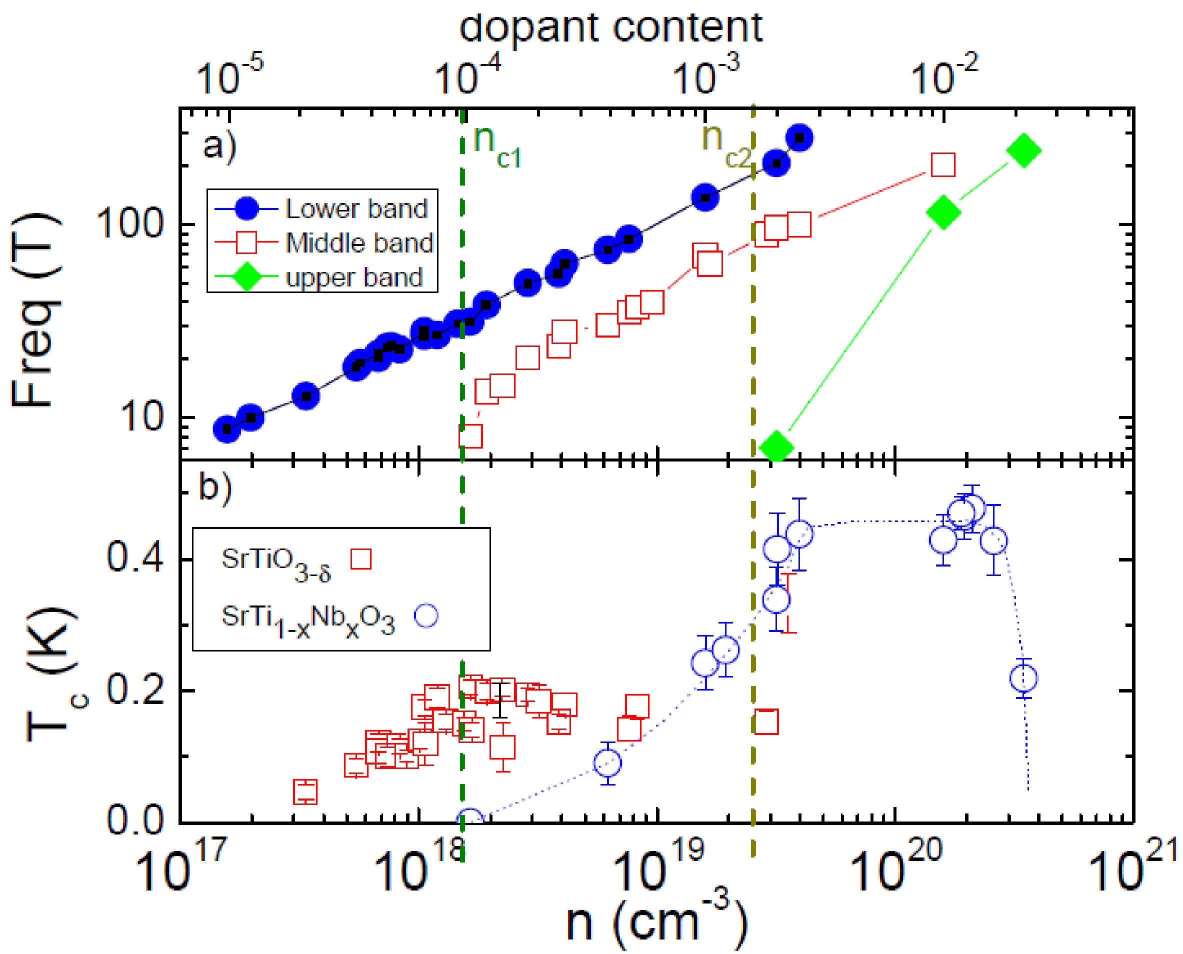
Superconducting domes and Lifshitz transitions in strontium titanate

