Magnetic order in the pseudogap phase of $YBa_2Cu_3O_{6+x}$

Philippe Bourges

Laboratoire Léon Brillouin-Saclay

Polarized elastic Neutron Scattering experiments

4F1 (LLB-Saclay)

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- **B. Fauqué, Y. Sidis (LLB-Saclay)**
- **S. Pailhès (PSI-Villigen) V. Hinkov (MPI-Stuttgart)**
- **X. Chaud (CRETA-Grenoble)**

Thanks: B. Keimer, L. Pinstchovius for samples.

Outline

1. **Cuprates and Pseudogap: circulating currents phase**
2. **Polarized neutron experiments**
3. **Results: magnetic order in underdoped $YBa_2Cu_3O_{6+x}$**
4. **Hidden order for the pseudogap phase**

Copper oxides superconductors : phase diagram

$\mathbf{La_{2-x}(Sr,Ba)_xCuO_4}$
$\mathbf{YBa_2Cu_3O_{6+x}}$

$\mathbf{Bi_2Sr_2CaCu_2O_{8+\delta}}$
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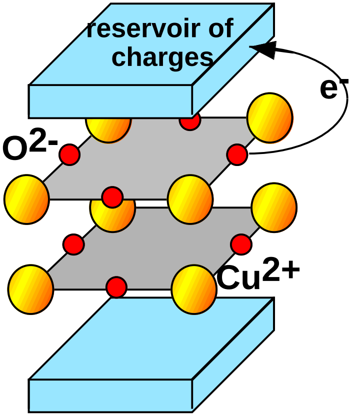

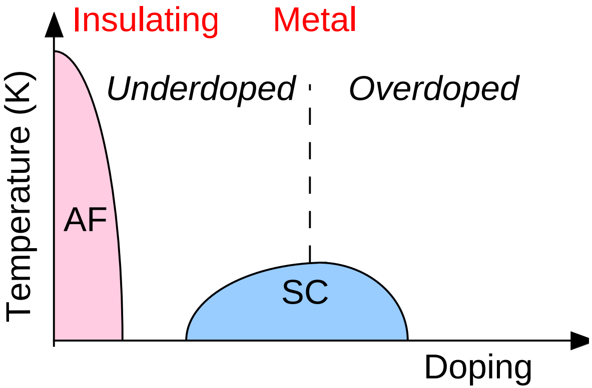

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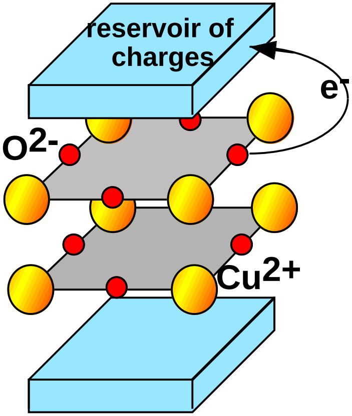

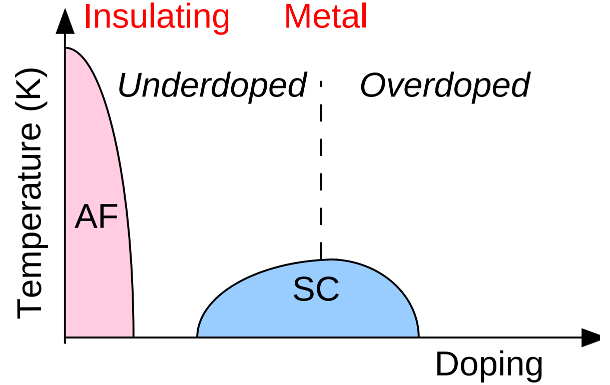

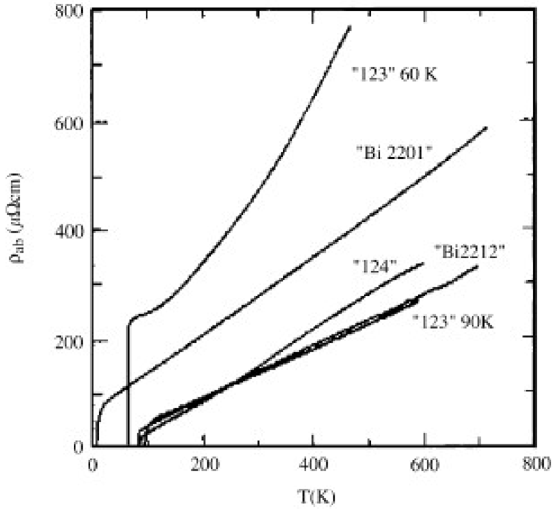

Normal state: "bad metal"

- $\rho \propto T$
- **ARPES: no well-defined Quasi-Particles above T_C**

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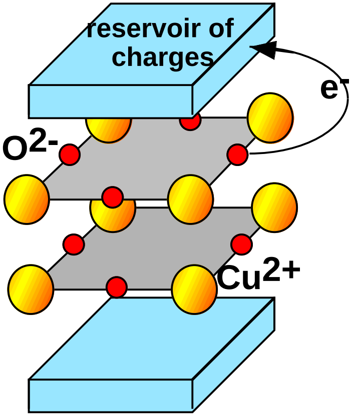

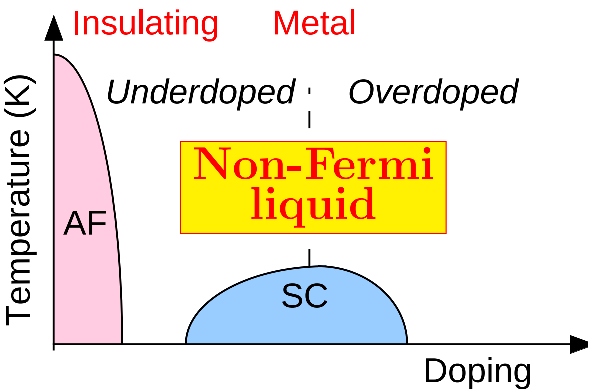

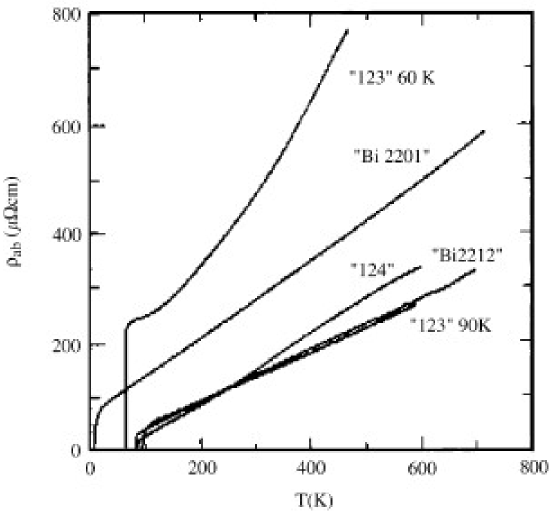

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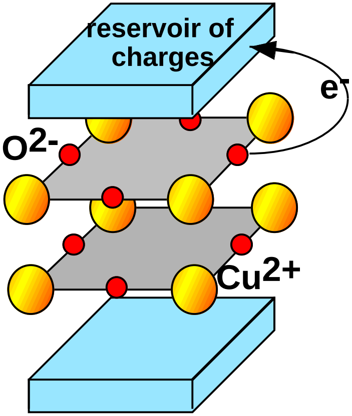

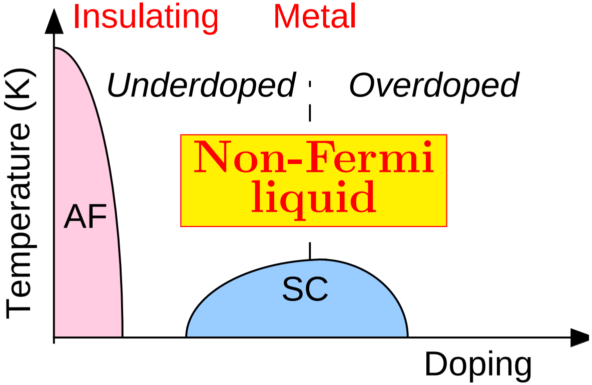

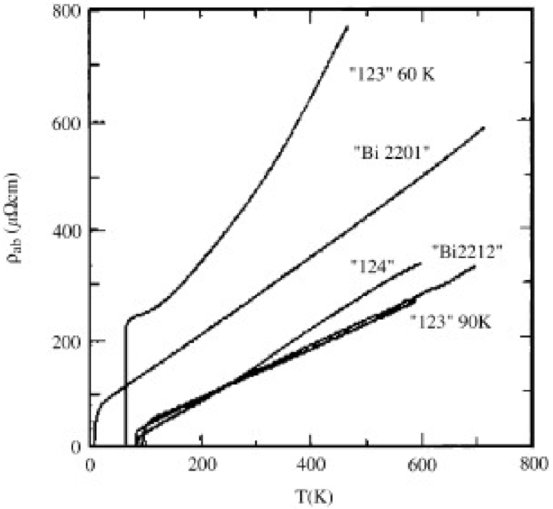

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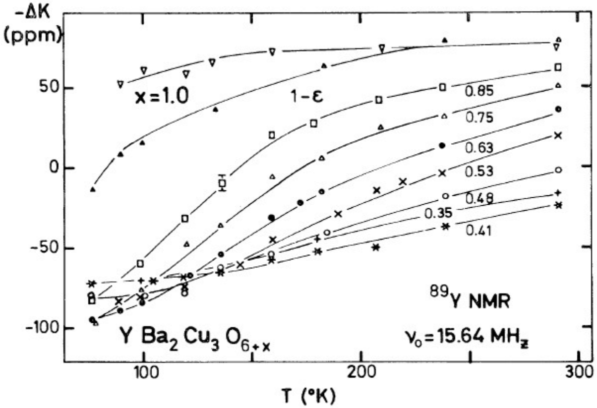
Role of AF fluctuations
Yvan Sidis

Underdoped state: Pseudogap

$YBa_2Cu_3O_{6+x}$

Susceptibility



^{89}Y NMR Knight shift

H. Alloul *et al.*, PRL 63, 1700 (1989).

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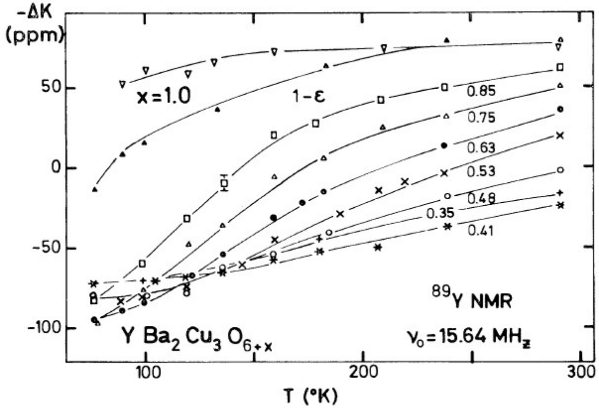

