Habilitation à Diriger des Recherches

Mardi 08 Juillet 2003
Amphi Blandin , 15h

Philippe Bourges

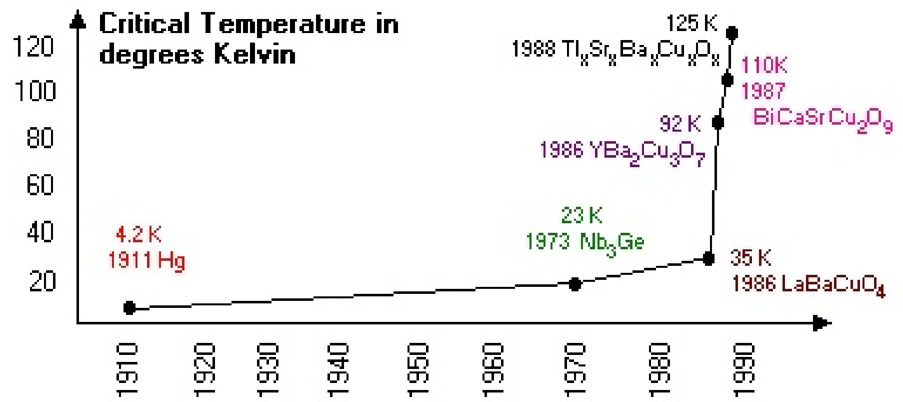
Dynamique de spins dans les oxydes de cuivre supraconducteurs à haute température critique

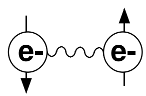
Jury constitué de : **H. Alloul**
C. Berthier
B. Hennion
H. Raffy
L.P. Regnault
C. Varma
C. Vettier

Supraconductivité à haute température critique

1987 Découverte supra-conductivité à haute température critique

$T_C^{max} \sim 135$ **K**





Mécanisme d'appariement ?

- **Gap supraconducteur : 2**$\Delta_{max} \sim 9k_BT_C$
  (**Théorie BCS : 2**$\Delta = 3.5k_BT_C$)

- **Supraconductivité non-conventionnelle : symétrie** d

- **Proximité d'une phase magnétique ordonné**
  (fermions lourds, Sr_2RuO_4**, ferromagnétiques** UGe_2**,...)**

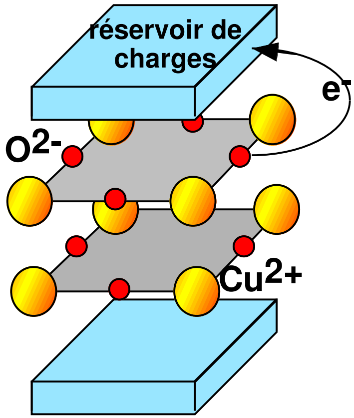
$\Rightarrow$ **Mécanisme d'appariement magnétique**

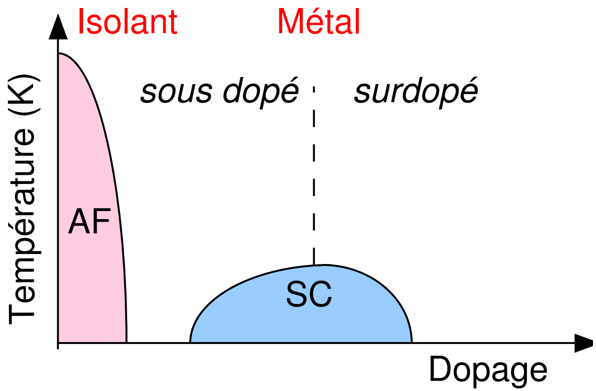
Oxydes de cuivre supraconducteurs : diagramme de phase

$La_{2-x}Sr_xCuO_4$
$YBa_2Cu_3O_{6+x}$

$Bi_2Sr_2CuO_{6+\delta}$
$Bi_2Sr_2CaCu_2O_{8+\delta}$
$Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$

$Tl_2Ba_2CuO_{6+\delta}$





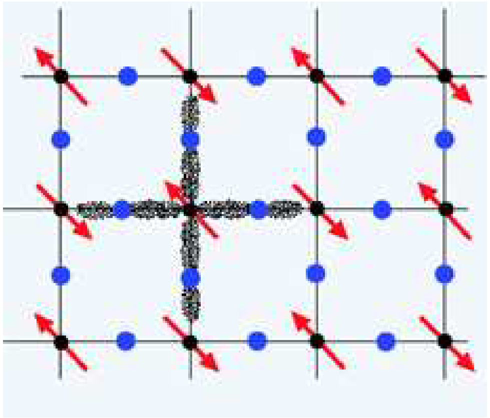
1. Dopage en trous des plans CuO_2 par transfert de charges

2. Rôle des corrélations antiferromagnétiques

3. Nature de l'état sous-dopé : Pseudo-gap et ordre caché ?

Cuprates : Système à électrons fortement corrélés

- **cuprates : structure bidimensionnelle**



$$H = U \sum_i n_{i\uparrow} n_{i\downarrow} - t \sum_{i,j,\sigma} c^\dagger_{i\sigma} c_{j\sigma}$$

- **plan CuO_2 dopage nul : isolant Mott-Hubbard**
  Etat de Néel, Cu^{2+} S=$\frac{1}{2}$,
  couplage antiferromagnétique Cu-O-Cu : $J = 120$ meV

- **dopage en trous : singulet Zhang-Rice**

- Autres interactions électroniques
- Couplage électron-phonon

Plan

1. Mode magnétique résonant (phase SC)
2. Corrélations magnétiques de l'état normal
3. Poids spectral $\Rightarrow$ mécanisme de la supraconductivité

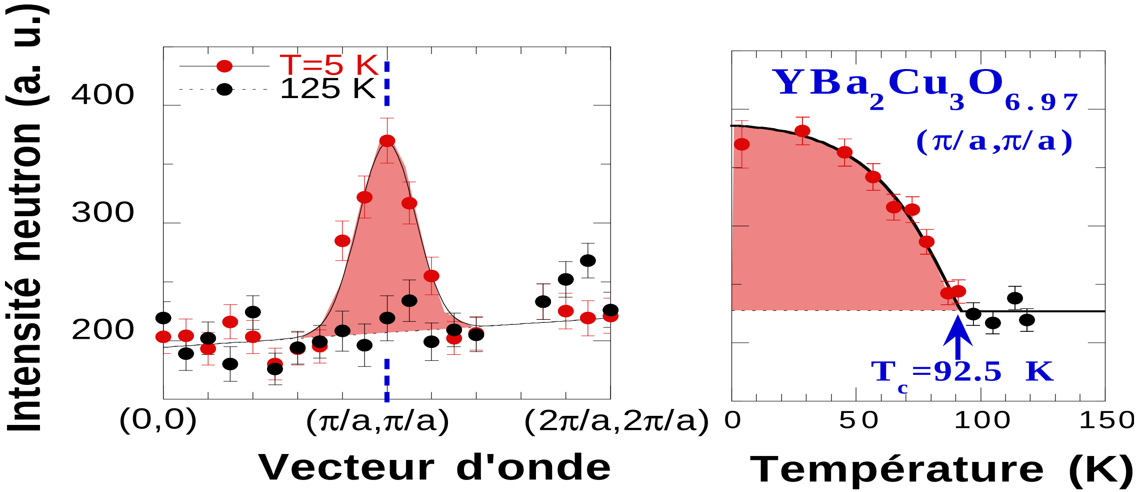
Diffusion inélastique de neutrons $\Rightarrow$ Fonction de diffusion:

$$S^{\alpha\beta}(Q,\omega) = \frac{1}{2\pi\hbar}\int_{-\infty}^{+\infty} dt\,\exp(-i\omega t) < S^{\alpha}_{Q} S^{\beta}_{-Q}(t) >$$

