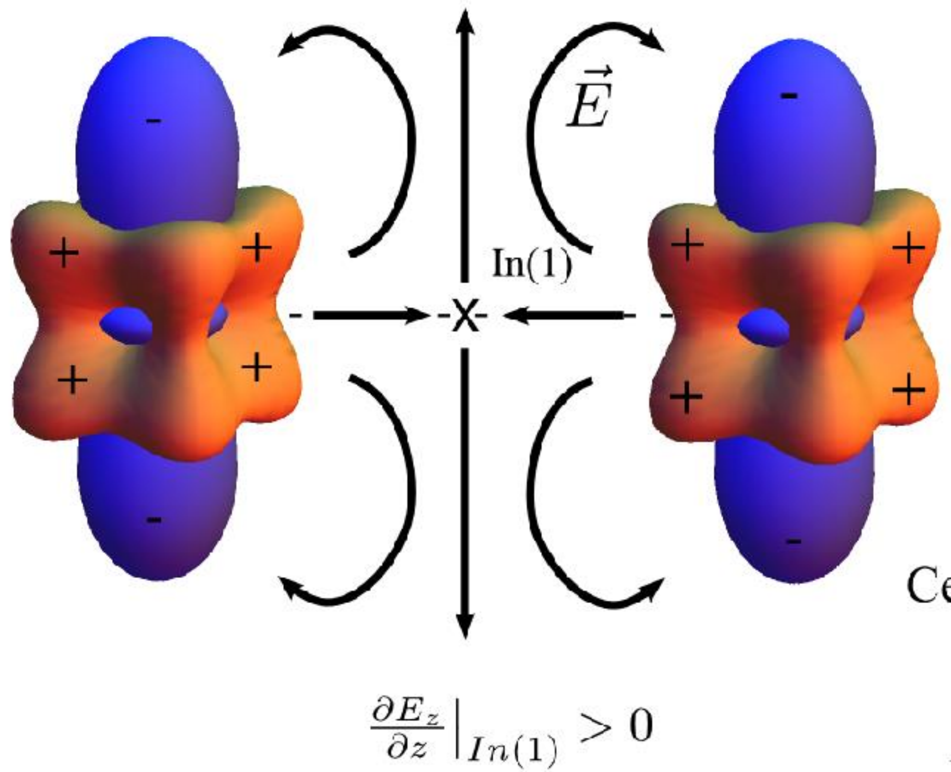
- Charge aspects
  - Composite condensate acquires a quadrupole moment



Measurable by sharp shifts in NQR or Mossbauer

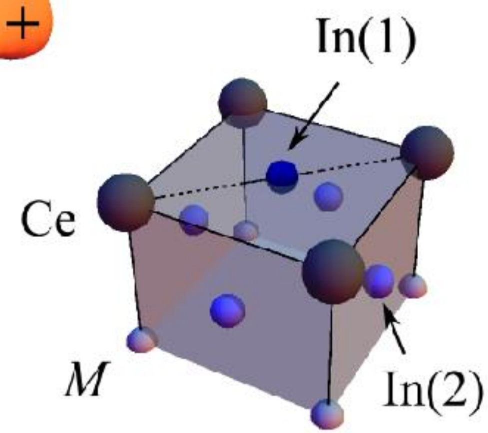
Electrostatically active composite condensate

- Charge aspects
  - Composite condensate acquires a quadrupole moment



$$\Delta\rho(\mathbf{x}) \propto V_1^2 \rho_{7+}(\mathbf{x}) - \Delta_2^2 \rho_6(\mathbf{x})$$

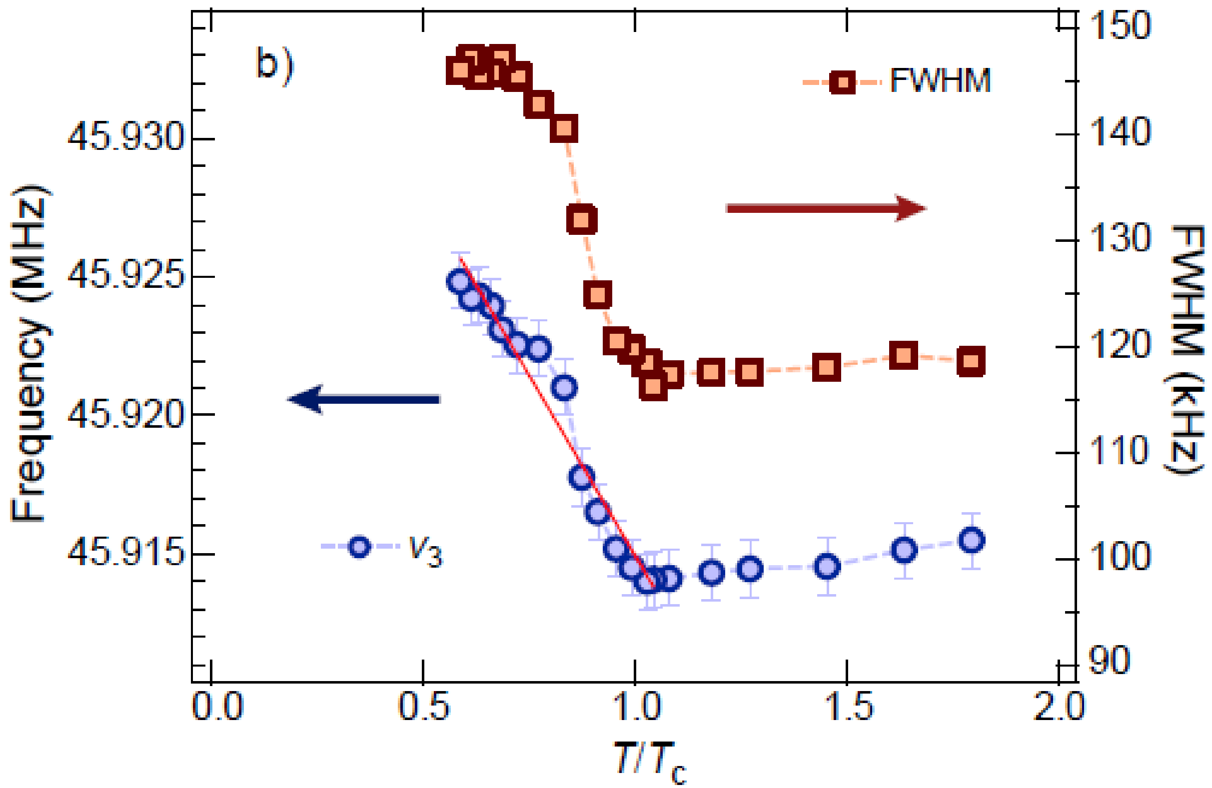
$$\Delta\nu_{NQR} \approx 5\mathrm{kHz/K} \times (T_c - T)$$



