KITP Workshop, Santa Barbara, July 11-15, 2005

t'-physics & inhomogeneity in high-Tc superconductors

K. Fujita, S. Uchida (Univ. of Tokyo)

Collaborators: A. Fujimori

H. Eisaki, S. Kashiwaya, A. Sugimoto (AIST, Tsukuba)

K. McElroy, J.C. Seamus Davis (Cornell)

Y. J. Uemura (Columbia)

Z.-X. Shen (Stanford)

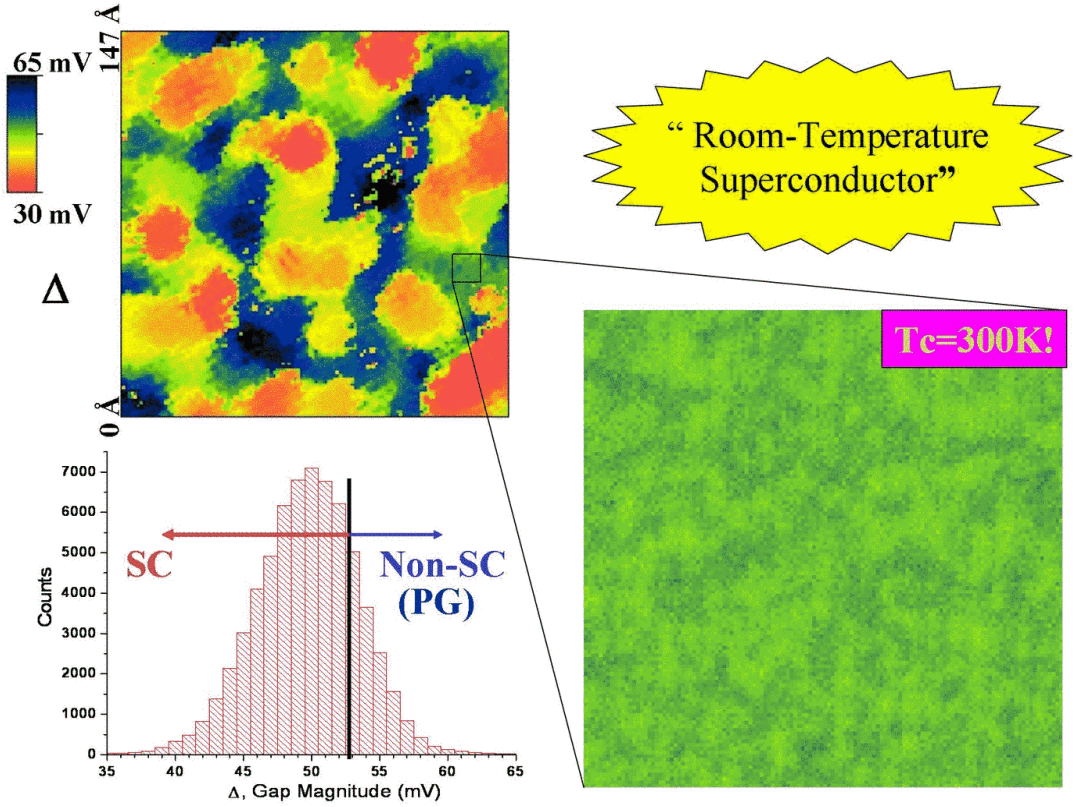
Gigantic Superconducting Gap *Cuprates*

$\Delta_0 \sim 50\ meV$ ←→ $T_c^{MAX} \sim 300K$!!

Real materials: $T_c^{MAX} \sim 150K$ $(2\Delta_0/k_B T_c \sim 8\text{-}10)$

MgB_2 : $\Delta \sim 7\ meV$ ←→ $T_c \sim 40\ K$ $(2\Delta/k_B T_c \sim 4)$

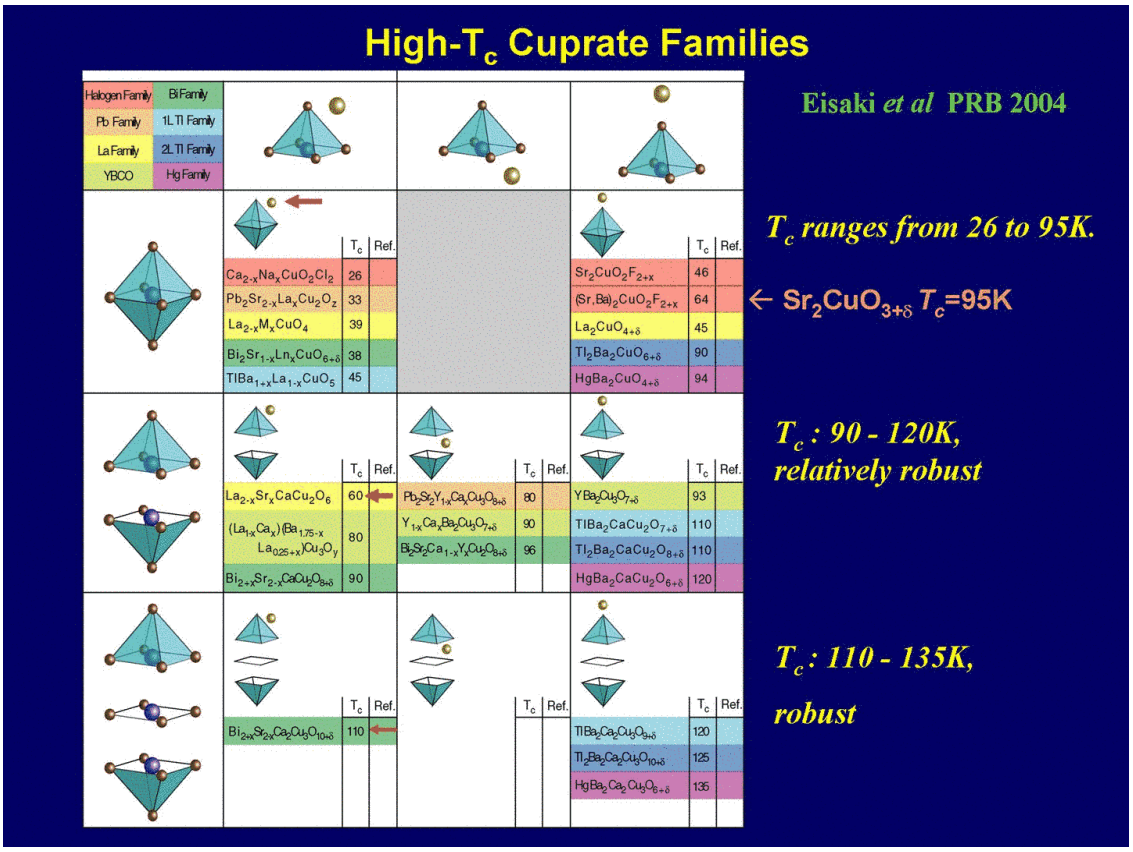
C_{60} : $\Delta \sim 5 - 7\ meV$ ←→ $T_c \sim 30\ K$ $(2\Delta/k_B T_c \sim 4\text{-}5)$