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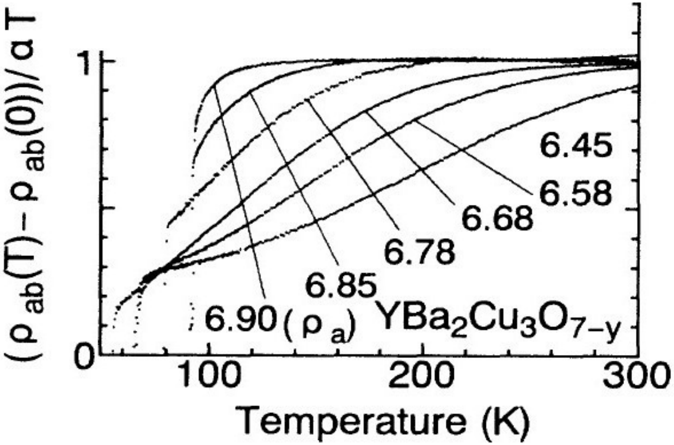

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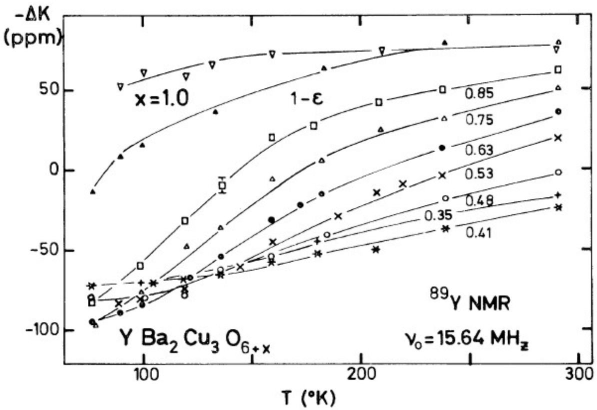

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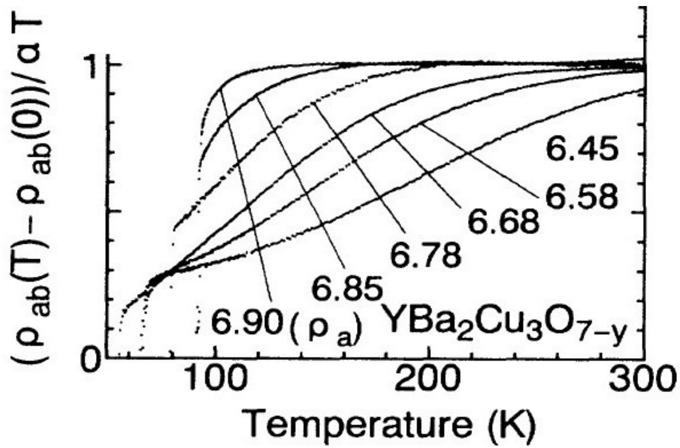

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Pseudogap behaviour in many physical properties below T*:

Transport, magnetic properties, Thermodynamics, Tunneling, ARPES, Raman scattering, Optical conductivity,...

J. Tallon et al, cond-mat/0211048

Anomalous normal state

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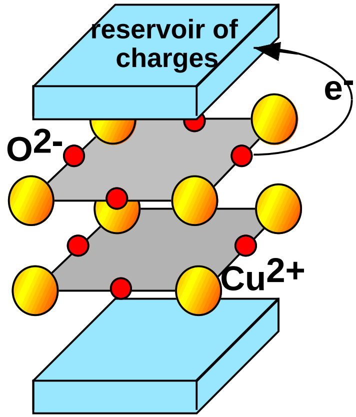
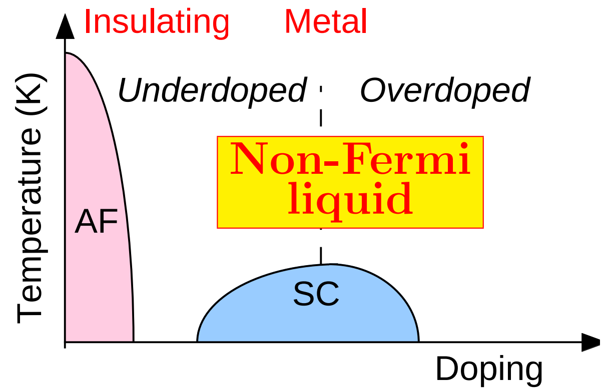
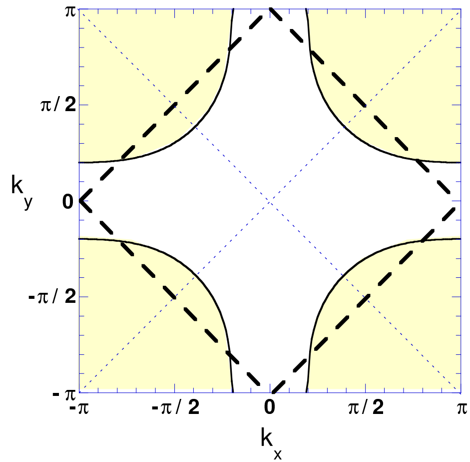




- 2D Fermi surface



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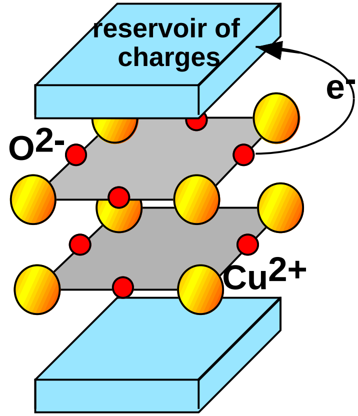
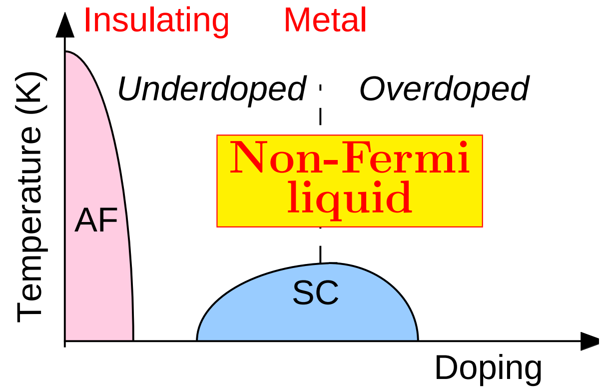


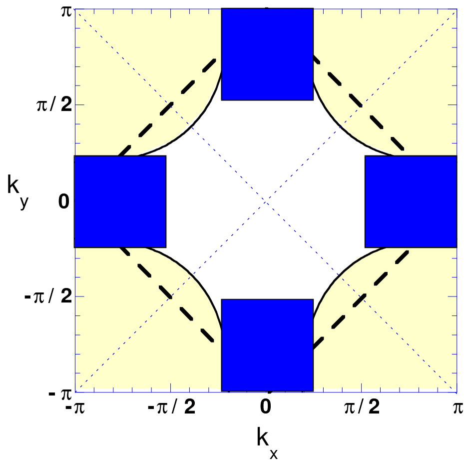


- 2D Fermi surface

- Fermi arcs

Underdoped state:

Pseudogap effect in magnetic and charge properties



Nature of underdoped phase: what is the Pseudo-gap ?

Pseudogap behaviour in many physical properties

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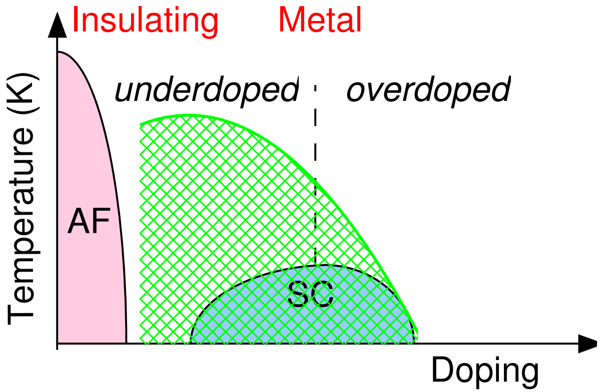

"Preformed pairs"

Phase coherence below T_C

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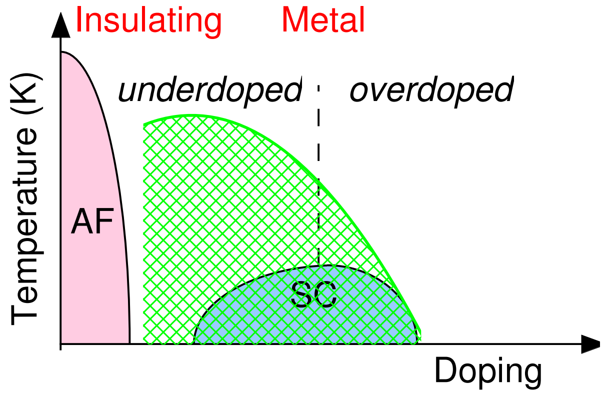

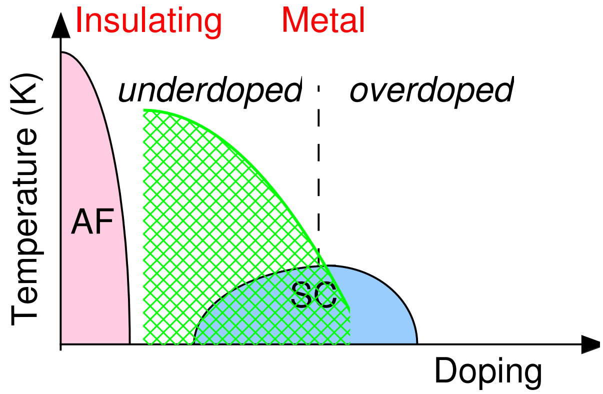

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Phase coherence below T_C

Competing order
Quantum critical doping

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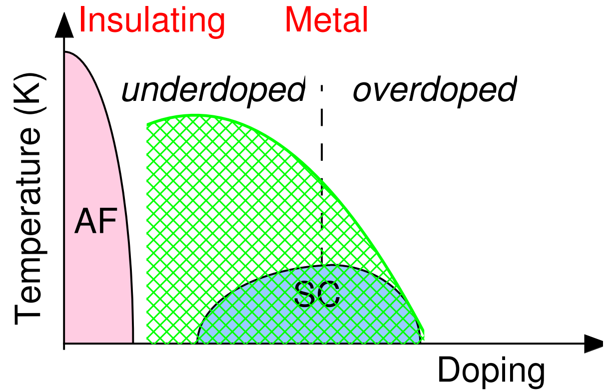

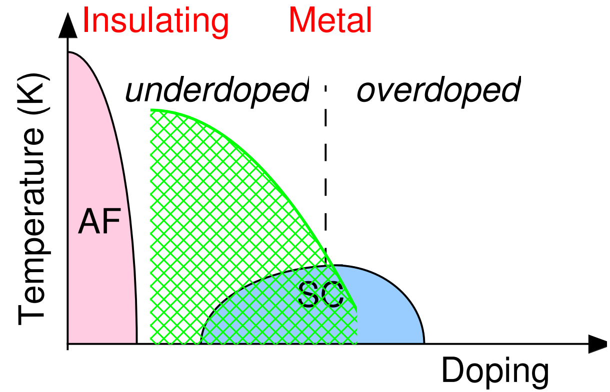

"Preformed pairs"
Phase coherence below T_C

Competing order
Quantum critical doping

Hidden order parameter: SDW, CDW, Circulating Currents, DDW,... (S.C. Zhang et al, C. Di Castro et al, C.M. Varma, S. Chakravarty et al, ...)

