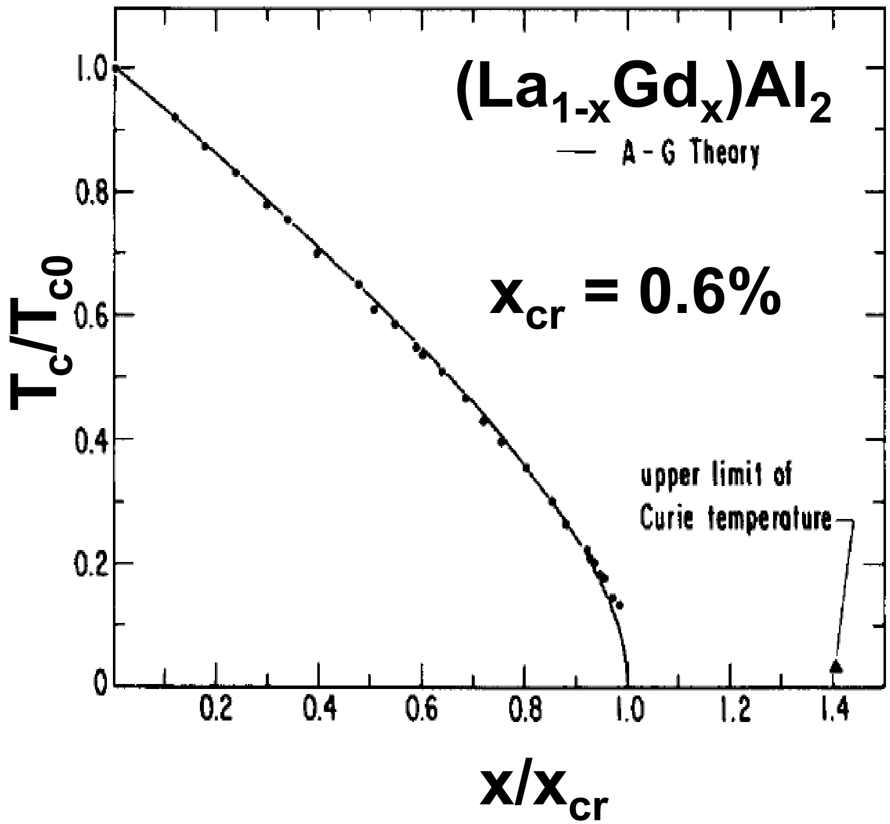
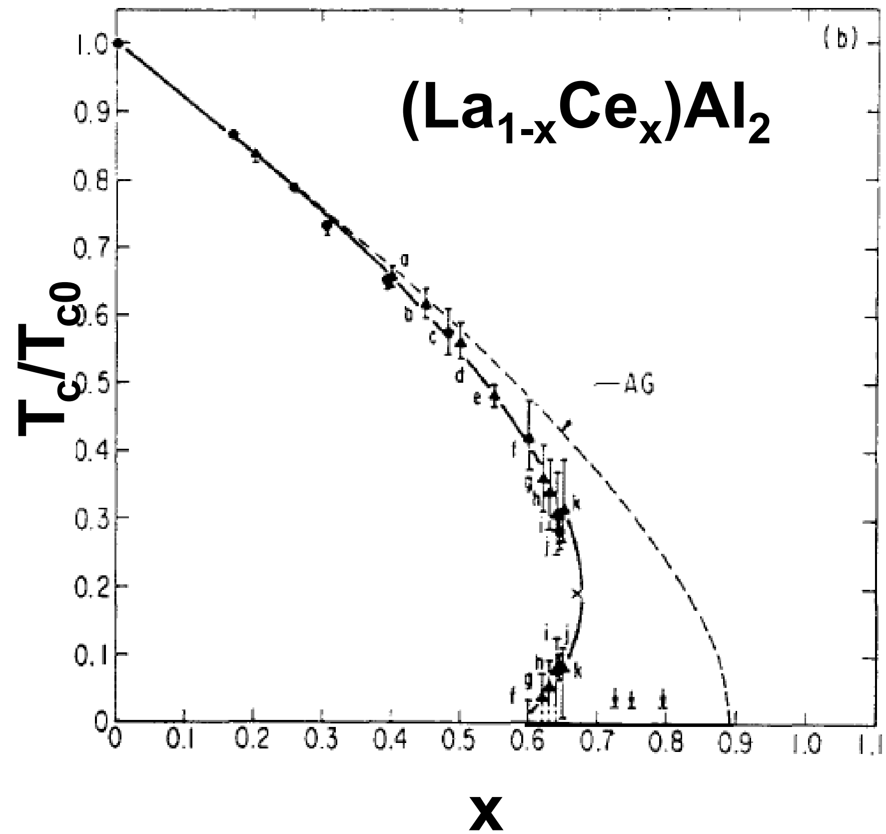
Superconductivity in Heavy Fermions

Outline:

- **Magnetism and the Kondo effect in f-electrons**
- **A brief history of heavy fermion superconductors**
- **Open questions**
- **Summary**

Common belief that magnetism is bad for SC

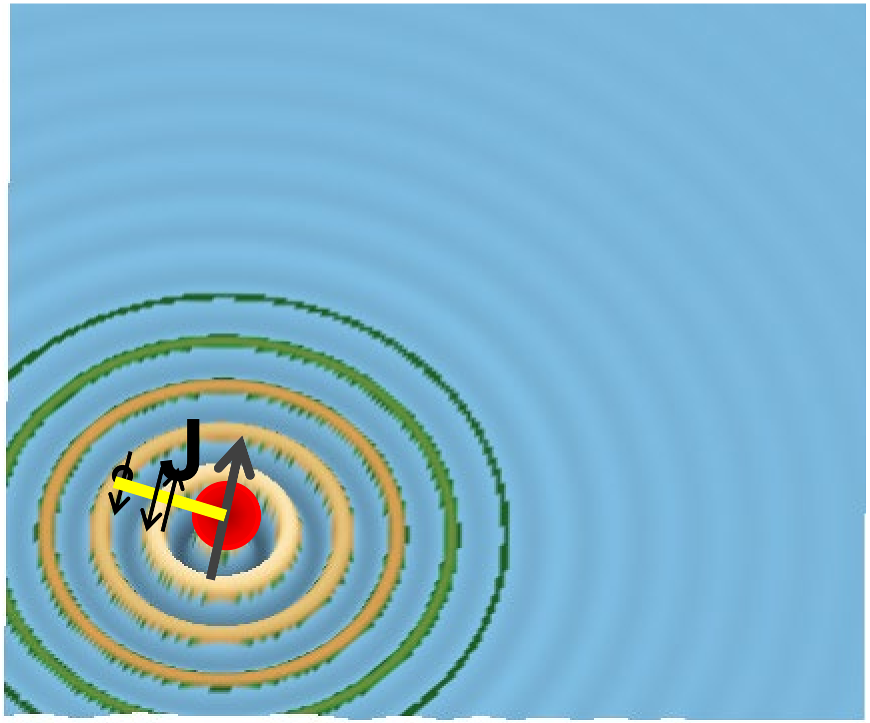




M. B. Maple, Phys. Lett. A **26**, 513 (1968)

M. B. Maple *et al*., SSC **11**, 829 (1972)

1 magnetic impurity: Kondo effect



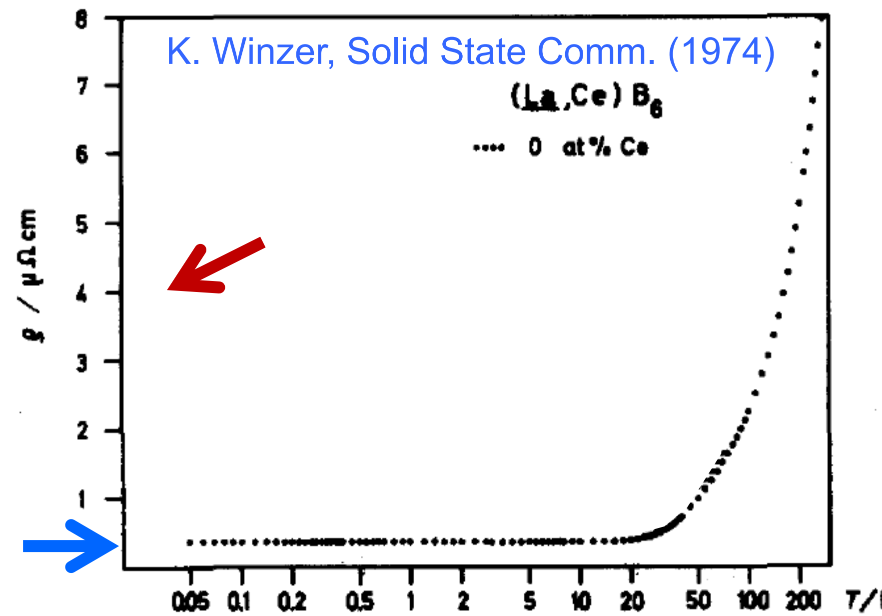
$$H = \sum_{<ij>} t c_i^{\dagger} c_j + h.c. + J \vec{S} \cdot \vec{s}(r_0)$$

Non-magnetic impurity:

Basically the same.

Magnetic impurity (ie. 4f):

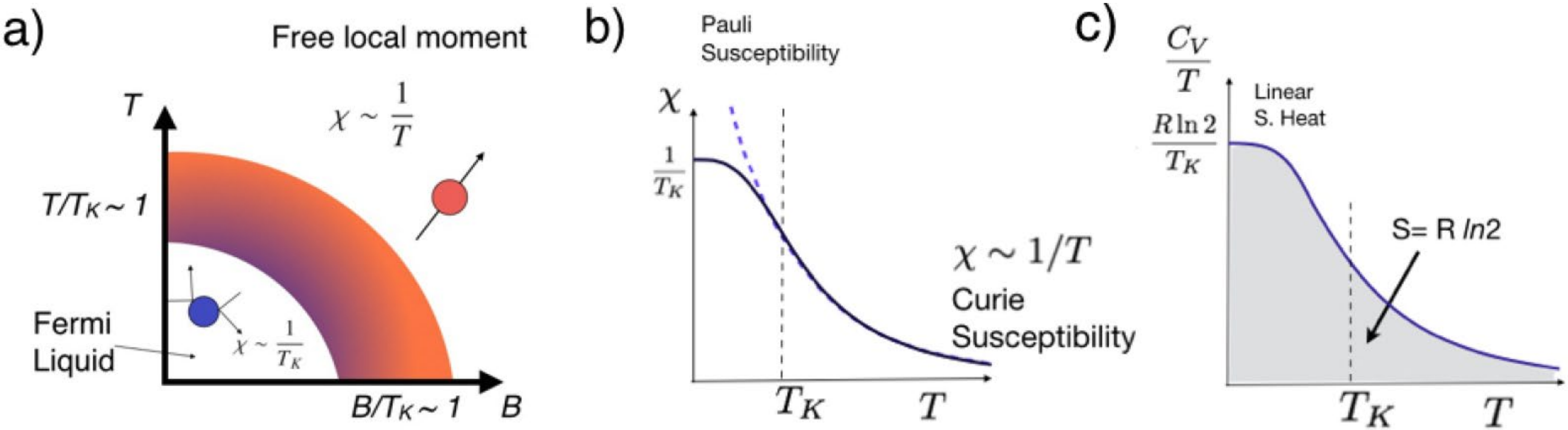
Kondo Screening

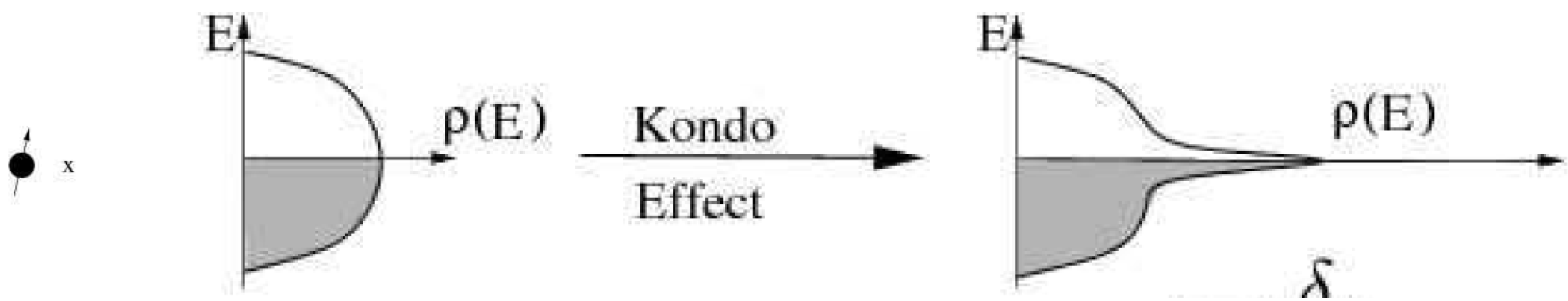


At T = 0, a renormalized Fermi liquid including an f-electron.

