Critical doping and superconductivity domes in doped strontium titanate

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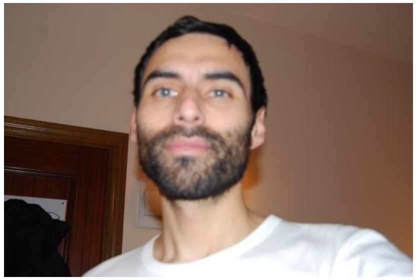
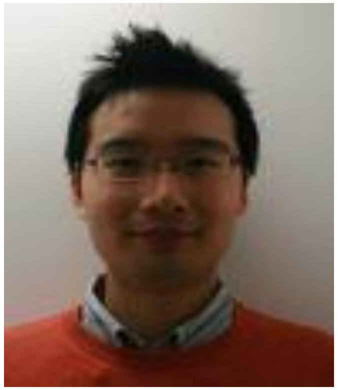


German Bridoux
Now in Bueons Aires



Zengwei Zhu
Now in Los Alamos

PHYSICAL REVIEW VOLUME 163, NUMBER 2 10 NOVEMBER 1967

Superconducting Transition Temperatures of Semiconducting $SrTiO_3$

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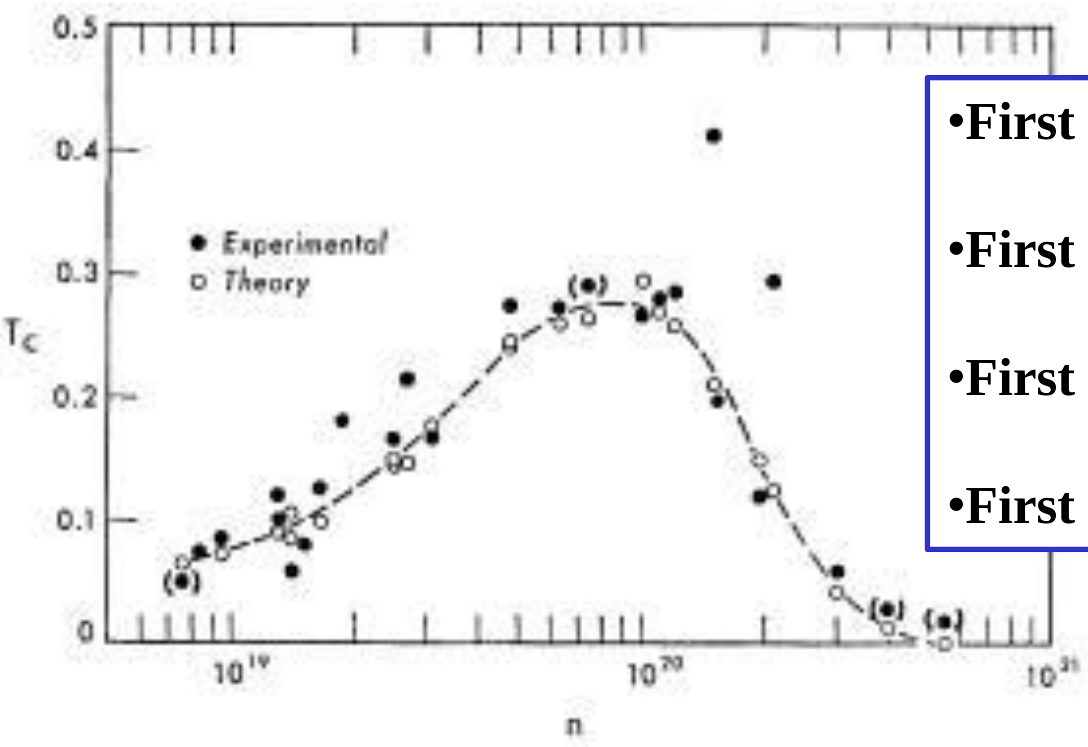
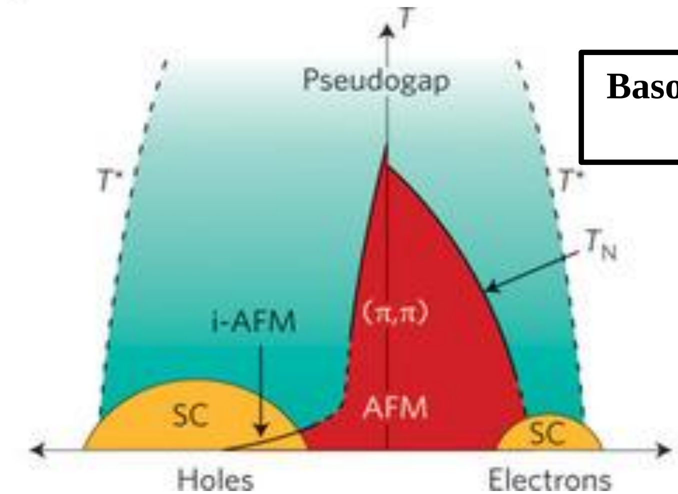
Department of Physics, University of California, Berkeley, California
AND
J. F. SCHOOLEY,‡ W. R. HOSLER,§ AND E. R. PFEIFFER
National Bureau of Standards, Washington, D. C.
(Received 5 July 1967)



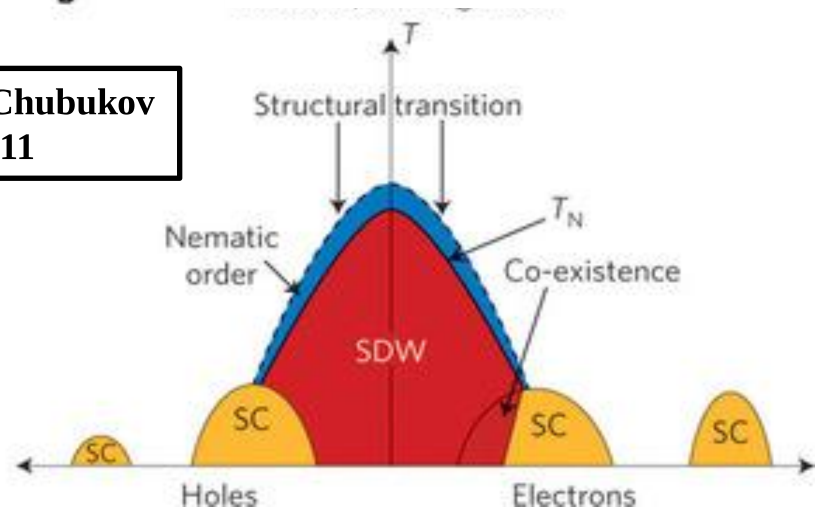
- •First **oxide** superconductor
- •First **multi-band** superconductor
- •First **semiconducting** superconductor
- •First superconducting **dome**

