Hidden Magnetic Texture in the Pseudogap Phase of High-Tc $YBa_2Cu_3O_{6+\delta}$

Dalila Bounoua

Laboratoire Léon Brillouin CEA-CNRS, CEA Saclay

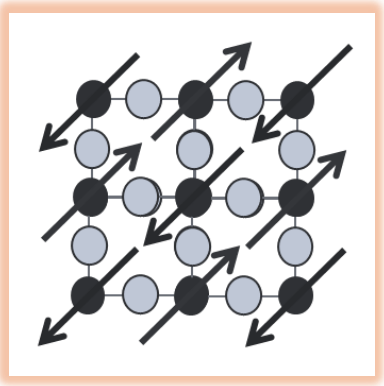
dalila.bounoua@cea.fr

Congrès Général des 150 ans de la Société Française de Physique

du 3 au 7 juillet 2023

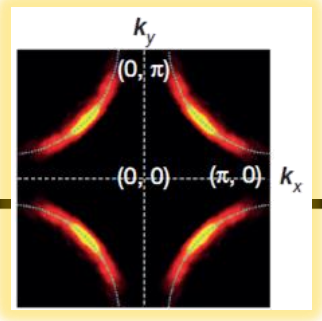
MC-21 Matériaux quantiques : des prédictions à l'observation

Generic Electronic Phase Diagram of Hole-Doped High-Tc Cuprates

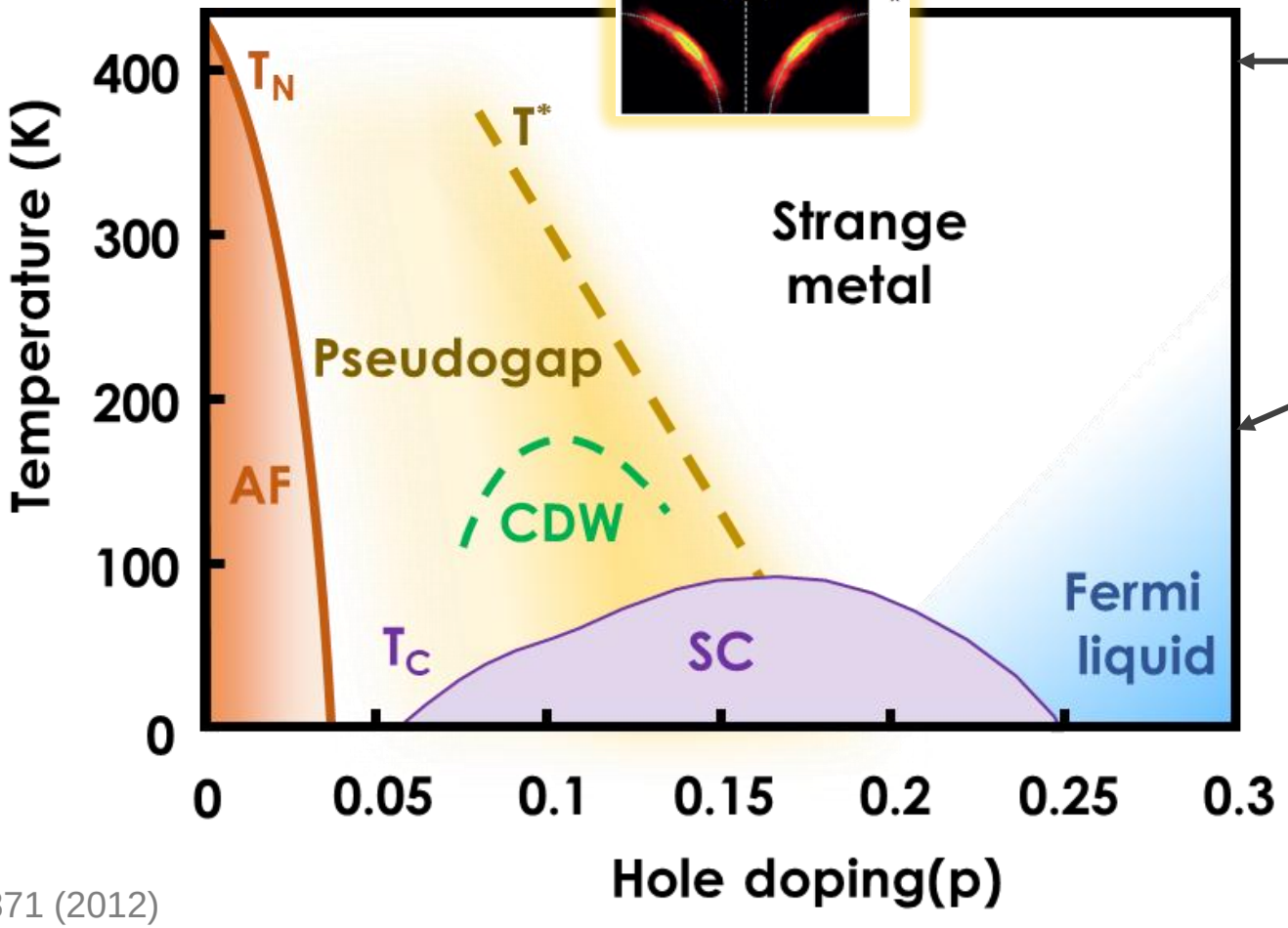


Antiferromagnetic
Mott insulator

Pseudogap



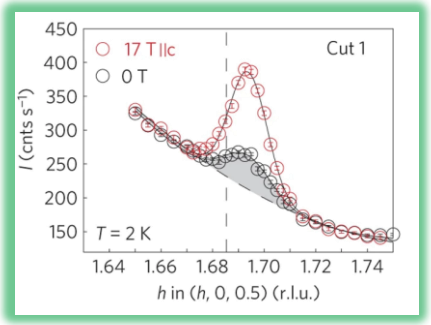
E Razzoli *et al,* New Jour of Phys, 12 (2010)



$\rho \propto T$

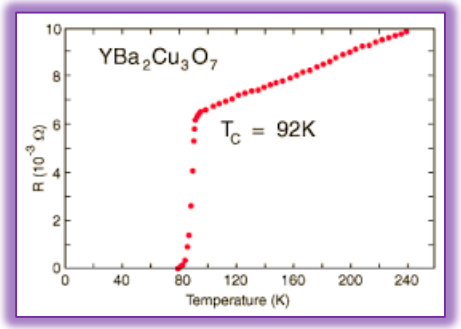
$\rho \propto T^2$

Charge Density
Wave



J. Chang et al., Nat. Phys 8, 871 (2012)

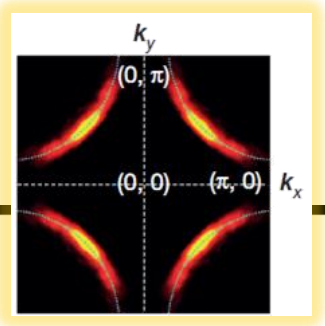
Superconducting state



M. K. Wu, et al., Phys. Rev. 58, 908 (1987)

The Pseudogap State

Pseudogap



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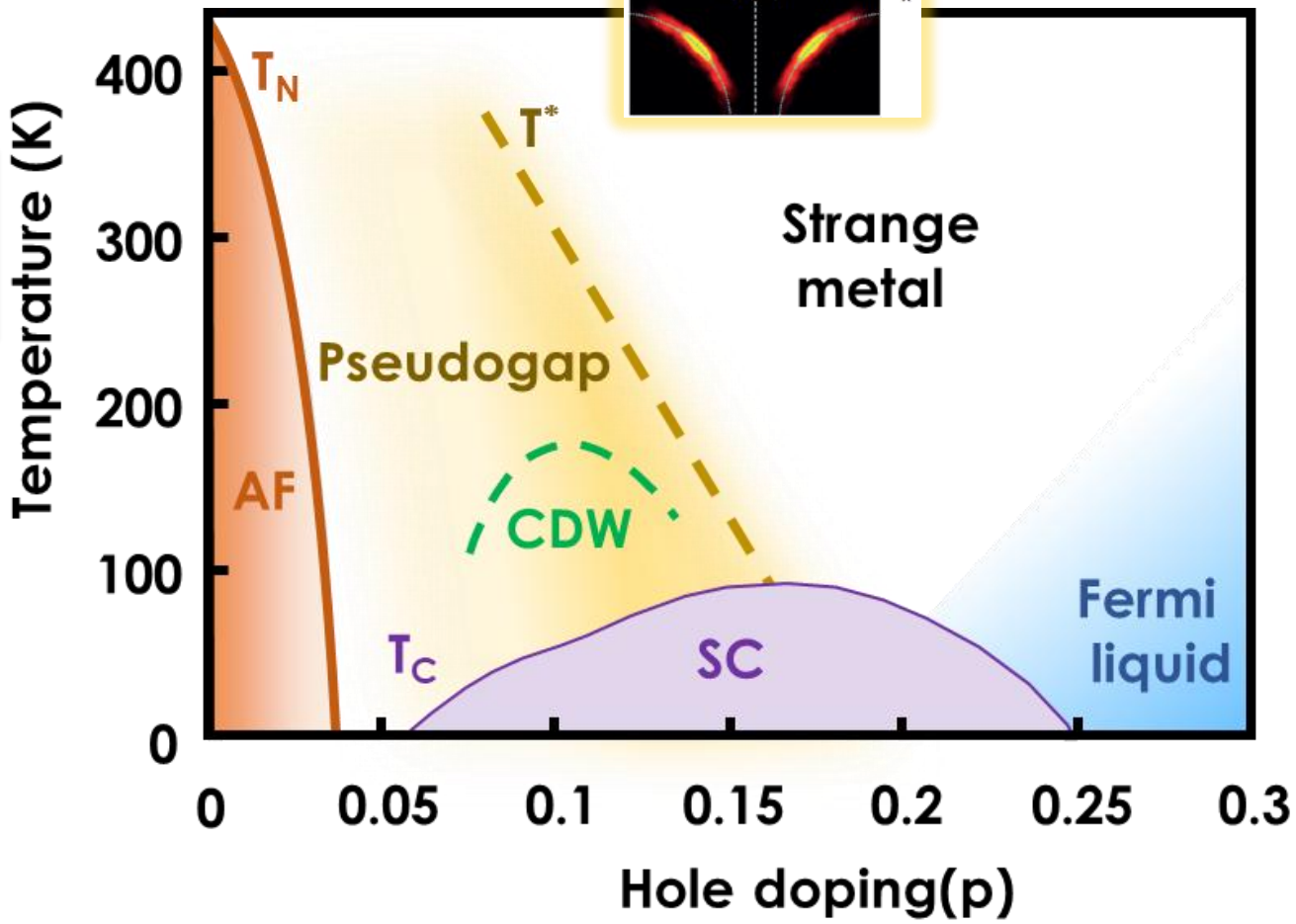
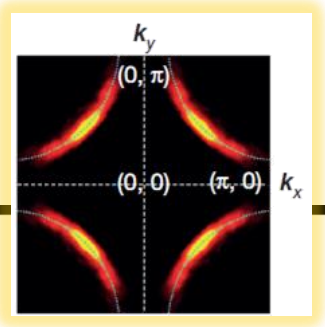
Pre-formed pairs? Preemptive to the SC state

Competing order parameter ?



The Pseudogap State

Pseudogap



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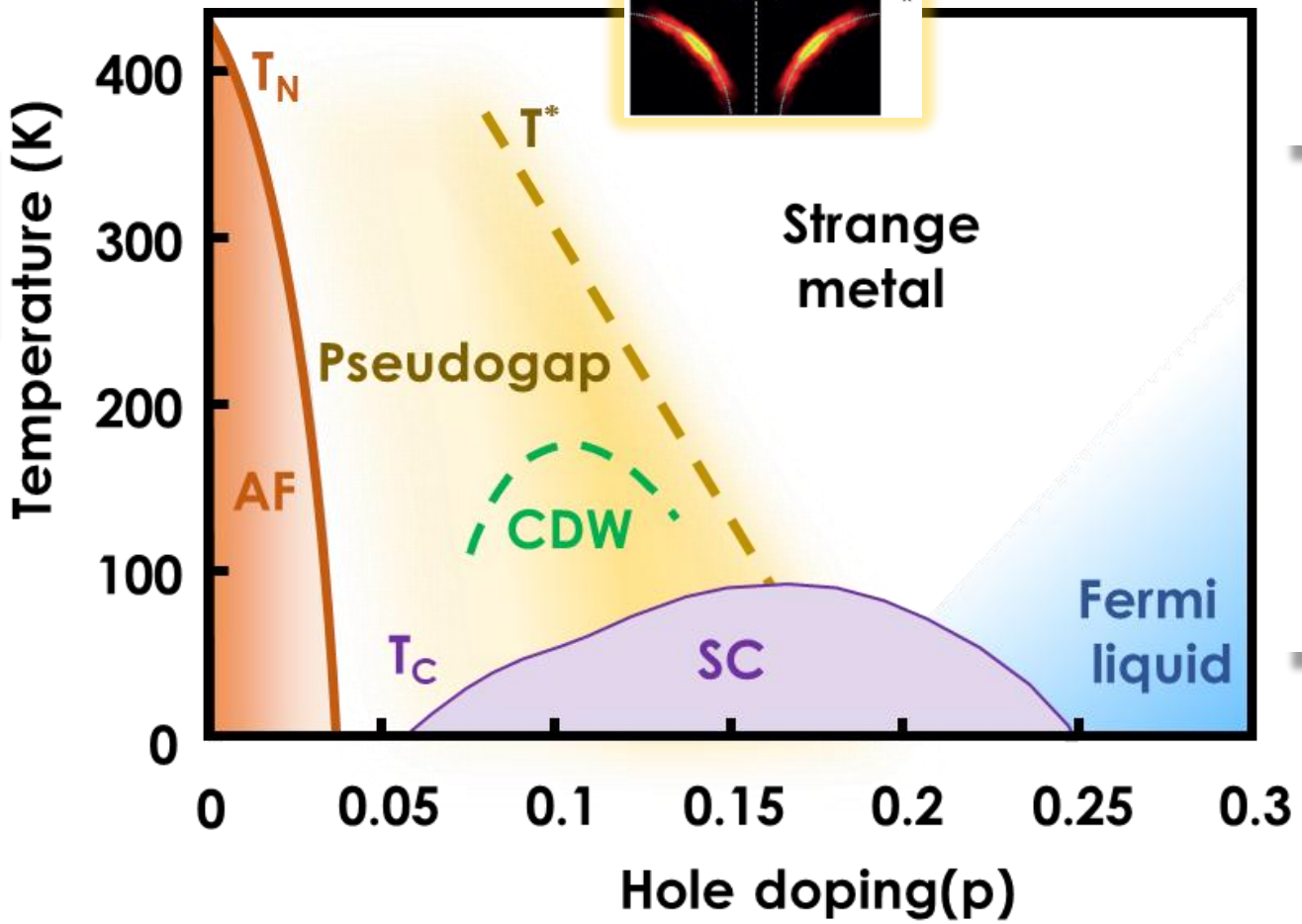


What causes the opening of the pseudogap ?

