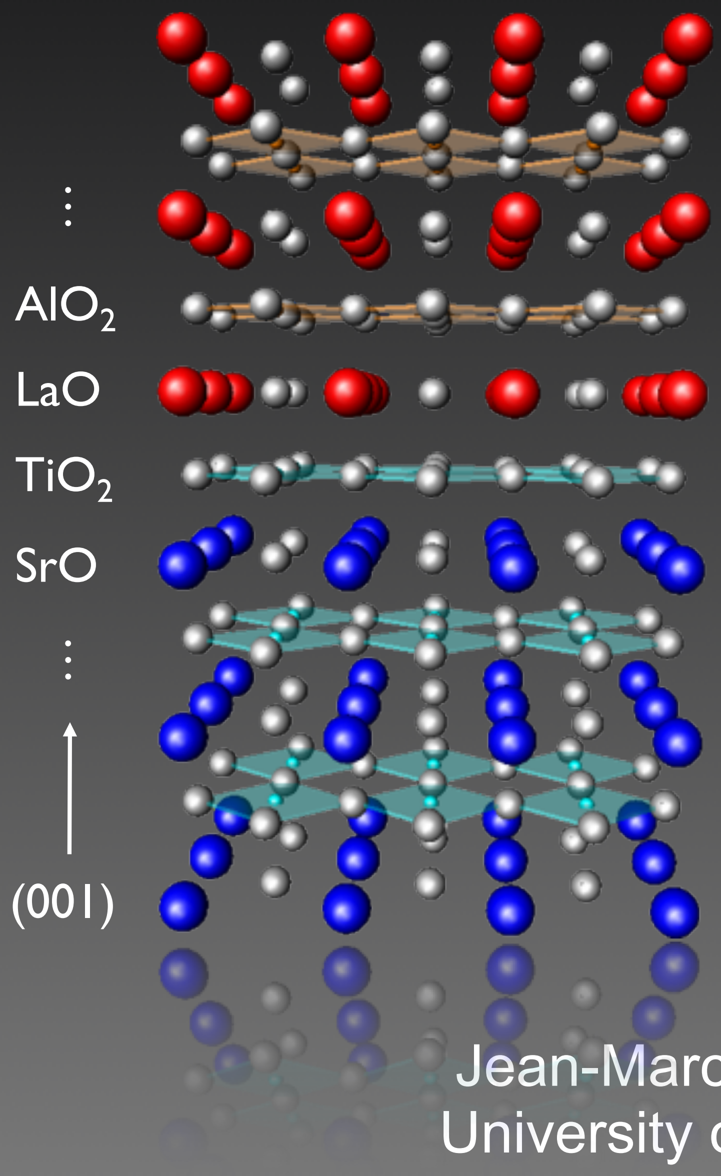
Confinement and Superconductivity at the $LaAlO_3/SrTiO_3$ Interface and Related Systems



$LaAlO_3$:

band insulator

$\Delta = 5.6\,\mathrm{eV}, \quad \kappa = 24$

$SrTiO_3$:

band insulator

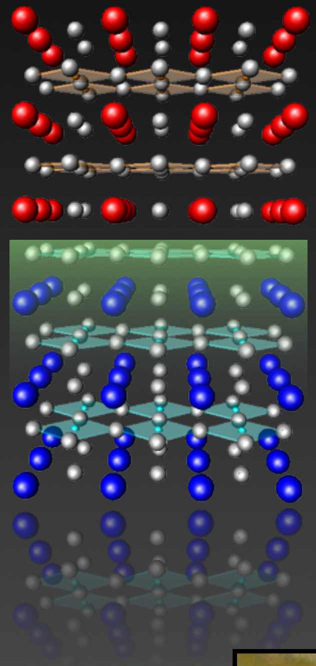
$\Delta = 3.2\,\mathrm{eV}, \quad \kappa\,(300\,\mathrm{K}) = 300$

