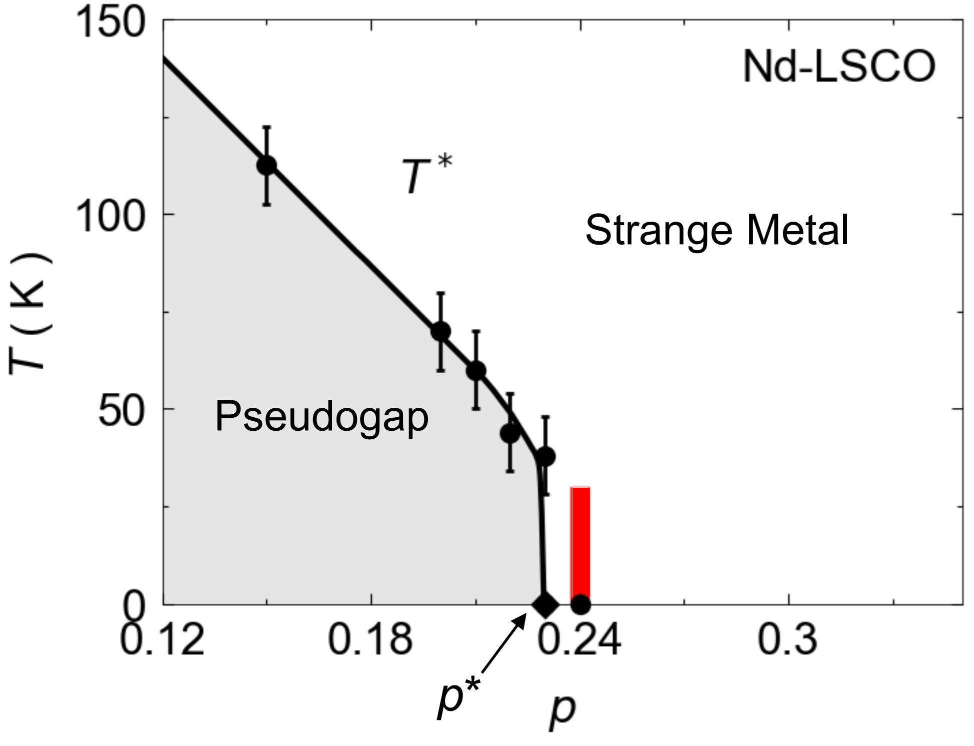
Planckian dissipation in a strange metal

Gaël Grissonnanche

College de France - Workshop on Strange Metals

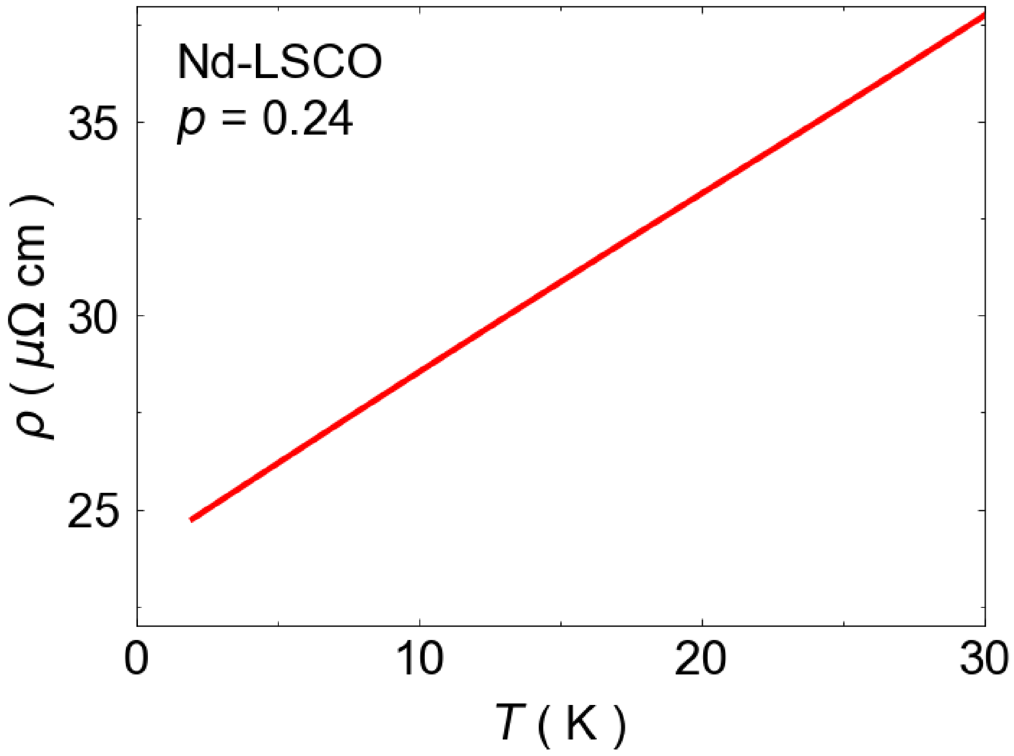
What is a strange metal?

Introduction



Collignon et al., PRB 2017

T resistivity

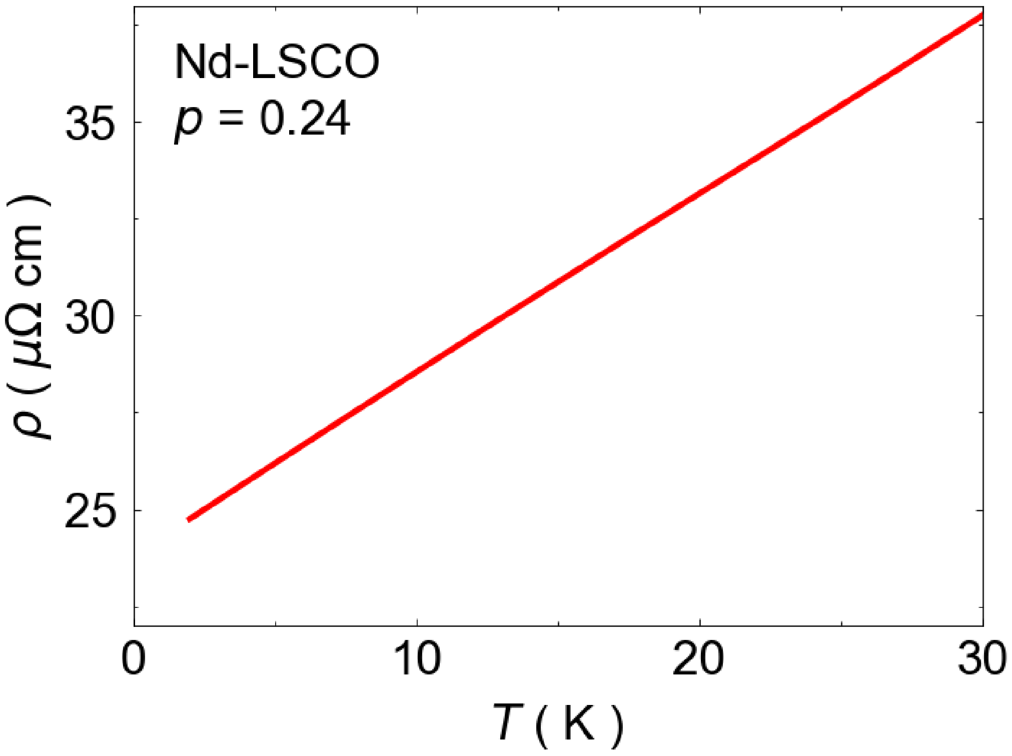


Daou et al. Nat. Phys. 2009

Introduction

$$\rho = \frac{m^*}{n\,e^2}\frac{1}{\tau}$$

T resistivity



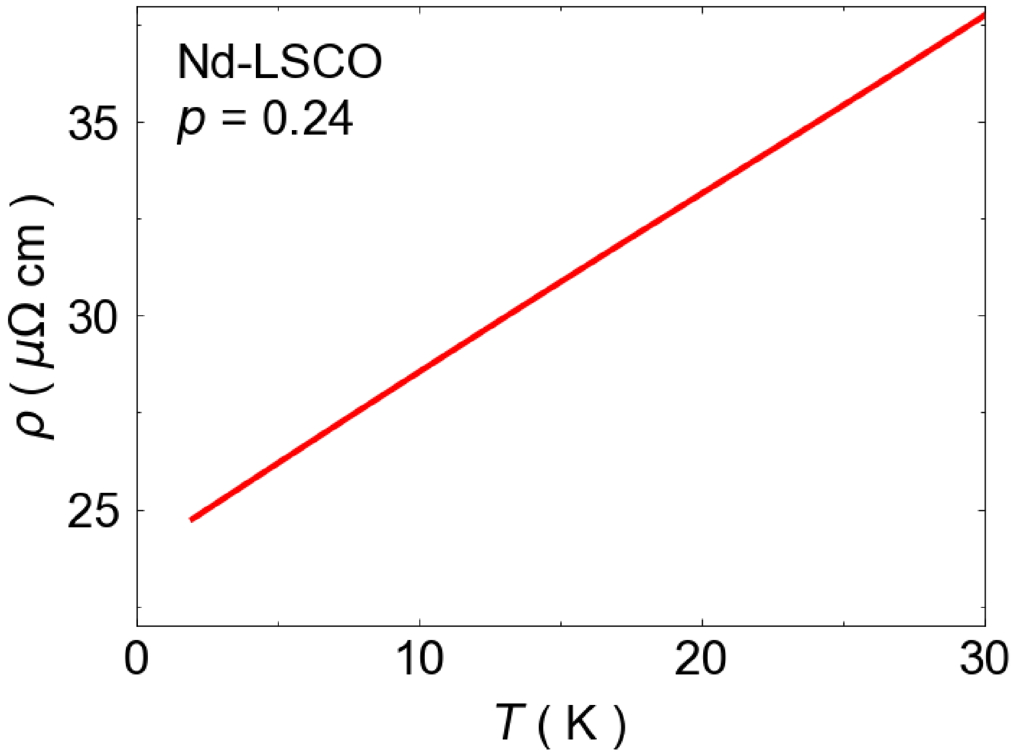
Daou et al. Nat. Phys. 2009

Introduction

Scattering rate $$\frac{1}{\tau} \sim T$$

$$\rho = \frac{m^*}{n\,e^2}\boxed{\frac{1}{\tau}}$$

T resistivity



Daou et al. Nat. Phys. 2009

Introduction

Planckian limit $$\frac{1}{\tau} = \alpha \frac{k_\mathrm{B} T}{\hbar}$$ with $\alpha \approx 1$

$$\rho = \frac{m^*}{n\, e^2} \boxed{\frac{1}{\tau}}$$

Bruin et al. Science 2013

Introduction

Planckian limit $$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$ with $\alpha \approx 1$

$$\rho = \frac{m^*}{n\, e^2} \boxed{\frac{1}{\tau}}$$

Material	Doping[a]	α
Bi2212	$p = 0.23$	1.1 ± 0.3
Bi2201	$p \sim 0.4$	1.0 ± 0.4
LSCO	$p = 0.26$	0.9 ± 0.3
Nd-LSCO	$p = 0.24$	0.7 ± 0.4
PCCO	$x = 0.17$	0.8 ± 0.2
LCCO	$x = 0.15$	1.2 ± 0.3
TMTSF	$P = 11$ kbar	1.0 ± 0.3

Bruin et al. Science 2013

Legros et al. Nature Physics 2019

QUESTION

With such strong scattering on electrons, what remains of what is known for metals?

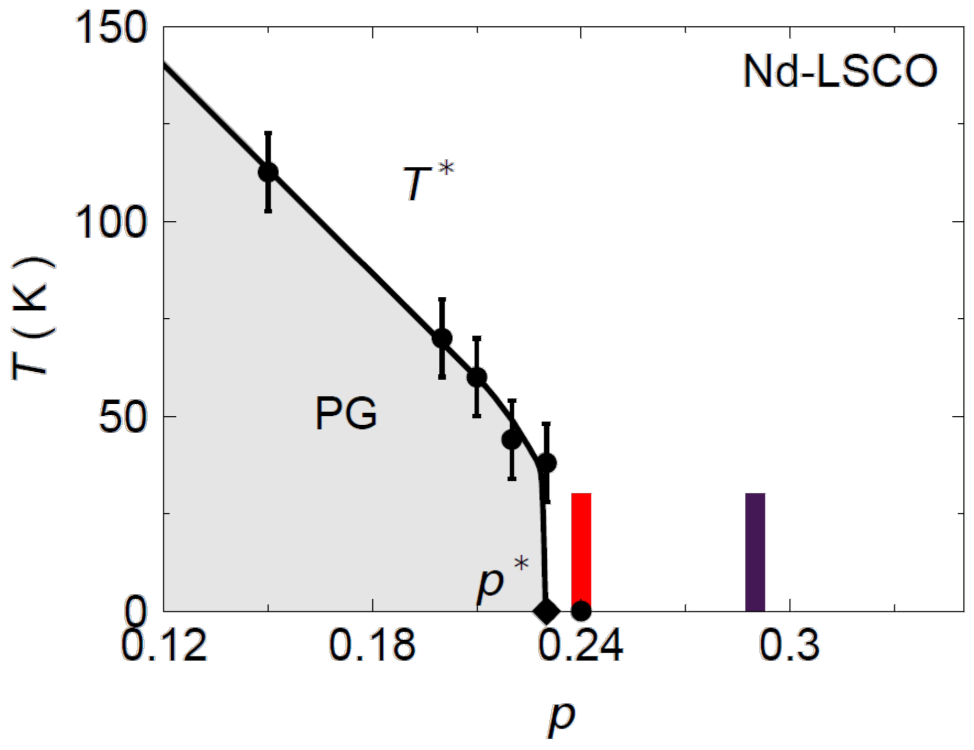
QUESTIONS

Is the Fermi surface strange?

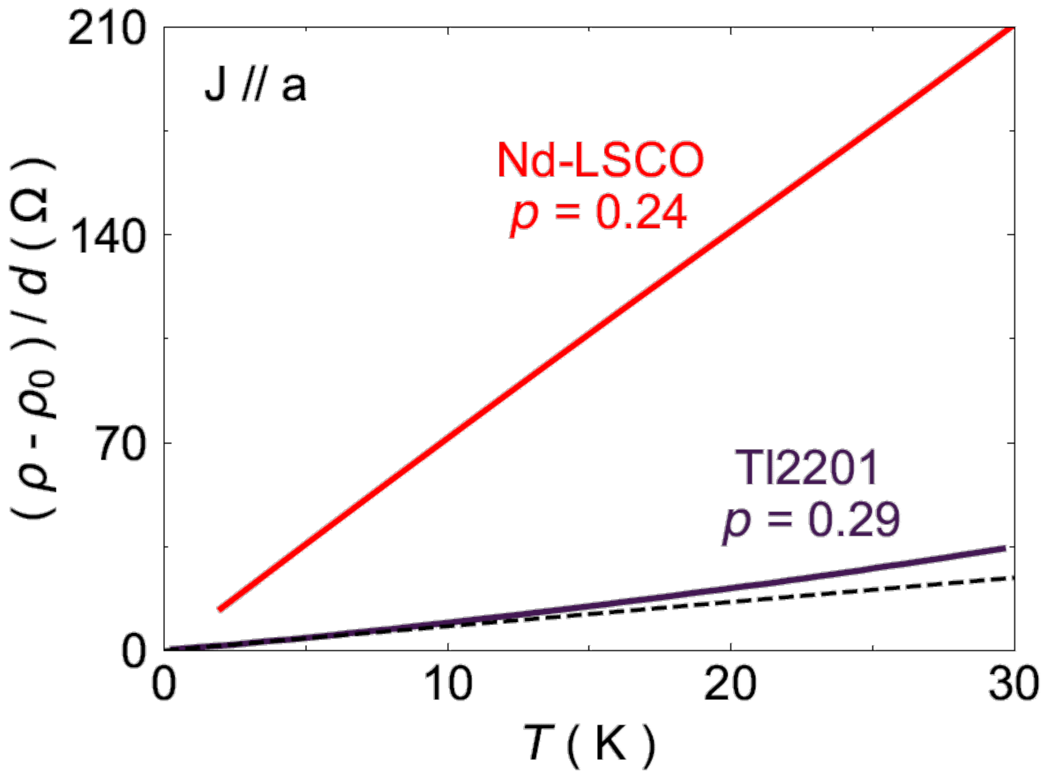
Is the scattering rate strange?

Are the other transport properties strange?

Introduction

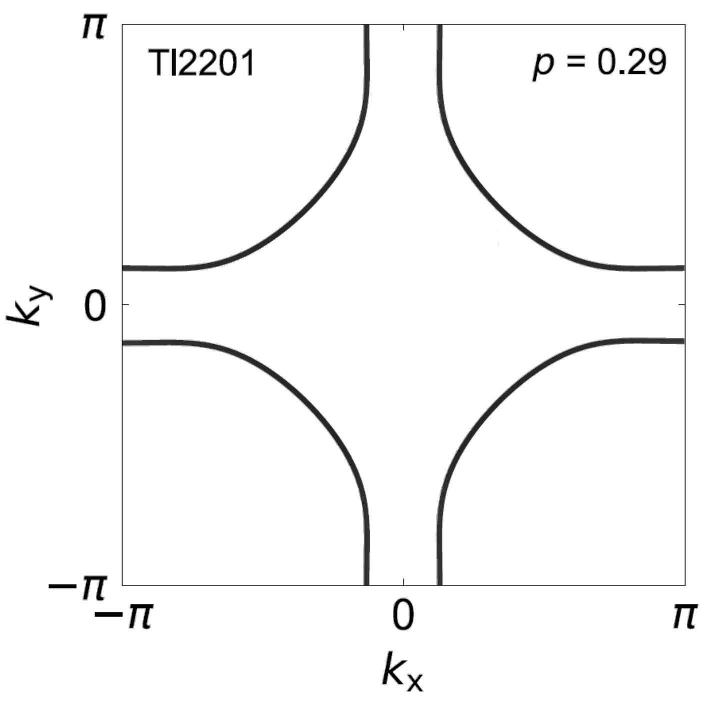


T+T^2 resistivity



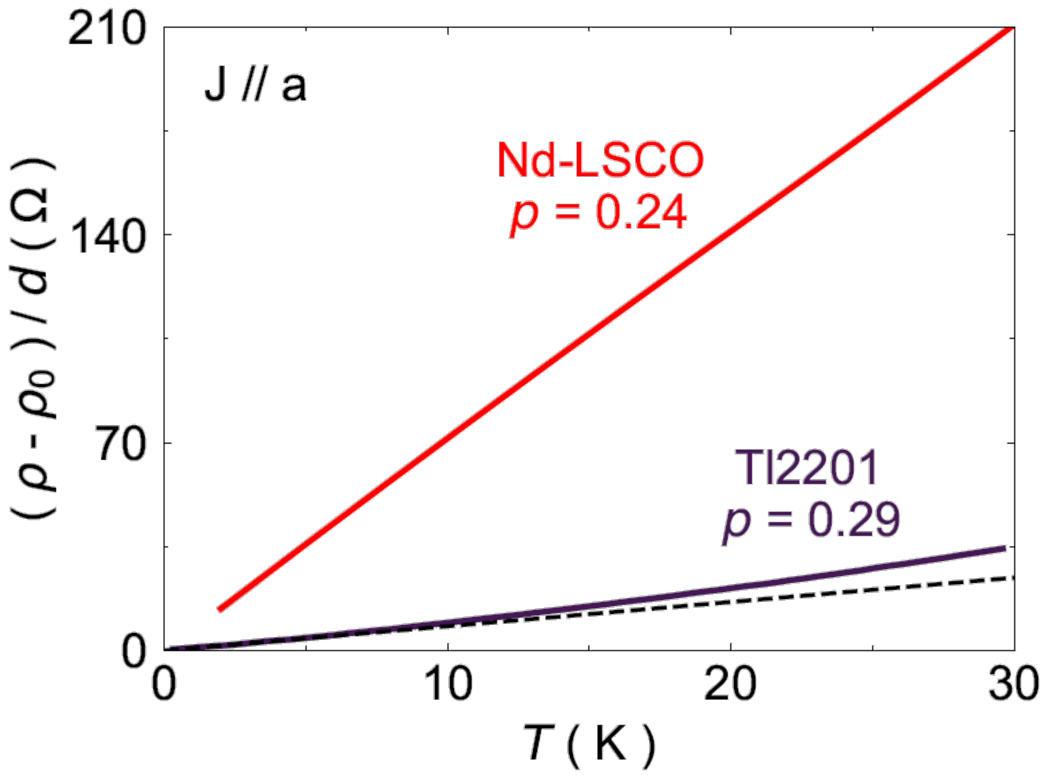
Daou et al. Nat. Phys. 2009
Proust et al. PRL 2002