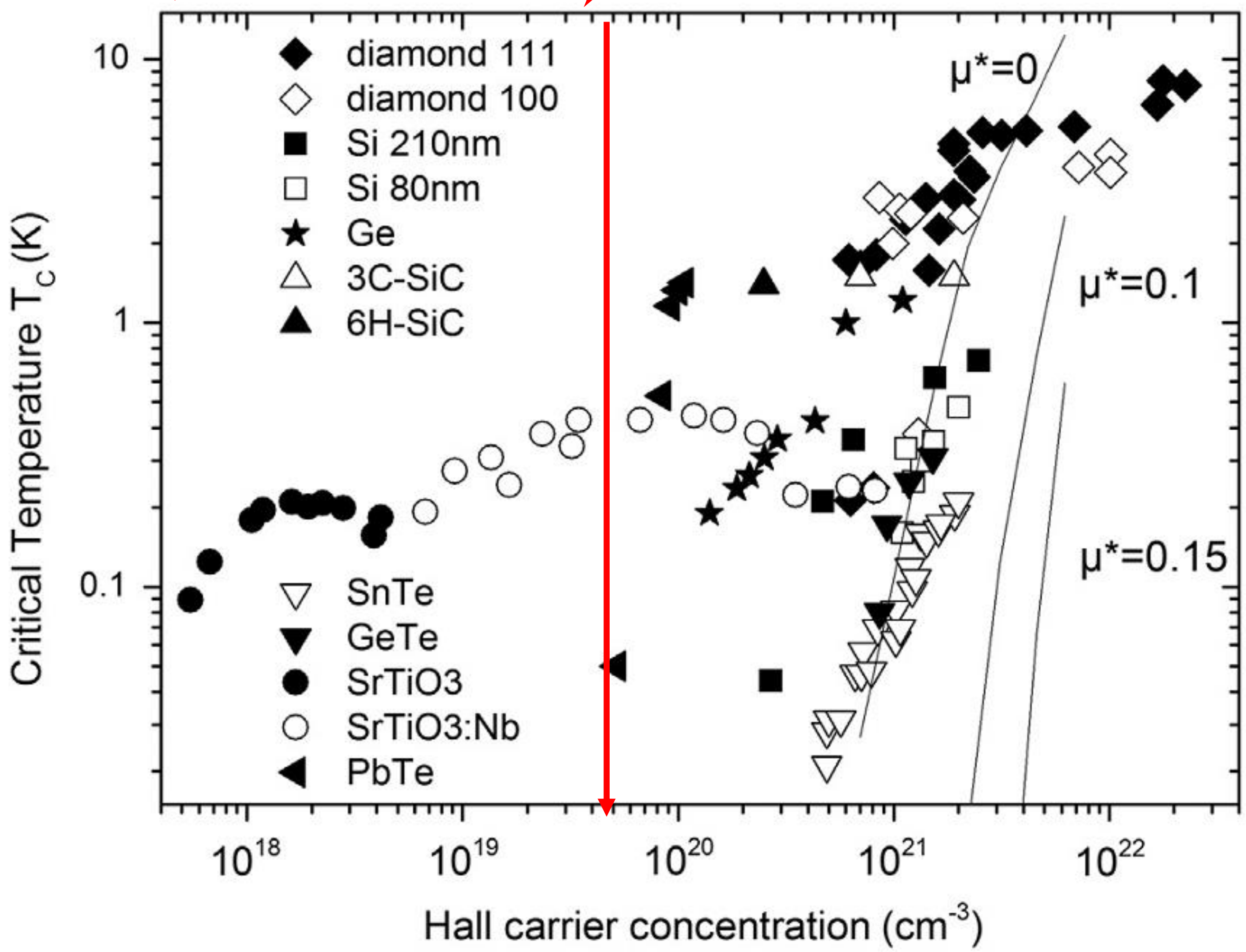
Kamran Behnia



$SrTiO_3$:The most dilute superonductor

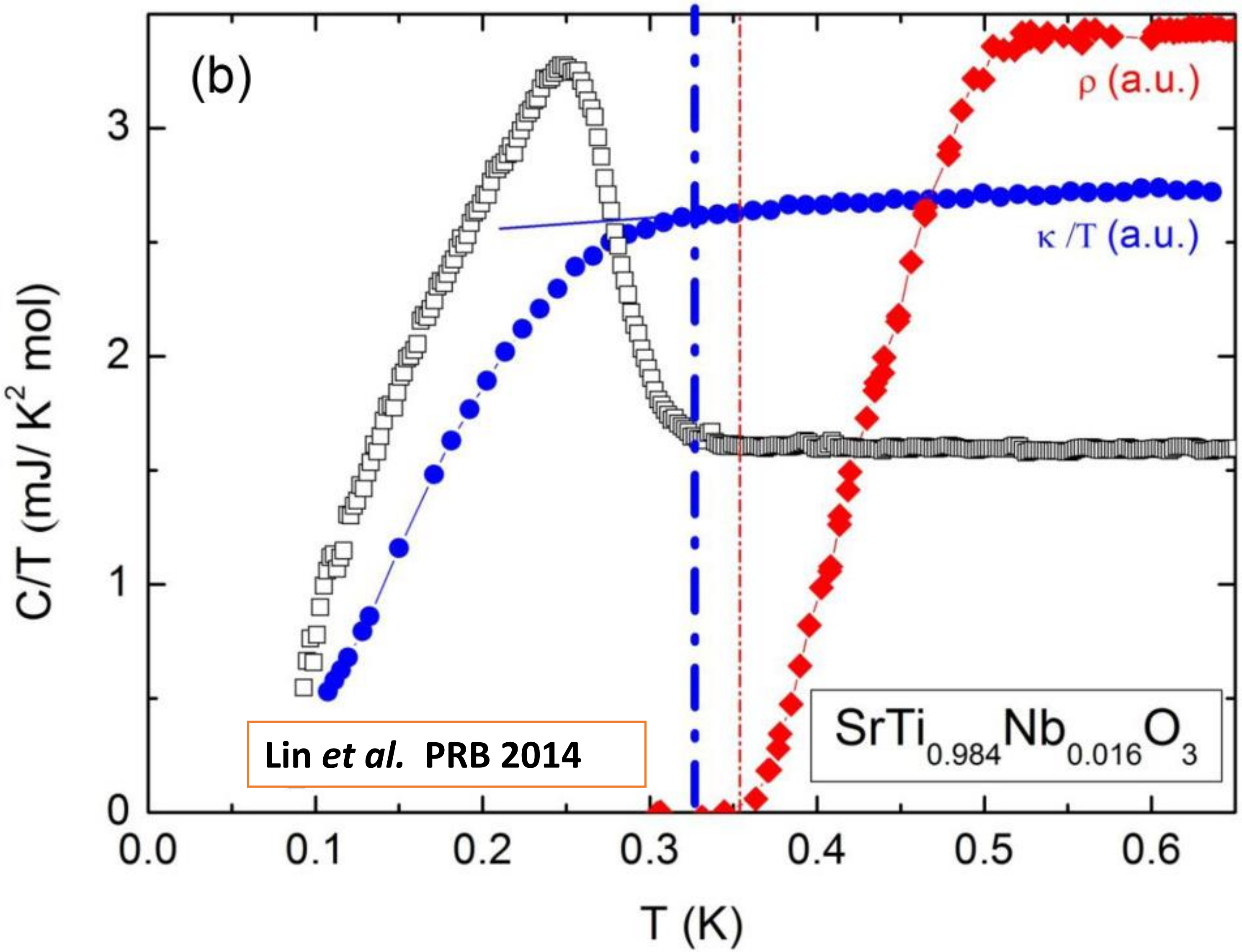
No other bulk superconductor

Bustarret Physica C 2015



- Superconductivity @n_{3D}= 3.5 10^{17} cm^{-3}
- Equivalent in density to n_{2D}= 5 10^{11} cm^{-3}
- Carrier density in superconducting magic angle bilayer graphene (n_{2D}~10^{12} cm^{-3})

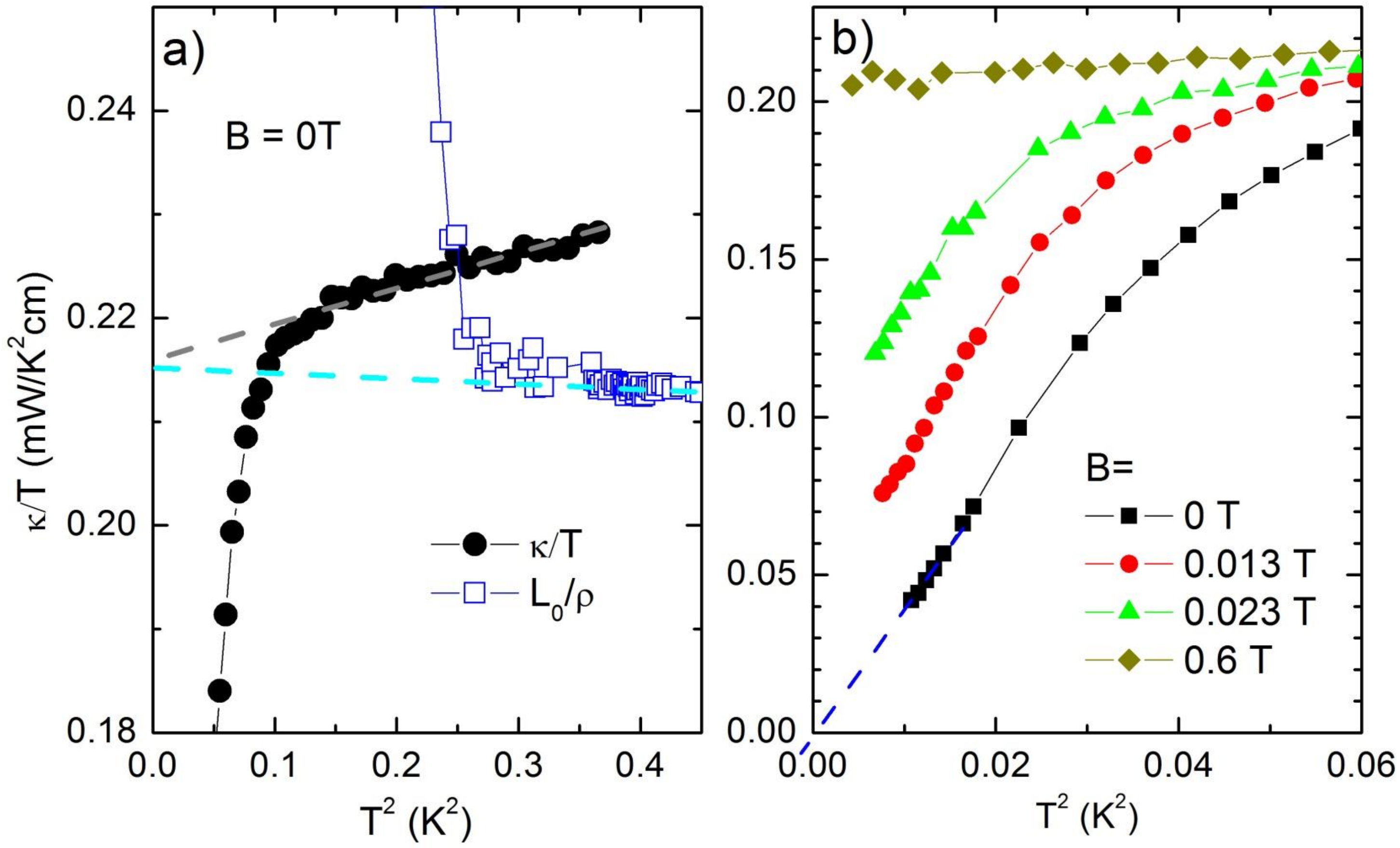
Superconductivity at optimal doping



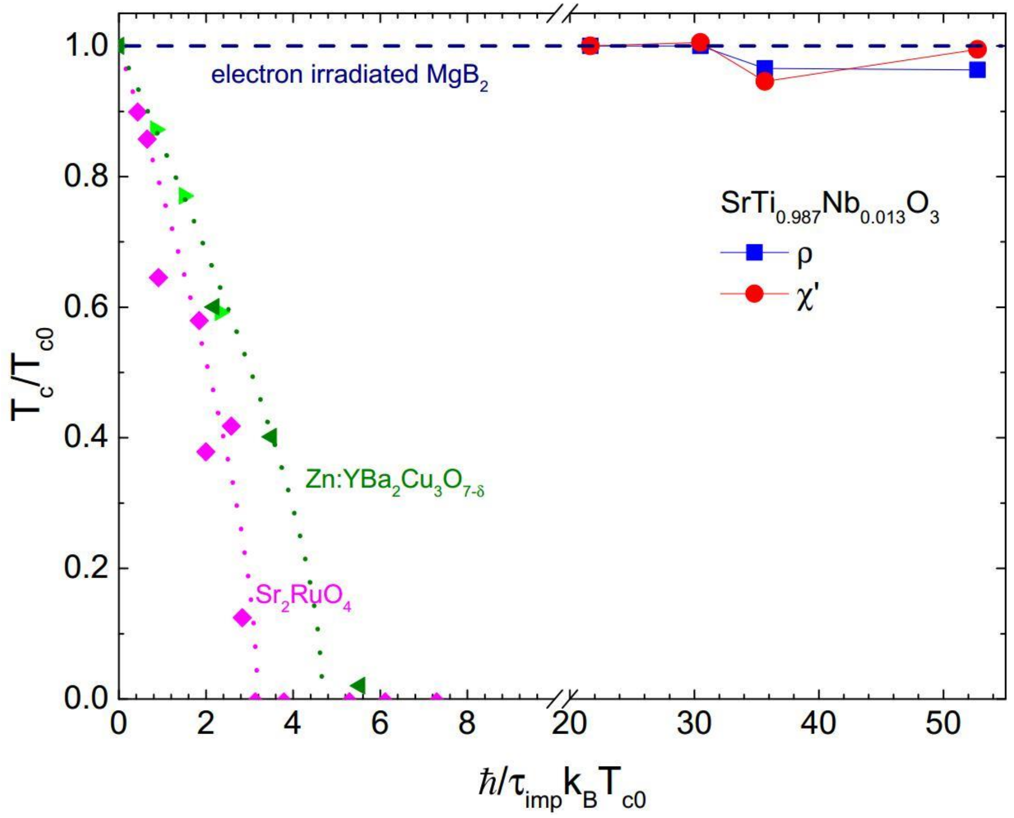
- The specific heat jump is slightly below the BCS weak-coupling value.
- γ_N=1.55 mJ/ K^2mol, (larger than copper with hundred times less électrons). The lowest band has a mass as large as $m^*=3.5m_e$.
- Bulk T_c is well below zero-resistive T_c.

