Quantum Oscillations, Magnetotransport and the Fermi Surface of cuprates

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Outline

- **Introduction to quantum oscillations**

- Quantum oscillations on both sides of the phase diagram

- The case for an electron pocket

- Cartography of the electron pocket

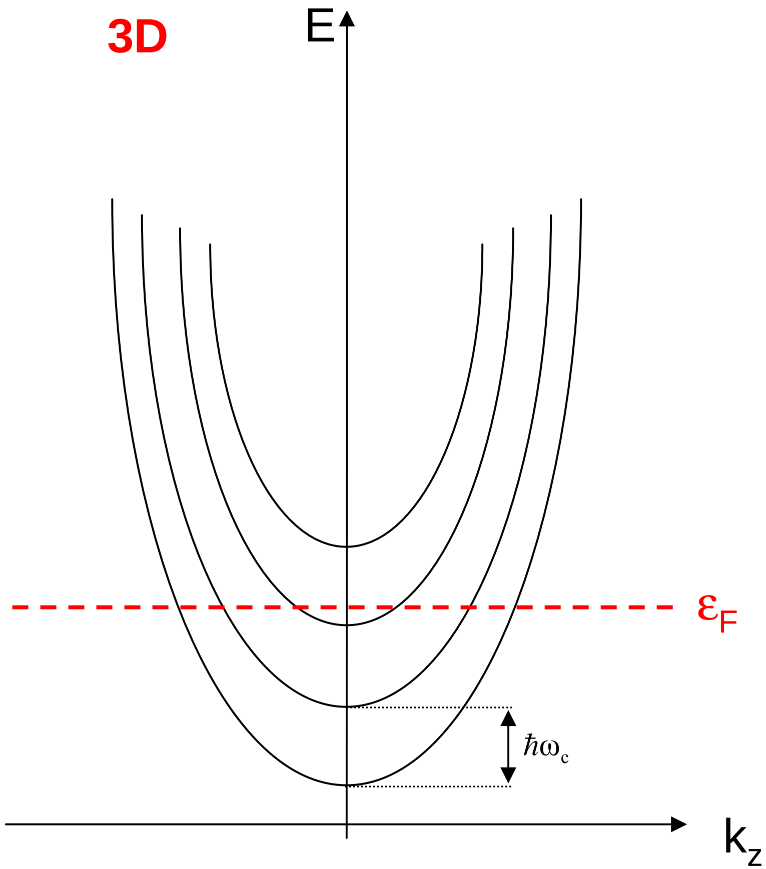
- Fermi surface reconstruction scenarios

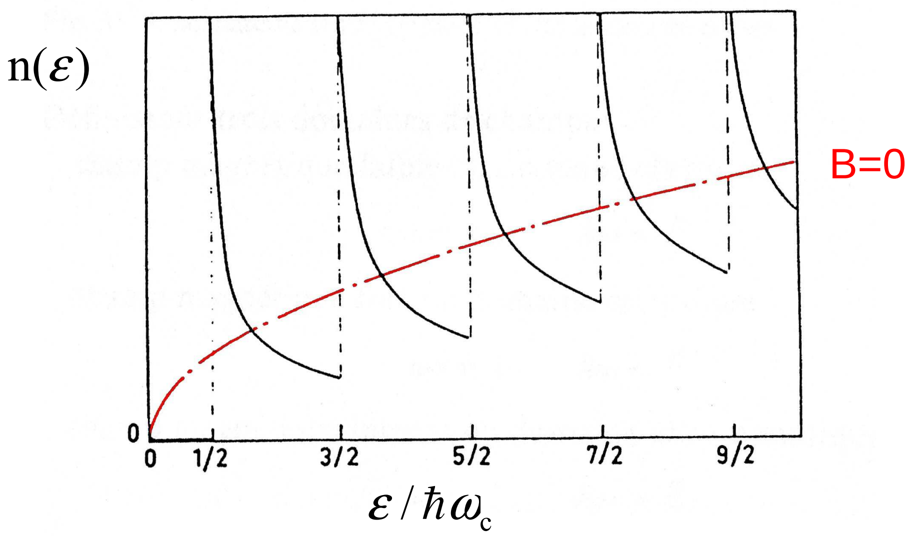
Quantum theory

$$E = E_z + E_\perp = \frac{\hbar^2 k_z^2}{2m} + \hbar\omega_c\left(n + \frac{1}{2}\right) \qquad \omega_c = \frac{qB}{m_c}$$

$$n(E) = 2\pi V\left(\frac{2m}{\hbar^2}\right)^{3/2}\hbar\omega_c\sum_{n=0}^{\infty}\frac{1}{\sqrt{E - \hbar\omega_c(n+0.5)}}$$

Density of states





⇓

Oscillation of most electronic properties

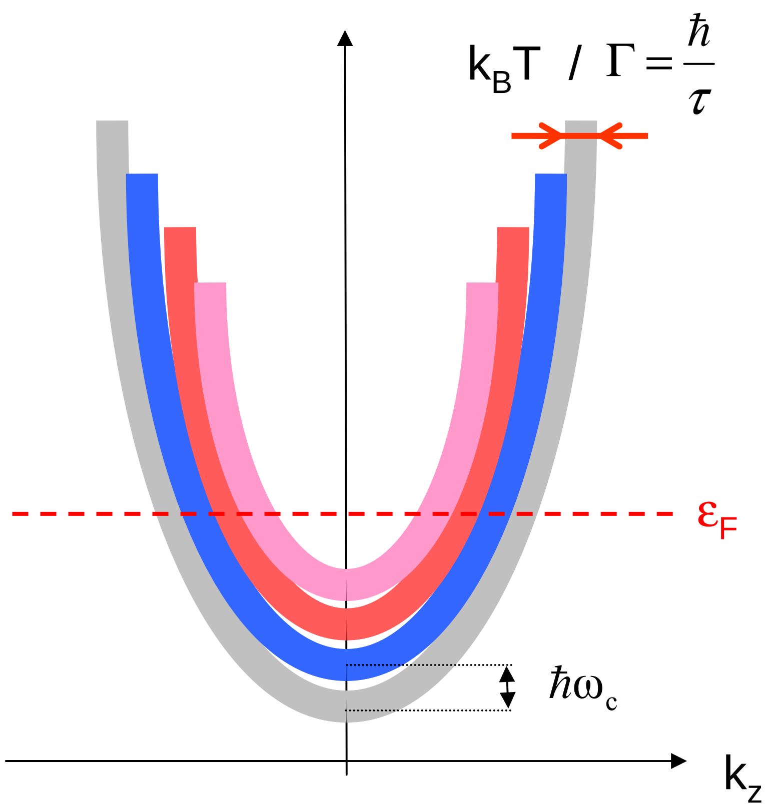
Magnetization: de Haas-van Alphen (dHvA)

Resistivity: Shubnikov-de Haas (SdH)

Quantum theory

Temperature / Disorder effects on quantum oscillations

$$\omega_c = \frac{eB}{m^*}$$



- **Low T measurements**

$$\hbar\omega_c > k_B T$$

- **Need high quality single crystals**

$$\hbar\omega_c > \frac{\hbar}{\tau} \quad \Rightarrow \quad \omega_c \tau > 1$$

Quantum theory

Lifshitz-Kosevich theory (1956)

$$\Delta R, \Delta M \propto R_T\, R_D\, R_S\, sin\left[2\pi\left(\frac{F}{B}-\gamma\right)\right]$$

$$\frac{F}{B}=\frac{\hbar}{2\pi q}\frac{A_F}{B}$$ Onsager relation $\Rightarrow$ A_F — Extremal area

$$R_T=\frac{X}{sh(X)} \quad \text{where } X = 14.694\times Tm_c / B$$ $\Rightarrow$ m^* — Cyclotron mass

$$R_D=\exp\left(-\frac{14.694\times T_D m_c}{B}\right)=\exp\left(-\frac{\pi}{\mu B}\right)$$ $\Rightarrow$ $T_D=\frac{\hbar}{2\pi k_B \tau}$ — Dingle temperature (mean free path)

$$R_S=\cos\left(\frac{\pi}{2}m_b^* g\right)$$ $\Rightarrow$ $m_b^* g$ — Spin factor (spin zero)

Direct measure of the Fermi surface extremal area

(but number of orbits ? location in k-space ?)

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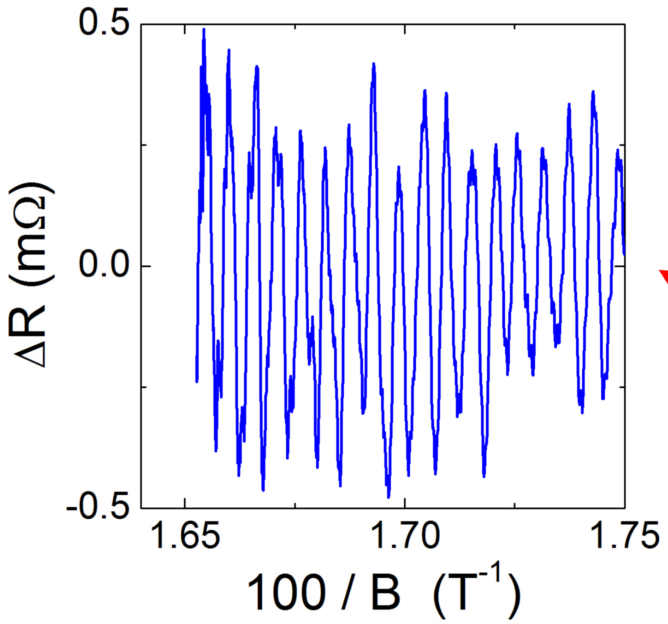
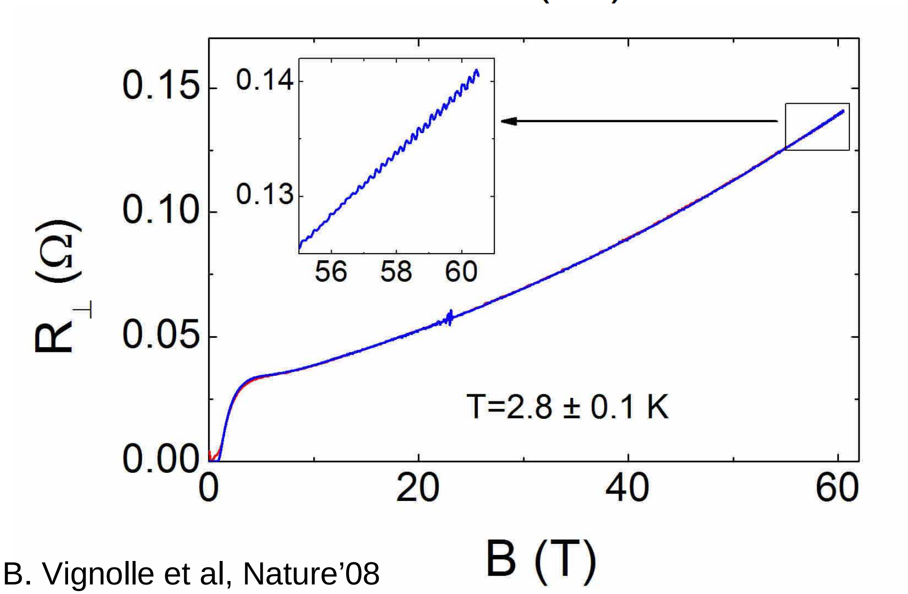
The overdoped case: $Tl_2Ba_2CuO_{6+\delta}$





B. Vignolle et al, Nature'08

Fermi surface of overdoped Tl-2201

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

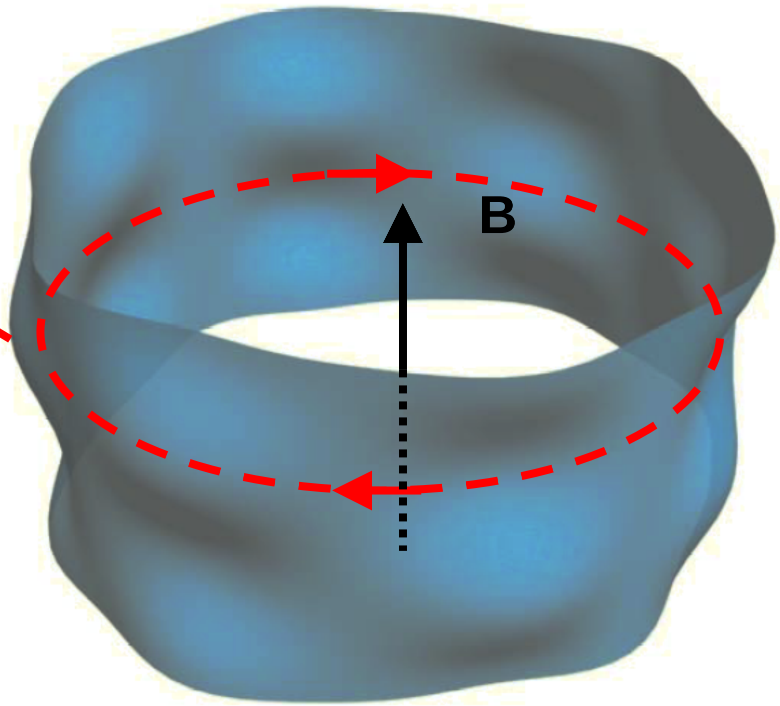


Photo credit: N. Hussey

Oscillation amplitude < 1% (1 mΩ)!

