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Science in High Magnetic Fields

FELIX
Free Electron Lasers for Infrared eXperiments

Bounding Transport and Chaos in Condensed Matter and Holography
Nordita, Stockholm
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Hall number and other anomalies in the strange metal phase of overdoped cuprates

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AMES, Iowa
Takeshi Kondo
Adam Kaminski

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Andrew Mackenzie

ISTEC, Tokyo
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Outline

(i) Introduction

(ii) Hole-doped cuprates

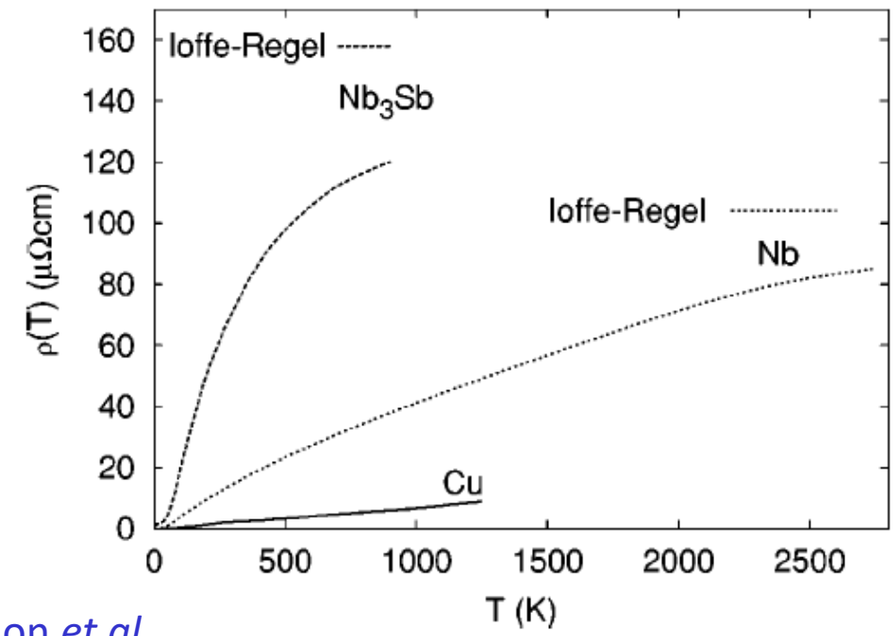
(iii) Pseudogap

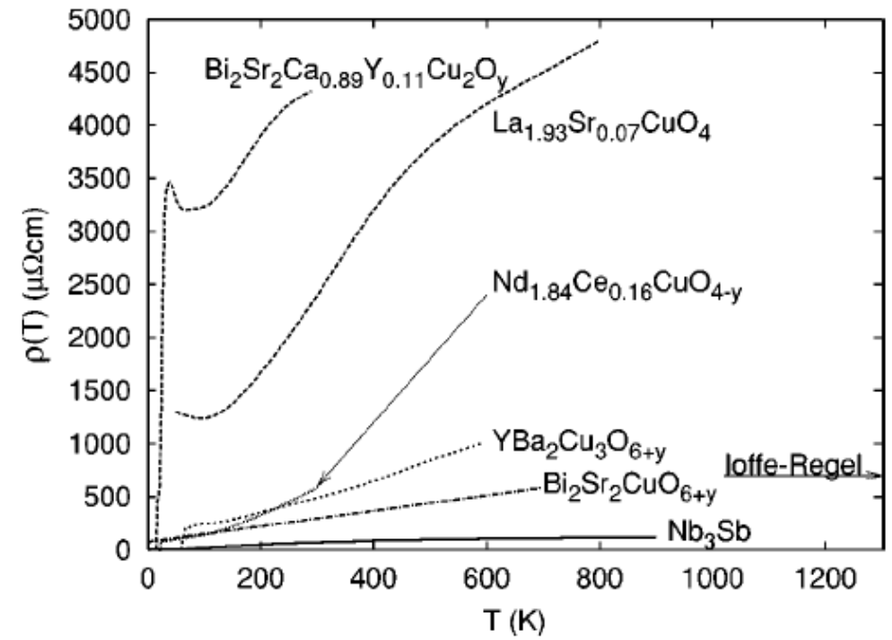
(iv) Hall number in strange metal phase

(v) Conclusions

Introduction

- High-T_c superconductivity borne out of the strange metal phase





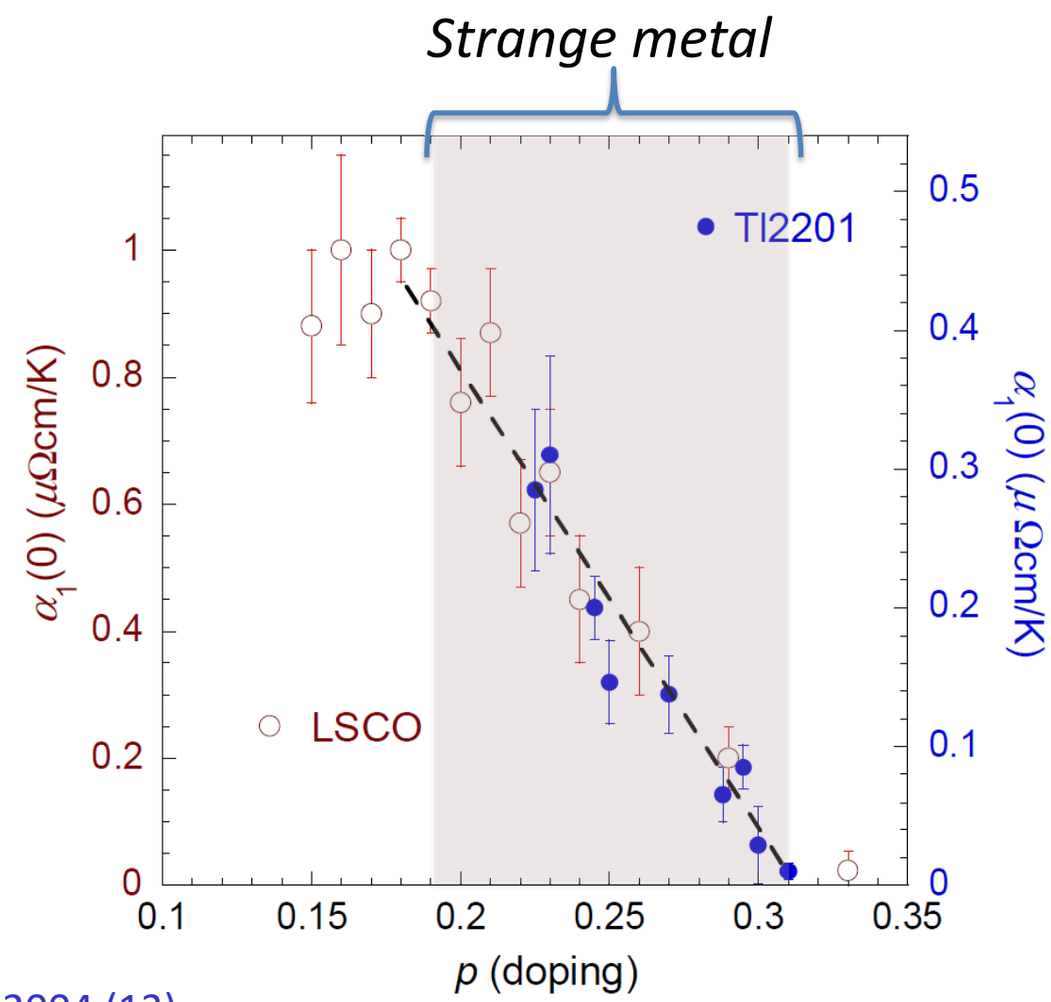
Gunnarsson *et al.*,
Rev. Mod. Phys. (2003)

Introduction

- High-T_c superconductivity borne out of the strange metal phase

$$\rho(T) = \alpha_0 + \alpha_1(0)T + O(T^2)$$

Coefficient of T-linear resistivity scales with T_c across the strange metal regime.



NEH *et al.*,
J. Phys. Conf. Ser. **449**, 012004 (13)

Introduction

- High-T_c superconductivity borne out of the strange metal phase
- Strange metal characterized by an extended (doping) range of *T*-linear resistivity that is distinct from conventional QC metals

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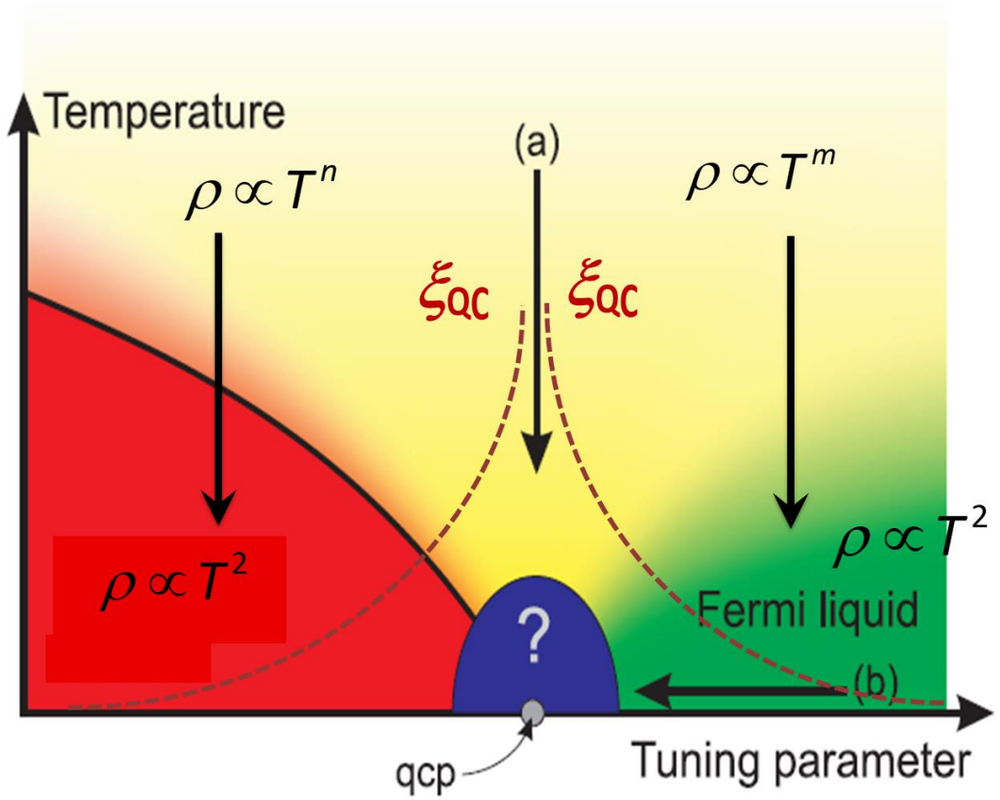
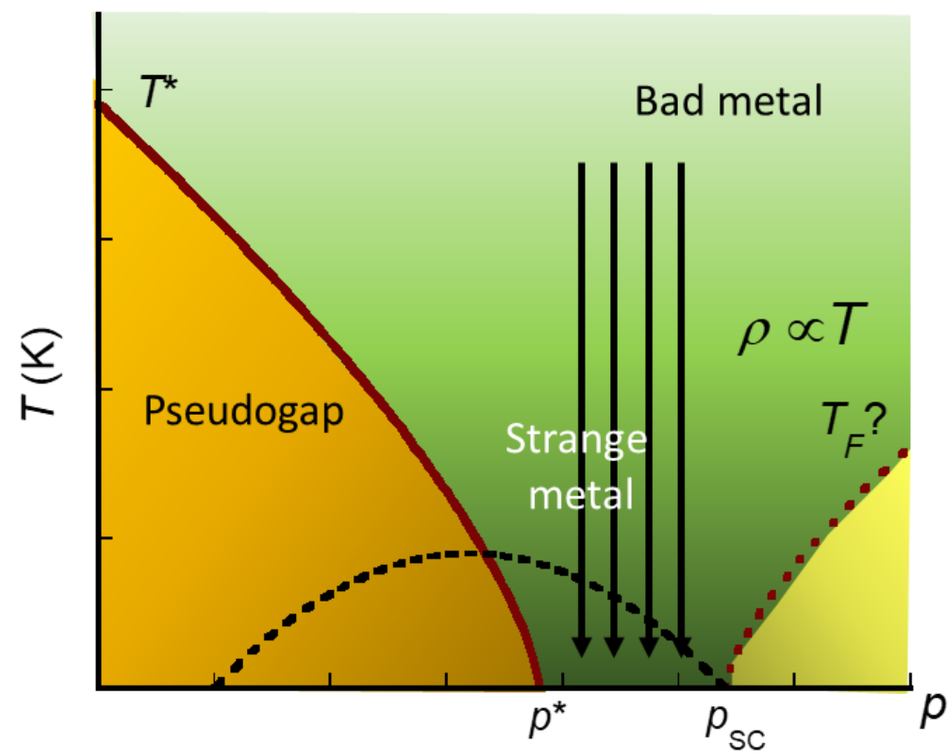
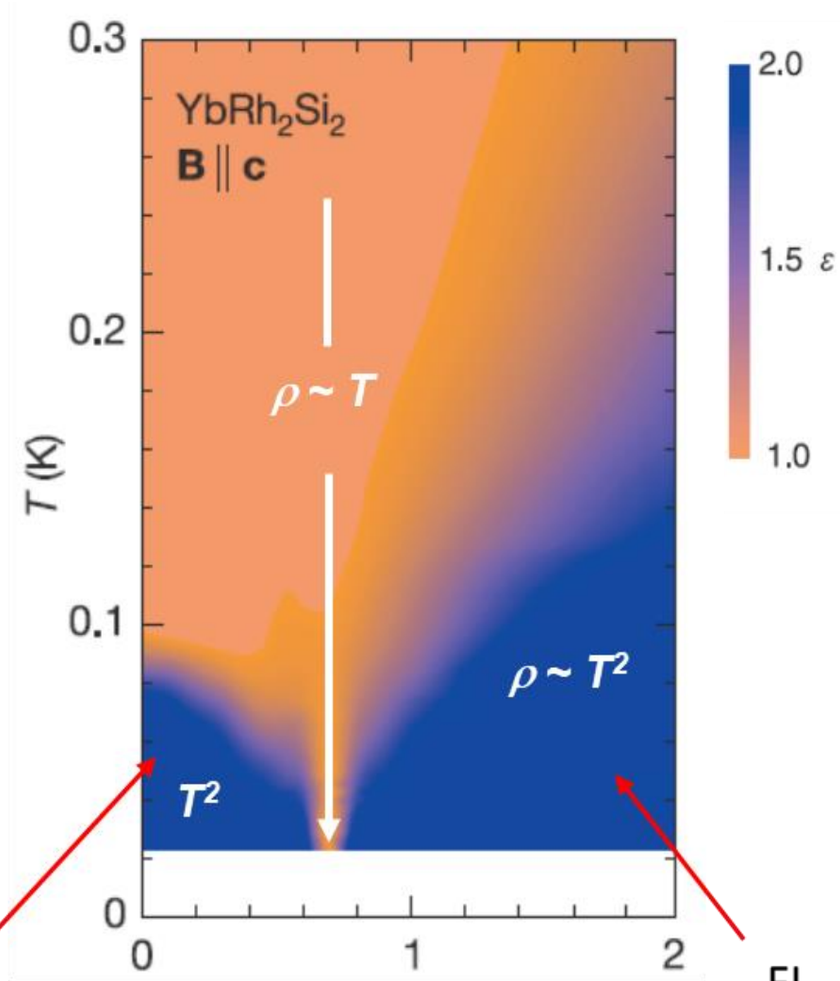




