Near the Superconducting Edge: Spin Confinement and Central Modes

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$YBCO_{6+x}$

No gap in normal *spin* response

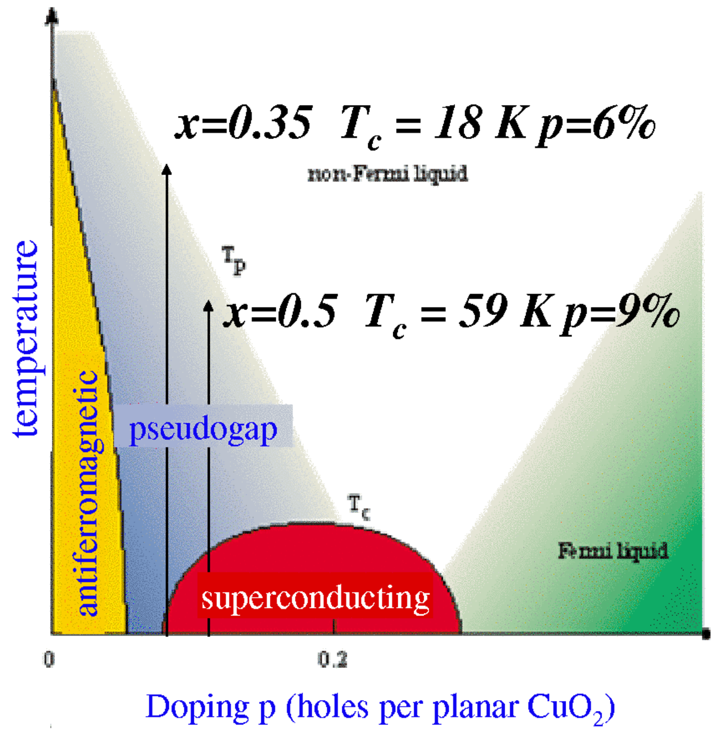
Incommensurate spin modulations at low energy and resonance grow in for $T < 2T_c$

Chris Stock et al

PRB **69**, 014502 '04

PRB **71**, Jan 1 '05

Cuprate Phase Diagram:



DISPERSION x=6.5

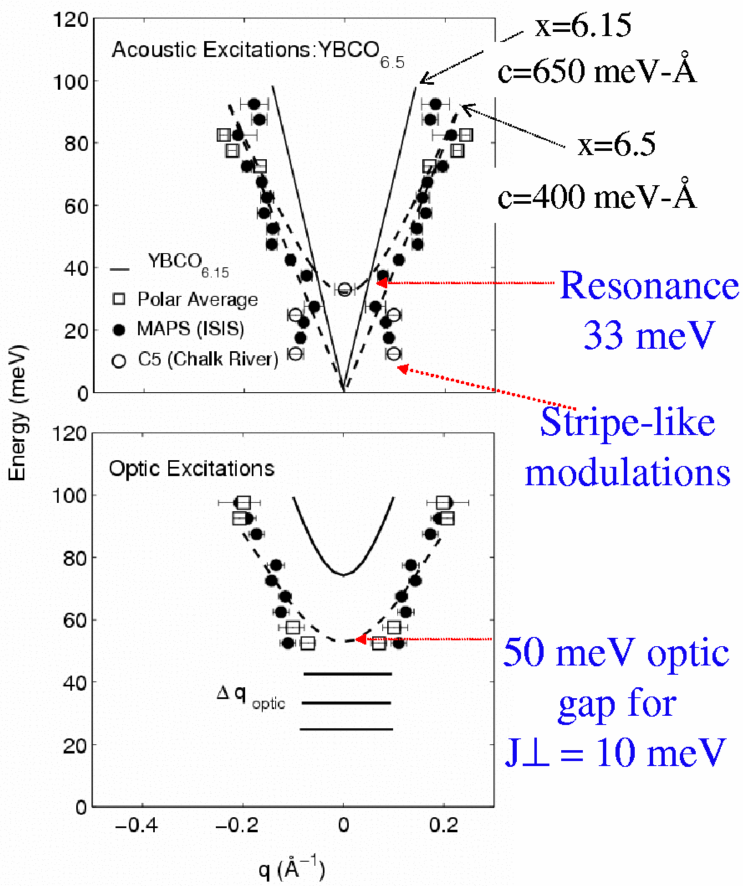
Wave vector increases with energy ω=cq centred on Q_{AF}

No 'silent' q-band like x=6.85 – Pailhes weak Landau damping

The velocity of c=400 meV-Å is reduced to 60% of the insulator.

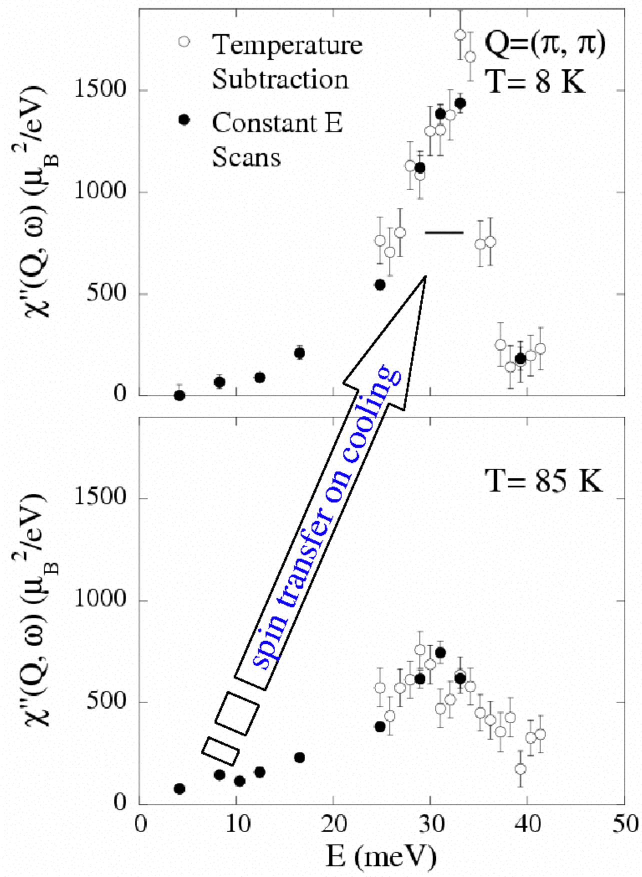
J// = 70 meV

J ⊥ = 10 meV



Resonance $YBCO_{6.5}$
T_c=59K

Has spin triplet symmetry (polarized neutrons)
- a particle-particle process seen via SC pairing?
- a particle-hole exciton below energies with Landau damping?
- spin response pushed up by SC gap energy?
- incoherence ?

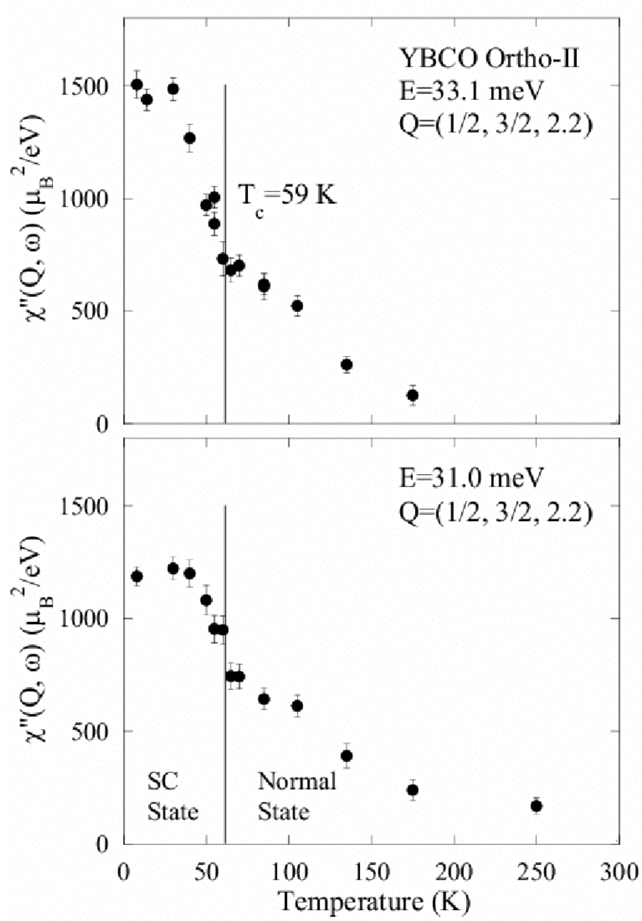


Resonance:
peak susceptibility

The resonance is ~40% preformed in the normal phase

Local pairs occur dynamically.

Pairs achieve coherence in the superconducting phase.



