Q=0 Magnetic order in the pseudogap state of cuprates superconductors

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Using polarized neutron diffraction: 4F1 (LLB-Saclay) & D7 (ILL-Grenoble)

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

There is a broken symmetry below T* which does not break the translation symmetry (Q=0) but breaks Time reversal symmetry

Intra unit cell antiferromagnetism (2 antiparallel moments)
Local Cu spins not enough ➔ another source of magnetism

Outline:

1) *Introduction*
2) *Short range correlations near optimal doping*
3) *Tilt of the moment: In-plane and out-of-plane Magnetic components*
4) *Phase diagrams: Q=0 magnetic order in the pseudogap state, CDW and nematic order*

Pseudo-Gap

- Mysterious phase which appears below T*
- Anomalous magnetic and charge properties

Common line at T*

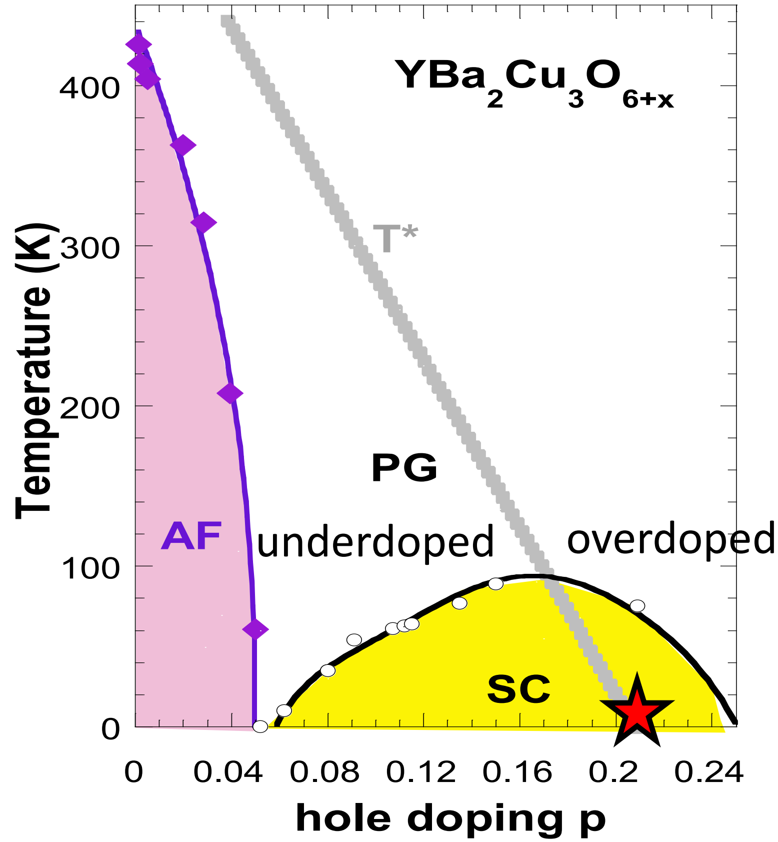
(Tallon & Loram)

Phase transition?

Which broken symmetry?

Heavy fluctuations around QCP

Superconducting mechanism?

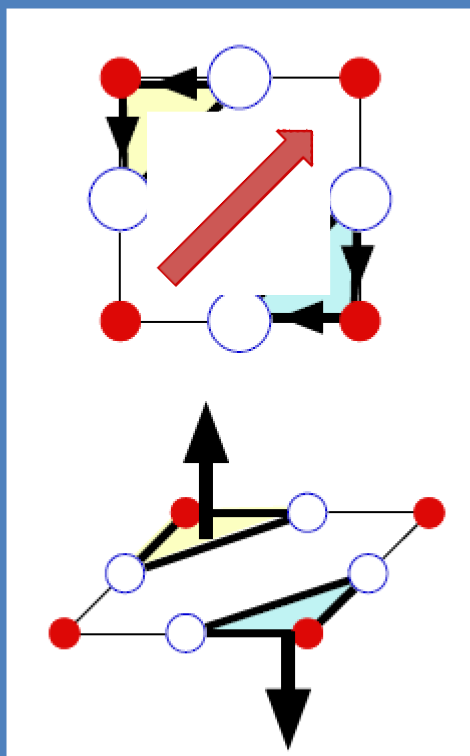


Quantum critical point

Motivation: CC-loop order, Intra-unit-cell magnetic order

C.M. Varma, PRB 1997; PRB 2006

Breaks Time-reversal symmetry



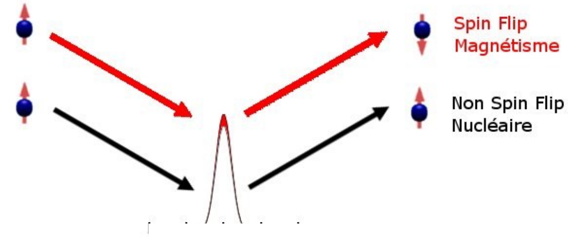
Toroidal moment

Staggered orbital moments

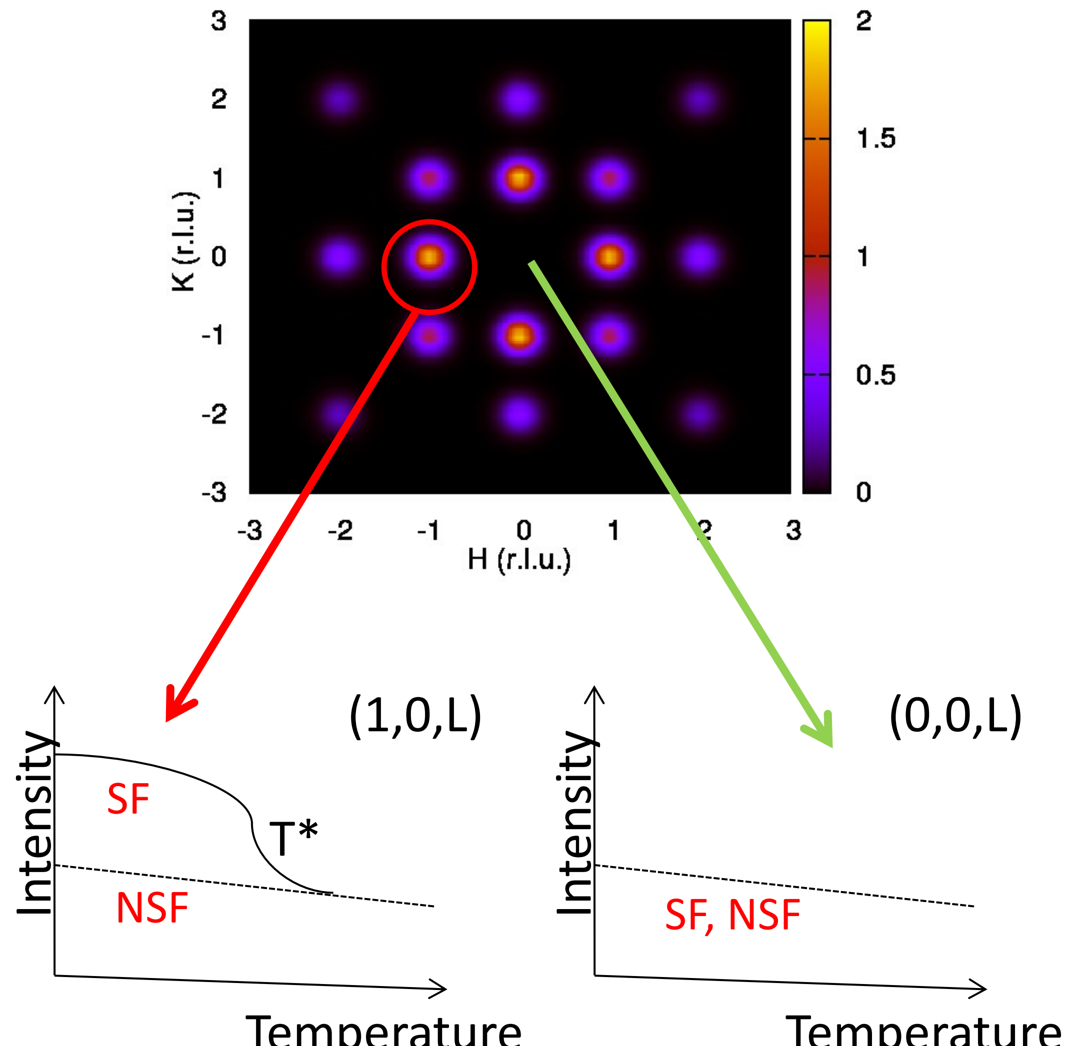
Q=0 AFM order

4 States/Domains

What are we looking for ?



Spin polarized neutron diffraction technique



Need for a polarized monochromatic neutron beam

• Nuclear Scattering

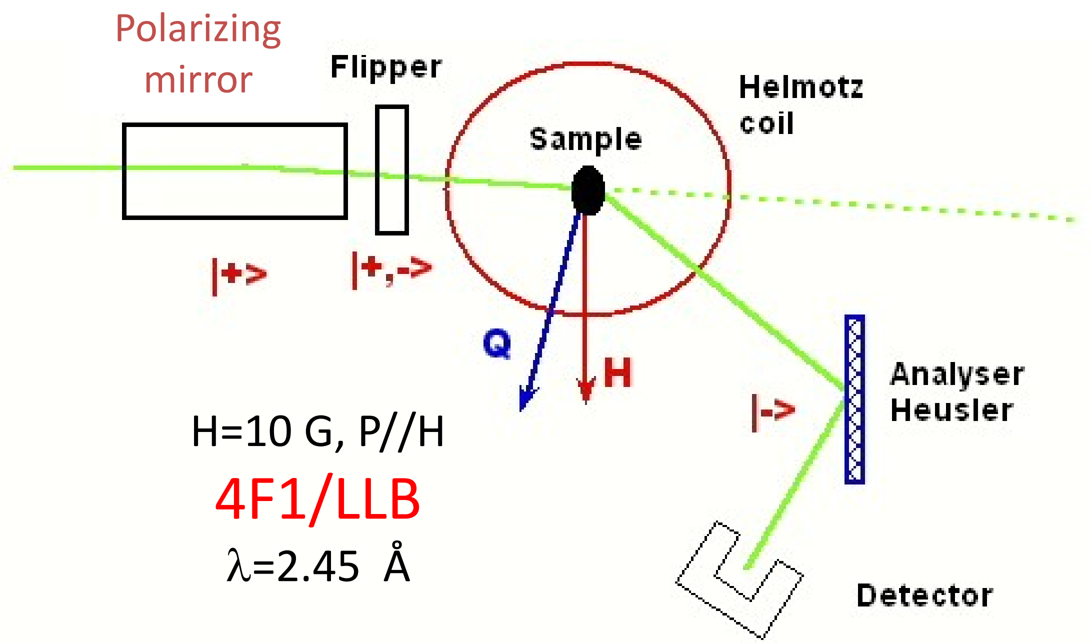
Non spin flip: $<-|F_N|->$

* Magnetic Scattering

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

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

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



Magnetic components $\perp \vec{Q}$

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

Flipping ratio:

