# Intra-Unit-Cell magnetic order in the pseudogap state of high-*Tc* superconductors

Y. Sidis

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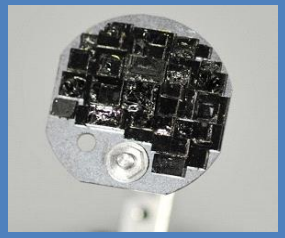
B. Fauqué (PHD:04-07), V. Balédent (PHD:07-10), L. Mangin-Thro (PHD)
(Laboratoire Léon Brillouin - Saclay)

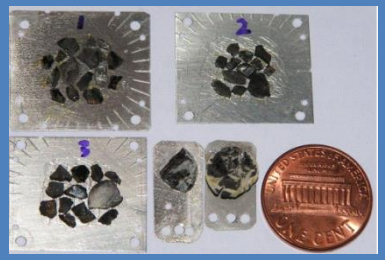
## Y123: $YBa_2Cu_3O_{6+x}$

- D. Haug, C.T. Lin, V. Hinkov (MPI Stuttgart)
- X Chaud (CRETA, Grenoble), A.Wildes (ILL-Grenoble)
- H.A. Mook (Oak Ridge, USA)



## Hg1201: $HgBa_2CuO_{4+x}$

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

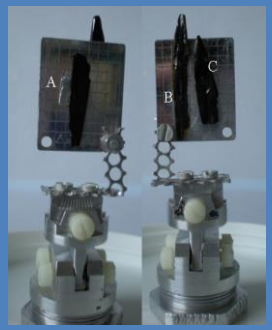


## La214: $La_{2-x}Sr_2CuO_4$

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


## Bi2212: $Bi_2Sr_2CaCu_2O_{8+x}$

- I. Laffez, F. Giovanneli (IUT-Bois),
S. De Almeida-Didry(PHD: 07-10)
- L. Ammor, A. Ruiter(LEMA-Tours)



# outline

1/ Introduction to the phenomenology of the Pseudo-gap
2/ Density wave instabilities vs Pseudo-gap
3/ Loop current  model of the Pseudo-gap
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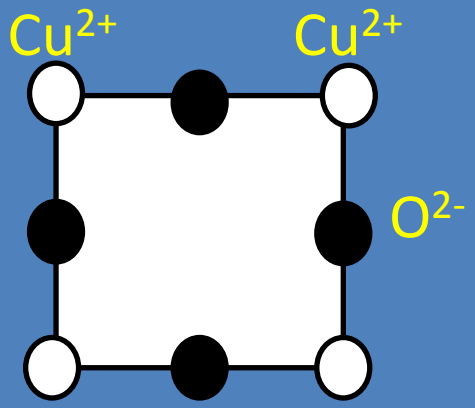
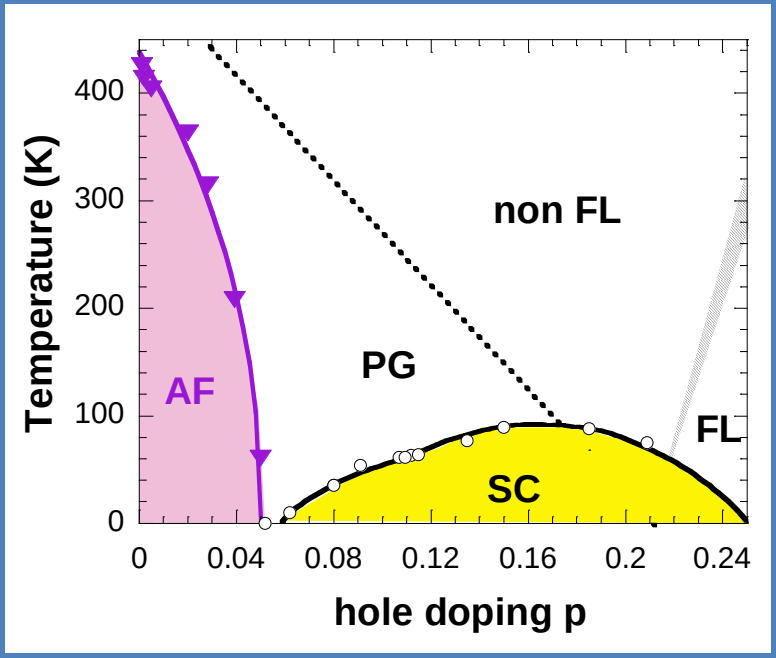
5/ Hole doping dependence of the IUC magnetic order
6/ Conclusion

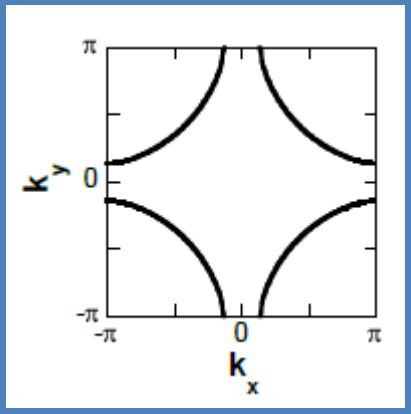
# Phase diagram of HTc cuprates and d-wave superconductivity



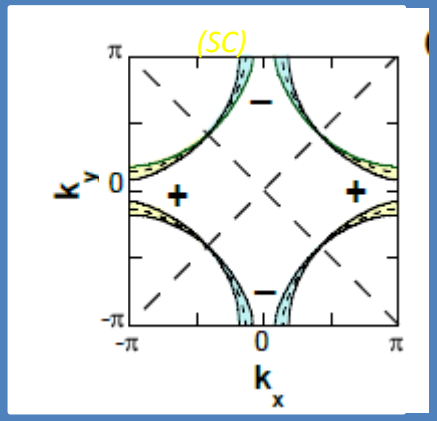




*2D Fermi surface $T > T_c$*

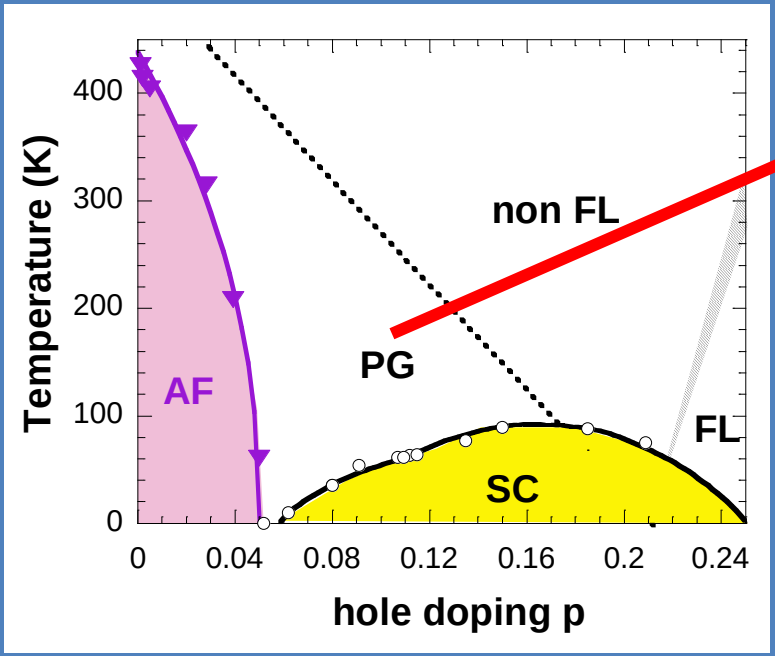
*(Fermi liquid)*




*d-wave superconducting gap $T < T_c$*



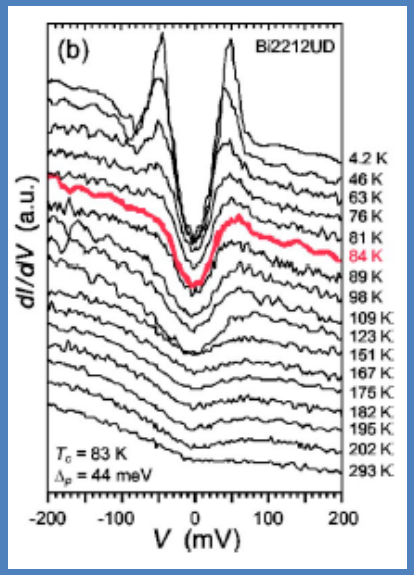
# Introduction to the physics of the pseudo-gap state




***Mysterious pseudo-gap state***

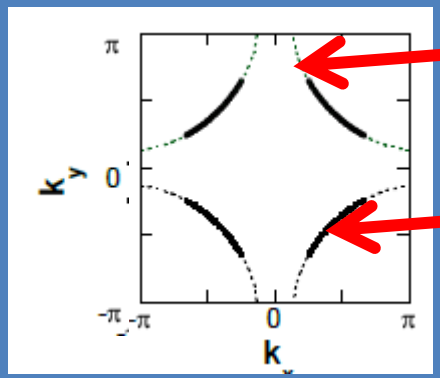
*- First observed in NMR measurements as an anomalous decrease of the uniform magnetic susceptibility*
*NMR: Alloul et al (PRL 1989)*

*- The pseudo-gap gives rise to severals anomalies at T* in transport and thermodynamic measurements*
*Review: Timusk, Rev. Mod Phys 2002*




*- Depletion of the electronic density of states at the Fermi level below T**

*Tunneling spectroscopy:*
*Renner, PRL 1998*

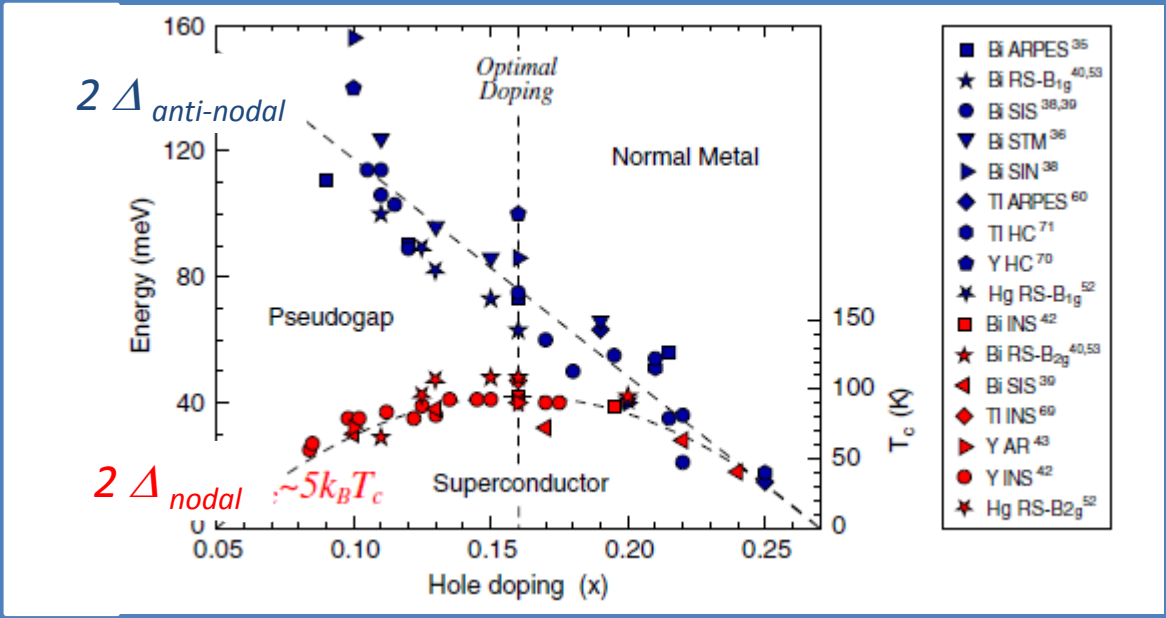



*Partial gap opening*

*Persistence of Fermi arcs*

*ARPES:*
*Kanigel, Nature 2006*

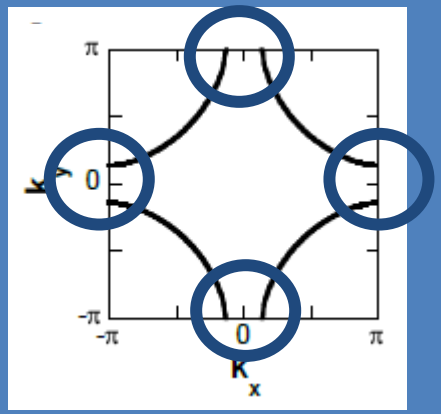
# Two Energy scales



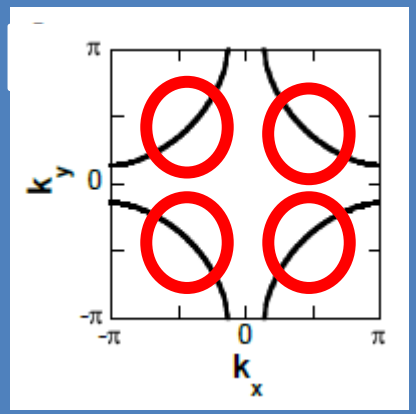

*Le Tacon, Nature Physics 2006*

*Hufner, Rep. Phys. Prog 2008*

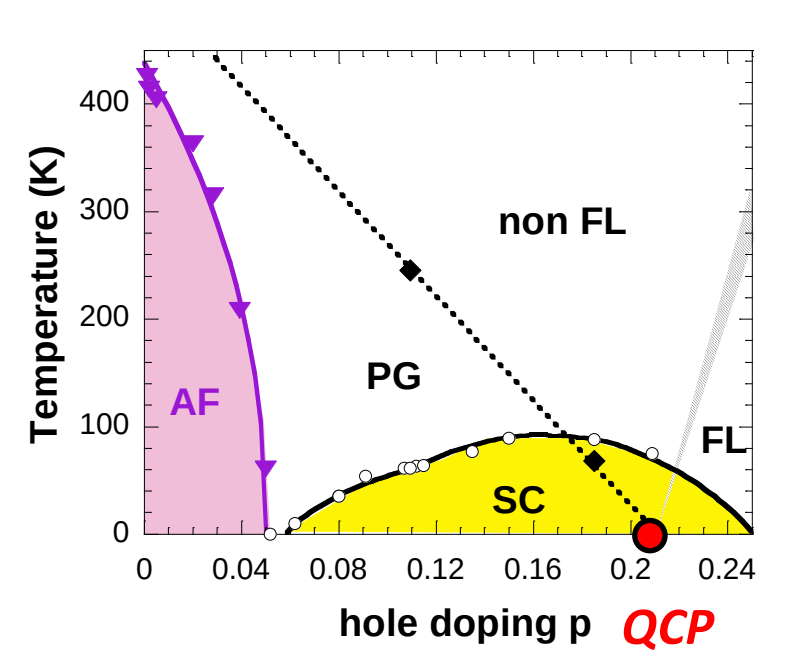
$\Delta$ *anti-nodal*




$\Delta$ *nodal*



# the PG phase is a true symmetry breaking state




***Resonant Ultra-sound spectroscopy***

A. Shekhter et al. *Nature* 2013

the pseudo-gap phase :

- a long range ordered state **YES**
- order parameter ?
- the broken symmetry ?

