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IAEA International Atomic Energy Agency

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Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

Neutron and X-Ray scattering study on cuprate superconductors.

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Trieste Aug.12 2008

Cuprate superconductivity and spin fluctuations

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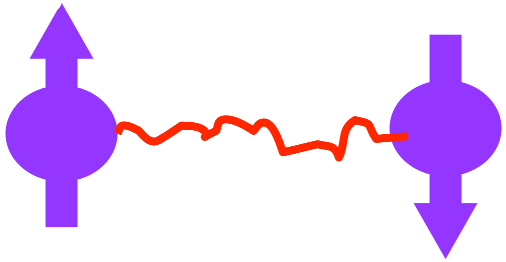
Science 317 June 2007

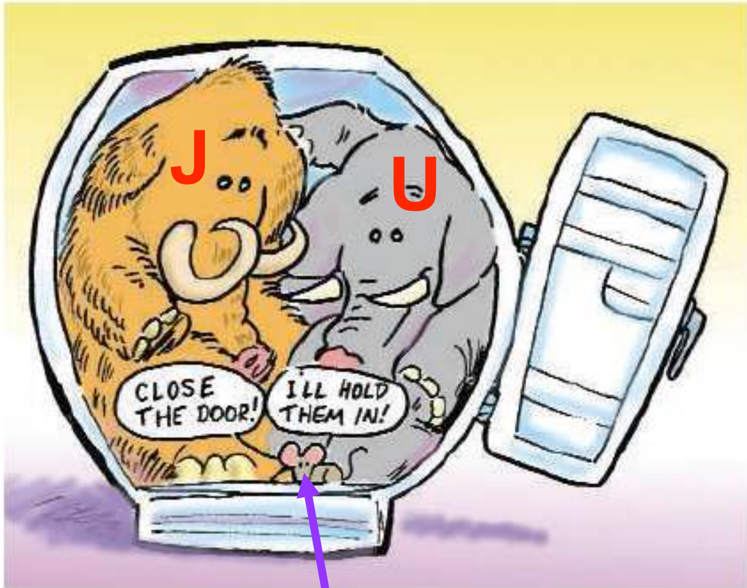
PHYSICS

Is There Glue in Cuprate Superconductors?

Philip W. Anderson

Many theories about electron pairing in cuprate superconductors may be on the wrong track.



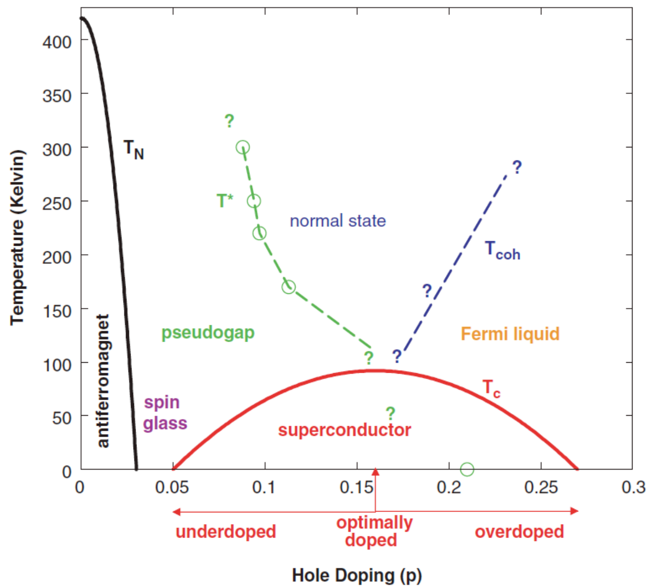


“We have a mammoth and an elephant in our refrigerator—do we care much if there is also a mouse?”

spin fluctuation ?
electron-phonon ?

High T_c cuprate superconductivity is still one the attractive field of material science

Figure 1 in M. Eschrig Adv. Phys. 55(2006)



many ?s in the phase diagram

Contents

1) Magnetic fluctuation of p-type cuprates (10min.)

2) Magnetic fluctuation of n-type cuprates (15min.)

3) "Magnetic" impurity-effect in p-type cuprates (15min.)

4) New pulsed neutron facility in J-PARC (3min.)

Advertisement

Magnetic scattering

$$S^{\alpha\beta}(\boldsymbol{Q},\omega) = \int_{-\infty}^{\infty} dt\, e^{-i\omega t} \sum_r e^{i\mathbf{Q}\bullet\mathbf{r}} \left\langle S_0{}^{\alpha}(0) S_r{}^{\beta}(t) \right\rangle$$

Neutron sees spin-spin correlation (two-particle correlation)

Dynamical magnetic susceptibility

$$\chi''(Q,\omega) = (1 - e^{-\hbar\omega/k_B T}) S(Q,\omega)$$

Local dynamical magnetic susceptibility

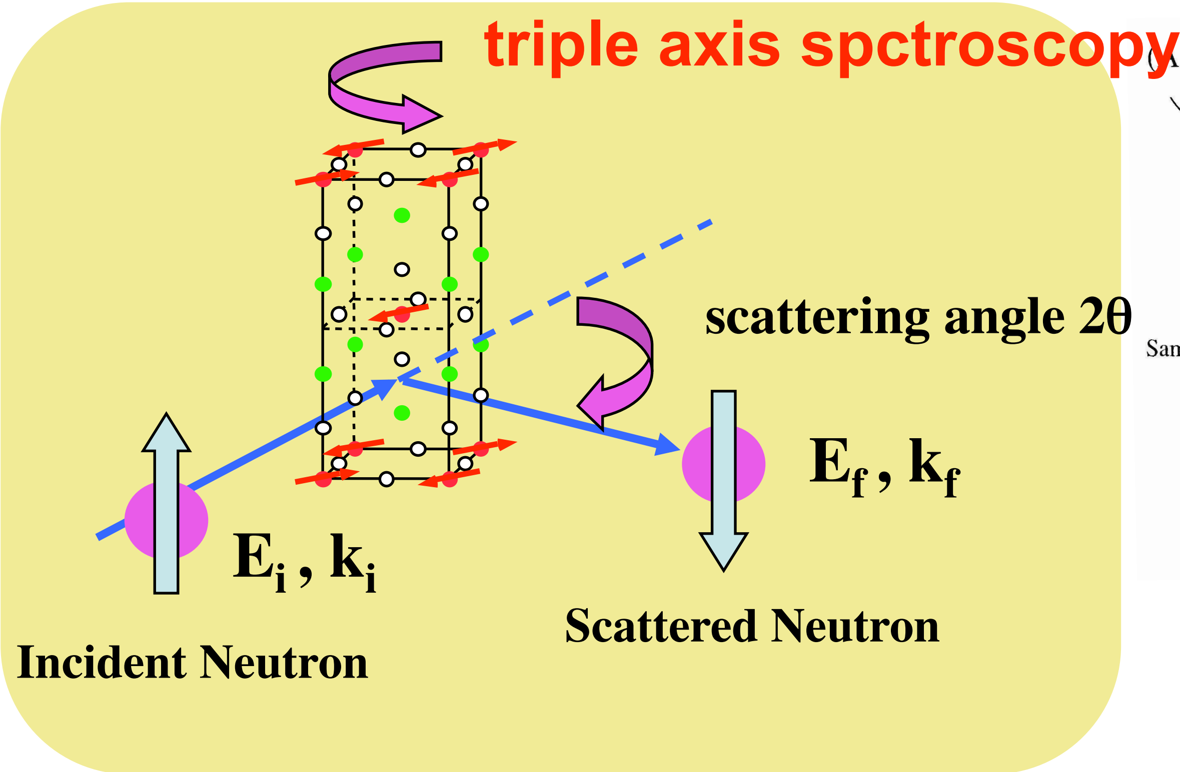
$$\chi''(\omega) = \int_{B.Z.} d\boldsymbol{Q}\, \chi''(Q,\omega)$$

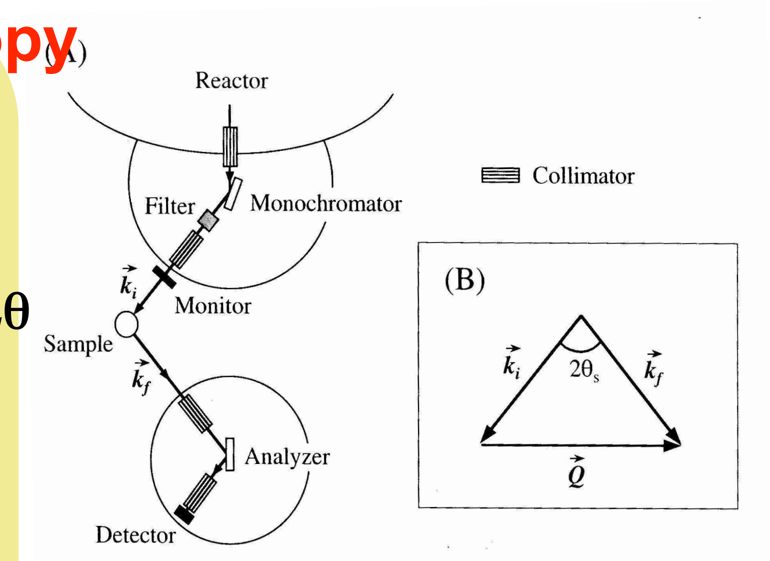
Instantaneous (t=0) spin correlation

$$S(\boldsymbol{Q}) = \int_{-\infty}^{\infty} d\omega S(\boldsymbol{Q},\omega)_{\mathbf{Q}:const.} \approx \int_{-Ei}^{\sim k_B T} d\omega S(\boldsymbol{Q},\omega)_{\mathbf{Q}:const.}$$

$$= \sum_r e^{i\mathbf{Q}\bullet\mathbf{r}} \left\langle S_0{}^{\alpha}(0) S_r{}^{\beta}(t) \right\rangle_{t=0}$$

What is neutron scattering experiment?



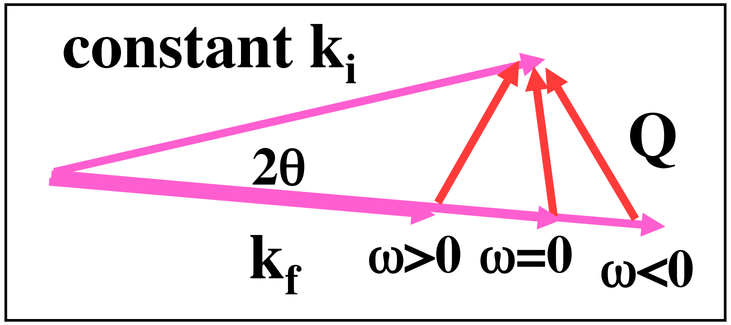


$E_i=(\hbar k_i)^2/2m$

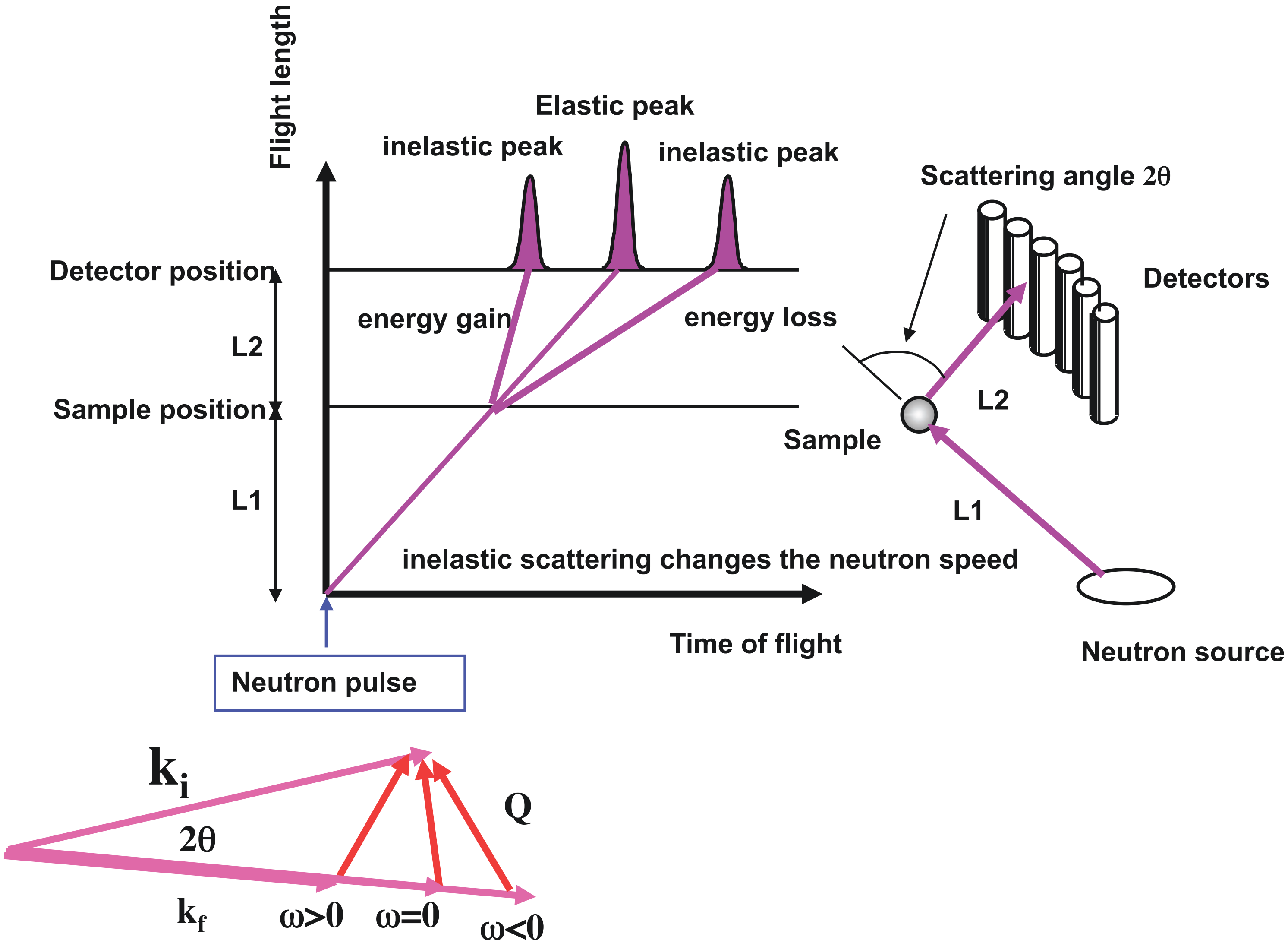
$E_f=(\hbar k_f)^2/2m$

$Q=k_i-k_f$

$\hbar\omega=E_i-E_f$



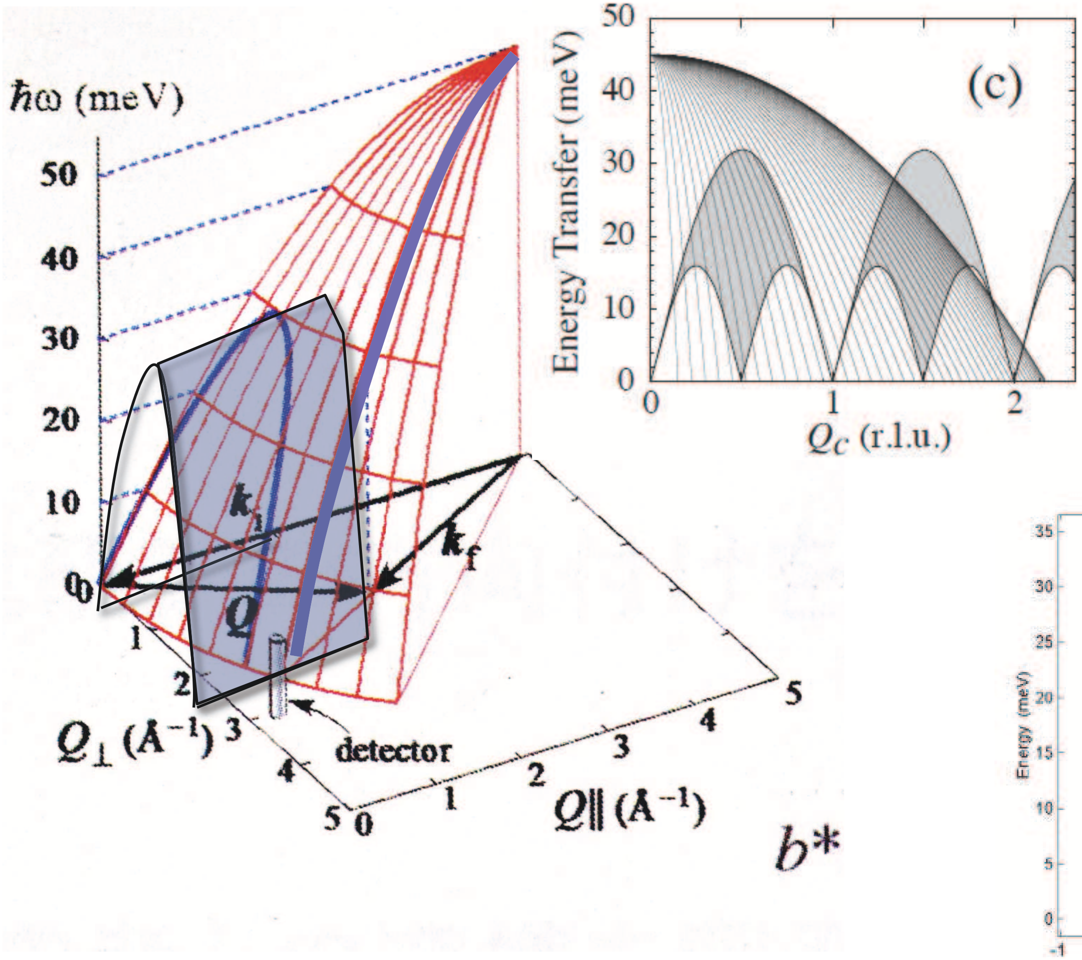
Inelastic scattering by monochromated beam



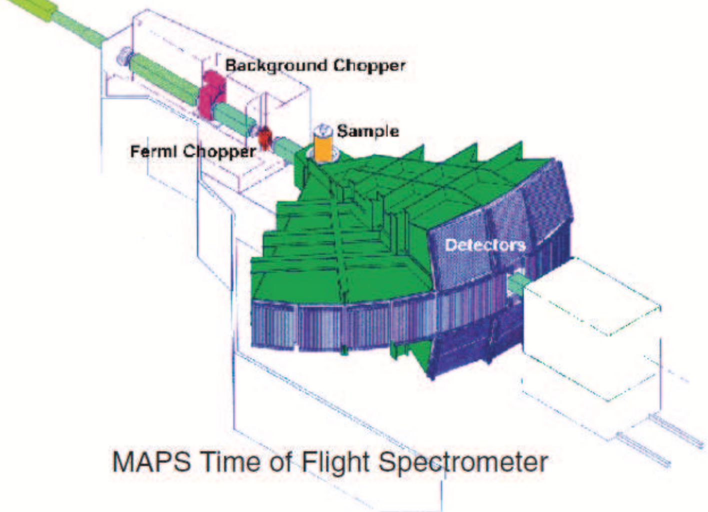
By using TOF method with monochromated beam inelastic signal can be obtained at fixed scattering angle

Scattered neutrons scan along a locus in a (Q,ω) space with a finite resolution

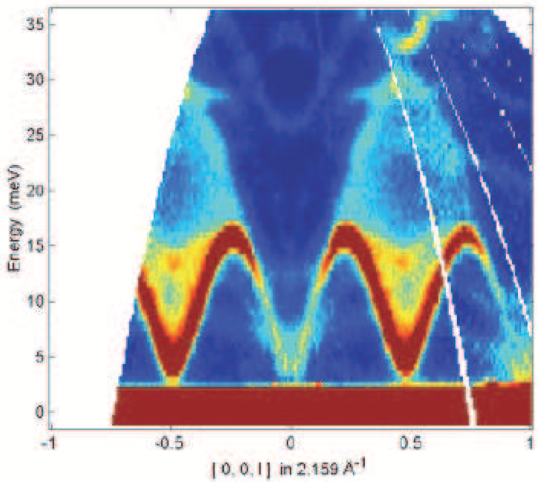
TOF-scan at a fixed scattering angle



Rutherford Appleton Lab.
Pulse neutron source ISIS



MAPS Time of Flight Spectrometer



Contents

1) Magnetic fluctuation of p-type cuprates (10min.)

interpretation of hour-glass type of magnetic excitation spectrum
-doping-induced two energy scales-

2) Magnetic fluctuation of n-type cuprates (15min.)