- **Originally much higher T_{c0} (≥ 300K)**

Gigantic SC Gap Magnitude

➔ ***"Why is T_c so low ?"***



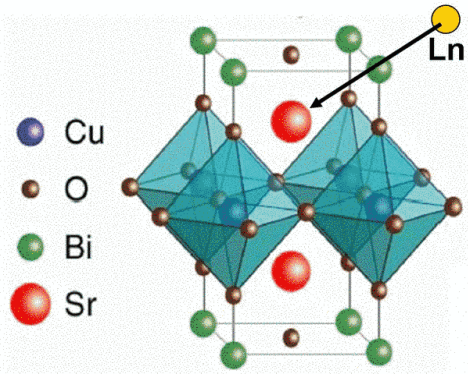
Out-of-plane factors:

apical oxygen, tilt of octahedra,

ionic-radius mismatch,… **disorder**

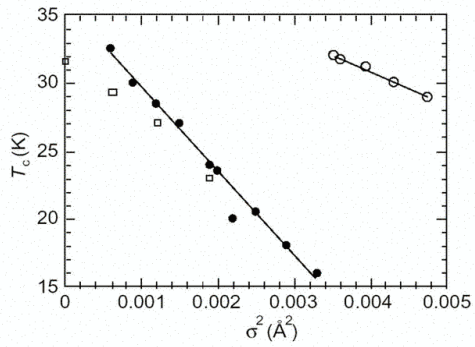
➔Appreciable influence on T_c *Convincing data ?*

➔Presence of *a parameter* sensitive to these factors



$$\sigma^2 = \langle r_A^2 \rangle - \langle r_A \rangle^2$$

Degree of disorder



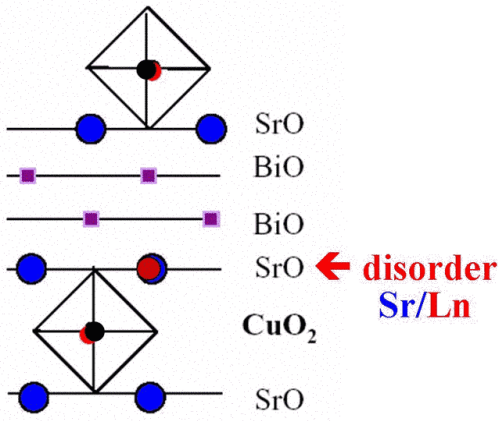
$(La,Nd)_{1.85}(Sr,Ca,Ba)_{0.15}CuO_4$

$Bi_{2.0}Sr_{1.6}Ln_{0.4}CuO_{6+\delta}$

Sr=1.12□

La=1.14□
Nd=1.04□
Eu=0.98□
Gd=0.97□

$Bi_2Sr_{1.6}Ln_{0.4}CuO_{6+\delta}$



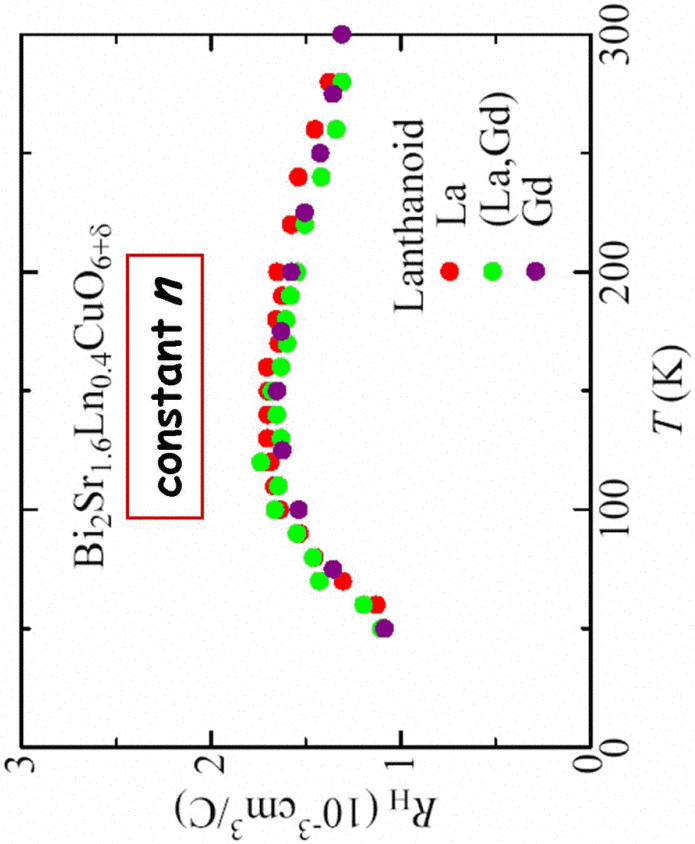
$Bi_2Sr_2Cu_2O_6$

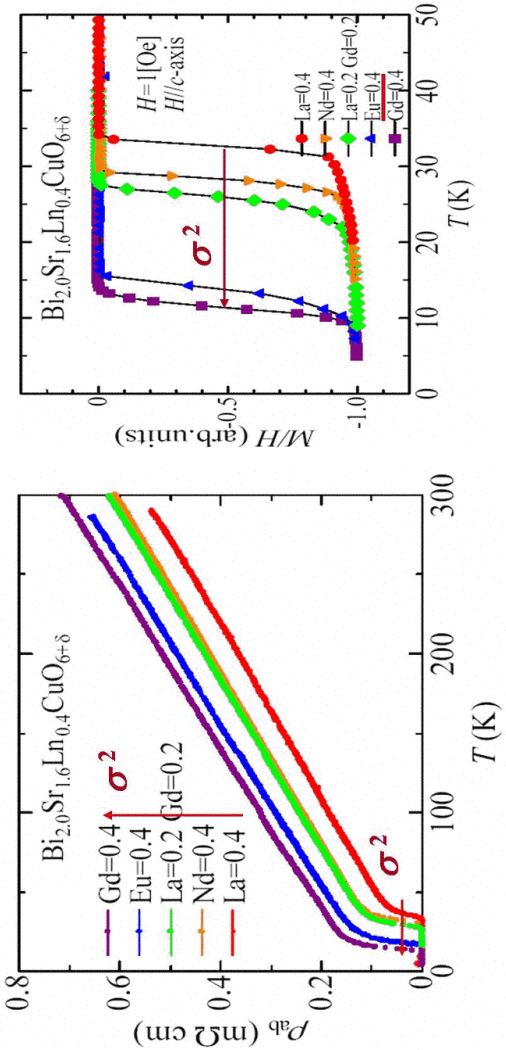
* No ***stripe*** instability

* ***n/x*** can be kept constant.

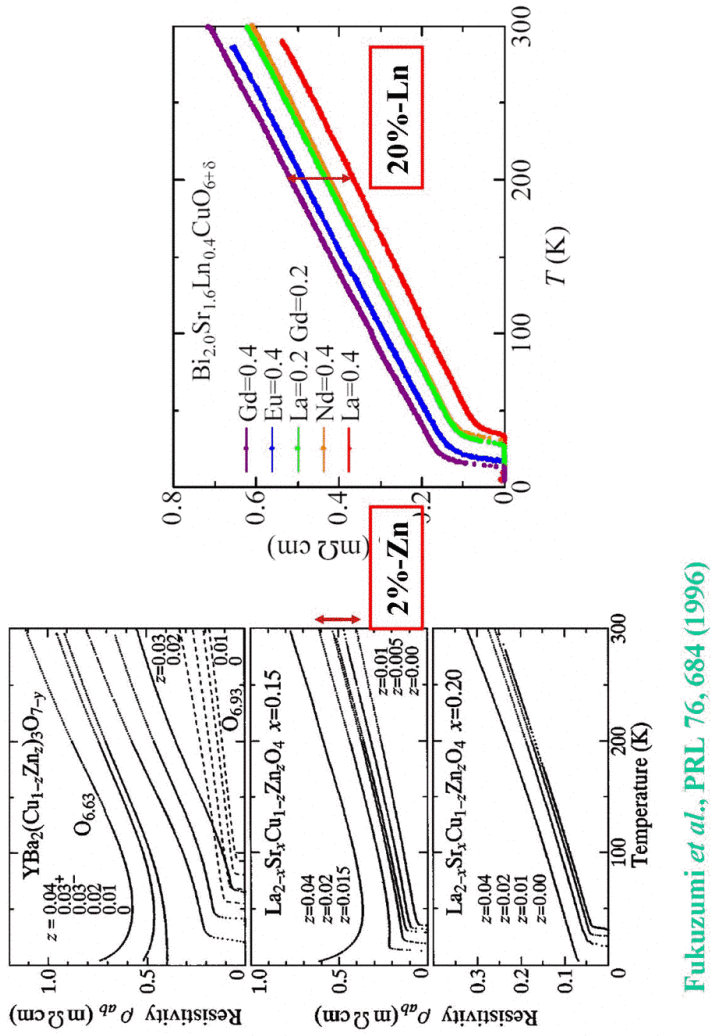
* **STM(ARPES)&μSR** measurements are possible.