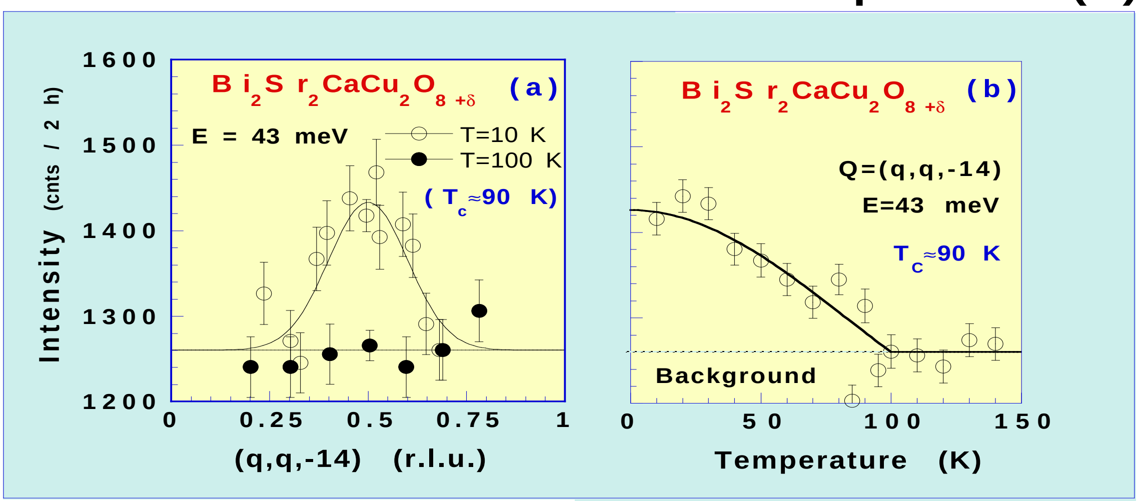
Susceptibilité magnétique:

$$S^{\alpha\beta}(Q,\omega) = \frac{1}{(g\mu_B)^2}\frac{1}{\pi}\{1+n(\omega)\} Im\chi^{\alpha\beta}(Q,\omega)$$

Resonance peak in the high-T_C superconductors

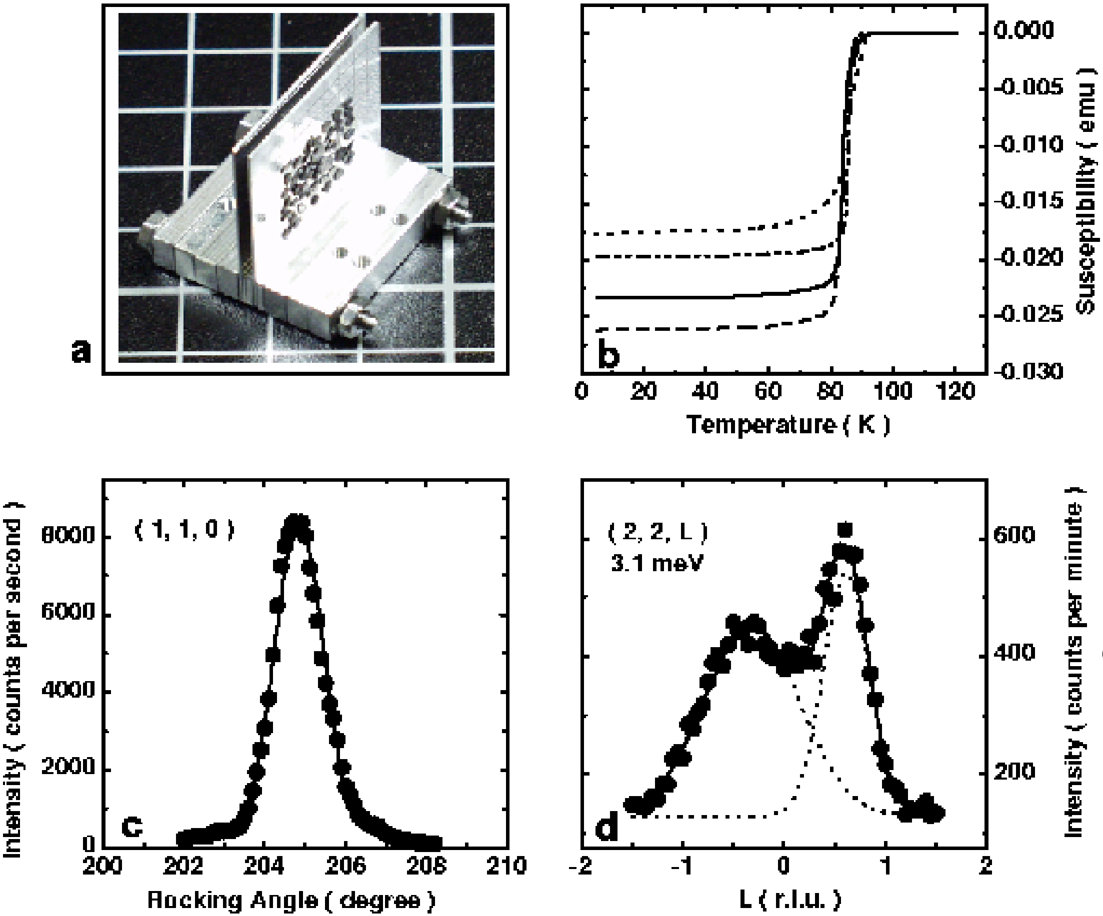


PRB, 53 876 (1996).



Nature, 398 588 (1999).

Resonance peak in $Tl_2Ba_2CuO_{6+\delta}$



$\sim$ Samples 0.5-2 mg

$T_C \simeq 90$ K

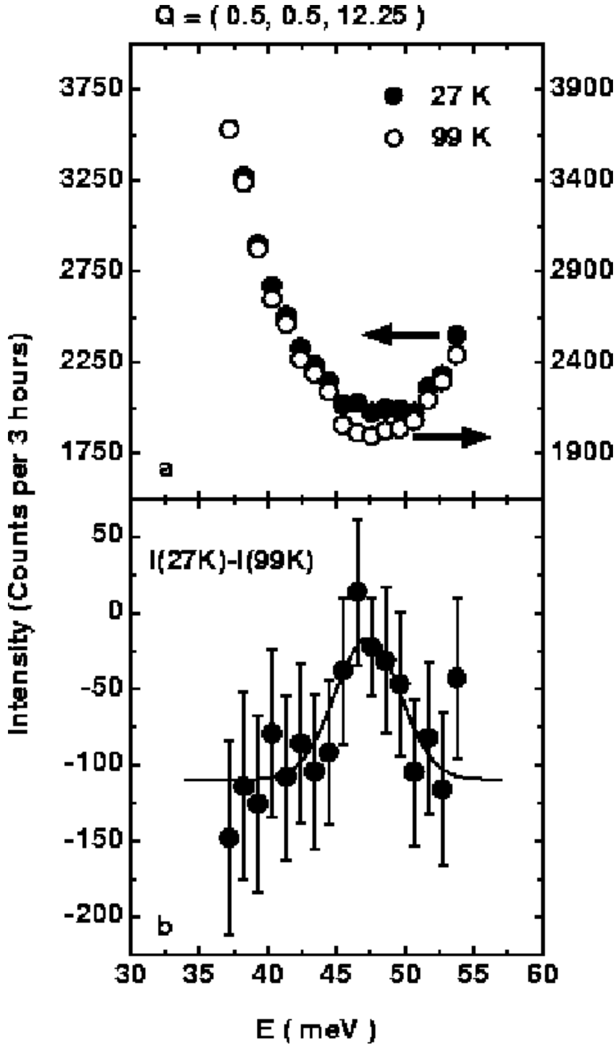
N.S. Berzigiarova, N.N.Kolesnikov (Chernogolovka, Russia)

