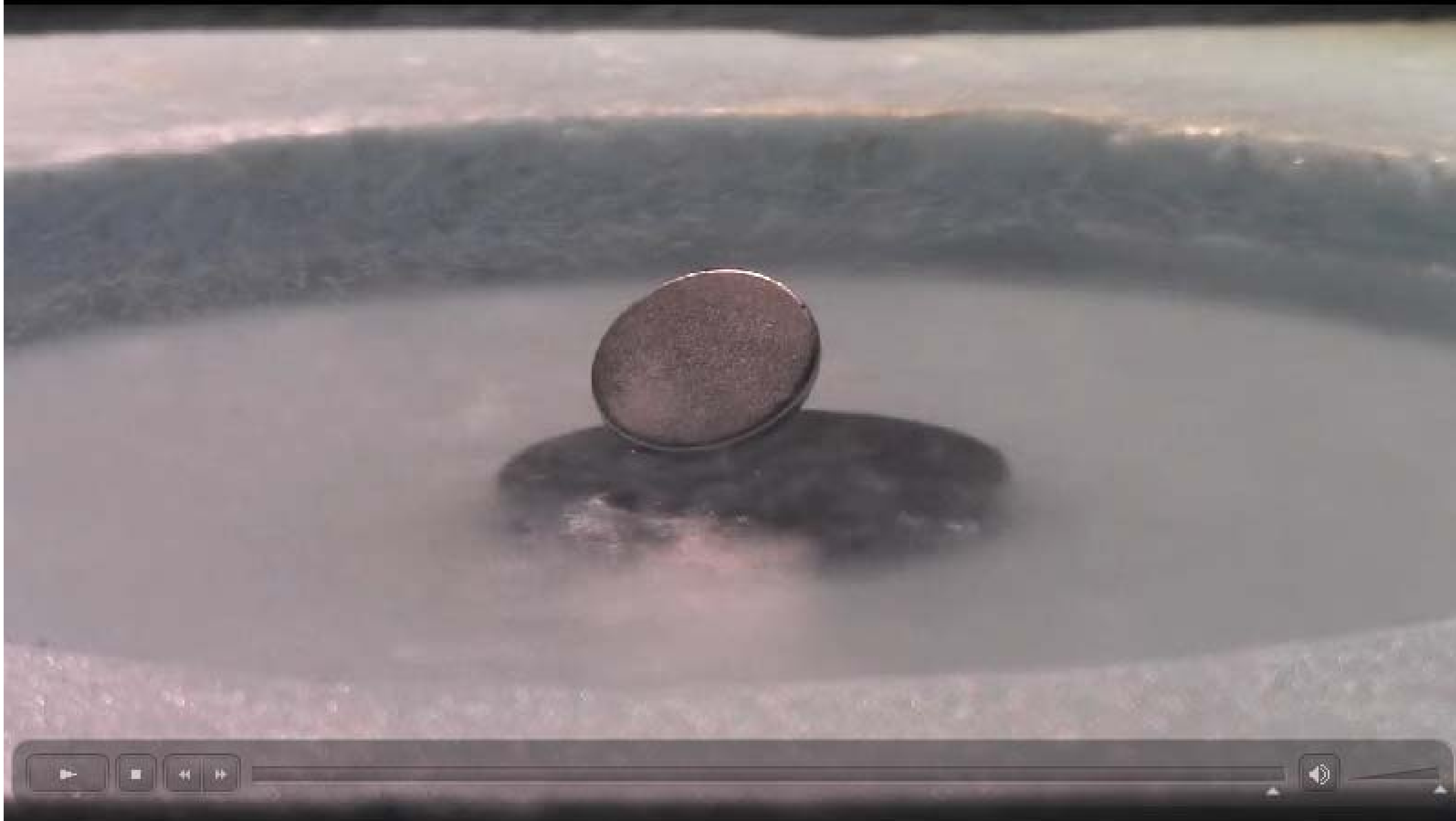
High-temperature superconductors: Where is the mystery?

A.-M. Tremblay

Strongly correlated systems: from models to materials
9 January 2014



Superconductivity

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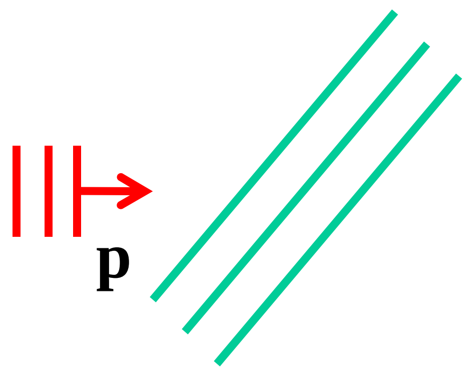
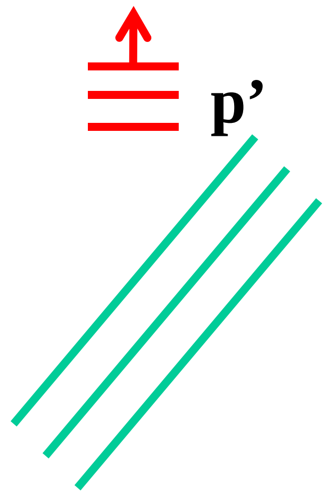
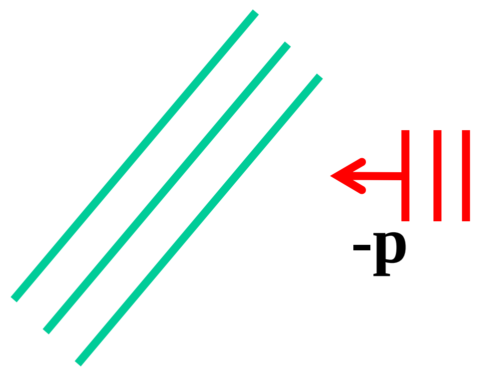
Attraction mechanism in the metallic state



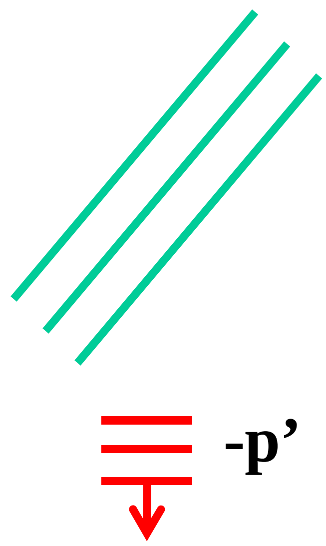
Attraction mechanism in the metallic state



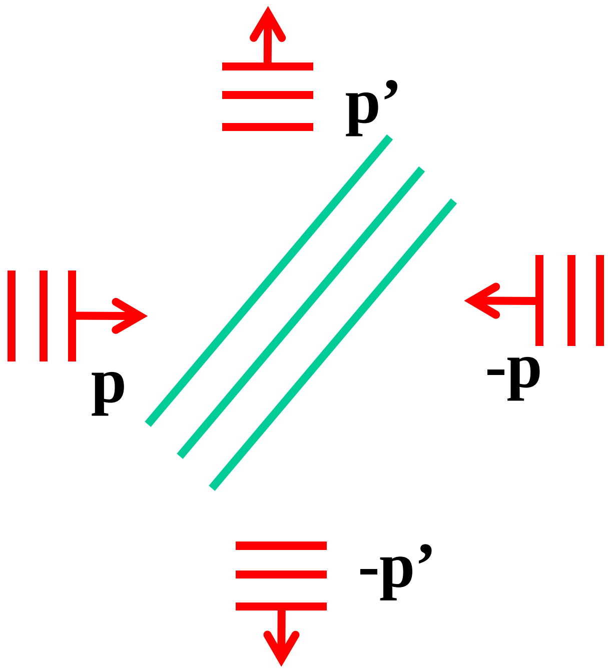
Attraction mechanism in the metallic state



Attraction mechanism in the metallic state



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

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« Conventional » Mott transition

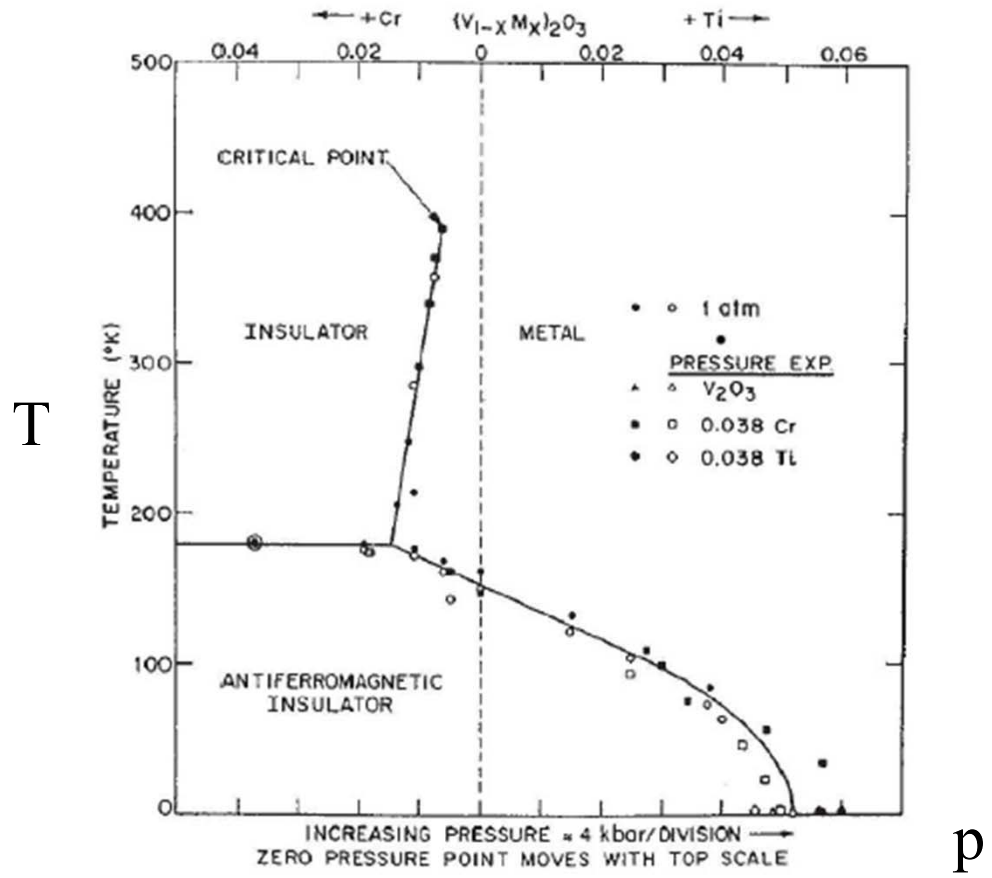
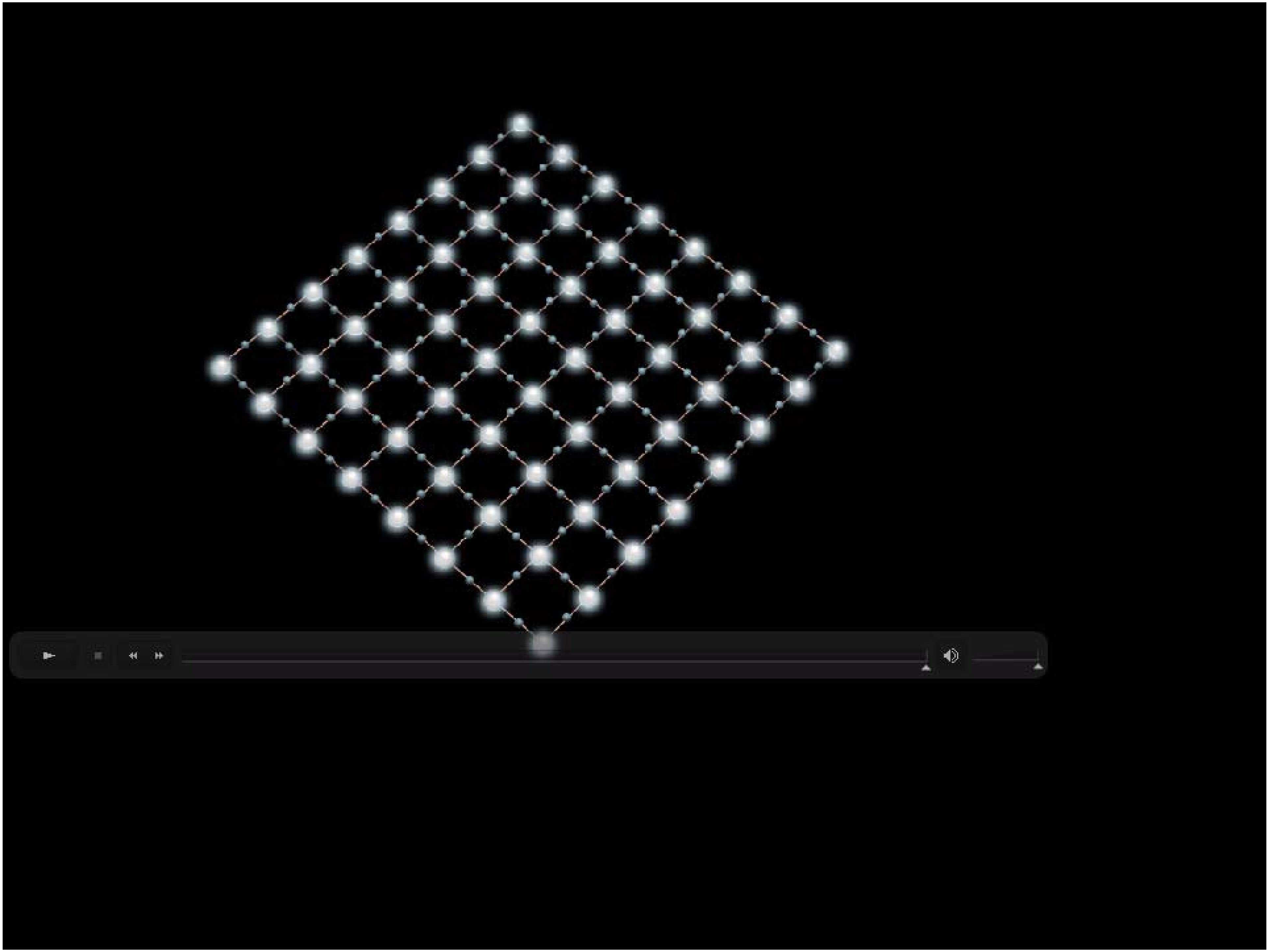


Figure: McWhan, PRB 1970; Limelette, Science 2003



High temperature superconductors

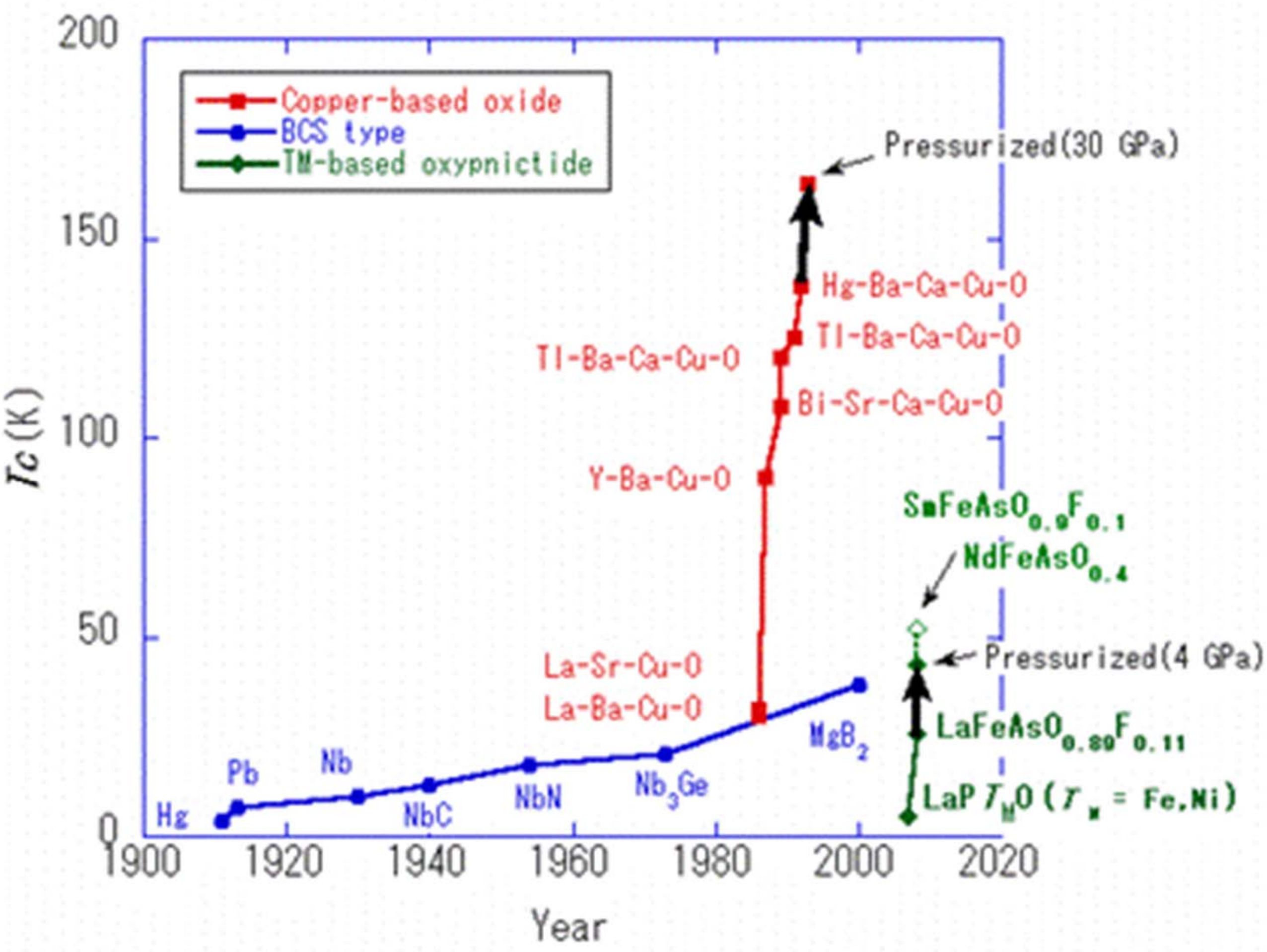
Failure of

BCS theory

Band structure

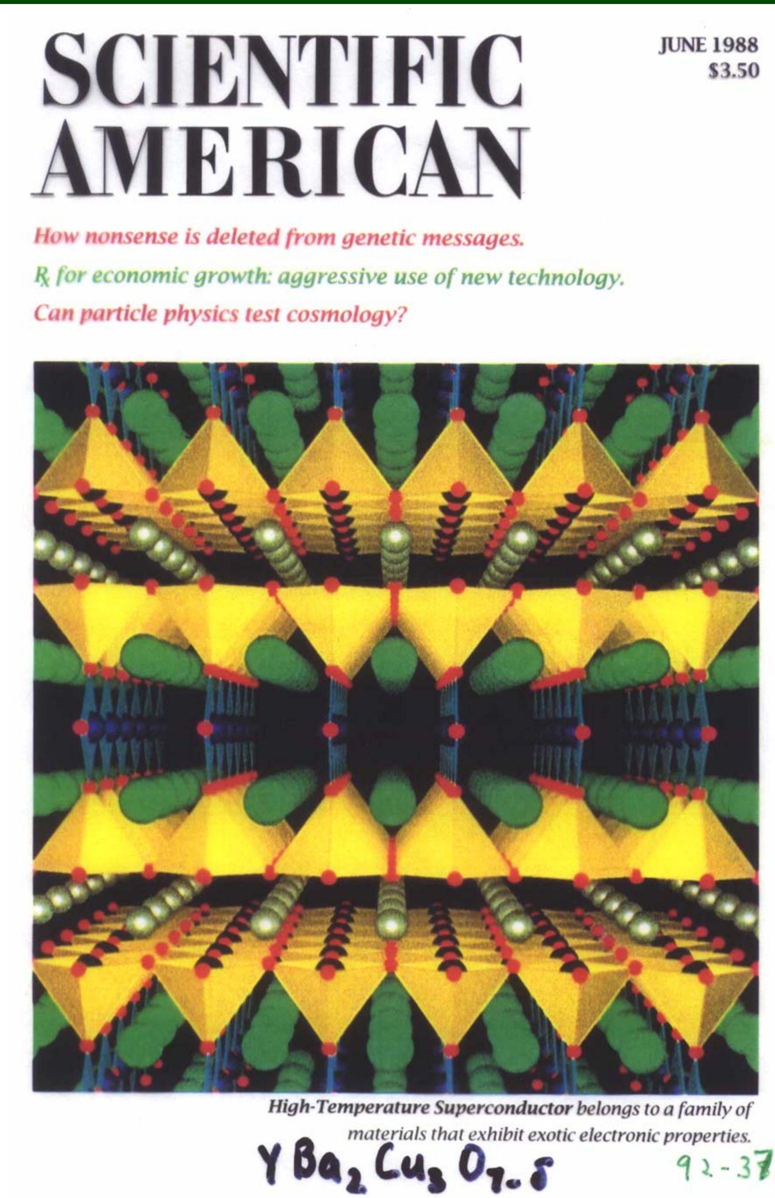
and more

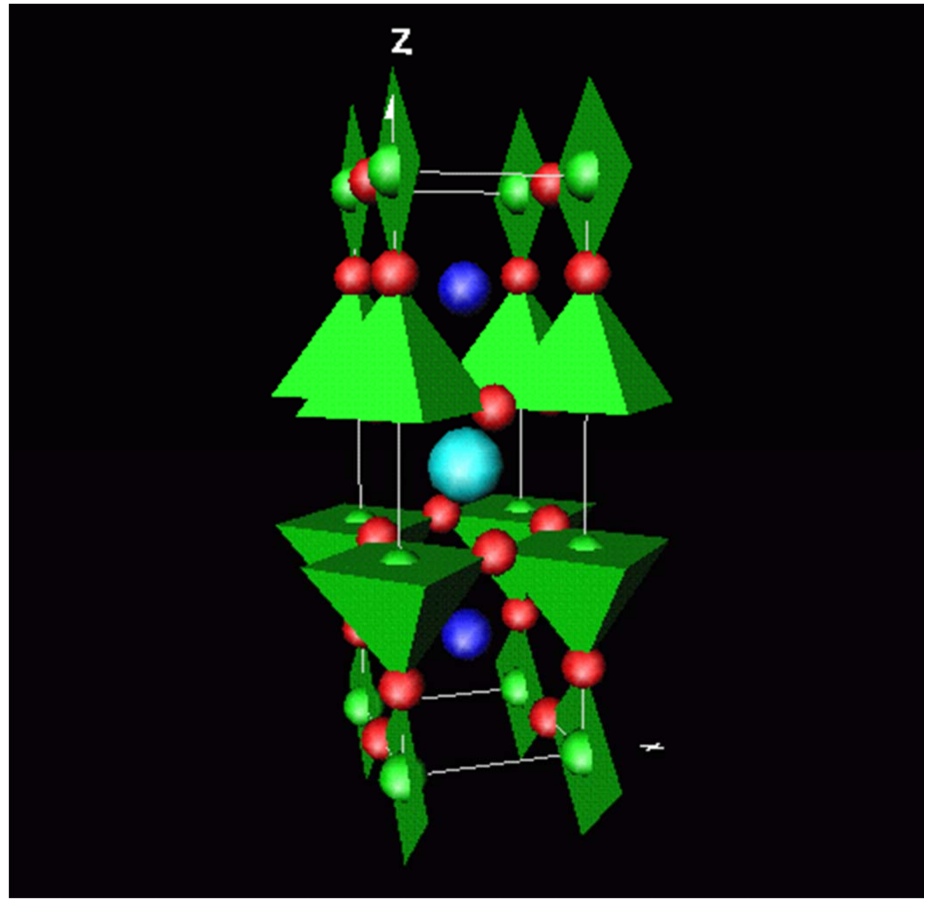
New and old superconductors



H. Takahashi: JPSJ Online—News and Comments [June 10, 2008]

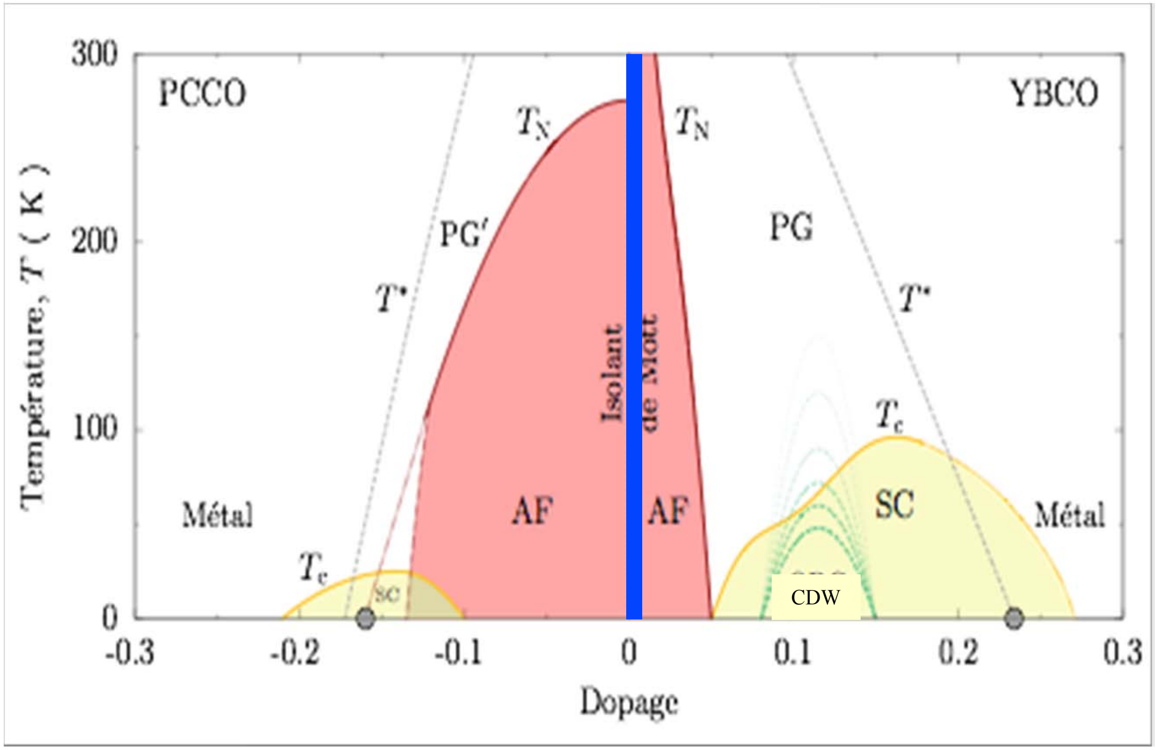
Atomic structure

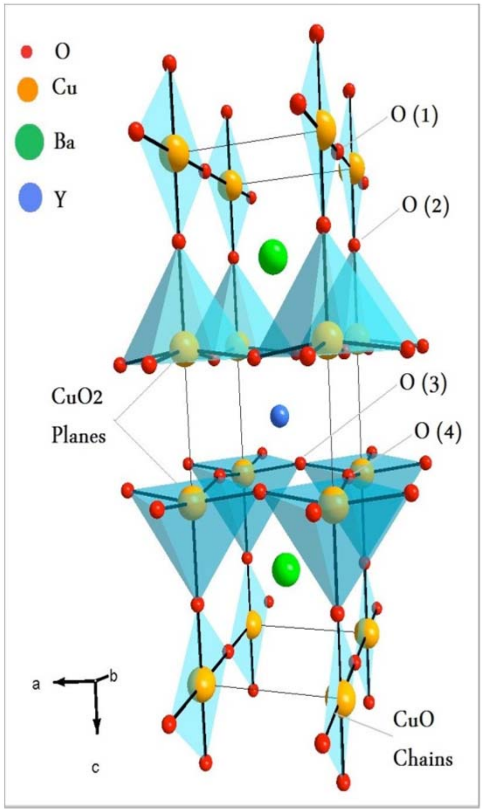




Our road map

Thèse de Francis Laliberté, Université de Sherbrooke





Conventional wisdom vs high Tc

- Transition metals
- Cubic
- Stay away from
  - O
  - Magnets
  - Insulators
- Stay away from theorists

