The Abdus Salam
International Centre for Theoretical Physics

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Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

New Structures in the Magnetic Excitations of La2-xSrxCuO4

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UNITED KINGDOM

New Structures in the Spin Excitations of $La_{2-x}Sr_xCuO_4$

Stephen Hayden
University of Bristol

University of BRISTOL

Talk Plan

- Introduction
- Spin Fluctuations in $La_{2-x}Sr_xCuO_4$
- Spin Excitations and the Pseudogap (one gap/two gap models)
- Spin fluctuation and the resonance in $YBa_2Cu_3O_{6+x}$

B. Vignolle et al,
Nat. Phys. 3, 163 (2007)

O. J. Lipscombe et al.,
PRL 99, 067002 (2007)

Collaborators

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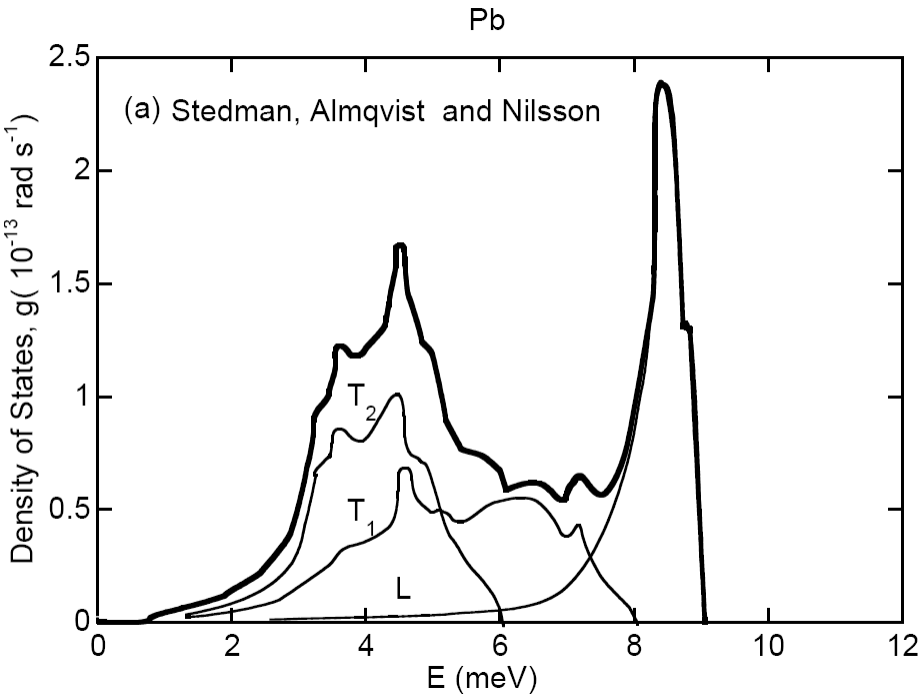
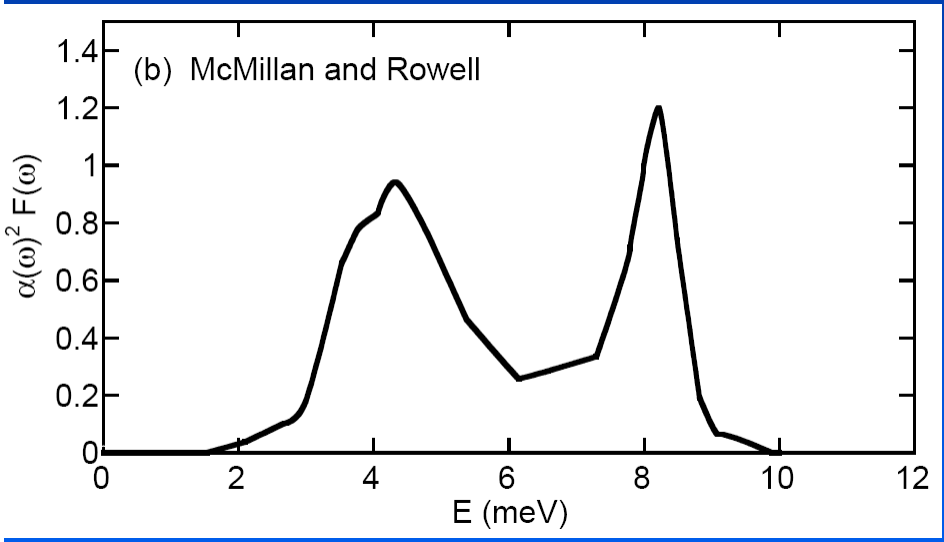
F. Dogan (Missouri-Rolla)

M. Mangkorntong (Tokyo)
M. Nohara (Tokyo)
Hide Takagi (Tokyo)

1)What excitations are relevant to pairing in the cuprates?

Pb





- phonon DOS, $F(\omega)$
- $\alpha^2(\omega) F(\omega)$ from SIS tunnelling

SIS Tunnelling in Conventional Superconductors

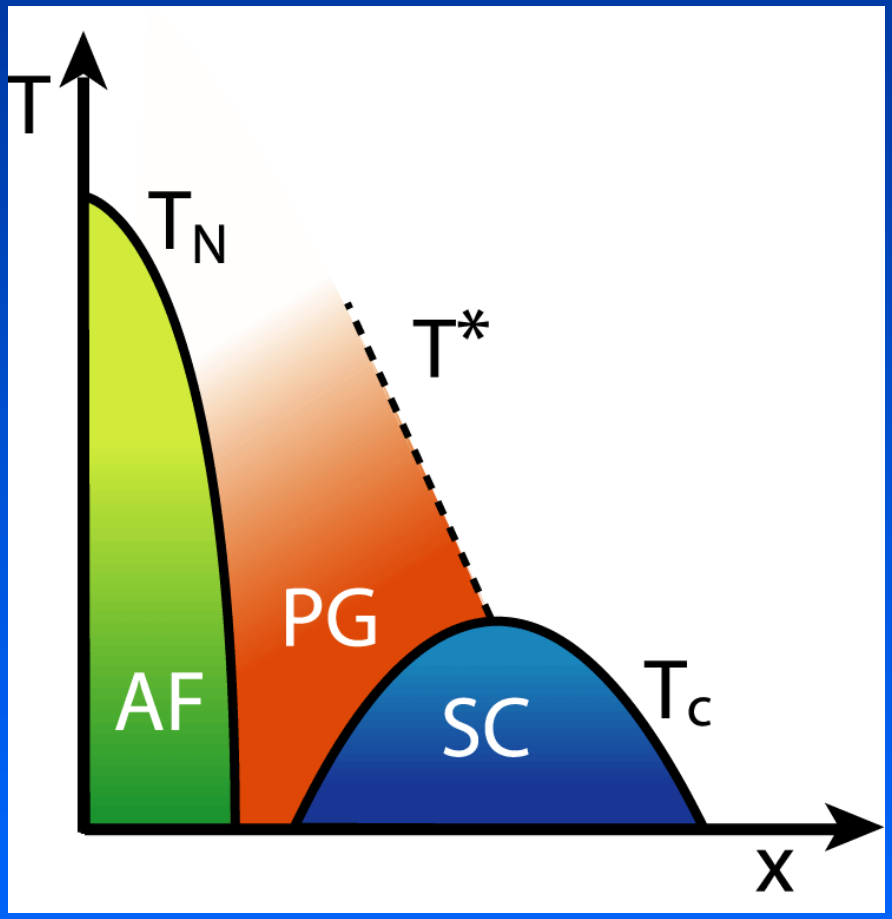
Direct Probes of Bosonic Excitations

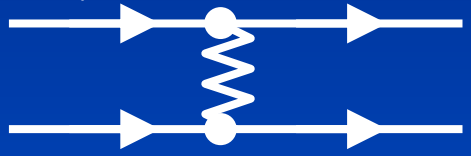
- neutrons
- x-rays
- Raman
- NMR
- .....

Electronic (quasiparticle) spectroscopies

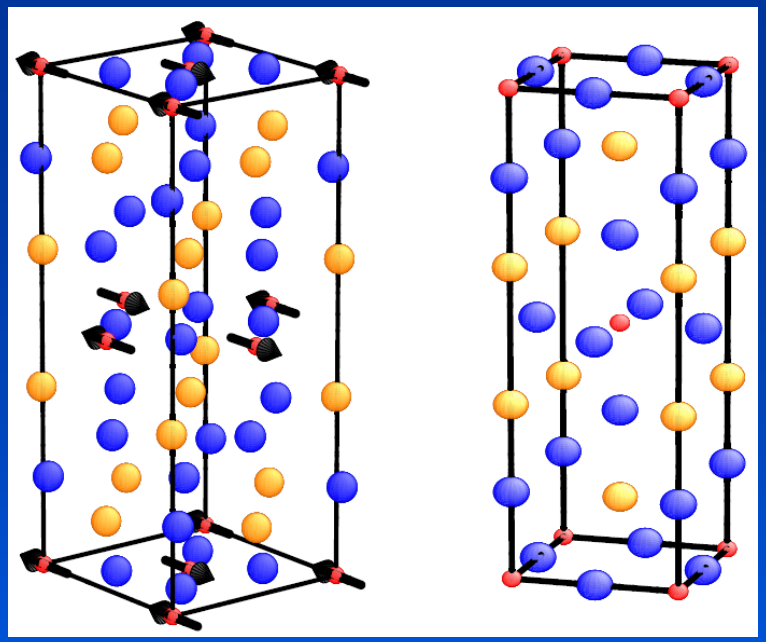
- ARPES
- Tunnelling
- Optical conductivity
- de Haas-van Alphen

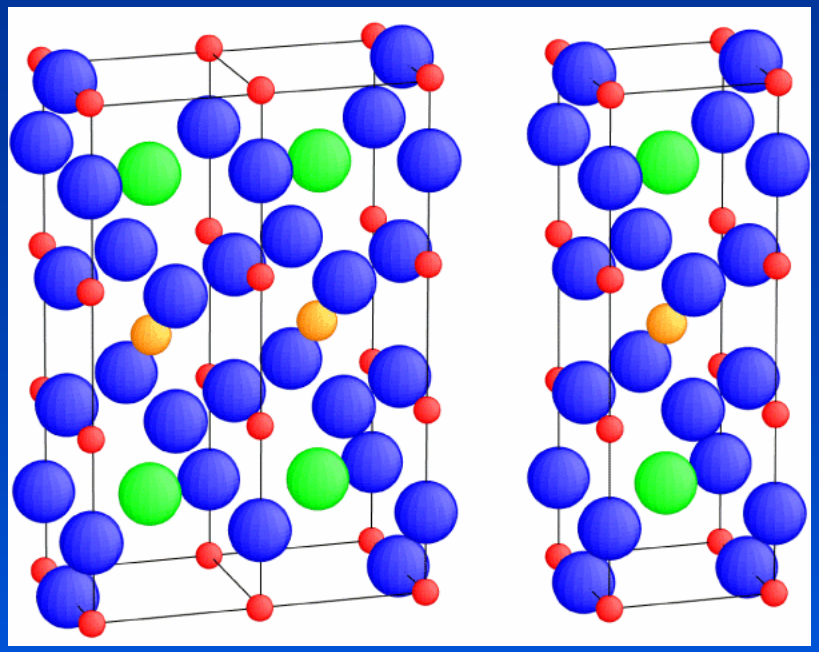
2)What is the relationship between the (magnetic) excitations and the phase diagram of the cuprates?



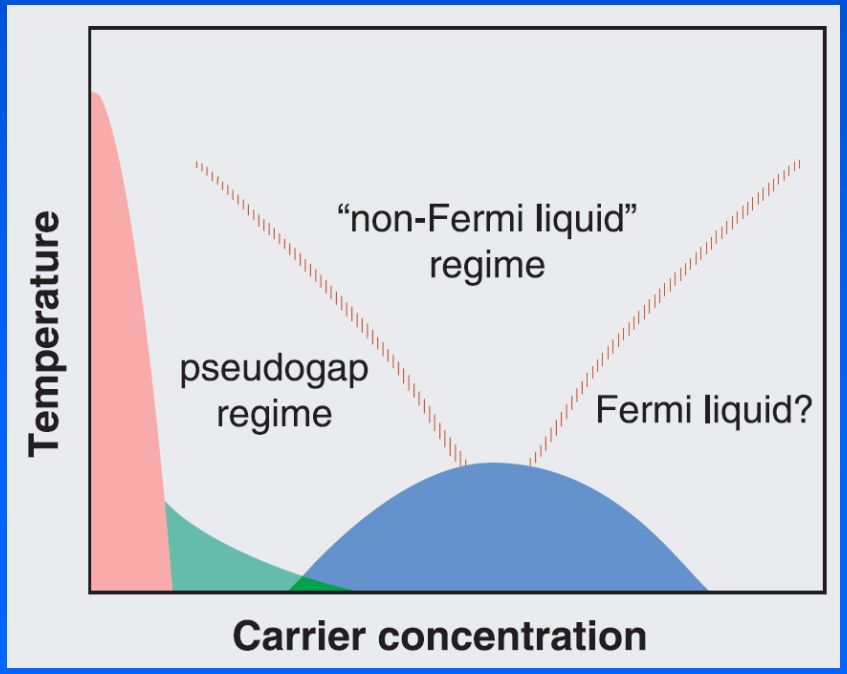


$\Rightarrow$ pseudogap

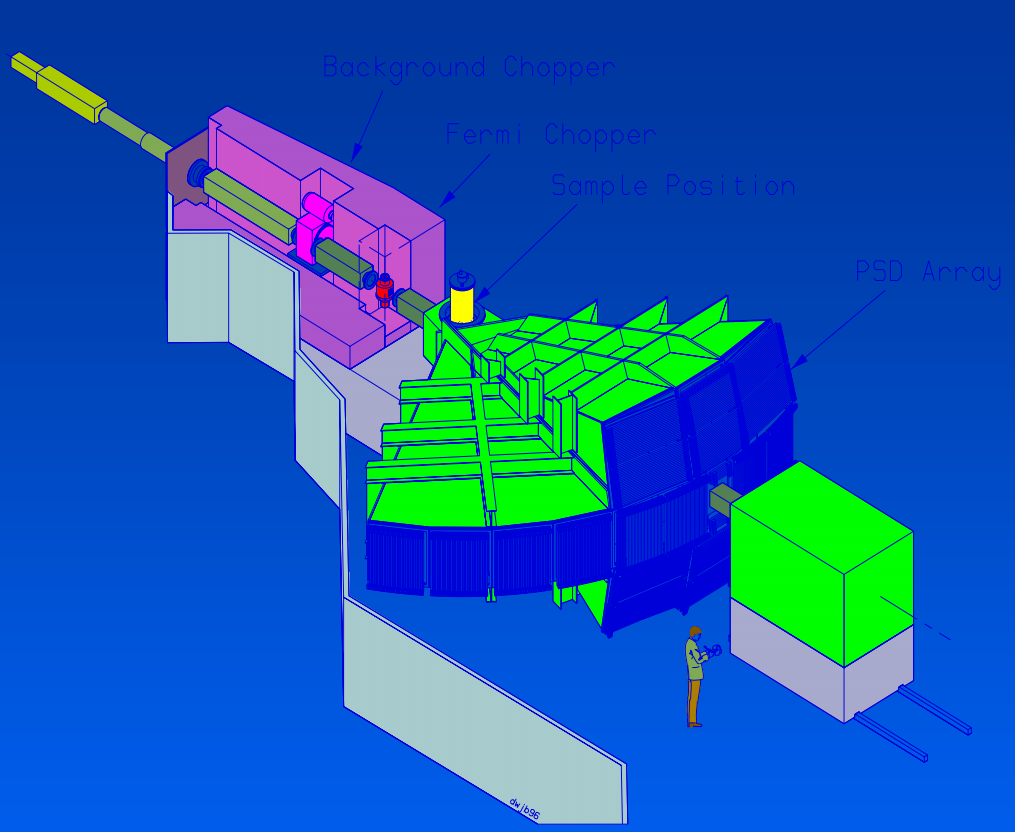




$La_{2-x}Sr_xCuO_4$



$YBa_2Cu_3O_{6+x}$



MAPS

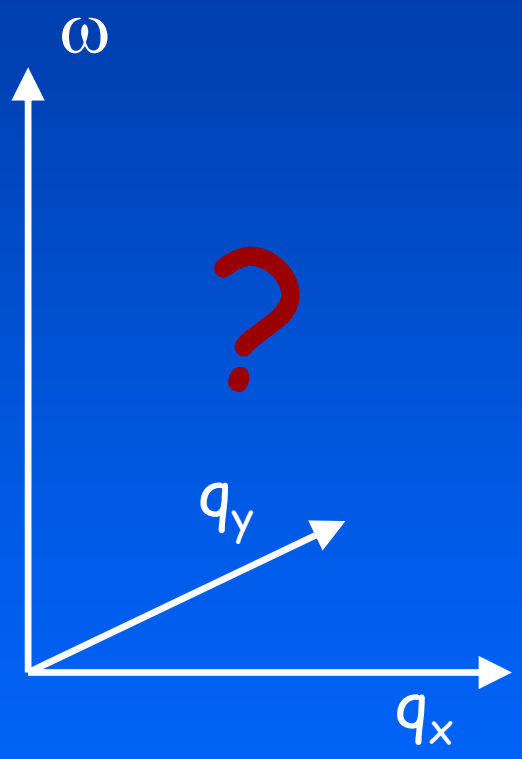
72 g $La_{1.78}Sr_{0.22}CuO_4$

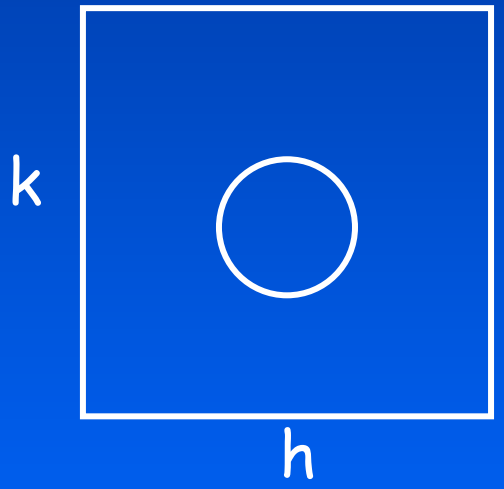
What does inelastic neutron scattering tell us?

$$\frac{d^2\sigma}{d\Omega\, dE} = (\gamma r_e)^2 \frac{k_f}{k_i} |F(\mathbf{Q})|^2 \left(\frac{2/\pi g^2 \mu_B^2}{1 - \exp(-\hbar\omega/kT)} \right) \chi''(\mathbf{Q}, \omega)$$

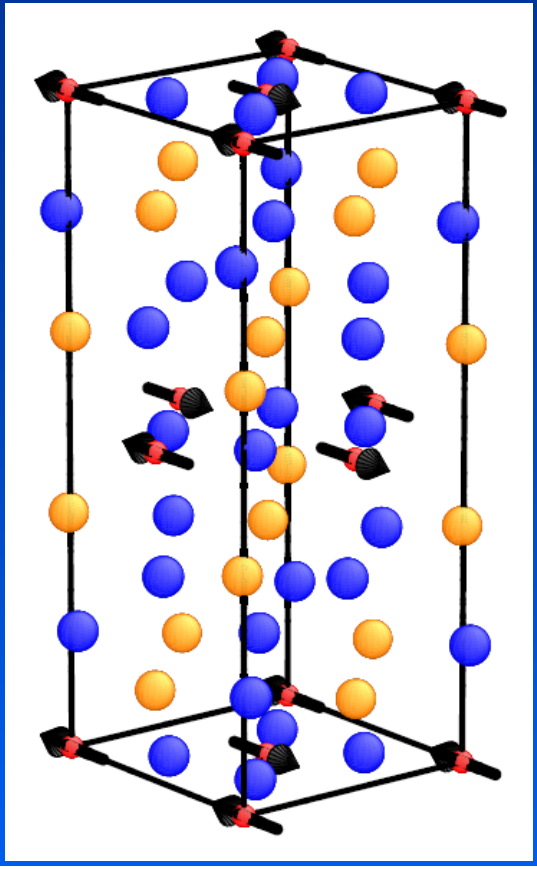
$$\chi''_{\text{local}}(\omega) = \frac{\int_{BZ} \chi''(\mathbf{Q}, \omega)\, d\mathbf{Q}}{\int_{BZ} d\mathbf{Q}}$$

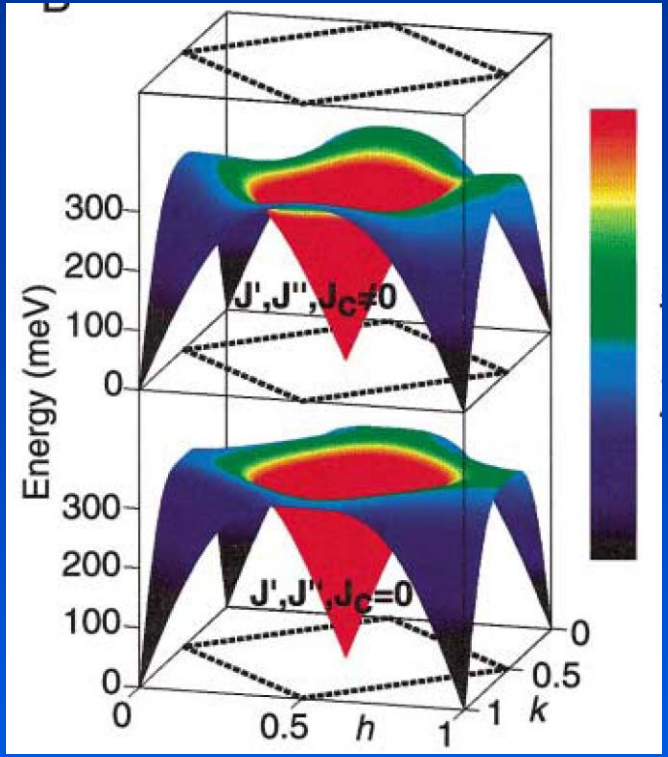
The response function $\chi''(q,\omega)$