$\sim$ 300 samples co-aligned (H.F. He)

$\Rightarrow$

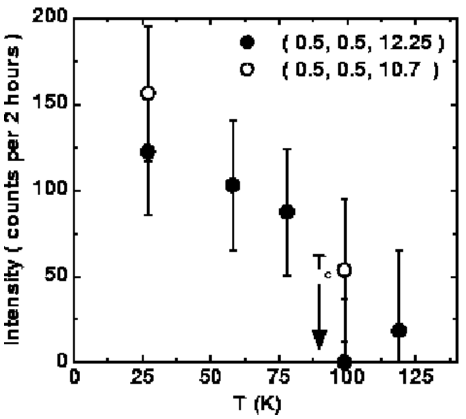
$m \sim 0.7$ g ~ 0.1 cm^3

Resonance peak in $Tl_2Ba_2CuO_{6+\delta}$



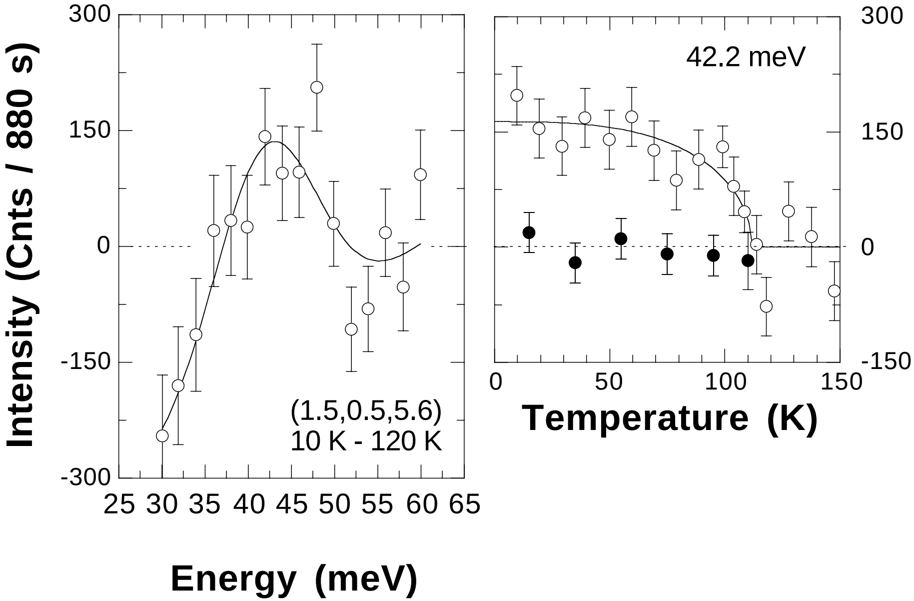
Energy scan
2T (LLB-Saclay)

Science 295 1045 (2002)



□ same spectral weight as $YBCO_7$

resonance peak in Bi2223



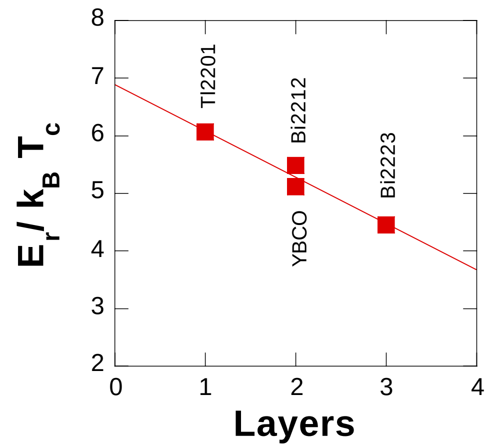
S. Bayrakci *et al.*, unpublished (2003).

3 layers

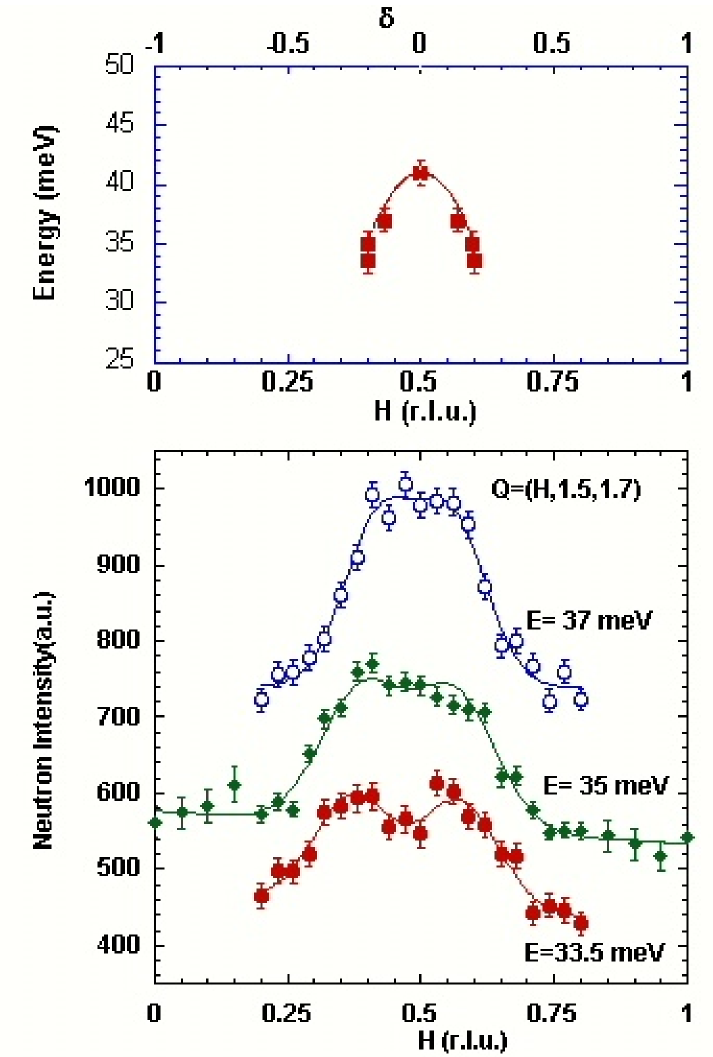
40 co-aligned single crystals

T_C=110 K

E_r=42.2 meV



Resonance peak dispersion



$\mathbf{YBa_2Cu_3O_{6.85}}$ ($T_C = 89$ **K**)

For $E \leq E_r =$ **41 meV**

Energy dependent
Incommensurate peaks
at $Q_\delta = (\pi/a \pm \delta, \pi/a)$
$\equiv (\pi/a, \pi/a \pm \delta)$

Only below T_C

$\neq$ **stripes**

science, 288 1234 (2000).

