Orbital-like Order in Several Families of Cuprates

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Do we have a broken symmetry below T* ?

Magnetic order in the pseudogap state of high-Tc cuprates
(examples in 4 different families: YBCO, Hg1201, LSCO, Bi2212)

Using polarized neutron diffraction over the last 6 years:
LLB-Saclay, ILL-Grenoble

***associated magnetic* excitations in Hg1201 (Yuan Li talk)**

Collaborators :

- V. Balédent (PHD), B. Fauqué, S. Pailhès, Y. Sidis
  (Laboratoire Léon Brillouin - Saclay)

$(Y,Ca)Ba_2Cu_3O_{6+x}$

- D. Haug, C.T. Lin, V.Hinkov (MPI Stuttgart)

- X Chaud (CRETA, Grenoble), LP Regnault (CEA Grenoble)
- H.A. Mook (Oak Ridge, USA)

$YBa_2Cu_3O_{6+x}$

- Yuan Li (MPI), G. Yu, M. Chan (University Minnesota)
- M. Greven (University Minnesota, USA)
- P. Steffens (ILL-Grenoble)

$HgBa_2CuO_{4+x}$

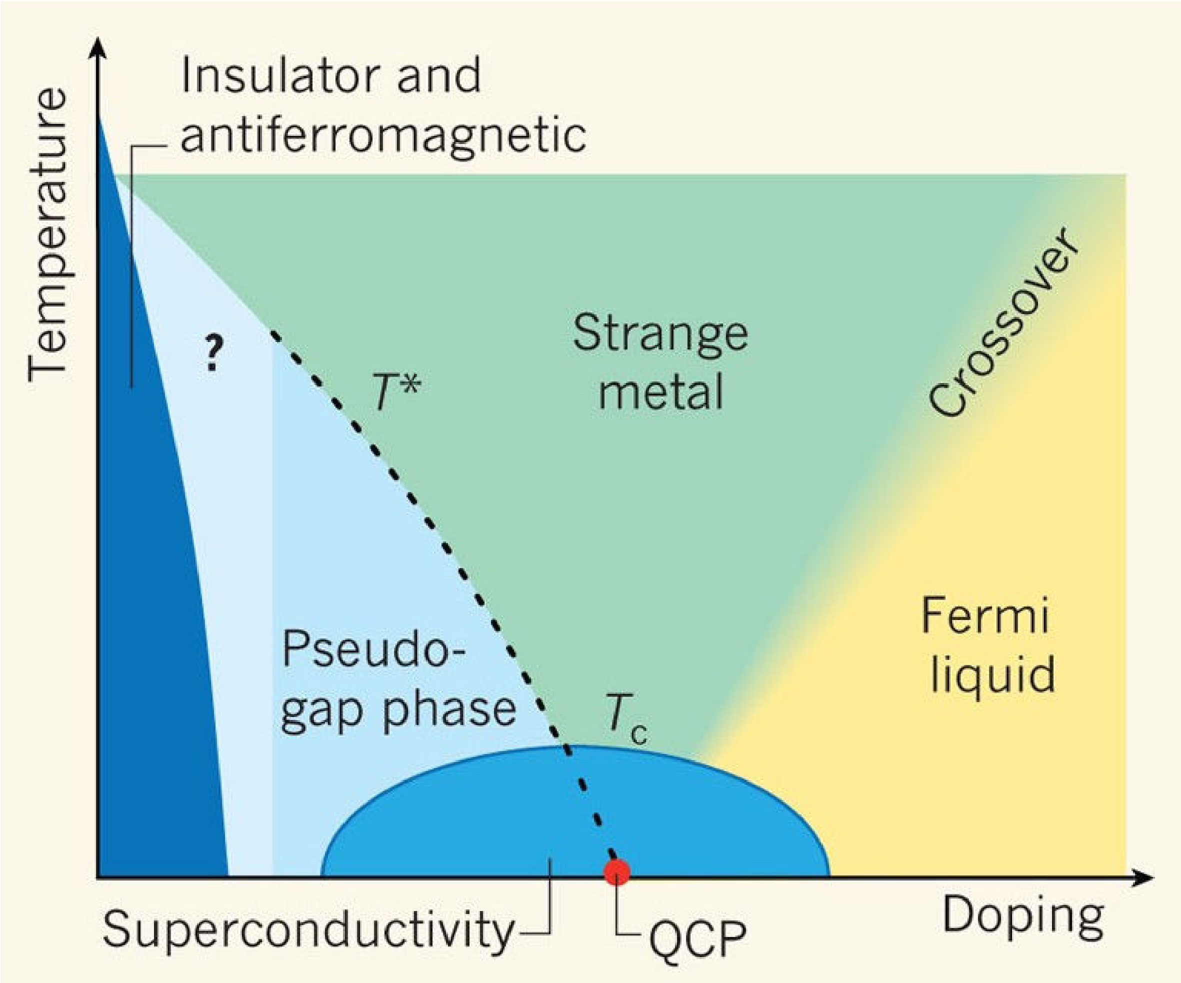
- K. Conder, E. Pomjakushina, N. Christensen (Riso),
  J. Mesot (PSI, Switzerland)

$La_{2-x}Sr_xCuO_4$

Outline:

1) Motivation: Loop-current order
2) Neutron scattering
3) Long range magnetic Q=0 AF order in YBCO and Hg1201
4) Preliminary result in Bi2212
5) Short range magnetic order in LSCO
6) Updated phase diagram in YBCO and Implications

Pseudo gap: Hidden Ordered State



Order parameter?

Broken symmetry?

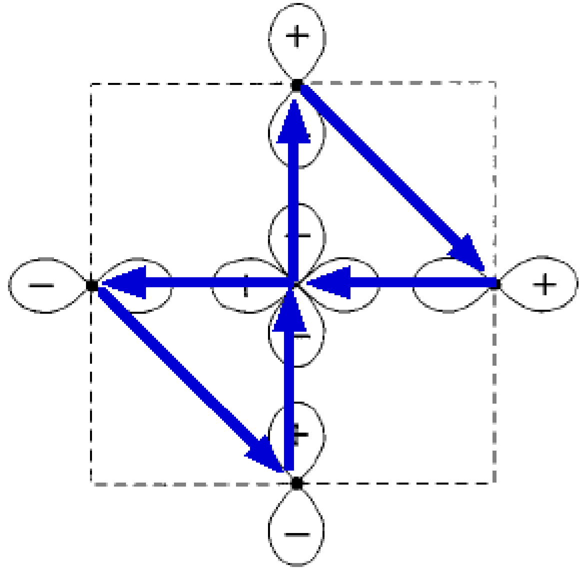
Quantum critical point?

Role of the related fluctuations in the SC pairing mechanism?

Hidden order parameter: Spin Density Wave, Charge DW,
more Exotic: Circulating current,
D-Density Wave,…
Electronic Liquid Crystal

Circulating Currents: C.M. Varma, PRB 73, 155113 (2006)

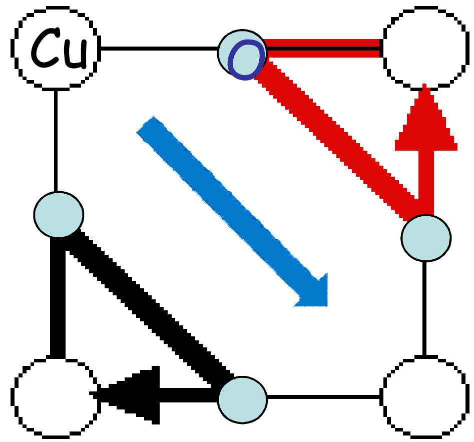
- 3-band Hubbard model: Cu(dx2−y2), O(2px), O(2py)



In each unit cell:

Toroidal moment

4 possible domains



2 current loops circulating clockwise and anti-clockwise => producing Orbital moments

Circulating currents: phase Θ_{II}

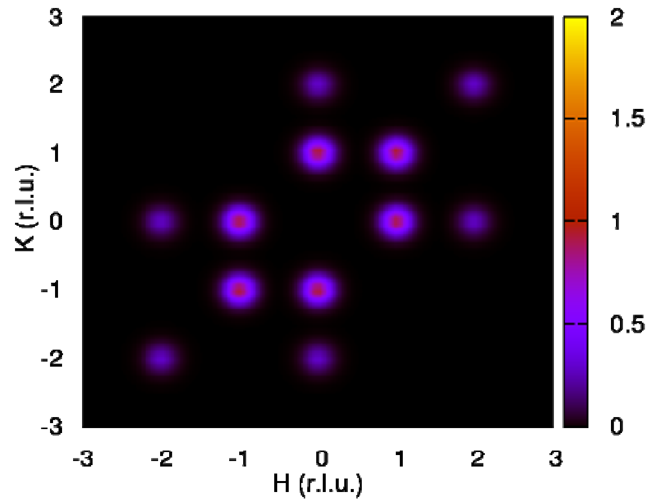
- Respects Translation Symmetry (q = 0 transition)
- Breaks Time-Reversal symmetry

➔ Dichroic signal in ARPES in BiSrCaCuO
Kaminski et al. Nature 416, 610 (2002).

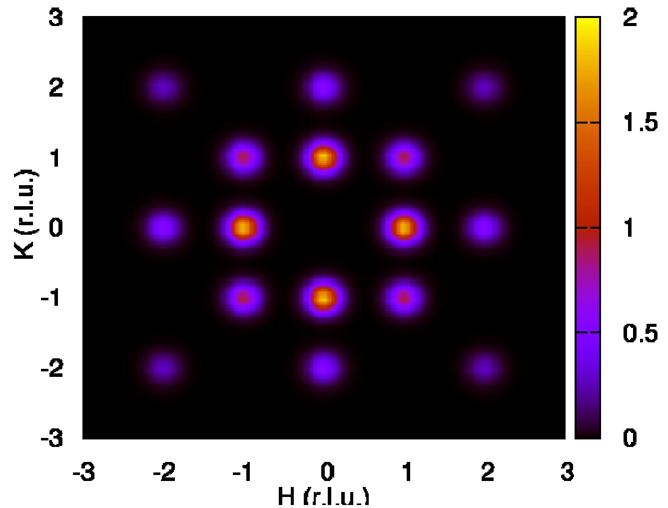
- Yields a sizeable magnetic moment of 0.1 μB

Circulating currents C.M. Varma, PRB (1997)(2006)

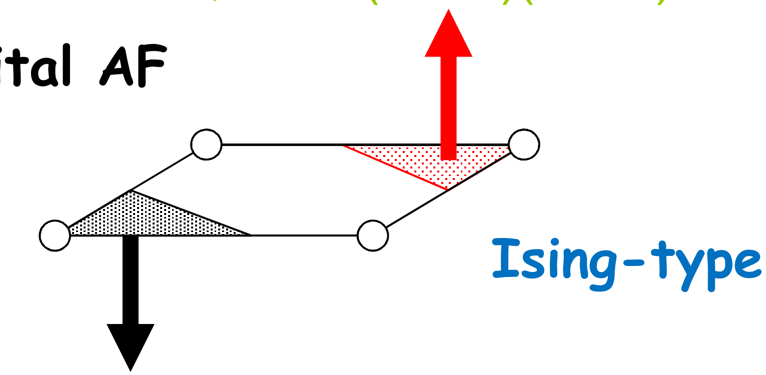
In k-space: Q=(H,K)



