The remarkable underlying ground states of cuprates

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LNCMI

http://www.emfl.eu

French high field facility

GRENOBLE

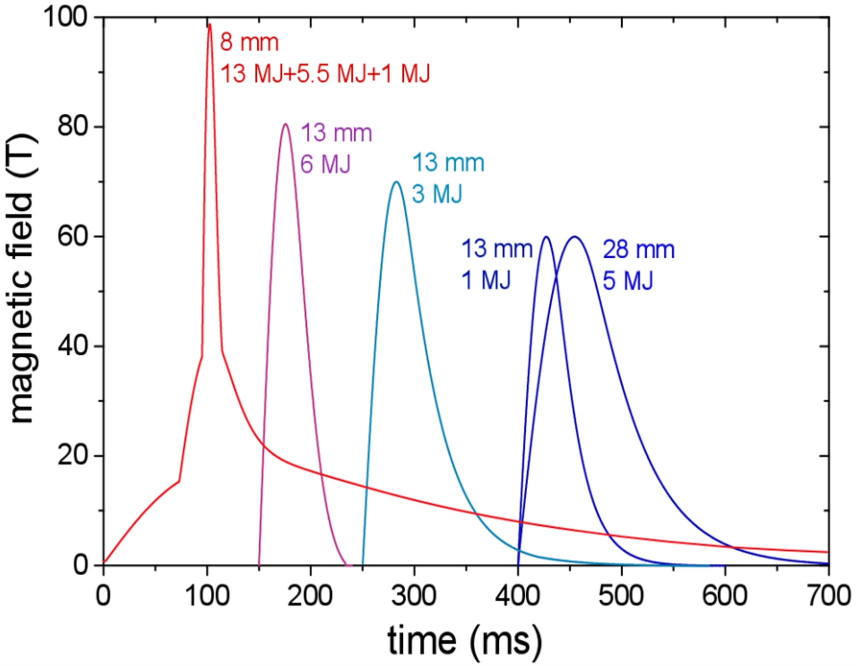
Steady fields up to 37 T

Hybrid project (2020)

34 T (R) + 9 T (SC) = 43 T

TOULOUSE

Pulsed fields up to 98.8 T



Collaborations

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Outline

- Unconventional superconductivity:
  the case of electron-doped cuprates

- Hole-doped cuprates
  - ✓ Fermi liquid phase
  - ✓ Strange metal and Planckian dissipation
  - ✓ Pseudogap phase:
    Charge Density Wave
    Quantum critical point?

C. Proust & L. Taillefer, *Annual Review of Condensed Matter Physics* **10**, 409 (2019)

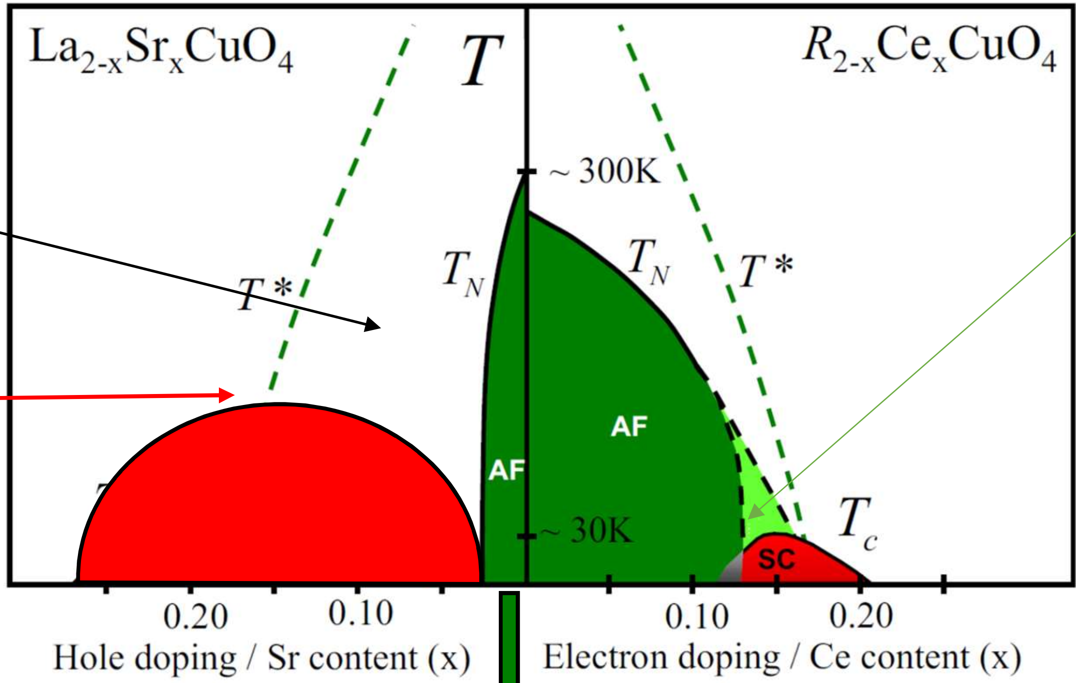
Phase diagram

Adapted from Armitage *et al*, *Rev. Mod. Phys.* **82** 2321 (2010)

Pseudogap

$YBa_2Cu_3O_y$

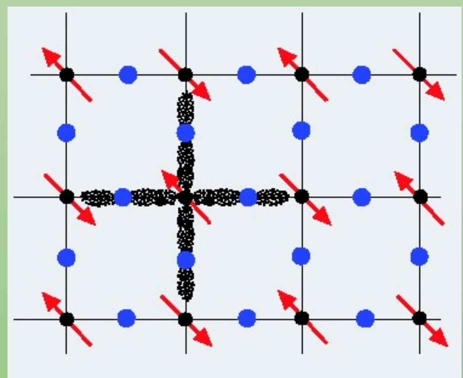
$T_c^{max} \approx 94$ K



Strong AF spin correlation

Mott insulator

½ filling
strong e-e repulsion
U >> *t*
AF ground state

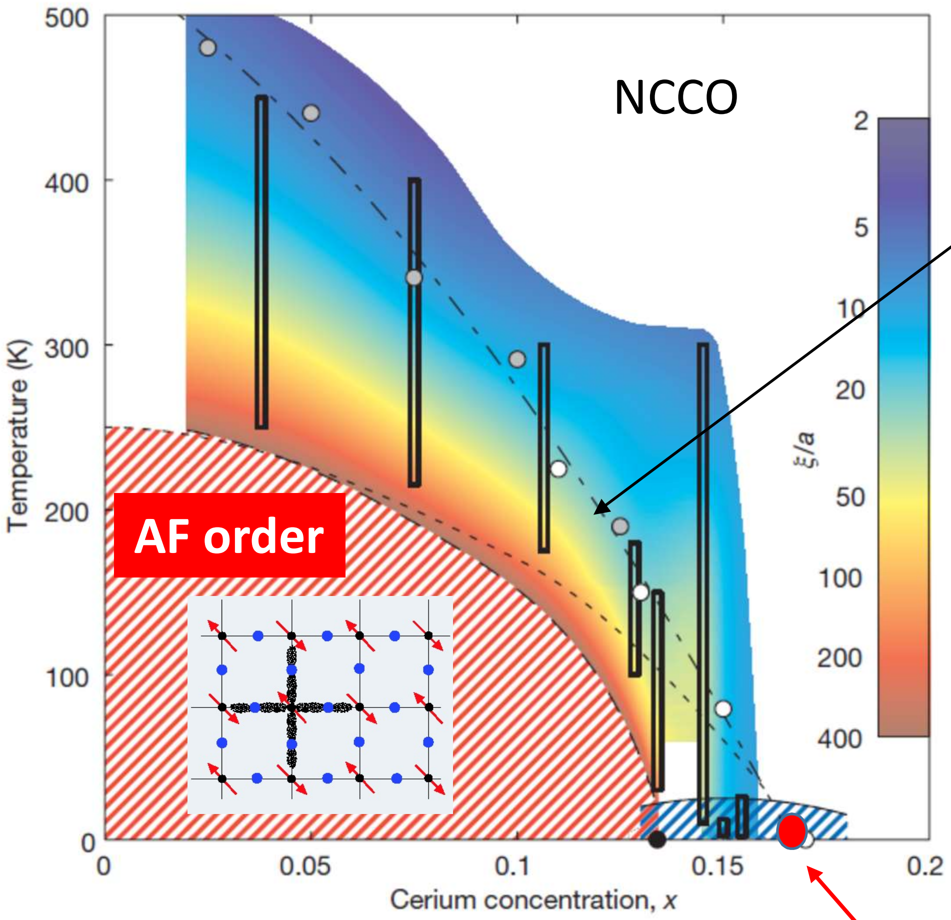


Hubbard Model

$$H = \sum_{\langle i,j \rangle, \sigma} t_{ij} c_{i\sigma}^{+} c_{i\sigma} + U\, n_{i\uparrow} n_{i\downarrow}$$

***U* (hole) > *U* (electron)**

Electron-doped cuprates



AF fluctuations

De Broglie: $\xi_{th} = \frac{\hbar v_F}{k_B T}$

If $\xi_{AF} \geq \xi_{th}$

Electron are sensitive to the AF order

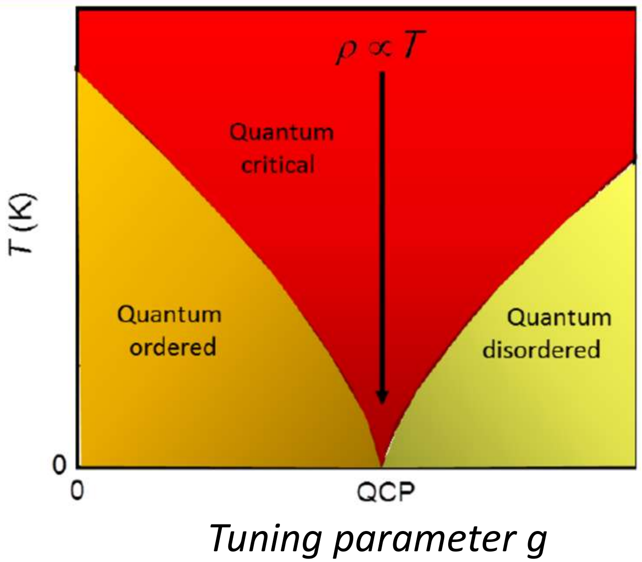
Inelastic neutron scattering

Quantum critical point (QCP)

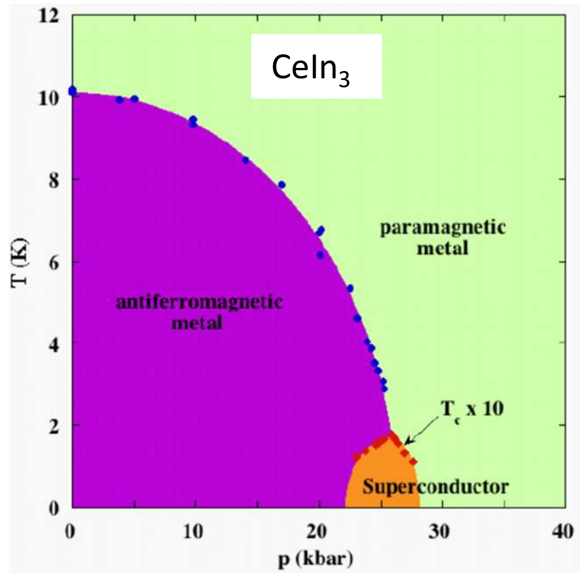
Motoyama *et al*, *Nature* **445** 186 (2007)

Analogy with other unconventional SC

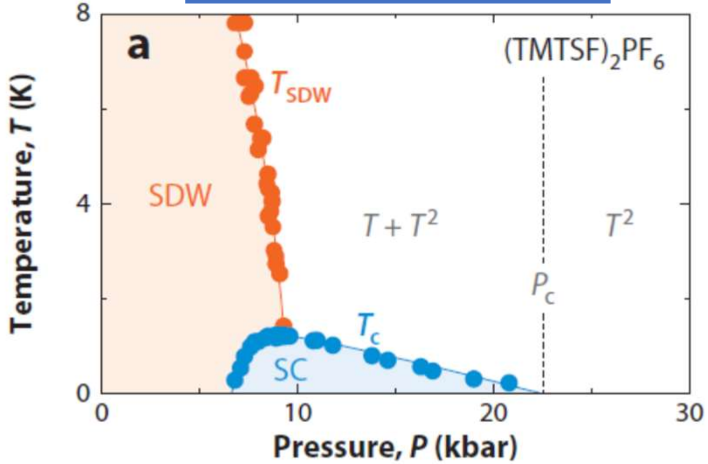
Phase transition driven by quantum fluctuations at T = 0



