Evidence for spin-fluctuation-mediated superconductivity in *n*-doped cuprates

Radboud Universiteit

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HFML
Science in High Magnetic Fields

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EMFL User Meeting
University of Nottingham
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Qihong Chen
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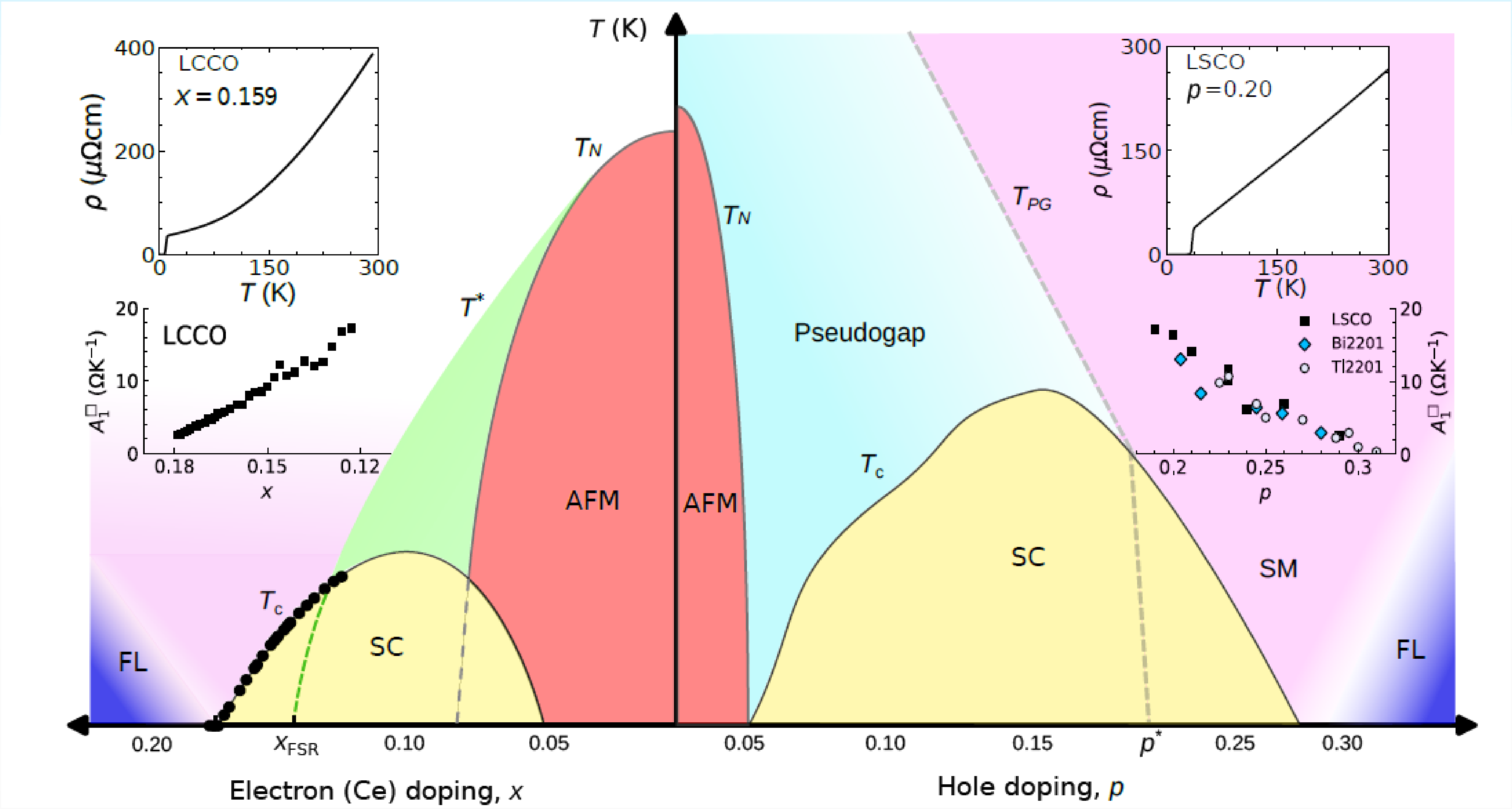
Roemer Hinlopen

Alessandro Cuoghi

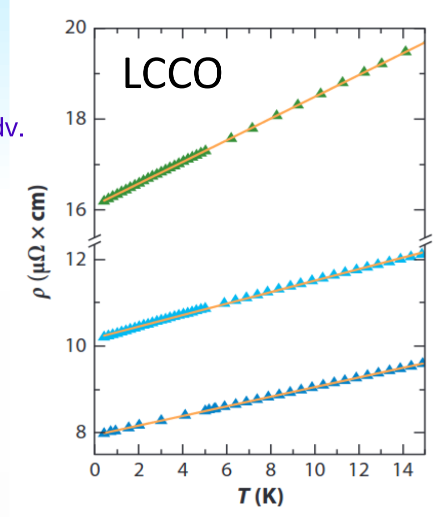
Phase diagram



Similarities…

T-linear resistivity

T. Sarkar *et al.*, Sci. Adv. **5**:eaav675 (2019)

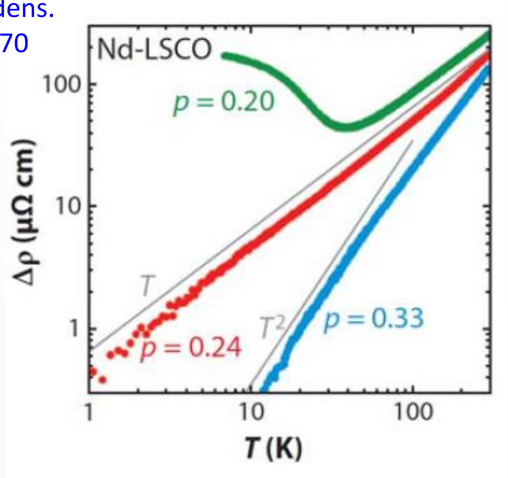


x=0.15

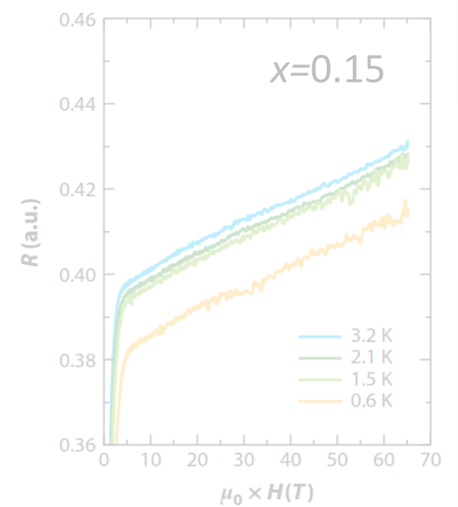
x=0.16

x=0.17

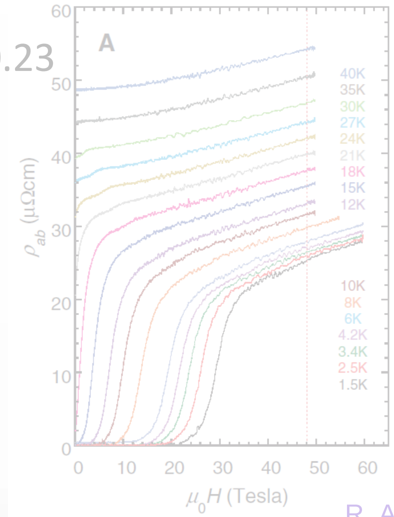
Taillefer, Annu. Rev. Condens. Matter Phys. 2010. 1:51–70



H-linear magnetoresistance

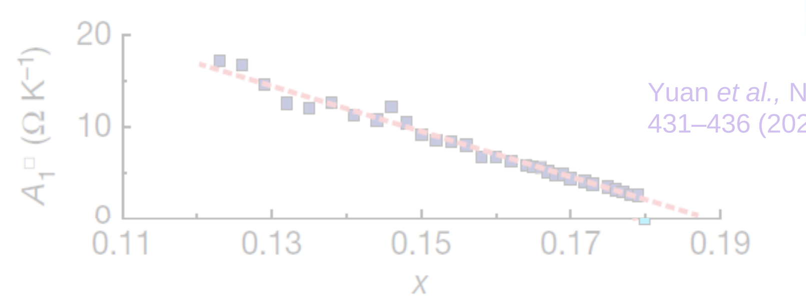


p=0.23

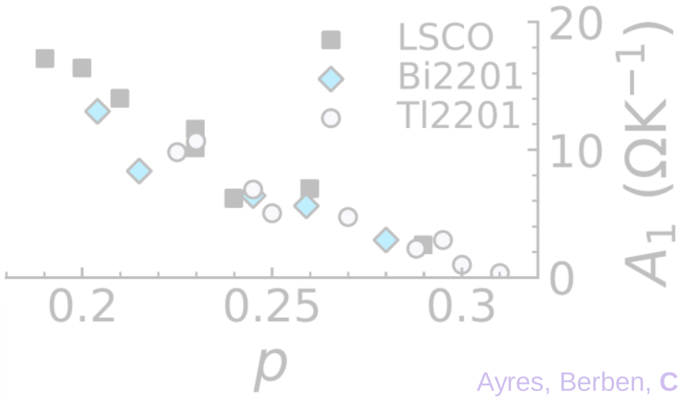


R. A. Cooper *et al.*, *Science* **323**, 603-607 (2009)

Scaling of *T*-linear resistivity and T_c



Yuan *et al.*, Nature **602**, 431–436 (2022)



Ayres, Berben, **CMD**, et al., arXiv:2203.04867

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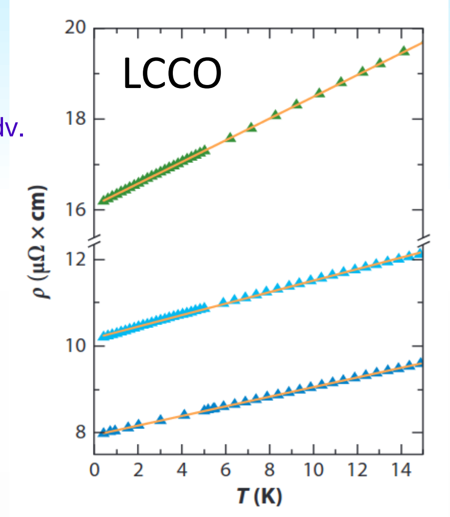

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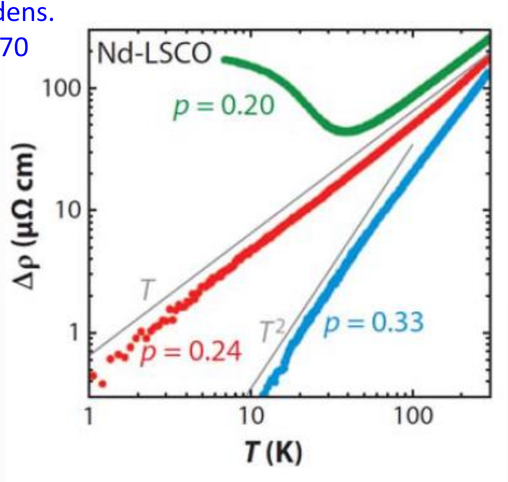

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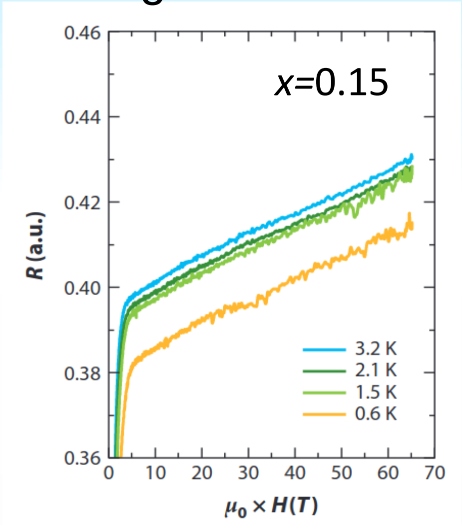

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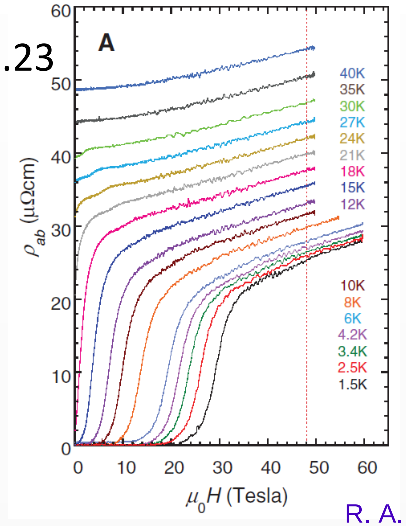

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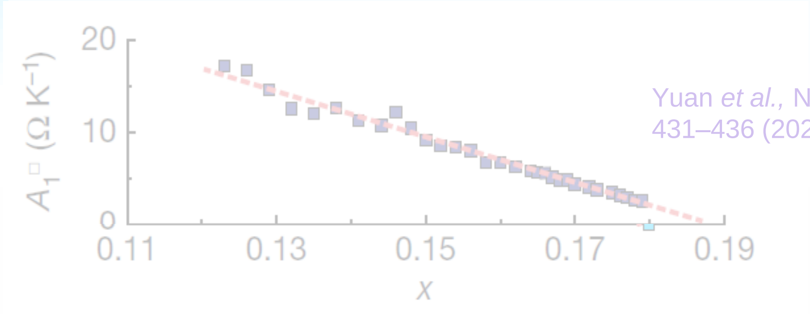

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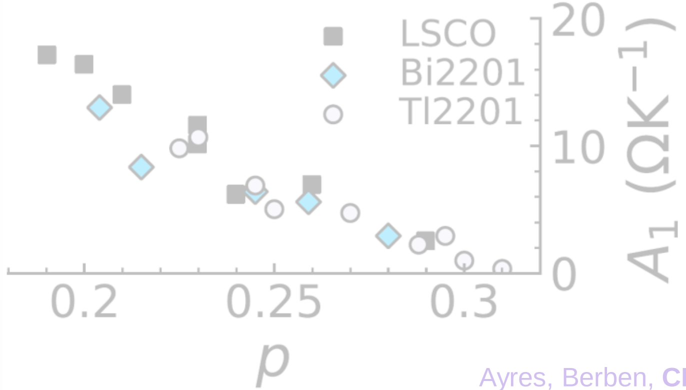

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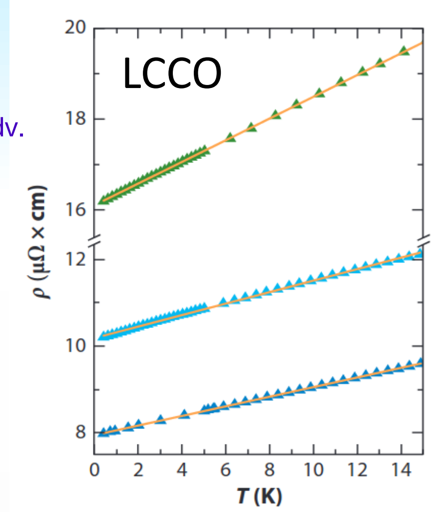

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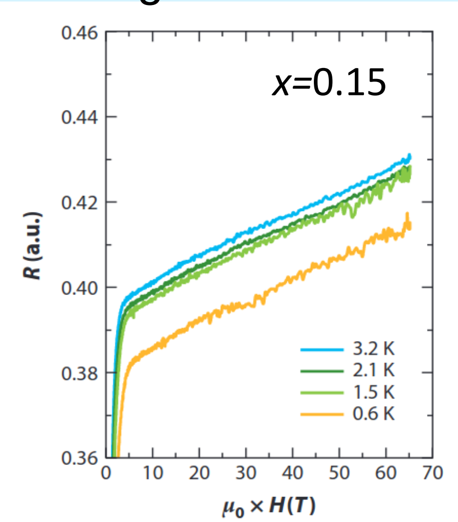