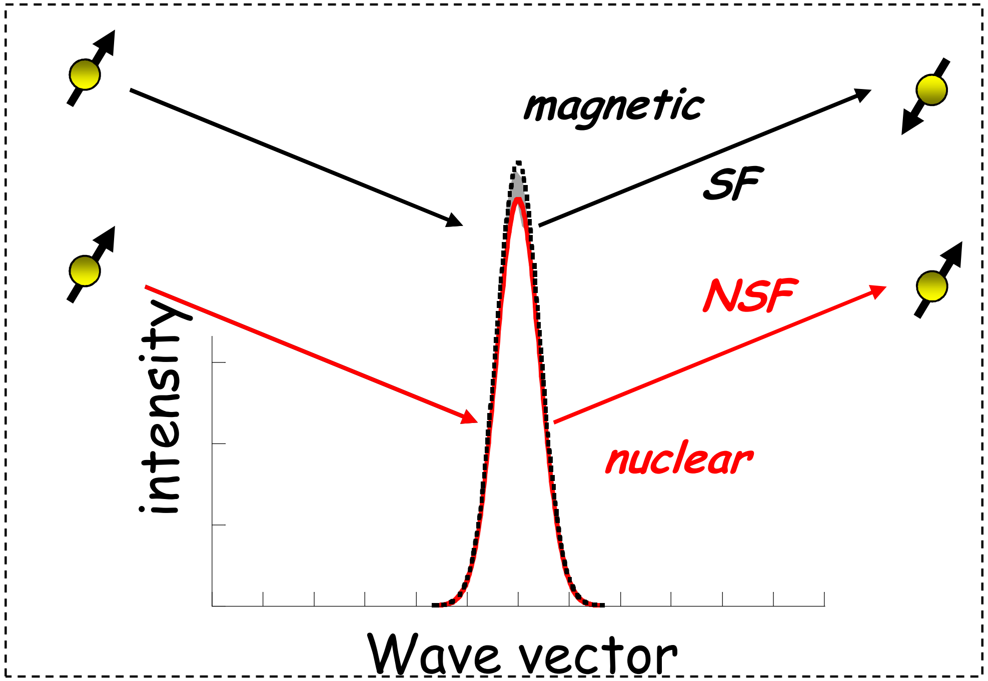
2 type of Domains at 90°



Q=0 Orbital AF

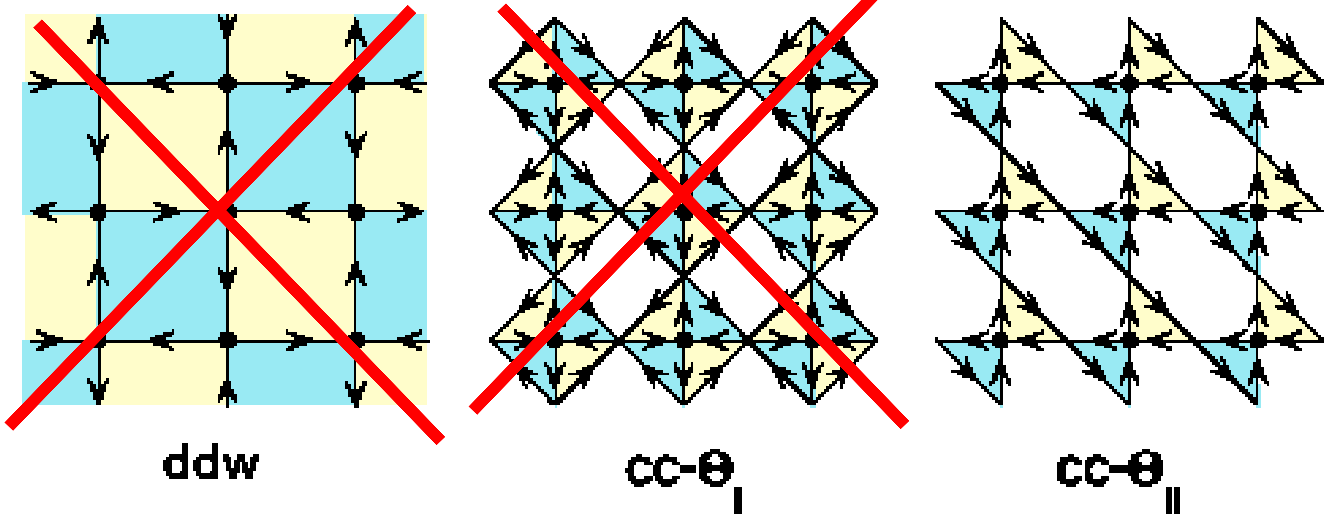


Orbital moments ($\perp CuO_2$ plane) measurable with neutron diffraction



Charge currents: DDW and Circulating currents

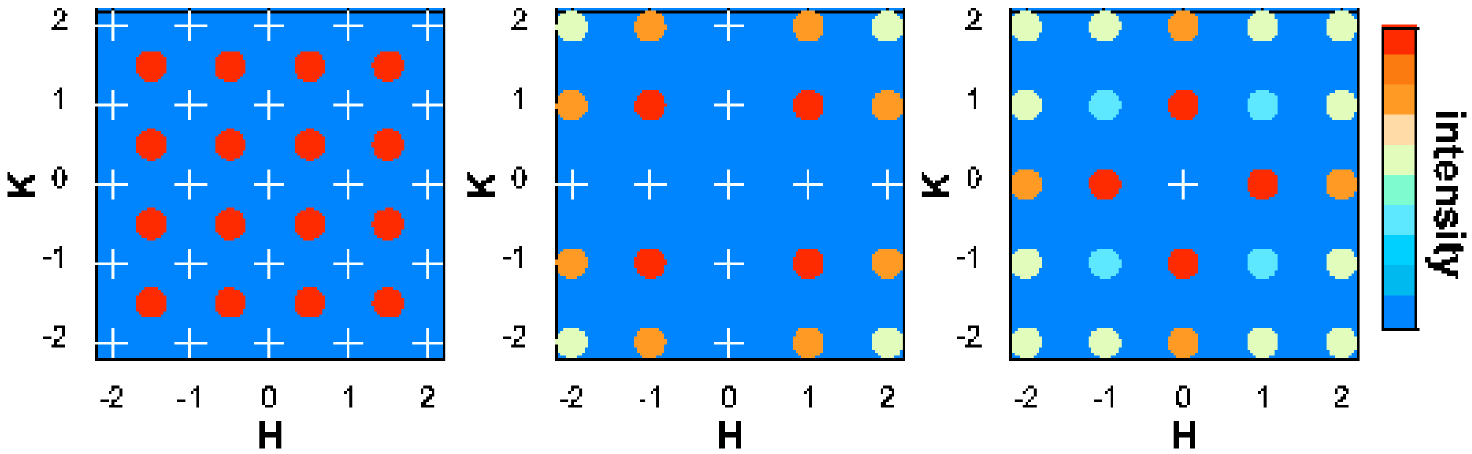
S. Chakravarty PRB (2001) C.M. Varma, PRB (1997)(2006)



CC-phases
NMR
Silent Probe

Orbital moments (2D Ising) → measurable with neutrons

In k-space: Q=(H,K)



Polarized neutron cross sections

- Potential due to magnetic field: $-\mu_{\mathrm{N}}.\mathrm{B}$

Magnetic field: **Spin** **Orbital**

$$\mathrm{B} = \mathrm{B_S} + \mathrm{B_L} = \frac{\mu_0}{4\pi}\{2\mu_B curl\Big(\frac{\mathrm{s} \wedge \hat{\mathrm{R}}}{R^2}\Big) + I\frac{d\mathrm{l} \wedge \hat{\mathrm{R}}}{R^2}\}$$

- Elastic cross section for a given moment $\vec{M}$:

$$\frac{d\sigma}{d\Omega} = r_0^2 \mid < \pm|\vec{\sigma}.\vec{M}_\perp|\pm > \mid^2$$

$\vec{\sigma}$: Pauli matrices and $\vec{M}_\perp = \sum_r \exp^{-i\vec{Q}\vec{r}}(\vec{Q} \wedge \vec{M} \wedge \vec{Q})$

Neutron spin $\frac{1}{2}$: $|+>$ and $|->$

- For a polarization $\vec{P}$ ($//$ $\vec{H}$) along a given direction z:

Non Spin-Flip: $< +|\vec{\sigma}.\vec{M}_\perp|+ >= M_{\perp,z}$ and $< -|\vec{\sigma}.\vec{M}_\perp|- >= -M_{\perp,z}$

Spin-Flip: $< +|\vec{\sigma}.\vec{M}_\perp|- >= M_{\perp,x} + iM_{\perp,y}$

$< -|\vec{\sigma}.\vec{M}_\perp|+ >= M_{\perp,x} - iM_{\perp,y}$

Polarized monochromatic neutron beam : 4F1-LLB

•Nuclear Scattering

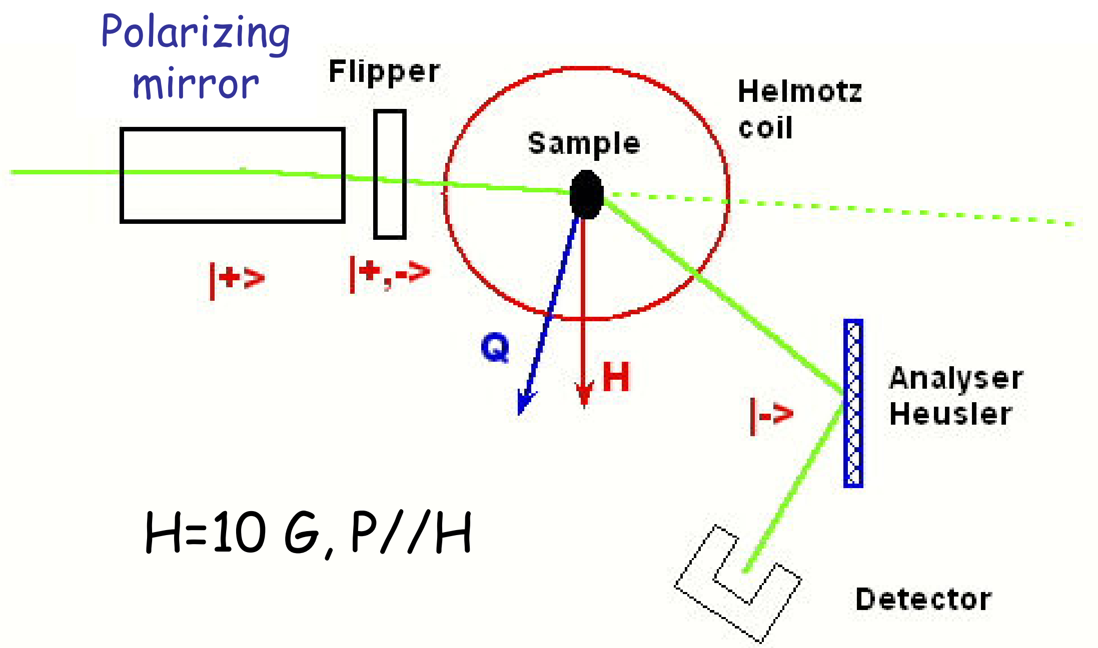
Non spin flip: $<-|F_N|->$

* Magnetic Scattering

$$F_M = < \pm|\vec{\sigma}.\vec{M}_\perp|- >$$

$$\vec{M}_\perp = \vec{Q} \wedge \vec{M}_Q \wedge \vec{Q}$$

$$\vec{M}_Q = \sum \vec{M} \exp^{-i\vec{Q}\vec{r}}$$

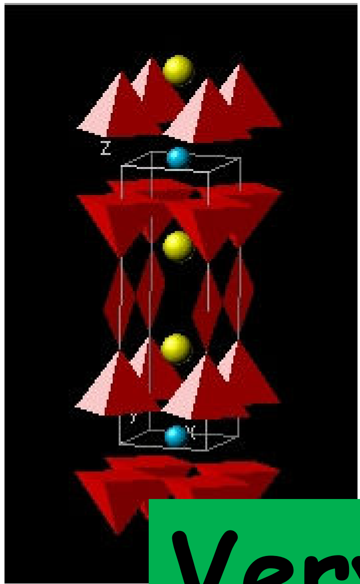


Flipping ratio:
R=NSF/SF=I^-/I^+ (R ~ 50)

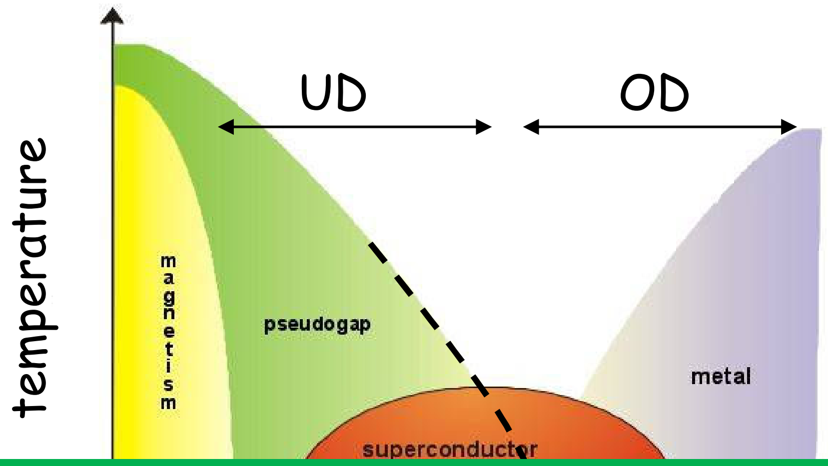
Magnetic components $\perp \vec{Q}$
Spin-flip components $\perp \vec{P}$

Neutron polarization:
p=$(I^- - I^+)/(I^- + I^+)$ ~ 96%

Polarized neutron scattering experiments on (Y,Ca)$Ba_2Cu_3O_{6+x}$



Generic phase diagram



$YBa_2Cu_3O_{6+x}$

A systematic study on 8 different samples (different origin, twinned [t] or detwinned [d])

(twinning: 10L=01L)

Very consistent picture

UD35 (x=0.45, Tc=35 K) [d]

UD54 (x=0.5, Tc=54 K) [t]

UD 61(x=0.6 , Tc=61 K) [t]

UD64 (x=0.6 , Tc=64 K) [d]

UD68 (x=0.75 ,Tc=75K) [t]

UD89 (x=0.85 ,Tc=89K) [t]

$Y_{0.85}Ca_{0.15}Ba_2Cu_3O_{6+x}$

OD75 (x=1, Tc=75 K) [t]

Underdoped $YBa_2Cu_3O_{6.6}$

H.Mook's sample (Tc=63 K) [t]

Polarized neutron results in YBCO: P//Q, Q=(0,1,1)

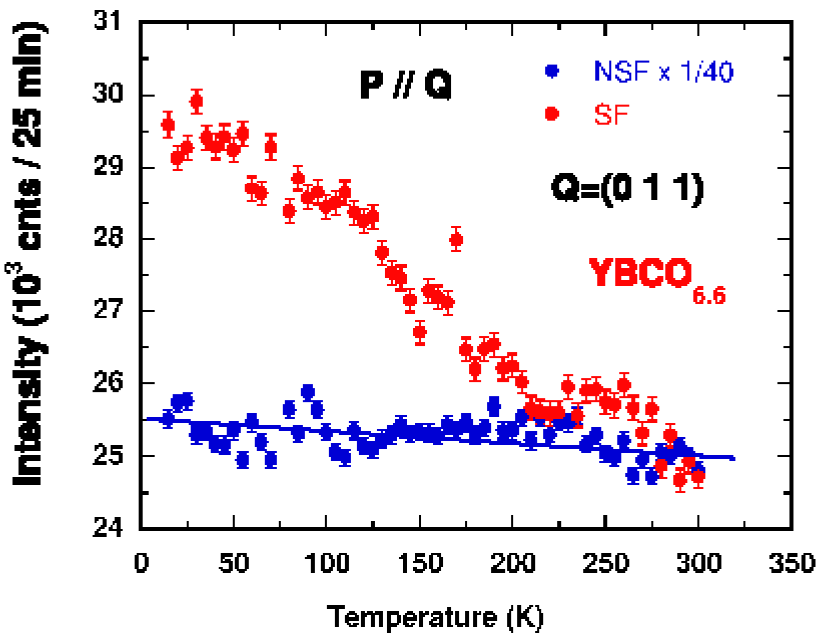
B. Fauqué et al, PRL 96 197001 (2006)

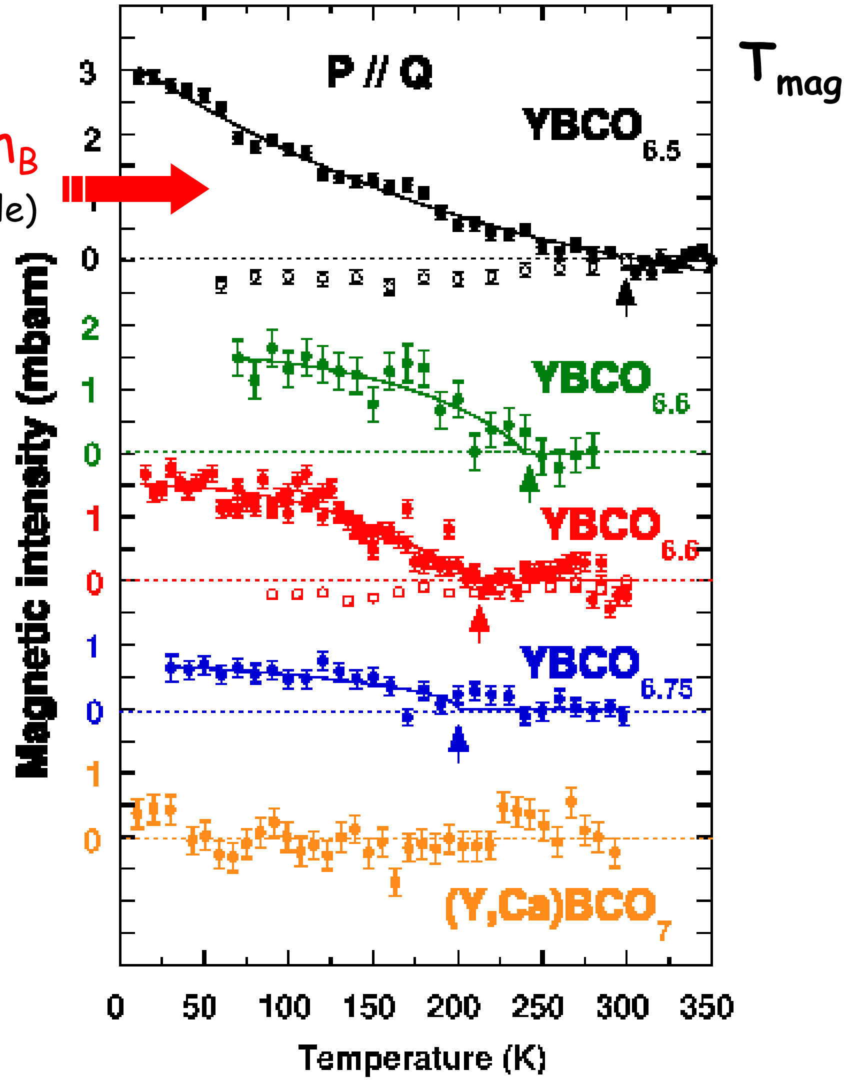
$$\mathrm{NSF:}\ \frac{d\sigma}{d\Omega} = |F_N|^2$$

$$\mathrm{SF:}\ \frac{d\sigma}{d\Omega} = |F_M|^2 + |F_N|^2/R$$

R: flipping ratio

m~0.1 m_B (per triangle)





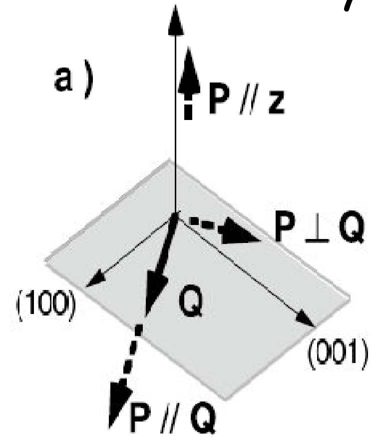
For Q=(0,1,1): $|F_N|^2/ |F_M|^2$ =400

N.B. L=1, weak nuclear Bragg peak

No effect on Q=(002) (open symbols)

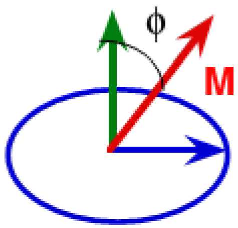
$YBCO_{6.6}$: H.A. Mook et al, PRB 020506(R) (2008).

