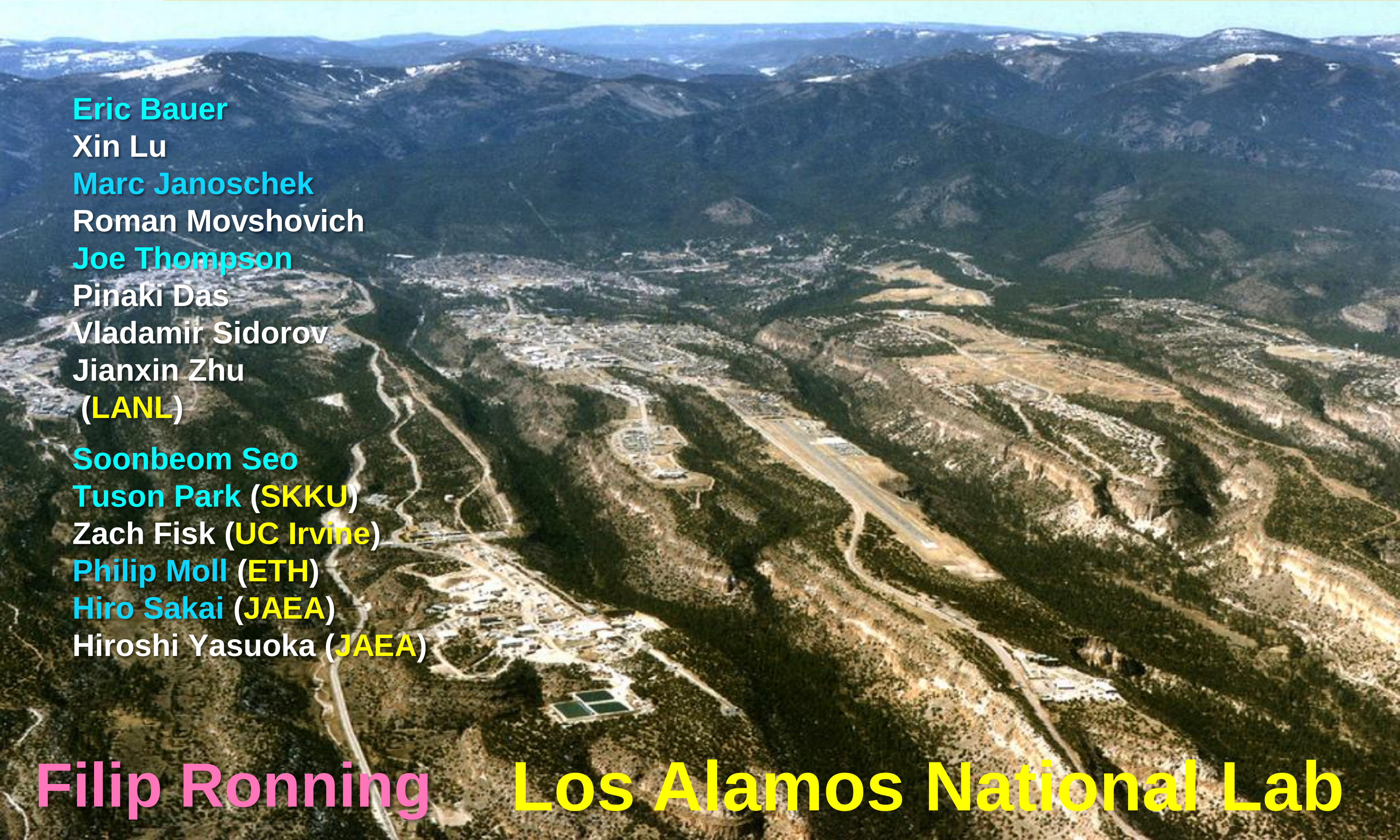
Heavy Fermion Superconductivity



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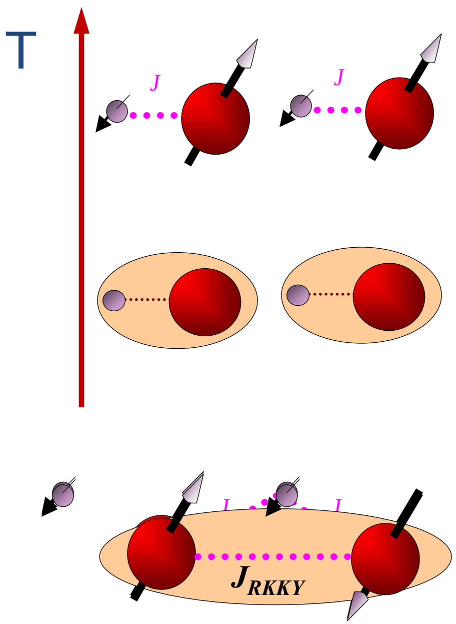
Outline:

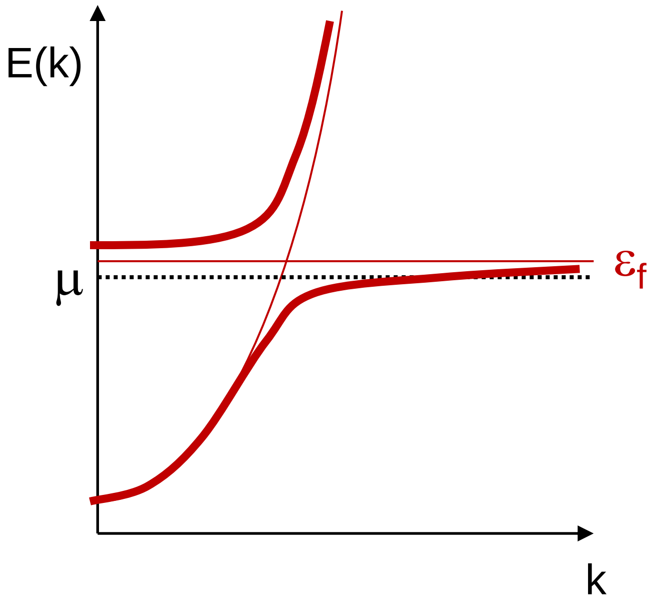
- **Heavy Fermion primer**
- **Superconductivity on the border of antiferromagnetism**
- **Non-universality of dopants**
- **Reduced Dimensionality**
  - **Localized → delocalized crossover**
- **Competing Electronic States (exposed with magnetic fields)**

Heavy Fermions

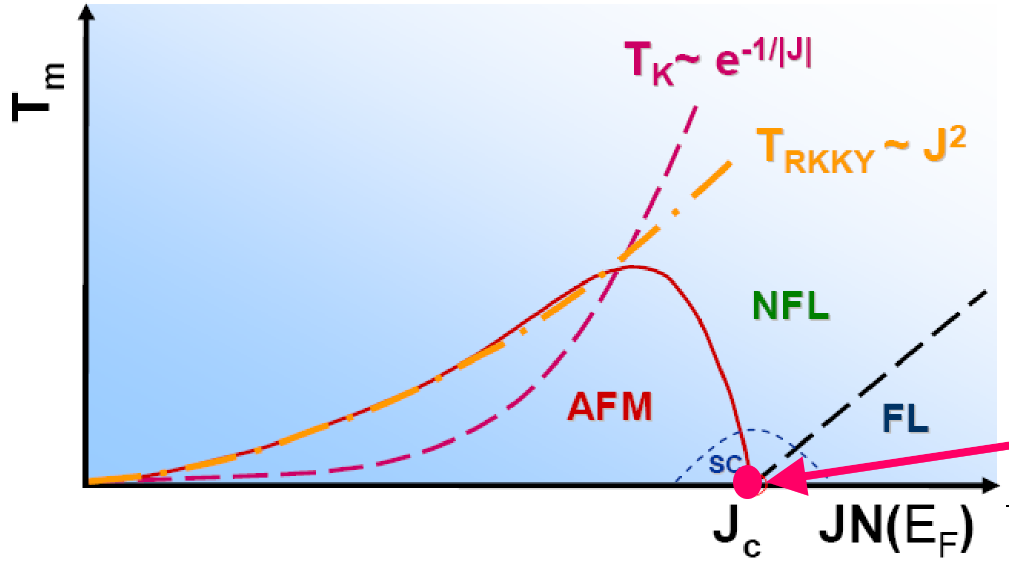


$m^* >> m_e$

How do individual *f* electrons condense into the Kondo liquid to form the heavy fermion state?



RKKY wins

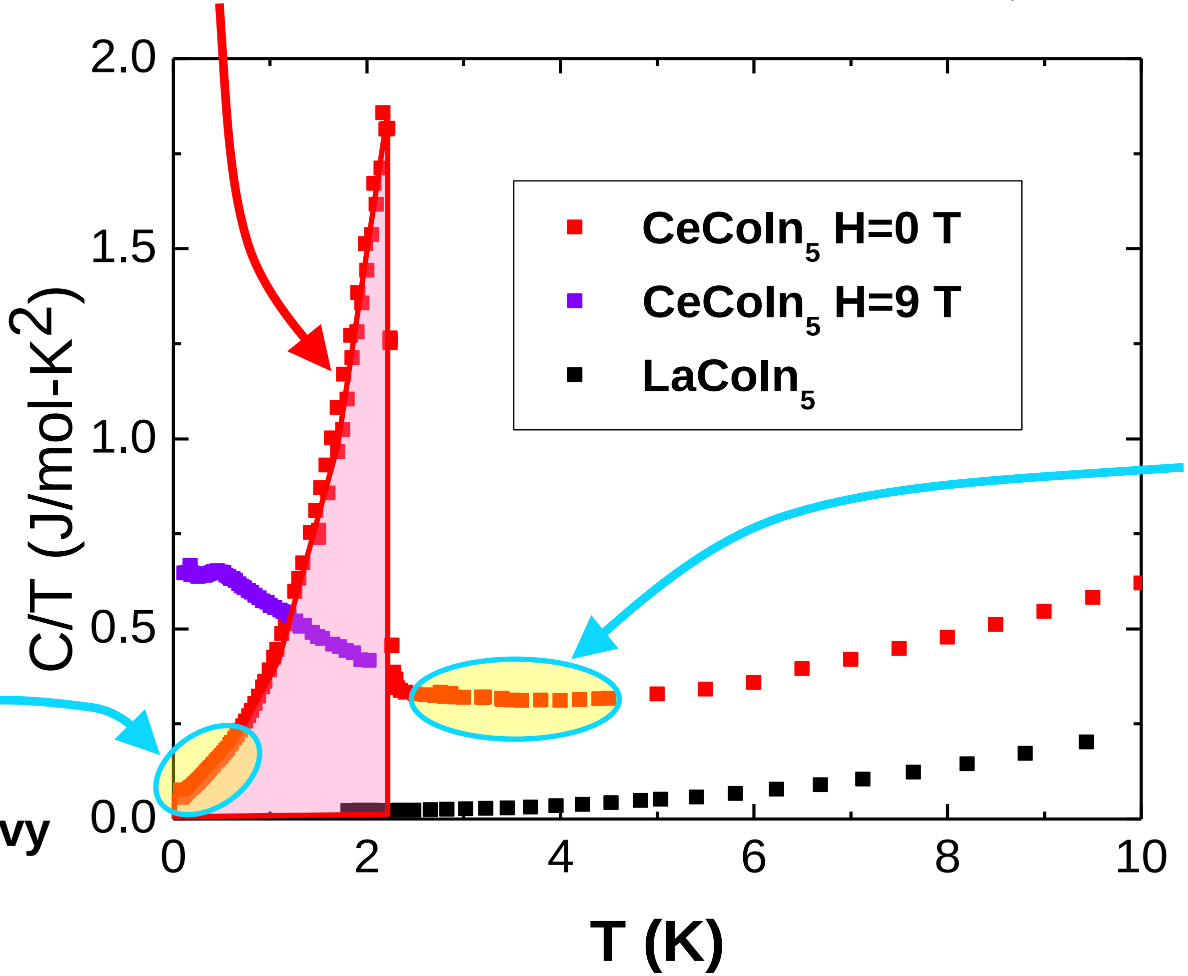


Kondo wins

Quantum Critical Point

Superconductivity in Heavy Fermions

- Large entropy goes into the SC state
- Stoichiometric → high purity, large m.f.p. (> 1μm)