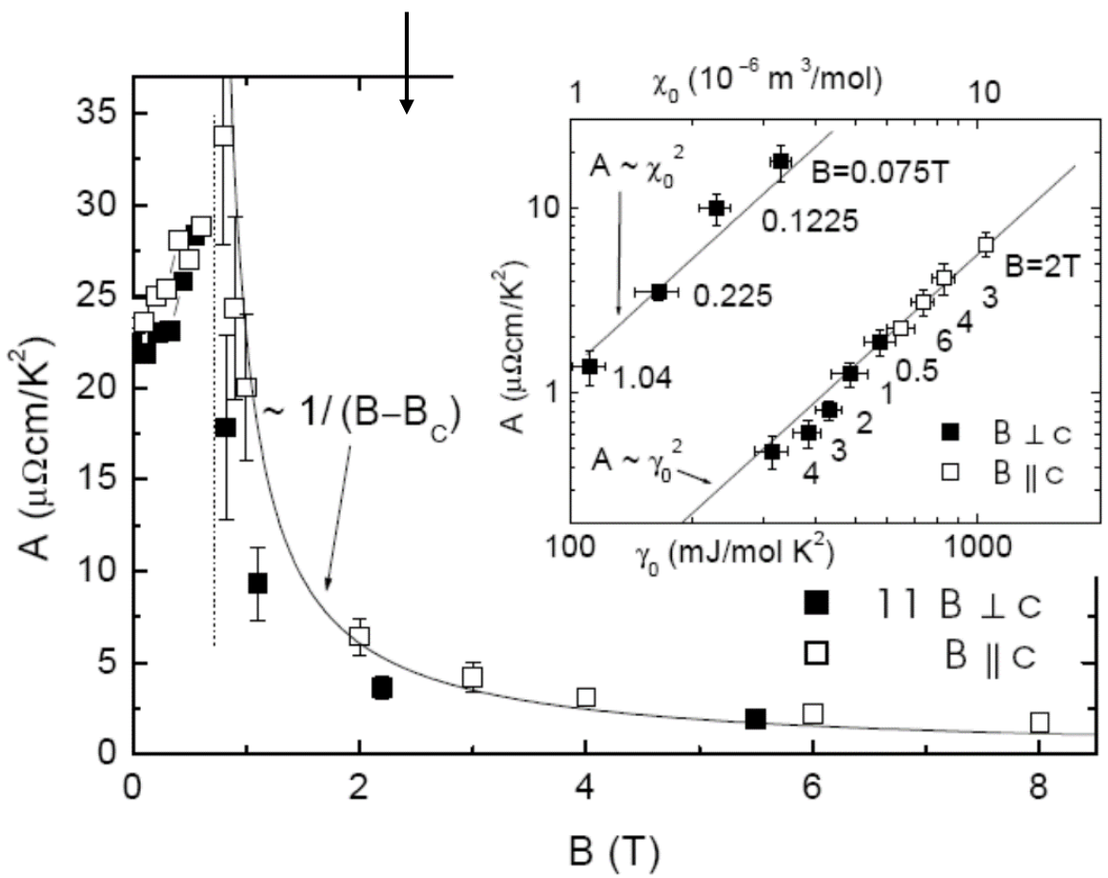
Introduction

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

Heavy fermions



A coefficient divergent on both sides of QCP

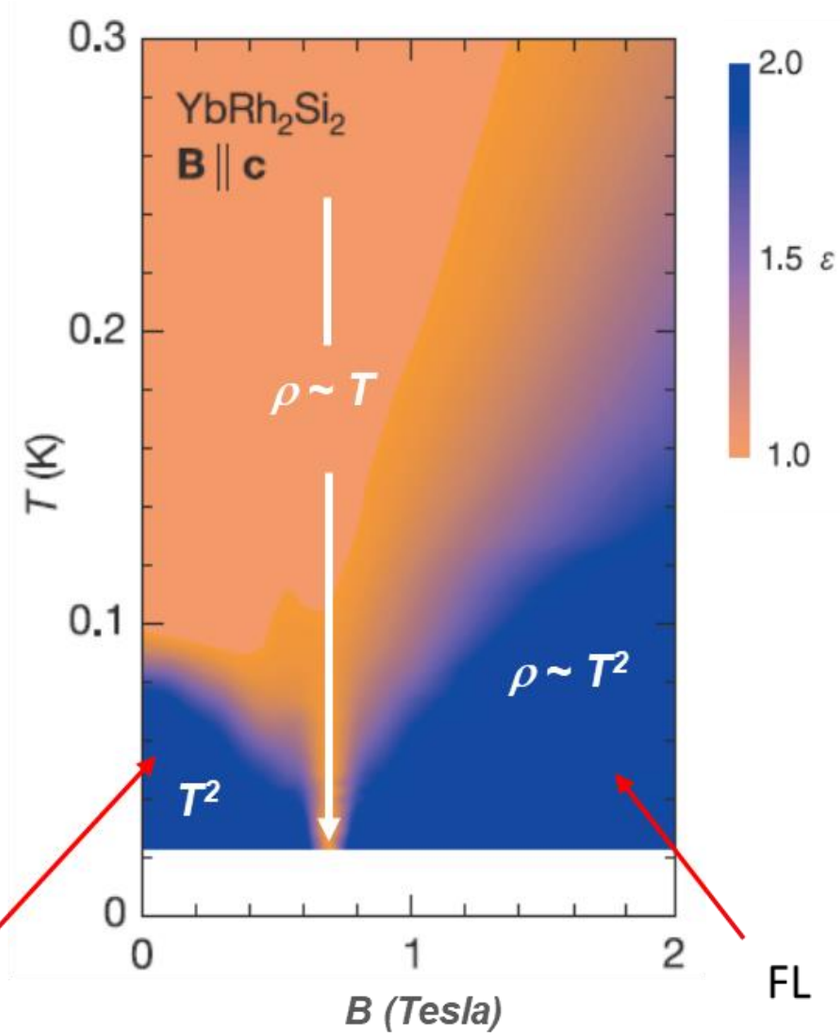


Custers *et al.*, *APPB* **34** 323 (03)

Introduction

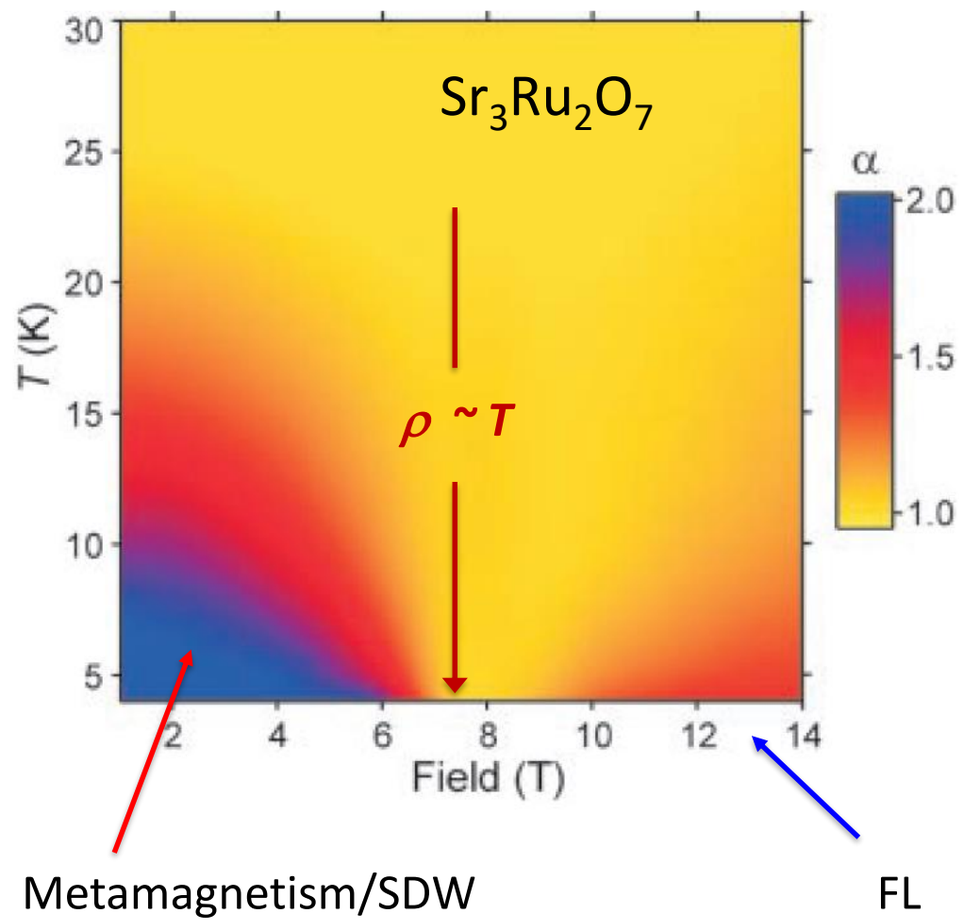
Custers *et al.*, *Nature* **424** 524 (03)

Heavy fermions



Ruthenates

Grigera *et al.*, *Science* **294** 329 (01)