Polarization analysis:



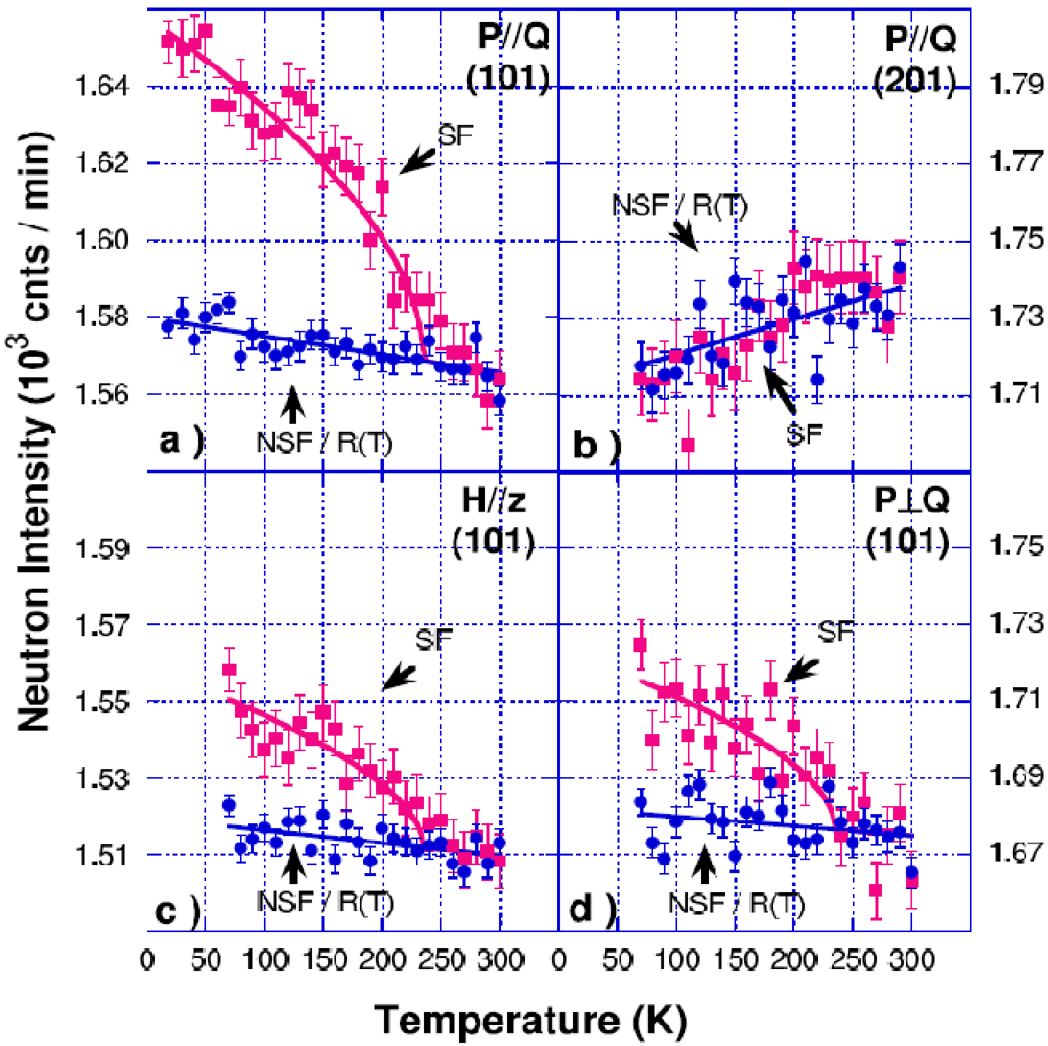
$$I_{\vec{P}//\vec{Q}} = I_{\vec{P}//\vec{z}} + I_{\vec{P}\perp\vec{Q}}$$

Angle (M,c*) ~ 45 deg

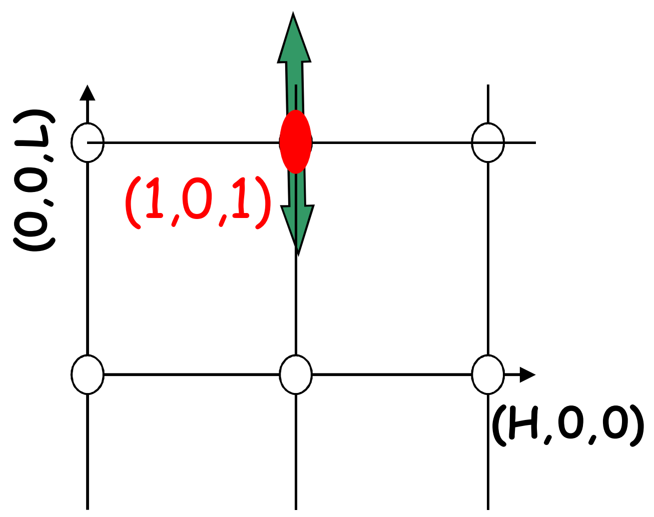


Weak or zero structure factor for Q=(2,0,1)

For Q=(1,0,1):



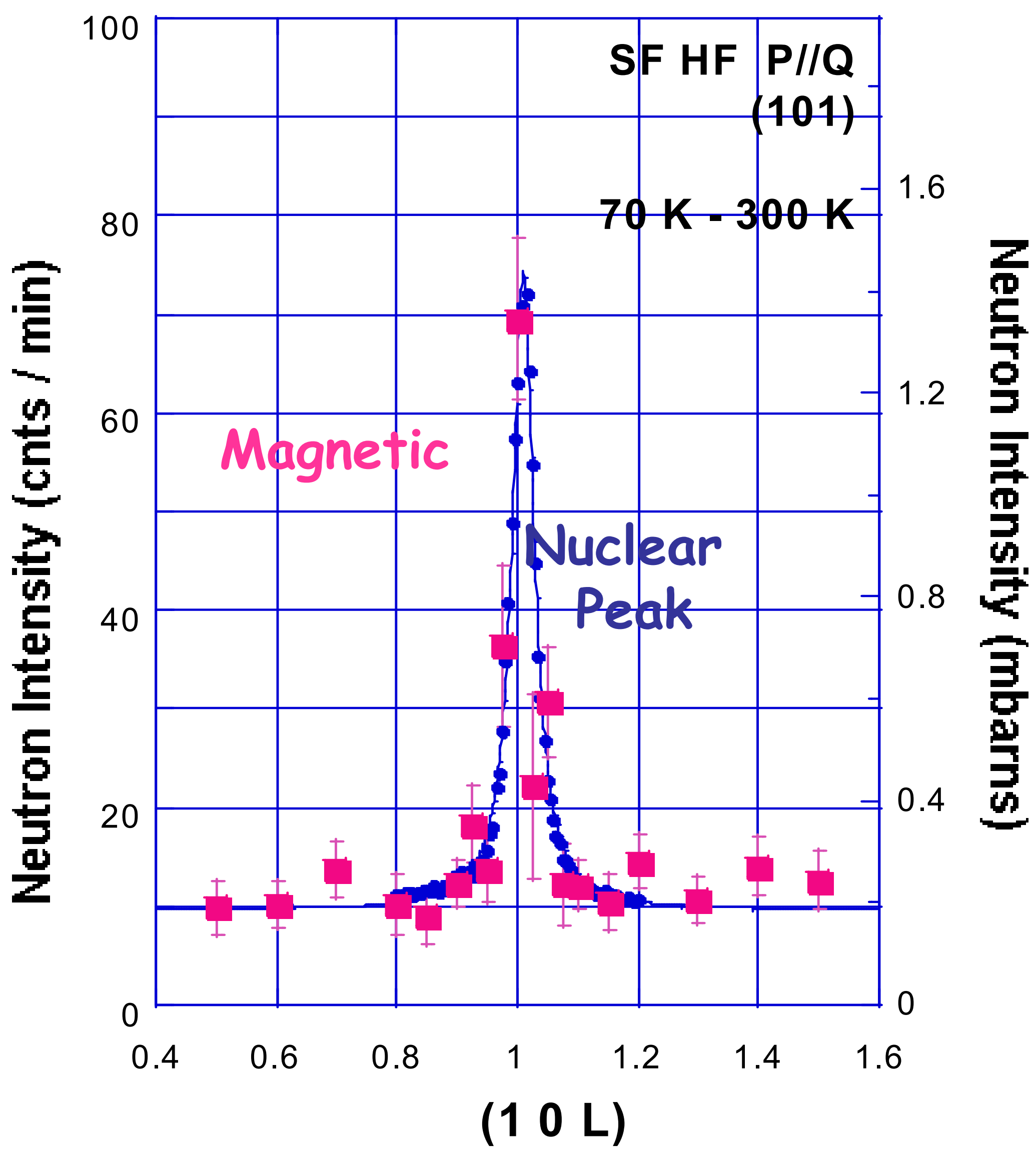
YBCO: Long range magnetic order



- L-scan

  Long range order

  (ξ>50 Å)

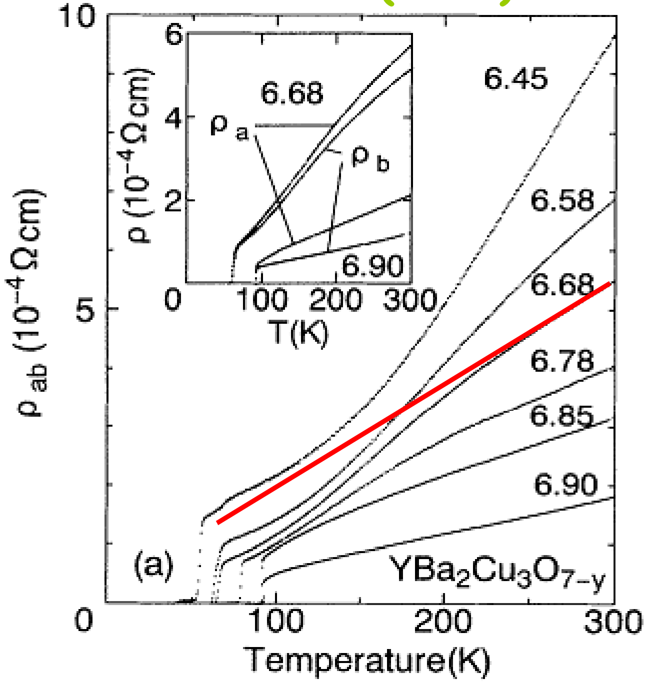


H.A. Mook et al, PRB 020506(R) (2008).

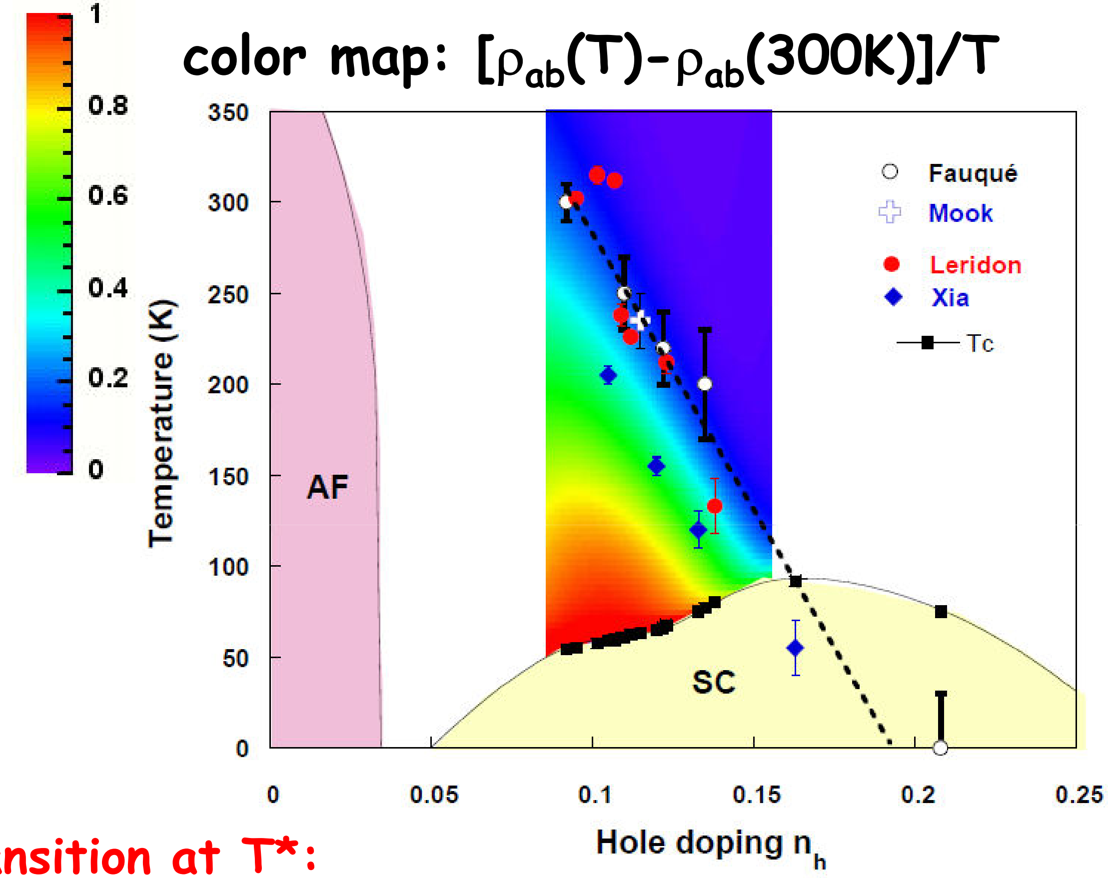
Phase diagram: Magnetic order at T_{mag} ~T^*