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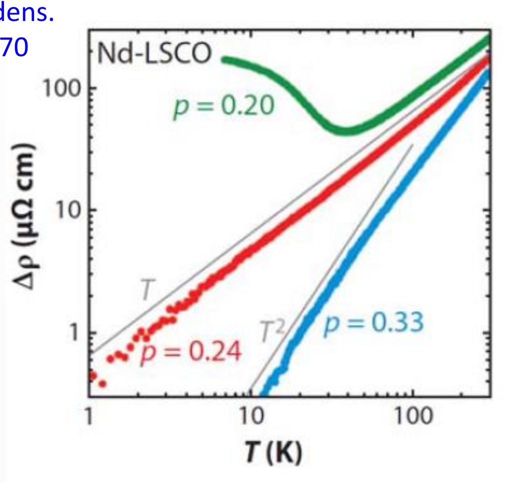

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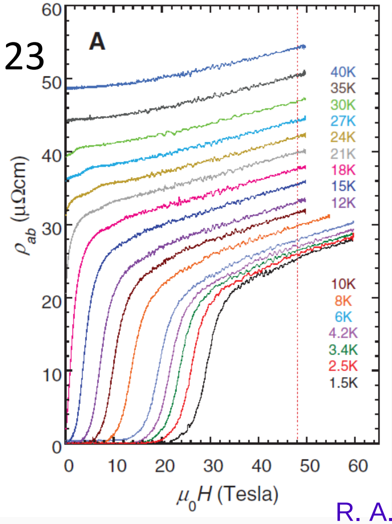

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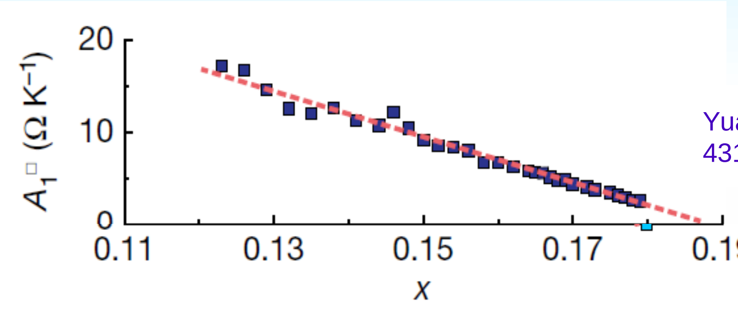
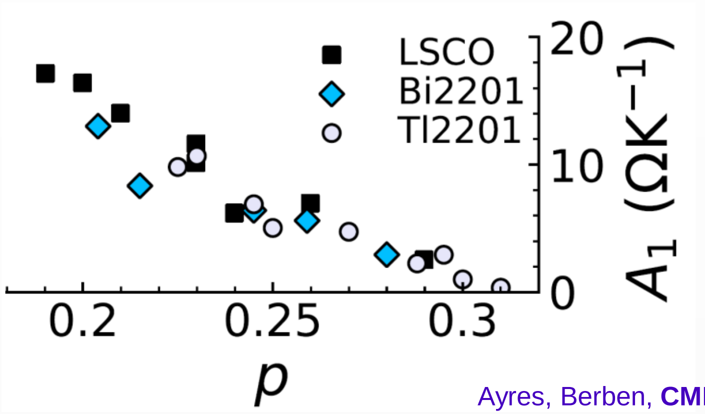


Yuan *et al.*, Nature **602**, 431–436 (2022)

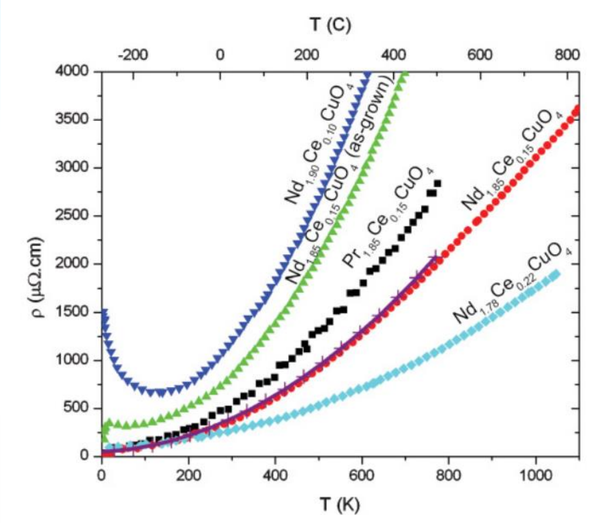


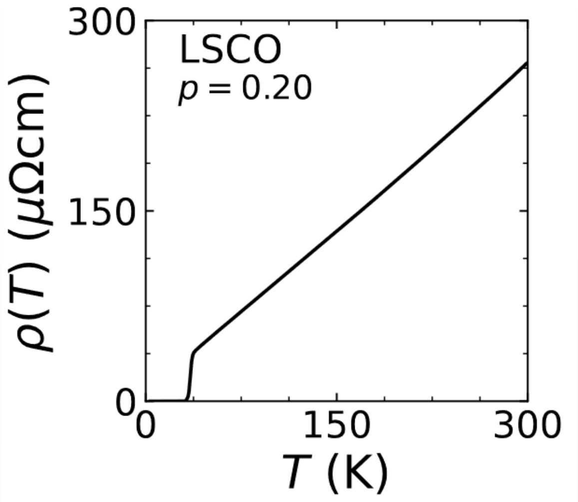
Ayres, Berben, **CMD**, et al., arXiv:2203.04867

…and differences

Quadratic resistivity at high-*T*.

P.L. Bach *et al.*, PRB **83**, 212506 (2011)

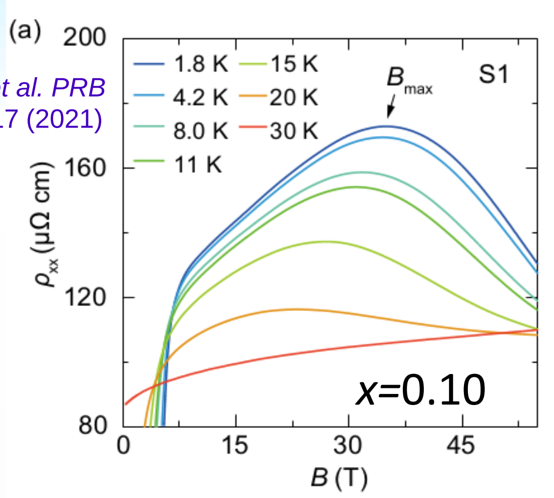


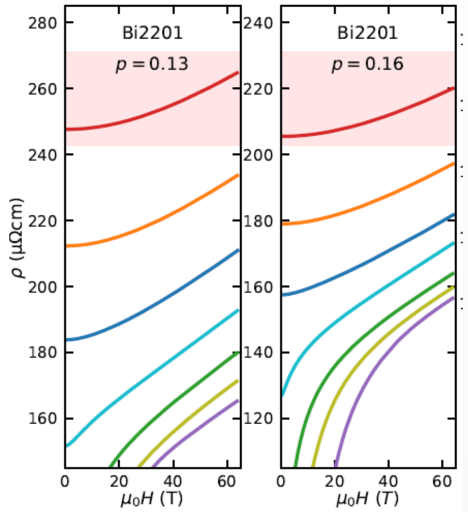


Ayres, Berben, **CMD**, et al., arXiv:2203.04867

Non-trivial MR in the AFM phase.

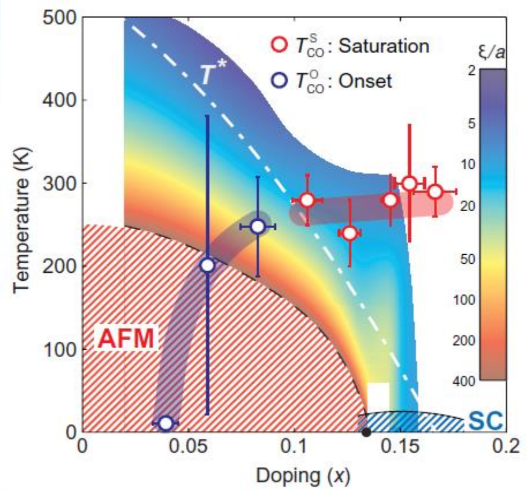
X. Zhang *et al. PRB* **103**, 014517 (2021)



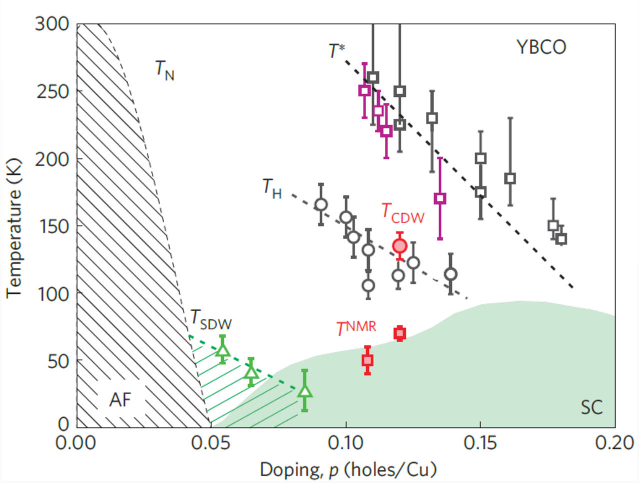


Minimal influence from CO.

da Silva Neto *et al.*, Sci. Adv. 2016; 2 : e1600782

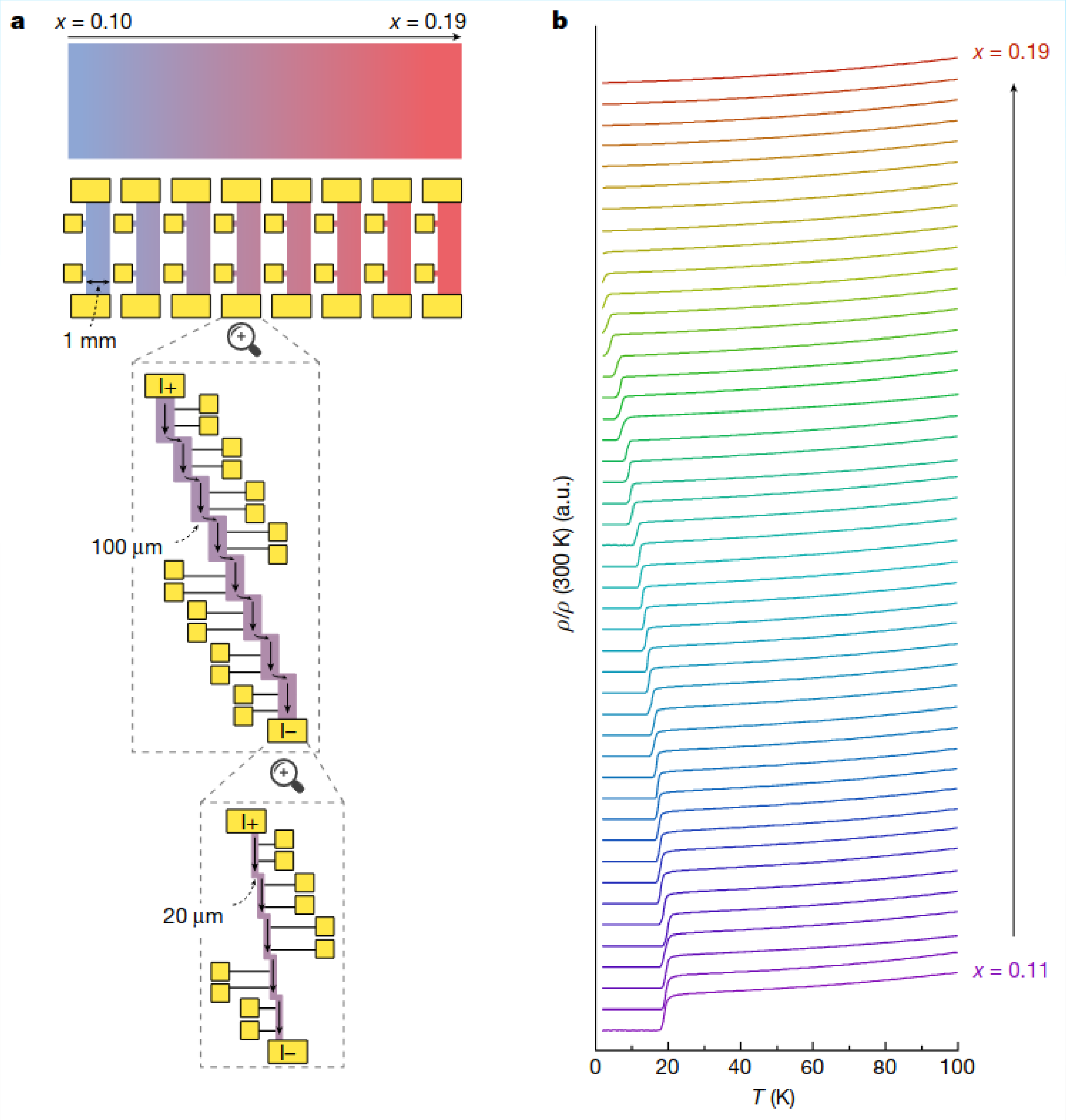


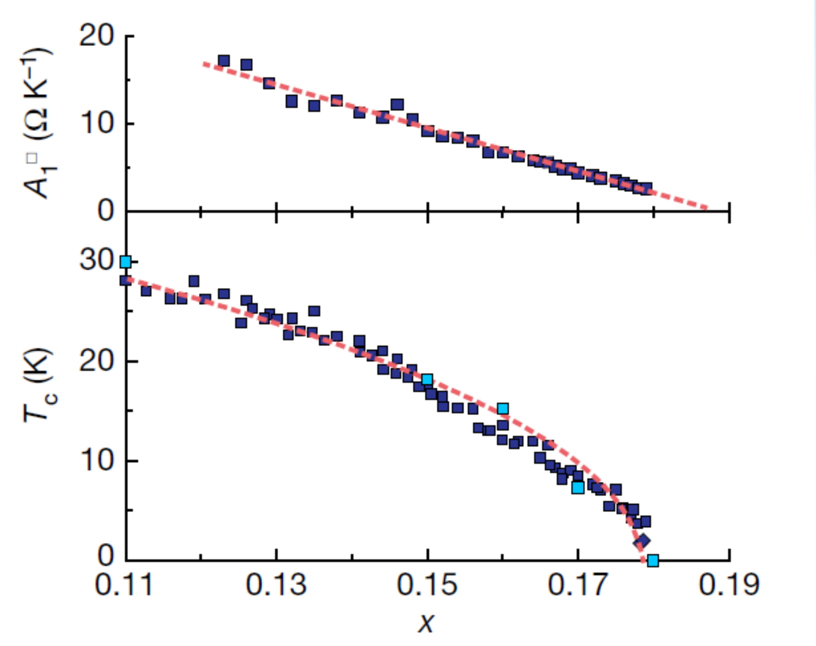
Chang *et al.*, Nat. Phys. **8**, 871-876 (2012)



How can we understand these differences between the electron- and hole-doped cuprates?