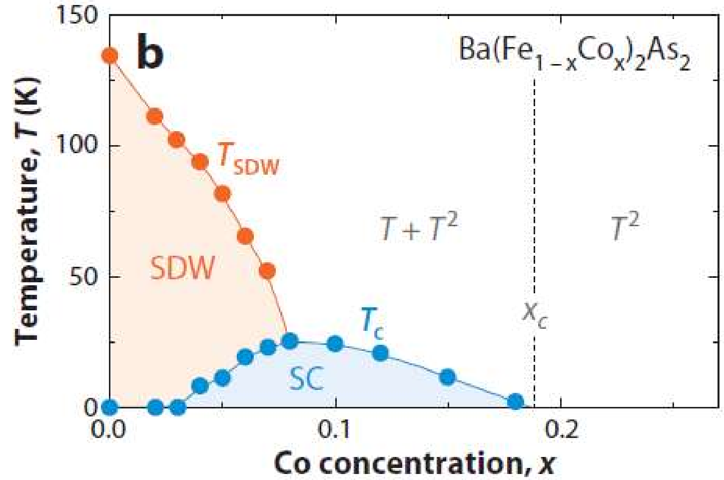
1979 **Heavy fermions**



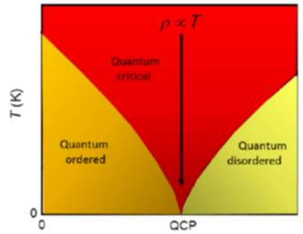
1980 **Organic conductors**

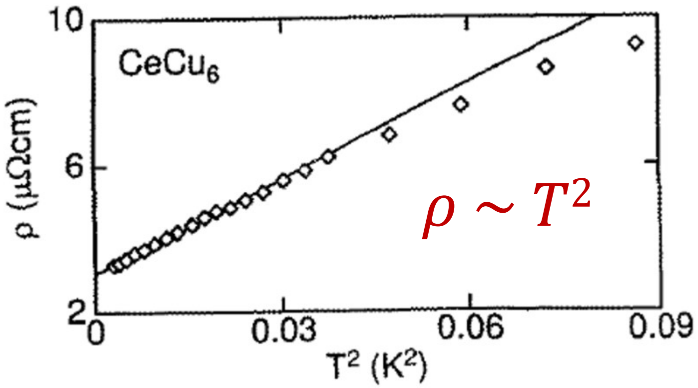


2008 **Pnictides**

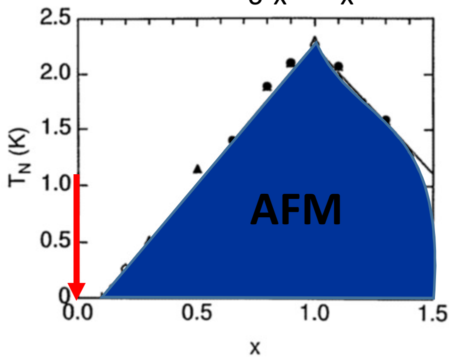


Quantum critical metals: Heavy fermions



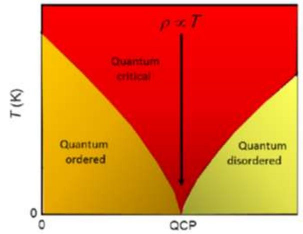


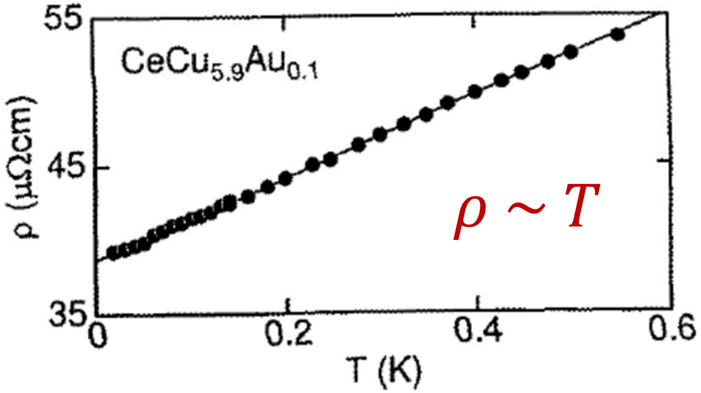
CeCu$_{6-x}$Au$_x$

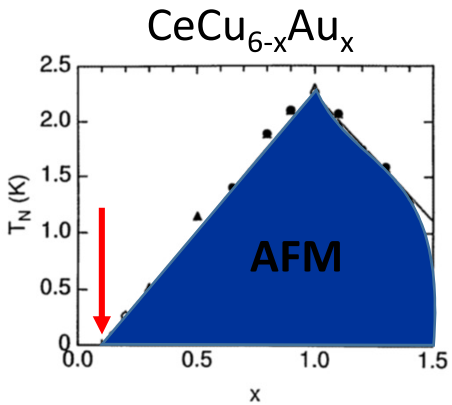


Lohneysen, *JPCM* **8** 9689 (1996)

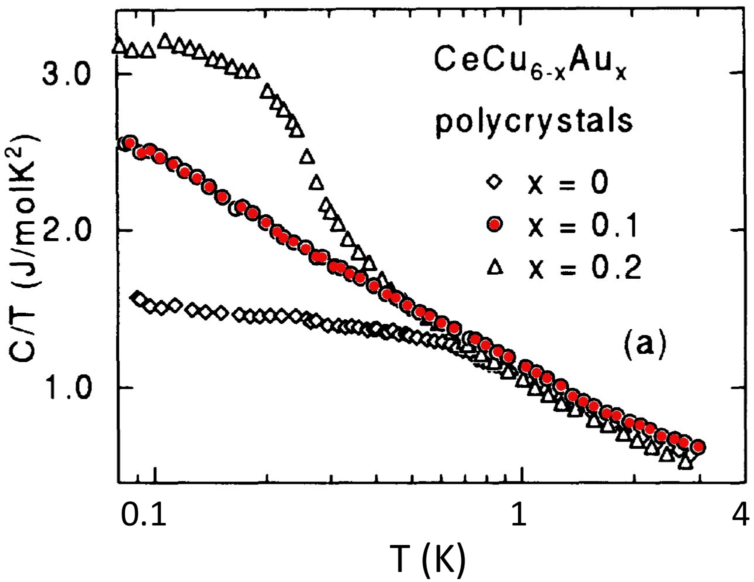
Quantum critical metals: Heavy fermions



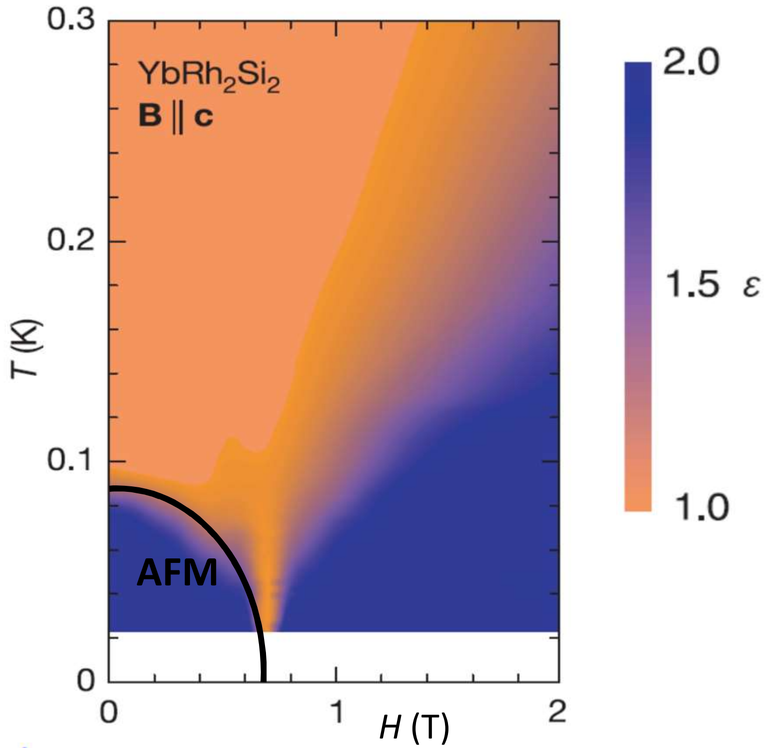




Lohneysen, *JPCM* **8** 9689 (1996)



$C_v \sim m^* \Rightarrow m^* \rightarrow \infty$ at a QCP !

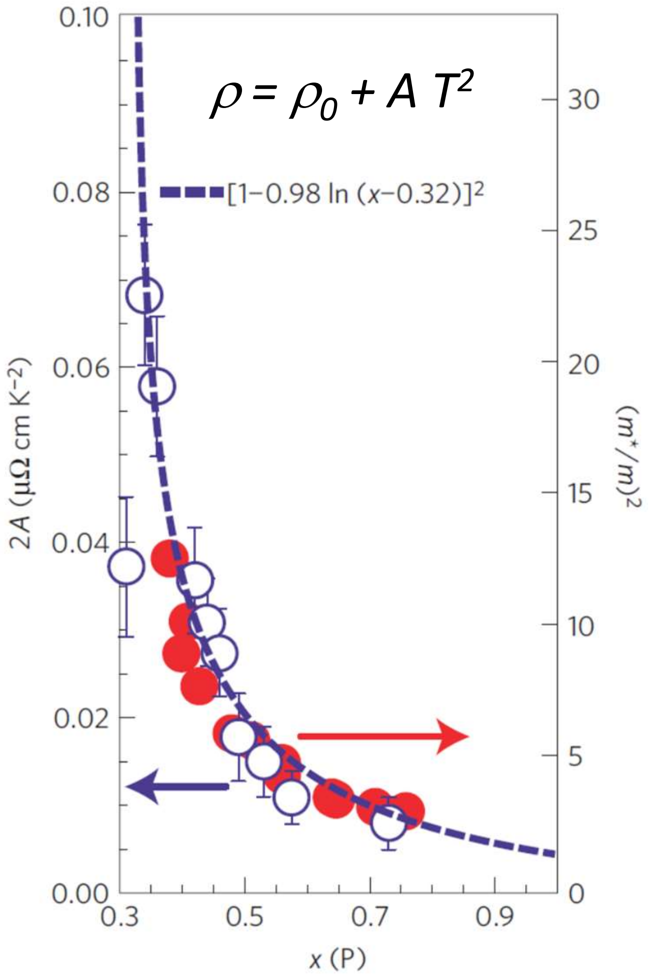


Custers *et al.*,
Nature **424** 524 (03)

$\rho = \rho_0 + A' T^{\varepsilon}$

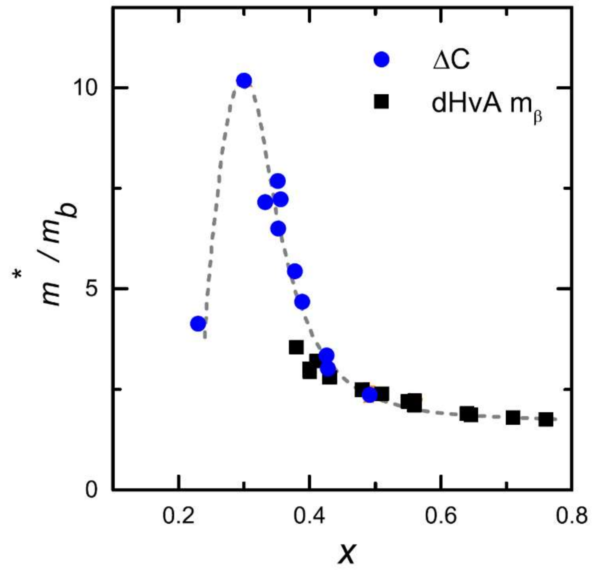
The case of pnictides

Enhancement of $A \propto (m^*)^2$



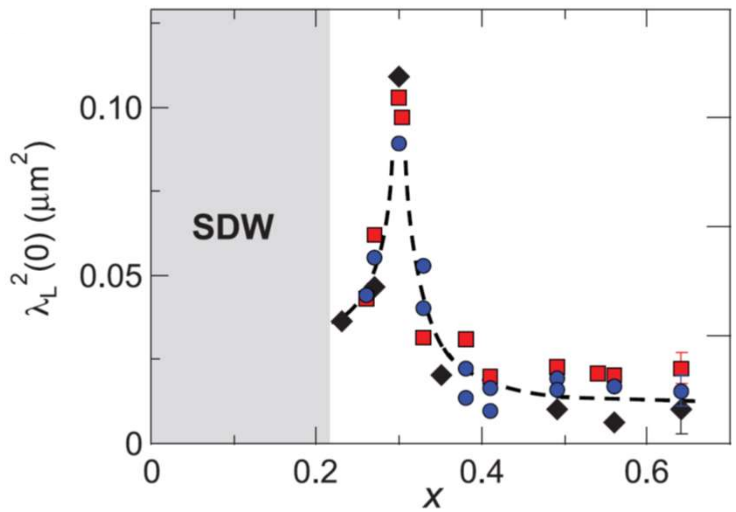
Analytis *et al*, *Nature Phys.* **10** 194 (2014)

Walmsley *et al*, *PRL* **110** 257002 (2013)



Enhancement of m*
seen by specific heat
and QO

$$\gamma = \frac{\Delta C}{1.4\,T_c} \propto m^*$$



Penetration depth

$$\lambda_L^{-2}(0) = \mu_0 e^2 \sum_i n_i / m_i^*$$

Hashimoto *et al*, *Science* **336** 1554 (2012)

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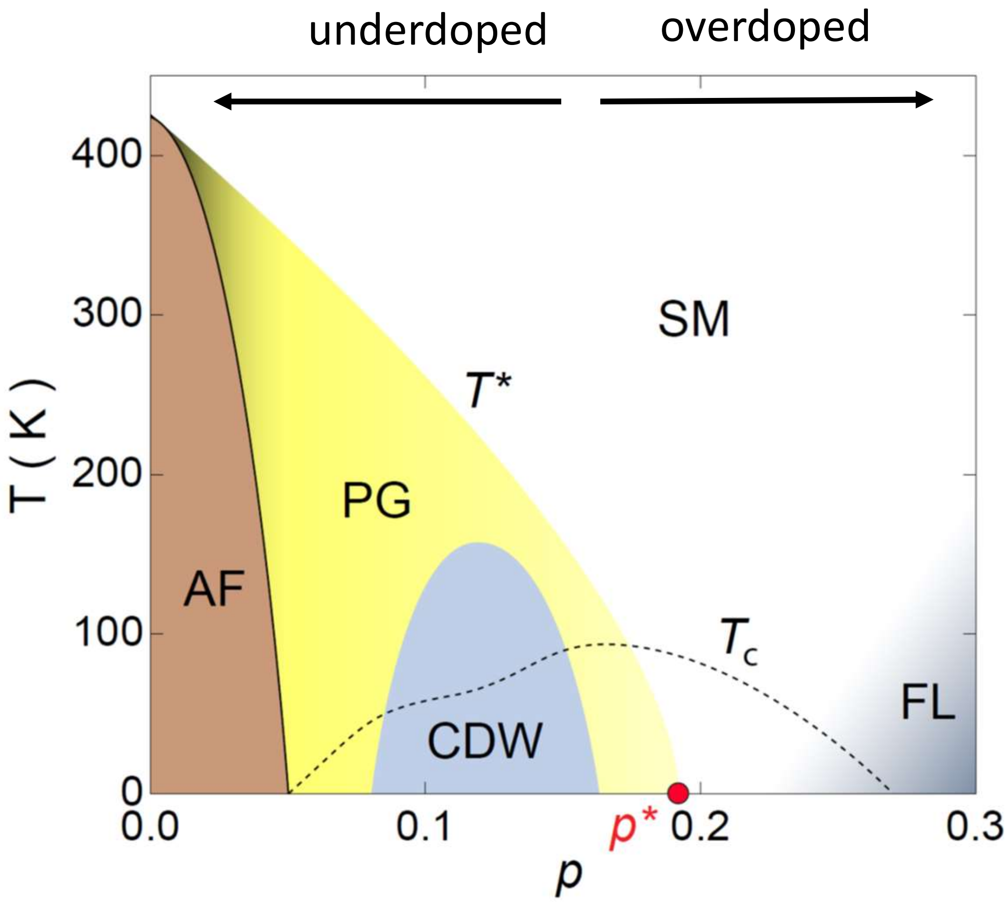
Hole-doped cuprate: roadmap