Resistivity in YBCO

T. Ito et al PRL 70 (1993) 3995



color map: $[\rho_{ab}(T)-\rho_{ab}(300K)]/T$



Other reports of a phase transition at T*:

- Polar Kerr effect
J. Xia, et al, PRL, 100, 127002 (2008)

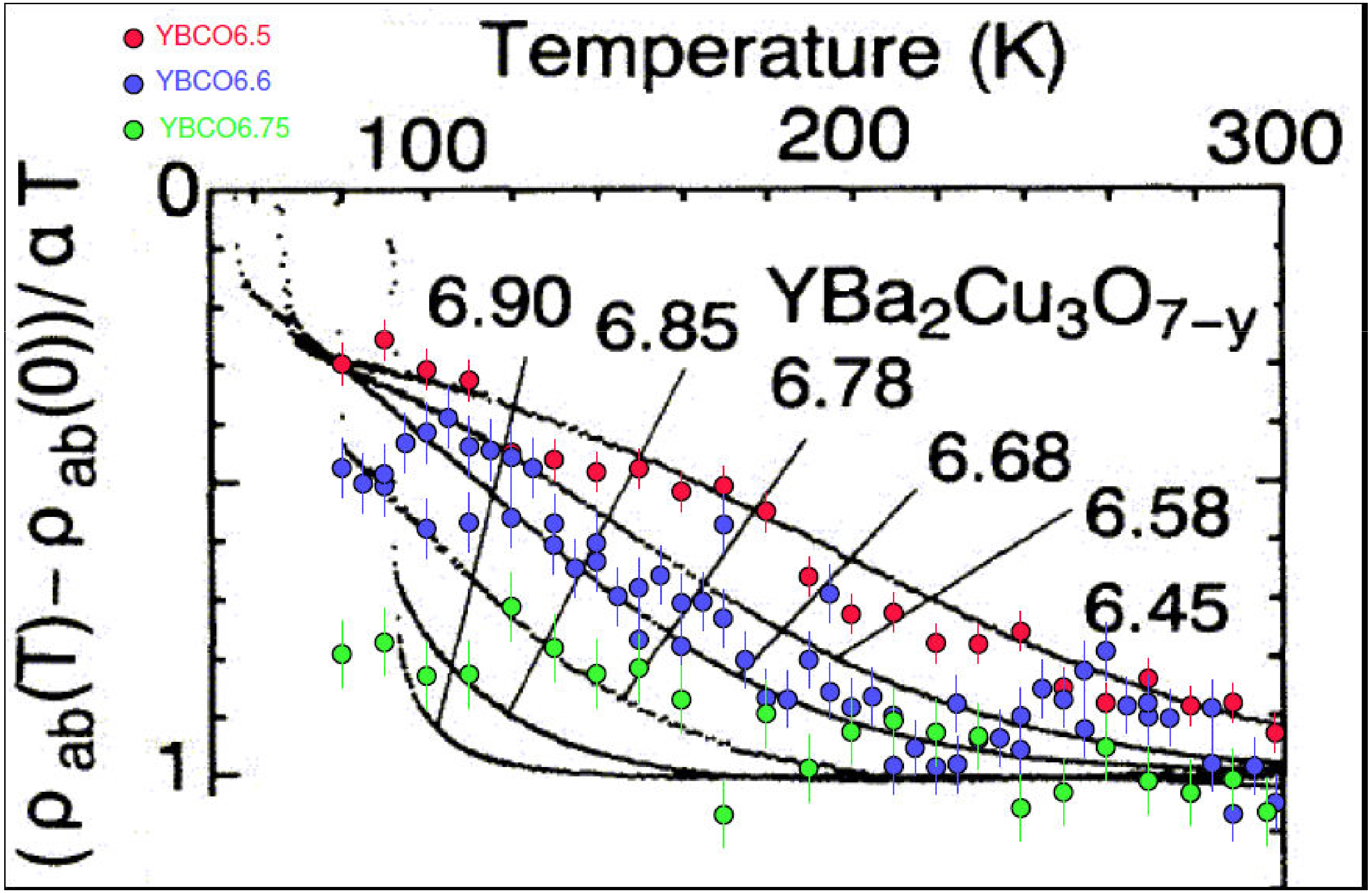
- Uniform magnetic susceptibility
B. Leridon et al EPL, 87, 17011, (2009)

- Resonant ultrasound spectroscopy
Arkady Shekhter

B. Fauqué et al, PRL 96 197001 (2006)
H.A. Mook et al, PRB 78 020506 (2008)

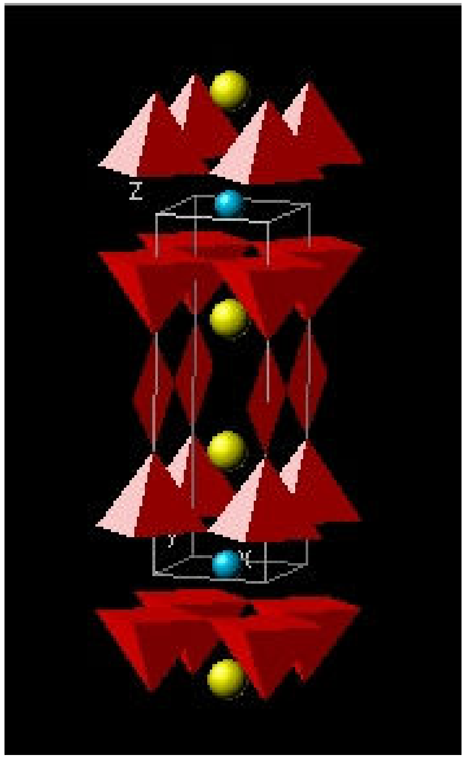
Comparison with resistivity

A single scaling factor with $|M|^2$ for all doping

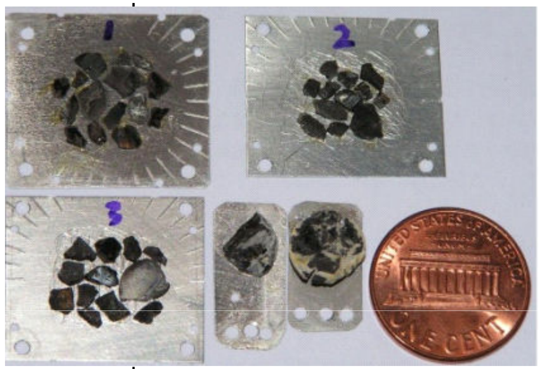


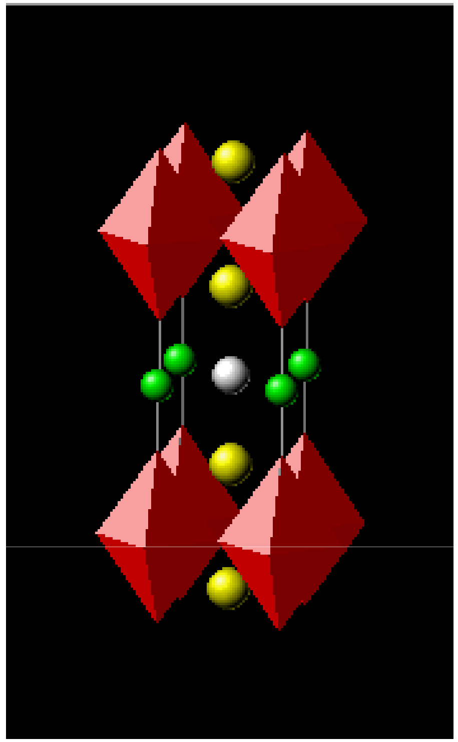
T. Ito et al PRL 70 (1993) 3995

From $YBa_2Cu_3O_{6+x}$ to $HgBa_2CuO_{4+x}$



- Orthorhombic
- 2 CuO_2 Planes
- distorded CuO_2 planes
- Cu-O pyramids





- Tetragonal
- 1 CuO_2 Plane
- Cu-O octaedra

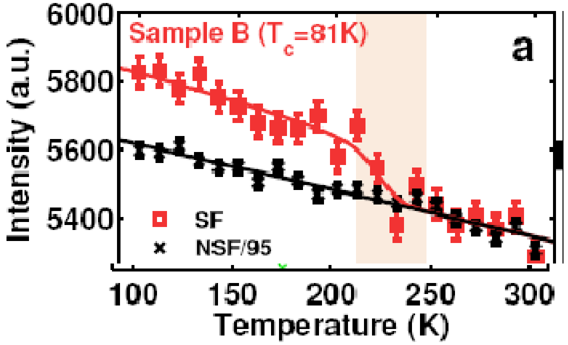
Breakthrough in single crystal synthesis in Hg1201:
mass ~ 1 g, M. Greven (Stanford/Univ Minnesota)
Zhao *et al.*, Adv. Materials, **18**, 3243 (2006).

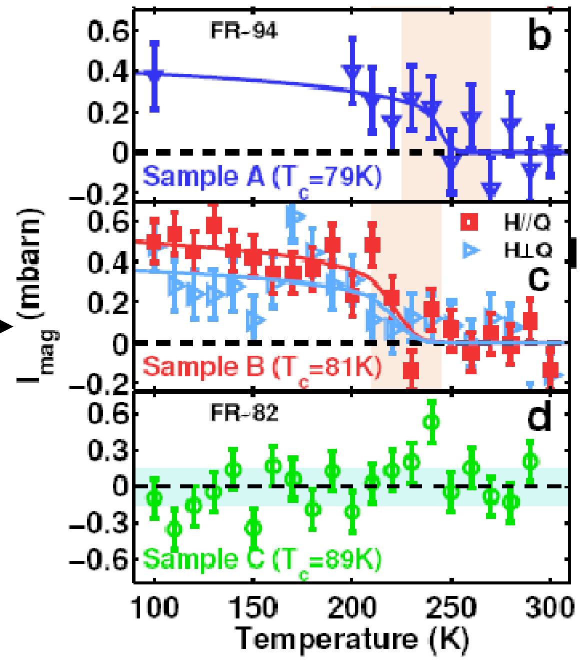
Polarized neutron results in Hg1201

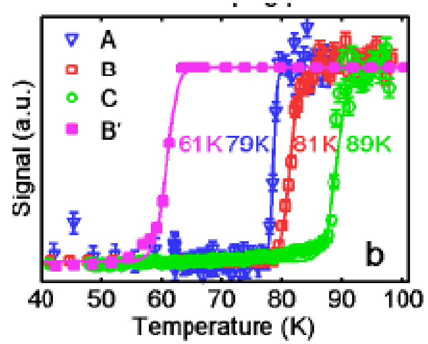
Yuan Li et al, Nature 455,372 (2008).

R> 90

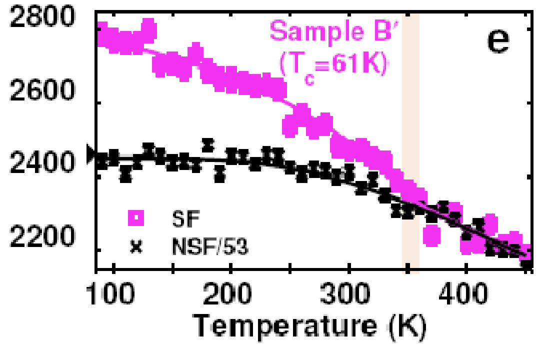
Q=(1,0,1)
P//Q

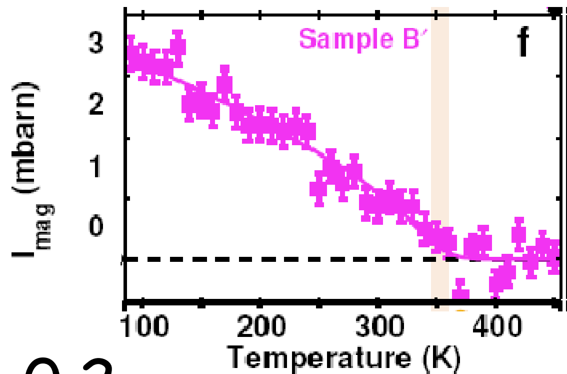




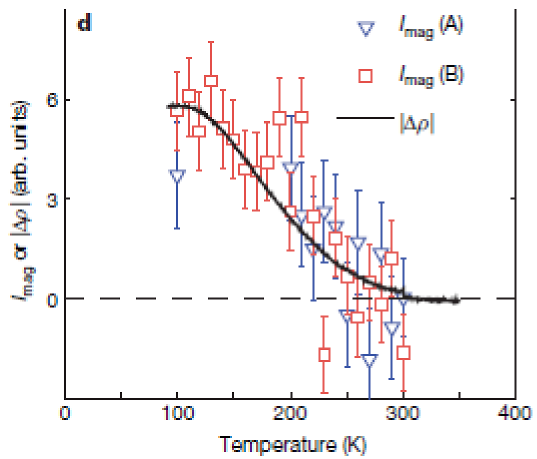


Comparison
Resistivity
$\Delta\rho$





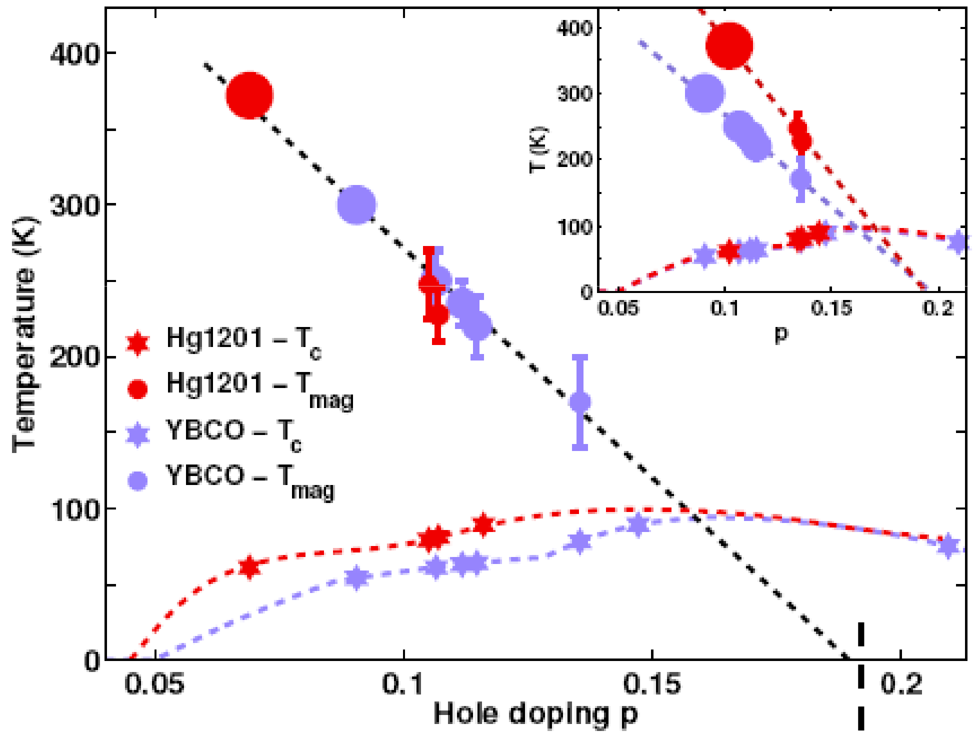
$m \sim 0.2\ \mu_B$



"Universal" phase diagram: from $YBa_2Cu_3O_{6+x}$ to $HgBa_2CuO_{4+x}$

B. Fauqué et al, PRL 96 197001 (2006)
H.A. Mook et al, PRB 78 020506 (2008)
Y. Li et al, Nature 455 372 (2008)

Q=0 AF Magnetic order at Tmag ~T*



	p	T_c (K)	T_{mag} (K)	I_{mag} (mb)
Y	0.091	54	300 ± 10	2.8 ± 0.3
Hg	0.069 (0.102)	61	372 ± 13	4.2 ± 0.3
Y	0.107	61	250 ± 20	1.7 ± 0.2
Y	0.112	63	235 ± 15	1.6 ± 0.2
Y	0.115	64	220 ± 20	1.5 ± 0.2
Y	0.135	78	170 ± 30	0.6 ± 0.1
Hg	0.105 (0.134)	79	248 ± 23	0.5 ± 0.1
Hg	0.107 (0.136)	81	228 ± 18	0.6 ± 0.1
Hg	0.116 (0.144)	89	N/A	< 0.15
Y	0.147	89	N/A	< 0.2
Y	0.209	75	N/A	< 0.1

T_{mag} -> 0 at p=0.19, expected end point of the pseudo-gap phase

NMR, Entropy, resistivity, ARPES….
Tallon and Loram, *Physica C* (2001,2004)

➔ *Quantum Critical Point*

Q=0 AFM, What are the implications ?