Resonance peak is a generic feature

⇒ Magnetic collective mode in Optimally doped cuprates: $T_c^{max} \geq 90$ K

	3-layers	2-layers		1-layer
Cuprates	Bi2223	YBCO	Bi2212	Tl-2201
Resonance energy (meV)	42	41	43	47
$E_r/k_B T_c$	4.4	5.1	5.4	6

□ $E_r < 2\Delta_{max} \sim 70$ meV $\sim 9 k_B T_c$

1. Particle-hole scenario: "Spin-exciton" model

   Onufrieva and Pfeuty PRB 65 054515 (2002)

   Abanov and Chubukov, Eschrig and Norman, PRL and PRB (2000-2002).

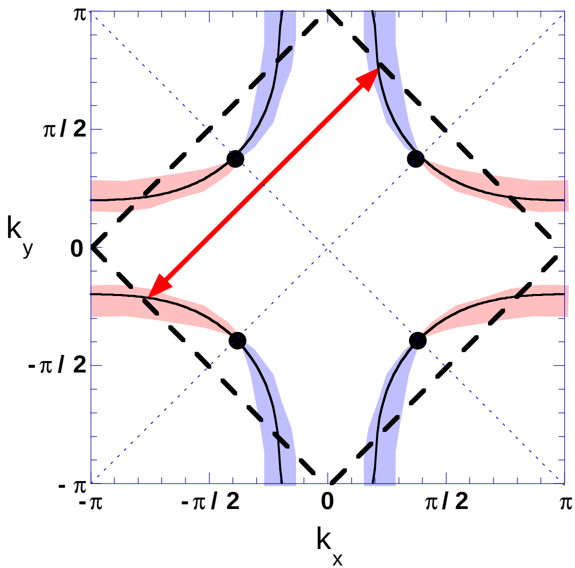
2. SO(5) (S.C. Zhang and Demler)

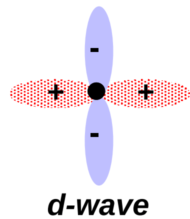
3. Nearly AF Liquid (D. Morr and D. Pines)

4. Stripes : Spin-waves emerging from incommensurate peaks

   Batista, Ortiz, and Balatsky, PRB 64 172508 (2001).

Particle-hole scenario





- ☐ **Fermi surface**
- ☐ **BCS spin susceptibility (Superconducting state)**
- ☐ **SC order parameter:** Δ_k
  $\Rightarrow$ **d-wave symmetry:**
  $\Delta_k \Delta_{k+Q_{AF}} < 0$
- ☐ $E_k = \sqrt{\Delta_k^2 + \epsilon_k^2}$

$$\chi^0(q,\omega) \propto \lim_{\epsilon \to 0} \sum_k [1 - \frac{\Delta_k \Delta_{q+k} + \epsilon_{q+k}\epsilon_k}{E_{q+k}E_k}] \frac{1 - f_{q+k} - f_k}{E_{q+k} + E_k - \hbar\omega - i\epsilon}$$

Coherence factor

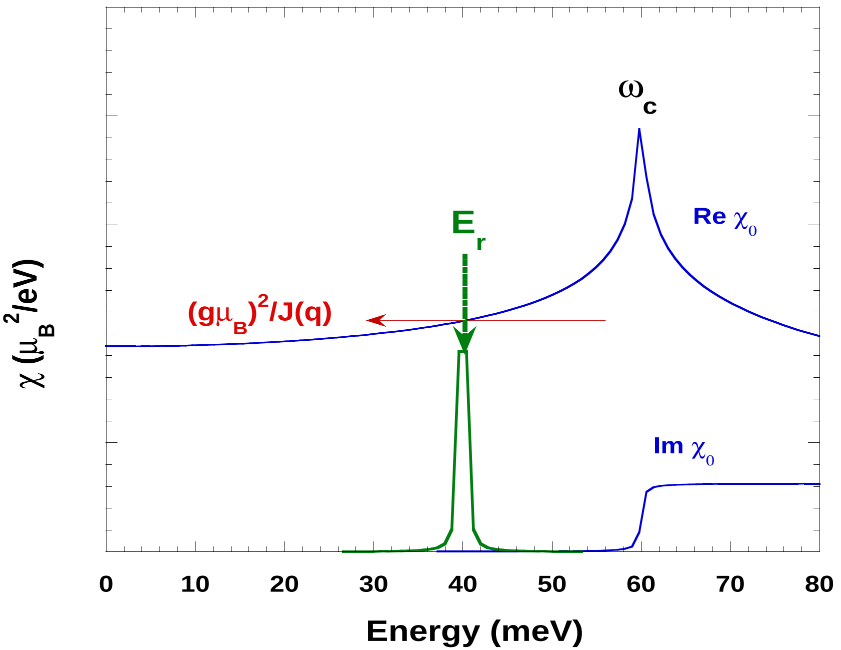
Threshold Particle-hole continuum

Collective mode: Spin exciton

Interactions $J(q)$ or U (RPA)

$$\chi(q,\omega) = \frac{\chi^0(q,\omega)}{1 - J(q)\chi^0(q,\omega)}$$

□ Resonance peak when $\mathbf{Re\chi_0(Q,E_r) = 1/J(Q)}$



In bilayer: $\mathbf{J(Q_{AF}) = J_{//} + J_{\perp}} \Rightarrow$

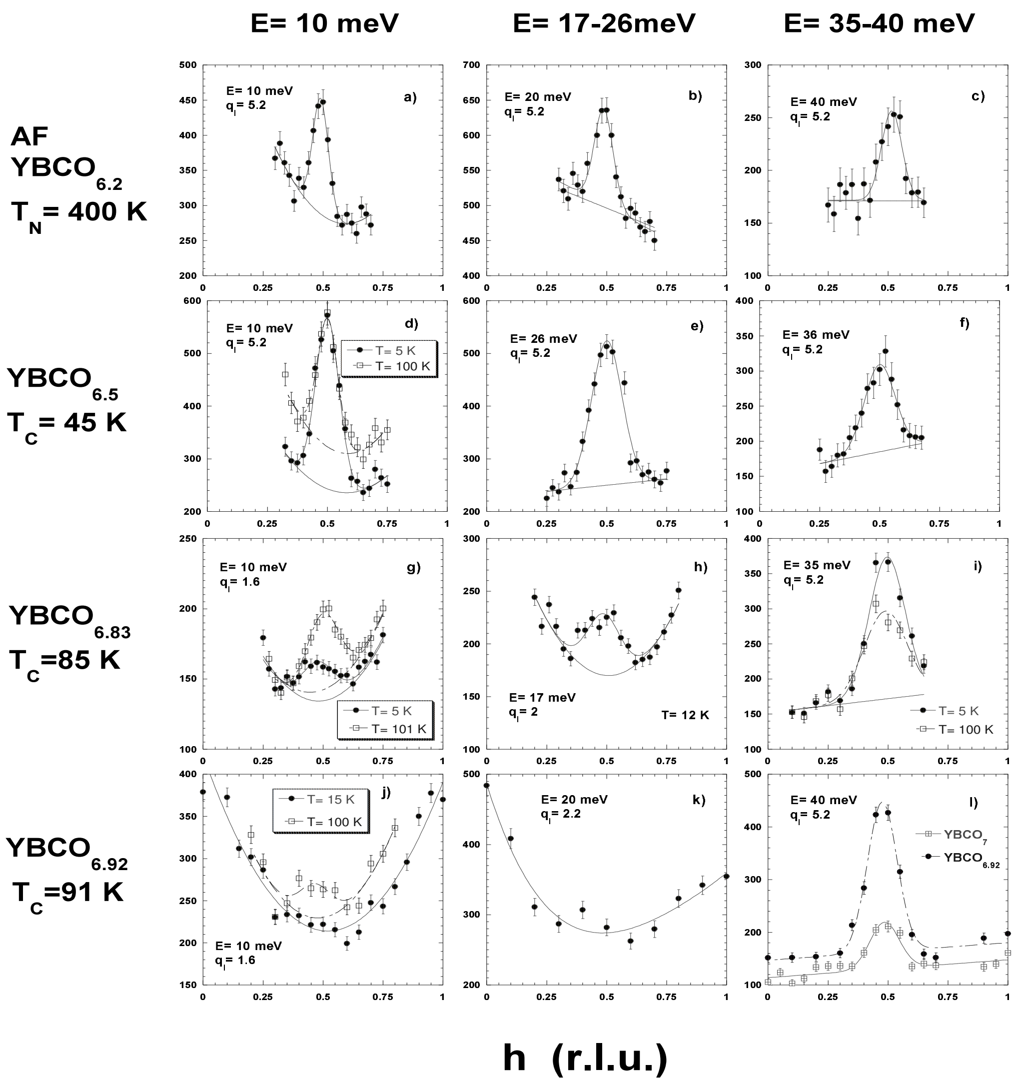
$\mathbf{E_r}$(1-layer) > $\mathbf{E_r}$(2-layers)