CDW Breaks the lattice translation symmetry but appears at much lower T

Discrete Symmetry Breaking at T*

Broken Symmetries

Time reversal

Polarized neutron diffraction
P.Bourges et al., C.R. Phys 22,1, (2022)

Parity

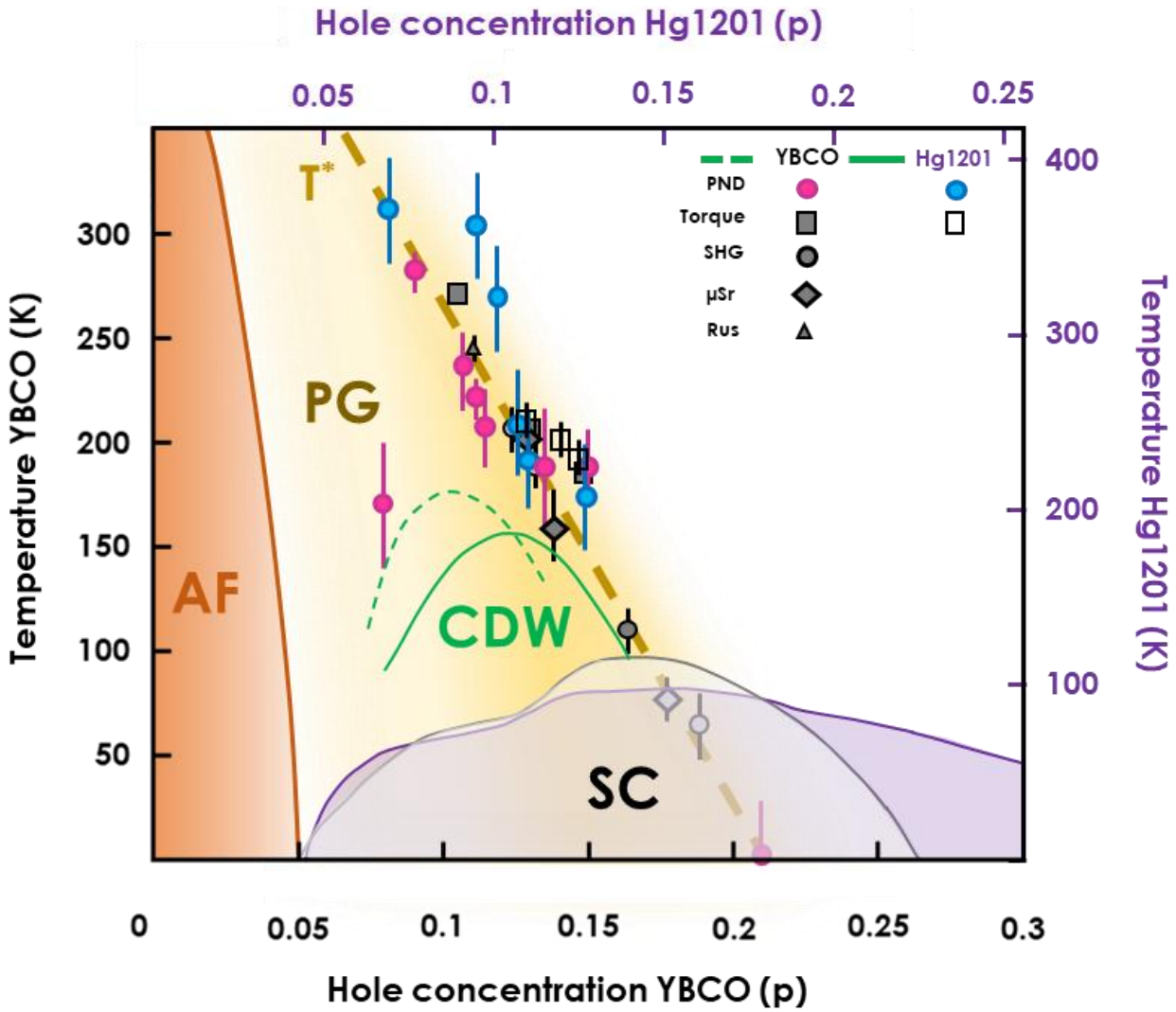
Second harmonic generation
L. Zhao *et al.*, Nat. Phys. **12**, 32 (2016).

C_4 rotation

Torque magnetometry
Y. Sato *et al.*, Nat. Phys. **13**, 1074 (2017).

Preserved symmetry

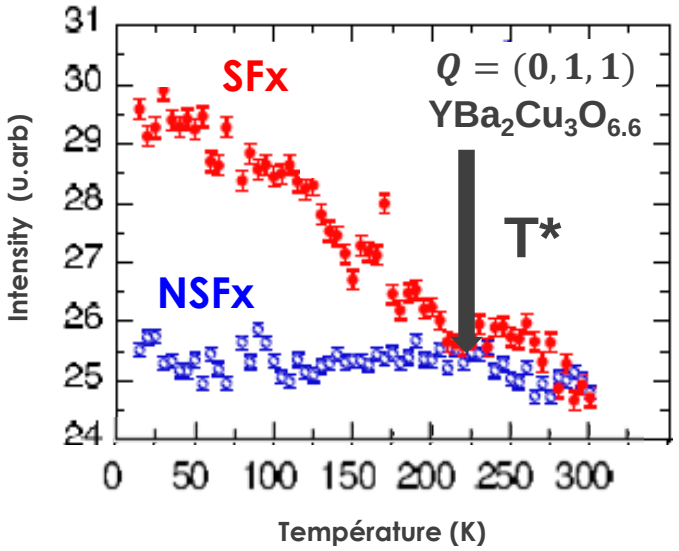
Lattice Translation

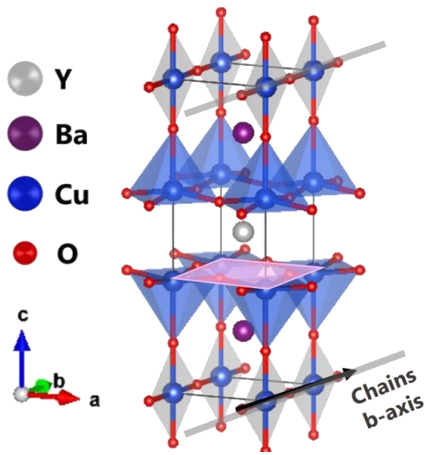


P.Bourges et al., C.R. Phys 22,1, (2022)

Hidden q=0 Magnetism in the Pseudogap Phase Seen by Polarized Neutron Diffraction

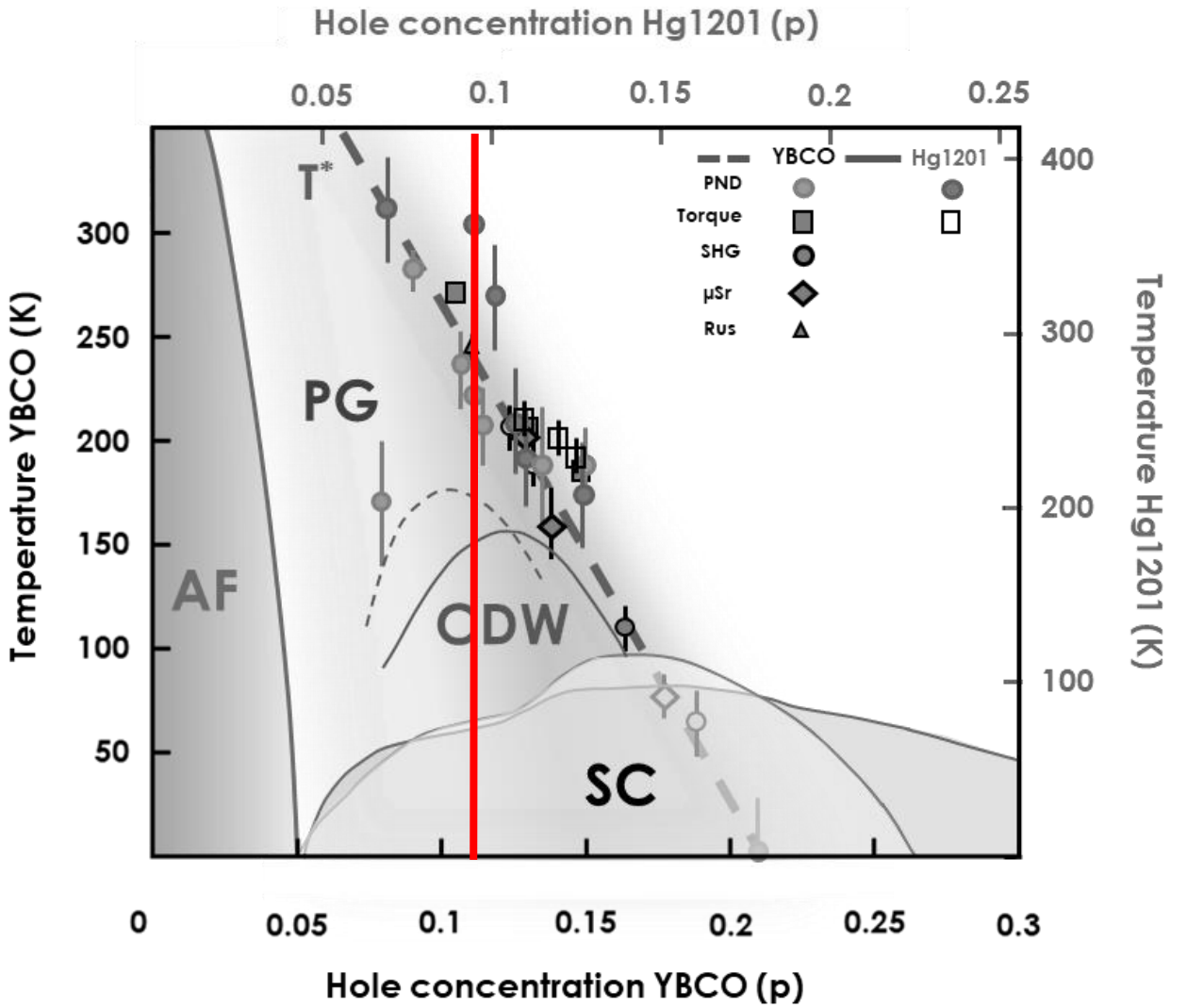
Polarized neutron diffraction





B. Fauqué *et al.*, Phys. Rev. Lett. 96, 197001 (2006)

q=0 or intra-unit cell magnetism



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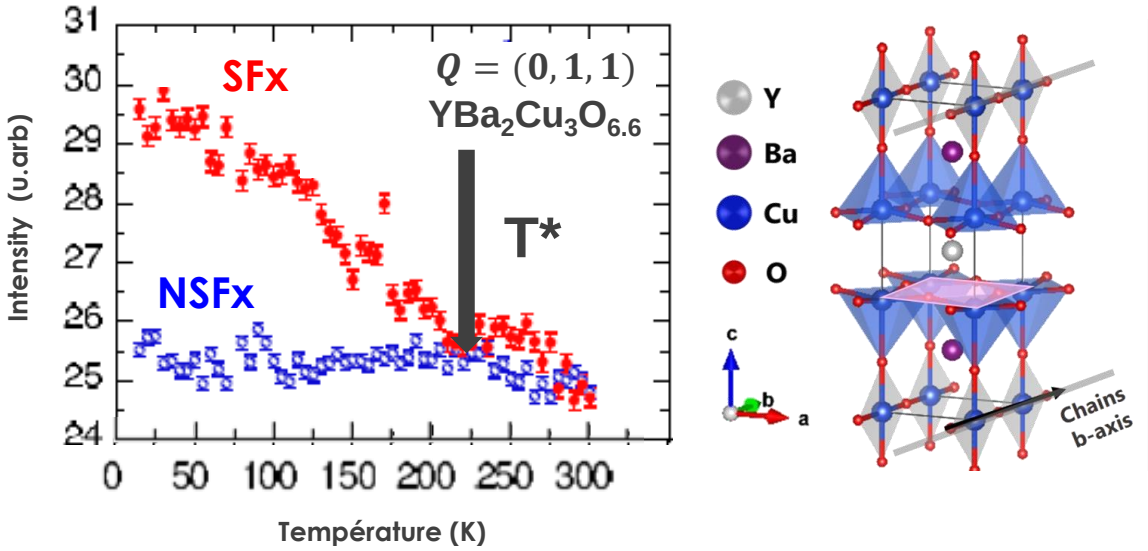
Polarized neutron diffraction



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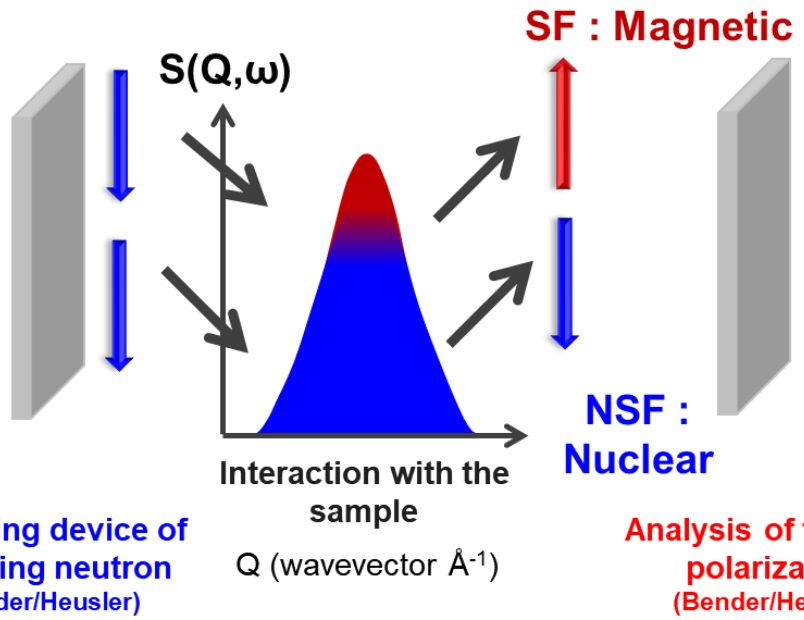
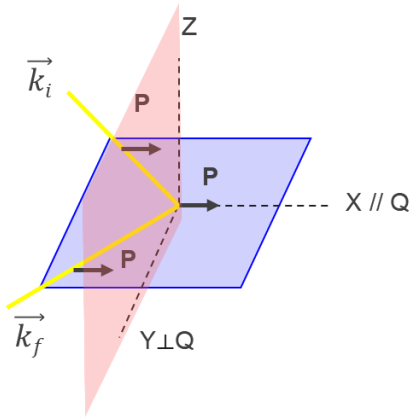