- Intra unit cell magnetism (2 antiparallel moments)

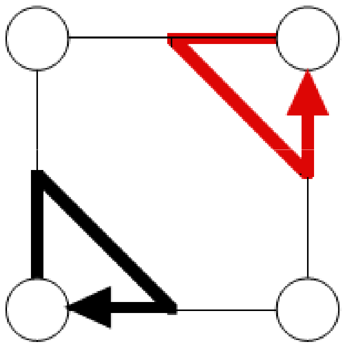
→ electronic nematicity by STM in Bi2212 M.J. Lawler et al Nature 2010

- Cu spins alone cannot account for this magnetic phase.
- One needs to reconsider the role of oxygens

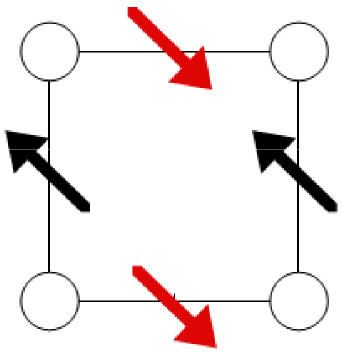
-Effective 1 band model → 3 bands Hubbard model

Seamus Davis talk

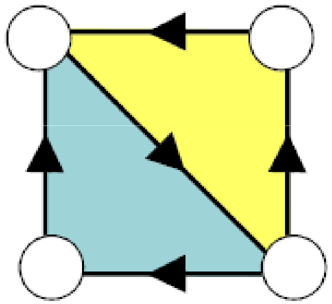
→ Orbital or spin magnetic moments ?



or



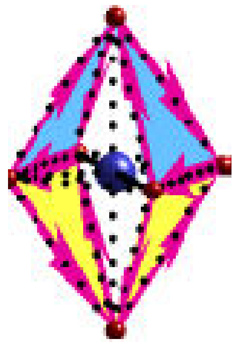
or even



Stanescu, Philipps PRB 69, 245104 (2002).

Chandra Varma talk

Spin moment on O sites (should have been detected by NMR.....)

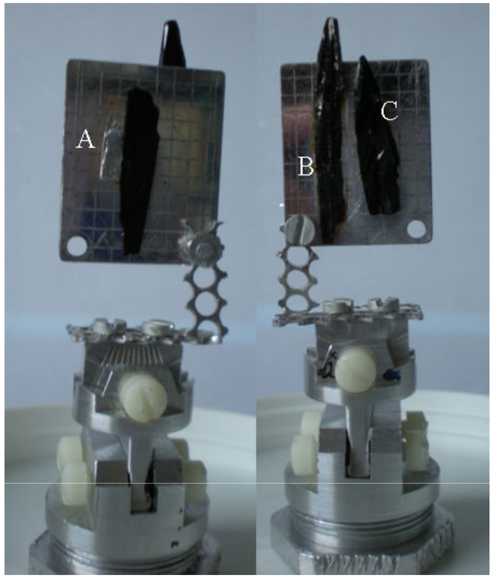


Quantum Monte-Carlo calculations

C. Weber et al, PRL 102, 017005 (2009).

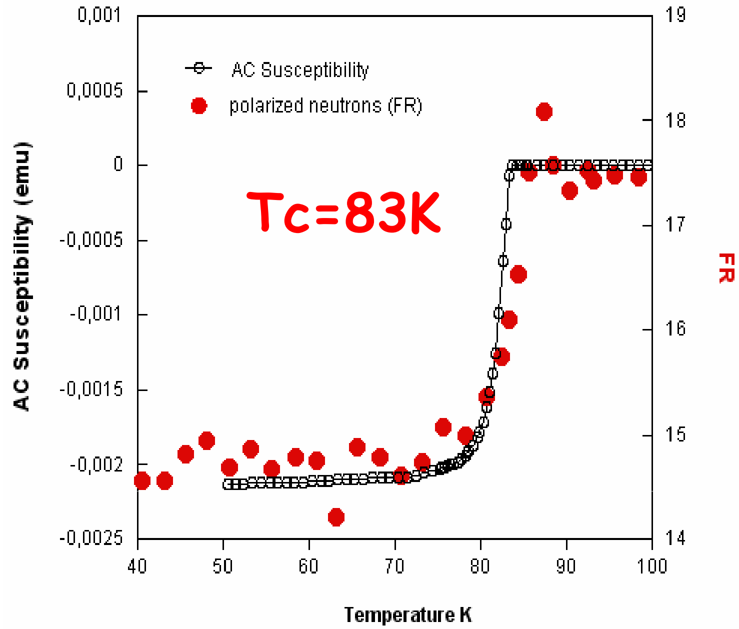
→ Angle (M,c*) ~ 45° .... Origin ?

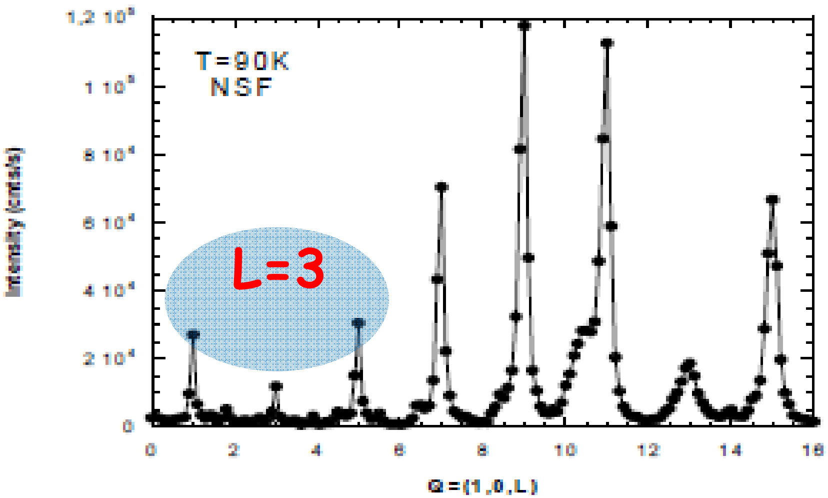
Preliminary results in $Bi_2Sr_2CaCu_2O_{8+\delta}$



Large single crystal growth

S. de Almeida
F. Giovanelli
I. Laffez
University of Tours (France)

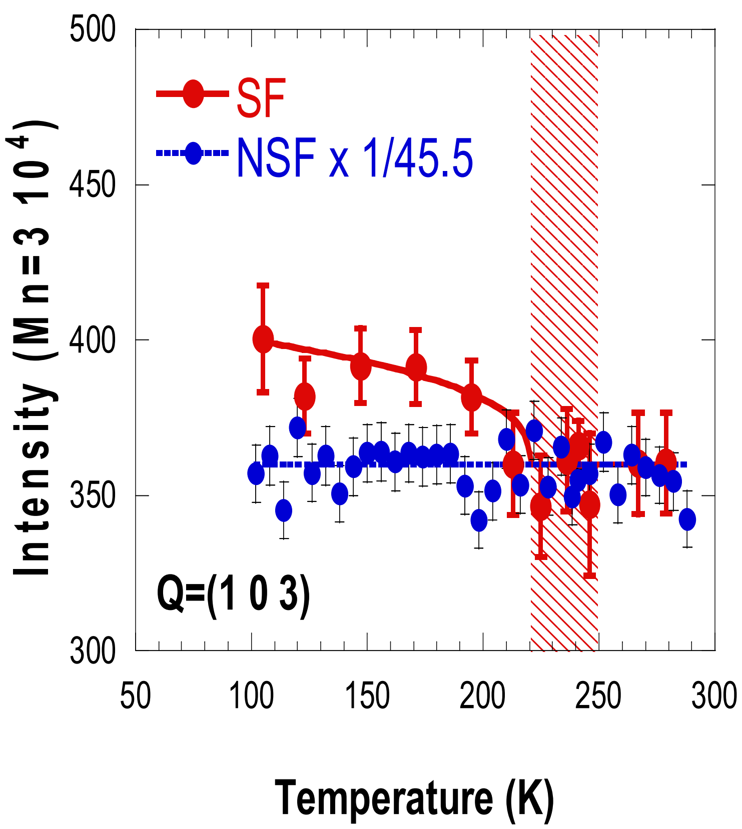


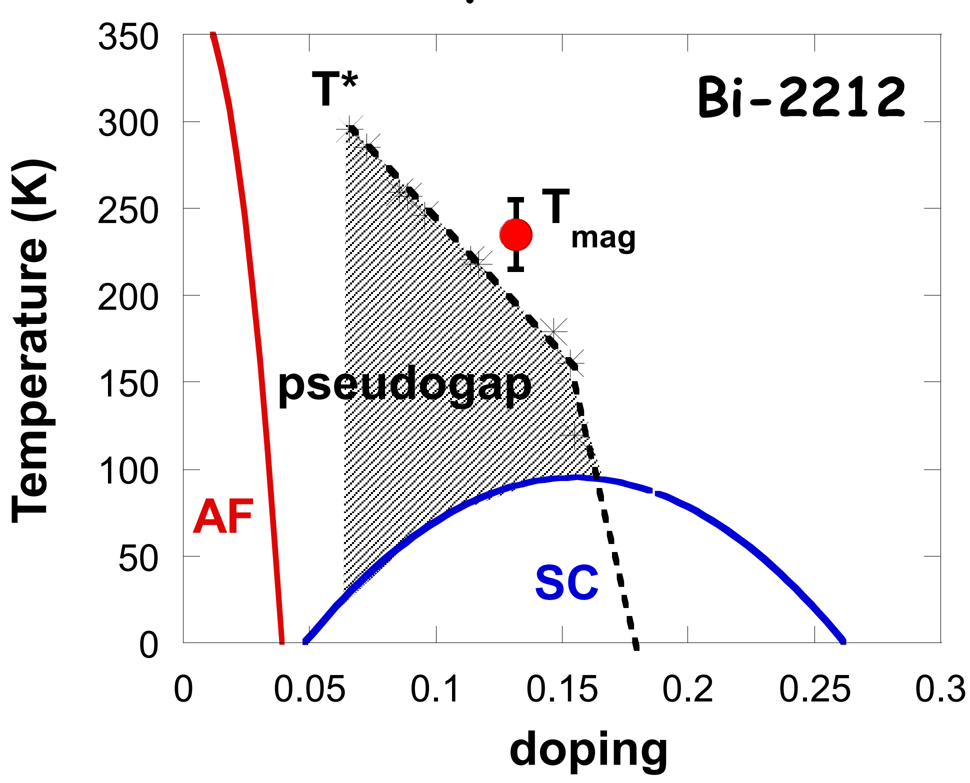


Annealed with $p(O_2)$=0.05 atm at 450°C

Bragg peaks at (10L) for L odd
(Tetragonal notations)
45 deg to the inc modulation