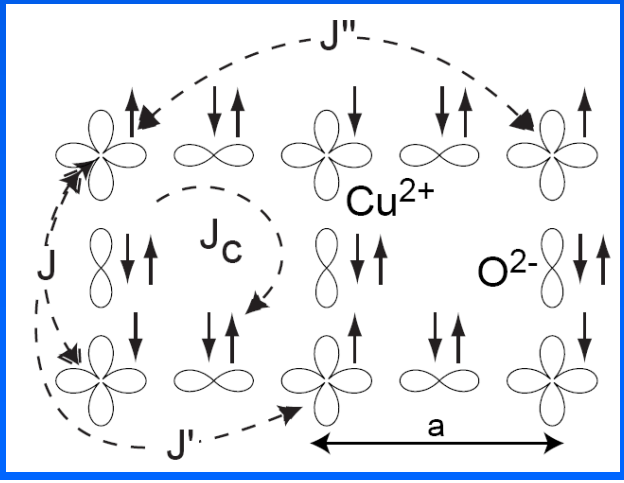


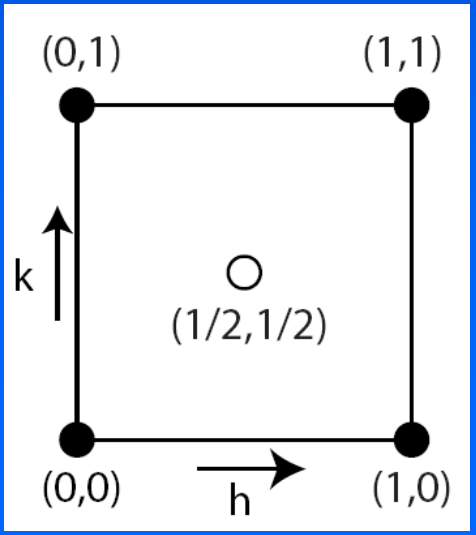


Example: spin waves in La_2CuO_4

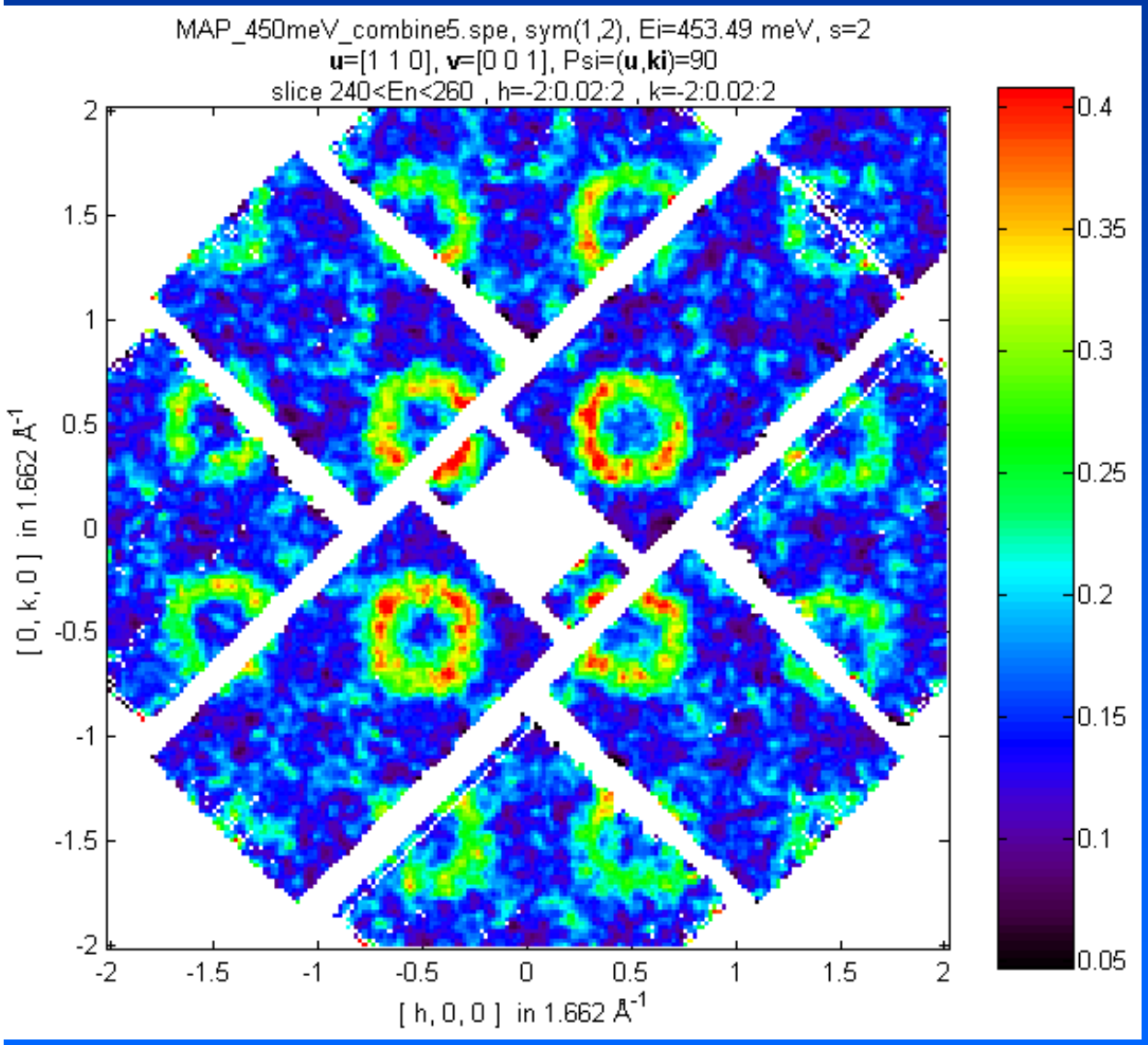




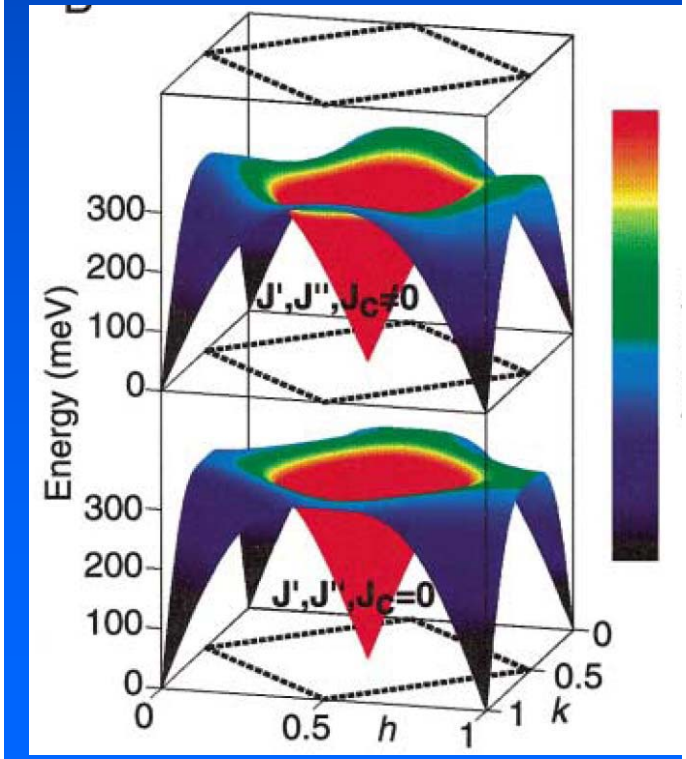




Example: spin waves in La_2CuO_4

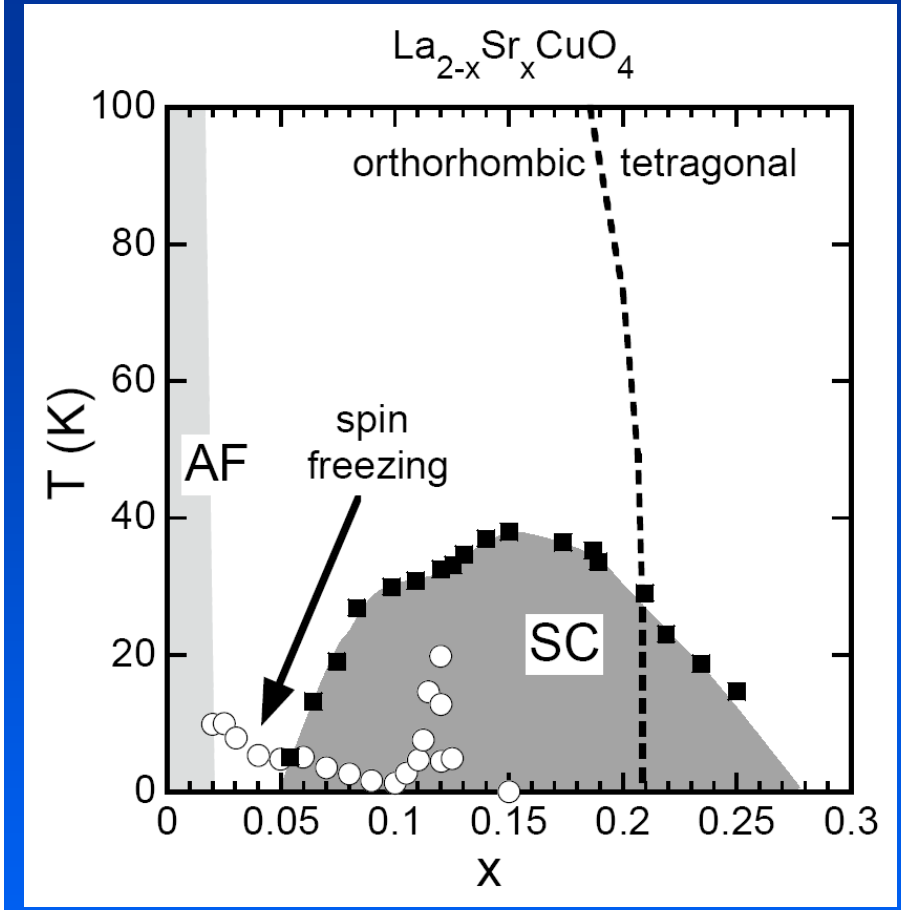


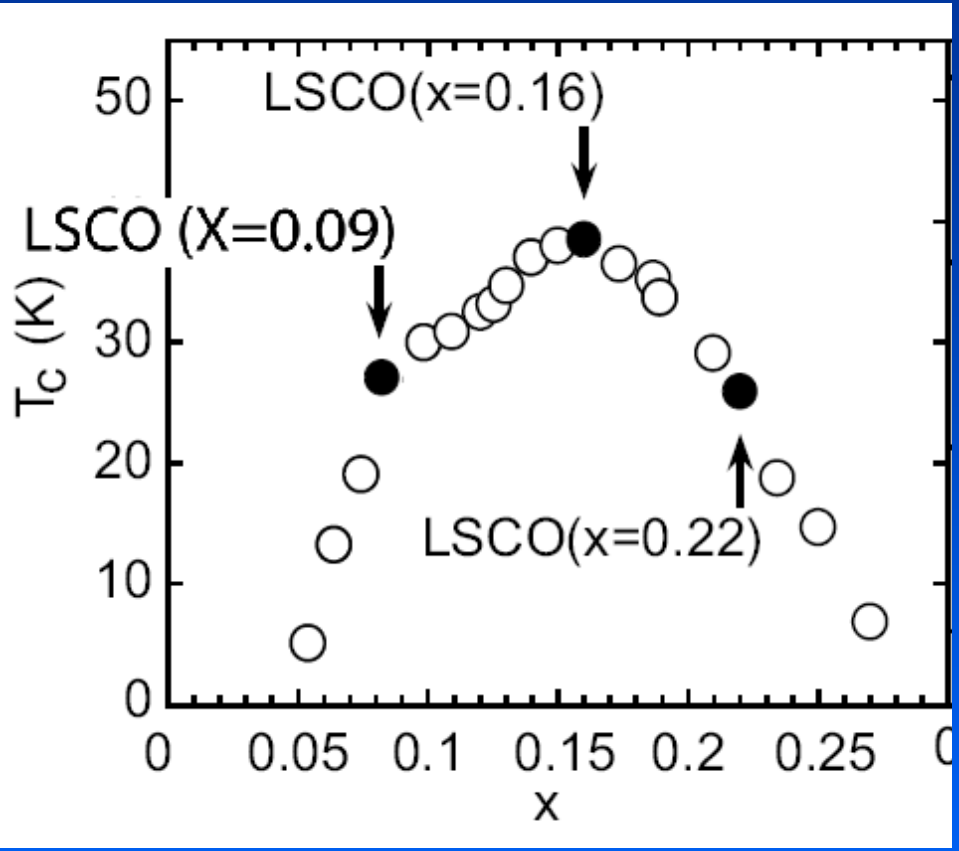
E=250 meV



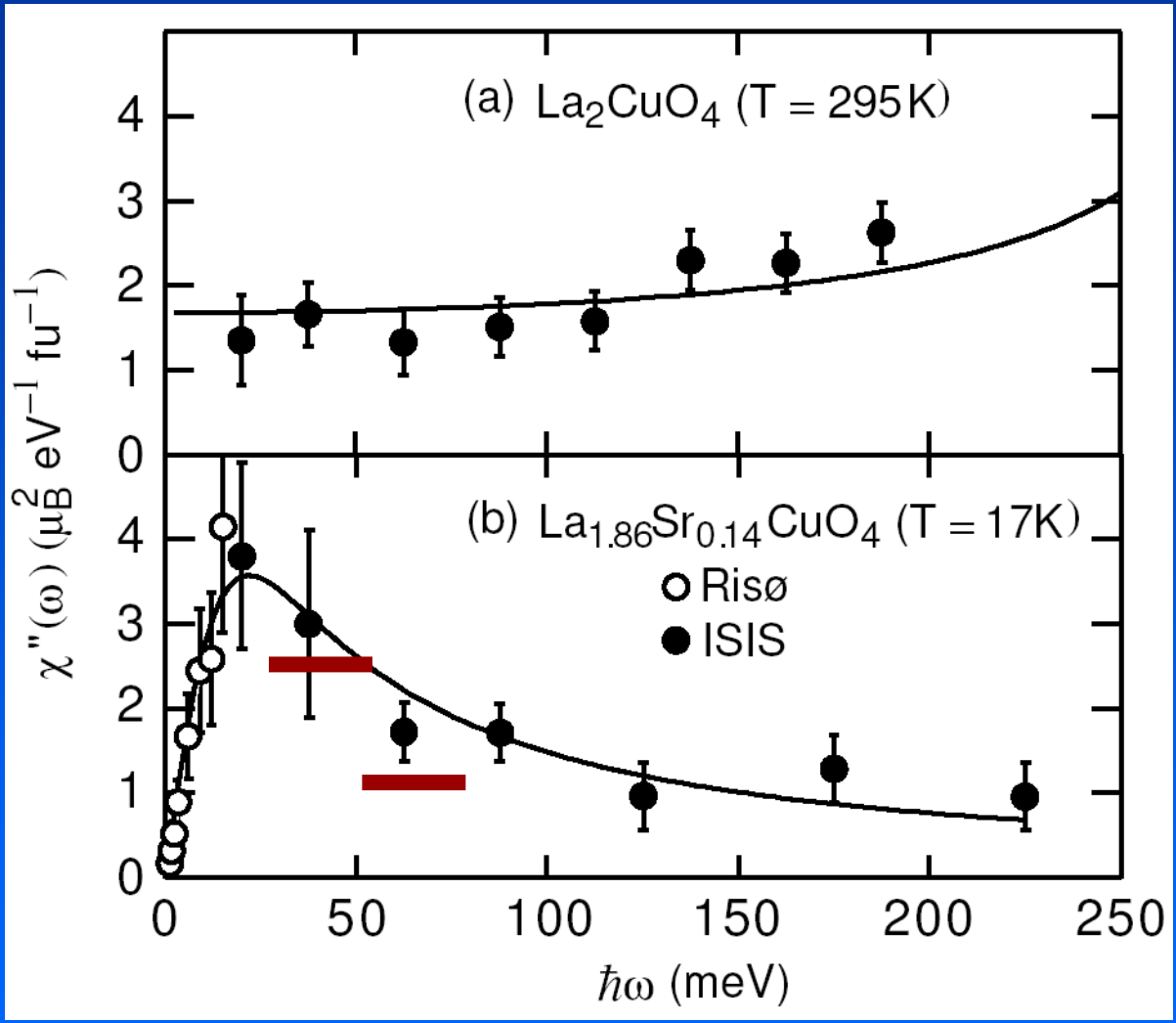
Spin Fluctuations in $La_{2-x}Sr_xCuO_4$ (new stuff)

$La_{2-x}Sr_xCuO_4$





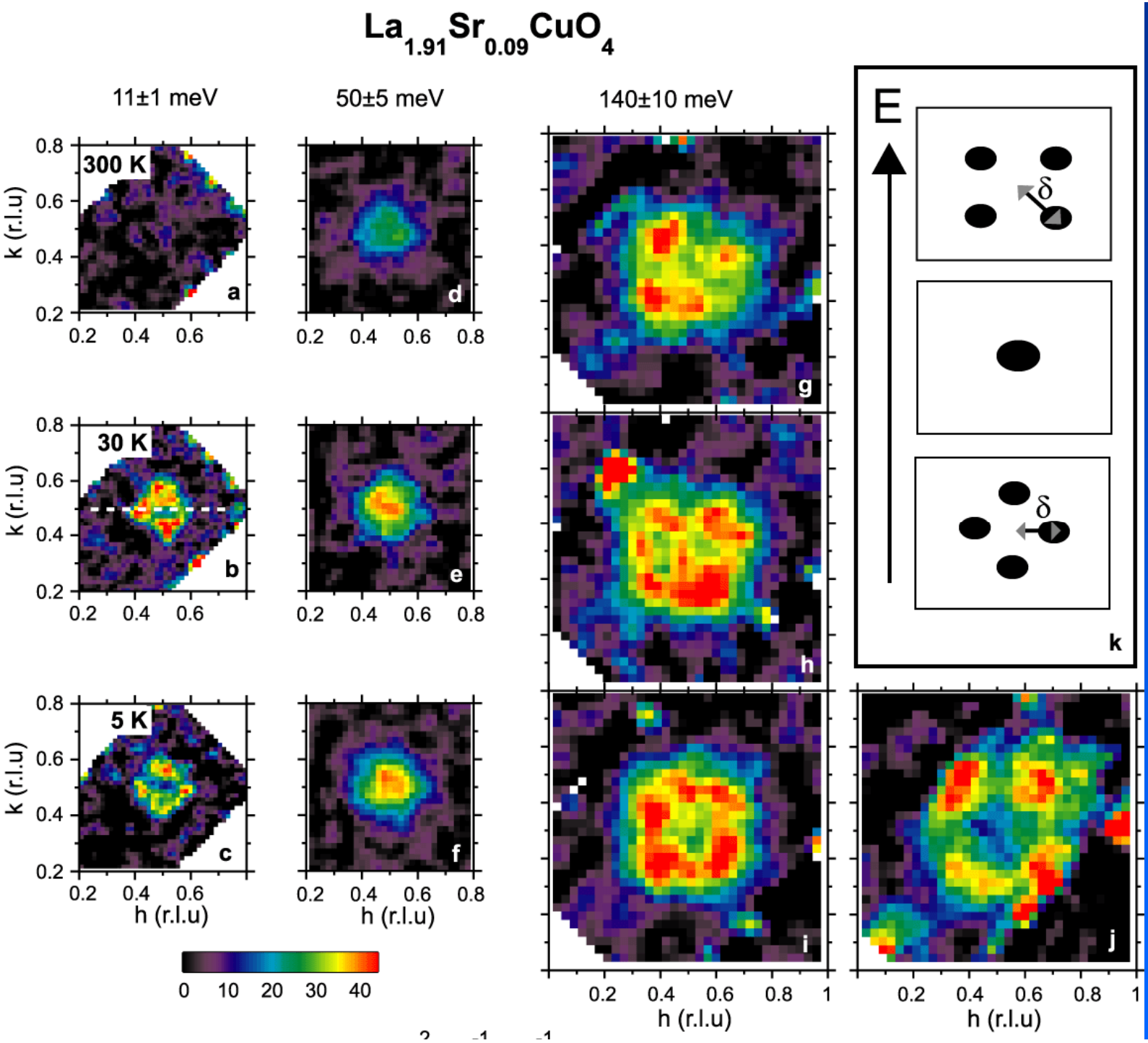
Spin excitations in $La_{2-x}Sr_xCuO_4$

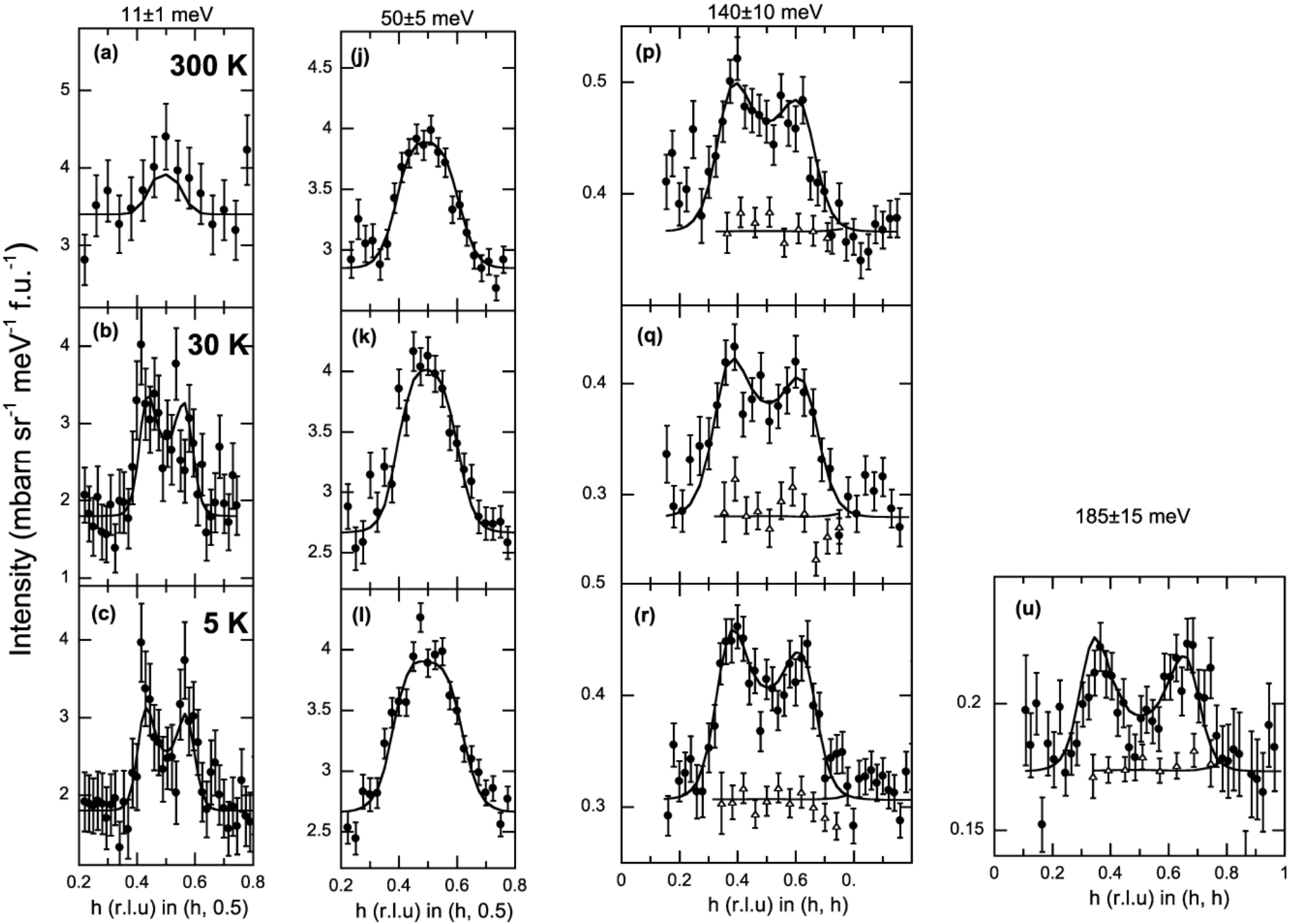


$La_{1.91}Sr_{0.09}CuO_4$ (underdoped)

$La_{1.84}Sr_{0.16}CuO_4$ (optimal)

$La_{1.78}Sr_{0.22}CuO_4$ (overdoped)


La1.91Sr0.09CuO4
11±1 meV
50±5 meV
140±10 meV
300 K
30 K
5 K
k (r.l.u)
h (r.l.u)
a
b
c
d
e
f
g
h
i
j
k
E
δ
δ
0 10 20 30 40


