Fale gęstości ładunku i lokalizacja nośników w fazie *pseudoprzerwy* w nadprzewodnikach miedziowych

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Vienna, Austria

AGH-UST Krakow, November 10, 2017

Plan

Zrozumienie diagramu fazowago niekonwencjonalnych nadprzewodników i istotnych oddziaływań

Fale gęstości ładunku (CDW) w $HgBa_2CuO_{4+\delta}$

- Rezonansowe rozproszenie i dyfrakcja promieni X

Niezależne punkty krytycze CDW i *pseudoprzerwy*

Zmiana gęstości ładunku przy przekroczeniu punktu krytycznego *pseudoprzewy p** in $YBa_2Cu_3O_{6+\delta}$

Lokalizacja ładunku w obrębie *pseudoprzerwy*

- Transport elektronowy w wysokich polach magnetycznych

AGH

LNCMI

Charge-density wave studied by X-rays

B. Yu
G. Yu
Y. Tang
N Barisic
M. Greven

I. Bialo
T. Kolodziej
A. Kozlowski

Electronic transport in high magnetic fields

B. Vignolle
S. Benhabib
D. Vignolles
C. Proust

S. Badoux
F. Laliberté
N. Doiron-Leyraud
L. Taillefer

D.A. Bonn
W.N. Hardy
R. Liang

Phase diagram of the cuprate superconductors

Mott insulator

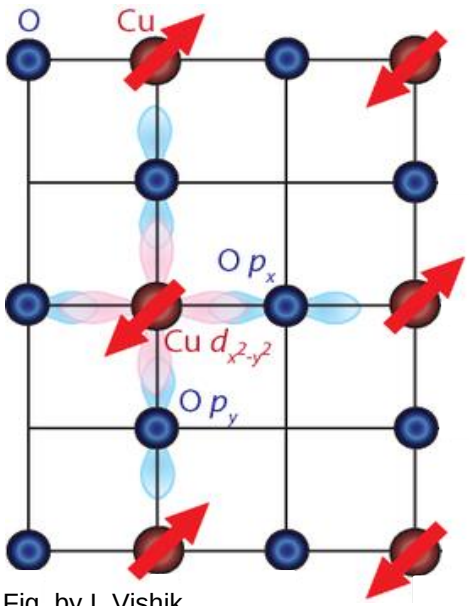
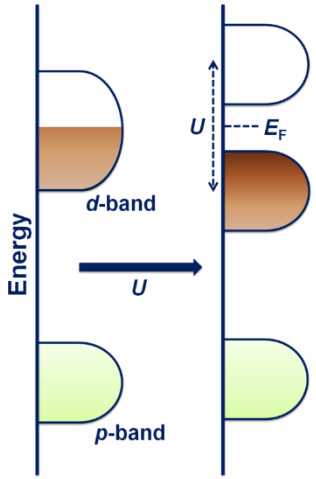
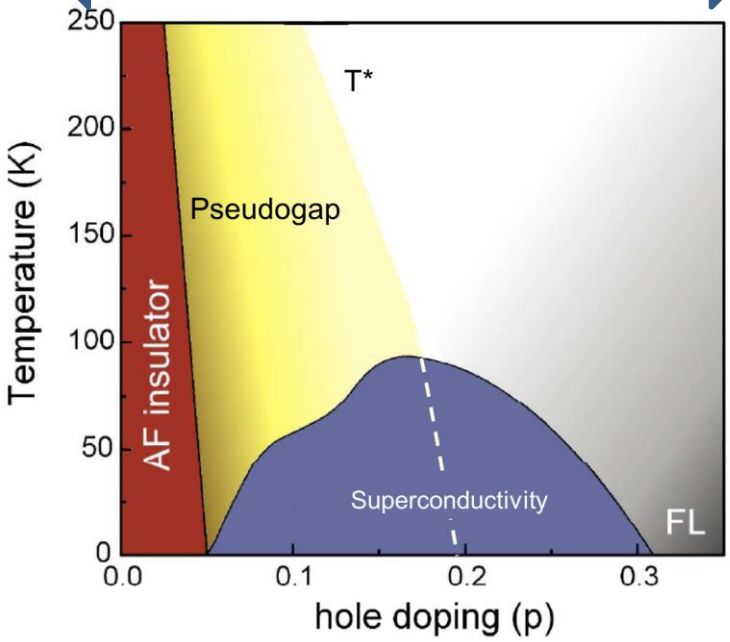


Fig. by I. Vishik



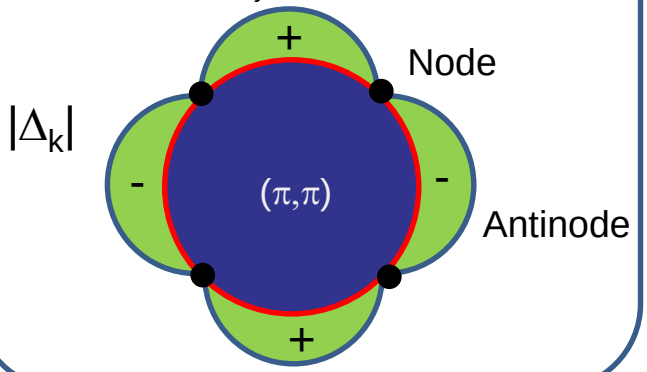
G. Kotliar, Phys. Today (2004)

Underdoped | Overdoped



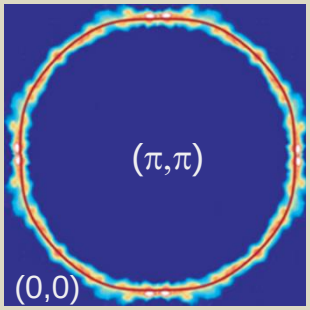
Superconductivity

$d_{x^2-y^2}$ symmetry



Fermi liquid

Overdoped
$Tl_2Ba_2CuO_{6+\delta}$



M. Platé *et al.*, PRL (2005)

Large Hole-like FS
Carrier density:
n* = 1 + *p

✓ Band structure calc.

C.O. Rodriguez PRB (1994)

✓ Wiedemann-Franz law

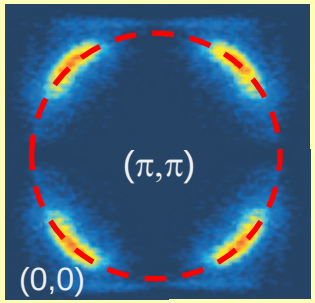
C. Proust *et al.*, PRL (2002)

$$\frac{\kappa}{\sigma T} \equiv L_0$$

Phase diagram of the cuprate superconductors

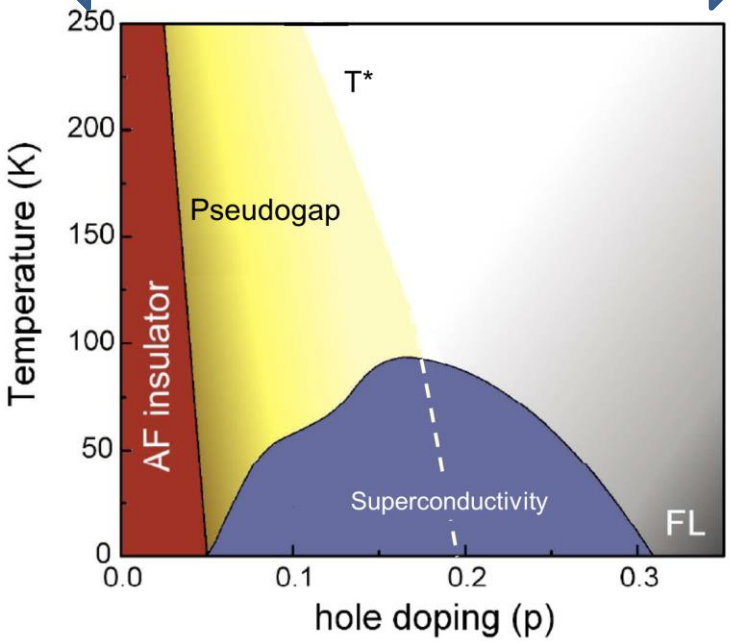
Pseudogap

Underdoped
$YBa_2Cu_3O_{6+\delta}$



M. A. Hossain *et al*., Nature Phys. (2008)

Underdoped | Overdoped



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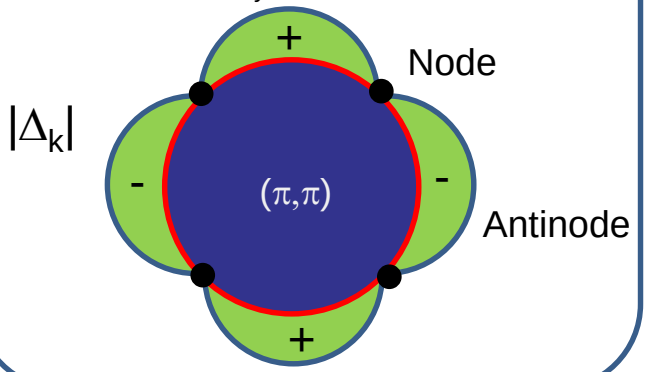
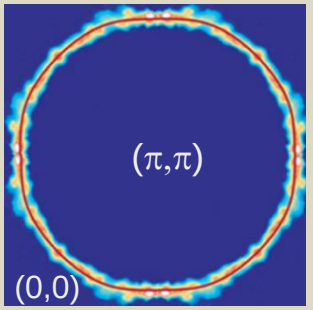


Fermi liquid

Overdoped
$Tl_2Ba_2CuO_{6+\delta}$



M. Platé *et al*., PRL (2005)

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Phase diagram of the cuprate superconductors

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Underdoped
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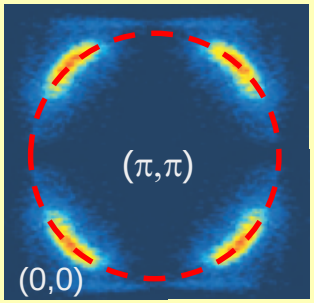
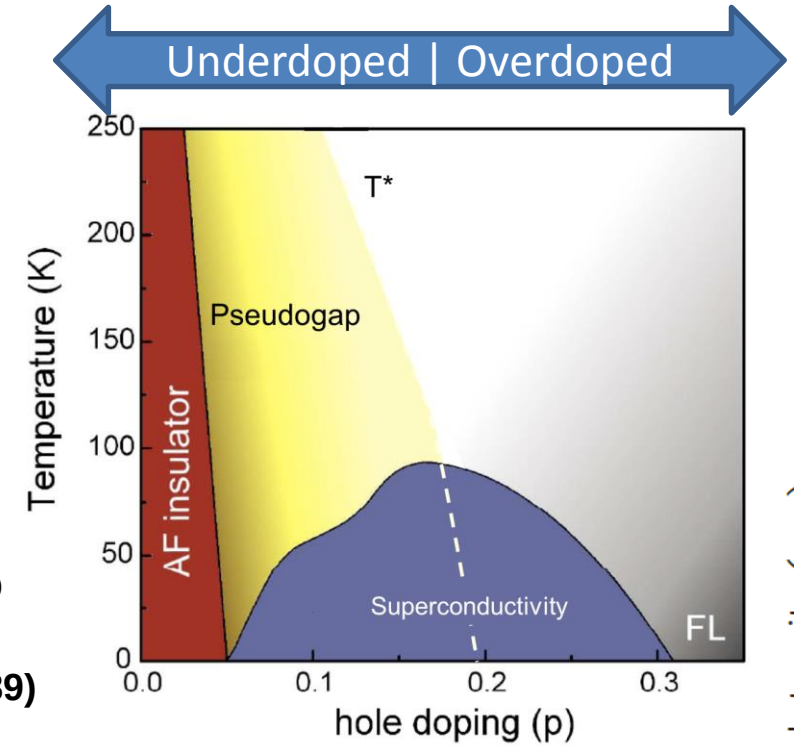
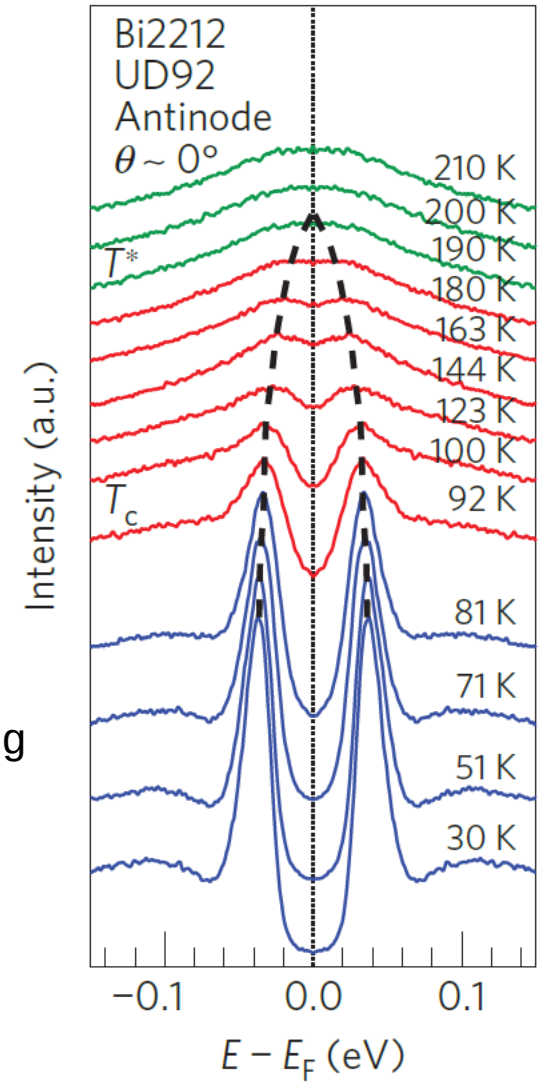


M. A. Hossain *et al*., Nature Phys. (2008)

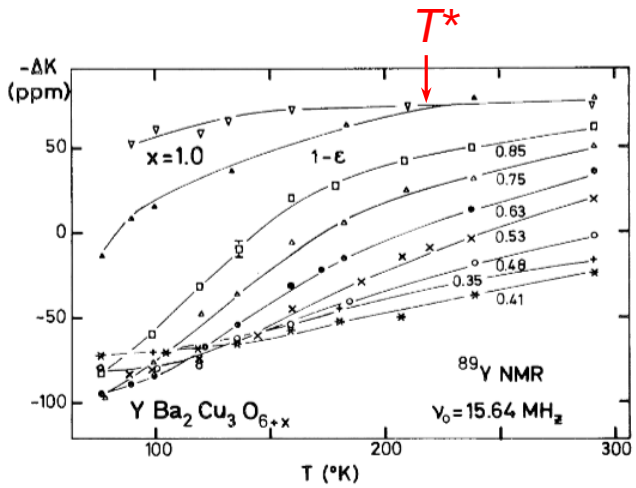


ARPES



M.Hashimoto et al. NPhysics . 10,483 (2014)

Discovery; ^{89}Y-NMR (1989)



