Influence of Disorder on the Physical Properties of the Cuprates

H. Alloul [1], J. Bobroff [1] and F. Rullier-Albenque [2]

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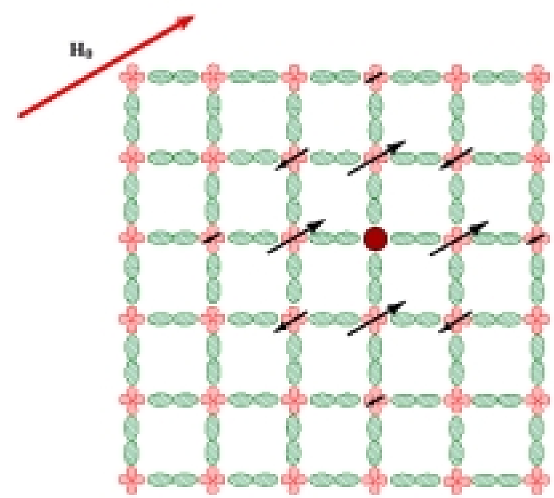
[4] *LCNS, CEA, Université Paris-Sud , Orsay*

[5] *CNRS, Grenoble.*



Native and controlled disorder in cuprates

- *Introduction*

  Phase diagram and open questions in cuprates

  Native and controlled disorder?

- *NMR as a probe of disorder*

  Comparison of different cuprate families

  YBCO6.6 and YBCO7 : homogeneous cases

- *Influence of controlled disorder on the phase diagram*

  Pseudogap crossover

  Superconducting dome and hole content

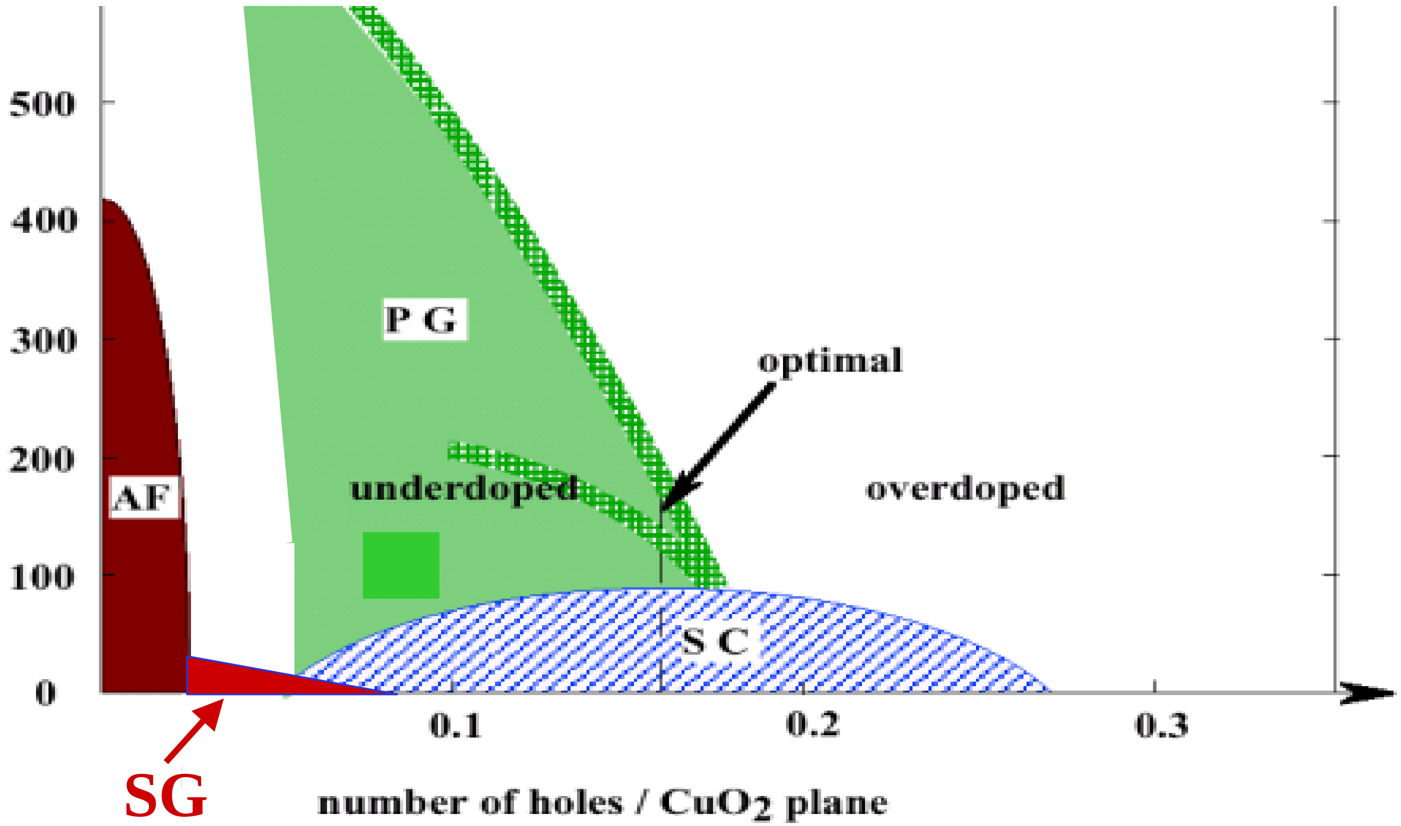
- *Nernst effect, phase coherence and preformed pairs*

  Nersnst effect in « pure » systems

  Disorder and phase coherence

- *Conclusion: Pseudogap and fluctuations*

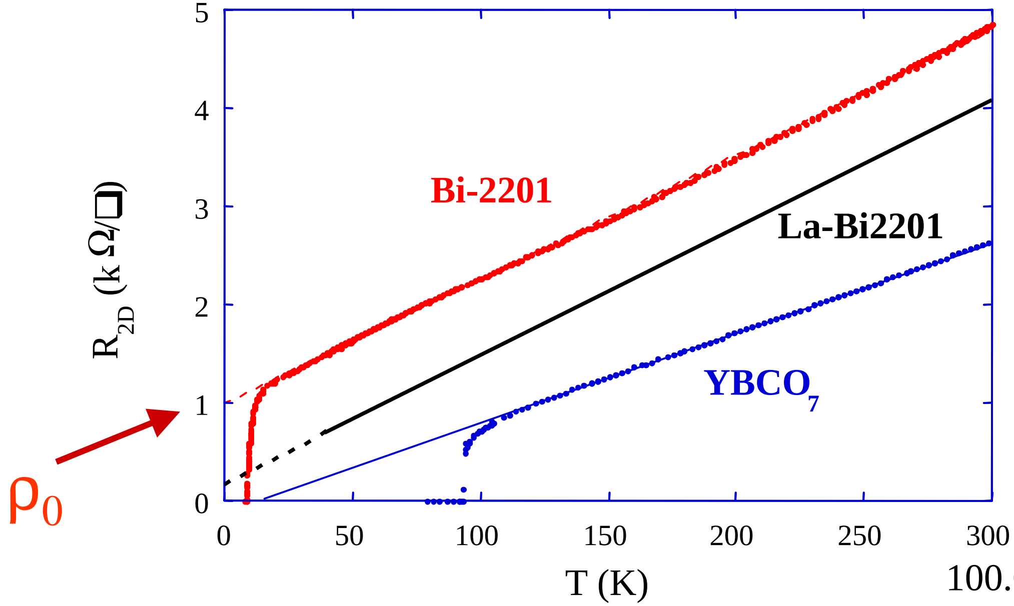
Generic Phase Diagram of the Cuprates ?



This shape of phase diagram is apparently generic

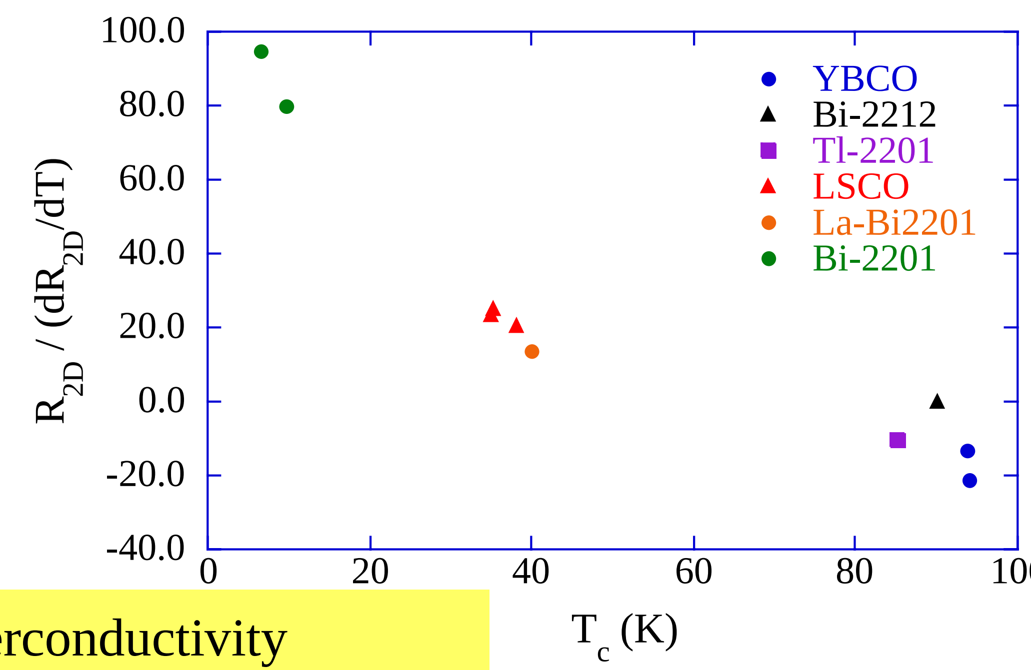
However the optimal Tc is not generic
and the hole concentration is not always well determined

Native disorder in the pure cuprate families



The optimum T_c and the residual resistivity ρ_0 depend on the family

Correlation between ρ_0 and optimum T_c



Disorder is detrimental to superconductivity

Some uncontrolled disorder is present in LSCO and Bi2201

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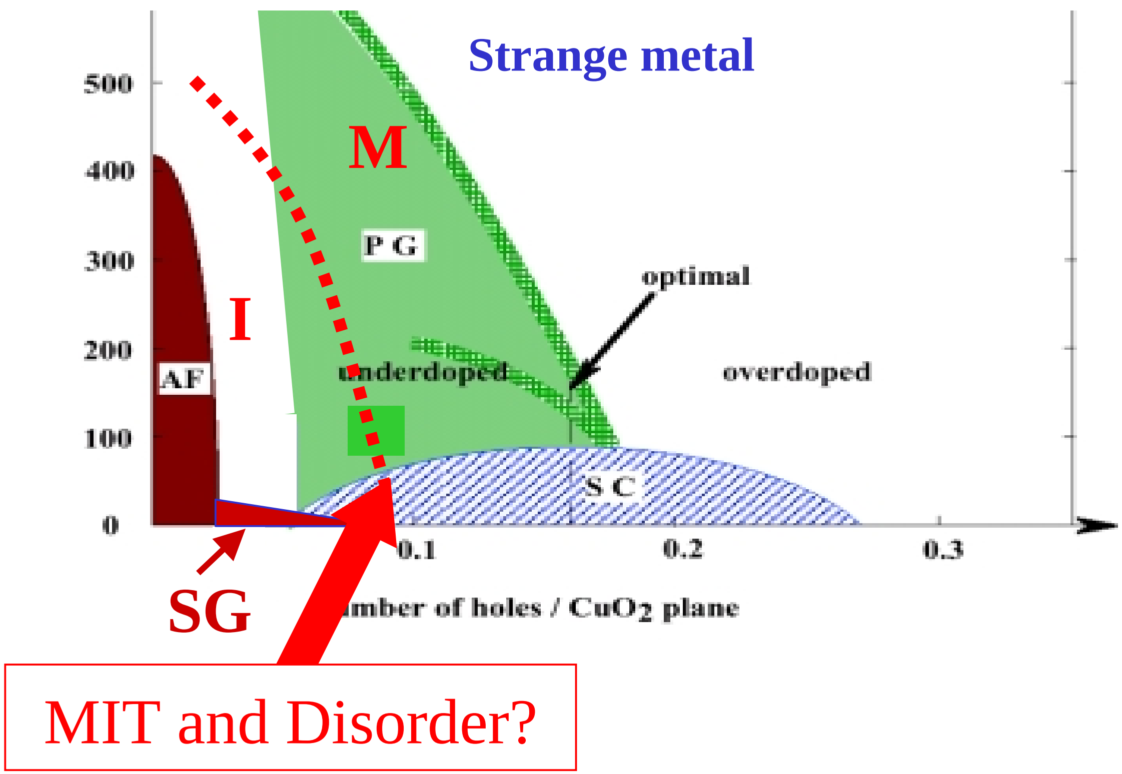
Where is located the Metal Insulator transition?

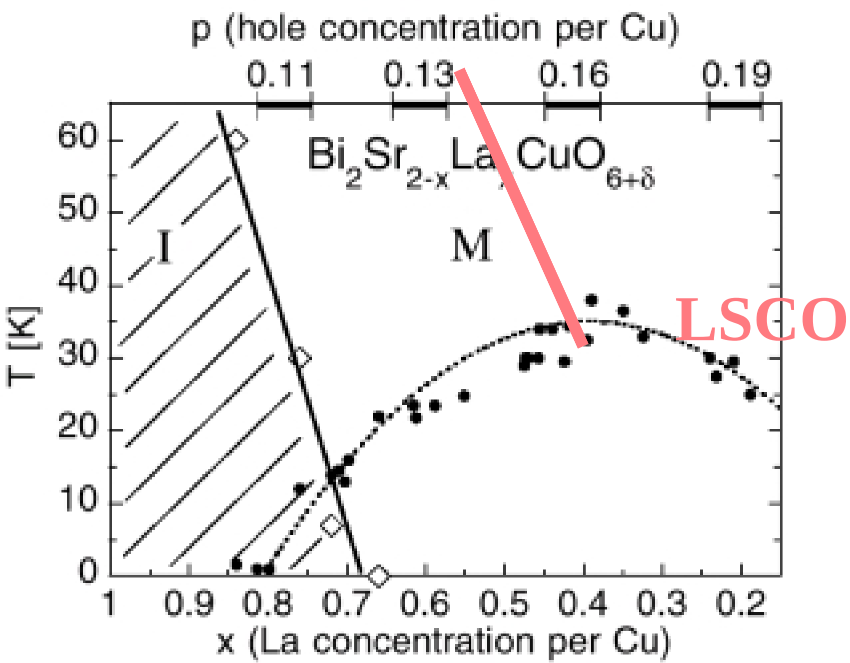


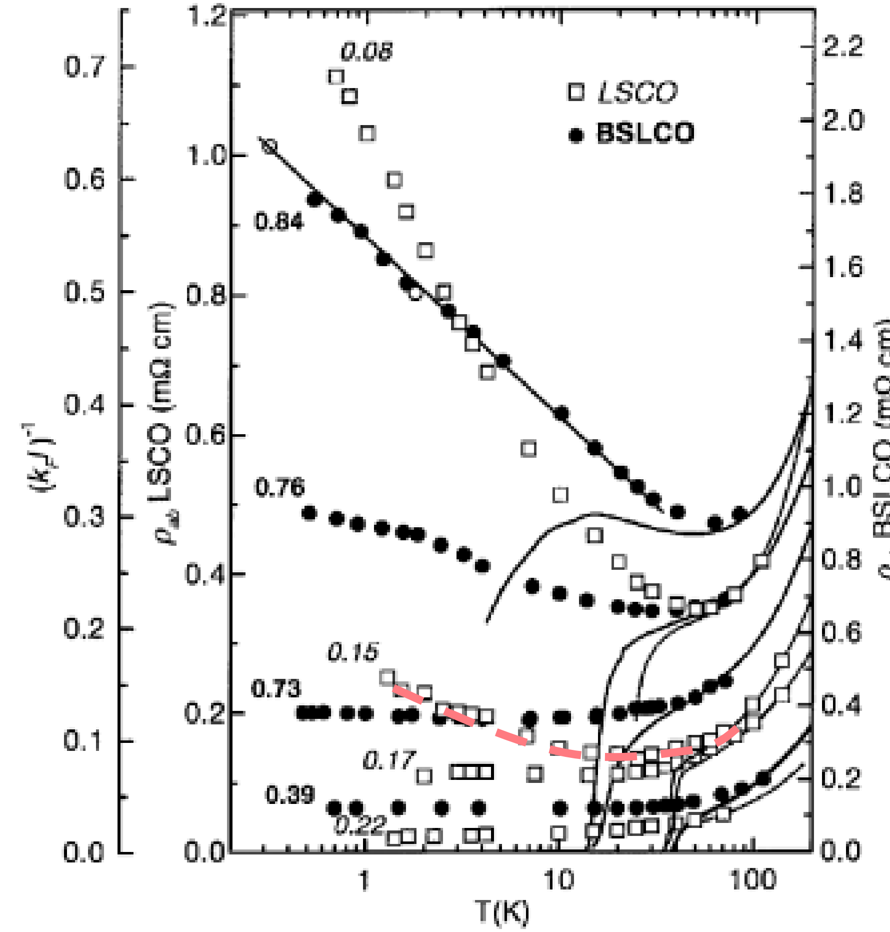
What about the MIT in « pure » cuprates ??

