Competing States and Their Consequences in Heavy-Fermion Systems

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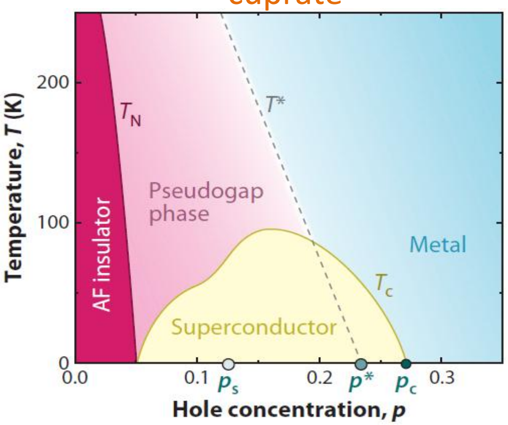
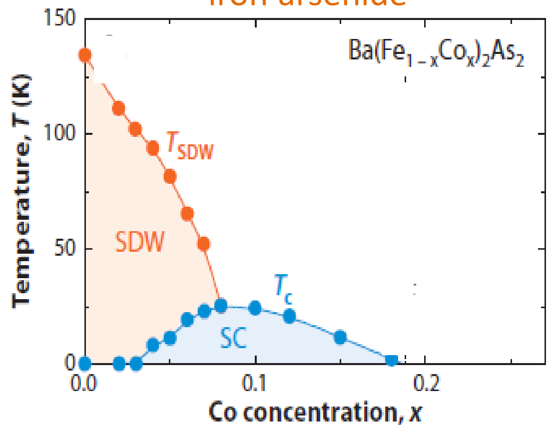
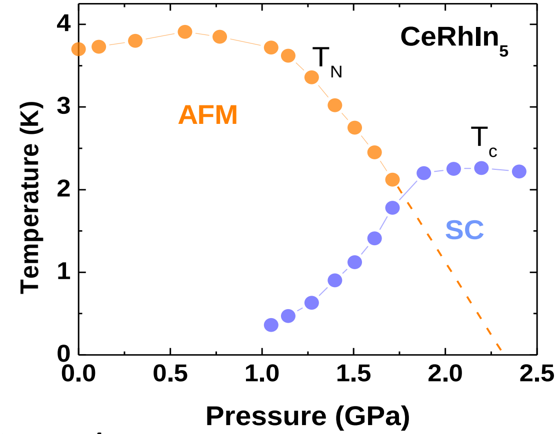
cuprate



iron arsenide



heavy fermion



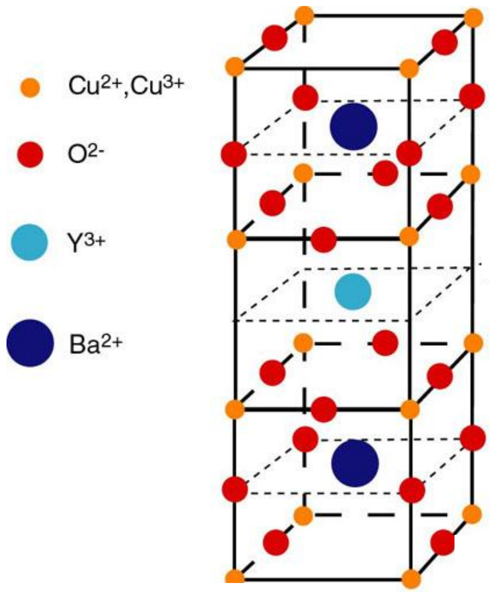
superconductivity in proximity to magnetic order

- Besides phase diagrams, are there other similarities among these classes of materials?
- If so, what are they and what is their relationship to nearby broken symmetries?

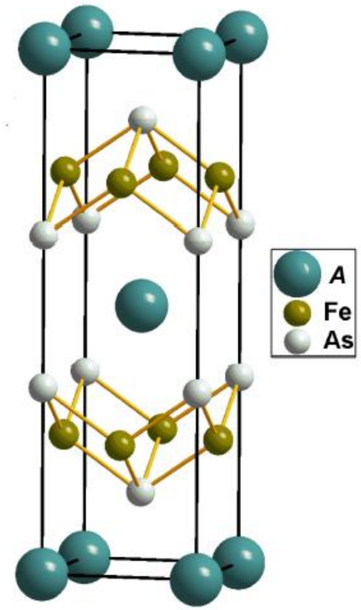
--- $CeRhIn_5$, $CeCoIn_5$ and $CeIrIn_5$ (the Ce115's)

crystal structures

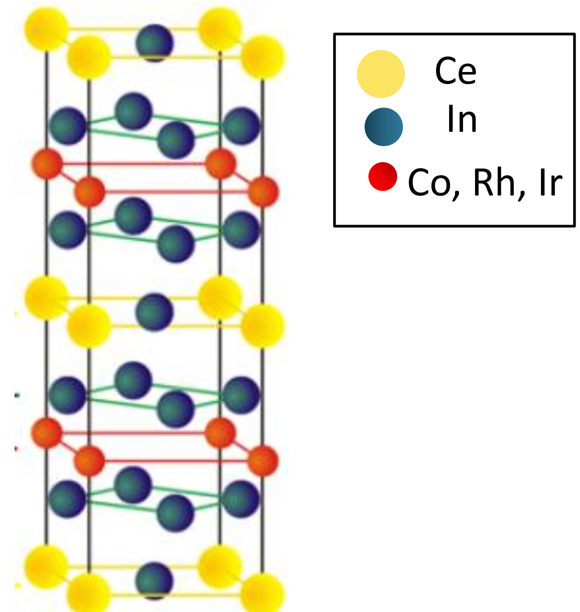
cuprate



iron arsenide

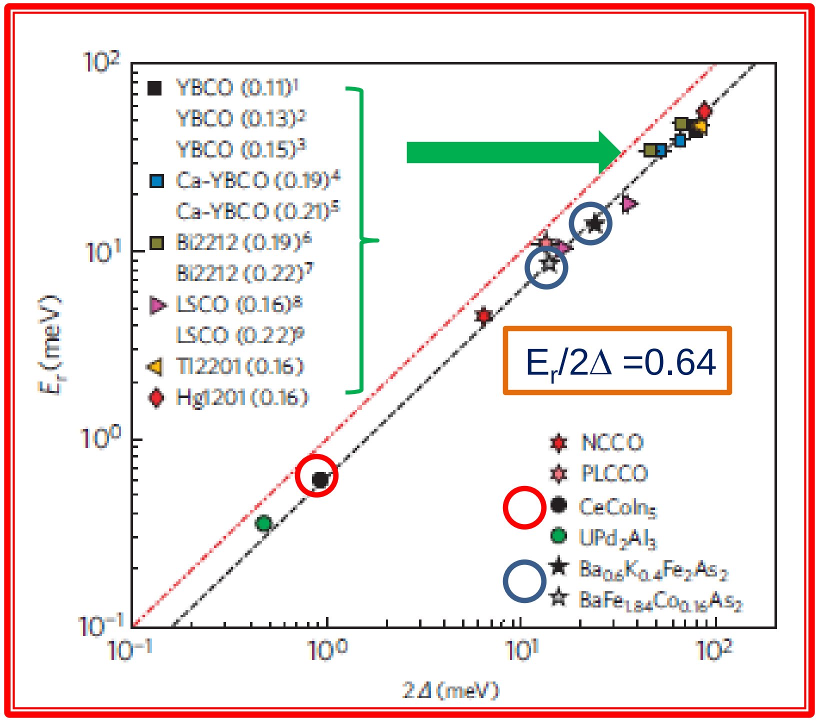


Ce115s



- all tetragonal, each with an active magnetic layer:
  - Cu-O layer in cuprates
  - Fe-As layer in iron arsenides
  - Ce-In layer in Ce115s

