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SMR 1232 - 6

XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

NEUTRON RESONANT MODE IN HIGH TEMPERATURE SUPERCONDUCTORS

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These are preliminary lecture notes, intended only for distribution to participants.

Neutron Resonant Mode in High Temperature Superconductors

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Outline:

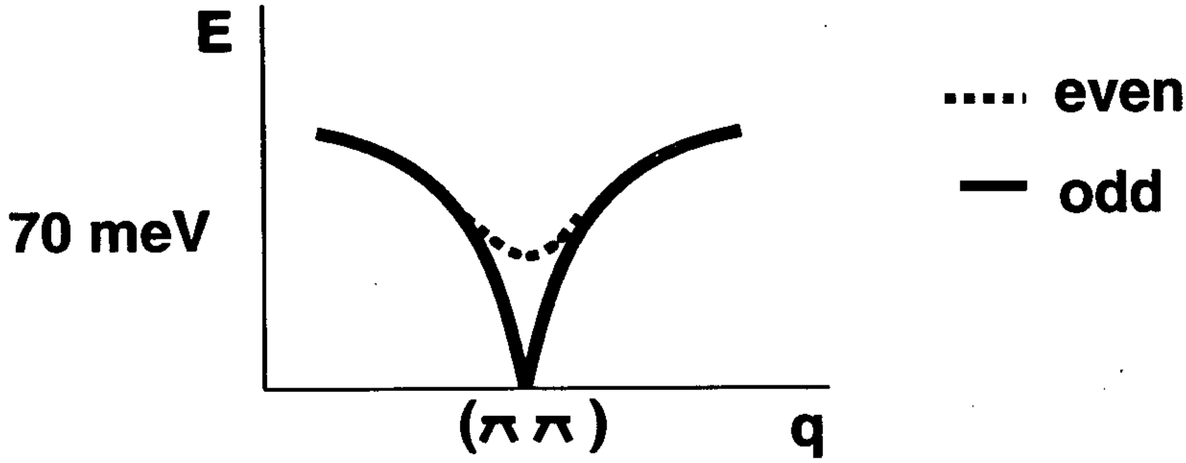
* Introduction: Resonant Mode in optimally doped and underdoped YBCO

* Resonant mode in optimally doped and overdoped BSCCO

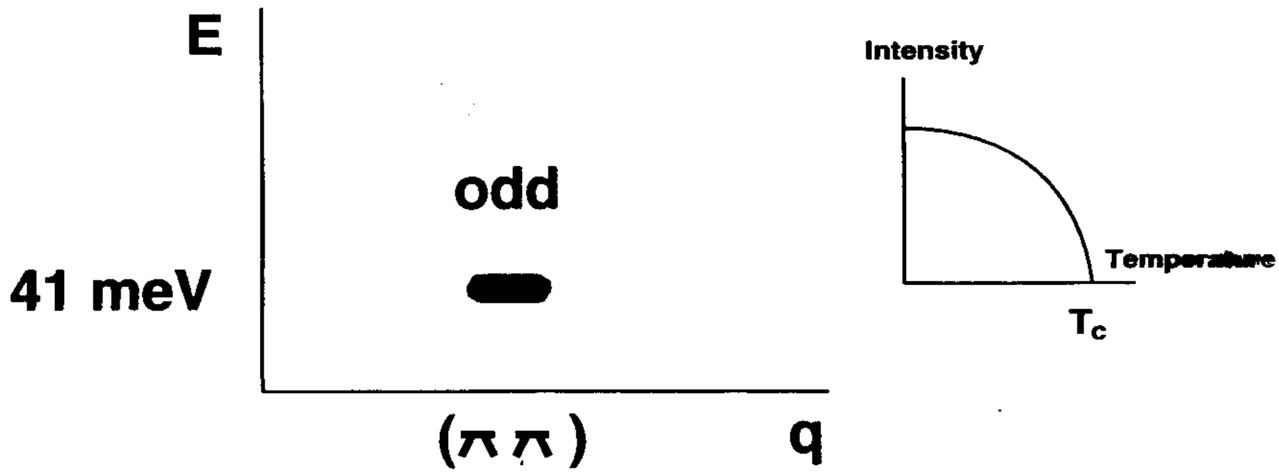
* Resonant mode and incommensurate peaks in near-optimally doped YBCO