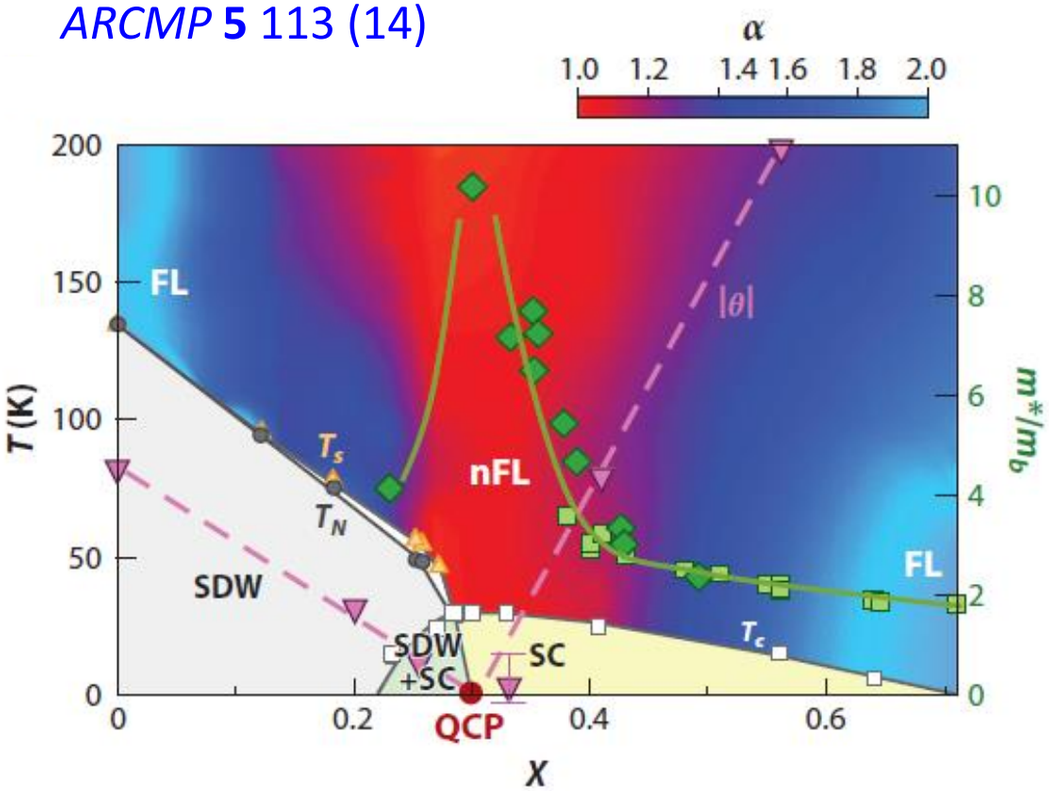
Introduction

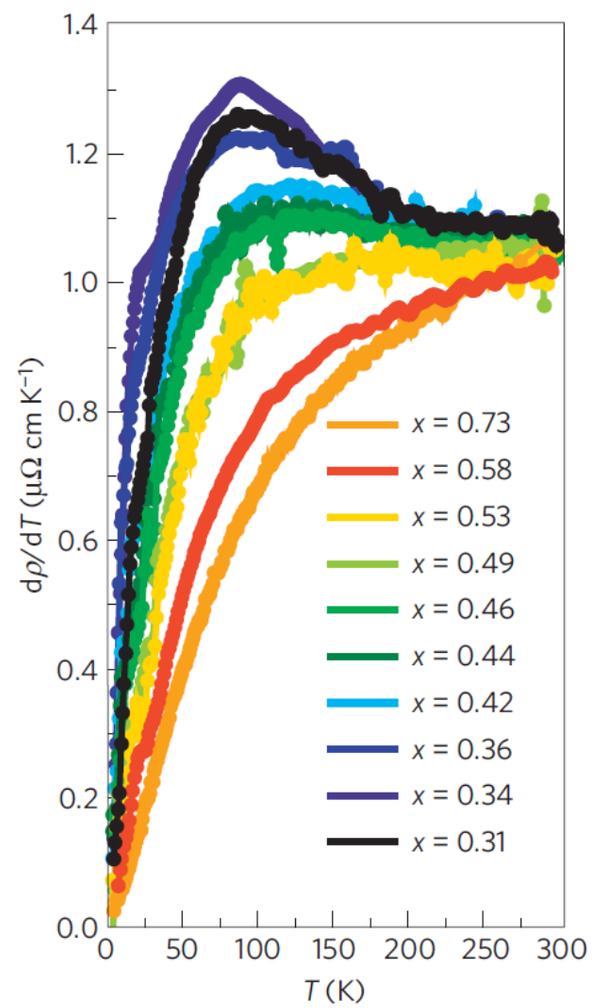
Pnictides

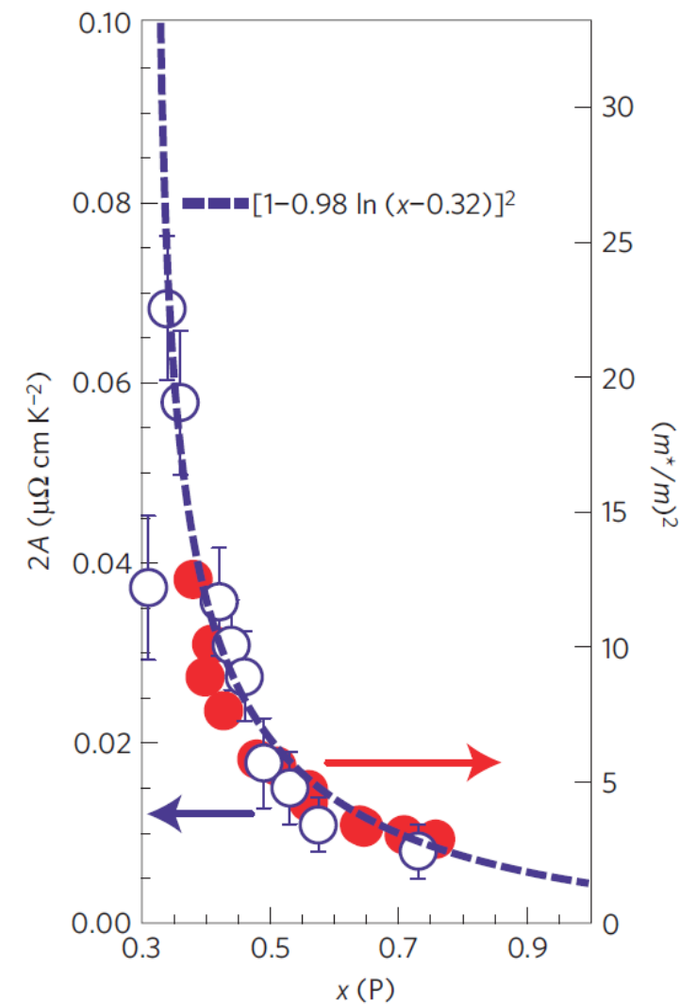
Shibauchi *et al.*, *ARCMP* **5** 113 (14)

$BaFe_2(As_{1-x}P_x)_2$

Analytis, NEH *et al.*, *Nature Phys.* **10** 194 (14)

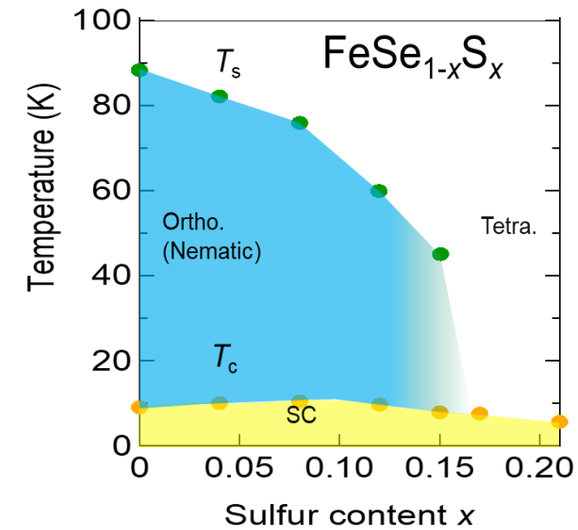






Suppressing superconductivity in a high magnetic field confirms QC behaviour

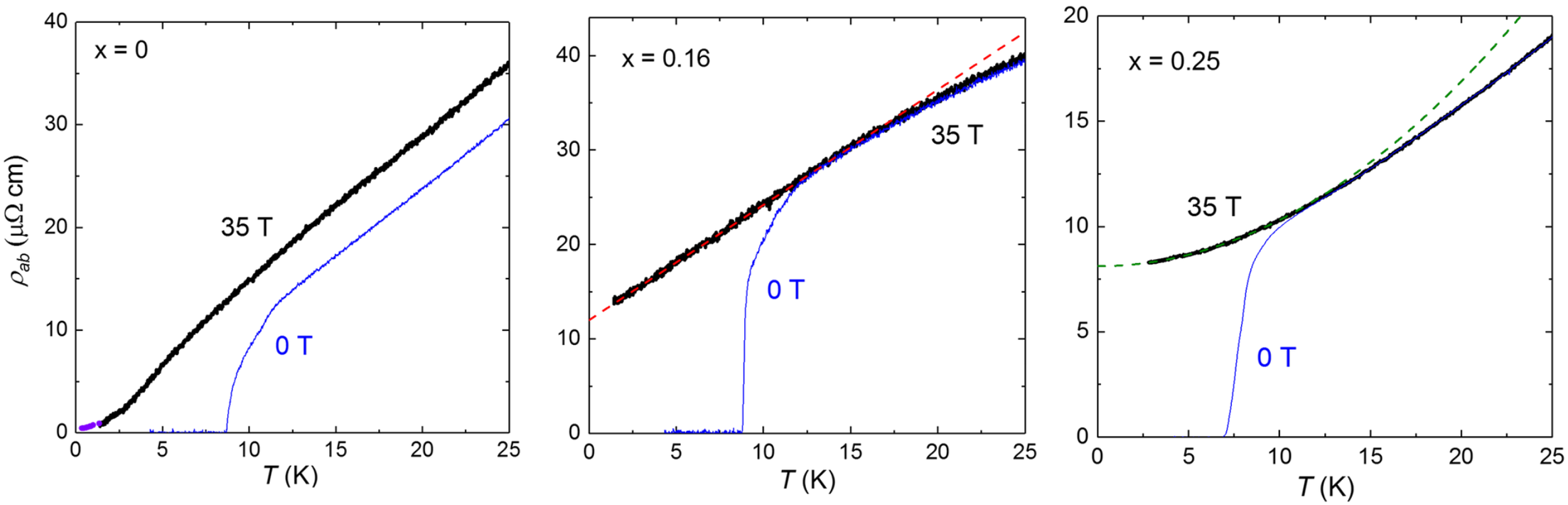
Introduction



Chalcogenides

Licciardello, NEH *et al.*, *Submitted* (18)

$FeSe_{1-x}S_x$



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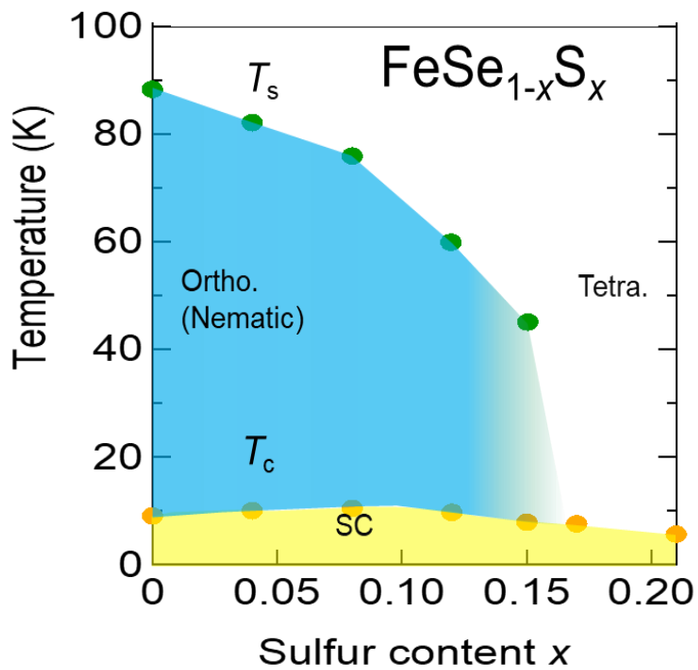
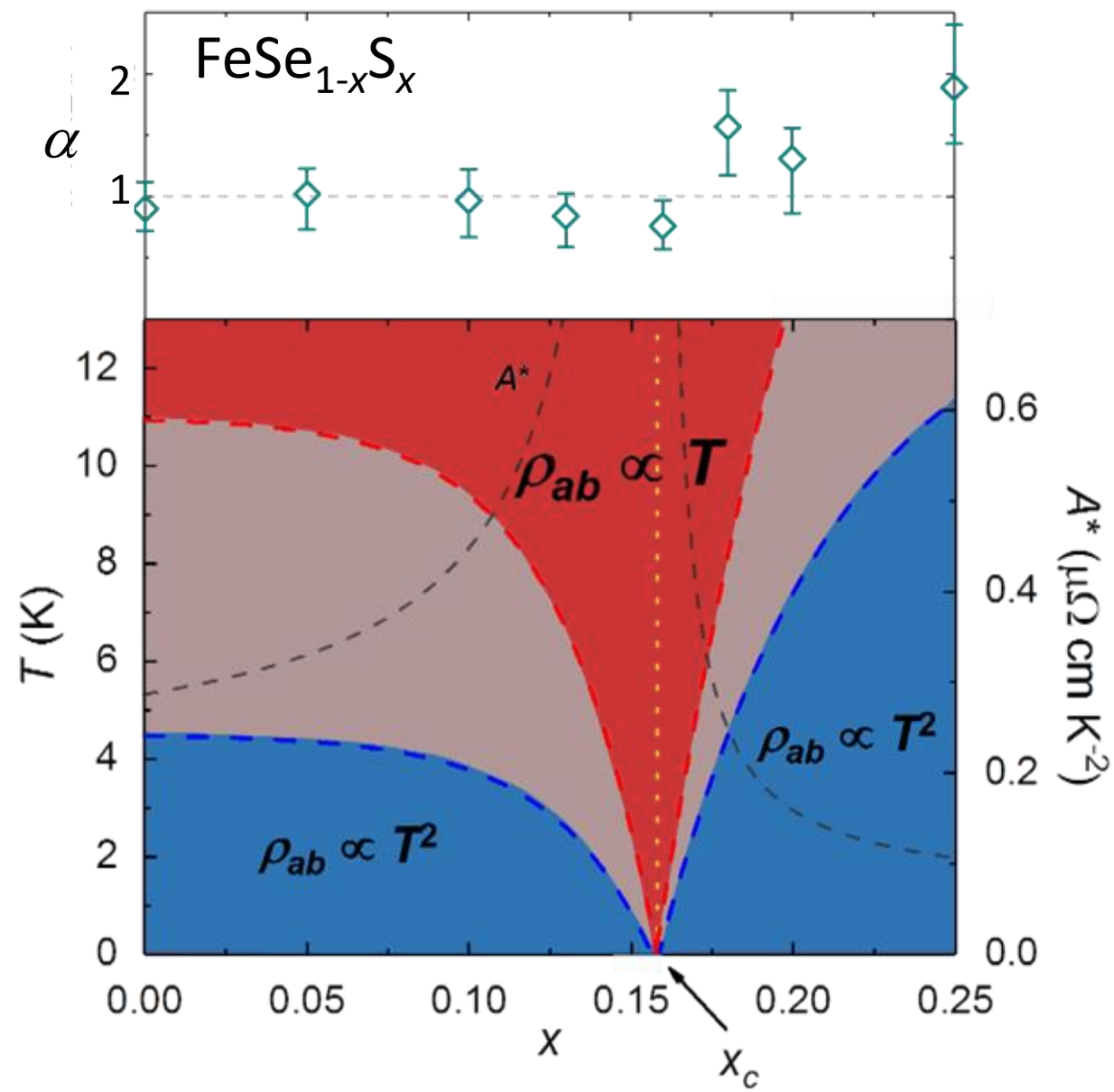
Licciardello, NEH *et al.*, *Submitted* (18)



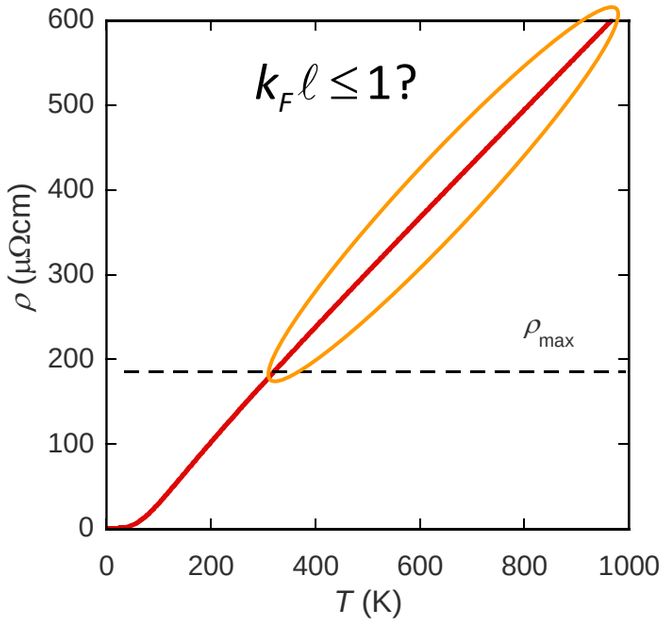
Inside QC fan, $\hbar/\tau = \alpha k_B T$

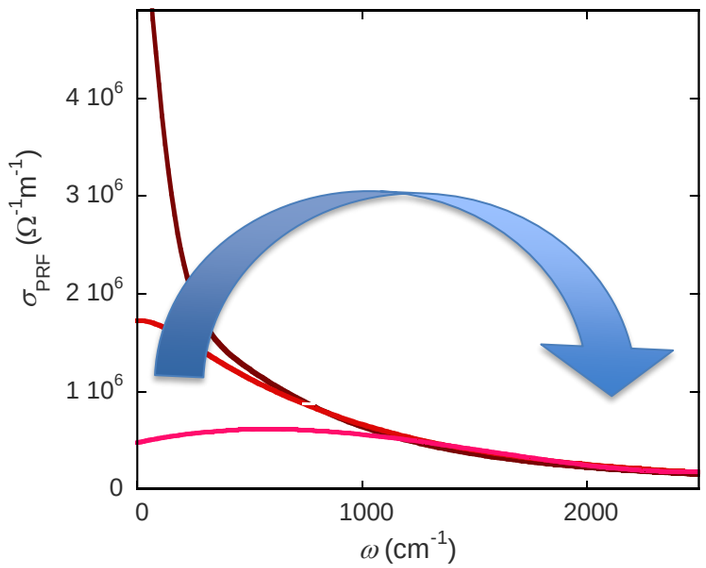


Introduction

- High-T_c superconductivity borne out of the strange metal phase
- Strange metal characterized by an extended (doping) range of *T*-linear resistivity that is distinct from conventional QC metals
- Bad metallic transport is a high-*T*, high-energy phenomenon, but strange metal transport may be a low-energy phenomenon