- Cu
- Layered
- Stay close to
  - O
  - Magnets
  - Insulators

2. The model

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

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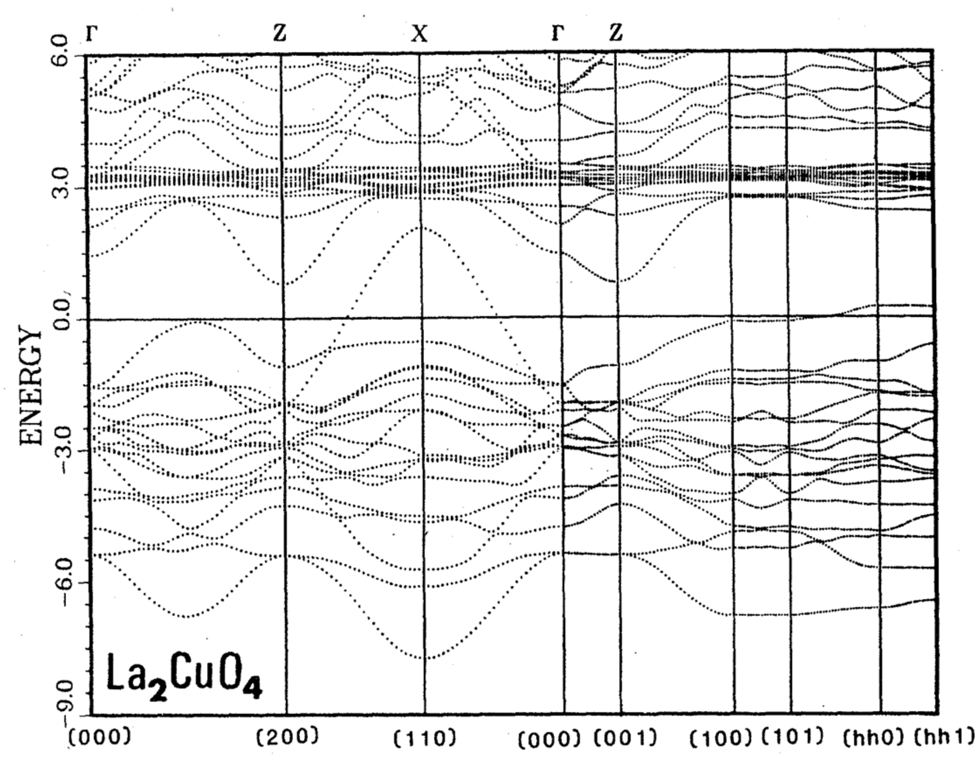
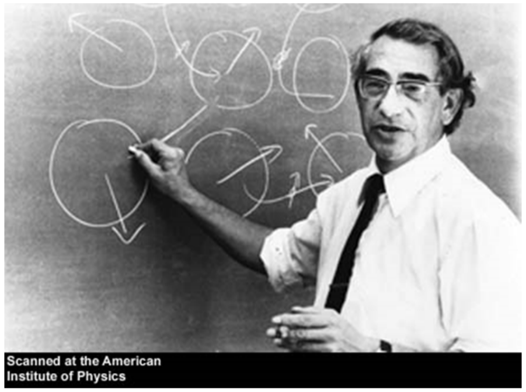
Band structure for high Tc

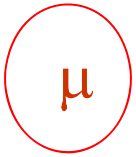


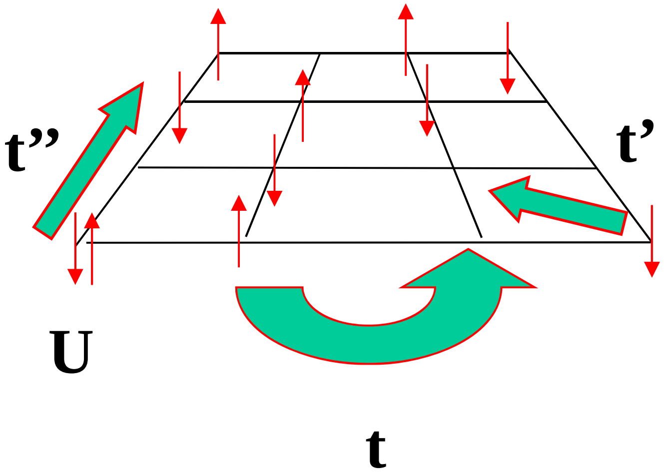
W. Pickett, Rev. Mod. Phys. 1989

Hubbard model



1931-1980





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

Attn: Charge transfer insulator

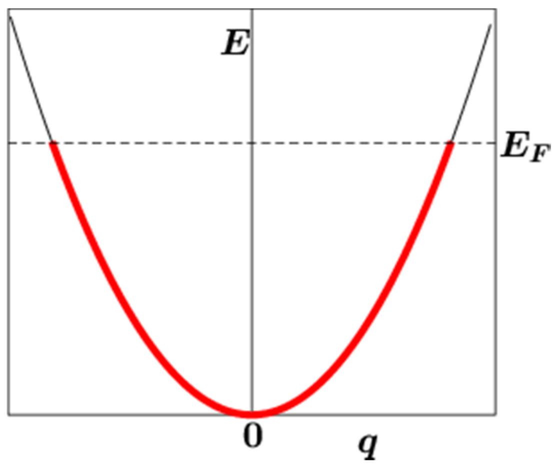
$U = 0$

$$H = -\sum_{<ij>\sigma} t_{i,j}\left(c_{i\sigma}^{\dagger} c_{j\sigma} + c_{j\sigma}^{\dagger} c_{i\sigma}\right)$$

$$c_{i\sigma} = \frac{1}{\sqrt{N}} \sum_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{r}_i} c_{\mathbf{k}\sigma}$$

$$H = \sum_{\mathbf{k},\sigma} \varepsilon_{\mathbf{k}} c_{\mathbf{k}\sigma}^{\dagger} c_{\mathbf{k}\sigma}$$

$$|\Psi\rangle = \prod_{\mathbf{k},\sigma} c_{\mathbf{k}\sigma}^{\dagger} |0\rangle$$



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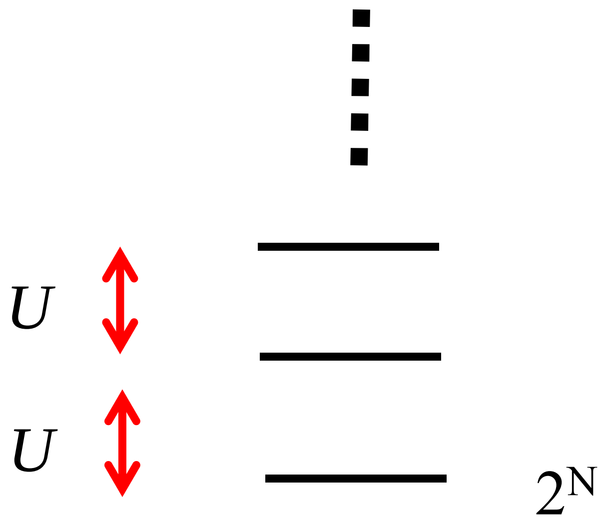
$t_{ij} = 0$

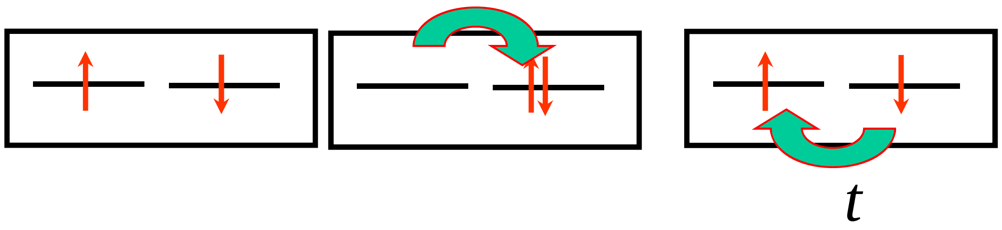
$$H = U\sum_i n_{i\uparrow} n_{i\downarrow}$$



$$|\Psi\rangle = \prod_{\mathbf{i}} c^{\dagger}_{\mathbf{i}\uparrow} \prod_{\mathbf{j}} c^{\dagger}_{\mathbf{j}\downarrow} |0\rangle$$

Interesting in the general case

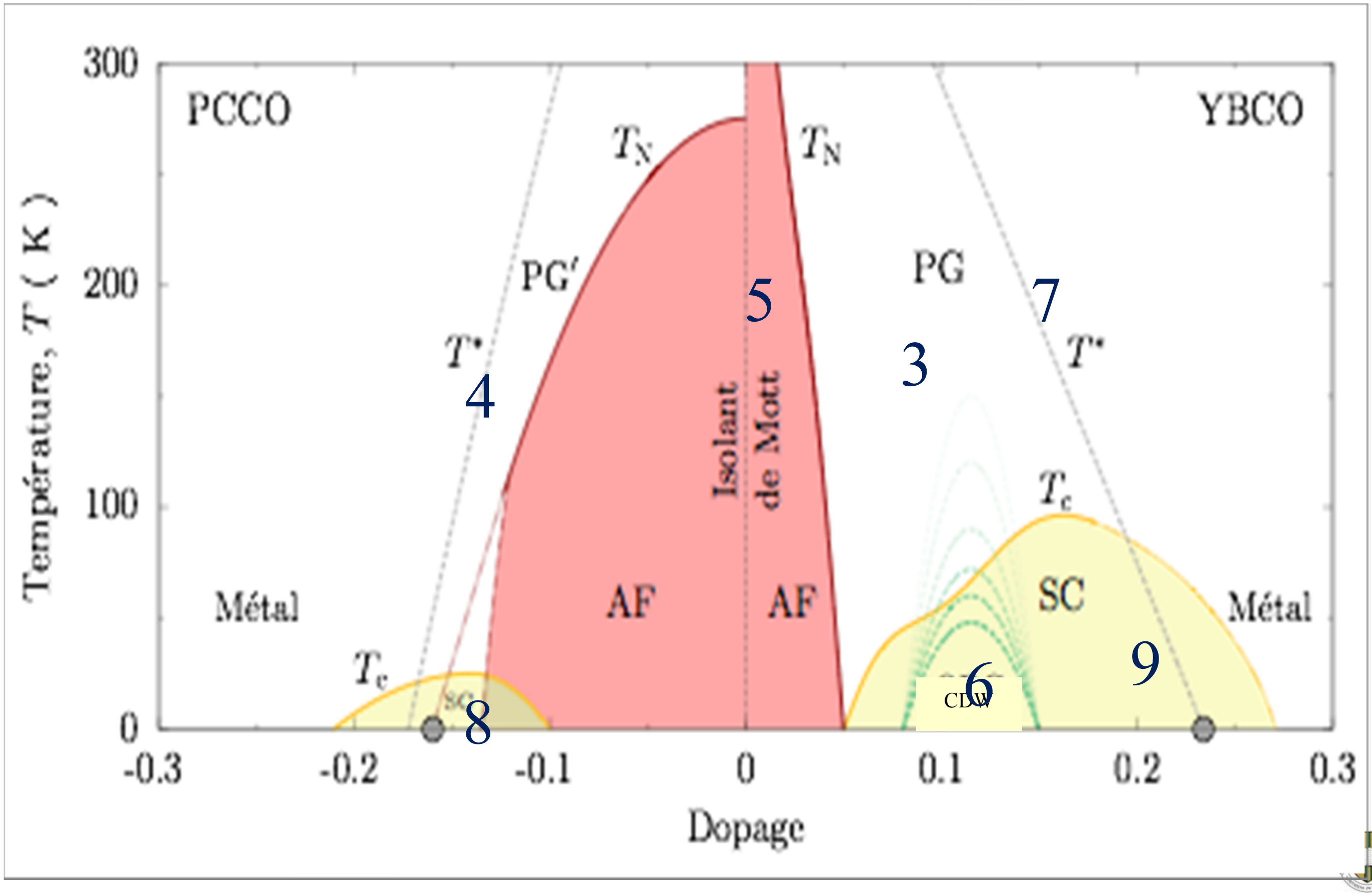
$$H = -\sum_{<ij>\sigma} t_{i,j} \left(c_{i\sigma}^{\dagger} c_{j\sigma} + c_{j\sigma}^{\dagger} c_{i\sigma} \right) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



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

Outline

For references, September 2013 Julich summer school
Strongly Correlated Superconductivity
http://www.cond-mat.de/events/correl13/manuscripts/tremblay.pdf



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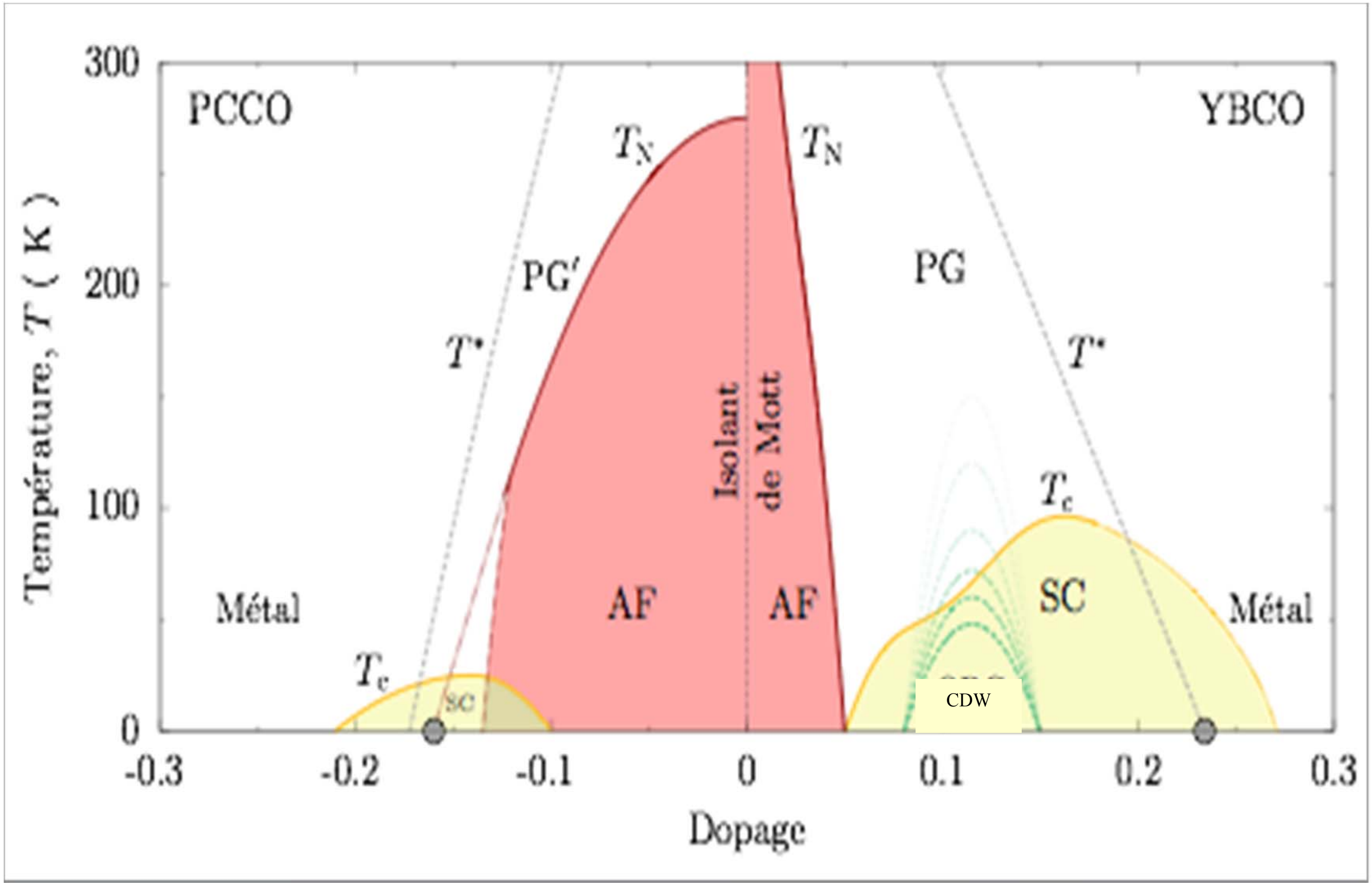
3. A normal, normal state?

Our road map

Thèse de Francis Laliberté,
Université de Sherbrooke



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« 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
  - Concept of Fermi liquid
  - Often hard to « derive » from first principles (fractionalization - gauge theories)

h-doped are strongly correlated: evidence from the normal state

Mott-Ioffe-Regel limit

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

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

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

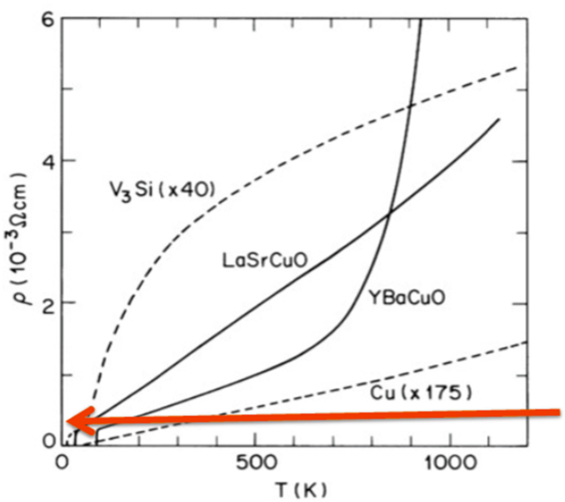
$$\ell = \left(\frac{\hbar k_F}{m}\right)\tau$$

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

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

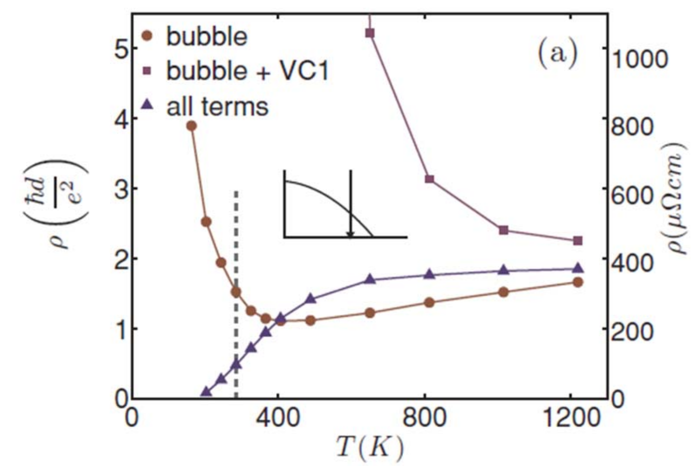
$$\sigma_{MIR} = \frac{e^2}{\hbar d}$$

Hole-doped cuprates and MIR limit



Gurvitch & Fiory
PRL 59, 1337
(1987)

MIR limit
Mean-free path
~ Fermi wavelength



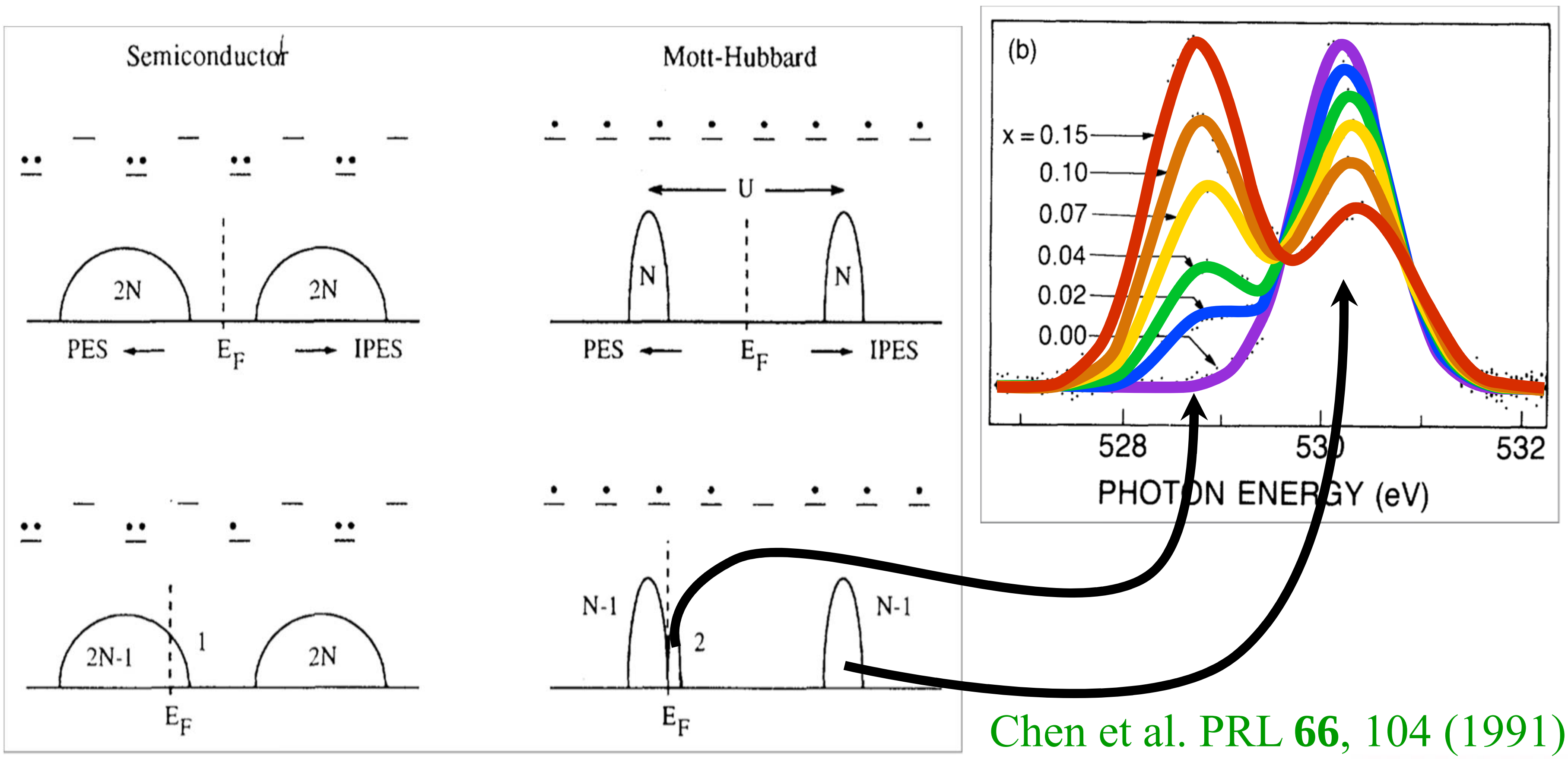
LSCO 17%, YBCO optimal

Dominic Bergeron & AMST
PRB 2011
TPSC

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

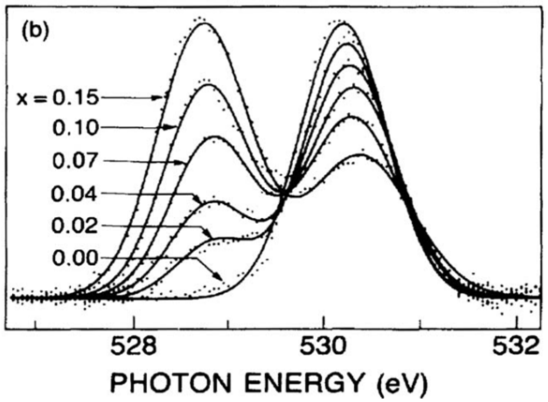
Optical and dc conductivity of the two-dimensional Hubbard model in the pseudogap regime and across the antiferromagnetic quantum critical point including vertex corrections

Experiment, X-Ray absorption

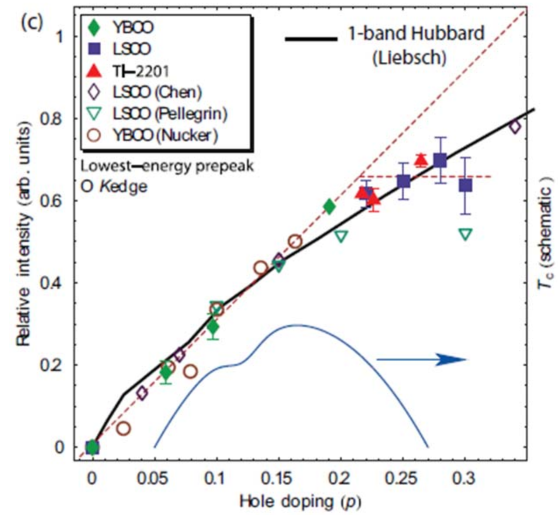


Chen et al. PRL **66**, 104 (1991)

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)

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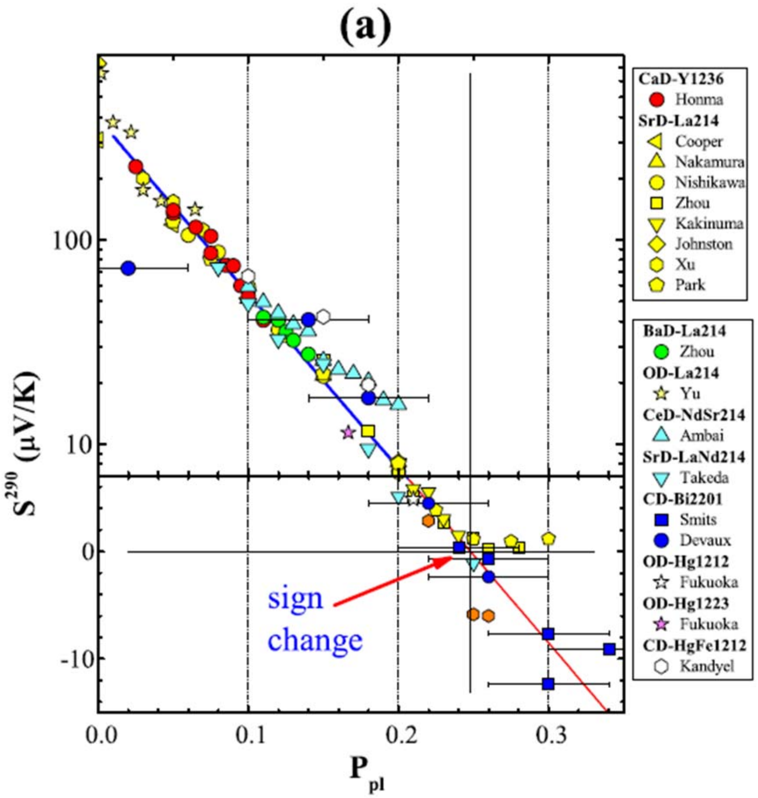
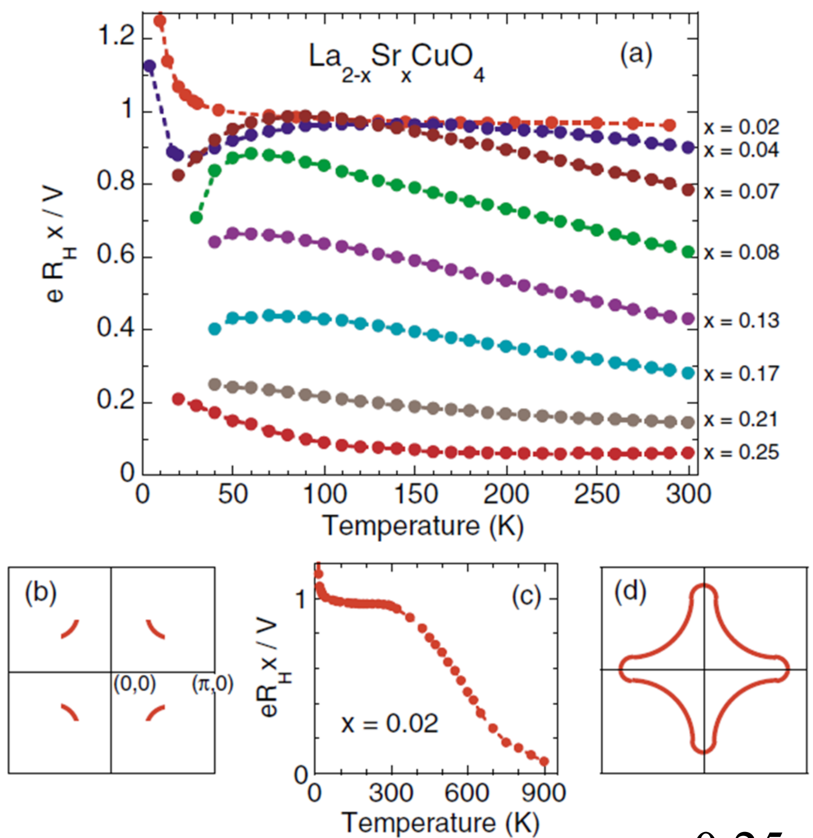
Thermopower