The neutron probes the magnetic component ⊥ to $\vec{Q}$ and P

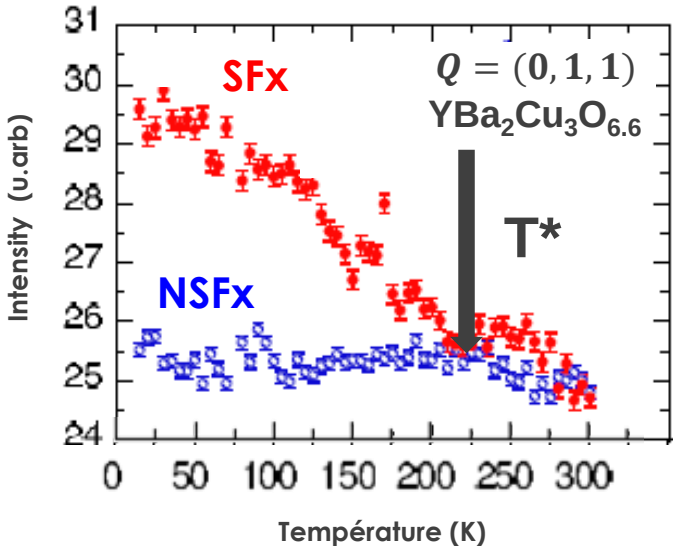


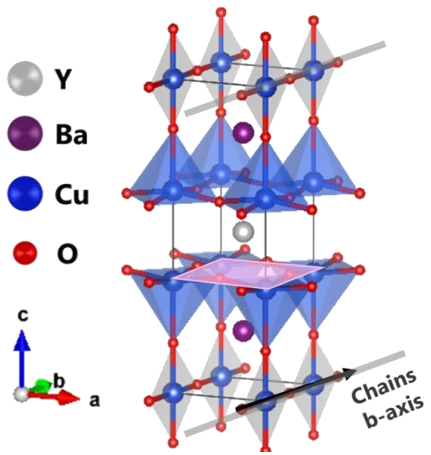
Polarization analysis to extract the amplitude and orientation of the magnetic moment

$$I_{SF_X} = \left|M_\perp^Y\right|^2 + \left|M_\perp^Z\right|^2 + BGR_{SF_X}$$
$$I_{SF_Y} = \left|M_\perp^Z\right|^2 + BGR_{SF_Y}$$
$$I_{SF_Z} = \left|M_\perp^Y\right|^2 + BGR_{SF_Z}$$

Hidden q=0 Magnetism in the Pseudogap Phase Seen by Polarized Neutron Diffraction

Polarized neutron diffraction

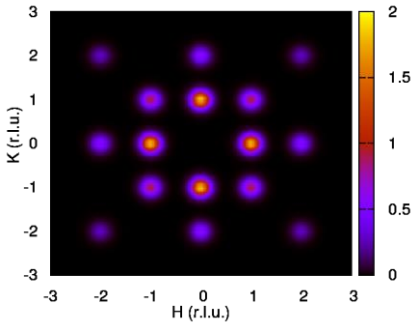


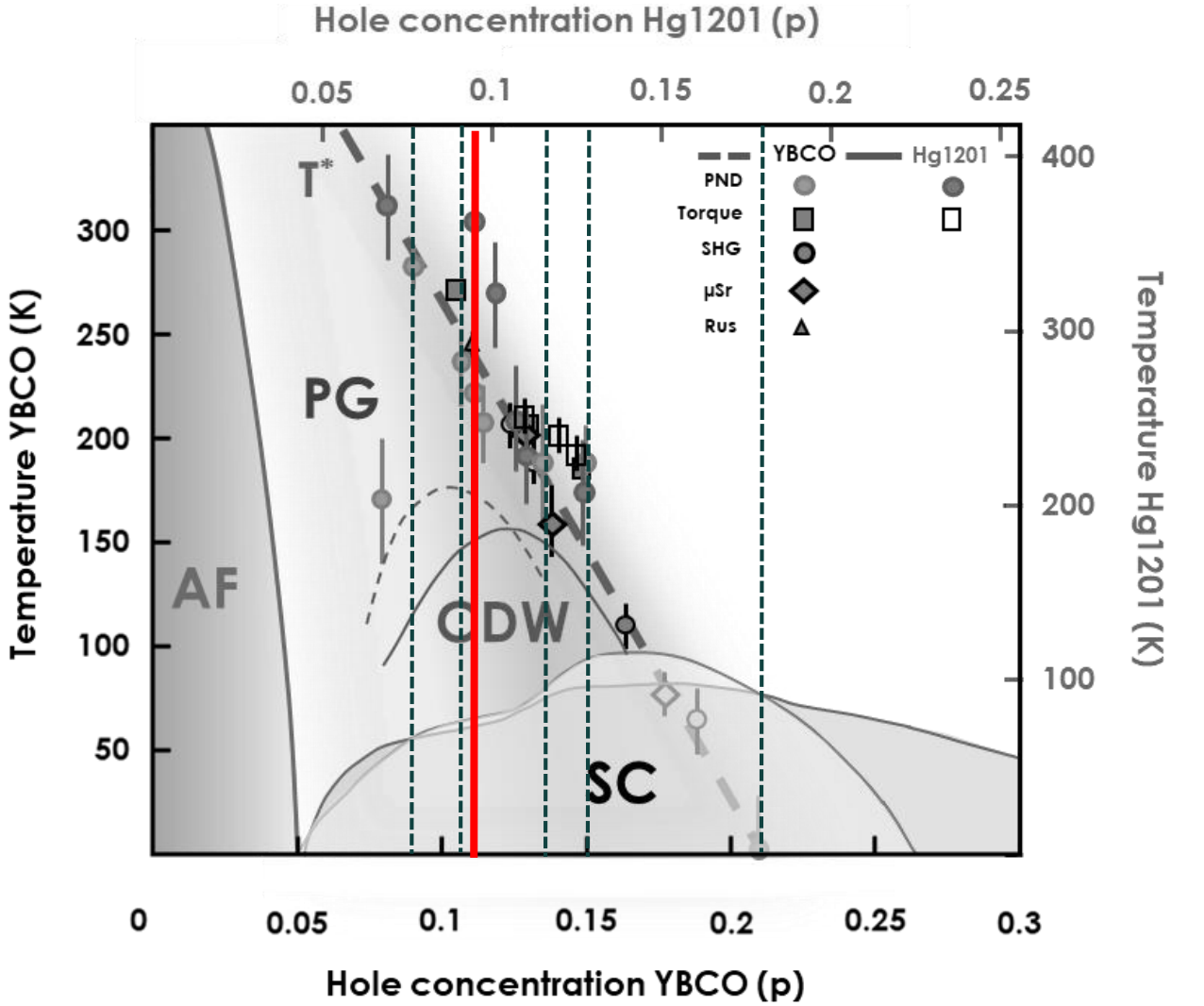


B. Fauqué *et al.*, Phys. Rev. Lett. 96, 197001 (2006)

Characteristics

- T_{mag}= T*
- Weak magnetic moment ~0.1 μ_B
  - Tilted out of plane
  - 3D and 2D correlations
  - Peculiar structure factor

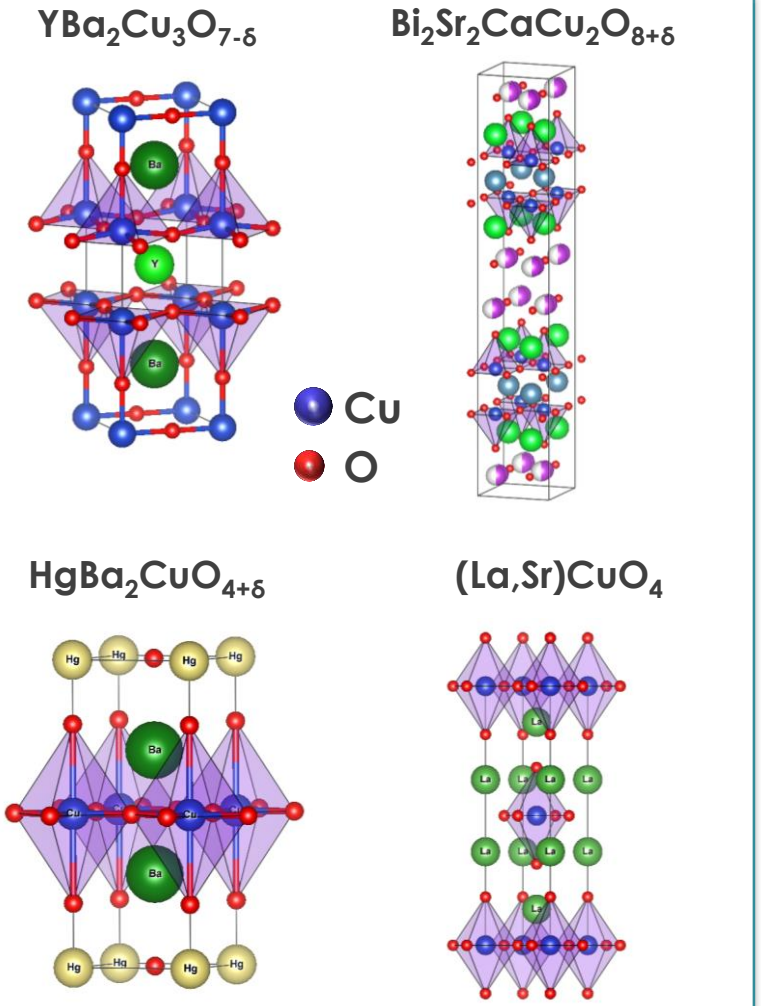




P.Bourges et al., C.R. Phys 22,1, (2022)

Hidden q=0 Magnetism in the Pseudogap Phase Seen by Polarized Neutron Diffraction

q=0 magnetism in 2D High-Tc cuprates



Characteristics

$T_{mag} = T^*$
Weak magnetic moment ~0.1 μB
Tilted out of plane
3D and 2D correlations
Peculiar structure factor

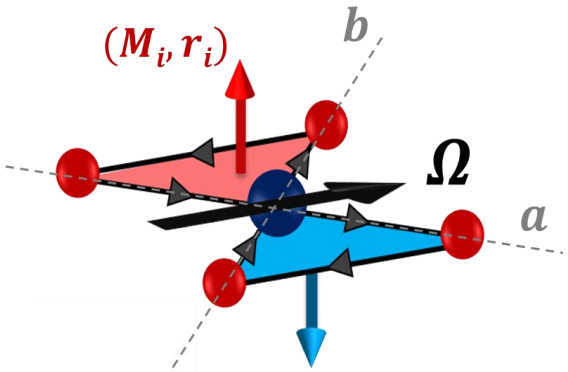
Preserved symmetry
Lattice Translation

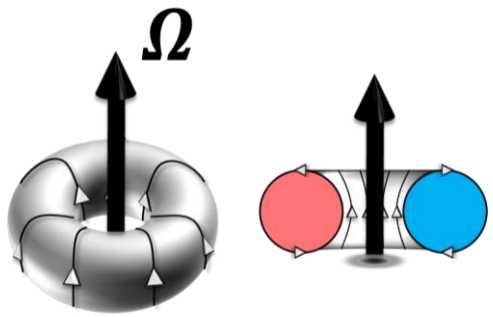
Broken Symmetries
Time reversal
Parity
C_4 rotation

Magneto-electric state
Microscopic description ?

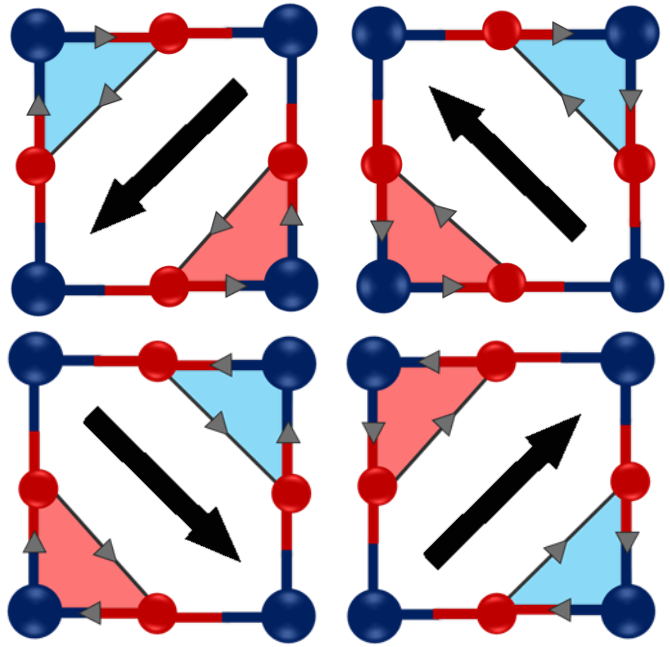
P.Bourges et al., C.R. Phys 22,1, (2022)

Magnetoelectric Loop Currents and Anapoles





$$\Omega = \sum m_i \times ri$$

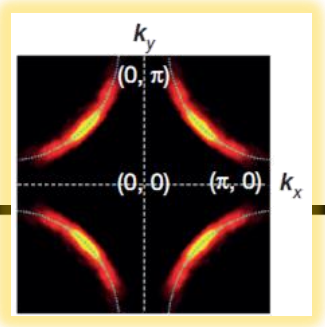


C.M. Varma, Phys Rev B **73**(15), 155113 (2006)
S. Sarkar *et al.,* Phys. Rev. B **100**, 214519 (2019)
M. S. Scheurer *et al.,* Phys. Rev. B **98**, 235126 (2018)
P. Chudzinski *et al.,* Phys. Rev. B **78**, 075124 (2008)

Order Parameter Of The Pseudogap Phase
Ancillary order parameter of the pseudogap
Ancillary order parameters in spin liquids
Quasi-1D Cuprates

The Pseudogap State

Pseudogap



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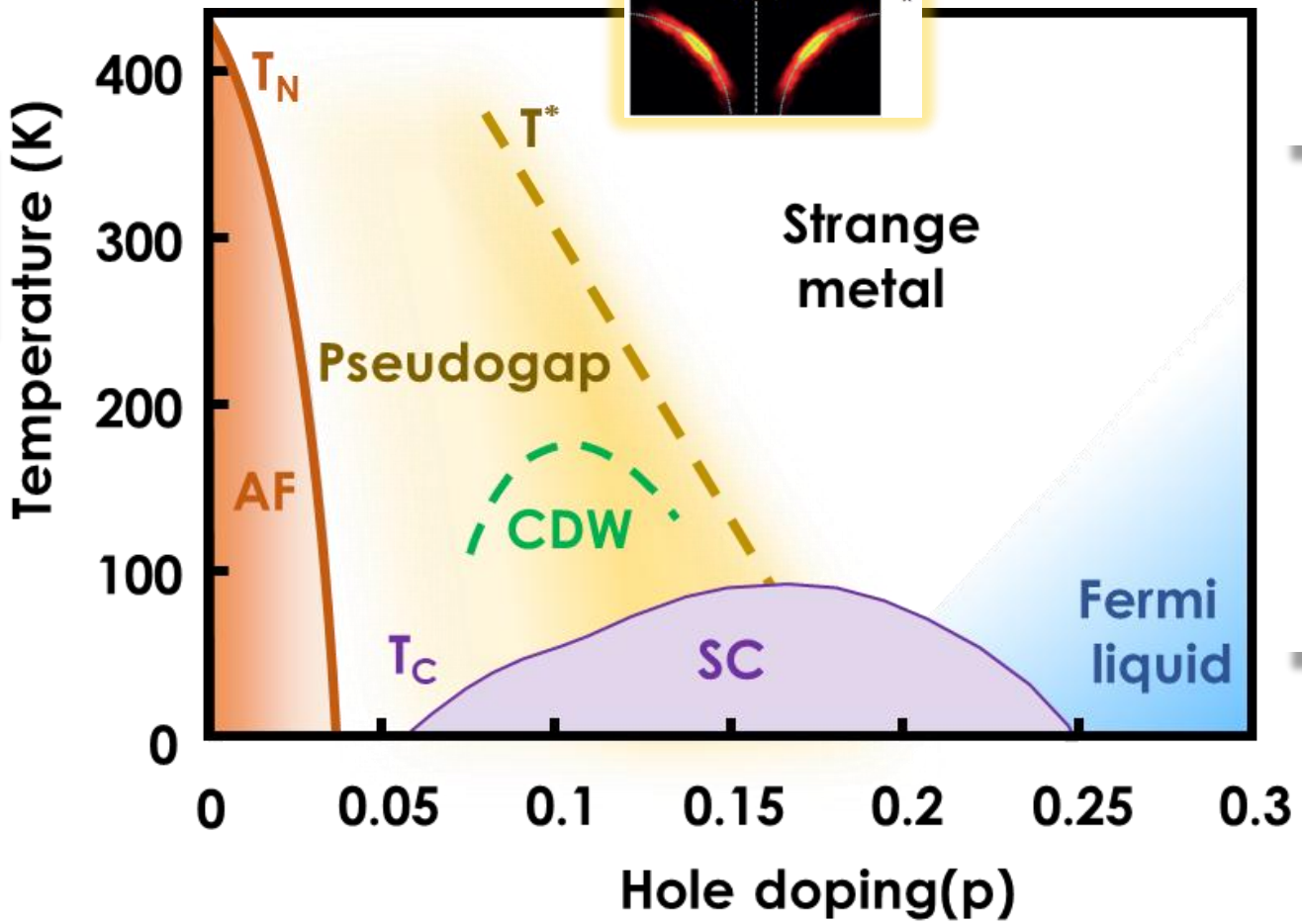
Pre-formed pairs? Preemptive to the SC state

Competing order parameter ?