NEH, Takenaka & Takagi, *Phil. Mag.* **84**, 2847 (04)





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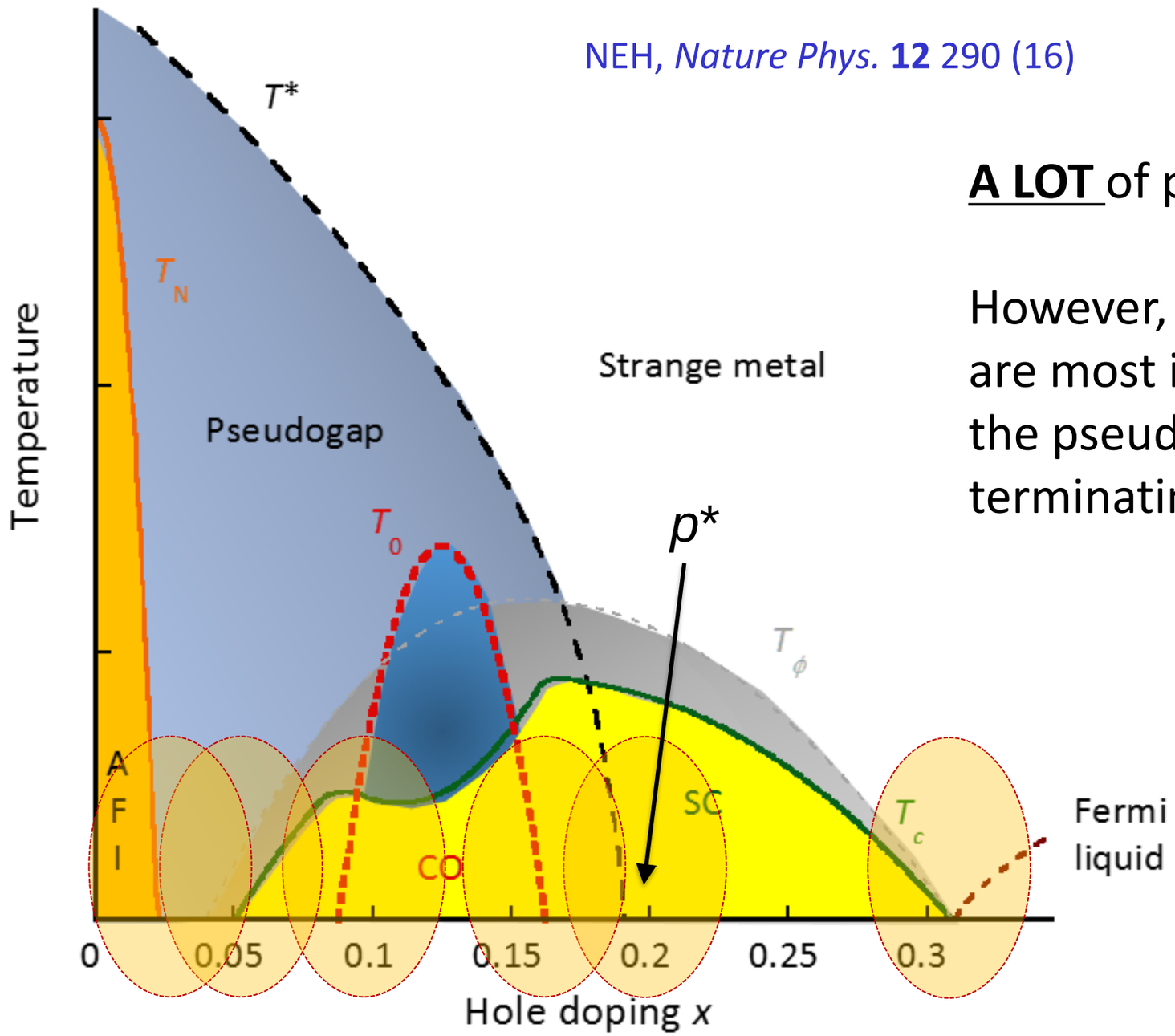
- Strange metal characterized by an extended (doping) range of *T*-linear resistivity that is distinct from conventional QC metals
- Bad metallic transport is a high-*T*, high-energy phenomenon, but strange metal transport may be a low-energy phenomenon
- The many recent claims of conventional QC behavior near p^* in hole-doped cuprates still need to be rigorously explored
- Here, I will introduce a **new aspect** of the strange metal physics of overdoped cuprates, relating to the **Hall number**.

Hole-doped cuprates

NEH, *Nature Phys.* **12** 290 (16)

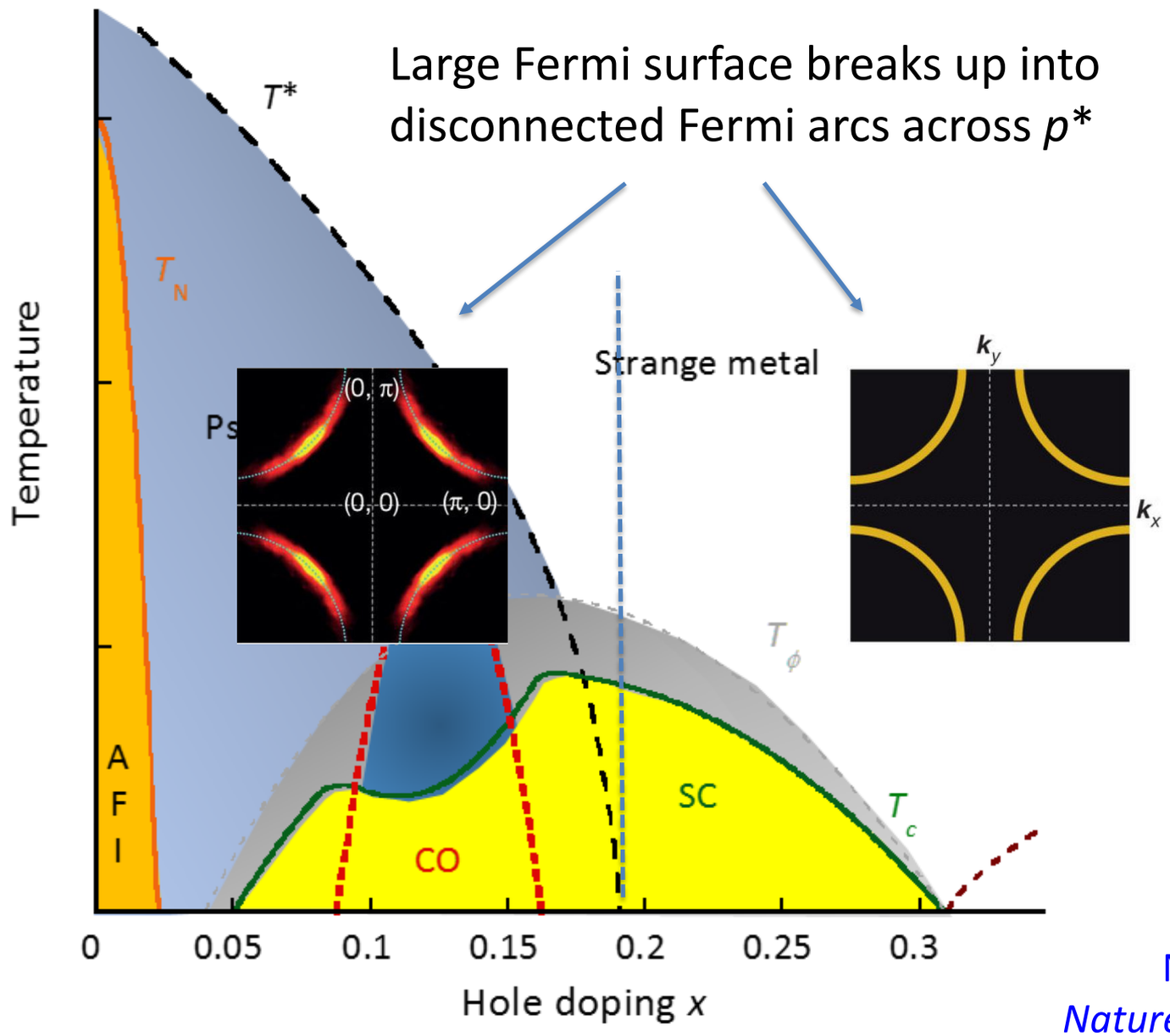


A LOT of potential QCPs!

However, the one we are most interested in is the pseudogap terminating at p^* 0.19

The enigmatic pseudogap in hole-doped cuprates

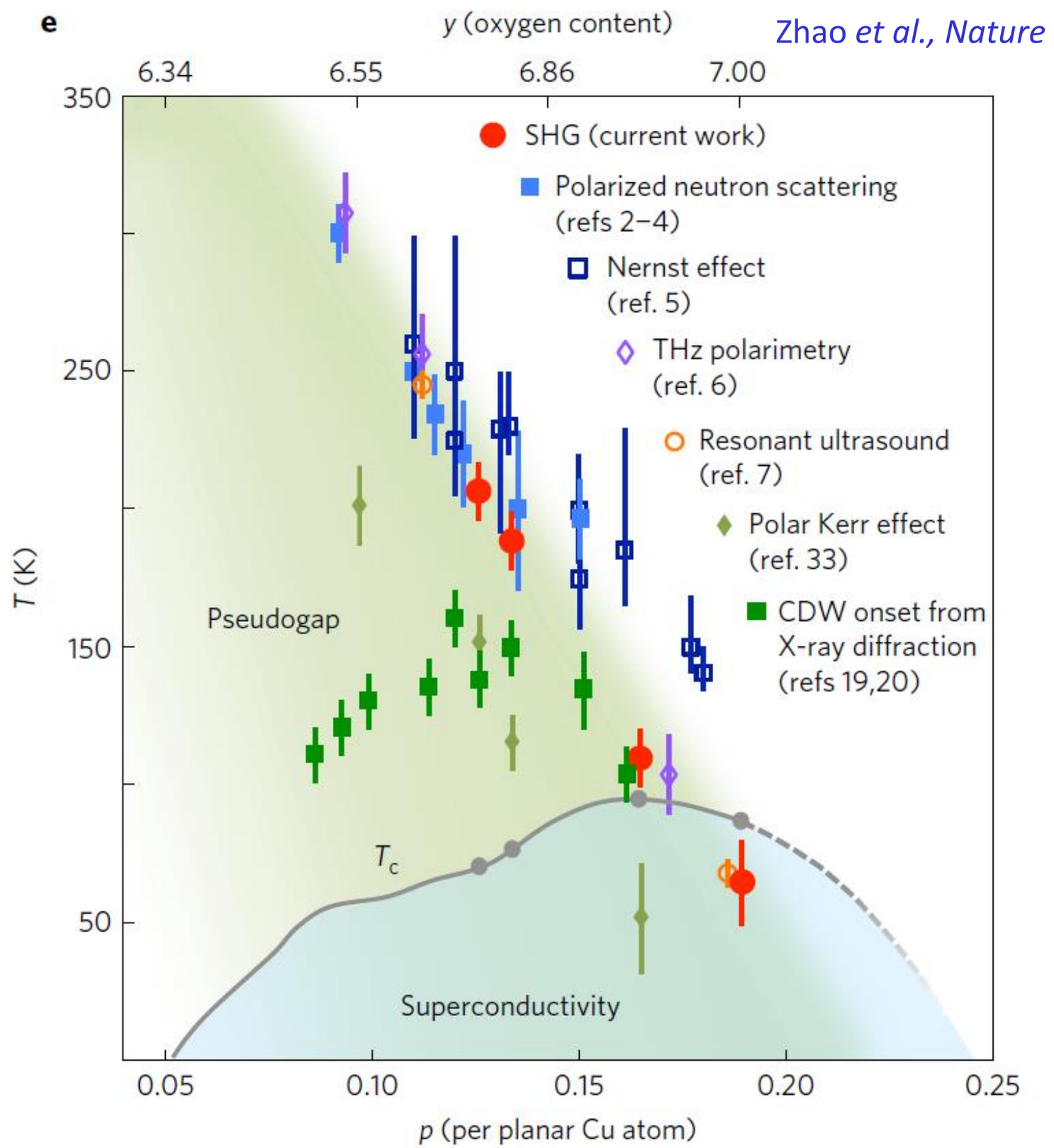
Large Fermi surface breaks up into disconnected Fermi arcs across *p**



ADMR - NEH *et al.*, *Nature* **425** 814 (03)
ARPES - Plate *et al.*, *PRL* **95**, 077001 (05)
QO - Vignolle, NEH *et al.*, *Nature* **455** 952 (08)

Norman *et al.*, *Nature* **392** 157 (98)

The enigmatic pseudogap in hole-doped cuprates



Zhao *et al., Nature Phys.* **13**, 250 (17)

