Impact of charge order on the electronic properties of underdoped cuprates

Cyril PROUST

Laboratoire National des Champs Magnétiques Intenses

Toulouse, France

Collaborations

LNCMI

F. Laliberté

W. Tabis

D. Vignolles

B. Vignolle

S. Badoux

S. Lepault

LNCMI

M-H. Julien

D. LeBoeuf

UNIVERSITÉ DE SHERBROOKE

L. Taillefer

N. Doiron-Leyraud

UBC

D. Bonn

B. Ramshaw

R. Liang

W. Hardy

SOLID STATE SPECTROSCOPY
MAX PLANCK INSTITUTE FOR SOLID STATE RESEARCH

B. Keimer

M. Le Tacon

T. Loew

UNIVERSITY OF MINNESOTA
Driven to Discover℠

M. Greven

N. Barisic

M. K. Chan

University of BRISTOL

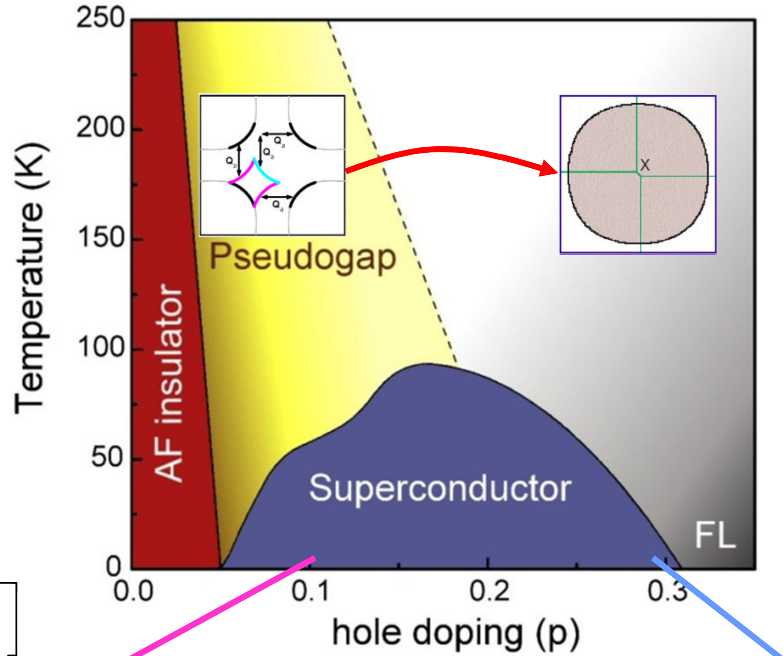
A. Carrington

N. Hussey

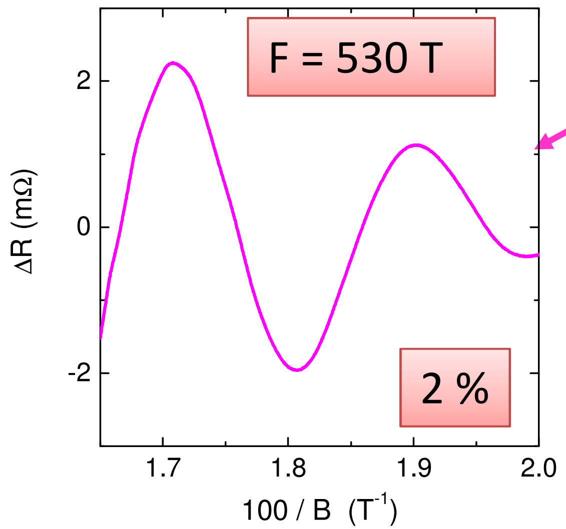
Quantum oscillations in hole-doped cuprate