At optimal doping, it is a s-wave superconductor

Lin *et al.* PRB 2014

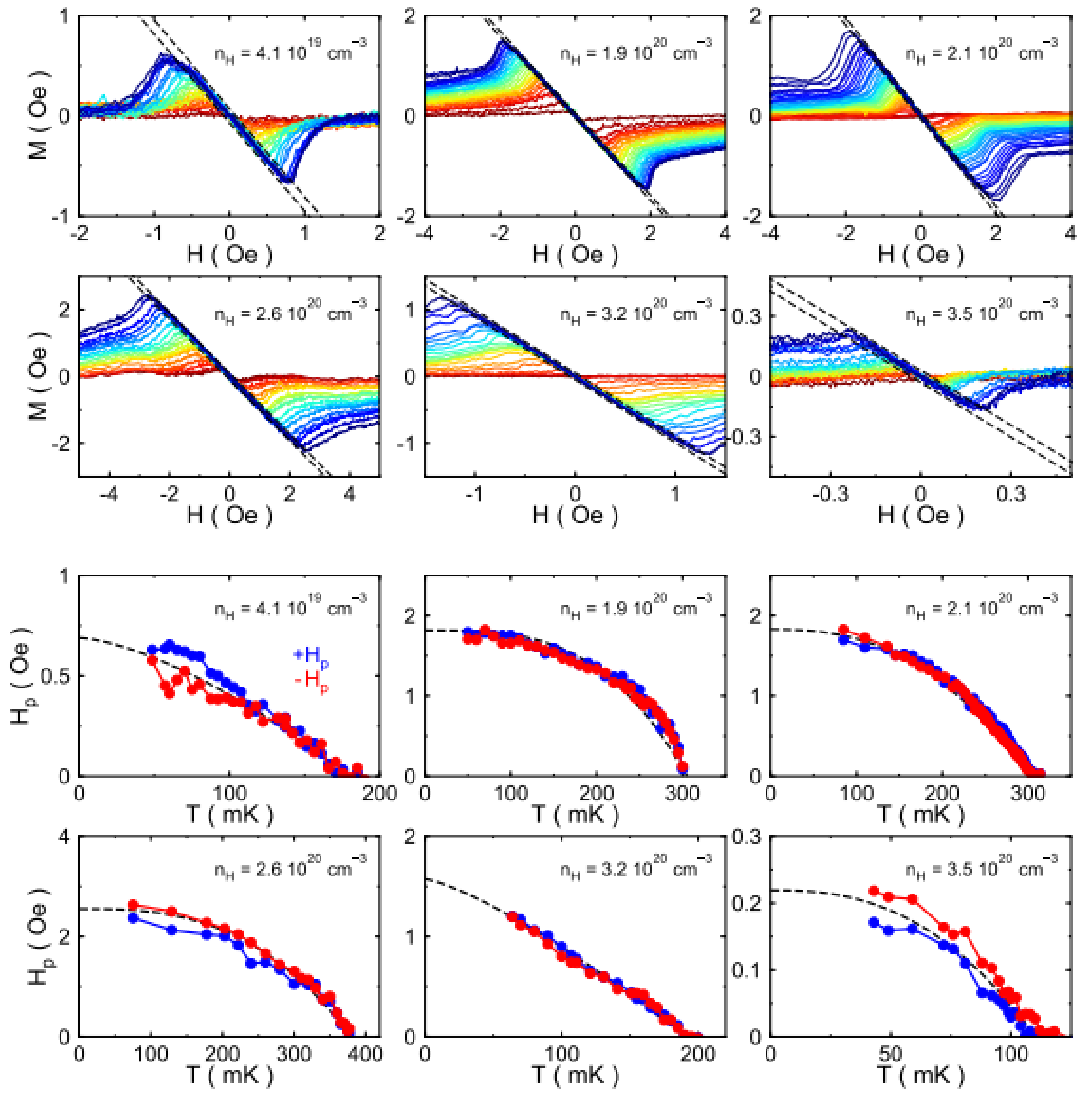


Lin et al., PRB 2015

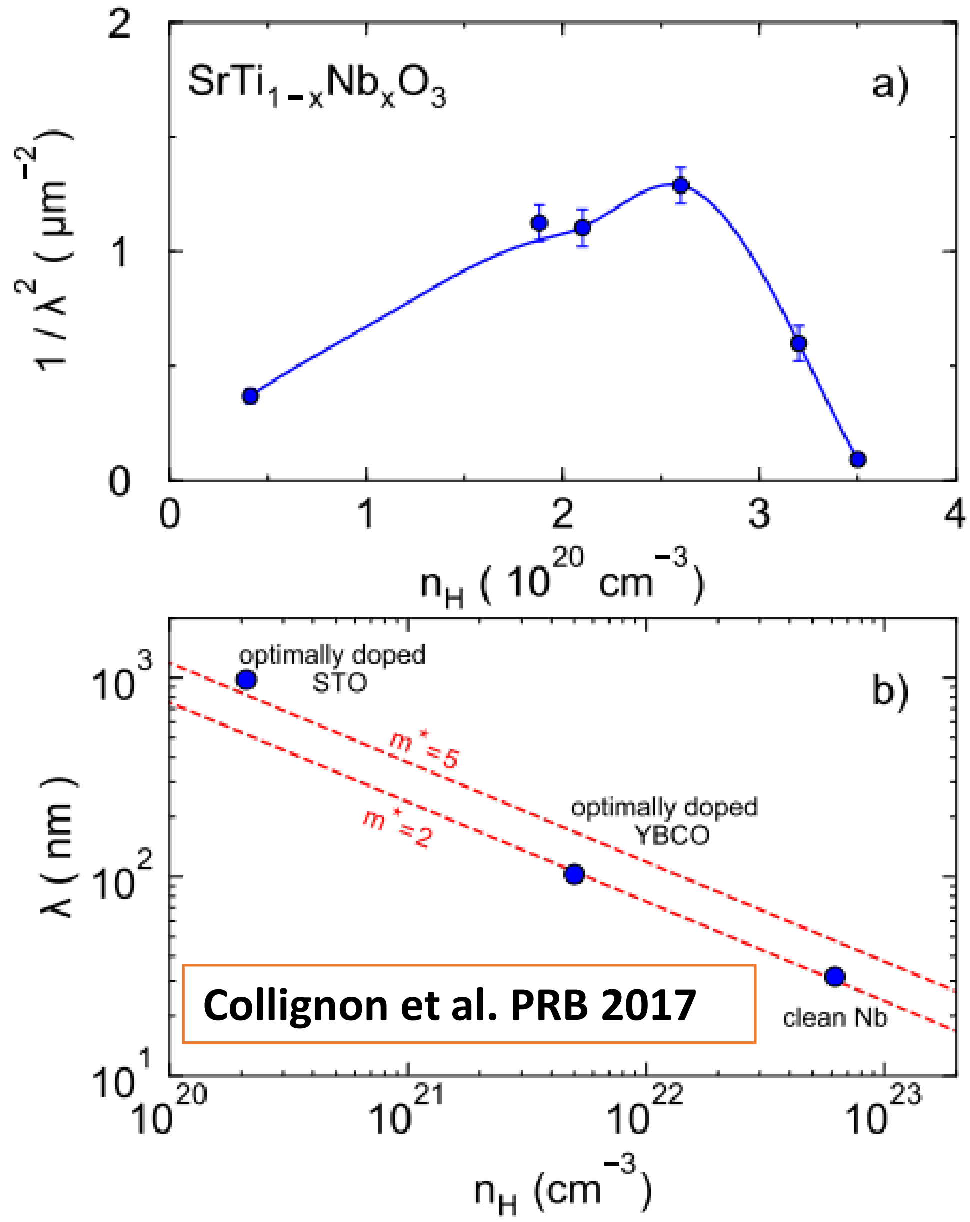