Q=0 AF Magnetic order in Bi-2212

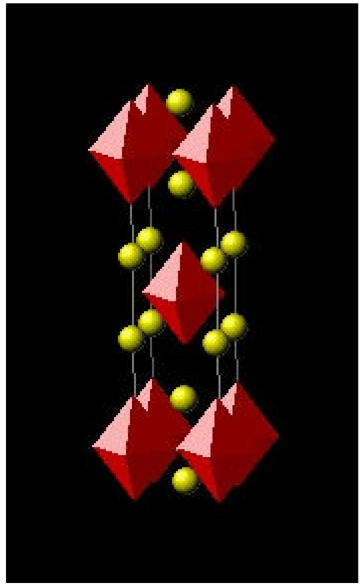


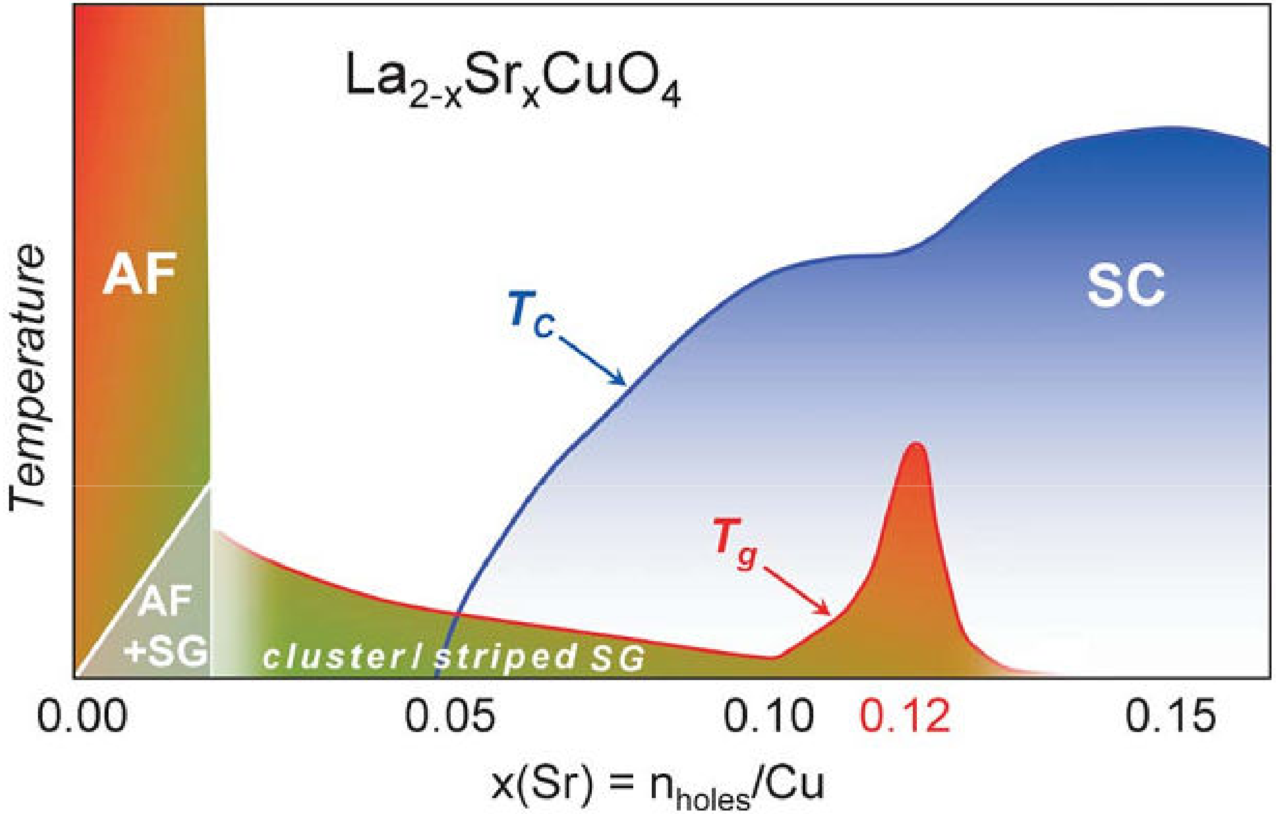


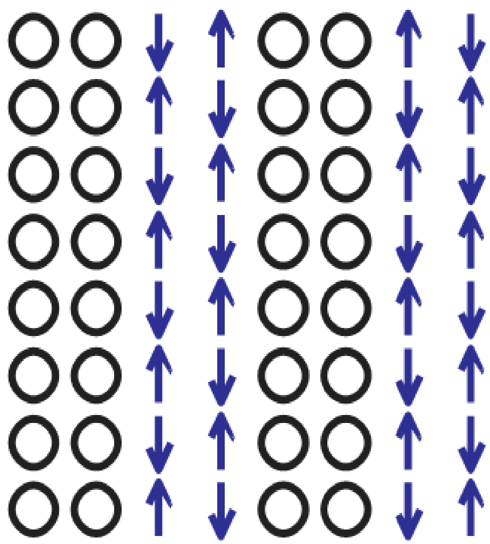
A. Kaminski et al, PRL, 90 207003 (2003)

LSCO case: Charge inhomogeneities: Stripes

Mitrovic et al, PRB 78 014504 (2008) *μSR, NMR,...*







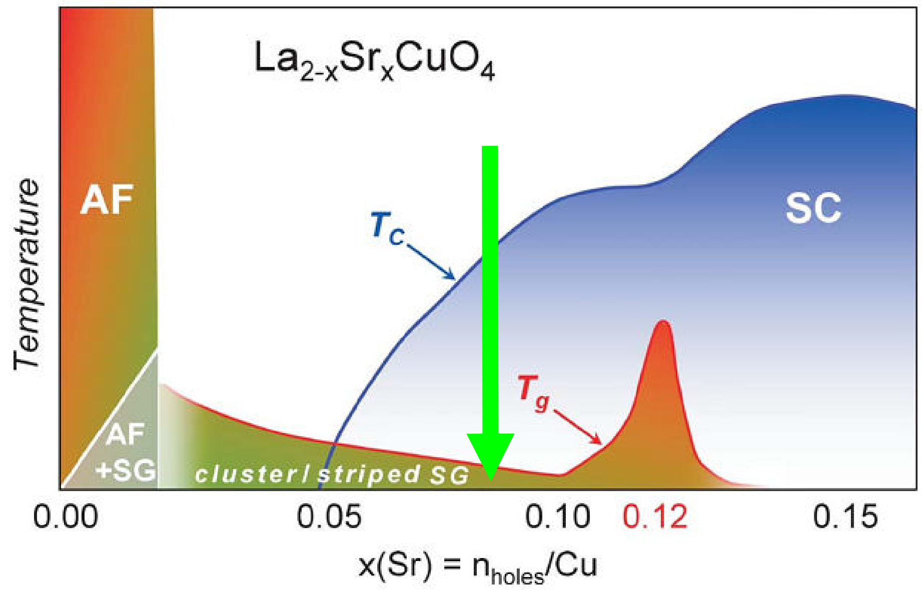
bond centered charge stripes

- Incommensurate AF fluctuations (Spin density wave)

  ➡ Fingerprint of dynamical stripes
- Static stripe phase for Nd co-doping or with Ba

Tranquada et al, Nature 1995, 2004

Lattice invariance and fourfold symmetry broken

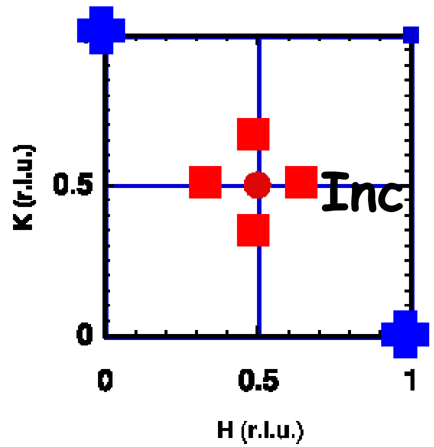


3 Samples (7 g) (from PSI, E. Pomjakushina)

co-aligned with x=0.085, Tc=22 K.

Tetragonal notations ➔

Orbital-like moments at Q=(10L)



Search for Static Q=0 AF order in $La_{1.915}Sr_{0.085}CuO_4$

Inverse Flipping Ratio : R^{-1}

(R^{-1}=SF/NSF)

Q=(1,0,1)

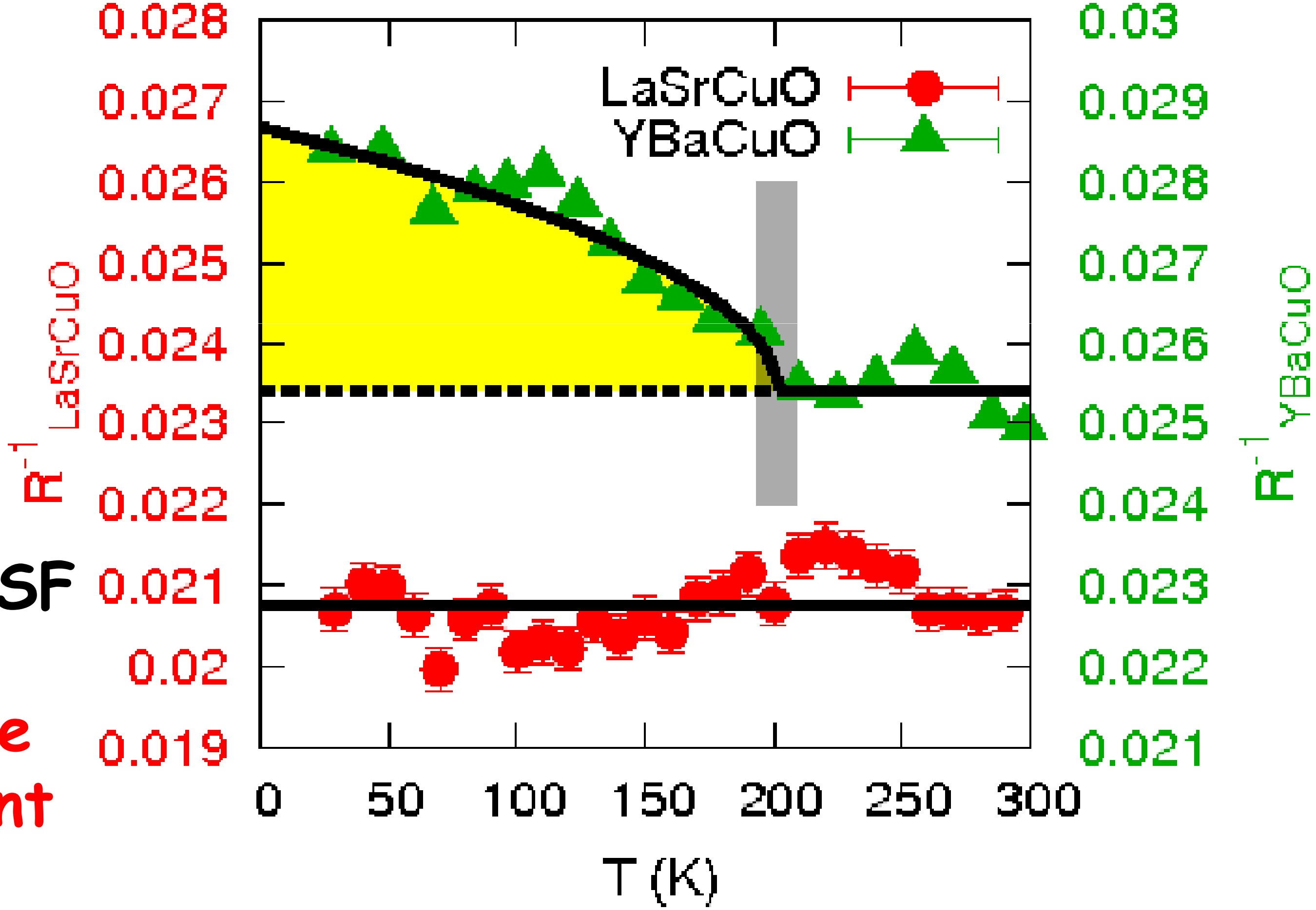
For **H//Q**

$R^{-1} = R_0^{-1} + M^2/NSF$

No Long Range ordered moment in LSCO

($M < 0.02\ \mu_B$)

YBCO6.6 from Fauqué et al, 2006

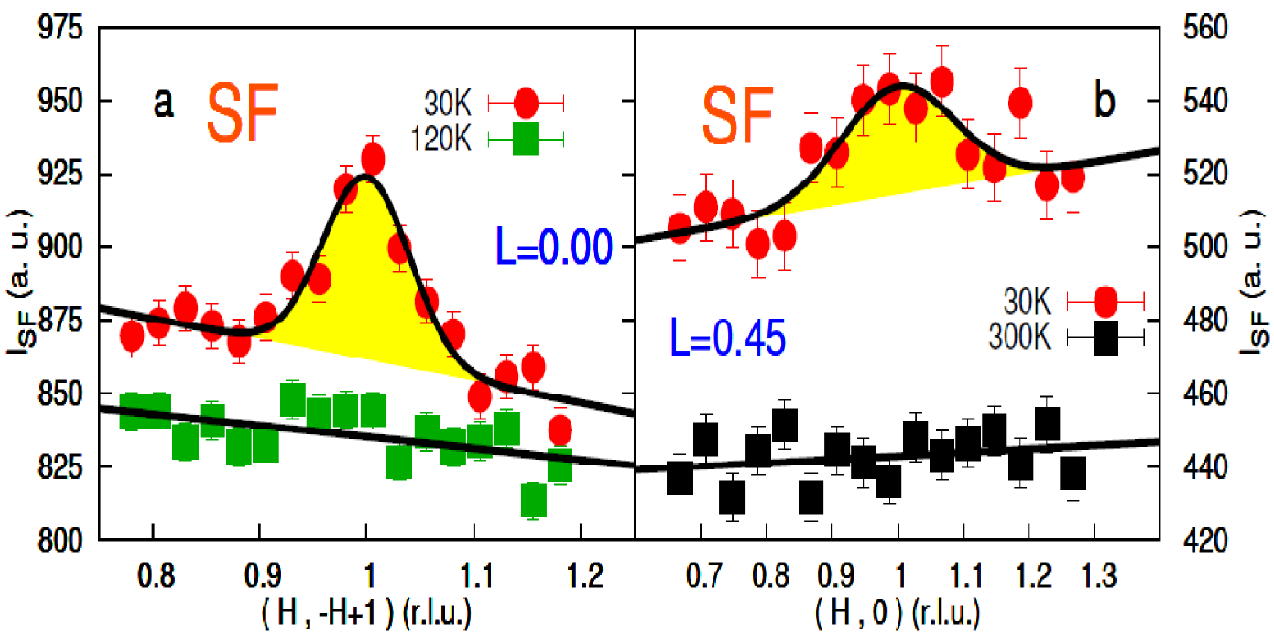


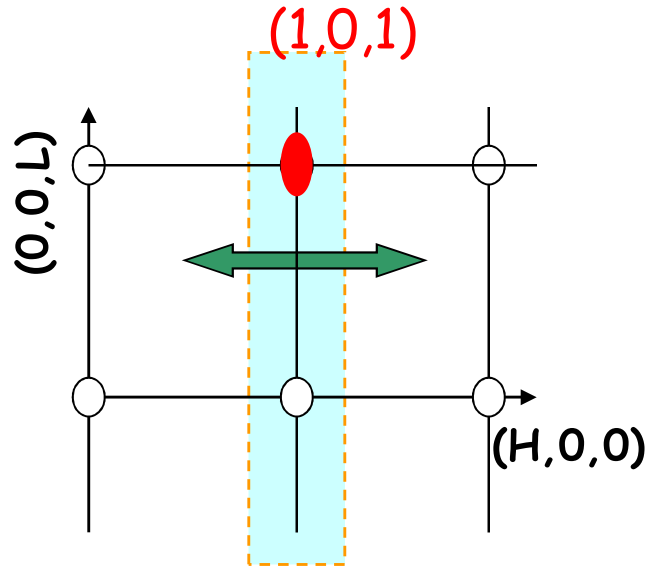
Bourges and Sidis, arXiv: 1101.1786

2D Short range magnetic correlations

$La_{1.915}Sr_{0.085}CuO_4$

Along 110 | Along 100





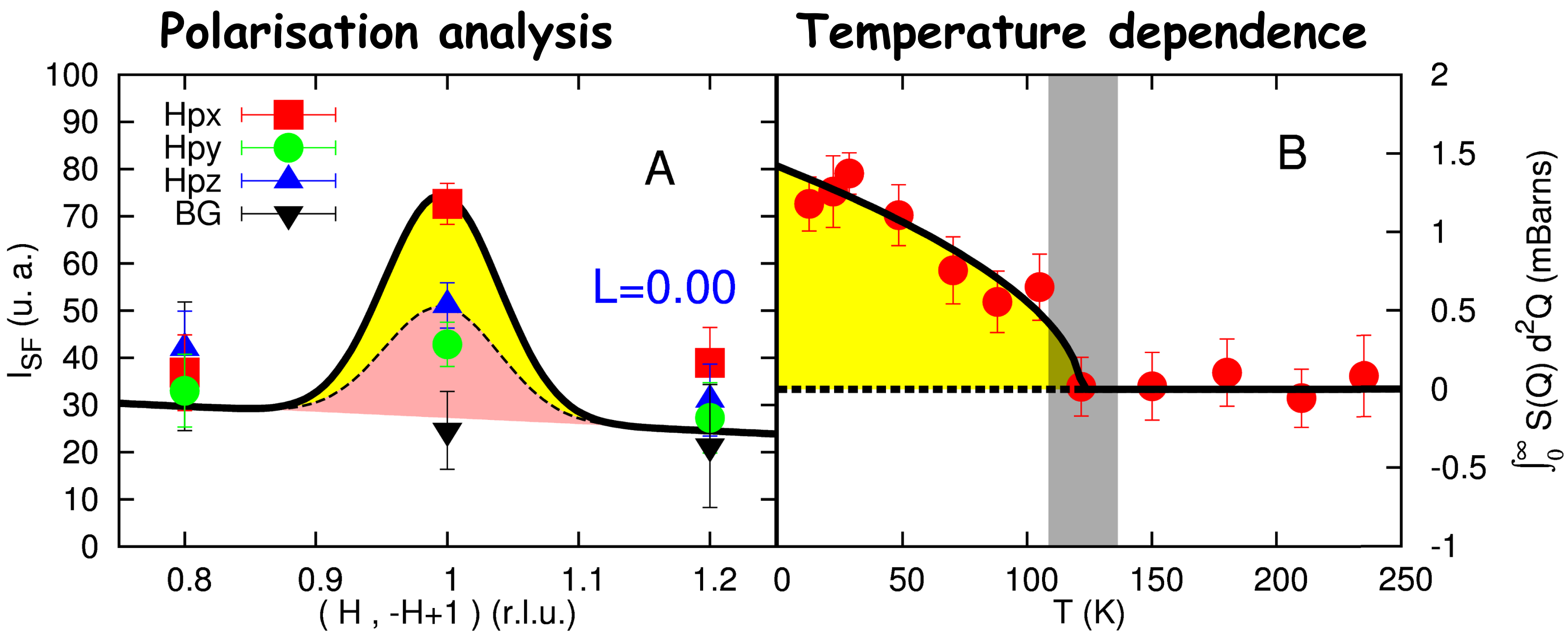
- 2D : Around Q=(1,0,L) any L
- Spin-flip
- H//Q
- No signal in NSF channel