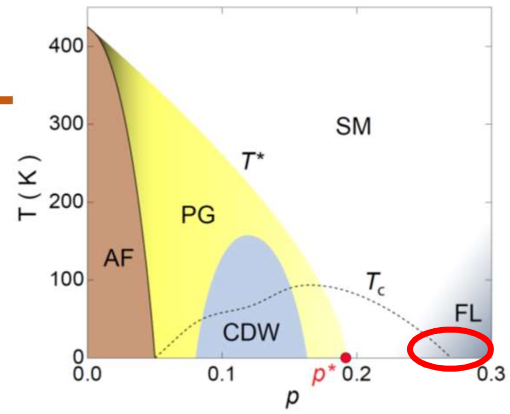


- AF: Mott insulator
- PG: Pseudogap
- SM: Strange metal
- FL: Fermi liquid

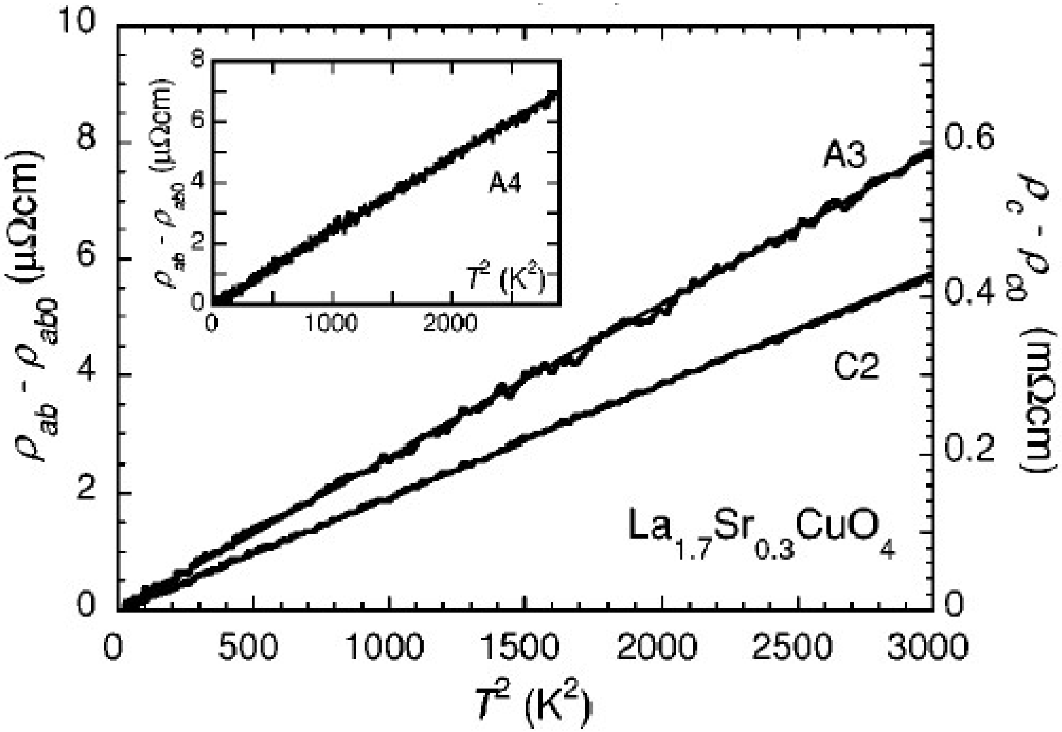
--- SC

Experimental approach:
Remove superconductivity with strong magnetic fields
Probe the underlying ground state

Fermi liquid phase



$\rho = \rho_0 + A\,T^2$



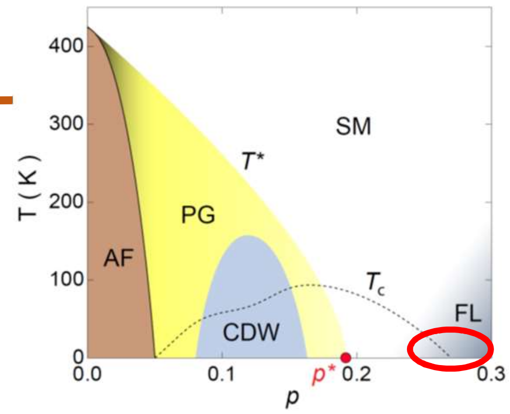
S. Nakamae *et al*, *PRB* **68** 100502 (2003)

Wiedemann-Franz law satisfied

$\Rightarrow$ electronic carriers of heat are fermionic excitations of charge e

C. Proust *et al*, *PRL* **89** 147003 (2002)

Fermi liquid phase



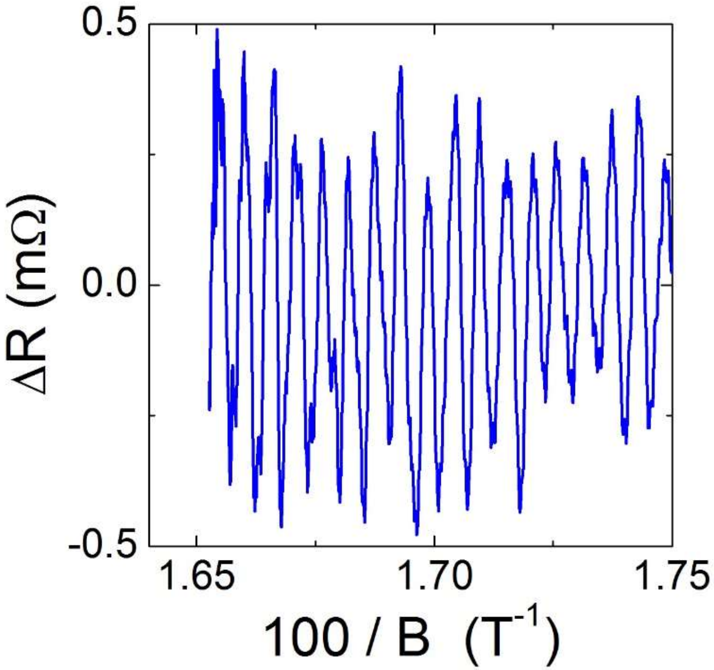
Quantum oscillations measurements :

- Consequence of Landau quantization
- Evidence for coherent Fermi surface (QP)

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

But also m^*, τ_{elastic}

Fermi surface of overdoped $TlBa_2CuO_{6+\delta}$ (Tl2201)



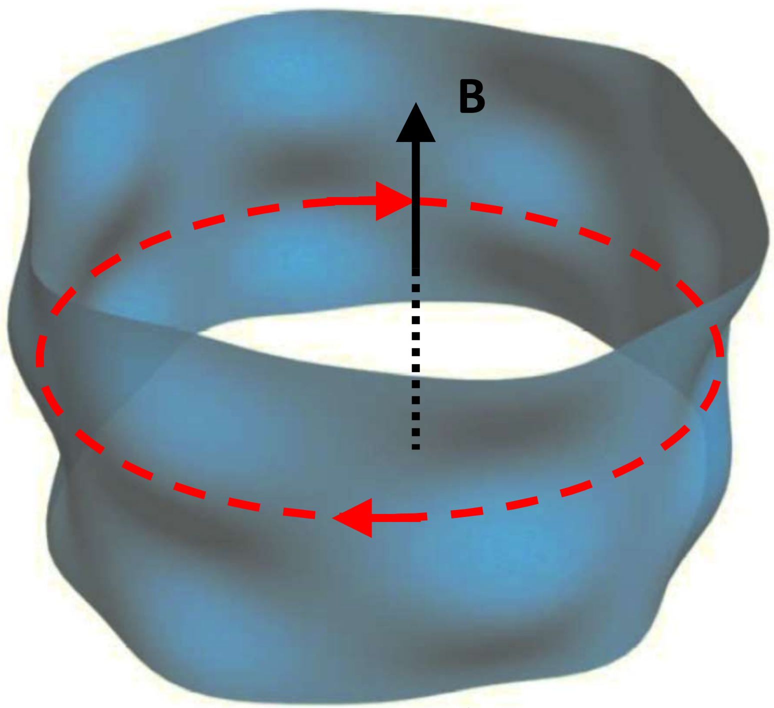


Photo credit: N. Hussey

B. Vignolle, CP *et al*, *Nature* **455** 952 (2008)

Fermi liquid phase

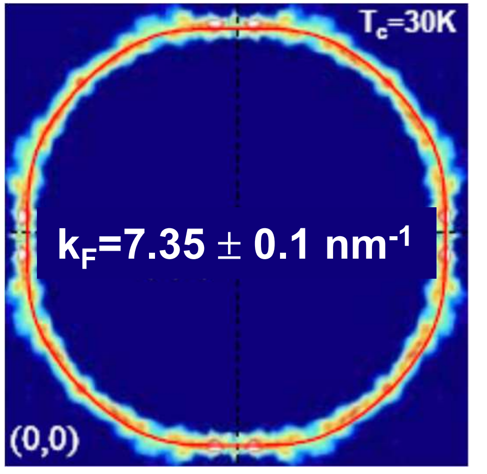
- F=18100 $\pm$ 50 T

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

$A_k = \pi k_F^2$ $\Rightarrow$ k_F=7.42 $\pm$ 0.05 nm^{-1}

(65 % of the FBZ)

ARPES



Platé *et al*, *PRL* **95** 077001 (2005)

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

$\Rightarrow$ Carrier density: *n* = 1.3 carrier /Cu atom (*n* = 1+*p* with *p* = 0.3)

- Excellent agreement between measurements and band structure calculations
- But strong renormalization of the effective mass: m^* = 5 $\pm$ 0.5 m_0
  $\Rightarrow$ electron-electron interactions

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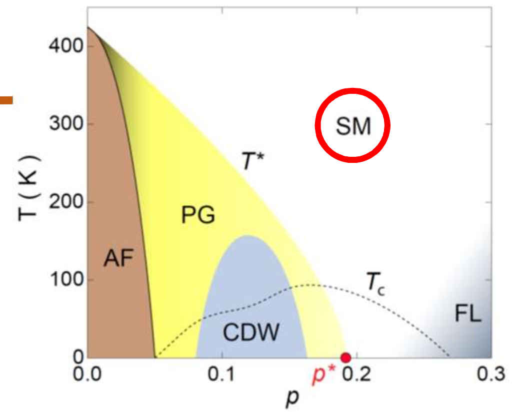
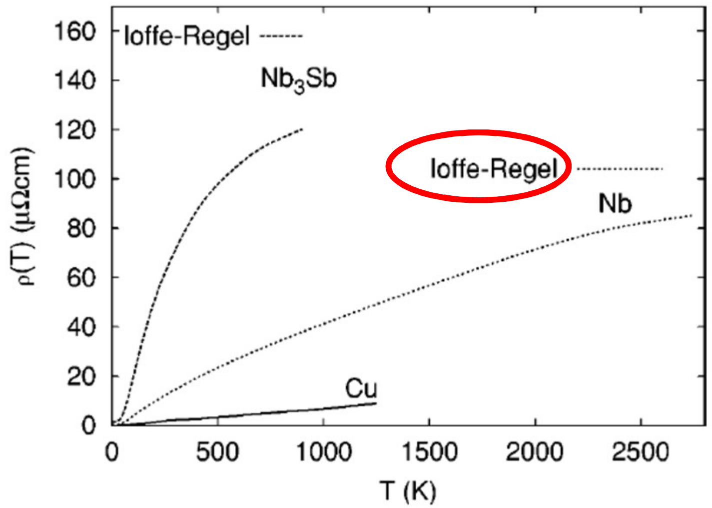
Strange Metal (SM) phase



Saturating resistivity in metals

Gunnarson *et al*. *RMP* **75** 1085 (03)

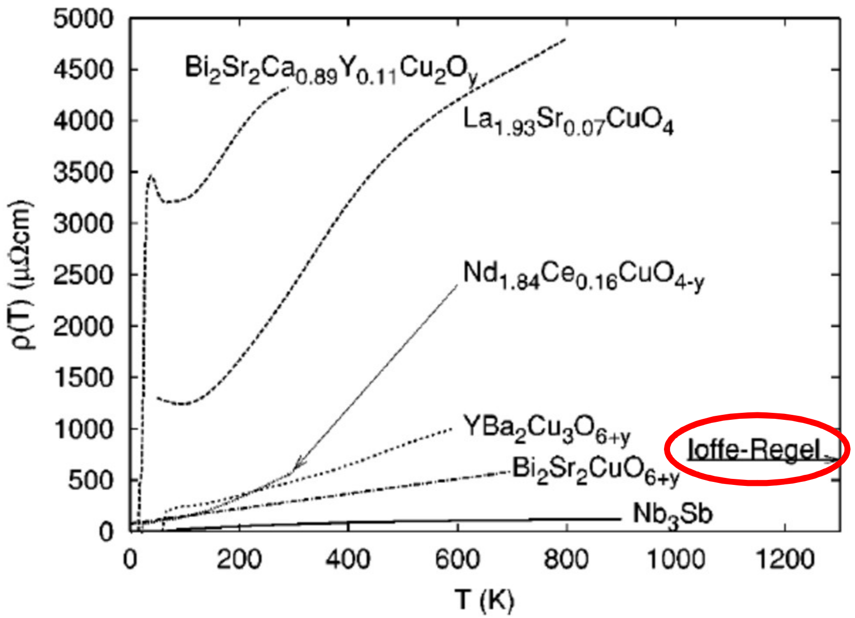


Band theory (QP) breaks down if $\ell < a$

$$\ell < \lambda_F = \frac{2\pi}{k_F}$$

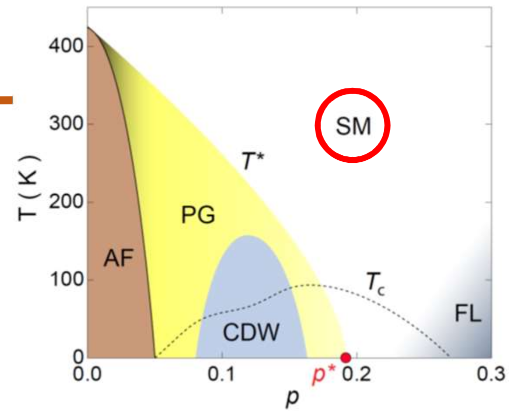
$$\boxed{k_F \ell < 1}$$

Non-saturating resistivity in cuprates !