Introduction



Abdel-Jawad et al. Nat. Phys. 2006

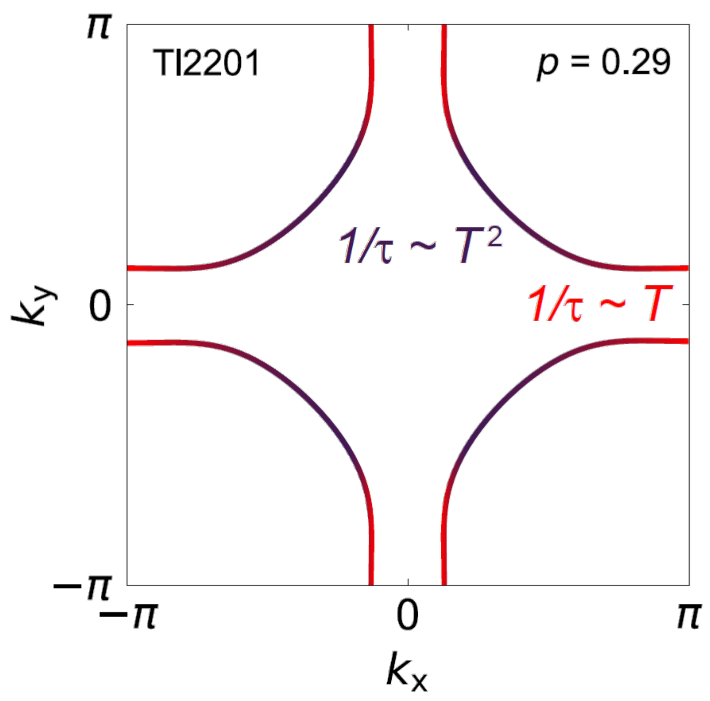
$T+T^2$ resistivity



Daou et al. Nat. Phys. 2009
Proust et al. PRL 2002

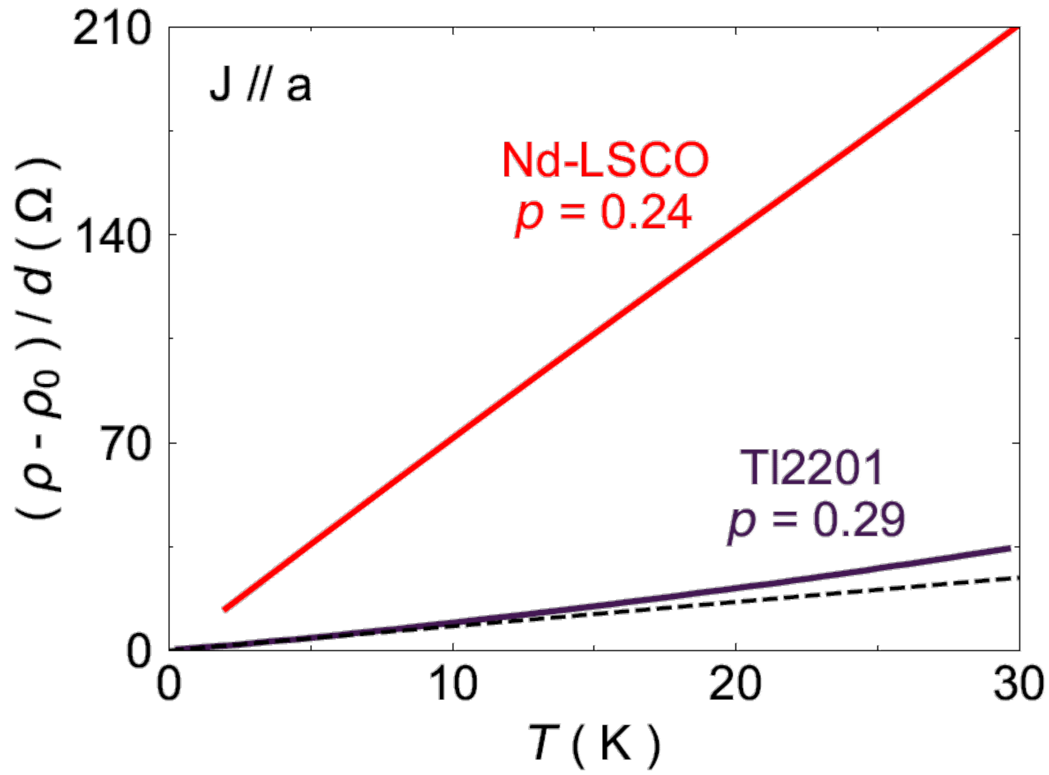
Introduction

Fermi surface



Abdel-Jawad et al. Nat. Phys. 2006

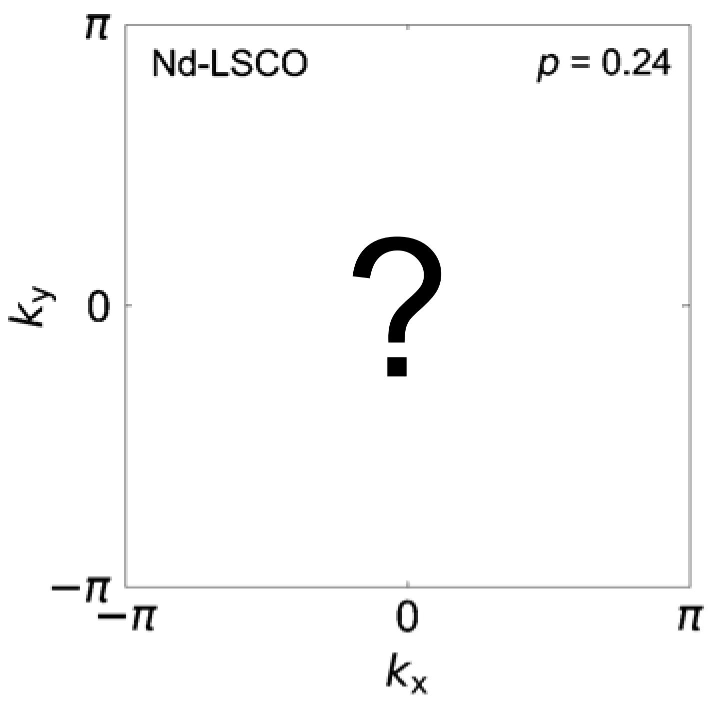
T+T^2 resistivity



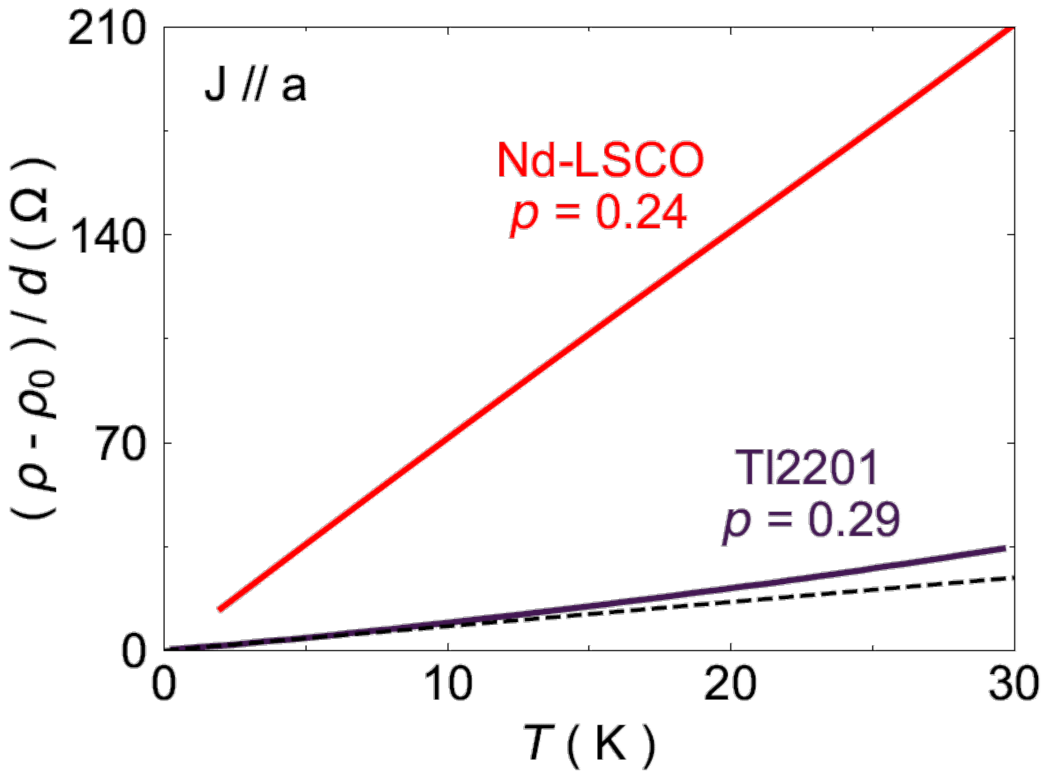
Daou et al. Nat. Phys. 2009
Proust et al. PRL 2002

Introduction

Fermi surface



T+T^2 resistivity



Daou et al. Nat. Phys. 2009
Proust et al. PRL 2002

Outline

Part 1: Is the Fermi surface strange?

Part 2: Is the scattering rate strange?

Part 3: Is the magnetoresistance strange?

Part 4: Is the Seebeck coefficient strange?

Outline

Part 1: Is the Fermi surface strange?

Part 2: Is the scattering rate strange?

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Part 4: Is the Seebeck coefficient strange?

Part 1 The Fermi surface

Grissonnanche et al., Nature 595, 667 (2021)

Fang*, Grissonnanche* et al., Nat. Phys. 18, 558 (2022)

Collaborators

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Anaëlle Legros
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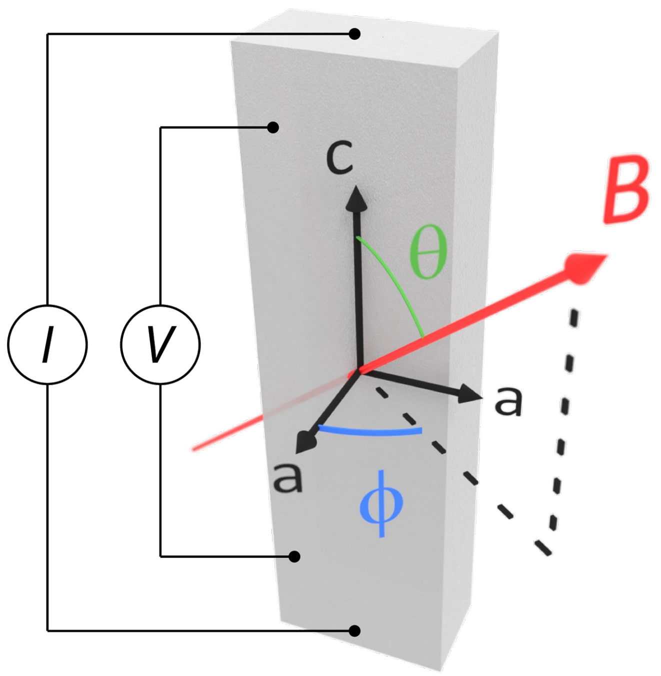
Jianshi Zhou