H. Alloul et al. PRL . 63,1700 (1989)
W.W. Warren et al. PRL .62,1193 (1989)

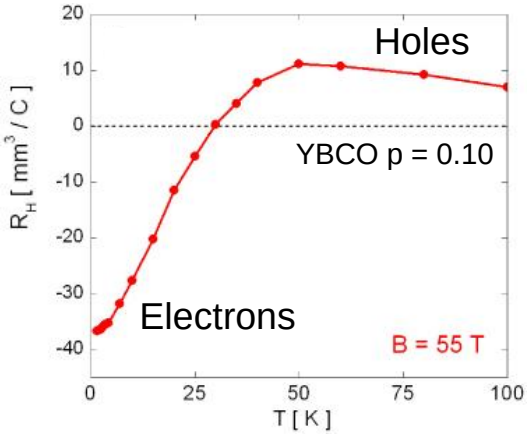
Other probes:

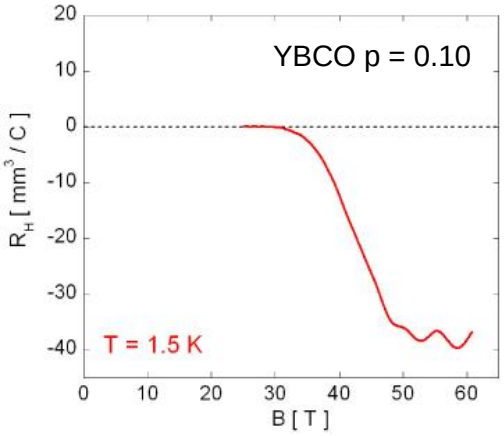
- Polarized neutron scattering
- Optical conductivity
- Raman scattering
- Kerr effect
- Ultrasound
- Electronic transport

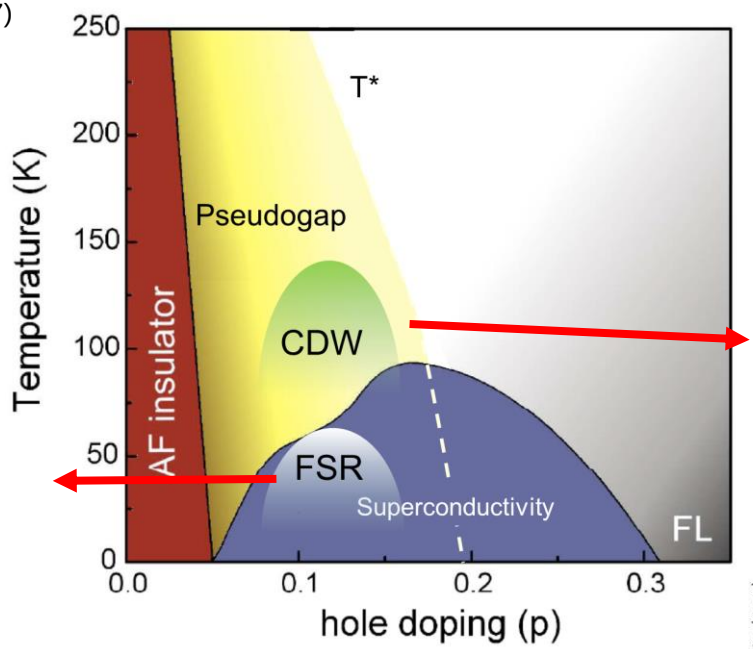
Phase diagram of the cuprate superconductors

Electronic transport:

N. Doiron-Leyraud *et al*., Nature (2007)
D. Le Boeuf *et al*., Nature (2007)

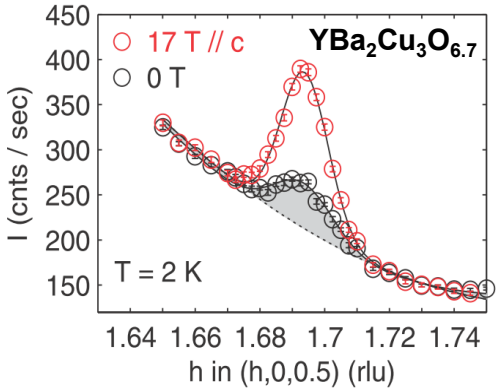


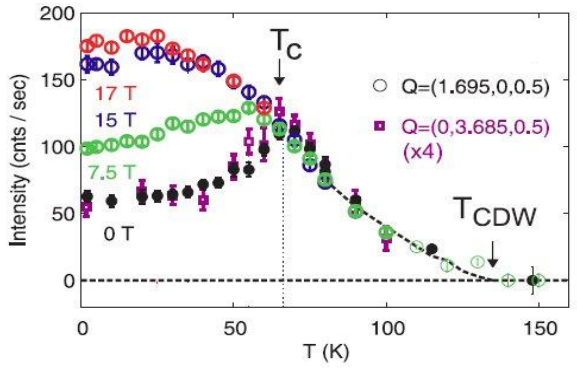




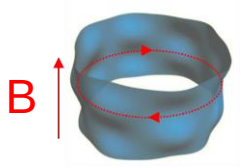
X-ray diffraction:

G. Ghiringhelli *et al*, Science (2012)
J. Chang *et al.*, Nature Phys. (2012)





- Slow quantum oscillations



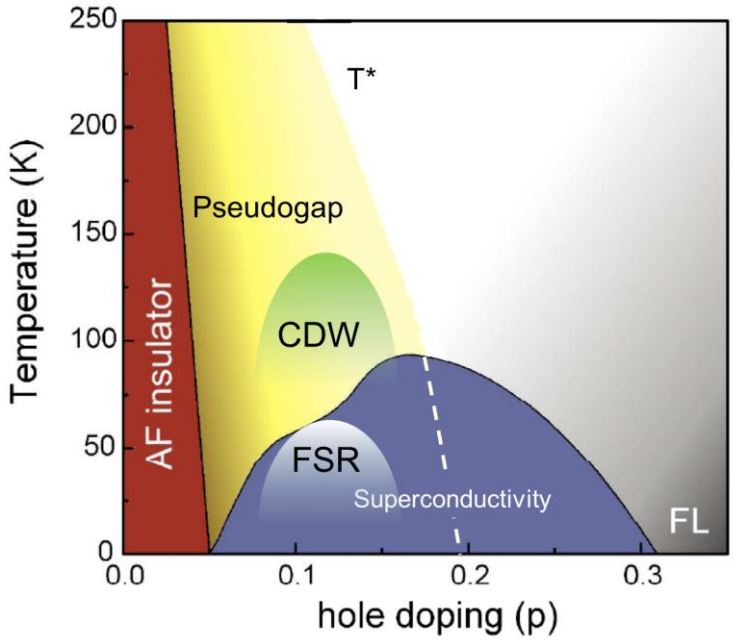
$$F = \frac{\phi_0}{2\pi^2} A_k$$

CDW order reconstructs the FS

Electron pocket
A_k ≈ 2 % of 1st Brillouin zone

Charge density wave order
q_a = (0.31, 0, 0.5), ξ_a = 16

Outline

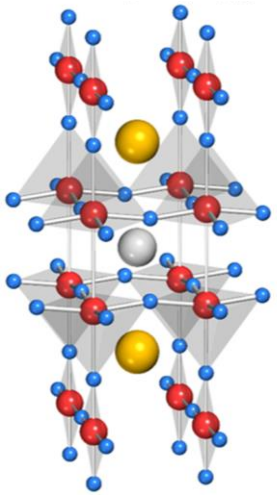


- What is the connection between CDW and the FSR?
- How is the CDW and the associated FSR related to the pseudogap phase?
- What are the signatures of the opening of the pseudogap?

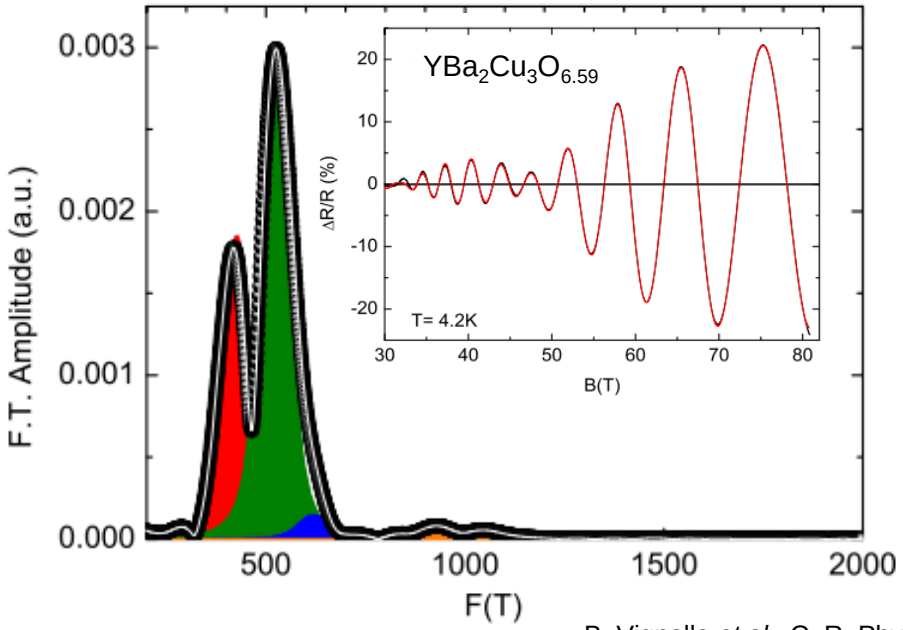
FS reconstruction by CDW order

What is the connection between CDW and the FSR?

$YBa_2Cu_3O_{6+d}$
YBCO

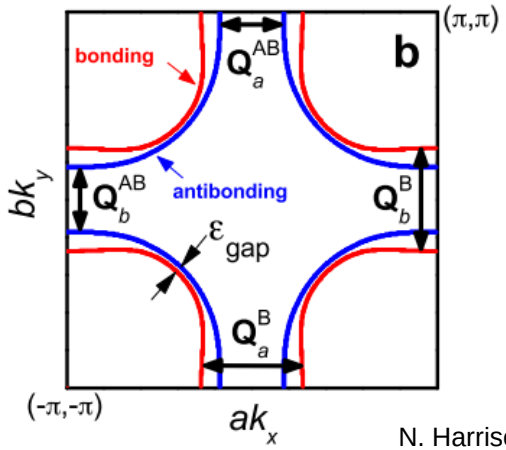


Quantum oscillations



B. Vignolle *et al.*, C. R. Physique 14 (2013)

Fermi surface



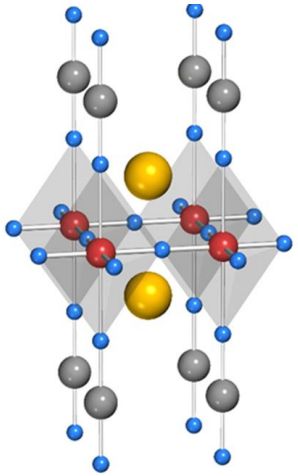
N. Harrison, S. Sebastian, NJP 2012

- Two CuO_2 planes
- Orthorhombic distortion
- Cu-O chains

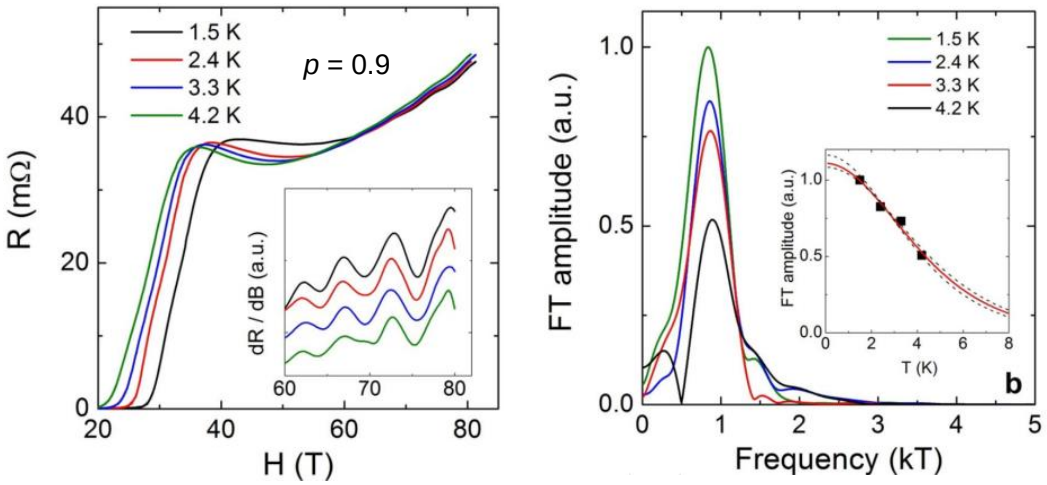
FS reconstruction by CDW order

What is the connection between CDW and the FSR?

$HgBa_2CuO_{4+d}$
Hg1201

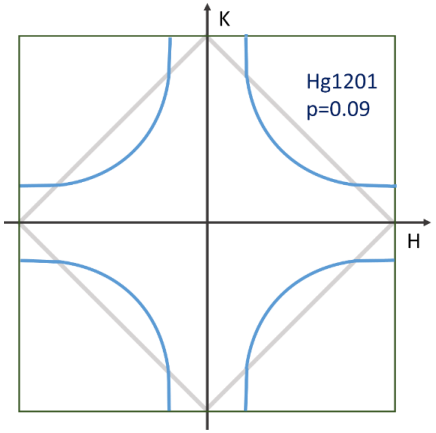


Quantum oscillations



N. Barisic *et al.*, Nature Physics (2013)

Fermi surface

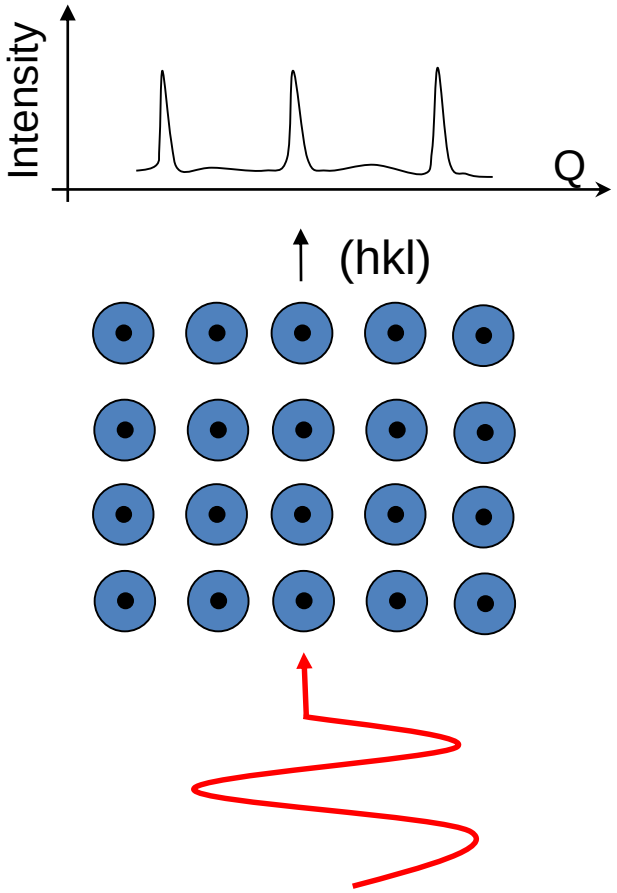


Charge density wave?