Topological change in Fermi surface

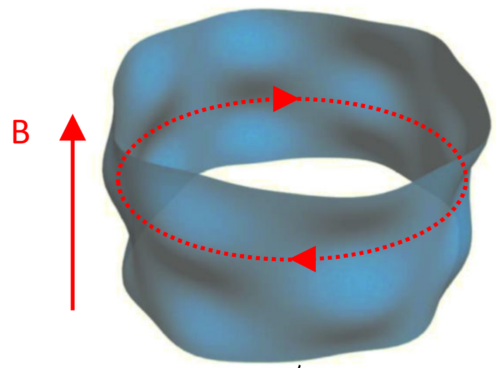
underdoped
$YBa_2Cu_3O_{6.5}$



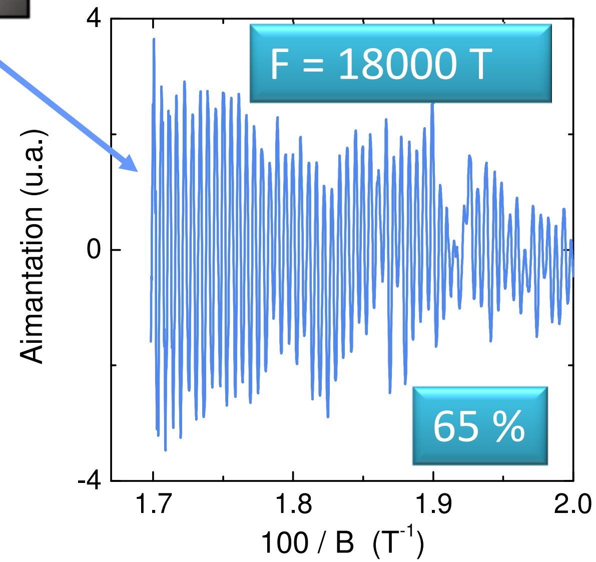
overdoped
$Tl_2Ba_2CuO_{6+\delta}$



N. Doiron-Leyraud et al, Nature'07



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



B. Vignolle et al, Nature'08

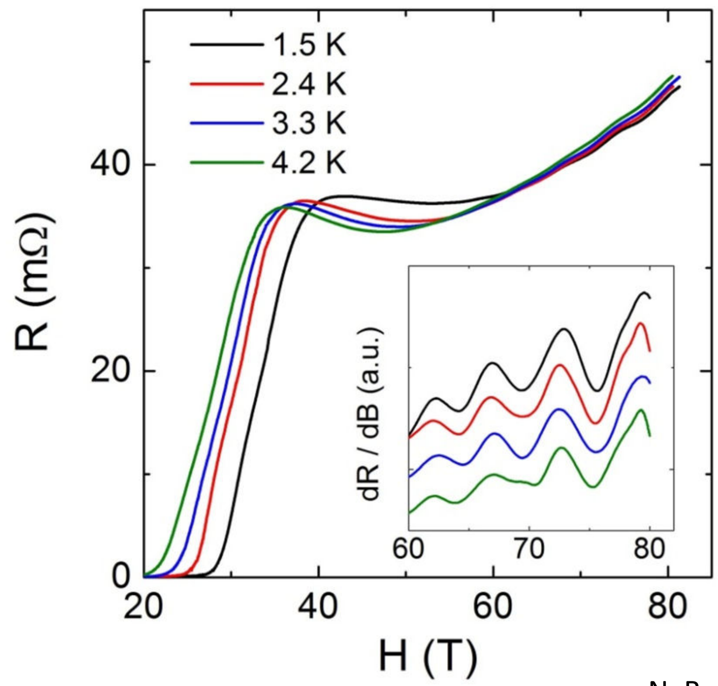
Ubiquity: Quantum Oscillations

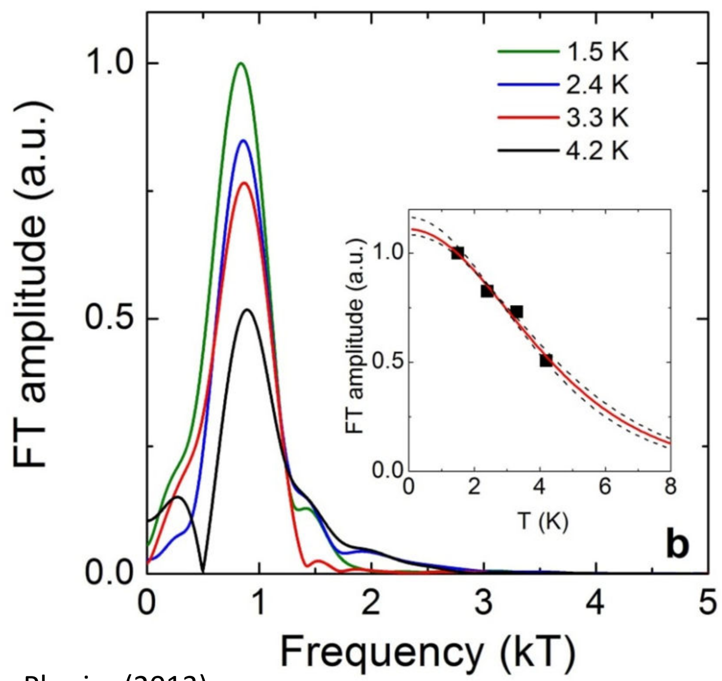
Quantum oscillation in $YBa_2Cu_3O_y$:

- Observed in **many probes**: electrical / thermal transport, magnetization, ultrasound, TDO, thermoelectricity
- Observed in the **doping range** between 9 % and 15 %

Quantum oscillations in single layer $HgBa_2CuO_{4+\delta}$:

$F = 840 \pm 30$ T and $m^* = 2.45 \pm 0.15\ m_e$



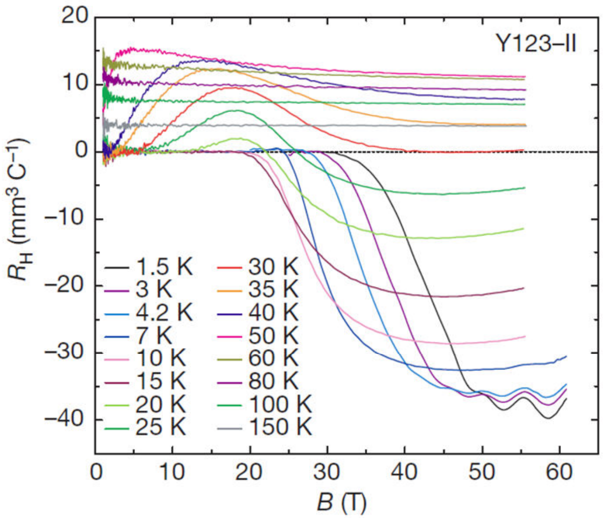


N. Barisic et al, Nature Physics (2013)

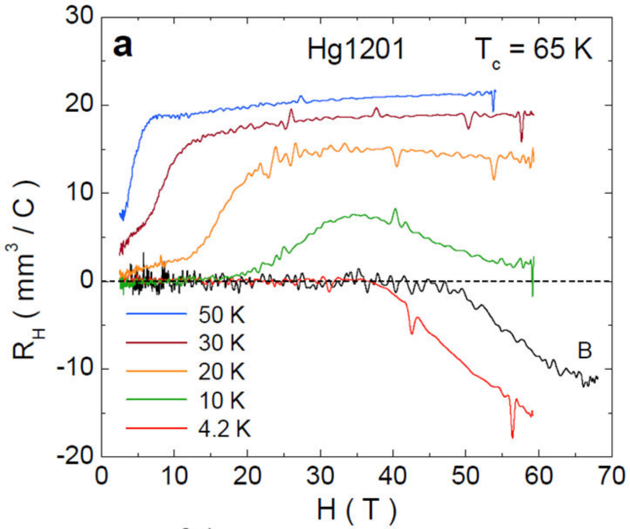
Ubiquity: Hall effect

$YBa_2Cu_3O_y$

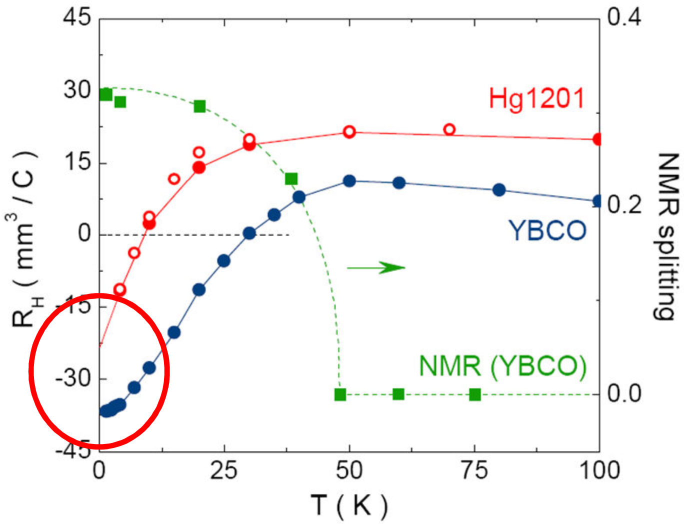
$HgBa_2CuO_{4+\delta}$



D. LeBoeuf et al, Nature'07



N. Doiron-Leyraud et al, PRX'13



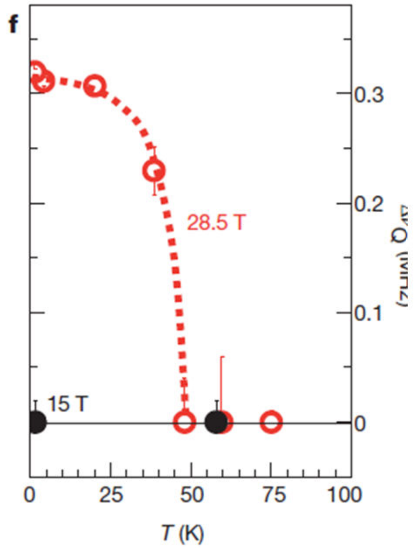
Electron pocket !