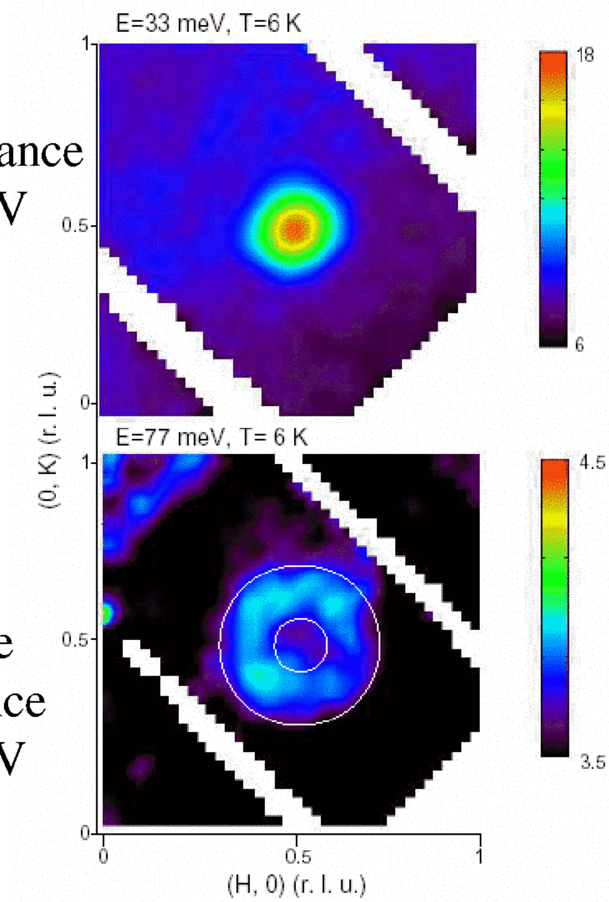
High energies :

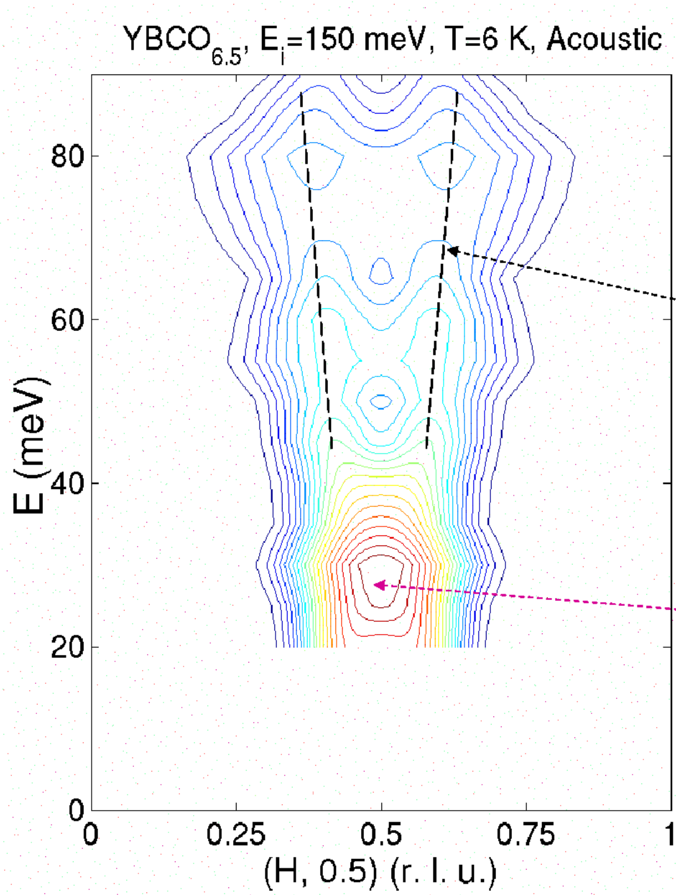
MAPS of smoke rings: intersection with cone of spin excitations

isotropic for 33<E<110 mev

On resonance 33 meV

Above resonance 77 meV



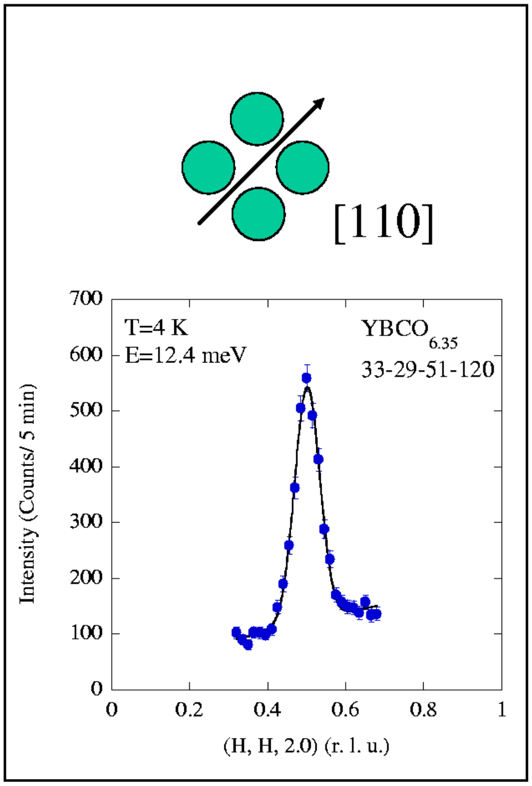


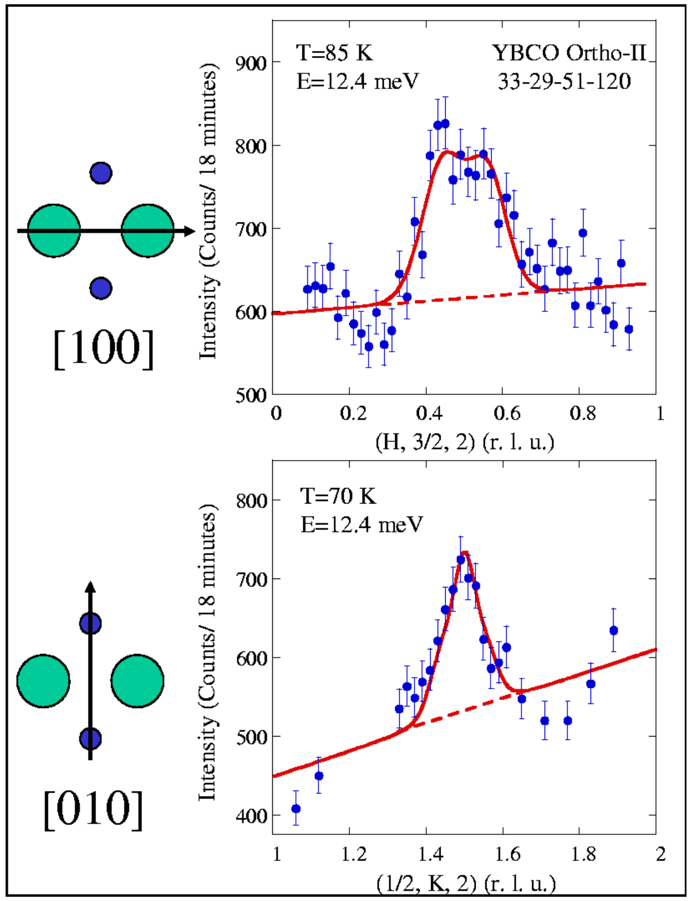
High-energy spin map in $YBCO_{6.5}$

Ridge of paramagnon velocity – from (π,π)

Resonance: Q-width same as for stripes below resonance

Incommensurate Structure:





Incommensurate fluctuations: STM charge modulation is twice the spin

matches nesting wave vector

For $YBCO_{6.5}$ (T_c=59 K), we plot from BSCCO Hoffmann, Science (2002)

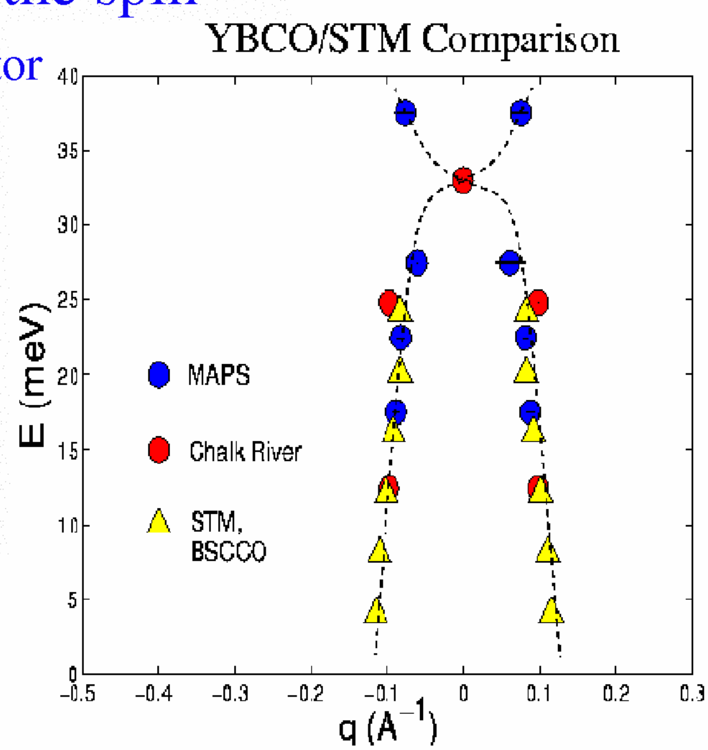
$q_{spin} = Q_{59}/2$
$= 0.08$ rlu

At 12 meV we observe

$q_{spin} = 0.06$ rlu$=0.10$ Å^{-1}

Q of BSCCO scaled by doping
E scaled by resonance energy

See Christensen *et al* 0403439 for optimally doped LSCO



Neutron data from Stock *et al* 0408071

Spin squared couples to charge density via Landau or via antiphase domains

Ensures that Qspin = ½ Qcharge

$(\pi+\delta_{spin}, \frac{1}{2})^2 == 2\,\delta_{spin} = \delta_{charge}$

If Qcharge follows spin then it is not a caliper of a Fermi surface dimension?

