Measuring up the Competition: Neutron Scattering Studies of Antiferromagnetism in Cuprate Superconductors

John Tranquada

BROOKHAVEN NATIONAL LABORATORY

BCS@50
October 11, 2007

Neutrons@75

NATURE [FEBRUARY 27, 1932

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The

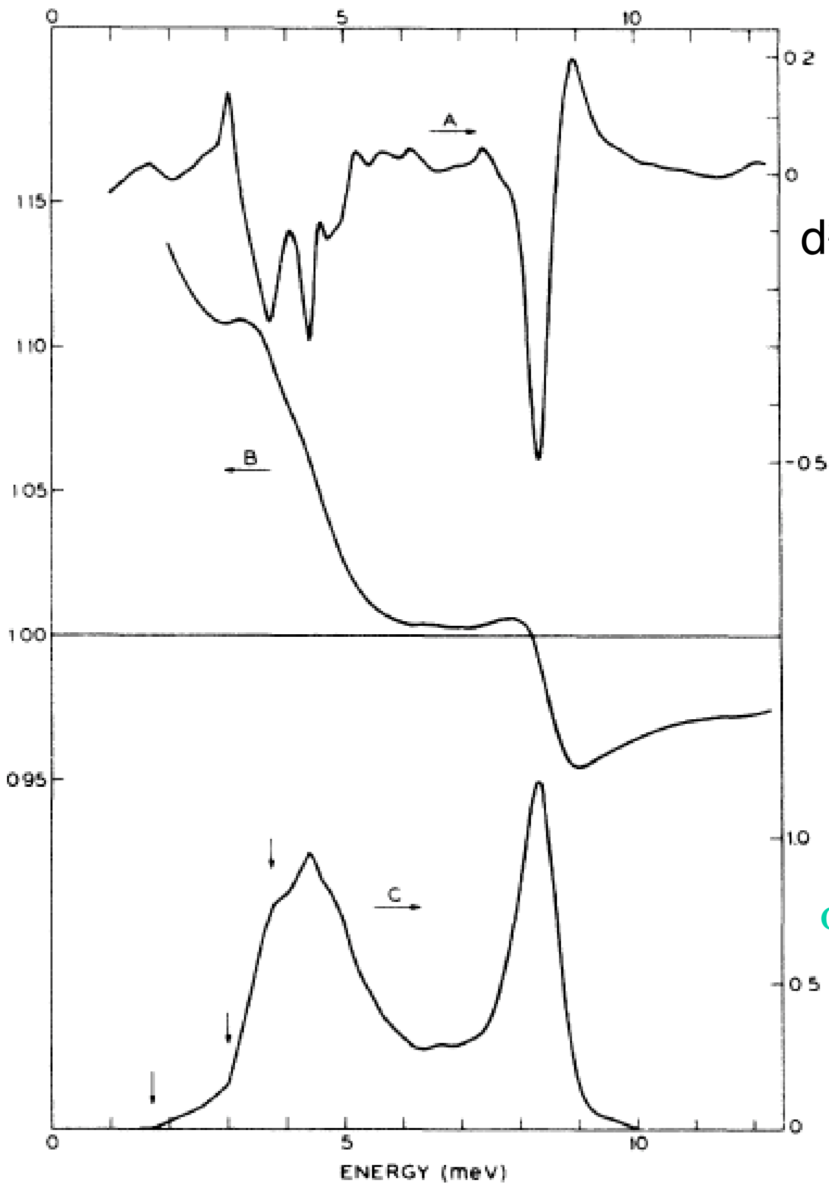
It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

J. CHADWICK.

Cavendish Laboratory,
Cambridge, Feb. 17.

James Chadwick

McMillan-Rowell: $\alpha^2F(\omega)$ in Pb



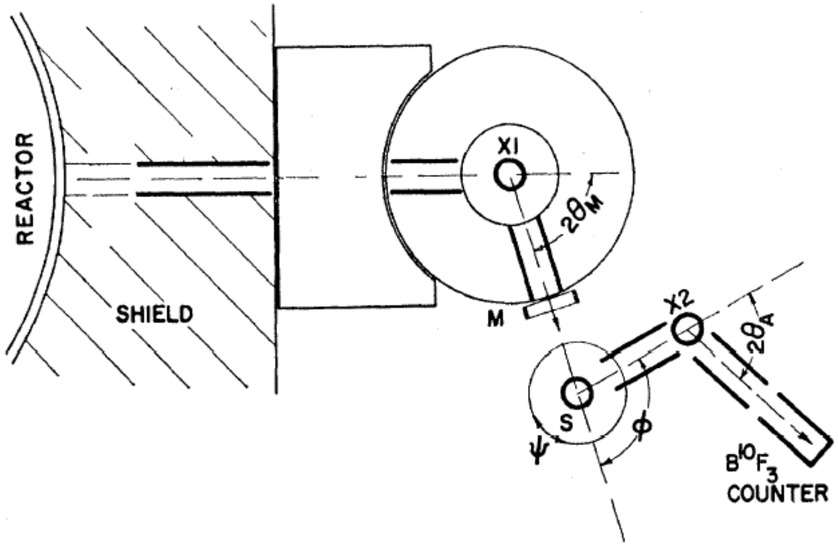
PRL **14**, 108 (1965)

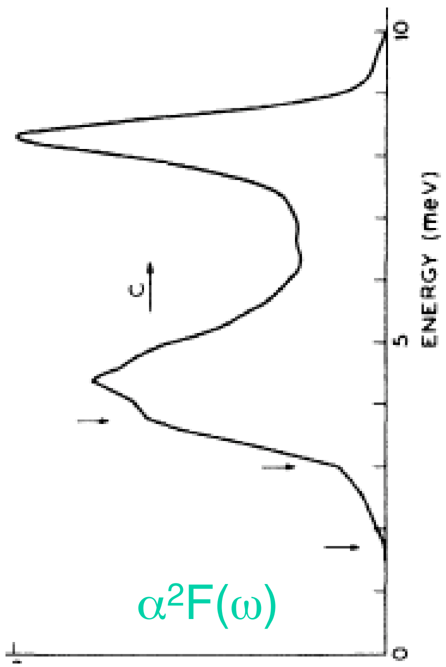
S-I-S tunnel junction

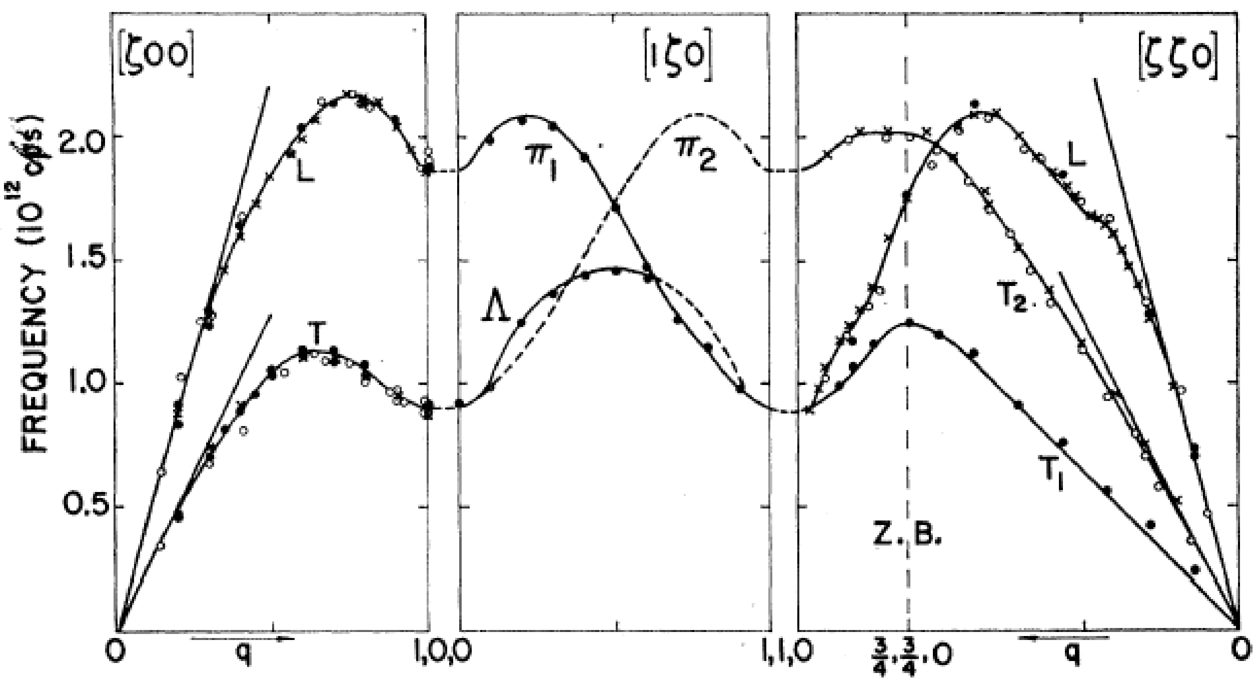
$\alpha^2F(\omega)$ ~ phonon density of states

Brockhouse: Phonons in Pb

PR **128**, 1099 (1962)







