Phase diagram of the cuprates: Where is the mystery?

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VERITATEM IN CHARITATE

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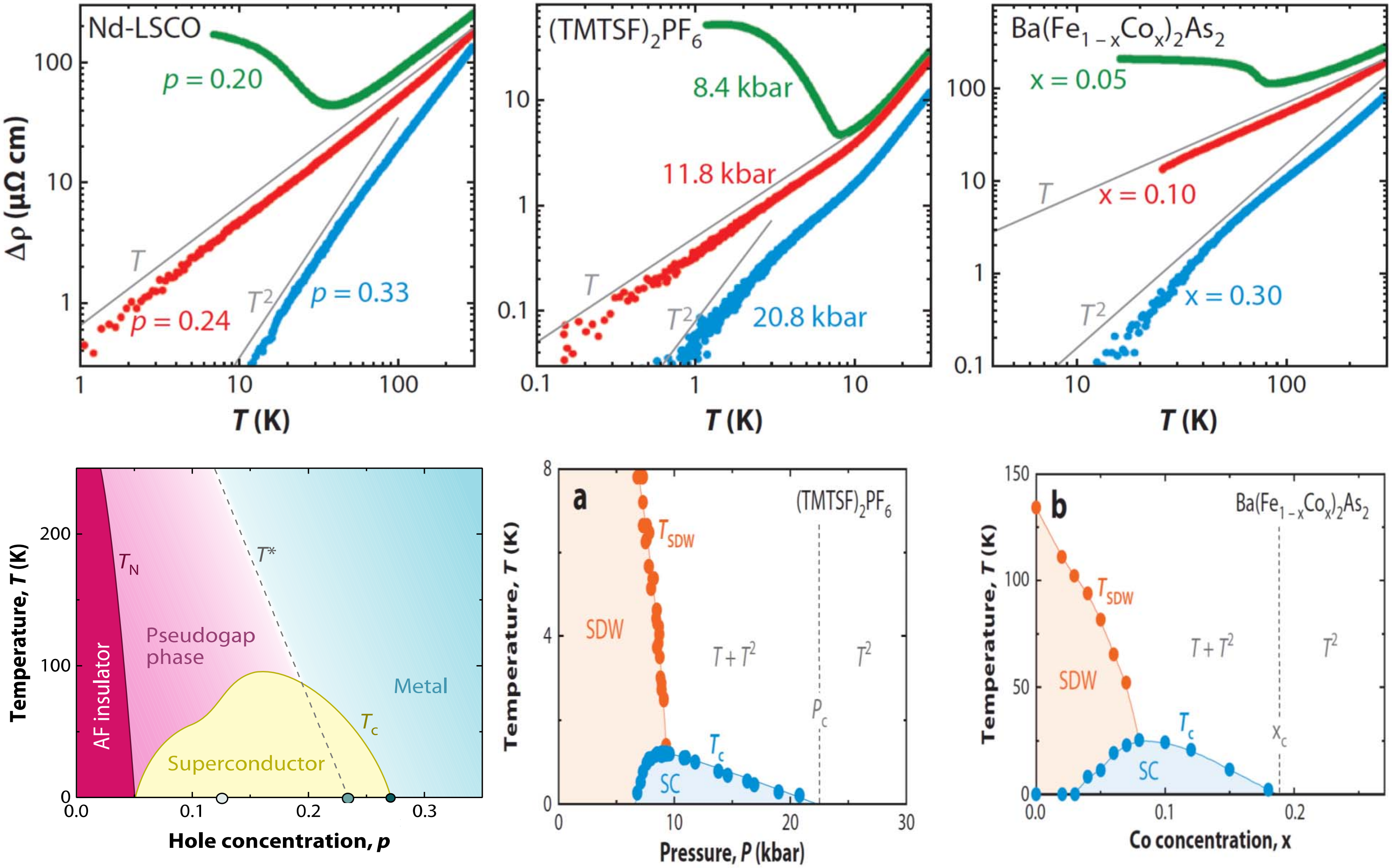
I- Similarities between phase diagram and quantum critical points

Quantum Criticality in 3 Families of Superconductors



L. Taillefer, Annual Reviews of CMP 2010

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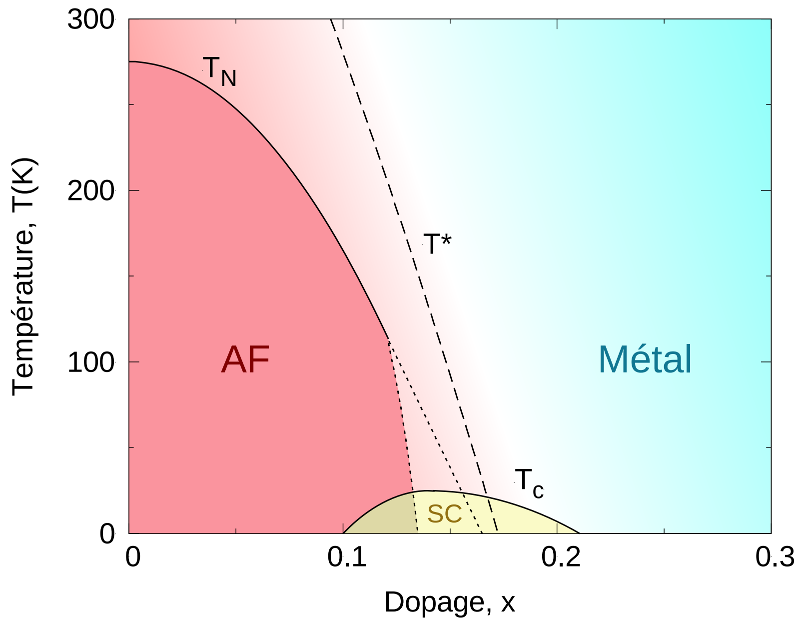
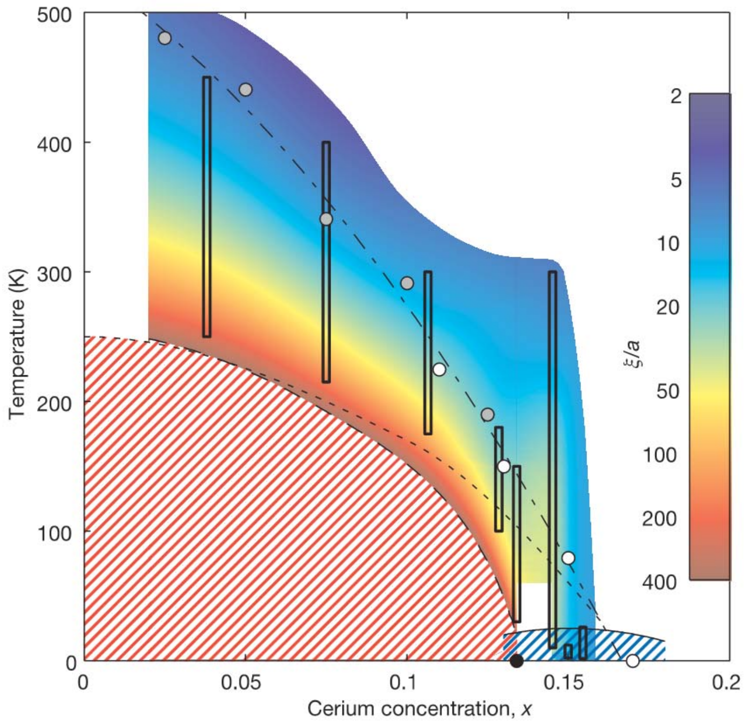
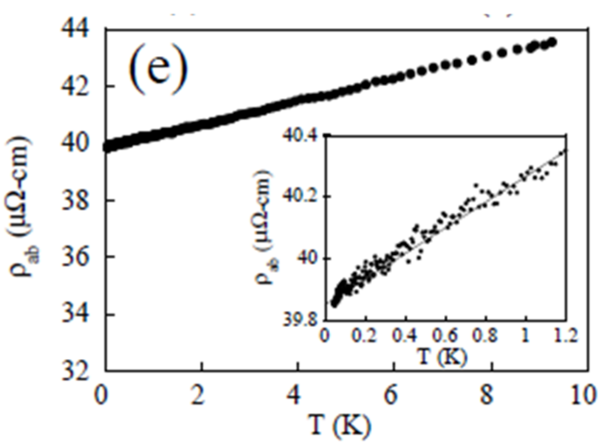
Electron-doped cuprates



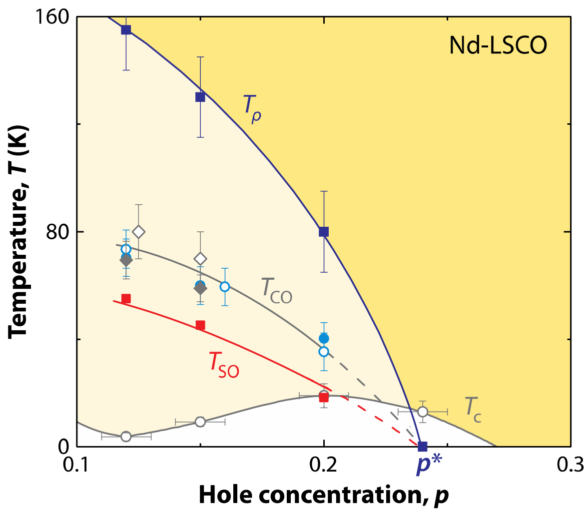


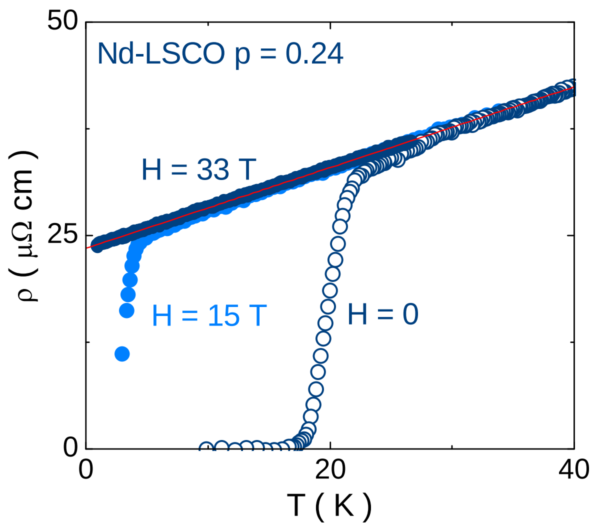
PCCO

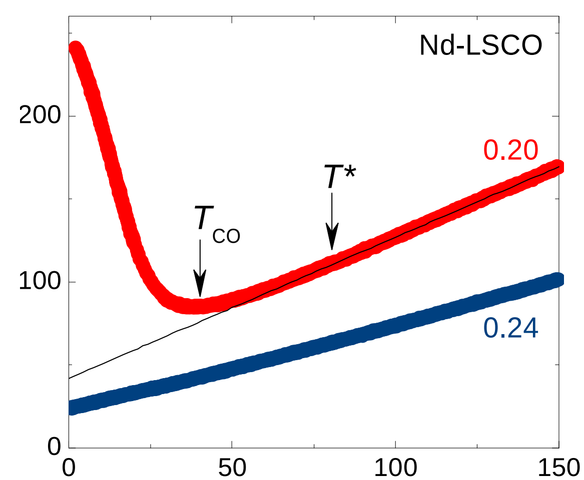


Fournier et al. PRL **81**, 4720 (1998)

Quantum critical point







Neutrons: Ichikawa *et al.*, PRL 2000

NMR: Hunt *et al.*, PRB 2001

X-rays: Niemoller *et al.*, EPJB 1999

$T^* \sim 2\ T_{CO}$

Daou *et al.*, Nature Physics 2009

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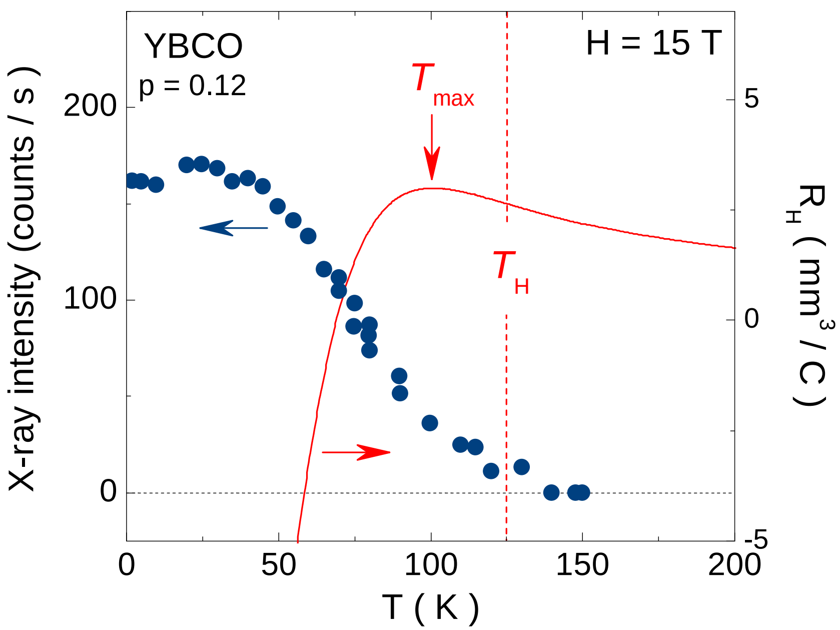
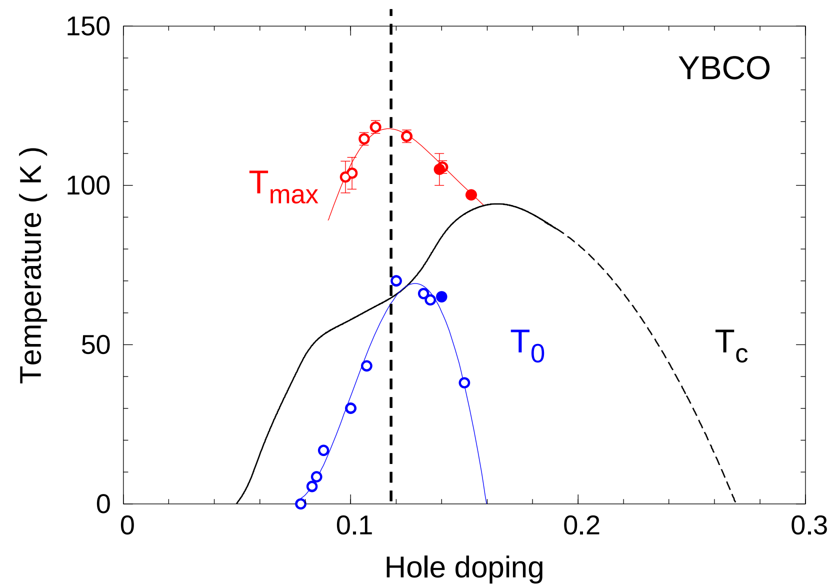
II- Charge order is the competing phase in the hole-doped cuprates

