The travel of charge and heat in $SrTiO_3$

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PSL

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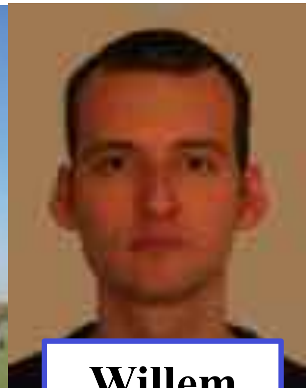
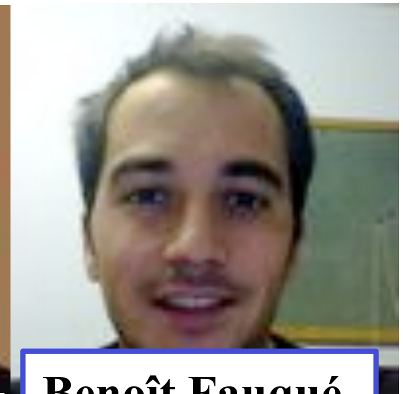


Willem Rischau



Benoît Fauqué

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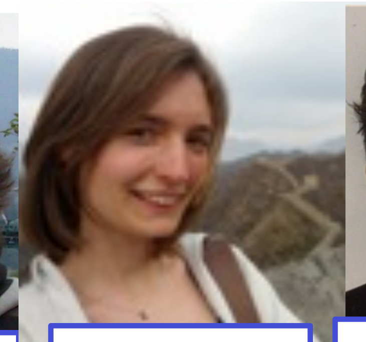

Lisa Buchauer

Alexandre Jaoui

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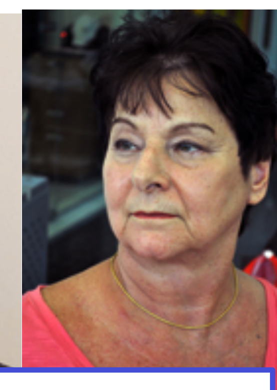
Raman scattering

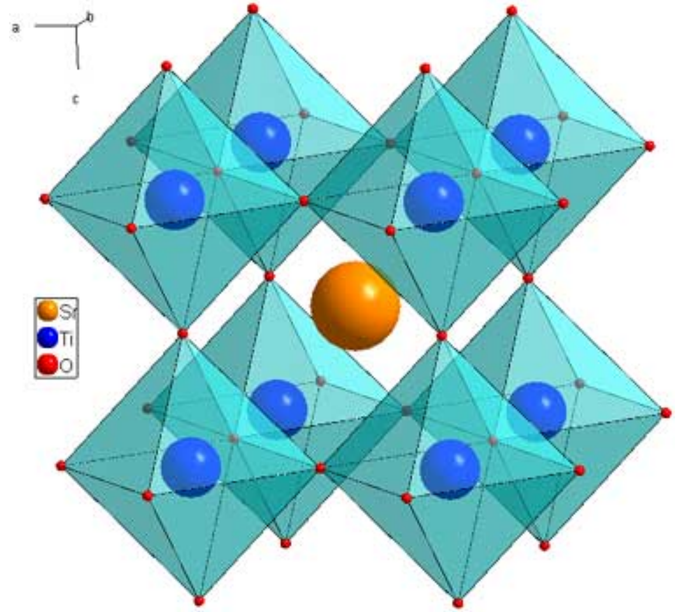
Joachim Hemberger
Cologne
Electric permittivity



Valentina Martelli, Juio Larrea & Elisa Saitovitch
CBPF, Rio de Janeiro
Thermal conductivity

Remarkable for many reasons

$SrTiO_3$



- TiO_6 octahedron
- SrO_{12} cuboctahedron

•…is superconducting upon doping *Schooley et al. (1964)*
•…is a water splitter *Mavroides et al. (1976)*
•…is a quantum paraelectric *Müller & Burkhard, (1979)*
•…exhibits second sound *Koreeda et al. (2007)*
•…displays flexoelectricity *Zubko et al. (2007)*
•…hosts interface superconductivity *Reyren et al. (2007)*
•…becomes magnetic with light *Rice et al. (2014)*

Outline

- Dilute Superconductivity

Intertwined with ferroelectricity

- Charge transport

Bohr radius and mobility

Low-temperatureT^2 resistivity

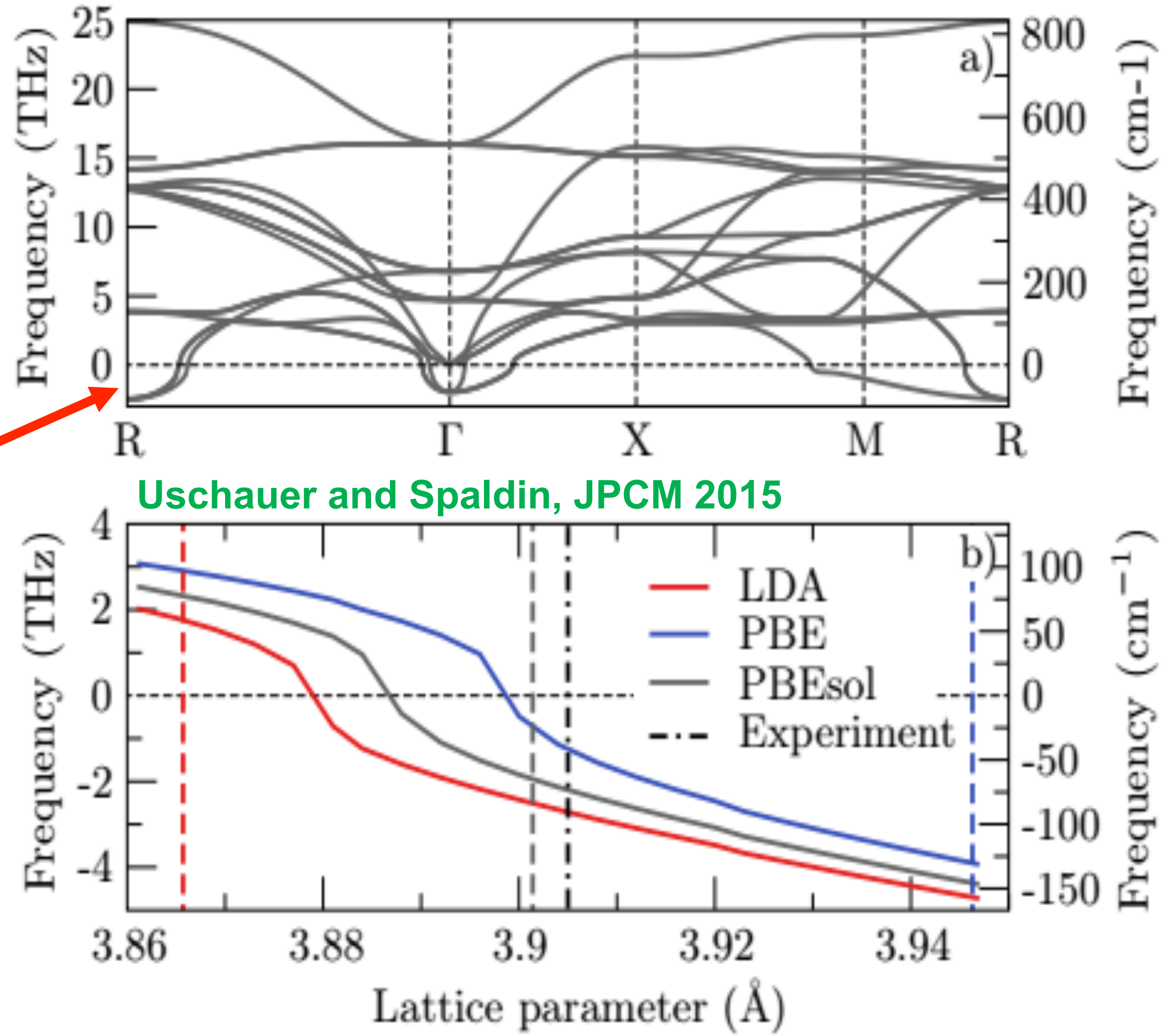
Room-temperature bad metallicity

- Heat transport

Phonon poseuille flow

Diffusivity and Planck time

Ab initio theory: this solid cannot be!



Uschauer and Spaldin, JPCM 2015

Imaginary phonon frequencies!

See also:

Lebedev, Phys. Sol. Stat. (2009)
Chodhuri *et al.*, PRB (2008)
Tadano & Tsuyenuki, PRB (2015)

Owes its very existence to zero-point quantum fluctuations!

PHYSICAL REVIEW B VOLUME 19, NUMBER 7 1 APRIL 1979

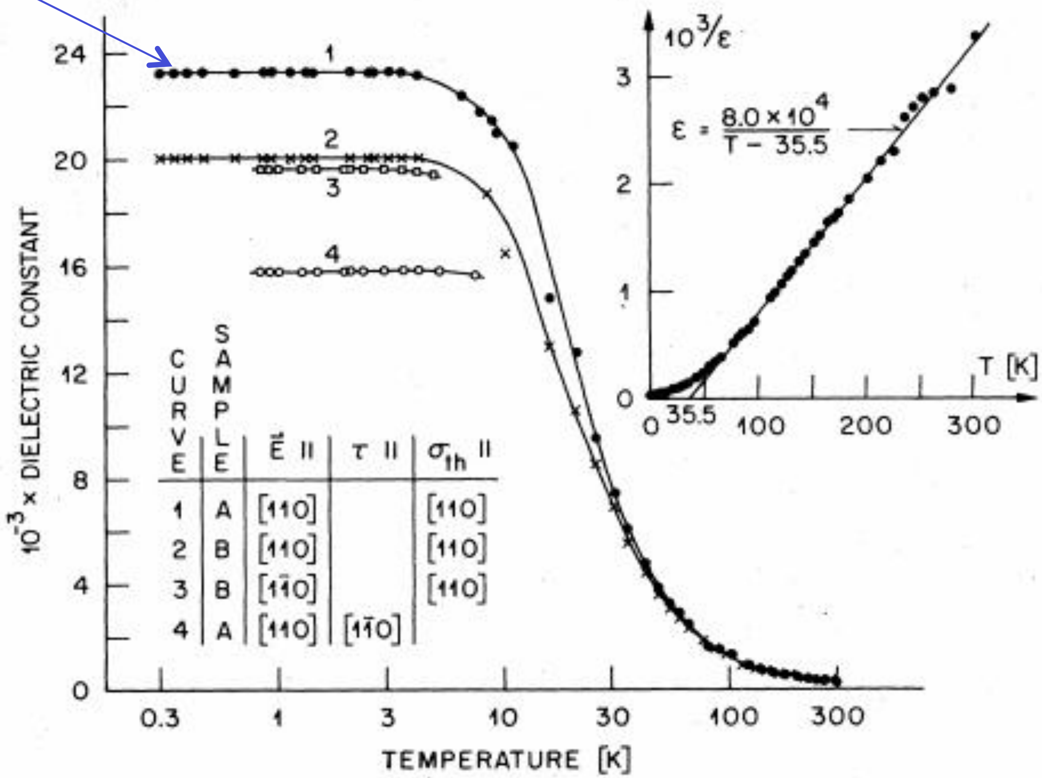
$SrTiO_3$: An intrinsic quantum paraelectric below 4 K

K. A. Müller
IBM Zürich Research Laboratory, 8803 Rüschlikon, Switzerland

H. Burkard *
Laboratory of Solid State Physics, ETH 8093 Zürich, Switzerland

(Received 19 July 1976; revised manuscript received 14 August 1978)

The dielectric coefficient becomes as large as $20000\varepsilon_0$!

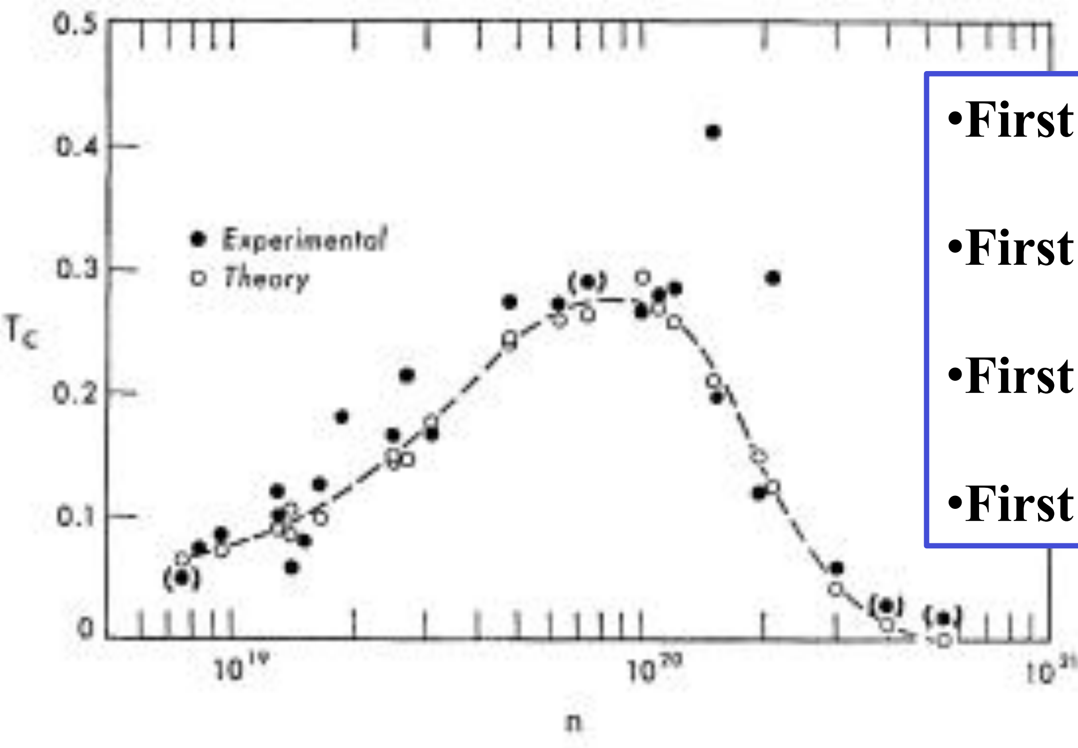


I. Dilute superconductivity

Superconducting Transition Temperatures of Semiconducting $SrTiO_3$

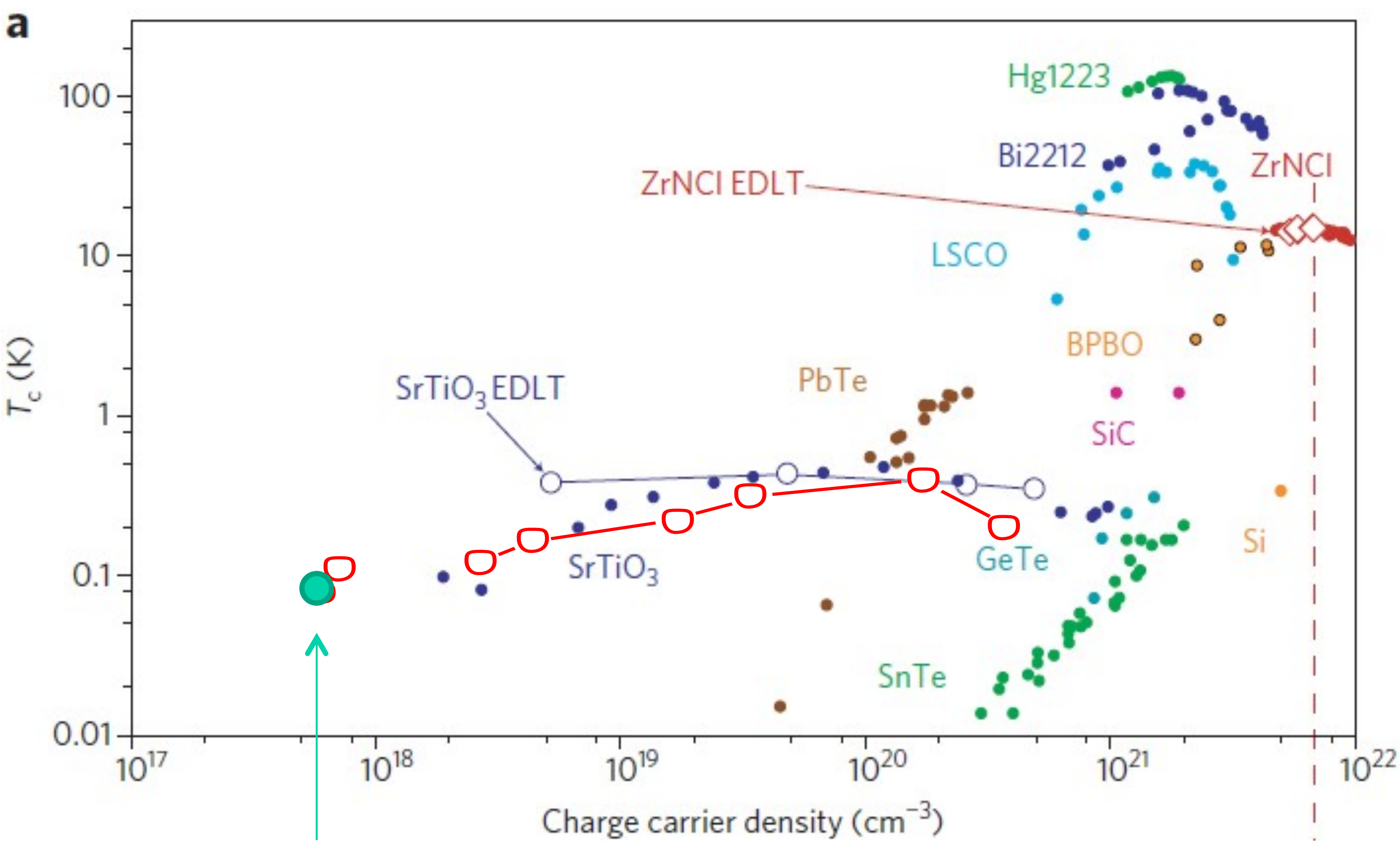
C. S. KOONCE* AND MARVIN L. COHEN†
Department of Physics, University of California, Berkeley, California
AND
J. F. SCHOOLEY,‡ W. R. HOSLER,§ AND E. R. PFEIFFER
National Bureau of Standards, Washington, D. C.