Nodeless gap! **Controlled disorder has no effect on T_c!**

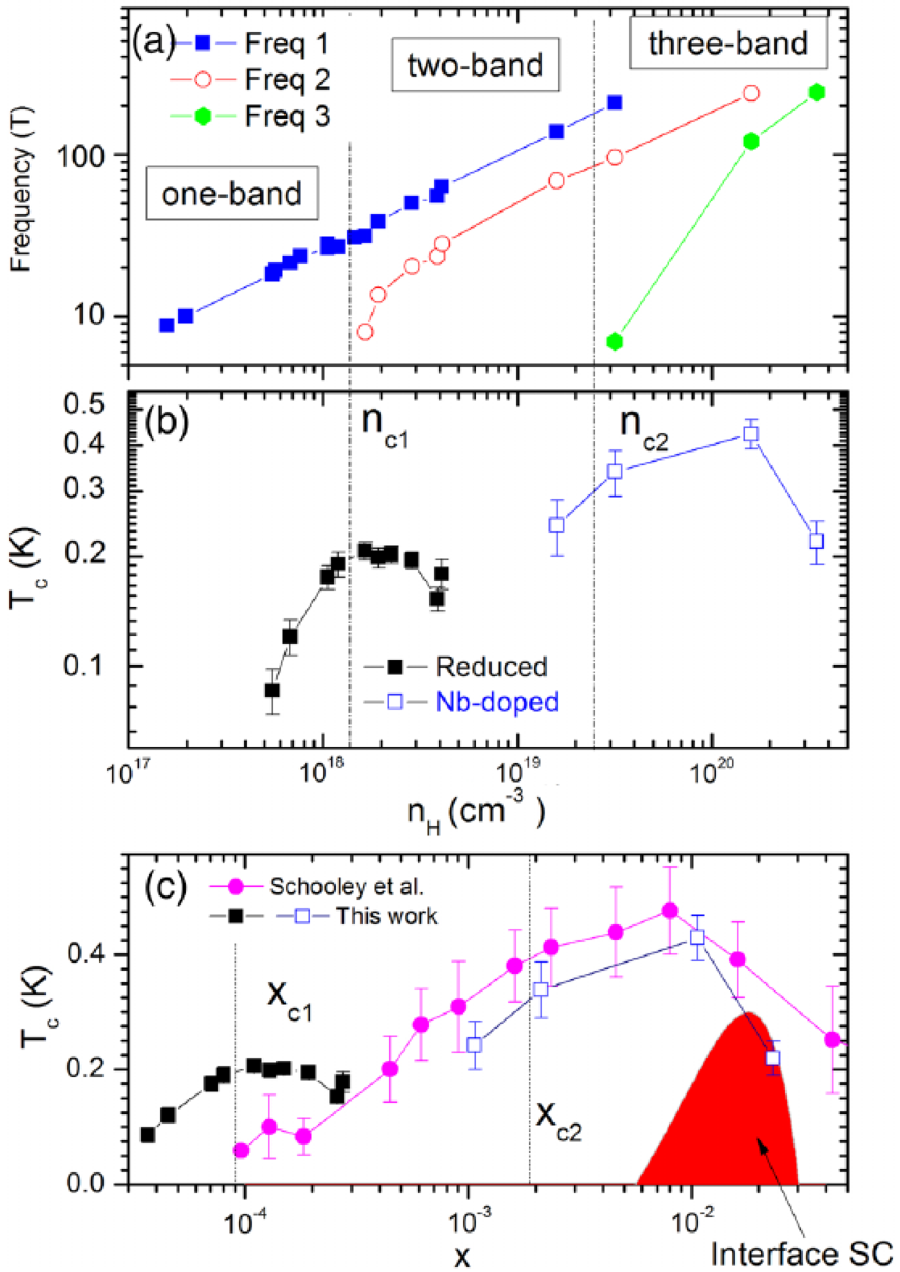
Superfluid density has a dome-like dependence

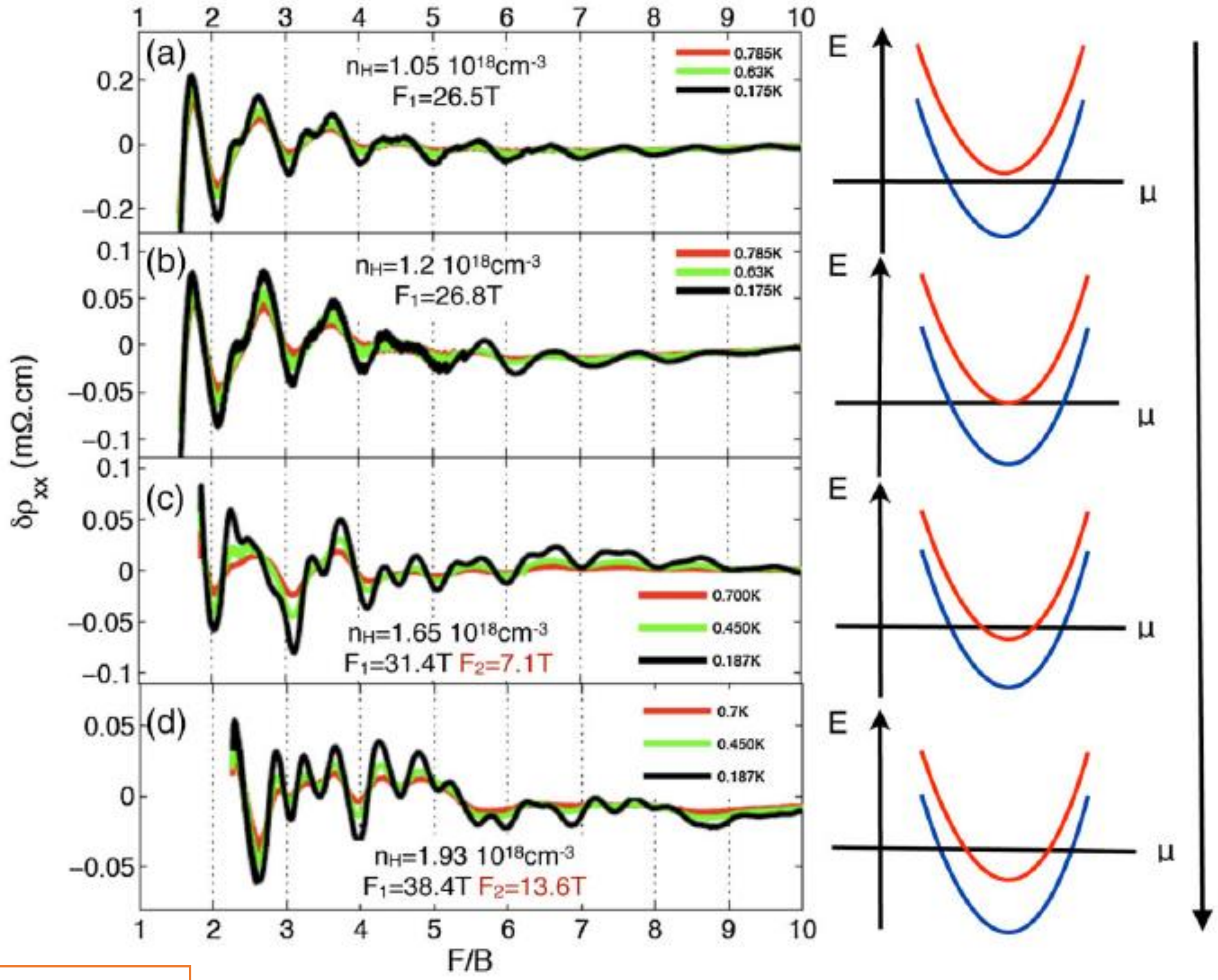


H_{c1} measured at different densities!



