



CIFAR
CANADIAN INSTITUTE
for ADVANCED RESEARCH

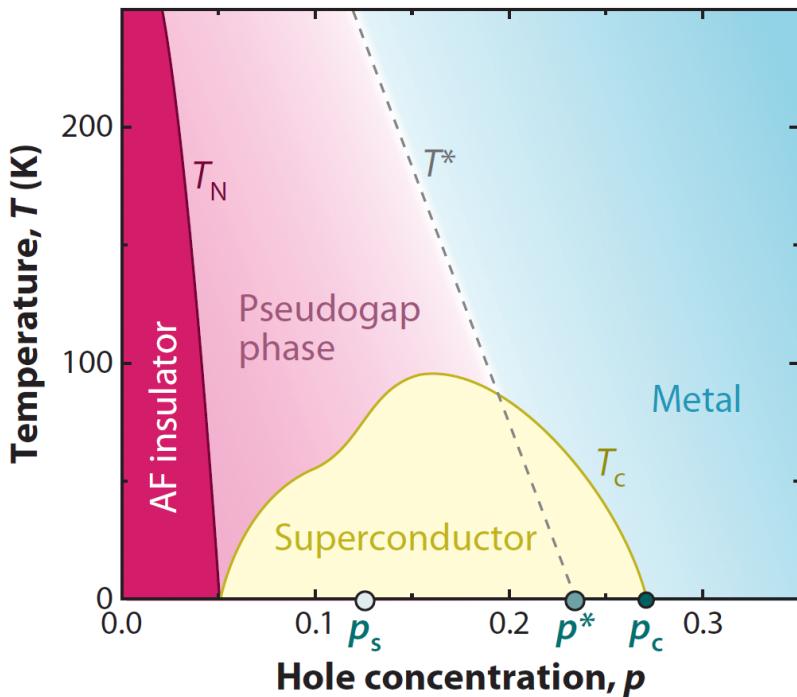
The two-way interplay of **Magnetism & Superconductivity**

Louis Taillefer
University of Sherbrooke
CIFAR Quantum Materials Program

QM Summer School, Montréal, 4 May 2010

Cuprates: questions

Cuprates

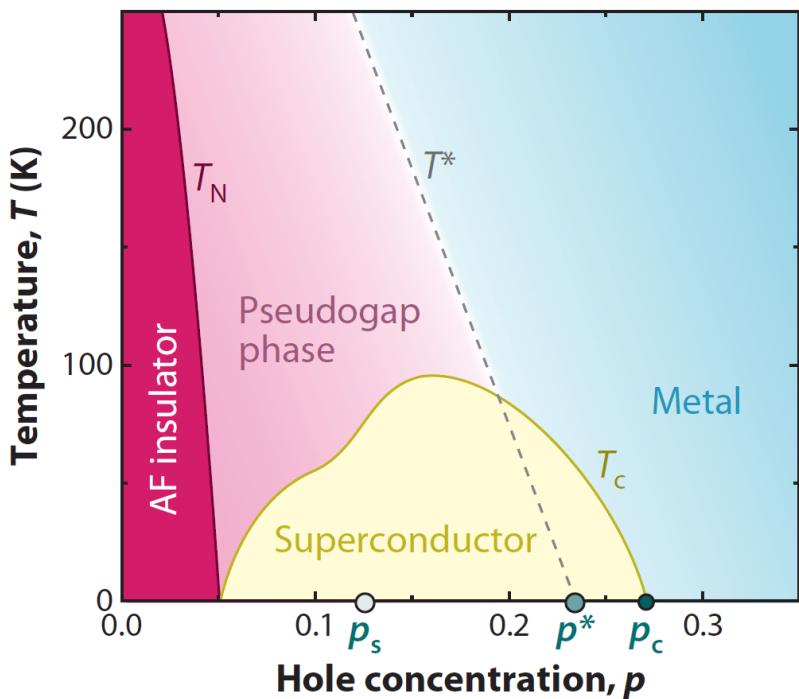


1 – What causes superconductivity ?

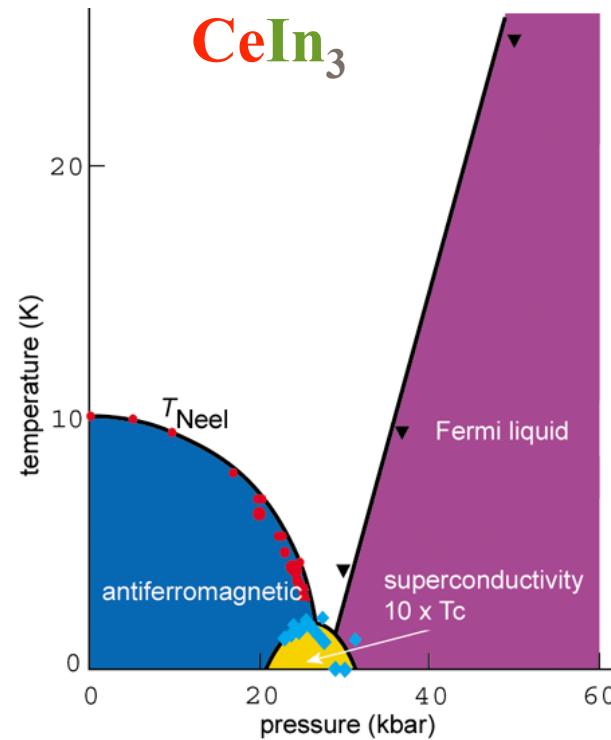
2 – What is the pseudogap phase ?