spin resonance

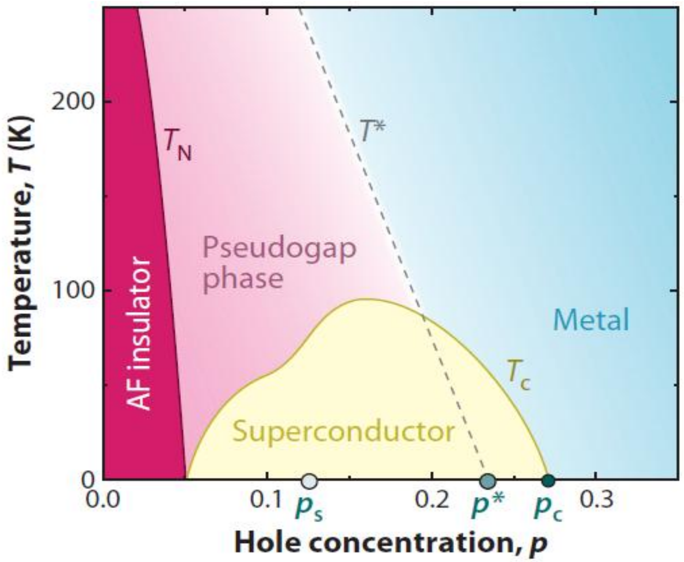


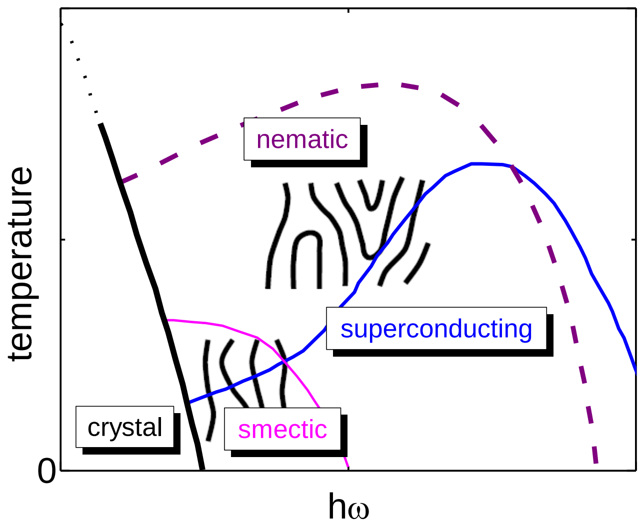
G. Yu et al., Nat. Phys. **5**, 873 (2009); similar conclusion by Y. Uemura Nat. Mat. **8**, 253 (2009)

- ratio of resonance energy E_r to 2Δ common to cuprates, iron arsenides, and heavy fermions

- statement about similarity in nodal gap symmetry and/or pairing mechanism? $d_{x^2-y^2}$ gap in cuprates and $CeCoIn_5$ (<u>all</u> Ce115s) but *d* or $s^{\pm}$ in Fe-arsenides

broken symmetries in the cuprates





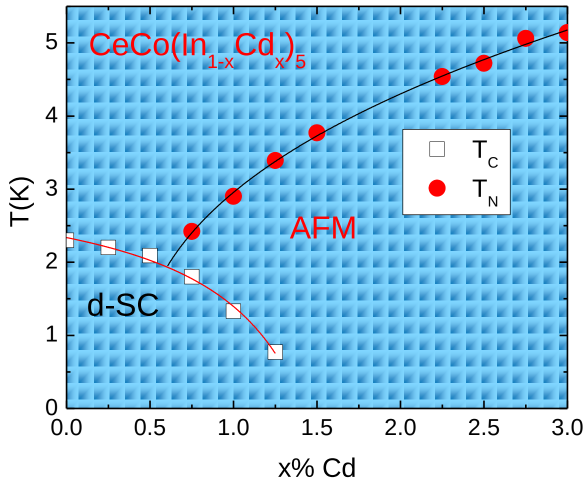
Kivelson, Fradkin, Emery, Nature **393**, 550 (1998)

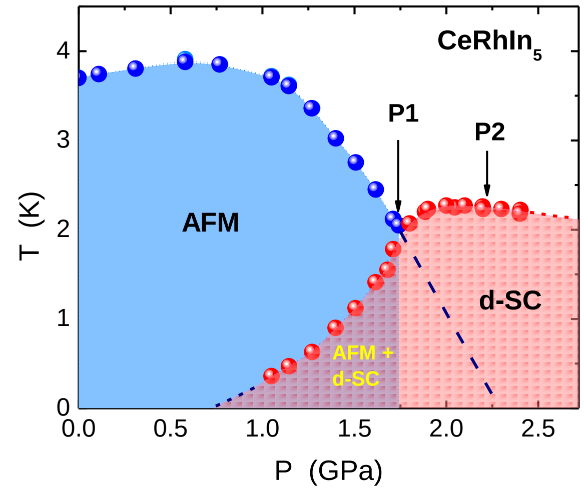
- pseudogap that encompasses much of the T-doping phase diagram above T_c:
  - d-density wave, orbital currents, preformed Cooper pairs, …? but known to break rotational symmetry of the lattice (electronic nematic state) (eg., Y. Ando et al., PRL **88**, 137005 (2002); V. Hinkov et al., Science **319**, 597 (2008), R. Daou et al., Nature **463**, 519 (2010))
- for T ~T*/2 and for doping near 1/8, emergence of incommensurate composite spin and/or charge density waves $\Rightarrow$ stripes, which break rotational and translational symmetry (electronic smectic state) (eg., M. Tranquada et al., Nature **429**, 534 (2004), P. Abbamonte et al., Nat. Phys. **1**, 155 (2005))

- theoretical suggestion: transverse zero-point fluctuations of magnitude hω 'melt' stripes to form electronic nematic, which may be conducive to *d*-SC
- extension of smectic and nematic phase boundaries into SC phase $\Rightarrow$ possibility of their real-space electronic texture being reflected in SC transition

Evidence for these broken symmetries in Ce115s?