11±1 meV
50±5 meV
140±10 meV
185±15 meV
(a)
300 K
(b)
30 K
(c)
5 K
(j)
(k)
(l)
(p)
(q)
(r)
(u)
Intensity (mbarn sr-1 meV-1 f.u.-1)
h (r.l.u) in (h, 0.5)
h (r.l.u) in (h, 0.5)
h (r.l.u) in (h, h)
h (r.l.u) in (h, h)

Modified Lorentzian Cross Section (Sato-Maki Cross section)

$$\chi''(\mathbf{Q},\omega) = \chi_\delta(\omega)\frac{\kappa^4(\omega)}{\left[\kappa^2(\omega)+R(\mathbf{Q})\right]^2}$$

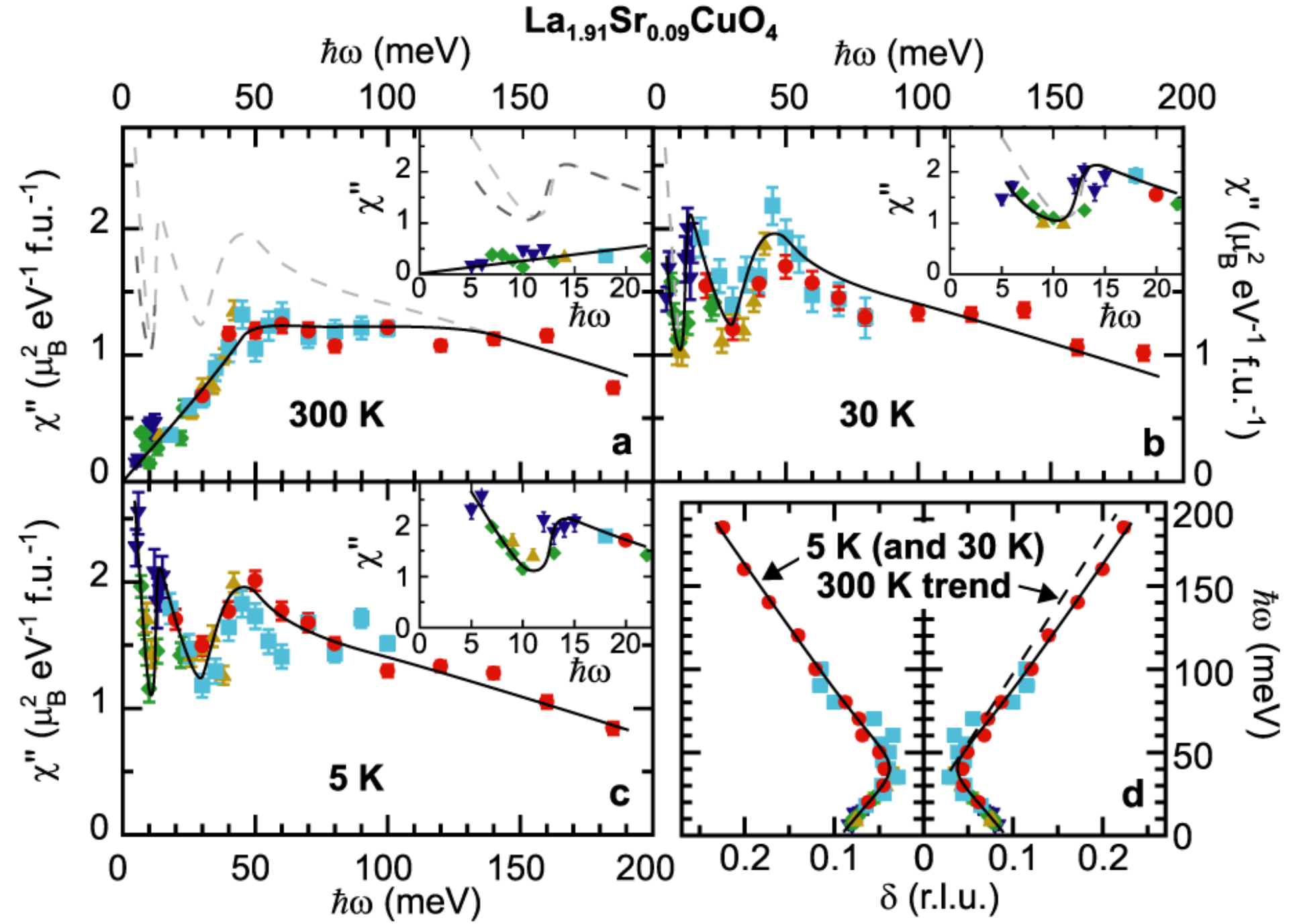
$$R(\mathbf{Q}) = \frac{\left[(h-\frac{1}{2})^2+(k-\frac{1}{2})^2-\delta^2\right]^2+\lambda(h-\frac{1}{2})^2(k-\frac{1}{2})^2}{4\delta^2}$$

$\chi_\delta(\omega)$ amplitude

δ incommensurability

$\kappa(\omega)$ inverse correlation length

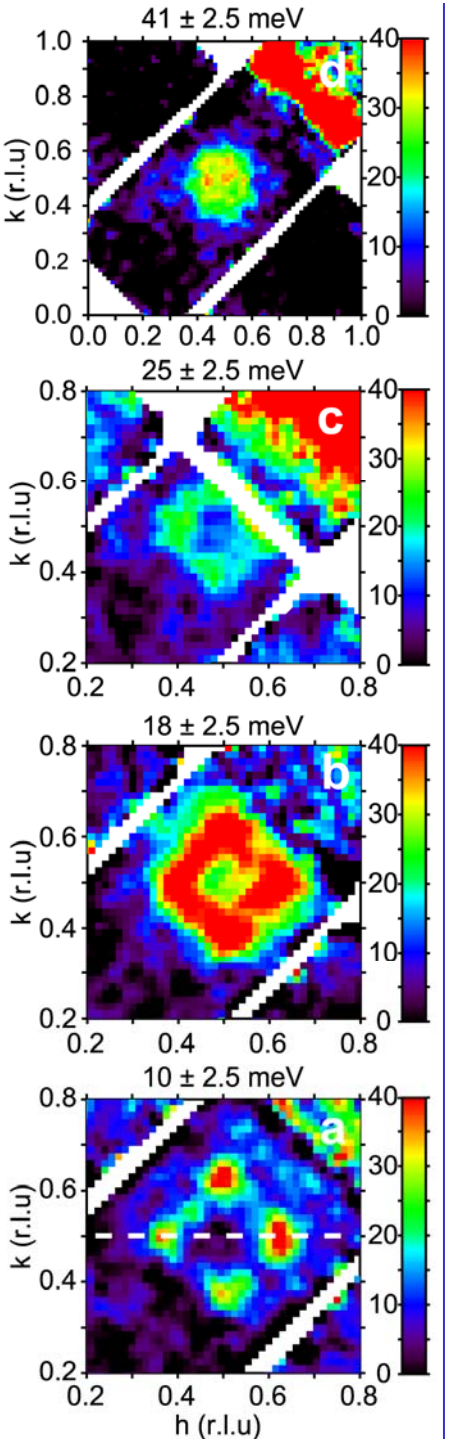
λ anisotropy parameter


La1.91Sr0.09CuO4
ħω (meV)
χ'' (μB2 eV-1 f.u.-1)
300 K
a
30 K
b
5 K
c
5 K (and 30 K)
300 K trend
d
δ (r.l.u.)

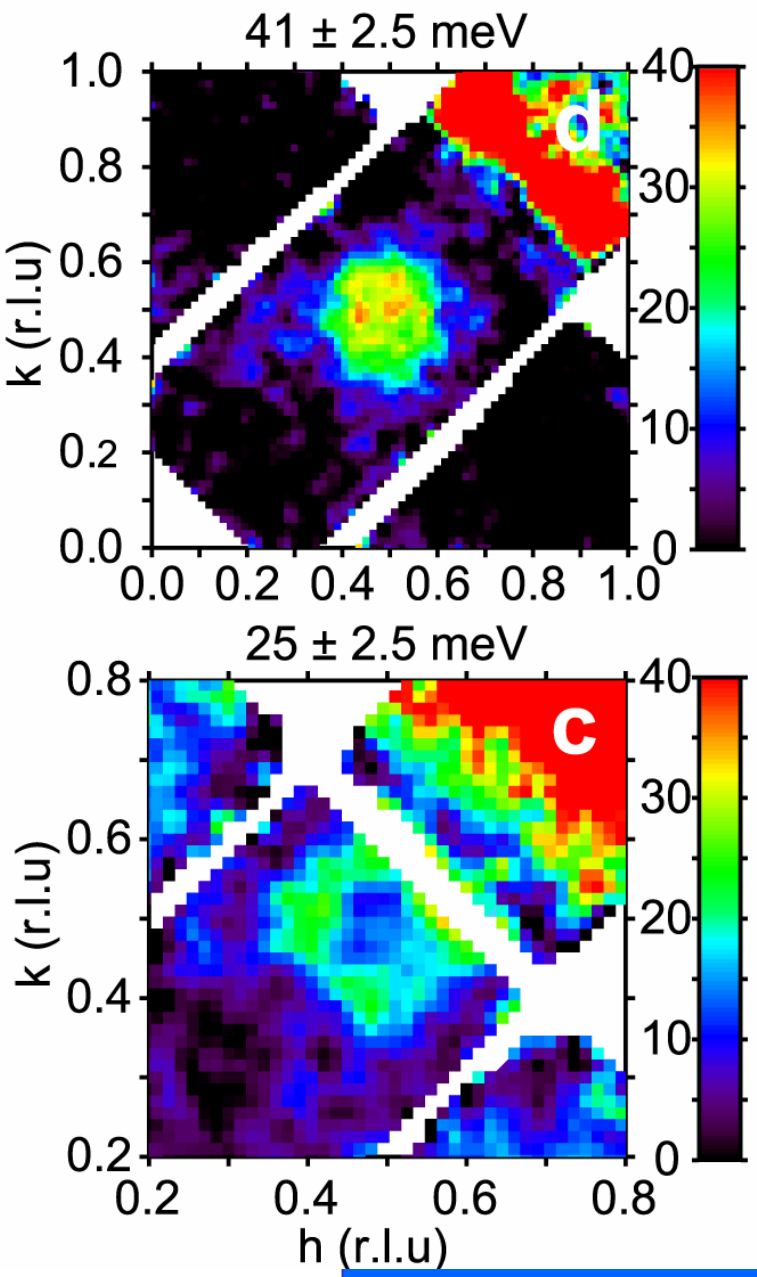
$La_{1.91}Sr_{0.09}CuO_4$ (underdoped)

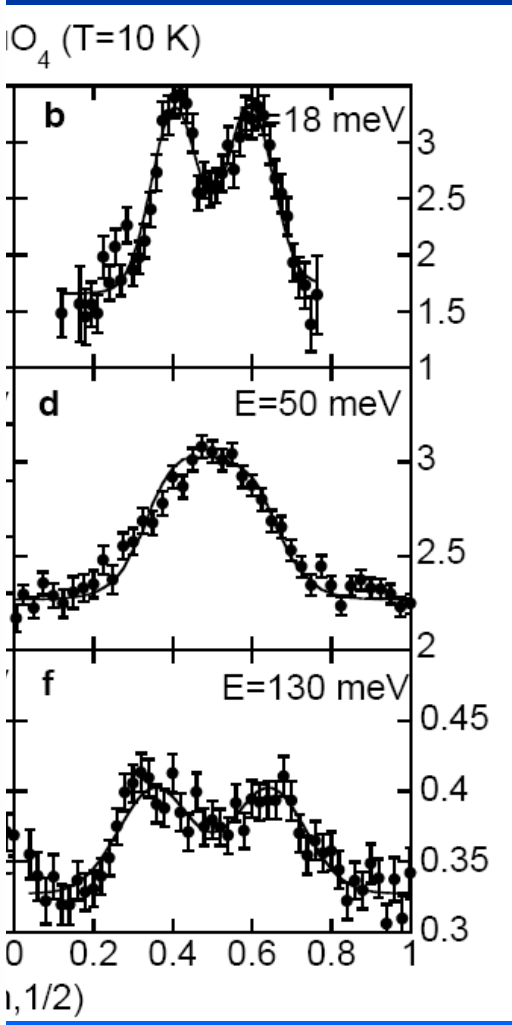
$La_{1.84}Sr_{0.16}CuO_4$ (optimal)

$La_{1.78}Sr_{0.22}CuO_4$ (overdoped)

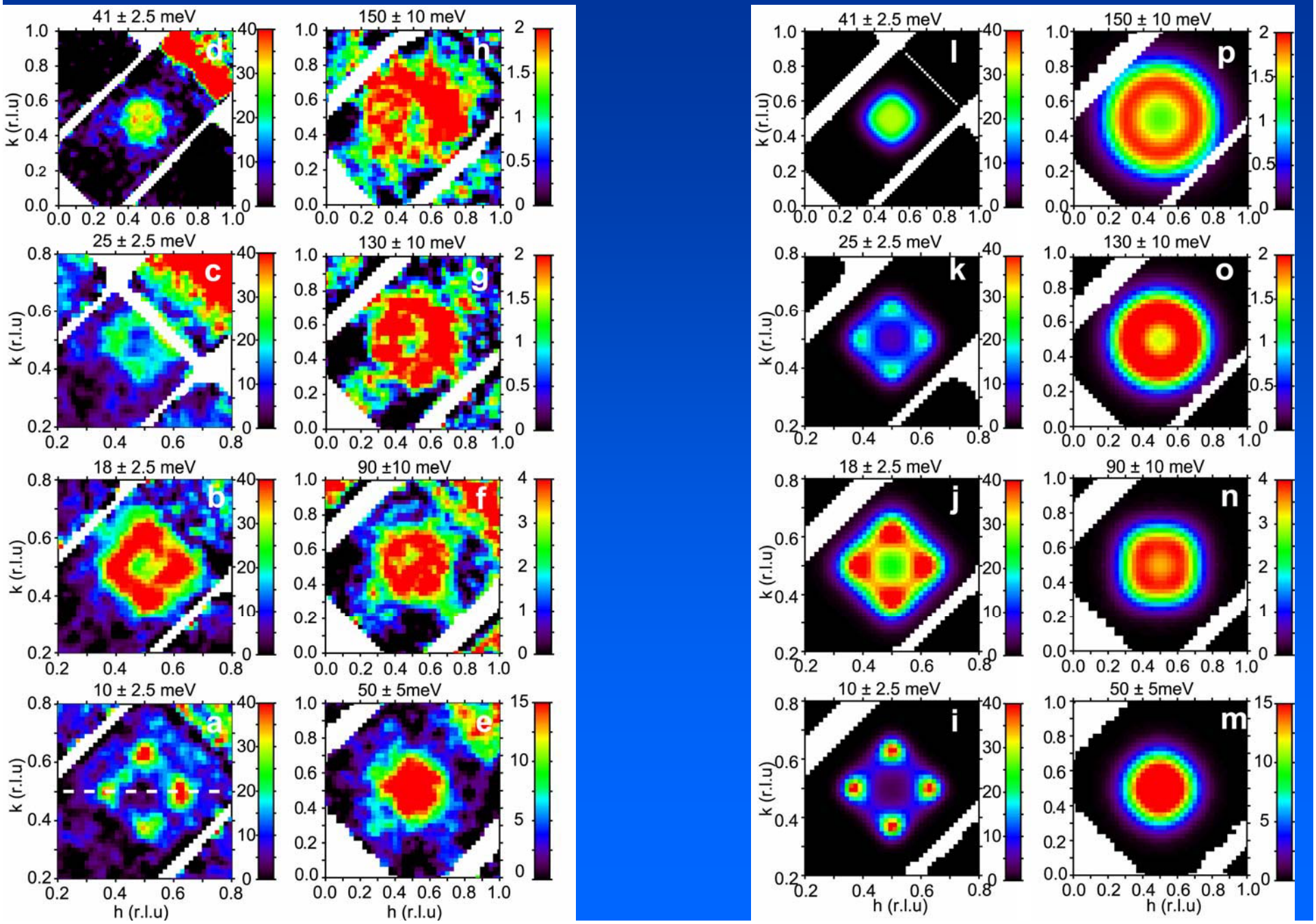

41 ± 2.5 meV
d
25 ± 2.5 meV
c
18 ± 2.5 meV
b
10 ± 2.5 meV
a
k (r.l.u)
h (r.l.u)

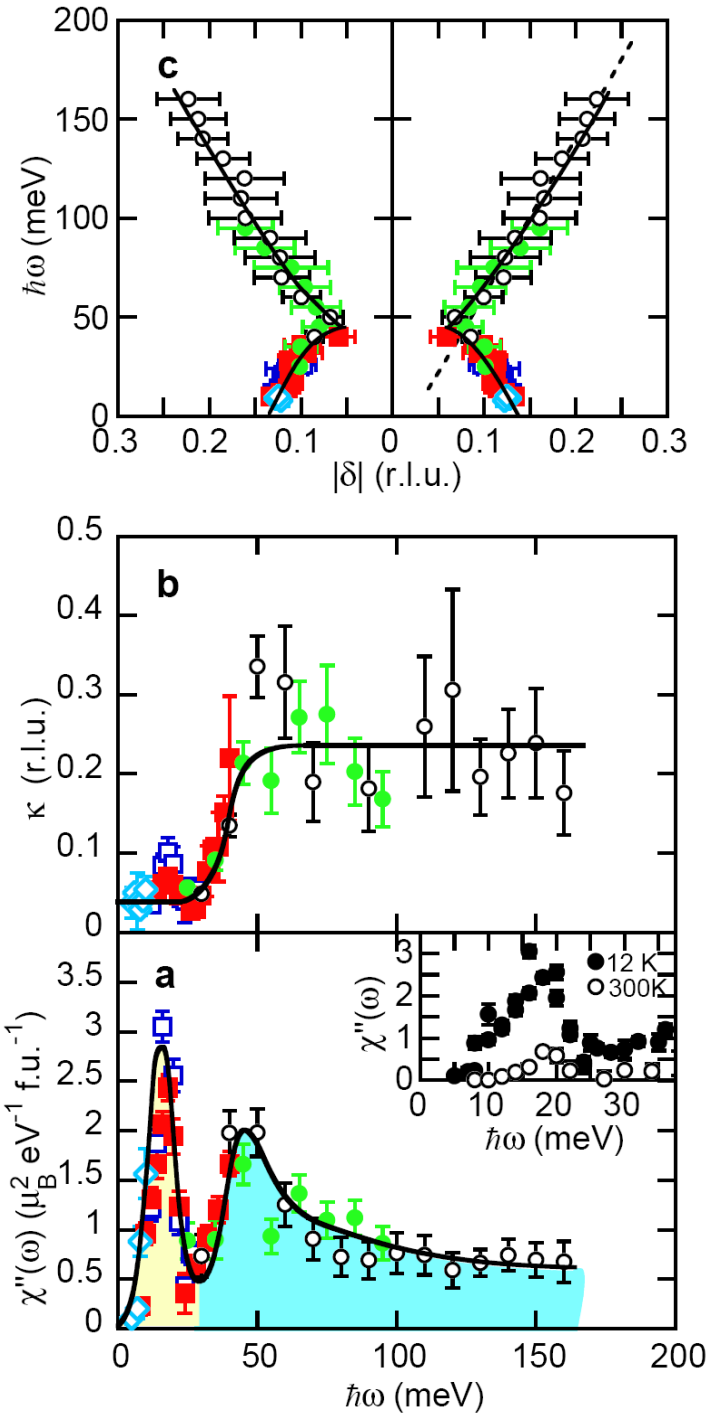
(T_c=38.5 K, MAPS)


41 ± 2.5 meV
d
25 ± 2.5 meV
c
k (r.l.u)
h (r.l.u)

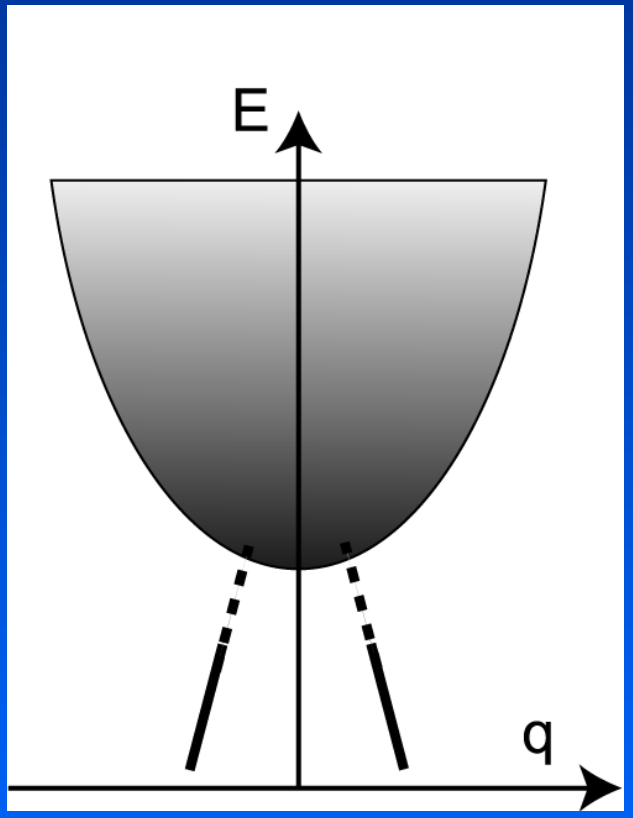

O4 (T=10 K)
b
18 meV
d
E=50 meV
f
E=130 meV
,1/2)