Charge currents: DDW and Circulating currents

S. Chakravarty *et al.*

PRB **63, 094503 (2001).**

C.M. Varma *et al.*

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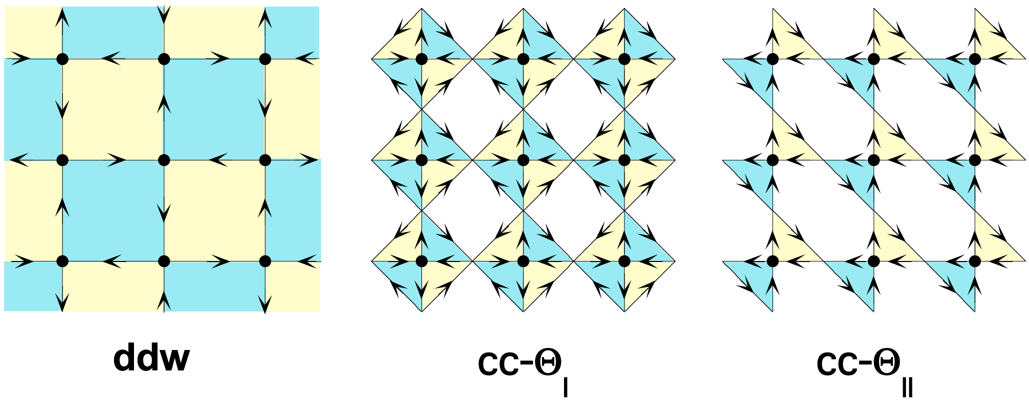

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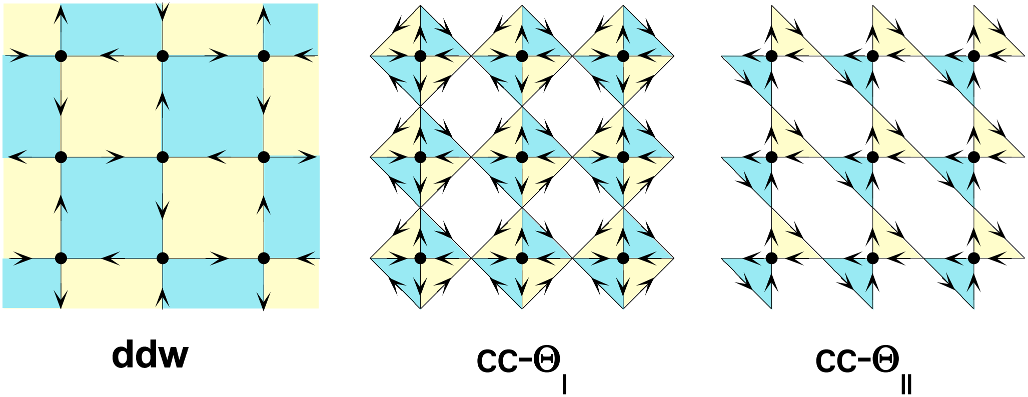

$\Rightarrow$ **Orbital moments $\perp$ CuO_2 plane** measurable with neutrons

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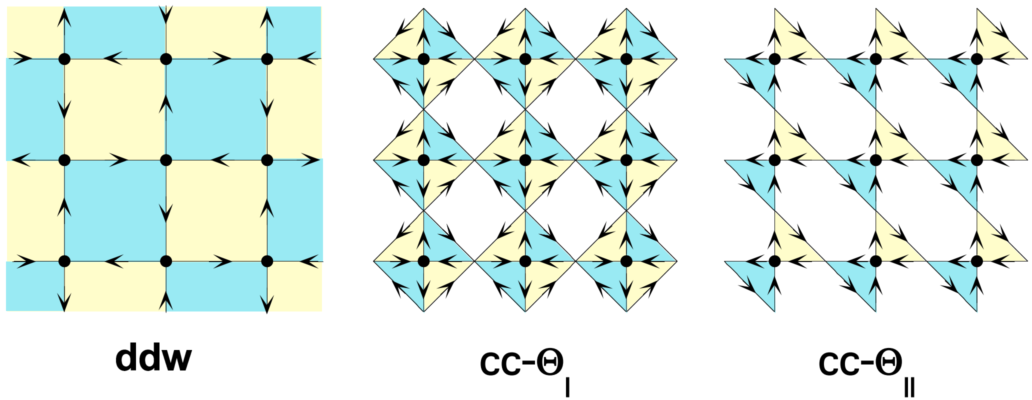
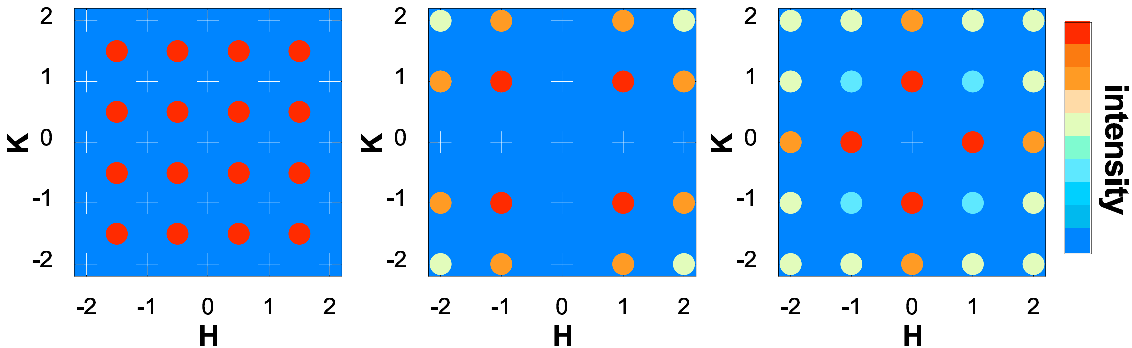


⇒ **Orbital moments ⊥ CuO_2 plane measurable with neutrons**



Circulating currents Phase Θ_{II}:

- Dichroism in ARPES $\Rightarrow$ Phase Θ_{II} Kaminski et al, *Nature* 416, 610 (2002)
(Not reproduced Borisenko et al, *Nature* 431, (2 September 2004)**)**

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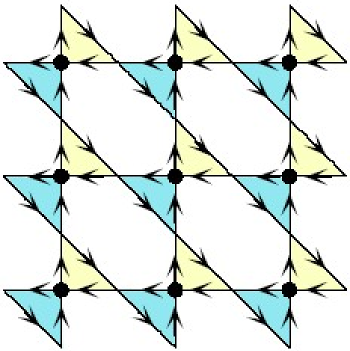
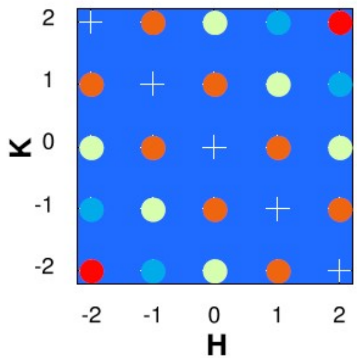
2 types of Domains:





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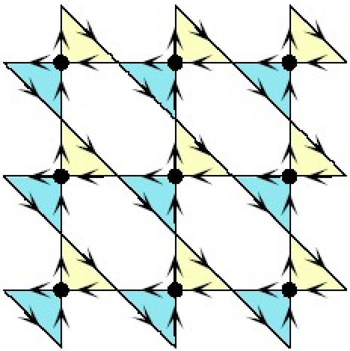

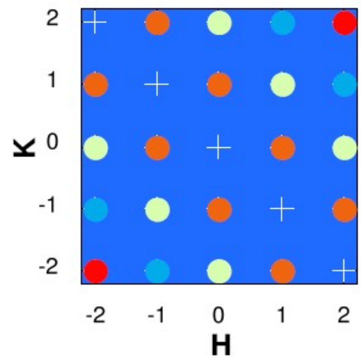

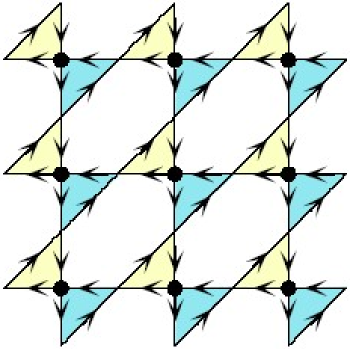

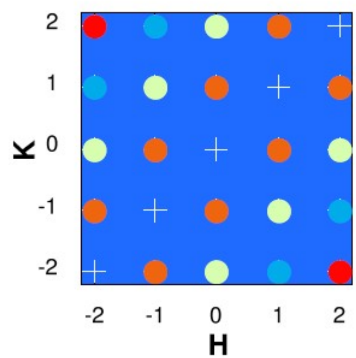

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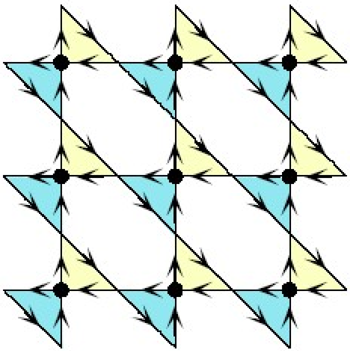
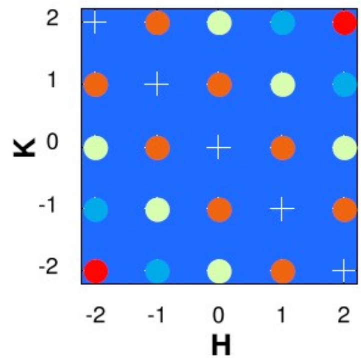
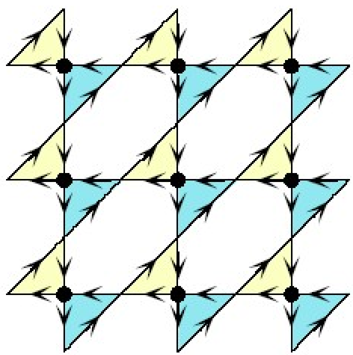
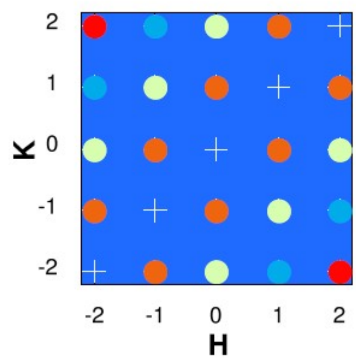