* A ***monolayer*** system
→maximal disorder effect





Fujita, Eisaki

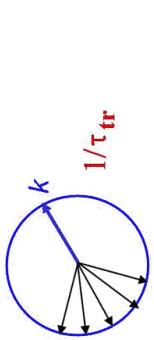


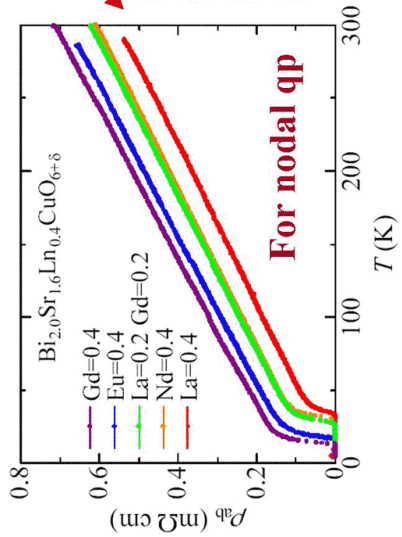
Fukuzumi *et al.*, PRL 76, 684 (1996)

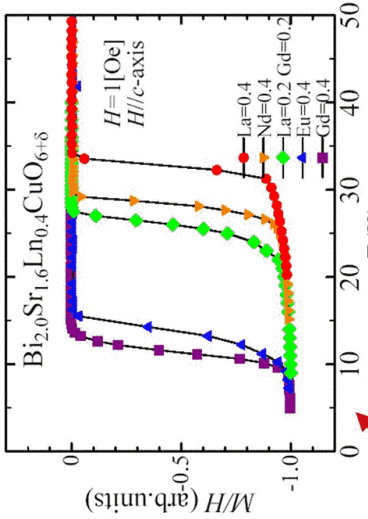
$Bi_{2.0}Sr_{1.6}Ln_{0.4}CuO_{6+\delta}$

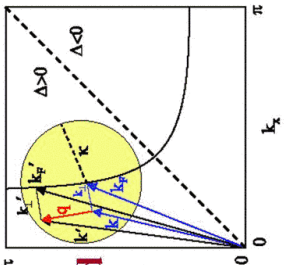
Elastic forward scattering

(Scalapino, Zhu, Hirschfeld)