Superconducting domes

Cuprates

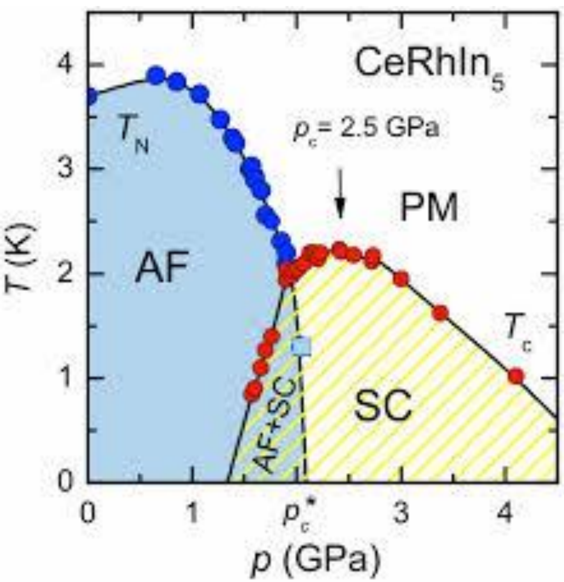


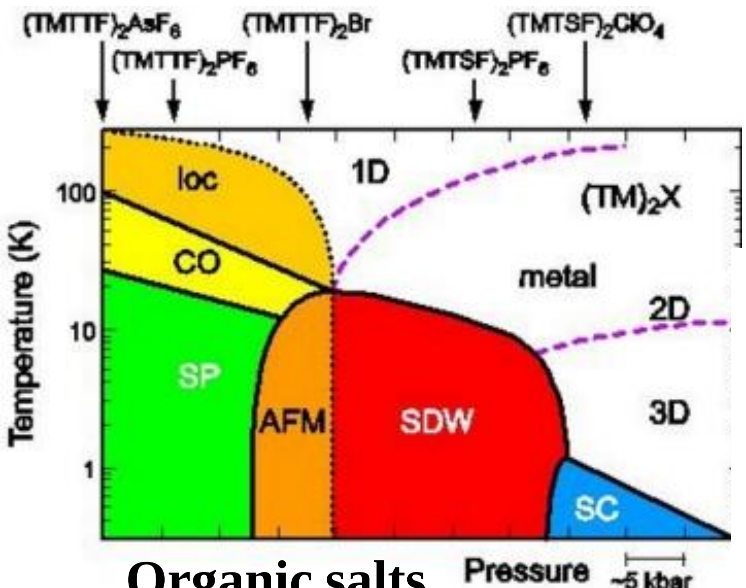
Pnictides



Basov & Chubukov 2011

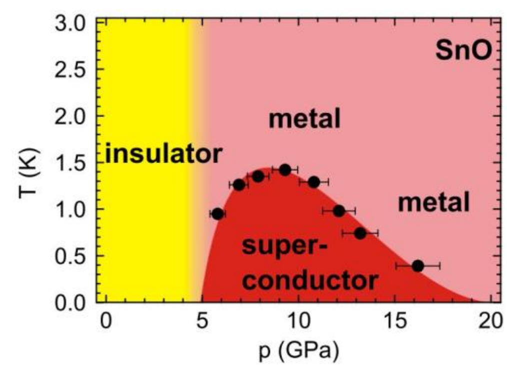
Heavy fermions



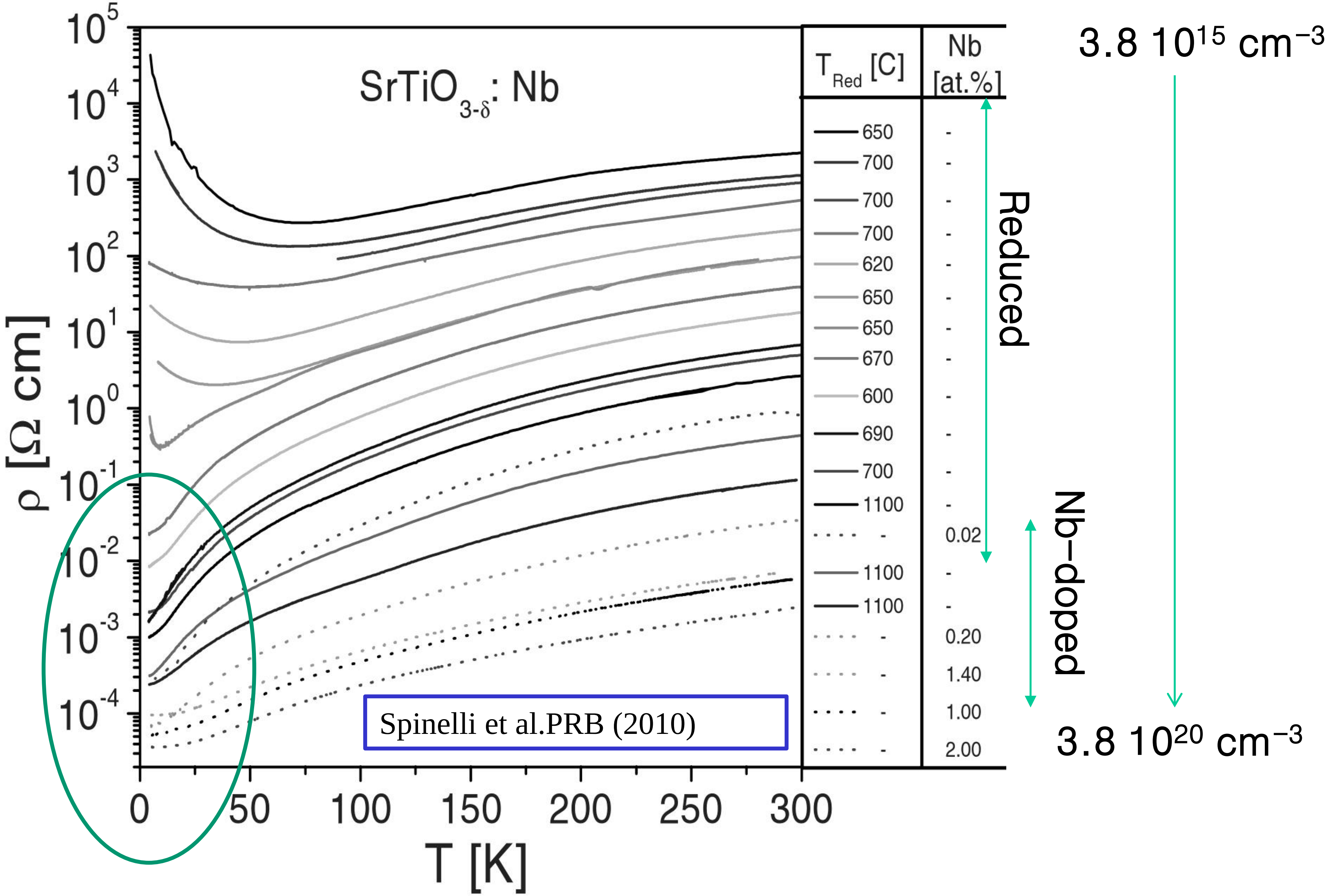


Organic salts

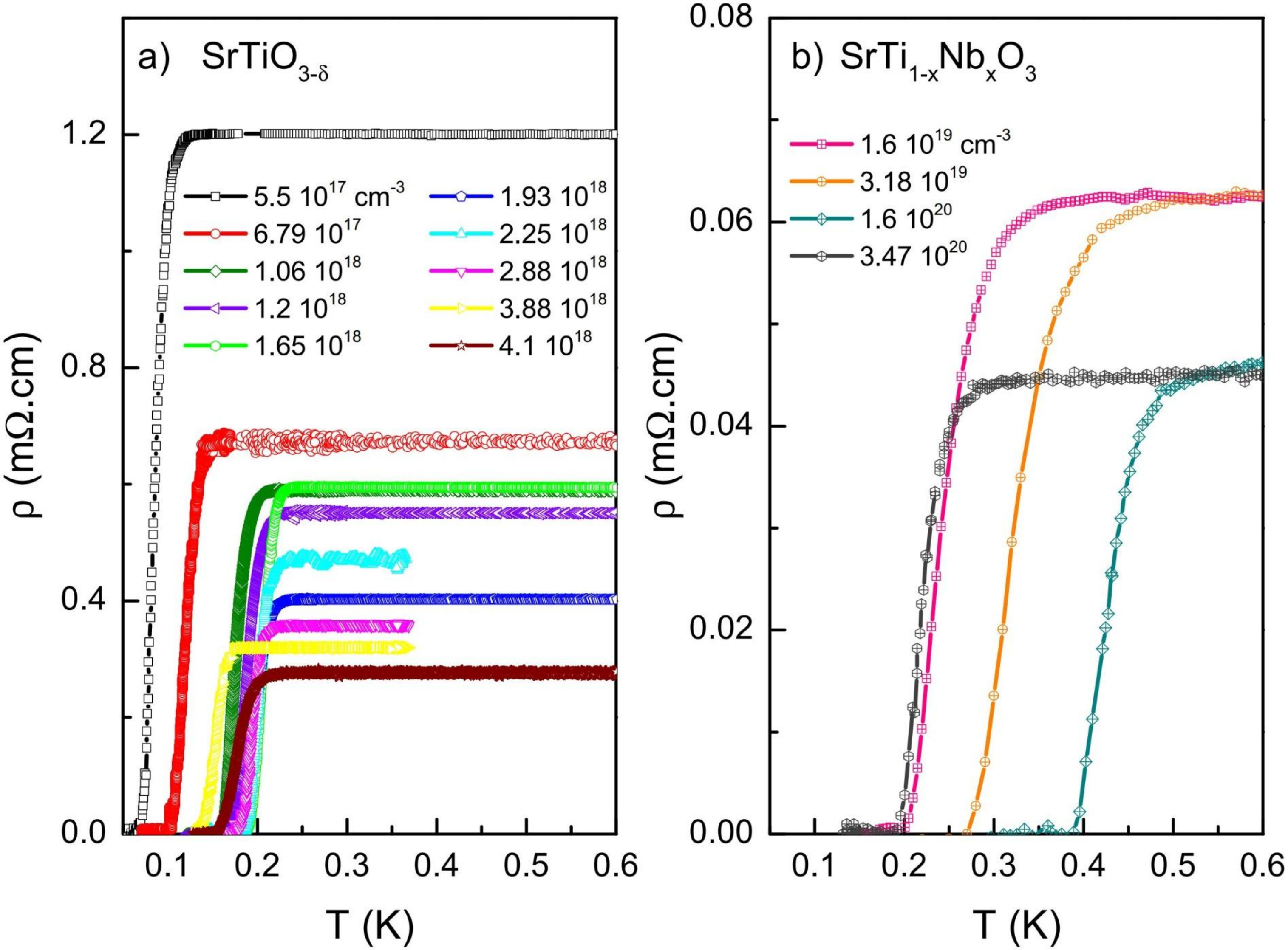
SnO



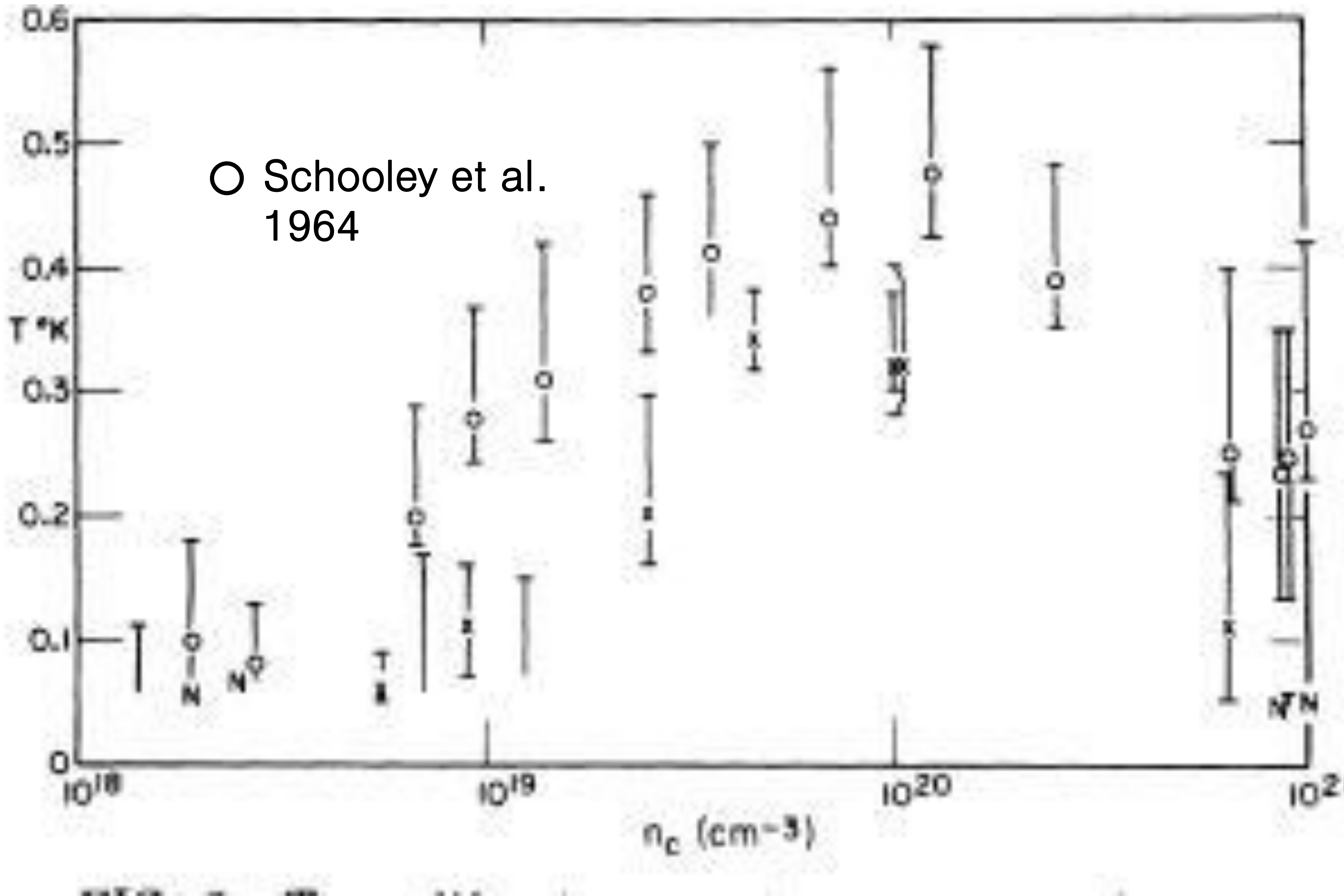
Doping can be tuned in commercially availabe crystals



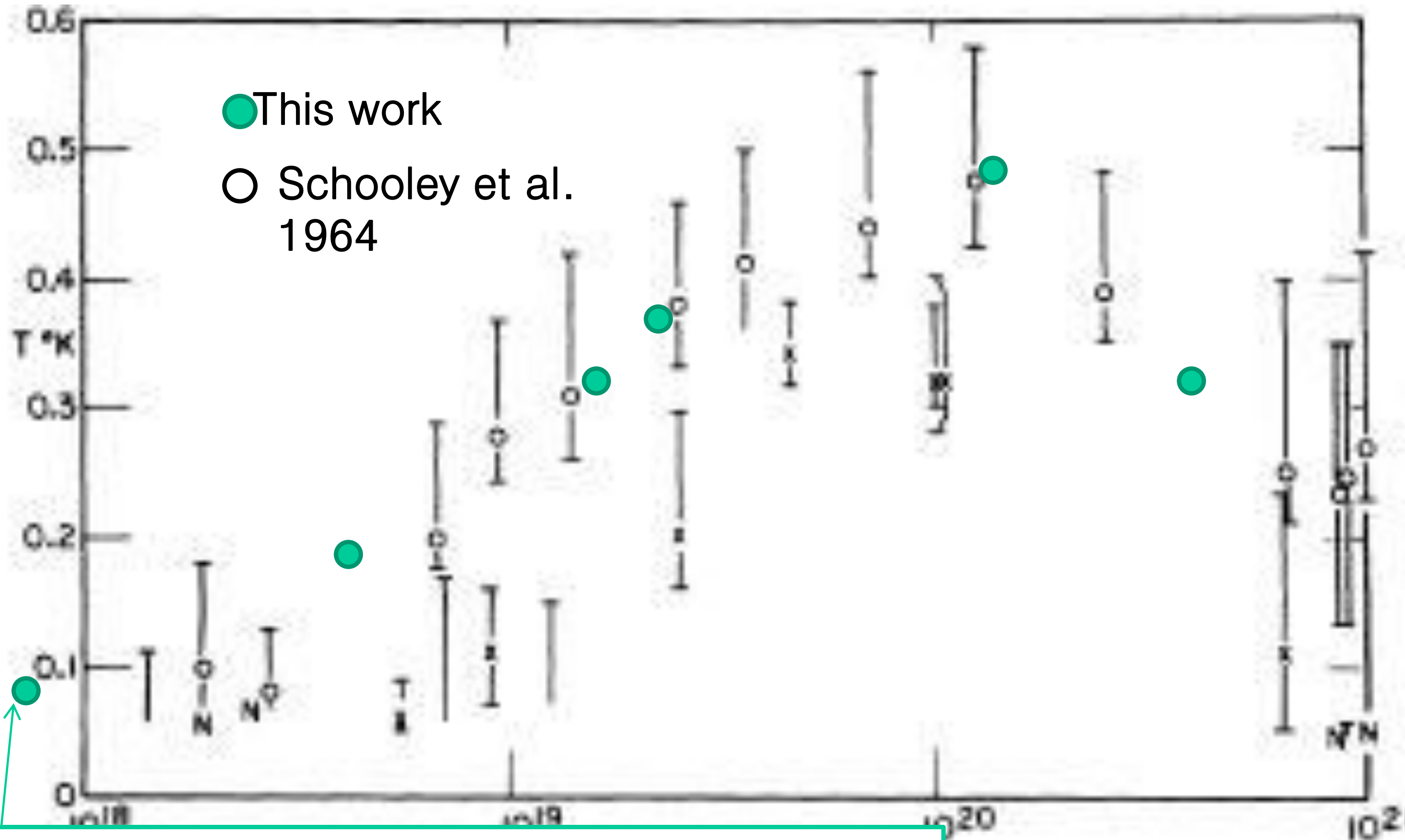
Resistive transitions



The superconducting dome

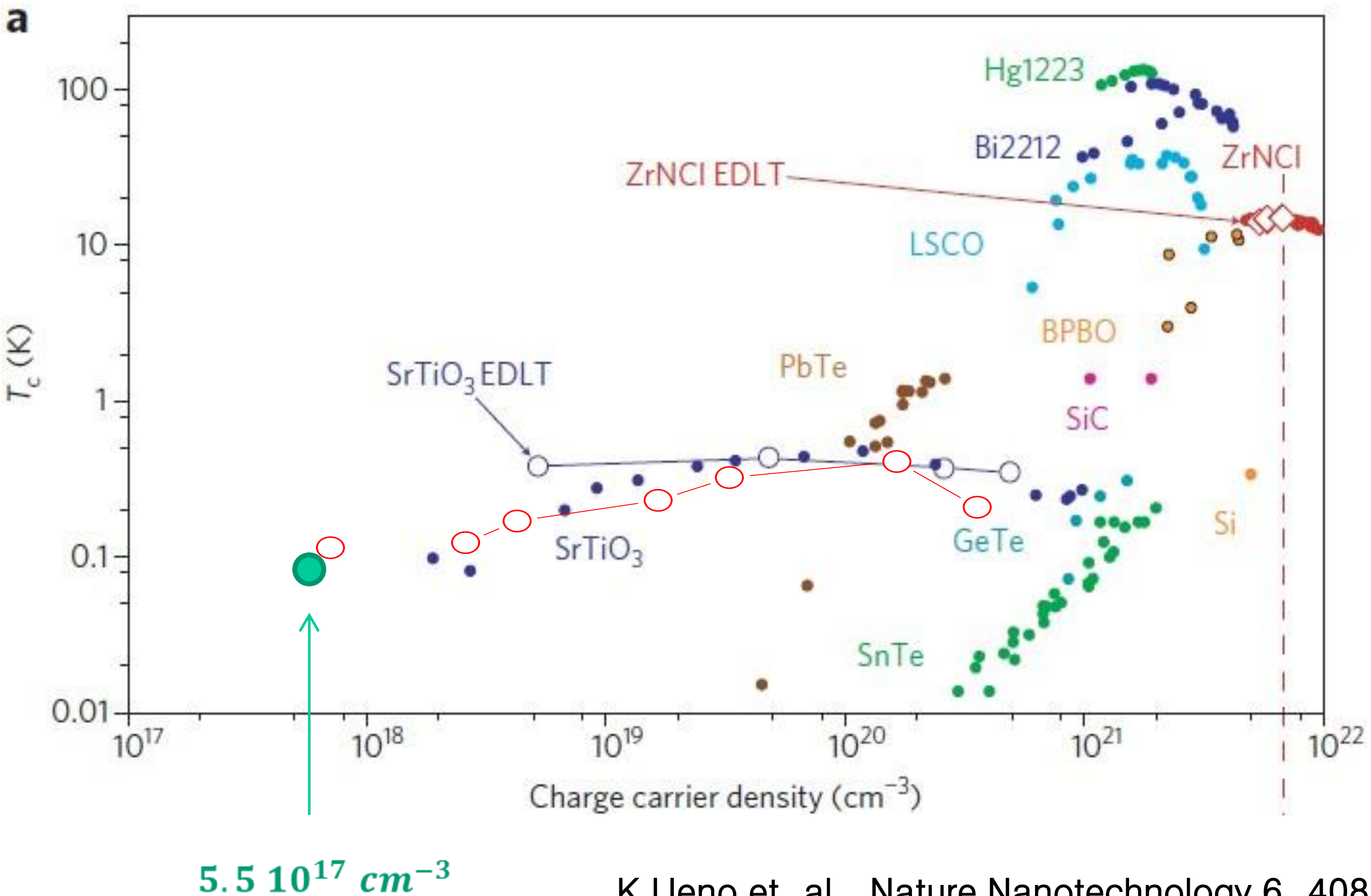


The superconducting dome



T_c = 86 mK@ n= 5.5 10^{17}

"Semiconducting" superconductors



K Ueno et. al., Nature Nanotechnology 6, 408 2011

STO is the most dilute superconductor

BAND MOTT

system	STO	PbTe:Tl	$Cu_xBi_2Se_3$	Si:B	C:B	SiC:B	YBCO
x_c	10^{-5}	$3\ 10^{-3}$	$9\ 10^{-2}$	$\sim 10^{-2}$	$\sim 10^{-2}$	$\sim 10^{-2}$	$5\ 10^{-2}$

Critical doping to induce superconductivity in doped insulators

X. Blase et al., Nature Materials 8, 375–382 (2009)

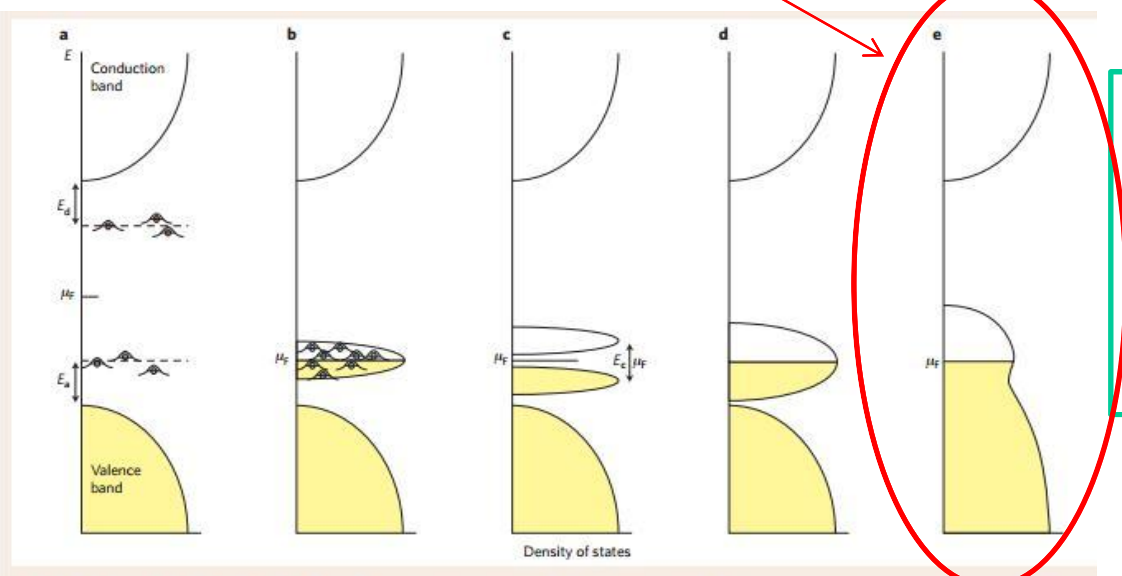


Figure B2 | Evolution of the electronic density of states and band structure with increasing p-type doping. Doping increases from **a** to **e**. Coloured area represents filled states.

Is the normal state:

- **An impurity-band metal?**
- **Or a metal with sharp Fermi surface?**

Fermi surface truncated by Landau tubes

Shoenberg 1984

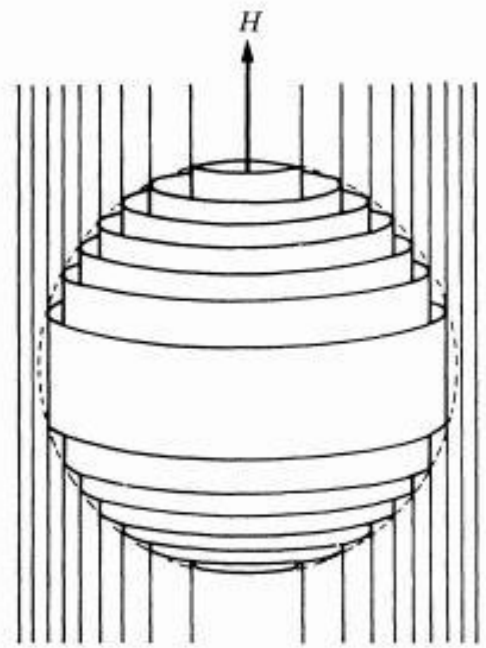


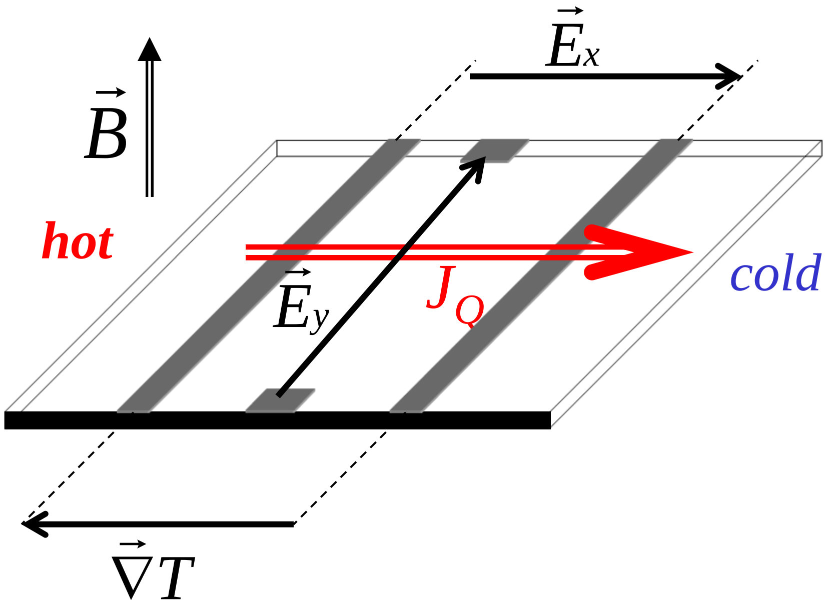
FIGURE 3. The permitted states in a magnetic field H lie on a series of discrete tubes specified by equation (1). At low temperature the occupied states lie within the Fermi surface (here supposed to be spherical). (After Chambers 1956.)