In plane Correlations length: $\xi = 2/\Delta q$

$\xi_{110} \sim 11$ Å $\xi_{100} \sim 8$ Å

V. Balédent et al, PRL **105**, 027004 (2010)

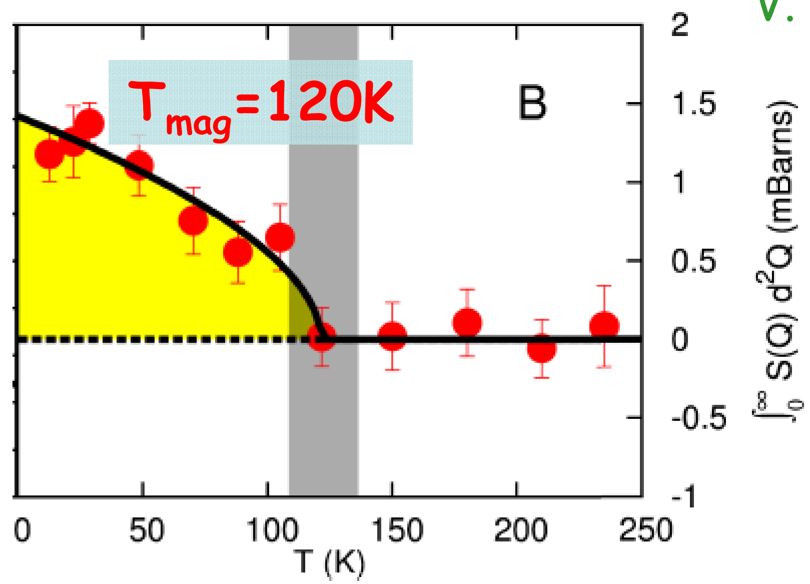
Polarization analysis and T-dependence : $La_{1.915}Sr_{0.085}CuO_4$



- T_{mag} ~ 120 K for 8.5% ➔ Lower than generally expected T*
- I(H//Q)=I(H//z)+I(H//y)
- I(H//z) ~ I(H//y) ➔ isotropic moments or angle (M,c*) ~ 45 deg
- Q-Integrated intensity (as Bragg scattering in $YBCO_{6.6}$)
  1.2 mbarns ➔ Local moment ~ 0.1 μ_B

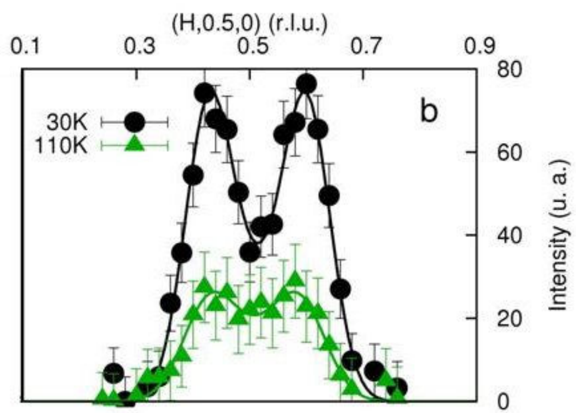
Temperature dependence of Q=0 AF order

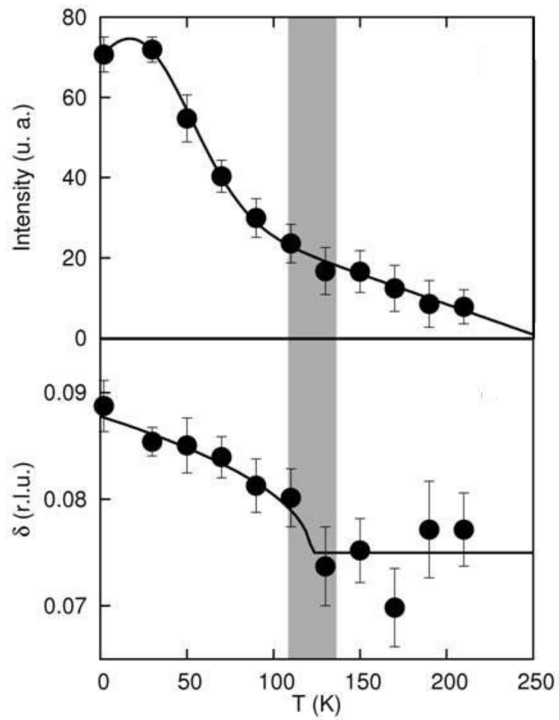
V. Balédent et al,PRL **105**, 027004 (2010)



interplay between the Q=0

AF order and IC fluctuations





Upturn of IC

intensity

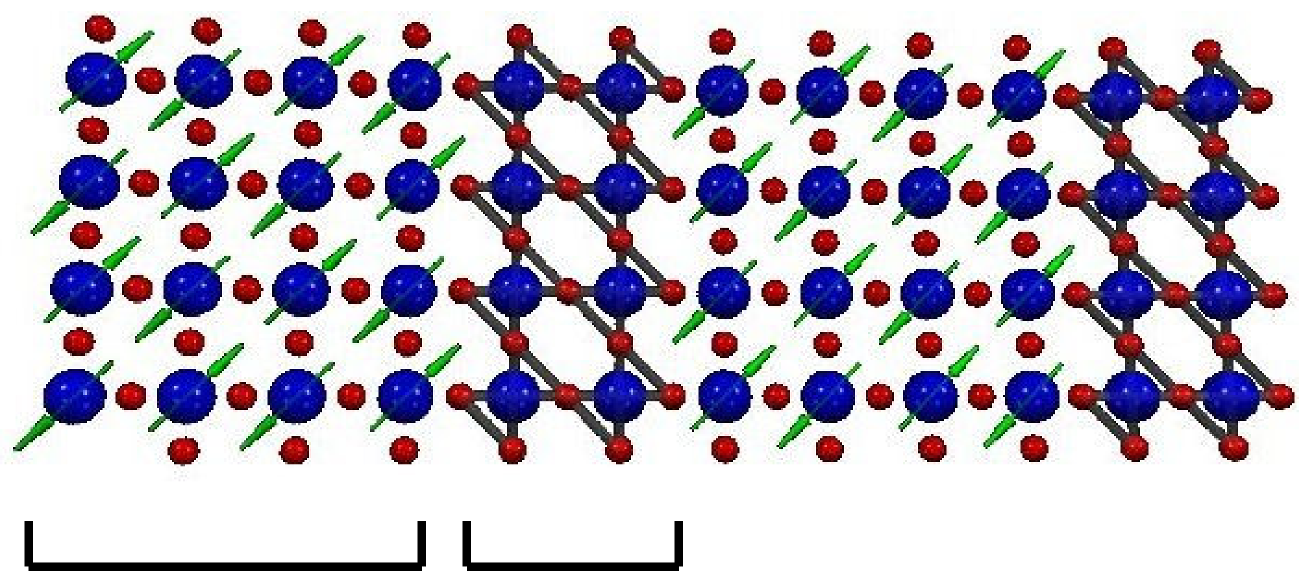
below T_{mag} ~120K

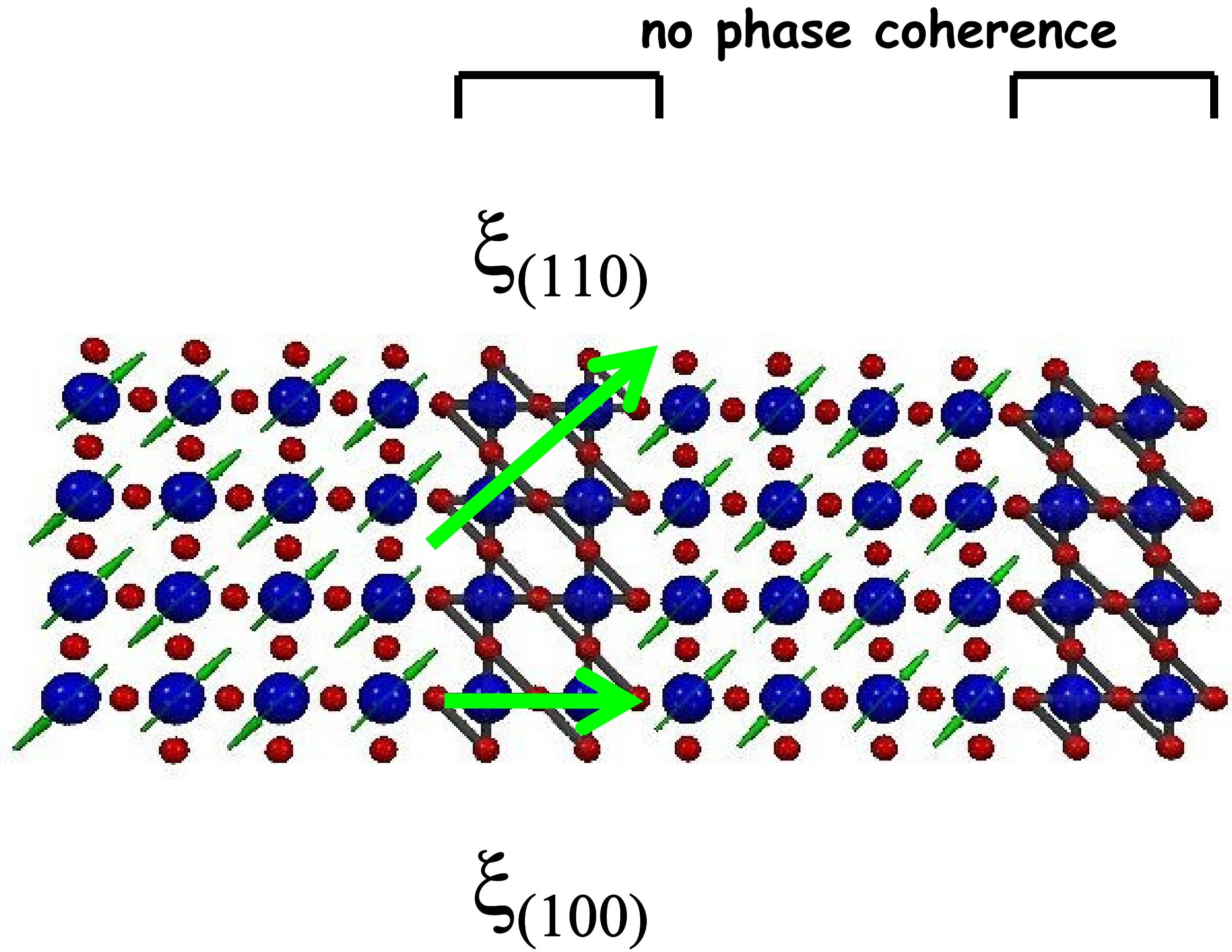
Unpolarized neutron E= 4 meV (2T-LLB)

Incommensurate magnetic fluctuations at $Q_{inc}=(1/2\pm\delta,1/2,0)$

Mixte phase ?

For x=0.085 ~ 1/12

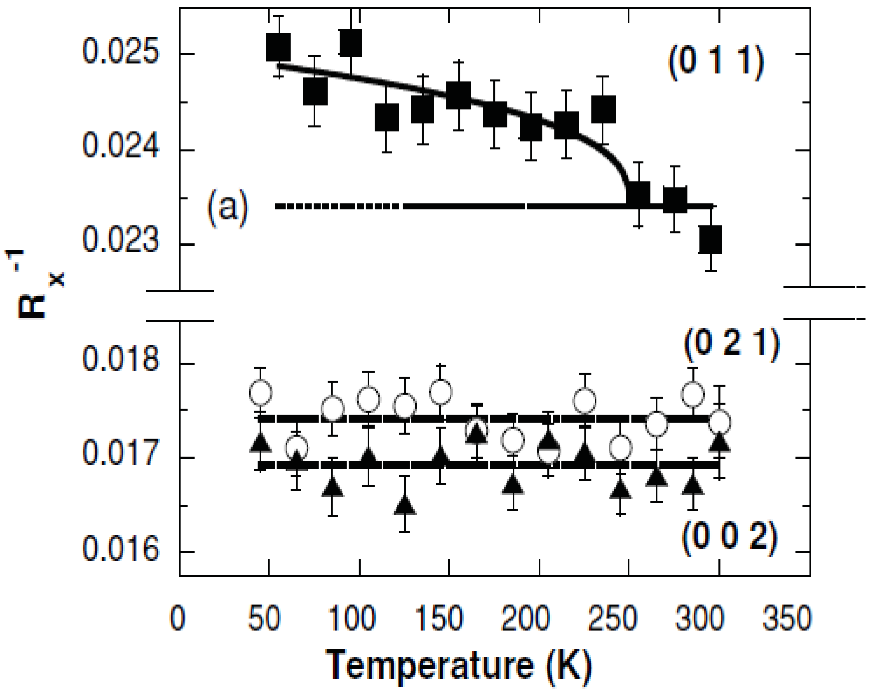



no phase coherence
$\xi_{(110)}$
$\xi_{(100)}$

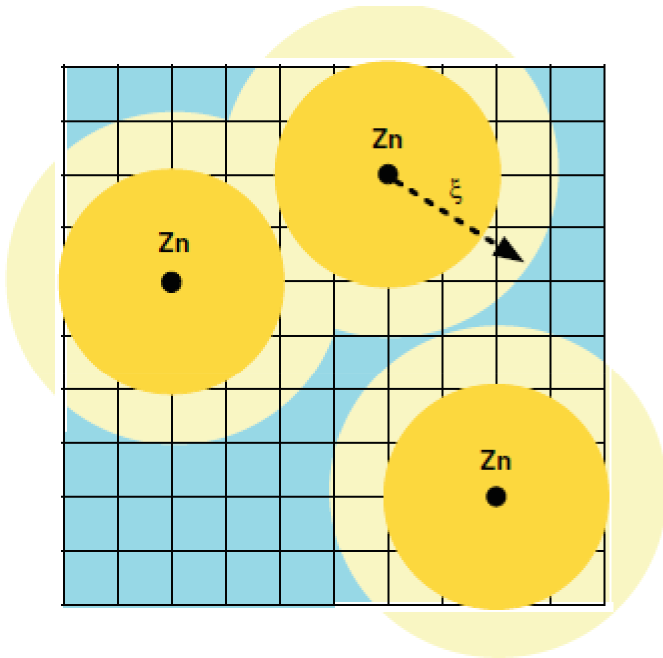
Zn(2%)-$YBa_2Cu_3O_{6.6}$: Tc = 30 K

Zn known not to change T* (NMR Knigh shift, Alloul et al, 1993)