Cd-doped $CeCoIn_5$



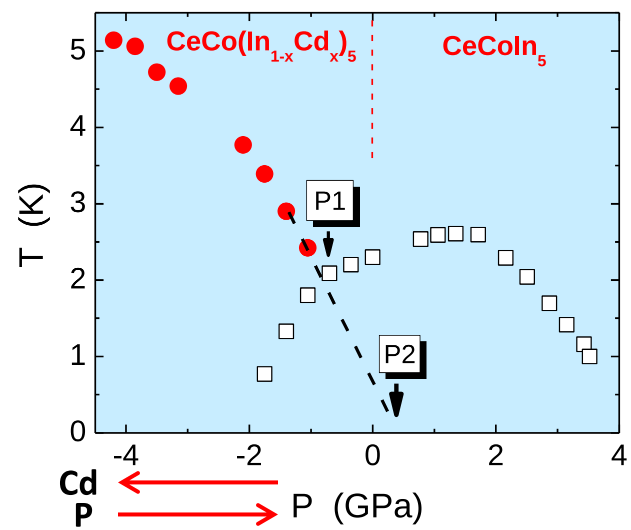


♦ large-moment commensurate AFM order induced by very dilute Cd substitution for In in $CeCoIn_5$ (L. Pham et al., PRL **97**, 056404 (2006); M. Nicklas et al, PRB **76**, 052401 (2007))

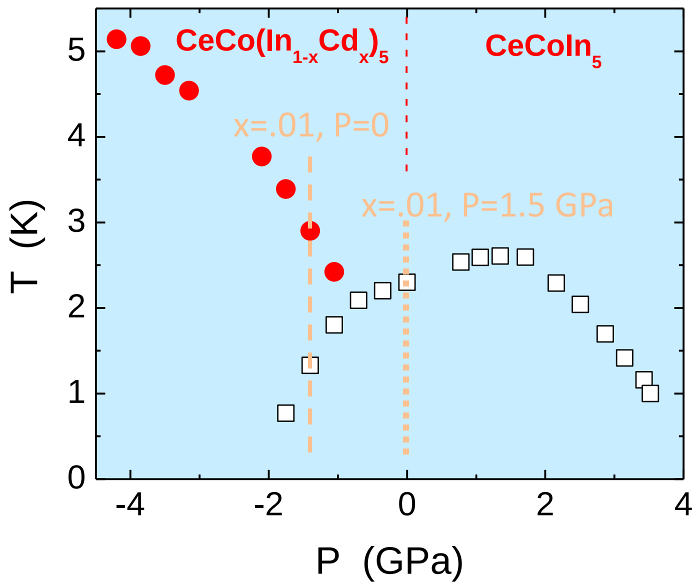
♦ for 0.007 < x < 0.0125 , microscopic coexistence of AFM and *d*-SC from NMR (R. R. Urbano et al., PRL **99**, 146402 (2007) and neutron diffraction, with $\xi_{AFM} \sim 3\xi_{GL}$ (S. Nair et al., PNAS **107**, 9537 (2010))

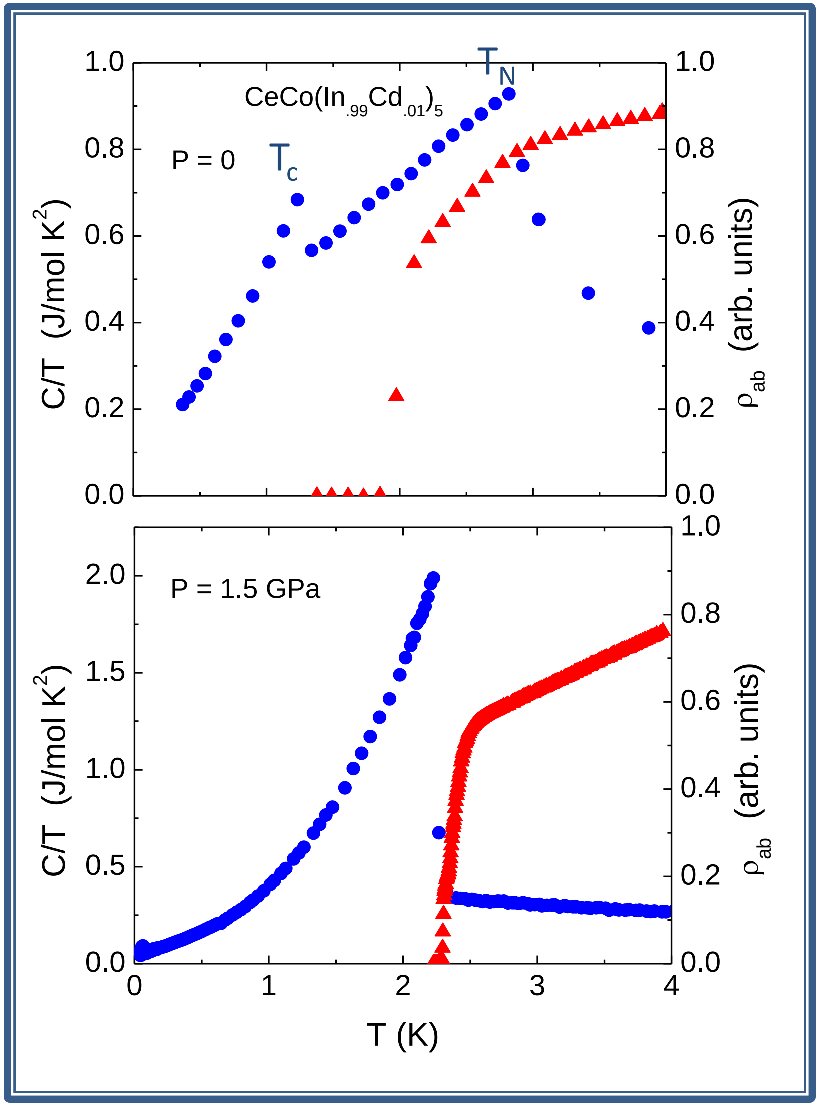
♦ acts as an effective negative pressure, creating a T-doping phase diagram that almost mirrors the T-P diagram for $CeRhIn_5$

♦ when combined with applied pressure, T-P diagram for Cd-doped and pure $CeCoIn_5$ similar to $CeRhIn_5$



bulk and resistive superconducting transitions



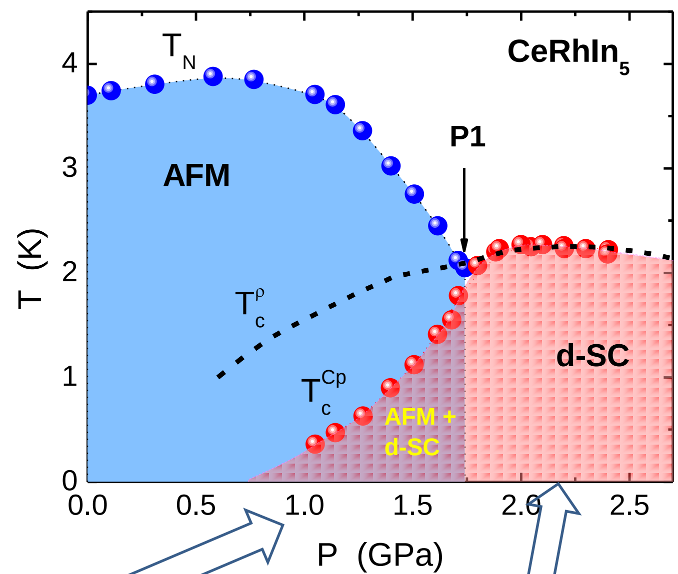


- at x=0.01 and P=0, $T_N > T_c$; $\rho \rightarrow 0$ well above the bulk T_c
- for same crystal at P=1.5 GPa, where evidence for magnetic order is absent, $\rho \rightarrow 0$ at the bulk T_c
- not an artifact of chemical disorder (pressure does not remove impurity scattering)