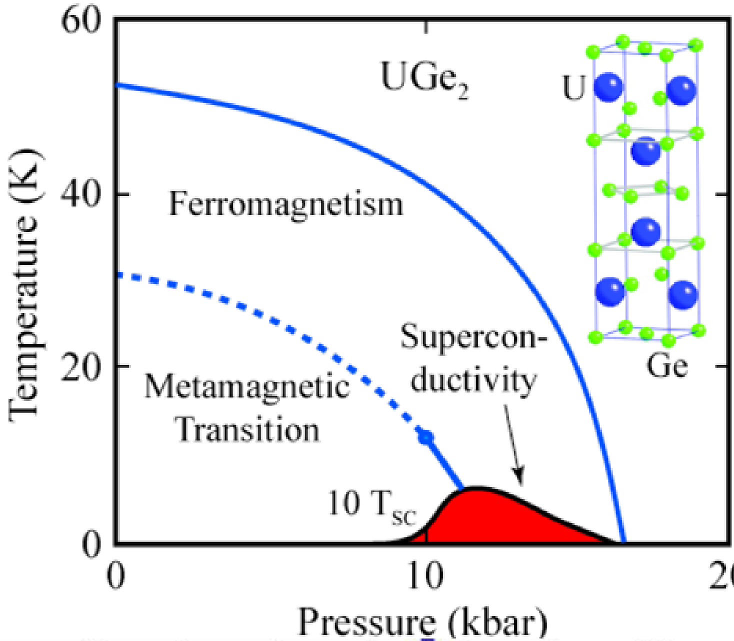


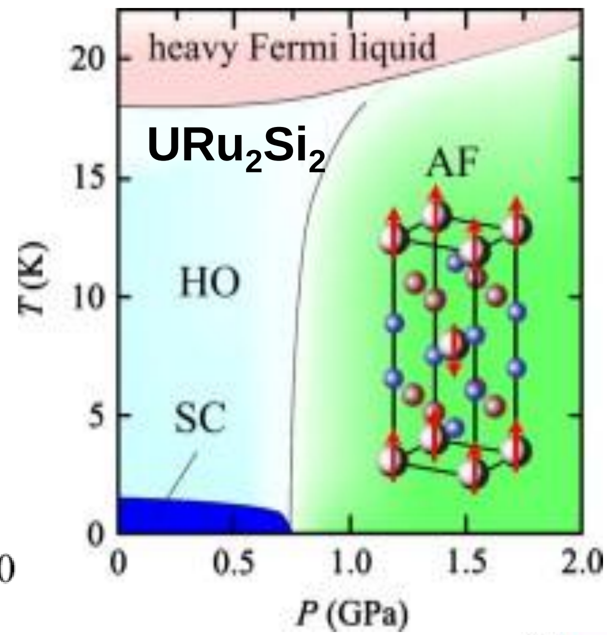
- Heavy Electrons

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

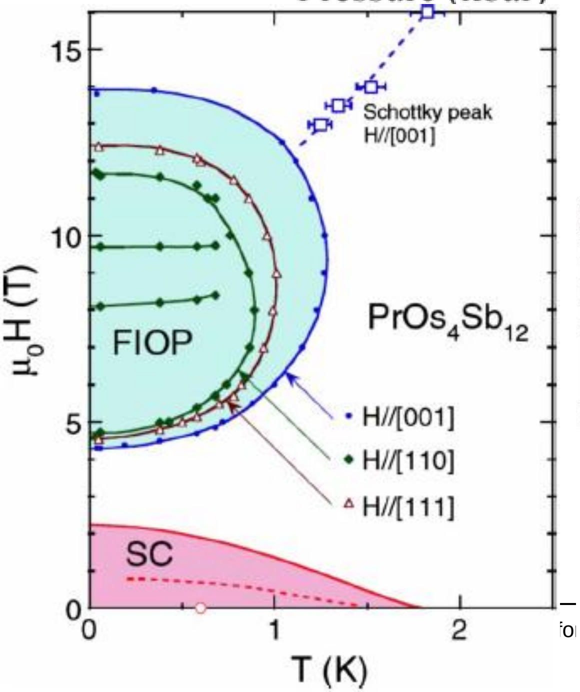
- small energy scale → highly tunable
- Nodal QP's
- that are heavy
- T_c/T_F similar to cuprates

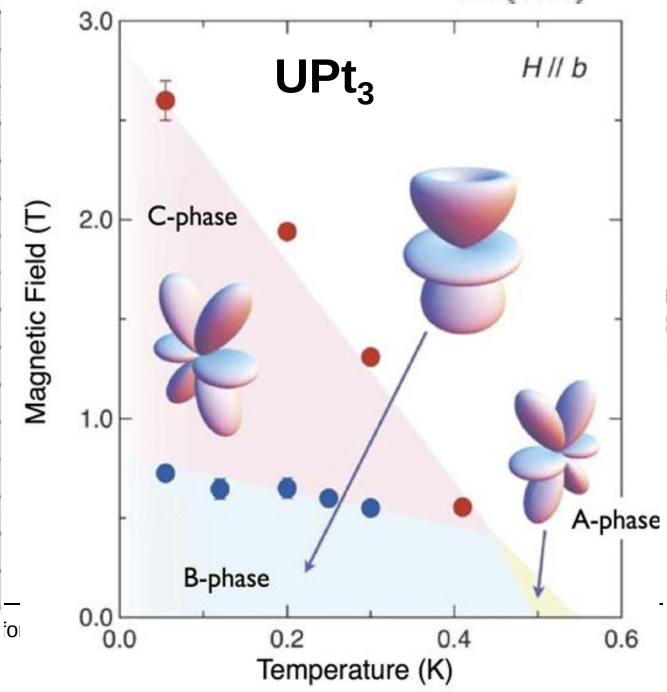
Many varieties of heavy fermion SC's exist:

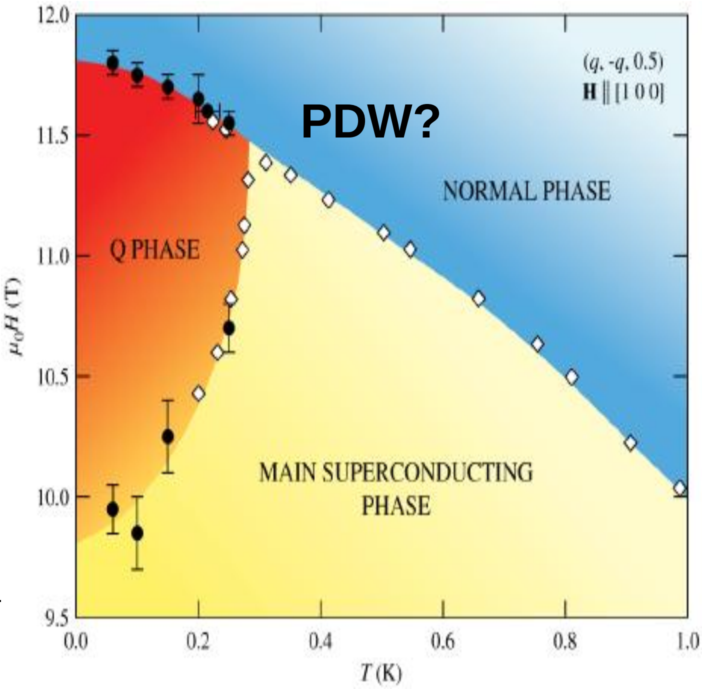




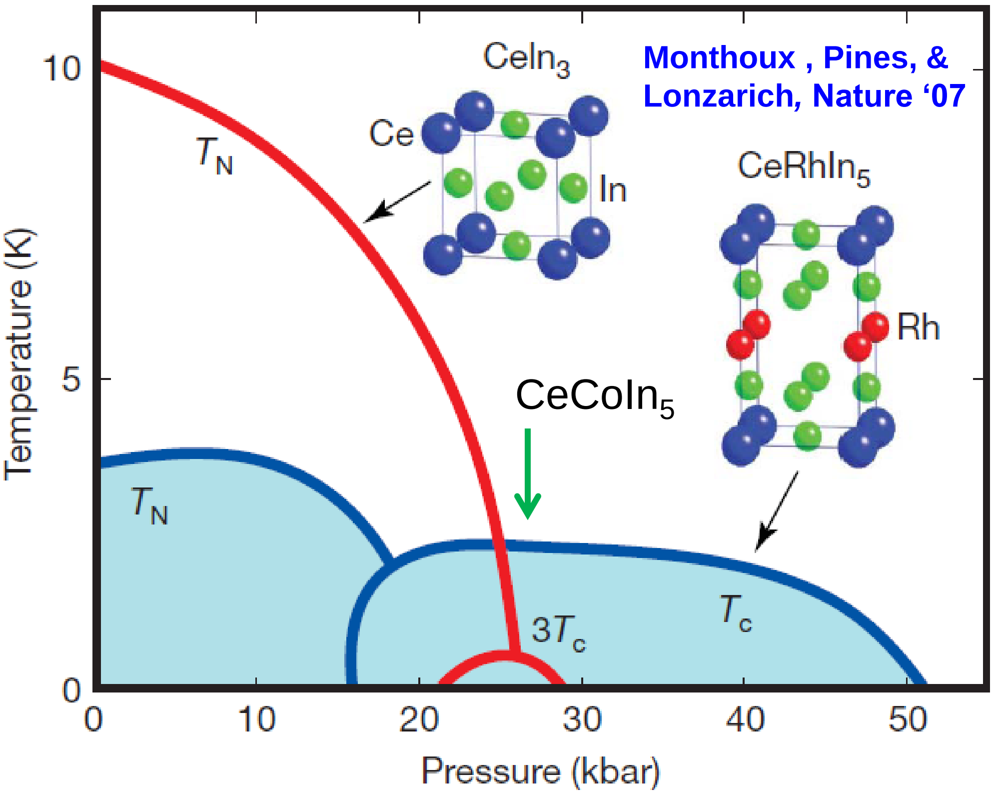
- **$YbAlB_4$**
  - -Very low T_c
- **$NpPd_5Al_2$**
- **$CePt_3Si$**
  - -Non-centrosymmetric
- **UPd_2Al_3**