The overdoped case: $Tl_2Ba_2CuO_{6+\delta}$

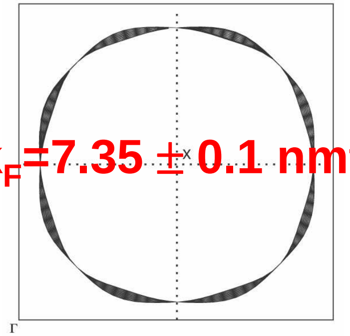
- F=18100 ± 50 T

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

$A_k = \pi k_F^2$ ⇒ k_F=7.42 ± 0.05 nm^{-1}

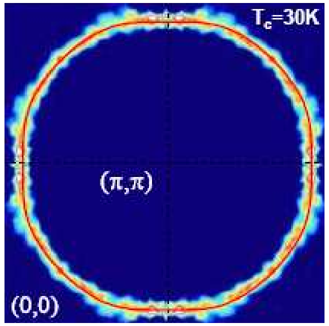
(65 % of the FBZ)

AMRO



Hussey *et al*, *Nature*'03

ARPES



Platé *et al*, PRB'05

Luttinger theorem : $$n = \frac{2A_k}{(2\pi)^2} = \frac{F}{\phi_0}$$

⇒ Carrier density: n=1.3 carrier /Cu atom (n=1+p with p=0.3)

Electronic specific heat: m^*=5 ± 0.5 m_0 ⇒ $\gamma_{el} = \frac{\pi N_A k_B^2 a^2}{3\hbar^2} m^* = 7 \pm 0.5\,\mathrm{mJ/mol.K^2}$

For overdoped polycristalline Tl-2201: $\gamma_{el} = 7 \pm 1\,\mathrm{mJ/mol.K^2}$ (Loram et al, Physica C'94)

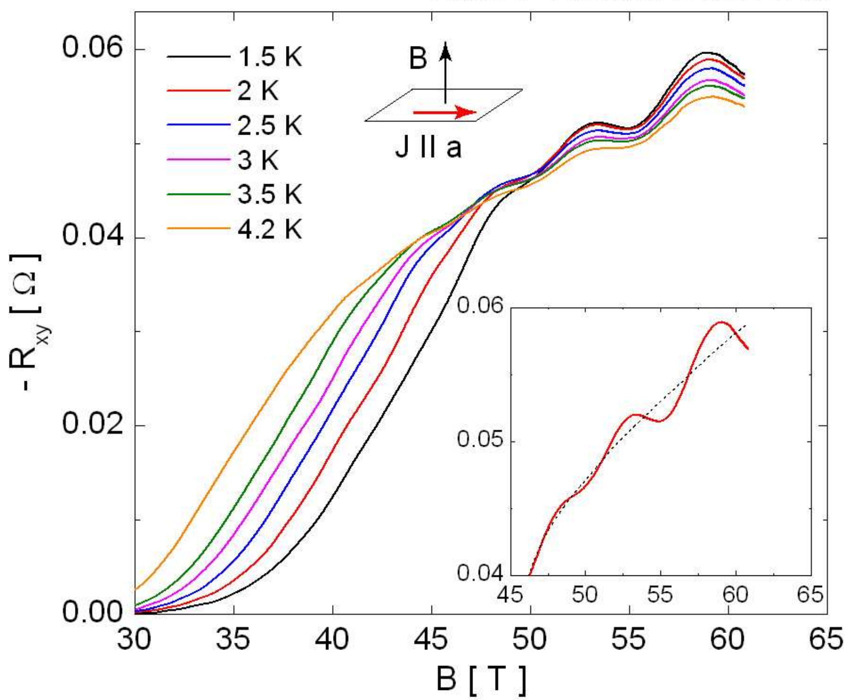
All the numbers are in excellent agreement with
- in-field probes: AMRO, Hall effect
- zero field probes: ARPES, thermodynamic …

Quantum oscillations in UD $YBa_2Cu_3O_{6.5}$

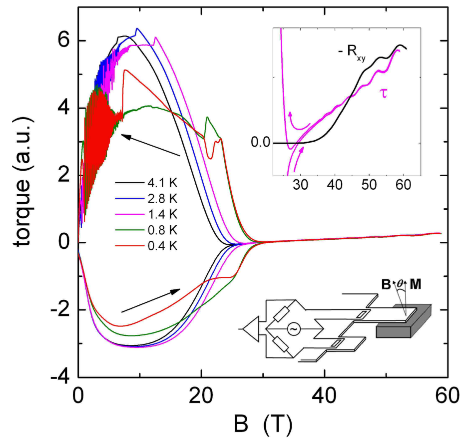
Shubnikov - de Haas

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

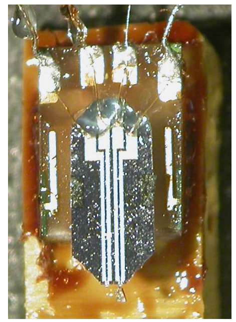
de Haas – van Alphen



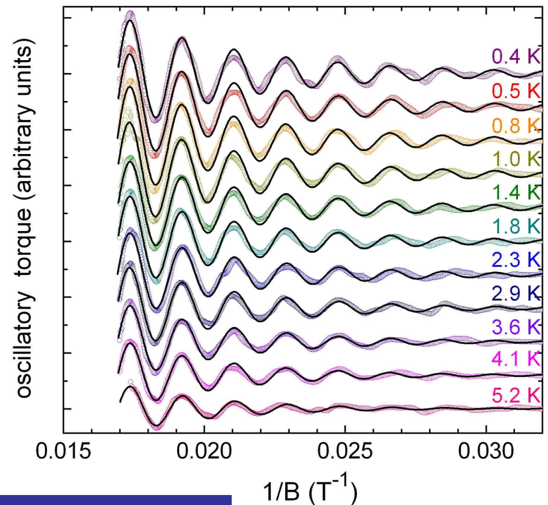
N. Doiron-Leyraud et al, Nature'07



D. Vignolles



Piezoresistif cantilever

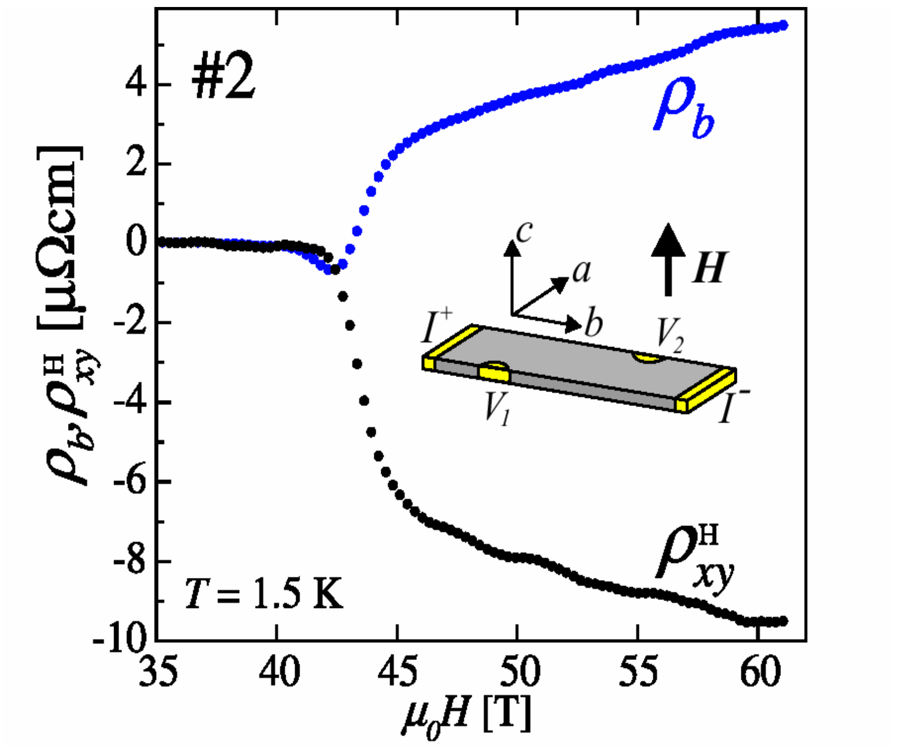


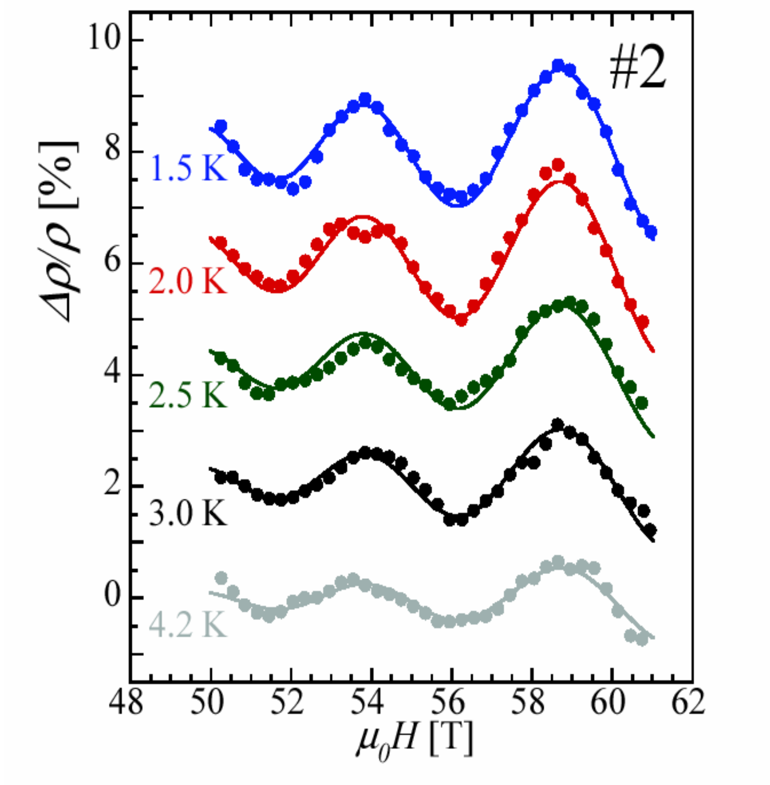
C. Jaudet et al, PRL'08

Frequency : F = (540 ± 4) T
Mass : m = (1.76 ± 0.07) m_0*

Closed pocket and coherent QP at low T

Quantum oscillations in UD $YBa_2Cu_4O_8$





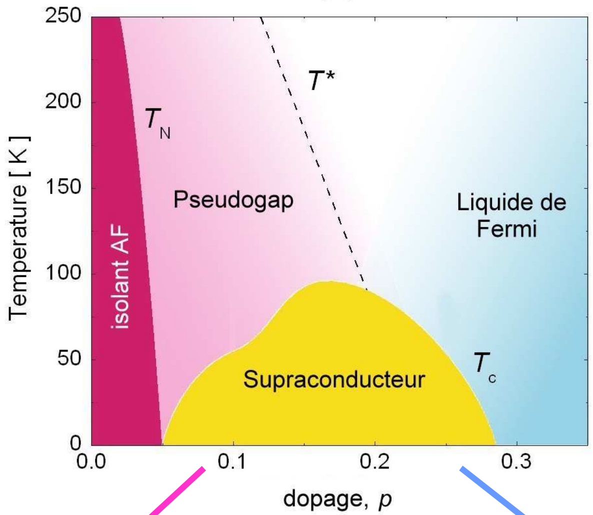
A. Bangura et al, PRL'08

Frequency : F = (660 ± 30) T
Mass : m = (2.7 ± 0.3) m_0*

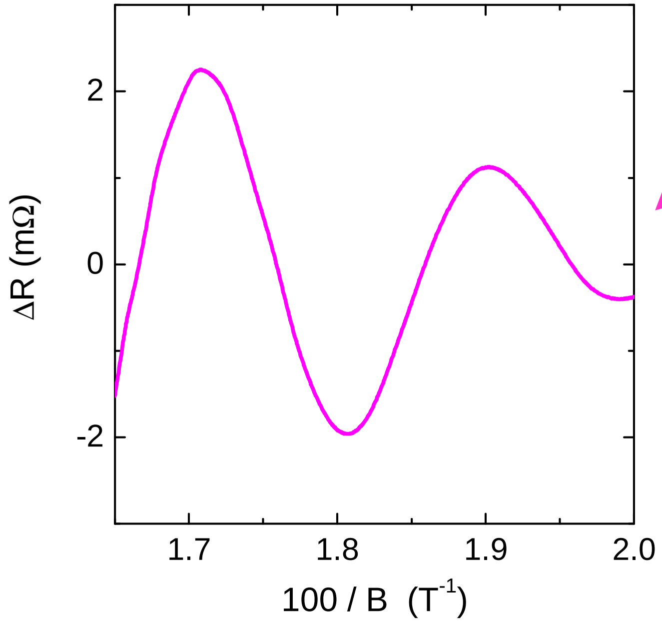
See also E.A Yelland et al, PRL'08

Quantum oscillations in HTSC

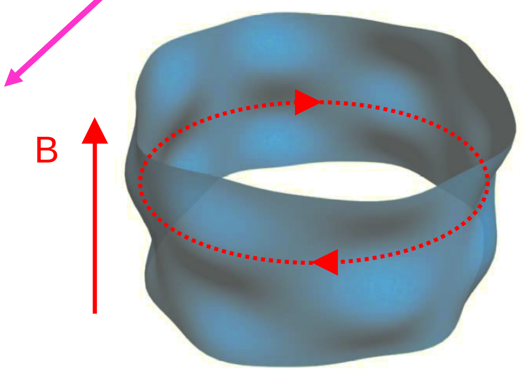
underdoped
$YBa_2Cu_3O_{6.5}$



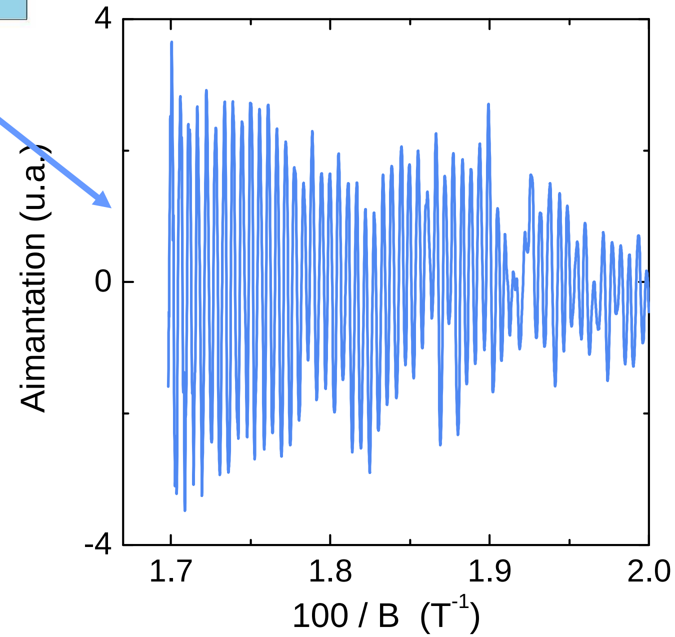
overdoped
$Tl_2Ba_2CuO_{6+\delta}$



N. Doiron-Leyraud et al, Nature’07



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



B. Vignolle et al, Nature’08

Implication of quantum oscillations

$YBa_2Cu_3O_{6.5}$

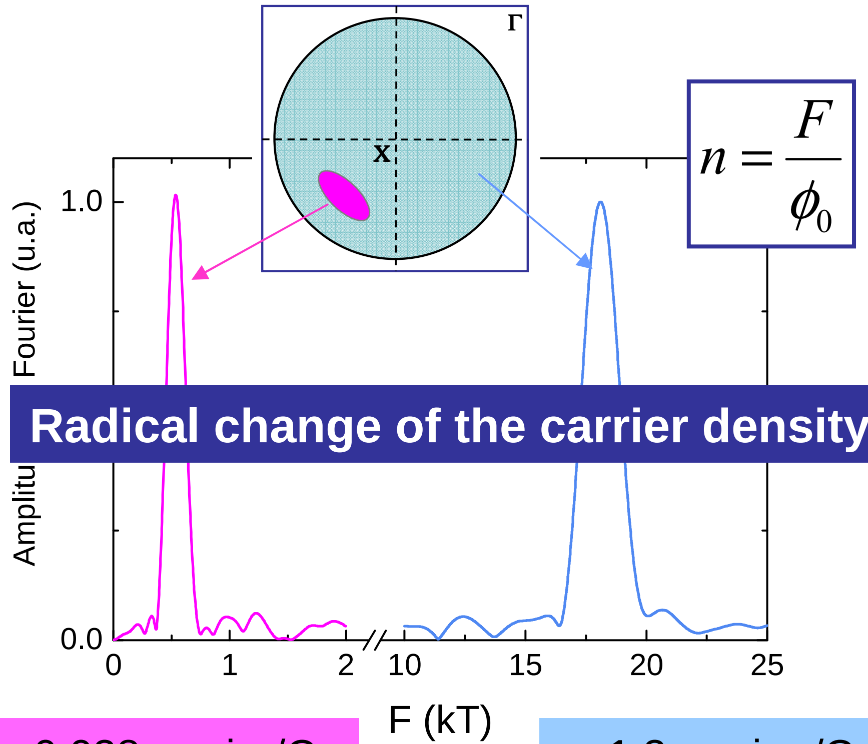
Frequency : F = (530 ± 20) T

A_k = *1.9 % of 1st Brillouin zone*

$Tl_2Ba_2CuO_{6+\delta}$

Frequency : F = (18100 ± 50) T

A_k = *65 % of 1st Brillouin zone*



Radical change of the carrier density

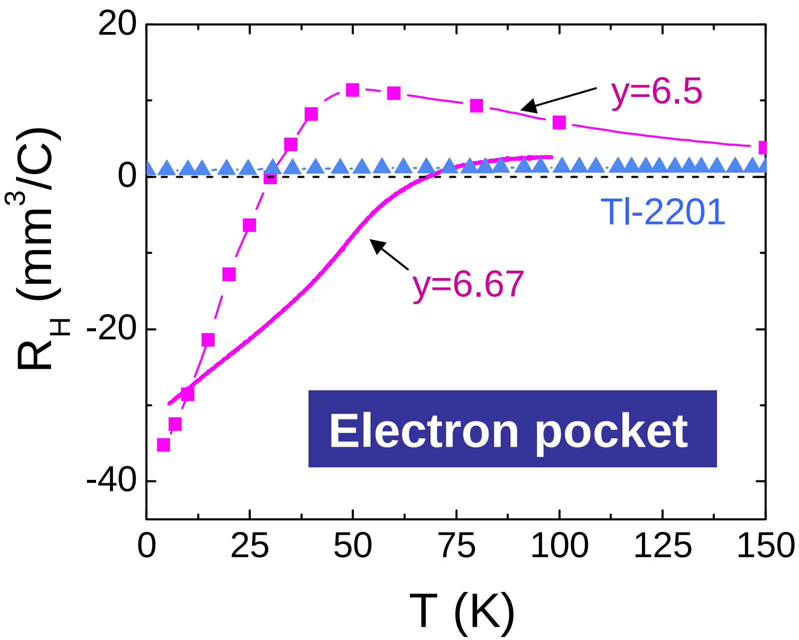
n=0.038 carrier/Cu

n=1.3 carrier /Cu

C. Jaudet et al, Physica B'09

Hall effect

(LeBoeuf et al, Nature'07)