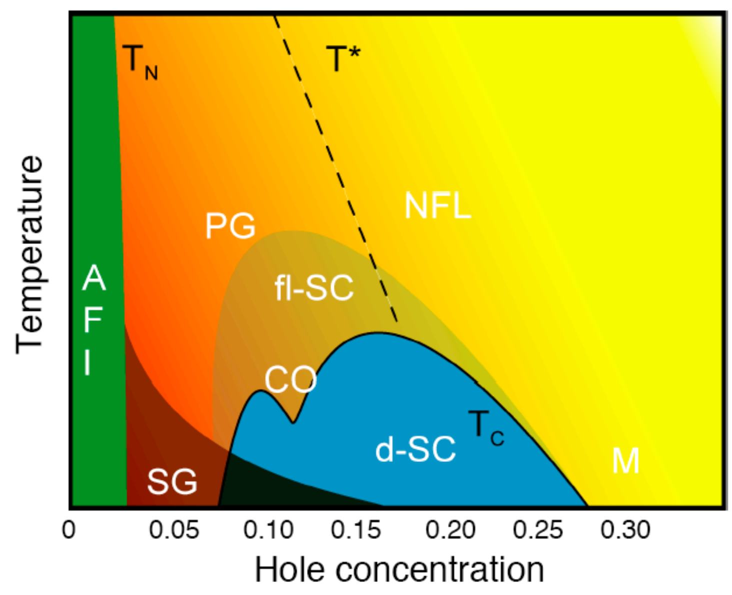
Antiferromagnetism + Superconductivity in Cuprates

- Do spin waves replace phonons in pair formation?
  - Measure spectrum and compare with $\alpha^2F(\omega)$?

- But what is the nature of the spin fluctuations?

- Does character of AF insulator survive into the SC regime?
  - If so, how do quasiparticles coexist?

- Does character change as soon as AF order is destroyed?
  - Is spin response due to quasiparticles?



What Neutrons Tell Us

- Locally AF correlations survive through optimal doping
  - Effective superexchange energy softens with doping
- AF correlations disappear with overdoping
- SC can induce a gap in the spin fluctuation spectrum
  - But spin gap is not essential to SC
- Coexistence of local AF correlations and mobile holes
  - Stripes provide a proven motif for coexistence
  - Even ordered stripes are compatible with high-temperature SC

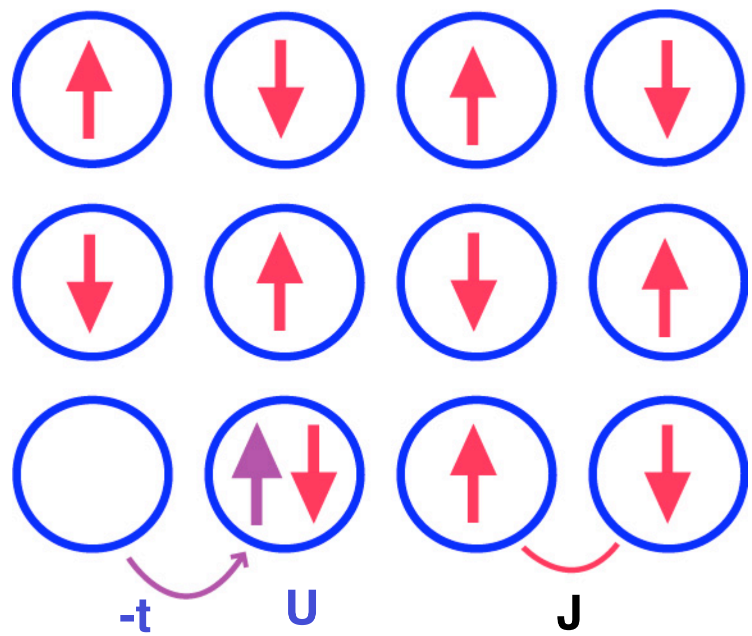
1/2-Filled Hubbard Model and Superexchange

1 orbital/site

1 electron/orbital

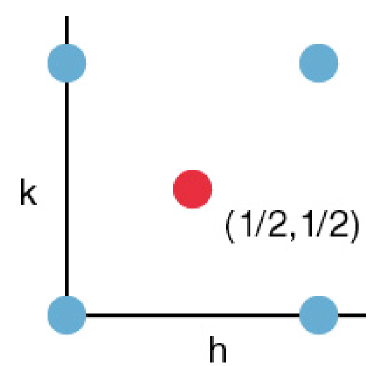
t = kinetic energy

U = onsite Coulomb repulsion



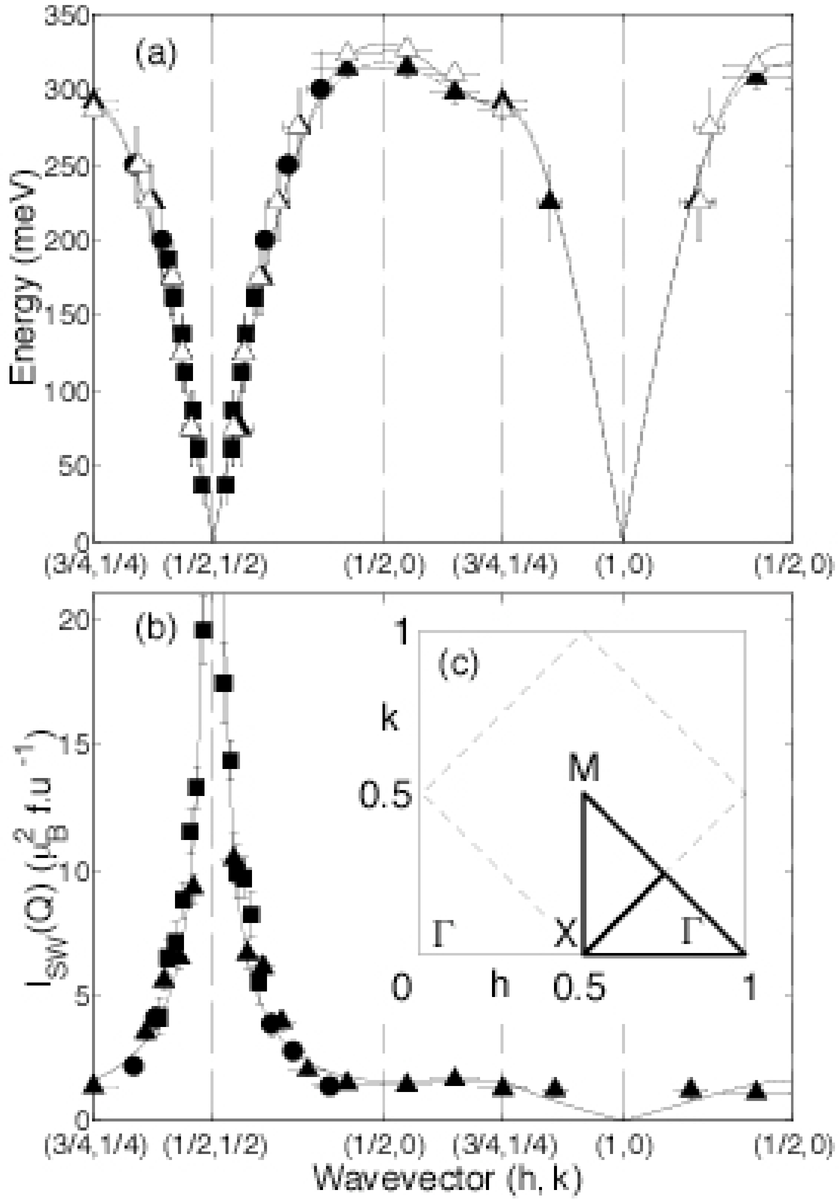
Coulomb repulsion
+
Pauli exclusion
$\Downarrow$
Antiferromagnetic superexchange

$\mathbf{J} = 4\mathbf{t}^2/\mathbf{U}$



P.W. Anderson (1959)

Spin waves in antiferromagnetic La_2CuO_4



Coldea *et al.*
PRL **86**, 5377 (2001)

Obtained by neutron scattering at ISIS

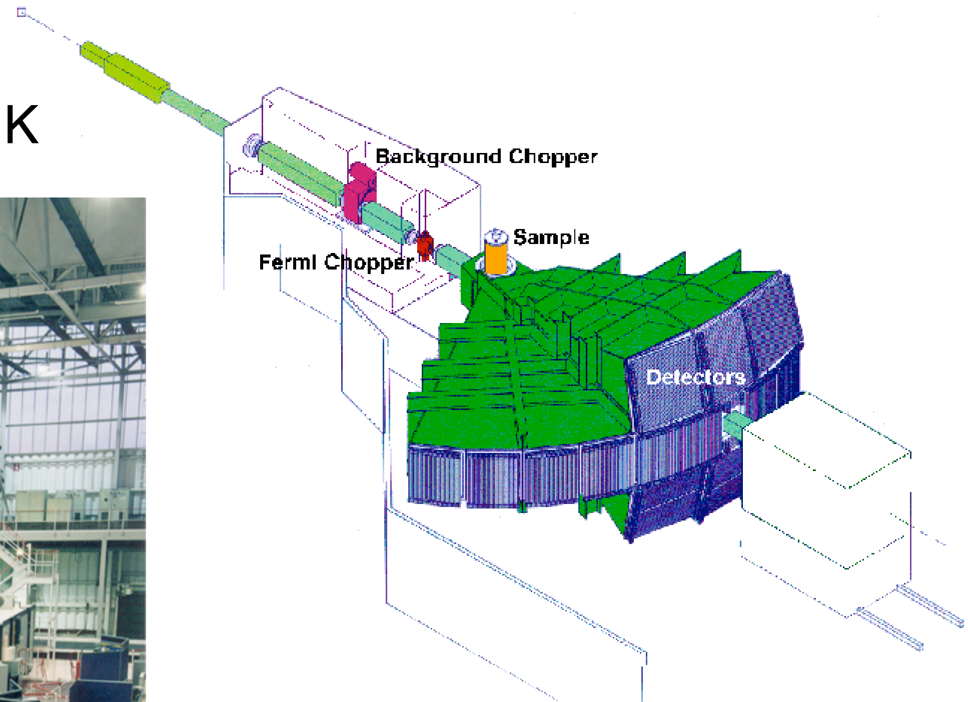
Well described by 1/2-filled Hubbard model