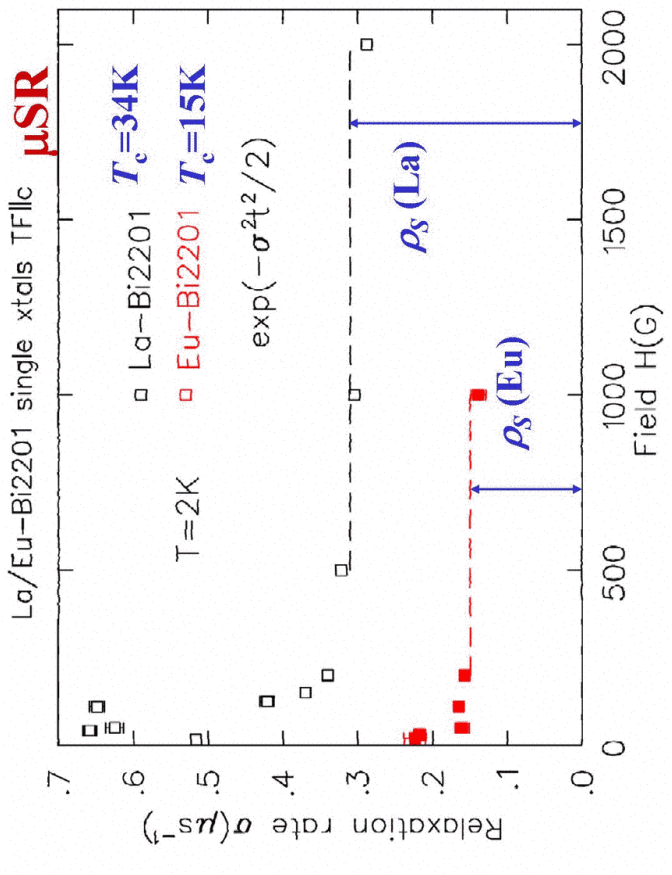




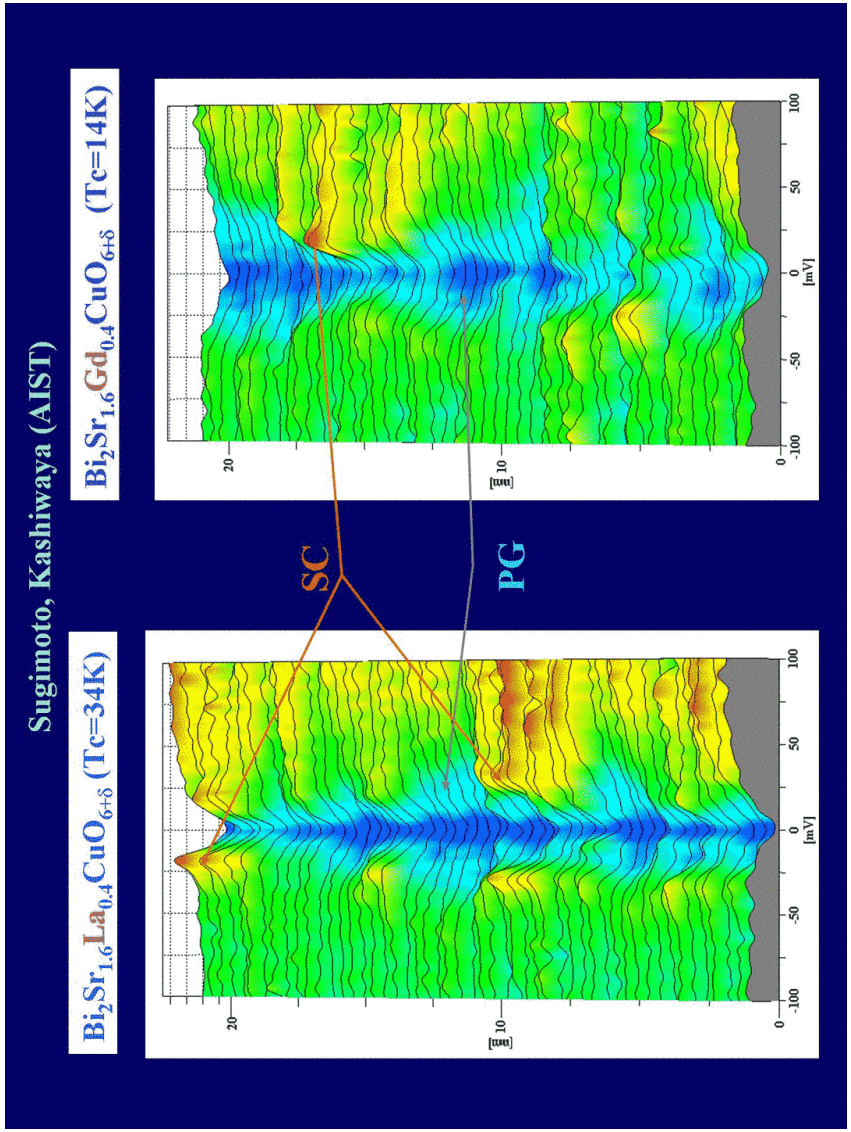


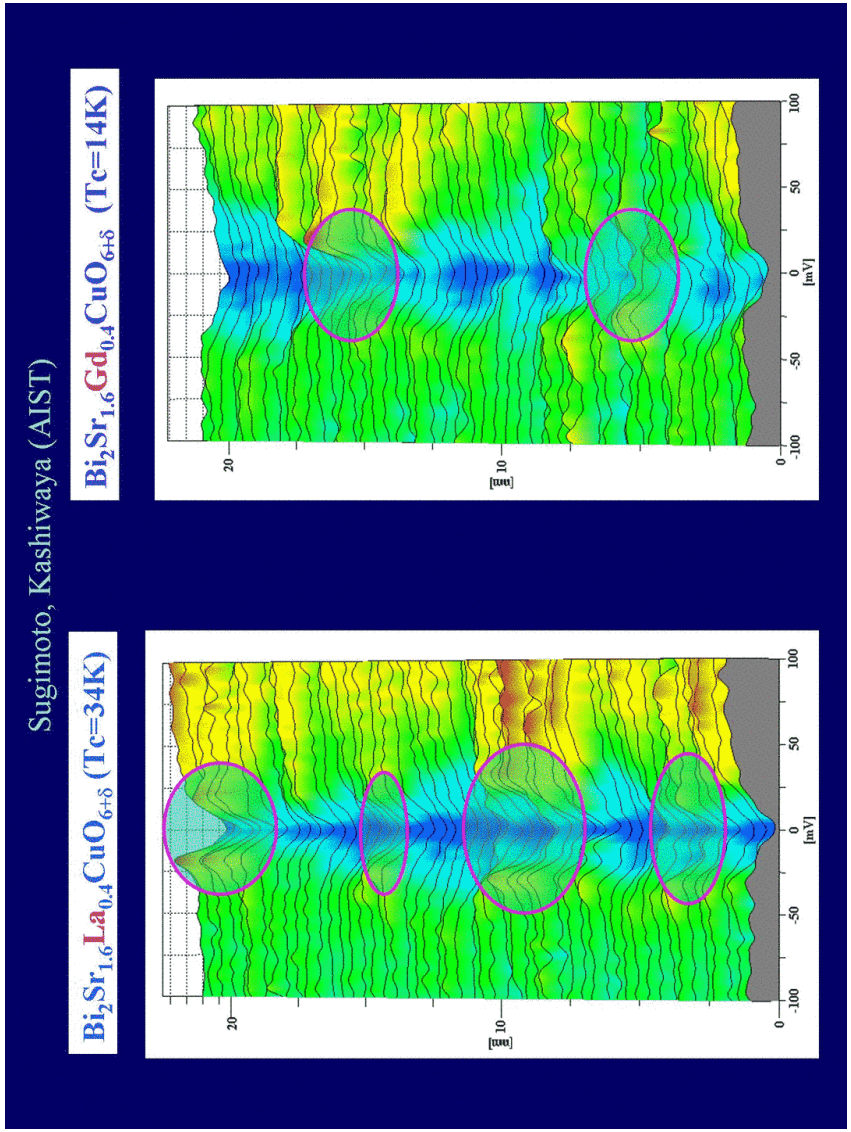
Elastic forward scattering also, for anti-nodal qp ?

The Anderson's theorem works !


La/Eu-Bi2201 single xtals TFIIc
μSR
La-Bi2201 T_c=34K
Eu-Bi2201 T_c=15K
T=2K
$\exp(-\sigma^2 t^2/2)$
ρ_S (La)
ρ_S (Eu)
Relaxation rate $\sigma(\mu s^{-1})$
Field H(G)
0
500
1000
1500
2000
.0
.1
.2
.3
.4
.5
.6
.7

Uemura

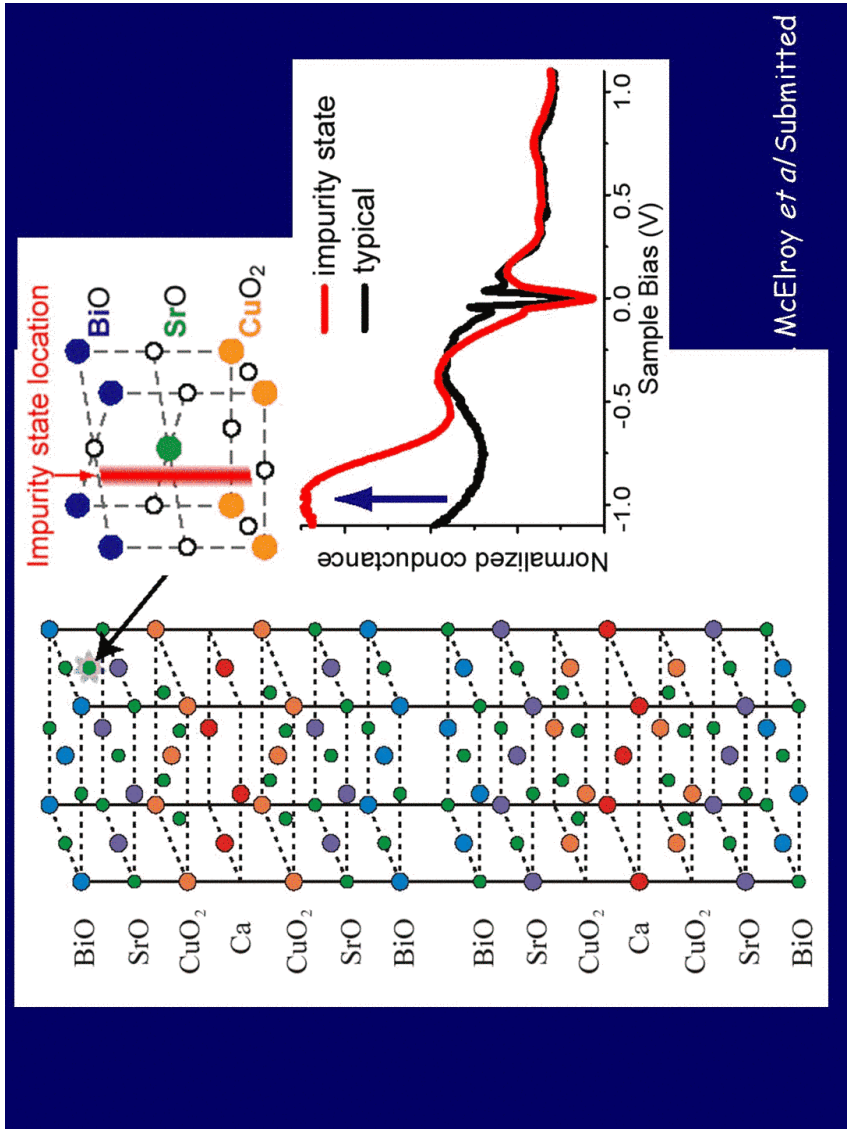

Sugimoto, Kashiwaya (AIST)
$Bi_2Sr_{1.6}La_{0.4}CuO_{6+\delta}$ (Tc=34K)
$Bi_2Sr_{1.6}Gd_{0.4}CuO_{6+\delta}$ (Tc=14K)
SC
PG
[nm]
[mV]