Charge order & FS reconstruction

YBCO





Charge order causes Fermi-surface reconstruction

X-rays: Chang *et al.*, Nature Physics 2012

Hall: LeBoeuf *et al.*, Nature 2007

LeBoeuf *et al.*, PRB 2011

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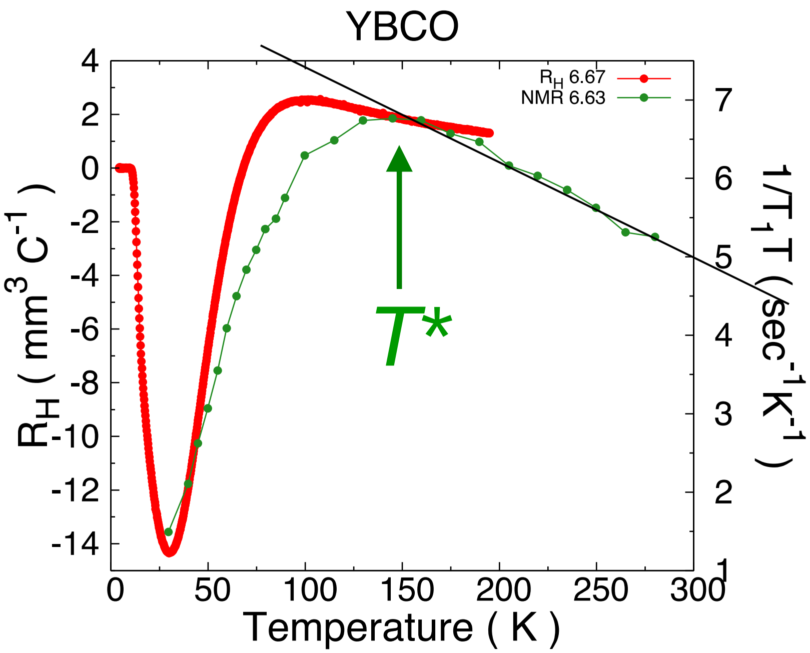
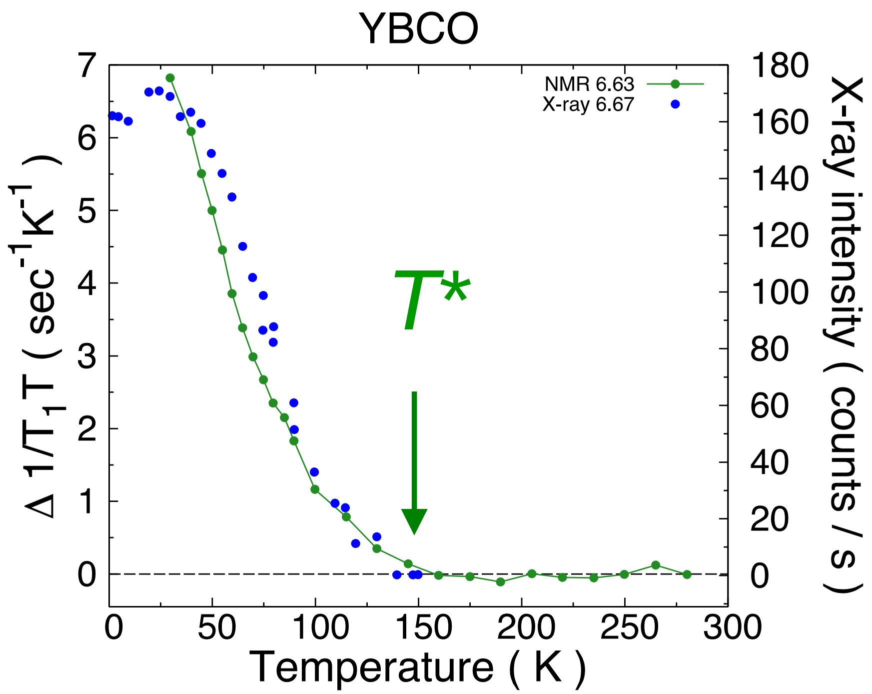
Pseudogap phase
YBCO

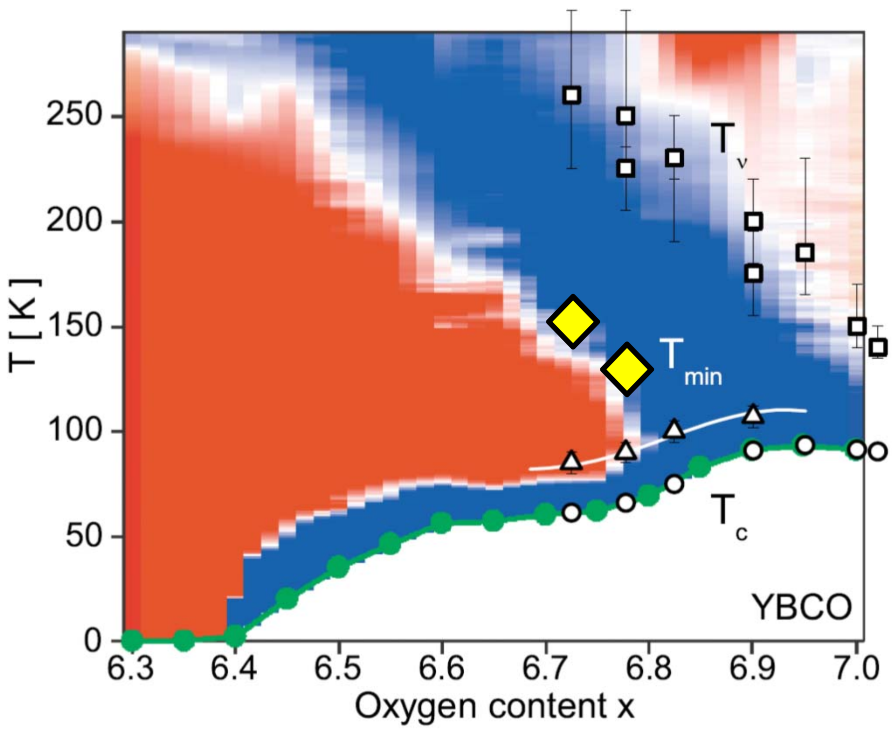
NMR



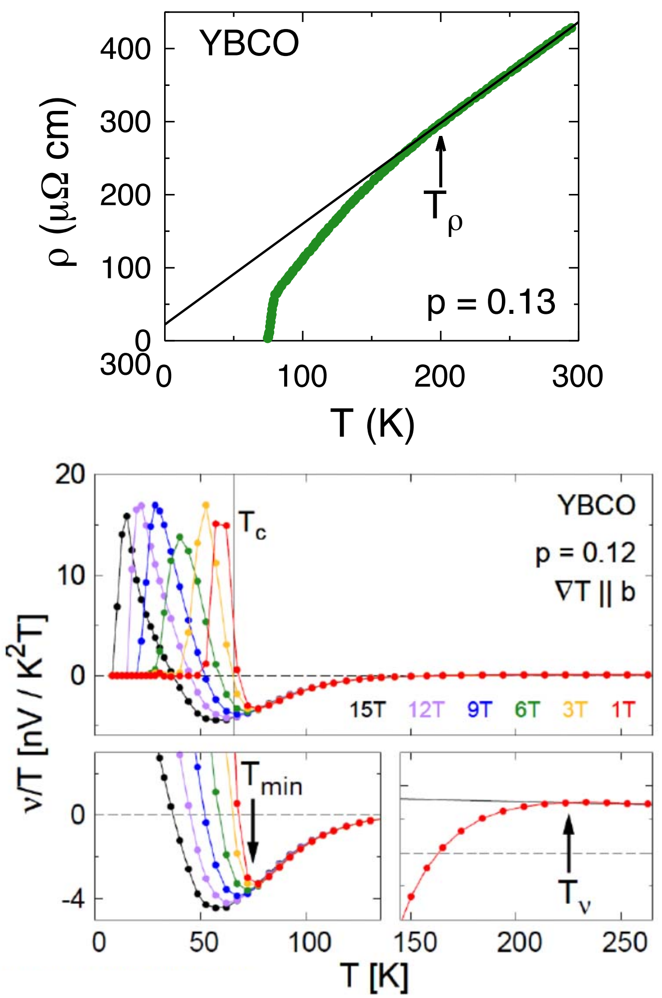


Pseudogap regime

YBCO



CDW onset :



Color map : Ando *et al.*, PRL 2004

Daou *et al.*, *Nature* **463**, 519 (2010)

III- Coefficient of linear term vs Tc

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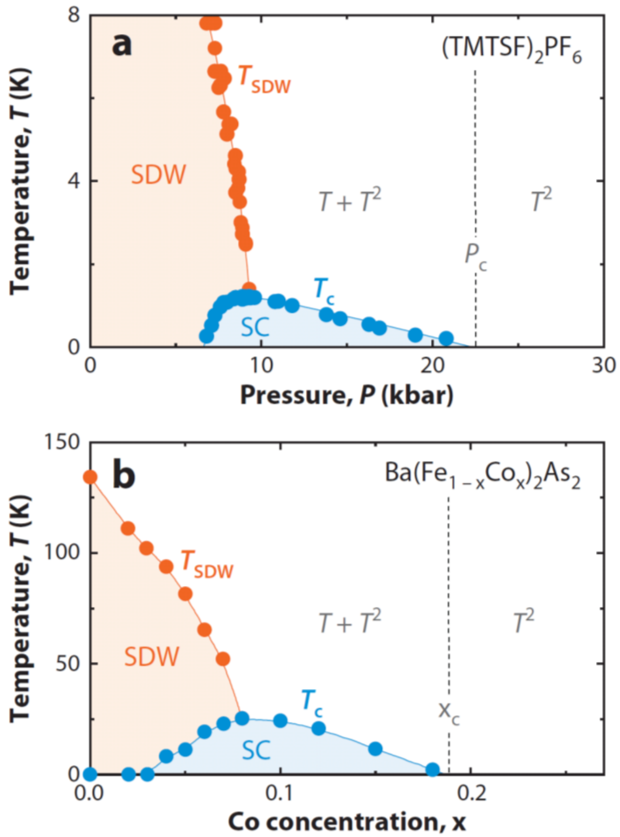
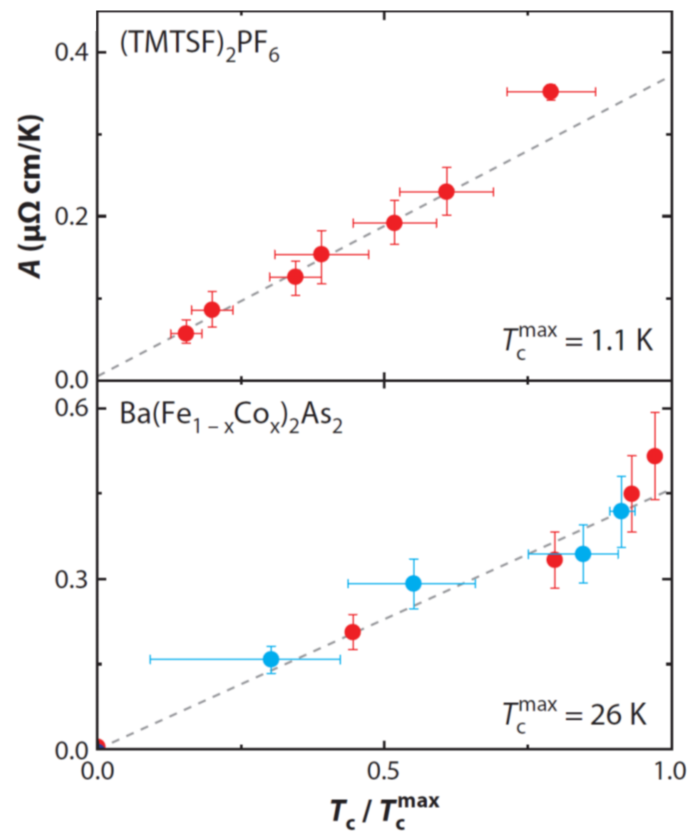
Organics & Pnictides

Bourbonnais, Sedeki, 2012

Organic

Pnictide

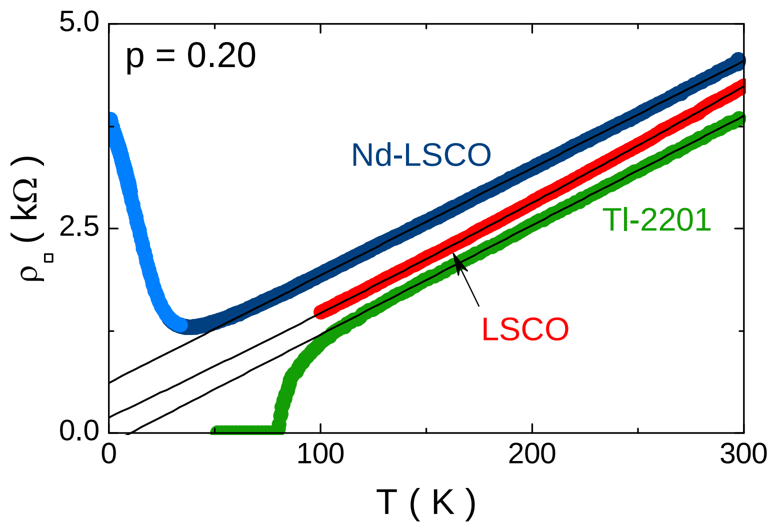


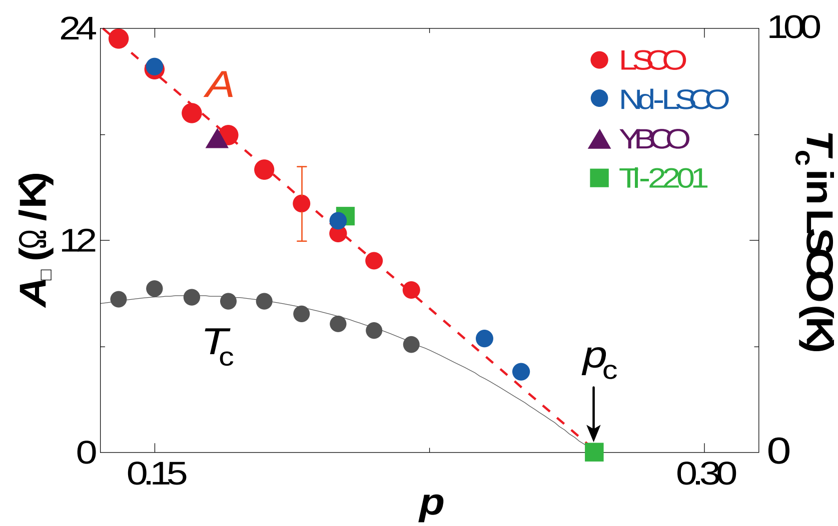


Doiron-Leyraud et al., PRB ***80****, 214531 (2009)*

Hole-doped cuprates

Linear-T resistivity





Linear-T resistivity is universal in hole-doped cuprates

Correlation between linear-T resistivity and T_c

Doiron-Leyraud *et al.*, arXiv:0905.0964

Taillefer, Annual Review of CMP **1**, 51 (2010)

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Outline

- Phases of matter: Strong vs weak coupling
- Standard model: pillars
- Breakdown of band theory + BCS
- Model
- QCP in e-doped near optimal doping
- Hole –doped cuprates as doped Mott insulators.