- ~~Two CuO_2 planes~~
- ~~Orthorhombic distortion~~
- ~~Cu-O chains~~

Resonant X-ray diffraction

CDW study in Hg1201



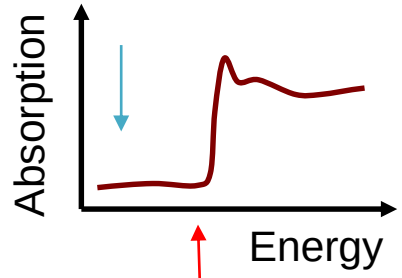
XRD spectrum depends on the spatial arrangements of the atoms

Structure factor

$$F(\vec{Q}) = \sum_j f_j \exp\left(i\vec{Q}\cdot\vec{r}_j\right)$$

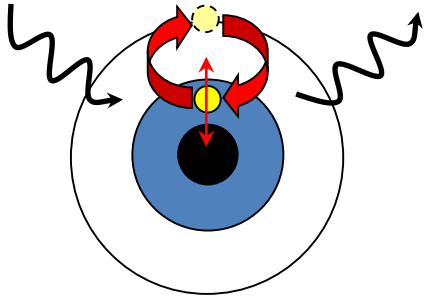
Atomic scattering factor

$$f(\vec{Q}) = \int_0^\infty \rho(\vec{r})\,\mathbf{exp}\left(i\vec{Q}\cdot\vec{r}\right)dr$$



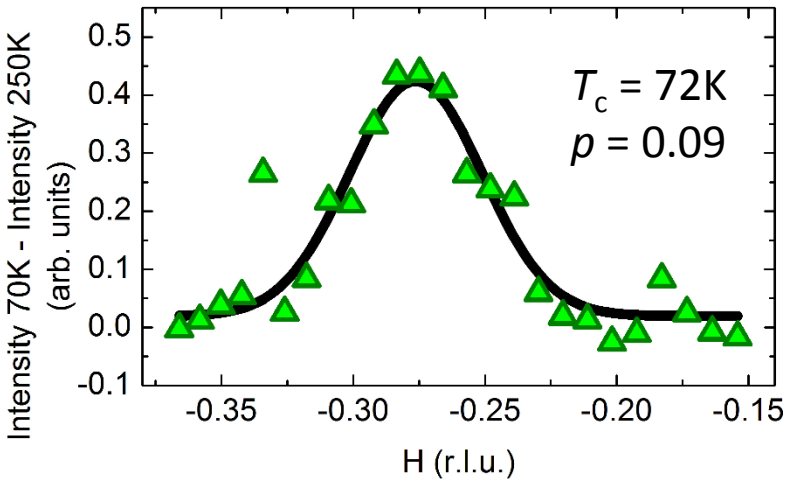
$$f(\omega) = f_0 + f'(\omega) + if''(\omega)$$

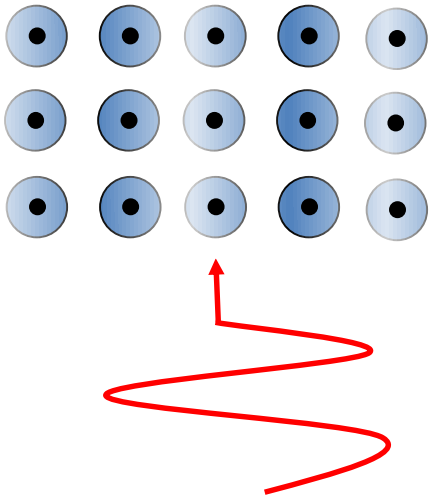
Resonant X-ray Diffraction



Charge-density wave order in Hg1201

Resonant X-ray Diffraction





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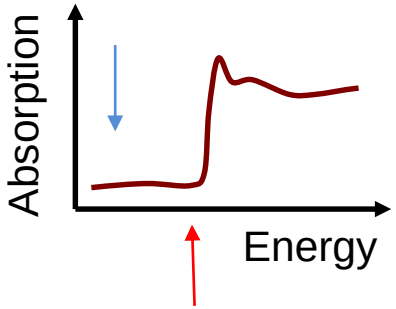

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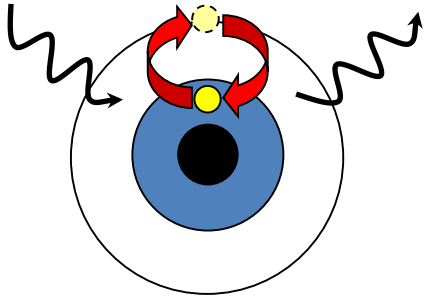
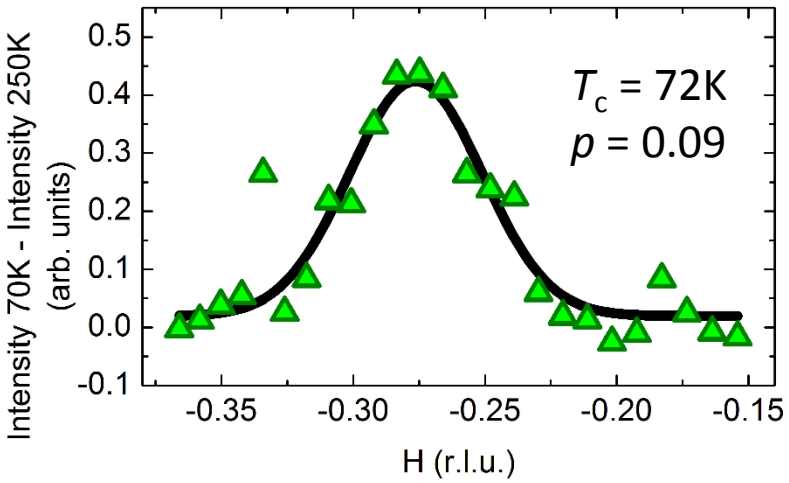
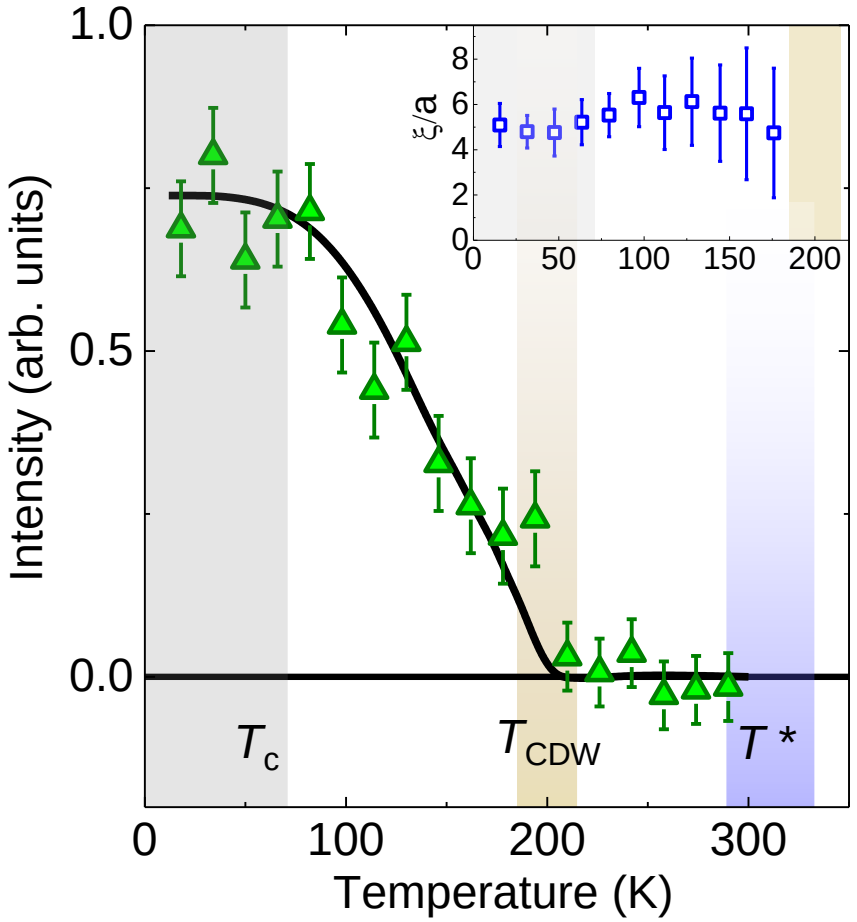
Resonant X-ray Diffraction



Charge-density wave order in Hg1201

Resonant X-ray Diffraction





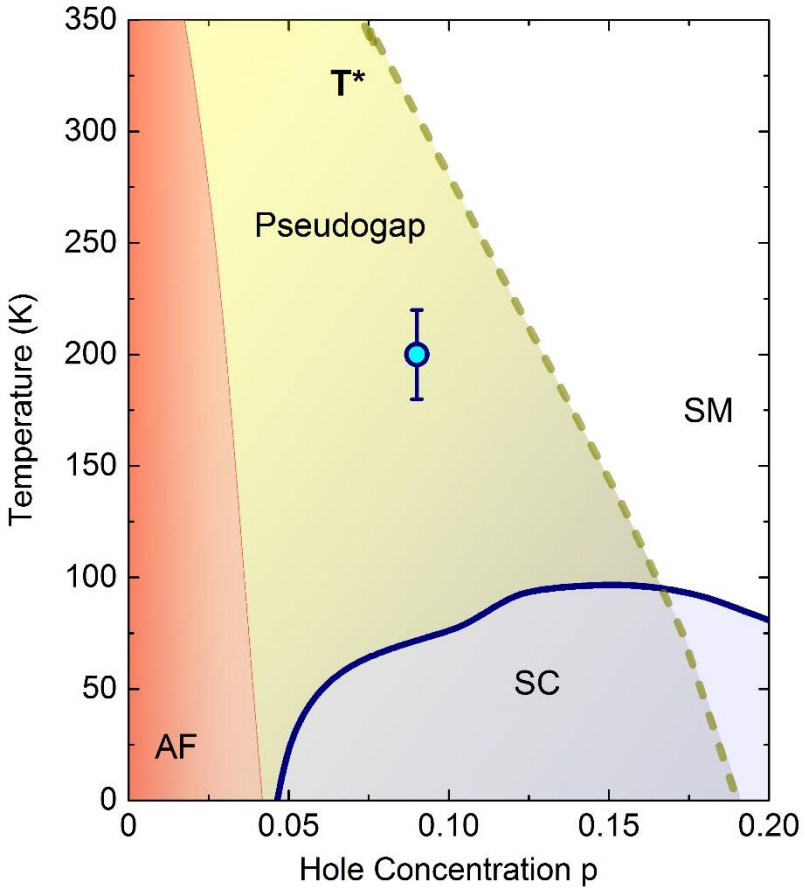
Incomensurate short-range CDW order:

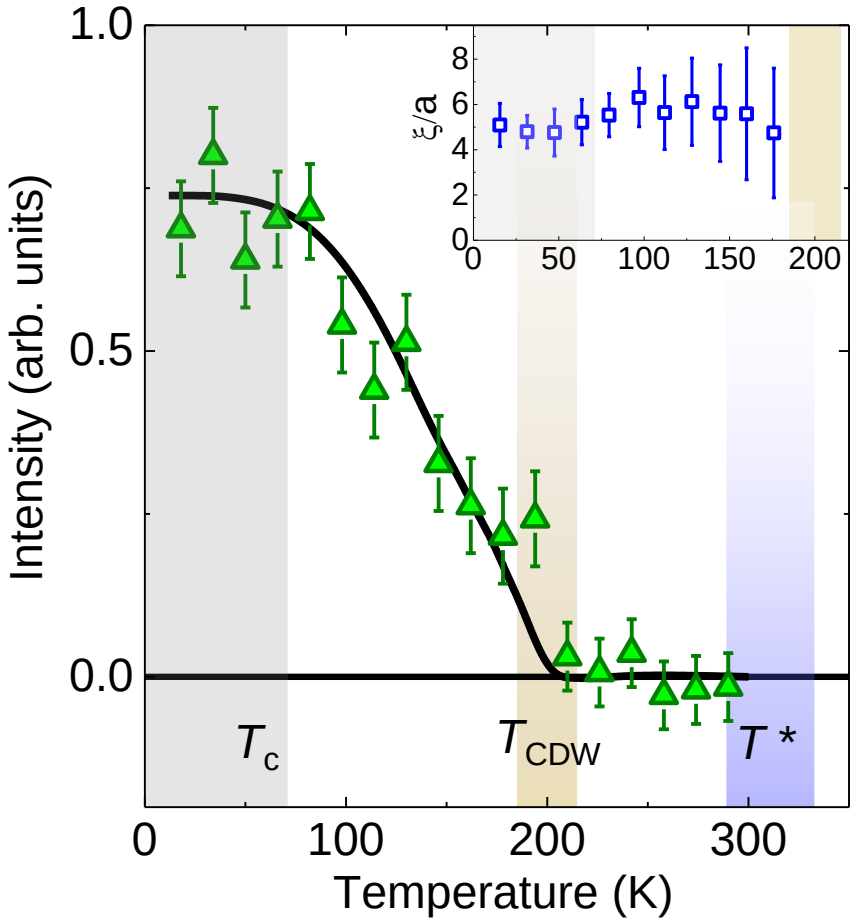
Wavevector:
q_{CDW} = 0.280(5) r.lu.