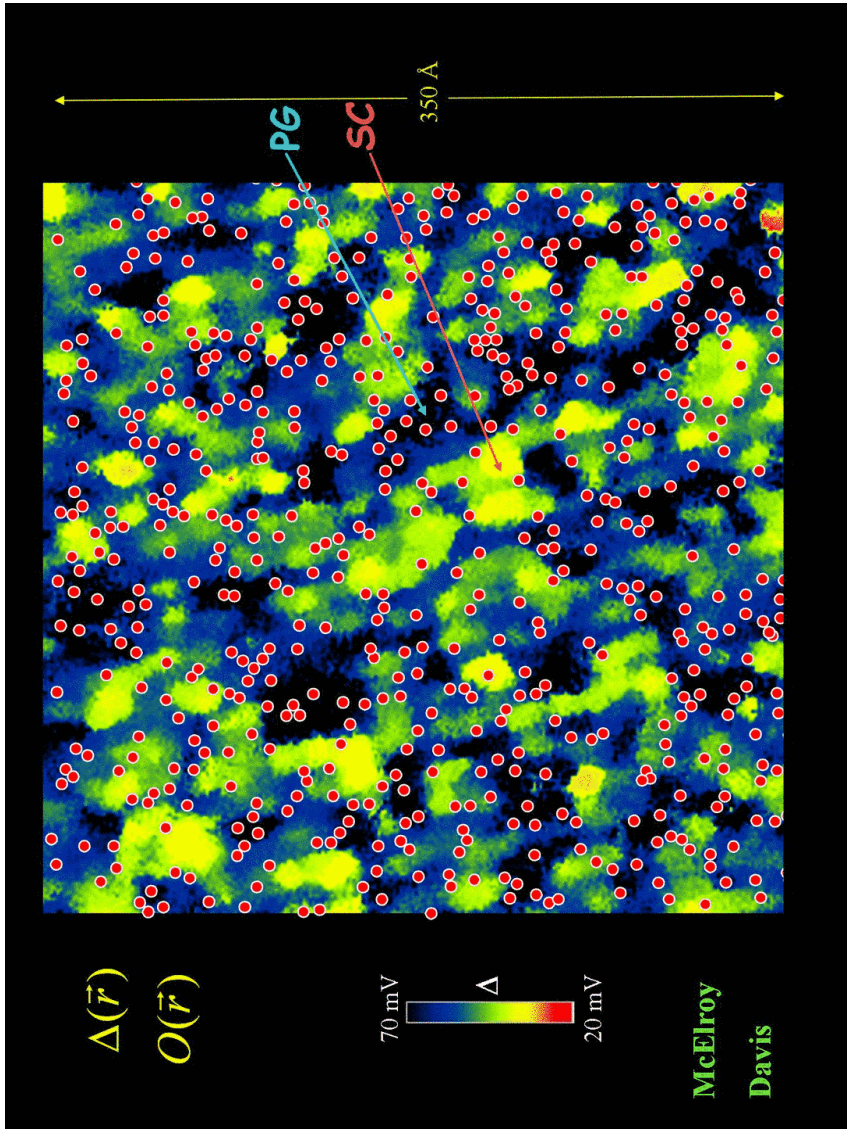


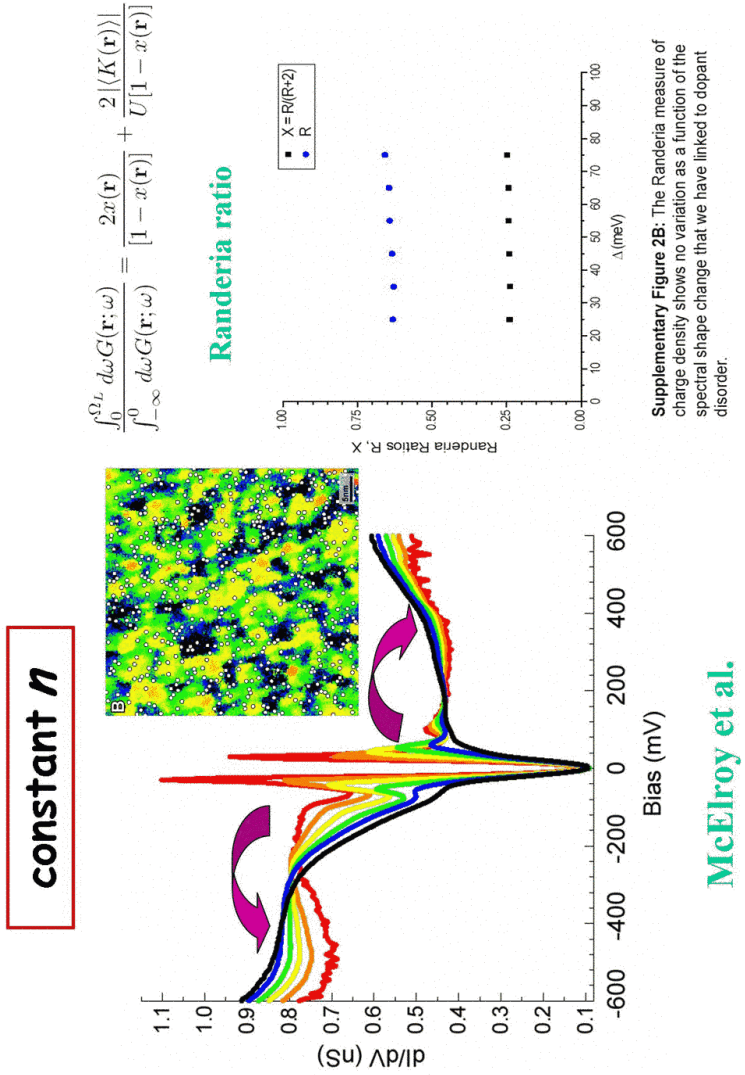
Experimental results on Bi2201

Out-of-plane disorder → ***Increase of PG area*** → ***Decrease in ρ_S***

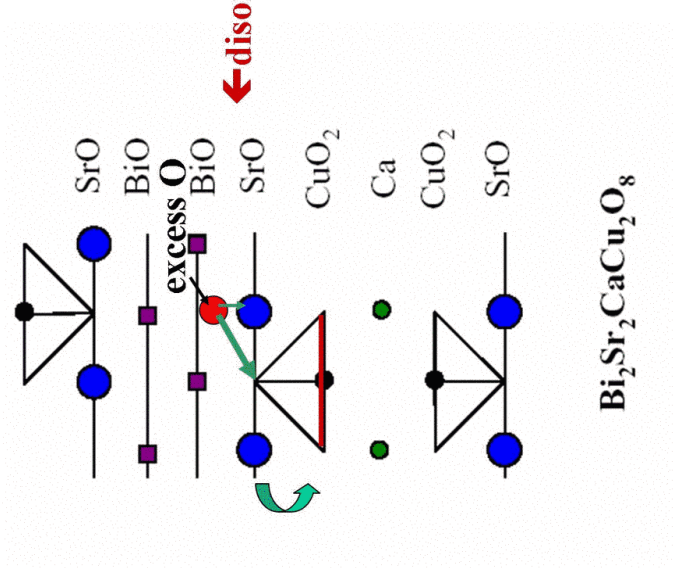
***n* ; constant**


Impurity state location
BiO
SrO
CuO2
BiO
SrO
CuO2
Ca
CuO2
SrO
BiO
BiO
SrO
CuO2
Ca
CuO2
SrO
BiO
impurity state
typical
Normalized conductance
-1.0
-0.5
0.0
0.5
1.0
Sample Bias (V)
McElroy et al Submitted


PG
SC
350 Å
Δ(r)
O(r)
70 mV
Δ
20 mV
McElroy
Davis



Supplementary Figure 2B: The Randeria measure of charge density shows no variation as a function of the spectral shape change that we have linked to dopant disorder.