3) "Magnetic" impurity-effect in p-type cuprates (15min.)

4) New pulsed neutron facility in J-PARC (5min.)

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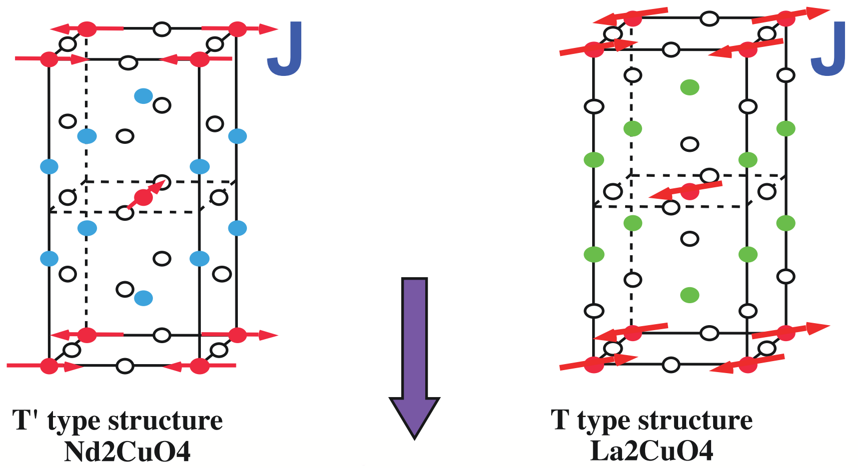
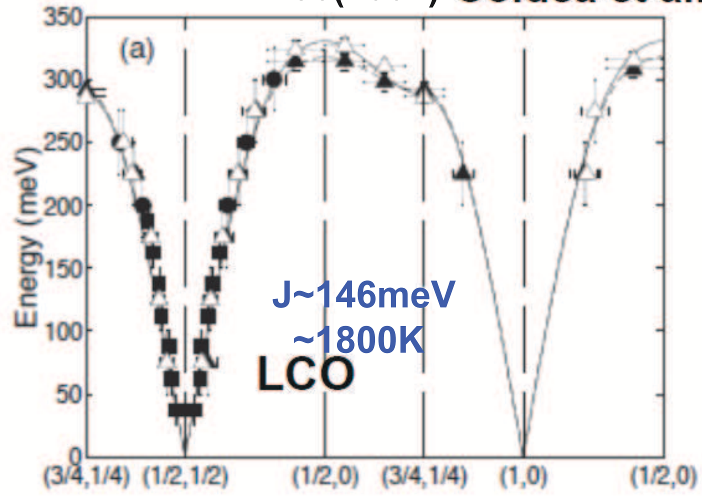
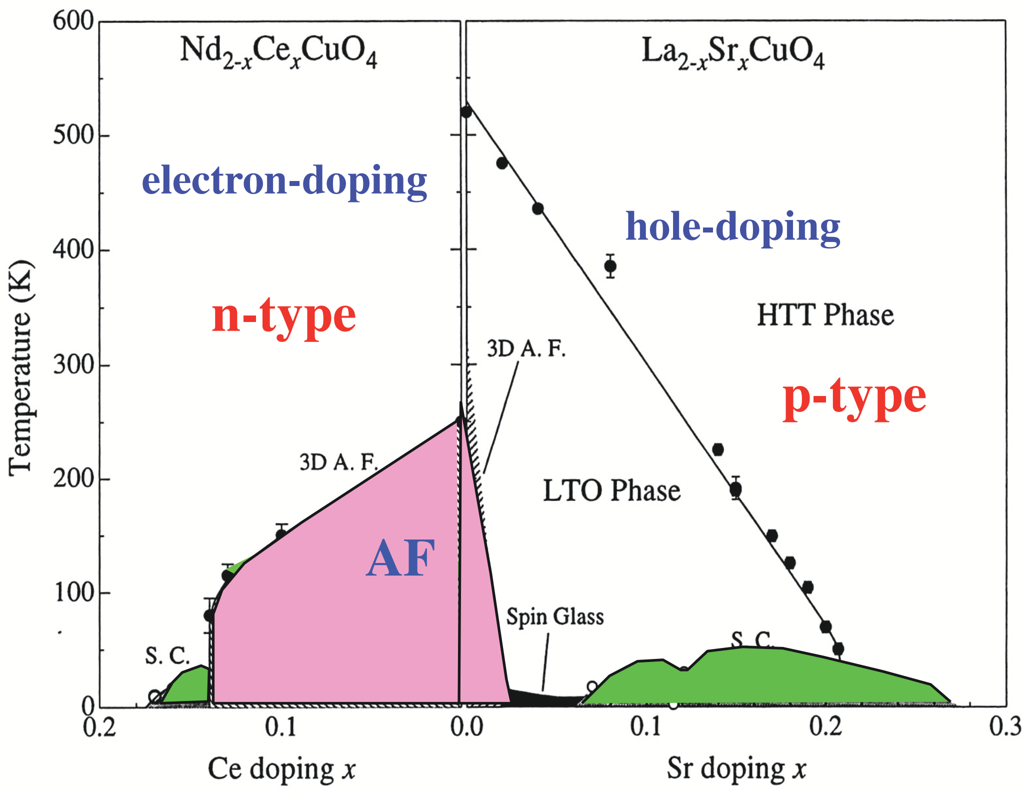
Carrier-doping into Mott insulators induces superconductor

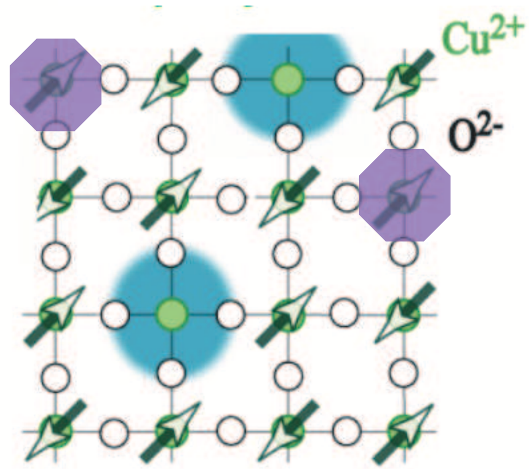


PRL 86(2001) Coldea et al.



J is strong enough to make paring

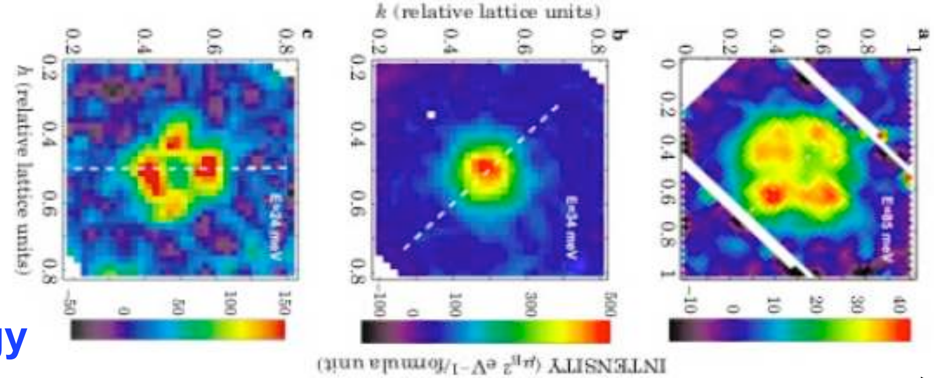




hole: ~O_{2p} orbital
electron: ~Cu_{3d} orbital
(two types of carriers ?)

Hourglass shape of magnetic excitation in superconducting phase

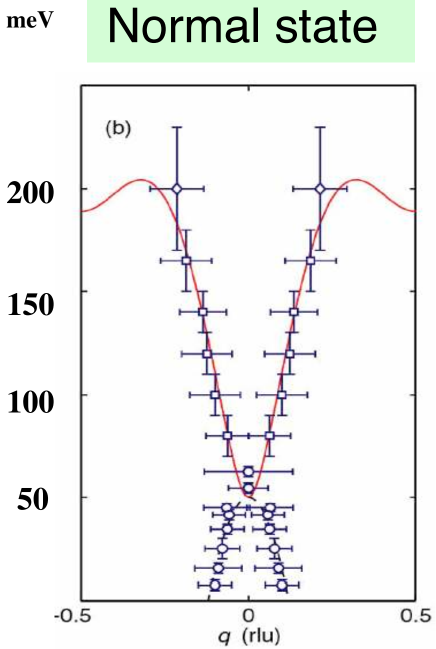
$YBa_2Cu_3O_{6.6}$
Superconducting state

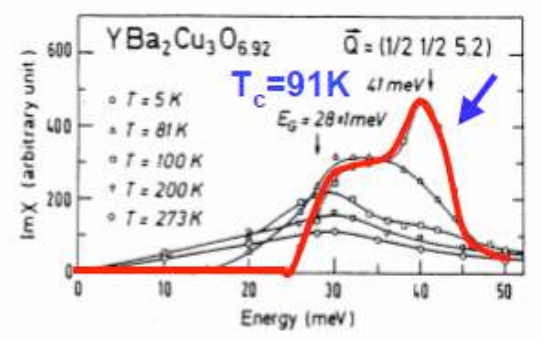


S. Hayden et. al, Nature 429 (2004)

low energy → high energy

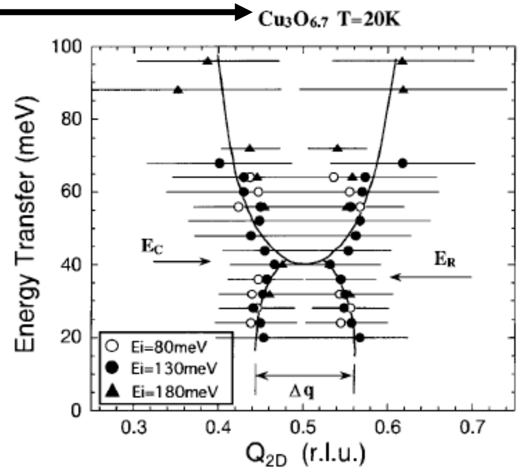
$La_{2-x}Ba_xCuO_4$
x = 1/8
Normal state





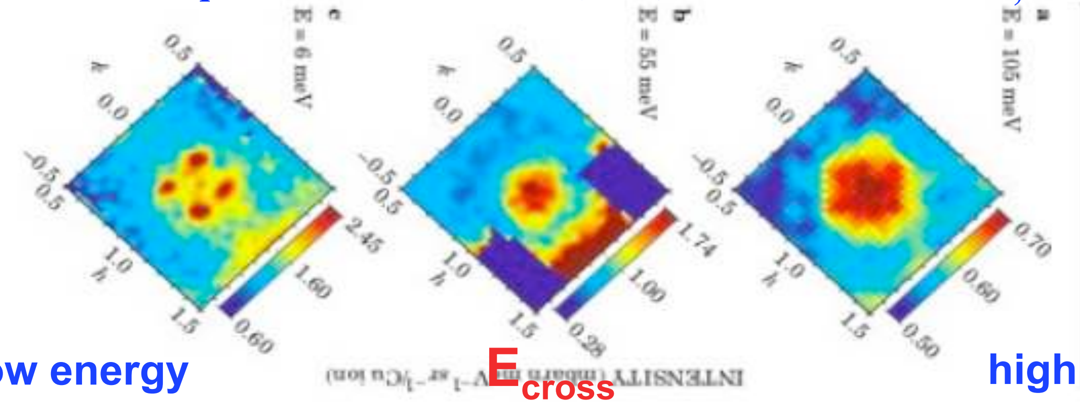
J. Rossot-Mignod et al., Physica C ('91)

E_{res}/E_{cross}



Arai et al., PRL(1999)

J.M. Tranquada et al. Nature 429 (2004)



E_{cross}

low energy → high energy

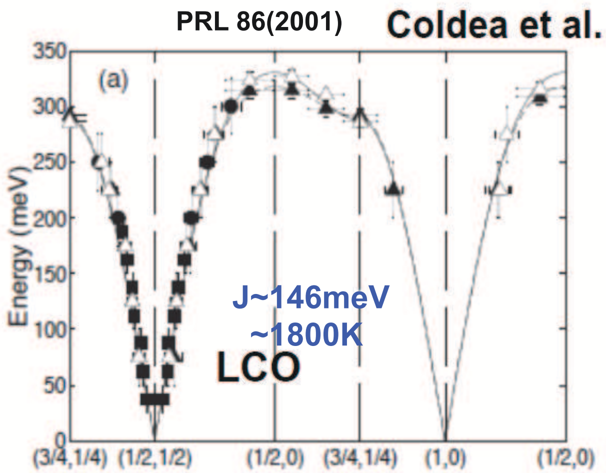
Our interpretation of hour glass type magnetic excitation

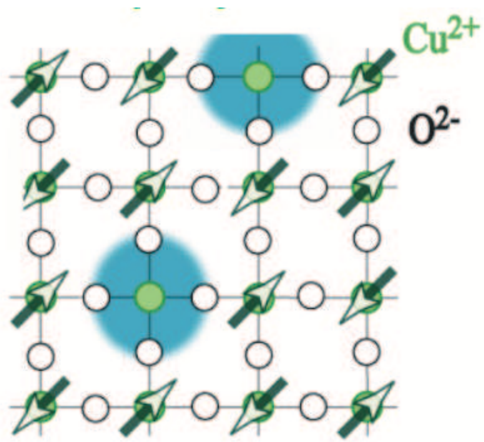
Two energy scales E_{cross} and J_{eff} can be defined

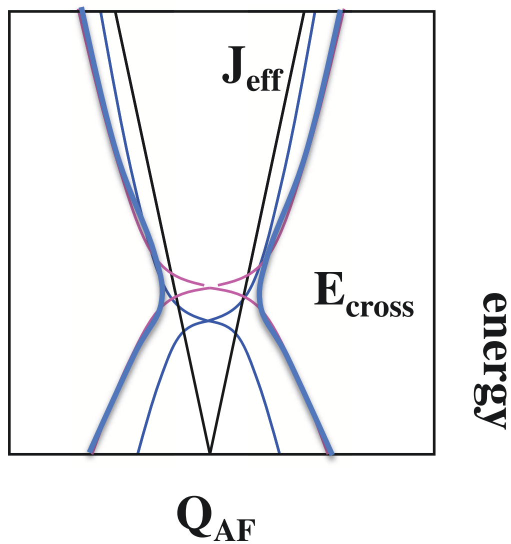
E_{cross} is the crossing energy between the downward and upward excitation. In YBCO, Bi2212, E_{cross} nearly corresponds to resonance peak energy.

J_{eff} is defined from the upward excitation.

E_{cross} (J_{eff}) decreases (increases) with decreasing doping and is continuously connected to the spin excitation of undoped Mott insulator

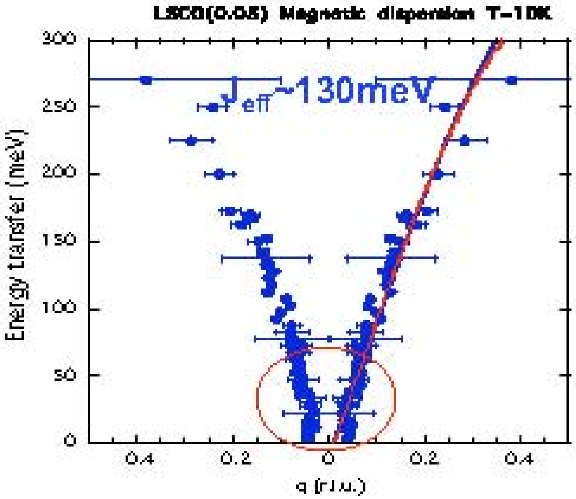


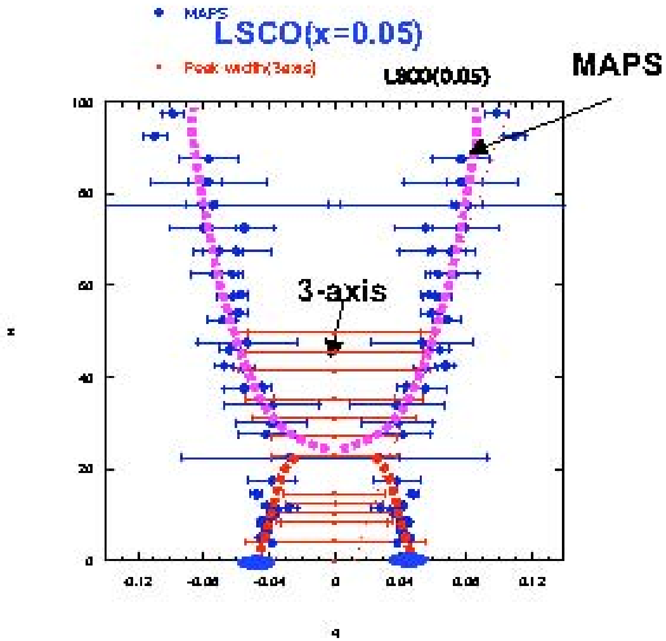




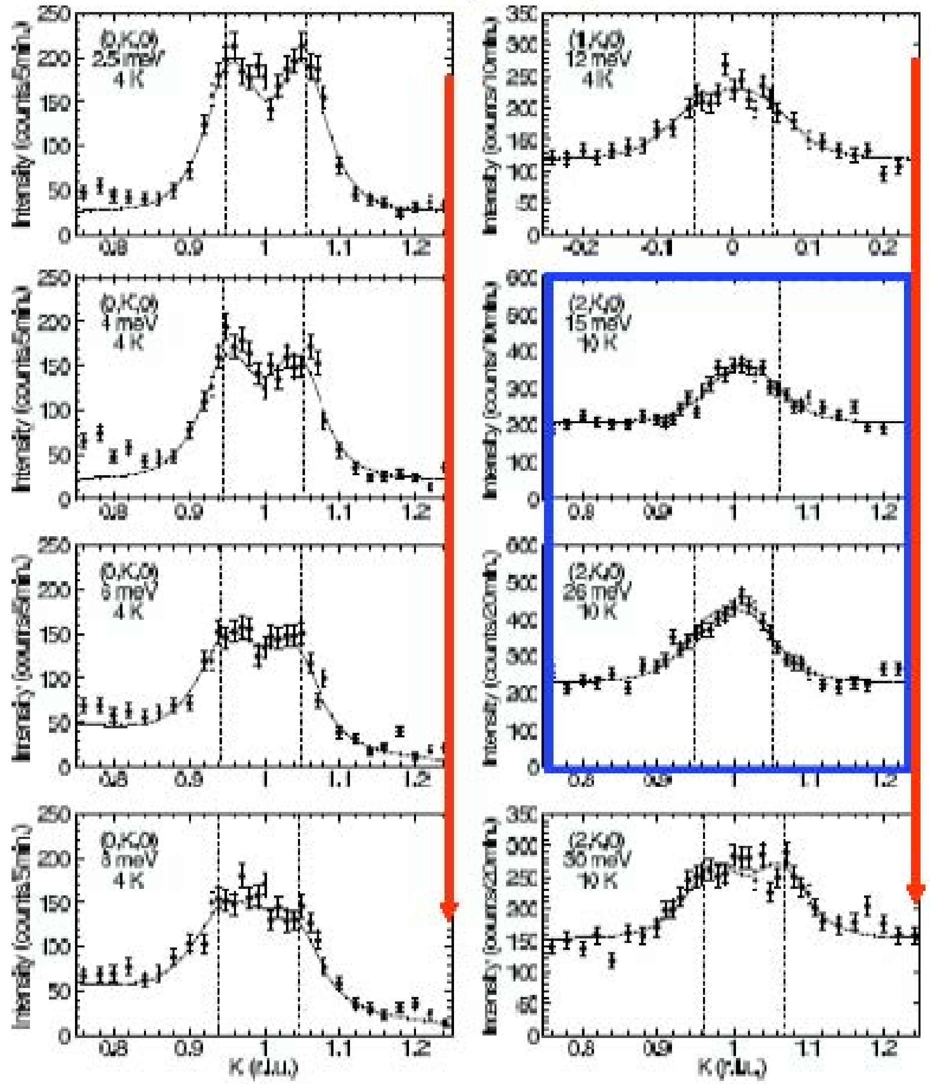
With dilute doping spin excitation is modified at low energy region

