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UCSD

Materials Trends in Different Classes of Superconductors from Heavy Fermion Compounds to Iron Pnictides and Beyond

M. Brian Maple
University of California, San Diego

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

NNSA
National Nuclear Security Administration

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH UNITED STATES AIR FORCE

Three classes of extraordinary superconducting materials

- Three classes of extraordinary superconducting materials discovered within past 3 decades
  - Heavy fermion f-electron compounds (~1980)

    T_c's up to ~several K (T$_c$ = superconducting critical temperature)
  - Layered copper oxide compounds (cuprates) (~1986)

    T_c's up to 133 K (165 K – high pressure!)
  - Iron pnictide and chalcogenide compounds (~2006)

    T_c's up to 56 K
- Striking similarities
  - "Unconventional" superconductivity (SC) (differs from "conventional" BCS SC)
  - SC often found to "emerge" from a magnetically-ordered phase upon variation of chemical composition (x) or pressure (P)
  - Same electrons involved in magnetism and superconductivity
  - Evidence for pairing of SC'ing electrons via spin fluctuations
    (cannot exclude possibility of other pairing scenarios, especially for the cuprates)
  - Strongly correlated electron materials
- Noteworthy differences
  - Values of T_c, crystal structures, pseudogap, underlying physics of the normal state, etc.

Outline

- Historical remarks about development of SC'ing materials
- Heavy fermion f-electron SC's
- Emergence of SC from magnetic order, unconventional SC, and electron pairing via spin fluctuations
- Copper oxide (cuprate) SC's
- Iron pnictide/chalcogenide SC's
- Evidence for strong electronic correlations
- New class of layered SC's based on $LnOBiS_2$ parent compounds
- Prospects for the future

Emphasis is on experiment, selected examples

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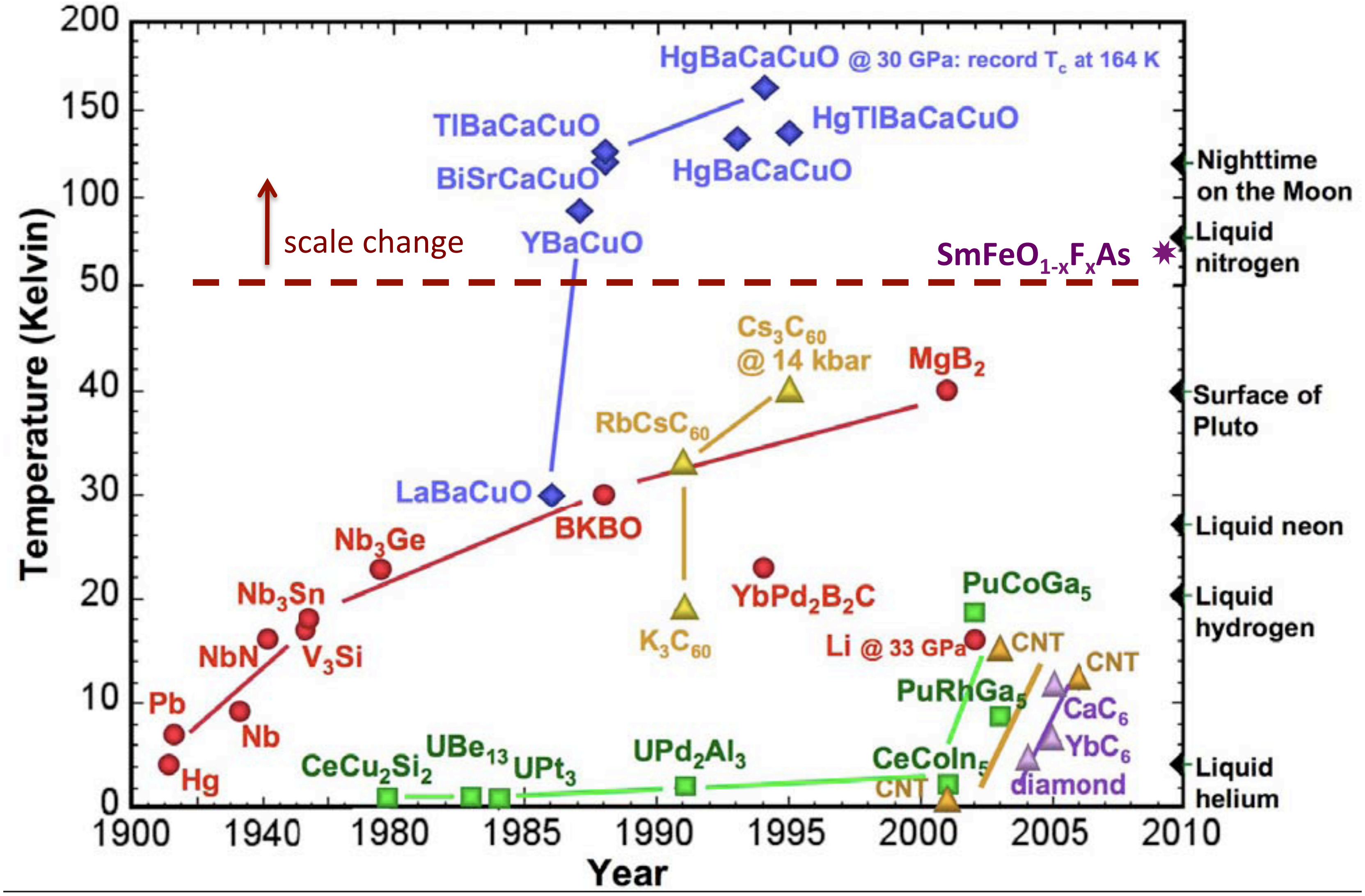
T_c vs time for various types of superconducting materials

1st breakthrough (1986) – cuprates: Max $T_c \approx 133$ K (165 K - high pressure) (COPPER AGE)

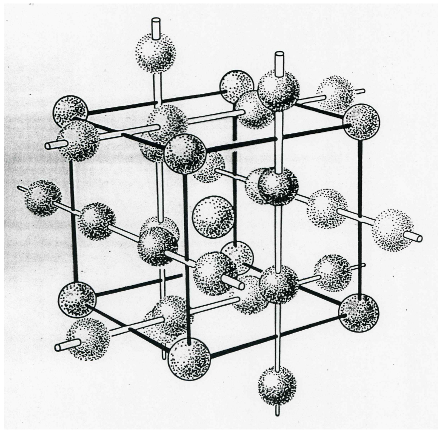
2nd breakthrough (2006) – iron pnictides: Max $T_c \approx 56$ K currently! (IRON AGE)

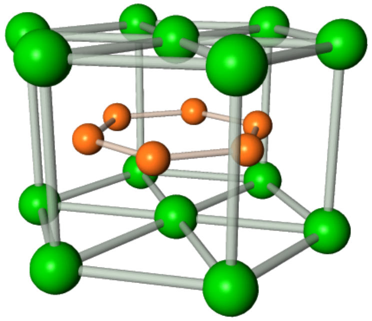


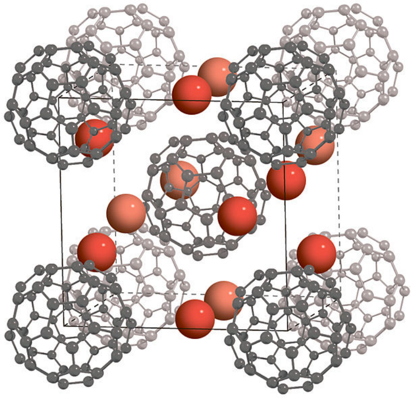
DOE BES Basic Research Needs for Superconductivity (2006)

Superconducting materials

	MATERIAL	T_c
• ALLOYS	NbTi	9.6 K
• COMPOUNDS	NbN	9.6 K
Borocarbide	(Lu/Y)Ni_2B_2C	23 K
"A15" Structure	Nb_3Sn	18 K
(β-W structure)	Nb_3Al	18.7 K
	Nb_3Ge	23 K
• RECENT	MgB_2	39 K
Fullerene	Cs_2RbC_{60}	33 K
	+ pressure of 15 kbar	40 K







- Certain structures favorable for SC; e.g., A15 structure, $ThCr_2Si_2$ structure (HF compounds, Fe pnictides)
- History of SC would be very different if discoveries of certain SC'ing materials had been made in a different order! (e.g., MgB_2!)

Conventional high T_c superconductors

Guide for searching for conventional high T_c superconductors

Matthias' "rules" (according to W. E. Pickett – 2001)

(1) Transition metals are better than simple metals

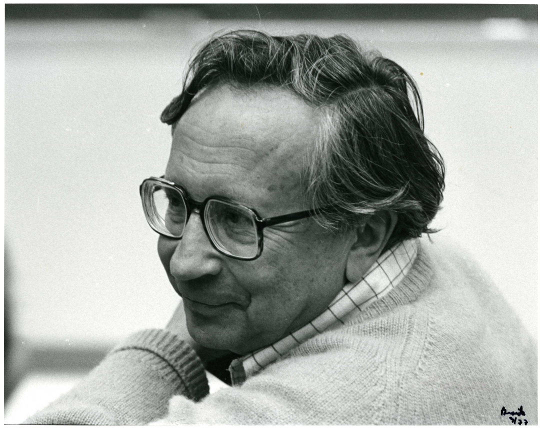
(2) Favorable valence electron per atom ratios [$N(E_F)$] (5 and 7)

(3) High symmetry is best, especially cubic

(4) Avoid oxygen

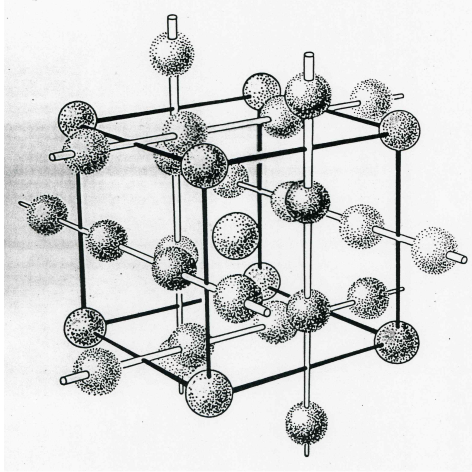
(5) Avoid magnetism

(6) Avoid theorists!

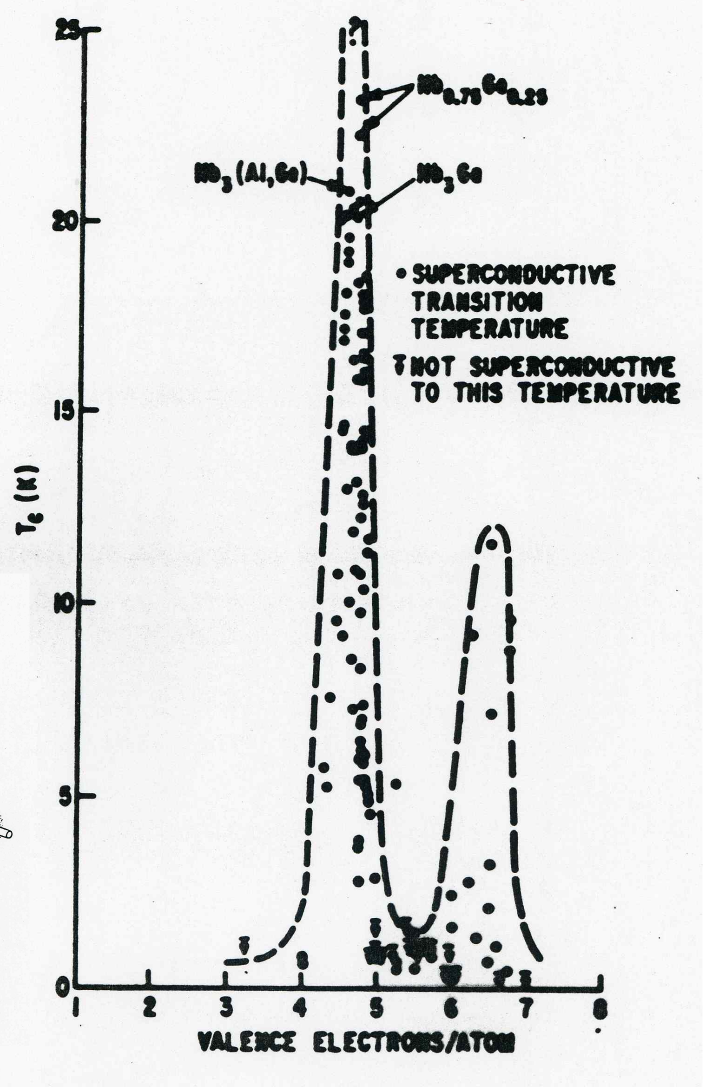


Bernd T. Matthias, 1980

Nb_3Sn



A15 compounds



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Heavy fermion superconductors

- Metallic f-electron compounds with enormous electronic specific heat coefficient γ as high as several J/mol-K^2! (Conventional metal: γ ~ several mJ/mol-K^2)
- Electron effective mass $m^* \sim 10^2\text{-}10^3\ m_e$!
- Based on lanthanide (Ln) and actinide (An) ions with partially-filled f-electron shell and unstable valence: e.g, Ln = Ce, Pr, Yb; An = U, Pu
- Localized f-electron states hybridized with conduction-electron states
- Kondo effect or valence fluctuations ⇒ strong electronic correlations
- Characteristic "Kondo" or "valence fluctuation" temperature T*
- $T \gg T^*$: Local moment behavior [i.e., $\chi(T) \approx N\mu_{eff}^2/3k_B(T + T^*)$]
- $T \ll T^*$: Nonmagnetic heavy Fermi liquid (FL)

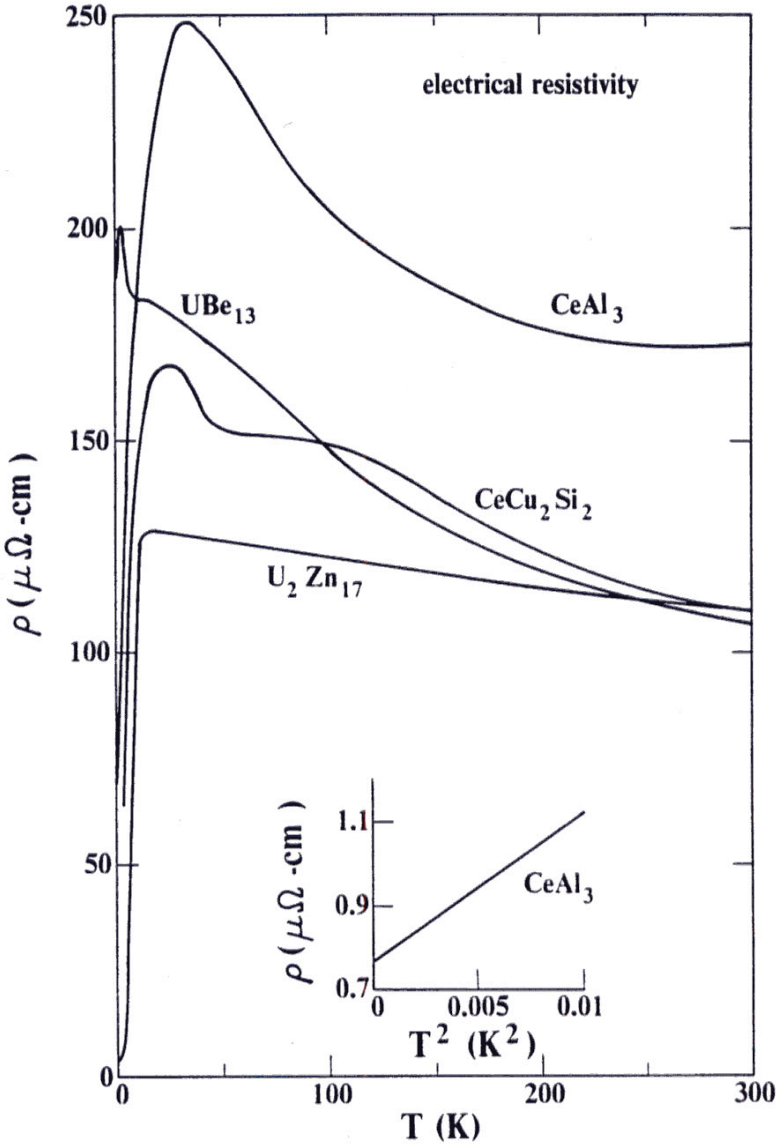
$$\chi(T) \rightarrow \chi_o \propto m^* \propto 1/T^*$$

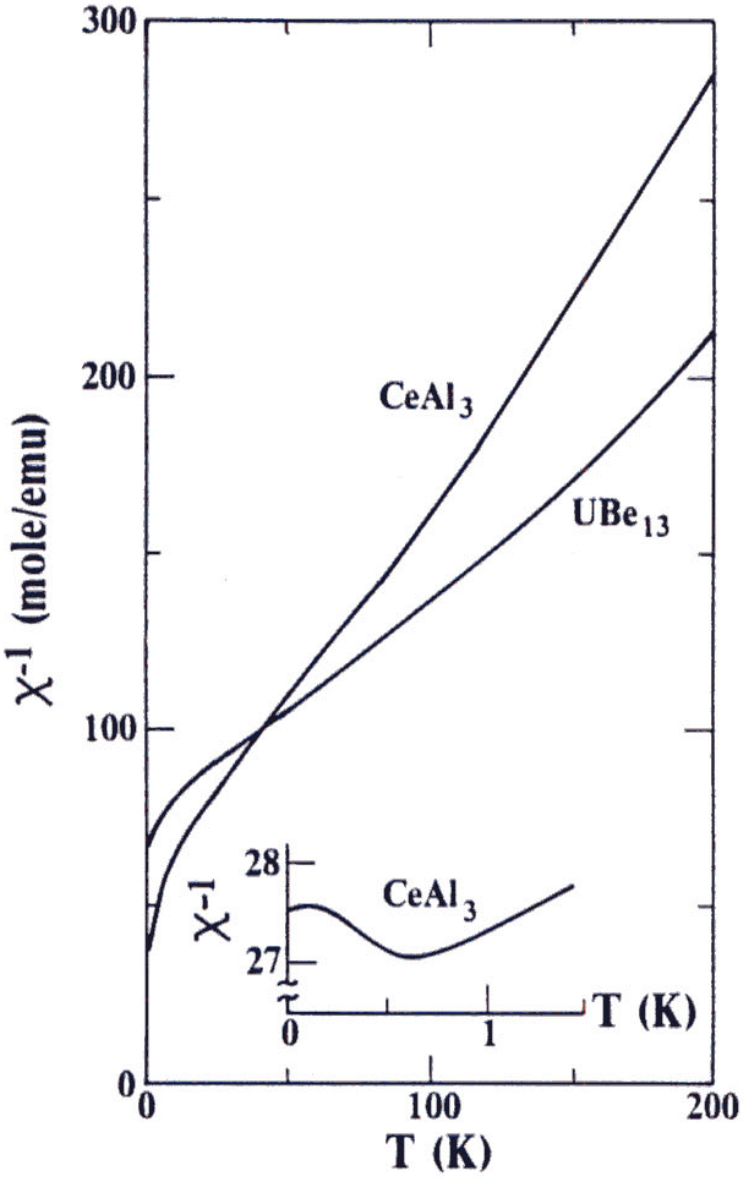
$$\gamma(T) = C_e(T)/T \rightarrow \gamma_o \propto m^* \propto 1/T^*$$ (as high as several J/mol K^2!)

$$R = (\chi_o/\mu_{eff}^2)/(\gamma_o/\pi^2 k_B^2) \approx 1$$ (Wilson-Sommerfeld ratio)

- Narrow resonance in N(E) near E_F (Kondo model: "Abrikosov-Suhl resonance")
- Heavy FL unstable to unconventional SC and magnetic order (RKKY)

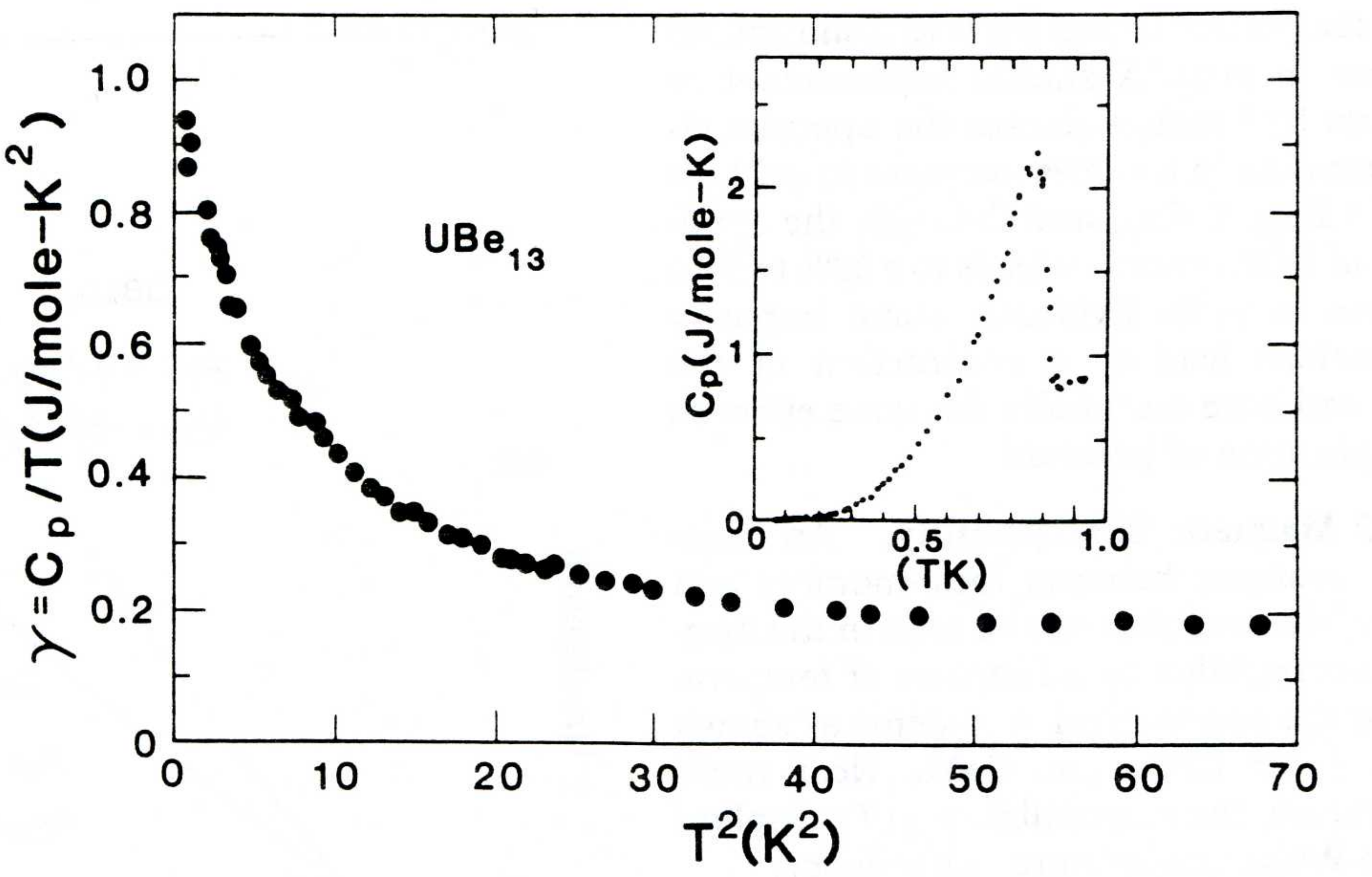
Electrical resistivity and magnetic susceptibility of heavy fermion compounds





After Fisk, Ott, Rice & Smith 86

Low temperature specific heat of UBe_{13}



- $\gamma(0) \approx 1$ J/mol-K^2 ⇒ $m^* \approx 10^2\, m_e$
- $\Delta C \approx \gamma T_c$ ⇒ heavy electrons responsible for large γ are involved in SC!