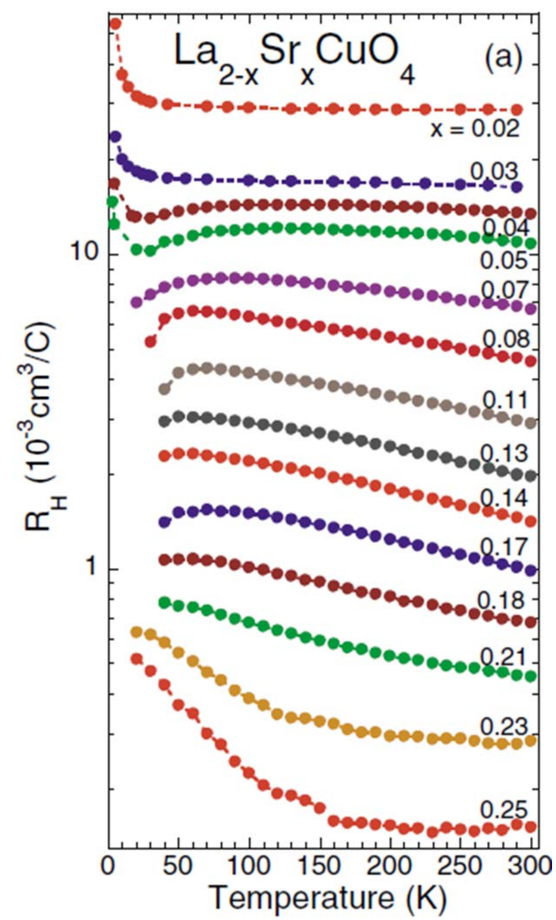


T. Honma and P. H. Hor, Phys. Rev. B **77**, 184520 (2008).

Hall coefficient

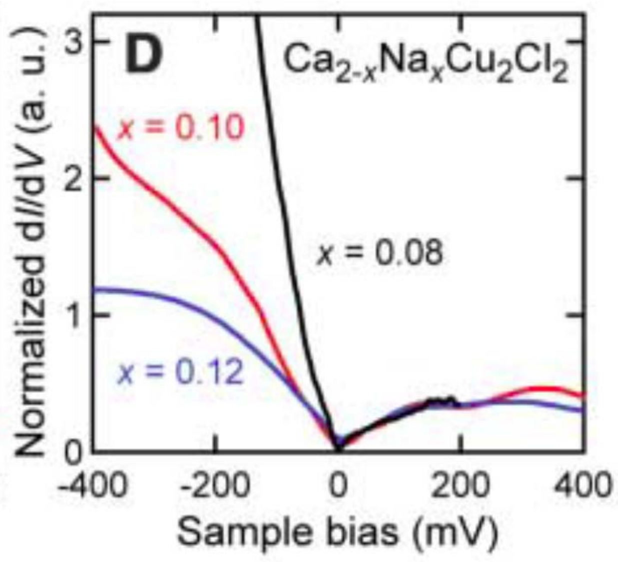


x = 0.25



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

Density of states (STM)

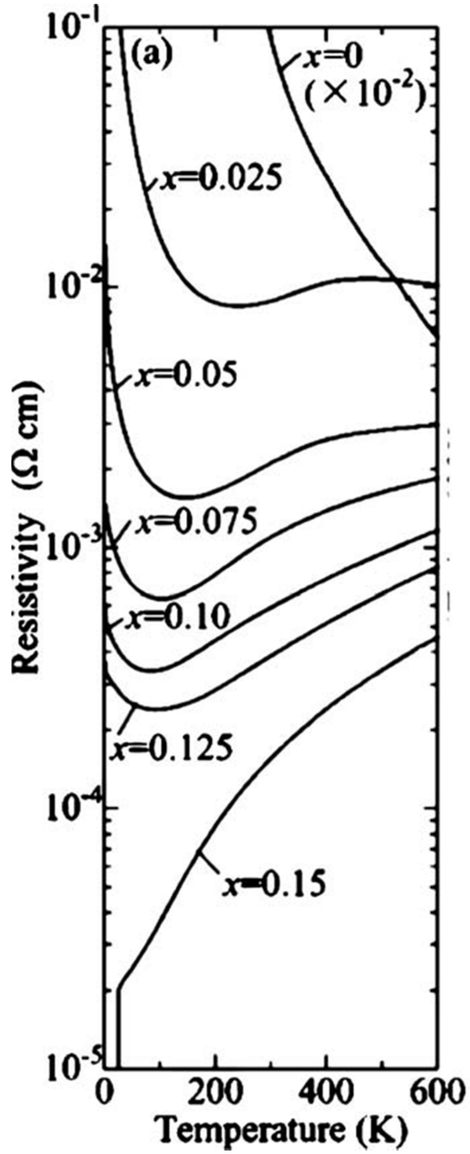


Khosaka et al. *Science* **315**, 1380 (2007);

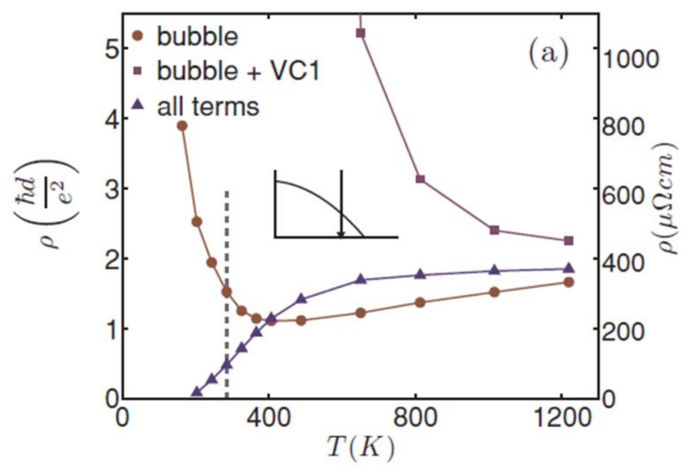
4. e-doped cuprates

Less strongly coupled: evidence from the normal state

Electron-doped and MIR limit



NCCO



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

Onose et al. 2004

Quantum critical points

e-doped

Our road map

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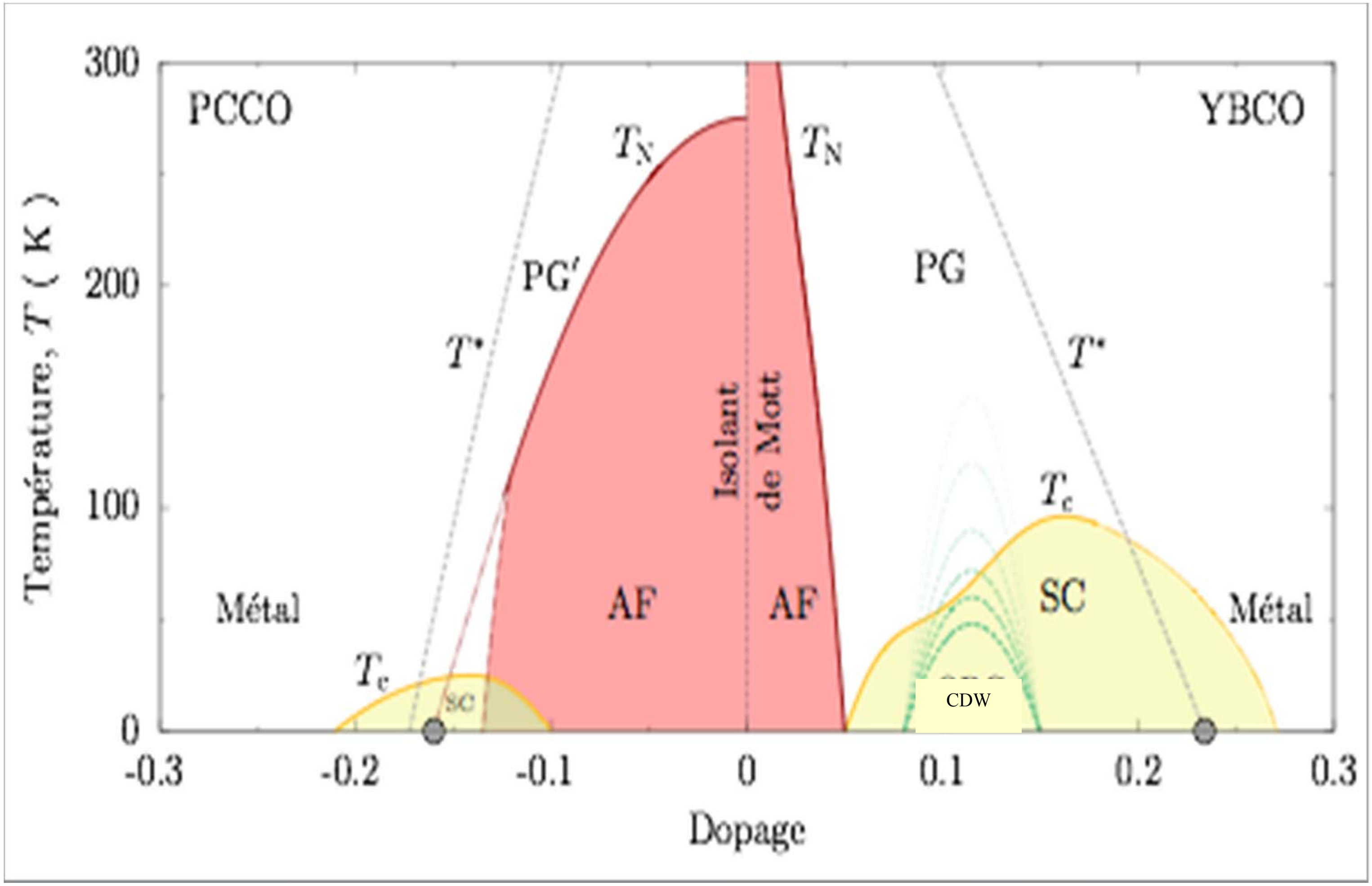
Université de Sherbrooke



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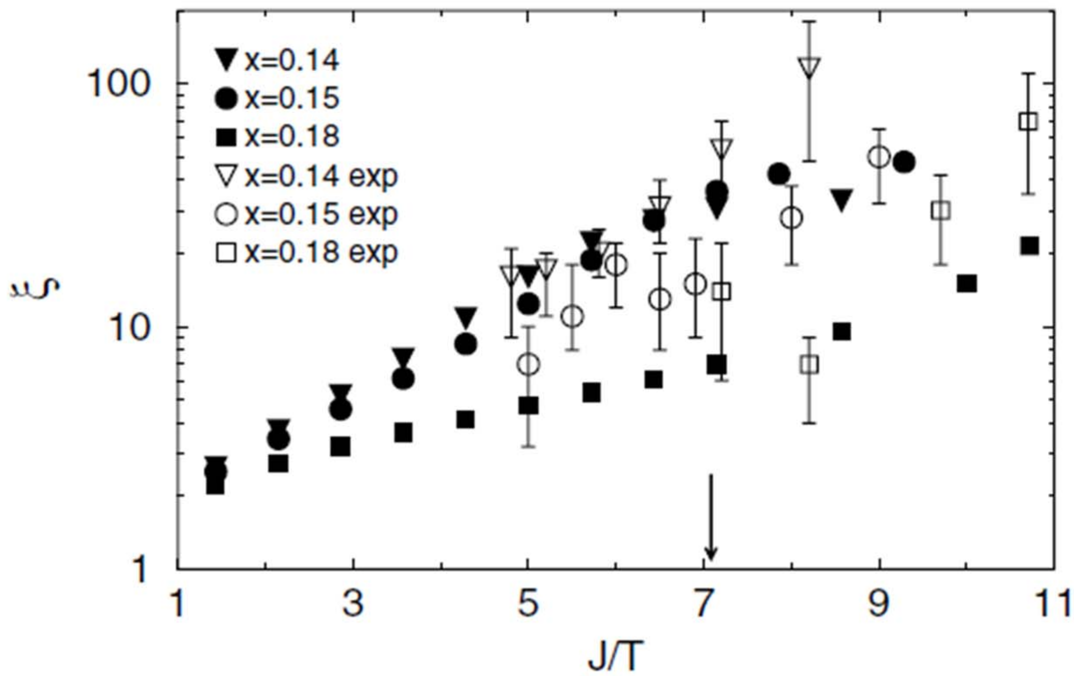
TPSC vs experiment for ξ



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).

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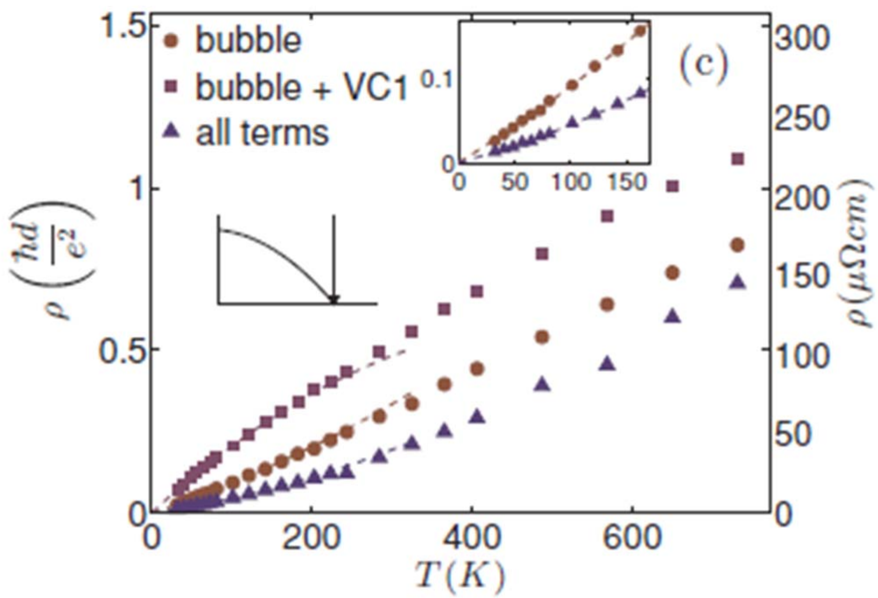
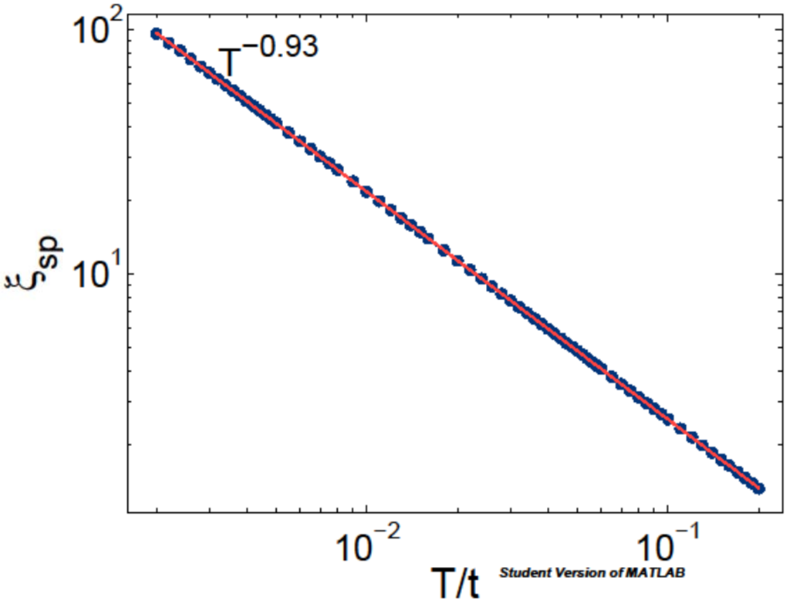
ξ(T) at the QCP

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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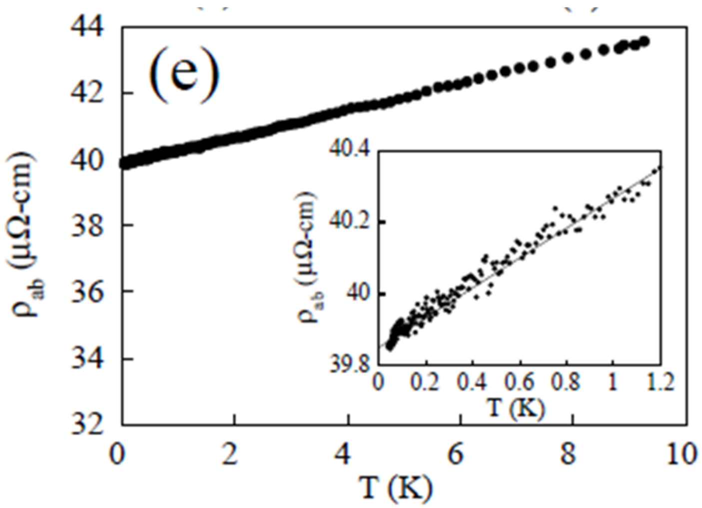
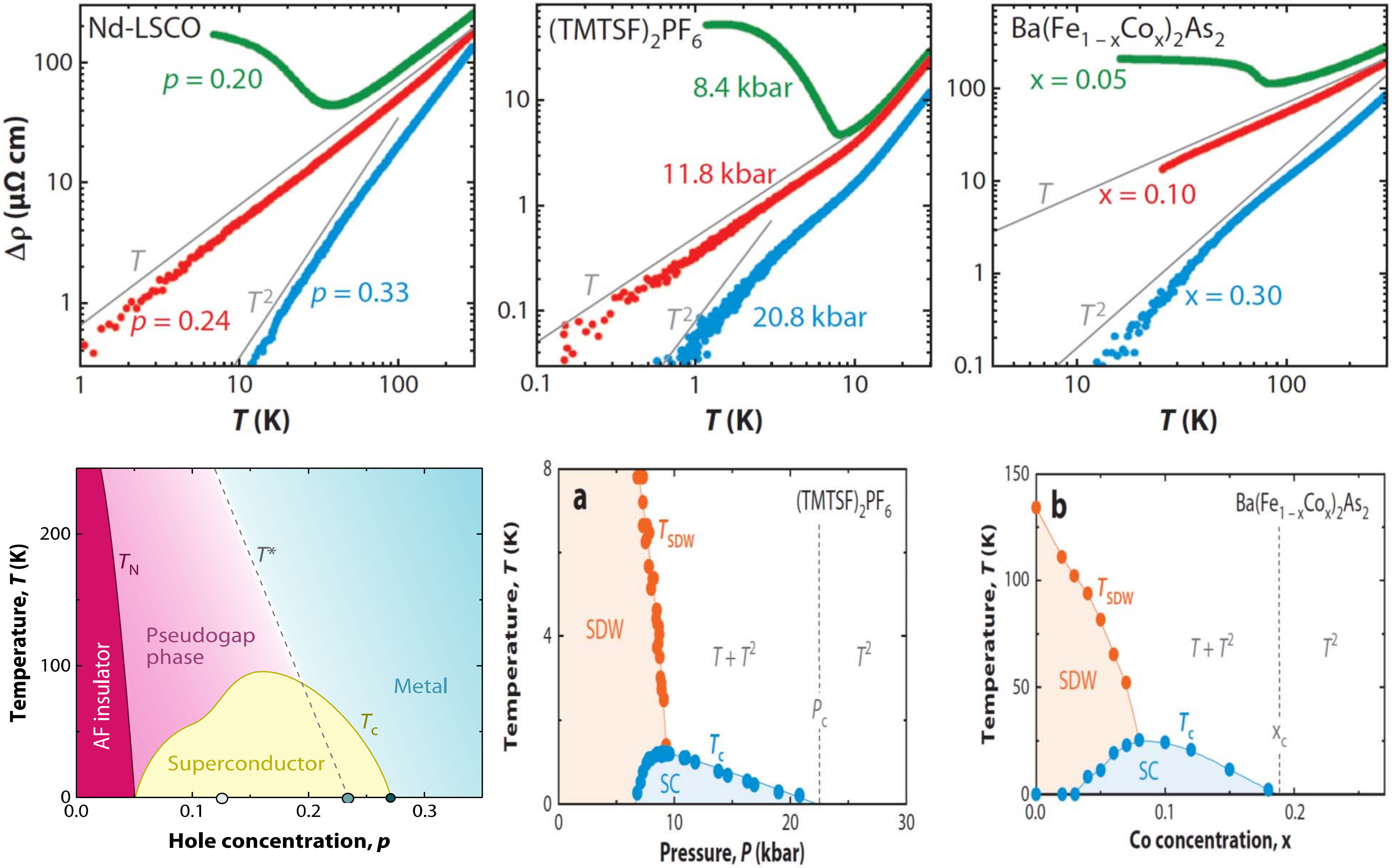
Linear resistivity



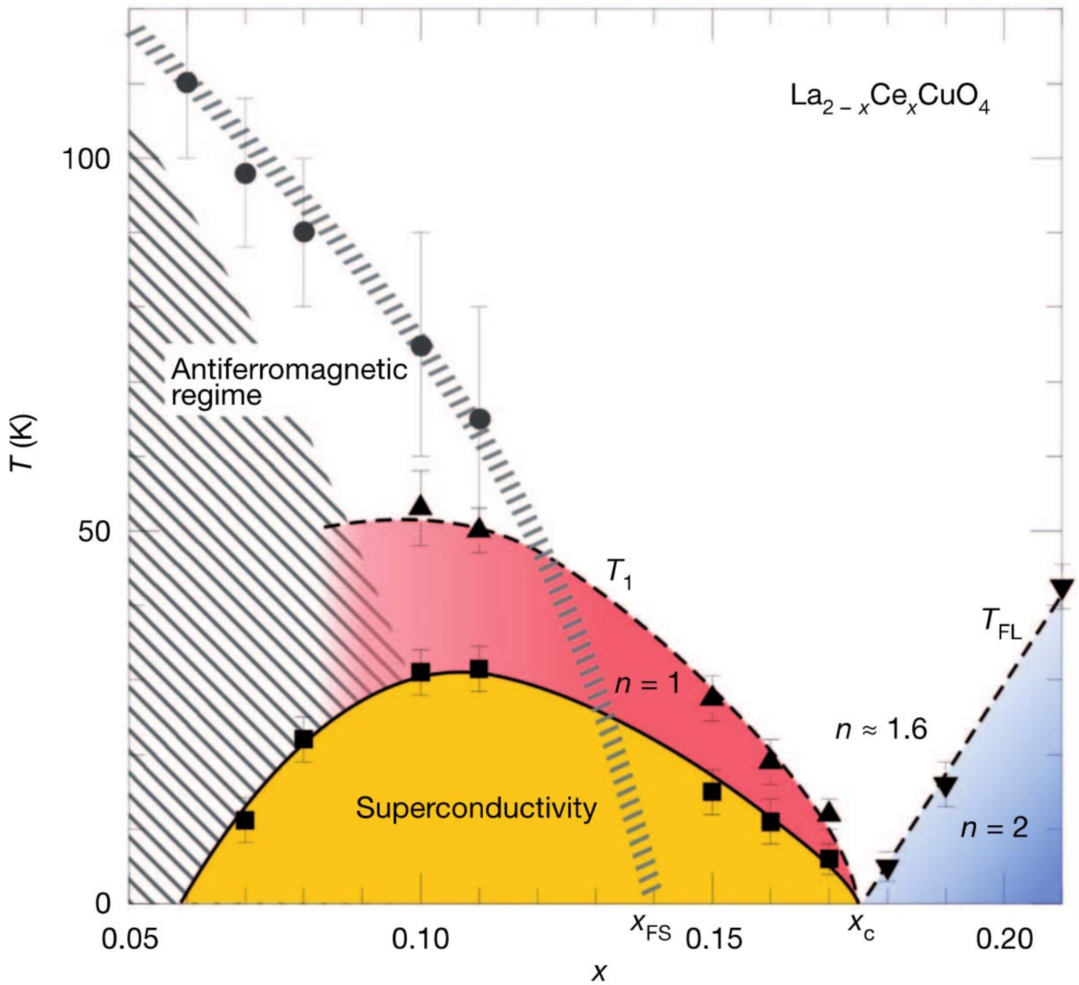
Fournier et al. PRL 1998

QCP and linear T dependence of R



L. Taillefer, Annual Reviews of CMP 2010

Another QCP



Jin et al. Nature 2011

Pseudogap

e-doped

Our road map

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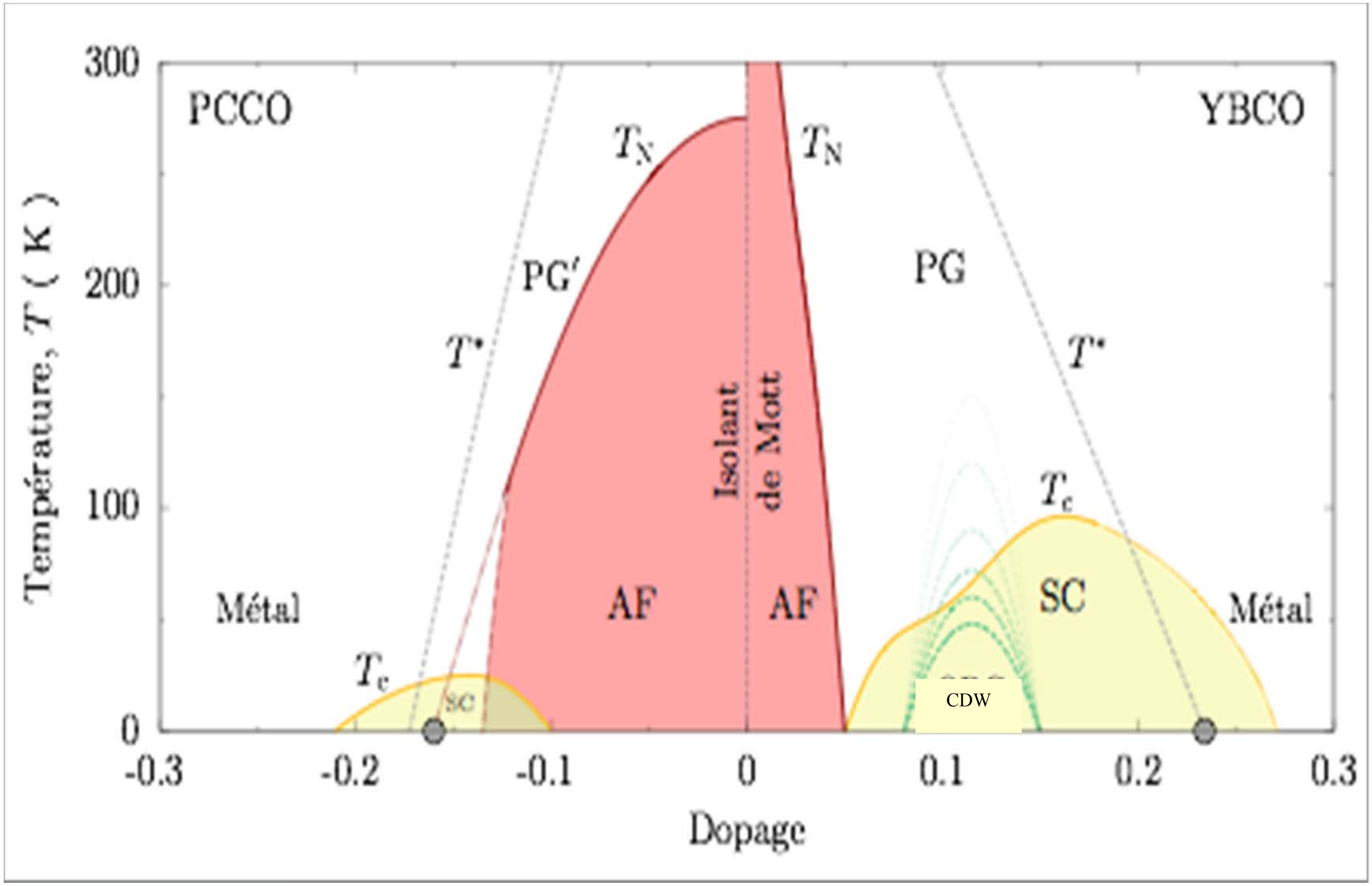