Combinatorial films



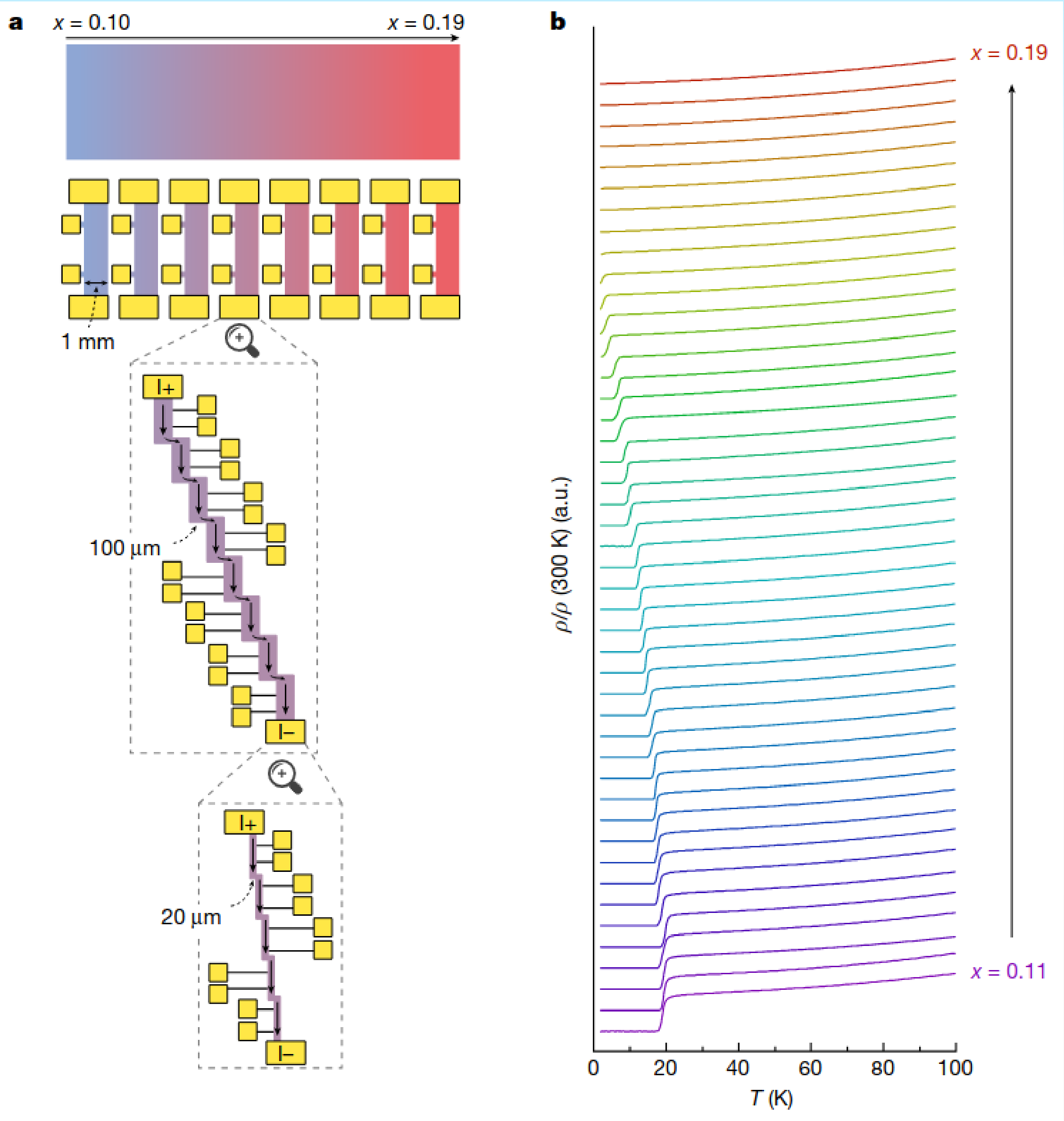


Combi thin films:

- Many doping levels across a single film
- Facilitates very systematic studies

Yuan *et al.*, Nature
602, 431–436 (2022)

Combinatorial films



Combi thin films:

- Many doping levels across a single film
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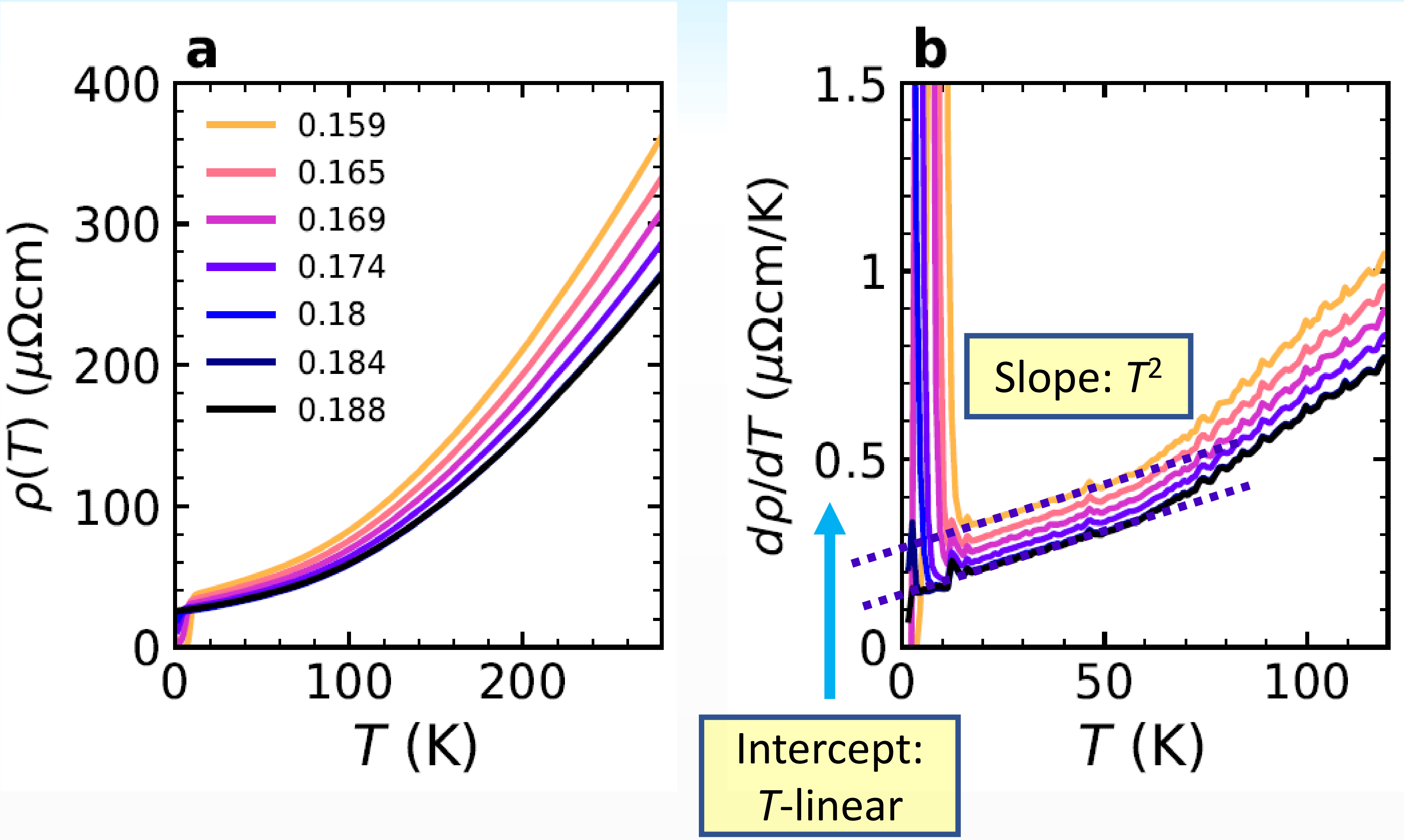
Yuan *et al.*, Nature **602**, 431–436 (2022)

HFML Science in High Magnetic Fields

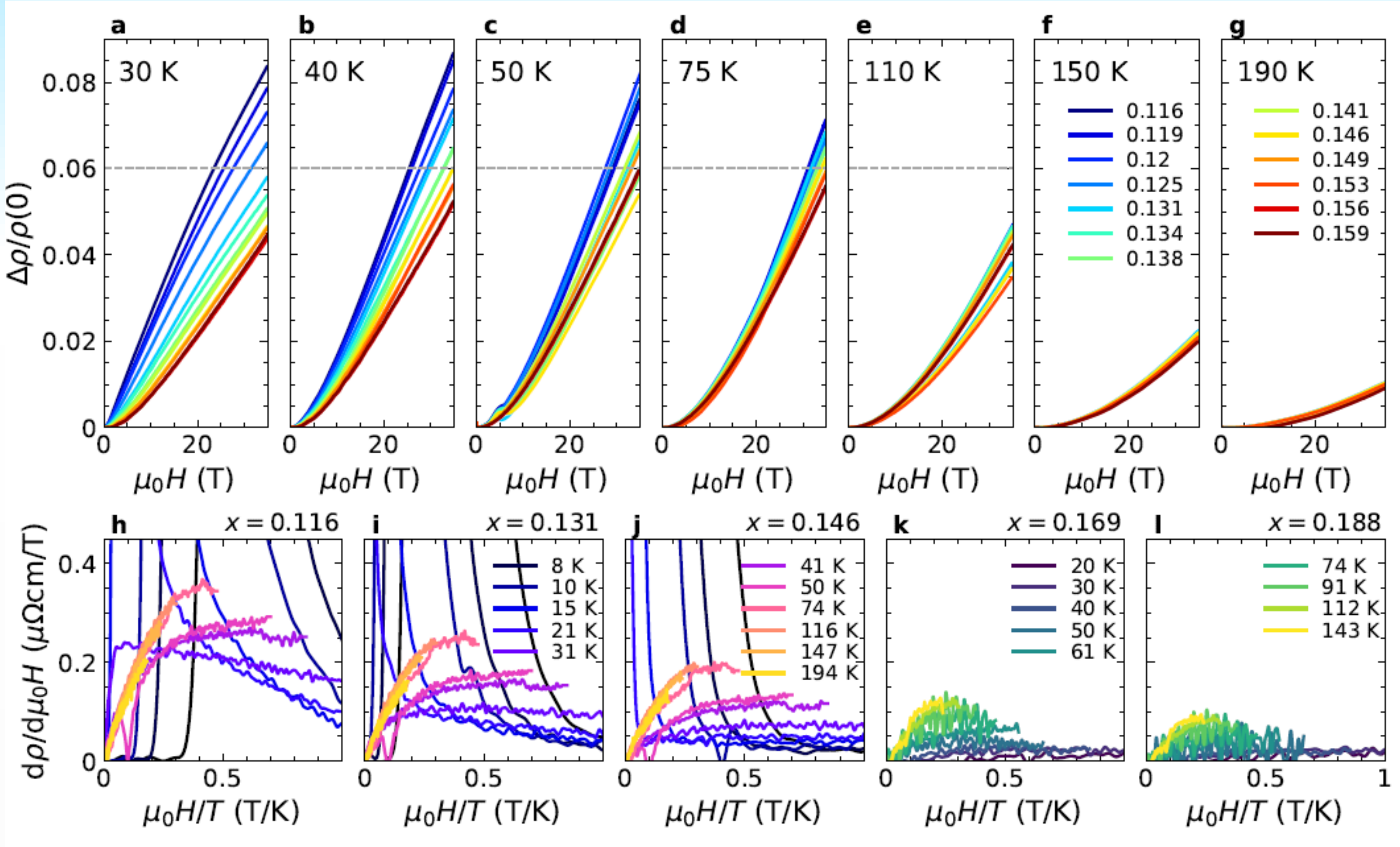
Zero-field



Intercept (T-linear component) is ***x*-dependent**

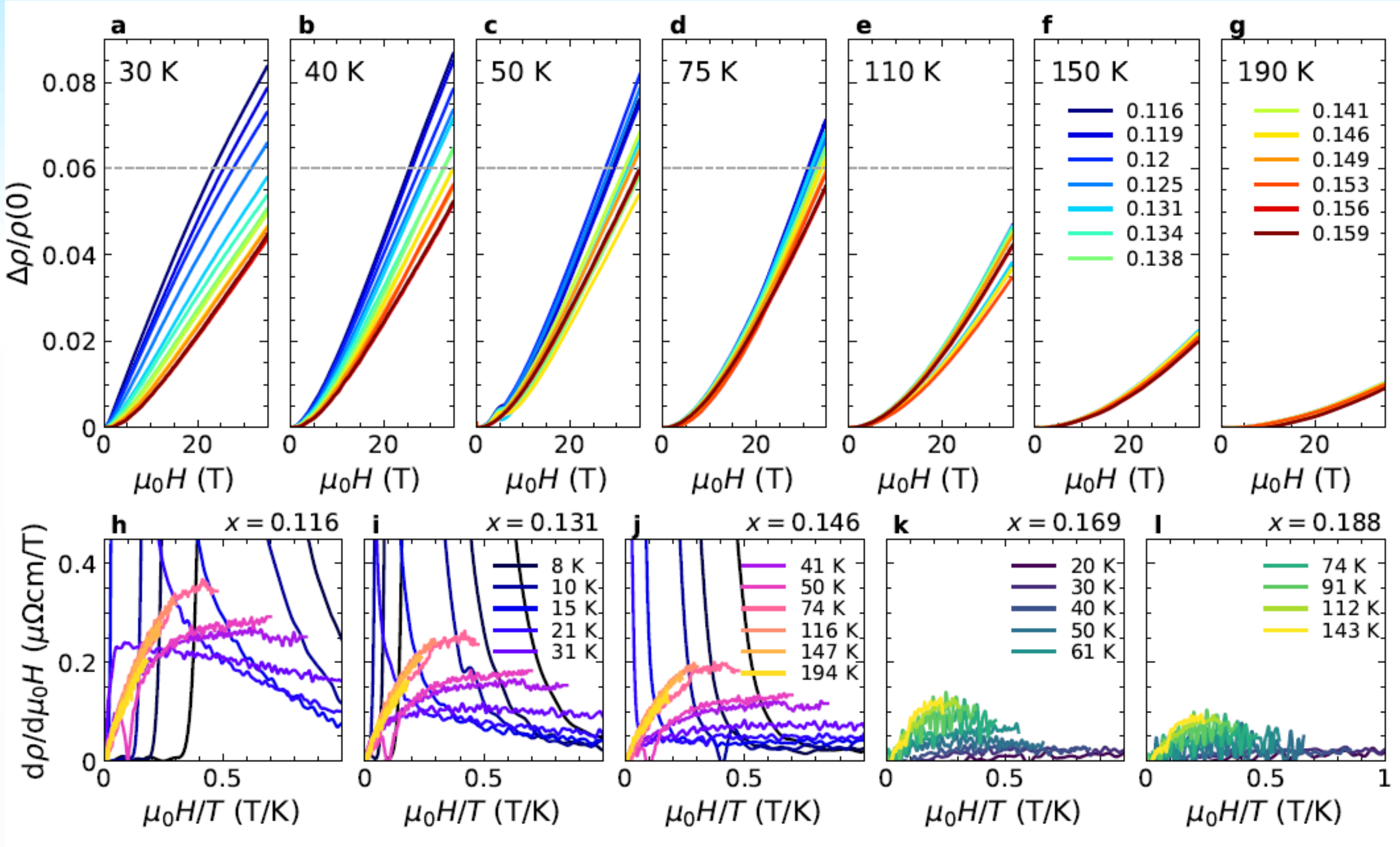
Slope (T^2 component) is ***x*-independent**

Magnetoresistance

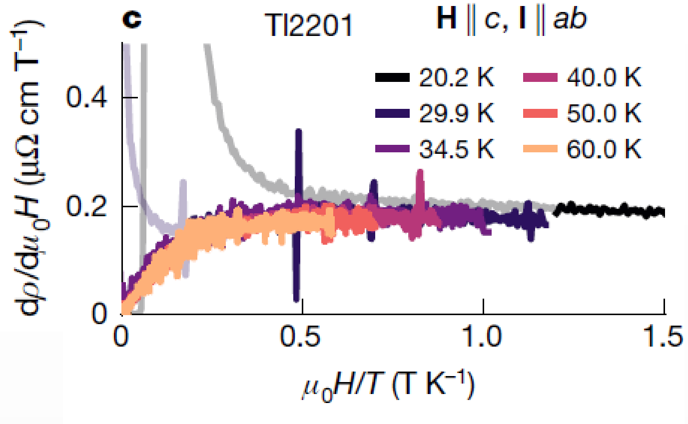


- H-linear MR at high fields for $x > x_{AFM}$.
- The decrease in MR as T is decreases implies that the anisotropy of ℓ decreases faster than ℓ itself.