After D. W. Hess, P. S. Riseborough, J. L. Smith, Enc. App. Phys. 7 (93)

Heavy fermion superconductors (partial list)

Superconducting at atmospheric pressure:

Compound	T_c (K)
$CeCoIn_5$	2.3
$CeCu_2Si_2$*	0.49
$CeIrIn_5$	0.4
U_6Fe	3.7
UPd_2Al_3*	2.0
URu_2Si_2*	1.5
UNi_2Al_3*	1.0
UBe_{13}	0.85
UPt_3*	0.55
URhGe*	0.4
$PrOs_4Sb_{12}$	1.8

* *Magnetic order*

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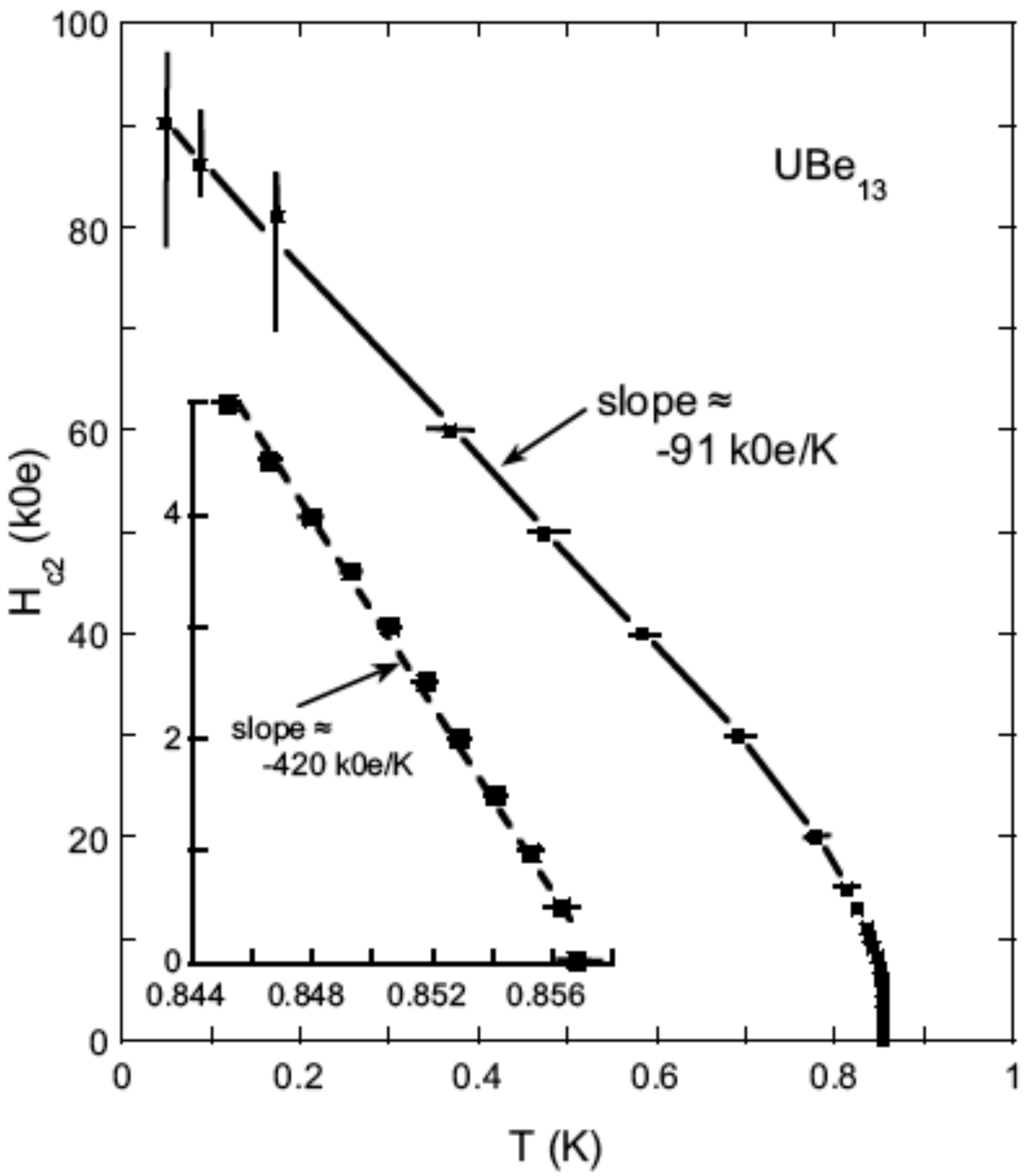
Superconducting under pressure:

Compound	T_c (K)	P (kbar)
$CeRhIn_5$*	2.2	21
Ce_2RhIn_8*	2	23
$CeCu_2Ge_2$*	~2	165
$CePd_2Si_2$*	0.43	28
$CeRh_2Si_2$*	0.26	11
$CeNi_2Ge_2$	0.23	23
$CeIn_3$*	0.17	25
UGe_2*	0.7	10

* *Magnetic order*

Upper critical field of UBe_{13}



- Upper critical field $H_{c2}(T)$:
- Unusual shape
- Enormous initial slope

  $(dH_{c2}/dT)_{Tc} \propto \rho\gamma$

  $\Rightarrow m^* \approx 300\ m_e$
- Orbital critical field

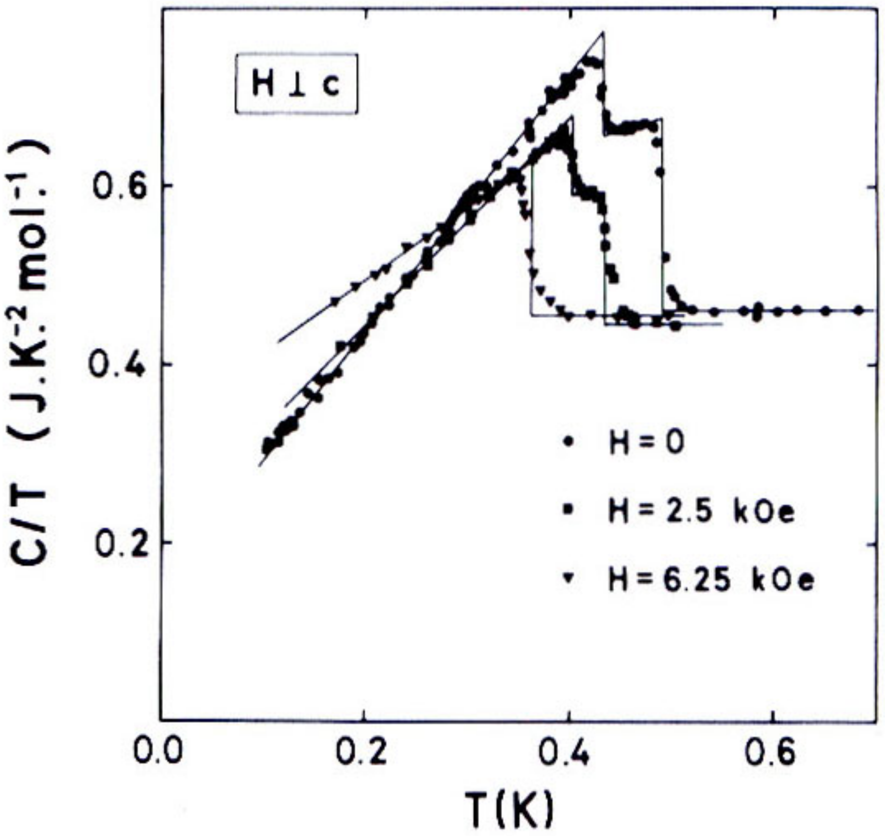
  $H_{c2}^*(0) \approx 250$ kOe
- Paramagnetic limiting

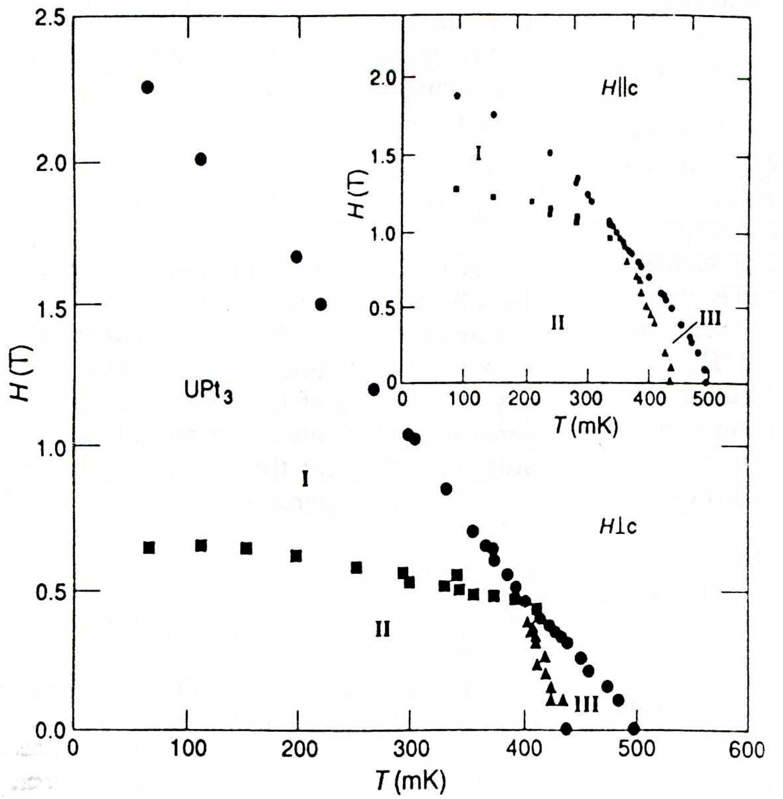
  $H_p = 18.4\ T_c$ [kOe] ≈ 16 kOe

  (w/o spin-orbit scattering)

M. B. Maple et al., PRL ***54*** *'85*

Multiple superconducting phases in UPt_3





- C(H,T) ⇒ two distinct SC'ing transitions
  Hasselbach, Taillefer, Flouquet (89)
- H – T phase diagram (sound velocity) ⇒ three distinct SC'ing phases
  *Adenwalla et al. PRL **65** (90)*

- Coupling between multicomponent SC'ing OP & AFM OP
- AFM: $T_N \approx 5$ K
  $\mu \approx 0.02\ \mu_B/U$ (basal plane)
  *Aeppli et al. JMMM **76** & **77** (88)*

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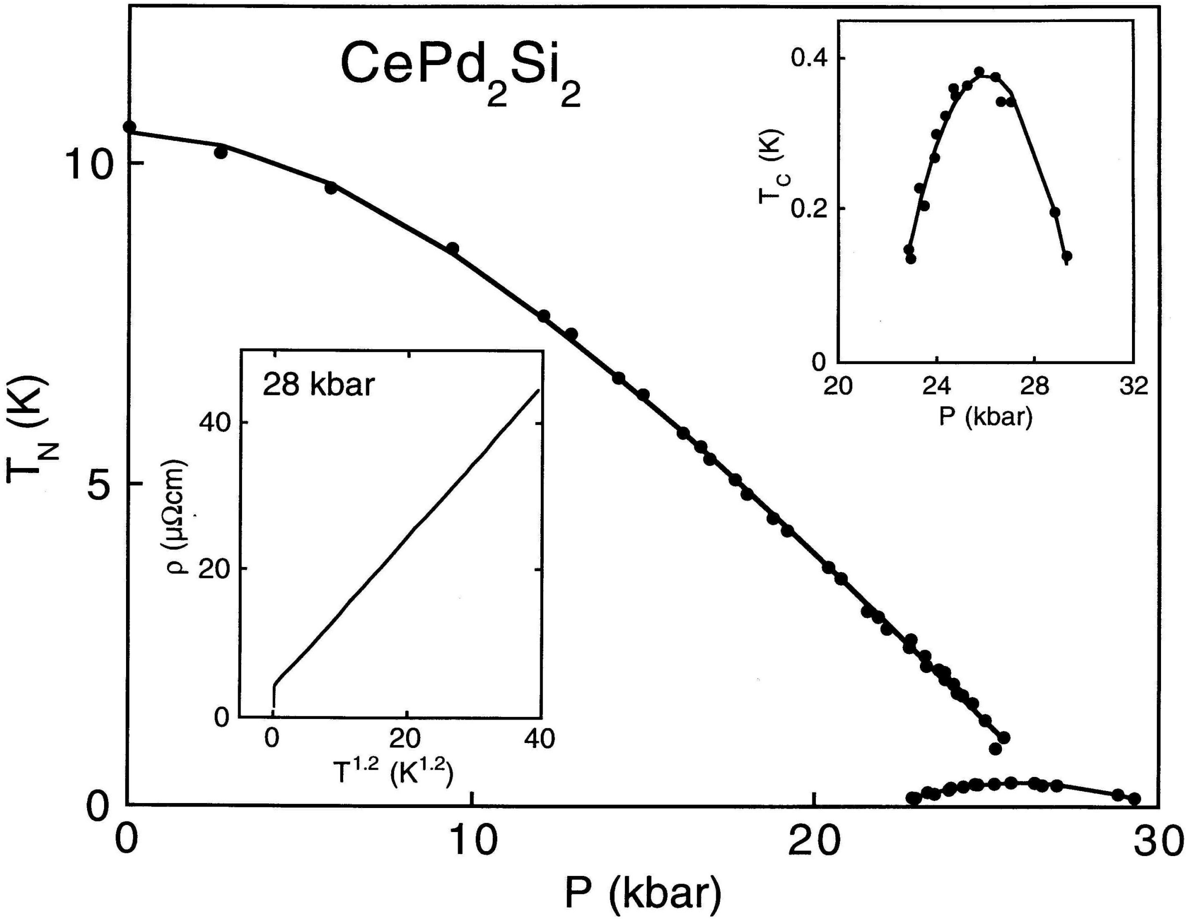
Superconductivity near pressure-induced AFM QCP



AFM QCP:

$P_c \approx 28$ kbar

NFL behavior:

$\rho(T) \approx \rho_o + AT^{1.2}$

($T_c \leq T \leq 40$ K)

SC'ing dome:

T_c(max) ≈ 0.4 K

Similar behavior for $CeIn_3$ under P

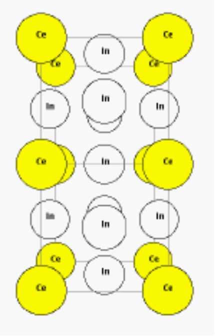
Julian, Lonzarich et al. (98)

Suggests AFM spin fluctuations responsible for NFL behavior in ρ(T) and SC'ing electron pairing

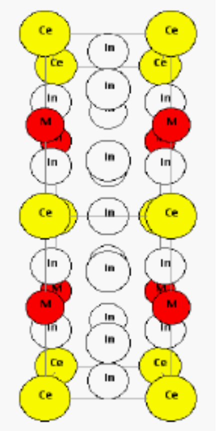
Emergence of SC near AFM QCP in $CeIn_3$ and $CeRhIn_5$

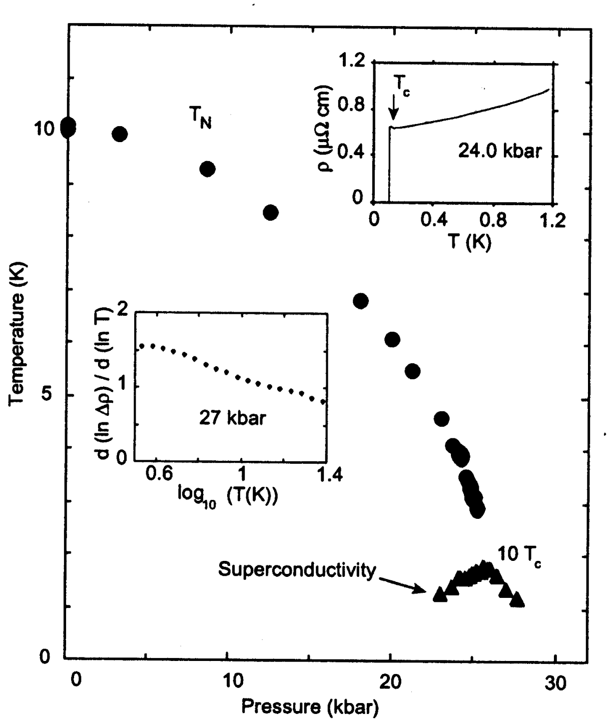
M = Co, Rh, Ir (isovalent)
"Layered" version of $CeIn_3$
$CeRhIn_5$: T_N = 3.8 K (AFM)
$CeCoIn_5$: T_c = 2.3 K (SC)
$CeIrIn_5$: T_c = 0.4/1.0 K (SC)