Two distinct superconductong domes

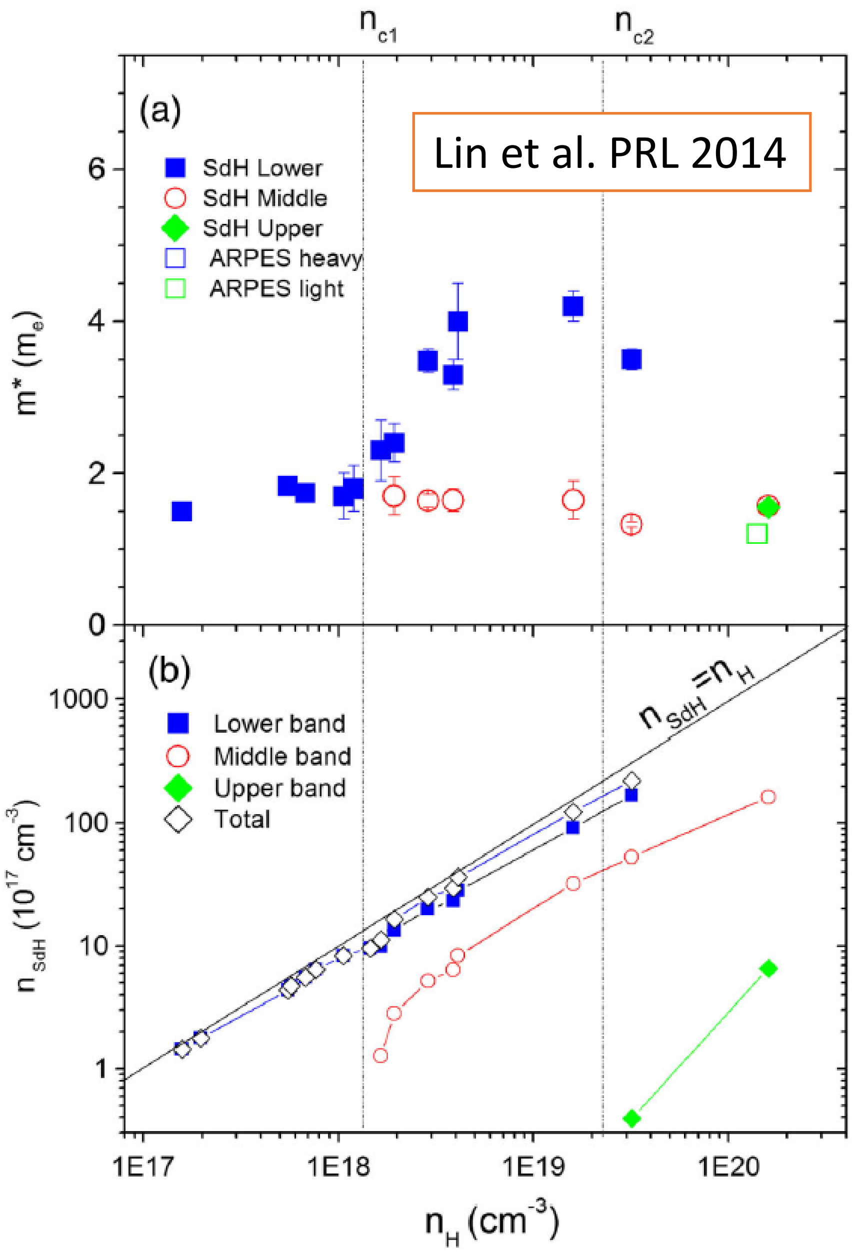


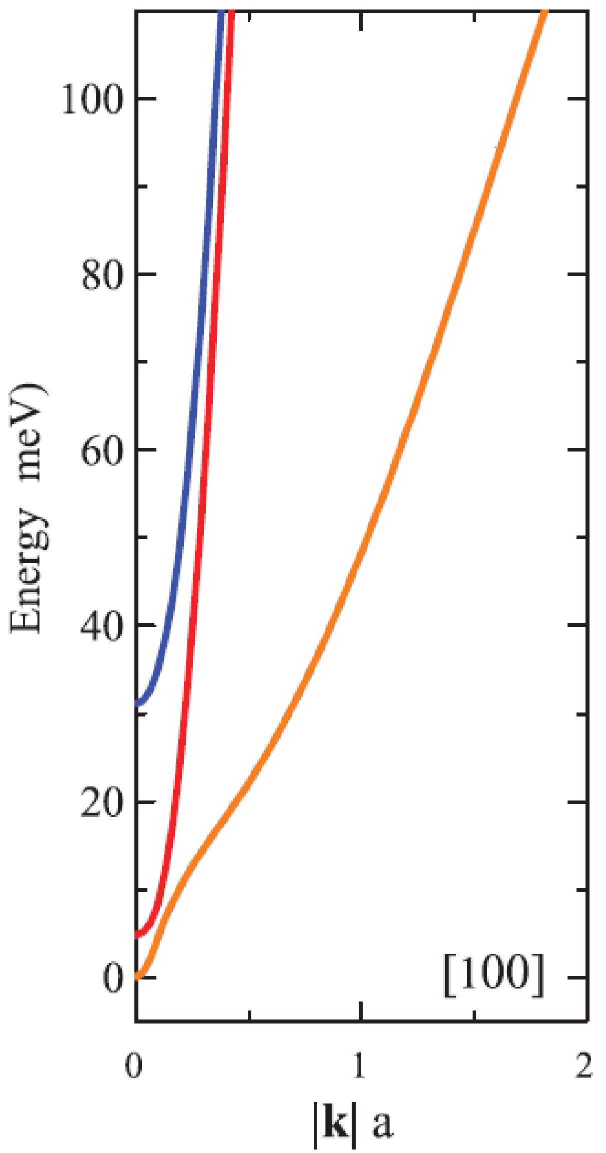


Lin et al. PRL 2014

Lifshitz transition at a critical doping

Fermiology: experiment and theory





van der Marel et al. PRB (2011)

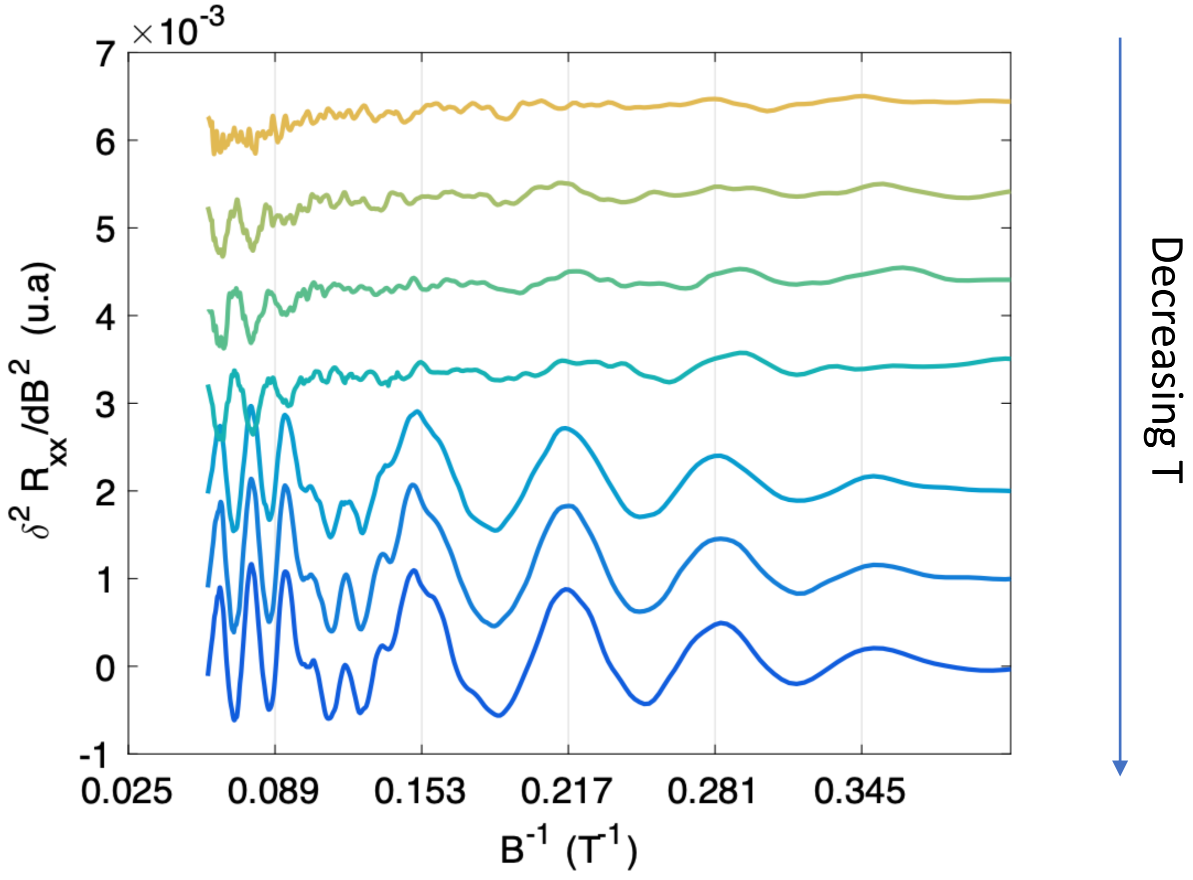
- The electron census works (n_H=n_{SdH})
- Experiment confirms DFT's expectations:

1) 3 FS pockets and 2 critical dopings at (roughly) the right concentration

2) Evolution of the mass with doping in the lowest band

Limits of the rigid band approximation (unpublished)

The evolution of the Fermi surface near the Lifshitz transition is not identical in $SrTiO_{3-\delta}$ and in $SrTi_{1-x}Nb_xO_3$.