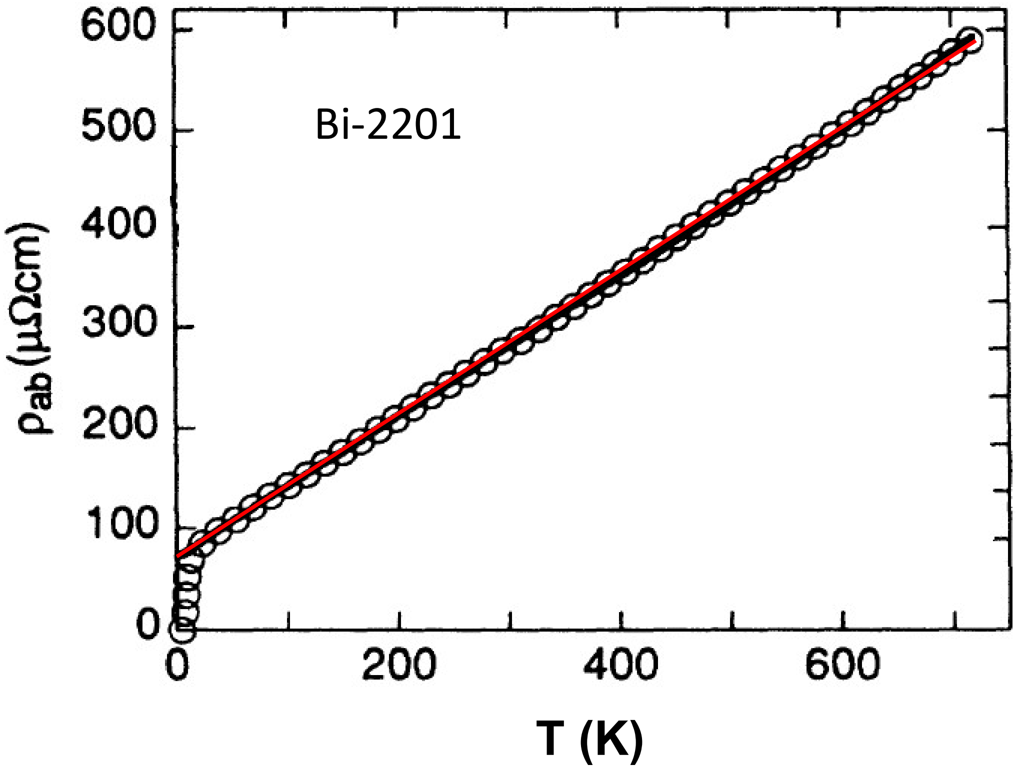
Incoherent transport ⇒ **Bad metals**

Strange Metal (SM) phase



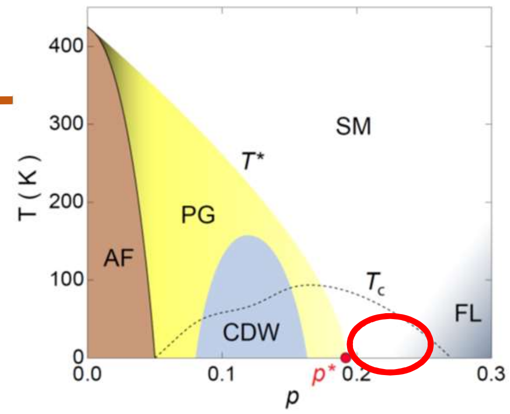
Linear resistivity

Martin *et al*. *PRB* **41**, 846 (1990)

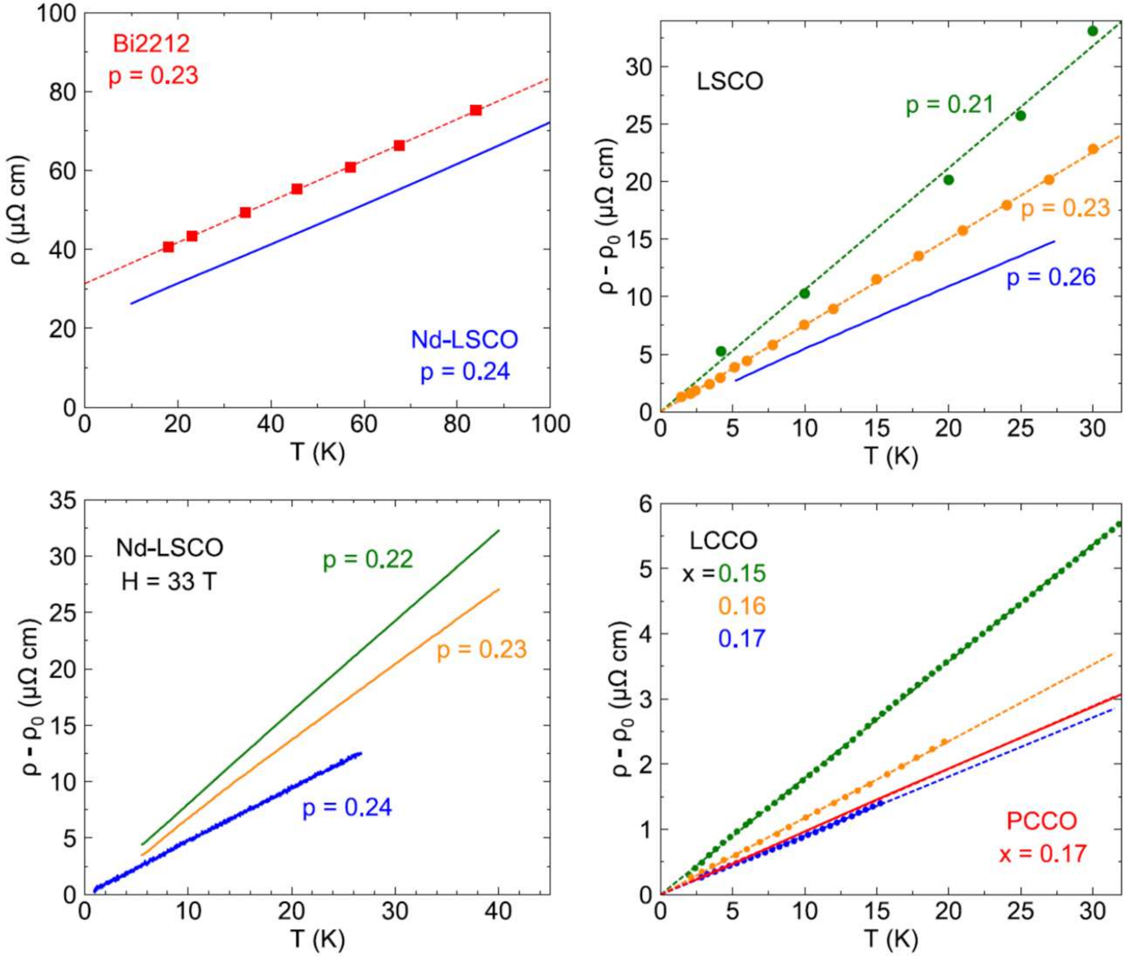


$\rho(T) \propto T$ from T_c = 7 K up to 700 K !!!

Strange Metal (SM) phase



Access ground state using high magnetic fields



Legros, CP *et al*. *Nature Physics* ***15**, 142* (2019)

T-linear resistivity observed at low T in many overdoped cuprates

$$\rho = \frac{m^*}{ne^2}\frac{1}{\tau} \propto \Gamma(T)$$

Planckian dissipation

<u>Proposal</u>: Strength of the *T*-linear resistivity is approximately given by a scattering rate that has a universal value, namely

Zaanen, *Nature* **430**, 512 (2004)

Bruin et al, *Science* **339** 804 (2013)

$$\frac{\hbar}{\tau} = k_B T$$

Drude formula: $\rho = \frac{m^*}{ne^2}\frac{1}{\tau}$

$T \to 0 \qquad \rho(T) = \rho_0 + A_1 T \quad \Rightarrow \quad A_1 = \alpha \frac{m^*}{n}\frac{k_B}{\hbar e^2}$ where $\alpha = \frac{\hbar/\tau}{k_B T}$

At 2D $\quad A_1^{\square} = \frac{A_1}{d} = \alpha \frac{h}{2e^2}\frac{1}{T_F}$ where $T_F = \frac{\pi\hbar^2}{k_B}\frac{nd}{m^*}$

Knowing ***n*** and ***m****, we can evaluate $A_1^{\square}$ and compare it to the experimental value

Planckian dissipation

Material		n (10^{27} m^{-3})	m^* (m_0)	A_1 / d (Ω / K)	h / ($2e^2\ T_F$) (Ω / K)	α
Bi2212	$p = 0.23$	6.8	8.4 ± 1.6	8.0 ± 0.9	7.4 ± 1.4	1.1 ± 0.3
Bi2201	$p \sim 0.4$	3.5	7 ± 1.5	8 ± 2	8 ± 2	1.0 ± 0.4
LSCO	$p = 0.26$	7.8	9.8 ± 1.7	8.2 ± 1.0	8.9 ± 1.8	0.9 ± 0.3
Nd-LSCO	$p = 0.24$	7.9	12 ± 4	7.4 ± 0.8	10.6 ± 3.7	0.7 ± 0.4
PCCO	$x = 0.17$	8.8	2.4 ± 0.1	1.7 ± 0.3	2.1 ± 0.1	0.8 ± 0.2
LCCO	$x = 0.15$	9.0	3.0 ± 0.3	3.0 ± 0.45	2.6 ± 0.3	1.2 ± 0.3
TMTSF	$P = 11$ kbar	1.4	1.15 ± 0.2	2.8 ± 0.3	2.8 ± 0.4	1.0 ± 0.3

$$\alpha = \frac{\hbar/\tau}{k_B T}$$

Fundamental and universal principle at play !

T-linear resistivity when Γ hits the Planckian limit
whatever the scattering process

“ What scatters may also pair ”

Legros, CP *et al. Nature Physics* ***15****, 142* (2019)

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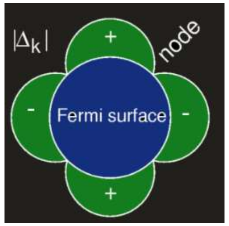
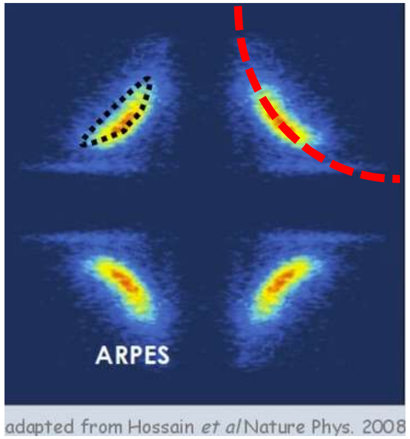
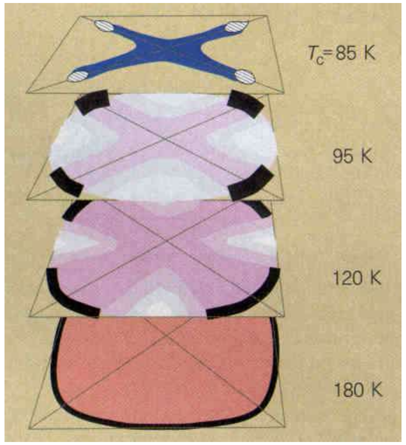
Pseudogap in hole-doped cuprates

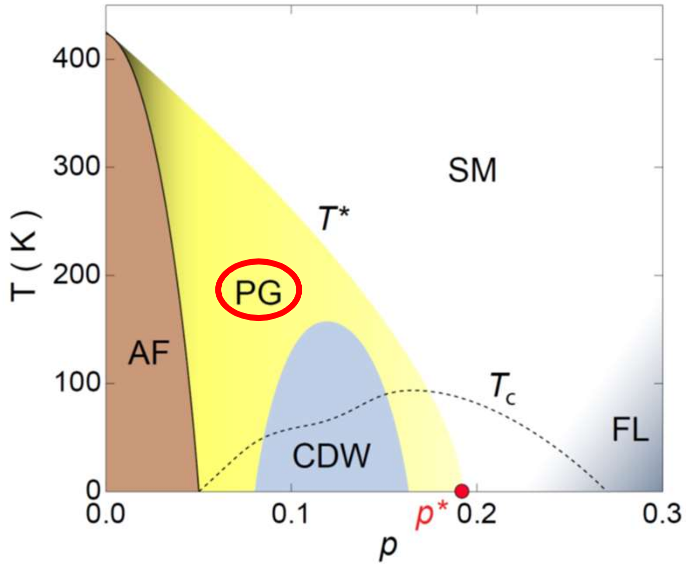


ARPES





M. Norman *et al*, Nature'98



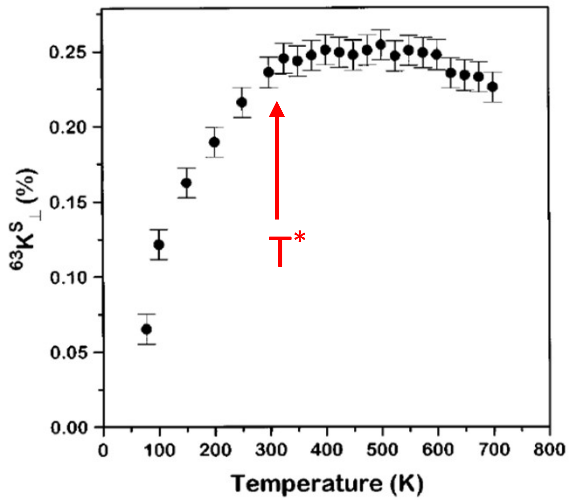
Partial suppression of the low energy excitation as seen by spectroscopy and thermodynamic probes and located at the anti-node

Doped Mott insulator ?

Phase with a distinct order parameter?