A many-body effect (Wilson renormalization)

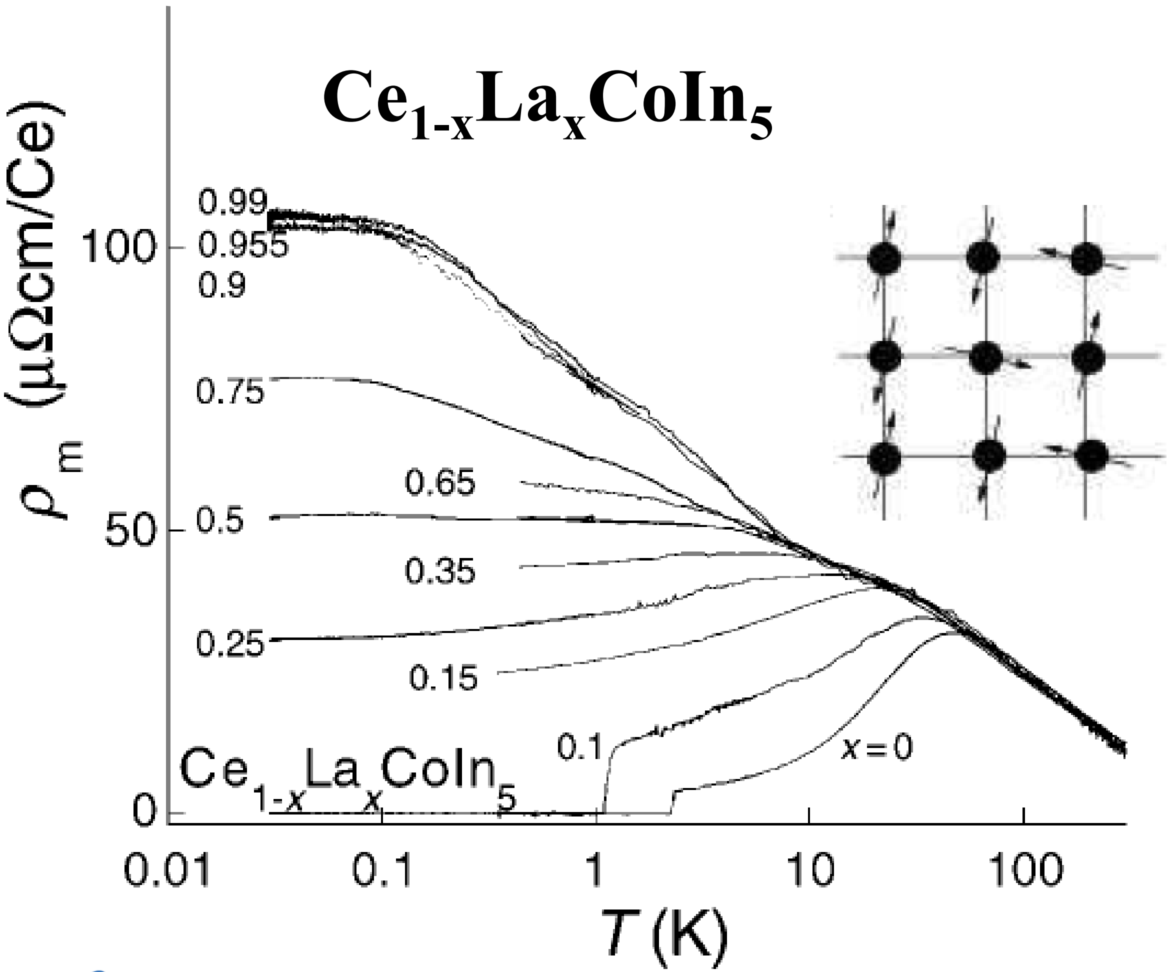
1 magnetic impurity: Kondo effect

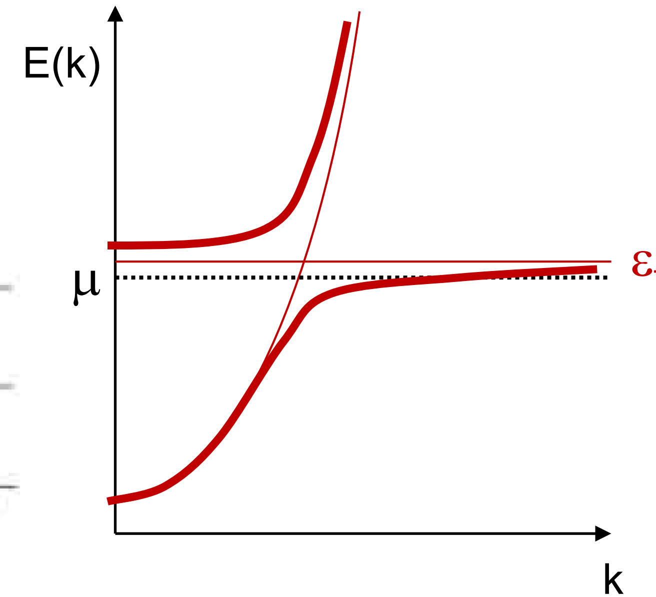




P. Coleman arXiv:cond-mat/0612006;
arXiv:1509.05769

New Kondo lattice fixed point

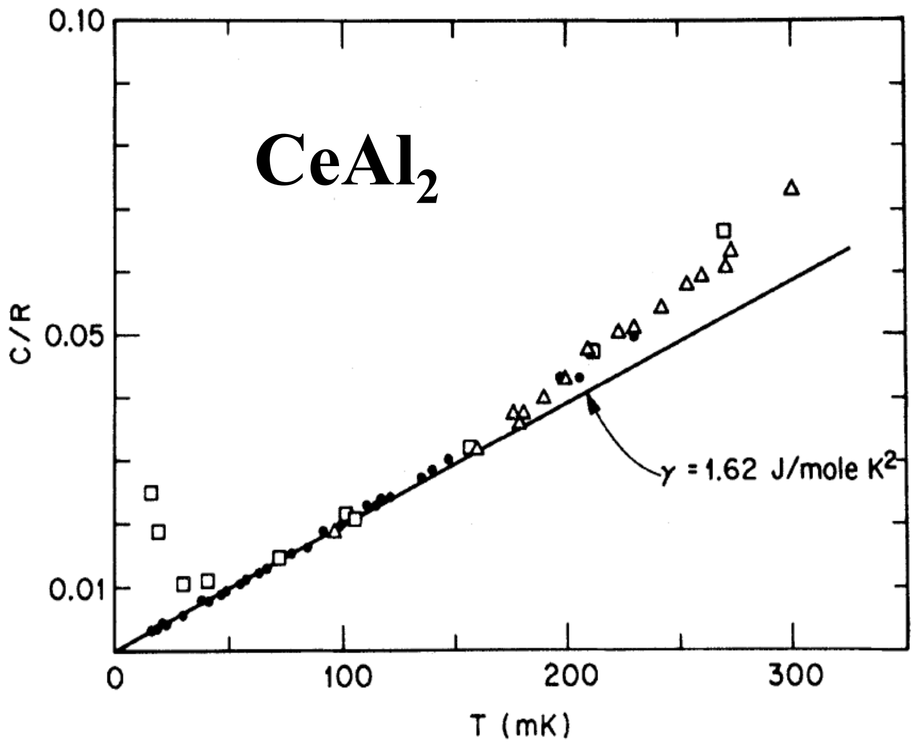


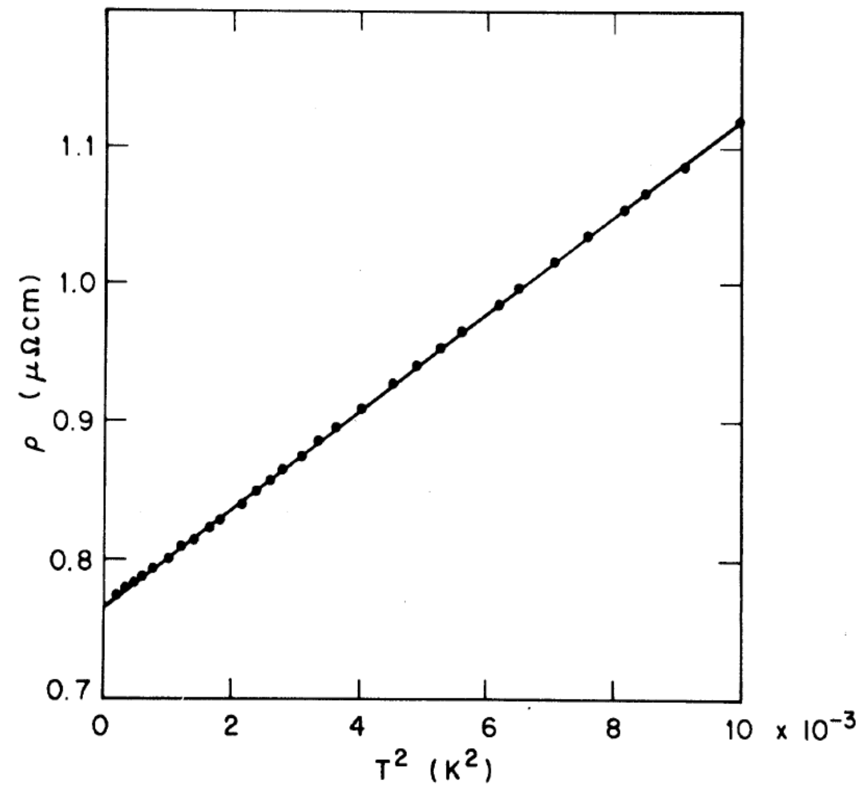


A new fixed point emerges in the Kondo lattice, but not well understood!