Superexchange dominates

J = 146 meV

Neutron scattering studies using MAPS at ISIS

ISIS at Rutherford-Appleton Lab, UK



MAPS
Time-of-flight spectrometer
for study of inelastic scattering

Area detector: ~ 40,000 pixels
2500 time channels

Toby Perring

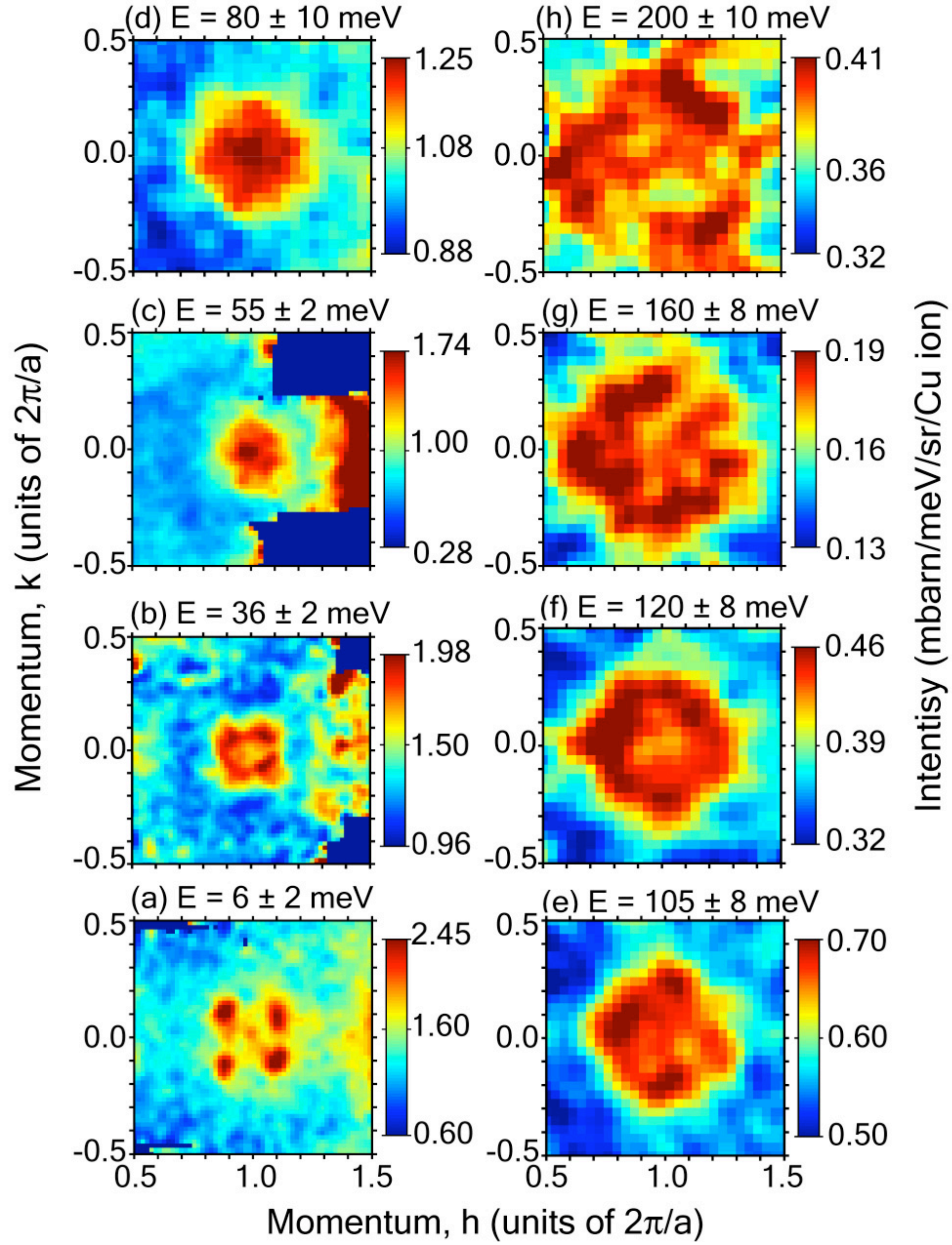
Constant-energy slices through magnetic scattering

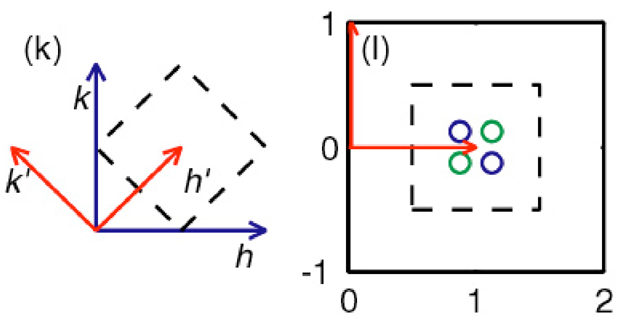
Stripe-ordered
$La_{1.875}Ba_{0.125}CuO_4$

T = 12 K

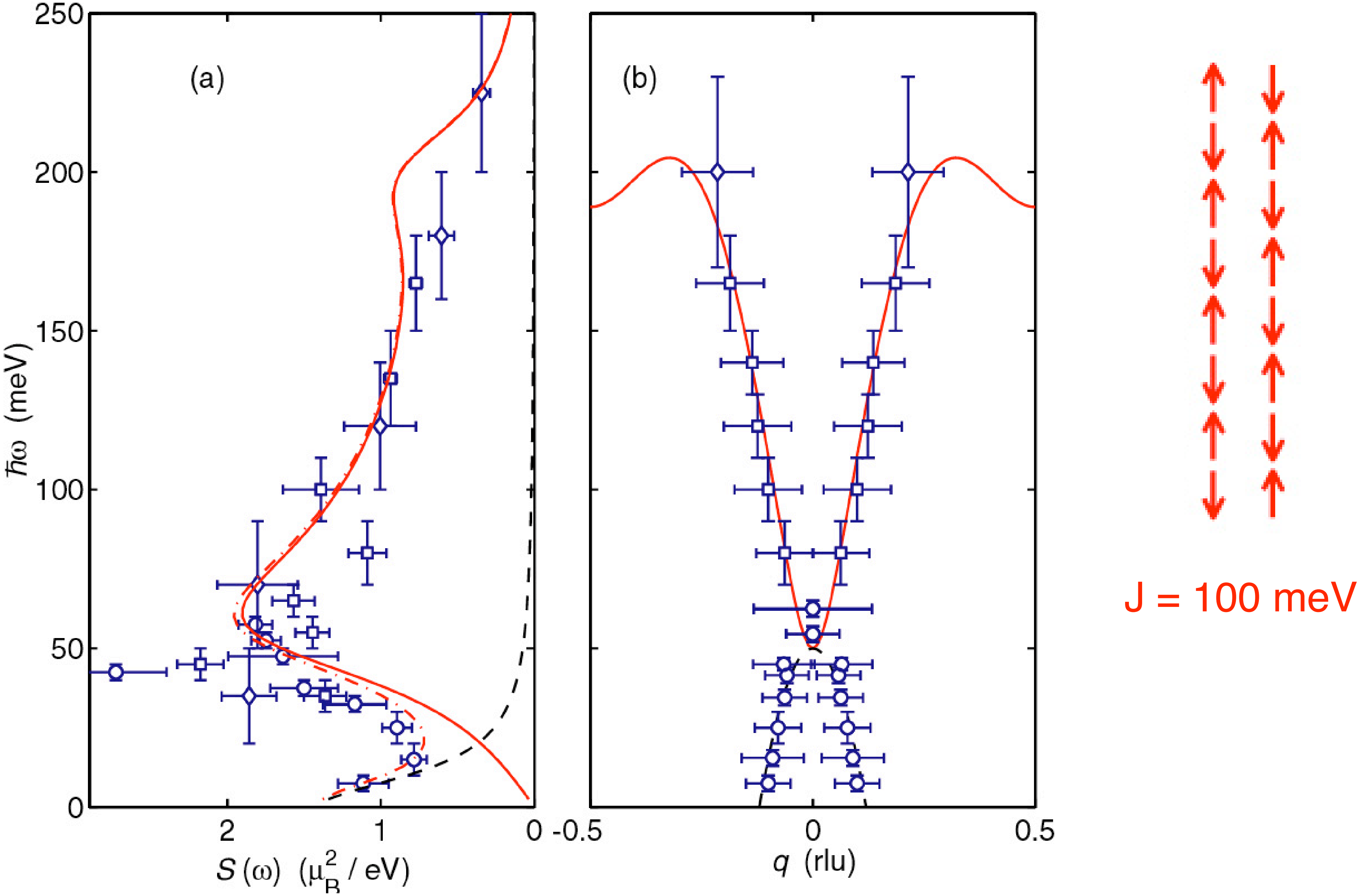
$T_c <$ 6 K

Nature **429**, 534 (2004)