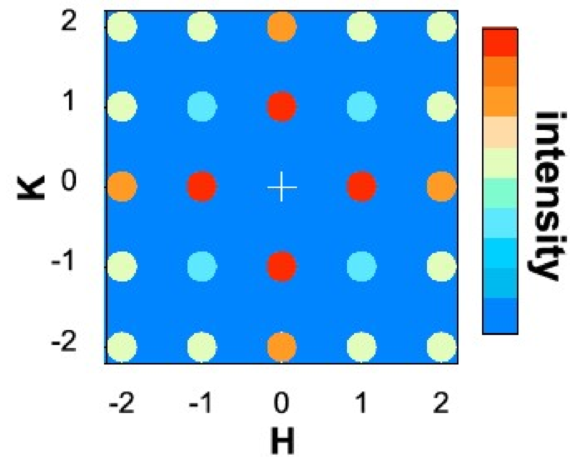




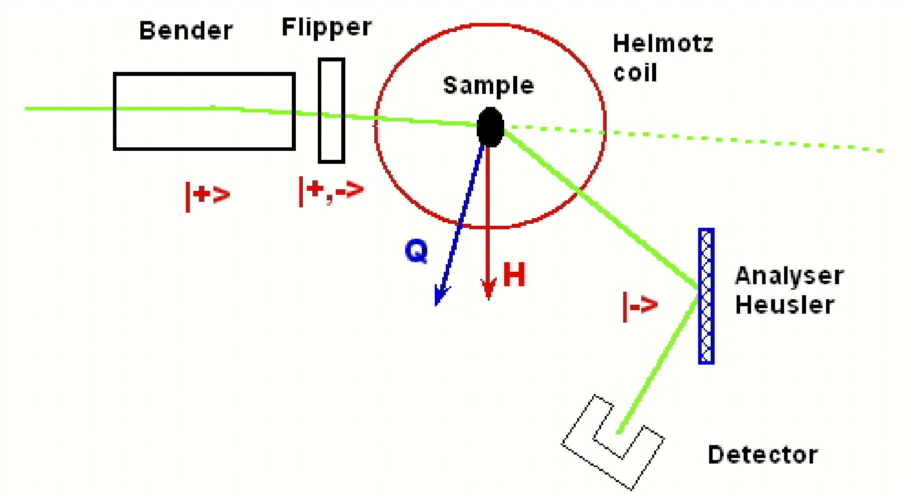
Structure factor:

$$|F_M|^2_{tot} =$$

$$\frac{1}{2}[|F_M|^2_{D1} + |F_M|^2_{D2}]$$



Polarized monochromatic neutron beam



$\mathbf{H} \simeq \mathbf{10\ G}$, $\vec{P}//\vec{H}$

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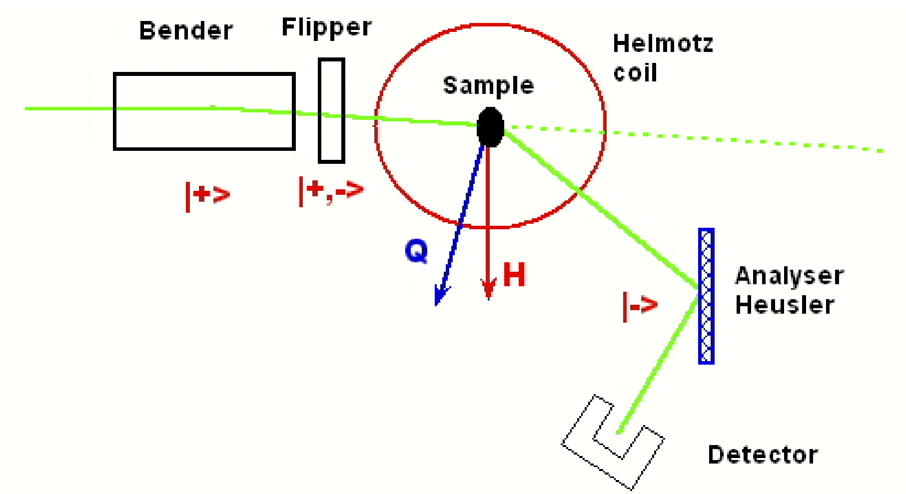

H $\simeq$ 10 G, $\vec{P}//\vec{H}$

Flipping ratio: R$\sim$ 30-50

Polarization: P$\sim$ 0.97-0.98

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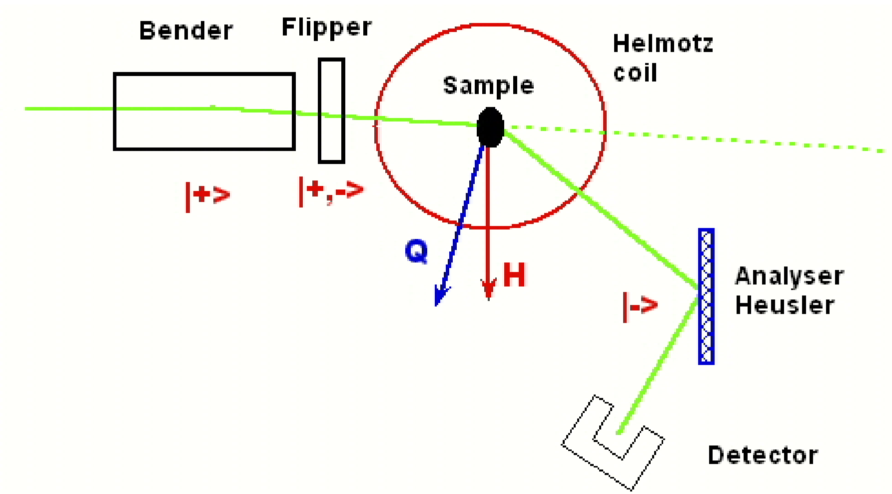

Magnetic scattering:

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

$\vec{\sigma}$: **Pauli matrices**

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

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

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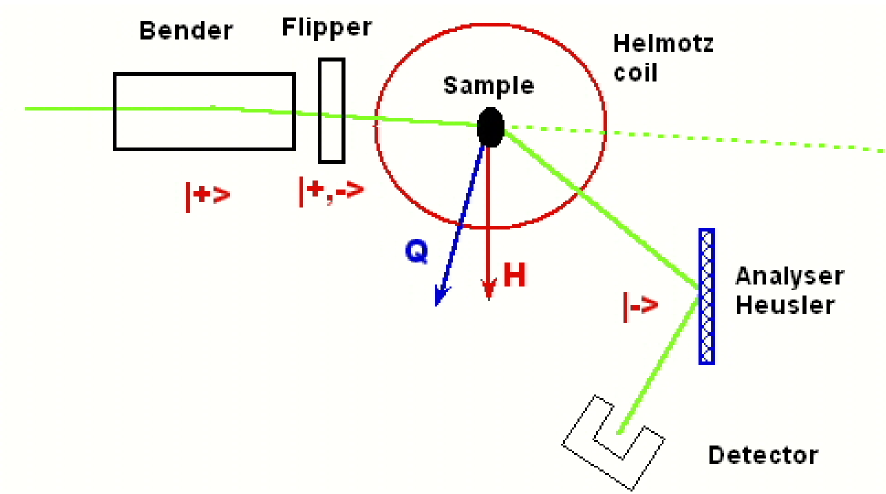

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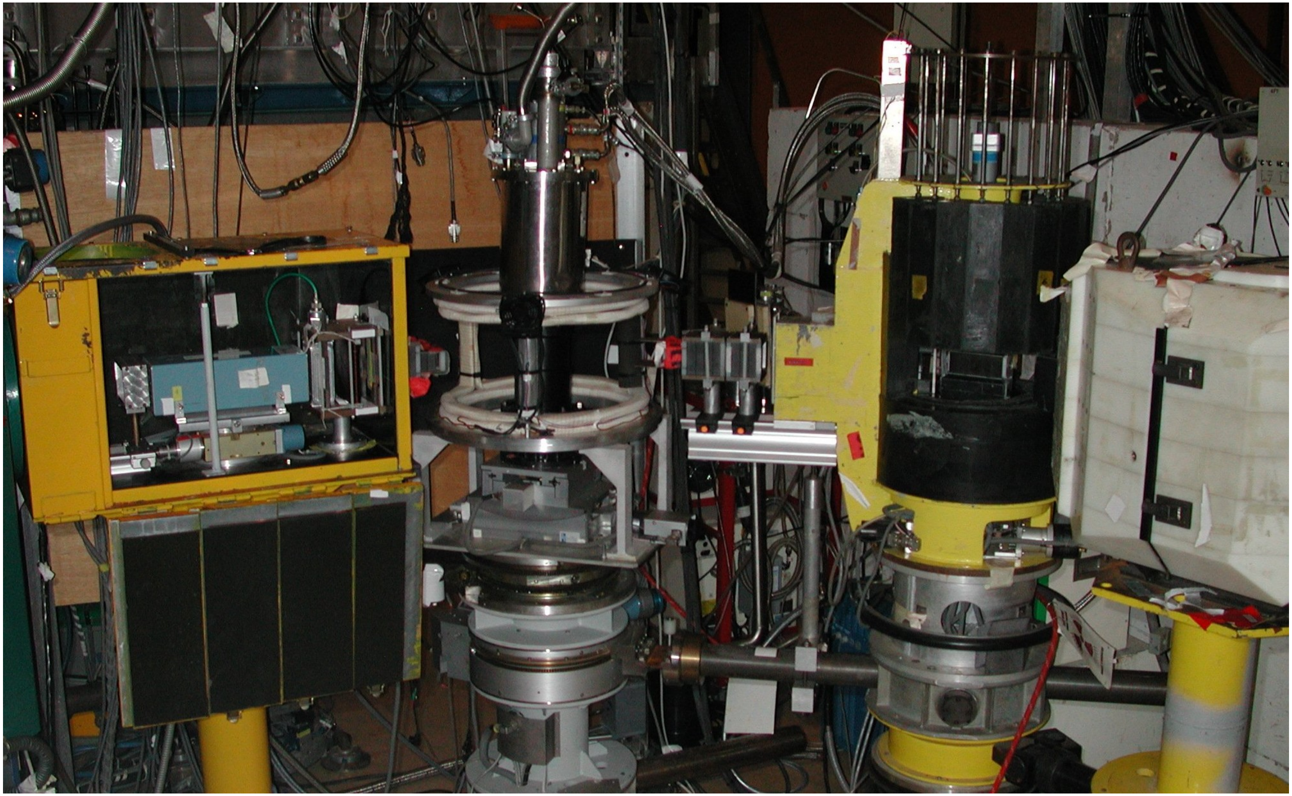
Magnetic components $\perp \vec{Q}$
Spin-flip components $\perp \vec{P}$

$\Rightarrow$ P//Q to maximize magnetism in the SF channel

Polarized cold neutron triple axis: 4F1 (LLB-Saclay)



A-type antiferromagnetism in Na_xCoO_2, x=0.82

S.P. Bayrakci et al, PRL 94, 157205 (2005)

- Spin dynamics ⇒ Propagation wavevector: Q=(001)
  ⇒ Polarized neutrons

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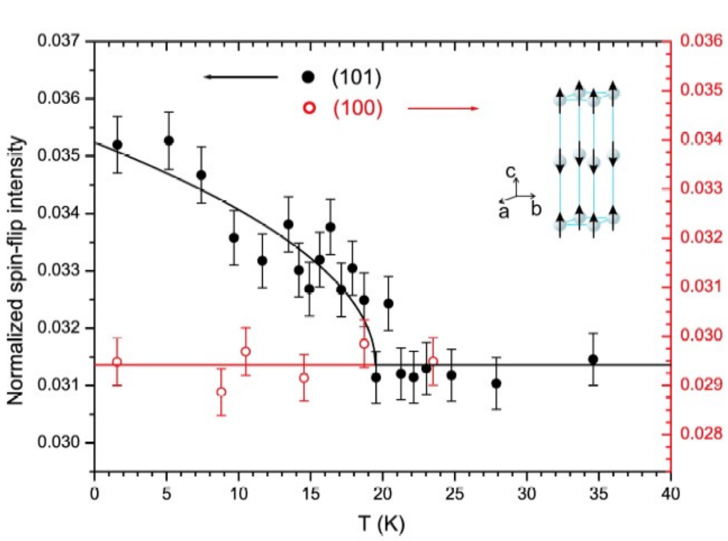
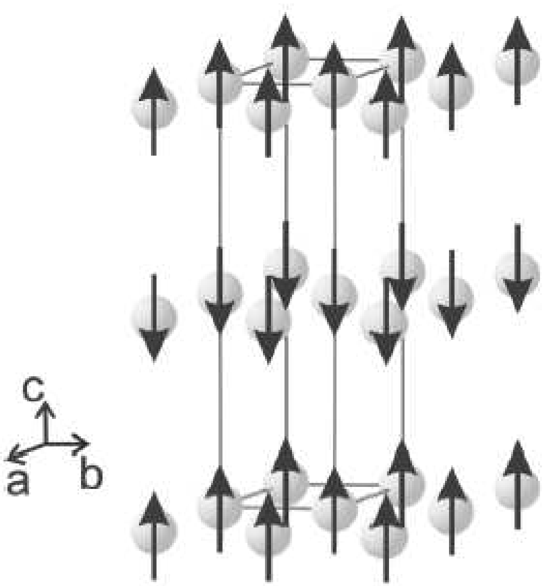
"Normalized spin-flip intensity": SF/NSF