Quantum oscillations!

Electrons share the same Fermi-Dirac distribution!

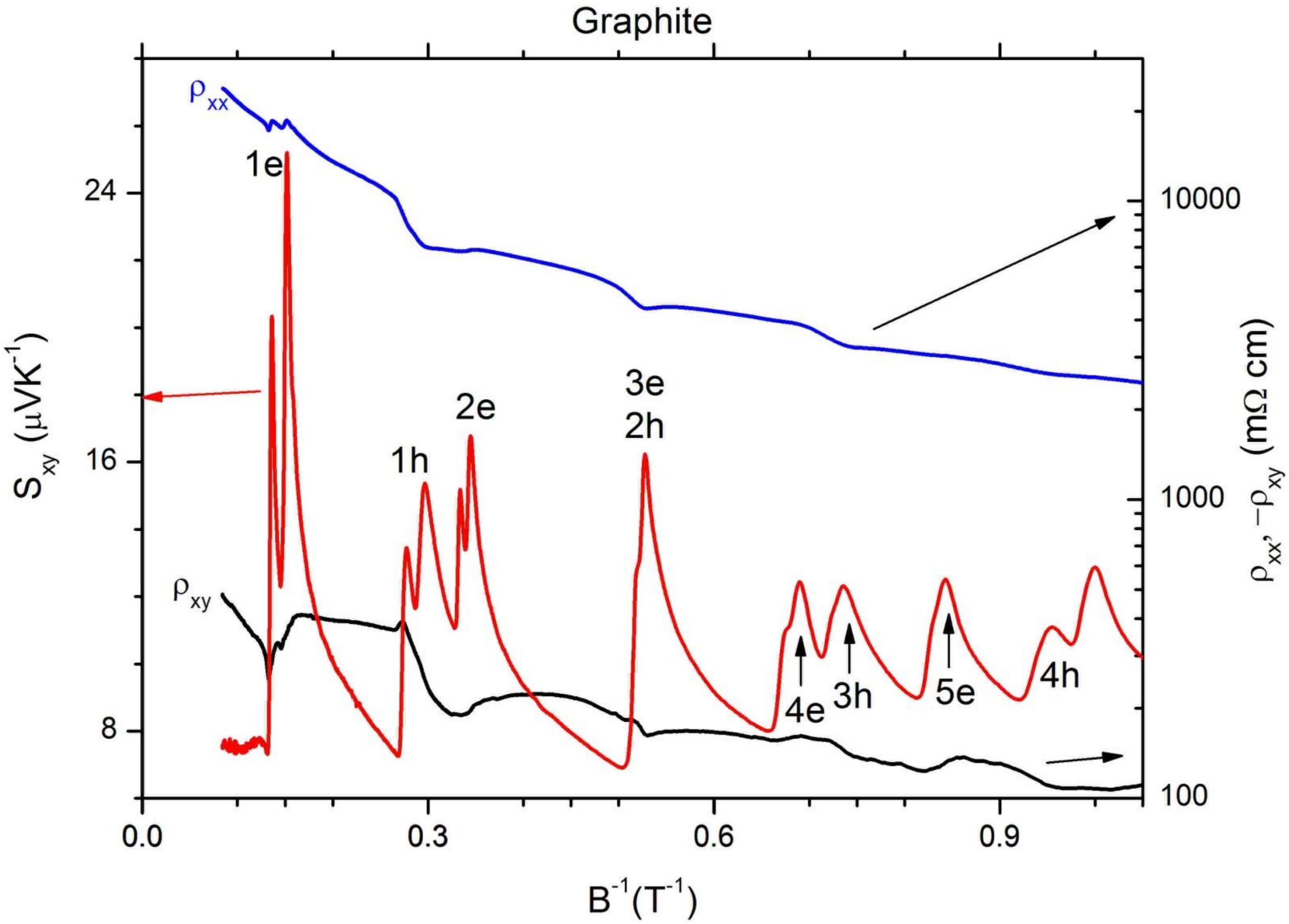
Nernst effect

- A thermal gradient, electrons produces an electric field.
- The Nernst effect refer to the transverse component of this field.

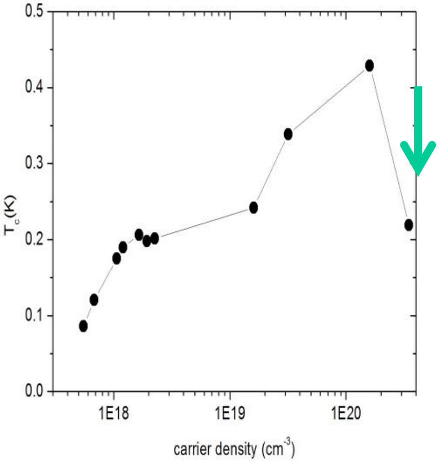


$$S = \frac{-E_x}{\nabla_x T} \qquad N = S_{xy} = \frac{-E_y}{\nabla_x T} \qquad \left[\nu = \frac{-E_y}{B_z \nabla_x T}\right]$$

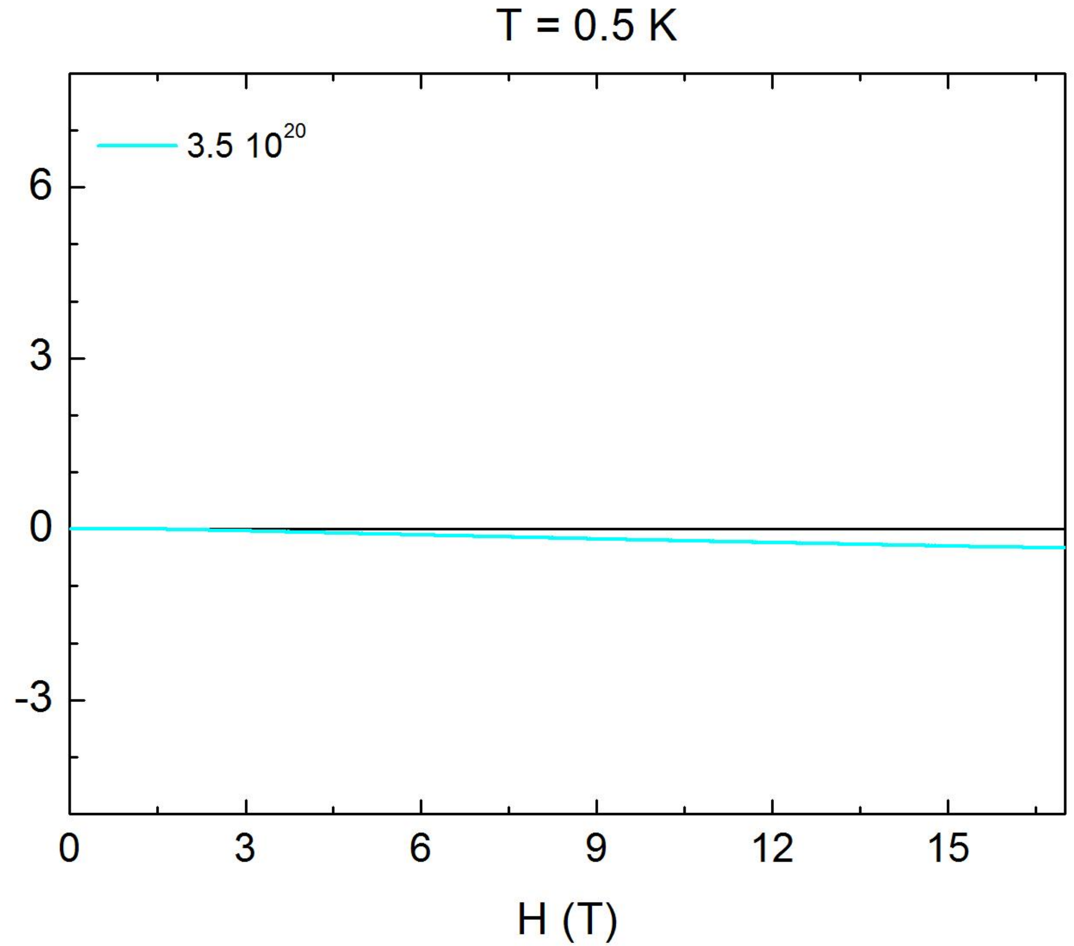
Sensitivity of the Nernst effect as a probe of Landau spectrum



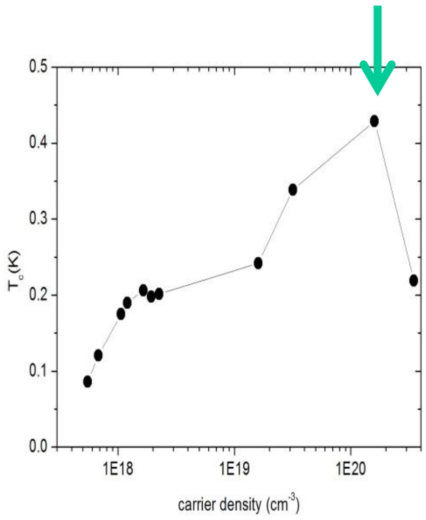
Emergence of Nernst oscillations with underdoping



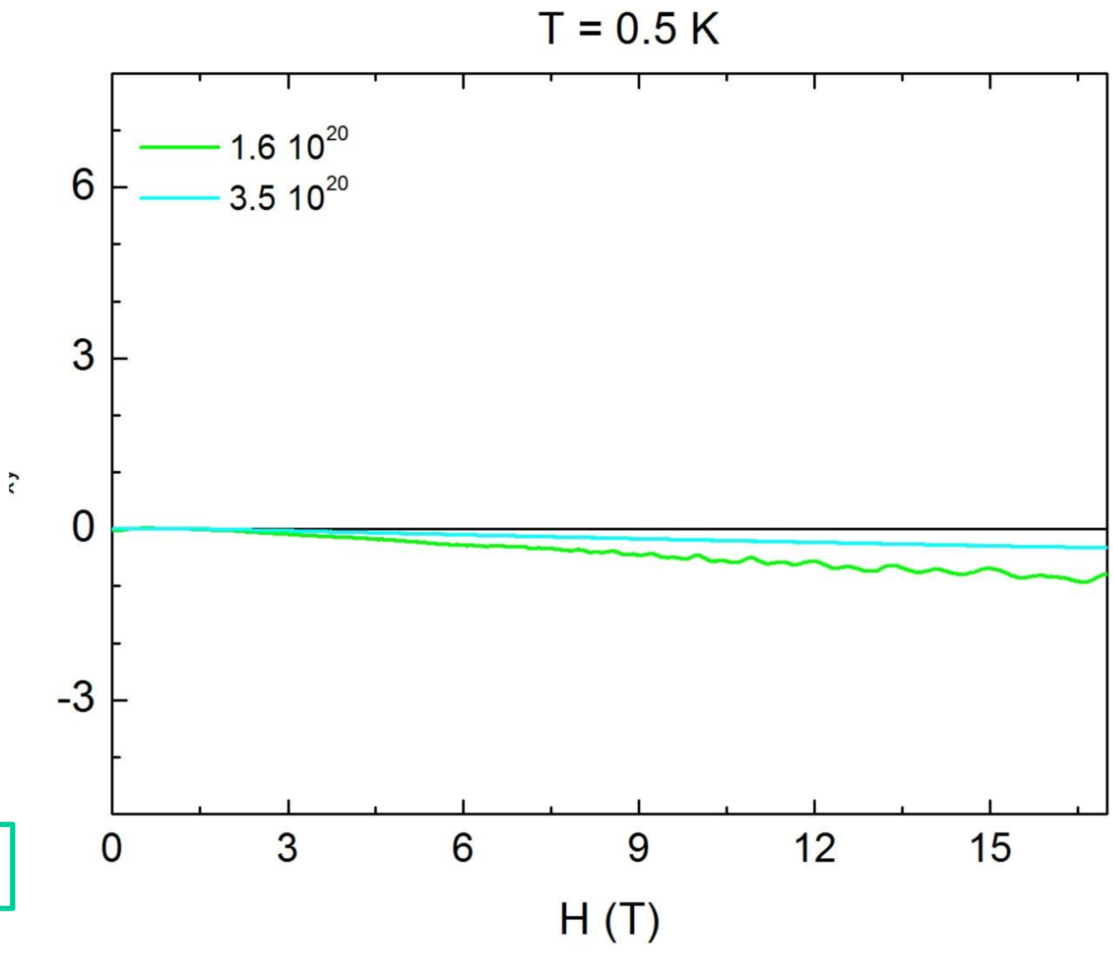
Lin et al., PRX 2013



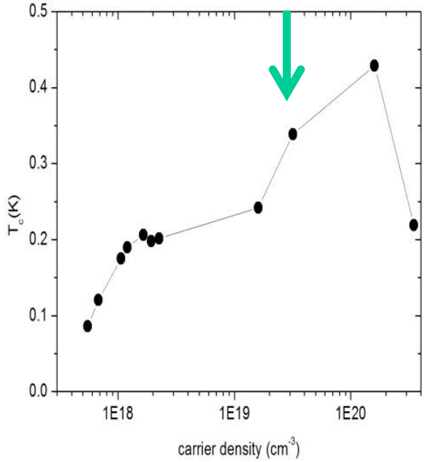
Emergence of Nernst oscillations with underdoping