Measurable by sharp shifts in NQR or Mossbauer

NQR shift observed in $PuCoIn_5$!

Sharp linear shift in NQR frequency seen at T_C in $PuCoIn_5$
Also seen in $PuRhIn_5$, $CeCoIn_5$

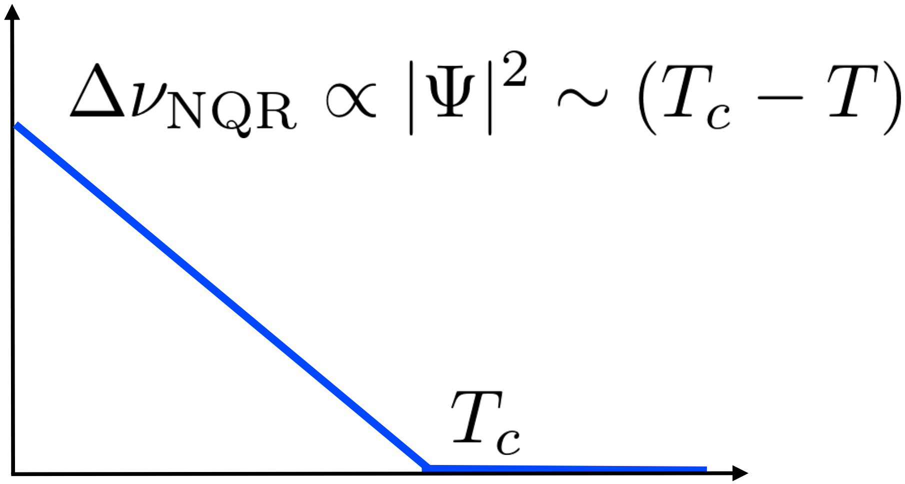


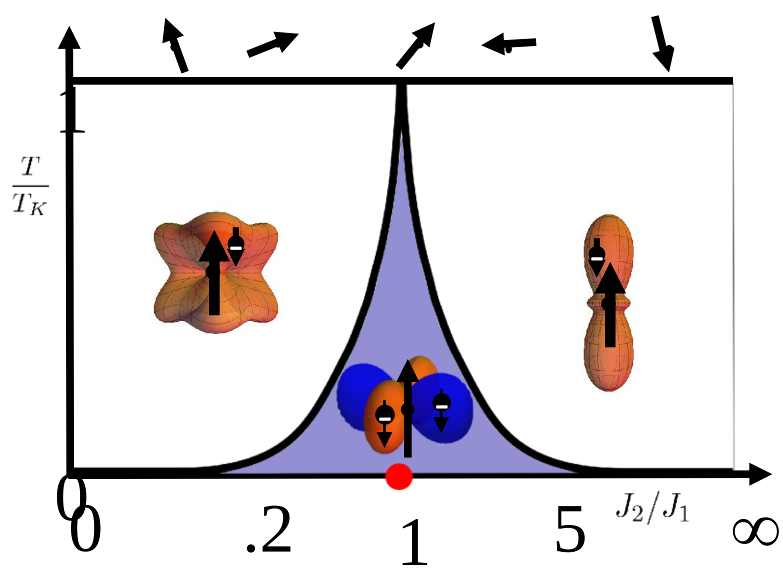
Koutroulakis et al New J. Phys. 16 053019 (2014)

NQR Shift

Three possible origins of NQR shift

- Change in lattice parameters
- Change in valence Δn_f (CP)
- Change in on-site symmetry (CP)





NQR Shift

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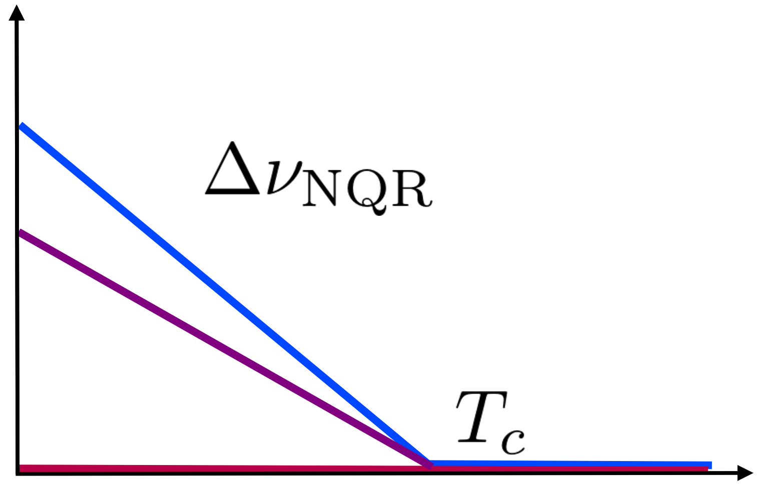