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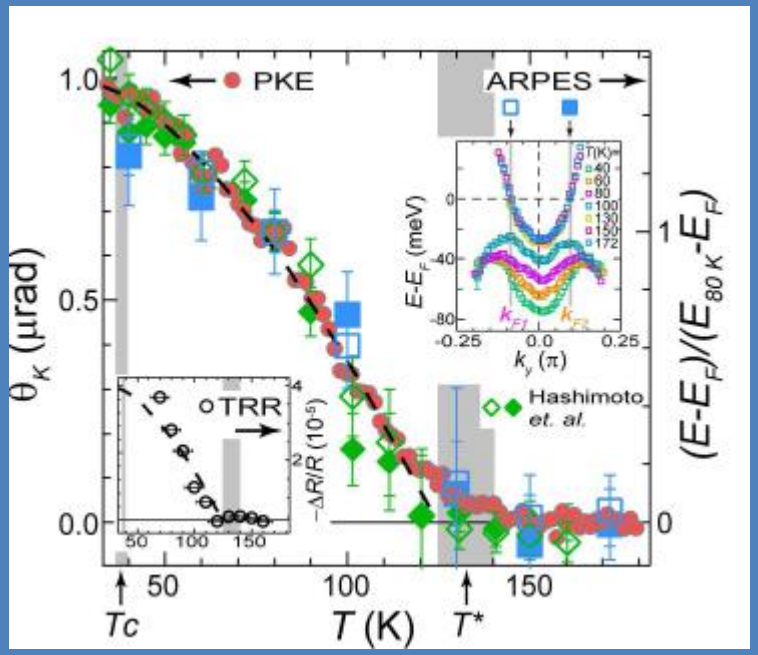
# Density Wave instability vs Pseudogap

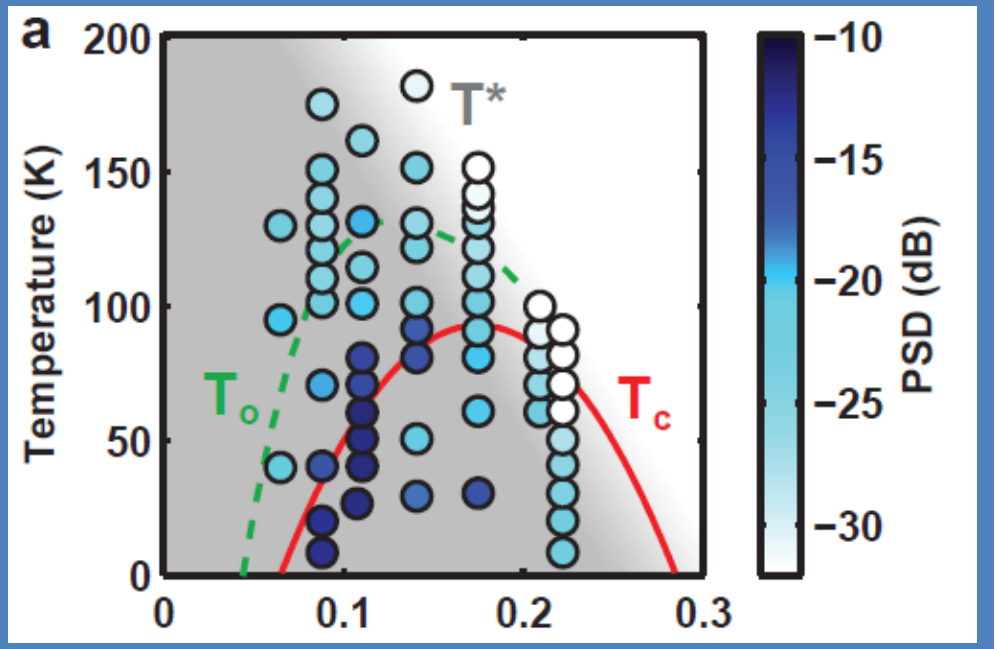
**$Pb_{0.55}Bi_{1.5}Sr_{1.6}La_{0.4}CuO_{6+\delta}$**
**(Pb-Bi2201, Tc = 38 K, T = 132 ± 8 K)**




*Anomalies at T* in :*
*- Polar Kerr Effect*
*- ARPES*
*- Time resolved Reflectivity*

*Rui Han He et al., Science 2011*

**$Bi_2Sr_2CaCu_2O_{8+\delta}$**
**(Bi2212)**

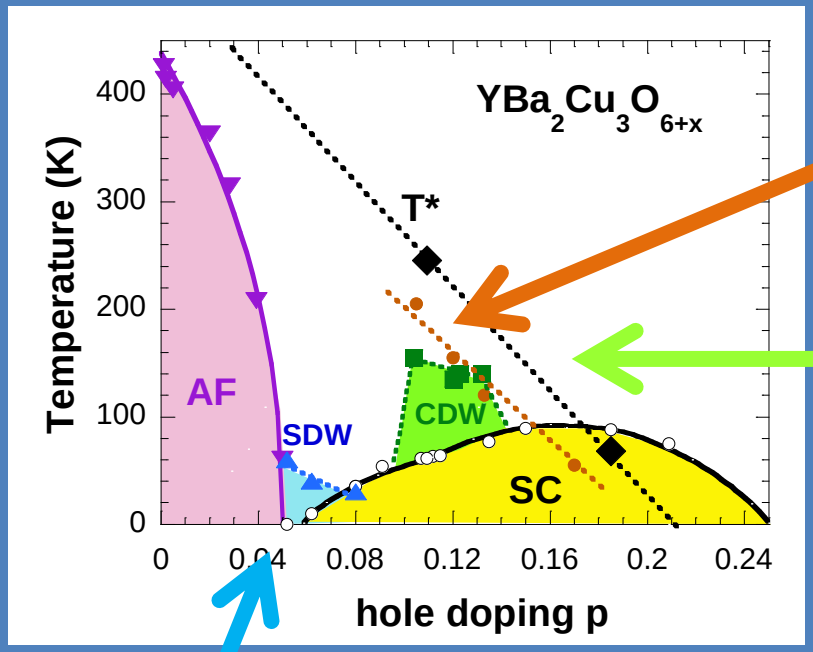



- *STM spectroscopy*
- *Fluctuating charge modulations at:*
- *Q* = (δ,0) and (0,δ) with δ ~ 1/4*

*C. V. Parker et al., Nature 2010*

# Density Wave instability vs Pseudogap

$YBa_2Cu_3O_{6+x}$



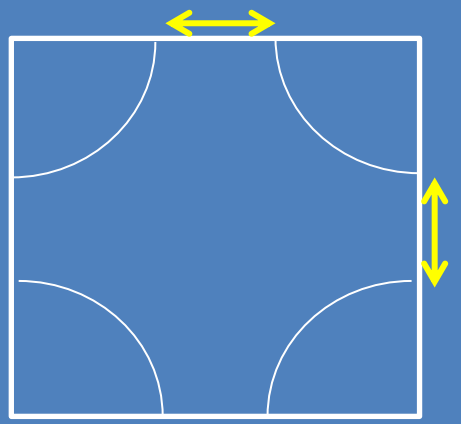

anomalous Kerr effect $T_k < T^*$

*Xia, PRL 2008*

Incipient CDW – $T_m < T^*$

- *$Q^* = (\delta,0)$ and $(0,\delta)$ with $\delta \sim 0.3$*

*Chang , Nature Phys. 2012*
*Ghiringhelli, Science 2012*



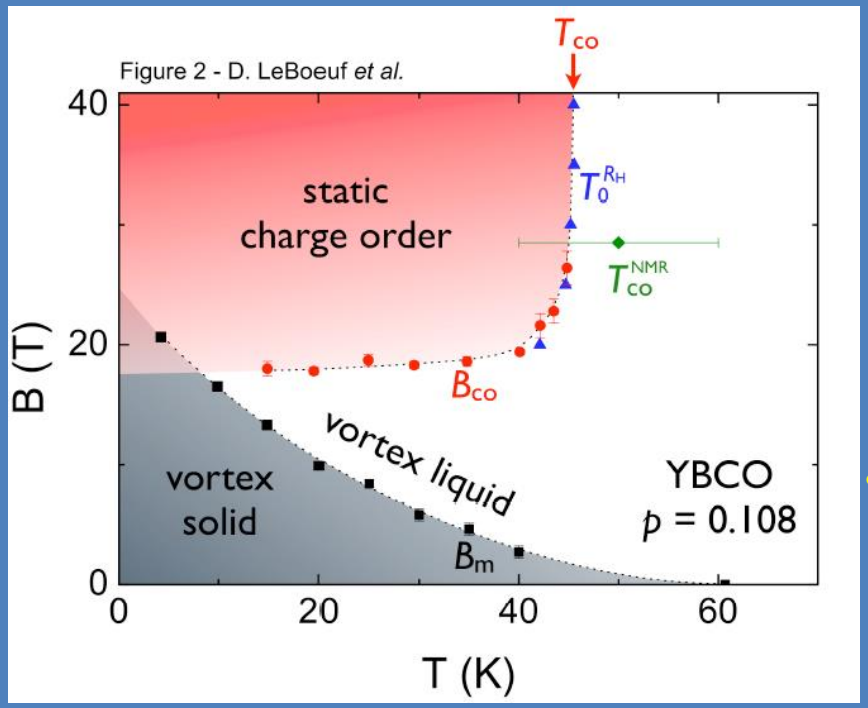
glassy SDW : $T_{SDW} << T^*$
(neutron, μSR, RMN)

*Haug, New J. Phys. 2010*

*T. Wu et al., PRB 2013*

# Density Wave instability vs Pseudogap

$YBa_2Cu_3O_{6+x}$




**anomalous Kerr effect $T_k < T^*$**

*Xia, PRL 2008*

**Incipient CDW – $T_m < T^*$**

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*Ghiringhelli, Science 2012*

**glassy SDW : $T_{SDW} << T^*$**
**(neutron, μSR, RMN)**

*Haug, New J. Phys. 2010*
*T. Wu et al., PRB 2013*

**Stable CDW under magnetic field &**
**Fermi surface reconstruction**
**(NMR, quantum oscillation, ultrasound)**

D. LeBoeuf, *Nature* 2007.
T. Wu et al., *Nature* 2011.
D. LeBoeuf et al., *Nature Physics* 2013.

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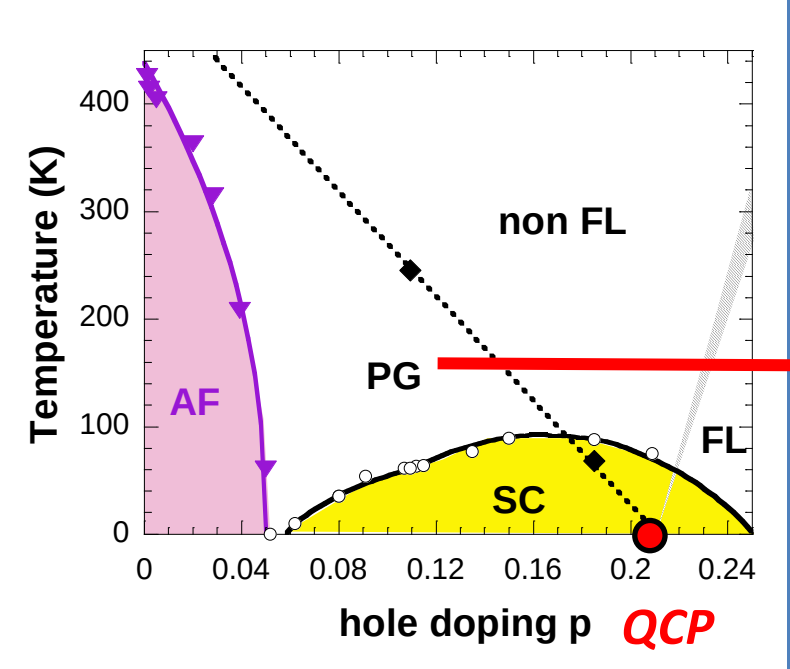
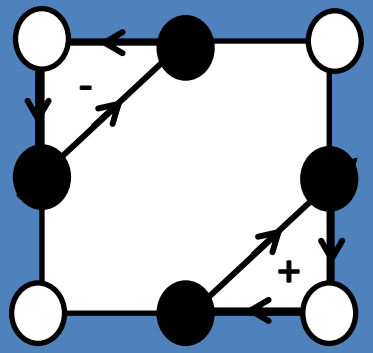
# The Loop Current model for the Pseudogap




*C.M. Varma, PRB 1997; PRB 2006*

3-band model



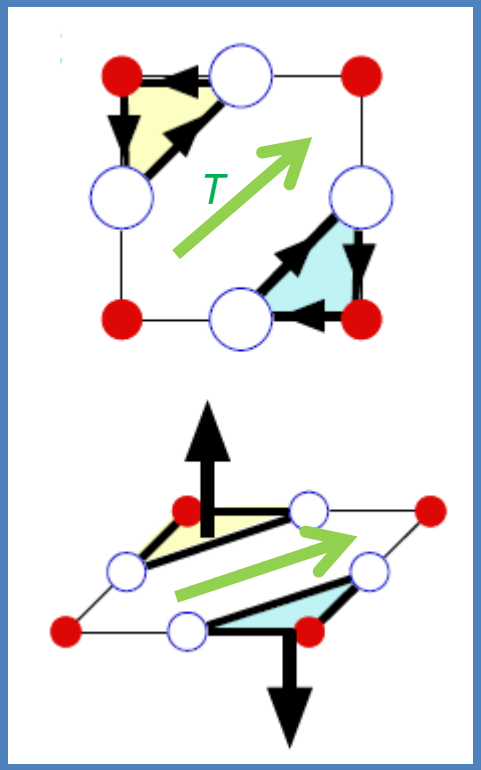

LC state : phase Θ-II

the pseudo-gap phase :

- a long range ordered state — **YES**
- order parameter — **Circulating Current loops in $CuO_2$ unit cell**
- the broken symmetry — **Time Reversal Symmetry**

LC order :
Intra-unit-cell magnetic order

*C.M. Varma, PRB 1997; PRB 2006*




*Staggered orbital-like moments*
*"a magnetic fingerprint "*

## What are we looking for ?

*1/ orbital-like moments*

$$\vec{m}$$

*2/ Magnetic quadrupole*

$$M_{ij} = \frac{1}{6}\int dV\,[3(x_i m_j + m_i x_j) - 2(\vec{x}\cdot\vec{m})\delta_{ij}]$$