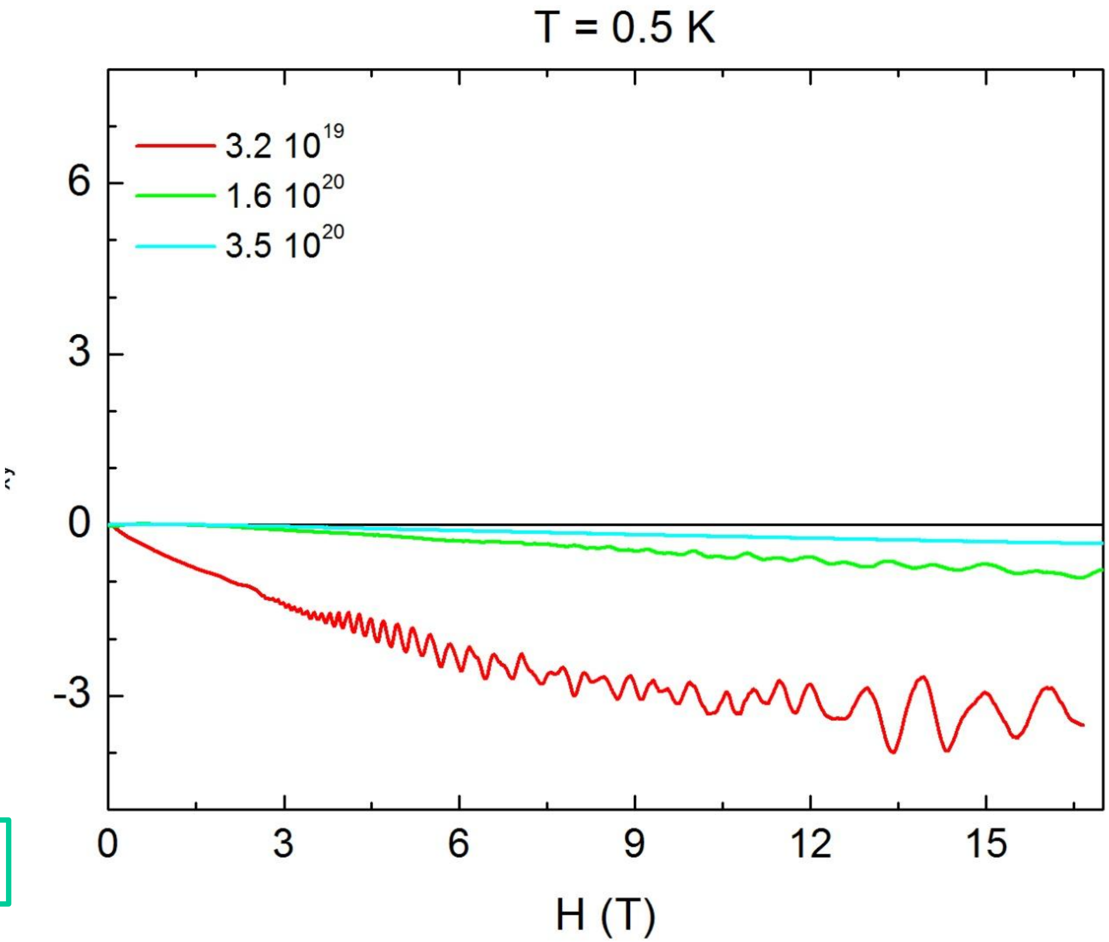
Lin et al., PRX 2013



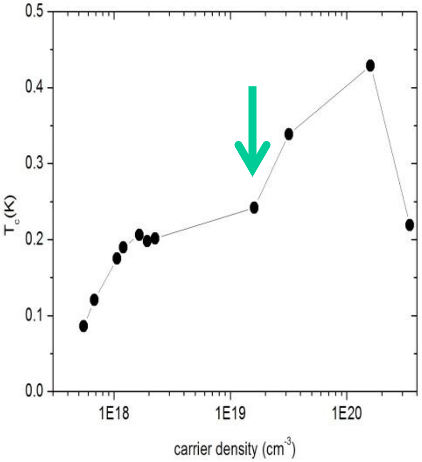
Emergence of Nernst oscillations with underdoping



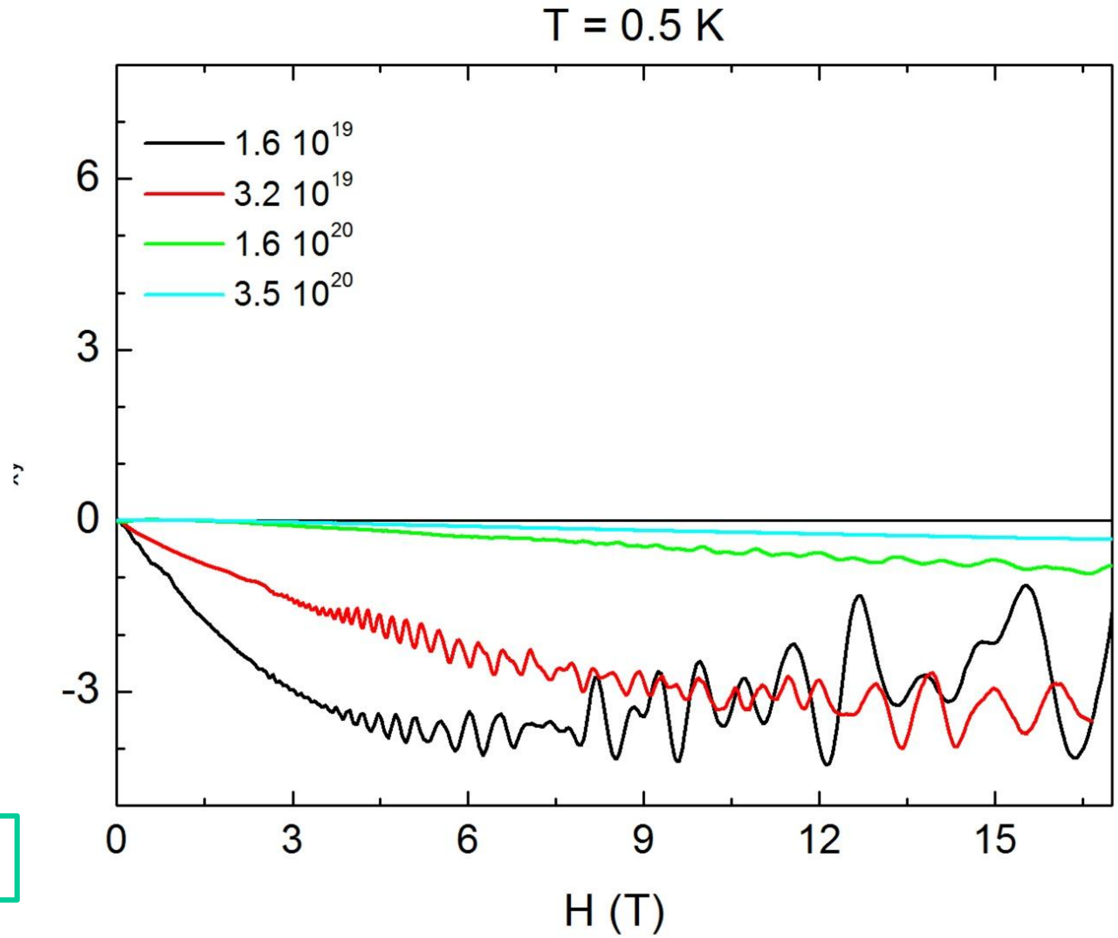
Lin et al., PRX 2013



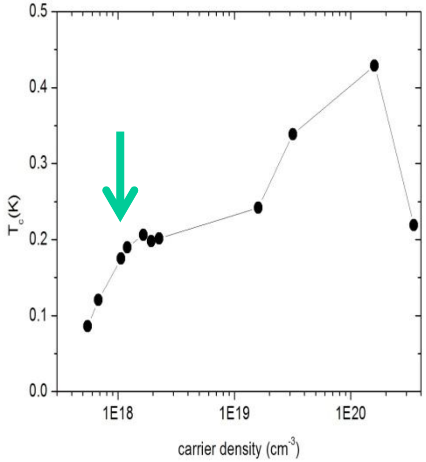
Emergence of Nernst oscillations with underdoping



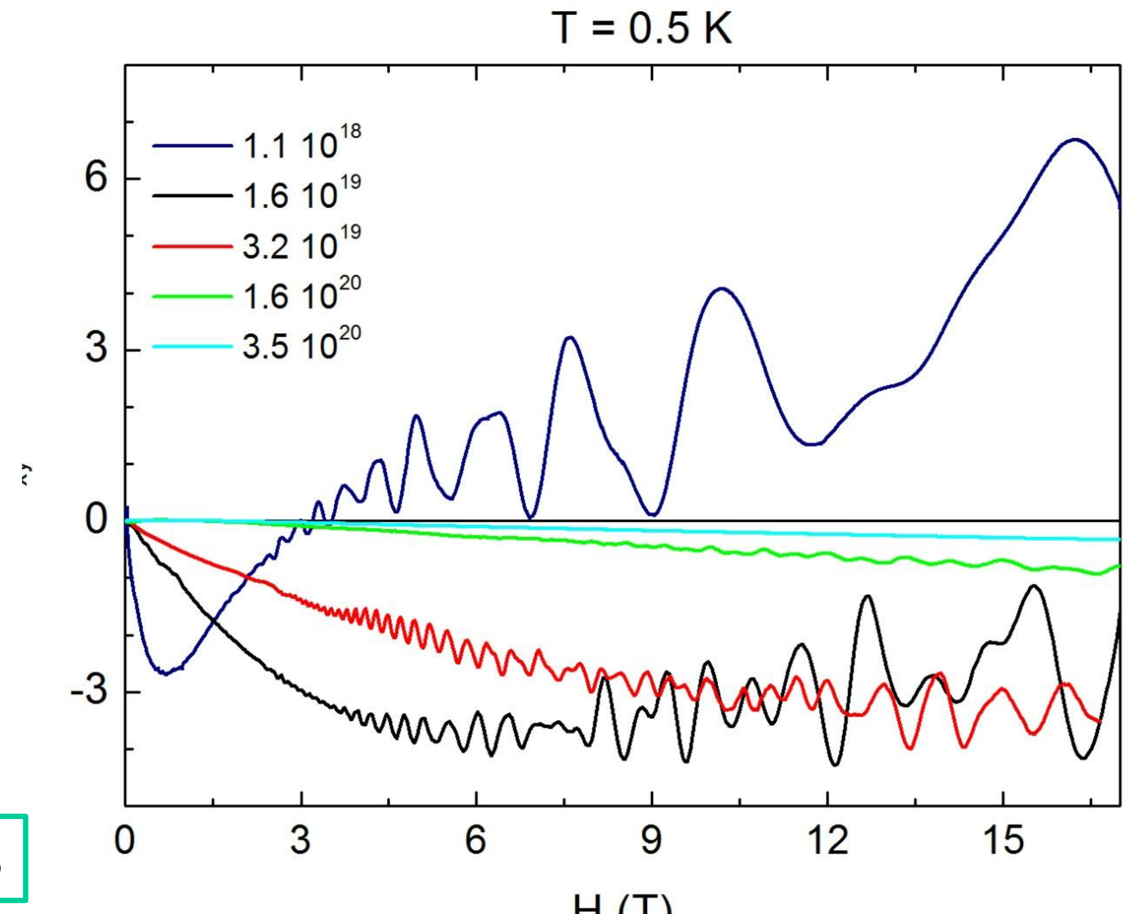
Lin et al., PRX 2013



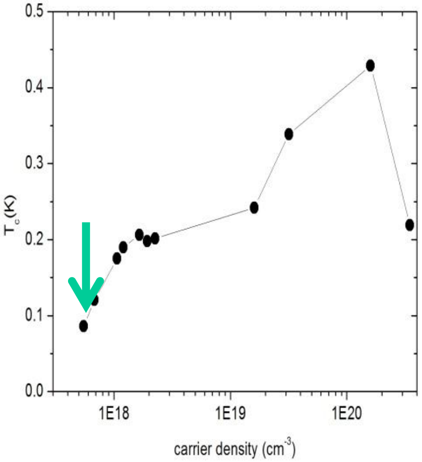
Emergence of Nernst oscillations with underdoping

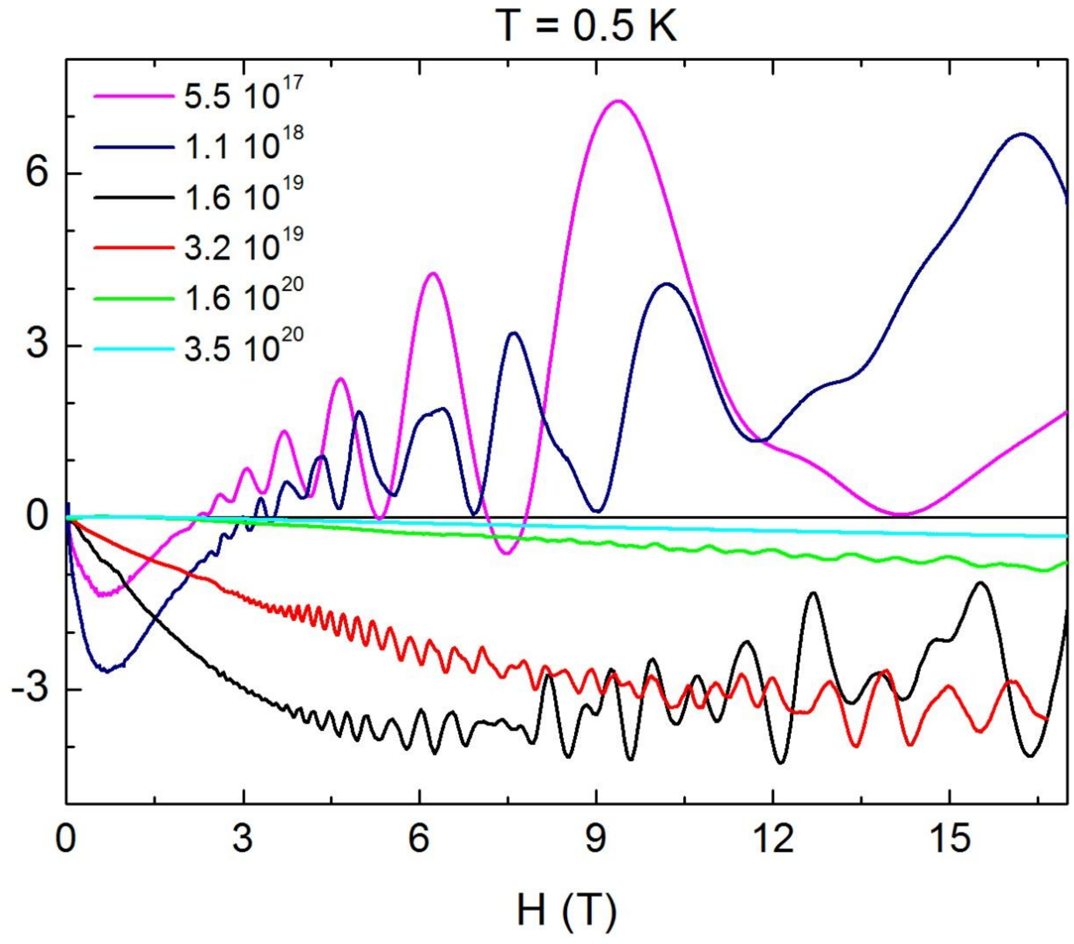


Lin et al., PRX 2013



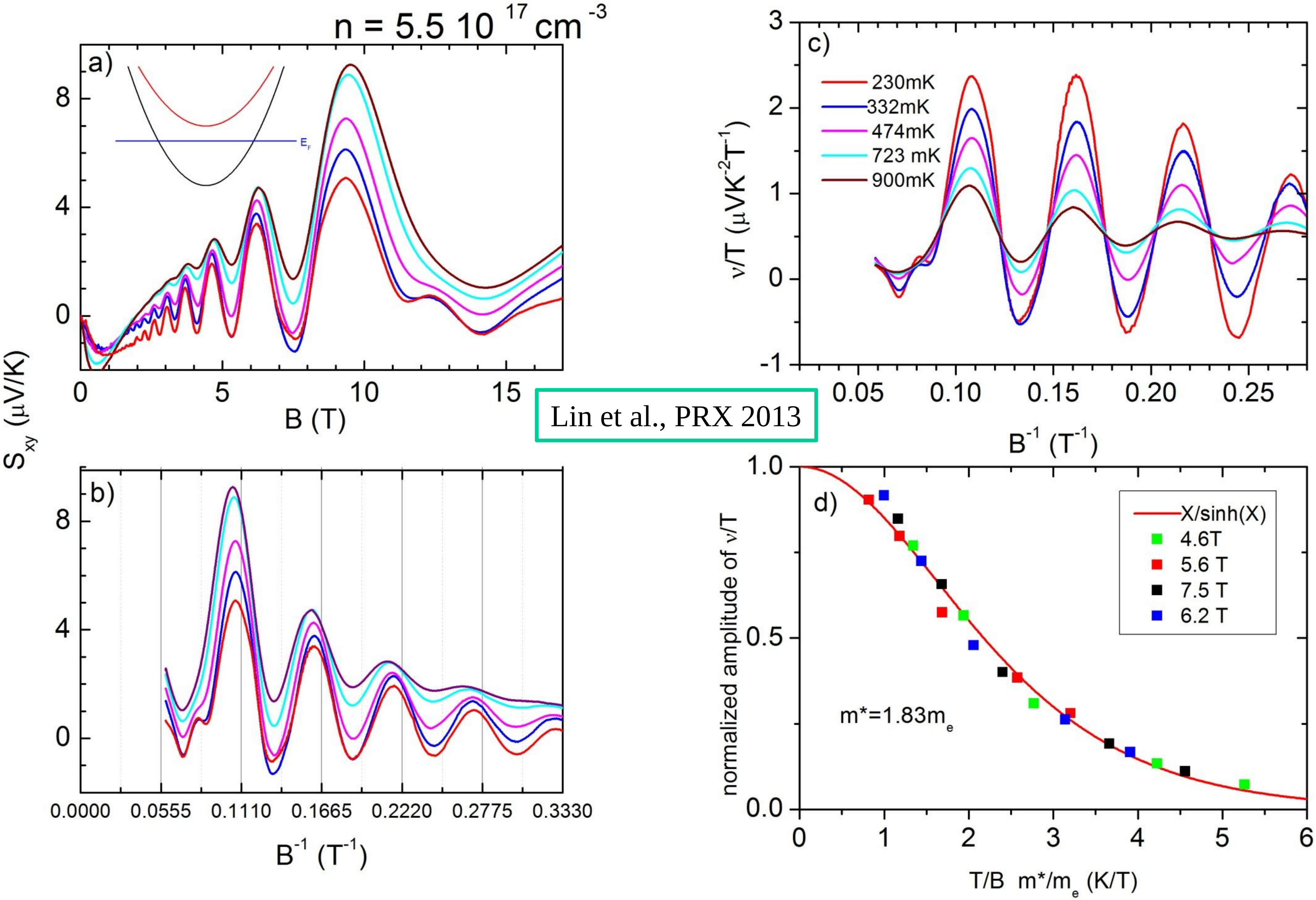
Emergence of Nernst oscillations with underdoping