Low *T* upturns in ρ(T)

MIT line depends of the cuprate family

Ono et al, PRL 2000





MIT associated with « intrinsic » disorder

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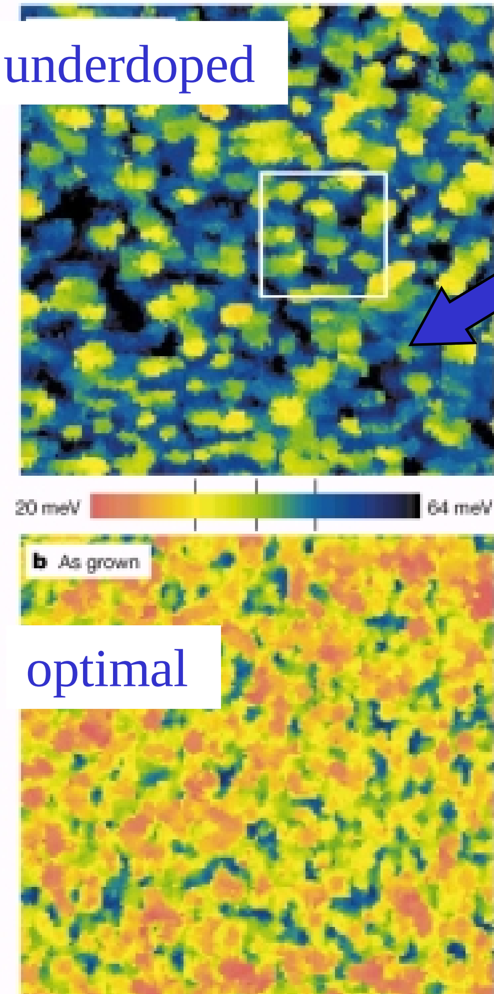
Inhomogeneities in BiSCCO viewed by STM

Cren *et al,PRL 84,147 (2000);   Howald et al PRB 64 10054-1(2001)*

underdoped



optimal

560 A

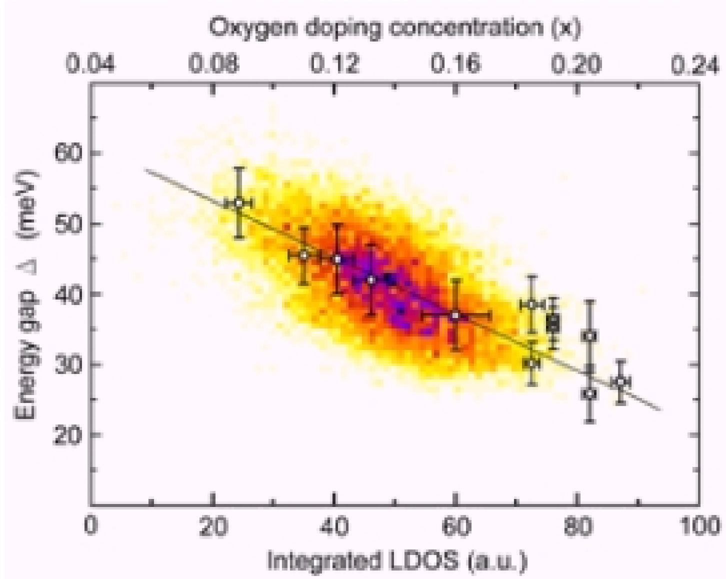
Lang *et al,Nature 412, 415 (2002)*

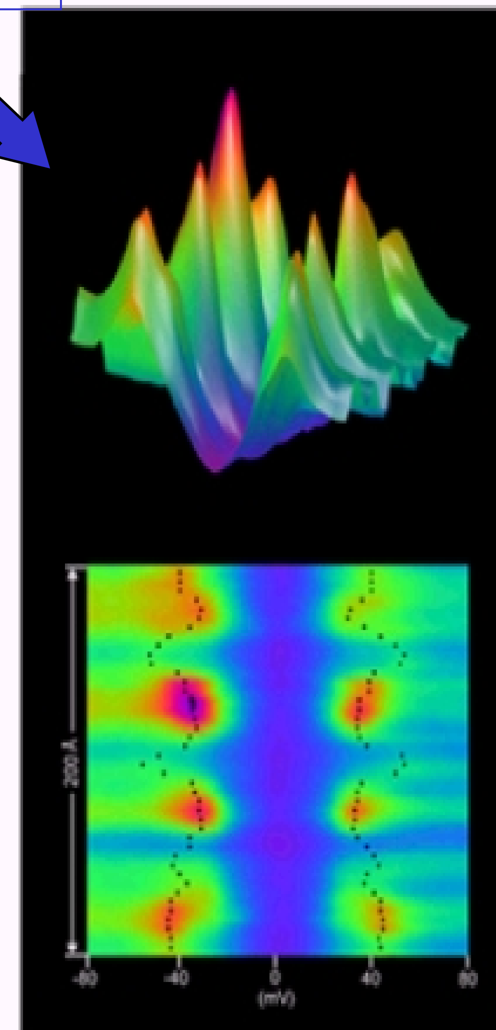
DOS depends on the STM tip location :

2D maps of the gap magnitude :

Pan *et al,Nature 413, 282 (2001)*

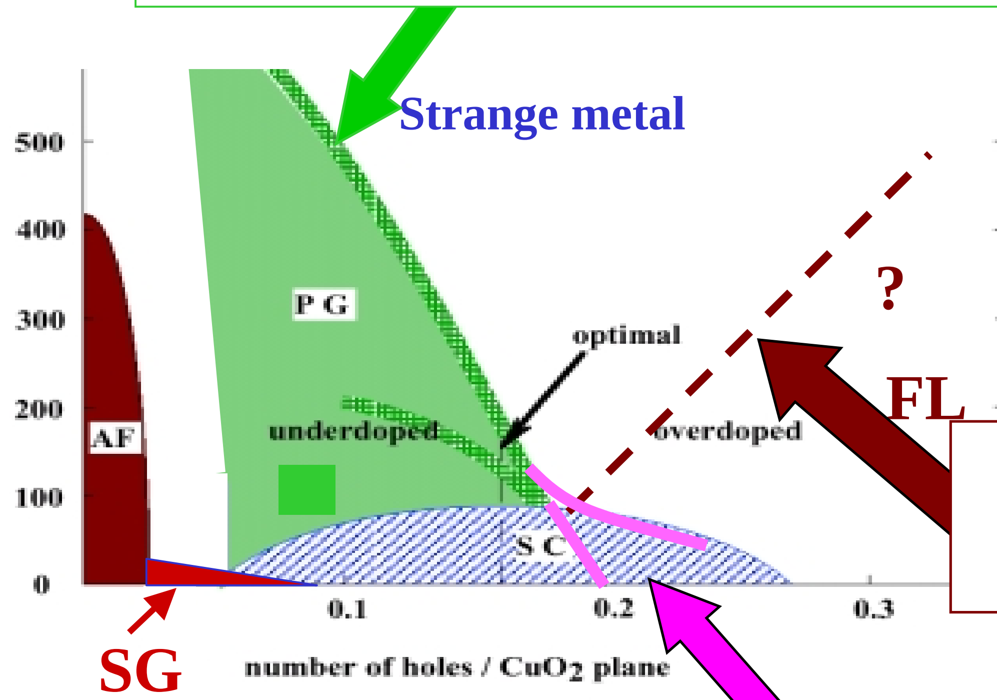
Local distribution of hole doping





Questions About the Phase Diagram

Pseudogap:
Phase transition? Crossover? Order parameter?
Preformed pairs?



Transition to a
Fermi liquid?

Pseudogap joins Tc
curve or QCP ??

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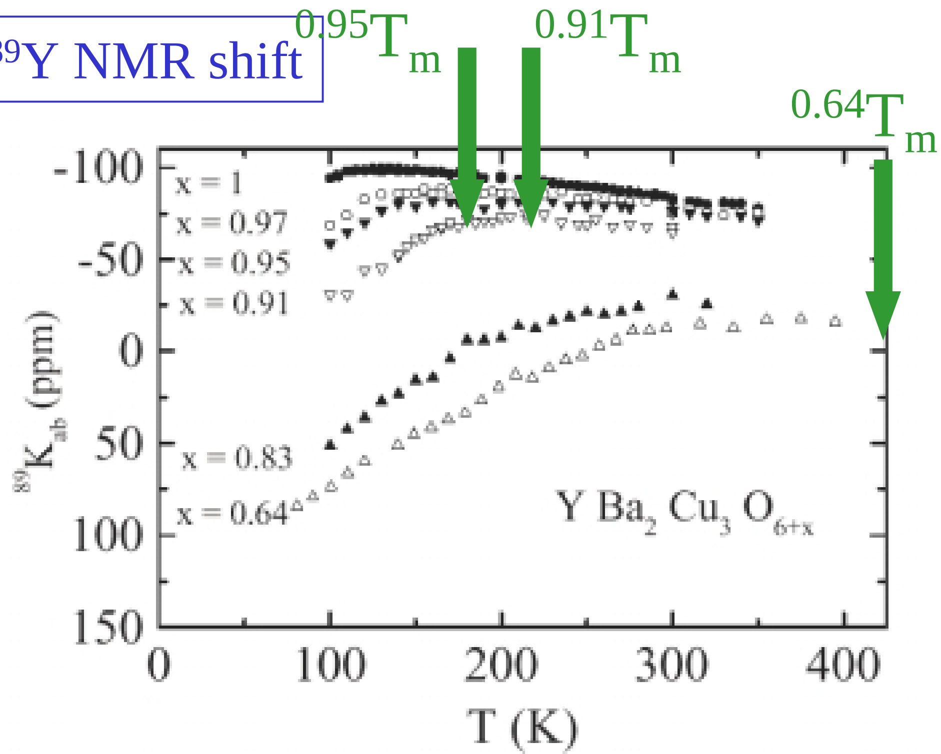
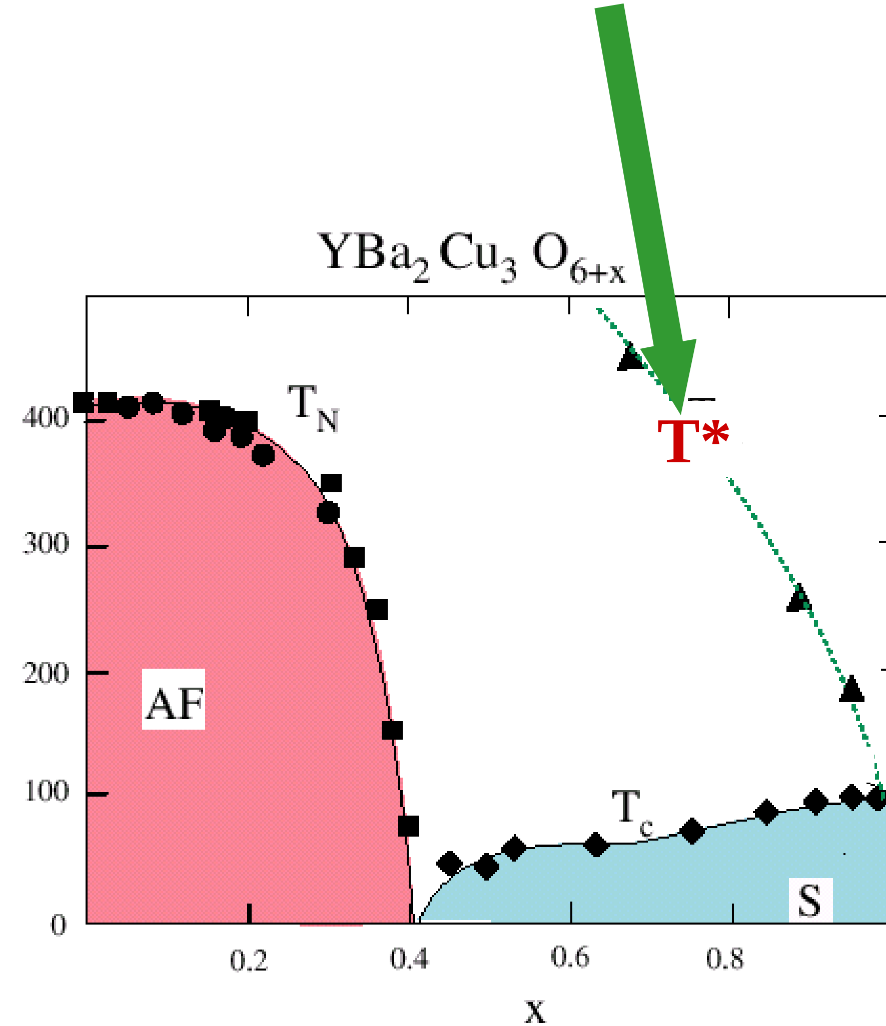
Phase Diagram and Pseudogap

^{89}Y NMR shift



Low T decrease of the susceptibility:

opening of the pseudogap



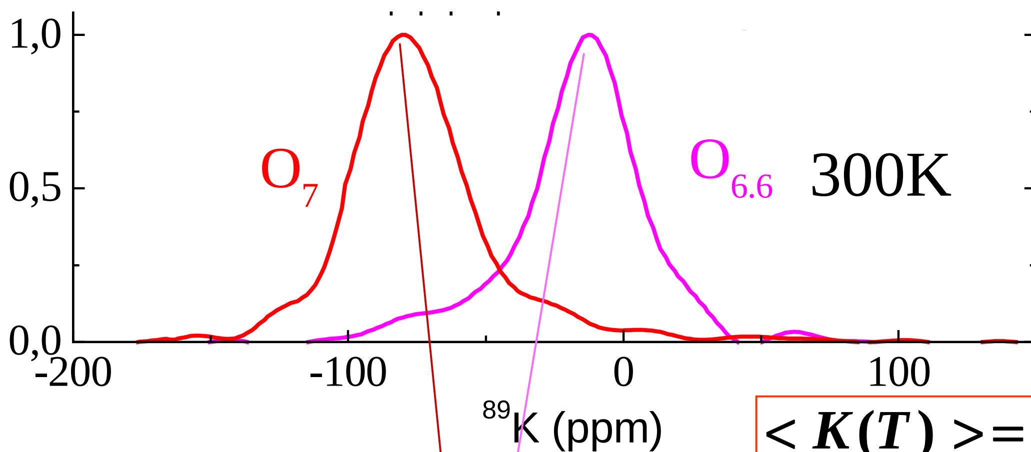
$$^{89}K(T) = \sigma + A\ \chi(T)$$

Chemical shift

Hyperfine coupling

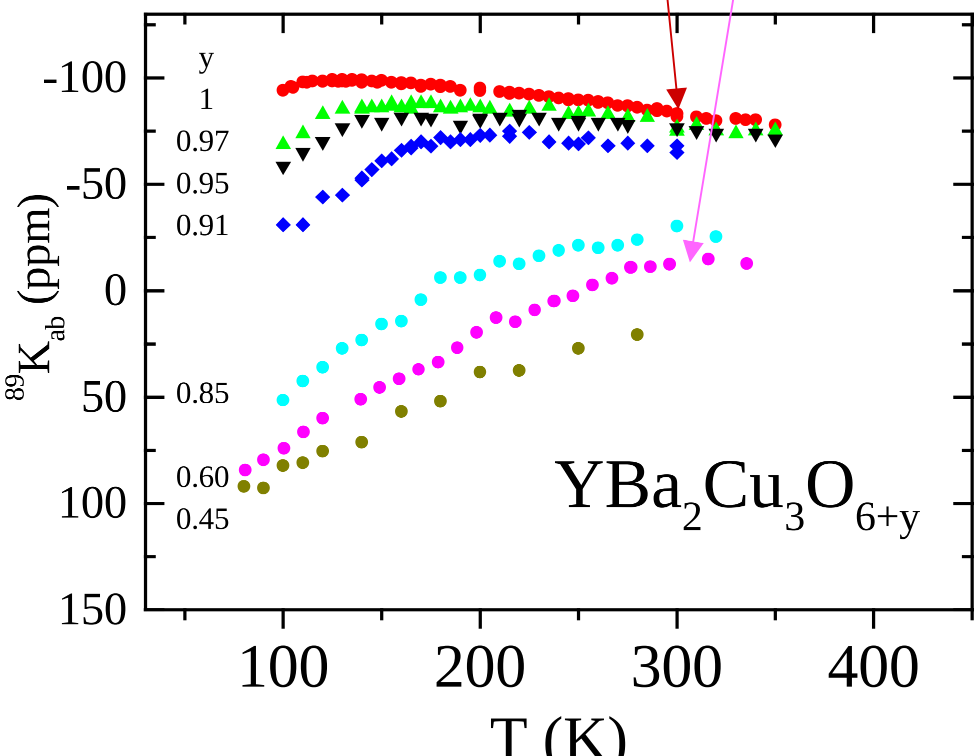
Alloul *et al*, PRL 1989

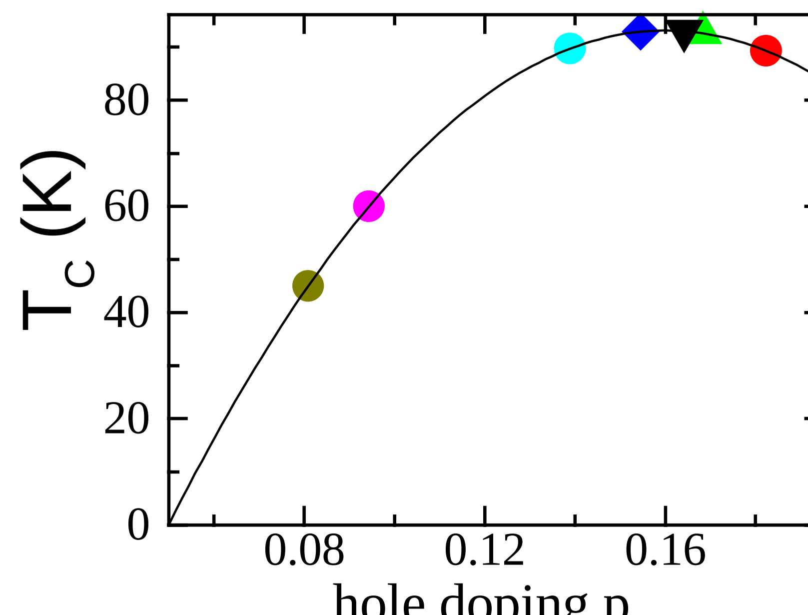
Average (or peak) NMR shifts



Mean value

$$\langle K(T)\rangle = \langle \sigma \rangle + \langle A \rangle \langle \chi(T) \rangle$$