*3/ Magnetic toroidal moment (anapole)*

$$\vec{T} = \int dV\,(\vec{x}\times\vec{m})$$

*S. Di Matteo et al., PRB 2012*

***Possible observation …..***

**a) Neutron scattering**

*Varma PRB 1997* *Fauque, PRL 2006*

**b) X-ray diffraction & absorption**

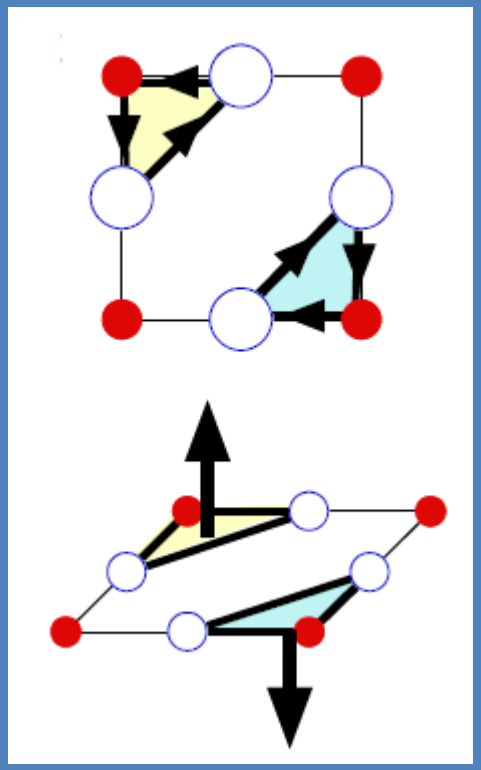
*Di Matteo, PRB 2003* *Kaminski, Nature 2002*

**c) Bi-refringence**

*Varma, arXiv1310.8275* *Armitage, arXiv 1310.2265*

LC order :
Intra-unit-cell magnetic order

*C.M. Varma, PRB 1997; PRB 2006*



*Staggered orbital-like moments*
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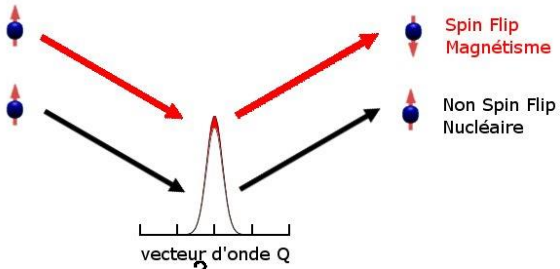
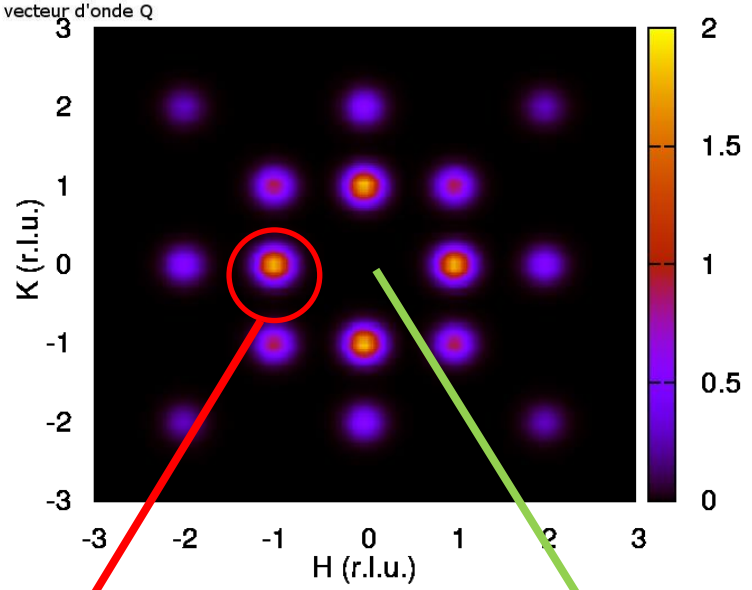
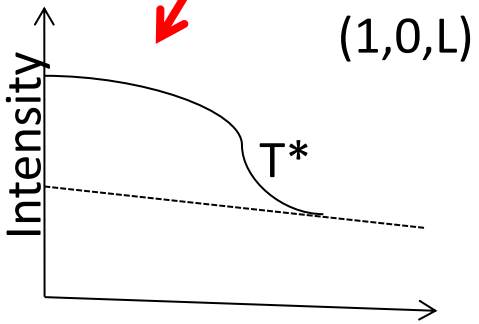
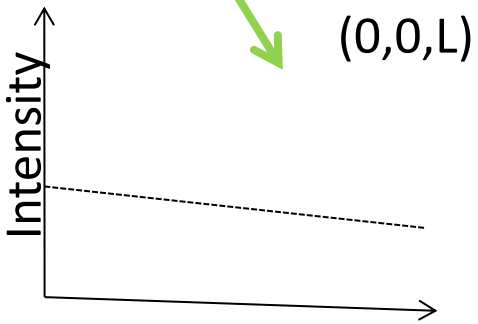
## What are we looking for ?




*Spin polarized neutron diffraction technique*



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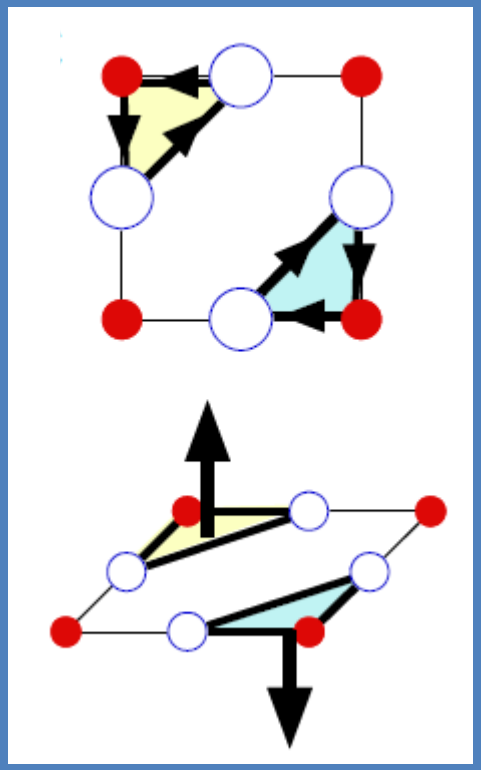
LC order :
Intra-unit cell magnetic order

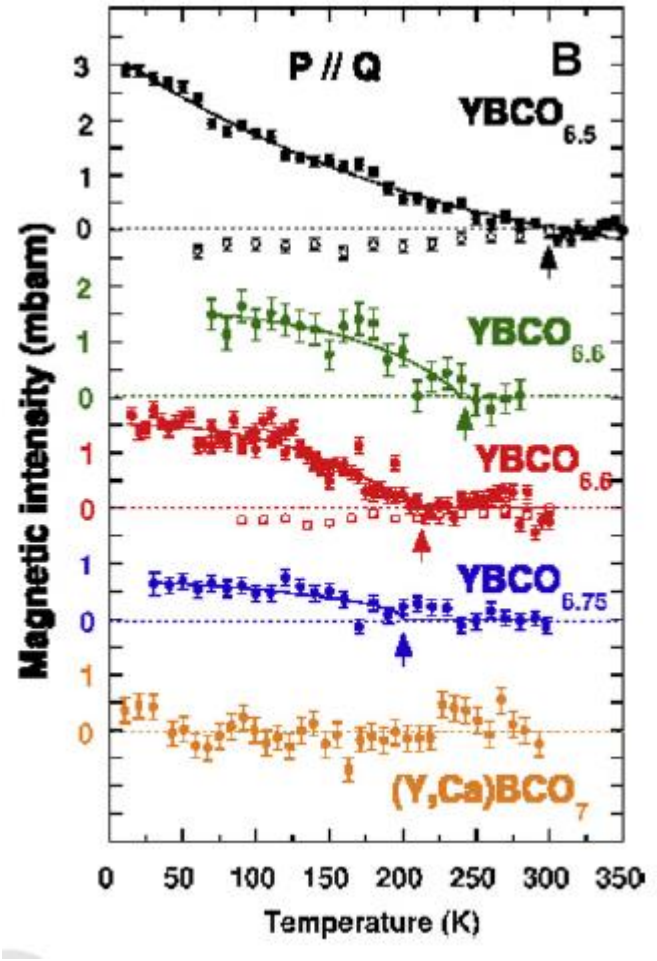
*C.M. Varma, PRB 1997; PRB 2006*



*Staggered orbital-like moments*
*"a magnetic fingerprint "*

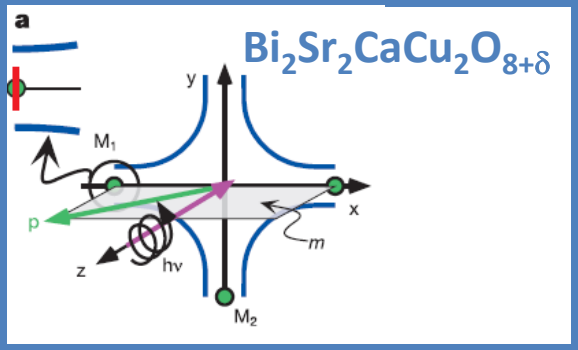
## Novel magnetic order in the pseudogap state