What is a phase of matter?

« Phase » and emergent properties

- Emergent properties
  - e.g. Fermi surface
    - Shiny
    - Quantum oscillations (in B field)
- Many microscopic models will do the same
  - Electrons in box or atoms in solid, Fermi surface
  - Often hard to « derive » from first principles (fractionalization - gauge theories)

Antiferromagnetic phase: emergent properties

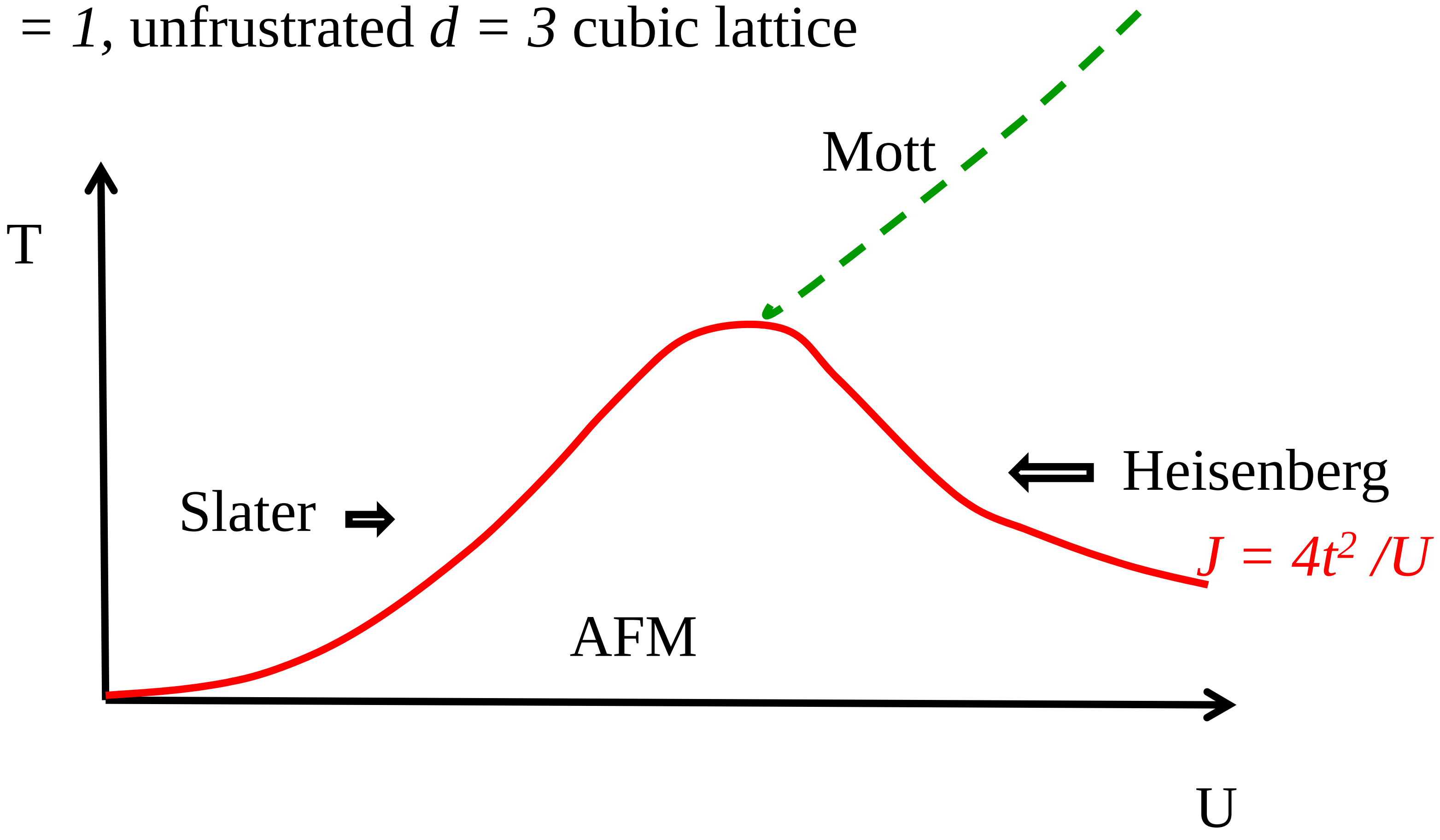
- Some broken symmetries
  - Time reversal symmetry
  - Translation by one lattice spacing
  - Unbroken Time-reversal times translation by lattice vector **a**
- – Spin waves
- – Single-particle gap

Differences between weakly and strongly correlated

- Different in ordered phase (finite frequency)
  - Ordered moment
  - Landau damping
    - Spin waves all the way or not to J
- Different, even more, in the normal state:
  - metallic in $d = 3$ if weakly correlated
  - Insulating if strongly correlated

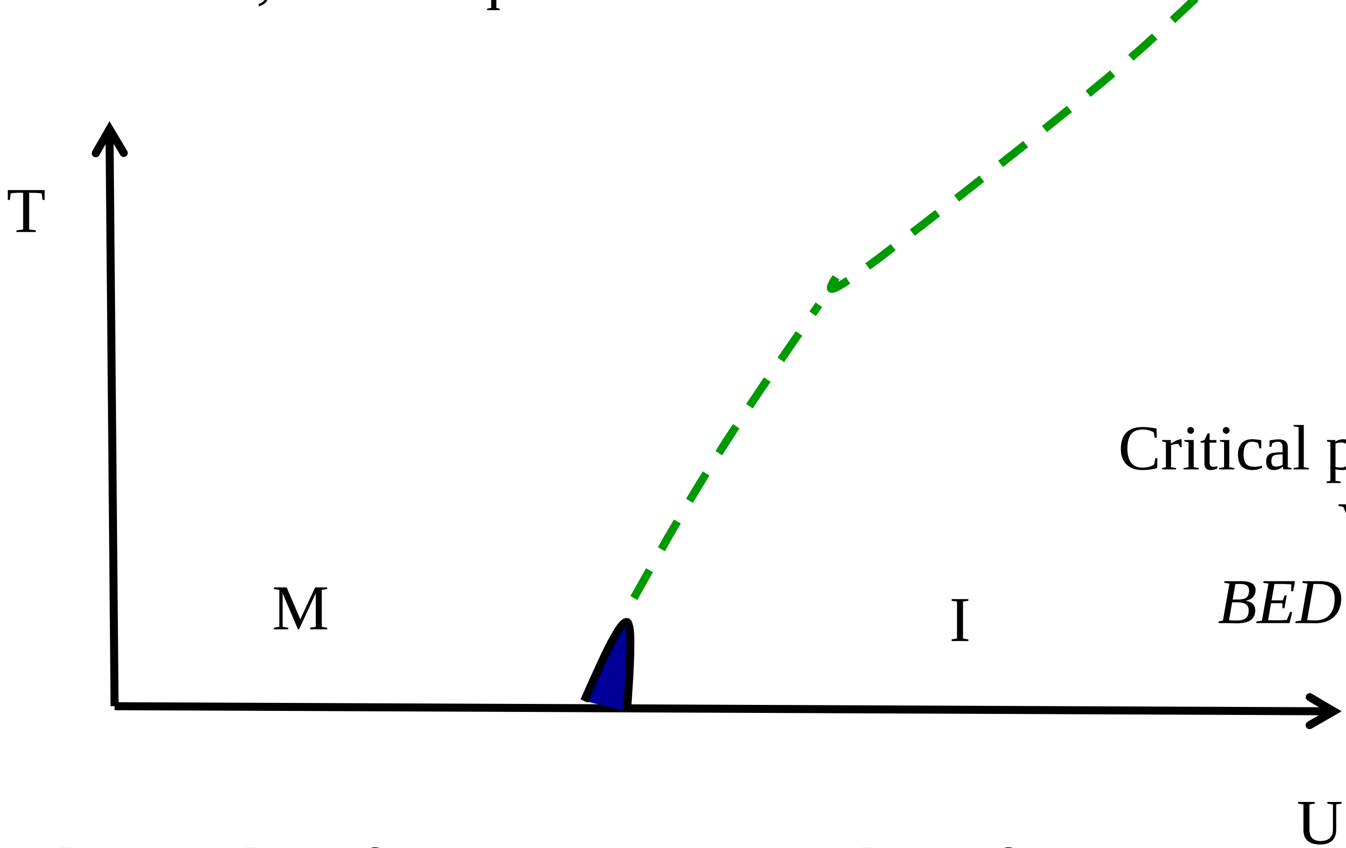
Local moment and Mott transition

n = 1, unfrustrated *d = 3* cubic lattice



Local moment and Mott transition

n = 1, d = 2 square lattice



Critical point visible in V_2O_3,
BEDT organics

Understanding finite temperature phase from a *mean-field theory* down to $T = 0$

Superconducting phase: identical properties

- Emergent:
  - Same broken symmetry *U(1)* for s-wave,
  - *U(1)* and C_{4v} for d-wave
  - Single-Particle gap, point or line node.
    - *T* dependence of C_p and κ at low *T*
  - Goldstone modes (Higgs)

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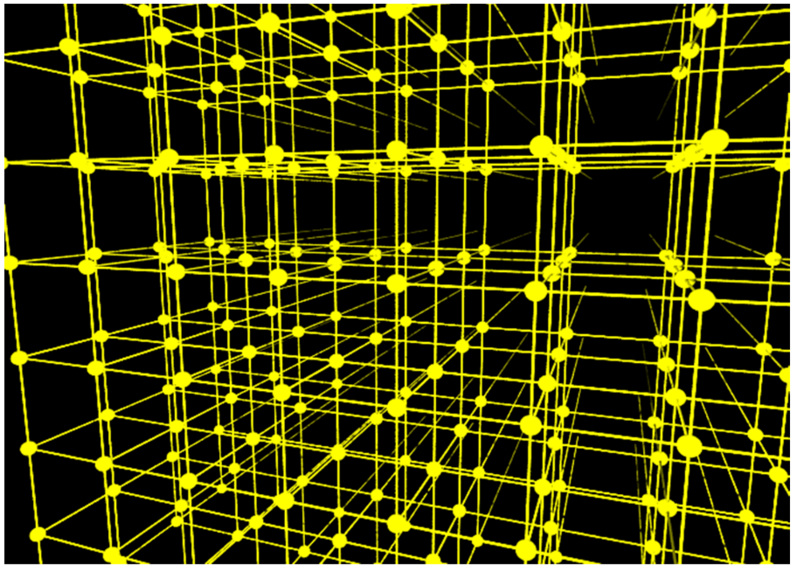
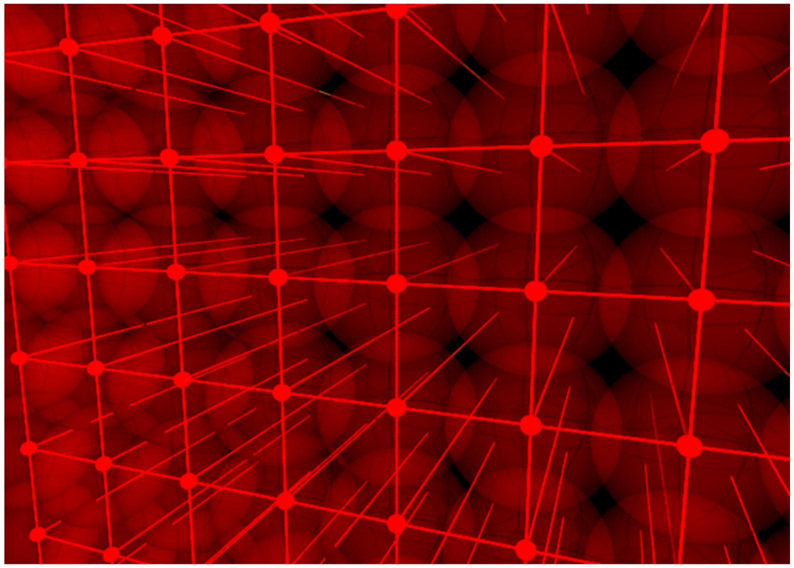
Superconductivity not universal even with phonons: weak or strong coupling

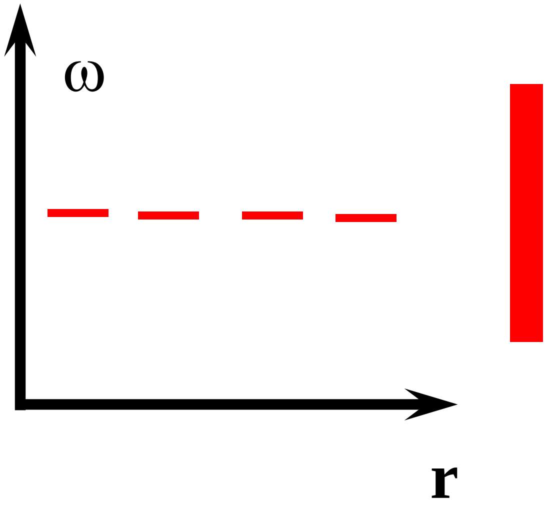
- In BCS universal ratios: e.g. $\Delta/k_B T_c$
  - Would never know the mechanism for sure if only BCS!