$CeIn_3$

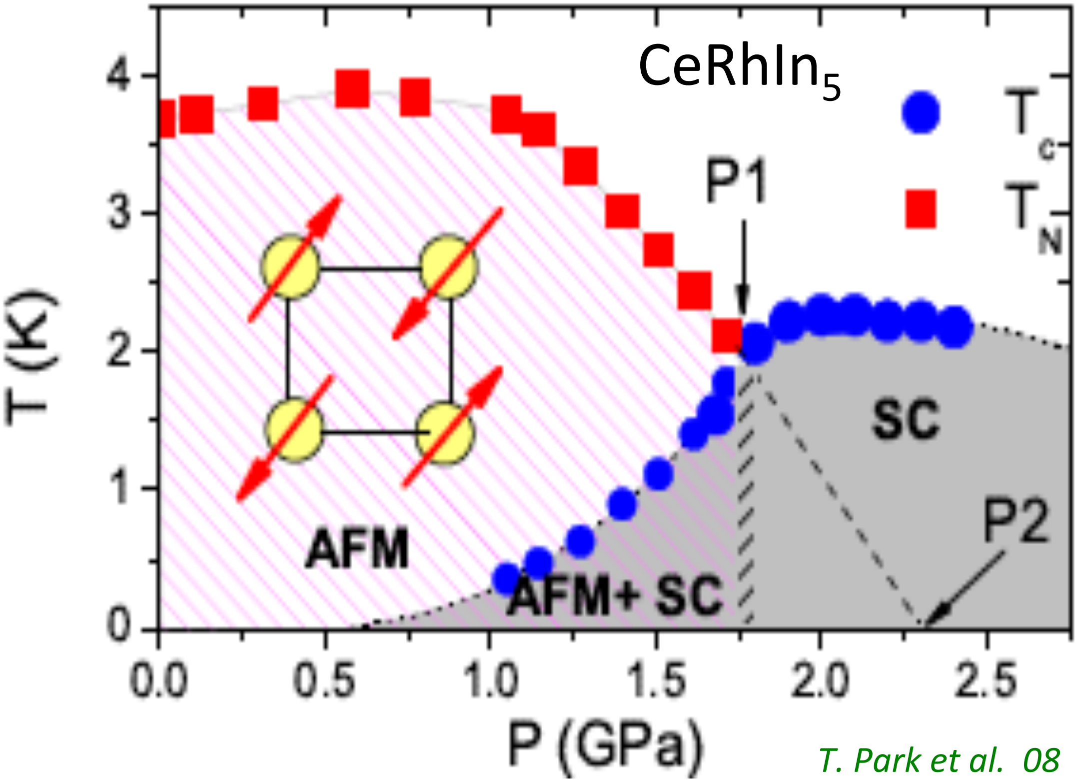


$CeMIn_5$





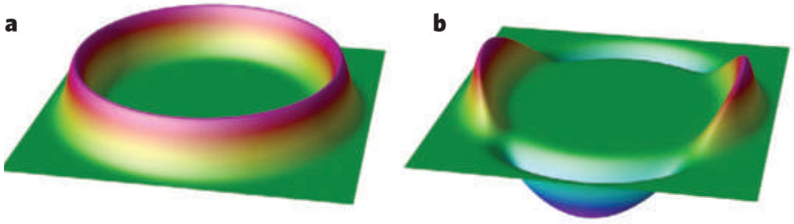
*Mathur et al., Nature **394**, 39 (98)*



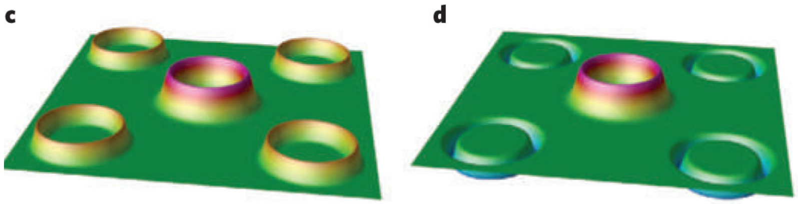
T. Park et al. 08

Electron pairing scenarios in superconductors

- Consider singlet spin pairing: ($\mathbf{k}\uparrow$,$-\mathbf{k}\downarrow$)
- Superconducting energy gap $\Delta(\mathbf{k})$:
  - s-wave – conventional BCS
    Nearly isotropic (nodeless) energy gap
    (e.g., Pb, Sn, Al)
  - d-wave – unconventional
    Anisotropic (nodal) energy gap
    (e.g., HF f-electron SC's, cuprate SC's)
  - s^{++}-wave – two band s-wave, same sign
    (e.g., MgB_2)
  - $s^{\pm}$-wave – two band s-wave, opposite sign
    (e.g., Fe-pnictides?)



s-wave d-wave

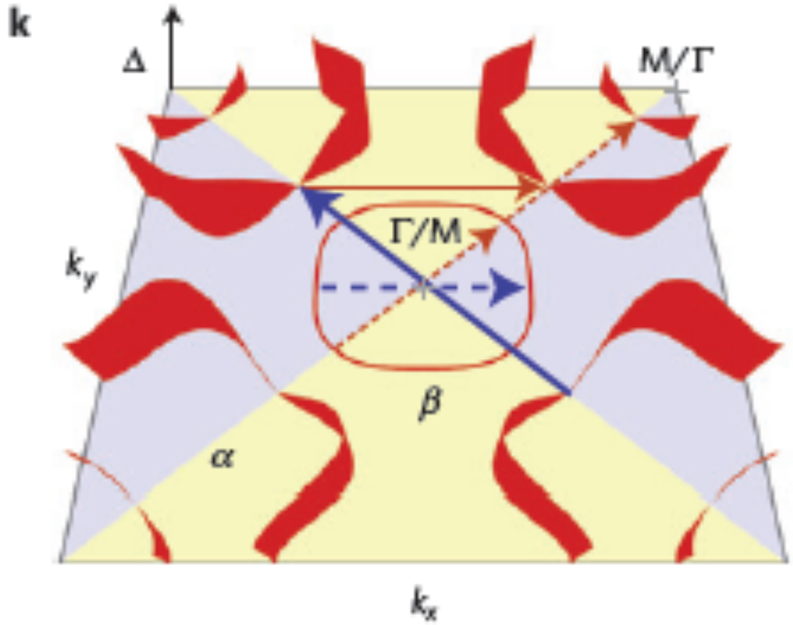


S^{++}-pairing $s^{\pm}$-pairing

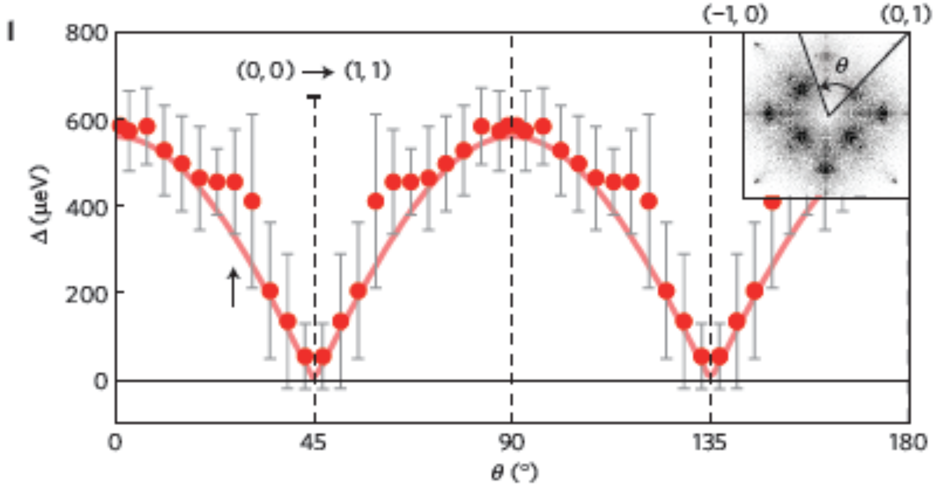
After I. I. Mazin, Nature ***464****, 183 (10)*

- Pairing of SC'ing electrons via spin fluctuations [Review: *D. J. Scalapino RMP* ***84****,1383 (12)*]
  - ○ Suppression of AFM or SDW order by chemical substitution or pressure
    ⇒ spin fluctuations peaked at ordering wave vector **Q**
  - ○ Repulsive interaction involving spin fluctuations rendered attractive via sign change in gap [Sgn $\Delta(\mathbf{k}+\mathbf{Q}) = -\text{Sgn}\,\Delta(\mathbf{k})$] ⇒ d-wave or $s^{\pm}$-wave pairing
  - ○ Spin resonance peak at $\mathbf{k} = \mathbf{Q}$ observed in INS experiments in SC'ing phase

Superconducting energy gap $\Delta(\mathbf{k})$ of CeCoIn$_5$ (STM)



- Fermi surfaces and energy gaps of CeCoIn$_5$ modeled using heavy QPI
- Primary gap occurs on high-**k** α-band with lines of gap-nodes along **k** = (0,0) ⟶ $(\pm1,\pm1)\pi/a_o$ directions ($d_{x^2-y^2}$ symmetry)
- Zero gap is shown on β sheet, but thermodynamic studies show both α and β bands gapped at lowest T



Measured $|\Delta(\theta_q)|$ compared with simplest multi-band gap structure $\Delta_\beta(\theta_k) \approx 0$ and $\Delta_\alpha(\theta_k)\cos(2\theta_k)$ with A = 600 μeV

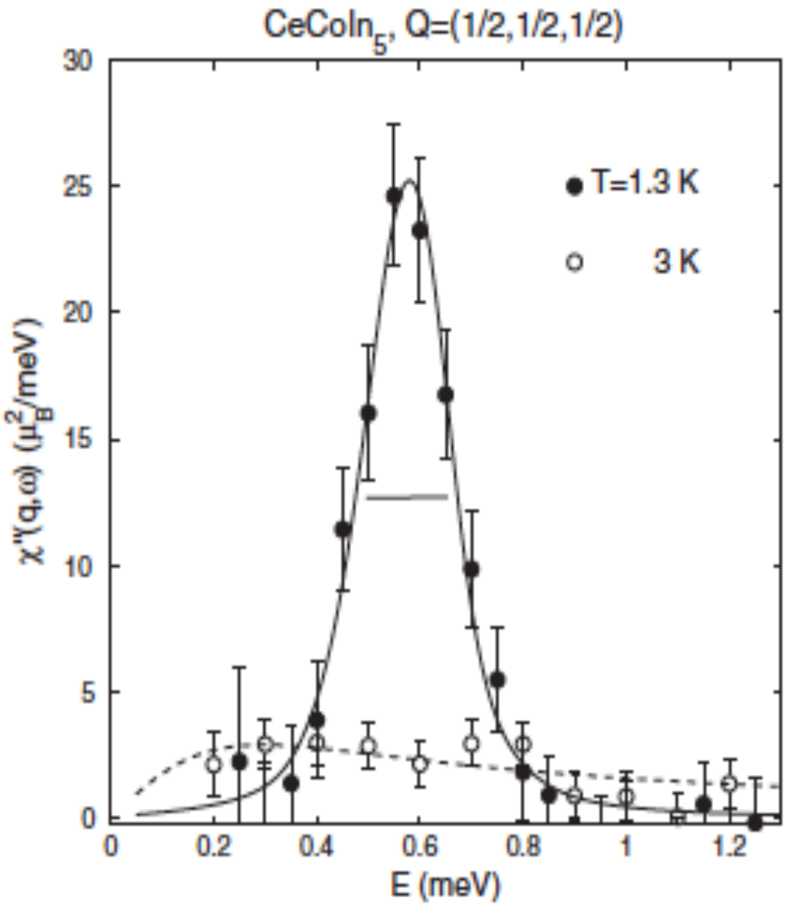
M. P. Allan et al., Nature Phys. (13)

Neutron spin resonance in the superconducting state

- Neutron spin resonance in SC'ing state at AFM or SDW wave vector **Q**
- First observed in cuprates (e.g., *Rossat-Mignod el al. '91; Mook et al. '93; Fong et al. '95,'99*)
- Spin-flip INS rate ∝ $\chi''(\mathbf{Q},\omega)$
- Requires gap sign change between regions on FS separated by momentum **Q** which contribute significantly to spin scattering:

  $$[\mathrm{Sgn}\Delta(\mathbf{k}+\mathbf{Q}) = -\,\mathrm{Sgn}\,\Delta(\mathbf{k})]$$

  (e.g., *Bulut, Scalapino, Scalletar '92; Monthoux, Scalapino '94*)



INS spin resonance in normal (dashed) & SC'ing (solid) states for HF compound CeCoIn$_5$ (T_c = 2.3 K) *Stock et al. '08*

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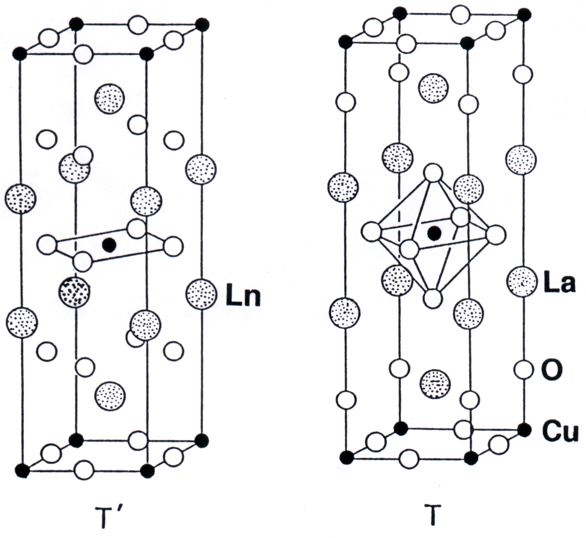
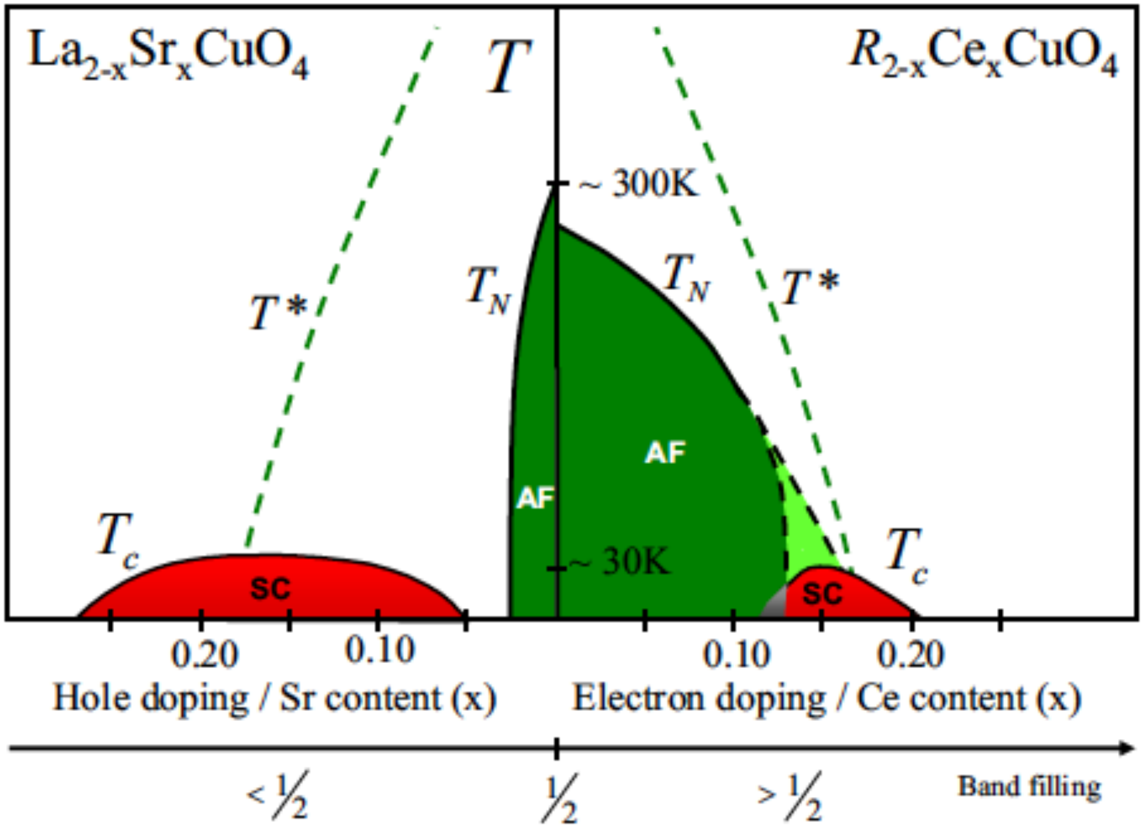
Electron- and hole-doped cuprate superconductors

- Parent compound – antiferromagnetic (AFM) Mott insulator
- Chemical substitution ⇒ generates electrons or holes in CuO_2 planes and suppresses AFM order ⇒ superconducting metal with high T_c



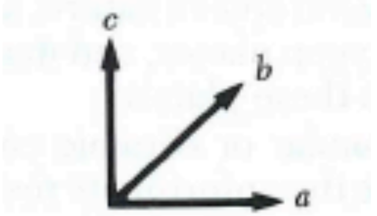


*After N. P. Armitage, P. Fournier, R. L. Greene, RMP **82**, 2421 (2012)*

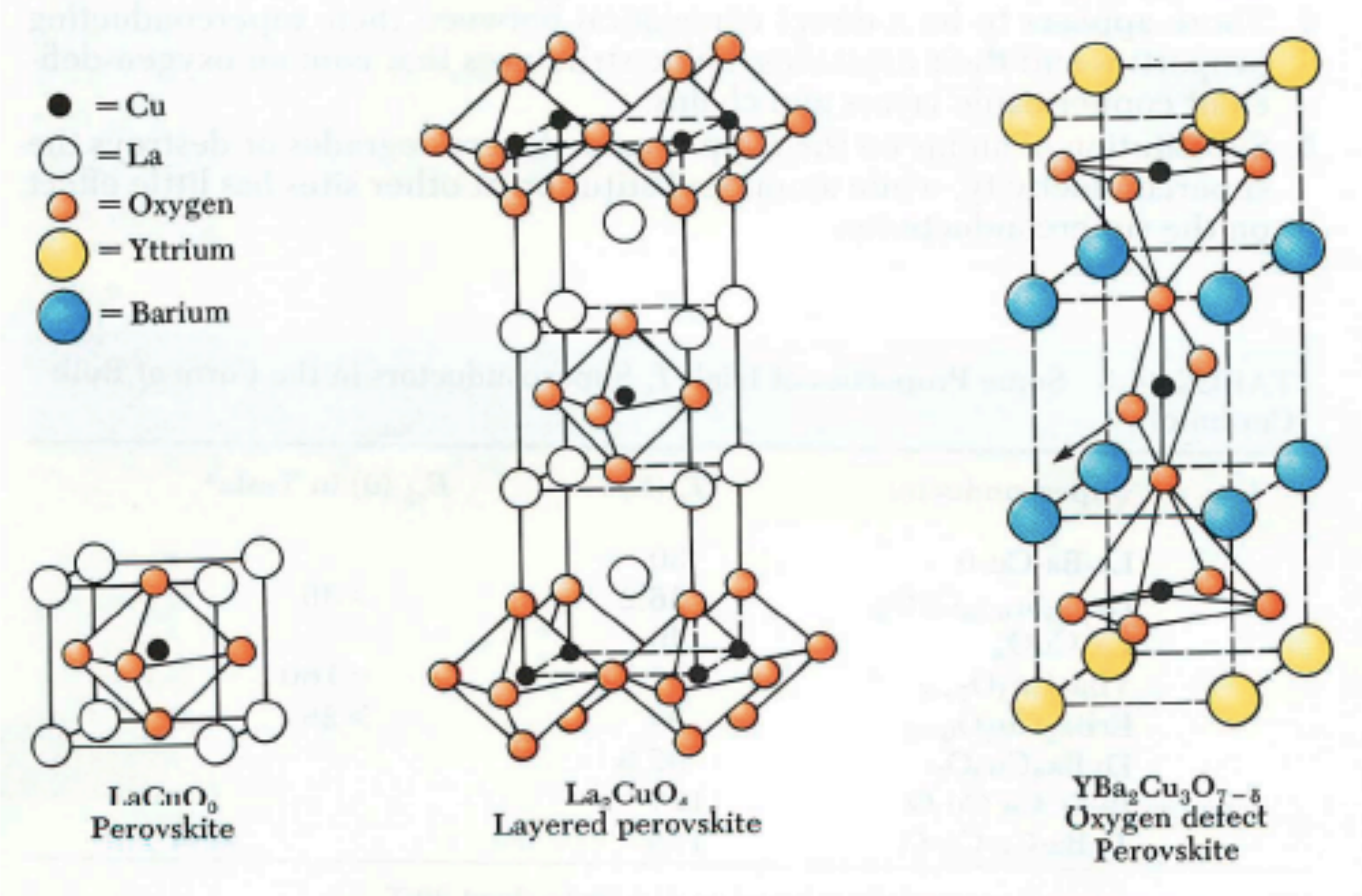
Crystal structures of high T_c cuprate superconductors

- Layered perovskite-like crystal structure
- Charge carriers move in CuO_2 plane