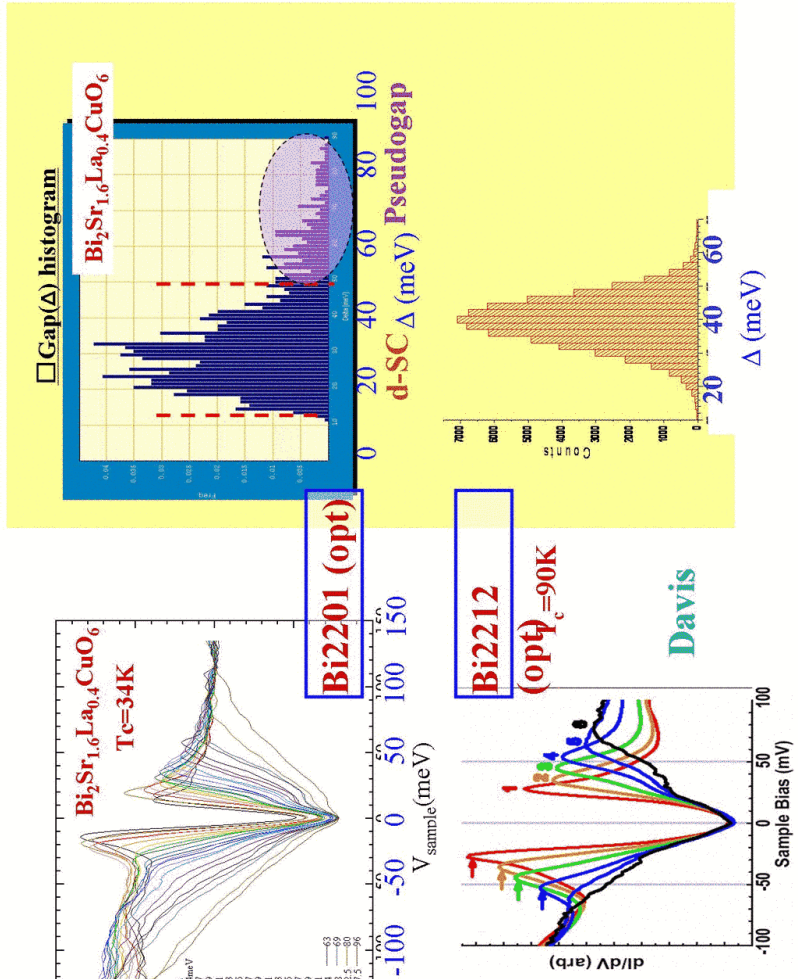


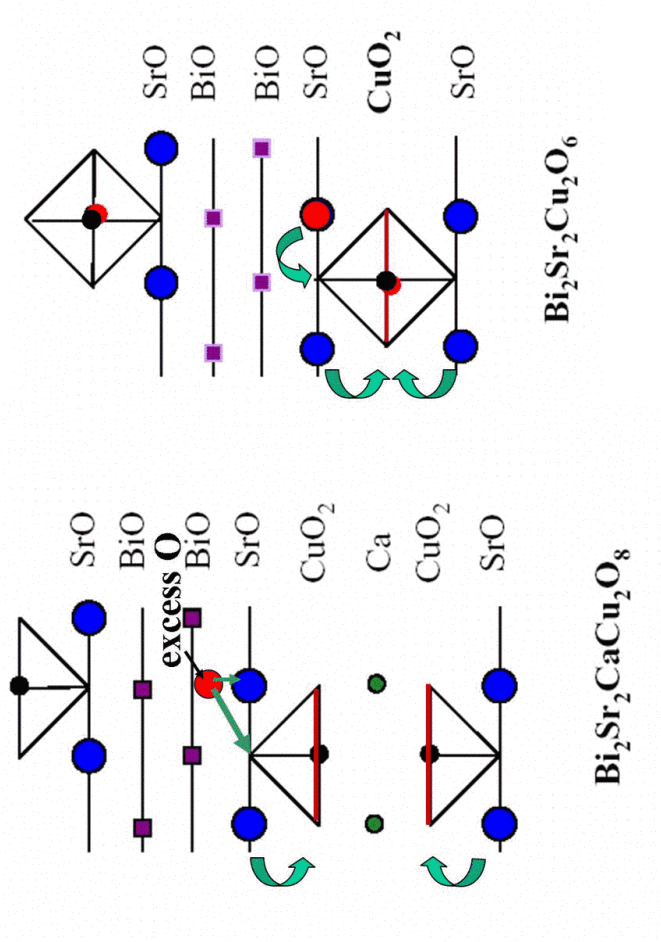
Experimental results on Bi2201&Bi2212

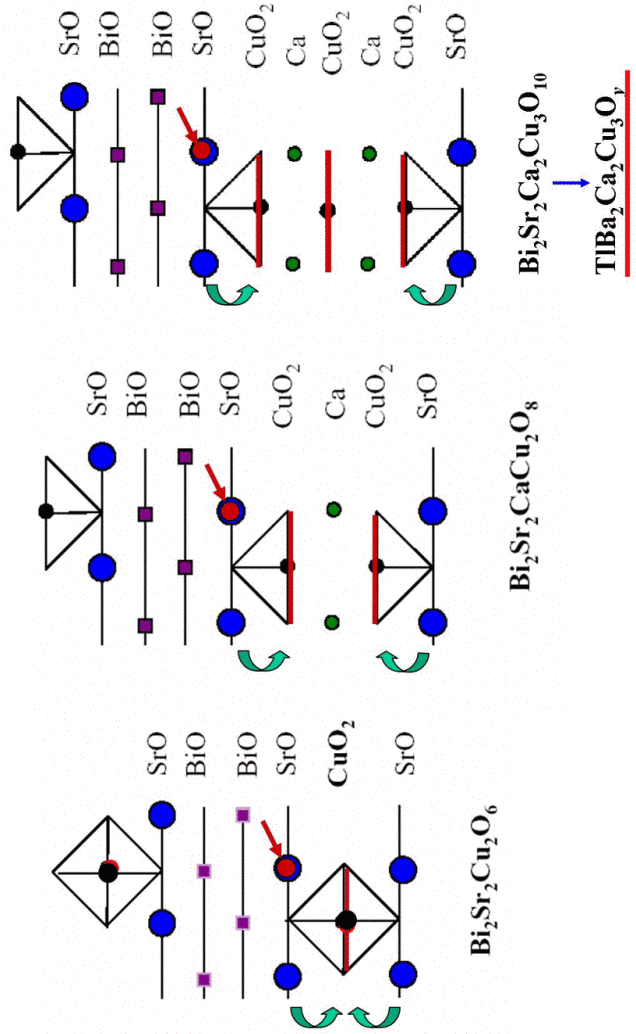
Out-of-plane disorder → *Increase of PG area* → *Decrease in ρ_S*