$YBa_2Cu_3O_y$

SHG – inversion/rotational SB

Neutrons – time-reversal SB

Nernst – rotational SB

THz polarimetry – mirror SB

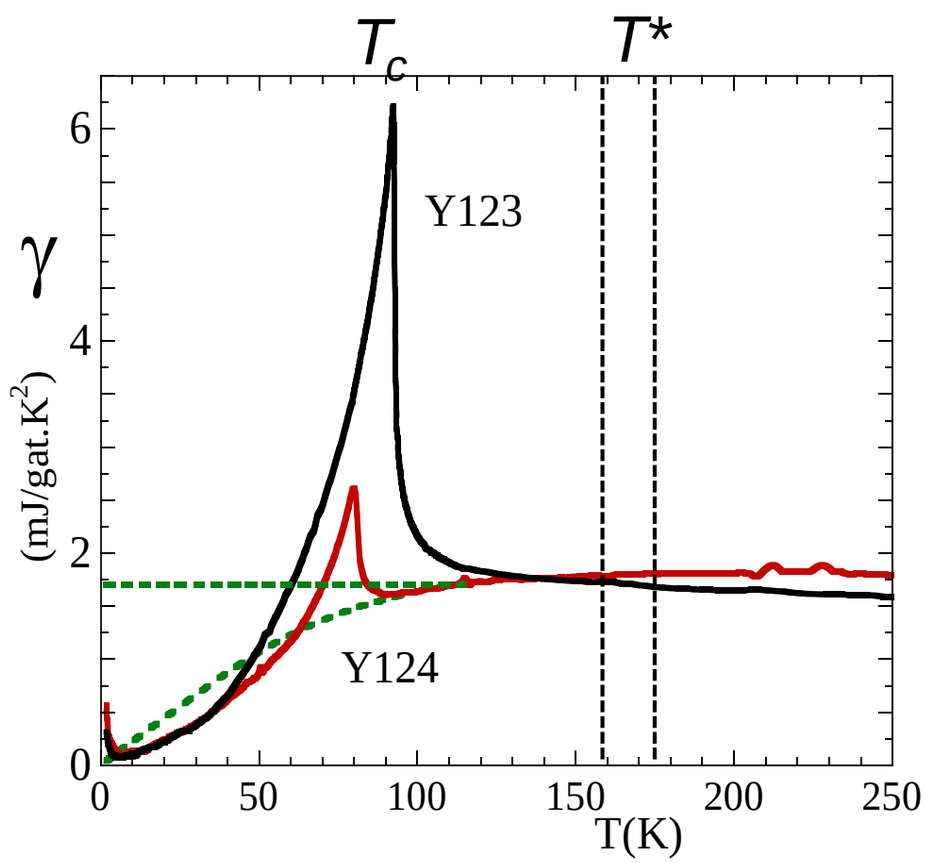
Ultrasound – thermodynamic signature

Polar Kerr – time-reversal SB

CDW – translational SB

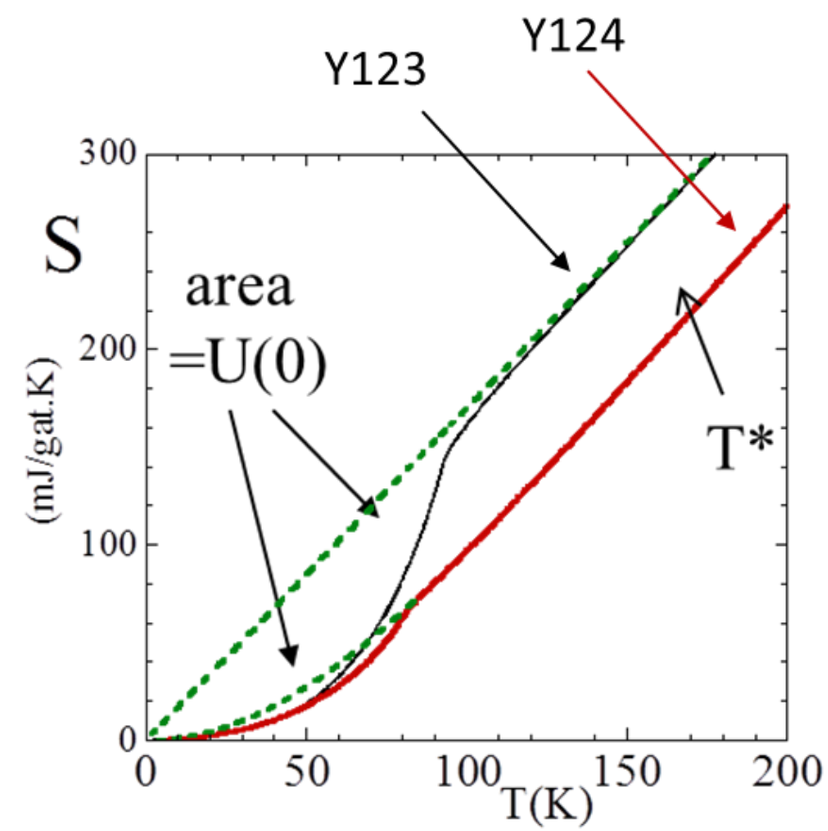
Thermodynamics of the pseudogap

Complete absence of a specific heat anomaly across *T**



Loram *et al.*, *APS March Meeting* (07)

More significantly, there appears to be a permanent entropy loss implies **<u>states-non-conserving gap</u>**.



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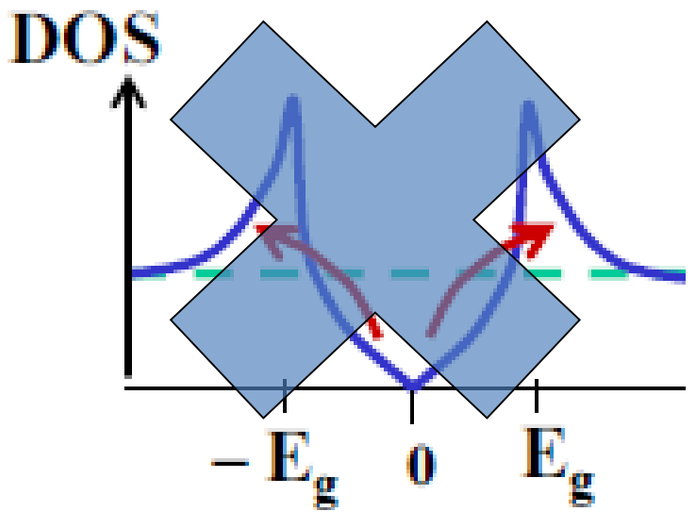
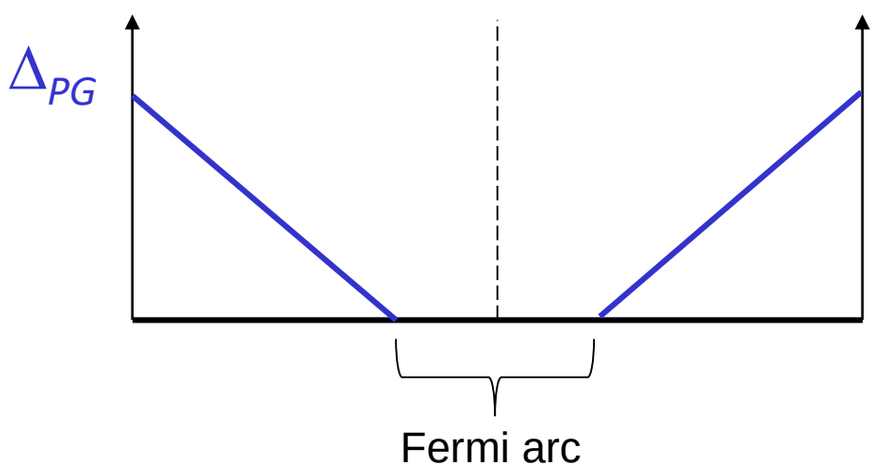


- Can be modelled with *d*-wave form – consistent with presence of Fermi arcs
- Leads to marked reduction in *U*(0)



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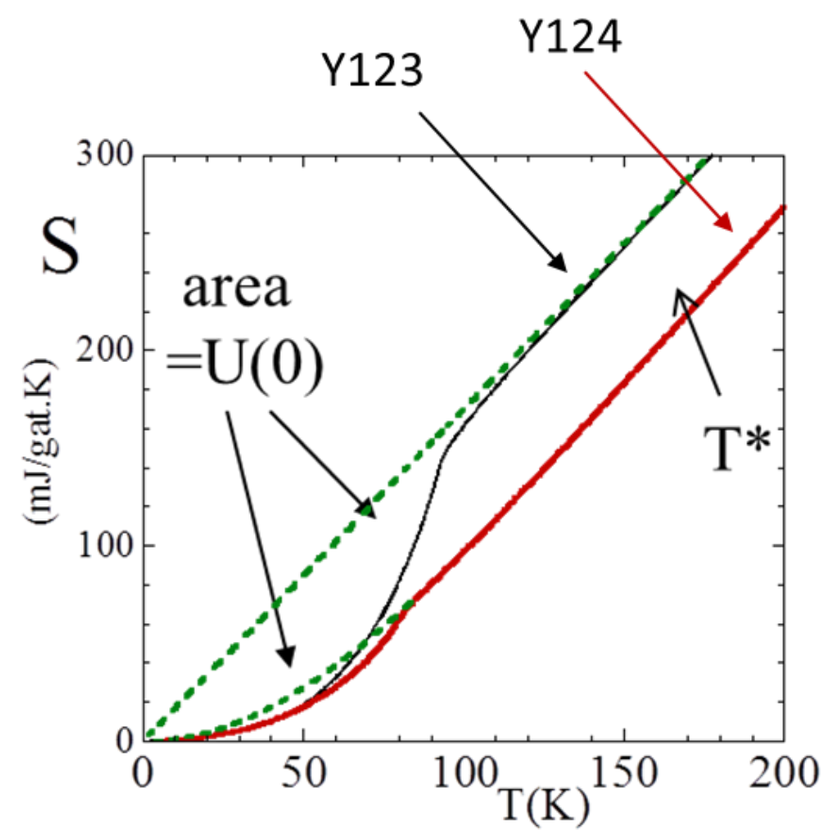
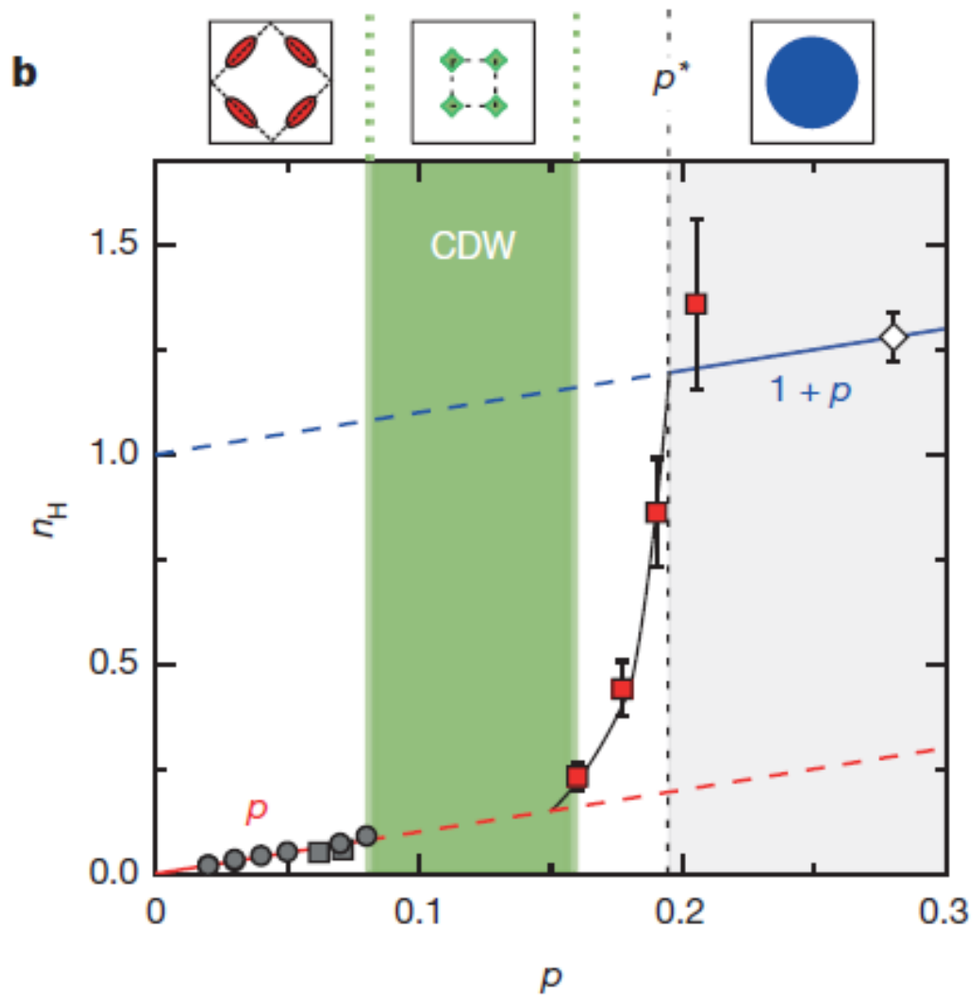


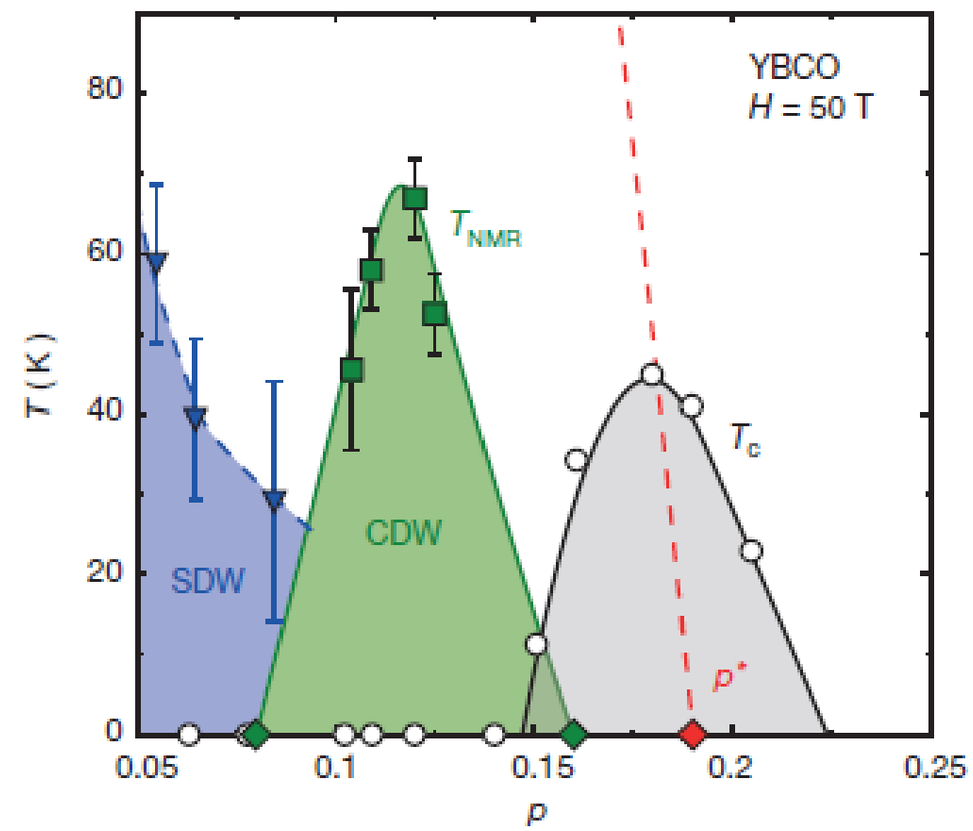
Loram *et al.*, *APS March Meeting* (07)

*Transition in Hall number across p**



$YBa_2Cu_3O_{7-\delta}$
(Y123)