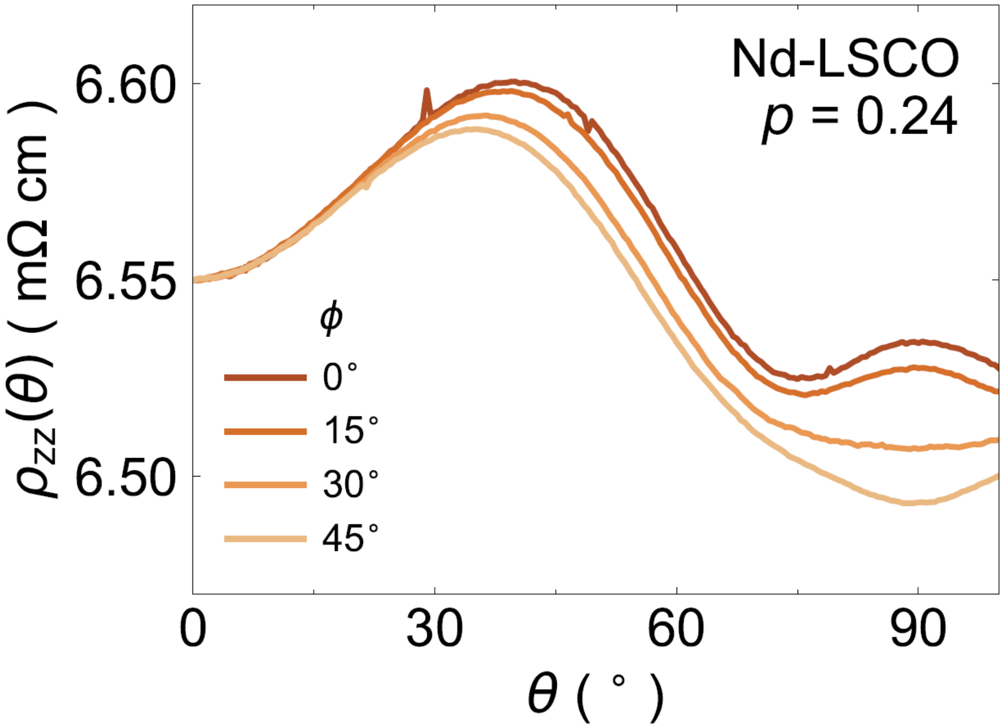
David Graf

Paul Goddard

Part 1 - Fermi surface

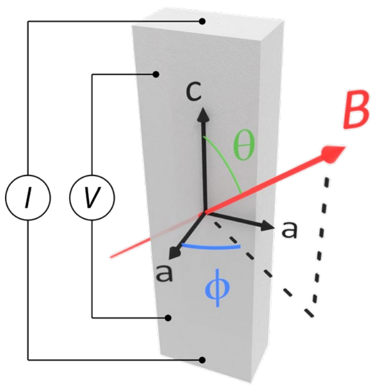
Angle Dependent MagnetoResistance



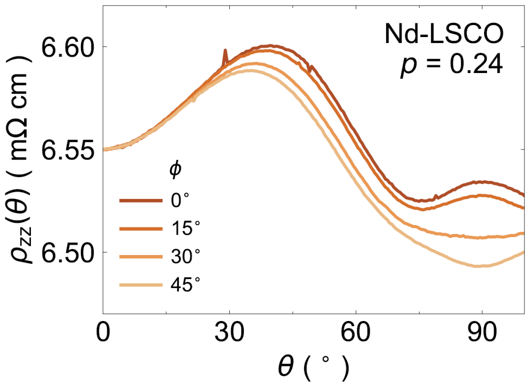


Part 1 - Fermi surface

Measure c-axis resistivity

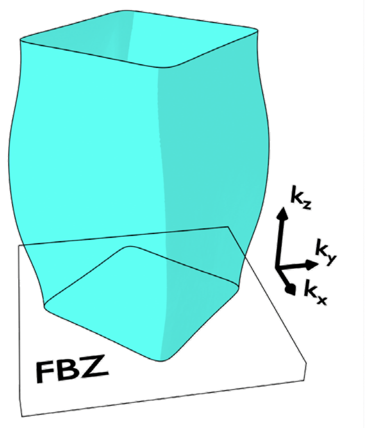


ADMR data

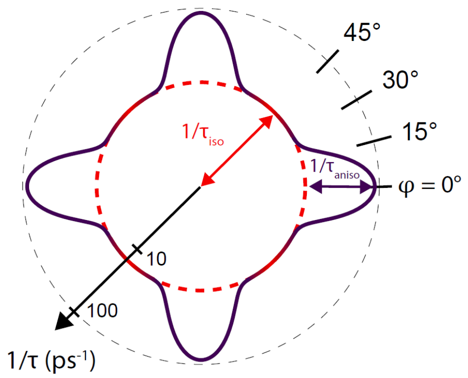


Boltzmann transport

Fermi surface

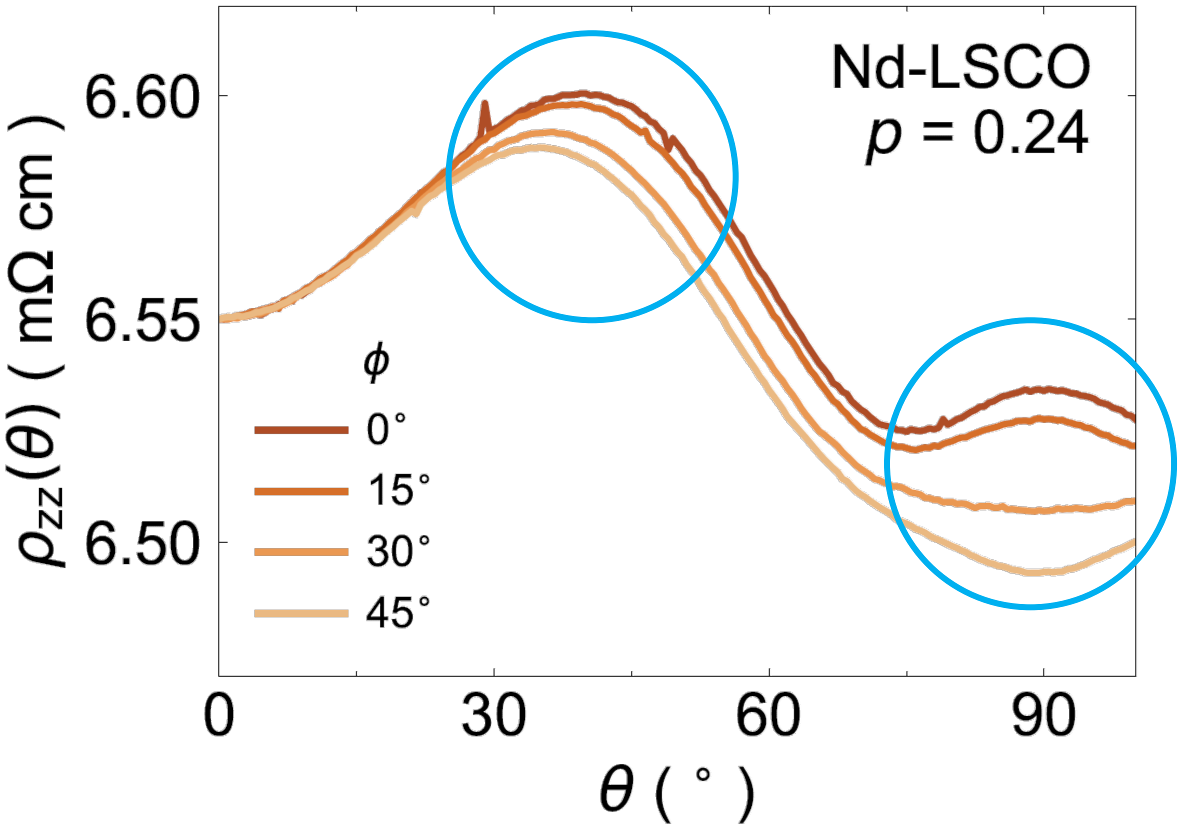


Scattering rate



Part 1 - Fermi surface

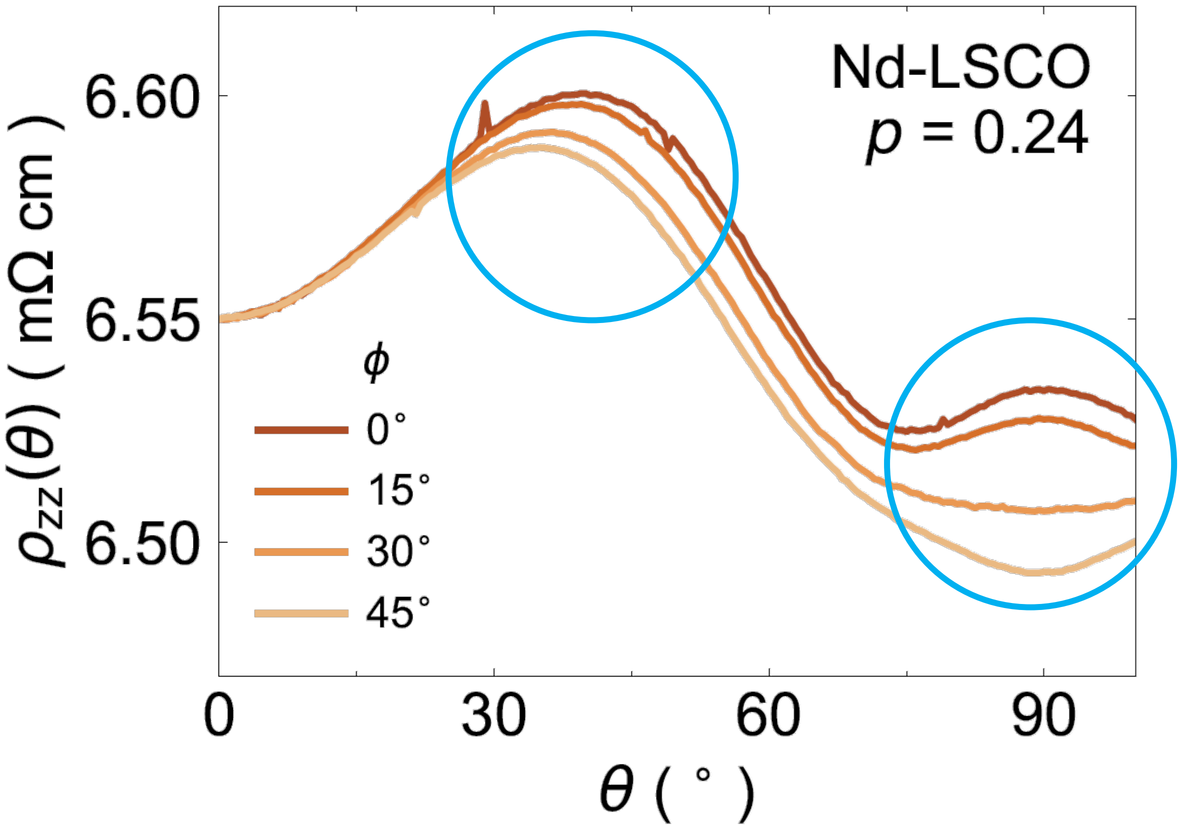
Data



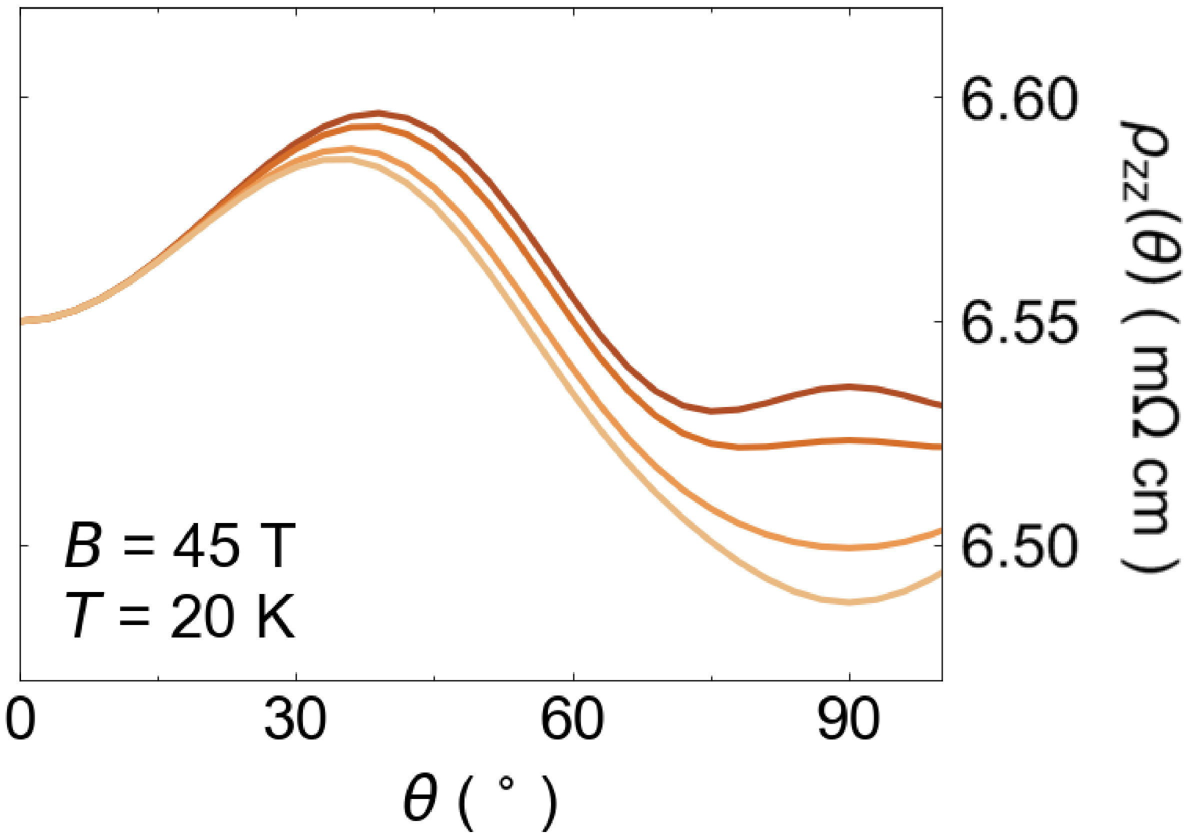
B = 45 T
T = 20 K

Part 1 - Fermi surface

Data

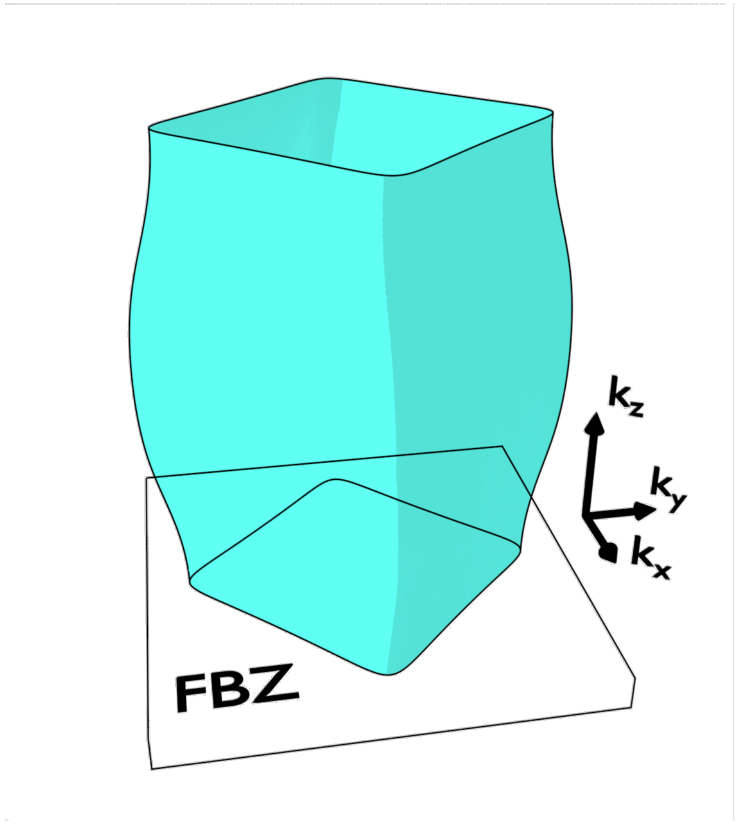


Calculations

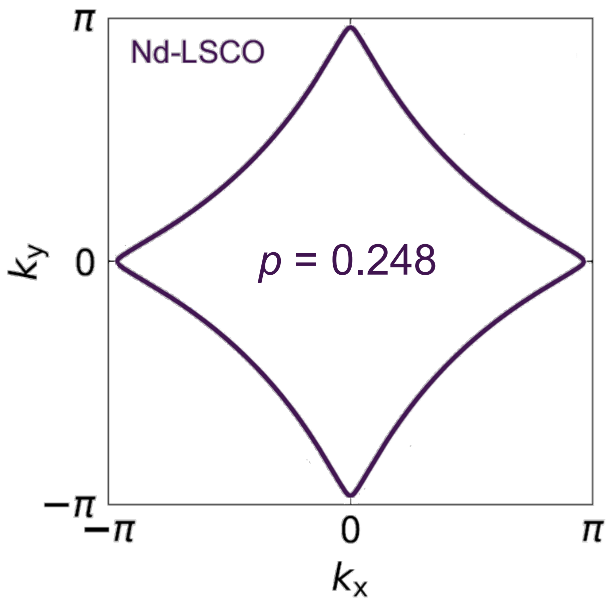


Part 1 - Fermi surface

Fermi surface

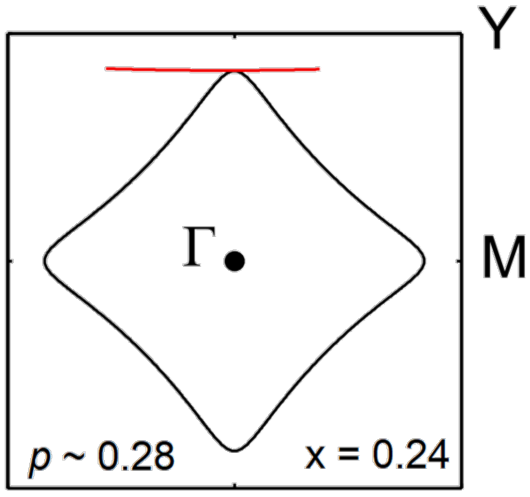


ADMR



Fang*, G.G.* et al. Nat. Phys. 2022

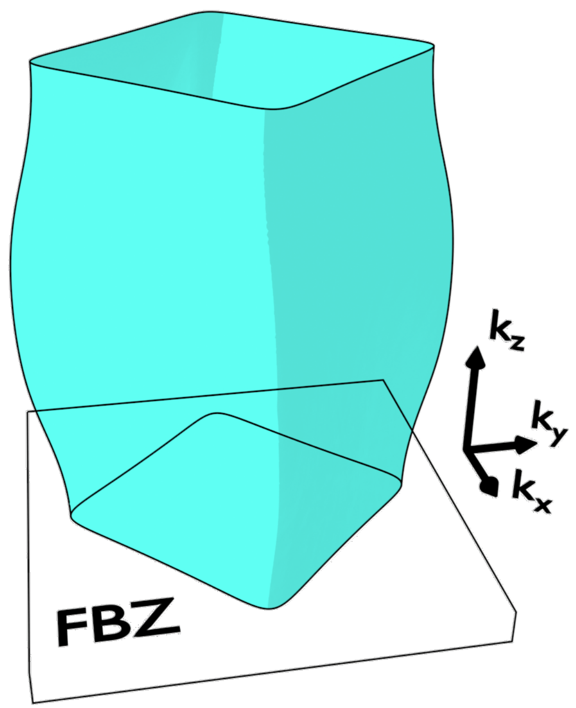
ARPES



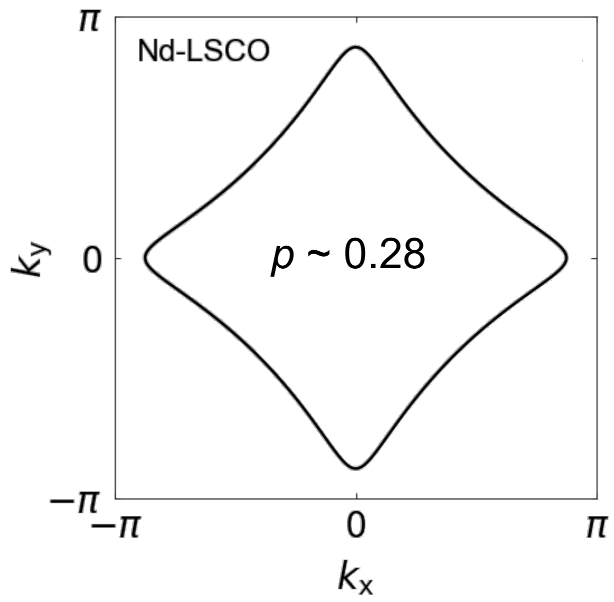
Matt et al., PRB 2015

Part 1 - Fermi surface

Fermi surface

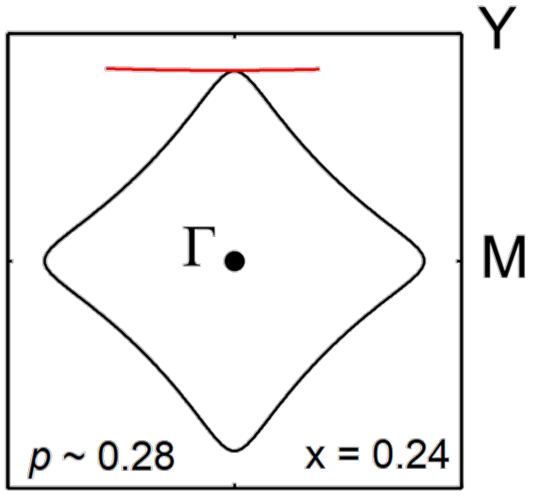


ADMR



Fang*, G.G.* et al. Nat. Phys. 2022

ARPES



Matt et al., PRB 2015

Part 1 - Fermi surface

CONCLUSION

No matter how strong interactions are between electrons, there is a well-defined Fermi surface in the strange metal

Outline

Part 1: Is the Fermi surface strange?

Part 2: Is the scattering rate strange?

Part 3: Is the magnetoresistance strange?

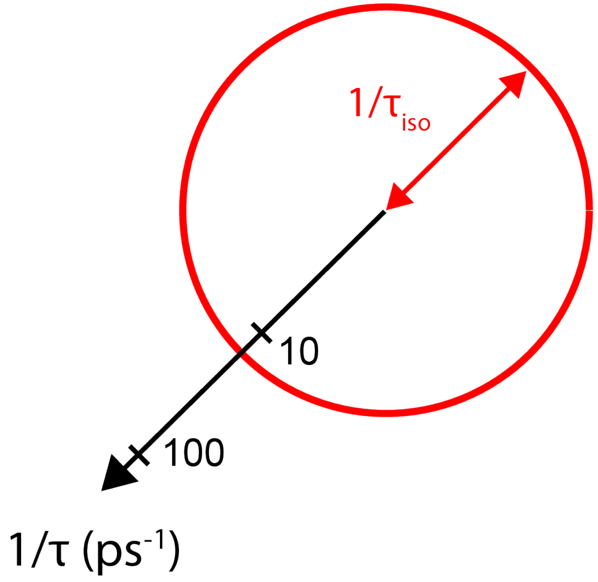
Part 4: Is the Seebeck coefficient strange?

Part 2 The scattering rate

Grissonnanche et al., Nature 595, 667 (2021)