$YBa_2Cu_3O_7$: T_c = 92 K

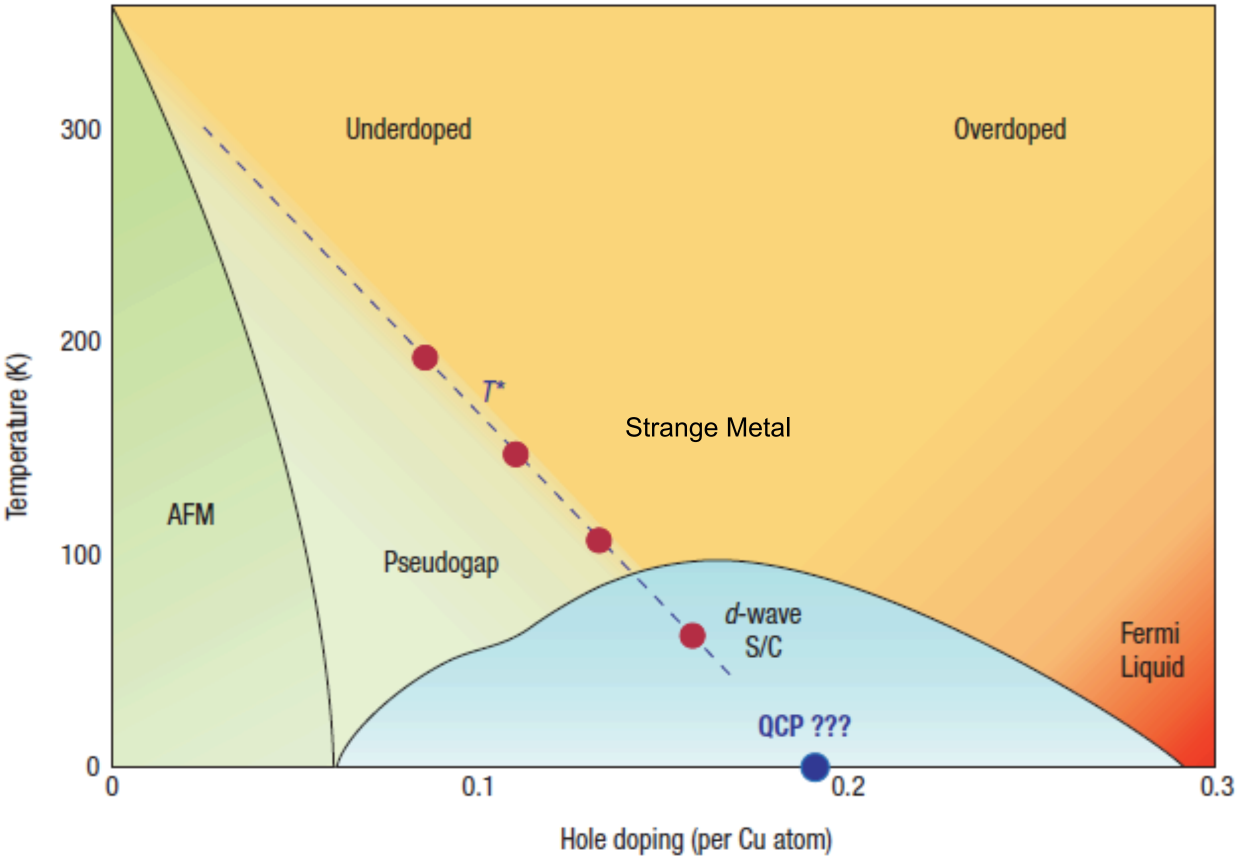


$La_{2-x}Sr_xCuO_4$: T_c ≈ 40 K



Generalized phase diagram for hole-doped cuprates

Generalized T – hole doping phase diagram for cuprates
*After D. M. Broun, Nature Physics **4**, 178 (2008)*



Pseudogap (PG) phase: Anomalous properties in transport, magnetic, thermodynamic, and optical properties at T* (pseudogap temperature)

Two major approaches to describe PG phase:

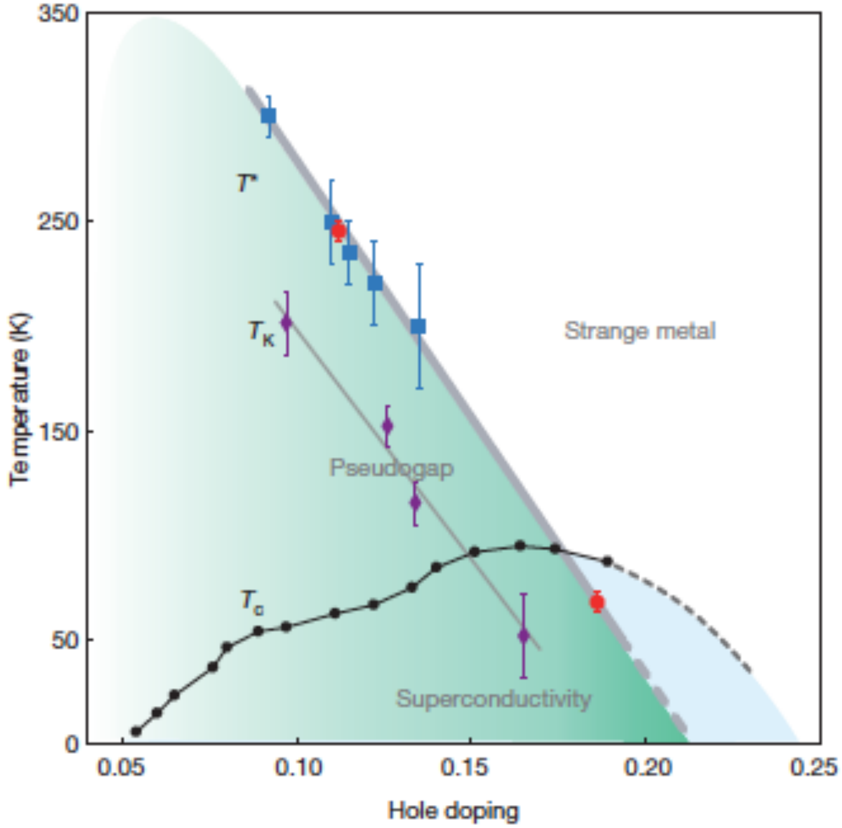
(1) T* represents crossover into state of preformed pairs with d-wave gap symmetry

(2) T* marks transition into distinct phase with broken symmetry that terminates at a QCP, typically inside SC'ing dome; e.g., CDW order, charge current loops

Recent experiments seem to favor alternative (2)

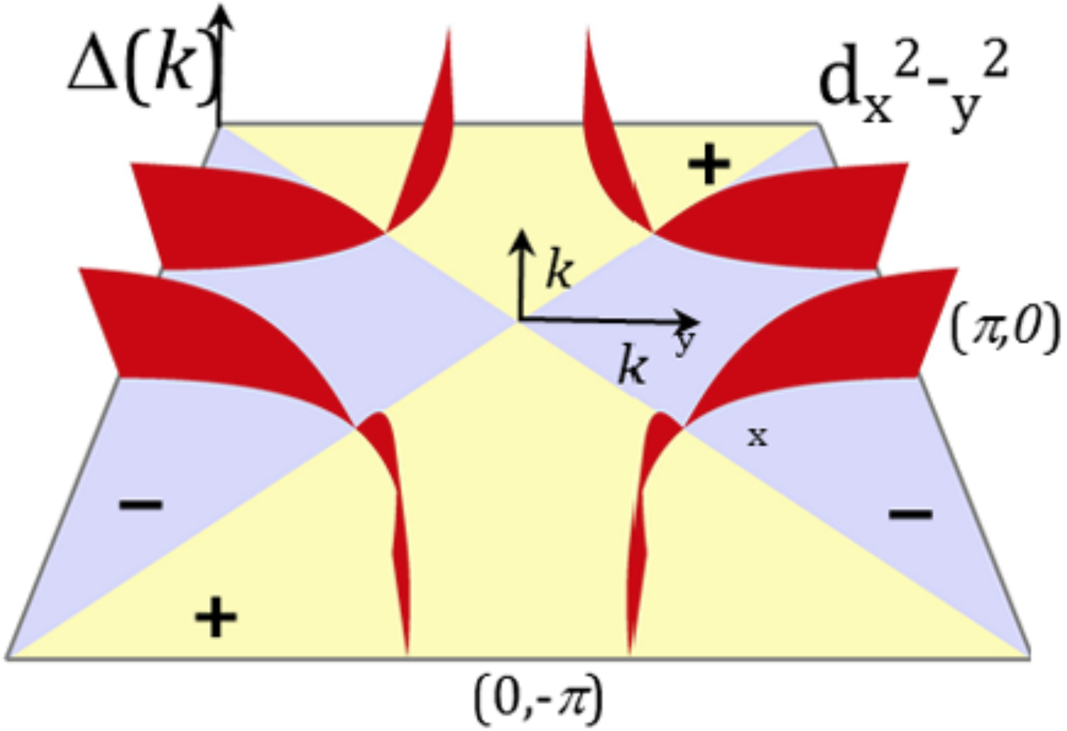
Evidence for symmetry breaking in pseudogap state

- Broken time reversal symmetry (TRS)
  - Polarized neutron diffraction
    - *B. Faqué et al., PRL (06)*
    - *Kaminski et al., Nature (02)*
    - *Y. Li et al., Nature (08)*
  - Polar Kerr effect
    - *J. Xia et al., PRL (08)*
- Broken rotational symmetry
  - Electrical resistivity
    - *Y. Ando et al., PRL (02)*
  - Inelastic neutron scattering (INS)
    - *C. Stock et al., PRB (04)*
    - *V. Hinkov et al., Nature Phys. (07)*
    - *V. Hinkov et al., Science (08)*
  - STM
    - *Y. Kohsaka et al., Science (07)*
    - *Y. Kohsaka et al., Nature (08)*
  - Nernst effect
    - *R. Daou et al., Nature (10)*
- Phase transition
  - RUS measurements
    - *A. Schekhter et al., Nature (13)*



After *A. Shekhter et al., Nature (13)*
Blue squares – neutron diffraction
Red circles – RUS
Purple diamonds – Kerr rotation
(onset of charge order – x-ray study)
J. Chang et al., Nature Phys. (12)]

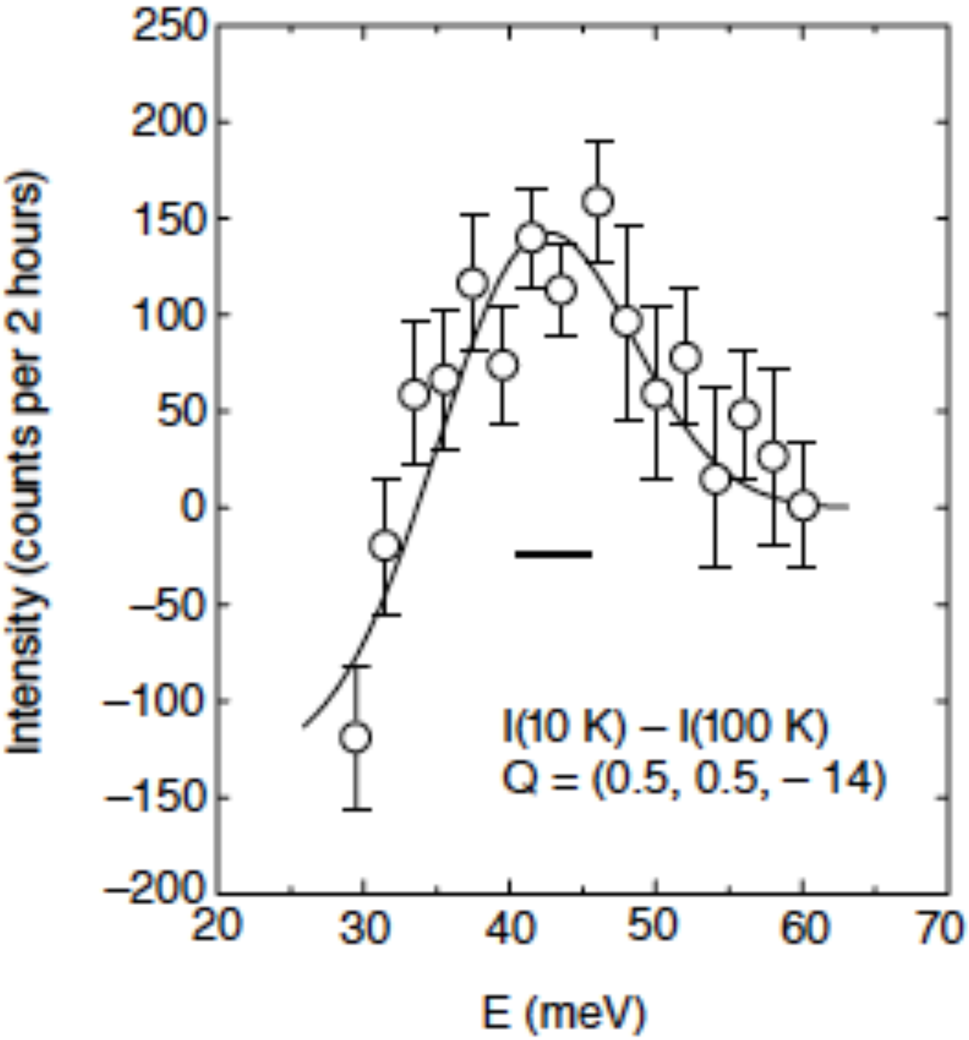
Superconducting energy gap $\Delta(\mathbf{k})$ of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (STM)



*After J. C. Davis (14); Y. Kohsaka et al., Nature **454**, 1072 (08)*

- Interaction mediated by AFM spin fluctuations peaked at momenta near (π,π)
- Links fermions in different "hot regions" of the BZ near (0,π), (π,0)
- Overall sign of interaction is positive (repulsive)
- d-wave gap changes sign between "hot regions" ⇒ d-wave component is <u>attractive</u>

Neutron spin resonance in the superconducting phase



I(10 K) – I(100 K) for $Bi_2Sr_2CaCu_2O_{8+\delta}$ at wave vector Q = (π/a, π/a) showing spin resonance at ~ 43 meV (T_c = 91 K)
Fong et al. '99

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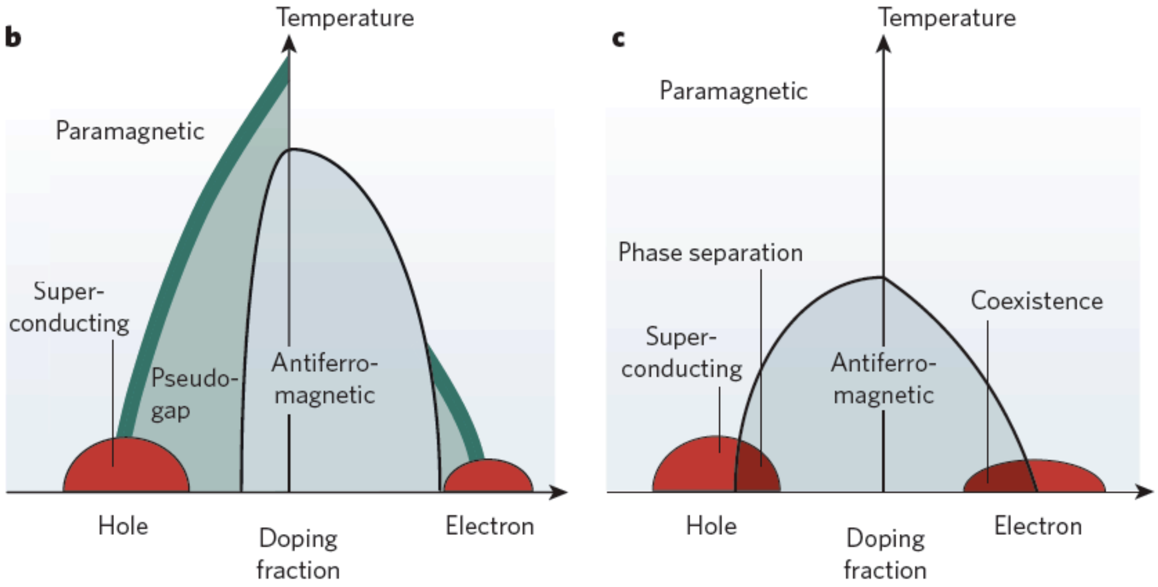
High T_c superconductivity in Fe pnictides/chalcogenides

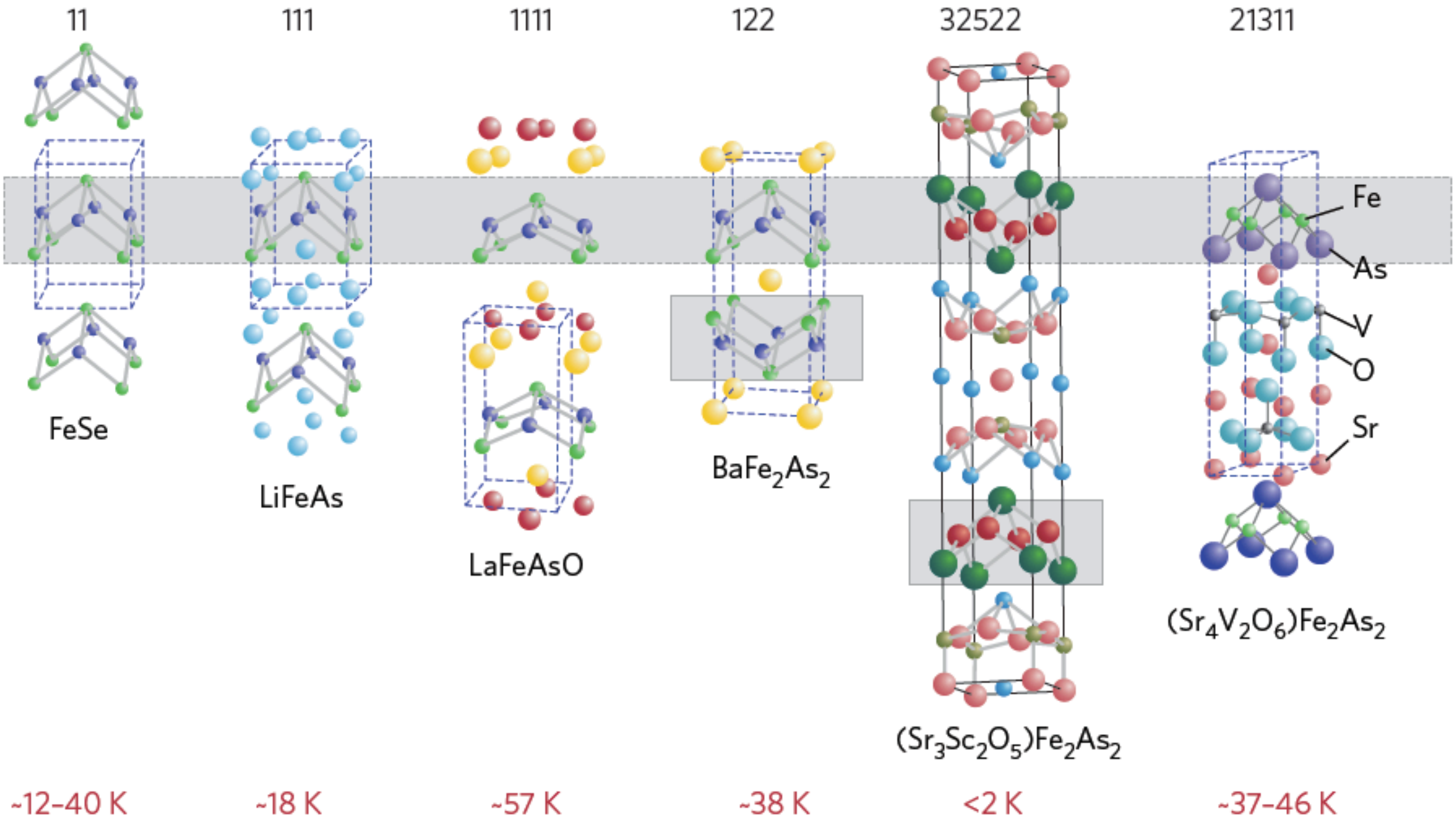
- Similarities to cuprates
  - “Layered” structures – FePn or FeCh layers and filler layers (charge reservoirs)
  - Proximity to magnetically ordered phase
- Differences from cuprates
  - Undoped parent compound is poor metal with AFM (SDW-type) order involving Fe μ’s (rather than AFM Mott insulator)
  - Electronic correlations weaker than in cuprates
- Symmetry of SC’ing OP: clues regarding electron pairing mechanism

  Depending on SC’ing material, evidence for
  - Nodal gap – d-wave
  - Nodeless gap – $s^{\pm}$
  - Pairing mechanism: spin fluctuations (assisted by phonons?)