quantum paraelectric

Jean-Marc Triscone
University of Geneva

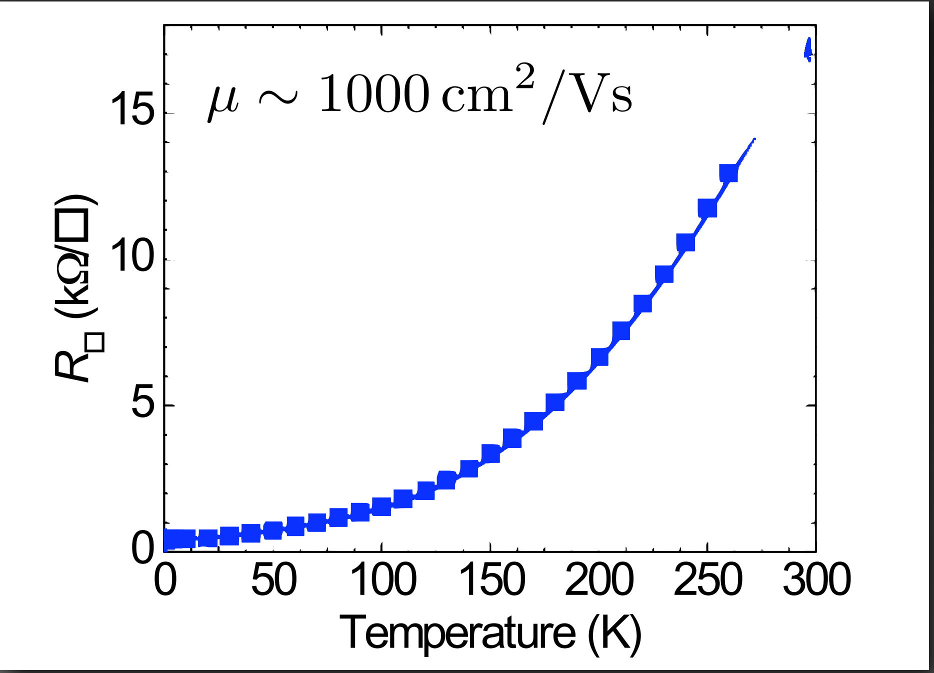
European Research Council
Established by the European Commission
UNIVERSITÉ DE GENÈVE
FNSNF
MaNEP SWITZERLAND

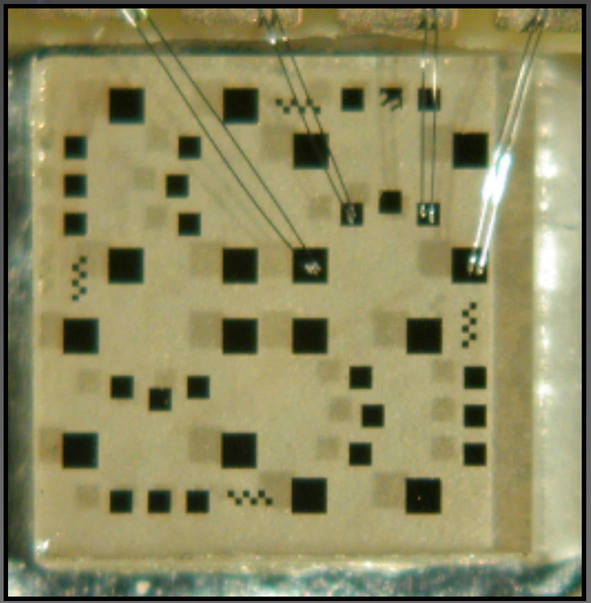
A conducting interface



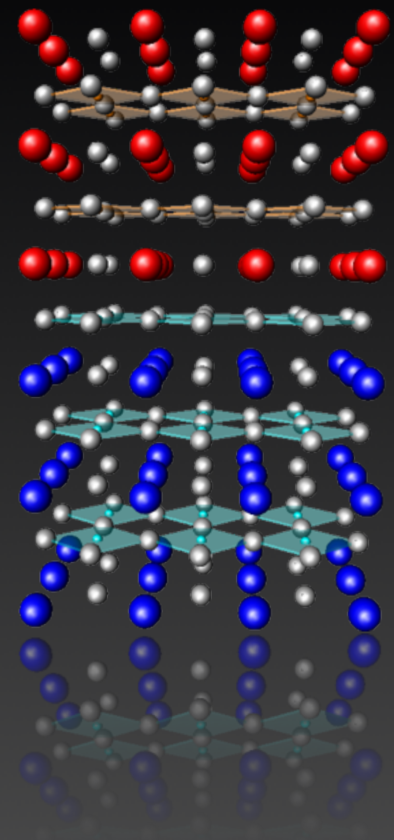
A high-mobility electron gas at the $LaAlO_3/SrTiO_3$ heterointerface

A. Ohtomo[1,2,3] & H. Y. Hwang[1,3,4] *Nature* **427**, 423 (2004)





Outline



-FE control of the SC properties

-Quantum confinement

-Bulk and interface SC

-SC at $((LaAlO_3)_{0.5}$-$(SrTiO_3)_{0.5})/SrTiO_3$ interfaces

-Spin orbit

-SC in $SrTiO_3$

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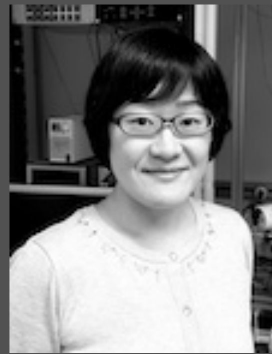
The «Geneva» $LaAlO_3/SrTiO_3$ Team