(Received 5 July 1967)



- First **oxide** superconductor
- First **multi-band** superconductor
- First **semiconducting** superconductor
- First superconducting **dome**

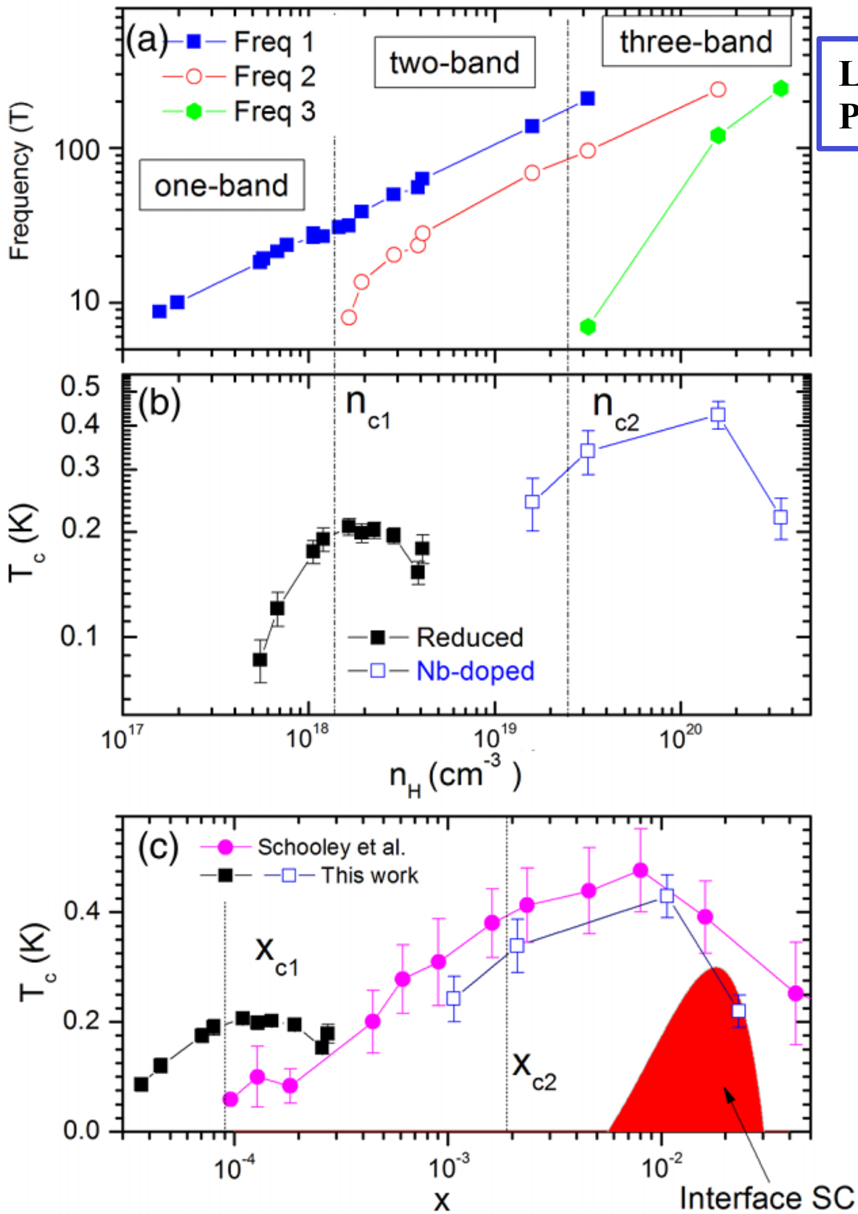
"Semiconducting" superconductors



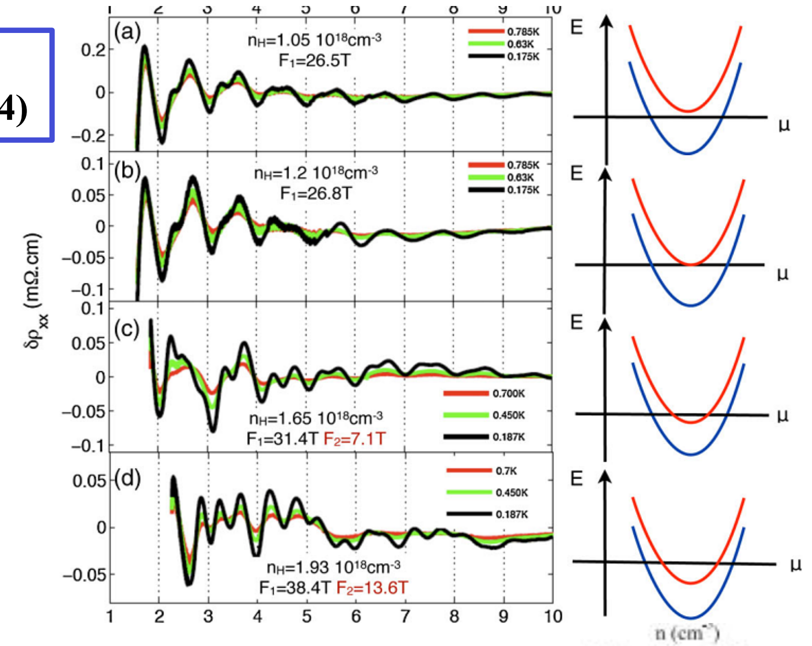
$5.5\ 10^{17}\ cm^{-3}$ **K Ueno et. al., Nature Nanotechnology 6, 408 2011**

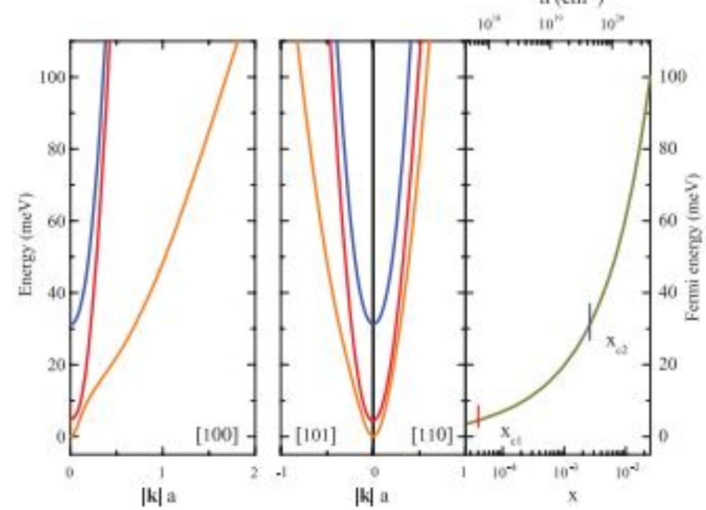
By far, the most dilute superconductor currently known

Bands and domes in n-doped STO!



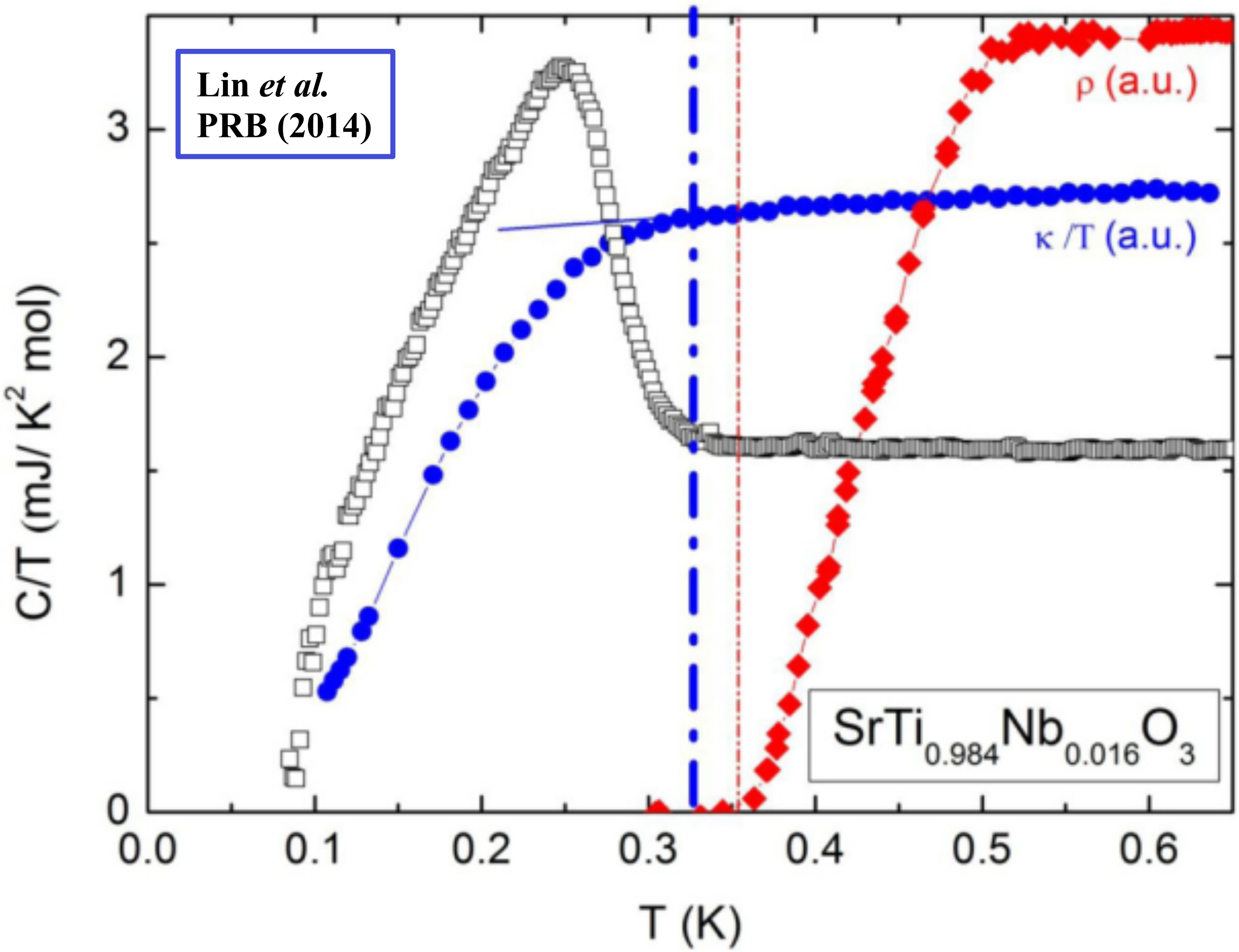
Lin *et al.* PRL (2014)





van der Marel, van Mechelen & Mazin, PRB (2011)

Superconducting transition seen by different probes



$\gamma = 1.55\, mJ/k\uparrow 2\ mol$

Compatible with:

m_1=3.8m_e
m_2=1.8m_e
m_3=1.8m_e

Theory on microscopic origin of pairing

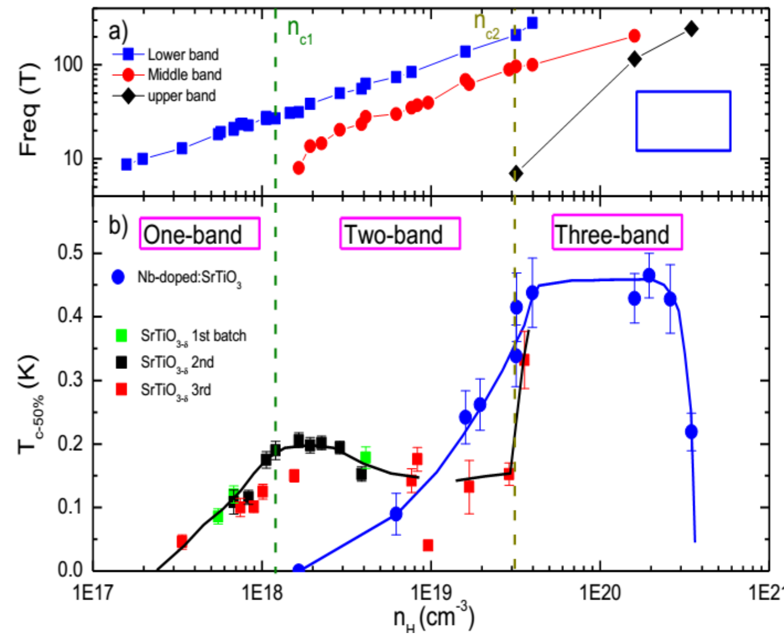
•Plasmons?
Takada 1980
P. A. Lee 2016

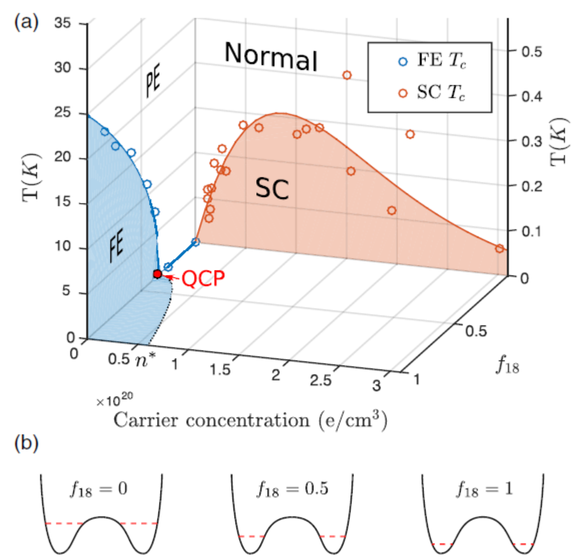
•A phonon Soft mode ?
Appel 1980

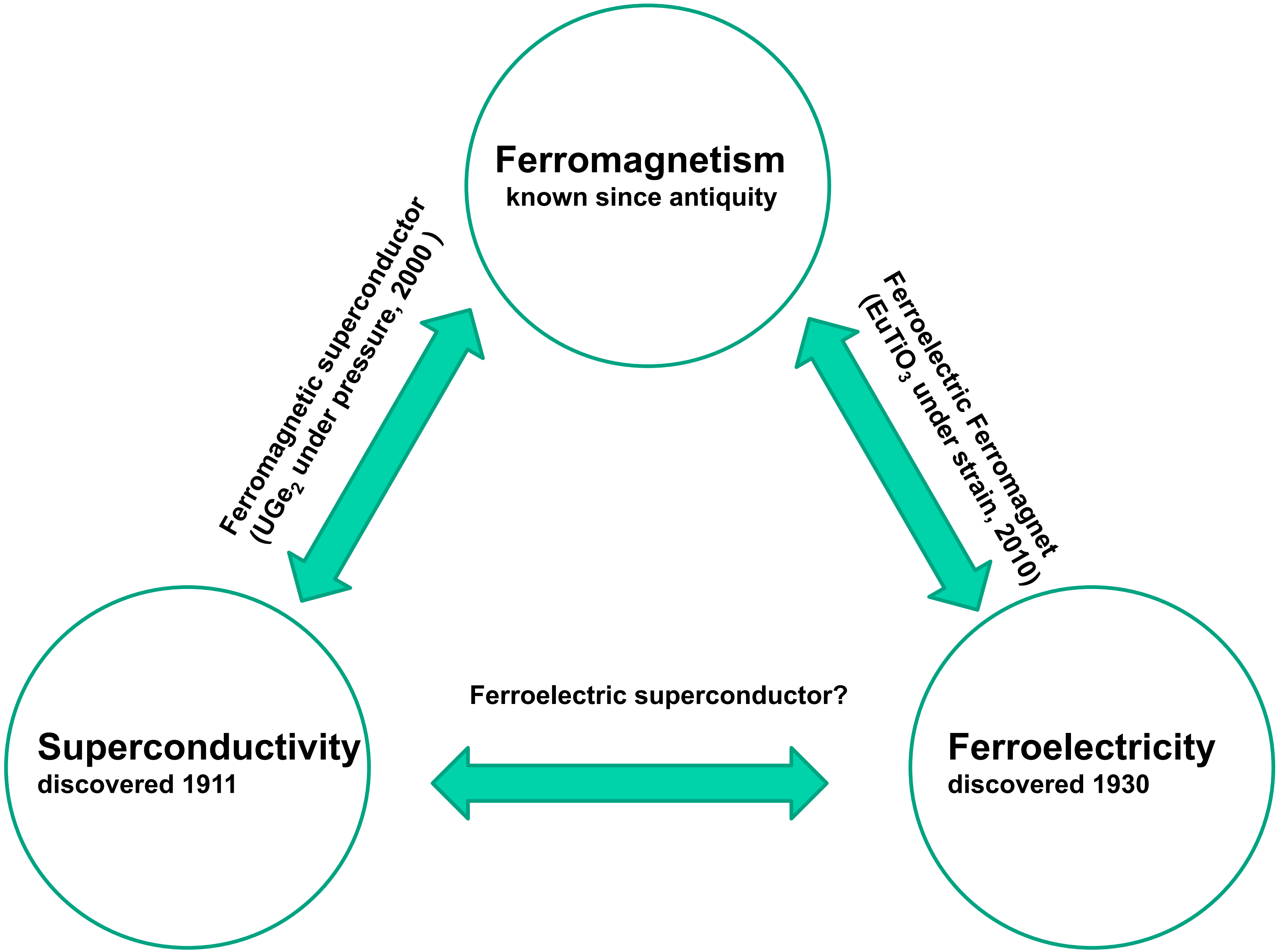
•Negative U superconductivity?
Geballe and Kivelson 2014

•Longitudinal optical phonons?
Gor'kov 2016

Ferroelectric quantum criticality?
Lonzarich *et al.* 2014
Balatasky *et al.* 2015

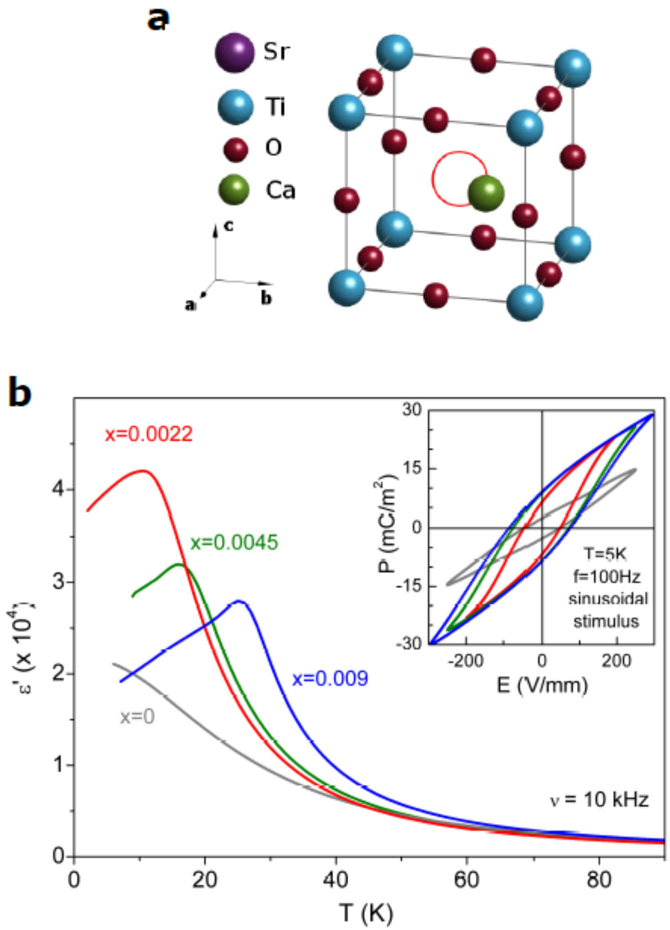




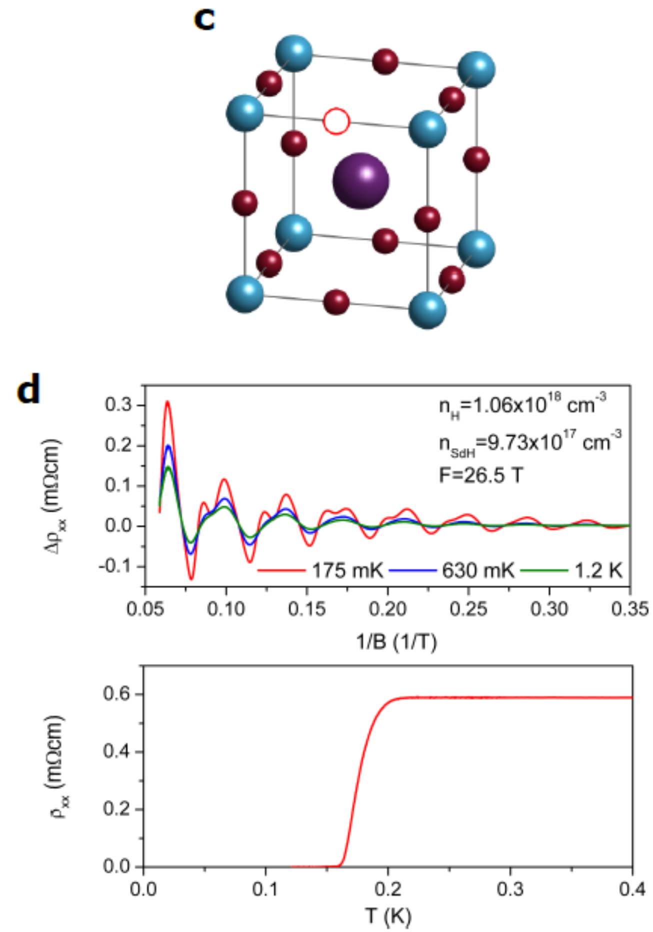


Ferromagnetism
known since antiquity
Ferromagnetic superconductor
(UGe2 under pressure, 2000)
Ferroelectric Ferromagnet
(EuTiO3 under strain, 2010)
Ferroelectric superconductor?
Superconductivity
discovered 1911
Ferroelectricity
discovered 1930