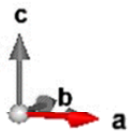


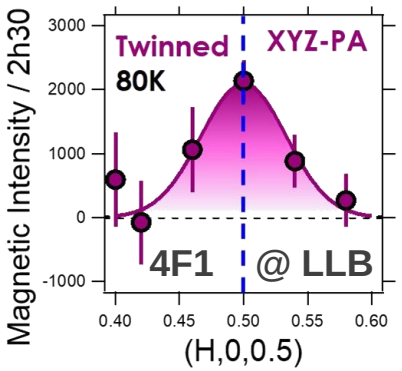
What causes the opening of the pseudogap ?

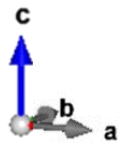
CDW Breaks the lattice translation symmetry but appears at much lower T

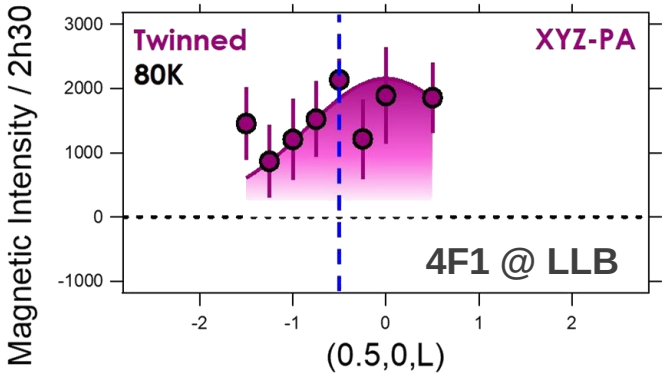
Translation Symmetry Breaking in the Pseudogap Phase of $YBa_2Cu_3O_{7-\delta}$

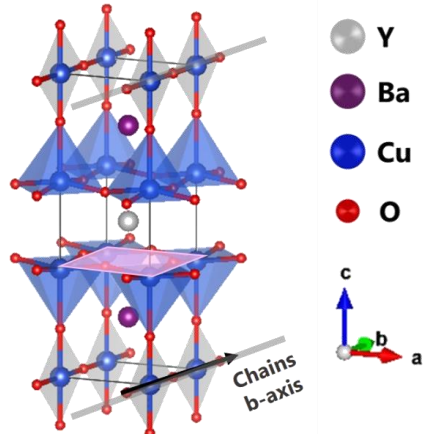
Twinned sample (Tc=61K)



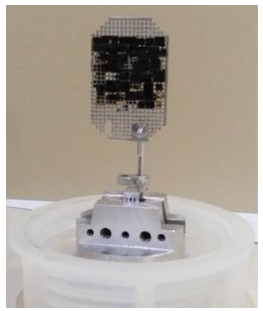


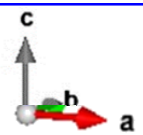


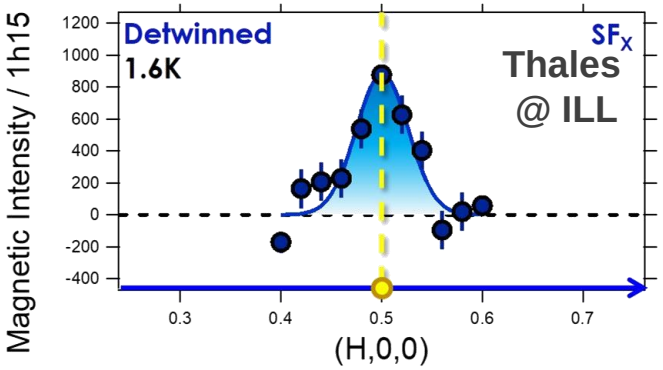


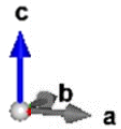


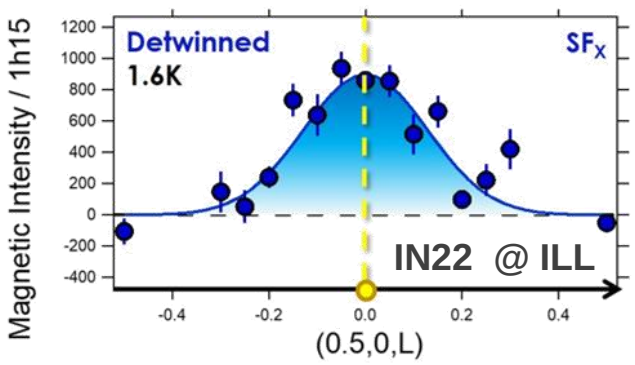
Detwinned sample (Tc=63K)

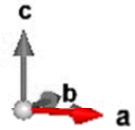


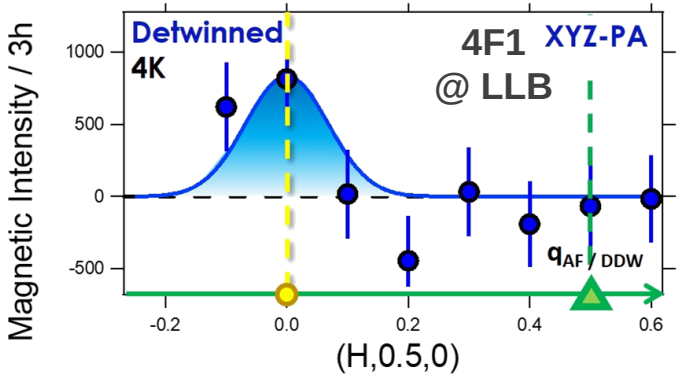












Magnetic scattering coming from the planes and doubling the Unit cell in the [a,b] plane

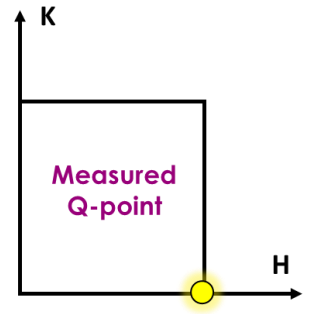
Correlation length of about 5-6 unit cells ~ 25 Å in-plane

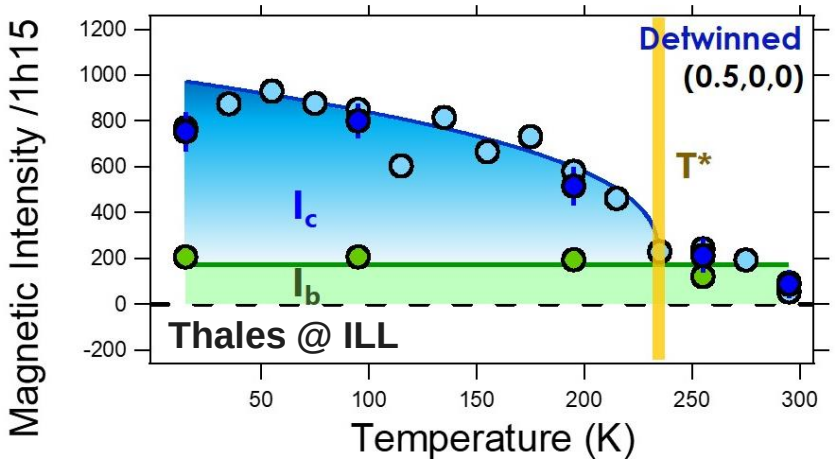
Diffuse scattering along the c-axis ➔ Very short correlation lengths along the c-axis

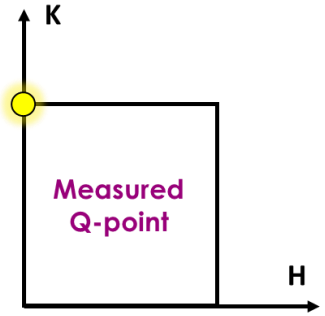
D. Bounoua et al., Nat. Comm. Phys 5, 268 (2022).

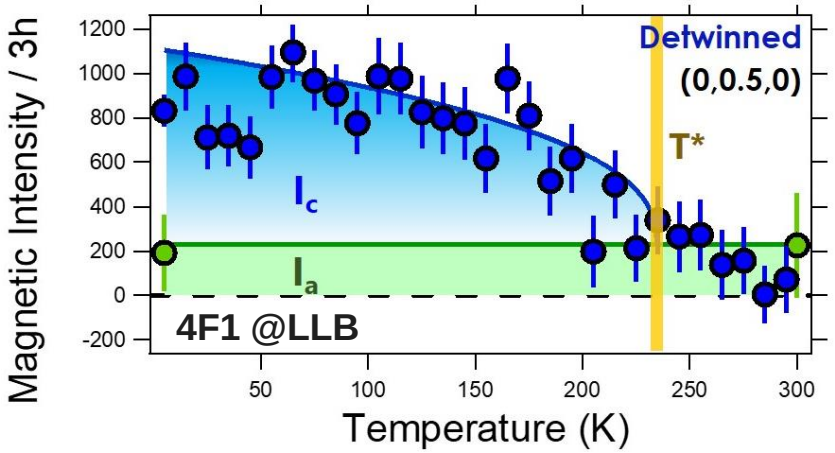
Translation Symmetry Breaking in the Pseudogap Phase of $YBa_2Cu_3O_{7-\delta}$

Temperature dependence

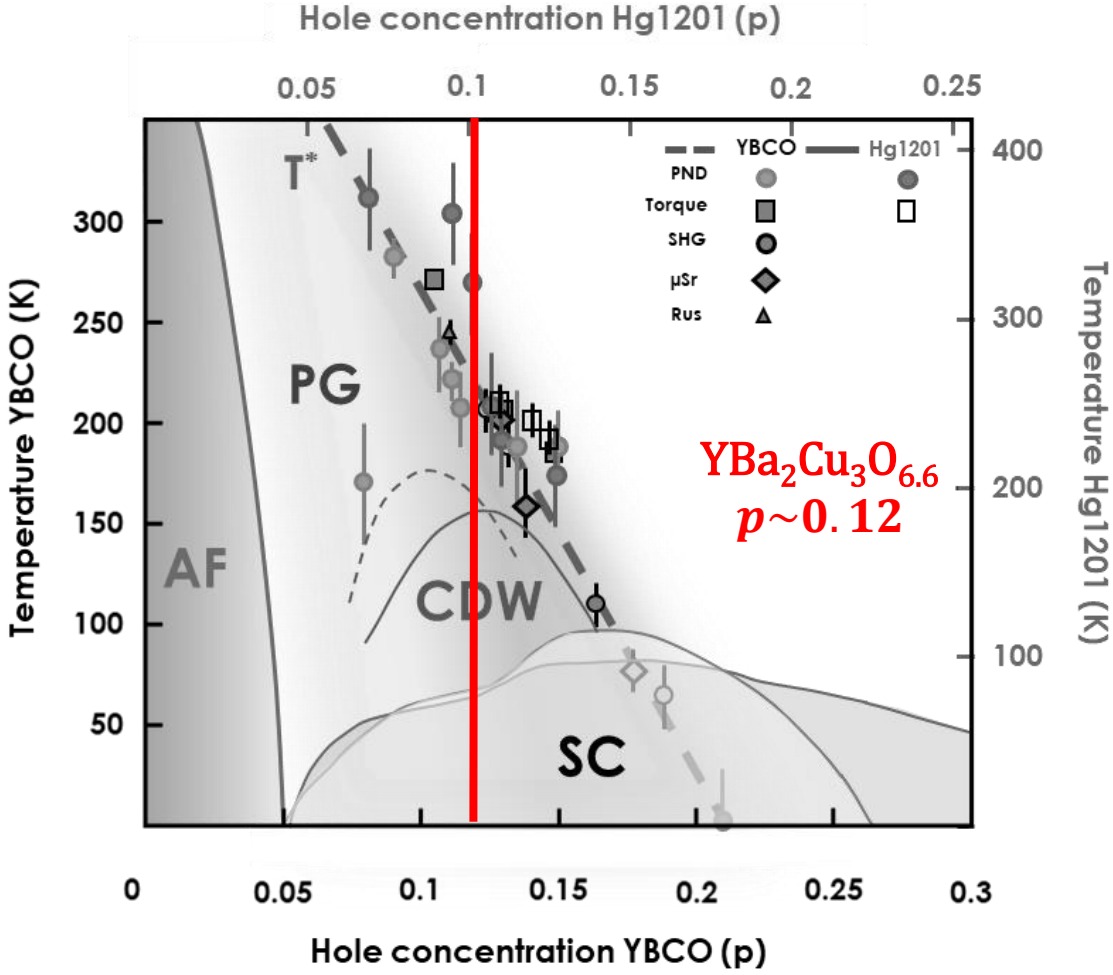








Signal appears at T*
Mainly out-of-plane (along the c-axis)