S. Nakatsuji *et al* PRL (2002)

New Kondo lattice fixed point: Heavy fermions



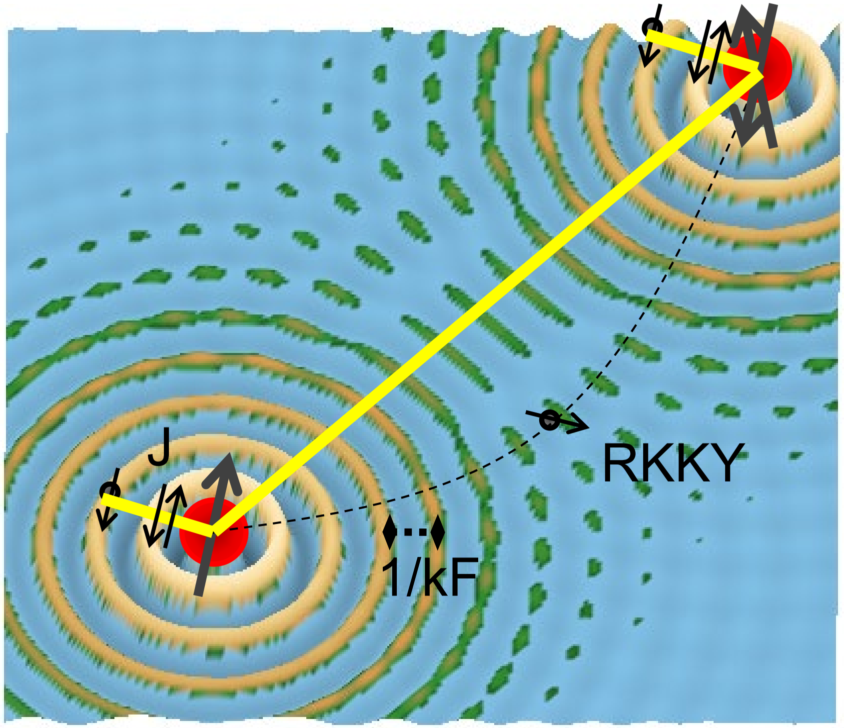


$$\frac{C}{T} \propto m^*$$

$$\frac{\rho}{T^2} \propto m^{*2}$$

K. Andres, J. E. Graebner, H. R. Ott, PRL 35, 1779 (1975)

Multiple magnetic impurities: RKKY effct



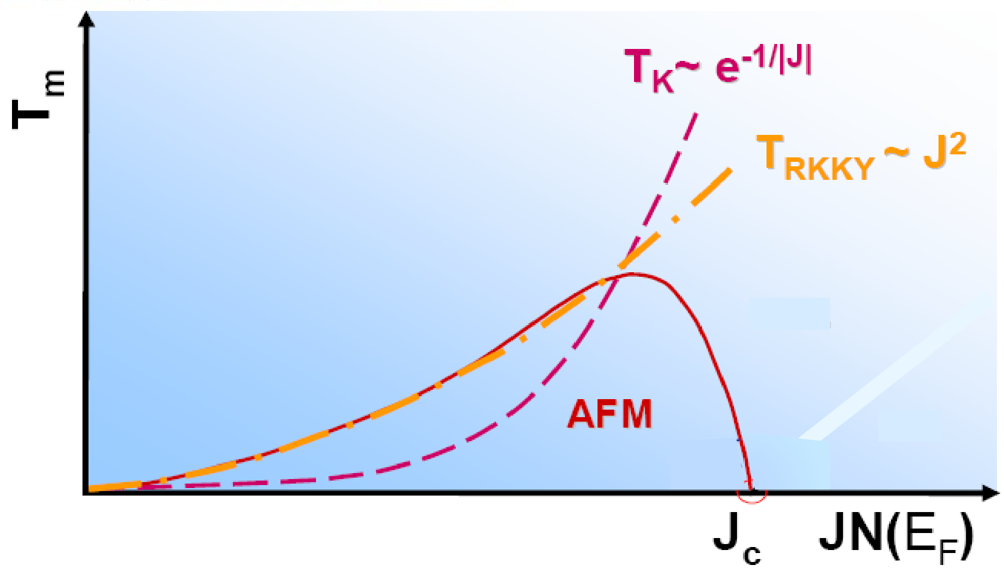
The Kondo scale is:

$$T_K \approx \exp(-1/J)$$

The RKKY scale is:

$$T_{RKKY} \approx J^2$$

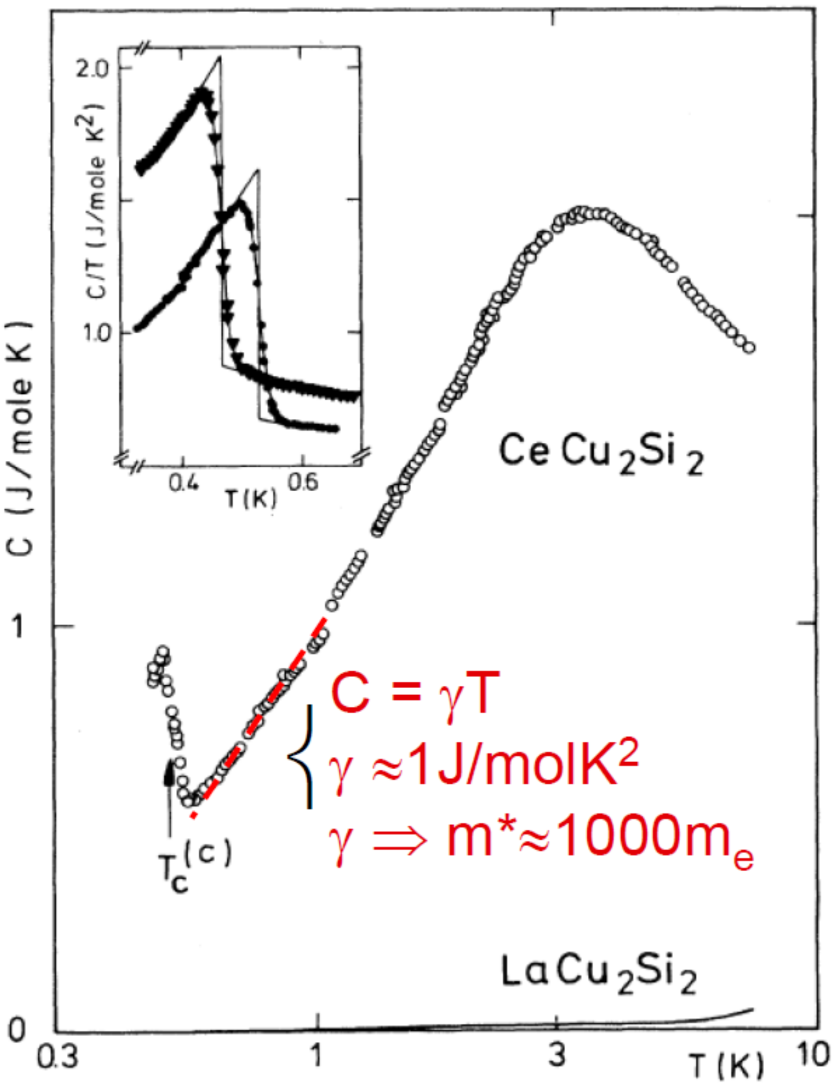
RKKY wins



Kondo wins

S. Doniach, 1978

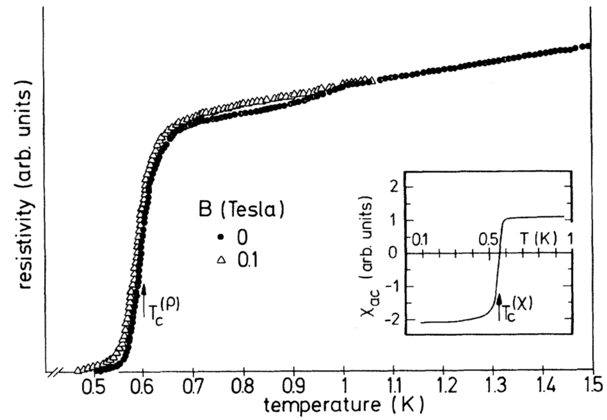
Surprise superconductivity in $CeCu_2Si_2$



Well below $T^* = 10$ K, a large γT term predominates the specific heat. We interpret this term as being due to very heavy fermion quasiparticles with degeneracy temperature $T_F \simeq T^*$.

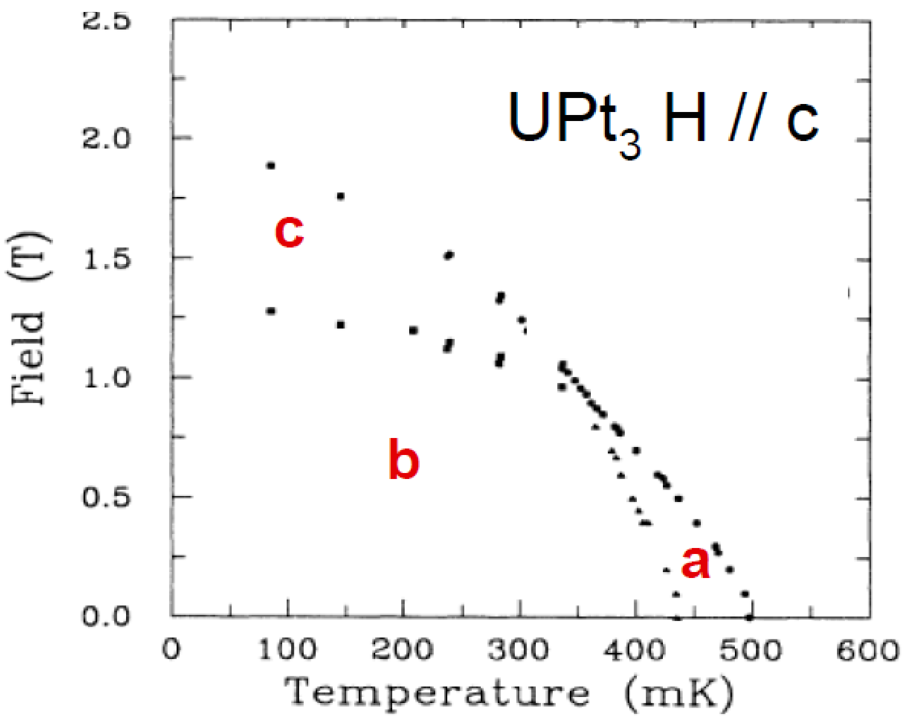
The size of the specific-heat jump at T_c, in proportion to γT_c, suggests that Cooper-pair states are formed by these heavy fermions.