Magnetoresistance



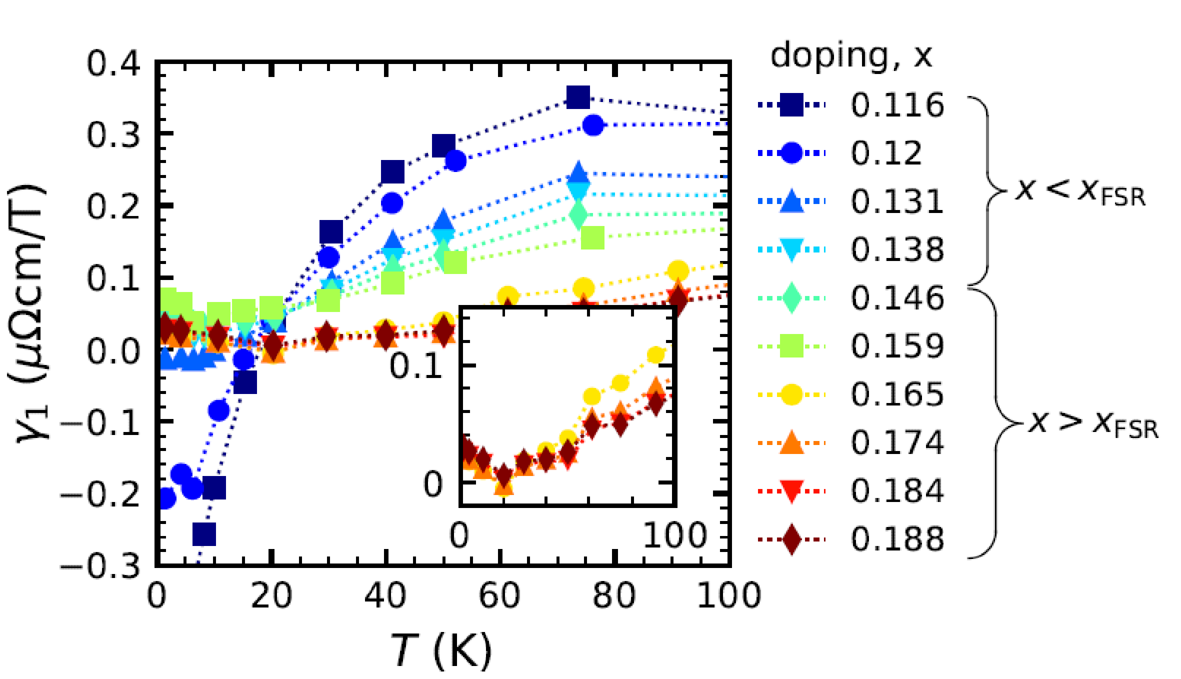
Ayres, Berben, et al.,
Nature **595**, 661-666 (2021)



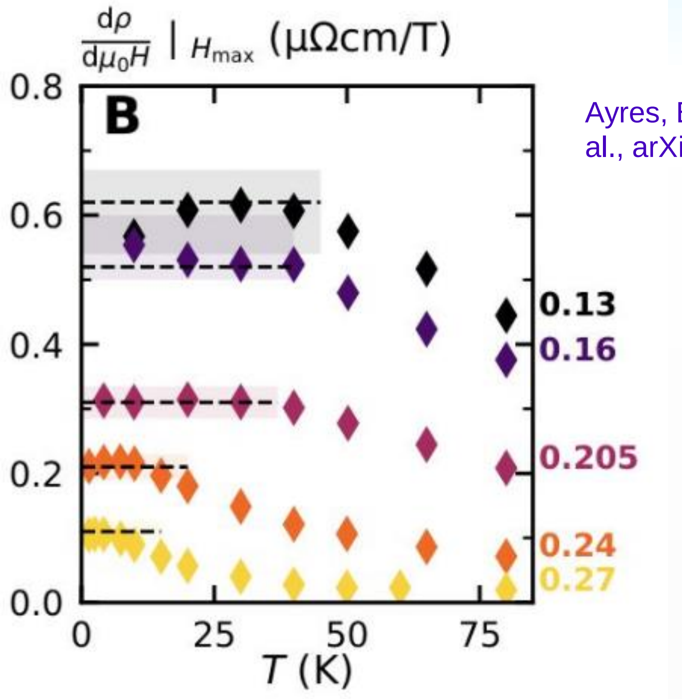
Stark contrast to H/T scaling seen in the p-doped cuprates

- H-linear MR at high fields for $x > x_{AFM}$.
- The decrease in MR as T is decreases implies that the anisotropy of ℓ decreases faster than ℓ itself.

Magnetoresistance



High field slope is always *T*-dependent.



Ayres, Berben, **CMD**, et al., arXiv:2203.04867

In *p*-doped cuprates, the high-field slope is scale-invariant.

Magnetoresistance

Using the data, can we extract a scattering rate that can model the data itself?

Can this provide hints to the origin of the unusual transport?

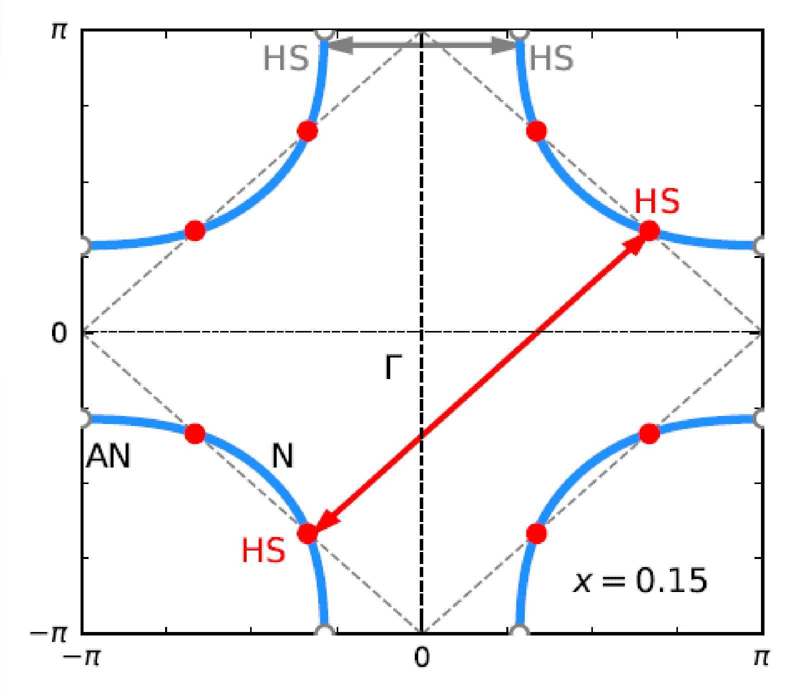
What does this tell us about superconductivity in *n*-doped cuprates?

Modelling

Solution of Boltzmann Equation for 2D materials:
Shockley-Chambers Tube Integral Formula

$$\sigma_{ij} = \frac{1}{4\pi^3}\int_{FS} d^2k \frac{1}{\hbar v_F} q v_i \int_0^\infty q v_j(-t) P(t) dt,$$

$$P_\phi(t) := \exp\left[-\int_0^t \frac{dt'}{\tau(t')}\right]$$



TB params:
Tang *et al.*, PRB **104**, 155125 (21)

Constructing the scattering rate

$$\tau^{-1}(\varphi, T, x) = \tau_{\text{imp}}^{-1} + \tau_{\text{HS}}^{-1}(\varphi) + g(x)\alpha_1 T \sin^2(2\varphi) + \alpha_2 T^2 \sin^2(2\varphi)$$

Constructing the scattering rate

$$\tau^{-1}(\varphi, T, x) = \tau_{\text{imp}}^{-1} + \tau_{\text{HS}}^{-1}(\varphi) + g(x)\alpha_1 T \sin^2(2\varphi) + \alpha_2 T^2 \sin^2(2\varphi)$$

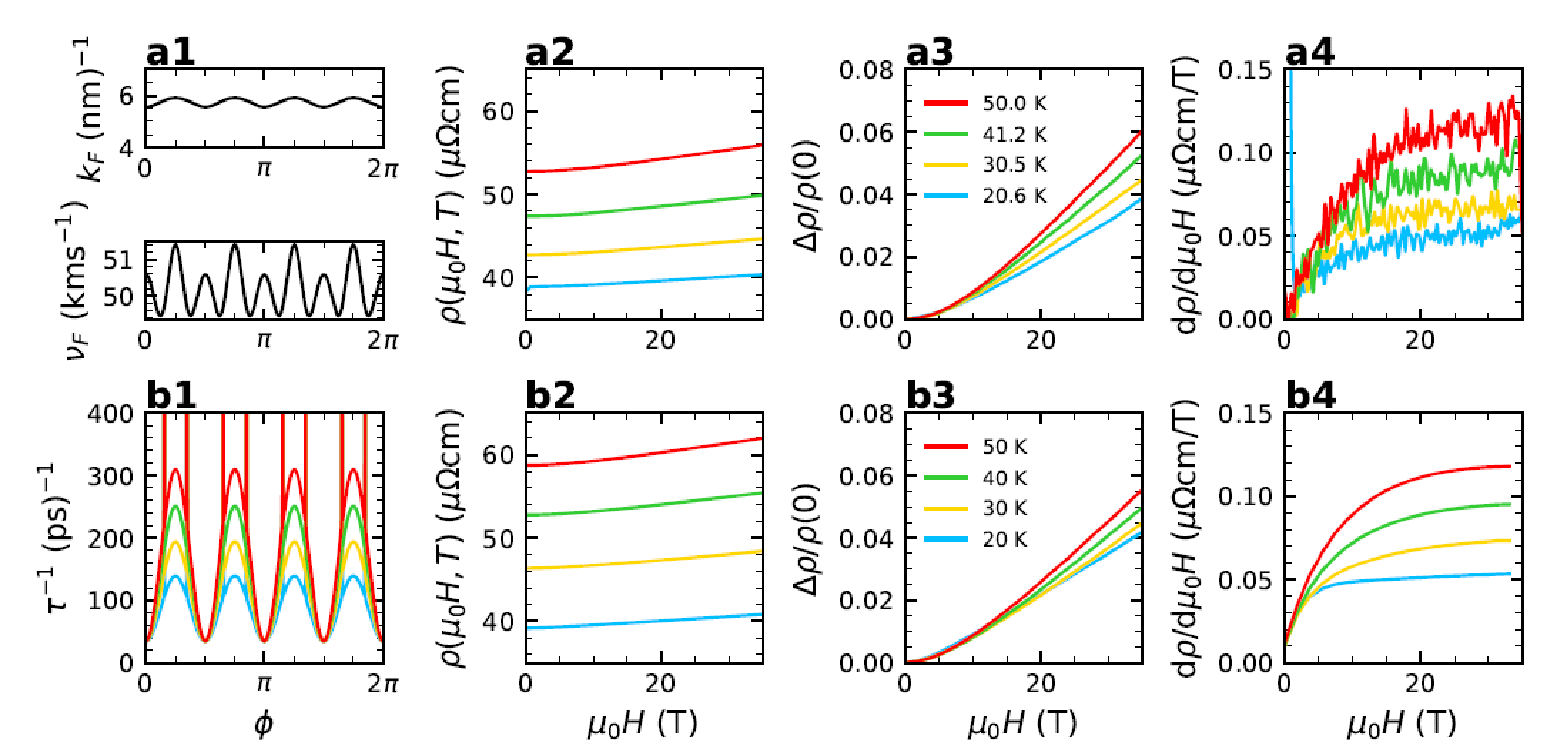
Impurity scattering

Hotspots – required for *H*-linear MR

Hinlopen *et al.*, PRR **4**, 033195 (2022)

Inelastic component – reflects *T*-dependence of zero-field resistivity, including *x*-dependence of *T*-linear component

Simulations x=0.159

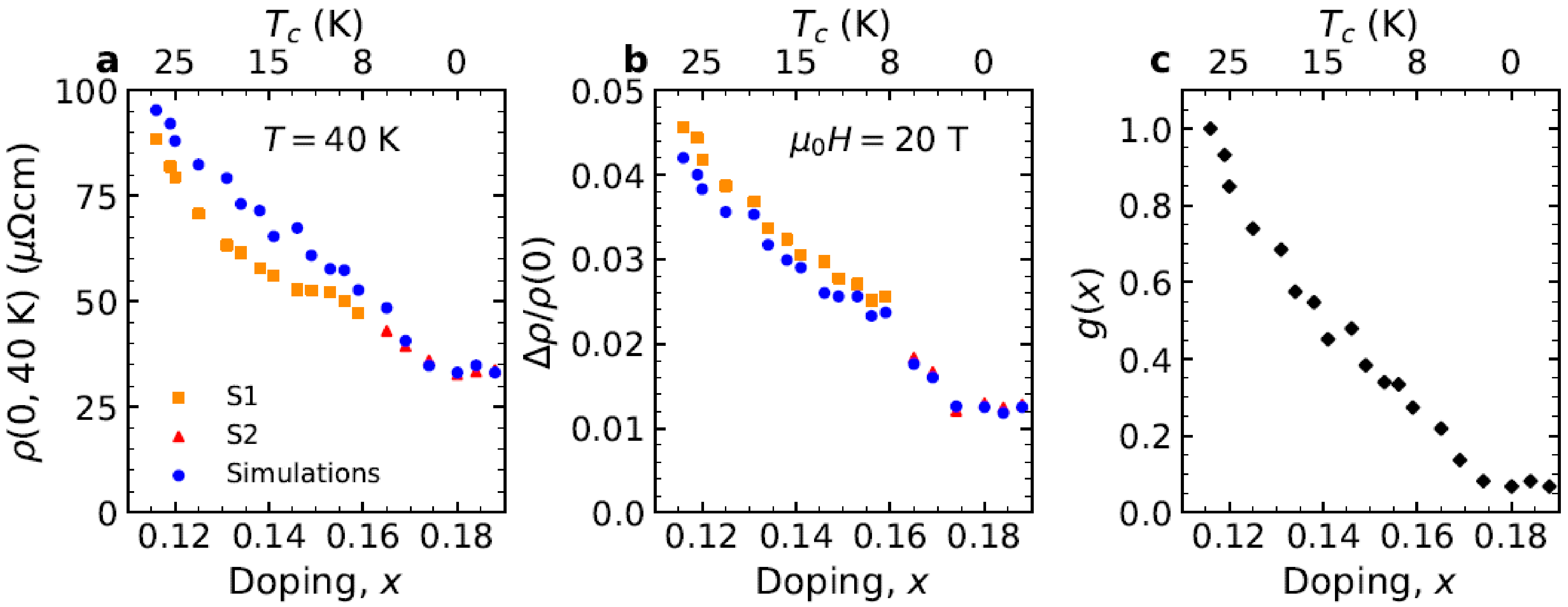


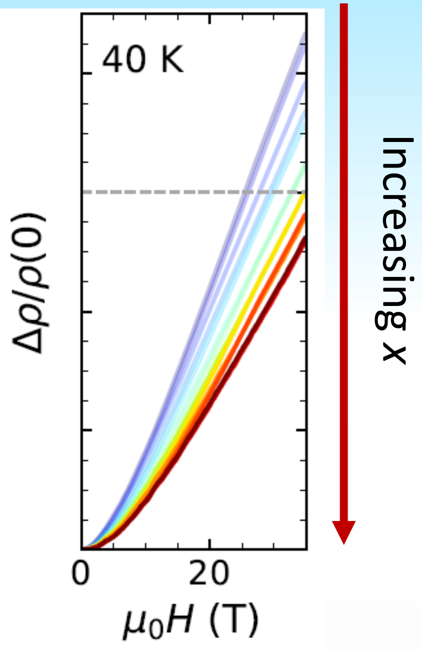
Data

Simulation

x-dependence

$$\tau^{-1}(\varphi, T, x) = \tau_{\text{imp}}^{-1} + \tau_{\text{HS}}^{-1}(\varphi) + g(x)\alpha_1 T \sin^2(2\varphi) + \alpha_2 T^2 \sin^2(2\varphi)$$

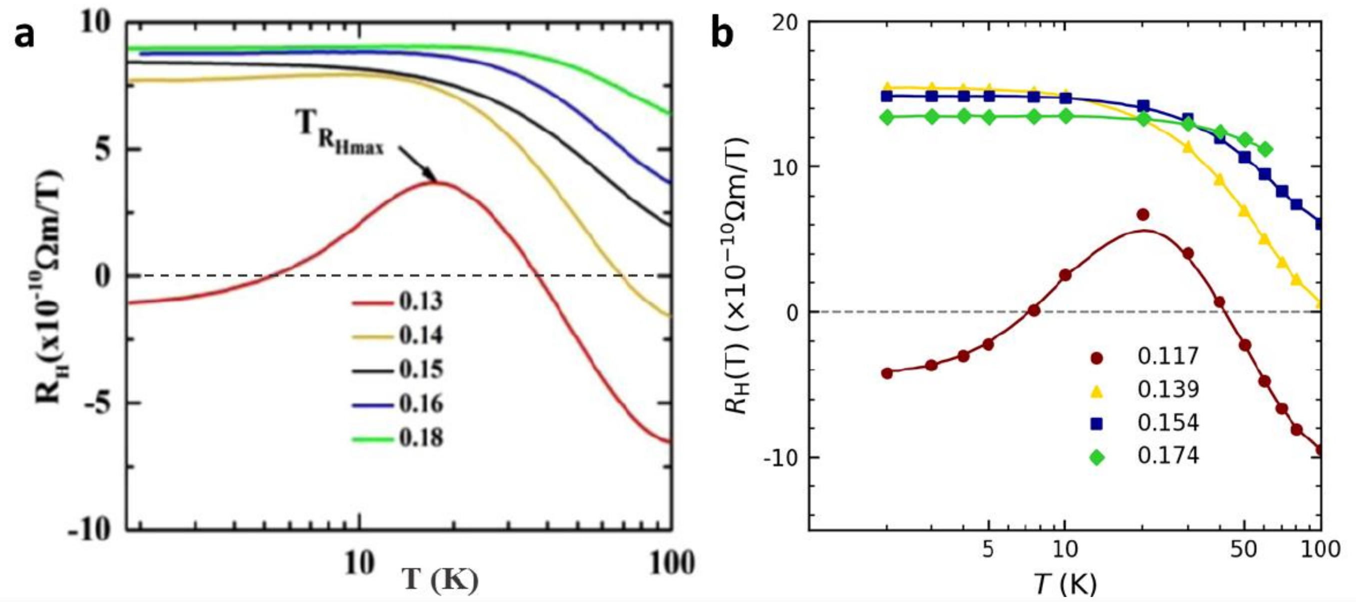




Verifying the Scattering rate: Hall Effect

R_H changes sign – even in the absence of a FSR

Use **current vertex corrections** to constrain the scattering rate



Sarkar *et al.*, PRB
96, 155449 (2017)

Yuan *et al.*, Nature
602, 431–436 (2022)

$$\vec{J}_k = \frac{1}{1-\epsilon_k^2}\left(\vec{v}_k + \epsilon_k \vec{v}_{k\pm Q}\right)$$

Current (hence velocity) vector at the hotspots is altered due to (π, π) scattering.