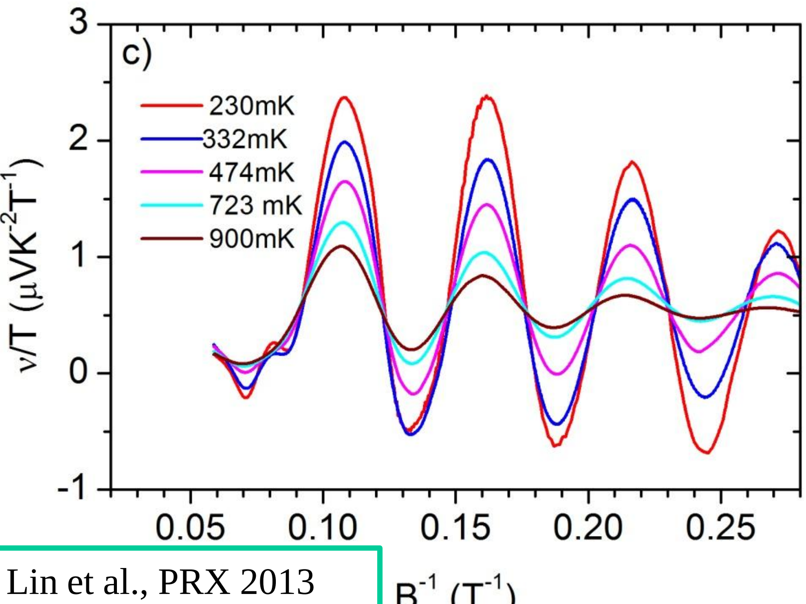
Lin et al., PRX 2013

A single frequency at the lowest concentration

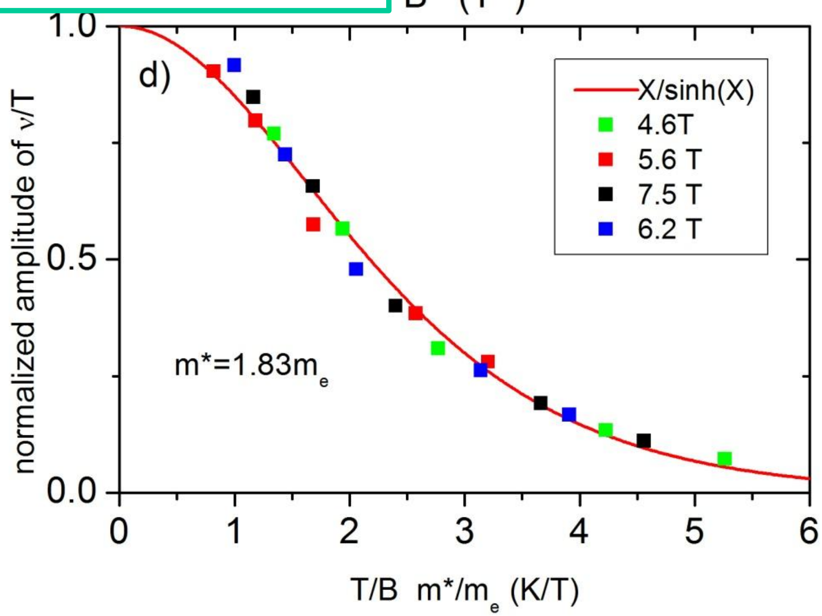


Lin et al., PRX 2013

A single frequency at the lowest concentration



Lin et al., PRX 2013



Frequency (=18.2 T)

$$F = \frac{\hbar}{2\pi e} A$$

FS Cross section

$$A = \pi k_F^2$$

FS volume

($n=4.4\ 10^{17}\ cm^{-3}$)

$1/eR_H = 5.5\ 10^{17}\ cm^{-3}$

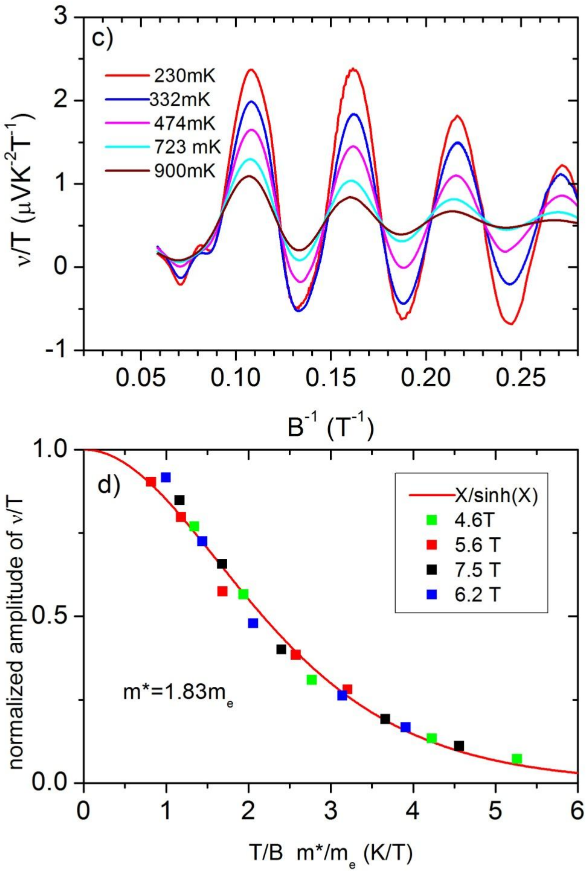
Effective mass

($m*=1.8m_e$)

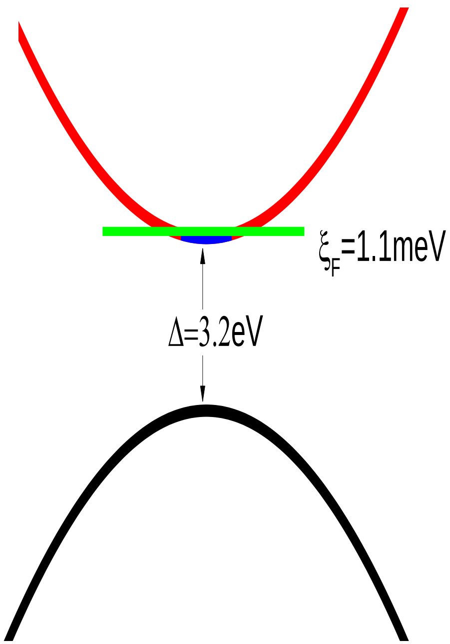
$$E_F = \frac{\hbar^2 k_F^2}{m*} = 13K$$

Two ways to estimate the Fermi energy

Quantum oscillations

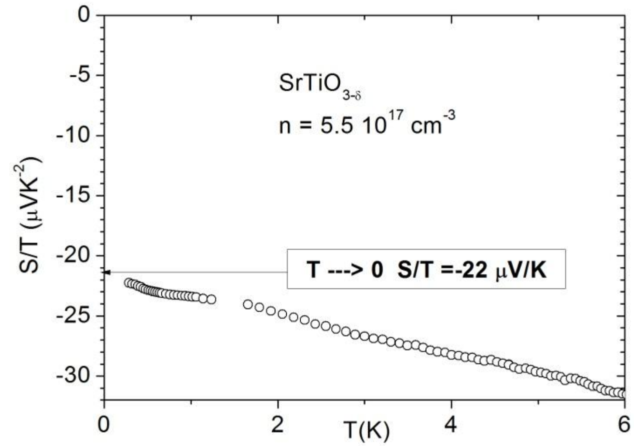


$T_F = 13$ k



Lin et al., PRX 2013

Low−temperature Seebeck coefficient



$S/T = (\pi^2/3)(k_B/e)\, 1/T_F$

$T_F = 12.9$ k

A serious challenge for phonon-mediated superconductivity!

@n= 5.5 10^{17} cm^{-3}

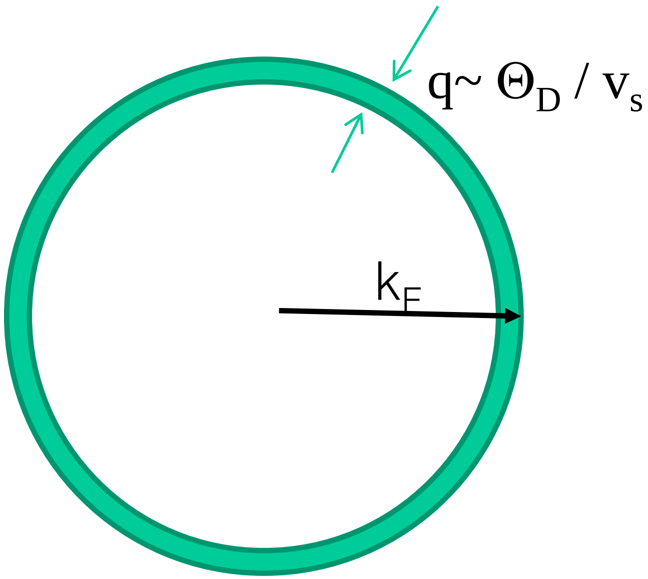
T_F (13 K) << Θ_D (400 K)

The standard BCS scenario needs $T_F >> \boldsymbol{\Theta_D}$!

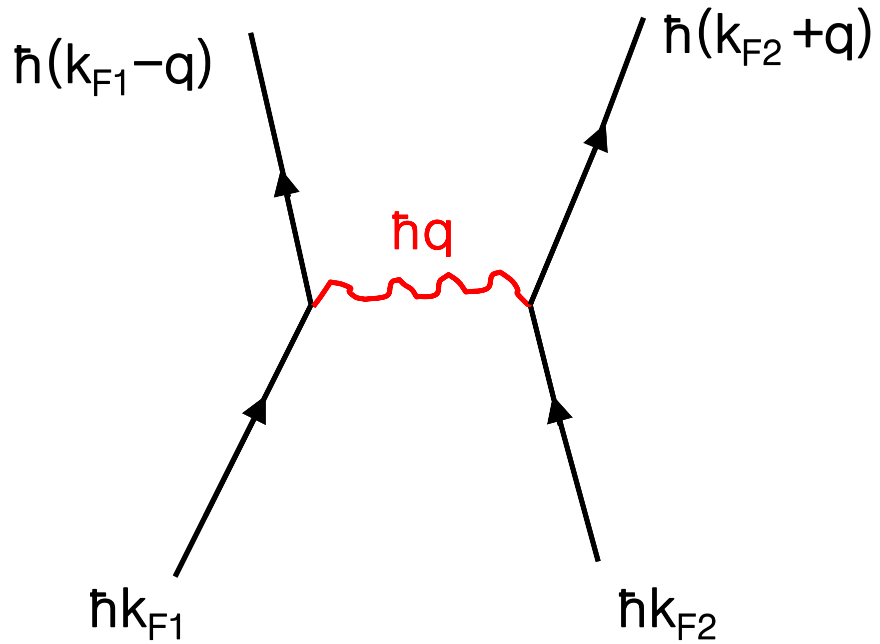
In all conventional (and most unconventional) superconductors, this inequality holds!

But the opposite is true in STO (as in most heavy-fermion superconductors)!

BCS Superconductivity



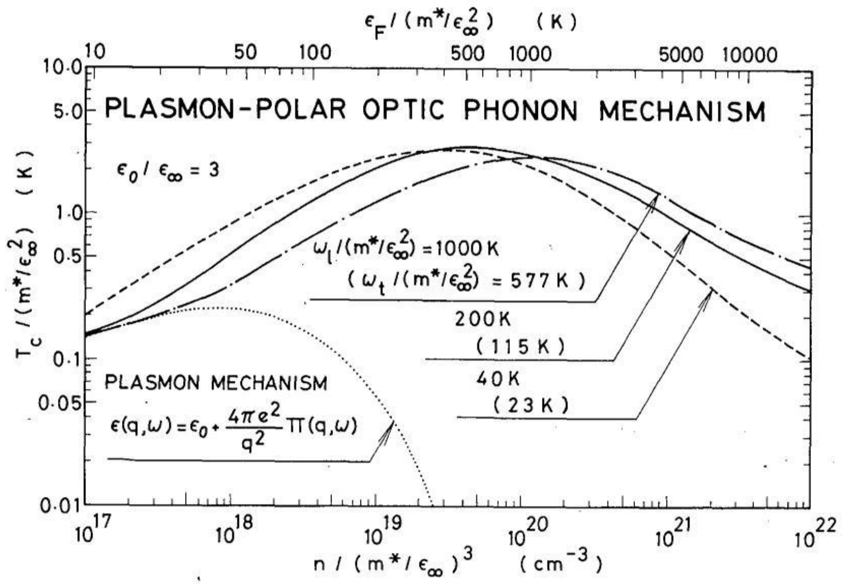
The attractive interaction is confined to a thin layer of electrons near the Fermi energy!



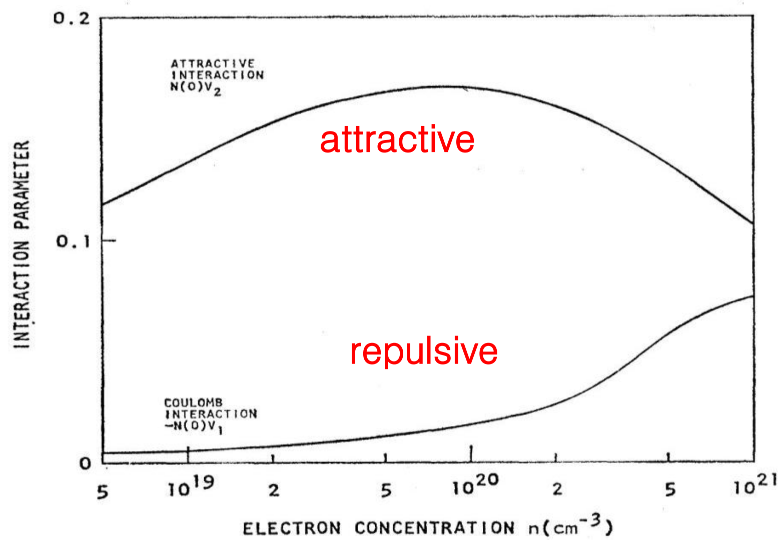
If not, Cooper pairs would not be stable!

Which low-energy boson is the glue?