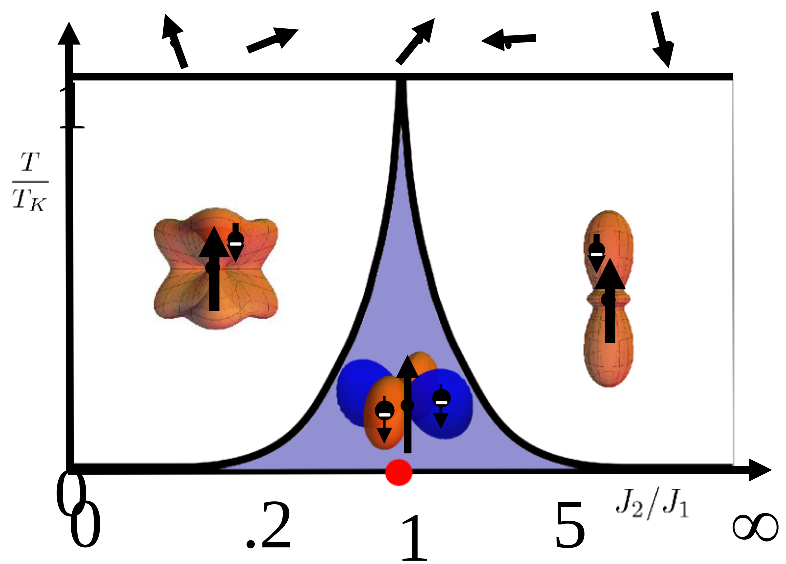

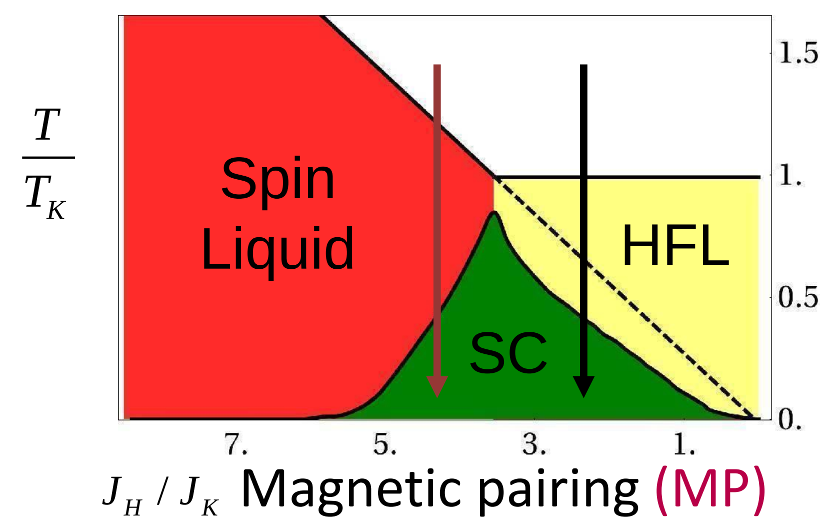

Magnetic pairing (MP)

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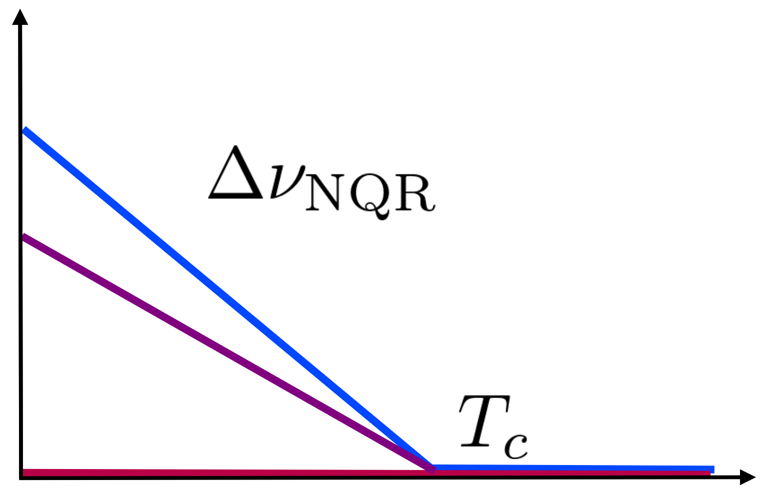
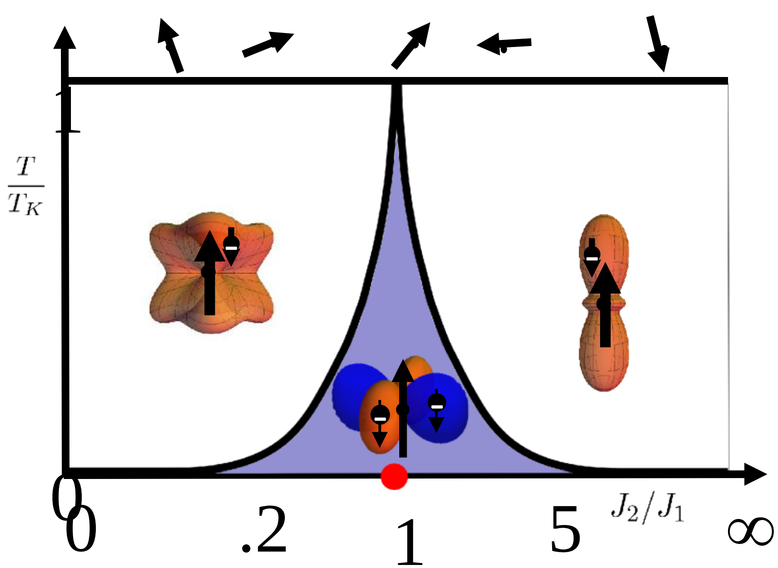
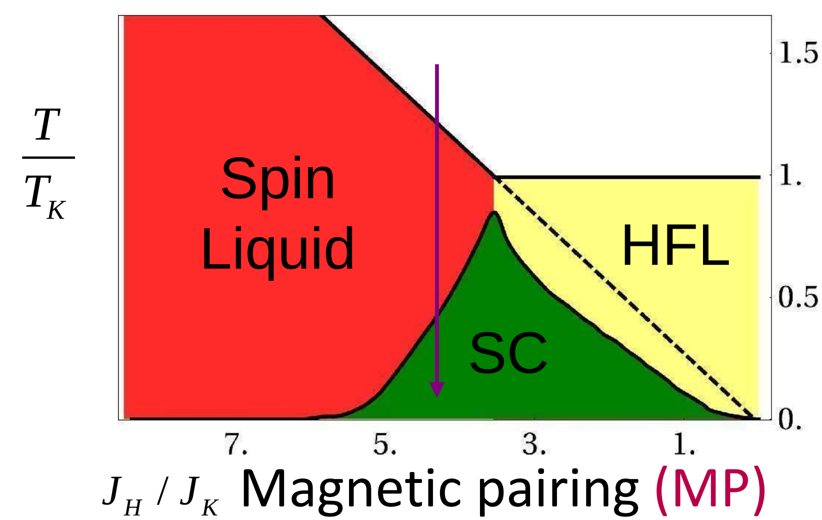