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Diverse contributions to the spectral shape

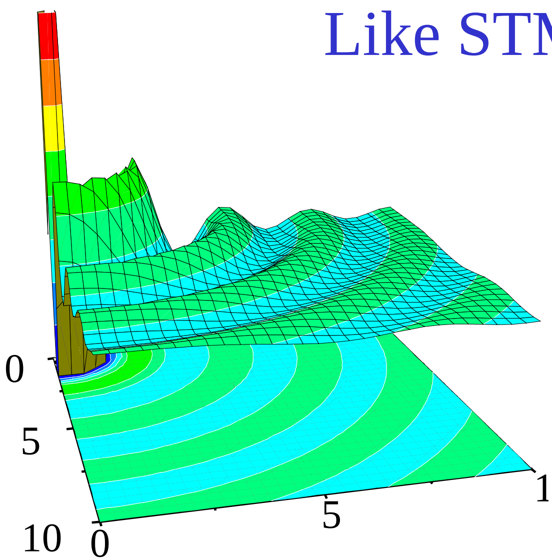
Macroscopic inhomogeneity of doping

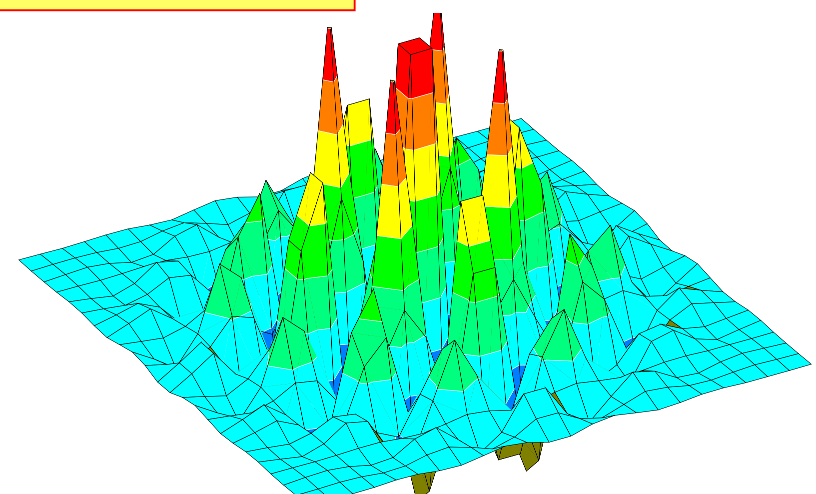
Large bulk samples (0.1 to 0.5 g)

Microscopic distribution of LDOS due to defects

Friedel charge oscillations

Like STM





But also , in correlated electron systems
Staggered magnetic response

Comparison of the one layer cuprate families

Planar ^{17}O NMR linewidths at optimal doping

TABLE I. The different monolayer compounds with the associated T_c and NMR oxygen width.

	T_c^{max}(K)	^{17}O full width kHz/% of K_s
$HgBa_2CuO_{4+\delta}$	95	30 kHz/50%
$Tl_2Ba_2CuO_{6+\delta}$	85	15 kHz/20% [11]
$La_{2-x}Sr_xCuO_4$	38	90 kHz/120% [12]
$Bi_2Sr_2CuO_6$	10	70 kHz/110% [10]

YBCO7
20% of Ks

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^{17}O NMR Evidence for a Pseudogap in the Monolayer $HgBa_2CuO_{4+\delta}$

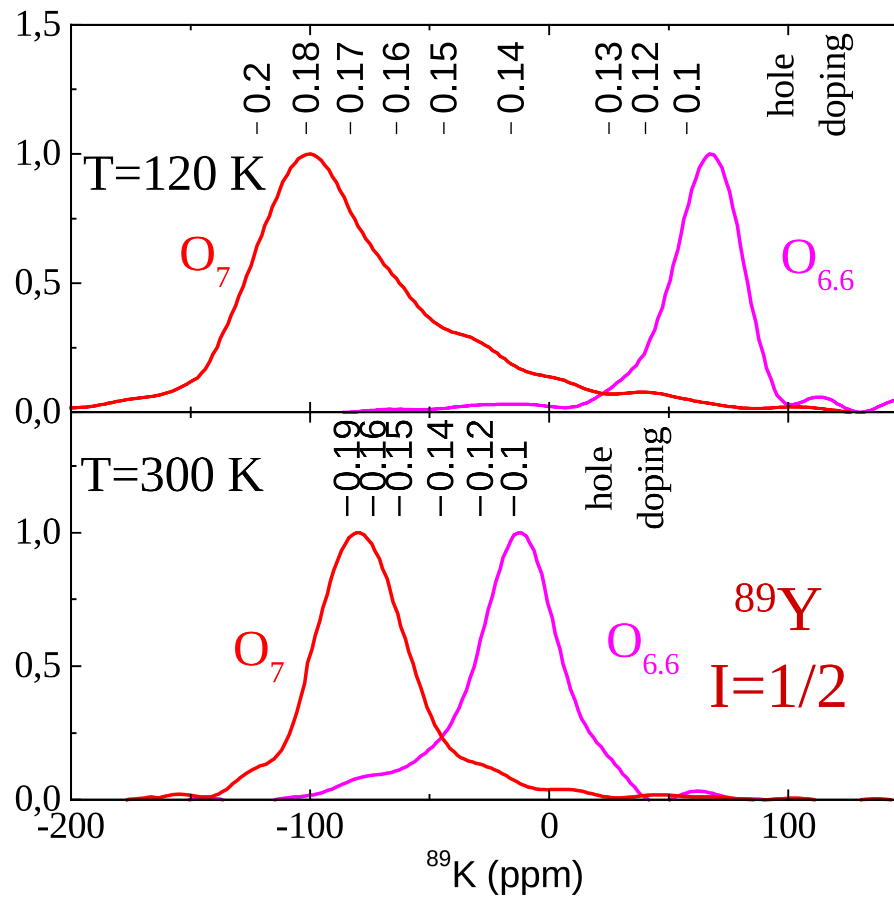
J. Bobroff,[1] H. Alloul,[1] P. Mendels,[1] V. Viallet,[2] J.-F. Marucco,[2] and D. Colson[2]
[1]*LPS, URA2 CNRS, 91405 Orsay Cedex, France*
[2]*CEA-Saclay, Service de Physique de l'Etat Condensé, DRECAM/SPEC, 91191 Gif sur Yvette Cedex, France*

NMR Spectra: histogram of the local contribtions

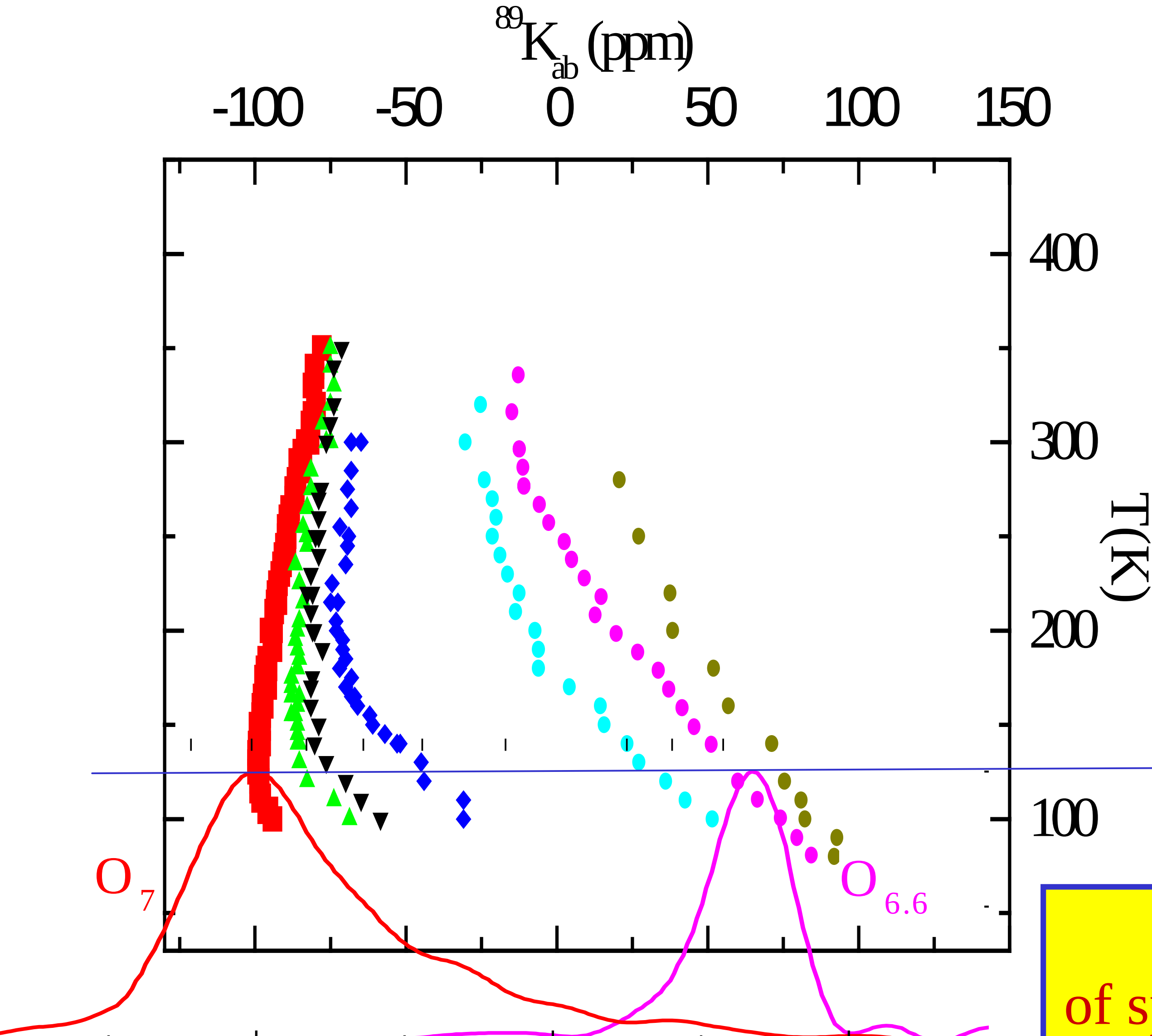
$$\boldsymbol{K(\mathbf{r}) = \sigma(\mathbf{r}) + A(\mathbf{r})\chi(\mathbf{r},T)}$$

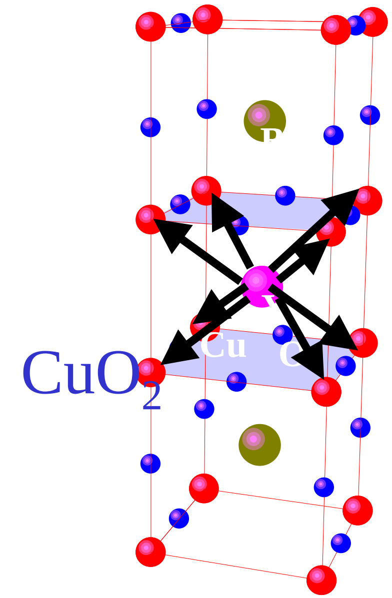
σ(**r**) and A (**r**) weakly depend on structural and bond disorder

The *T* variation of spectrum shape can be assigned to a distribution of hole content reflected by that of χ(T)



NMR Spectra: histograms of the local hole density

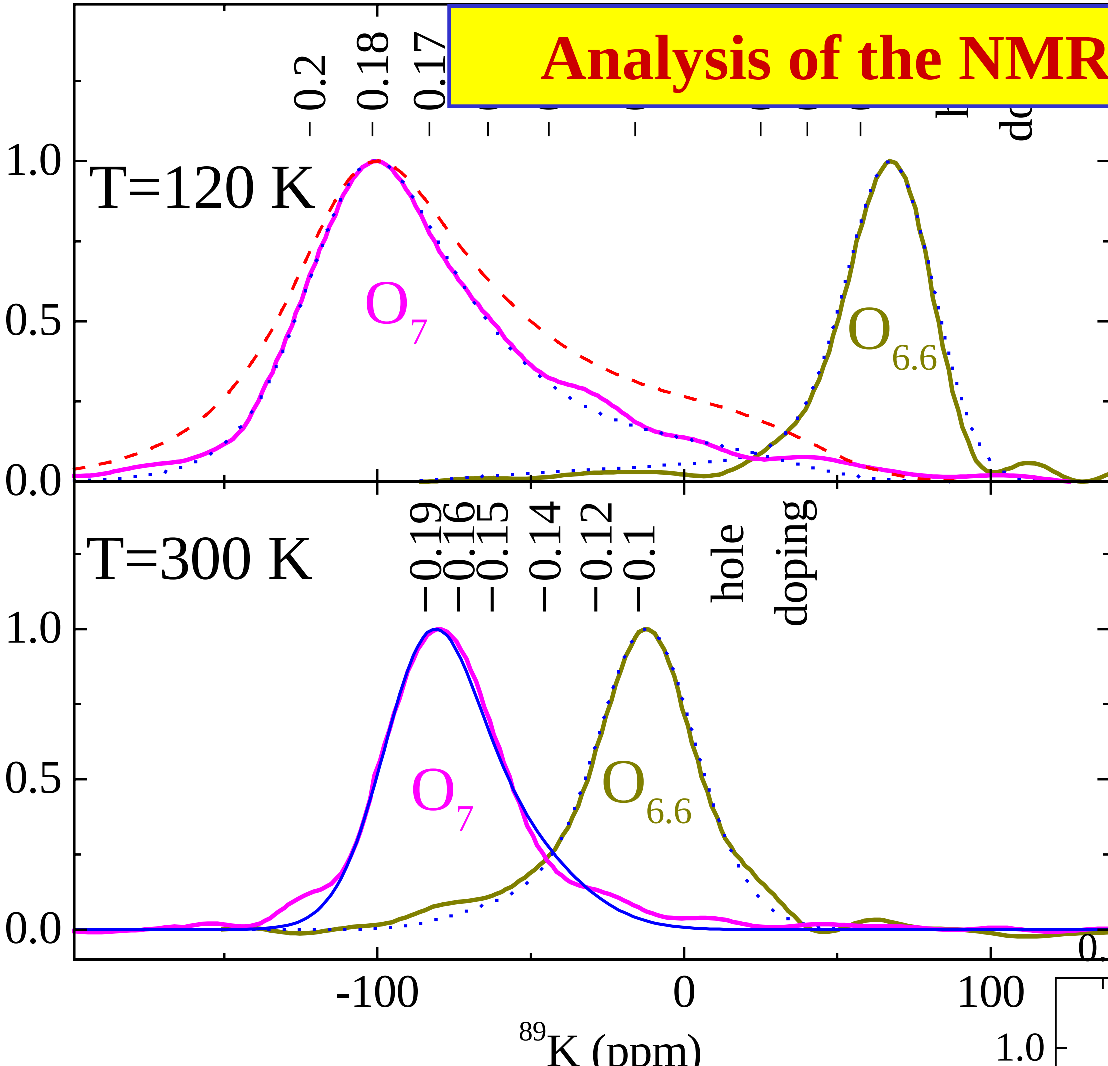




At 120K

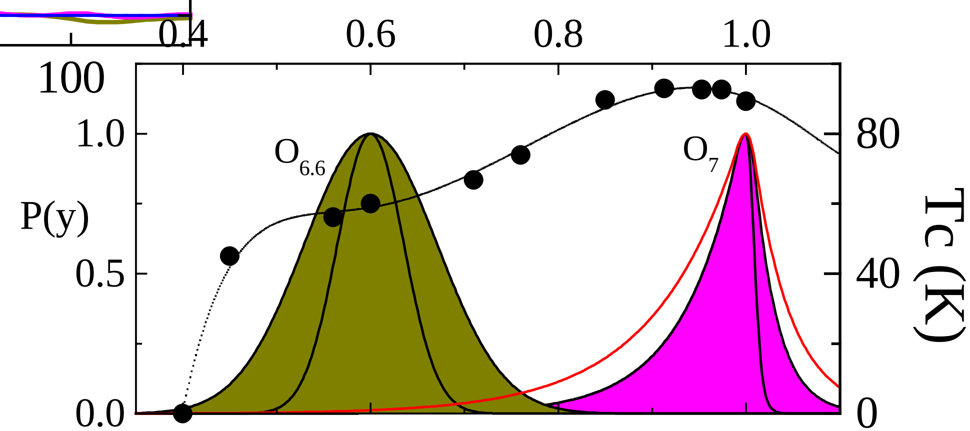
Nearly no overlap of spectra for $O_{6.6}$ and O_7