$Sr_{1-x}Ca_xTiO_3$ (0.002<x<0.02)
Ferroelectric

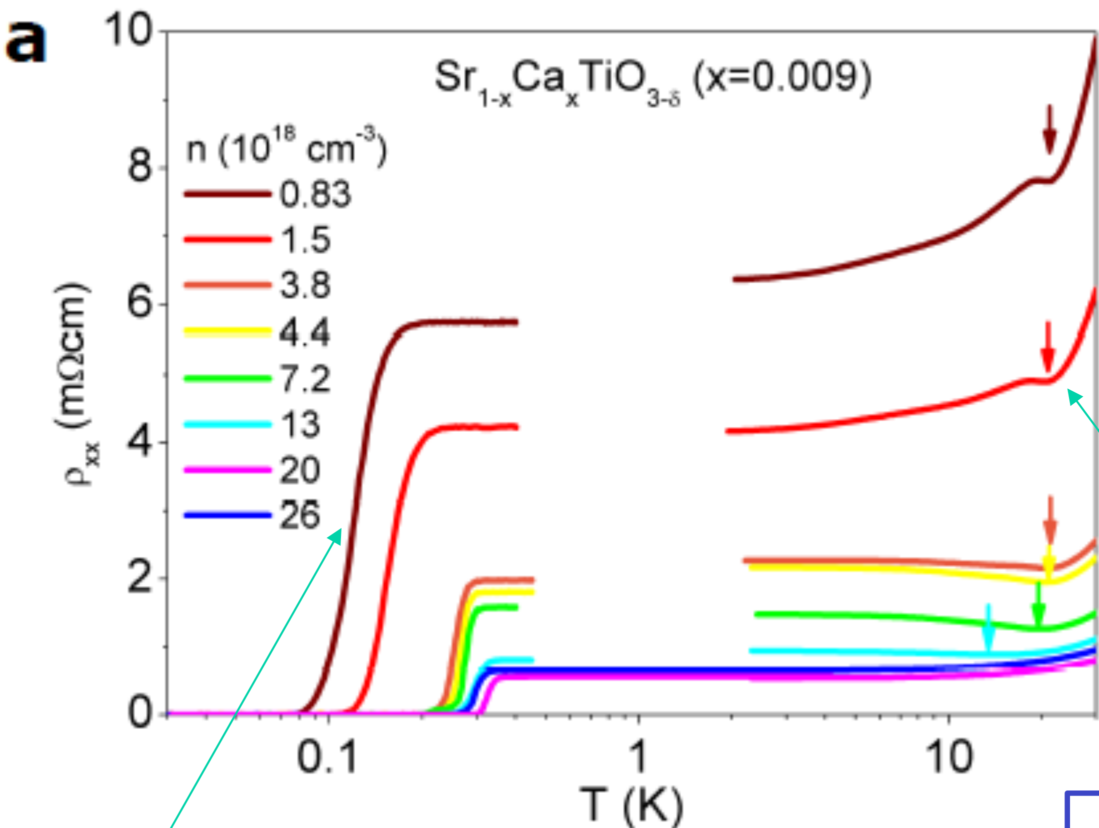


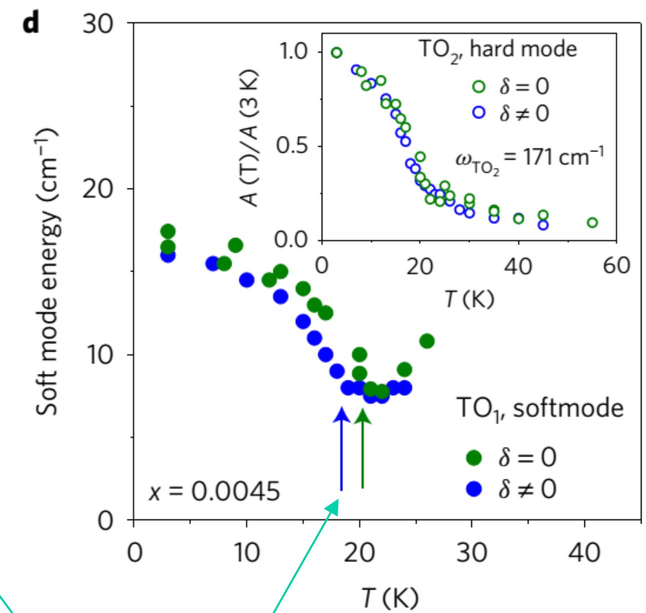
$SrTiO_{3-\delta}$ (10^{-5}<δ<10^{-2})
Metal & superconductor



What happens to these two orders if both substitutions happen at the same time?

Two phase transitions in metallic samples

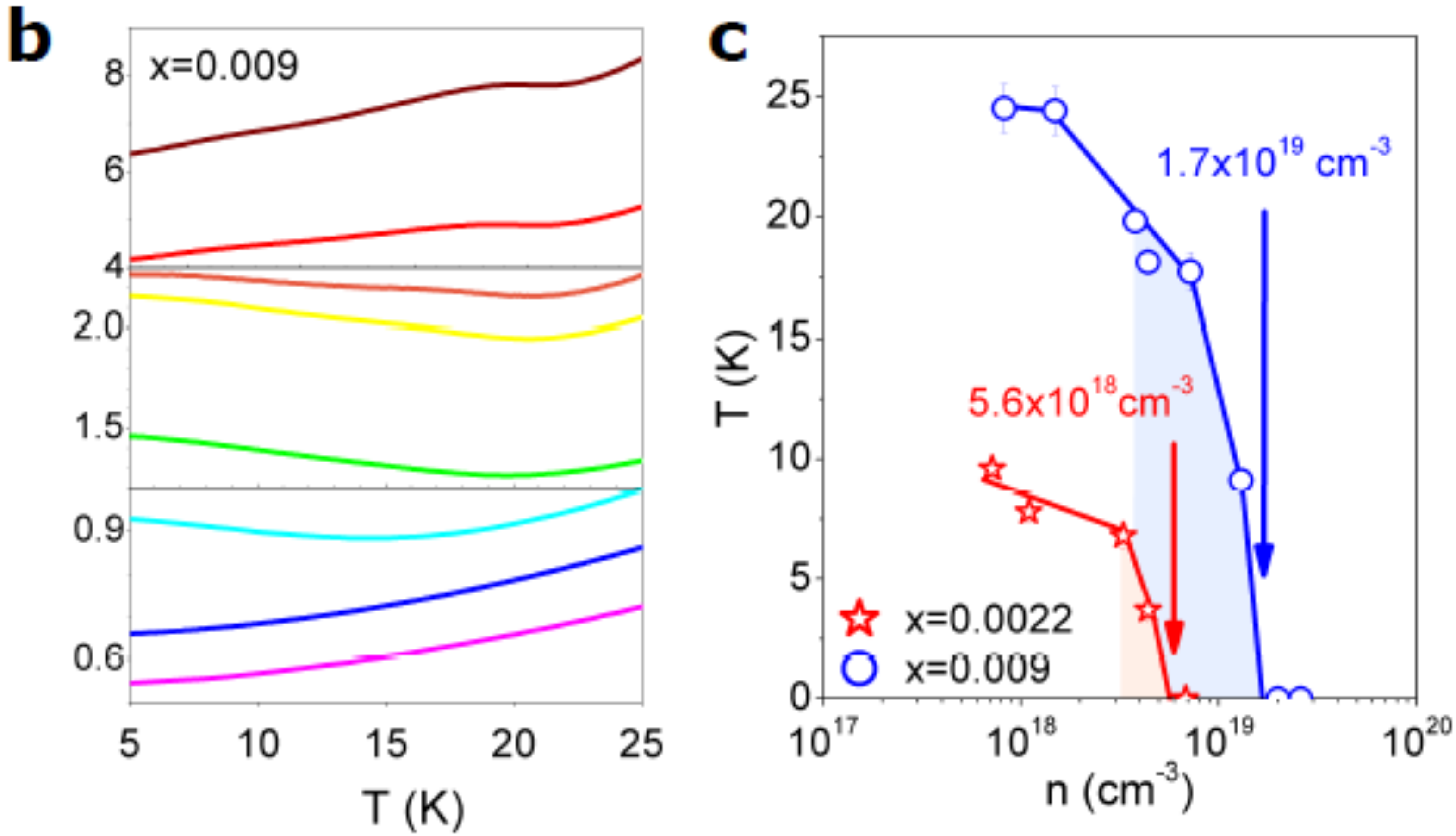




Superconducting transition

- Ferroelectric-like transition
- Raman scattering: no difference between the insulator and the dilute metal!

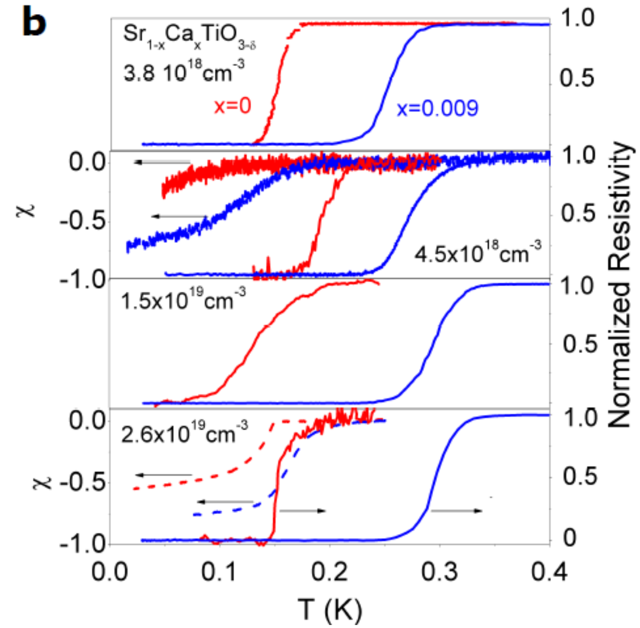
Destruction of the ferroelctric order

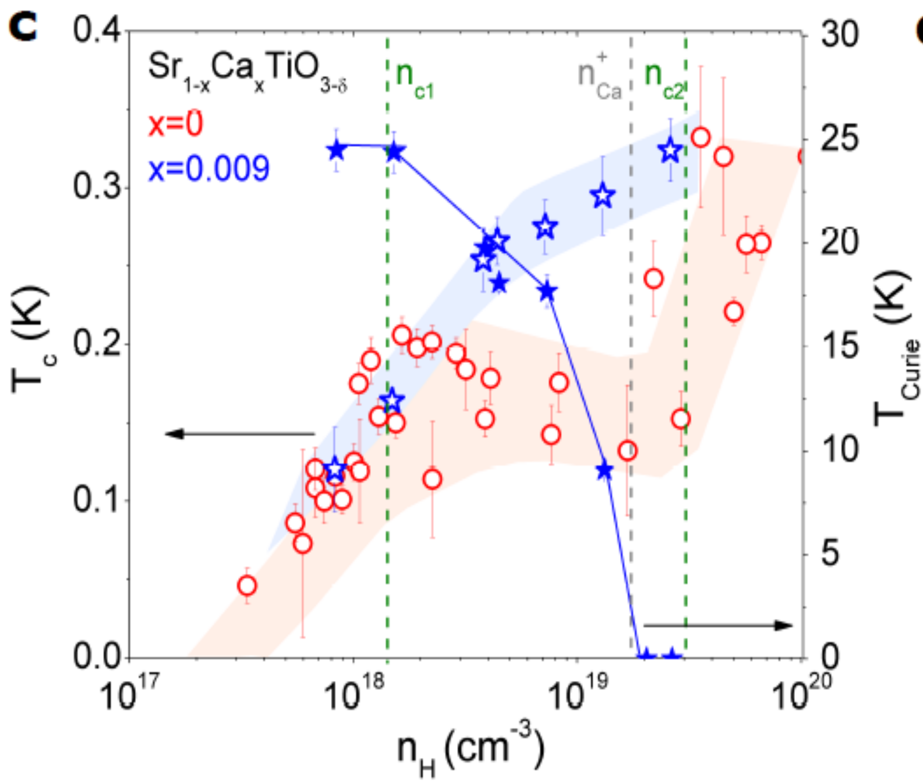


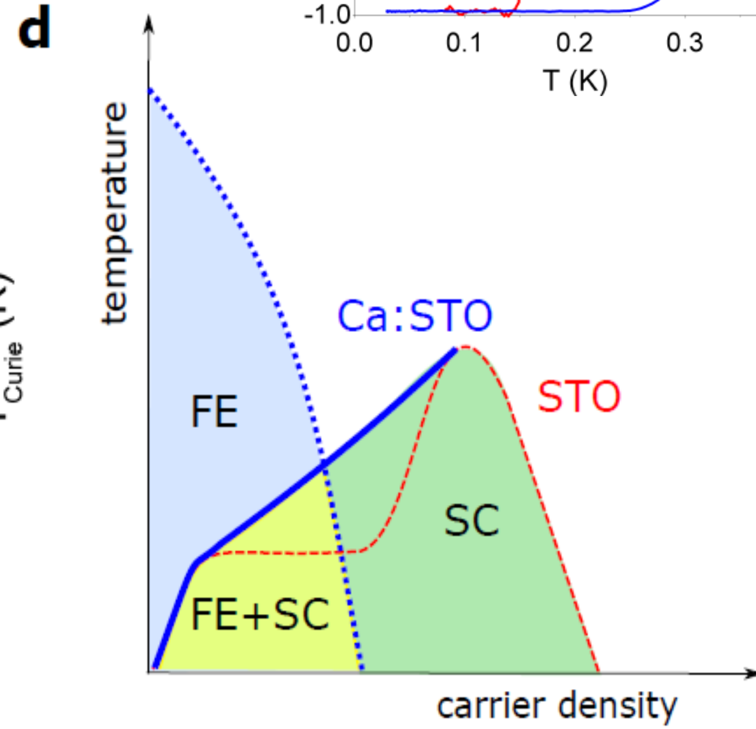
A Quantum Phase Transition at a critical doping, which scales with Ca content

Ferroelectric quantum criticality?

Rischau *et al.*, Nature Physics (2017)







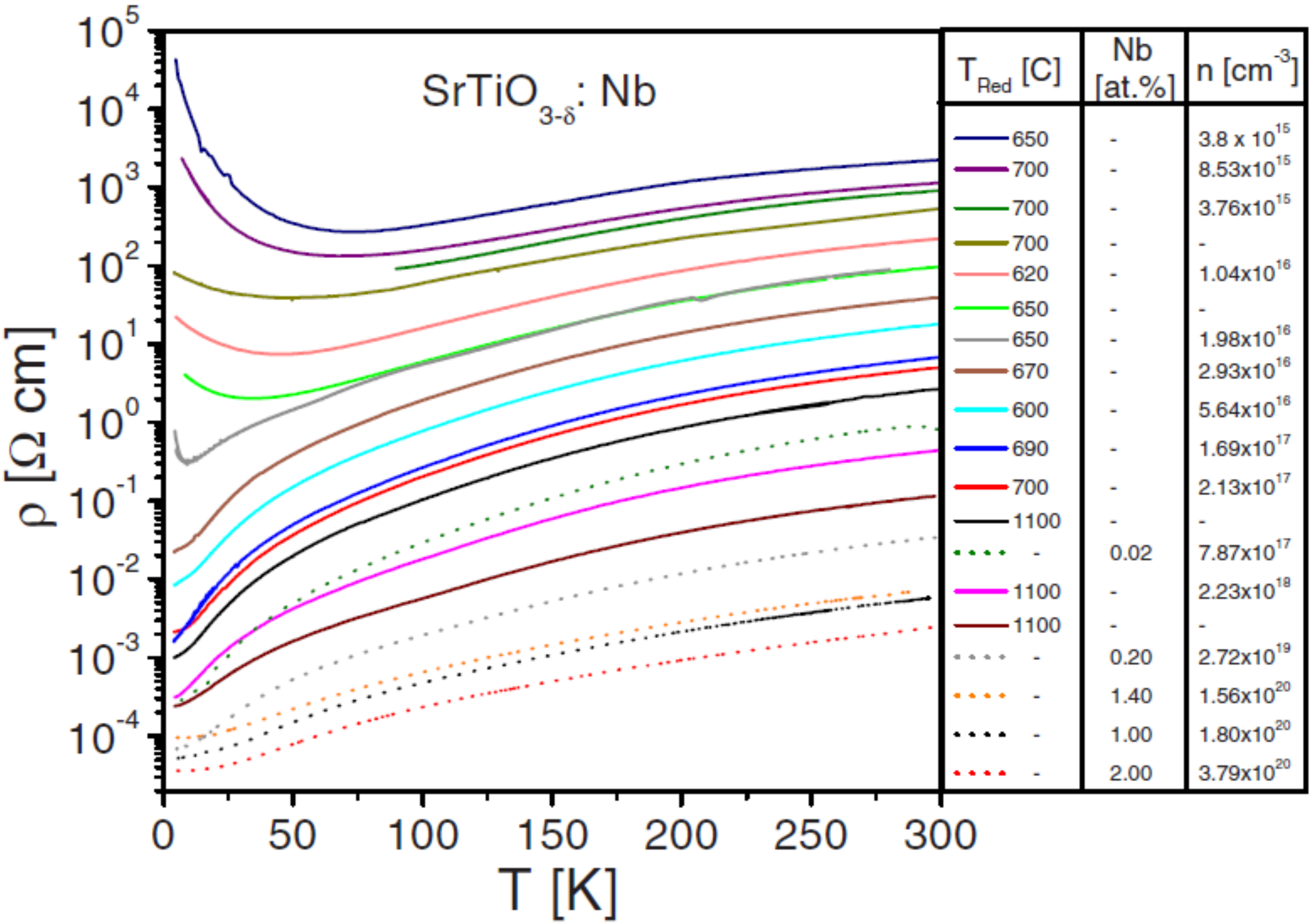
See also van der Marel's recent work on O^{18} substitution!