Scenarios for the Fermi surface

Small Pockets

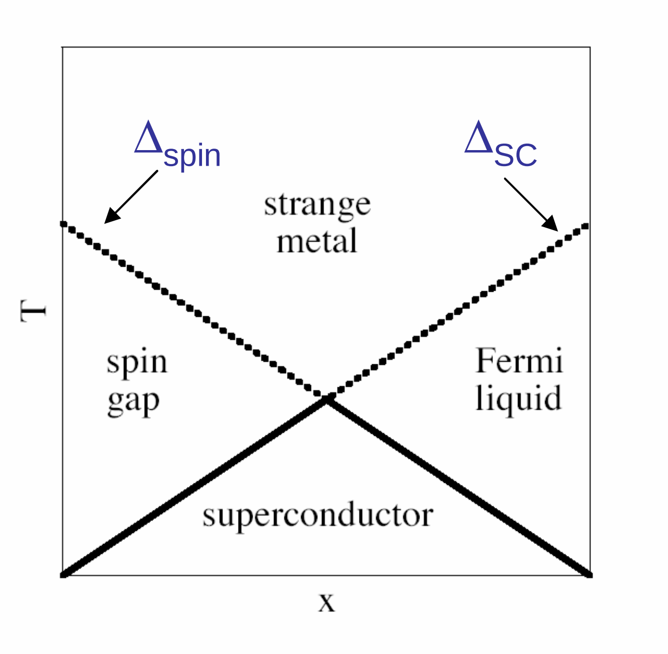
~~LDA~~

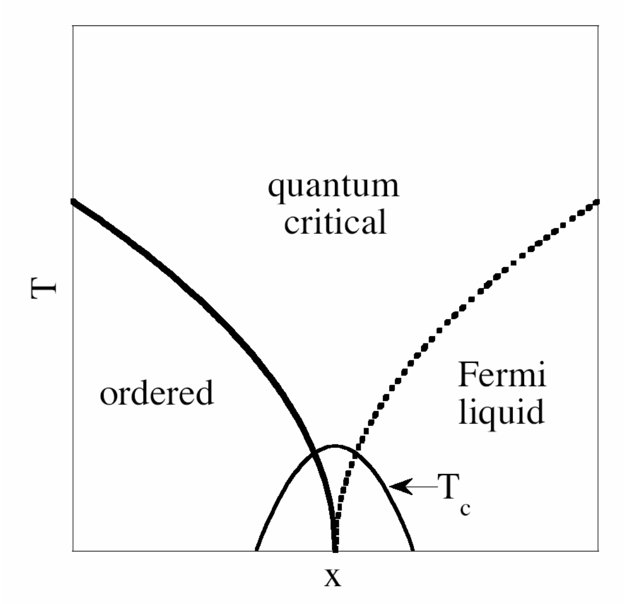
Doped Mott Insulator

Competing order

e.g. 4 nodal hole pockets

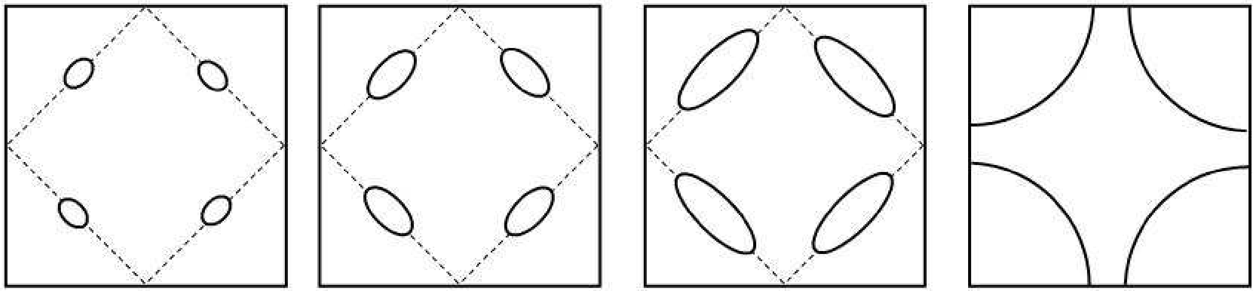
e.g. FS reconstruction



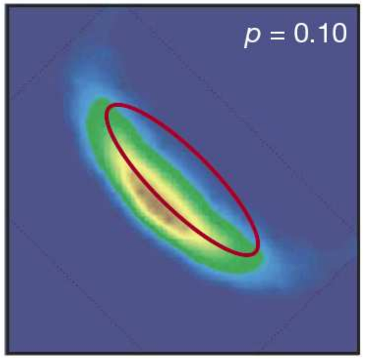


Doped Mott insulator scenario

four-nodal hole pockets e.g. doped Mott insulator



ARPES in Na-CCOC



K. Shen *et al.*, Science (2005)

BUT

- Negative Hall effect (electron like)

- Luttinger theorem for 2D FS:

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

$YBa_2Cu_3O_{6.5}$ *F = 530 T ⇒ 0.15 carriers per planar Cu atom !!! (0.1)*

$YBa_2Cu_4O_8$ *F = 660 T ⇒ n = 0.19 carriers per planar Cu atom !!! (0.14)*

Scenarios for the Fermi surface

Small Pockets

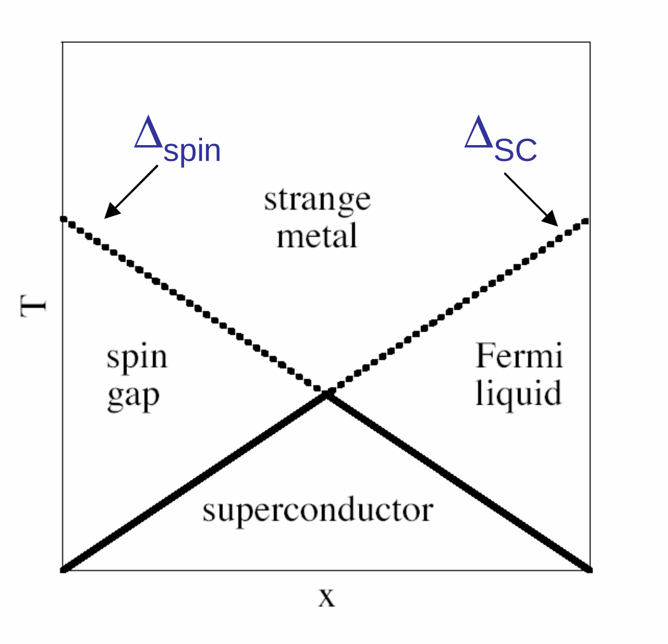
LDA

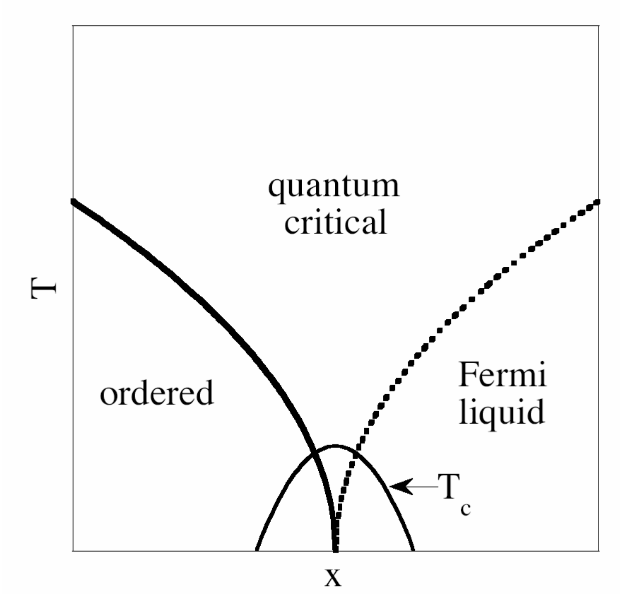
Doped Mott Insulator

e.g. 4 nodal hole pockets

Competing order

e.g. FS reconstruction

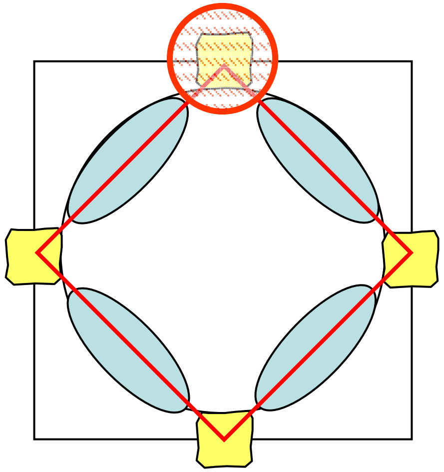




Fermi surface reconstruction

AF / *d*-DW order

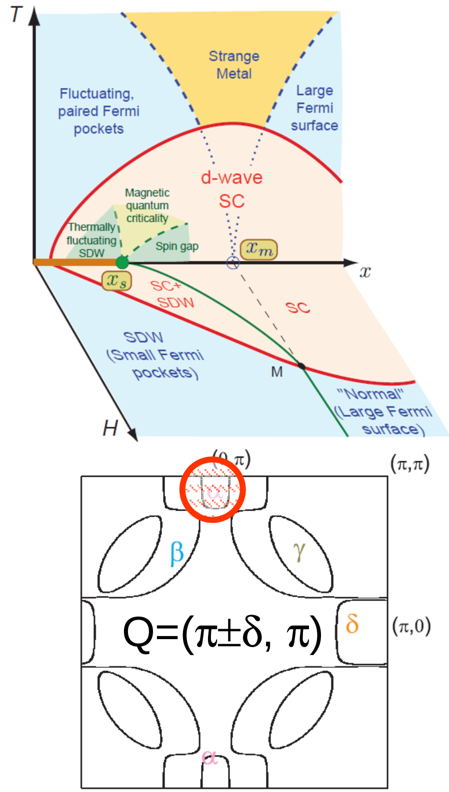
(Rice, Chakravarty)



$Q=(\pi, \pi)$

(Field induced) SDW

(Sachdev, Harrison)

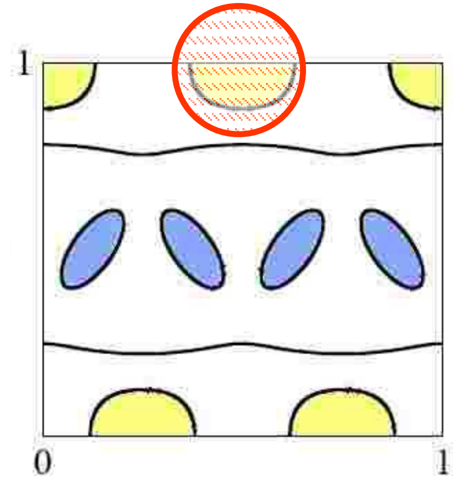


$Q=(\pi\pm\delta, \pi)$

Stripes

(Millis and Norman, Vojta)

CDW / SDW



$Q=(3\pi/4, \pi)$

Fermi surface reconstruction scenarios $\Rightarrow$ electron pocket at the anti-node

Outline

• Introduction to quantum oscillations

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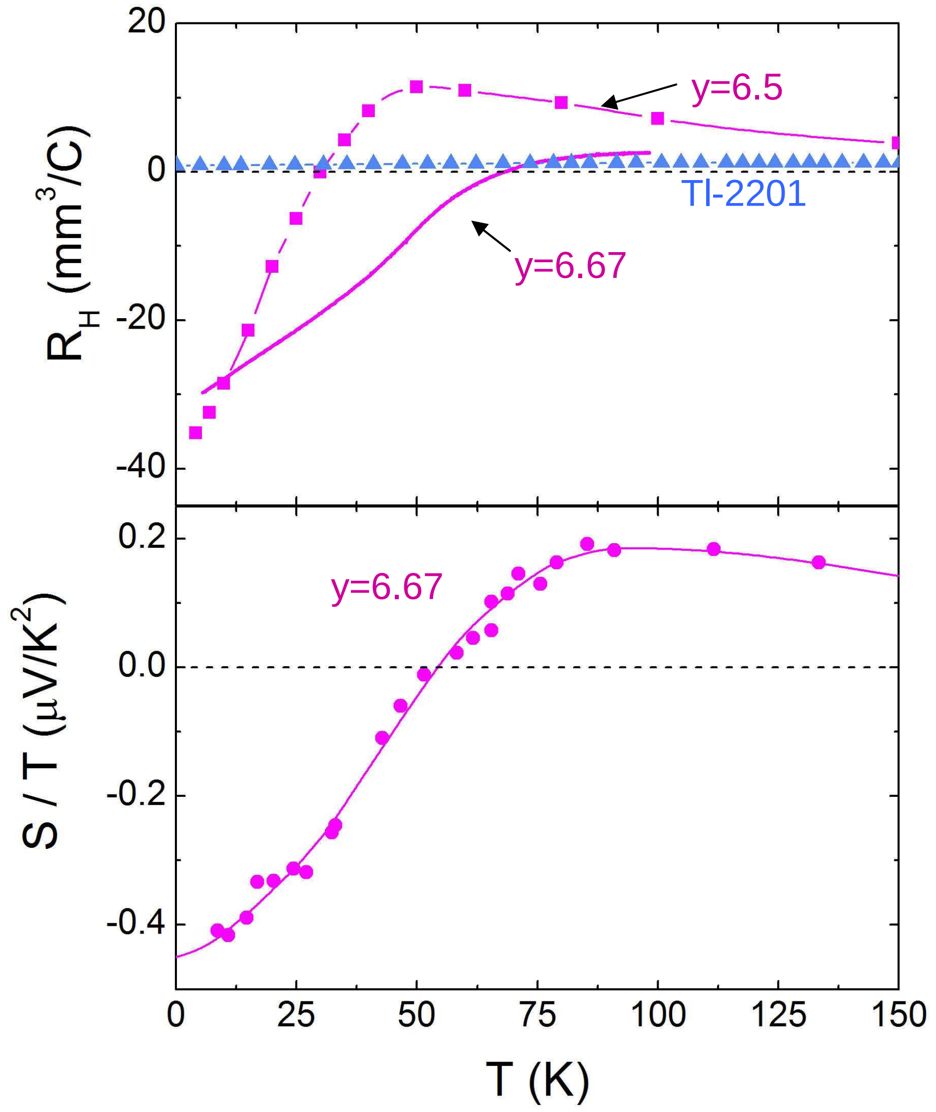
• **The case for an electron pocket**