NMR: Pseudogap for T<T* (crossover)

Co-discovered by H. Alloul group in Orsay

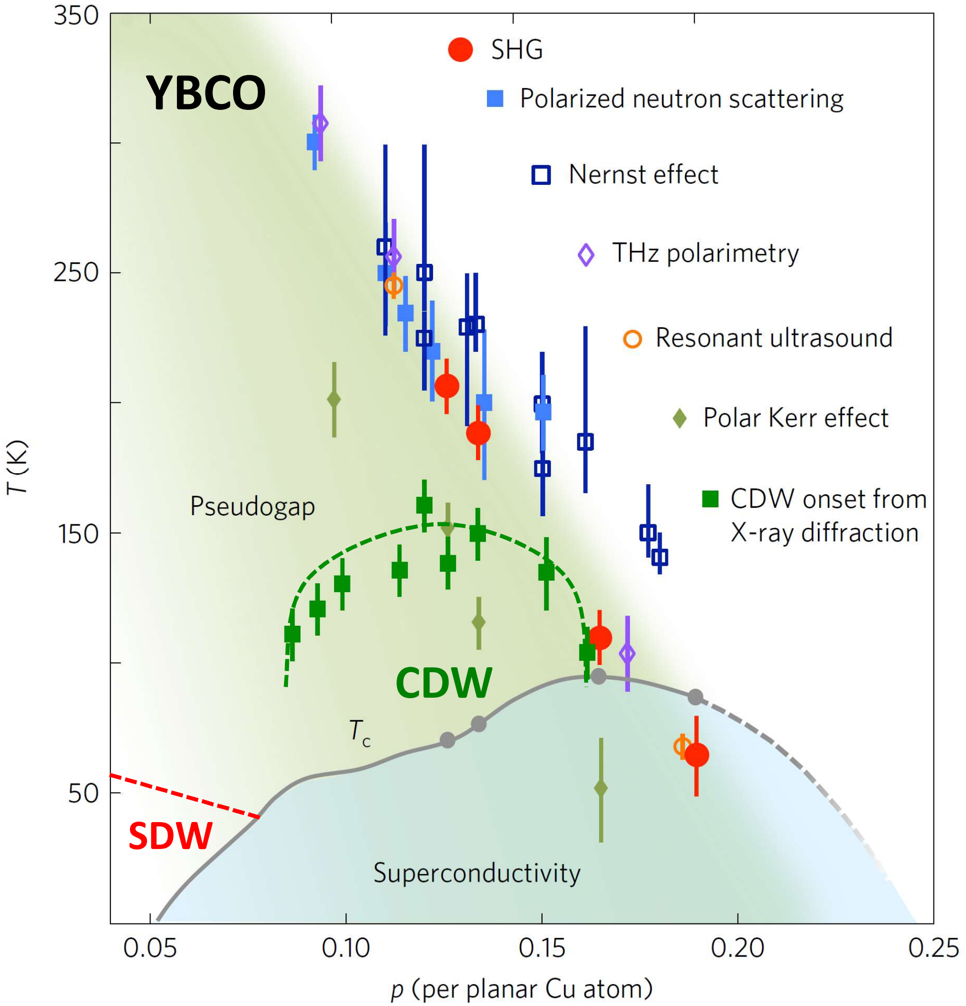


Curro et al, PRB 56, 877 (1997)

$K \propto \chi'(q{=}0, \omega) \propto$ DOS

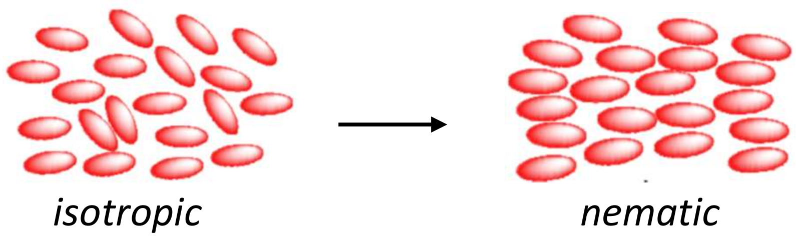
Pseudogap in hole-doped cuprates

Pseudogap phase hosts a variety of quantum orders !

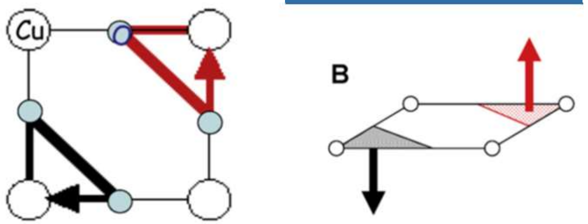


Adapted from Zhao et al, *Nature Phys.* **13**, 250 (2017)

Nematic phase



Current Loop



Intra-unit cell current loop

Q=0 order Instability of the pseudogap (but can boost T_c)

SDW = Spin Density Wave

CDW = Charge Density Wave

Pseudogap: CDW phase

- Discovery of 'stripe order' (intertwined charge and spin modulations) in Nd-LSCO by neutron diffraction

  Tranquada et al. *Nature* **375**, 561 (1995)

- Discovery of charge modulations by STM in Bi-based cuprate

  Hoffman et al. *Science* **295**, 466 (2002)
  Hanaguri et al. *Nature* **430**, 1001 (2004)
  Wise et al. *Nature Phys.* **4**, 696 (2008)

Nature **447**, 565 (2007)

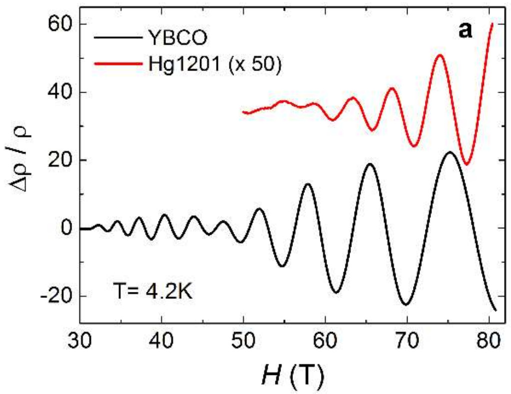
- **Quantum oscillations and the Fermi surface in an underdoped high-T_c superconductor**

  Nicolas Doiron-Leyraud[1], Cyril Proust[2], David LeBoeuf[1], Julien Levallois[2], Jean-Baptiste Bonnemaison[1], Ruixing Liang[3,4], D. A. Bonn[3,4], W. N. Hardy[3,4] & Louis Taillefer[1,4]

Underdoped $YBa_2Cu_3O_{6.5}$ T_c ~ 60 K

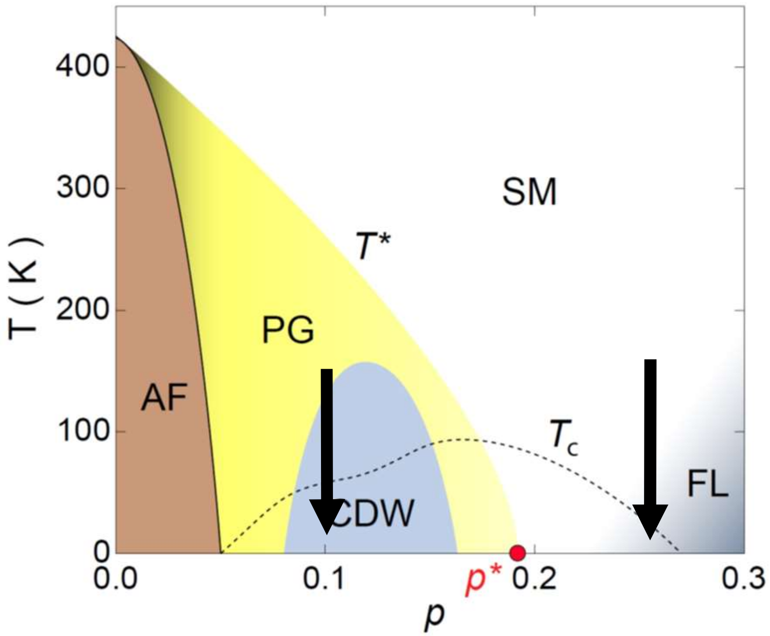
CDW phase

Underdoped
$YBa_2Cu_3O_{6.5}$
$HgBa_2CuO_{4+\delta}$

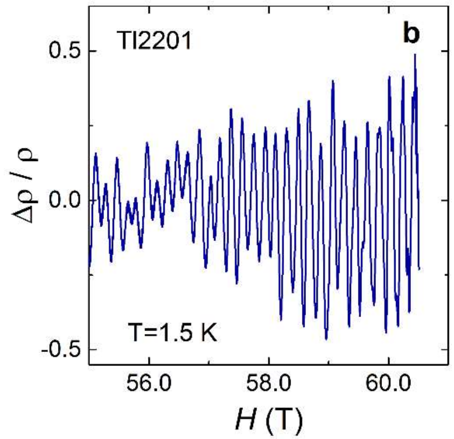


N. Doiron-Leyraud, CP *et al.*
Nature **447**, 565 (2007)

N. Barisic, CP *et al.*
Nature Phys. **9** 761 (2013)



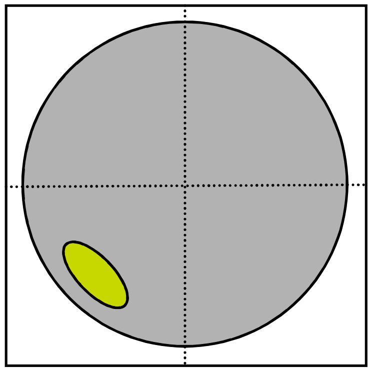
Overdoped
$Tl_2Ba_2CuO_{6+\delta}$



B. Vignolle, CP *et al.*
Nature **455** 952 (2008)

Carrier density: *n = 1 + p*

Frequency : F = (530 ± 20)T
A_k = 2 % of 1st Brillouin zone

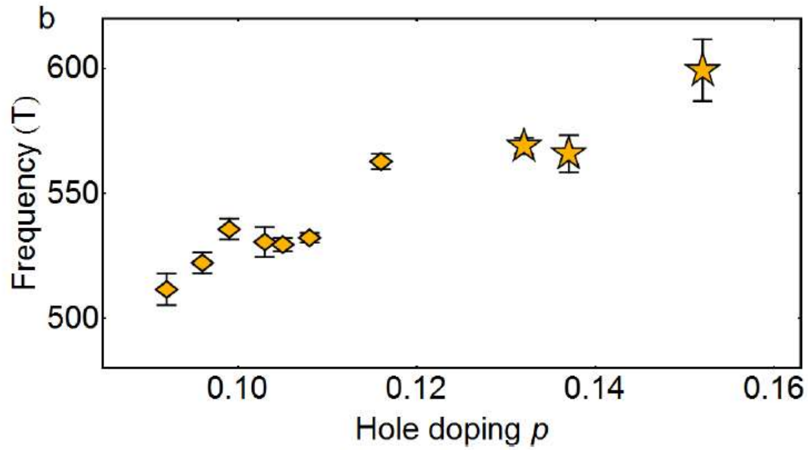


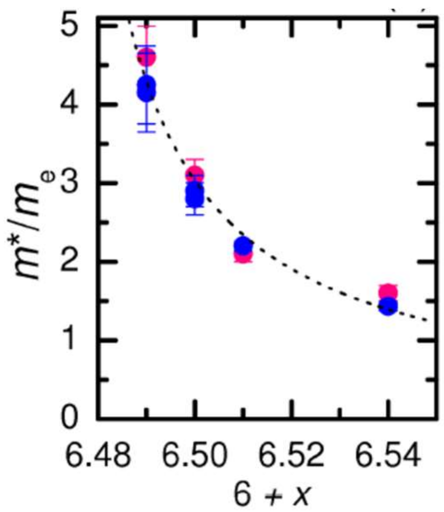
Frequency : F = (18100 ± 50) T
A_k = 65 % of 1st Brillouin zone

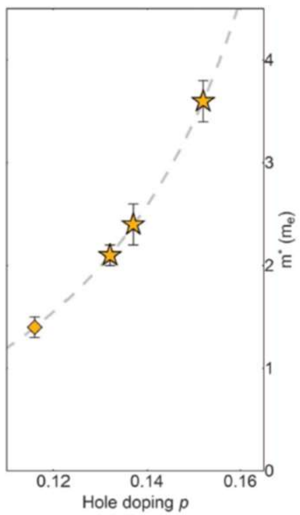
Drastic change of Fermi surface topology

Doping dependence of QOs in YBCO

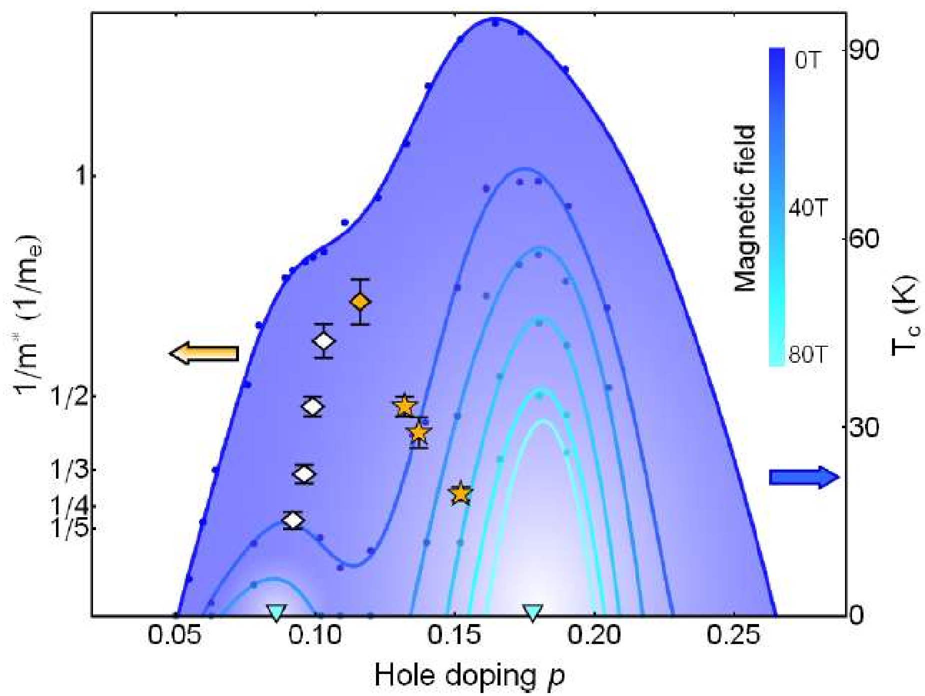
Observed in the **doping range** between 9 % and 15 %







Effective mass

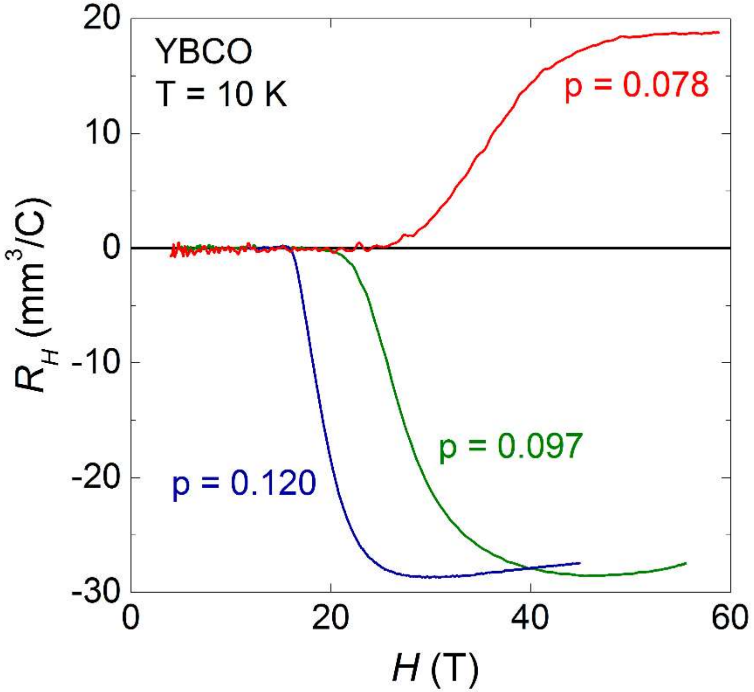


Sebastian *et al*. *PNAS* **107** 6175 (2010)