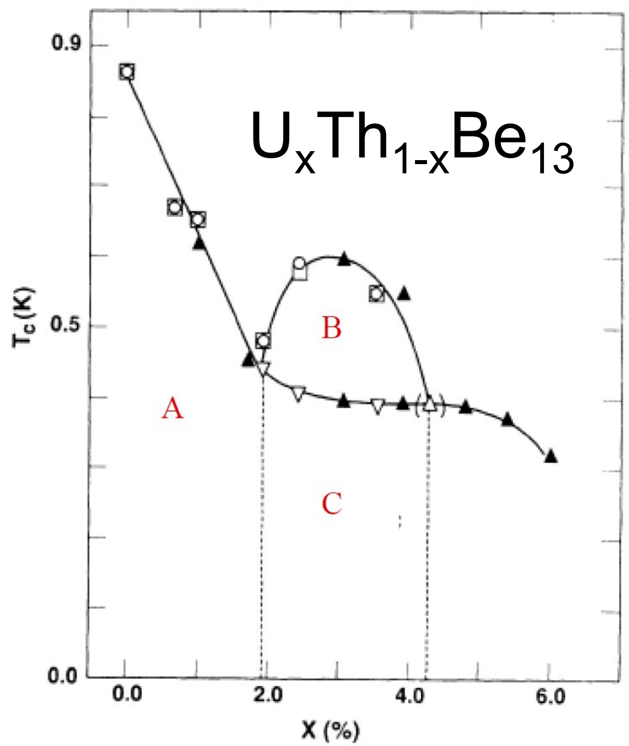
Since the Debye temperature, Θ, is of the order of 200 K,[5] we find $T_c < T_F < \Theta$ with $T_c/T_F \simeq T_F/\Theta \simeq 0.05$. This suggests that $CeCu_2Si$ (i) behaves as a "high-temperature superconductor" and (ii) cannot be described by conventional theory of superconductivity which assumes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



F. Steglich *et al* PRL (1979)

U-based SCs – unconventional superconductivity

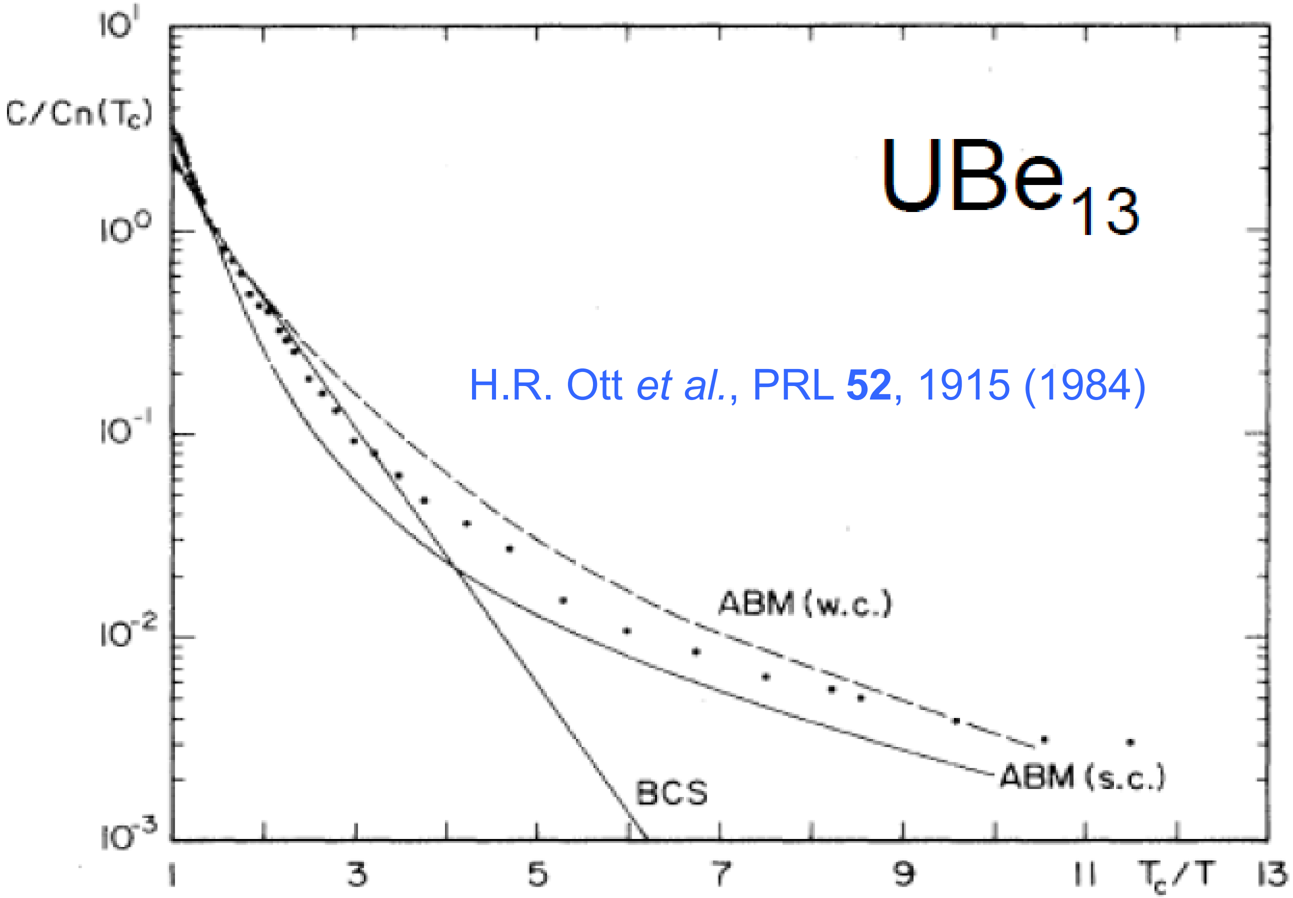




In the mid 80's superconductivity in UBe_{13} and UPt_3 confirmed the $CeCu_2Si_2$ results. There also appeared multiple superconducting phases.

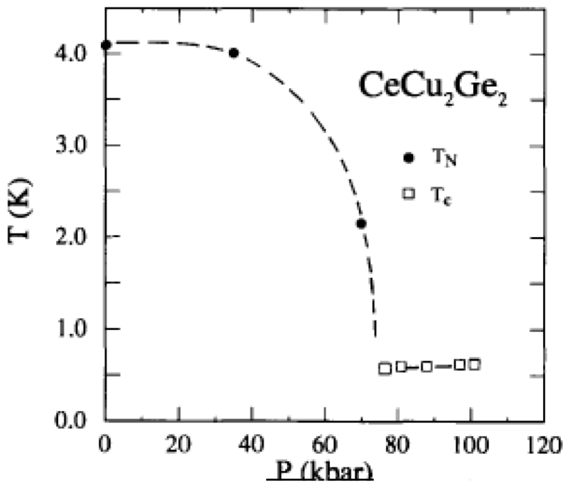
R.A. Fisher *et al*. PRL **62**, 1411 (1989); G. Bruls *et al*., PRL **65**, 2294 (1990); S. Andenwalla *et al*., PRL **65**, 2298 (1990); H.R. Ott *et al*., PRB **31**, 1651 (1985)

U-based SCs – unconventional superconductivity

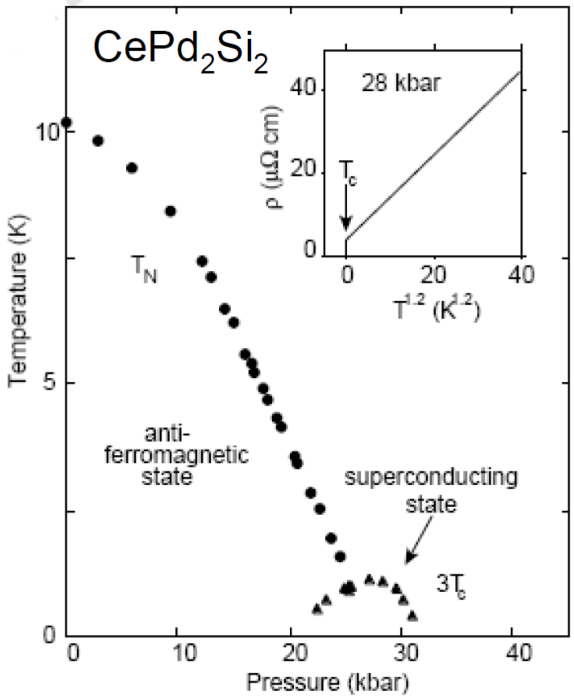


The observation of power laws in specific heat suggested nodal behavior with an unconventional order parameter.

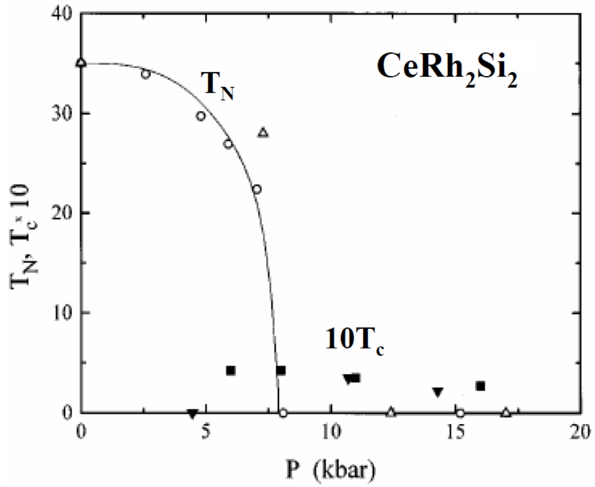
Superconductivity on the border of AF instabilities



D. Jaccard *et al*., Phys. Lett. A **163**, 475 (1992)



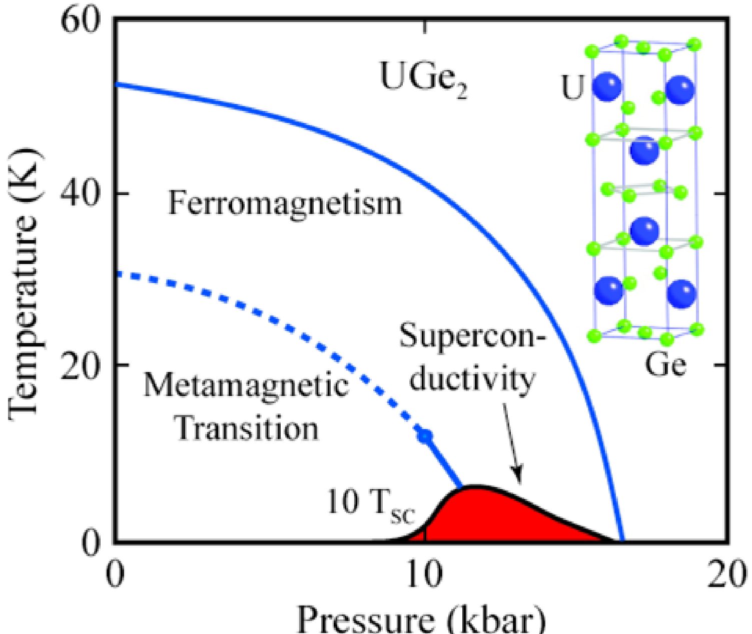
F. M. Grosche *et al*., Physica B **224**, 50 (1996)