Correlation length:
ξ_a = 5 ± 1

W. Tabis *et al.*, Nature Comm. (2014)

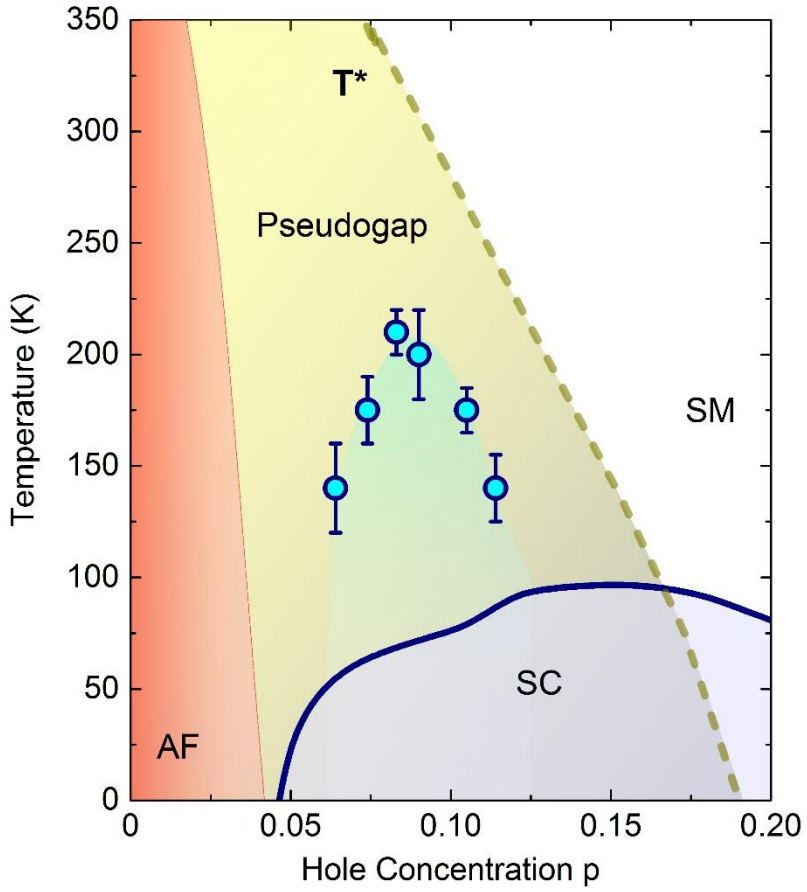
Charge-density wave order in Hg1201

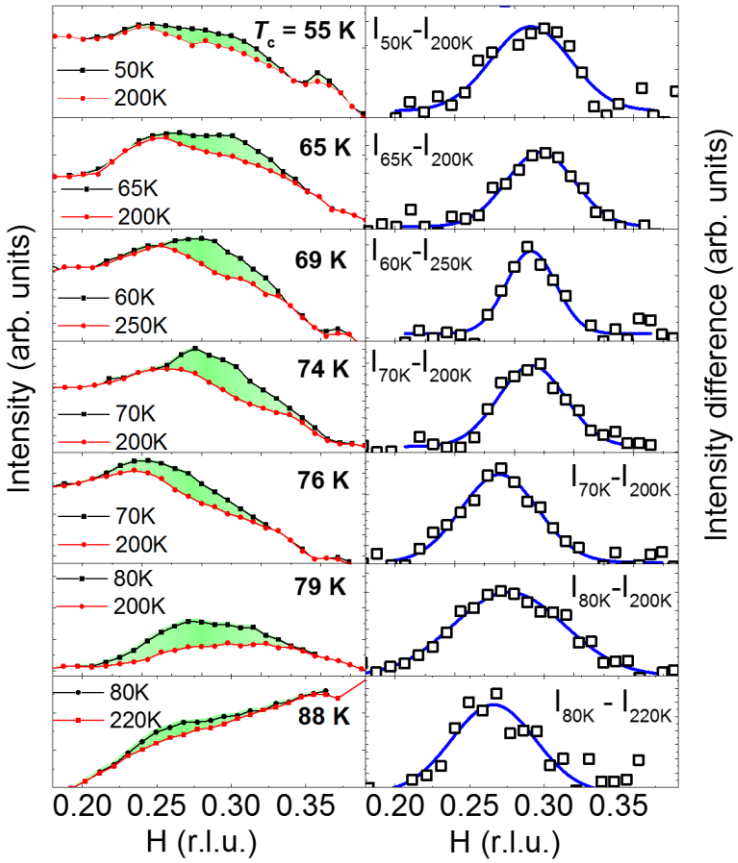




W. Tabis *et al.,* Nature Comm. (2014)

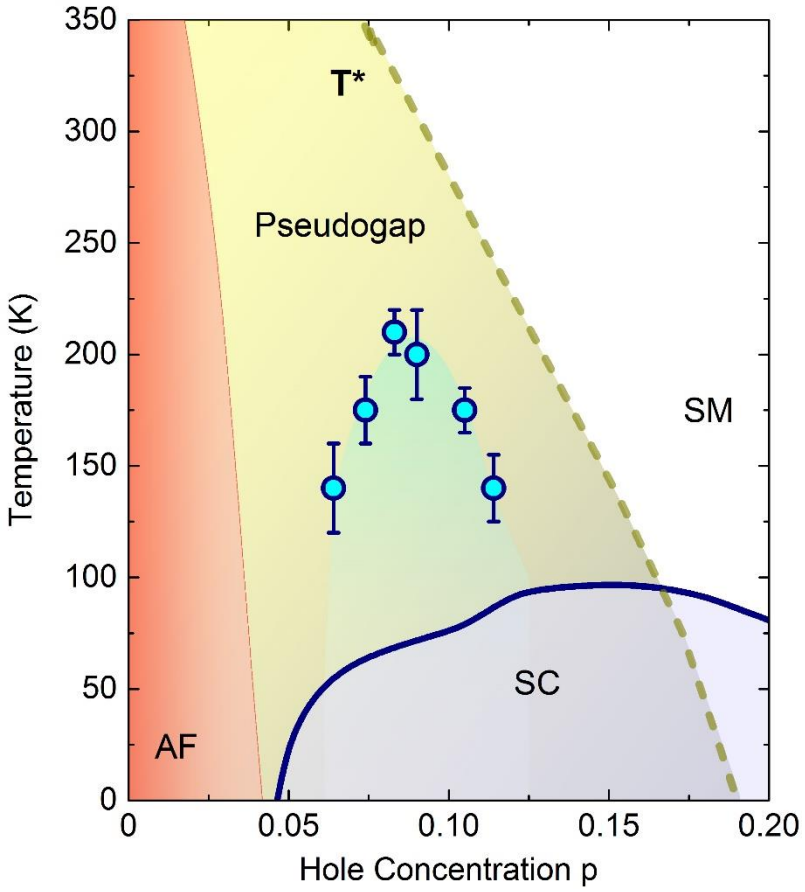
Doping dependence of the CDW in Hg1201

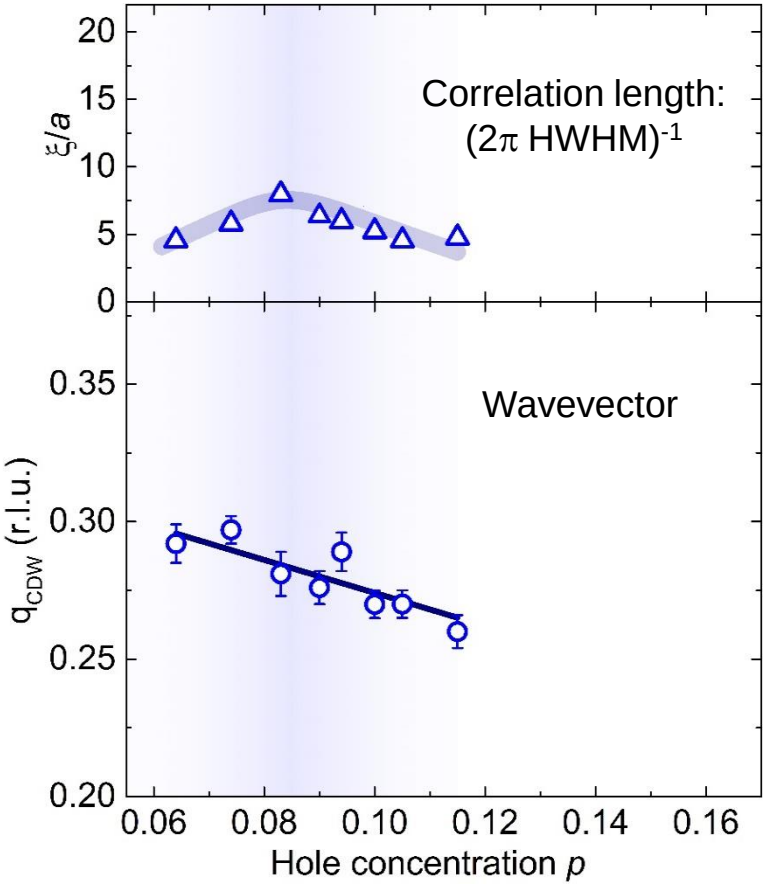




W. Tabis *et al.*, Phys Rev B (2017)

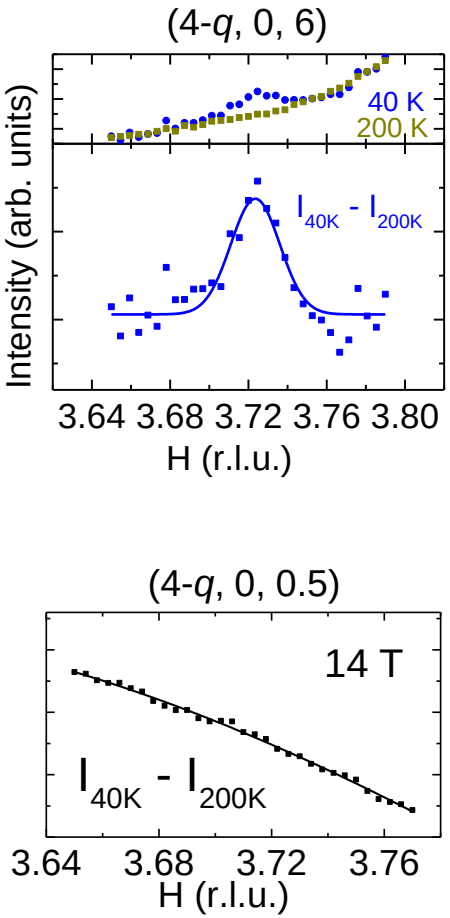
Doping dependence of the CDW in Hg1201

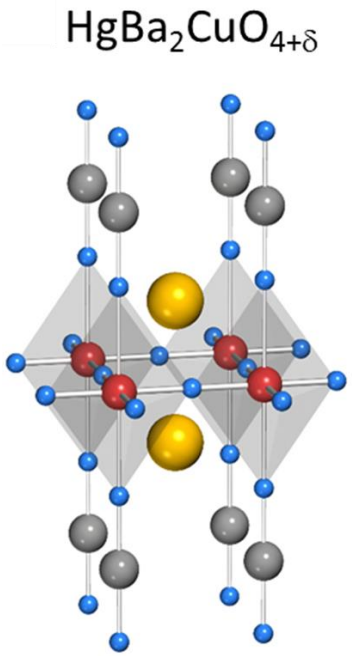


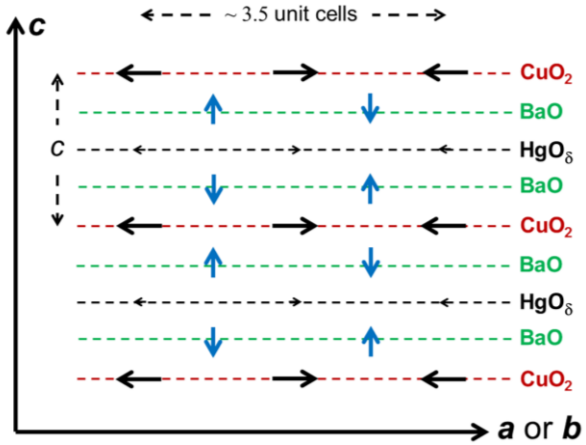


W. Tabis *et al.*, Phys Rev B (2017)

Hard X-ray diffraction in Hg1201



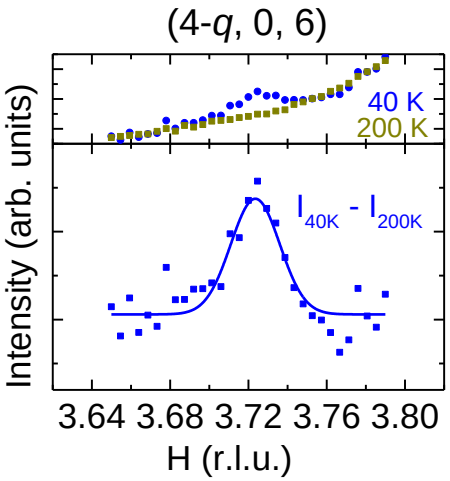


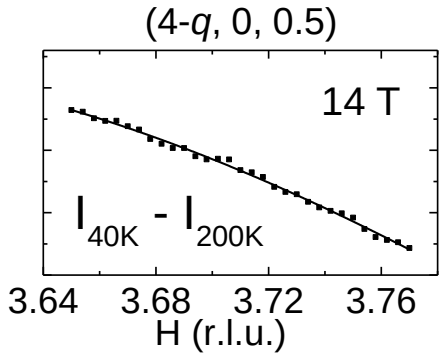


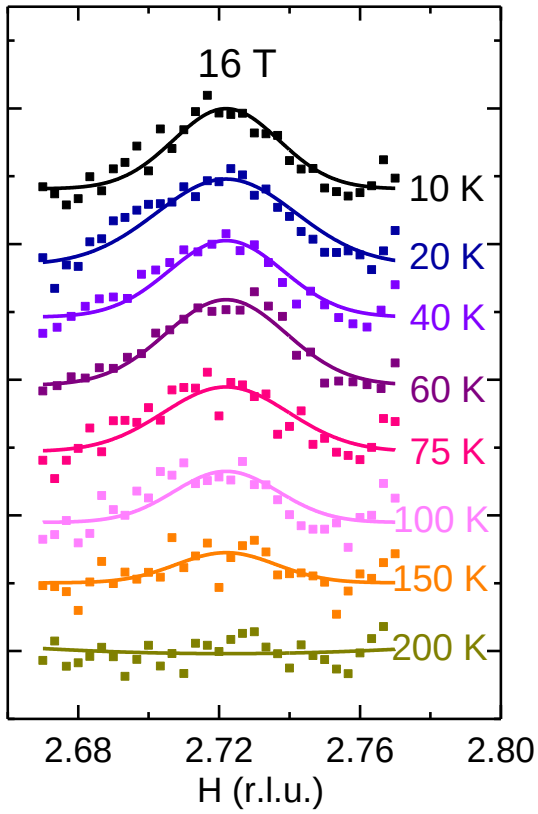
W. Tabis *et al.*, Phys Rev B (2017)

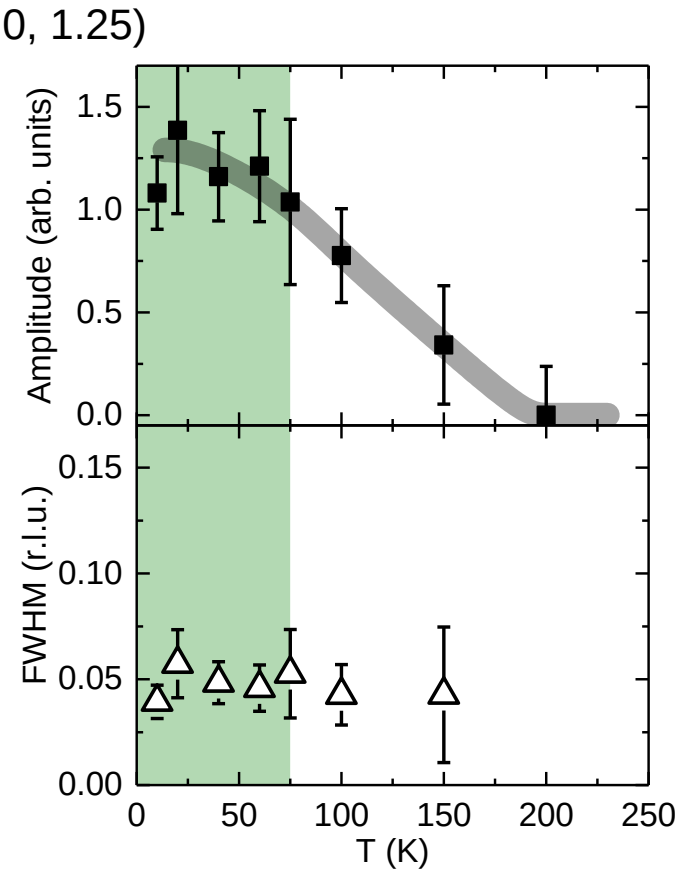
CDW order in Hg1201 causes mainly in-plane displacements within CuO_2 layer