Stefano Gariglio

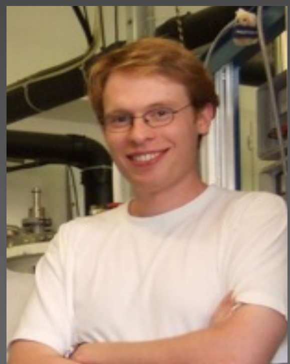
Margherita Boselli

Adrien Waelchli

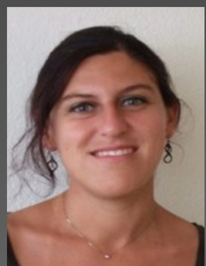


Ritsuko Eguchi

Andrea Caviglia
(now in Delft)



Nicolas Reyren
(CNRS Paris)



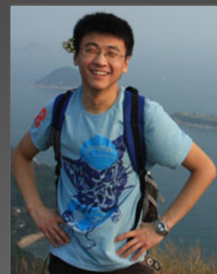
Claudia Cancellieri
(now at EMPA)

Daniela Stornaiuolo
(now in Naples)

Wei Liu
(KLA-Tencor US)

Alexandre Fête
(UNIGE)

Zhenping Wu
(now in Beijing)



Denver Li
(now at Stanford)

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and collaboration with

Marc Gabay (Orsay)

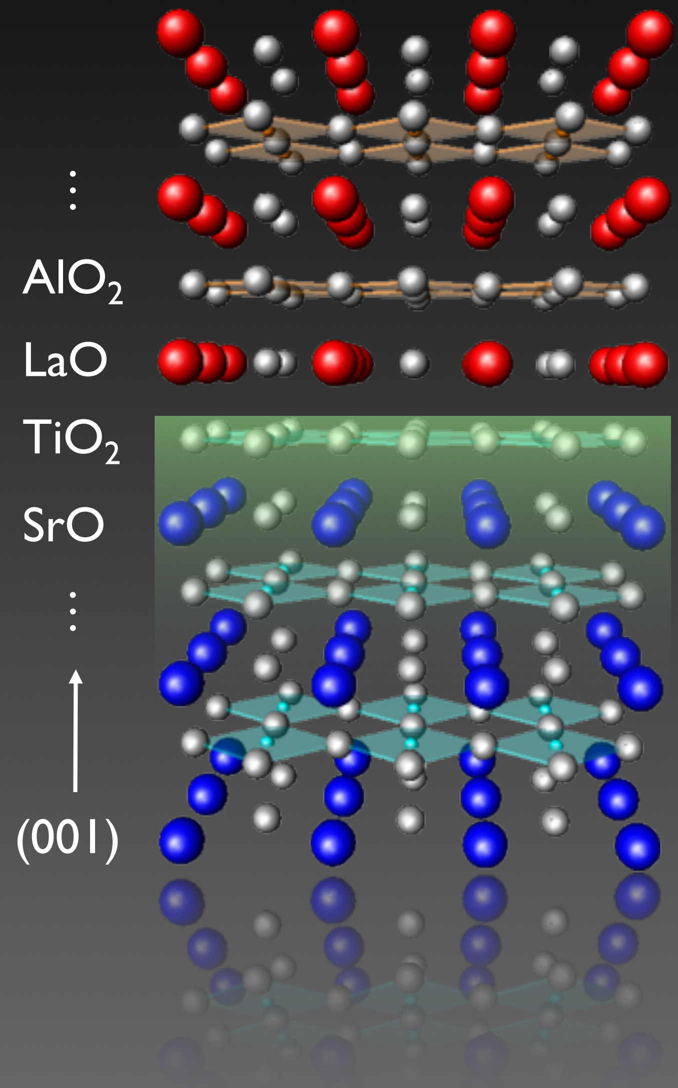
Philippe Ghosez (Liège)

Jochen Mannhart
(MPI Stuttgart)

Odile Stéphan
(Orsay)