$R = NSF/SF = I^-/I^+$ ($R \sim 50$)

P//Q to maximize magnetism in the Spin-flip channel

Neutron polarization:

$p = (I^- - I^+)/(I^- + I^+) \sim 96\%$

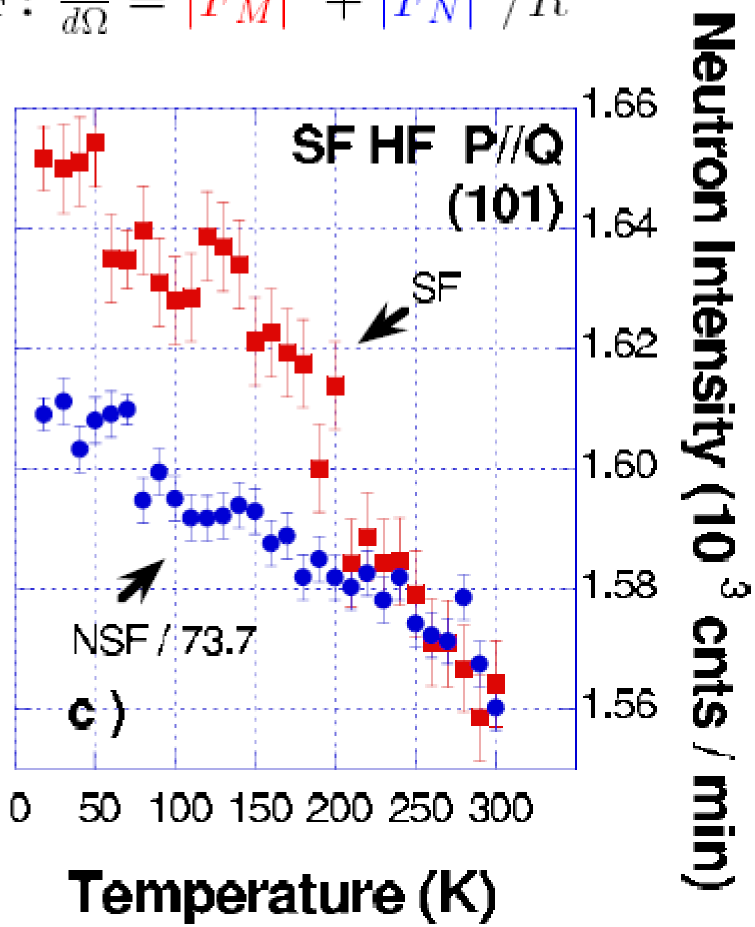
$$\textbf{NSF:}\ \frac{d\sigma}{d\Omega} = |F_N|^2$$

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

Underdoped $YBCO_{6.6}$: Long range Intra unit Cell magnetic order

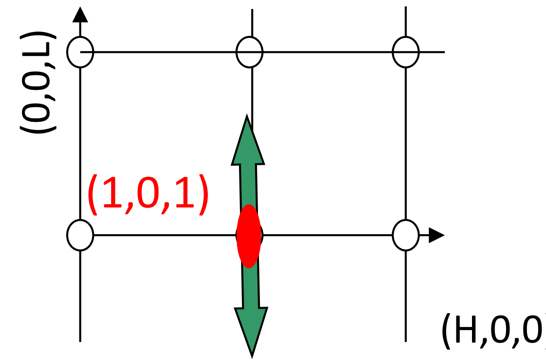
$$\text{NSF:}\ \frac{d\sigma}{d\Omega} = |F_N|^2$$

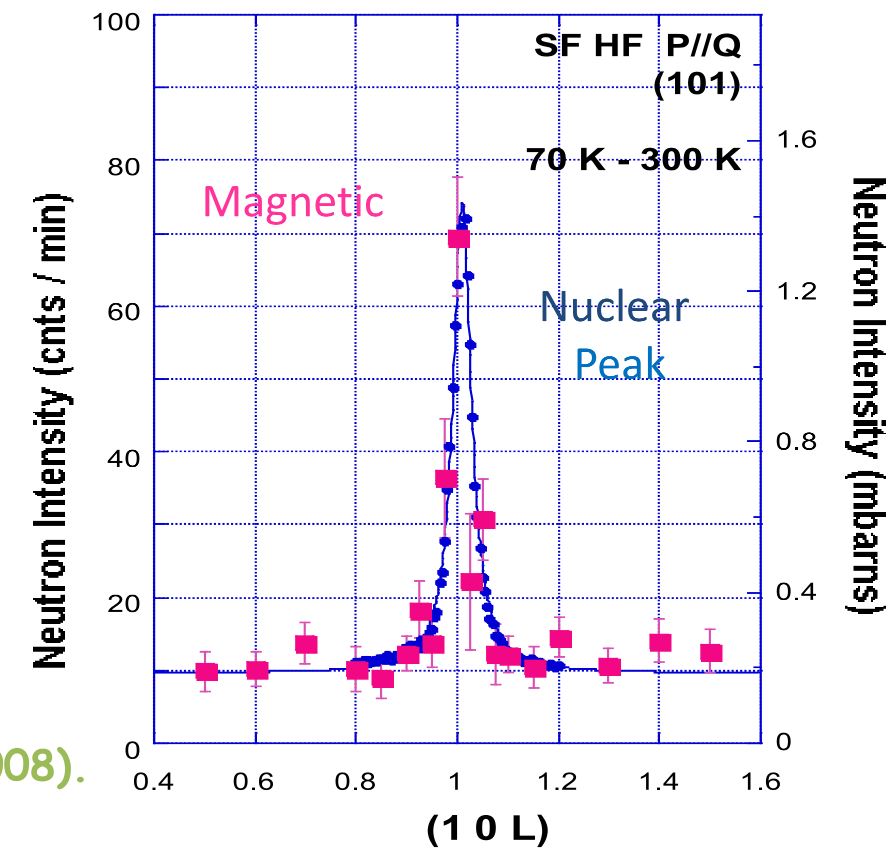
$$\text{SF:}\ \frac{d\sigma}{d\Omega} = |F_M|^2 + |F_N|^2/R$$



L-scan

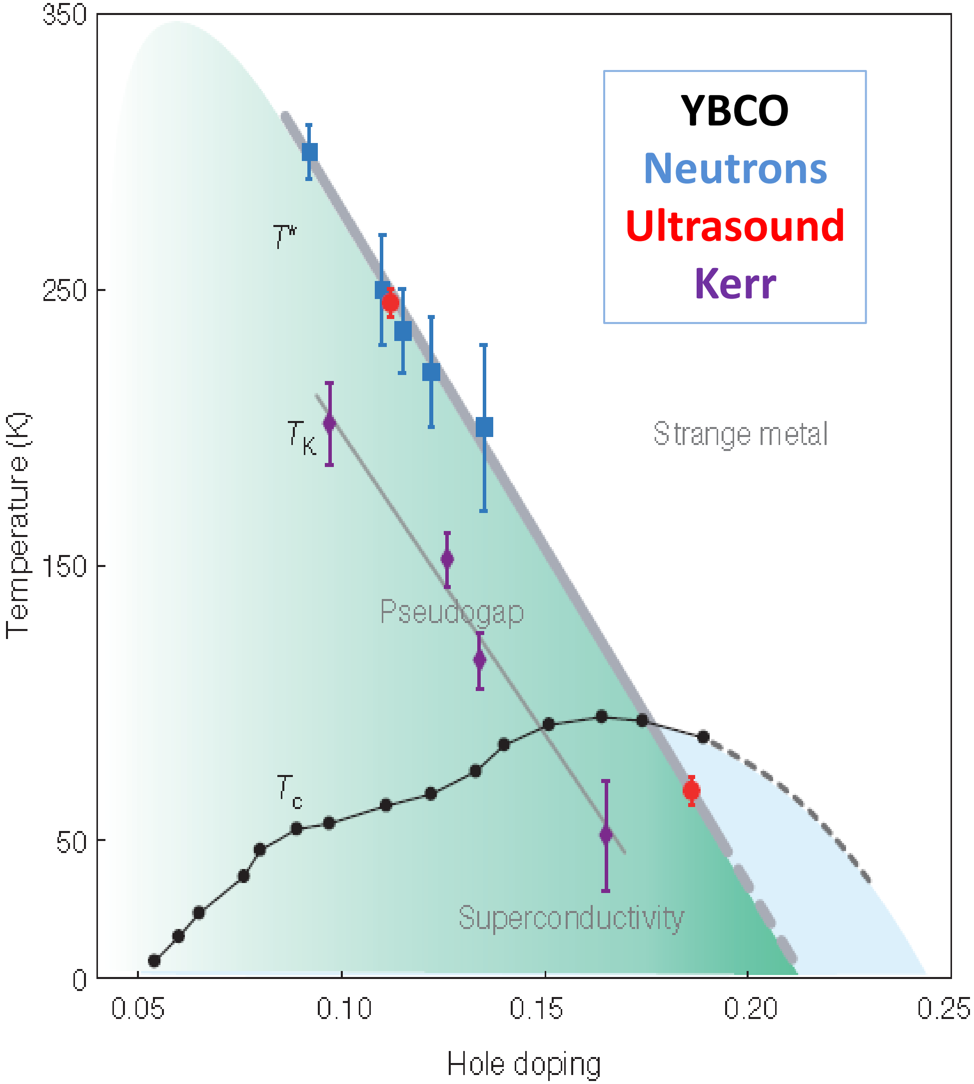
(ξ_c >75 Å)





H.A. Mook et al, PRB 78 020506(R) (2008).
see also B. Fauqué et al, PRL (2006).