* Influence of S=0 and S=1 impurities on the resonant mode

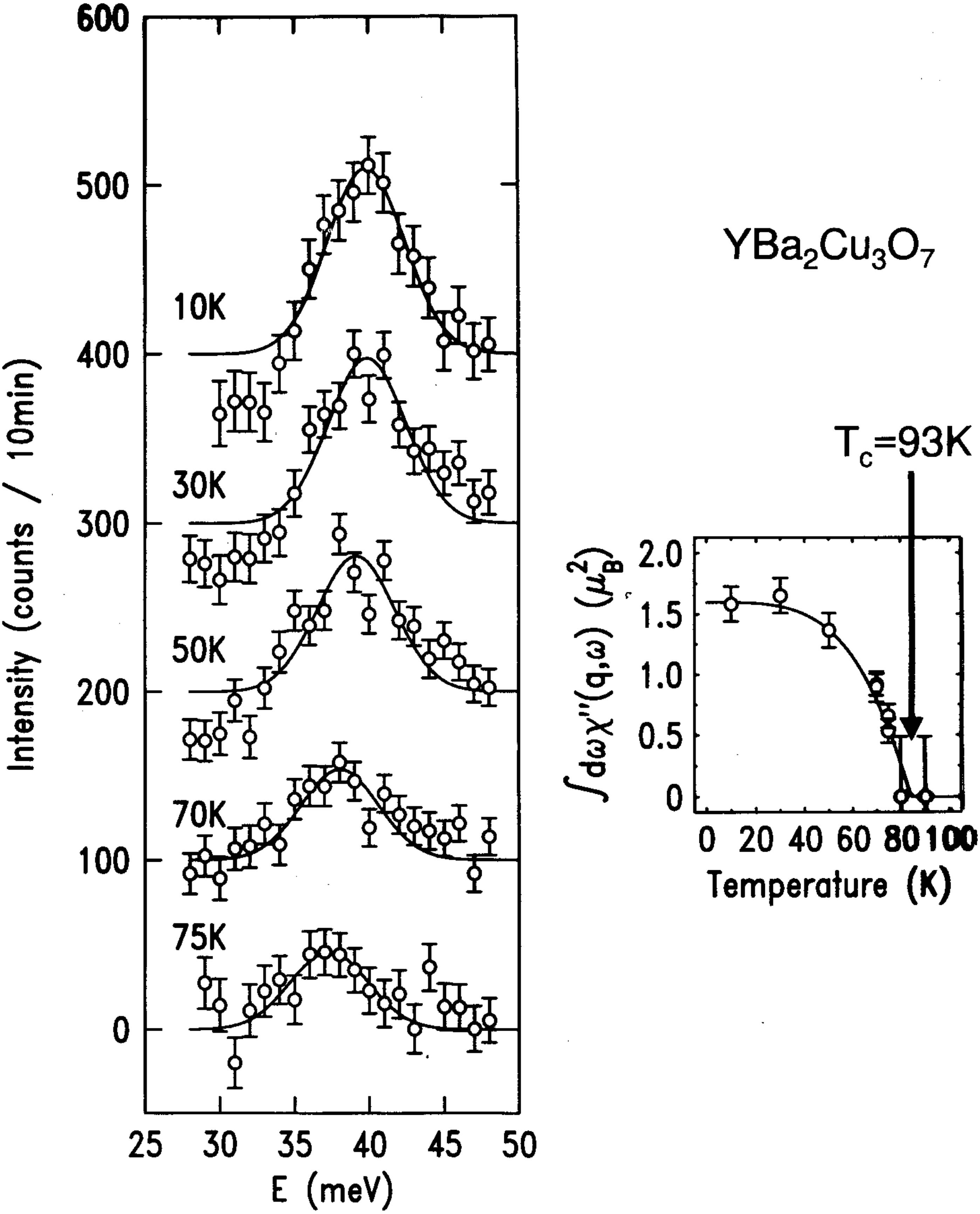
Magnetic Excitations



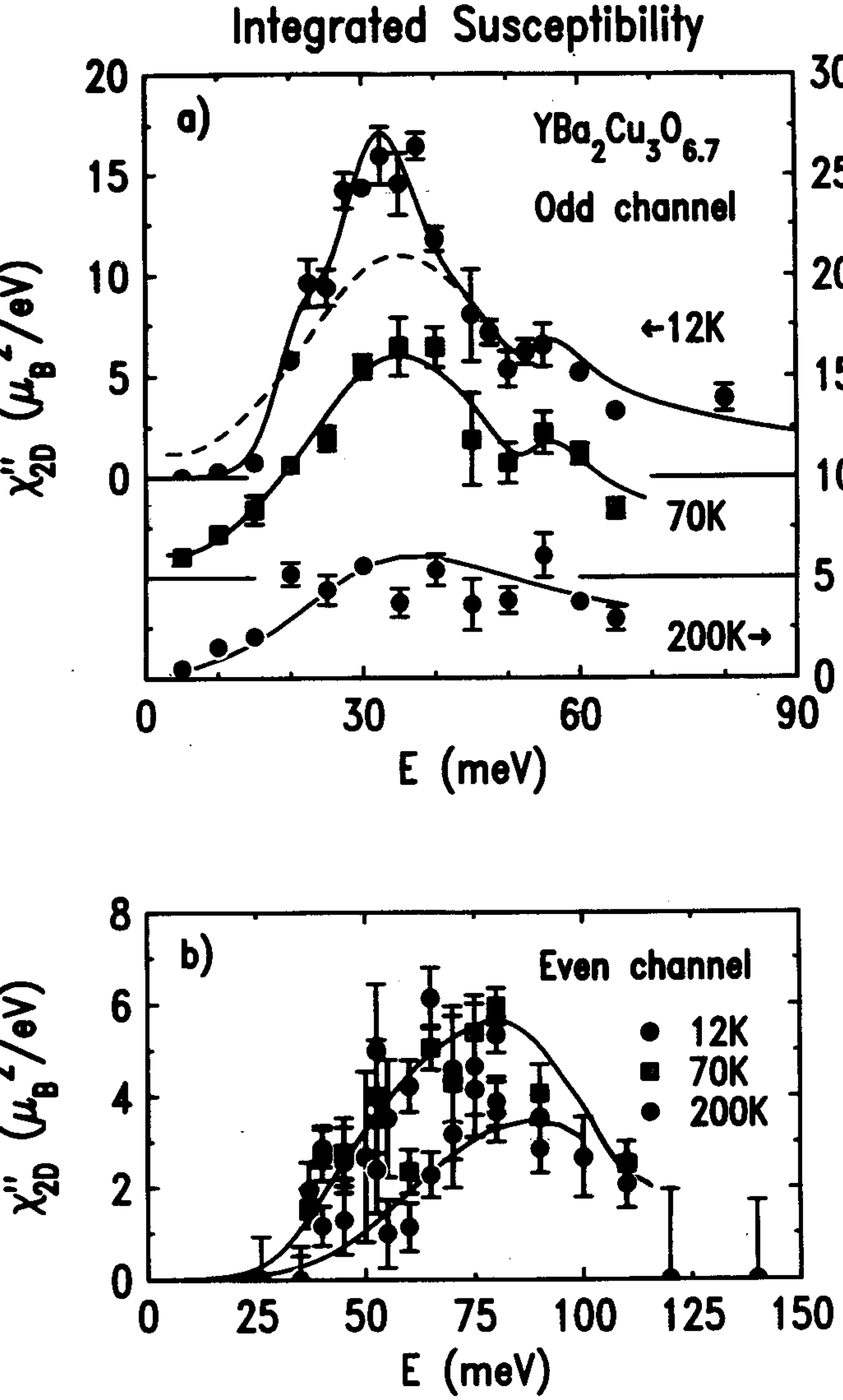
$YBa_2Cu_3O_6$



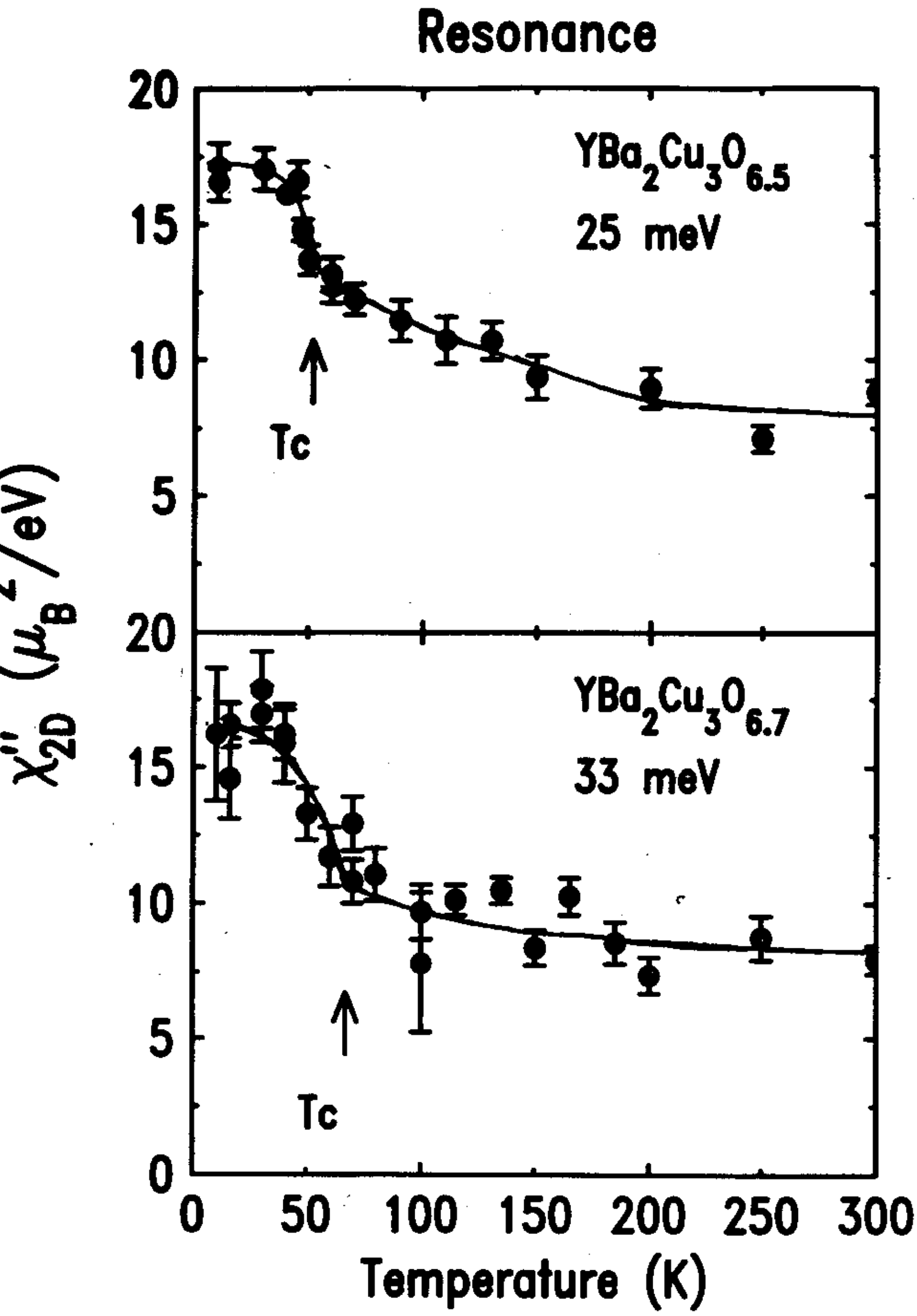
$YBa_2Cu_3O_7$



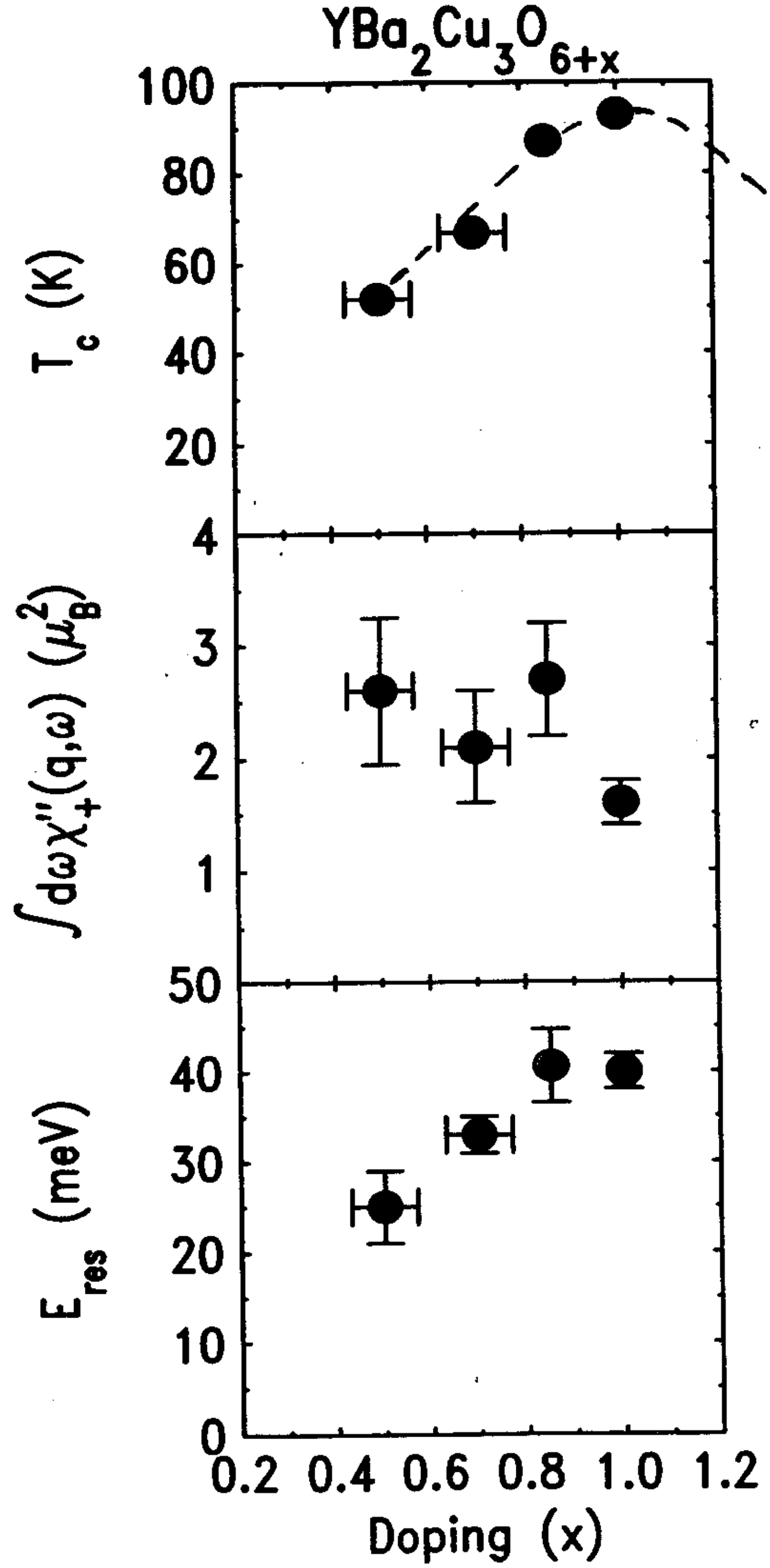
Foug et al., PRB 1996



Foug et al., PRB 2000



Resonance
$YBa_2Cu_3O_{6.5}$
25 meV
$YBa_2Cu_3O_{6.7}$
33 meV
Tc
Tc
χ''_{2D} (μ_B^2/eV)
Temperature (K)
0
5
10
15
20
0
50
100
150
200
250
300