Magnetic pairing gives $\Delta\nu_{\rm NQR}$ only below "spin liquid" – $CeRhIn_5$? ***Not*** $CeCoIn_5$

Composite pairing *always* gives $\Delta\nu_{\rm NQR}$

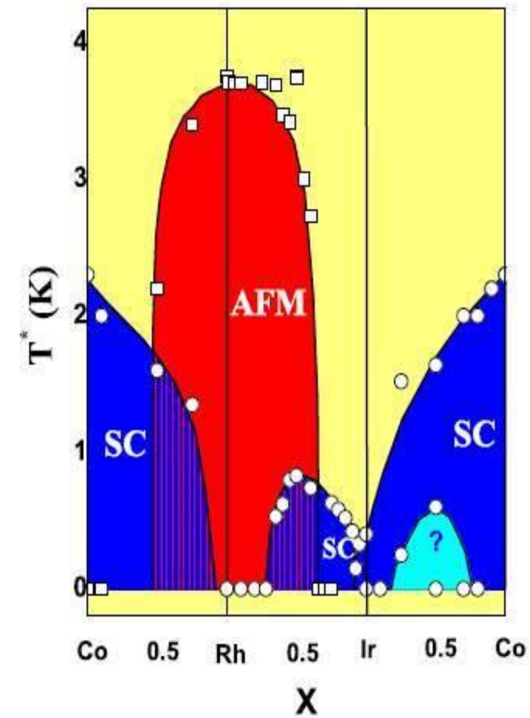




Magnetic pairing (MP)

Magnetic pairing appears ubiquitous

Sarrao and Thompson, JPSJ (2007)



But…

- Two domes in Ce*M*In_5 (*M = Co,Rh,Ir)*
  - *Tuning between composite and magnetic pairing*
- Superconductivity without magnetism
  - *Not required for composite pairing*
- Extremely robust to disorder *on the f-site*
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- Nodeless superconductivity in $Ce_{1-x}Yb_xCoIn_5$ (x > .2)
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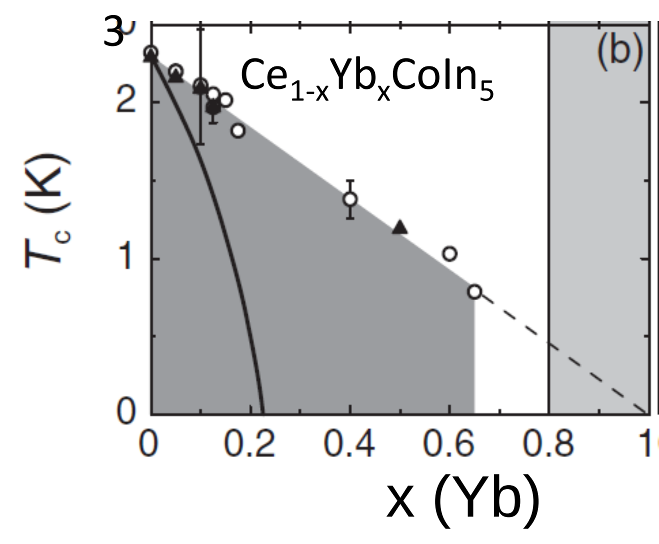
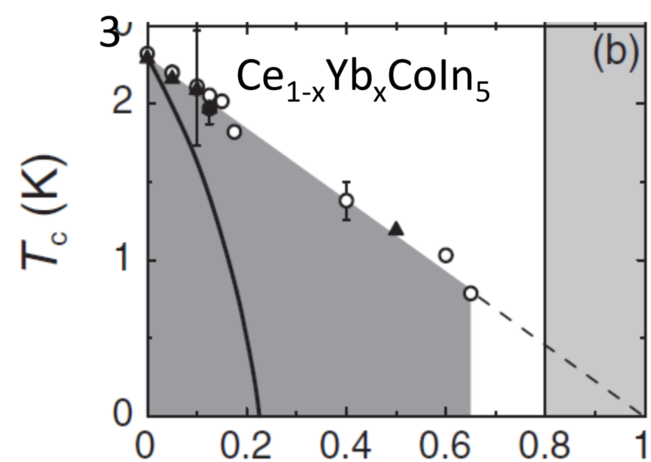


L. Shu et al PRL 2011

Superconductivity in Yb-doped $CeCoIn_5$

- $Ce_{1-x}R_xCoIn_5$ superconducts out to x ~ .25-.33
- Both T_c and T* are unexpectedly unaffected by these Kondo holes
- Yb-doped $CeCoIn_5$ seems to be special
  - Superconducts out to nominal x_n ~ 1 (!)