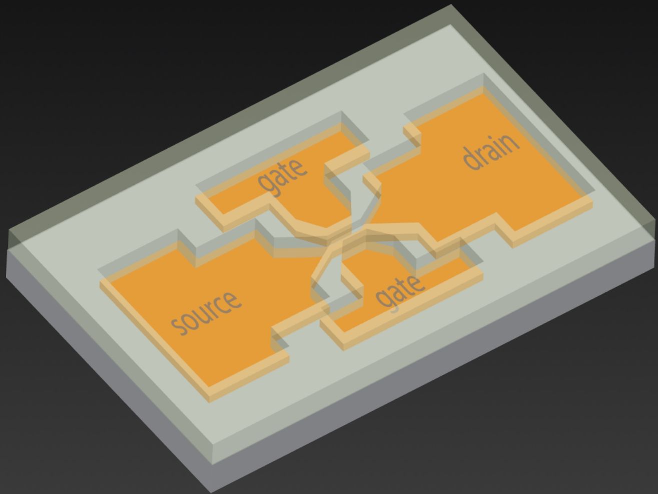
and their groups

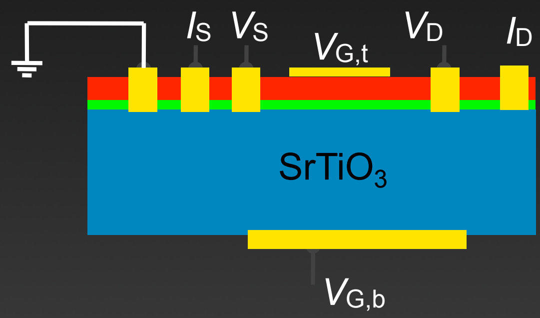
Doping Control - Field Effect

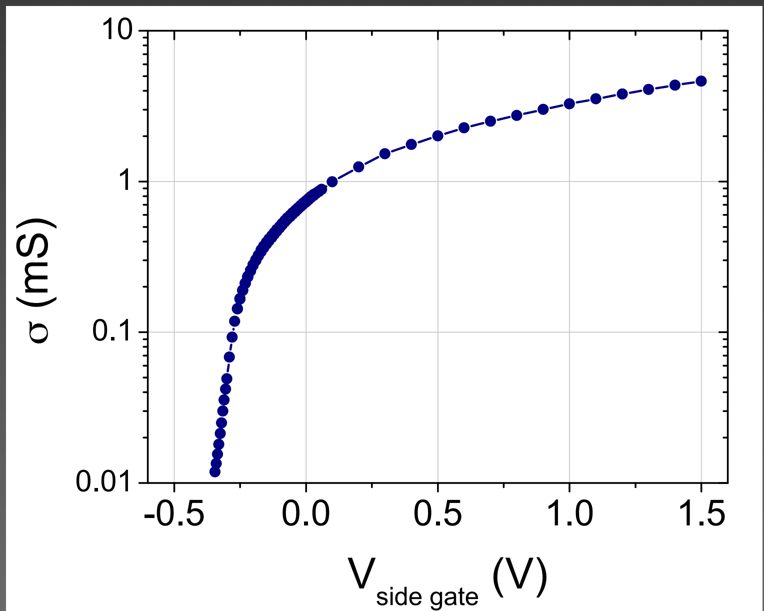


~2-8×10^{13}/cm^{2}

Transport and field effect control