Conclusion

- The scattering rate of LCCO is correlated with a coupling parameter which is due to antiferromagnetic spin fluctutations.
- The correlation between the coupling parameter and T_c implies that superconductivity in *n*-doped cuprates is mediated by antiferromagnetic spin fluctuations.
- The differences between *n*- and *p*-doped cuprates imply that the same conclusion cannot be drawn for *p*-doped cuprates.

European Magnetic Field Laboratory

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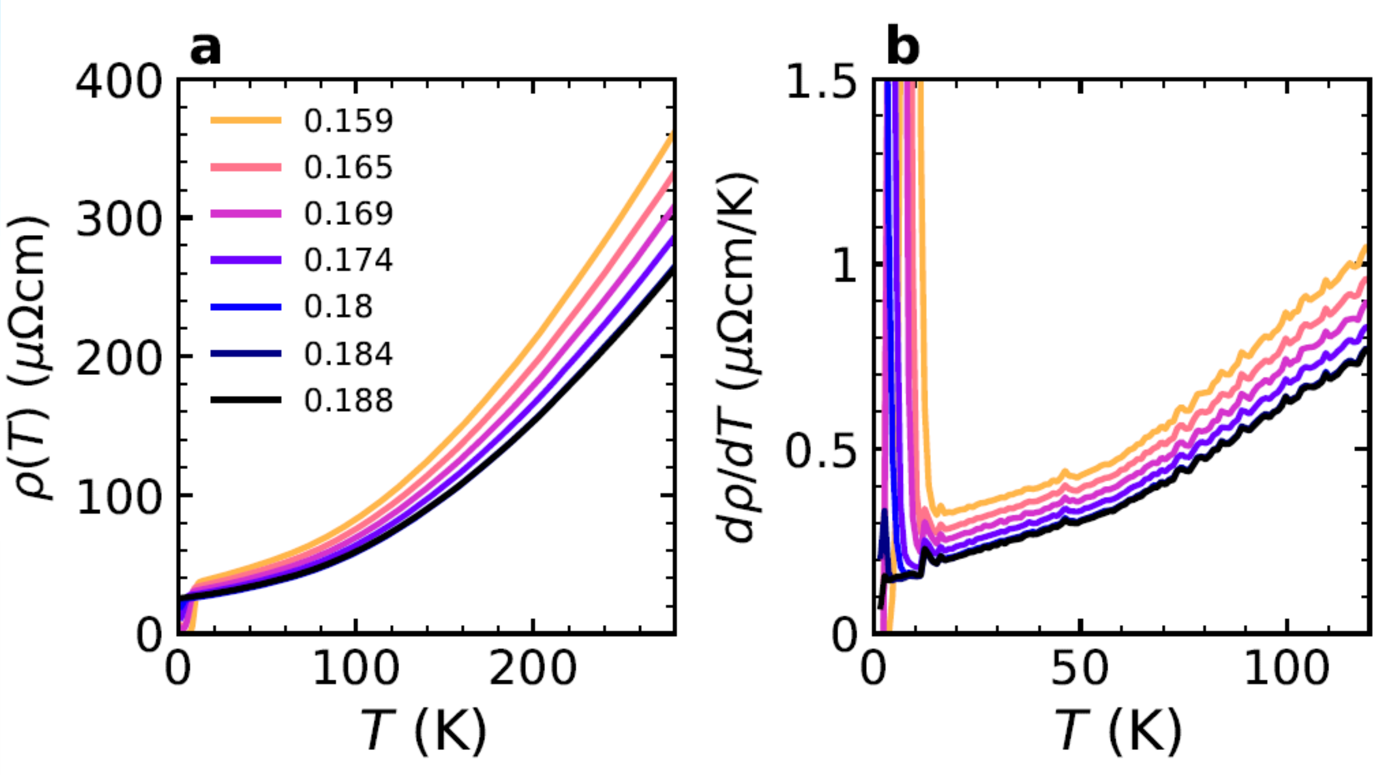
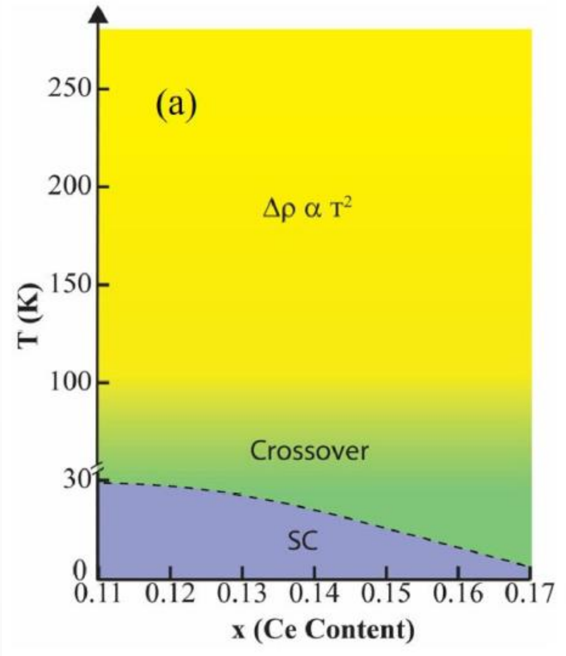
Extra slides

Zero-field

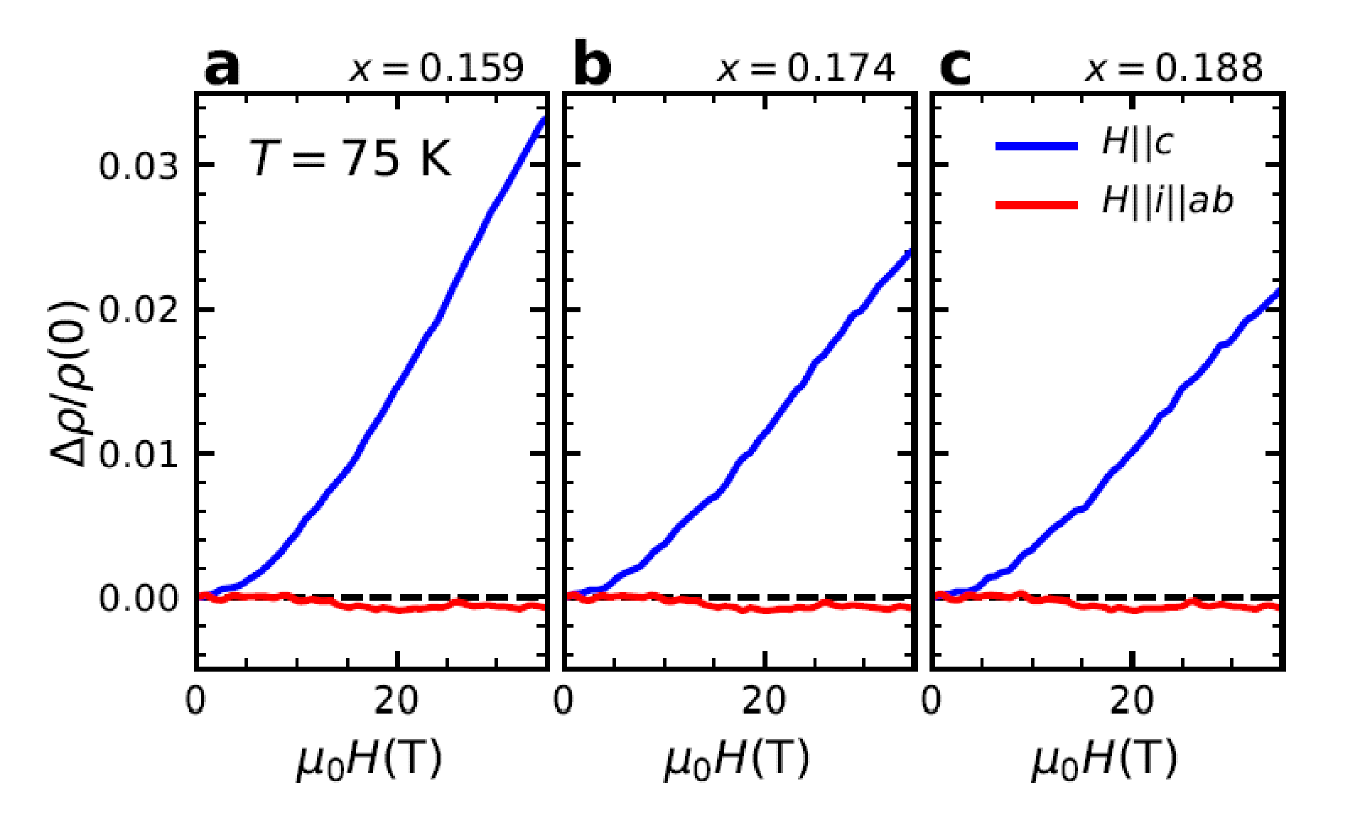


Derivative shows an *x*-dependent *T*-linear component of the resistivity and an *x*-indendent T^2 component below 70 K