Reconstruction of the FS into electron (and hole) pockets below a critical doping p^*

Broken symmetry = charge order

High field NMR in underdoped YBCO

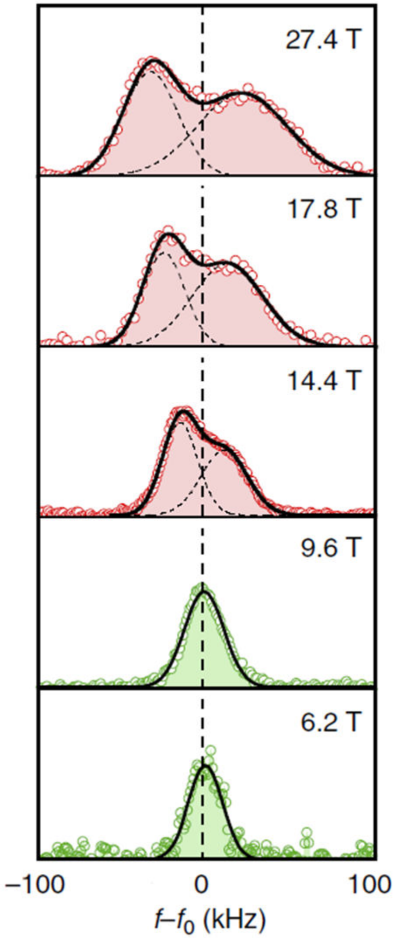
(M-H. Julien, LNCMI-Grenoble)



T. Wu et al, Nature’11

Broken translational symmetry by **charge order**

No spin order !

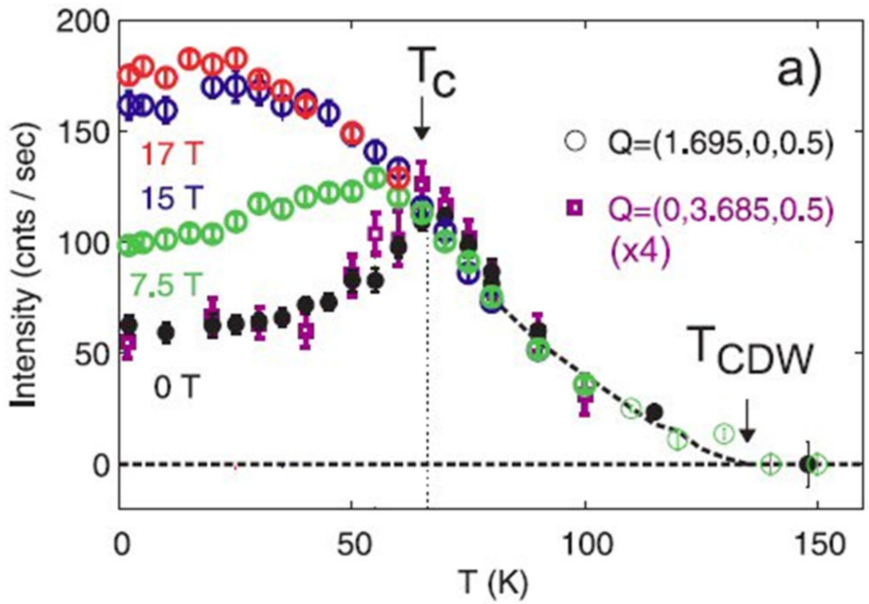


T. Wu et al, Nature Commun.’13

Threshold field

High energy x-ray diffraction in underdoped YBCO

2D charge fluctuations up to T=150 K with an incommensurate periodicity



J. Chang *et al*, Nature Physics’12
G. Ghiringhelli *et al*, Science’12
A. Achkar *et al*, PRL’13 …

Charge order detected between 8 % < p < 16 %

But also X-ray in Hg1201 (Q ≈ 0.28)

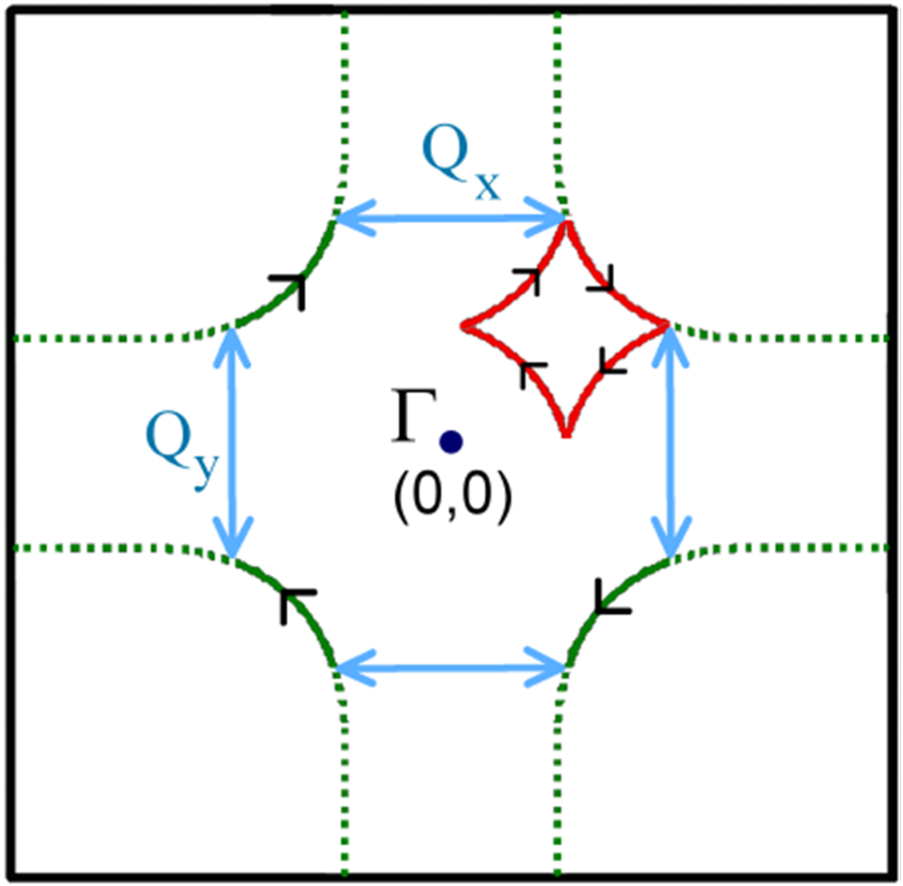
W. Tabis et al, Nature Commun.’14

Link between QO and CDW

Can we reconcile quantum oscillations and the transport properties in YBCO with the Fermi surface reconstructed by a biaxial charge order ?