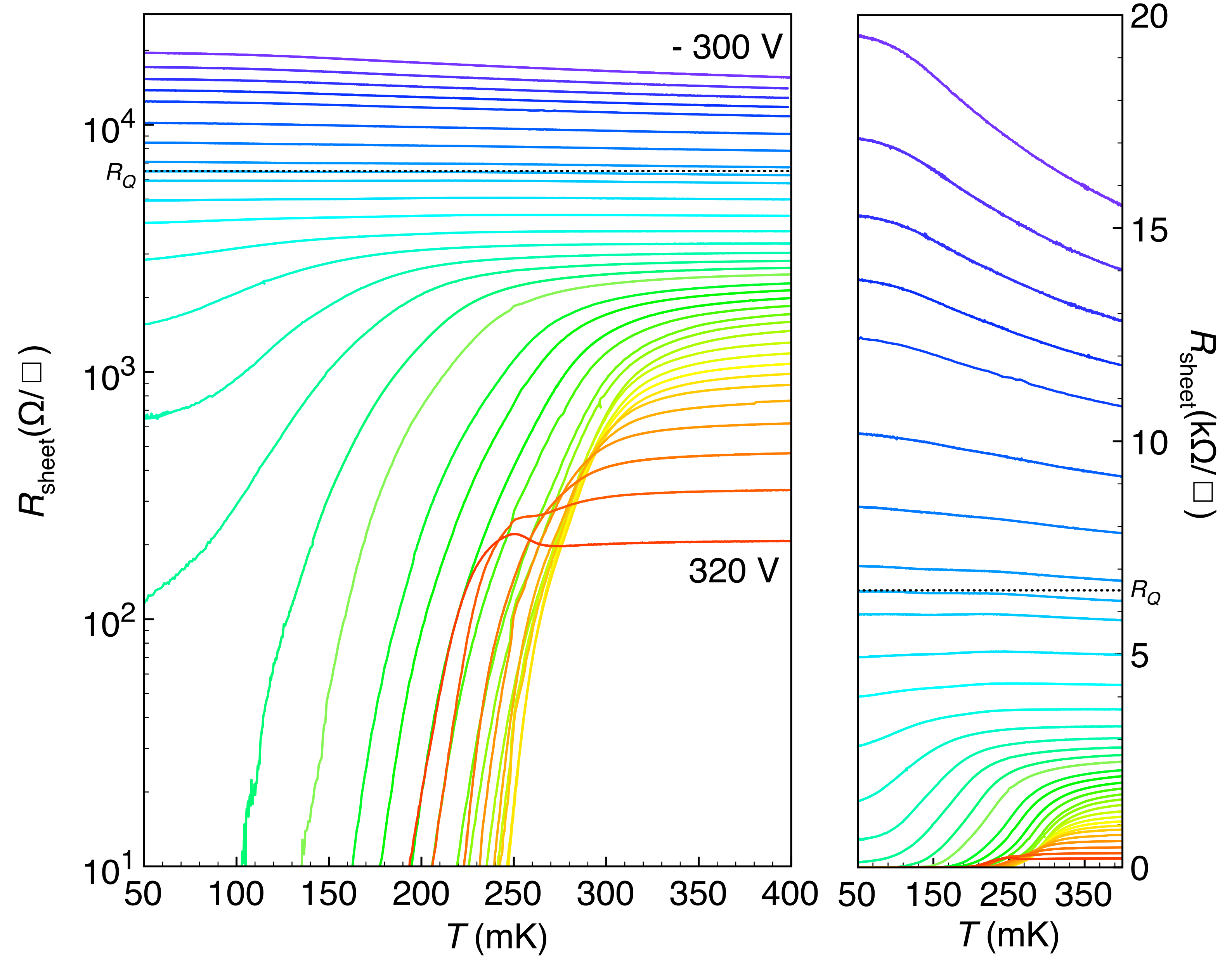






Side gating

Modulation of SC



A.D. Caviglia *et al*, Nature **456**, 625 (2008)

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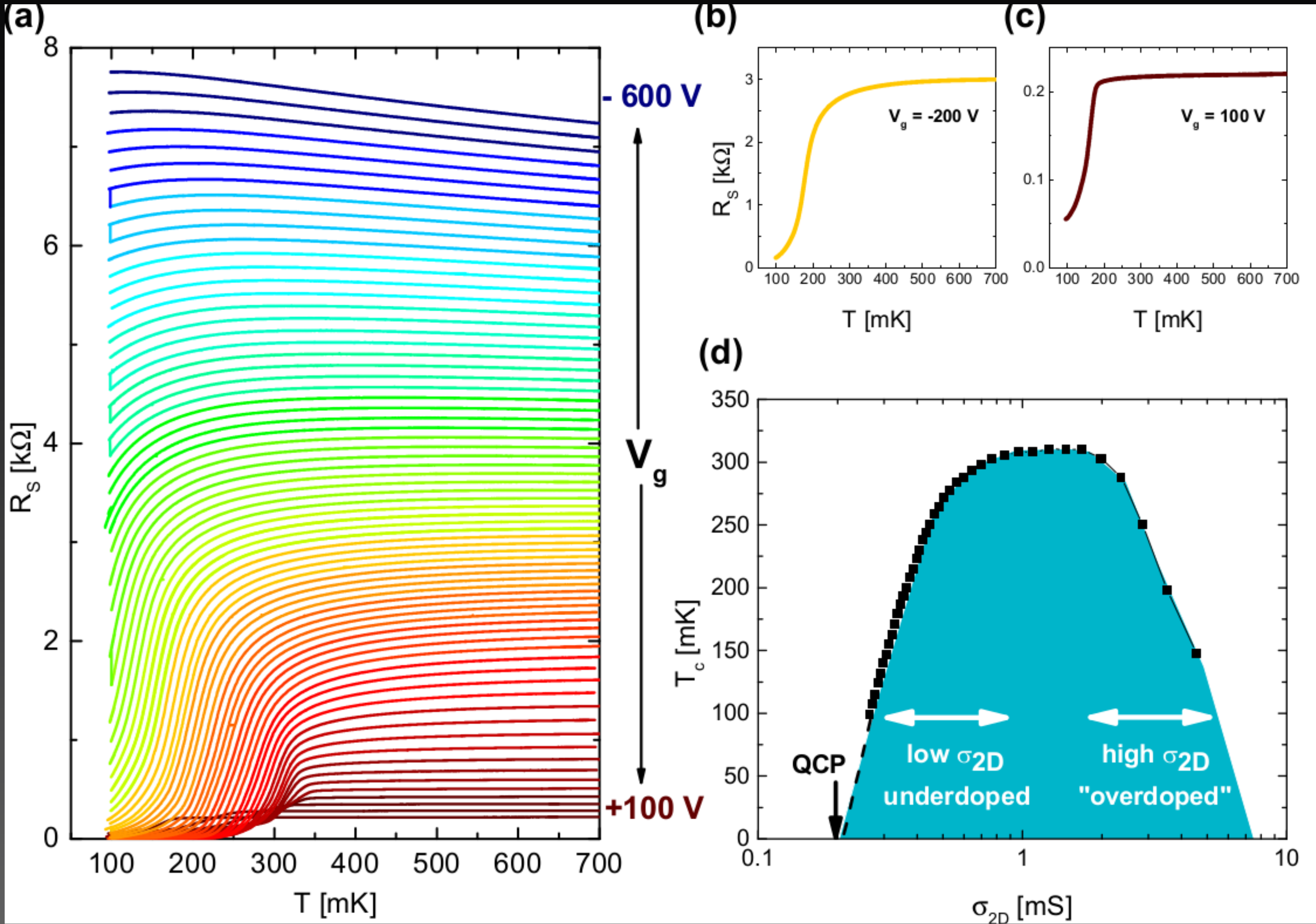