data $La_{1.84}Sr_{0.16}CuO_4$ (MAPS) fitted response



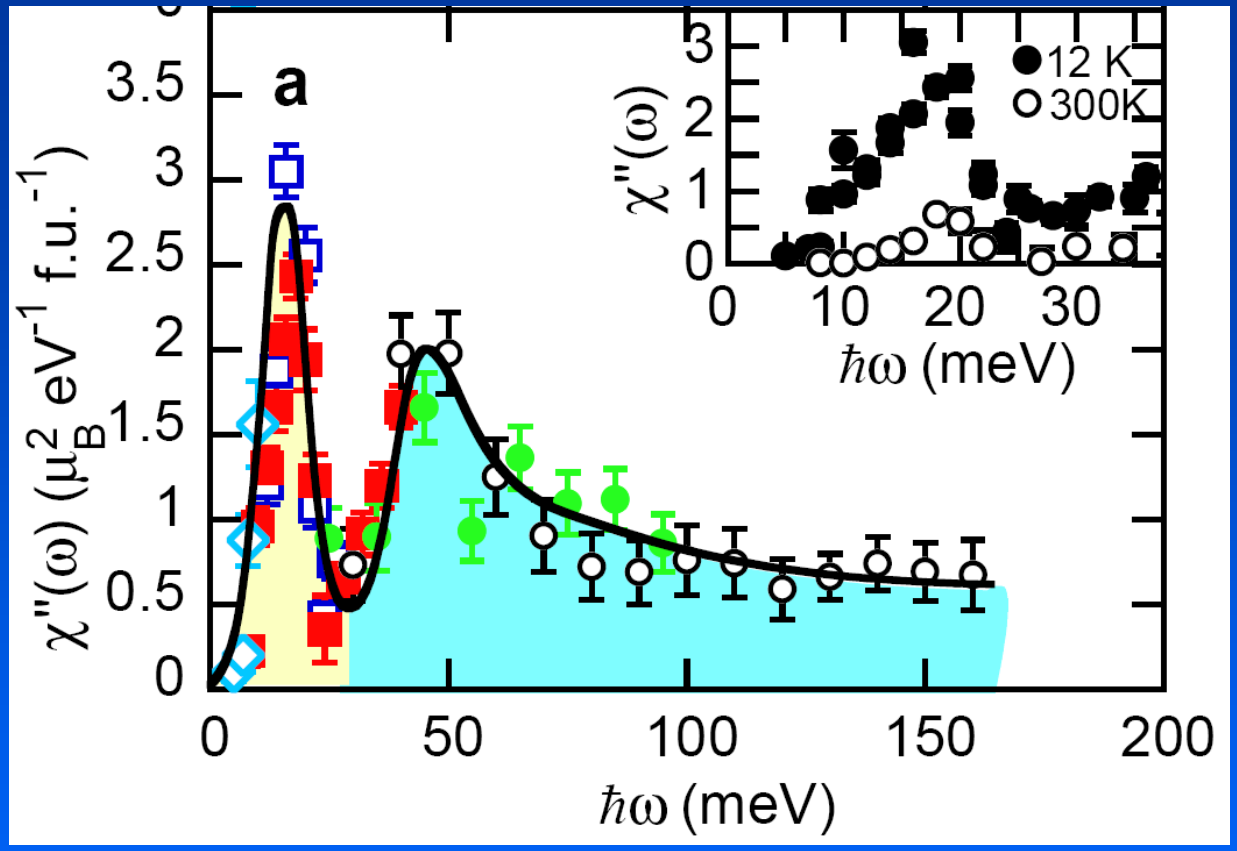


fitted parameters



$$\chi''(\omega) = \int \chi''(\mathbf{Q},\omega) d^3Q / \int d^3Q$$

$La_{1.84}Sr_{0.16}CuO_4$



key features

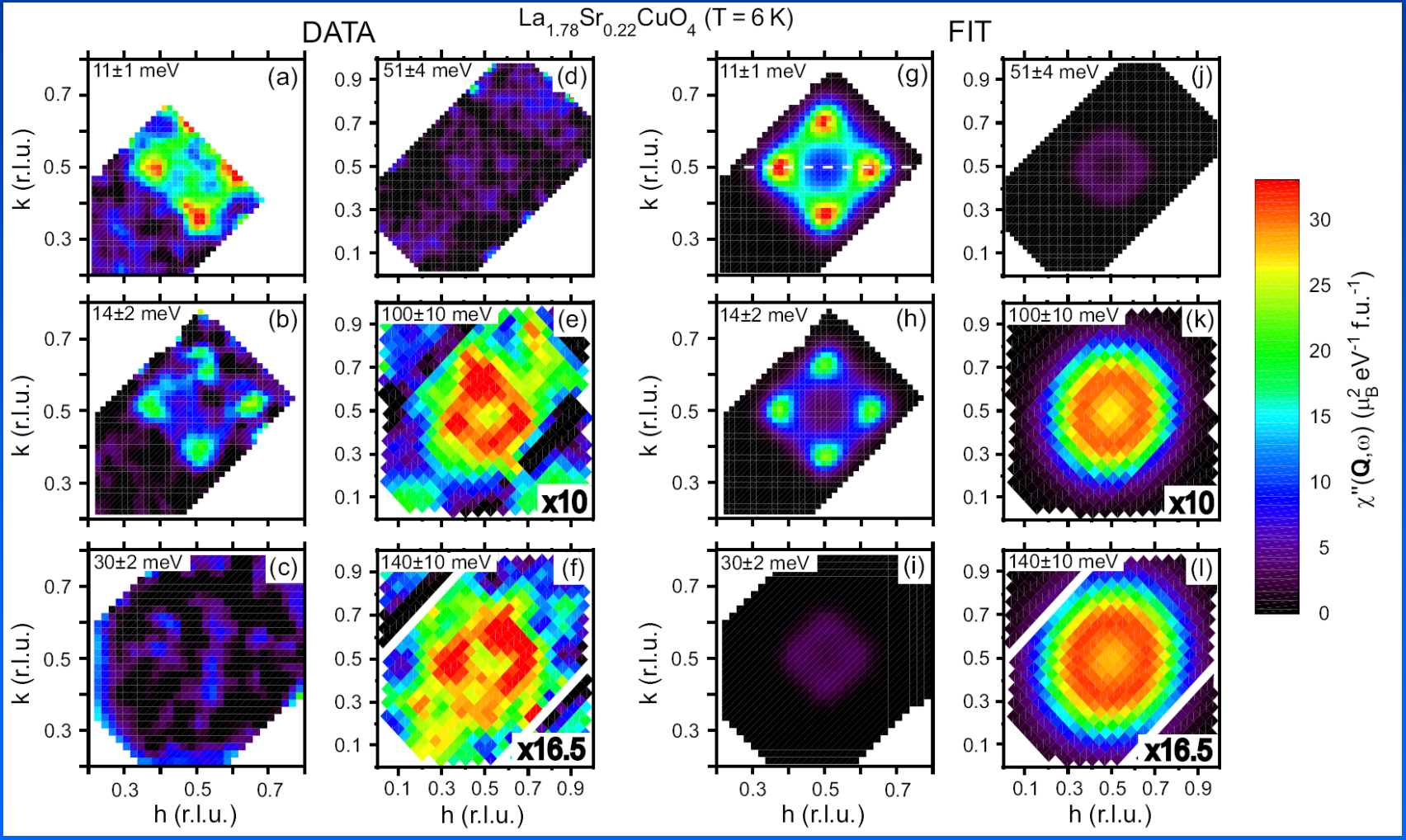
- double-peaked structure (two energy scales 18,50 meV)
- rapid broadening of pattern near 40 meV
- possible "rotation of pattern" at high energies

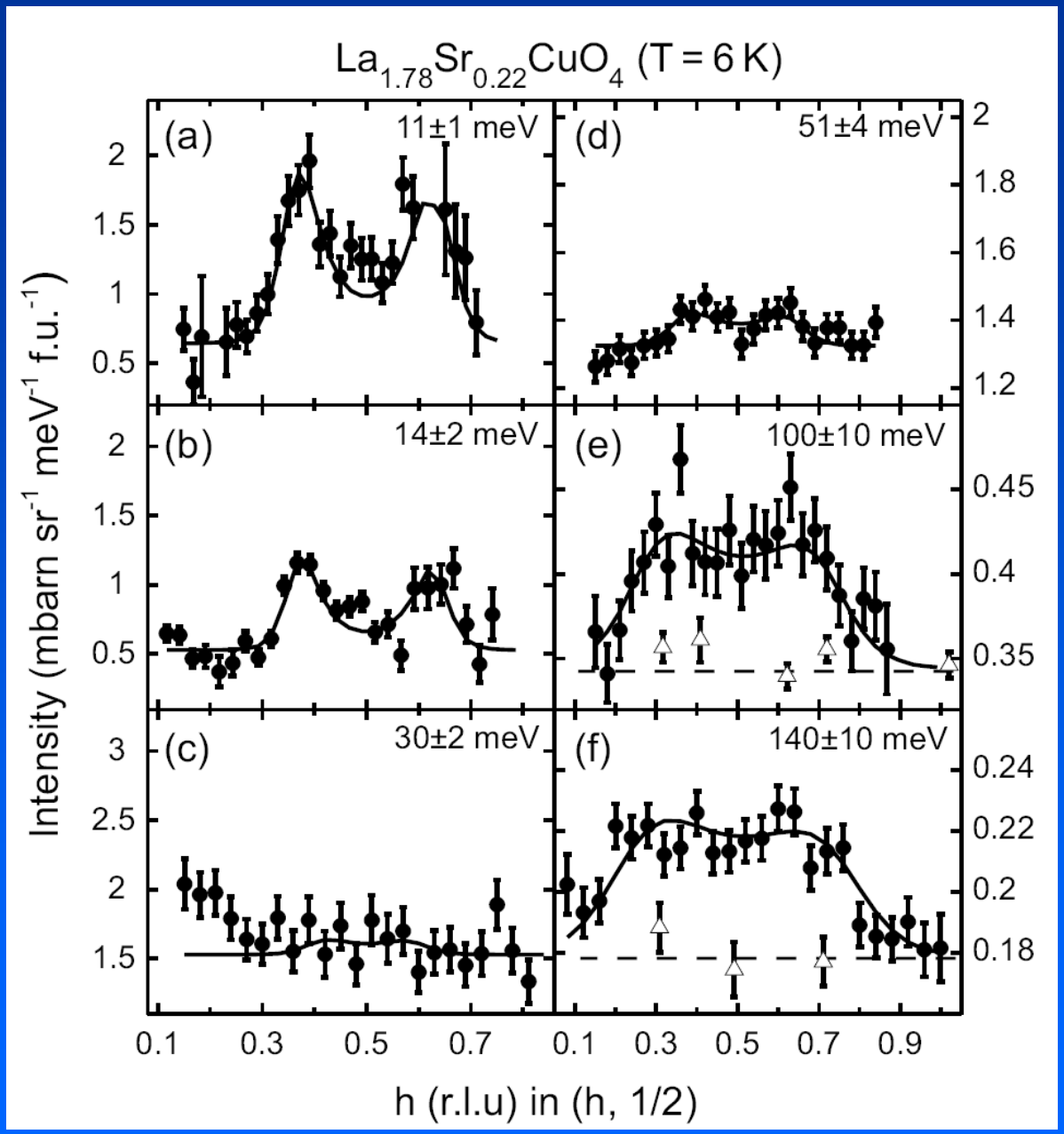
$La_{1.91}Sr_{0.09}CuO_4$ (underdoped)

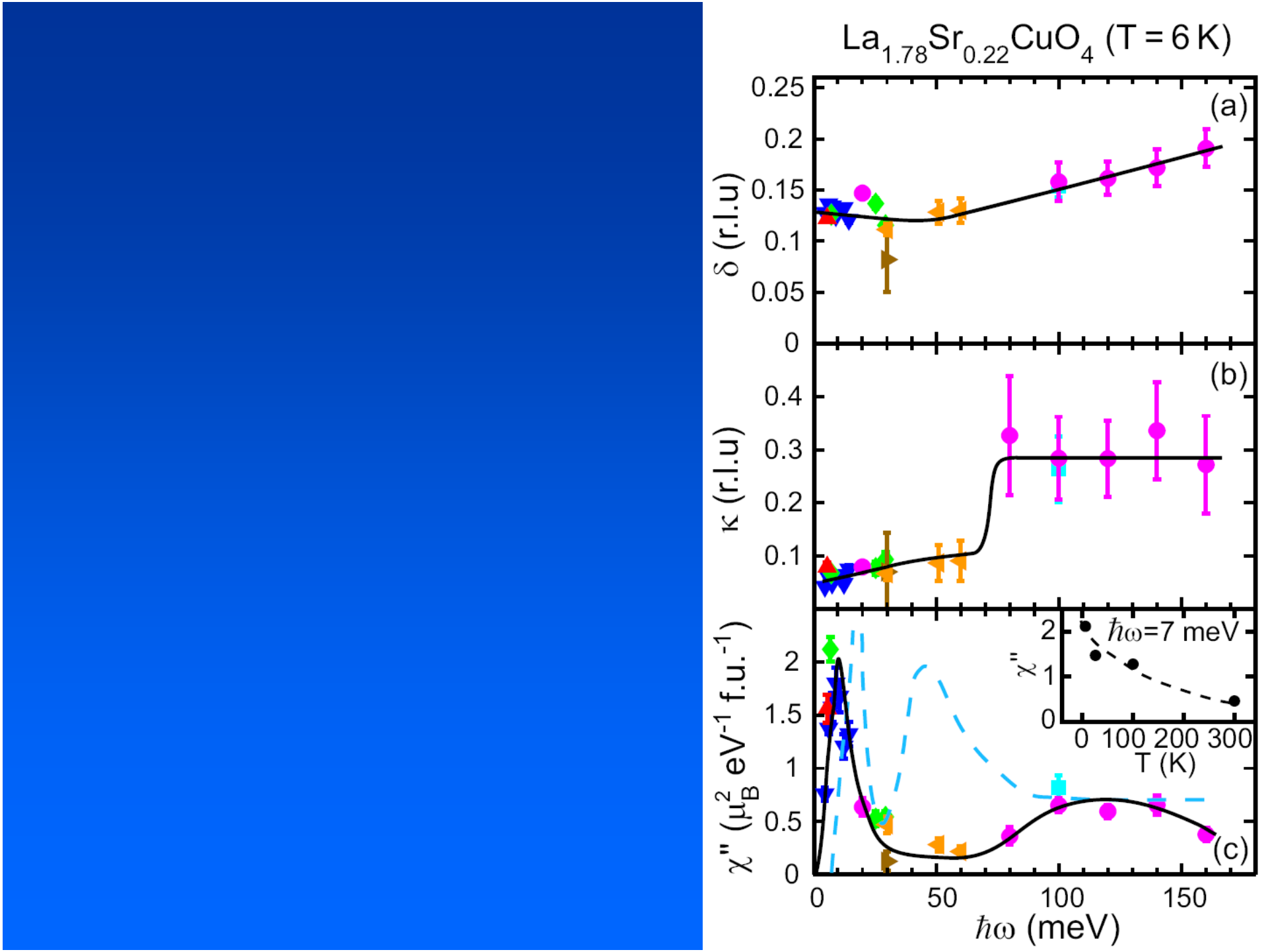
$La_{1.84}Sr_{0.16}CuO_4$ (optimal)

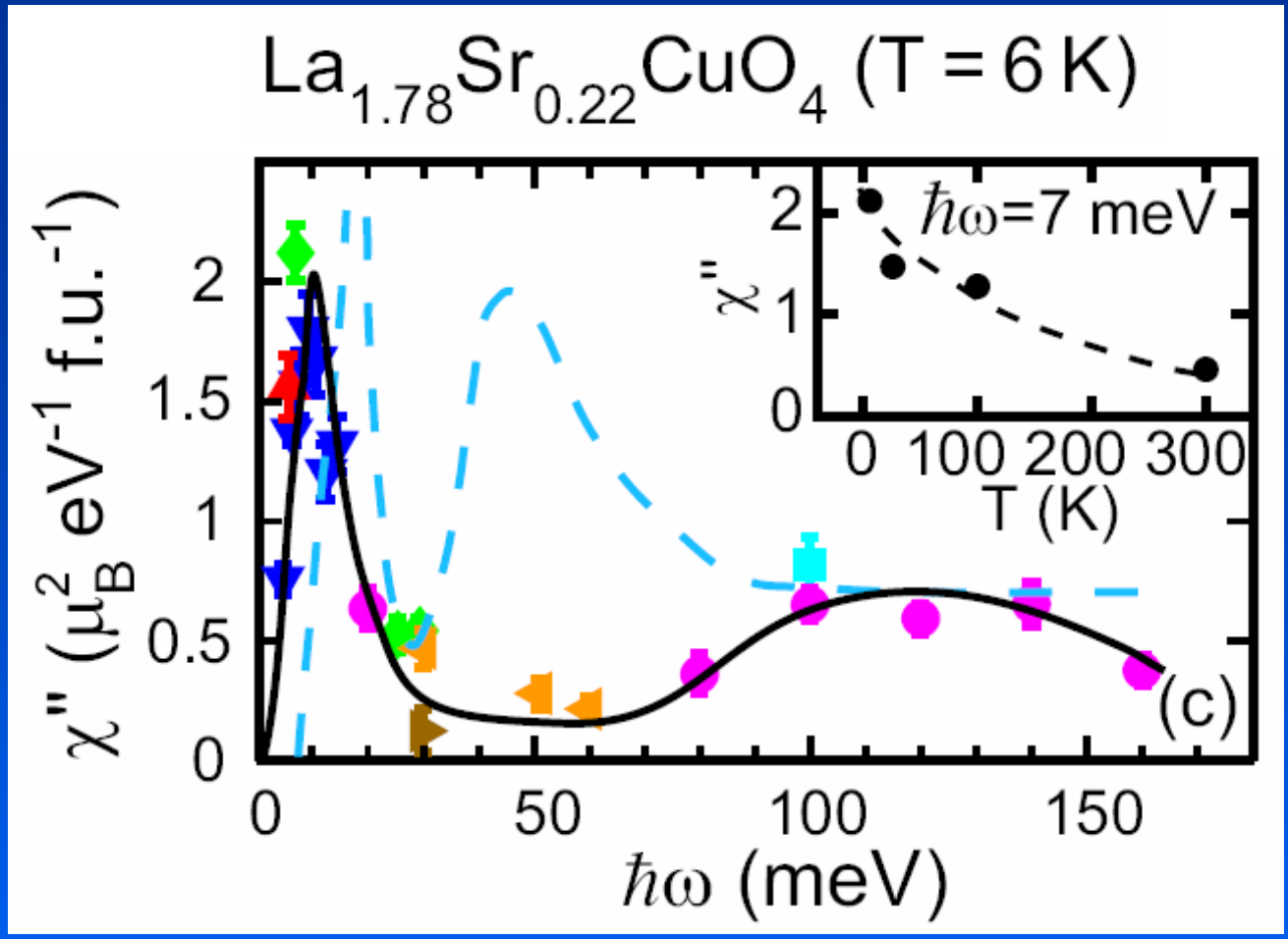
$La_{1.78}Sr_{0.22}CuO_4$ (overdoped)

$La_{2-x}Sr_xCuO_4$ (x=0.22, T_c=26K) Overdoped Sample

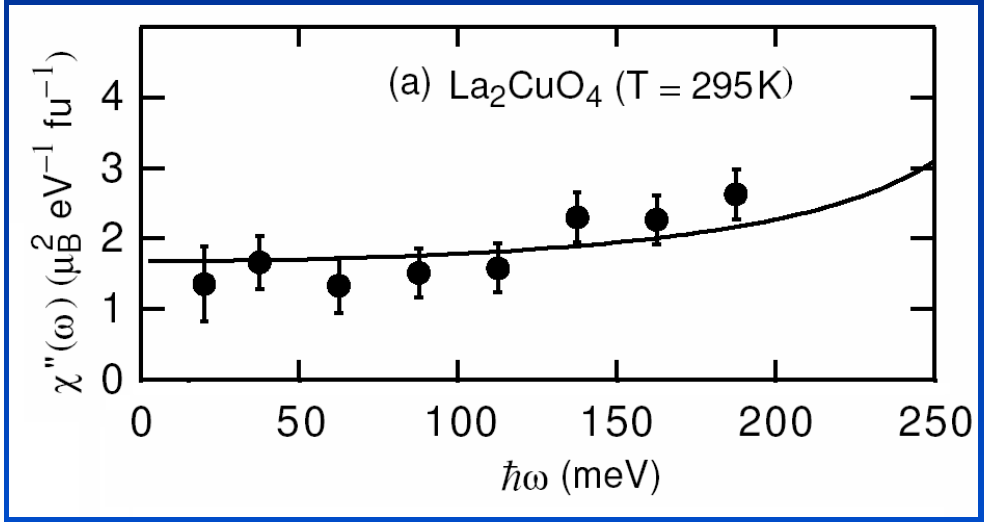


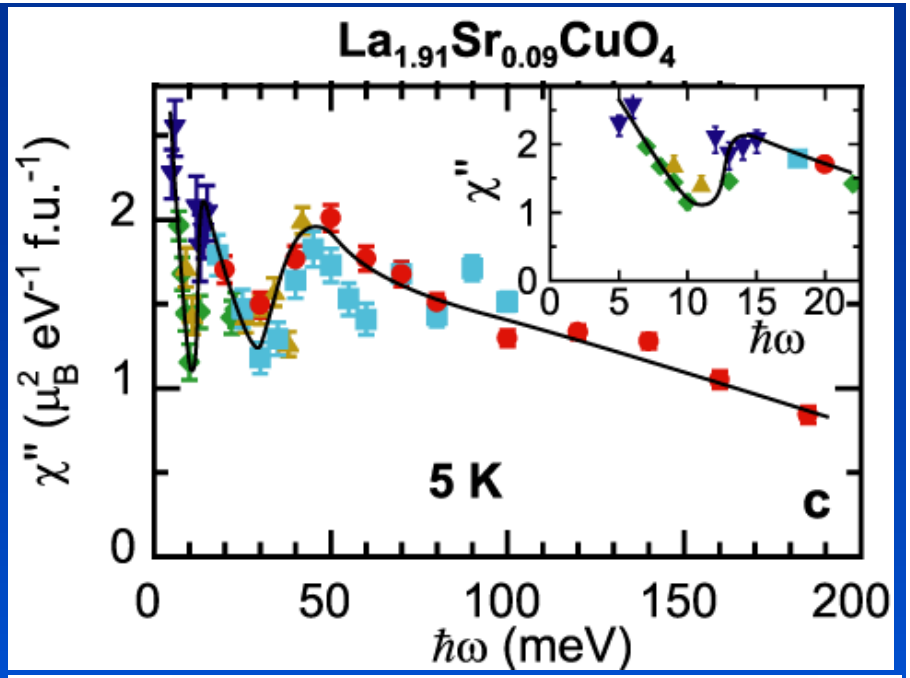

La1.78Sr0.22CuO4 (T = 6 K)
(a)
11±1 meV
(d)
51±4 meV
(b)
14±2 meV
(e)
100±10 meV
(c)
30±2 meV
(f)
140±10 meV
Intensity (mbarn sr-1 meV-1 f.u.-1)
h (r.l.u) in (h, 1/2)

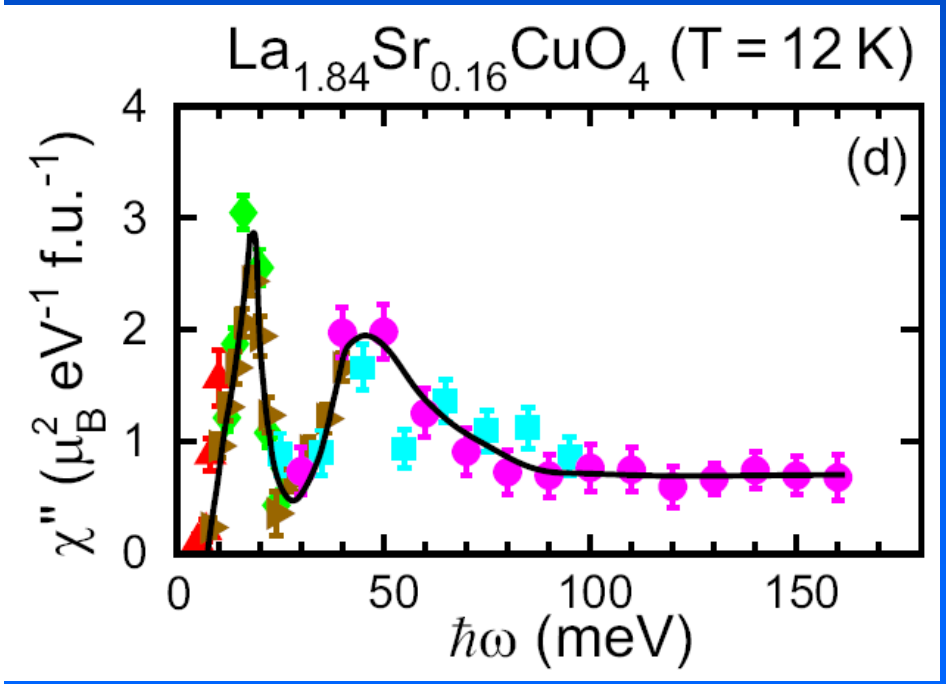

La1.78Sr0.22CuO4 (T = 6 K)
(a)
δ (r.l.u)
0.25
0.2
0.15
0.1
0.05
0
(b)
κ (r.l.u)
0.4
0.3
0.2
0.1
(c)
χ'' (μB2 eV-1 f.u.-1)
2
1.5
1
0.5
0
0
50
100
150
ħω (meV)
ħω=7 meV
χ''
2
1
0
0 100 200 300
T (K)