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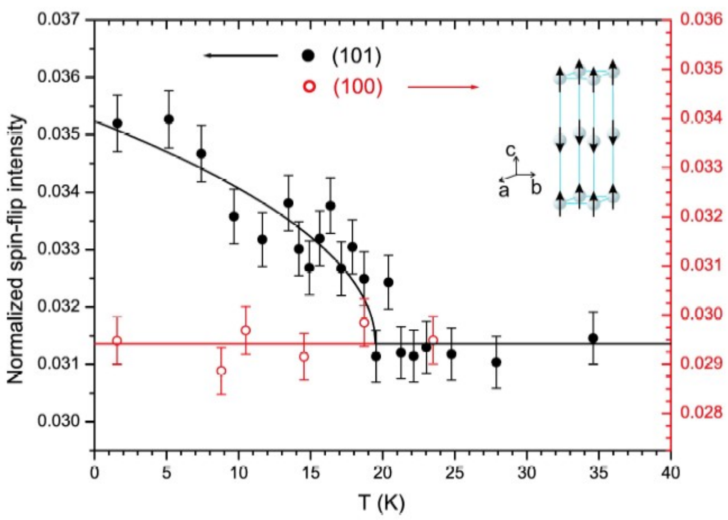

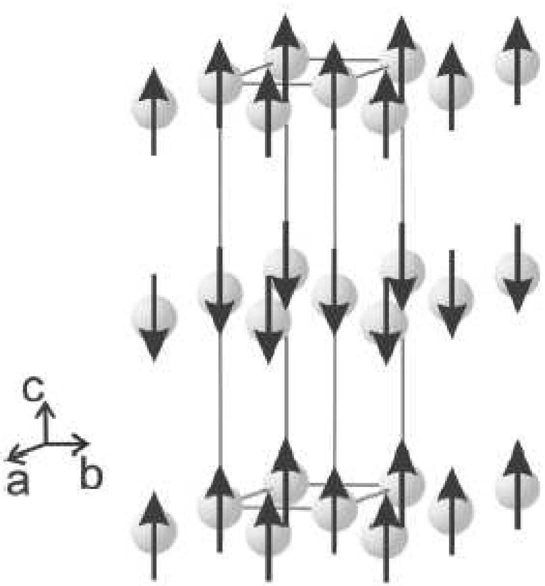

- Ferromagnetic planes AF coupled: decoration of the unit cell
- Small moments: m≃ 0.13 μ_B /Co

Polarized magnetic diffraction at k_I = 2.662 $Å^{-1}$

- Magnetism expected on Q=(1,0,L)≡(0,1,L) in Phase Θ_{II}

- Weak Nuclear Bragg peaks: L=1,2

- For $\vec{P}//\vec{Q}$, All magnetism ⇒ **Spin-Flip**

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

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

$R \sim \mathbf{40}$

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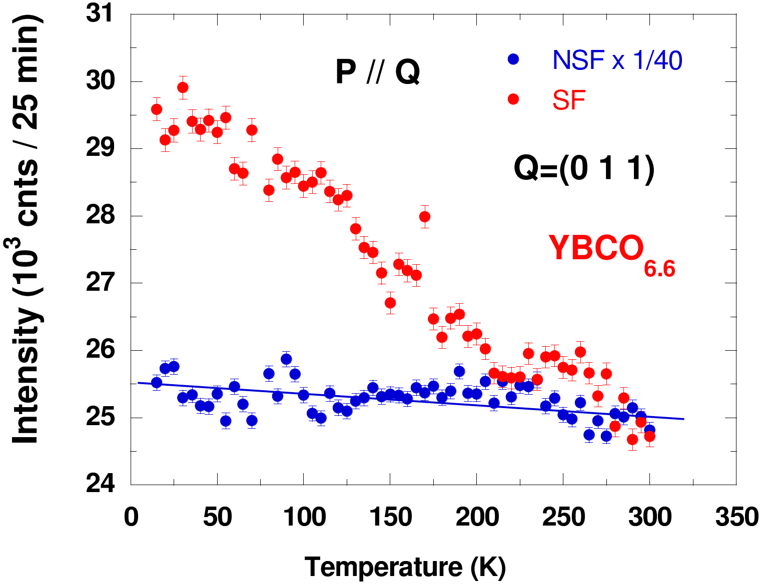
$R \sim 40$

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

Detwinned sample

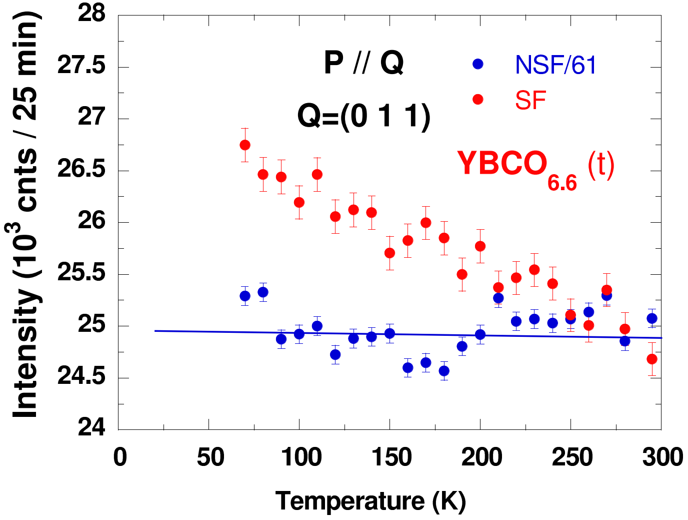


B. Fauqué et al, PRL 96, 197001 (2006)

Raw data Spin-Flip and Non-Spin-Flip: $\vec{P}//\vec{Q}$,

Twinned samples: Q=(0,1,1)≡(1,0,1)

$\mathrm{YBCO}_{6.6}$(t): $T_C = 61$ **K**



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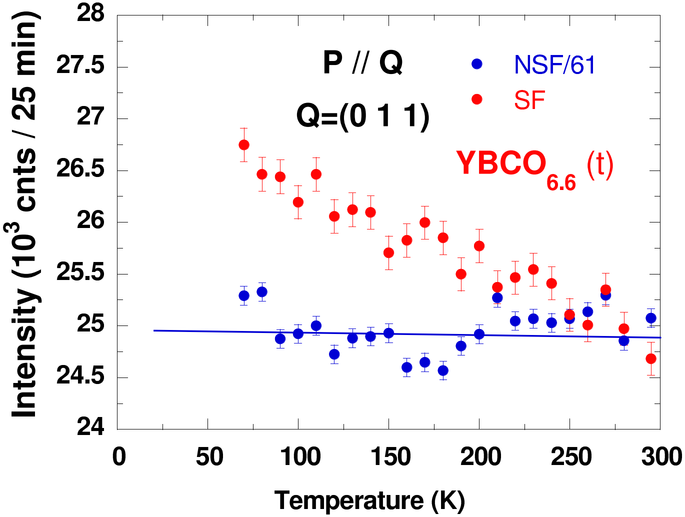
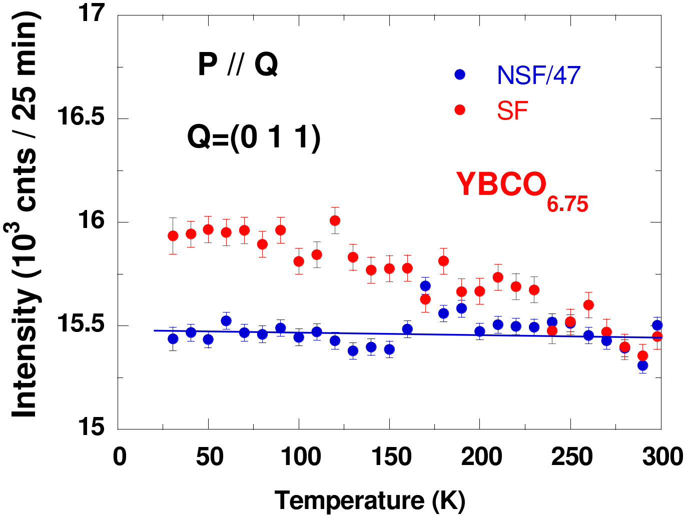
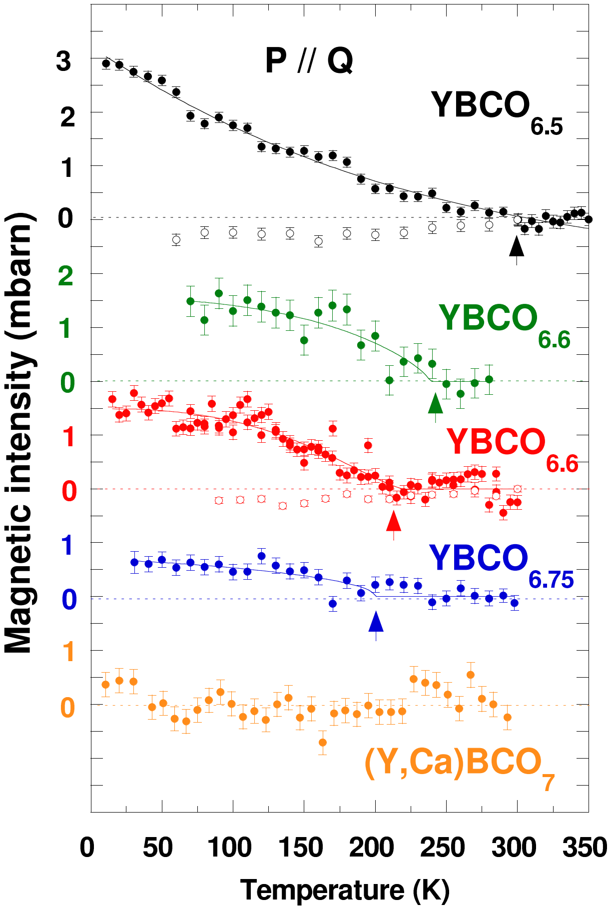