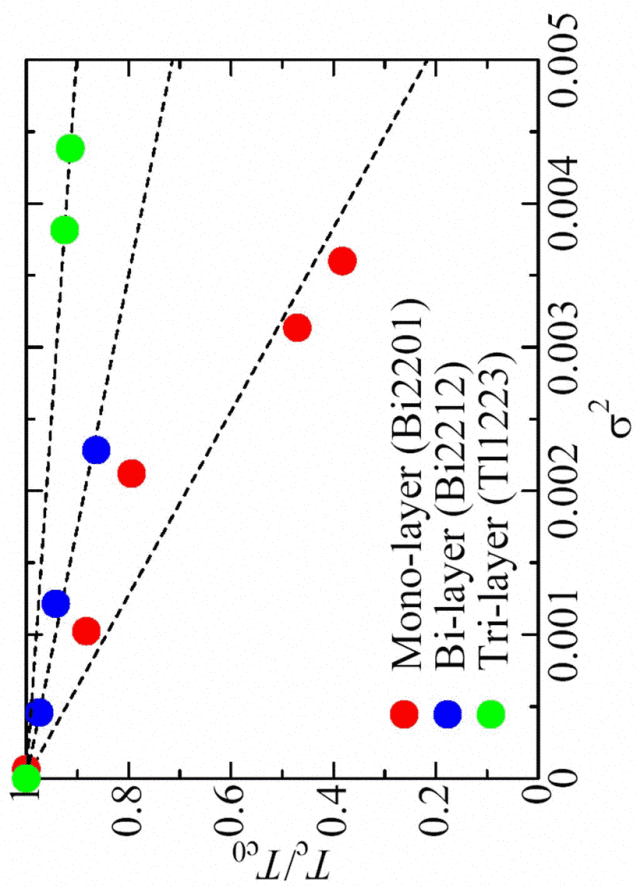
PG is stabilized

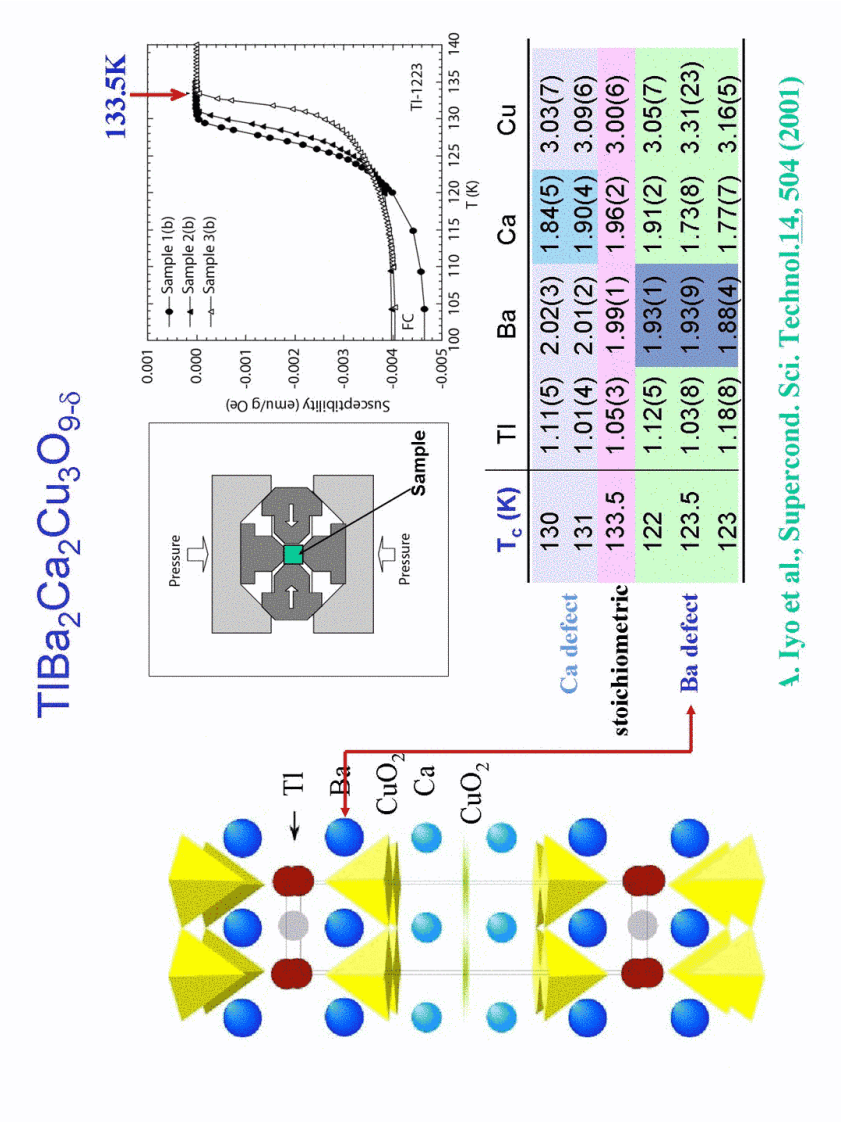
n ; constant




SrO
BiO
excess O
BiO
SrO
CuO_2
Ca
CuO_2
SrO
$Bi_2Sr_2CaCu_2O_8$
SrO
BiO
BiO
SrO
CuO_2
SrO
$Bi_2Sr_2Cu_2O_6$


SrO
BiO
BiO
SrO
CuO_2
SrO
$Bi_2Sr_2Cu_2O_6$
SrO
BiO
BiO
SrO
CuO_2
Ca
CuO_2
SrO
$Bi_2Sr_2CaCu_2O_8$
SrO
BiO
BiO
SrO
CuO_2
Ca
CuO_2
Ca
CuO_2
SrO
$Bi_2Sr_2Ca_2Cu_3O_{10}$
$TlBa_2Ca_2Cu_3O_y$



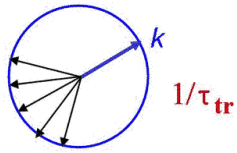


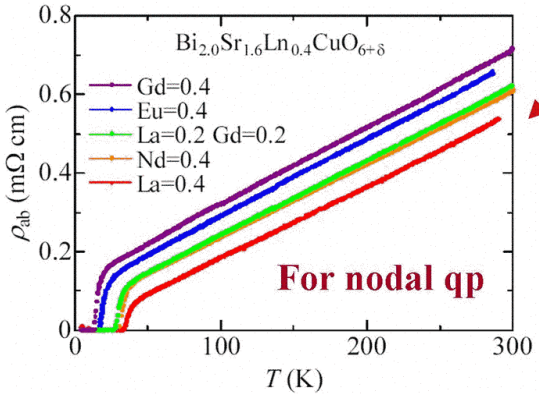
T_c (K)	Tl	Ba	Ca	Cu
130	1.11(5)	2.02(3)	1.84(5)	3.03(7)
131	1.01(4)	2.01(2)	1.90(4)	3.09(6)
133.5	1.05(3)	1.99(1)	1.96(2)	3.00(6)
122	1.12(5)	1.93(1)	1.91(2)	3.05(7)
123.5	1.03(8)	1.93(9)	1.73(8)	3.31(23)
123	1.18(8)	1.88(4)	1.77(7)	3.16(5)

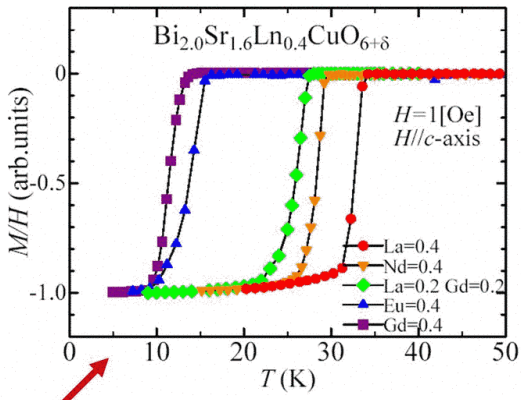
$Bi_{2.0}Sr_{1.6}Ln_{0.4}CuO_{6+\delta}$

Elastic forward scattering

(Scalapino, Zhu, Hirschfeld)