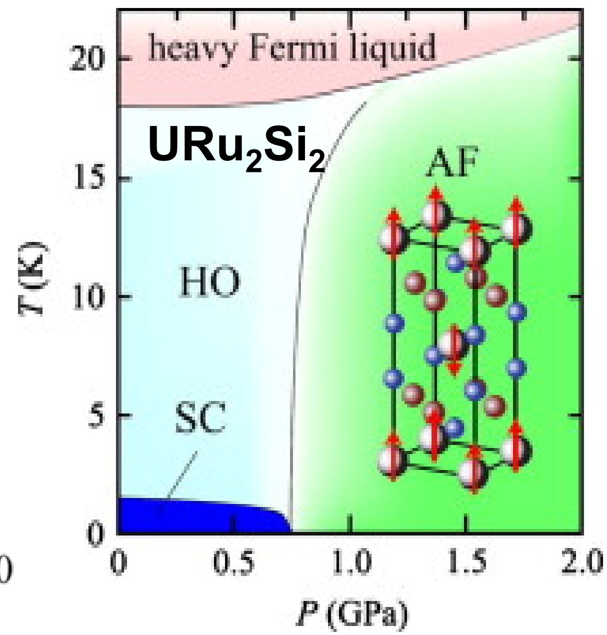


R. Movshovich *et al*., PRB **53**, 8241 (1996)

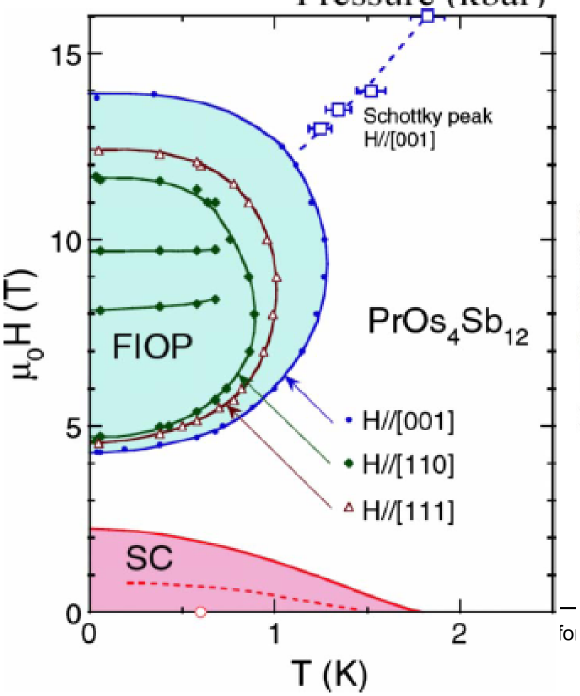
“The one place we know where to find superconductors is at the quantum critical point of cerium based antiferromagnets” ~ Zach Fisk

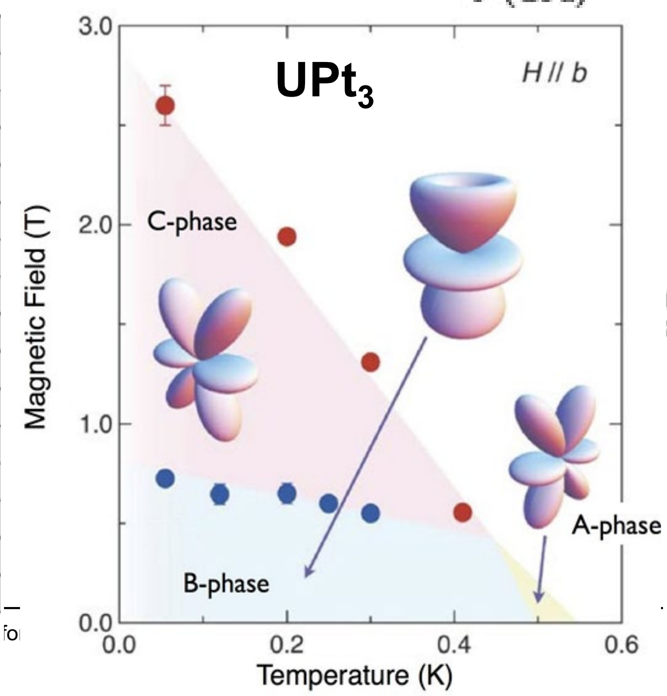
Many varieties of heavy fermion SC's exist:

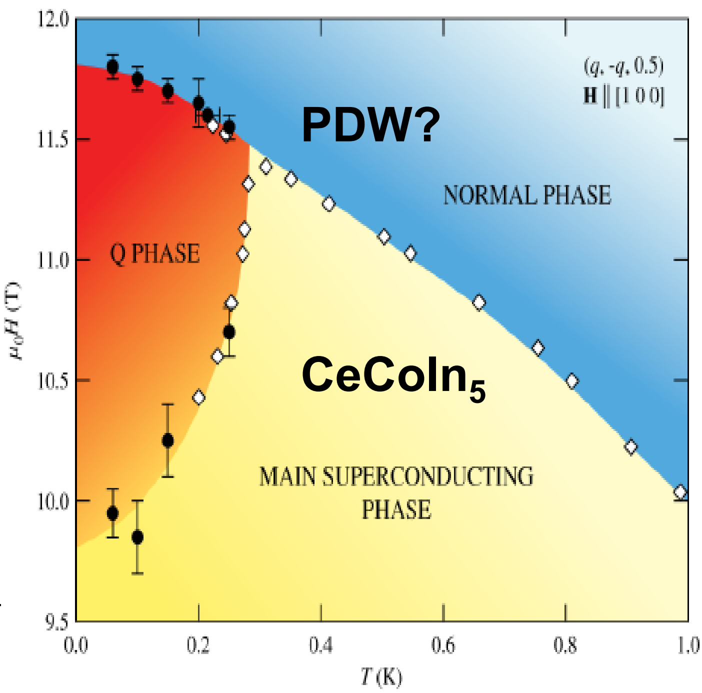




- **YbAlB$_4$**
  - -Very low T_c
- **NpPd$_5$Al$_2$**
- **CePt$_3$Si**
  - -Non-centrosymmetric
- **UPd$_2$Al$_3$**



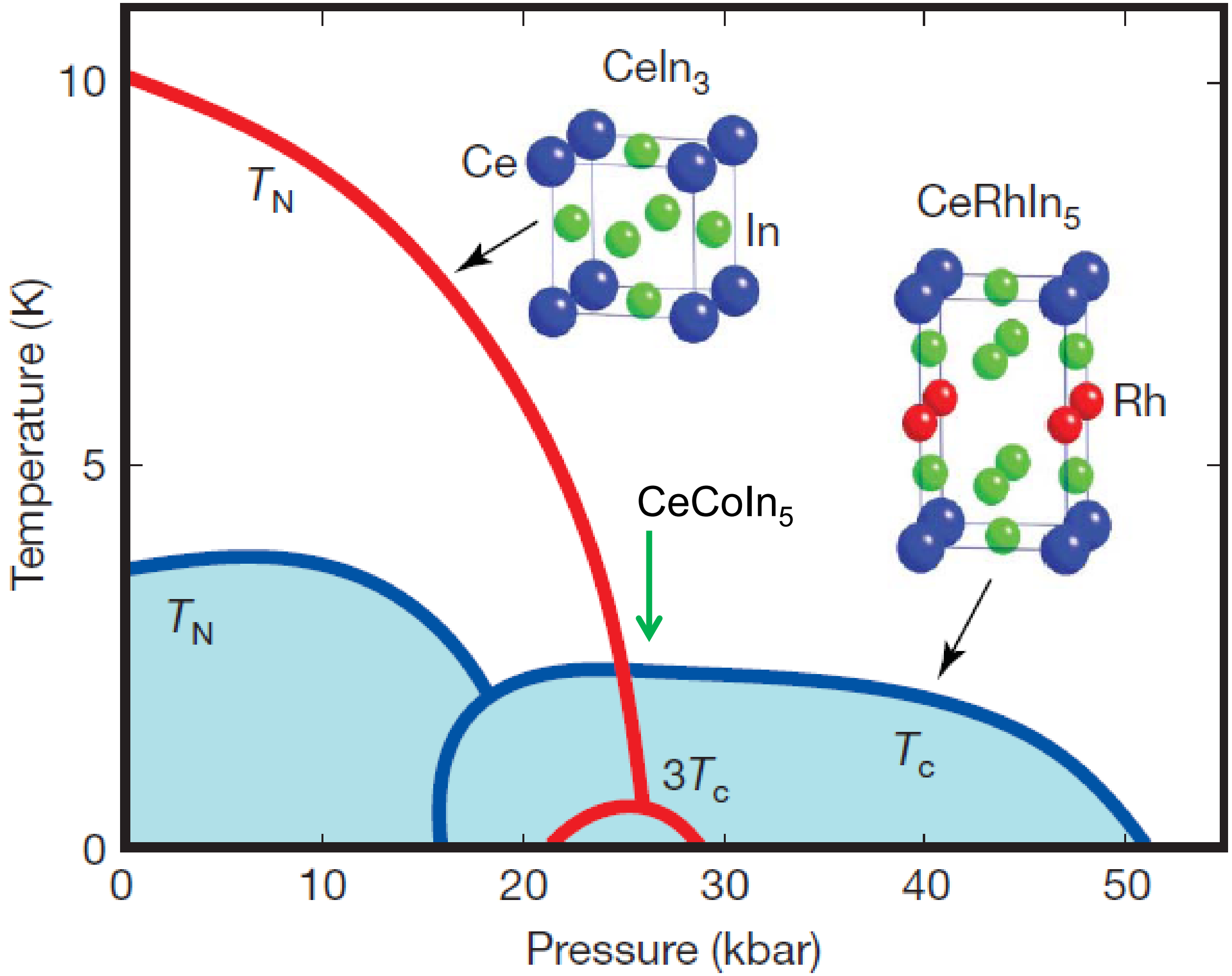


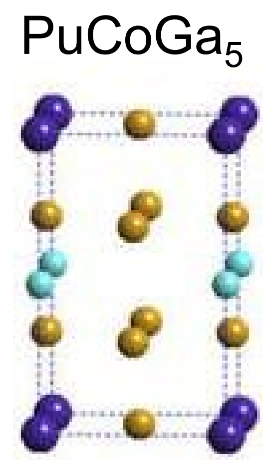


Open Questions

What is the pairing mechanism?

Open Questions: Role of Dimensionality



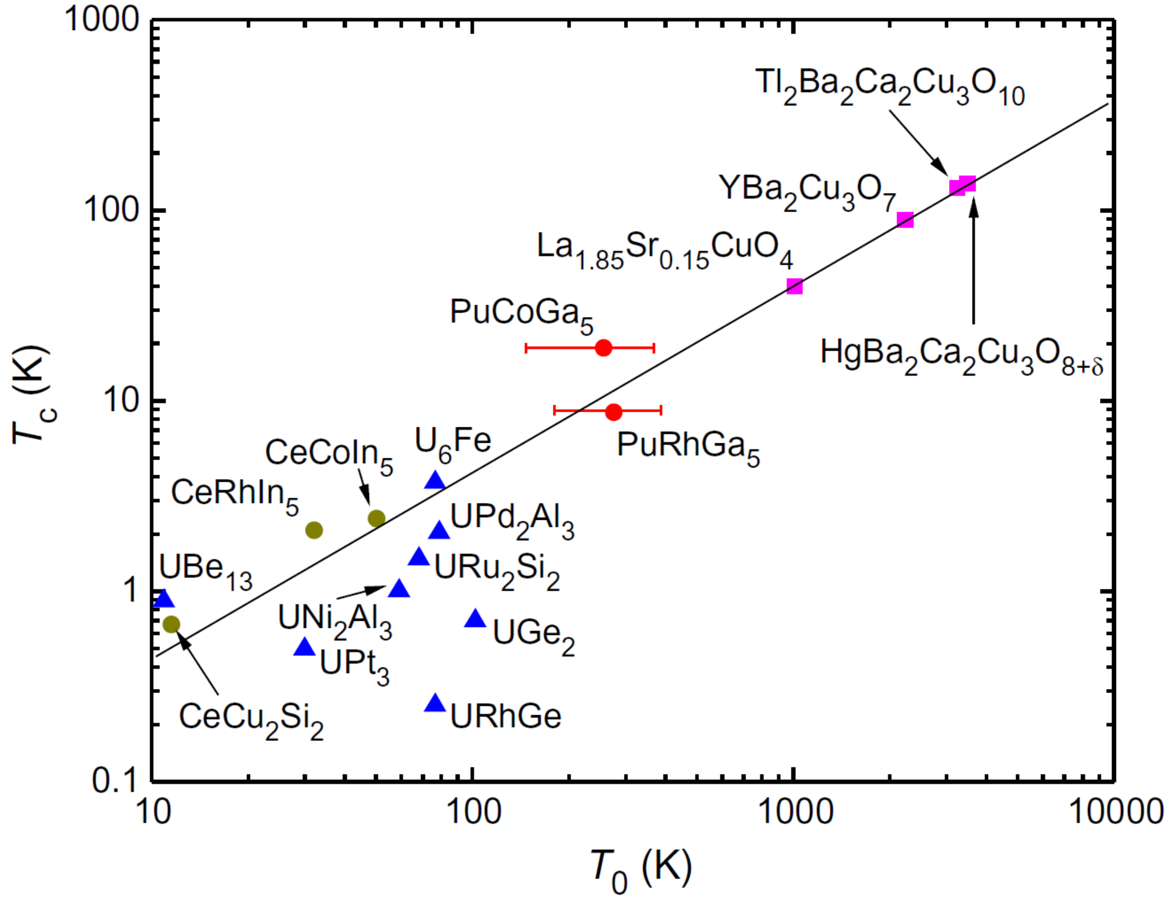


T_c = 19 K

N.D. Mathur *et al*. Nature **394**, 39 (1998); H. Hegger *et al*., PRL **84**, 4986 (2000); Monthoux, Pines and Lonzarich, Nature (2007)