Fong et al., PRB 2000

Spin Susceptibility in a BCS Superconductor

$$\chi_0(q,\omega) = \Sigma_k \{$$

coherence factor Fermi factor

$$\frac{1}{2}\left(1+\frac{\varepsilon_k\varepsilon_{k+q}+\Delta_k\Delta_{k+q}}{E_kE_{k+q}}\right)\frac{f(E_{k+q})-f(E_k)}{\omega-(E_{k+q}-E_k)+i\delta}$$

scattering of thermally excited pairs

$$+\frac{1}{4}\left(1-\frac{\varepsilon_k\varepsilon_{k+q}+\Delta_k\Delta_{k+q}}{E_kE_{k+q}}\right)\frac{1-f(E_{k+q})-f(E_k)}{\omega+(E_{k+q}+E_k)+i\delta}$$

pair annihilation

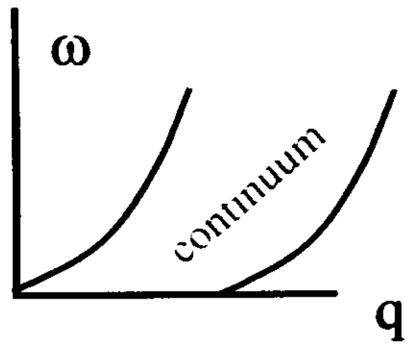
$$+\frac{1}{4}\left(1-\frac{\varepsilon_k\varepsilon_{k+q}+\Delta_k\Delta_{k+q}}{E_kE_{k+q}}\right)\frac{f(E_{k+q})+f(E_k)-1}{\omega-(E_{k+q}+E_k)+i\delta}\}$$

pair creation

ε_k band dispersion

$$E_k = \sqrt{\varepsilon_k^2 + \Delta_k^2}$$

Strong-Correlation Model

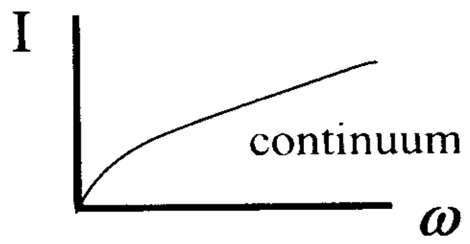


Starting point:
band susceptibility $\chi_0(q,\omega)$

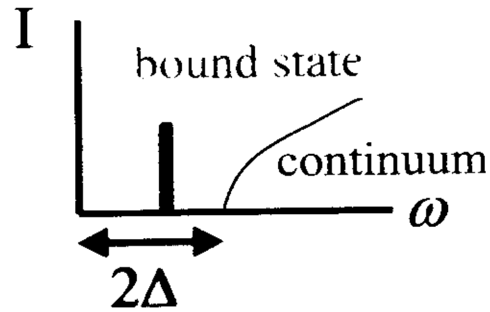
Renormalization of $\chi_0(q,\omega)$ by interactions:

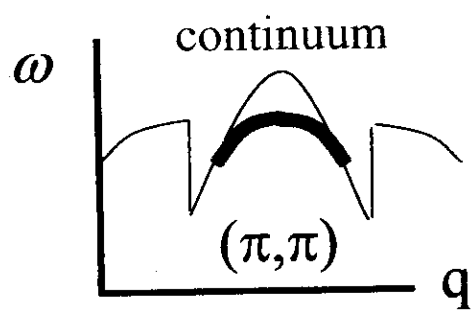
Stoner model: $$\chi(q,\omega) = \frac{\chi_0(q,\omega)}{1 - J(q)\,\chi_0(q,\omega)}$$

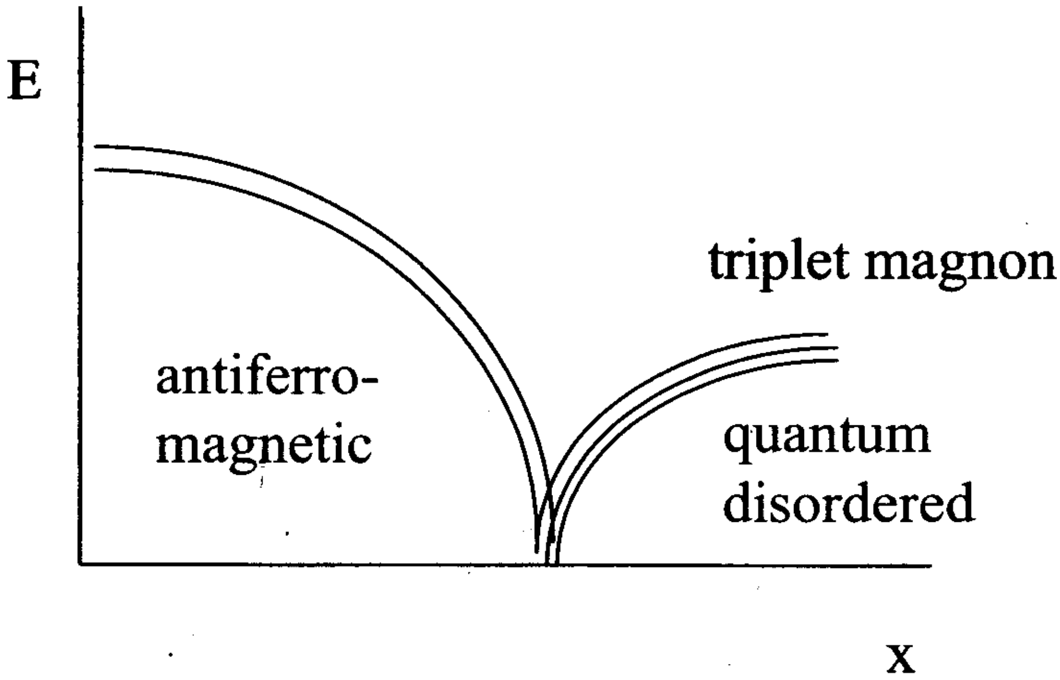
$T > T_c$

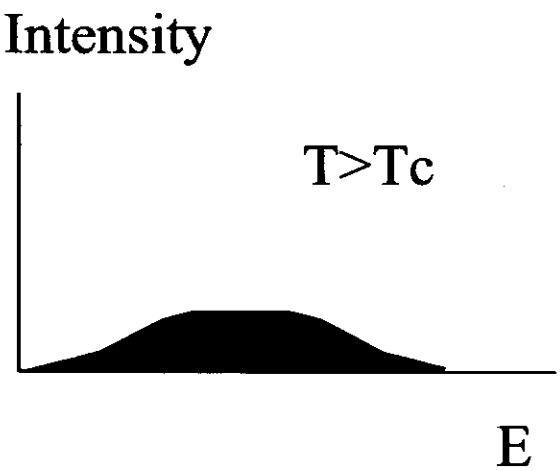


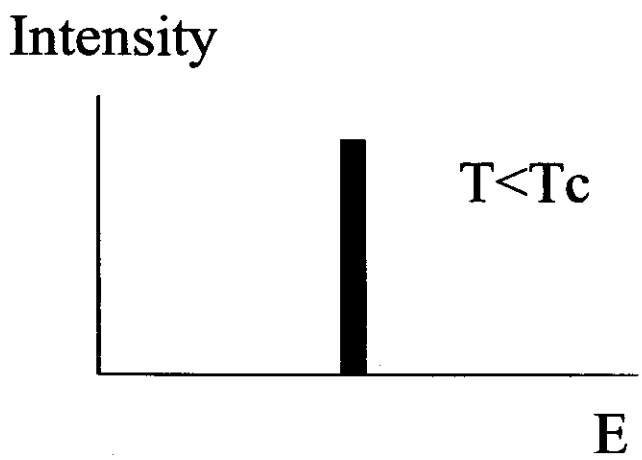
$T < T_c$











strong quasiparticle damping

no quasiparticle damping

SO(5) Model

Resonance peak is pseudo-Goldstone mode of symmetry group linking antiferromagnetism (3-comp. order parameter) and d-wave superconductivity (2 comp. order parameter)

symmetry exact at quantum critical point (E_{res}=0)