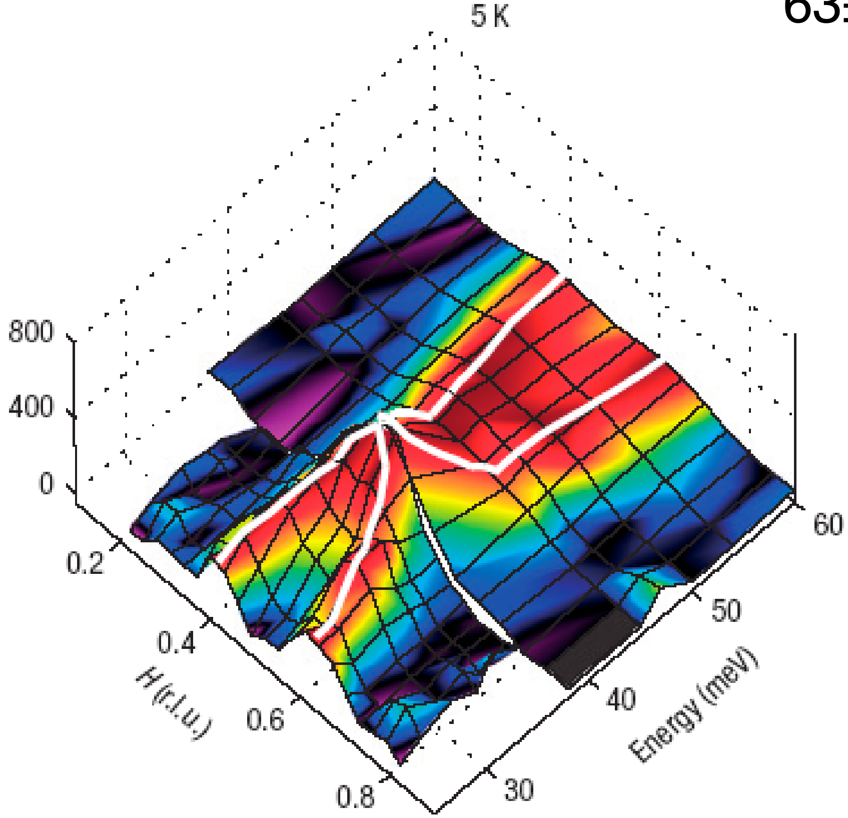


$La_{1.875}Ba_{0.125}CuO_4$ spectrum

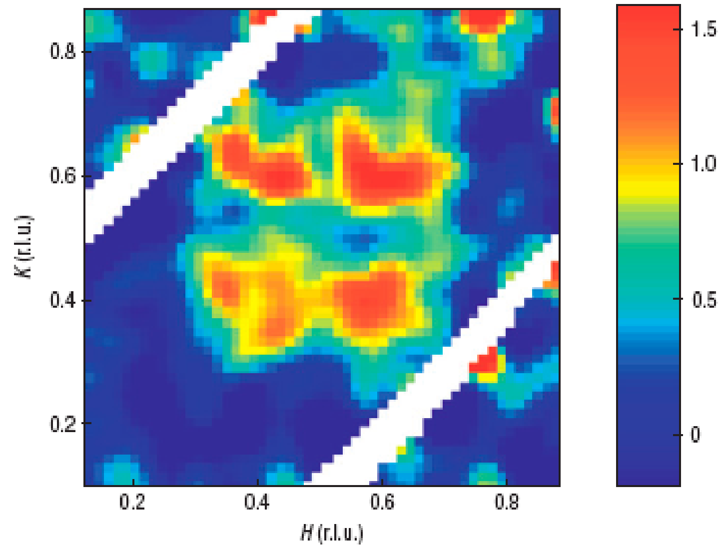


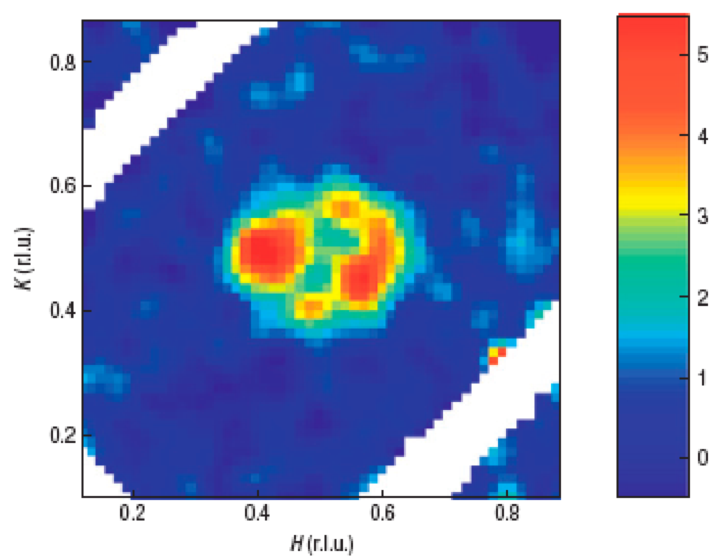
De-twinned $YBa_2Cu_3O_{6.6}$ T_c = 61 K

Hinkov *et al.*, Nature Phys. (2007)



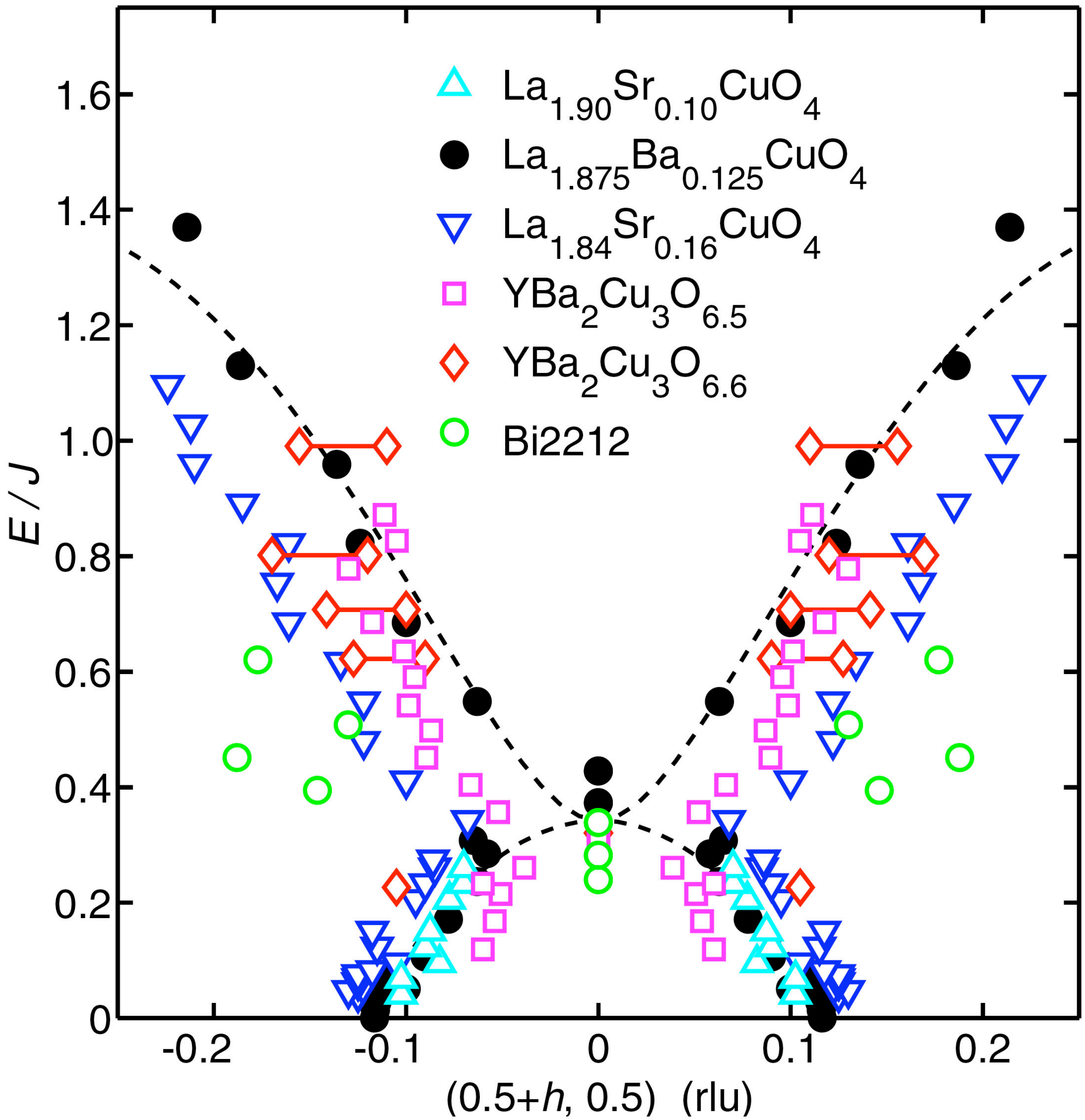
63±5 meV





30±3.5 meV

Comparison of spin fluctuations in doped cuprates



LSCO	J = 146 meV
YBCO	J = 106 meV
Bi2212	$J \approx J_{LSCO}$

Christensen et al., PRL (2004)