Analysis of the NMR Spectra



Fits of the spectra at all *T*

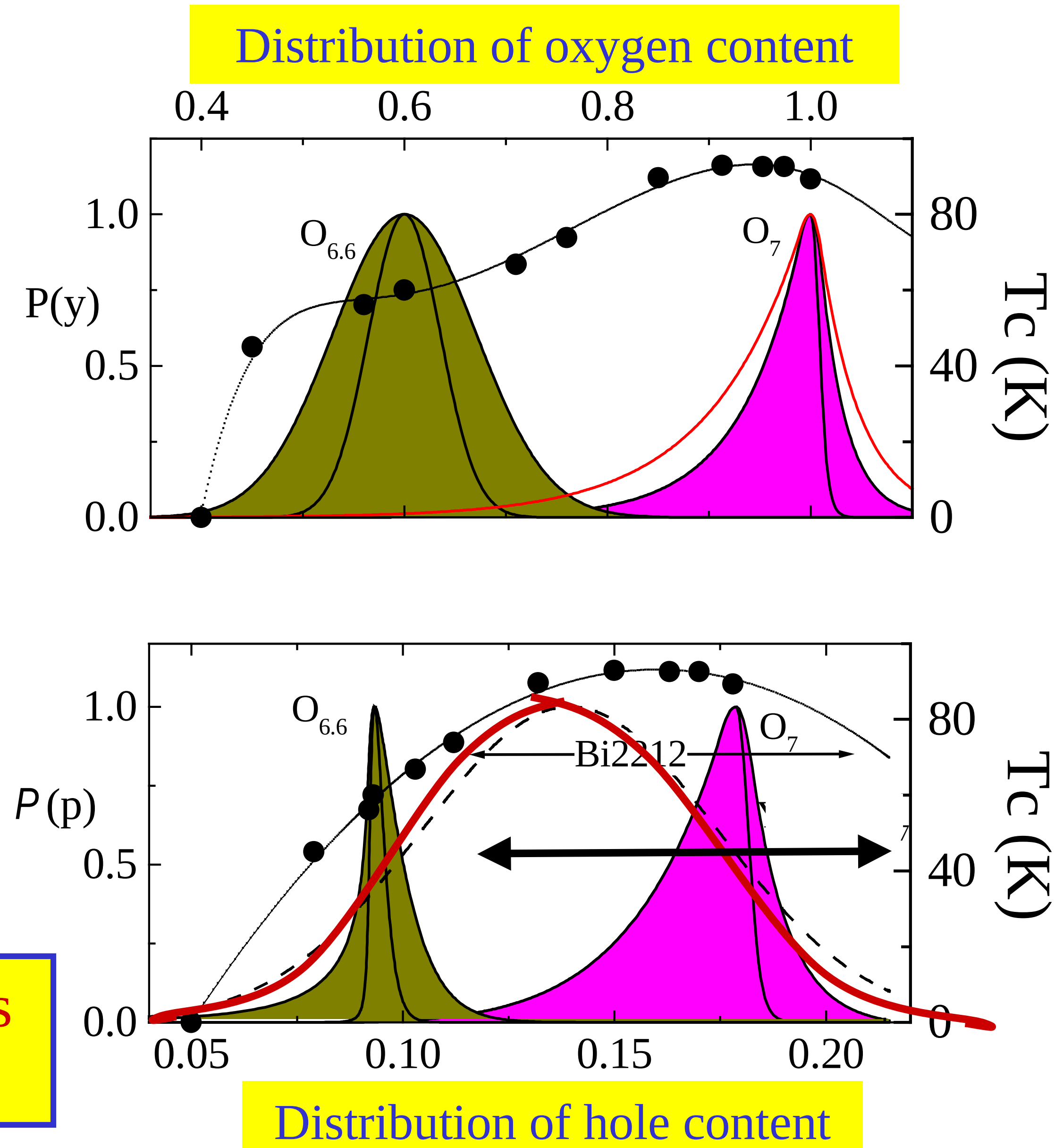
Distribution of oxygen content



Bobroff, Alloul *et al*, *PRL 89, 2002*

Analysis of the NMR Spectra

The maximum distribution of hole content is
- much narrower than in Bi2212 or LSCO
- seen on large samples (0.5g)
- likely of macroscopic origin



YBCO is very homogeneous
No charge segregation

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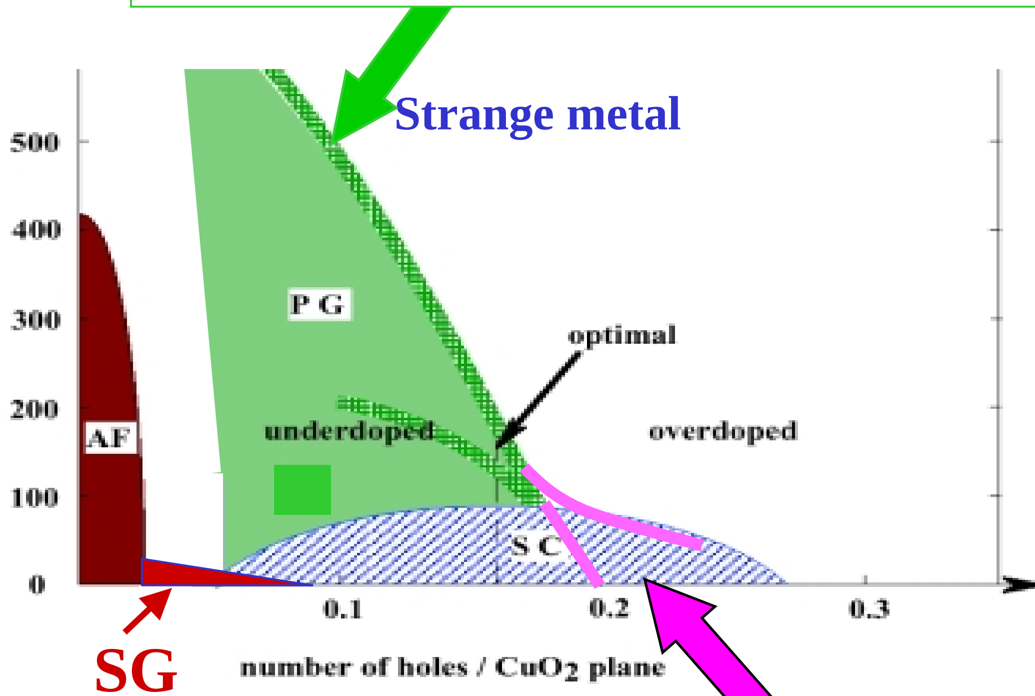


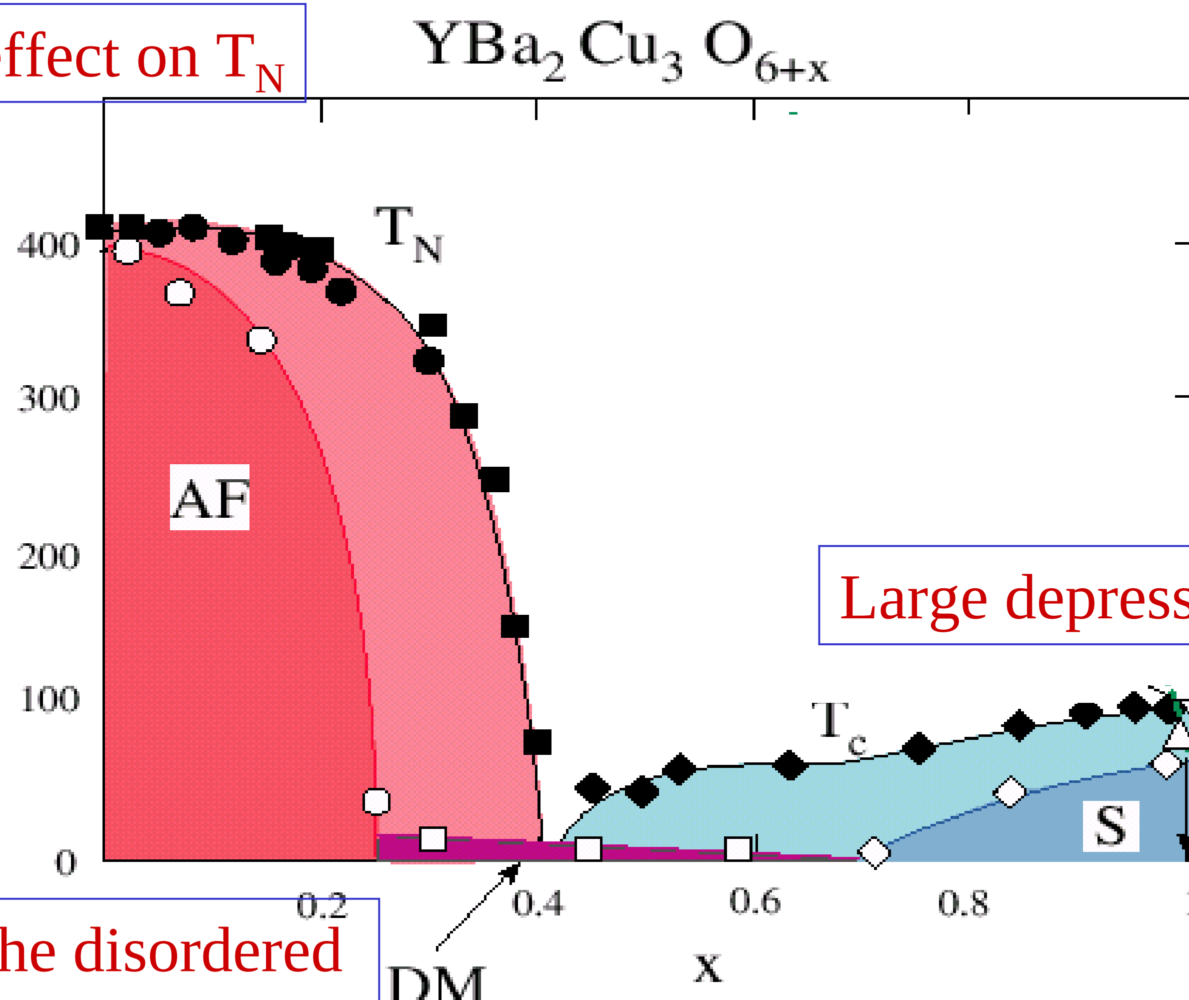
Pseudogap joins Tc curve or QCP ??

Influence of defects on the phase diagram

$YBCO_{6+x}$ + 4%Zn → $YBCOZ_{6+x}$

No change of hole doping

Dilution effect on T_N



Large depression of T_c

Increase of the disordered magnetism range

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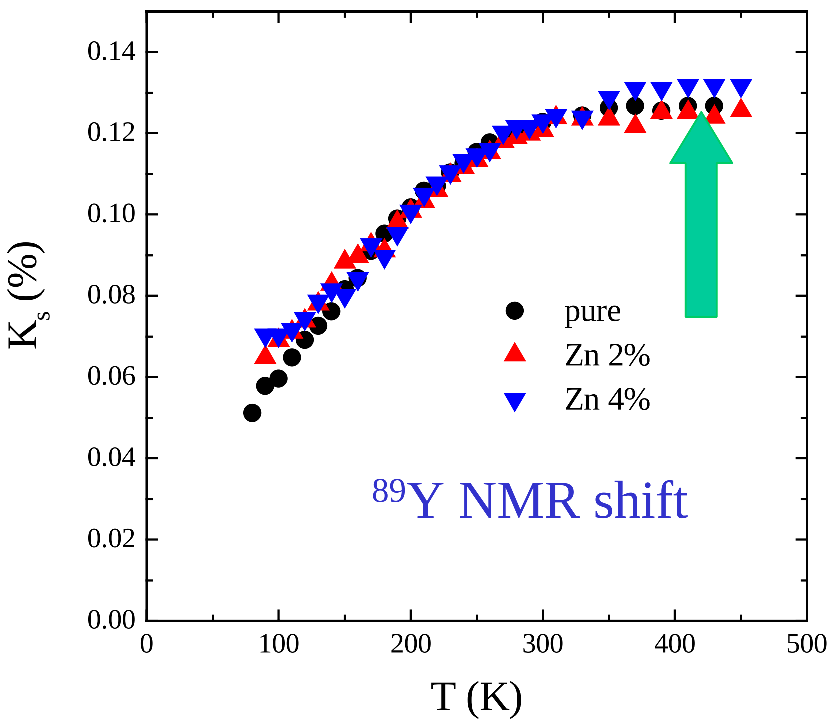
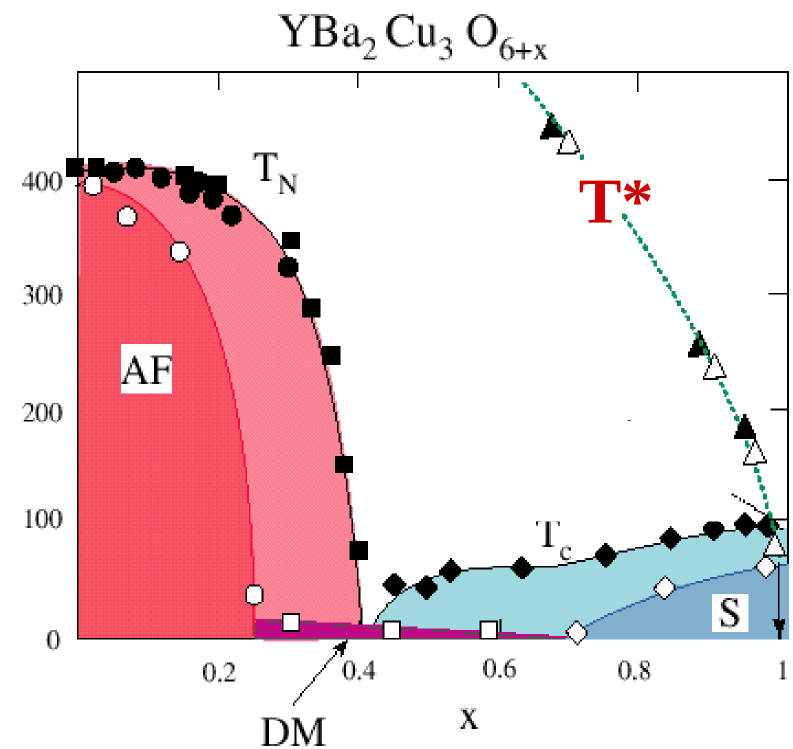
Influence of defects on the pseudogap

$YBCO_{6+x}$ + 4%Zn → $YBCOZ_{6+x}$

No change of hole doping

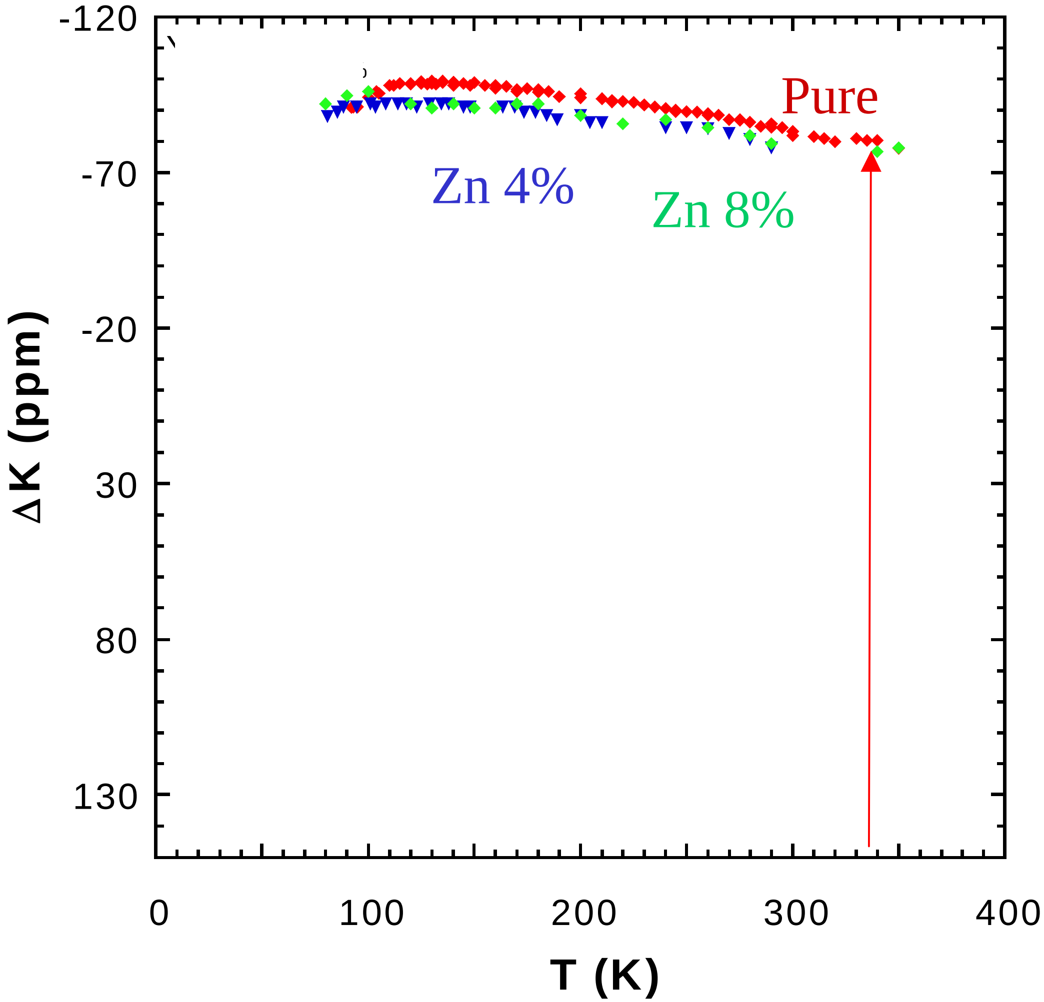


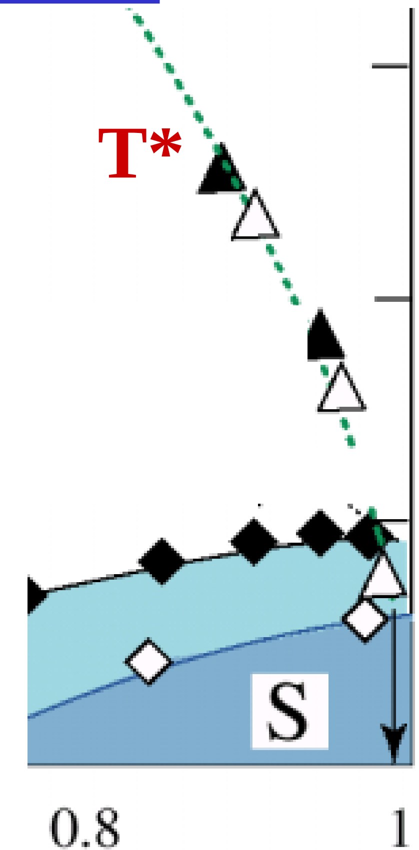


No change of T* : the pseudogap is not sensitive to disorder

Influence of defects on the pseudogap

^{89}Y NMR for slightly overdoped YBCO7





No detectable pseudogap in the overdoped system

QCP?

