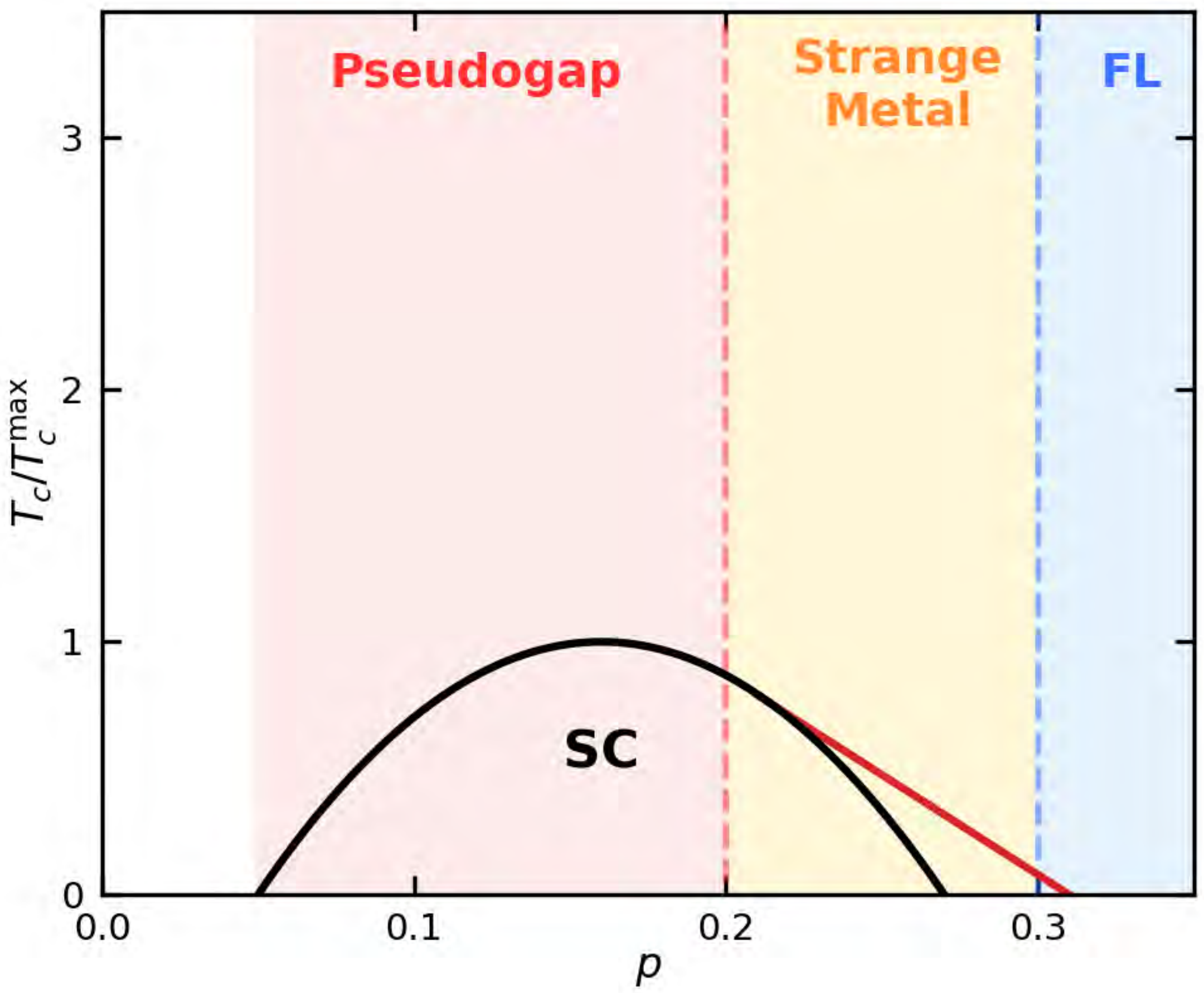

Compartmentalizing the cuprate strange metal

1) **Introduction**
2) **'Boltzmann' transport in the cuprate strange metal (ADMR, Hall)**
3) **'non-Boltzmann' transport in the cuprate strange metal (in-plane MR)**
4) **MR scaling across p^* and p_{SC}**
5) **Superconductivity within strange metal regime**

Thanks

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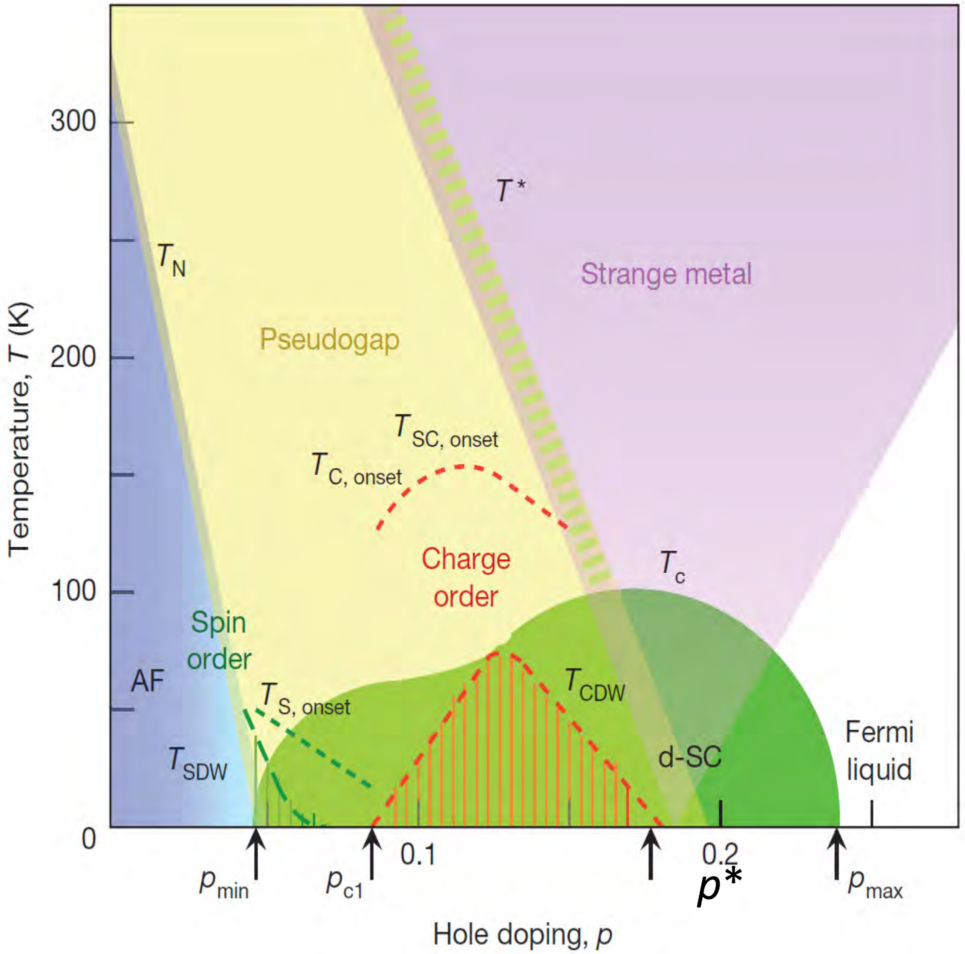
Amsterdam
Mark Golden
Erik van Heumen
Yingkai Huang

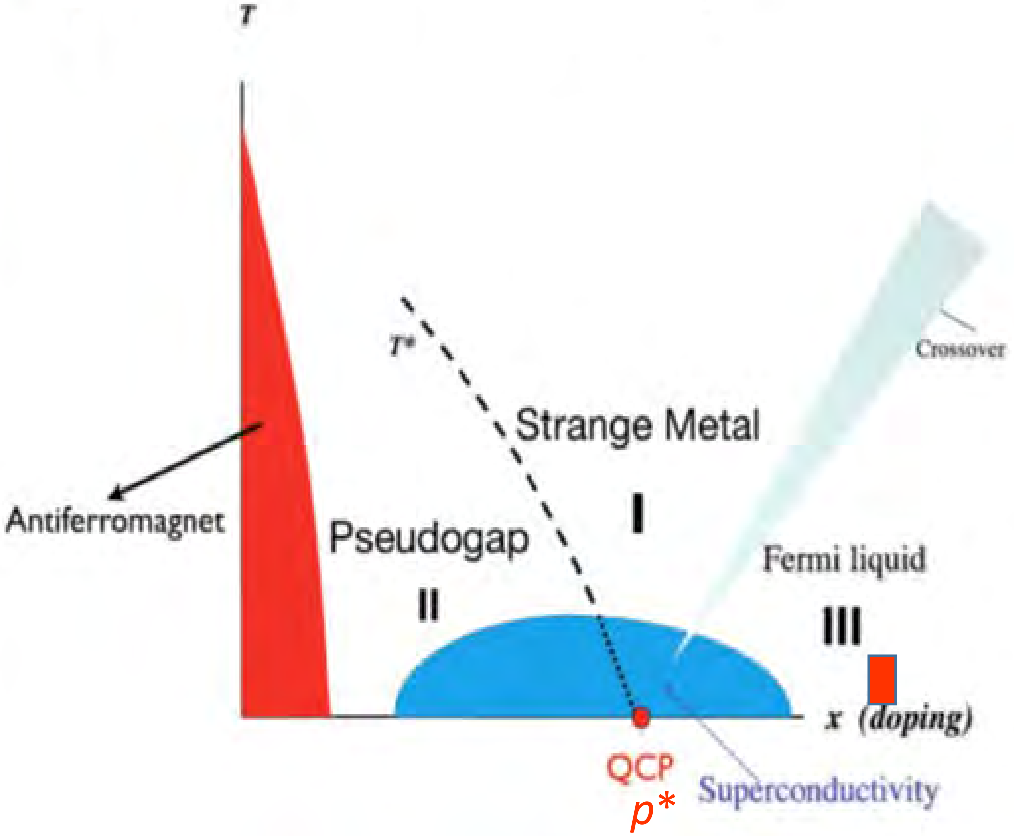
Leiden
Milan Allan
Jan Zaanen

Introduction

Keimer *et al.*, *Nature* **518** 179 (15)



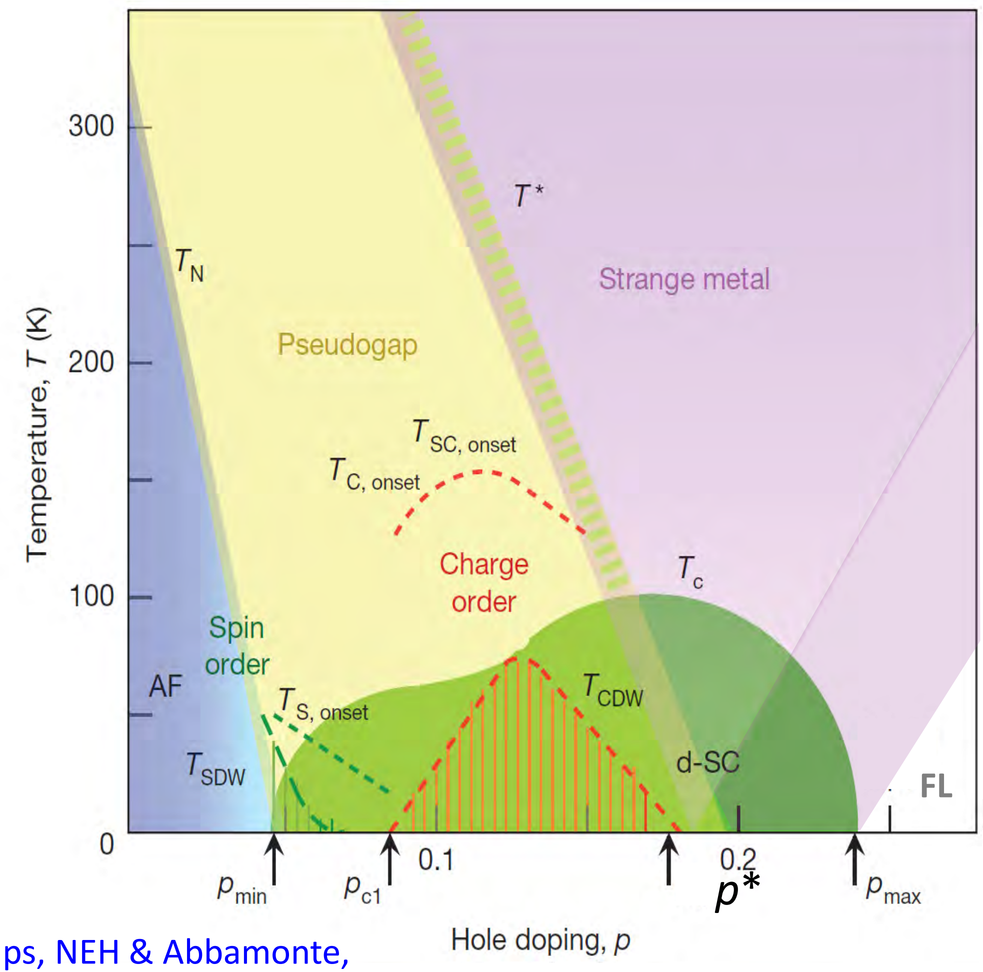
Varma, *RMP* **92** 031001 (20)



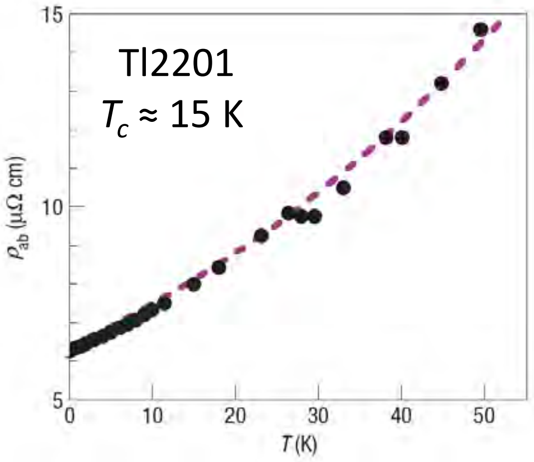
- Hole-doped cuprate phase diagram often depicted as though overdoped regime beyond p^* is a Fermi-liquid

Introduction

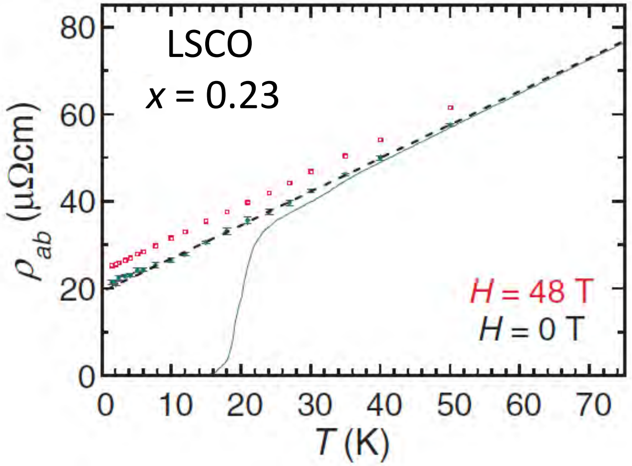
Keimer *et al.*, *Nature* **518** 179 (15)



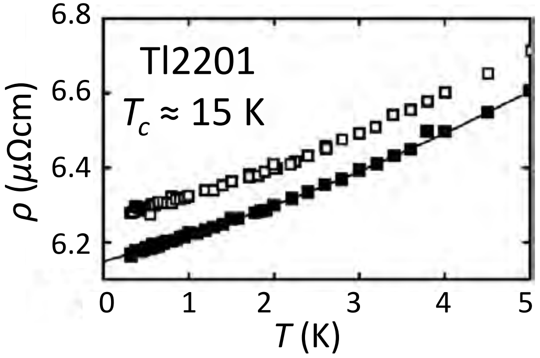
Phillips, NEH & Abbamonte, *2205.12979* (22)



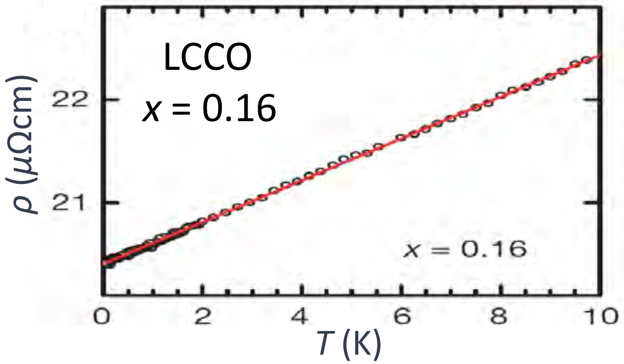
Mackenzie *et al.*, *PRB* **53** 5848 (96)



Cooper *et al.*, *Science* **323** 603 (09)



Proust *et al.*, *PRL* **89** 147003 (02)

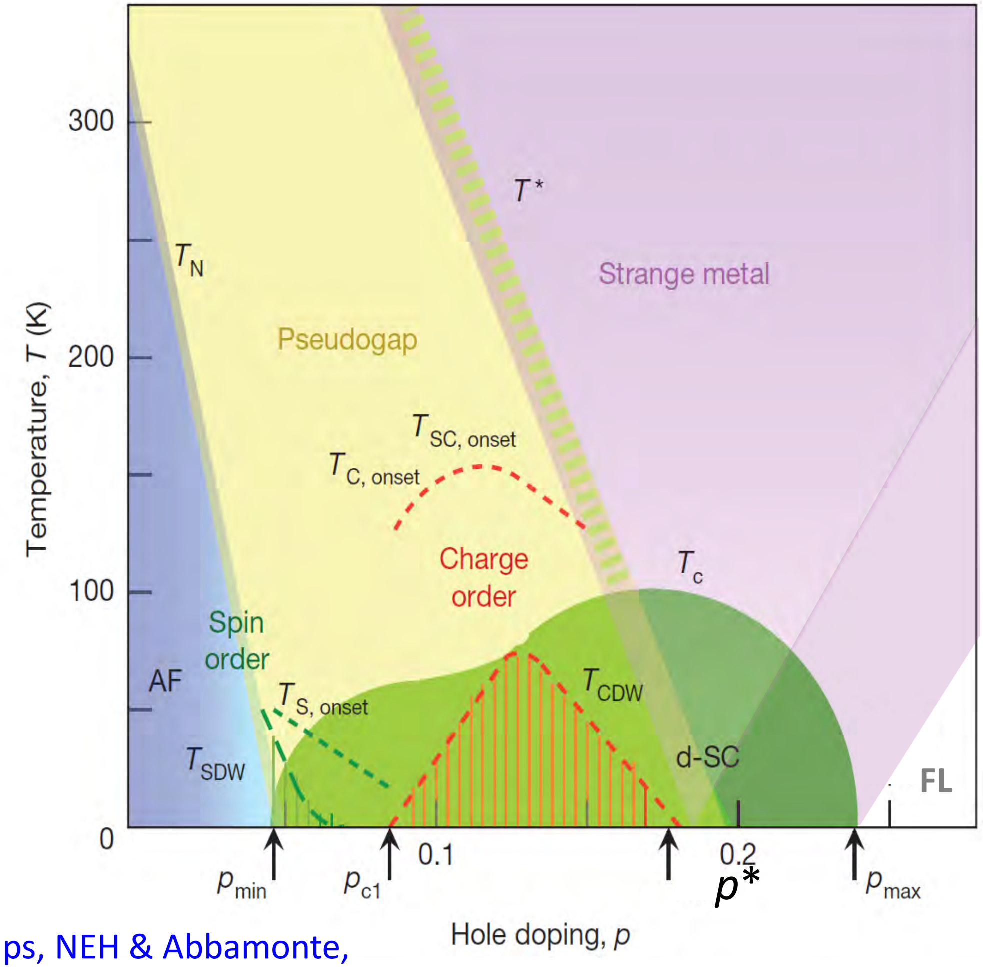


Jin *et al.*, *Nature* **476** 73 (11)

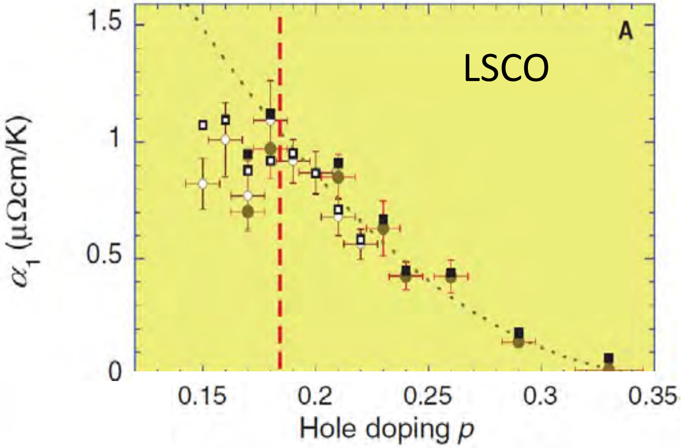
- Hole-doped cuprate phase diagram often depicted as though overdoped regime beyond p^* is a Fermi-liquid

Introduction

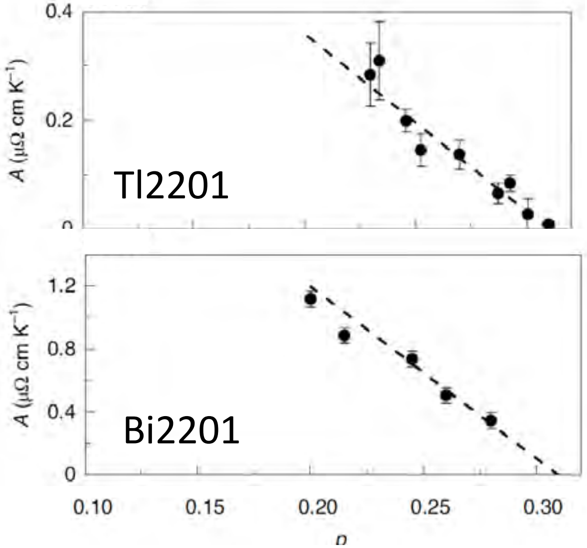
Keimer *et al.*, *Nature* **518** 179 (15)