Cuprates: questions

Cuprates



Heavy fermions



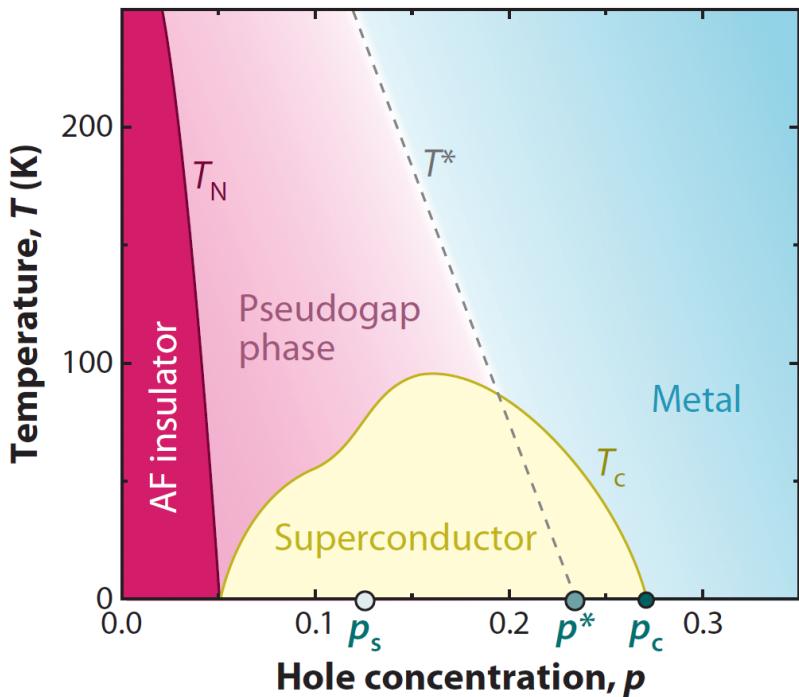
N. Mathur et al., Nature 1998

QM Summer School

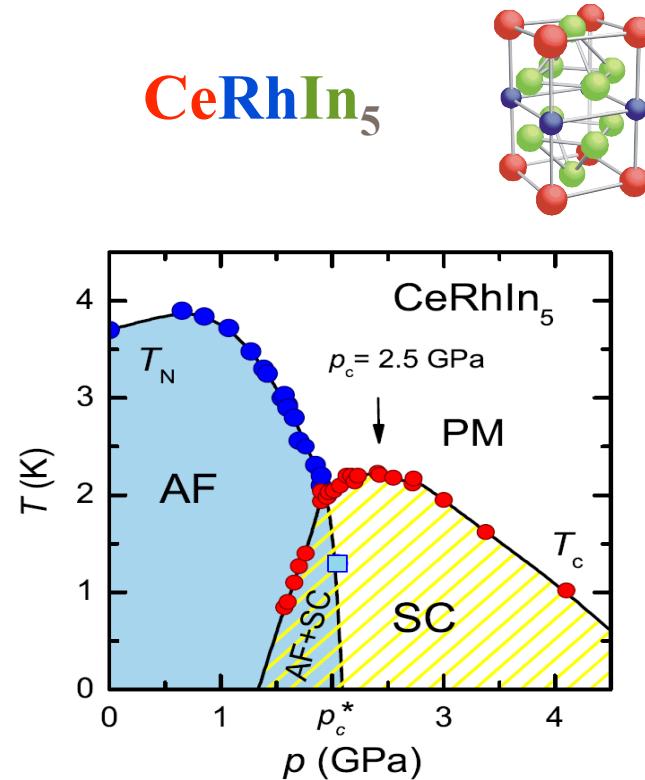
4 May 2010

Cuprates: questions

Cuprates



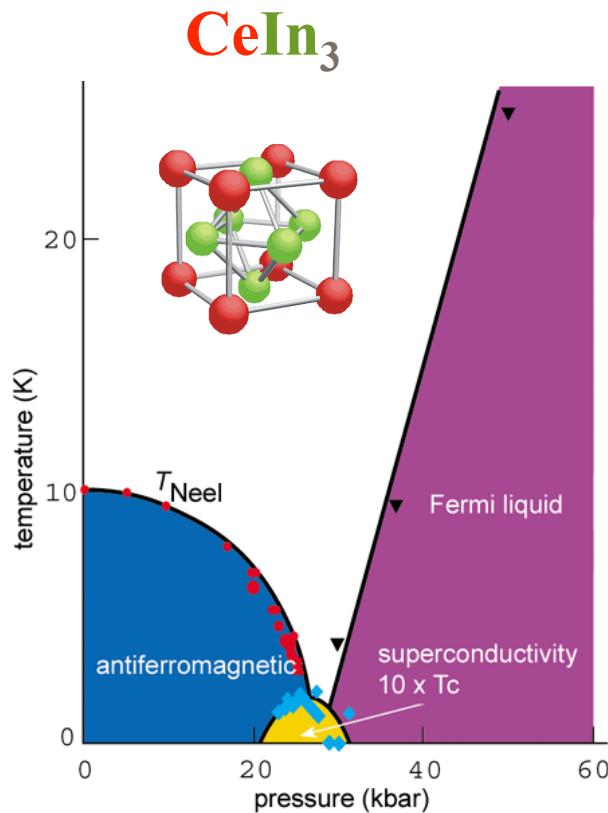
Heavy fermions



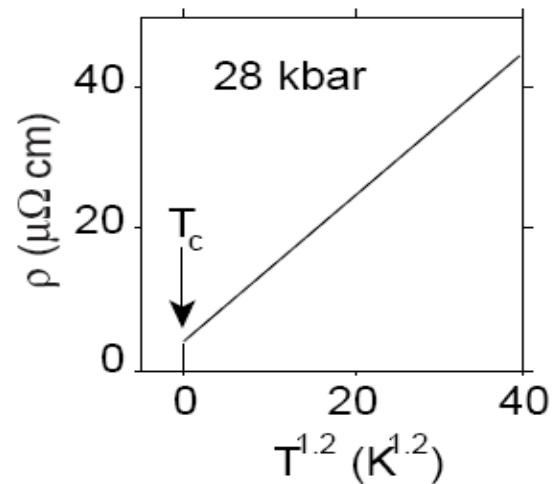
G. Knebel et al., arXiv 2010

Quantum Criticality

Heavy fermions

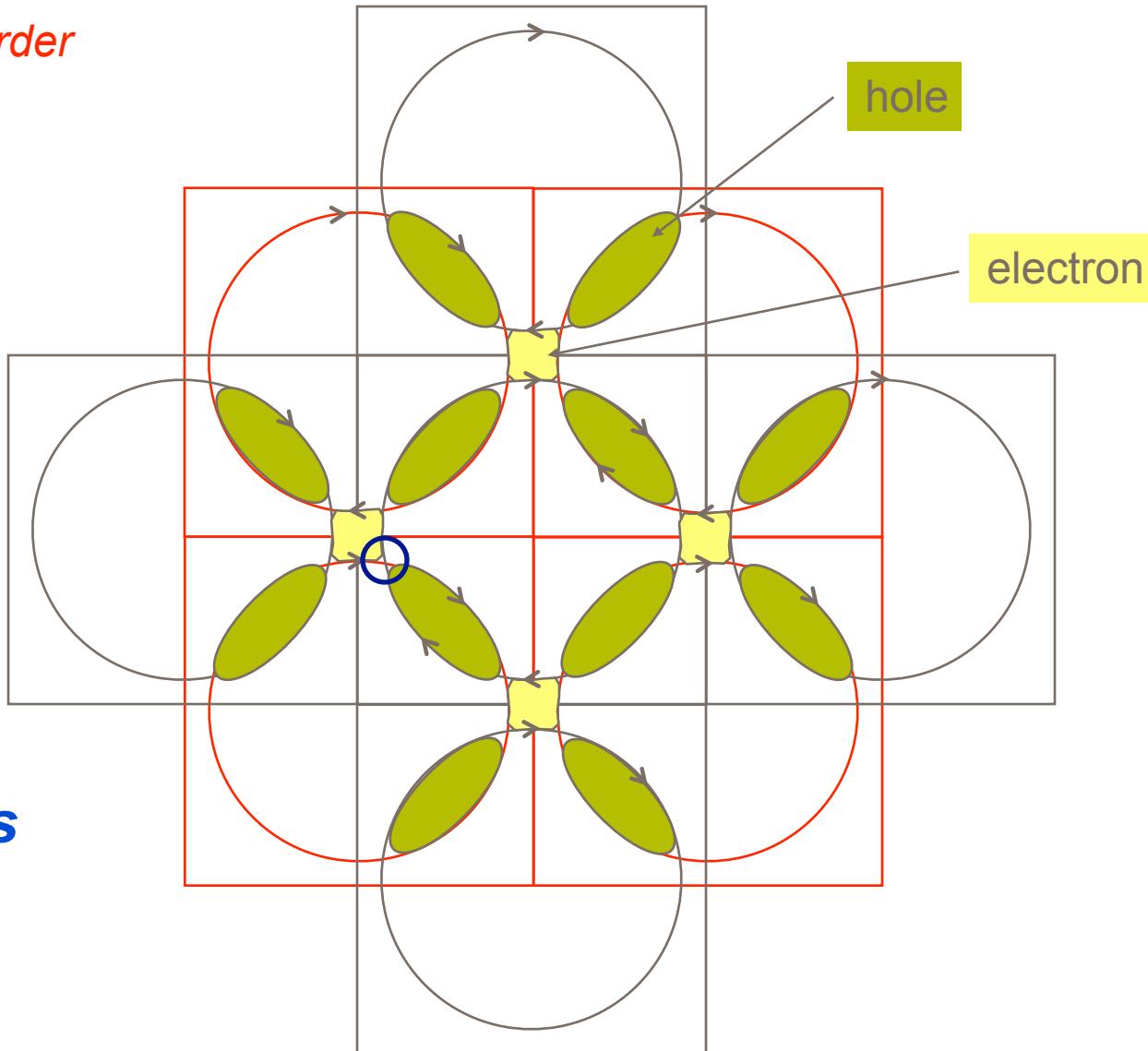


N. Mathur et al., Nature 1998



Fermi surface reconstruction

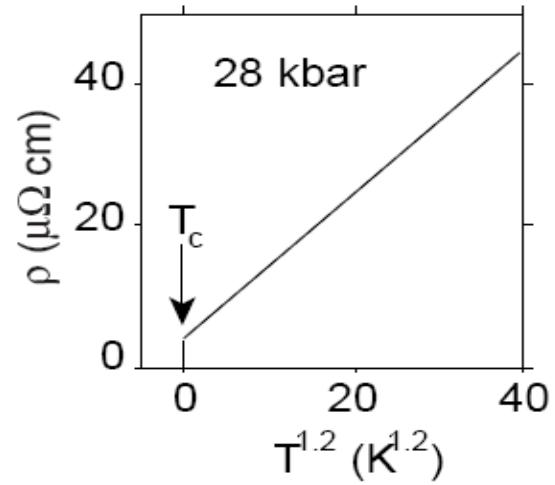
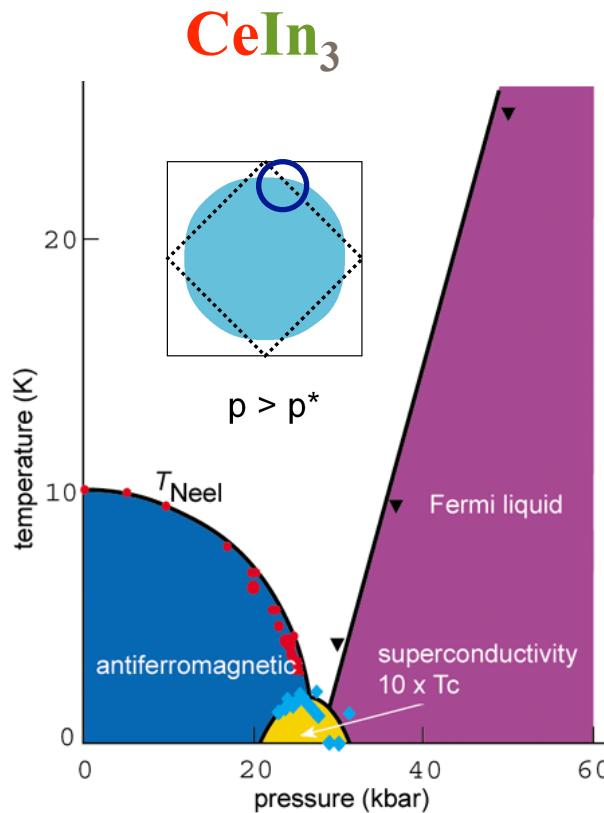
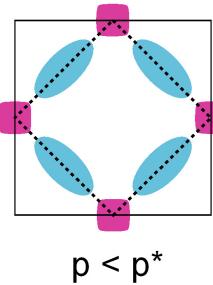
(π, π) AF order



Quantum Criticality

Heavy fermions

Hot spots

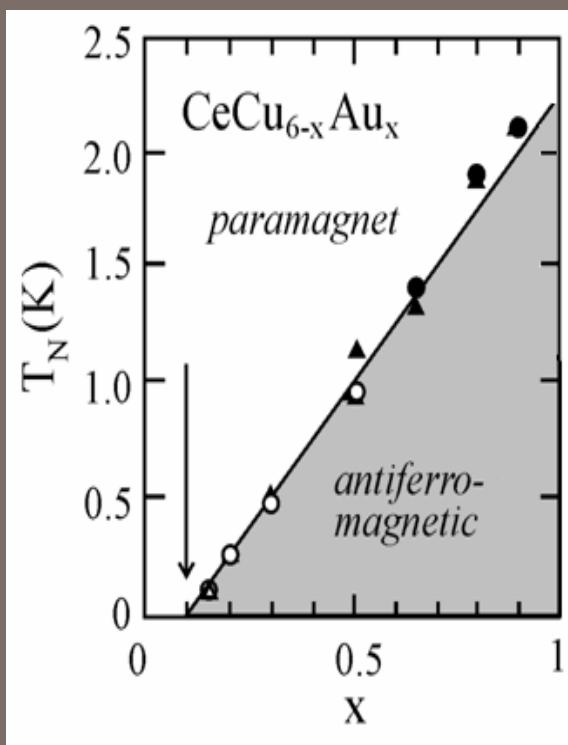


???

Heavy-Fermion Quantum Criticality

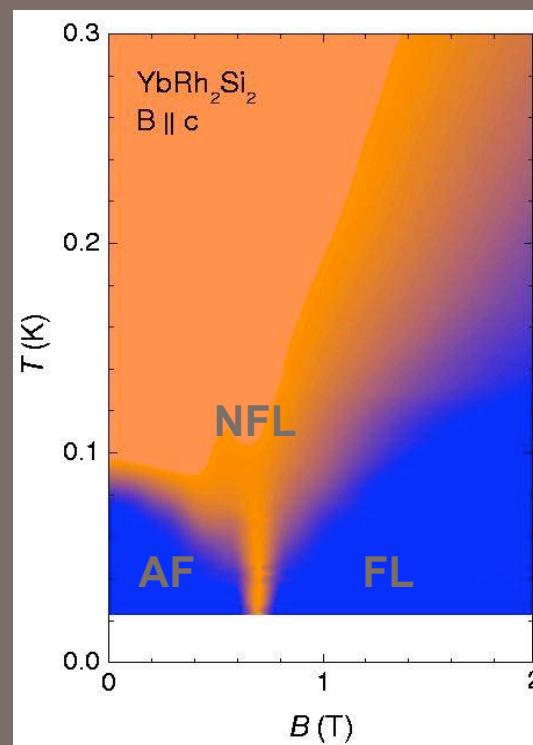
Tuning parameters:

- composition



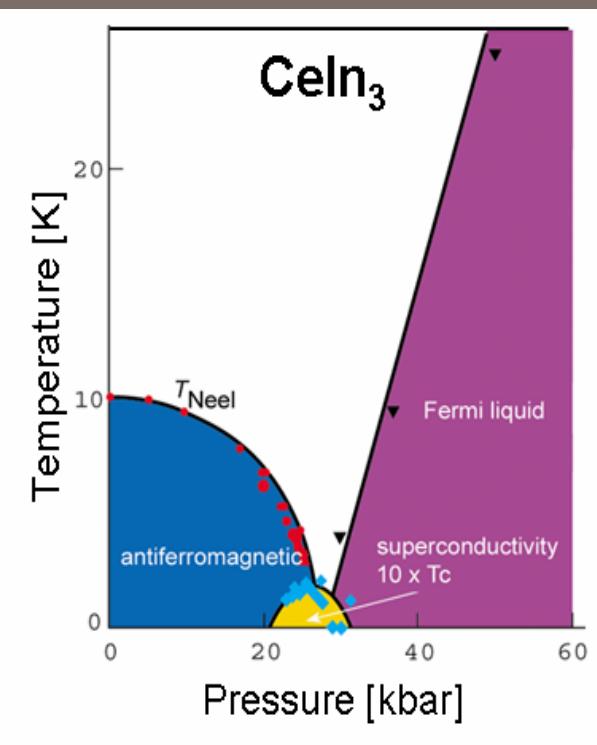
H. v. Löhneysen *et al.* (1994)

- magnetic field



J. Custers *et al.* (2002)

- pressure

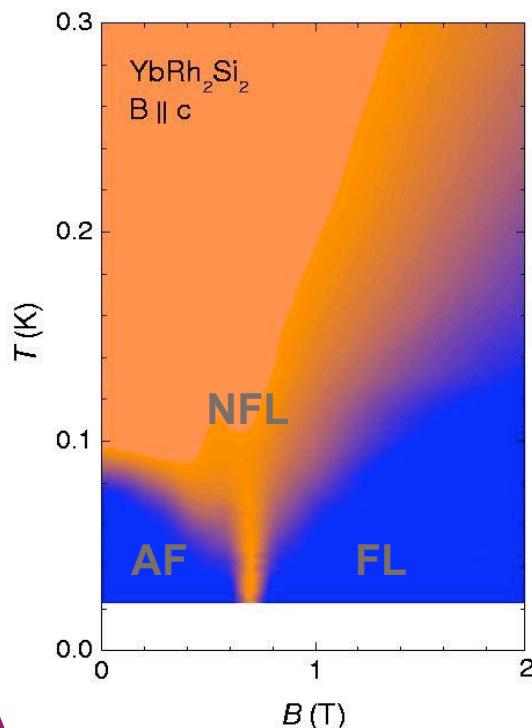


N.D. Mathur *et al.* (1998)

Heavy fermions: questions

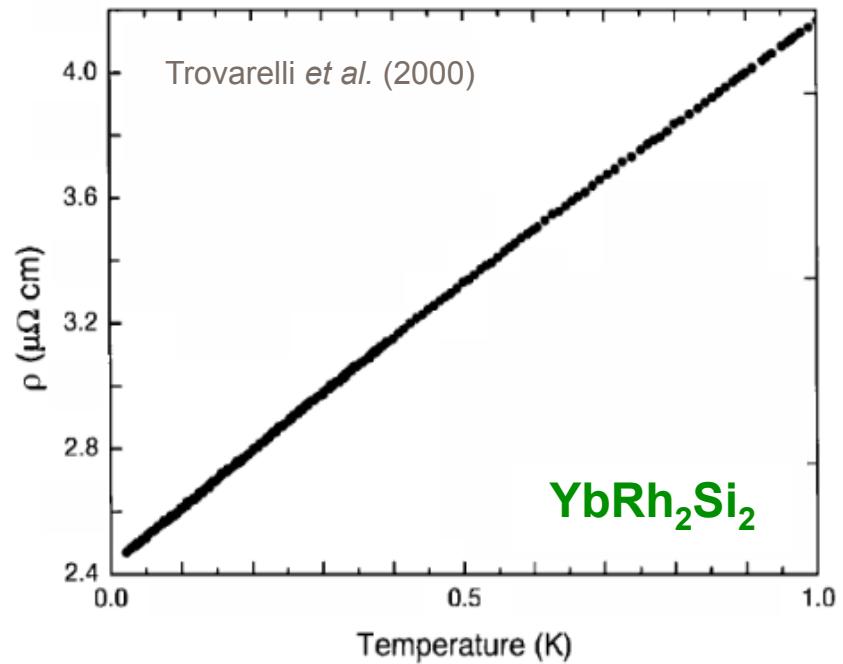
1 – What causes superconductivity ?

2 – What causes NFL behaviour ?