Fermi surface reconstruction

Qualitative FSR by biaxial charger order

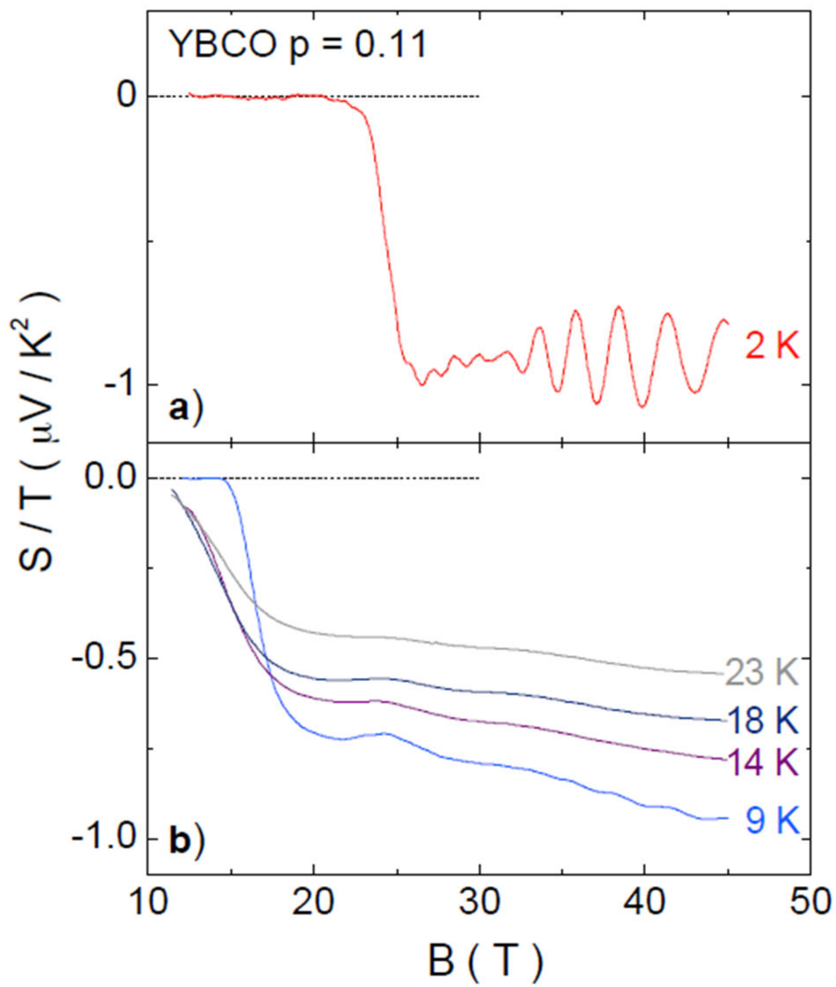


Other pockets ?