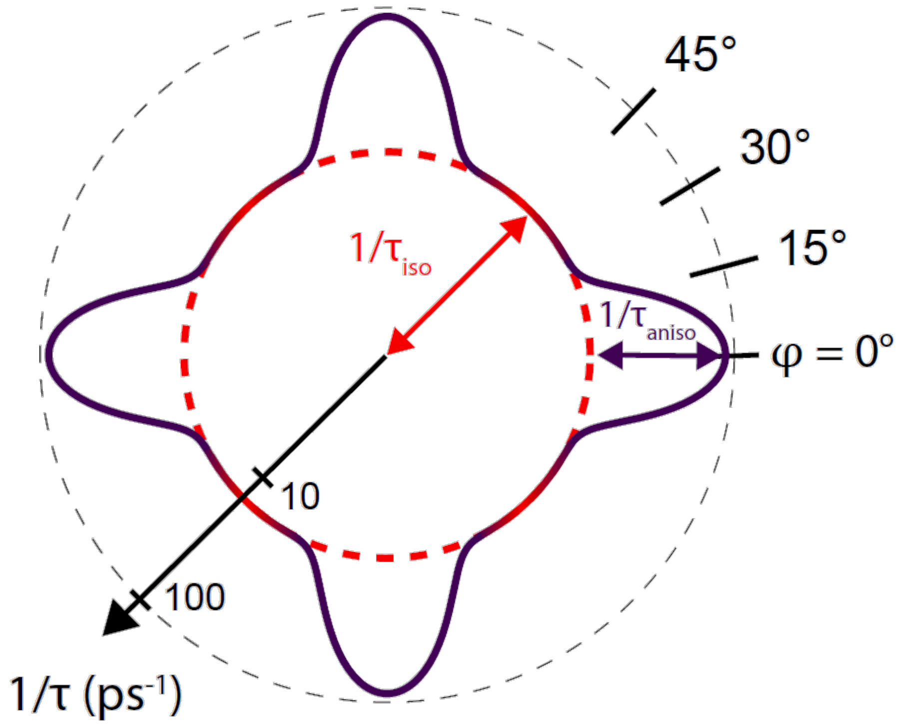
Part 2 - Scattering rate

Scattering rate $\qquad {}^{1}/_{\tau(k)} = {}^{1}/_{\tau_{iso}}$



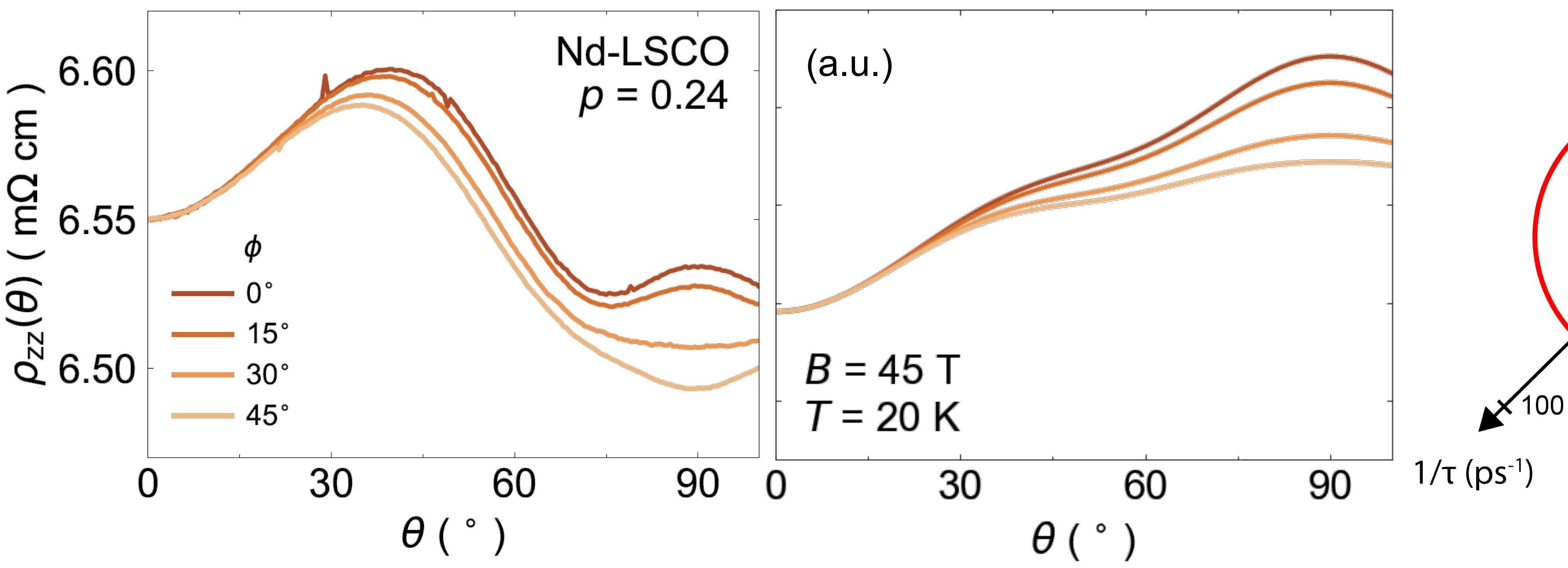
Part 2 - Scattering rate

Scattering rate $$1/_{\tau(k)} = 1/\tau_{iso} + 1/\tau_{aniso}(k)$$



Part 2 - Scattering rate

Data | Calculations | Scattering rate

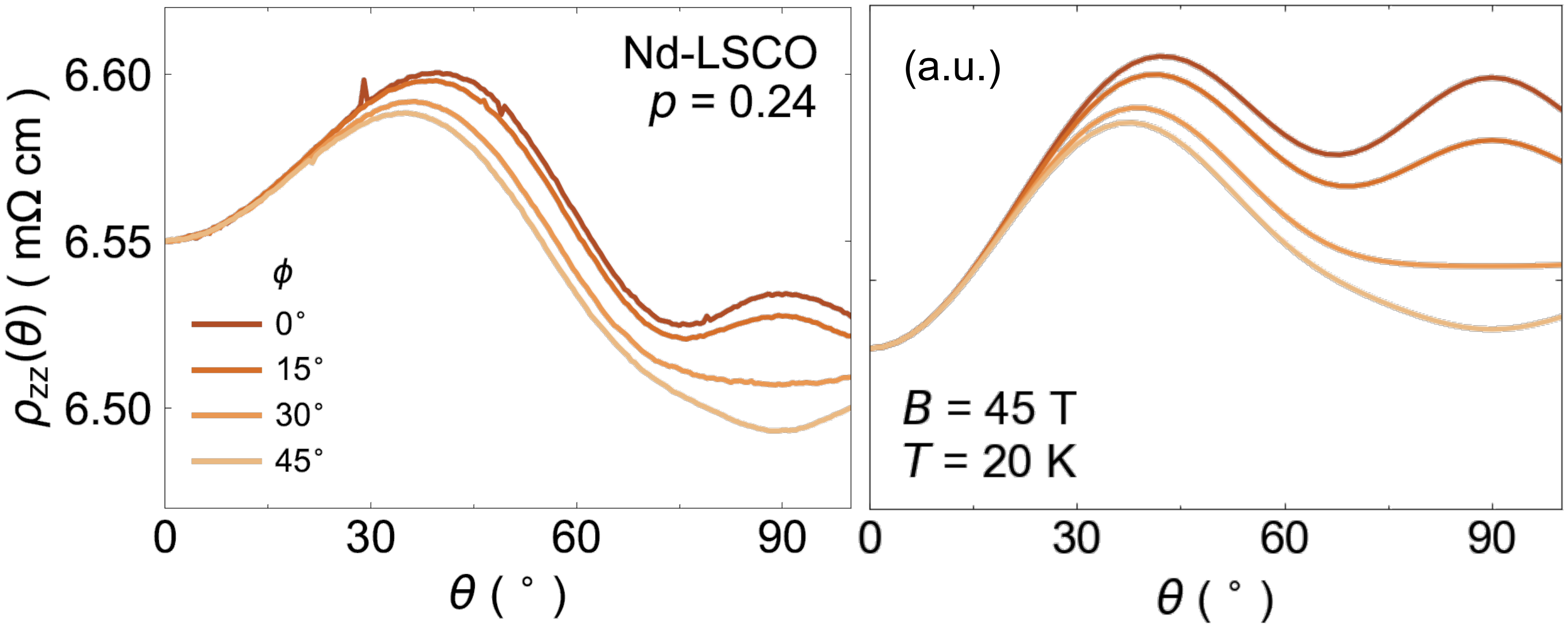


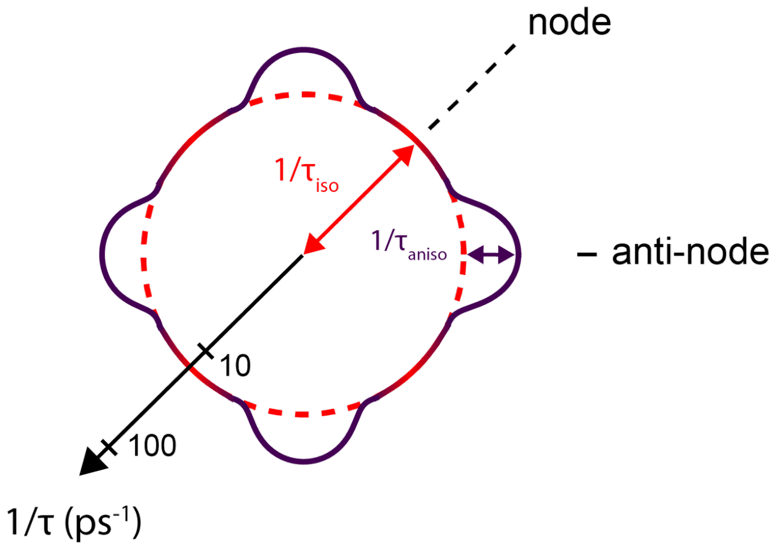
Part 2 - Scattering rate

Data

Calculations

Scattering rate



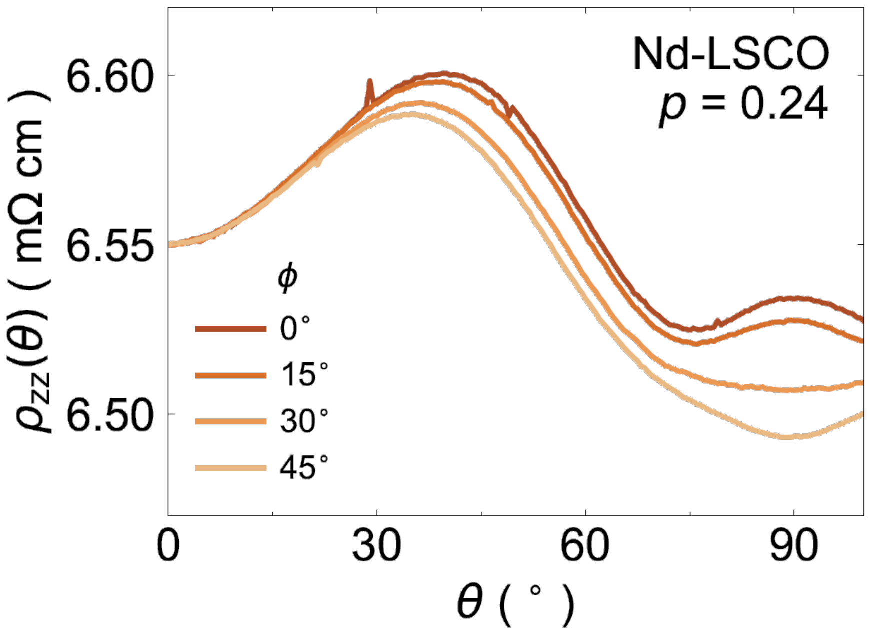


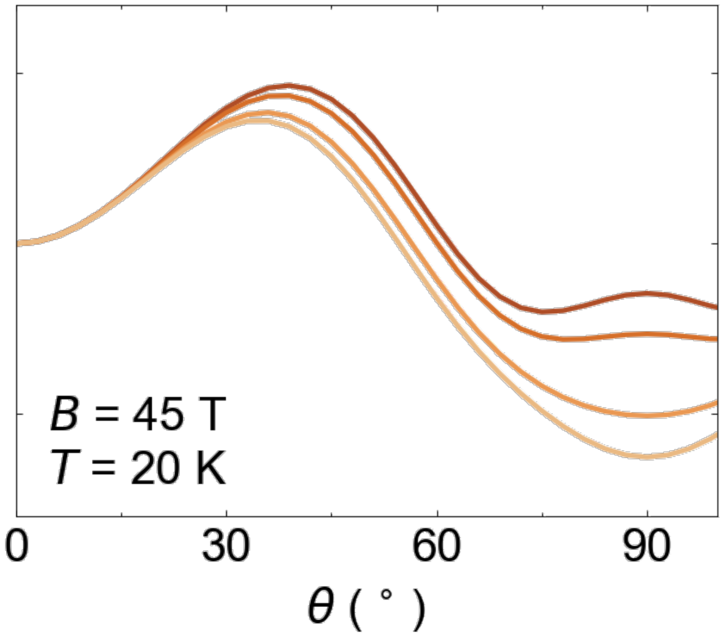
Part 2 - Scattering rate

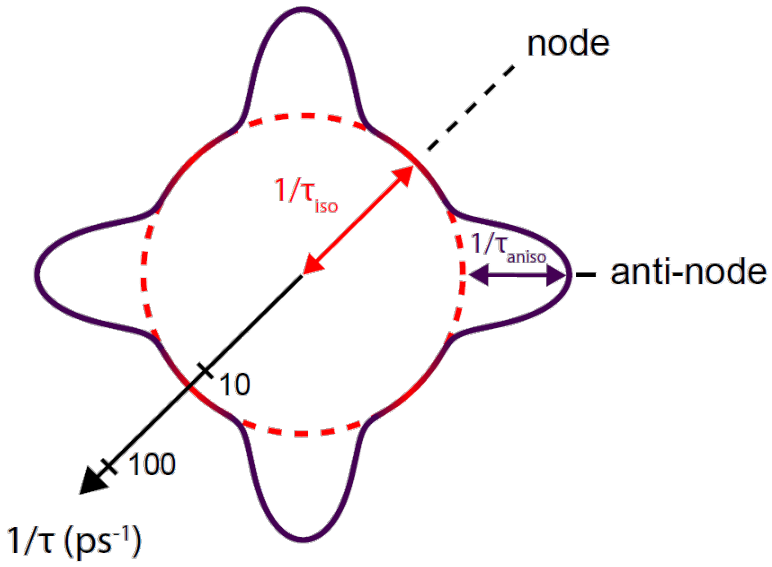
Data

Calculations

Scattering rate



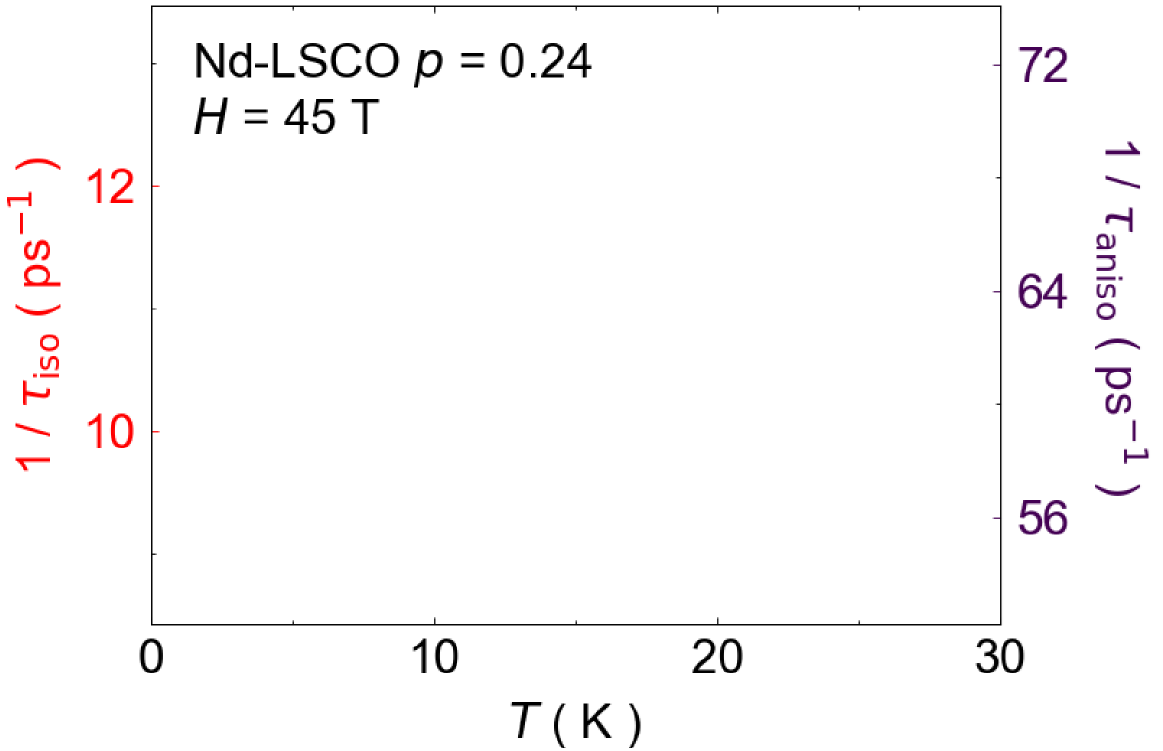




Part 2 - Scattering rate

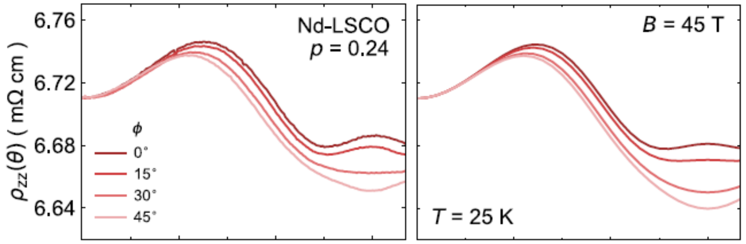
Scattering rate

$$1/_{\tau(k)} = 1/\tau_{iso} + 1/\tau_{aniso}(k)$$



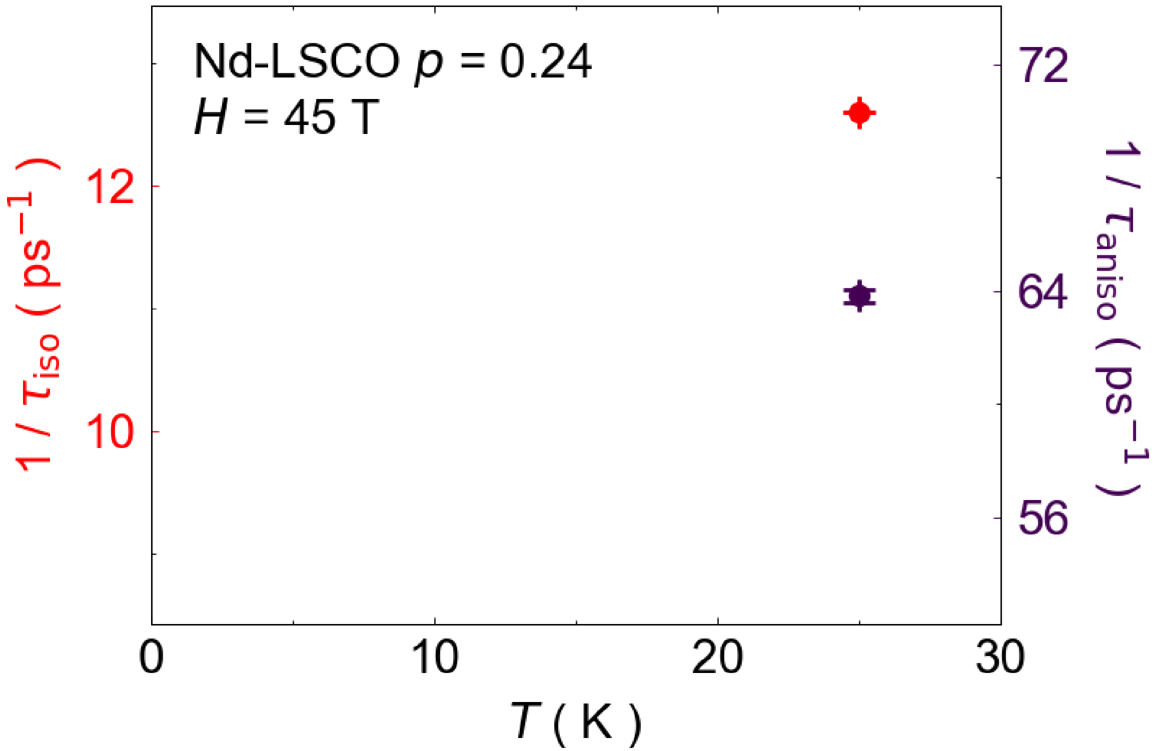
Part 2 - Scattering rate

Data Calculations

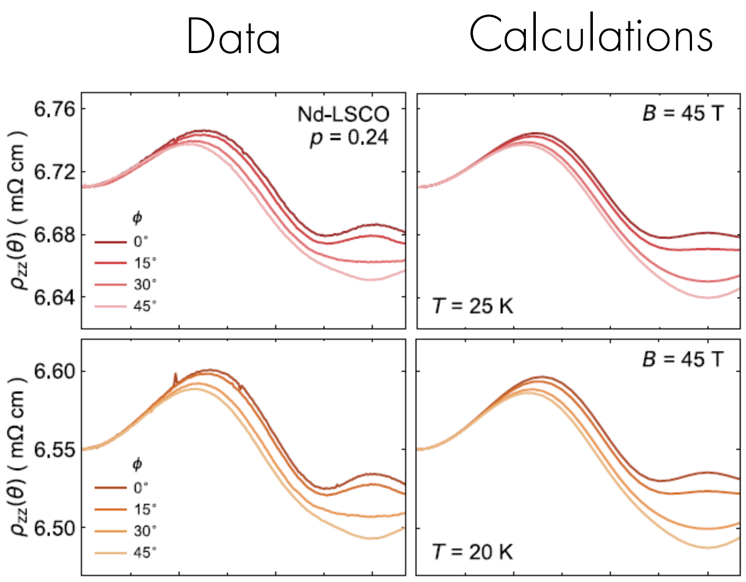


Scattering rate

$$1/\tau(k) = 1/\tau_{iso} + 1/\tau_{aniso}(k)$$

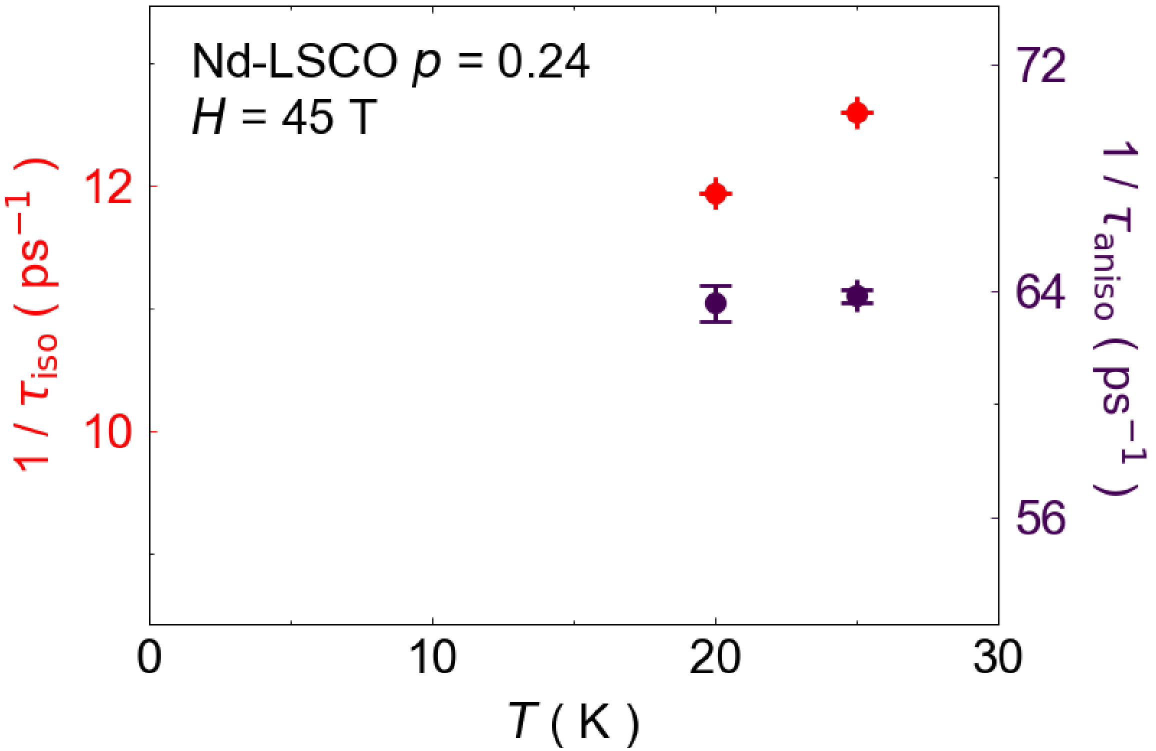


Part 2 - Scattering rate

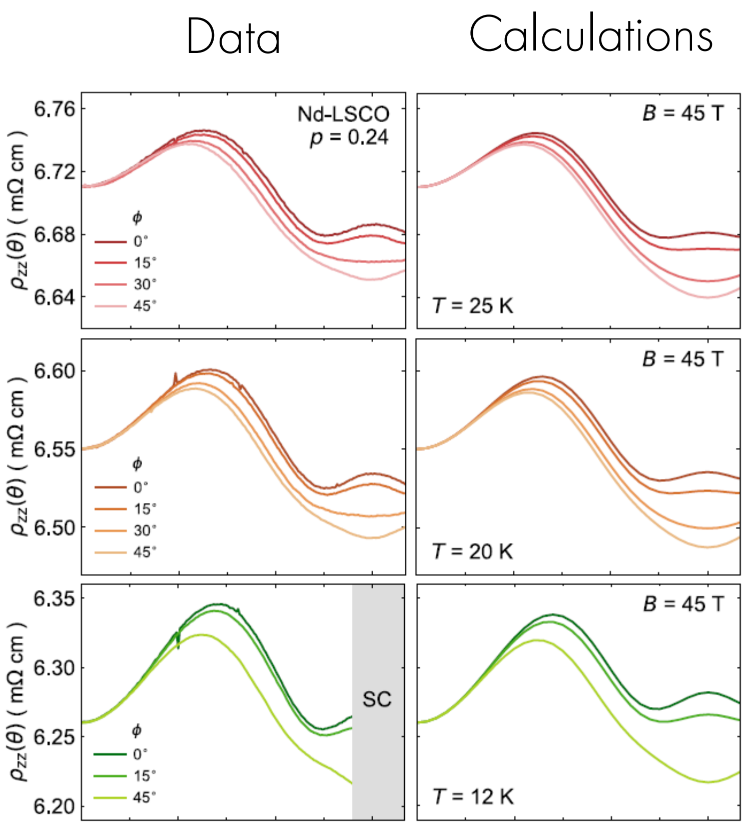


Scattering rate

$$ {}^{1}/_{\tau(k)} = {}^{1}/\tau_{iso} + {}^{1}/\tau_{aniso}(k) $$

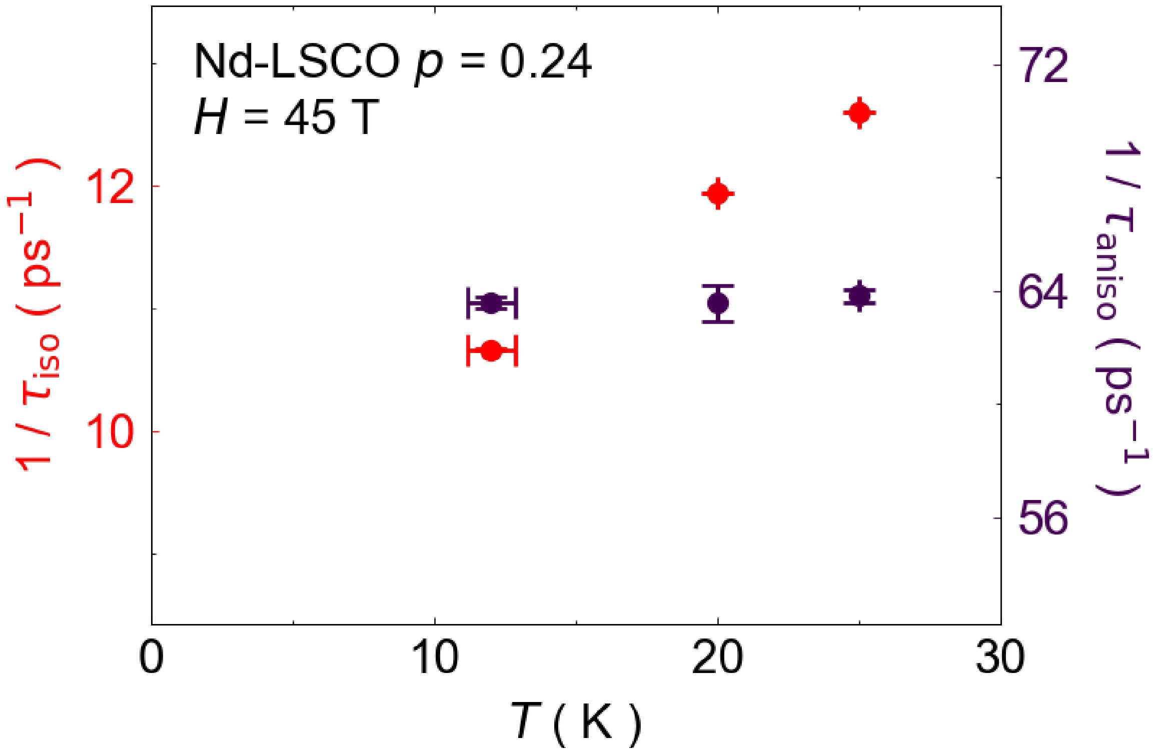


Part 2 - Scattering rate