Order in the PG state (match T* resistivity)



Other reports of a phase transition at T* in YBCO :

- Resonant ultrasound spectroscopy
  A. Shekhter, et al, Nature,497, 75 (2013)

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

- Optical birefringence
  Y. Lubashevsky, Phys. Rev. Lett. 112, 147001, (2014)

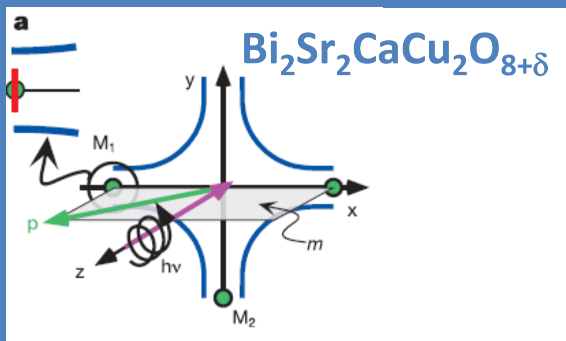
- Polar Kerr effect (μrad) at T_K
  J. Xia, et al, PRL, 100, 127002 (2008)

Intra-unit cell nematicity by STM in Bi2212
M.J. Lawler et al Nature 2010
different electronic density on both oxygens: Ox and Oy

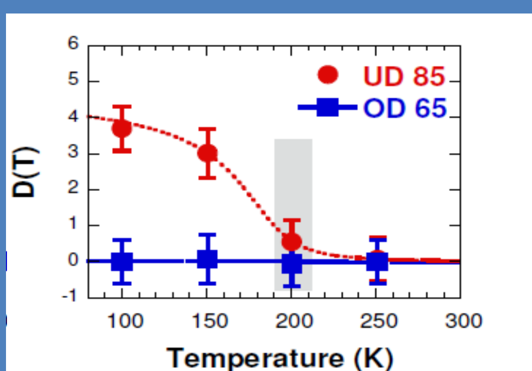
➔ No evidence in magnetic local probes (μSR, NQR, NMR) Time-scale ?

LSCO: Mac Dougall, PRL (2008)
YBCO: Sonier, PRL (2008), Wu (2014)
Y124: Strassle PRL (2011)
Hg1021: Mounce, PRL (2013)

Broken time-reversal symmetry
ARPES

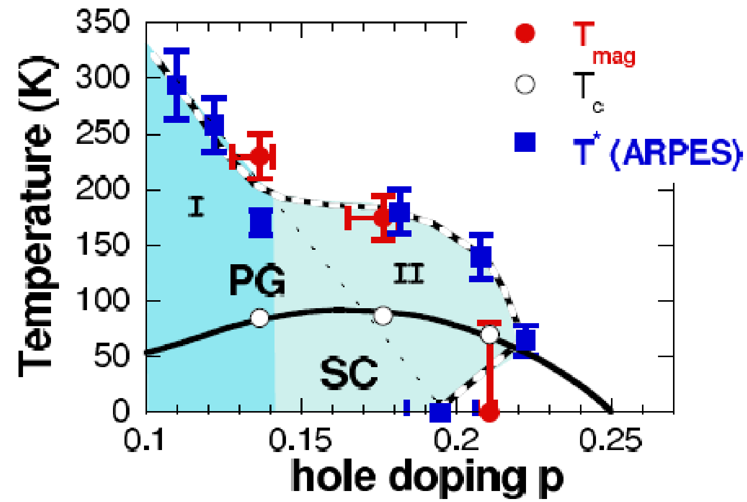


Dichroism in ARPES at the M point



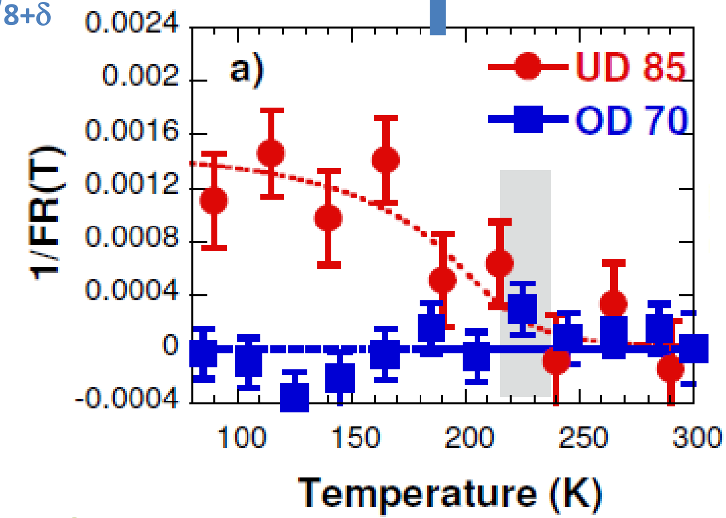
Kaminski, Nature 2002

Broken time-reversal symmetry
Polarized neutron diffraction



L. Mangin-Thro et al, PRB (2014)
ARPES: I. Vishik et al, PNAS (2012)

$Bi_2Sr_2CaCu_2O_{8+\delta}$



Y. Sidis & P. Bourges arXiv 1306.5124

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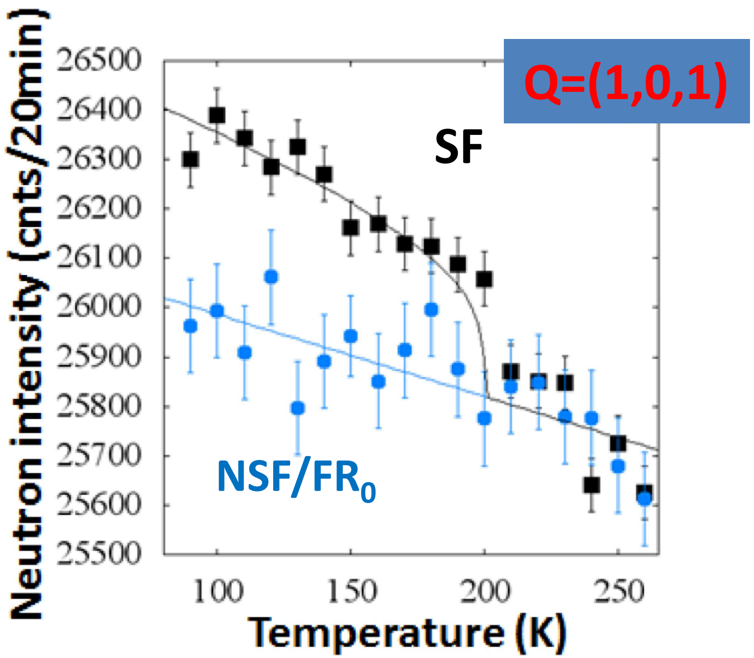
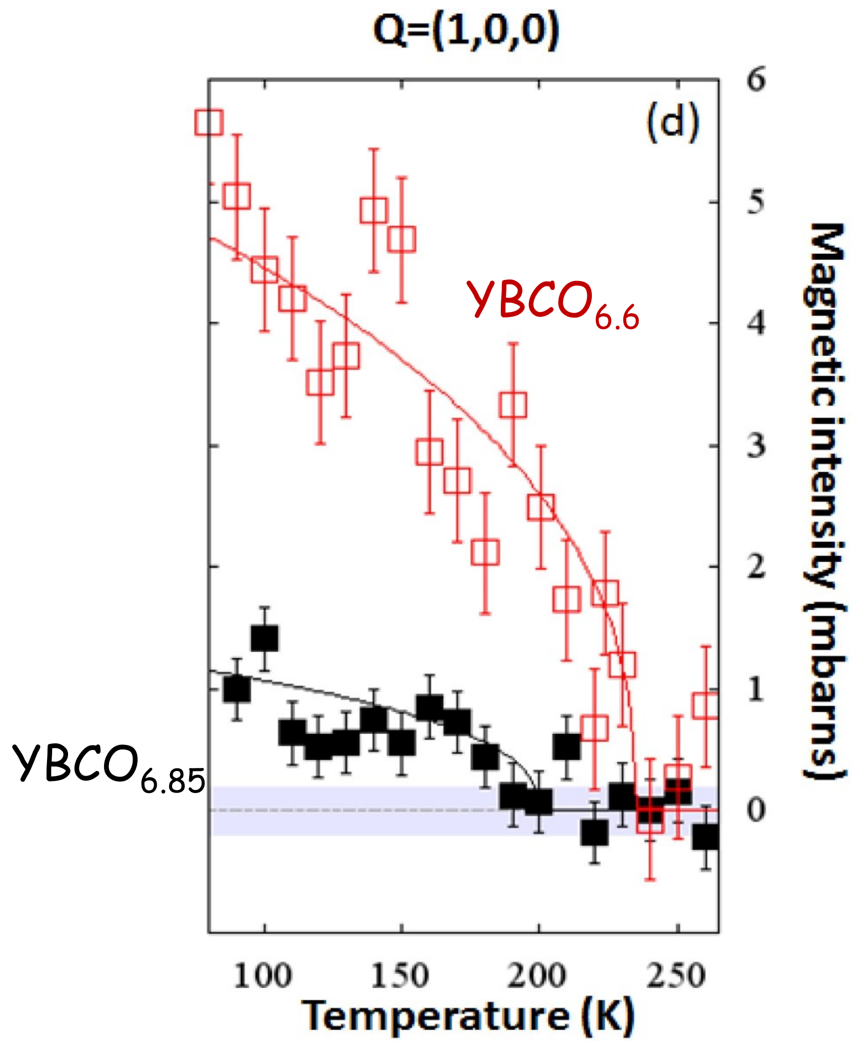
$YBCO_{6.85}$: nearly optimally doped

$YBa_2Cu_3O_{6.85}$:Tc=89 K , p=0.15





1/Flipping Ratio=FR^{-1}=SF/NSF = FR_0^{-1} + M^2/NSF

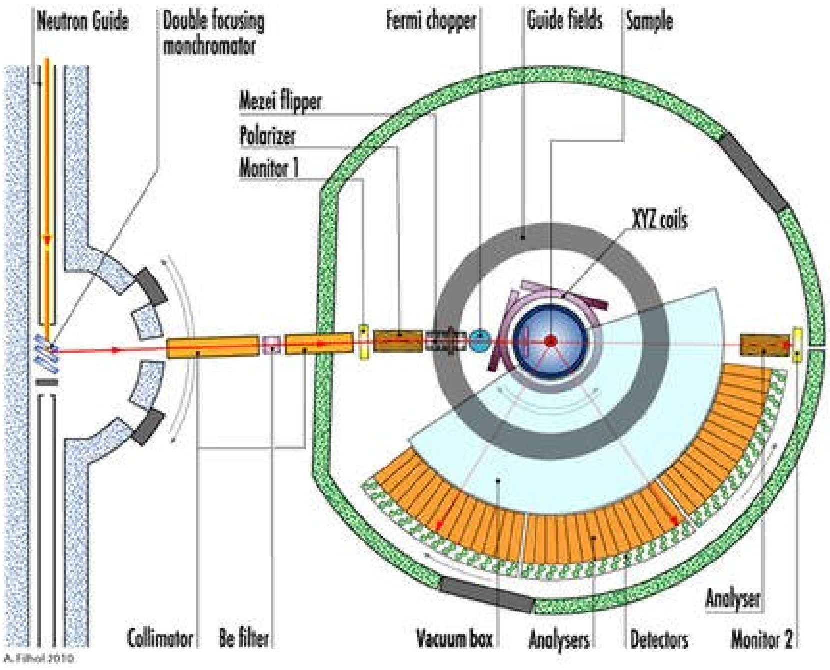
- FR_0^{-1} calibrated on 004 and 200
- T_{mag} ~ 200 K