Hard X-ray diffraction in Hg1201



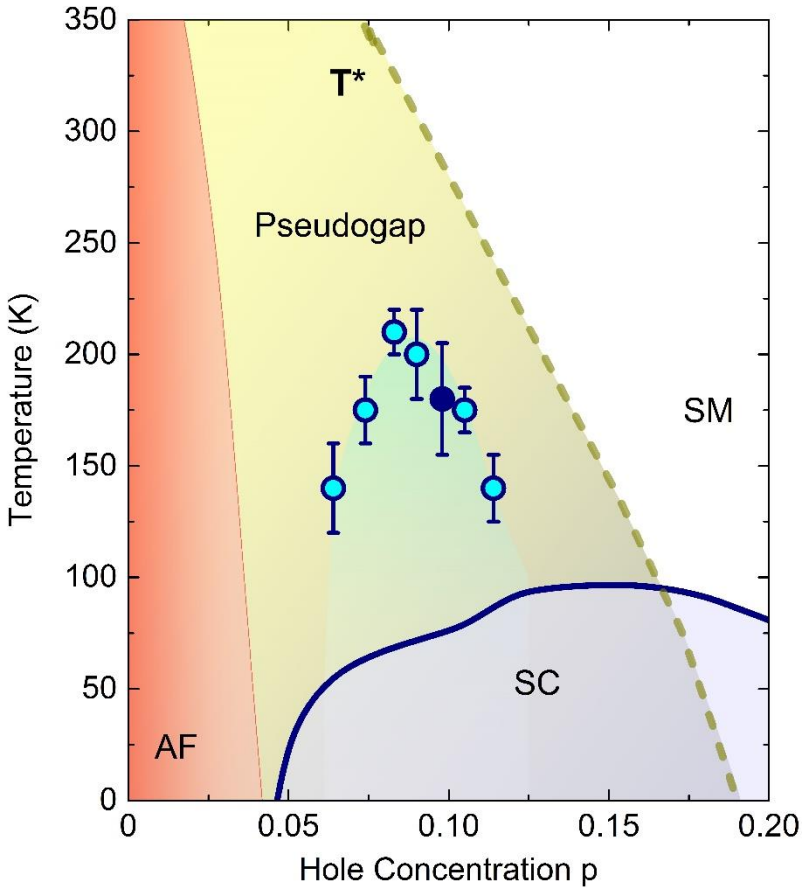


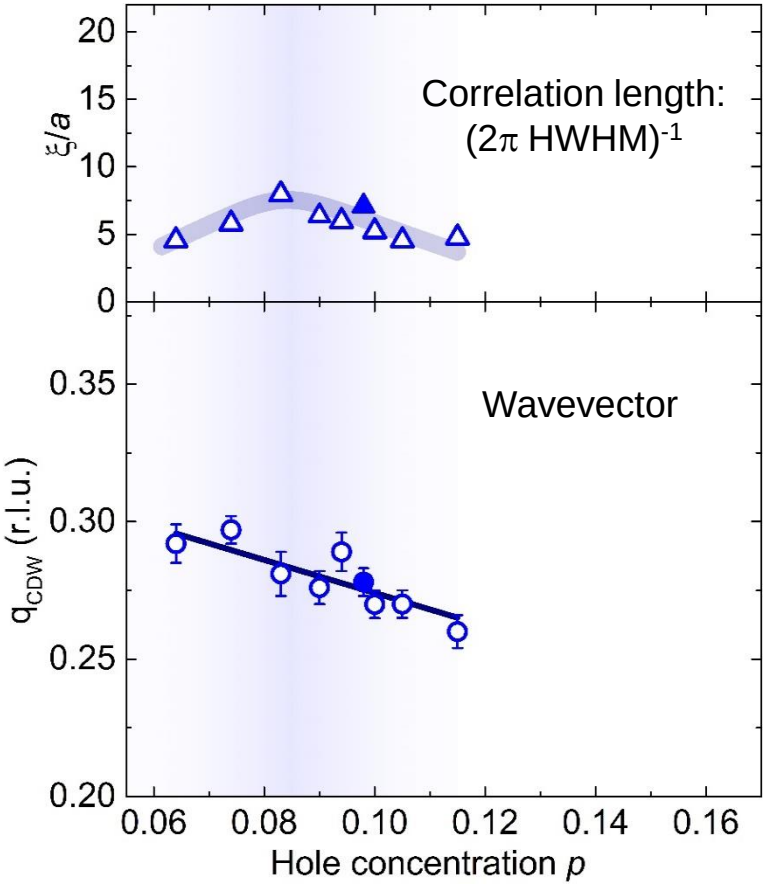




W. Tabis *et al.,* Phys Rev B (2017)

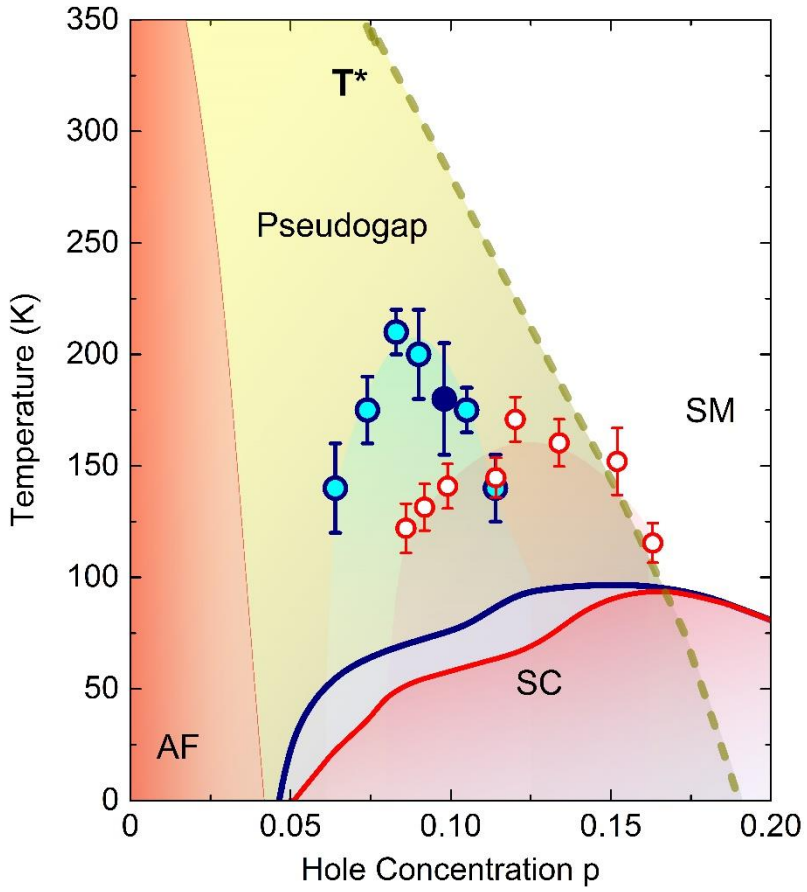
Doping dependence of the CDW in Hg1201



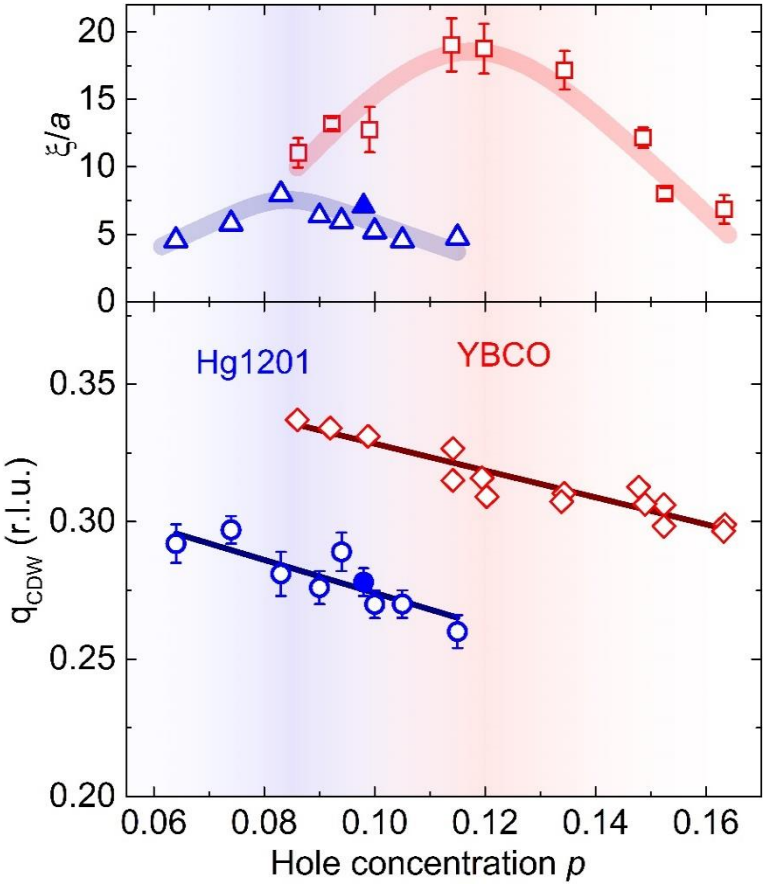


W. Tabis *et al.*, Phys Rev B (2017)

Doping dependence of the CDW in Hg1201 and YBCO



W. Tabis *et al.*, Phys Rev B (2017)



Blanco-Canosa *et al.*, Phys. Rev B (2014)

Universal CDW order in the underdoped cuprates

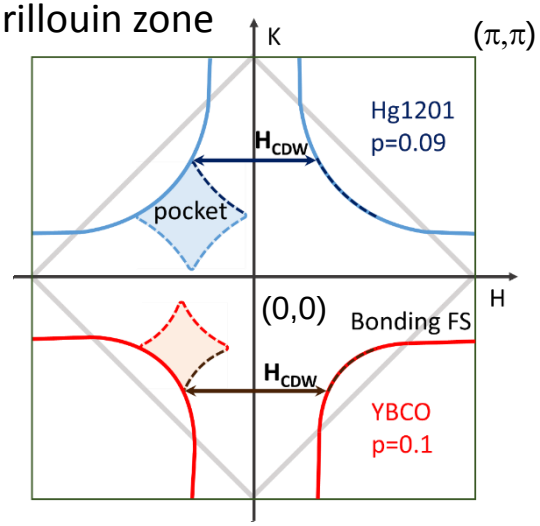
How is the CDW order related to the FSR?

Hg1201

Reciprocal space

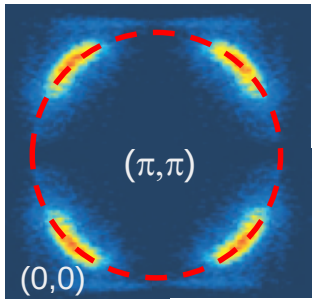
CDW order

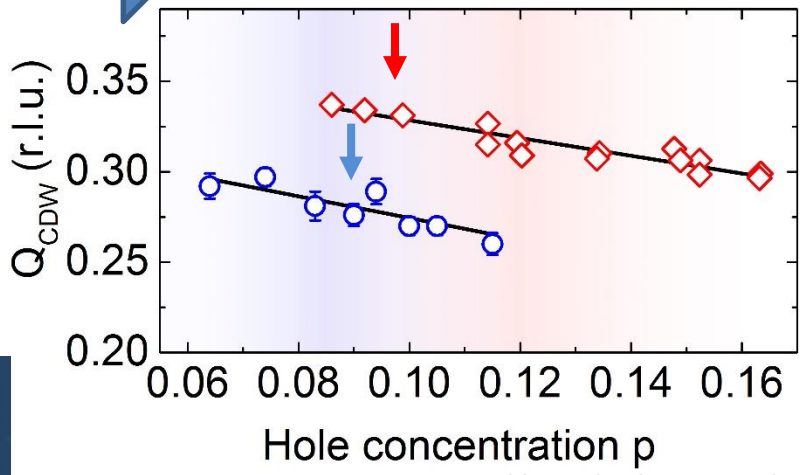
2-D Brillouin zone



W. Tabis *et al.,* Nature Comm. (2014)

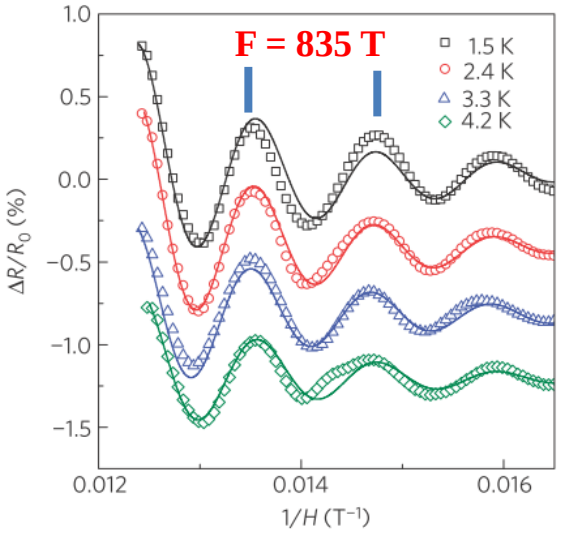
Pseudogap





W. Tabis *et al.,* Phys Rev B (2017)

Quantum oscillations



N. Barisic *et al.*, Nature Physics (2013)

H_{CDW} = 0.28 r.l.u. A_{EP} = 3 %BZ

Bidirectional CDW reconstructs the FS into electron pocket

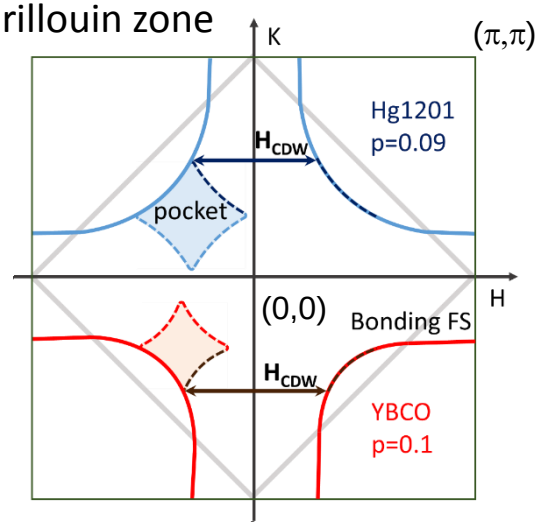
How is the CDW order related to the FSR?