$\mathrm{YBCO}_{6.75}(\mathrm{t})$ - $T_C = 78$ **K**



Novel magnetic order: $\vec{P}//\vec{Q}$



Q=(0,1,1)≡(1,0,1)

$$|F_M|^2 = |F_N|^2[SF/NSF - 1/R]$$

$$YBa_2Cu_3O_{6+x}$$

x	$T_{c,onset}$ (K)	T_{mag}(K)
$O_{6.5}$(t)	ud 54	300 ± 10
$O_{6.6}$(t)	ud 61	250 ± 20
$O_{6.6}$(d)	ud 64	220 ± 20
$O_{6.75}$(t)	ud 78	170 ± 30
Ca(15%) – O_7(t)	od 75	≃0

t: twinned, d: detwinned

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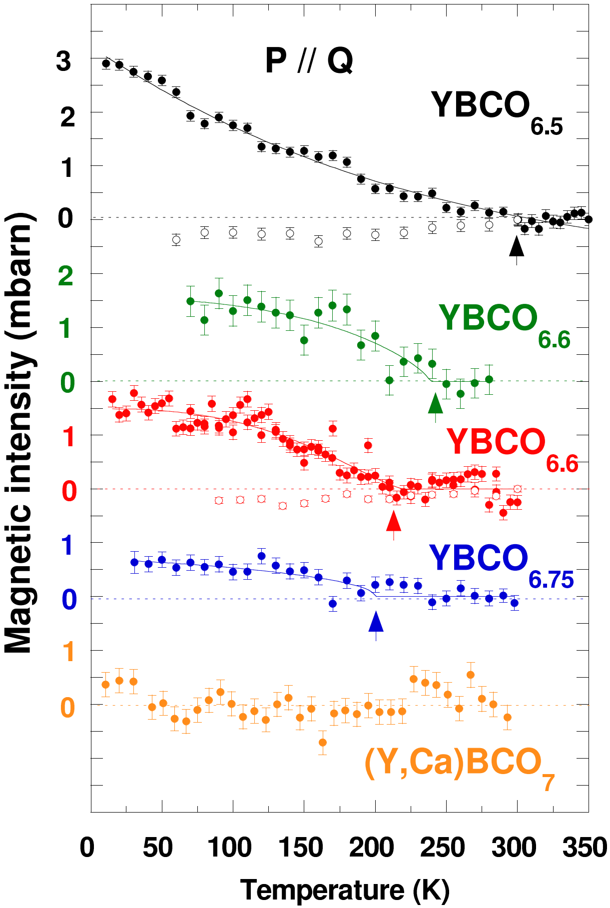

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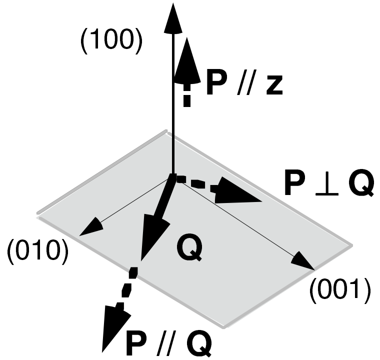
No effect on Q=(0,0,2)
(open symbols)

Polarization dependence: Q=(0,1,1)

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



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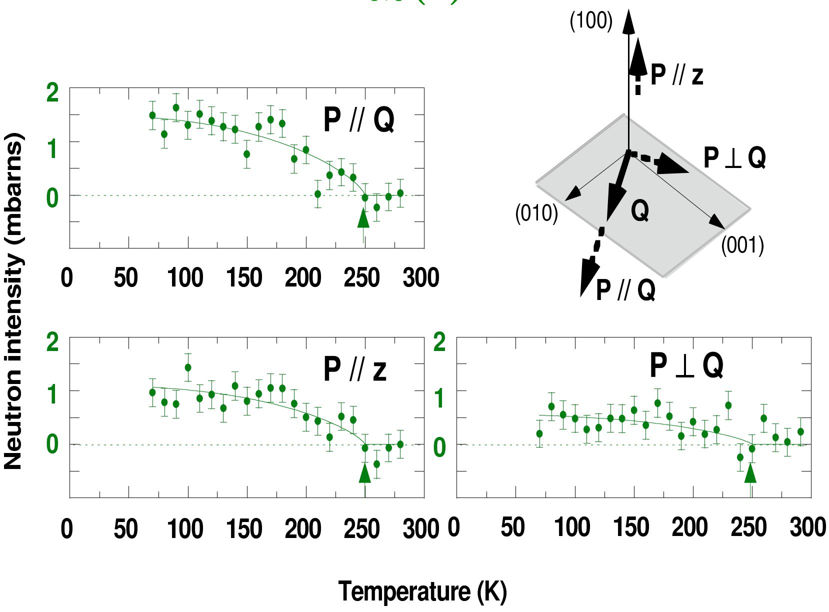
$YBCO_{6.6}$(t)



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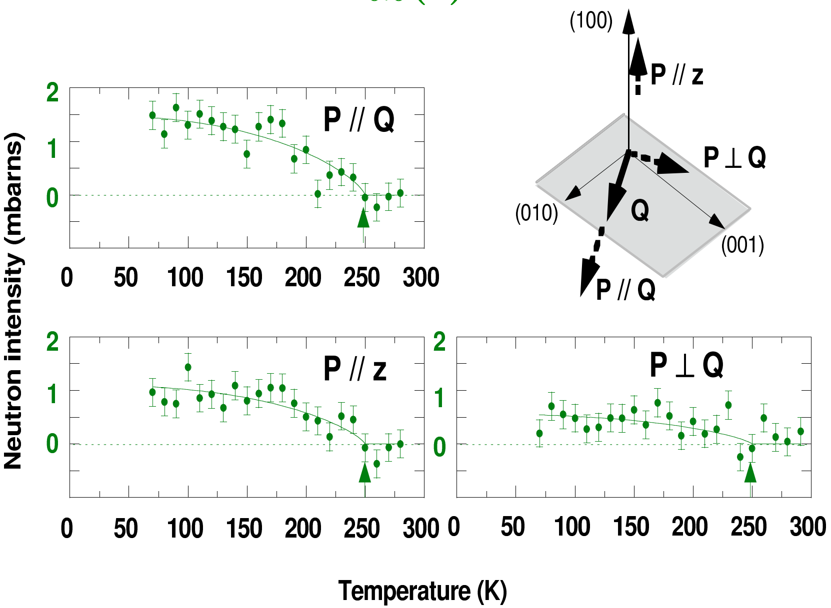

$\vec{M} = (M_a, M_b, M_c)$
at $\vec{Q} = (H, K, L)$

$\vec{P}//\vec{z}$**:**
I= $0.1\frac{1}{2}(|M_a|^2 + |M_b|^2) + 0.9|M_c|^2$

$\vec{P} \perp \vec{Q}$**:**
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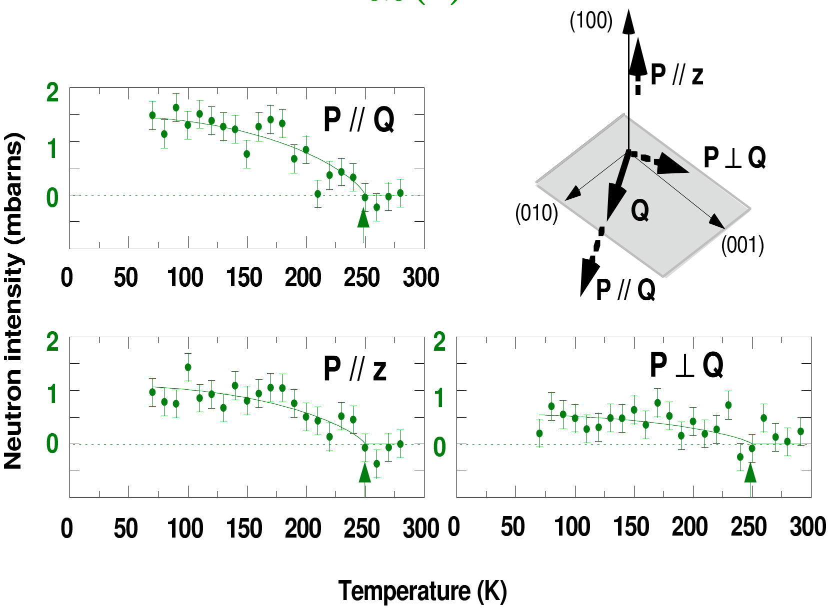

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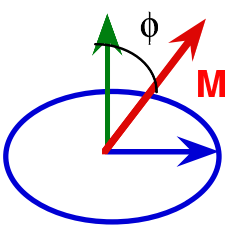
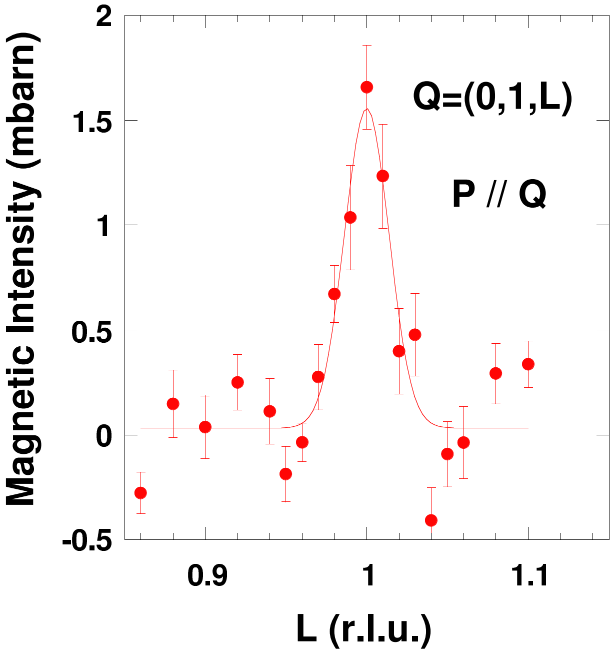
$$\tan(\phi) = \sqrt{\frac{M_a^2+M_b^2}{M_c^2}}$$



$$\Rightarrow \phi = 45° \pm 20°$$

Momentum dependencies in $YBCO_{6.5}$(t): $\vec{P}//\vec{Q}$

$$I_{SF}(75K) - I_{SF}(275K)\frac{I_{NSF}(75K)}{I_{NSF}(275K)}$$



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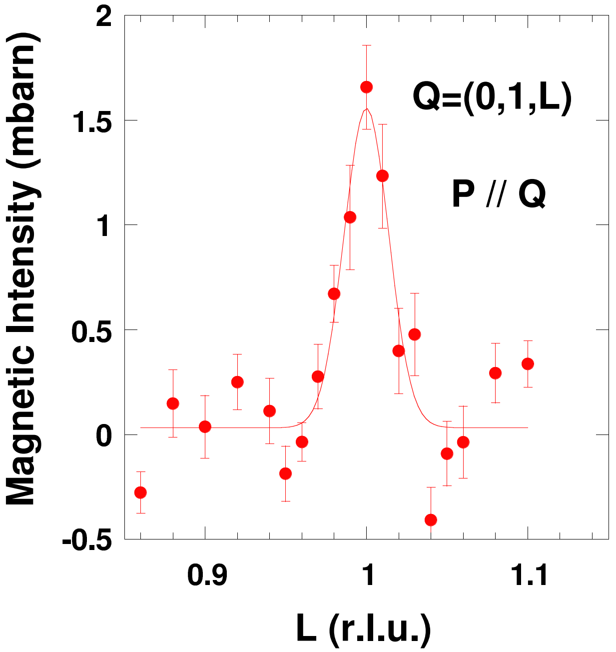