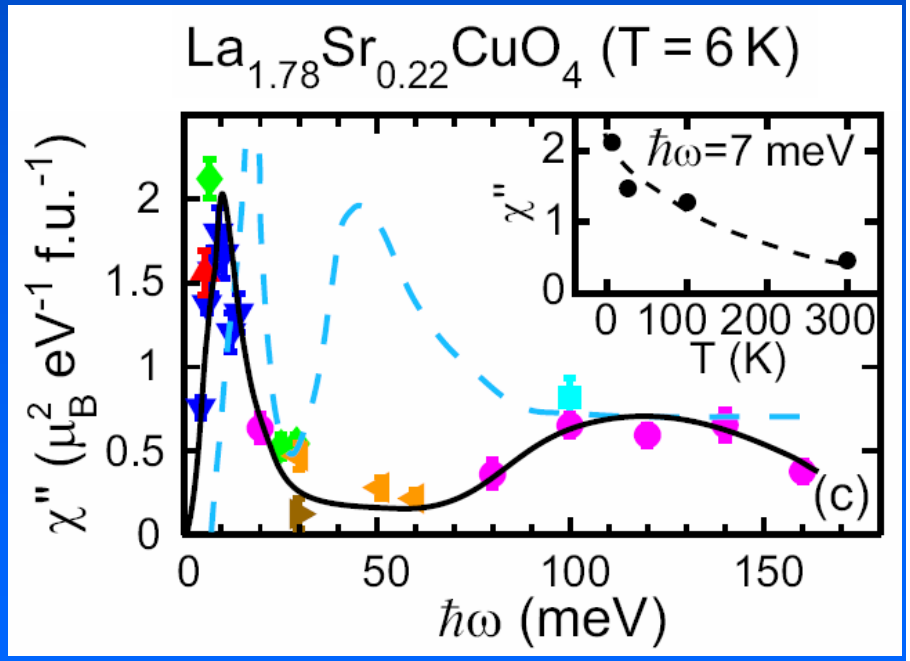

La1.78Sr0.22CuO4 (T = 6 K)
χ'' (μB2 eV-1 f.u.-1)
ħω (meV)
0
0.5
1
1.5
2
0
50
100
150
(c)
χ''
ħω=7 meV
0
1
2
0 100 200 300
T (K)

Evolution with doping

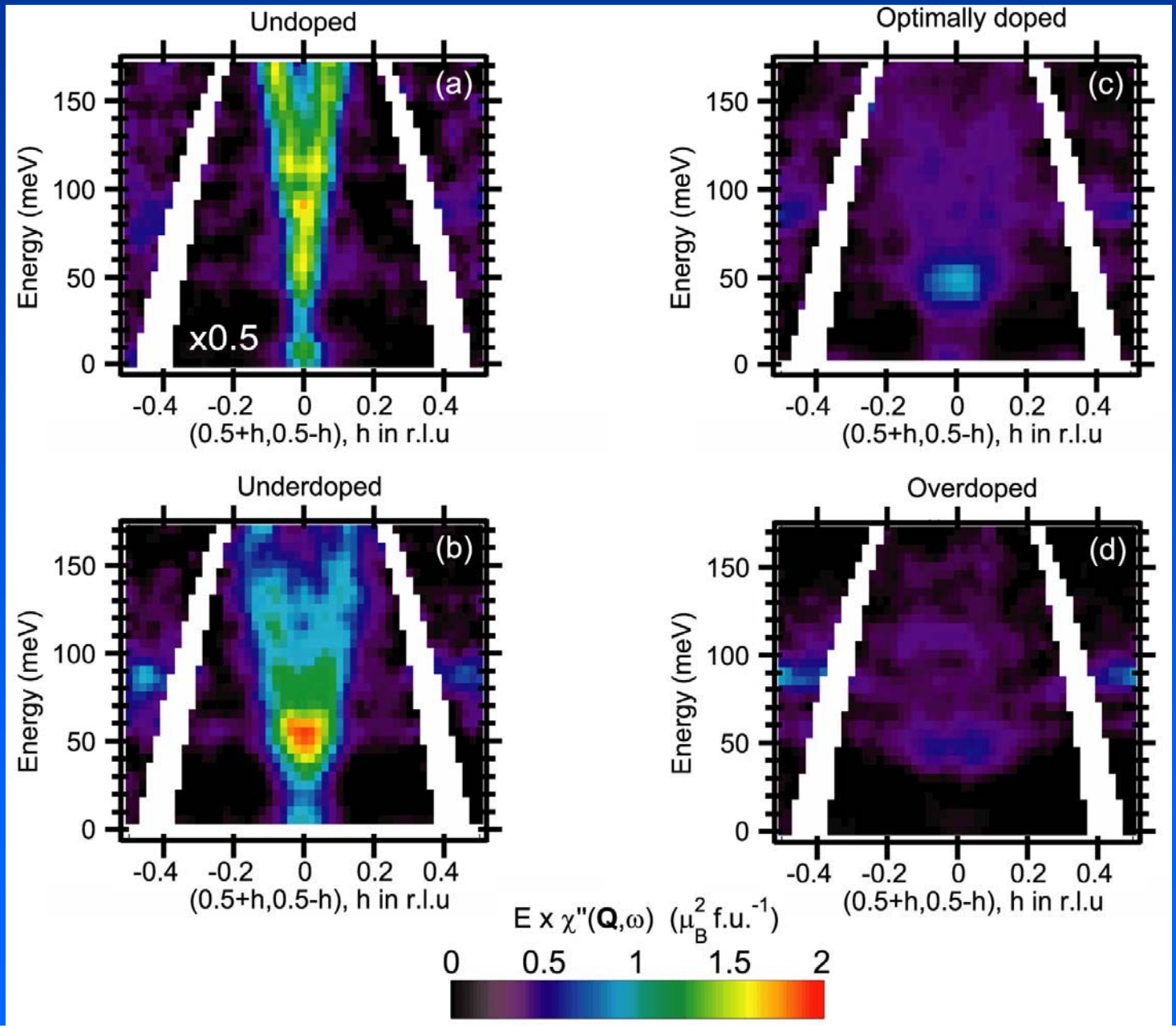




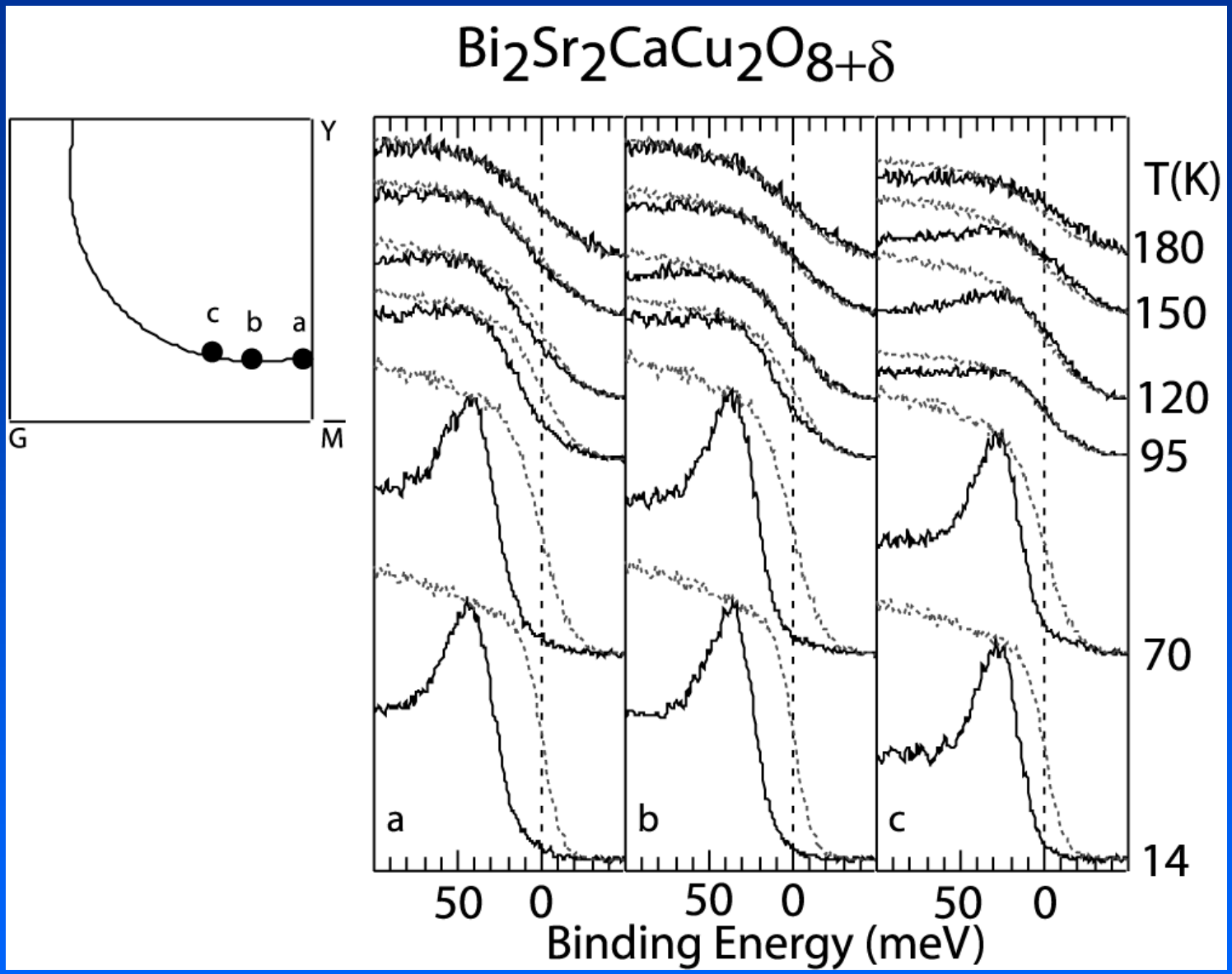




The evolution of $\chi''(q,\omega)$ in $La_{2-x}Sr_xCuO_4$ with doping



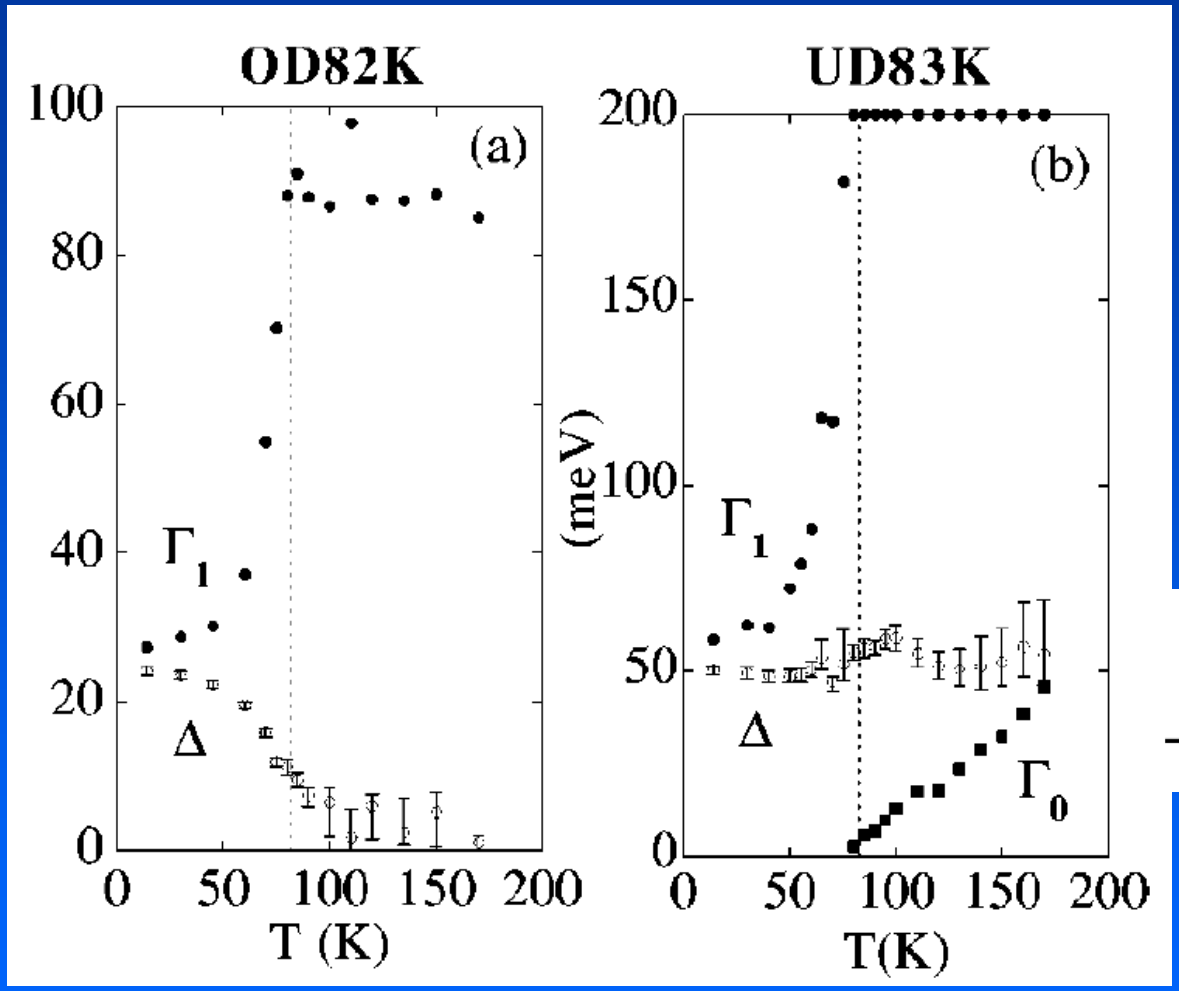
Spin Excitations and the Pseudogap



APRES Pseudogap in Bi2212

Norman et al, Nature 392, 157 (1998)

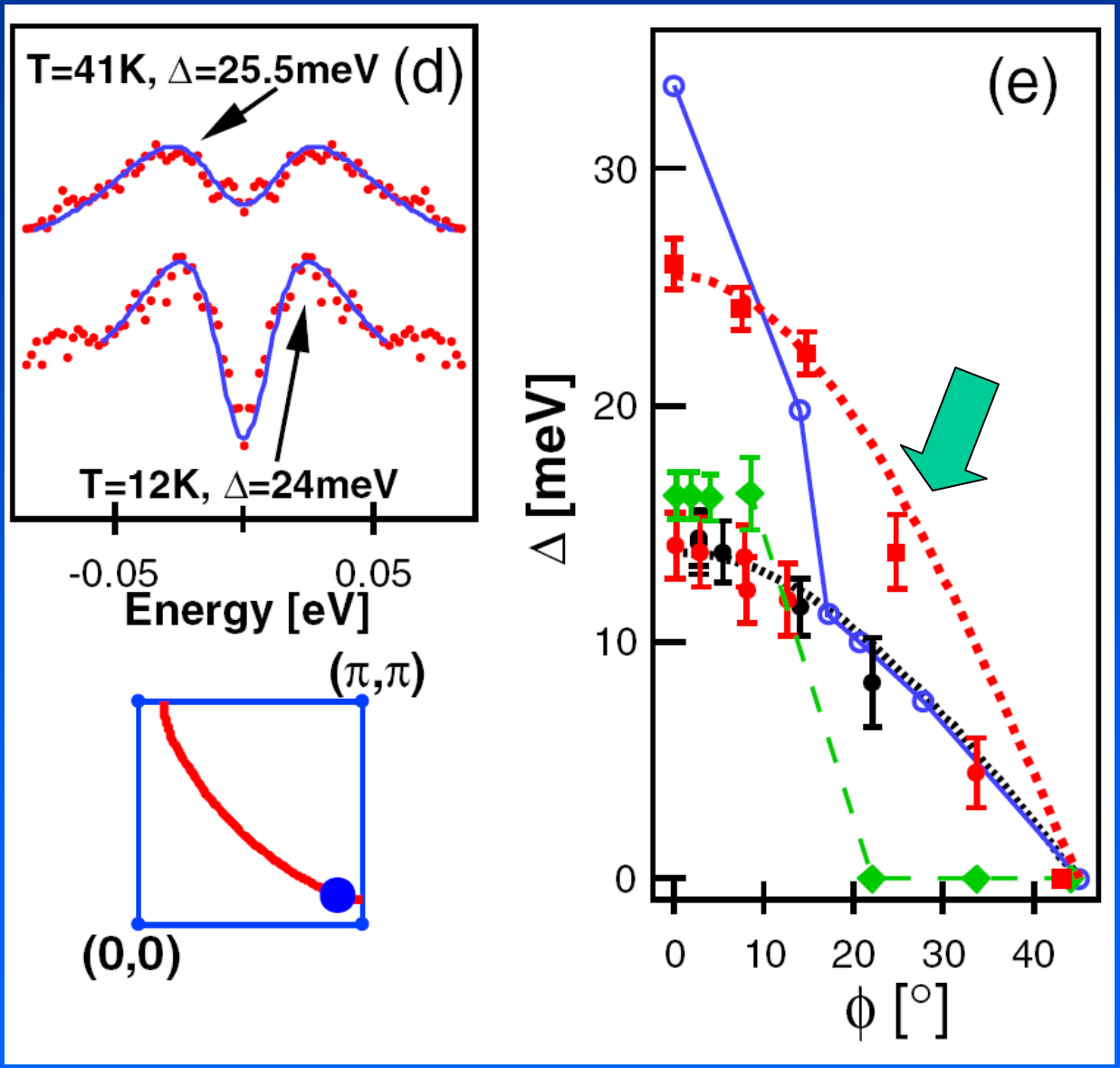
Phenomenological self energy



$$\Sigma(\mathbf{k},\omega) = -i\Gamma_1 + \Delta^2/(\omega + i\Gamma_0)$$

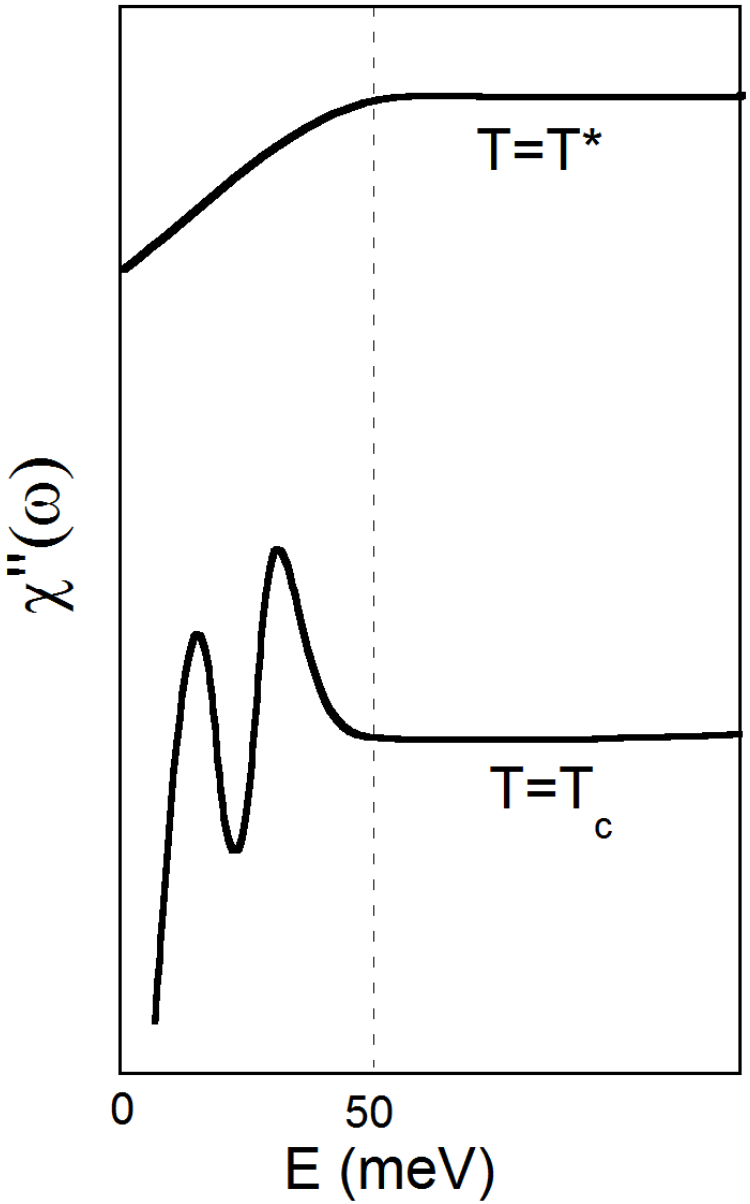
M. R. Norman *et al. PRB* **57**, R11093 (1998).