Tranquada et al., Nature (2004)

Stock et al., PRB (2005)

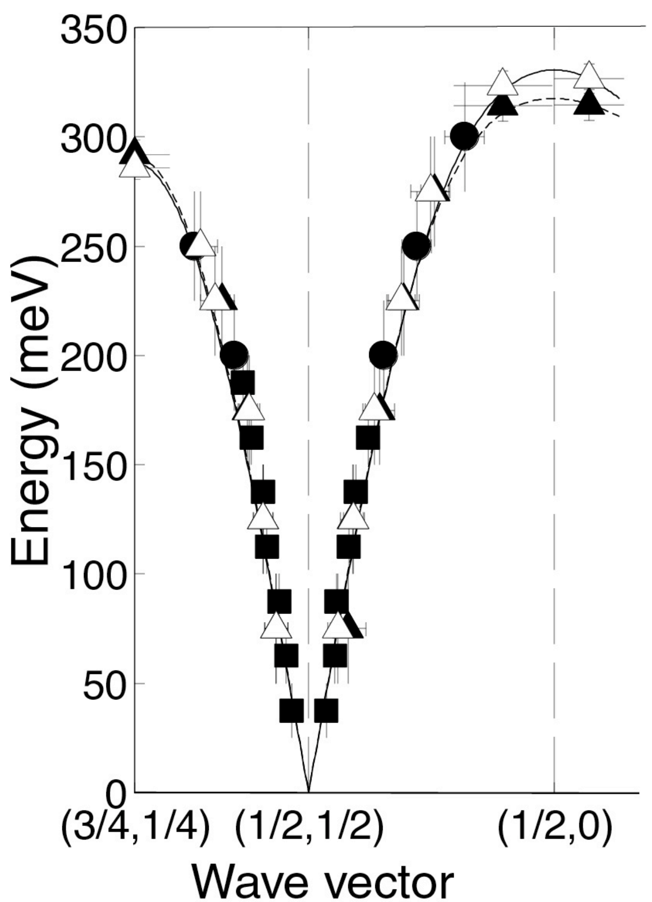
Hayden et al., Nature (2004)

Vignolle et al., Nature Phys. (2007)

G. Xu et al., (unpublished)

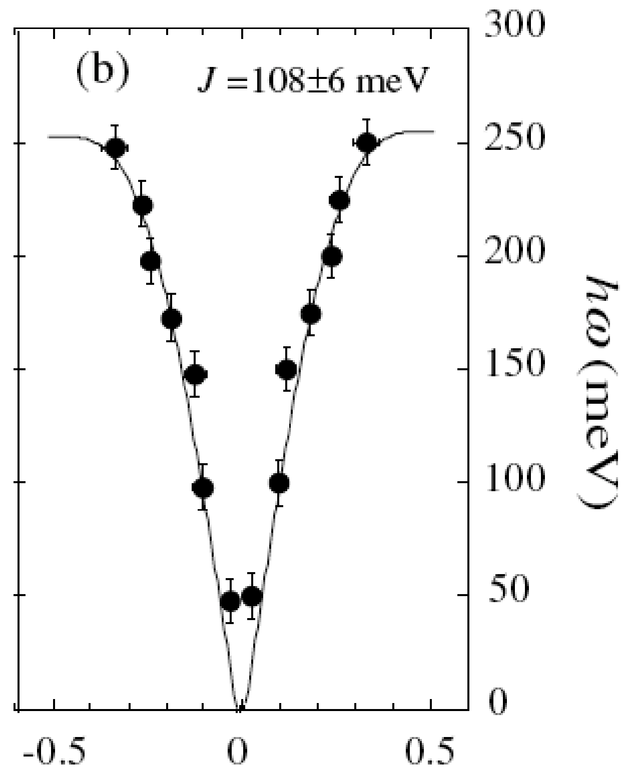
Magnetic spectrum in $La_{2-x}(Sr,Ba)_xCuO_4$

x = 0



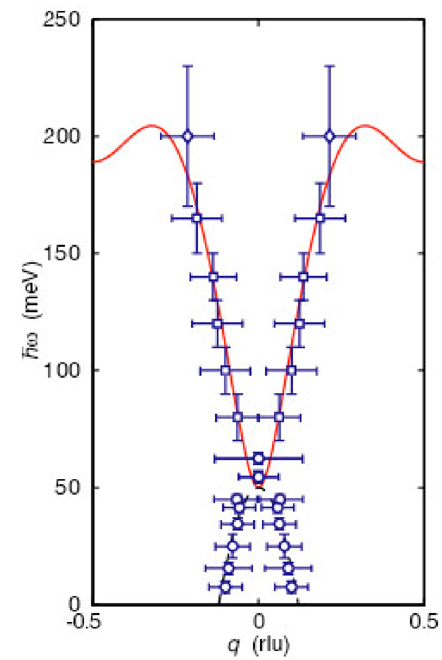
Coldea *et al.*, PRL (2001)

x = 0.05



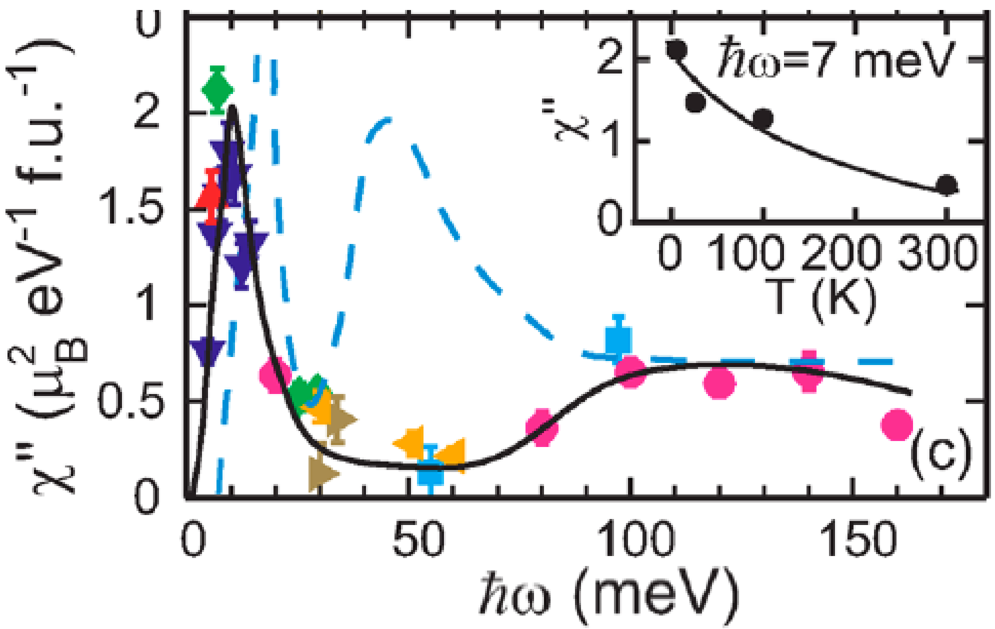
Goka *et al.*, Physica C (2003)

x = 0.125

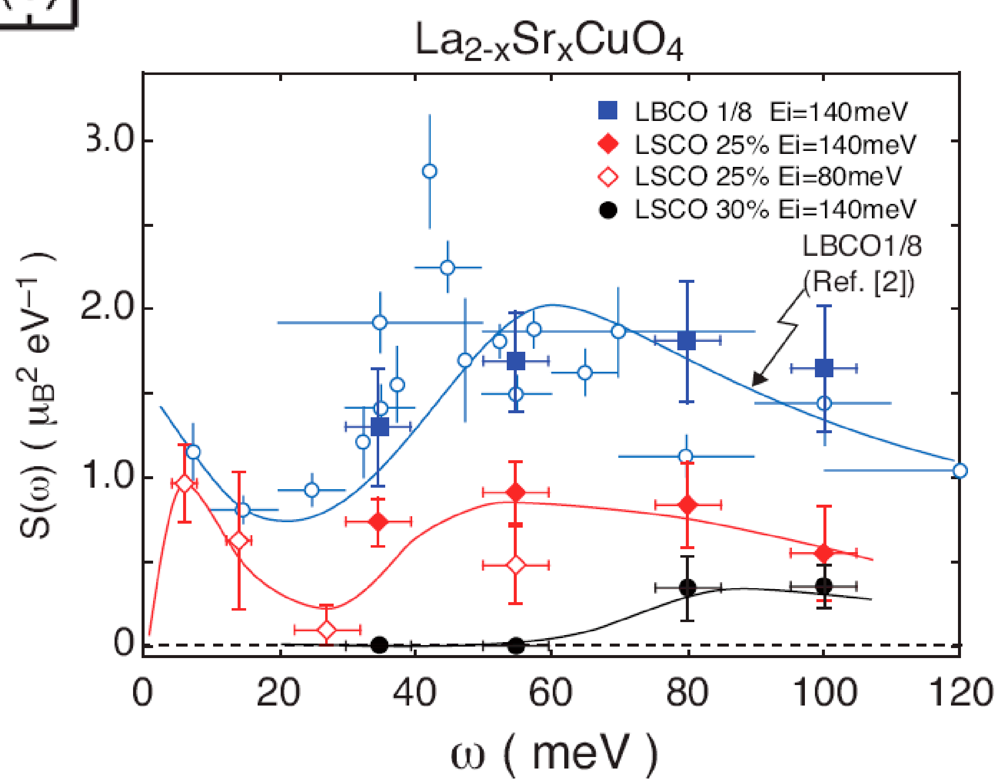


Tranquada *et al.*, Nature (2004)