T. Sarkar *et al.*, PRB **98**, 224503 (2018)

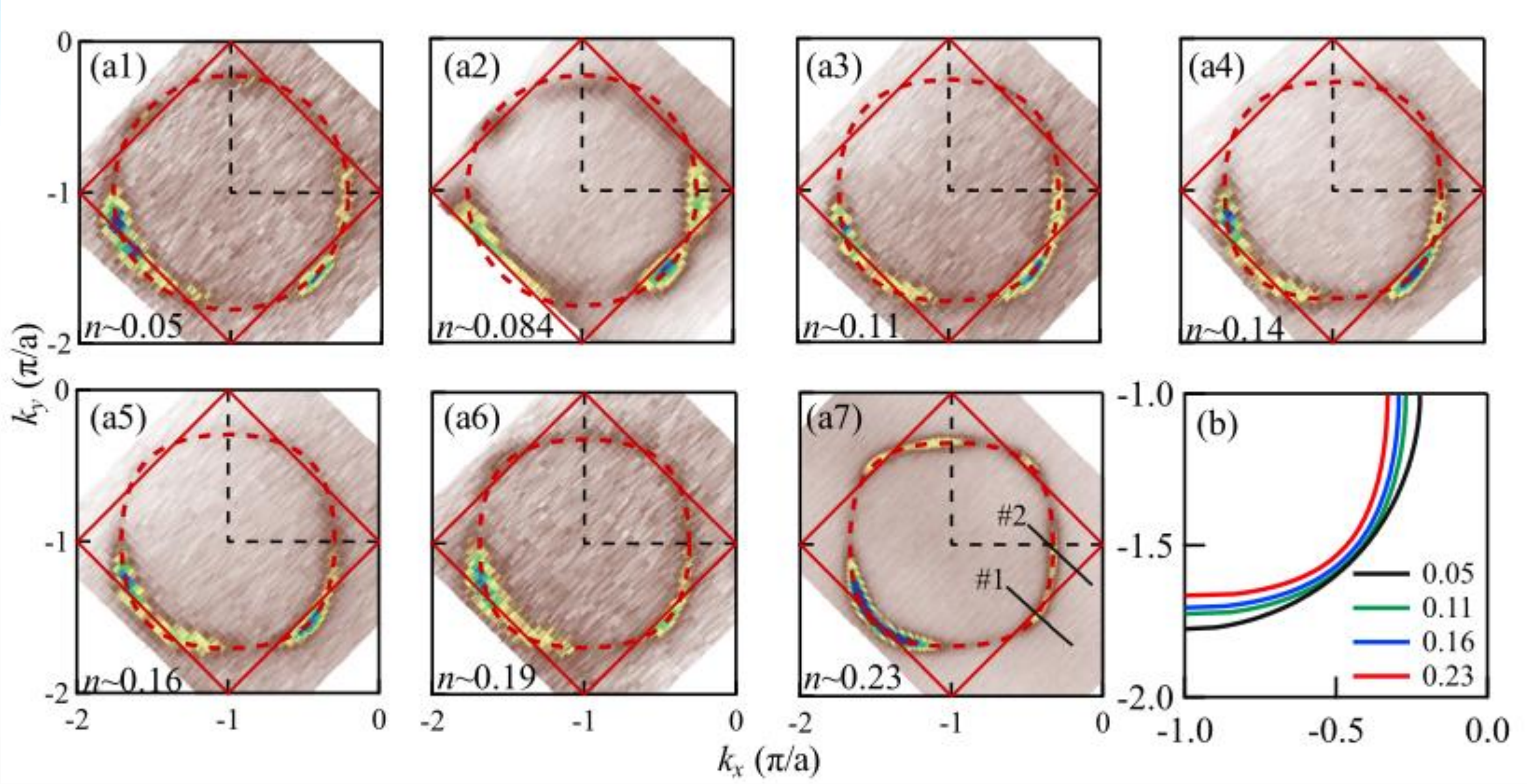


Magnetoresistance



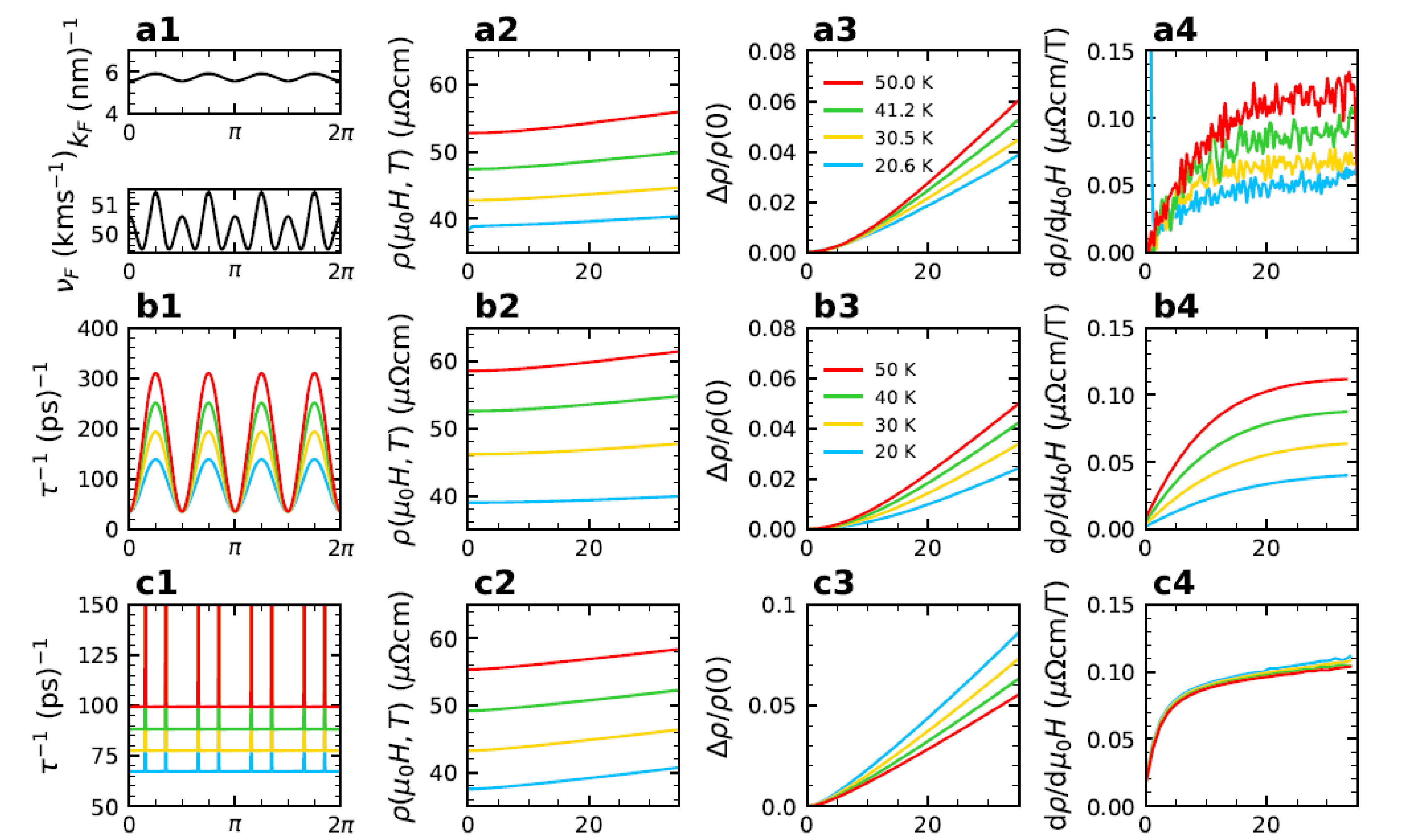
Anisotropic MR…

Fermiology of LCCO from ARPES

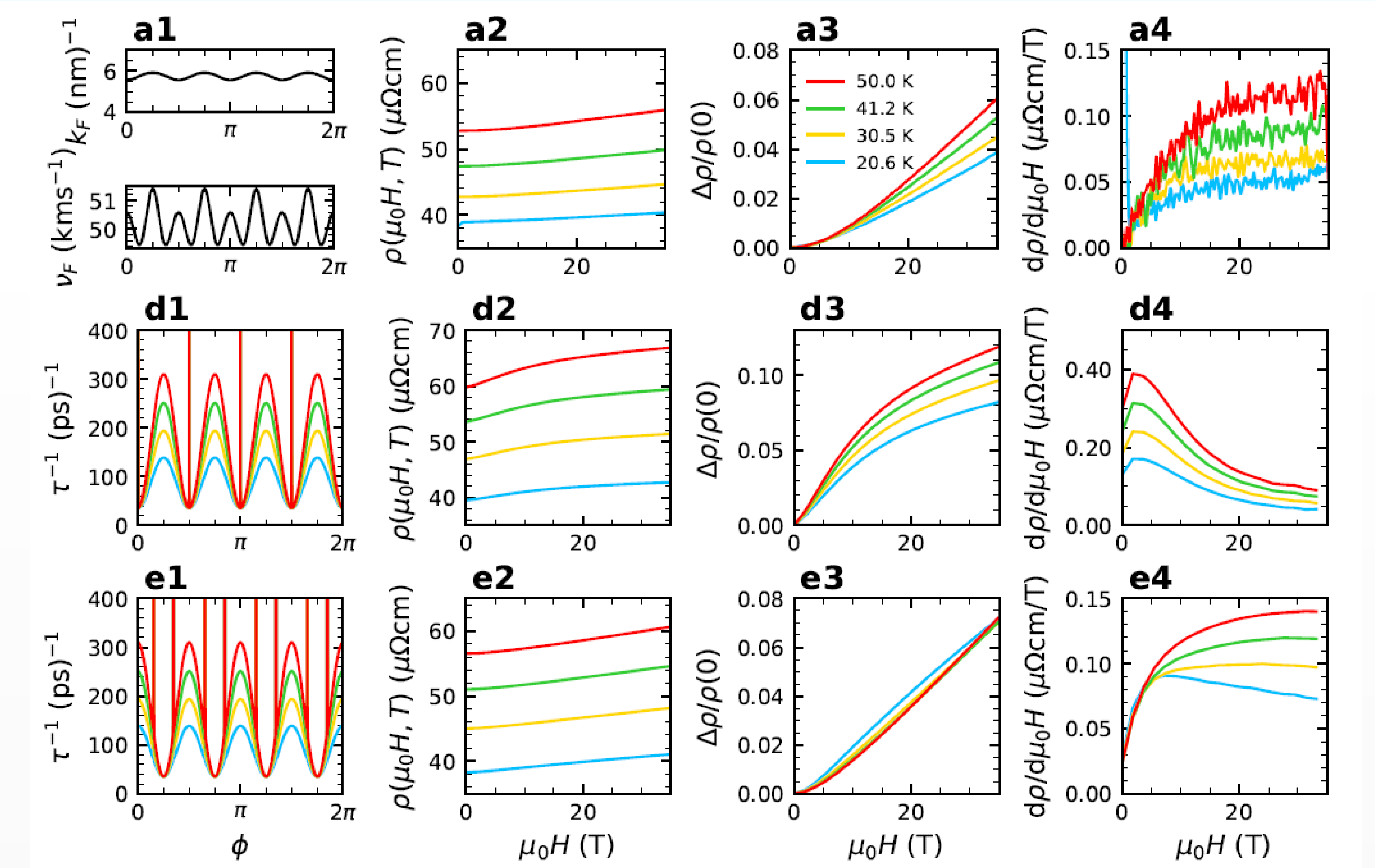


Tang *et al.*, *PRB* **104**, 155125 (2021)

Testing other scattering rates



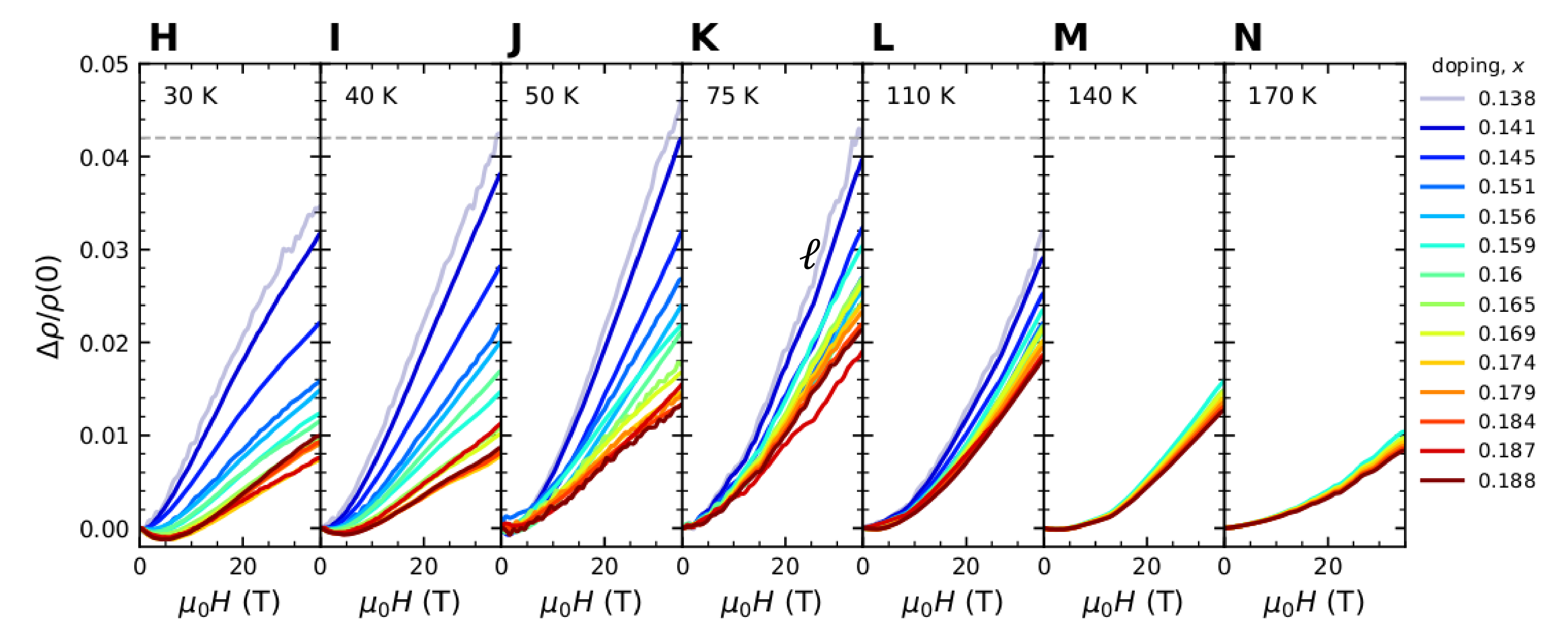
Testing other scattering rates



Comparison between *n*- and *p*-doped

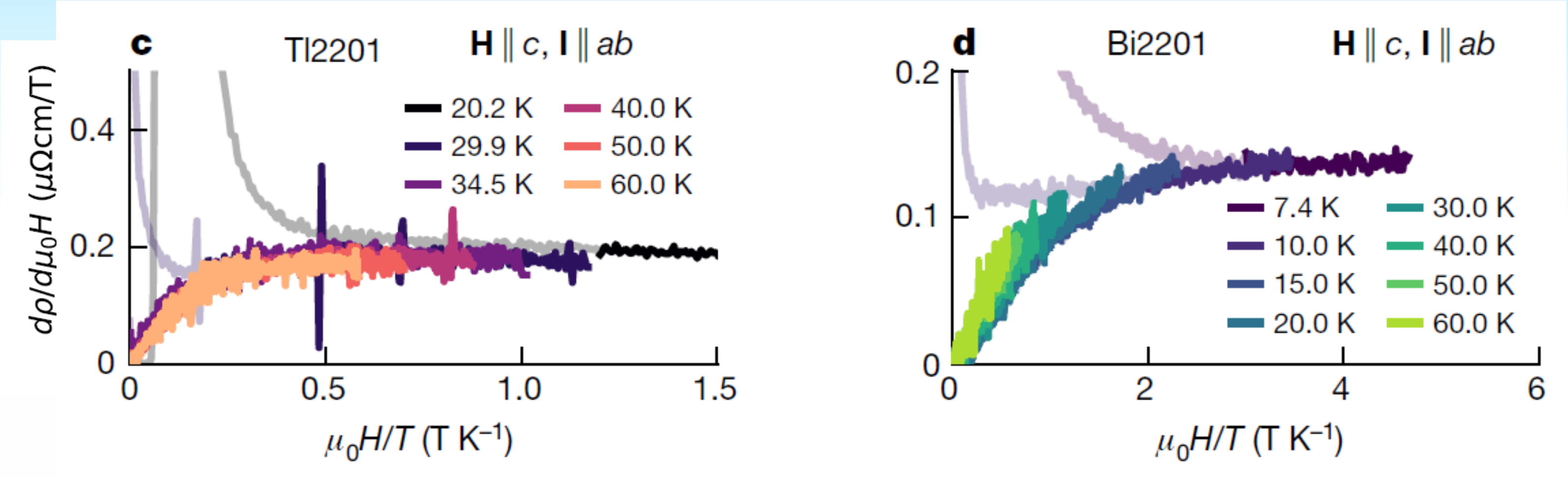
	p-doped	*n*-doped
$\rho(T) \sim T$	Yes - all *T*	Yes - T<20 K
Planckian	Yes	No
H-linear MR	Yes	Yes
Kohler's scaling	No	No
H/*T* scaling	Yes	No
Orientation independent	Yes	No
T-independent slope	Yes	No

Film 2 – MR



H
I
J
K
L
M
N
30 K
40 K
50 K
75 K
110 K
140 K
170 K
ℓ
Δρ/ρ(0)
0.05
0.04
0.03
0.02
0.01
0.00
0
20
μ0H (T)
doping, x
0.138
0.141
0.145
0.151
0.156
0.159
0.16
0.165
0.169
0.174
0.179
0.184
0.187
0.188

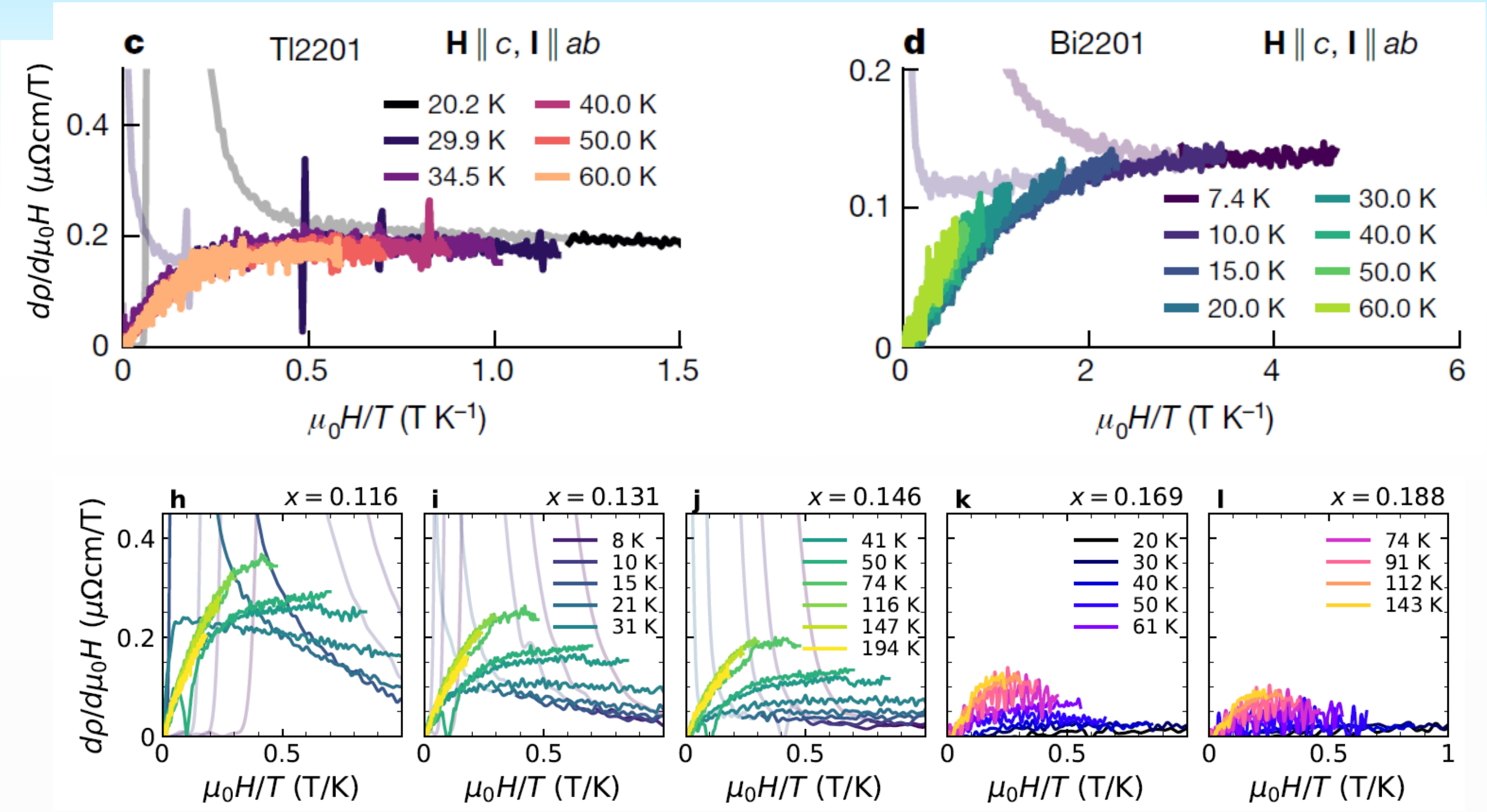
Magnetoresistance



Ayres, Berben *et al.*, Nature **595**, 661 (21)