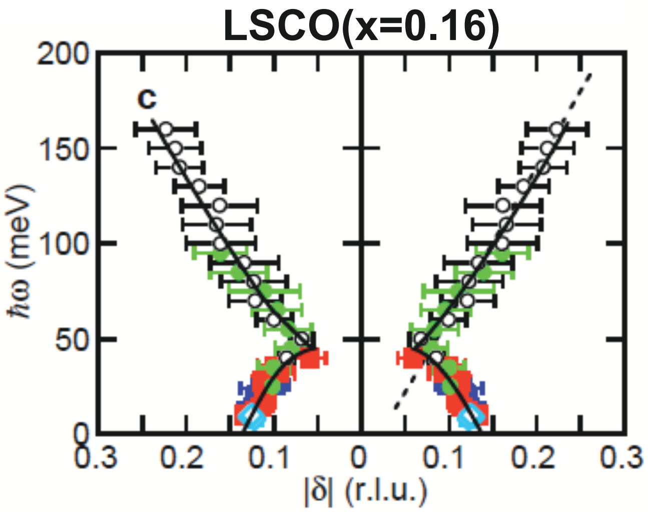
E_{cross}~20meV



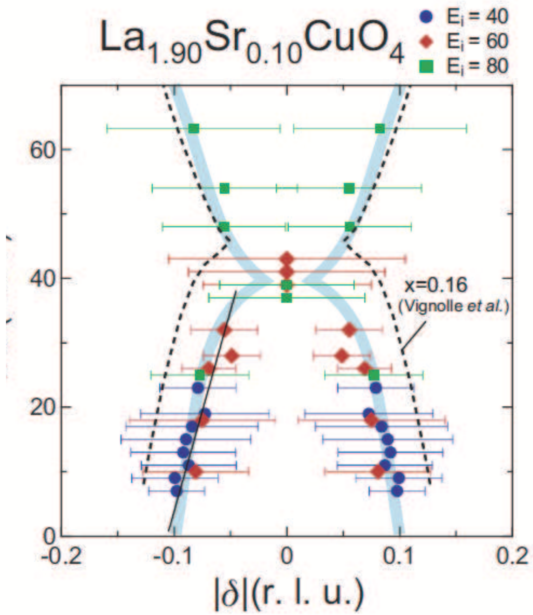


LSCO(x=0.04)

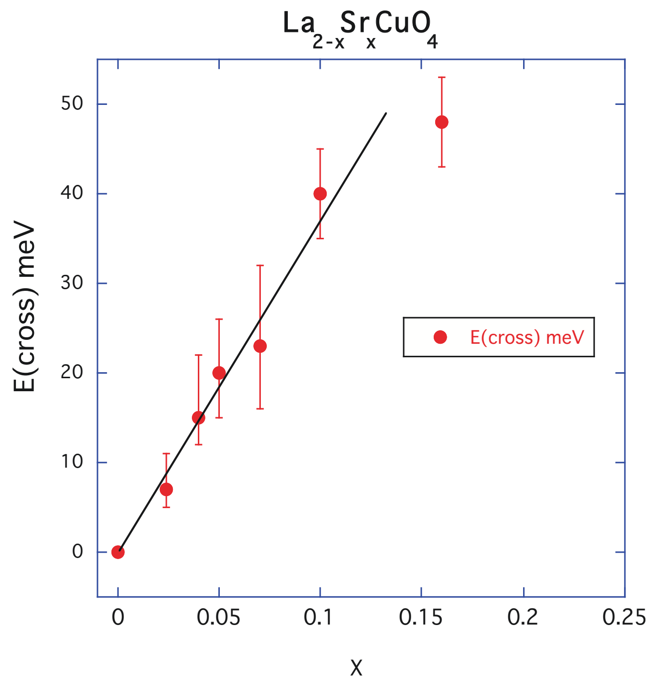


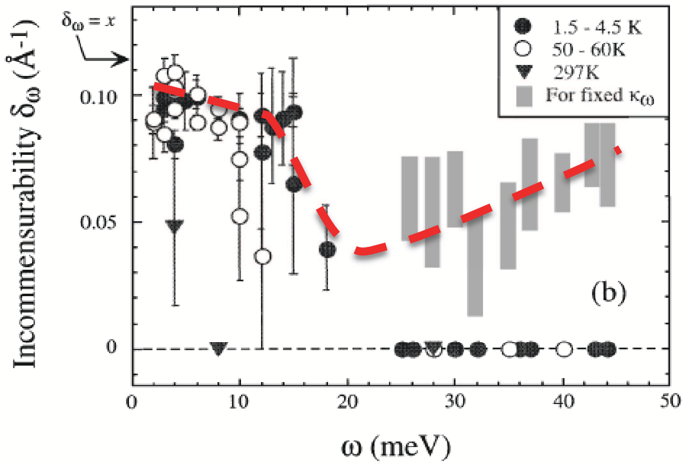


Vignolle et al.(2007)



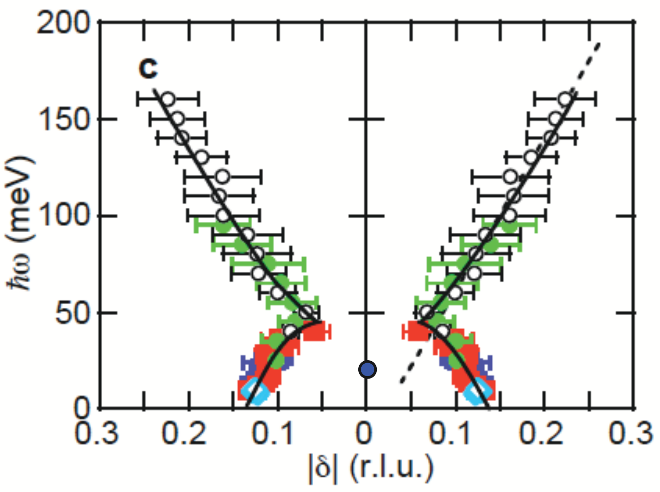
Kofu et al.



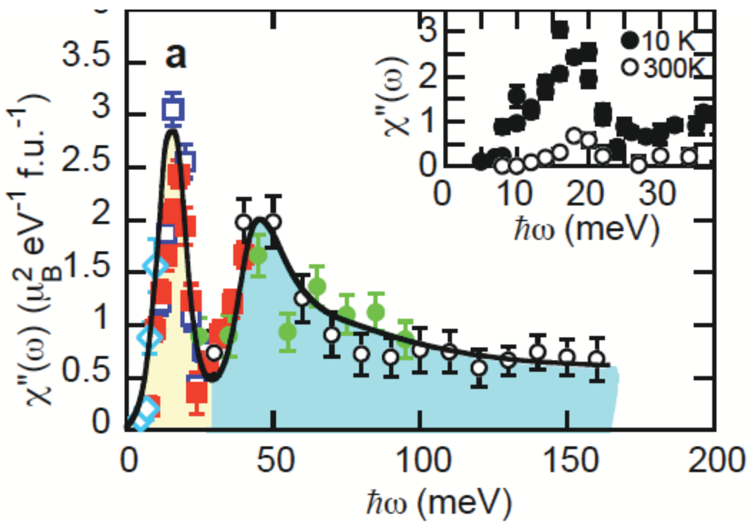


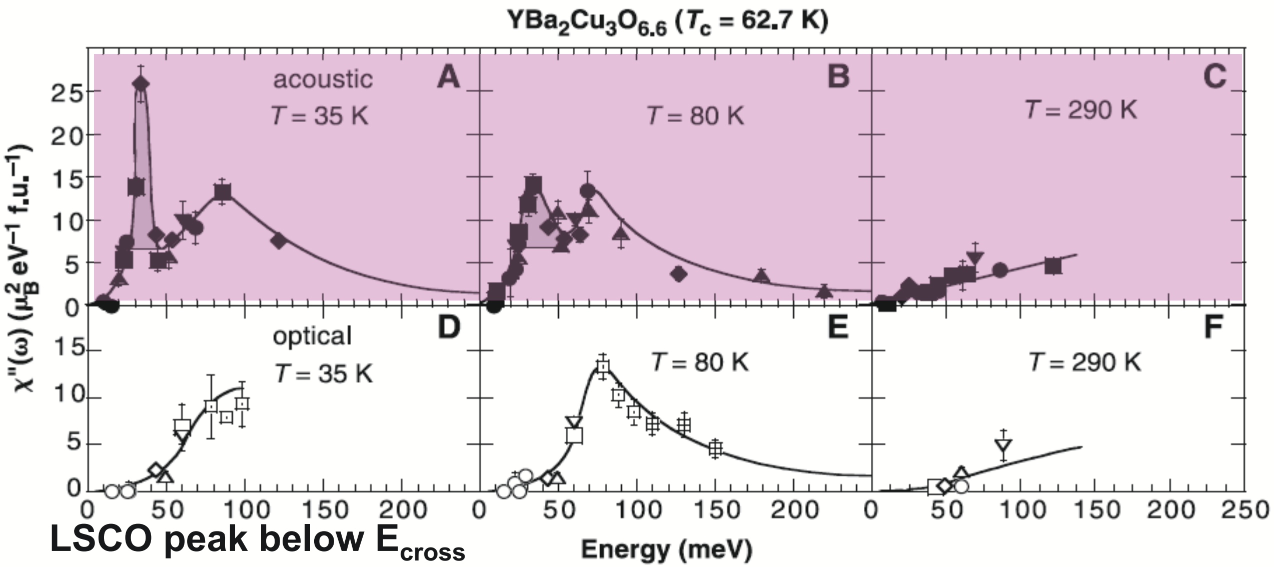
Similarity between LSCO(optimally doped) and YBCO(underdoped)

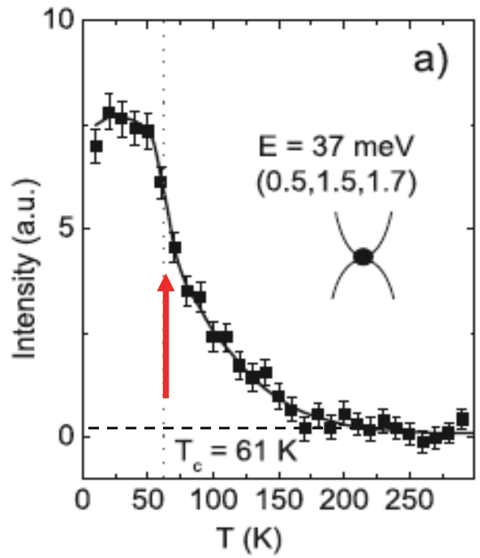
B. Vignolle et al., cond-mat/0701151



LSCO(x=0.16)





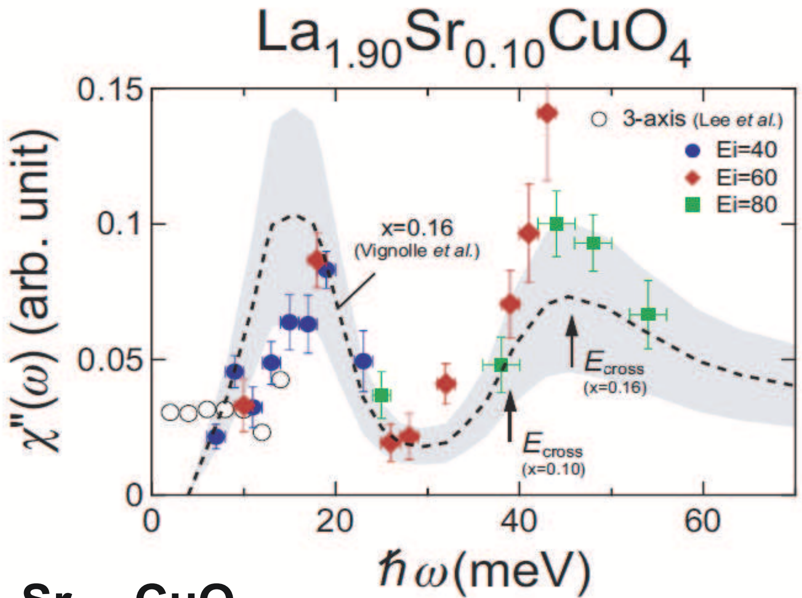


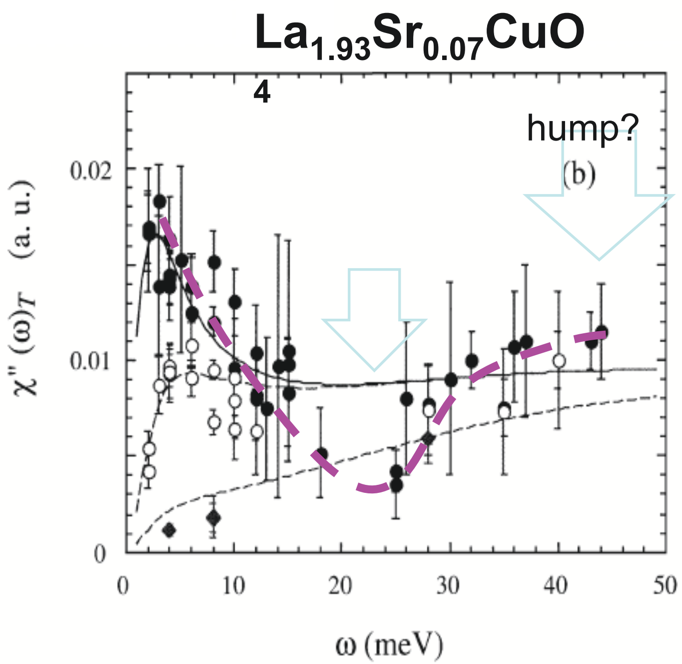
LSCO peak below E_{cross}
YBCO peak near E_{cross}

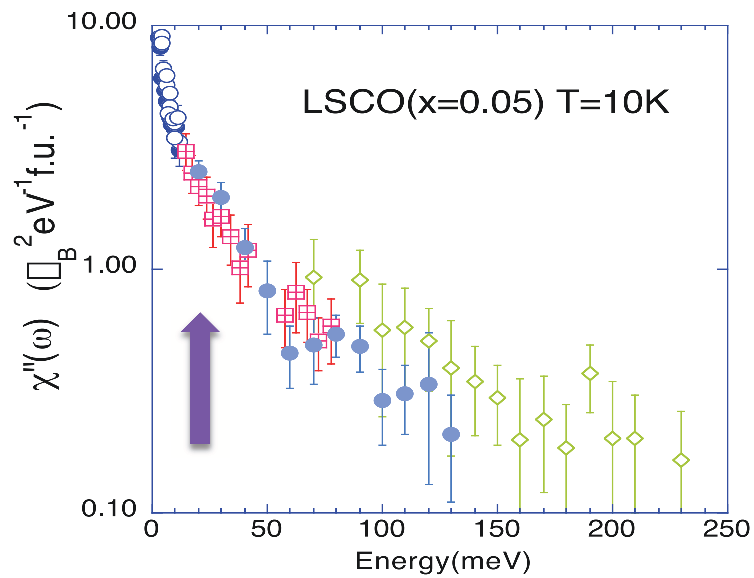
P. Dai et al., Science (1999)

V. Hinkov et al., cond-mat/0601048

E_{cross} does not correspond to the hump energy in $\chi''(\omega)$



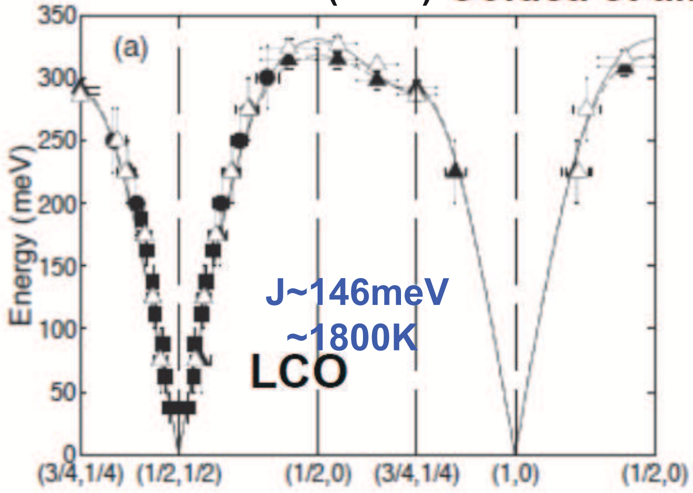


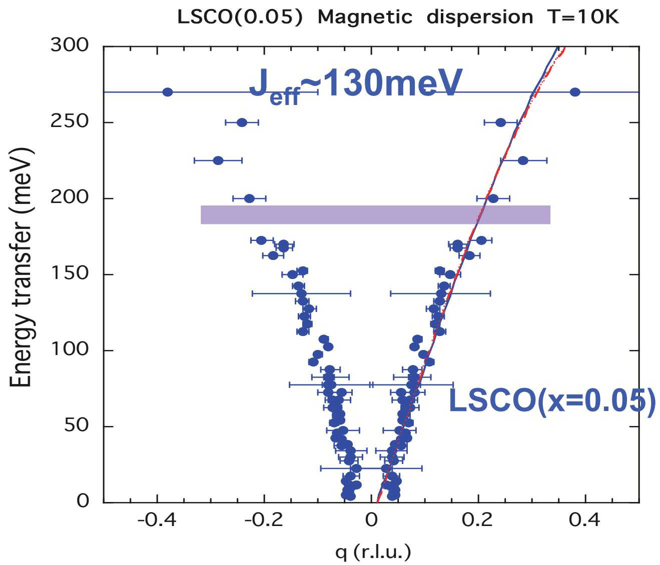


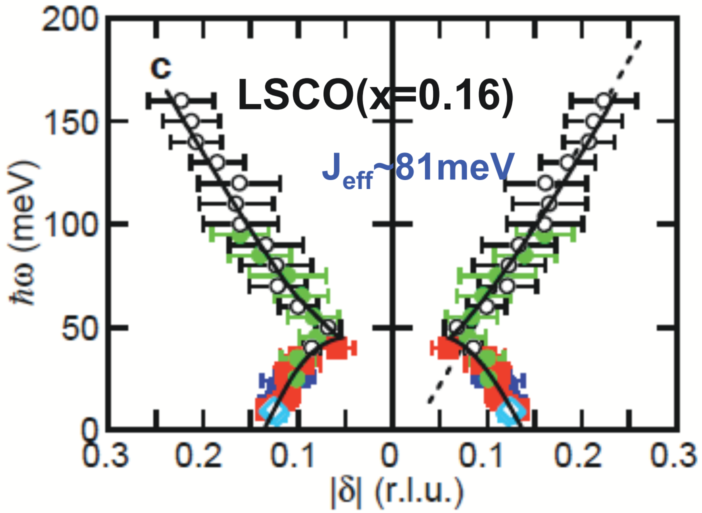
We can also define higher energy scale : renormalized J, J_{eff}

J_{eff} decreases with increasing doping

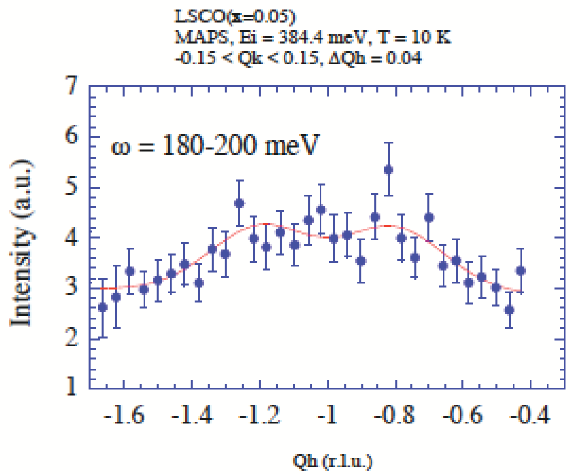
PRL 86(2001) Coldea et al.