- Plasmons?
(cf. Takada)



- A phonon Soft mode ?
(cf. Appel)



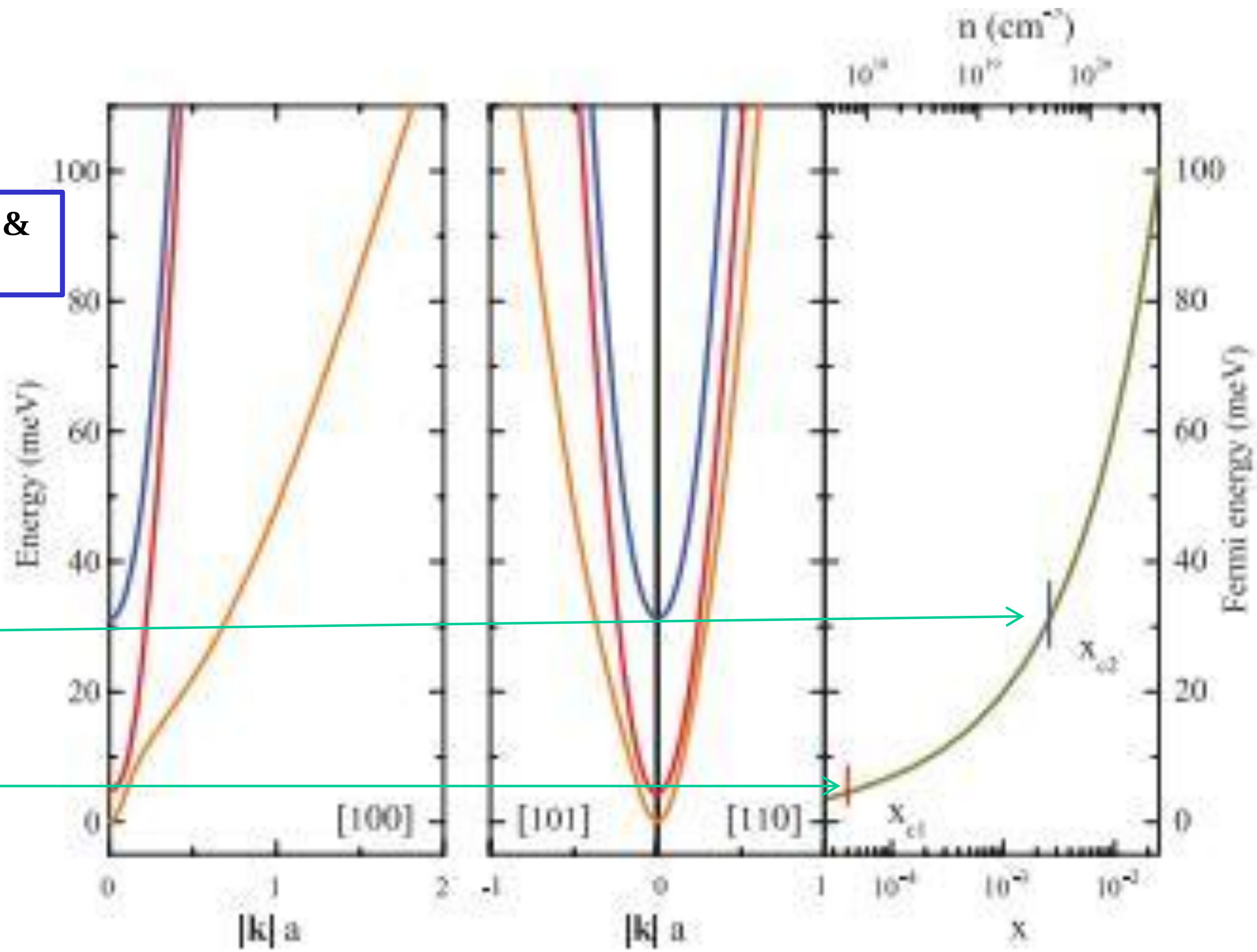
- Ferroelectric quantum criticality?
(cf . Lonzarich)

Theoretical band structure in $SrTiO_3$ by virtual crystal approximation

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

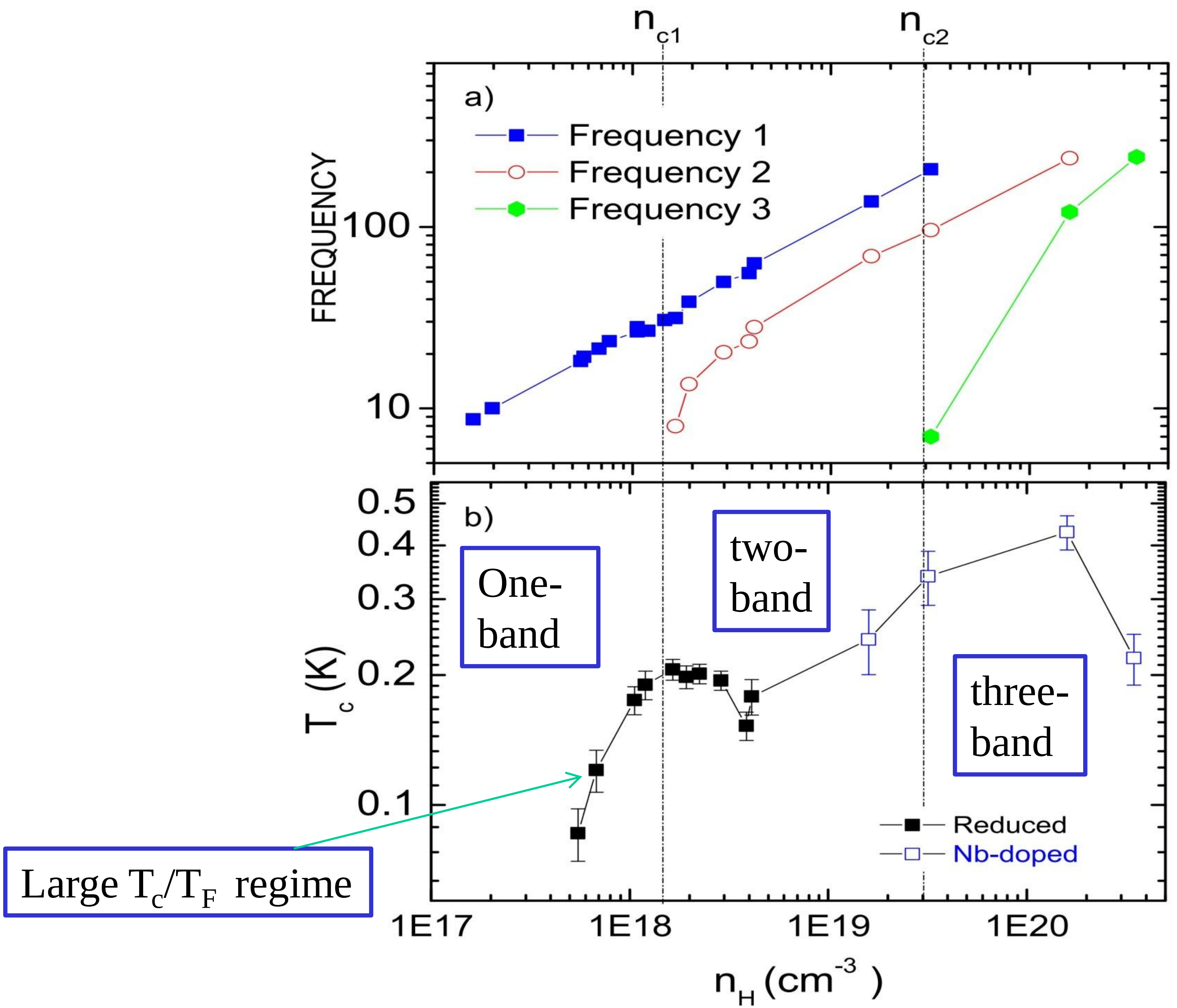
X_{c2}=4.4 10^{19} cm^{-3}

X_{c1}=6.8 10^{17} cm^{-3}

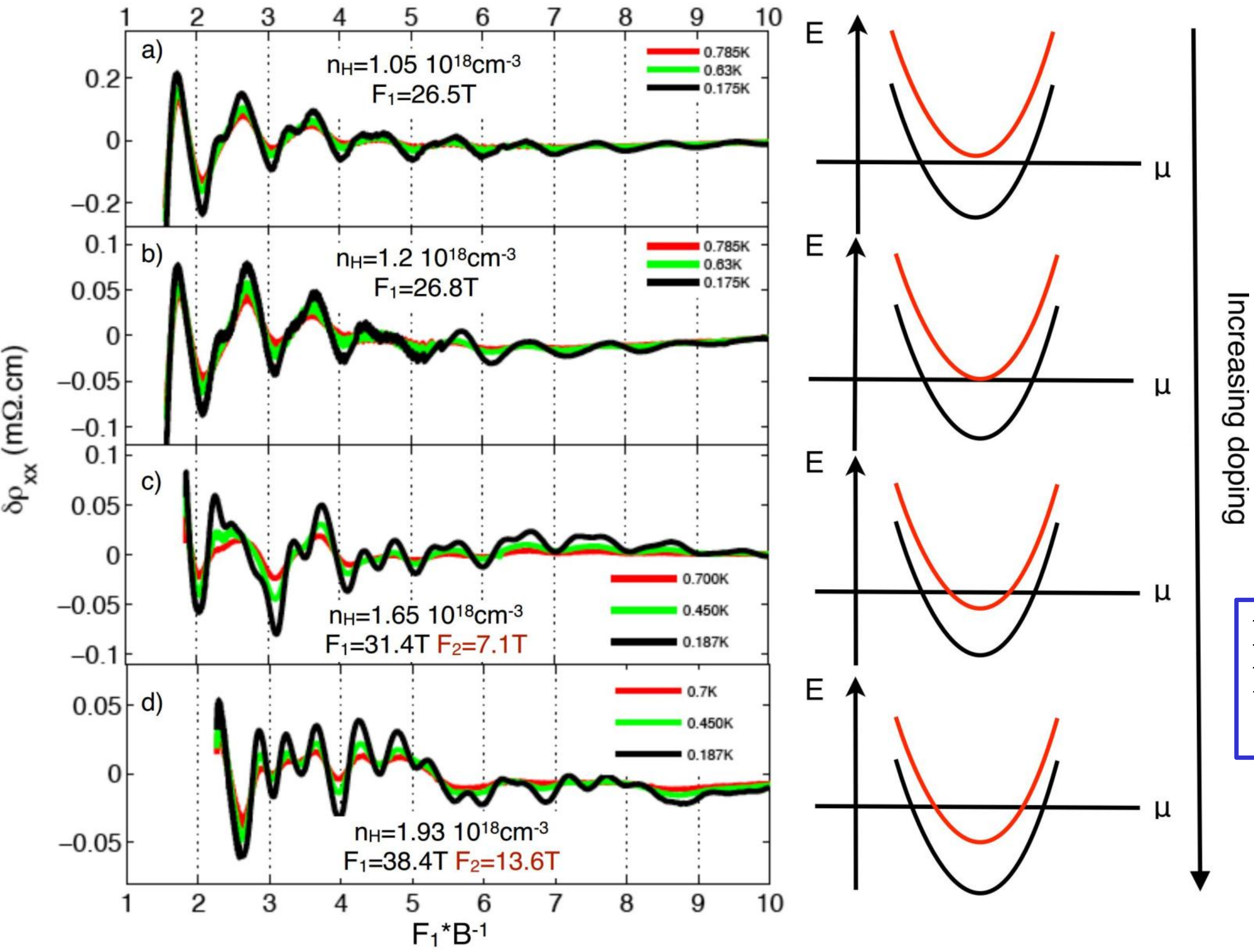


- Threefold degeneracy of a band centered at Γ-point is lifted.
- The three bands are to be succesively filled.

Bands and domes!



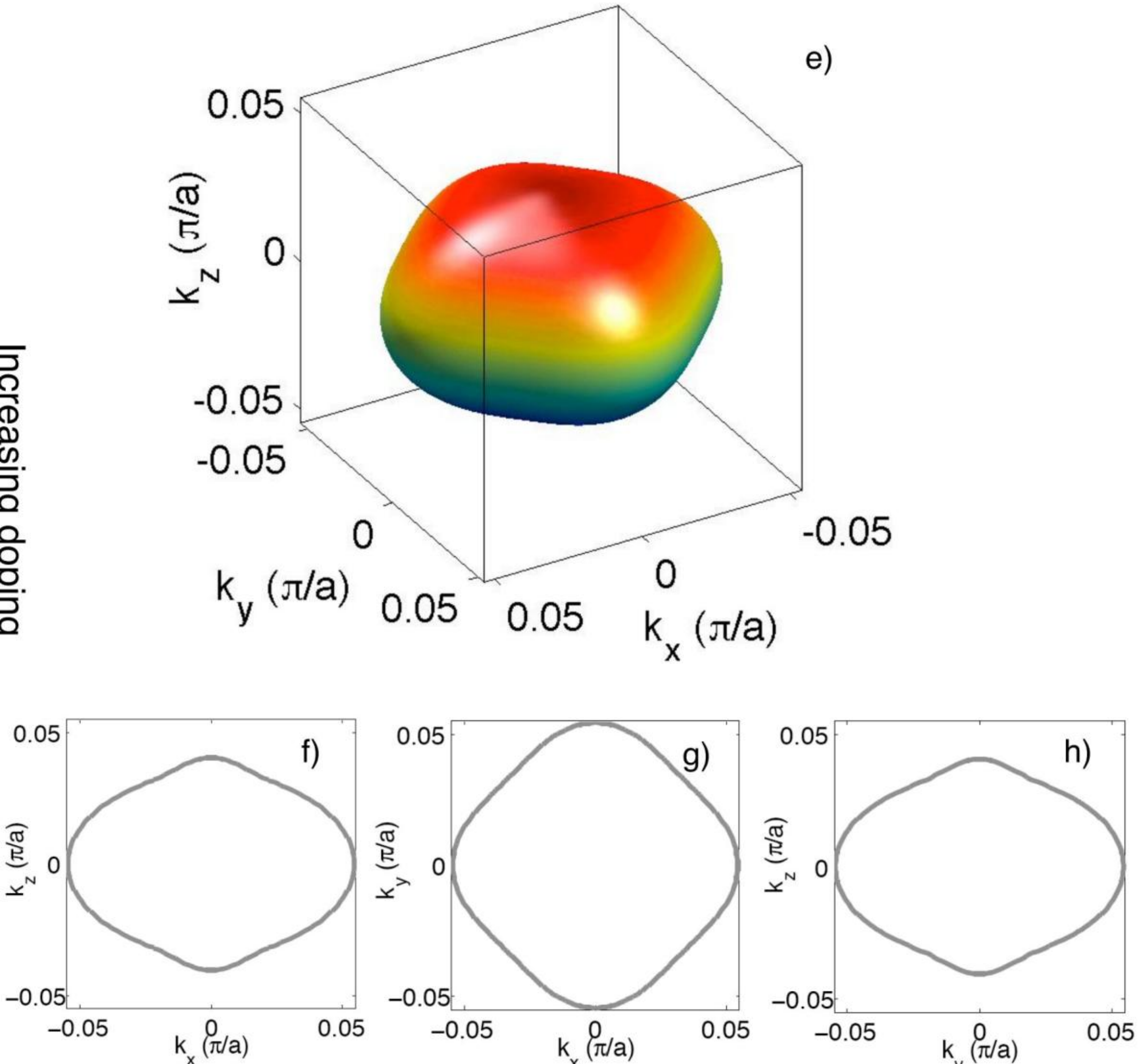
The first critical doping



Emergence of a new frequency !

Lin *et al.* PRL in press (2014)

Origin of split peaks

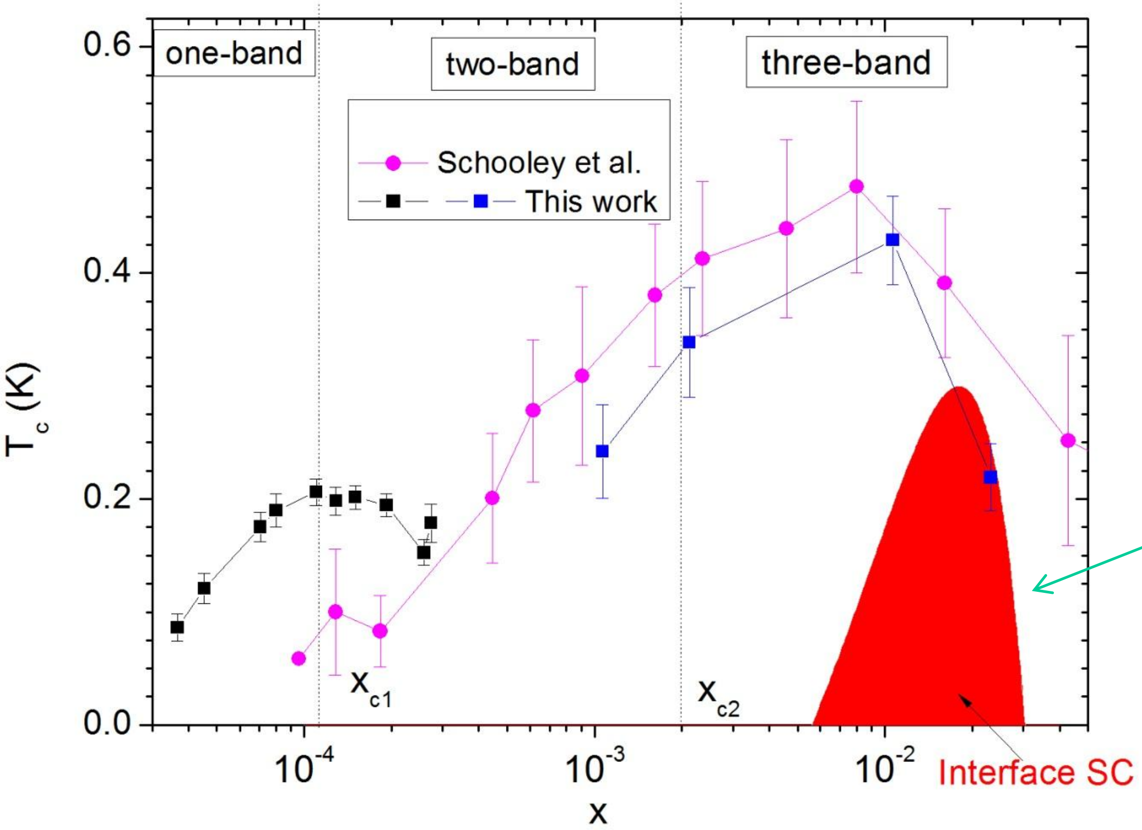


Anisotropy of Femi surface ~ 1.3
S. J. Allen *et al.*
PRB (2013)

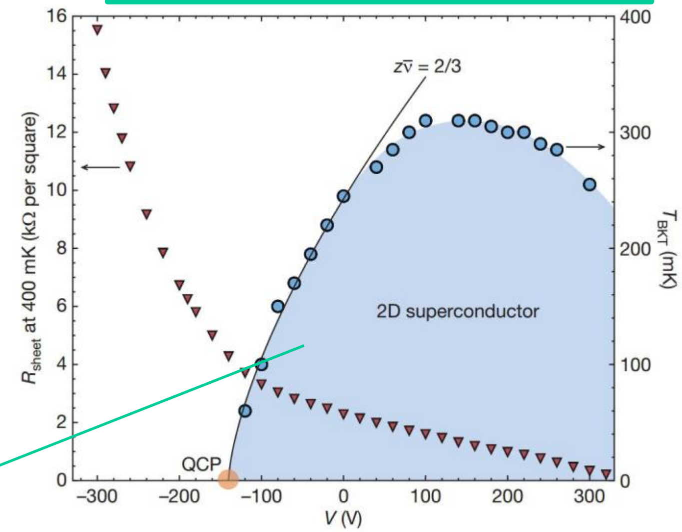
The three faces of the Fermi surface in a multi-domain sample.