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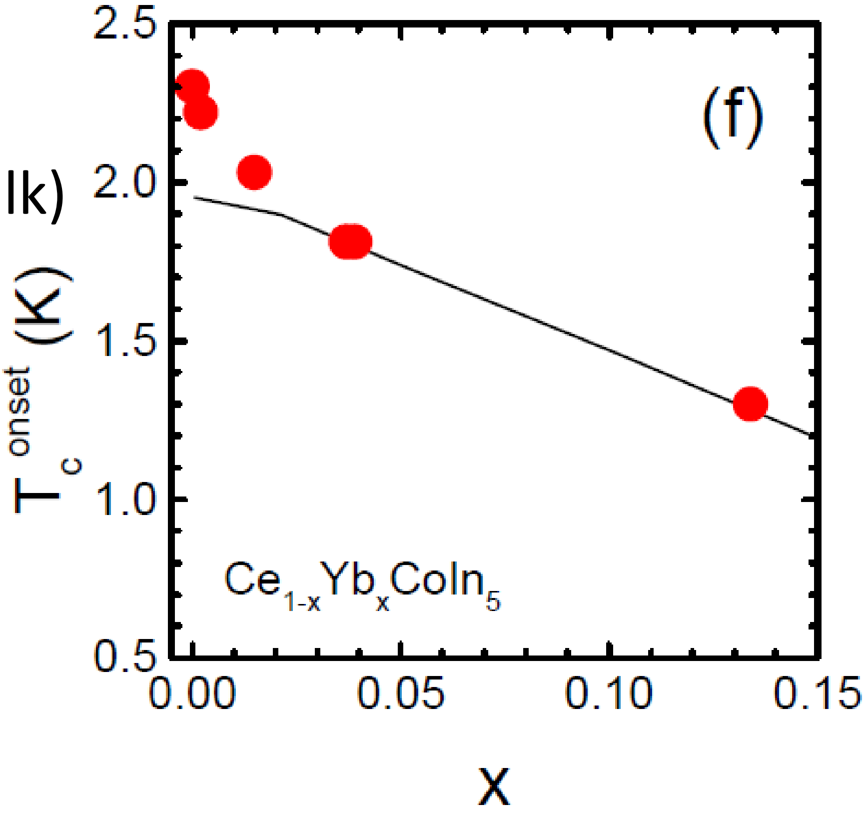
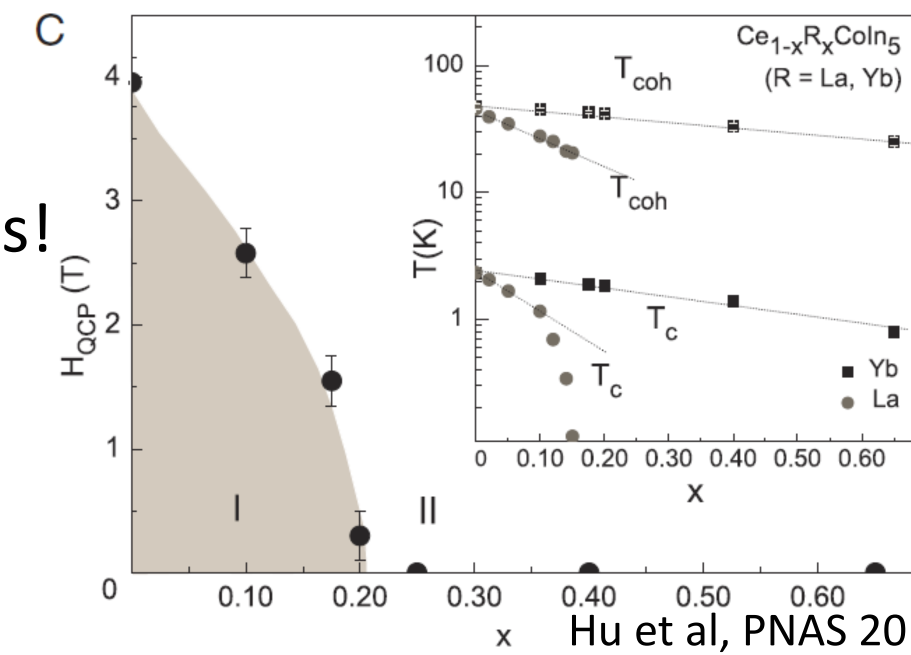
  - Superconducts out to nominal x_n ~ 1 (!)
  - New data shows actual x ~ x_n/3 (resolves discrepancy between films +bulk)