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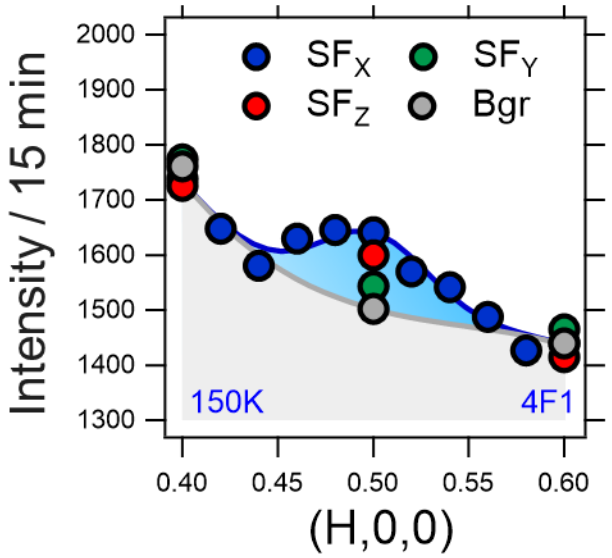
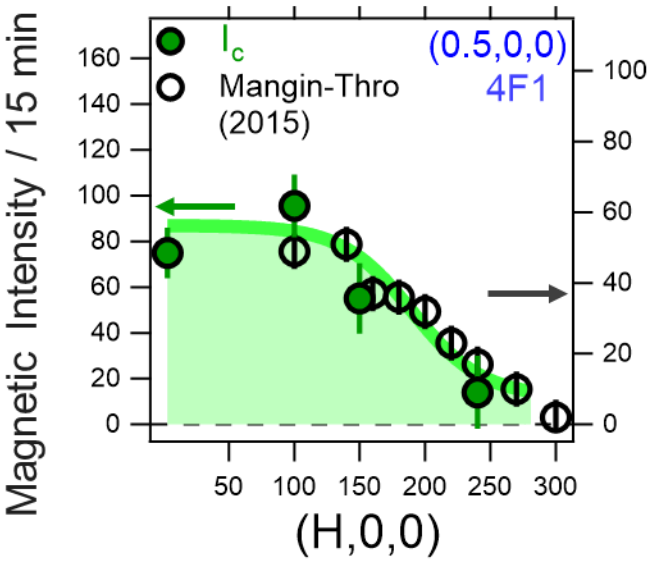
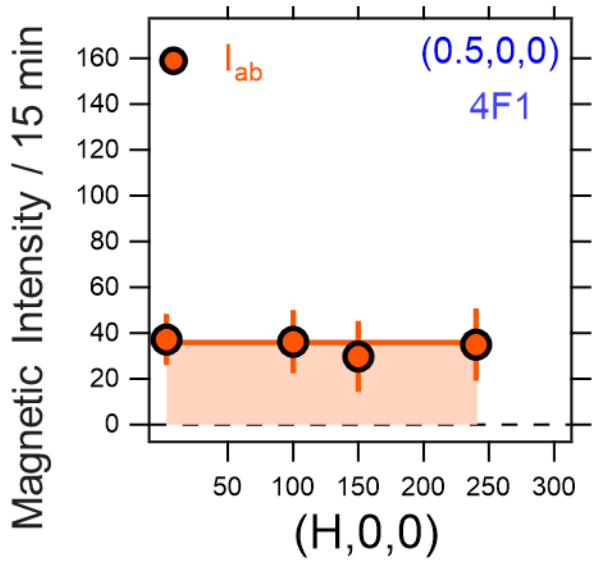
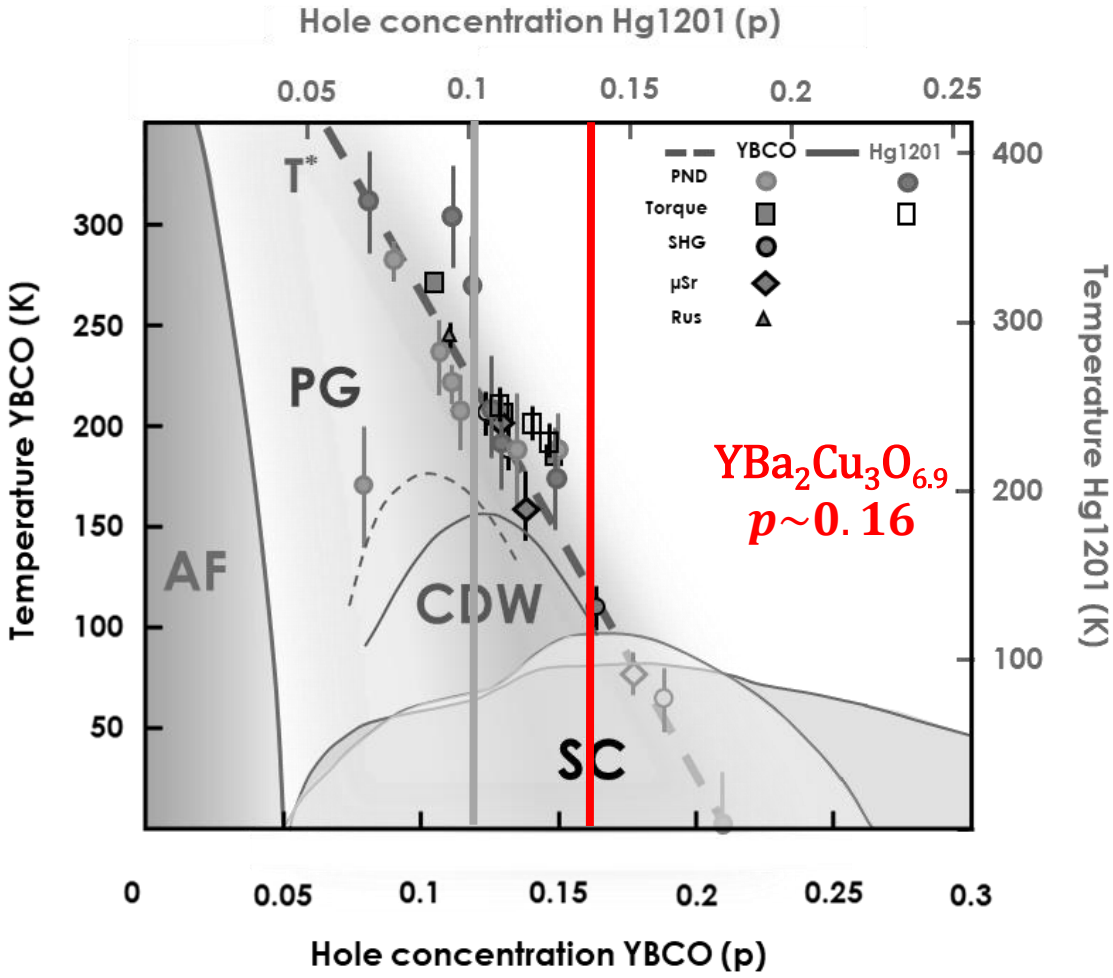


Prof. Xin Yao
School of Physics and Astronomy
Shanghai Jiao Tong University







D. Bounoua et al., arXiv:2302.01870 (under review in Phys. Rev. B)

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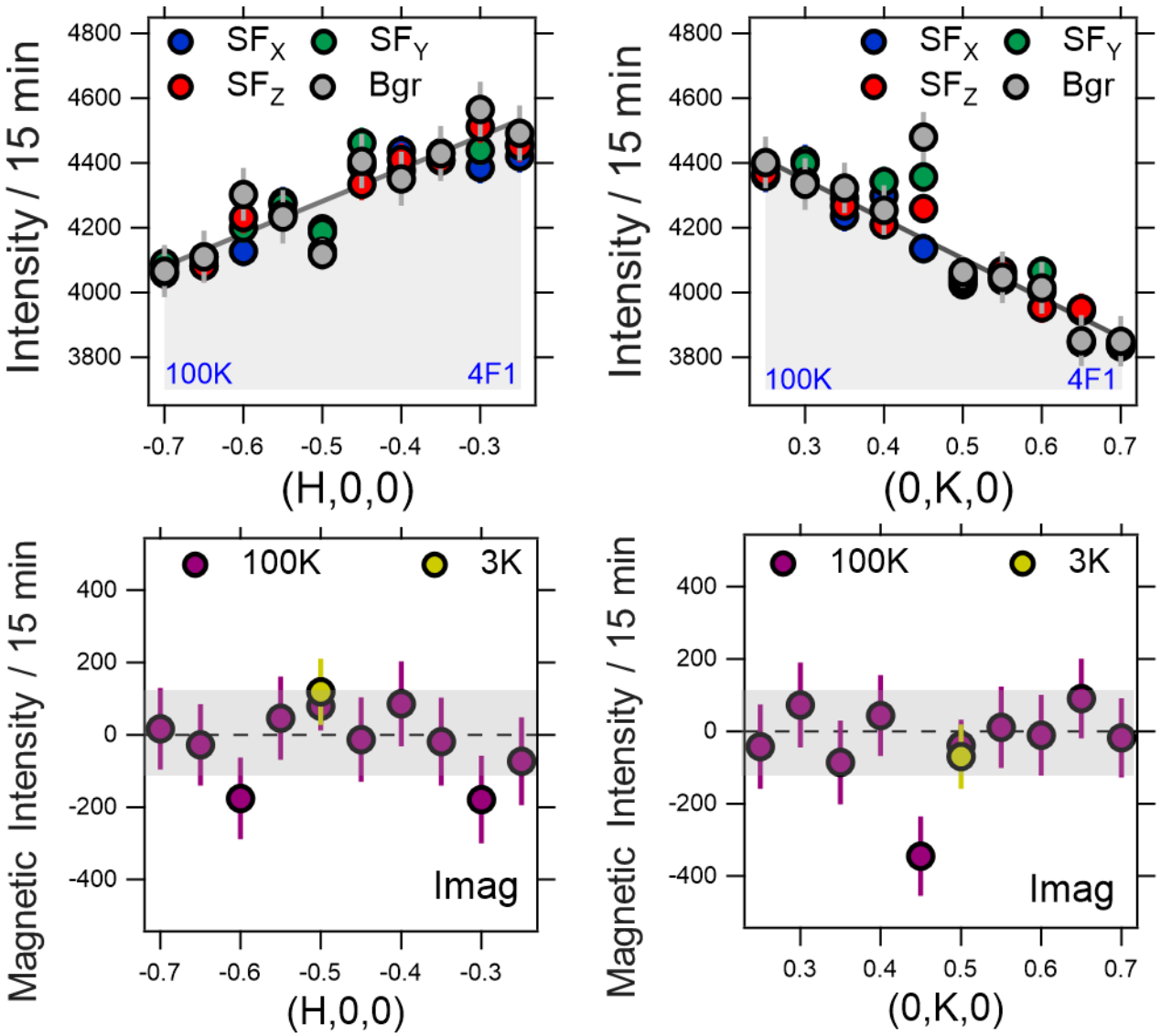

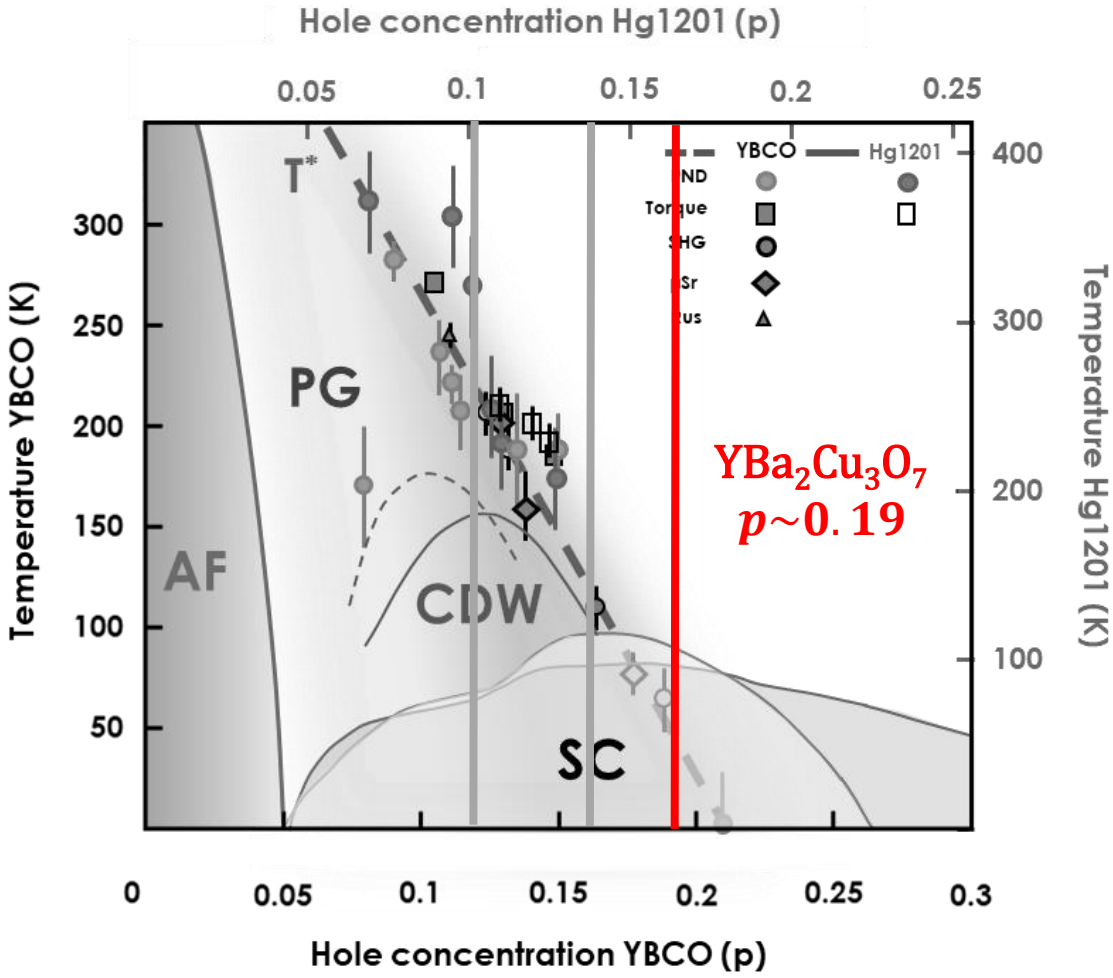

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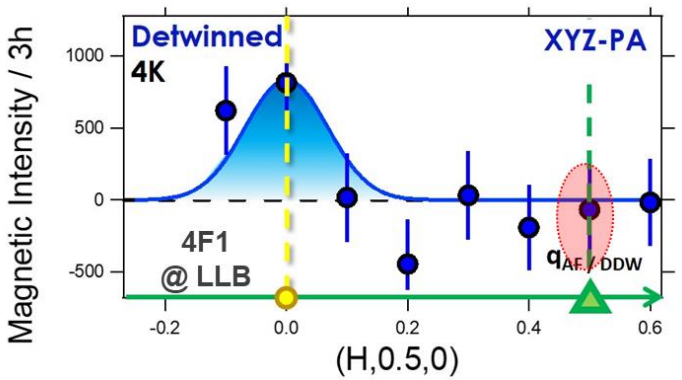
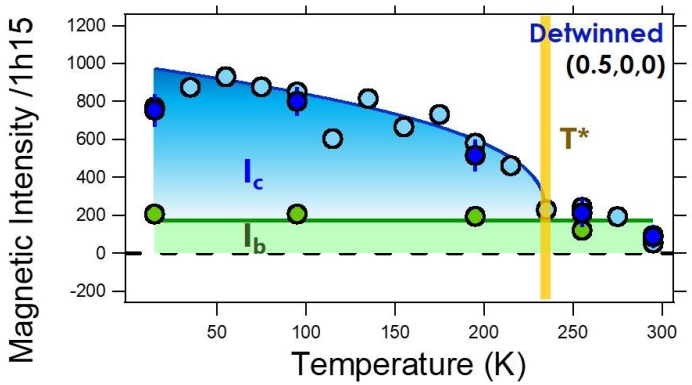
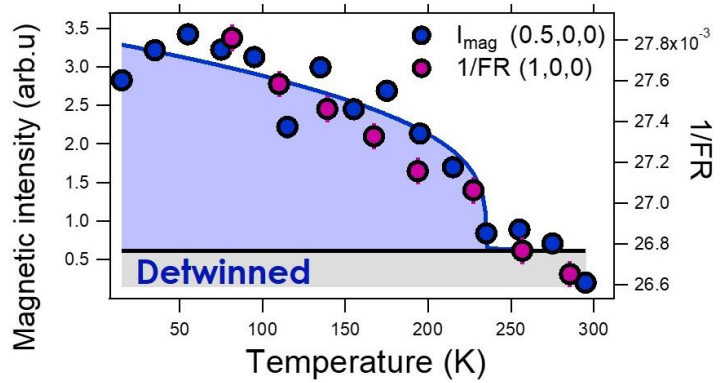
Translation Symmetry Breaking in the Pseudogap Phase of $YBa_2Cu_3O_{7-\delta}$