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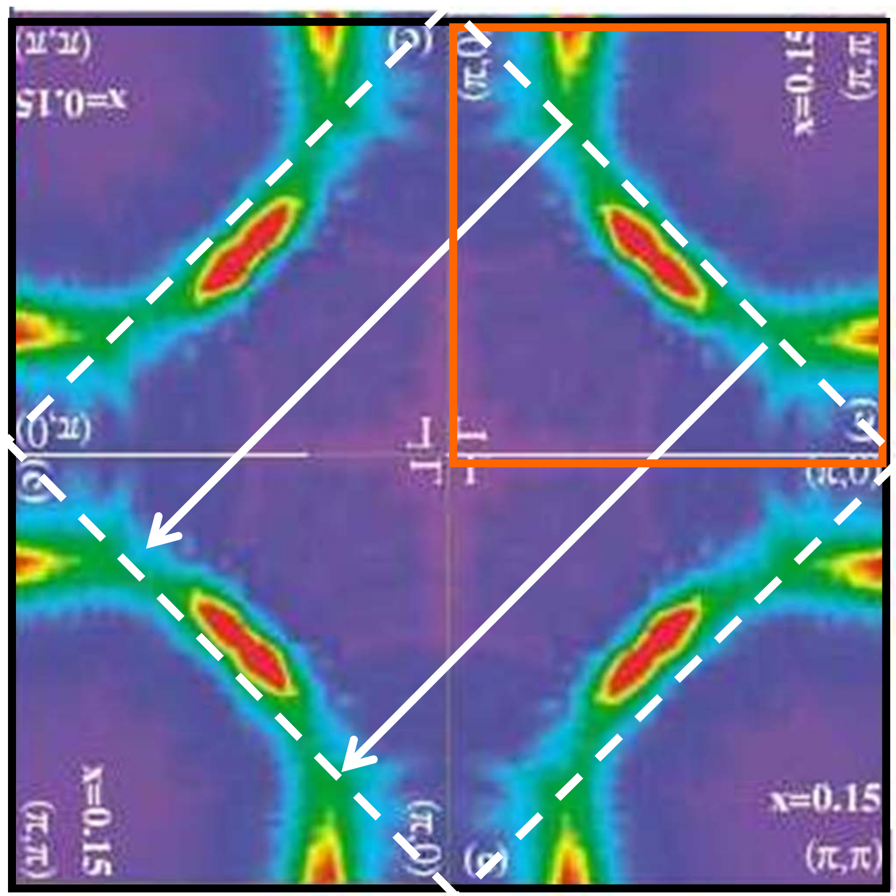
Hot spots from AFM quasi-static scattering

Mermin-Wagner

$d = 2$



Vilk, A.-M.S.T (1997)
Kyung, Hankevych, A.-M.S.T., PRL, 2004

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

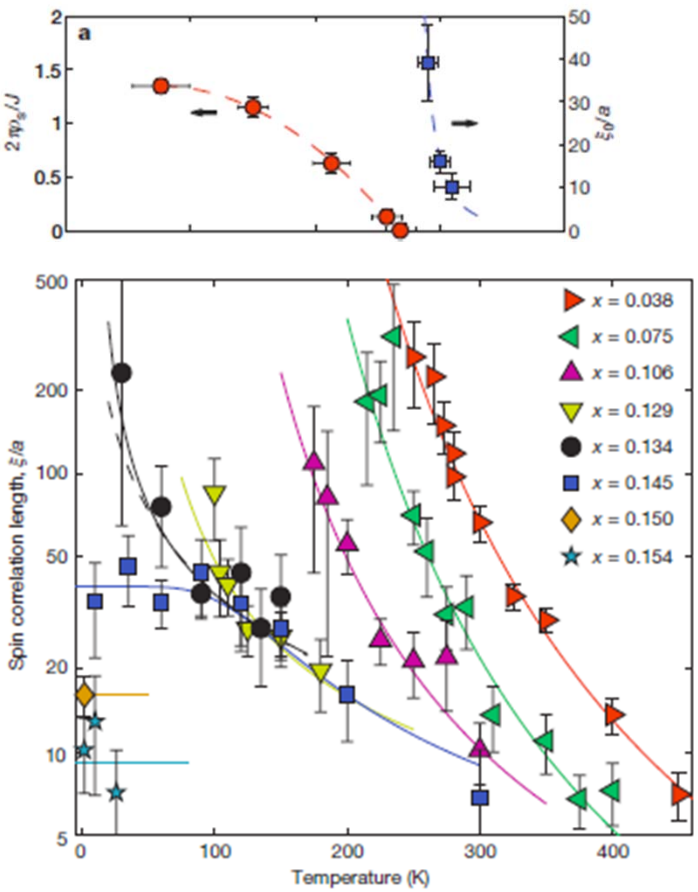
Motoyama, E. M. et al.. 445, 186–189 (2007).

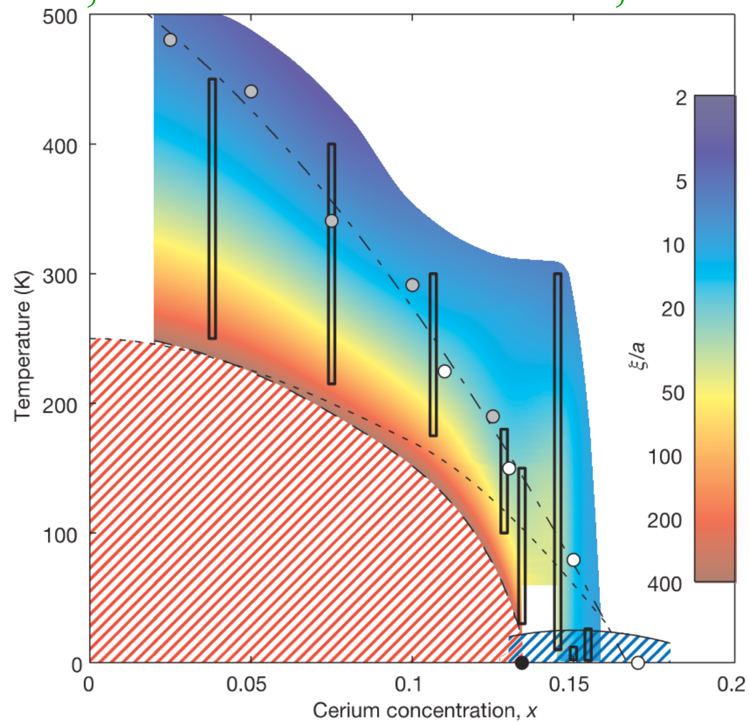
Armitage et al. PRL 2001

e-doped cuprates: precursors

NCCO

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

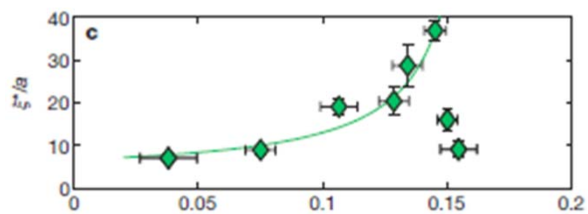




z = 1

Vilk, A.-M.S.T (1997)

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



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

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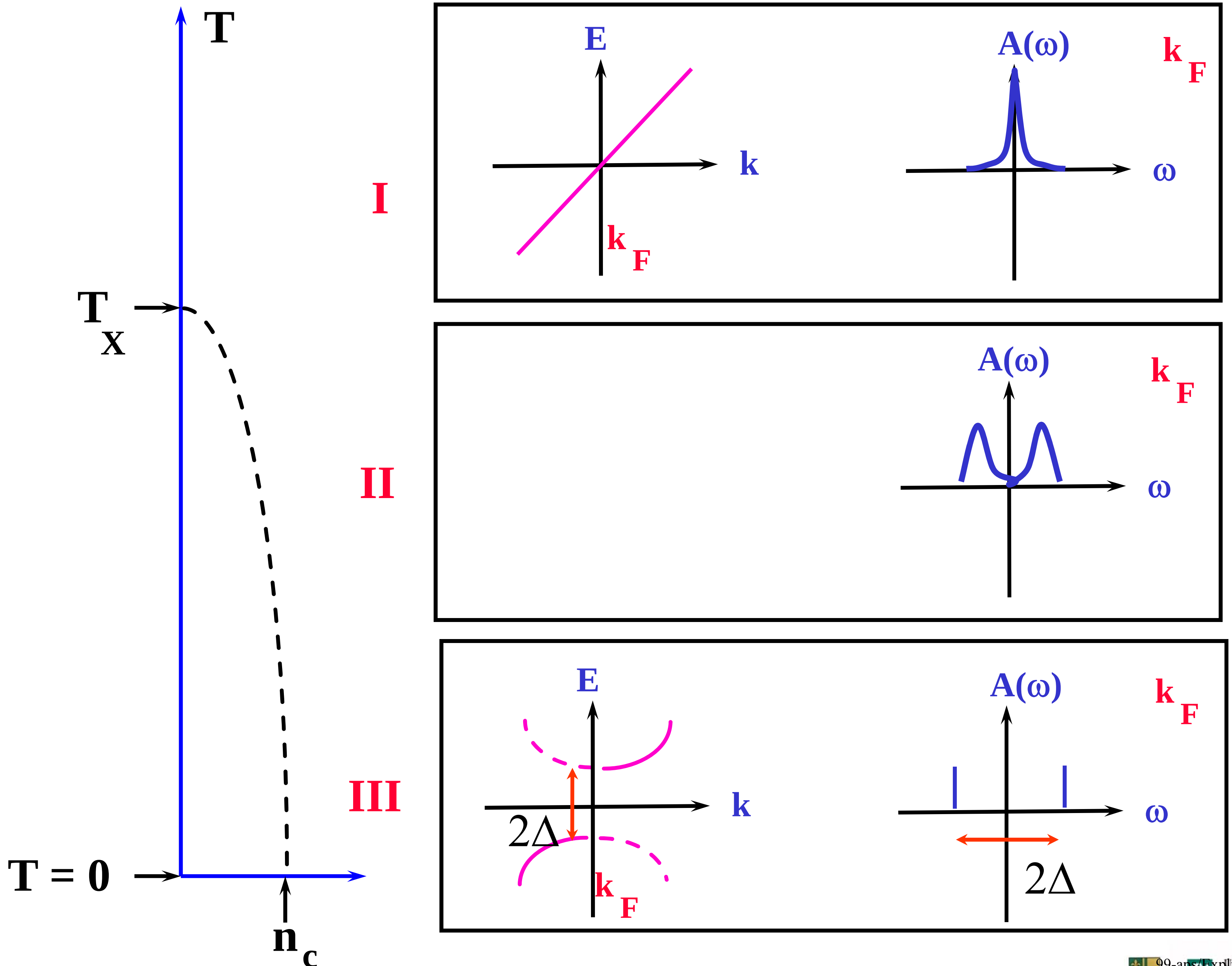
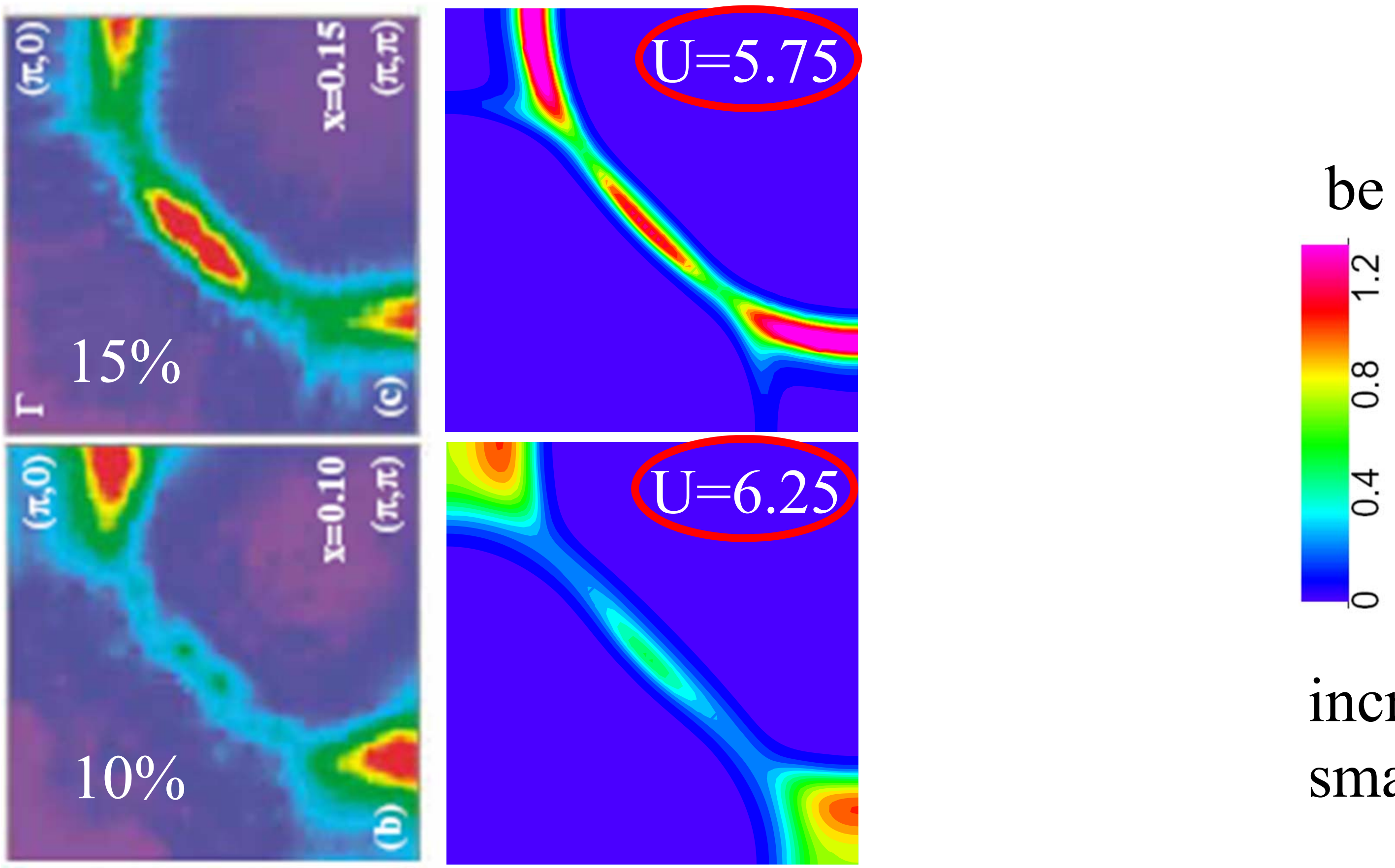


T
T_X
T = 0
n_c
I
E
k
k_F
A(ω)
ω
k_F
II
A(ω)
ω
k_F
III
E
k
2Δ
k_F
A(ω)
ω
2Δ
k_F

Fermi surface plots

Hubbard repulsion *U* has to…



be not too large

increase for smaller doping

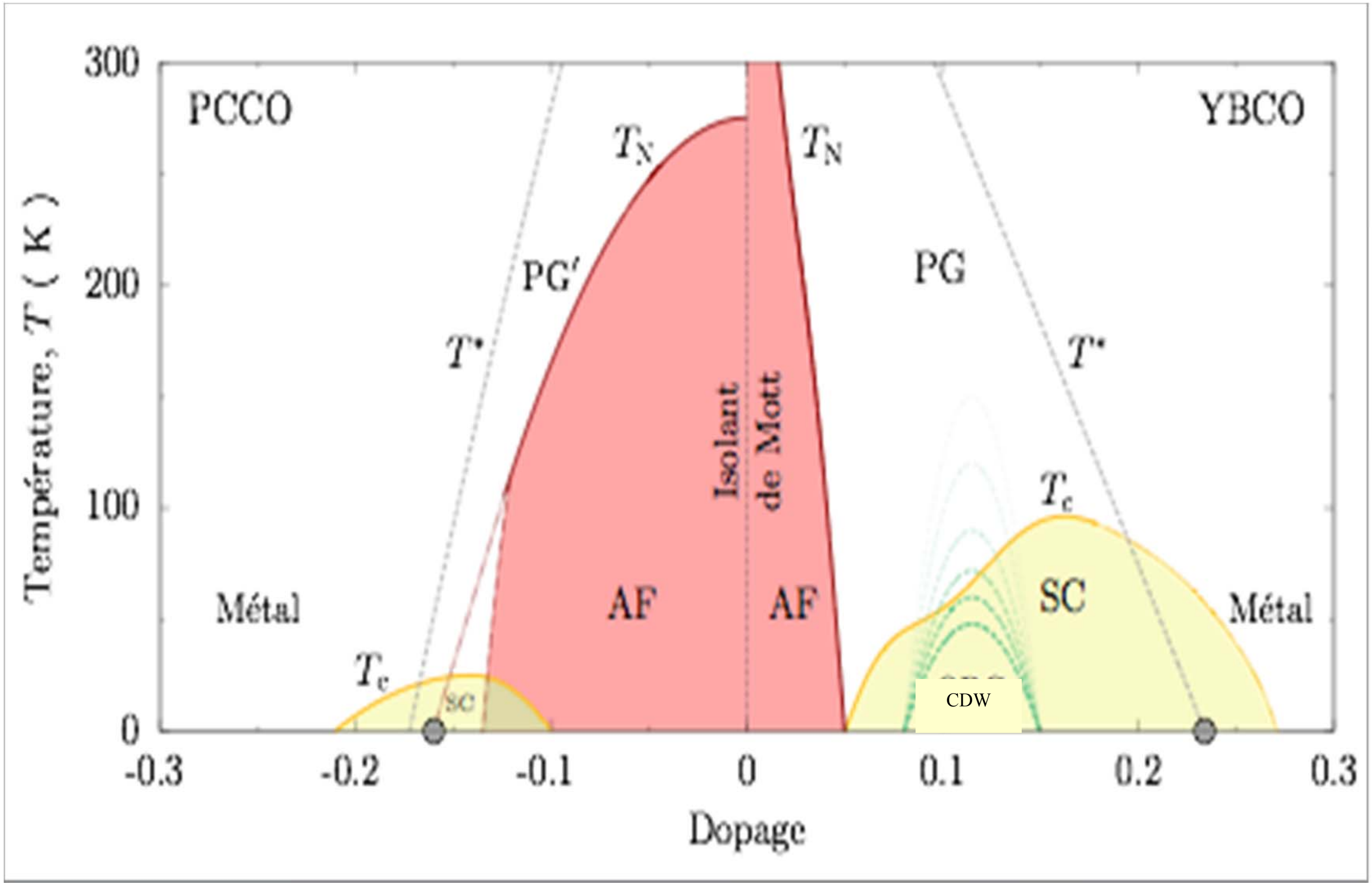
B.Kyung *et al.*,PRB **68**, 174502 (2003)

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

5. Weakly and strongly correlated antiferromagnets

What is a phase?

Our road map



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Antiferromagnetic phase: emergent properties

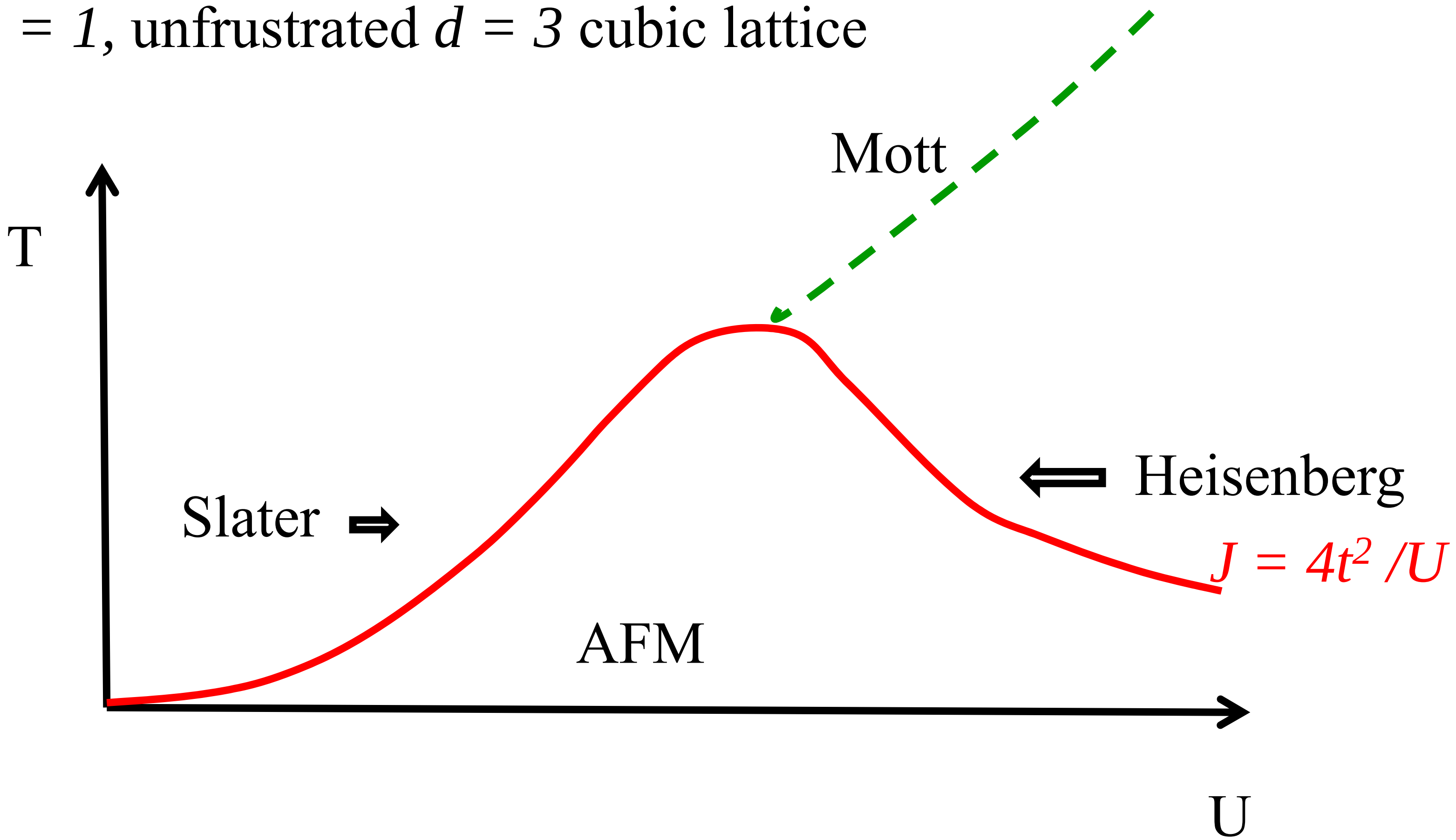
- Some broken symmetries
    - Time reversal symmetry
    - Translation by one lattice spacing
    - Unbroken Time-reversal times translation by lattice vector **a**
  - Spin waves
  - Single-particle gap

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
  - Pressure dependence of T_N