Kim et al, arXiv: 1404.3700
Jang et al, arXiv:1407.6725

Superconductivity in Yb-doped $CeCoIn_5$

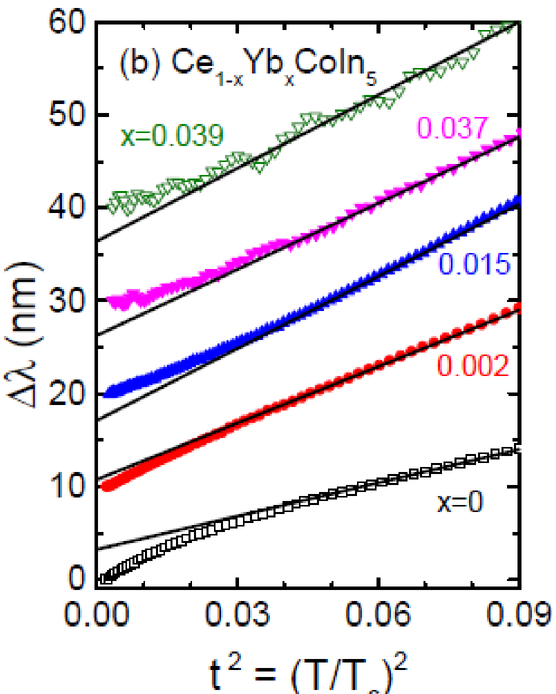
- Yb-doped $CeCoIn_5$ seems to be special
  - Yb is mixed valent (n_f ~ 2.3)
- Unusual quantum criticality, suppressing H_{QCP} at x_n = .2
- Lifshitz transition in dHvA at x_n=.2
  - Hole doping removes Fermi surface
- Superconductivity becomes nodeless!
  - Also at x_n = .2

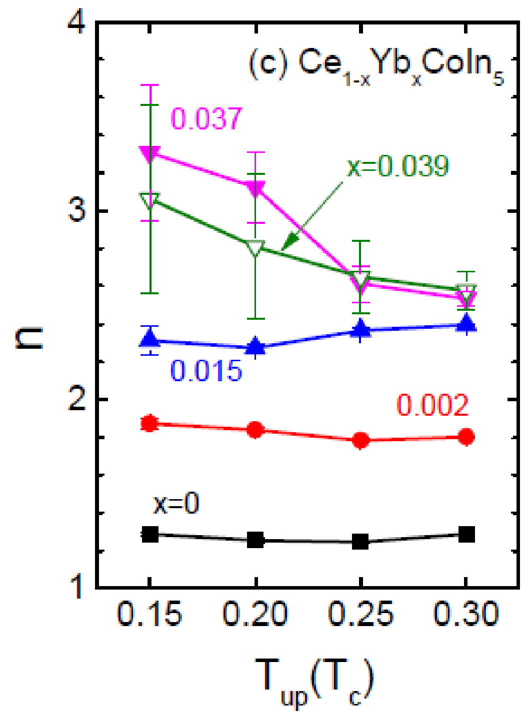


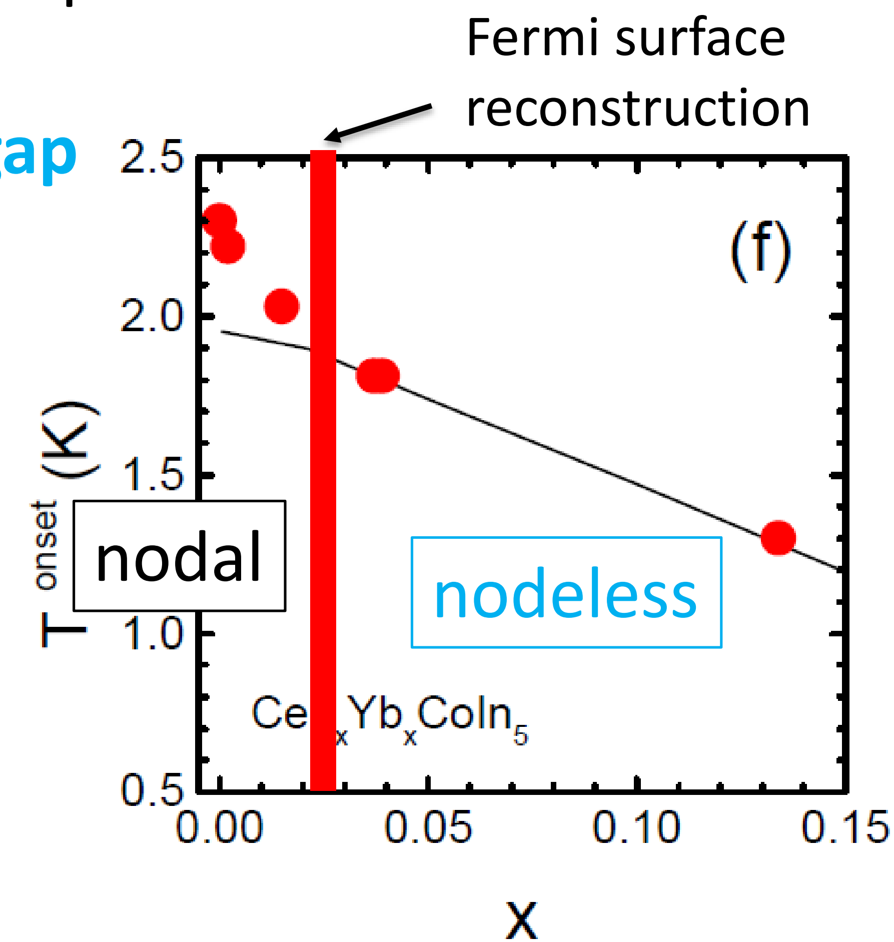
Hu et al, PNAS 2013

Nodeless superconductivity in $Ce_{1-x}Yb_xCoIn_5$

- Pure $CeCoIn_5$ is a nodal superconductor (d_{x2-y2})
- The penetration depth approaches $\Delta\lambda \sim T$ for very clean samples
  - $\Delta\lambda \sim T^2$ for dirtier samples (dirty d-wave)
- Beyond a critical x_c, the penetration depth goes as $\Delta\lambda \sim T^n$ $n > 3$
  - Inconsistent with nodes => **full gap**