p-doped : *H/T* quadrature scaling indicative of incoherent carriers

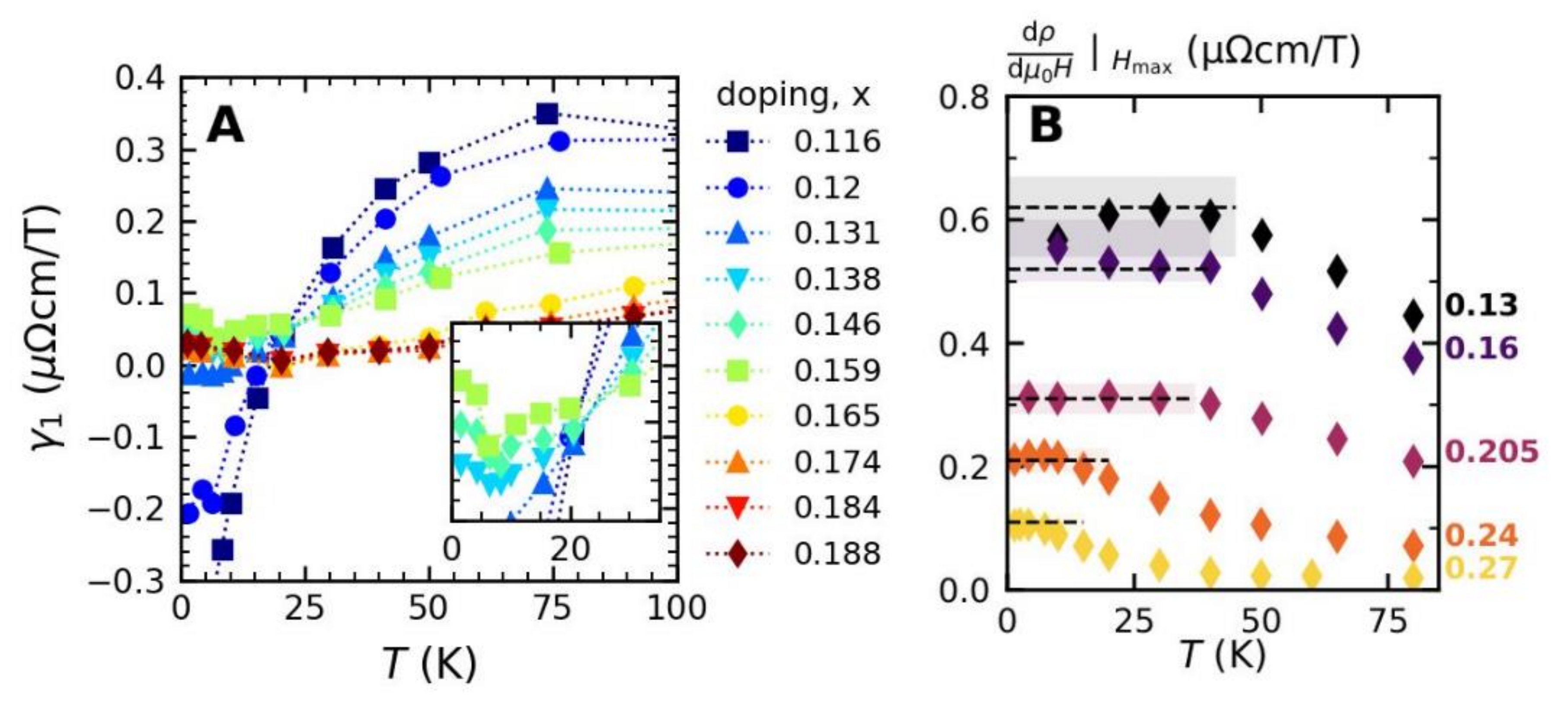
Magnetoresistance



Ayres, Berben *et al.*, Nature **595**, 661 (21)

n-doped : *H/T* scaling breaks down at an *x*-independent *T* ~ 70 K

Magnetoresistance

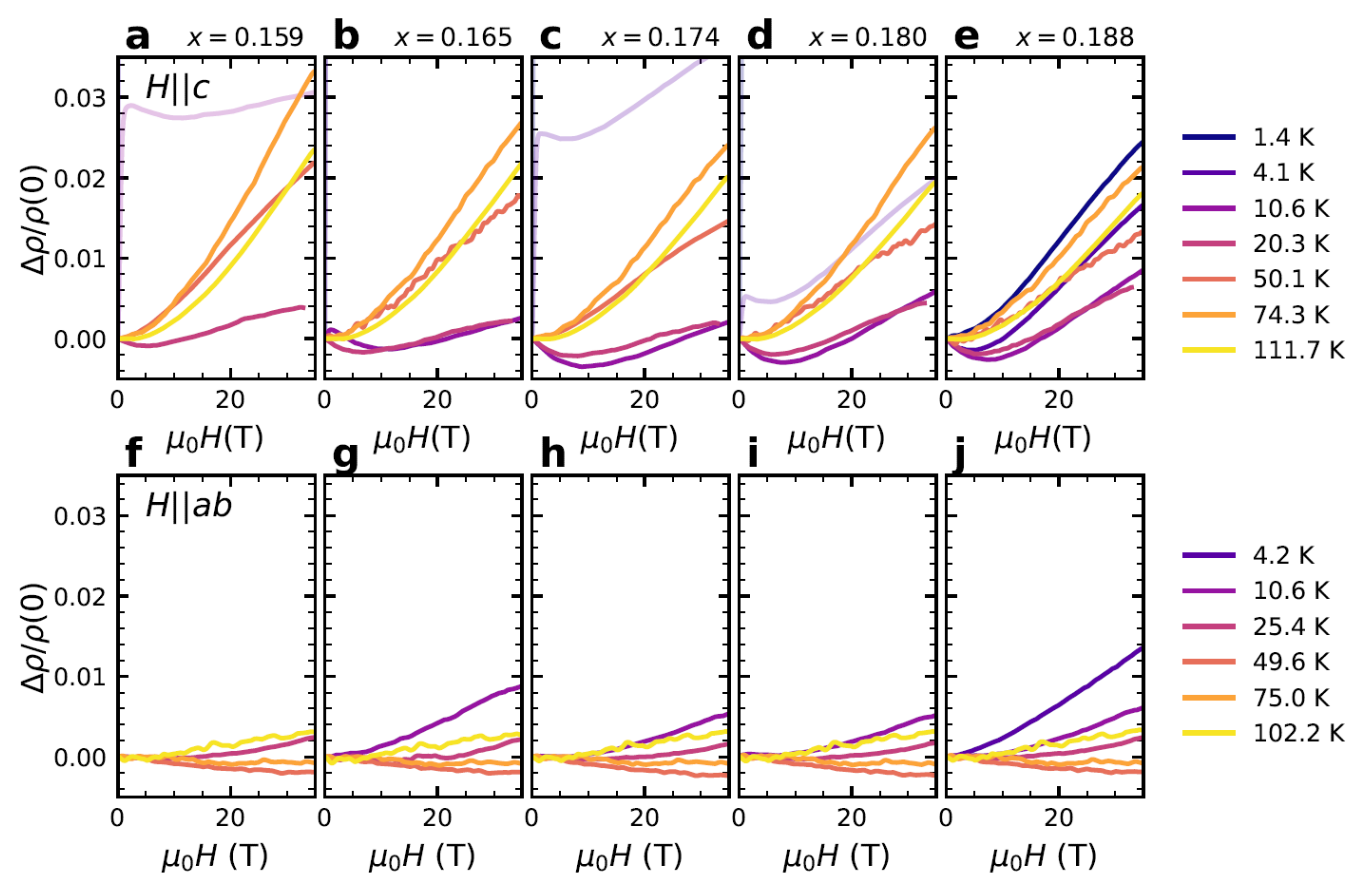


MR between 30-33 T

p-doped: slope becomes constant at low-*T*

n-doped: slope never becomes constant

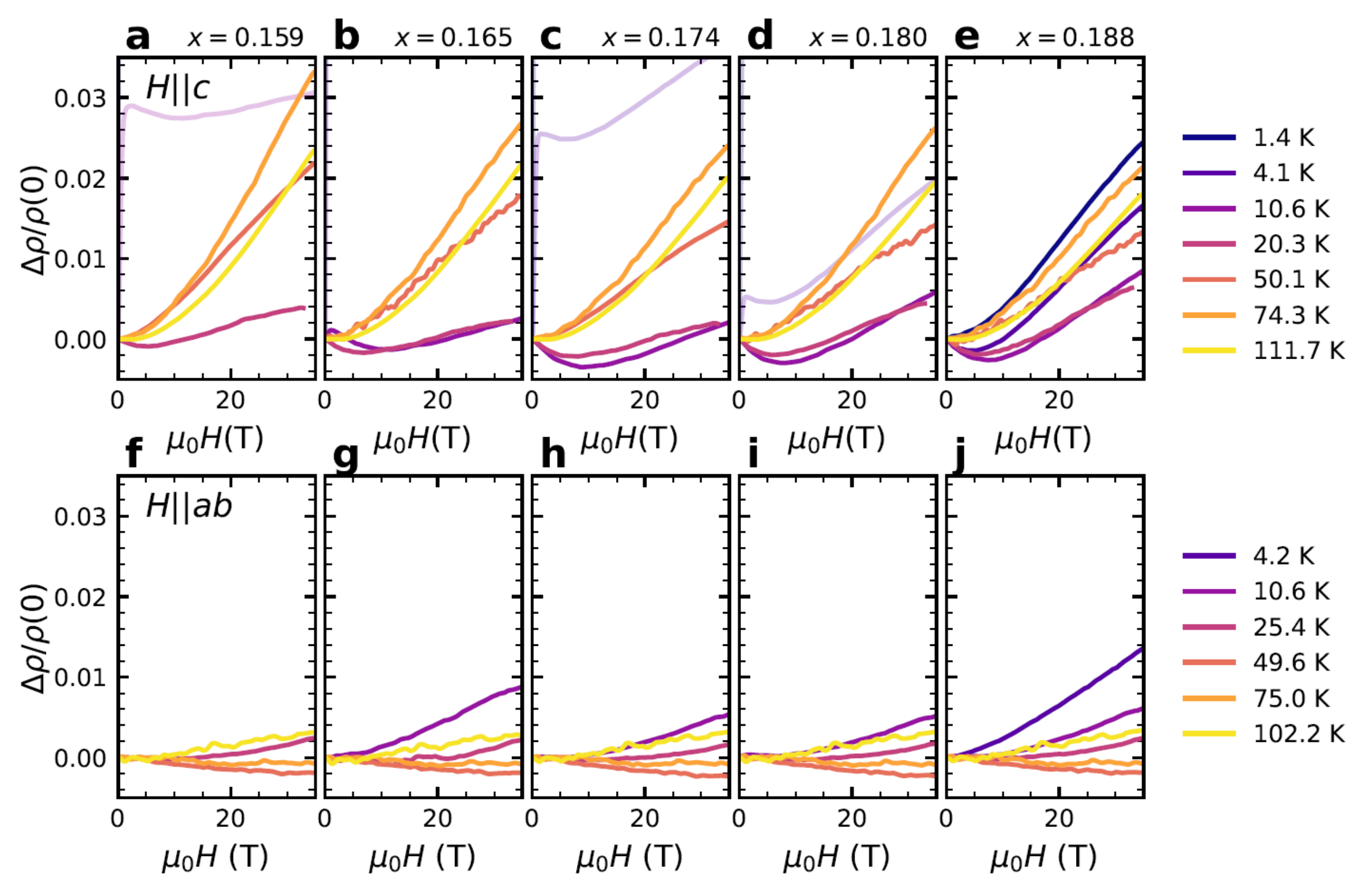
In-plane MR



MR is anisotropic – as is expected from a Lorentz-force free configuration.

This, again, is in stark contrast to the *p*-doped cuprates.

In-plane MR



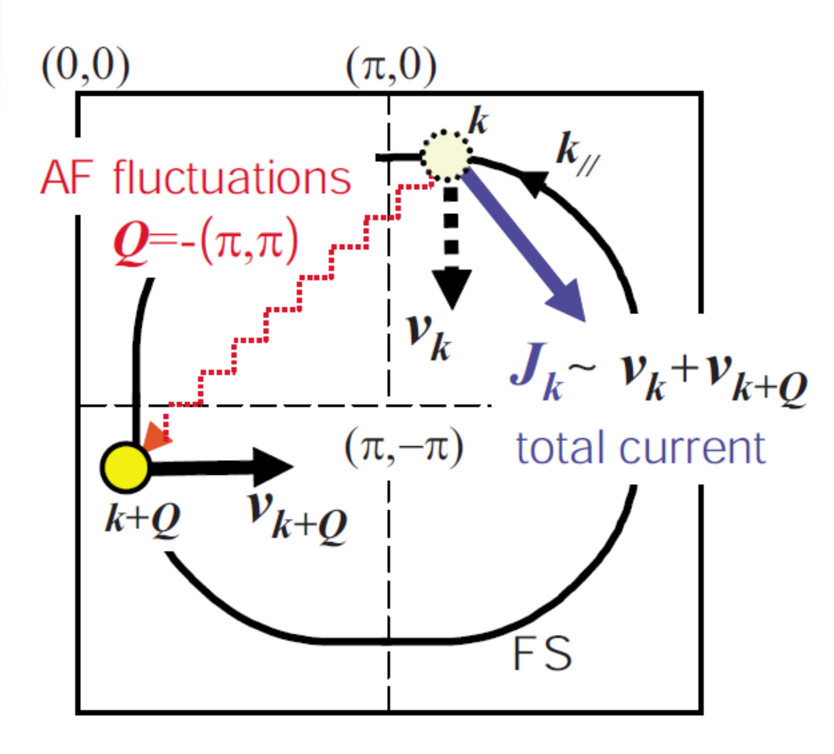
MR is anisotropic – as is expected from a Lorentz-force free configuration.

This, again, is in stark contrast to the *p*-doped cuprates.

This begs the question:

Can the MR of n-doped cuprates be described within a conventional framework?