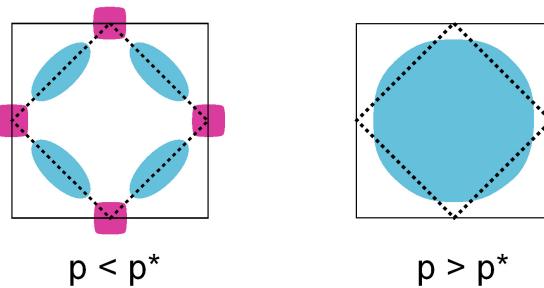
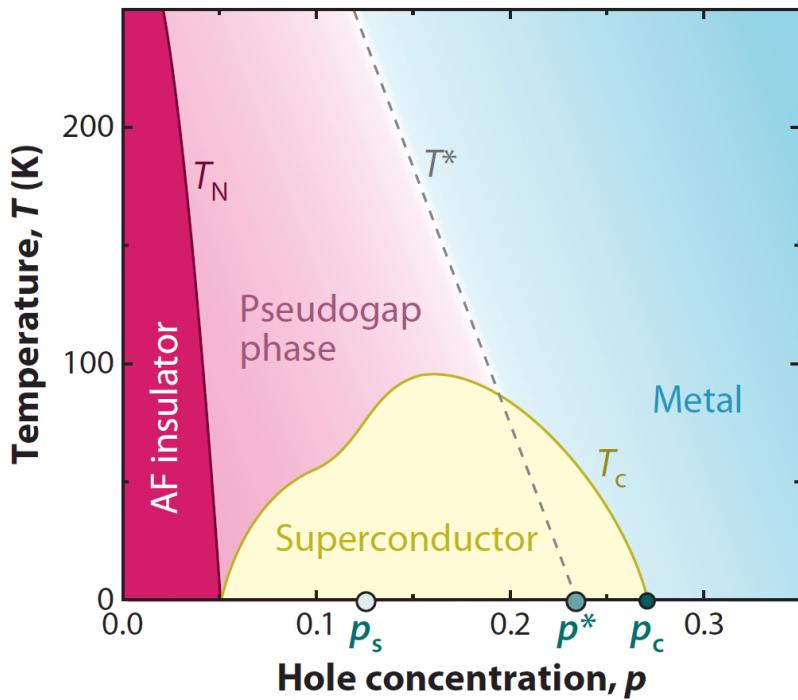
J. Custers *et al* (2002)

Linear- T resistivity



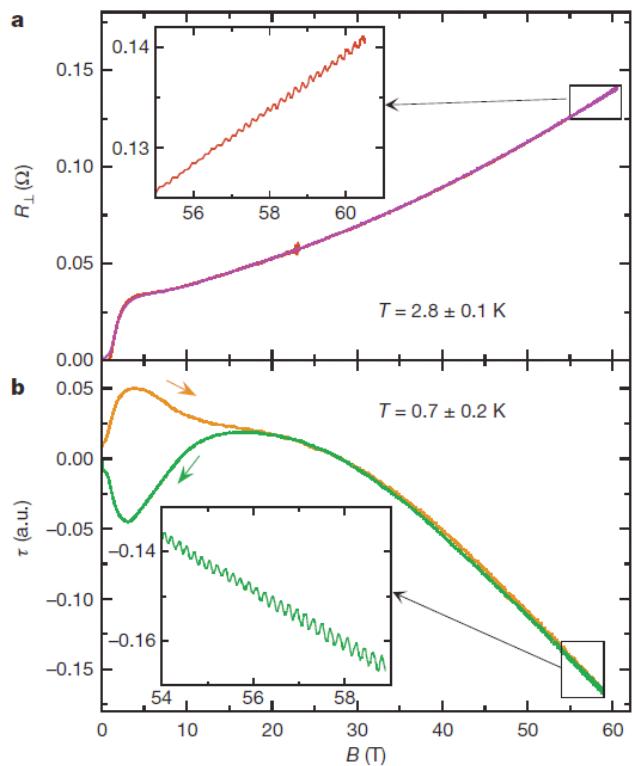
YbRh_2Si_2

Cuprates: Fermi surface reconstruction ?



Quantum oscillations in cuprates

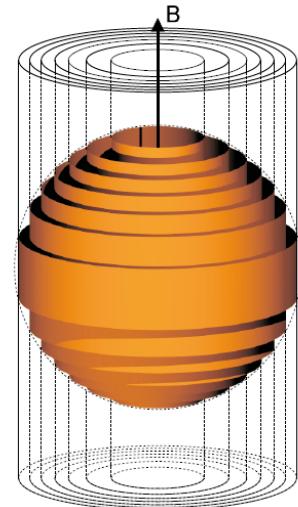
B. Vignolle et al., 2008



Landau quantization

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

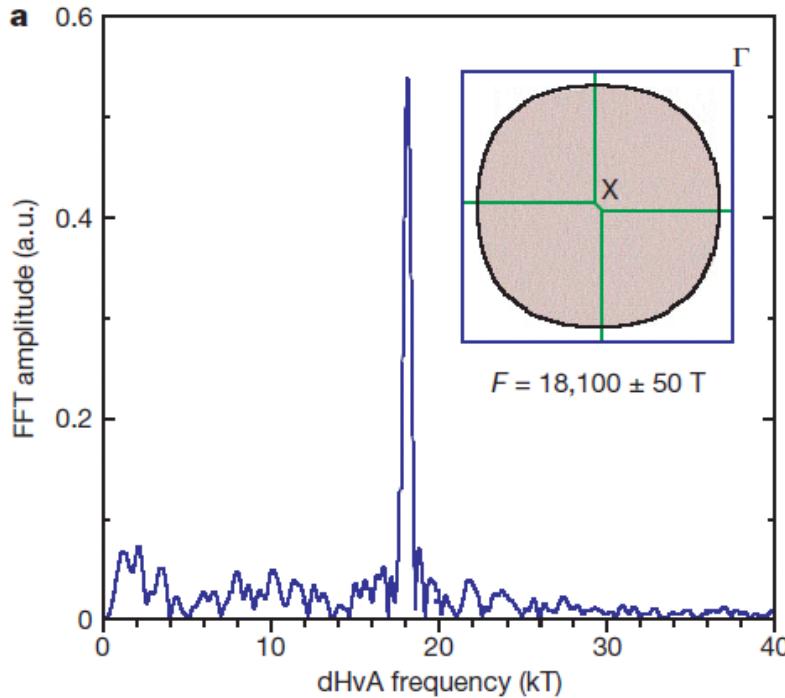
$$F = \frac{\Phi_0}{2\pi^2} A_k$$



Overdoped TI-2201 $p = 0.3$

Quantum oscillations in cuprates

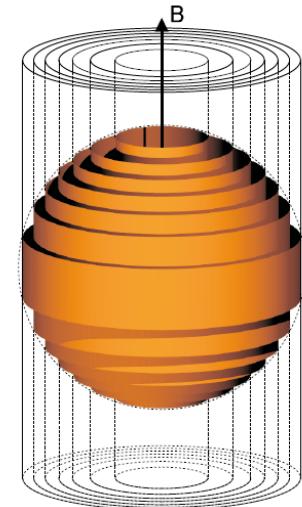
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Landau quantization

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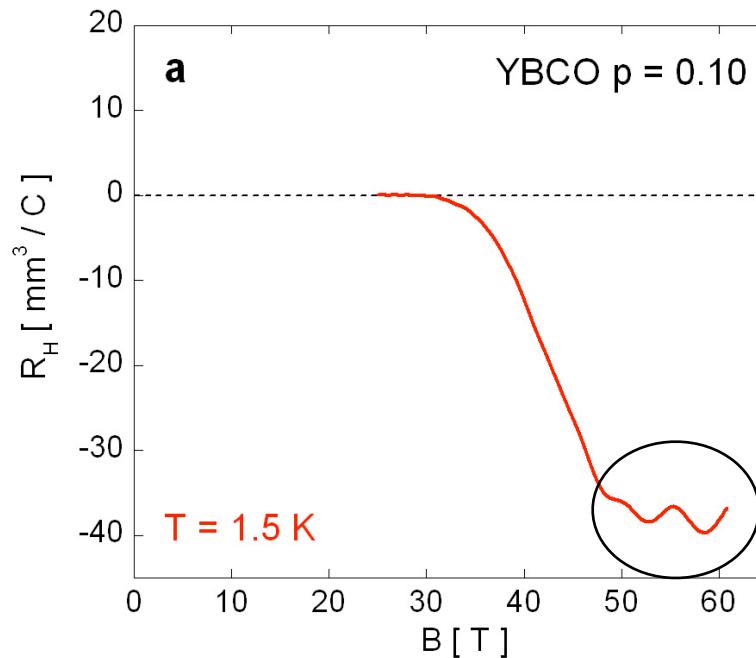
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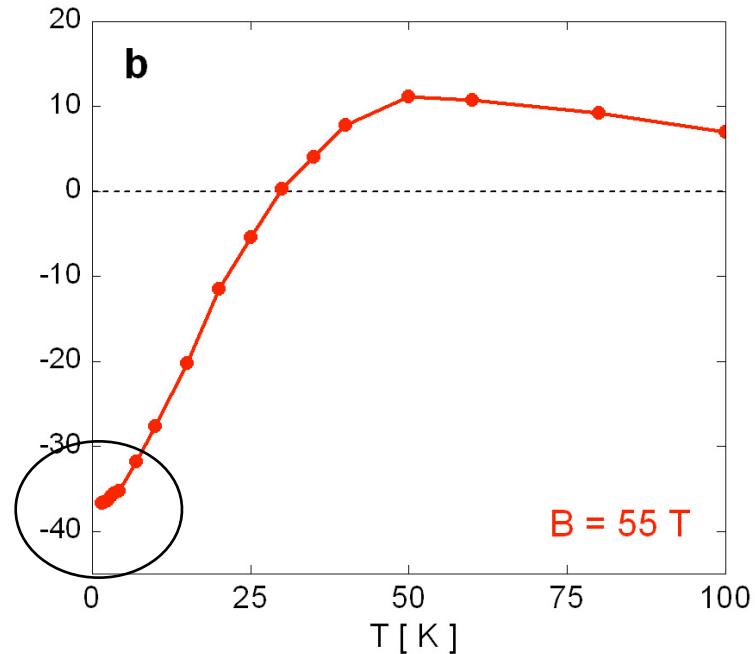
Overdoped TI-2201 $p = 0.3$

Quantum oscillations in cuprates

N. Doiron-Leyraud et al., Nature 2007



D. LeBoeuf et al., Nature 2007



Quantum oscillations

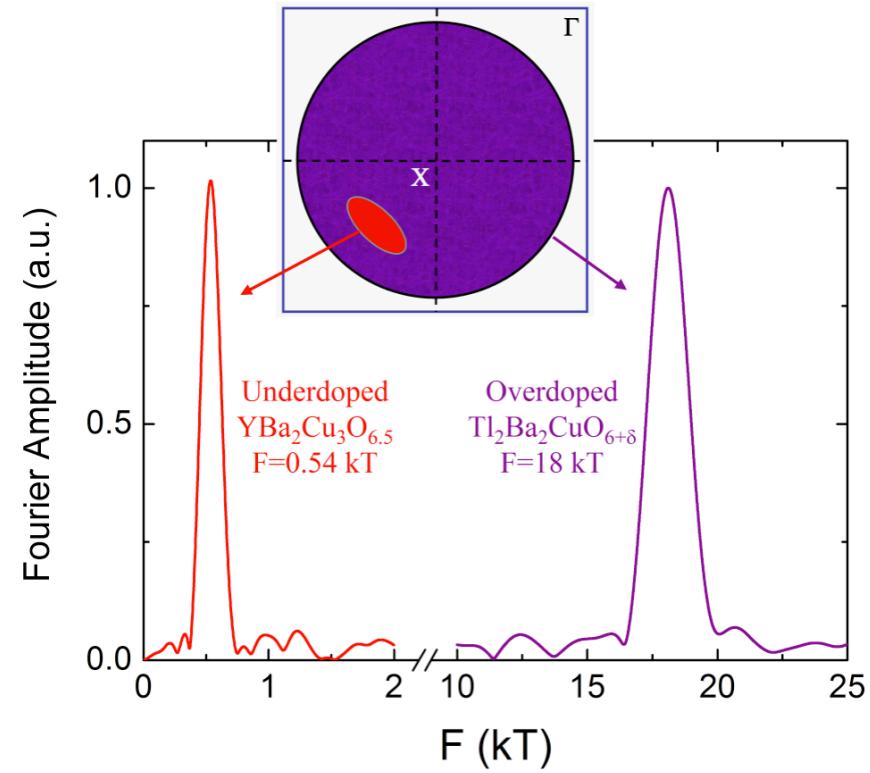
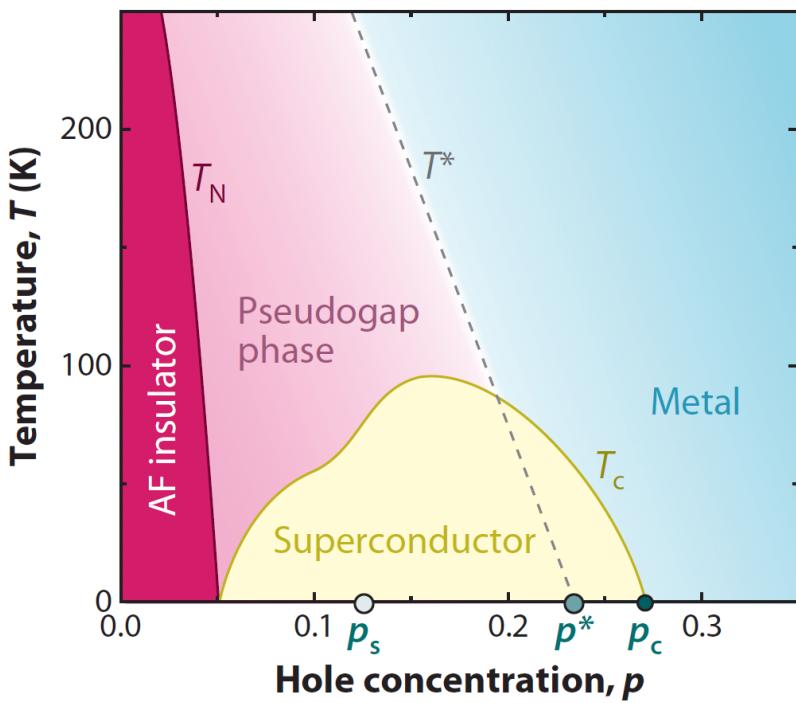
$R_H < 0$

Fermi surface includes a small *electron pocket* !