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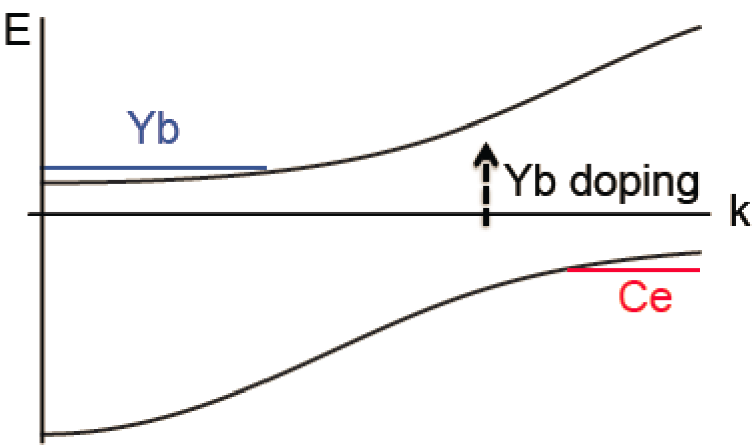
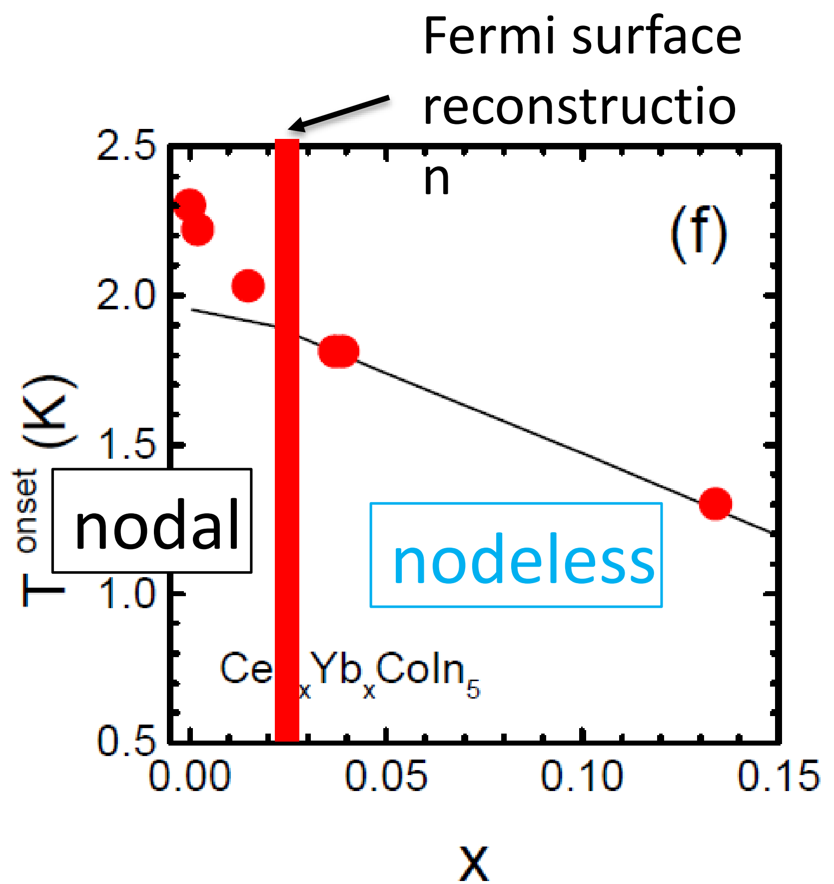
Nodeless superconductivity in $Ce_{1-x}Yb_xCoIn_5$

- $Ce_{1-x}Yb_xCoIn_5$ is a ***fully gapped*** superconductor beyond $x_n = .2$
- How can Yb doping induce nodeless superconductivity?
  - Adds holes, adjusts Fermi surface
  - Fermi sheet disappears, but T_c is smooth!





- Composite pairing does not require a FS
  - Can exist even below a Kondo insulator

Kim et al, arXiv: 1404.3700
Erten, Flint, Coleman, arXiv:1402.7361

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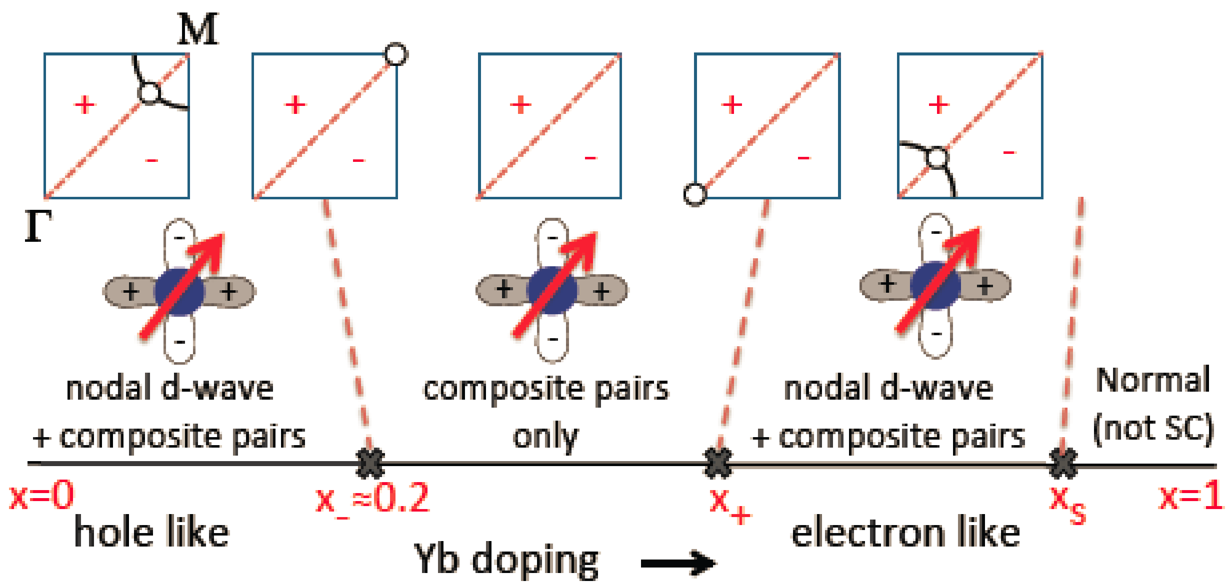