II. Mysteries of charge transport

Carrier density can be tuned over a wide range

Spinelli et al.PRB (2010)

$3.8\ 10^{15}\ cm^{-3}$



Reduced

Nb-doped

$3.8\ 10^{20}\ cm^{-3}$

Do we understand:

- Zero-temperature conductivity?

Yes, Mobility is high because Bohr radius is long!

- Conductivity below the degeneracy temperature?

Maybe, T-square resistivity is expected in a Fermi liquid, but…

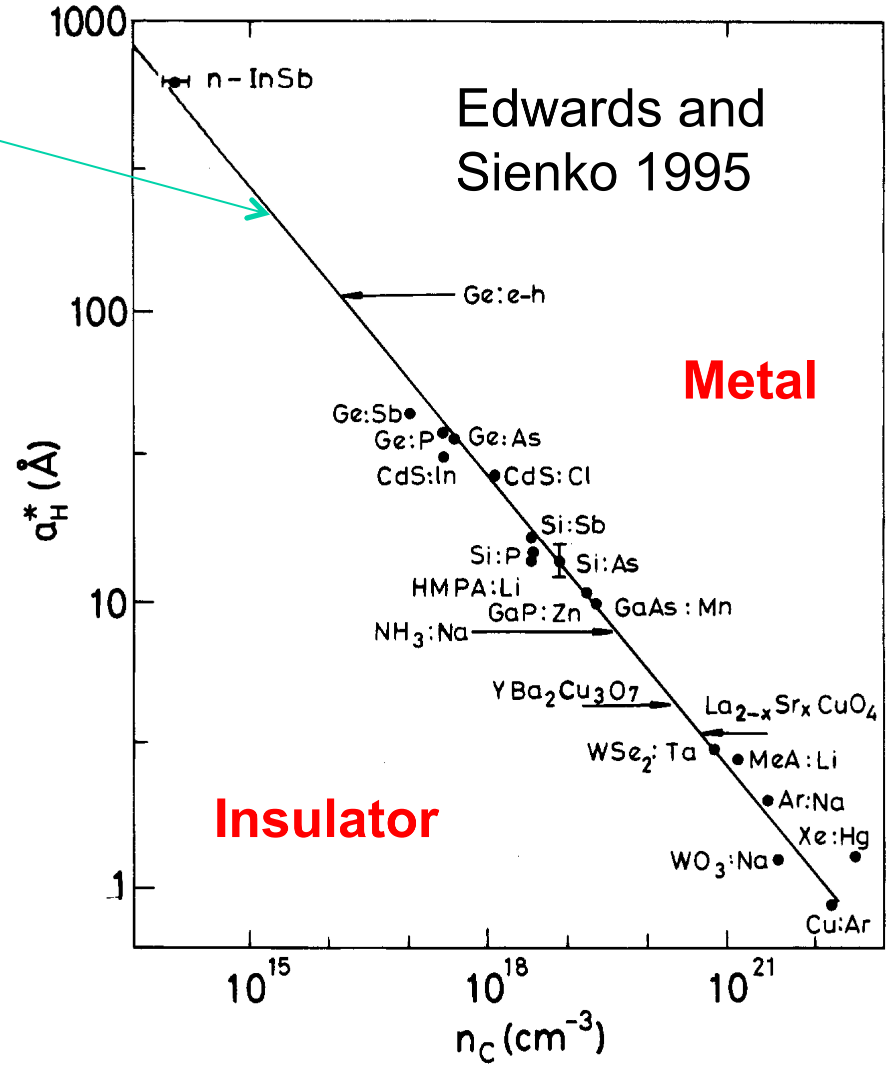
- Conductivity at room-temperature and above?

No, the Drude picture leads to an unbearable paradox!

Mott criterion for metal-insulator transition

STO

$$a_B n^{1/3} \cong 0.25$$



In STO

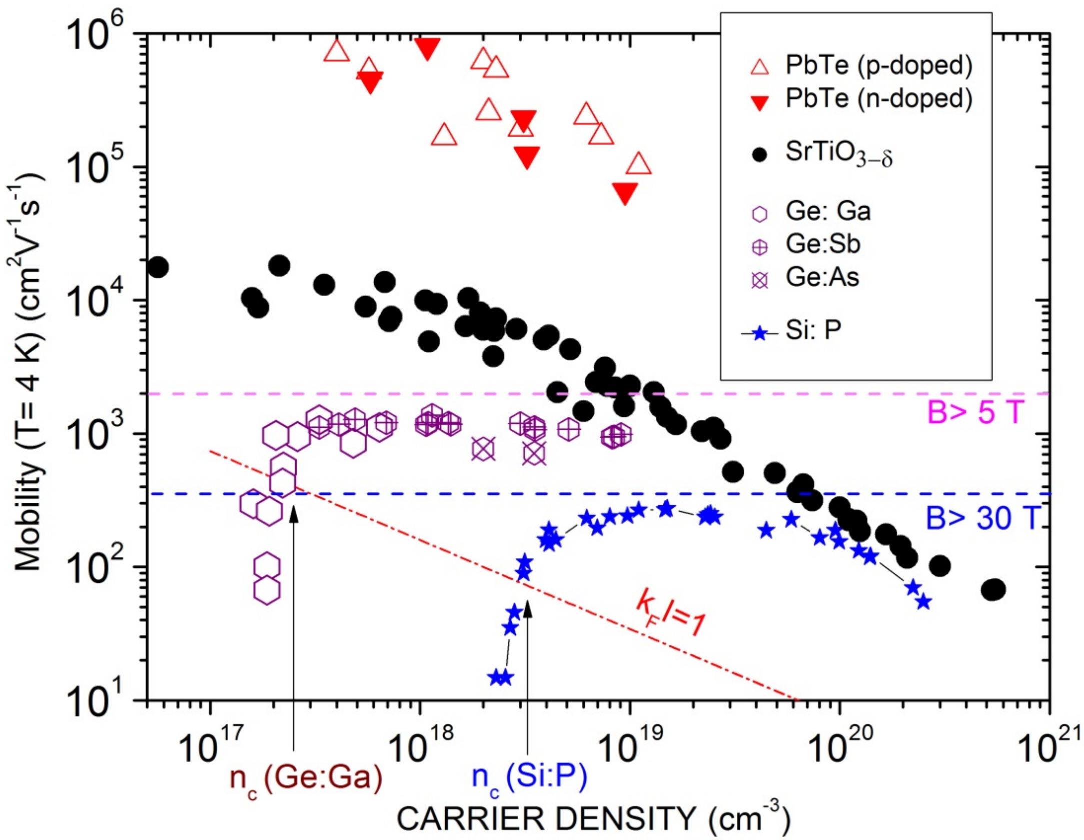
$m^* = 1.8\ m_e$

$\varepsilon = 1.8\ 10^4$

$a_B =$ **600 Å**

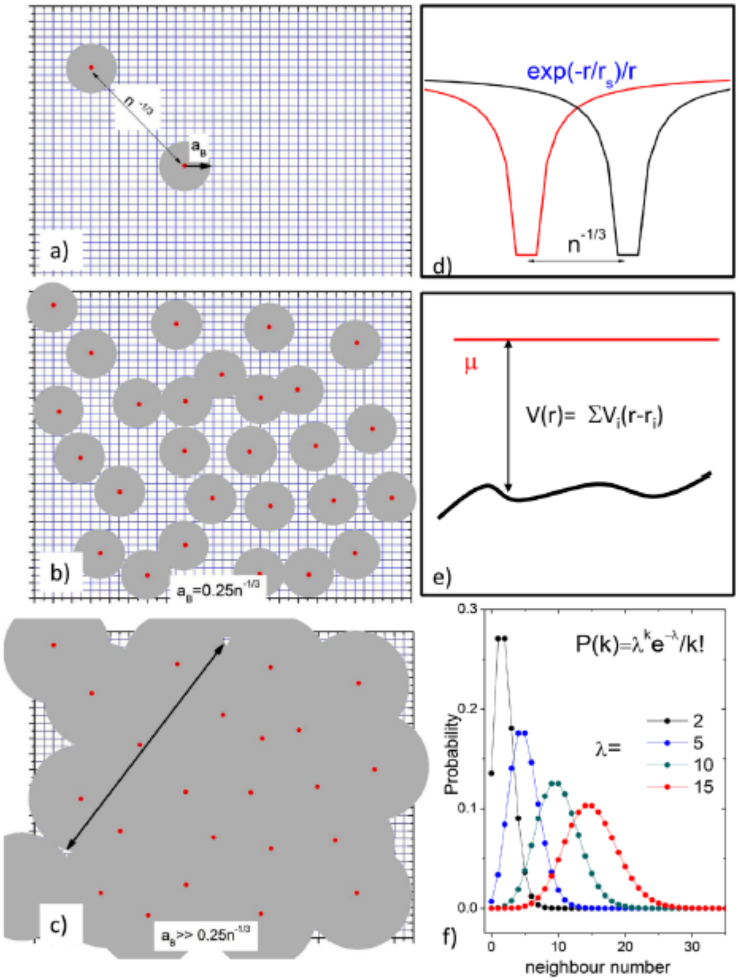
Electron mobility and the Bohr radius in shallow Fermi seas

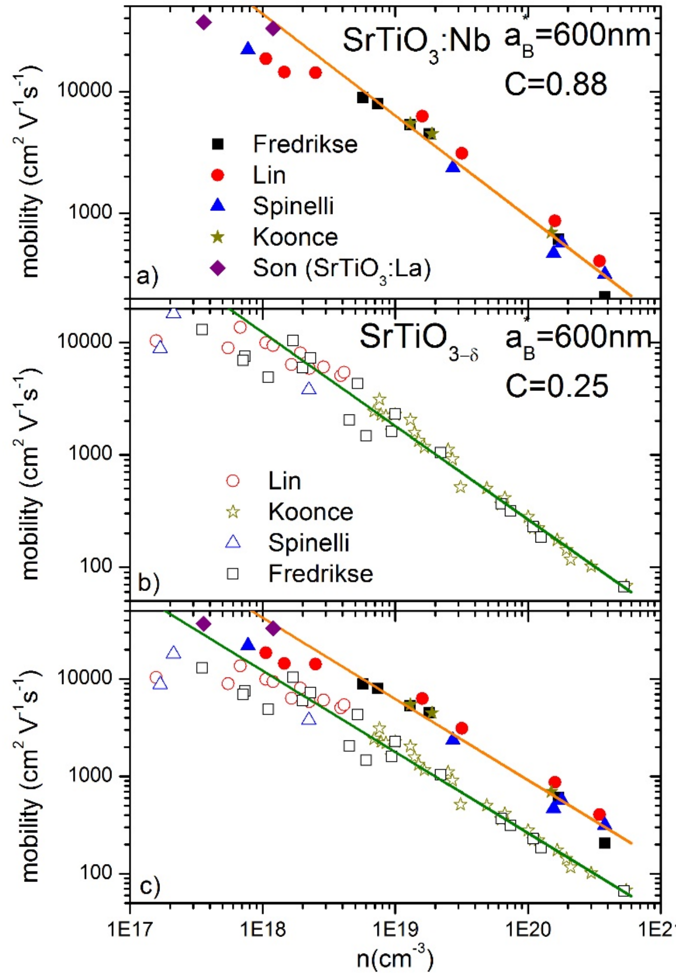
	Dielec. ($\varepsilon_r/\varepsilon_0$)	m^*/m_0	Bohr radius (nm)
STO	20000	1.8	600
PbTe	1000	0.07	800
Si	12.5	0.45	1.5
Ge	16	0.24	3.5



The longer the Bohr radius, the higher the mobility!

Electron mobility depends on Bohr radius





Probability of islands when the Fermi seafloor is carved by a random distribution of dopants

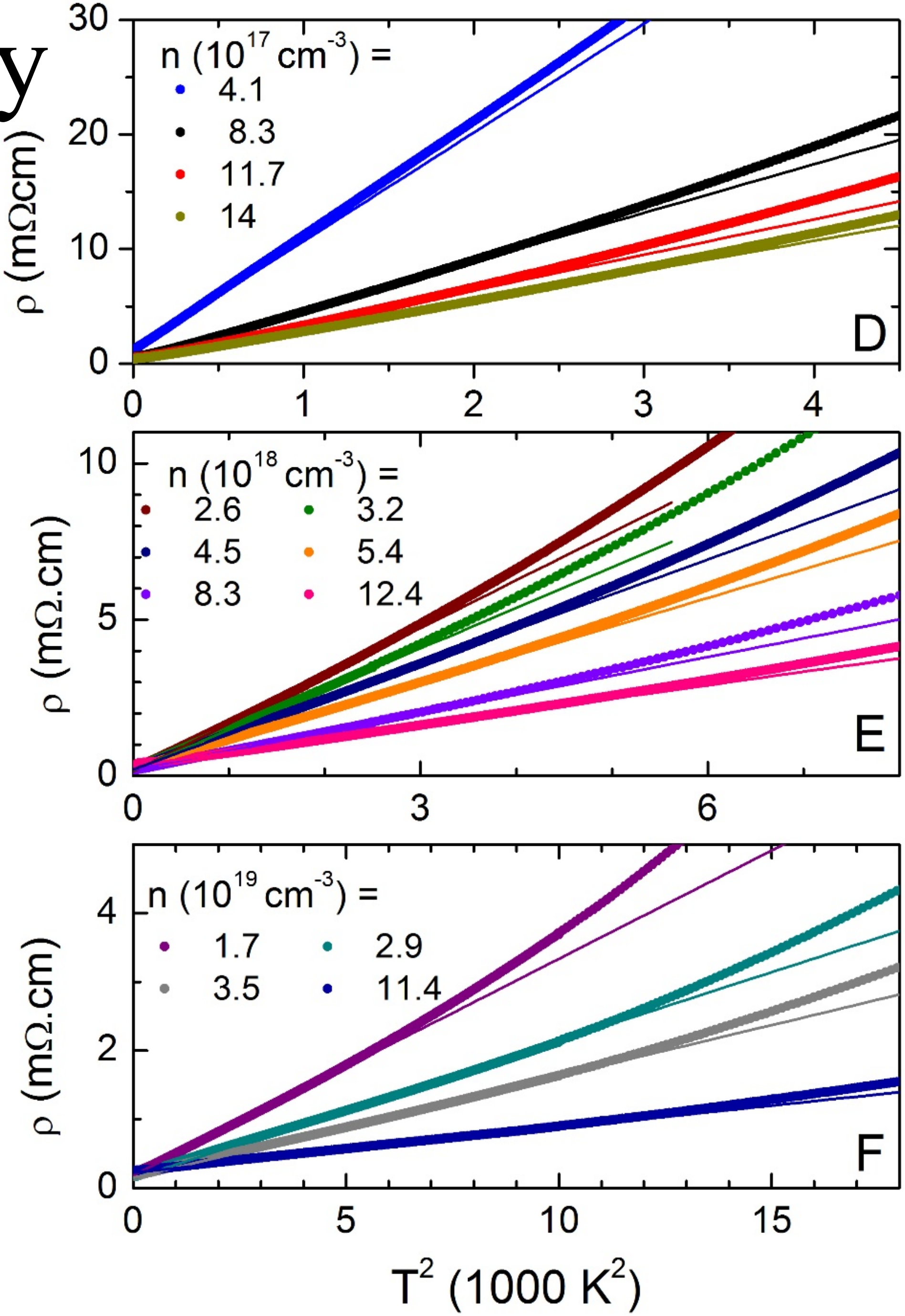
$$\mu \propto a_B^{1/2} n^{-5/6}$$

KB, JPCM 2015

T-square resistivity

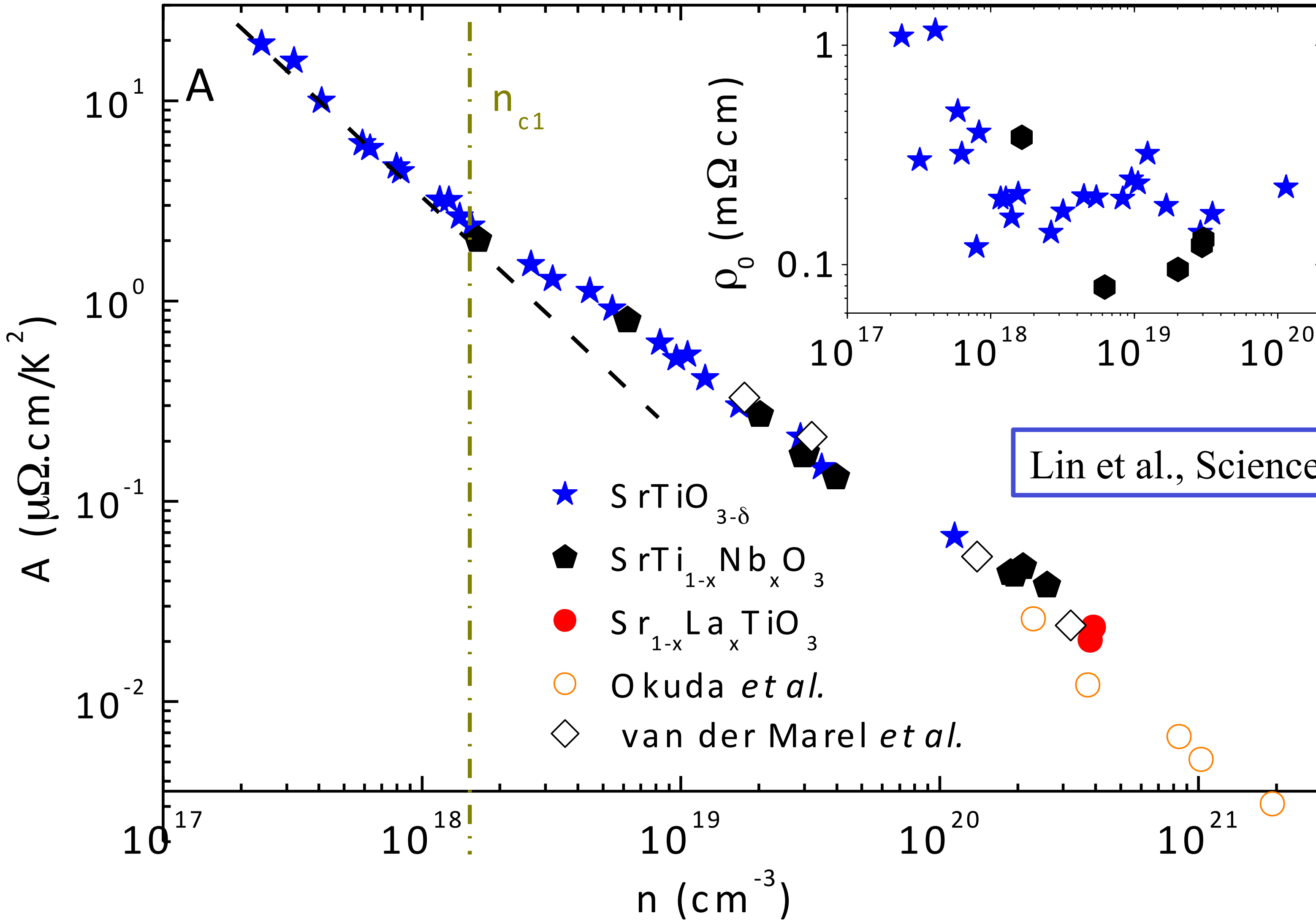
$$\rho=\rho_0 + AT^2$$

- Resistivity remains T^2 even for $n \sim 10^{-5}$
- The prefactor of T^2 resistivity decreases with increasing doping.