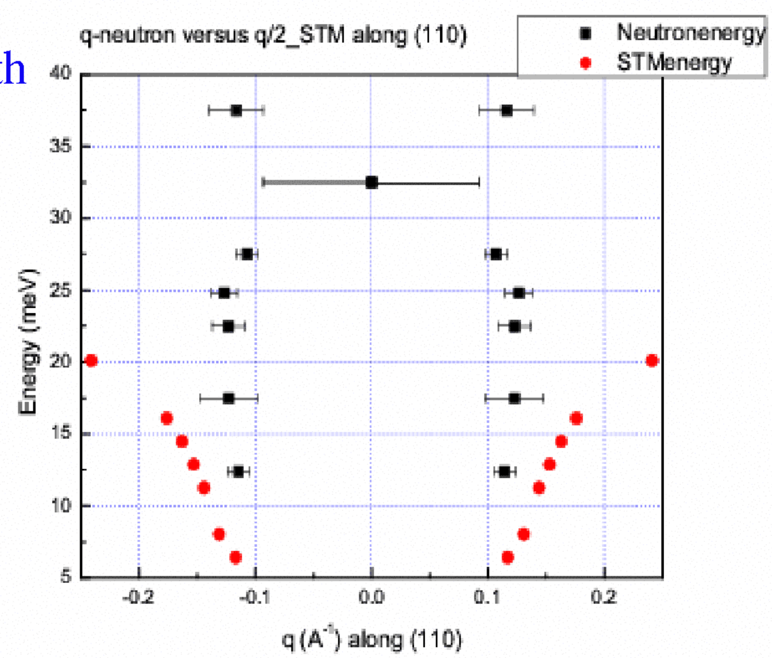
t-J model – linear in spin – quadratic in charge:

$$H = t\sum_{i,j(i)}(b_i + b_j^{\dagger})h_i^{\dagger}h_j + \tfrac{1}{4}J\sum_{i,j(i)}(b_i^{\dagger}b_i + b_j^{\dagger}b_j + b_i b_j + b_i^{\dagger}b_j^{\dagger})$$

Spin-charge coupling fails along (110)

q-STM expands with energy
q-neutron remains constant

Hence relation to STM is not generally valid

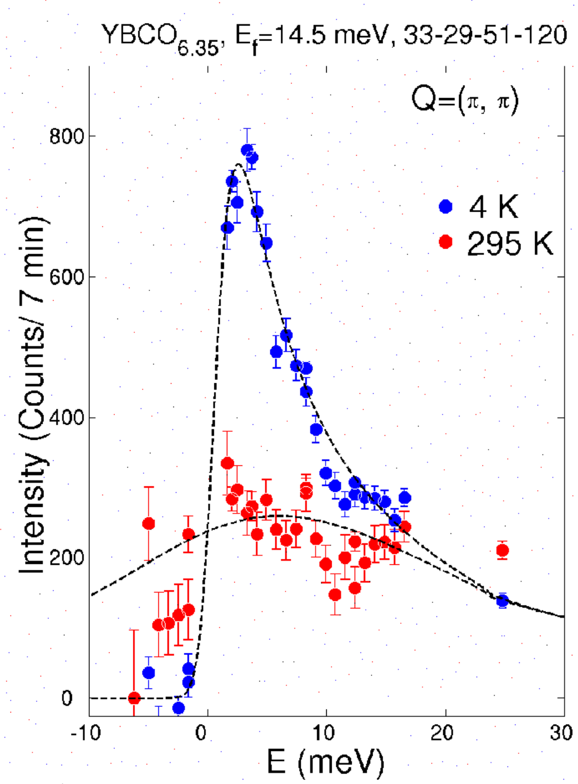


We find that checkerboards with a commensurate (π, π) background are not low-energy states of t-J model and can only be stabilized with large external potentials.

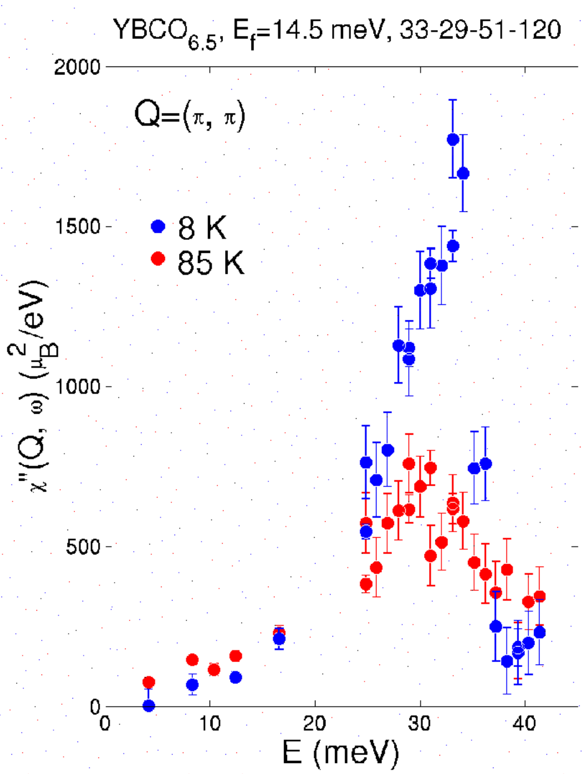
White, Scalapino PRB **70**, 220506(R) (2004)

Contrasting Low-energy Spectrum: x=6.35 and 6.5

T_c=18 K 3 meV

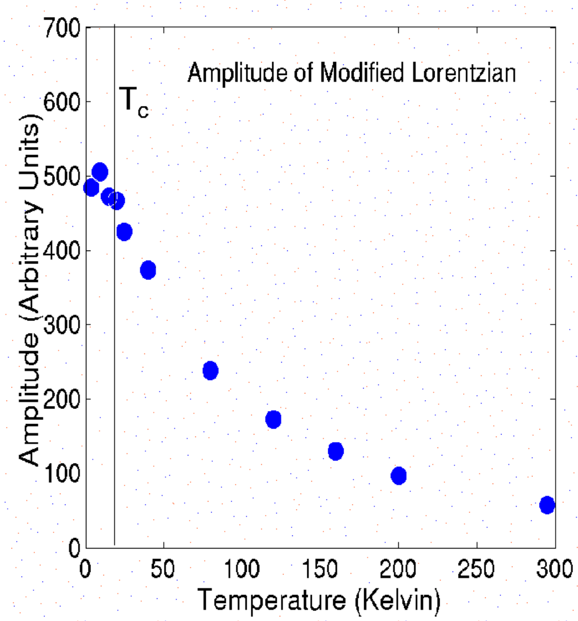


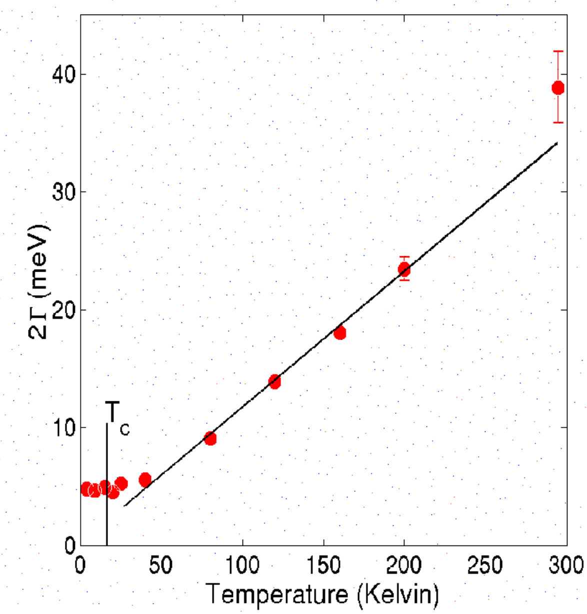
T_c=59 K 33 meV



$YBCO_{6.35}$: Modified Lorentzian

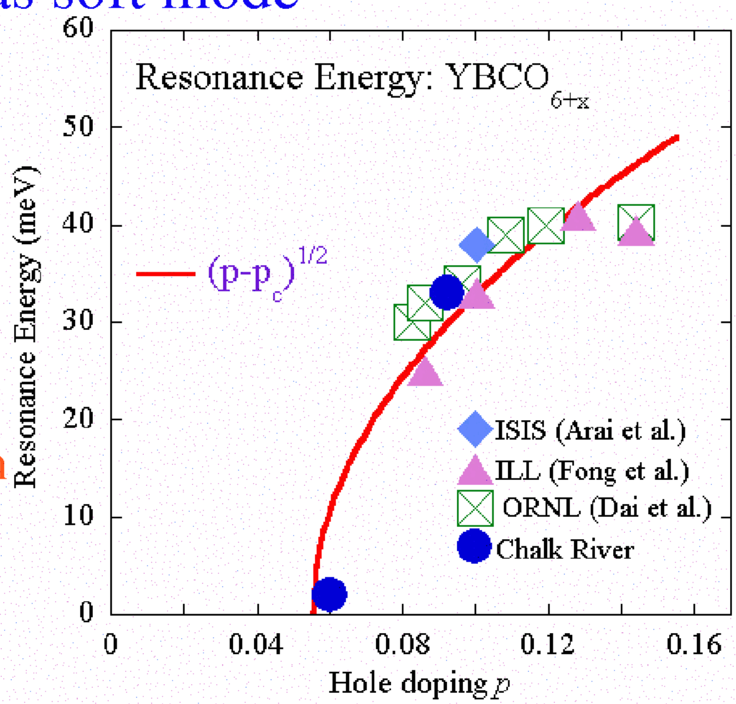
Resonance is overdamped with a relaxation rate ~ 2.5 meV ~ 0.6 ps^{-1}