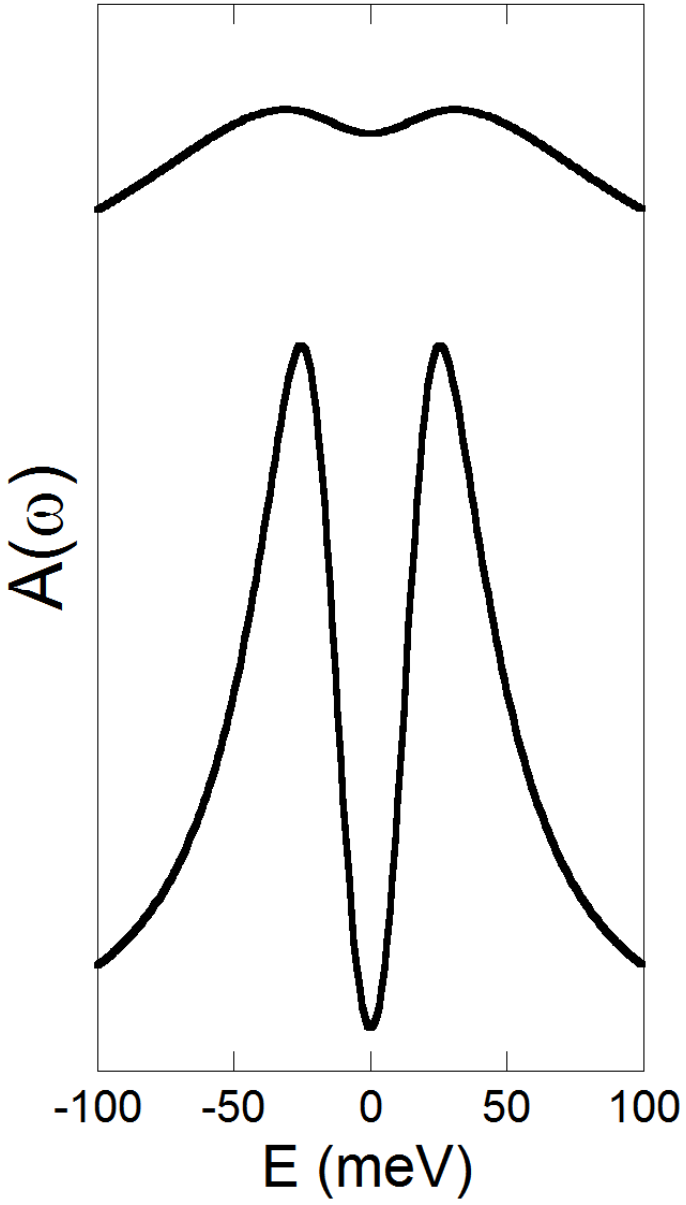
Pseudo gap and ARPES in $La_{1.895}Sr_{0.105}CuO_4$

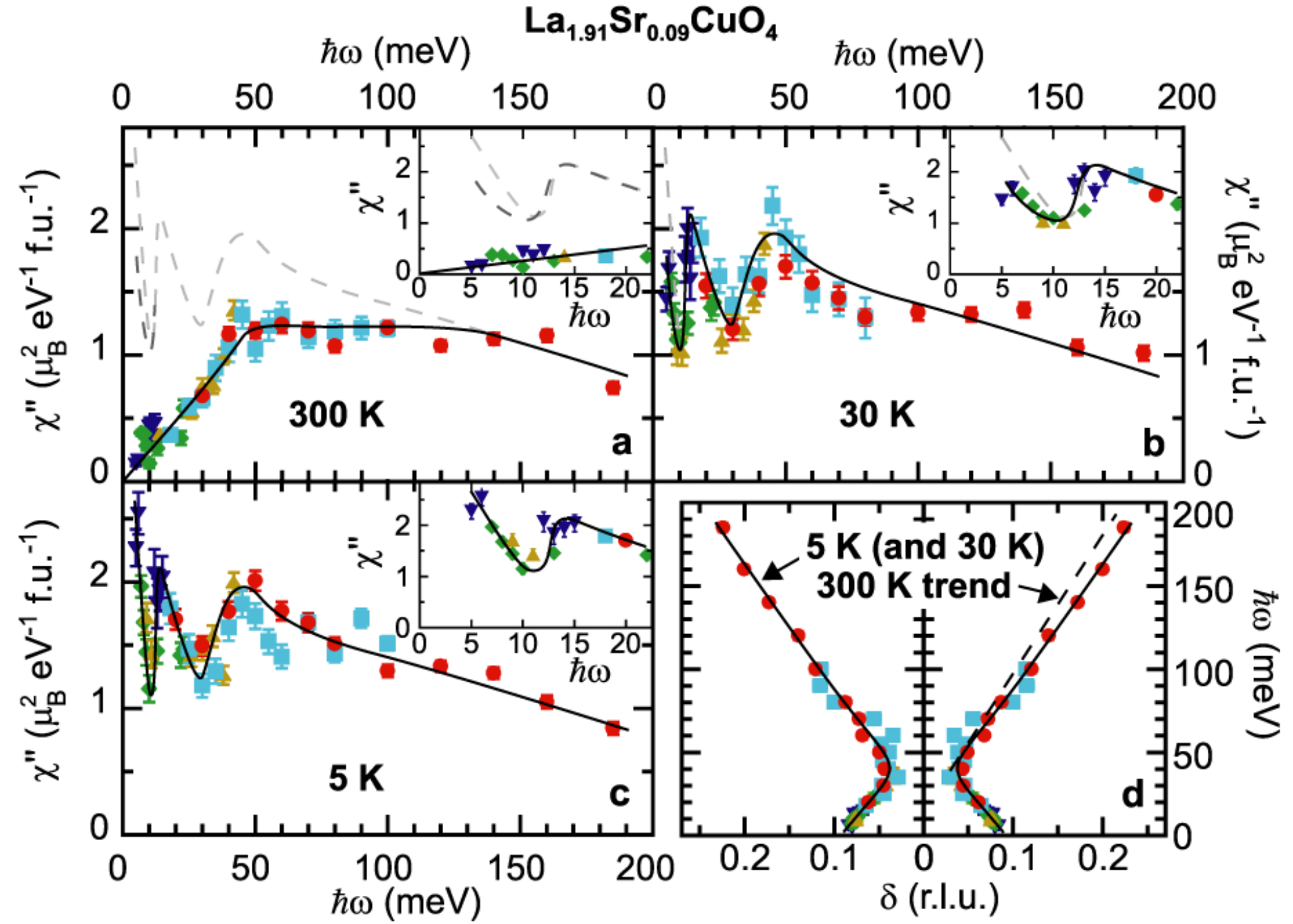


Shi et al. PRL 101, 047002 (2008)

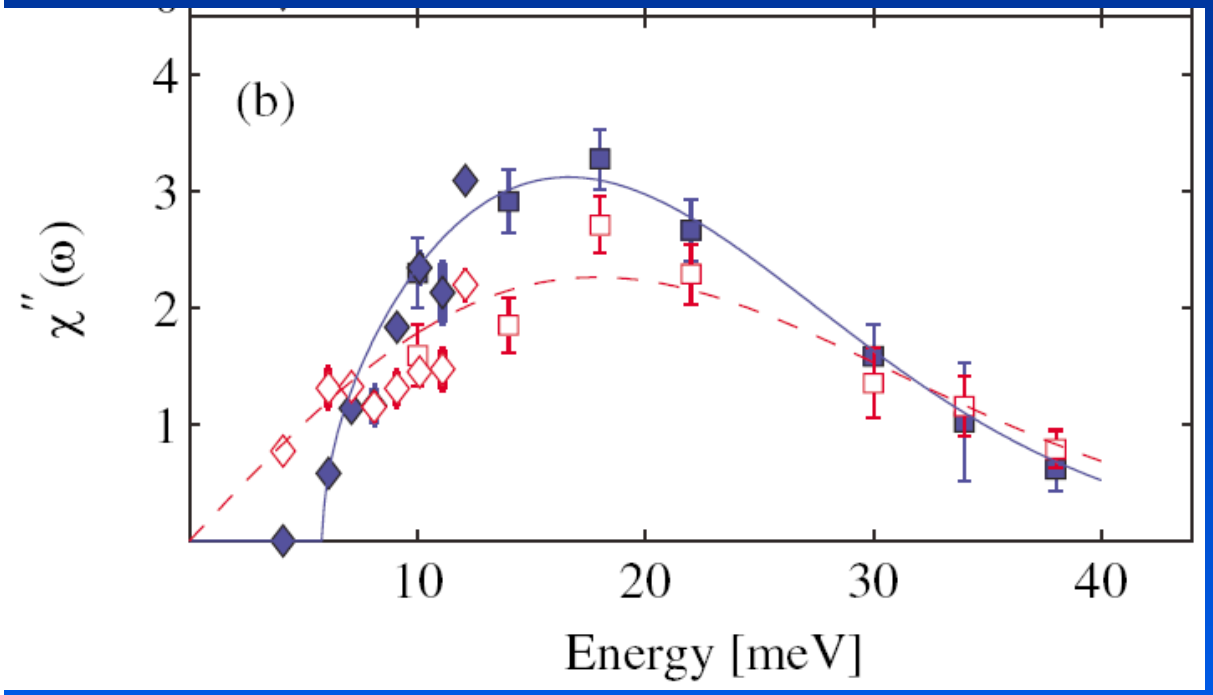
Effect of Pseudogap

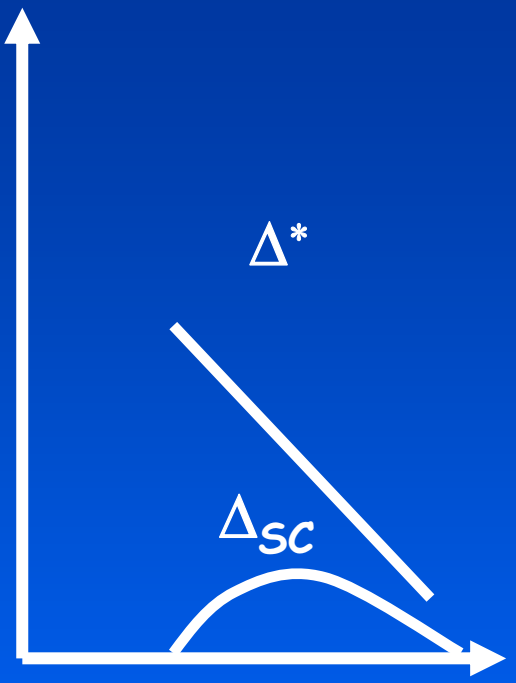





La1.91Sr0.09CuO4
ħω (meV)
χ'' (μB2 eV-1 f.u.-1)
300 K
a
30 K
b
5 K
c
5 K (and 30 K)
300 K trend
d
δ (r.l.u.)

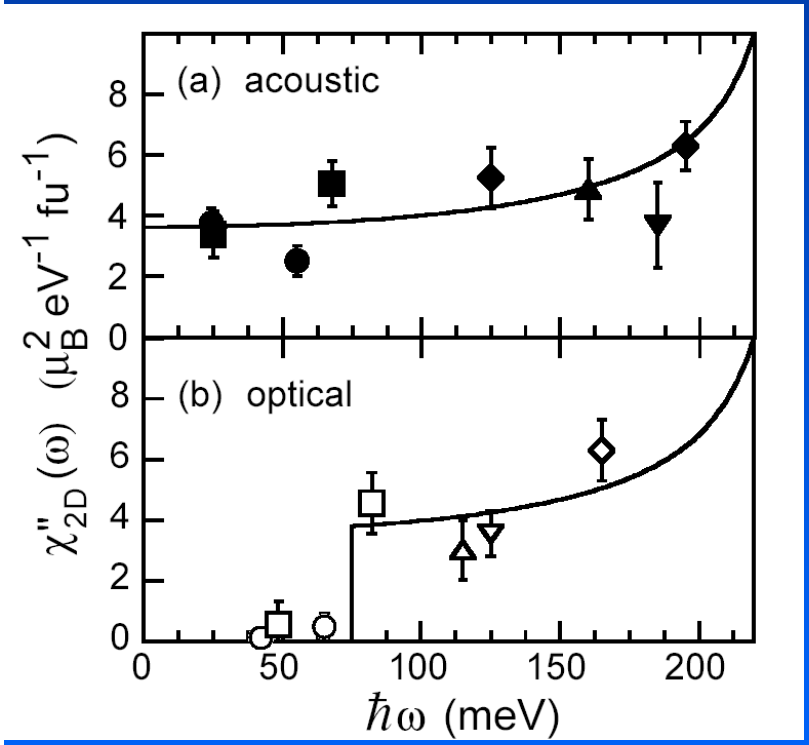
Superconducting Gap- One Gap or Two ..... ?





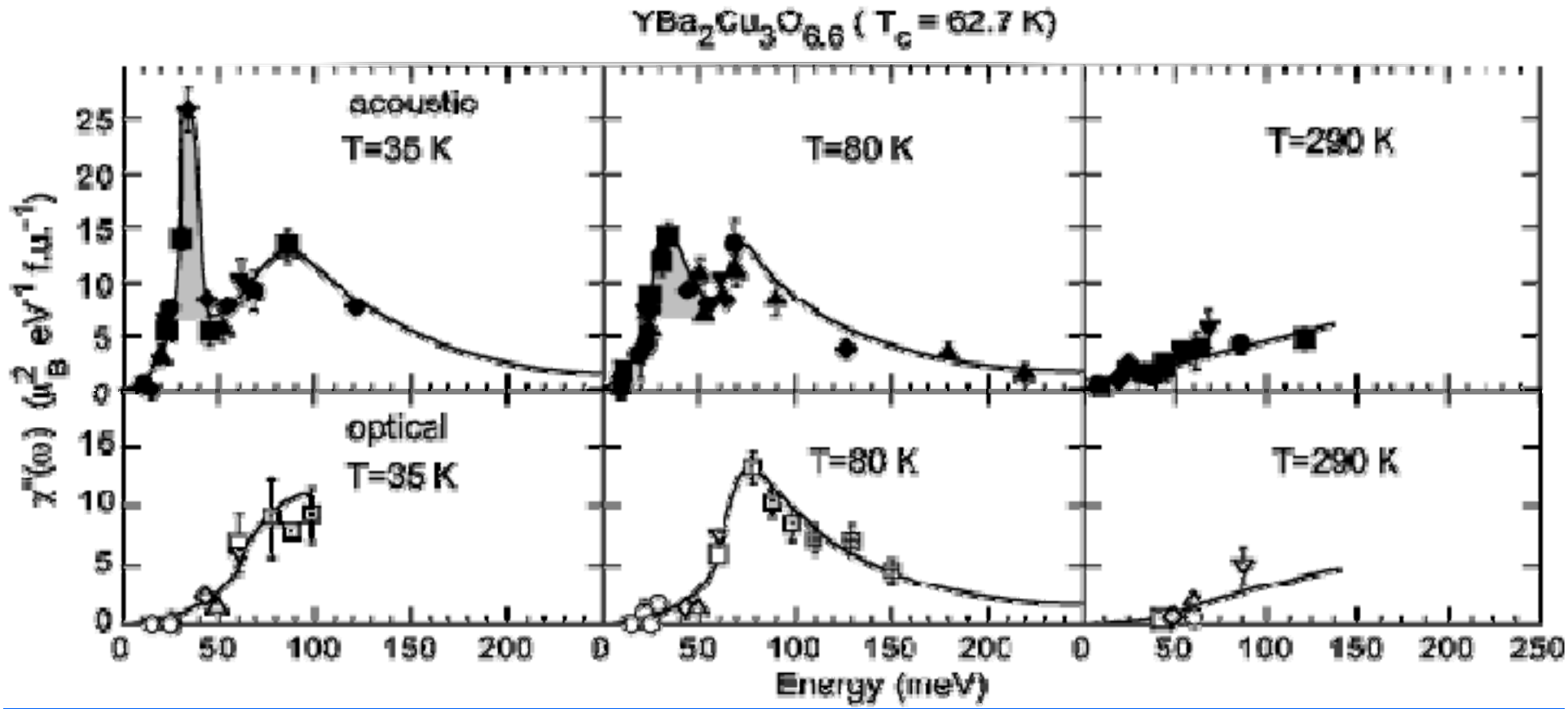
Spin Fluctuations and the Resonance in $YBa_2Cu_3O_{6+x}$ (older stuff)

The local susceptibility of $YBa_2Cu_3O_{6.15}$ (antiferromagnet)



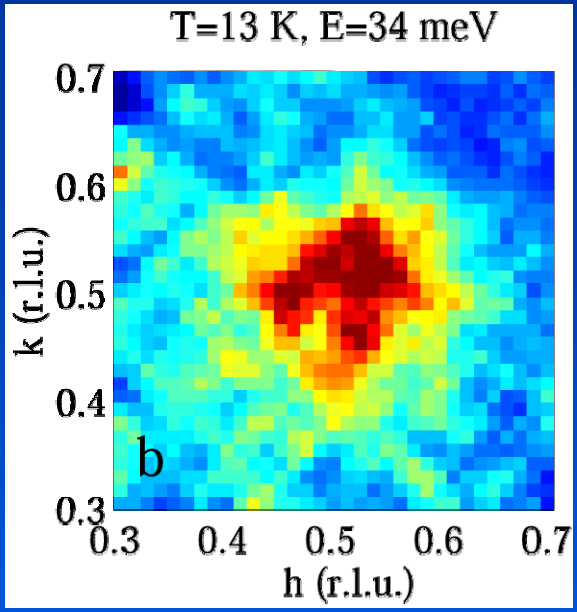
S. M. Hayden, G. Aeppli, T. G. Perring, H. A. Mook, F. Dogan, Phys. Rev. B **54**, R6905-R6908 (1996).

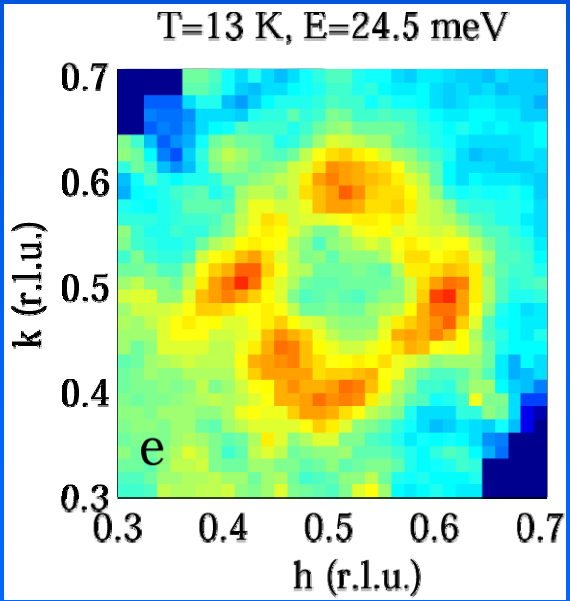
The local susceptibility of $YBa_2Cu_3O_{6.6}$



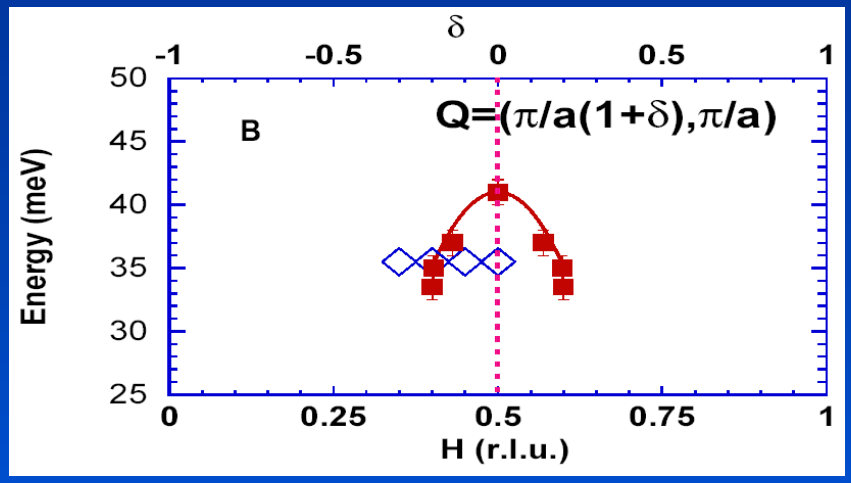
P. Dai, H. A. Mook, S. M. Hayden, G. Aeppli, T. G. Perring, R. D. Hunt, F. Dogan, Science 284, 1344 (1999); see also Bourges, PRB (1997) and Stock, PRB (2004)

$YBa_2Cu_3O_{6.6}$





$YBa_2Cu_3O_{6.85}$

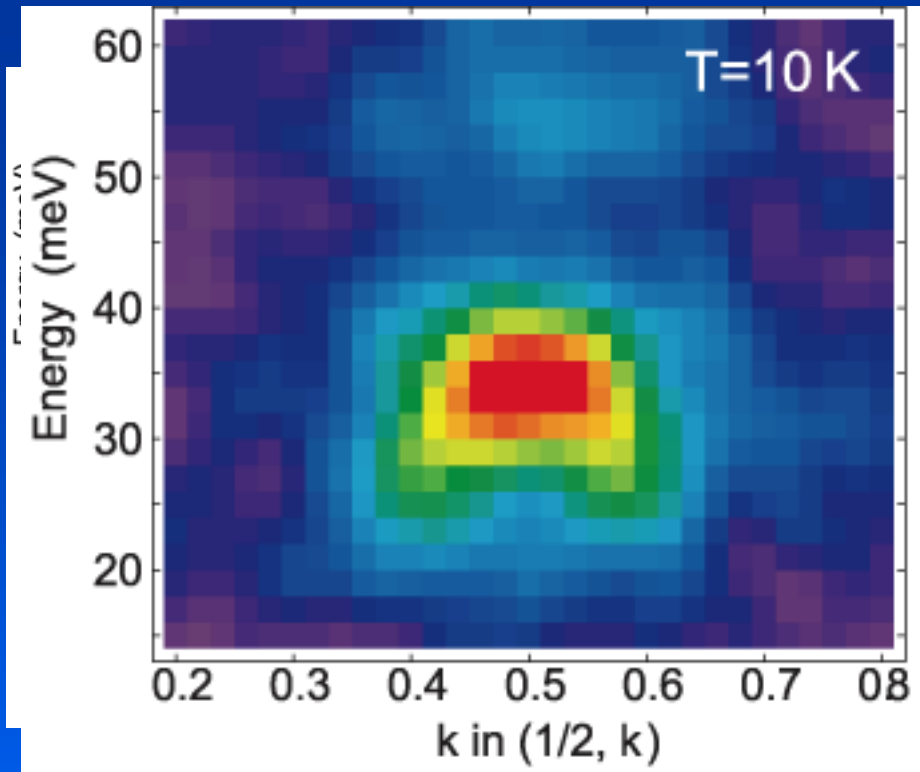


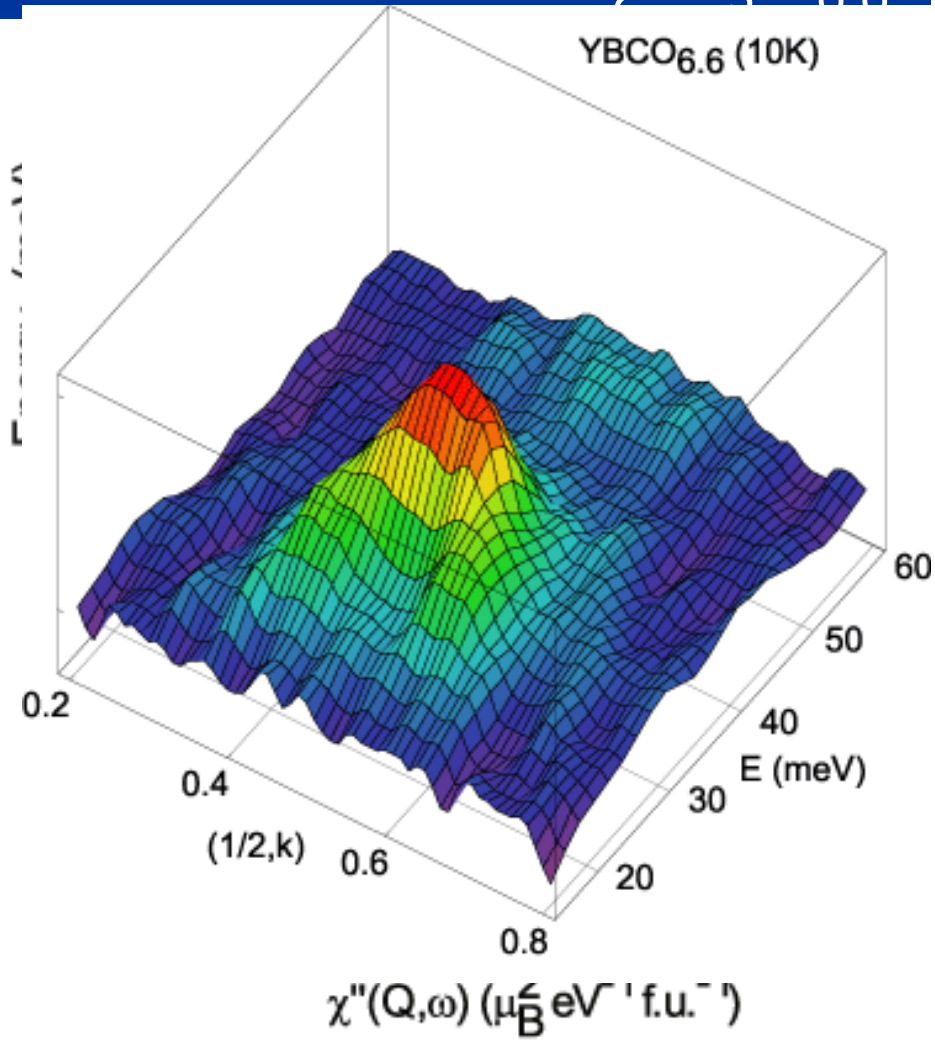
P. Bourges, Y. Sidis, H. F. Fong, L. P. Regnault, J. Bossy, A. Ivanov, and B. Keimer, 2000, Science **288**, 1234.