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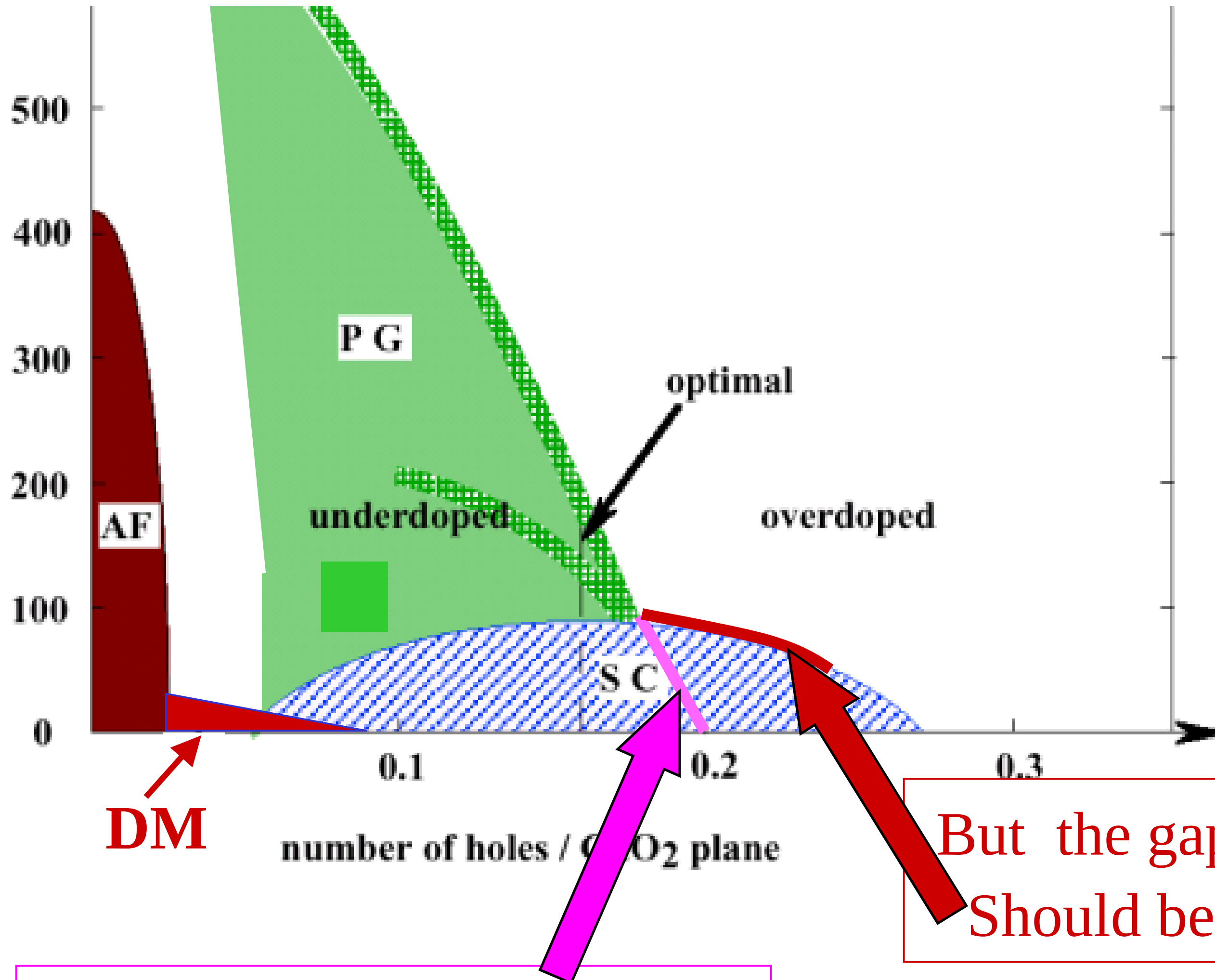
Continuation of the pseudogap line



But the gap which would remain Should be sensitive to disorder

No experimental sign for a pseudogap below the superconducting dome

So a drastic change does occur for slight overdoping

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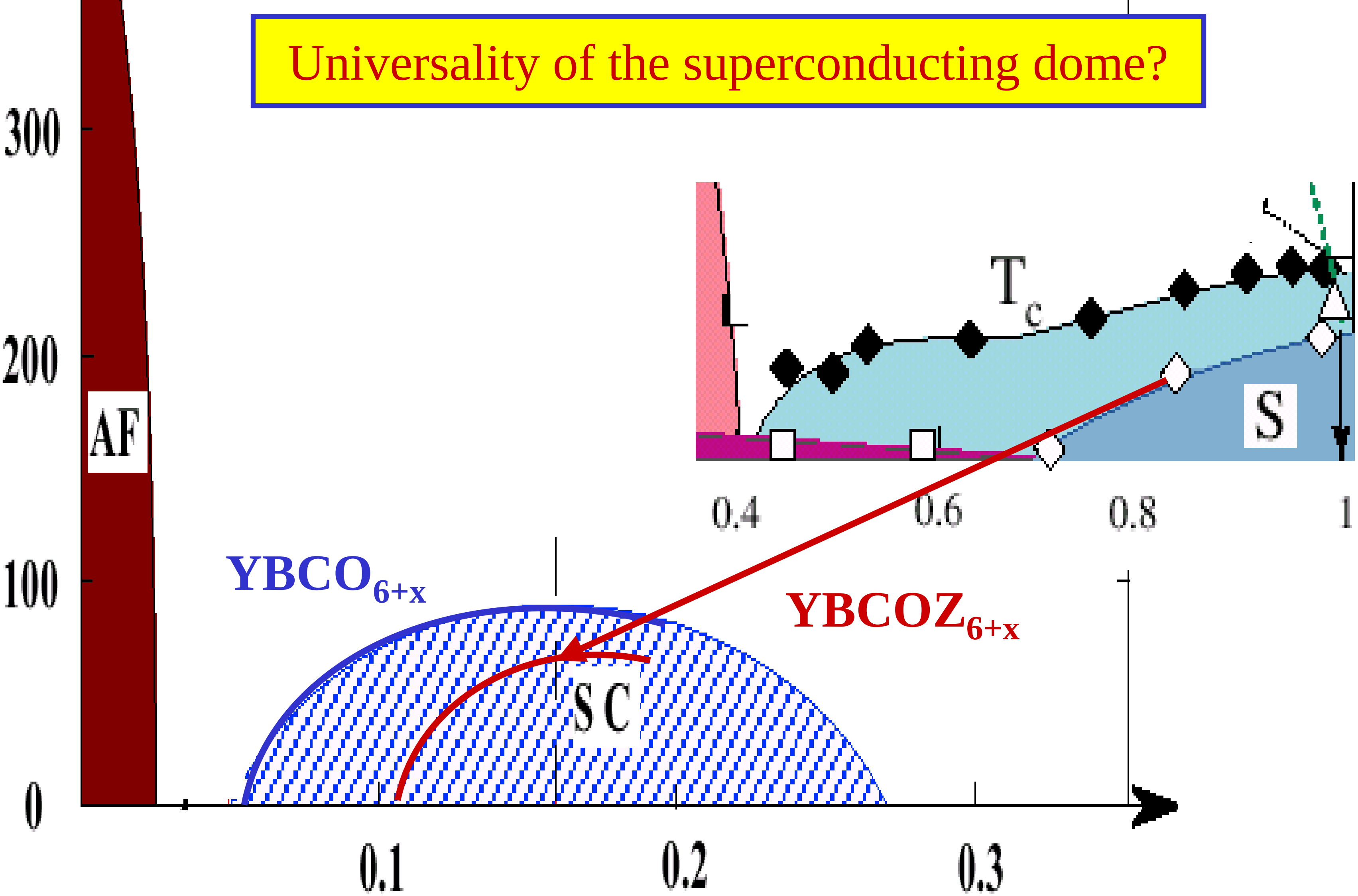
Universality of the superconducting dome?



In presence of disorder it is dangerous to map the superconducting dome to get the hole doping

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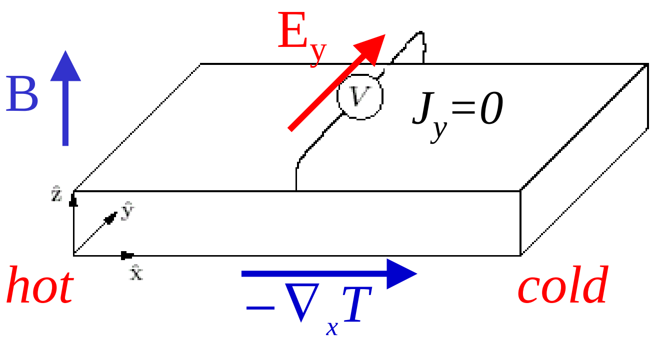
The Nernst effect



Transverse Electric field E_y in response to a temperature gradient $\nabla_x T$ in presence of a perpendicular magnetic field B

Nernst effect : very small in normal metal - cancellation of Sondheimer

$$B = 0 \qquad J_x = \sigma E_x + \alpha(\nabla_x T) \qquad J_x = 0 \;\Rightarrow\; E_x = -\frac{\alpha}{\sigma}\nabla_x T = -S\,\nabla_x T$$

$$B \neq 0 \qquad J_y = \sigma E_y + \sigma_{yx} E_x + \alpha_{yx}(\nabla_x T) \qquad J_y = 0 \;\Rightarrow\; E_y = \left[\frac{\alpha_{xy}}{\sigma} - S\tan\Theta_H\right](-\nabla_x T)$$

Nernst coefficient

$$\nu_N = \frac{E_y}{(-\nabla_x T)B} = \left[\frac{\alpha_{xy}}{\sigma} - S\tan\Theta_H\right]\frac{1}{B}$$

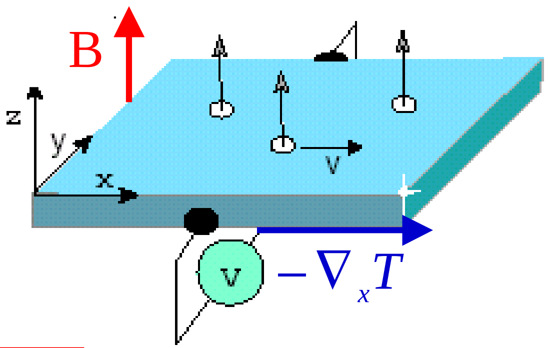
S thermopower
σ conductivity
Θ_H Hall angle

Counterflows of hot and cold electrons ➡ opposite voltages nearly cancel

Nernst effect in the mixed state of superconductors

Mobile vortices move under the application of a thermal gradient $\nabla_x T$

$$F_{th} = -S_\Phi \nabla_x T$$



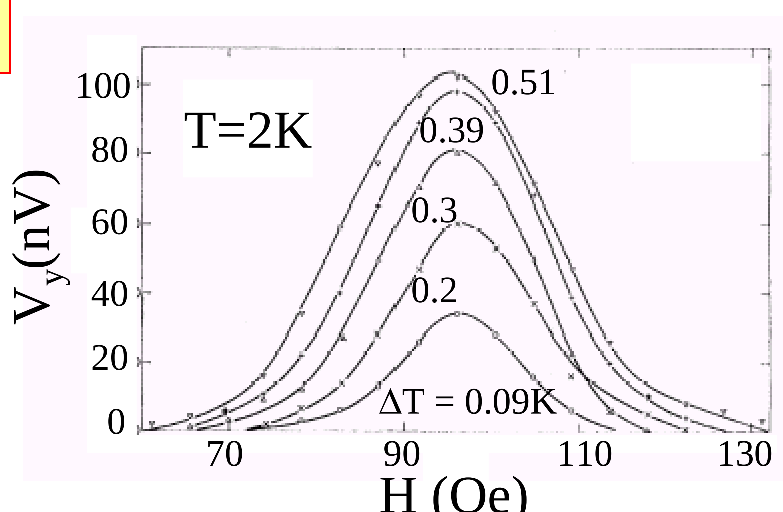
Josephson relation

$$E_y = \vec{v} \wedge \vec{B}$$

voltage transverse to the direction of flow

$$v_S = \frac{E_y}{(-\nabla_x T)B} > 0$$

Indium

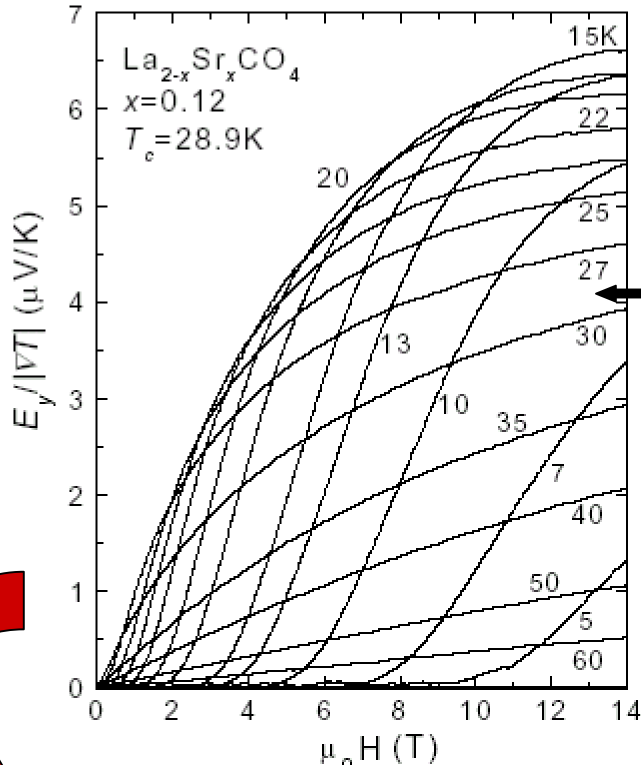


Powerful probe for detecting mobile vortices in the mixed state of superconductors

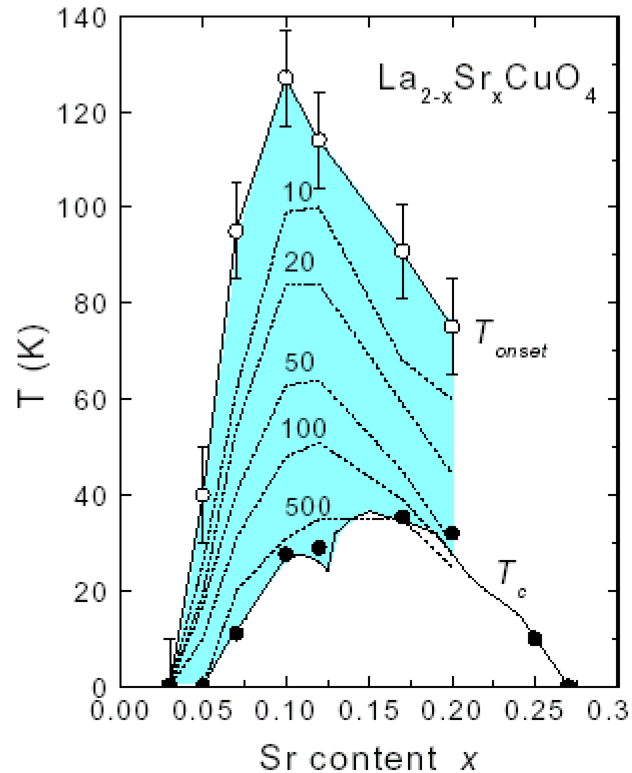
V.A. Rowe and R.P. Huebener, Phys. Rev. 185 (1969)