*Spin polarized neutron diffraction technique*

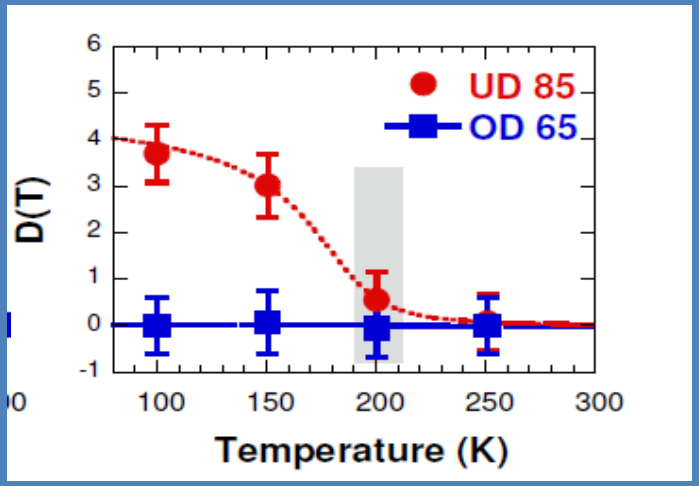



*B. Fauqué et al., PRL 2006*
*H.A. Mook et al., PRB 2007*

## Broken time-reversal symmetry
## ARPES

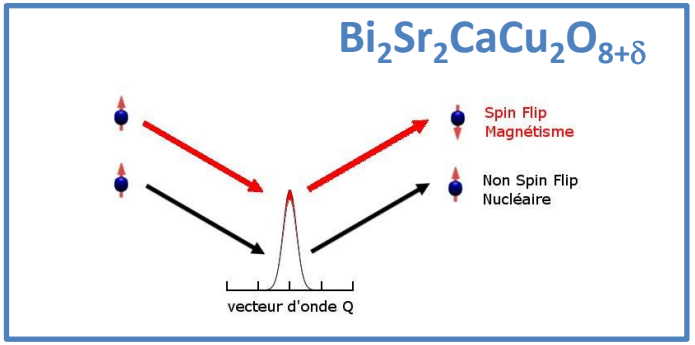



*Dichroism in ARPES*

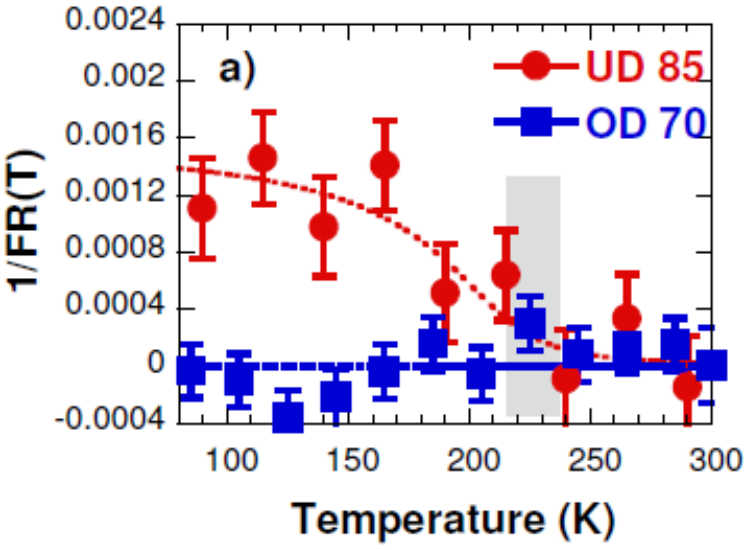



*Kaminski, Nature 2002*

## Broken time-reversal symmetry
## Polarized neutron difffraction

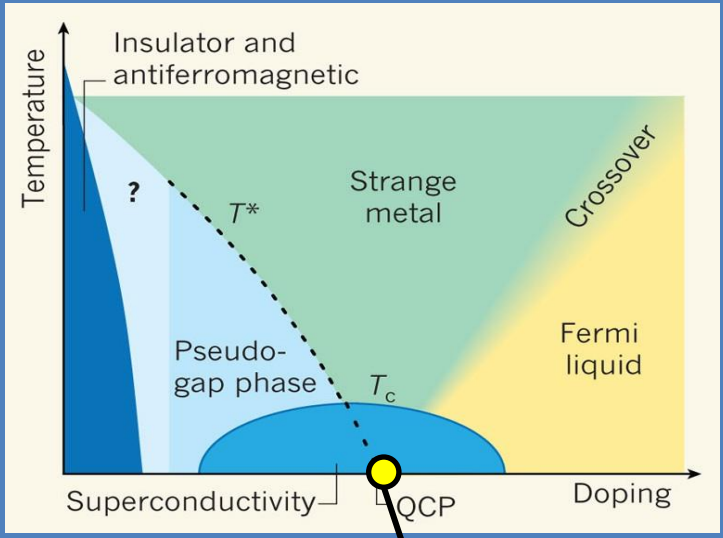



***polarized neutron***




*S. De Almeida-Didry, PRB 2012*
*Y. Sidis & P. Bourges, arXiv:1306.5124*

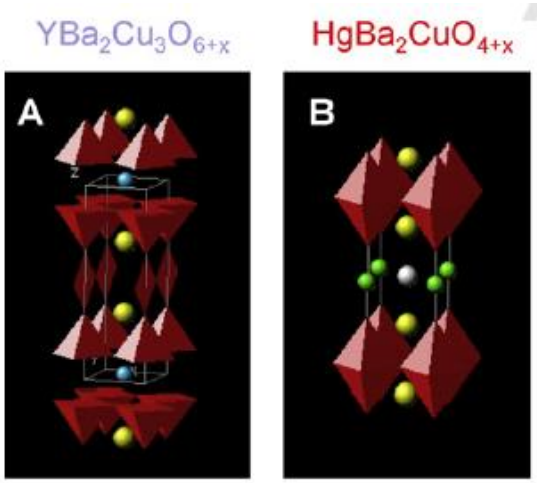
## Generic phase diagram

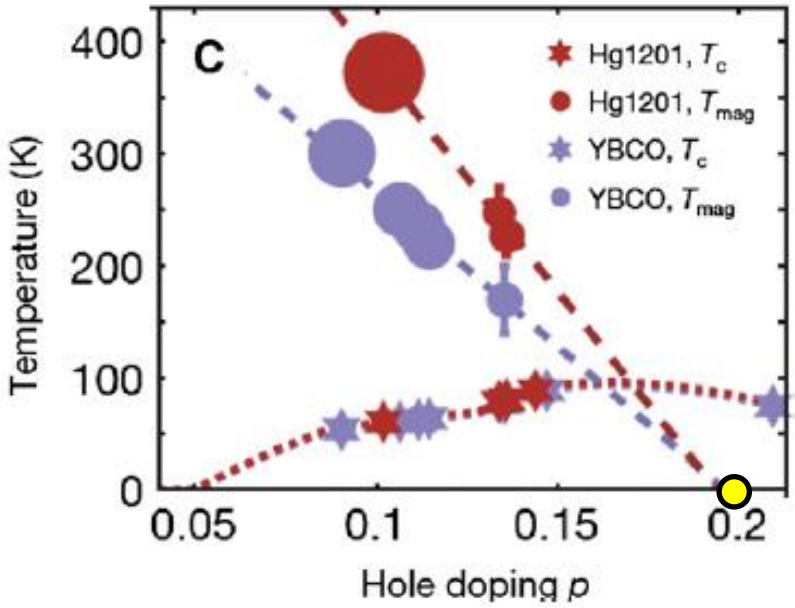



*Quantum critical point ?*

*Tallon & Loram Physica C 2000*

## Novel magnetic order in the pseudogap state




*Y. Li et al., Nature 2008*

*Y. Li et al., PRB 2011*

*P. Bourges & Y. Sidis, C.R. Physique 2011*

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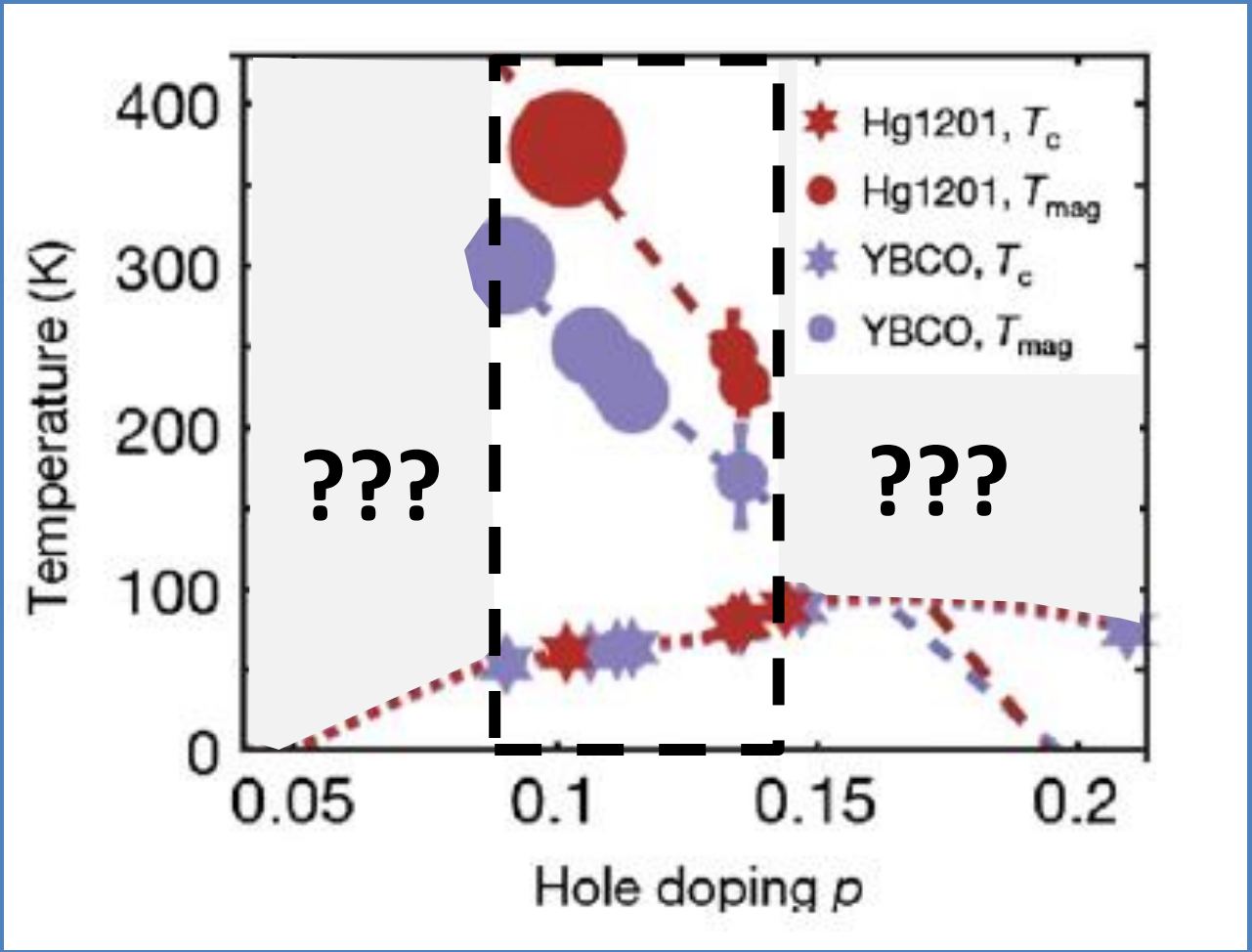
# From lightly to optimally doped cuprates

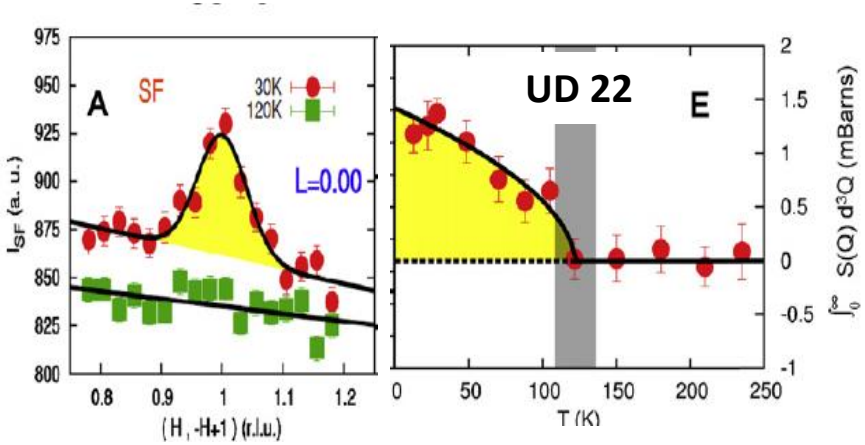



*Y. Li et al., Nature 2008*

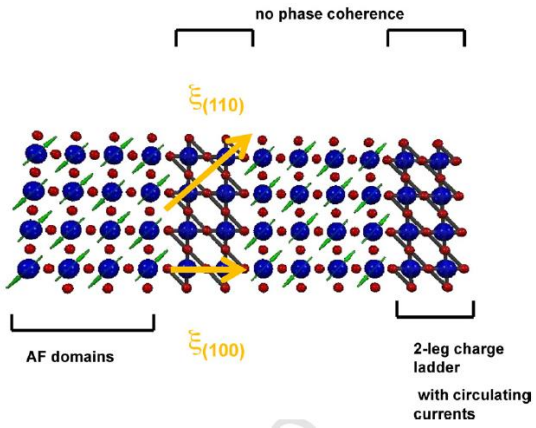
*P. Bourges & Y. Sidis, C.R. Physique 2011*

# From lightly to optimally doped cuprates

## $La_{2-x}Sr_xCuO_4$ *(p ~ 0.08) $T_{mag}$ ~120 K*

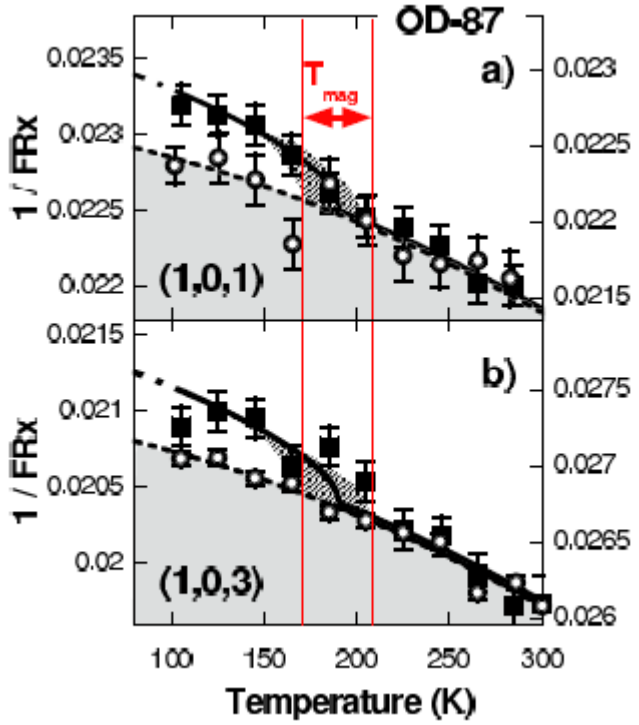



2D short range order / $\xi_{100}$ ~2 a $\xi_{110}$ ~3 a




*V. Balédent et al, PRL 2010*

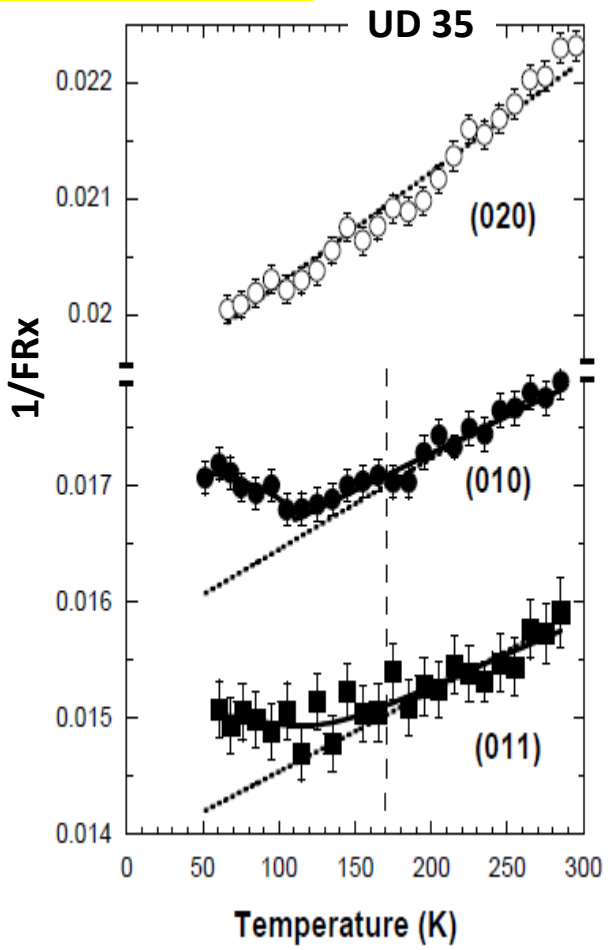
## $Bi_2Sr_2CaCu_2O_{8+\delta}$ *(p ~ 0.18) $T_{mag}$ ~190 K*




*De Almeida-Didry et al, PRB-RC 2012*
*L. Mangin-Thro et al, unpublished*

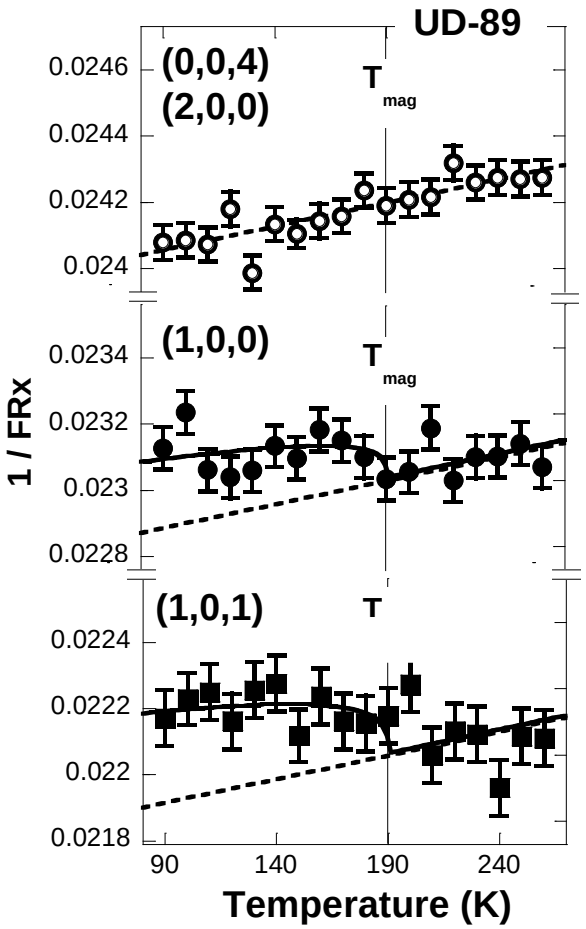
# From lightly to optimally doped $YBa_2Cu_3O_{6+x}$