$\rho_s = \rho_0 - \alpha T^{(1-2)}$ $\rho_s = \rho_0 - \beta T^{(3-4)}$ $\rho_s = \rho_0 - \alpha T^{(1-2)}$

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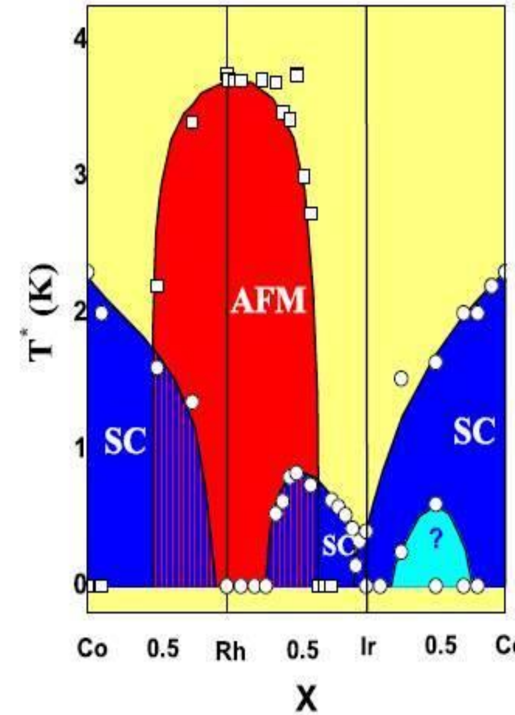

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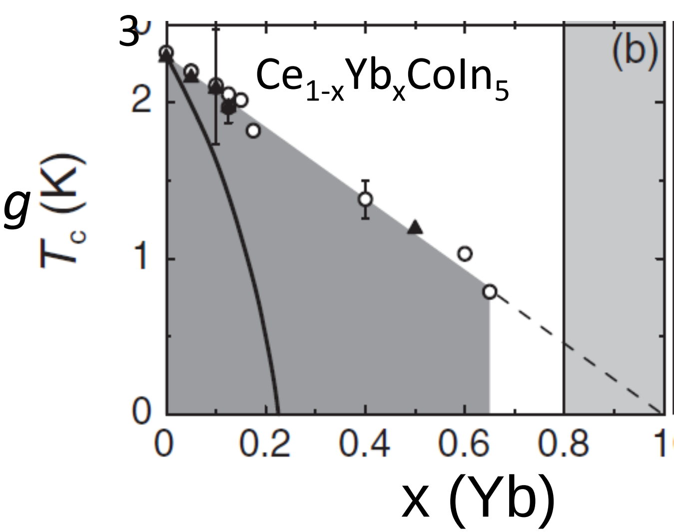
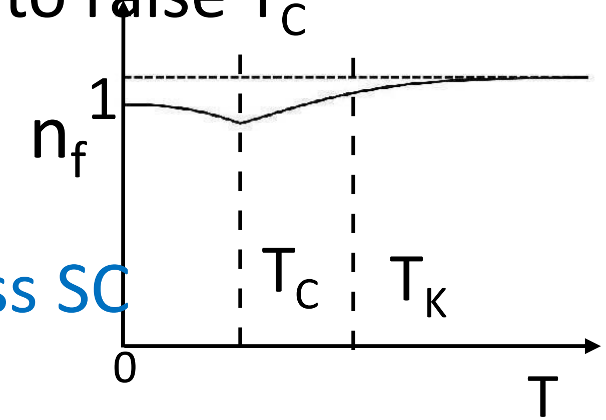
- Nodeless superconductivity in $Ce_{1-x}Yb_xCoIn_5$ (x > .2)
  - *Composite pairing doesn't require an underlying Fermi surface*
- Many Ce superconductors, only one Yb
  - *Magnetism doesn't discriminate, but composite pairing is inactive in Yb compounds*



L. Shu et al PRL 2011

Conclusions

- Two electrons in orthogonal Kondo channels can screen the same local moment to form a composite pair
- Composite pairing produces d-wave, singlet pairs
  - Can work in tandem with magnetic pairing to raise T_C
- To resolve the two – look at the charge:
  - Suggestive: NQR shift
  - Suggestive: robustness to disorder, nodeless SC
  - Smoking gun: valence shift



R. Flint, M. Dzero and P. Coleman, Nature Physics 4, 643(2008)
R. Flint and P. Coleman, Phys. Rev. Lett. 105, 246404 (2010)
R. Flint, A.H. Nevidomskyy and P. Coleman, Phys. Rev. B 84, 064514 (2011)

Open questions

- How does disorder affect different pairing mechanisms?
- Quantum criticality related to two channel Kondo physics?
- Can composite pairing be extended to other materials? (d-electron 115s?)
- Tandem pairing in other materials (eg – nematic fluctuations aiding magnetic pairing)
- Relationships to pair-density wave in Q-phase of $CeCoIn_5$?