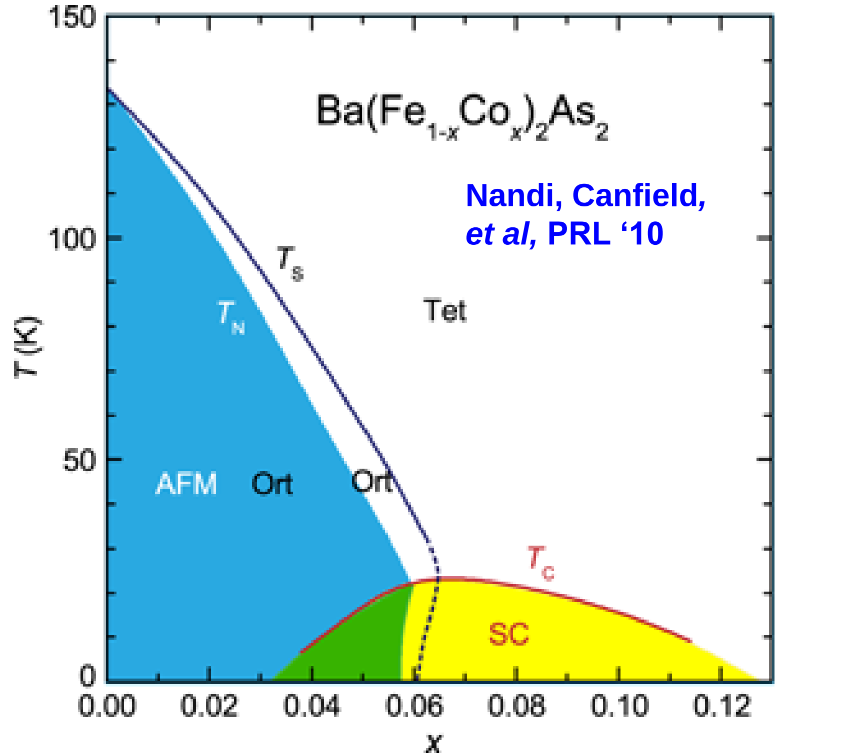






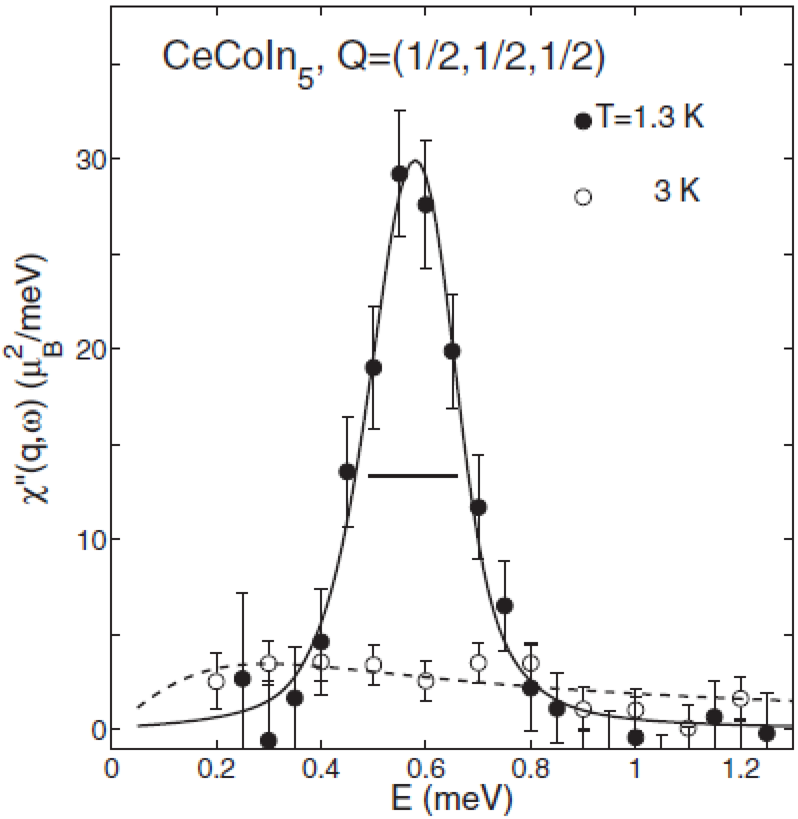
SC in proximity to Antiferromagnetism

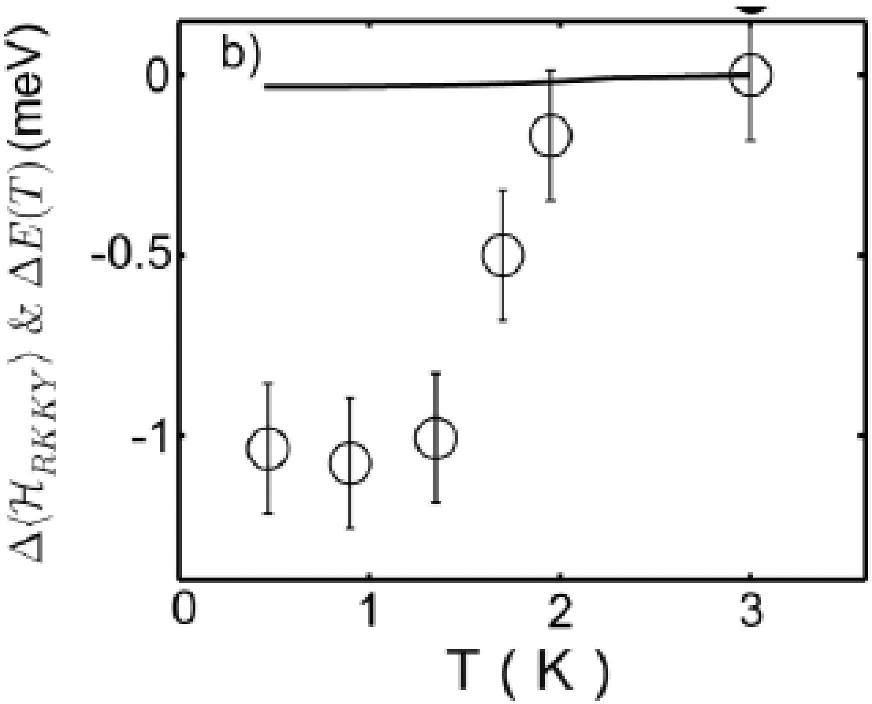




- Phase diagram generic for Cerium heavy fermion SC's
- Parent compound is an AF metal
- T_c/T_F ~ 0.1
- SC is unconventional (power laws/sign changing OP)
- Tunable with doping or pressure.
- Spin Fluctuations…

Potential strength of spin fluctuations: $CeCoIn_5$





C. Stock, *et al*. PRL '08

$$\Delta E_{ex} = \frac{1}{(g^2\mu_B^2)} \int_0^\infty \frac{d\omega}{\pi} [n(\omega)+1] \int_{BZ} d\boldsymbol{q} J(\boldsymbol{q}) [\chi_N''(\boldsymbol{q},\omega) - \chi_S''(\boldsymbol{q},\omega)]$$

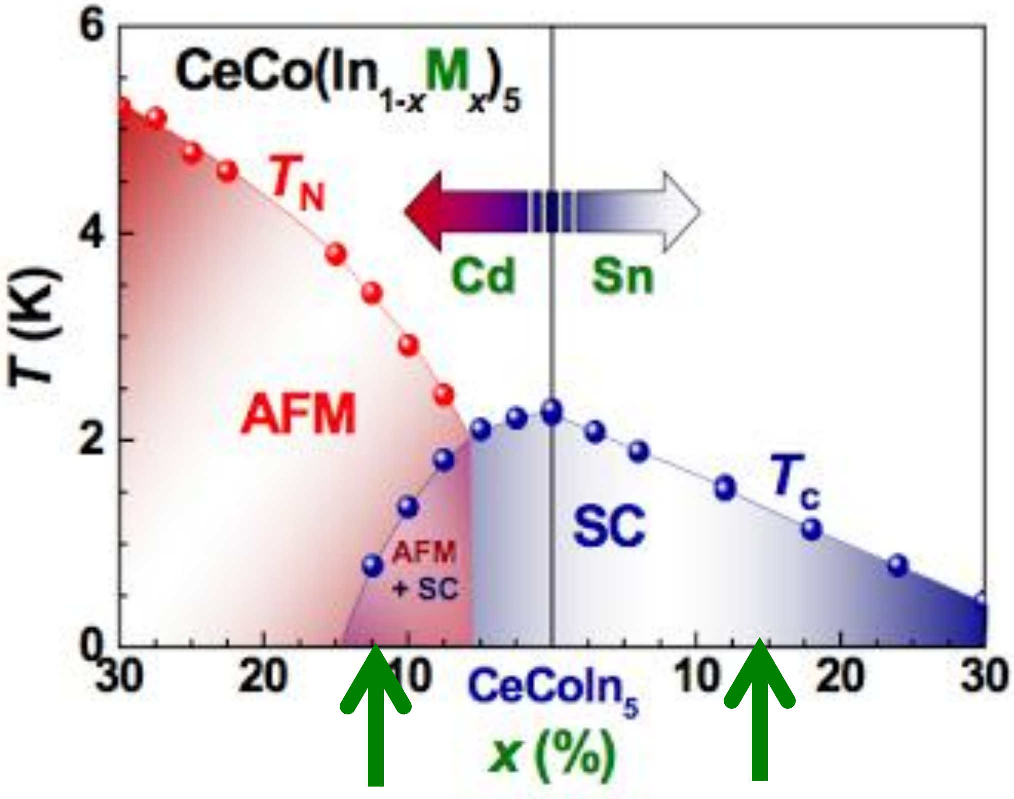
Change in magnetic energy is 100 x SC condensation energy (from heat capacity)

Cd vs Sn doping in $CeCoIn_5$

A Tale of Two Dopants

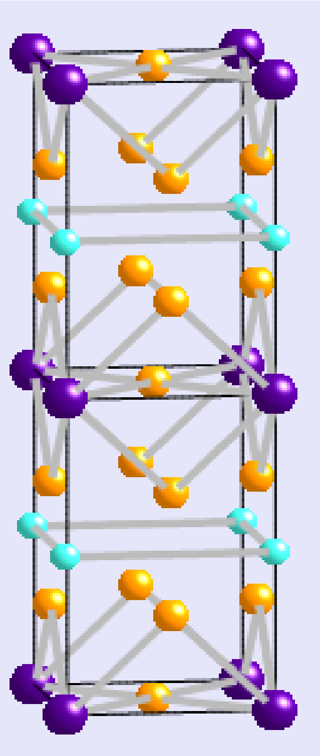
Doping $CeCoIn_5$: Analog of $CeRhIn_5$ (P)?

hole and electron doping is both electronic tuning and pair breaking.



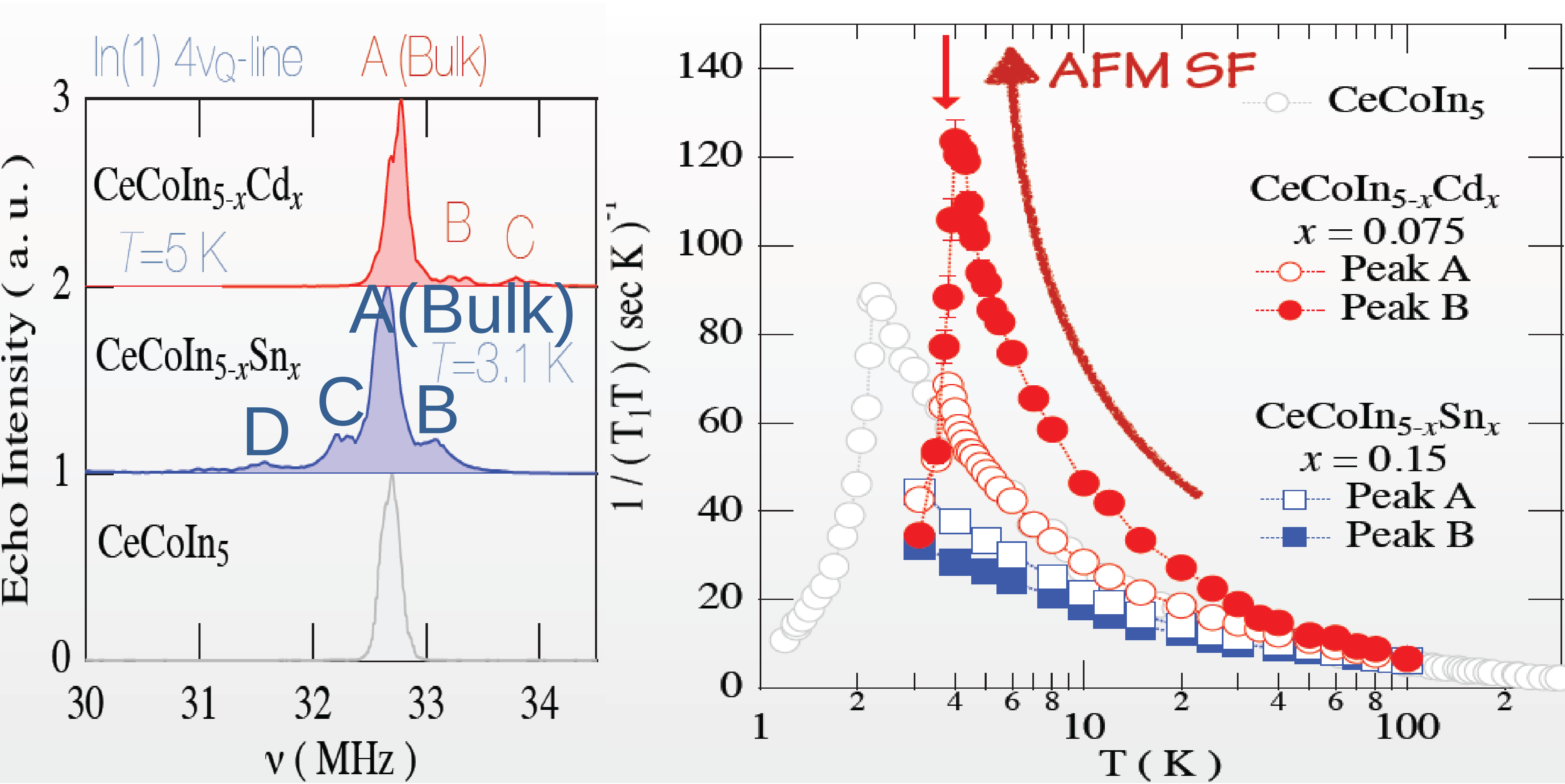
L. Pham, *et al*. PRL ’06

E.D. Bauer, *et al*. PRB ‘06



Globally, doping looks like a chemical pressure effect, but details differ…

NMR study

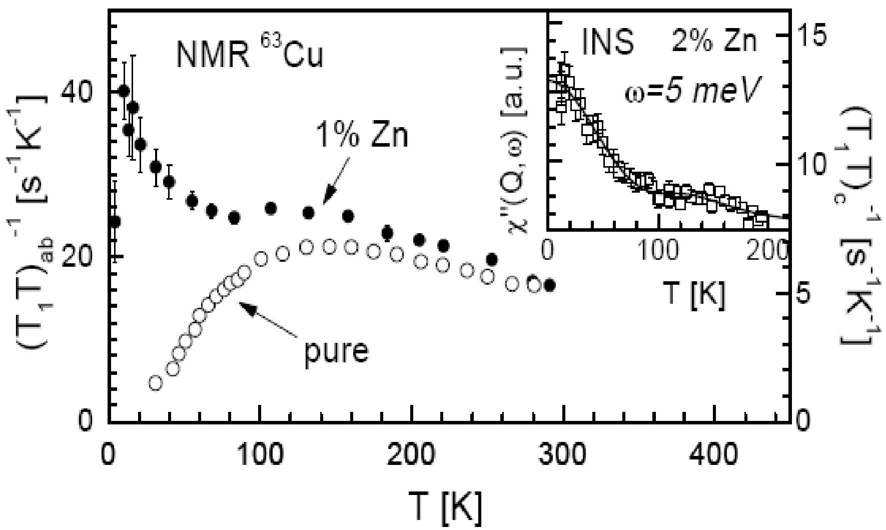


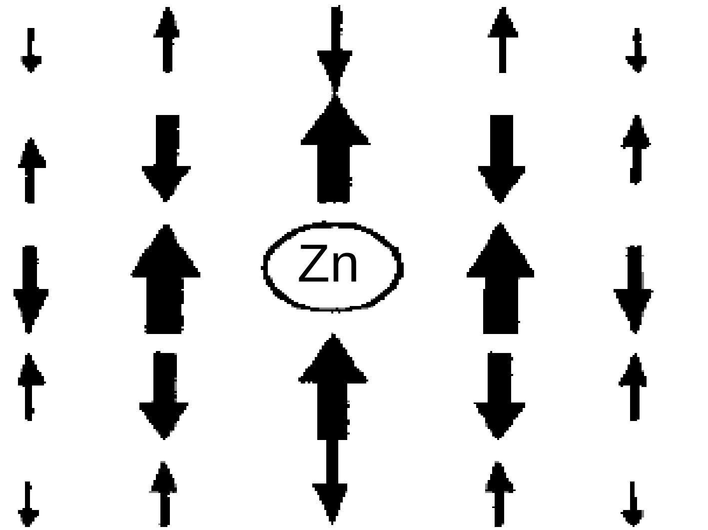
H. Sakai, *et al*. unpublished

Cd = "AFM droplets"