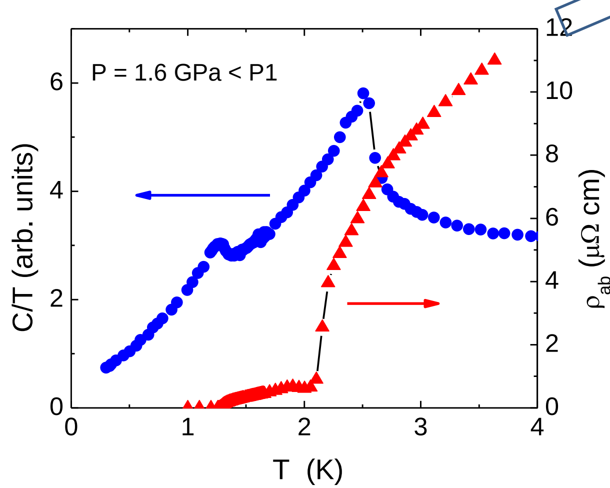
⇒ an intrinsic effect due to coexisting *commensurate* (½, ½, ½) antiferromagnetism

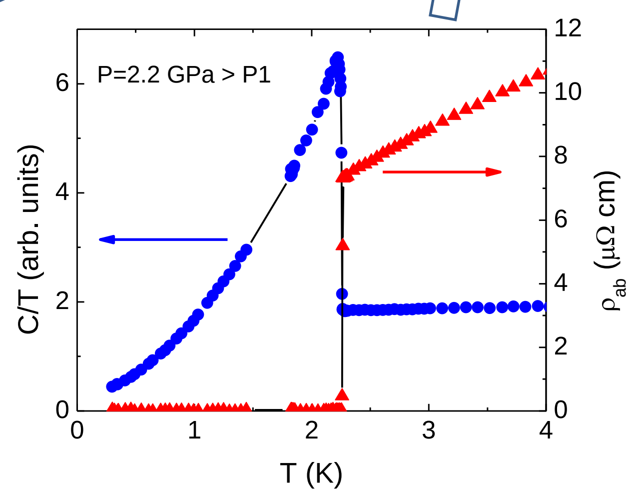
$CeRhIn_5$

- ♦ for P < P1, microscopic, homogeneous coexistence of incommensurate (½, ½, δ) AFM order and *d*-wave superconductivity (T. Mito et al., PRL **90**, 077004 (2003))
- ♦ pronounced difference between initial sharp drop in ρ_{ab} toward zero and bulk T_c from specific heat, with difference decreasing as P → P1 (G. Knebel et al., JPCM **16**, 8905 (2004))
- ♦ above P1, eg 2.2 GPa, where AFM is absent, in-plane resistive and bulk T_c coincide



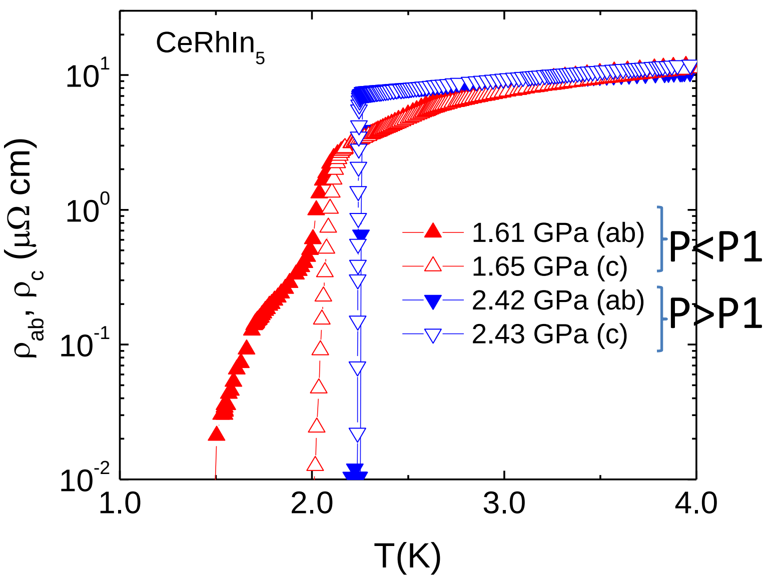
- ♦ at, eg. 1.6 GPa < P1, drop in ρ_{ab} followed by a 'tail' that reaches zero at T_c

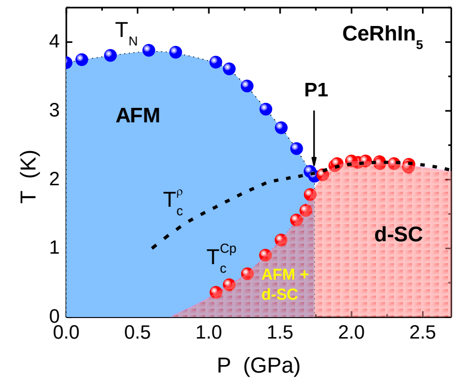




- ♦ reproducible with 10^3 change in measuring current ⇒ an intrinsic response to coexisting antiferromagnetism in these very pure single crystals, *irrespective* of commensurate (Cd-doped $CeCoIn_5$) or incommensurate order ($CeRhIn_5$) T. Park et al., PRL (in press)

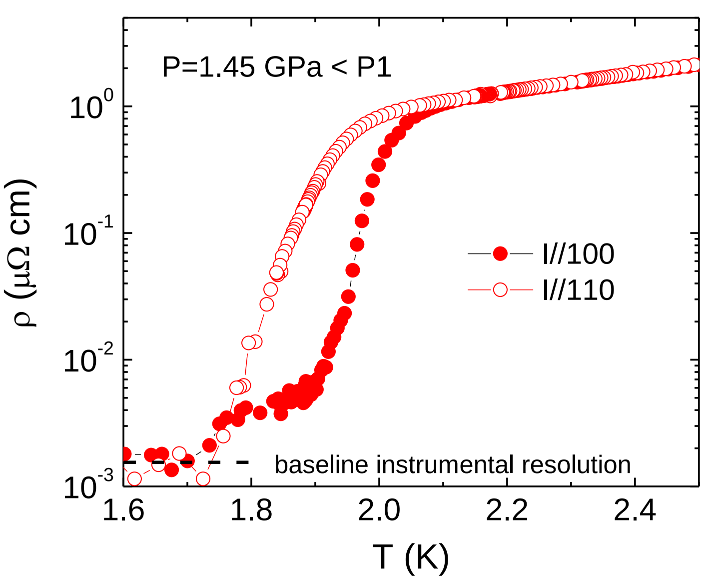
anisotropy in the resistive transition





◆ in coexistence region, 'tail' in ρ_{ab} but ρ_c // [001] drops sharply to zero well above bulk $T_c \Rightarrow$ some form of textured superconductivity