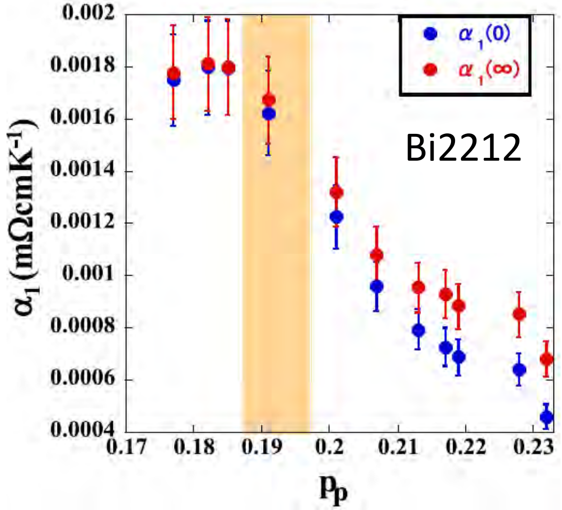
Phillips, NEH & Abbamonte, *2205.12979* (22)



Cooper *et al.*, *Science* **323** 603 (09)

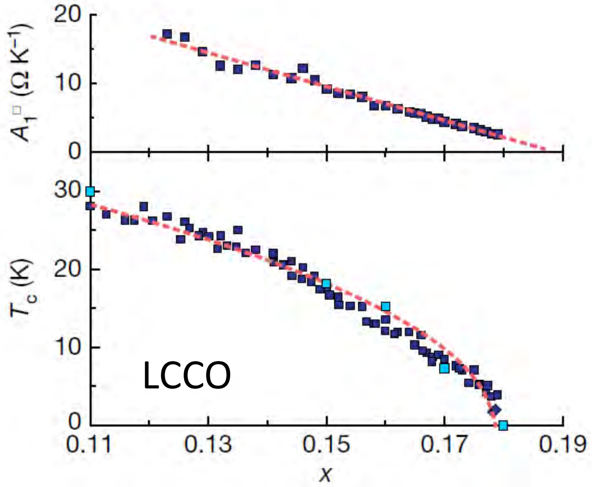


Putzke *et al.*, *Nat. Phys.* **17** 826 (21)



Harada *et al.*, *PRB* **105** 085131 (22)

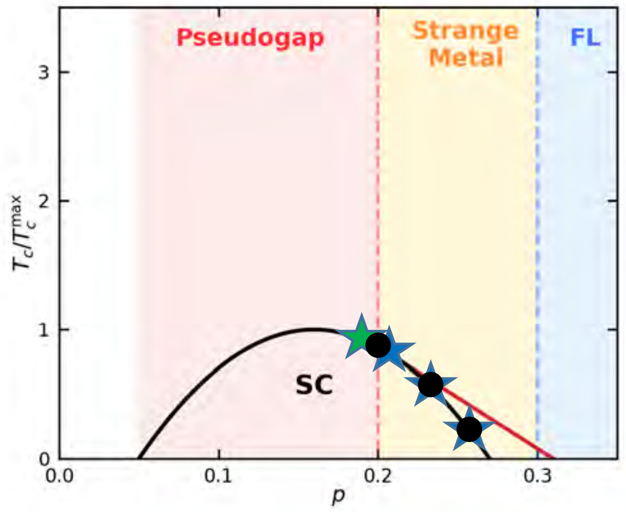
Legros *et al.*, *Nat. Phys.* **15** 142 (19)



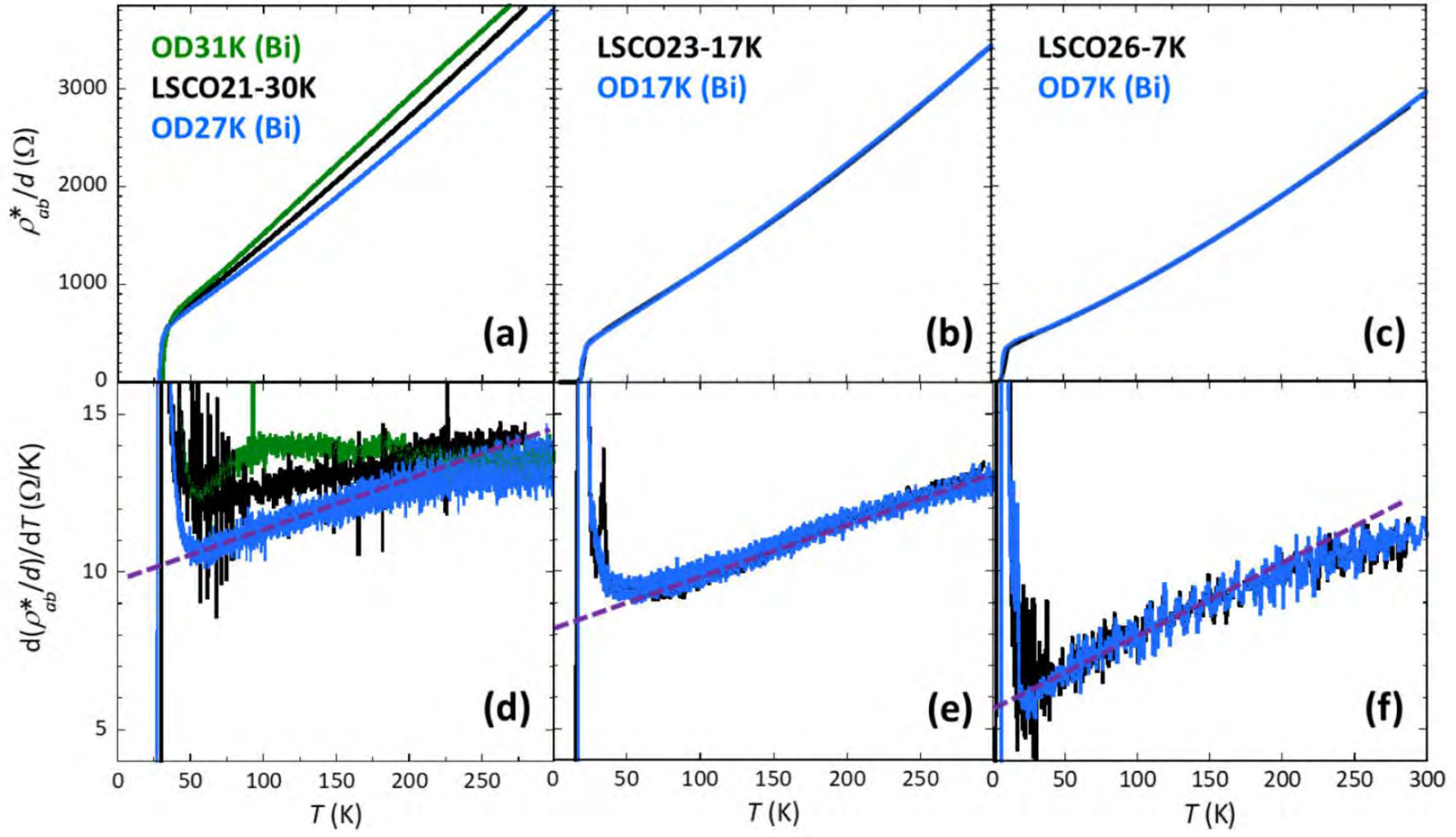
Yuan *et al.*, *Nature* **602** 431 (22)

Jin *et al.*, *Nature* **476** 73 (11)

Introduction

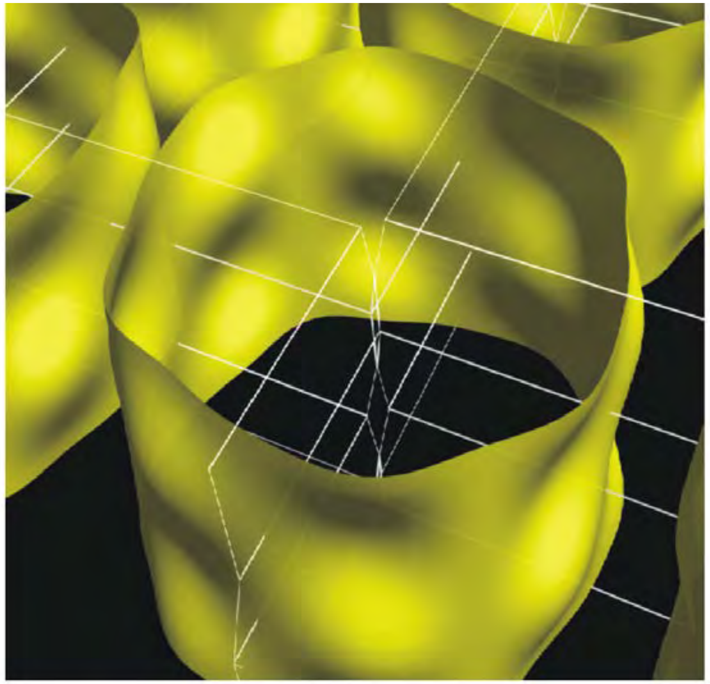


Berben *et al.*, *PRM* **6** 044804 (22)

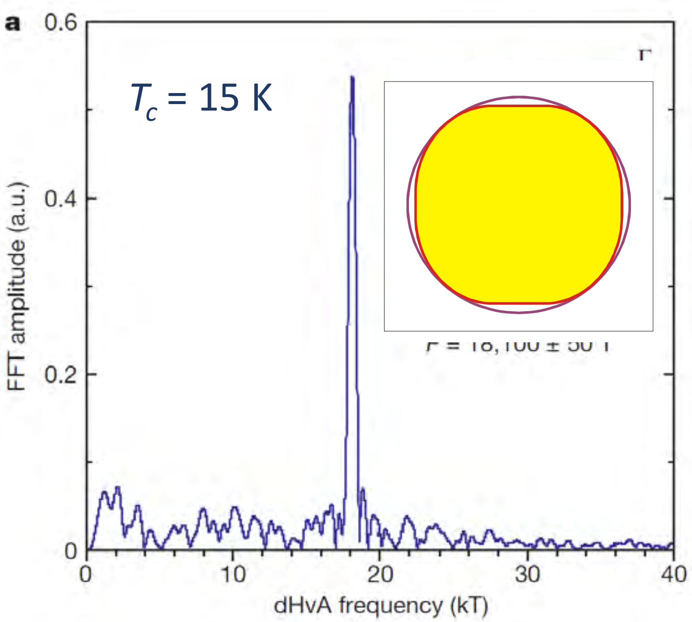


Fermiology of overdoped cuprates

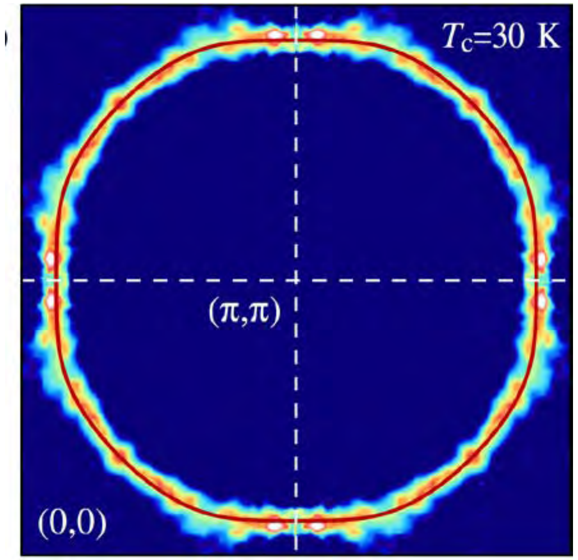
NEH *et al.*, *Nature* **425** 813 (03)



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



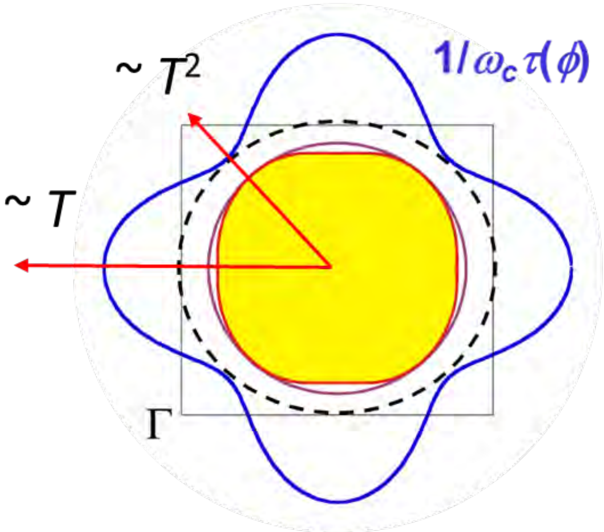
Platé *et al.*, *PRL* **95** 077001 (05)



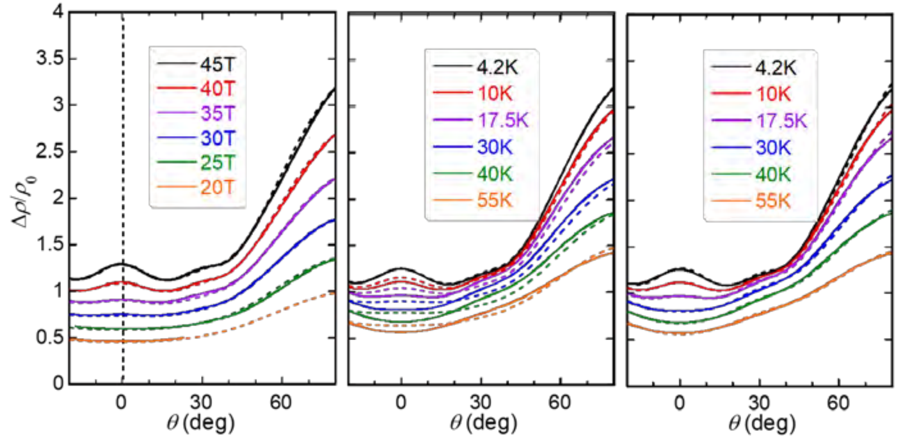
- ADMR, QO and ARPES measurements on OD Tl2201 all indicate large FS containing 1 + *p* holes

Boltzmann transport within SM regime

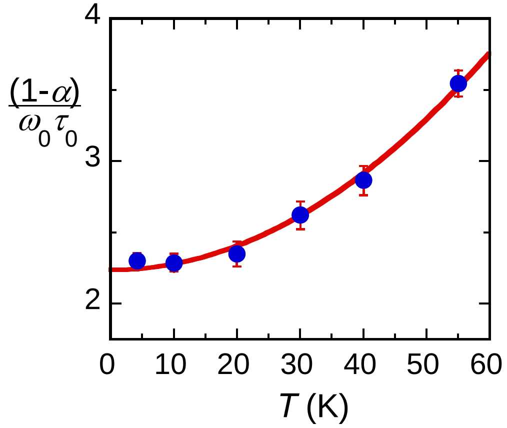
Tl2201 $T_c \approx 15$ K



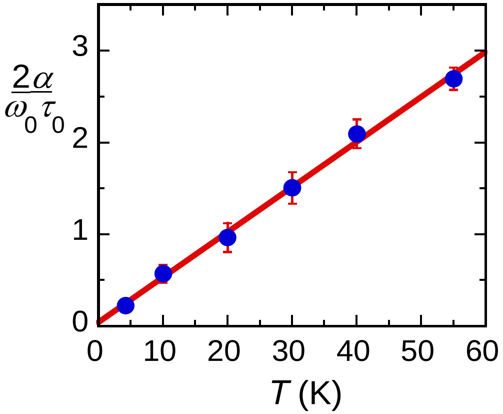
Abdel-Jawad *et al.*, *Nat. Phys.* **2**, 821 (06)



- *T*-dependent ADMR provided evidence of anisotropy in *T*-linear scattering rate



$\Gamma_{iso}(T)$ at the nodes



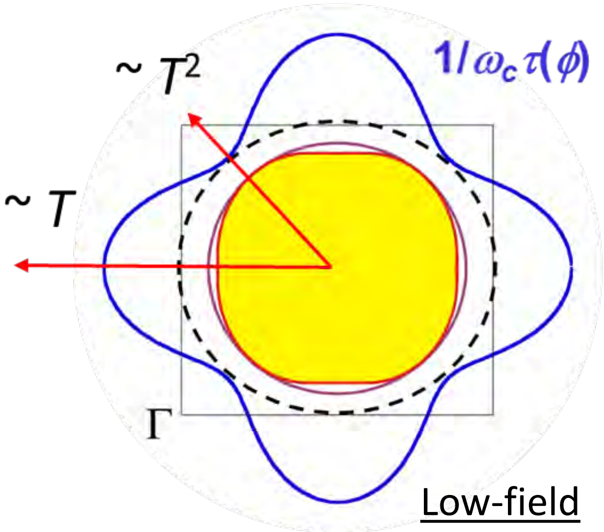
$\Gamma_{aniso}(T)$ at anti-nodes

Boltzmann / Shockley-Chambers

$$\sigma_{ij} = \frac{e^3 B}{2\pi^2\hbar^2 c}\int_0^{2\pi} d\phi \int_0^{\infty} d\phi' \frac{v_i(\phi)v_j(\phi-\phi')}{\omega_c(\phi)\omega_c(\phi-\phi')} \exp\left(\int_{\phi}^{\phi'} \phi''/\omega_c(\phi'')\tau(\phi'')d\phi''\right)$$

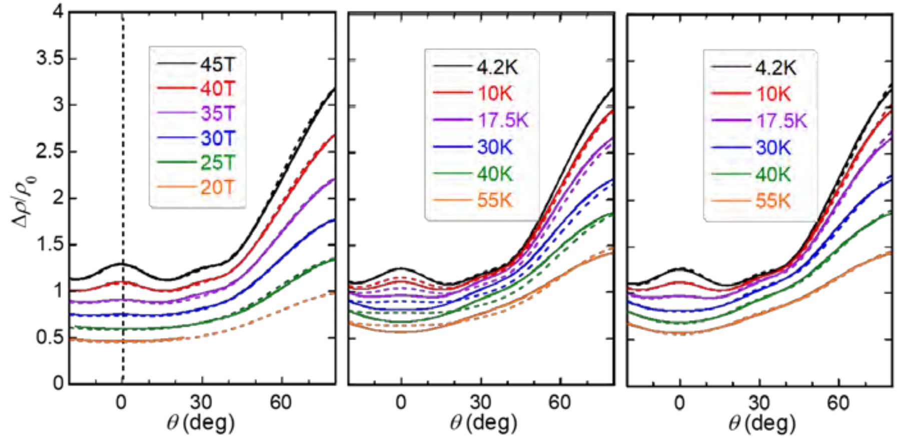
Boltzmann transport within SM regime

Tl2201 $T_c \approx 15$ K



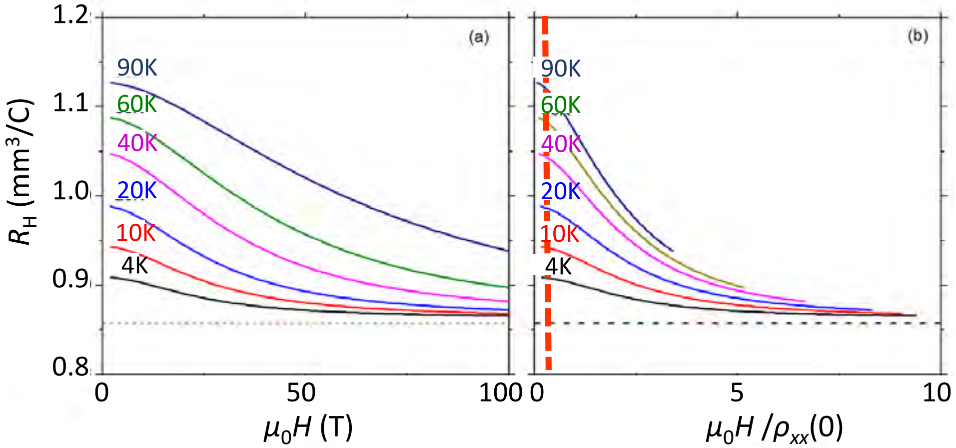
Low-field

Abdel-Jawad *et al.*, *Nat. Phys.* **2**, 821 (06)

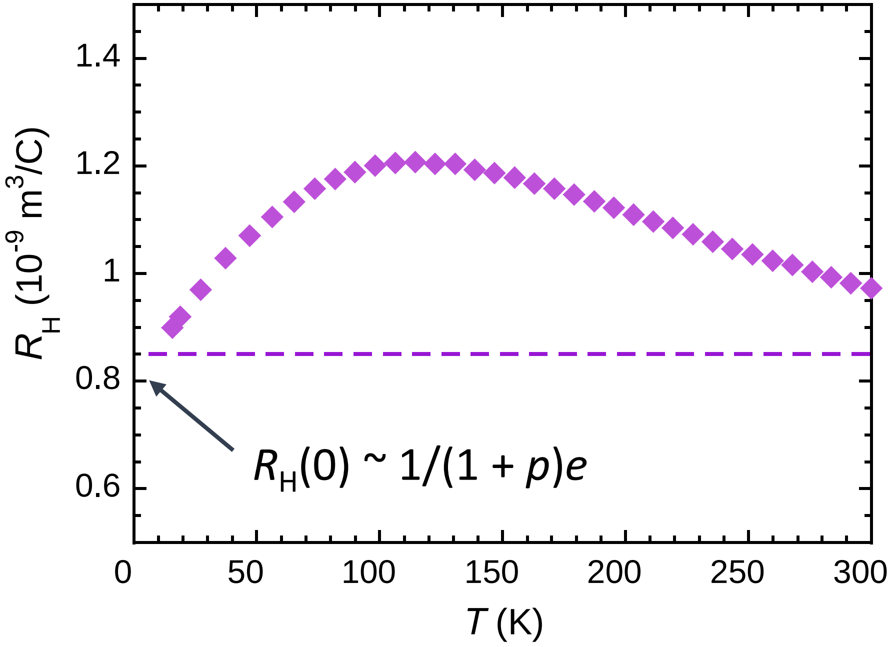


- T-dependent ADMR provided evidence of anisotropy in T-linear scattering rate
- ADMR parameterization reproduces $R_H(T)$ reasonably well.
- Same parameterization should also govern field-dependence of $R_H(T)$