Magnetic weight disappears with over-doping

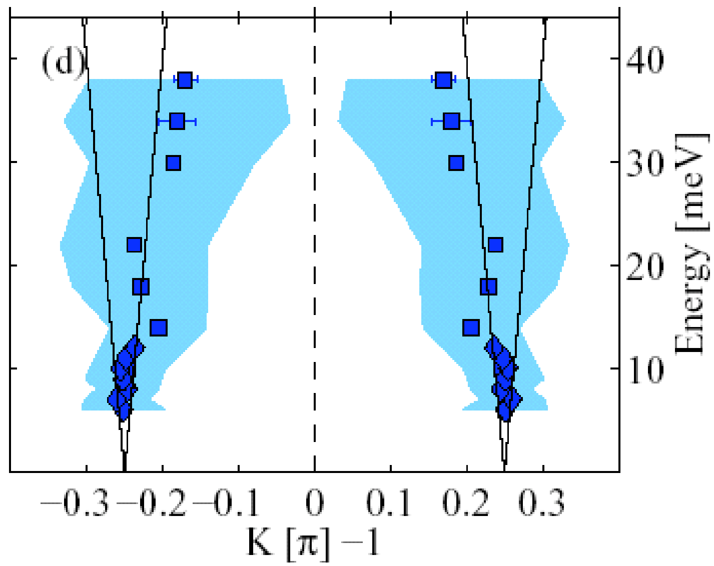


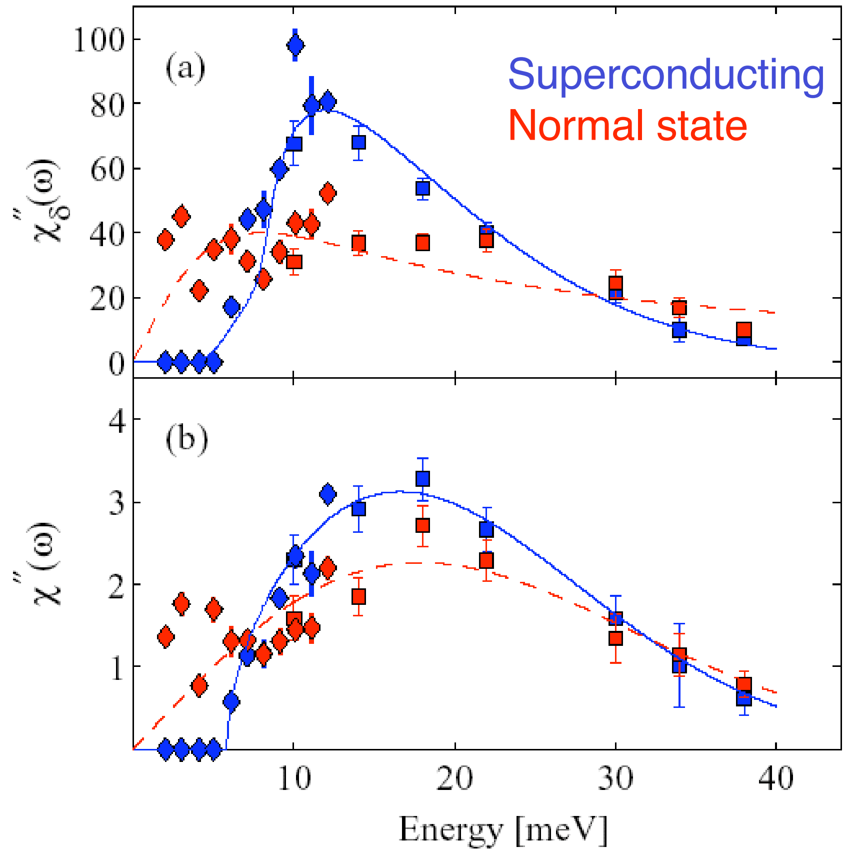
LSCO x = 0.22
Lipscombe *et al.*, PRL (2007)



Wakimoto *et al.*, PRL (2007)