*I. I. Mazin, Nature **464**, 183 (10)*

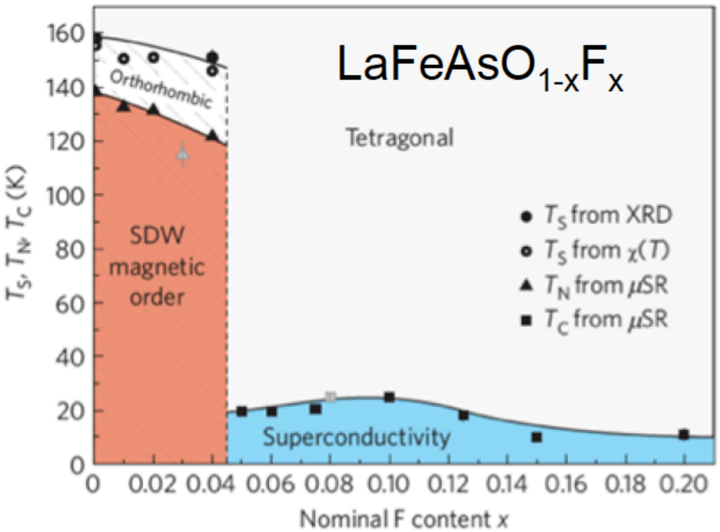


Transition metal pnictide/chalcogenide structures

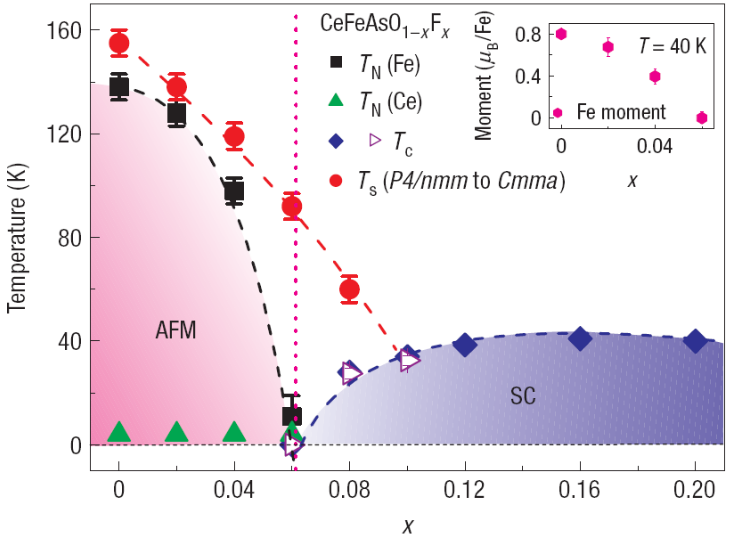


- Multinary compounds with different structures that contain TPn and TCh layers
- Many chemical substitutions possible → enormous number of compounds!!
- Opportunity to search for high T_c SC and other ordered phases
- High T_c SC often found in proximity of other ordered phases

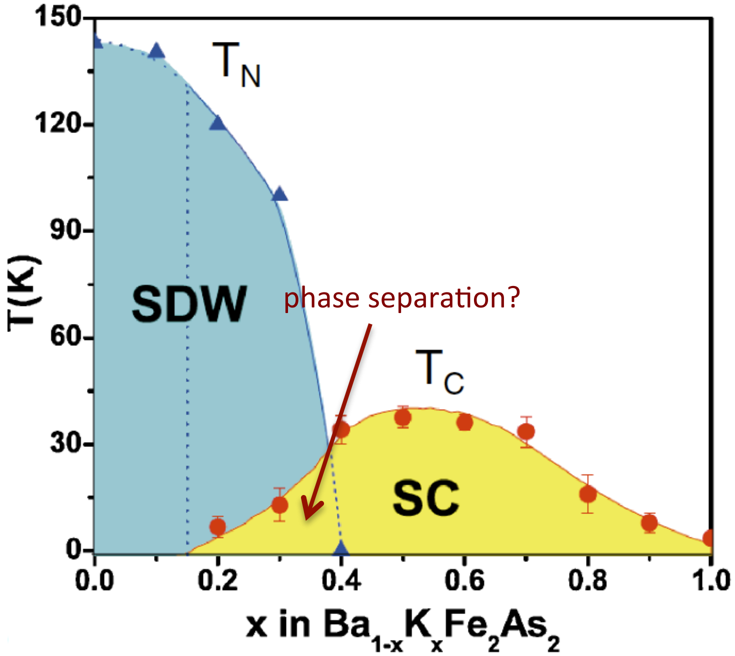
$T - x$ phase diagrams of Fe pnictide systems



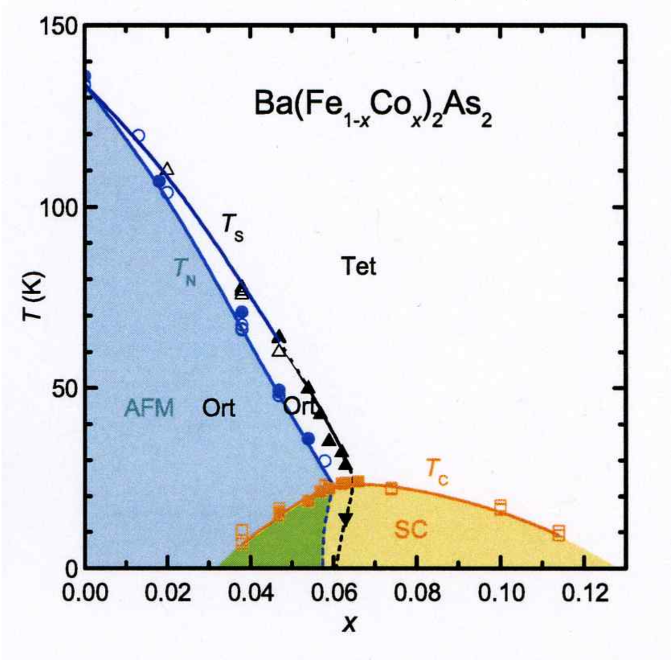
*H. Luetkens et al.,Nature Materials **8**, 305 (2009)*



J. Zhao et al., Nature Materials 7 (2008)

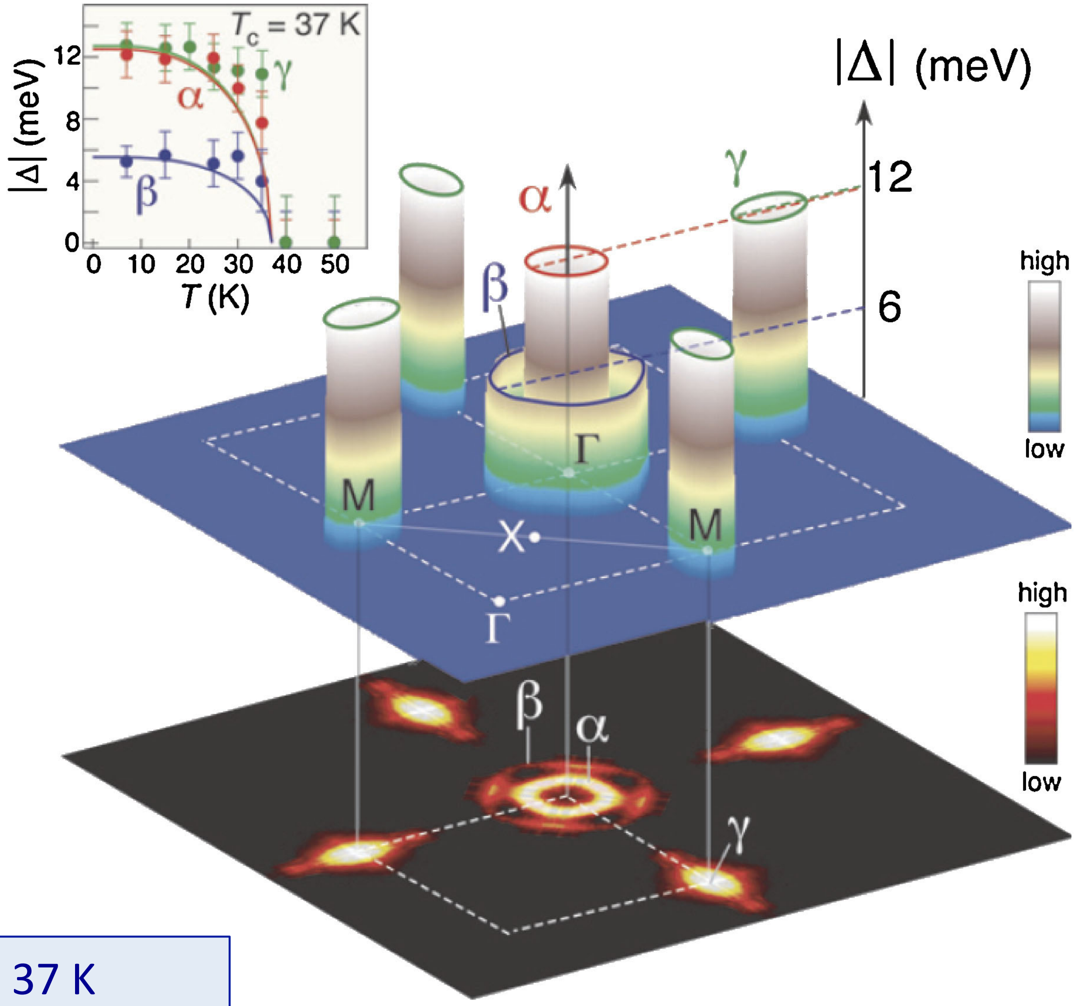


H. Chen et al., Europhys. Lett. 85, 17006 (2009)



S. Nandi et al., PRL 104, 057006 (2010)

Fermi surface and superconducting gap of $Ba_{0.6}K_{0.4}Fe_2As_2$ from ARPES

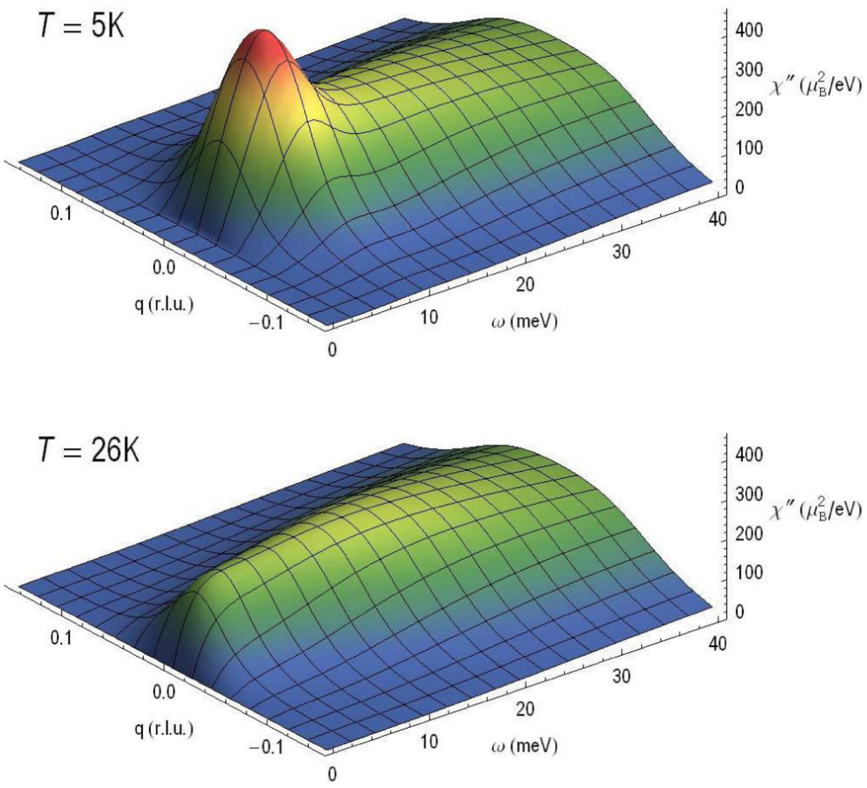


- $Ba_{0.6}K_{0.4}Fe_2As_2$: T_c = 37 K
- SC'ing energy gap Δ on α, β, γ FS sheets measured at 15 K
- Inset: T-dependence of Δ

H. Ding et al., Europhys. Lett. (08)

Neutron scattering resonance in SCing state

- Fe pnictide parent compounds: SDW with wave vector close to FS nesting wave vector
- Suppression of SDW by substitution of nonmagnetic element produces SC
- Neutron scattering resonance at wave vector of SDW in SC'ing state observed by means of INS
- Resonance associated with scattering between different regions of the FS with opposite sign of SC'ing OP



$Ba(Fe_{0.925}Co_{0.075})_2As_2$ single crystal
(T_c = 25 K)

D. S. Inosov et al., Nature Phys. 6,178 (2010)

- χ'' of $Ba(Fe_{0.925}Co_{0.075})_2As_2$ single crystal in SCing (top) and normal (bottom) states vs 2D in-plane wave vector $q = |Q - Q_{AF}|$ and ω [Q_{AF} = (1/2, 1/2 , L) r.l.u.]

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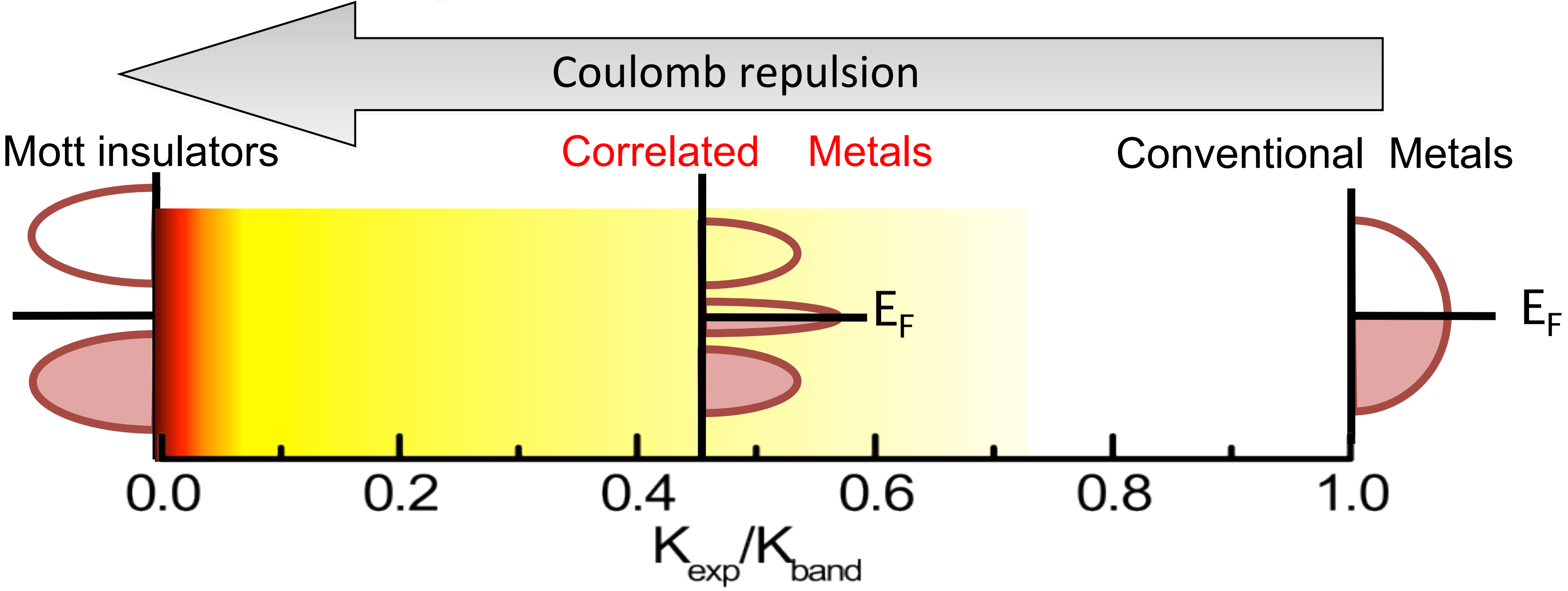
An IR probe of electronic correlations



***M.Qazilbash J. Hamlin, R. E. Baumbach, L. Zhang, D.J. Singh, M.B. Maple, and D.N. Basov et al. Nature-Physics 5, 647 (2009)
A.J. Millis et al. PRB 72, 224517 (2005)***

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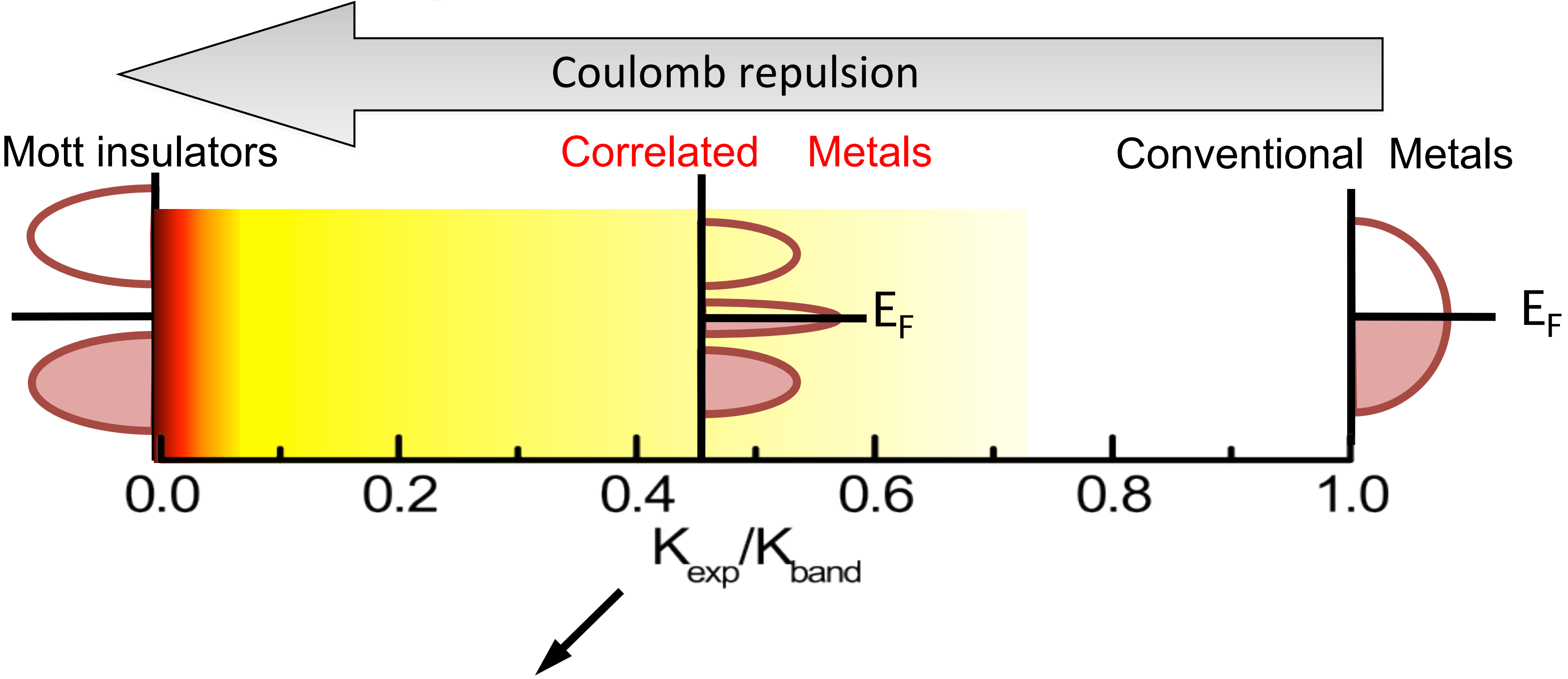

Paul Drude

$$K_{exp} = \int \sigma_1^{Drude}(\omega)\,d\omega$$

M.Qazilbash J. Hamlin, R. E. Baumbach, L. Zhang, D.J. Singh, M.B. Maple, and D.N. Basov et al. Nature-Physics 5, 647 (2009)
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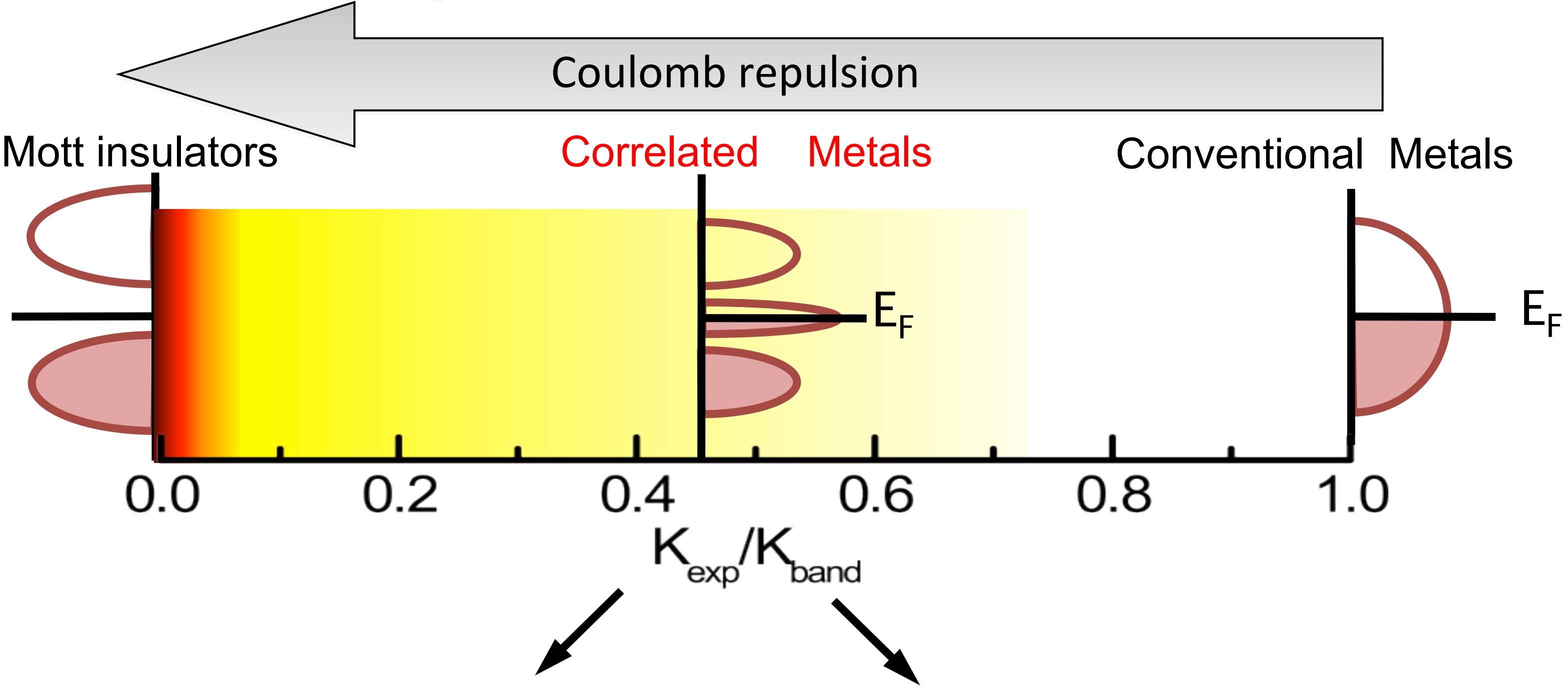