Lin et al., Science (2015)

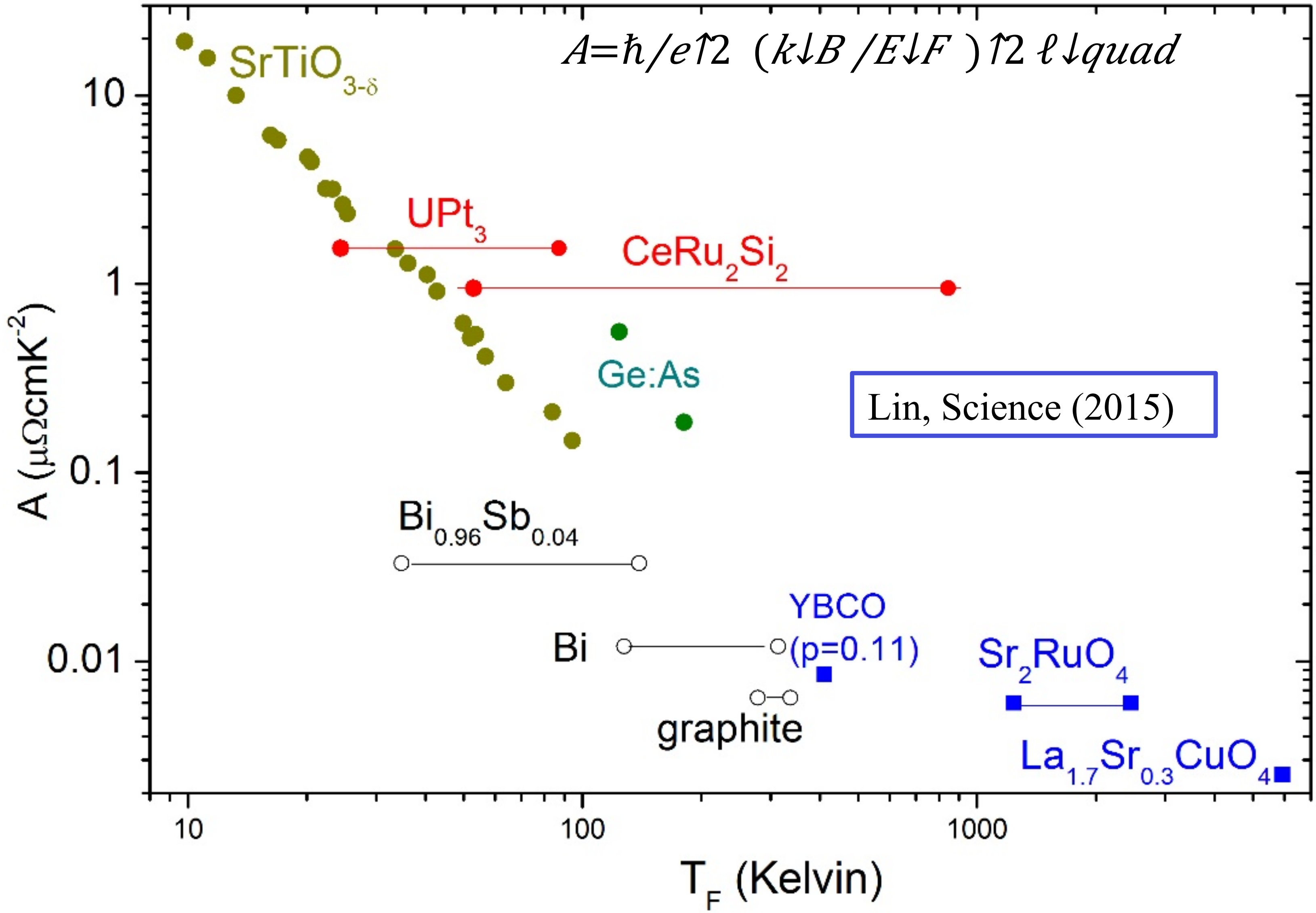
T-square resistivity

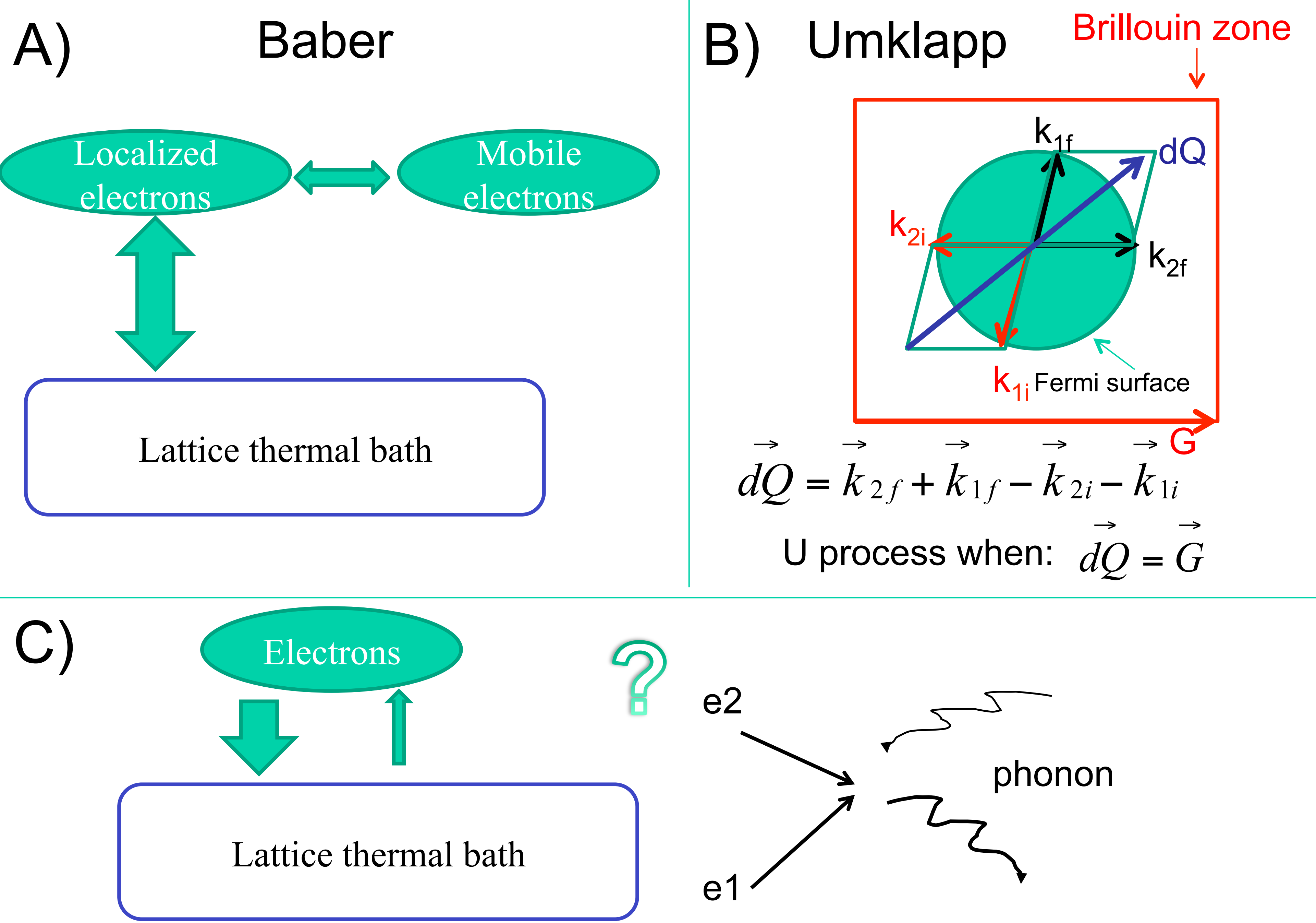


Lin et al., Science (2015)

A can be tuned over four orders of magnitude!

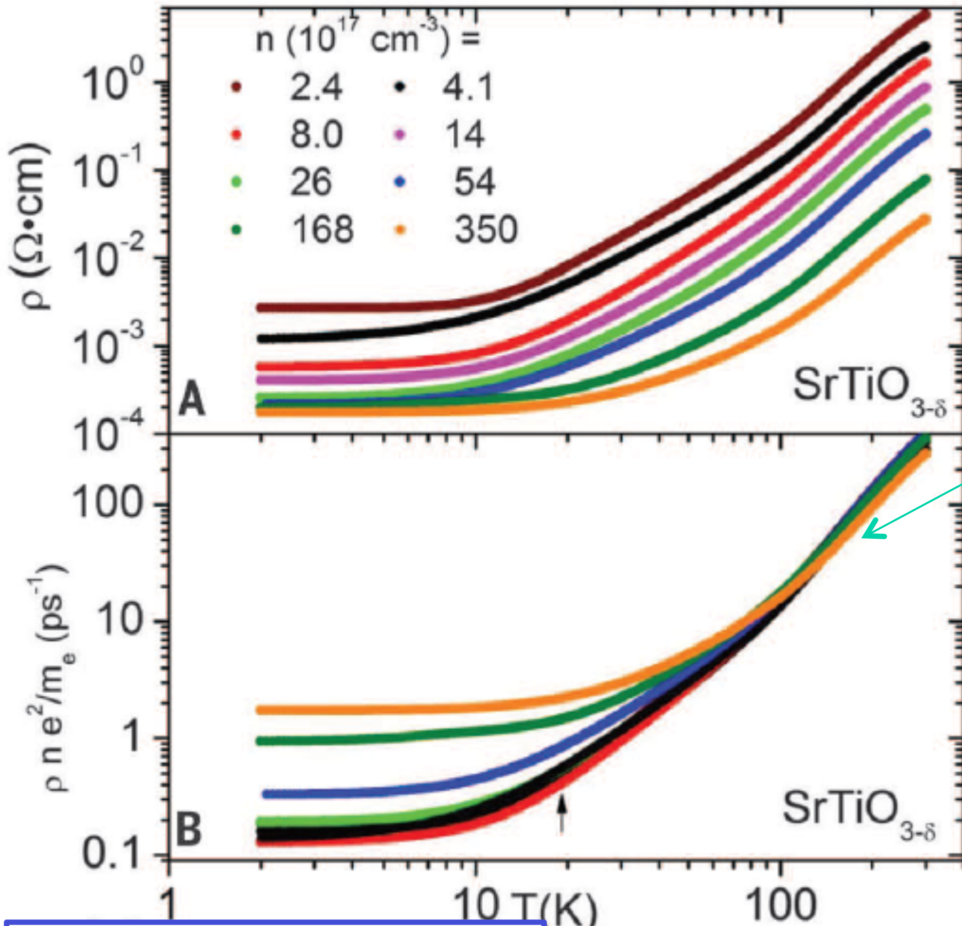
T-square resistivity



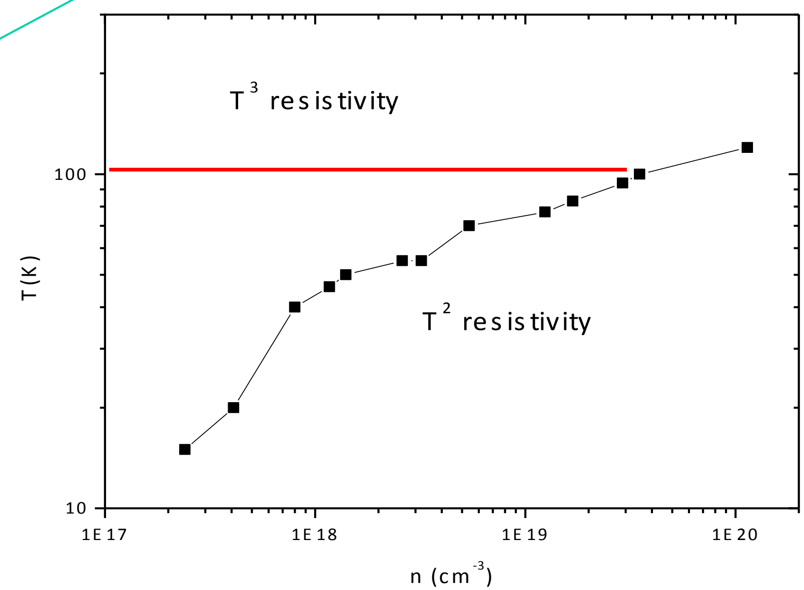


How can e-e scattering relax momentum in absence of A and B ?

High temperature cubic resistivity



Lin et al., Science (2015)



PHYSICAL REVIEW VOLUME 155, NUMBER 3 15 MARCH 1967

Electron Mobility in Semiconducting Strontium Titanate

O. N. TUFTE AND P. W. CHAPMAN
Honeywell Corporate Research Center, Hopkins, Minnesota
(Received 18 October 1966)

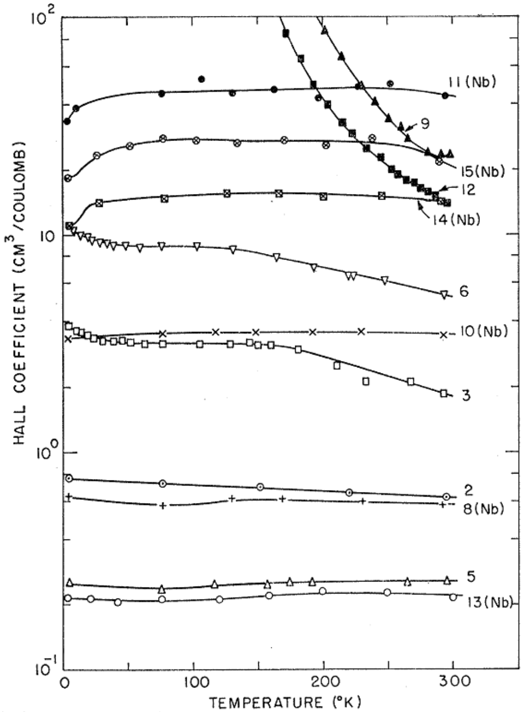


FIG. 2. The temperature dependence of the Hall coefficient in semiconducting $SrTiO_3$.

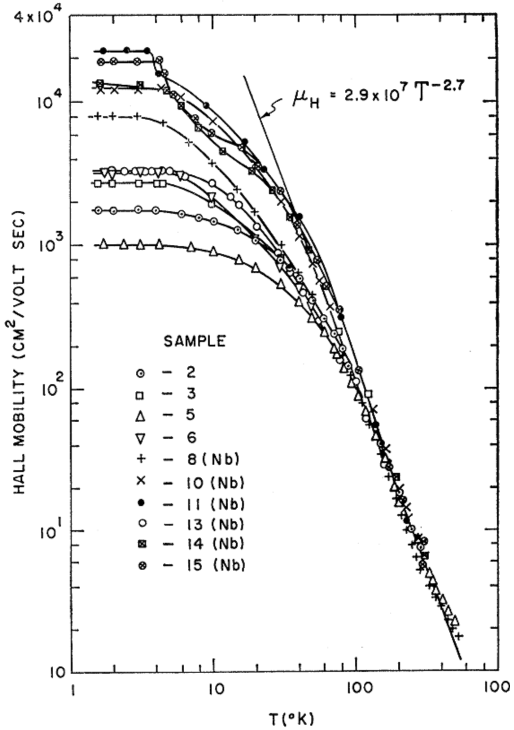
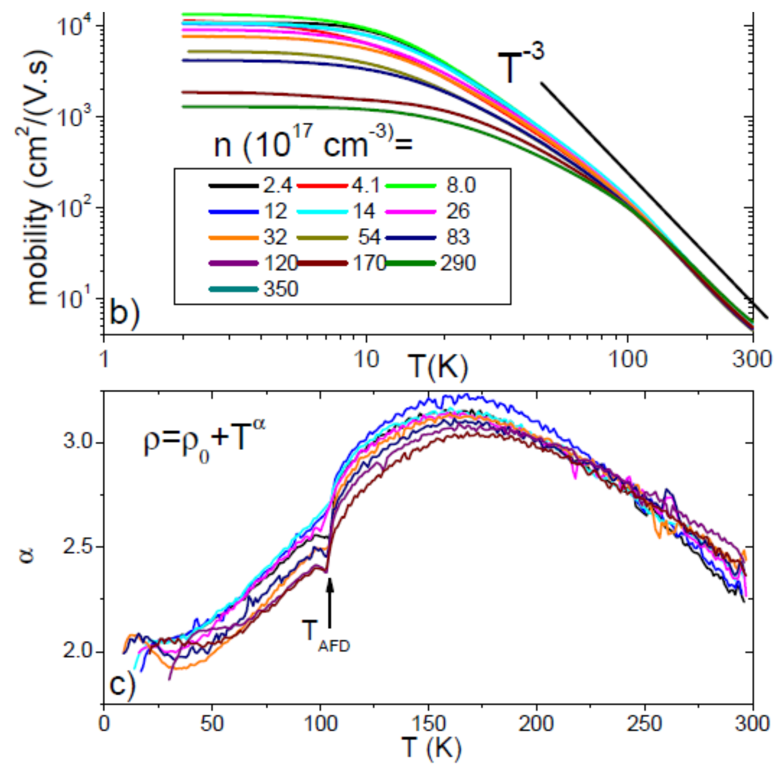


FIG. 4. The temperature dependence of the Hall mobility in semiconducting $SrTiO_3$.