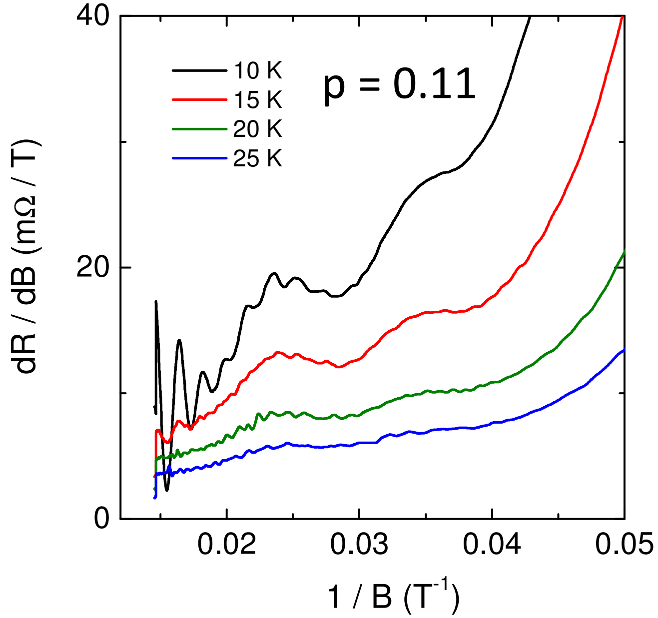
S. E. Sebastian et al, RPP’12

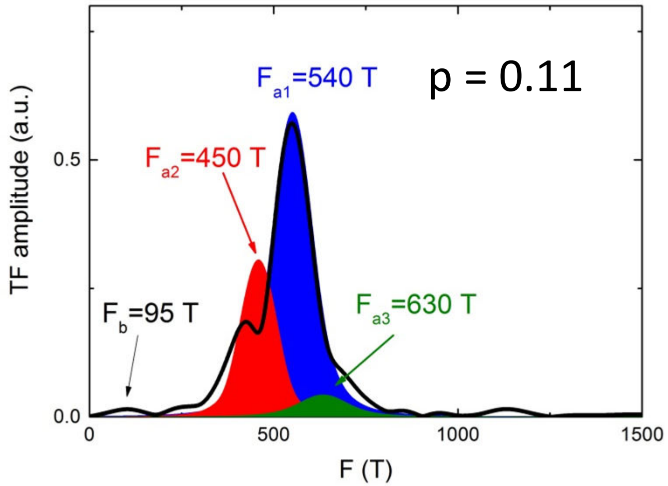
Discovery of a new frequency in YBCO

Thermopower (Taillefer's group)
Tallahassee



c-axis resistivity
Toulouse

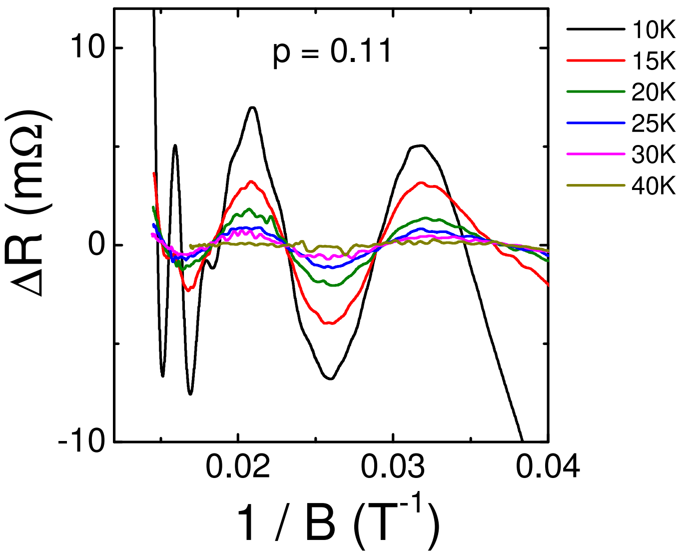


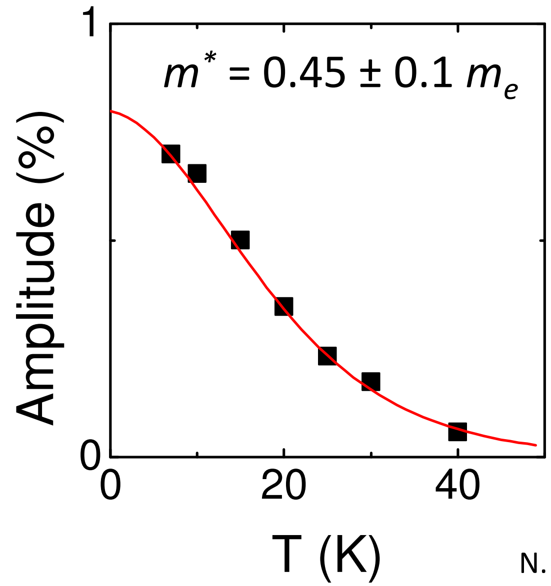


N. Doiron-Leyraud *et al*, Nature Commun.'15

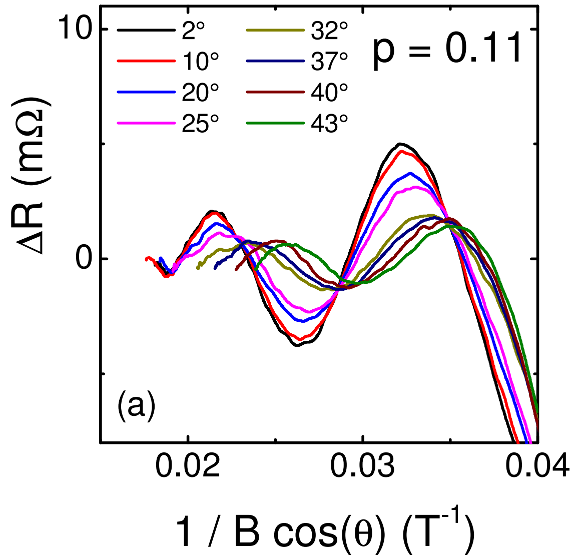
Effective mass / angle dependence

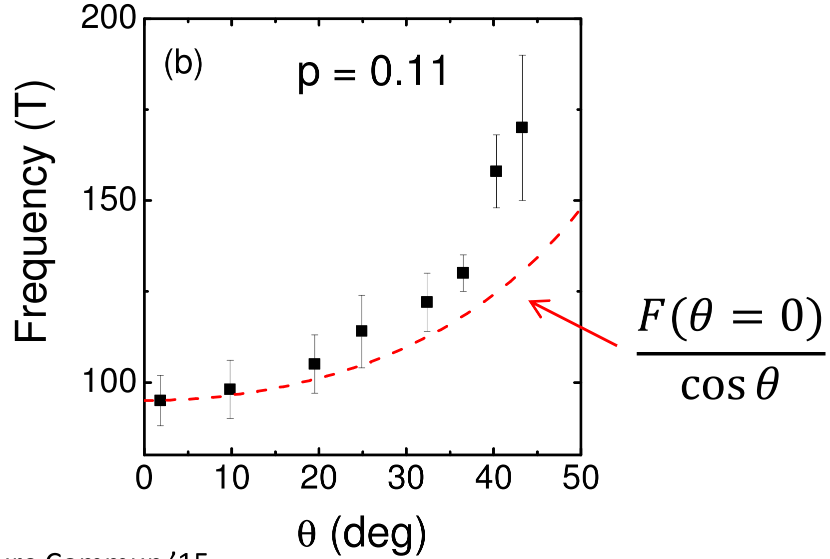
Temperature dependence





Angle dependence





N. Doiron-Leyraud *et al*, Nature Commun.'15

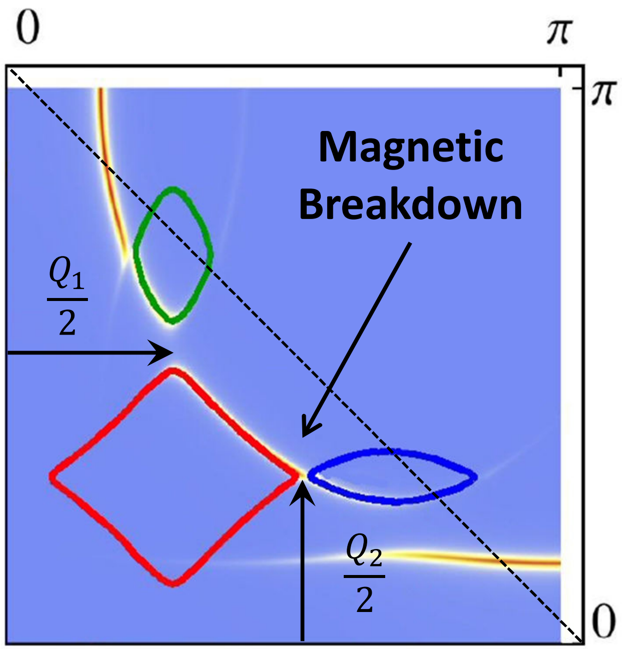
Connecting QO with FSR by charge order

Fermi surface reconstruction by a bond density wave

Anisotropic biaxial CDW

hole

electron

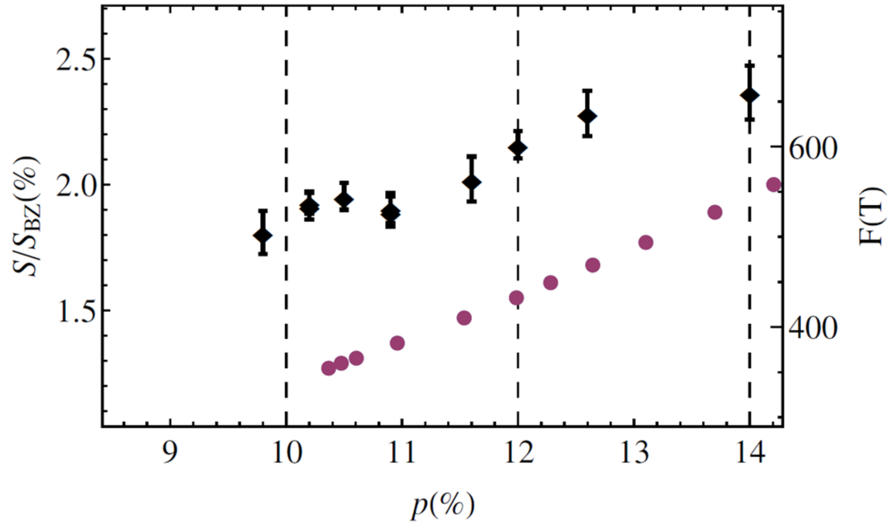


hole

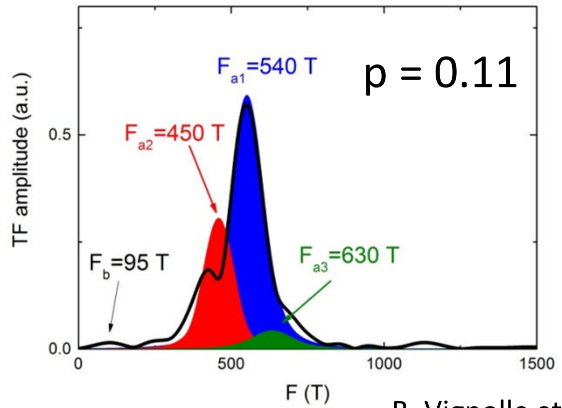