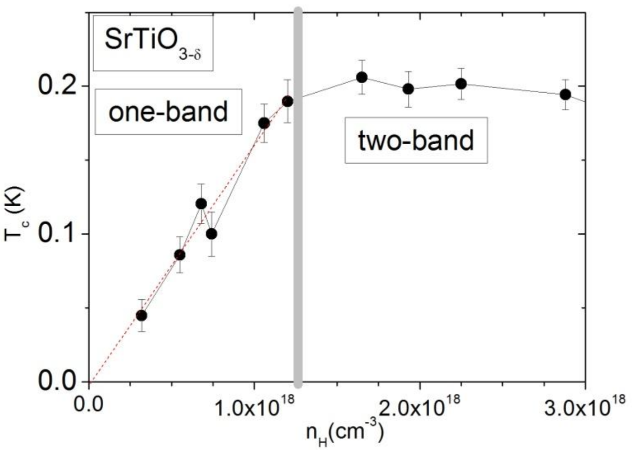
Old and new phase diagrammes

Lin *et al.* PRL in press (2014)

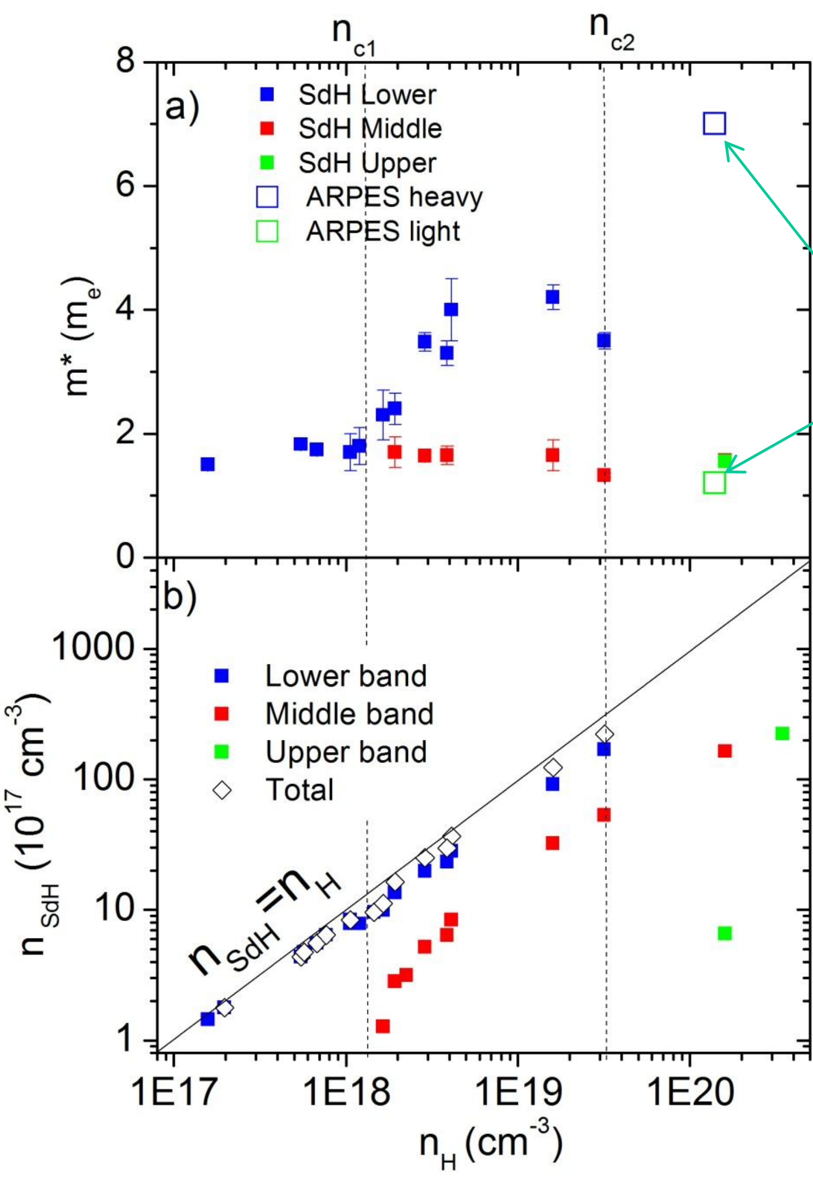


Caviglia *et al.*, Nature (2008)





Evolution of cyclotron mass with doping

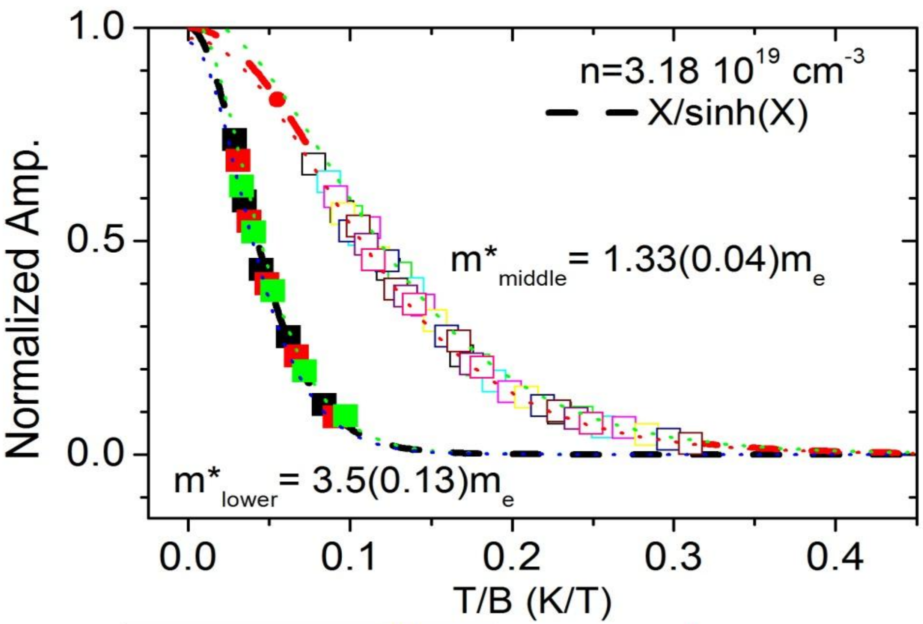


The effective mass in the lower band suddenly rises above n_{c2}!

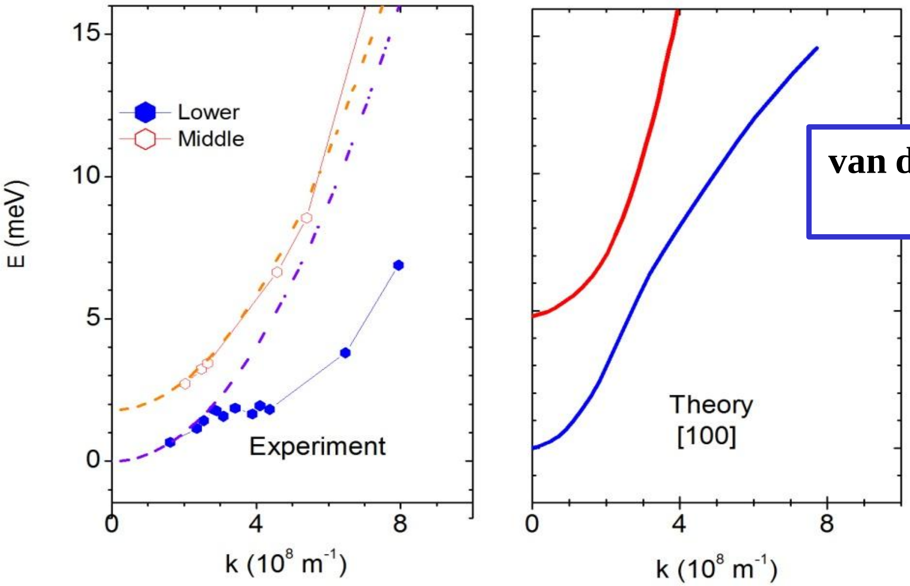
ARPES data

The number of carriers in each band!

Non-parabolic dispersion of the lower band



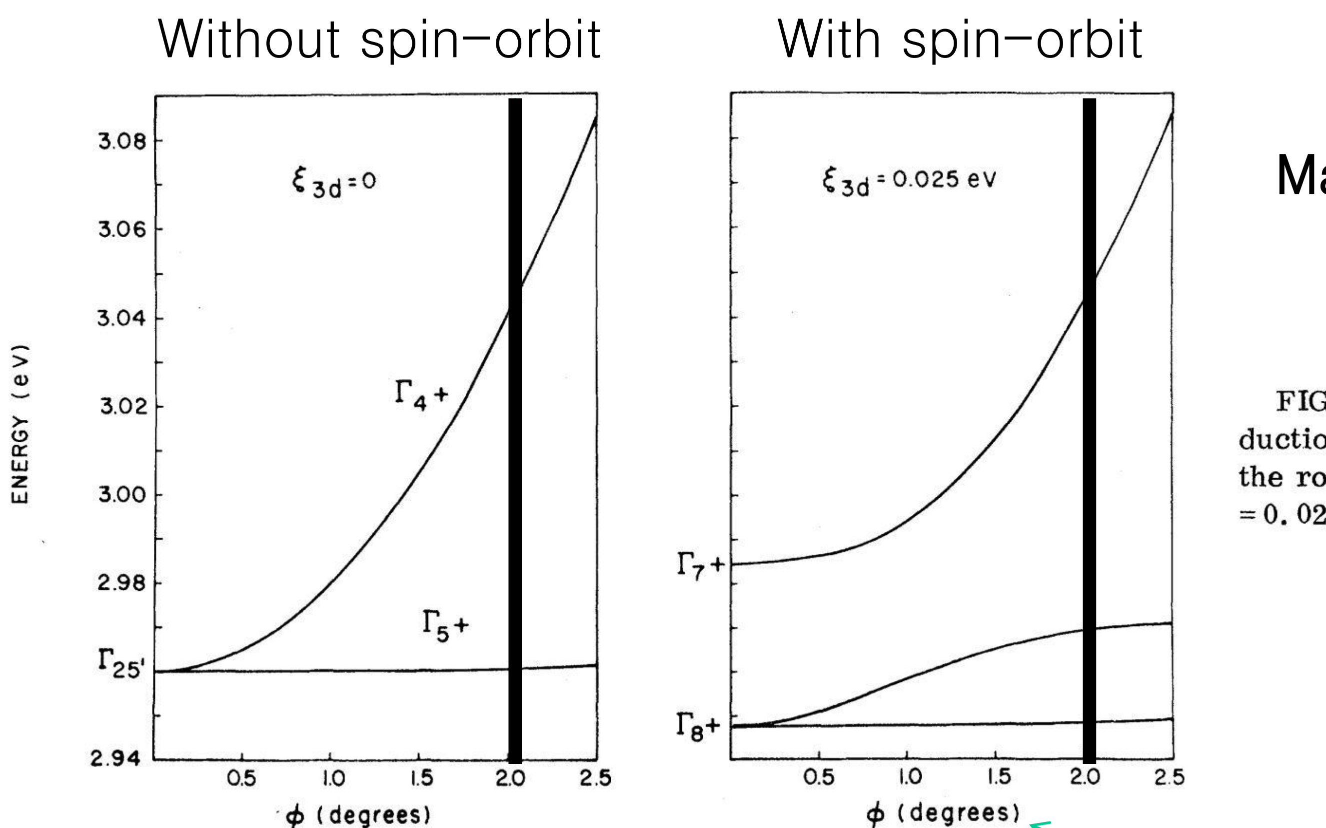
	Experiment	Ab initio Theory
m* (m_e)	1.8	0.7-0.9
n_{c1} ($10^{17}cm^{-3}$)	12	6.8
Δ (meV)	2.2	5



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

Where does the mass enhancement come from?

Band hierarchy crucially depends on the sign of the crystal field parameter



Matheiss PRB 1972

FIG. 3. Splitting of the $SrTiO_3$ conduction-band minimum as a function of the rotation angle φ with $\xi_{3d} = 0$ and $\xi_{3d} = 0.025$ eV.

Matheiss' crystal field parameters would make the middle band non-parabolic!

Summary

- When one oxygen out of 10^5 is missing in $SrTiO_3$, it superconducts and has a sharp Fermi surface.

- The smallest Fermi surface to suffer a superconducting instability emerges in the context of an extremely long Bohr radius.

- Mechanism of superconductivity and symmetry of the order parameter remain open issues. Superconductivity is strong coupling at small wave-vector and small energy.

What is a metal?

"Everyone knows what a metal is and can describe many of its characteristics.

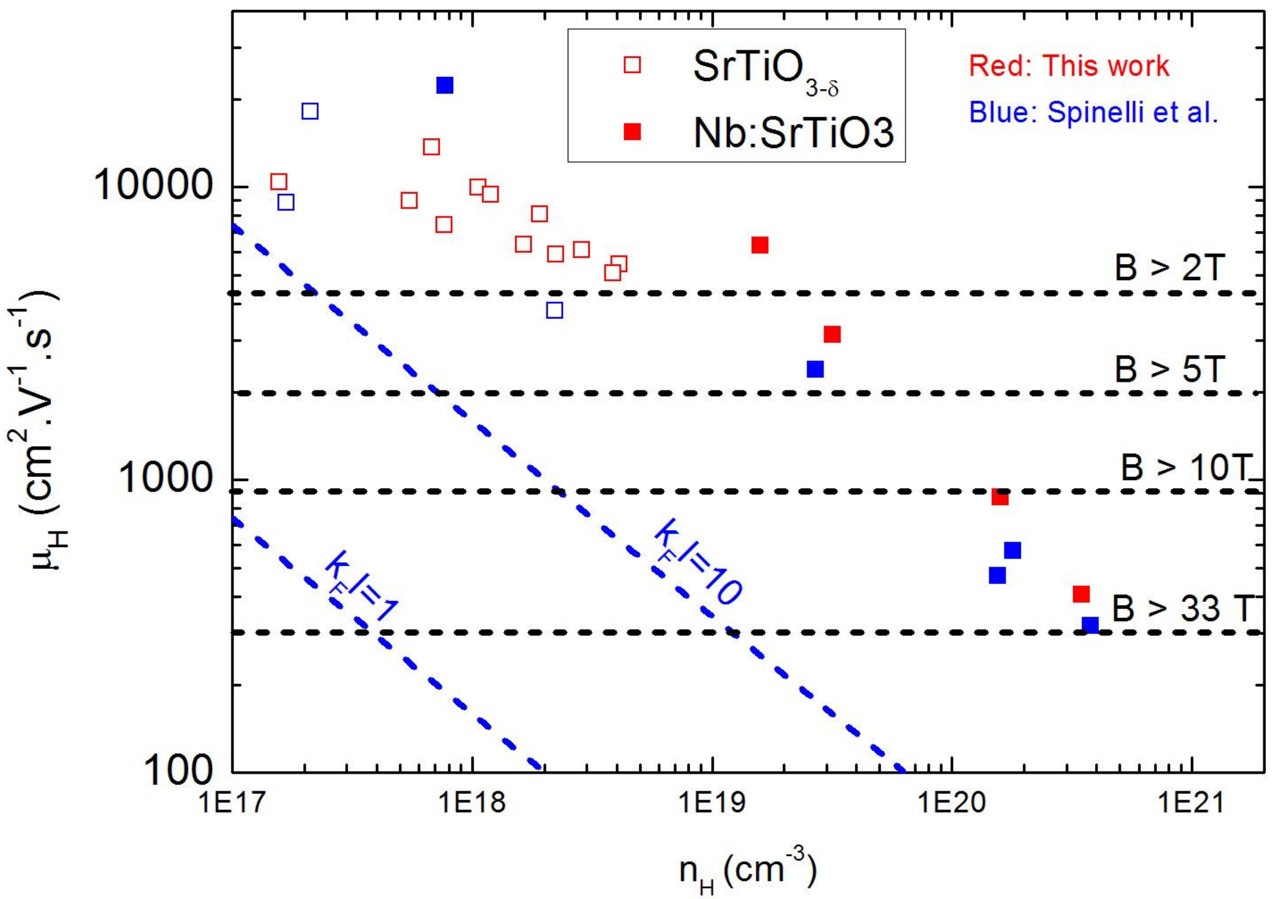
It is safe to say, however, that few people would define a metal as a 'solid with a Fermi surface'.