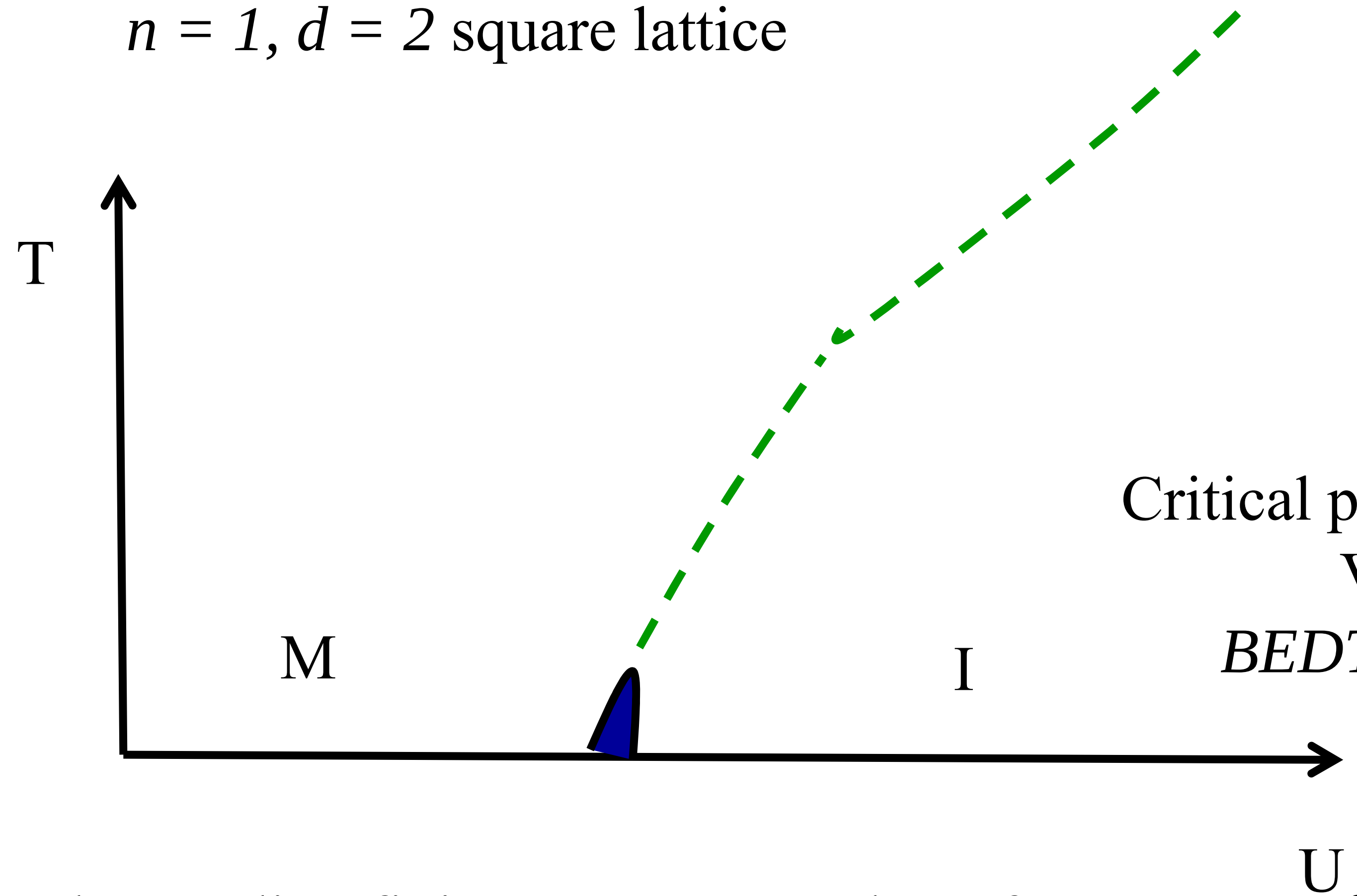
Local moment and Mott transition

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



Local moment and Mott transition

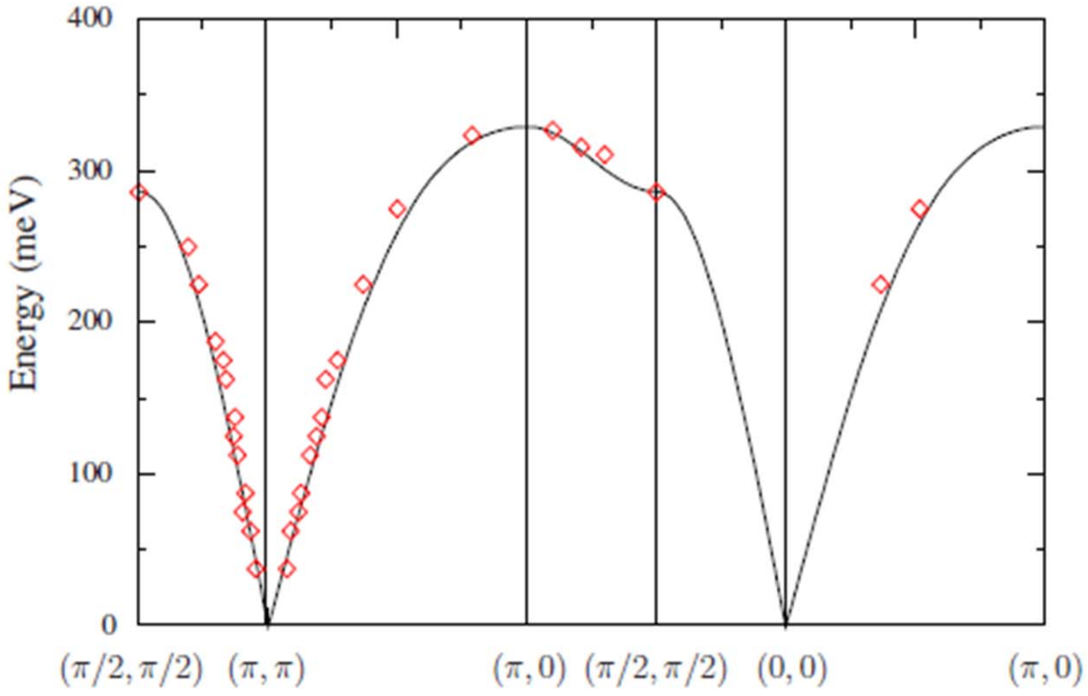
n = 1, d = 2 square lattice



Critical point visible in V_2O_3, *BEDT* organics

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

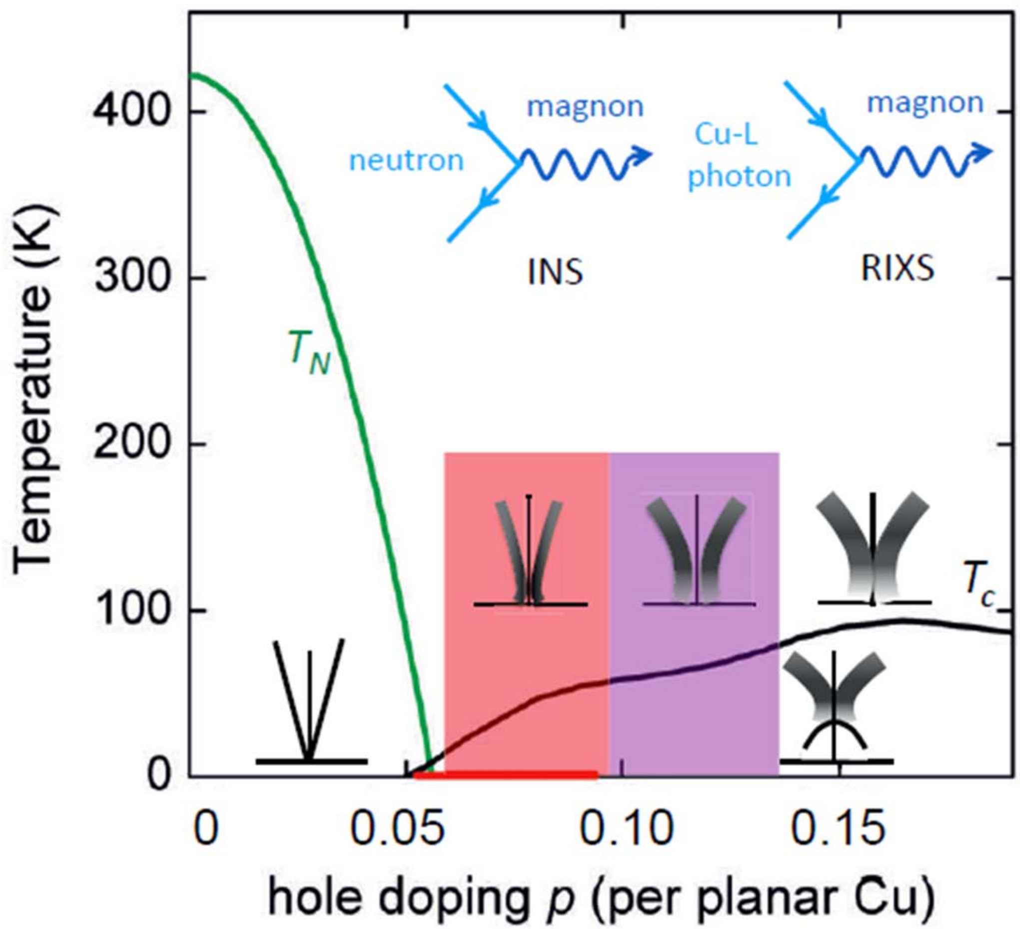
High Tc: almost Heisenberg model



Delannoy et al. PRB **79** (2009)
Dalla Piazza, Phys. Rev. B **85** (2012)

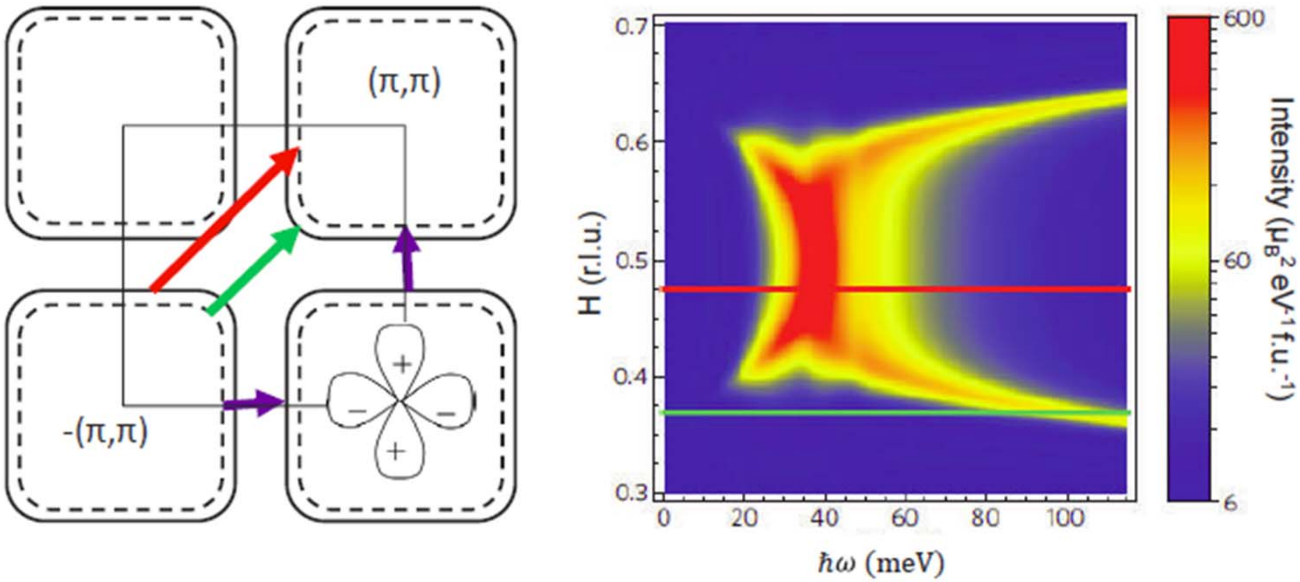
U ~ 8 to 10t

Summary, magnetic excitation spectrum



Keimer, Julich summer school 2013

Spin fluctuations, energy momentum



Note resonnance in superconducting state

Above *100 meV* almost doping independent (RIXS)

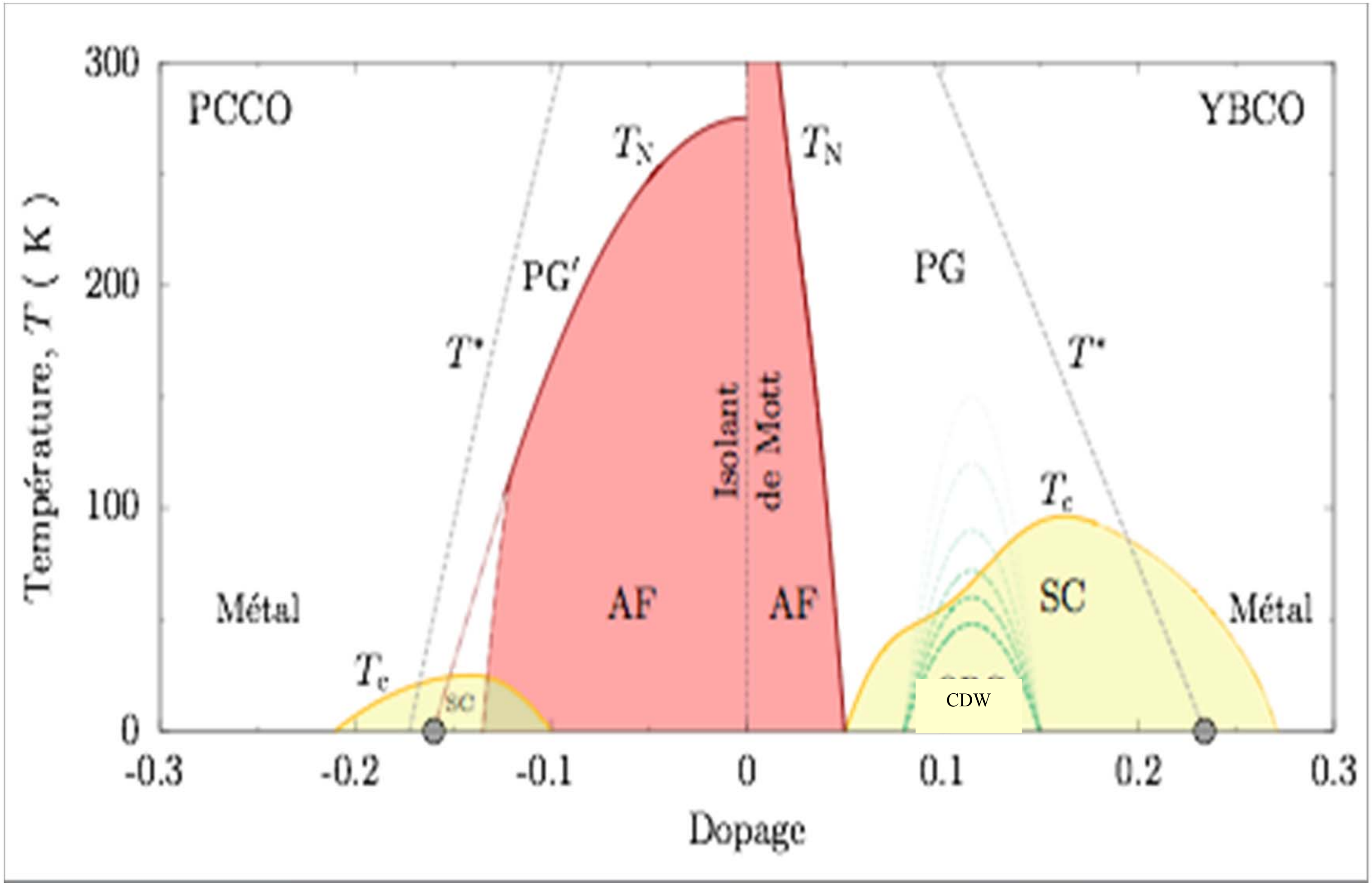
Keimer, Julich summer school 2013

6. Charge Density Wave

h-doped

Our road map

Thèse de Francis Laliberté, Université de Sherbrooke



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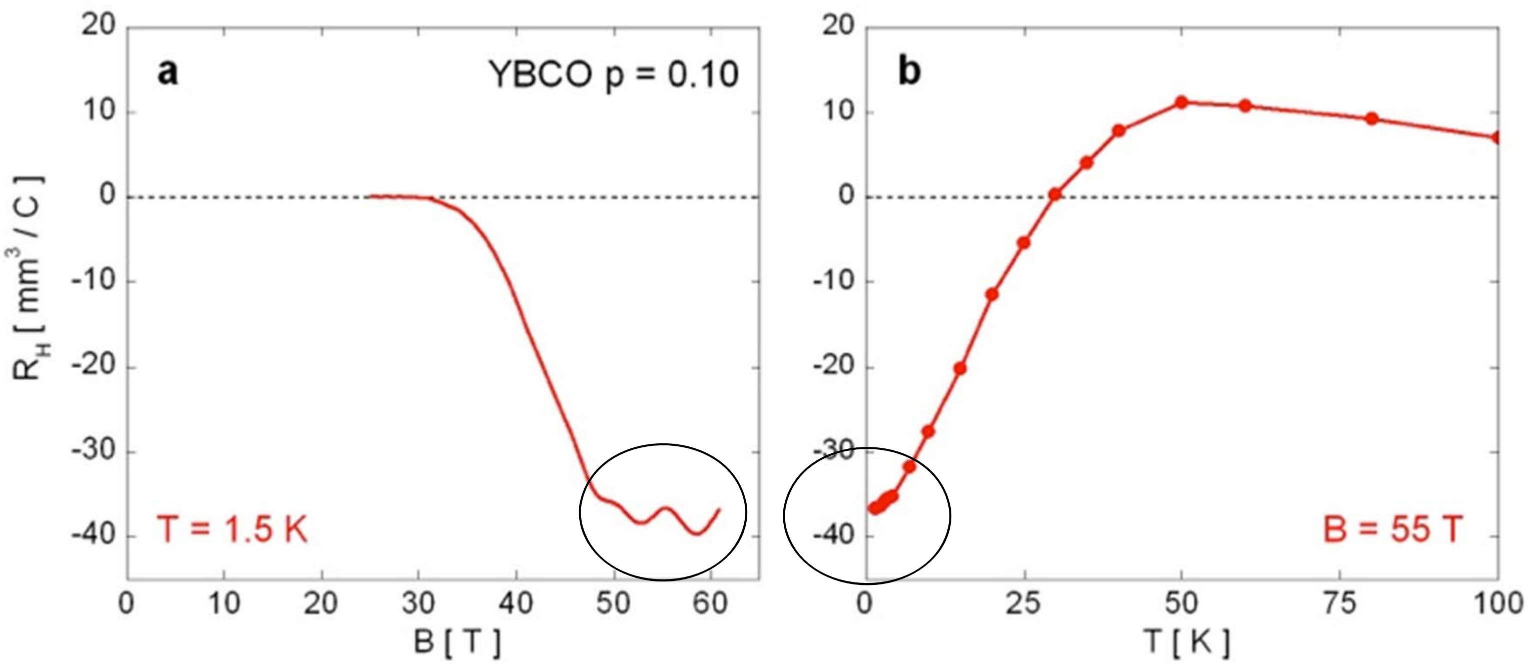
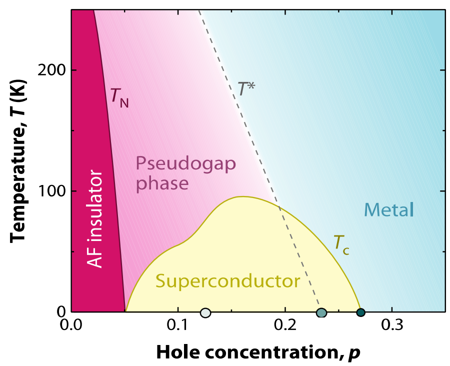
Quantum oscillations in cuprates: 2007

N. Doiron-Leyraud et al., Nature 2007 *D. LeBoeuf et al., Nature 2007*



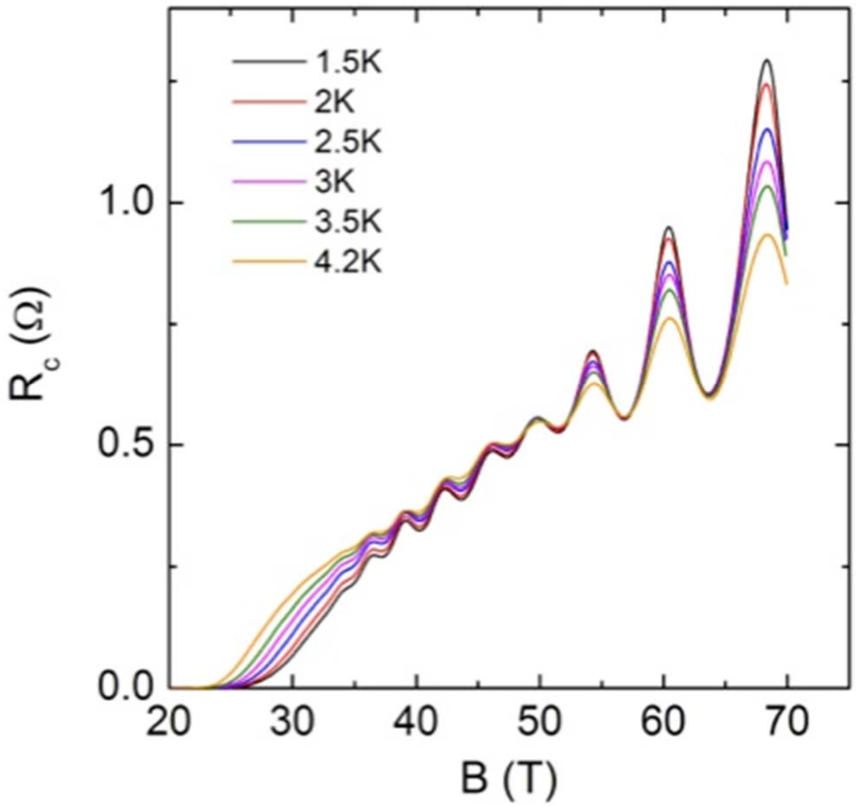


Quantum oscillations ***R_H < 0***

Fermi surface includes a small *electron* pocket !

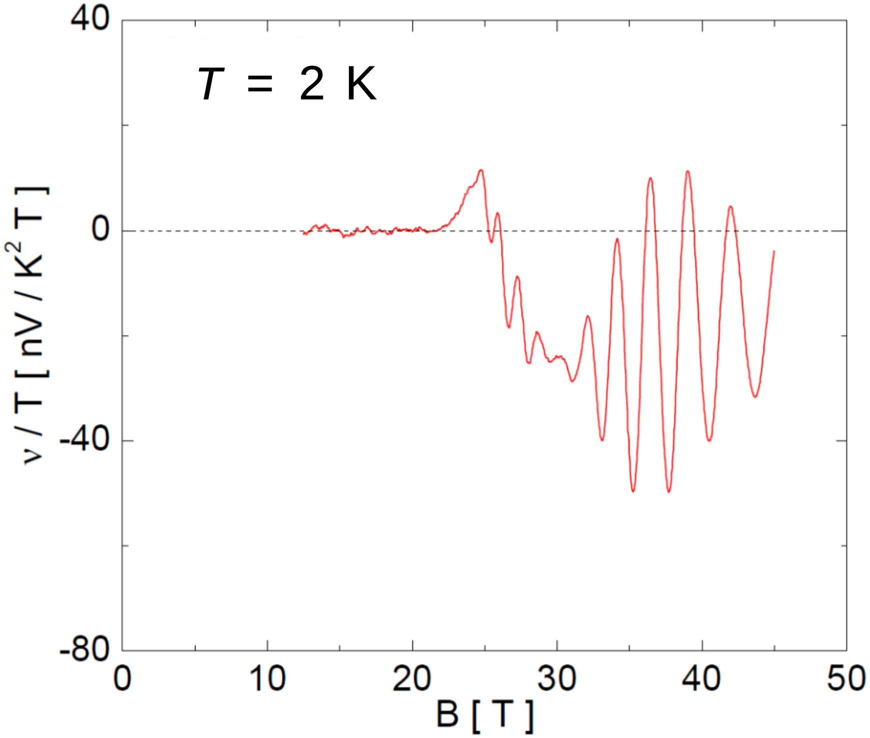
Quantum oscillations in cuprates: 2013

Resistance



LNCMI, Toulouse

Nernst



NHMFL, Tallahassee

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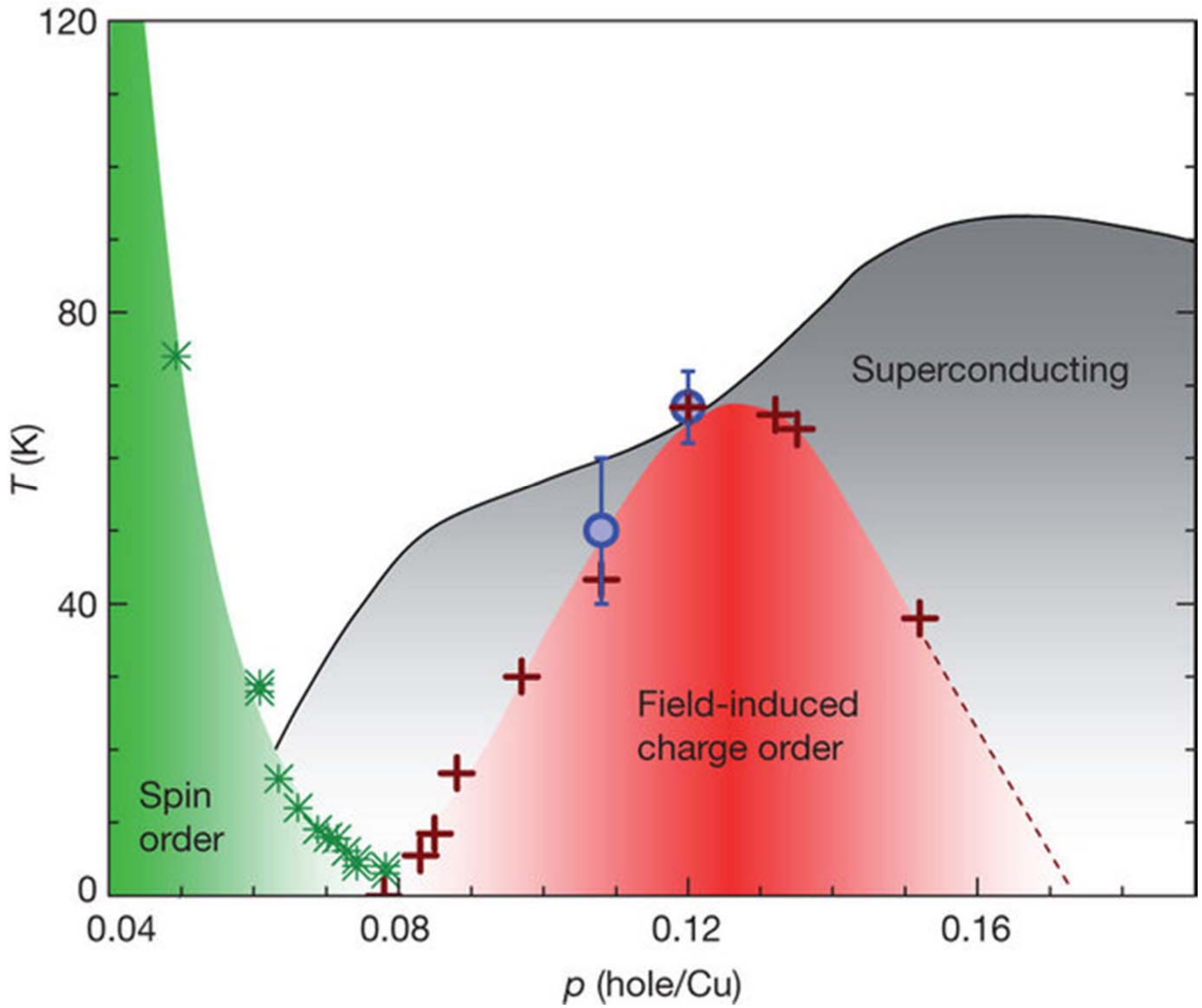
Stripes and reconstructed Fermi surface



Wu et al. Julien, Nature **477**, 191–194 (2011)

nature physics

LETTERS

PUBLISHED ONLINE: 14 OCTOBER 2012 | DOI: 10.1038/NPHYS2456

Direct observation of competition between superconductivity and charge density wave order in $YBa_2Cu_3O_{6.67}$

J. Chang[1,2★], E. Blackburn[3], A. T. Holmes[3], N. B. Christensen[4], J. Larsen[4,5], J. Mesot[1,2], Ruixing Liang[6,7], D. A. Bonn[6,7], W. N. Hardy[6,7], A. Watenphul[8], M. v. Zimmermann[8], E. M. Forgan[3] and S. M. Hayden[9]