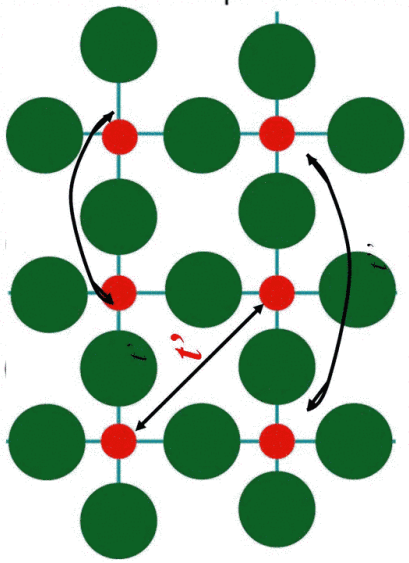


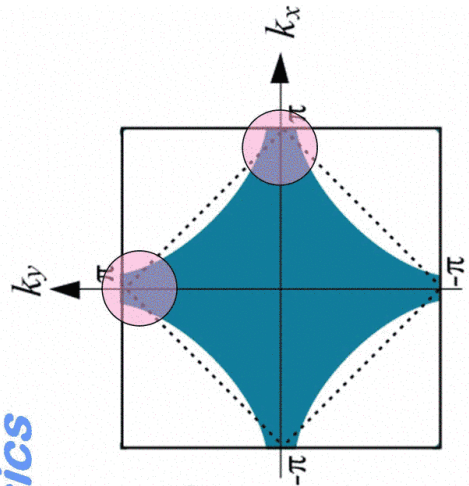
Serious effect on the electronic state near antinodes / antinodal qp

How does disorder influence the electronic state near antinodes ?

What is a parameter that influences ρ_S (or T_c) without changing n ?

t' Physics



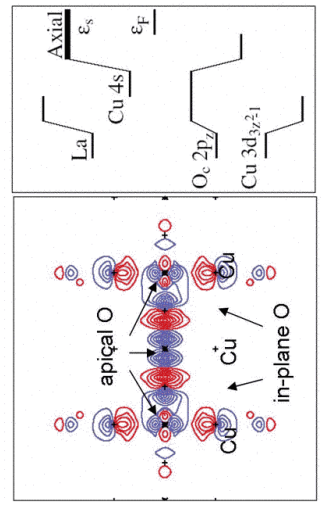


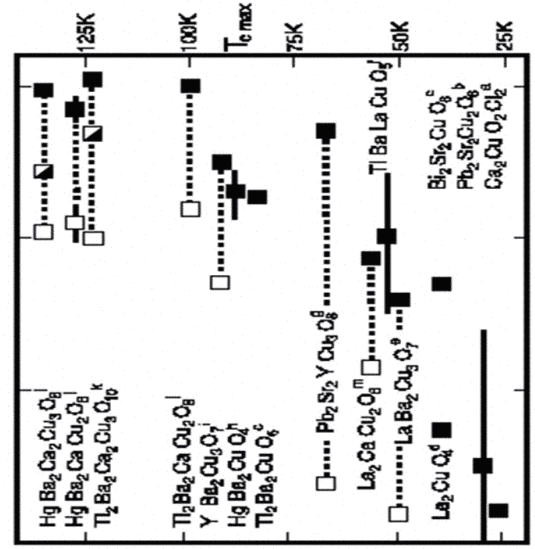
$$E(\boldsymbol{k}) = -2t(\cos k_x a + \cos k_y a) - 4t' \cos k_x a \cos k_y a - 2t''(\cos 2k_x a + \cos 2k_y a) + E_0$$

$$E(\pi,0) \propto t' + \ldots$$

Role of apical oxygen

Hole wavefunction in CuO_2 plane





Effects of apical oxygen on t'

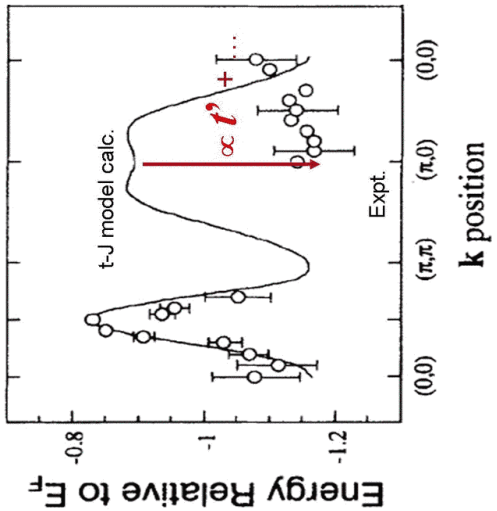
short ← **Cu-apical O distance** → **long**

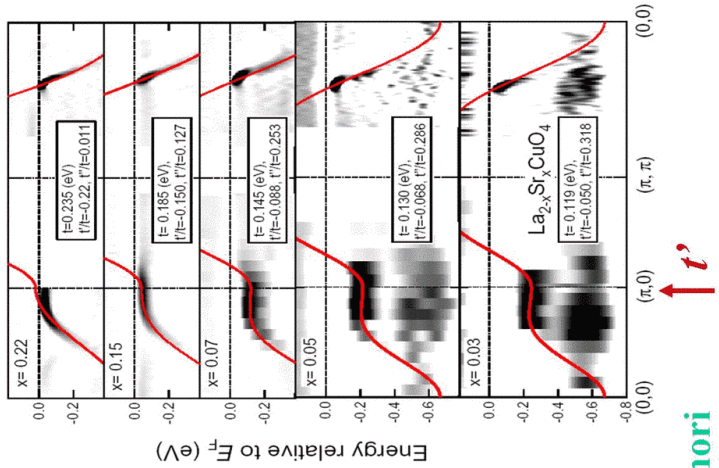
strong ← influence of Cu 4s, O 2p_z → weak

small ← $|t'|$ → **large**

$|t'|$ *small* $|t'|$ *large*

E. Pavarini et al., PRL '01

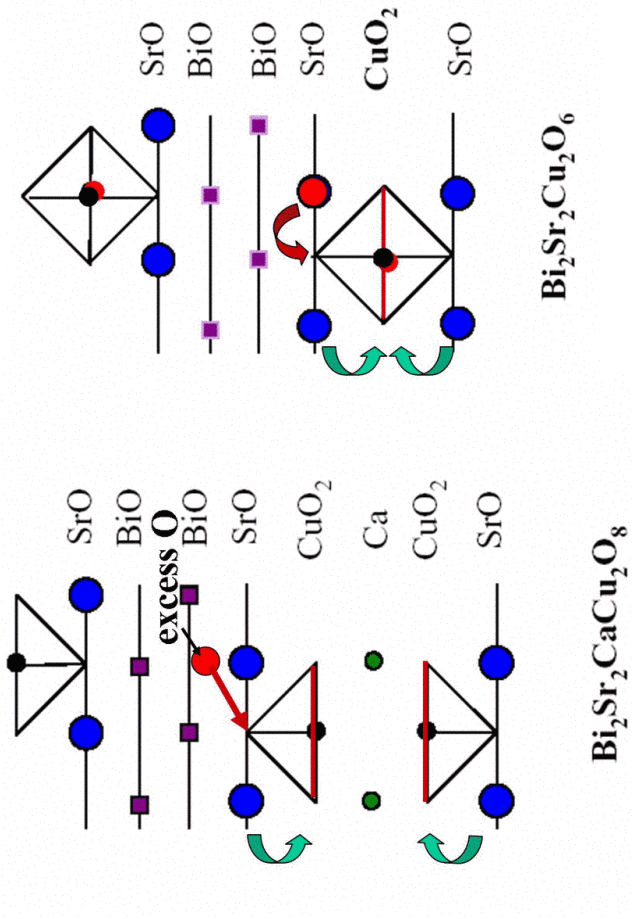




Band dispersion in $Sr_2CuCl_2O_2$

B.O. Wells et al. PRL '95

Fujimori



Possible Scenario

Out-of-plane disorder → *Local lattice distortion* → *Local t' modulation* → *Increase of PG area* → *Decrease in* ρ_S

Source of inhomogeneity

n ; constant

Nunner, Hirschfeld; cond-mat 0504693

t': pairing interacton