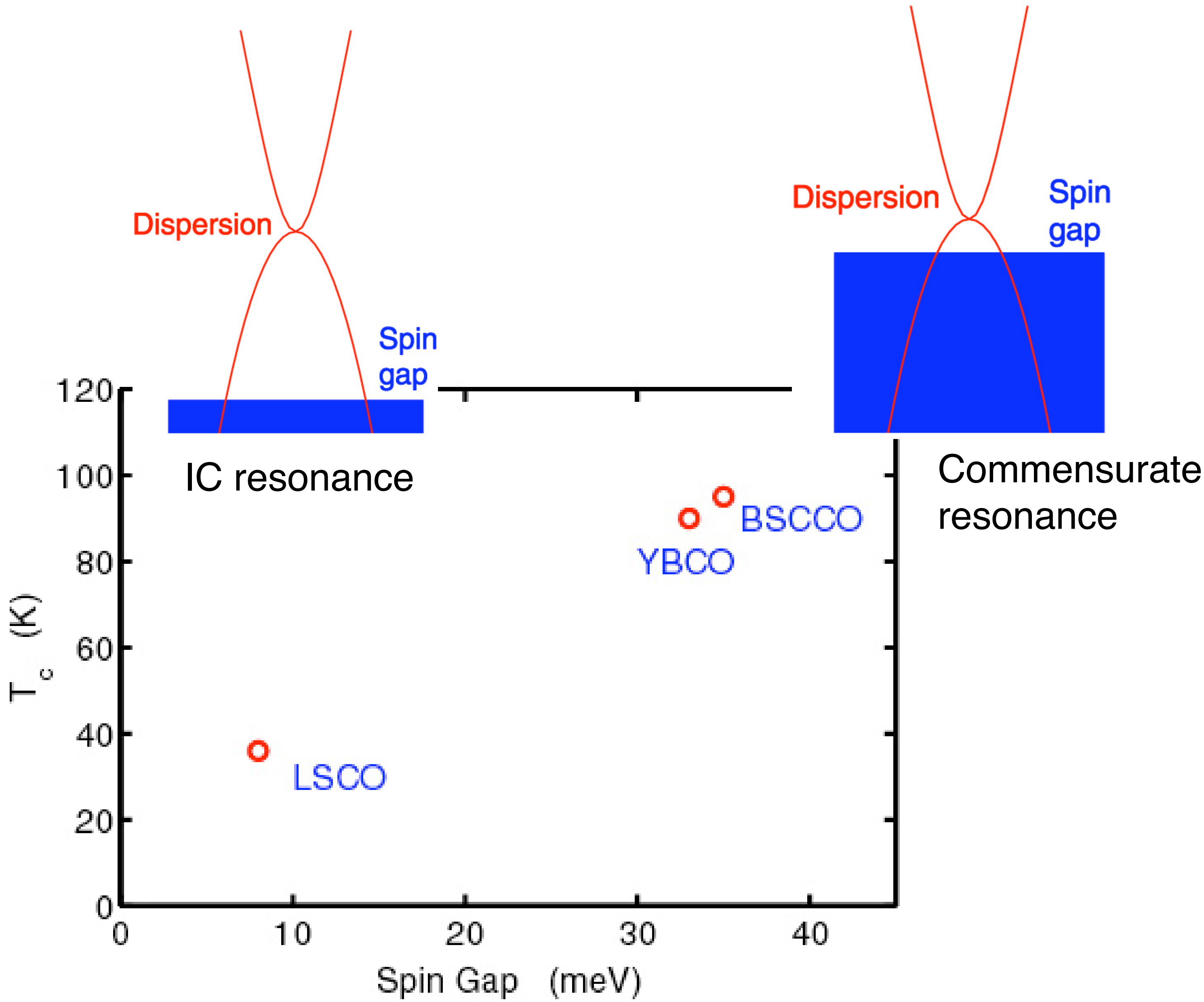
Spin gap in $La_{2-x}Sr_xCuO_4$



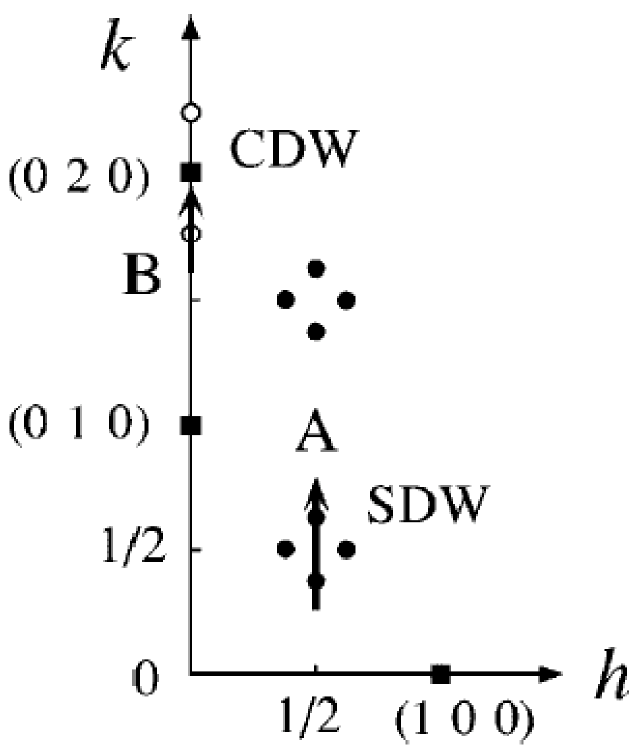


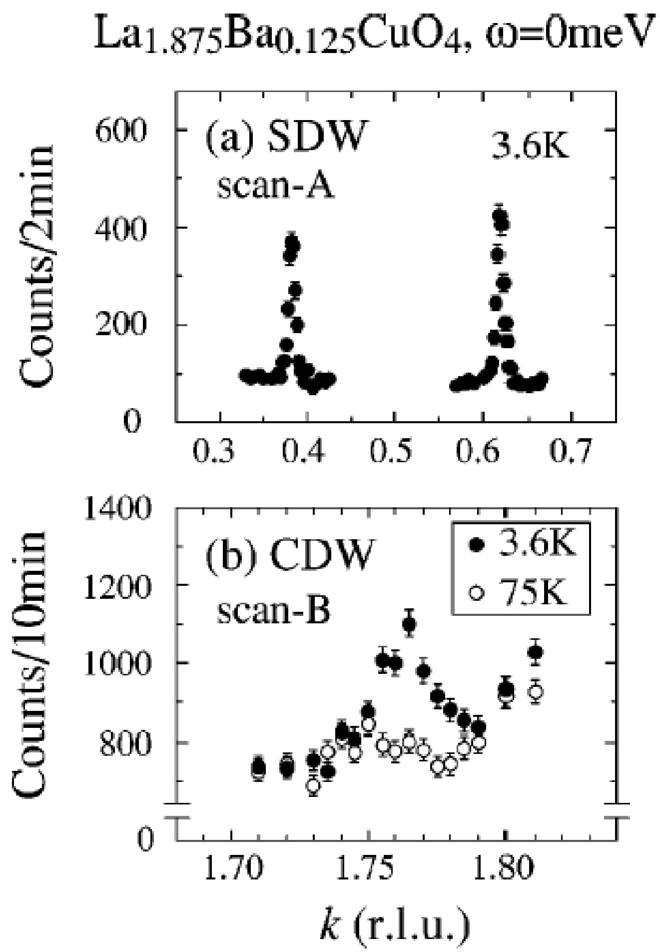
LSCO x = 0.16
Christensen *et al*.
PRL **93**, 147002 (2004)

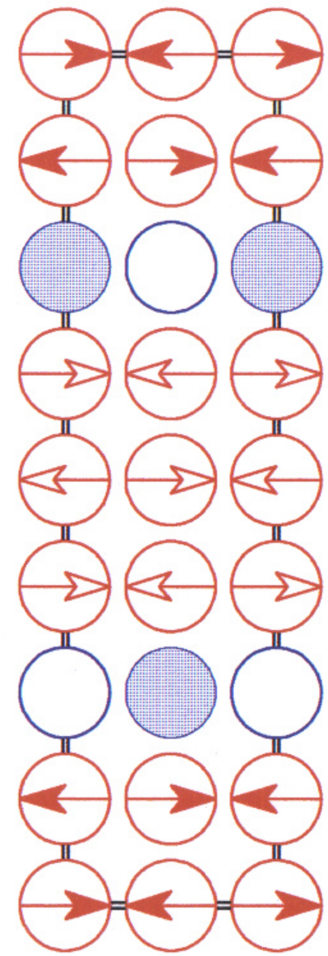
Optimally-doped cuprates



Charge and spin stripe order in $La_{1.875}Ba_{0.125}CuO_4$



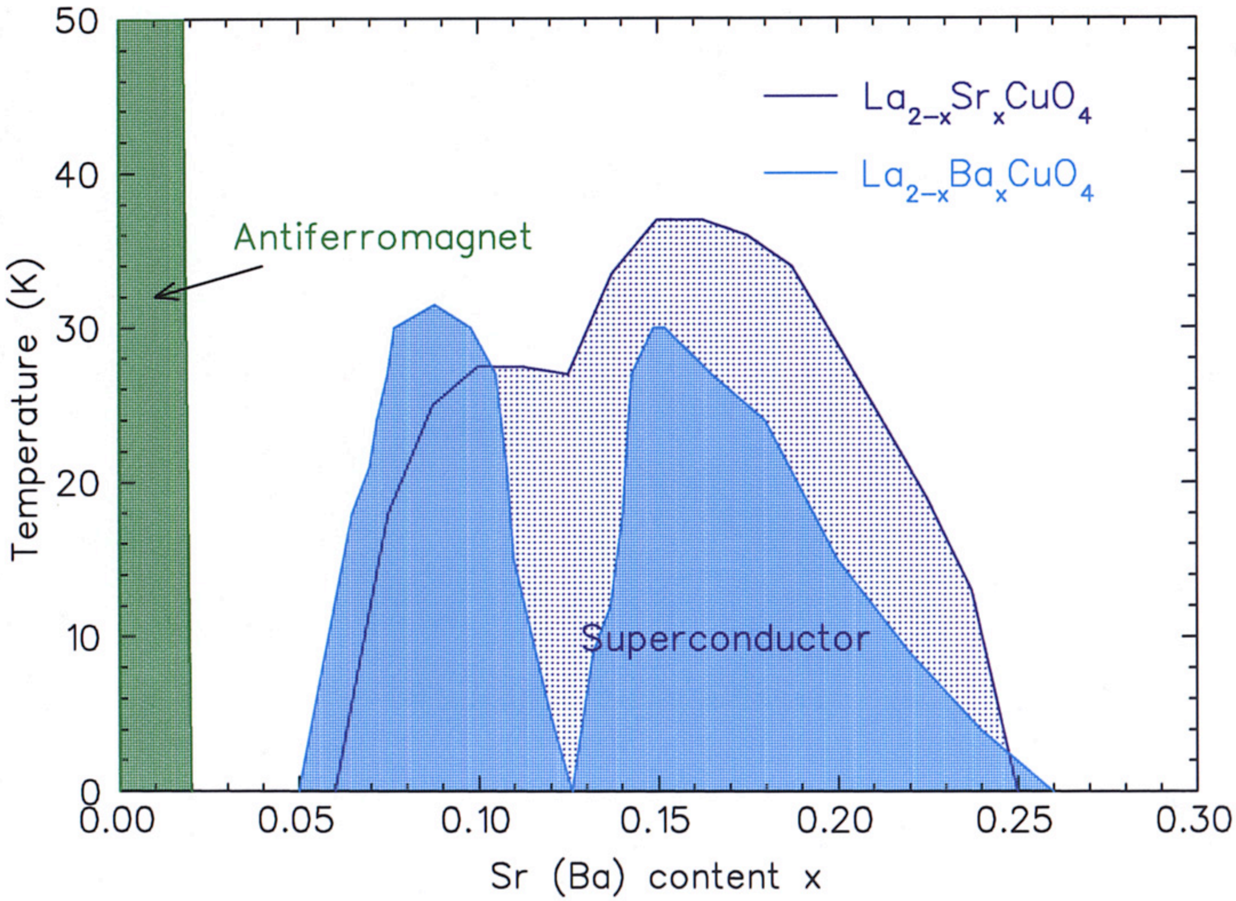




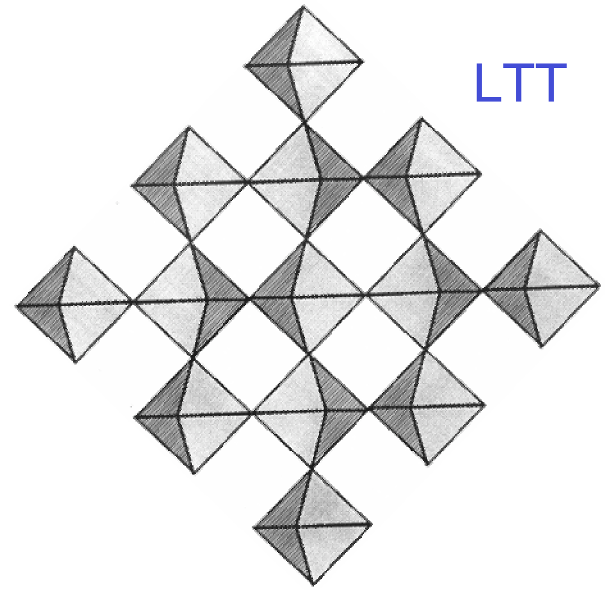
Fujita *et al.*, PRB (2004)