Anomalous Nernst effect in the normal state of cuprates

$La_{2-x}Sr_xCuO_4$



$\leftarrow T_c$



Significant Nernst signal at T>Tc

Effect pronounced in underdoped samples

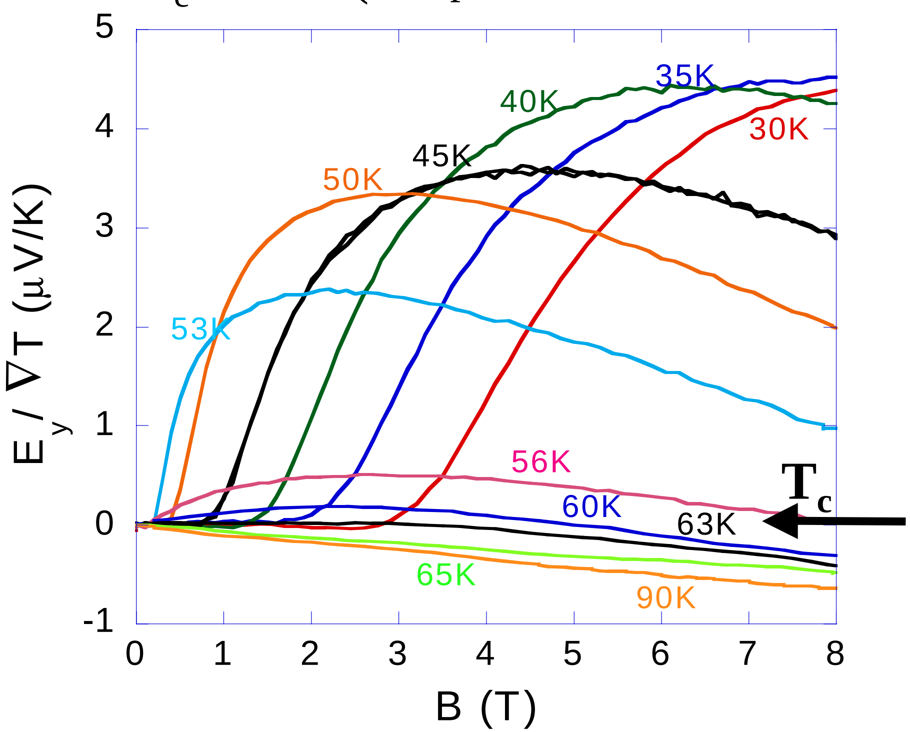
Signature of superconducting fluctuations
in the normal state
T_c = loss of long range phase coherence

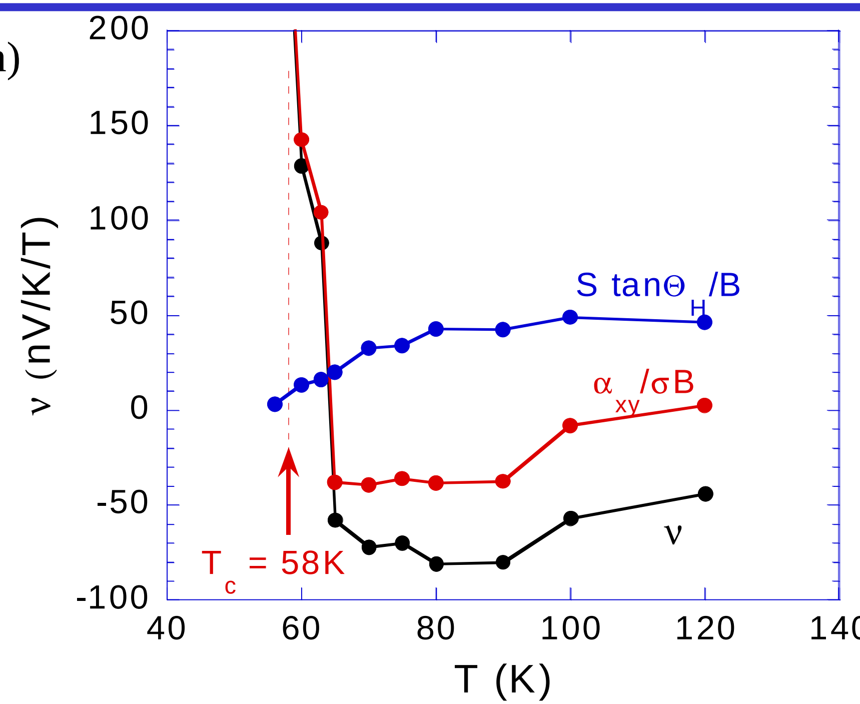
Possible implications for the physics
of the pseudogap regime
preformed pairs ?

Wang et al, PRB 64 (2001)

Nernst effect in pure underdoped $YBCO_{6.6}$

T_c = 58K (mid-point of the resistive transition)





$$\nu = \frac{E_y}{(-\nabla_x T)B} = \left[\frac{\alpha_{xy}}{\sigma} - S\tan\Theta_H\right]\frac{1}{B}$$

$$\alpha_{xy} = \alpha_{xy}^s + \alpha_{xy}^n$$

Rapid drop of the Nernst signal at T_c

Negative contribution
in the normal state

Difficult to determine the onset
of superconducting Nernst signal
with high accuracy

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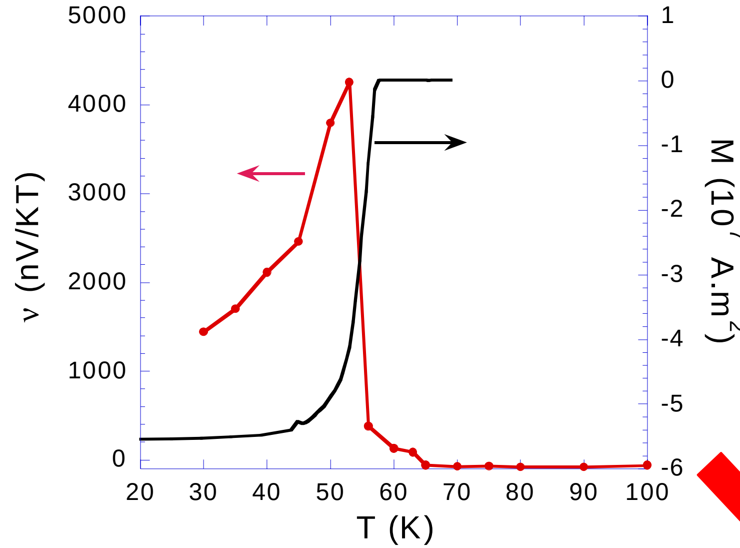
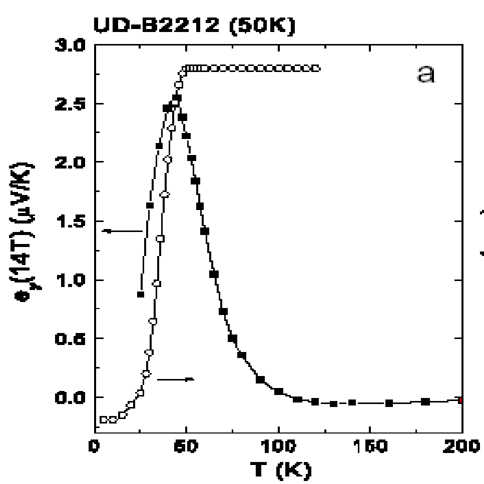
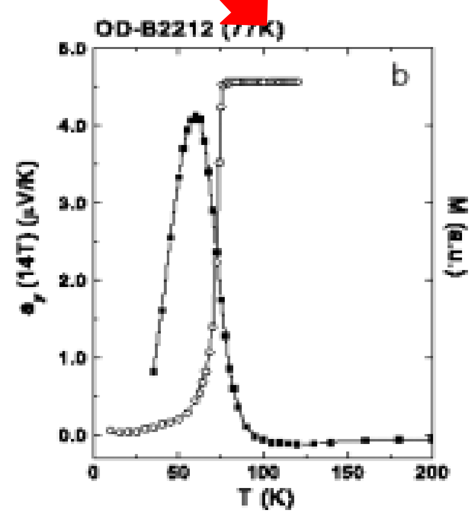
Nernst effect in pure $YBCO_{6.6}$

$YBCO_{6.6}$



Underdoped Bi-2212



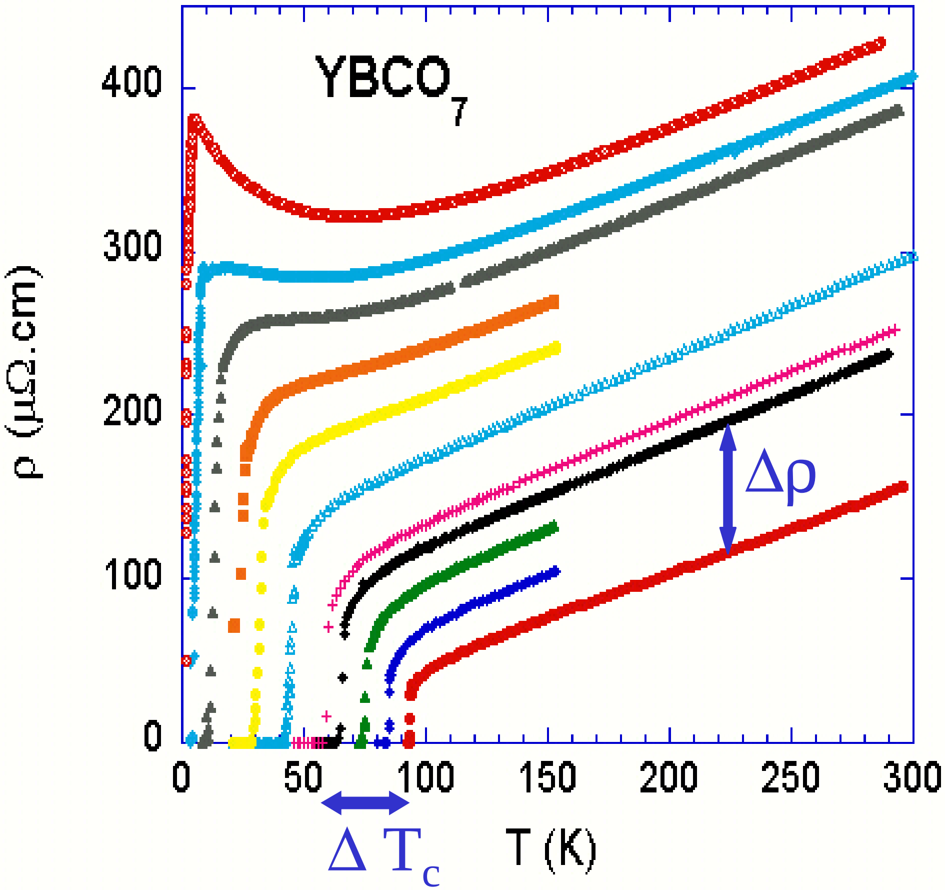


Overdoped Bi-2212

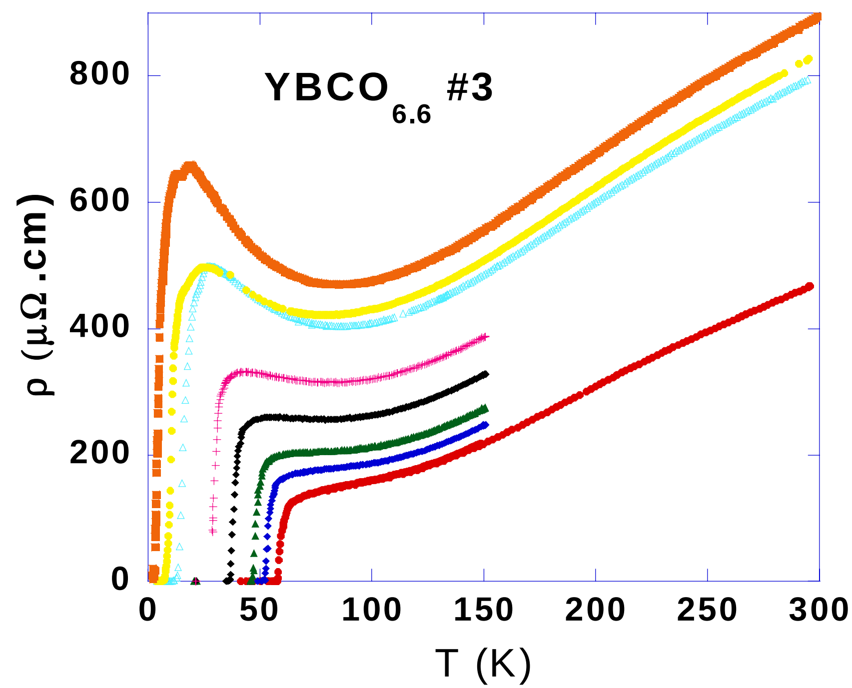
N.P. Ong et al, cond-mat/0312213 (2003)

Question : is there an anomalous Nernst signal in the normal state of $YBCO_{6.6}$?

Influence of irradiation defects on the superconducting properties



Same single crystal



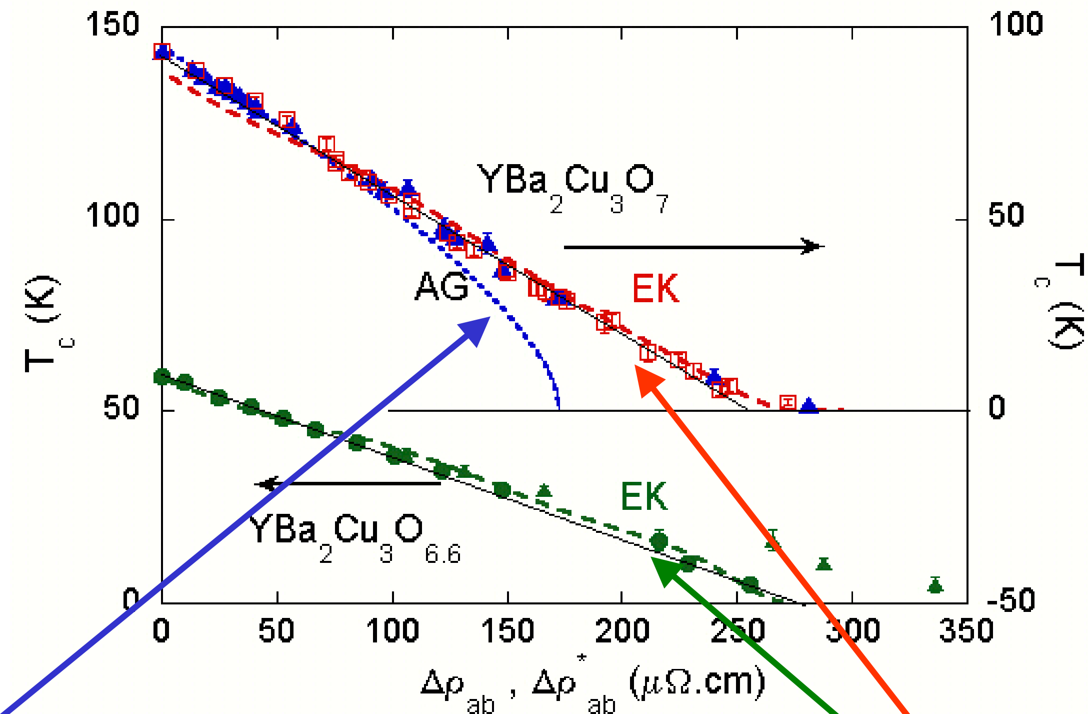
The transition curves remain very sharp ➡ **Homogeneous damage**

Excellent control of defect content down to $T_c = 0$

T_c depression induced by disorder

T_c decreases quasi linearly with defect content down to T_c =0

F. Rullier-Albenque et al, PRL 91 (2003)



Superconductivity
in bad metals

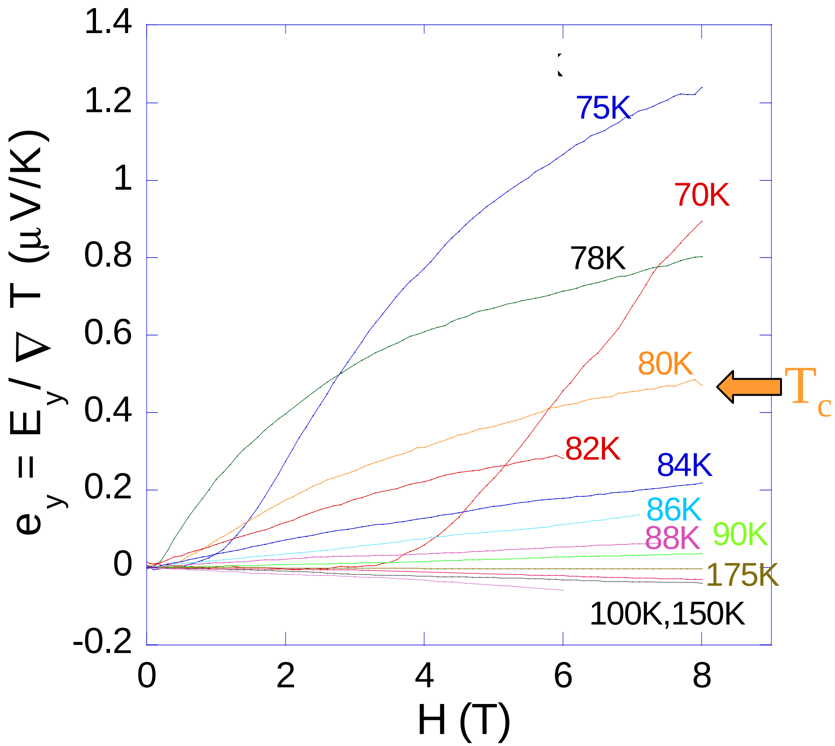
**Pair-breaking
Abrikosov-Gorkov
theory**