Sn ≈ homogeneous

Zn doped cuprates





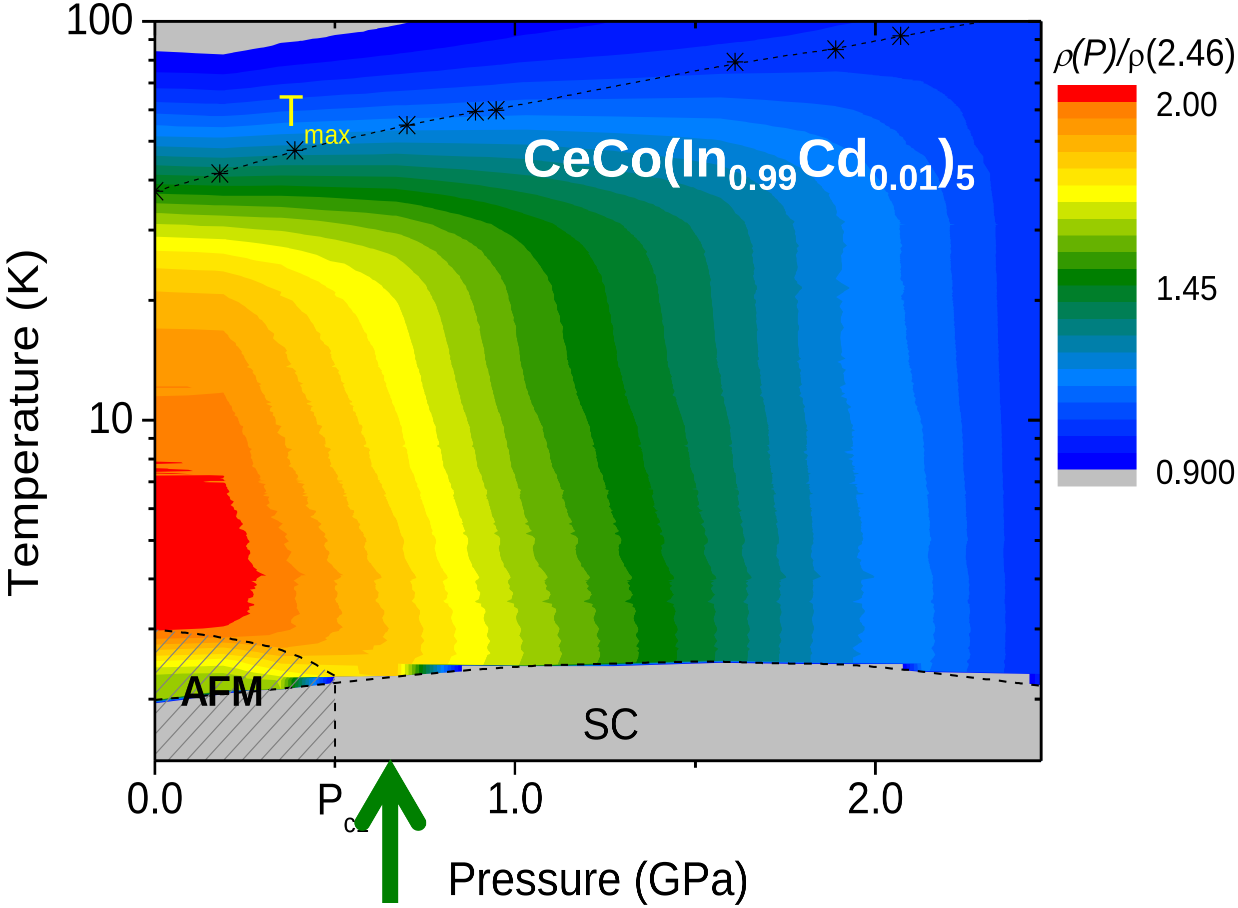
$YBa_2(Cu_{0.99}Zn_{0.01})_3O_{6.7}$ (left) and $YBa_2Cu_3O_{6.63}$ (right ordinate).
Inset: neutron scattering of $YBa_2(Cu_{0.99}Zn_{0.02})_3O_{6.7}$
- Julien et al., Phys. Rev. Lett. 84, 3422 (2000)

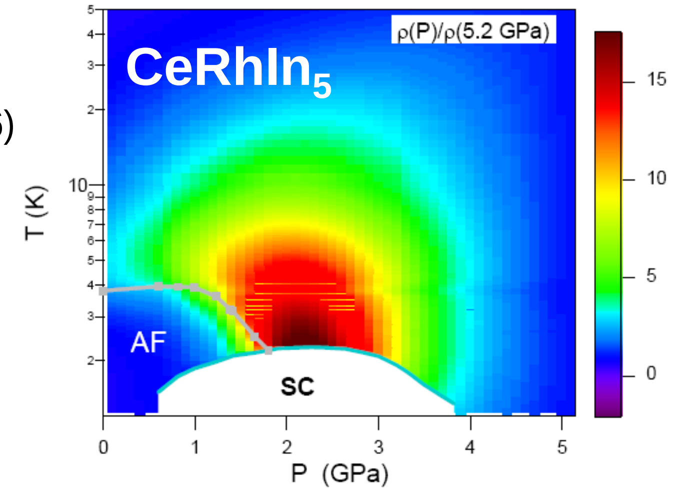
Zn induces staggered moment at surrounding Cu sites: a competing order is revealed by Zn impurity

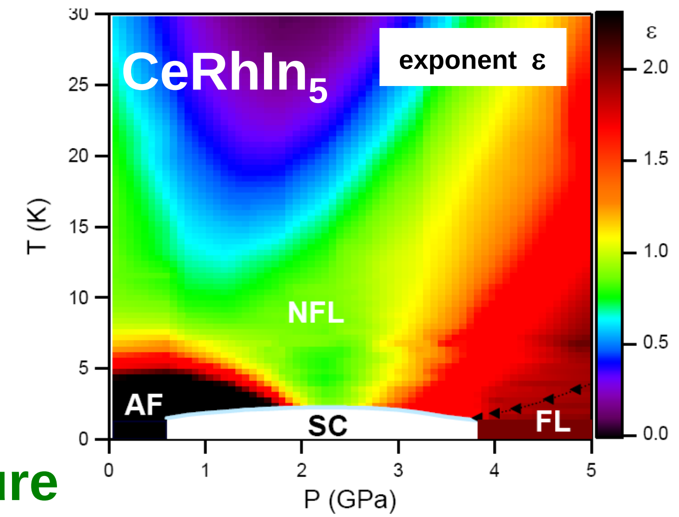
Caution: Intrinsic disorder is already present from hole doping through oxgen vacancy

Avoided criticality in Cd-doped $CeCoIn_5$

S. Seo, T. Park *et al* Nat. Phys. (2013)



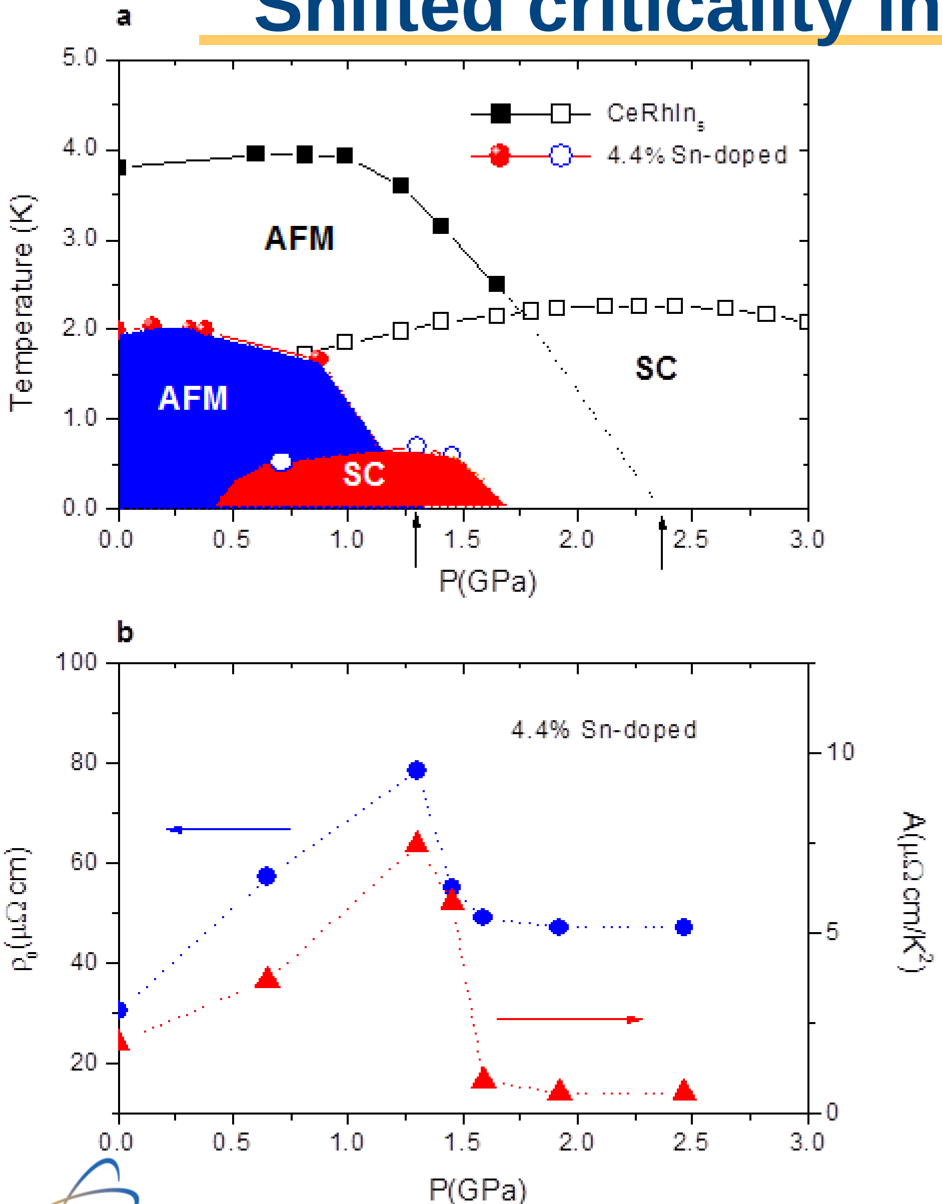


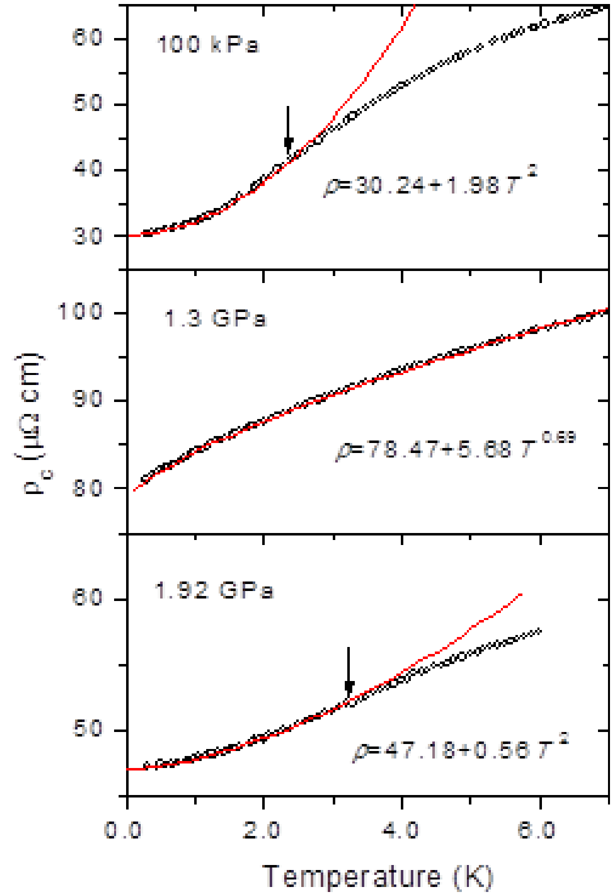


T. Park, *et al*. Nature '08

- **Global phase diagram reversible with pressure**
- **No singularity in the resistivity at the nominal QCP**
- **Cd is a weak pair breaker**