Putzke *et al.*, *Nat. Phys.* **17**, 826 (21)

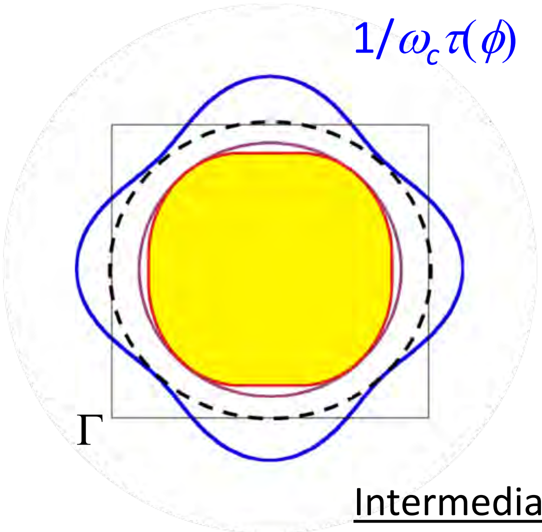


Simulated ρ_{xy}/H response

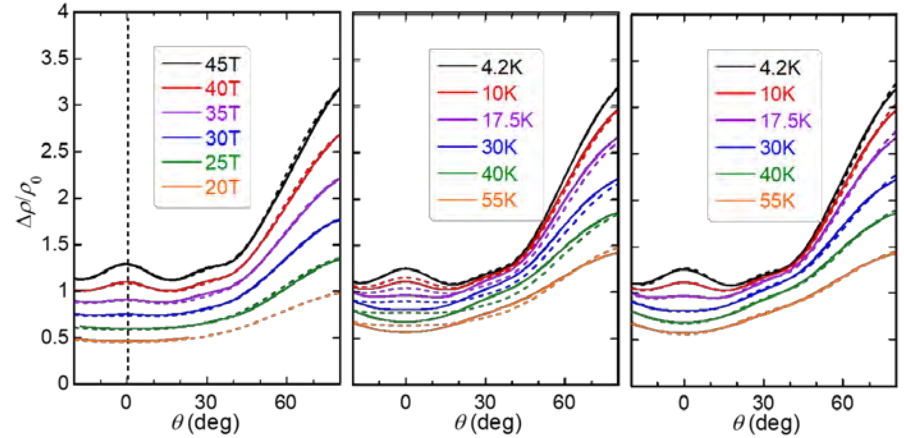


Boltzmann transport within SM regime

Tl2201 $T_c \approx 15$ K



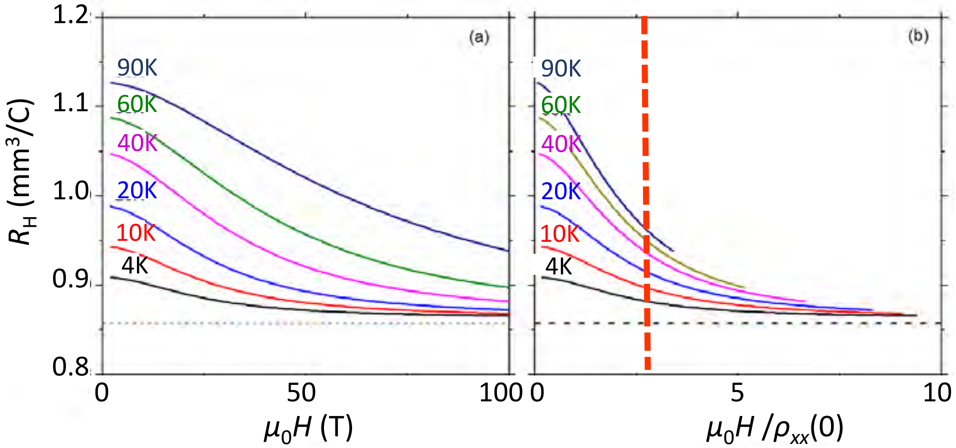
Abdel-Jawad *et al.*, *Nat. Phys.* **2**, 821 (06)



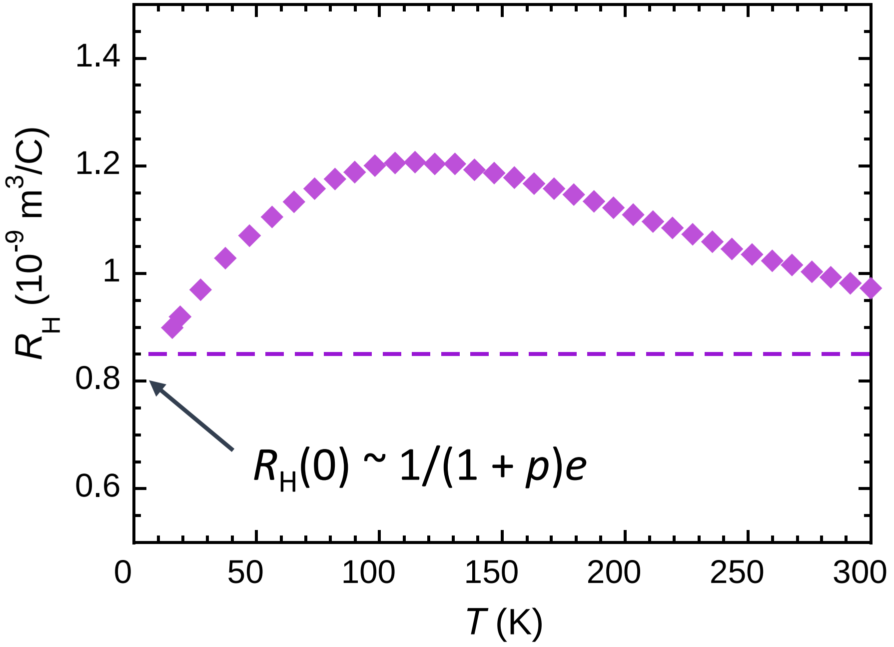
- T-dependent ADMR provided evidence of anisotropy in T-linear scattering rate
- ADMR parameterization reproduces $R_H(T)$ reasonably well.
- Same parameterization should also govern field-dependence of $R_H(T)$

Intermediate-field

Putzke *et al.*,
Nat. Phys. **17**, 826 (21)

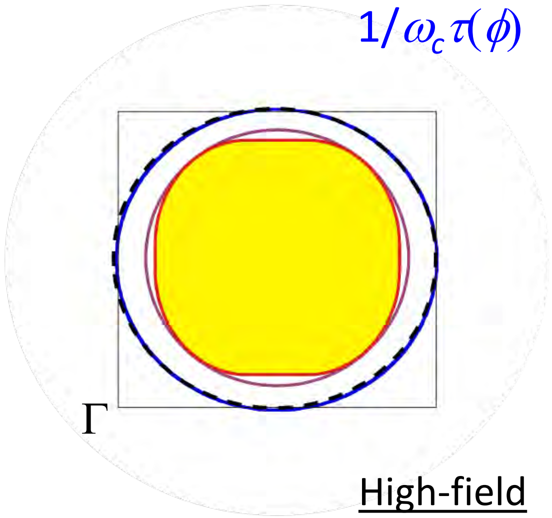


Simulated ρ_{xy}/H response



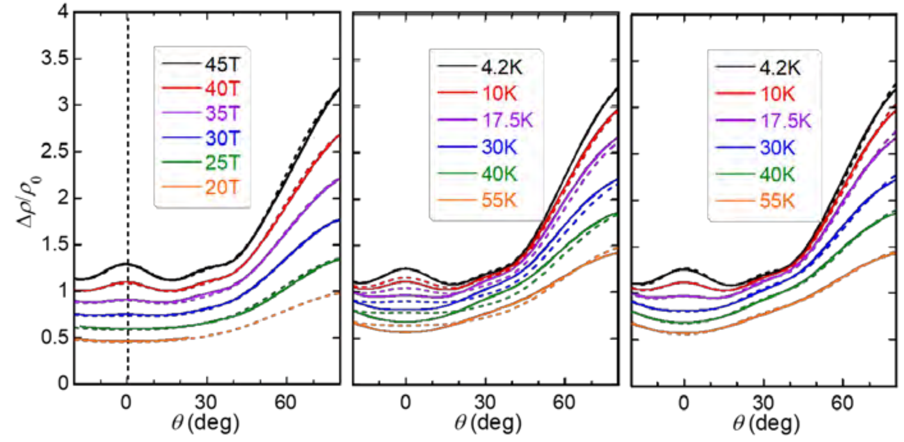
Boltzmann transport within SM regime

Tl2201 $T_c \approx 15$ K



High-field

Abdel-Jawad *et al.*, *Nat. Phys.* **2**, 821 (06)



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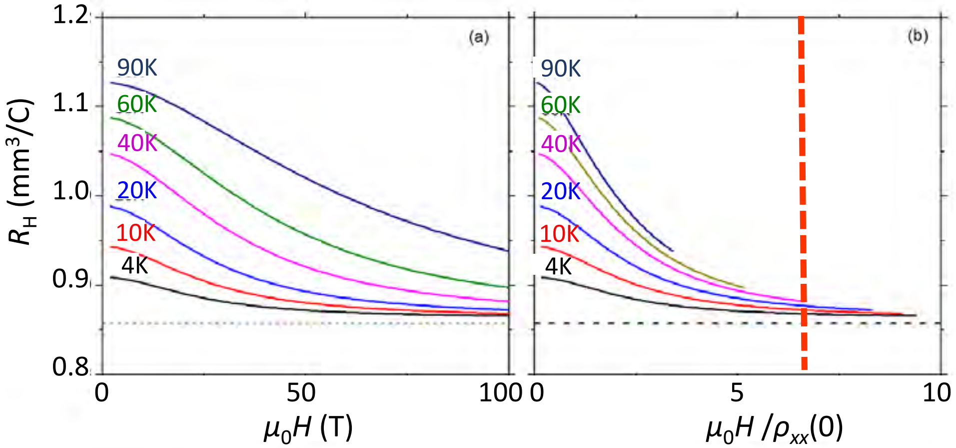
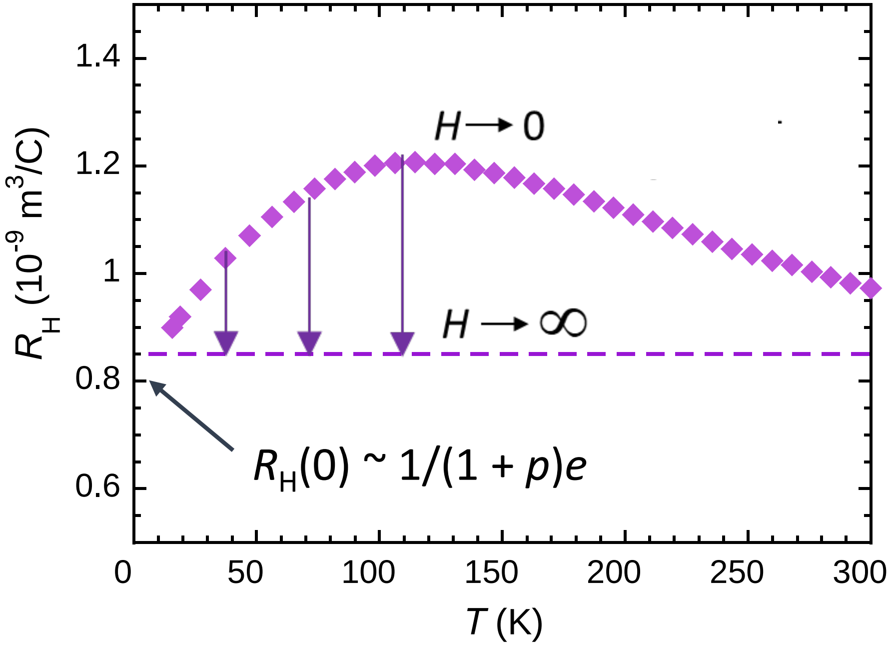
- Same parameterization should also govern field-dependence of $R_H(T)$

Putzke *et al.*, *Nat. Phys.* **17**, 826 (21)

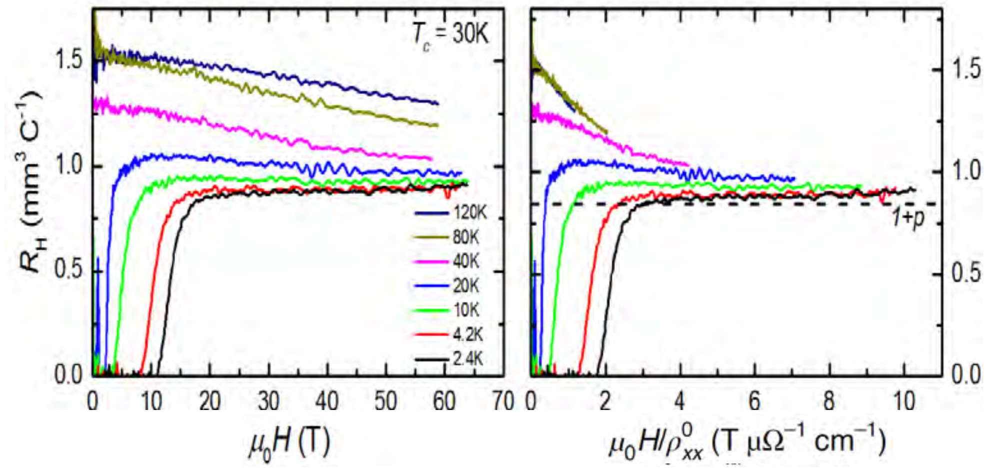


Simulated ρ_{xy}/H response



Boltzmann transport within SM regime

Tl2201 $T_c \approx 30$ K

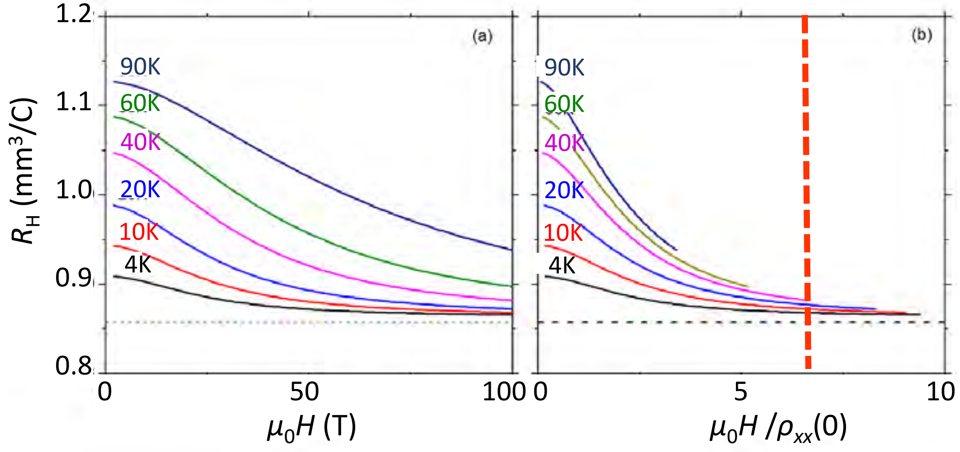


Note that R_H is H-independent at lowest T, indicating recovery of isotropic Γ

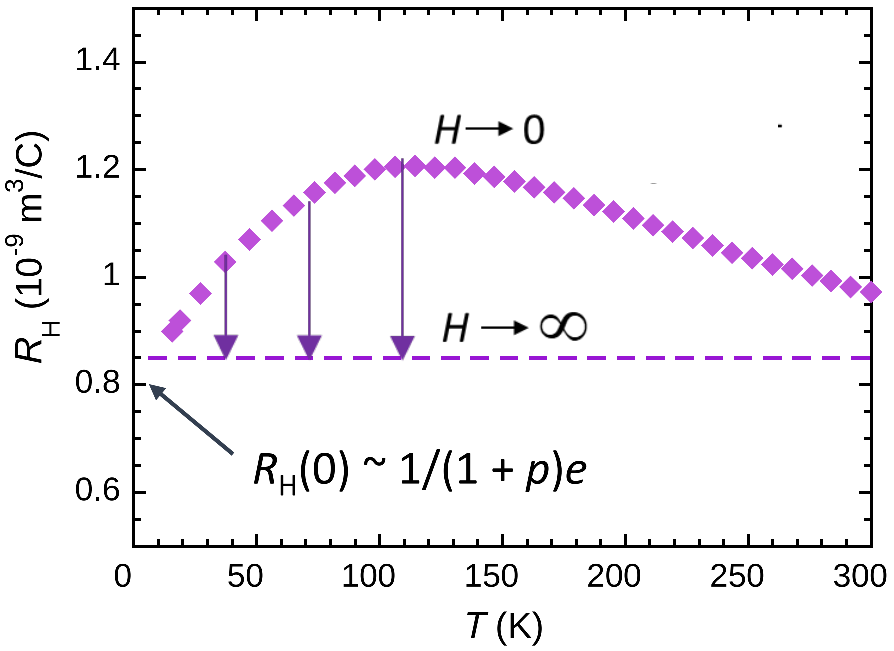
- T-dependent ADMR provided evidence of anisotropy in T-linear scattering rate
- ADMR parameterization reproduces $R_H(T)$ reasonably well.
- Same parameterization should also govern field-dependence of $R_H(T)$

Actual ρ_{xy}/H response

Putzke *et al.*, *Nat. Phys.* **17**, 826 (21)

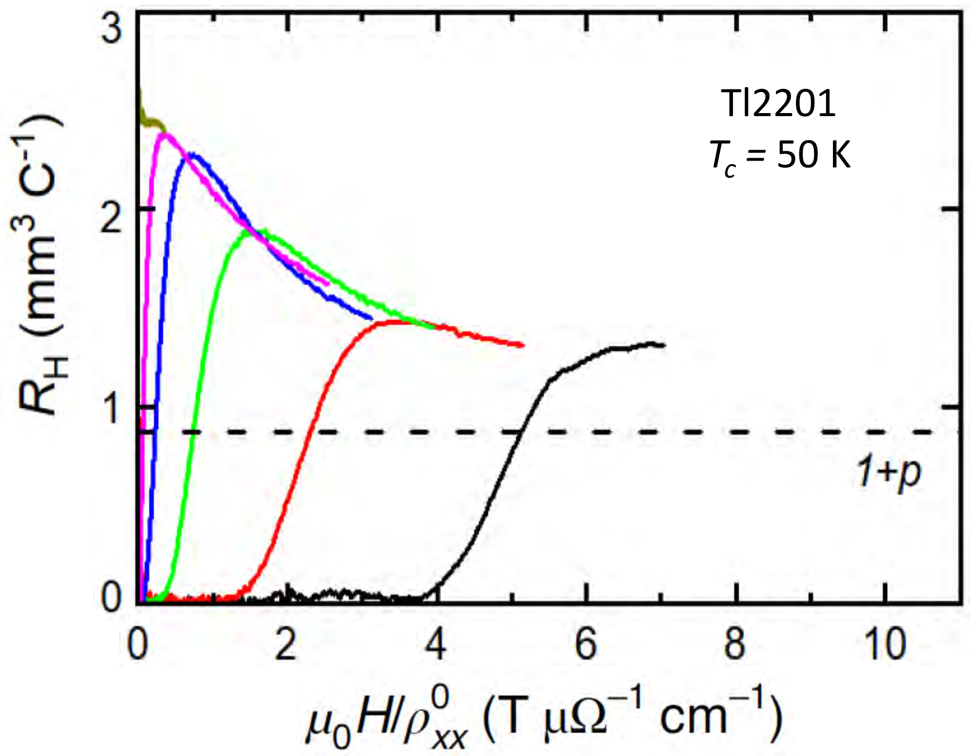


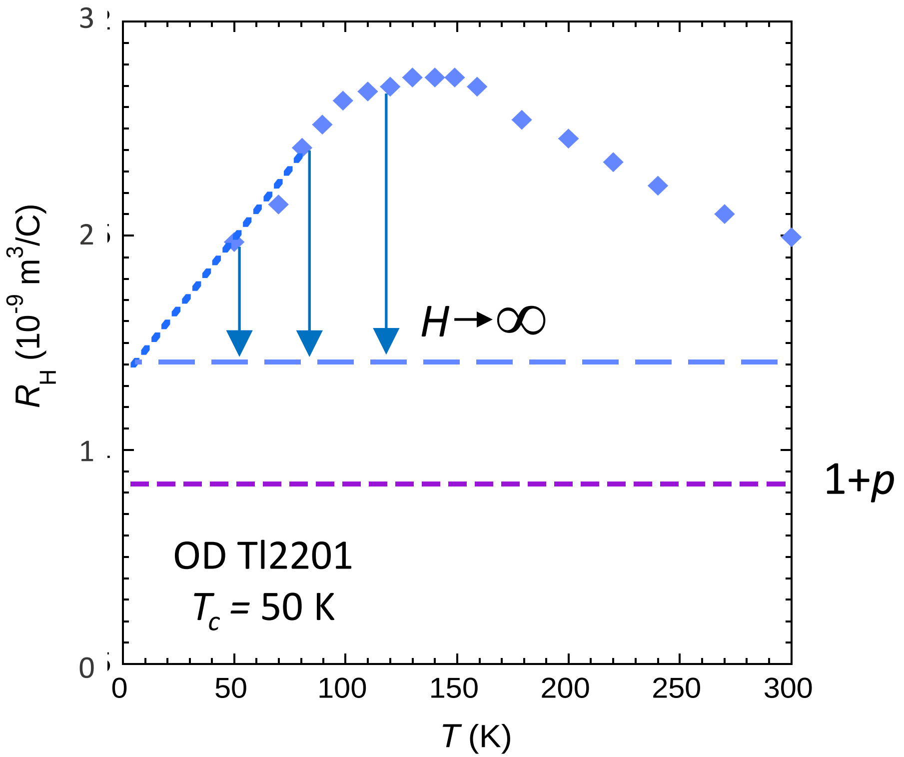
Simulated ρ_{xy}/H response



Boltzmann transport within SM regime

Putzke *et al.*, *Nat. Phys.* **17**, 826 (21)