The resonance as soft mode

The resonance is critical: it is ***the soft-mode*** at the superconducting phase boundary - but not the pairing boson



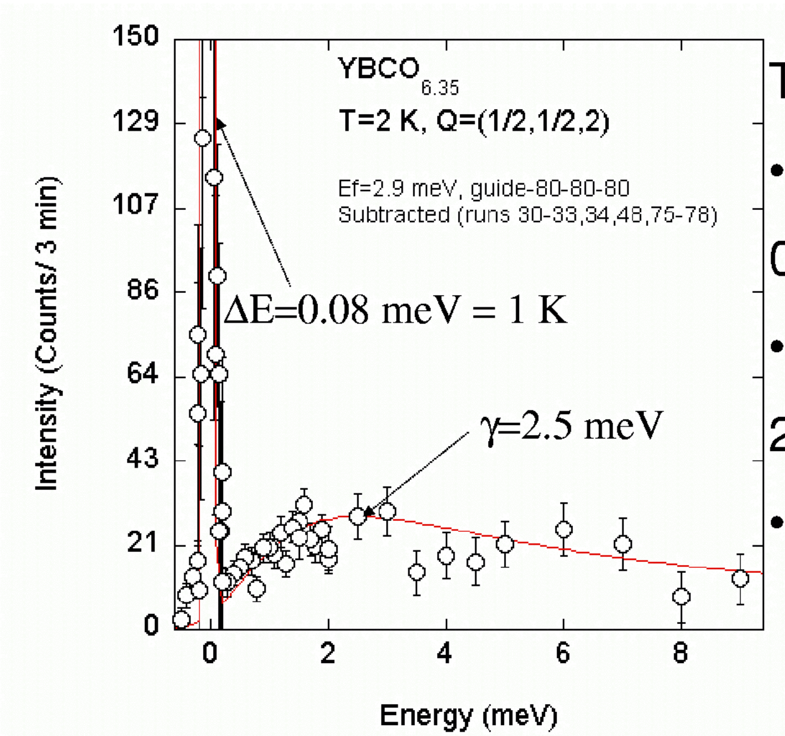
It tracks

$\mathbf{T_c \sim (p-p_c)^{1/2}}$

not the doping, p~δ, nor ladder width

It drives the transition from superconductor to antiferromagnet.

A new lower energy scale: below damped resonance lies a Central mode: 30 times lower in energy & 150 times stronger.



Two energy scales:

- Central Peak

0.08 meV

- Damped resonance

2.5 meV

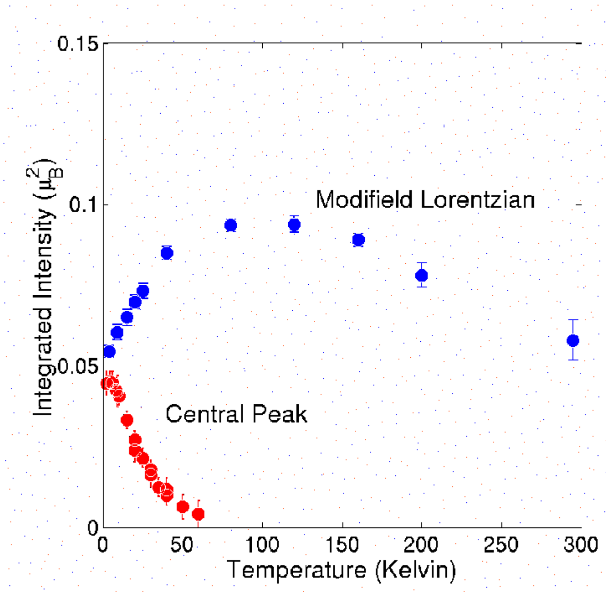
- Are they coupled?

$YBCO_{6.35}$: conserved total moment– sample is single-phase.

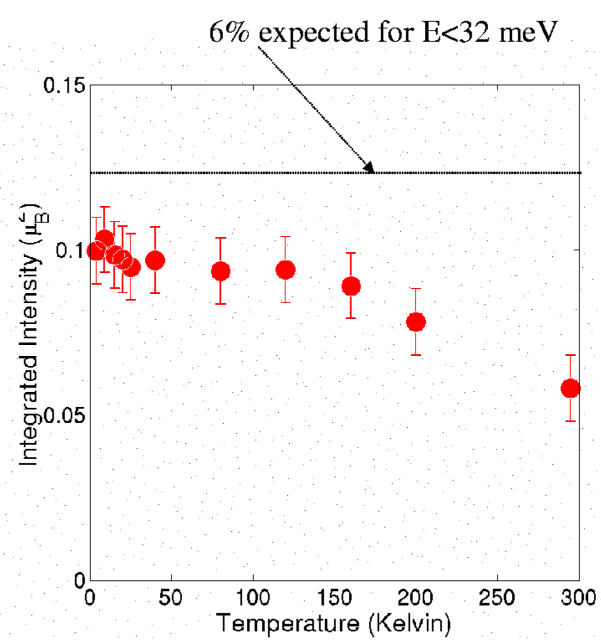
$$S(S+1) = Z_\chi \frac{1}{\pi}\int d\omega \int d^3q\,[n(\omega)+1]\,\chi''(q,\omega)$$

$$Z_\chi \sim 0.5$$

Soft mode drives central mode



Full moment to 32 meV detected



Triplet spin fluctuations

$\chi^{xx} = \chi$

all x, all ω

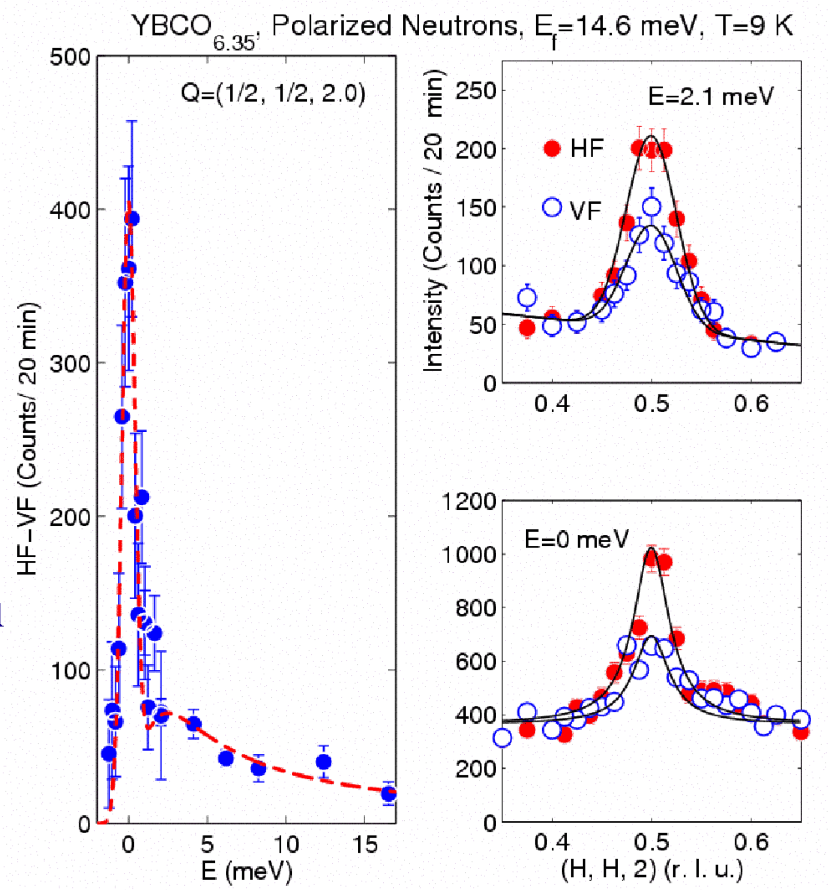
∴ holes cant spins

Schraiman Siggia

-Short-range in space

8 cells

-Slow in time



Spins behave as 3D coupled bilayers

Correlation length

ξ_c=8 ± 2 Å~ 1 cell

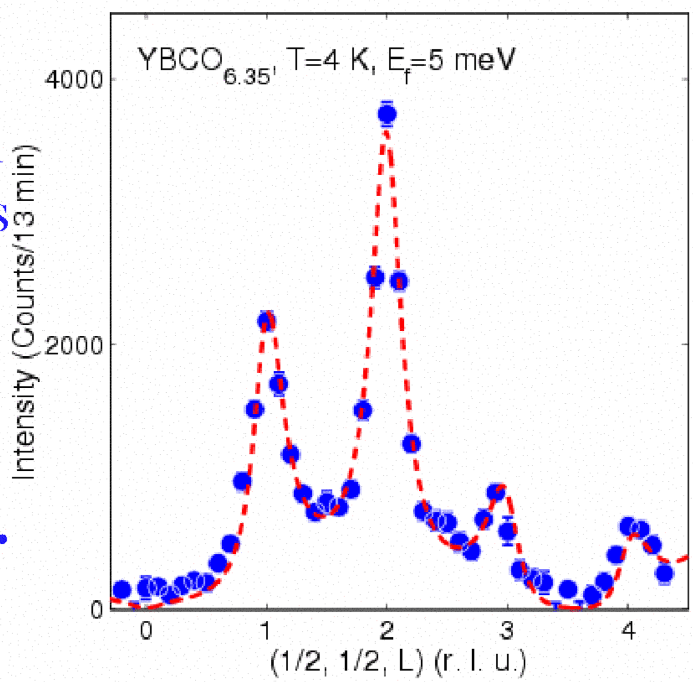
AF between planes

In-plane

ξ_{xy} =8 cells

∴Not Bragg LRO.