• Cartography of the electron pocket

•Fermi surface reconstruction scenarios

Hall and Seebeck coefficients



Hall

LeBoeuf et al,
Nature'07

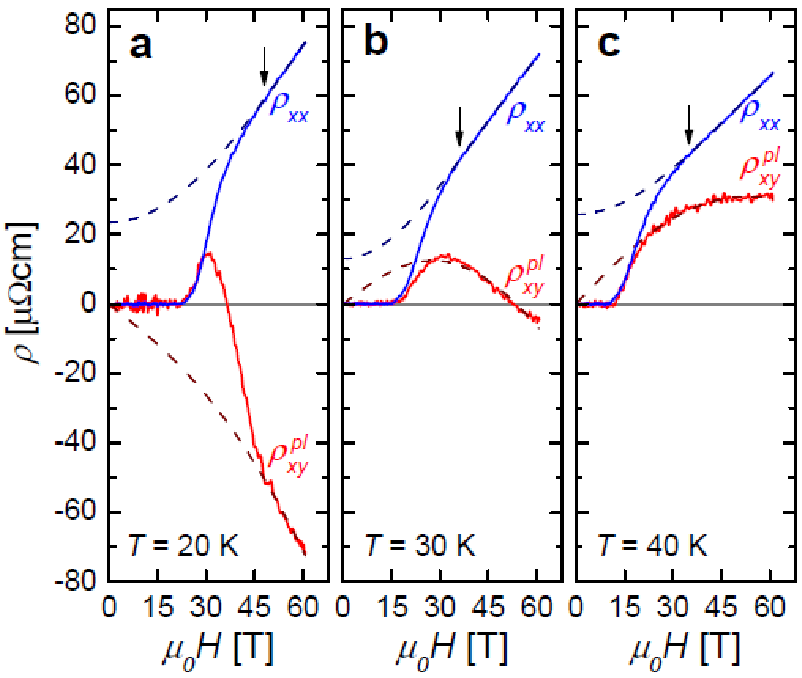
Seebeck

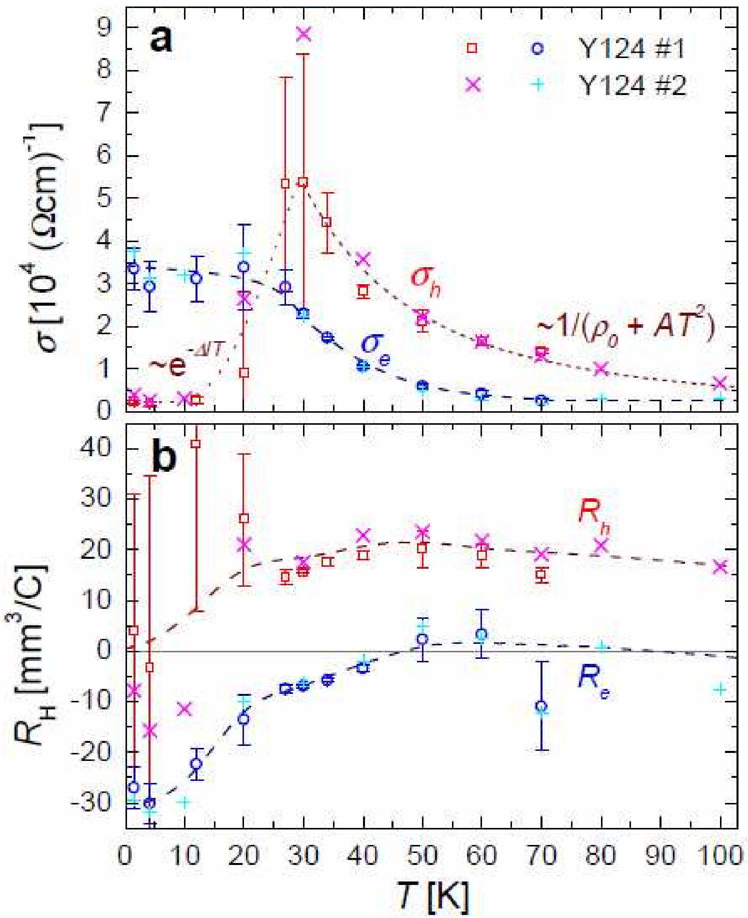
Chang et al,
PRL'10

Two bands model in Y248

$$\rho_{xx}(H) = \frac{(\sigma_h + \sigma_e) + \sigma_h\sigma_e(\sigma_h R_h^2 + \sigma_e R_e^2)H^2}{(\sigma_h + \sigma_e)^2 + \sigma_h^2\sigma_e^2(R_h - R_e)^2 H^2}$$

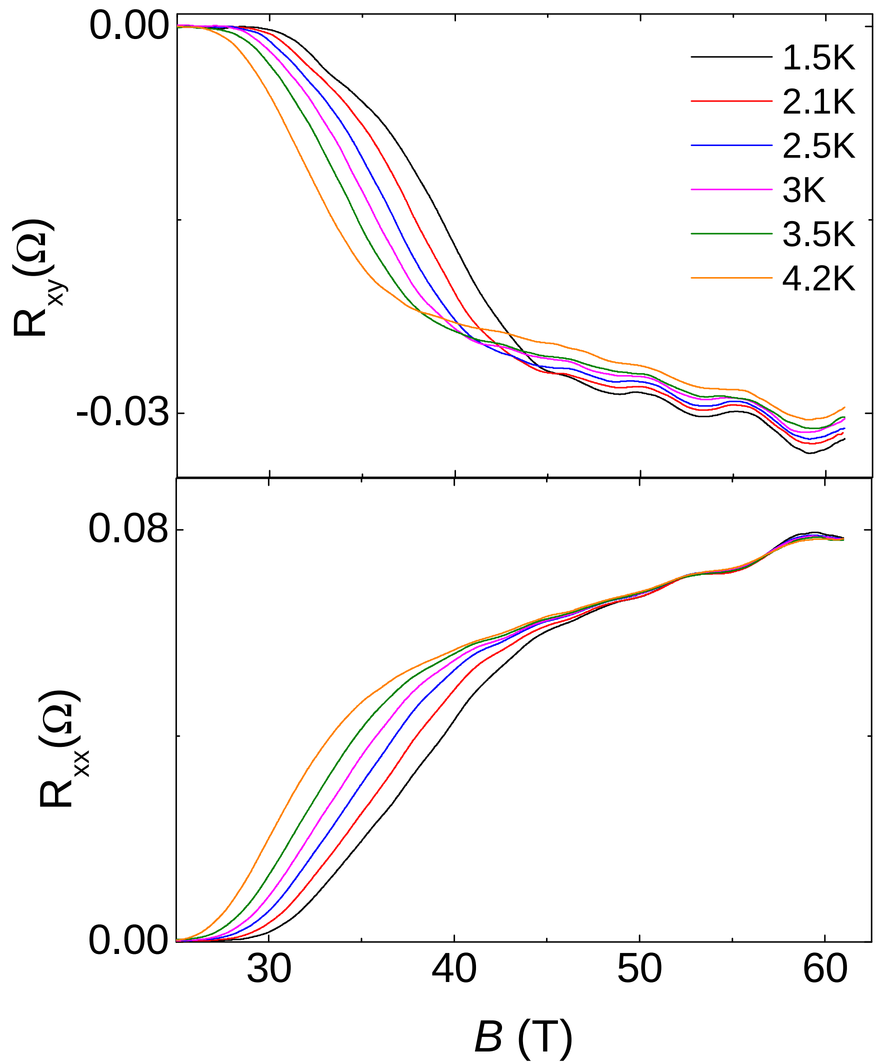
$$\rho_{xy}(H) = \frac{\sigma_h^2 R_h - \sigma_e^2 R_e - \sigma_h^2\sigma_e^2 R_h R_e (R_h - R_e)H^2}{(\sigma_h + \sigma_e)^2 + \sigma_h^2\sigma_e^2(R_h - R_e)^2 H^2} H$$



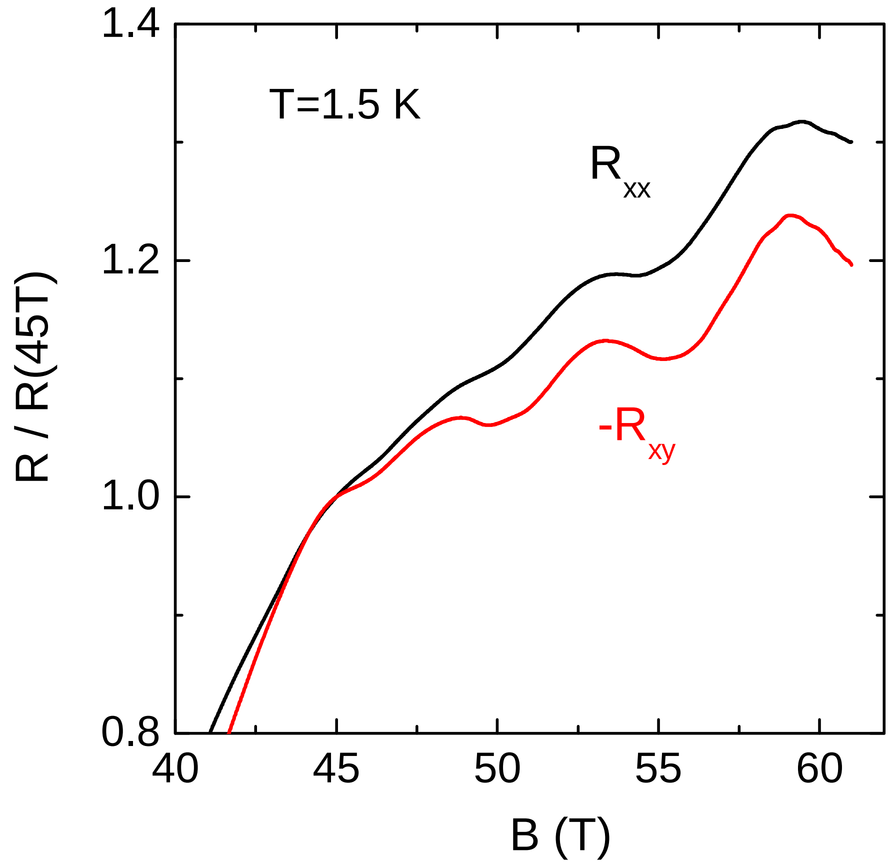


P. Rourke et al, PRB'10

π-shift in Rxx and Rxy



C. Jaudet et al, Physica B'09



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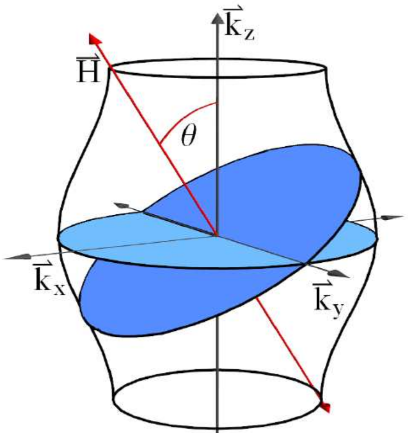
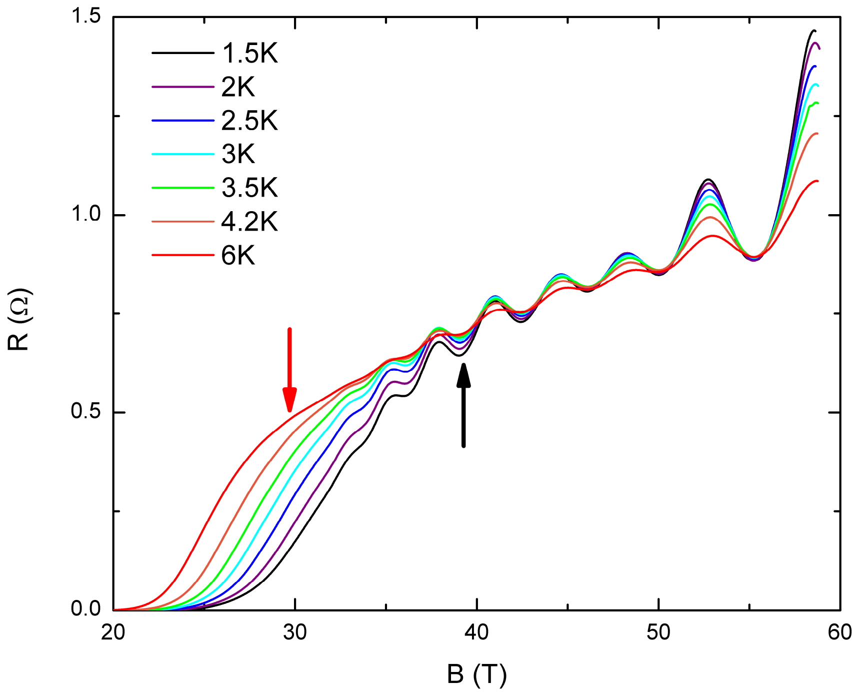
Angle-dependence of QO in $YBa_2Cu_3O_{6.6}$

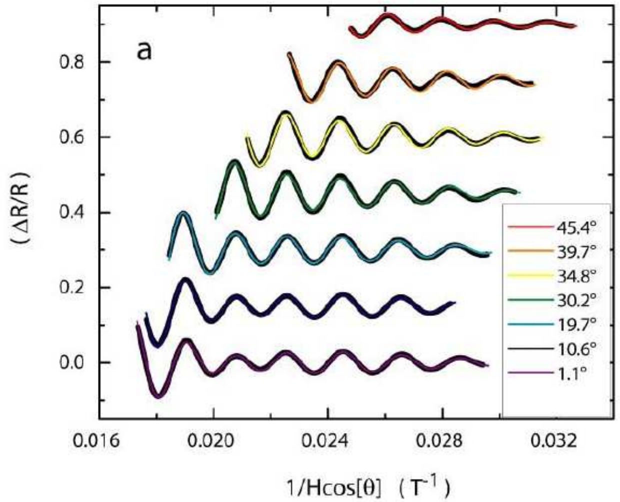


$$\rho_{osc}/\rho_o = AR_T R_D R_s \sin\left(2\pi\left(\frac{F}{H\cos\theta} - \gamma\right)\right) J_0\left(2\pi\frac{\Delta F}{H\cos\theta} J_0\left(k_F c \tan\theta\right)\right)$$

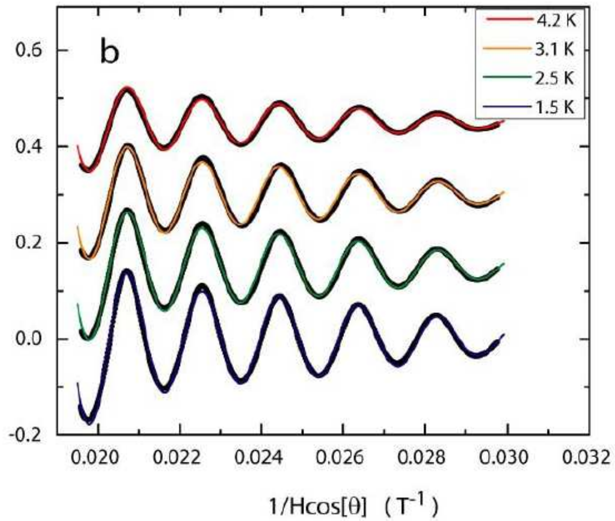
NO F_β frequency !