S. Gariglio et al. APL Mat. 4, 060701 (2016)

See also C. Bell et al. PRL 103, 226802 (2009)

In $LaTiO_3/SrTiO_3$ J. Biscaras et al. PRL 108, 247004 (2012)

Quantum Confinement and Electronic Structure

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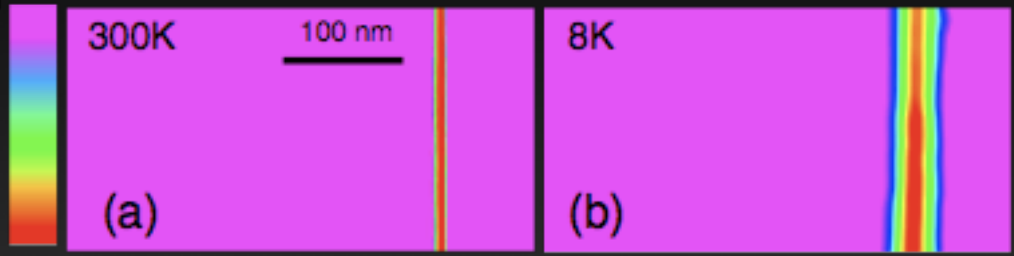
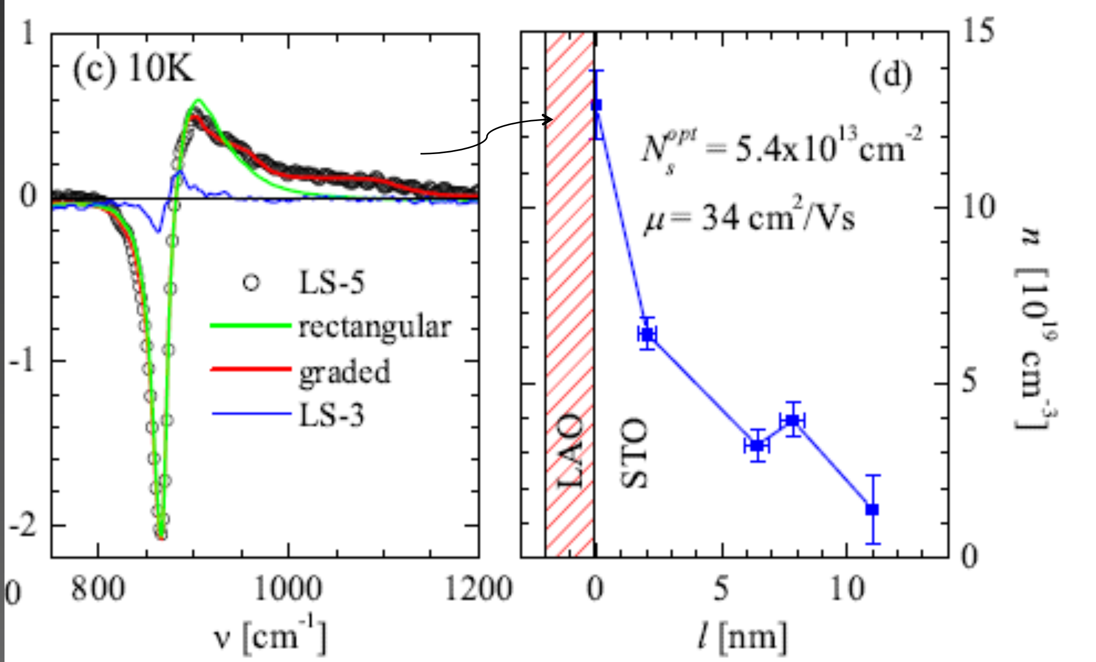
Confinement and electronic structure