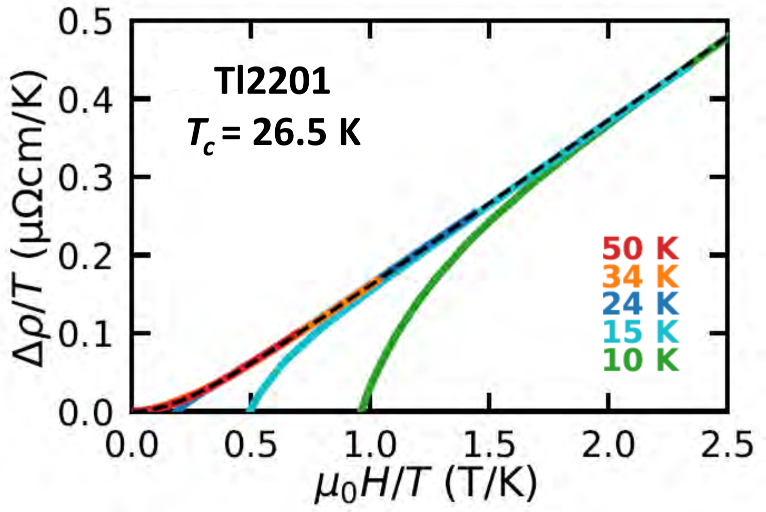


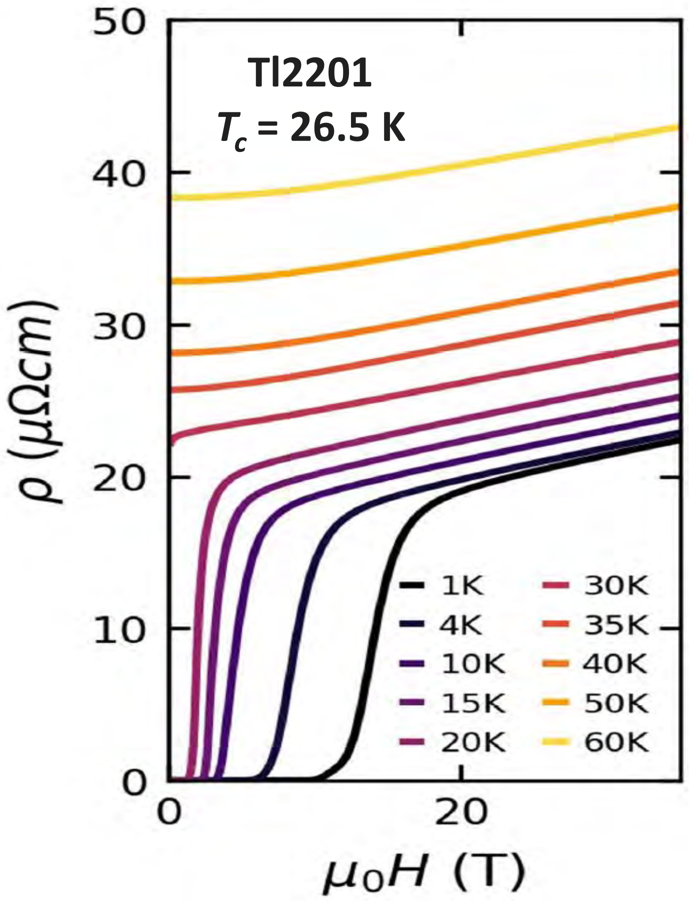
- In higher T_c Tl2201 samples, drop in R_H with field also seen implying anisotropic scattering still responsible for *H*- and *T*-dependent $R_H(T)$. However, absolute value of $R_H(0)$ is now shifted up, suggesting loss of states *at all T.*

- With decreasing hole doping (increasing T_c), $R_H(H)$ <u>*does not*</u> asymptotically reach the value consistent with $n_H = 1 + p$

non-Boltzmann transport in SM regime

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

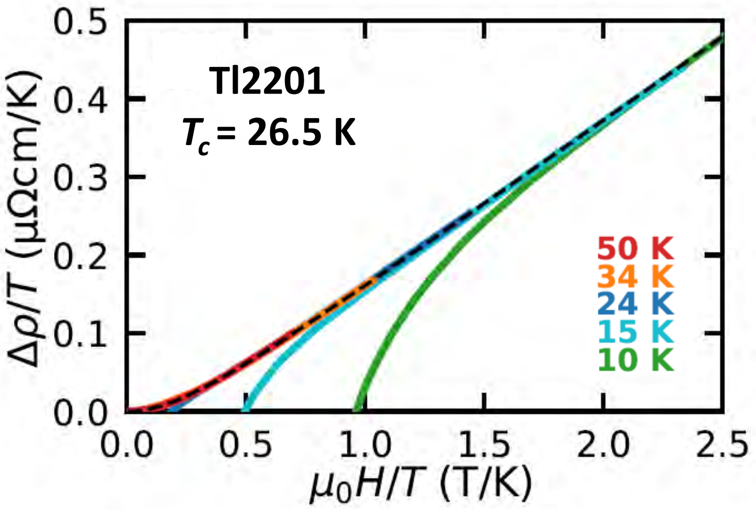


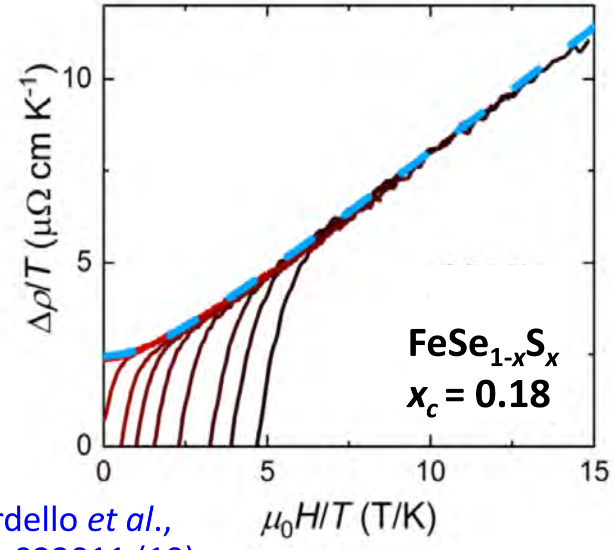


- In-plane MR shows crossover to *H*-linearity at highest fields with *T*-independent slope
- $\Delta\rho/T$ scales with H/T

non-Boltzmann transport in SM regime

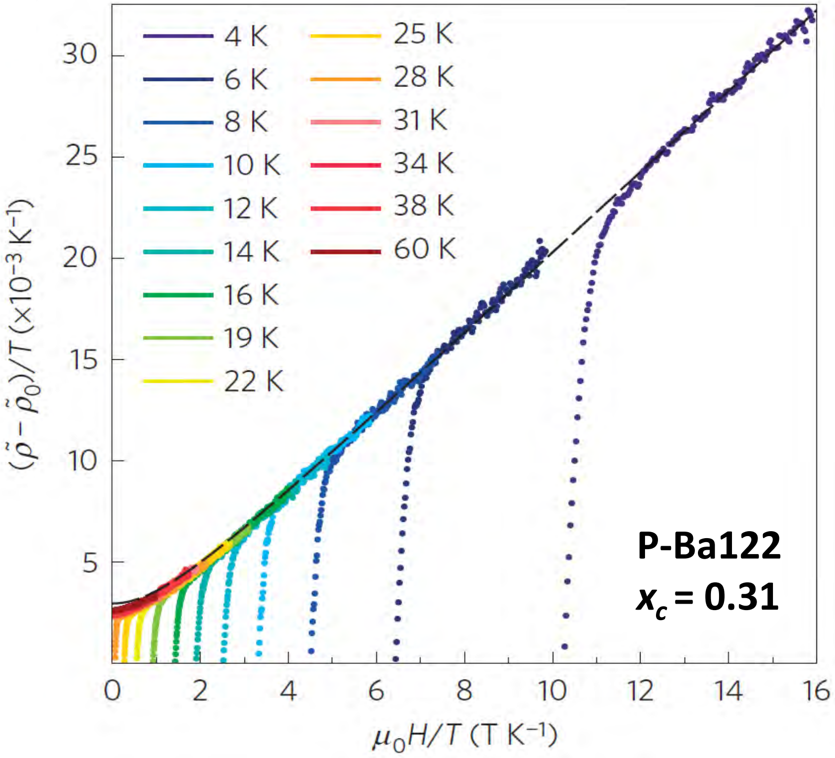
Ayres, Berben *et al.*, *Nature* **595**, 661 (21)



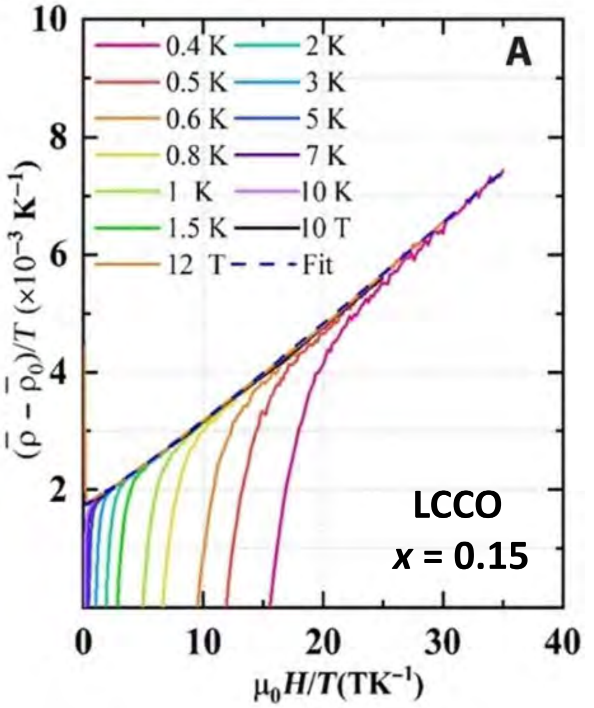


Licciardello *et al.*, *PRR* **1**, 023011 (19)

Hayes *et al.*, *Nat. Phys.* **12**, 916 (16)



Sarkar *et al.*, *Sci. Adv.* **5**, eaav6753 (19)

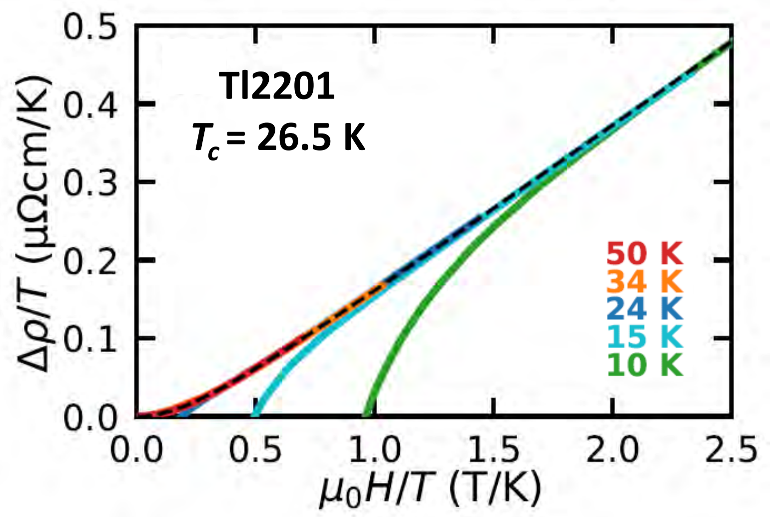


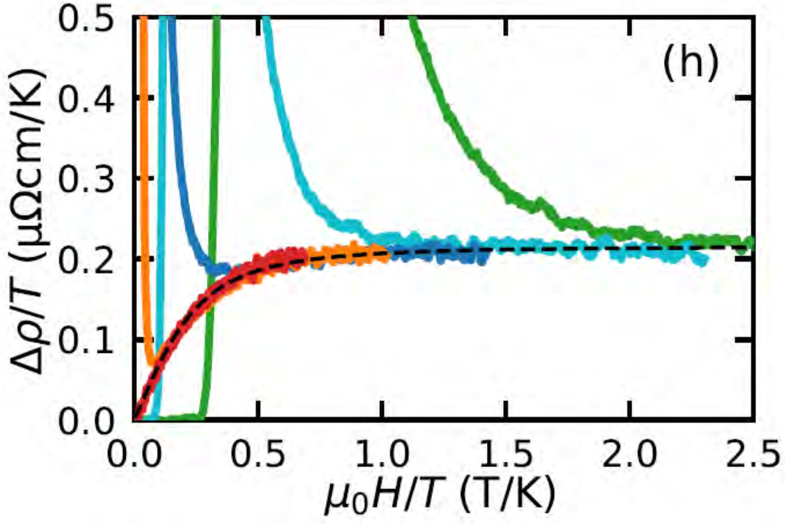
$$\rho(H,T) = \rho(0,0) + \sqrt{(\alpha k_B T)^2 + (\gamma \mu_B \mu_0 H)^2}$$

- $\Delta\rho/T$ scales with H/T and follows quadrature form similar to that seen in pnictides, chalcogenides and *n*-doped cuprates **near their respective magnetic and nematic QCPs**.

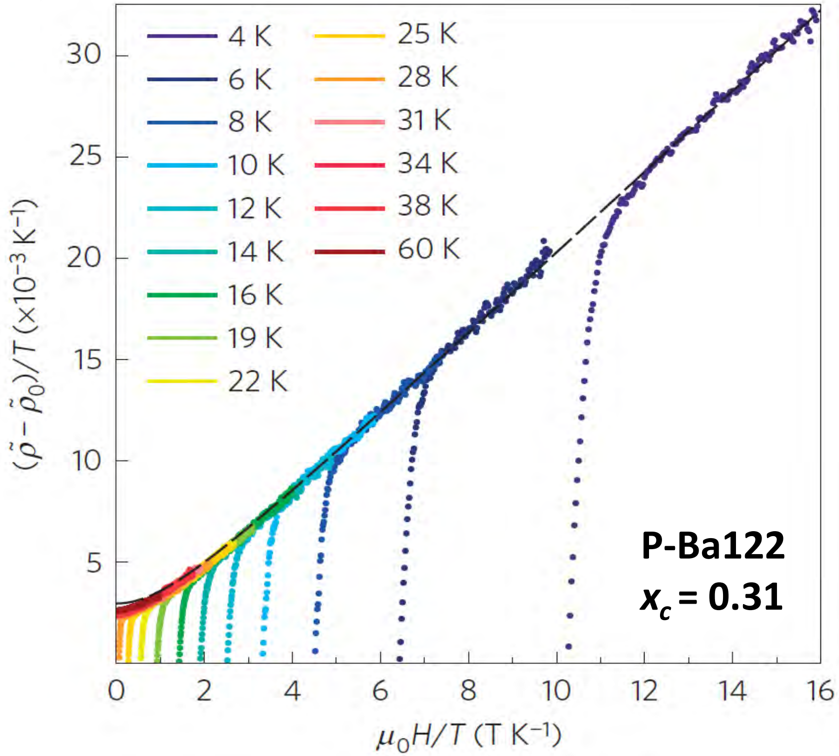
non-Boltzmann transport in SM regime

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

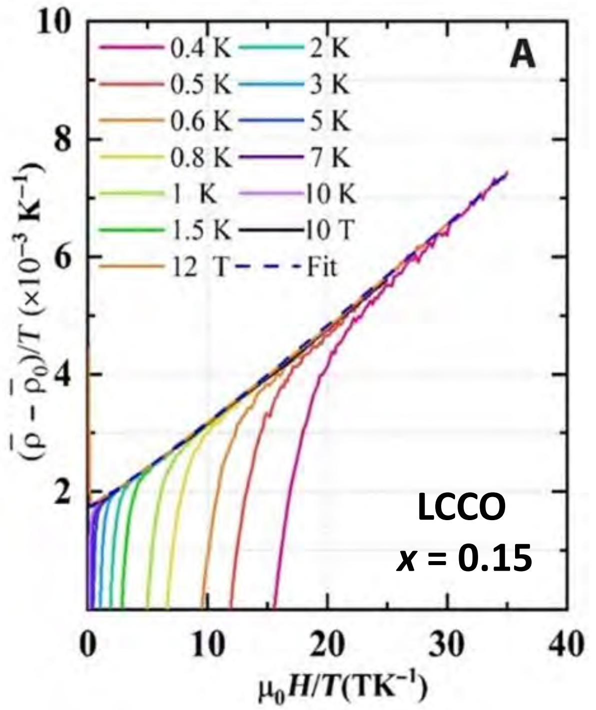




Hayes *et al.*, *Nat. Phys.* **12**, 916 (16)



Sarkar *et al.*, *Sci. Adv.* **5**, eaav6753 (19)

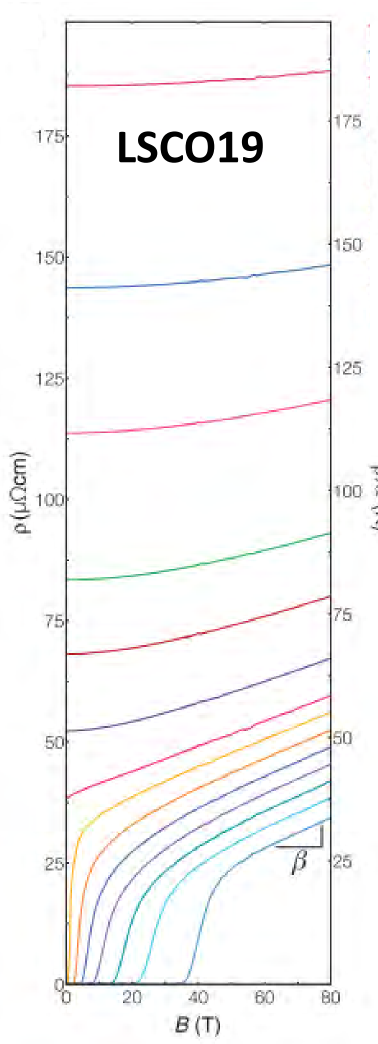


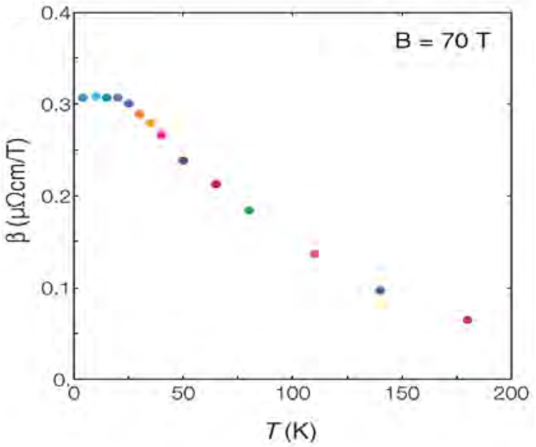
$$\rho(H,T) = \mathcal{F}(T) + \sqrt{(\alpha k_B T)^2 + (\gamma \mu_B \mu_0 H)^2}$$

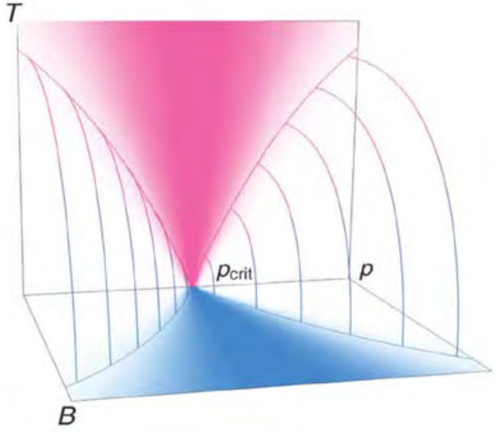
- $\Delta\rho/T$ scales with H/T and follows quadrature form similar to that seen in pnictides, chalcogenides and *n*-doped cuprates **near their respective magnetic and nematic QCPs**.

non-Boltzmann transport in SM regime

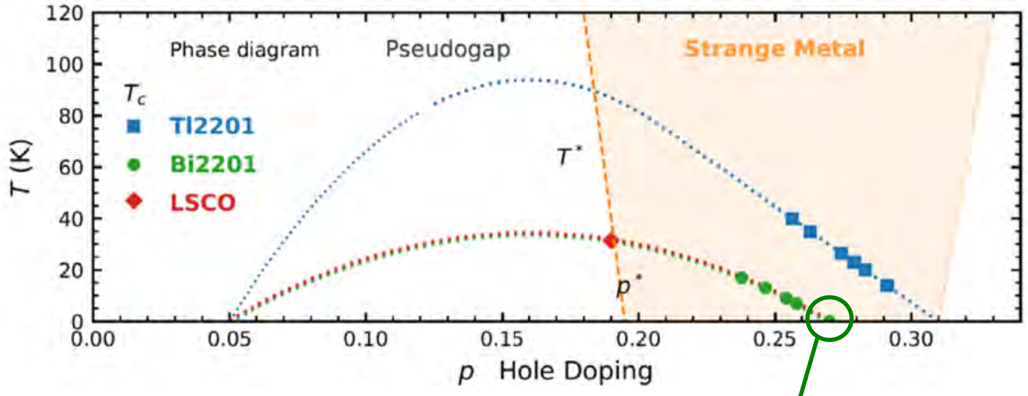
Ayres, Berben *et al.*, *Nature* **595**, 661 (21)