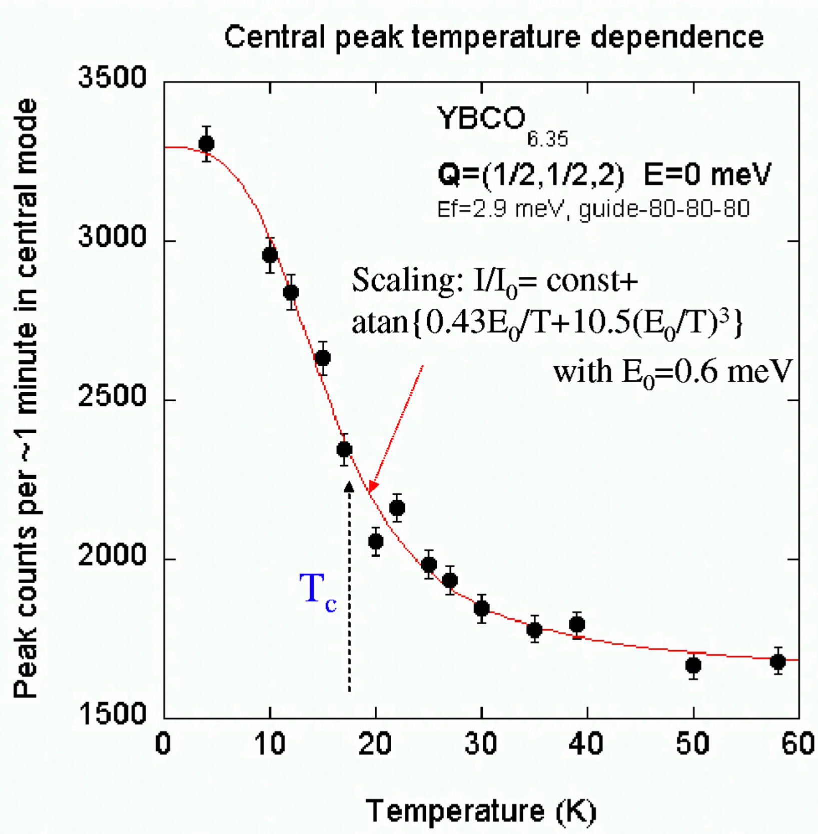
– glass phase coexists with SC



Central peak grows as $T \rightarrow 0$ but $T_c(p,0,T)$ is subcritical

Spin amplitude ignores T_c

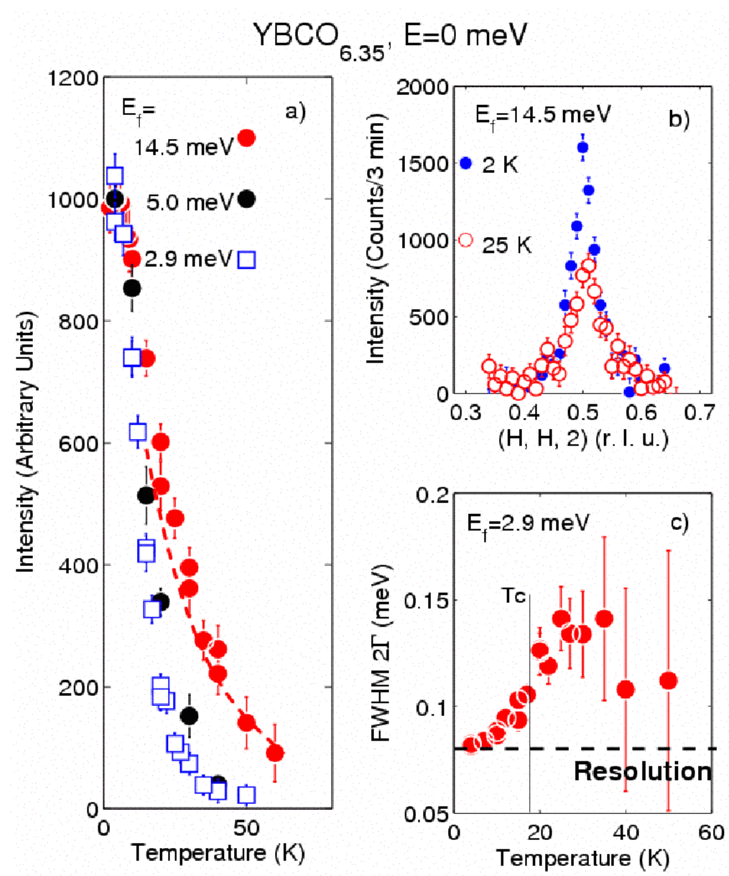
Finite DOS at $\omega=0$ since ξ finite $C_v(T)$, $\rho(T)$, $K(T)$?



Central peak T, q & $\gamma(T)$

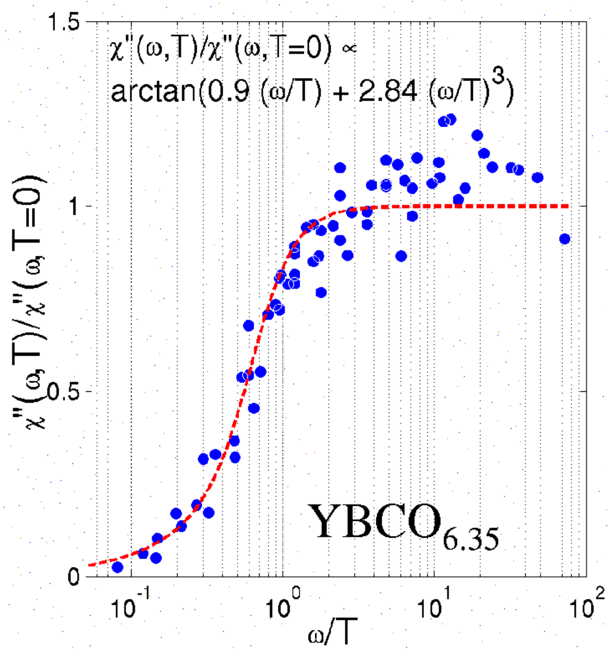
- strong spin weak SC response

- only $\gamma=\tau^{-1}$ senses T_c

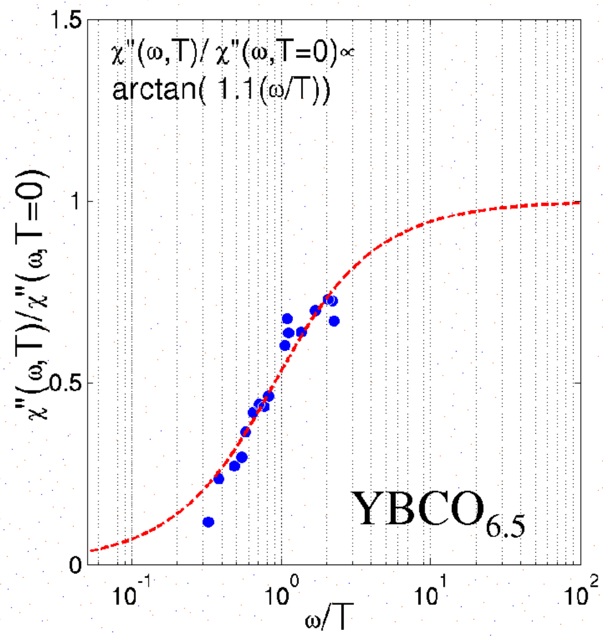


ω/T Scaling: $I(\omega,T)/I(\omega,T=0) \sim \arctan(\omega/a_1T + (\omega/a_2T)^3 + \ldots)$

T above and below T_c=18K ω<30meV



$T>T_c$=59 K ω<20 meV
farther from QCP?