Shifted criticality in Sn-doped $CeRhIn_5$

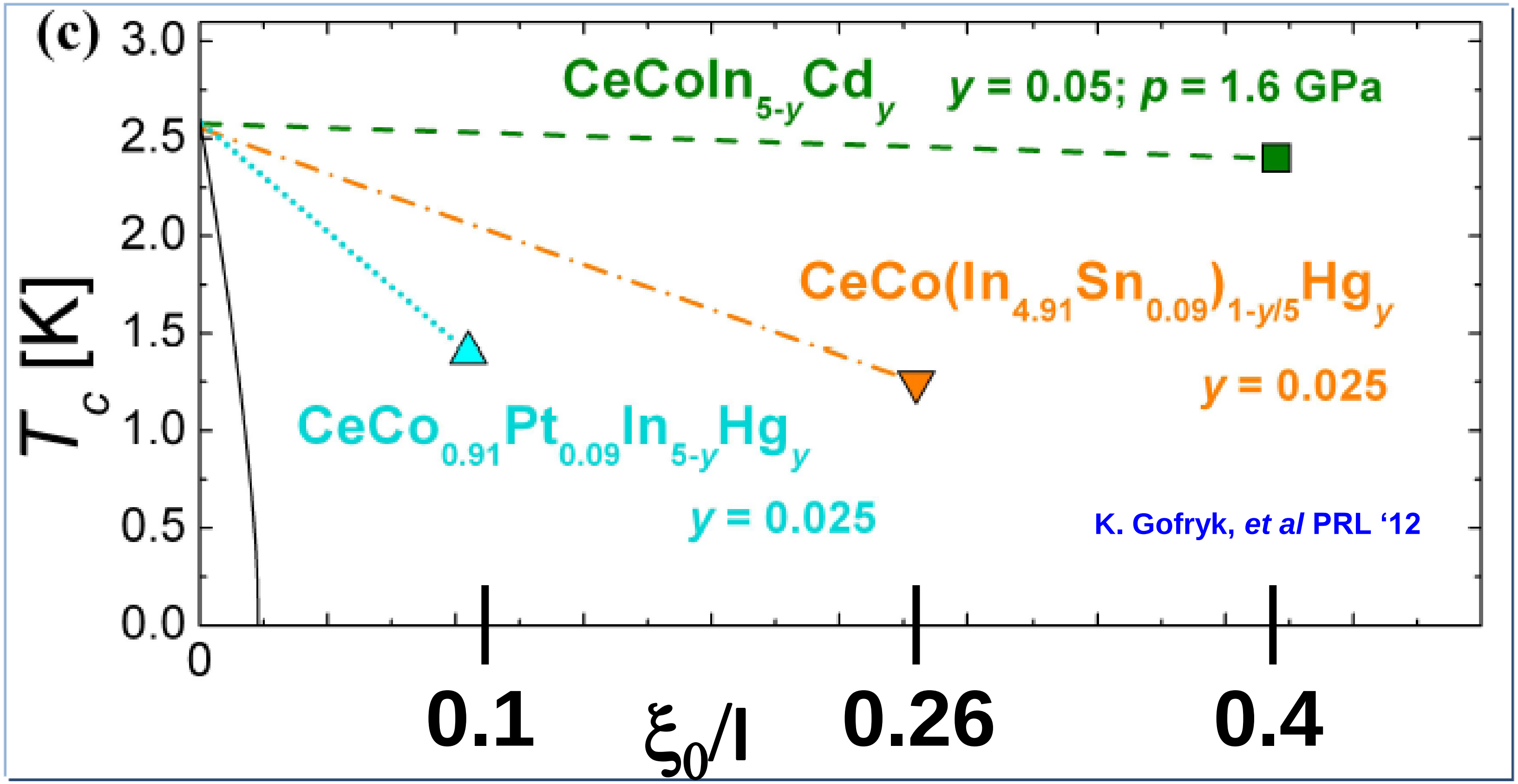




Sn acts as positive pressure plus pair breaking

S. Seo, T. Park *et al* unpublished

Robustness to impurity scattering: $CeCoIn_5$



Little doubt that this system is d_{x2-y2}. Robustness likely due to strong coupling and extreme multiband.

Are inhomogeneous dopants less pair-breaking than homogeneous ones?

Are filled shells less pair breaking (ie. Cd and Zn)?

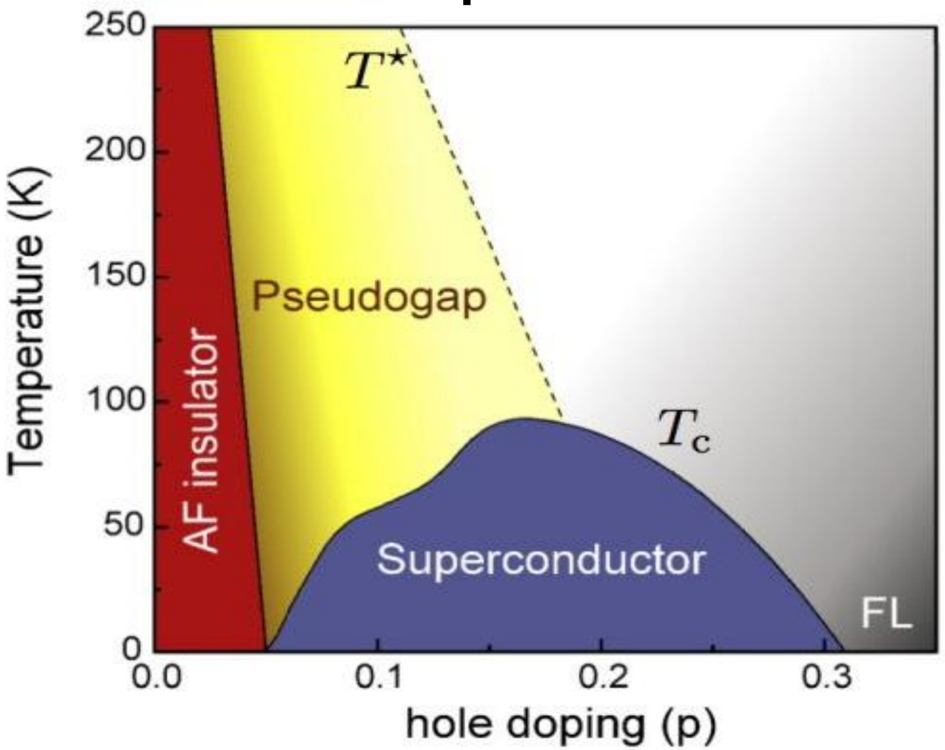
Inhomogeneity can obscure signatures of criticality!

Dimensionality

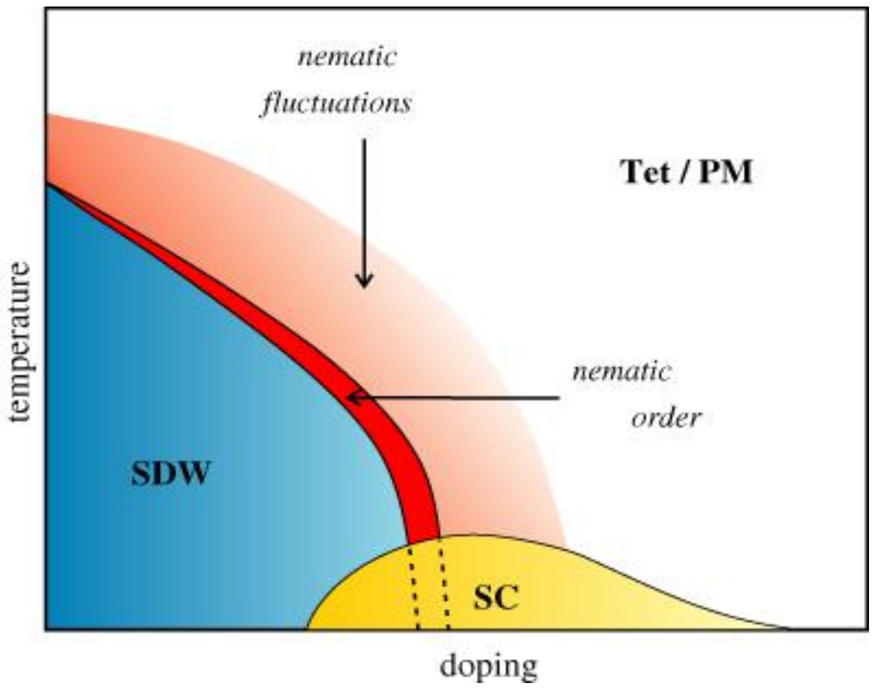
(Localization → delocalization crossover)

Criticality in Spin and Charge degrees of freedom

cuprates

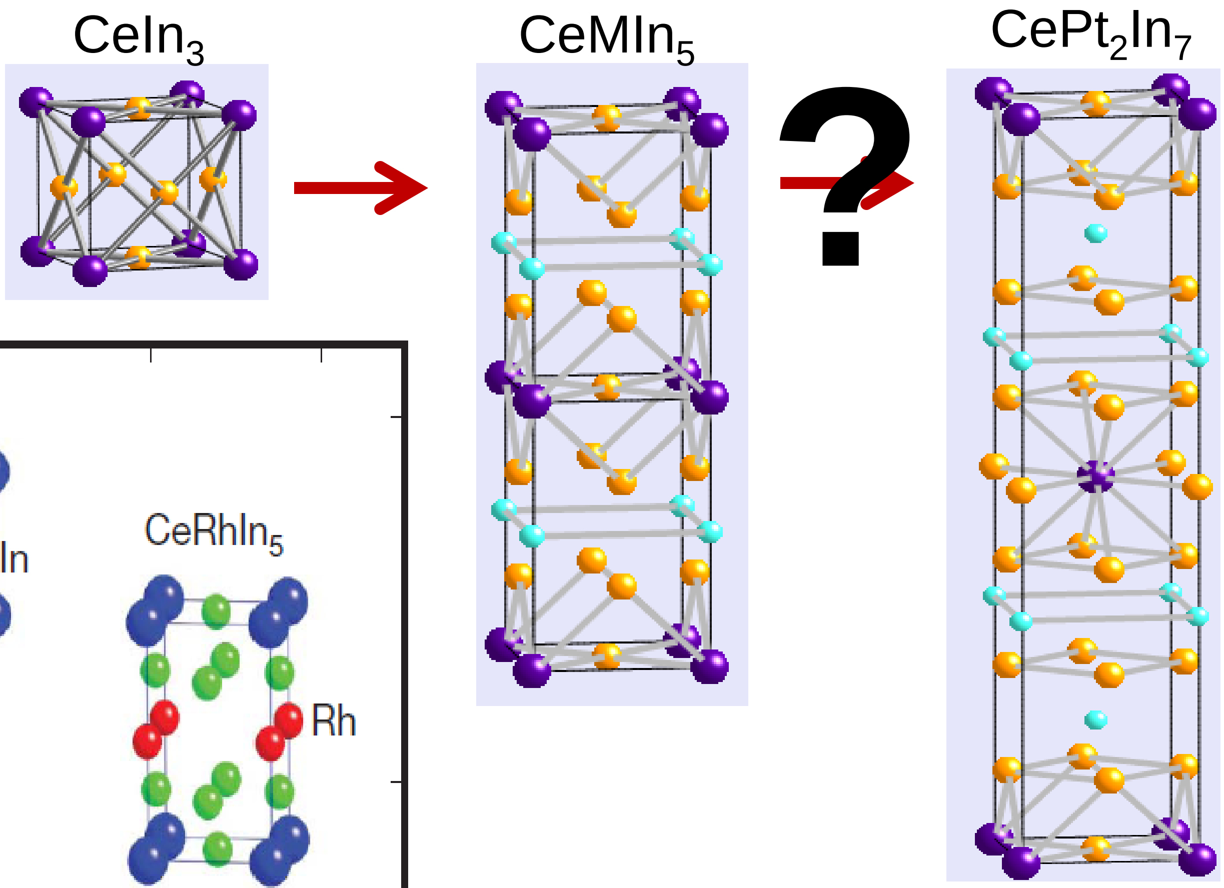


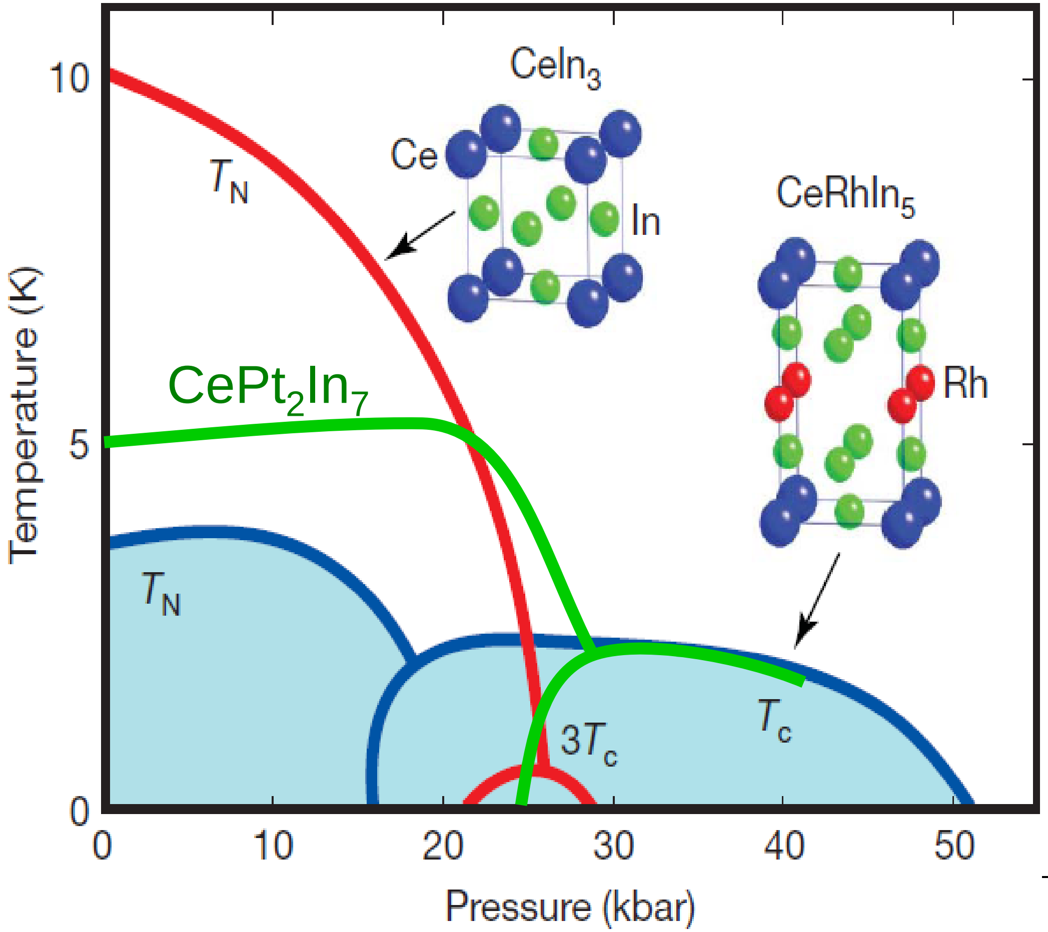
pnictides



FS ~ x ⟷ FS ~ 1-x

Dimensionality?