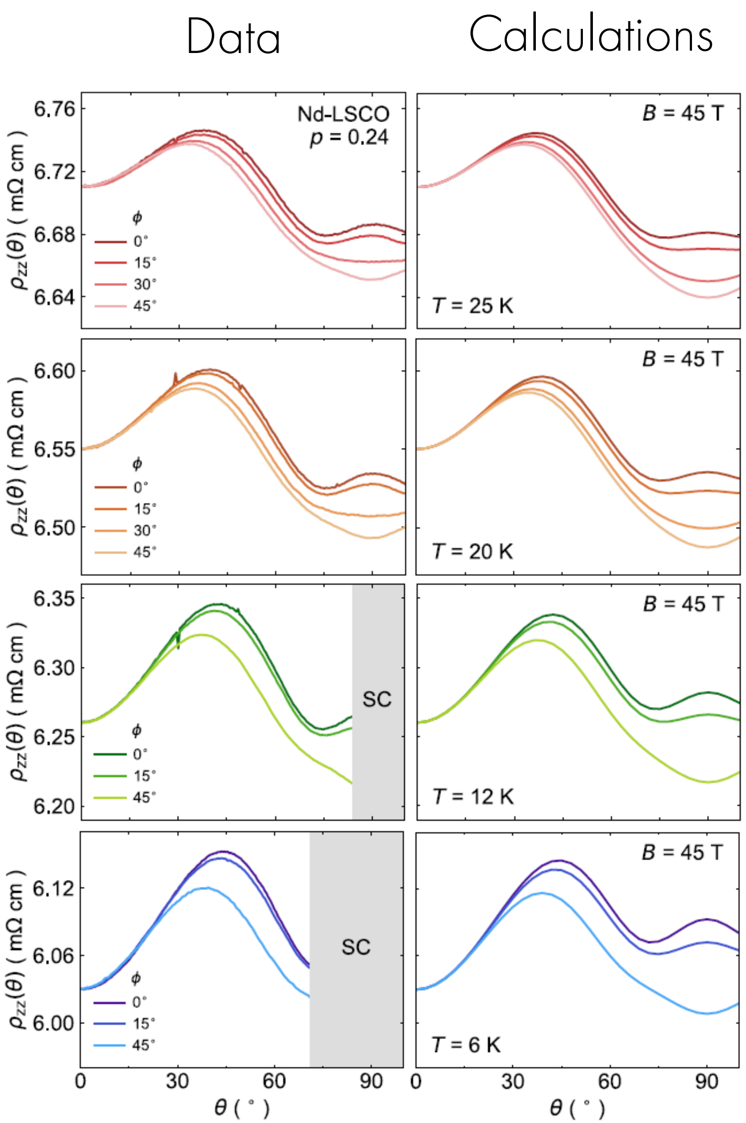


Scattering rate

$$\frac{1}{\tau(k)} = \frac{1}{\tau_{iso}} + \frac{1}{\tau_{aniso}}(k)$$

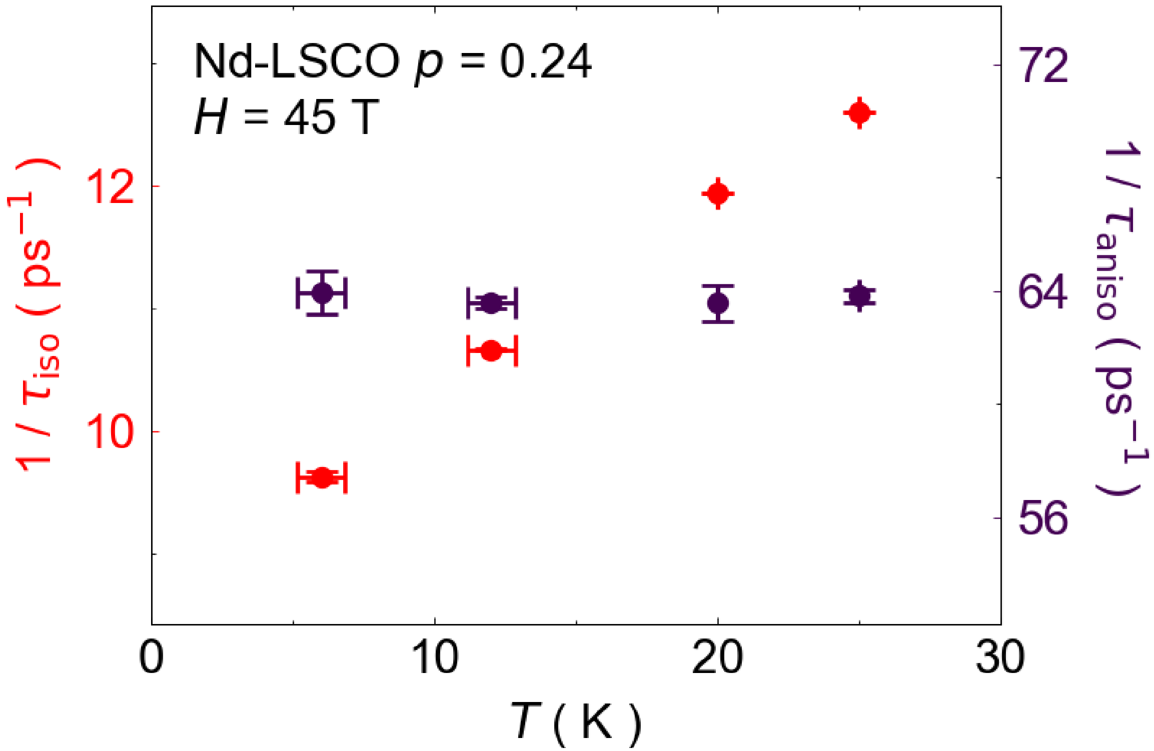


Part 2 - Scattering rate



Scattering rate

$$^{1}/_{\tau(k)} = {}^{1}/\,\tau_{iso} + {}^{1}/_{\tau_{aniso}}\,(k)$$



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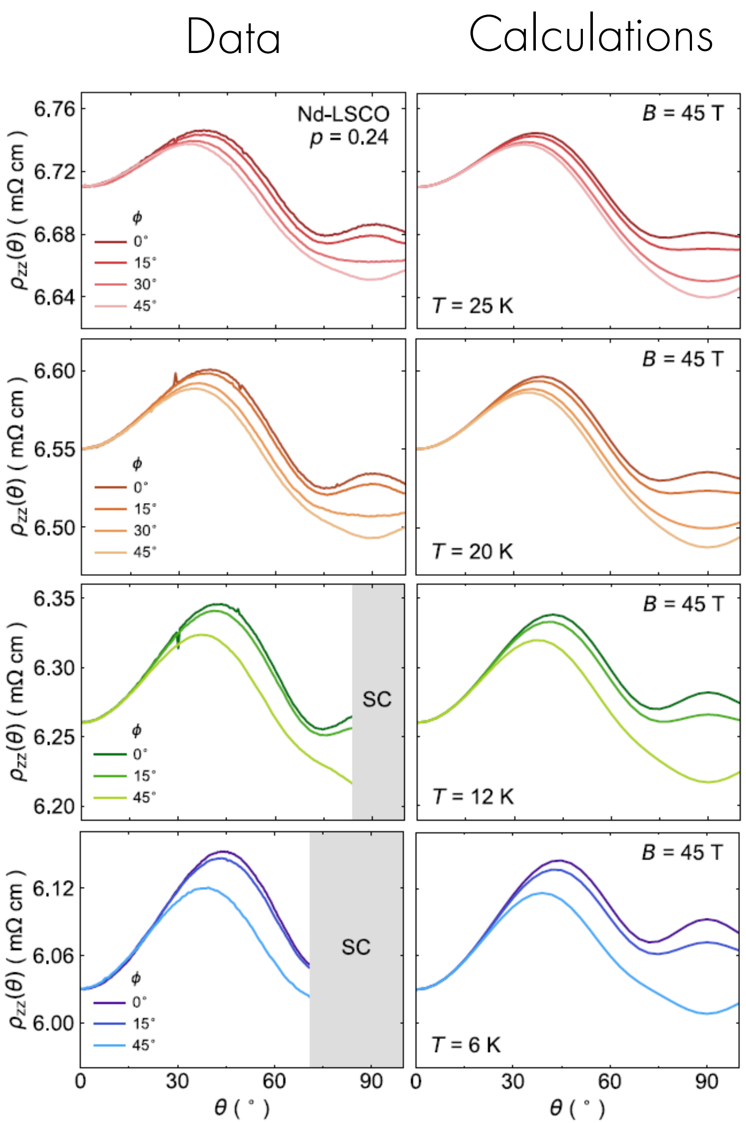
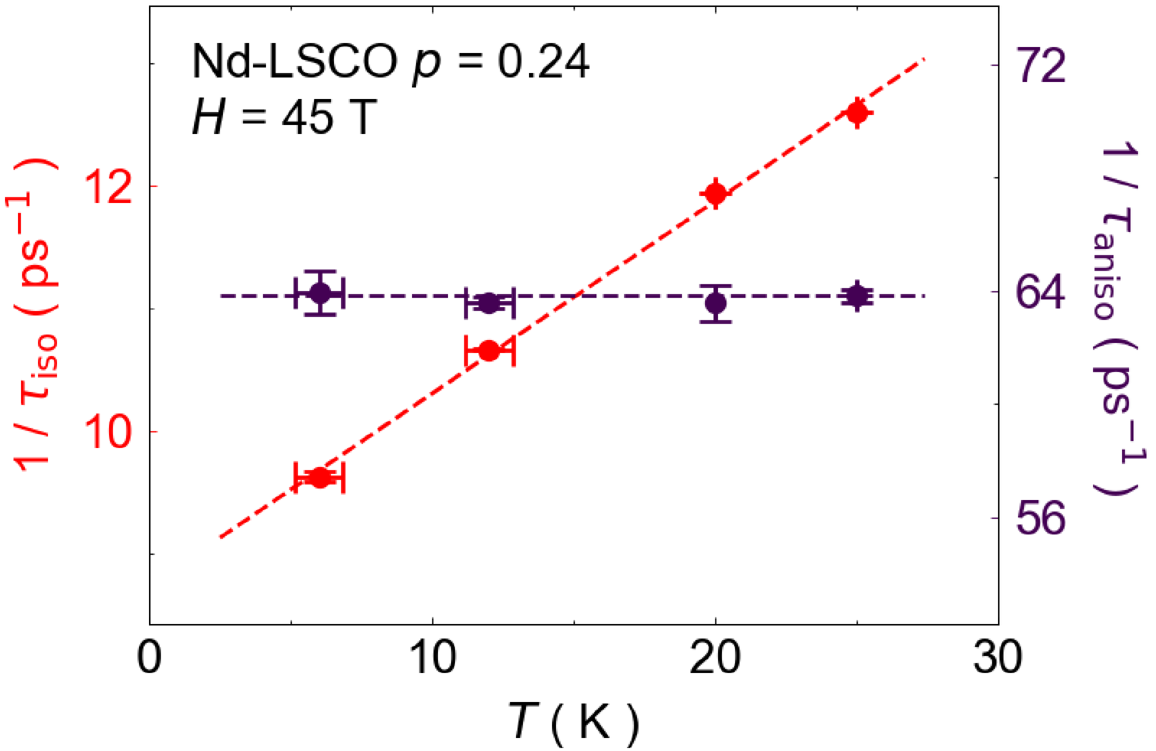


Scattering rate

$$^{1}/_{\tau(k)} = {}^{1}/\tau_{iso} + {}^{1}/\tau_{aniso}(k)$$



Part 2 - Scattering rate

- 1st result: anisotropy is elastic

- 2nd result: Isotropic T-linear scattering rate

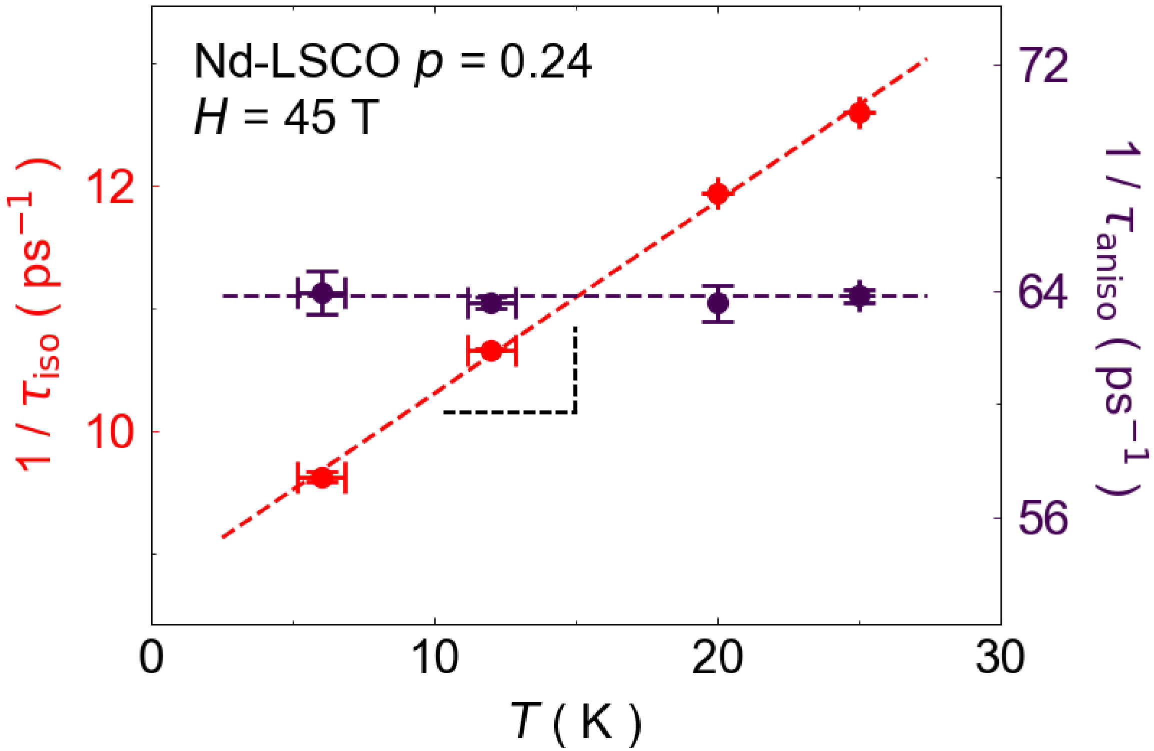
- 3rd result: Planckian limit

$$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$

$$\boxed{\alpha = 1.2 \pm 0.4}$$

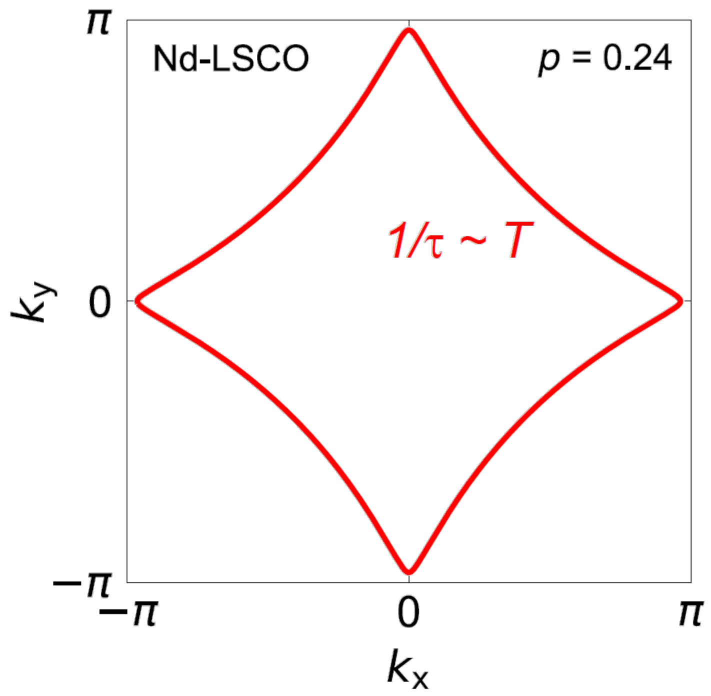
Scattering rate

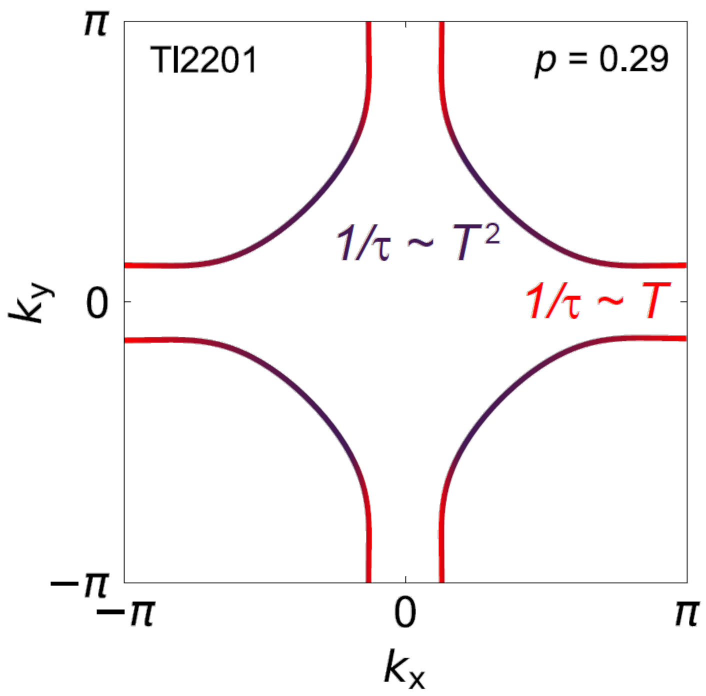
$$1/\tau(k) = 1/\tau_{iso} + 1/\tau_{aniso}(k)$$

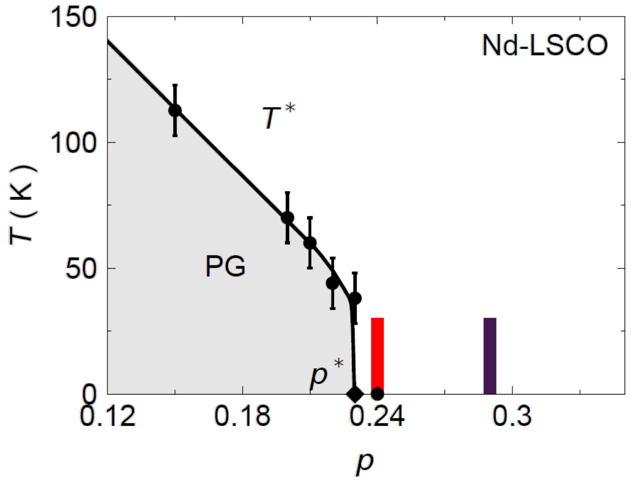


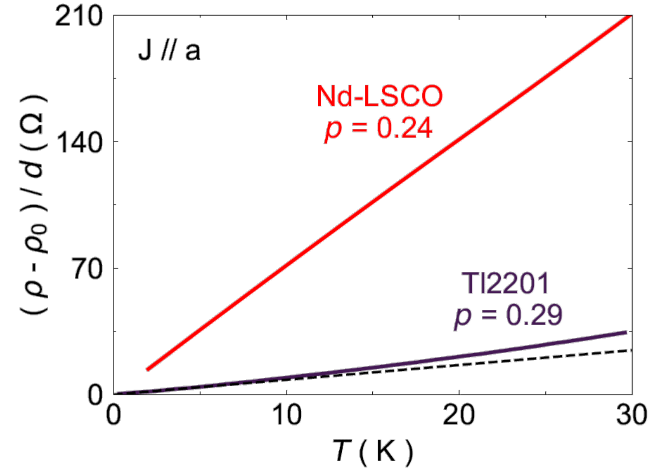
Part 2 - Scattering rate

From T-linear to T-quadratic



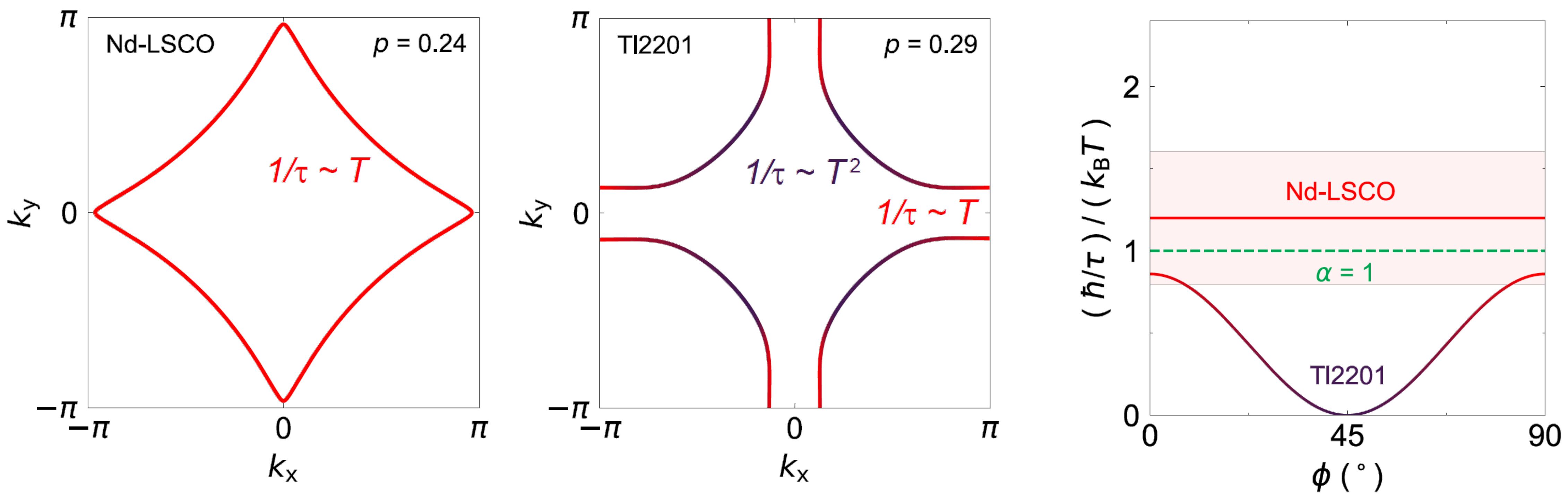






Part 2 - Scattering rate

To Planckian scattering



CONCLUSIONS

1. ADMR directly measures the momentum-dependent scattering rate and finds an isotropic, T-linear scattering rate of Planckian magnitude.