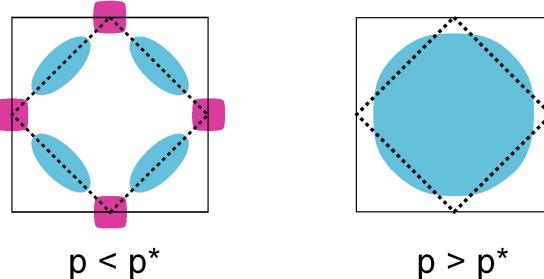
Underdoped YBCO $p = 0.1$

QM Summer School
4 May 2010

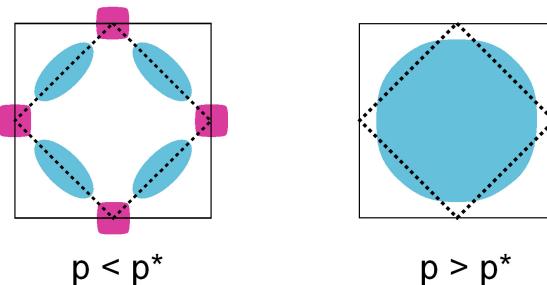
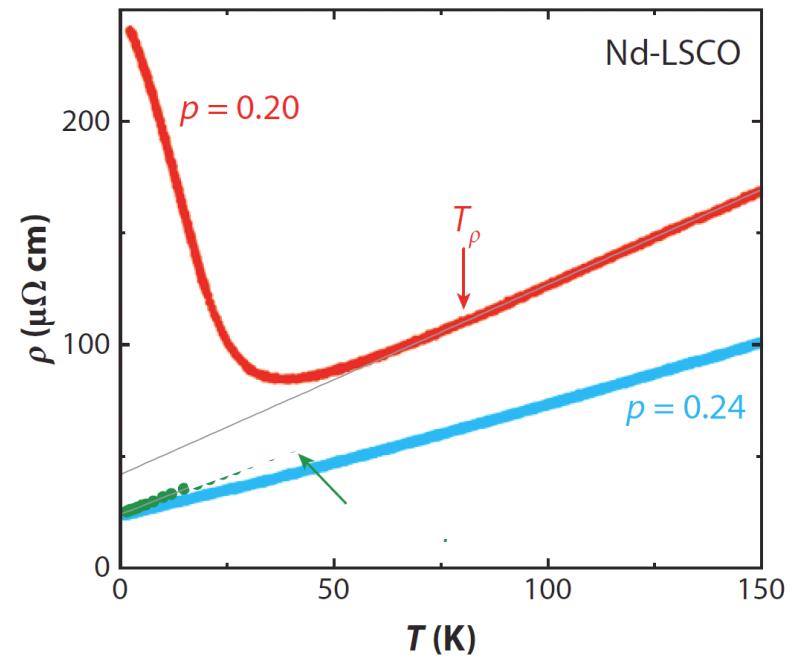
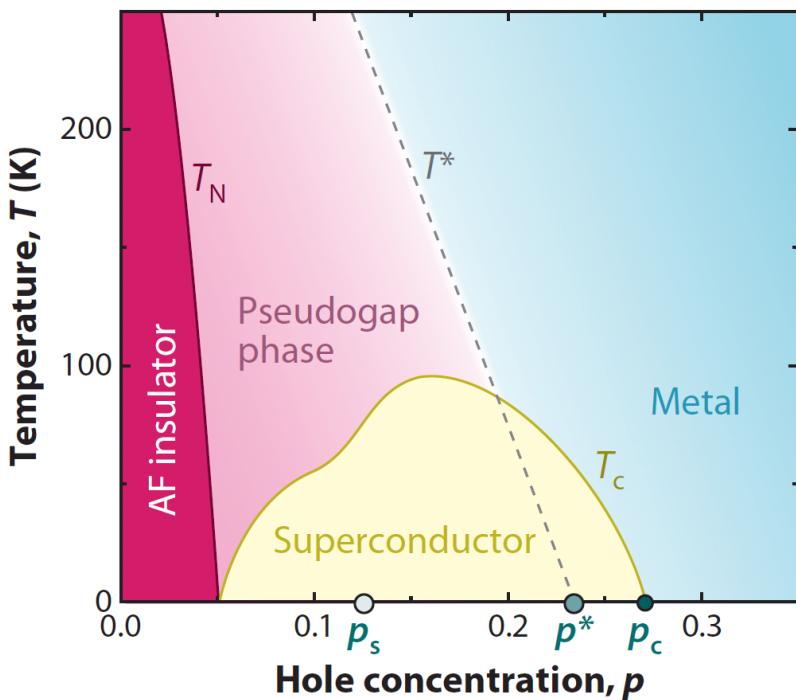
Cuprates: Fermi surface reconstruction



C. Proust et al., 2009

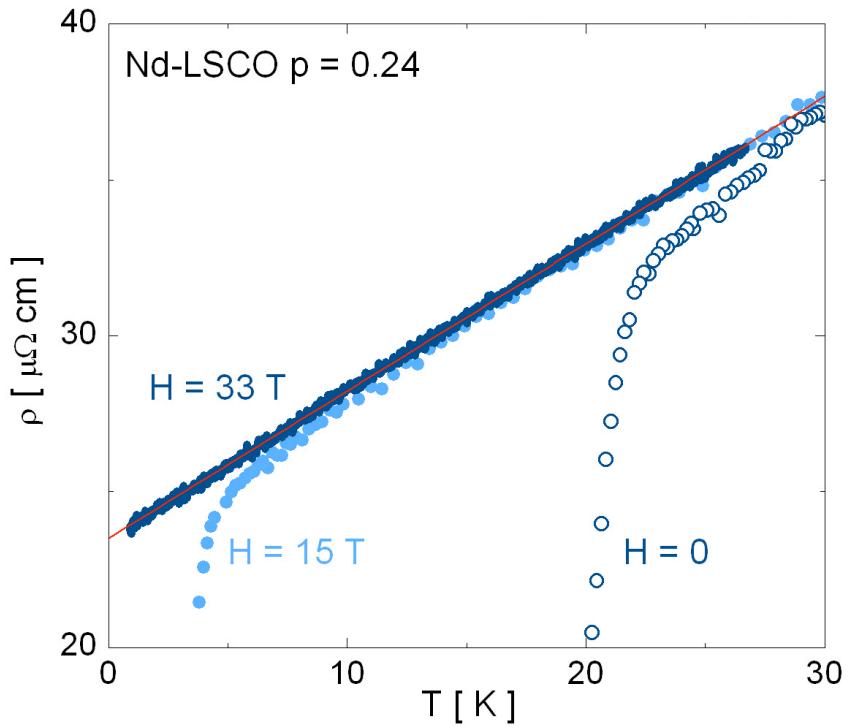
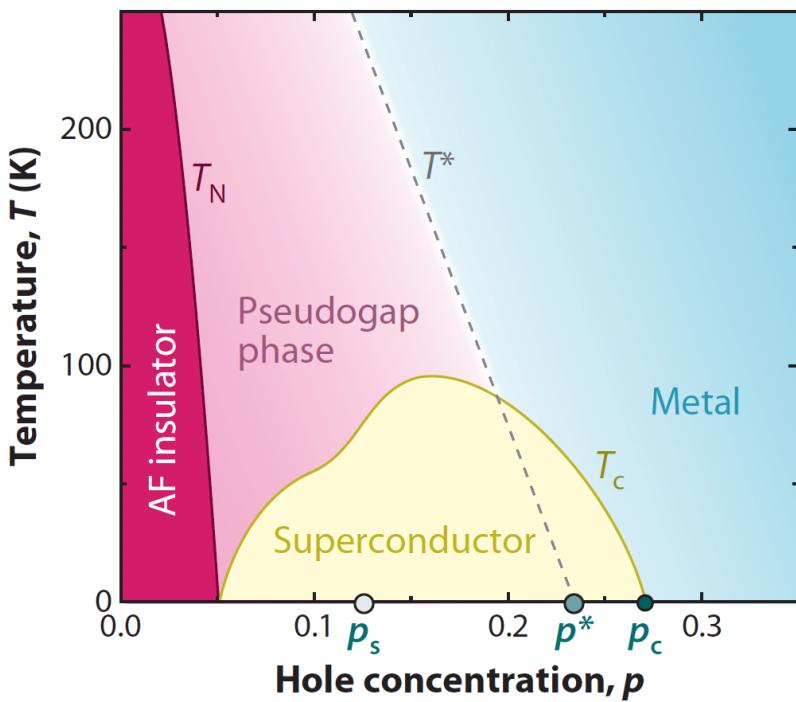


Cuprates: Quantum critical point



R. Daou et al., *Nature Physics* 2009

Cuprates: Linear-T resistivity

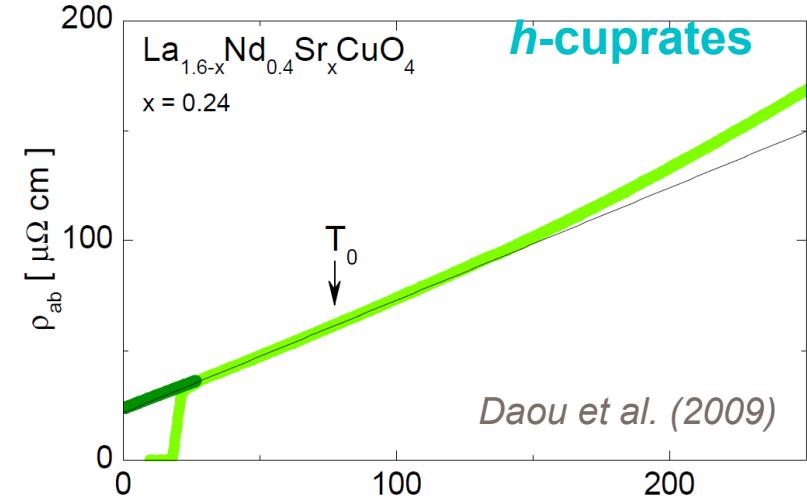
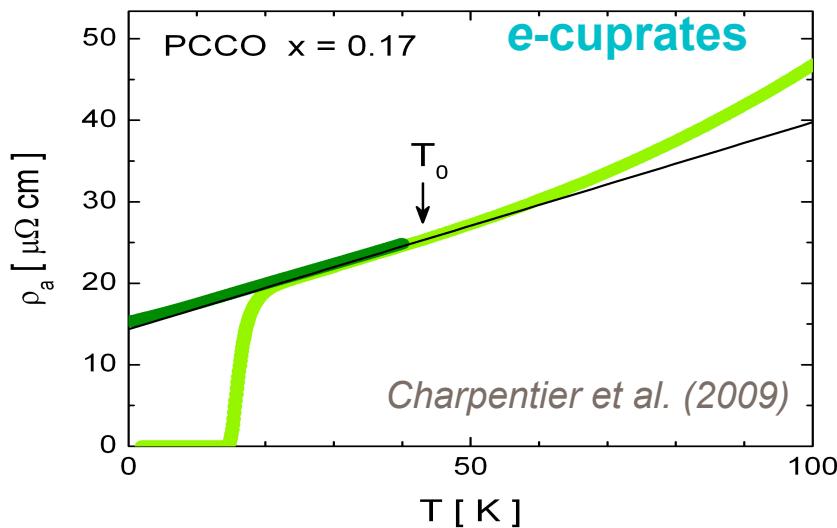
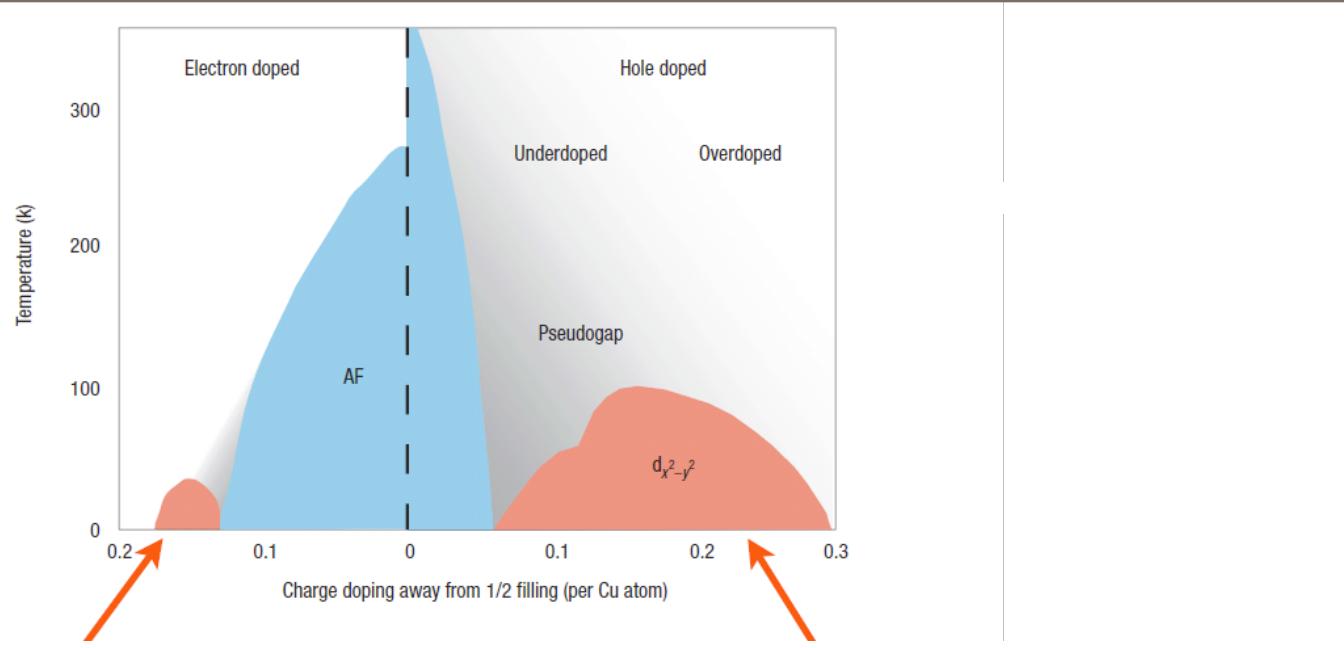