No magnetic signal at q=$(\frac{1}{2},\frac{1}{2},0)$

➔ Not collinear antiferromagnetism

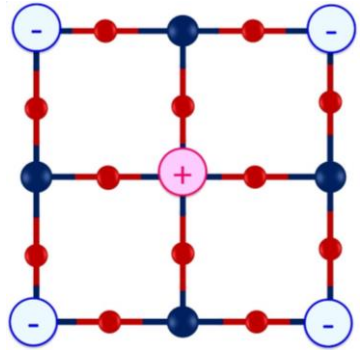
➔ No flux-like phase (DDW)

Magnetic moment orientation mainly out-of-plane

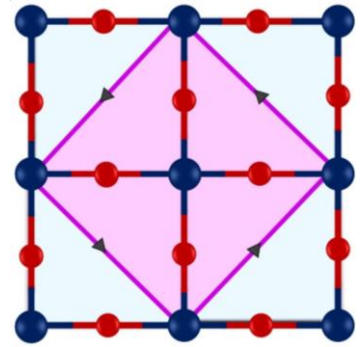
Same temperature dependence as q=0 magnetism

Possible models

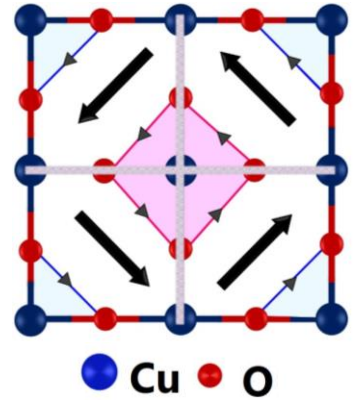
1 site over 2 with opposite magnetic moments orientation



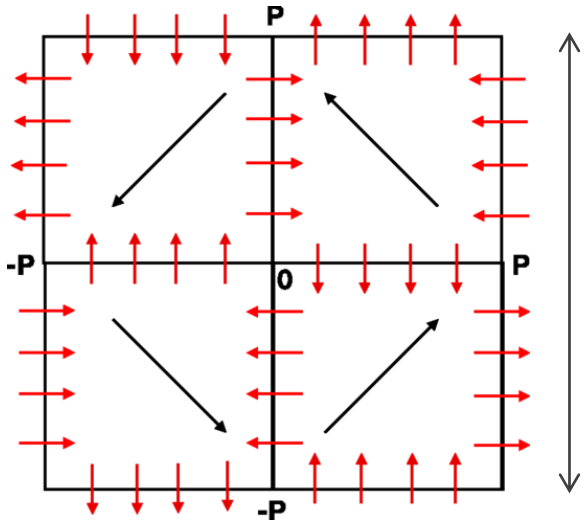
DDW-like phase with currents Between Cu-sites rotated by 45°



LT breaking loop currents model

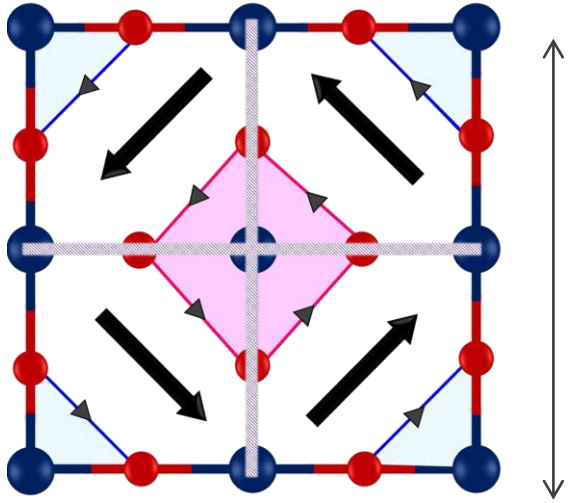


Translation Symmetry Breaking in the Pseudogap Phase of $YBa_2Cu_3O_{7-\delta}$



2P
P= several CuO_2 cells

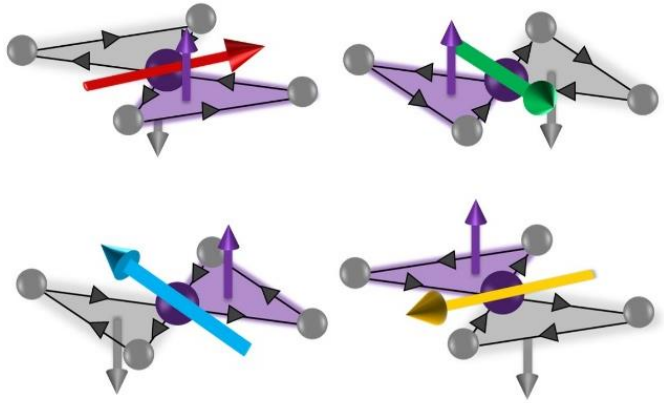
C. M. Varma, Phys. Rev. B 99, 224516 (2019).