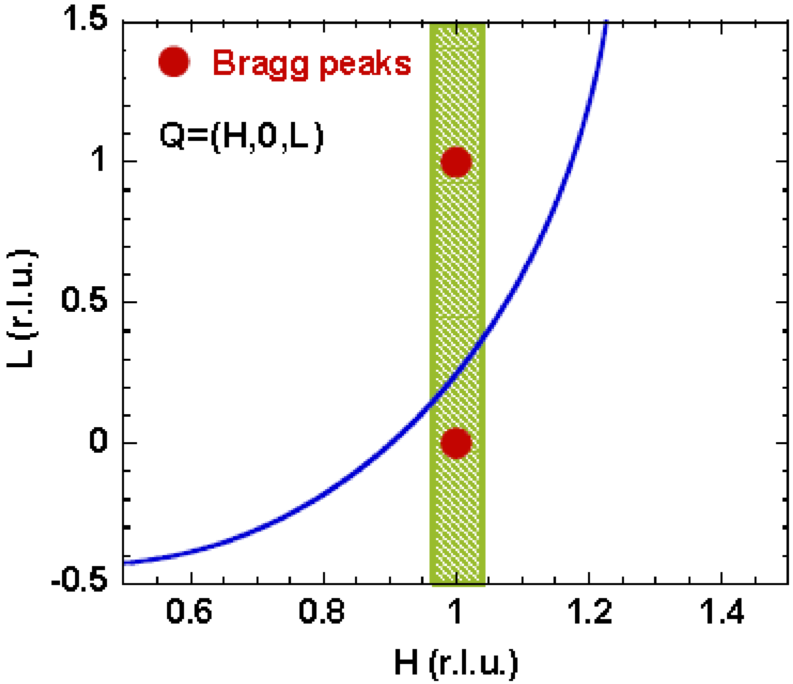
L. Mangin-Thro et al, ArXiv 1501.04919

Magnetic intensity on Q=(100) and Q=(101)
(4 times weaker than YBCO6.6)

Multi-detectors diffratometer: D7 (ILL)

- Polarized neutron with 120 detectors → H-scan
- XYZ polarization analysis → magnetic intensity
- Range of correlations (λ ~ 5 Å, cold neutrons, good q-resolution)





$YBCO_{6.85}$: Short range magnetic order

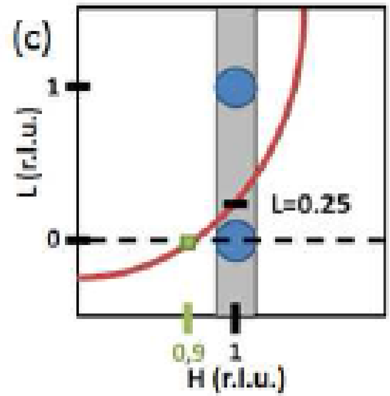
Finite inplane Correlations

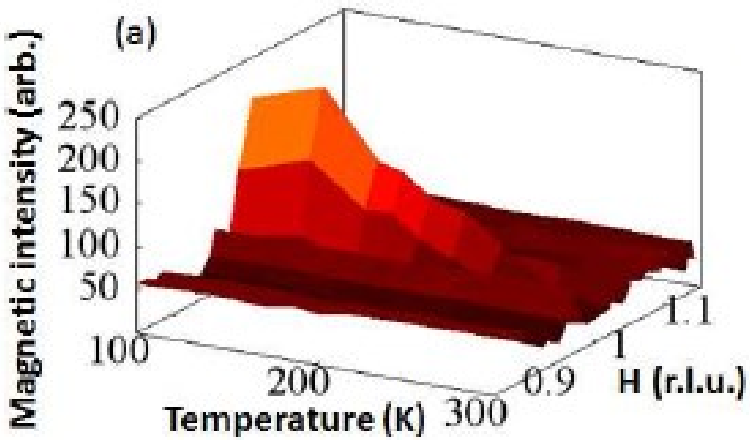
T=100K

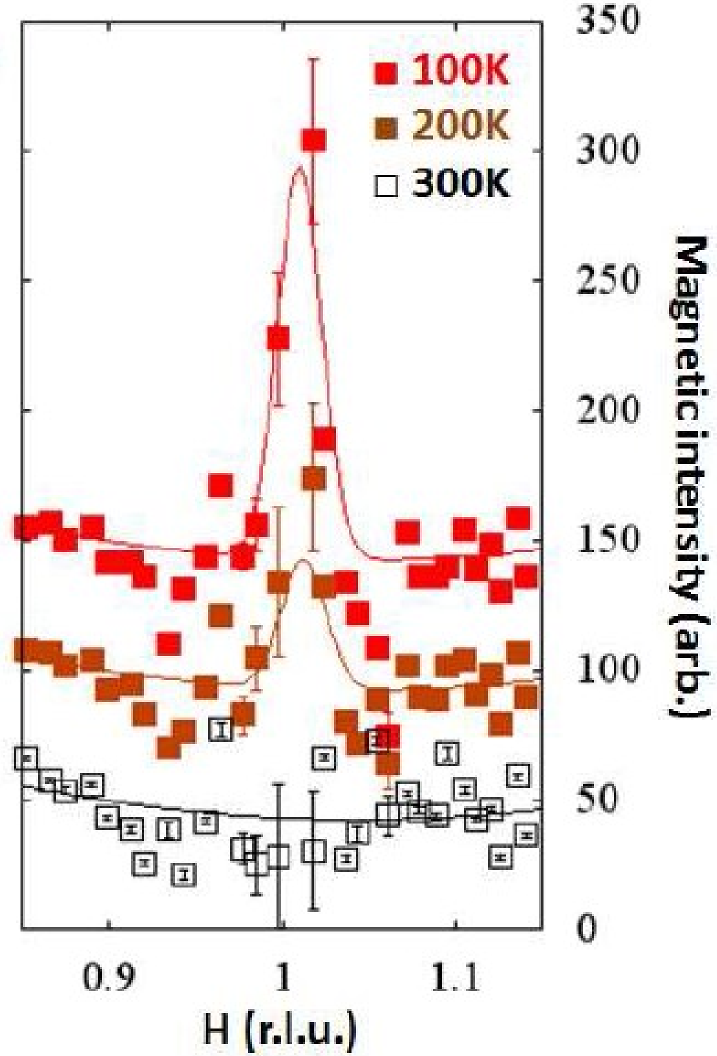
ξ_{ab} ~ 20a ~ 75 Å

$\xi_{ab} > \xi_{CDW}$ ~ 8a

ξ_{ab} :no clear T-dependance





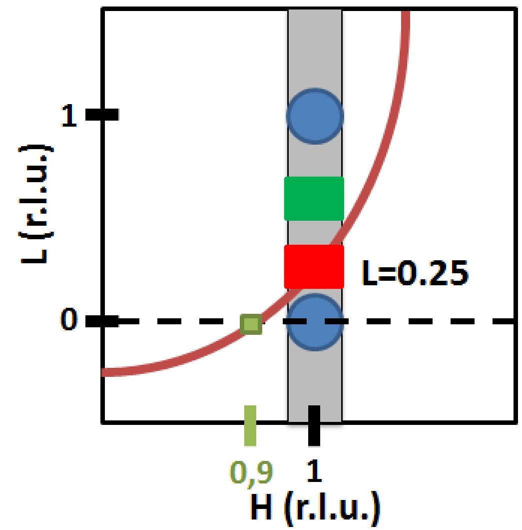


L. Mangin-Thro et al, ArXiv 1501.04919

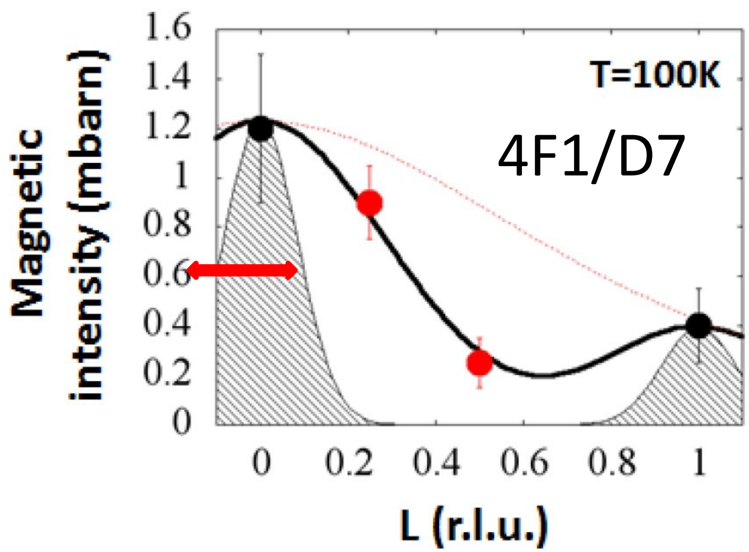
H-integrated intensity

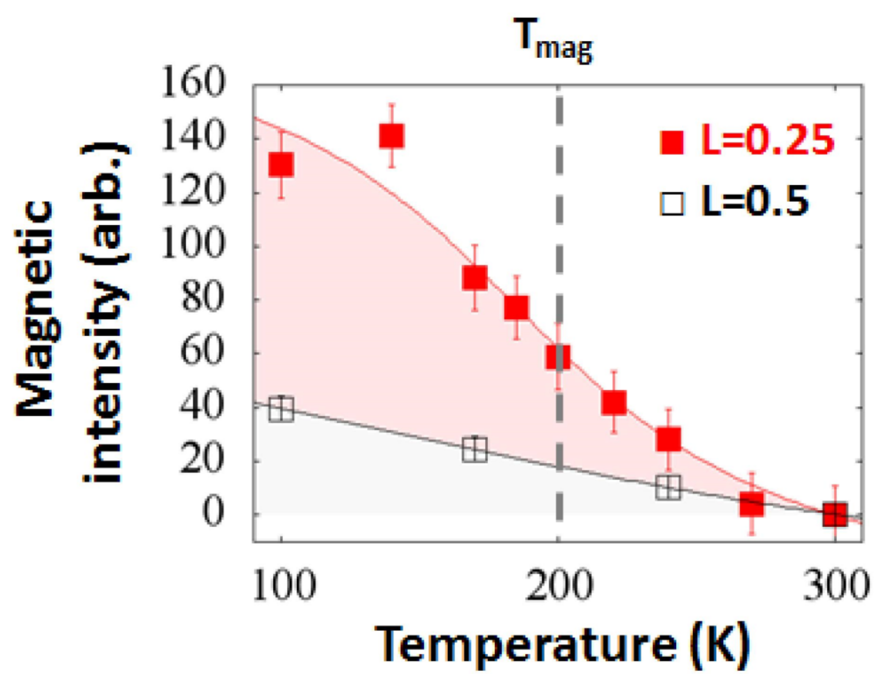
$$\overline{I} = \sum_{i=1}^{N} I_i/N = \overline{BG} + I_0 \frac{\Delta q}{q_N - q_1}\sqrt{\frac{\pi}{4\ln 2}}$$