**P ~0.08 $T_{mag}$ ~ 170 K**




*V. Balédent et al, PRB 2011*

**P ~0.15 $T_{mag}$ ~ 190 K**

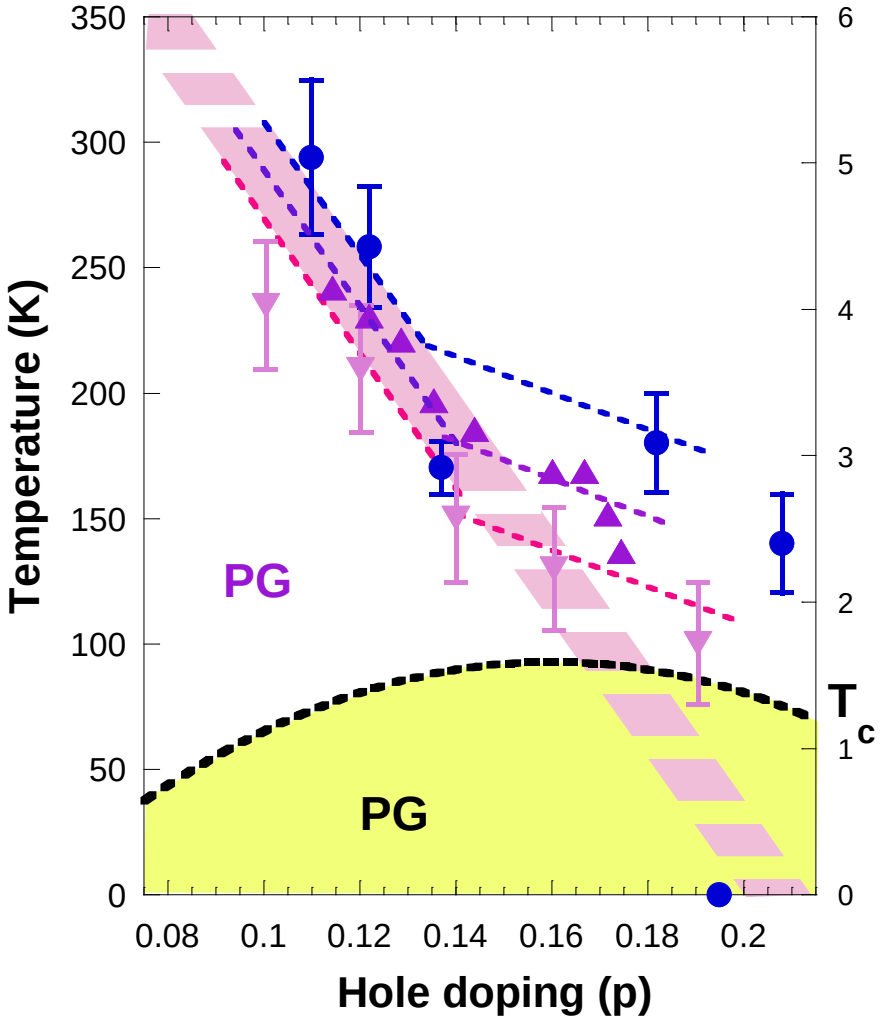


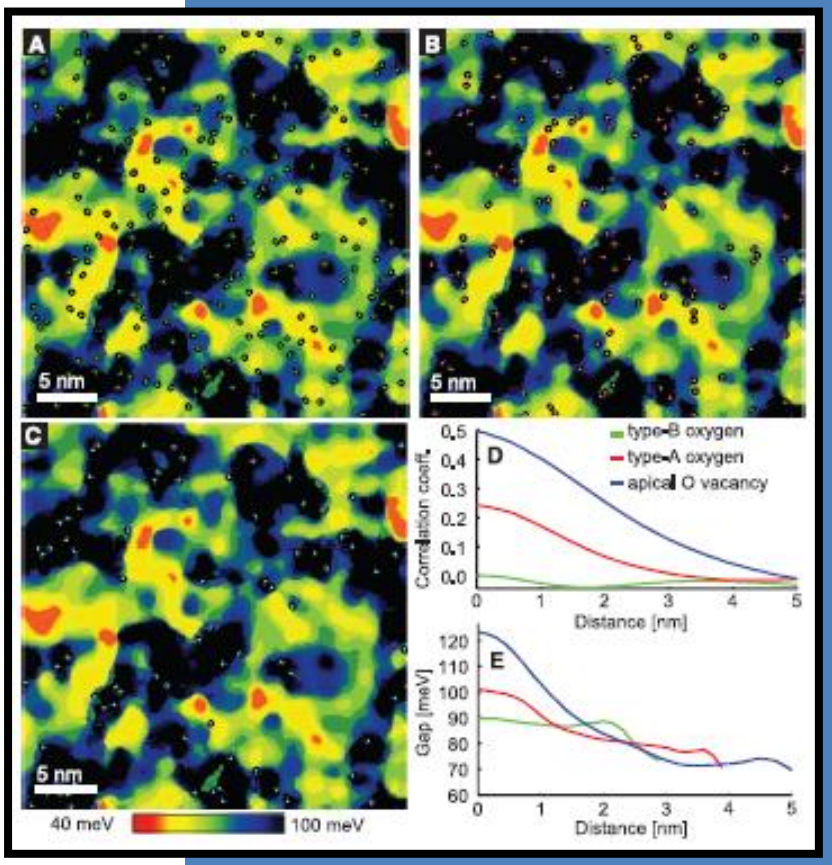

*L. Mangin-Thro et al, unpublished*

# Phase diagram

Bi2212 - T* ARPES
Bi2212 - T* $\rho_{ab}$
Bi2212 - T* ERS

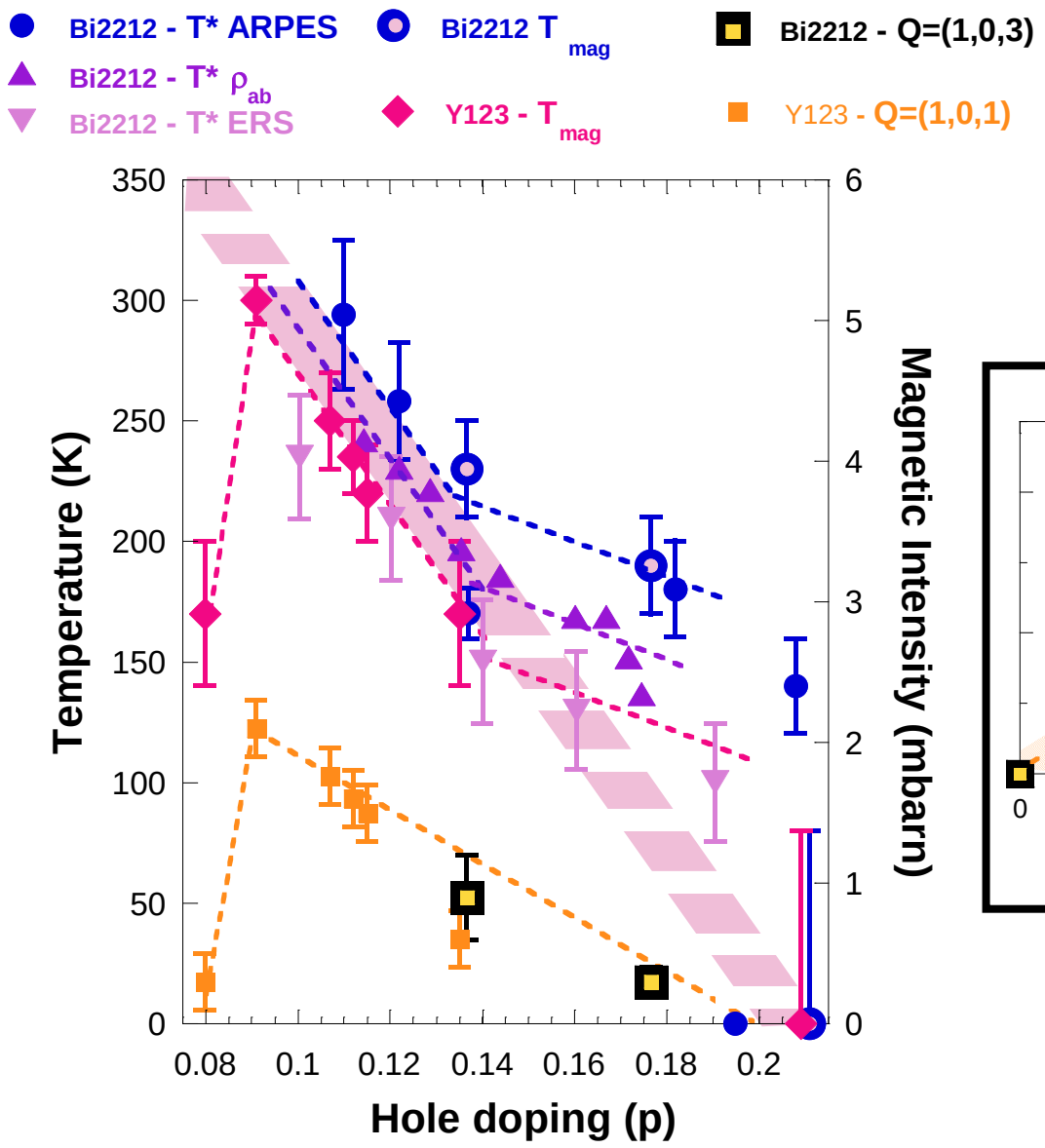
*I. Vishik et al, PNAS 2012*
*H. Raffy et al, Physica C 2007*
*A. Sacuto et al, CR Phys. 2011*