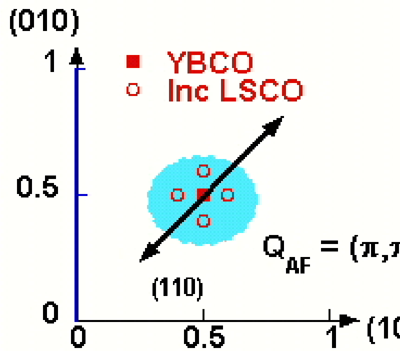
BSCO-Optimal doping:

$\Delta_{max} = 35$ **meV ARPES** (J. Mesot et al PRL 1999)

$\omega_c = 1.8\Delta_{max} = 63$ **meV** <=> $E_r = 43$ **meV** $\simeq 1.2\Delta_{max}$

Fluctuations magnétiques: vue d'ensemble

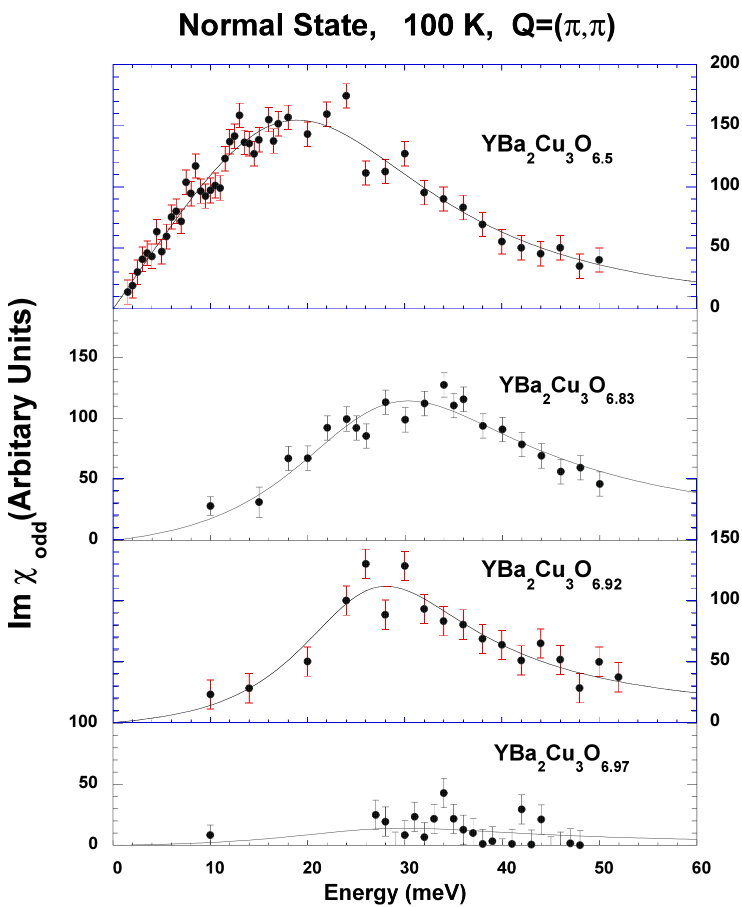




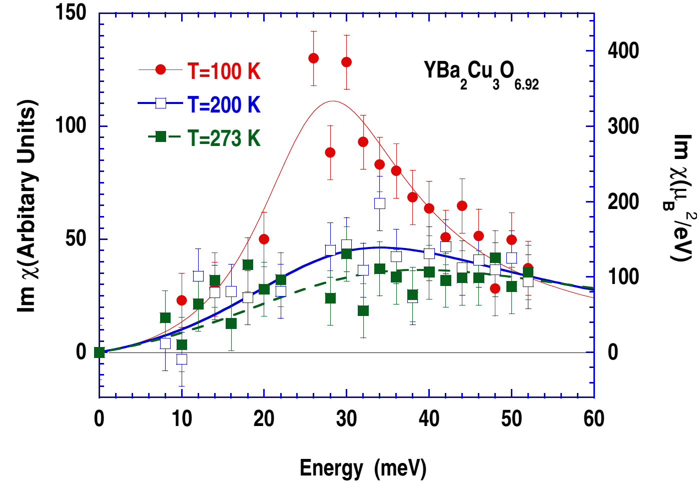
Même échantillon $YBa_2Cu_3O_{6+x}$ (J.Y. Henry)

Même spectromètre 2T (LLB)

Excitations magnétiques état normal à Q_{AF}



Dépendance en température x=0.92



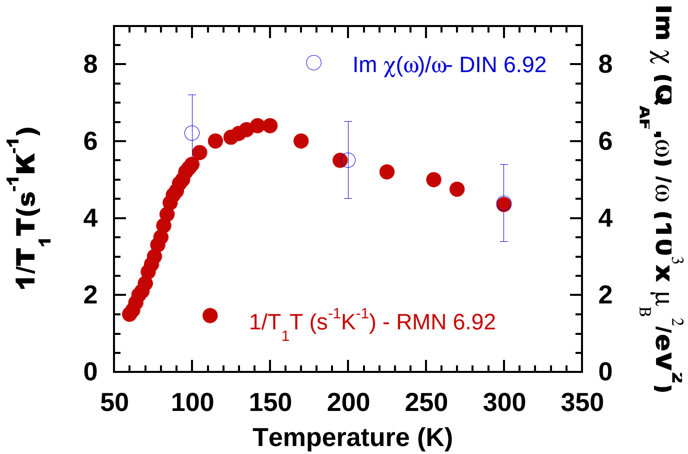
$$\textbf{Im } \chi^{AF} \sim \textbf{100-300 } \mu_B^2/\textbf{eV}$$

$$>>$$

$$Im\chi_0 \sim \textbf{1/t} \sim \textbf{3-5 } \mu_B^2/\textbf{eV}$$

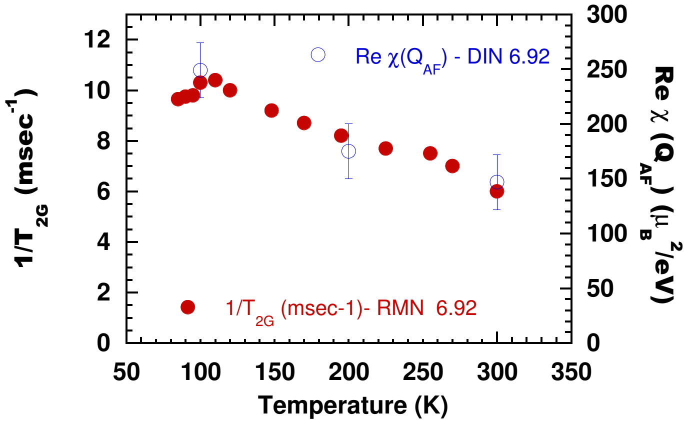
(susceptibilité uniforme)

Comparaison: Neutrons/RMN



J.A. Gillet, thèse Grenoble (1994).