Spin response of soft mode driving a defect mode

à la antiferroelectric SrTiO3

Halperin Varma '76

$$\chi^{-1} = \omega_0^2 - \omega^2 - i\omega[\Gamma + \delta^2/(\gamma - i\omega)]$$

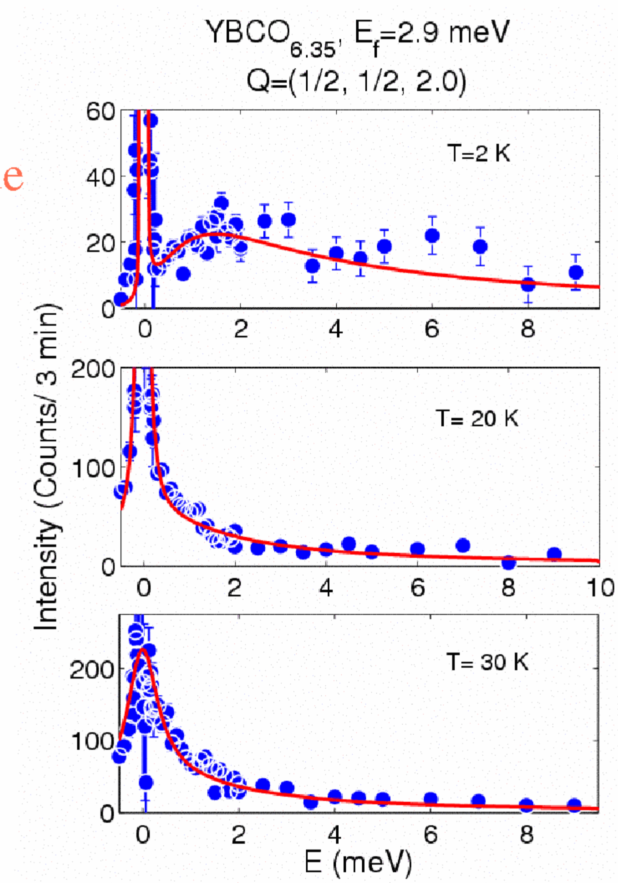
$\gamma << \omega_0, \Gamma$

2 K ω_0=0.65 meV

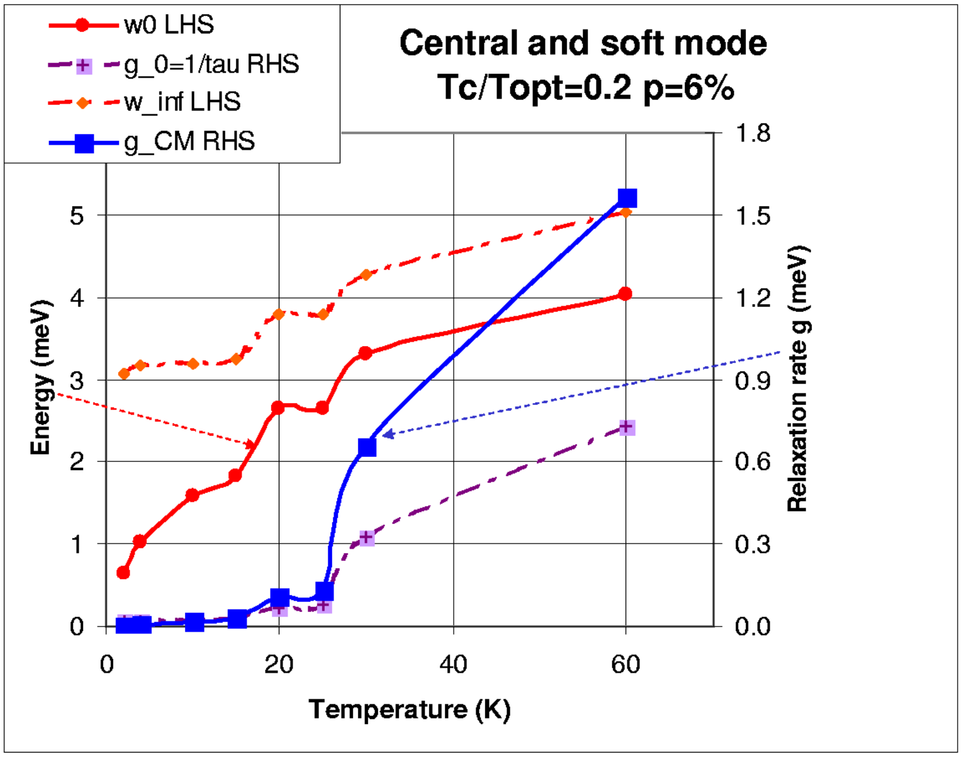
γ=0.07 meV (0.8 K)

Γ=6.5 meV

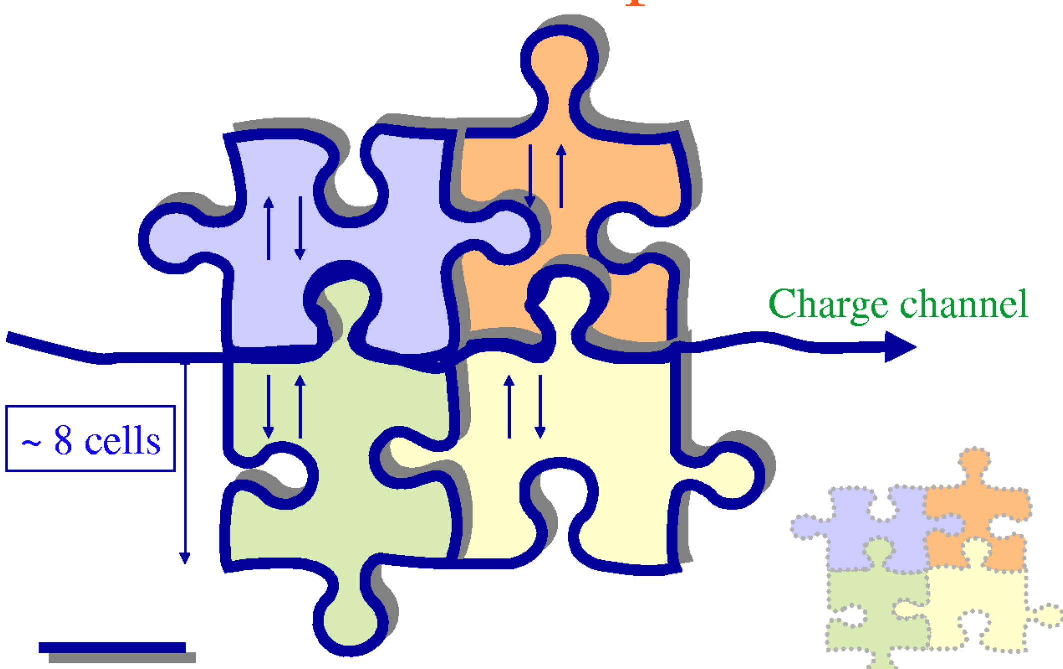
Coupling δ=3.0 meV



Slow hopping of driven "defect"
What is the slow object?



Guessed texture of spins and carriers



Superconducting fermion channels wrapping the spin clusters

Glassy spins confined in in **antiphase** islands

Large islands of AF correlated spins (8×8) entirely turn over only very slowly. As doping decreases the hopping rate slows – hence CM for p=6% not for 9%

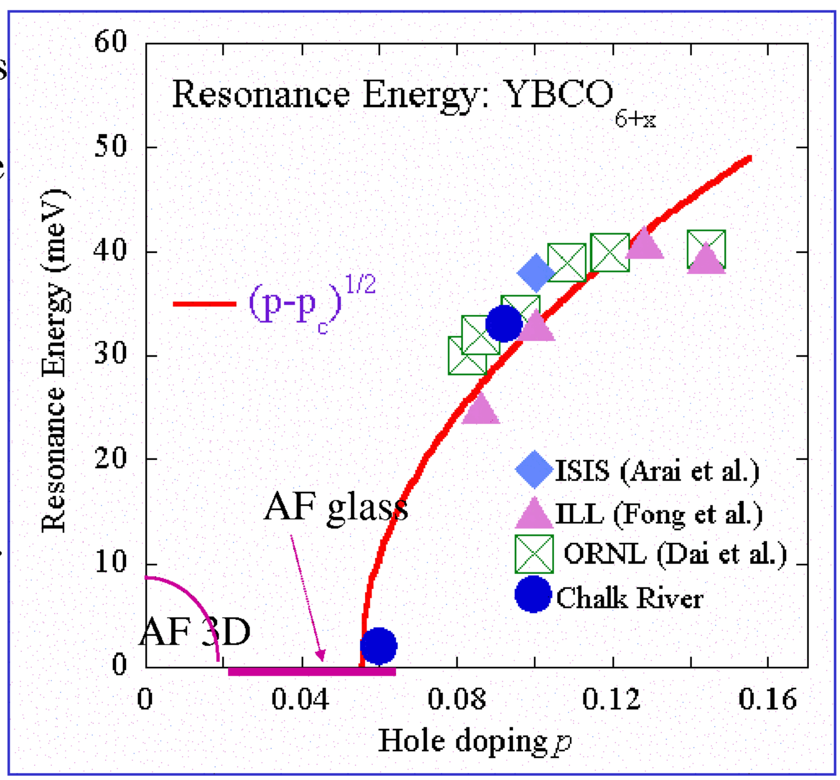
Spins in adjacent islands are coupled through a frustrated (ferro) charge region (antiphase domains at large p)

Soft spin resonance has same symmetry as the central mode to which it transfers its weight - CM means non-zero spin DOS.

Holes break the spin rotation invariance- QCP to glass?

SC boundary is far from the critical AF point but SC coexists with a nearly critical glass phase. But farther from dome QPT!

YBCO phase diagram



Low p:
AF spin correlations suppress charge density up to a large pseudogap.

Medium p:
AF correlations suppressed by SC below SC spin gap $\chi(\omega) \sim \omega$ q_inc; transfer up to E_res. SW above.

Large p: SF too weak to see below E_res

No D-density-wave peak at E=0 in YBCO nor a spin gap

Dynamic stripes at low energy signify spin-charge domains

Resonance is a fingerprint of SC d-wave DOS and shows that local pairs exist dynamically in the normal phase

At high energy the isotropic spin wave cone is recovered - it is well defined in q but overdamped in E

The approach to the antiferromagnetic insulator is driven by a soft-mode collapse of the resonance

No SC-AF coexistence:near the SC transition the spins are confined; AF LR-ordered state does not coincide with the SC boundary

Stripes and spin confinement show that spin-charge spatial separation takes place at medium and small doping

Separation contrasts with periodic spin-fermion theories

End of KITP talk.