The formation of the resonance mode in $YBa_2Cu_3O_{6.6}$

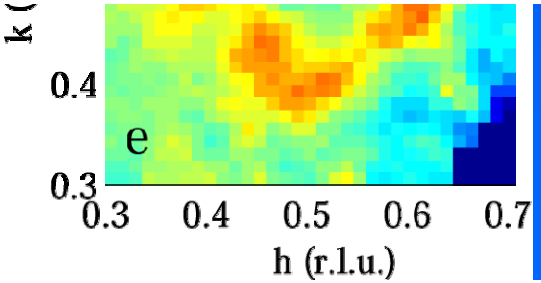
H. A. Mook, P. Dai., S. M. Hayden, G. Aeppli, T. G. Perring, F Dogan, Nature **395**, 580-582 (1998).

The formation of the resonance mode in $YBa_2Cu_3O_{6.6}$

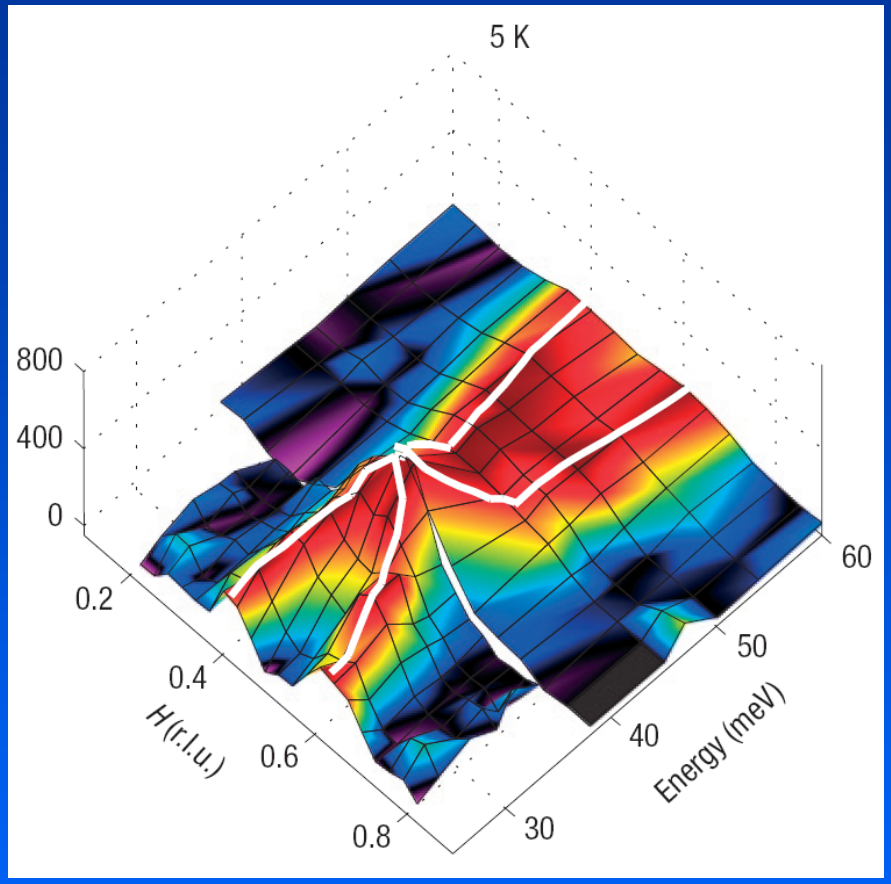


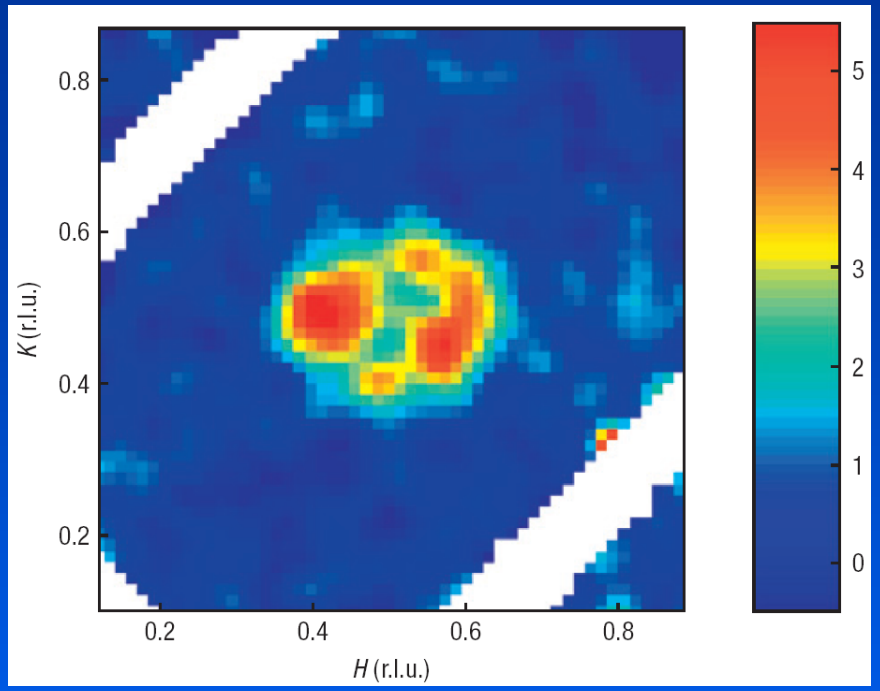


Hayden et al, Nature 429, 534 (2004)



$YBa_2Cu_3O_{6.6}$

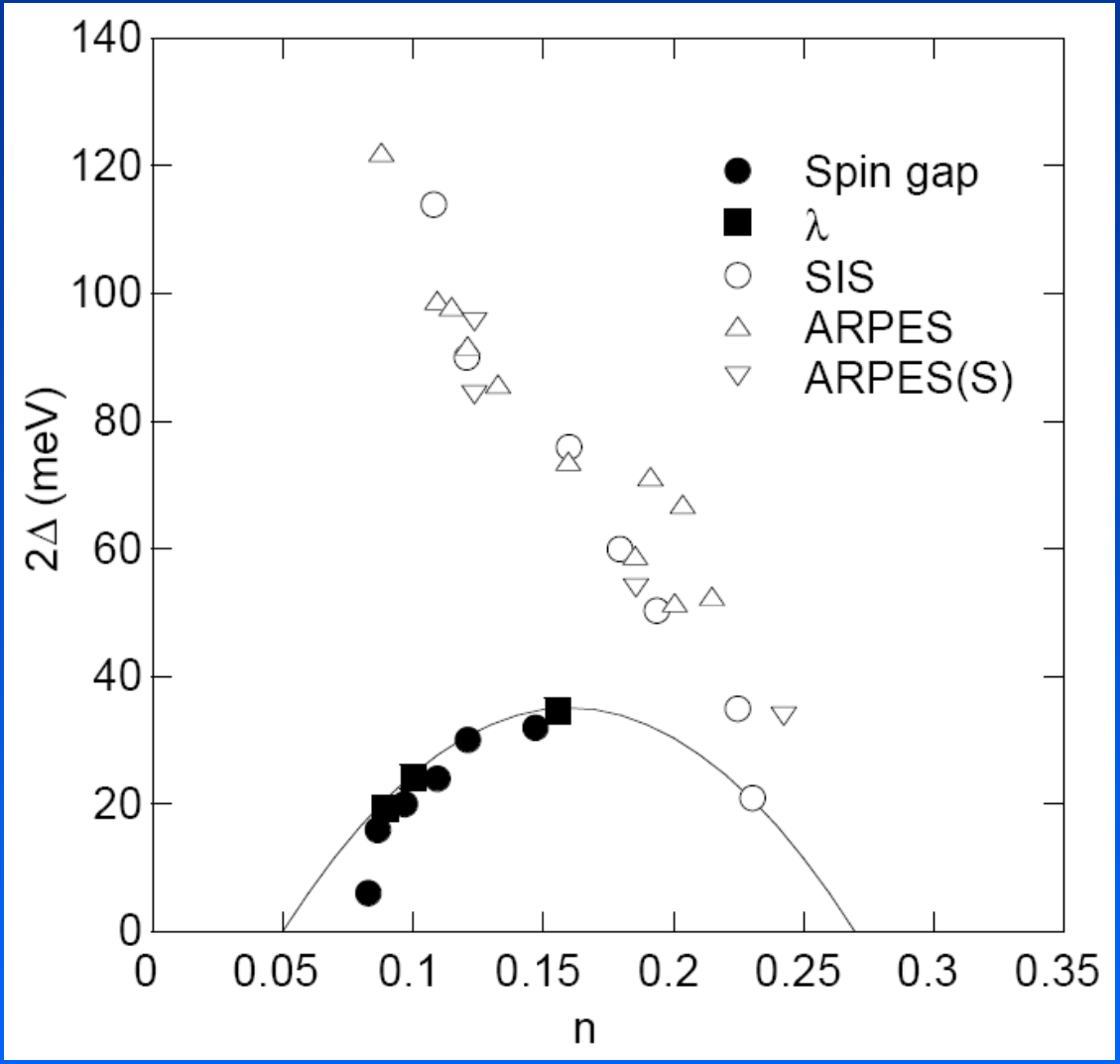




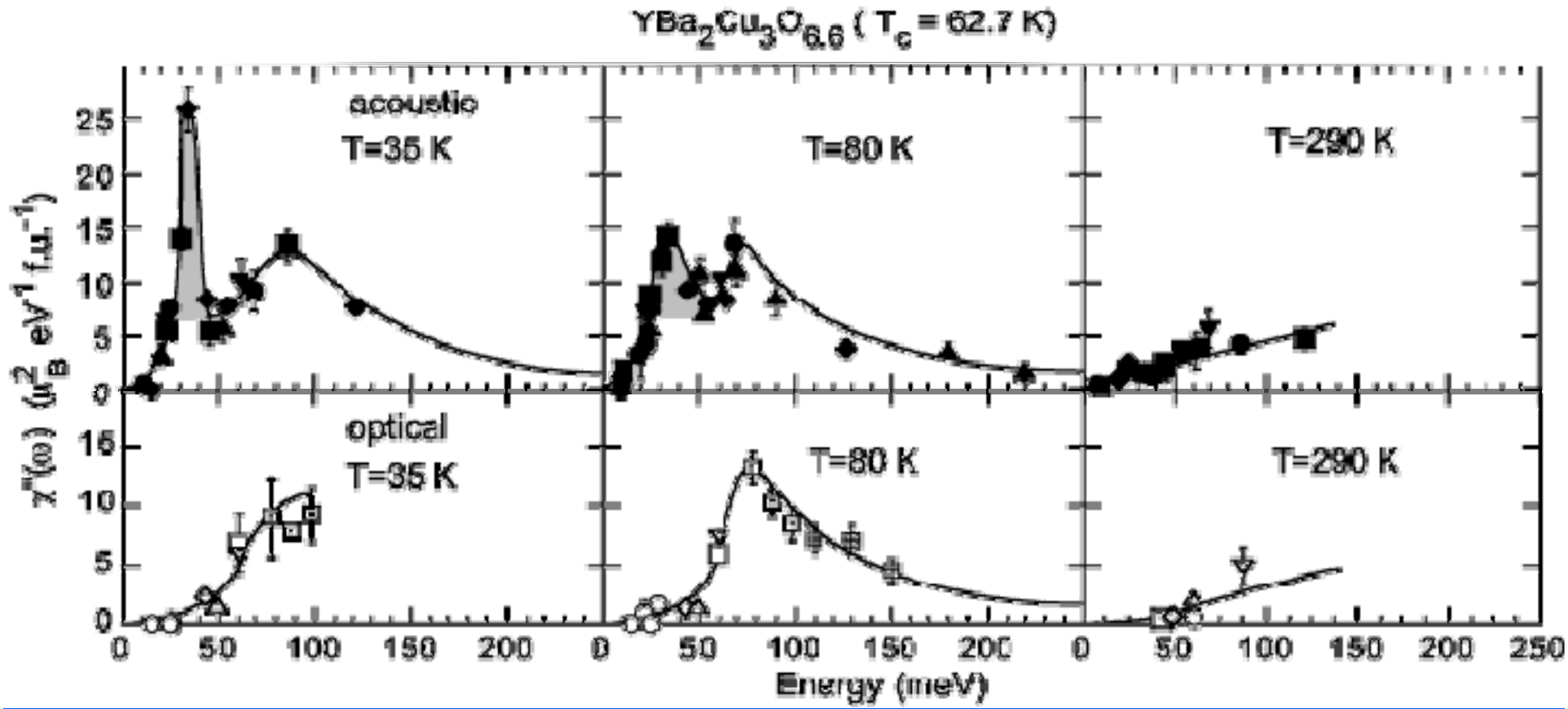
E=34 meV

similar results on detwinned crystals:-
V. Hinkov et al. Nature Physics 3, 780 (2007)

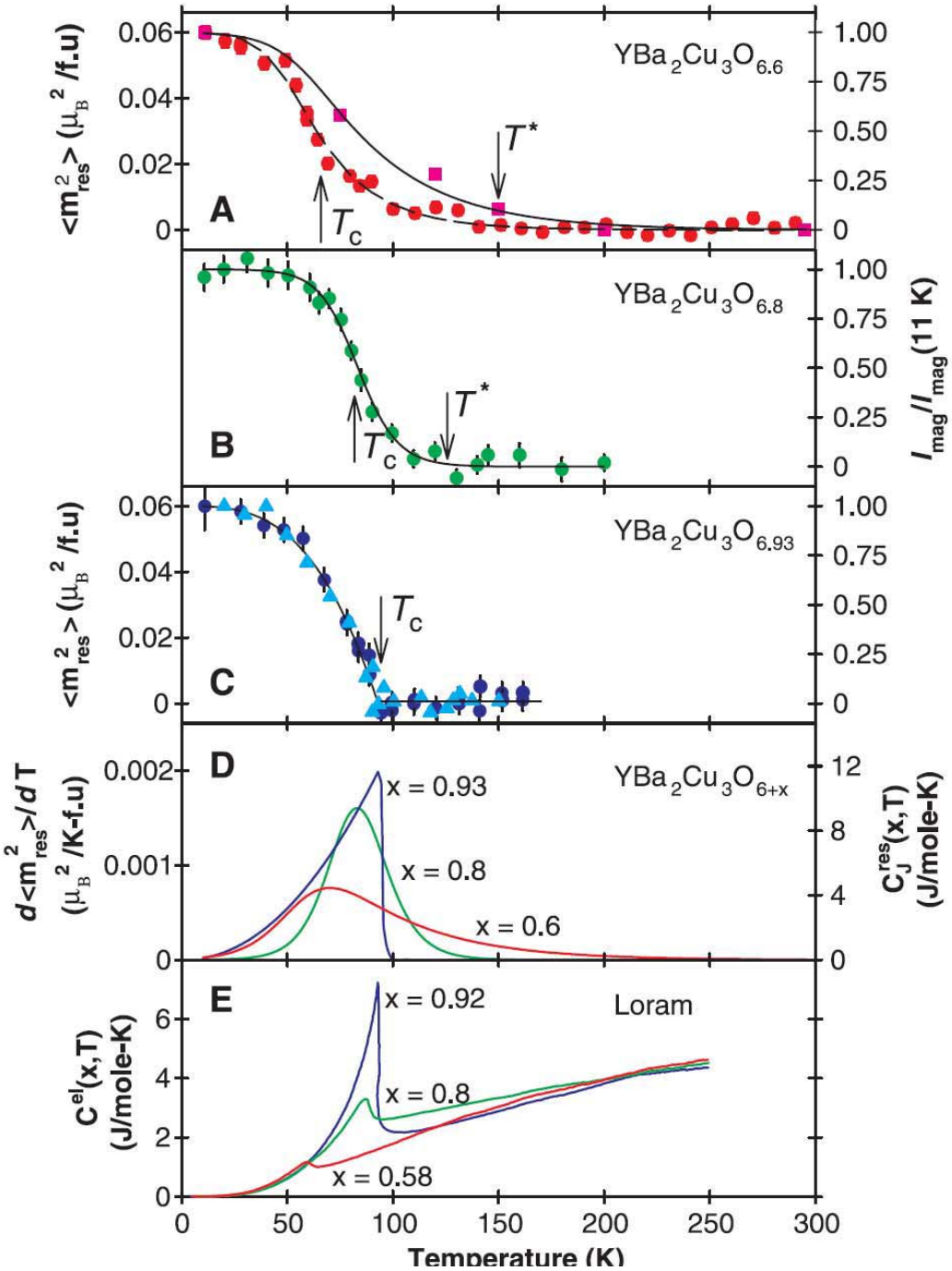
"Superconducting spin gap"

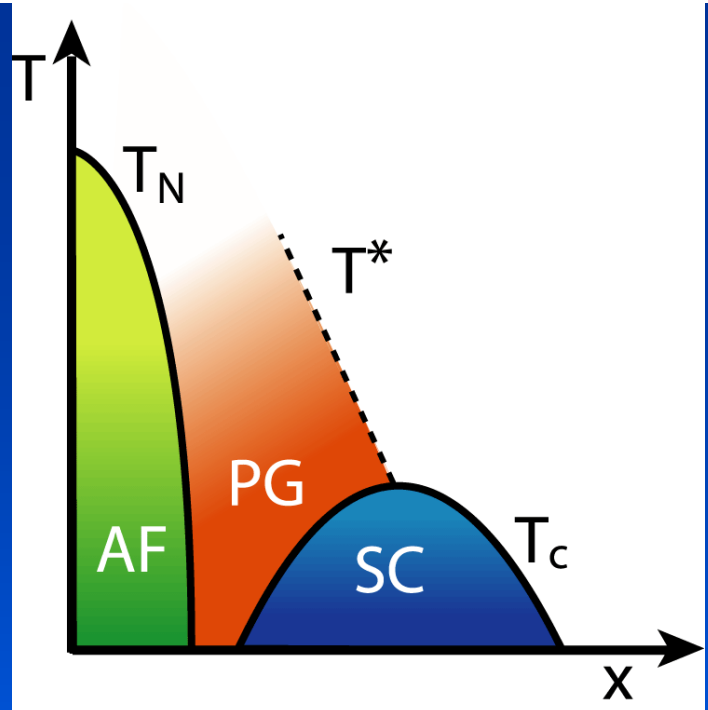


The local susceptibility of $YBa_2Cu_3O_{6.6}$



P. Dai, H. A. Mook, S. M. Hayden, G. Aeppli, T. G. Perring, R. D. Hunt, F. Dogan, Science 284, 1344 (1999); see also Bourges, PRB (1997) and Stock, PRB (2004)

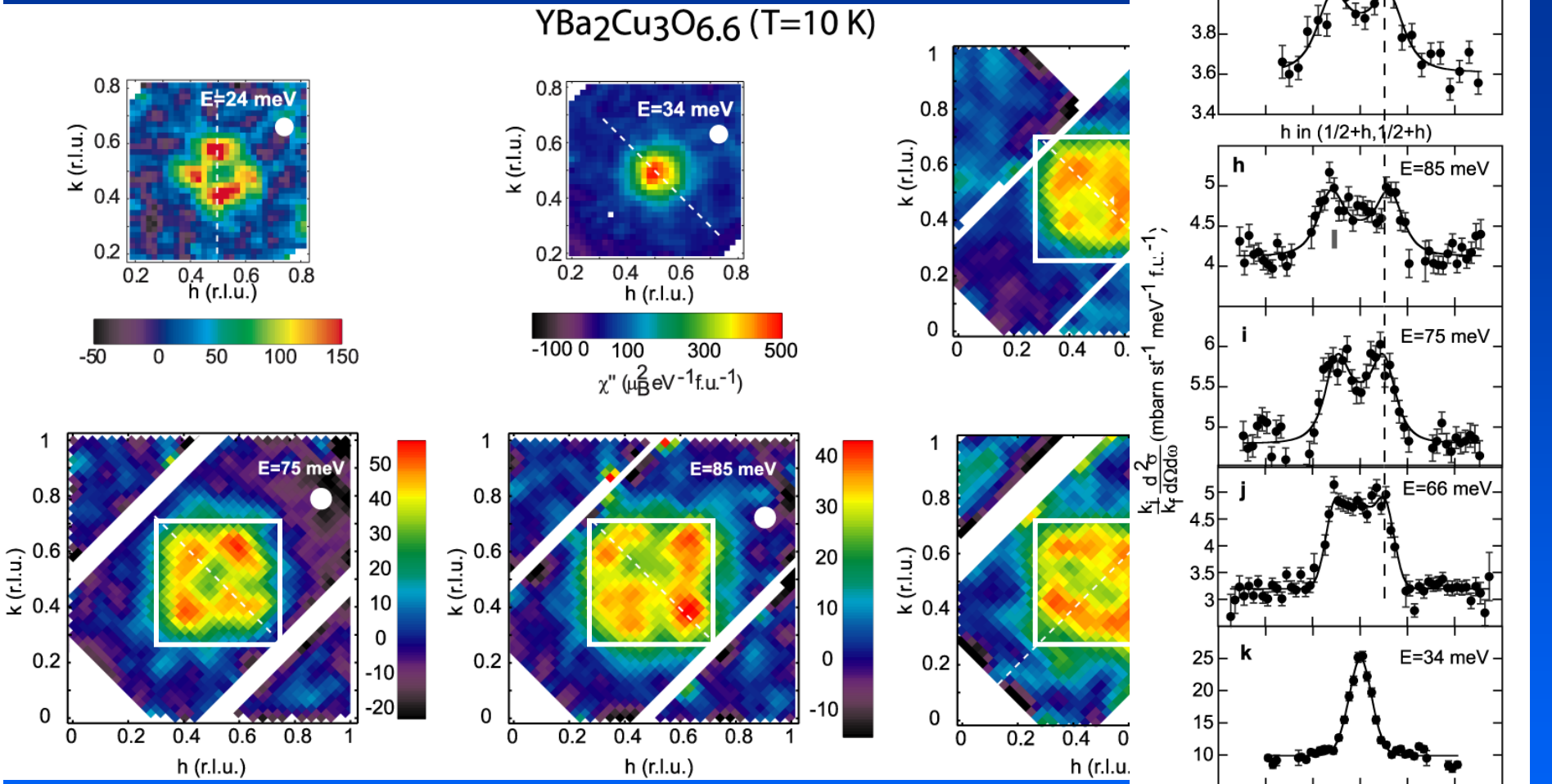




Resonance Intensity

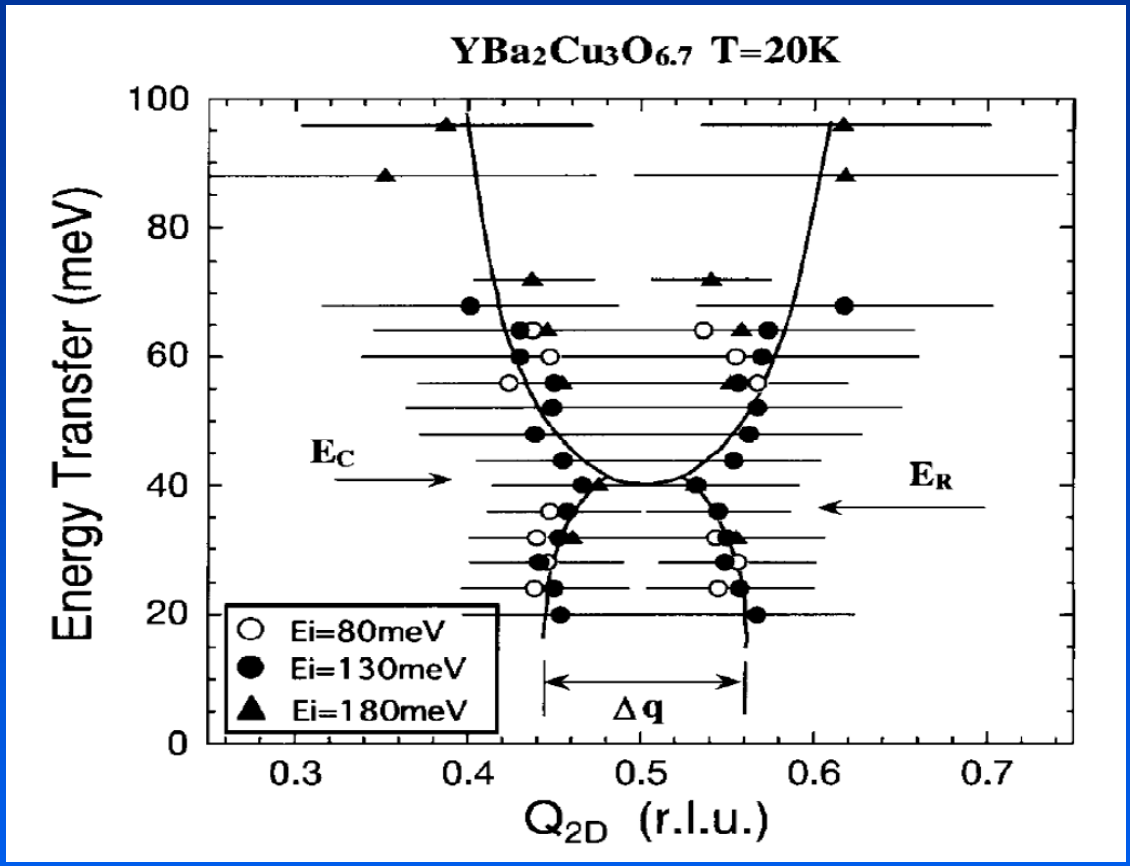
Dai et al., Science 284, 1344 (1999)