◆ above P1, ρ_{ab} and $\rho_c \rightarrow 0$ at same temperature

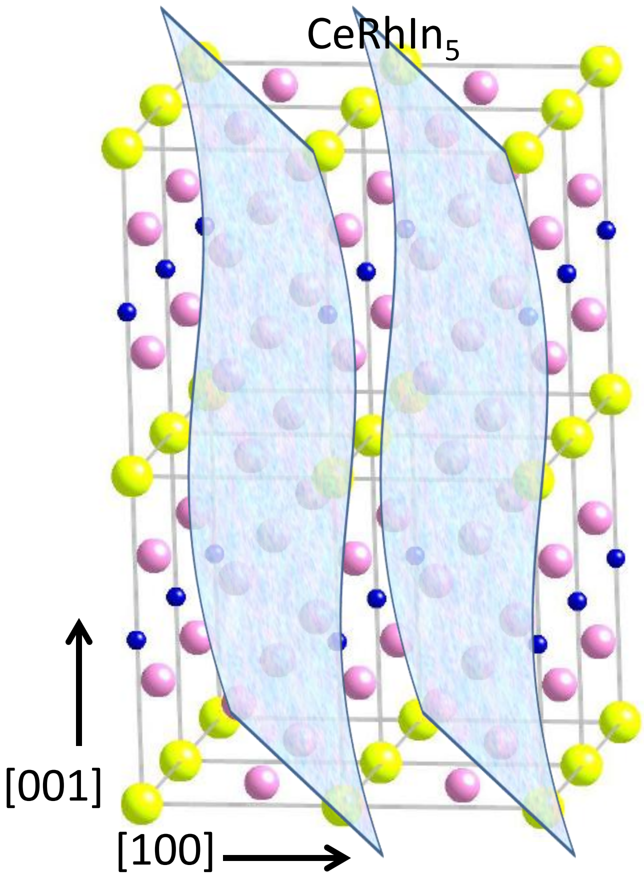


T. Park et al., PRL (in press)

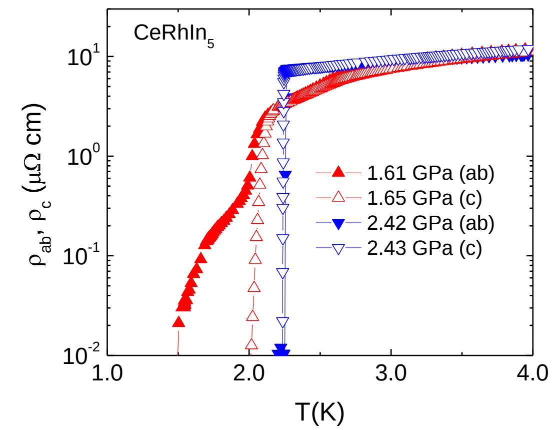
◆ in-plane symmetry breaking in the coexistence region:

- drop in ρ // [100] at a higher temperature than ρ // [110], which does not have a 'tail'
- not due to a structural distortion from crystal's tetragonal symmetry (Aso et al., JPSJ **78**, 073703 (2009))
- difference between ρ // [110] and ρ // [100] approaches zero as P→ P1

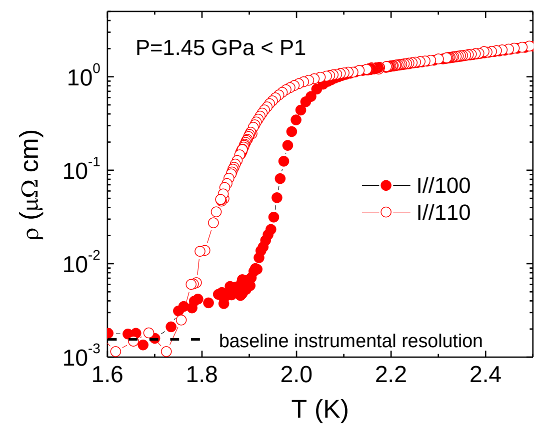
physical picture of anisotropy



◆ for $T>T_c$, formation of (probably 'patchy') lamellae that allows a zero-resistance path from one side of crystal to the other for current flow parallel to [001]

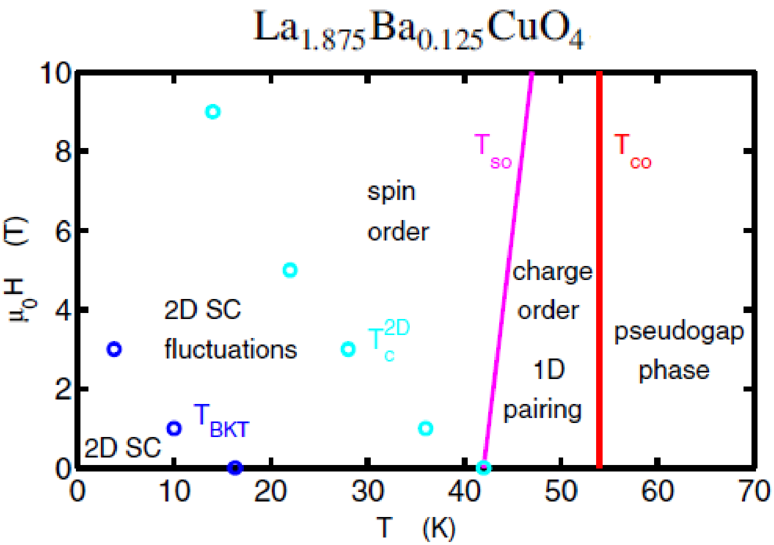


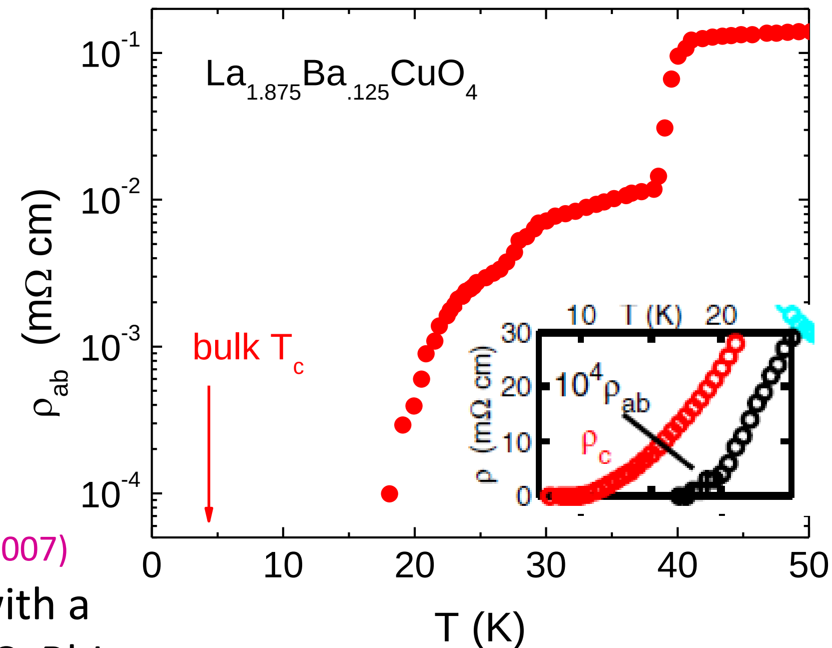
◆ at lower T, but still > T_c, Josephson coupling between patchy lamellae forms a superconducting network along [100] and [110], with eventual bulk phase coherence at T_c