Lin *et al.*
NPJ Quant. Mat. 2017

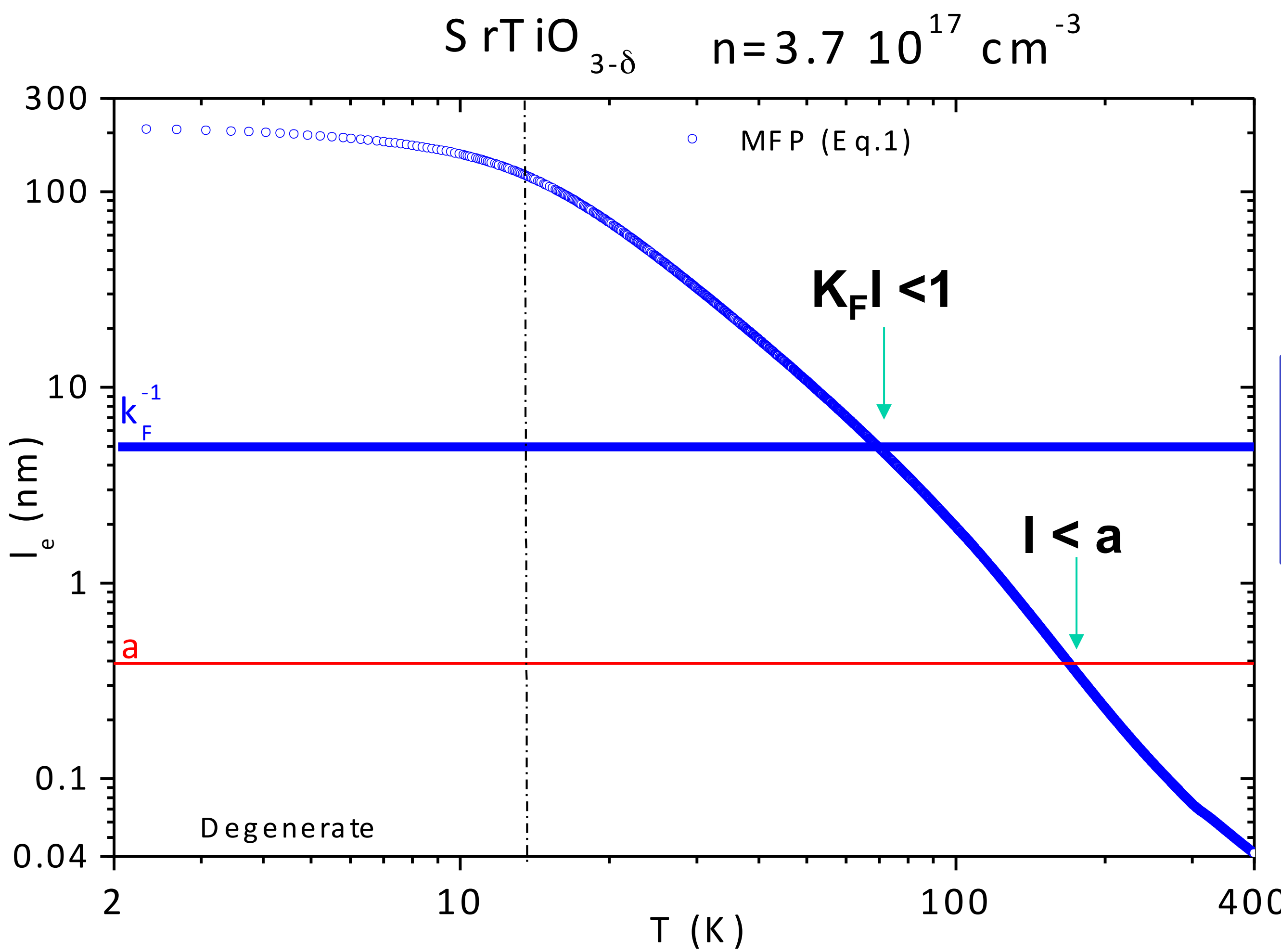


Similar data by
- Susanne Stemmer group, Santa Barbara
- Chris Leighton group, Minesotta
- Bhattacharya et al., Argonne

Drude conductivity

$$\sigma = \frac{ne^2\tau}{m^*} = \frac{1}{3\pi^2}\frac{e^2}{\hbar}k_F^2\ell_e$$

Knowing the carrier concentration, one can extract mean-free-path!



Mean-free-path below two conceivable floors!

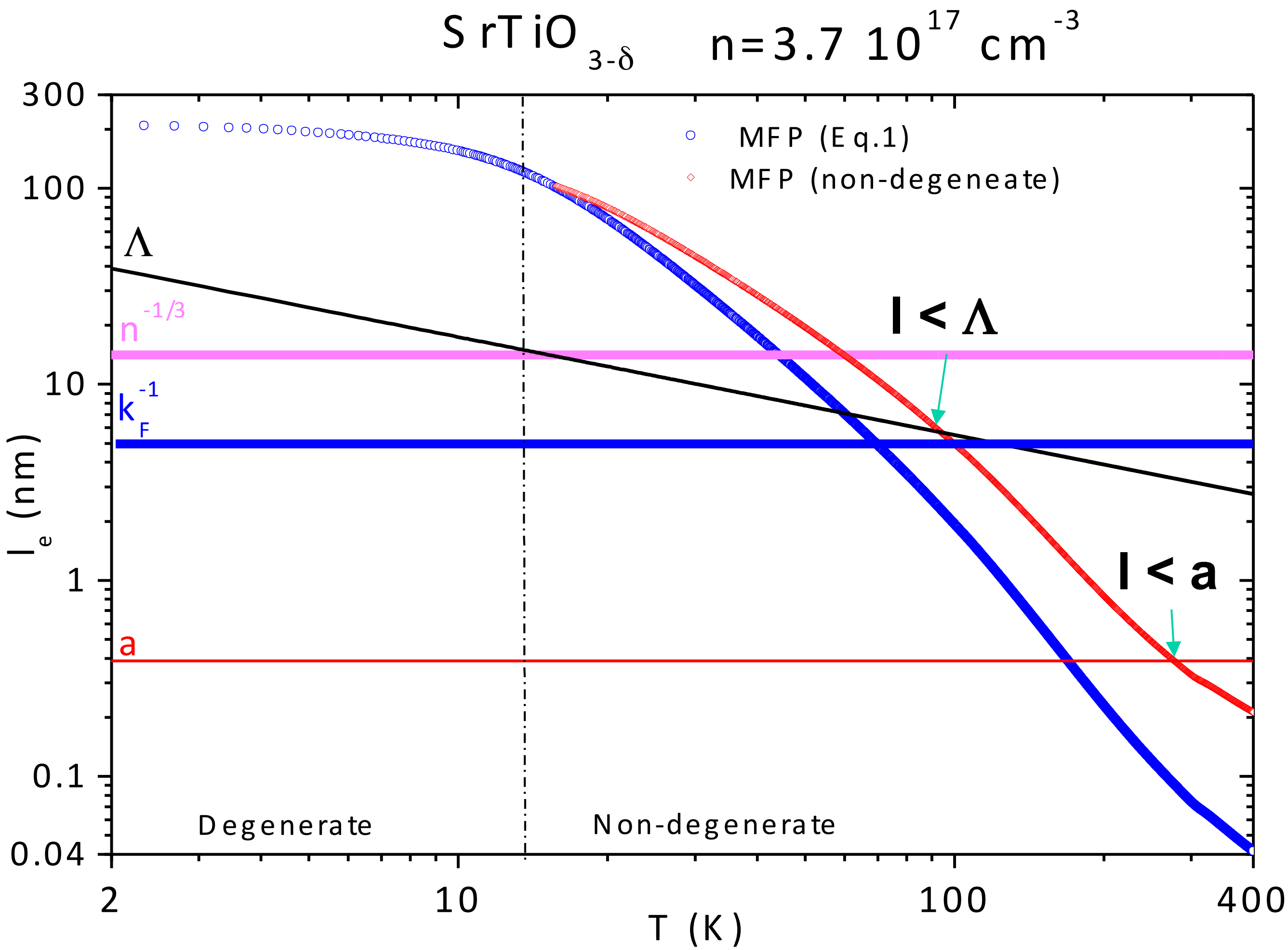
Drude conductivity

$$\sigma = \frac{ne^2\tau}{m^*} = \frac{1}{3\pi^2}\frac{e^2}{\hbar}k_F^2\ell_e$$

For non-degenerate carriers, velocity is thermal (and not Fermi).

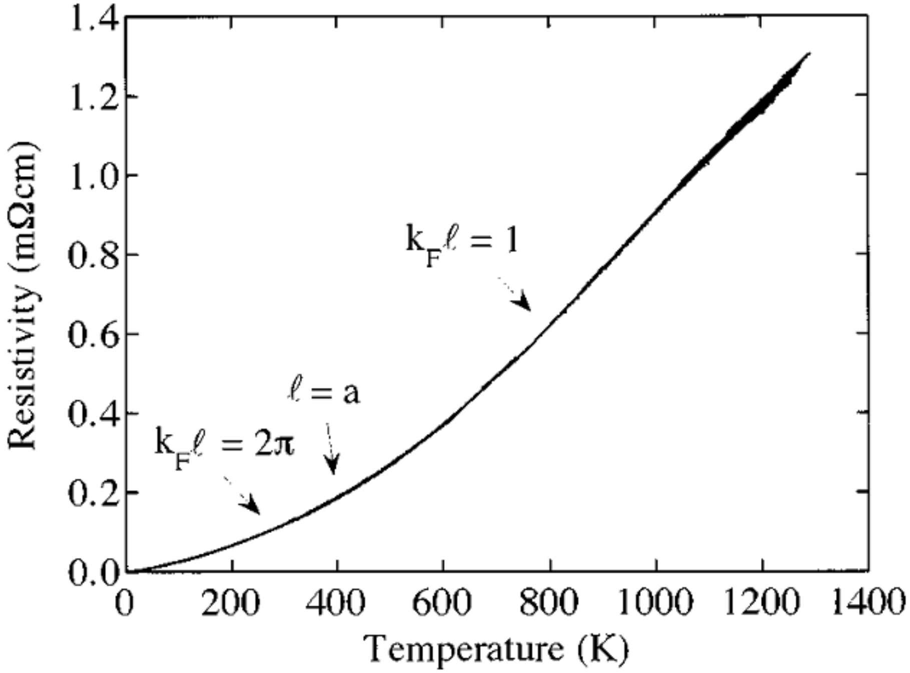
$v_F = hk_F / m^*$

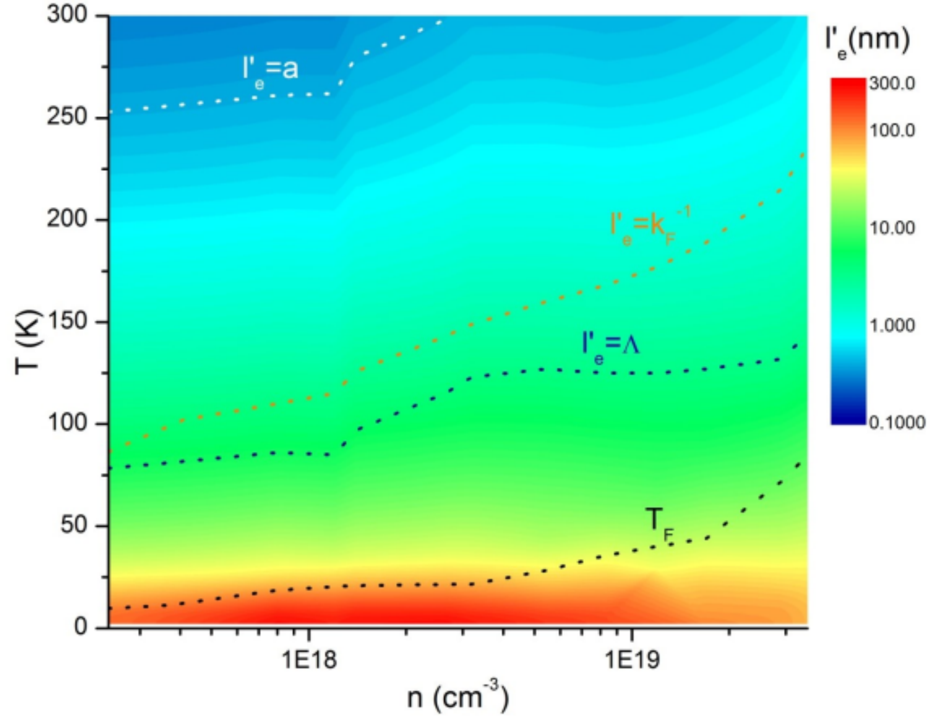
$v_T = \sqrt{2} k_B T / m$



Mean-free-path falls below any conceivable floor!

The MIR limit exceeded at cryogenic temperatures!



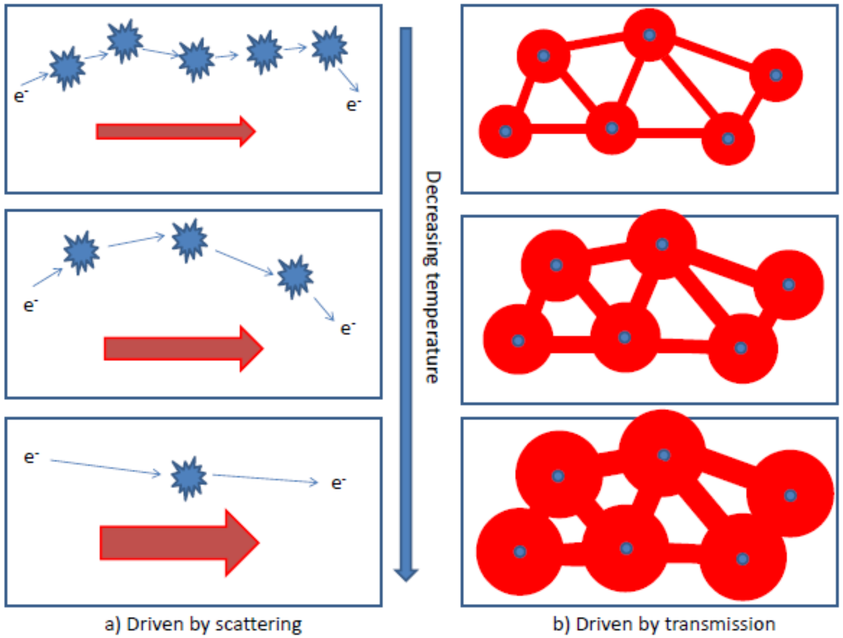


Sr_2RuO_4
Tyler et al. 1998

$SrTiO_{3-\delta}$

Compound	k_F (nm^{-1})	ρ(400K) (mΩcm)	ℓ(400K)(nm)	$k_F\ell$ (400K)	$T_{k_F\ell=1}$ (K)	Reference
$La_{1.72}Sr_{0.18}Cu0_4$	6.6	0.32	0.35	2.2	850	[4, 34]
$YBa_2Cu_4O_8$	1.4	0.36	0.8	1.1	450	[35, 36]
Sr_2RuO_4	5.6	0.2	0.38	2.1	800	[37]
$SrTiO_{3-\delta}$ (n=4 10^{17} cm^{-3})	0.24	5900	0.03	0.07	70	This work

Two pictures of metallicity

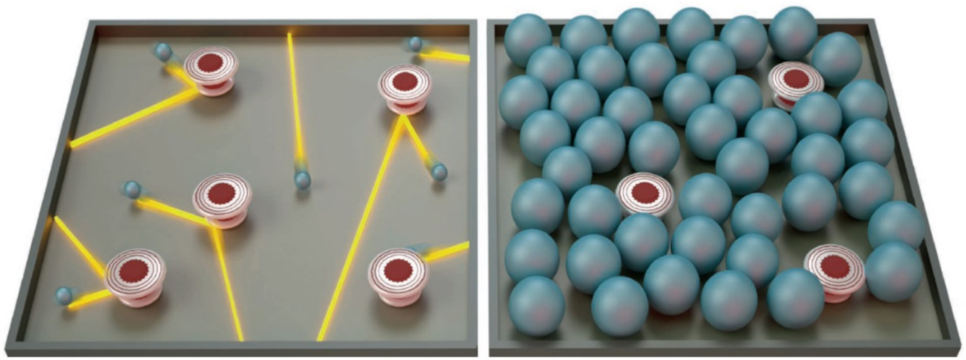


PHYSICS

Electrons go with the flow in exotic material systems

Electronic hydrodynamic flow—making electrons flow like a fluid—has been observed

By **Jan Zaanen**



Distinguishing different flow regimes. (**Left**) In conventional metals, the flow of electrical current is due to electrons (balls) moving independently as a consequence of quantum physics while scattering against crystal imperfections (bumpers). (**Right**) In normal fluids such as water, the molecules collide with each other, equilibrating in a macroscopic fluid that is described by the theory of hydrodynamics. Electrons in particular solids that form strongly interacting quantum systems are also found to exhibit hydrodynamic transport properties (*1–3*).

Lattice polarizability

Electron viscosity

ARTICLES
PUBLISHED ONLINE: 23 DECEMBER 2014 | DOI: 10.1038/NPHYS3174
nature physics