$\Rightarrow$ **Long range order at 75 K**

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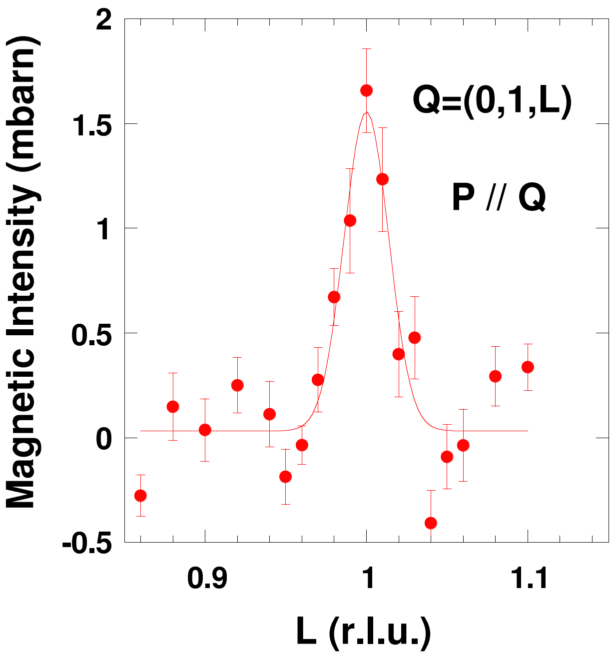
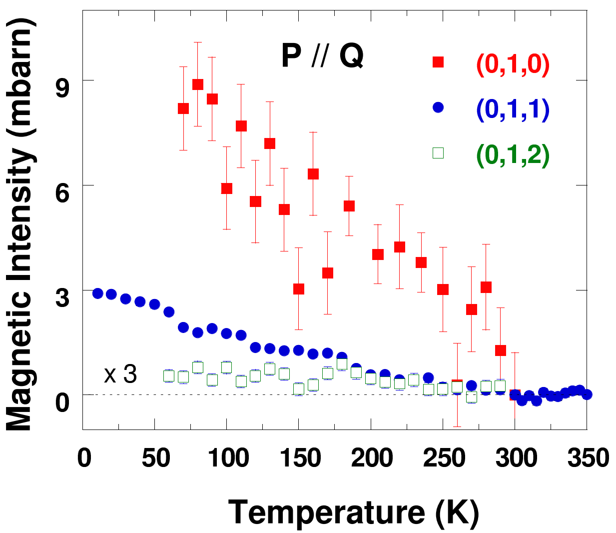


$|F_M|^2 =$
$|F_N|^2[SF/NSF - 1/R]$



- L-dependence:
as $\cos(\pi z L)^2$

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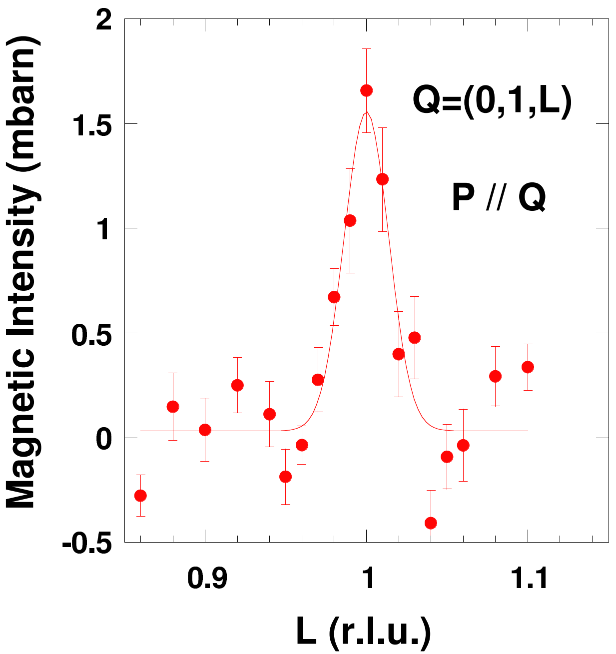

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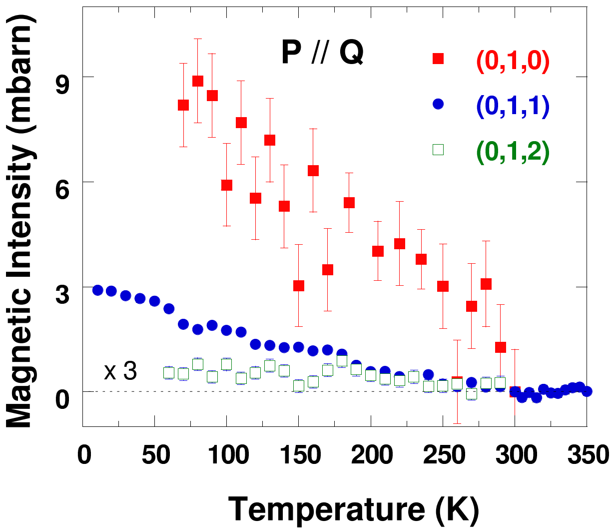

- L-dependence: as $\cos(\pi z L)^2$

$\Rightarrow$ parallel moments within a bilayer

Magnetic order in underdoped $YBa_2Cu_3O_{6+x}$:

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

- preserves Translationnal Symmetry of the Lattice

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- Weak intensity $\sim$ 2 mbarns $\Rightarrow$ M $\sim$ 0.05 to 0.1 μ_B
  (assuming weakly dependent magnetic form factor)

Which model: orbital or spin moments ?

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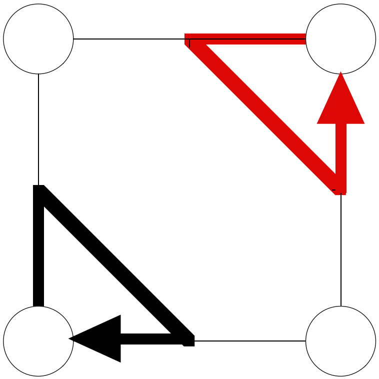
Orbital moments



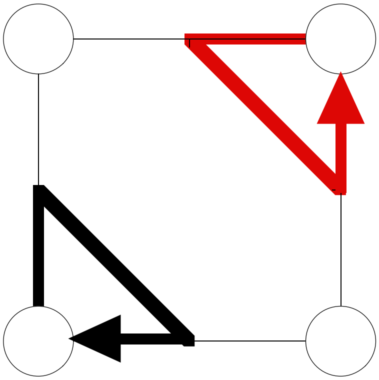
Circulating Currents
Phase Θ_{II}

Simon and Varma, PRL 89 247003 (2002)

C.M. Varma, PRB 73, 155113 (2006)

Which model: orbital or spin moments ?

Orbital moments



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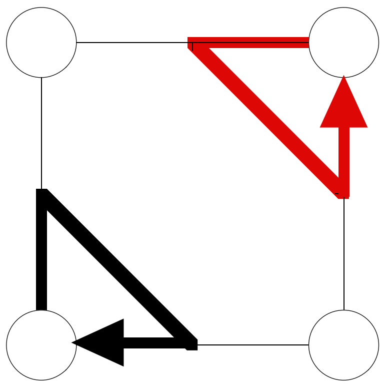

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V. Aji and C.M. Varma cond-mat/0605468

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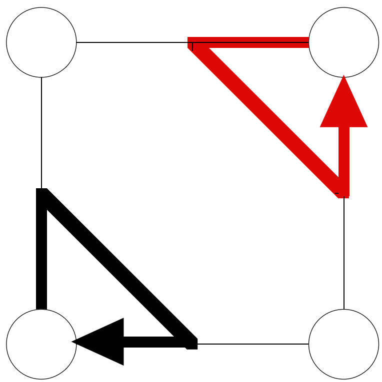
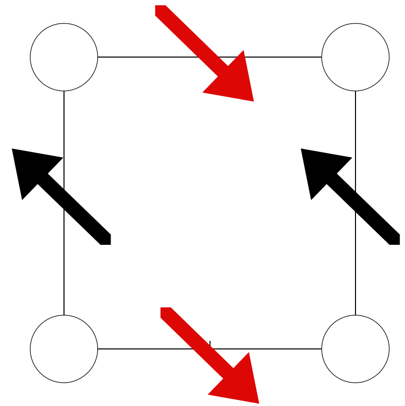


Spins on oxygen sites



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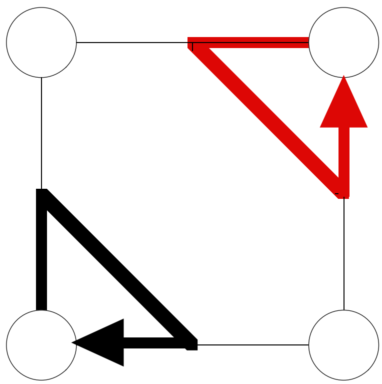

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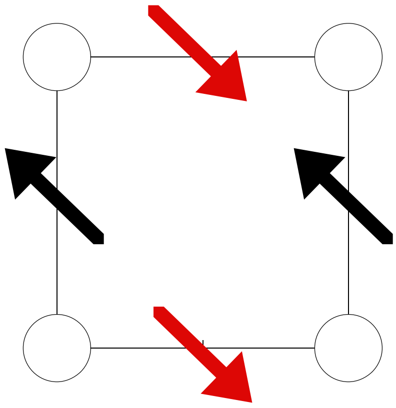

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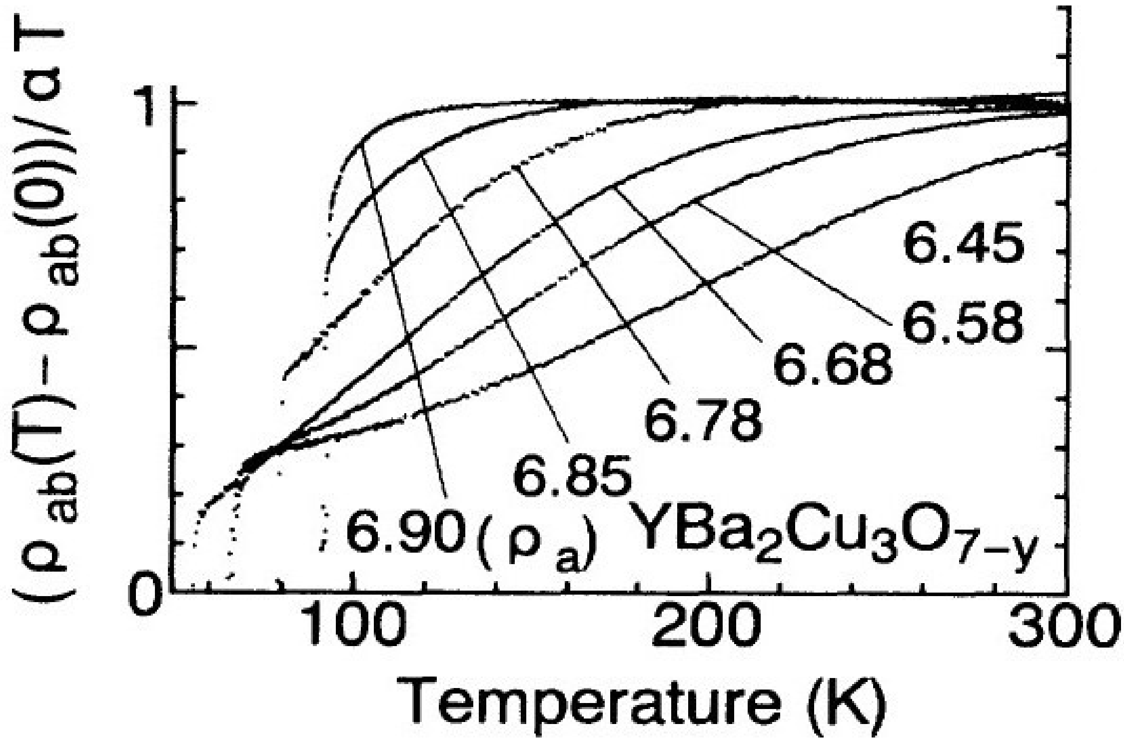
Relation with the Pseudogap: Resistivity