Hg1201

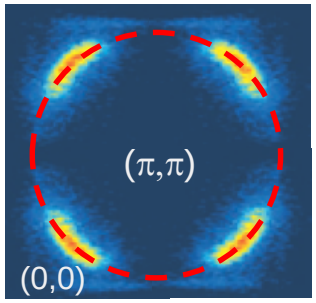
Reciprocal space

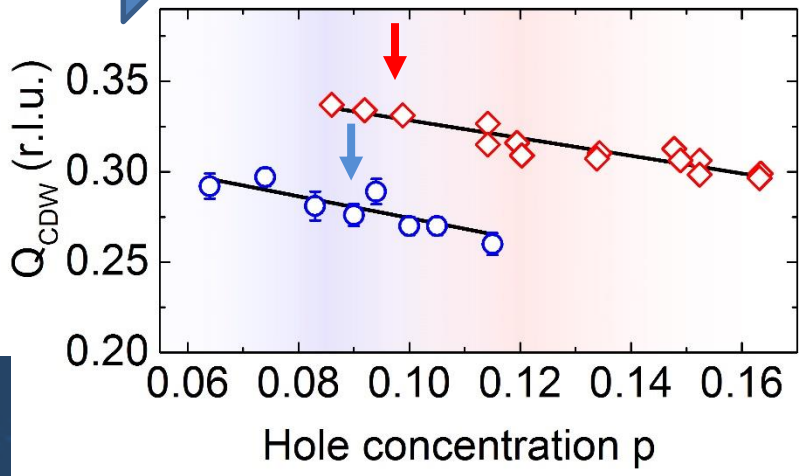
CDW order

2-D Brillouin zone



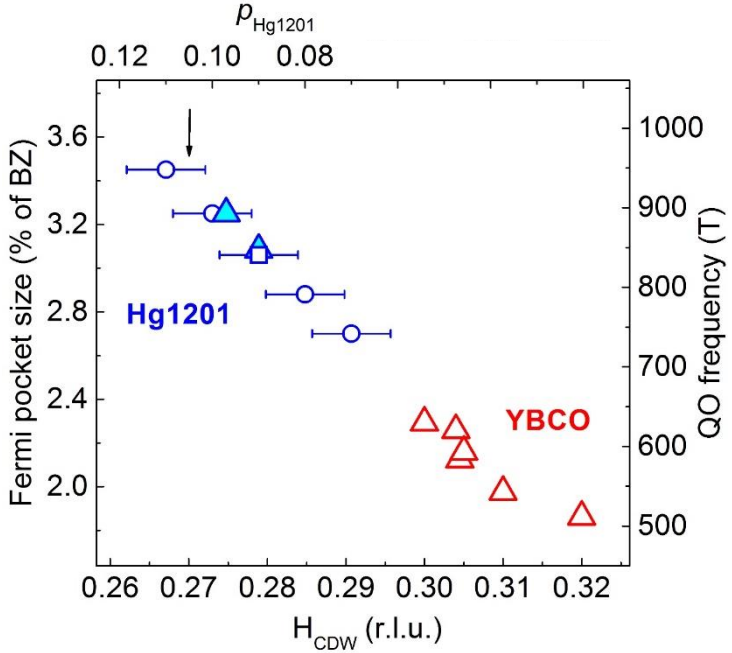
Pseudogap





W. Tabis *et al.*, Nature Comm. (2014)

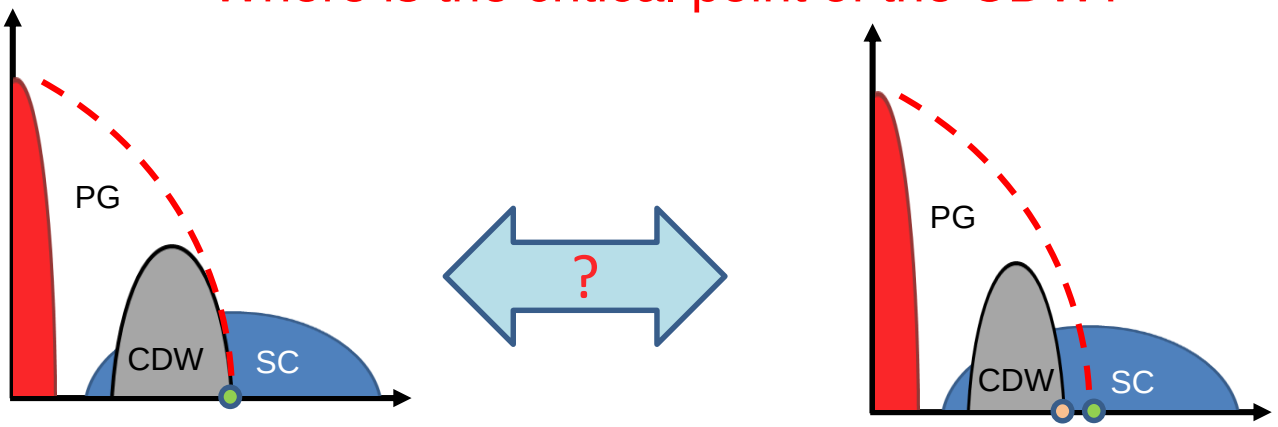
H_{CDW} = 0.28 r.l.u. A_{EP} = 3 %BZ



Bidirectional CDW reconstructs the FS into electron pocket

How is the CDW related to the pseudogap?

- Where is the critical point of the CDW?

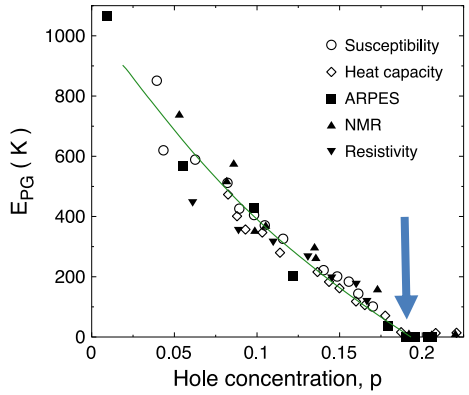


$p_{FSR} = p^*$ $p_{FSR} \neq p^*$

T. Senthil, arXiv: 1410.2096

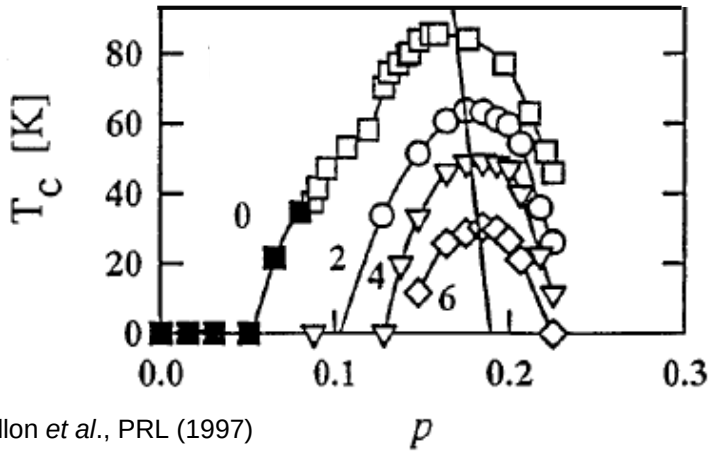
- Critical point of the pseudogap in YBCO

Pseudogap energy



$p^* = 0.19$

Suppression of T_c by Zn imp.

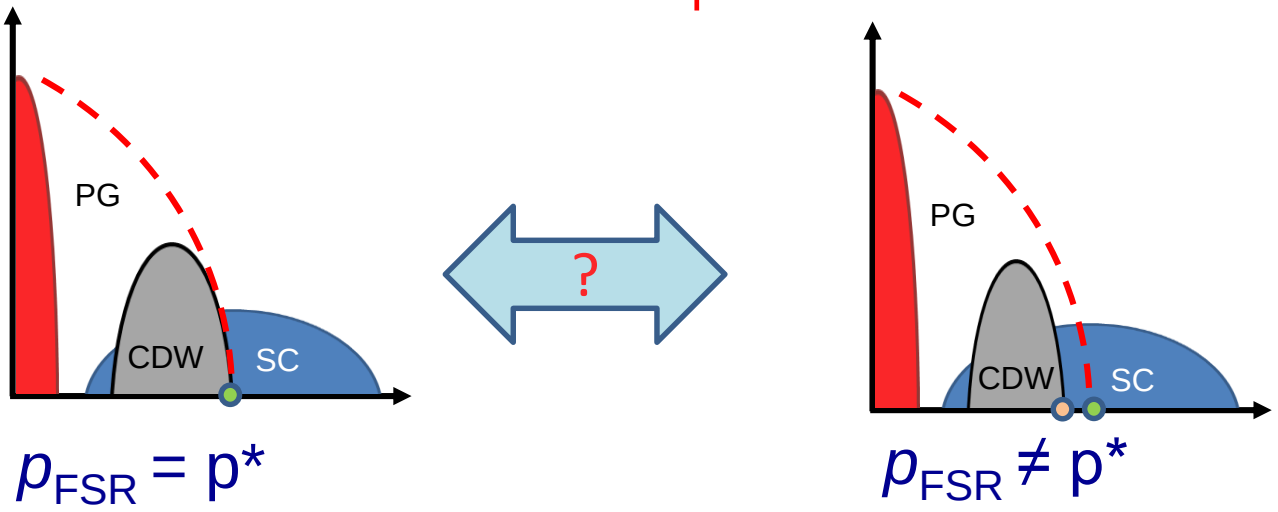


Tallon & Loram, Phys. C (2001)

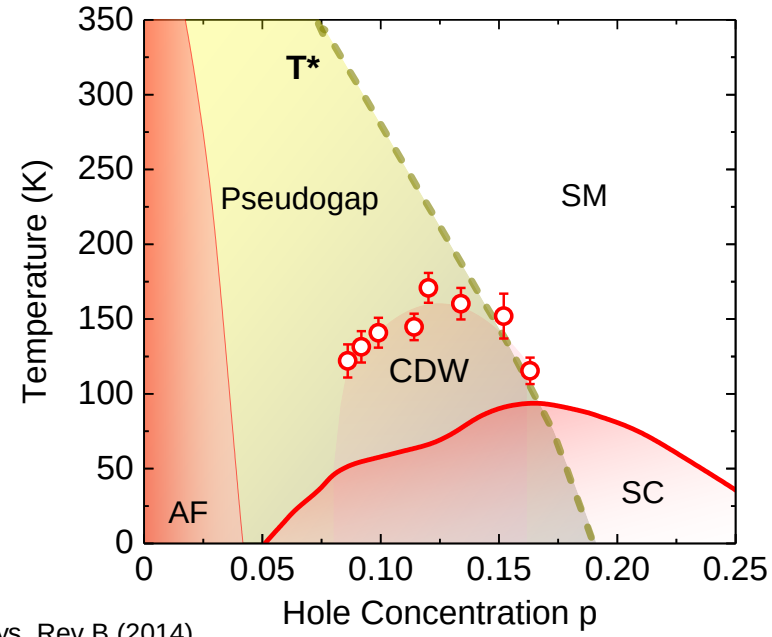
Tallon *et al.*, PRL (1997)

How is the CDW related to the pseudogap?

- Where is the critical point of the CDW?

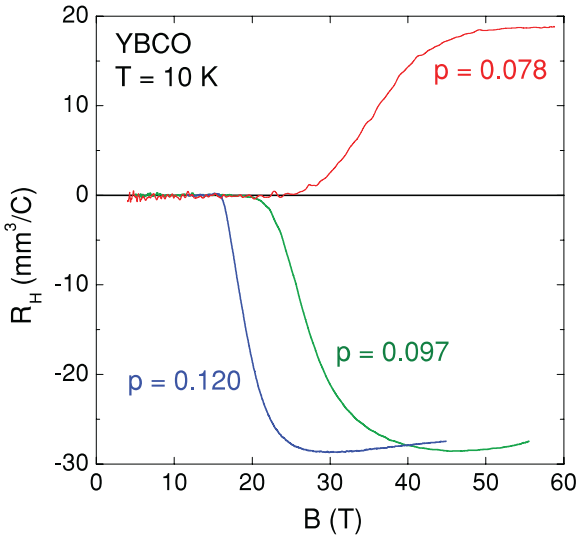


$p_{FSR} = p^*$ $p_{FSR} \neq p^*$



Blanco-Canosa *et al*., Phys. Rev B (2014)

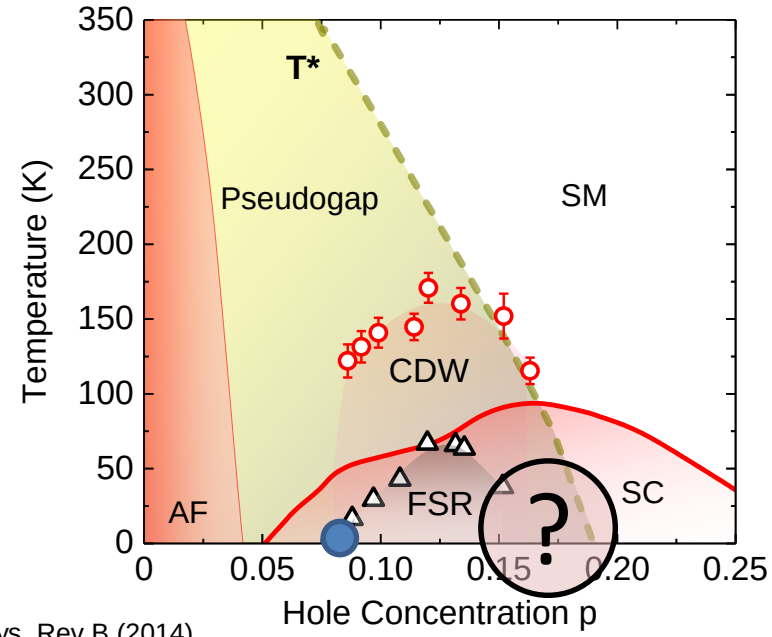
How is the CDW related to the pseudogap?



D. LeBoeuf *et al*., PRB (2011)

Negative Hall coefficient indicates appearance of the **electron pockets**

CDW ⟺ FSR



Blanco-Canosa *et al*., Phys. Rev B (2014)

Beginning of the reconstruction

$p_1 = 0.08$

$p_{FSR} = ?$

High Magnetic Field Laboratory LNCMI-Toulouse

By O. Portugal

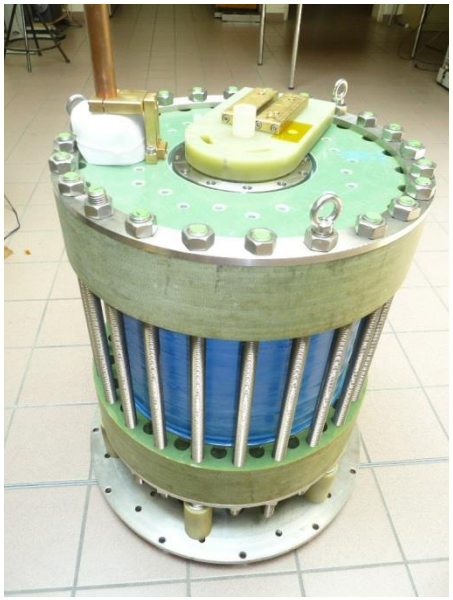
Extension of the lab.:

6 explosion-proof magnet cells

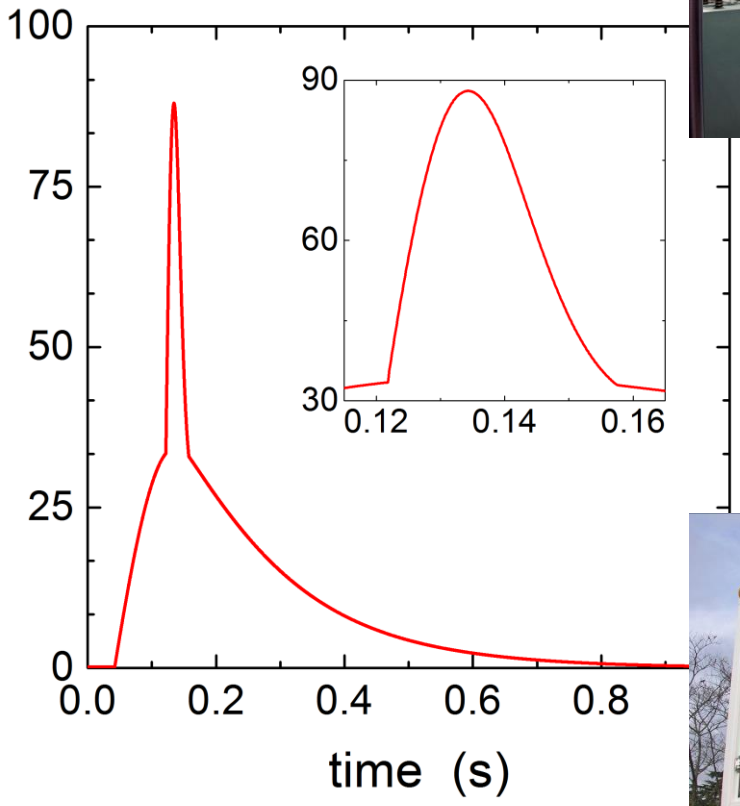
Large experimental space

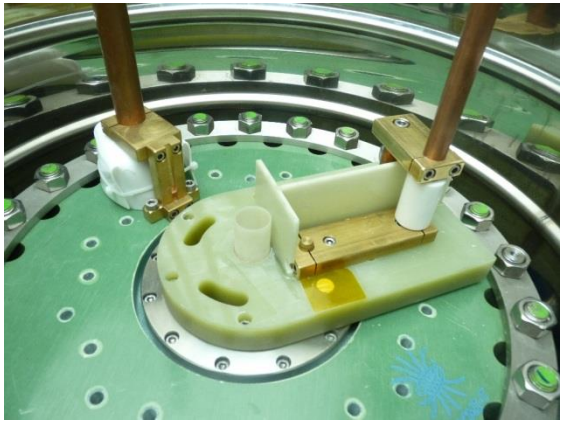
Machine shops & prep rooms

90 T pulsed field magnet at LNCMI-Toulouse



14 MJ generator

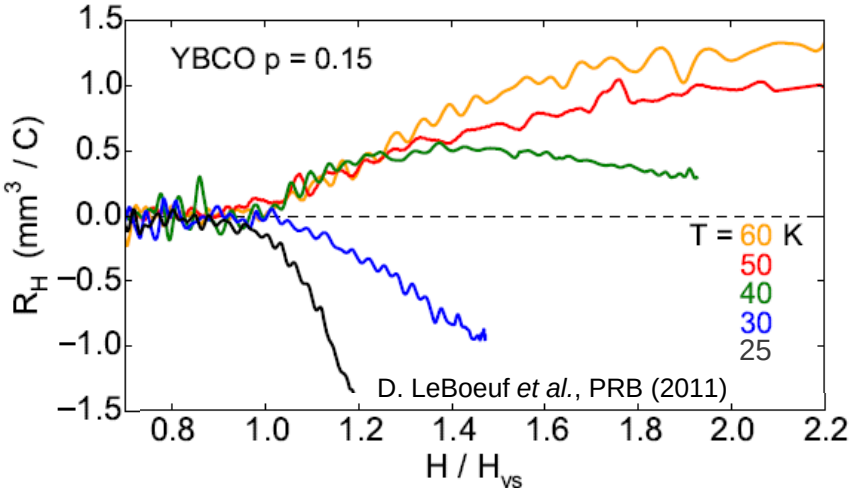


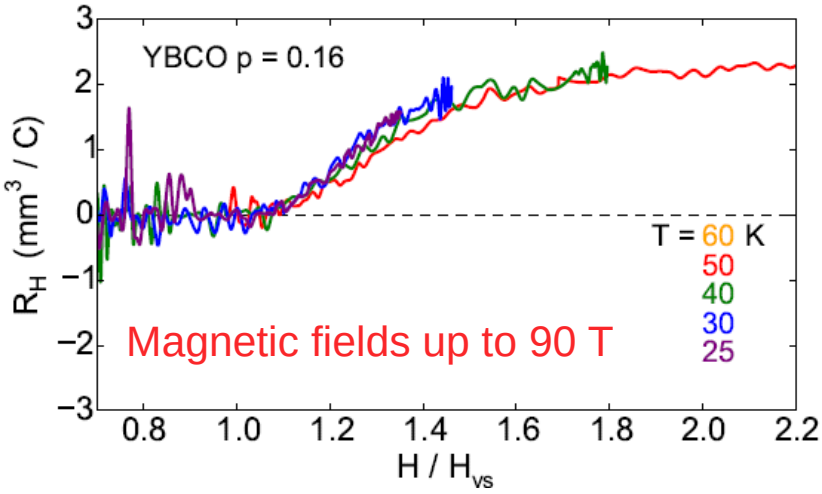


6 MJ generator

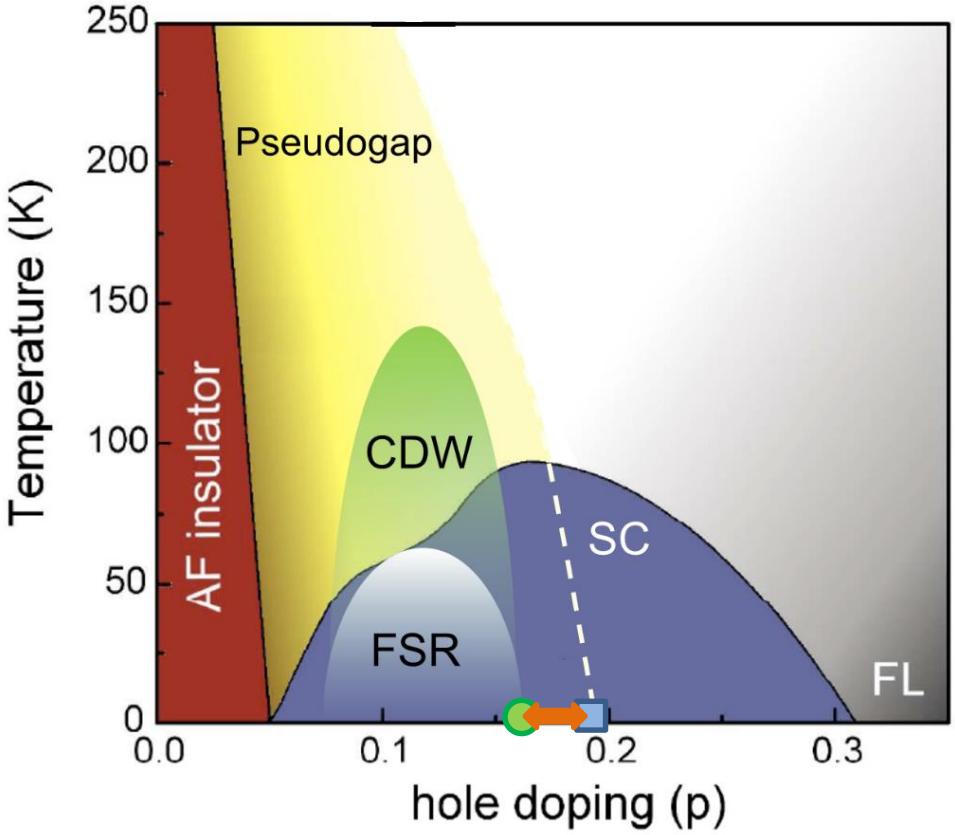
Fermi surface reconstruction in YBCO

Where does the Fermi surface reconstruction ends?





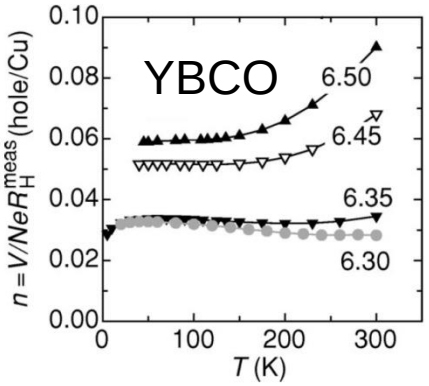
S. Badoux, W. Tabis *et al.,* Nature (2016)



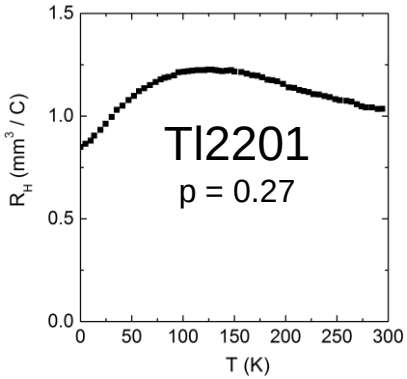
CDW and PG;
distinct critical points

Change of the carrier density

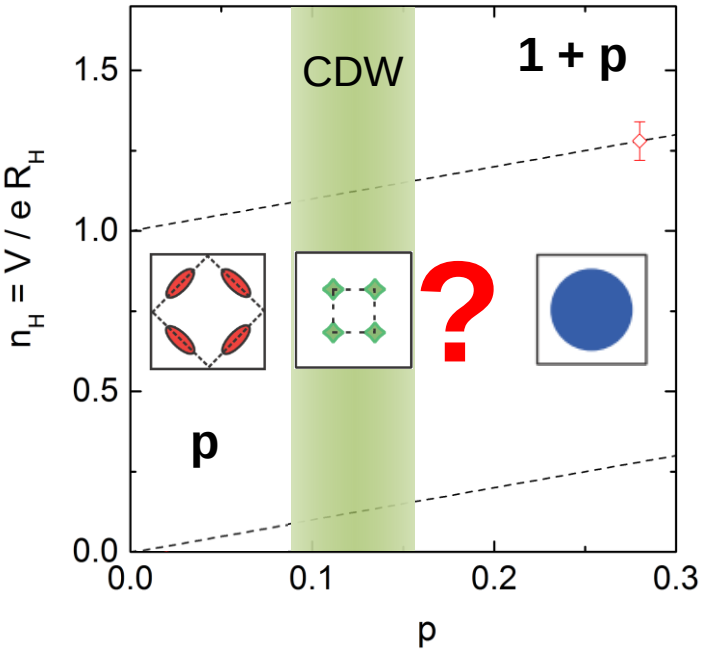
Where does the transition from ***n = 1 + p*** to ***n = p*** occur?

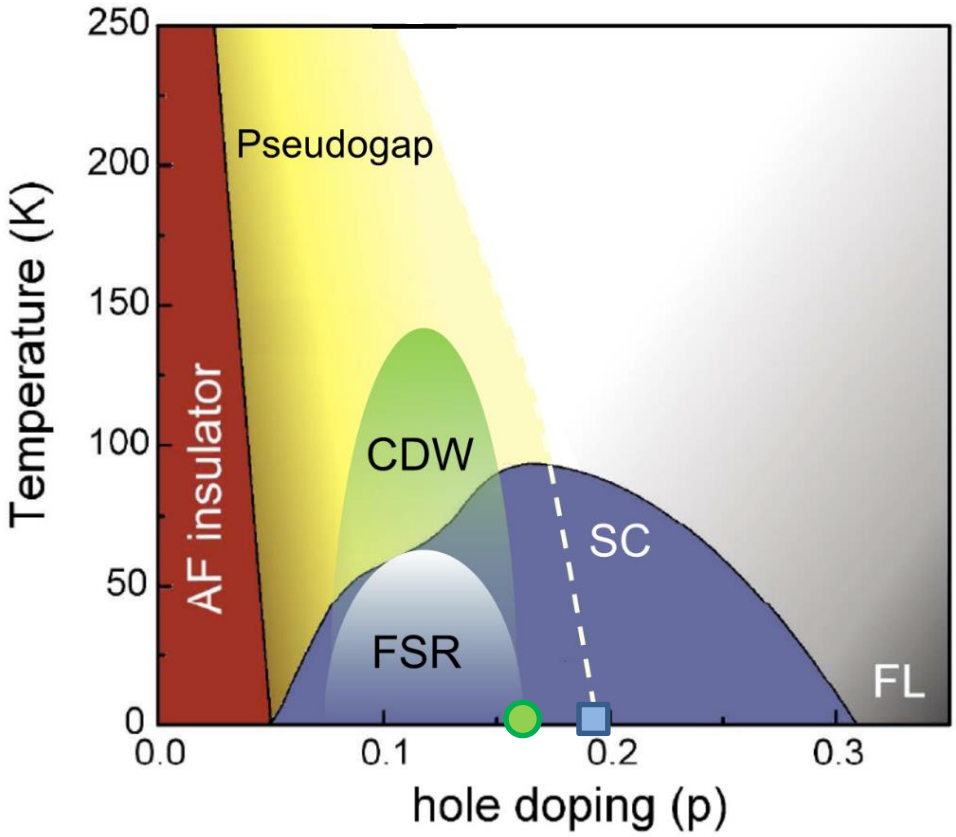


K. Segawa *et al.*, PRB (2004)



A.P. MacKenzie *et al.*, PRB (1996)

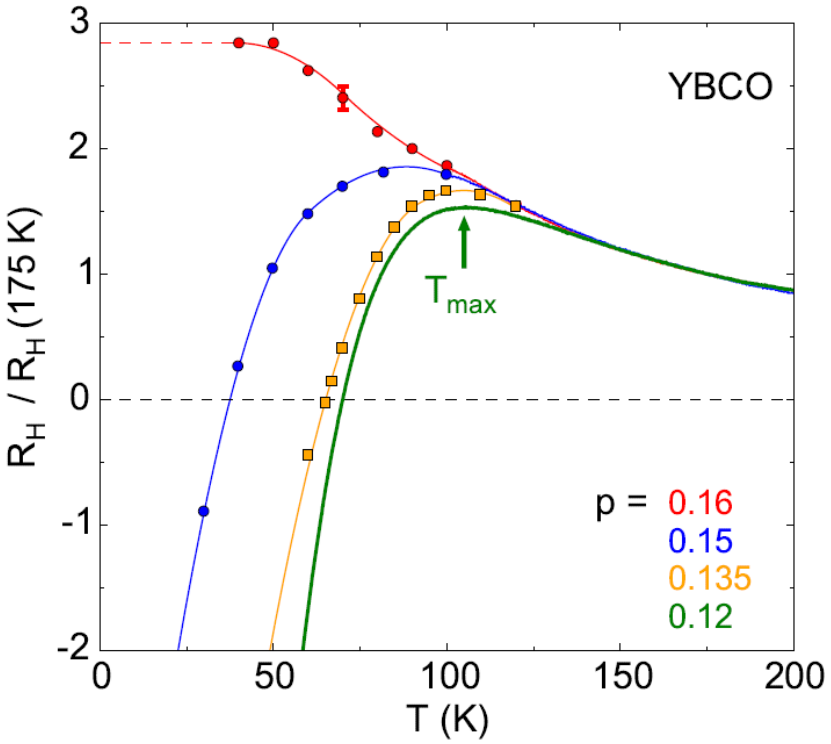


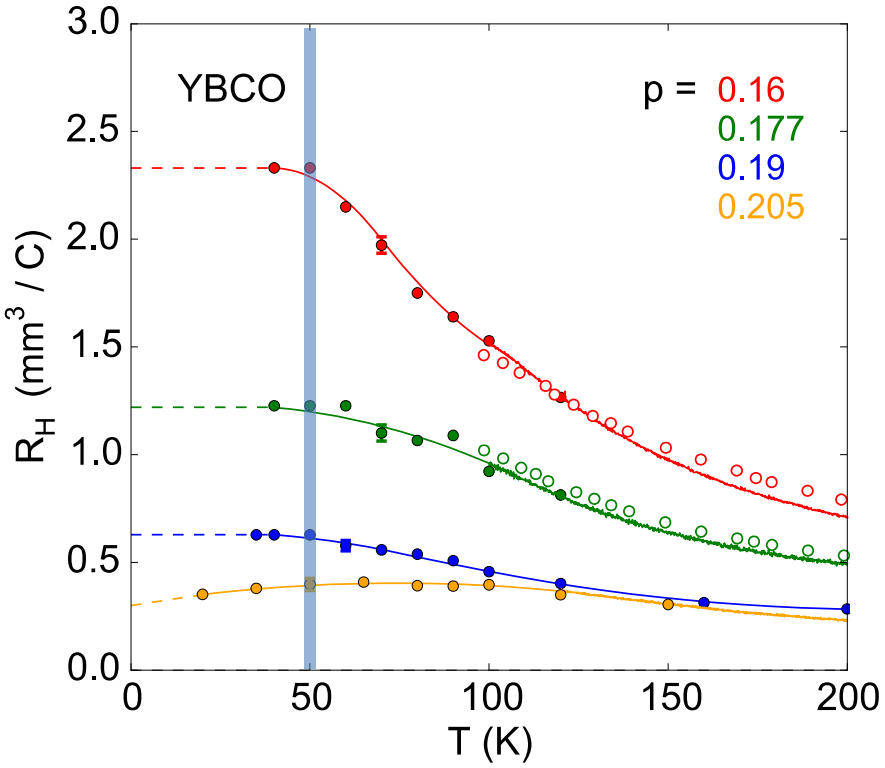


Carrier density: $n_H = \frac{V}{eR_H}$

[n_H] = [carrier / Cu atom]