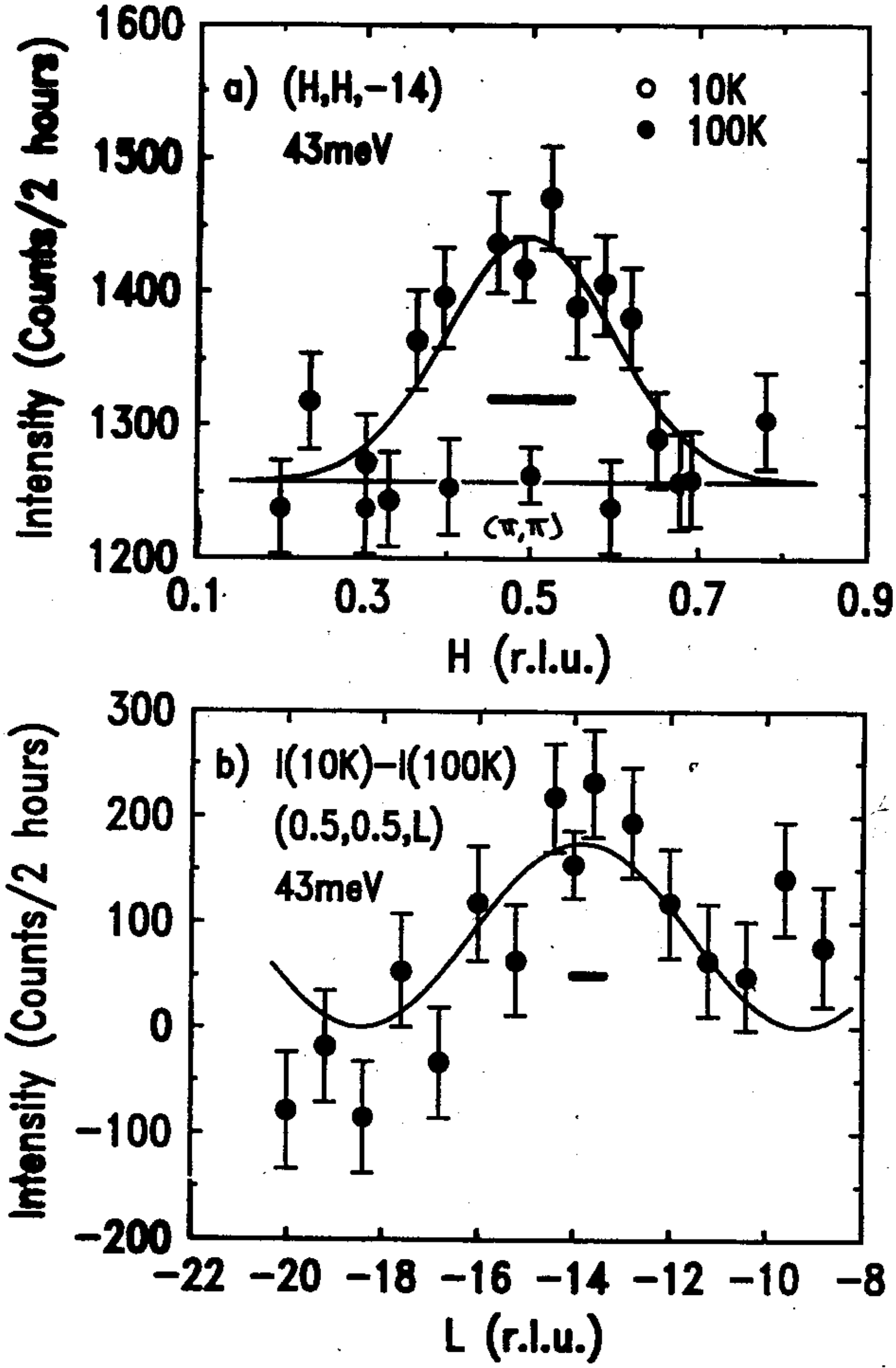
in superconducting phase:

$$I_{res} \propto \frac{\Delta^2}{n\,J^2}$$

$$E_{res} \propto n\,J$$

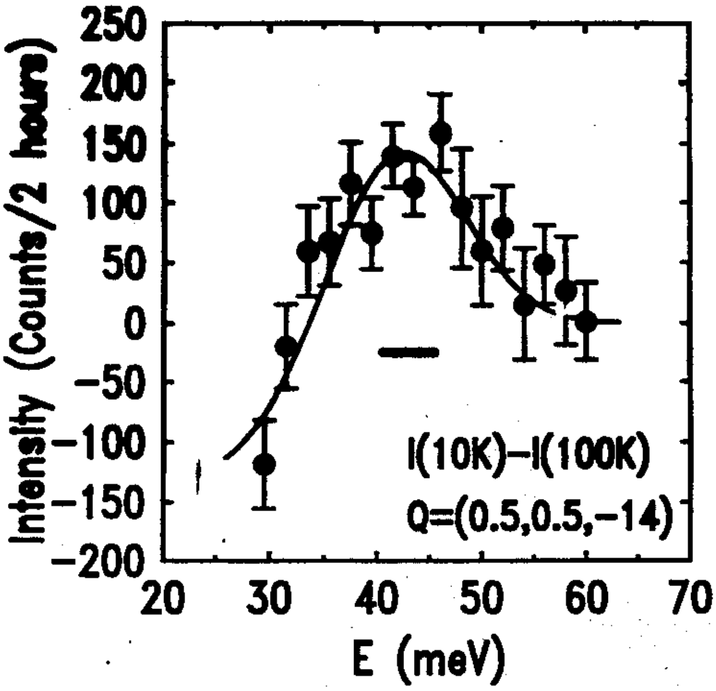
$Bi_2Sr_2CaCu_2O_{8+\delta}$ ($T_c = 92K$)

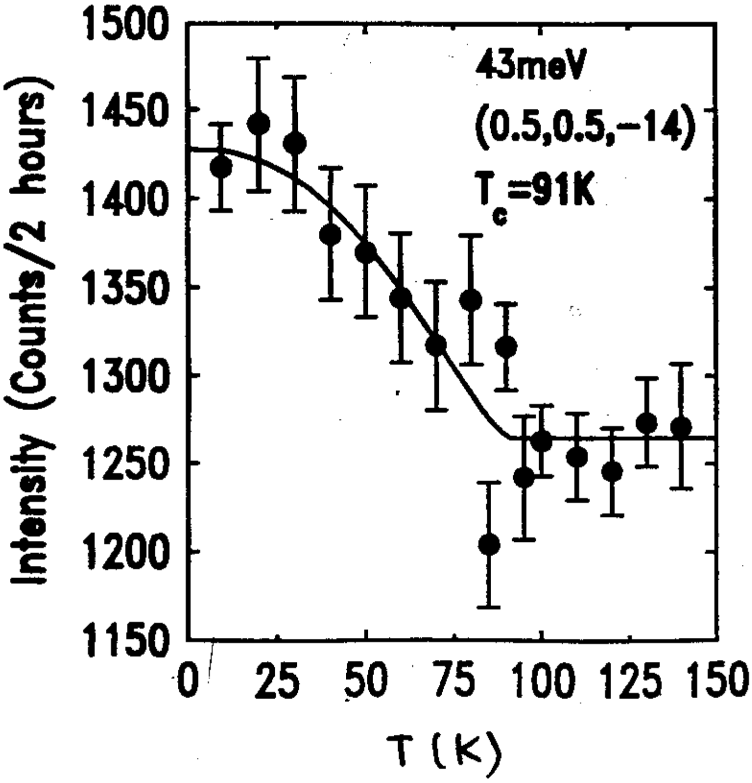
$0.08 cm^3$ single crystal



Fong et al., Nature (...