(Over ~ 10 detectors)



$YBCO_{6.85}$





hardly correlated along c

T=100K: Δql=0.65 rlu, ξ_c ~ 0.5 c

L. Mangin-Thro et al, ArXiv 1501.04919

Doping dependence of the peak intensity

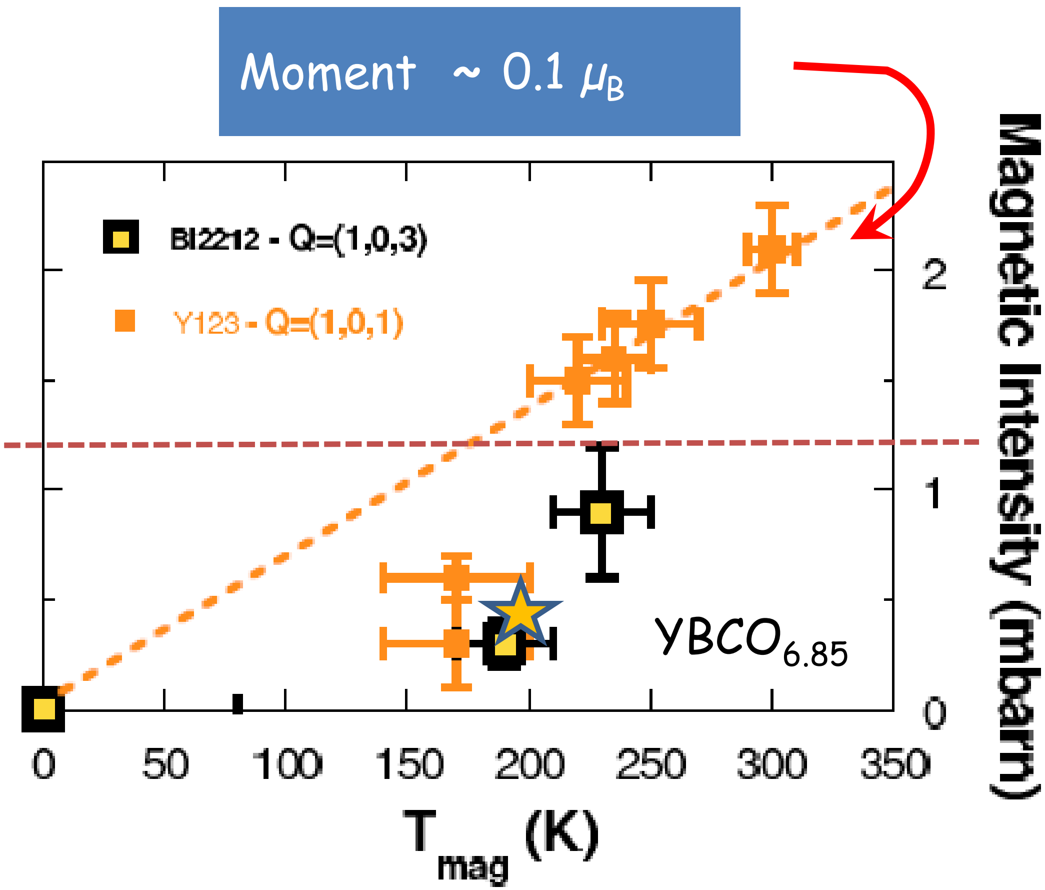
Magnetic intensity vs Tmag

p ~0.09

Long range correlations (underdoped)

p ~0.13

Short range Correlations (near optimal doping)



L. Mangin-Thro et al, Phys. Rev. B 89, 094523 (2014)

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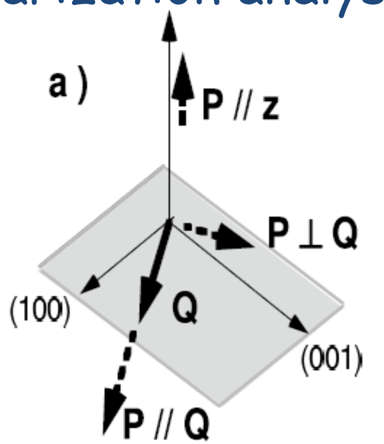
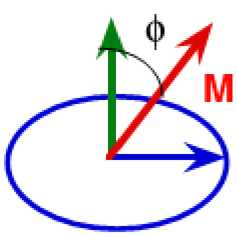
$YBCO_{6.6}$: H.A. Mook et al, PRB 020506(R) (2008).

Polarization analysis:



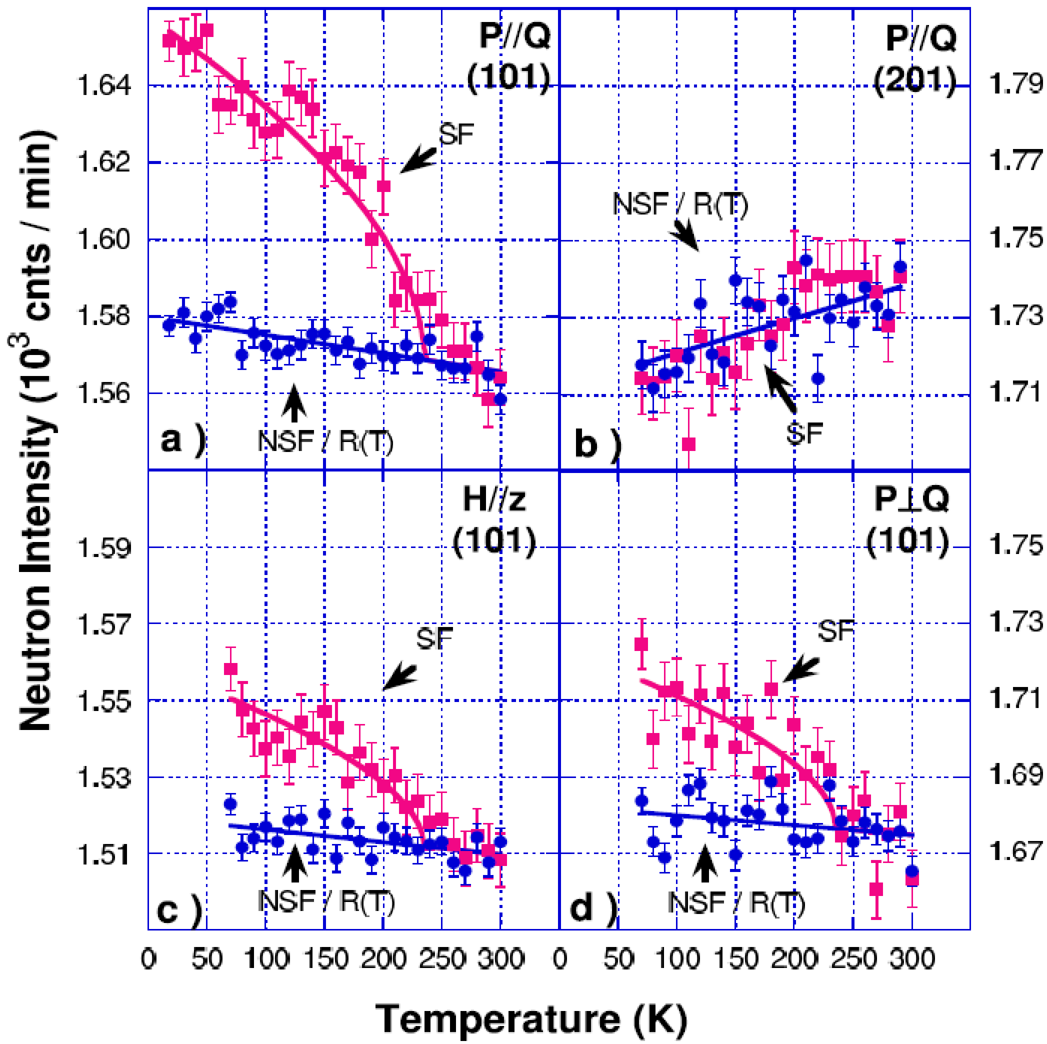
$$I_{\vec{P}//\vec{Q}} = I_{\vec{P}//\vec{z}} + I_{\vec{P}\perp\vec{Q}}$$

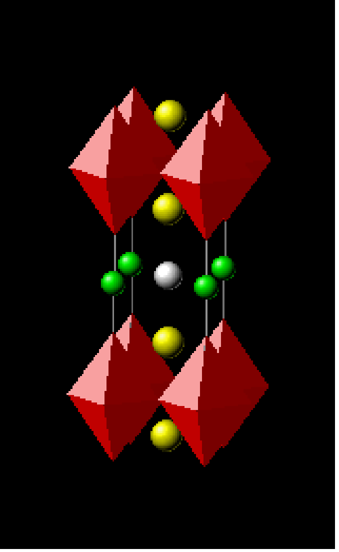
Angle (M,c*) ~ 45 deg



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

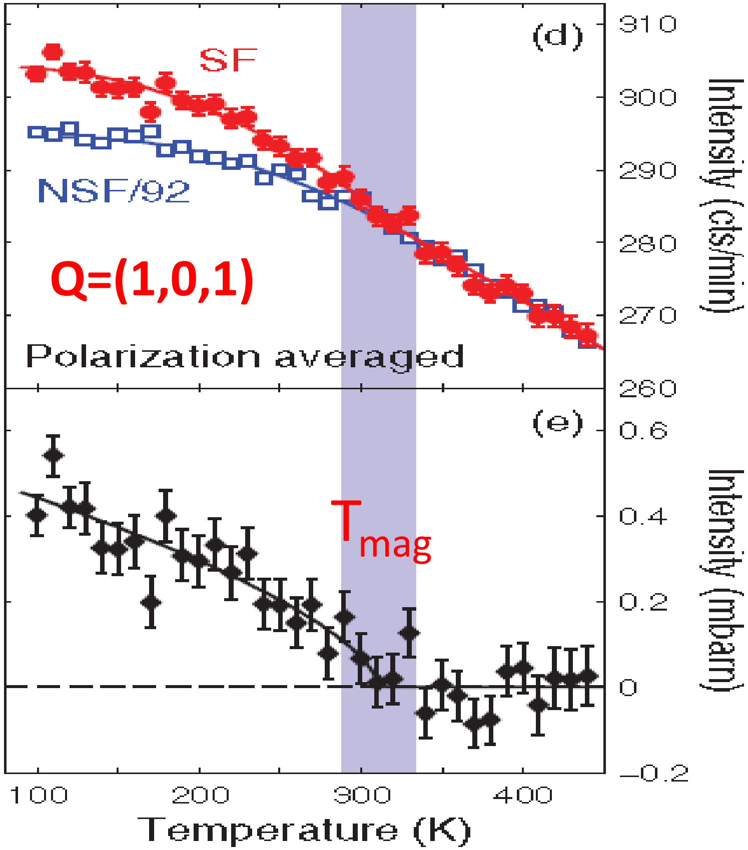
For Q=(1,0,1):