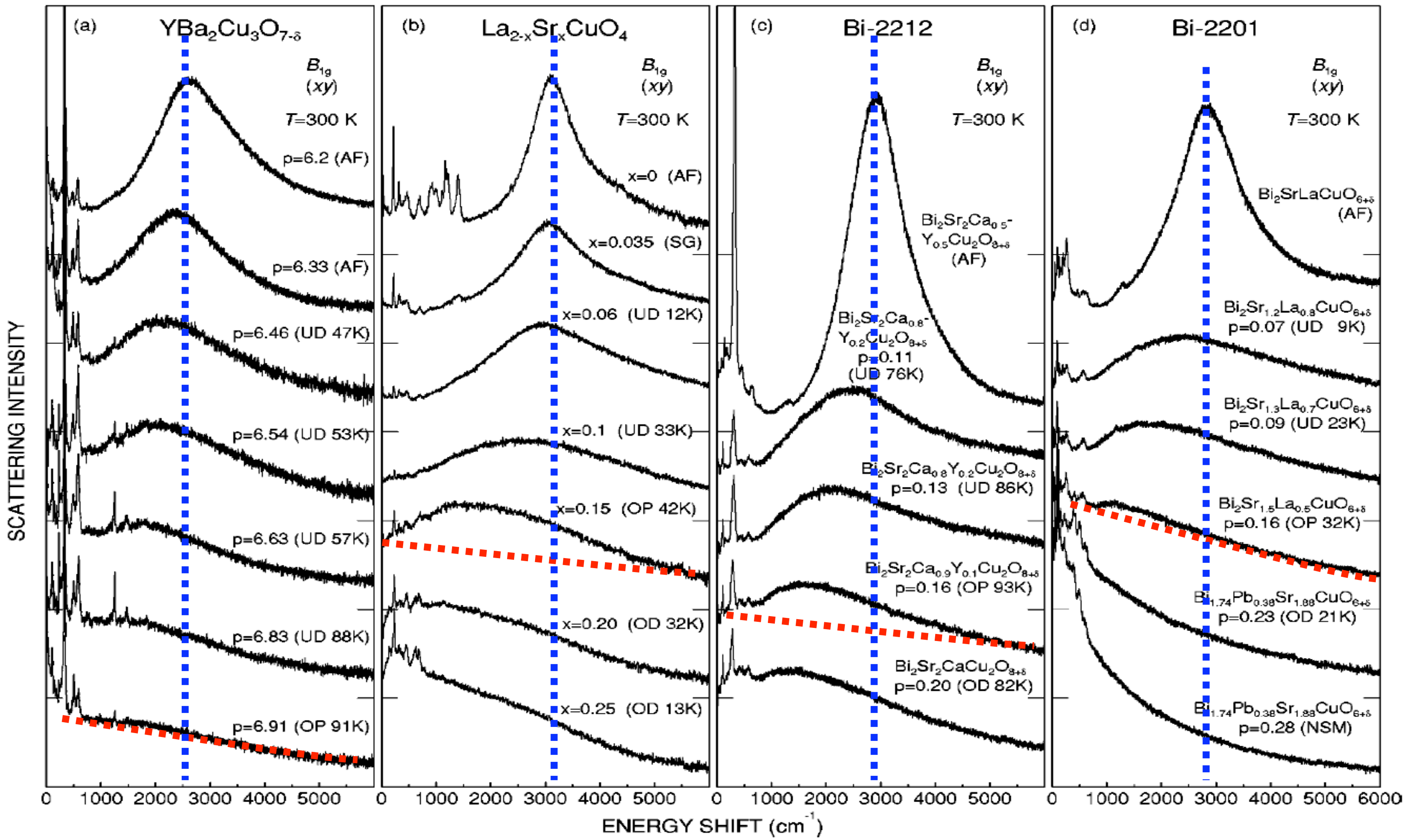






Vignolle et al.(2007)





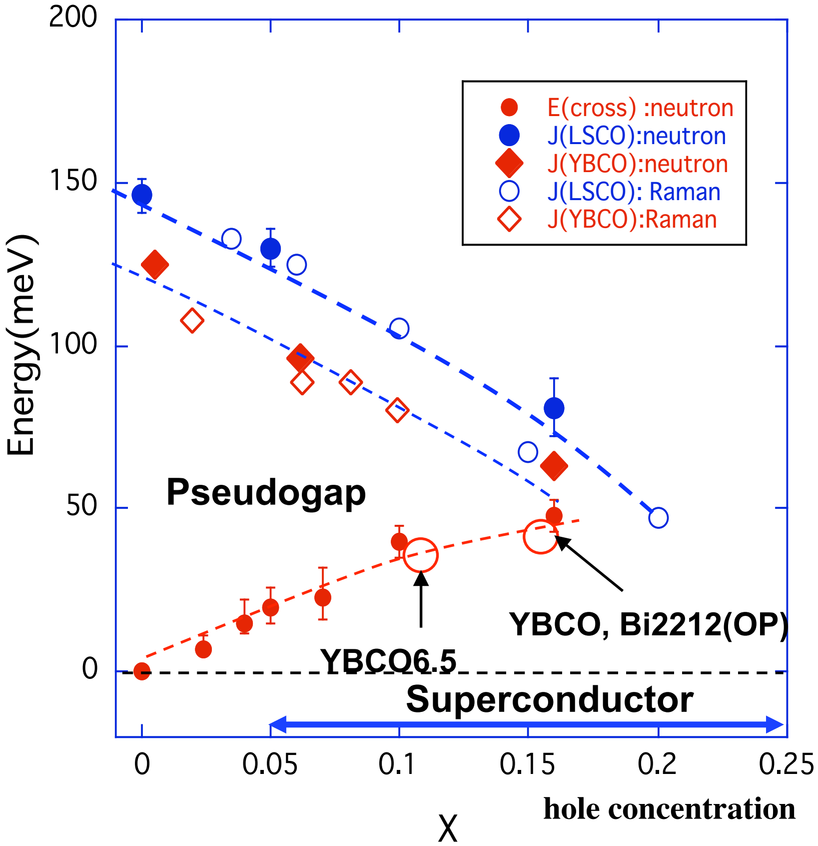
Sugai et al., PRB(2003)

Peak position of two-magnon scattering is proportional to renormalized J(x)
---> J(x) well corresponds to J_{eff} by neutron scattering

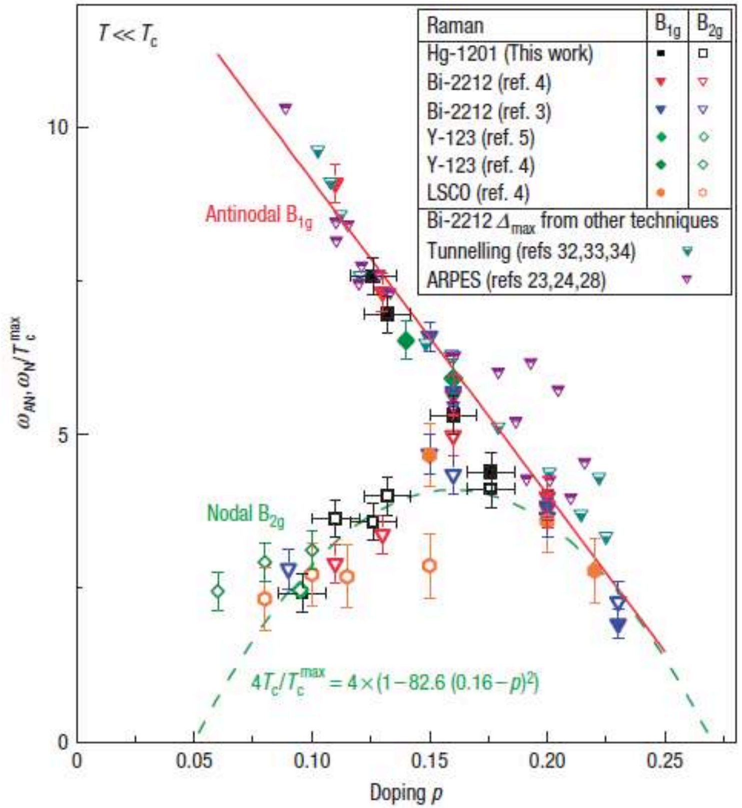
Spin dynamics

Two energy scales in charge dynamics

Doping dependence of E_{cross} and J_{eff}



Tacon et al., Nature Physics 2(2006)



Contents

1) Magnetic fluctuation of p-type cuprates (10min.)

2) Magnetic fluctuation of n-type cuprates (15min.)

doping dependence in the overdoped superconducting phase

3) "Magnetic" impurity-effect in p-type cuprates (15min.)

4) New pulsed neutron facility in J-PARC (5min.)

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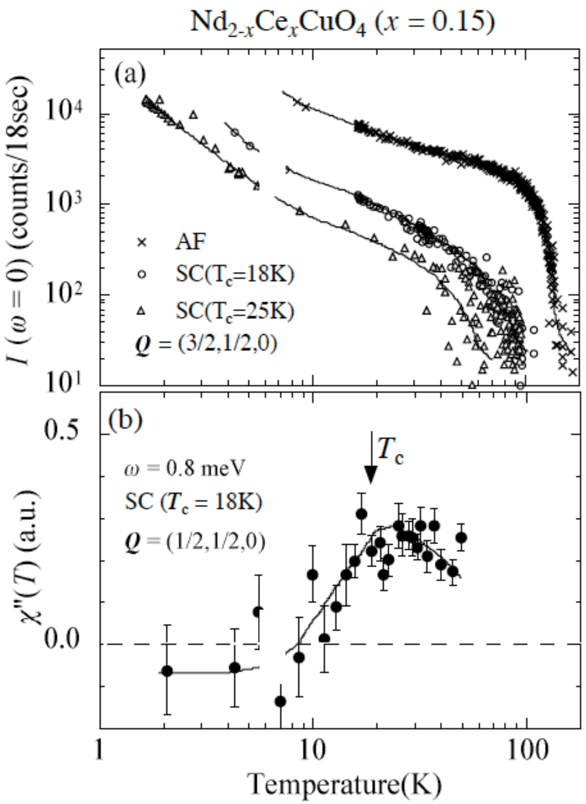
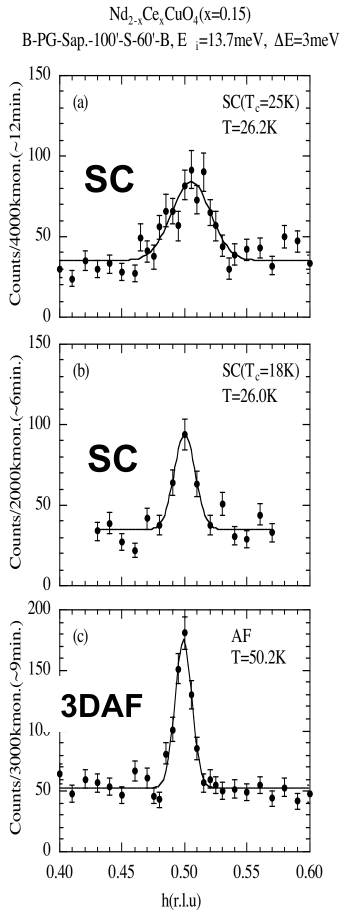
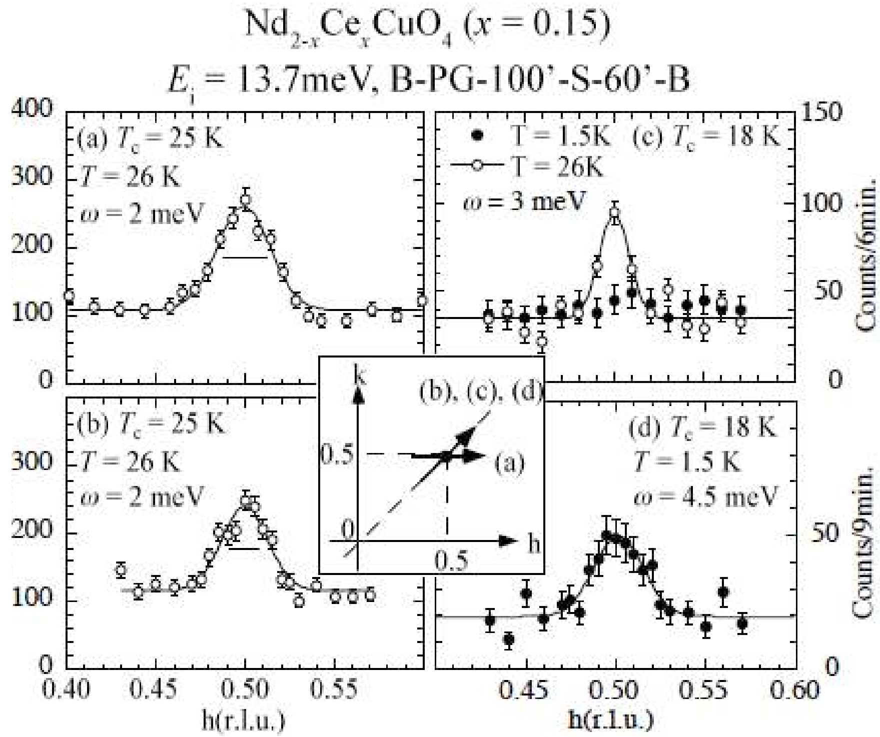
n-type cuprates : SC and AF ordered phases are touched

commensurate spin correlation in both SC and AF phase







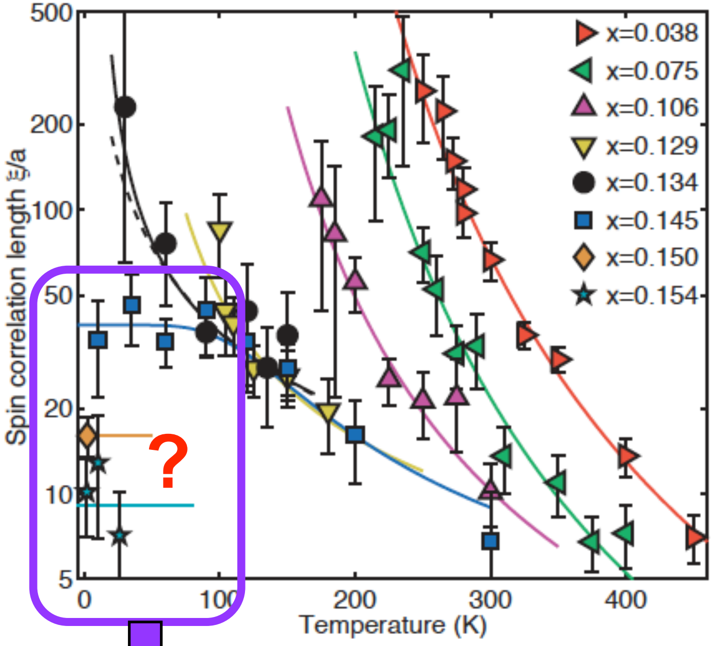
Yamada et al., PRL 90(2003)

Two types of spin fluctuations in n-type cuprate NCCO

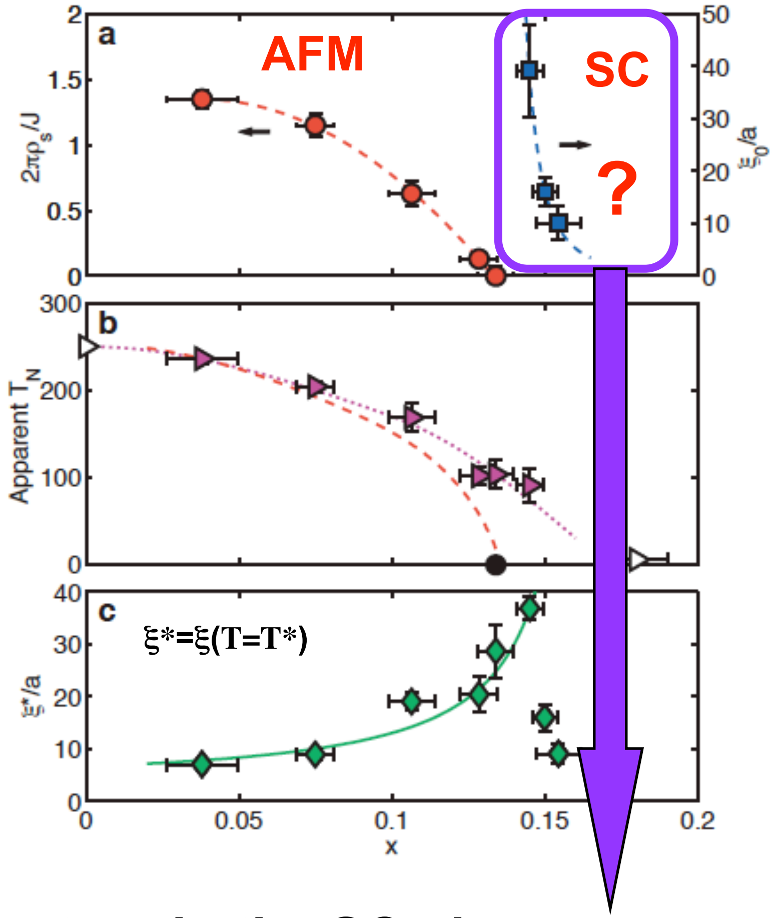
J_{eff} from instantaneous spin correlation length in paramagnetic state

$$\xi(x,T) = A(x)\exp(2\pi\rho_s(x)/T)$$

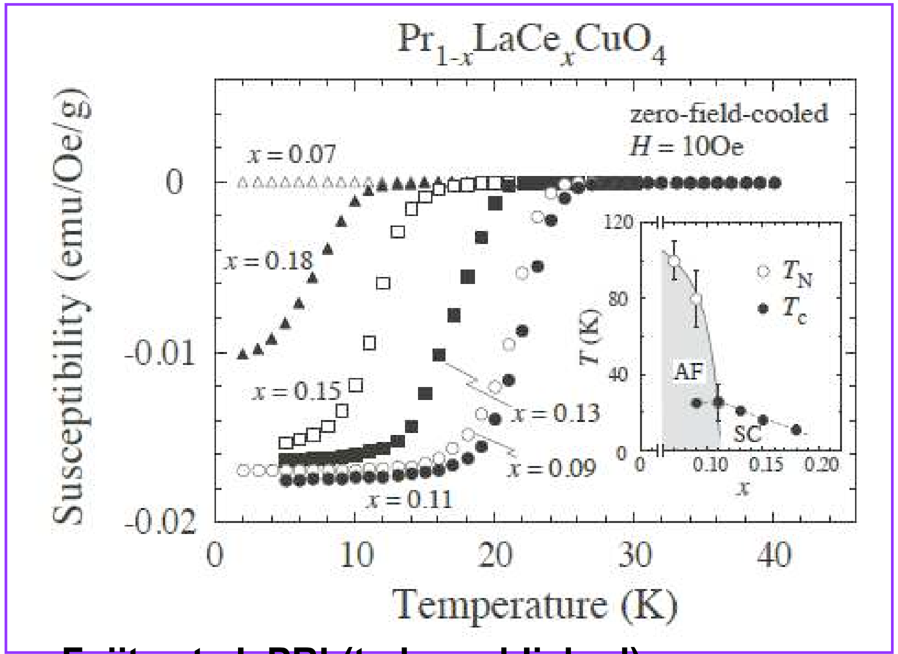
$\rho_s(x)$: **spin stiffness ∝ J_{eff}**