T. Ito *et al.*, PRL 70, 3995 (1993).

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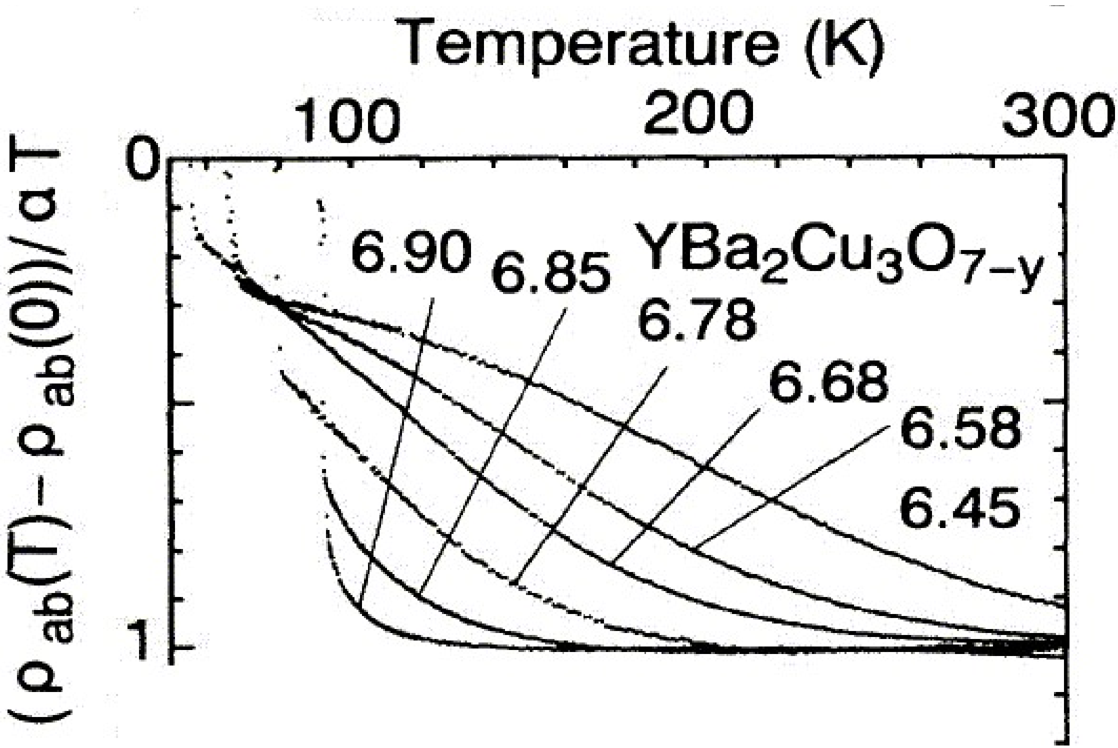

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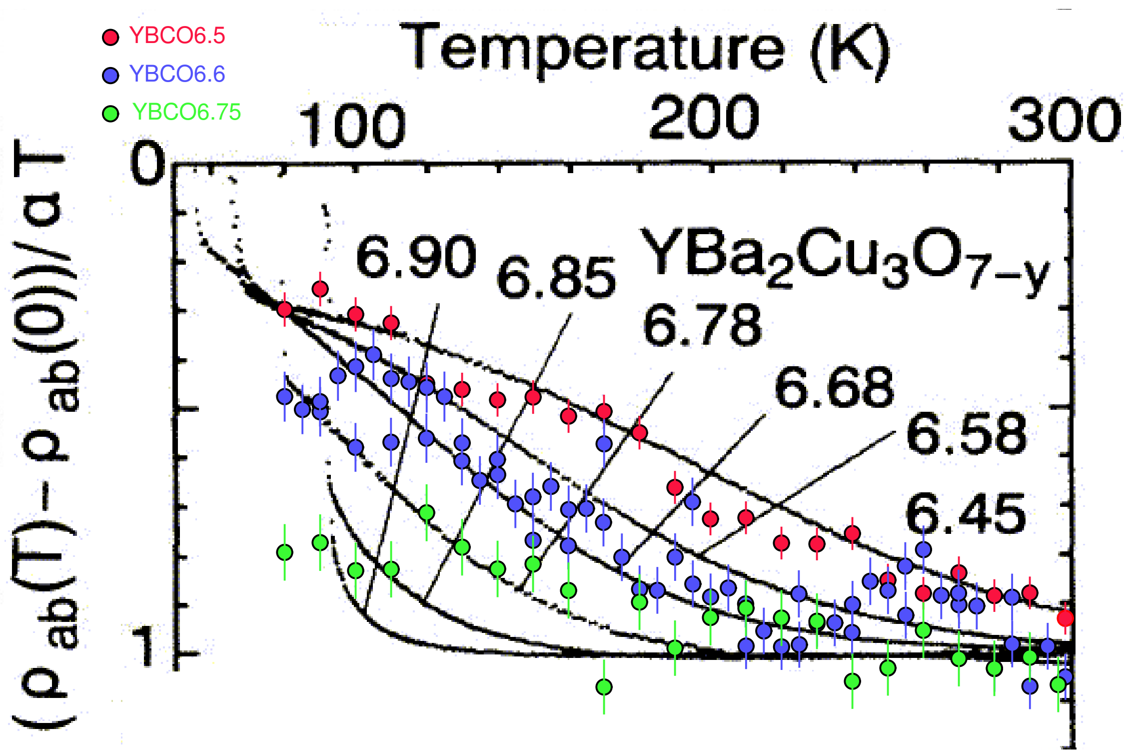

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Phase diagram: magnetic order at T*

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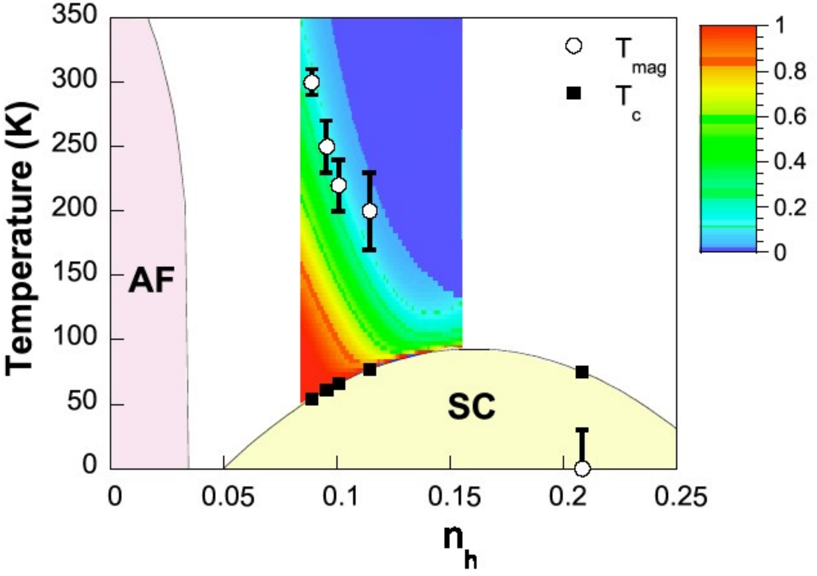
⇒ Hidden order parameter for the pseudogap phase

$$\delta R(T) = 1 - [\rho_{ab}(T) - \rho_{ab}(0)]/(\alpha T)$$



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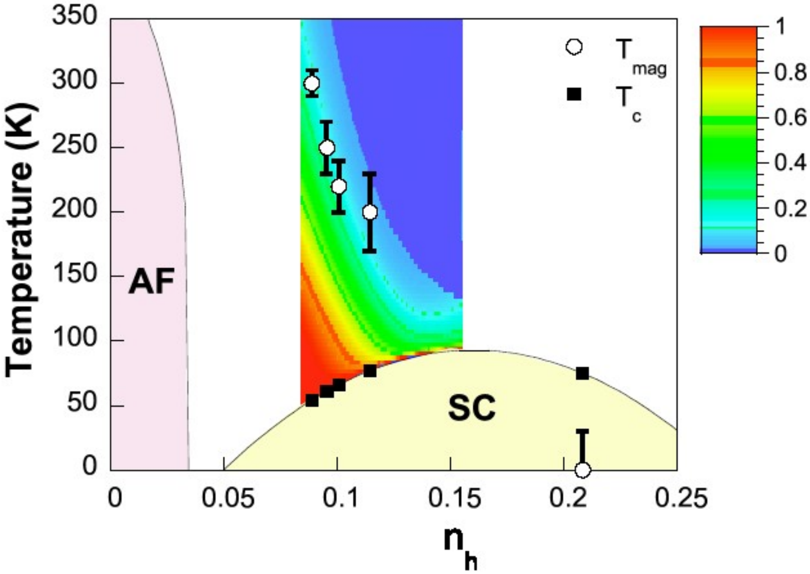

⇒ Magnetic decoration of the unit cell

Circulating Currents phase Θ_{II} C.M. Varma, PRB 73, 155113 (2006)

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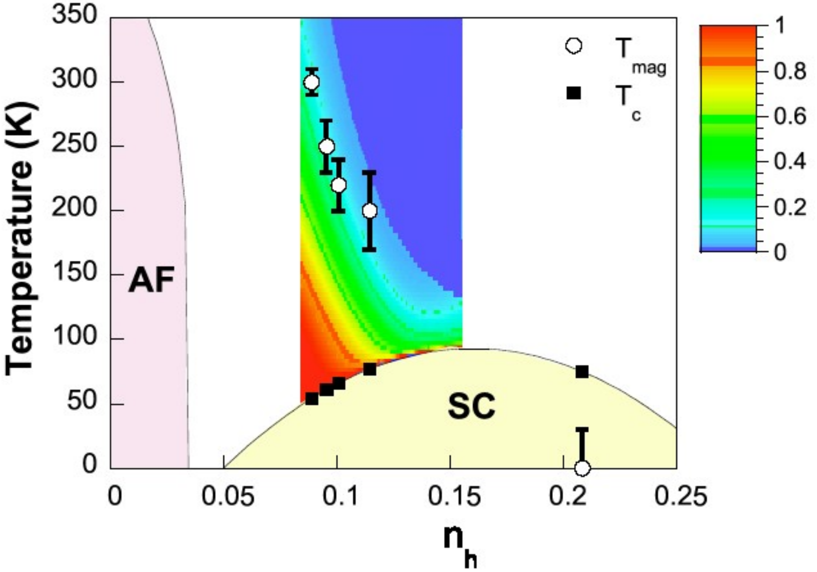

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Circulating Currents phase Θ_{II} C.M. Varma, PRB 73, 155113 (2006)

⇒ 3 band Hubbard model