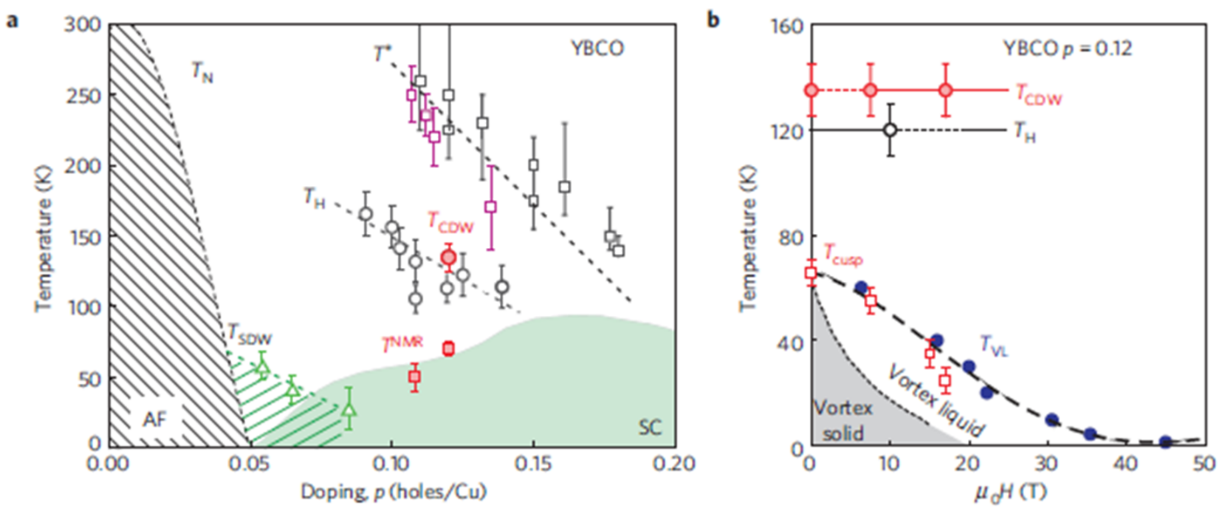
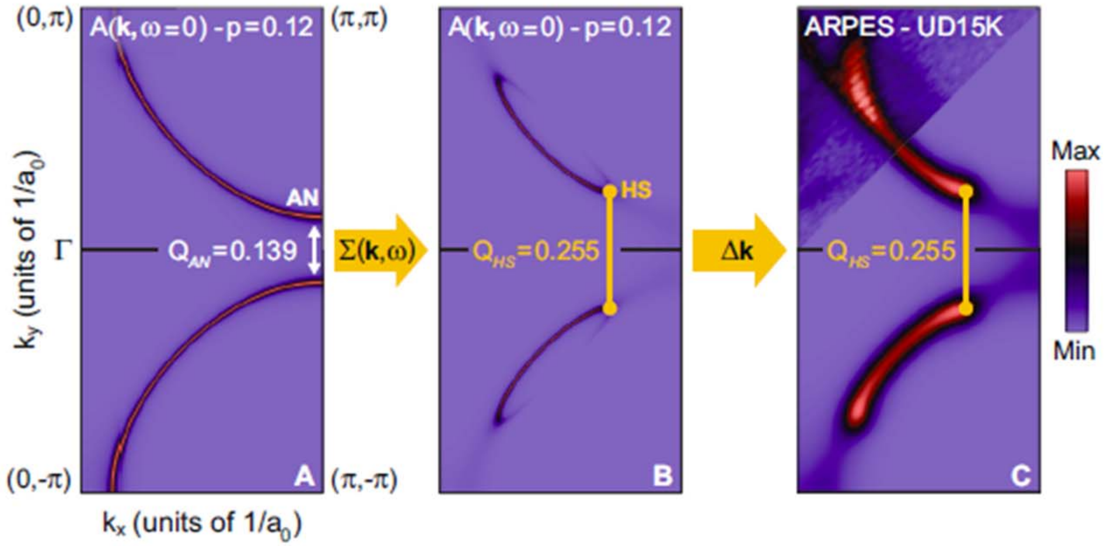


Figure 4 | Phase diagram of $YBa_2Cu_3O_{7-x}$. a, Doping dependence of the antiferromagnetic ordering temperature T_N, the incommensurate spin-density wave order T_{SDW} (green triangles; ref. 21), the superconducting temperature T_c and the pseudogap temperature T^* as determined from the Nernst effect[30] (black squares) and neutron diffraction[29] (purple squares). Notice that the Nernst effect[30] indicates a broken rotational symmetry inside the pseudogap region, whereas a translational symmetry preserving magnetic order is found by neutron scattering[29]. Below temperature scale T_H (black circles), a larger and negative Hall coefficient was observed[26] and interpreted in terms of a Fermi surface reconstruction. Our X-ray diffraction experiments show that in YBCO $p=0.12$ incommensurate CDW order spontaneously breaks the crystal translational symmetry at a temperature T_{CDW} that is twice as large as T_c. T_{CDW} is also much larger than T^{NMR} (red squares), the temperature scale below which NMR observes field-induced charge order[13]. **b**, Field dependence of T_{CDW} (filled red circles) and T_{cusp} (open squares), the temperature below which the CDW is suppressed by superconductivity, compared with T_H (open black circle) and T_{VL} (filled blue circles), the temperature where the vortex liquid state forms[26]. Error bars on T_{SDW}, T_H, T_{NMR}, and T^* are explained in refs 21,26,30,33. The error bars on T_{CDW} and T_{cusp} reflect the uncertainty in determining the onset and suppression temperature of CDW order from Fig. 2.

KE

Fermi surface vs wave vector of instability



Comin et al. arXiv:1312.1343

Da Silva Neto, arXiv:1312.1347 (also in BSCCO)

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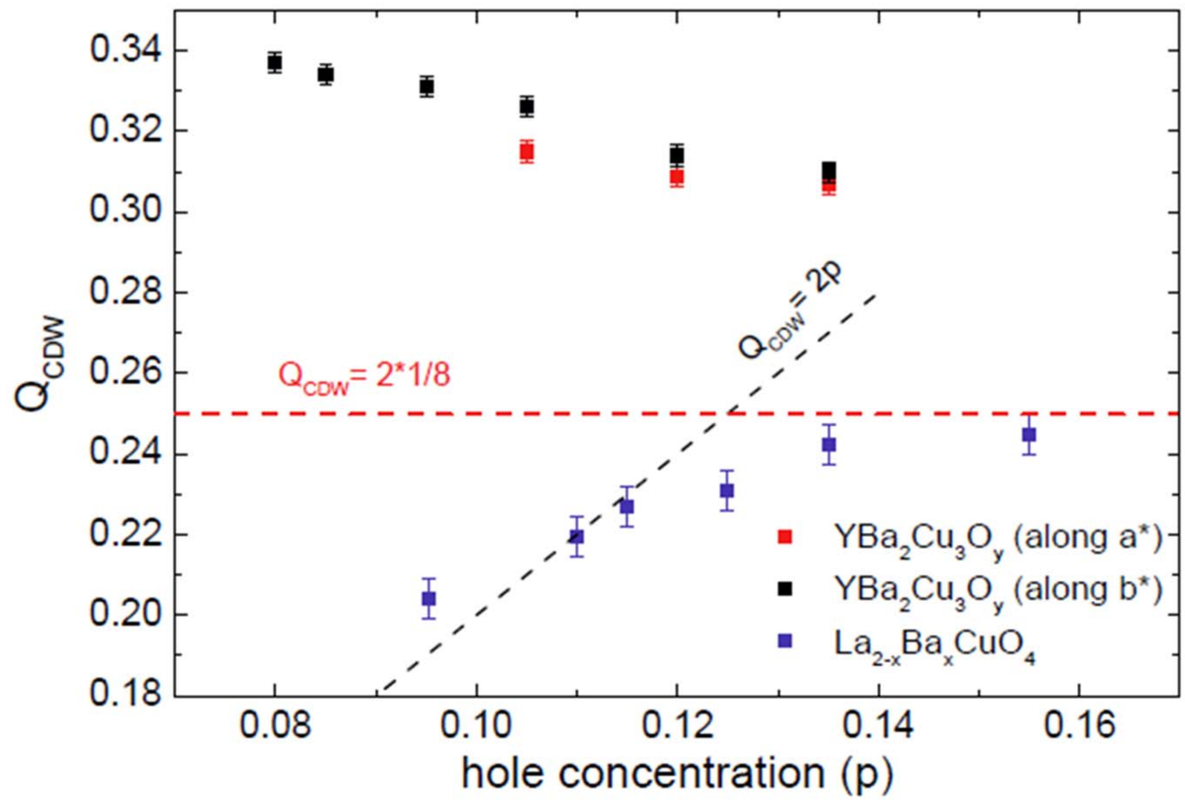
Wave vector



Keimer, Julich summer school 2013

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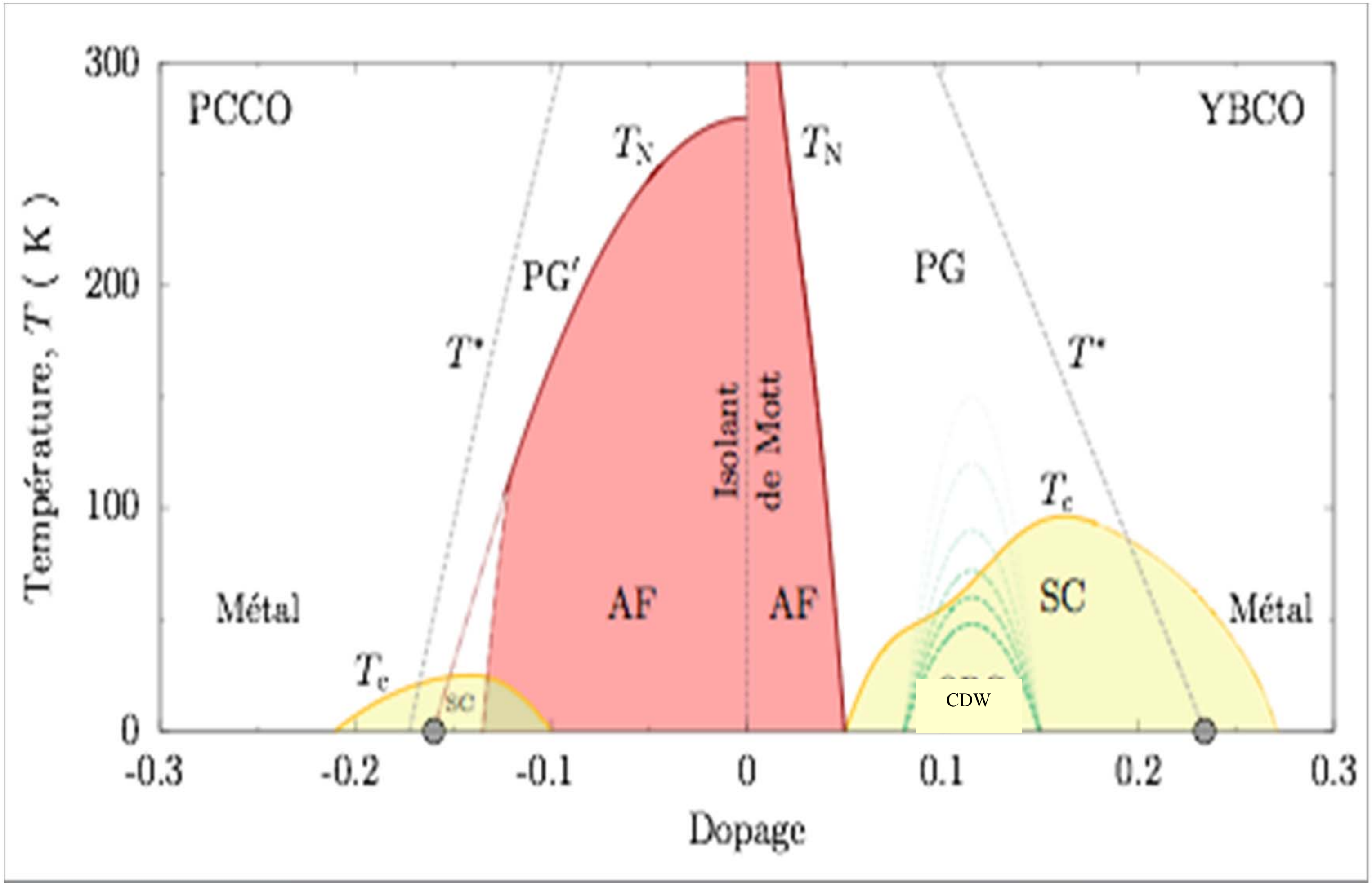
7. Pseudogap

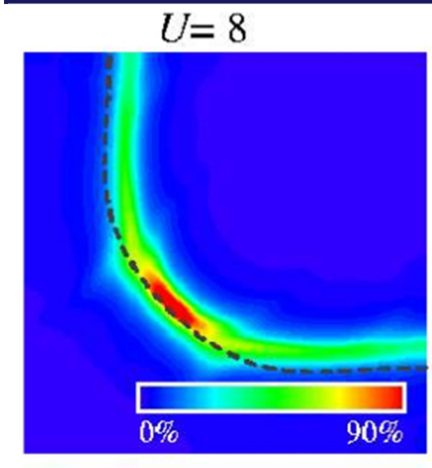
h-doped

Our road map

Thèse de Francis Laliberté, Université de Sherbrooke

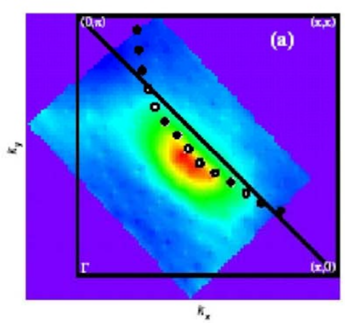


Hole-doped 17%, U=8t (CPT)

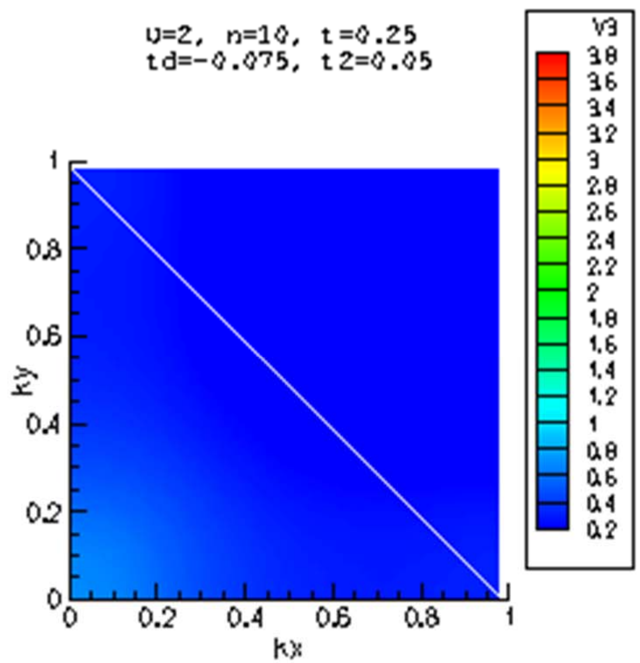


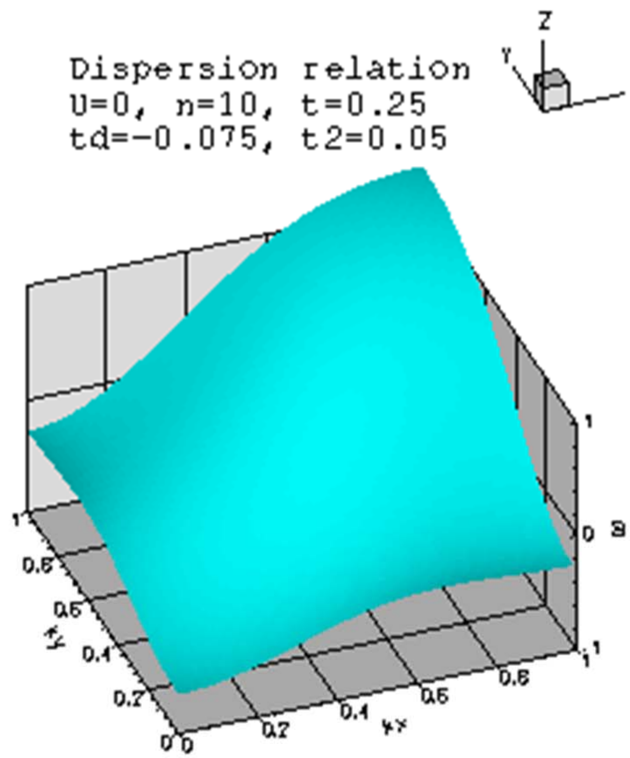
Sénéchal, AMT, PRL (2004)

Hole-doped, 10%



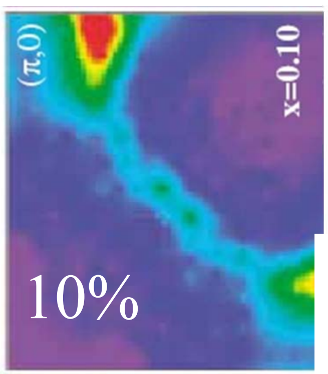
F. Ronning et al. Jan. 2002, $Ca_{2-x}Na_xCuO_2Cl_2$

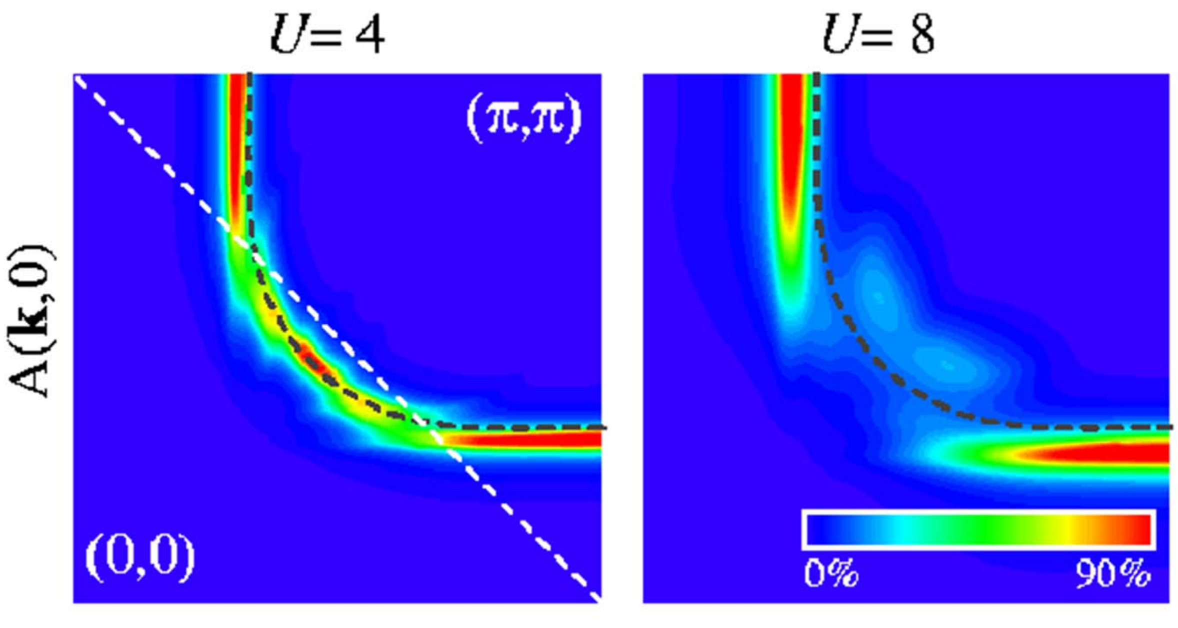




Ronning *et al.* (PRB 2003)

Electron-doped (17%) (CPT)





$t' = -0.3t$
$t'' = 0.2t$

$\eta = 0.12t$
$\eta = 0.4t$

Armitage *et a*
PRL 2003

Sénéchal, AMT,
PRL (2004)

How does the pseudogap develops as a function of T ?

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NMR Knight shift?

H. Alloul arXiv:1302.3473

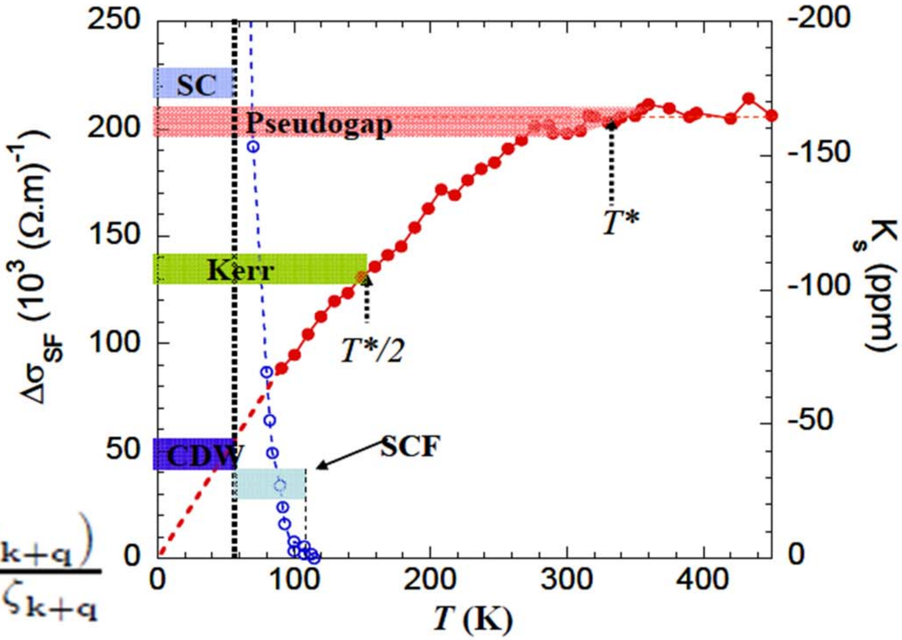
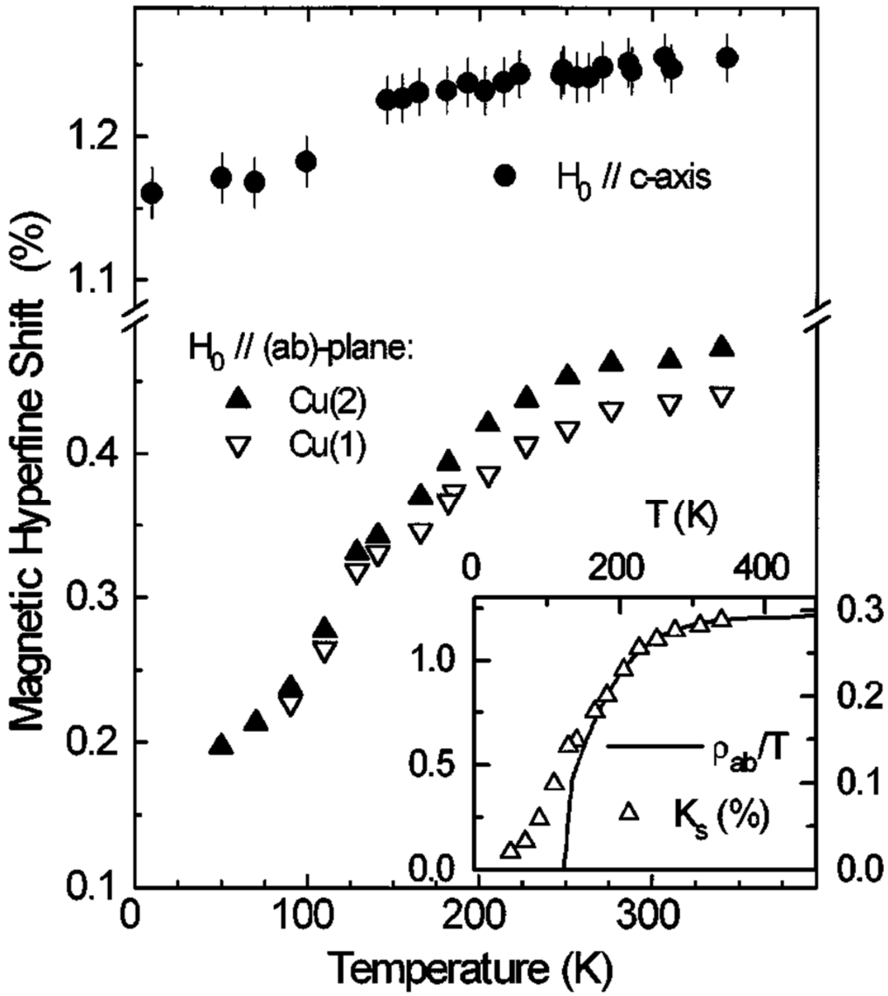


Fig 1 Spin contribution K_s to the ^{89}Y NMR Knight shift [11] for $YBCO_{6.6}$ permit to define the PG onset T^*. Here K_s is reduced by a factor two at $T\sim T^*/2$. The sharp drop of the SC fluctuation conductivity (SCF) is illustrated (left scale) [23]. We report as well the range over which a Kerr signal is detected [28], and that for which a CDW is evidenced in high fields from NMR quadrupole effects [33] and ultrasound velocity data [30]. (See text).