A. Allais et al, Nature Commun.'14

Q_1, Q_2 measured by x-ray

$Q_1, Q_2 \neq Q_{\text{anti-nodal}}$ AND $Q_1, Q_2 \neq Q_{\text{hot spot}}$



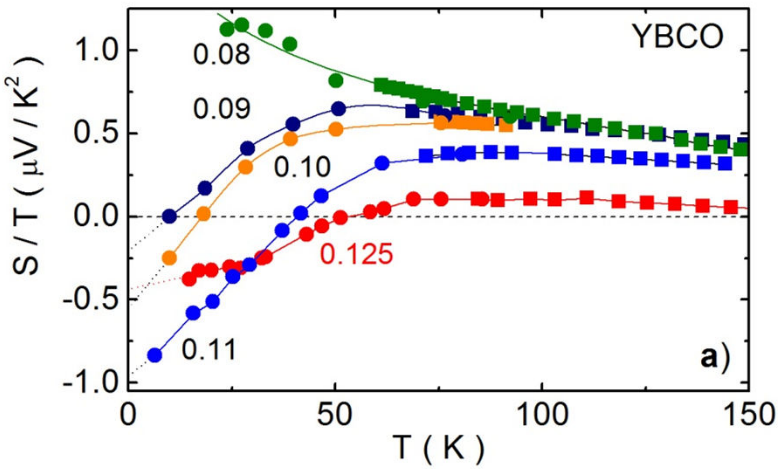
$F_{\text{electron}} / F_{\text{hole}} \approx 5$



B. Vignolle et al, CRAS12

⇒ two-step process for the Fermi surface reconstruction: Pseudogap + CDW

The case for an extra hole pocket

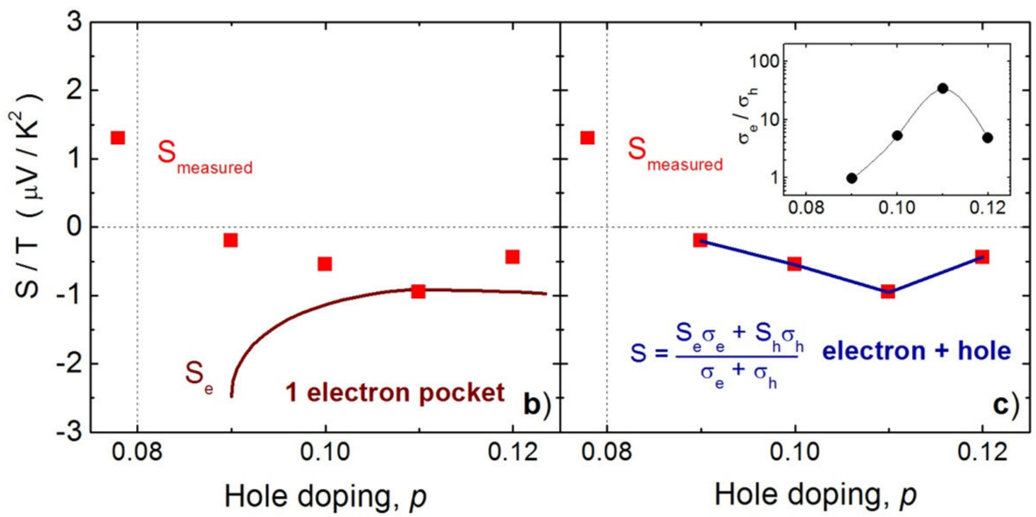


Doping dependence of Thermopower in YBCO

F. Laliberté et al, Nat. Comm’11

$$\frac{S}{T} \propto \frac{1}{T_F}$$

$$\frac{S_e(p)}{T} \propto \frac{m_e{}^* (p)}{F_e(p)}$$



Two band model

$$\frac{S}{T} = \frac{S_e\,\sigma_e + S_h\,\sigma_h}{\sigma_e + \sigma_h}$$

F_h = 95 T
$m_h{}^*$=0.45

$\Rightarrow$ Need for a two band model to explain the doping dependence of Seebeck