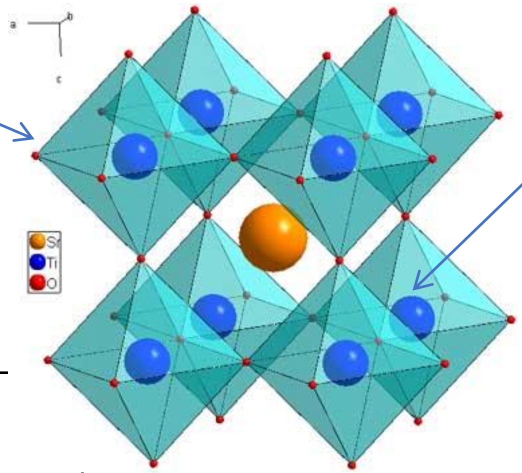


Nb-doped STO (1.6 10^{18} cm^{-3})
Made in Harold Hwang's lab, Stanford

Doping by oxygen vacancies and by Nb Substitution : superconductivity

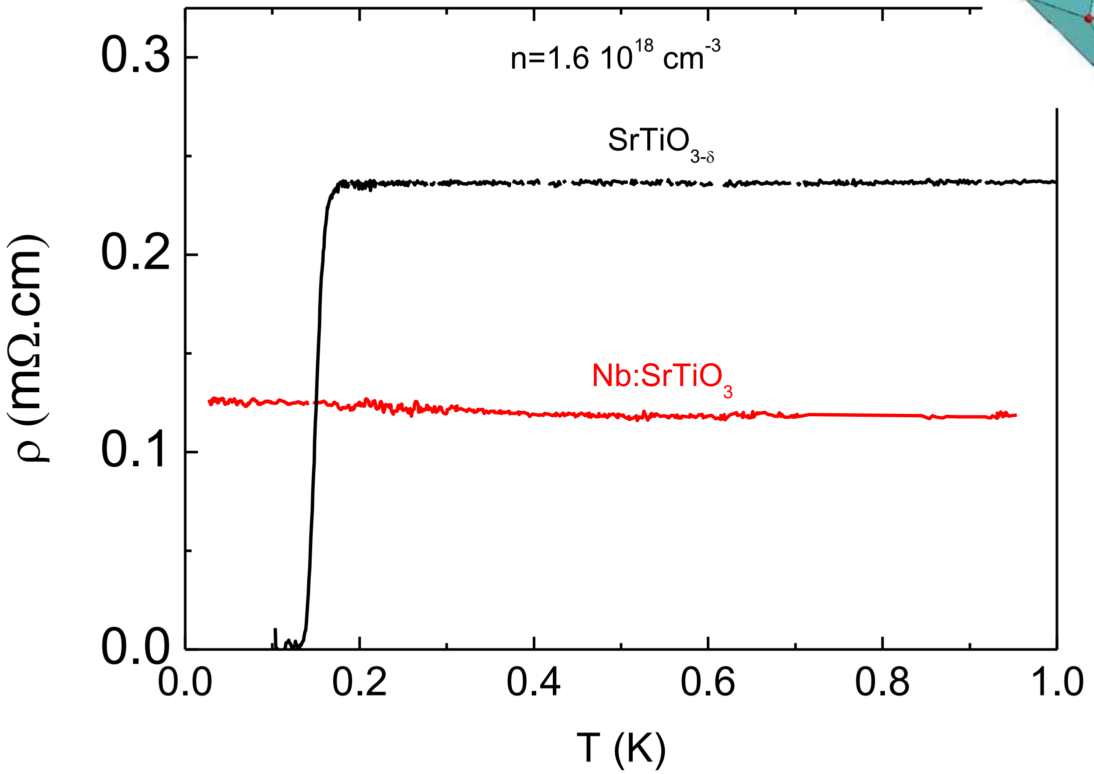
Oxygen vacancy

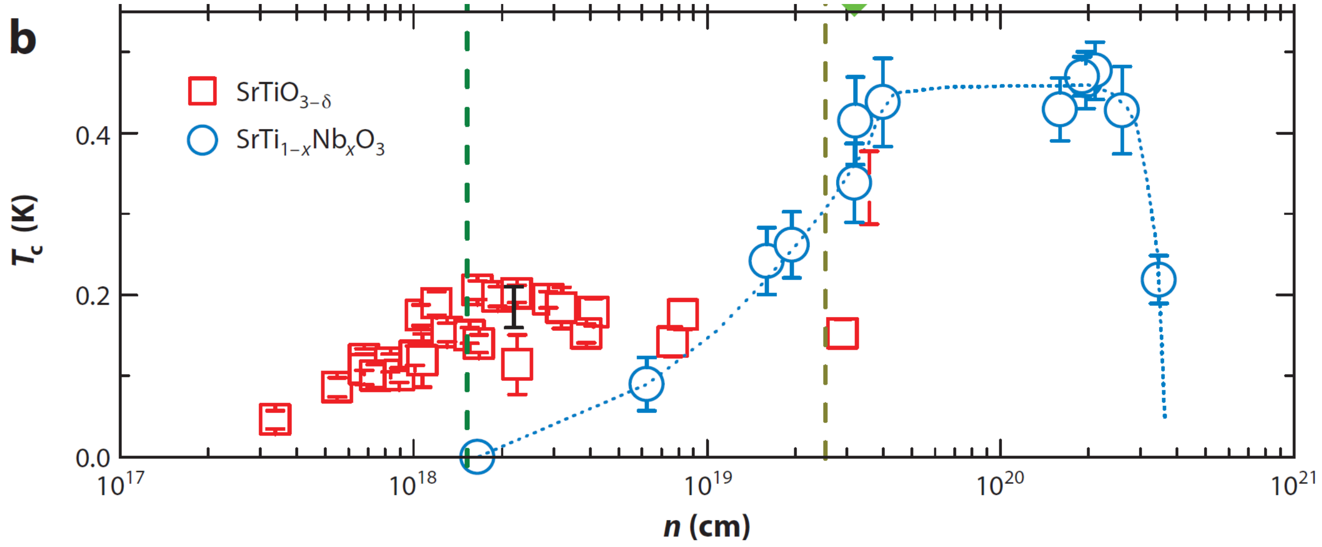
introduces two electrons at a vertex!



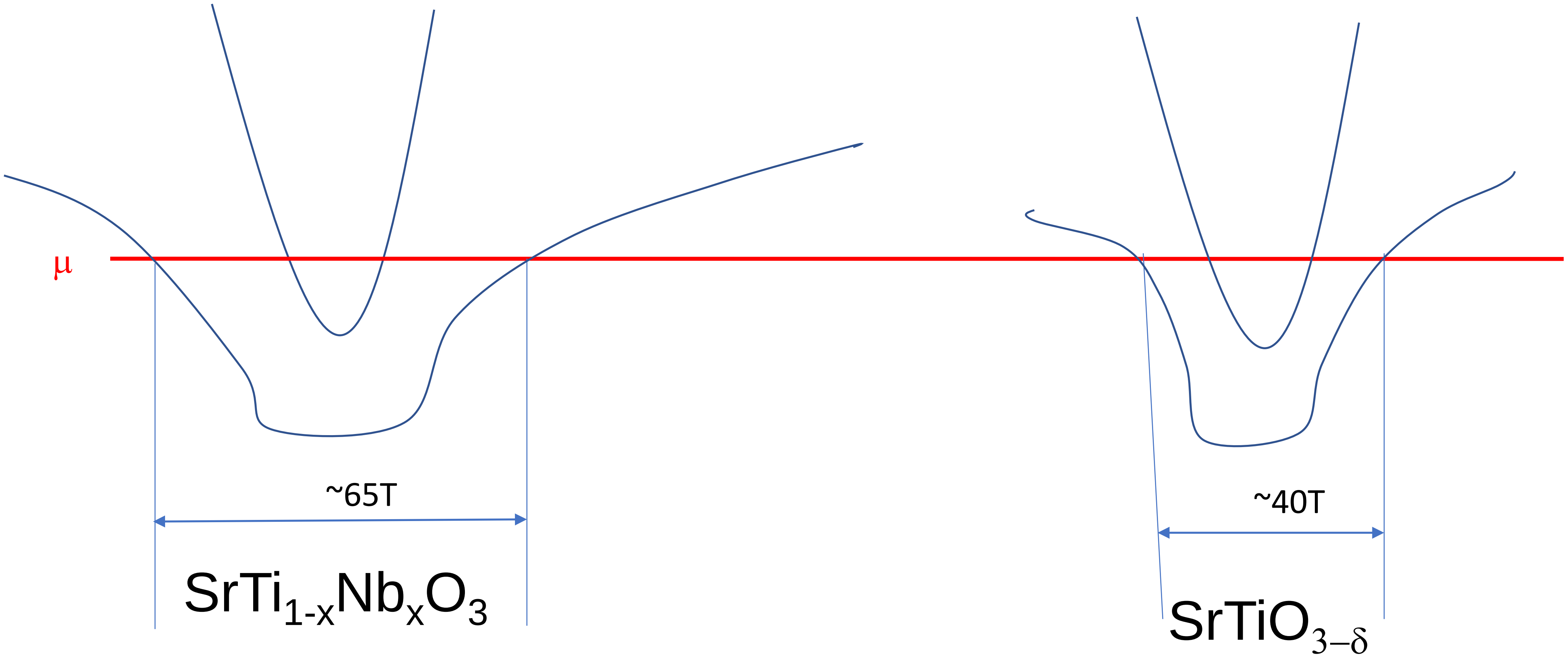
Nb substitution

introduces one electron at the center





The lower Fermi radius is larger with Nb susbtitution



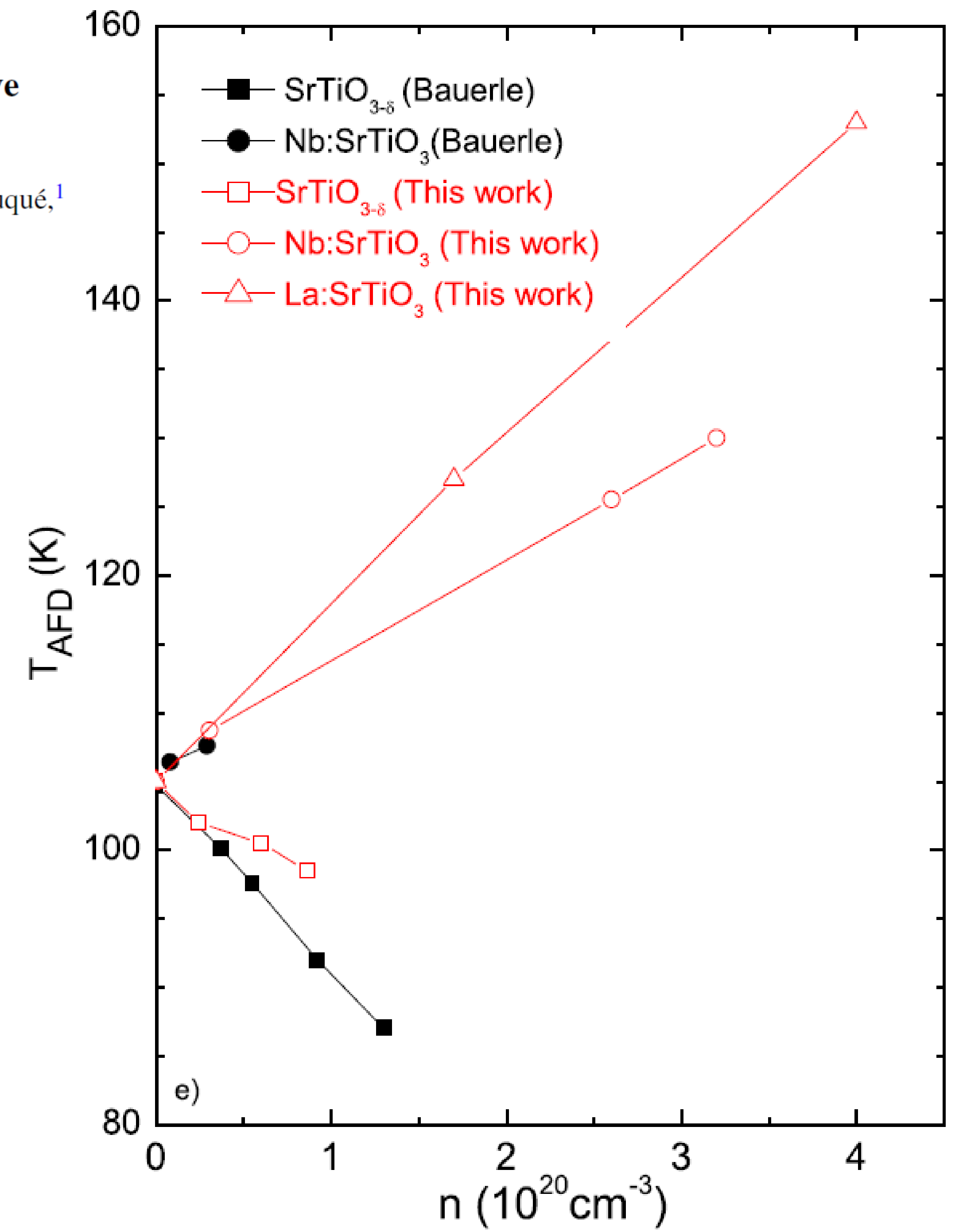
- This is a ‘horizontal’ gap. It may imply a vertical gap.
- Absence of superconductivity in Nb-doped STO is concomittant with a larger interband gap!