B. Ramshaw et al, to be published in Nature Physics



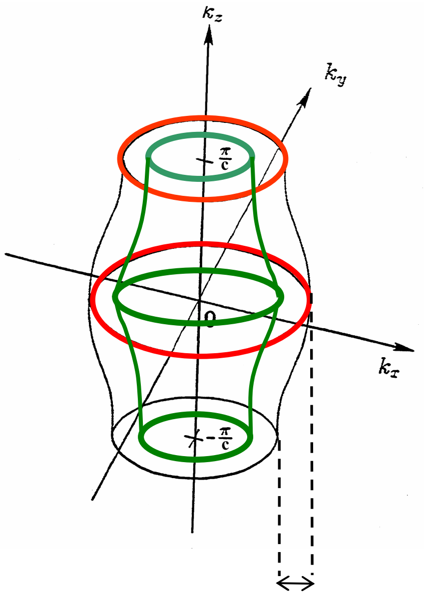
Angle dependence



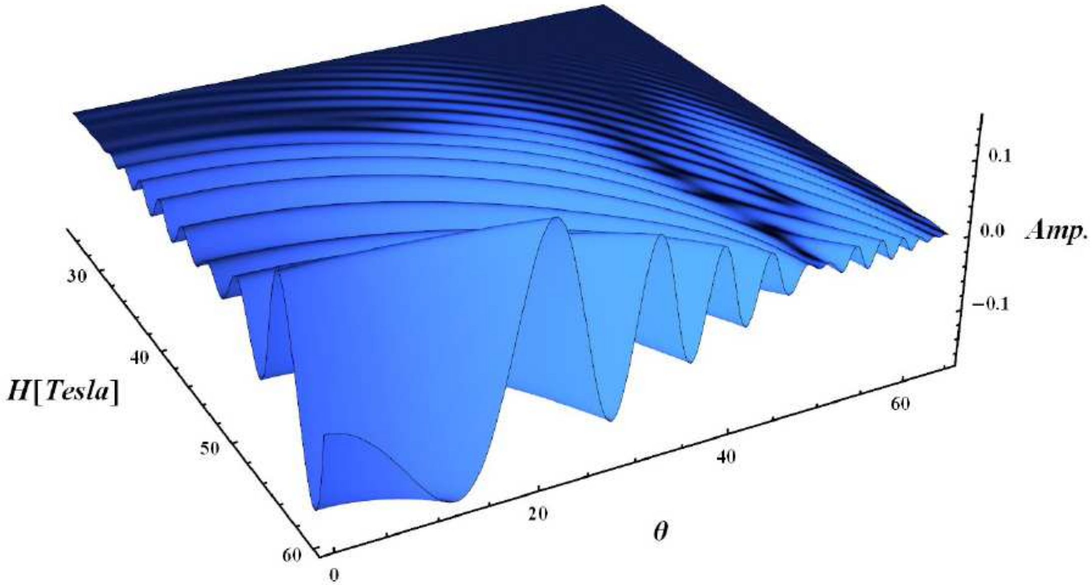
Temperature dependence

Angle-dependence of QO in $YBa_2Cu_3O_{6.6}$

	Surface 1	Surface 2
$F(T)$	478	526
$\Delta F(T)$	37.7	3.5
m^*/m_e	1.5	1.7
gm_s/m_e	2.1	3.2
$T_D(K)$	5.8	6.4
γ	3.5	1.1
A	13	18.5



$$\Delta F = \frac{4m^* t_\perp}{e\hbar}$$



Bilayer splitting + Warping

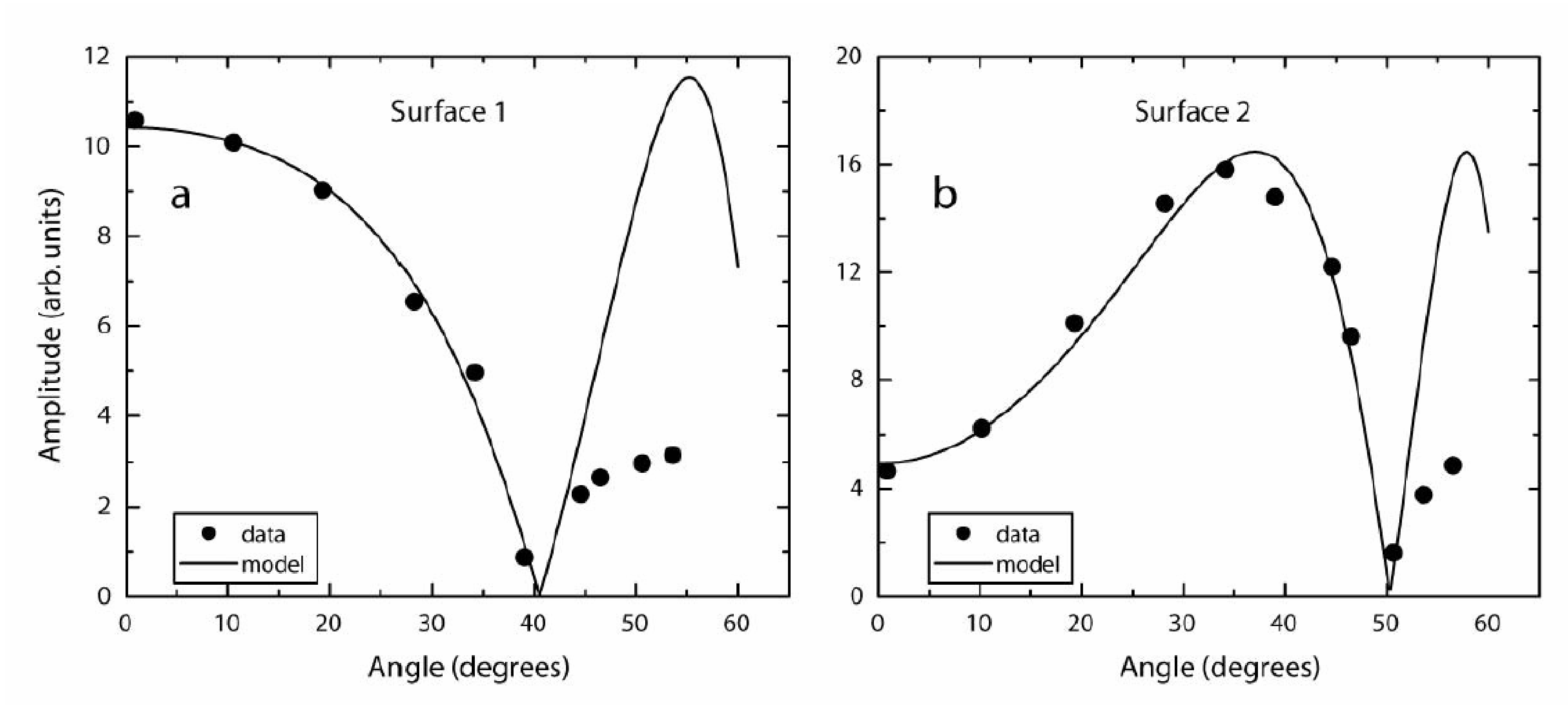
c-axis coherence

ΔF=90 T

⇓

$t_\perp$~1.3 meV (15 K)

Spin zero phenomena



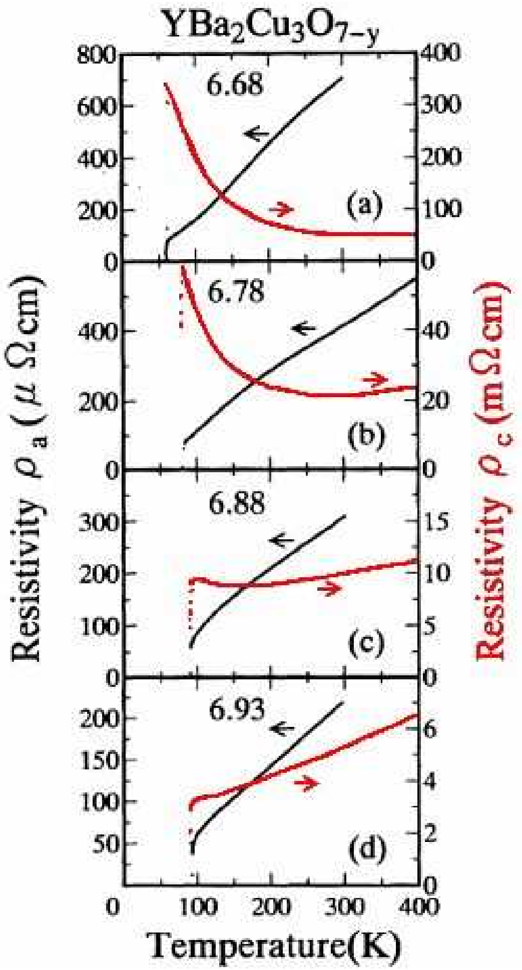
⇒ Staggered moments have a large component along the field direction

Not compatible with a pure AF scenario !

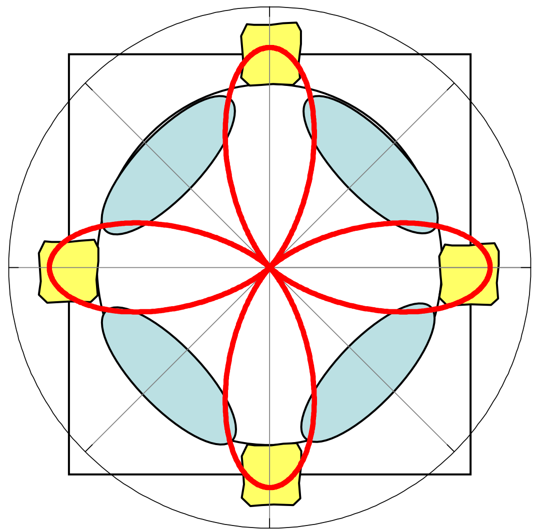
B. Ramshaw et al, to be published in Nature Physics

Location of the electron pocket

c-axis Resistivity in YBCO



K. Takenaka et al, PRB'94

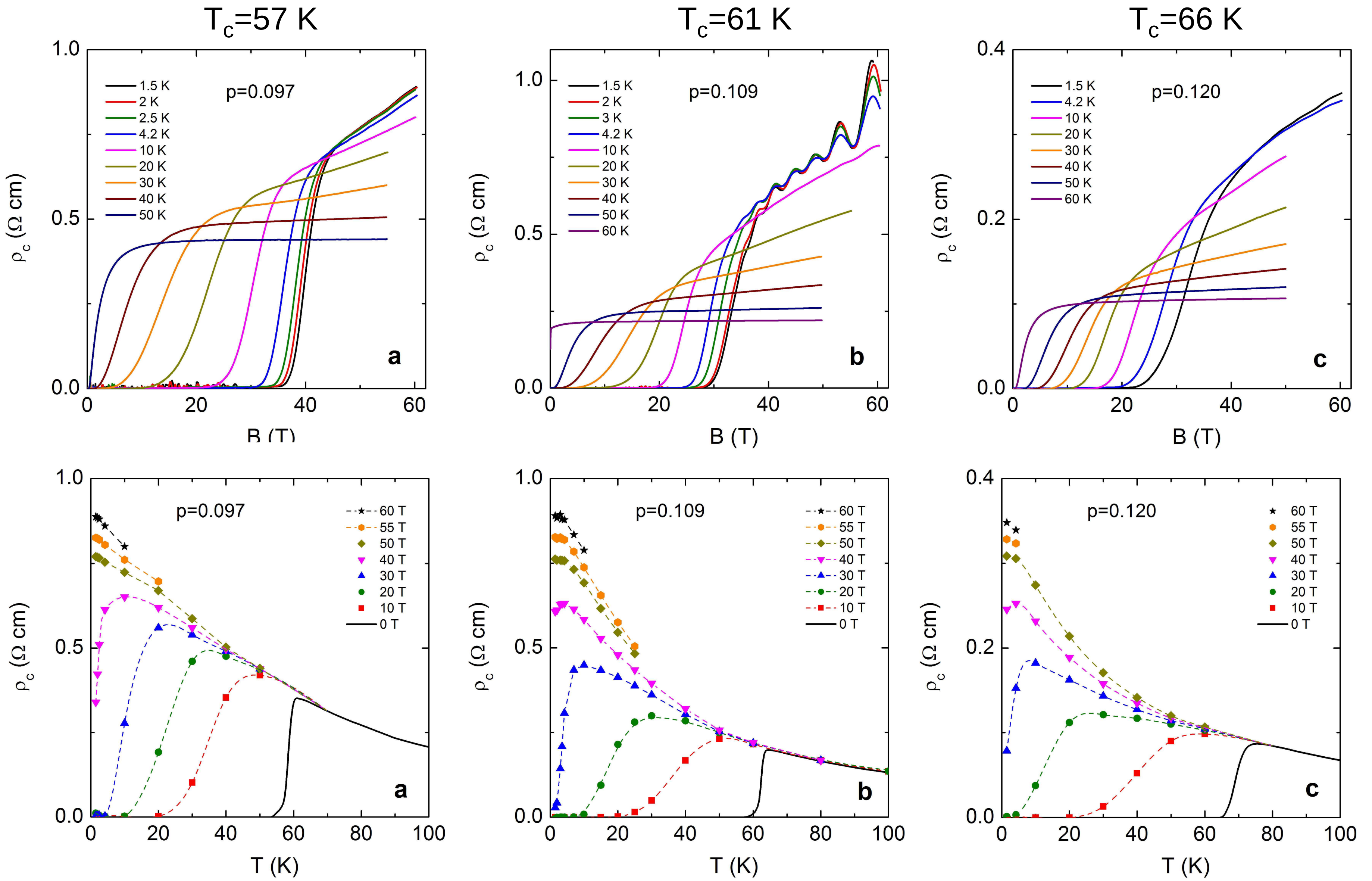


$$t_\perp(k) = \frac{t_\perp}{4}\left[\cos(k_x a) - \cos(k_y a)\right]^2$$

$$\sigma_c = \frac{4e^2 c t_\perp^2 m^* \tau_c}{\pi \hbar^4}$$

<u>Scenario</u>: Charge confinement in the CuO_2 plane ($\rho_c \to \infty$ as $T \to 0$) ?