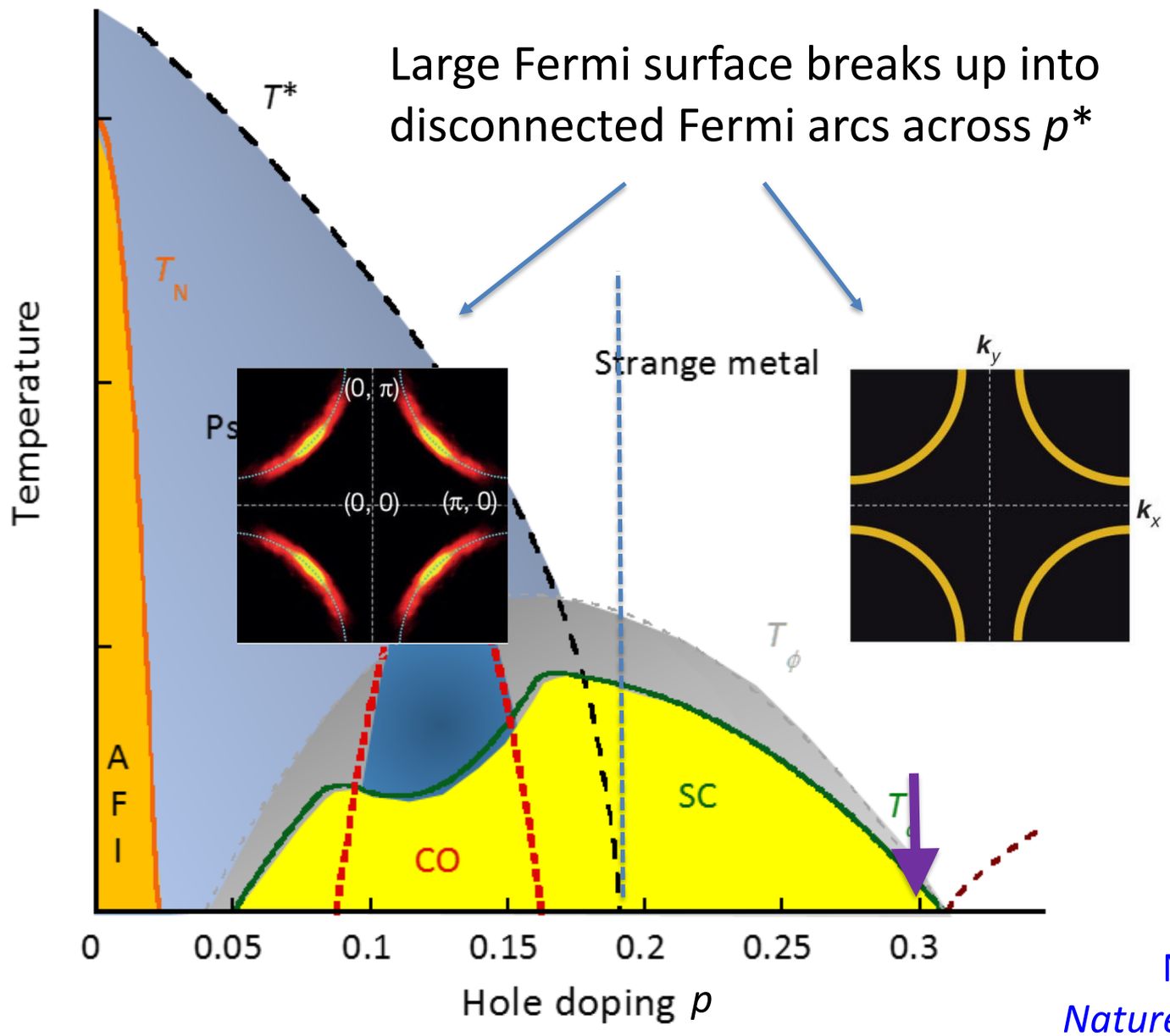
Badoux *et al.*,
Nature **531** 210 (16)



Measurements of Hall coefficient in $T = 0$ limit (in high magnetic fields) show a sharp transition from $1 + p$ to p across p^*, interpreted as a sudden loss of charge carriers – most likely those states near the zone boundary.

*Transition in Hall number across p**

Large Fermi surface breaks up into disconnected Fermi arcs across *p**



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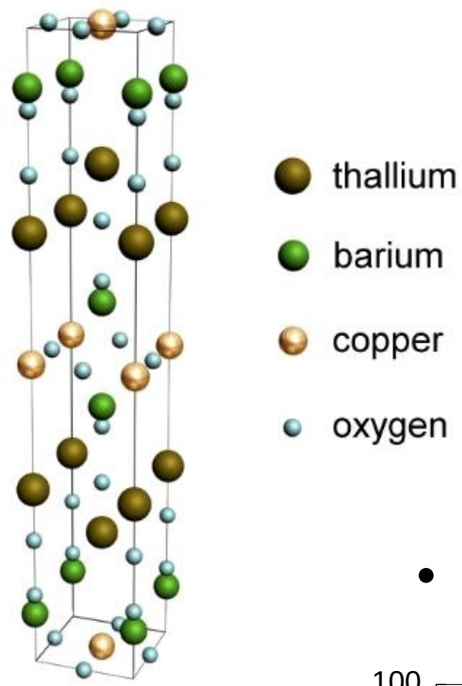
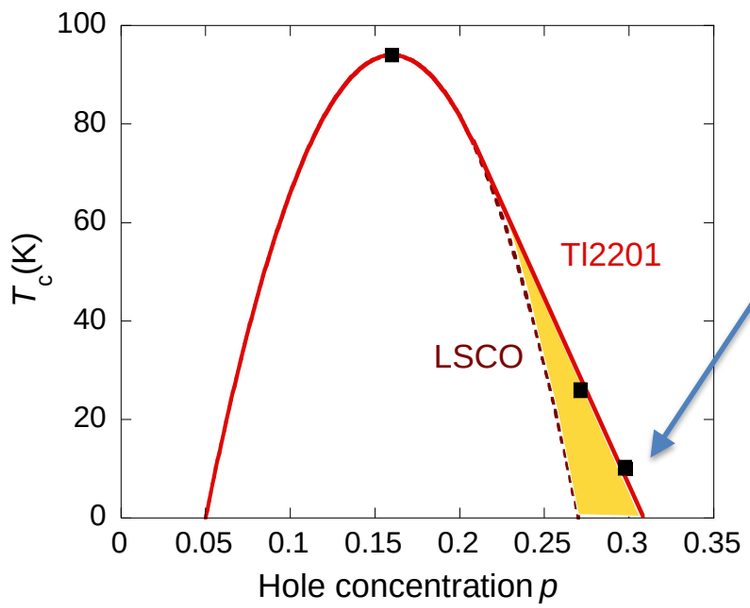
Norman *et al.*, *Nature* **392** 157 (98)

Hall number at high doping

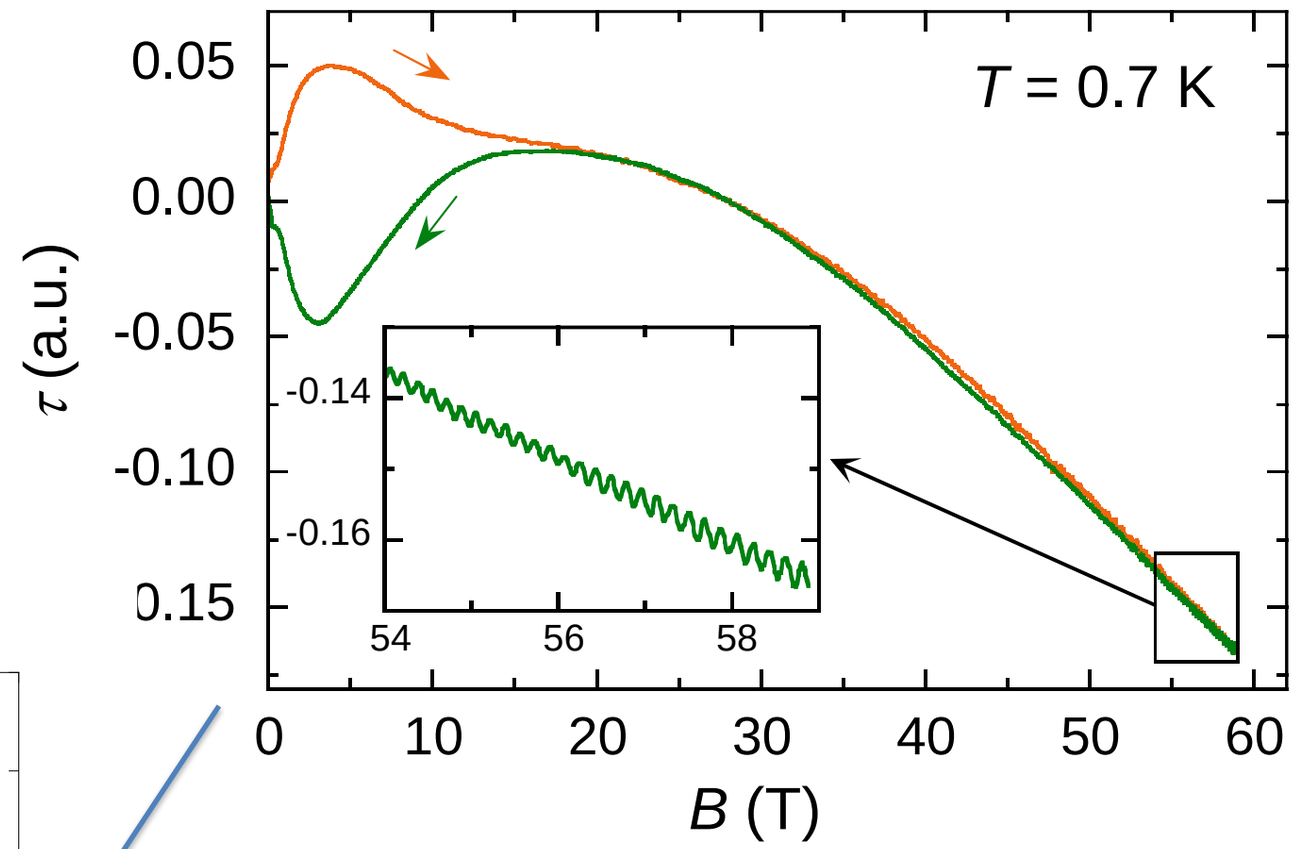


$Tl_2Ba_2CuO_{6+\delta}$
(Tl2201)

- No chains
- Single-layer cuprate



Vignolle, NEH *et al.*, *Nature* **455** 952 (08)