PHYSICAL REVIEW B **94**, 035111 (2016)

Nonmonotonic anisotropy in charge conduction induced by antiferrodistortive transition in metallic $SrTiO_3$

Qian Tao,[1,2] Bastien Loret,[1] Bin Xu,[3,4] Xiaojun Yang,[1,2] Carl Willem Rischau,[1] Xiao Lin,[1] Benoît Fauqué,[1] Matthieu J. Verstraete,[3] and Kamran Behnia[1,*]

The doping dependence of the onset of the tetragonal transition is also strongly dopant-dependent.



Common Fermi-liquid origin of T^2 resistivity and superconductivity in n-type $SrTiO_3$

D. van der Marel,[1] J. L. M. van Mechelen,[1] and I. I. Mazin[2]
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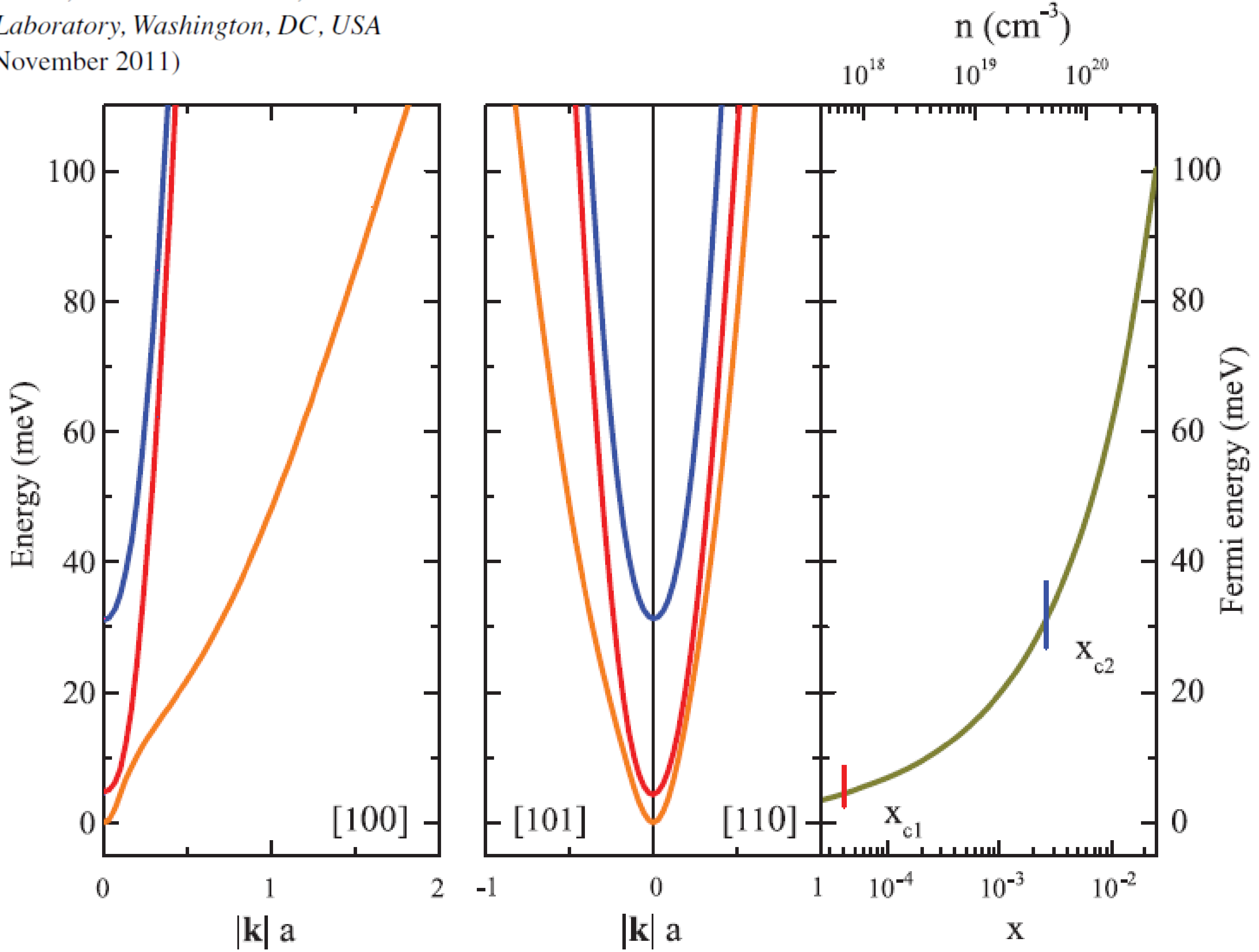
(Received 14 September 2011; published 10 November 2011)

The most significant differences between the results presented here and Matheiss' results[40] are the much smaller crystal-field parameter $D = 2.2$ meV obtained here as compared to $D = -33$ meV obtained from a tight-binding fit to Matheiss' bands, and the fact that the sign is opposite. The resulting Fermi surface of the lowest band is therefore quite different; in the present calculation, it is in fact similar to Fermi surface of the cubic phase shown in Fig. 4 (taking 2% doping), and has six arms extending along [100], [010], and [001] directions. The arms along the z axis are slightly longer than those along x and y, but on the scale of Fig. 4 this is not a perceptible difference. In contrast, Mattheiss's Fermi surfaces (see Fig. 6 of Ref. 40) have four arms along [100] and [010] and none along [001]. Gregory *et al.*[41] studied



Summary

- The superconducting dome in strontium titanate extends over three orders of magnitude in concentration ($10^{-5}<x<0.02$).

- Only oxygen reduced samples are superconducting below $x<0.001$.

- The the Fermi surface in oxygen-reduced and Nb-doped samples differ near the Lifshitz transition. Does dilute superconductivity requires a small interband gap?

- Superconductivity and the Fermi surface evolution in PbTe and in SnTe are also dopant dependent (Ian Fisher and co-workers). The rigid band approximation is not rigorously true.