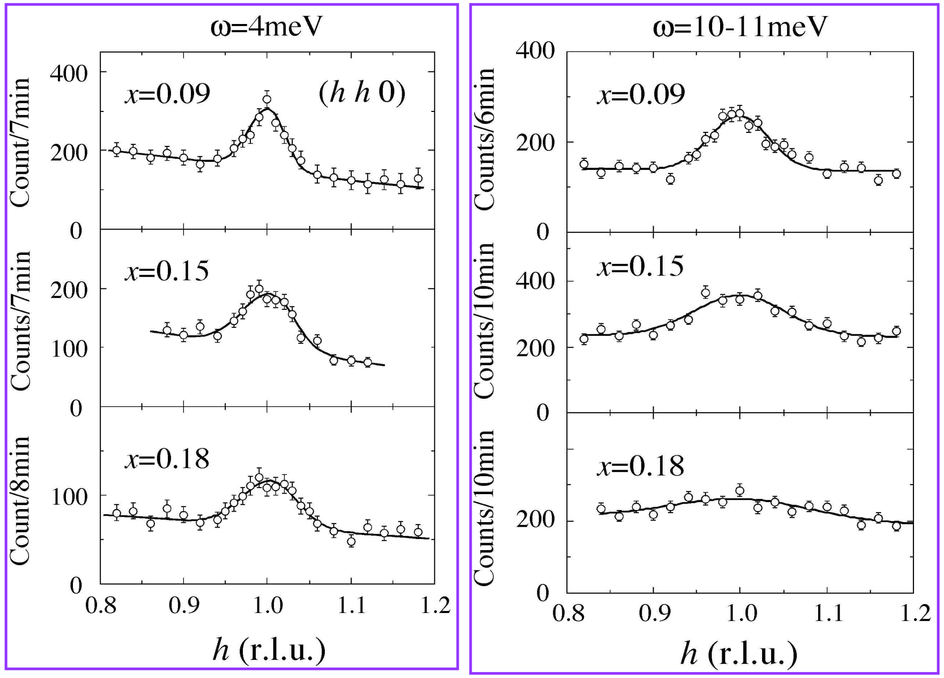
Motoyama et al., Nature 445(2007)

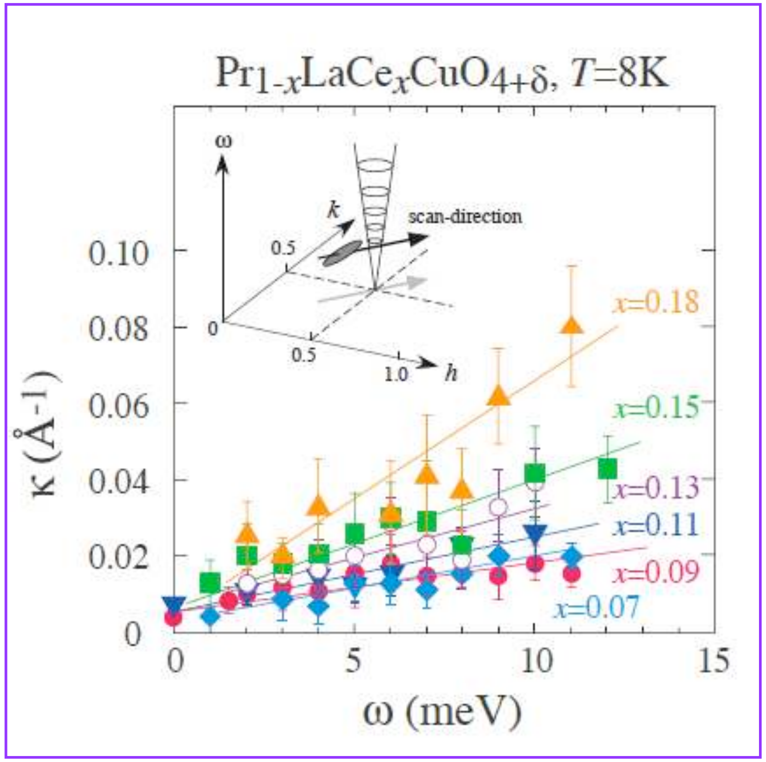


ξ(T) saturates at low temperature in the SC phase

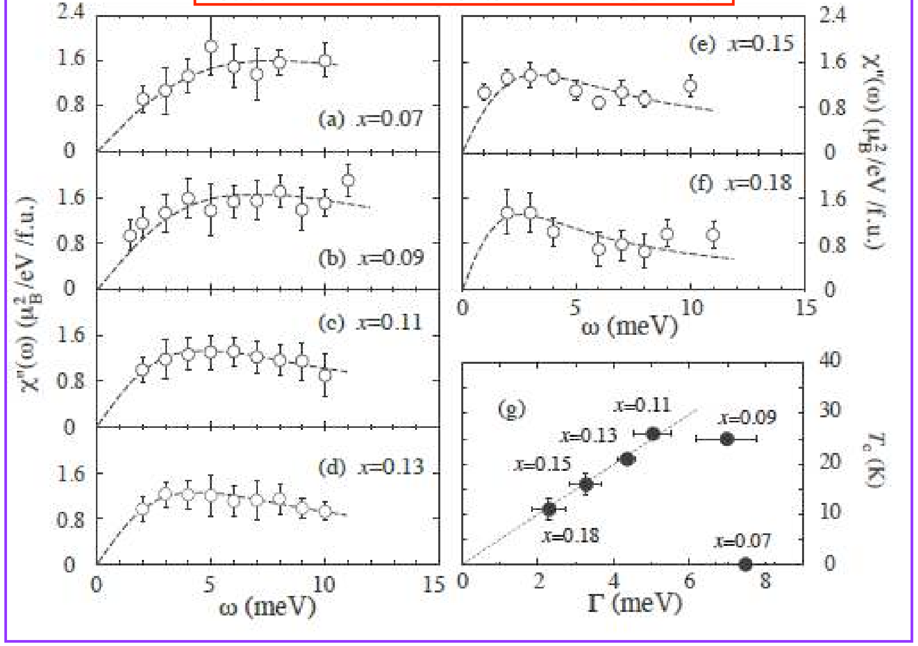


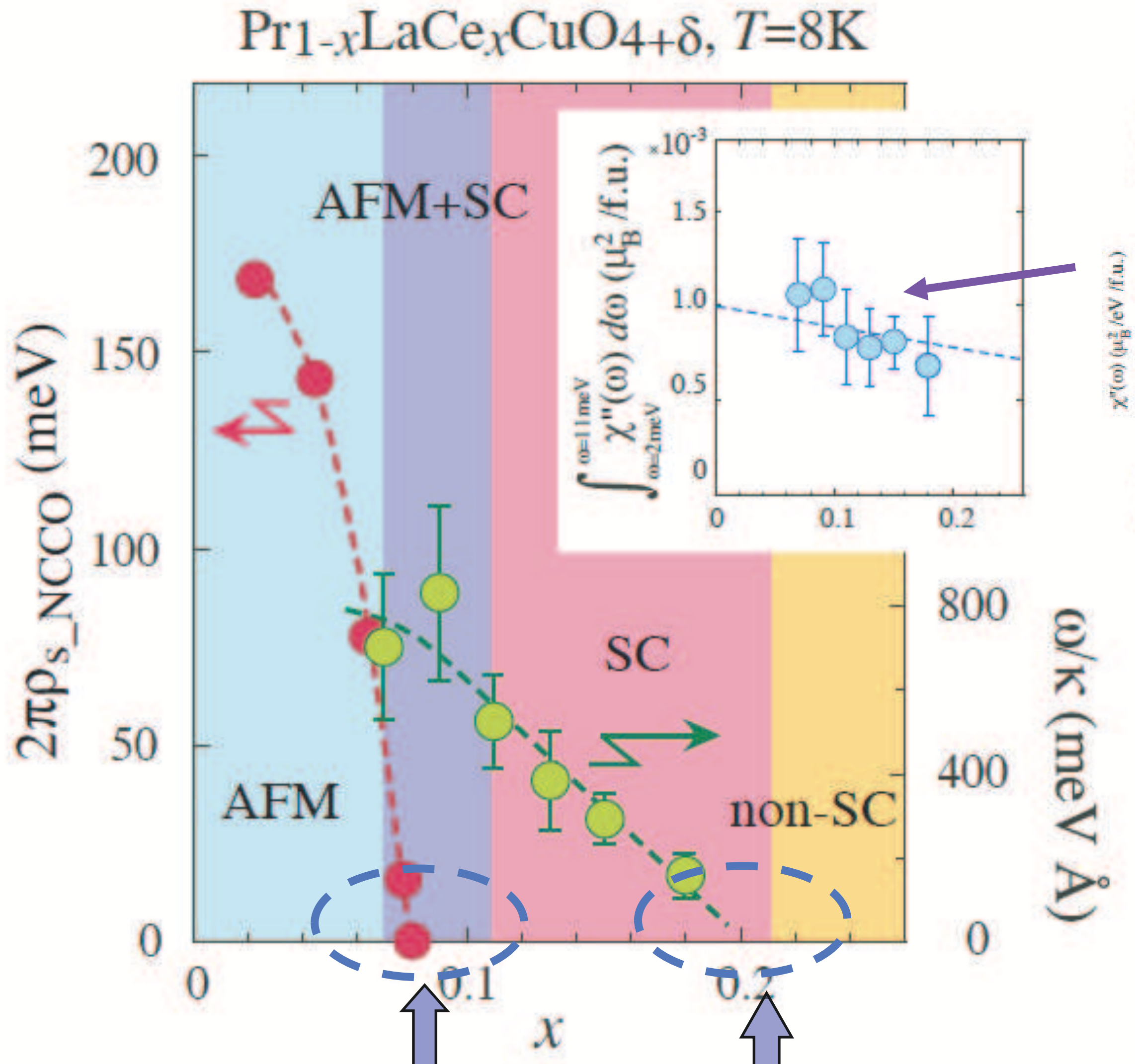
Fujita et al.,PRL(to be published)

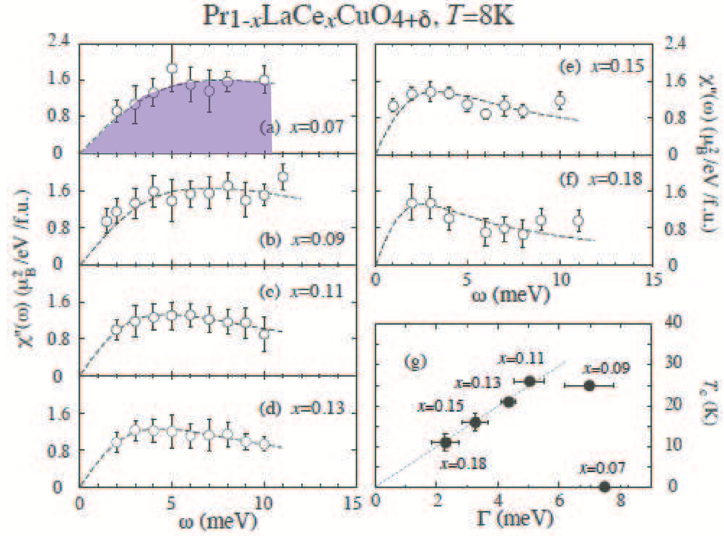


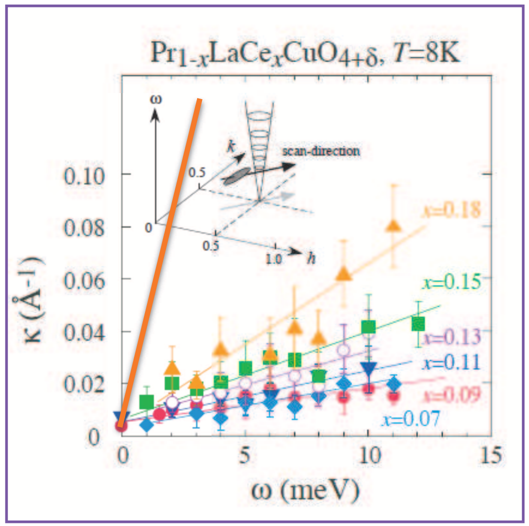


$$\chi'' \propto \Gamma\omega/(\Gamma^2 + \omega^2)$$



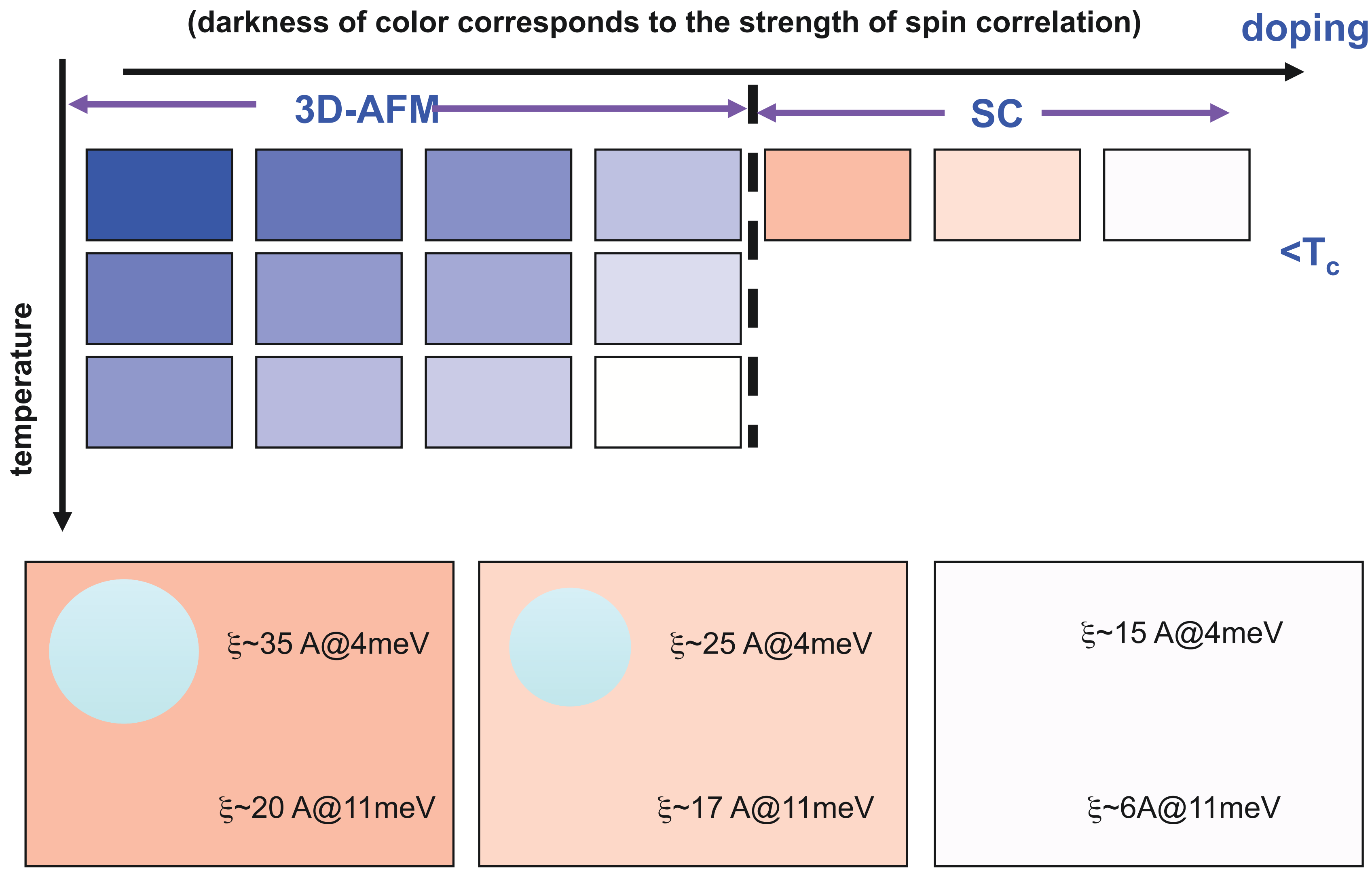




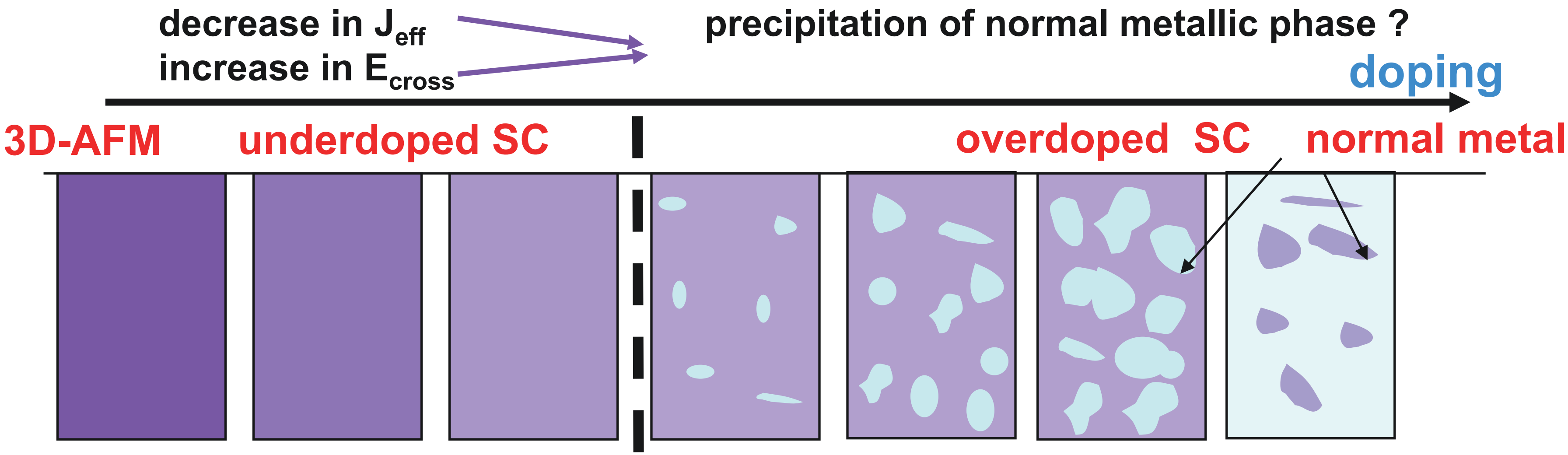


instantaneous spin stiffness disappears at AFM-SC boundary

low energy spin stiffness disappears at SC-metal(non-SC) boundary

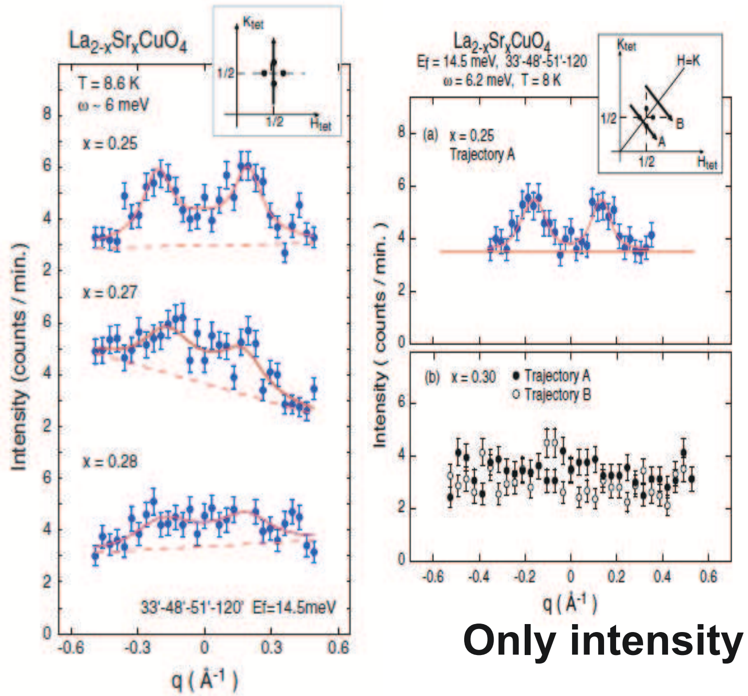


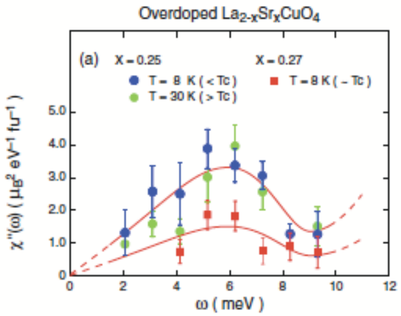
continuous reduction of spin stiffness upon doping

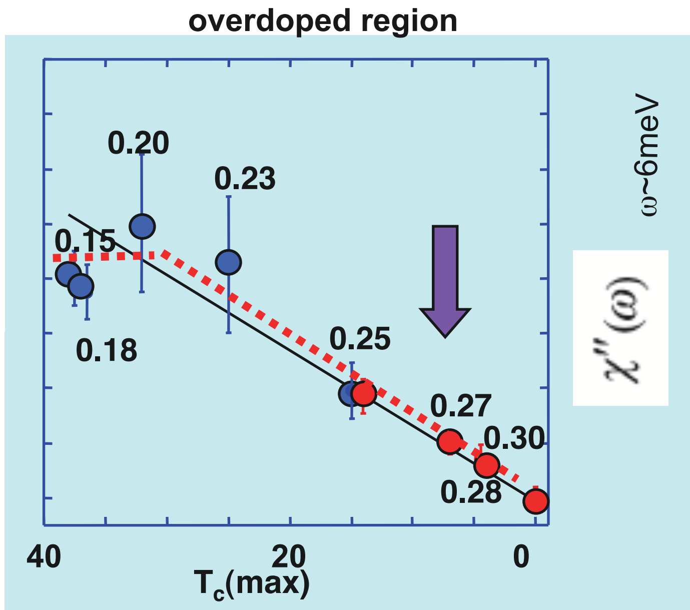


(darkness of color corresponds to the strength of spin correlation)

Wakimoto et al., PRL(2006)







Only intensity dominantly changes

N-type cuprates are normal ?