◆ broken rotational symmetry ⇒ smectic- or nematic-like network of textured superconductivity

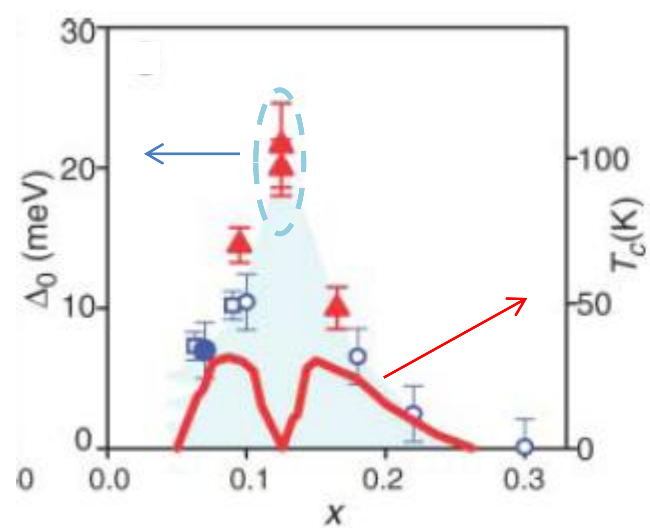
comparison to Ba-doped La_2CuO_4





Q. Li et al., PRL **99**, 067001 (2007)

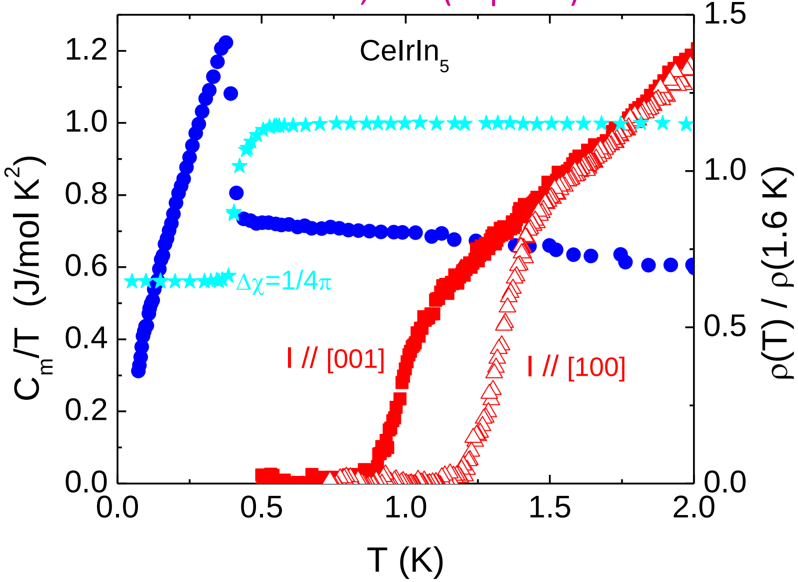
- resistive transition far above bulk T_c and with a temperature dependence similar to $\rho_{[100]}$ in $CeRhIn_5$
- temperature for transition in $\rho_{[001]} < \rho_{ab}$
- interpreted as phase-fluctuating 2D superconductivity with maximum antinodal gap but much reduced T_c because of static stripes, which compete with SC -- at least at 1/8 doping in this material
- also evidence for a pseudogap in $CeRhIn_5$ below P1 (T. Mito et al., PRL **90**, 077004 (2003)); direct connection to texture not possible but suggestive



T. Valla et al. Science **314**, 1914 (2006)

$CeIrIn_5$

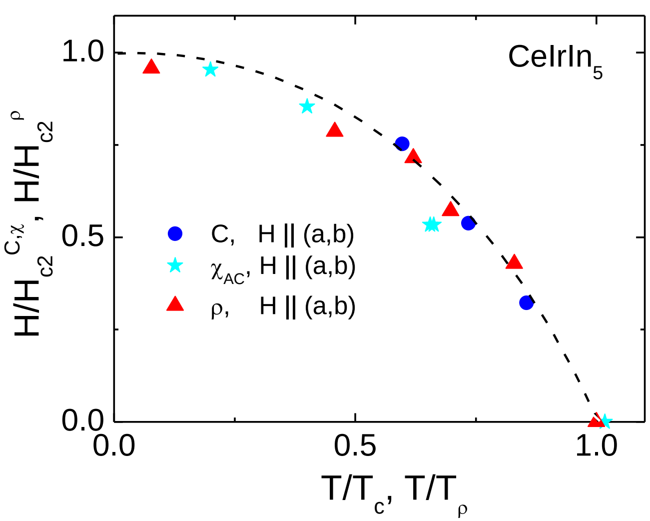
T. Park et al., PRL (in press)



◆ bulk T_c at 0.4 K but $\rho \rightarrow 0$ at $T \approx$ 1K or higher

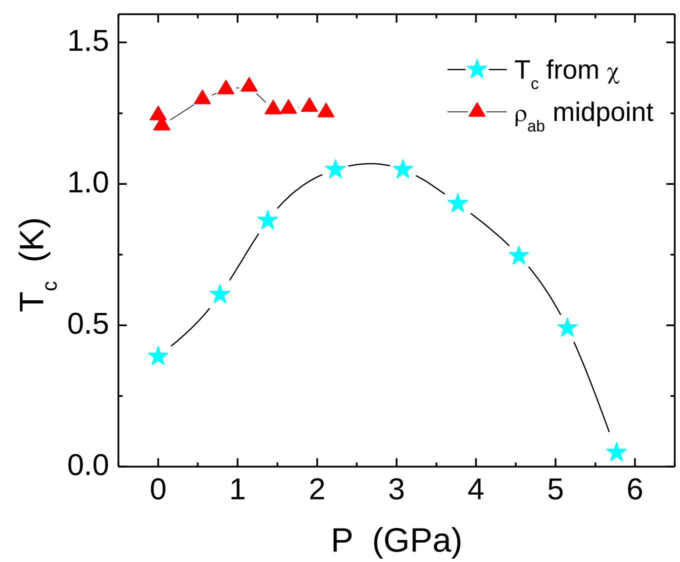
◆ counter to $CeRhIn_5$, zero resistance state at a higher temperature for I//[100] vs I //[001] but like Ba-doped $La_2CuO_4 \Rightarrow$ textured SC

◆ scaling of field dependence of T_c from bulk and resistive measurements $\Rightarrow$ same Cooper pairs at both transitions