R. Daou et al., Nature Physics 2009

Quantum criticality !



e-doped cuprates: Quantum criticality



Superconductivity & Quantum Criticality

Two major phenomena : SUPERCONDUCTIVITY
QUANTUM CRITICALITY

Two big questions : Pairing mechanism ?
 Mechanism for non-Fermi-liquid behaviour ?

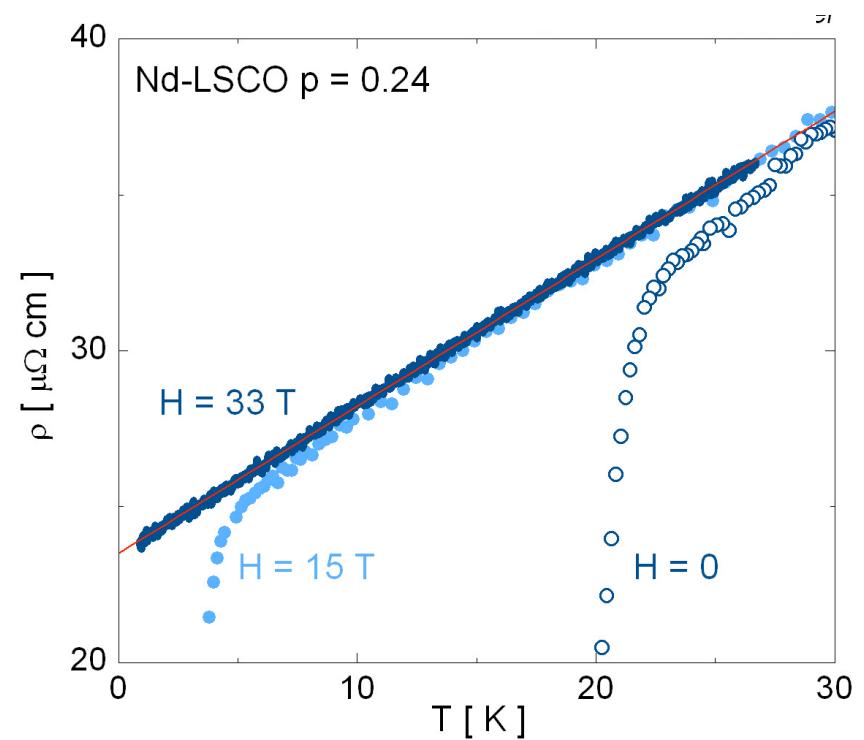
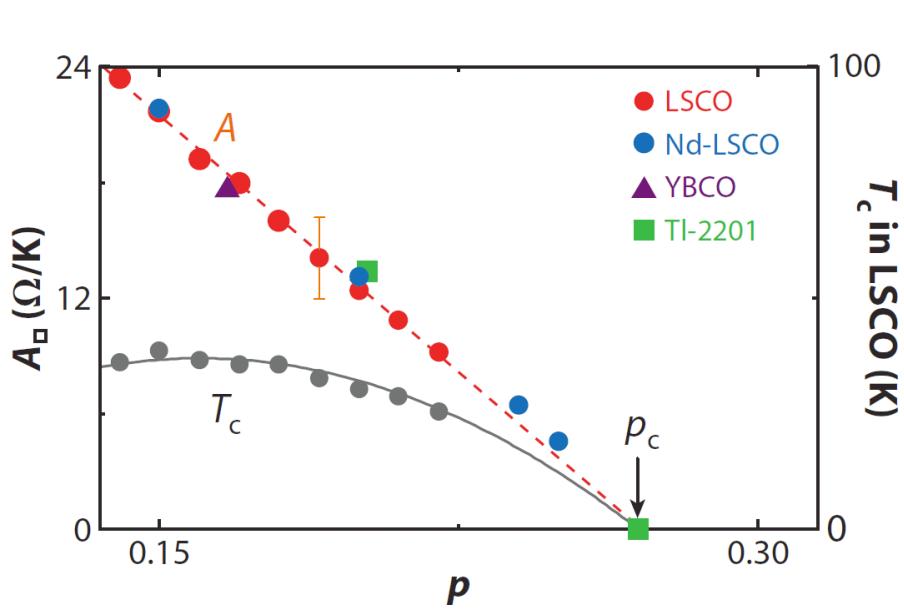
The answer : Coupling of Pairing correlations
 & Spin fluctuations

A reference : L. Taillefer
Scattering and pairing in cuprate superconductors
Annual Review of Condensed Matter Physics
arXiv:1003.2972

A clue.



Cuprates: Linear-T resistivity



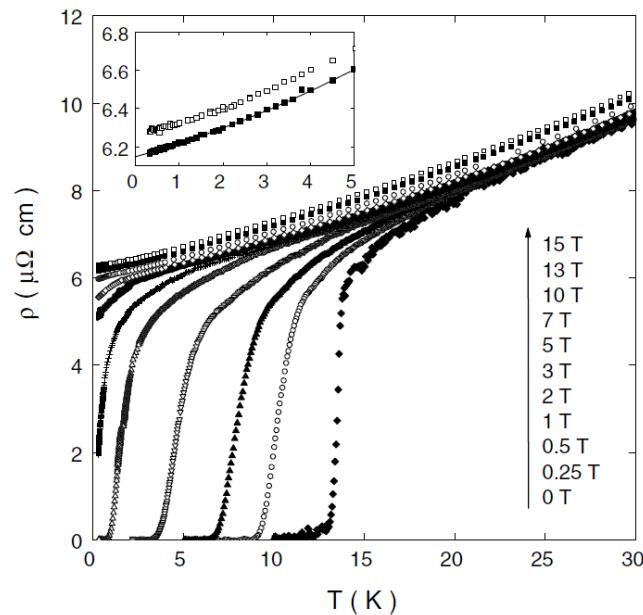
N. Doiron-Leyraud et al., arXiv:0905.0964