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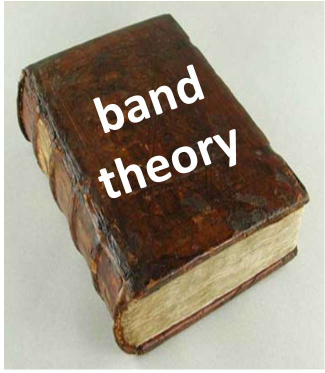

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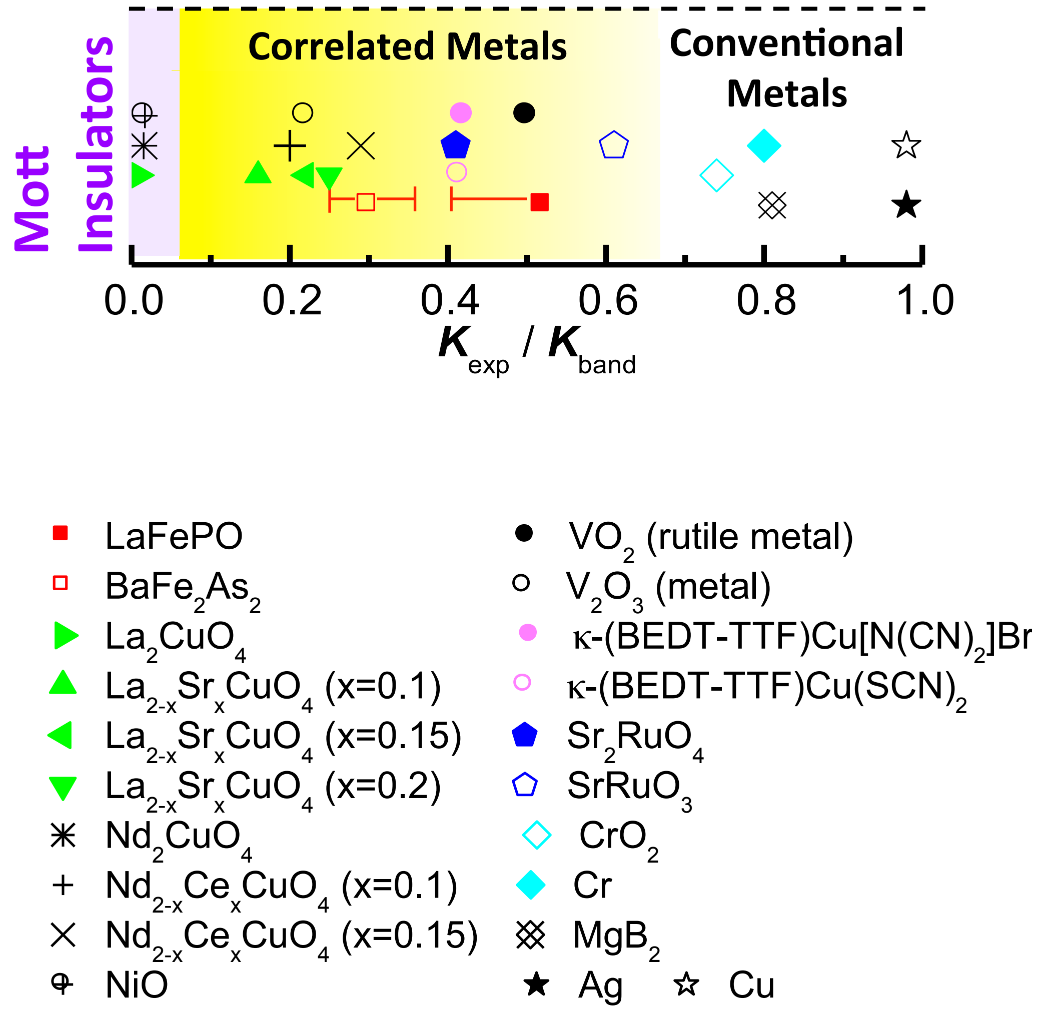
Electronic correlations in pnictides



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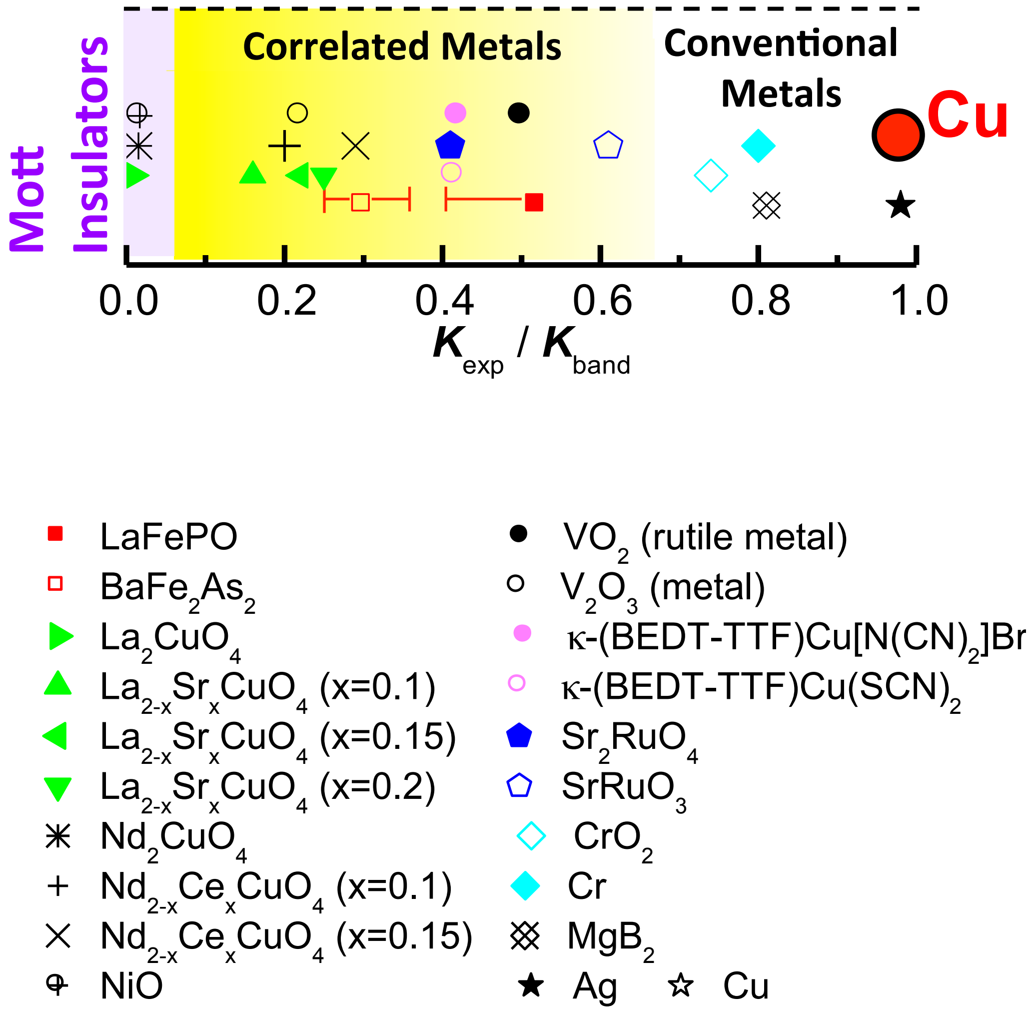

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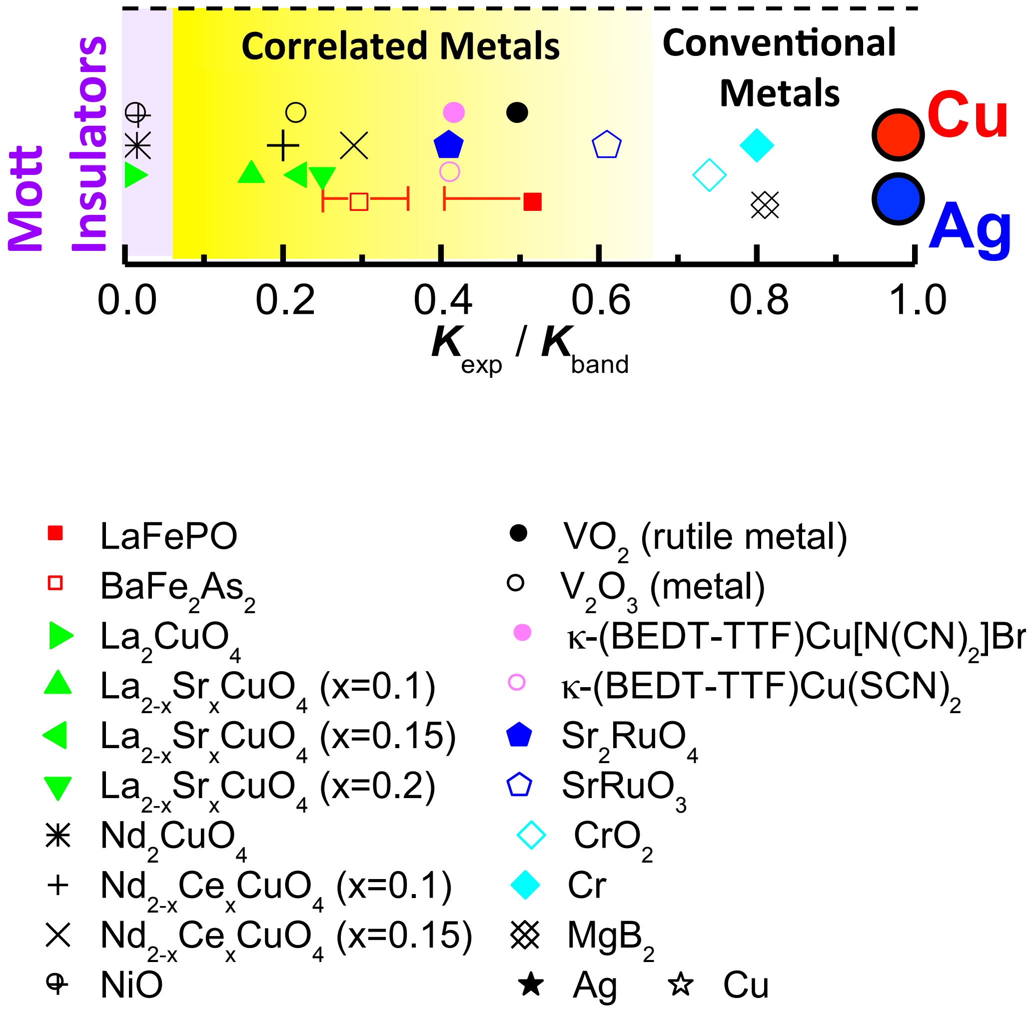

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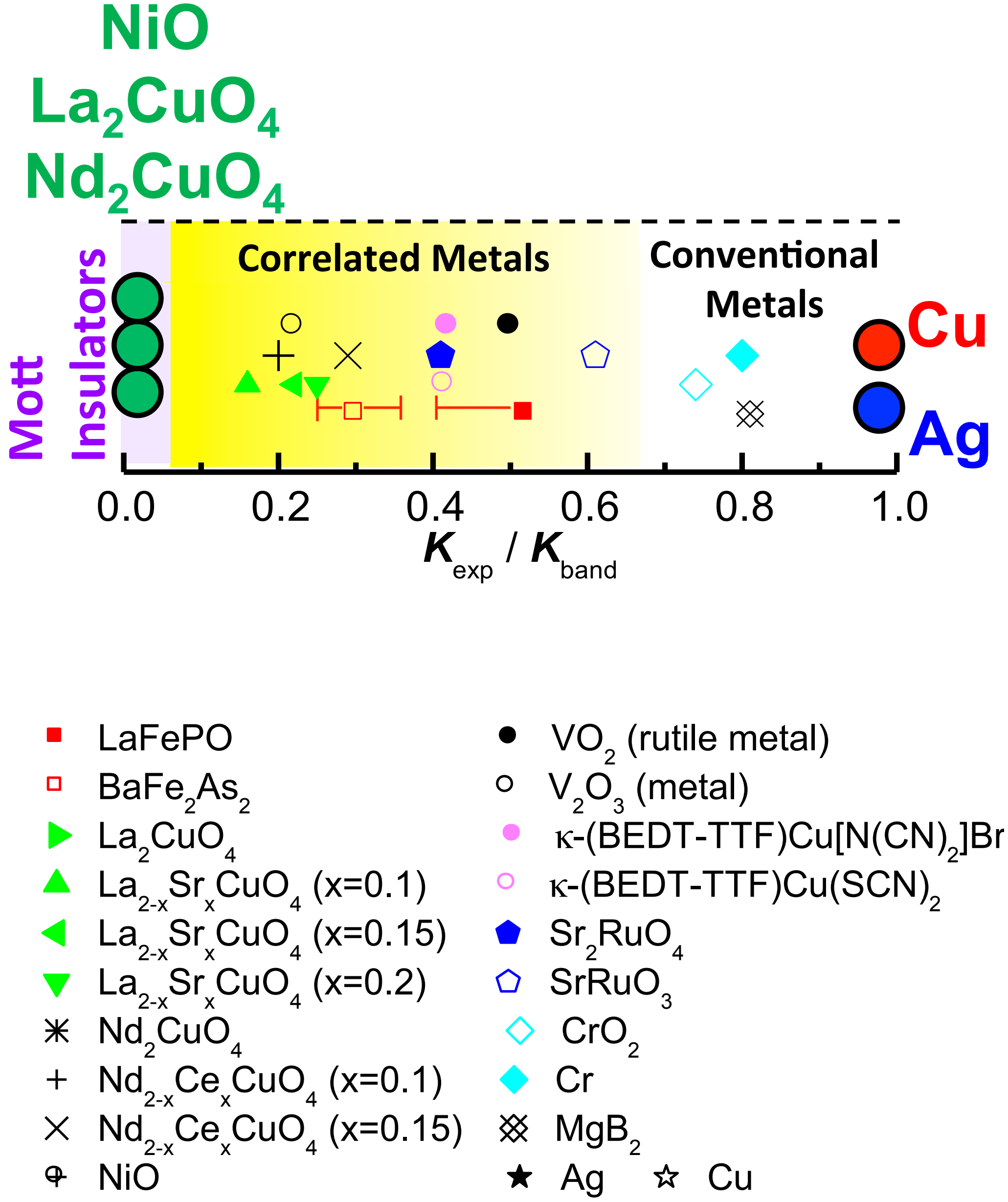

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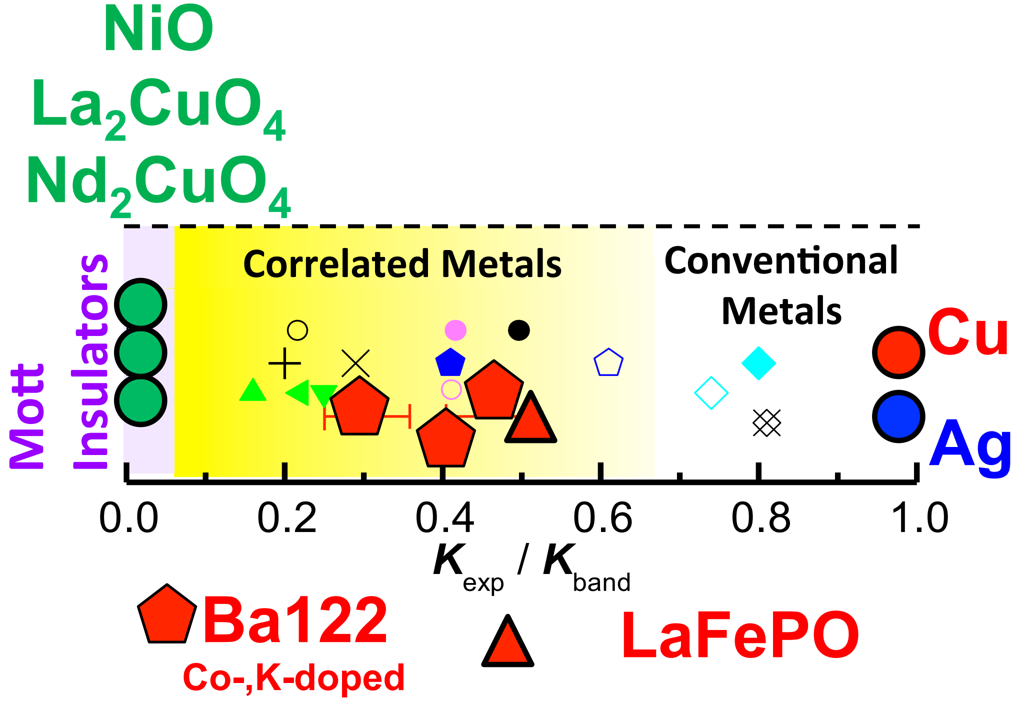

■ LaFePO
□ BaFe$_2$As$_2$
▶ La$_2$CuO$_4$
▲ La$_{2-x}$Sr$_x$CuO$_4$ (x=0.1)
◀ La$_{2-x}$Sr$_x$CuO$_4$ (x=0.15)
▼ La$_{2-x}$Sr$_x$CuO$_4$ (x=0.2)
✳ Nd$_2$CuO$_4$
\+ Nd$_{2-x}$Ce$_x$CuO$_4$ (x=0.1)
× Nd$_{2-x}$Ce$_x$CuO$_4$ (x=0.15)
⊕ NiO

● VO$_2$ (rutile metal)
○ V$_2$O$_3$ (metal)
● κ-(BEDT-TTF)Cu[N(CN)$_2$]Br
○ κ-(BEDT-TTF)Cu(SCN)$_2$
⬟ Sr$_2$RuO$_4$
⬠ SrRuO$_3$
◇ CrO$_2$
◆ Cr
⊗ MgB$_2$
★ Ag ☆ Cu

M.Qazilbash J. Hamlin, R. E. Baumbach, L. Zhang, D.J. Singh, M.B. Maple, and D.N. Basov et al. Nature-Physics 5, 647 (2009)
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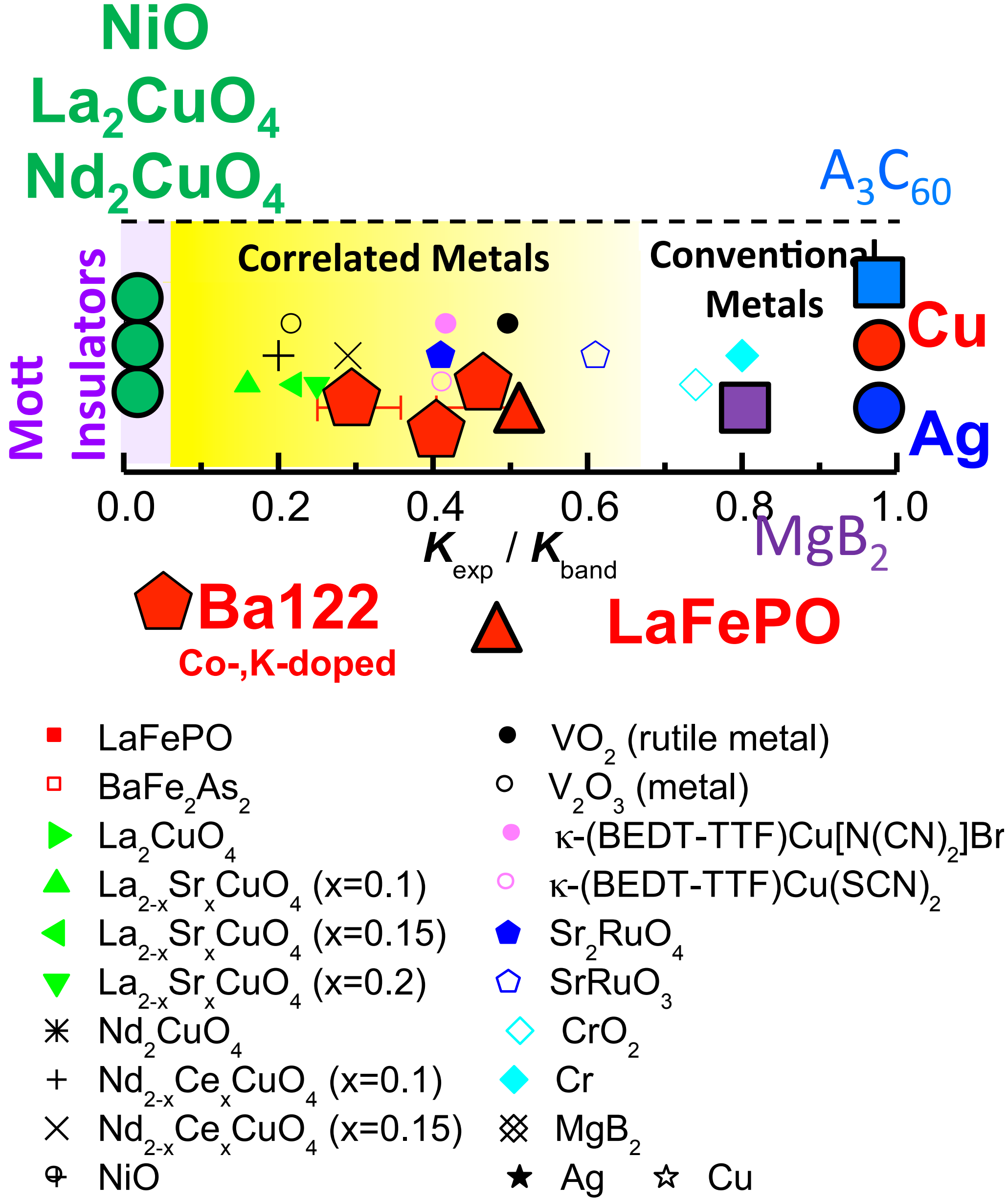