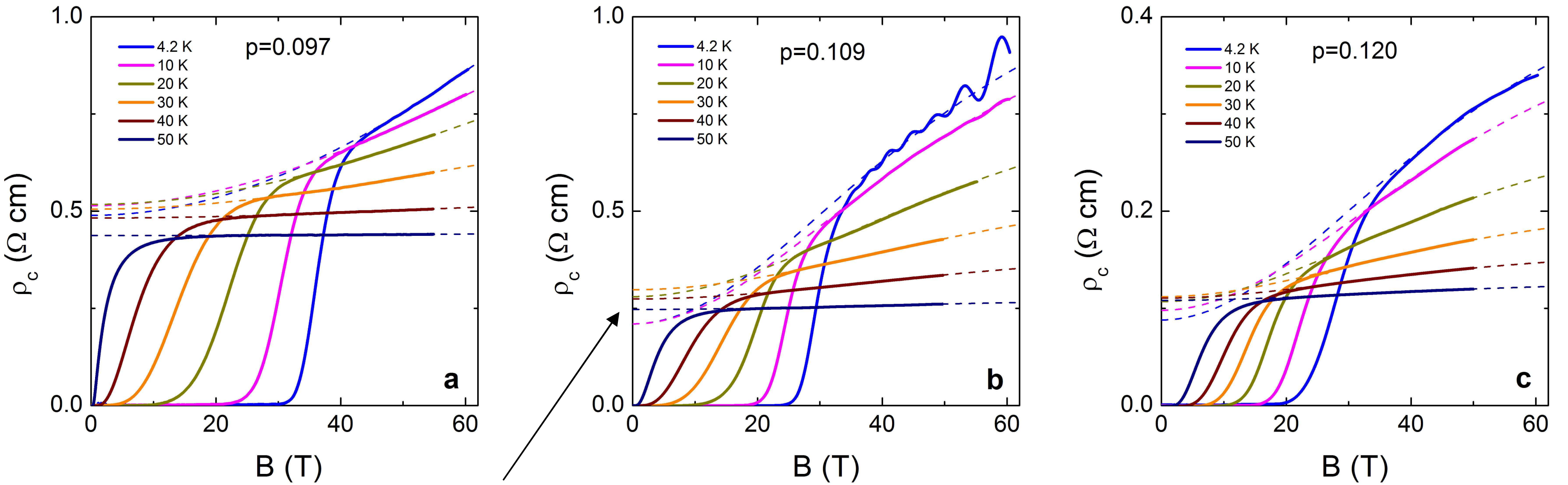
c-axis magnetoresistance in UD YBCO



B. Vignolle et al, unpublished

Extrapolation of the magnetoresistance

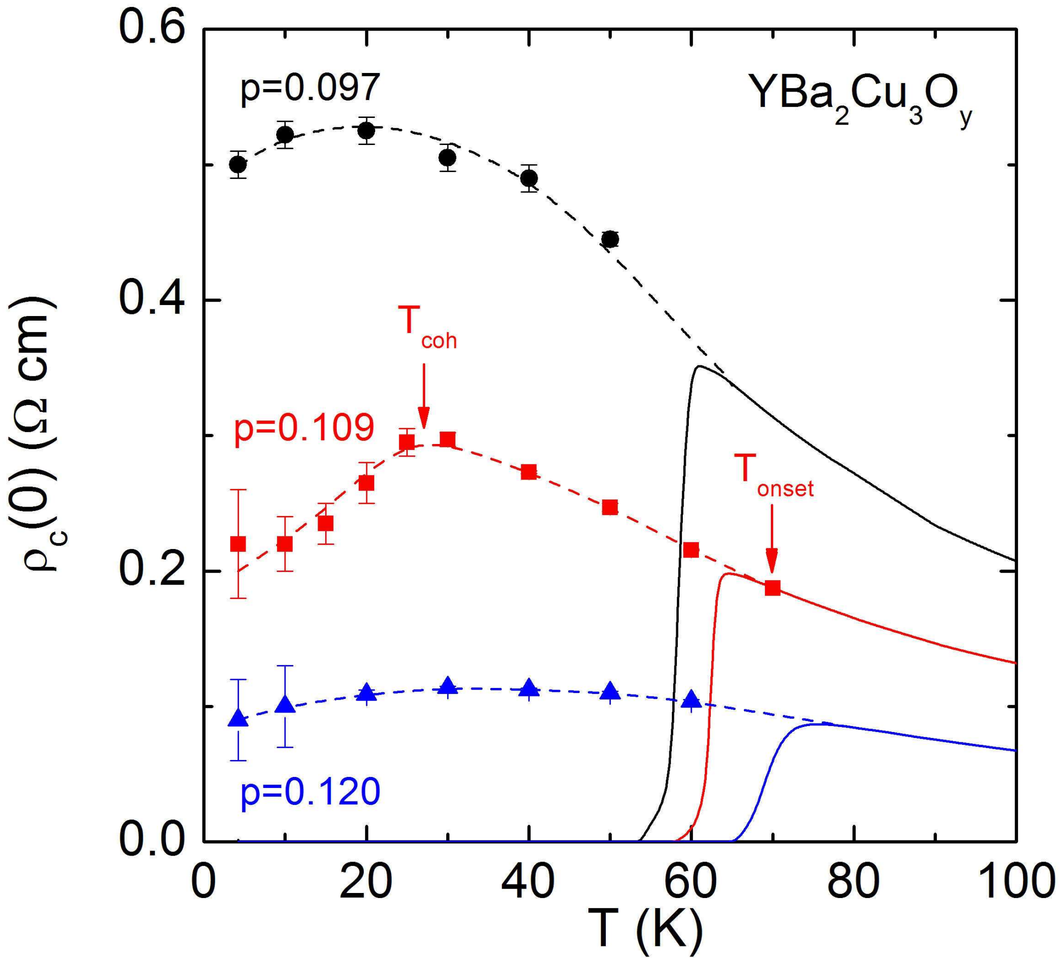
Two-band model: $$\rho(B) = \frac{(\mu_h + \mu_e) + \mu_h \mu_e (\mu_h R_h^2 + \mu_e R_e^2) B^2}{(\mu_h + \mu_e)^2 + \mu_h^2 \mu_e^2 (R_h + R_e)^2 B^2} = \rho_0 + \frac{\alpha B^2}{1 + \beta B^2}$$



$\rho_c(0)$: extrapolated zero-field resistivity

B. Vignolle et al, unpublished

Temperature dependence of $\rho_c(0)$



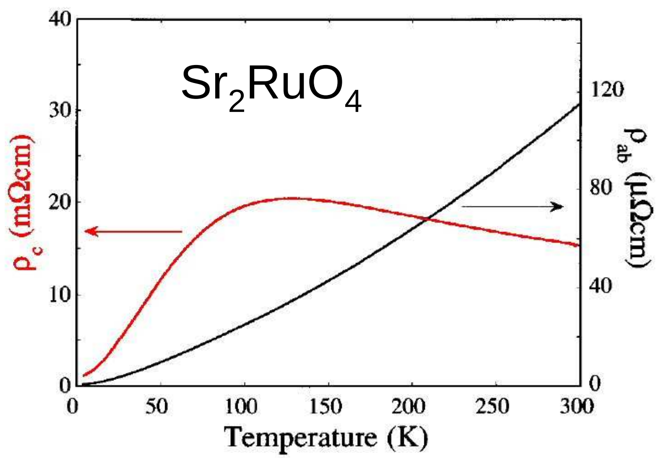
3D Fermi Surface in underdoped YBCO!

Cross-over:

Incoherence → Coherence

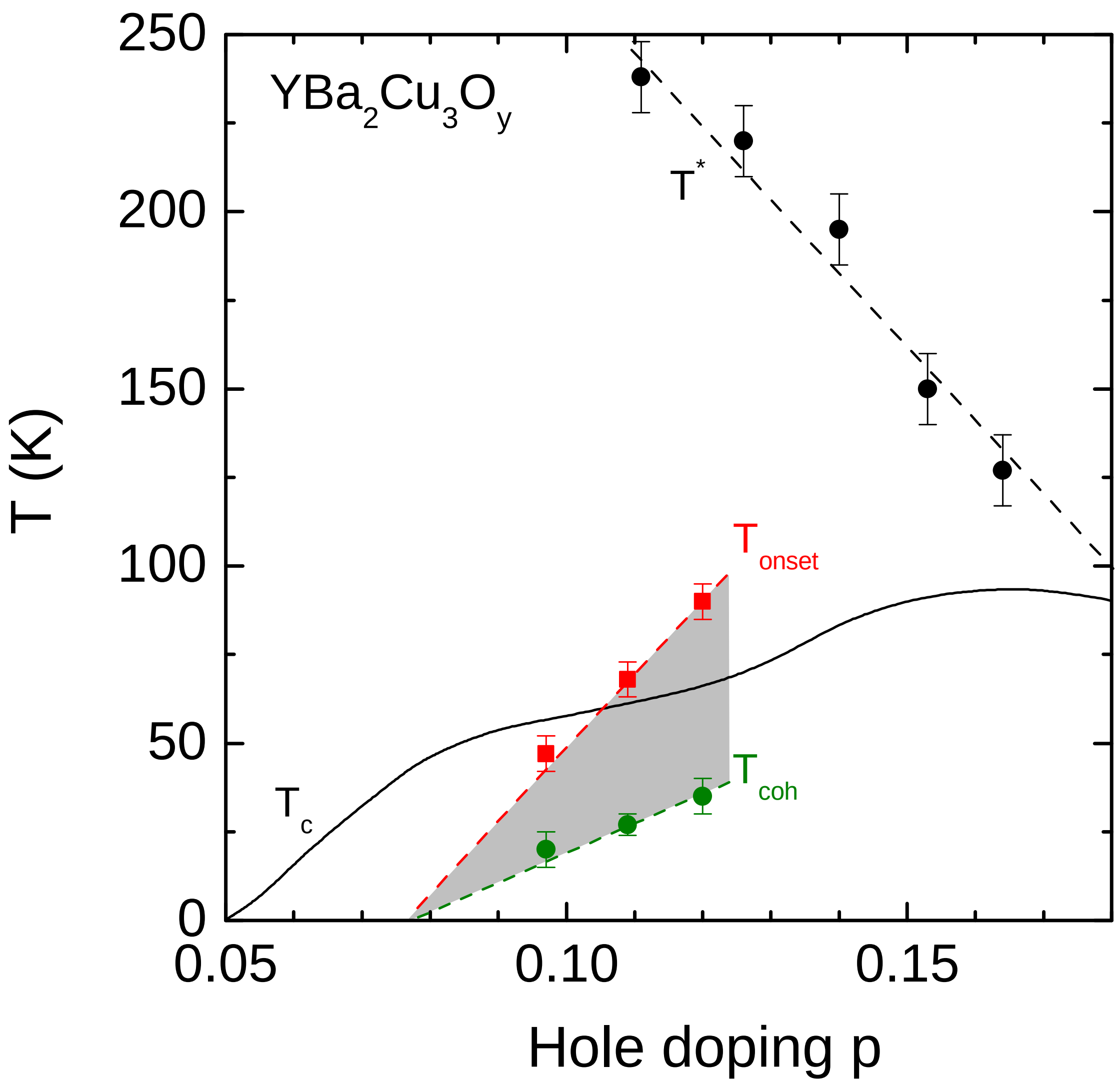
$T_{coh}=27 \pm 5$ K for p=0.109

Good agreement with
$t_\perp$~15 K from QO



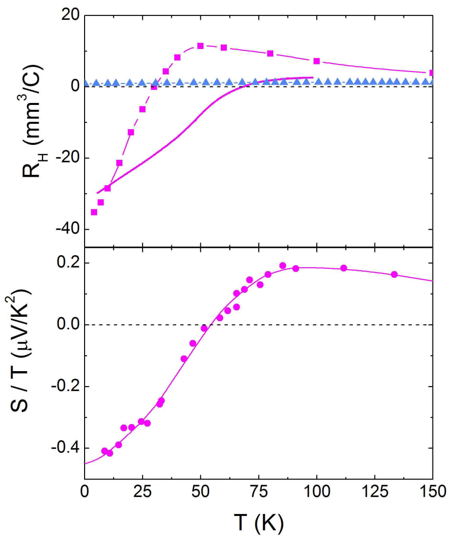
B. Vignolle et al, unpublished

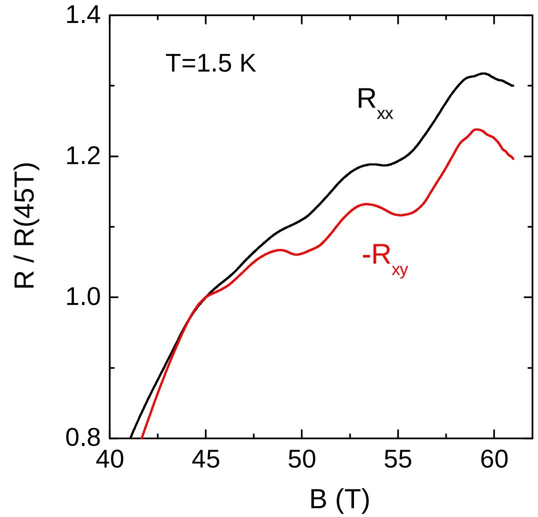
Phase diagram

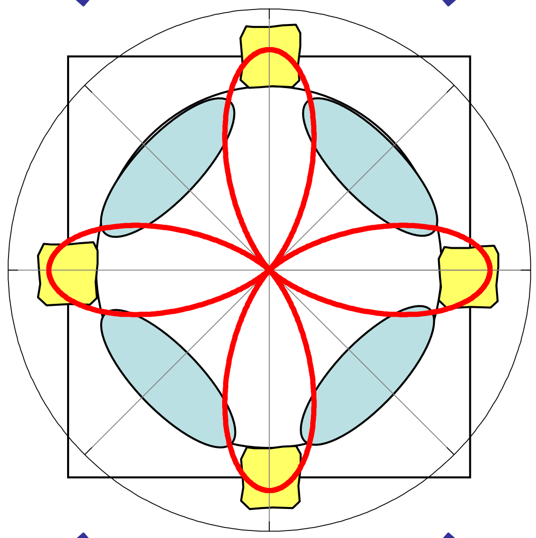


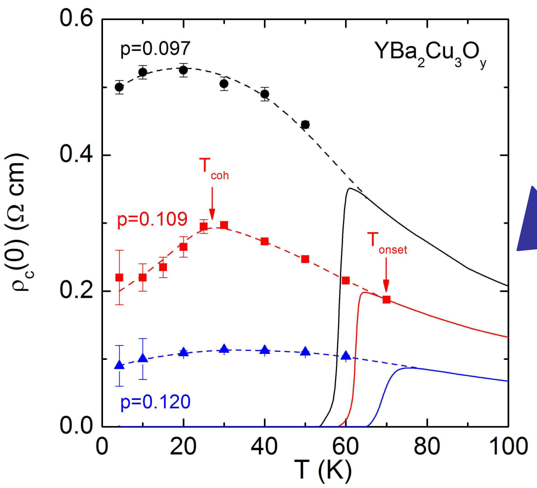
B. Vignolle et al, unpublished

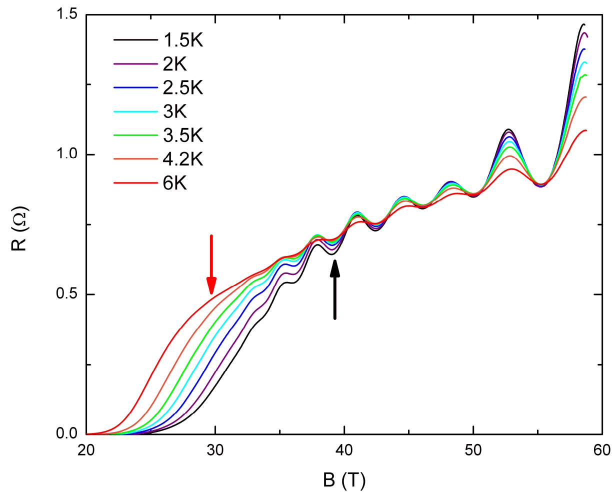
Electron pocket at the anti-node





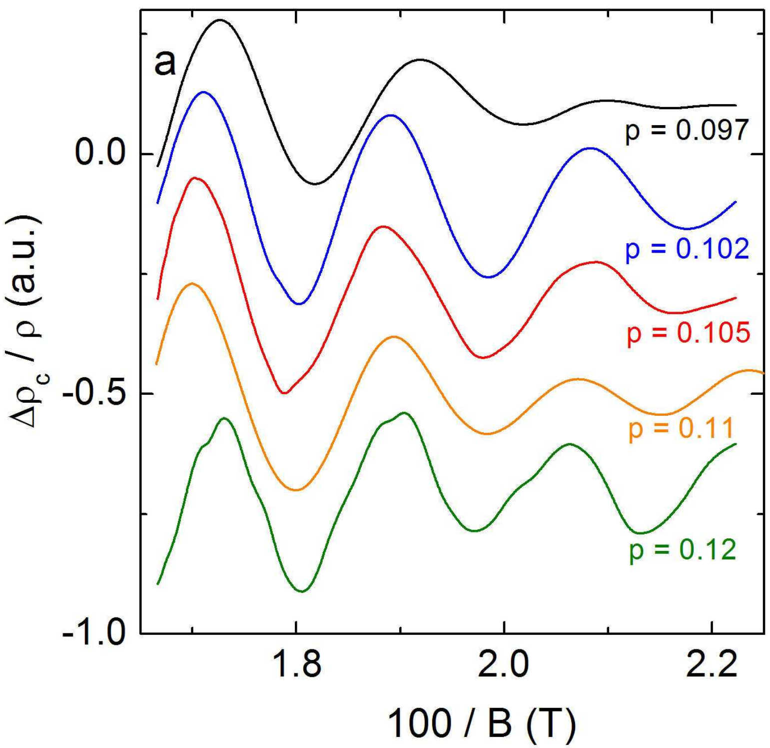


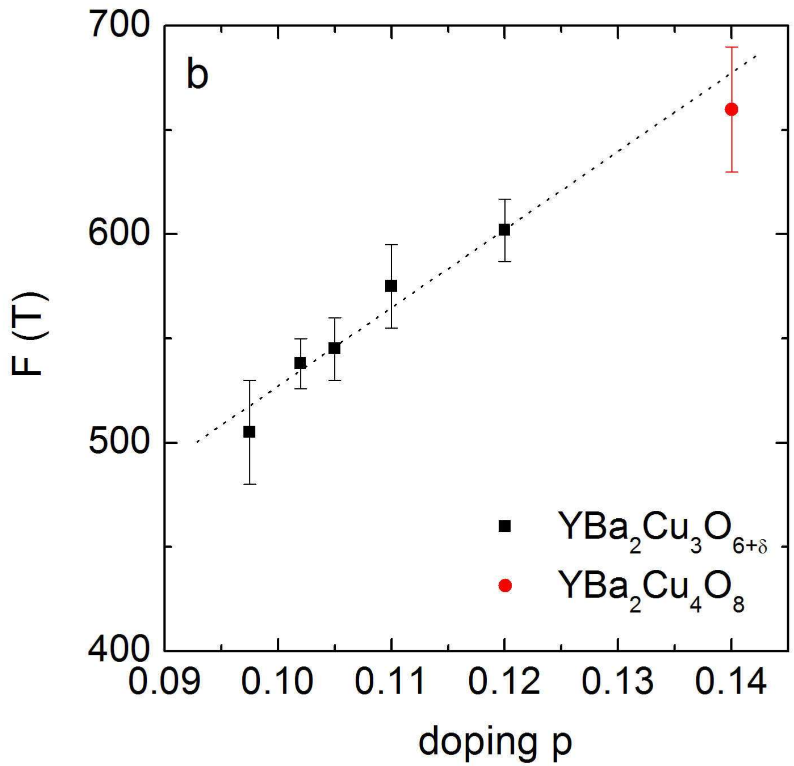




Doping dependence of QO

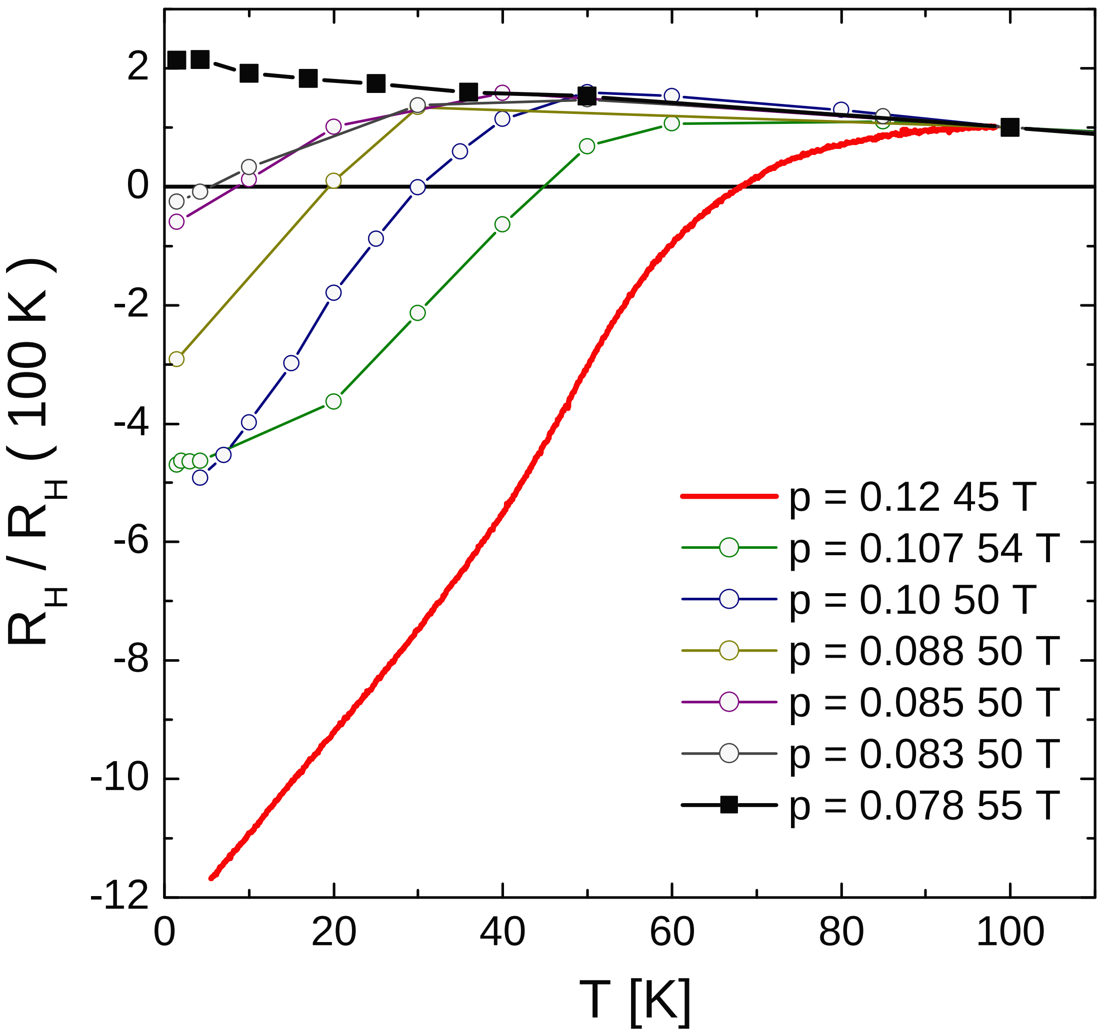
c-axis magnetoresistance in underdoped $YBa_2Cu_3O_y$