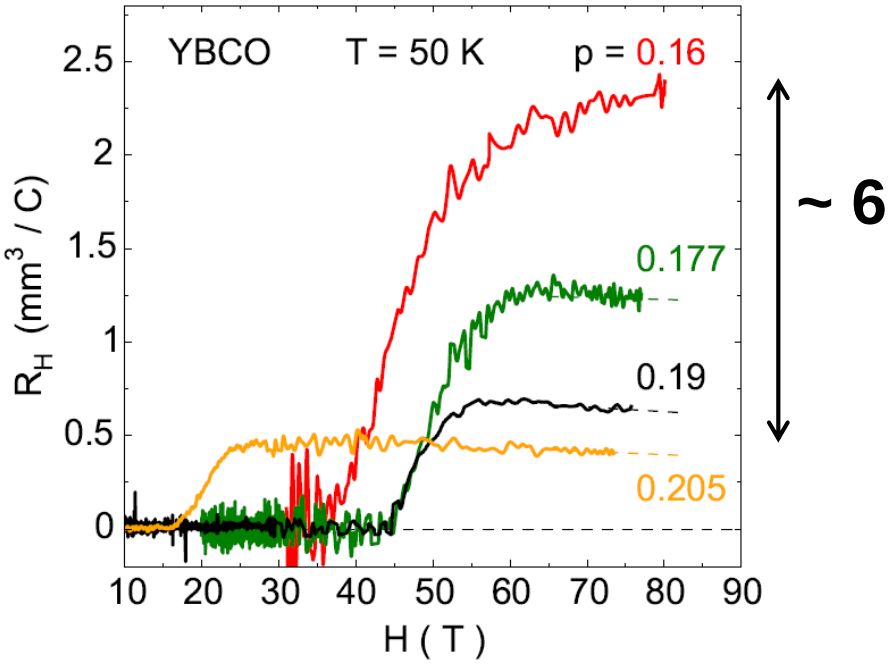
Doping evolution of the Hall coefficient in YBCO

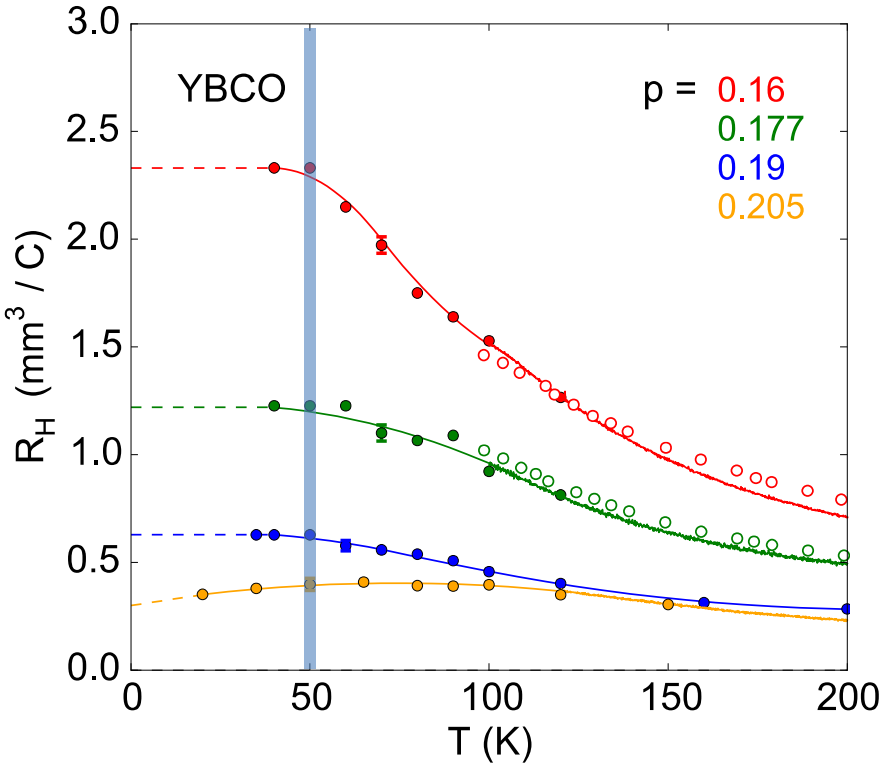




Hall coefficient: $R_H = \frac{tR_{xy}}{B}$

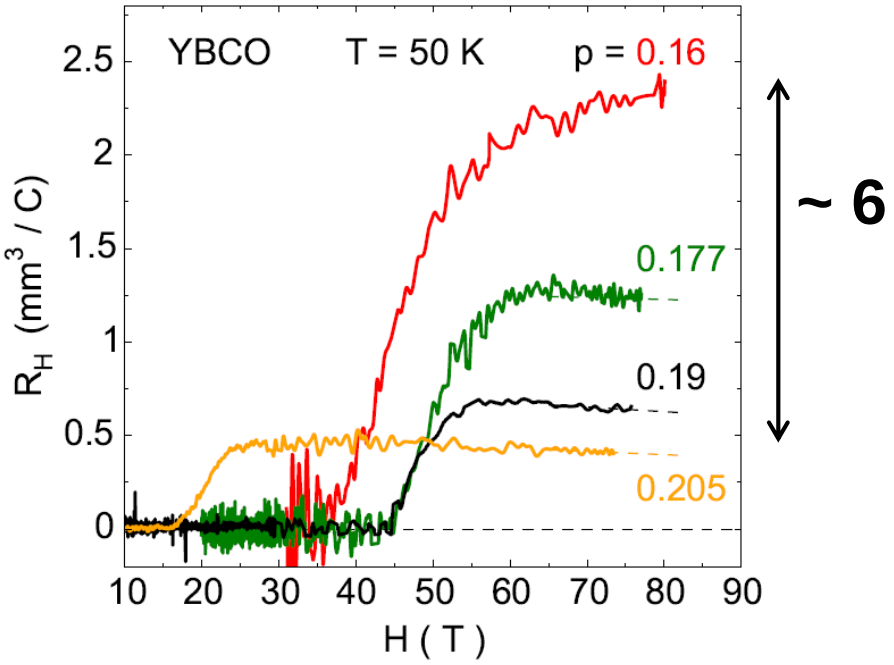
Doping evolution of the Hall coefficient in YBCO



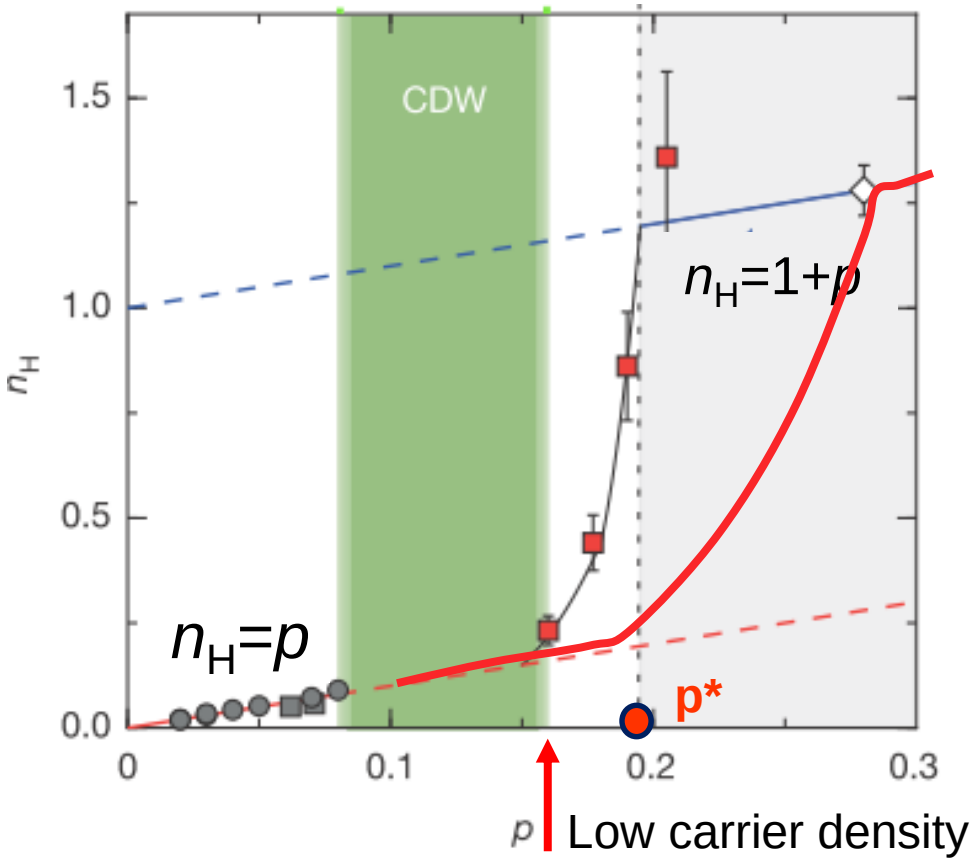


Hall coefficient: $R_H = \frac{tR_{xy}}{B}$

Change of the carrier density



Carrier density: $n_H = \frac{V}{eR_H}$



S. Badoux, W. Tabis *et al.,* Nature (2016)

Change in the carrier density
from ***n = p*** to ***n = 1 + p*** occurs at ***p****

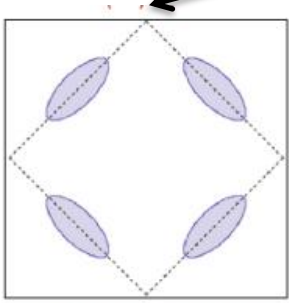
Scenarios of the FS evolution

AF Mott insulator

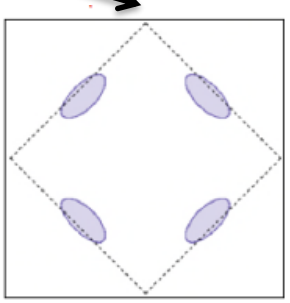
Translational symmetry broken

NO Translational symmetry broken

AF metal
Q = (π, π)
n = p
e.g. electron doped



AFM-Metal with hole pockets



Metal with hole pockets but without LRO AFM

e.g. FL*, YZR
n = p

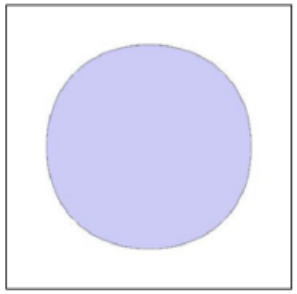
CDW

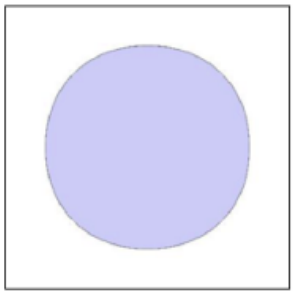
FSR

p^*

p

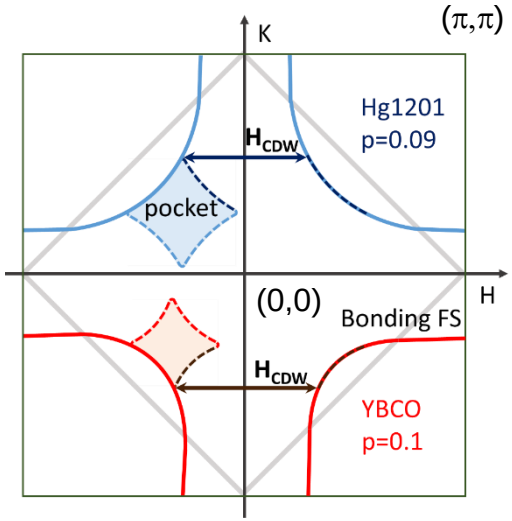
n = 1+p

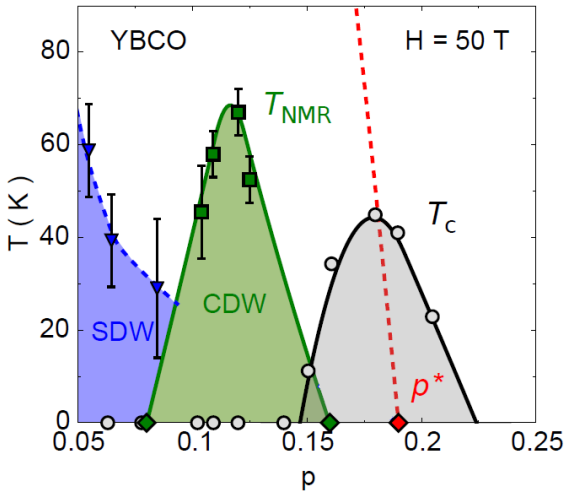


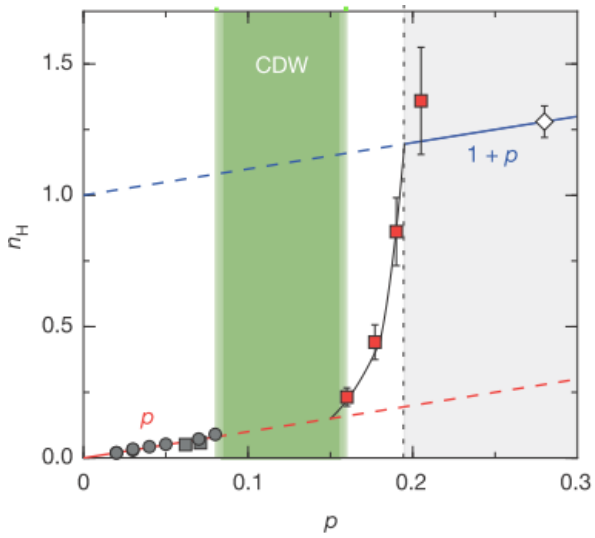


n = 1+p

Summary







- Universal **CDW** order in Hg1201 and YBCO, reconstructs FS into electron pockets.
- **Charge order** and **pseudogap** have distinct critical point in YBCO
- Localization of a carrier is a signature of the pseudogap, reflected in the increase of the resistivity at low T