ESPCI, Paris

Zengwei Zhou (2009-12) *Now Wuhan*

Xiao Lin (2012-15) *Now Hangzhou*

Willem Rischau (2015-17) *Now Geneva*

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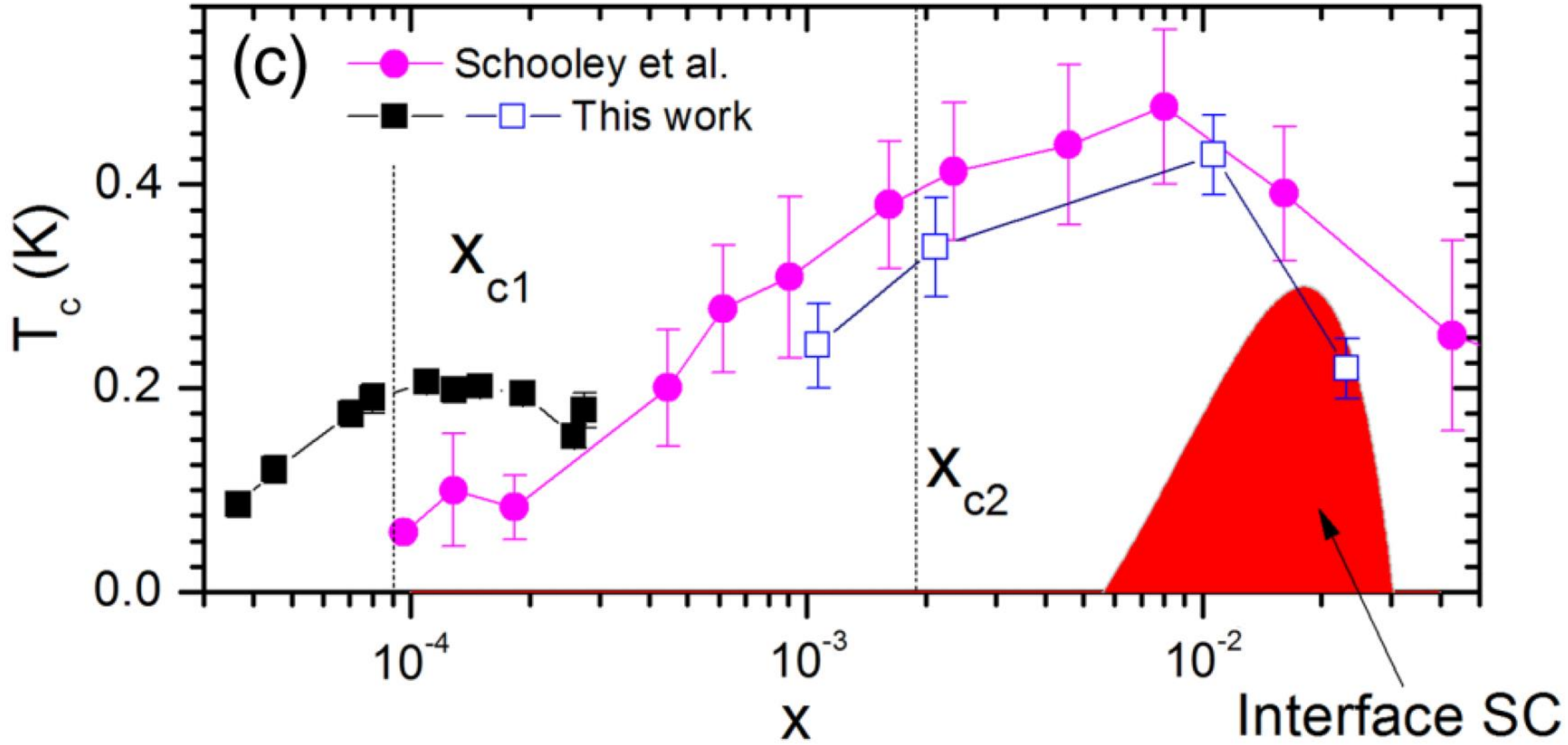
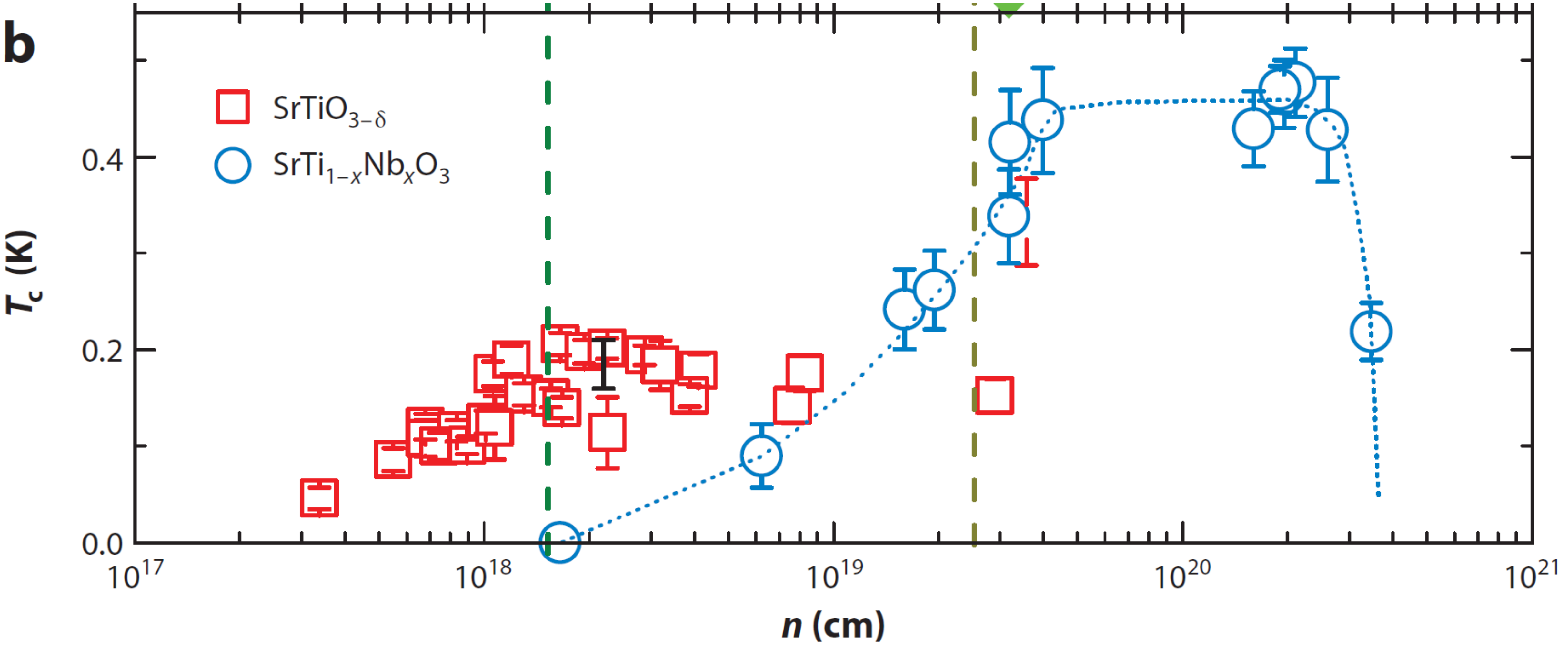
Lin et al.

PRL **112**, 207002 (2014)



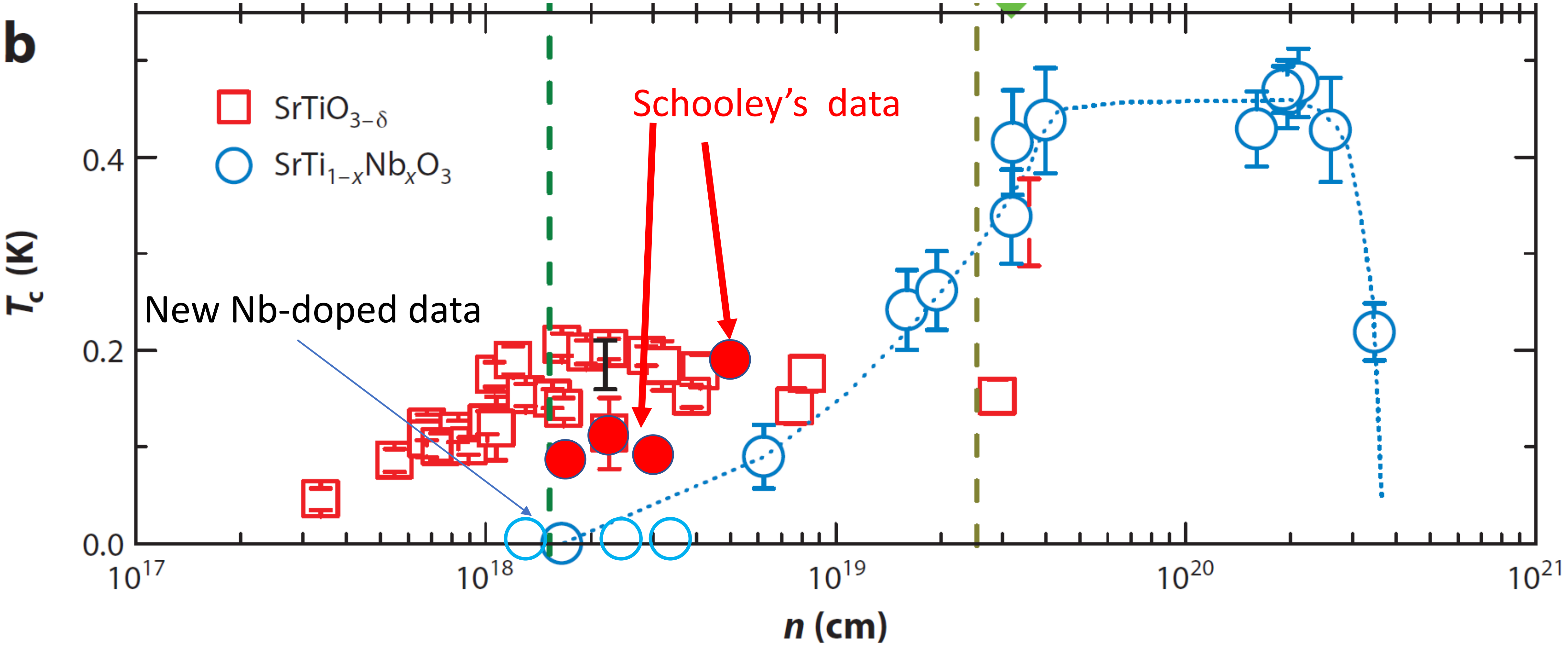
Collignon *et al.*

Annual Review of Condensed Matter Physics, 2019



Collignon *et al.*

Annual Review of Condensed Matter Physics, 2019



Strong sample dependence of Tc in the dilute limit

- Possible origin: uncontrolled magnetic impurities.

Surface magnetism of strontium titanate

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Number of magnetic scattering centers per mobile electron varies from sample to sample.

Table 1. Chemical analysis of 3*d* impurities in (100) crystals (parts per billion).

Supplier	Fe	Co	Ni
A	226	10	337
B	5234	407	32
C	576	21	597
D	98	26	20