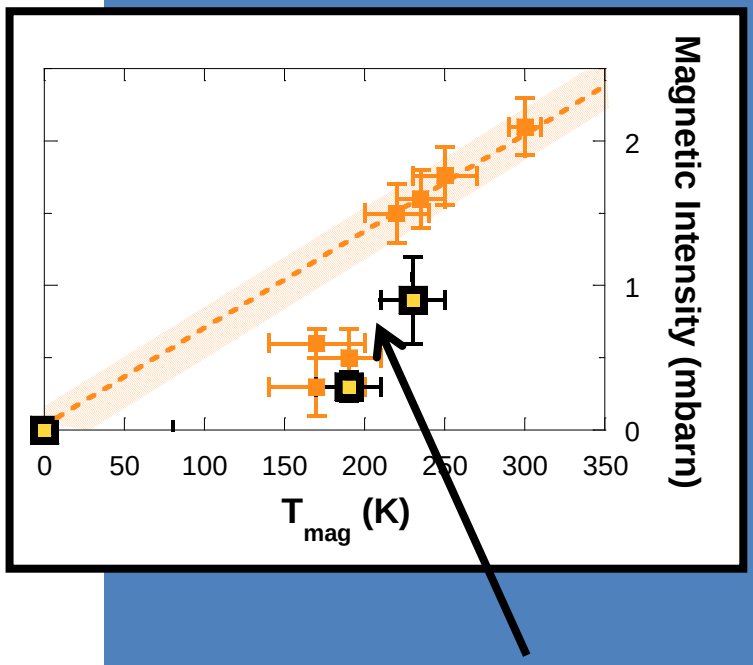


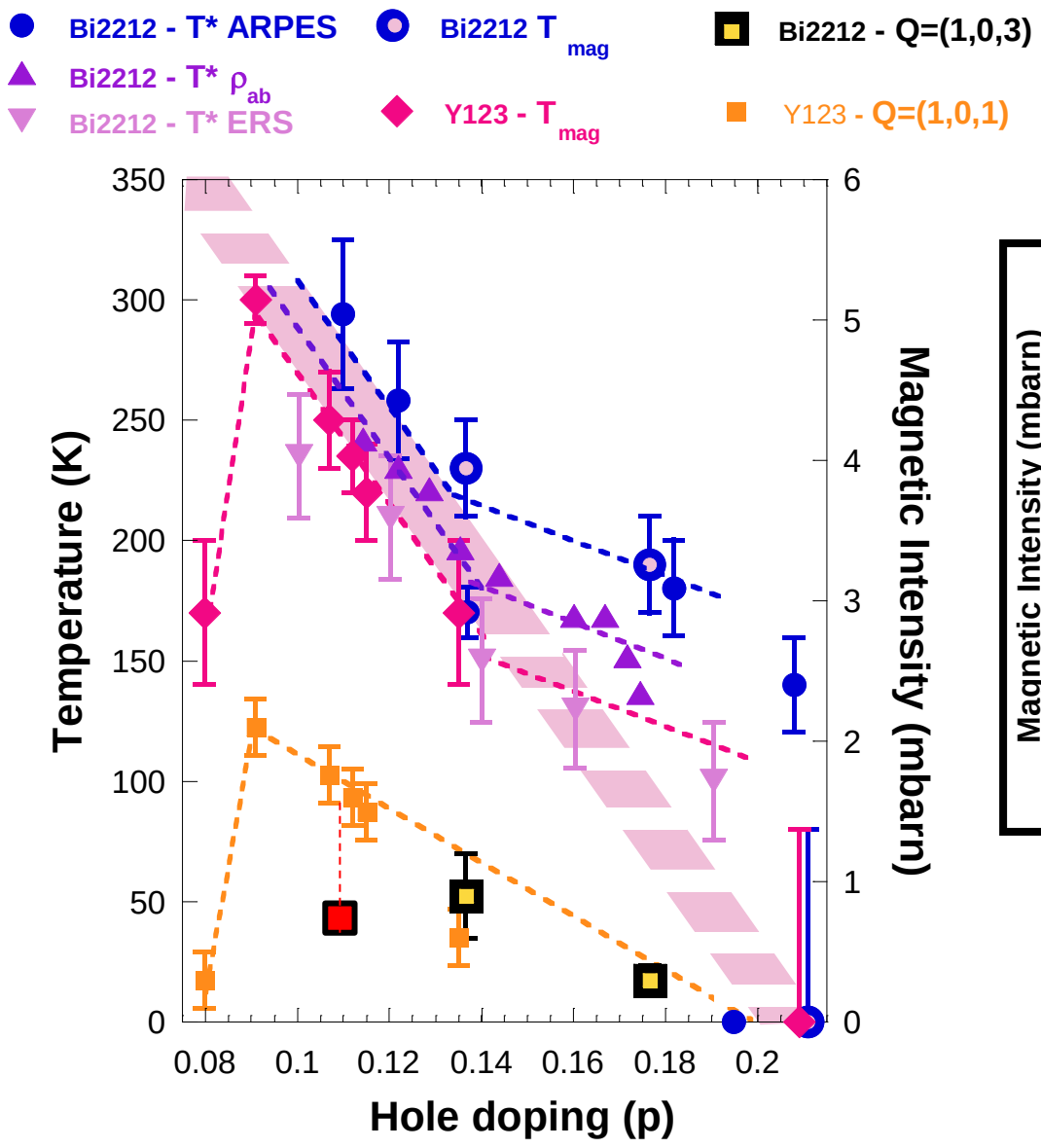

*K. McElroy et al, Science 2005*
*I. Zeljkovic et al, Science 2012*

*L. Mangin-Thro et al, in preparation 2013*

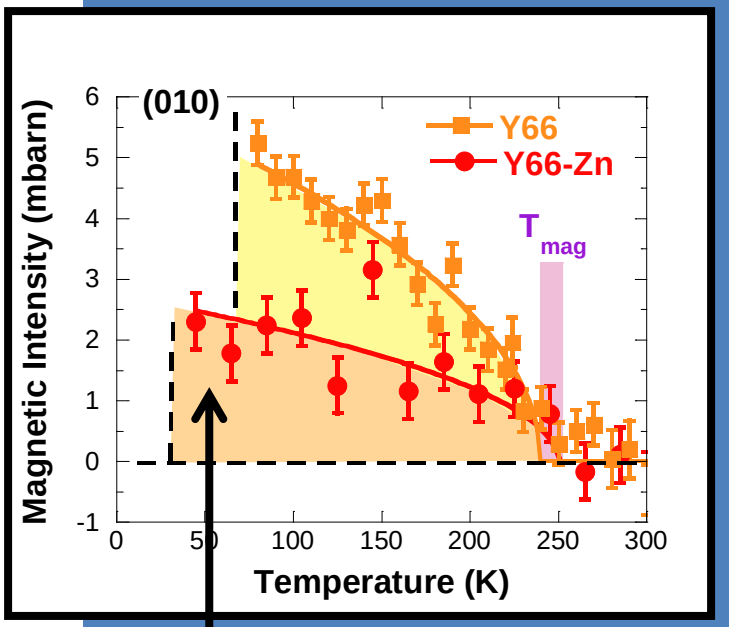



*Shortening of the magnetic correlation length ?....*

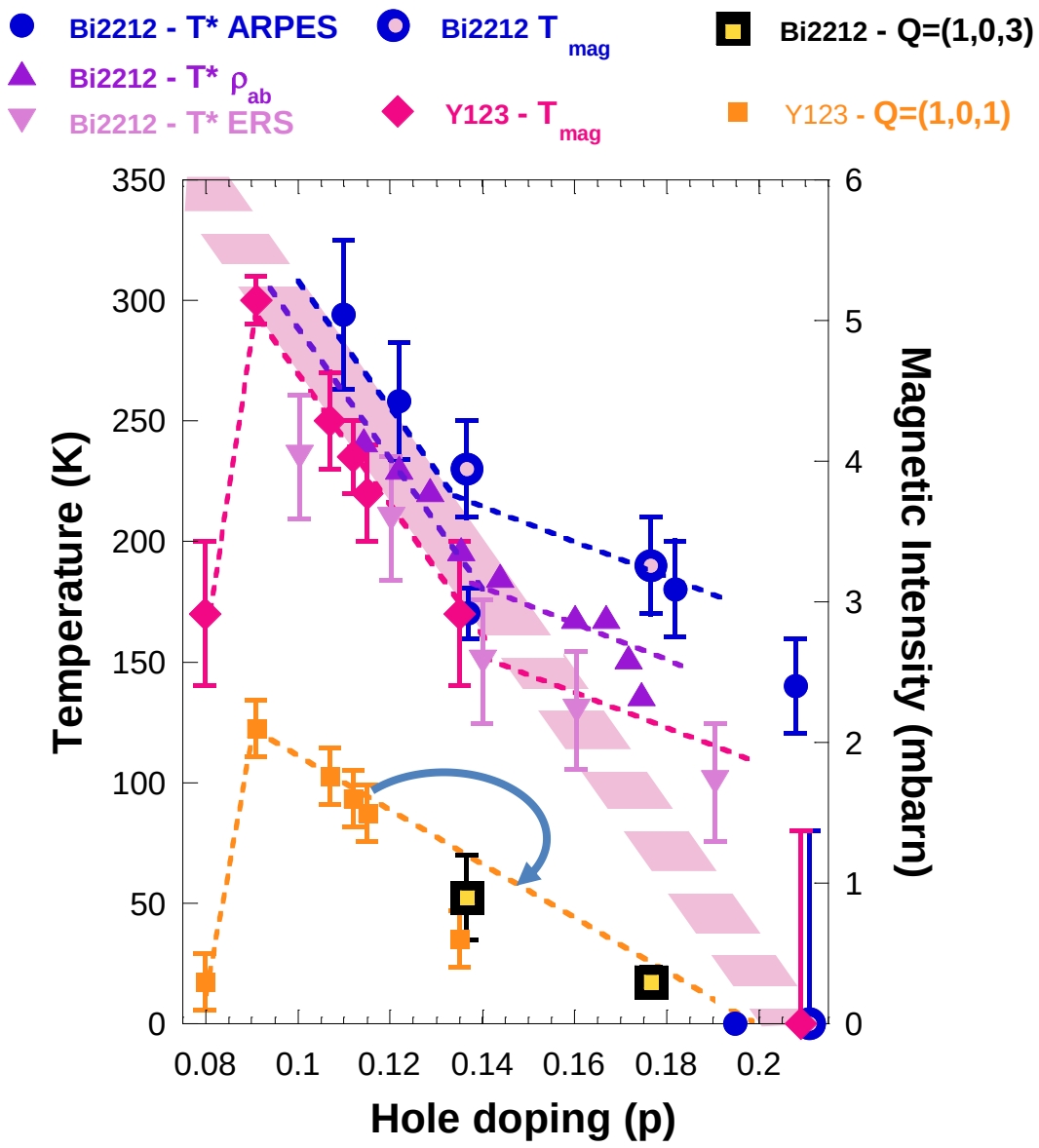



*L. Mangin-Thro et al, in preparation 2013*

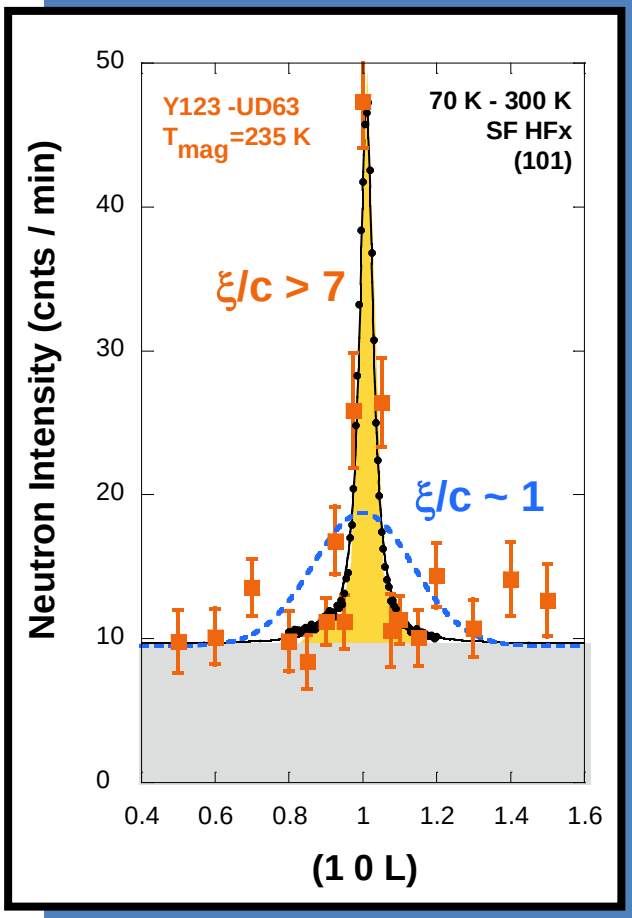



***Shortening of the magnetic correlation length ?....***
***Role of disorder ?....***

*V. Baledent et al., PRB 2011*




*L. Mangin-Thro et al, in preparation 2013*




*H.A. Mook et al., PRB 2008*

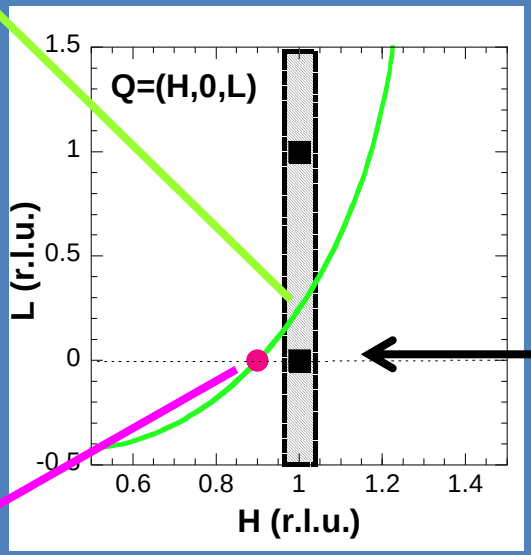
# $YBa_2Cu_3O_{6+x}$ : shortening of the correlation length