High-energy magnetic excitations in YBa_2Cu_3



Hayden et al, Nature 429, 534 (2004)

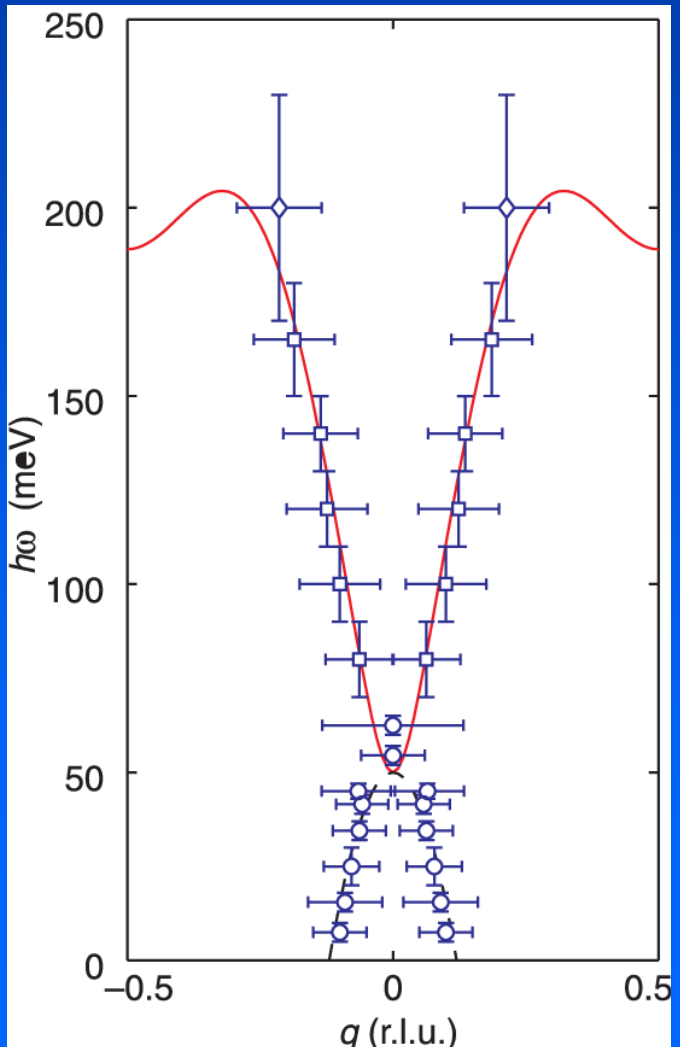
Hourglasses……

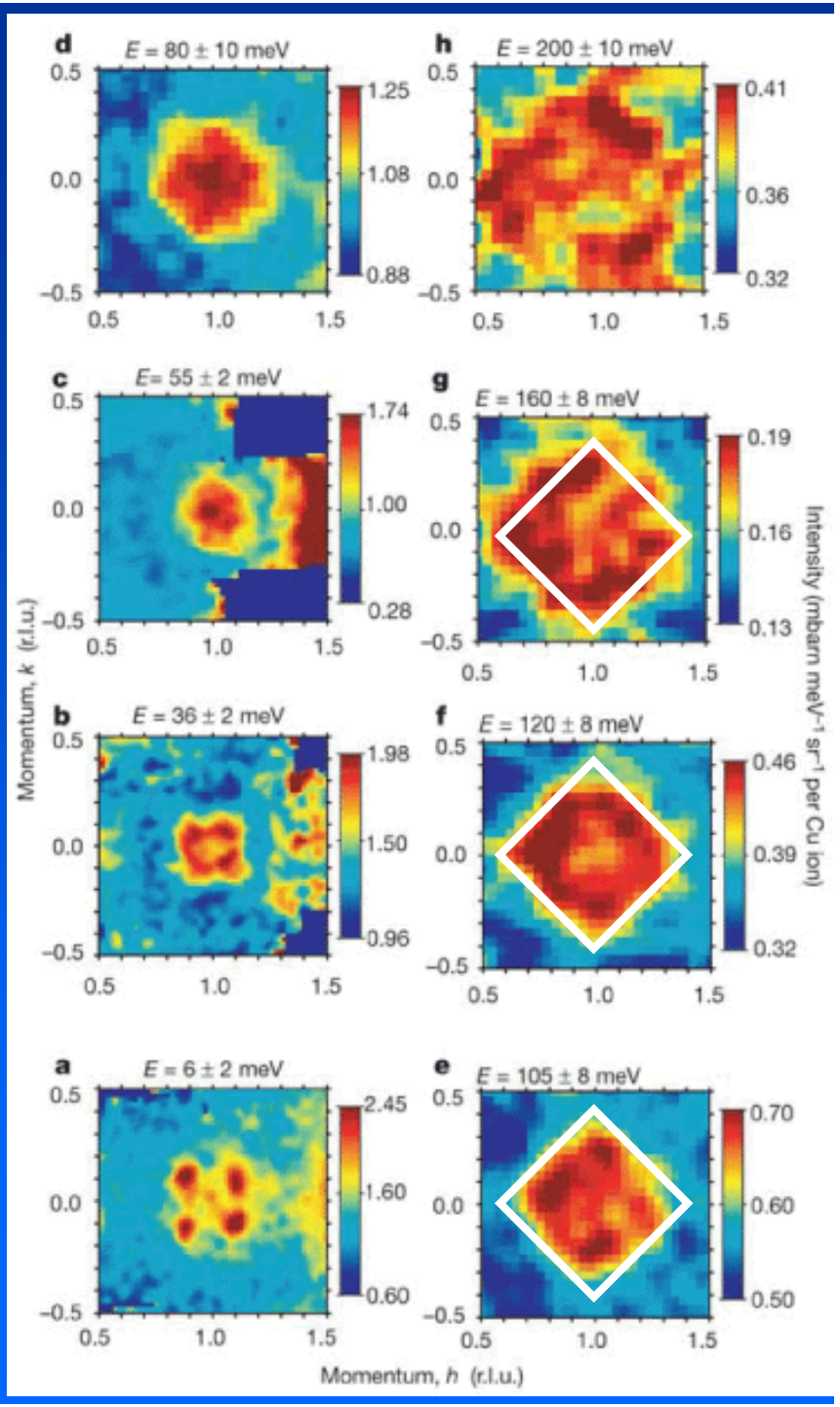


M. Arai et. al, PRL (1999)

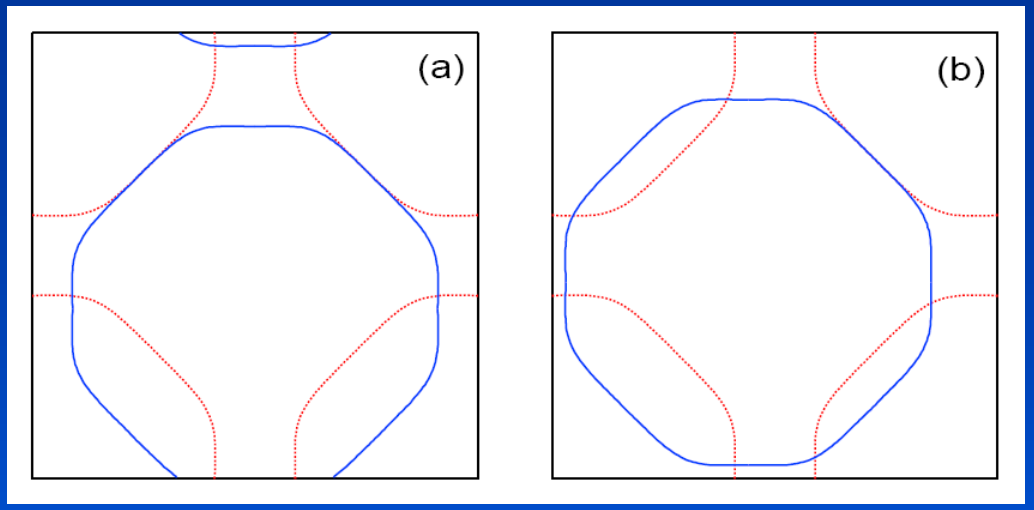
$La_{1.875}Ba_{0.125}CuO_4$

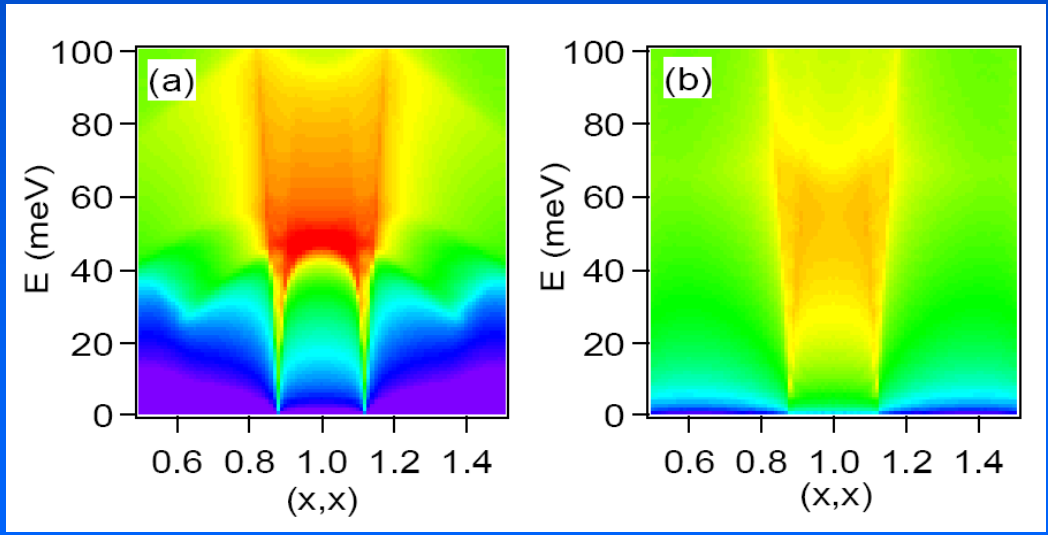
J. M. Tranquada , H. Woo, T. G. Perring , H. Goka ,G.D.Gu, G.Xu, M. Fujita, K. Yamada, Nature **429**, 534 (2004).





RPA calculations of $\chi(q,\omega)$

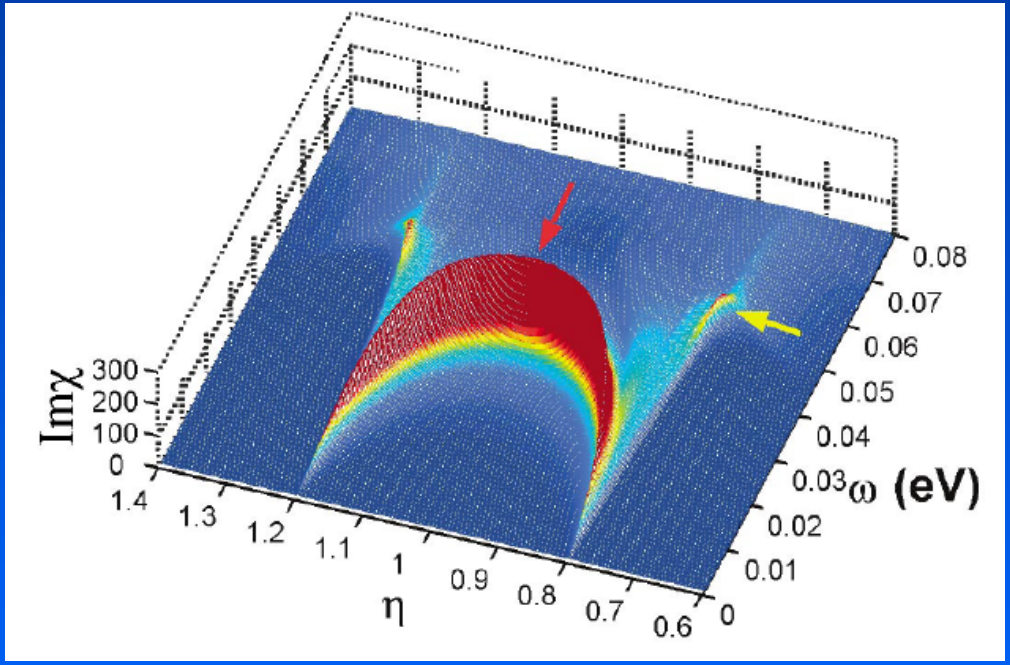




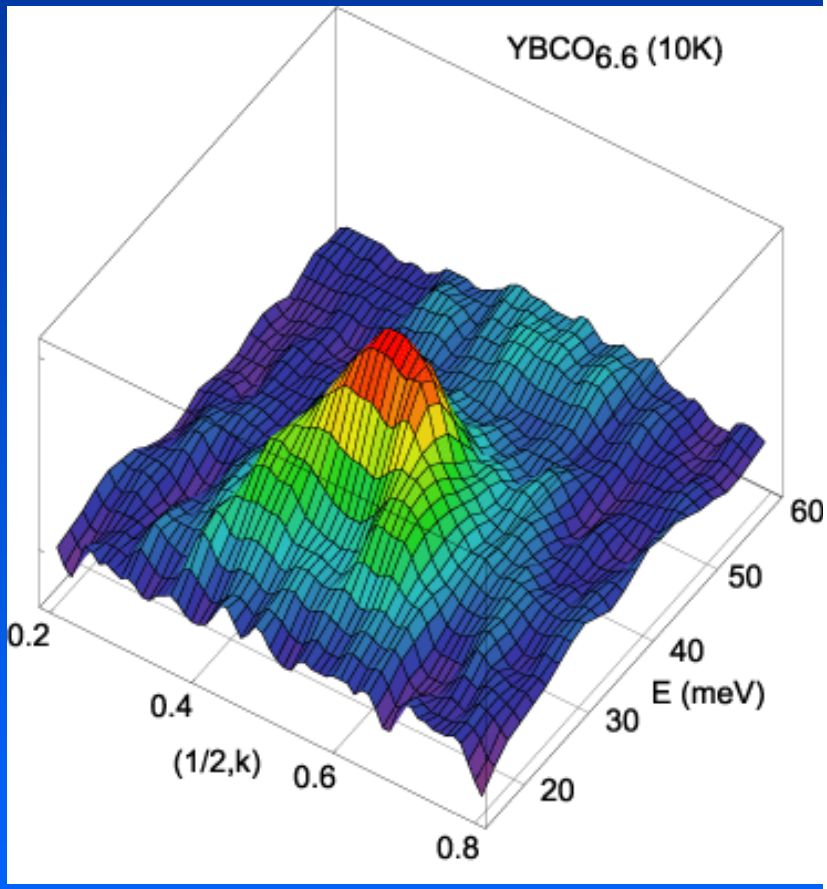
Results depend on details of band structure ⇒ Accurate knowledge required

e.g. M. R. Norman, PRB 2007

Is there a "Resonance" mode in $La_{2-x}Sr_xCuO_4$?

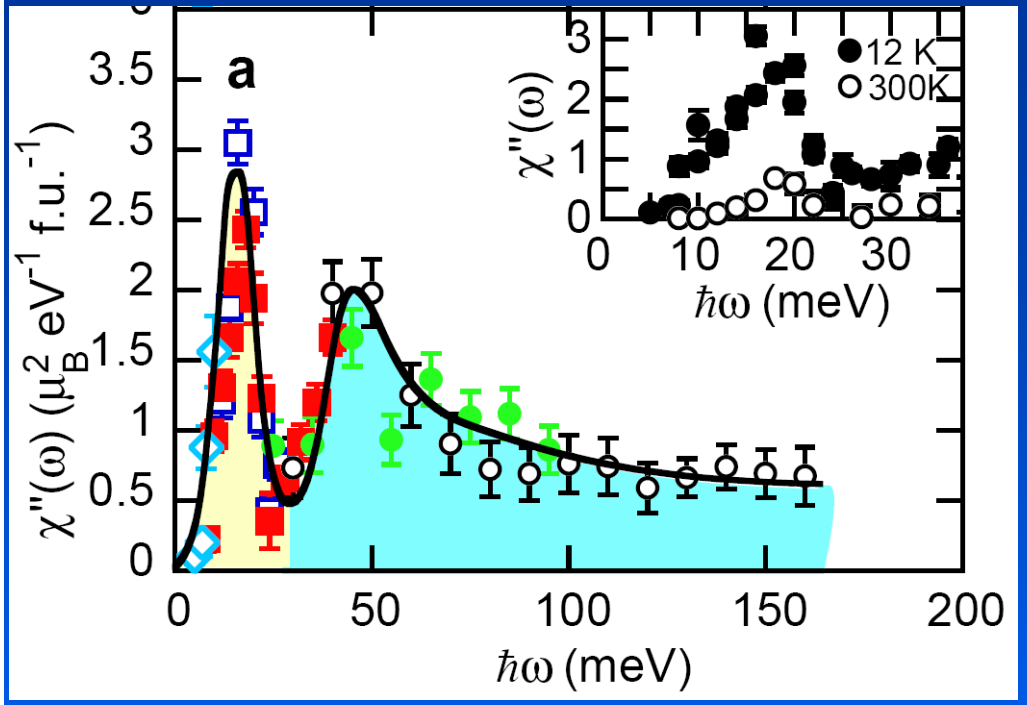


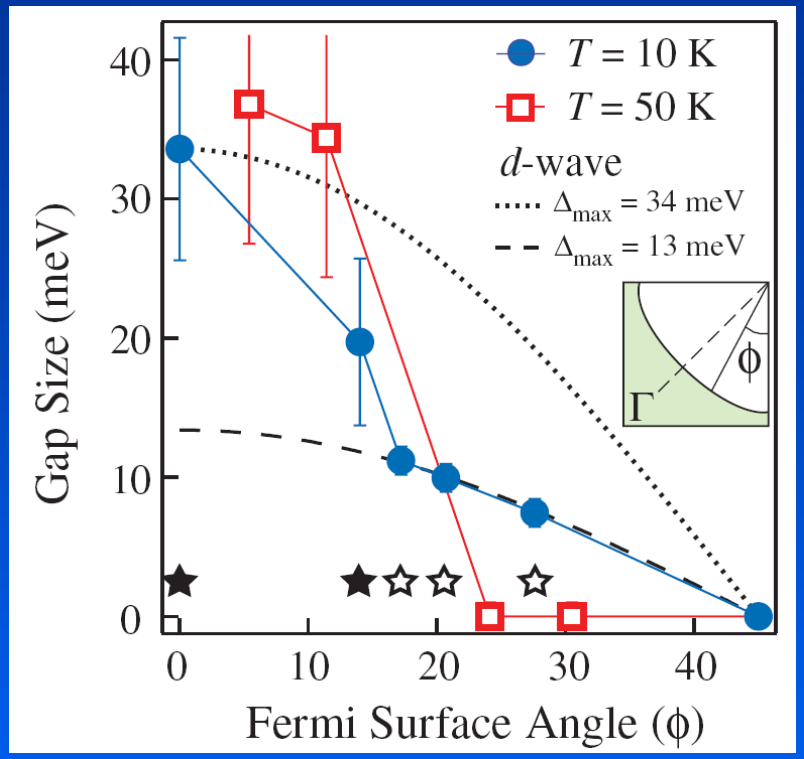
e.g. I. Ememin et al., PRL **94**, 147001 2005

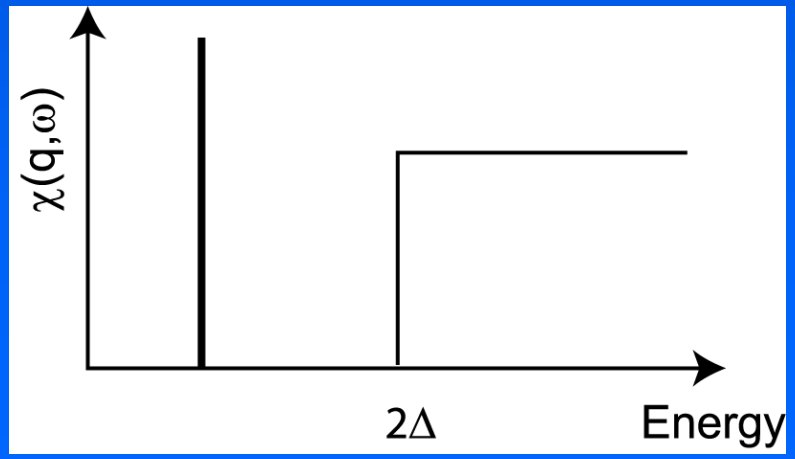


S. M. Hayden, et al, Nature **429**, 531 2004.

Possibly ....







LSCO ARPES
K. Terashima et al., prl 99, 017003 (2007)

Summary

Summary

- double-peaked structure at optimal doping
- overdoping results in the collapse of the 50 meV peak

Is 50 meV peak responsible for SC?