Noninteracting case:

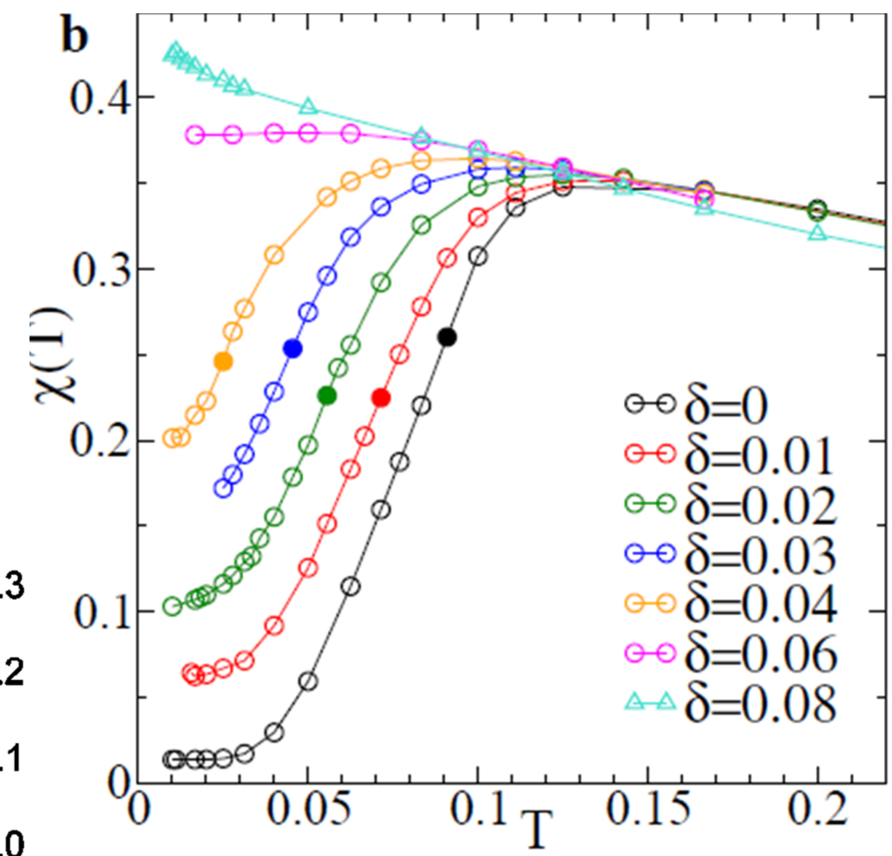
$$\chi^{0R}_{nn}(\mathbf{q},\omega) = -2\int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{f(\zeta_\mathbf{k})-f(\zeta_{\mathbf{k+q}})}{\omega+i\eta+\zeta_\mathbf{k}-\zeta_{\mathbf{k+q}}}$$

Spin susceptibility



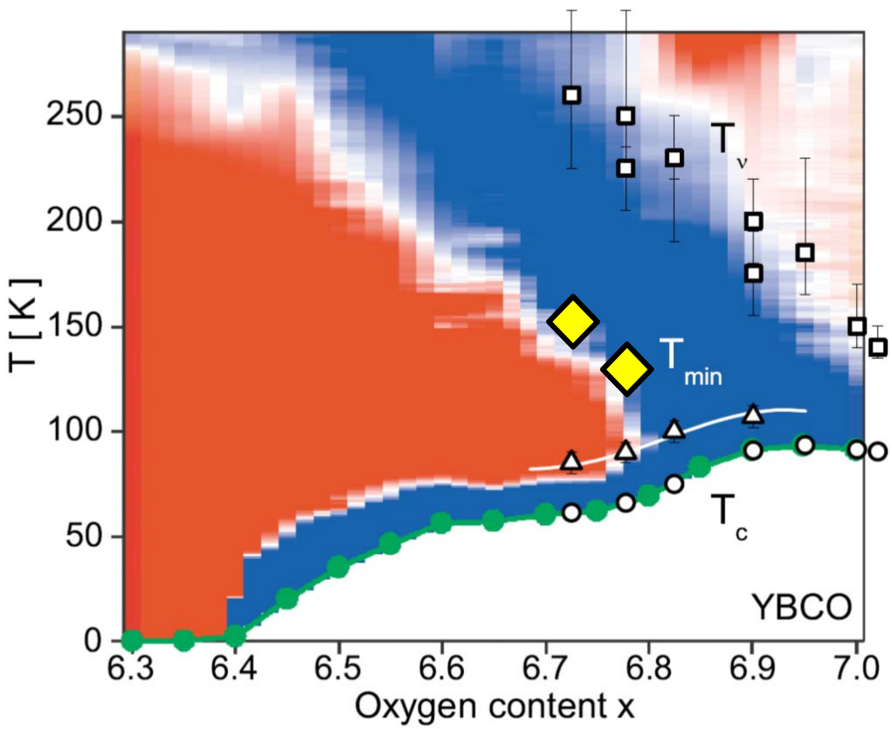
Underdoped Hg1223

Julien et al. PRL **76,** 4238 (1996)



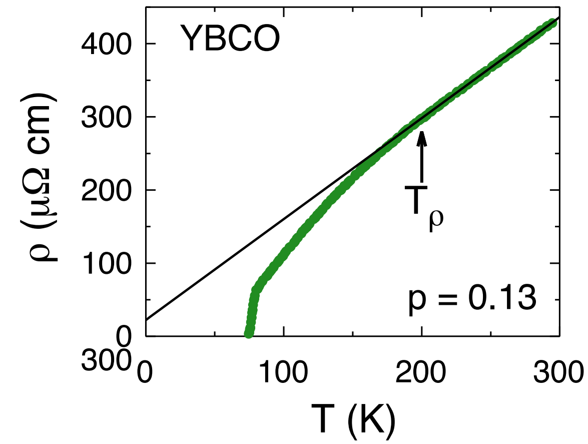
Sordi et al. Scientific Repts. 2012

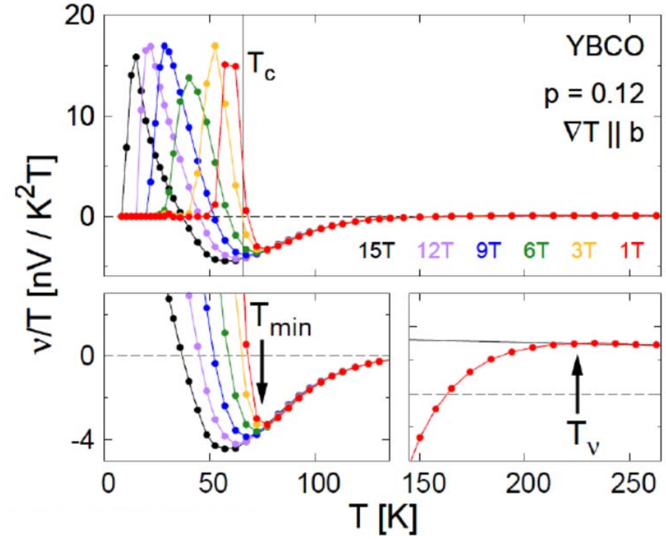
Pseudogap from transport



CDW onset :

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





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

3 measurements: Kerr, ARPES, TRR

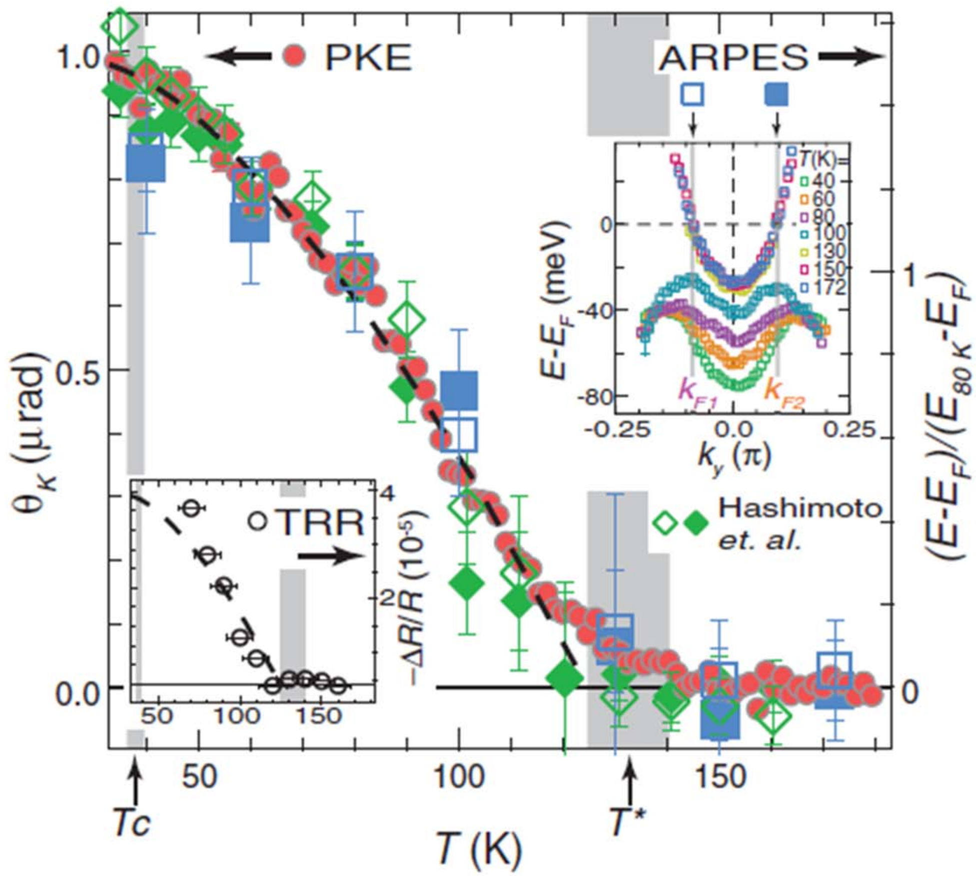


Fig. 3. Temperature dependence of Kerr rotation (θ_K) measured by PKE, in comparison with that of the binding energy position of the EDC maximum at k_F given by ARPES [reproduced from fig. S1F and (*29*)]. ARPES results are normalized to the 80 K values (free from the interference of fluctuating superconductivity). The dashed black curve is a guide to the eye for the PKE data, showing a mean-field–like critical behavior close to T^* [see additional discussion in (*27*)]. (**Left inset**) Temperature dependence of the transient reflectivity change measured by TRR (right axis). The dashed black curve (left axis) is reproduced from the main panel. Error bars (if not visible) are smaller than the symbol size. (**Right inset**) Dispersion of the EDC maximum at various temperatures above T_c, summarizing the results of Figs. 2A and 4A and fig. S1, A to E. All data were taken on samples from the same growth and annealing batch, except those reproduced from (*29*) on differently annealed samples.

He et al, Science

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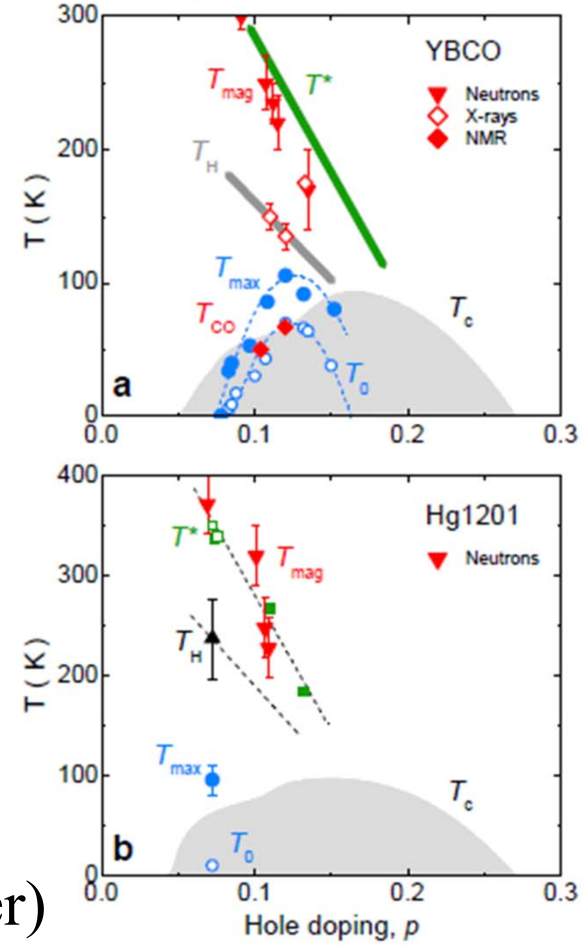
From transport measurements same signatures in single layer material HgBaCuO

Hall and Nernst Coefficients of Underdoped $HgBa_2CuO_{4+\delta}$: Fermi-Surface Reconstruction in an Archetypal Cuprate Superconductor

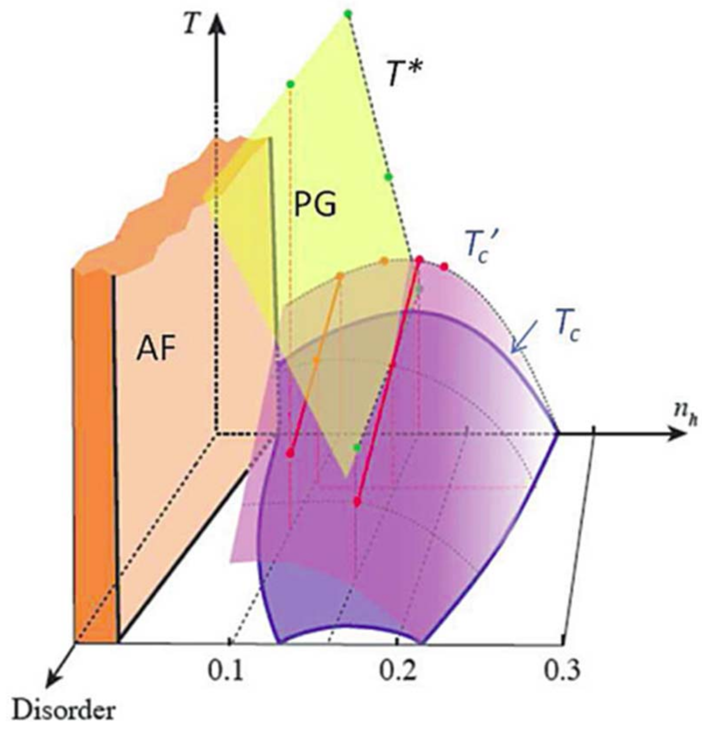
Nicolas Doiron-Leyraud,[1,*] S. Lepault,[2] O. Cyr-Choinière,[1] B. Vignolle,[2] F. Laliberté,[1] J. Chang,[1] N. Barišić,[3] M. K. Chan,[3] L. Ji,[3] X. Zhao,[3,4] Y. Li,[5] M. Greven,[3] C. Proust,[2,6] and Louis Taillefer[1,6,†]



31 oct 2012

Also, Nernst very anisotropic at T* (Taillefer)

Pseudogap not from SC fluctuations
Effect of disorder



F. Rullier-Albenque, H. Alloul, and G.Rikken,
Phys. Rev. B **84**, 014522 (2011).

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Pseudogap not from SC fluctuations

Torque magnetometry,
Hg1201
Bi2201
LSCO

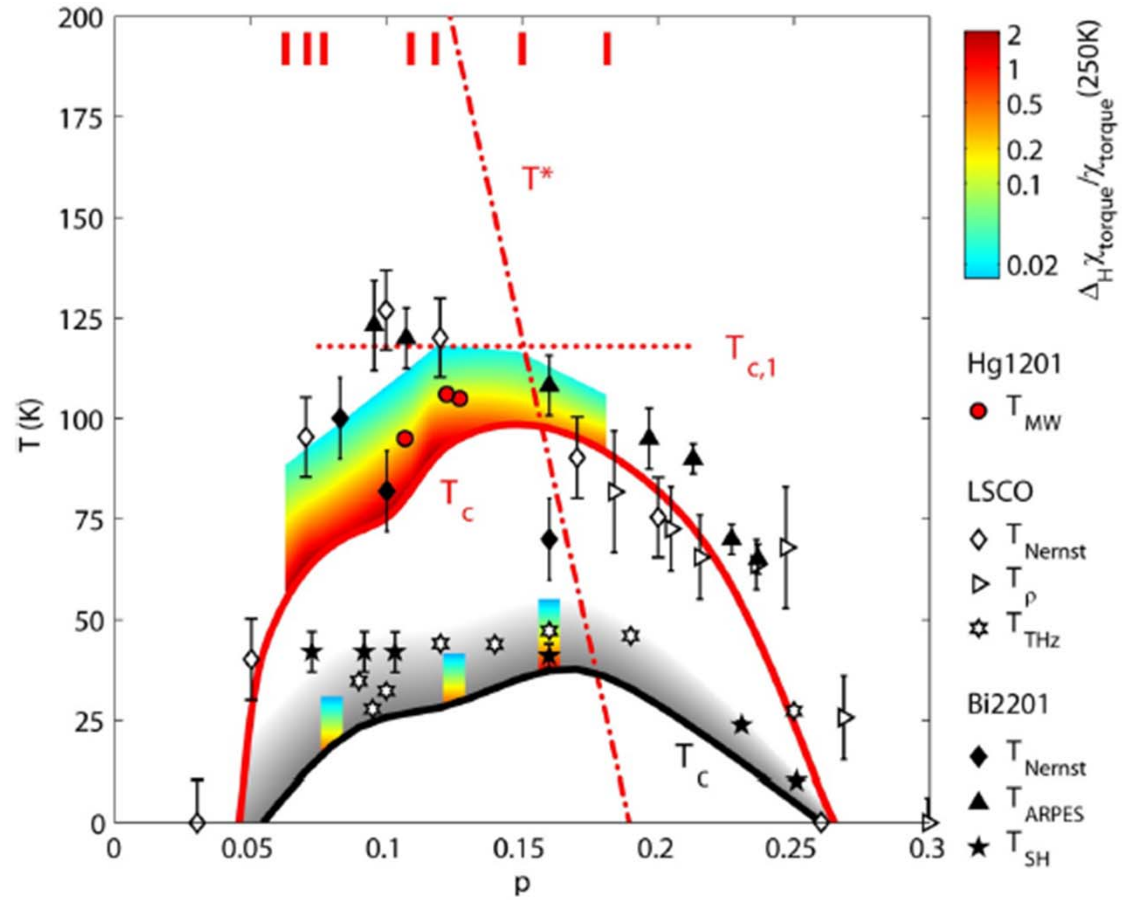
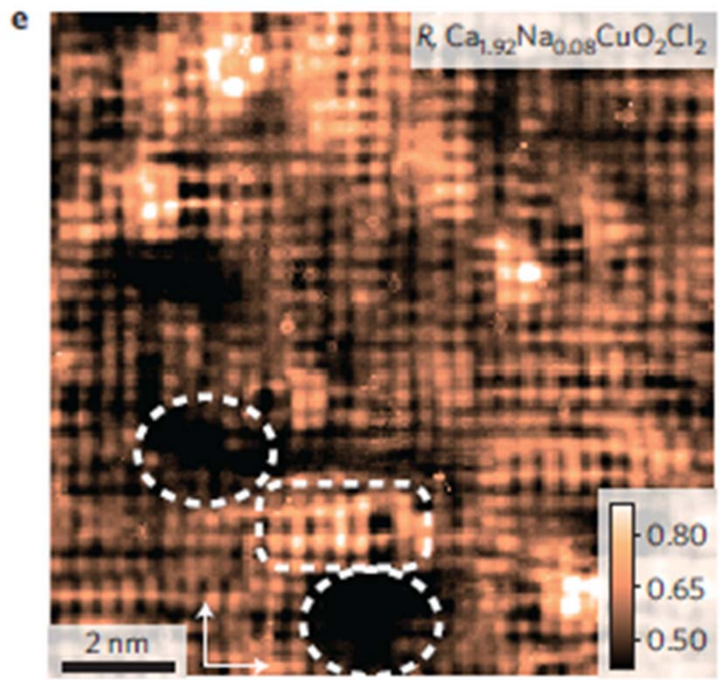


Figure 4 | **Phase diagram.** The color contour shows $\log_{10}(\Delta_H\chi_{torque}/\chi^{250}_{torque})$ for Hg1201 (same data as in Fig. 3d, but for wider temperature range), obtained from an interpolation of measurements of seven samples (indicated by vertical red bars), and for optimally-doped Bi2201 and underdoped LSCO (p = x = 0.08 and 0.125). The grey shaded area indicates schematically the extent of SC fluctuations in LSCO and

Yu et al. cond-mat/1210.6942

Intra-unit cell nematic order: STM

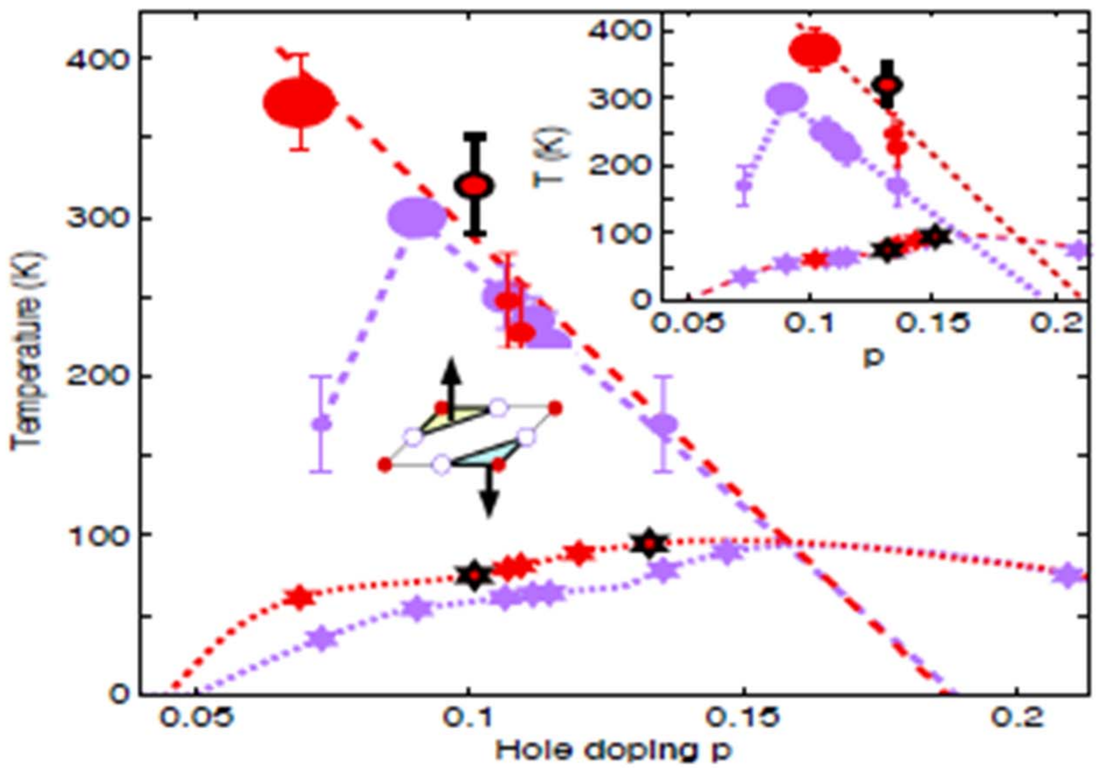


Kohsaka et al. Nature Physics 2012

Loop current order (Varma)

YBaCuO : Bourges et al.

HgCaCuO: Greven et al.



8. Superconductivity in general

Analog to weakly and strongly correlated antiferromagnets

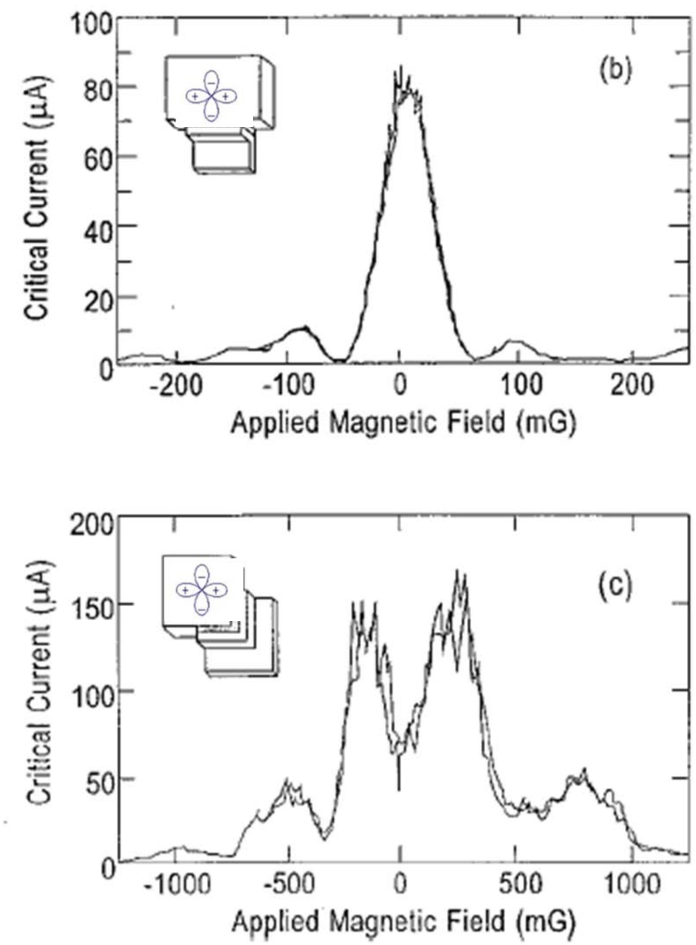
Superconducting phase: identical properties

- 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)

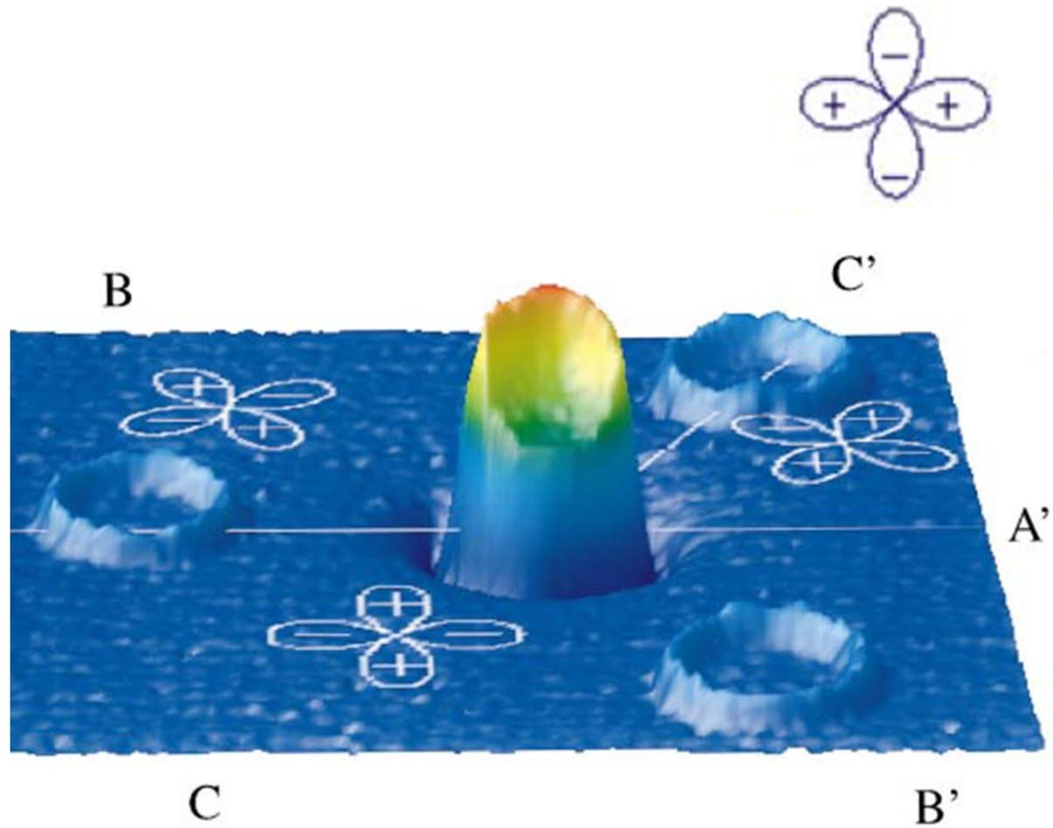
Superconductivity not universal even with phonons: weak or strong coupling

- In BCS universal ratios: e.g. $\Delta/k_B T_c$
  - Would never know the mechanism for sure if only BCS!
  - N.B. Strong coupling in a different sense

High Tc are d-wave (interference)



Wollman et al. PRL 1993



Tsuei Kirtley, Rev. Mod. Phys. 2000

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Two emergent universal laws ?

Basov

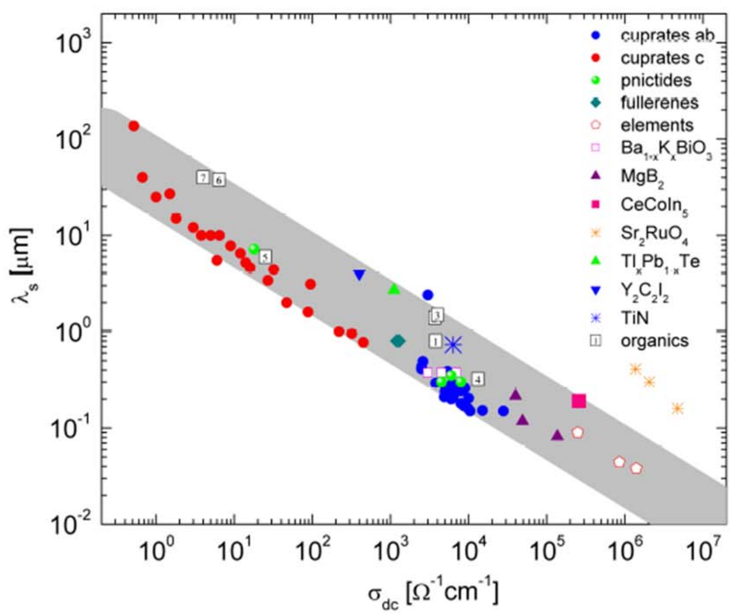

FIG. 1. **Basov scaling plot, Eq. (1).** The gray stripe corresponds to $\lambda_s = (45 \pm 25)\sigma_{dc}^{-0.5}$. Only data from optical spectroscopies (IR and MW SI) are included in the plot. The data points are from: cuprates *ab*-cuprates *c*-axis [2], pnictides [13, 14], elements [2], TiN [15], $Ba_{1-x}K_xBiO_3$ [16], MgB_2 [17, 18], organic SC [19–21], fullerenes [22], heavy fermion $CeCoIn_5$ [23], negative-U induced SC $Tl_xPb_{1-x}Te$ [24] and $Y_2C_2I_2$ [25].