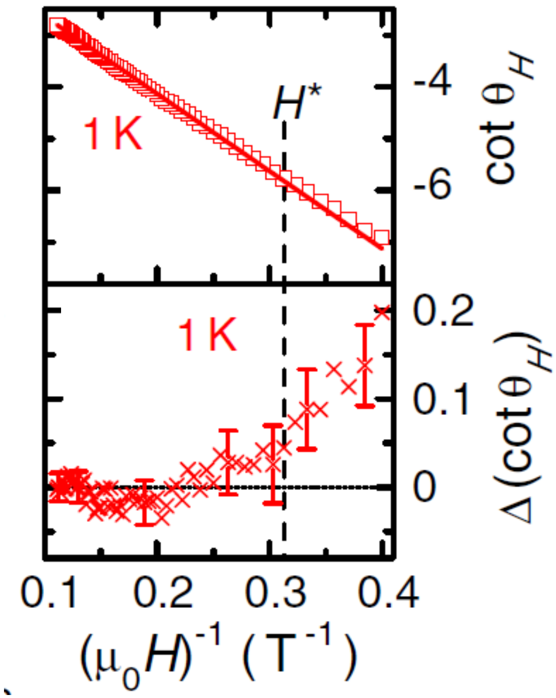


C. Petrovic et al., Europhys. Lett. **53**, 354 (2001)

◆ no obvious phase transition except *d*-SC, but non-monotonic $T_c(P) \Rightarrow$ some coexisting phase competing with SC?



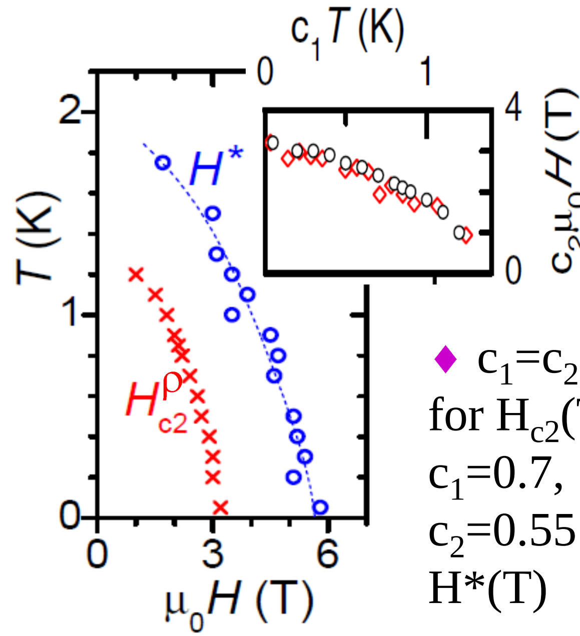
precursor state in $CeIrIn_5$



♦ deviation from $\cot\theta_H \propto 1/H \Rightarrow$ decrease in Hall mobility below H*(T)

S. Nair et al. PRL **100**, 137003 (2008)

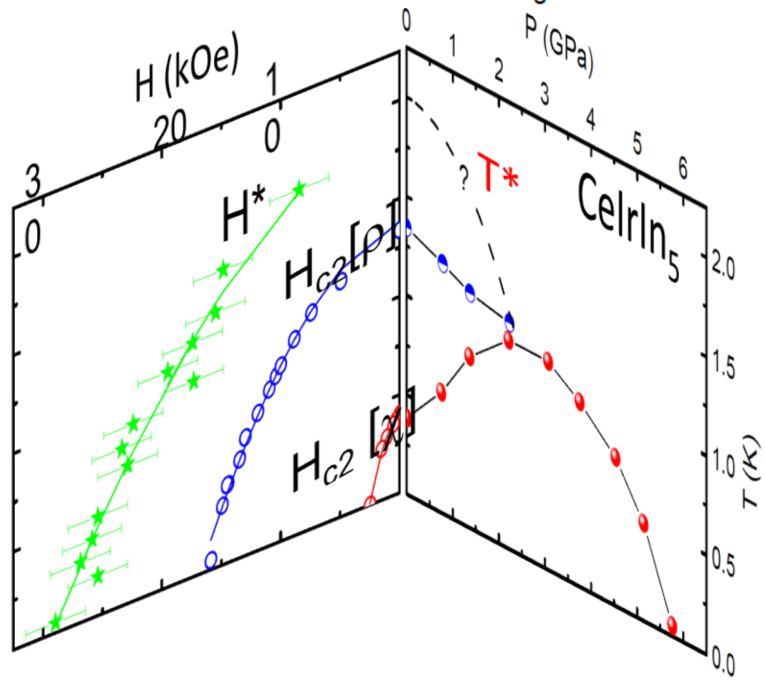
♦ scaling H*(T) onto H_{c2}(T) $\Rightarrow$ superconductivity and H* related



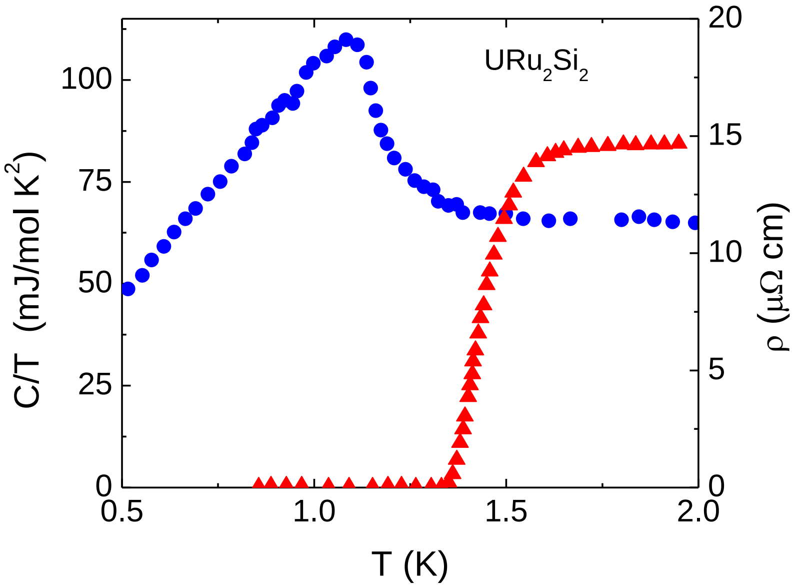
♦ $c_1=c_2=1$ for H_{c2}(T); $c_1=0.7$, $c_2=0.55$ for H*(T)