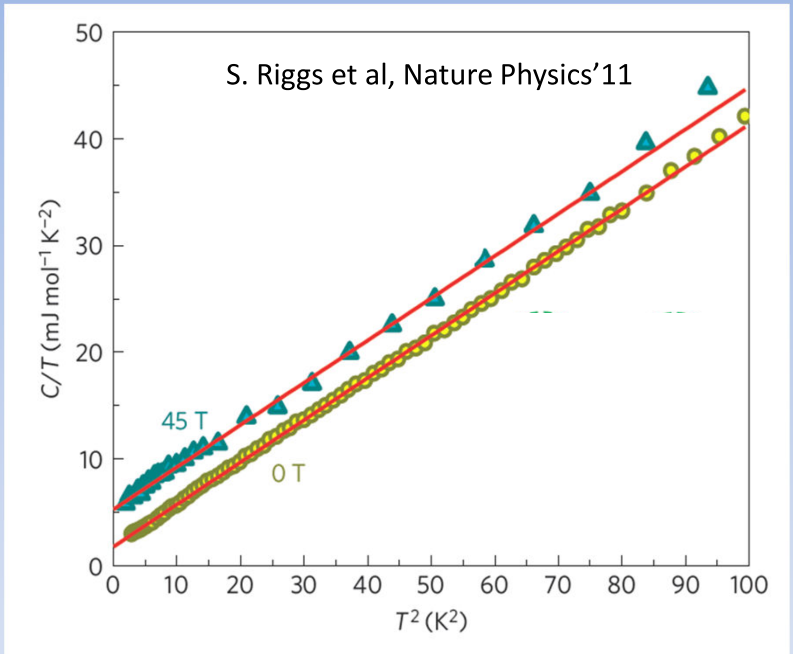
N. Doiron-Leyraud *et al*, Nature Commun.’15

The "Thermodynamic police"

Electronic coefficient of the specific heat : $\gamma = (1.46\,\mathrm{mJ\,K^{-2}\,mol}) \sum_{i} (n_i m_i^* / m_0)$

$m^*_{electron}$ = 1.7 ± 0.2 m_0 and m^*_{hole} = 0.45 ± 0.1 m_0

γ^{theo} = 7.6 ± 0.8 mJ.mol^{-1}.K^{-2} for 1 electron + 2 hole pockets (+ bilayer)



YBCO (p~0.11):
γ_{el} (B=45 T, T→0) ~ 5.0 ± 1 mJ mol^{-1} K^{-2}

Recent measurements in Grenoble:
(C. Marcenat, T. Klein et al)

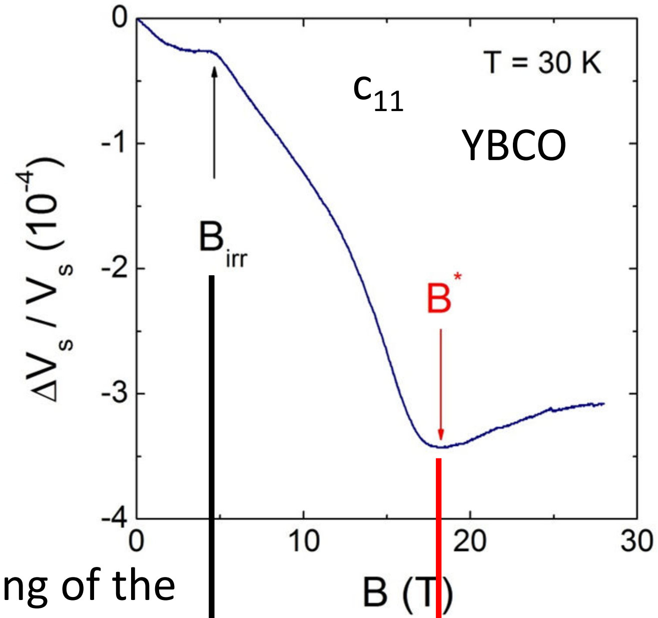
YBCO p = 0.11 :

γ_{el} (B=30 T, T→0) = 7 ± 1.5 mJ K^{-2} mol^{-1}

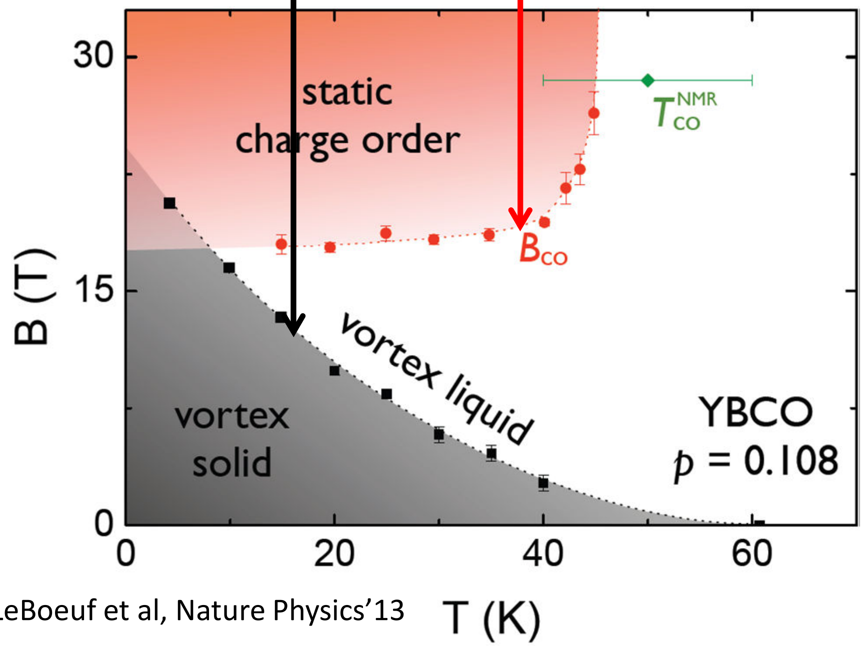
Sound velocity measurements

Where does the thermodynamic phase transition take place ?

High fields sound velocity in YBCO



Melting of the vortex lattice



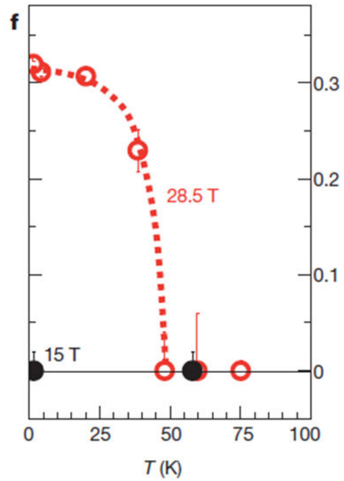
D. LeBoeuf et al, Nature Physics'13

<u>Sound velocity</u>: thermodynamic quantity related to the elastic constants of a solid

$$v_s^{\ 2} = \frac{c_{ij}}{\rho} \qquad \text{where} \qquad c_{ij} = \frac{\partial^2 F}{\partial \varepsilon_i \partial \varepsilon_j}$$