Homes

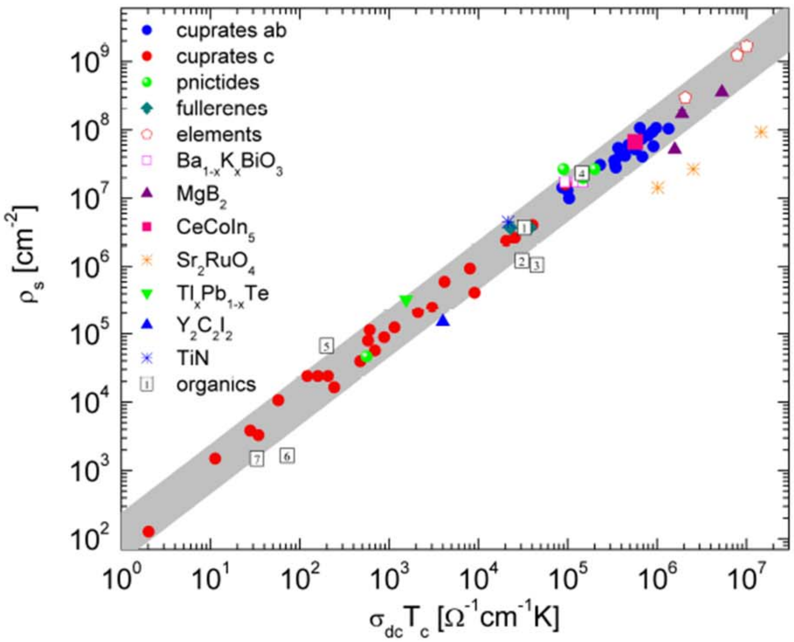

FIG. 2. **Homes' scaling plot, Eq. (2).** The gray stripe corresponds to $\rho_s = (110 \pm 60)\,T_c\,\sigma_{dc}$. The data points are the same as in Fig. 1.

Dordevich et al. arXiv:1305.0019v1

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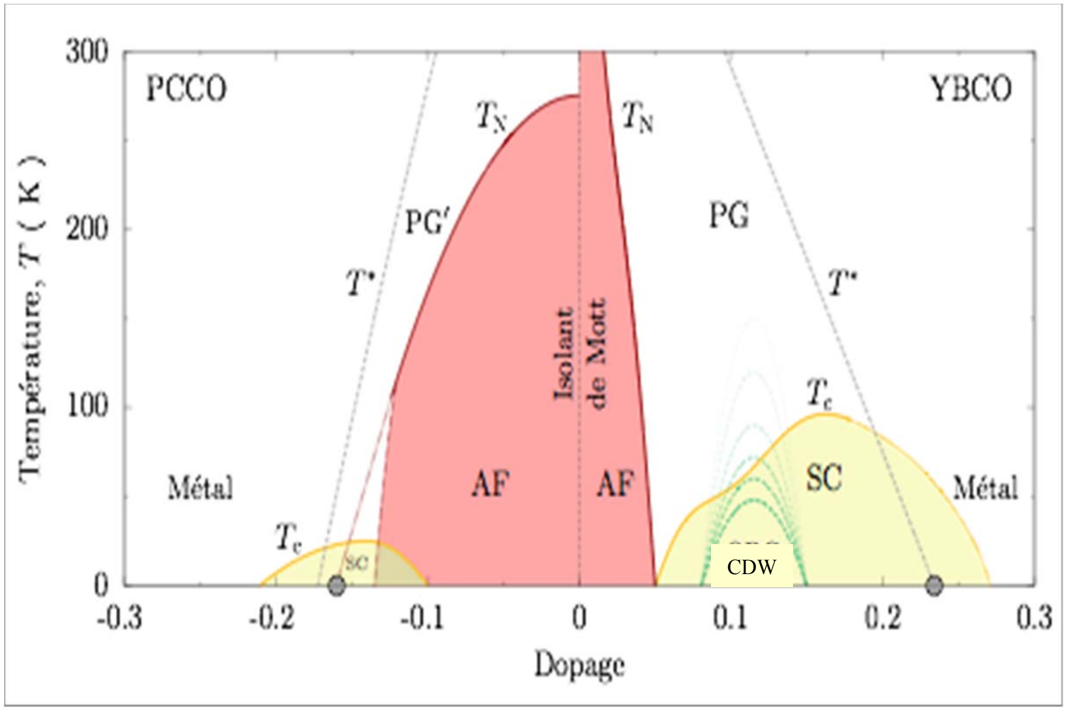
High-temperature superconductors

Thèse de Francis Laliberté,
Université de Sherbrooke



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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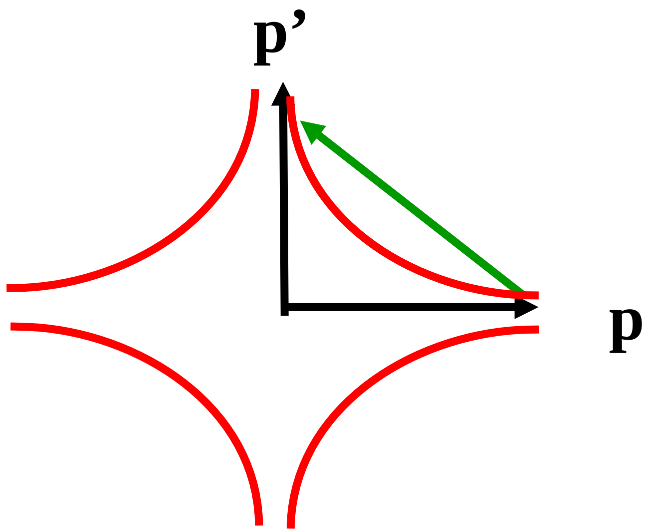
8. Superconductivity

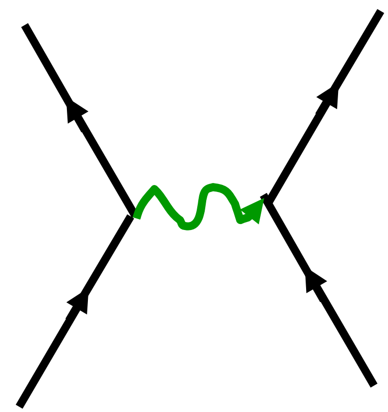
a. Weakly correlated case

(e-doped ?)

Cartoon « BCS » weak-coupling picture

$$\Delta_{\mathbf{p}} = -\frac{1}{2V}\sum_{\mathbf{p}'} U(\mathbf{p}-\mathbf{p}')\frac{\Delta_{\mathbf{p}'}}{E_{\mathbf{p}'}}\left(1-2n\left(E_{\mathbf{p}'}\right)\right)$$





Béal–Monod, Bourbonnais, Emery
P.R. B. **34**, 7716 (1986).

Exchange of spin waves?
Kohn-Luttinger
T_c with pressure

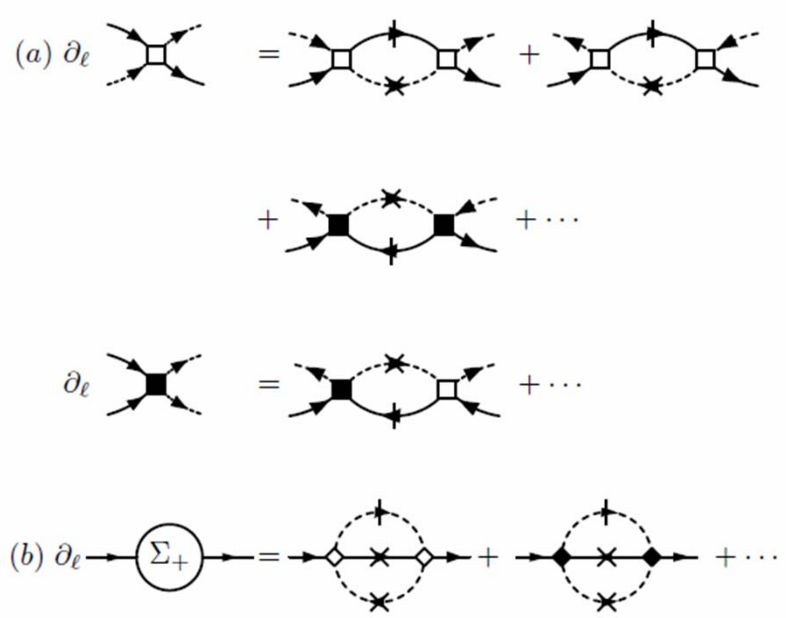
D. J. Scalapino, E. Loh, Jr., and J. E. Hirsch
P.R. B **34**, 8190-8192 (1986).

Kohn, Luttinger, P.R.L. **15**, 524 (1965).

P.W. Anderson Science 317, 1705 (2007)

Weak coupling methods

- Functional renormalization group



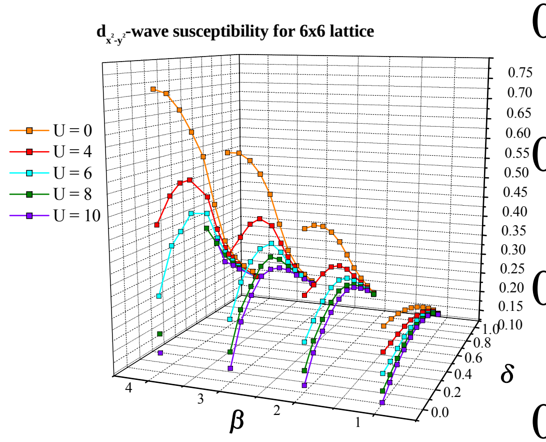
Zanchi, Schultz 2000
Honerkamp, Salmhofer 2000 +
Bourbonnais Sedeki PRB 2012

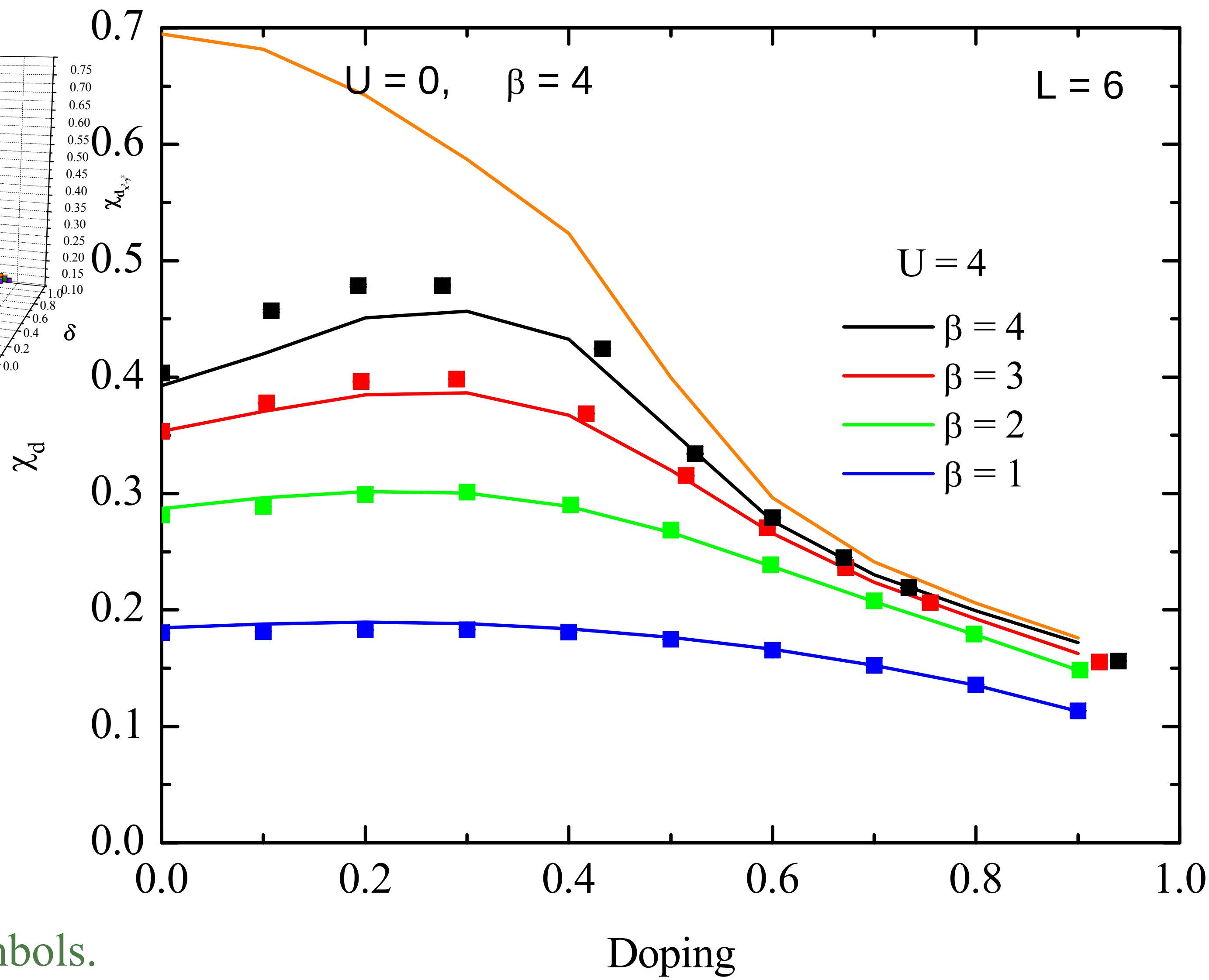
- Weak coupling perturbation theory

S. Maiti and A.V. Chubukov: arXiv:1305.4609

Results from TPSC

Satisfies Mermin-Wagner

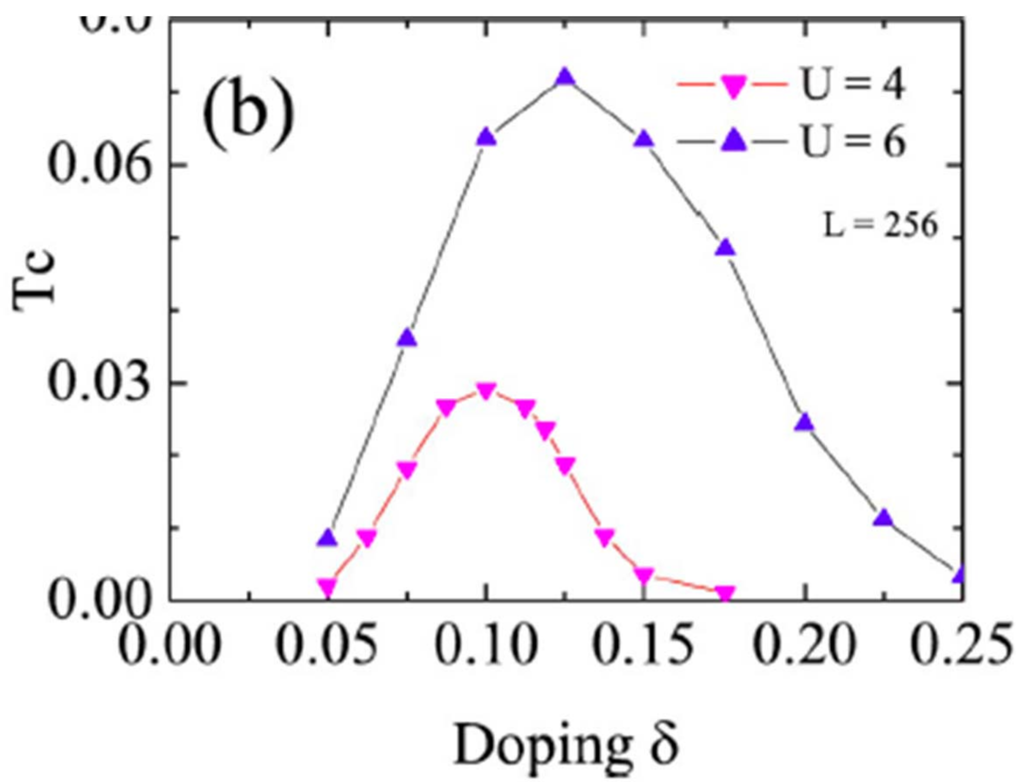




QMC: symbols.

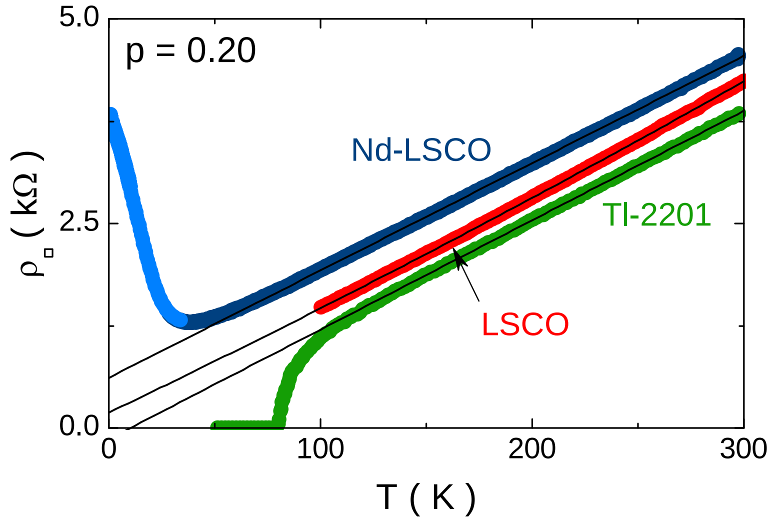
Solid lines analytical. Kyung, Landry, A.-M.S.T., PRB 2003

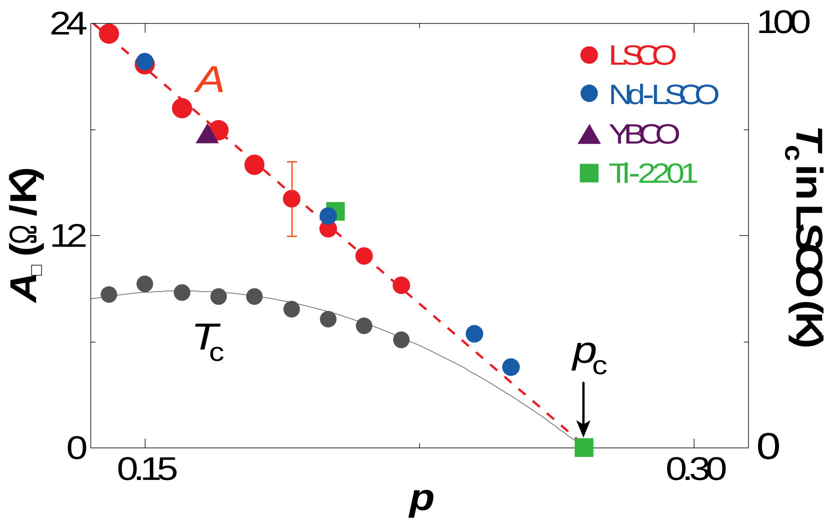
Tc from TPSC



Kyung et al. PRB **68** (2003)

Correlation between T_c and coefficient of linear T dependence





Linear-T resistivity is universal in hole-doped cuprates

Correlation between linear-T resistivity and T_c

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

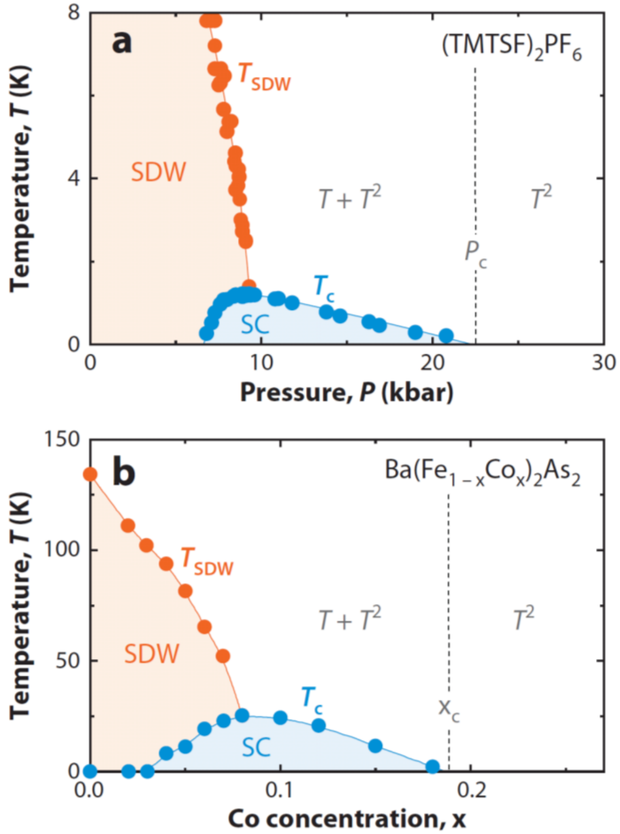
Taillefer, Annual Review of CMP **1**, 51 (2010)

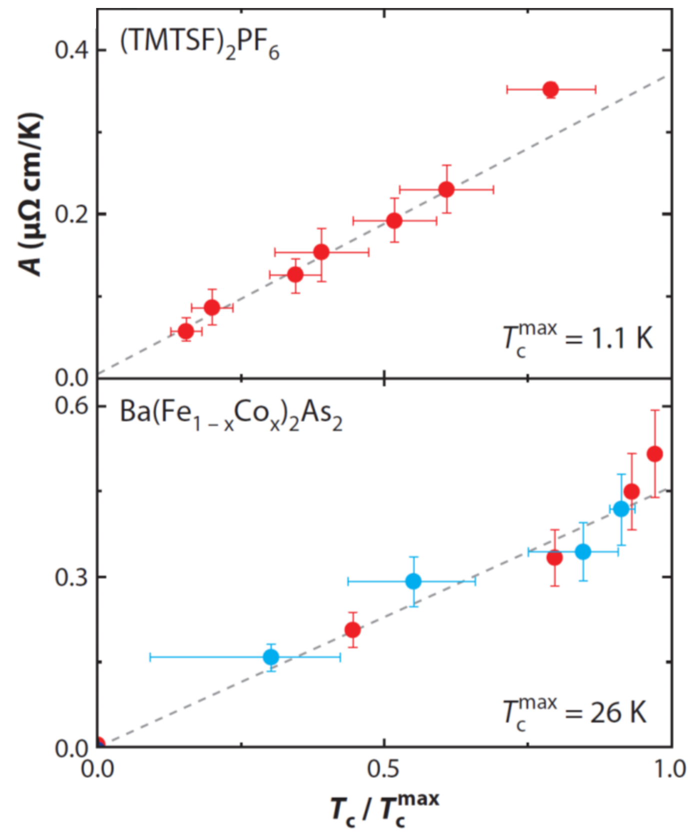
Linear T coefficient of R and T_c in other systems

Bourbonnais, Sedeki, 2012

Organic

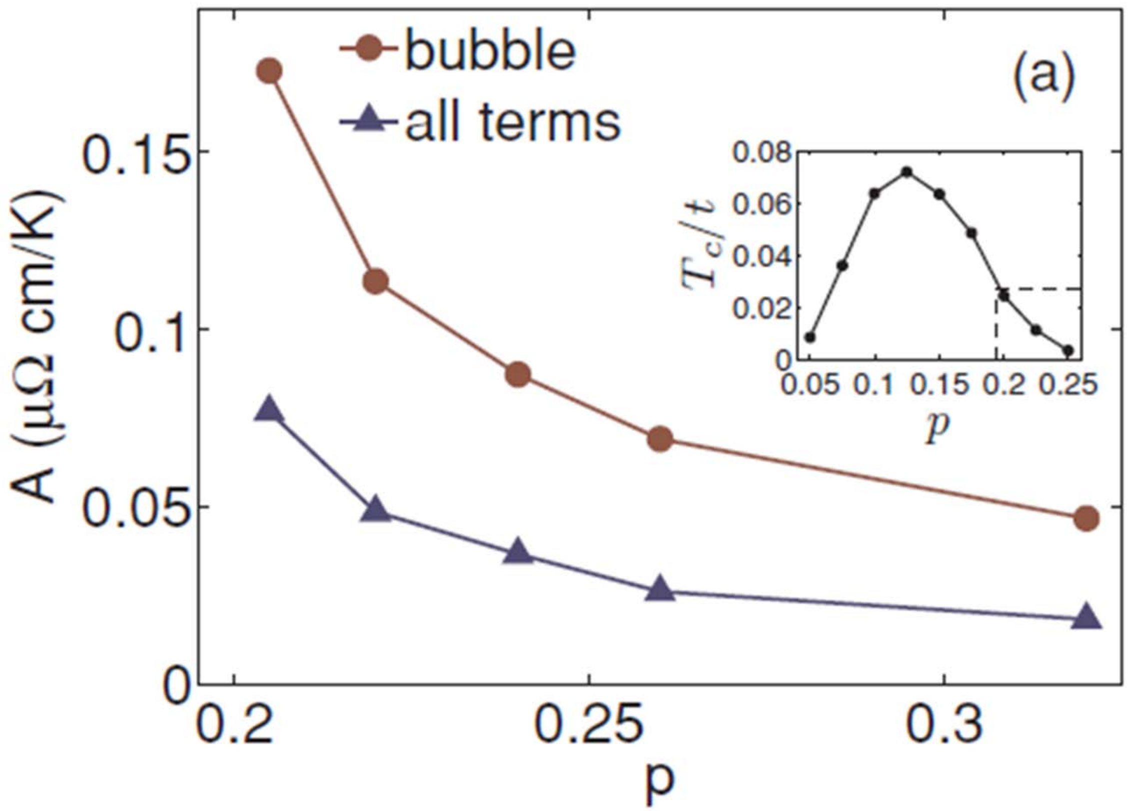
Pnictide





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

Correlation resistivity vs T_c



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

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8. Superconductivity

b. Strong coupling point of view

A cartoon strong coupling picture

P.W. Anderson Science 317, 1705 (2007)

$$J\sum_{\langle i,j\rangle}\mathbf{S}_i\cdot\mathbf{S}_j = J\sum_{\langle i,j\rangle}\left(\frac{1}{2}c_i^\dagger\vec{\sigma}c_i\right)\cdot\left(\frac{1}{2}c_j^\dagger\vec{\sigma}c_j\right)$$

$$d = \langle\hat{d}\rangle = 1/N\sum_{\vec{k}}(\cos k_x - \cos k_y)\langle c_{\vec{k},\uparrow}c_{-\vec{k},\downarrow}\rangle$$

$$H_{MF} = \sum_{\vec{k},\sigma}\varepsilon(\vec{k})c_{\vec{k},\sigma}^\dagger c_{\vec{k},\sigma} - 4Jm\hat{m} - Jd(\hat{d}+\hat{d}^\dagger) + F_0$$

Pitaevskii Brückner:

Pair state orthogonal to repulsive core of Coulomb interaction

Miyake, Schmitt–Rink, and Varma

P.R. B **34**, 6554-6556 (1986)

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Strongly correlated superconductors

- T_c does not scale like order parameter
- Superfluid stiffness scales like doping
- Superconductivity can be largest close to the metal-insulator transition
- Resilience to near-neighbor repulsion

The view from dynamical mean-field theory (I am not supposed to do this)

International summer school on Computational Methods for Quantum Materials

26 May - 6 June 2014

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