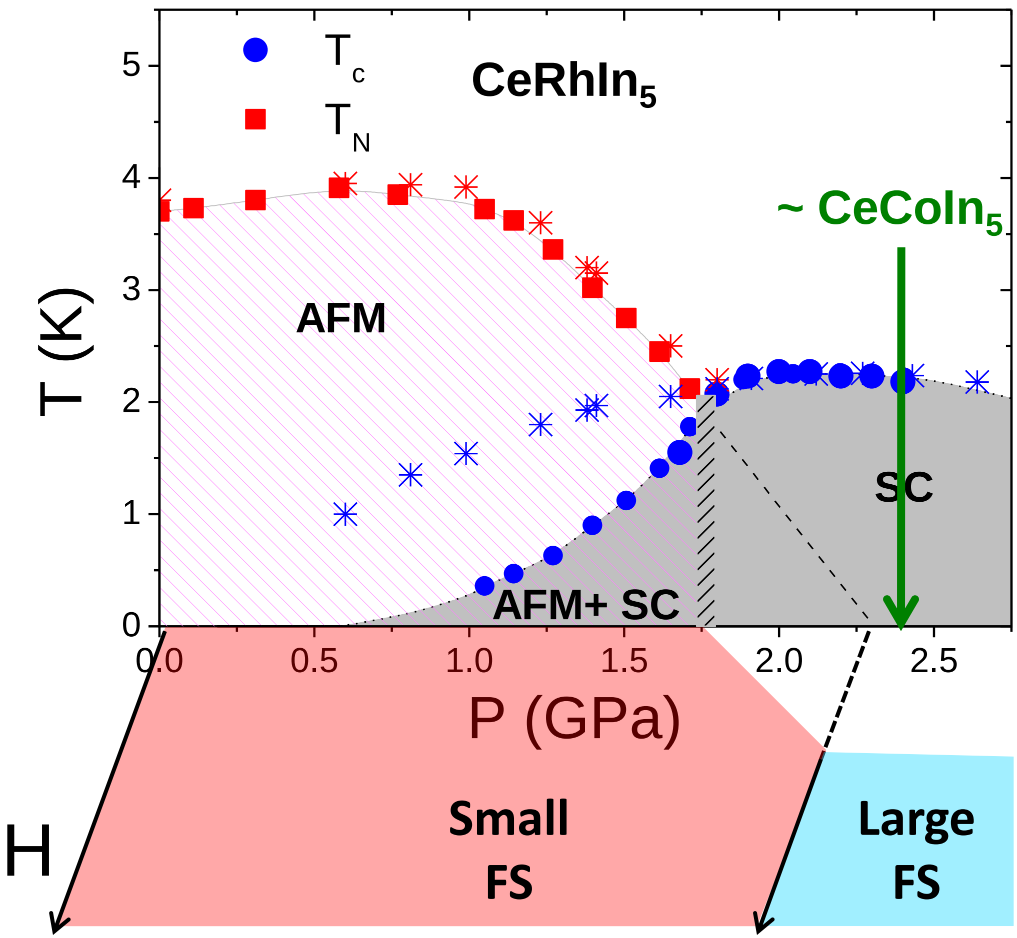


$CePt_2In_7$: A promising candidate

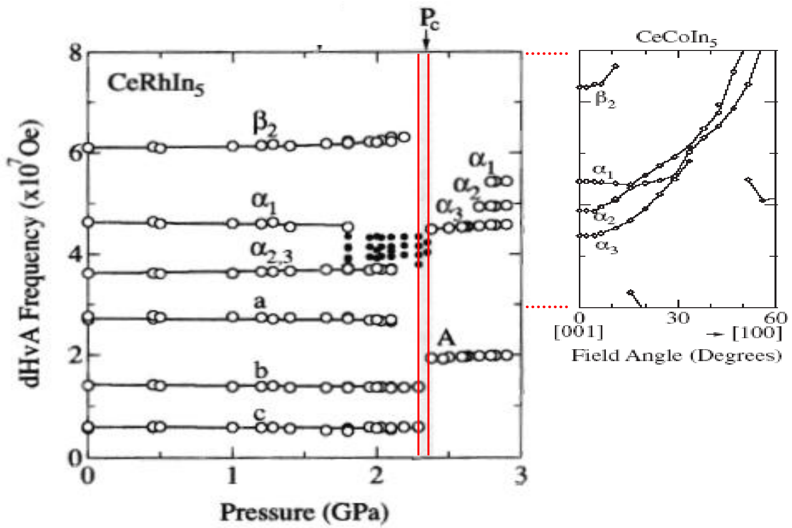
Superconducting!

But T_c not enhanced

Criticality in Spin and Charge degrees of freedom



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



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

At the QCP:

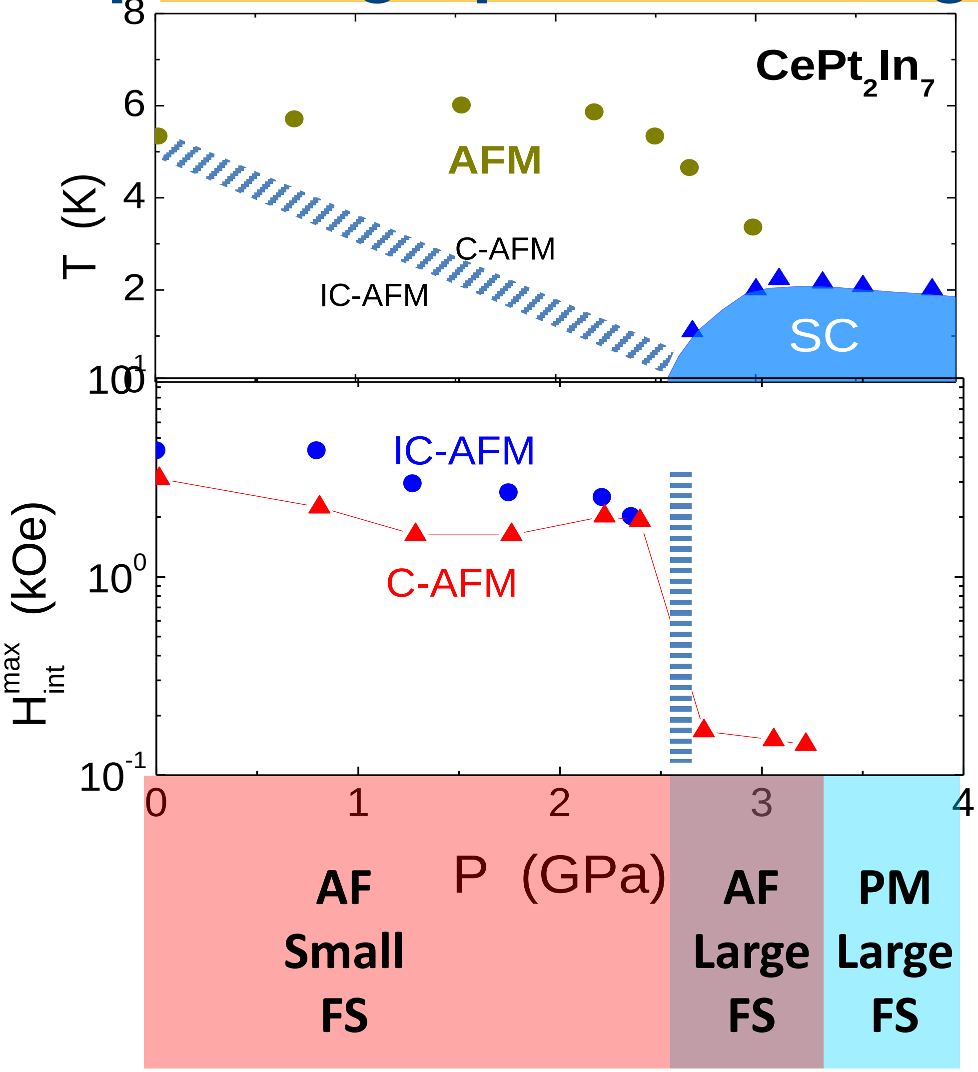
***Spin* has critical behavior**

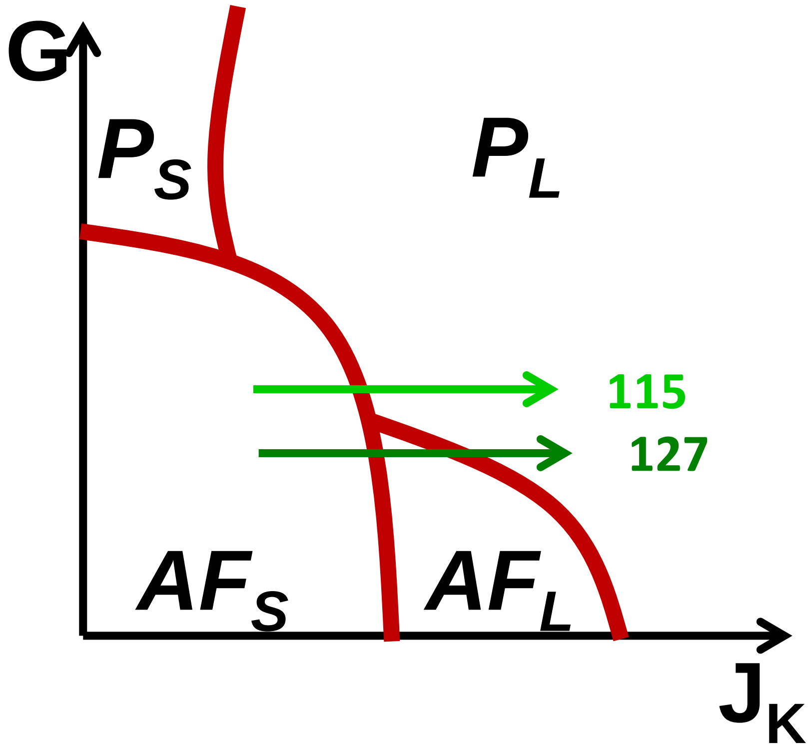
+

***Charge* has critical behavior**

Which instability is more important for SC?

Separating Spin and Charge Criticality in $CePt_2In_7$





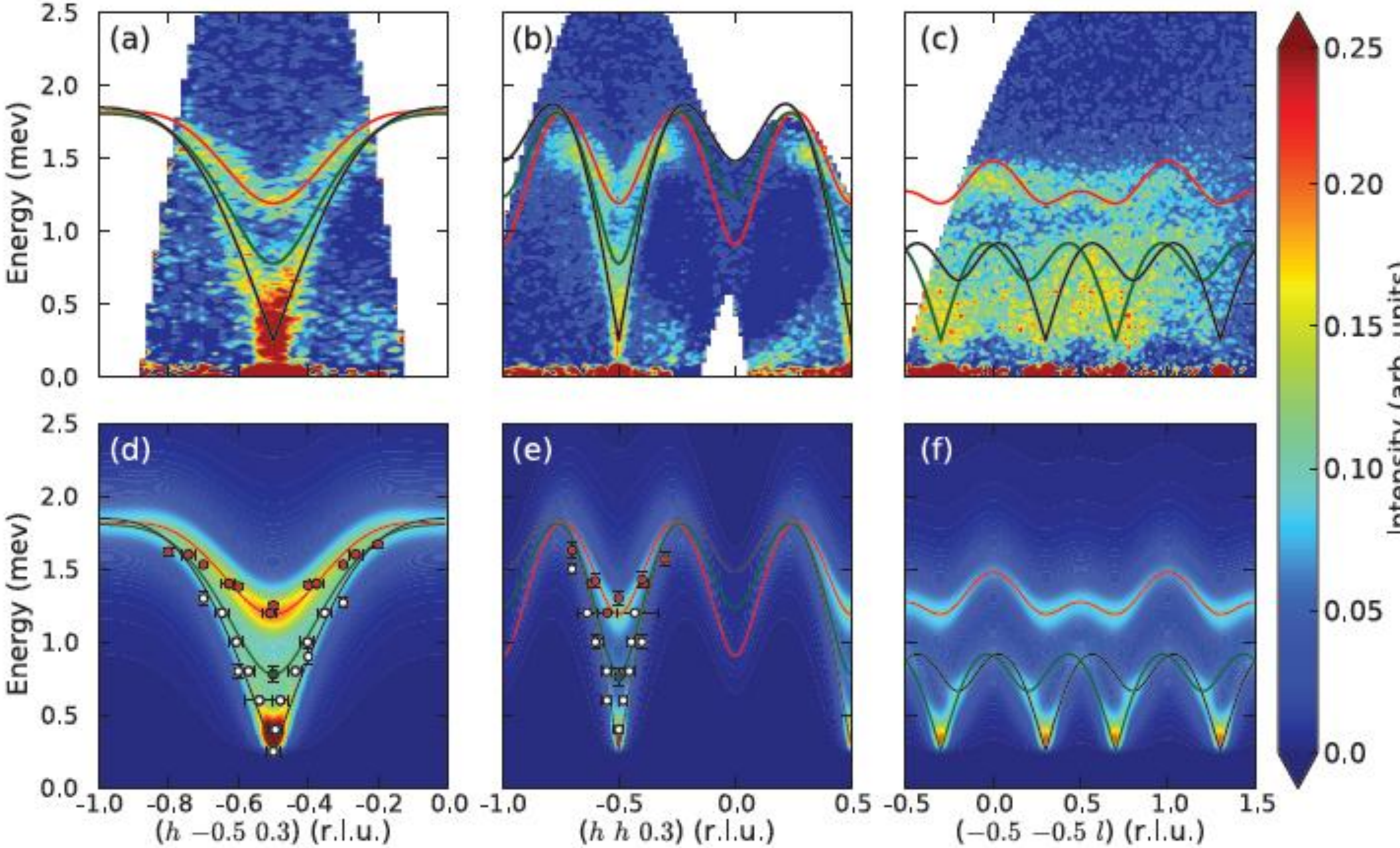
Q. Si, Phys. Status Solidi B 247, 476 (2010)