$La_{2-x}Ba_xCuO_4$

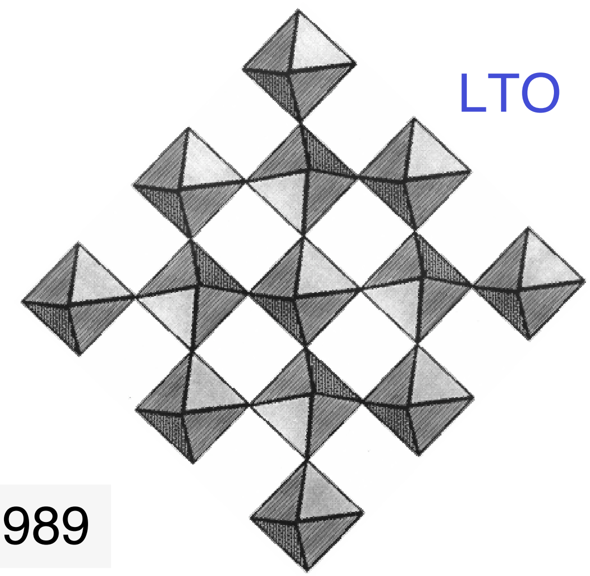
1/8 problem



Moodenbaugh *et al.*, 1988



LTT

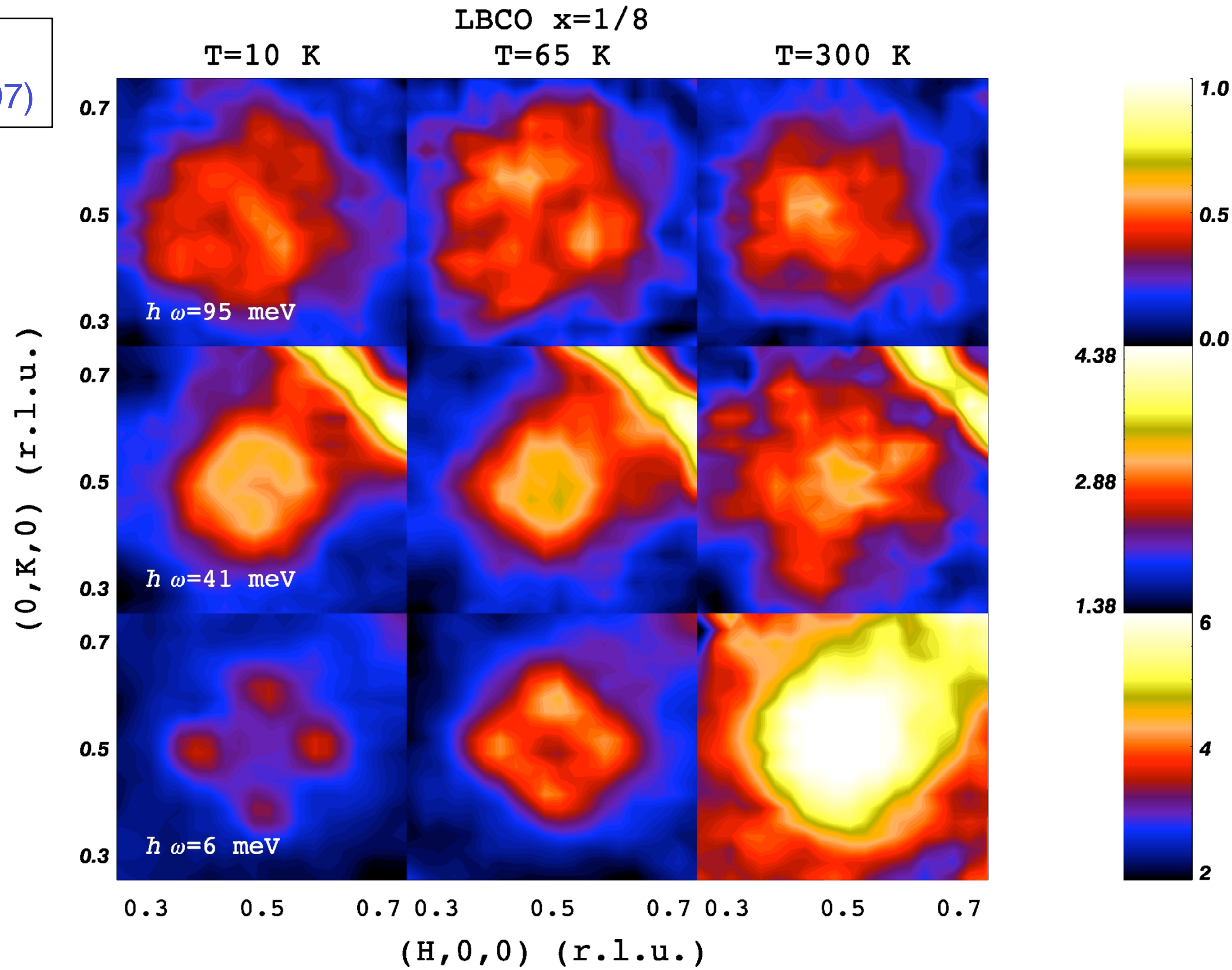


LTO

Axe *et al.*, 1989

T-dependence of spin excitations in LBCO (x=1/8)

G. Xu *et al.*,
Phys. Rev. B (2007)



Stripe order: yes no no

Evidence for 2D superconducting fluctuations

$La_{1.875}Ba_{0.125}CuO_4$

$\rho_c / \rho_{ab} > 10^4$
for $T < 40$ K

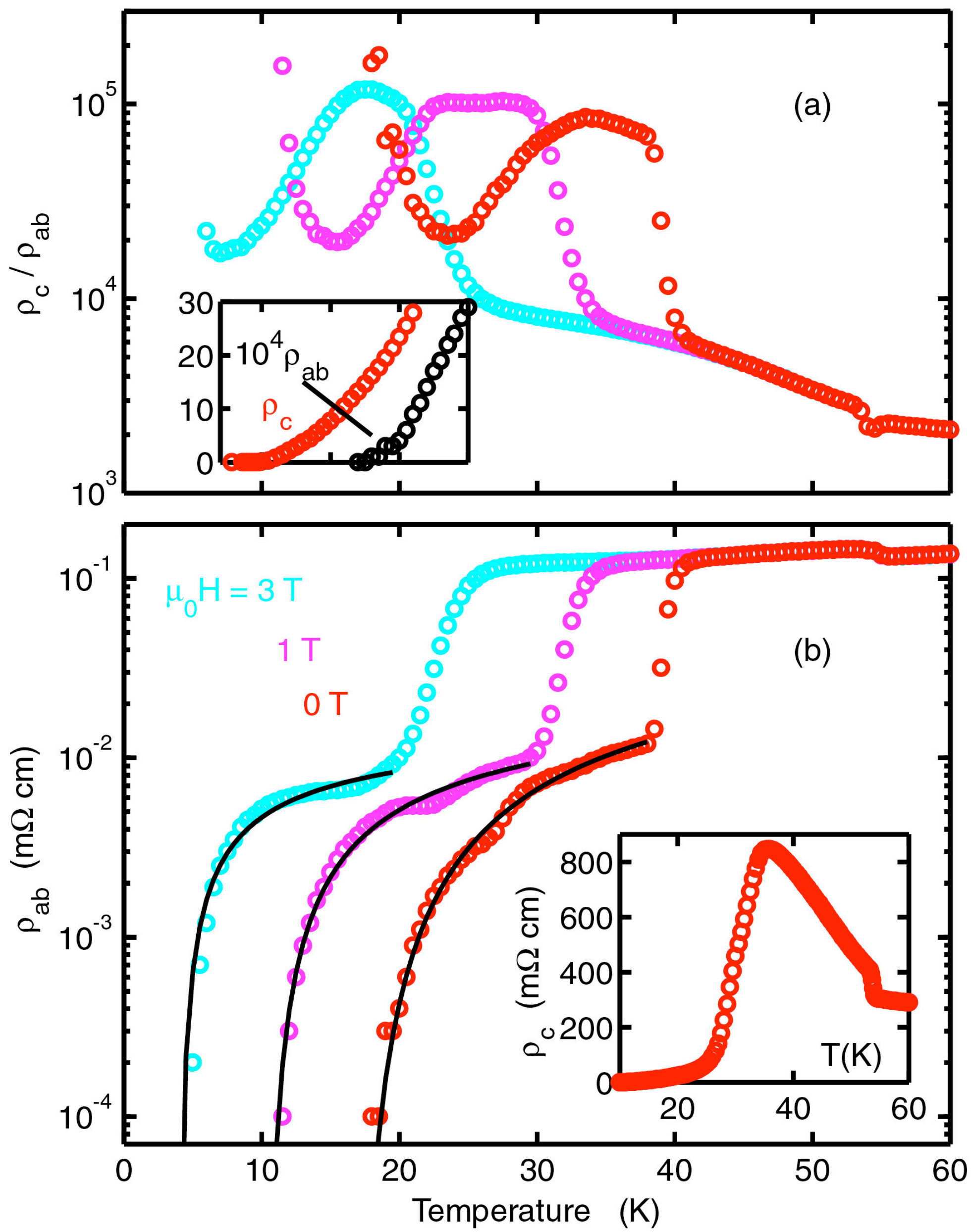
Q. Li *et al.*, PRL (2007)

Resistivity of a 2D superconductor for $T > T_{KT}$:

$$\rho = \rho_n \exp(a(T-T_{KT})^{-1/2})$$

Halperin + Nelson (1979)

$T_{KT} = 16$ K



Conclusions

- AF spin fluctuations in cuprate superconductors
  - Soften with doping
  - Disappear in the overdoped regime
- AF spin fluctuations are characteristic of the correlated insulator
- Stripes provide a way for AF character to survive in doped system
  - Stripe order is compatible with superconductivity