$\xi_{100}$ ~10-20 a

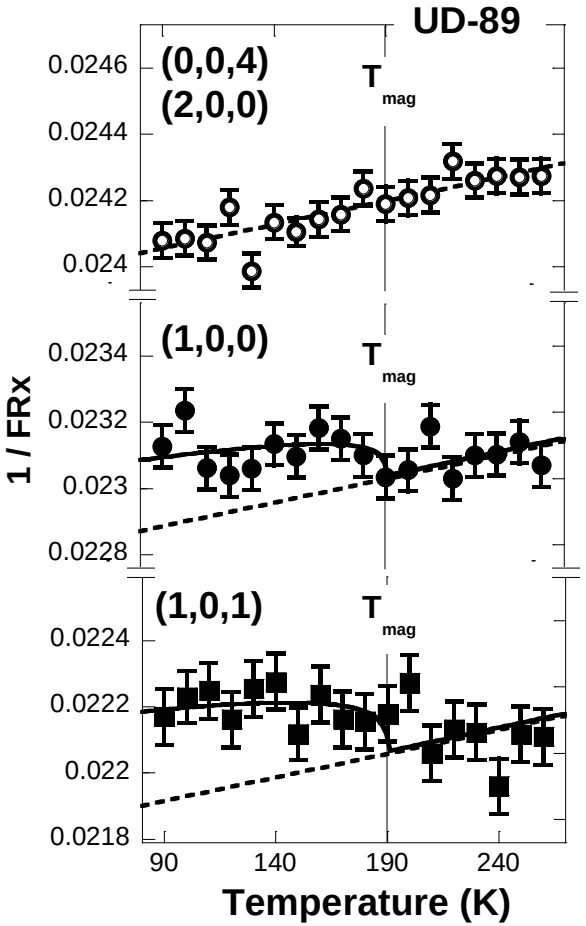
critical fluctuations

**ILL-D7**
**ki=1,3 $A^{-1}$**

**LLB-4F1**
**ki=2.57 $A^{-1}$**

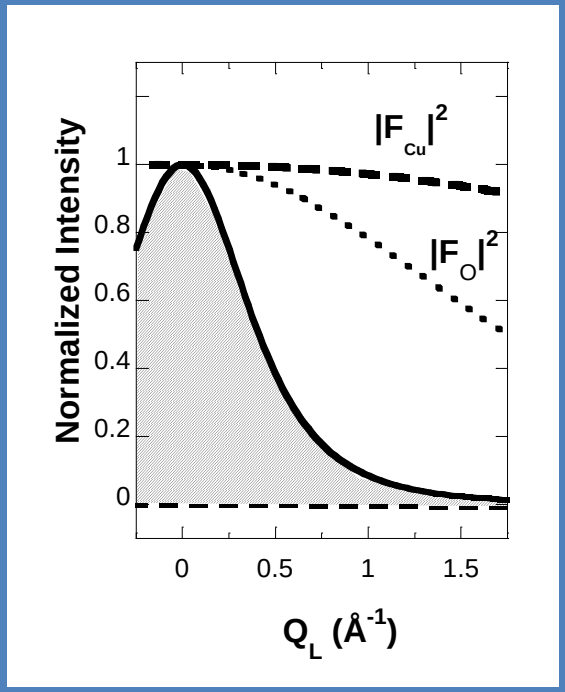


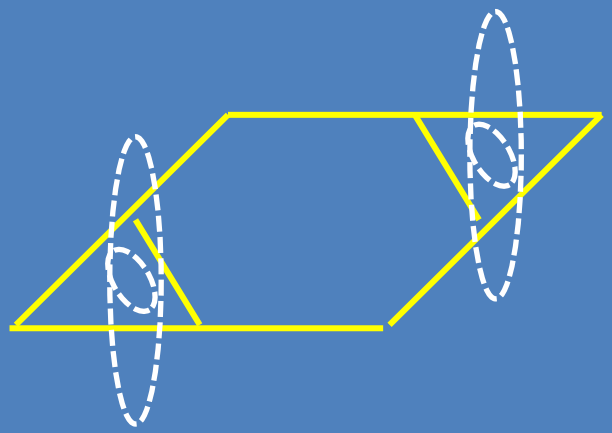

**P ~0.15 $T_{mag}$ ~ 190 K**




*L. Mangin-Thro et al, unpublished*

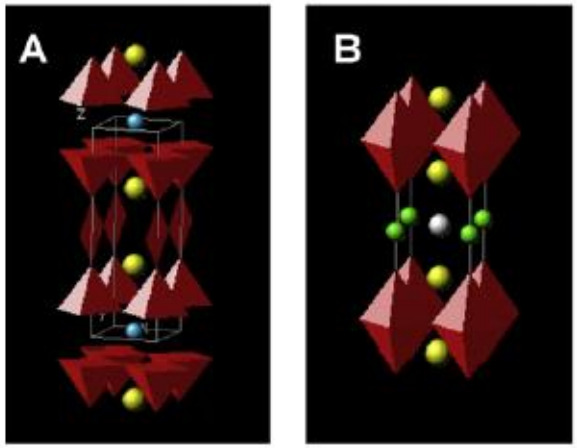
# Magnetic form factor

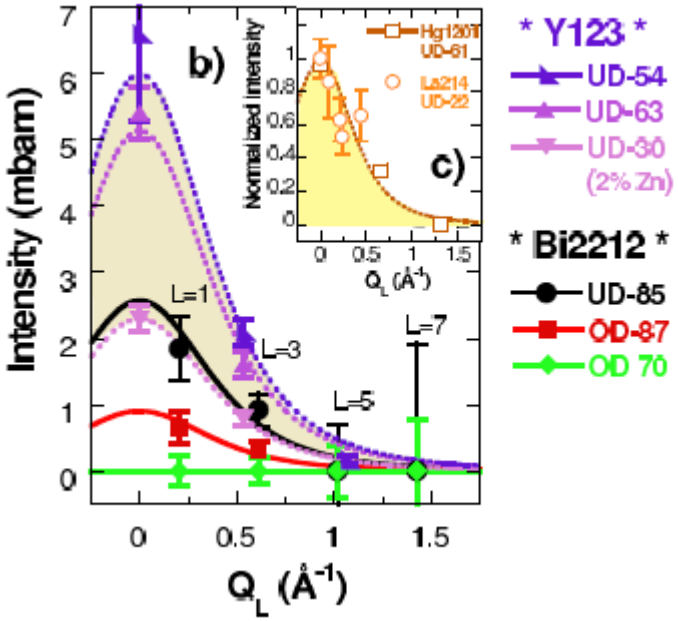


# Unusual magnetic order

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



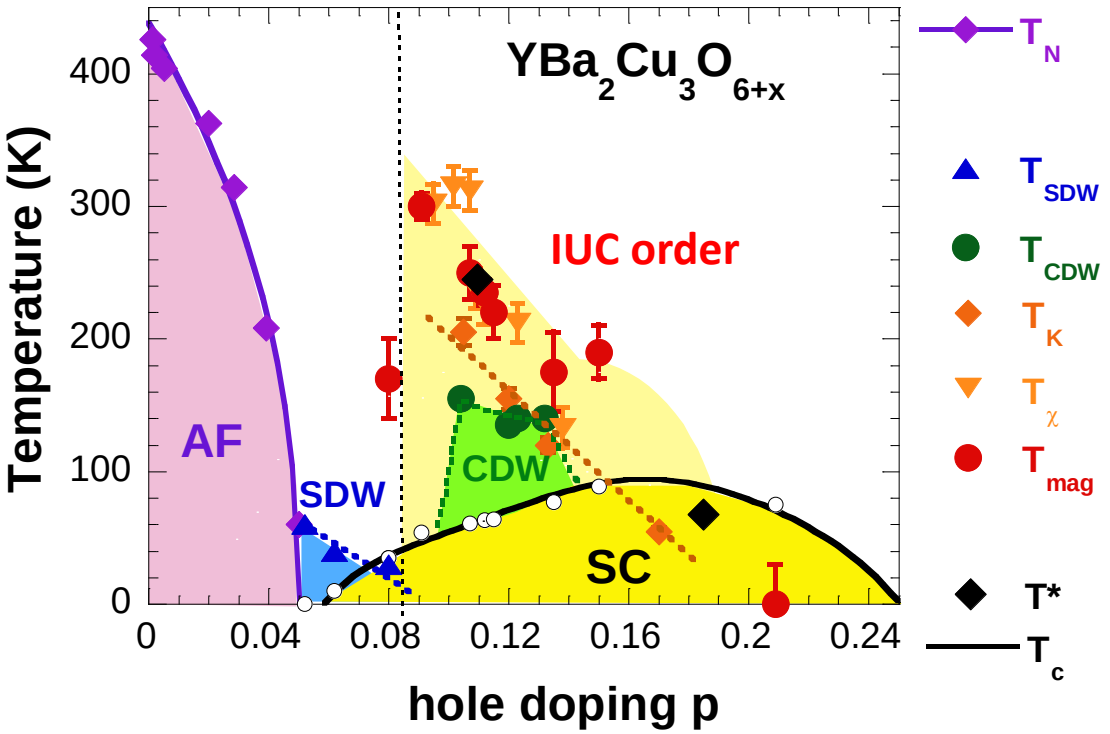

*De Almeida-Didry et al, PRB-RC 2012*

*L. Mangin-Thro et al, unpublished*

# outline

1/ Introduction to the phenomenology of the Pseudo-gap
2/ Density wave instabilities vs Pseudo-gap
3/ Loop current  model of the Pseudo-gap
4/ Intra-unit-cell magnetic order & Pseudo-gap
5/ Hole doping dependence of the IUC magnetic order
6/ Conclusion

# Pseudogap
# Density wave instabilities
# IUC order




**glassy SDW**

*Haug, New J. Phys. 2010*

**IUC magnetic order**

*Balédent, PRL 2011*

**Anomaly in the 2nd derivative of the magnetization**

*Leridon, EPL 2009*

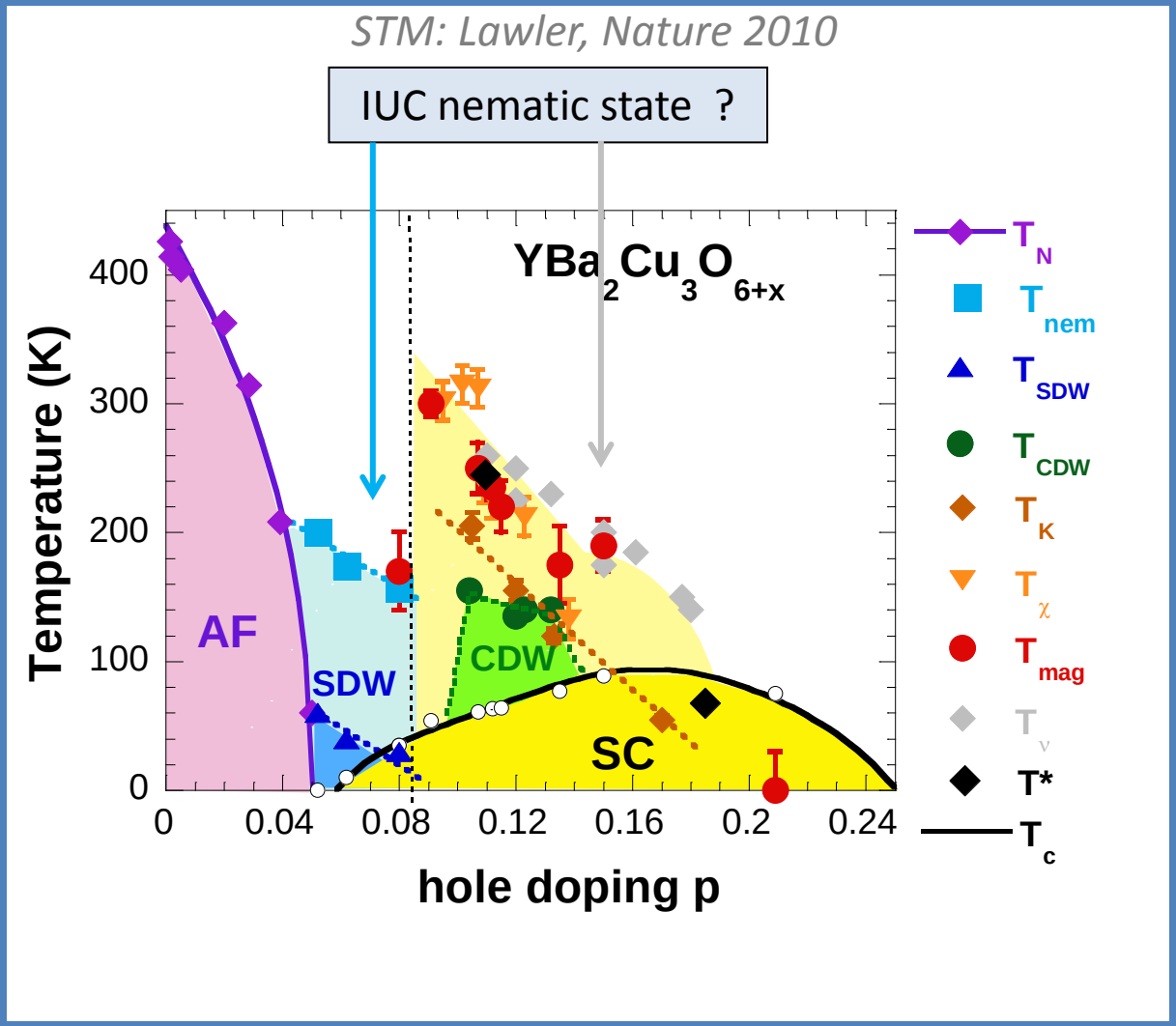
**Kerr effect**

*Xia, PRL 2008*

**Incipient CDW**

*Chang , Nature Phys. 2012*
*Ghiringhelli, Science 2012*

# Pseudogap
# Density wave instabilities
# IUC order(s)




Broken rotational symmetry
In spin fluctuations

glassy SDW

*Haug, New J. Phys. 2010*

IUC magnetic order

*Balédent, PRL 2011*

Anomaly in the 2nd derivative of the magnetization

*Leridon, EPL 2009*

a-b anisotropy in Nernst coefficient

*Daou, Nature 2010*

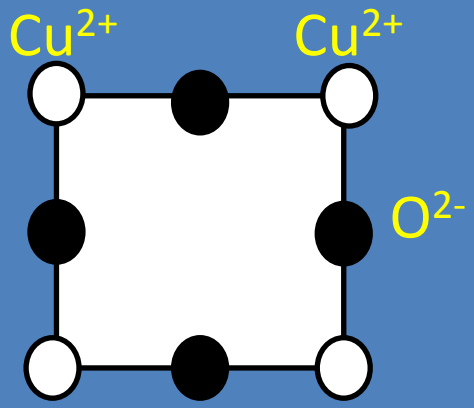
Kerr effect

*Xia, PRL 2008*

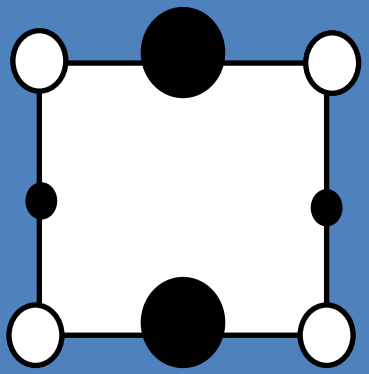
Incipient CDW

*Chang , Nature Phys. 2012*
*Ghiringhelli, Science 2012*

# Conclusion: Mind the oxygen !.....

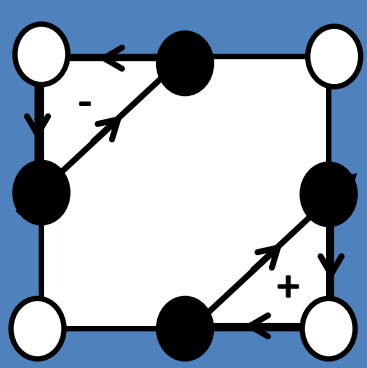



IUC- charge order (Q=0)
Electronic nematic state

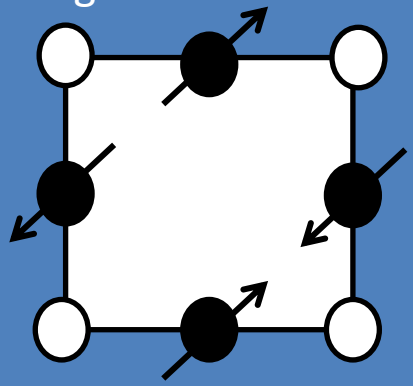


*Fischer & Kim,*
*PRB 2011, PRB 2012*

IUC- magnetic order (Q=0)
Orbital magnetism

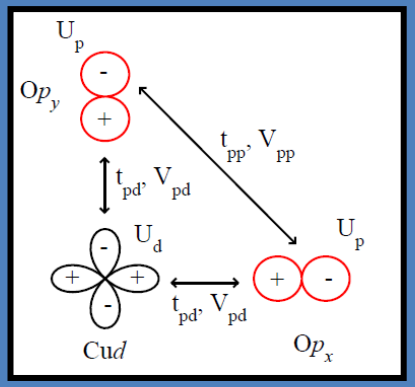


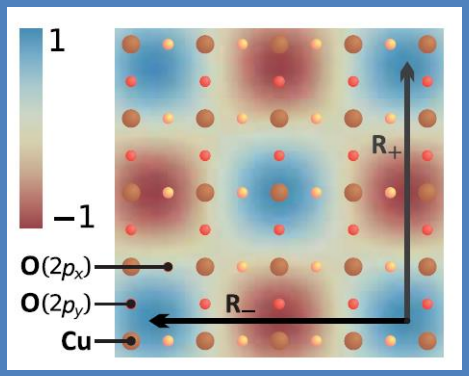

*C.M. Varma,*
*PRB 2006*



A.S. Moskvin,
JETP Lett. 2012

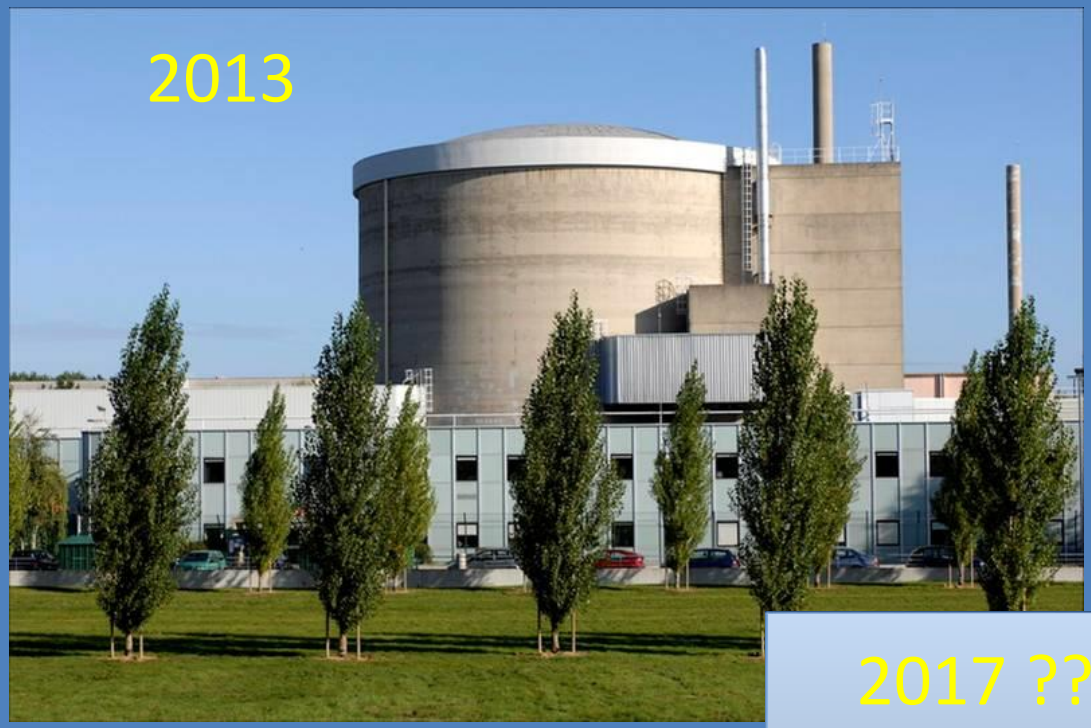
Multi-band model



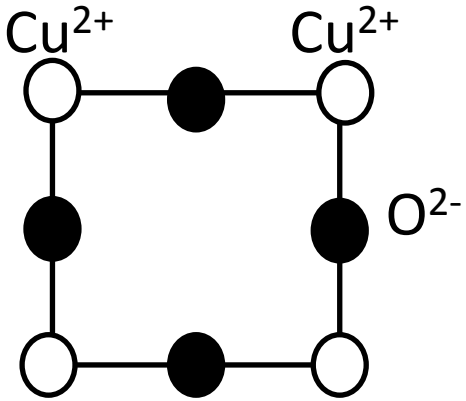

Quadrupolar Charge order ($Q^* \neq 0$)