Theory of universal incoherent metallic transport

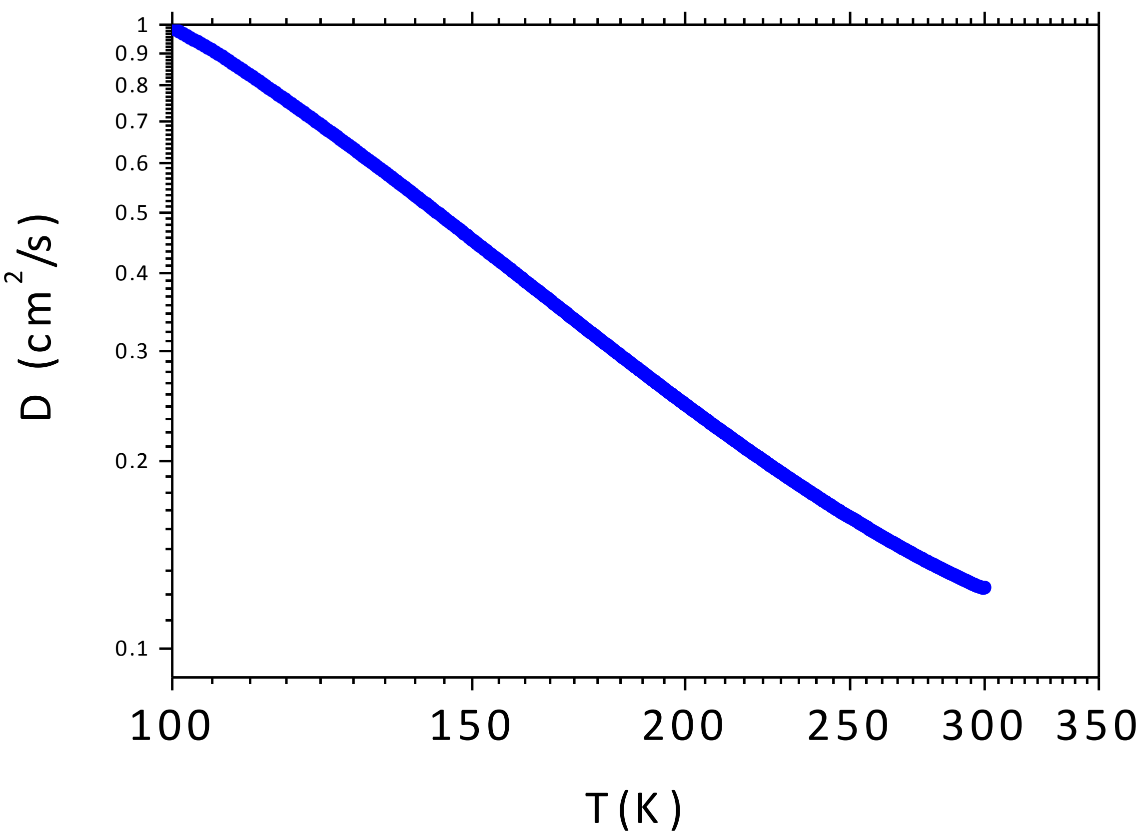
Sean A. Hartnoll

An upper boundary to the magnitude of diffusion constant

$$D \gtrsim \hbar v_F^2/(k_B T)$$

Charge diffusion constant can be extracted from mobility

$$D = \frac{\mu k_B T}{e}$$



Charge diffusion constant in dilute metallic STO

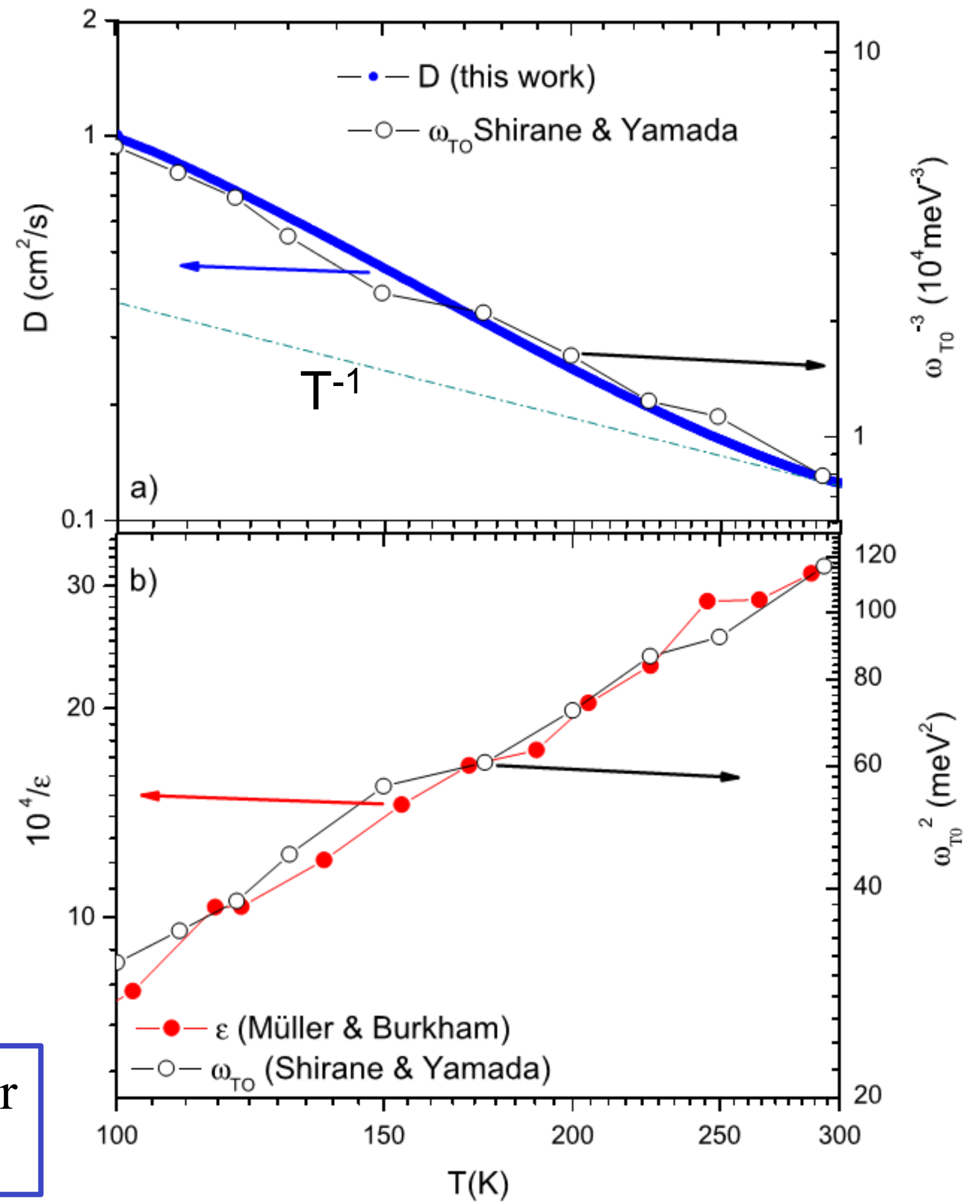
- decreases faster than T^{-1}
- tracks permittivity (or TO frequency)

$$D = \frac{\mu k_B T}{e}$$

$$\mu k_B T \propto \omega_{T0}^{-3} \propto \epsilon / \omega_{T0}$$

$$\frac{\epsilon_0}{\epsilon_\infty} = \left(\frac{\omega_L}{\omega_T}\right)^2$$

Lyddane-Sachs-Teller scaling

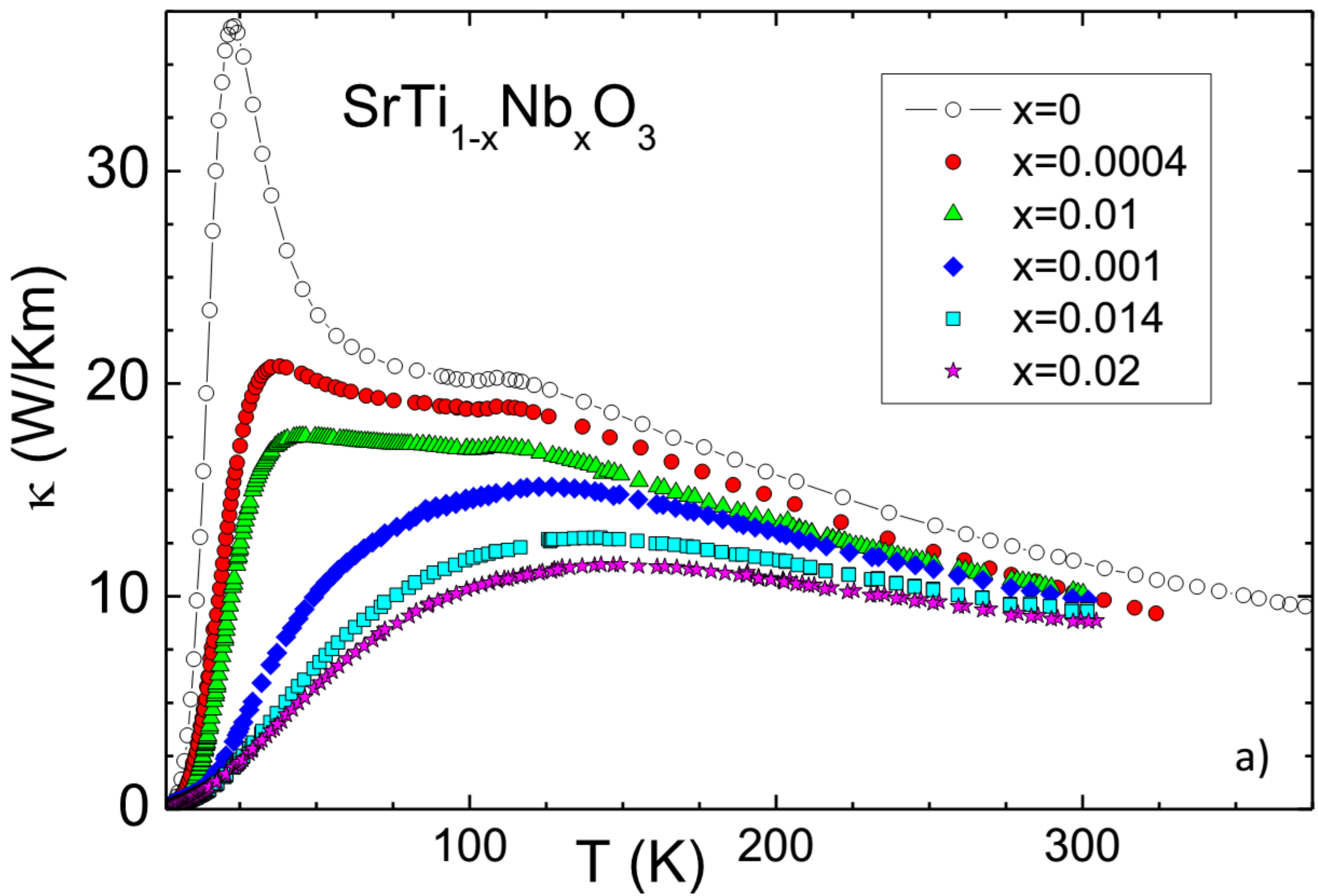


III. Heat transport

Poiseuille flow

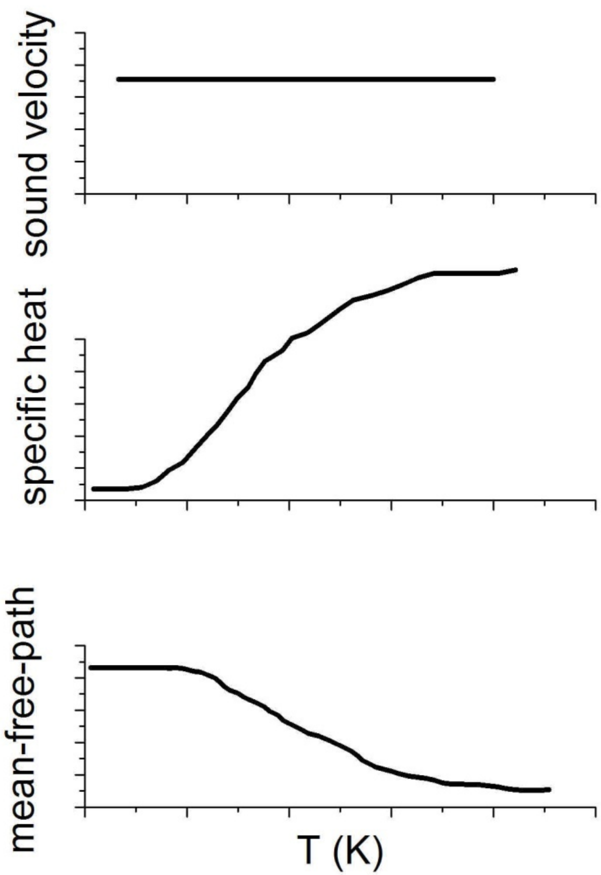
Thermal diffusivity

Martelli et al. unpublished



Thermal conductivity of insulators

$\kappa = 1/3\ C\ v\ l$



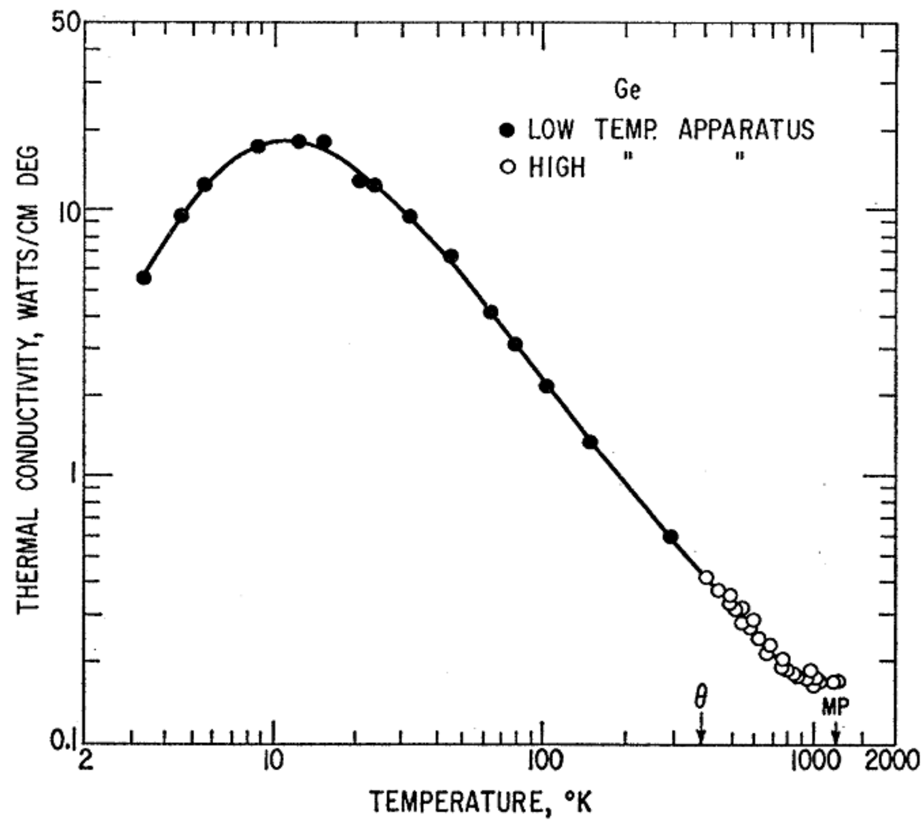


FIG. 5. The low- and high-temperature K versus T results for Ge.

Phonon hydrodynamics

Table 1 | Classification of thermal transport regimes.

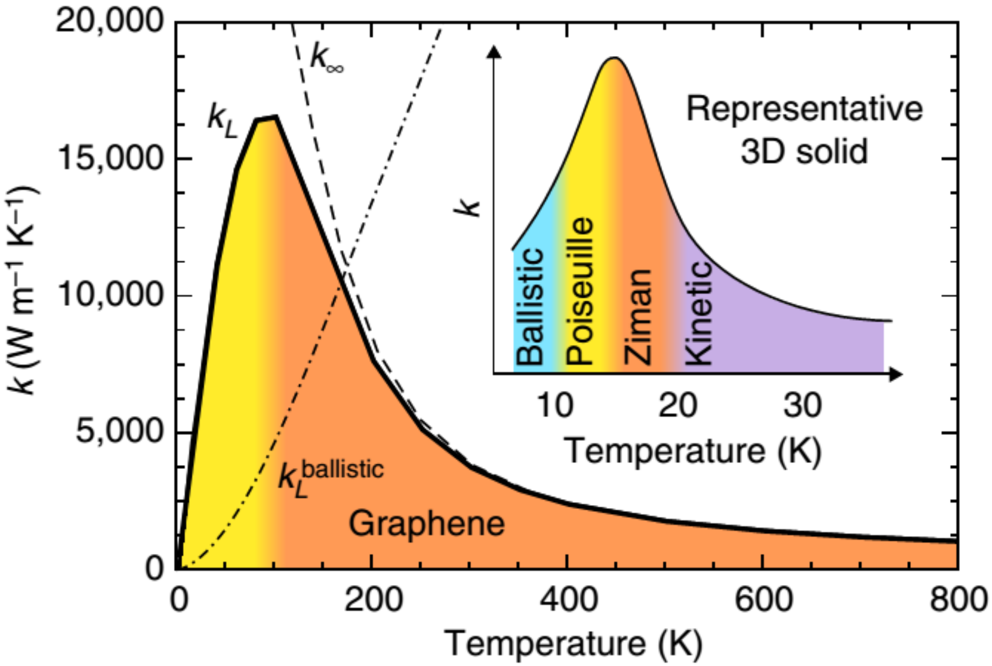
Ballistic	$\mathcal{E} \gg \mathcal{N}$ and $\mathcal{E} \gg \mathcal{R}$
Poiseuille	$\mathcal{N} \gg \mathcal{E} \gg \mathcal{R}$
Ziman	$\mathcal{N} \gg \mathcal{R} \gg \mathcal{E}$
Kinetic	$\mathcal{R} \gg \mathcal{N}$ and $\mathcal{R} \gg \mathcal{E}$

Classification of different regimes of thermal conductivity as a function of the linewidths of different scattering events: normal ($\mathcal{N}$), resistive ($\mathcal{R}$—combining both Umklapp and isotopic) and extrinsic ($\mathcal{E}$). Poiseuille and Ziman hydrodynamics are characterized by dominant $\mathcal{N}$ scattering against all other mechanisms.

A. Cepellotti et al., Nature Commun. 2014

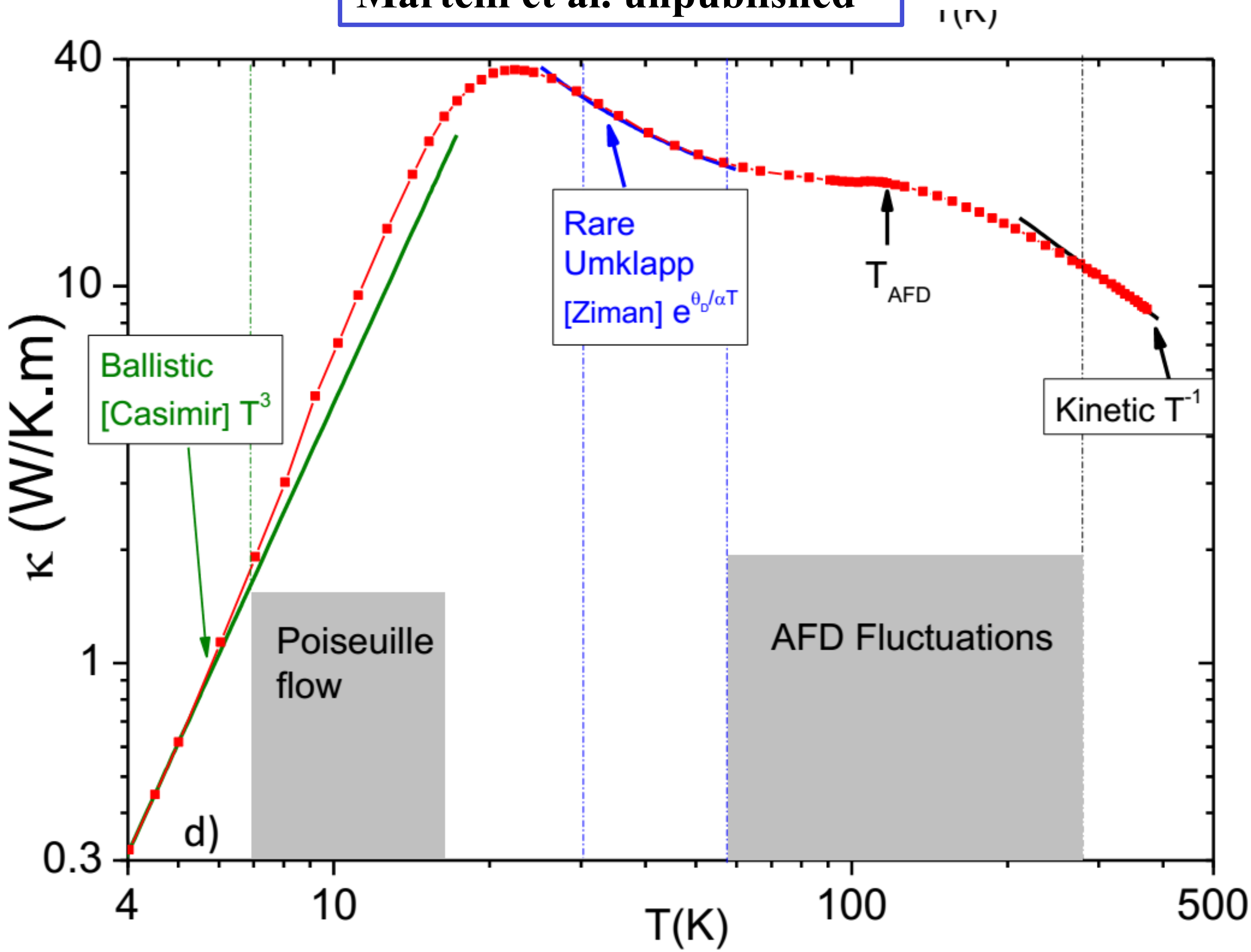
See also:

- **Guyer & Krumhansl (1966)**
- **Gurzhi (1968)**
- **Beck, Meyer & Thellung (1974)**



Regimes of heat transport in strontium titanate

Martelli et al. unpublished



Poiseuille flow and second sound

Normal scattering >> Extrinc scattering >> Resistive scattering

Observed only in a handful of solids:

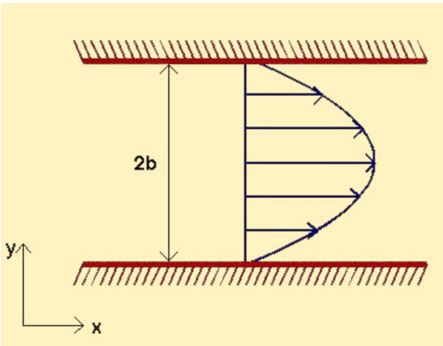
^{4}He for SS [15, 47, 48] and PF [13, 14, 49, 50] ,
^{3}He for SS [51] and PF [52] ,
NaF for SS [53 to 56] ,
Bi for SS [57] and PF [58] .