R. Daou et al., Nature Physics 2009

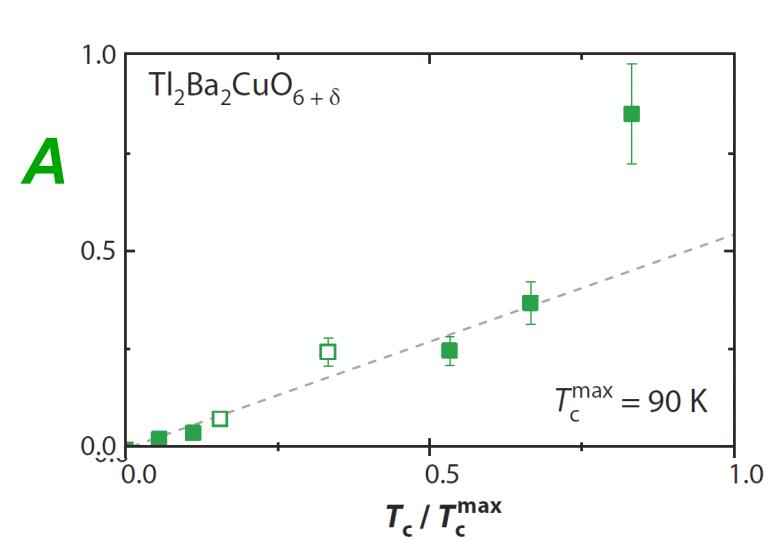


Cuprates: Linear-T resistivity & T_c

C. Proust et al., PRL 2002



N. Doiron-Leyraud et al., arXiv:0905.0964



Manako et al., PRB 1992

Empirical correlation : **Linear- T resistivity** \longleftrightarrow T_c

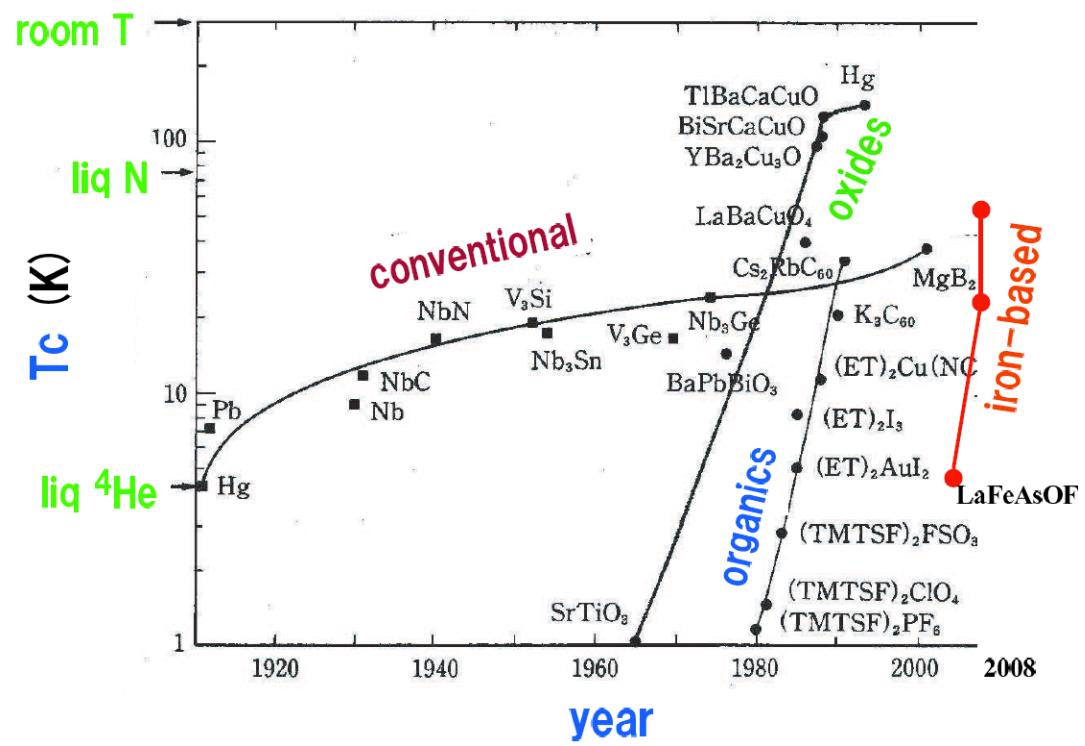
The New Superconductors

1979 – Heavy fermions

1980 – Organics

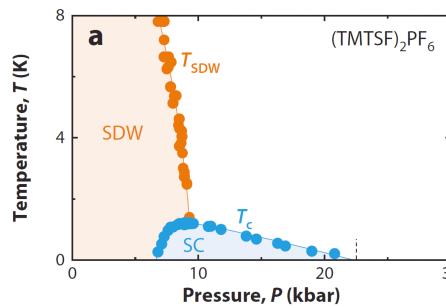
1986 – Cuprates

2008 – Pnictides

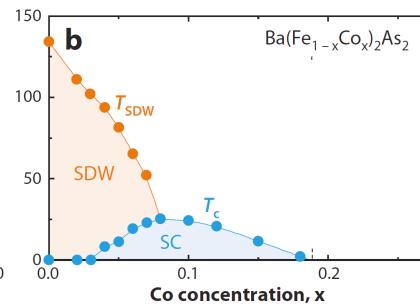


The New Superconductors

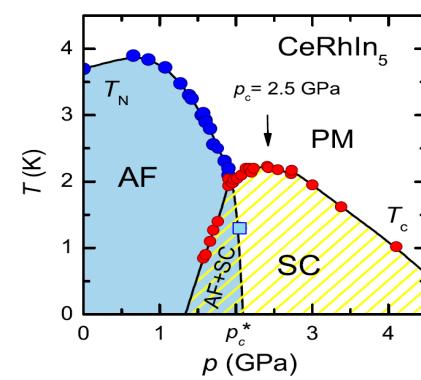
Organics



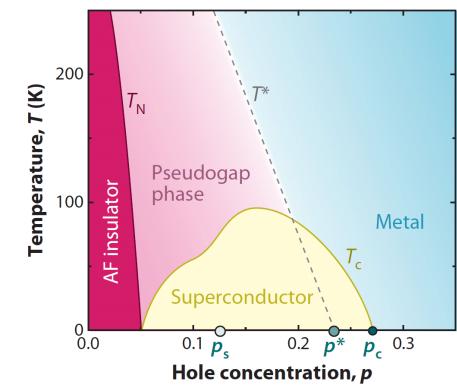
Pnictides



Heavy fermions



Cuprates



T_c 1 K

25 K

2 K

100 K

T_N 10 K

150 K

4 K

400 K

1D

~2D

3D

2D

1 band

4 bands

5 bands

1 band

Theory

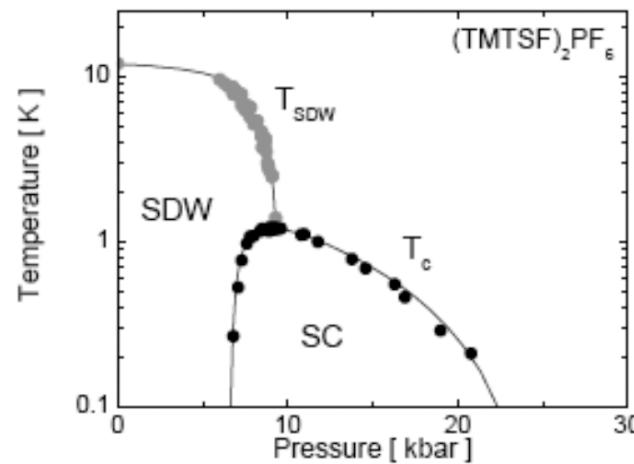
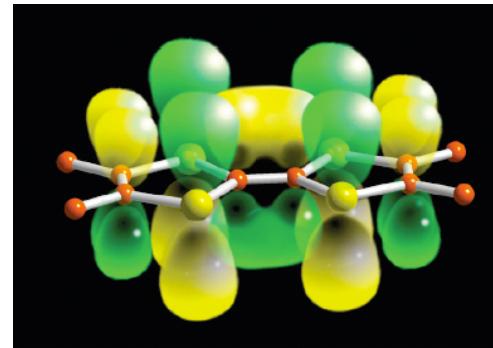
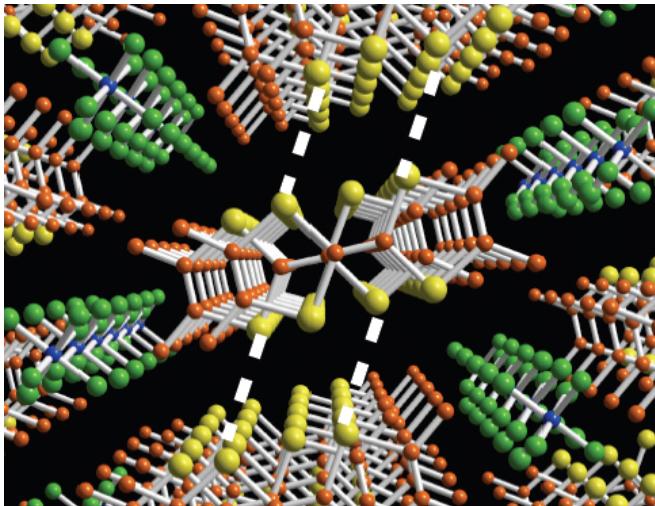
Kondo

Mott
Pseudogap

Organics: the Bechgaard salts

High-purity, stoichiometric crystals, tuned by pressure

Bechgaard



Jérôme

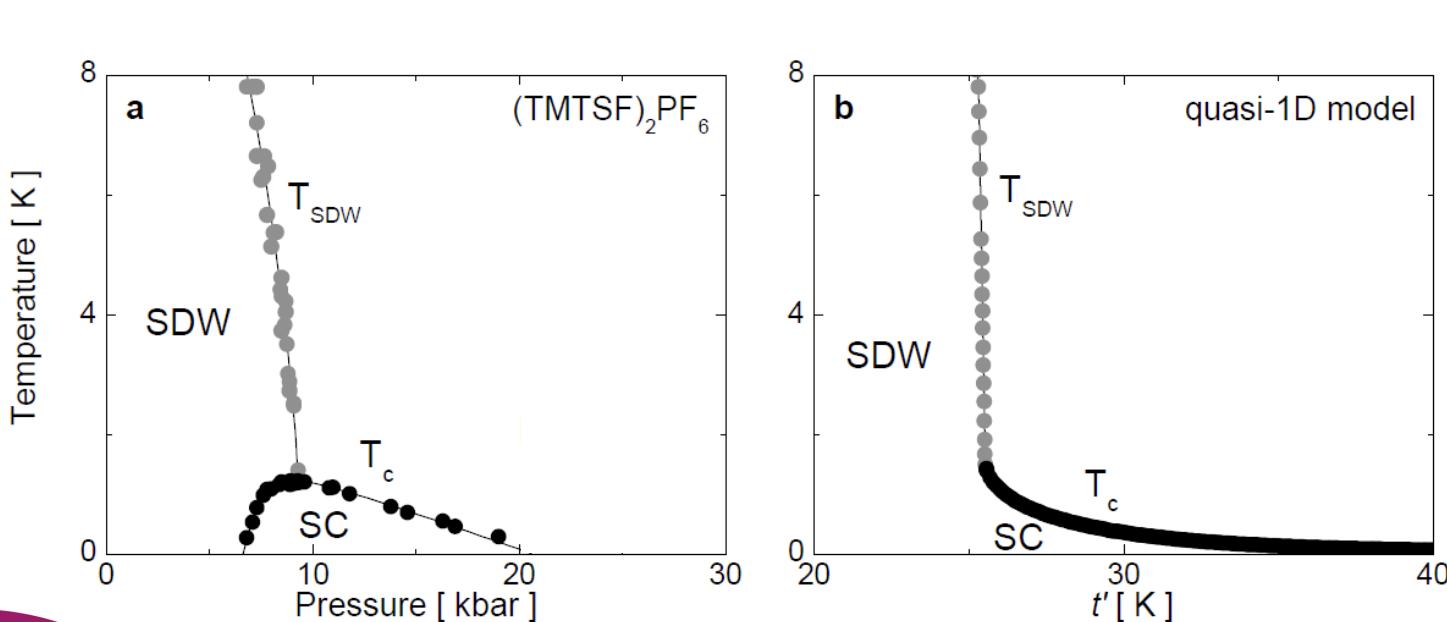
Organics: Samples, Theory & Experiment

SAMPLES: Crystals and contacts

Jérôme



THEORY: Functional renormalization group approach



Bourbonnais et al. (2009)



Bourbonnais

Organics: Samples, Theory & Experiment

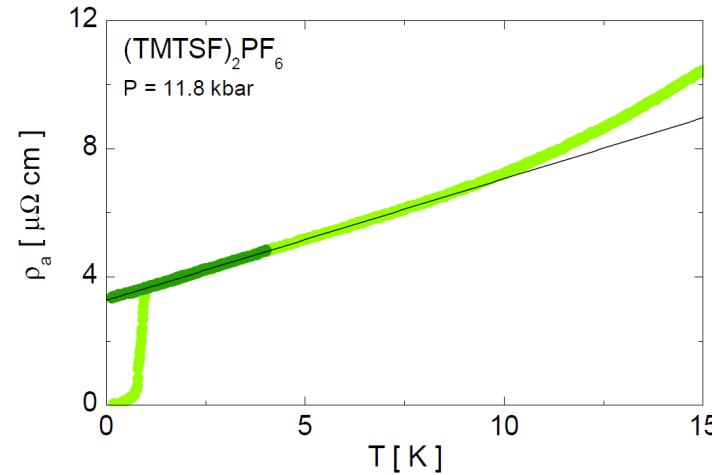
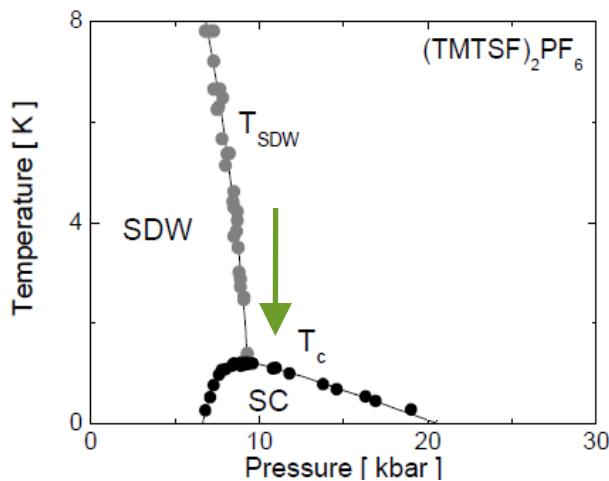
SAMPLES: Crystals and contacts

Jérôme



THEORY: Functional renormalization group approach

EXPERIMENT: Resistivity at low T and high P



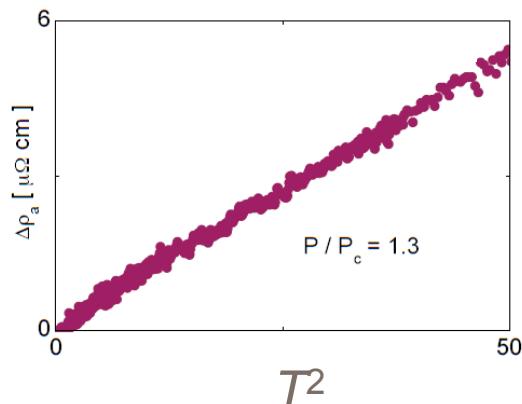
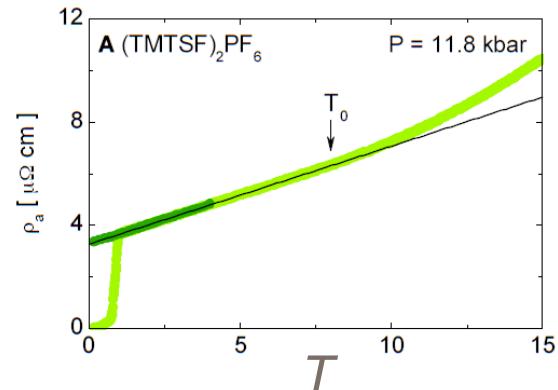
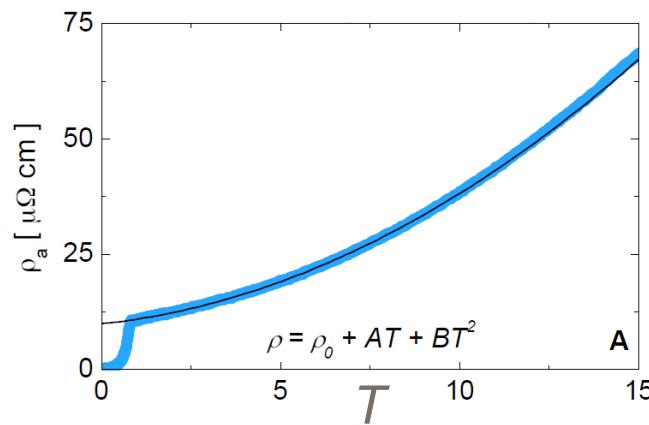
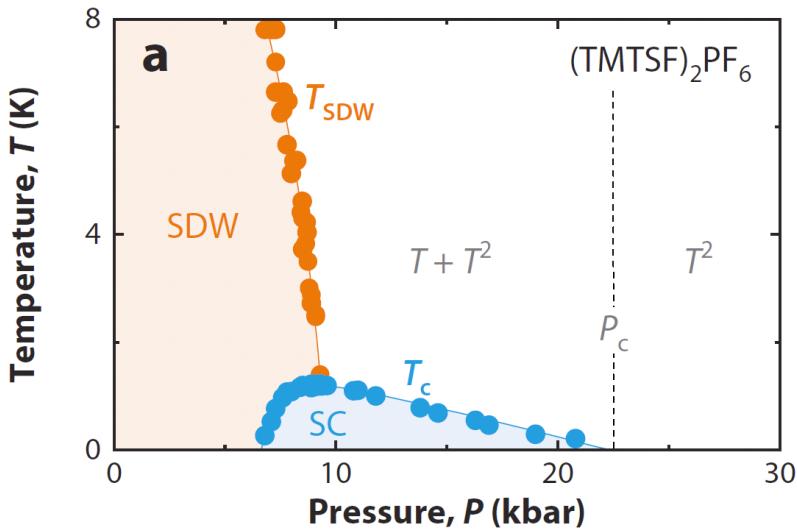
Doiron-Leyraud et al., PRB 80, 214531 (2009)