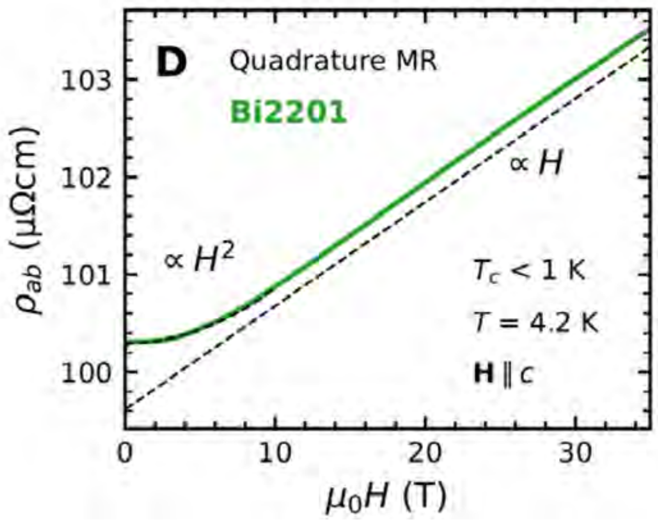






Giraldo-Gallo *et al.*, *Science* **361** 479 (18)

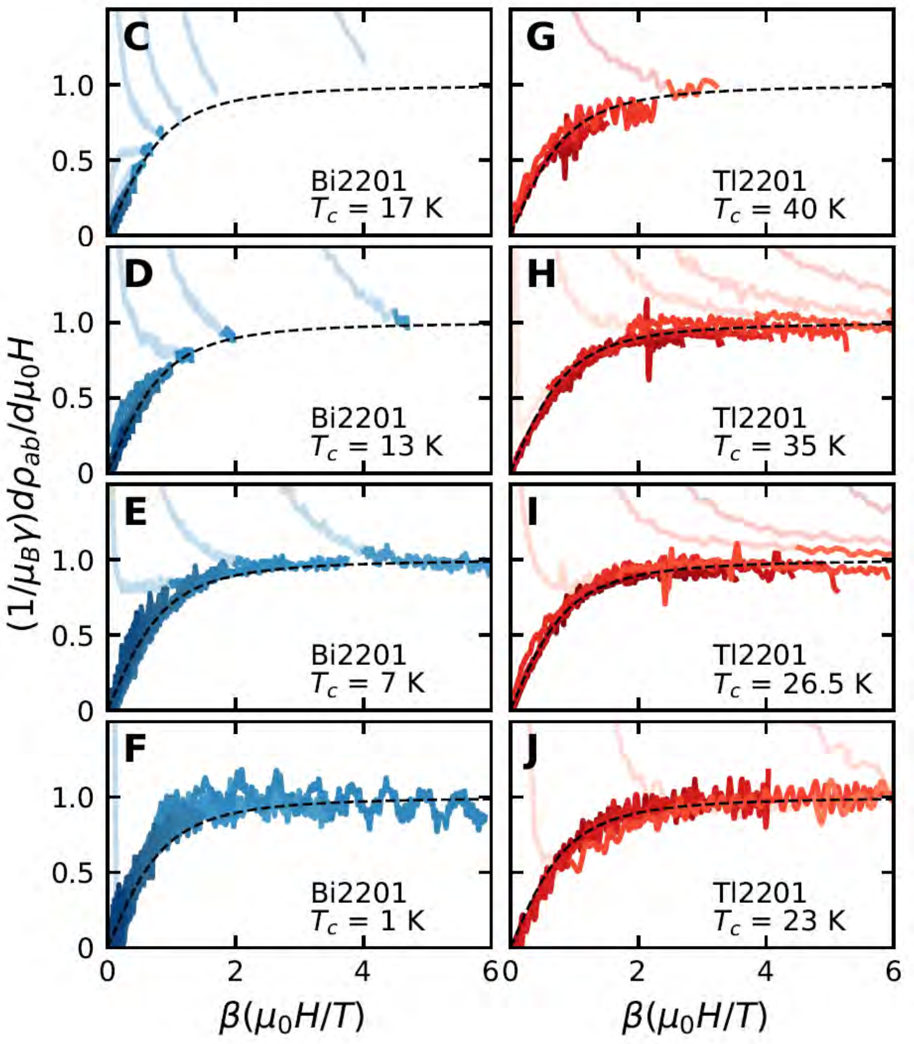


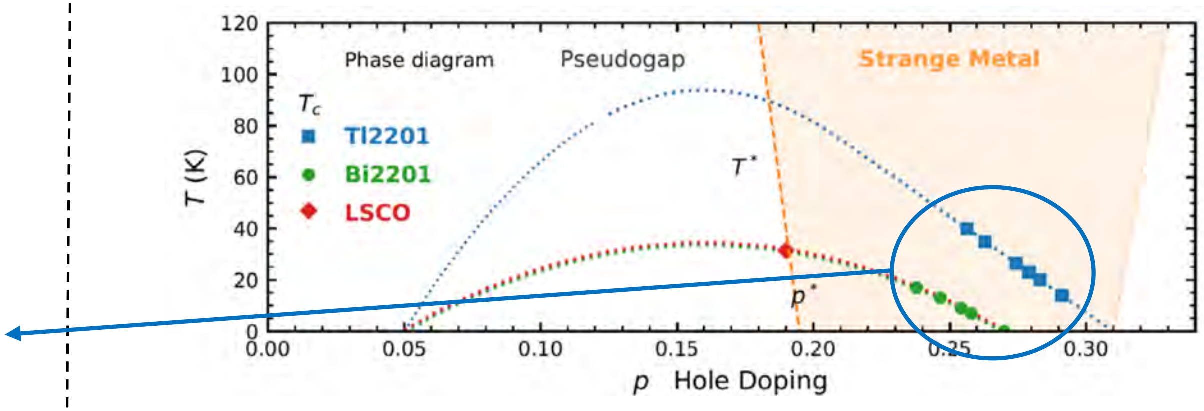


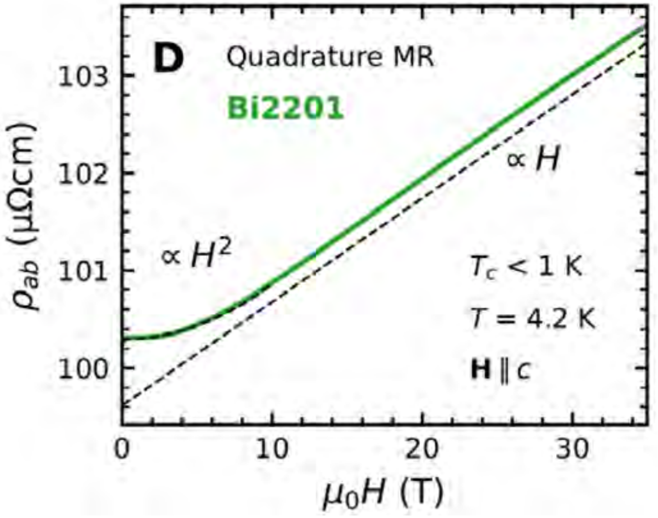
- Same *H*-linear MR found very far from *p**

non-Boltzmann transport in SM regime

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





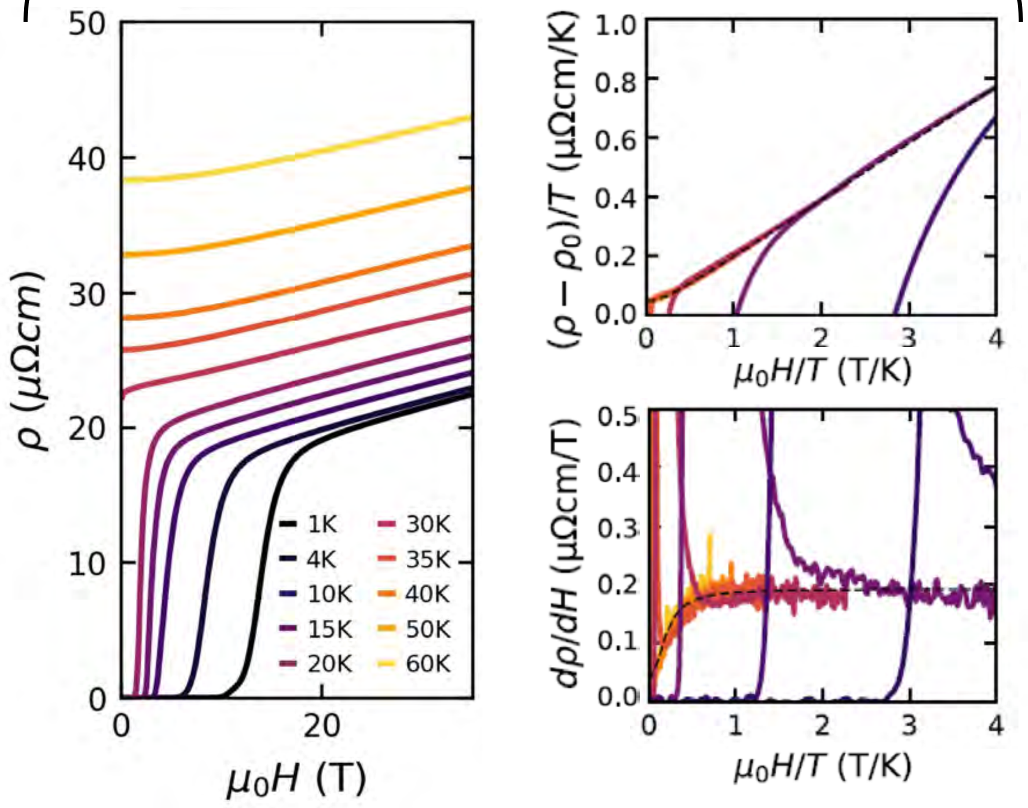


- Same behaviour observed across broad doping range
- Same *H*-linear MR found very far from *p**

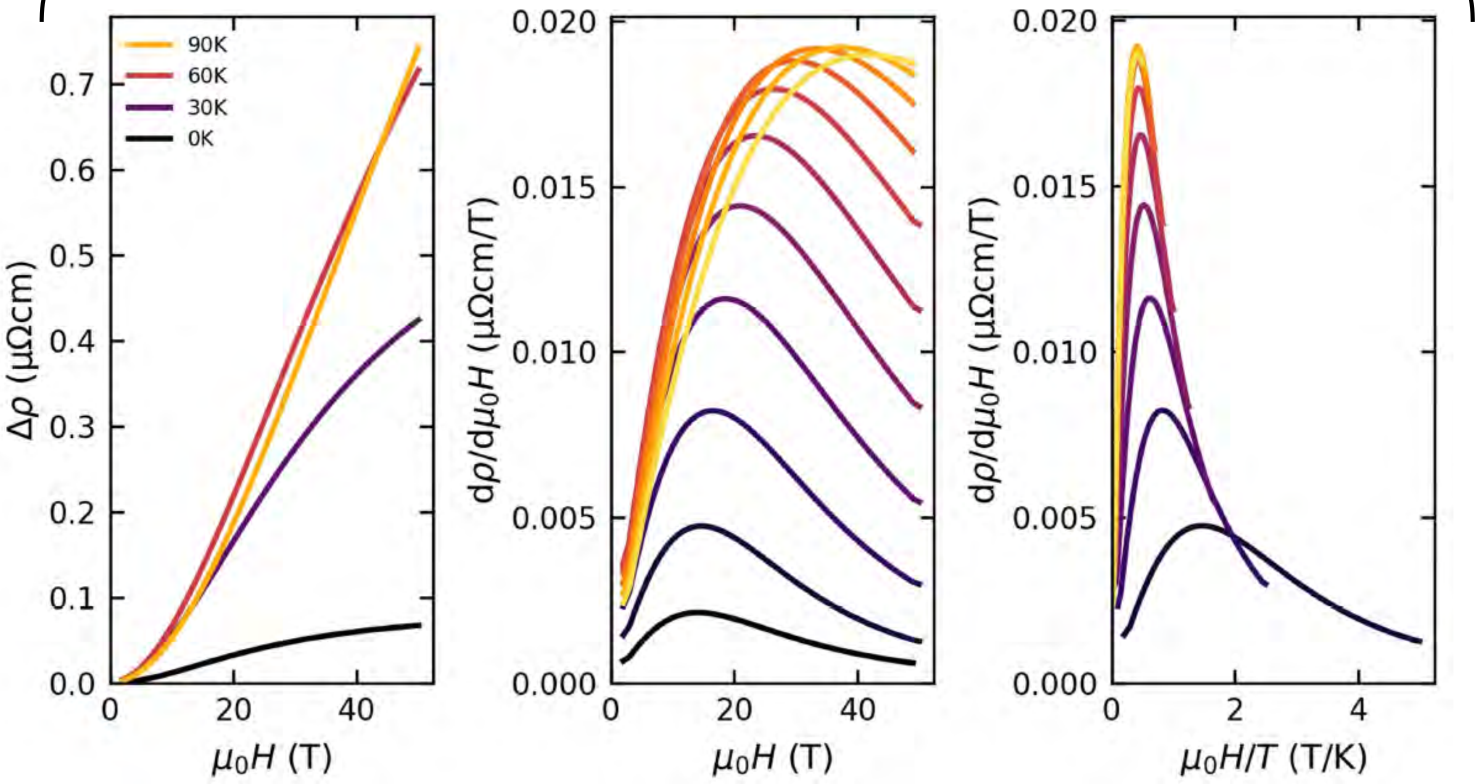
non-Boltzmann transport in SM regime

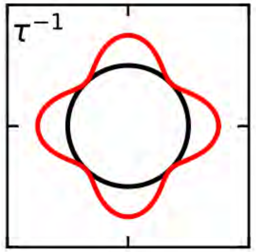
Ayres, Berben *et al.*, *Nature* **595**, 661 (21)

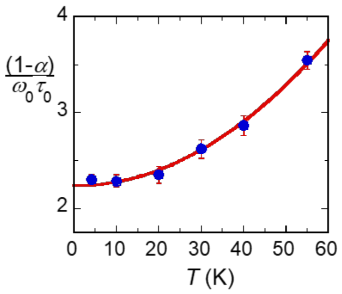
Data

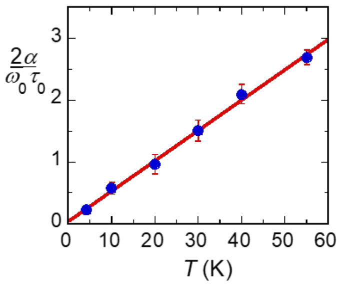


ADMR/Hall parameterization









Simulated MR:

- More than an order of magnitude smaller than the actual MR
- Shows tendency to saturate at relatively modest fields.
- No quadrature H/T scaling

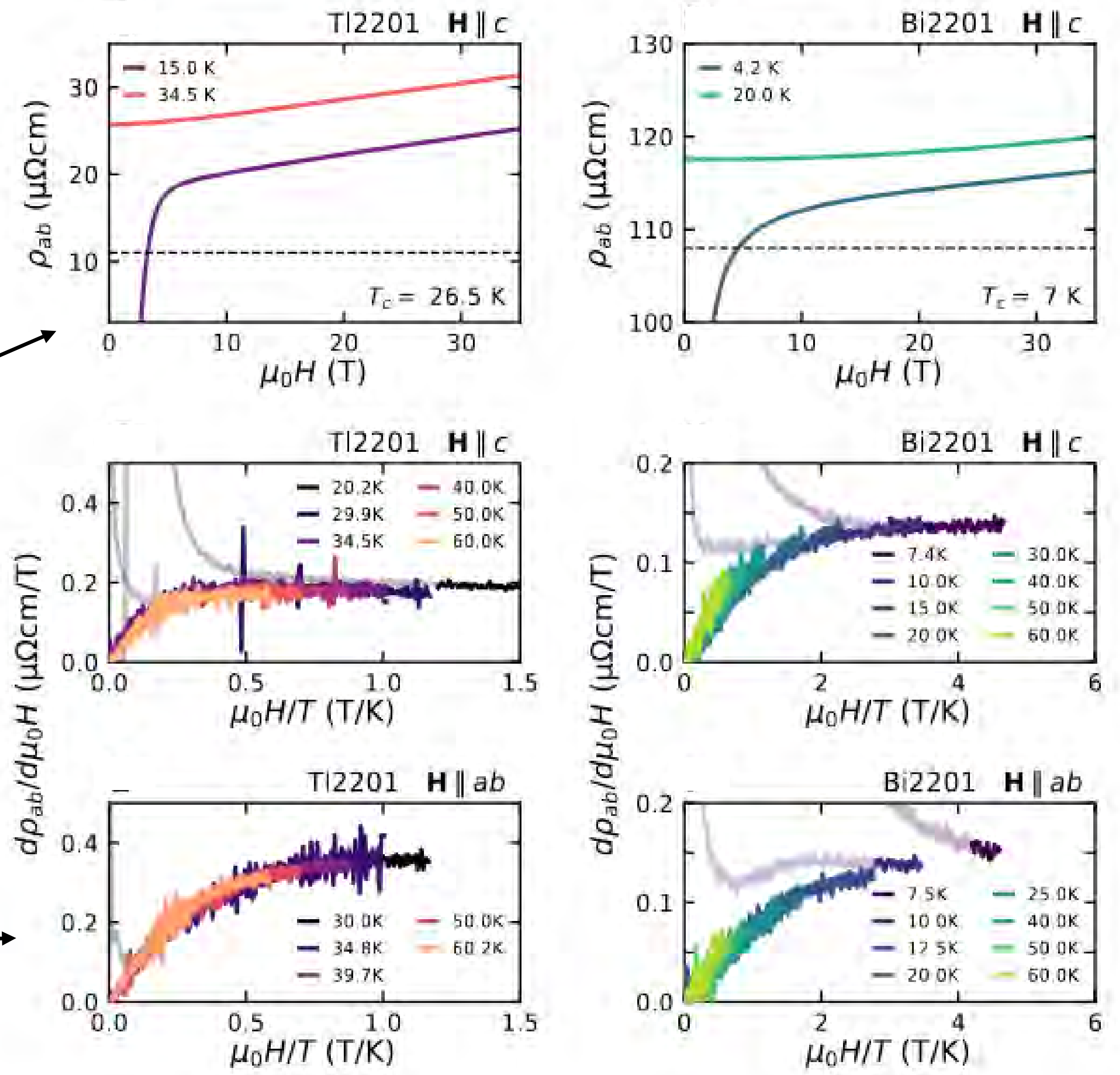
Boltzmann transport in SM regime

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

Recall Kohler's rule

$$\frac{\Delta\rho}{\rho(0)} \approx (\omega_c\tau)^2 \propto \left(\frac{H}{\rho(0)}\right)^2$$

- MR orders of magnitude larger than expected from estimate of $\omega_c\tau$
- MR of same magnitude for Tl2201 and Bi2201, despite 10 x larger ρ_0 in latter
- No angle dependence in MR



MR scaling across p^* and p_{SC}

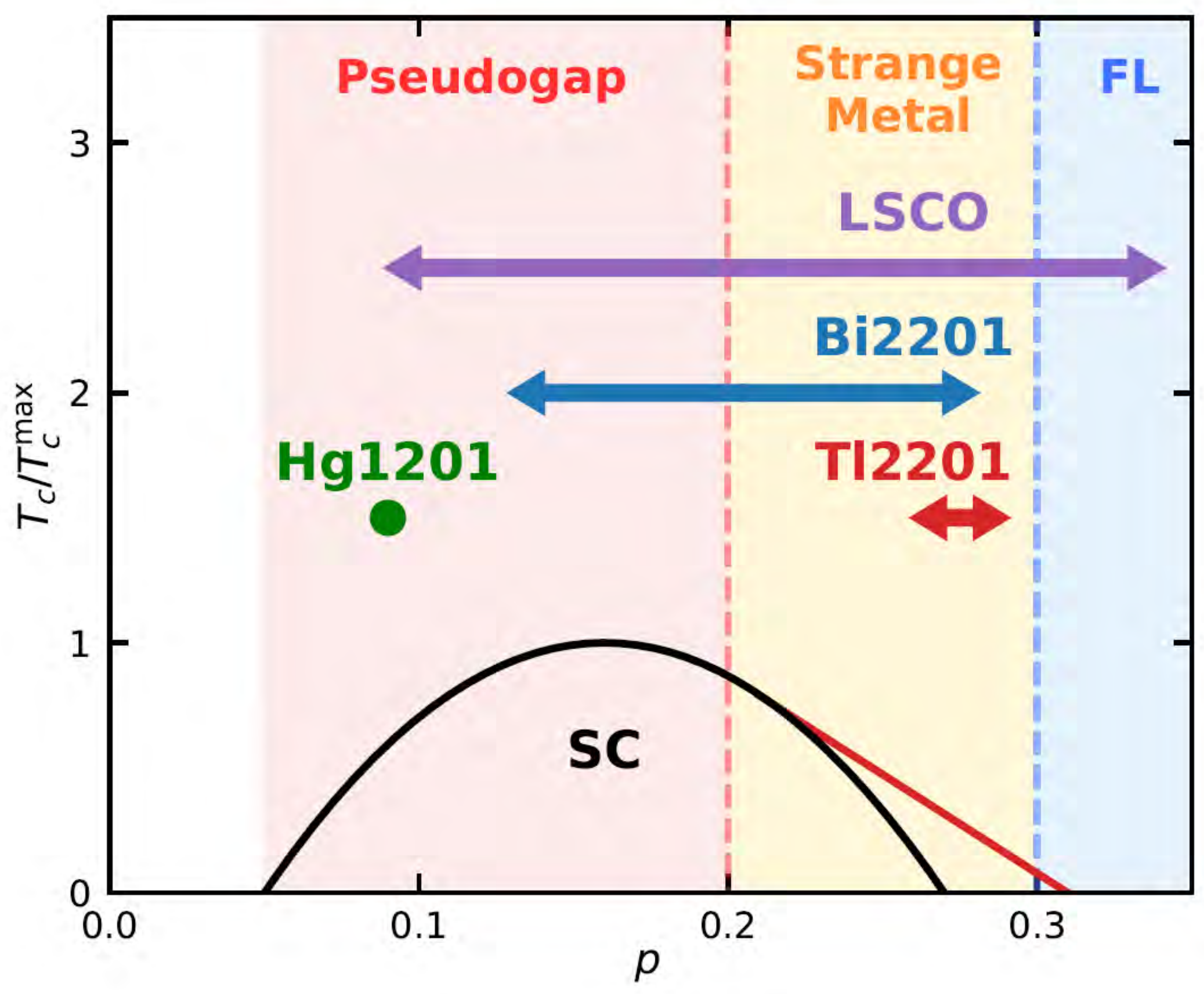
Berben, Ayres *et al.*, *2203.04867*

Q1: Does the *H*-linear slope have a dependence on T_c or p that can be linked to the *T*-linear component of $\rho_{ab}(T)$?