Magnetic fluctuations in n-type high-T_c superconductors reveal breakdown of fermiology

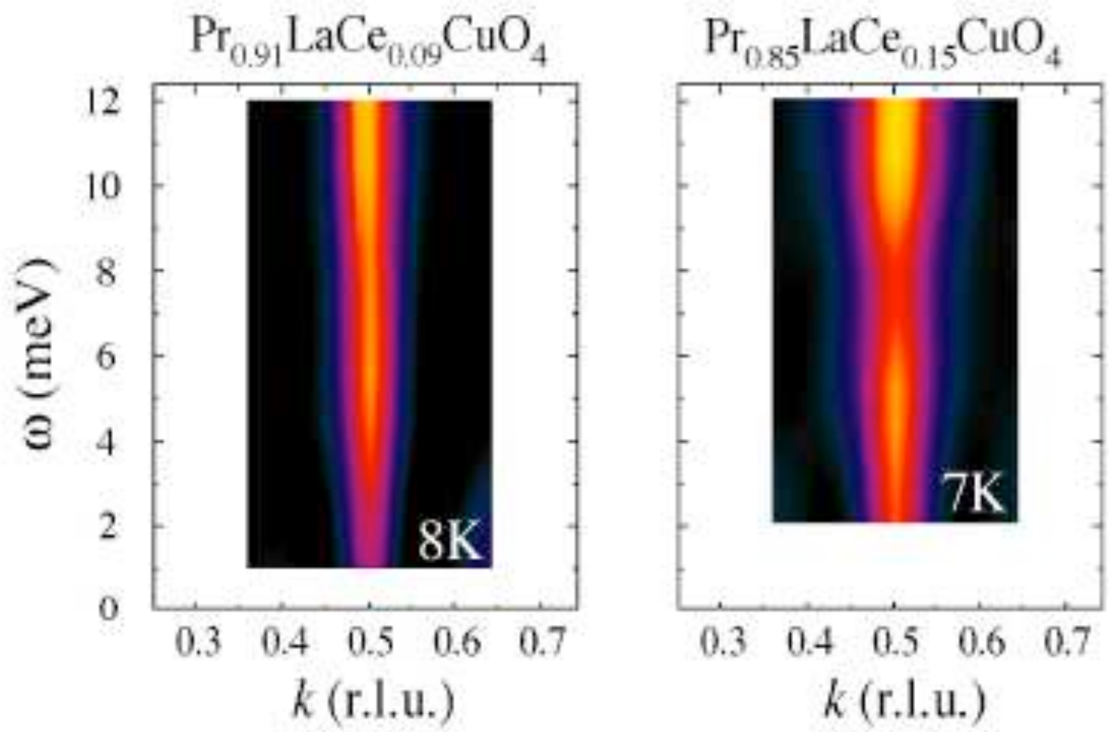
F. Krüger[1], S. D. Wilson[2], L. Shan[3], S. Li[2], Y. Huang[3], H.- H. Wen[3], S.-C. Zhang[4], Pengcheng Dai[2,5], J. Zaanen[1]

cond-mat 07054424

Electron-doping

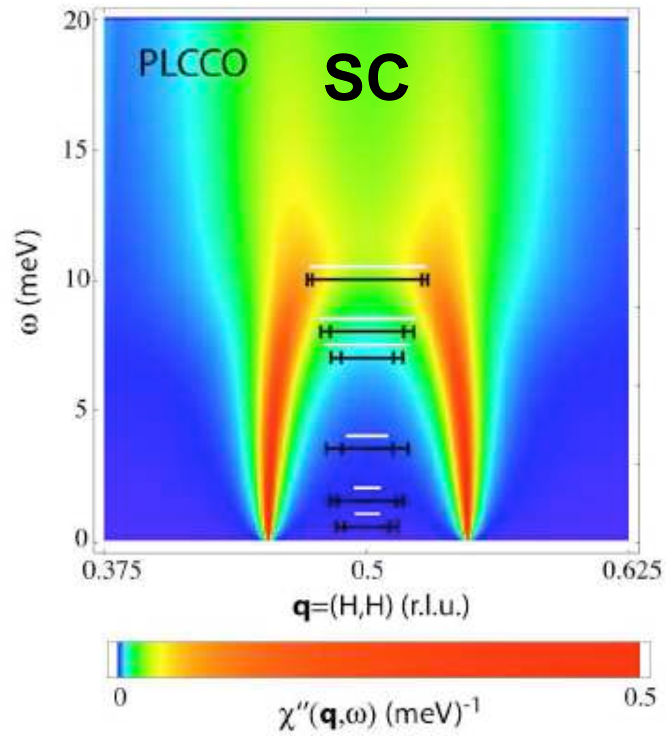
Fermi liquid model cannot reproduce commensurate low energy spin fluctuations in electron-doped cuprates

Experiment



AF **SC**

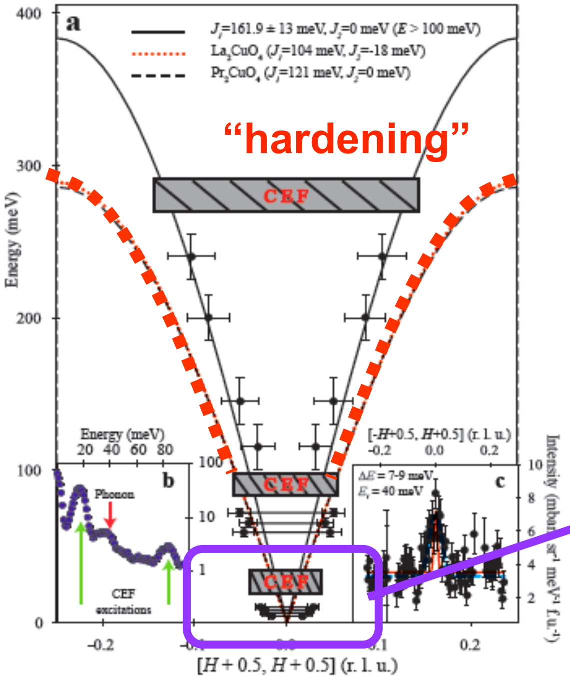
Fermi liquid model calculation



Krüger et al.,cond-mat 07054424

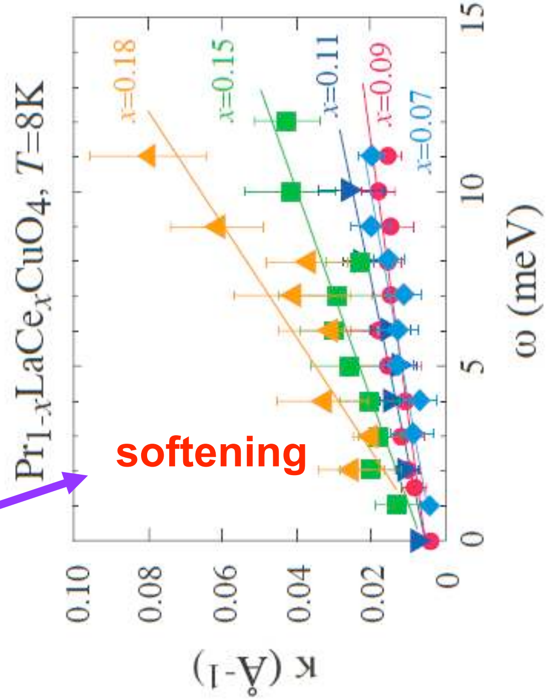
The high energy magnetic excitation is also anomalous

MAPS



"hardening"

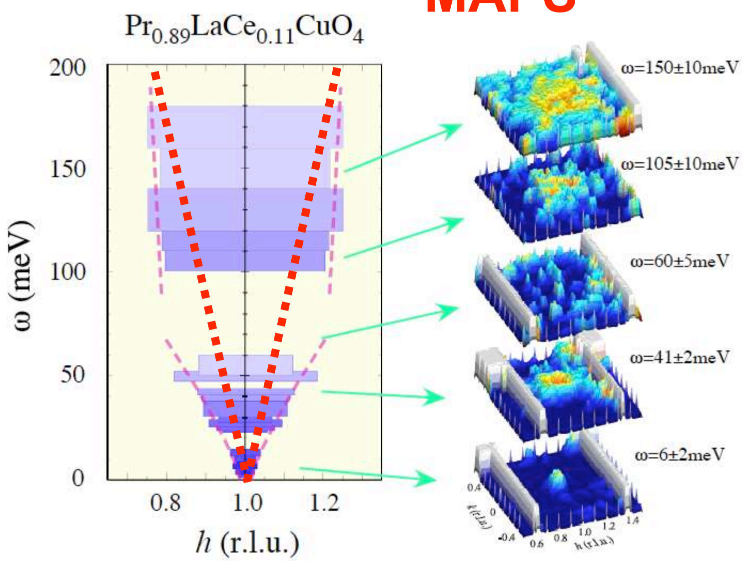
softening



Wilson et al.PRL(2006)

"Hardening" at high energies, softening at low energies !

MAPS

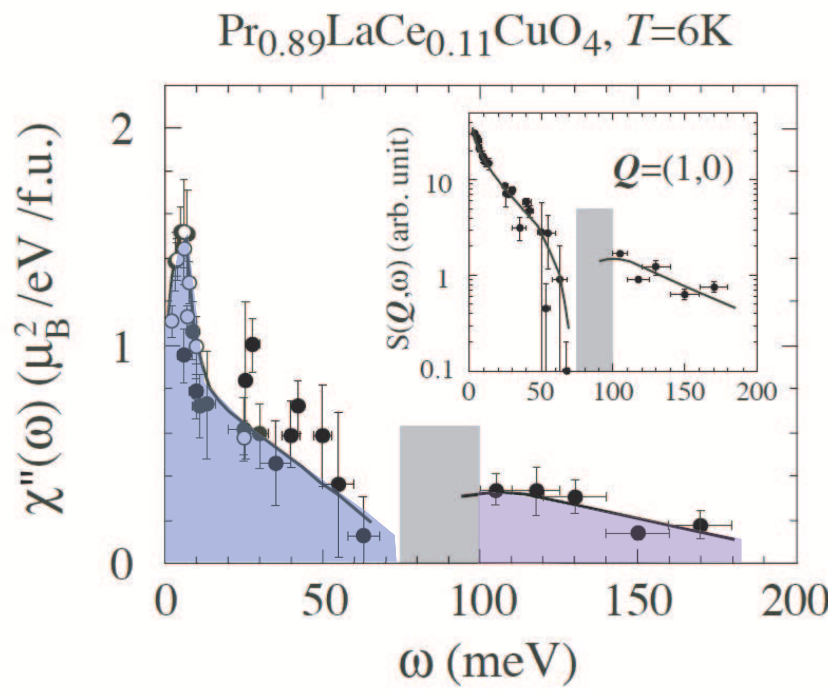


Fujita et al., JPSJ(2006)

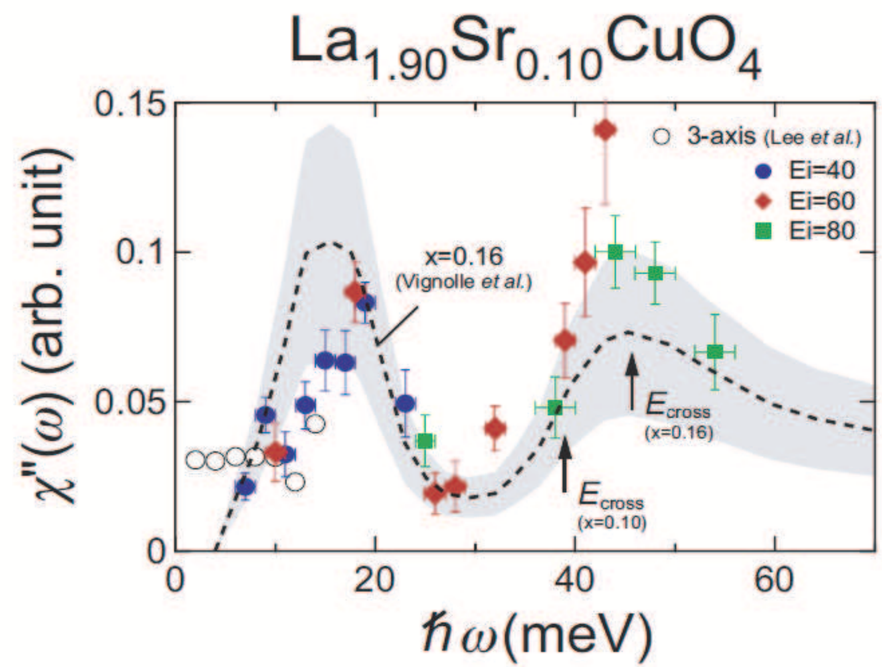
Different from spin-wave-type excitation in SC phase ?

Pencil shape excitation?

Dual nature in magnetic excitations in n-type?



Fujita et al.JPSJ, 75 ('06)



Future experiment including polarization analysis will clarify this issue

Contents

1) Magnetic fluctuation of p-type cuprates (10min.)

2) Magnetic fluctuation of n-type cuprates (15min.)

3) "Magnetic" impurity-effect in p-type cuprates (15min.)

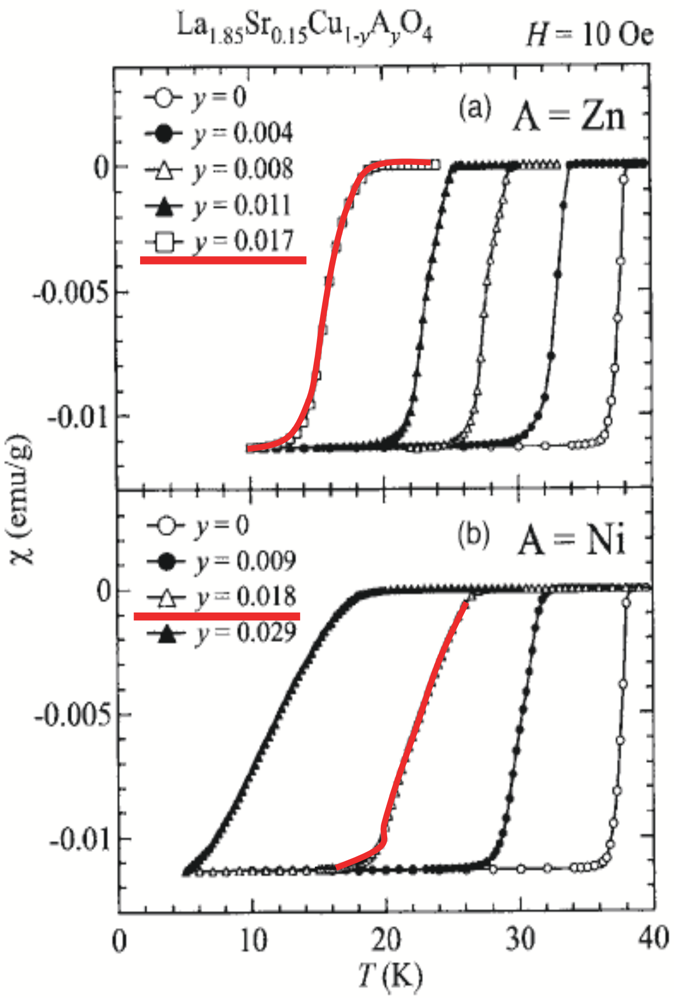
Ni-impurity in not magnetic impurity but charge one

4) New pulsed neutron facility in J-PARC (5min.)

Advertisement

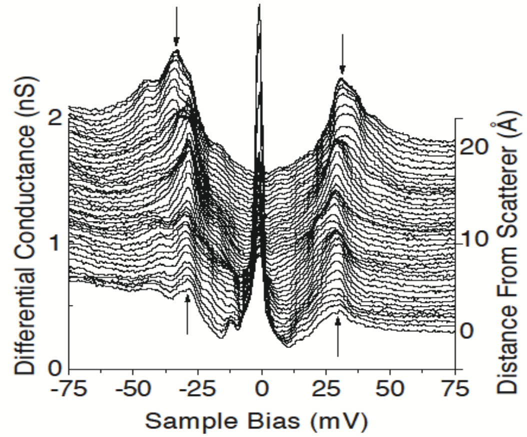
Uniqueness of Ni-impurity in doped cuprates

Robust superconductivity around Ni

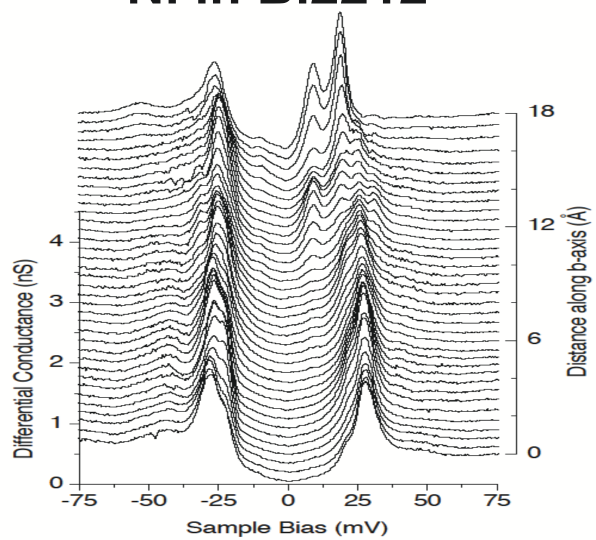


Kofu et al., PRB (2006)