C. Berthier et al, J. Phys I, 6, 2205 (1997).



RMN du noyau ^{63}Cu: sonde Q_{AF}

Temps de relaxation spin-réseau:

$$\frac{1}{^{63}T_1 T} \sim \lim_{\omega \to 0} \sum_Q |A(\mathbf{Q})|^2 \frac{Im\chi(Q,\omega)}{\omega}$$

Accord de l'évolution en fonction de la température

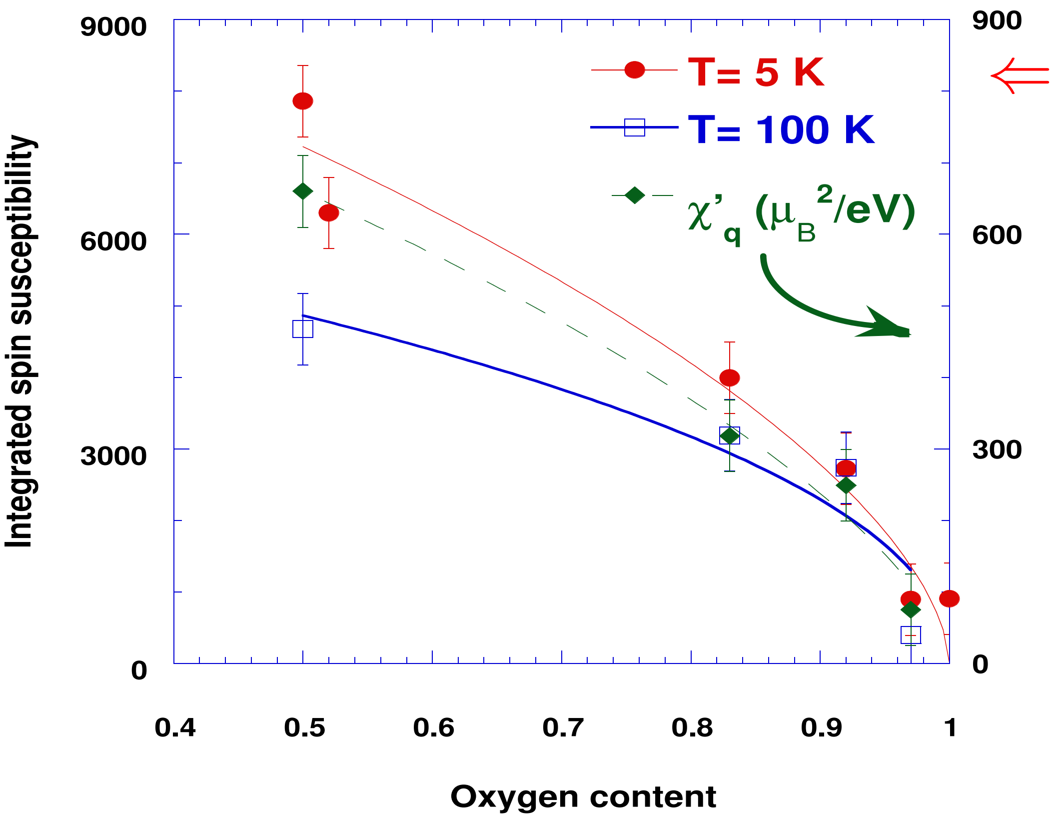
☐ Facteur d'échelle 3-4 trop grand
⇒ problème dépendance en Q

Temps de relaxation spin-spin:

$$\frac{1}{^{63}T_{2G}^2} \sim \sum_Q \left[|A(\mathbf{Q})|^4 (Re\chi(Q))^2 - (|A(\mathbf{Q})|^2 Re\chi(Q))^2 \right]$$

Total magnetic spectral weight

$$\int_0^{50\mathrm{meV}} d\omega Im\chi(Q_{AF},\omega)$$



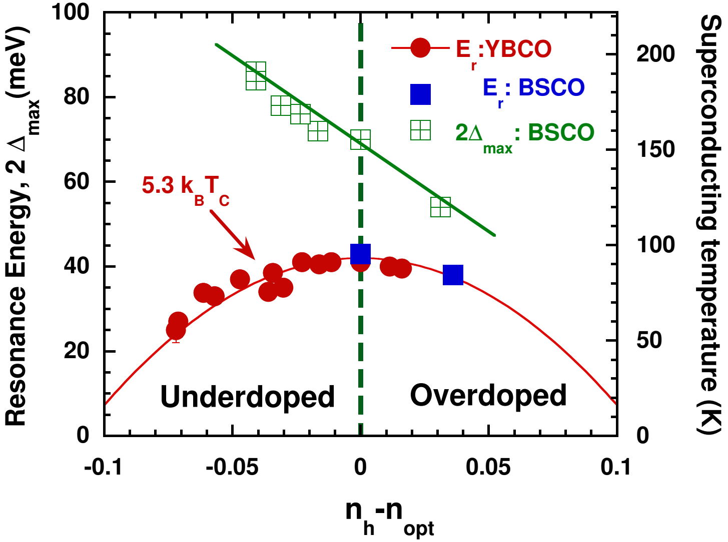
⇐ ∼ 30 % magnetic spectrum of undoped YBCO

∼ Pseudo-gap

cond-mat/0009373

Impact on electronic properties:

$$E_r \propto 5.3 k_B T_C$$



cond-mat/0211227.

- Single particle electronic spectrum (ARPES)

  J.C. Campuzanno et al,

  P.D. Johnson et al, J. Fink et al

- Tunelling

  Zasadzinski et al,

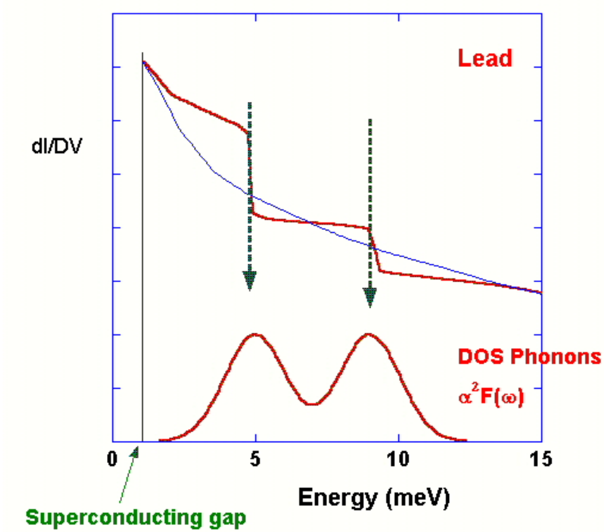
  PRL 87 067005(2001).