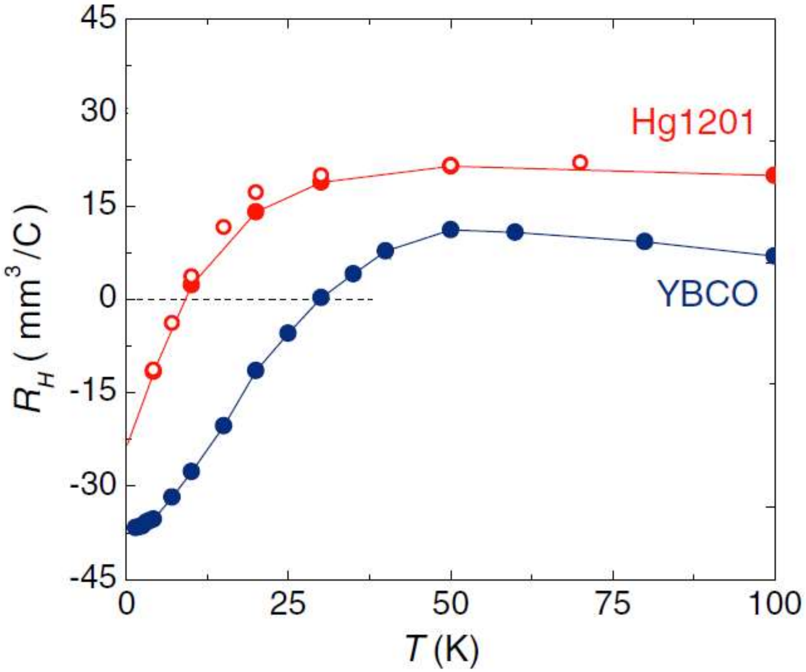
Ramshaw *et al*. *Science* **348** 317 (2015)

CDW phase

Hall effect in YBCO and Hg1201



LeBoeuf, CP *et al*. *Nature* **450** 533 (2007)
LeBoeuf, CP *et al*., *PRB* **83**, 054506 (2011)



Doiron-Leyraud, CP *et al*. *PRX* **3** 021019 (2013)

$R_H < 0$ in the CDW phase $\Rightarrow$ Electron pocket !

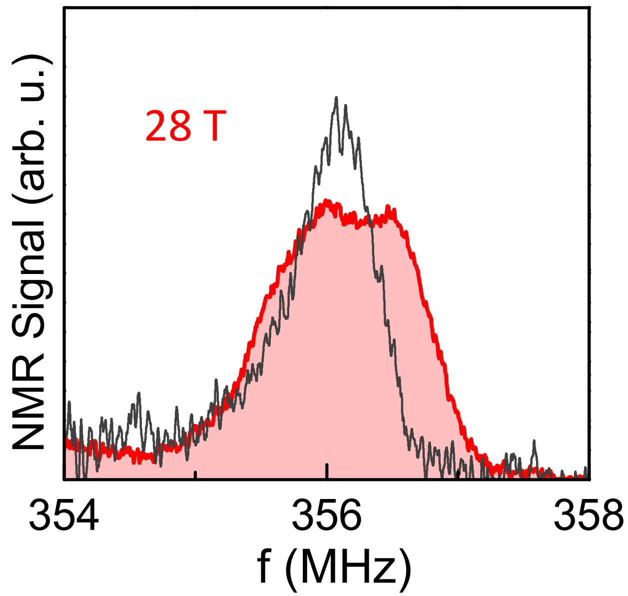
Fermi surface reconstruction by a 'hidden' order

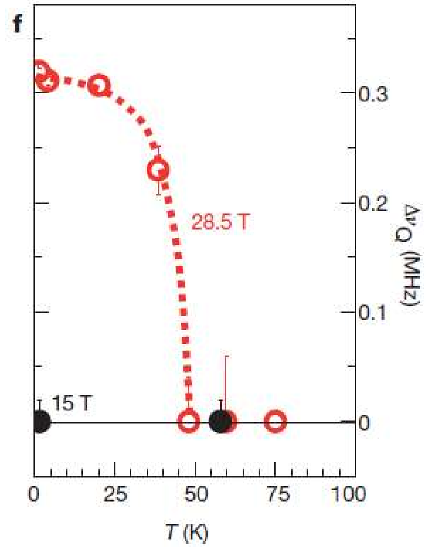
Hidden order = CDW

High field NMR in underdoped YBCO

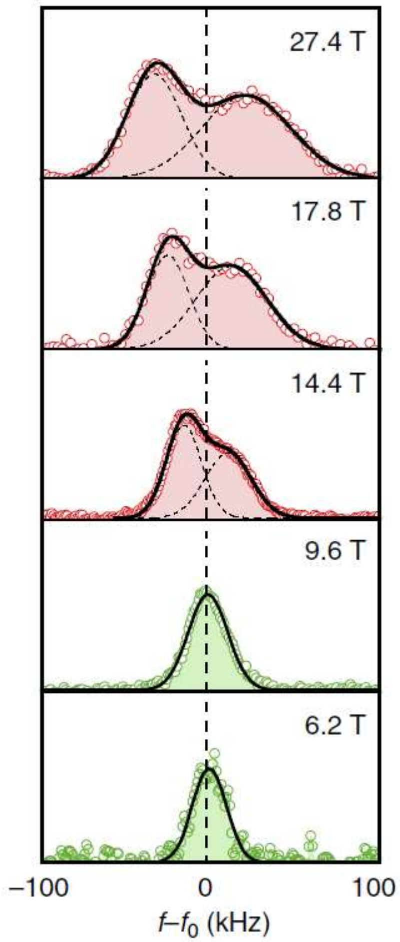
(M-H. Julien, LNCMI-Grenoble)

Wu *et al*. *Nature* **477** 191 (2011)





Threshold field



Wu *et al*. *Nature Comm.* **4** 2113 (2013)

Broken translational symmetry by **charge order**

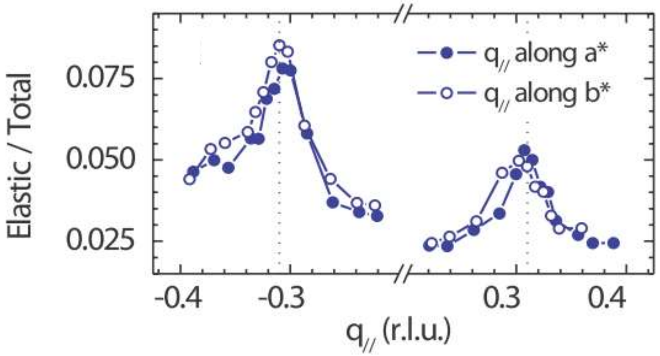
No spin order !

~~**STRIPE**~~

X-ray measurements

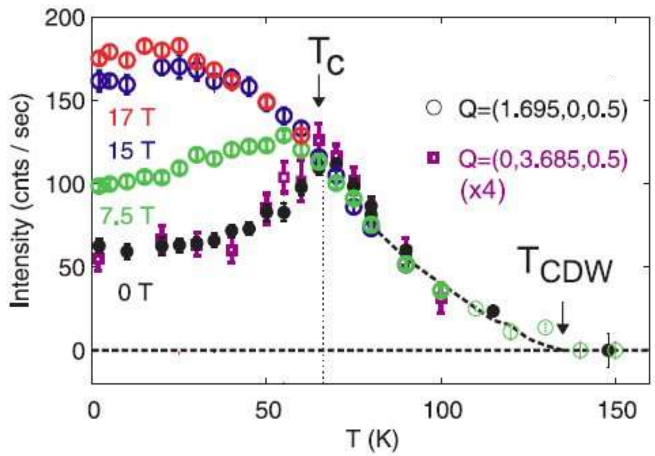
X-ray scattering and diffraction

- Biaxial CDW up to T=150 K

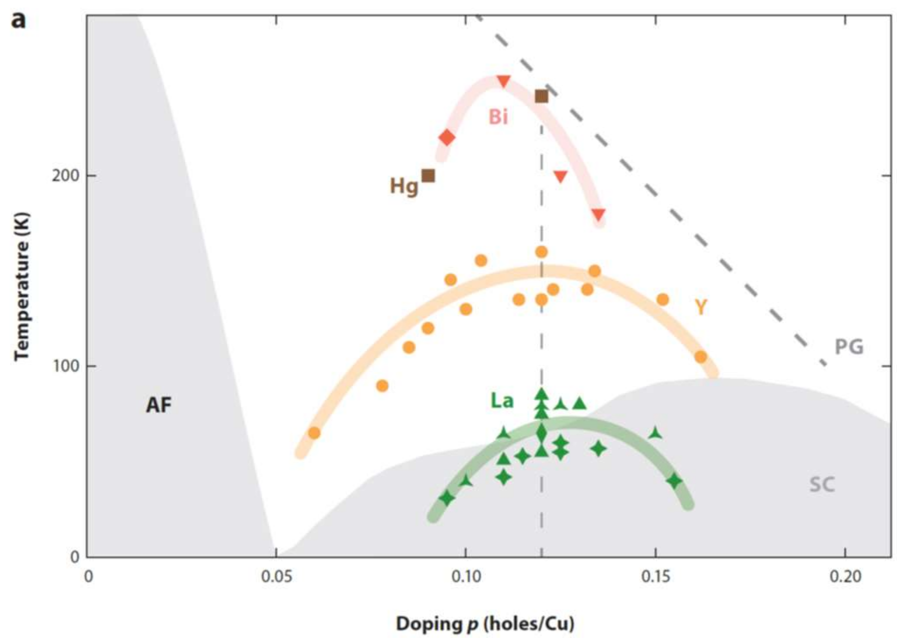


Ghiringhelli *et al*. *Science* **337** 821 (2012)

- Competition between CDW and SC

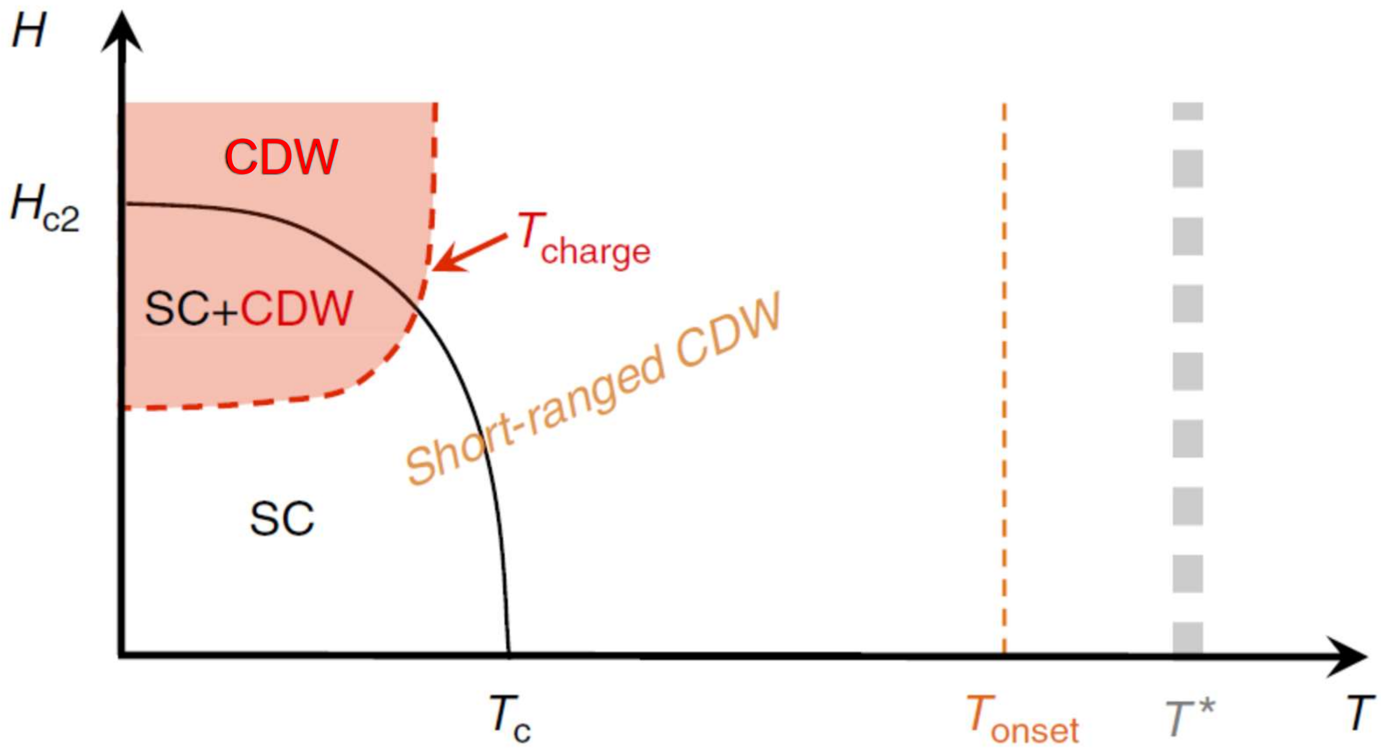


Chang *et al*. *Nature Phys.* **8** 871 (2012)



Comin & Damascelli, *ARCMP* **7**, 369 (2016)

Short-ranged vs long-ranged CDW in YBCO



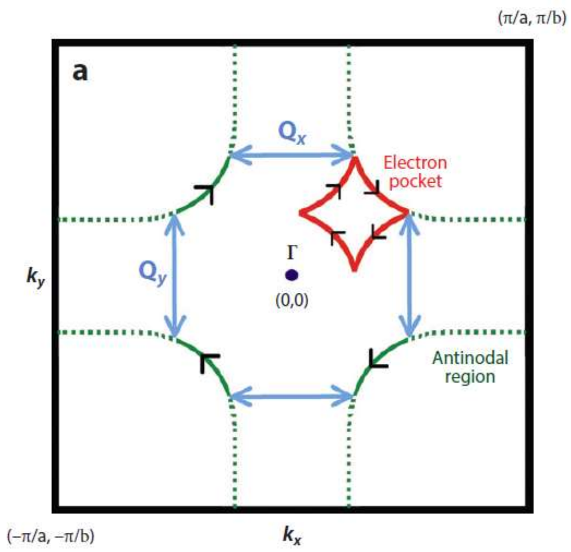
3D CDW

- Unidirectional $Q_b(0,\delta_b,1)$
- Long range $\xi \approx 310$ Å $\approx 80\ a$
- $H > H_{co}$