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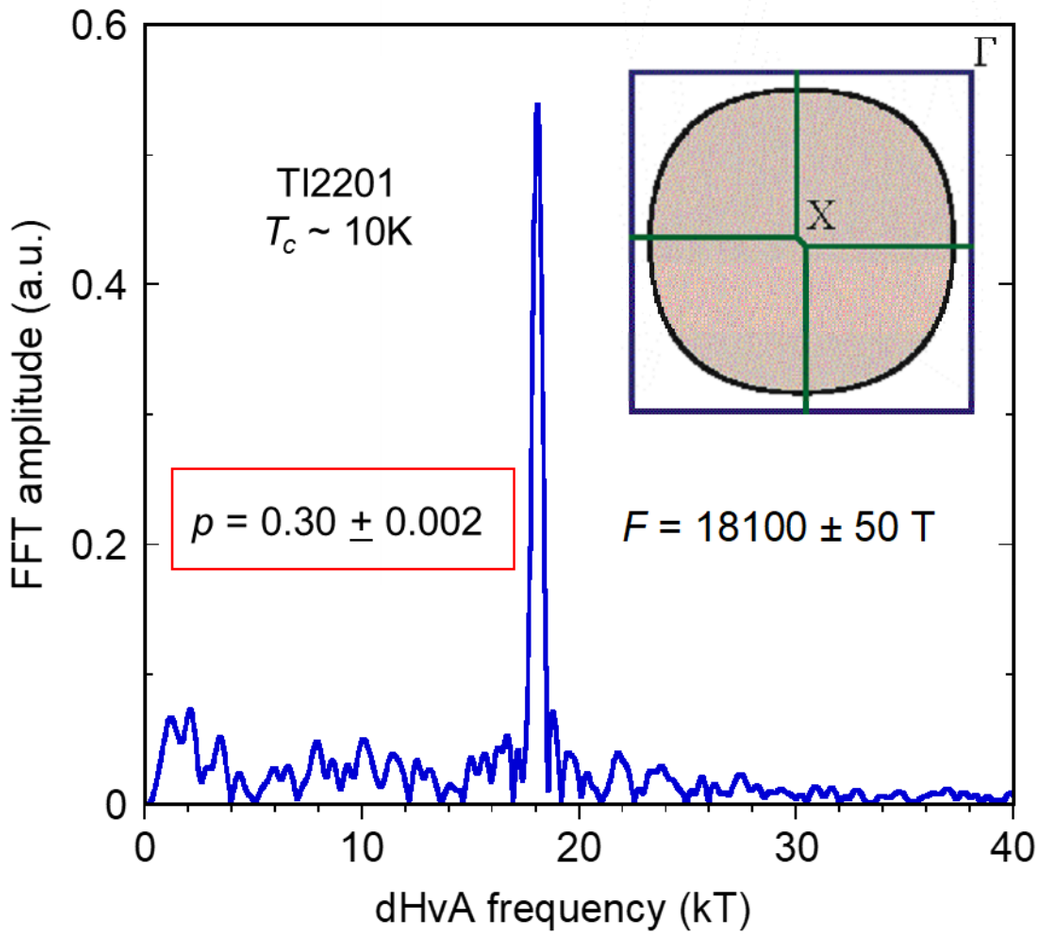
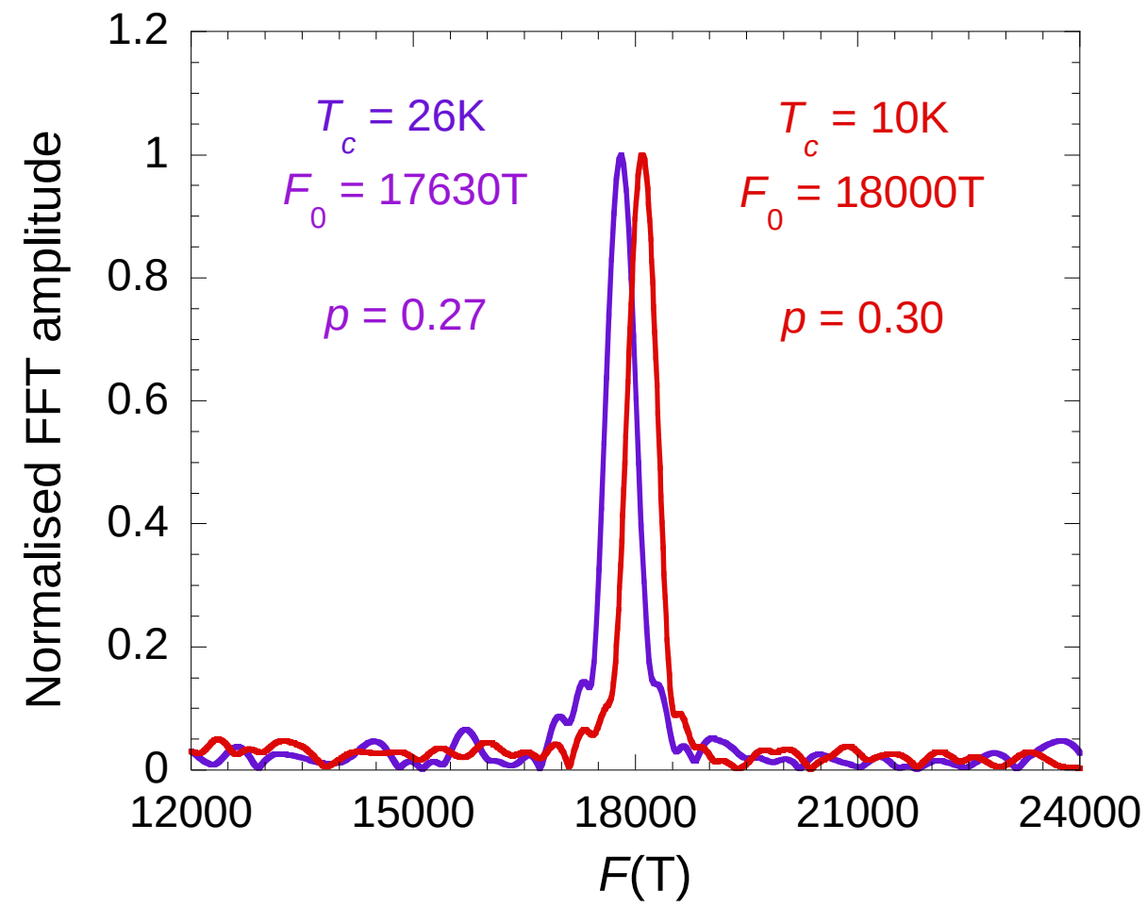
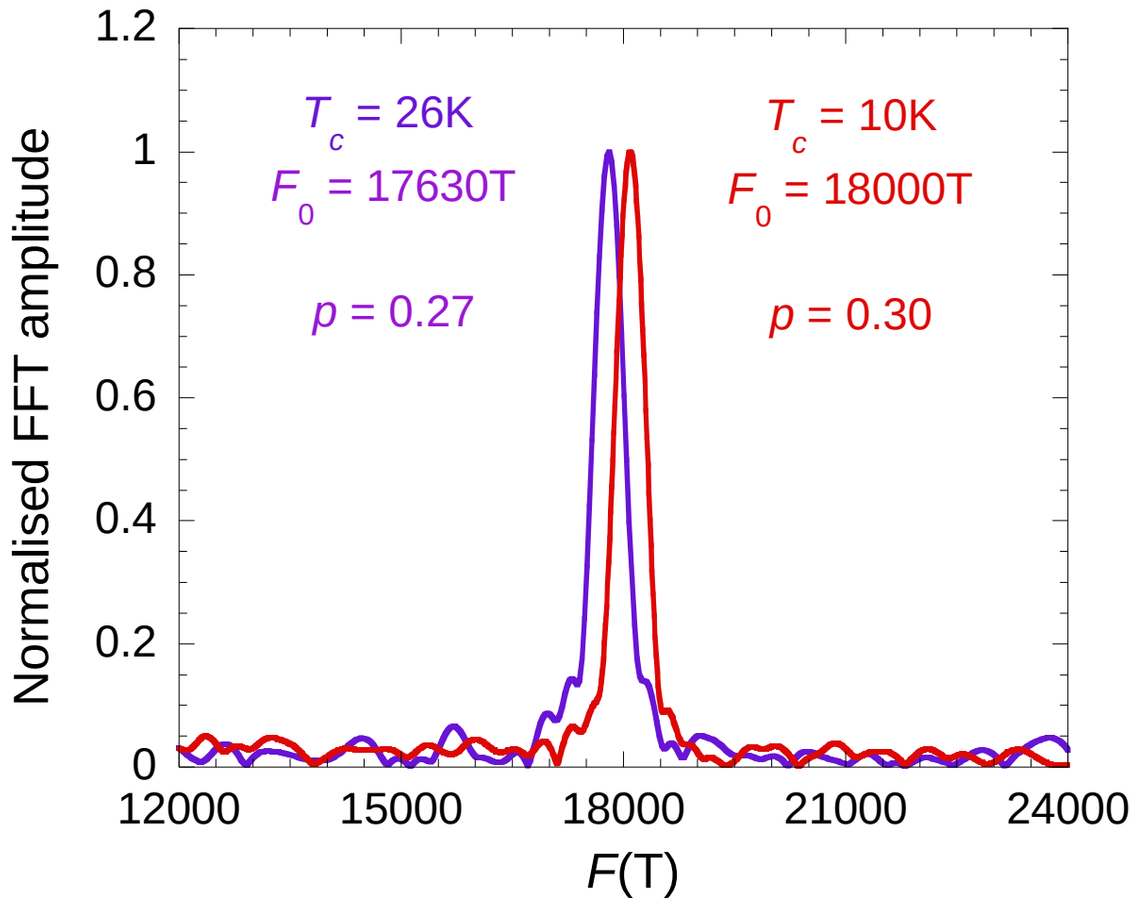


Bangura, NEH *et al.*, *PRB* **82** 140501 (10)

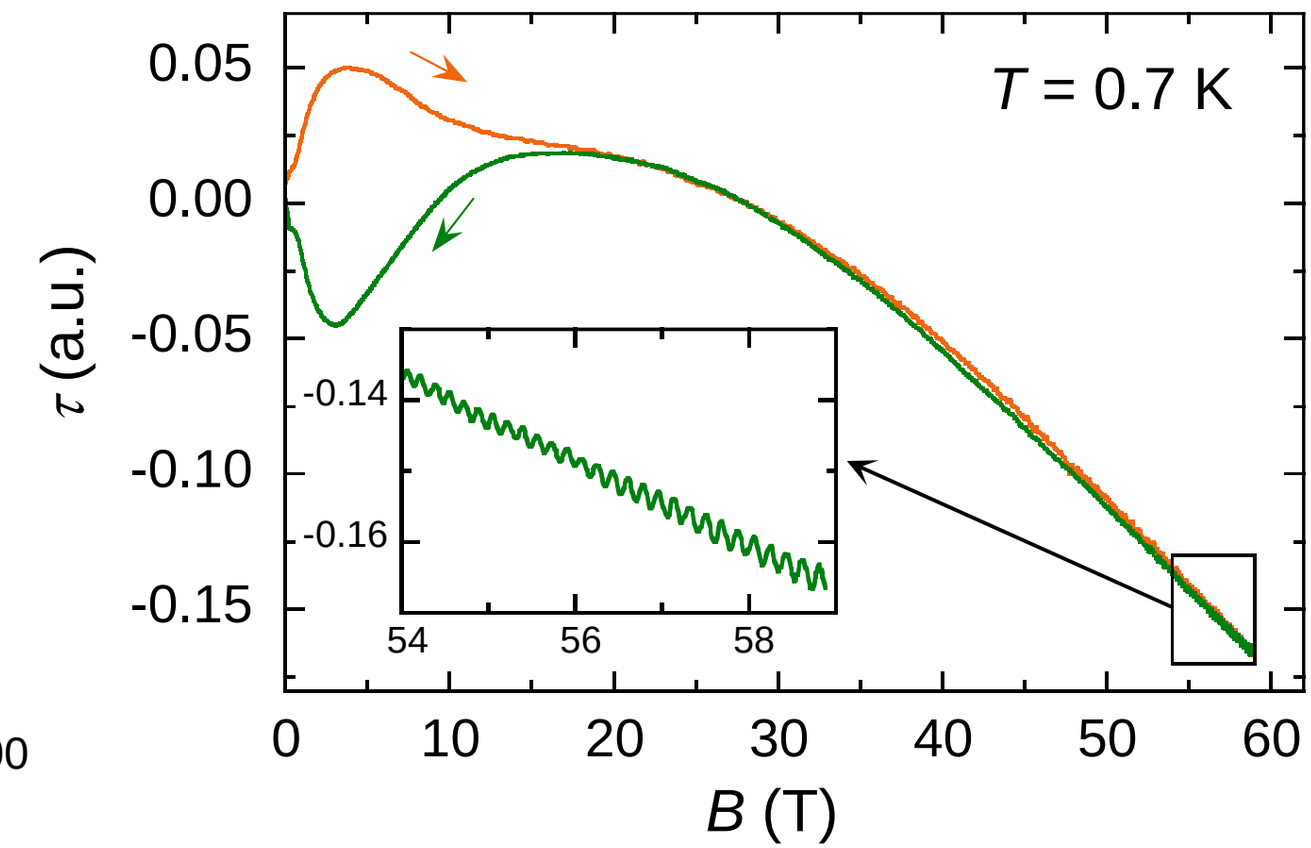


Tl2201 is extremely electronically homogeneous

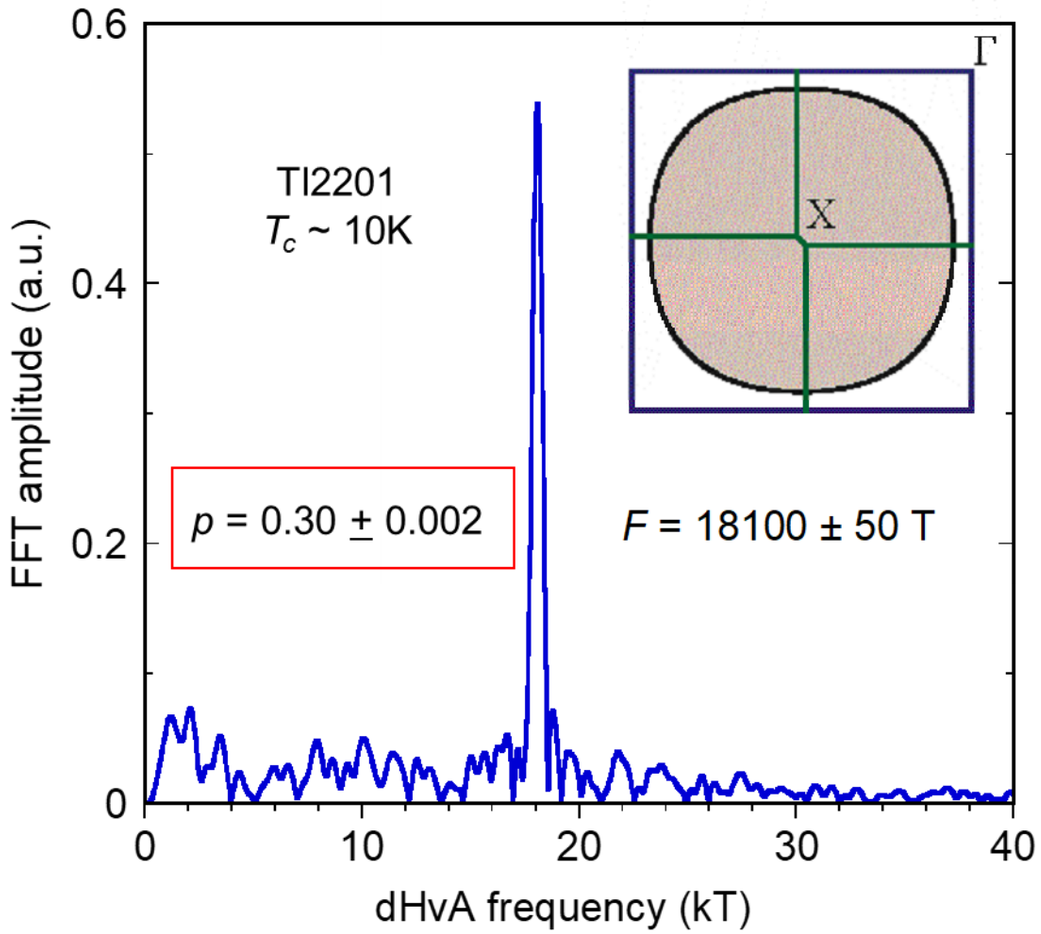
Hall number at high doping



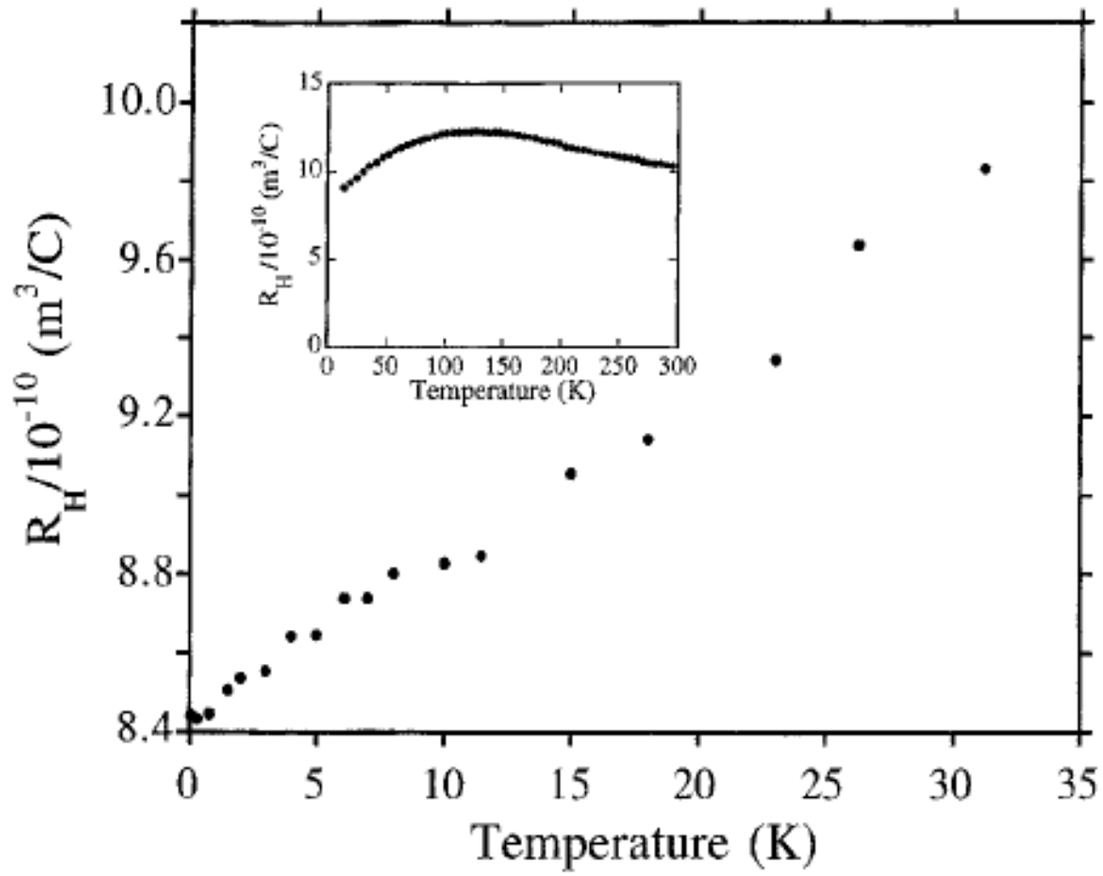
Vignolle, NEH *et al.*, *Nature* **455** 952 (08)