The following are background and related slides.

Spin response and NMR in $YBCO_{6.5}$

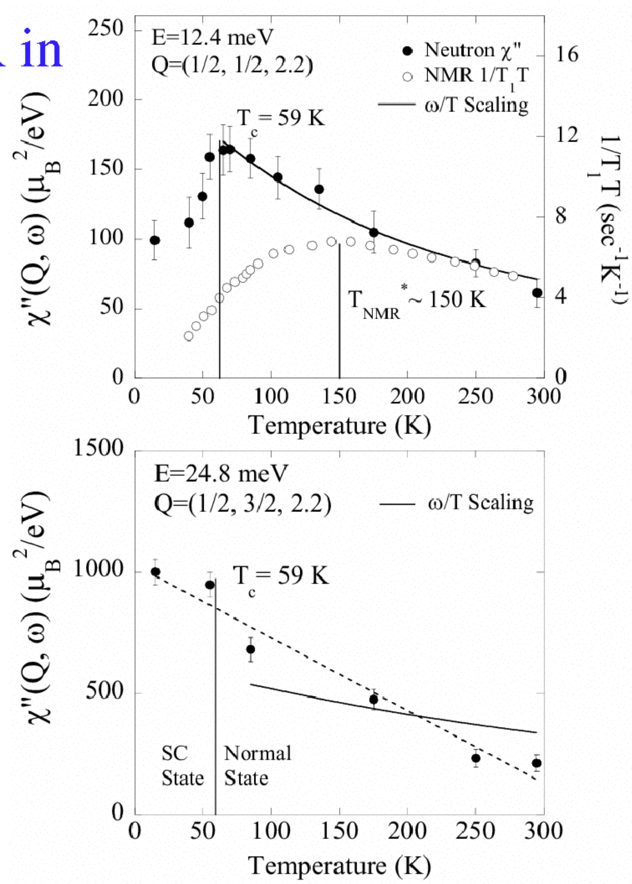
- grows on cooling

-shows no pseudogap decrease below T* NMR

- is suppressed below T_c by the superconducting order but only for E< 16 meV

- SC gap is ~$3.5T_c$ ~20 meV

- pseudogap is ~ 100 meV (Norman)



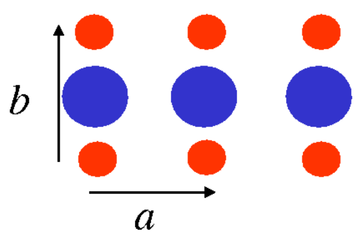
Chain Oxygen Staging and Superstructures ($YBCO_{6+x}$):

O

Cu

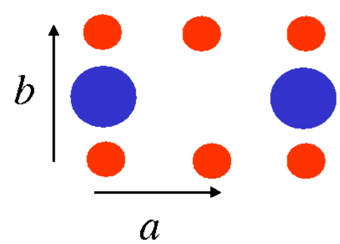
Ortho–I Phase:

x=1.0



Ortho–II Phase:

x=0.5



Ortho–III Phase:

x=0.67 F-F-E

x=0.33 F-E-E

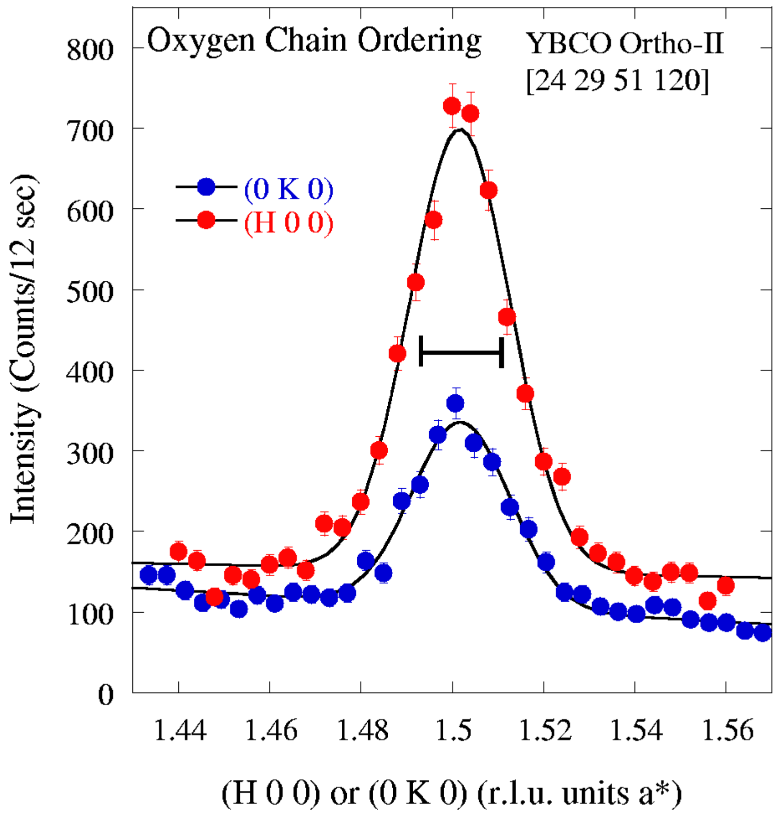
N. H. Andersen *et al.*

Physica C **317-318**,

259 (1999).

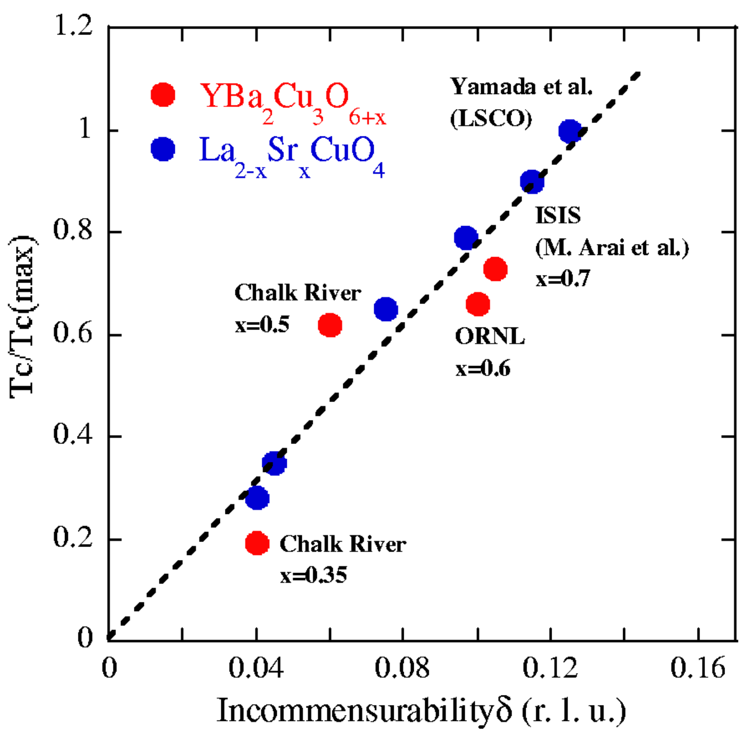
Oxygen order

- Ortho-II ordered (every second chains filled)
- Oxygen ordered (correlation length of 100 Angstroms)
- Detwinned (70% single domain)

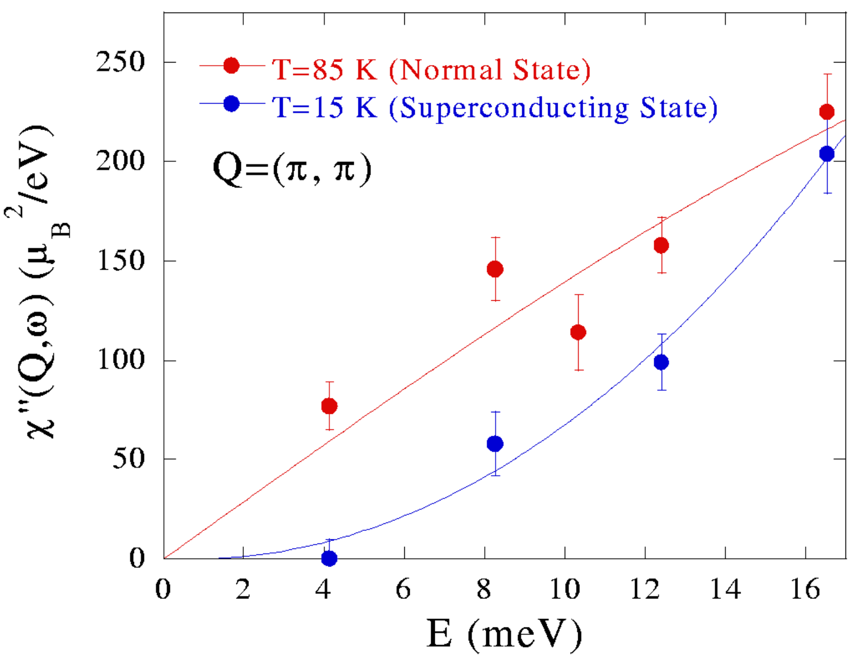


Yamada Plot: T_c ~ Incommensurability

- $T_c \sim \delta$ (Yamada et al.)
- A universal relation for YBCO and possibly all cuprates?
- Not for $\delta < \delta_c$ $p<p_c$