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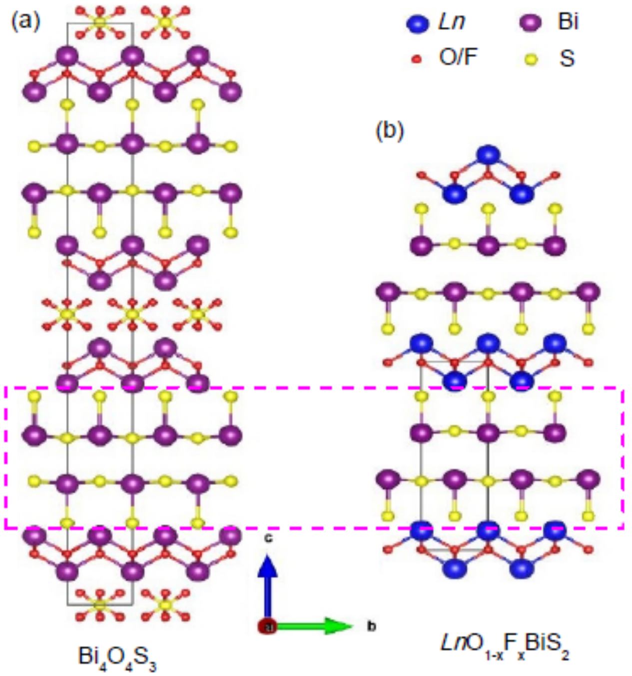
Superconductivity in BiS_2-based materials

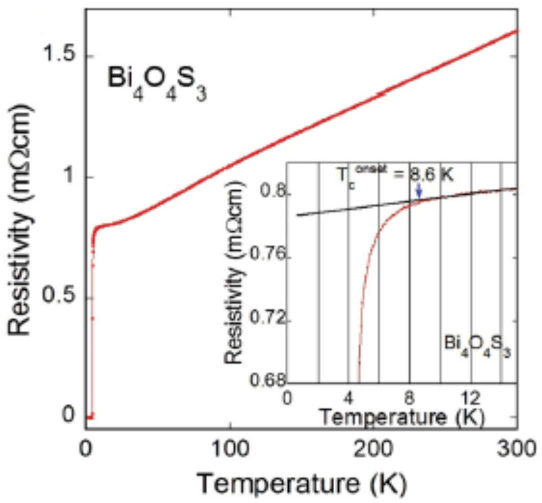


$Bi_6O_4S_4(SO_4)_{1-x}$

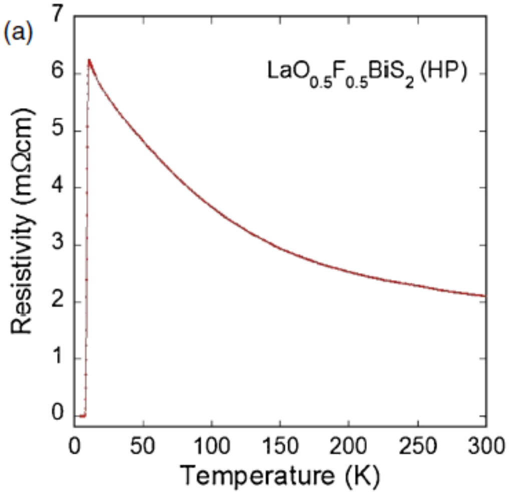
$Bi_4O_4S_3$ (x = 0.5)

$LaOBiS_2$

$CeOBiS_2$ structure



*Mizuguchi et al., PRB **86**, 220510(R) (2012)*

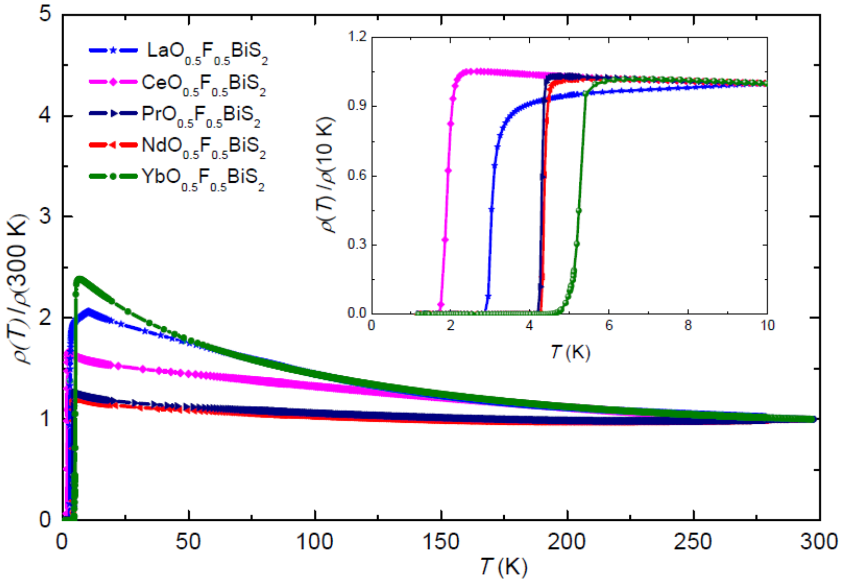


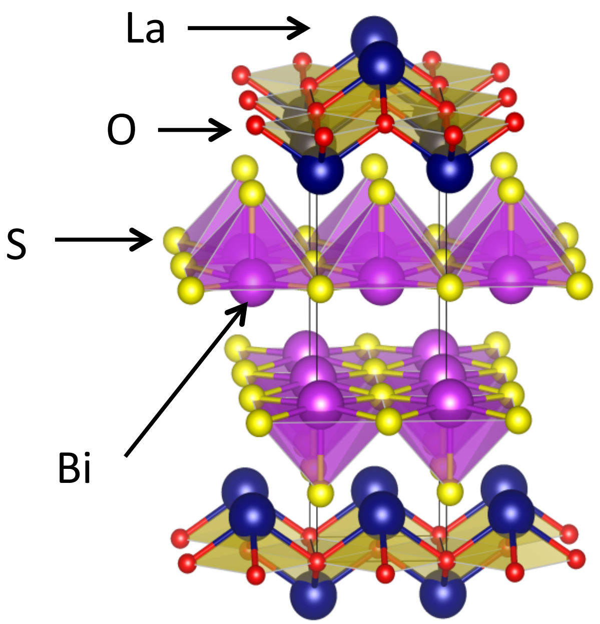
*Mizuguchi et al., JPSJ **81**, 114725 (2012)*

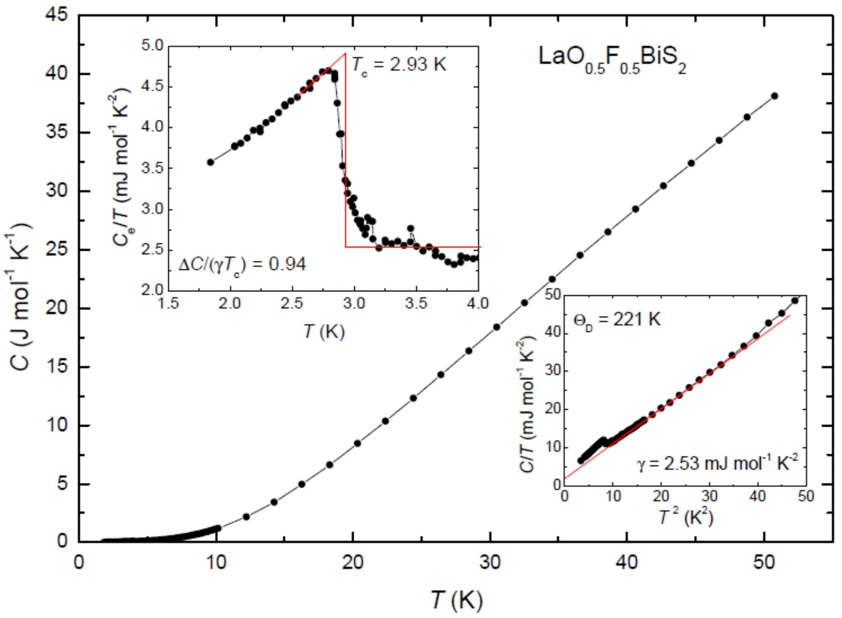
Material	T_c	Reference
$Bi_4O_4S_3$	4.7 K	*Mizuguchi et al., PRB **86**, 220510(R) (2012)*
$LaO_{0.5}F_{0.5}BiS_2$	10.6 K/3.1 K	*Mizuguchi et al., JPSJ **81**, 114725 (2012)*
$CeO_{0.5}F_{0.5}BiS_2$	1.89 K	*Yazici et al., and Xing et al., PRB **86**, 214518 (2012)*
$PrO_{0.5}F_{0.5}BiS_2$	4.29 K	*Yazici et al. and Jha et al., J. SC. Nov. Mag. **26**, 499 (2013)*
$NdO_{0.5}F_{0.5}BiS_2$	4.37 K	*Yazici et al. and Demura et al., J. Phys. Soc. Jpn.,**82** (2013)*
$YbO_{0.5}F_{0.5}BiS_2$	5.30 K	*Yazici et al., Phil. Mag. **93**, 673 (2013)*

Superconductivity in $LnO_{1-x}F_xBiS_2$ compounds

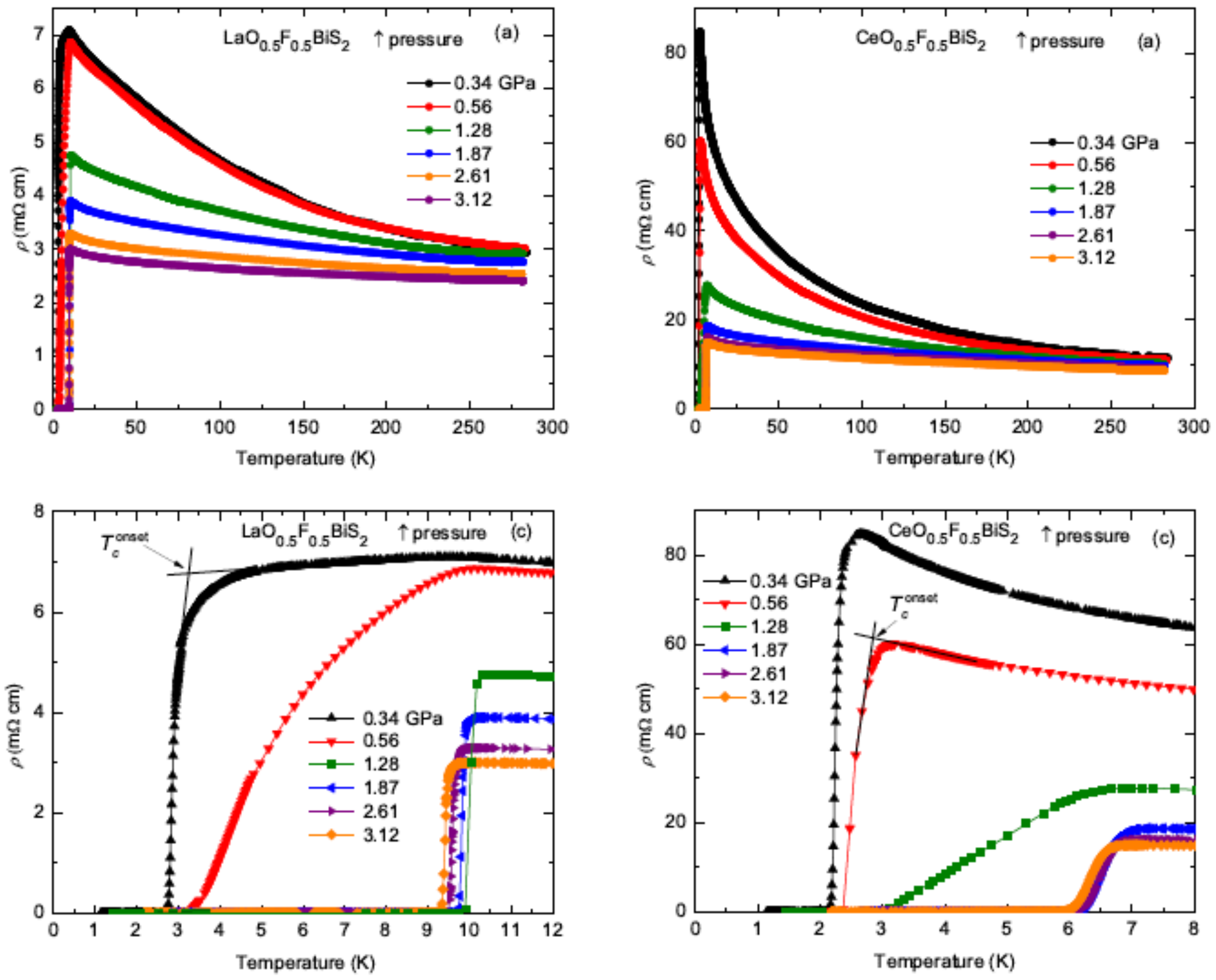
- SC of $LaO_{0.5}F_{0.5}BiS_2$ – $T_c \approx 8.5$ K (HP synthesis)
  Mizuguchi et al., JPSJ ***81****, 114725 (2012)*
- SC of $LnO_{0.5}F_{0.5}BiS_2$ for *Ln* = Ce, Pr, Nd, Yb (electron doping via F substitution)
  Yazici et al., Phil. Mag. ***93****, 673 (2013)*
- SC of $LnOBiS_2$ induced by electron doping via substitution of tetravalent Ti, Zr, Hf, Th
  Yazici et al., PRB ***87****, 174512 (2013)*







Electrical resistivity of $LnO_{05}F_{0.5}BiS_2$ (Ln = La, Ce) under pressure



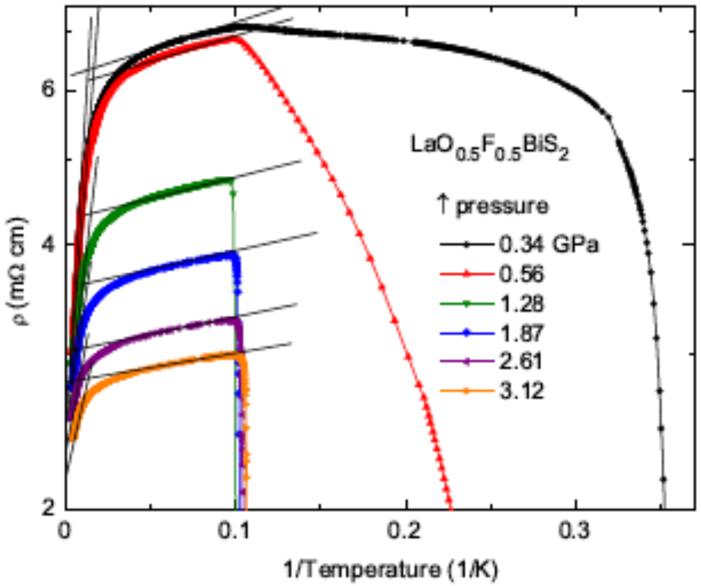
Left panel:
$LaO_{0.5}F_{0.5}BiS_2$

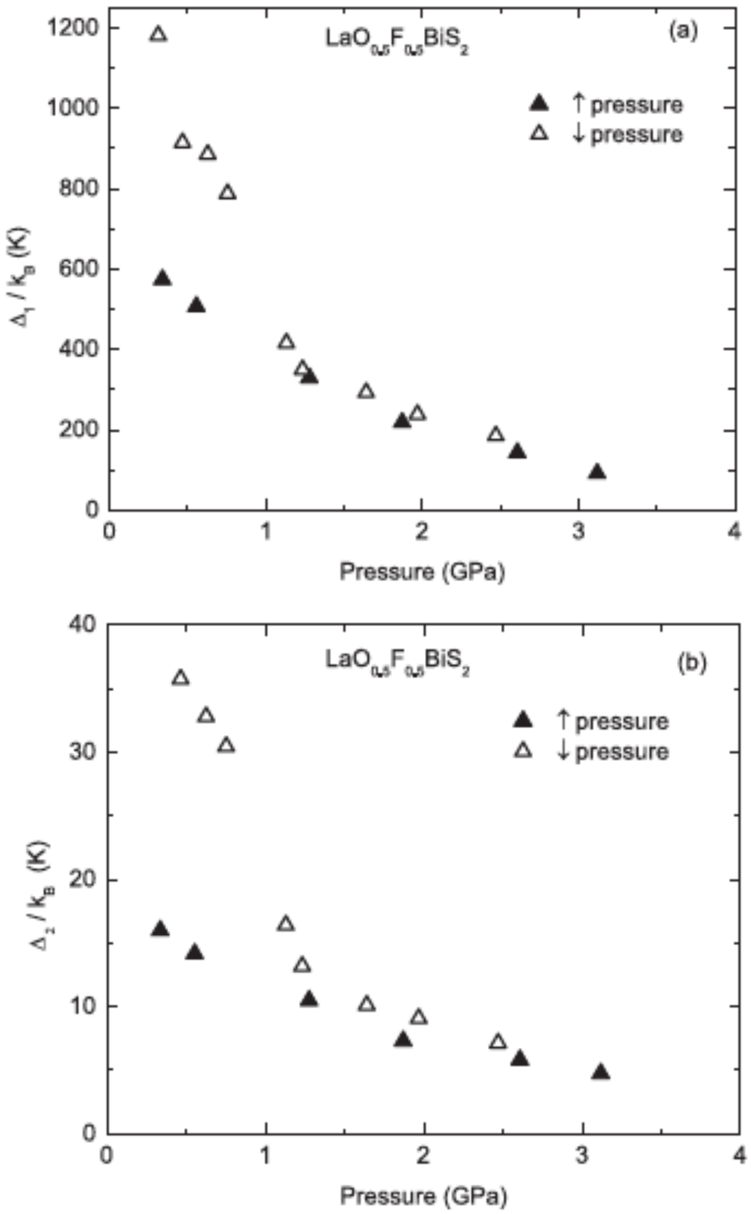
Right panel:
$CeO_{0.5}F_{0.5}BiS_2$

C. T. Wolowiec et al., Phys. Rev. B ***88****, 064503 (2013)*

- Reversible semiconductor-metal transition under *P*
- Reversible transition between low and high T_c superconducting phases under *P*