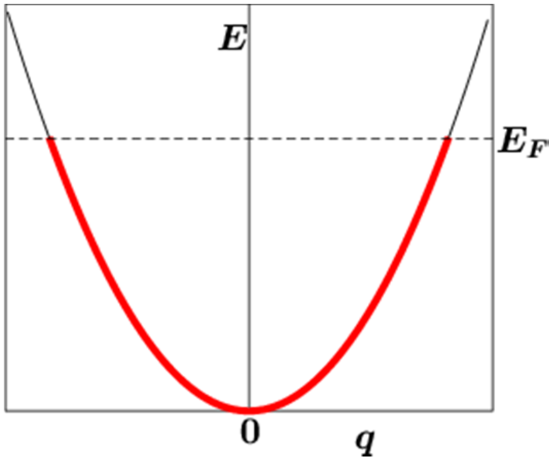
Two pilars of Solid State Physics

How to make a metal





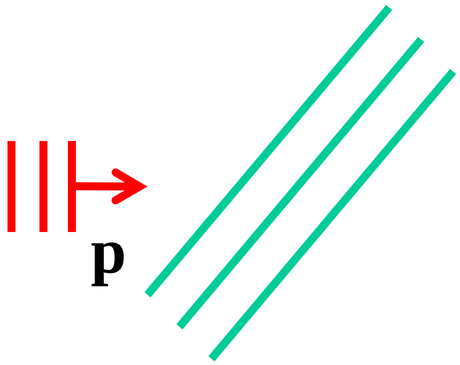




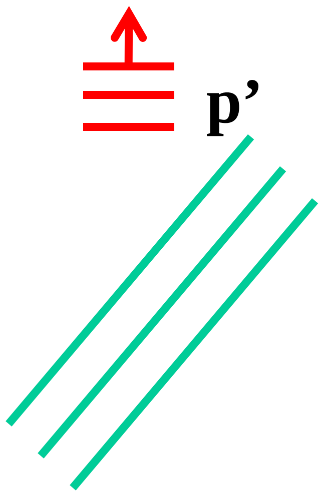
Courtesy, S. Julian

Superconductivity

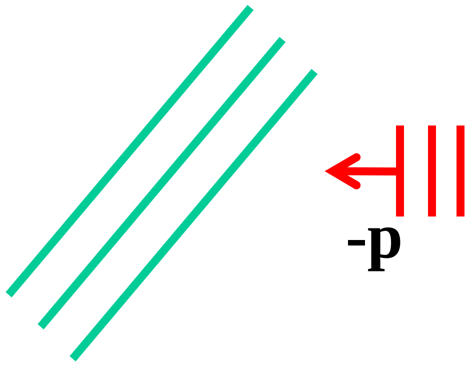
Attraction mechanism in the metallic state



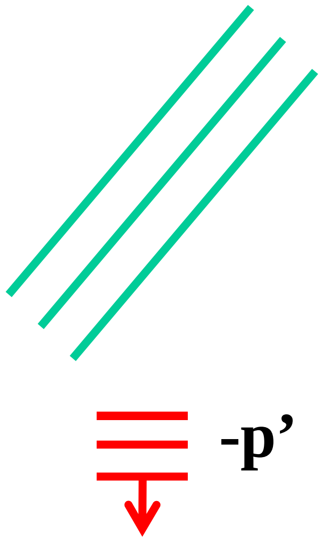
Attraction mechanism in the metallic state



Attraction mechanism in the metallic state



Attraction mechanism in the metallic state



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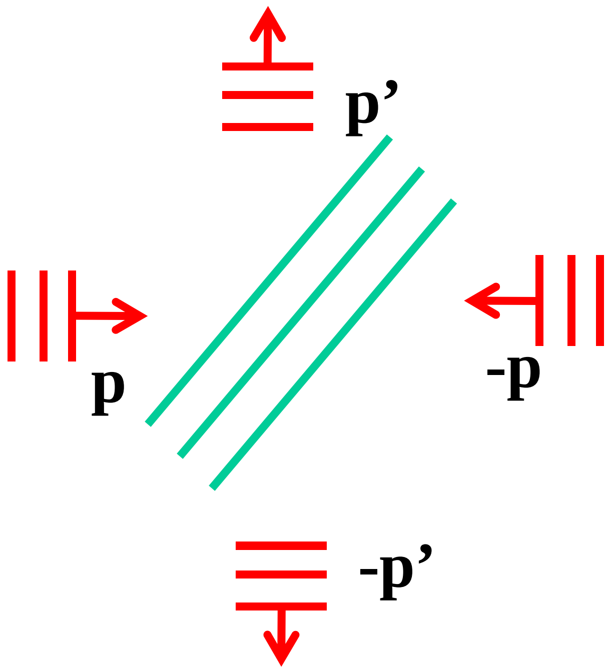
Attraction mechanism in the metallic state



#1 Cooper pair, #2 Phase coherence

$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow}$$

$$E_P = \sum_{\mathbf{p},\mathbf{p}'} U_{\mathbf{p}-\mathbf{p}'} \left(\langle \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \rangle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} + \psi_{\mathbf{p}\uparrow,-\mathbf{p}\downarrow} \left\langle \psi^*_{\mathbf{p}'\uparrow,-\mathbf{p}'\downarrow} \right\rangle \right)$$

$$|\mathrm{BCS}(\theta)\rangle = \ldots + e^{iN\theta}|N\rangle + e^{i(N+2)\theta}|N+2\rangle + \ldots.$$

Breakdown of band theory
Half-filled band is metallic?

Half-filled band: Not always a metal

NiO, Boer and Verway

Peierls, 1937

Mott, 1949

« Conventional » Mott transition

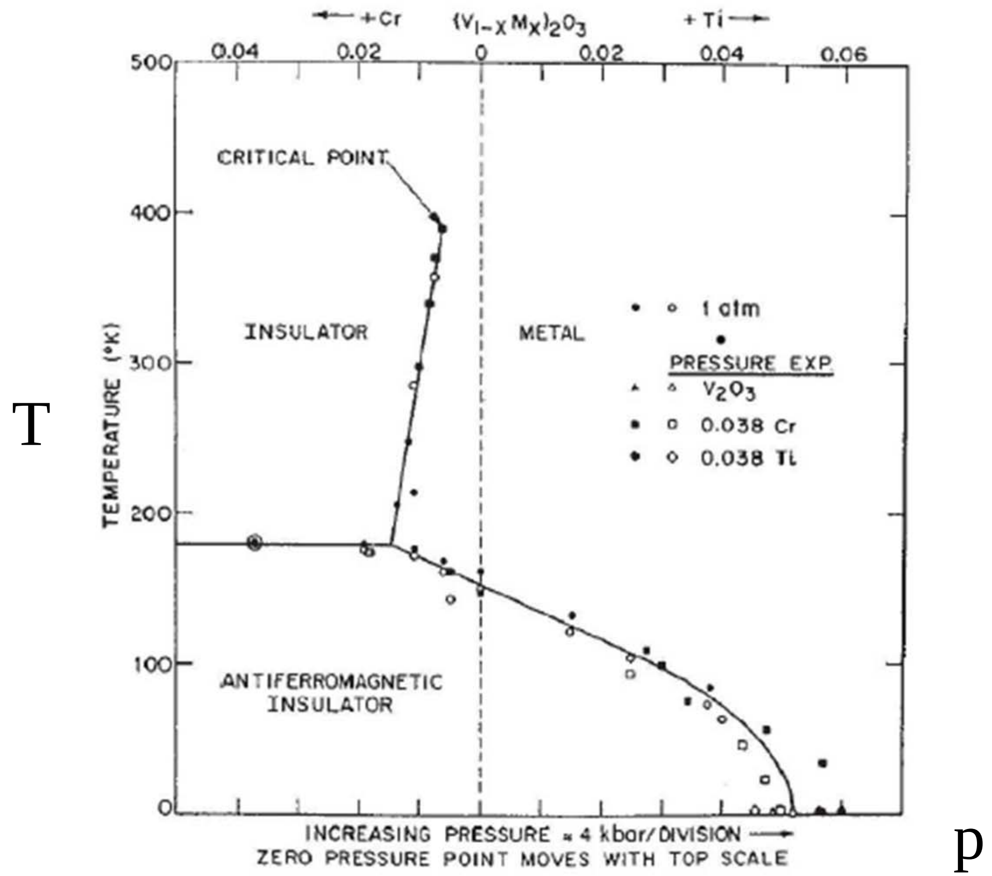
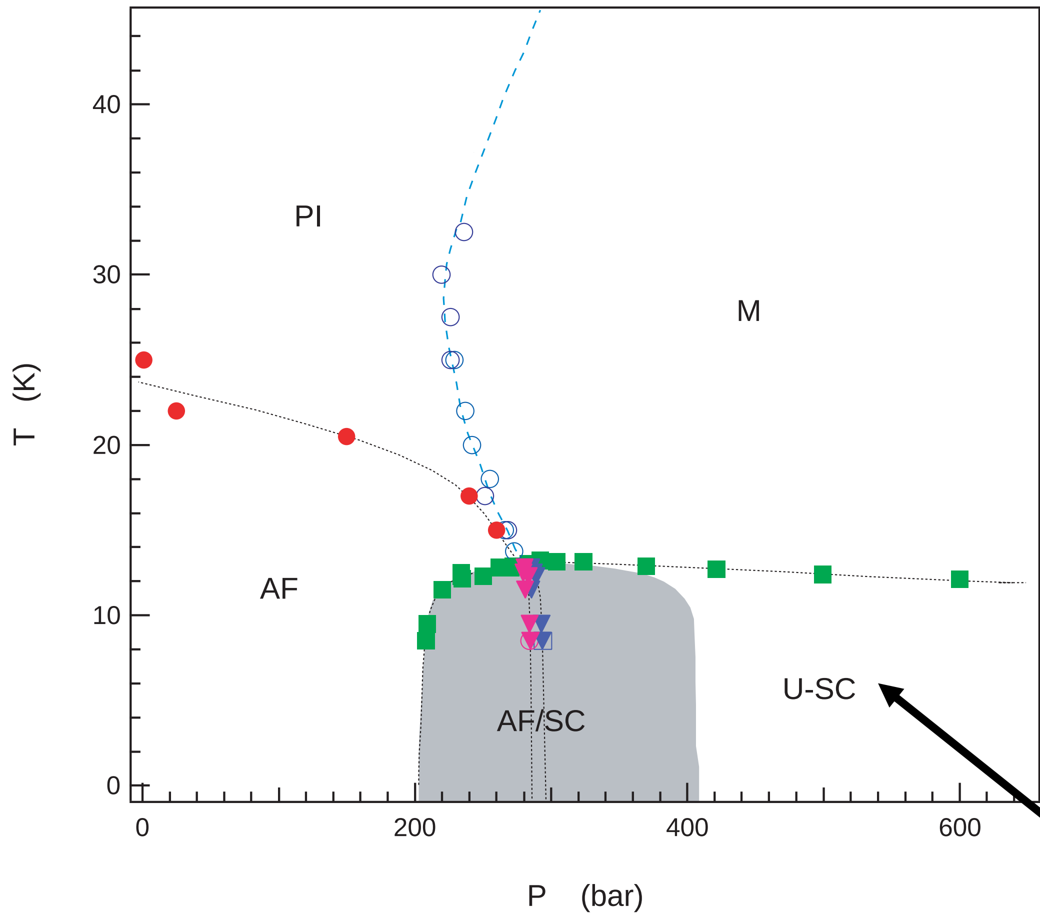
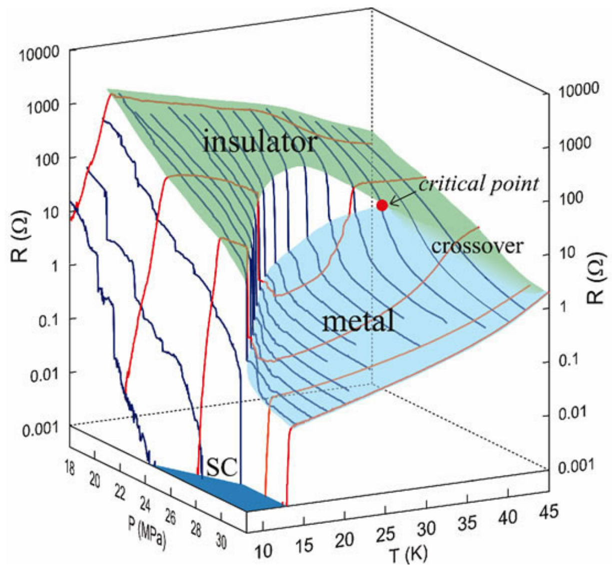


Figure: McWhan, PRB 1970; Limelette, Science 2003

Experimental phase diagram for Cl





F. Kagawa, K. Miyagawa, + K. Kanoda
PRB **69** (2004) +Nature **436** (2005)

B_g for C_{2h} and B_{2g} for D_{2h}

Powell, McKenzie cond-mat/0607078

Phase diagram (X=$Cu[N(CN)_2]Cl$)

S. Lefebvre et al. PRL **85**, 5420 (2000), P. Limelette, et al. PRL 91 (2003)

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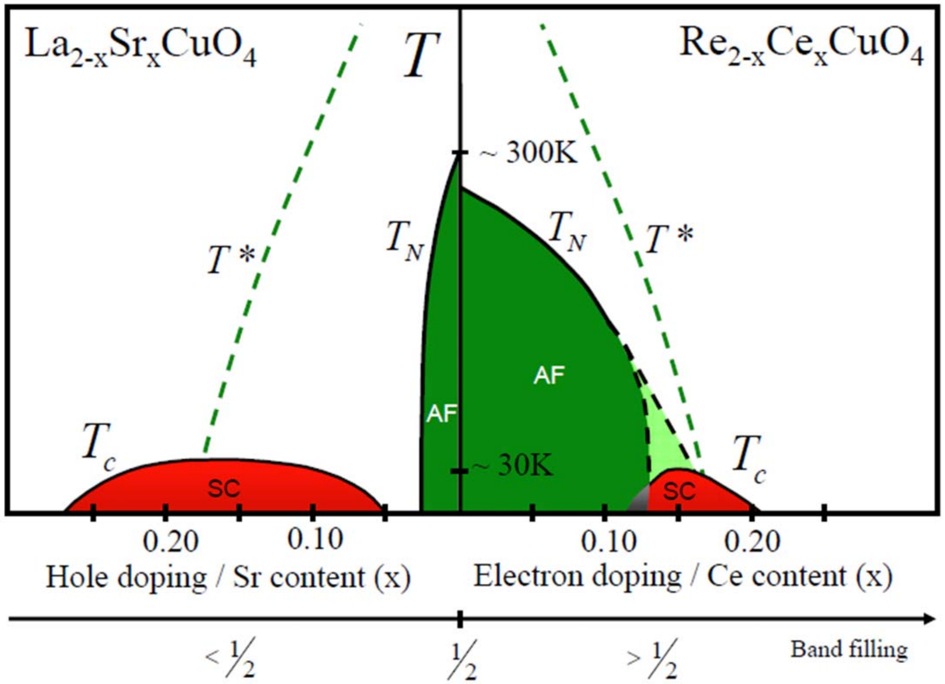
Where is the mystery?