RT d<7nm

12 nm at low T

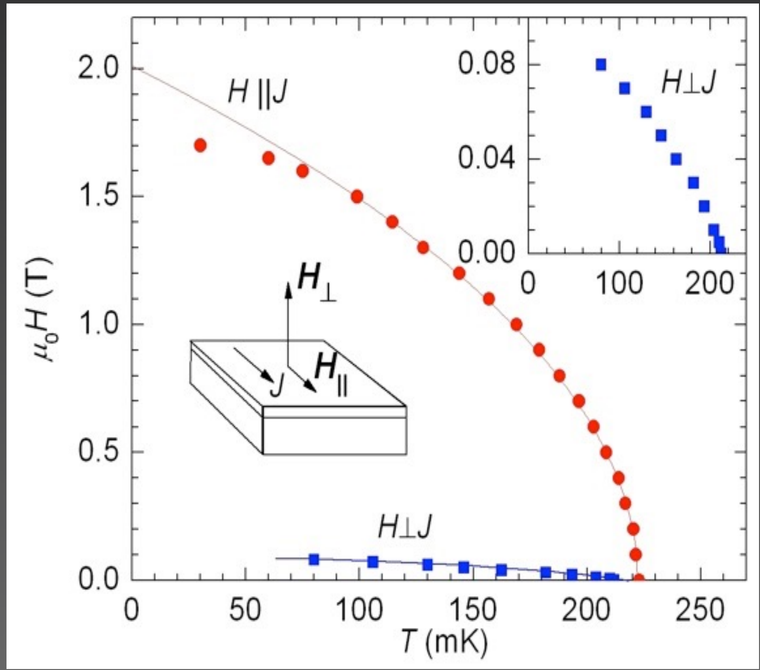


M. Basletic et al, Nat. Mater. 7, 621 (2008)
O. Copie et al, Physical Review Letters. **102**, 216804 (2009)



A. Dubroka et al, PRL **104**, 156807 (2010)

11 nm at 10K