1/Flipping Ratio=R^{-1}=SF/NSF = R_0^{-1} +M^2/NSF



Same Tmag but weaker intensity



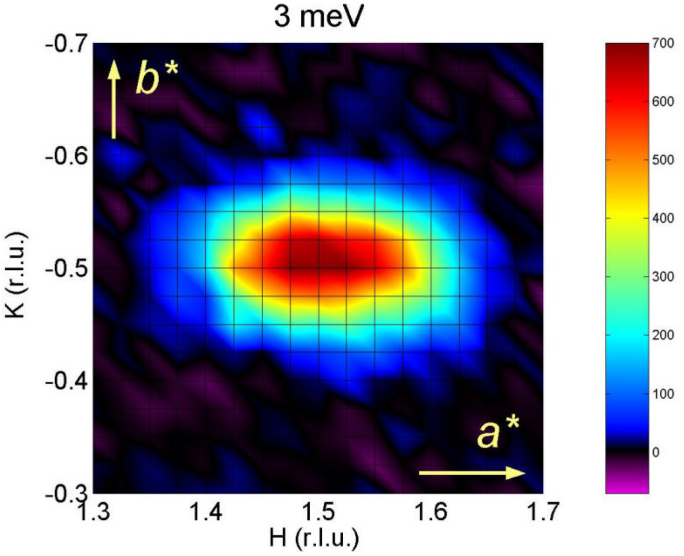
Swiss cheese model

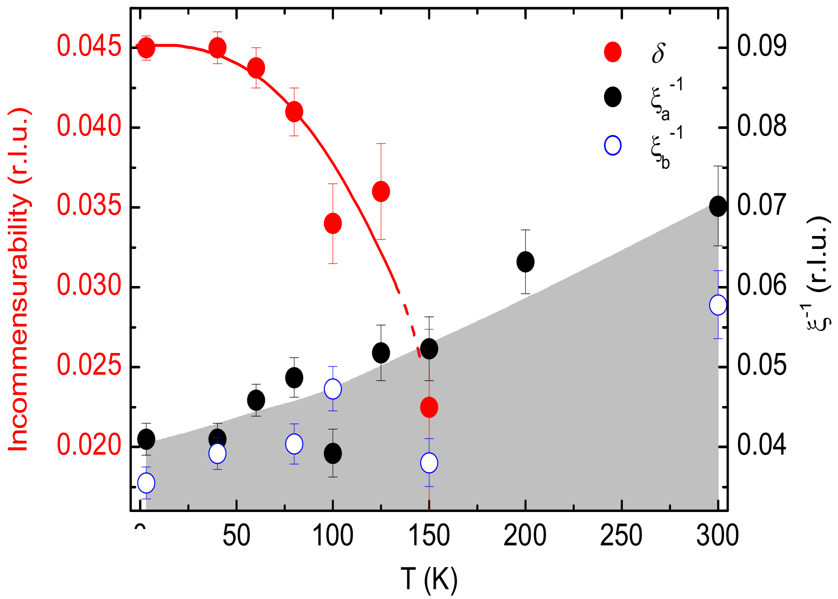
V. Balédent et al., *PRB* 83, 104504 (2011).

Zn induces low energy incommensurate spin excitations near (π,π)

V. Suchaneck et al., PRL, 105, 037207 (2010).

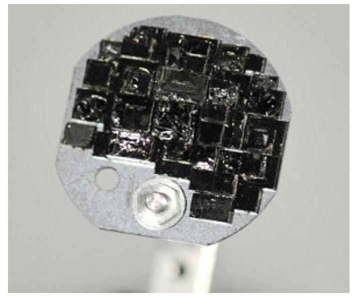
Detwinned $YBa_2Cu_3O_{6.45}$



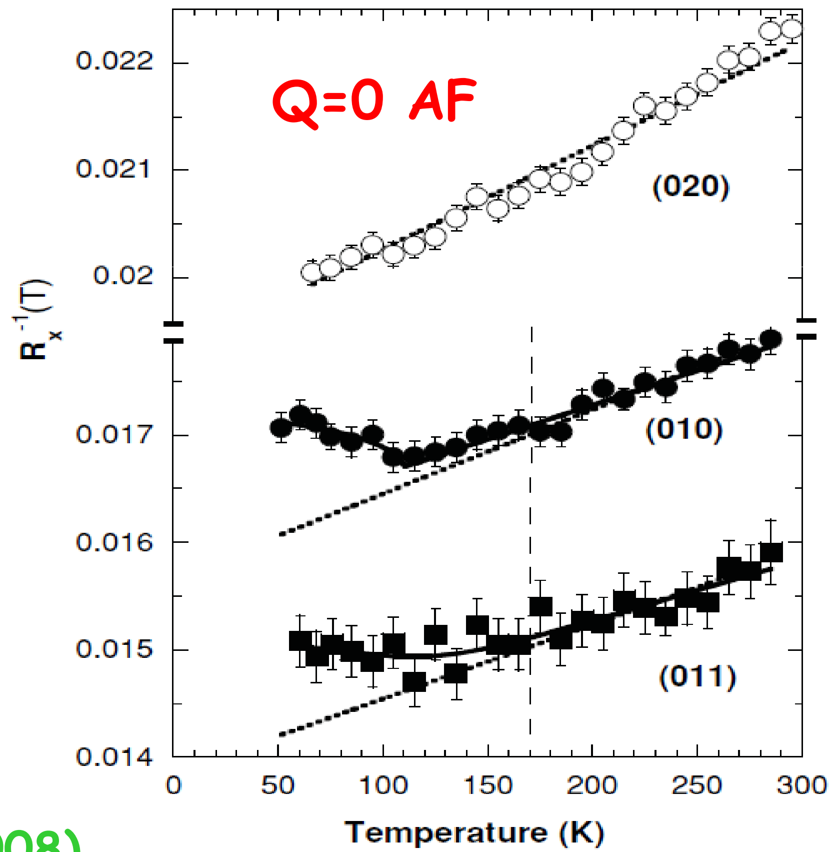


T_C =35K, Hole doping= 0.085

(D. Haug, MPI Stuttgart)



R^{-1}=SF/NSF = R_0^{-1} +M^2/NSF



Hinkov et al., *Science* 319, 597 (2008).

⇒ Electronic nematic liquid state (ELC)

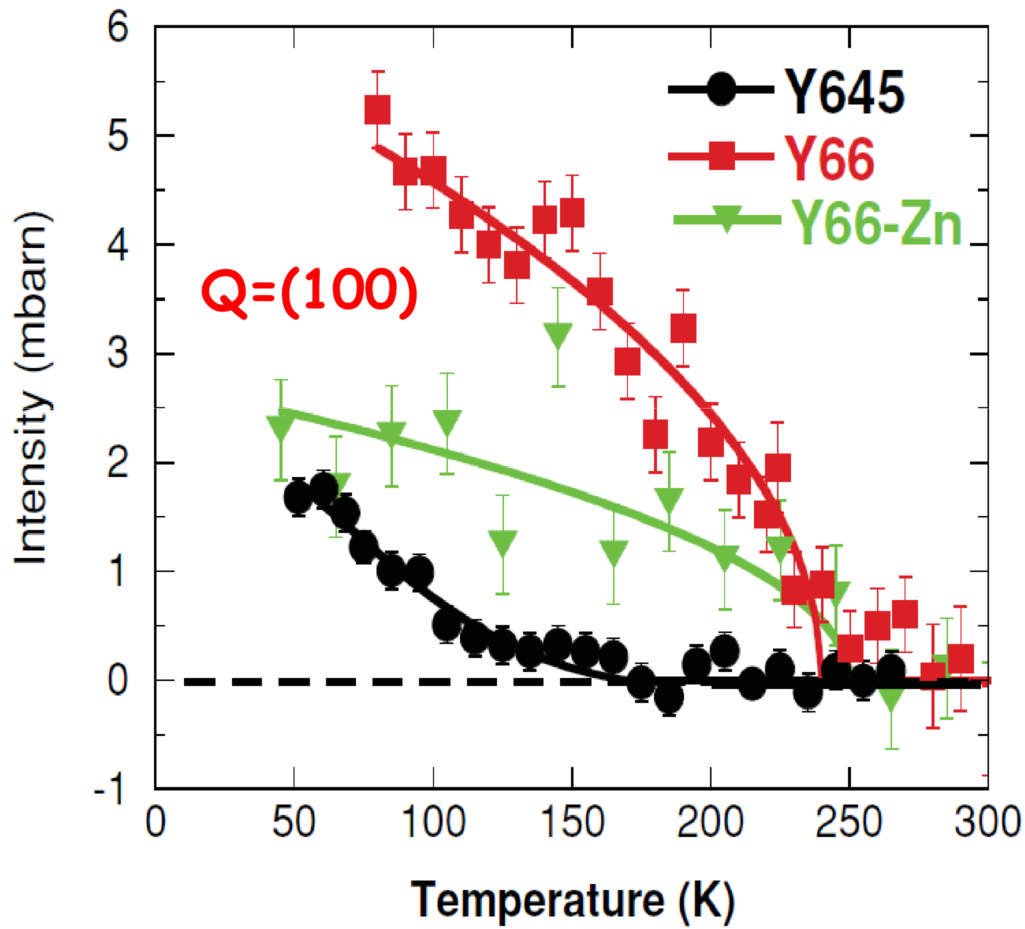
Comparaison Q=0 AF Bragg peak intensity in YBCO

V. Baledent et al., *PRB* 83, 104504 (2011).

Near 9%
Tmag decreases with doping

whereas

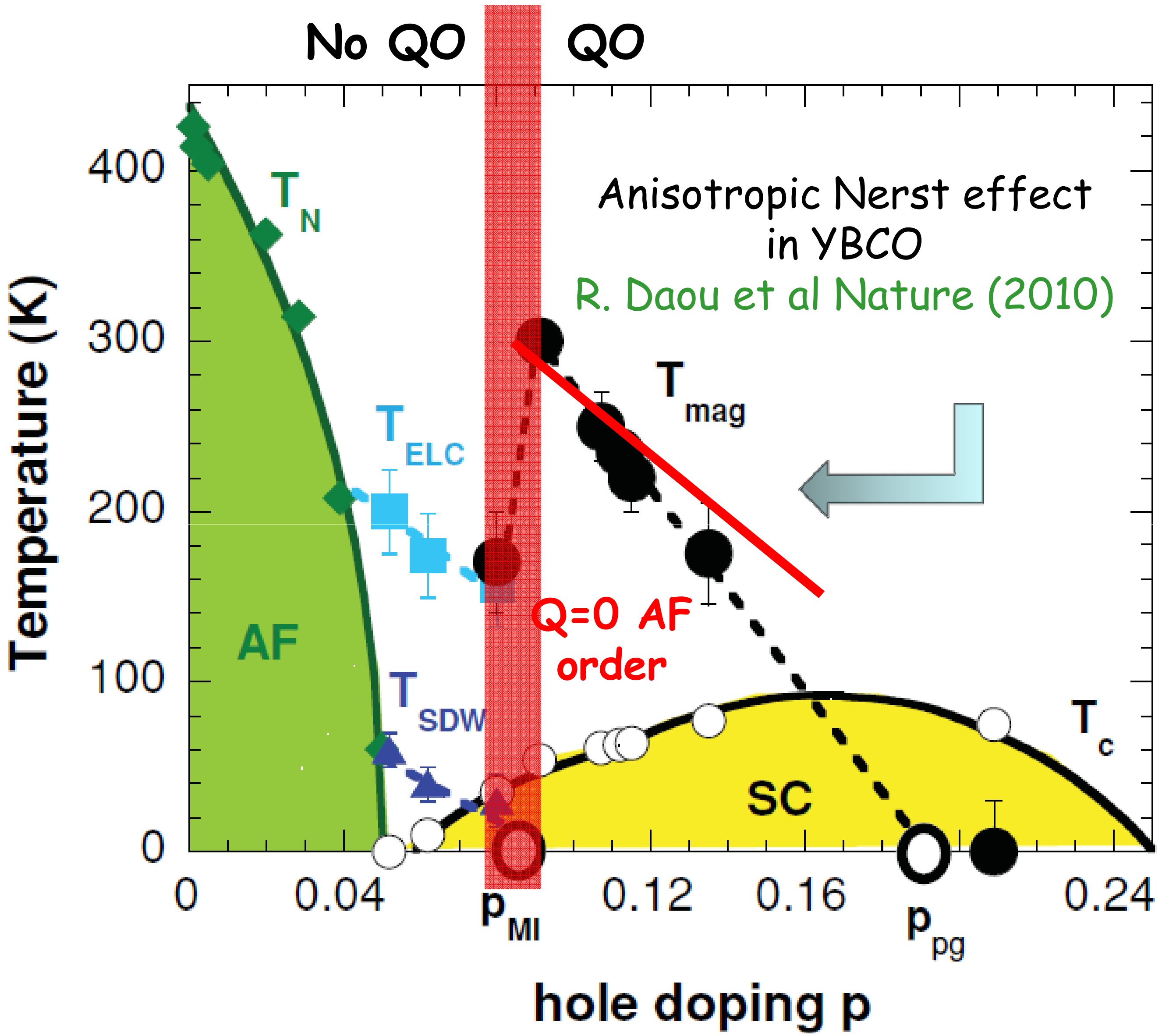
It is generally assumed that T* increases
(No compelling evidence that this is correct for T* above Room Temperature)



IN YBCO6.45

Q=0 AF order develops close to T_{mag} ~150K ~ $T_{nematic}$

YBCO: Updated Phase diagram



V. Baledent et al., *PRB* 83, 104504 (2011).

Conclusions:

- *Technique: Polarized neutron diffraction*
- *Result: Magnetic order in the pseudogap state of high-*Tc *cuprates* in 4 different families: YBCO, Hg1201, LSCO,Bi2212
- Implication: There is a broken symmetry below T* which does not break the translation symmetry but breaks Time reversal symmetry

Bourges and Sidis, arXiv: 1101.1786

⇒ Hidden order parameter of the pseudogap phase having the symmetry proposed for the loop current order
(talk Chandra Varma)

⇒ There are associated specific magnetic excitations
(next talk, Yuan Li)