Q2: What happens to MR scaling below p^* as we enter into pseudogap regime?

Q3: What happens beyond the superconducting dome? Does Kohler's scaling re-appear at high doping?

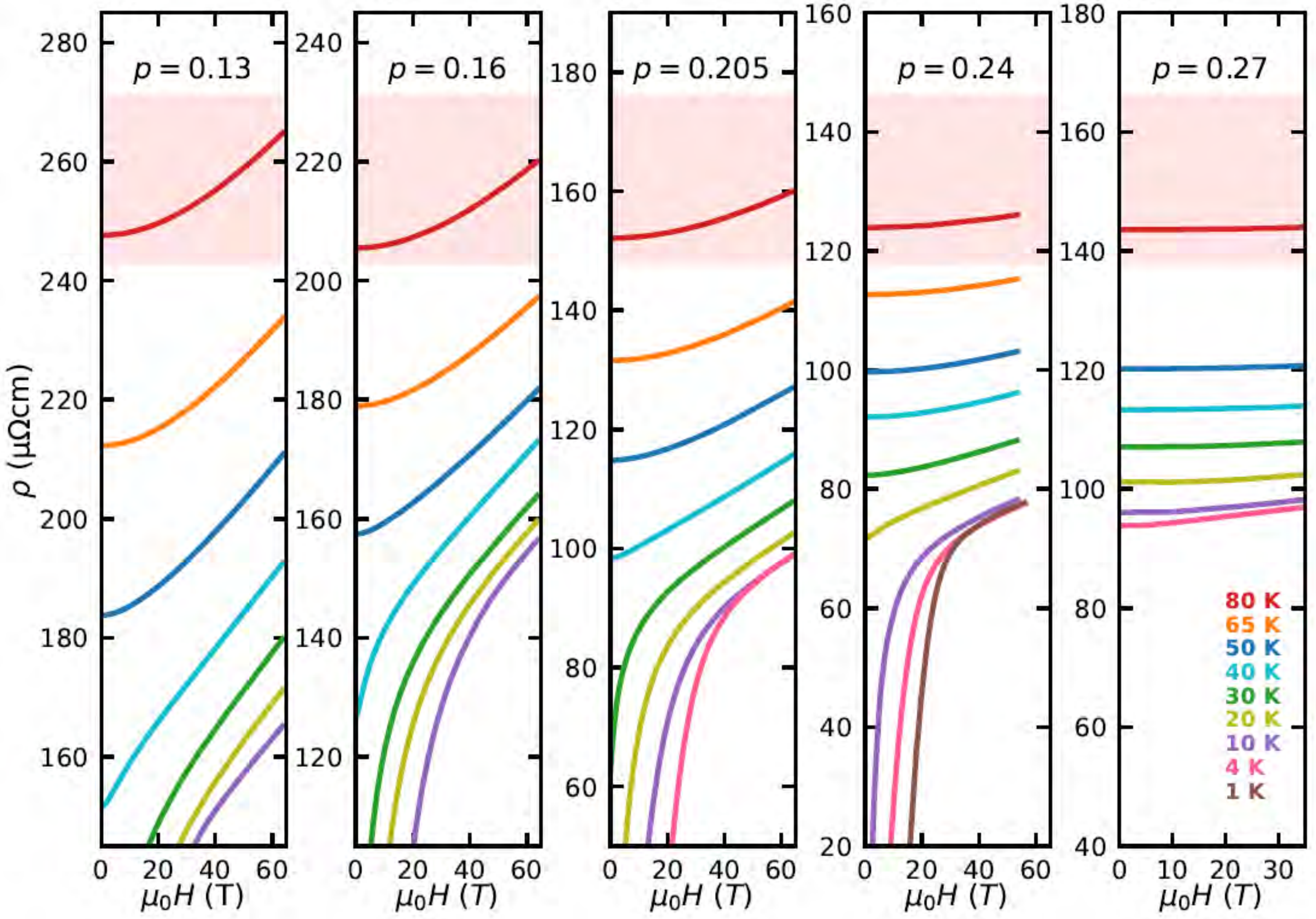
Q4: What is the link between H/T quadrature MR and modified Kohler scaling in optimally & under-doped cuprates?



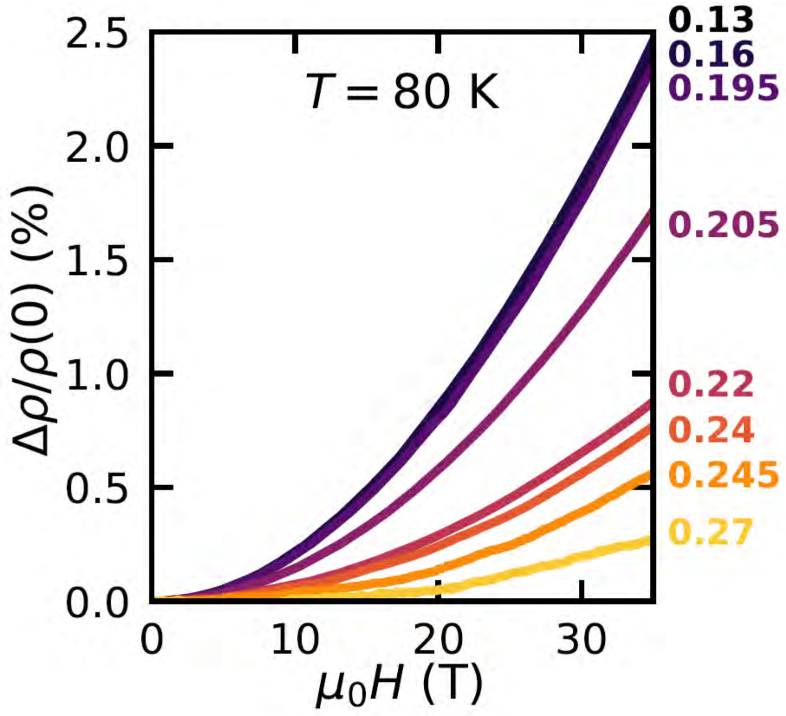
Q1: *H*-linear MR vs. *p*

Berben, Ayres *et al.*, *2203.04867*

Bi2201



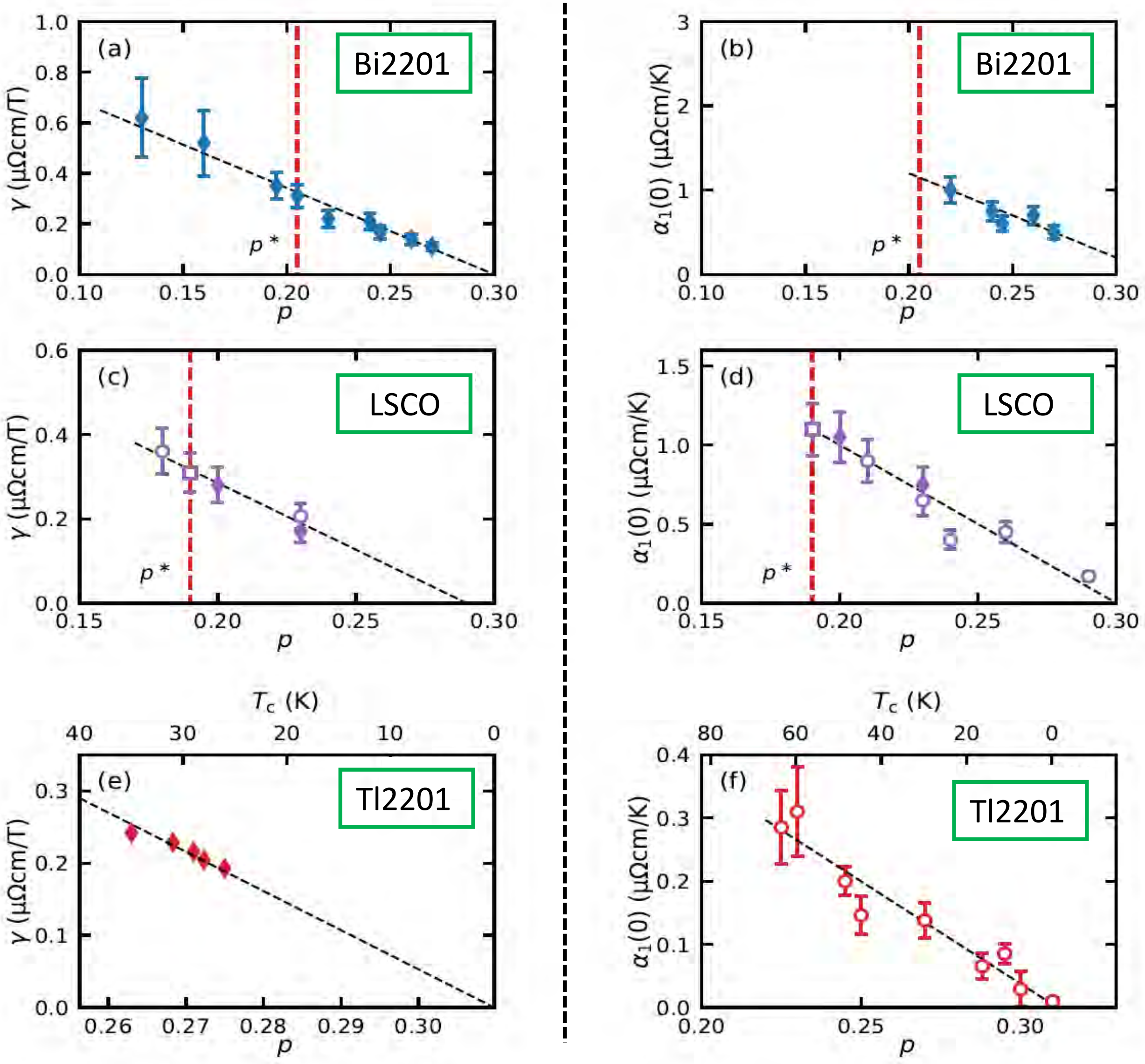
- At a fixed temperature, there is a clear doping dependence in the magnitude of the MR… even when normalized to $\rho(0)$.



Q1: *H*-linear MR vs. *p*

Berben, Ayres *et al.*, 2203.04867

***H*-linear MR slope** | ***T*-linear $\rho(T)$ coefficient**

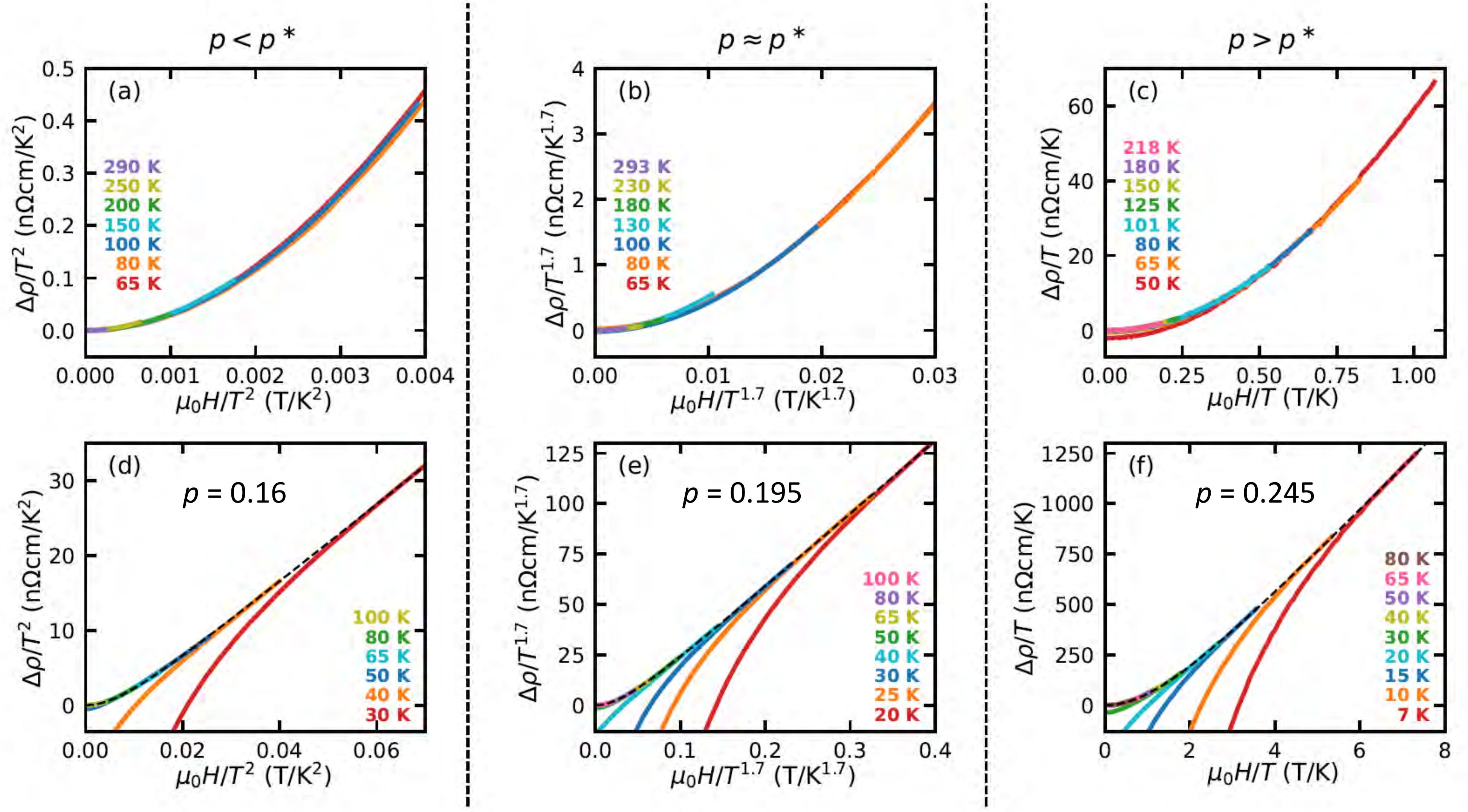


- Beyond p^*, the *H*-linear MR slope found to show a similar variation with *p* (or T_c) as the coefficient of the *T*-linear zero-field resistivity for all three families.
- Below p^*, *H*-linear slope continues to rise with decreasing *p*, which we attribute to a loss of carriers inside the pseudogap regime.
- Suggests that within strange metal regime, *T*-linear resistivity and *H*-linear MR are indeed intrinsically linked.

Q2: MR scaling across $p*$

Berben, Ayres *et al.*, *2203.04867*

Bi2201



***H*/*T*² scaling** | ***H*/*T*ⁿ scaling** | ***H*/*T* scaling**

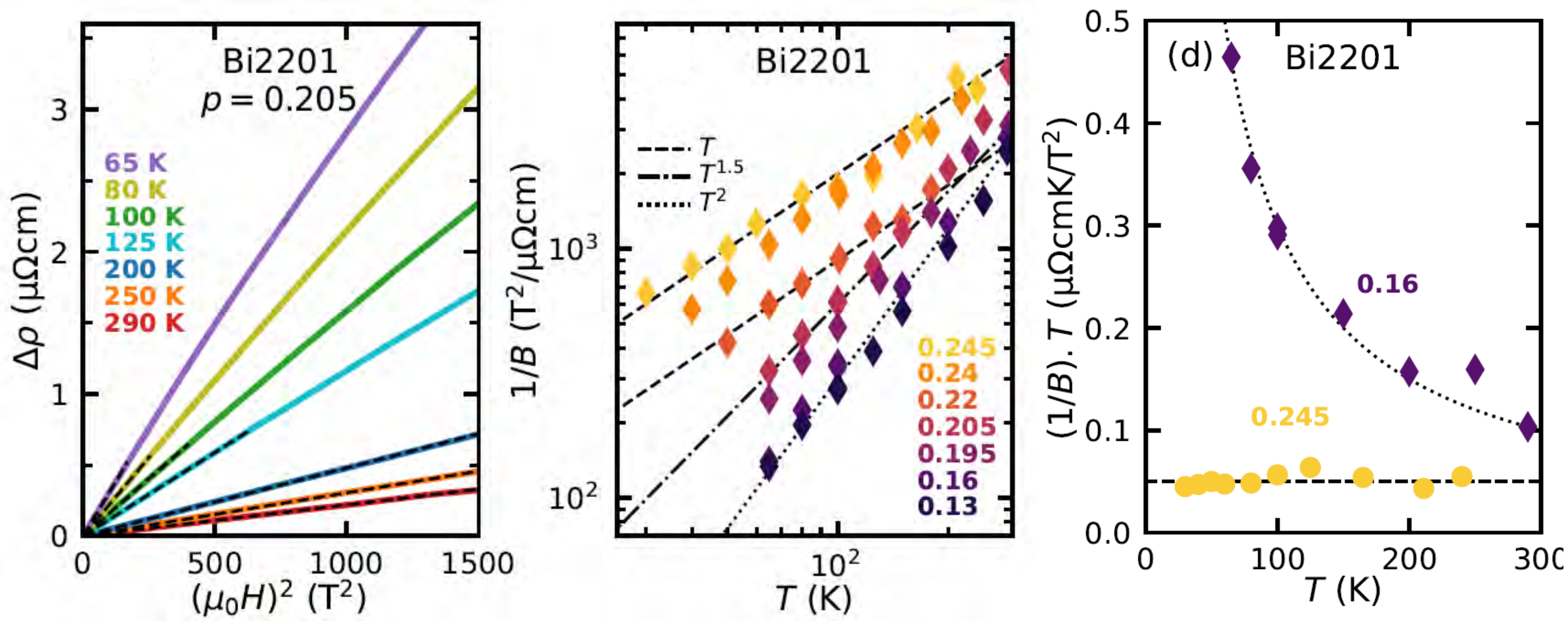
Q2: MR scaling across $p*$

Berben, Ayres *et al.*, *2203.04867*

Another way to reveal type of scaling behavior observed is to look at T-dependence of the slope B of the low-field MR

$$\Delta\rho(H,T) = B(T)(\mu_0 H)^2$$

(Recall that for Kohler's or modified Kohler's rule, $\Delta\rho(H) = \frac{(\mu_0 H)^2}{\rho(0)}$ or $\Delta\rho(H) = \frac{\rho(0)}{cot^2\theta_H}(\mu_0 H)^2$)



Power-law scaling observed in normal state of all SC samples with variable exponent *m*

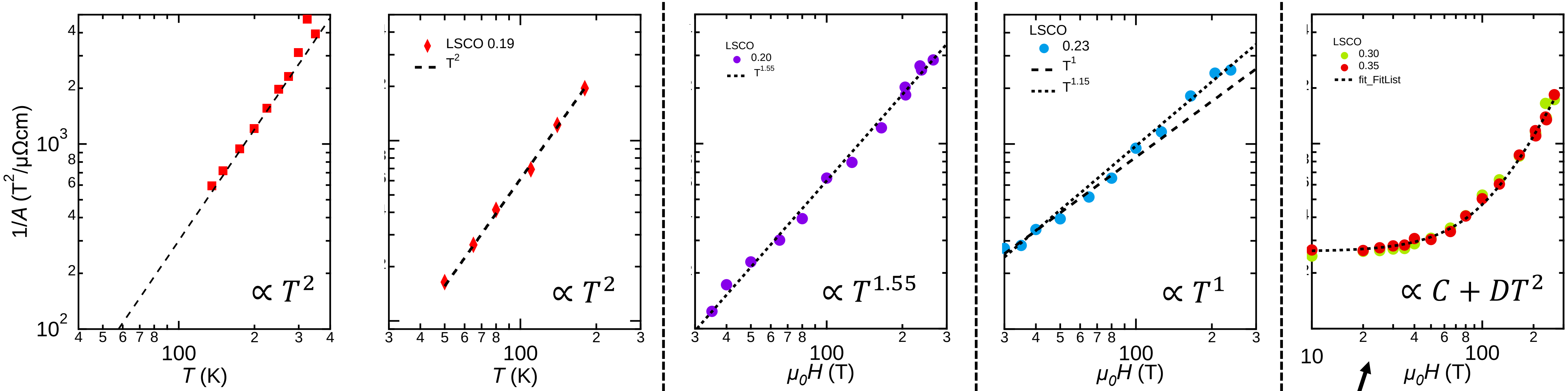
Q3: MR scaling across p_{SC}

Berben, Ayres *et al.*, *2203.04867*

Only with LSCO can we access the non-SC state on the overdoped side ($p > 0.27$), but the advantage is we can compare directly across the different regimes. Here we plot the T-dependence of the inverse of the low-H H^2 coefficient within the different regimes:

LSCO

$p < p^*$		$p \approx p^*$	$p^* < p < p_{SC}$	$p > p_{SC}$
$x = 0.16$	$x = 0.19$	$x = 0.20$	$x = 0.23$	$x = 0.30, 0.35$



Harris *et al.*, *PRL* **75**, 1391 (95)

Giraldo-Gallo *et al.*, *Science* **361**, 479 (18)

Recovery of Kohler scaling beyond strange metal regime.