- Optical data

  Carbote et al, Munzar et al

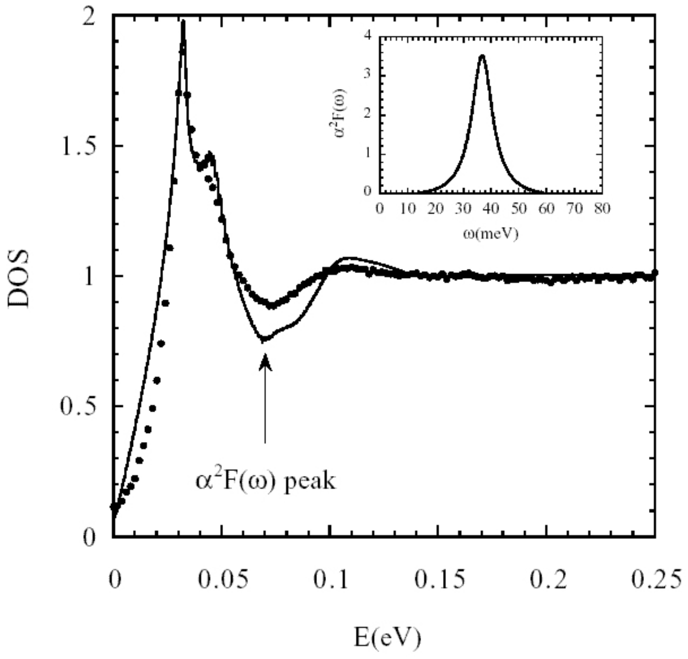
- Raman scattering

Tunneling Junction



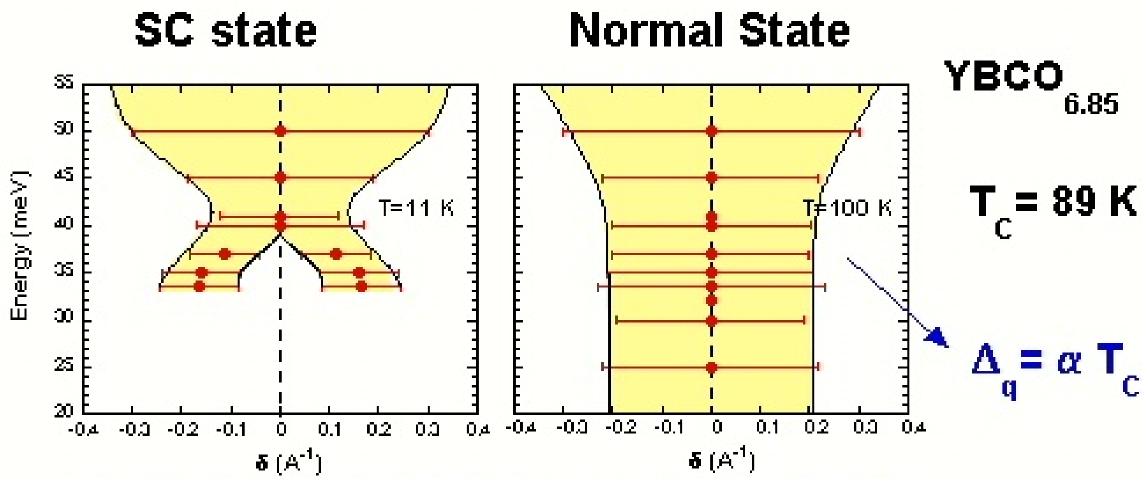
J.R. Schrieffer, Theory of Superconductivity (1964)

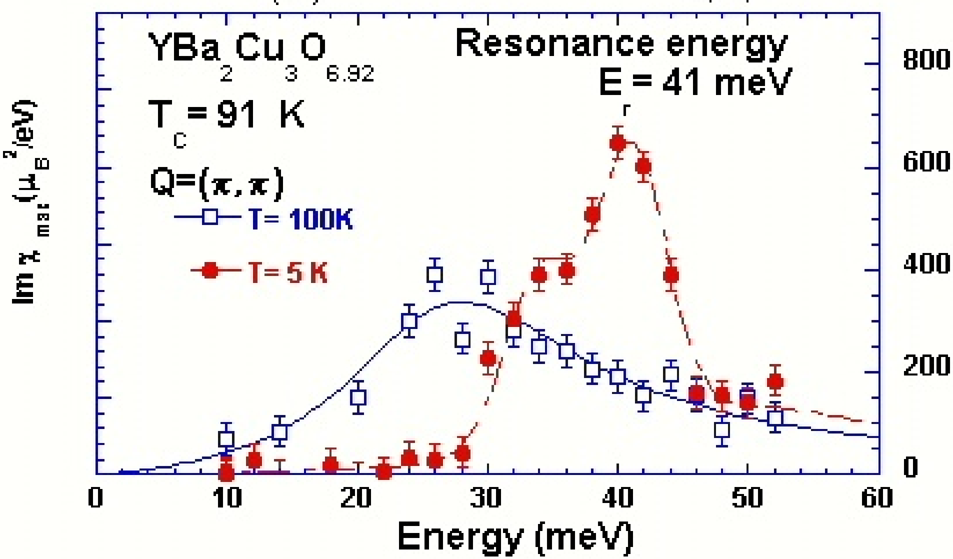
☐ Strong coupling analysis



J.F. Zasadzinski et al, preprint.

SC state *vs* Normal state





Spectral weight Redistribution in **Q** and ω across T_C

cond-mat/9902067

Conclusion/Perspectives

1. **Mode magnétique collectif (phase SC): $T_c^{max} \geq 90$ K**
   Pas présent dans $La_{2-x}Sr_xCuO_4$ ($T_c^{max} \simeq 37$ K),
   ni $Bi_2Sr_2CuO_{6+\delta}$ ($T_c^{max} \simeq 27$ K)

2. **Fortes corrélations magnétiques de l'état normal**

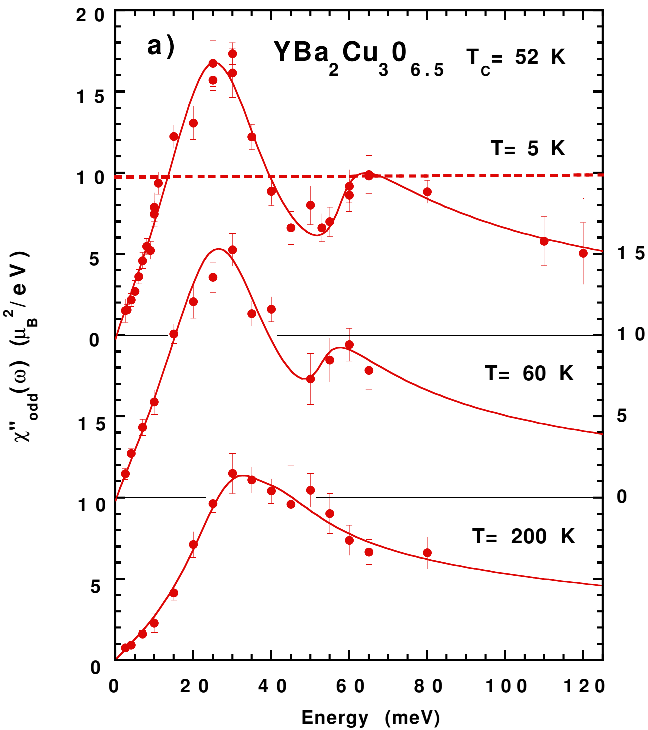
   - **Forte dépendance en dopage: $YBa_2Cu_3O_{6+x}$**
     quasiment pas détectable au dopage optimal:
     $Bi_2Sr_2CaCu_2O_{8+\delta}$, $Tl_2Ba_2CuO_{6+\delta}$
   - **Accord $La_{2-x}Sr_xCuO_4$**
     (à part position en vecteur d'onde incommensurable)
   - **Pas de signal détecté dans $Bi_2Sr_2CuO_{6+\delta}$**

3. **Etat surdopé: YBCO-Ca**

4. **Role du magnétisme en comparaison avec Sr_2RuO_4 et $Na_{0.35}CoO_2, H_2O$**

Local Susceptibility: $Im\chi_{loc}(\omega) = \int_{ZB} d^2\mathbf{q} Im\chi(\mathbf{q},\omega) / \int_{ZB} d^2\mathbf{q}$

$YBa_2Cu_3O_{6.5}$



PRB, 56 11439 (1997).