High-temperature superconductors

Armitage, Fournier, Greene, RMP (2009)



What is under the dome?
Mott Physics away from $n = 1$

- Competing order
  - Current loops: Varma, PRB **81,** 064515 (2010)
  - Stripes or nematic: Kivelson et al. RMP 75 1201(2003); J.C.Davis
  - d-density wave : Chakravarty, Nayak, Phys. Rev. B **63**, 094503 (2001); Affleck et al. flux phase
  - SDW: Sachdev PRB **80**, 155129 (2009) ...
- Or Mott Physics?
  - RVB: P.A. Lee Rep. Prog. Phys. **71,** 012501 (2008)

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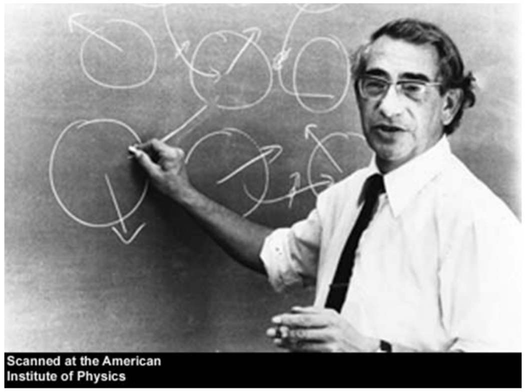
Anomalous properties

- Strong particle-hole asymmetry in DOS even in SC state.
- Mott Ioffe-Regel limit
- Spectral weight transfer in XAS
- No sharp phase transition at pseudogap
- Carriers are hole measured with respect to half-filling (Hall, thermopower etc…)
- Superfluid density not BCS

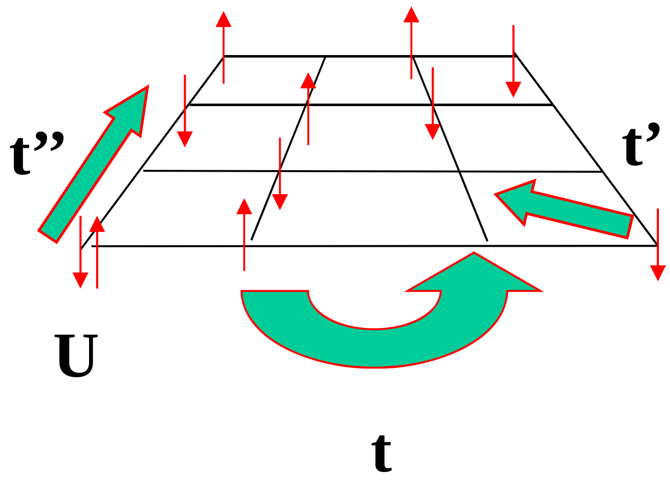
Model

Hubbard model

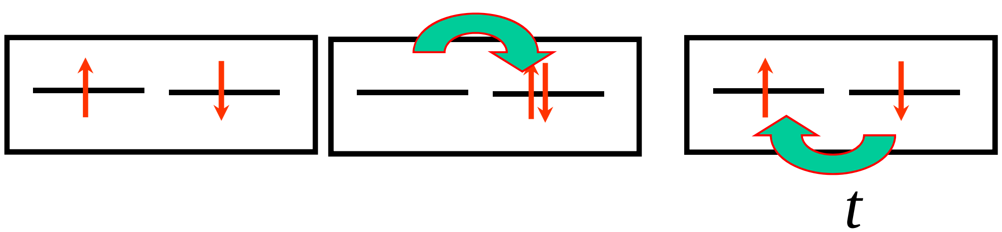


1931-1980

μ



$$H = -\sum_{<ij>\sigma} t_{i,j}\left(c^\dagger_{i\sigma}c_{j\sigma} + c^\dagger_{j\sigma}c_{i\sigma}\right) + U\sum_i n_{i\uparrow}n_{i\downarrow}$$



$t = 1$

Effective model, Heisenberg: $J = 4t^2/U$

The normal state is not always normal
A first case: MIR

Mott-Ioffe-Regel limit

$$\sigma = \frac{ne^2\tau}{m}$$

$$n = \frac{1}{2\pi d}k_F^2$$

$$\sigma = \left(\frac{1}{2\pi d}k_F^2\right)\frac{e^2\tau}{m}$$

$$\ell = \left(\frac{\hbar k_F}{m}\right)\tau$$

$$\sigma = \frac{1}{2\pi d}k_F e^2\left(\frac{\ell}{\hbar}\right)$$

$$k_F\ell = \frac{2\pi}{\lambda_F}\ell \sim 2\pi$$

$$\sigma_{MIR} = \frac{e^2}{\hbar d}$$

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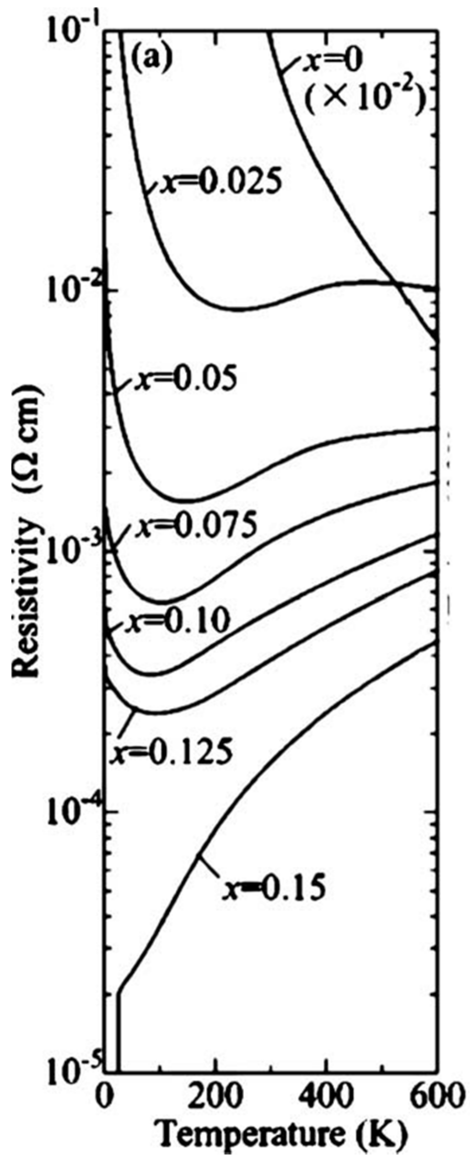
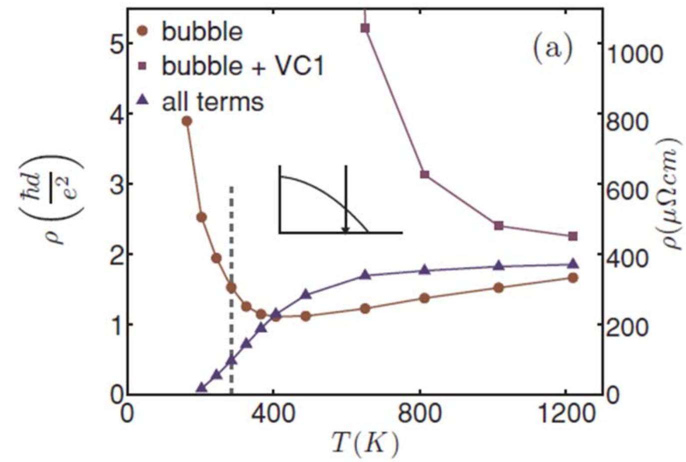
Electron-doped and MIR limit



NCCO



Dominic Bergeron et al. TPSC
PRB **84**, 085128 (2011)

Onose et al. 2004

Quantum criticality vs AFM in e-doped

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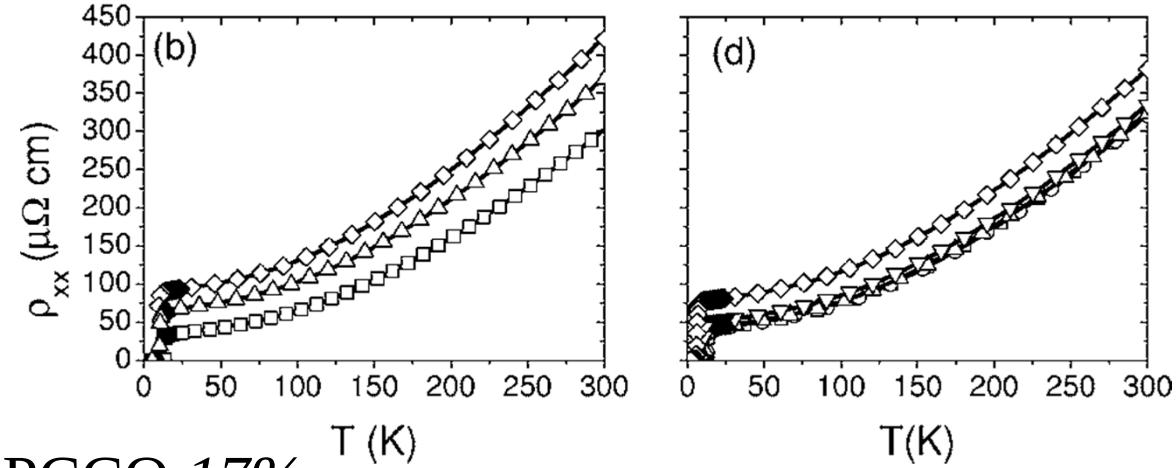
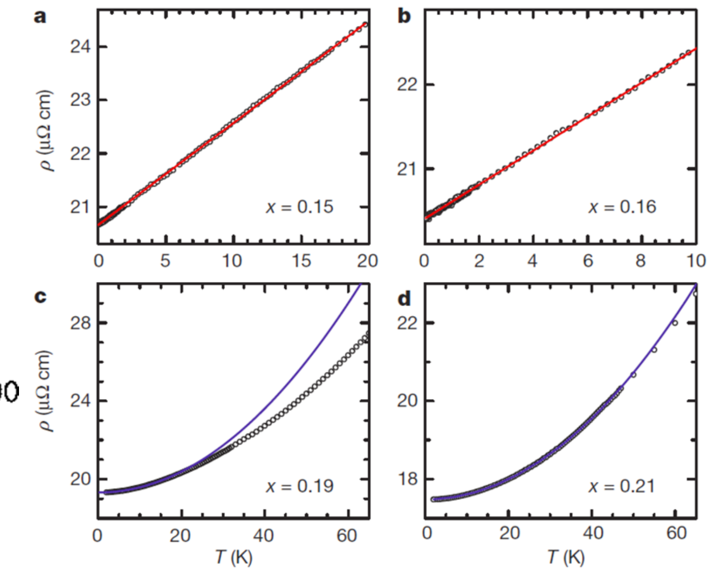
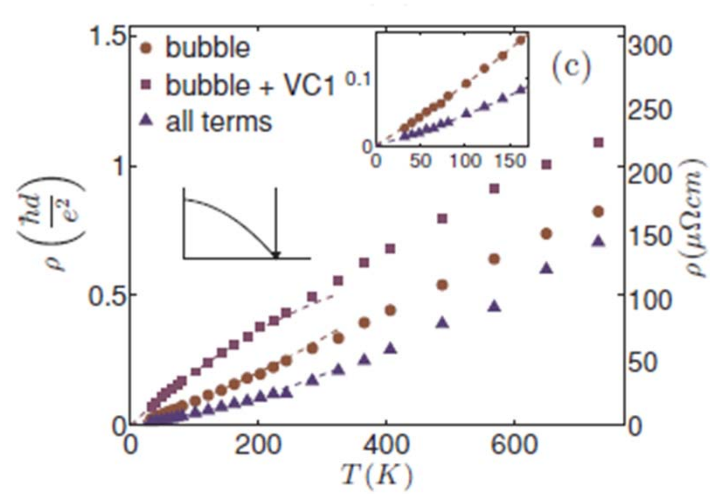
Electron-doped and MIR limit



PCCO *17%*

Higgins et al. PRB 73, 104510 (2006)





LCCO

Jin et al., Nature 2011

Dominic Bergeron et al. TPSC
PRB **84**, 085128 (2011)