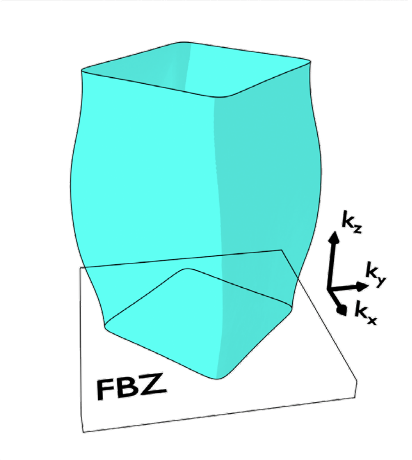
2. Pure T-linear resistivity occurs when the scattering rate reaches the Planckian limit for all directions of electron motion

3. The semi-classical approach seems to work to describe the ADMR of the strange metal in cuprates

Part 2 - Scattering rate

Boltzmann transport

Band structure



Scattering rate

$$1/\tau(k,T) = 1/\tau_0(k) + \frac{\alpha k_B T}{\hbar}$$

→ What else can we explain with this information?

Outline

Part 1: Is the Fermi surface strange?

Part 2: Is the scattering rate strange?

Part 3: Is the magnetoresistance strange?

Part 4: Is the Seebeck coefficient strange?

Part 3 Magnetoresistance

Ataei et al., arXiv:2203.05035

Collaborators

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Sven Badoux
Nicolas Doron-Leyraud
Louis Taillefer

LNCMI

Vincent Oliviero
Siham Benhabib
David Vignolles
Cyril Proust

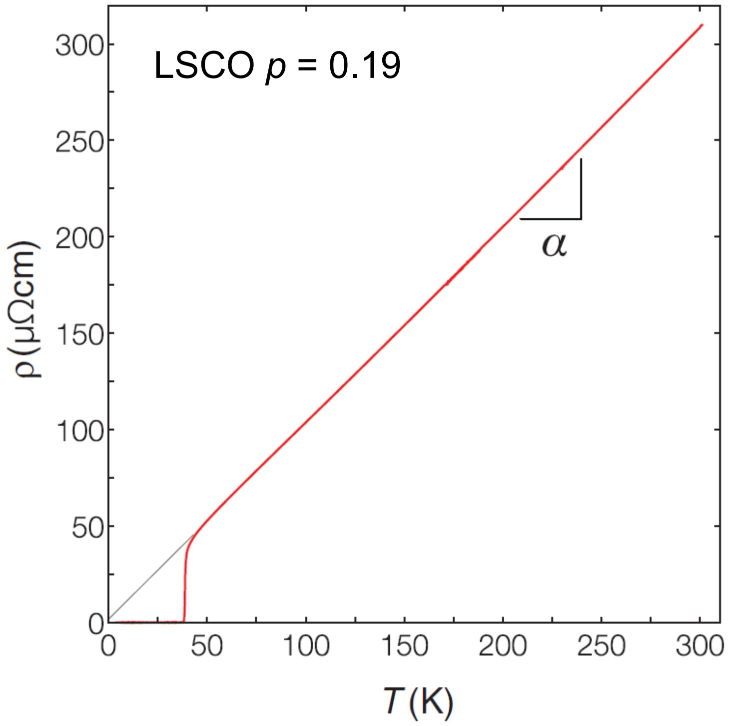
Jianshi Zhou

Shimpei Ono

Hidenori Takagi

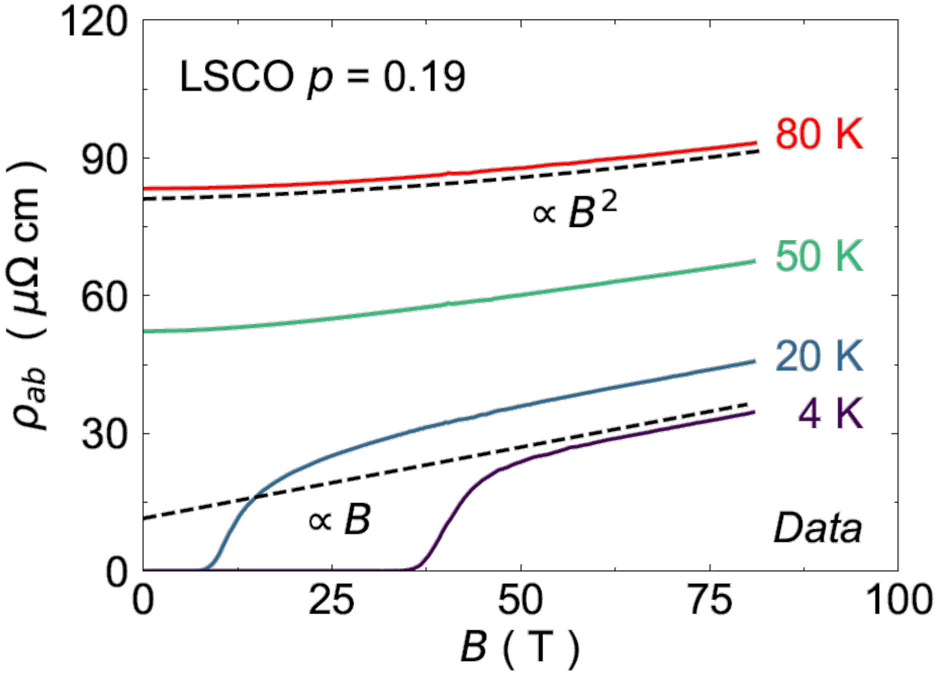
Part 3 - Magnetoresistance

T-linear R



Cooper et al., Science 2009

B-linear MR



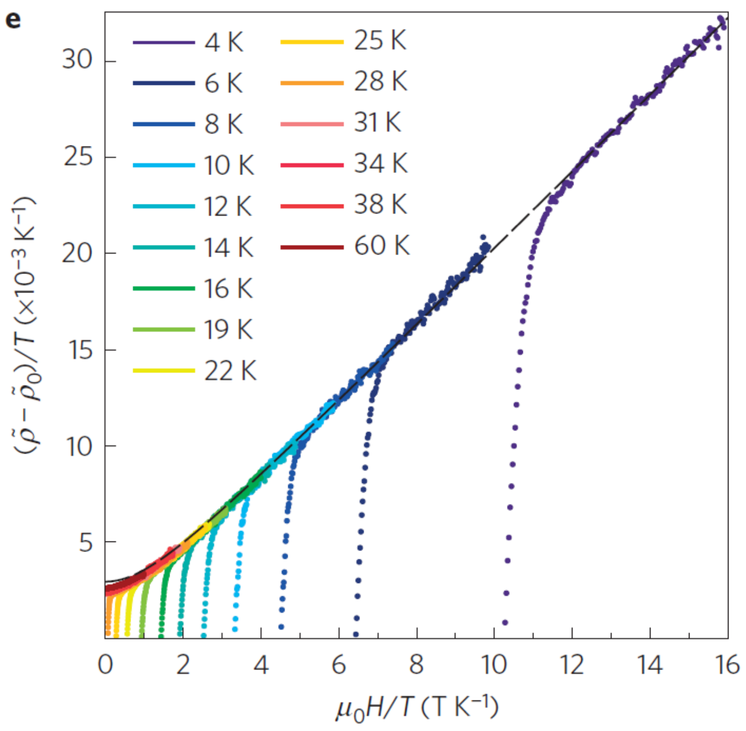
Giraldo-Gallo et al., Science 2018

Part 3 - Magnetoresistance

Quadrature scaling

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

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

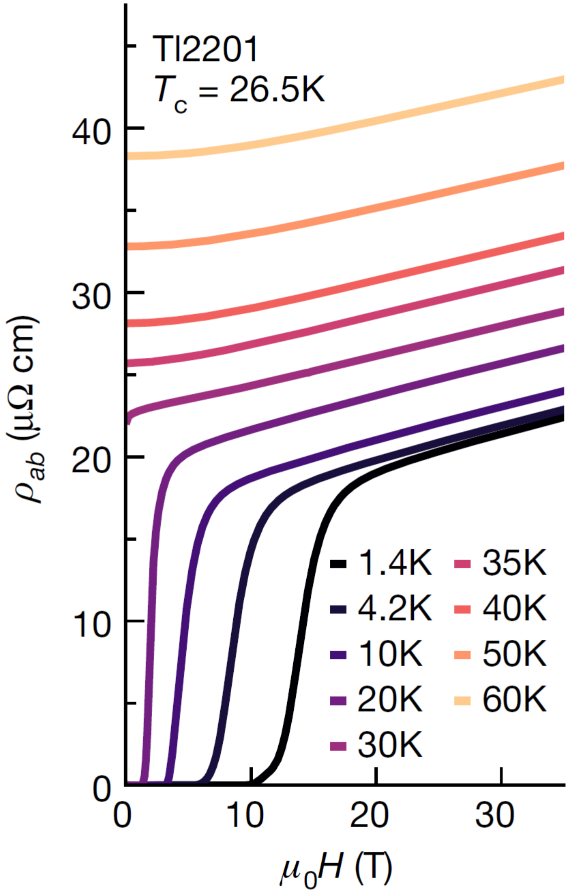


Hayes et al., Nat. Phys. 2016

Part 3 - Magnetoresistance

Quadrature scaling

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



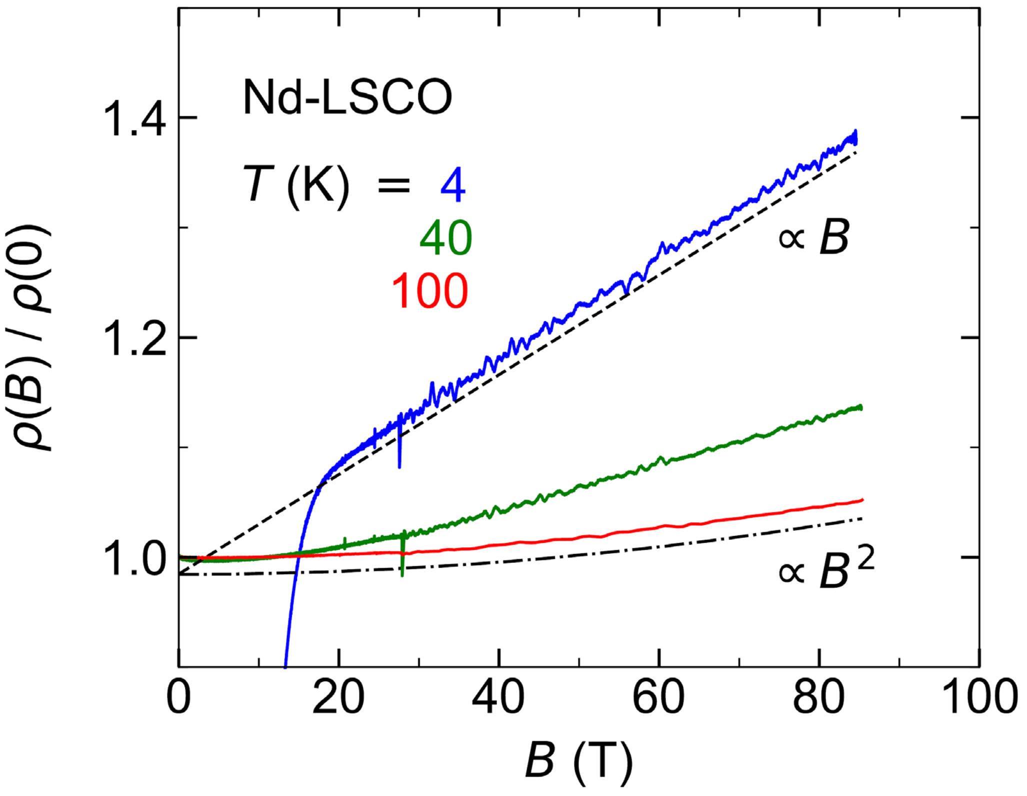
Ayres et al., Nature 2021

Part 3 - Magnetoresistance

QUESTION

Is B-linear MR another facet of Planckian dissipation?

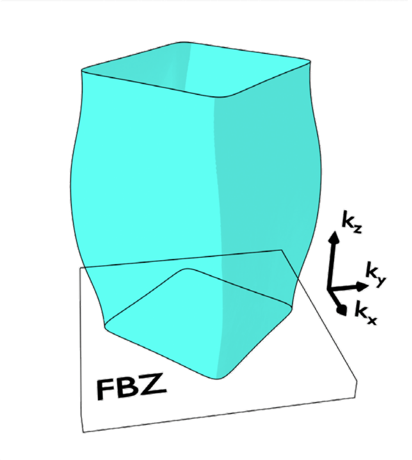
Part 3 - Magnetoresistance



Part 3 - Magnetoresistance

Boltzmann transport

Band structure

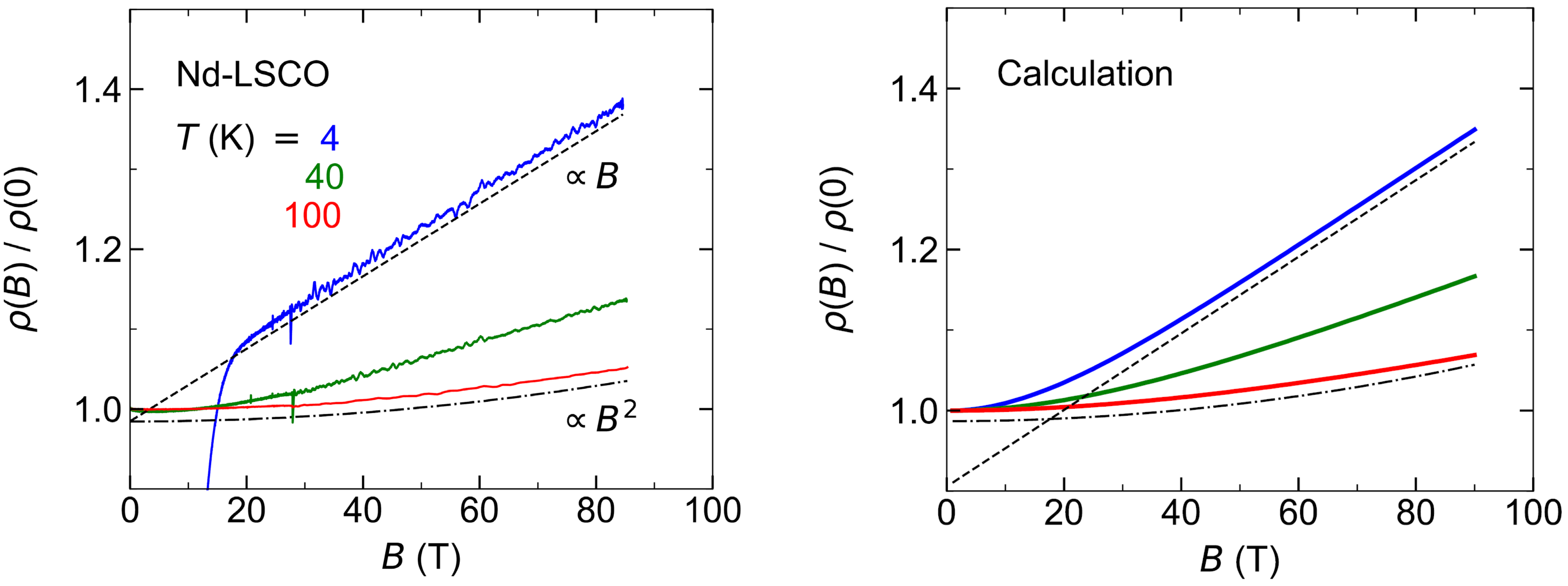


Scattering rate

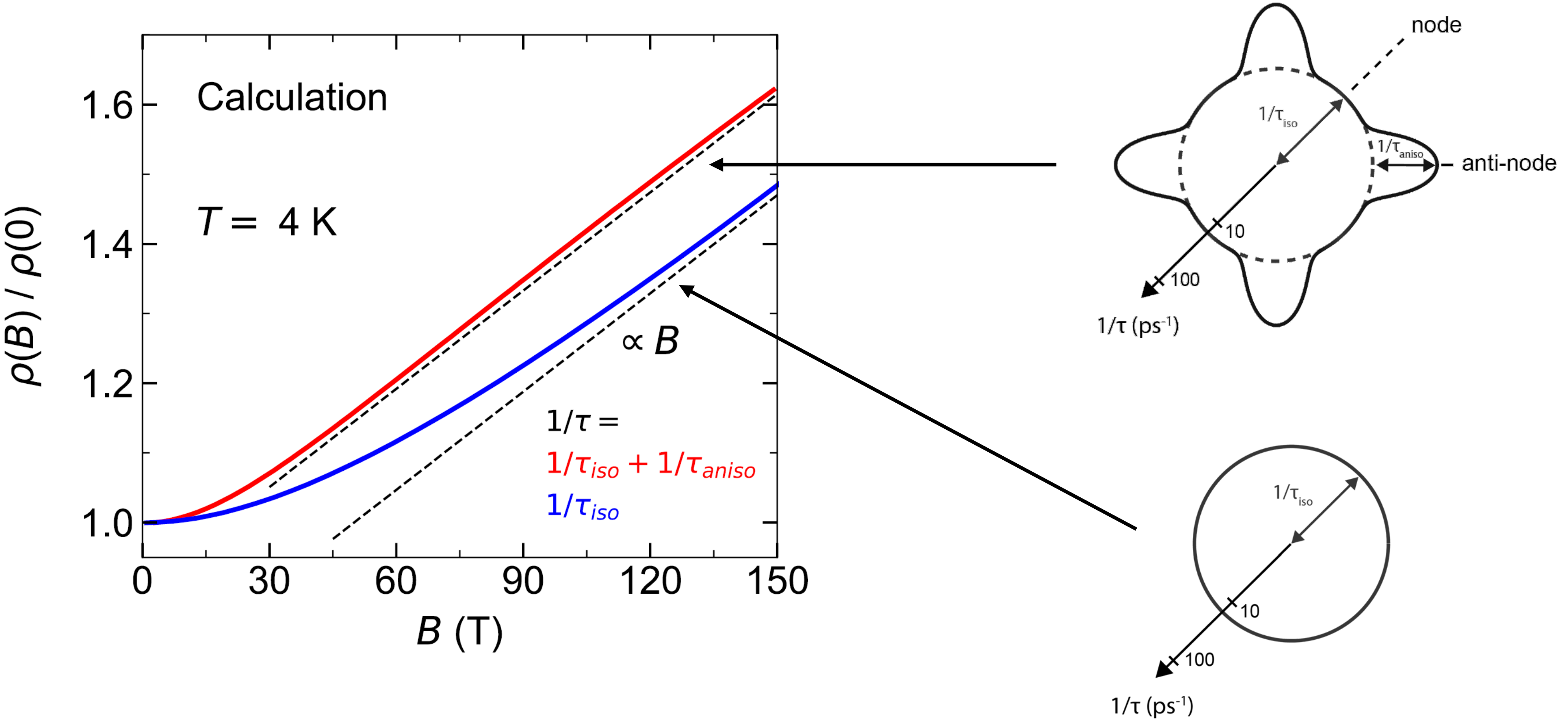
$$^1/_{\tau(k,T)} = {^1/_{\tau_0(k)}} + \frac{\alpha k_B T}{\hbar}$$

→ Can it predict *B*-linear MR?