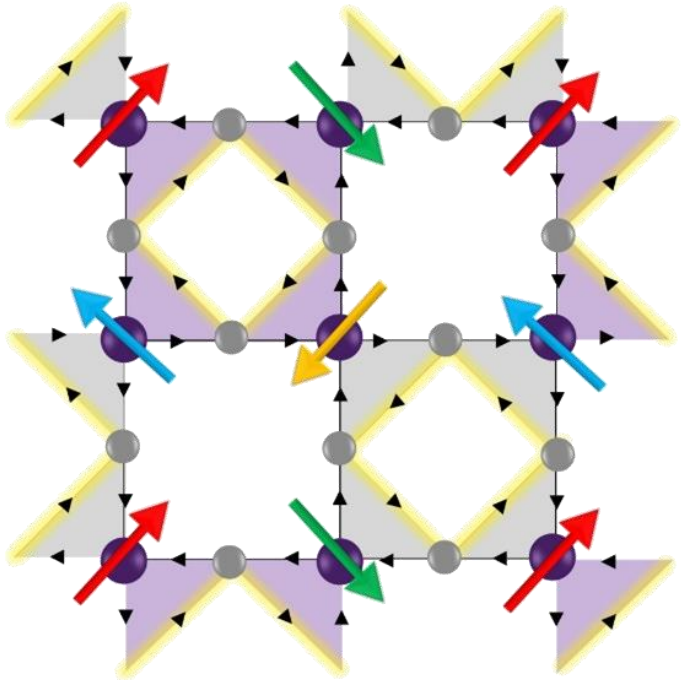
2P
P=1 CuO_2 cell

Cu

O



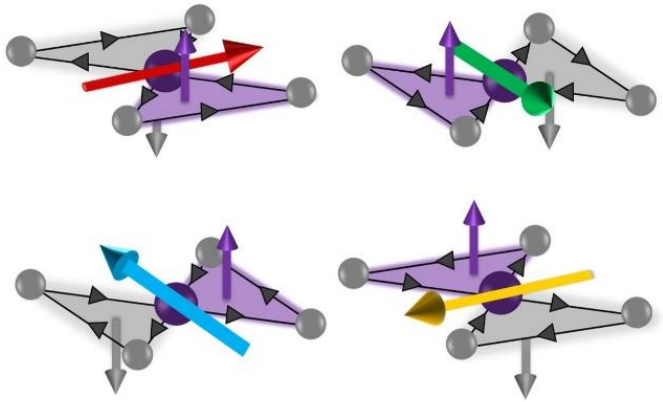
4 degenerate states



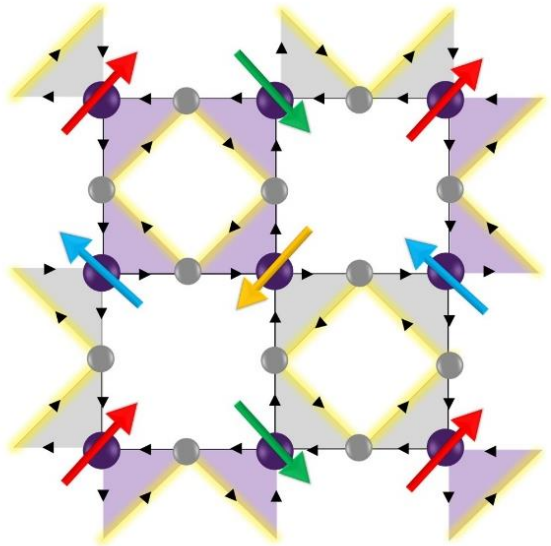
2x2 unit cell

D. Bounoua et al., Nat. Comm. Phys 5, 268 (2022).

Translation Symmetry Breaking in the Pseudogap Phase of $YBa_2Cu_3O_{7-\delta}$

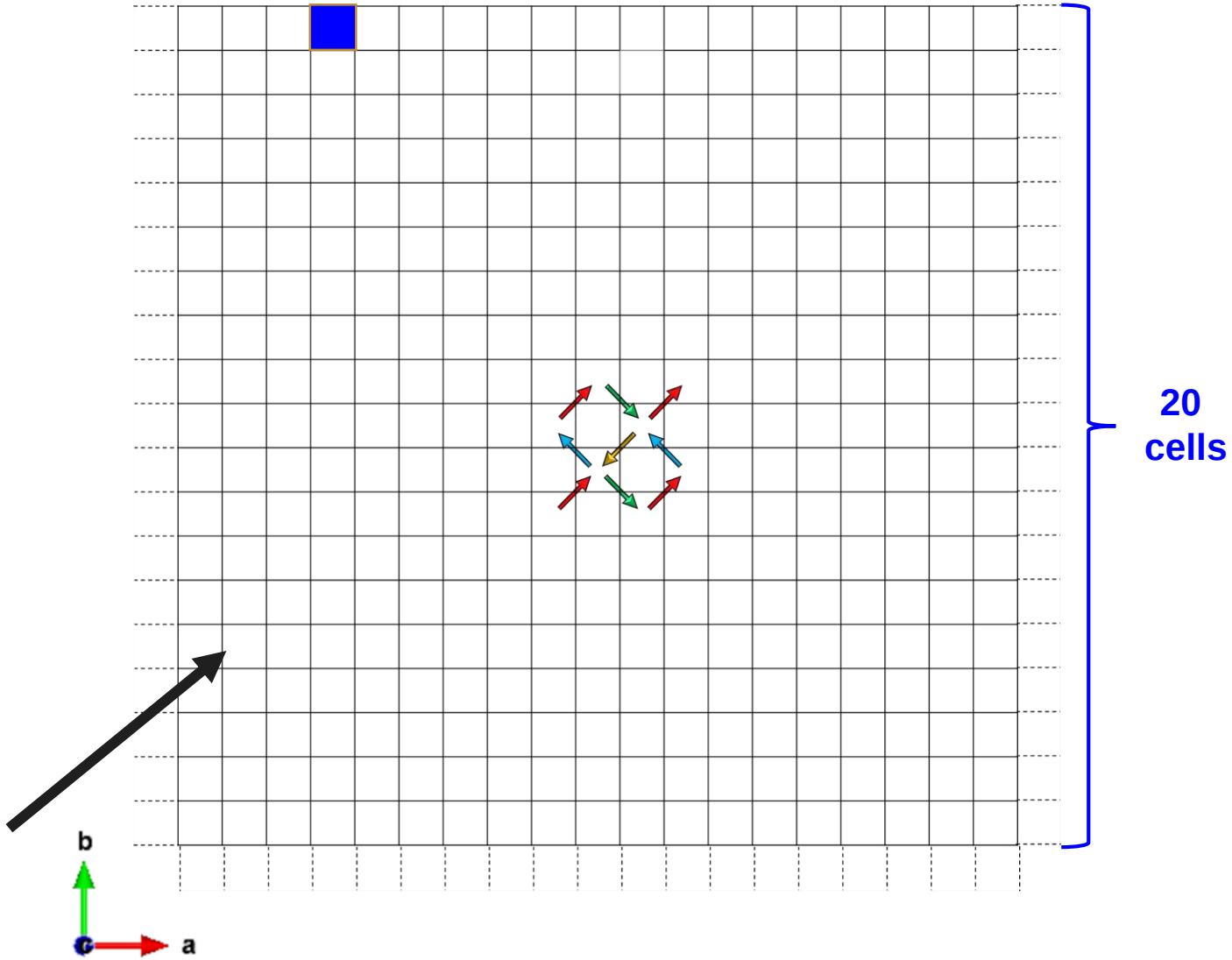


4 degenerate states



2x2 unit cell

CuO_2 unit cell



D. Bounoua et al., Nat. Comm. Phys 5, 268 (2022).

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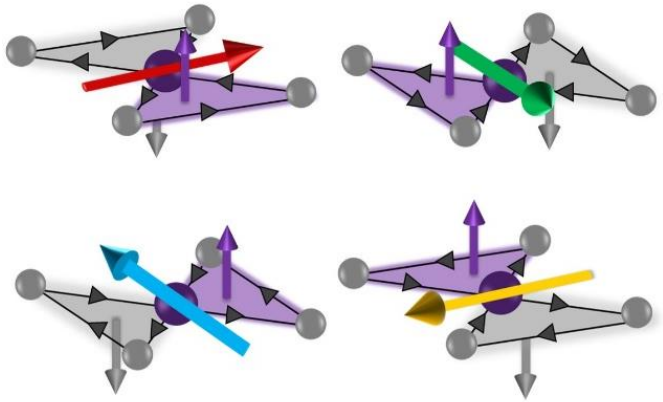
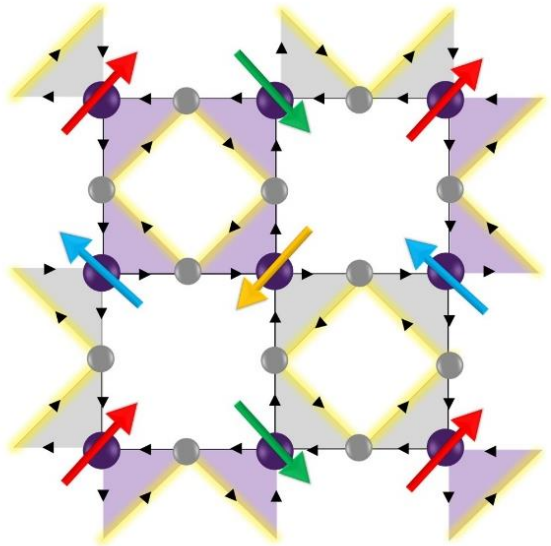
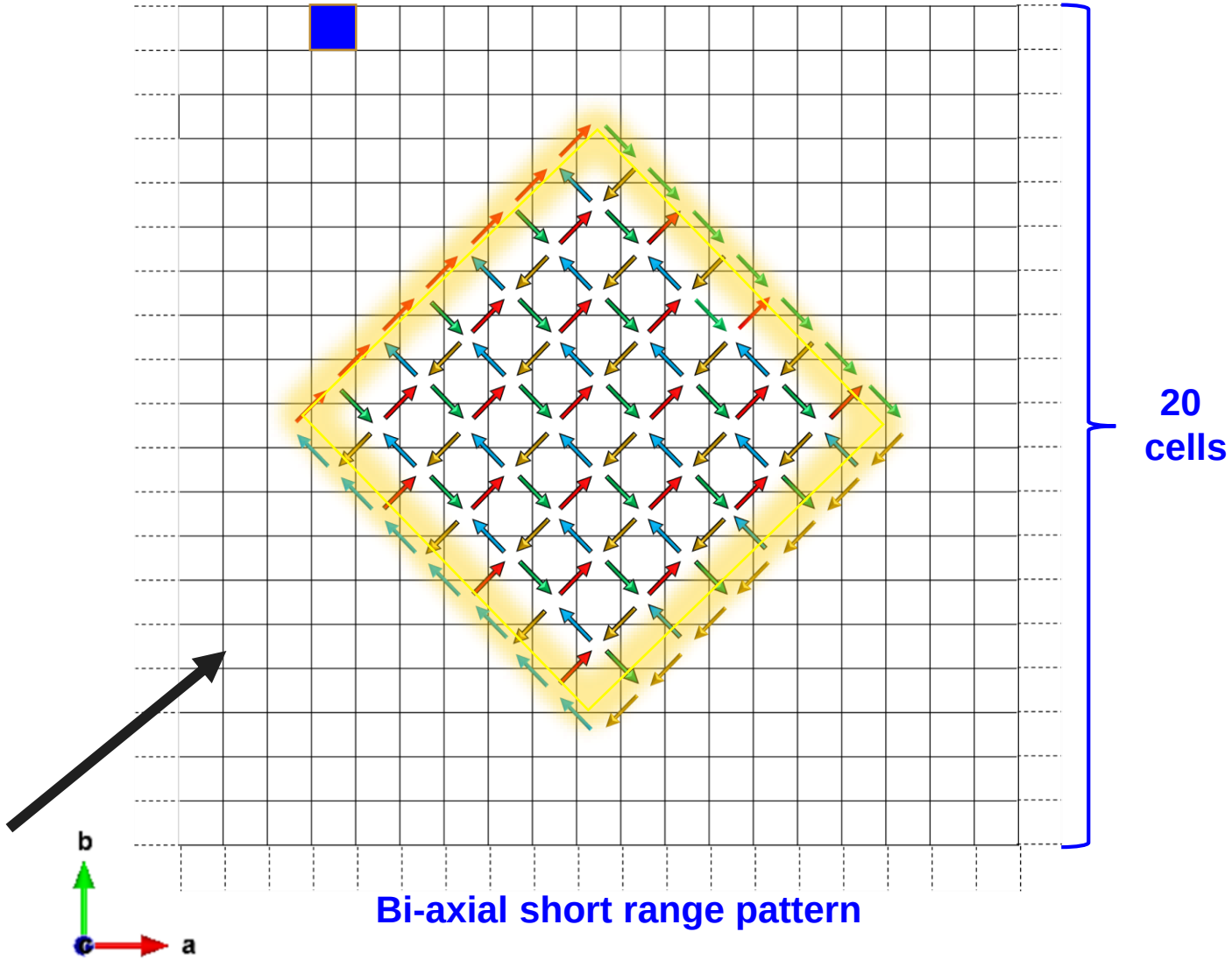


4 degenerate states



2x2 unit cell

CuO_2 unit cell

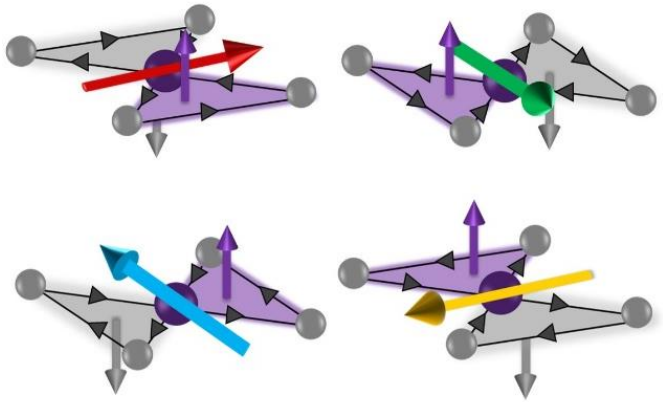


20 cells

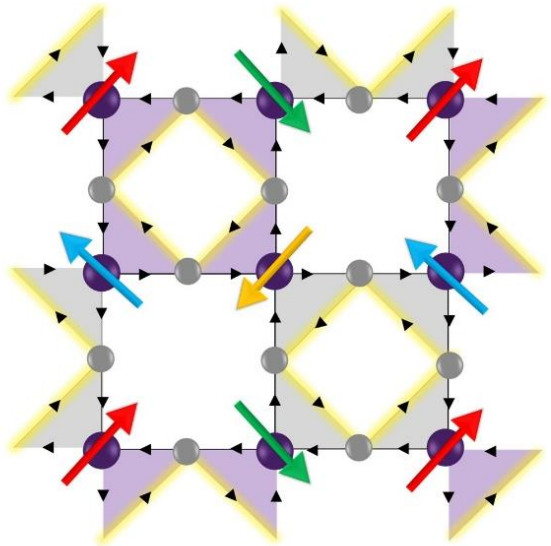
Bi-axial short range pattern

D. Bounoua et al., Nat. Comm. Phys 5, 268 (2022).

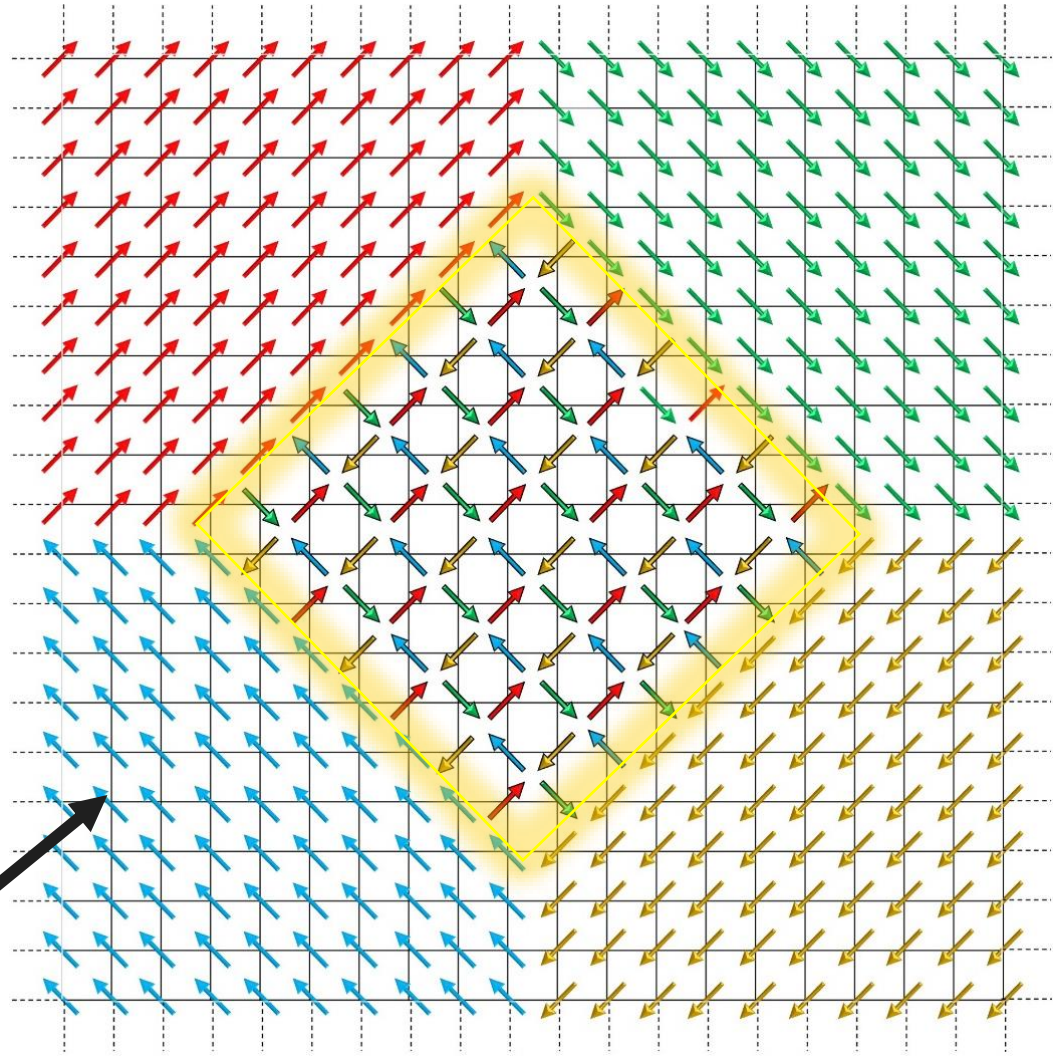
Translation Symmetry Breaking in the Pseudogap Phase of $YBa_2Cu_3O_{7-\delta}$



4 degenerate states



2x2 unit cell

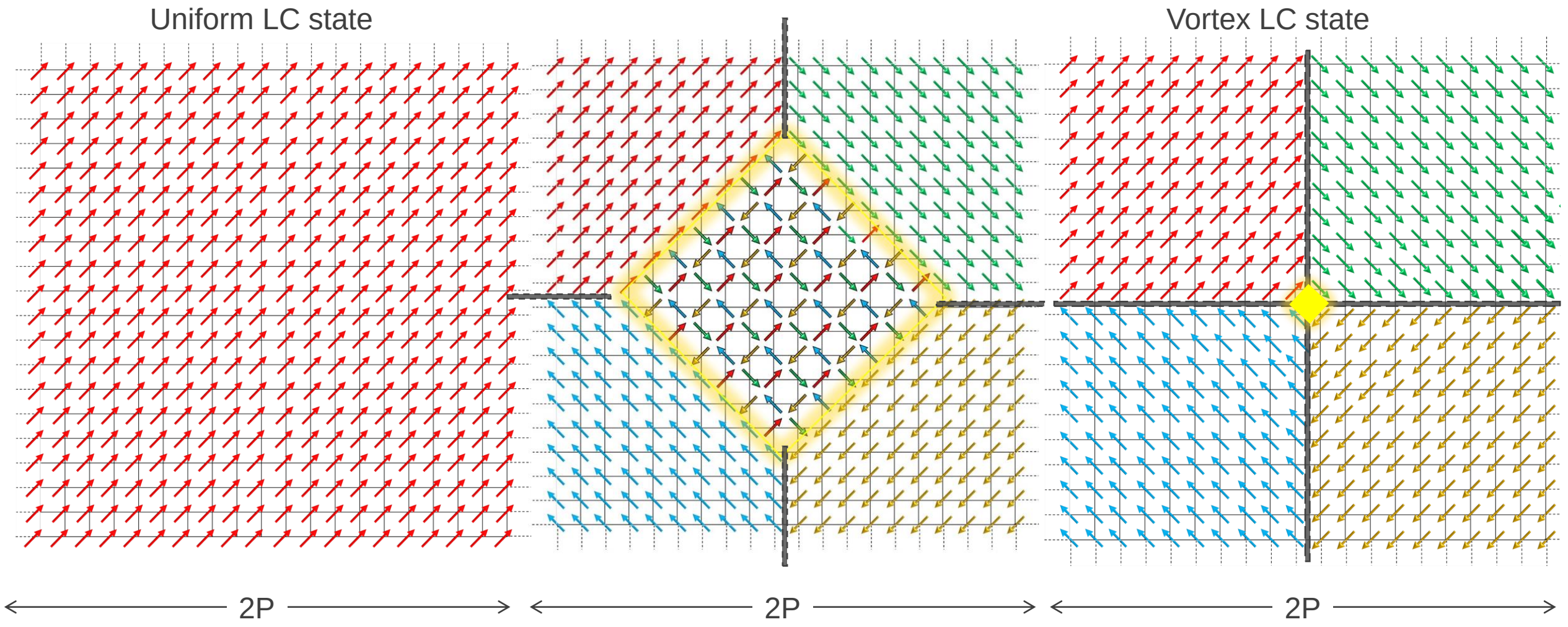


q=0 domains

Bi-axial short range pattern connecting larger q=0 domains

D. Bounoua et al., Nat. Comm. Phys 5, 268 (2022).

Translation Symmetry Breaking in the Pseudogap Phase of $YBa_2Cu_3O_{7-\delta}$



C.M. Varma, Phys Rev B **73**(15), 155113 (2006)