□ Similar to $La_{1.86}Sr_{0.14}CuO_4$

S.M. hayden et al, 76, 1344, PRL (1996)

Nearly AF Liquid

(Moriya et al, Pines et al)

$$\chi(\mathbf{q},\omega) = \frac{\chi_{AF}}{1 + (q\xi)^2 - (\omega/\Delta)^2 - i(\omega/\omega_{sf})}$$

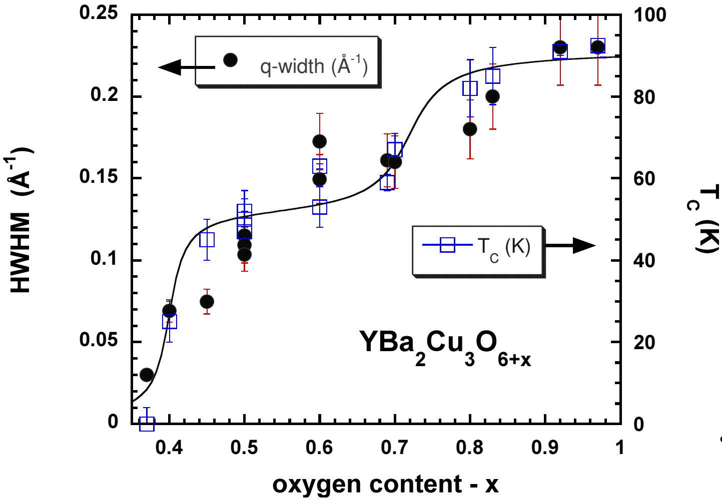
$$\Downarrow$$

$$\chi^{2D}_{NAFL}(\omega) \simeq \frac{\chi_{AF}}{4(\xi/a)^2}\left[\frac{1}{2} + \frac{1}{\pi}\mathrm{arctg}\left[\omega_{sf}\frac{\omega^2 - \Delta^2}{\omega\Delta^2}\right]\right]$$

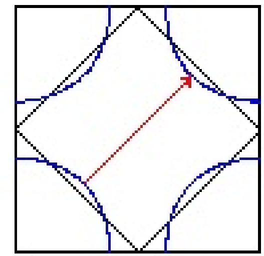
Dépendance en vecteur d'onde

□ $La_{2-x}Sr_xCuO_4$:
Pics incommensurables

□ $YBa_2Cu_3O_{6+x}$: Largeur en Q



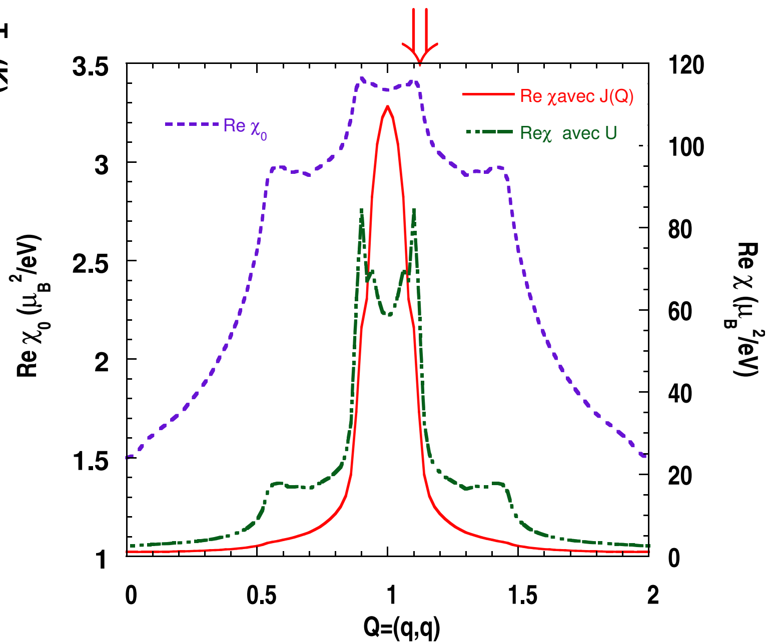
PRL, 82 5337 (1999).



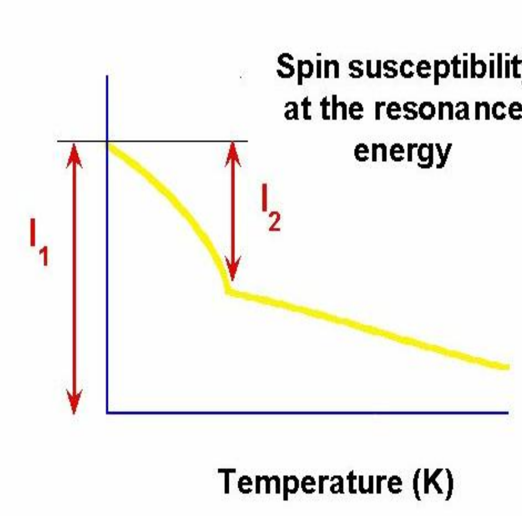
vecteur d'onde "node-node"

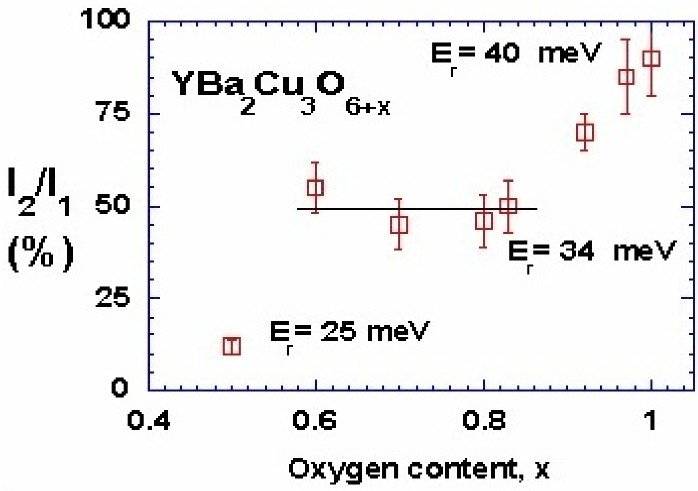
susceptibilité RPA:

$$\chi(q) = \frac{\chi^\circ(q)}{1-J(q)\chi^\circ(q)} \quad \Rightarrow$$



Resonance peak spectral weight





☐ **For all doping:** $\int d^3Q d\omega Im\chi(Q,\omega) \simeq \mathbf{0.05}\ \mu_B^2$

$\Rightarrow$ **about 2 % magnetic spectrum of undoped YBCO**

☐ **Is it enough to explain electronic anomalies ?**

Kee, Kivelson and Aeppli, PRL, 88, 257002 (2002) **vs**

Abanov, Chubukov, Eschrig, Norman and Schmalian, Phys. Rev. Lett., 89, 177002 (2002)