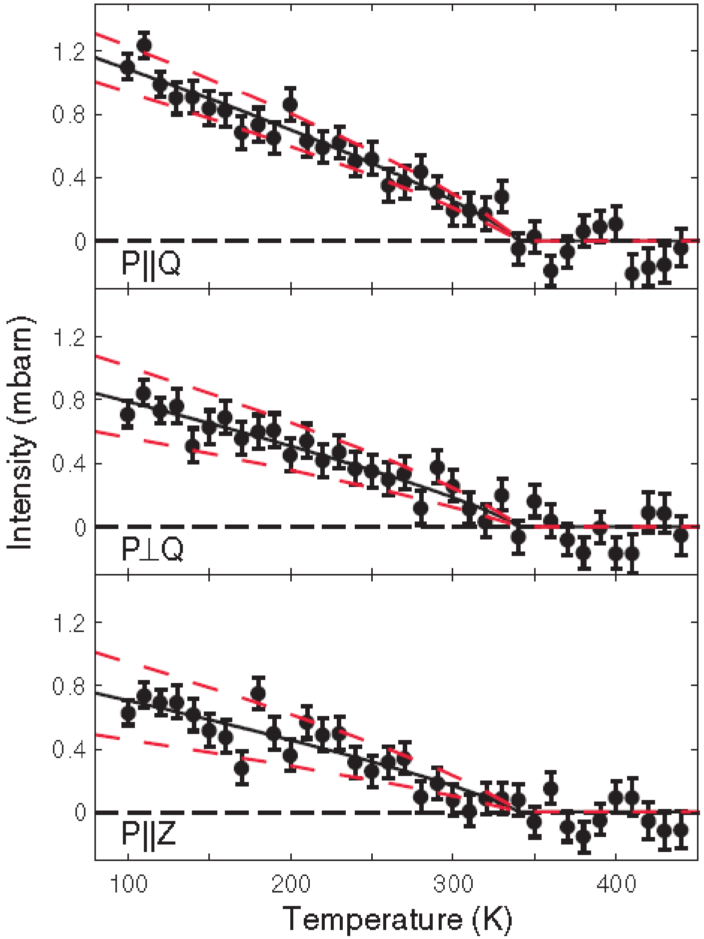


One CuO_2 layer

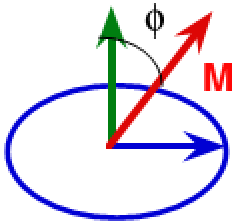
$HgBa_2CuO_{4+d}$:Tc=75 K



Magnetic intensity

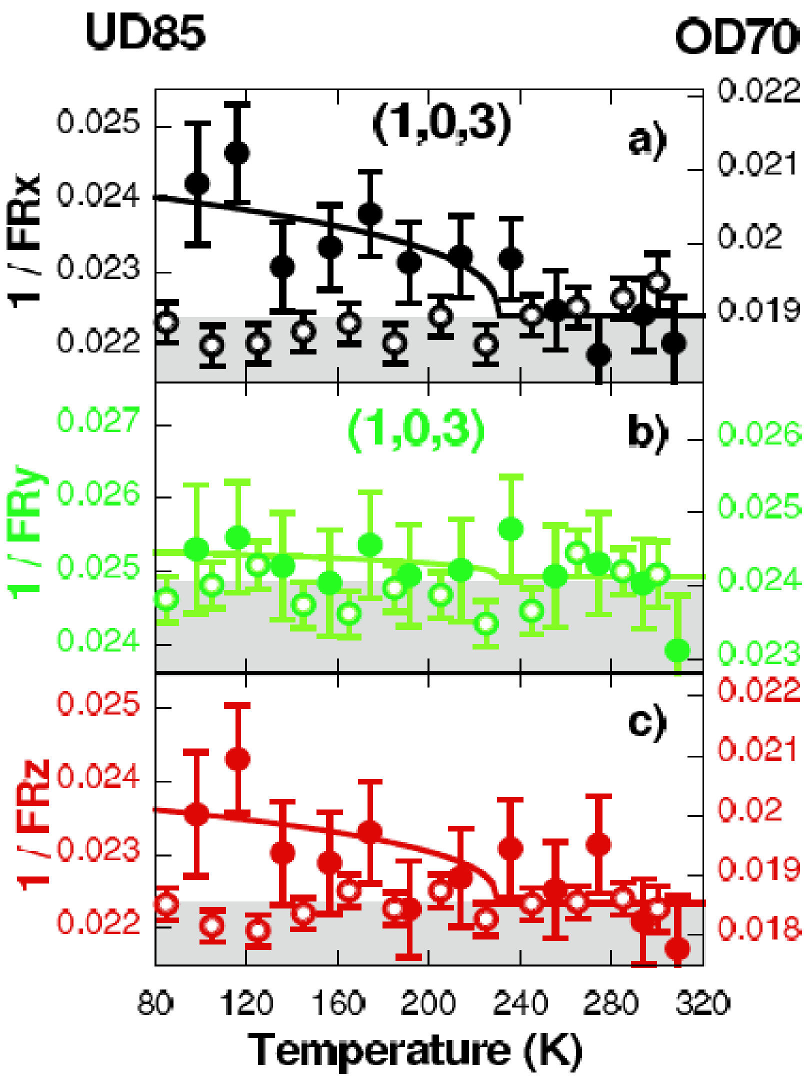


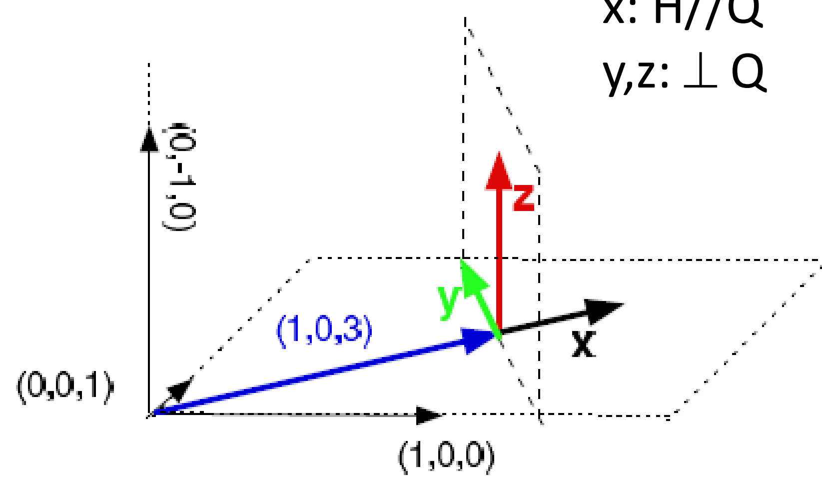
Angle (M,c*) ~ 45 deg



Y. Li et al, PRB, 84 224508 (2011); Nature 455,372, (2008)

Polarization analysis: $Bi_2Sr_2CaCu_2O_{8+\delta}$





- *Angle (M,c*) ~ 20 ± 20 deg*

L. Mangin-Thro et al, Phys. Rev. B 89, 094523 (2014)

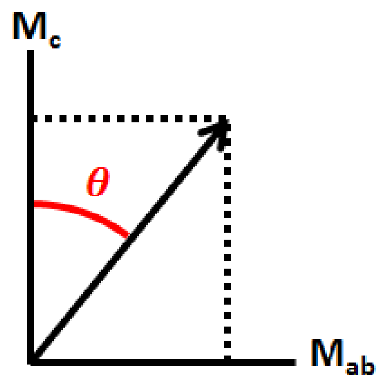
$YBCO_{6.85}$: Polarization analysis D7/H-integrated intensity

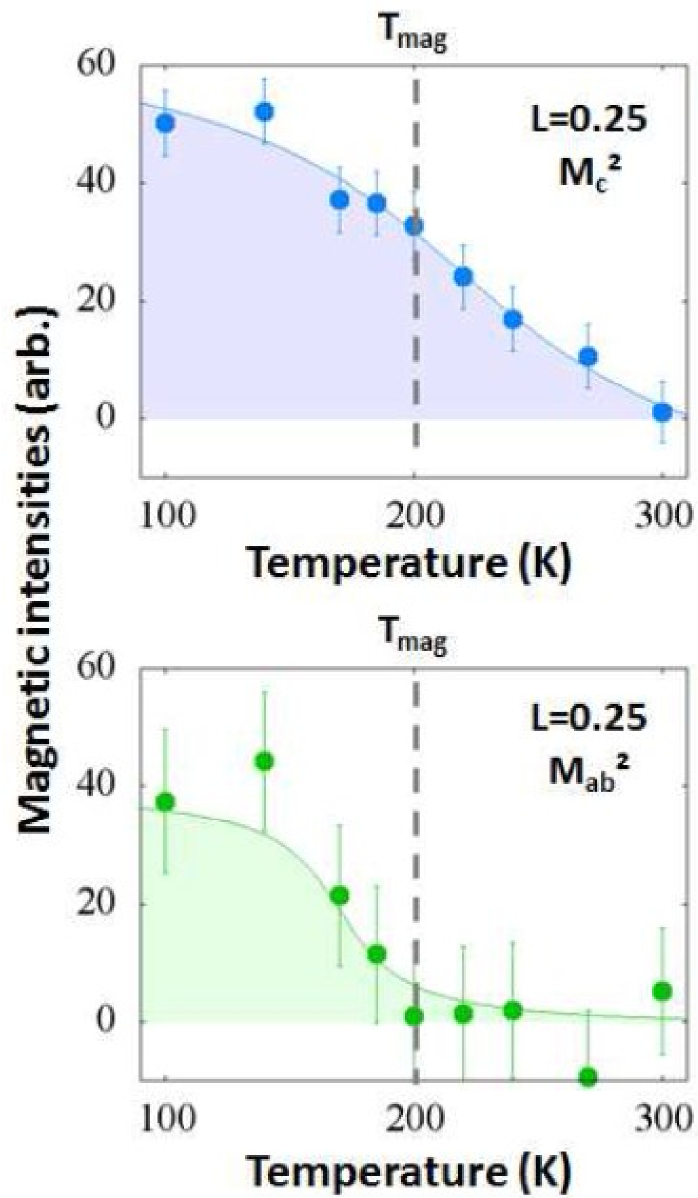
Magnetic Components

$$I_Z^{SF} \propto (1-q_l^2)M_c^2 + \frac{q_l^2}{2}M_{ab}^2 \sim M_c^2$$

$$I_Y^{SF} \propto \frac{1}{2}M_{ab}^2 + I_Z\ sin^2\beta$$

$$I_X^{SF} \propto \frac{1}{2}M_{ab}^2 + I_Z\ cos^2\beta$$



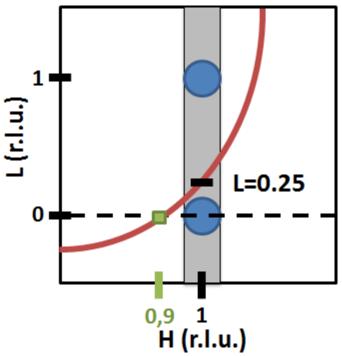


- Ising Character above T_{mag}
(as expected for Loop Currents)