Semiconducting energy gaps for $LaO_{05}F_{0.5}BiS_2$

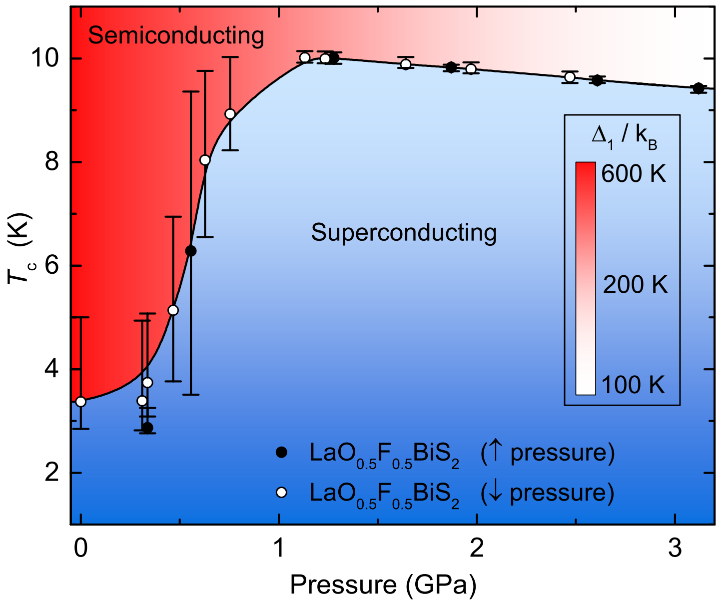


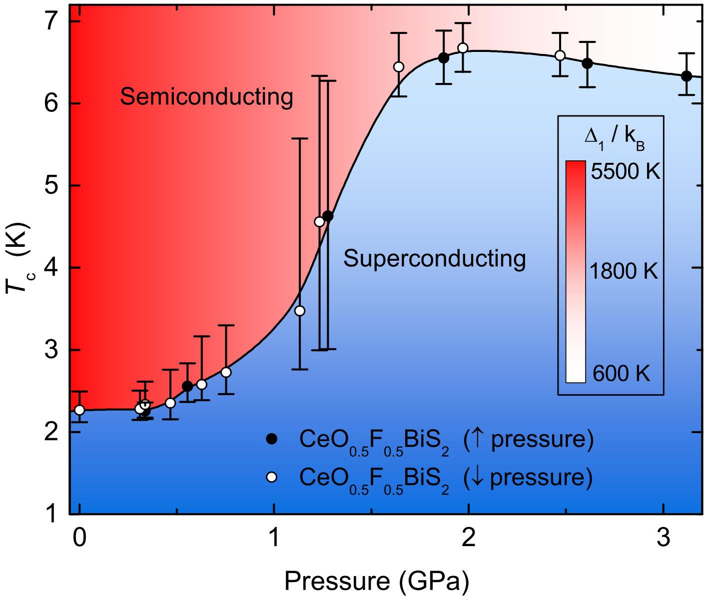


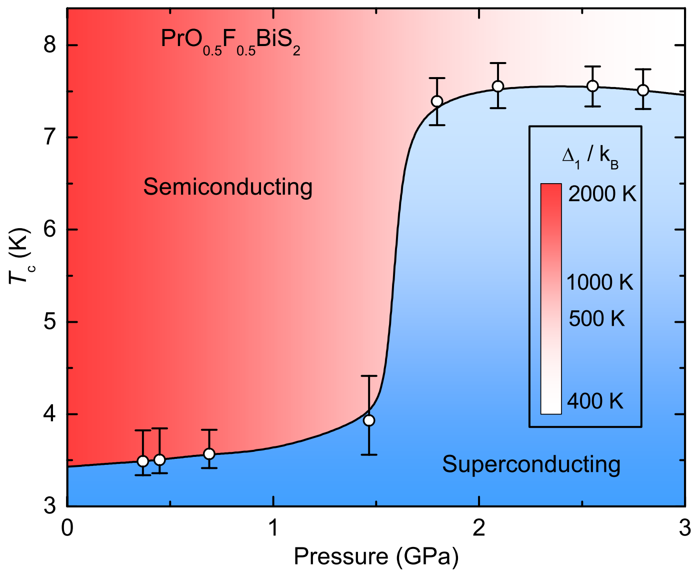
- $\rho(T) = \rho_o \exp(\Delta/T) \Rightarrow \ln[\rho(T)] = \ln(\rho_o) + \Delta/T$
- Extract Δ from plot of $\ln[\rho(T)]$ vs $1/T$
- $\Delta_1 \approx 600$ K and $\Delta_2 \approx 17$ K for P = 0.34 GPa
- Δ_1 and Δ_2 both decrease rapidly with P and exhibit kink near $P_t \approx 1.2$ GPa
- Δ_1 – intrinsic? Δ_2 – impurity level?
- Δ_1, Δ_2 hysteretic – $P < P_t$; reversible – $P > P_t$
- Similar results: *H. Kotegawa et al., J. Phys. Soc. Jpn. 81, 103702 (2012)*

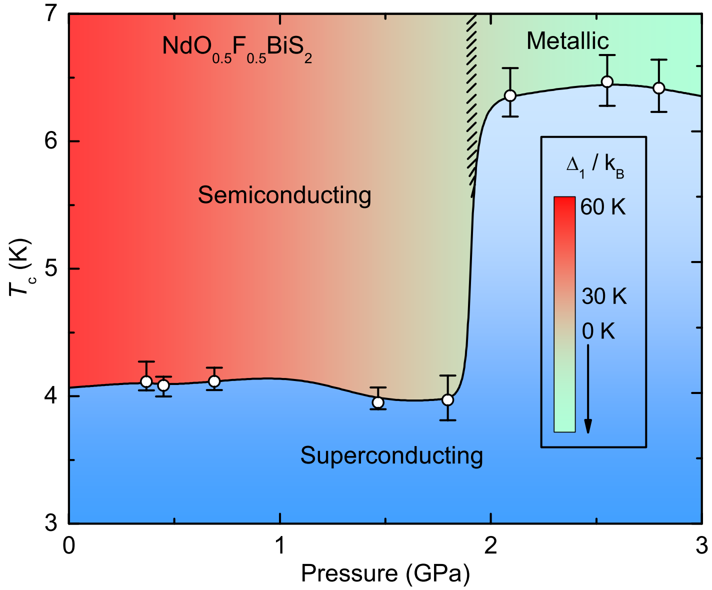
*C. T. Wolowiec, D. Yazici, B. D. White, K. Huang, M. B. Maple, Phys. Rev. B **88**, 064503 (2013)*

Pressure dependence of T_c and Δ_1 for $LnO_{05}F_{0.5}BiS_2$ (Ln = La, Ce, Pr, Nd)

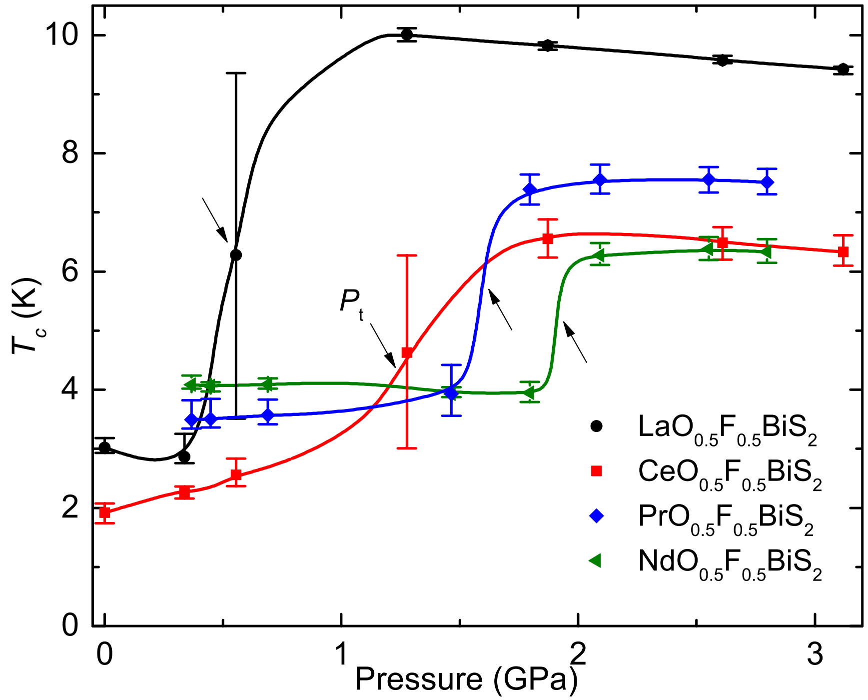


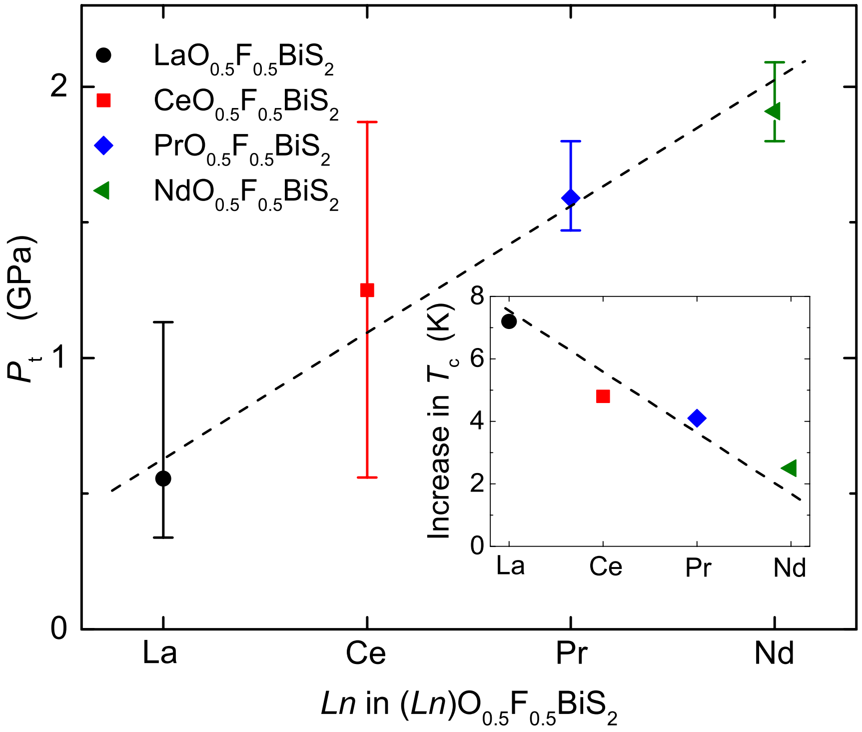






Transition pressure P_t vs rare earth atomic number



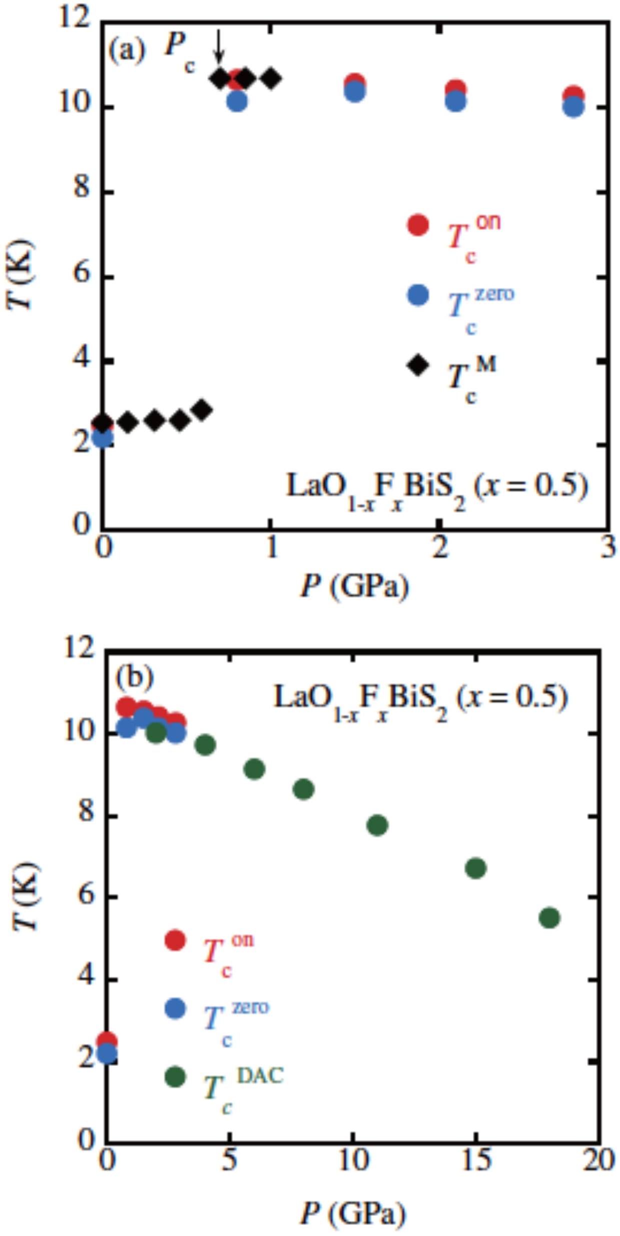


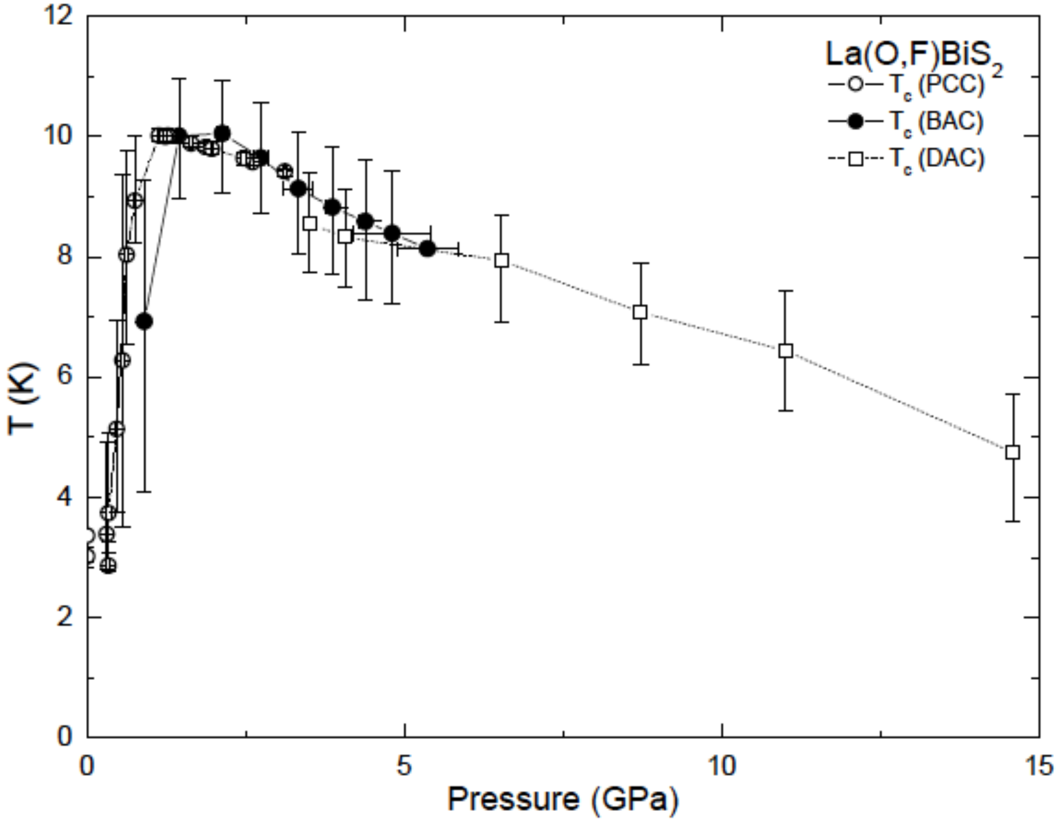
- P_t increases with *Ln* atomic number
- Increase in T_c at P_t decreases with Ln atomic number
- Conjecture: Structural transition occurs at P_t
- Evidence of structural transition at $P_t \approx 1$ GPa in $LaO_{0.5}F_{0.5}BiS_2$

  R. Kumar et al., 2013

  *T. Tomita et al., JPSJ **83**, 063704 (2014)*

Pressure dependence of T_c of $LaO_{0.5}F_{0.5}BiS_2$ to 20 GPa





C. A. McElroy et al. (2013) (UCSD)

*T. Tomita et al., JPSJ **83**, 063704 (2014)*

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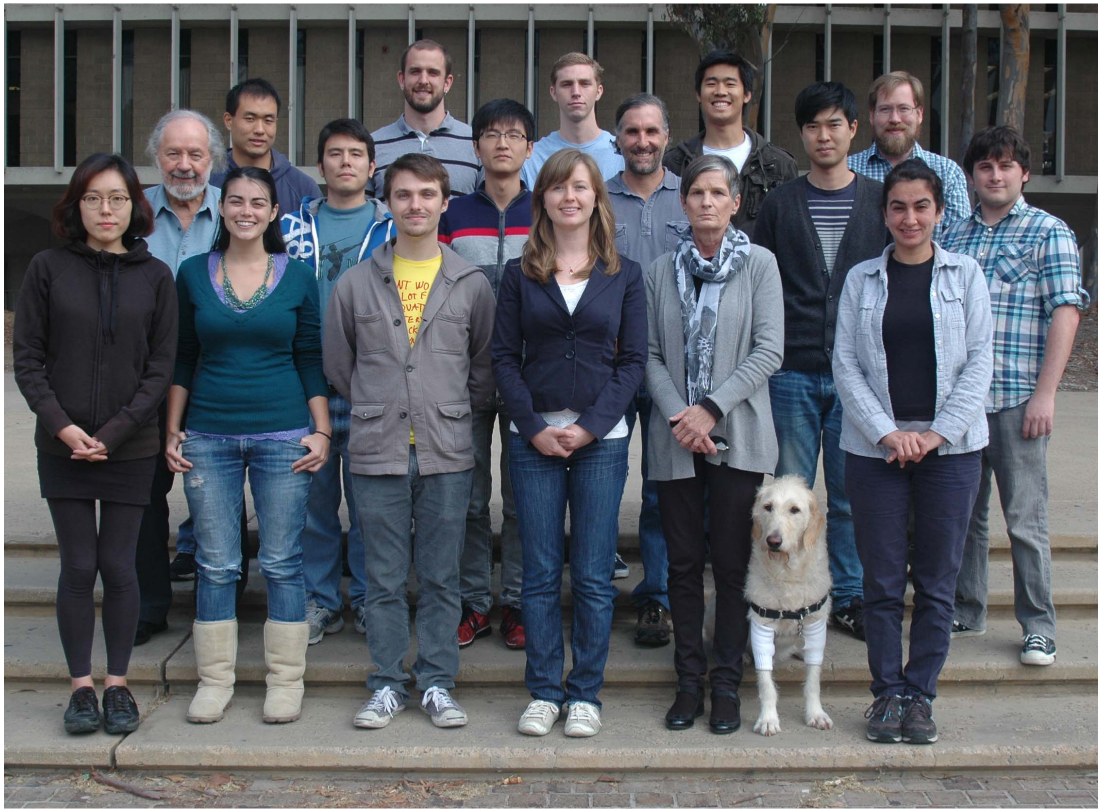
Summary

- Brief survey of the basic properties of heavy fermion f-electron, cuprate, and iron pnictide/chalcogenide materials
- "Unconventional" SC often found to "emerge" from a magnetically-ordered phase upon variation of chemical composition or pressure
- Evidence for pairing of SC'ing electrons via spin fluctuations
- Cannot exclude other pairing scenarios, especially for the cuprates
- No "smoking gun" test for pairing mechanisms – need preponderance of evidence!
- Correlated electron materials
- New class of layered SC's based on $LnOBiS_2$ parent compounds
- Have not discussed emergence of SC from other spin and charge ordered phases (e.g., FM – UGe_2; CDW – $LnTe_3$; quadrupolar order – $PrOs_4Sb_{12}$; "hidden order" – URu_2Si_2)

Prospects for the future

- Many new superconducting materials with high (and, hopefully, higher!) values of T_c remain to be discovered
- Superconductivity near room temperature no longer seems impossible!
- Where should one look for new high T_c superconductors?
- A new set of guiding principles to replace Matthias' "rules" is suggested by the superconductors with the highest values of T_c (> 40 K)
- One might look for:
    - ✦ Correlated electron materials
    - ✦ Complex materials containing many different types of atoms
    - ✦ Materials containing elements with partially-filled d- and f-electron shells
    - ✦ Materials containing oxygen
    - ✦ Materials with layered crystal structures with low symmetry
    - ✦ Materials that exhibit magnetism
    - ✦ Probably not a good idea to avoid theorists

UCSD RESEARCH GROUP



CURRENT GROUP

Alex Breindel
Kevin Huang
Sooyoung Jang
Inho Jeon
Nor Kanchanavatee
Colin McElroy
Naveen Pouse
Duygu Yazici
Christine Coffey (Assistant)
Camus ("Lab"radoodle)
Ben White
Chris Wolowiec

RECENT GROUP ALUMNI

Ryan Baumbach (NHMFL, FSU)
Eric Bauer (LANL)
Nick Butch (NIST)
James Hamlin (UF)
Pei-Chun Ho (CSU, Fresno)
Marc Janoschek (LANL)
Jason Jeffries (LLNL)

Johnpierre Paglioni (U. Maryland)
Todd Sayles (Quantum Design)
Lei Shu (Fudan U., China)
Ben Taylor (SPAWAR)
Tatsuya Yanagisawa (Hokkaido U.)
Vivien Zapf (NHMFL, LANL)
Diego Zocco (KIT, Germany)

END