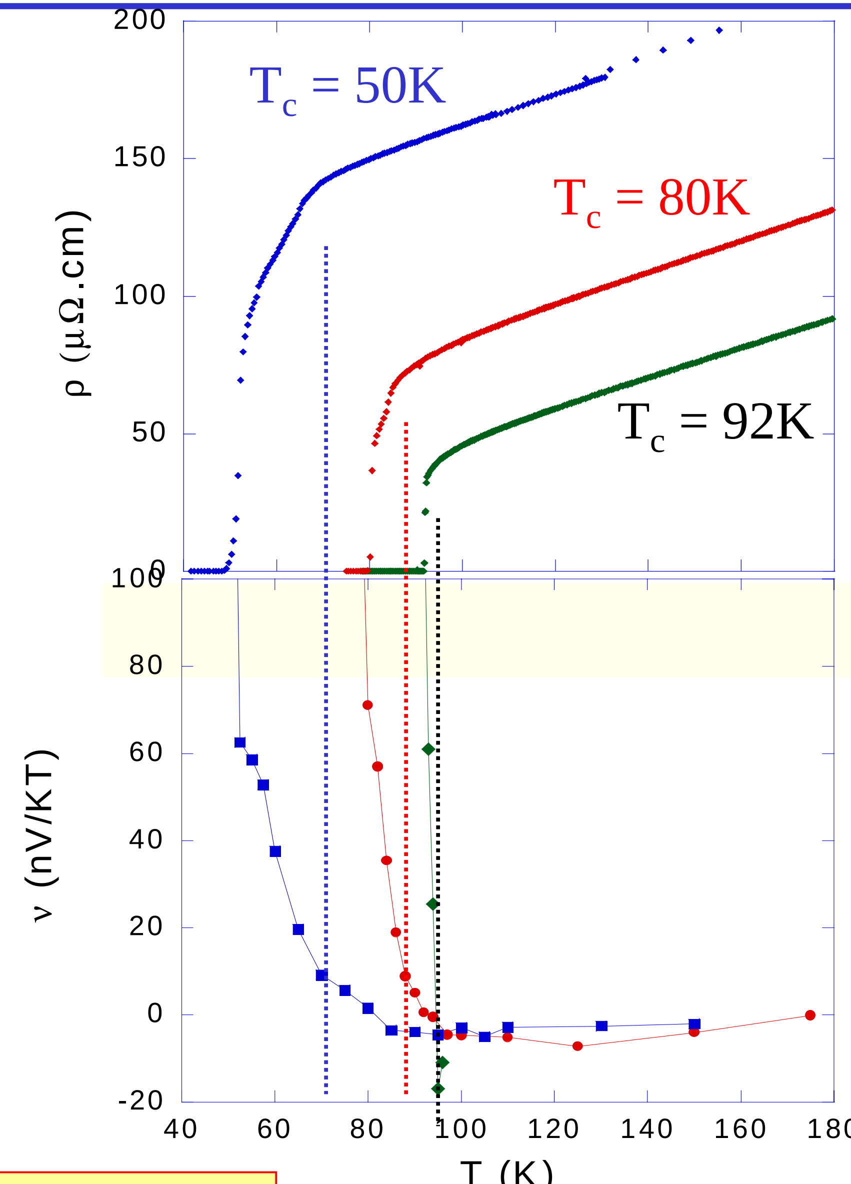
**Loss of phase
coherence by quantum
phase fluctuations**
(Emery and Kivelson)

Question : Does this loss of phase coherence induce a Nernst signal ?

Nernst effect in irradiated $YBCO_7$

Irradiated $YBCO_7$ - T_c ~ 80K





A Nernst signal survives above T_c in presence of disorder

The Nernst signal persists nearly to the T_{c0} of the pure crystal

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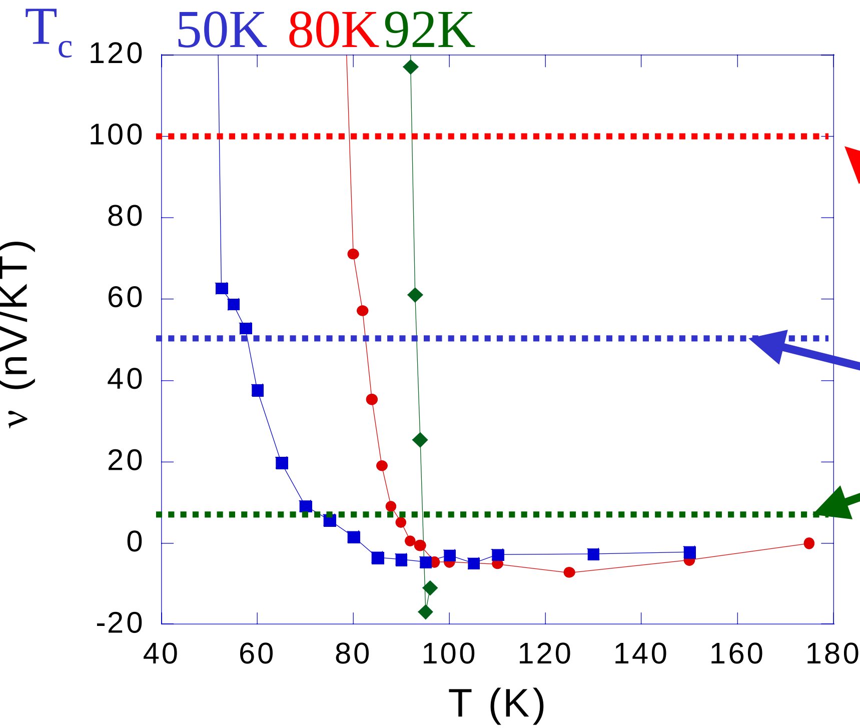
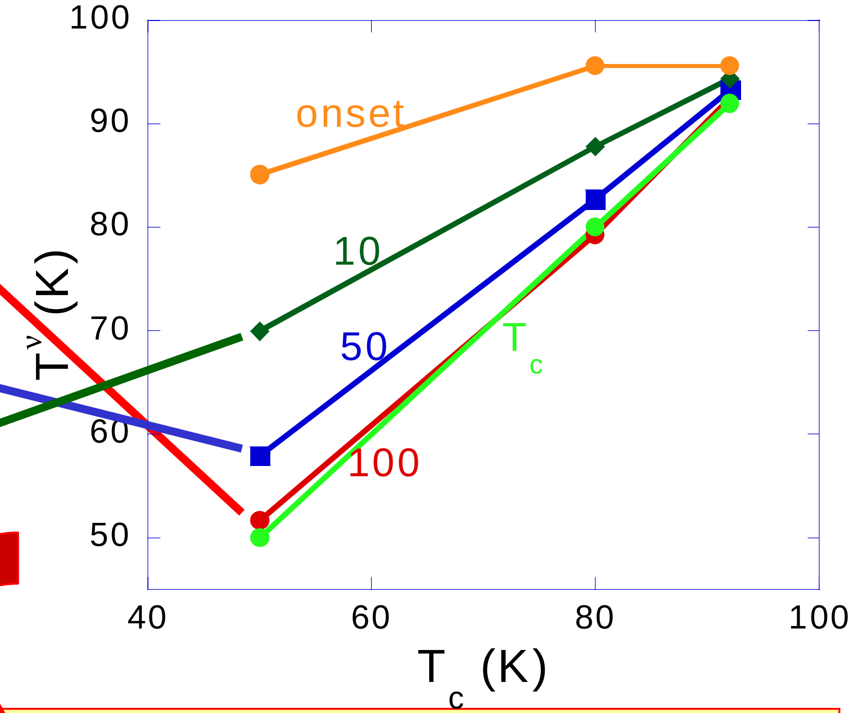
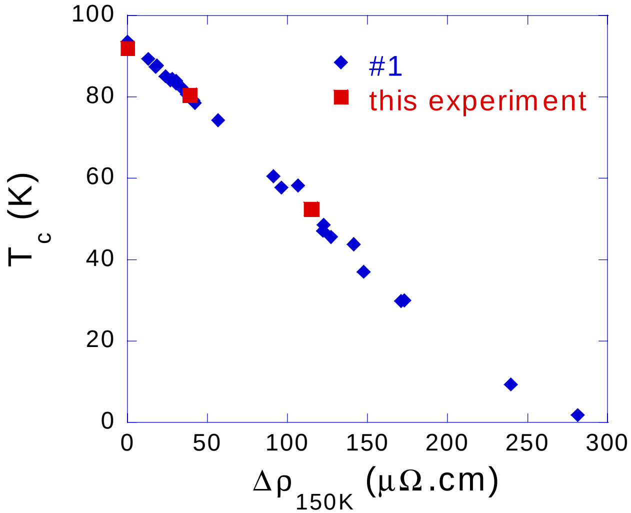
Nernst effect in irradiated $YBCO_7$



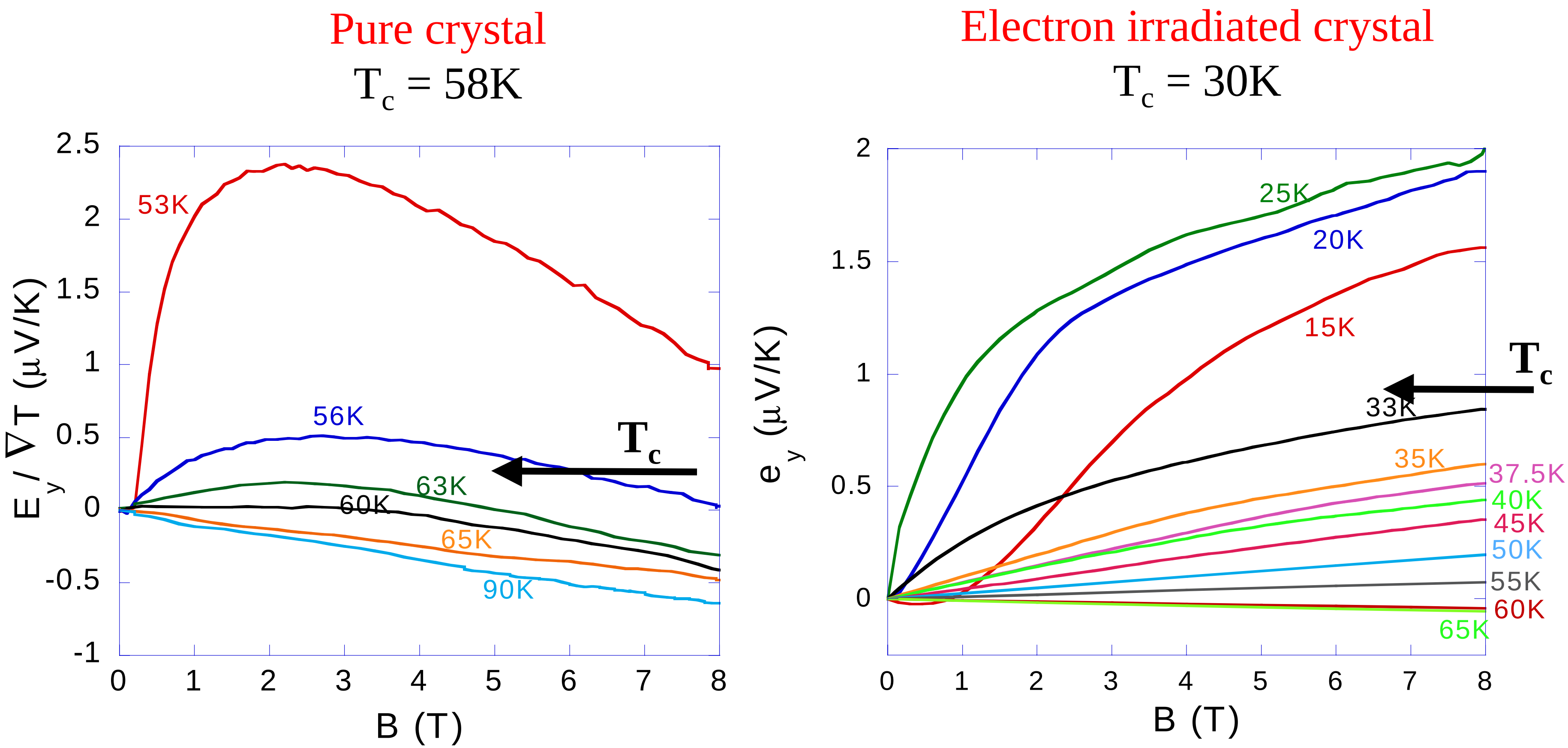


In $YBCO_7$
part of the decrease in T_c can be
attributed to a loss of phase coherence



Compatible with our interpretation of
the quasi-linear decrease of T_c with disorder

Nernst effect in irradiated underdoped $YBCO_{7-\delta}$



The Nernst signal persists well above T_c in irradiated underdoped $YBCO_{6.6}$

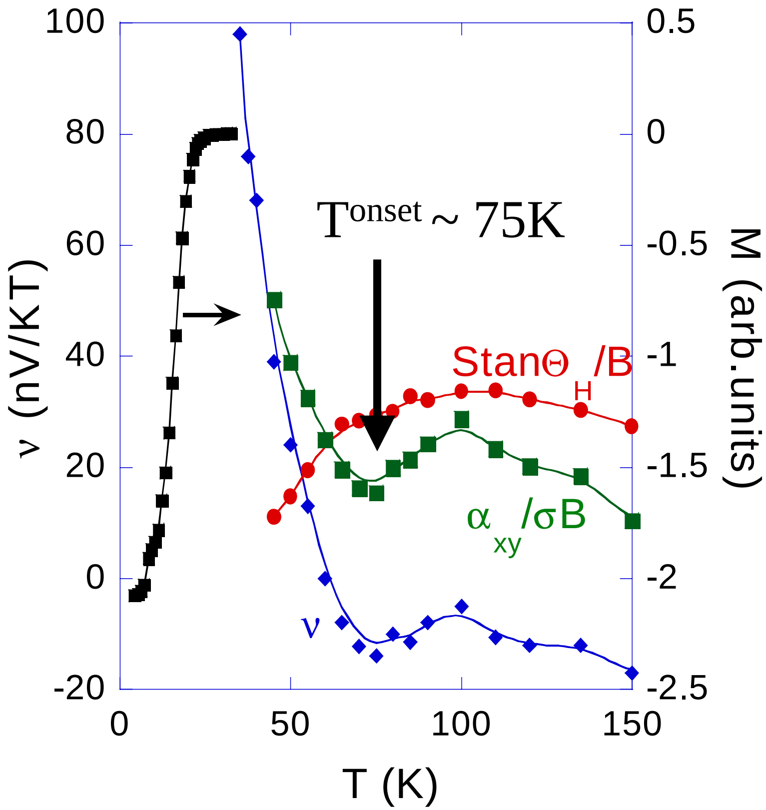
The negative contribution decreases with disorder

Nernst effect in irradiated $YBCO_{6.6}$

Electron irradiated $YBCO_{6.6}$

T_c = 30K (resistive transition)

T_c = 24.6K (onset of magnetization)



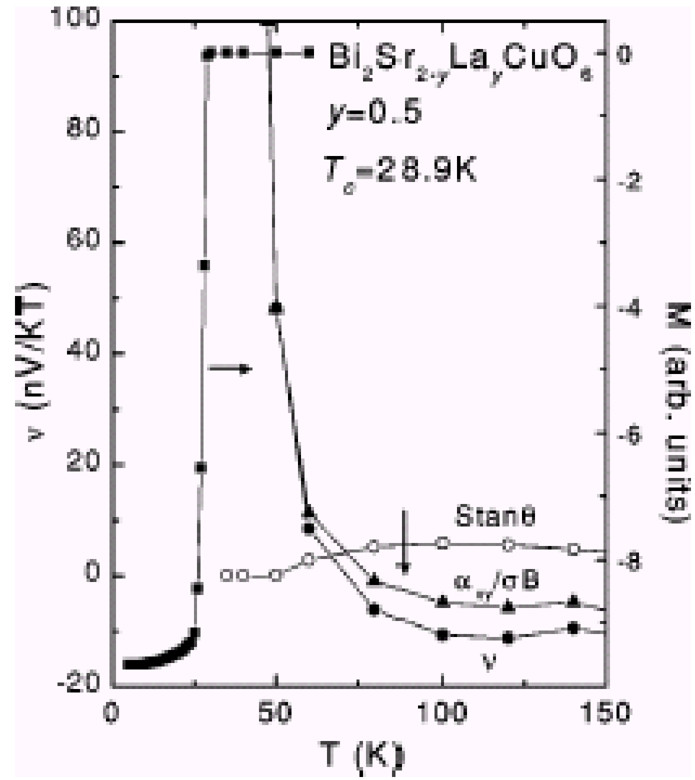
$$\nu = \frac{E_y}{|\nabla_x T| B} = \left[\frac{\alpha_{xy}}{\sigma} - S \tan \Theta_H \right] \frac{1}{B}$$