Phonon Hydrodynamics in Solids

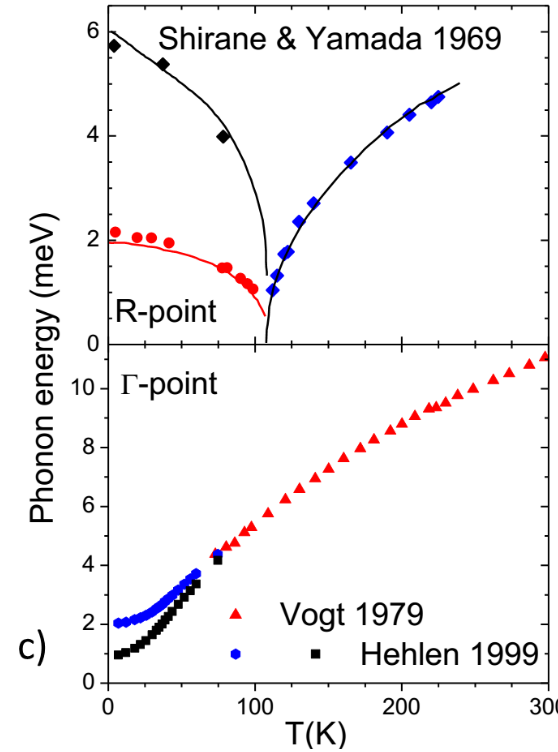
phys. stat. sol. (a) **24**, 11 (1974)

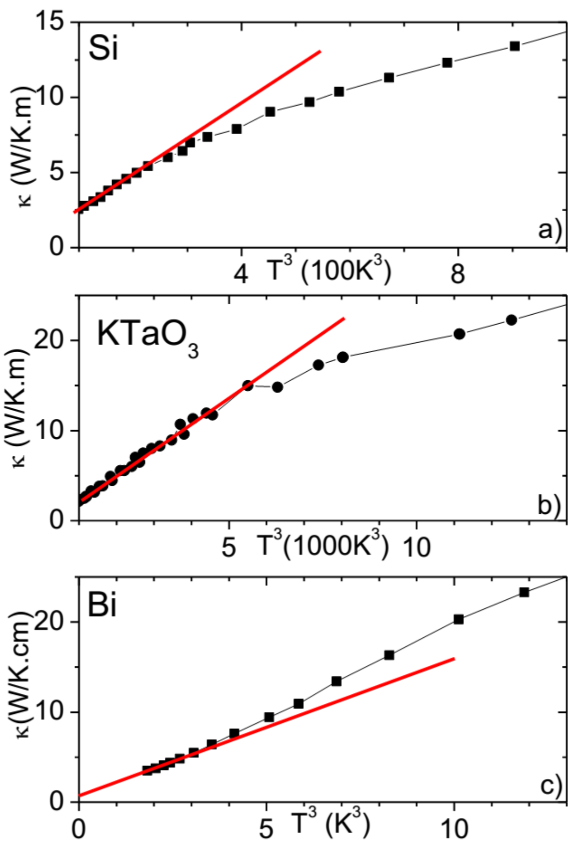
H. Beck (a)[1]), P. F. Meier (b)[2]), and A. Thellung (c)

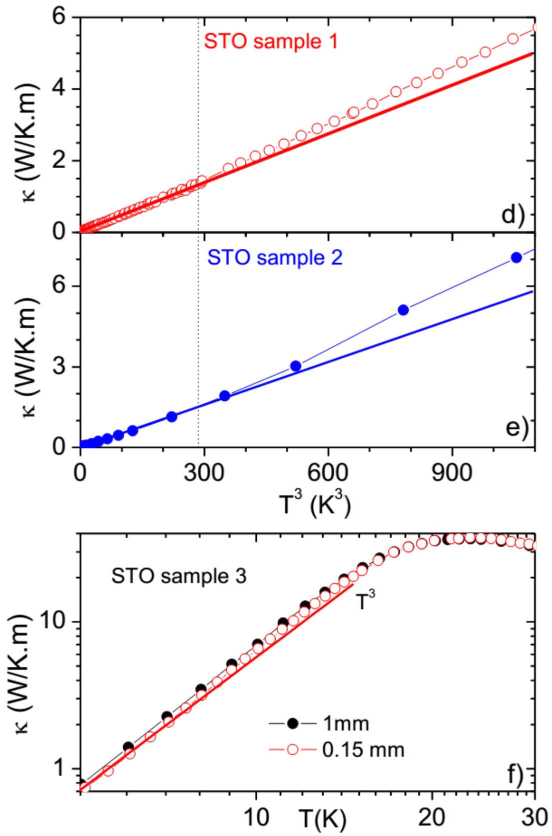
Hallmark of Poiseuille flow: faster than T^3 thermal conductivity



Normal scattering events are multiplied due to soft modes



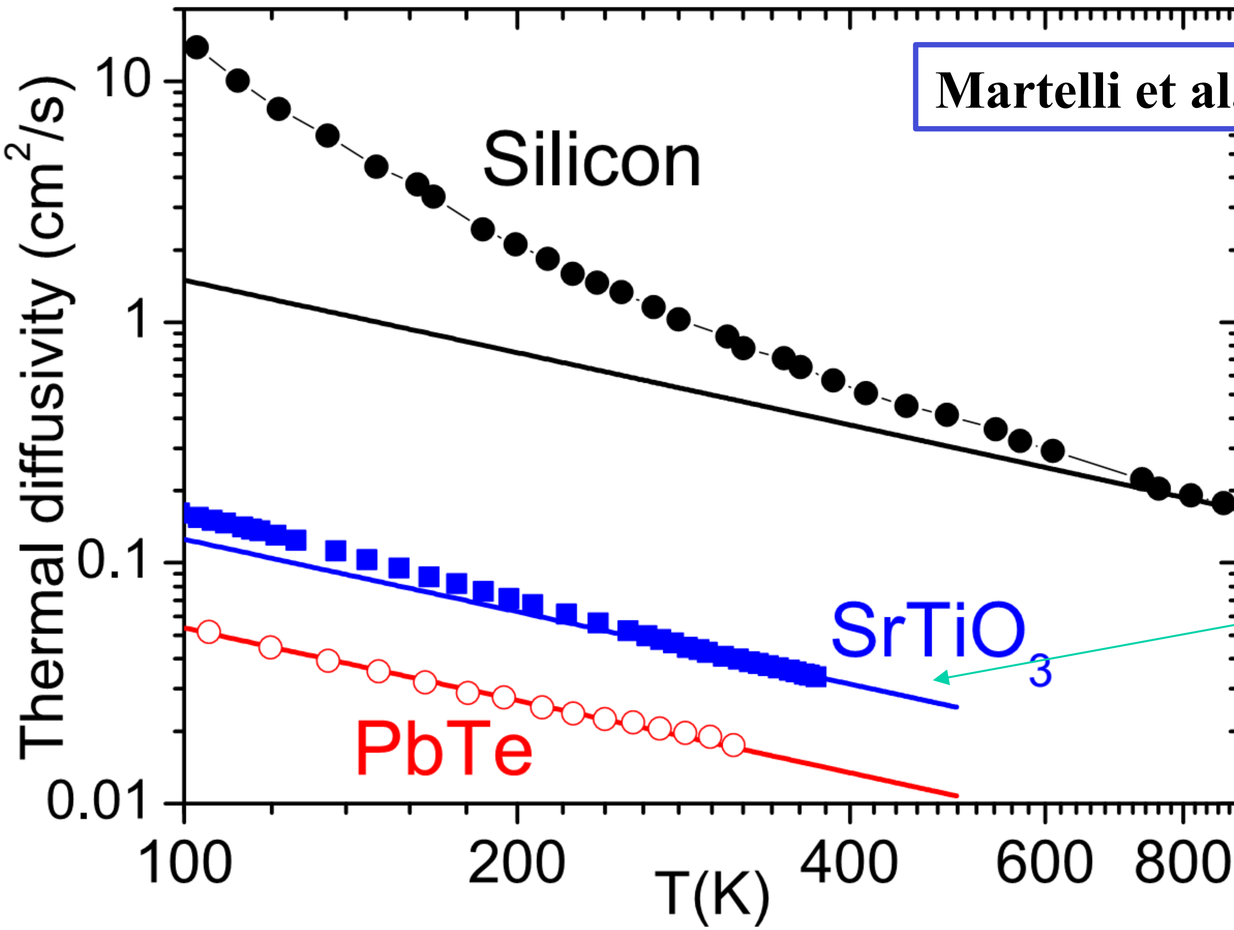




Previously seen only in Bi and He crystals

High-temperature thermal diffusivity

D=κ/C



Martelli et al. unpublished

$D = 2\pi/3\ s v_s^2$

Planck time: $\tau_P = \hbar / k_B T$

Umklapp ph-ph scattering

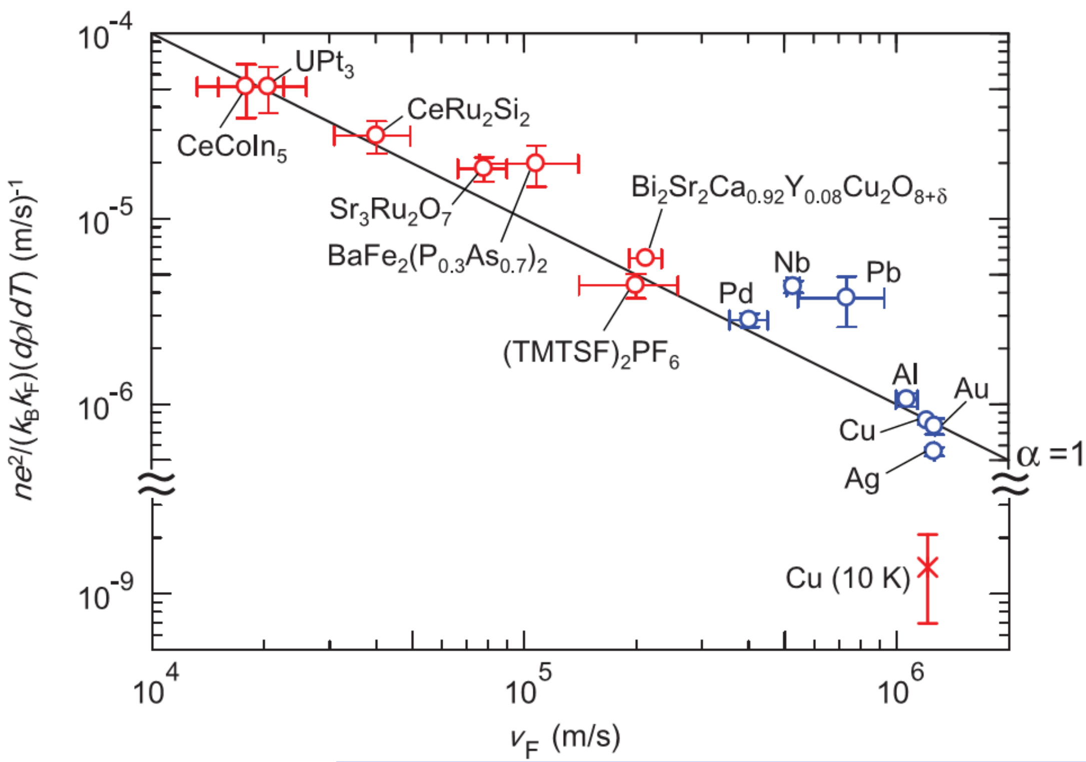
Planck time detected in metallic charge conductivity

Similarity of Scattering Rates in Metals Showing *T*-Linear Resistivity

J. A. N. Bruin,[1] H. Sakai,[1] R. S. Perry,[2] A. P. Mackenzie[1]

Science 2013

$$\tau_P = \hbar / k_B T$$

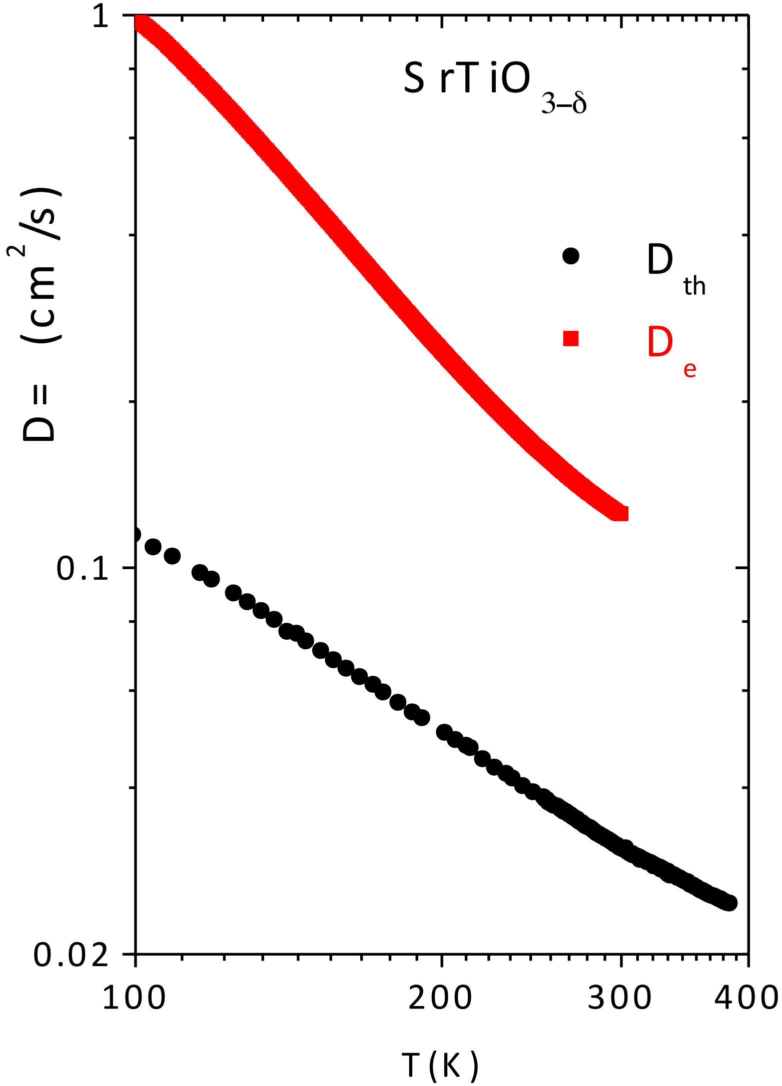


$$\sigma = \frac{ne^2\tau}{m^*} = \frac{ne^2\tau v_F}{\hbar k_F}$$

$$\alpha = \frac{\rho}{T}\frac{e^2}{2\pi k_B d}\sum_i M_i\, k_{Fi} v_{Fi}$$

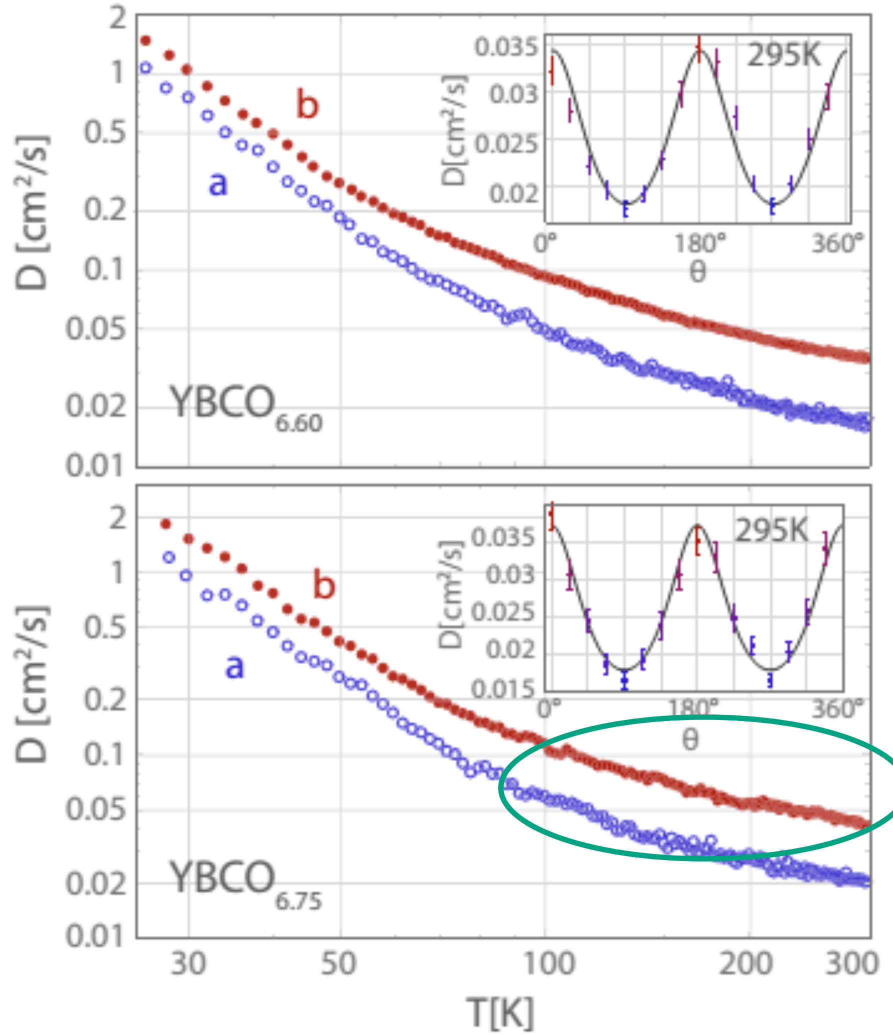
First postulated by Sachdev and Zaanen in the augties

Thermal and electrical diffusivity



Anomalous thermal diffusivity in underdoped $YBa_2Cu_3O_{6+x}$

Jiecheng Zhang[a,b], Eli M. Levenson-Falk[a,b], B. J. Ramshaw[c], D. A. Bonn[d,e], Ruixing Liang[d,e], W. N. Hardy[d,e], Sean A. Hartnoll[b], and Aharon Kapitulnik[a,b,f,1]



Charge diffuses faster, but not much!

Summary

- With one oxygen out of 10^5 missing, $SrTiO_3$ becomes an intriguing superconductor in the vicinity of an intertwined ferroelectric order.
- Its metallicity cannot be accounted by Boltzmann-Drude picture. Polarons may be in charge. But we have no theory.
- The host insulator displays Poiseuille flow of phonons, only seen in a handful of solids, thanks to the presence of soft modes.
- Charge and heat diffusivity are to be put under scrutiny.