Zn in Bi2212



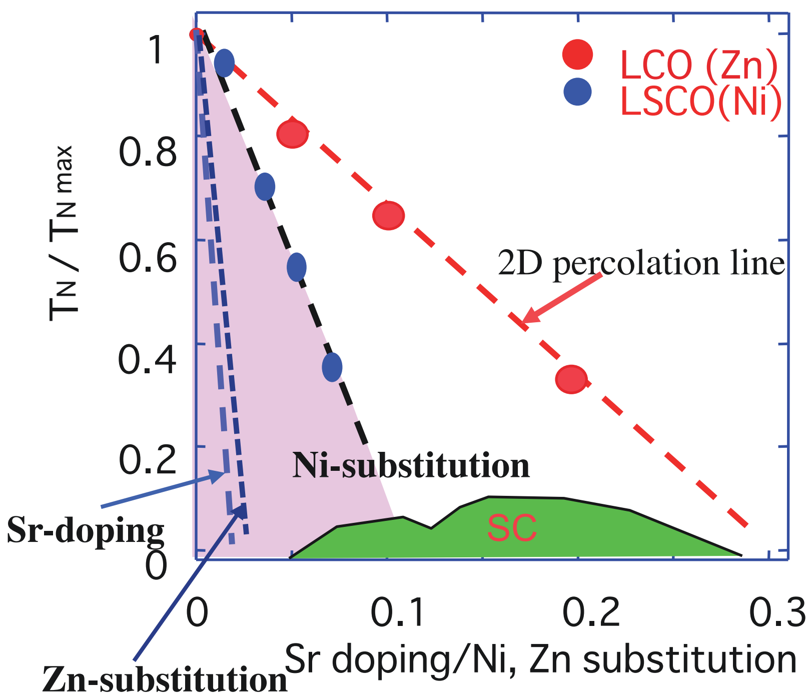
Ni in Bi2212

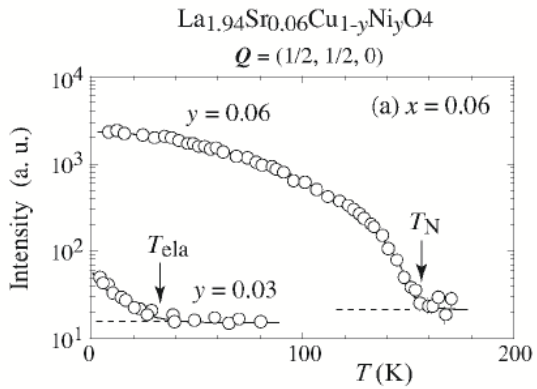


J.C. Davis's group

Effect of Ni-impurity on spin correlation

Ni–induced AF order in $La_{2-x}Sr_xCu_{1-y}Ni_yO_4$

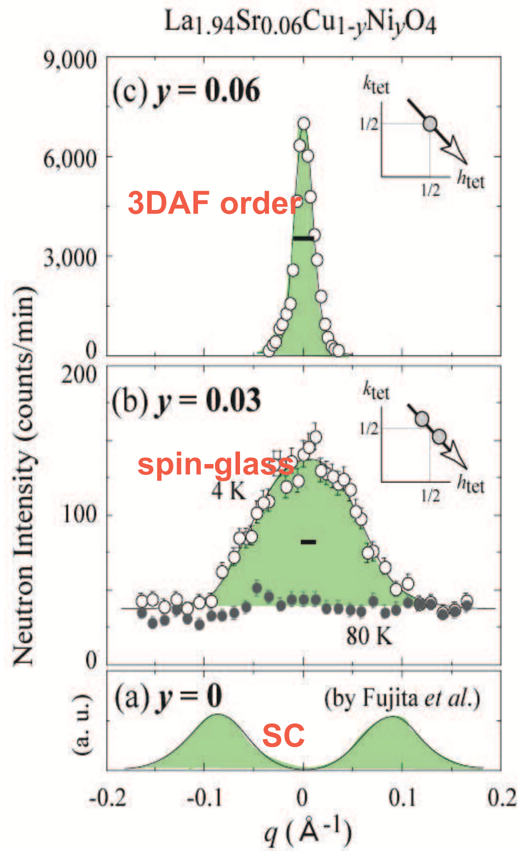




Ni-impurity recovers 3DAF order

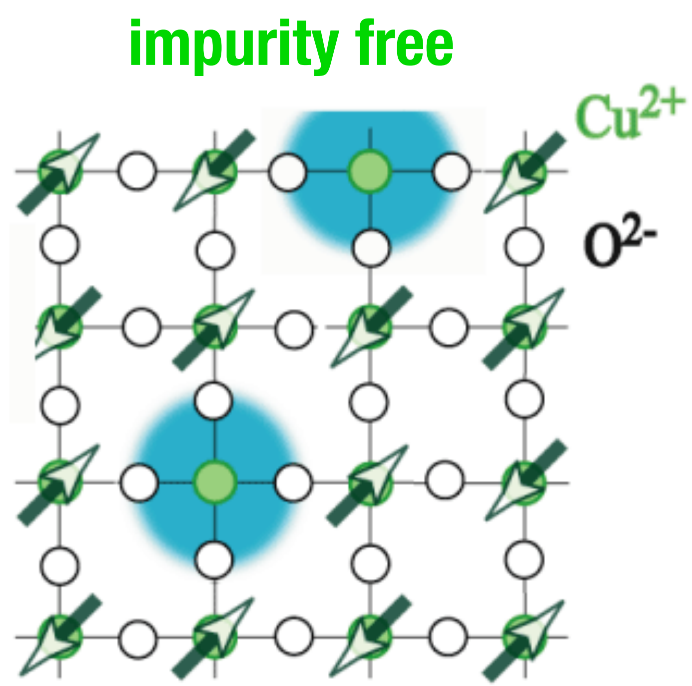
hole-doping 3DAF order => spin-glass => SC

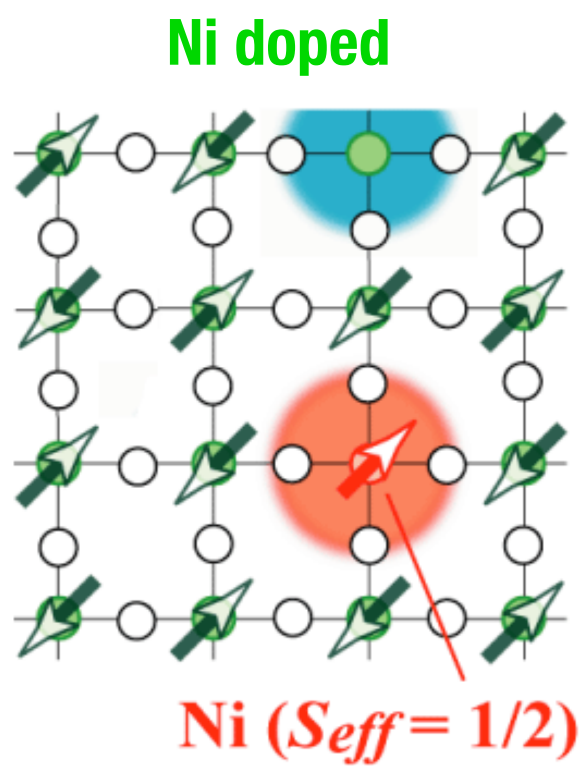
Ni-doping 3DAF order <= spin-glass <= SC



Ni-impurity reduces effective (mobile) hole concentration (Blotter effect)

There must be two types of holes by Ni-doping

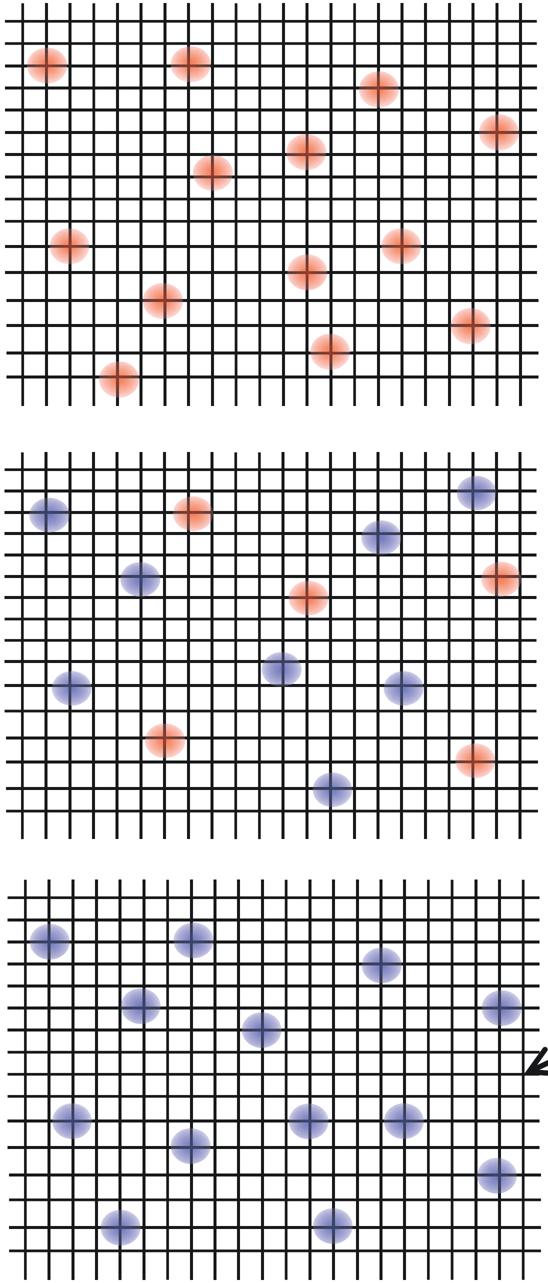


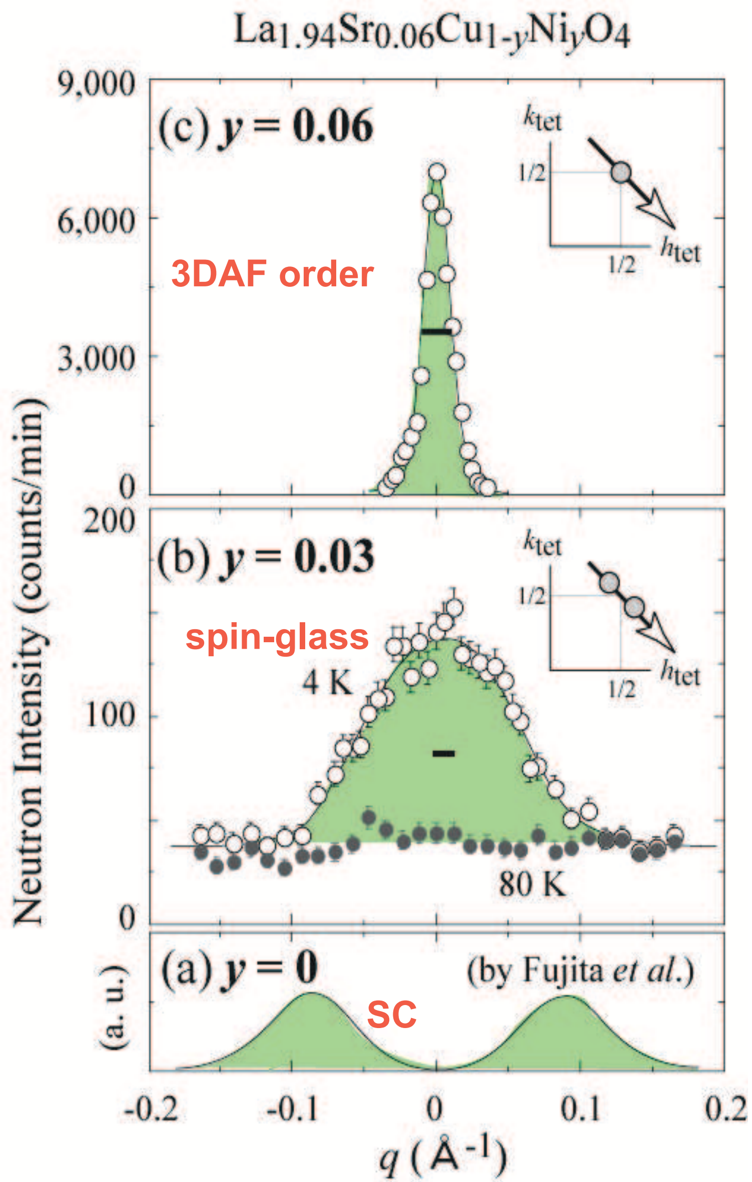


Itinerant Zhang-Rice singlet

Itinerant holes
+ Localized holes

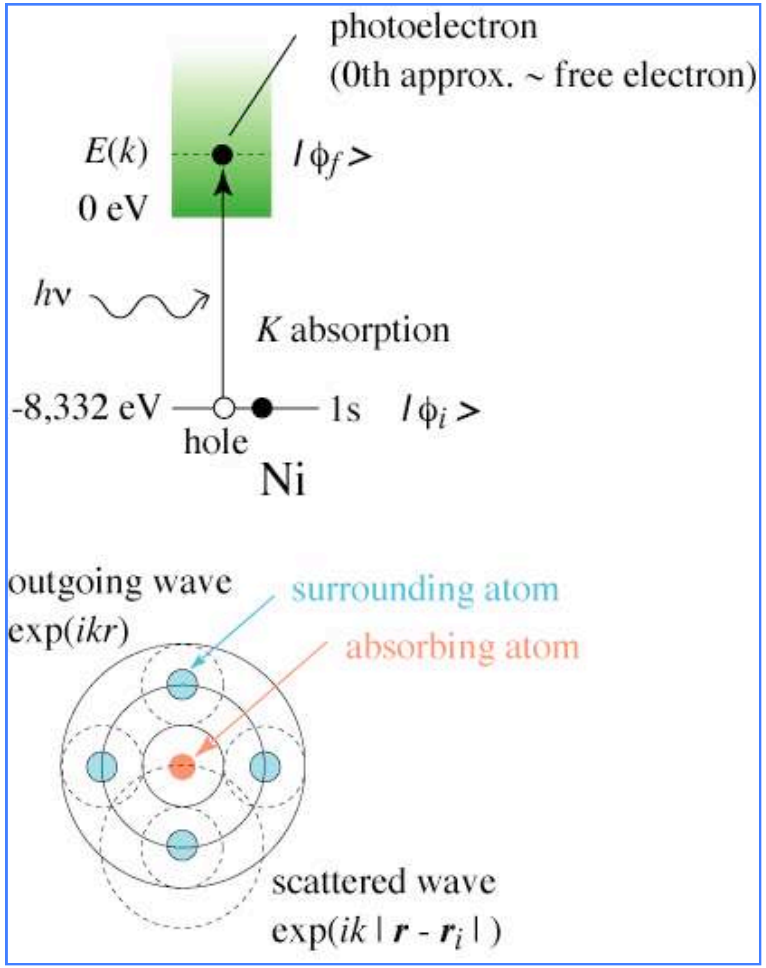
Ni-impurity is not a magnetic impurity but a nearly pure charge impurity in doped cuprates

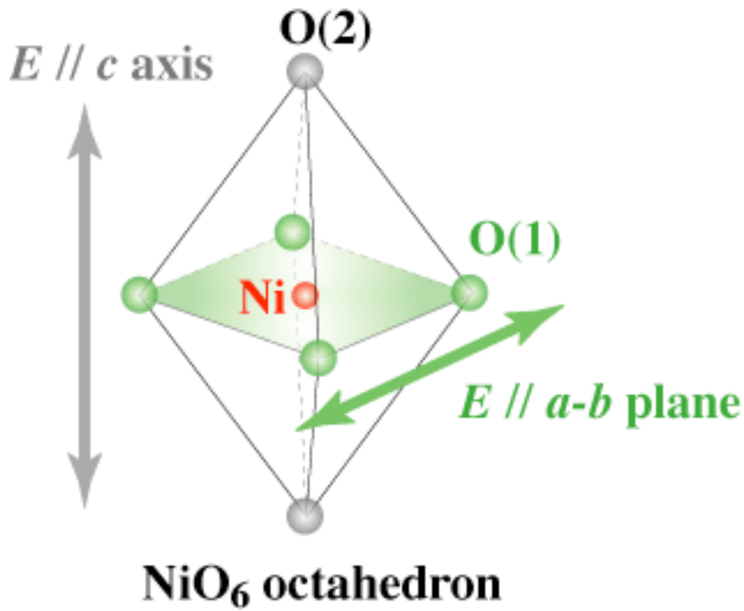




XAFS experiment (SPring-8, linearly polarized, Ni K-edge, T=300 K)

Site-selective measurement (local structure around ~1% Ni impurity)





EXAFS raw data

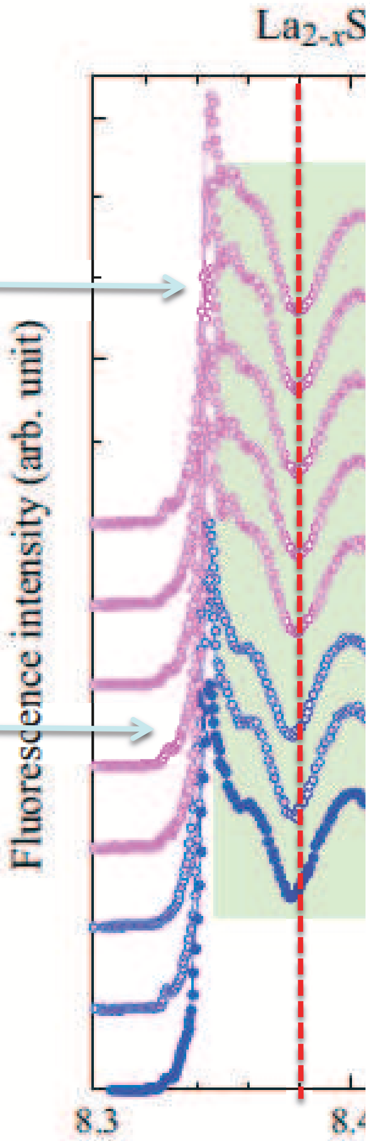
Two groups of single crystal

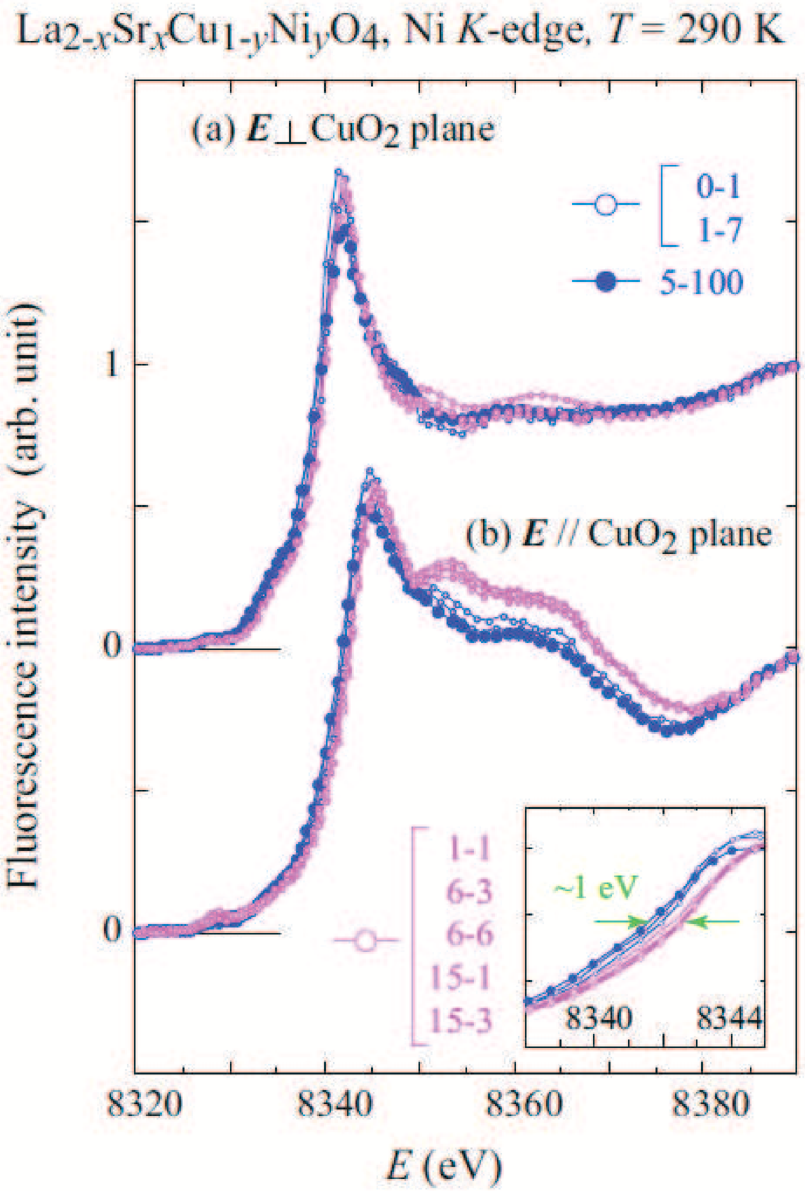
Hole rich group (All Ni trap hole)