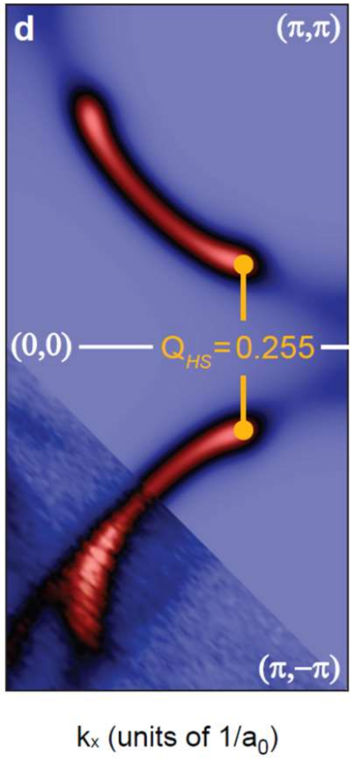
2D CDW

- Bidirectional $Q_a(\delta_a,0,0.5)$ $Q_b(0,\delta_b,0.5)$
- Short range $\xi \approx 70$ Å $\approx 20\ a$ but static
- Zero magnetic field

FSR by biaxial CDW order



Harrison & Sebastian, *NJP* **14** 095023 (2012)



Comin & Damascelli, *ARCMP* **7**, 369 (2016)

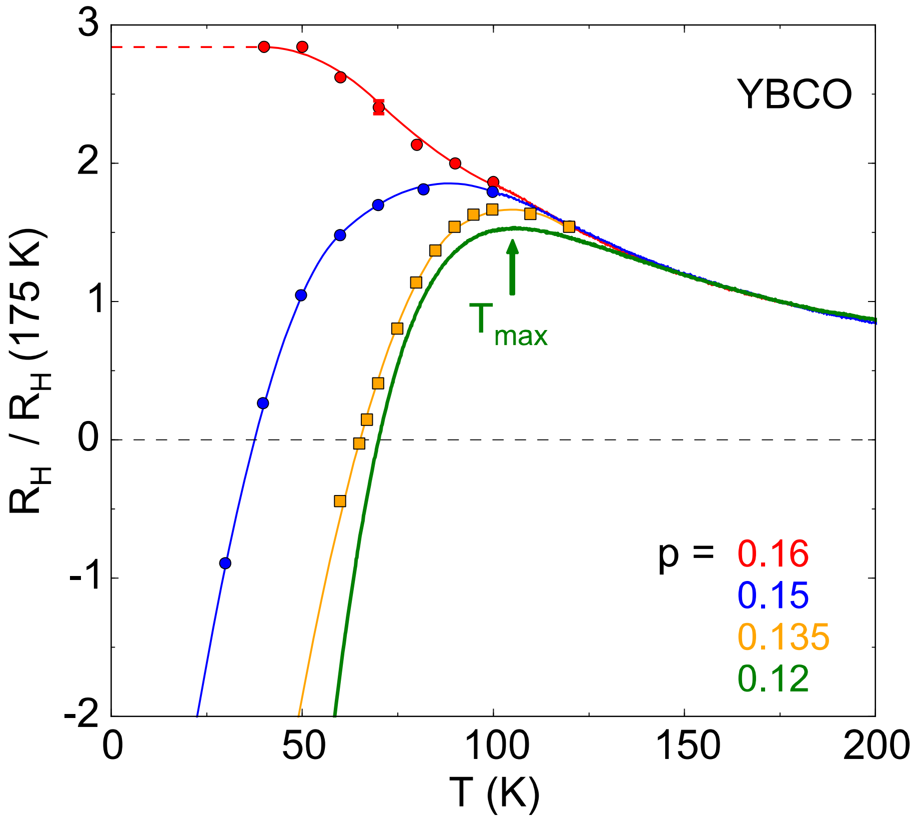
⇒ Fermi surface reconstruction in 2 steps: Pseudogap + CDW

Not a conventional CDW!

No nesting wavevector but driven by strong electron-electron correlations

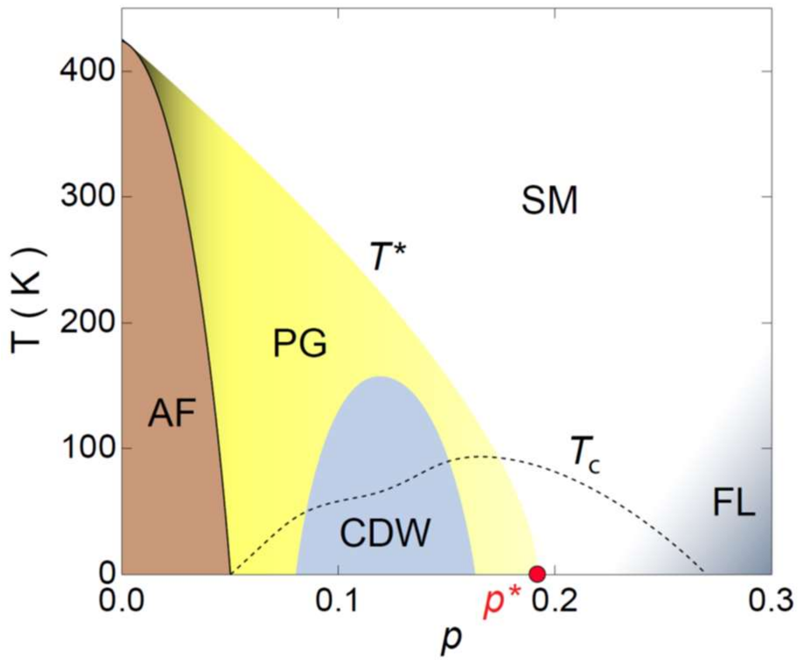
Pseudogap and CDW phase

$R_H < 0 \Rightarrow$ signature of the Fermi surface reconstruction by CDW



LeBoeuf, CP *et al.*, PRB **83**, 054506 (2011)

Badoux, CP *et al.*, Nature **531**, 210 (2016)

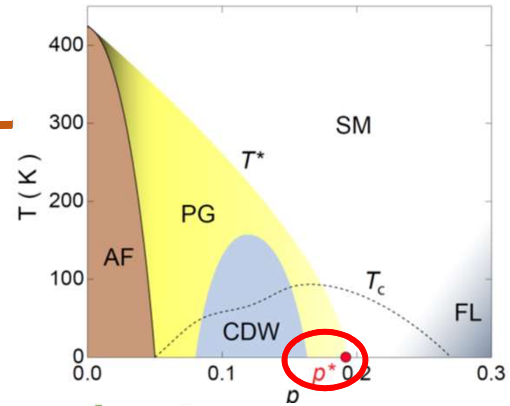


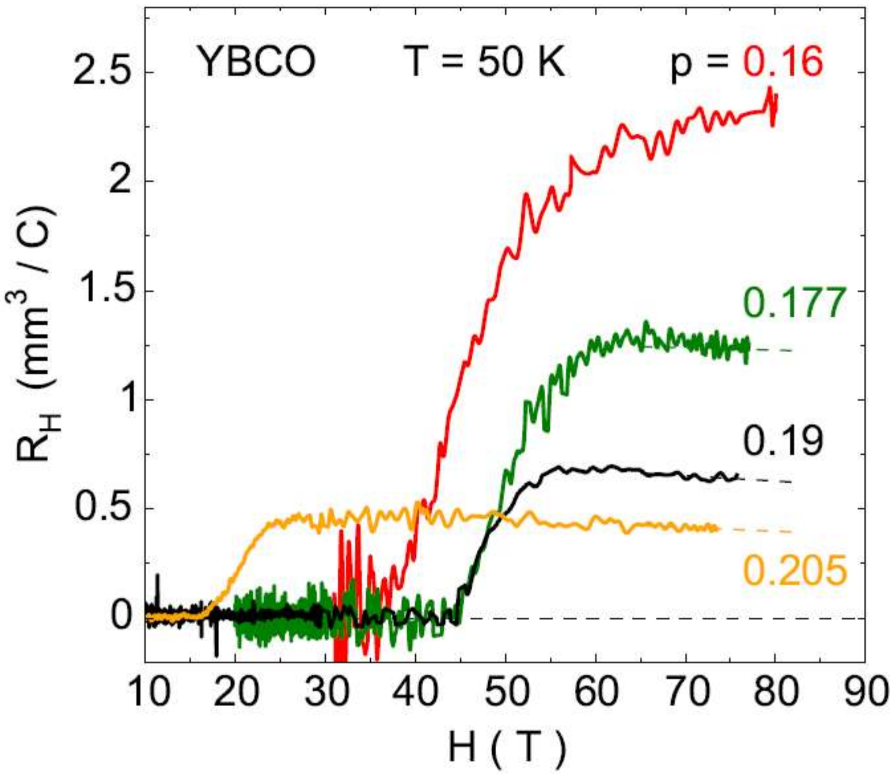
✓ the critical point of pseudogap and of CDW are distinct and well separated.

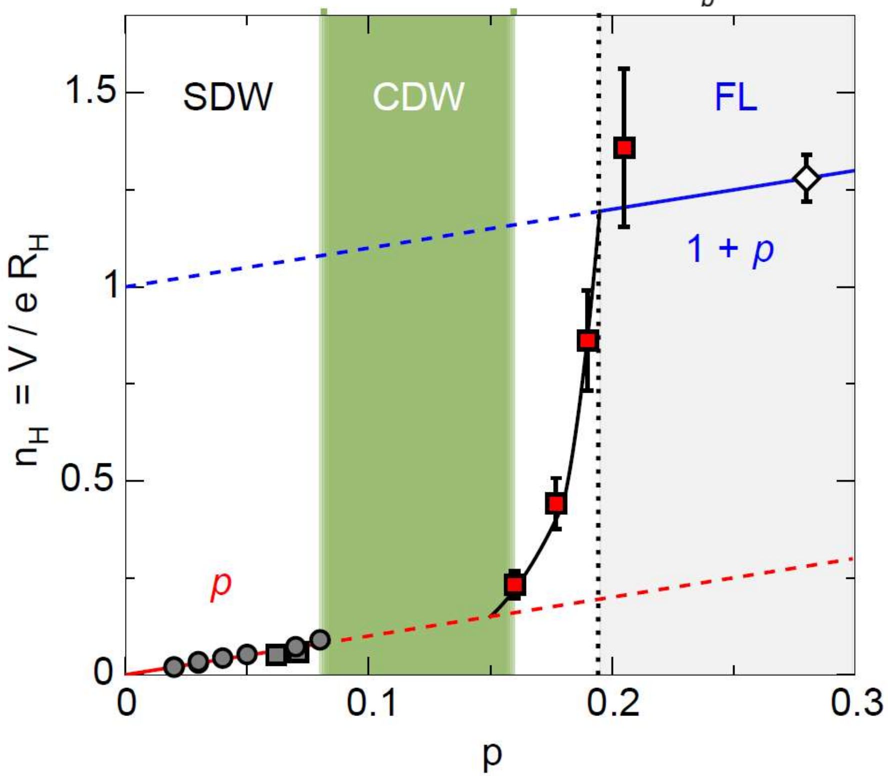
CDW = instability of the pseudogap

Confirmed by high field sound velocity measurements: Laliberté, CP *et al.*, NJP QM **3**, 11 (2018)

Drop of the carrier density at p^*



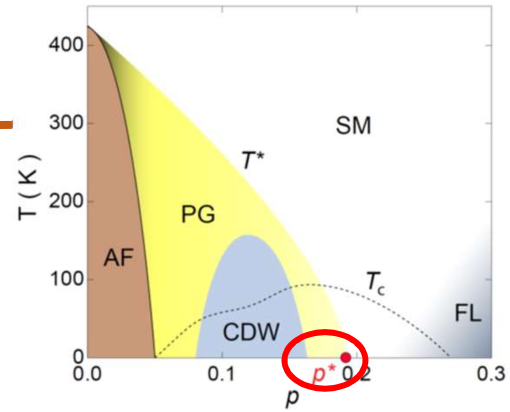


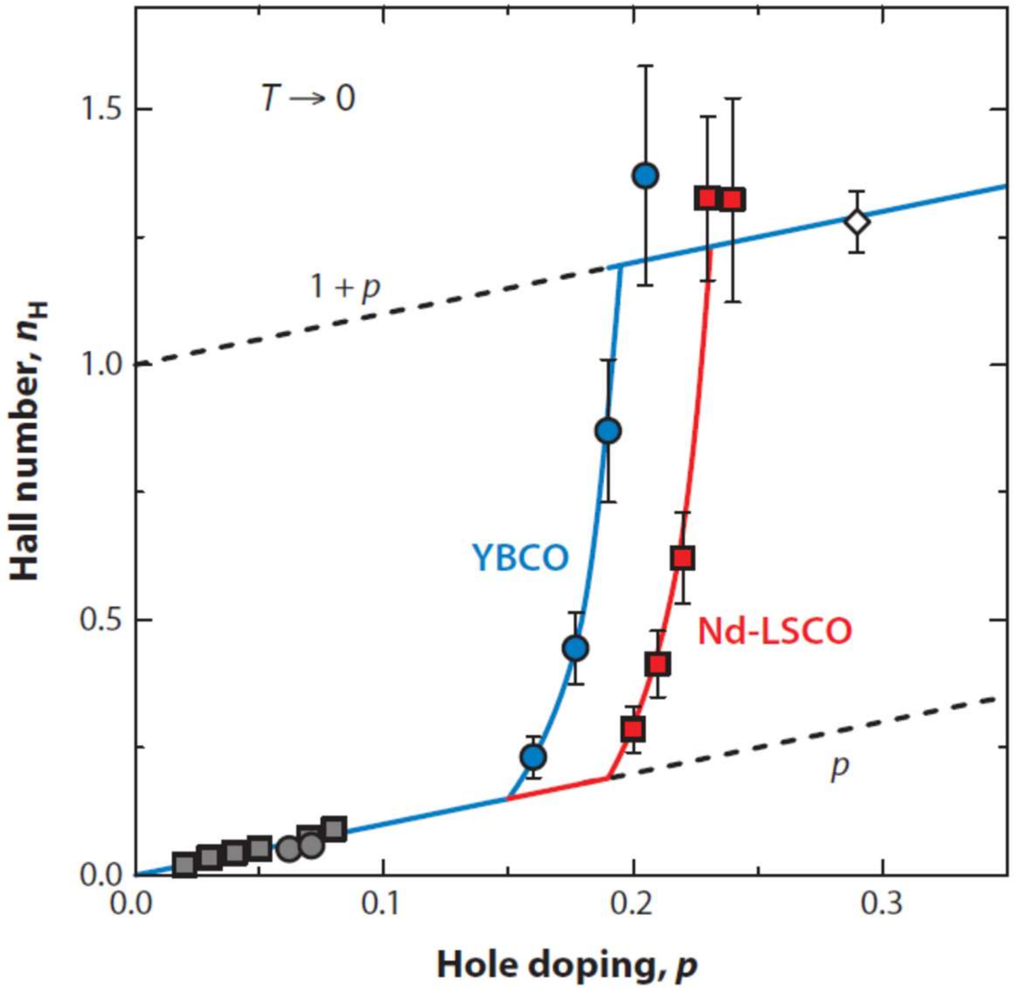


Pseudogap = sharp drop of carrier density from *n* = 1 + *p* to *n* = *p*

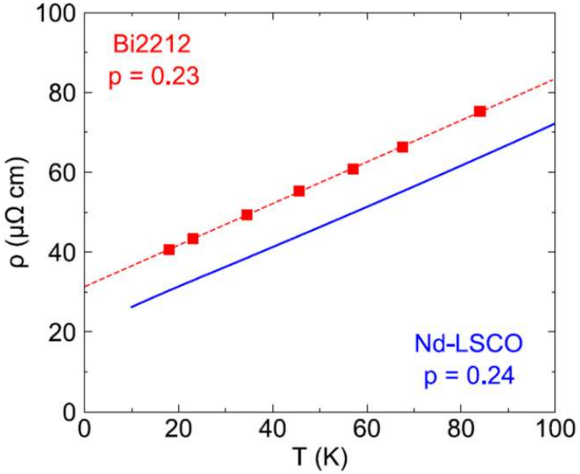
Badoux, CP *et al*., Nature **531**, 210 (2016)