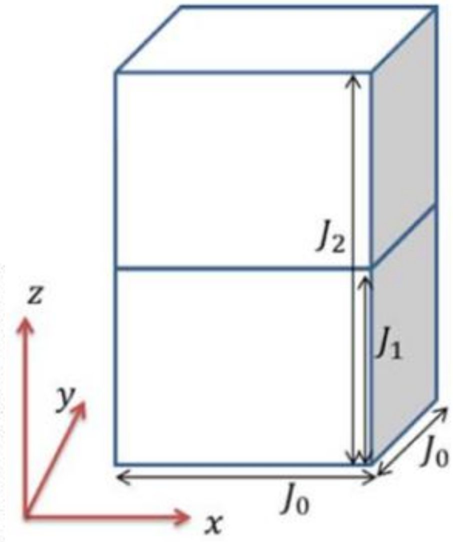
P. Coleman & A. Nevidomskyy, JLTP 161, 182 (2010)

H. Sakai, et al. PRL (2014)

Why would $CePt_2In_7$ have less "G" than $CeRhIn_5$?

Spin Waves in $CeRhIn_5$





J_0= 0.37 meV,
J_1 = 0.05 meV
J_2 = 0.809 J_1
Δ = 0.82

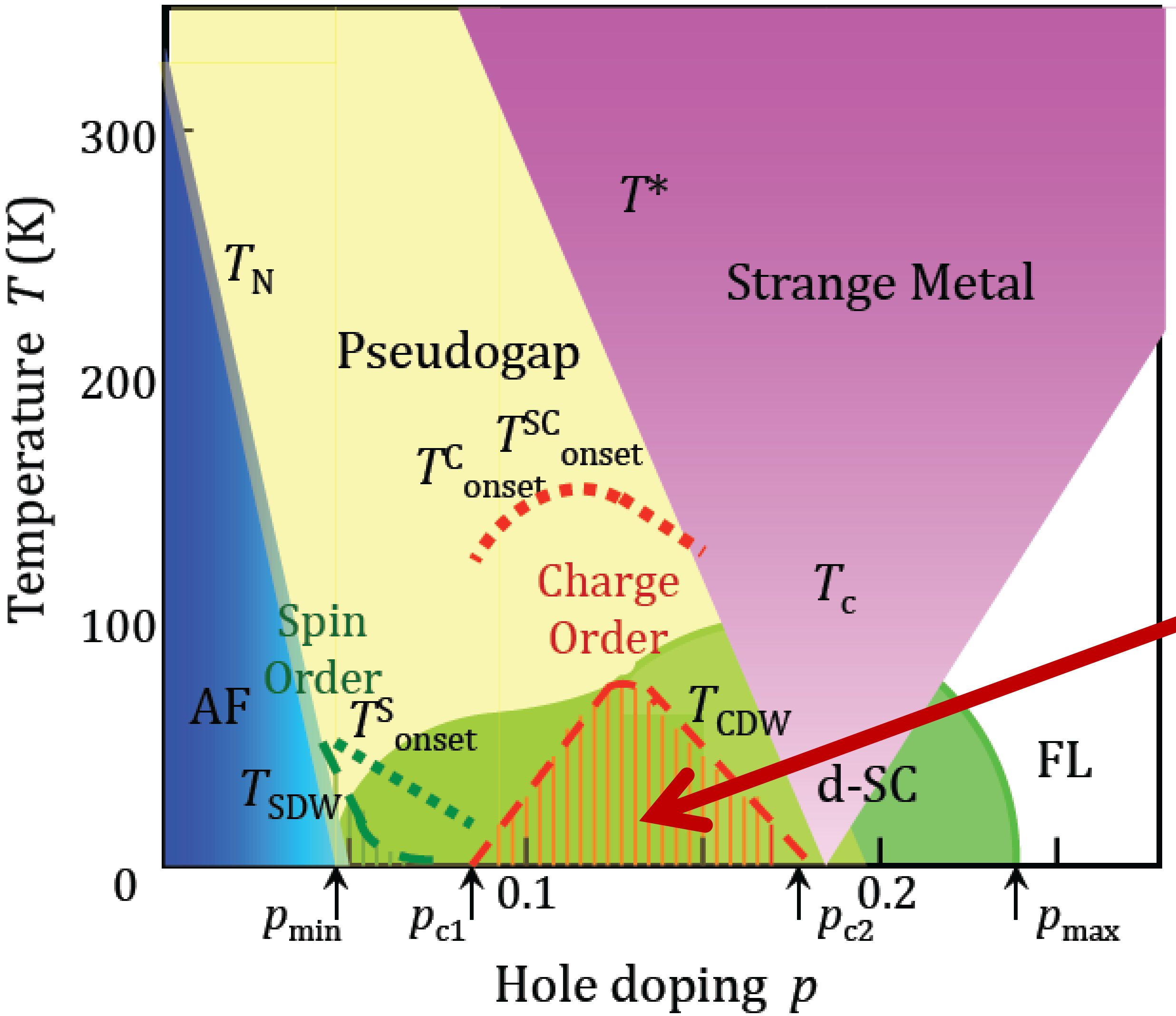
$$\mathcal{H} = \sum_{ij} \left[J_{ij} \left(n_i^x n_j^x + n_i^y n_j^y \right) + \Delta J_{ij} n_i^z n_j^z \right]$$

The existence of a spin gap, Δ_{sg} **= 0.25 meV**, is unexpected for the ordered **Q** = (½, ½, 0.297) moments.