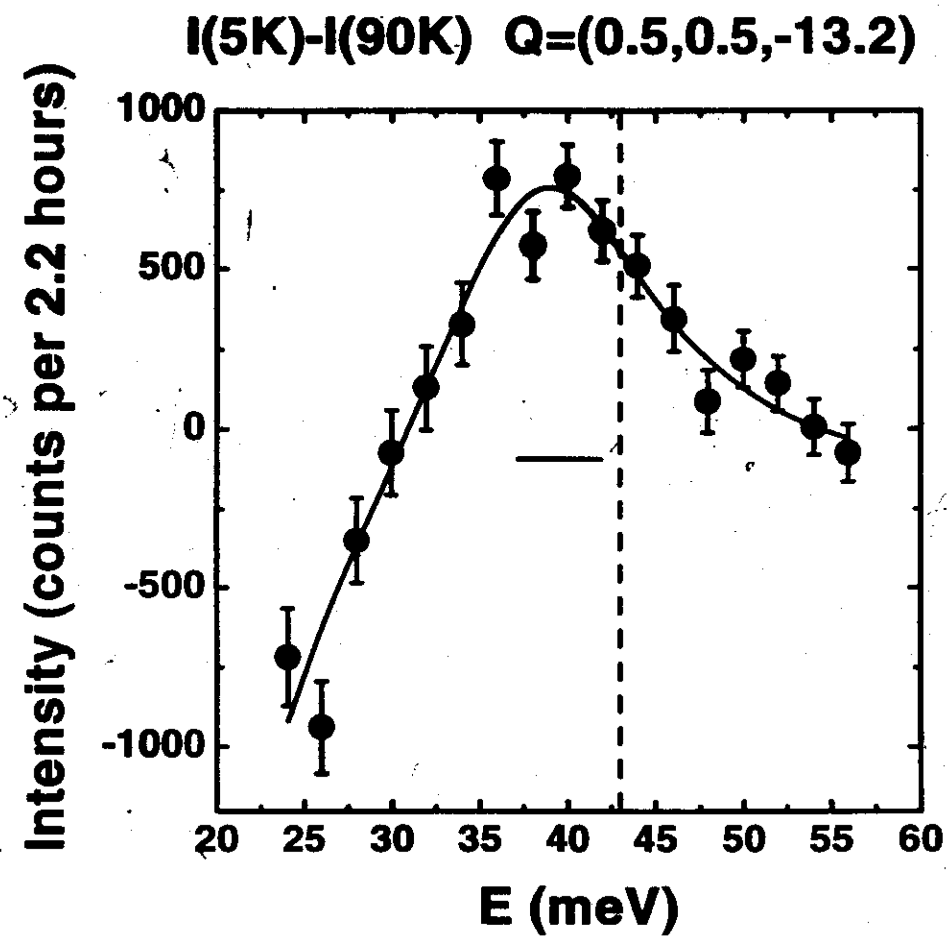
$Bi_2 Sr_2 Ca Cu_2 O_{8+\delta}$

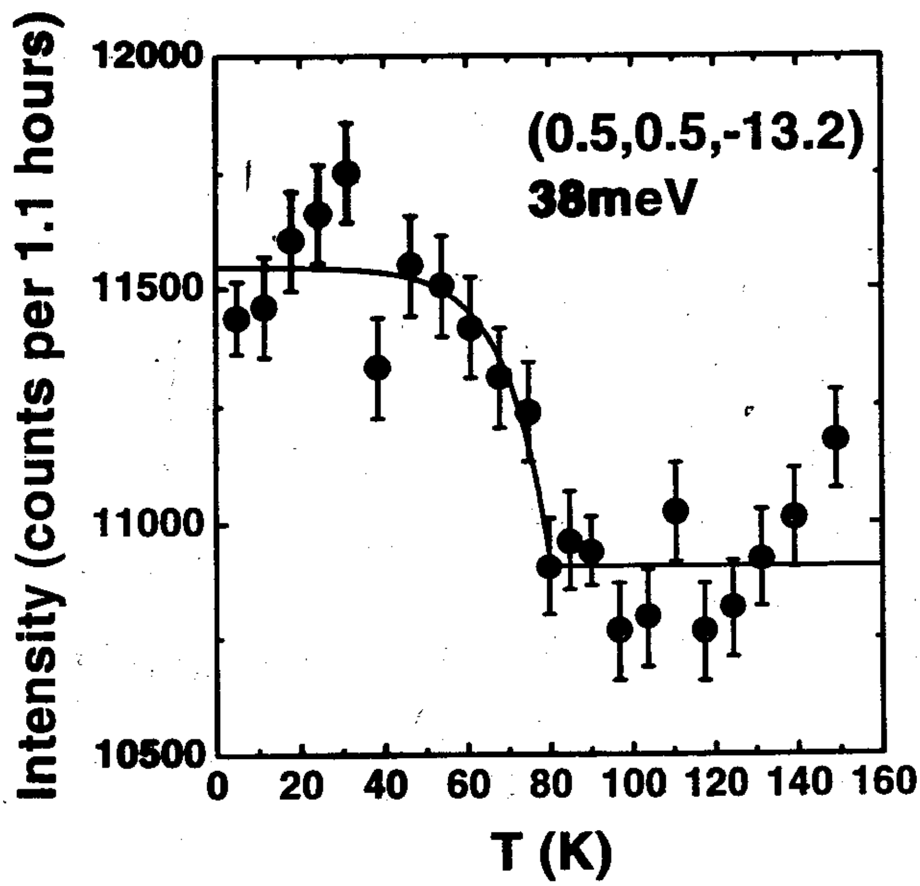




Fong et al.
Nature (99)

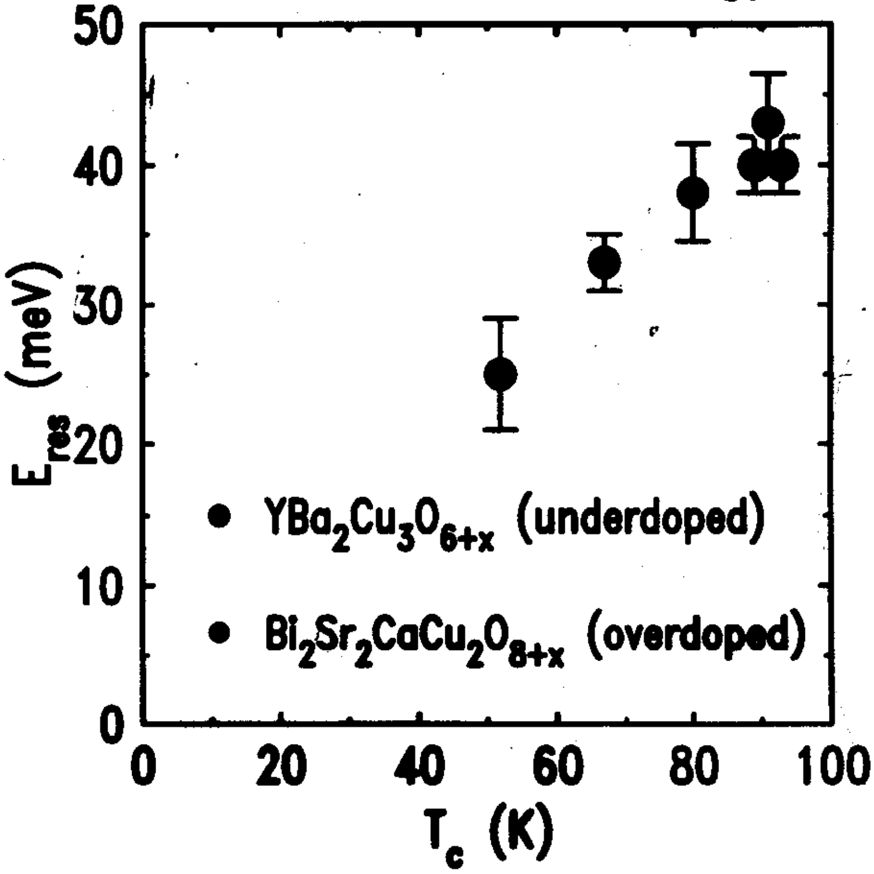
Overdoped $Bi_2 Sr_2 Ca Cu_2 O_{8+\delta}$ ($T_c = 83$ K)





(0.5,0.5,-13.2)
38meV
Intensity (counts per 1.1 hours)
12000
11500
11000
10500
0
20
40
60
80
100
120
140
160
T (K)

Resonance Peak Energy



$$\frac{E_{res}}{kT_c} \sim 5.5$$

$YBa_2Cu_3O_{6.85}$ (T_c = 87K)

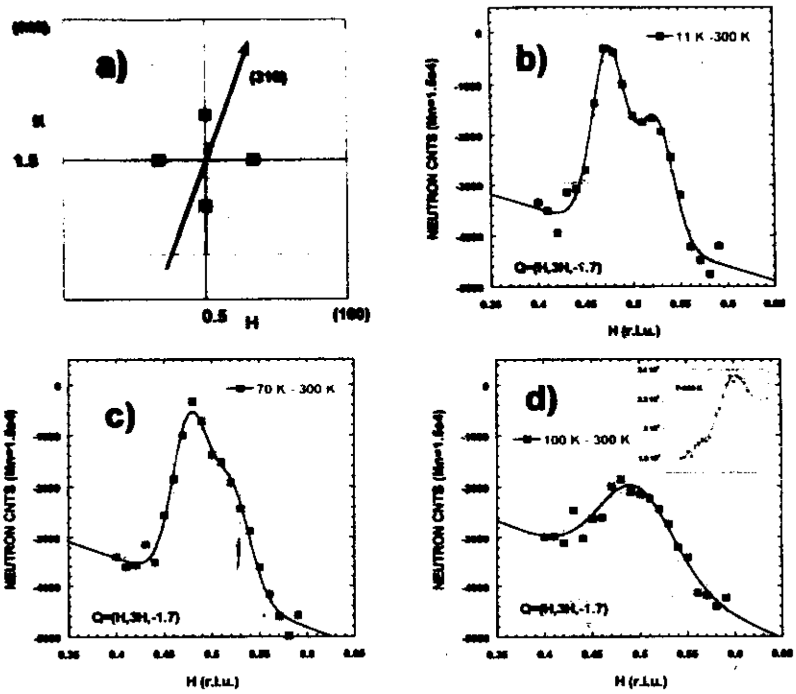
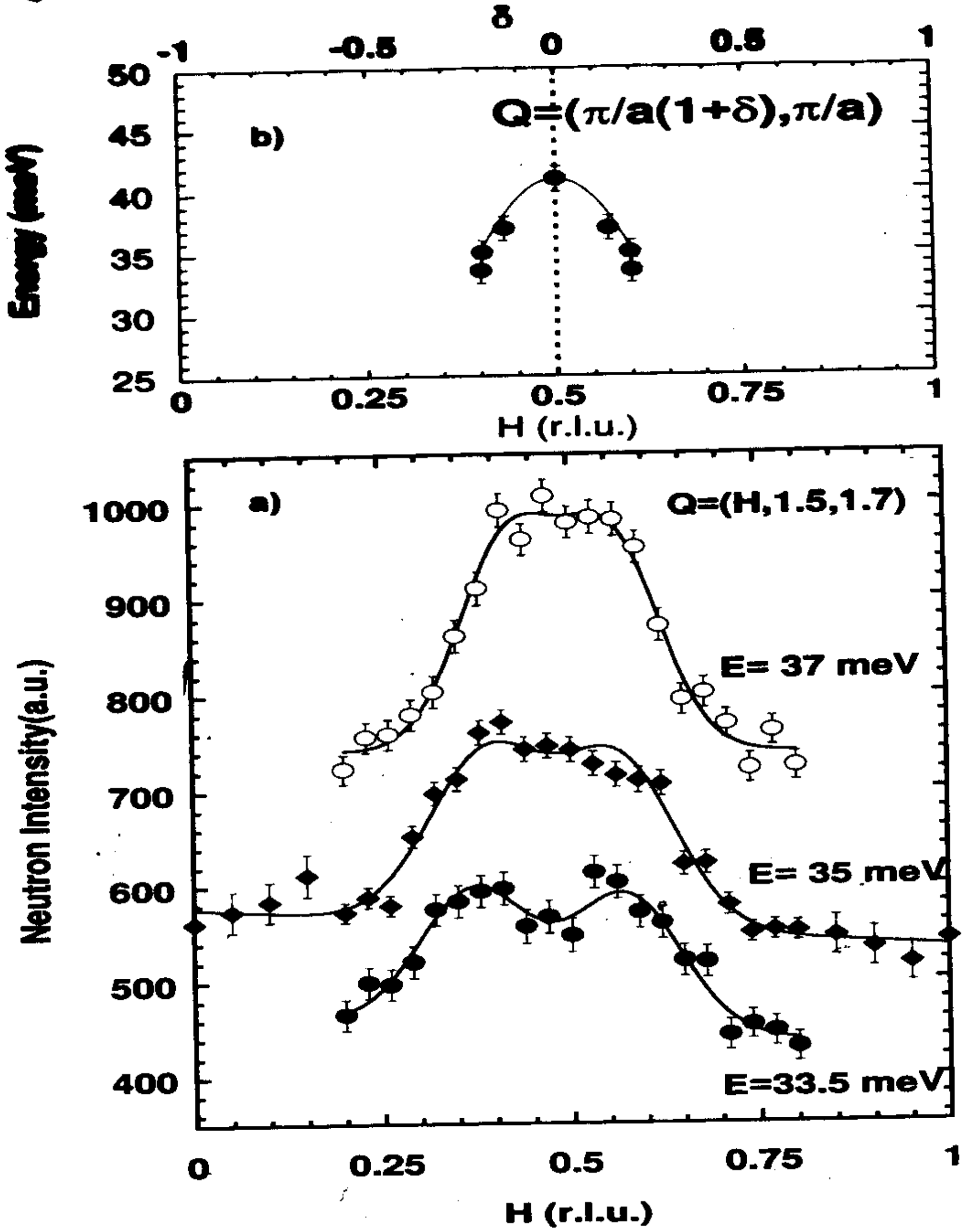
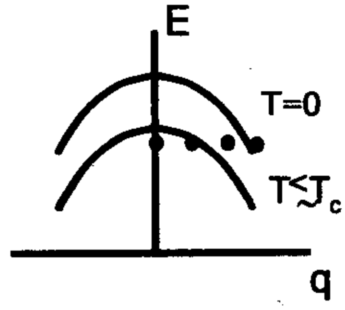