- Tilt appears below T_{mag}
(40 deg at 100K)

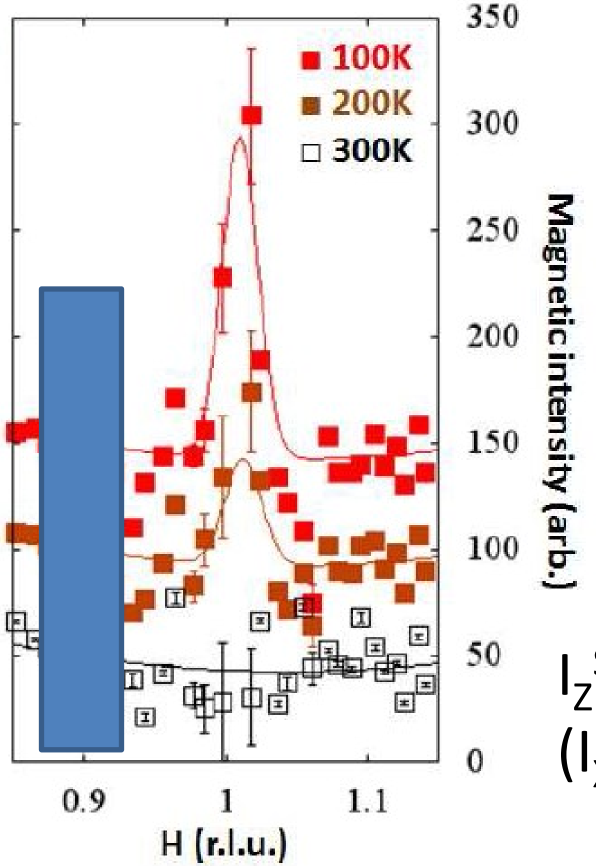
L. Mangin-Thro et al, ArXiv 1501.04919

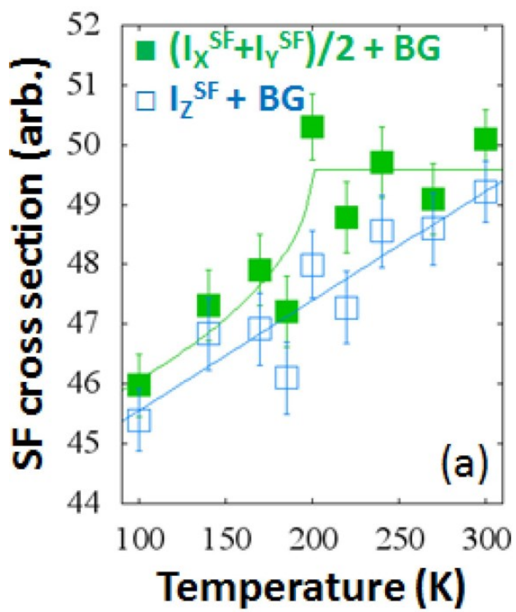
Diffuse scattering

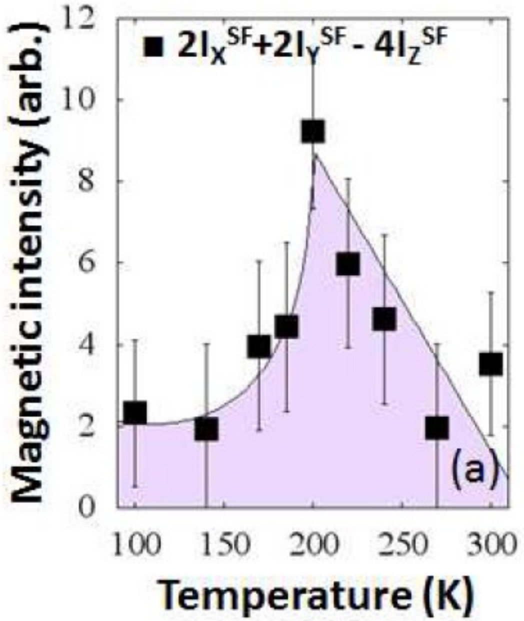


Q ~ (0.9,0,0)

« Critical behaviour »







$I_Z^{SF} = M_C^2 + BG$

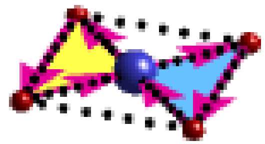
$(I_X^{SF} + I_Y^{SF})/2 = (M_C^2 + M_{ab}^2)/2 + BG$

Jump at Tmag

$\alpha\ (M_{ab}^2 - M_C^2)$

Tilt why ?

- Loop order



Spin-orbit coupling in CC phase

V. Aji & C.M. Varma, PRB 78, 094421 (2008).

Quantum superposition of the 4 states

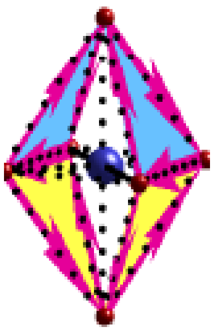
Y. He & C.M. Varma, PRB 86, 035124 (2012).

- Loop order on the CuO_6 octaedra

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

S. Lederer & S. Kivelson *PRB*85, 155130 (2012)

not ok: tilt=0 for L=0

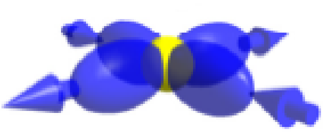


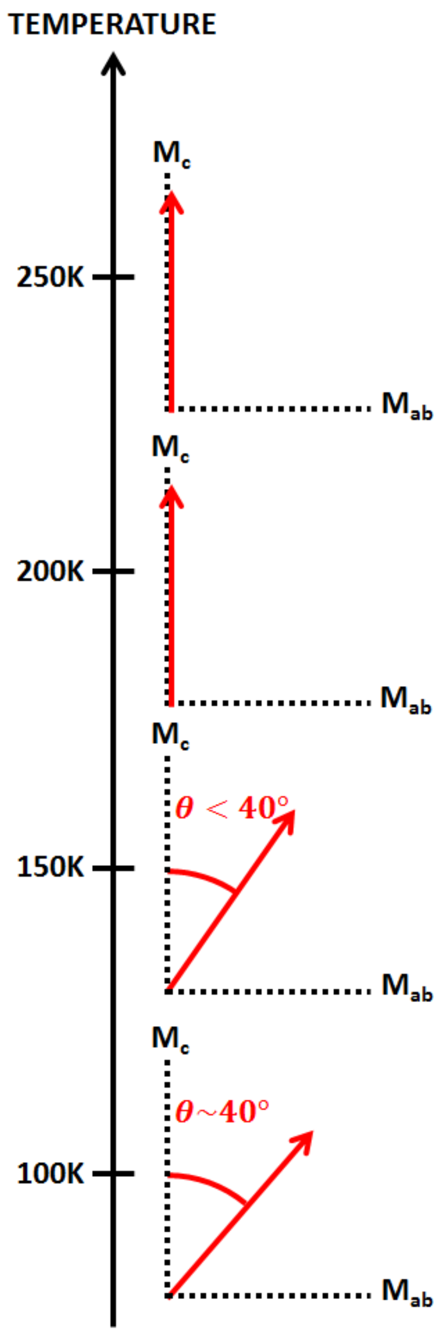
- Neutron cross-section:

Parity odd operators (broken inversion)

Magnetic quadrupole

S.V. Lovesey et al, ArXiv 1408.5562





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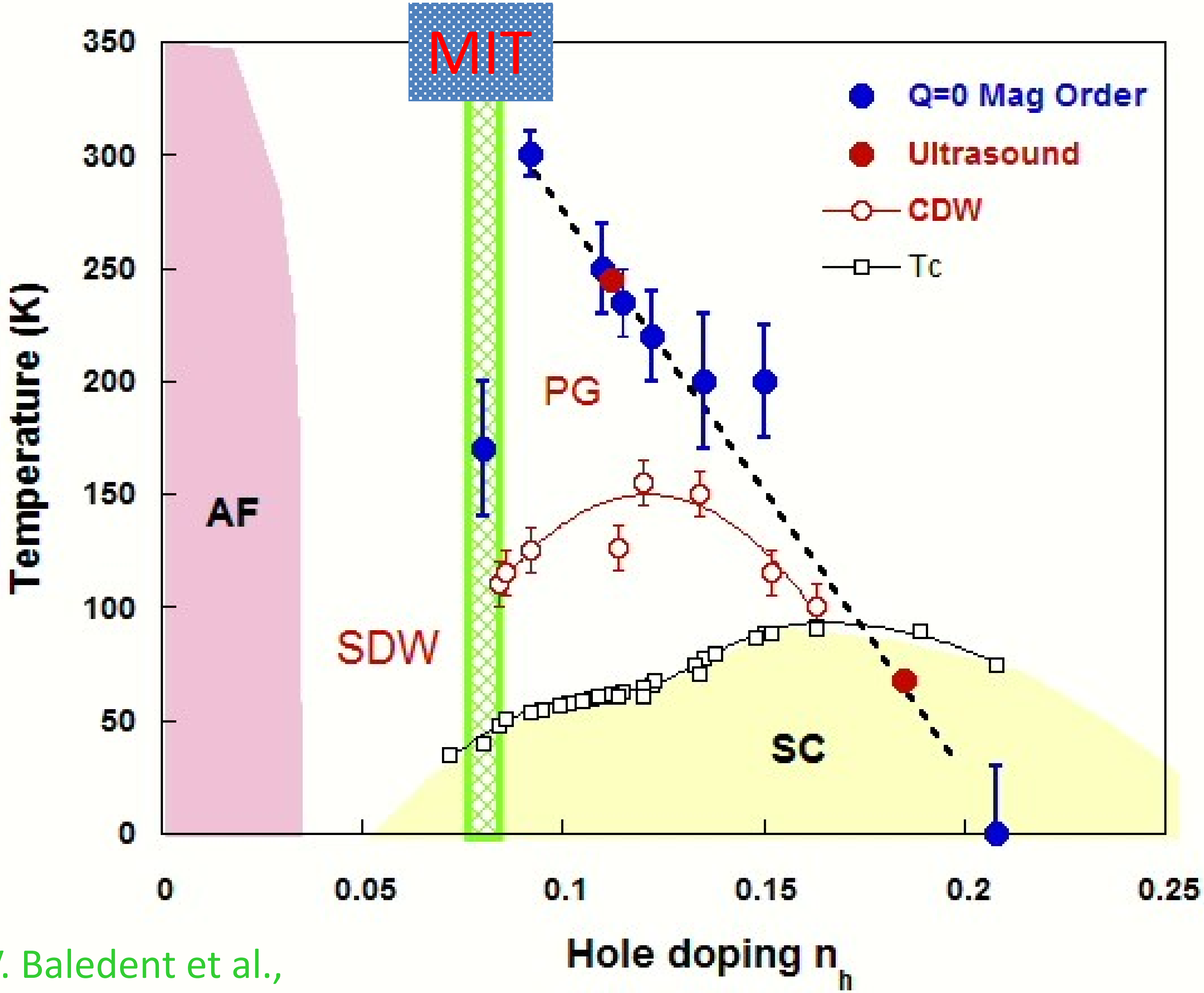
YBCO phase diagram: comparison with CDW