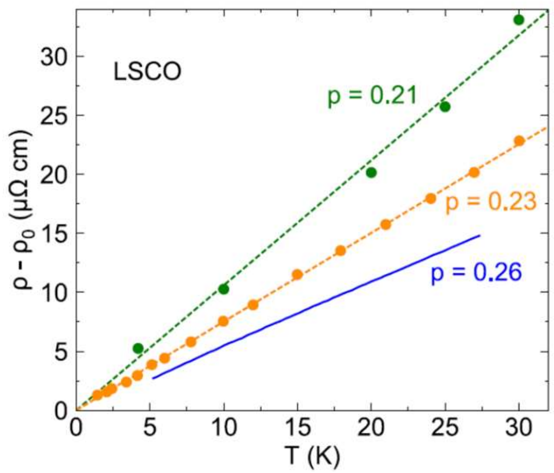
*Drop of the carrier density at p**





Pseudogap and quantum criticality

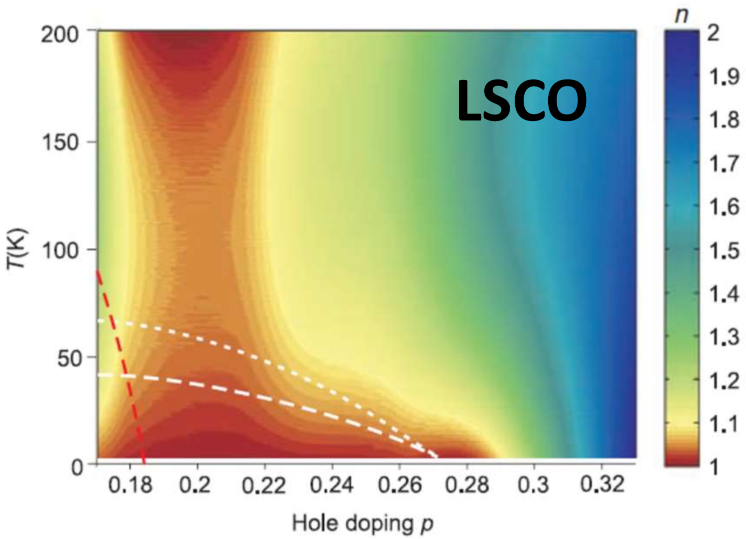




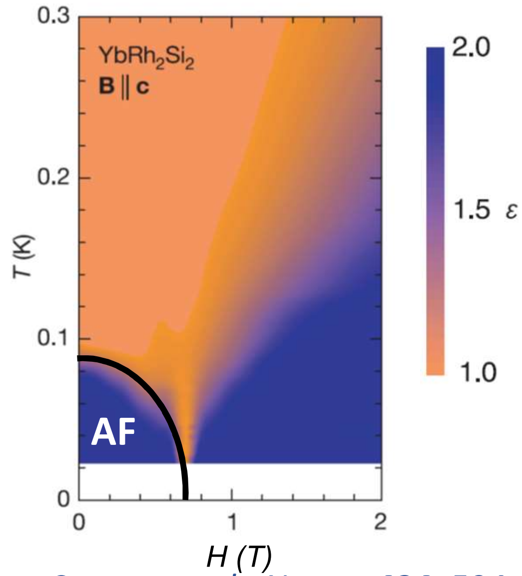
T-linear resistivity observed in many overdoped cuprates

$$\Gamma(T) \approx \ k_B T$$

$$\Delta\rho_{ab}(T) = \alpha_n T^n$$



Cooper, CP *et al.*, *Science* **323**, 603 (2009)



Heavy Fermions

$$\rho = \rho_0 + A' \, T^{\varepsilon}$$

Custers *et al.*, *Nature* **424**, 524 (2003)

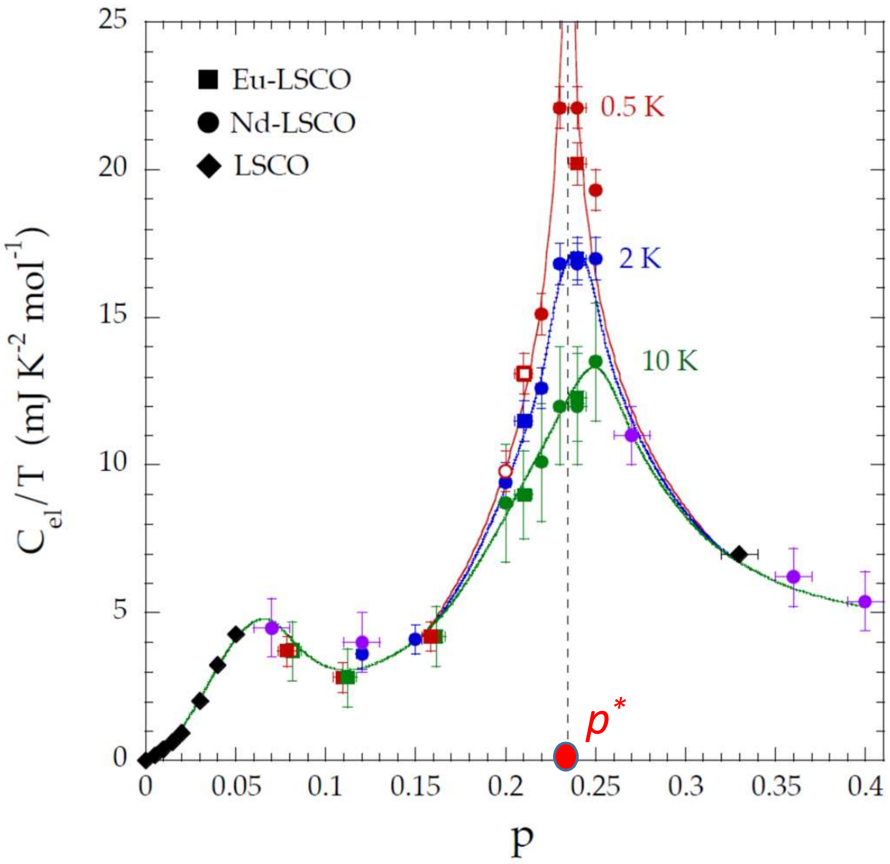
Pseudogap and quantum criticality

T. Klein, C. Marcenat / L. Taillefer

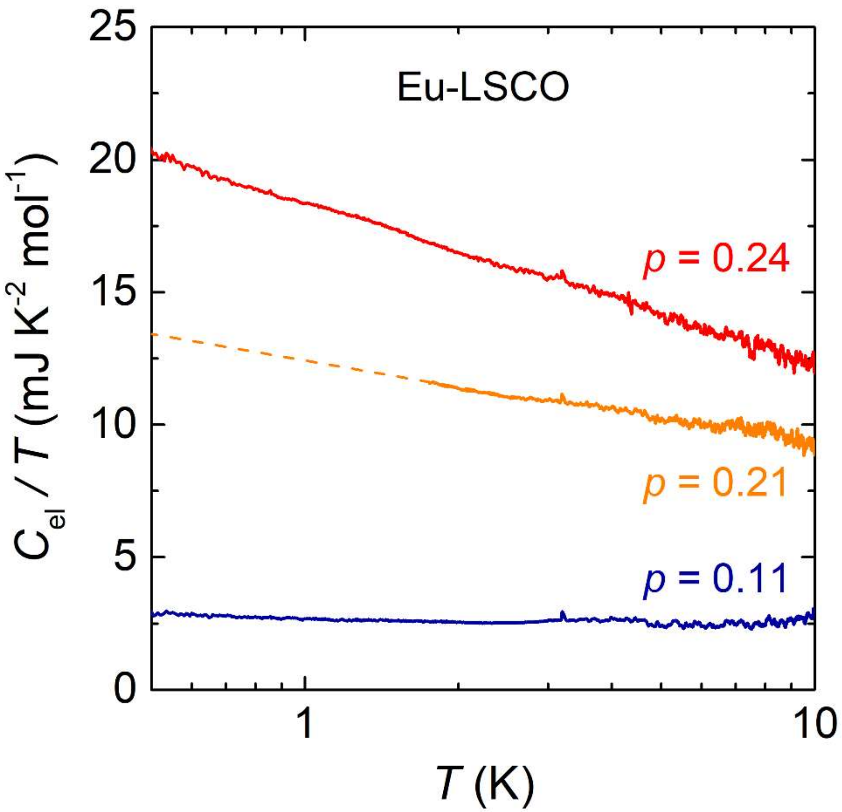
Thermodynamic 'police' $\gamma = \frac{\pi N_A k_B^2}{3\hbar^2} a^2 m^*$

Peak in the electronic specific heat at low *T*

$C_v \sim \ln \frac{1}{T}$

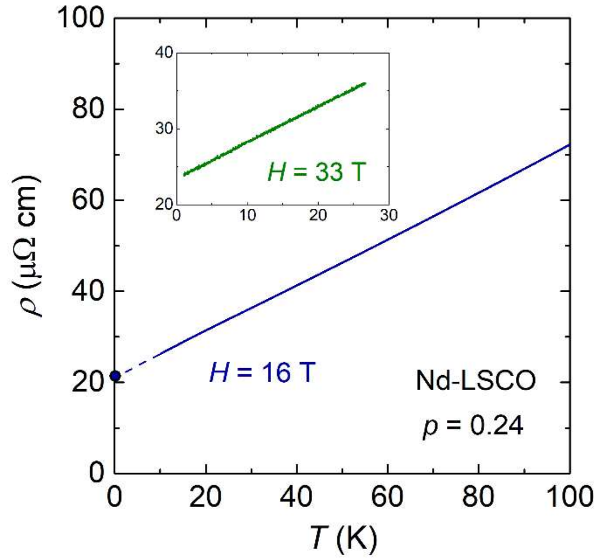


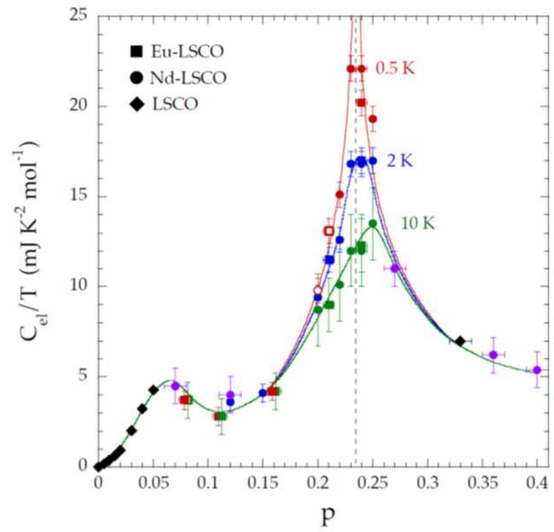
Michon et al, *Nature* **567**, 218 (2019)

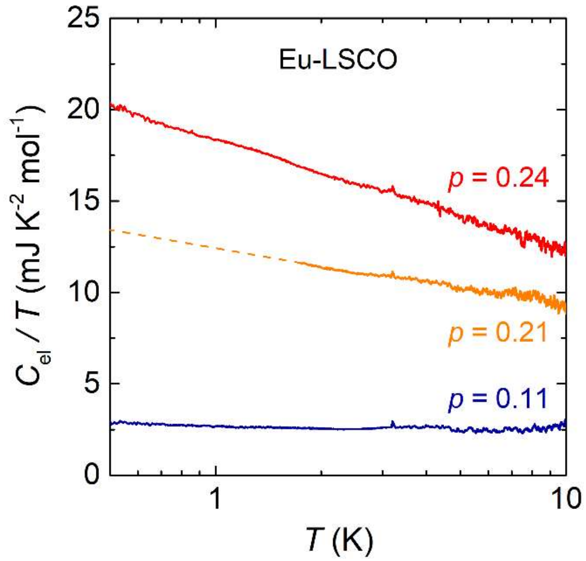


Pseudogap and quantum criticality

Classical signatures of QCP







However a diverging length scale is still missing in hole-doped cuprate !

e.g. in heavy fermions: AF correlation length $\xi_{AF} \rightarrow \infty$

as tuning parameter $g \rightarrow$ QCP

Conclusion

- Cuprates have the highest T_c and host new states of matter due to strong electronic correlations (pseudogap, bad metal behavior…).

- Pseudogap is unique to hole-doped cuprate and hosts a variety of quantum orders identified recently.

- There are classical signatures of quantum criticality at the pseudogap critical point but a diverging length scale is still missing.

- High magnetic fields to remove superconductivity have play a major role in probing the underlying ground state at low temperature where signatures are sharper.

C. Proust & L. Taillefer, *Annual Review of Condensed Matter Physics* **10**, 409 (2019)