Fig 2



near-optimally doped $YBa_2Cu_3O_{6.85}$ (T_c = [illegible])


E
T=0
T≲T_c
q

$YBa_2Cu_3O_{6.85}$

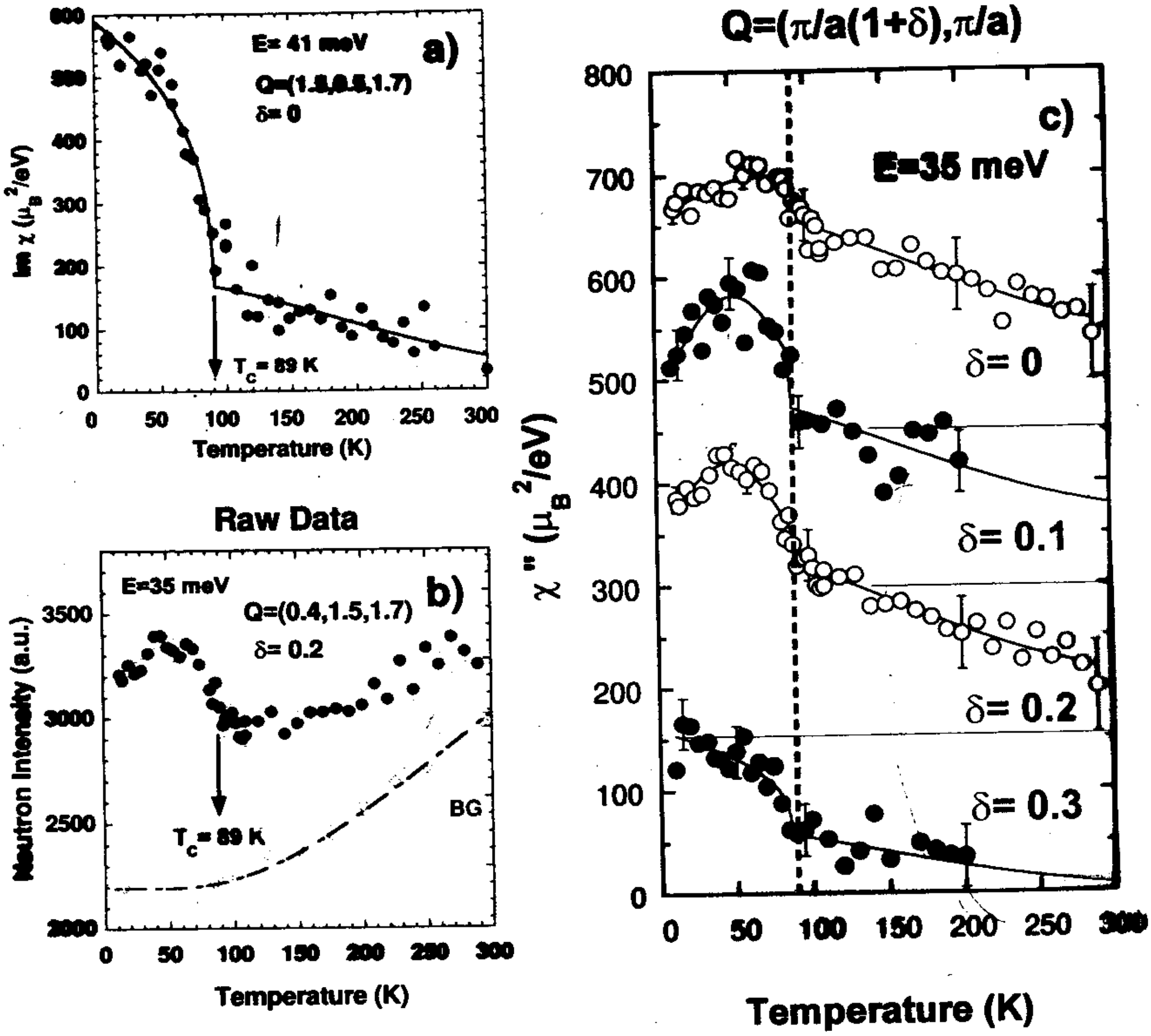
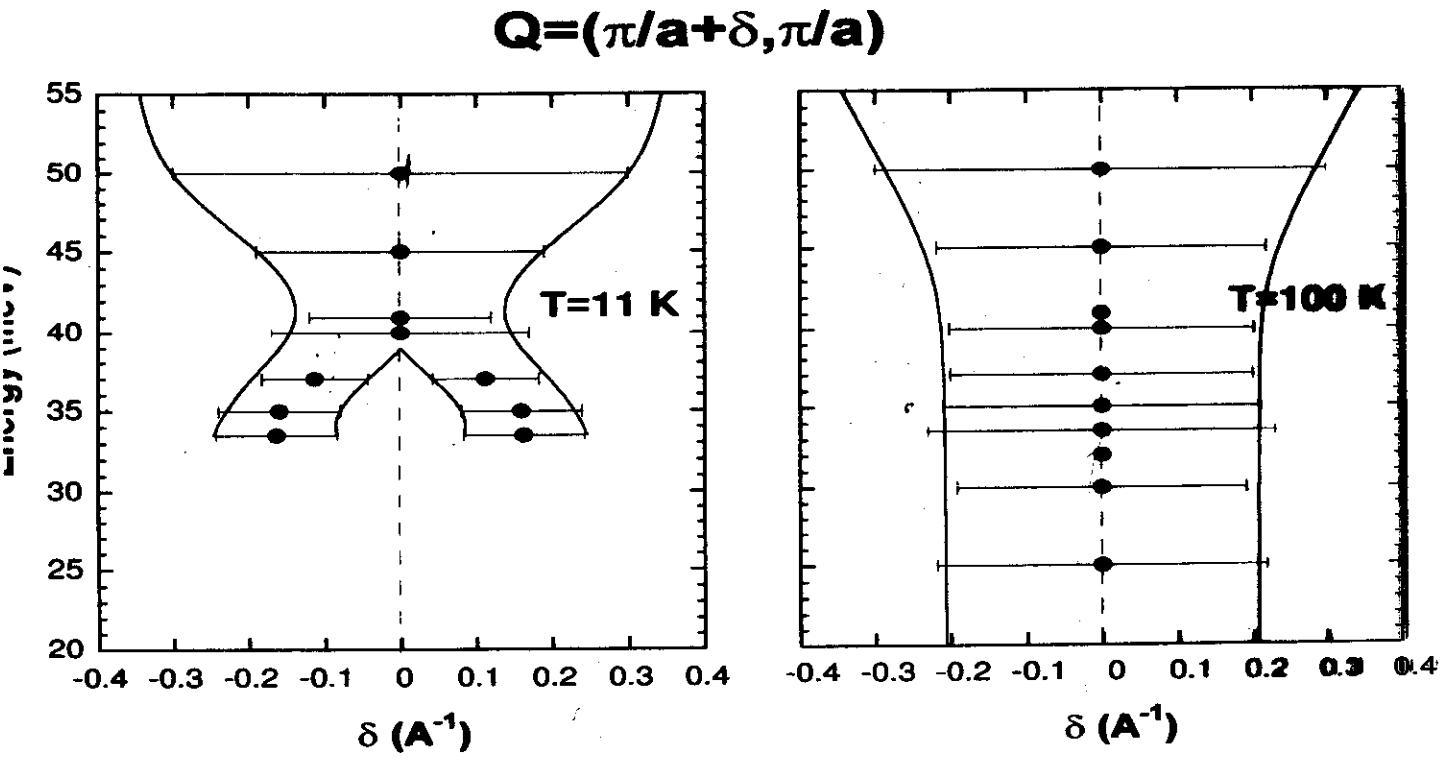


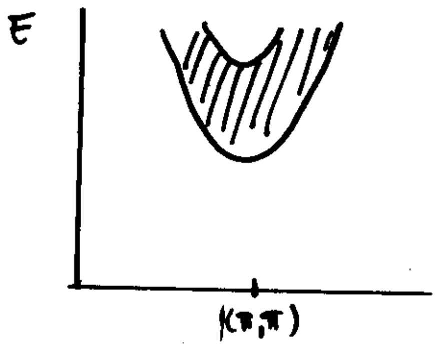
Fig 3:

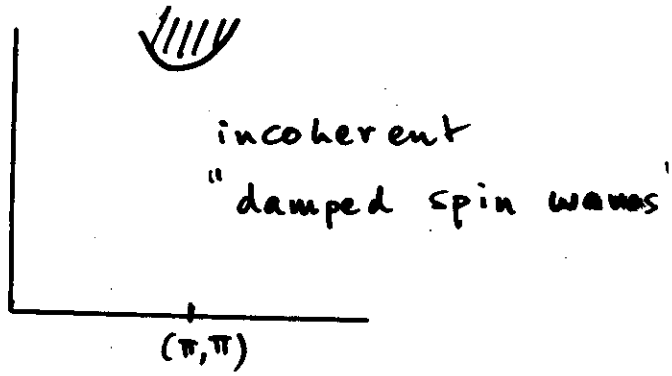


Bourges et al., Science (00

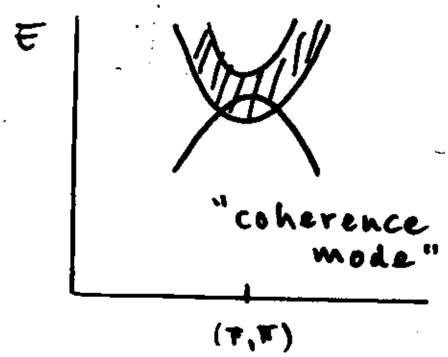
One way to look at the spectra:

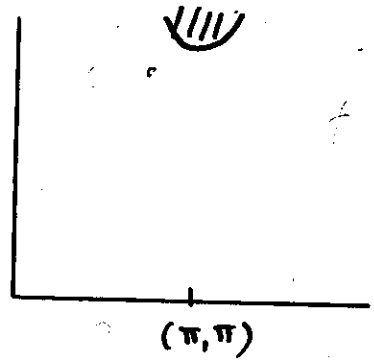
$T > T_c$ odd even





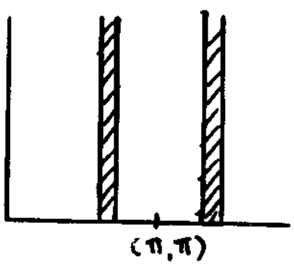
$T < T_c$



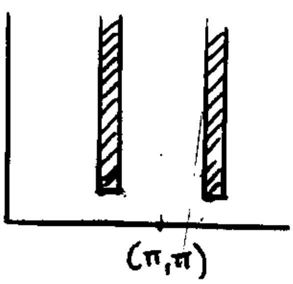


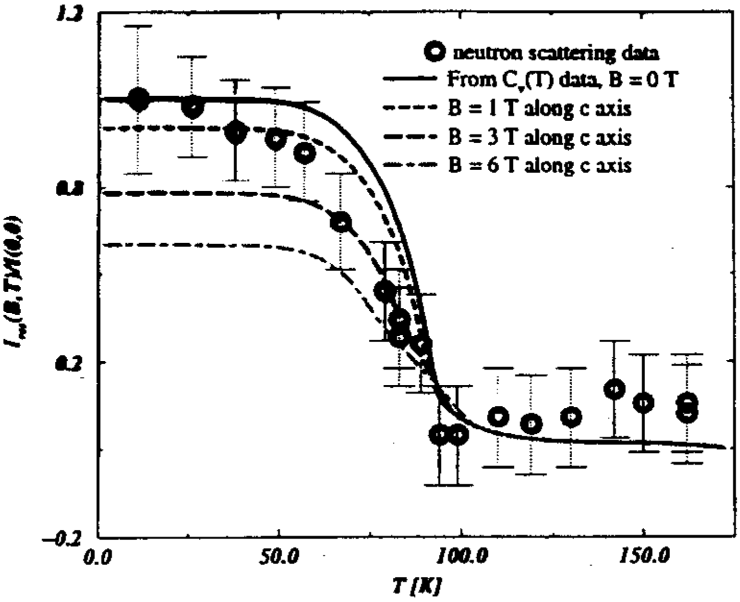
compare LSCO:

$T > T_c$



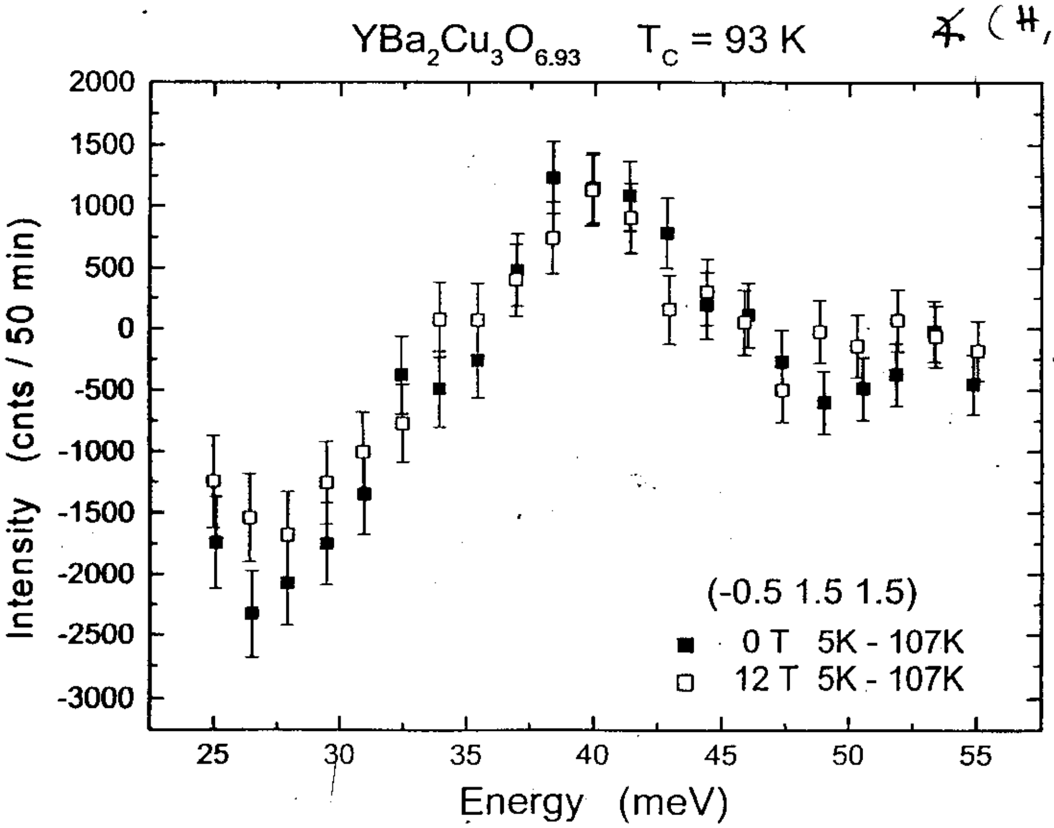
$T < T_c$





B. Janko, cond-mat/9912

$\measuredangle(H,c) = 17^\circ$



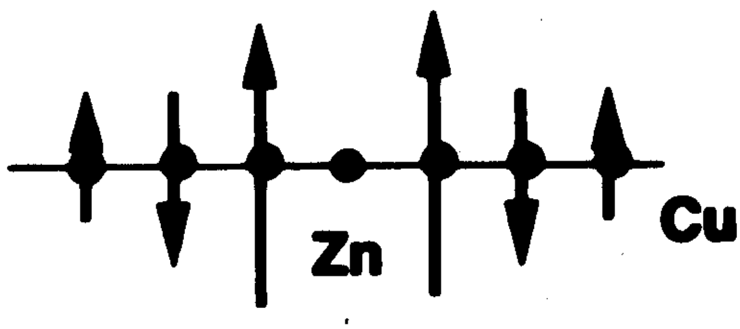
Impurity Effects

ordinary superconductors:

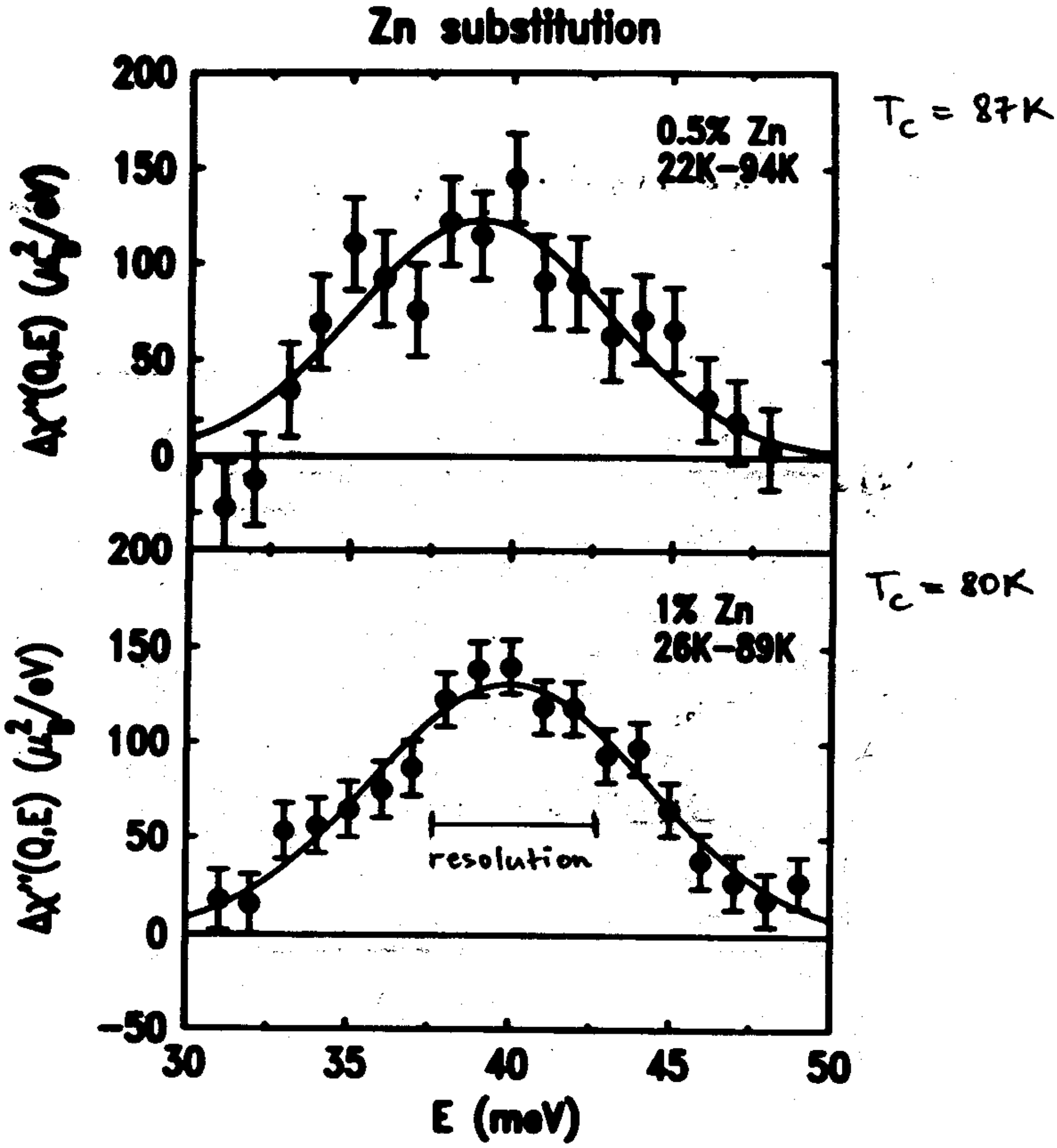
nonmagnetic impurities: weak effect
magnetic impurities: strong effect