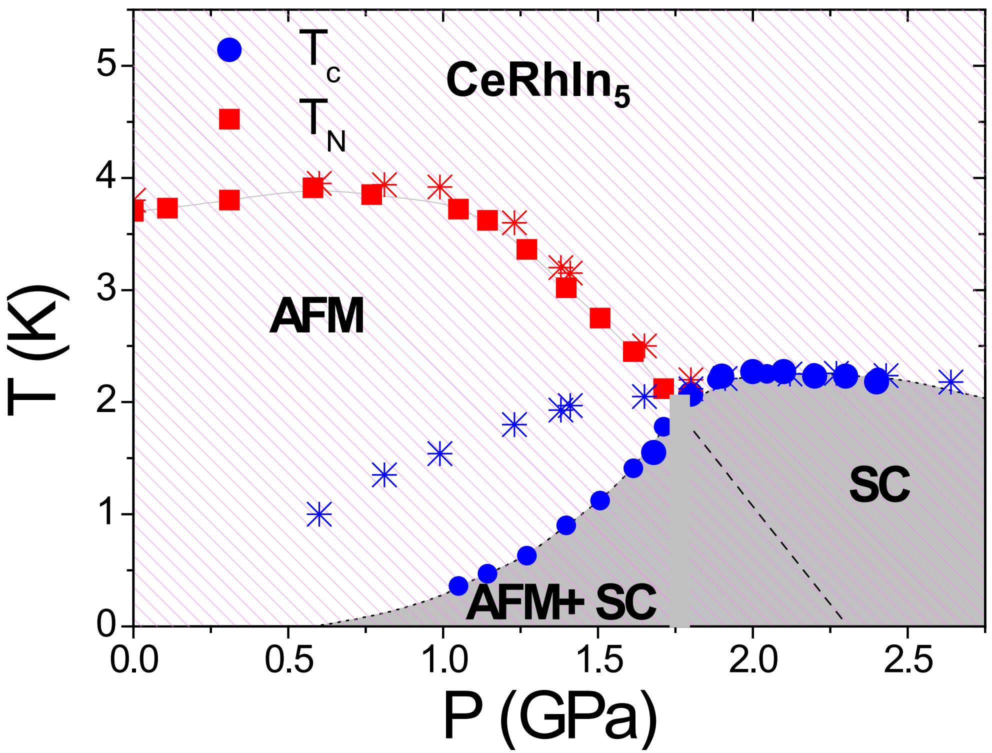
Layered structures good for superconductivity

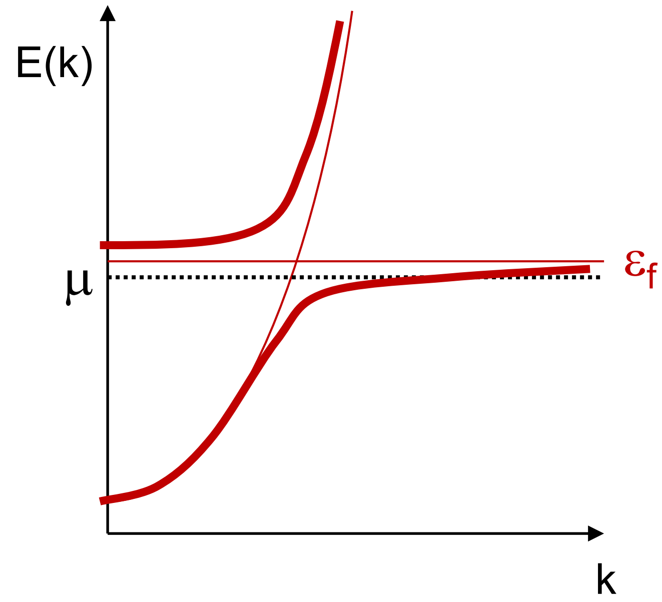
Tc set by strength of spin fluctuations



J.L. Sarrao, and J.D. Thompson, J. Phys. Soc. Jpn. **76,** 051013 (2007)

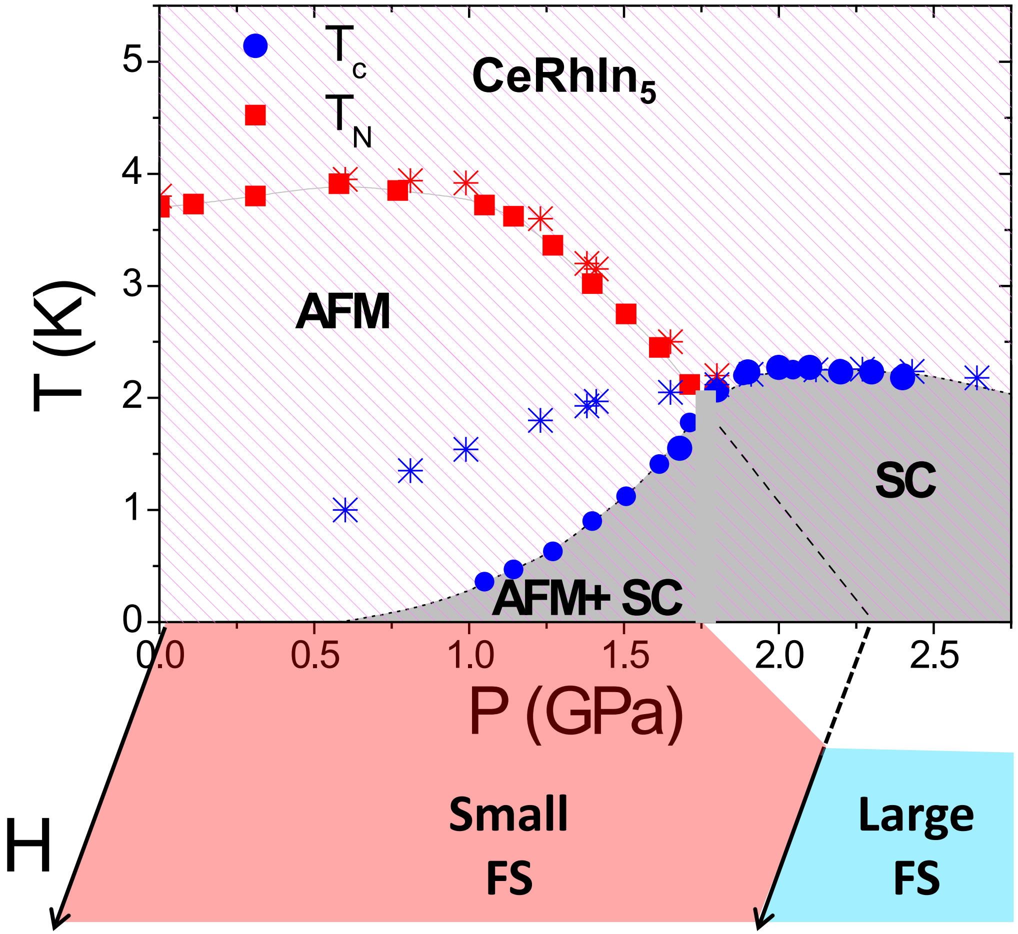
Open Questions: Spin and Charge Fluctuations