Bourbonnais



Doiron-Leyraud

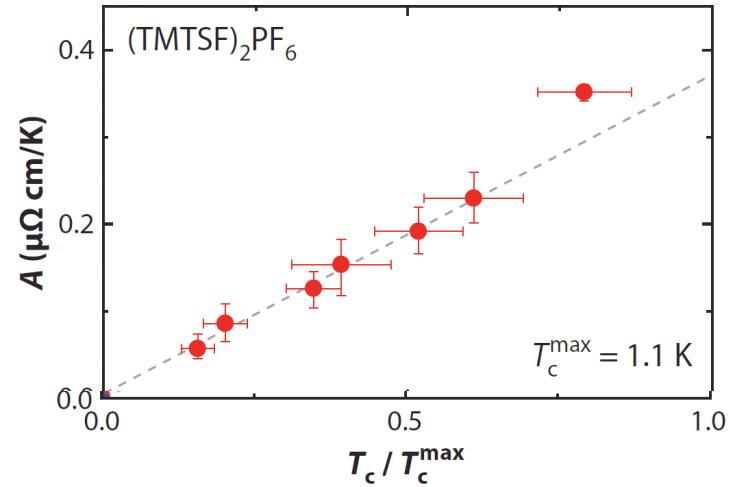
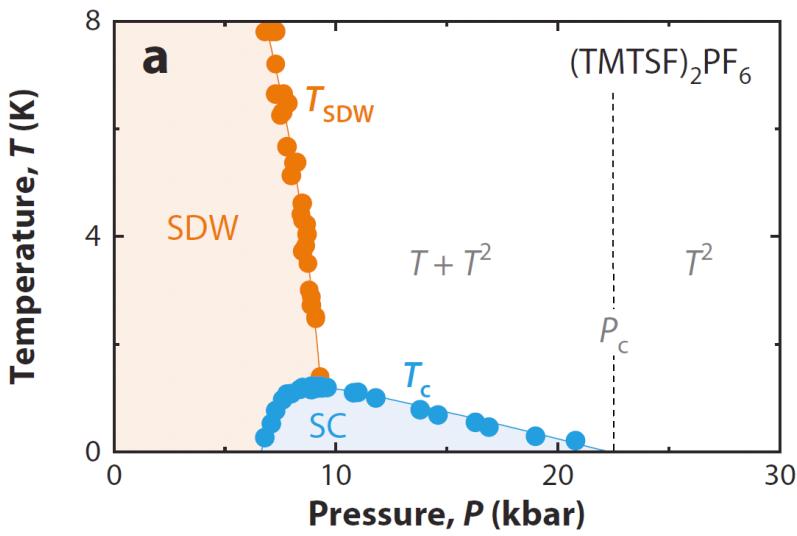
Organics: Resistivity



Doiron-Leyraud et al., PRB 80, 214531 (2009)

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Organics: Resistivity

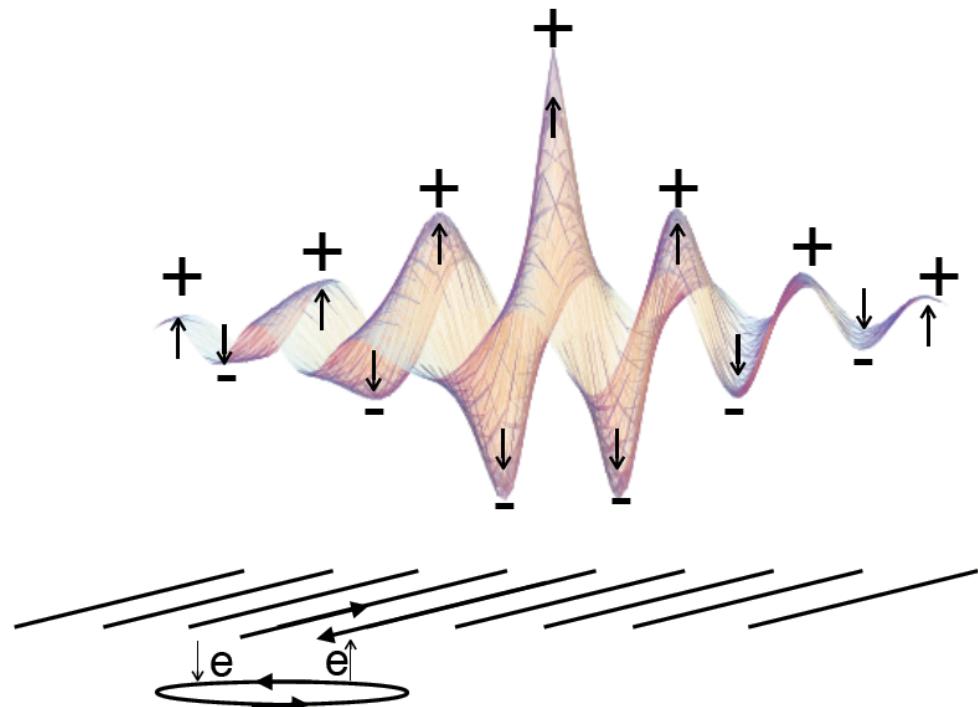


Experimental discovery : Linear- T resistivity $\longleftrightarrow T_c$

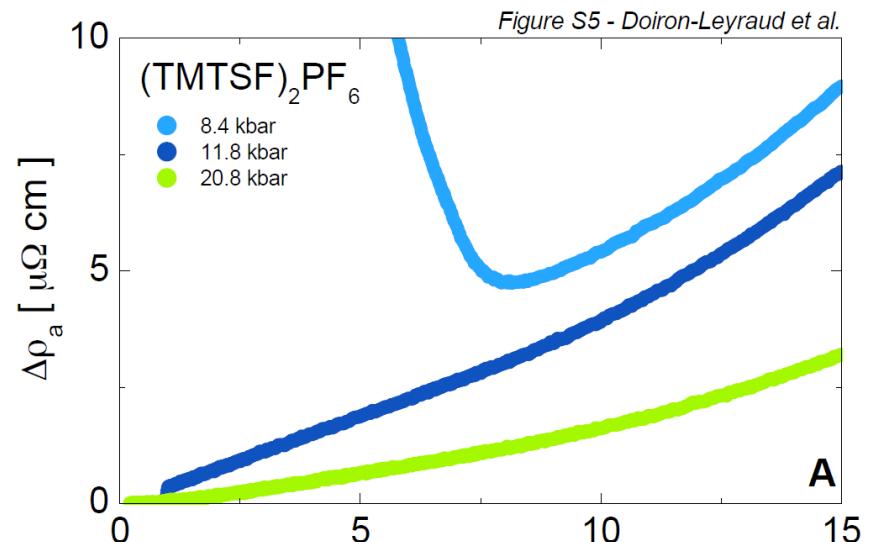
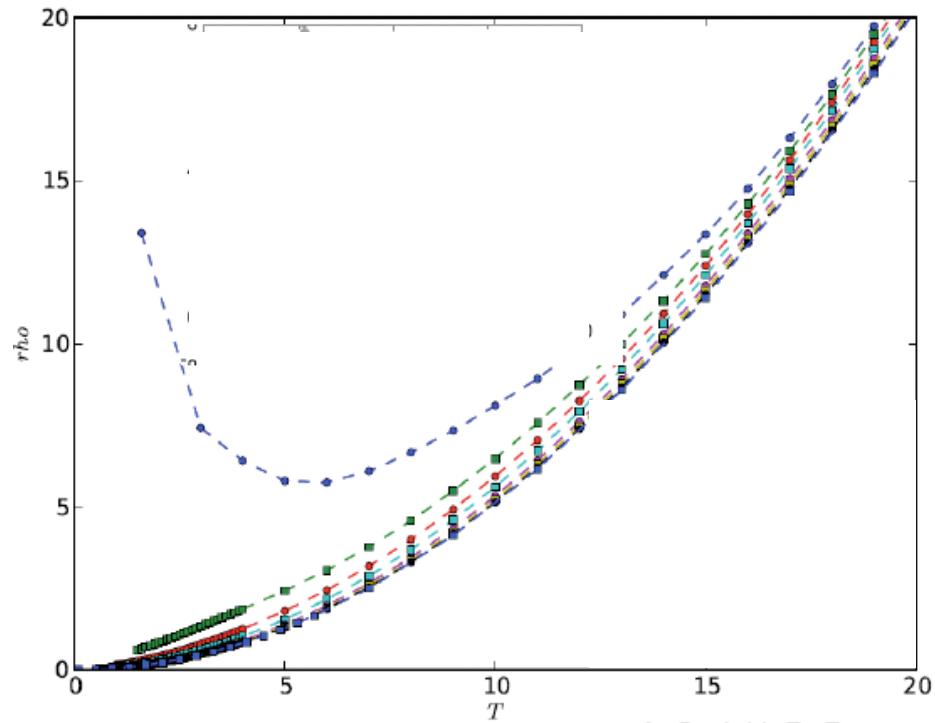


Magnetism & Superconductivity

Two-way interplay : AF spin fluctuations \rightarrow *d*-wave pairing



Organics: Theory vs Experiment



Magnetism & Superconductivity

Two-way interplay : AF spin fluctuations → d -wave pairing
pairing correlations → spin fluctuations

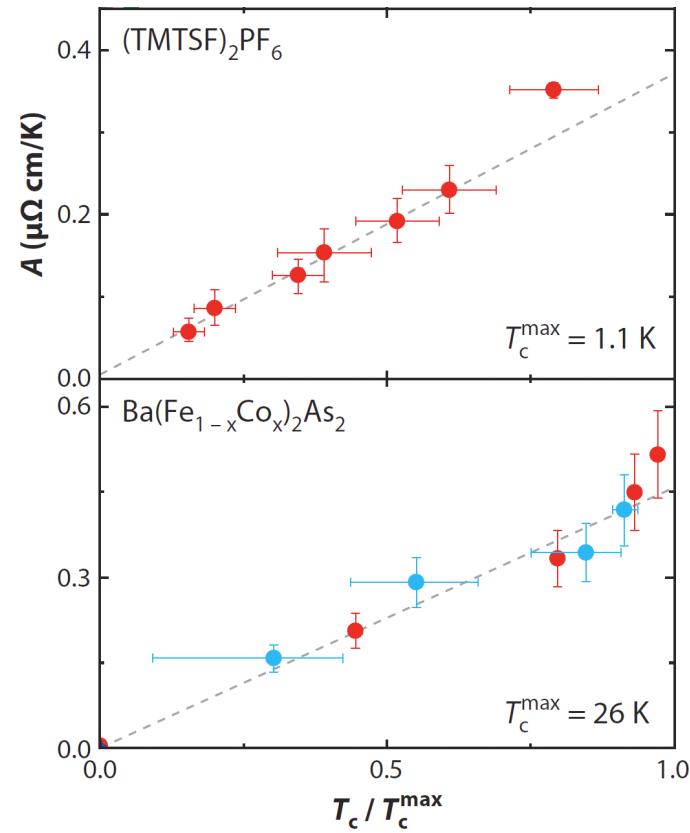
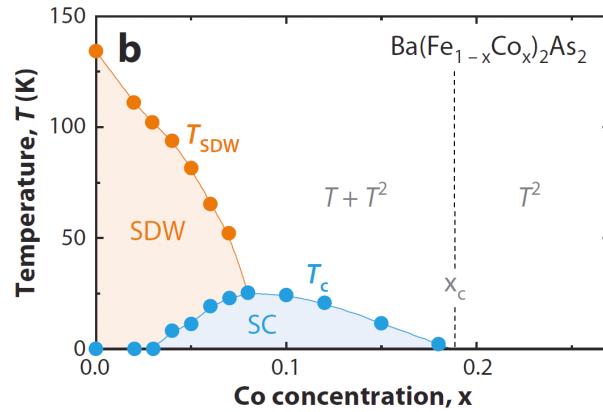
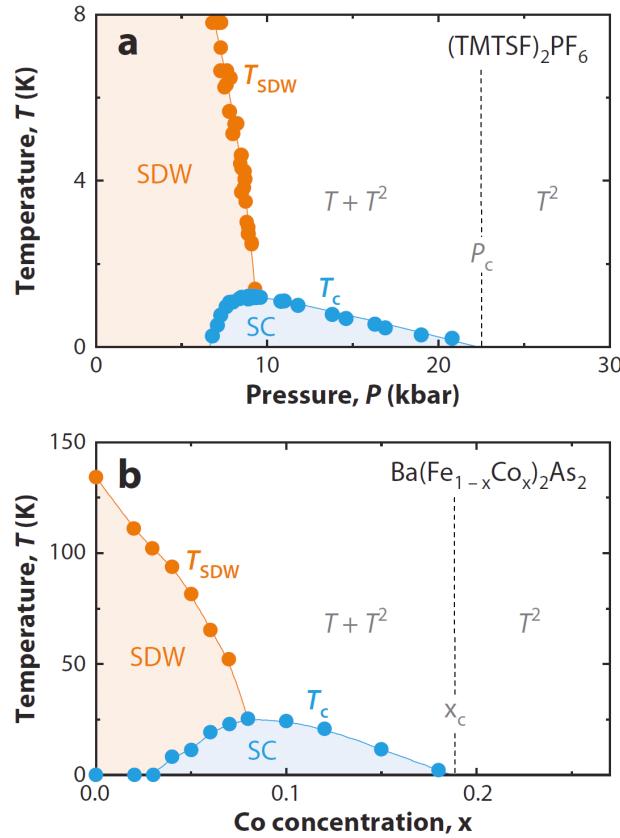
Experimental fingerprint: linear- T resistivity ↔ T_c