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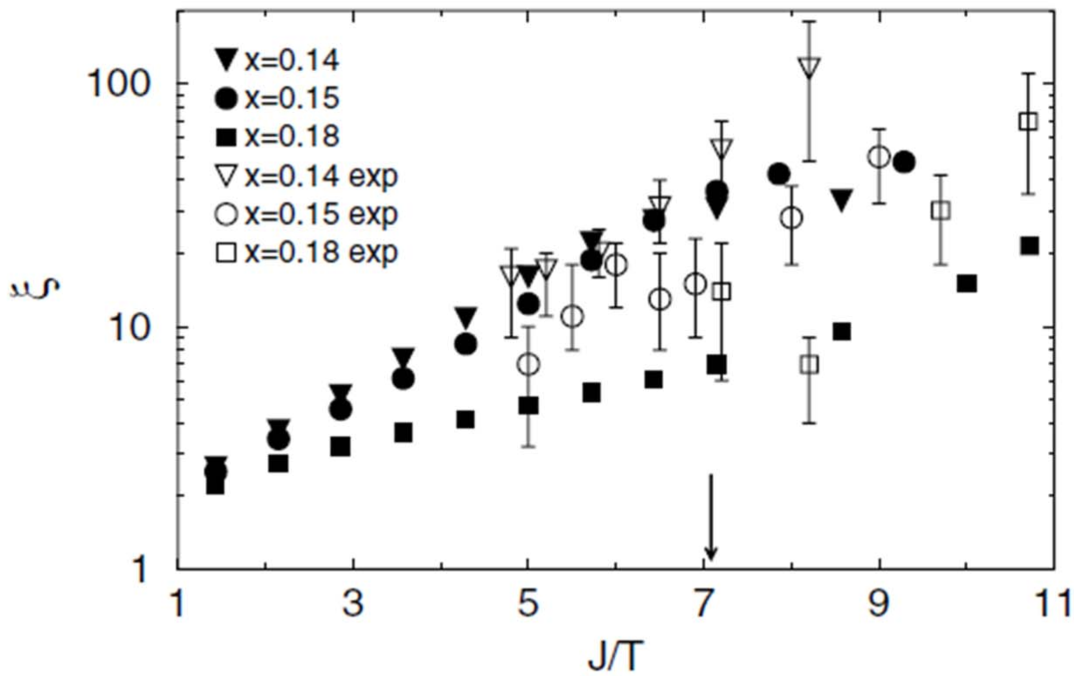
TPSC vs experiment for ξ



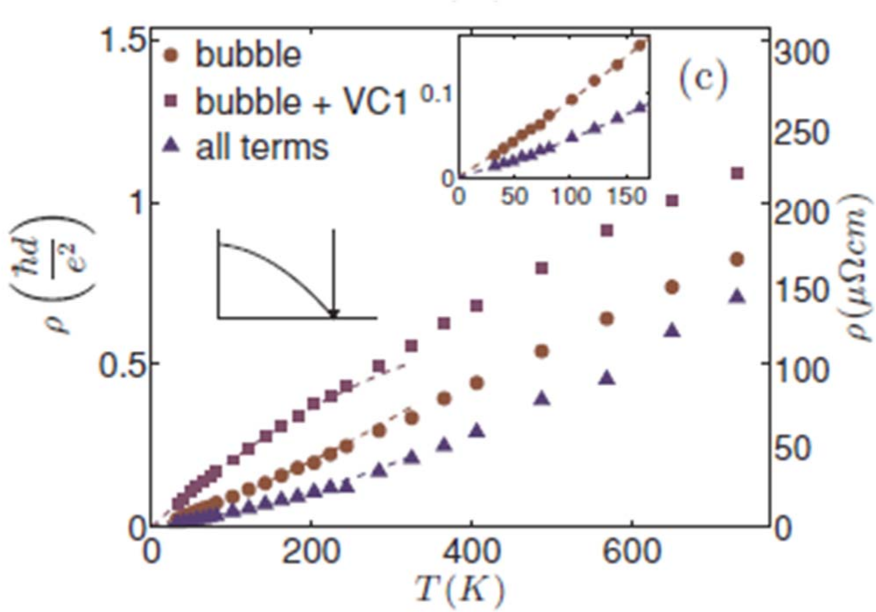
Kyung et al. PRL **93**, 147004 (2004)

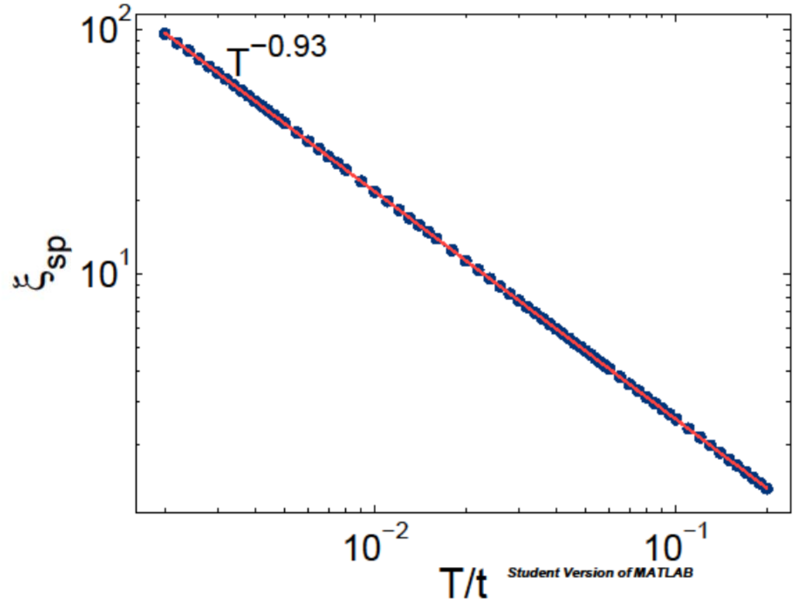
P. K. Mang et al., Phys. Rev. Lett. 93, 027002 (2004).
M. Matsuda et al., Phys. Rev. B 45, 12 548 (1992).

ξ(T) at the QCP

NCCO

Matsui et al. PRB 2007





z = 1 Motoyama, Nature 2007

U=6, t'=-0.175, t"=0.05, n=1.2007

Dominic Bergeron TPSC

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AFM QCP means there is also a pseudogap driven by AFM fluctuations

Three broad classes of mechanisms for pseudogap

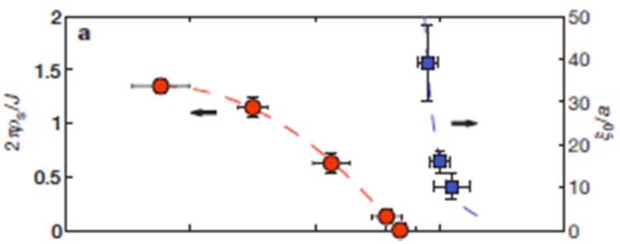
- Rounded first order transition
- *d =2* precursor to a lower temperature broken symmetry phase
- Mott physics

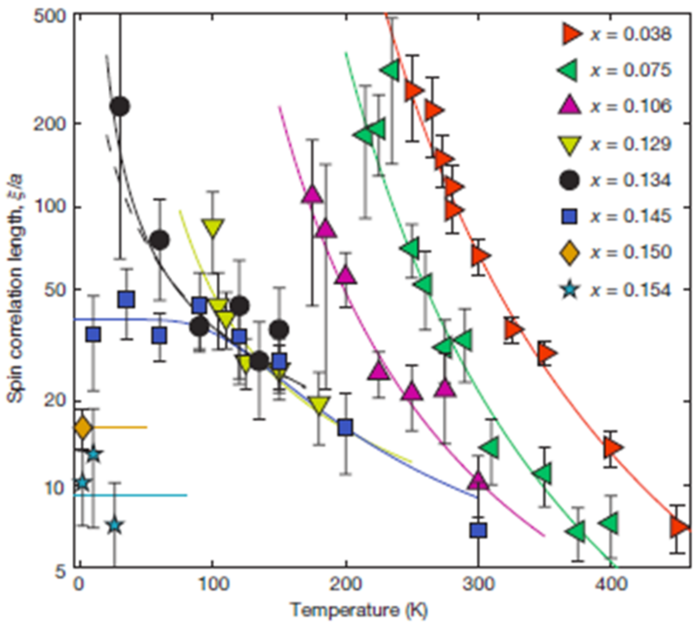
- Competing order
  - Current loops: Varma, PRB **81,** 064515 (2010)
  - Stripes or nematic: Kivelson et al. RMP 75 1201(2003); J.C.Davis
  - d-density wave : Chakravarty, Nayak, Phys. Rev. B **63**, 094503 (2001); Affleck et al. flux phase
  - SDW: Sachdev PRB **80**, 155129 (2009) ...
- Or Mott Physics?
  - RVB: P.A. Lee Rep. Prog. Phys. **71,** 012501 (2008)

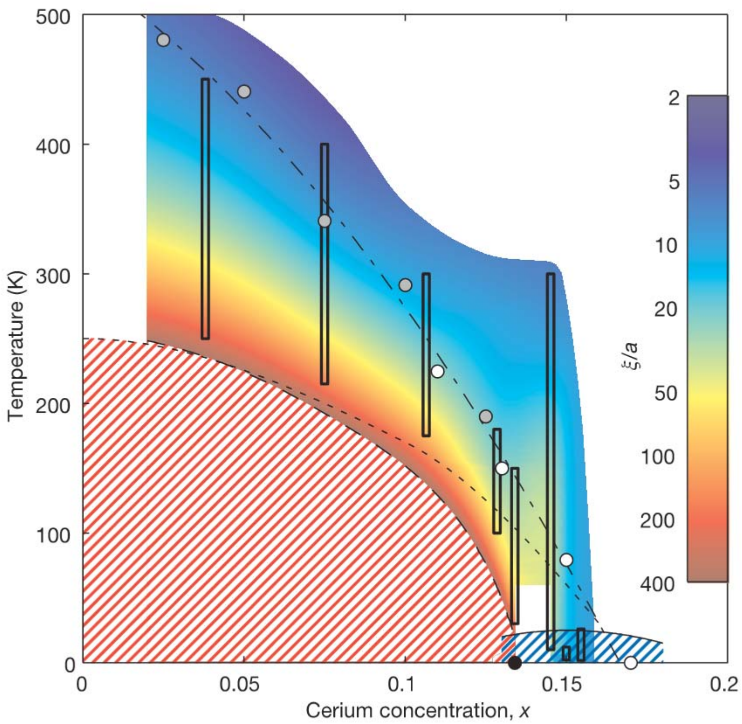
E-doped quantum critical

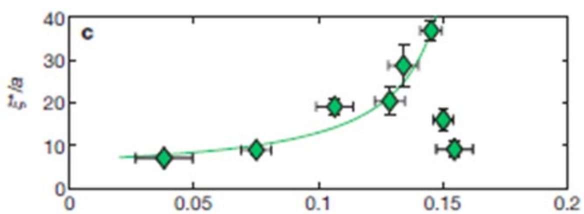
NCCO

Motoyama, E. M. et al.. Nature 445, 186–189 (2007).





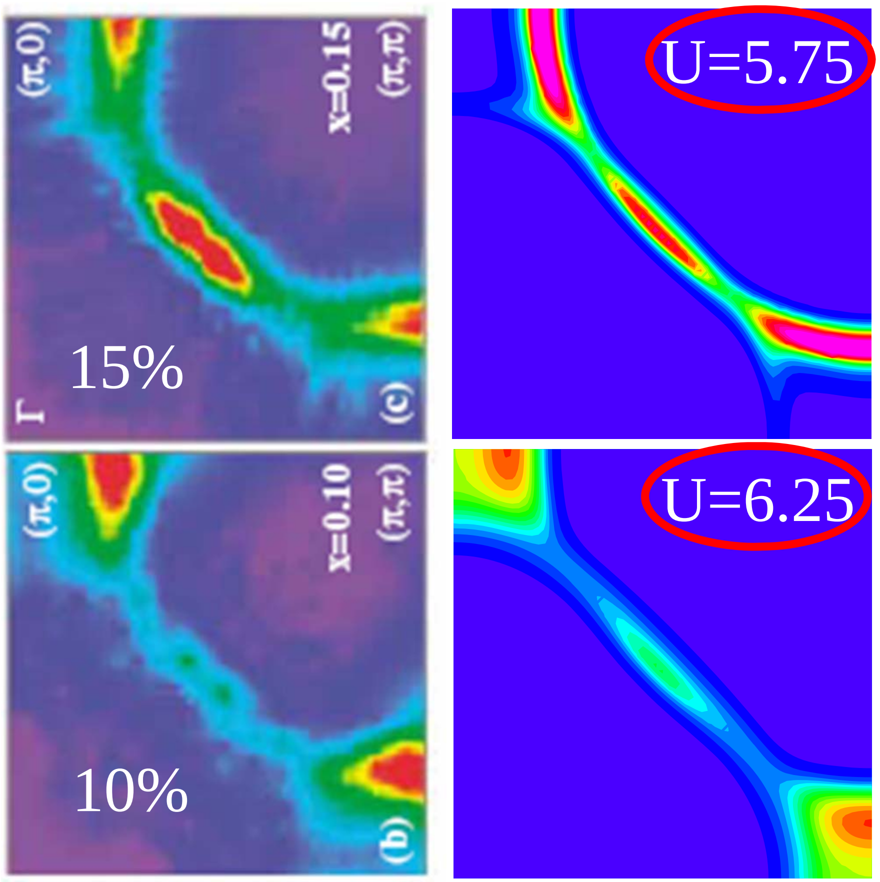




$$\xi^* = 2.6(2)\xi_{th}.$$

Fermi surface plots

Hubbard repulsion *U* has to…



be not too large

increase for
smaller doping

B.Kyung *et al.*,PRB **68**, 174502 (2003)