Hall number at high doping

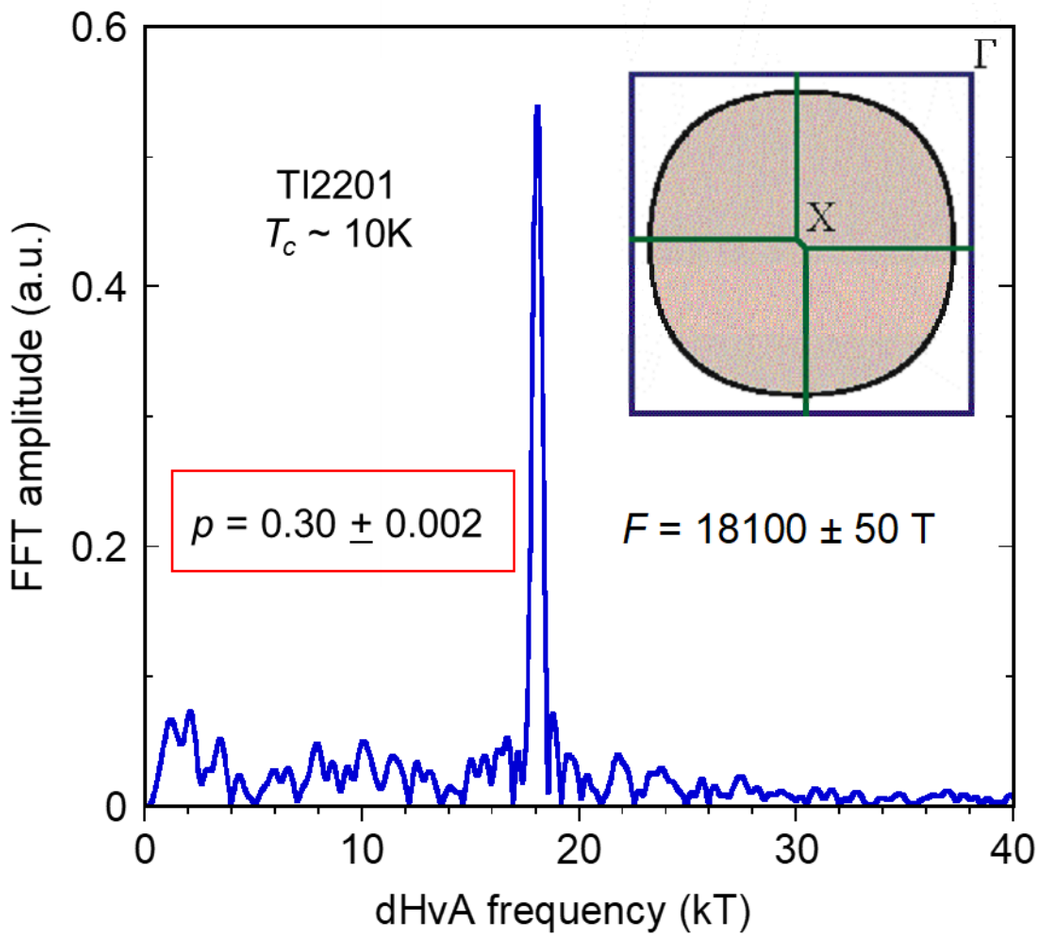


Mackenzie *et al.*, *PRB* **53** 5848 (96)



$$R_H = \frac{V_c}{e(1+p)} = \frac{a^2 c}{1.3e} = 8.3\times10^{-10}\,\mathrm{m}^3/\mathrm{C}$$

Hall number at high doping



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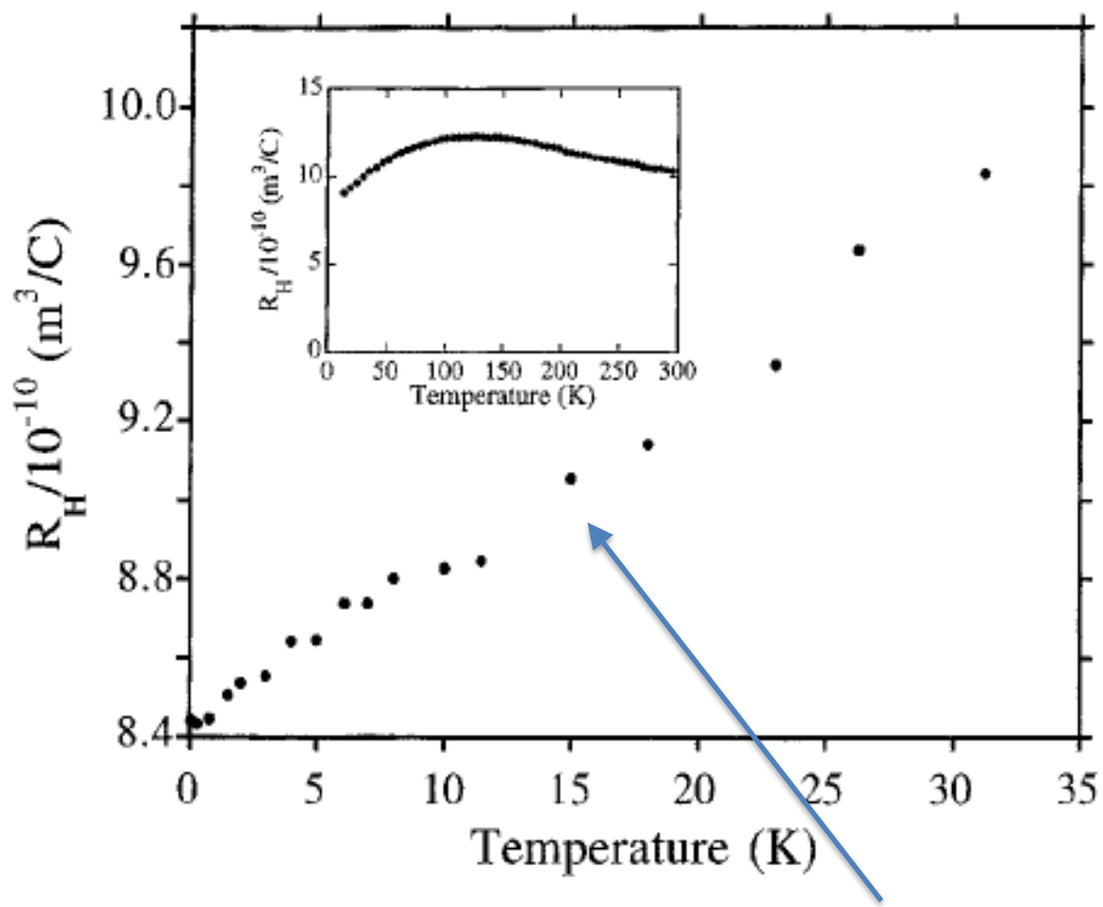
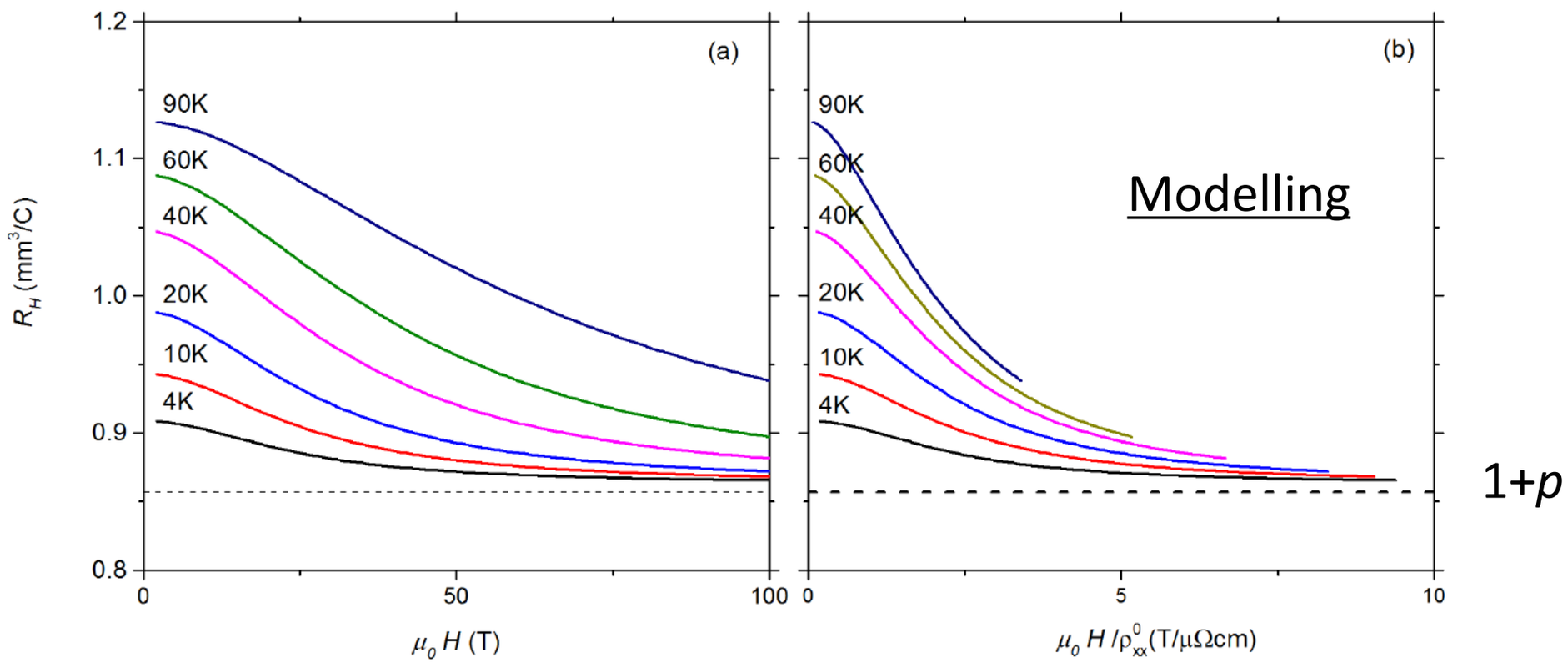


$$R_H = \frac{V_c}{e(1+p)} = \frac{a^2 c}{1.3e} = 8.3\times10^{-10}\,\mathrm{m}^3/\mathrm{C}$$

Growth of $R_H(T)$ possibly due to developing anisotropy in the mean-free-path

Hall number at high doping

Putzke *et al.*, in preparation

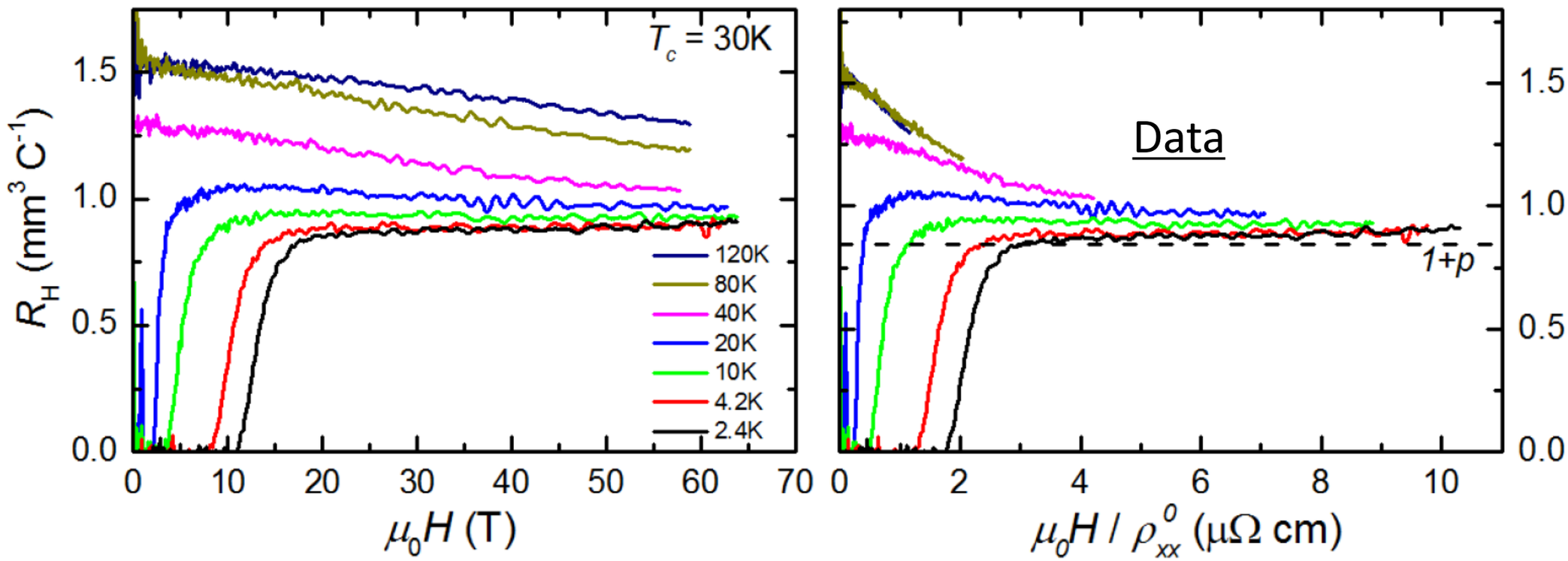


$$\sigma_{ij} = \frac{e^3 B}{2\pi^2 \hbar^2 c \omega_c^2} \int_0^\pi d\phi \int_0^\infty d\phi' v_j(\phi) v_j(\phi - \phi') e^{G(\phi - \phi') - G(\phi)}$$

$$G(\phi) = \int d\phi / [\omega_c(\phi)\tau(\phi)]$$

Hall number at high doping

Putzke *et al.*, in preparation



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$$G(\phi) = \int d\phi / [\omega_c(\phi)\tau(\phi)]$$

Conclusions

- Reduced Hall carrier density in the overdoped strange metal regime of cuprate superconductors
- Anti-correlated with the growth of the *T*-linear resistivity
- Suggestive of two-fluid charge dynamics in strange metal phase
- Loss of Hall carrier density persists beyond *p** - unlikely to be due to pseudogap or Fermi arc formation
- May be connected to coherent-incoherent crossover within strange metal phase