This may nevertheless be the most meaningful definition of a metal and provides a precise explanation of the main physical properties "

A. R. Mackintosh

Scientific American 1963

Consequences of high mobility



- Quantum oscillations visible at accesible magnetic fields
- Localisation is avoided at low concentration

Two-Band Superconductivity in Nb-Doped $SrTiO_3$

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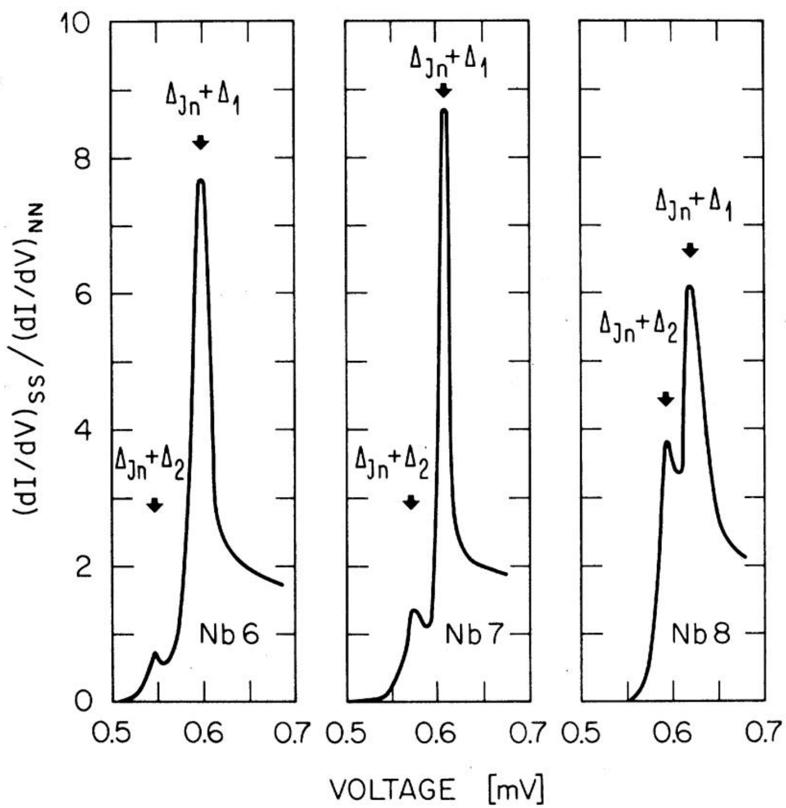
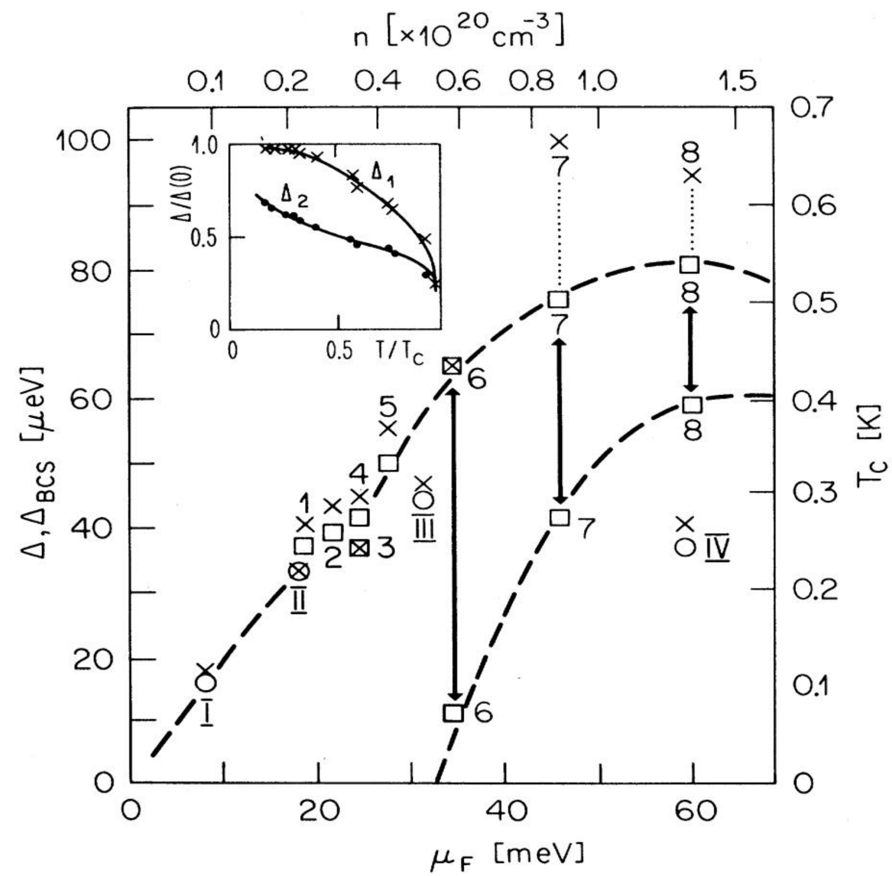
(Received 8 April 1980)

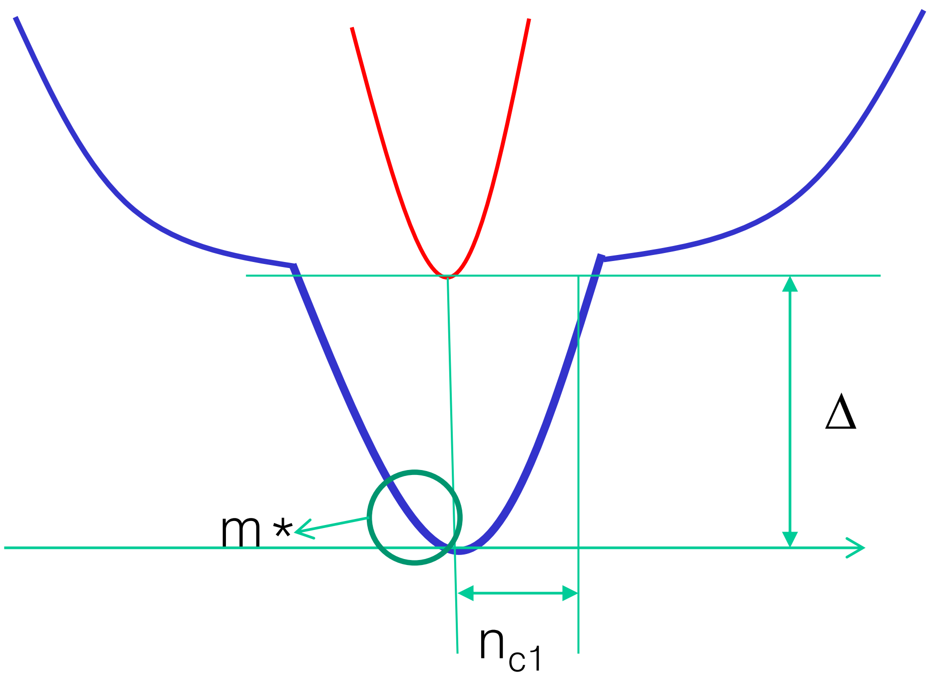
Two-band superconductivity seen by tunneling!





Theory and experiment

	Experiment	Ab initio Theory	References
m^* (m_e)	1.8	0.7-0.9	1, 2, 3
n_{c1} ($10^{17}cm^{-3}$)	12	6.8	1
Δ (meV)	2.2	5	1



Theoretical references:

1. van der Marel, van Mechelen & Mazin, PRB (2011)
2. Janotti, Steiauf & Van de Walle, PRB (2011)
3. Shirai & Yamanaka, JAP

Where does the mass enhancement come from?

The $Sr_{1-x}La_xTiO_3$ system

Metal close to the band insulator

Okuda et al., 2001

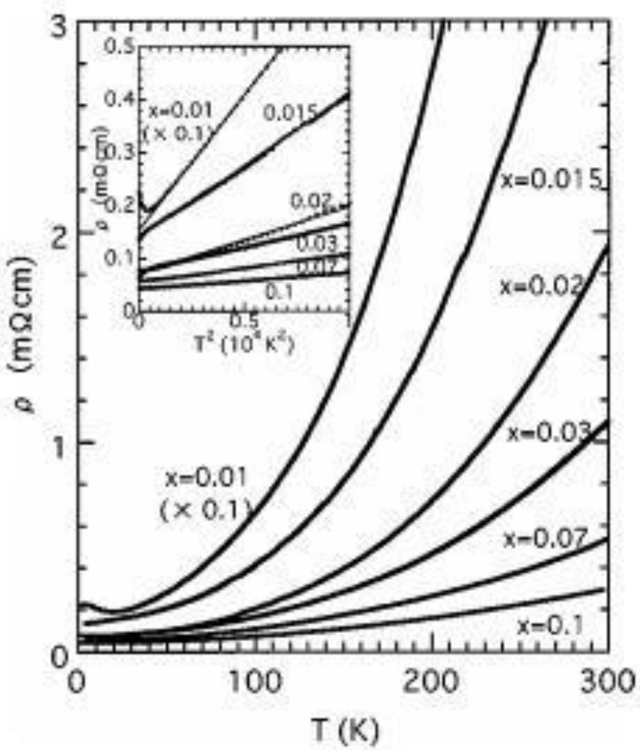
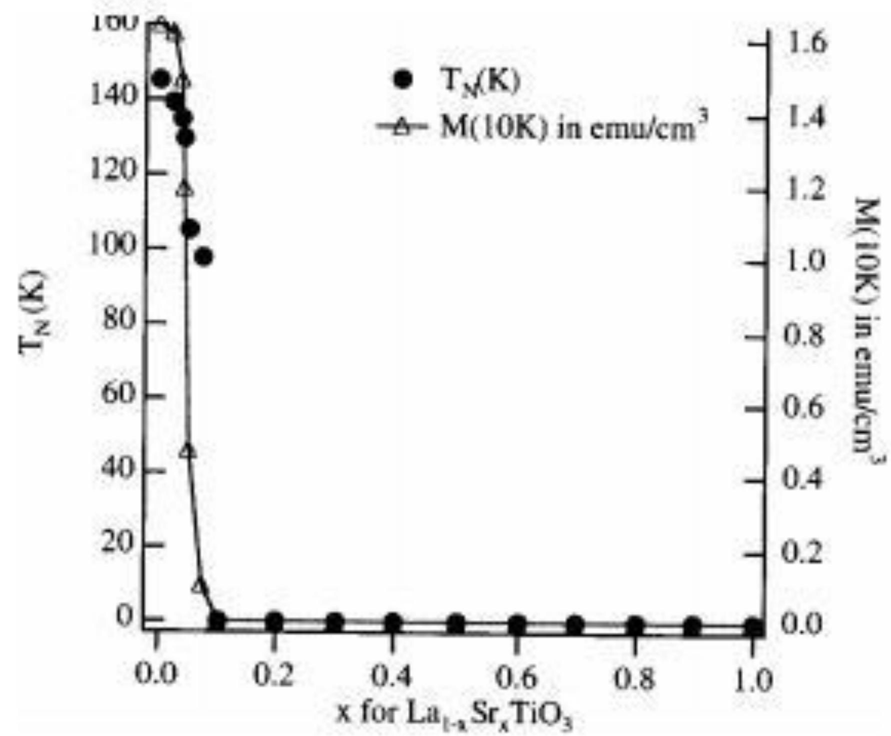


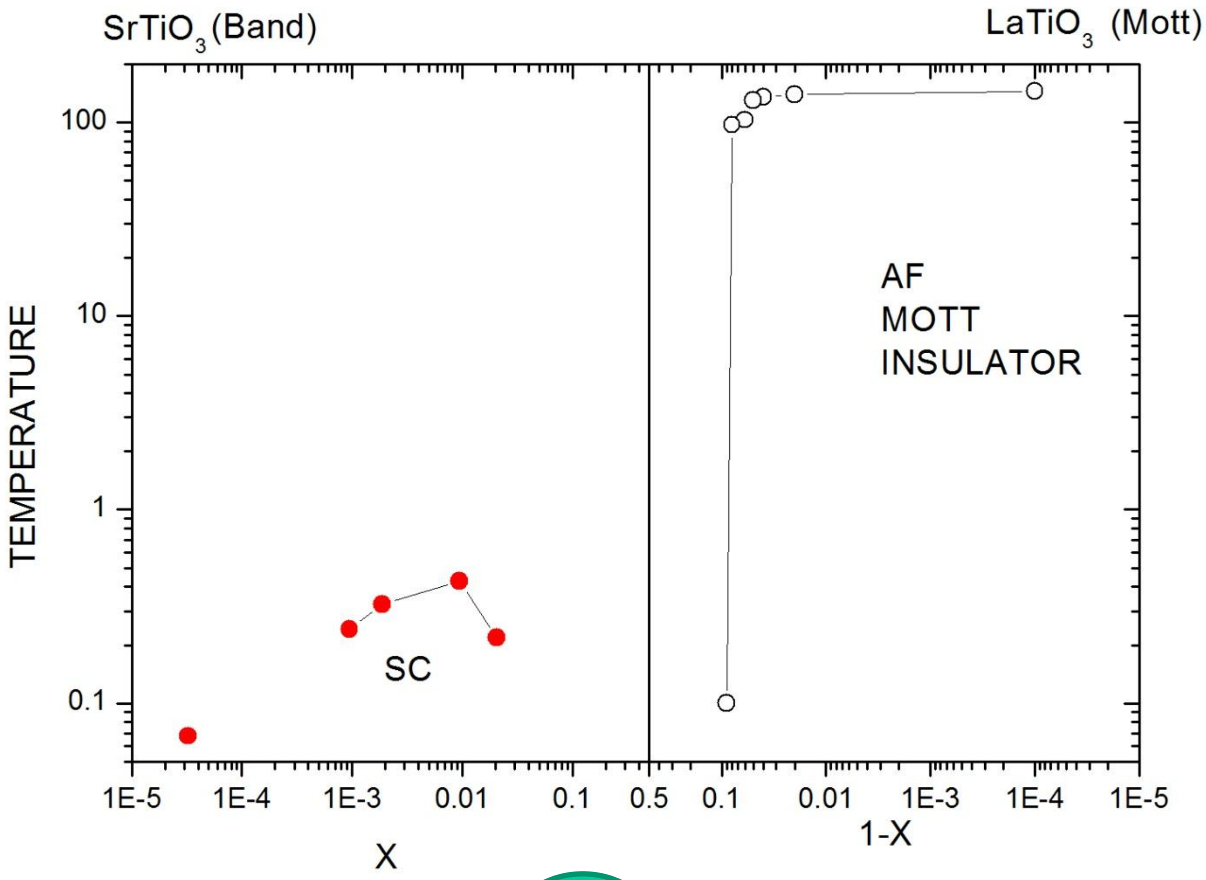
FIG. 1. Temperature (T) dependence of resistivity (ρ) for $Sr_{1-x}La_xTiO_3$ with various x values. Below 100 K, the resisitivites for all compounds are almost proportional to T^2. The inset shows a ρ vs T^2 plot below 100 K.

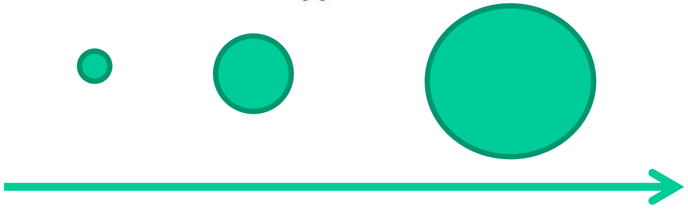
Robust AF close to the Mott insulator

Hayes et al., 1999



The $Sr_{1-x}La_xTiO_3$ system





The Fermi surface grows and then suddenly vanishes!