Zn in cuprates:

- $3d^{10}$: "nonmagnetic", but
- *transport* experiments indicate efficient scattering of conduction electrons
- *magnetization* and *NMR* experiments show local magnetization

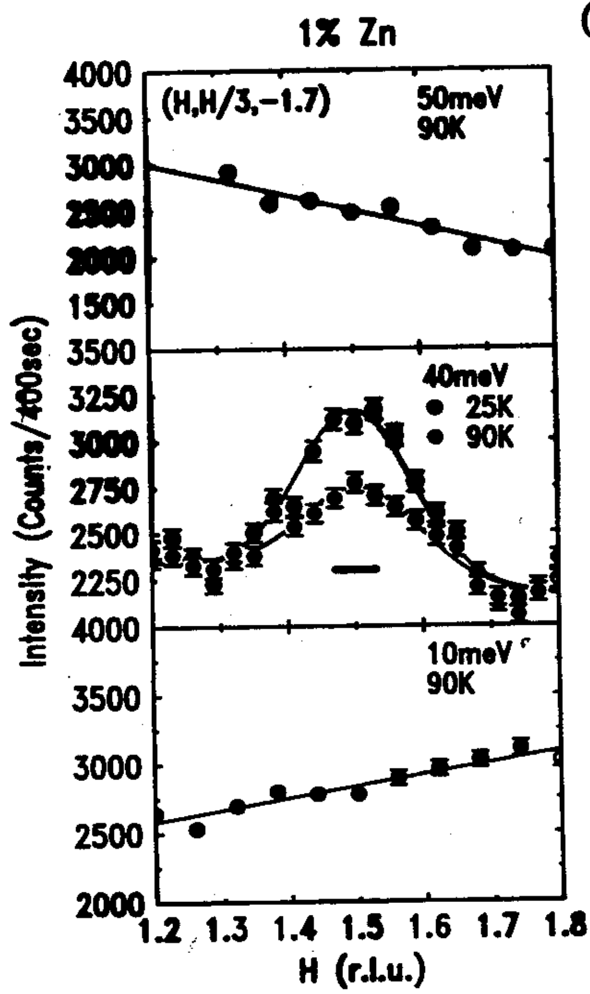


- *neutron* experiments (at high Zn concentrations) shows low energy magnetic fluctuations

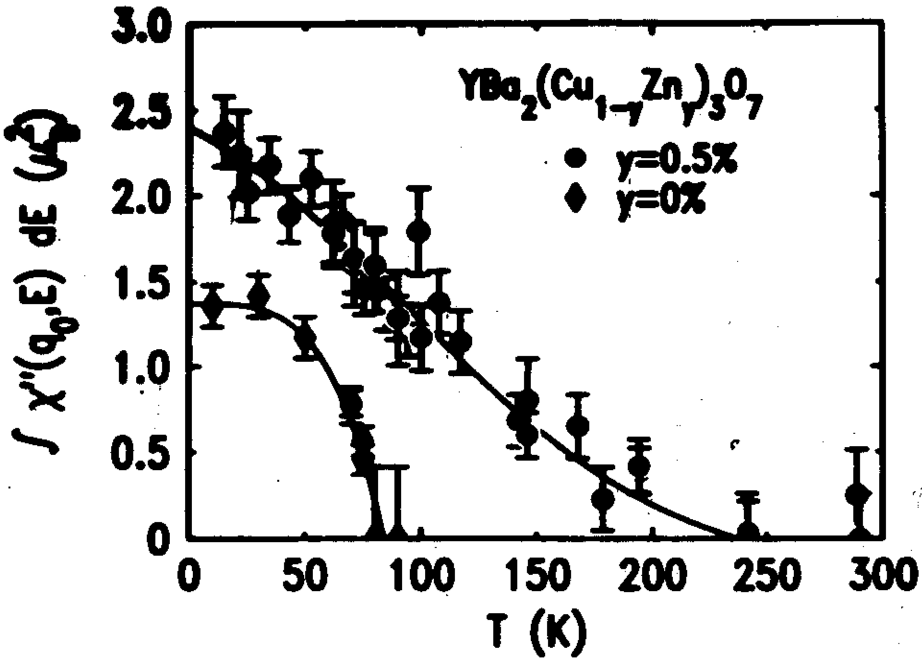


Zn substitution
0.5% Zn
22K–94K
T_c = 87K
1% Zn
26K–89K
T_c = 80K
resolution
Δχ''(Q,E) (μ_B^2/eV)
E (meV)

(Tc = 80 K)



1% Zn
(H,H/3,-1.7)
50meV
90K
40meV
25K
90K
10meV
90K
Intensity (Counts/400sec)
H (r.l.u.)
4000
3500
3000
2500
2000
1500
3250
2750
2250
1.2
1.3
1.4
1.5
1.6
1.7
1.8

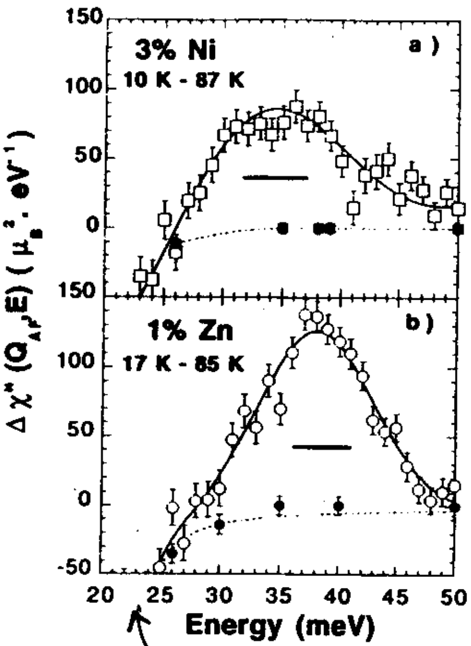


observable spectral weight at low temperature (μ_B^2)

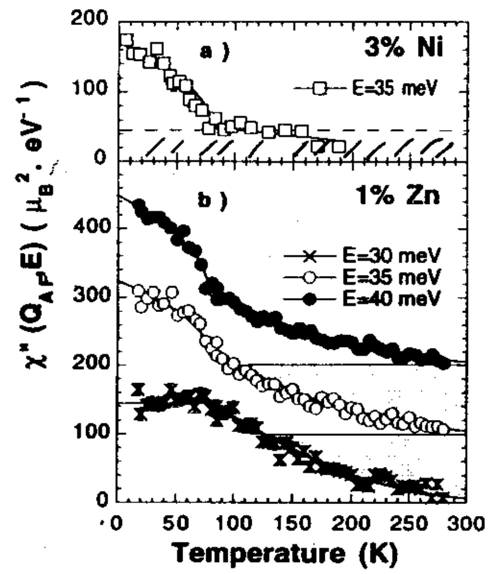
	YBCO7	YBCO7 : 0.5% Zn
$\int dE\ \chi''(\pi,\pi,E)$	1.6 ± 0.5	2.2 ± 0.5
$\int d^2q\, dE\ \chi''(\vec{q},E)$	0.048	0.058
	removed completely (within detection limit) above T_c	half removed above T_c

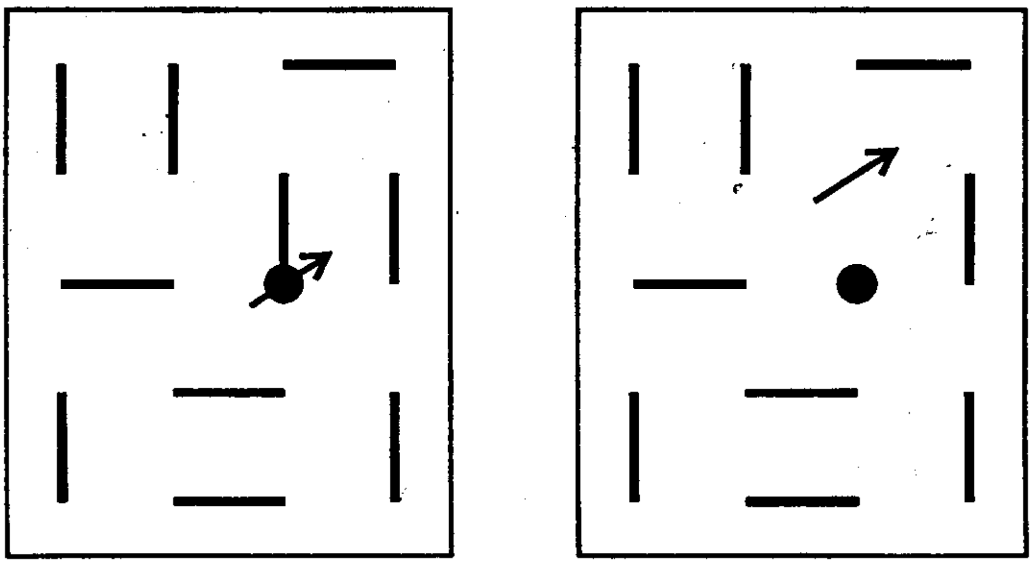
Fong et al., PRL (99)

$$\frac{E_{res}}{kT_c} \sim 5.5$$



oversubtraction due to phonon background





S=1 impurity   S=0 impurity

Kilian et al., cond-mat 9904315

Conclusions:

* Resonant mode energy determined by Tc, not doping

* Incommensurate peaks disappear above Tc, follow same temperature dependence as resonant mode

* S=0 and S=1 impurities affect resonant mode strongly and *differently*