Organics & Pnictides

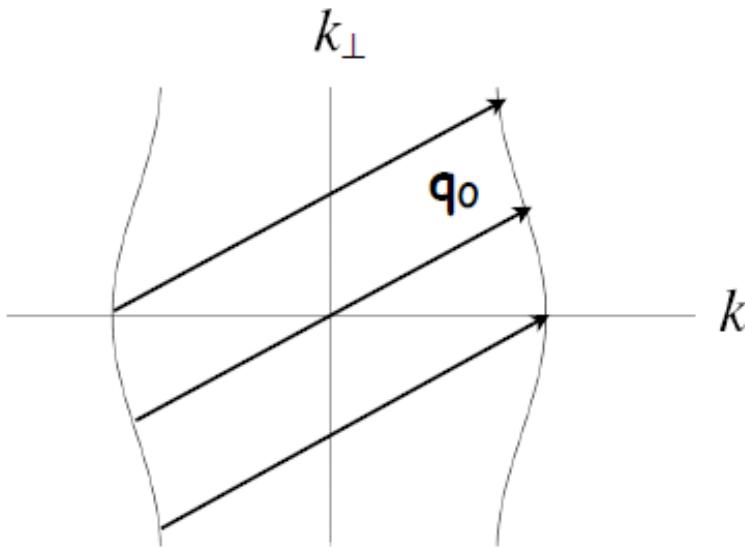
Organic

Pnictide

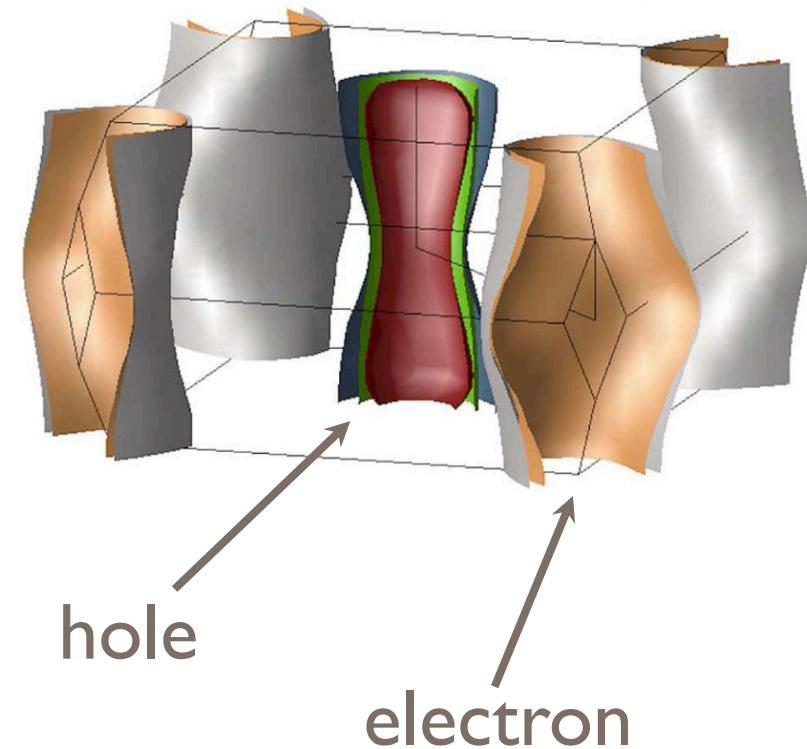


Organics & Pnictides

Organic

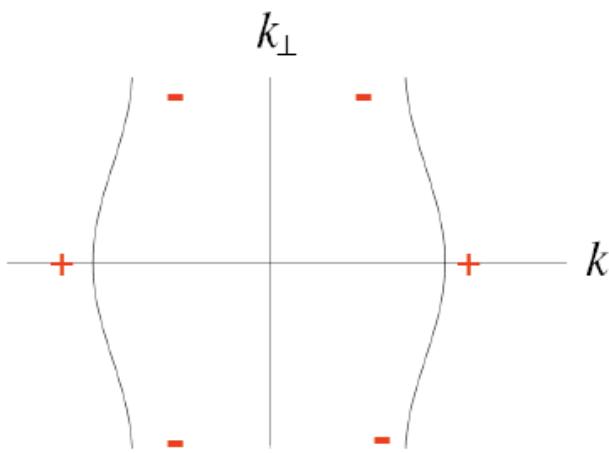


Pnictide



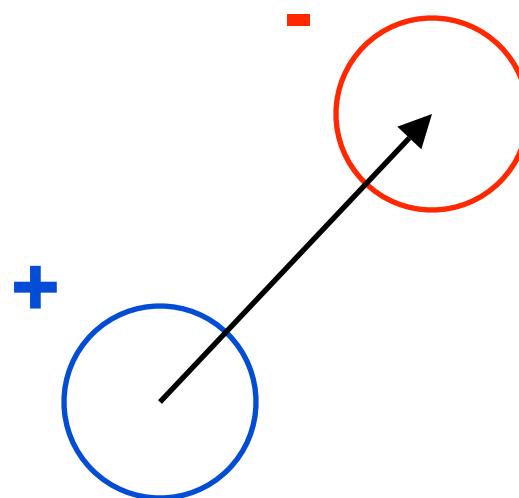
Organics & Pnictides

Organic



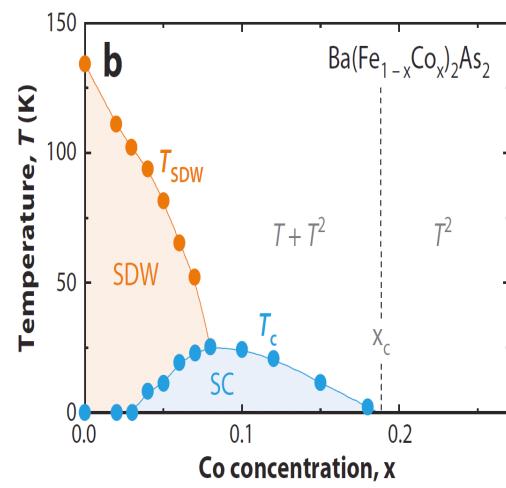
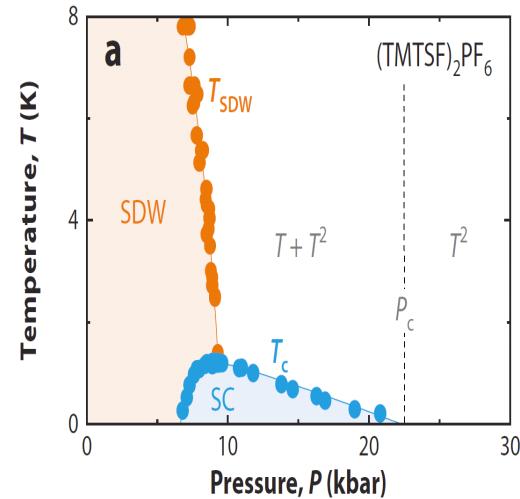
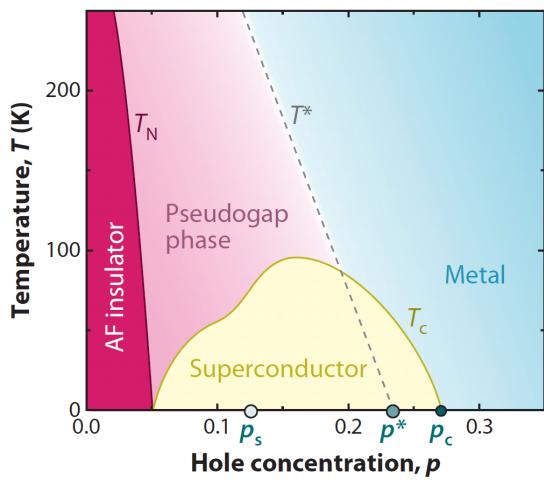
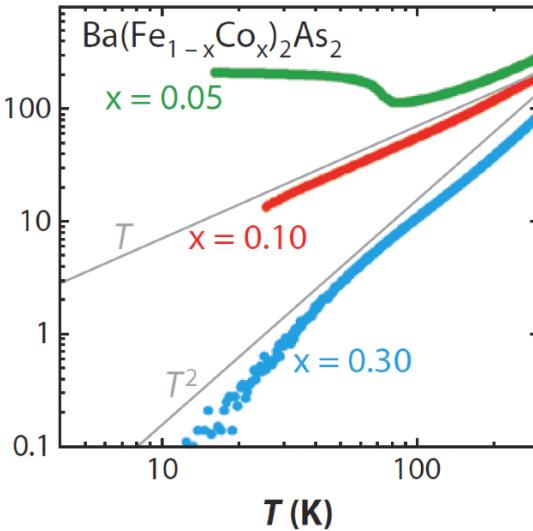
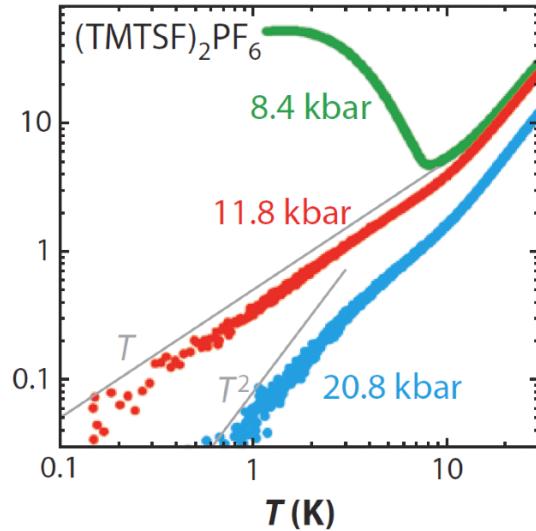
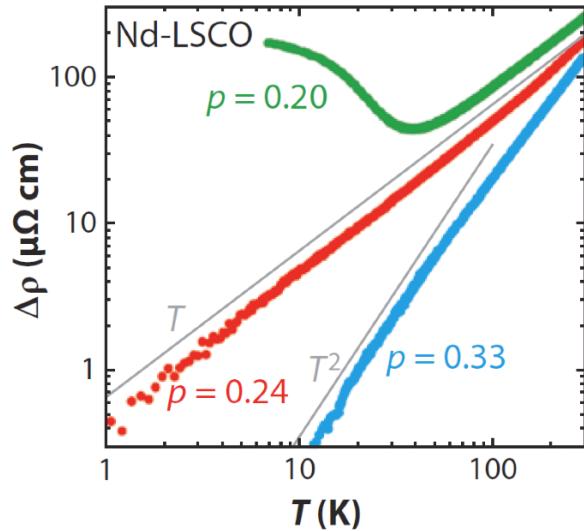
d

Pnictide



s_{\pm}

Quantum Criticality in the New Superconductors

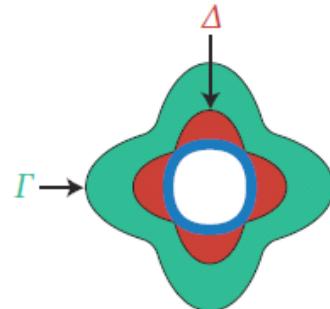


Conclusion

Two-way interplay : AF spin fluctuations → d -wave pairing
pairing correlations → spin fluctuations

Experimental fingerprint: linear- T resistivity $\leftrightarrow T_c$

Angular dependence : scattering rate \leftrightarrow gap



The end

Thank you.