D. Bounoua et al., Nat. Comm. Phys **5**, 268 (2022).

C. M. Varma, Phys. Rev. B 99, 224516 (2019).

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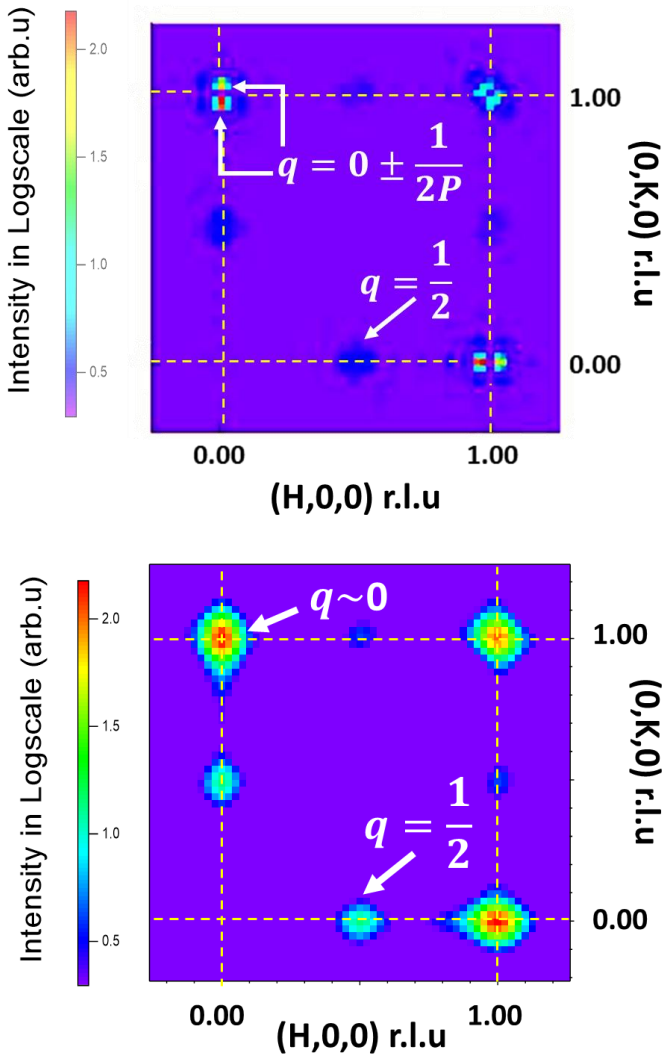
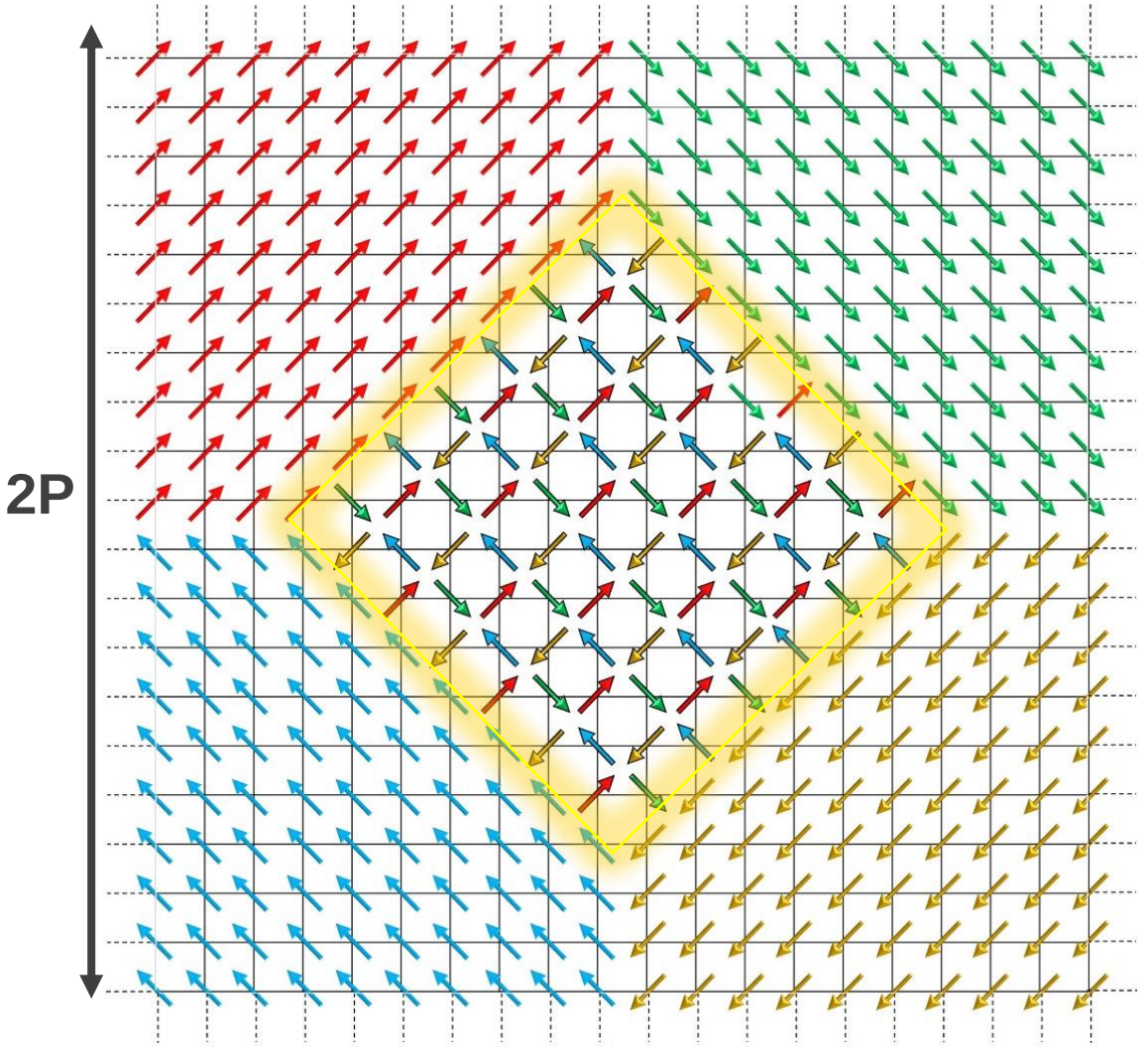


Translation Symmetry Breaking



Bi-axial short range pattern connecting larger q=0 domains

D. Bounoua et al., Nat. Comm. Phys 5, 268 (2022).

Conclusion

- Intra Unit Cell magnetism observed in the pseudogap state of high-Tc cuprates in 4 different families: YBCO, Hg1201,Bi2212, LSCO ➔ **Large ferro-anapolar domains**

  P.Bourges et al., C.R. Phys 22,1, (2022)

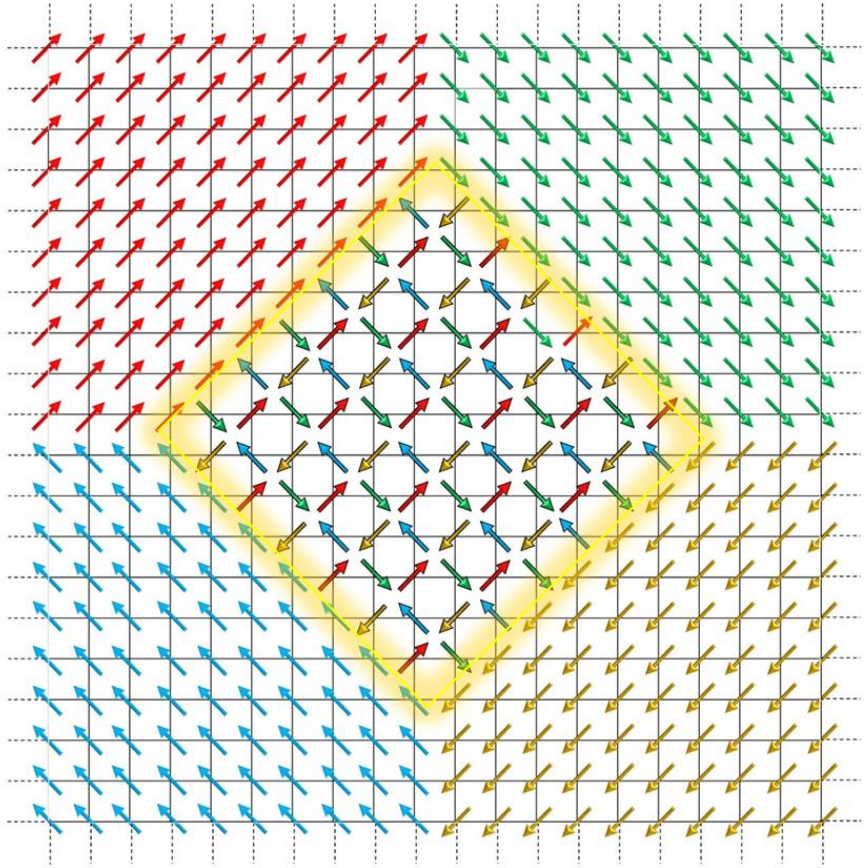
- Hidden short range magnetism $(\pi,0) \equiv (0,\pi)$ in YBCO ➔ **Anapolar vortex pattern**

  D. Bounoua et al., Nat. Comm. Phys 5, 268 (2022).

  D. Bounoua et al., arXiv:2302.01870 (under review in Phys. Rev. B)

- Probe the existence of the q=1/2 phase in other cuprates compounds

- Search for incommensurate magnetic response at the shoulders of the Bragg peak



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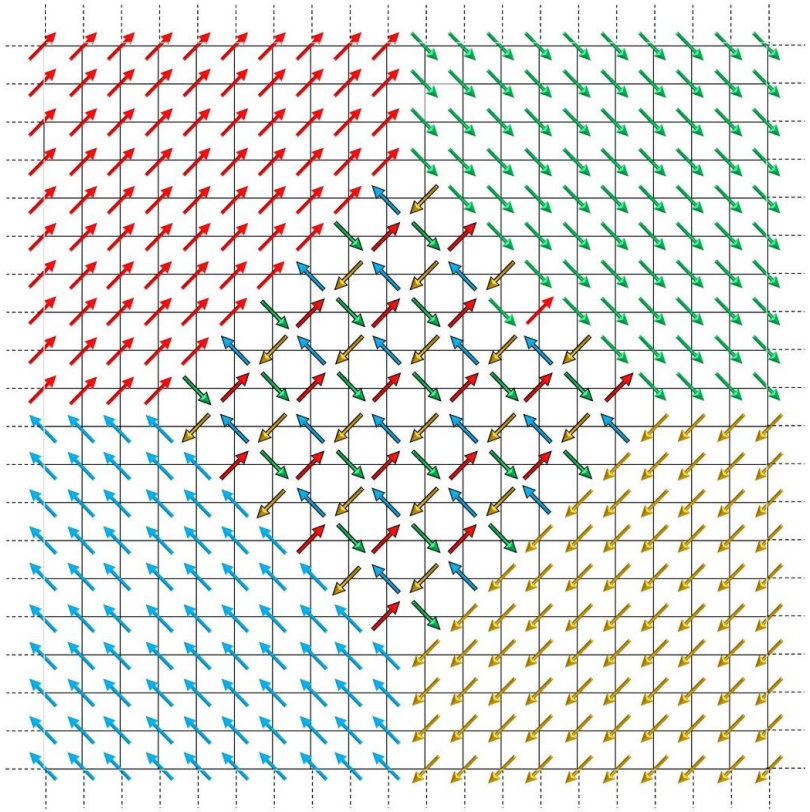
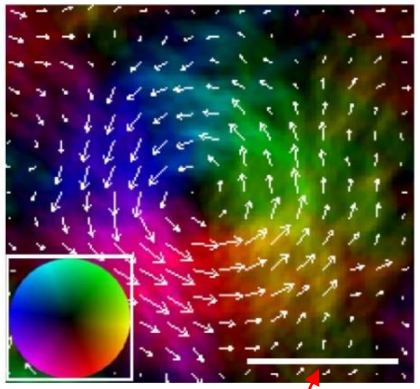
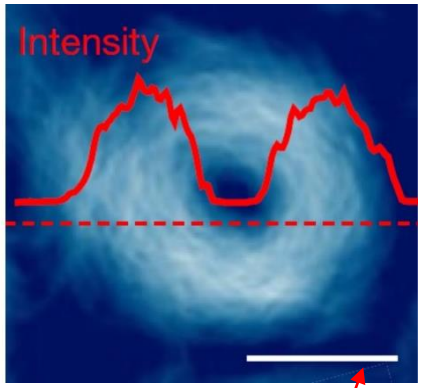
Thank you for your attention!

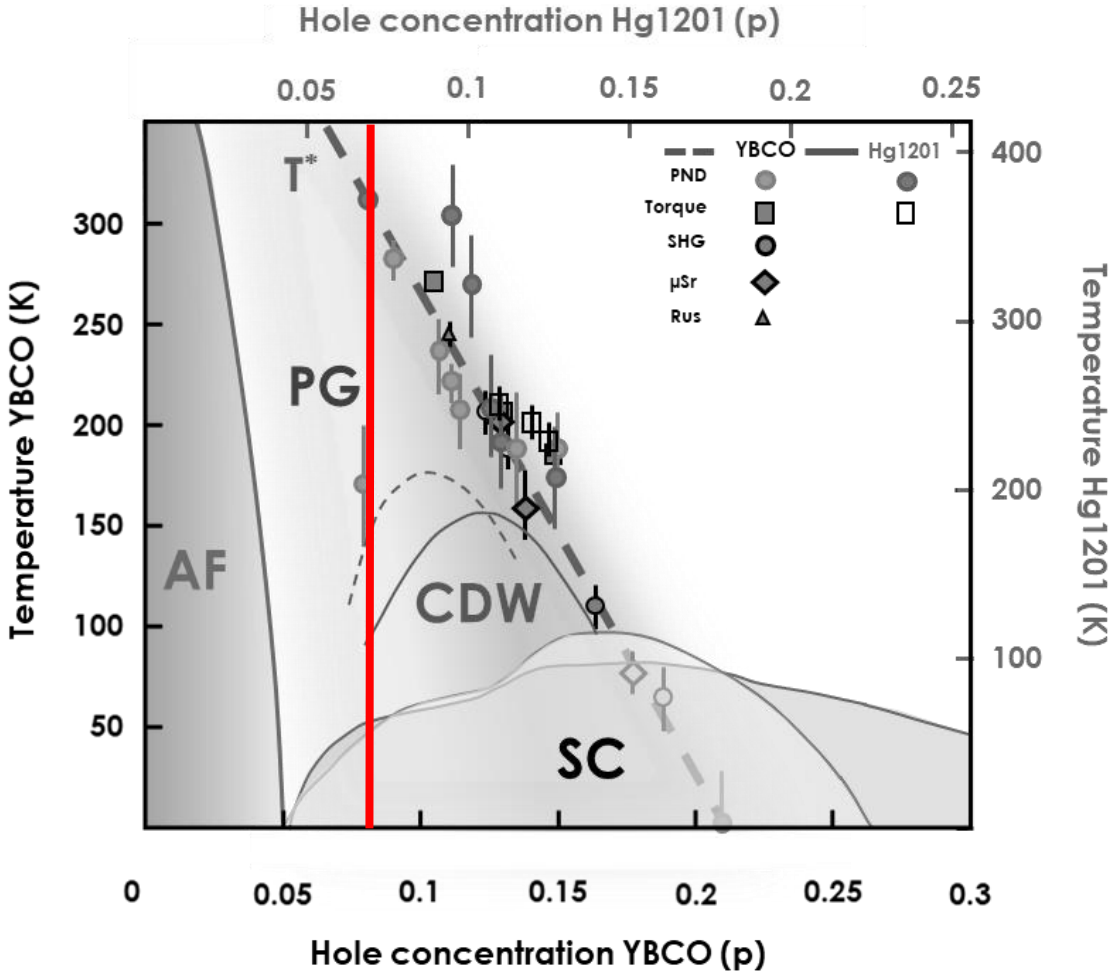
Hidden Magnetic Texture in the Pseudogap Phase of High-Tc $YBa_2Cu_3O_{7-\delta}$

Magnetic texture seen by Lorentz Transmission Electron Microscopy in $YBa_2Cu_3O_{6.5}$









Z. Wang et al., Nature 615, 405 (2023)