Part 3 - Magnetoresistance



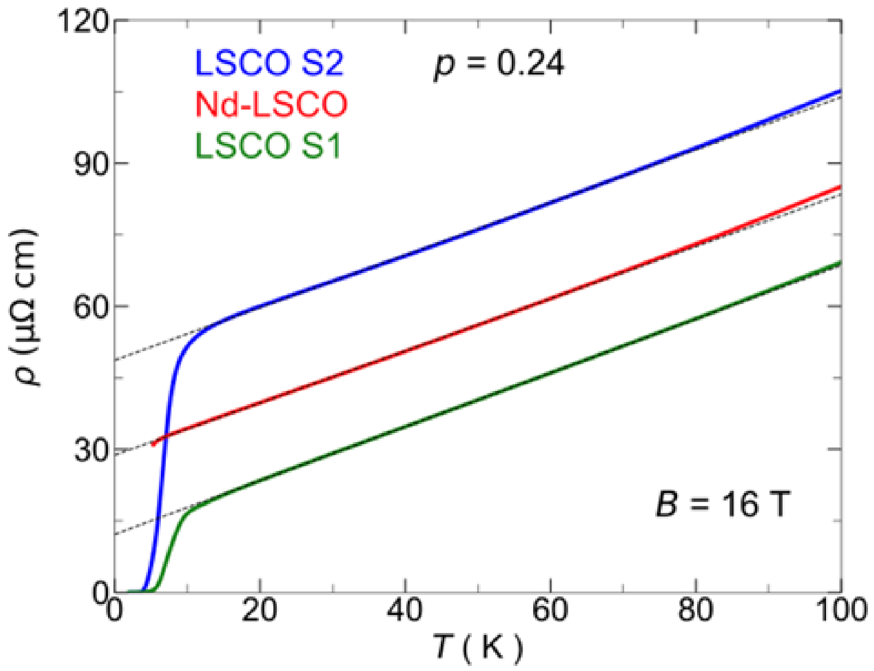
Part 3 - Magnetoresistance

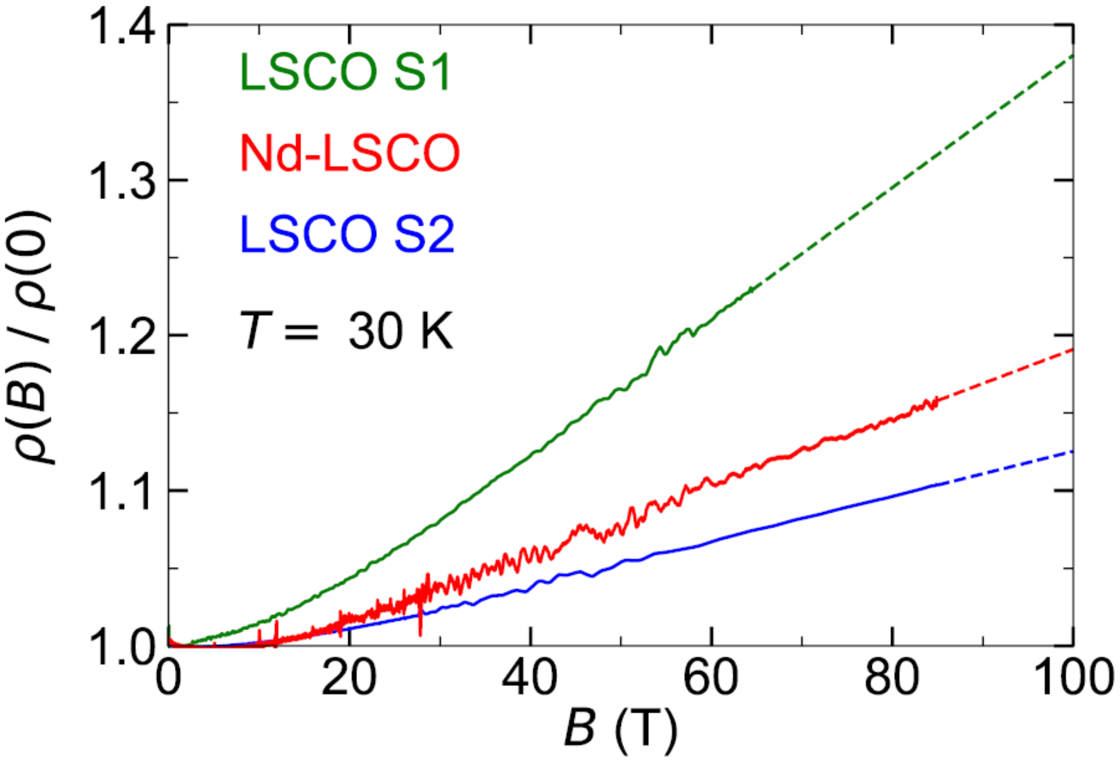


Hinlopen et al., arXiv:2201.03292

Part 3 - Magnetoresistance

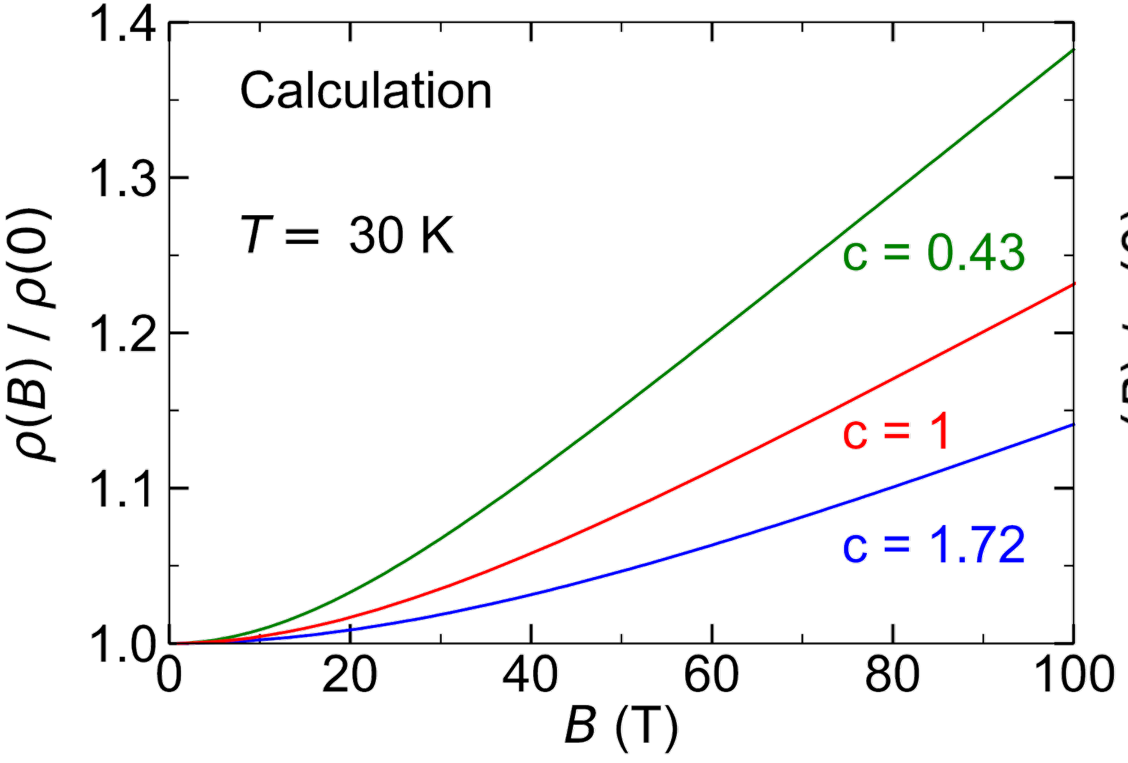
Impurity levels

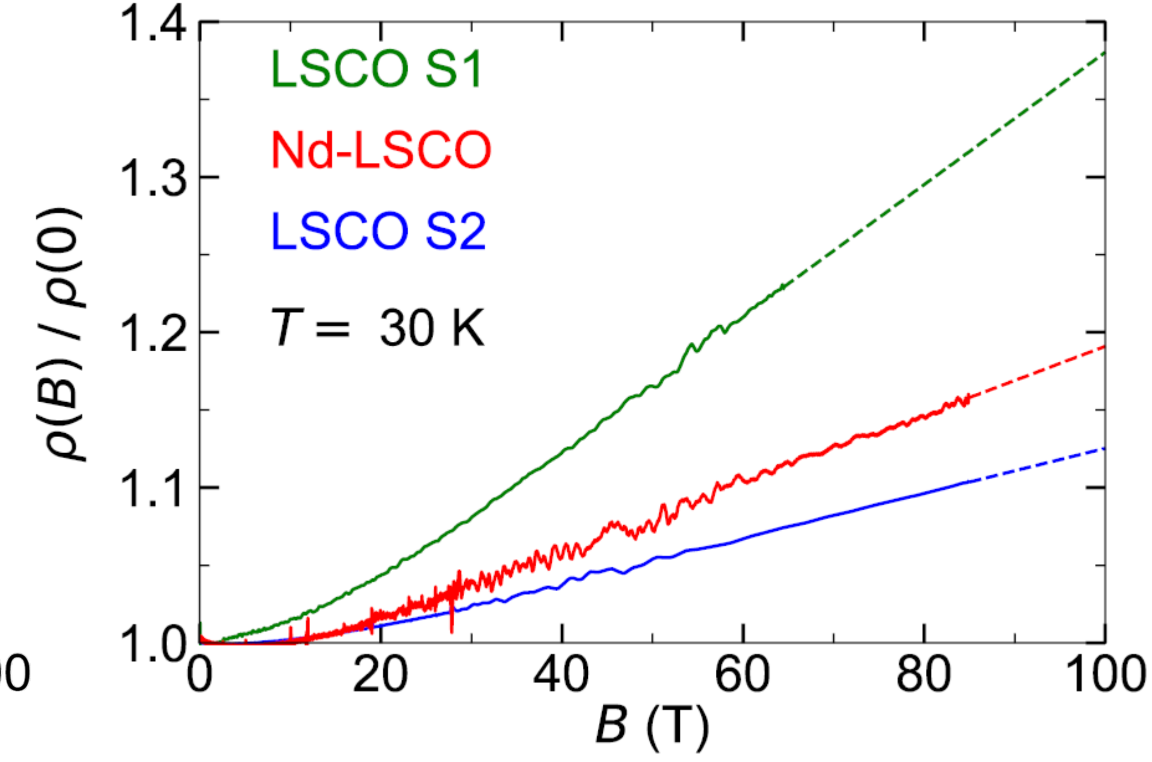




Part 3 - Magnetoresistance

Impurity levels





Part 3 - Magnetoresistance

CONCLUSION

Electrons with Planckian scattering seem to obey standard orbital motion in a magnetic field

Outline

Part 1: Is the Fermi surface strange?

Part 2: Is the scattering rate strange?

Part 3: Is the magnetoresistance strange?

Part 4: Is the Seebeck coefficient strange?

Part 4 Seebeck coefficient

Gourgout*, Grissonnanche* et al., PRX 12, 011037 (2022)

Georges & Mravlje PRR 3, 043132 (2021)

Collaborators

Experiment

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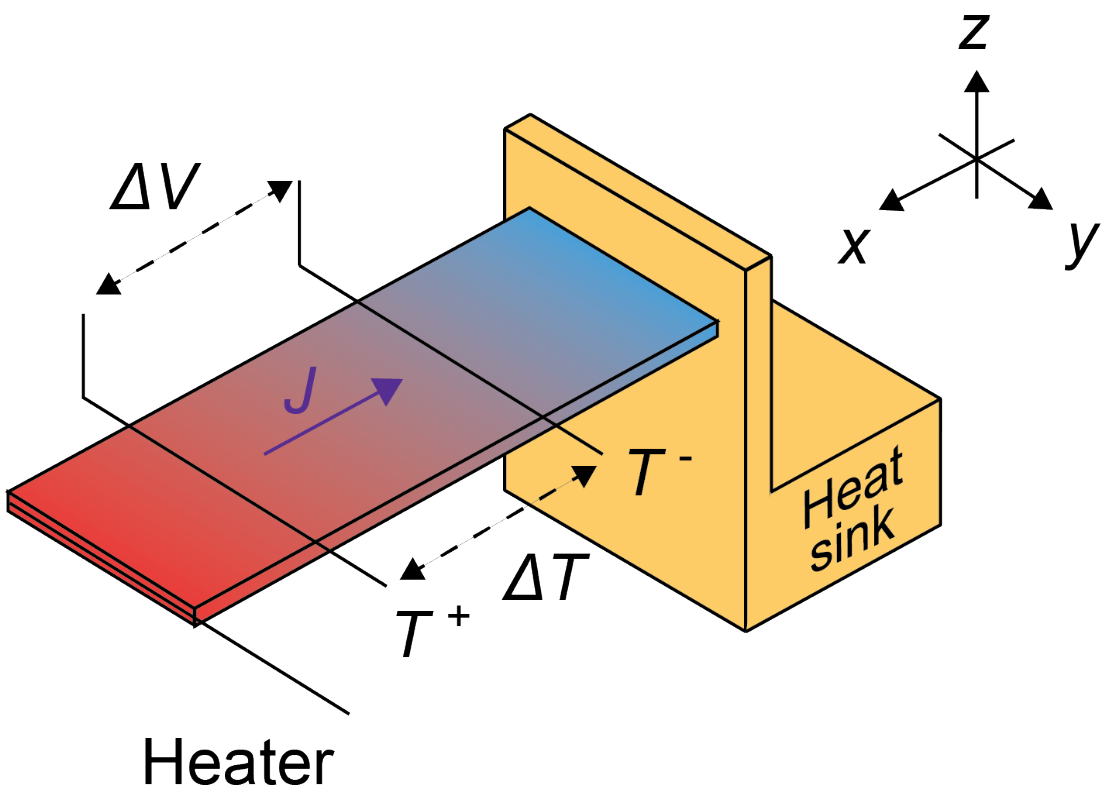
Jožef Stefan Institute