" 1-1 " Sr1% & Ni1%

Ni rich group (Most of Ni does not trap hole)

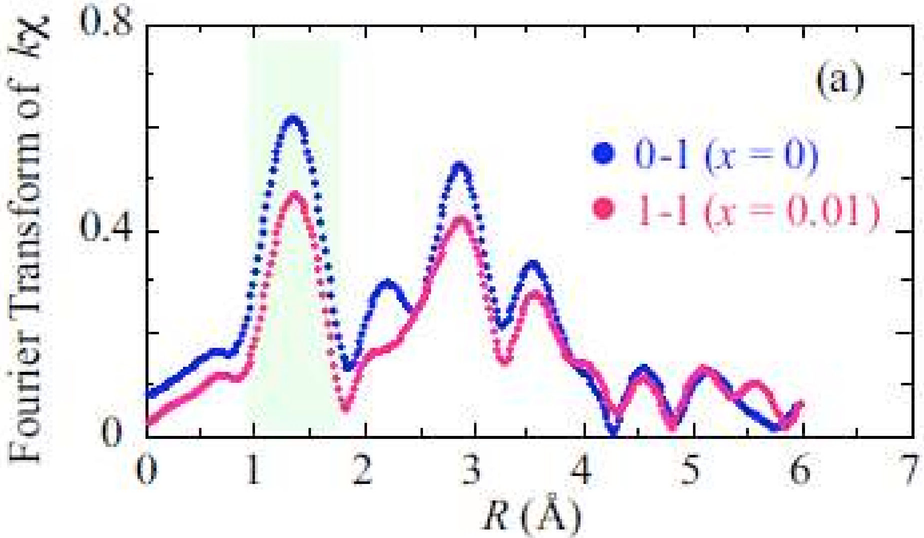
" 0-1 " Sr0% & Ni1%

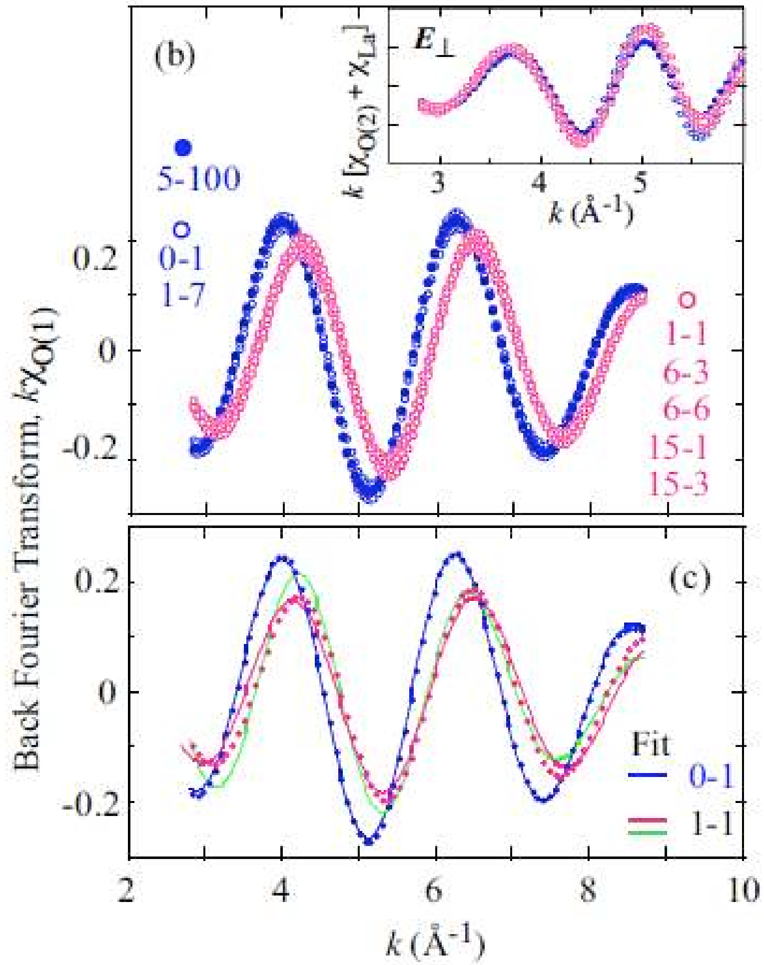




EXAFS analyses

$La_{2-x}Sr_xCu_{0.99}Ni_{0.01}O_4$, $T = 290$ K, Ni K-edge, $\boldsymbol{E}_{//}$





$$\chi(k) = \sum_{i \text{ shell}} \chi_i(k) , \quad (1)$$

$$\chi_i(k) = C_i \, F_i(k) \exp(-2\sigma_i^2 k^2) \frac{\sin\left(2kR_i + \Phi_i(k)\right)}{kR_i^2} \quad (2)$$

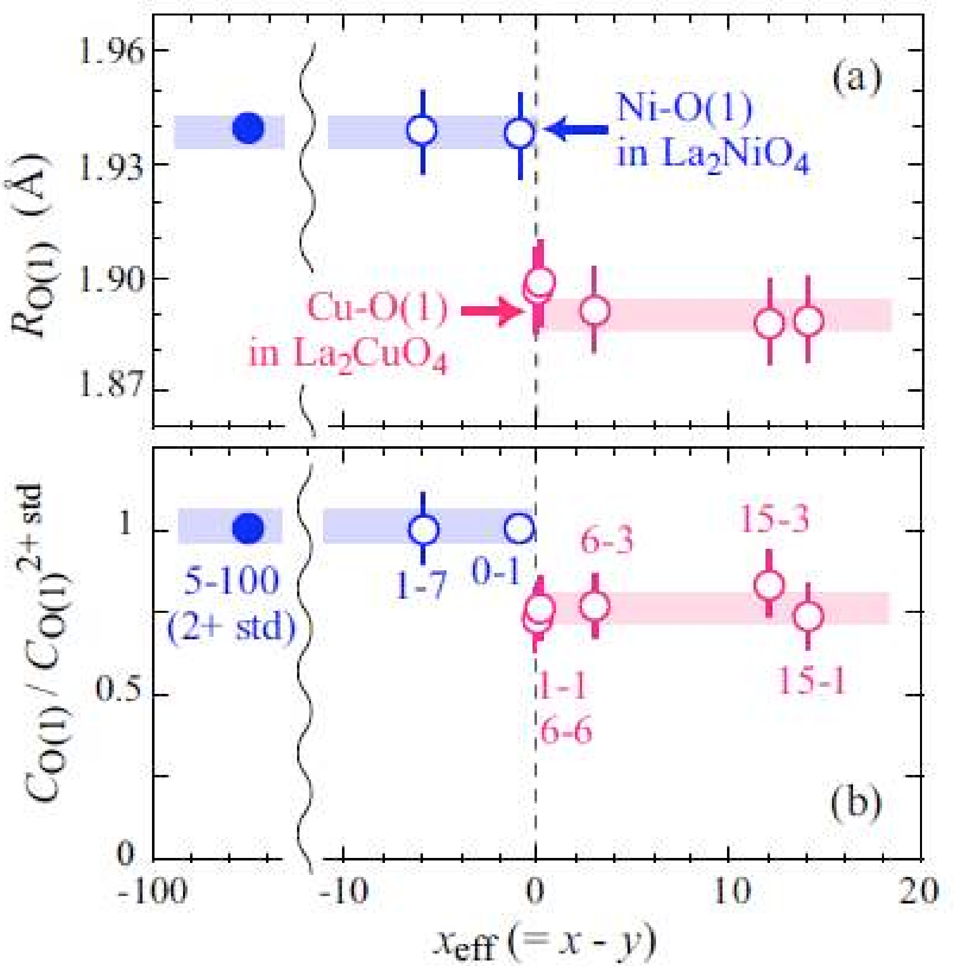
2 types of local in-plane structure around Ni impurity

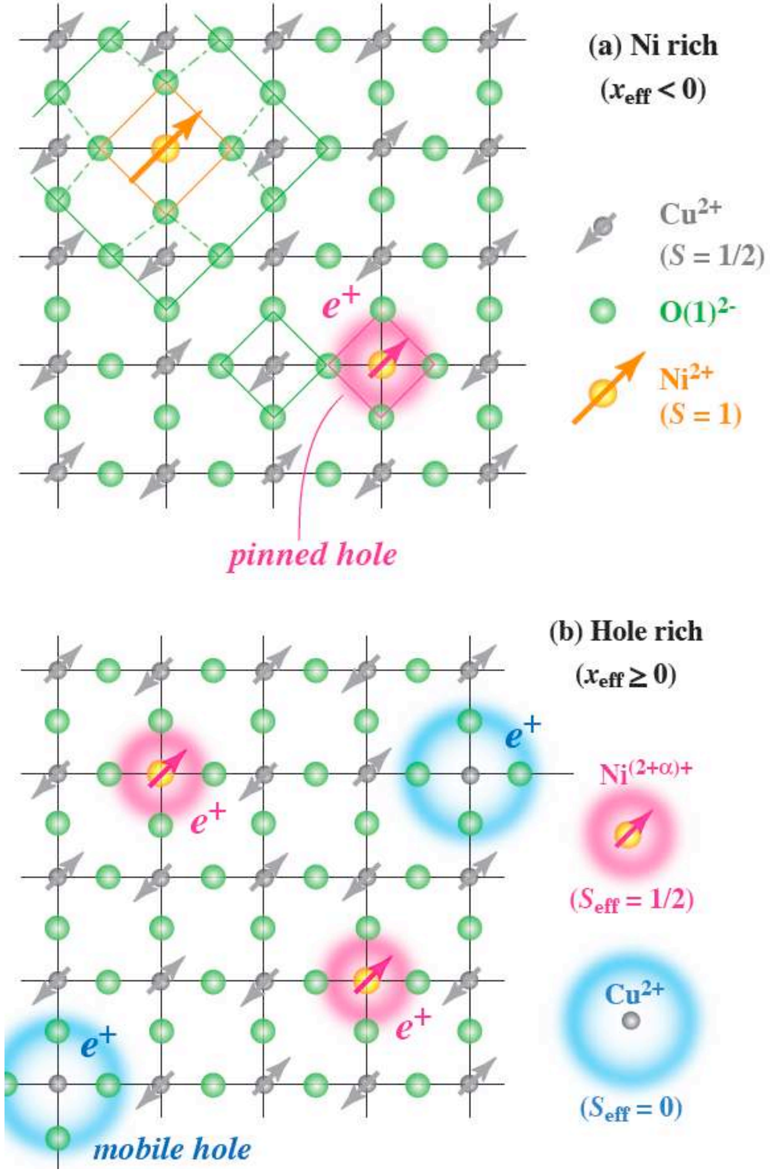
----→ two types of Ni states Ni^{2+} and $Ni^{(2+\alpha)+}$

EXAFS results

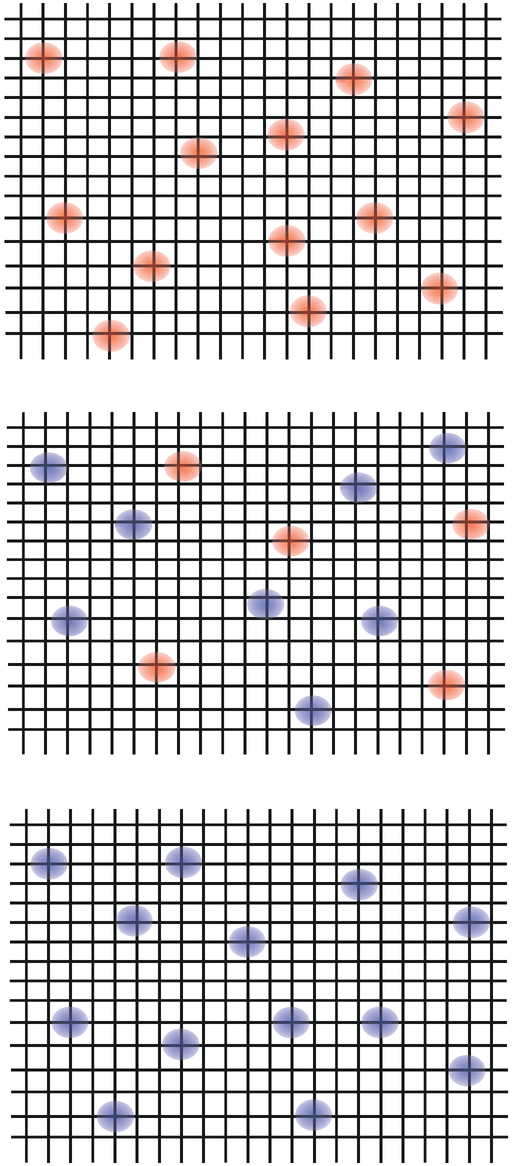
hole-trapped state of Ni=3d^7 or 3d$^8\underline{L}$
→ S= 1/2 with similar local structure around Cu

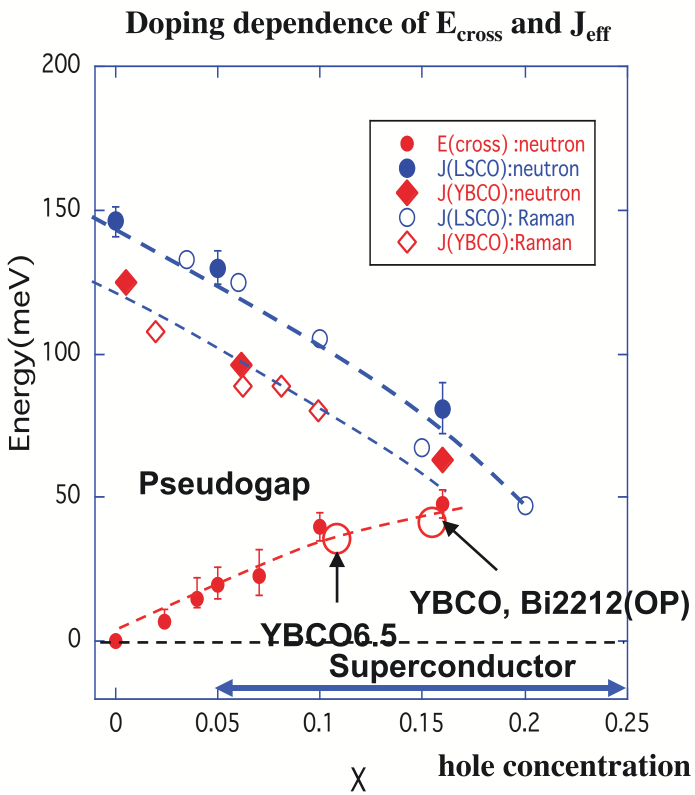
Ni-O(1) parameter





Ni-substitution effect on magnetic excitation



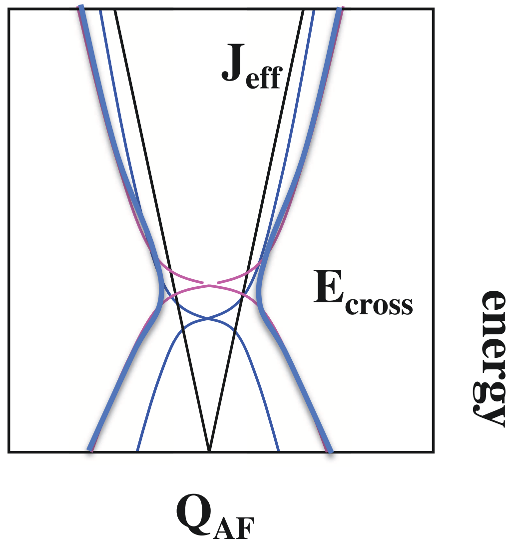


Increase of J_{eff}

?

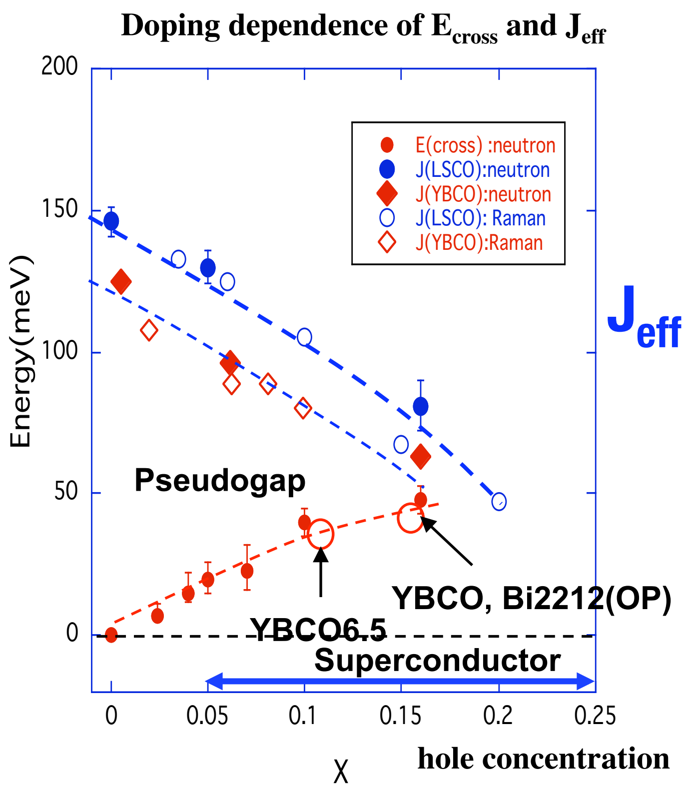
reduction of effective hole concentration

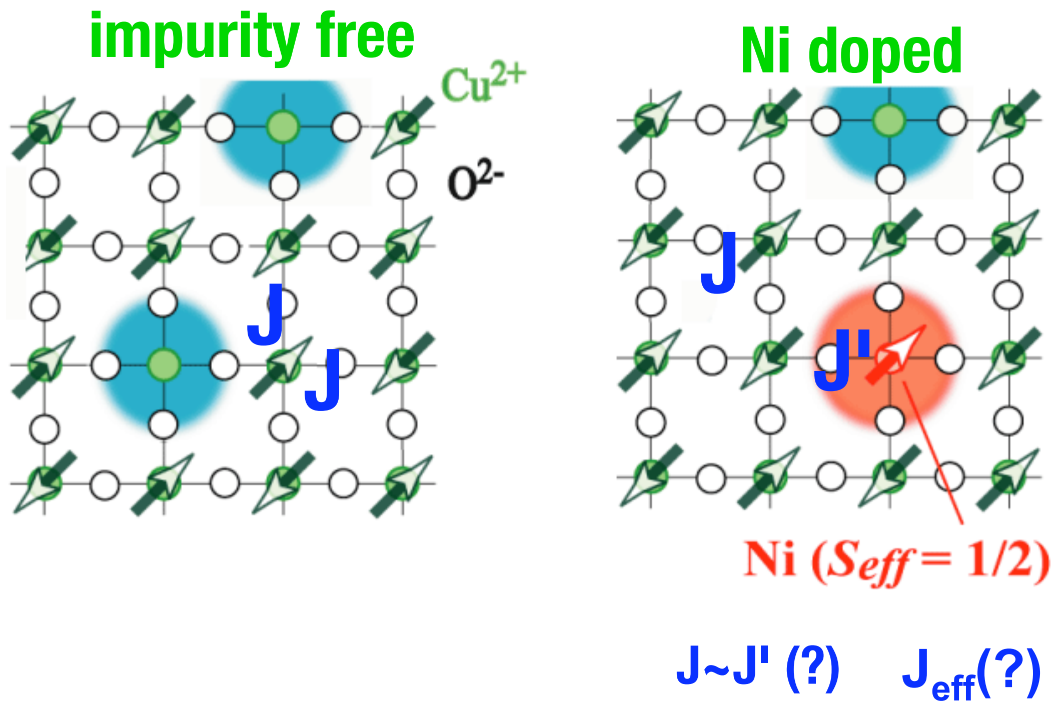
reduction of E_{cross} ?



Unique feature of Ni-impurity including the robust SC against Ni can be qualitatively explained by the blotter effect of Ni-impurity in the doped cuprates

In order to sustain high-Tc SC, 2D antiferromagnetic framework with s=1/2 is necessary






Thank you for attention