Directional probe: propagation / polarization

B_{co} → thermodynamic signature of phase transition

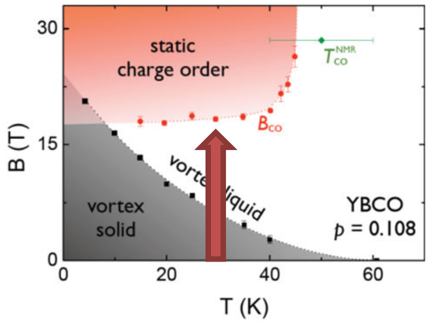


Comparison with NMR
⇒ charge order

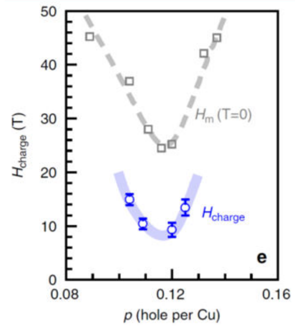
Simple group theory argument:

⇒ Charge modulation both along **a** and **b**-axis

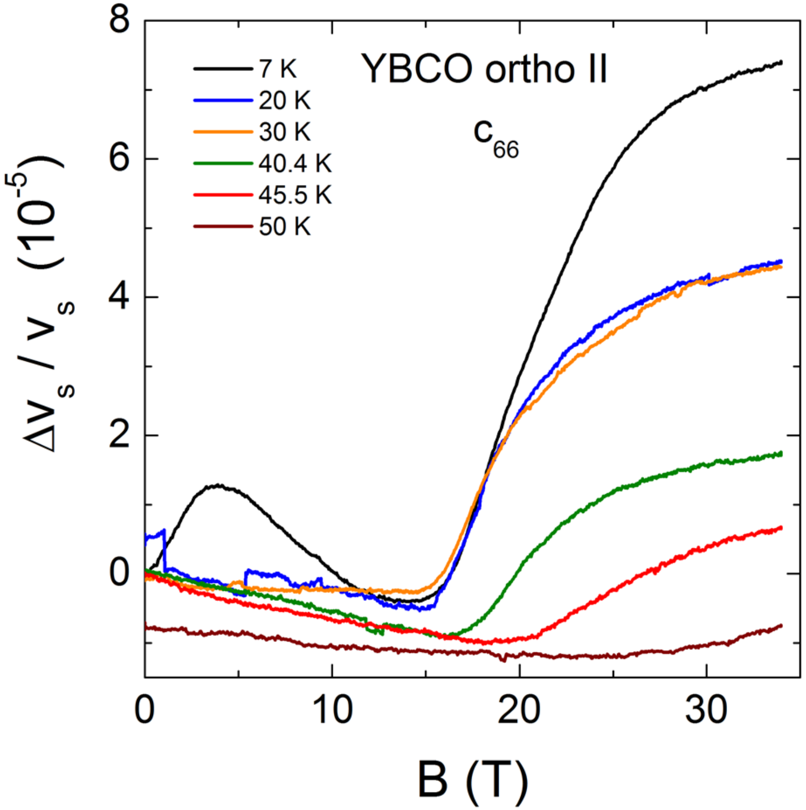
Threshold field

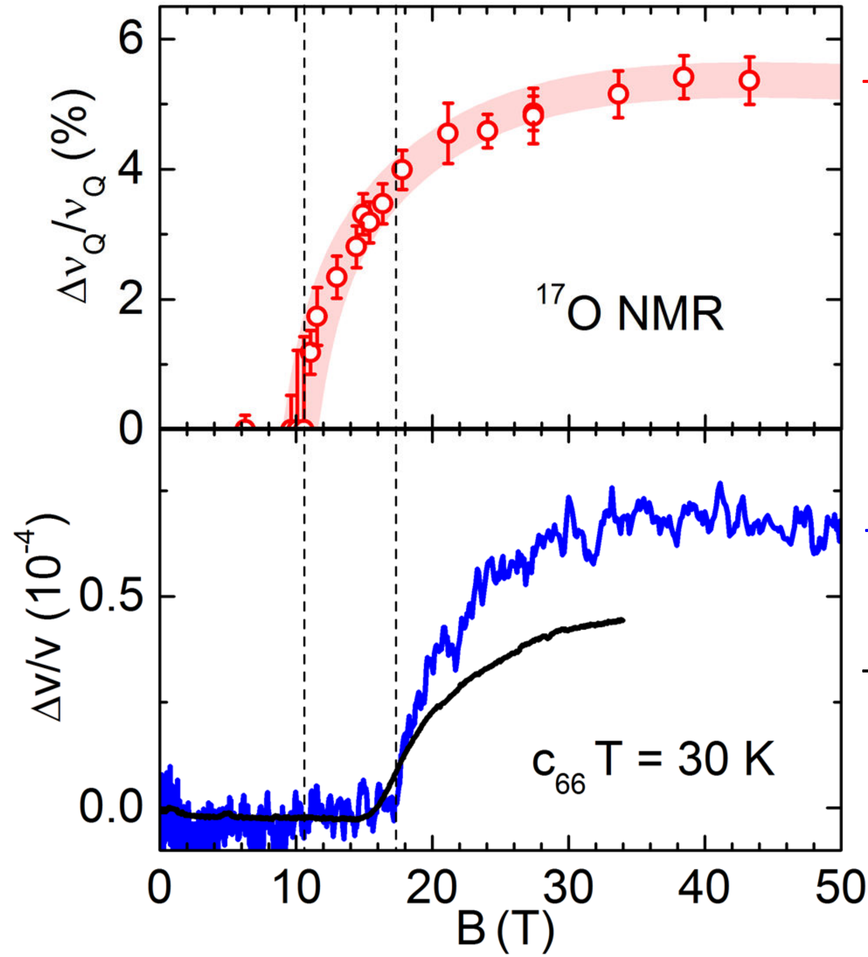


Comparaison c_{66} - NMR



Field dependence of c_{66}





p=0.104
T_c= 59.6K

p=0.108
T_c= 60.7 K

p=0.109
T_c= 61.5 K

Conclusion / open questions

- Fermi surface reconstruction by biaxial charge order $\Rightarrow$ electron + hole pockets

- Reconciliation of quantum oscillation and transport properties with x-ray results if pseudogap effect on the Fermi surface is taken into account

- Phase transition detected by ultrasound at low T and above a threshold field both in the field and temperature dependences of the sound velocity

> - Analogy with stripe ?
>
> Fermi surface reconstruction produces electron pocket in criss-crossed stripe model
>
> - CDW correlation length measured by x-ray versus cyclotron orbit of quantum oscillations