Hankevych, Kyung, A.-M.S.T., PRL, sept. 2004

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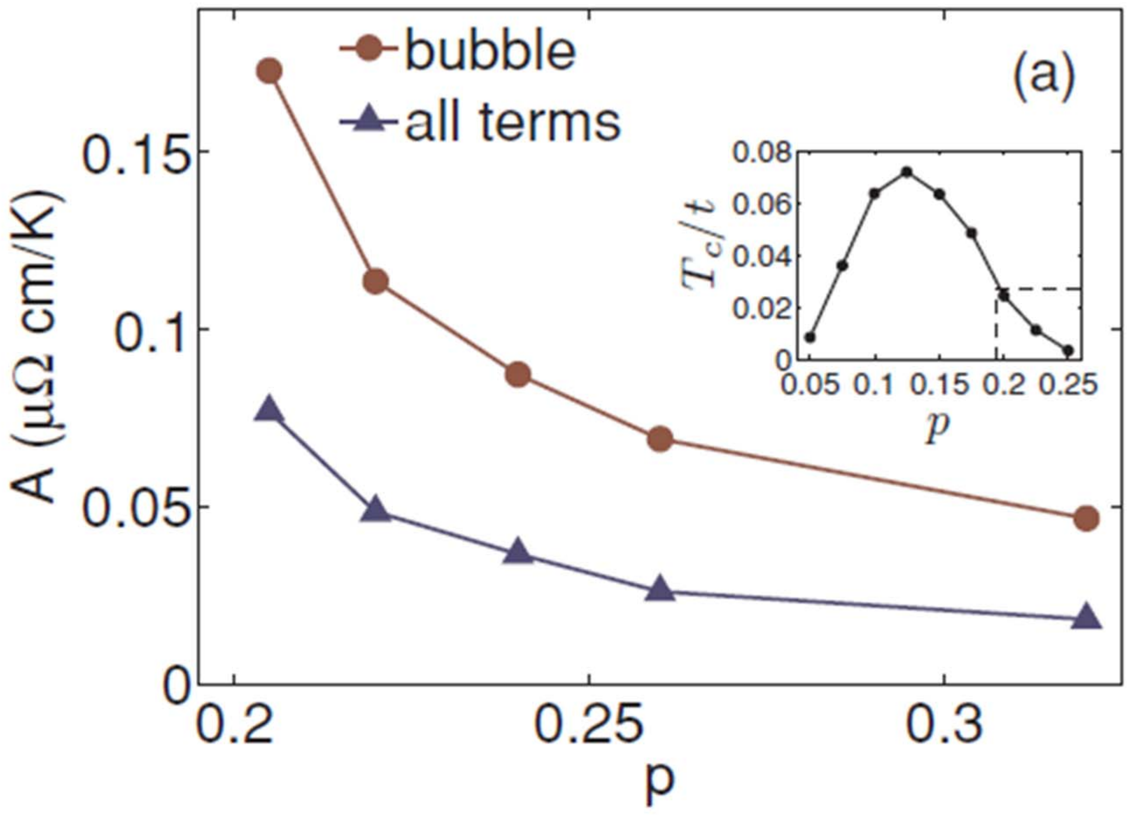
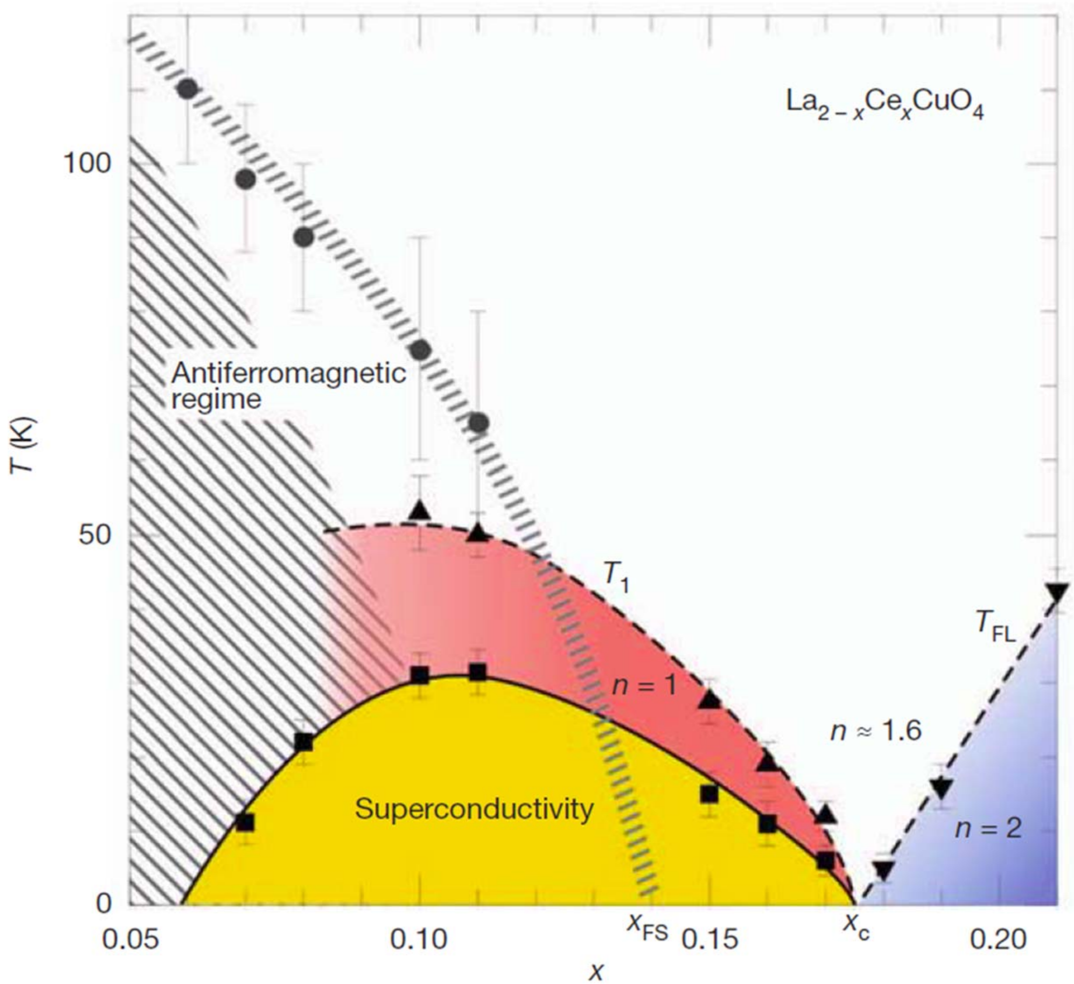
Correlation resistivity vs T_c



Dominic Bergeron et al. TPSC
PRB **84**, 085128 (2011)

Extended quantum criticality



Jin et al. Nature 2011

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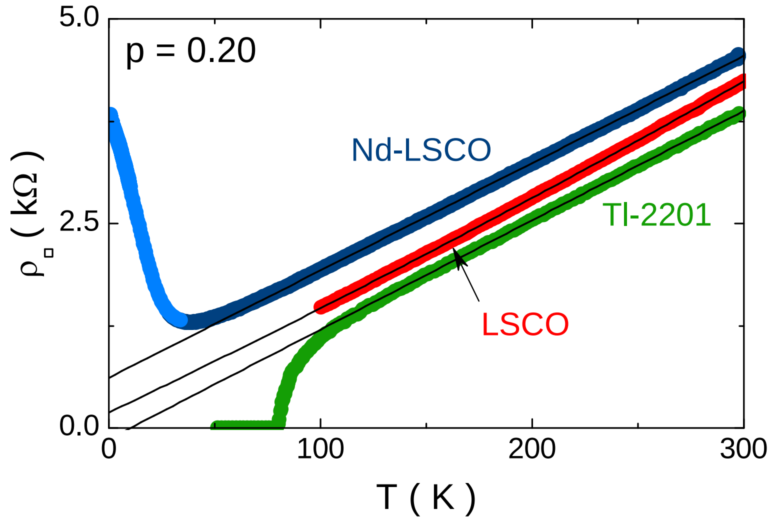
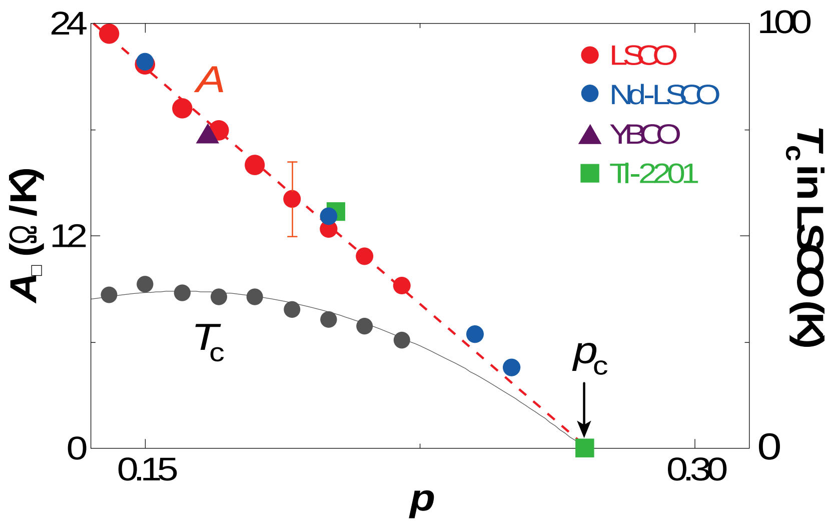
Hole-doped cuprates as Mott insulators

Hole-doped cuprates

Linear-*T* resistivity





Linear-T resistivity is universal in hole-doped cuprates

Correlation between linear-T resistivity and T_c

Doiron-Leyraud *et al.*, arXiv:0905.0964

Taillefer, Annual Review of CMP **1**, 51 (2010)

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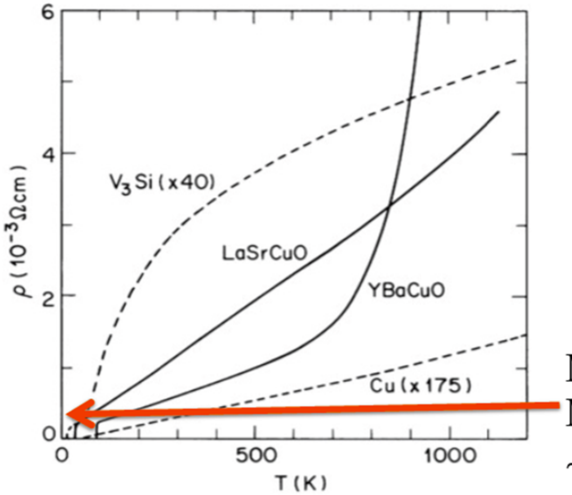
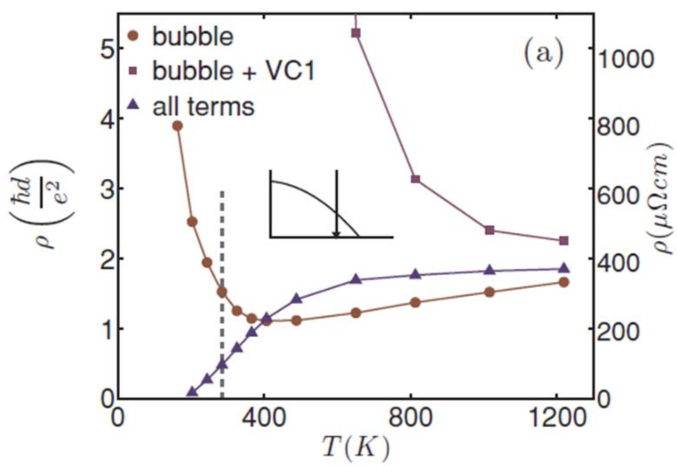
Hole-doped cuprates and MIR limit



Gurvitch & Fiory
PRL 59, 1337
(1987)

MIR limit
Mean-free path
~ Fermi wavelength



LSCO 17%, YBCO optimal

Dominic Bergeron TPSC

PHYSICAL REVIEW B **84**, 085128 (2011)

Optical and dc conductivity of the two-dimensional Hubbard model in the pseudogap regime and across the antiferromagnetic quantum critical point including vertex corrections

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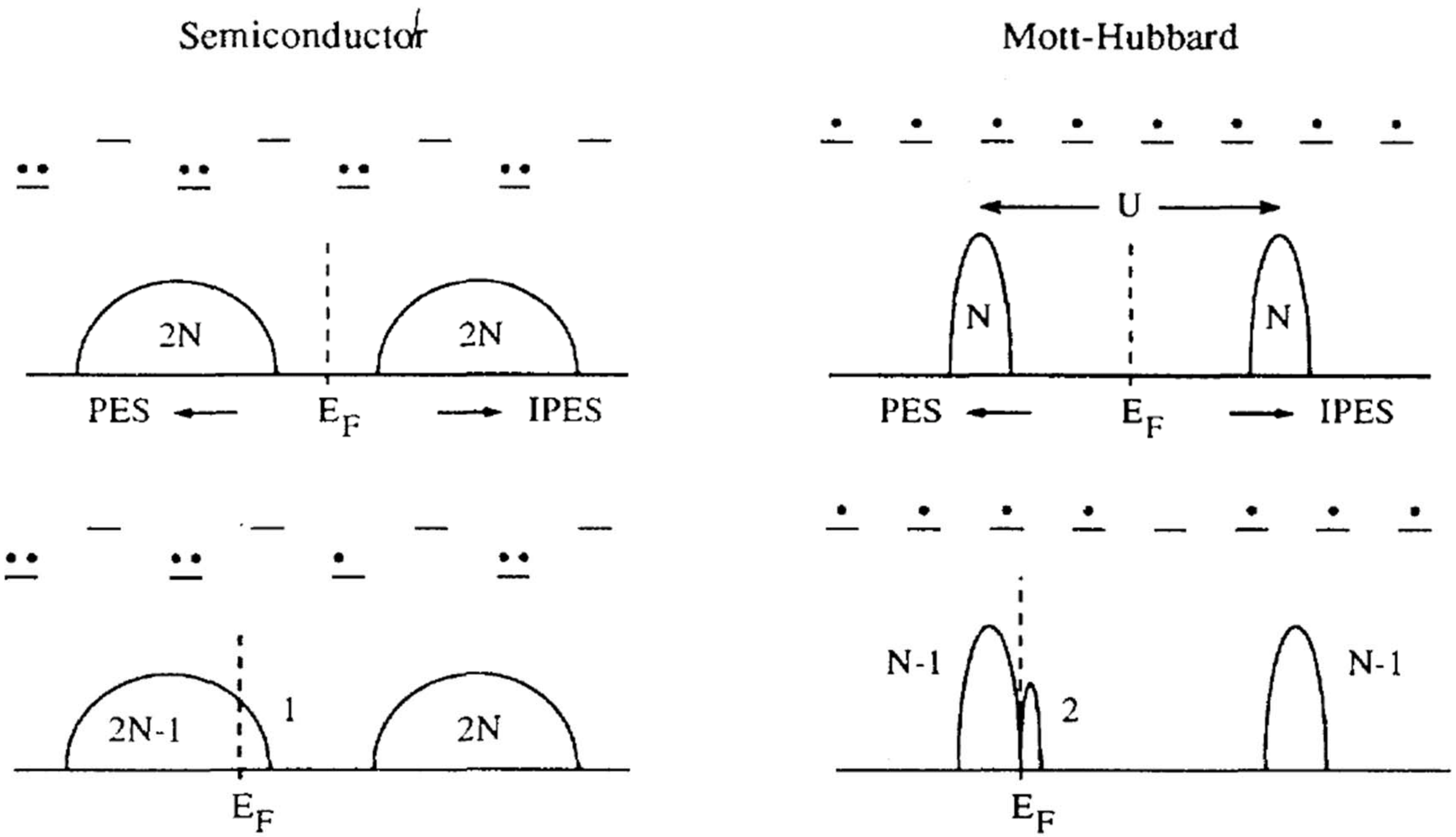
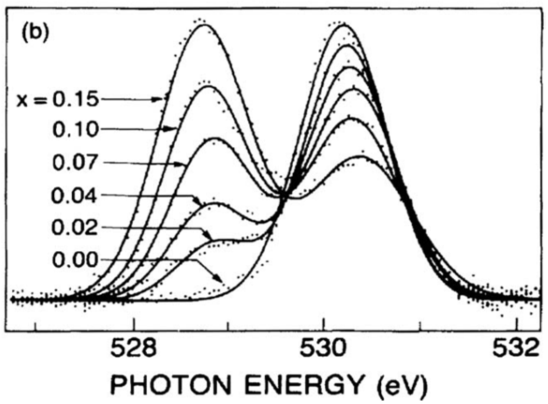
Spectral weight transfer