Perhaps $CeRhIn_5$ is a more frustrated system than $CePt_2In_7$

P. Das, M. Janoschek, et al. ArXiv: 1408.6585

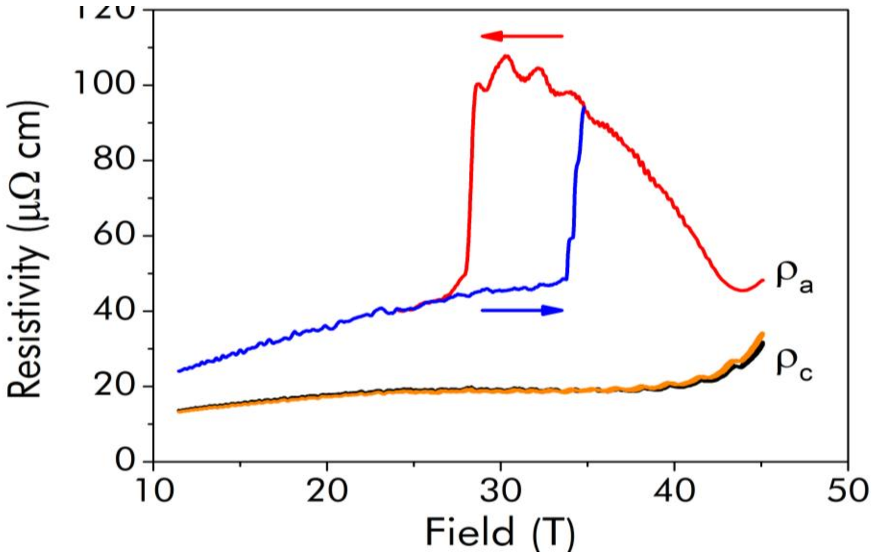
Competing Phases

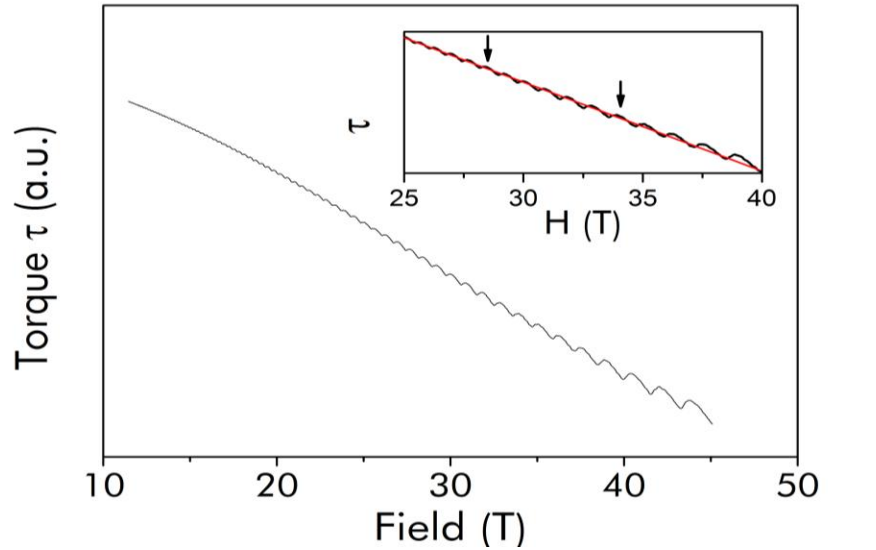


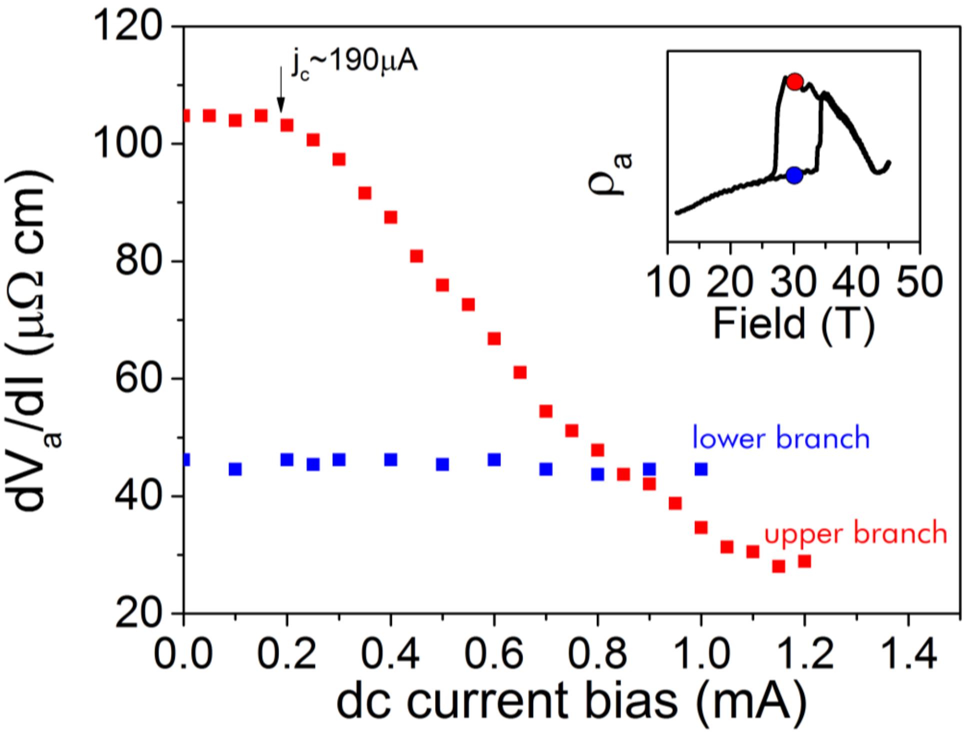
B. Keimer, et al.
ArXiv: 1409.4673

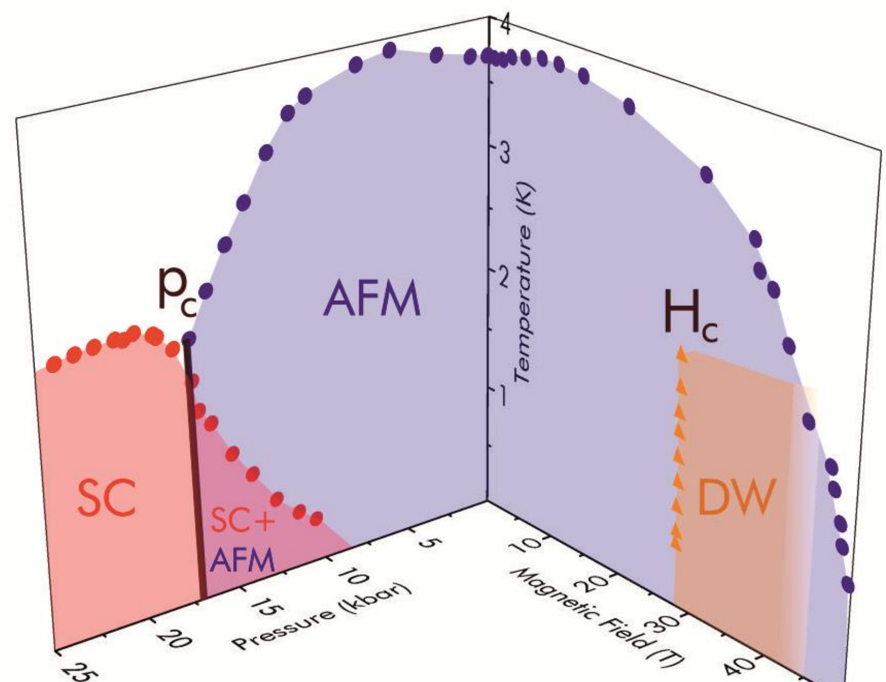
A field induced density wave

A field induced density wave in $CeRhIn_5$



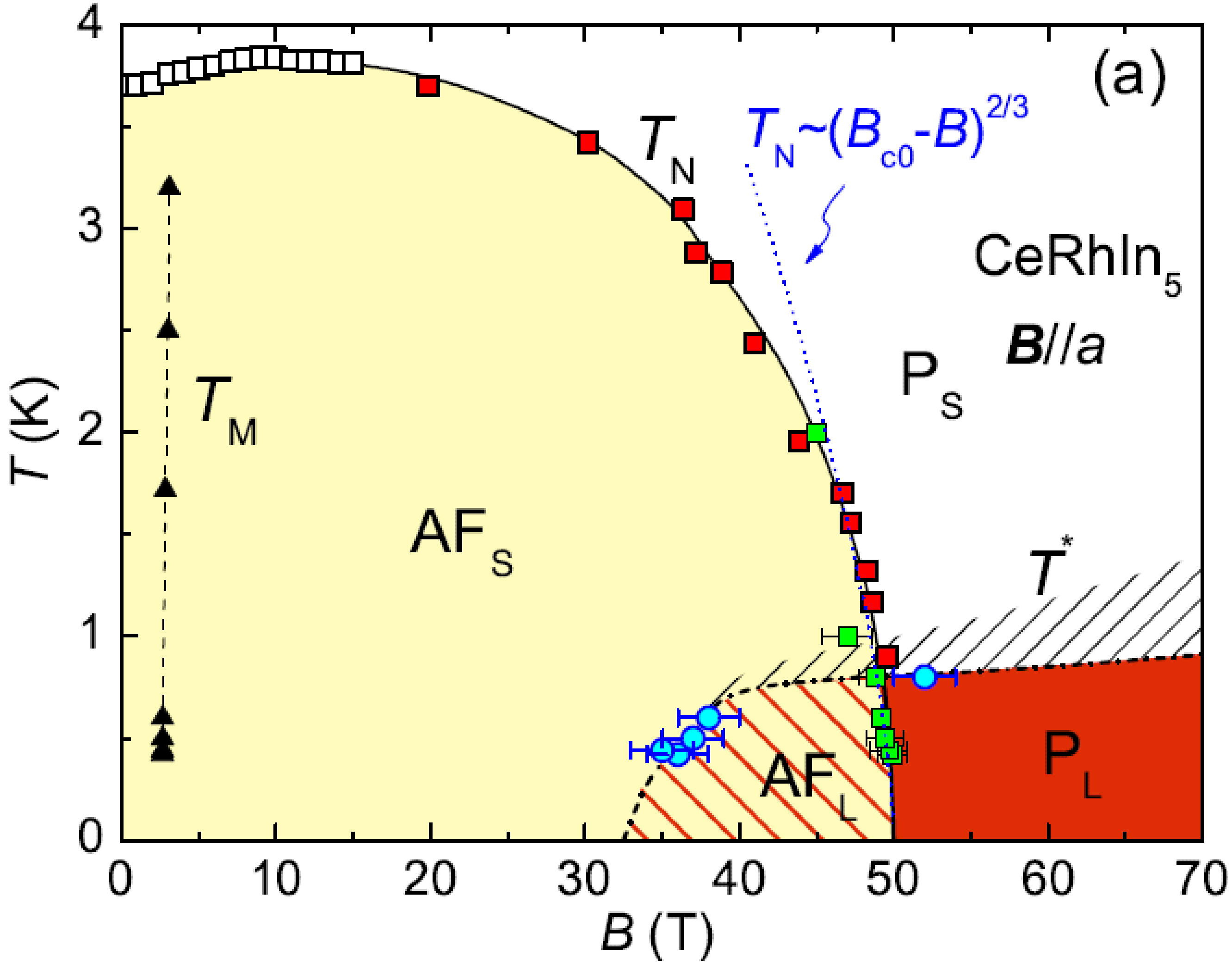






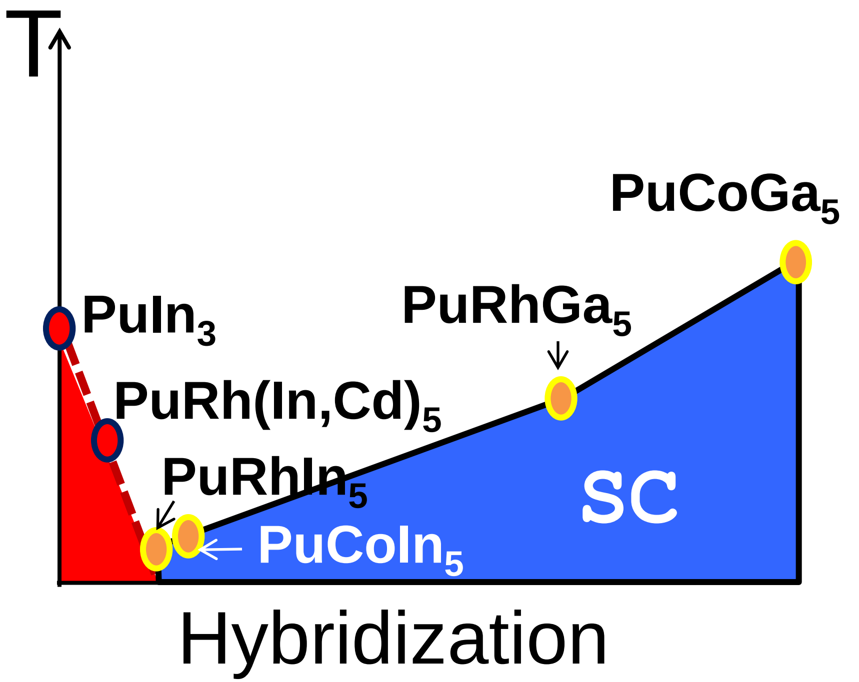
P. Moll, et al. unpublished

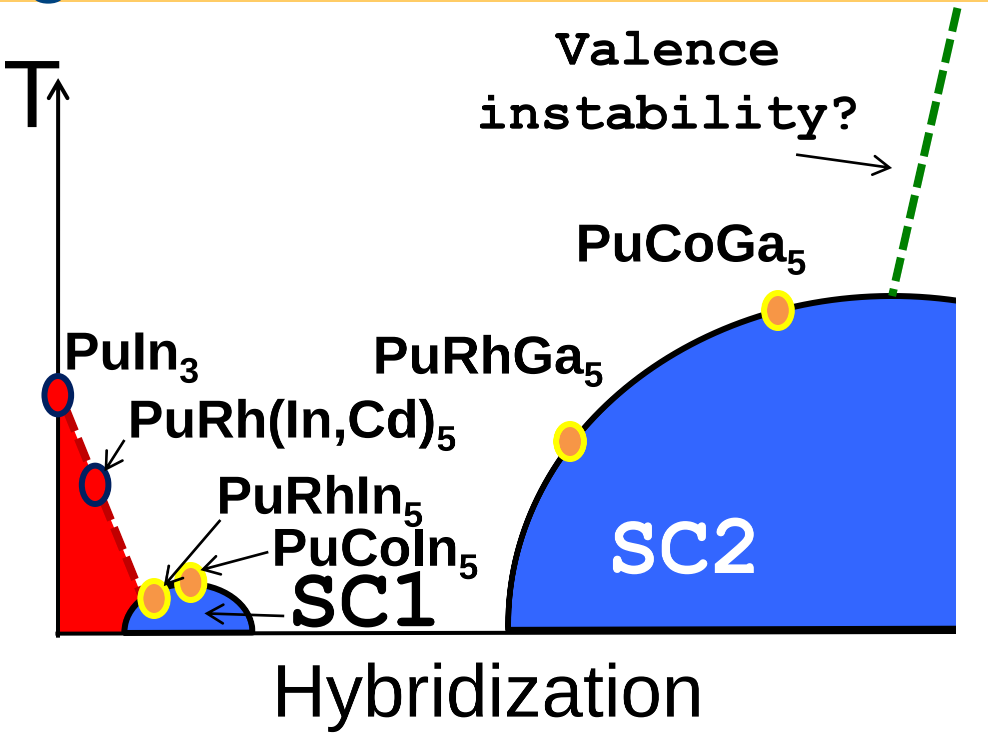
f-delocalization with field in $CeRhIn_5$



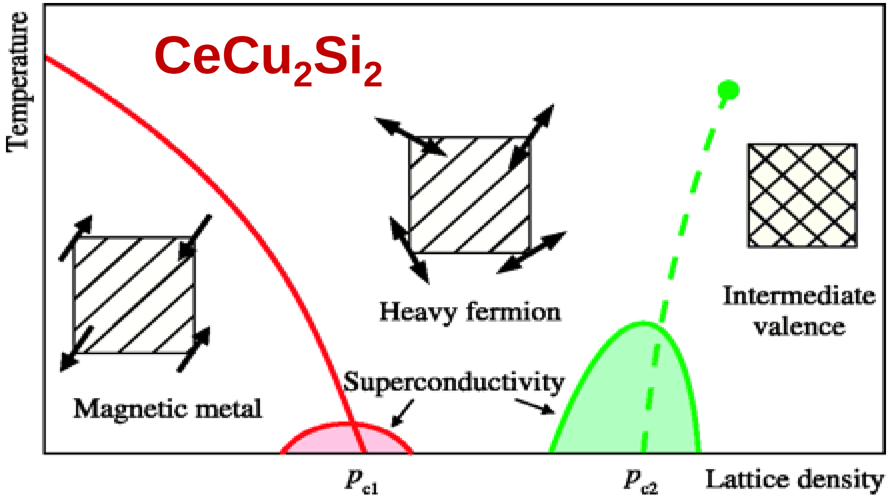
L. Jiao et al. ArXiv: 1308.0294

2 Alternative Phase Diagrams for Pu-based SC





E.D. Bauer, *et al*. JPCM (2012)

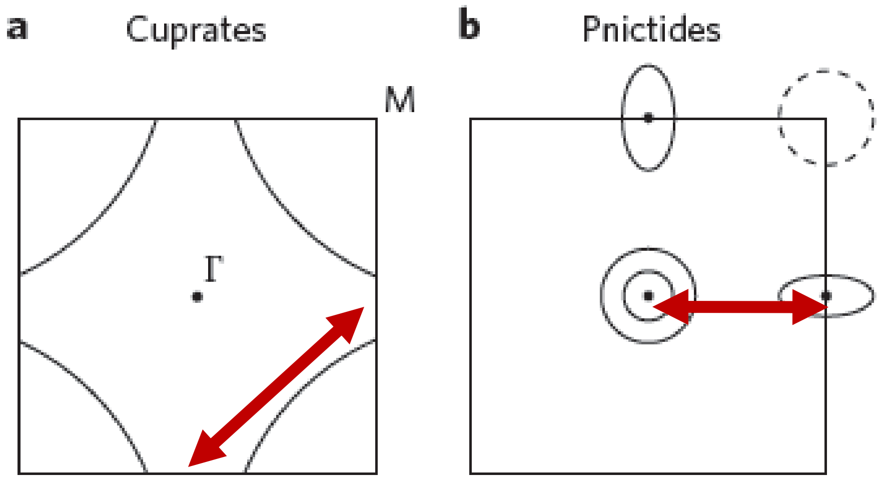


H. Yuan, *et al*. Science (2003)

A weak coupling perspective

Superconductivity occurs when pairing fluctuations ($\Gamma(q,\omega)$) match the charge susceptibility $X_Q(q,\omega)$. And we assume $\Gamma(q,\omega) \sim X_s(q,\omega)$

$$\Delta(\mathbf{k}) = -\sum_{\mathbf{k}'} \Gamma(\mathbf{k},\mathbf{k}') \frac{\Delta(\mathbf{k}')}{\sqrt{|\epsilon_{\mathbf{k}'}|^2 + |\Delta(\mathbf{k}')|^2}}$$



- Electronic structure determines energy scales and nesting properties of $X_Q(q,\omega)$: The overall energy scale $T_F \sim T_K$
- The magnetic structure $X_s(q,\omega)$ is determined by the RKKY interaction (indirectly determined by electronic structure);

Does a weak coupling perspective have additional challenges for heavy fermions?

Summary

- **Many similarities between superconductivity in heavy fermions, cuprates, and Fe-based superconductors.**

New "Matthias' rules" for unconventional SC's:

- **Proximity to AF good.**
- **Have large spin fluctuation energy scale.**
- **Charge fluctuations with AF fluctuations even better?**
  - **What is the source of multiple SC instabilities?**
- **Avoid pair breaking. How?**
  - **Pairing occurs at ~2 Δ; inhomogeneity.**
- **Layered tetragonal structures are good.**
- **???**

Accelerate design process with machine learning.