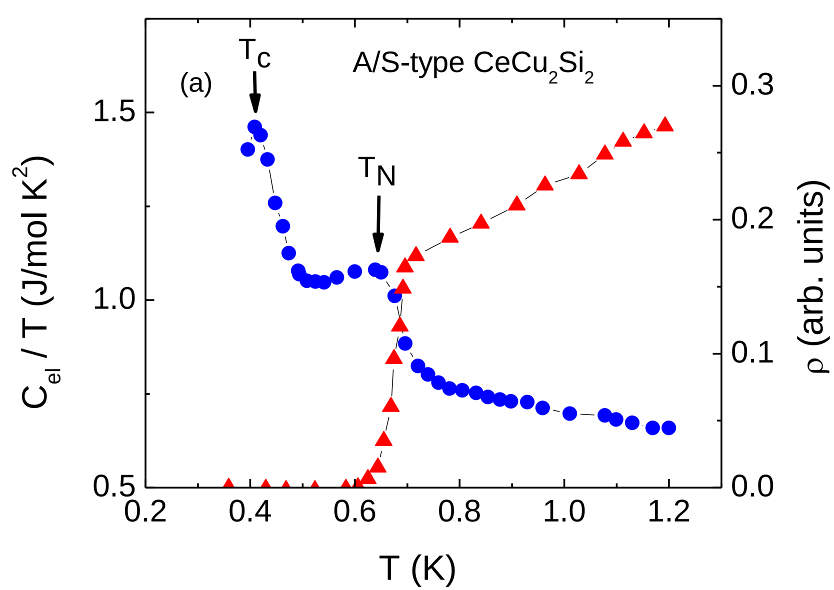
♦ not a phase transition but a pseudogap-like electronic state that appears at zero field near 2 K

♦ speculate that the pseudogap-like phase is the origin of superconducting texture in $CeIrIn_5$



Ce115s not alone

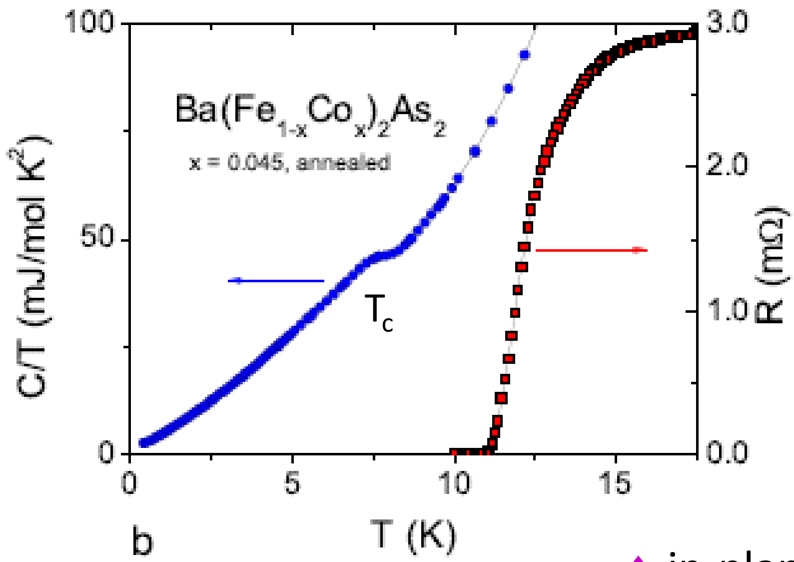




- nematic hidden order state below 17.5 K that breaks rotational symmetry (R. Okazaki et al., Science **331**, 429 (2011))
- resistive transition invariably at a temperature higher than bulk T_c (E. Hassinger et al., PRB **77**, 115117 (2008))

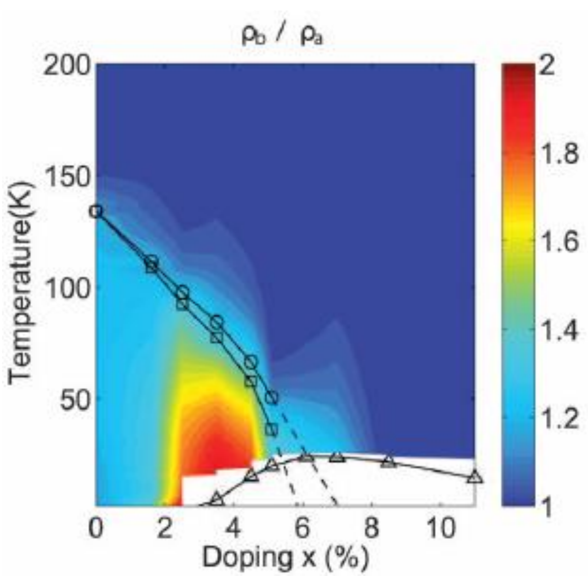
- A/S-type crystals, T_c below weak incommensurate spin-density wave transition
- resistive transition much above T_c (E. Lengyel, PhD thesis, Tech. Univ. Dresden, (2007))

iron–asenides

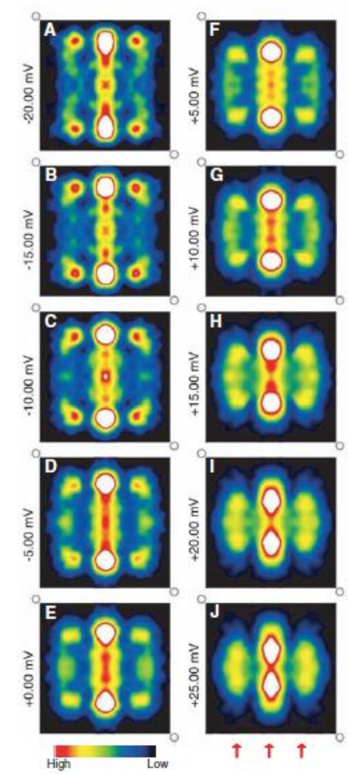


♦ difference between resistive and bulk T_c when rotational-symmetry is spontaneously broken in Co-doped $BaFe_2As_2$ and $CaFe_2As_2$

♦ in-plane resistive anisotropy in de-twinned Co-doped $BaFe_2As_2$ (J-H. Chu et al., Science **329**, 824 (2010)) -- not due to orthorhombic distortion ⇒ electronic nematic



♦ C_4 structural to C_2 electronic symmetry in quasi-particle interference maps of $CaFe_{1.94}Co_{.06}As_2$ (T.-M. Chung et al., Science **327**, 181 (2010) ⇒ electronic nematic



summary and outlook

♦ evidence for anisotropically textured superconductivity from a comparison of resistive and bulk transitions and, where studied, for rotational symmetry breaking by the texture

♦ not a ‘dirt’ effect but an intrinsic response to the presence of a coexisting order, irrespective of whether that phase is large-moment commensurate (Cd-doped $CeCoIn_5$) or incommensurate ($CeRhIn_5$) AFM, a weak incommensurate spin-density wave (A/S-$CeCu_2Si_2$), a pseudogap-like state ($CeIrIn_5$) or a nematic electronic state (URu_2Si_2)

♦ absence of texture once coexisting order is suppressed, eg in all Ce115’s

♦ similarity to Ba-doped La_2CuO_4 in which symmetry-breaking pseudogap and stripe phases known to be present

♦ spontaneous broken rotational symmetry and difference between resistive and bulk transitions in Co-doped $BaFe_2As_2$ and $CaFe_2As_2$ (T.-M. Chung et al., Science **327**, 181 (2010); J-H. Chu et al., Science **329**, 824 (2010))

♦ To what extent is the physics of textured superconductivity the same in these classes of correlated materials?

♦ What do these effects imply about the relationship between superconductivity and coexisting broken symmetries?