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

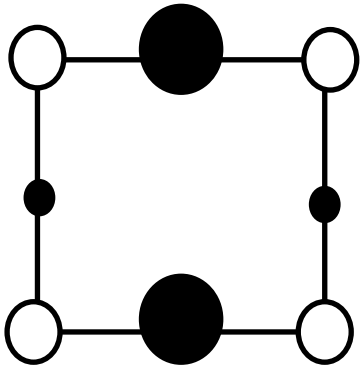



Orphée
Laboratoire Léon Brillouin

$CuO_2$ unit cell

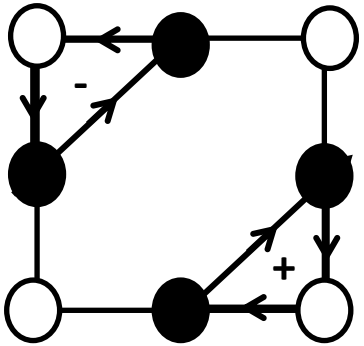


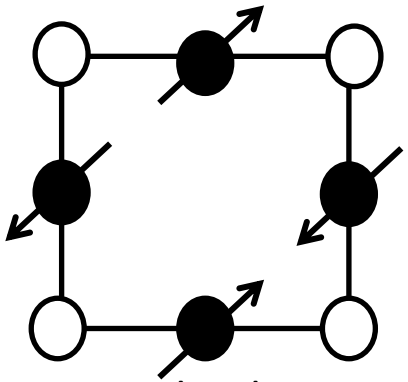

IUC- charge order (Q=0)
Electronic nematic state



IUC- magnetic order (Q=0)
Orbital magnetism

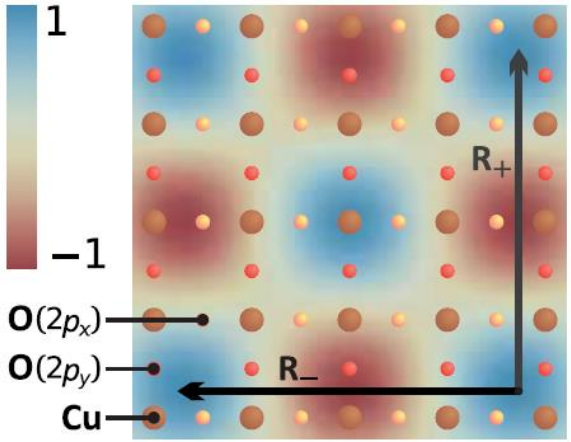
Loop curents



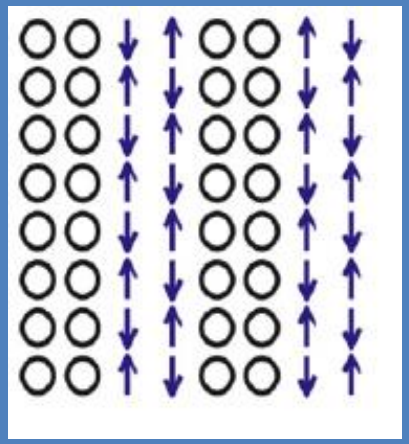
Spin or orbital moments

QWD order (Q≠ 0)



# Current loops versus other spin/charges instabilities

## Charge & spin stripes



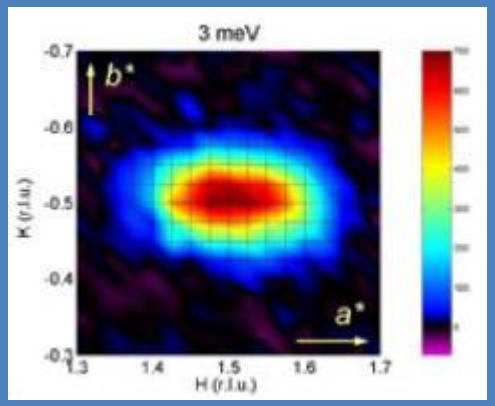
Breaks the $C_{4v}$ rotational symmetry + the lattice translation invariance (when static)

$La_{2-x}Ba_xCuO_4$
$(La,Nd)_{2-x}Sr_xCuO_4$

*Tranquada, Nature 1995*

## Charge & spin nematicity

the $C_{4v}$ rotational symmetry is spontaneously broken: a ***net a-b anisotropy shows up in transport and neutron scattering measurements***



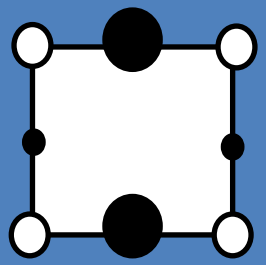

$YBa_2Cu_3O_{6+x}$

*Ando, PRL 2002*
*Hinkov , science 2008*
*Daou, Nature 2010*

## Intra-unit-cell nematicity

the $C_{4v}$ rotational symmetry is spontaneously within the unit cell :

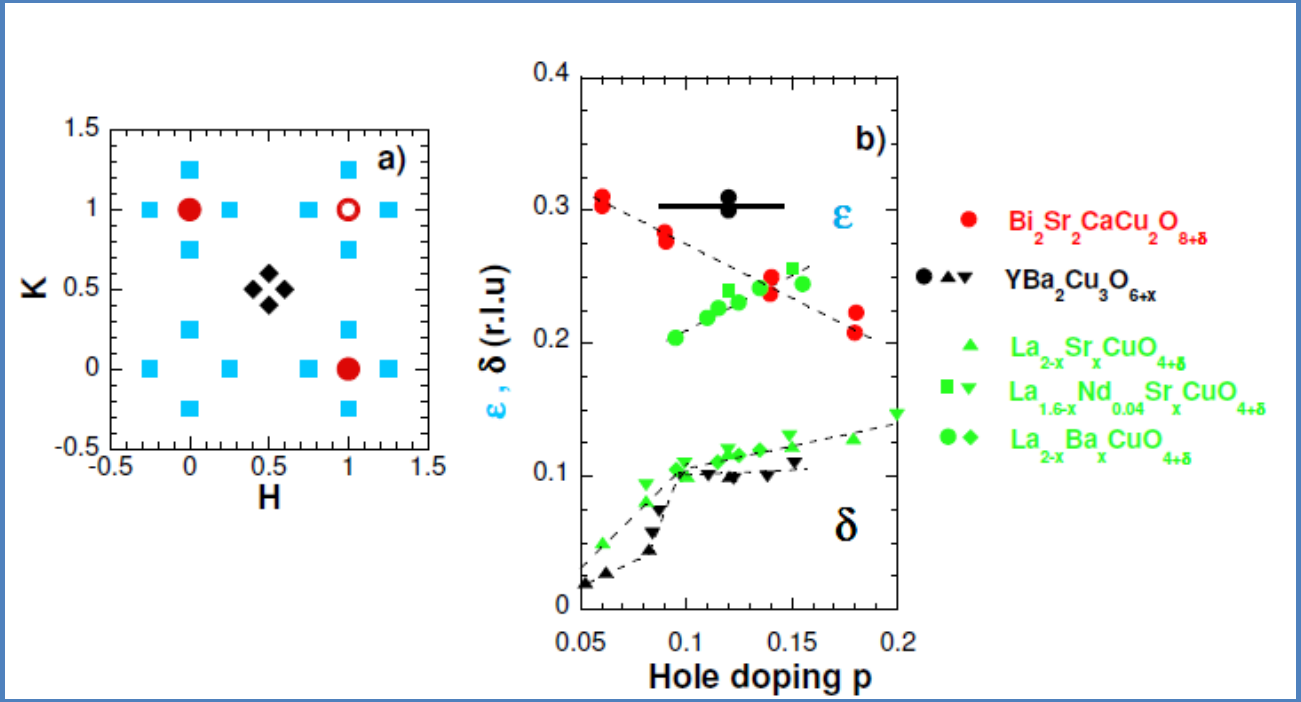
***Oxygens along a and b do not play the same role according to STM measurements***



$Bi_2Sr_2CaCu_2O_{8+\delta}$

*Lawler, Nature 2010*
*Fischer & Kim, PRB 2011*

# Characteristic wave vectors




**q=0 IUC order(s)**

**$q_{CDW}$ = ± (ε, 0 ) and / or (0, ε )**

**$q_{SDW} = q_{AF}$ ± (δ, 0 ) and / or (0, δ )**

***La124***

**** X-ray + neutron***

*Tranquada , Treatrise of high temperature superconductivity, eds J R Schrieffer2007*

*Yamada , PRB 1998*

*Tranquada ,Nature 1995*

*Axe, PRB 1996*

*Tranquada , PRL 1997*

*Niemöller ,EPJ B 1999*

*Zimmermann , EPJ B 1998*

*Hucker, PRB 2011*

***Y123***

**** X-ray***

*Chang , arXiv:1206.4333*

*Ghiringhelli, arXiv:1207.0915*

**** Neutron***

*Haug, New J. Phys. 2010*

*Dai , PRB 2001*

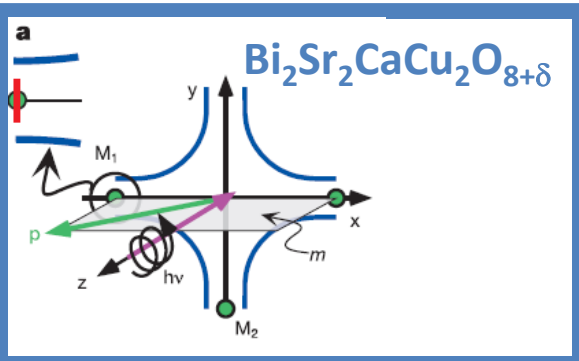
***Bi2212***

** STM*

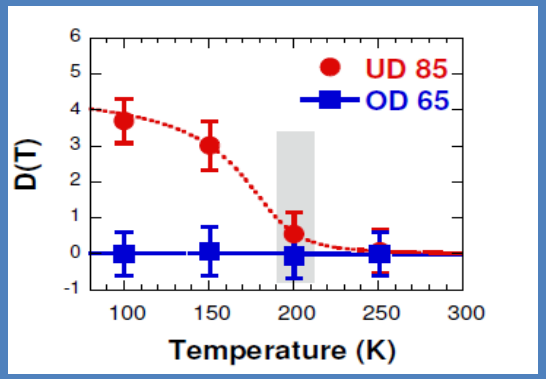
*Y. Kohsaka, Nature 2008*

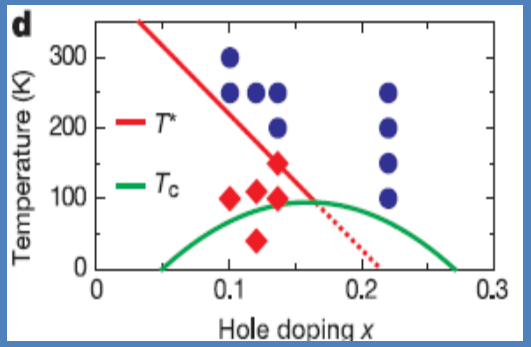
*Mesaros, Science 2011*

## Broken time-reversal symmetry ARPES




*Dichroism in ARPES*

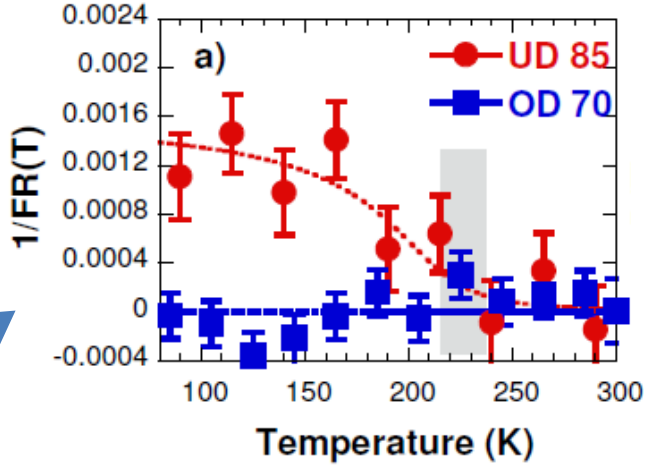


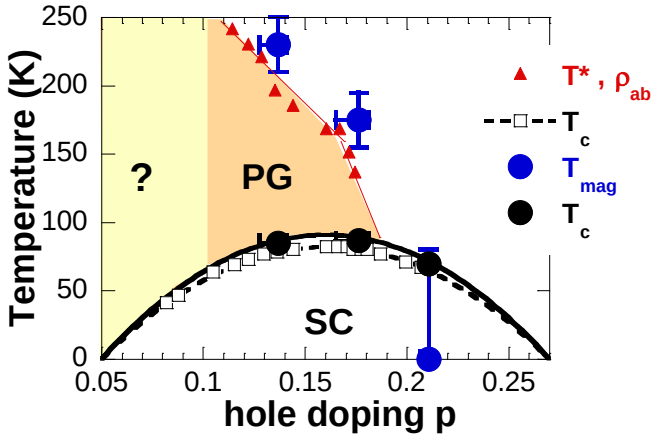




*Kaminski, Nature 2002*

## Broken time-reversal symmetry Polarized neutron difffraction

$Bi_2Sr_2CaCu_2O_{8+\delta}$

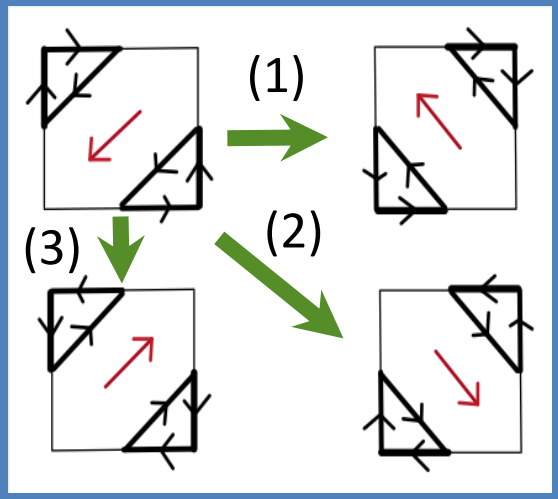


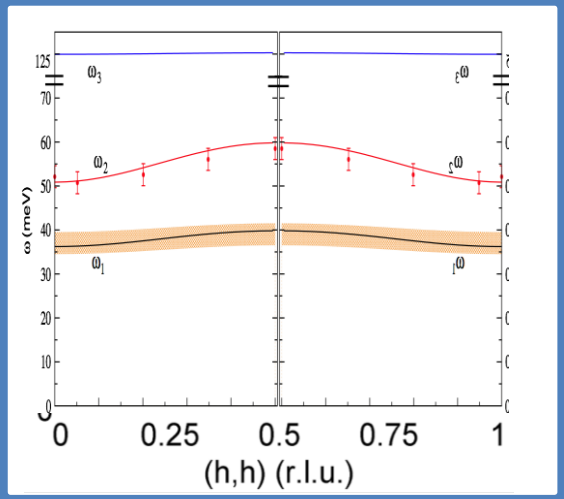




*S. De Almeida-Didry, to appear in PRB 2012*
*(ab-resistivity) H. Raffy et al., Physica C 2007*

# Quantum *flips* from the ground

*He & Varma, PRL 2011*




*Dynamic hallmark*

## Collective magnetic excitations

*Y. Li et al, Nature 2010*
*Y. Li et al, Nat. Phys. 2012*

**Hg1201**