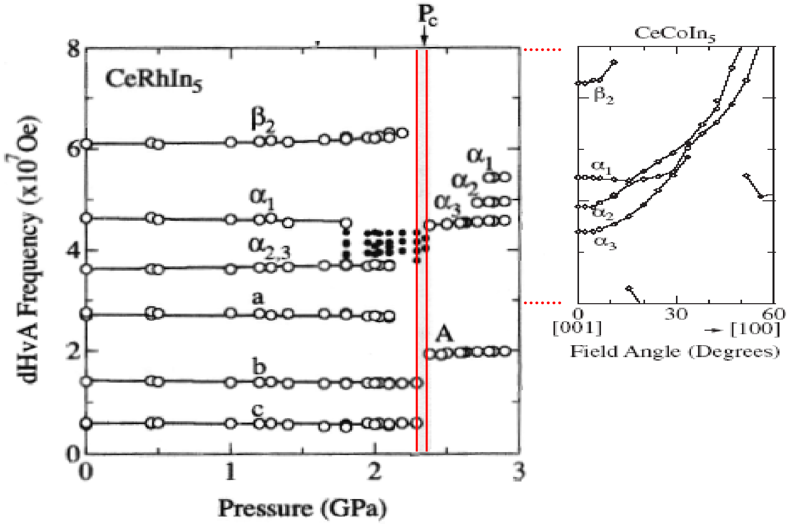


H. Hegger, *et al.* PRL (2000)
T. Park, *et al.* Nature (2008)

Open Questions: Spin and Charge Fluctuations



H. Hegger, *et al.* PRL (2000)
T. Park, *et al.* Nature (2008)



H. Shishido *et al*., JPSJ (2005)

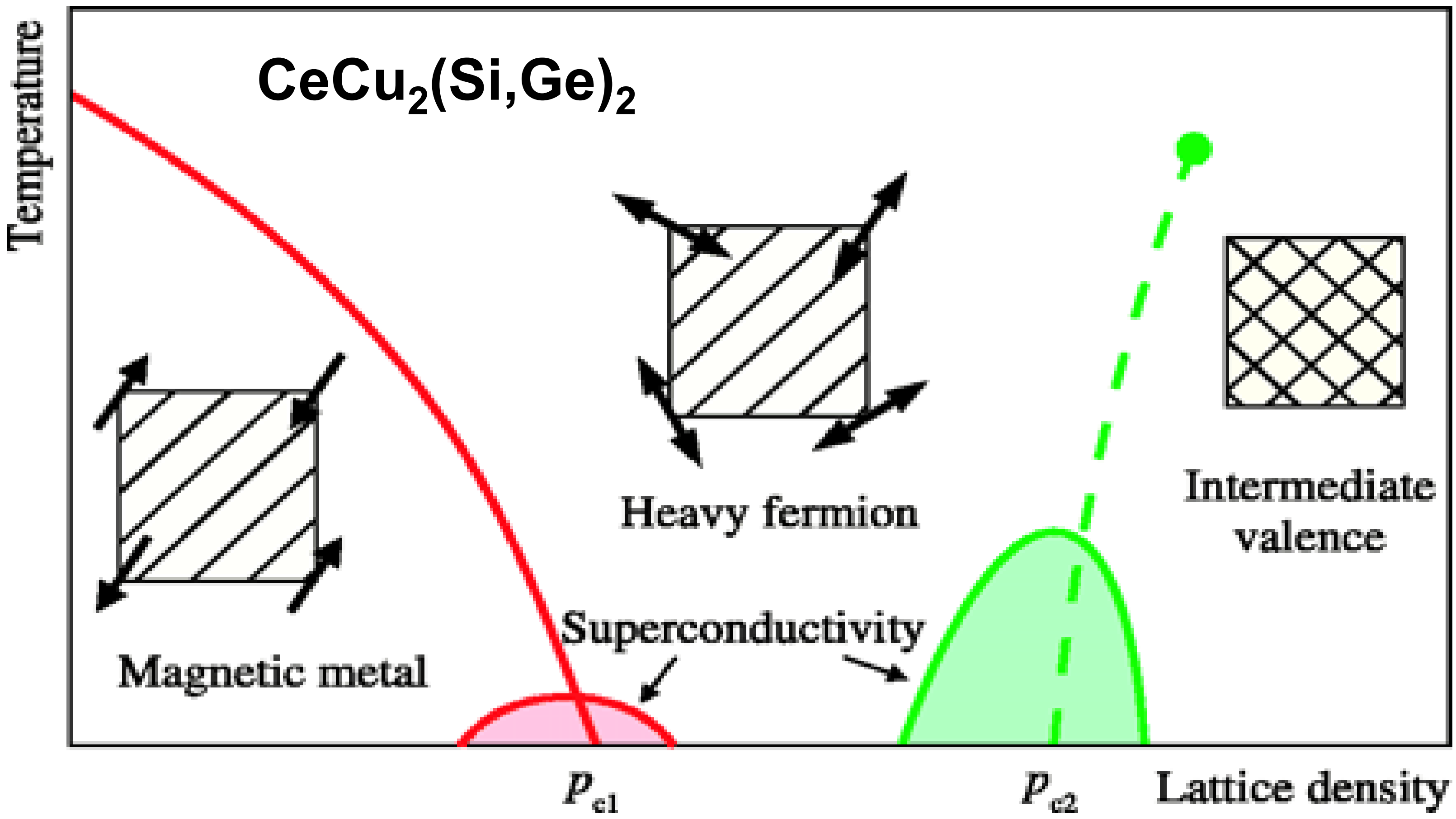
At the QCP:

***Spin* has critical behavior**

+

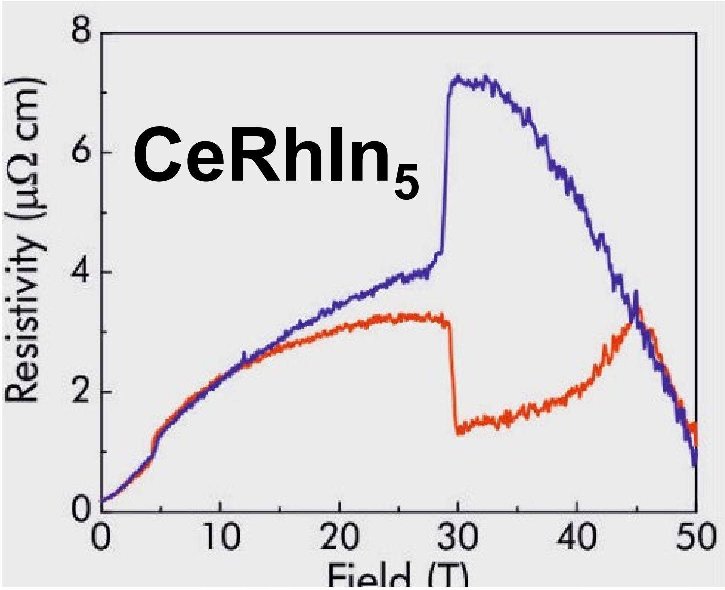
***Charge* can have critical behavior**

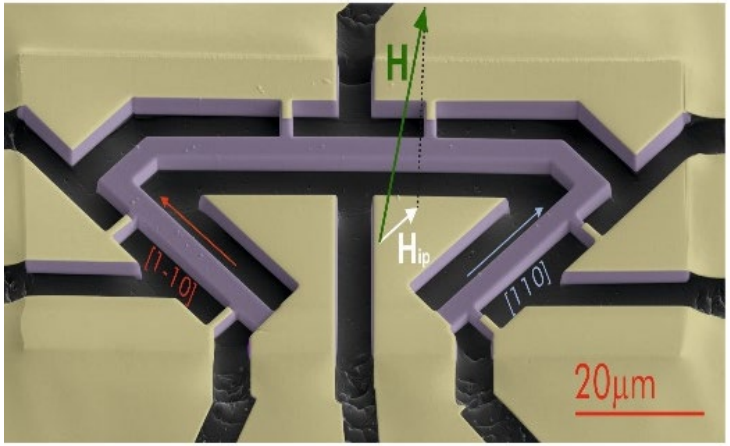
Open Questions: Spin and Charge Fluctuations