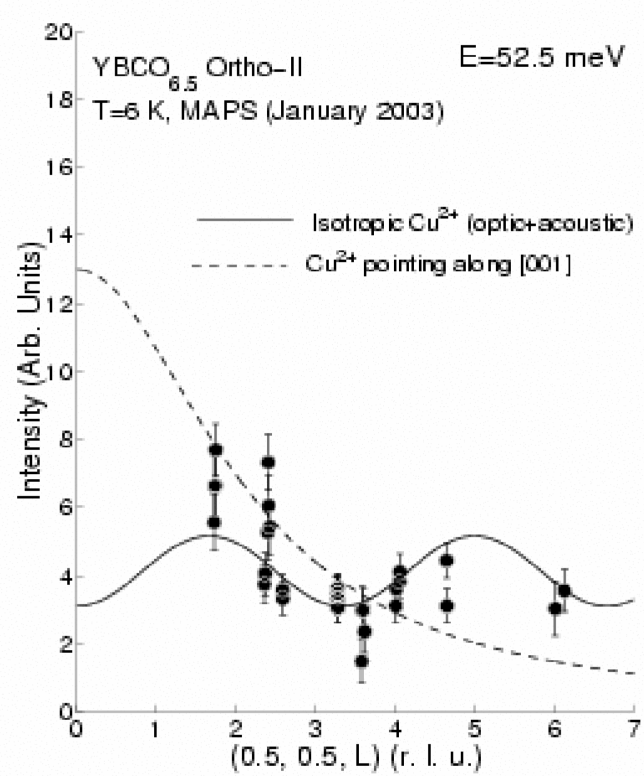


$YBCO_{6.5}$ Low-energy Excitations
(Gapless but Suppression at low temperatures)



Orbital currents?

The form factor falls slowly like a local spin, not the fast Q^{-4} falloff for plaquette currents

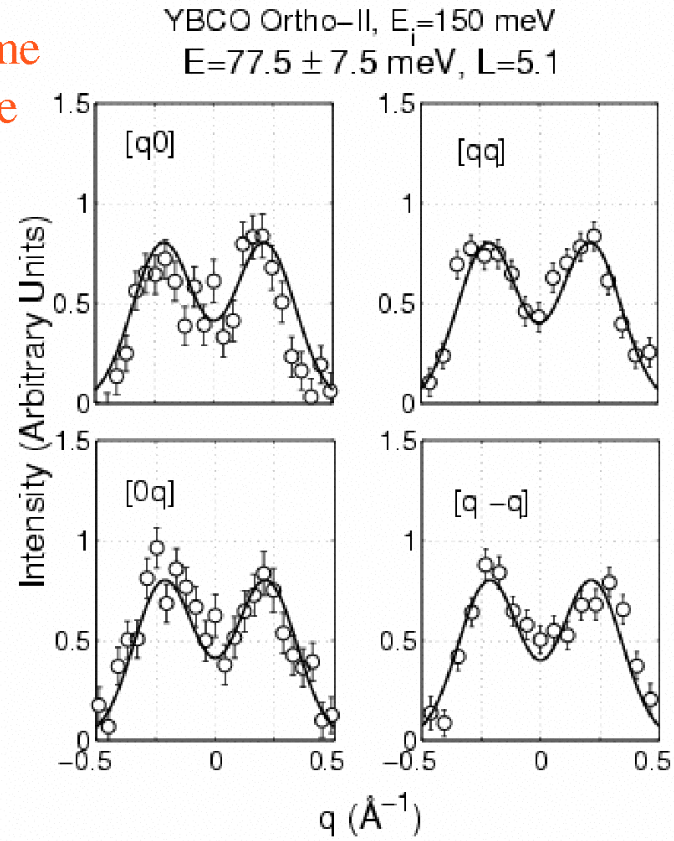


The wave vector
and intensity are the same
in all directions in plane

-A symmetric cone of
spin excitations
- q opens with energy.

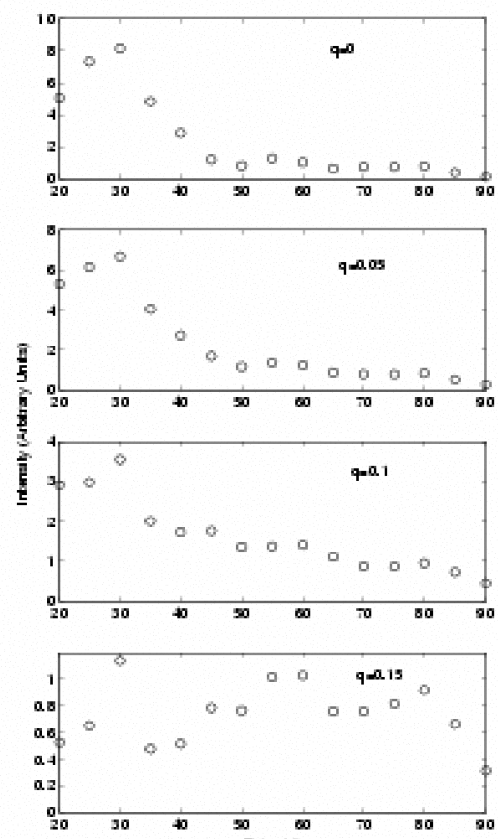
-Not a square pattern
as for x=6.6 (Hayden)
- q fixed with energy

- Dispersion centred
on (π,π)
as in Tranquada on
LBCO 2004



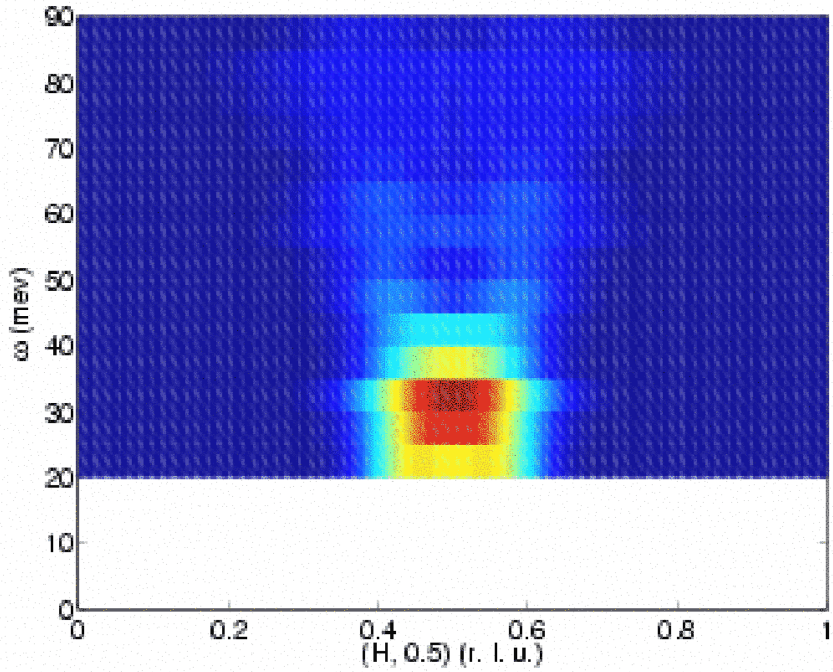
YBCO6.35

Overdamped spin fluctuations at all momenta



Spin fluctuations in $YBCO_{6.35}$

emanating from the resonance at 33 meV



Muons: coexistence of AF and SC?

Muons
Sanna 0403608
- Coexistence of magnetism and superconductivity

-Neutrons say no: no LRO

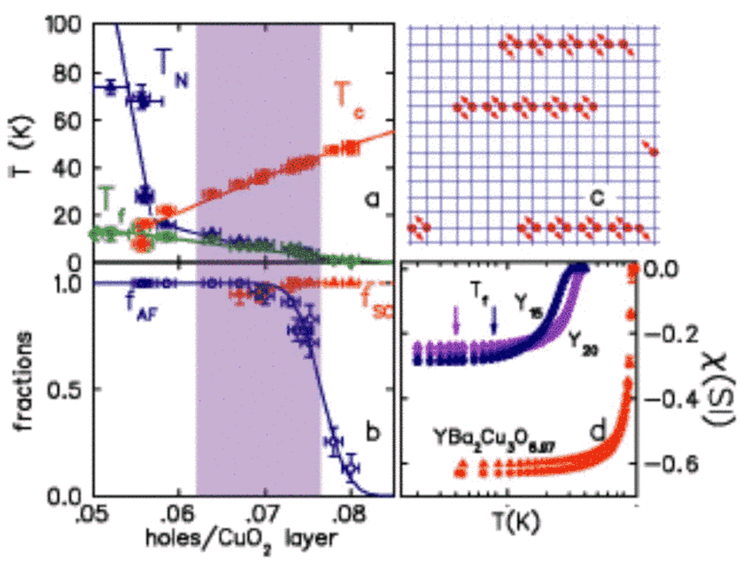


FIG. 3: Samples Y_{8-24}. a) magnetic transition temperatures (▲ from w_L, ♦ from T_1^{-1}) and SC critical temperature T_c, vs. hole concentration h; three samples show a distinct $T_N > T_f$. b) Muon volume fractions vs. h: AF (○, at $T=0$ K) and SC (▲, for $T_f \leq T \leq T_c$. c) Sketch of a stripe superconductor. d) SQUID susceptibility in $YBa_2Cu_3O_{6.97}$, Y_{15} (h=0.70) and Y_{20} (h=0.75): $H = 1$ Oe, FC (▲) and ZFC (●).