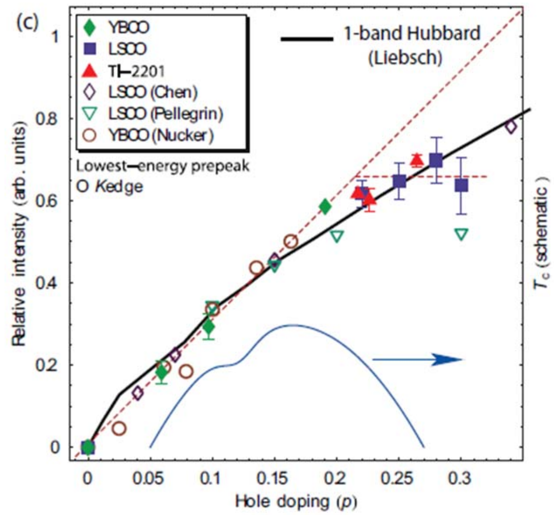


Meinders *et al.* PRB **48**, 3916 (1993)

Experiment: X-Ray absorption



Chen et al. PRL **66**, 104 (1991)

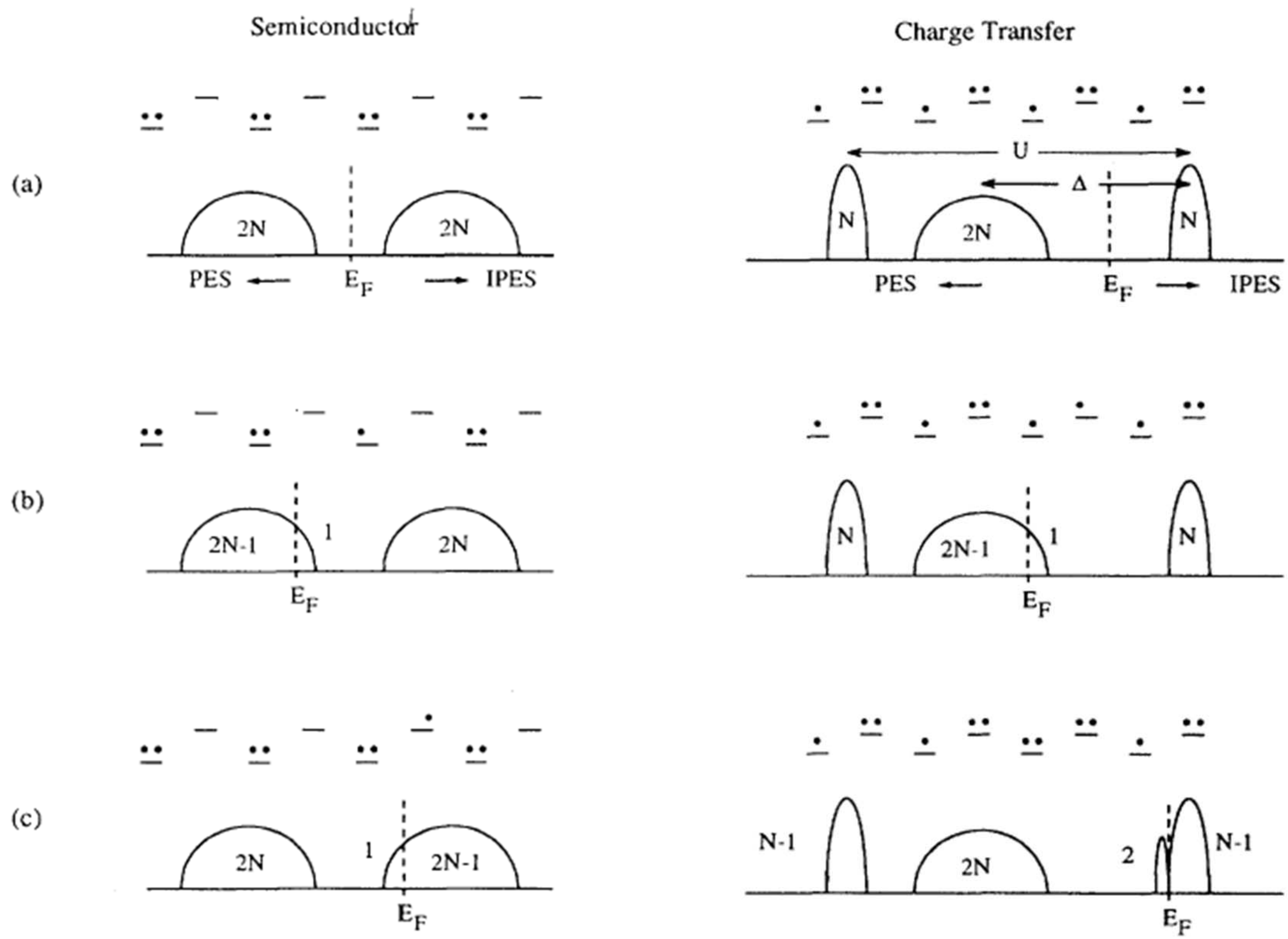


Peets et al. PRL **103**, (2009),
Phillips, Jarrell PRL , vol. **105**, 199701 (2010)

Number of low energy states above ω = 0 scales as *2x* +
Not as 1+x as in Fermi liquid

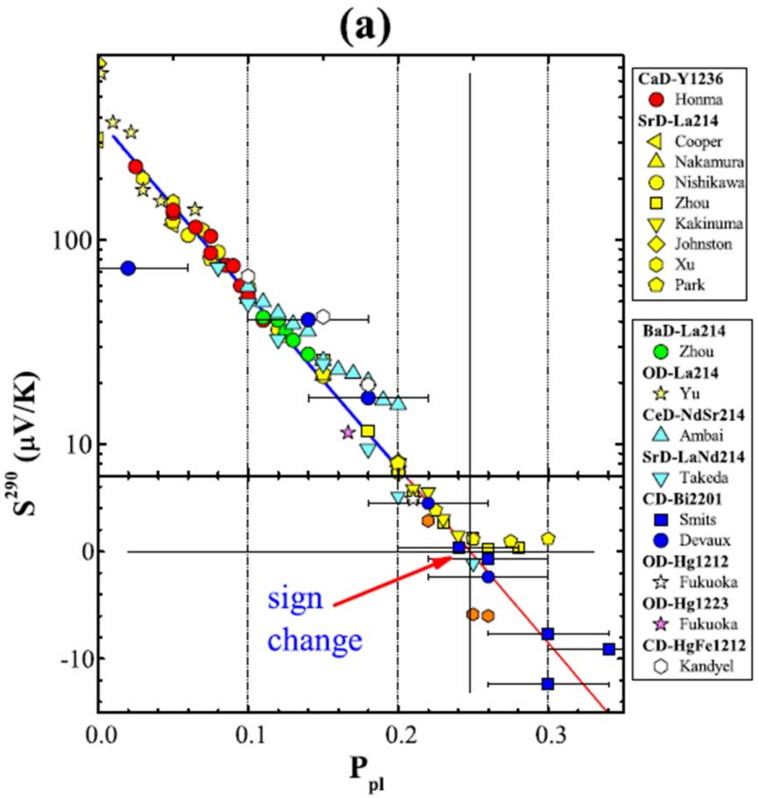
Meinders *et al.* PRB **48**, 3916 (1993)

Charge-transfer insulator



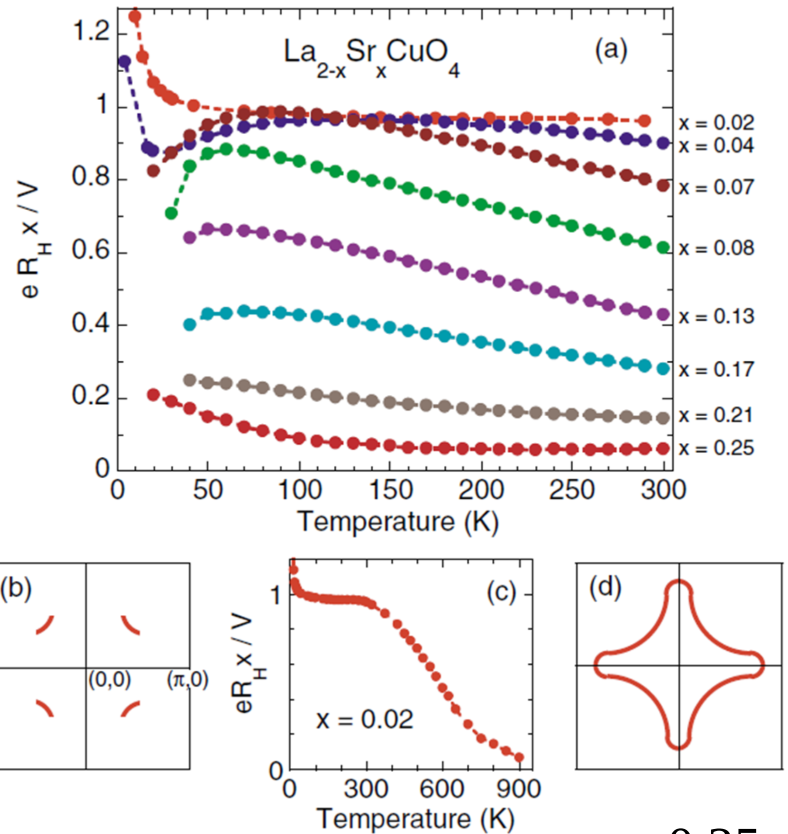
Meinders *et al.* PRB **48**, 3916 (1993)

Thermopower

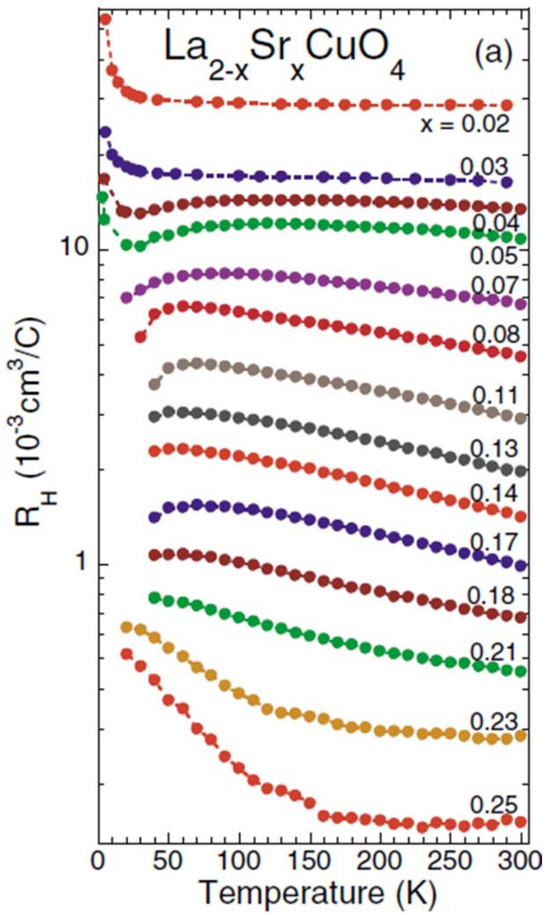


T. Honma and P. H. Hor, Phys. Rev. B **77**, 184520 (2008).

Hall coefficient



x = 0.25



Ando et al. PRL **92**, 197001 (2004)

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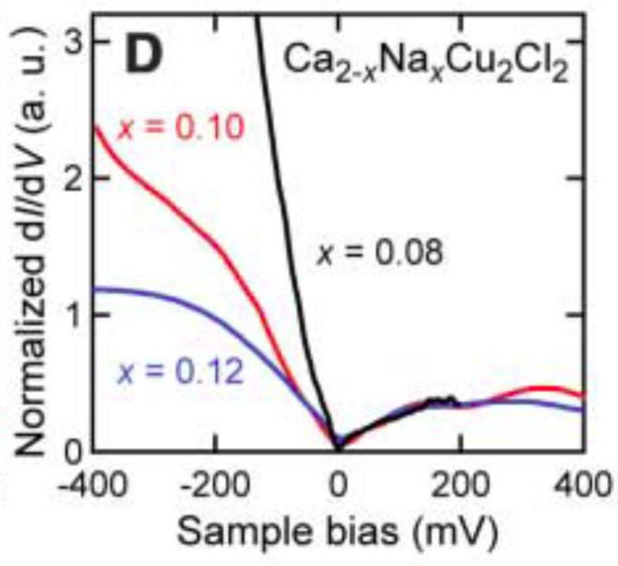
Density of states (STM)



Khosaka et al. *Science* **315**, 1380 (2007);