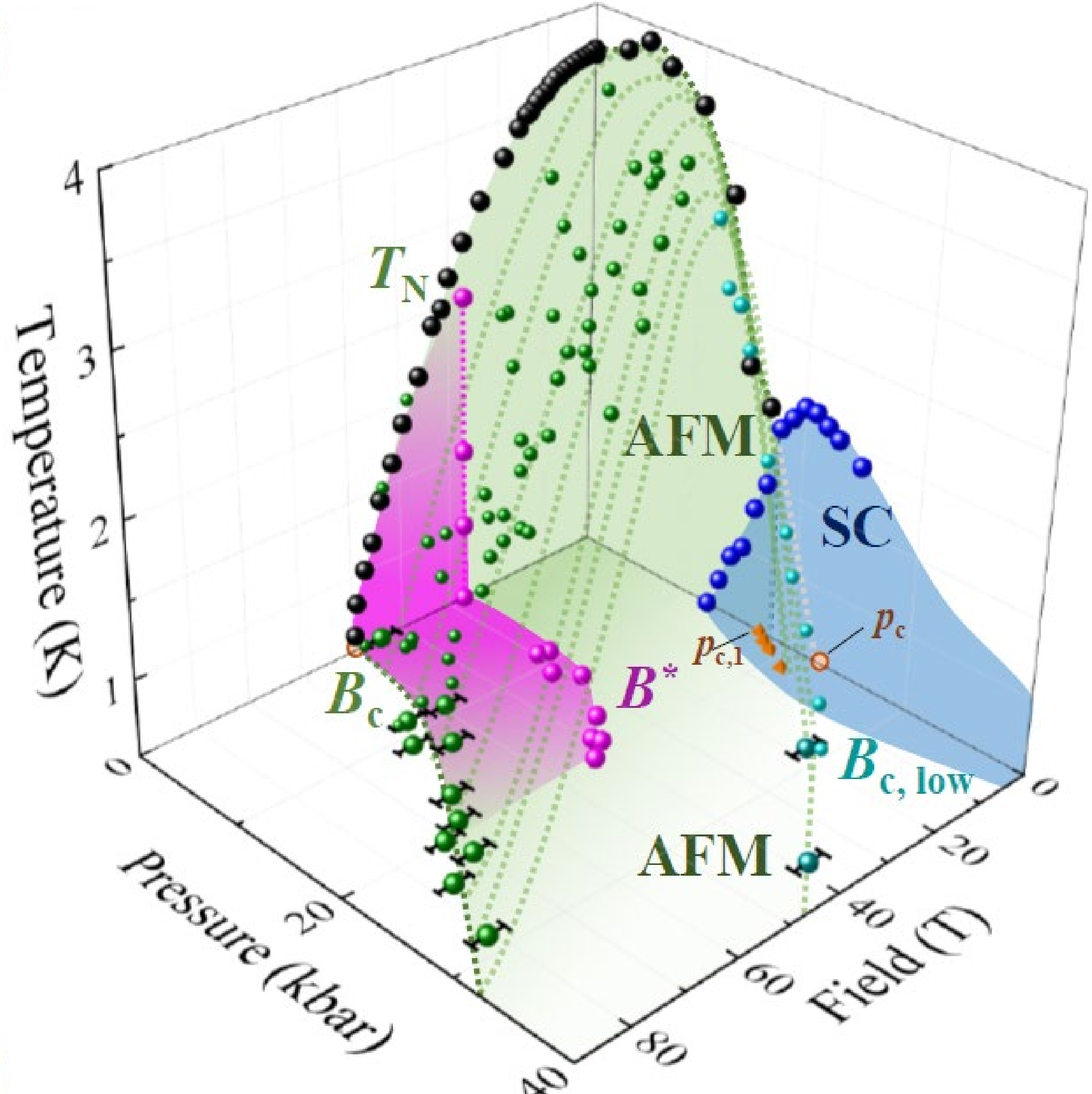


H. Yuan, *et al*. Science (2003)

Open Questions: Role of competing phases

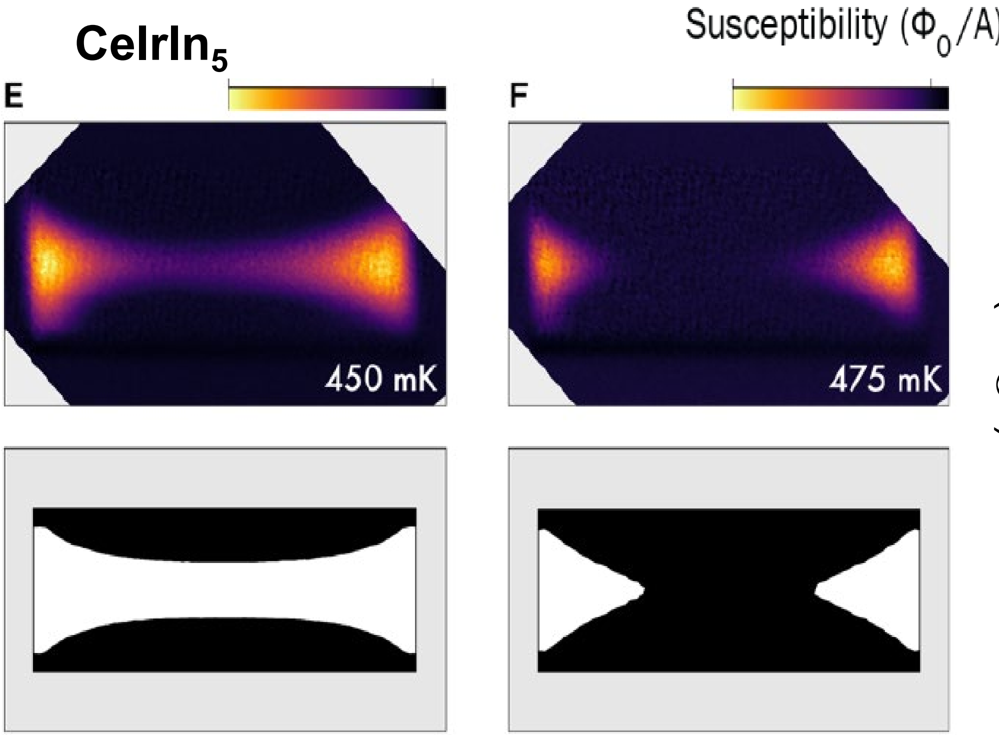


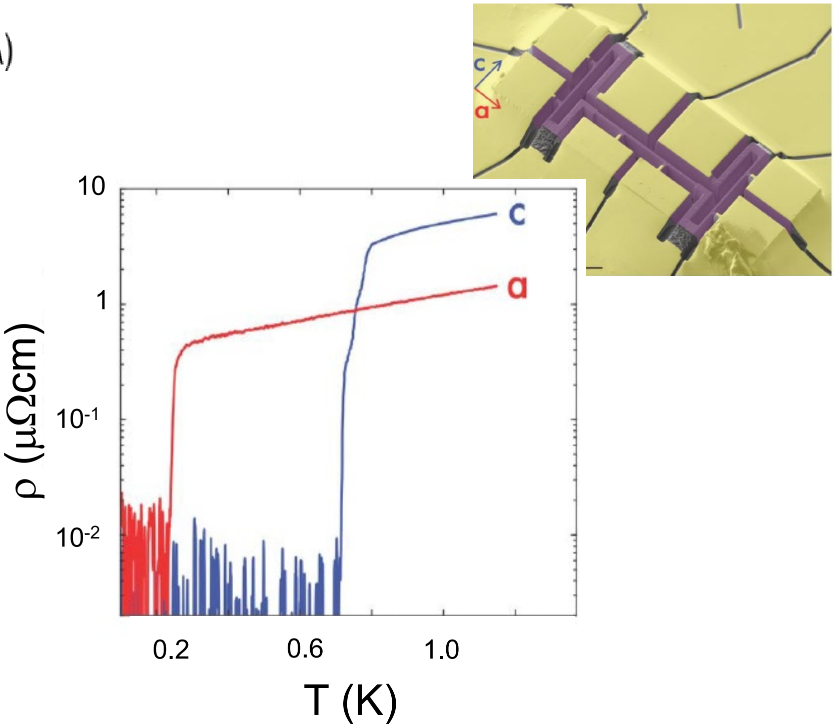




F. R. et al. Nature (2018)
T. Helm et al. ArXiv:1902.00970 (2008)

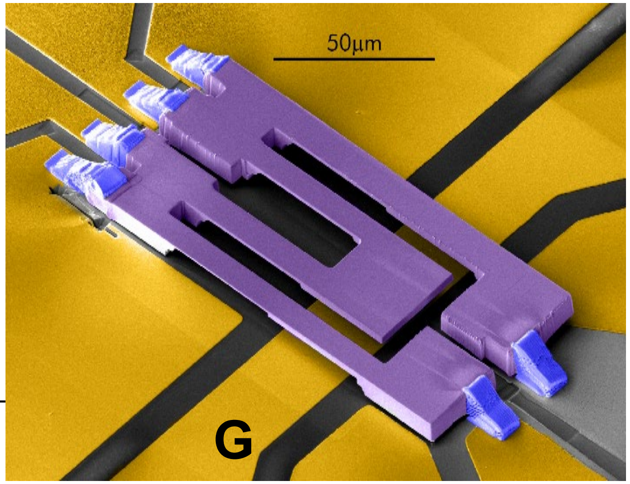
Highly tunable ground states





M. Bachmann, *et al*. ArXiv:1807.05079

Small energy scales leads to highly tunable ground states. Can one make a superconducting switch on this premise?

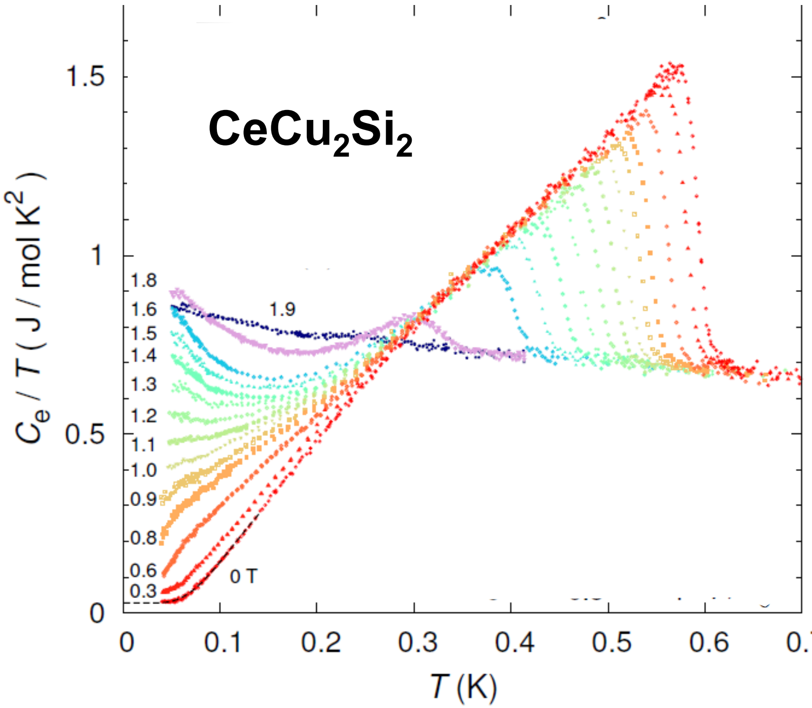


Open Questions: Superconducting Order Parameter

$CeCoIn_5$: $d_{x2\text{-}y2}$ UPt$_3$: E_{2u}

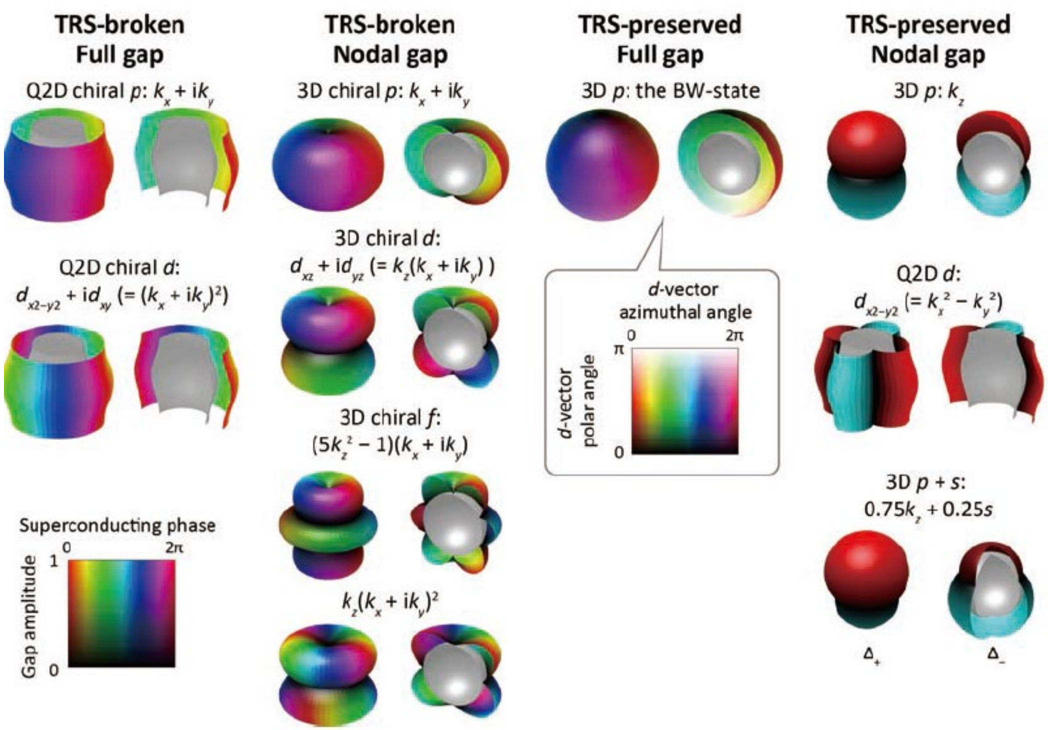
In general, very few phase sensitive experiments exist

$CeCu_2Si_2$ was generally believed to be a d-wave SC, until...



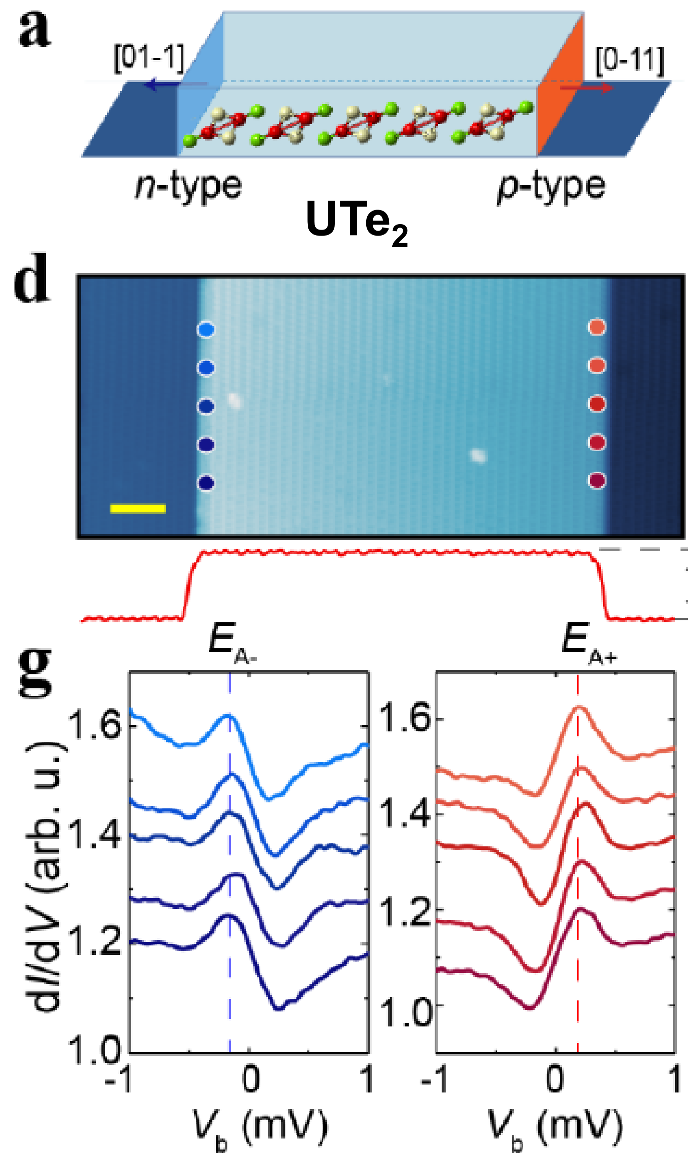
S. Kittaka *et al.*, PRL **112**, 067002 (2014)

Open Questions: Topological Superconductivity



S. Yonezawa DOI : 10.22661/AAPPSBL.2016.26.3.03

Spin-orbit coupling is strong in f-electrons



L. Jiao, *et al*. arXiv:1908.02846

Advantages and Disadvantages of HF SCs

Advantages

- **Small Energy Scales (highly tunable!)**
- **Often Stoichiometric (Ultra high purity – mean free paths > 1 um !)**
- **T_c varies by 2 orders of magnitude (0.2K in $CeIn_3$ – 20 K in $PuCoGa_5$)**
- **Physics often analogous to 3d physics**
  - E.g. In $CeCoIn_5$ T_c/T_F = 2.3 K/41 K = 0.056 which is even greater than the high T_c cuprates T_c/T_F = 95 K/2400 K = 0.040
- **Strong spin-orbit coupling good for topologically non-trivial states**

Disadvantages

- **Small Energy Scales (normal state not well understood or characterized!)**
- **Complex electronic structures**
- **U and Pu are radioactive (can be a feature)**

Thank you!