MR scaling across $p*$ and p_{SC}

Berben, Ayres *et al.*, *2203.04867*

There are thus 3 types of scaling:

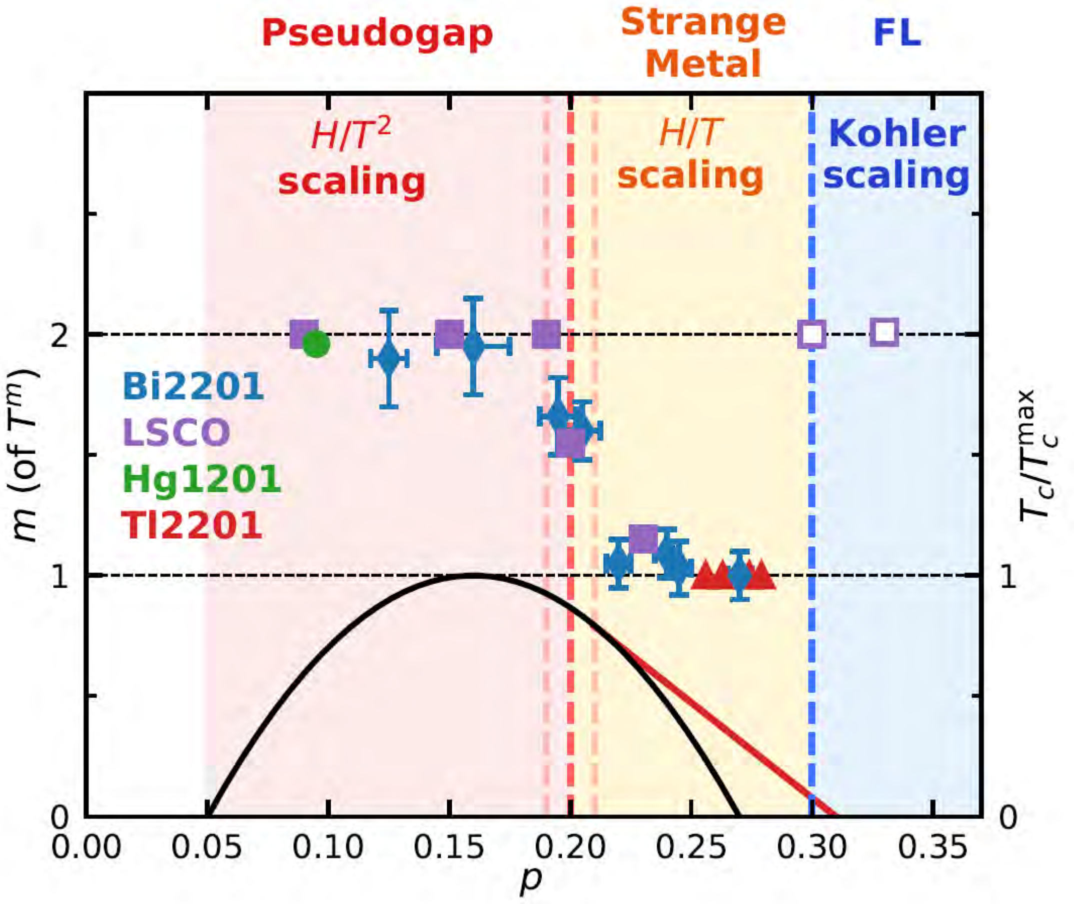
***H/T*²** scaling below $p*$
H/T scaling for $p_{sc} > p > p*$
Kohler scaling for $p > p_{sc}$

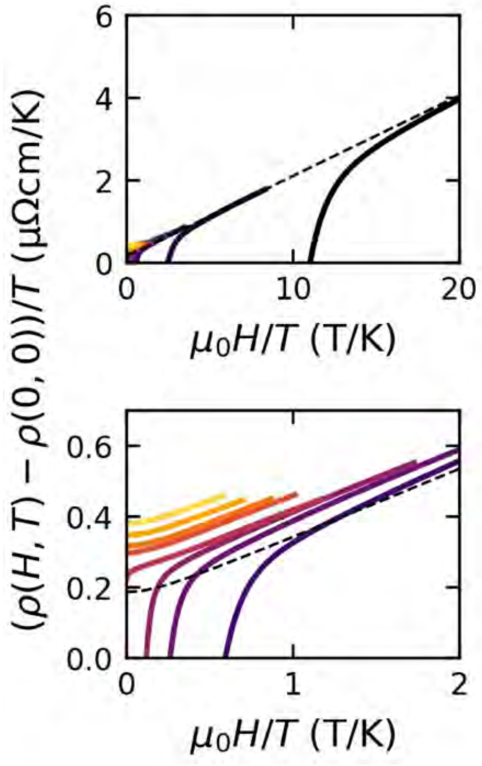
$$\rho(H,T) = \mathcal{F}(T) + \sqrt{(\alpha_m T^m)^2 + (\gamma\mu_0 H)^2}$$

'Some other Contribution' — Quadrature MR

$$\mathcal{F}(T) = \rho_0 + A_1 T + A_2 T^2$$

$$A_1 T + \alpha k_B T = \alpha_1(0) T$$





Other component does not appear to contribute to in-plane MR, but is visible in the *c*-axis MR and in-plane Hall effect

\- **DUAL CHARACTER OF STRANGE METAL**

4) Q4: Power-law scaling and MKR

Modified Kohler scaling

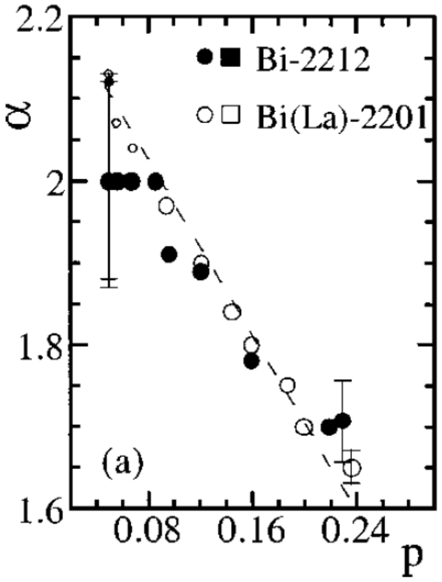
$$\frac{\Delta\rho}{\rho(0)} \approx (tan\theta_H)^2 \propto \left(\frac{H}{cot\theta_H}\right)^2$$

$$cot\theta_H \propto A + BT^{\alpha}$$

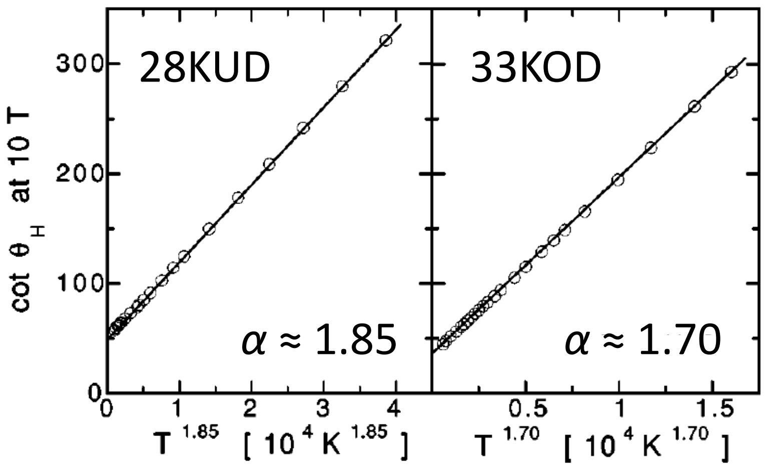
$$\frac{\Delta\rho}{\rho(0)} \propto \left(\frac{1}{A + BT^{\alpha}}\right)^2$$

Bi2201

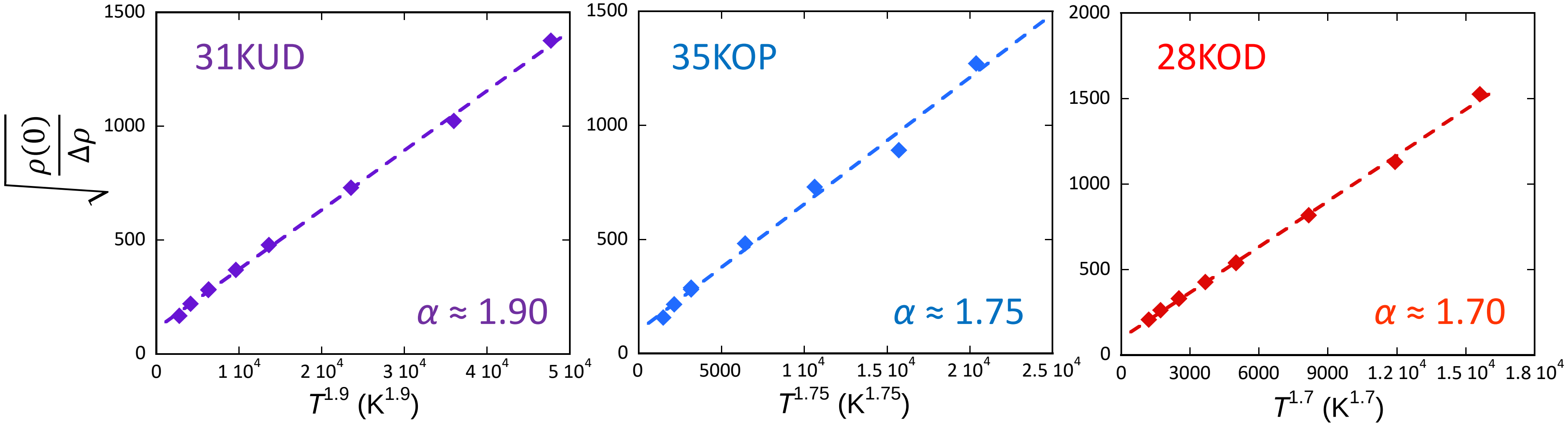
Konstantinovic *et al.*, *PRB* **62** R11989 (00)



Ando + Murayama, *PRB* **60** R6991 (99)



$$\Rightarrow \sqrt{\frac{\rho(0)}{\Delta\rho}} \propto A + BT^{\alpha}$$



4) Q4: Power-law scaling and MKR

Berben, Ayres *et al.*, *2203.04867*

Modified Kohler scaling

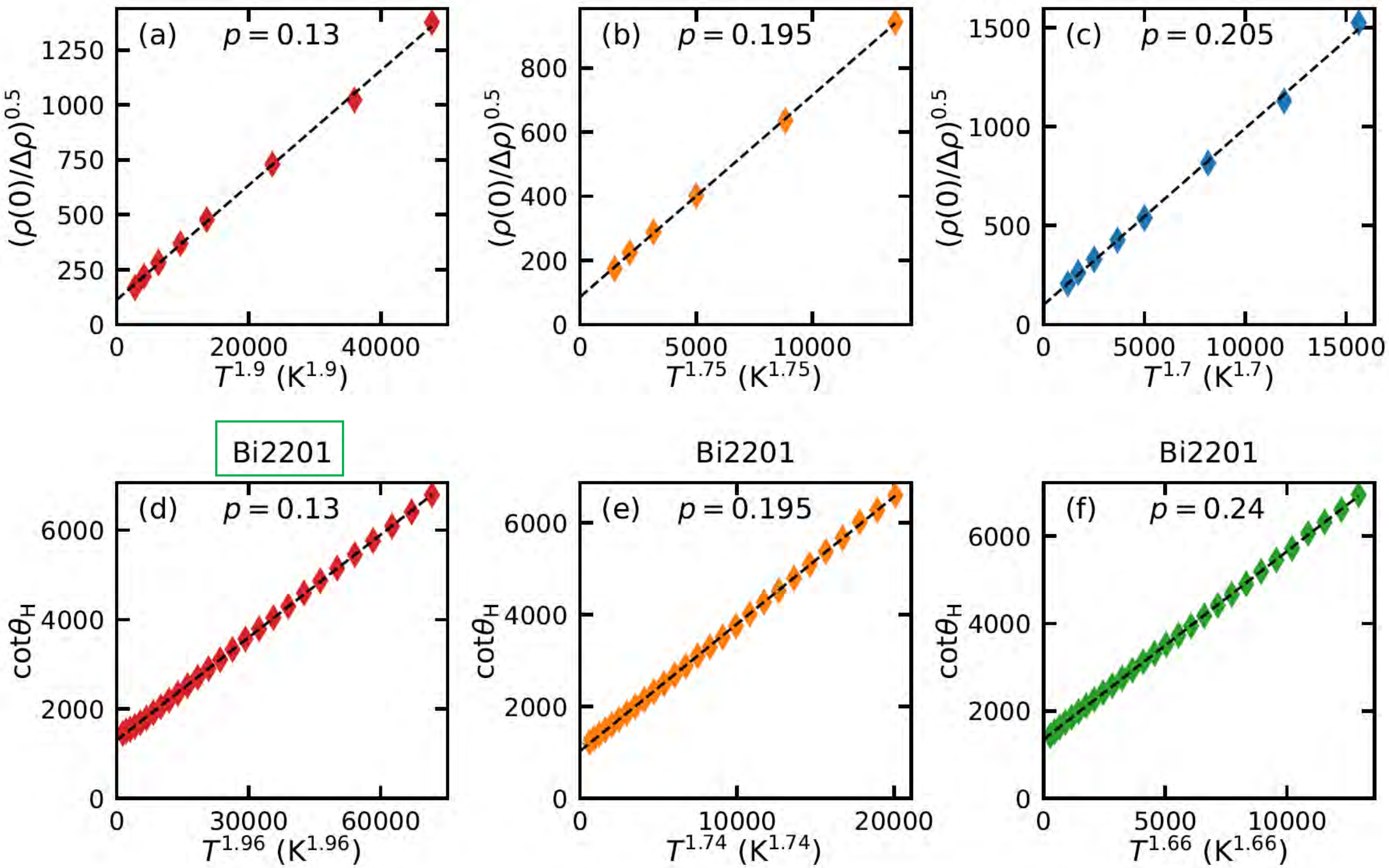
$$\frac{\Delta\rho}{\rho(0)} \approx (tan\theta_H)^2 \propto \left(\frac{H}{cot\theta_H}\right)^2$$

$$cot\theta_H \propto A + BT^{\alpha}$$

$$\frac{\Delta\rho}{\rho(0)} \propto \left(\frac{1}{A + BT^{\alpha}}\right)^2$$

$$\Rightarrow \sqrt{\frac{\rho(0)}{\Delta\rho}} \propto A + BT^{\alpha}$$

Although $\Delta\rho$ is a pure power law, the relative MR inherits a residual term from $\rho(T)$.



Possible sources of *H*-linear MR

Mesoscopic disorder

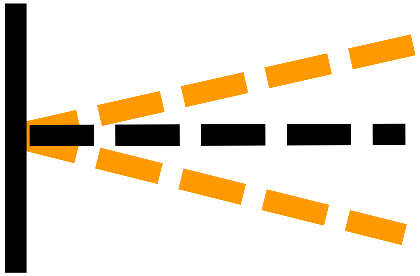
Singleton, *PRM* (20)
Boyd & Phillips, *PRB* (19)
Patel *et al.*, *PRX* (18)

Hot spots

Koshelev, *PRB* (16)
Maksmovic *et al.*, *PRX* (20)
Grissonnanche *et al.*, *Nature* (21)

Sharp FS corners

Koshelev, *PRB* (13)
Maksmovic *et al.*, PRX(20)
Grissonnanche *et al.*, Nature (21)



Zeeman coupling

Banerjee *et al.*, *PRB* (21)
Marino & Arouca, *SST* (21)

Possible sources of *H*-linear MR

Mesoscopic disorder

Singleton, *PRM* (20)
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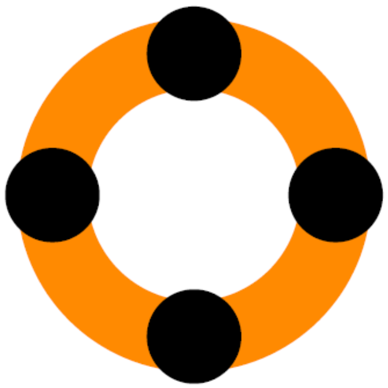
Patel *et al*., *PRX* (18)



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Maksmovic *et al*., PRX(20)
Grissonnanche *et al*., Nature (21)

Impeded cyclotron motion

Hinlopen et al. 2201.03292

Many origins can be generalized by a modification of BTE incorporating a bound for cyclotron motion somewhere on the Fermi surface.

$$\sigma_{ij} = \frac{e^2}{4\pi^3\hbar}\int_{FS} d^2k \int_0^{bound} dt\, \frac{v_i(0)}{v_F(0)} v_j(-t) \exp\left(-\frac{t}{\tau_0}\right)$$

$$\sigma_{xx} = \frac{e^2 k_F^2}{2\pi^2\hbar c}\int_0^{\pi/2} d\phi \int_0^{-\phi/\omega_c} dt\, \frac{v_x(0)}{v_F(0)} v_x(-t) \exp(-t/\tau_0)$$

Unable to account for absence of $\rho(0)$ in MR scaling

Possible sources of H-linear MR

Mesoscopic disorder

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Boyd & Phillips, *PRB* (19)
Patel *et al.*, *PRX* (18)

Hot spots

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Maksmovic *et al.*, PRX(20)
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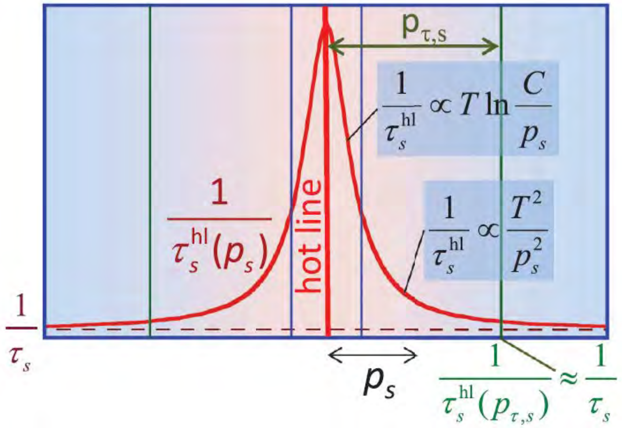

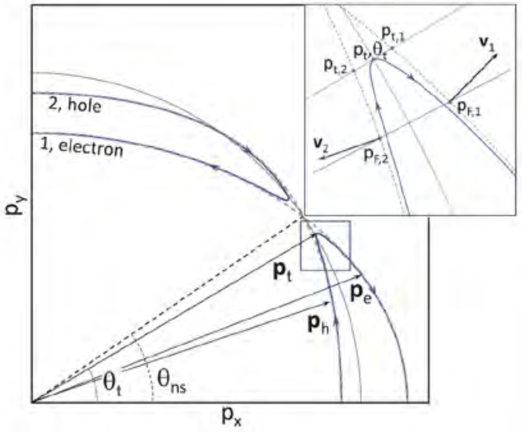

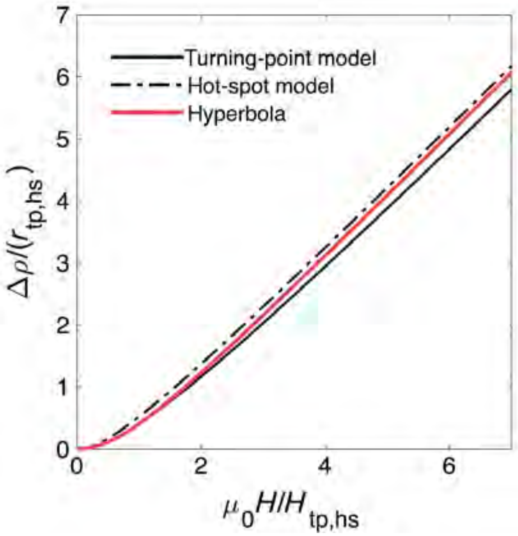

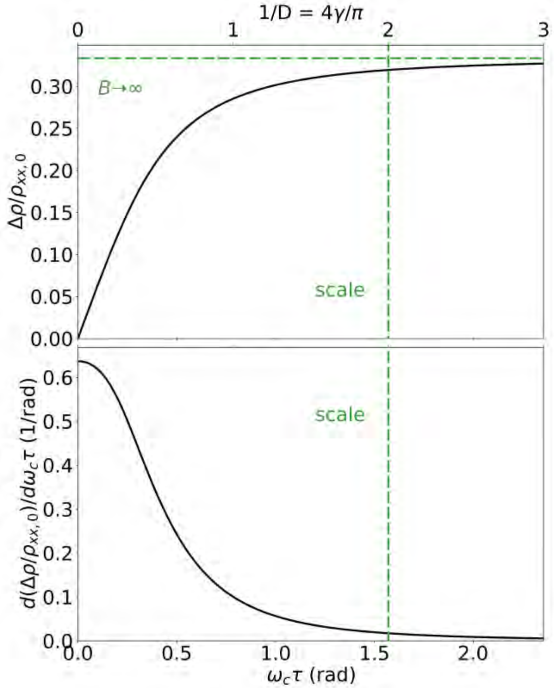

Hinlopen *et al.*, *2201.03292*

- Applied to pnictides
- H-linearity will eventually give way to saturation

Possible sources of *H*-linear MR

Mesoscopic disorder

Singleton, *PRM* (20)
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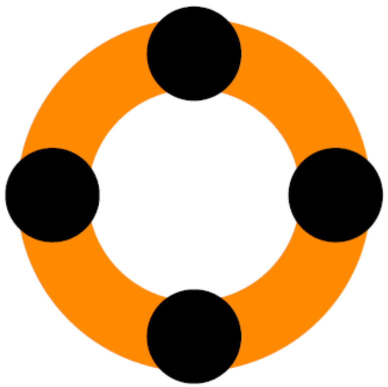
Patel *et al*., *PRX* (18)