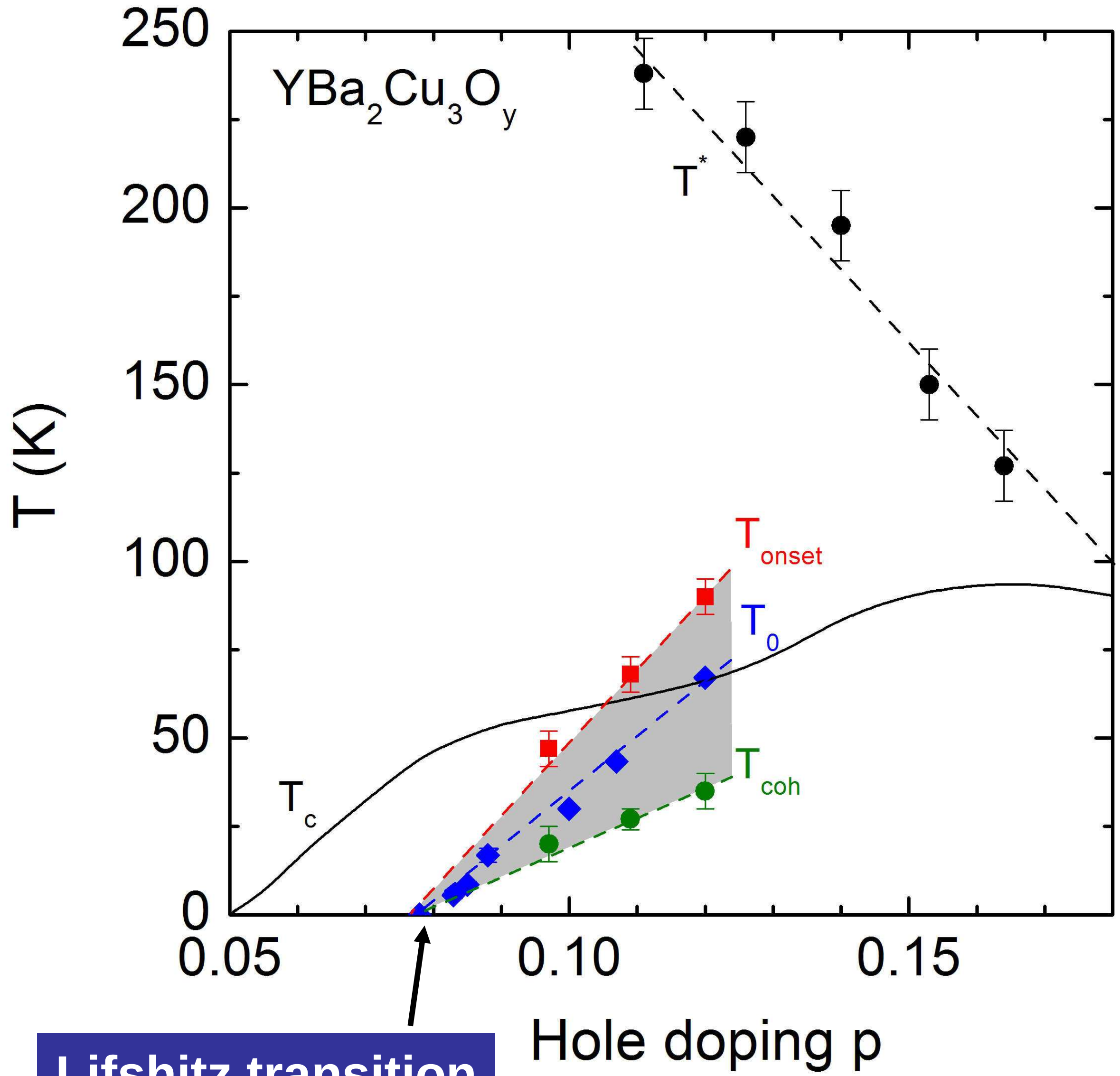
Doping dependence of the Hall effect

No sign change below p~0.08



D. LeBoeuf et al, arXiv: 1009.2078

Phase diagram



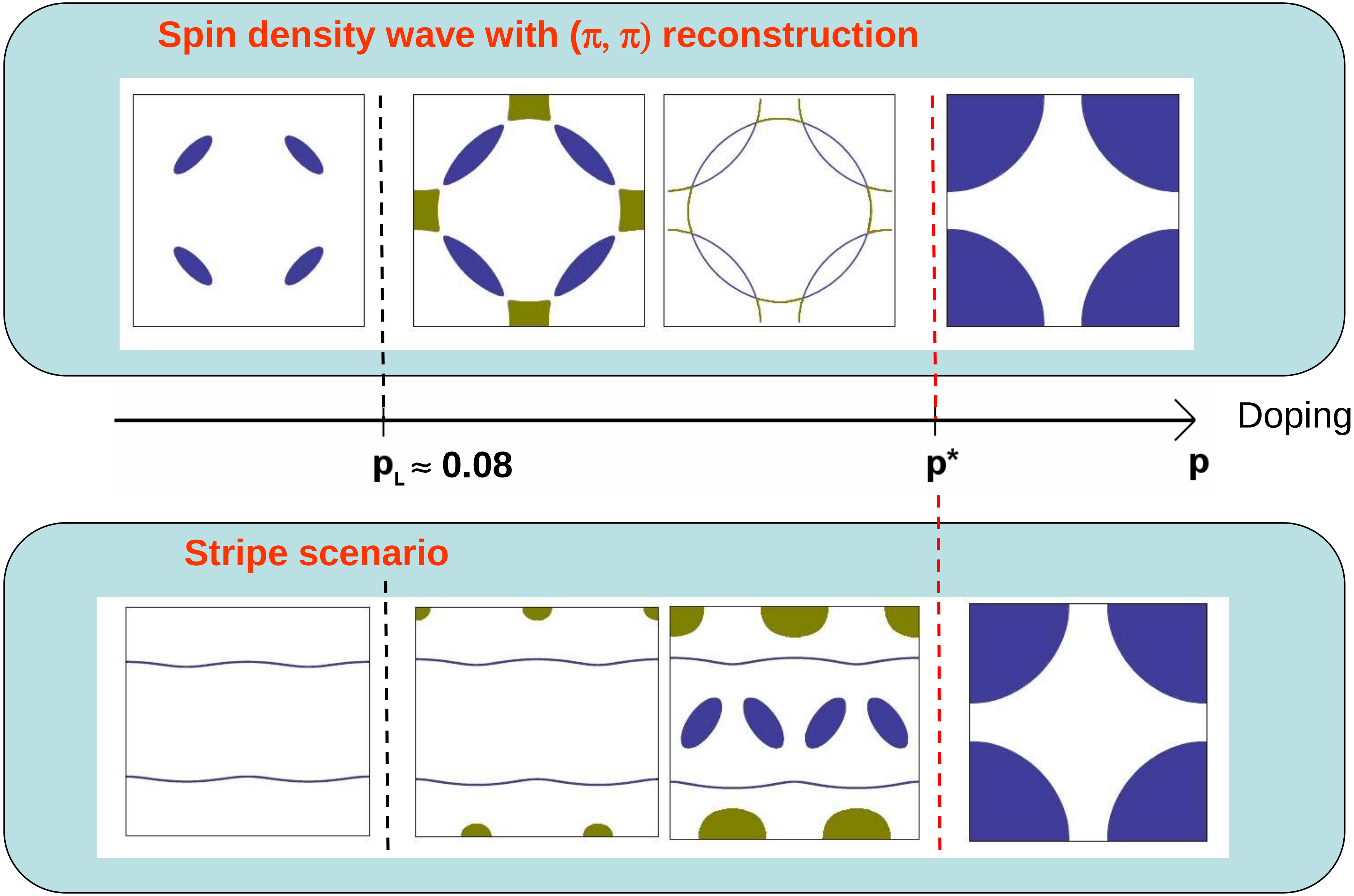
Lifshitz transition

B. Vignolle et al, unpublished

Outline

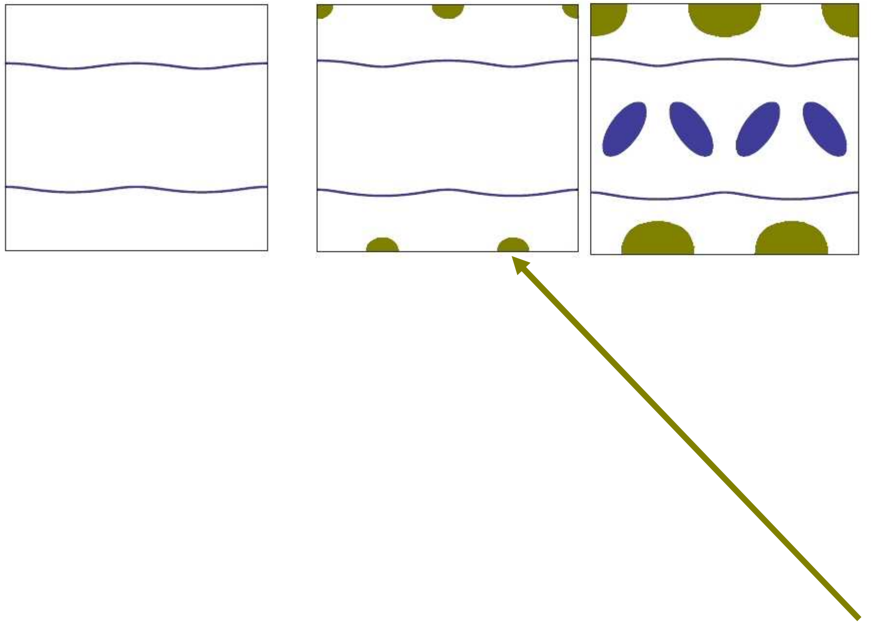
- Introduction to quantum oscillations
- Quantum oscillations on both sides of the phase diagram
- The case for an electron pocket
- Cartography of the electron pocket
- **Fermi surface reconstruction scenarios**

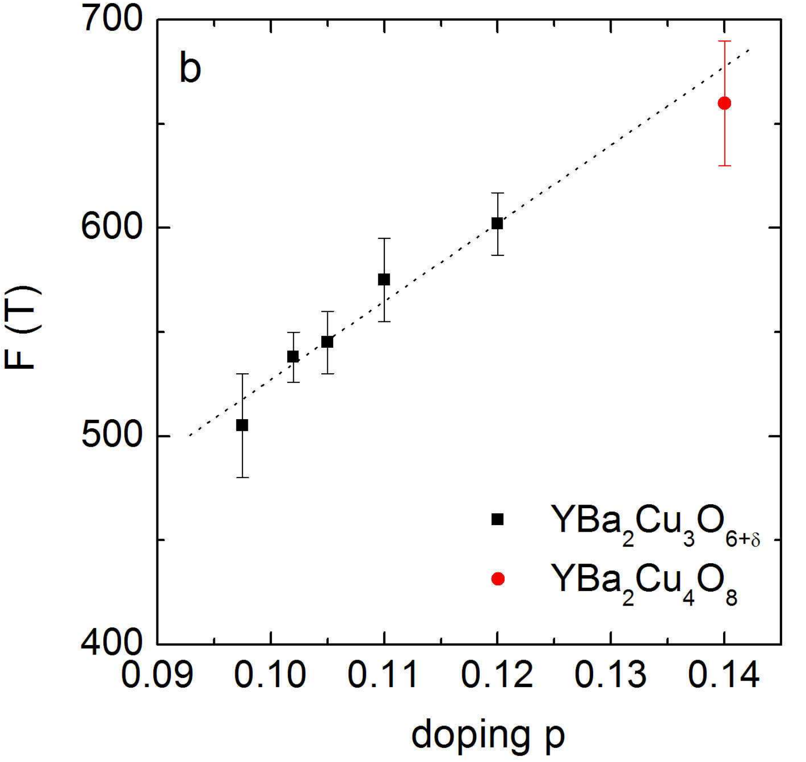
Lifshitz transition



Only one QO frequency

Stripe scenario

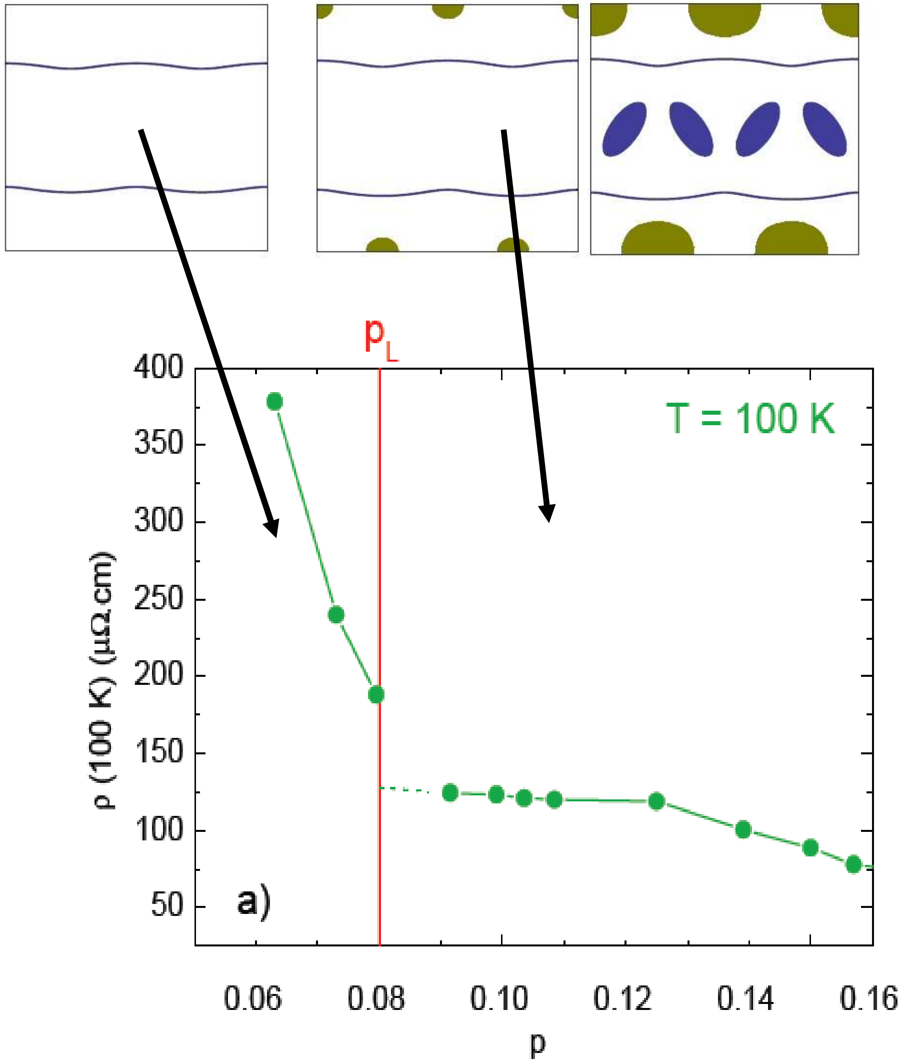




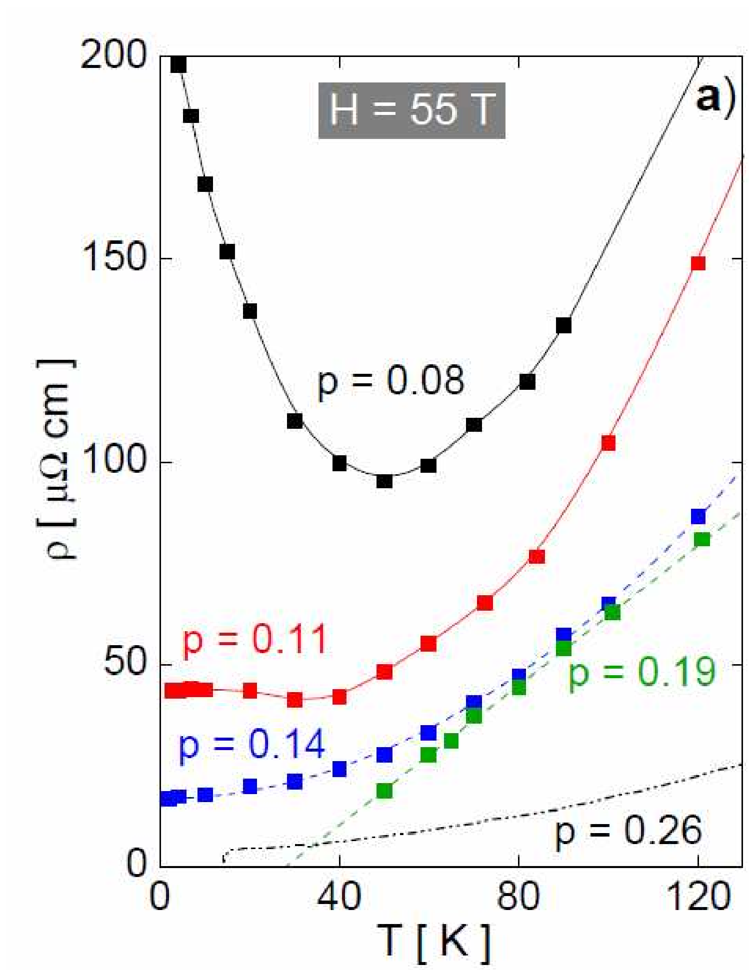
Metal-insulator cross-over

Stripe scenario

In-plane resistivity

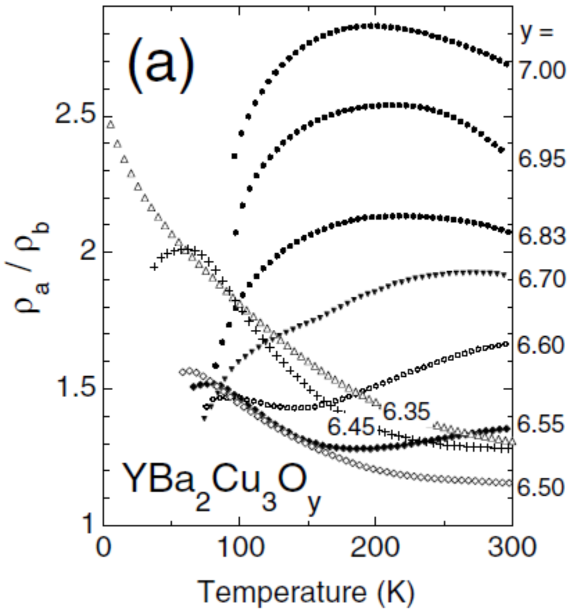


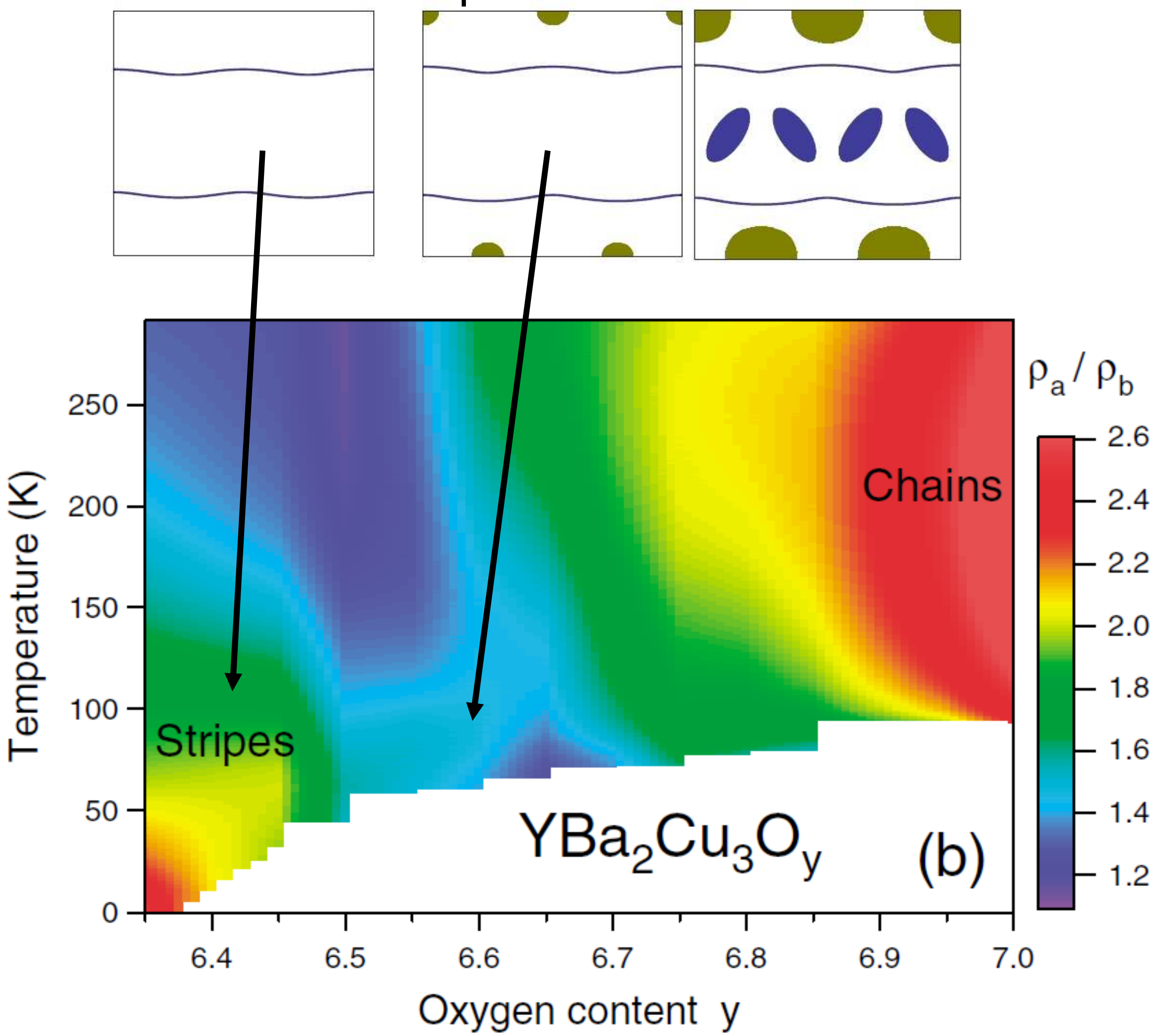
From Y. Ando et al, PRL’04



D. LeBoeuf et al, arXiv: 1009.2078

In-plane anisotropy





Y. Ando et al, PRL'02

Conclusion

✓ Evidence of closed and coherent FS in UD YBCO and OD Tl-2201

✓ Small pockets vs large orbit
Evidence of electron pocket

⇓

Reconstruction of the FS

✓ If pseudogap causes reconstruction ⇒ results in overdoped Tl2201 argue for a QCP hidden by the SC dome

✓ Restoration of the coherence along *c*-axis at low T in underdoped YBCO

3D Fermi surface
Fermi liquid behavior