Pure underdoped

$Bi_2 Sr_{2-y} La_y Cu O_6$

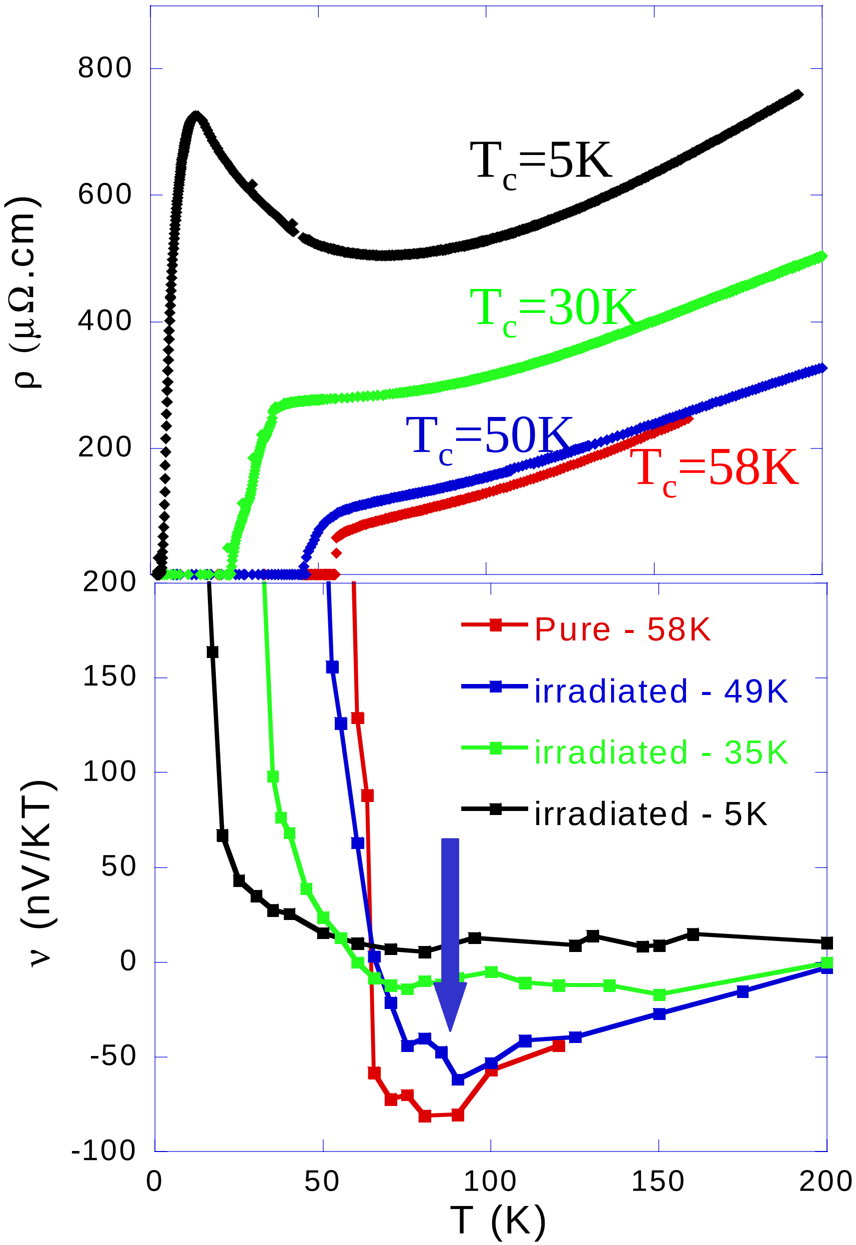
y=0.5 - T_c = 28.9K

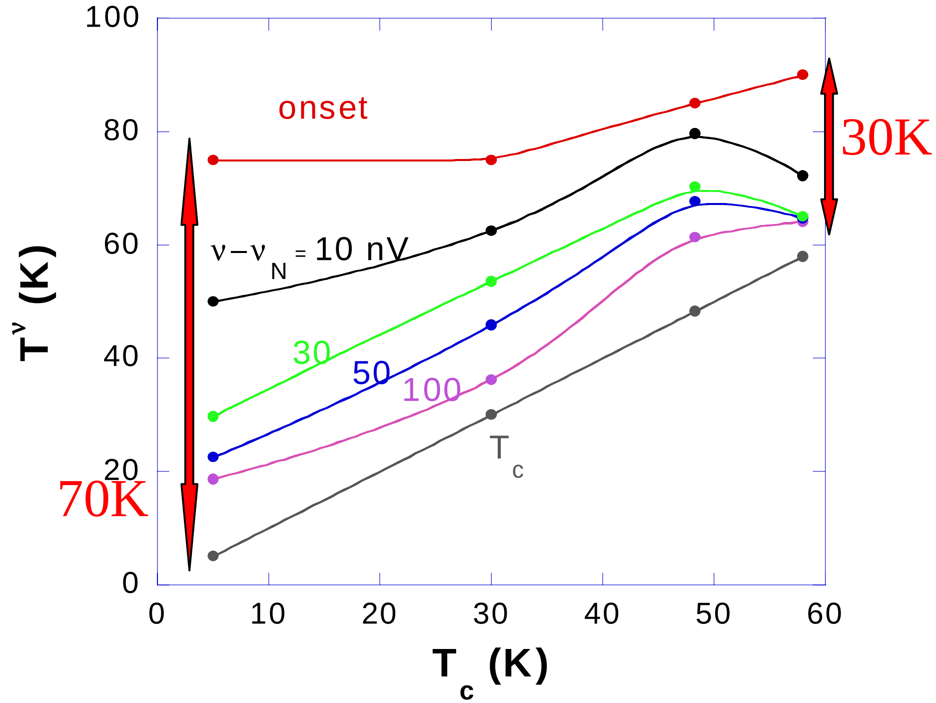
Wang et al, PRB 64 (2001)



Strong similarity between irradiated $YBCO_{6.6}$ and « pure » $Bi_2 Sr_{2-y} La_y Cu O_6$

Nernst effect in irradiated $YBCO_{6.6}$





T_{onset} is nearly the same for all the samples

The fluctuation regime increases with disorder

The Nernst signal induced in the normal state is more pronounced in $YBCO_{6.6}$ than in $YBCO_7$

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Native and controlled disorder in cuprates

- *Introduction*
  - Phase diagram and open questions in cuprates
  - Native and controlled disorder?
- *NMR as a probe of disorder*
  - Comparison of different cuprate families
  - YBCO6.6 and YBCO7 : homogeneous cases
- *Influence of controlled disorder on the phase diagram*
  - Pseudogap crossover
  - Superconducting dome and hole content
- *Nernst effect, phase coherence and preformed pairs*
  - Nersnst effect in « pure » systems
  - Disorder and phase coherence
- *Conclusion: Pseudogap and fluctuations*

Conclusions

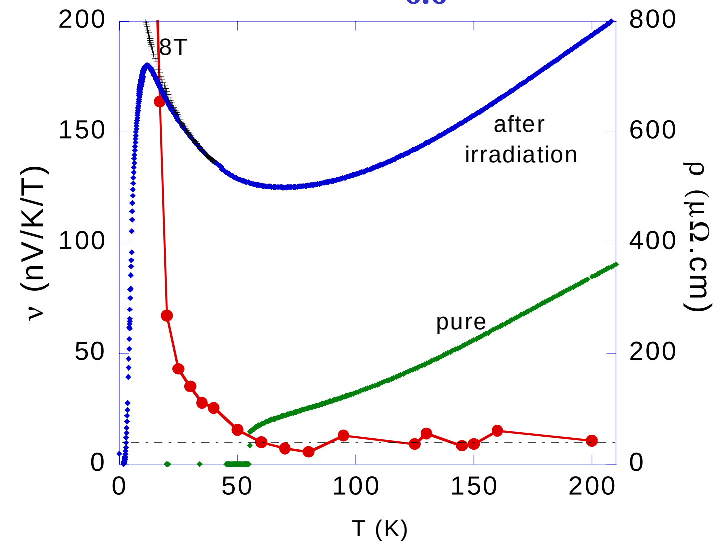
Influence of defects on T_c : loss of phase coherence

Introduction of defects

↓

Increase of the regime of superconducting fluctuations from T_c to ~ T_{c0} of the pure sample

$YBCO_{6.6}$



The effect of disorder on Nernst signal is stronger in underdoped crystals
Superconducting pairs survive in the normal state of disordered crystals

No link between Nernst signal and pseudo-gap in pure $YBCO_{6.6}$

Our results suggest that the Nernst signal seen in « pure » compounds could be associated to the presence of uncontrolled defects

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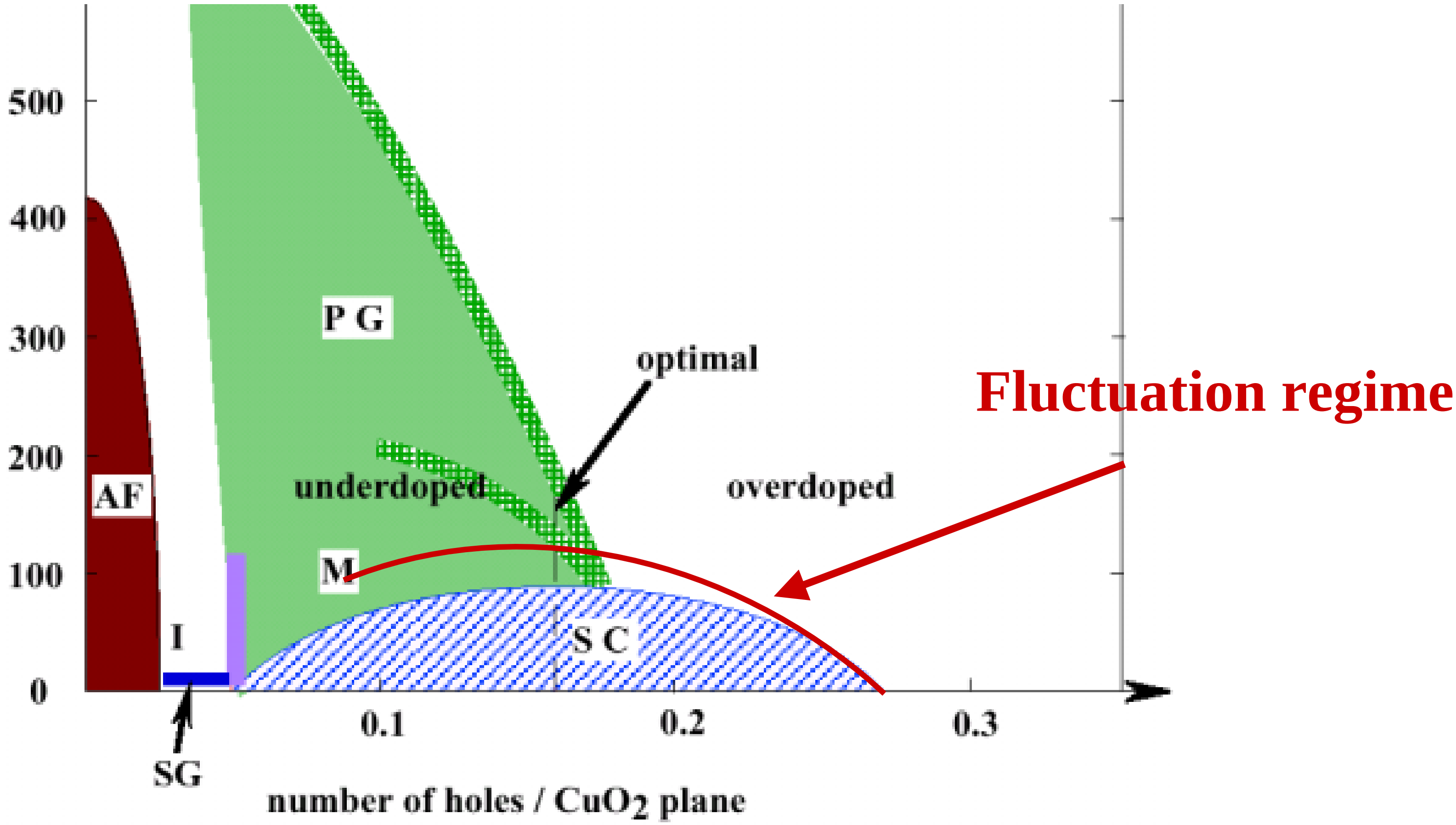
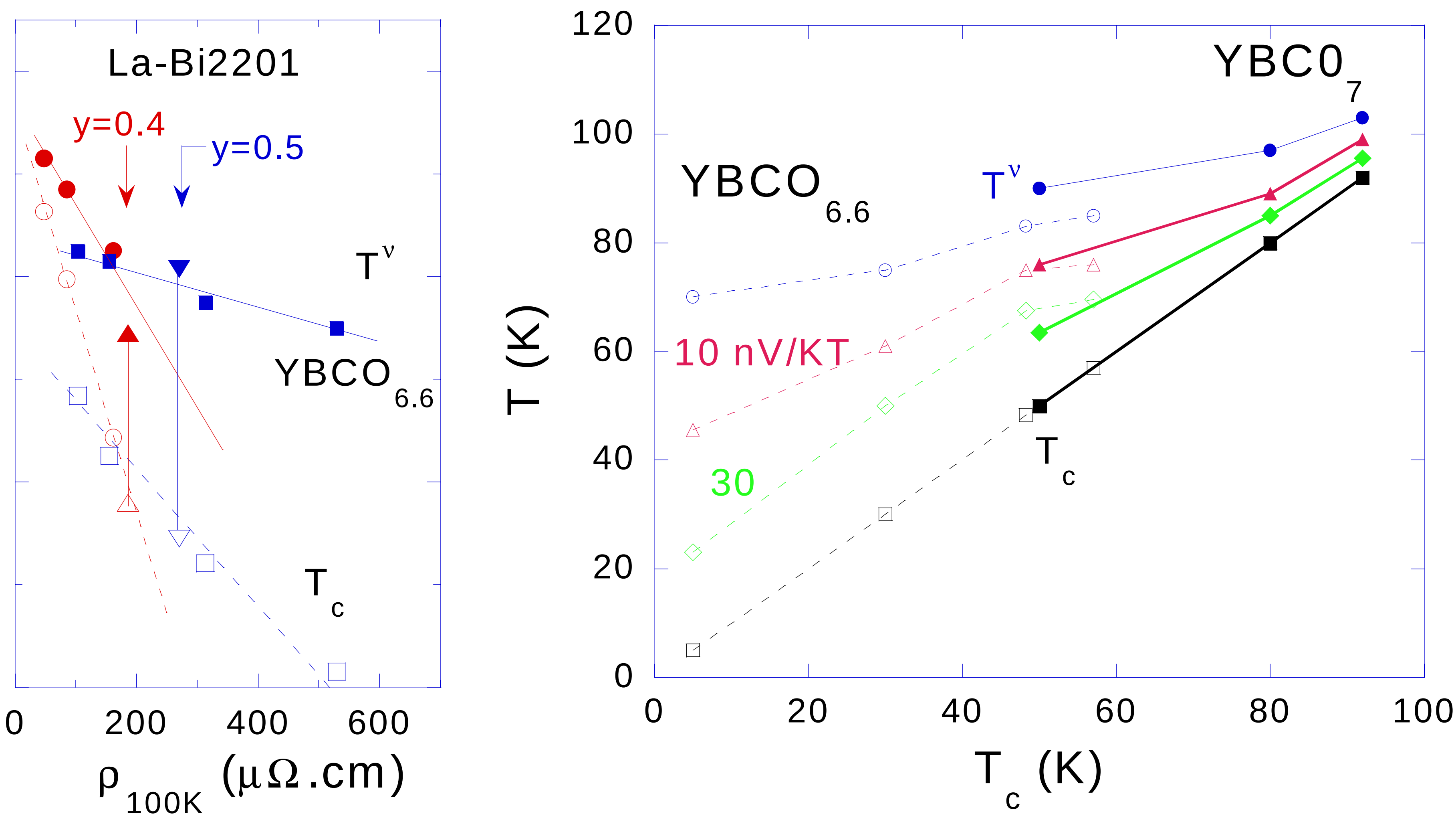
Importance of the fluctuation regime ?



In presence of disorder the fluctuation regime extends well above Tc.

Some techniques do not differentate Pseudogap and fluctuation regime


La-Bi2201
y=0.4
y=0.5
T^ν
YBCO 6.6
T c
0
200
400
600
ρ 100K (μΩ.cm)
120
100
80
60
40
20
0
T (K)
YBC0 7
YBCO 6.6
T^ν
10 nV/KT
30
T c
0
20
40
60
80
100
T c (K)