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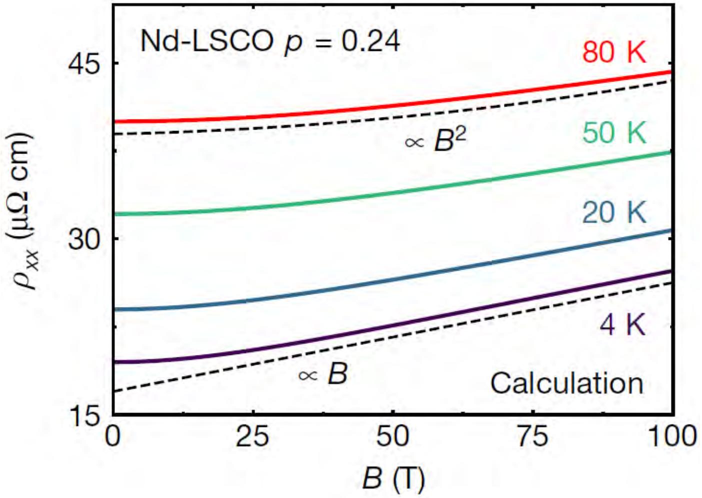
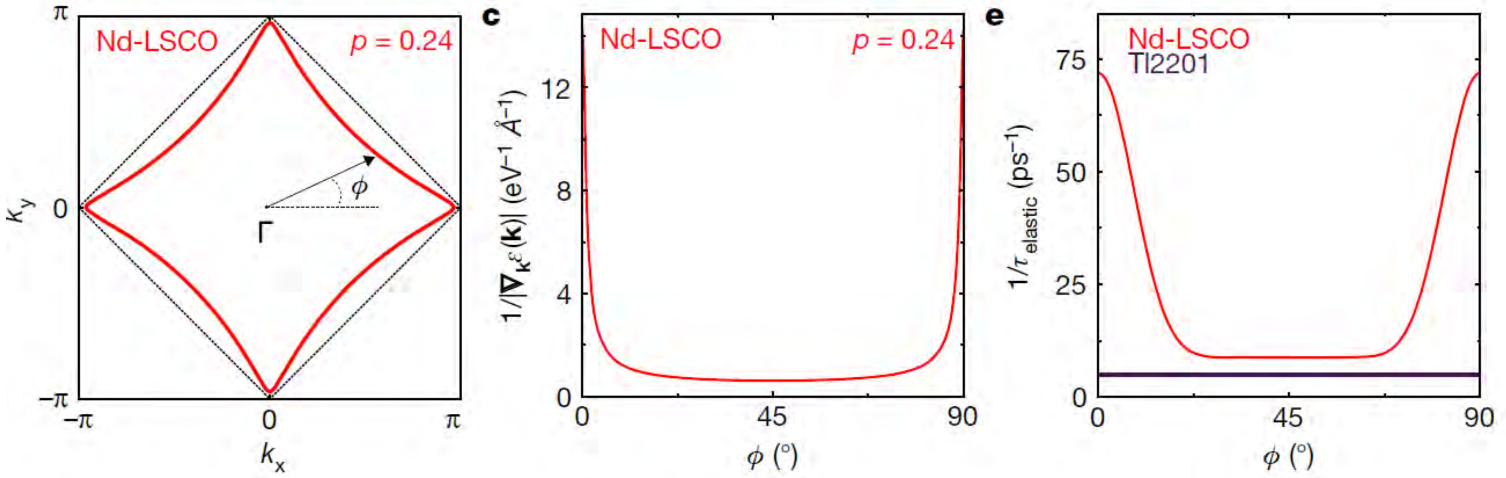


- Applied to cuprate near p^*
- Contains both sharp corners and extreme anisotropy.
- Not clear parameterization gives H/T scaling



Possible sources of *H*-linear MR

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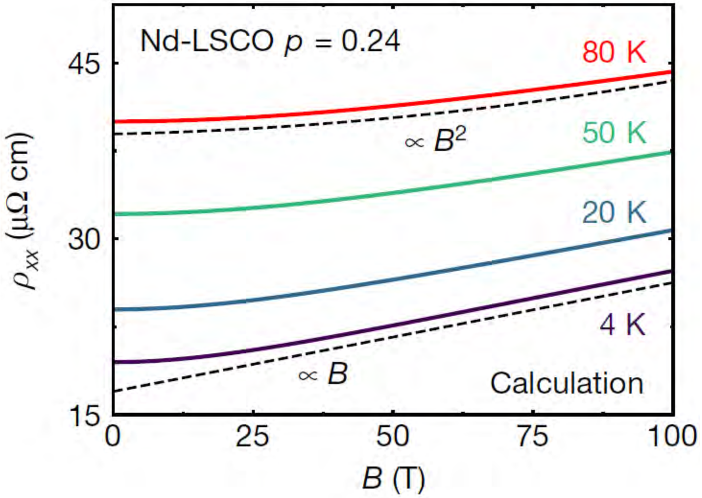
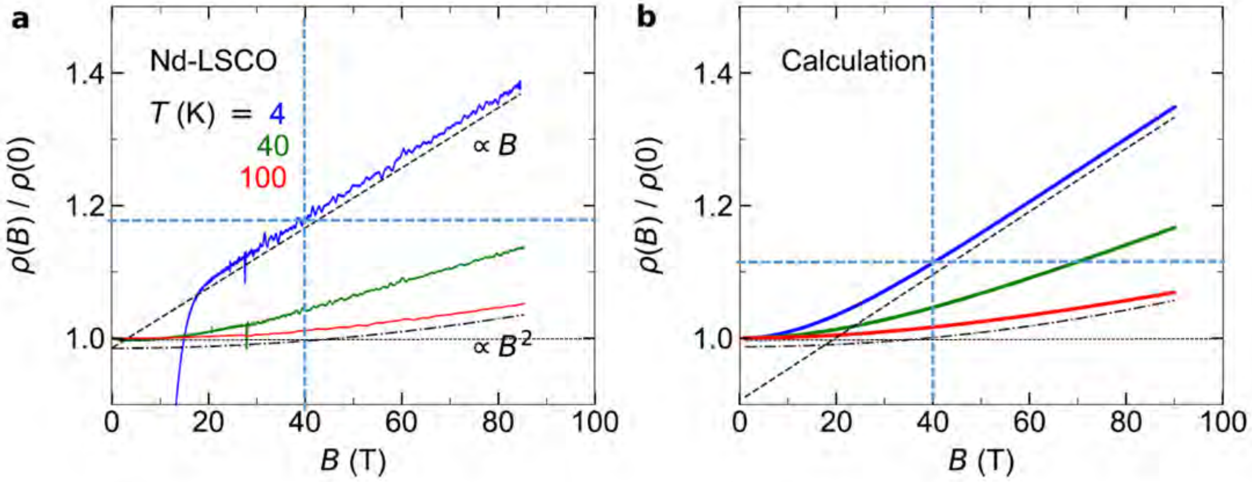


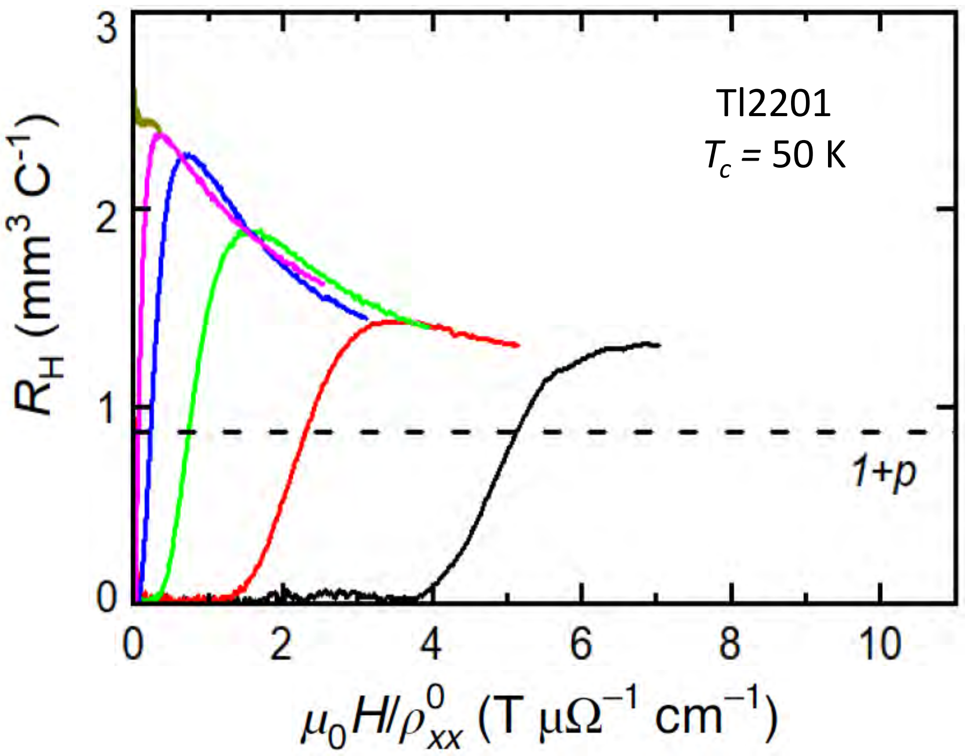


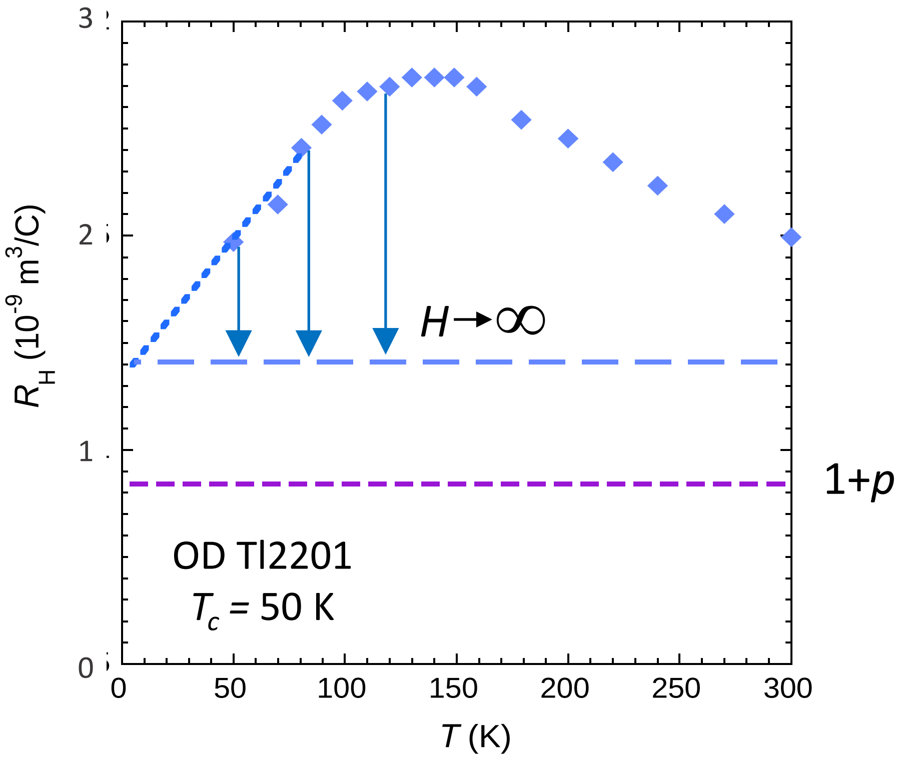
Ataei *et al.*,
2203.05035 (22)

- Applied to cuprate near p^*
- Contains both sharp corners and extreme anisotropy.
- Not clear parameterization gives H/T scaling
- Similar parameterization cannot work for Tl2201

Superconductivity within SM regime

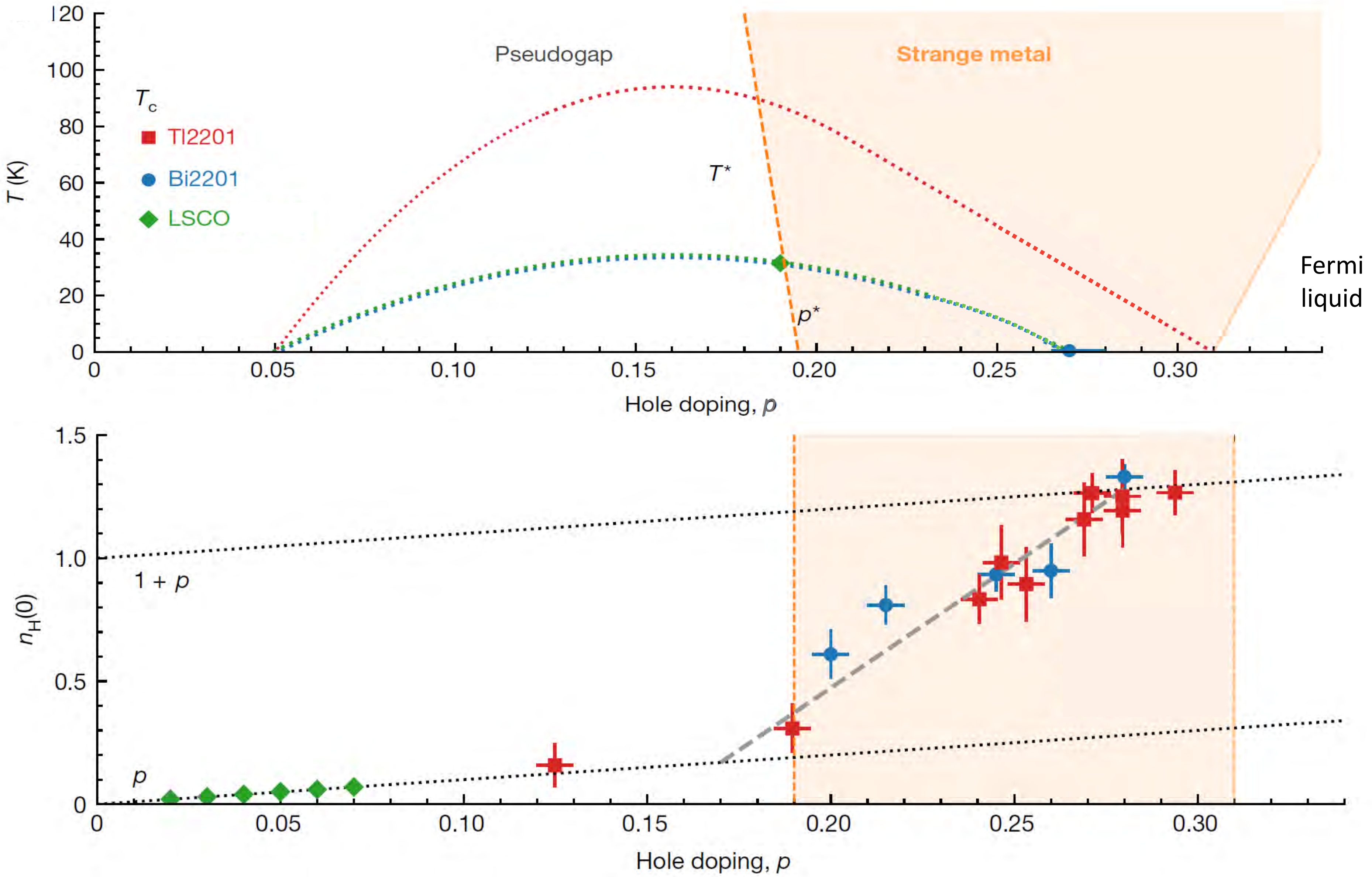
Putzke *et al.*, *Nat. Phys.* **17**, 826 (21)



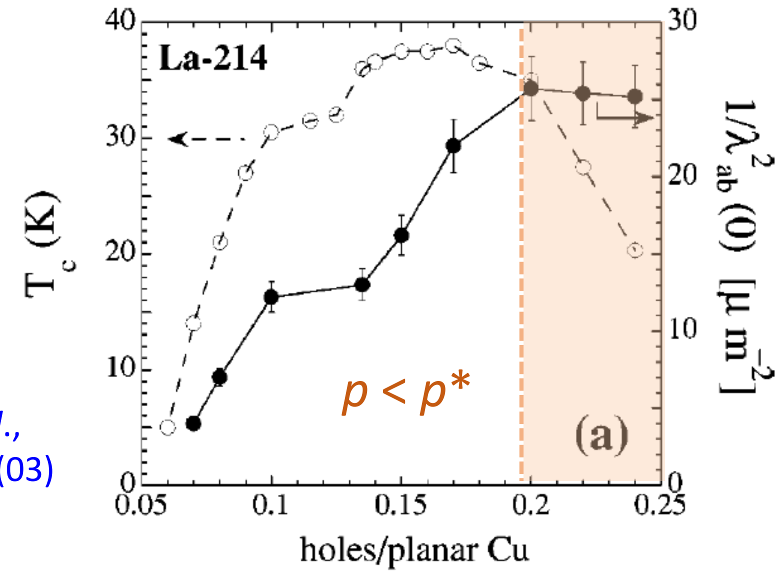


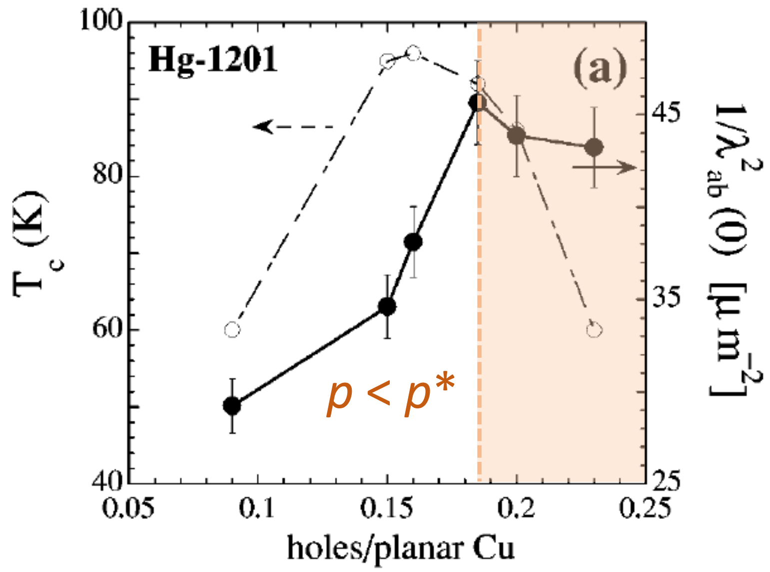
- In higher T_c Tl2201 samples, drop in R_H with field also seen implying anisotropic scattering still responsible for *H*- and *T*-dependent $R_H(T)$. However, absolute value of $R_H(0)$ is now shifted up, suggesting loss of states *at all T.*
- With decreasing hole doping (increasing T_c), $R_H(H)$ *does not* asymptotically reach the value consistent with $n_H = 1 + p$

Superconductivity within SM regime

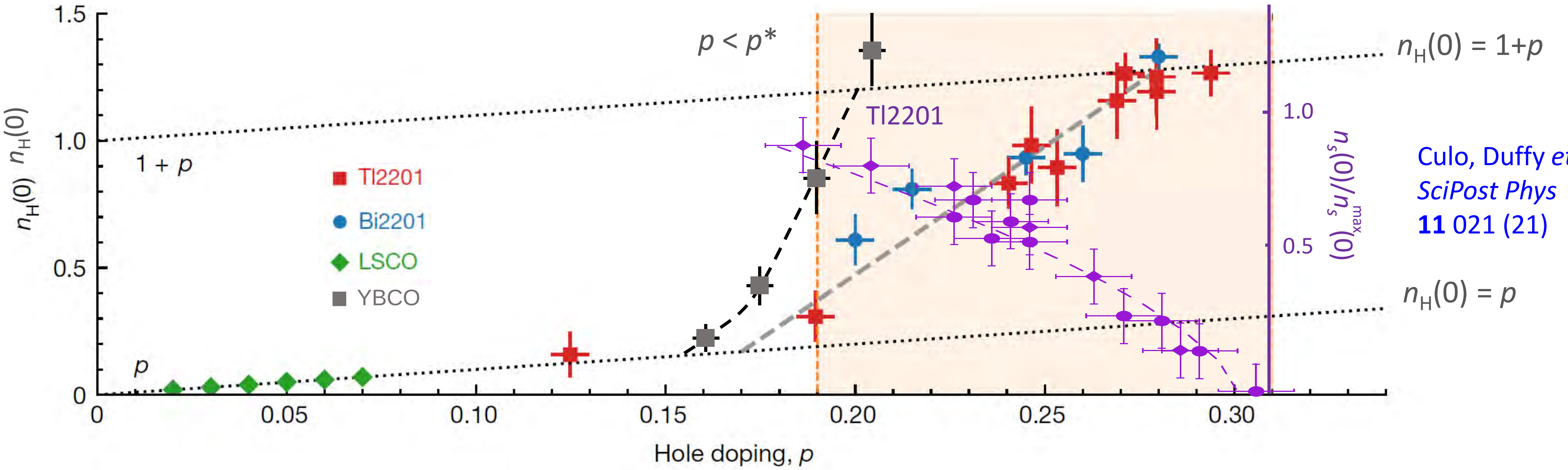


Superconductivity within SM regime





Panagopoulos *et al.*,
PRB **67** 220502(R) (03)



Culo, Duffy *et al.*,
SciPost Phys
11 021 (21)

Summary

- New features in the transport properties of the strange metal of hole-doped cuprates
- (Anti)-correlation between the drop in $n_H(0)$ and the growth of the T-linear component of $\rho(T)$
- Low-T MR H-linear at high field and shows H/T scaling and signatures of incoherence
- Evidence for two-components in the conductivity – one Boltzmann-like, the other non-Boltzmann
- Pseudogap likely gaps out ‘Planckian’ carriers, leading to crossover to H/T^2 scaling in the MR
- HTS borne out of strange metal phase with dual character – but which one is responsible?