Jernej Mravlje

Part 4 - Seebeck coefficient

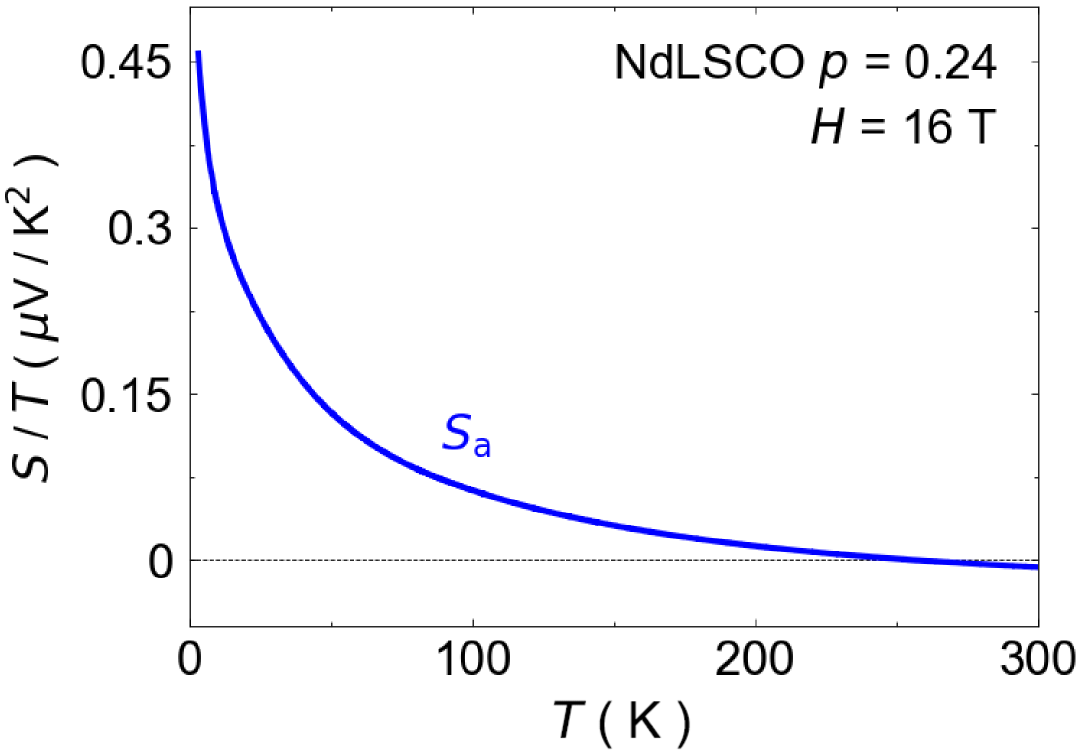


Seebeck

$$\boxed{S = -\frac{\Delta V}{\Delta T}}$$

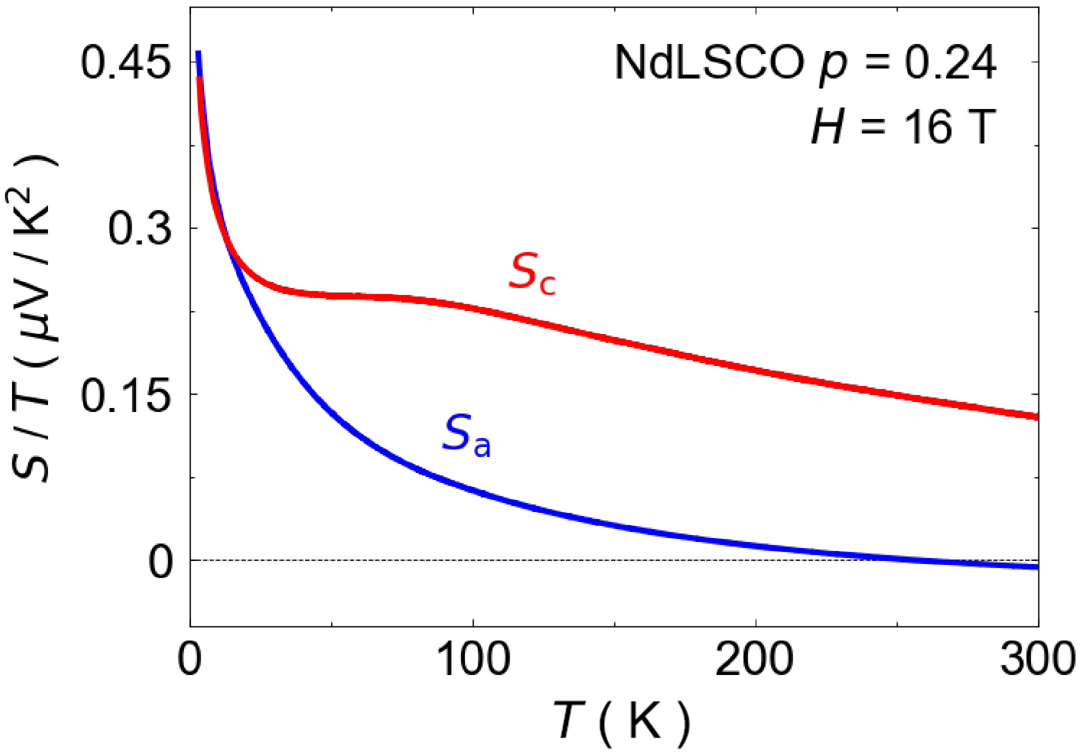
Part 4 - Seebeck coefficient

Data



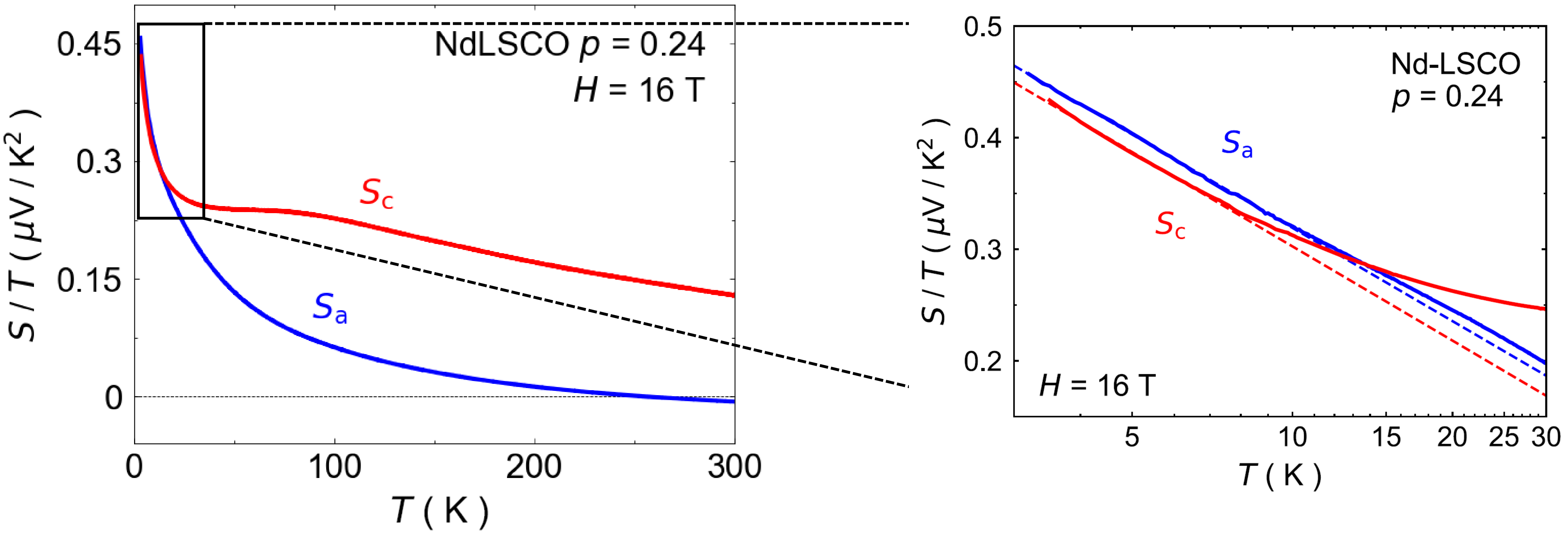
Part 4 - Seebeck coefficient

Data



Part 4 - Seebeck coefficient

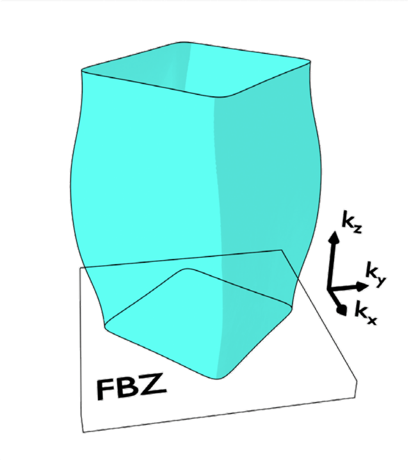
Data



Part 4 - Seebeck coefficient

Boltzmann transport

Band structure



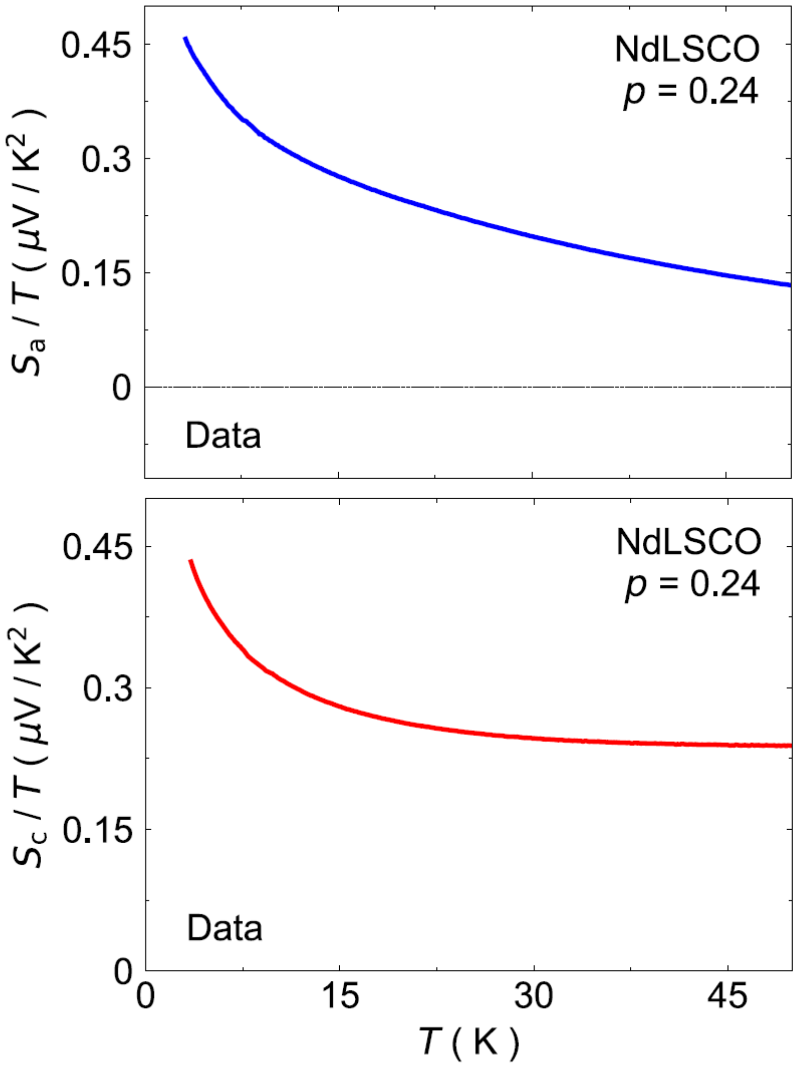
Scattering rate

$$1/\tau(k,T) = 1/\tau_0(k) + \frac{\alpha k_B T}{\hbar}$$

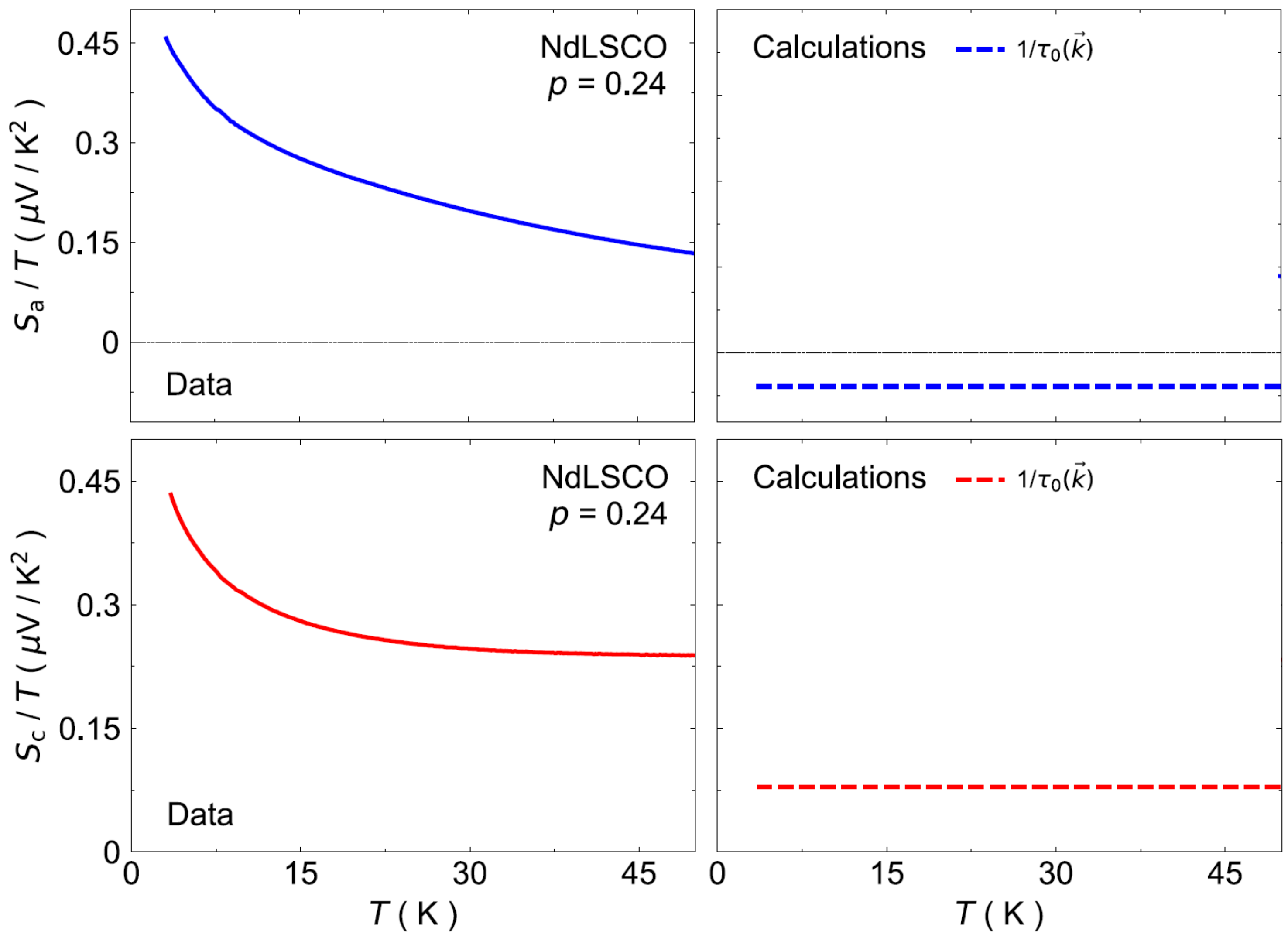
$\longrightarrow$

Can it predict
the Seebeck coefficient?

Part 4 - Seebeck coefficient



Part 4 - Seebeck coefficient



The band structure
ALONE
fails to explain Seebeck

Part 4 - Seebeck coefficient

To tune the sign of Seebeck
the scattering rate must be energy dependent

$$^{1}/_{\tau(T)} = \frac{\alpha k_B T}{\hbar}$$

Georges & Mravlje PRR 2021

Part 4 - Seebeck coefficient

To tune the sign of Seebeck
the scattering rate must be energy dependent

$$1/\tau_{\mathrm{MFL}}(\epsilon, T) = \sqrt{\left(\frac{\alpha k_B T}{\hbar}\right)^2 + (\alpha\epsilon)^2}$$

Marginal Fermi Liquid

Georges & Mravlje PRR 2021

Part 4 - Seebeck coefficient

To tune the sign of Seebeck
the scattering rate must be particle-hole asymmetric!

$$1/\tau_{\mathrm{SMFL}}(\epsilon, T) = \sqrt{\left(\frac{\alpha k_B T}{\hbar}\right)^2 + (a_{\pm}\epsilon)^2}$$

Skew Marginal Fermi Liquid

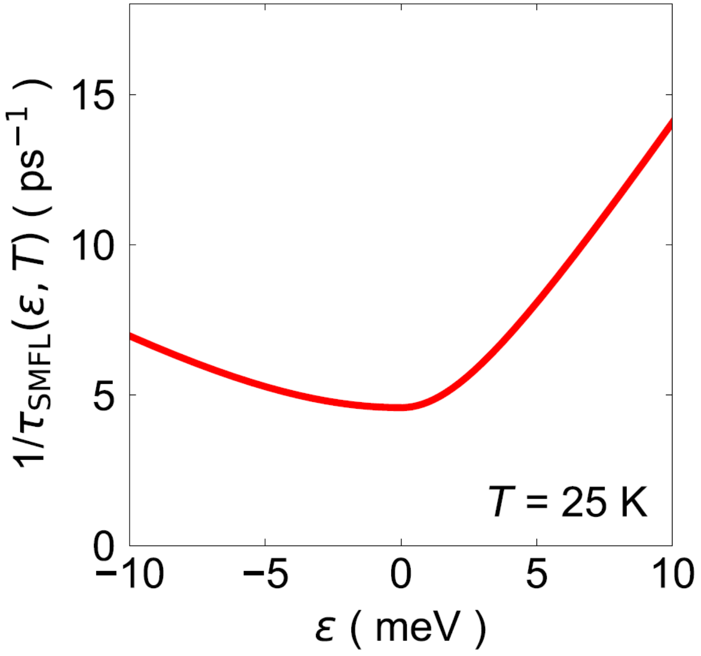
$a_+ \neq a_-$ for $\epsilon > 0$ and $\epsilon < 0$
and $\alpha = 1.2$ from ADMR

Georges & Mravlje PRR 2021

Part 4 - Seebeck coefficient

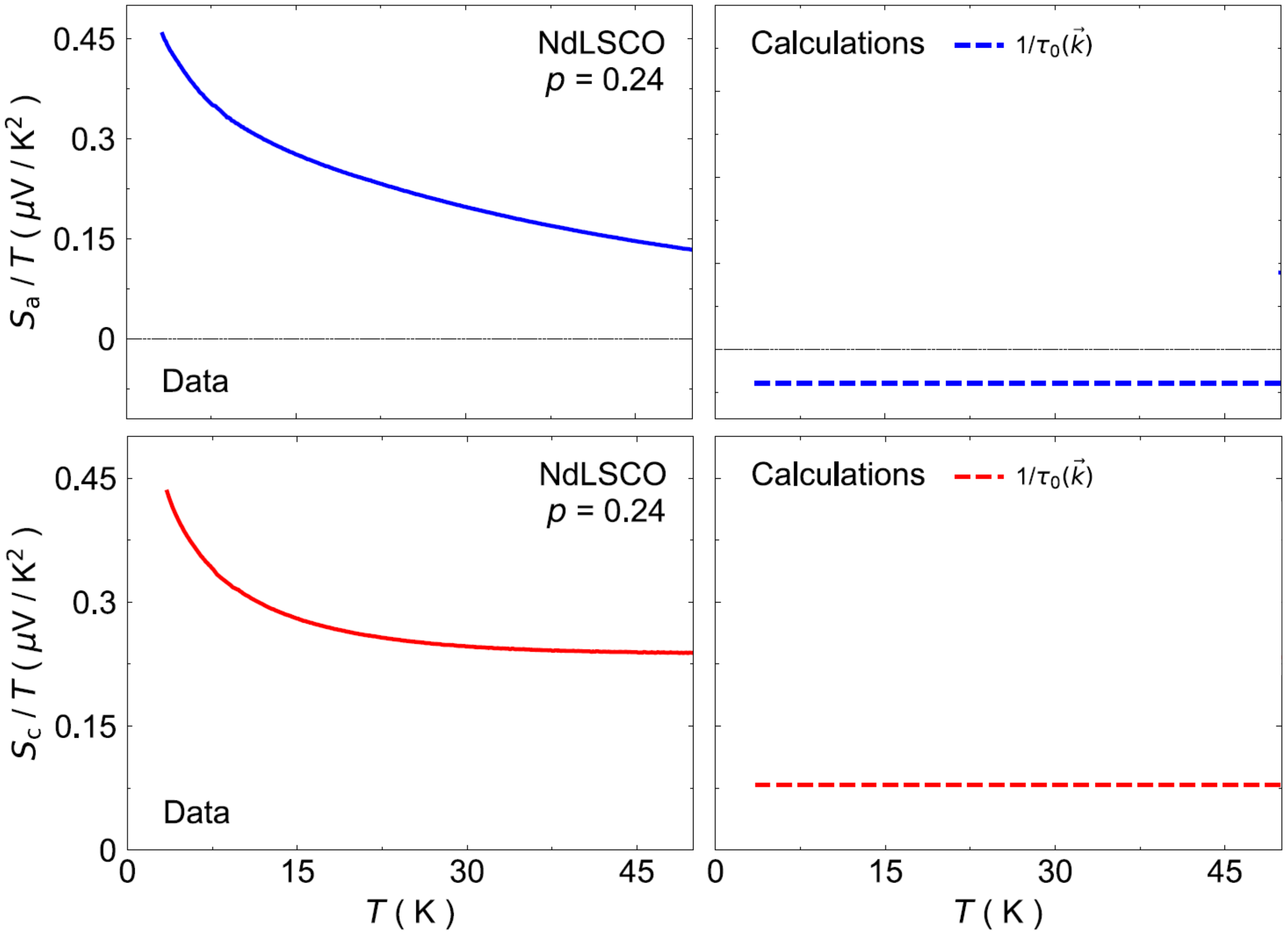
To tune the sign of Seebeck
the scattering rate must be particle-hole asymmetric!

$$^{1}/_{\tau_{\mathrm{SMFL}}(\epsilon,T)} = \sqrt{\left(\frac{\alpha k_B T}{\hbar}\right)^2 + (a_{\pm}\epsilon)^2}$$

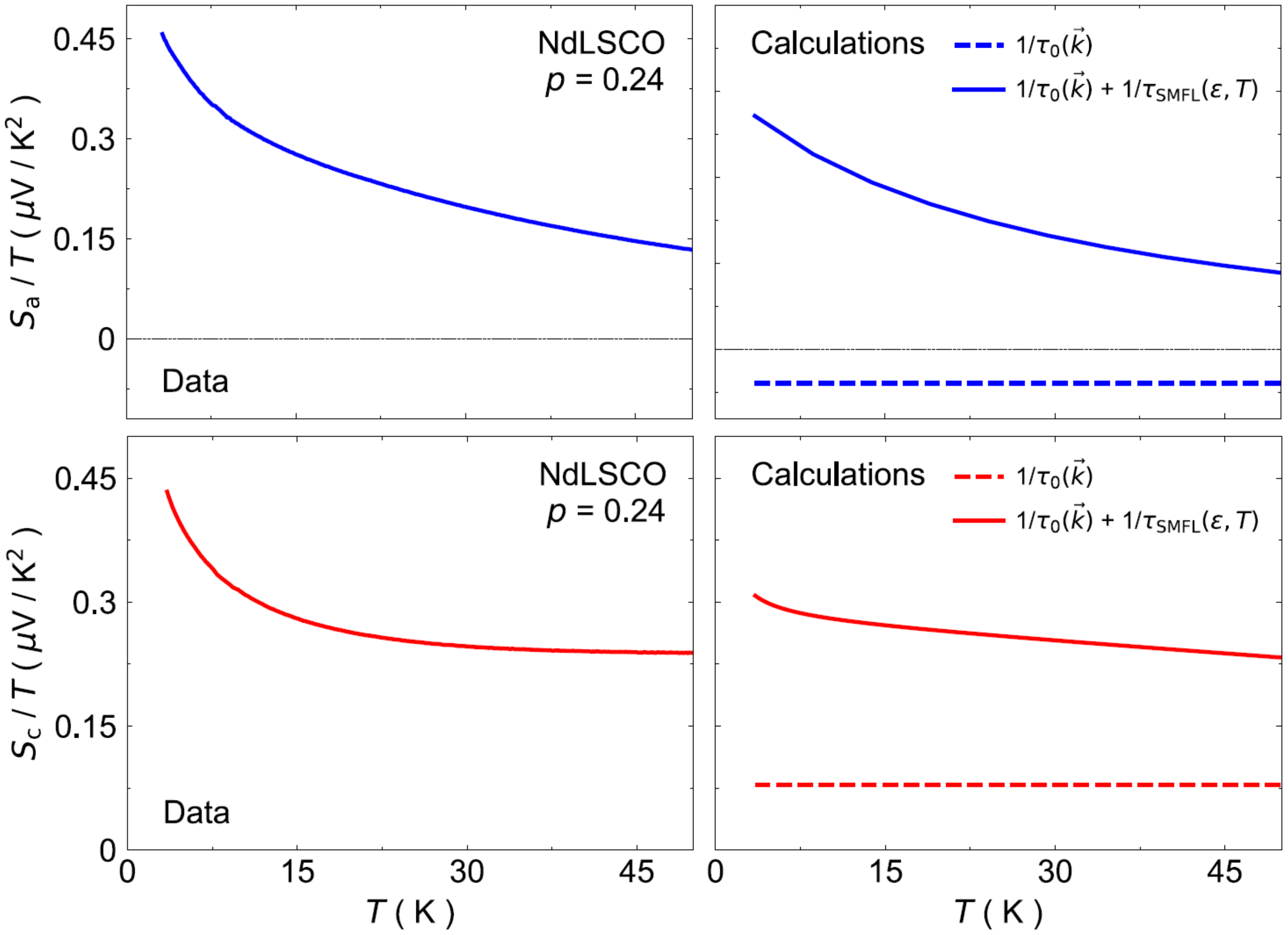


Georges & Mravlje PRR 2021

Part 4 - Seebeck coefficient

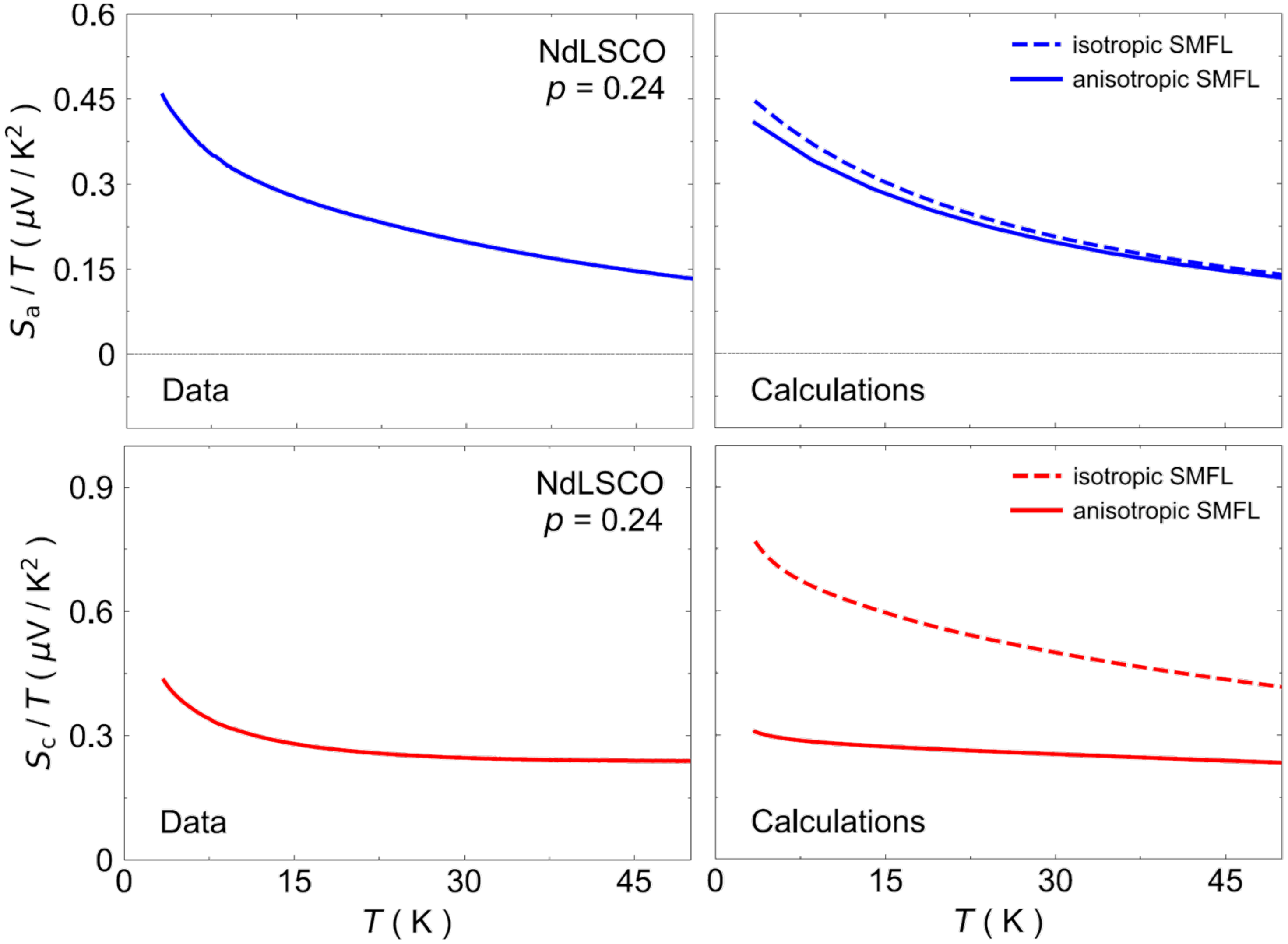


Part 4 - Seebeck coefficient



The Seebeck coefficient has now the right SIGN and AMPLITUDE

Part 4 - Seebeck coefficient



The ANISOTROPY of the elastic scattering rate is essential to explain c-axis Seebeck

CONCLUSION

The Seebeck coefficient reflects another aspect of the strange metal and the Planckian dissipation,
with an addition of an intrinsic particle-hole asymmetry
and that obeys ϵ/T scaling.

Conclusion

Boltzmann transport

Part 1: Is the Fermi surface strange? No

Part 2: Is the scattering rate strange? Yes

Part 3: Is the magnetoresistance strange? No(?)

Part 4: Is the Seebeck coefficient strange? Yes