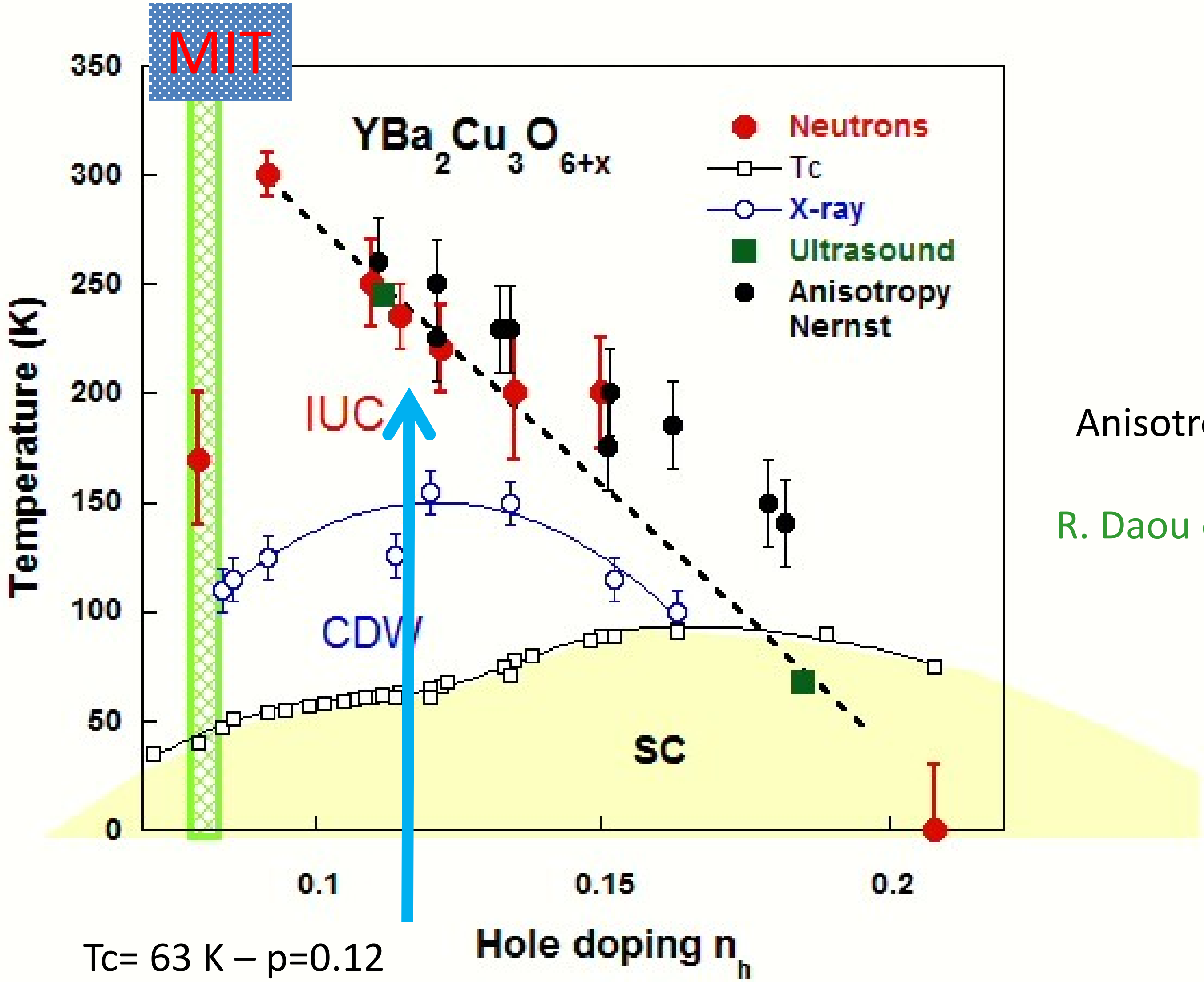
V. Baledent et al.,

PRB 83, 104504 (2011).

CDW: S Blanco-Canosa et al, PRB 90 054513 (2014)

Bourges and Sidis, C.R. Physique (2011) and J. Phys. Conf. Ser 449 012012 (2013)

YBCO phase diagram: comparison with CDW



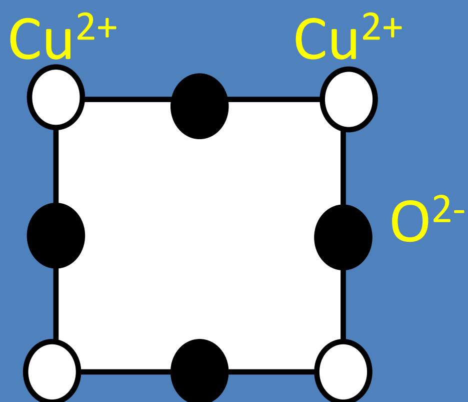
Anisotropic Nernst effect in YBCO
R. Daou et al Nature (2010)

Tc= 63 K – p=0.12
(twin free)

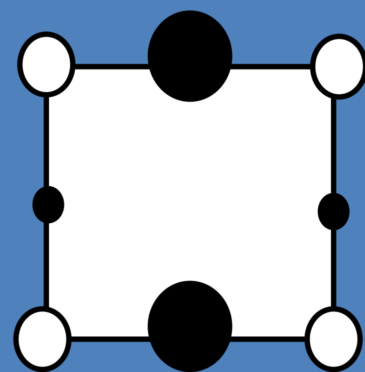
CDW: S Blanco-Canosa et al, PRB 90 054513 (2014)

Bourges and Sidis, C.R. Physique (2011) and J. Phys. Conf. Ser 449 012012 (2013)

Pseudogap ? Mind the oxygen !......

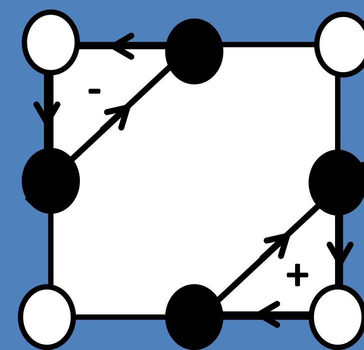


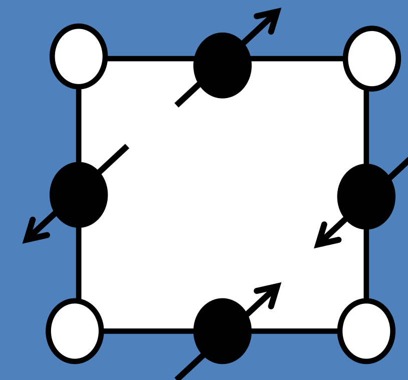
STM
IUC- charge order (Q=0)
Electronic nematic state



Fischer & Kim,
PRB 2011, PRB 2012
Davis & DH Lee

Polarized Neutron
IUC- magnetic order (Q=0)
Orbital magnetism

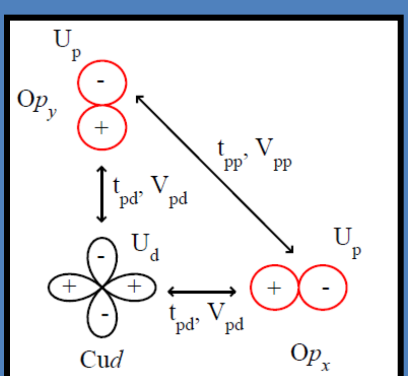


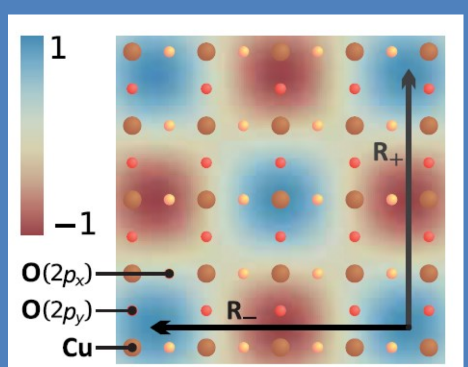


C.M. Varma,
PRB 2006

A.S. Moskvin,
JETP Lett. 2012

Multi-band model





Spin-fermion model
(Sachdev, Chubukov, Efetov et al)

Quadrupolar Charge order
on CuO bonds

K. B. Efetov, H. Meier, and C. Pépin,
Nature Physics 2013

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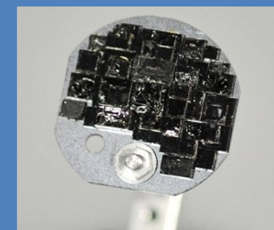
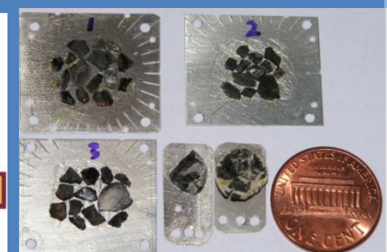
(Laboratoire Léon Brillouin - Saclay)

$YBa_2Cu_3O_{6+x}$



- D. Haug, T. Loew, V. Hinkov (MPI Stuttgart)
- X Chaud (CRETA, Grenoble), L.P. Regnault (CEA Grenoble)
- A. Wildes (ILL-Grenoble)
- H.A. Mook (Oak Ridge, USA)

$HgBa_2CuO_{4+x}$



- Mun Chan (University Minnesota) , Yuan Li (Peking Univ)
- Guichuan Yu, Yang Tang M. Greven (University Minnesota)
- P. Steffens (ILL-Grenoble)

$La_{2-x}Sr_2CuO_4$

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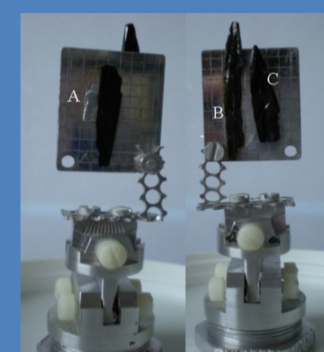
$Bi_2Sr_2CaCu_2O_{8+x}$



- I. Laffez, F. Giovanneli (IUT-Blois, France),
  S. De Almeida-Didry(PHD: 08-11)