Current vertex corrections



G. Jenkins *et al.*, PRB **81**, 024508 (2010)
H. Kontani, Rep. Prog. Phys. **71**, 026501 (2008)

$$\sigma_{xy} = \frac{-e^3 B}{2\pi^2 \hbar^2 c} \int_0^{2\pi} \ell_x \frac{\partial \ell_y}{\partial \varphi} d\varphi$$

Scattering between two points causes a modification of the velocity vector at those two points

Current vertex corrections

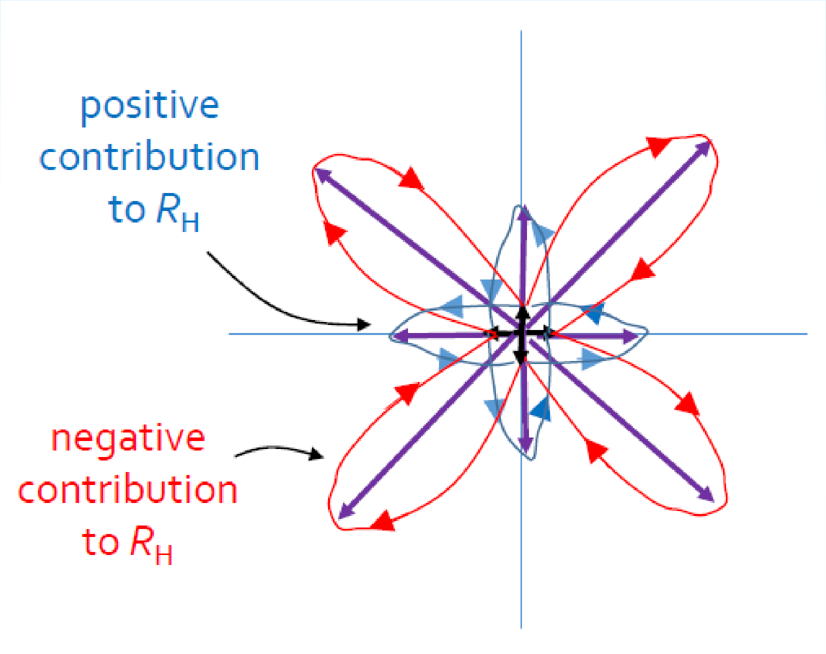
$$\sigma_{xy} = \frac{-e^3 B}{2\pi^2 \hbar^2 c} \int_0^{2\pi} \ell_x \frac{\partial \ell_y}{\partial \varphi} d\varphi$$

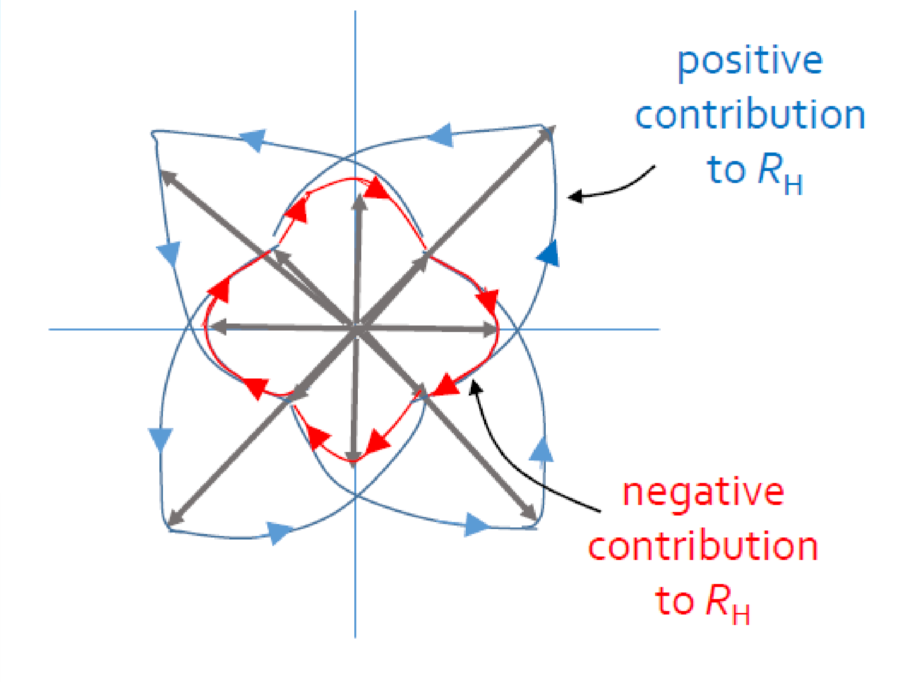
$$\ell \propto v_F$$

→ A change in v_F causes a change in ℓ

Could this help distinguish between hotspots at the antinodes and hotspots at the AFMBZ boundary?

Current vertex corrections



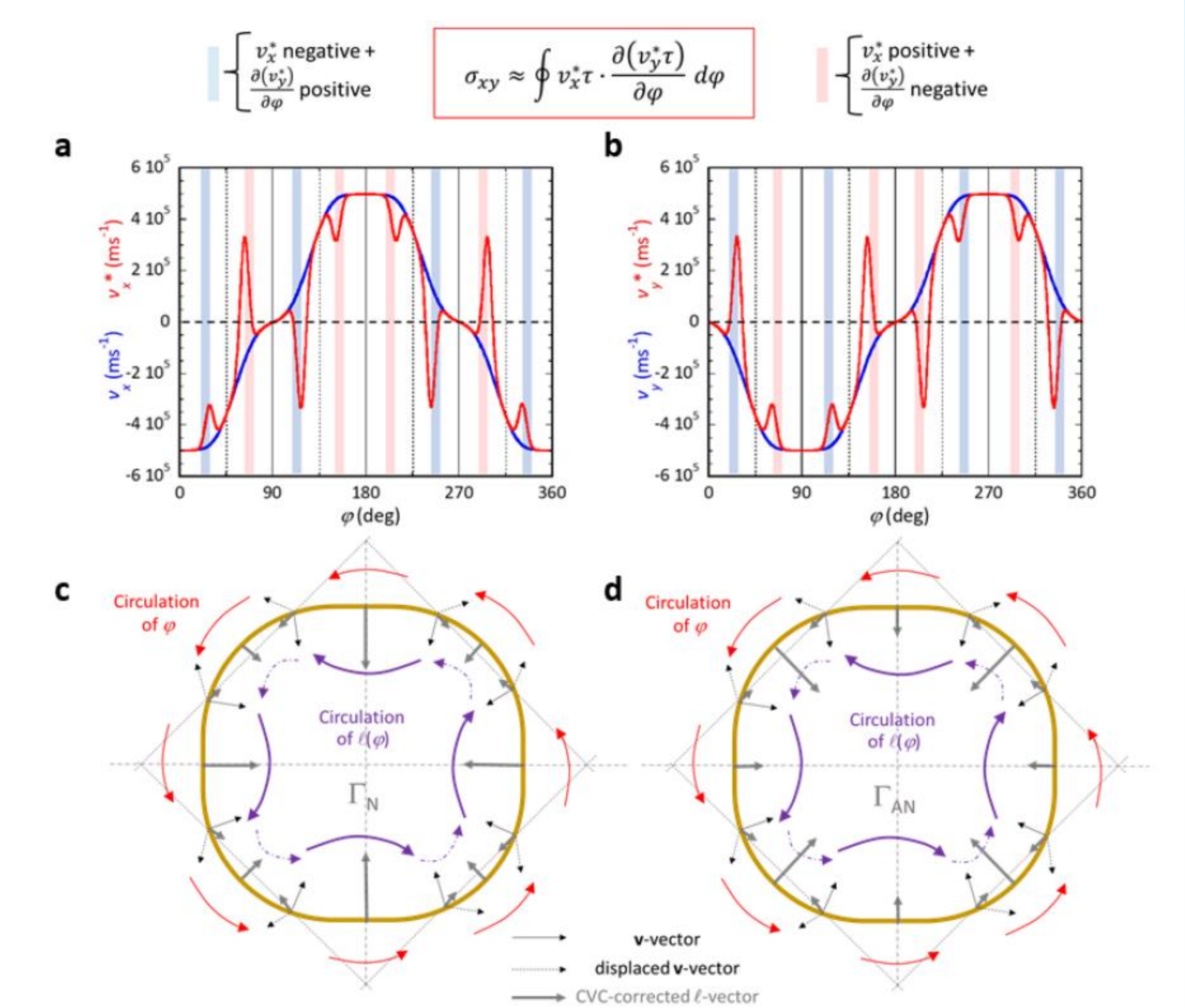


AN hotspots
Charge CVCs

AFMBZ hotspots
Spin CVCs

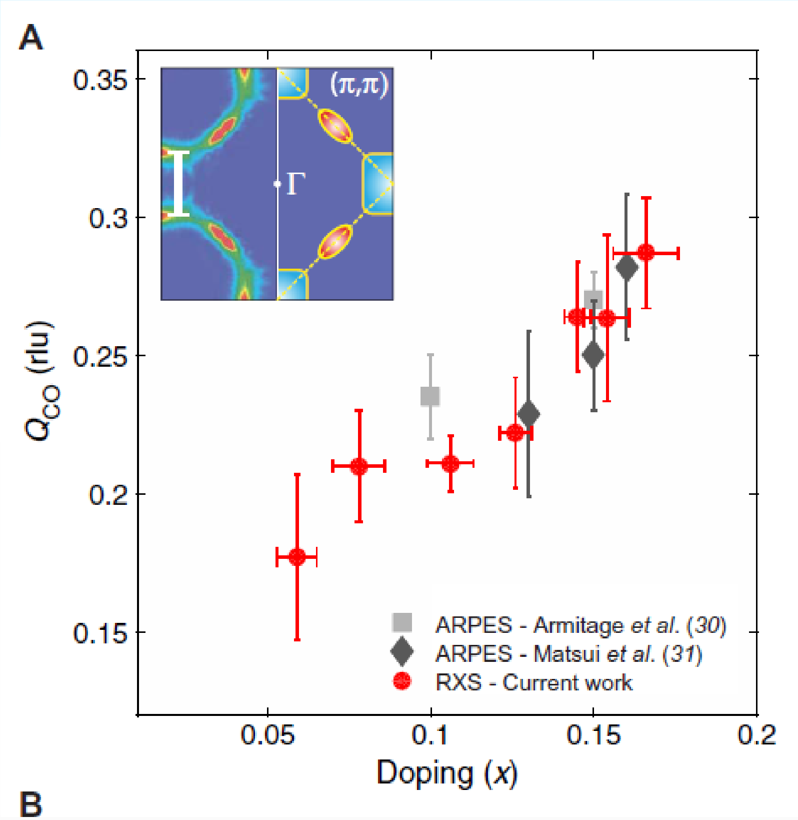
If employing CVCs can account for the sign change in R_H, we can distinguish between spin and charge…
→ Work in progress!

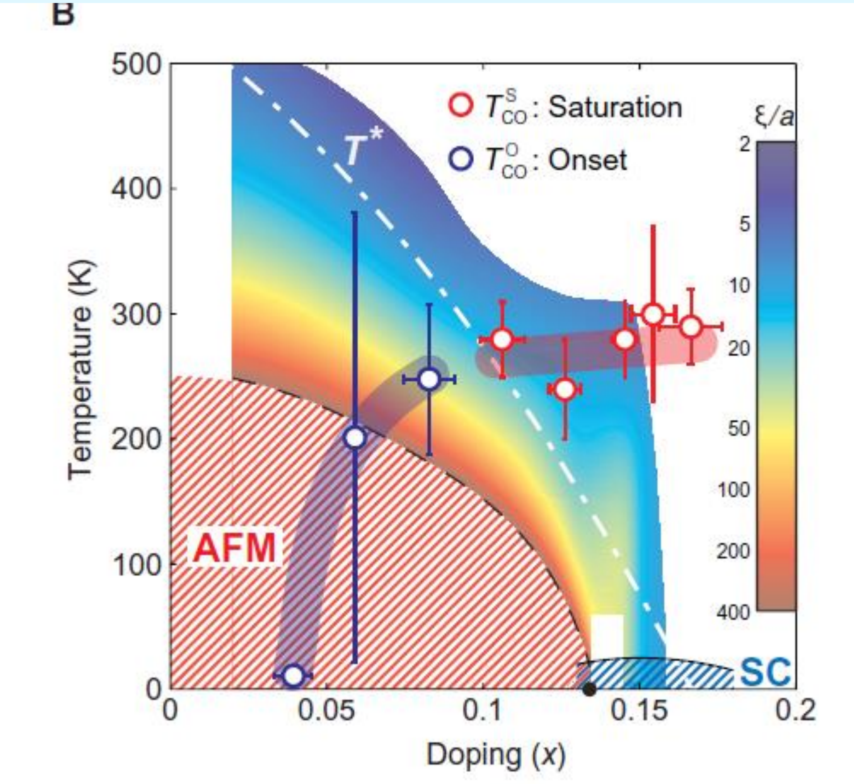
CVCs



v_x^* negative + $\frac{\partial(v_y^*)}{\partial\varphi}$ positive
$\sigma_{xy} \approx \oint v_x^*\tau \cdot \frac{\partial(v_y^*\tau)}{\partial\varphi}\, d\varphi$
v_x^* positive + $\frac{\partial(v_y^*)}{\partial\varphi}$ negative
a
b
v_x (ms^{-1}) v_x^* (ms^{-1})
v_y (ms^{-1}) v_y^* (ms^{-1})
φ (deg)
c
d
Circulation of φ
Circulation of $\ell(\varphi)$
Γ_N
Γ_{AN}
v-vector
displaced v-vector
CVC-corrected ℓ-vector

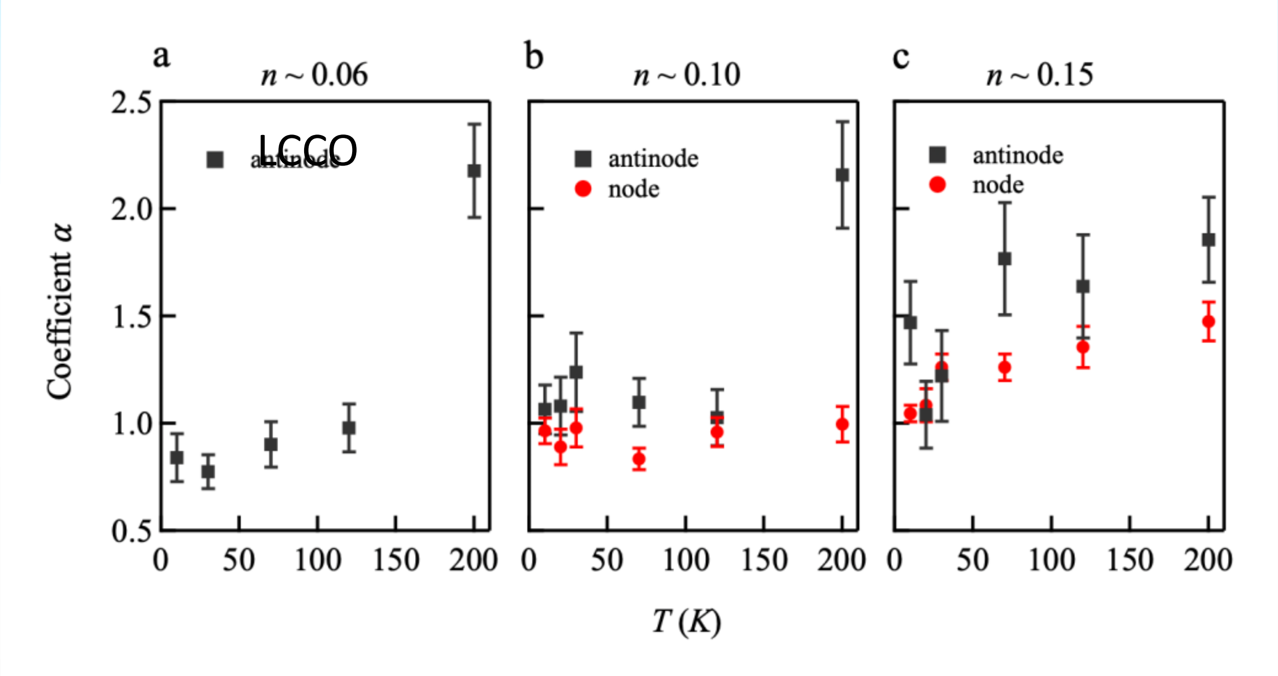
Charge order in *n*-doped cuprates



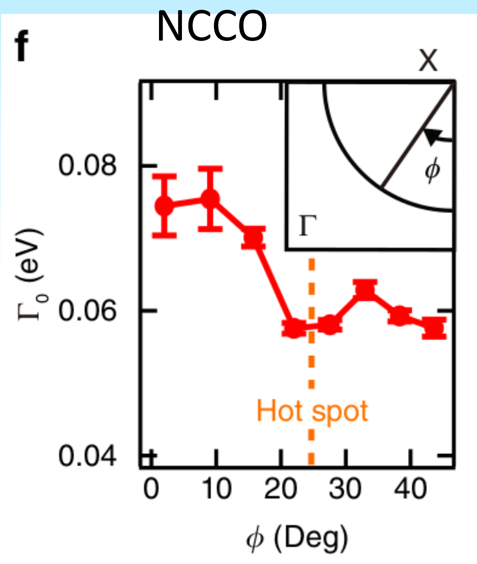


da Silva-Neto, Sci. Adv. (2016)

Experimentally-derived scattering rate



C. Y. Tang *et al.*, npj Quant. Mater (2022)



Horio *et al.*, Nat. Commun 2016

He *et al.*, PNAS (2018)