N. Reyren et al. APL **94**, 112506 (2009)

10 nm

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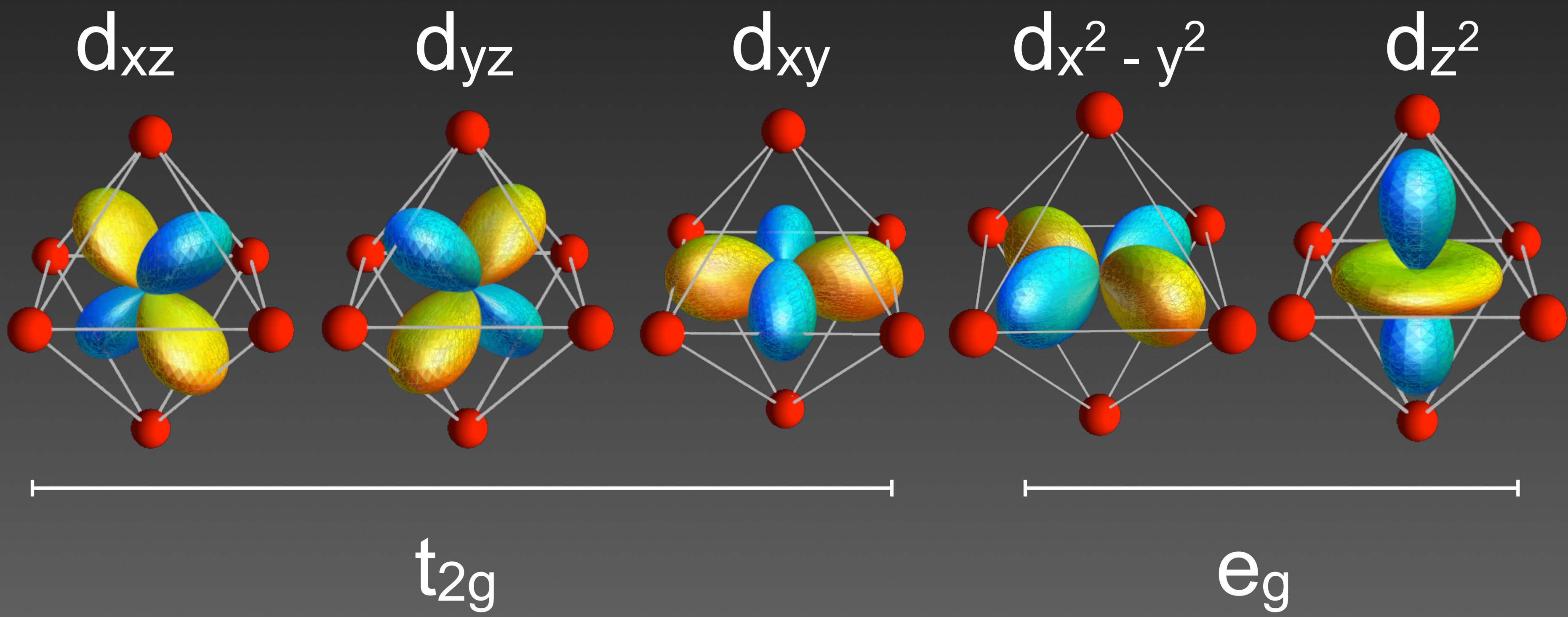
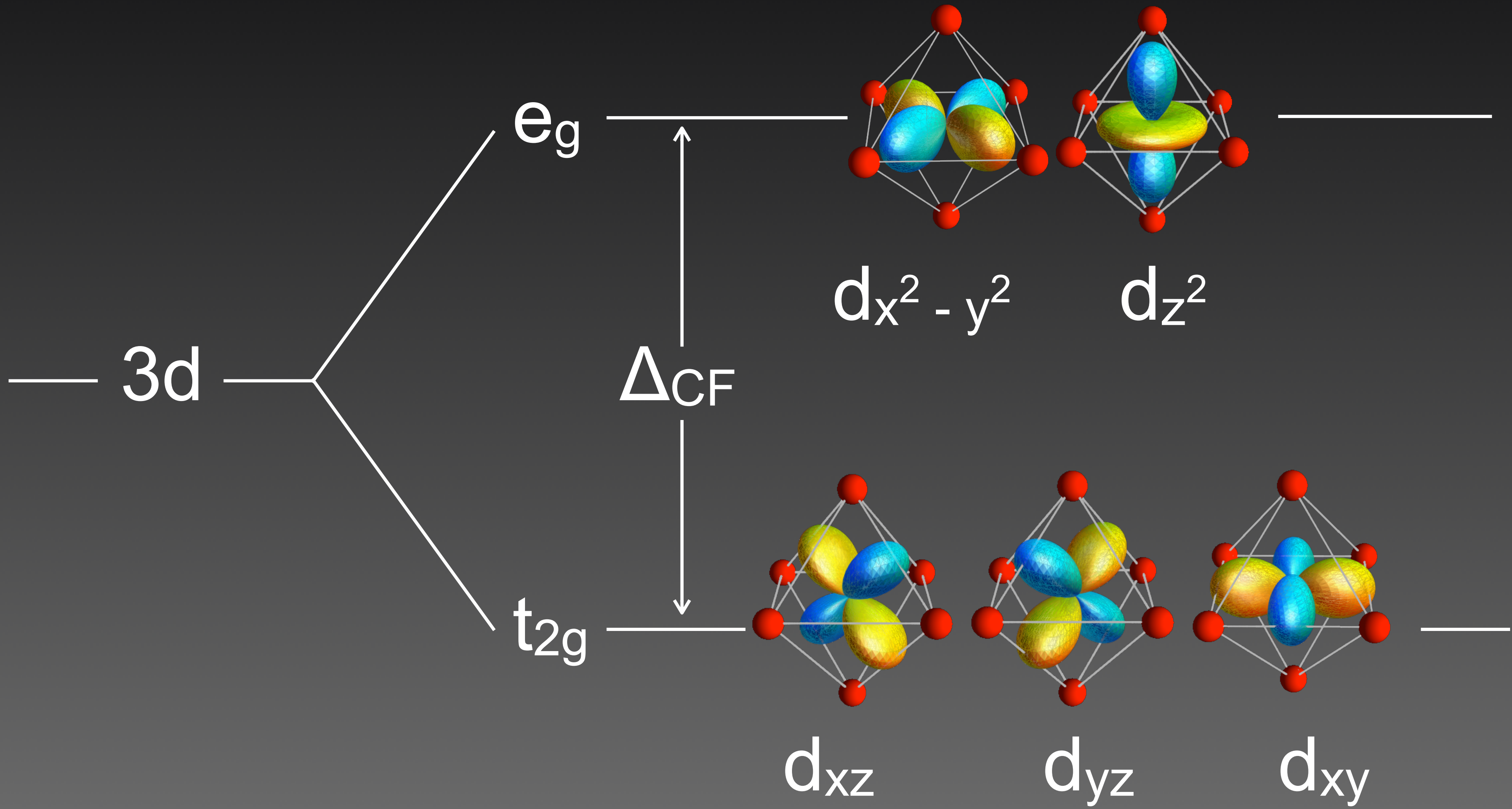
At the interface, the electrons are on the $SrTiO_3$ side, in the Ti 3d band

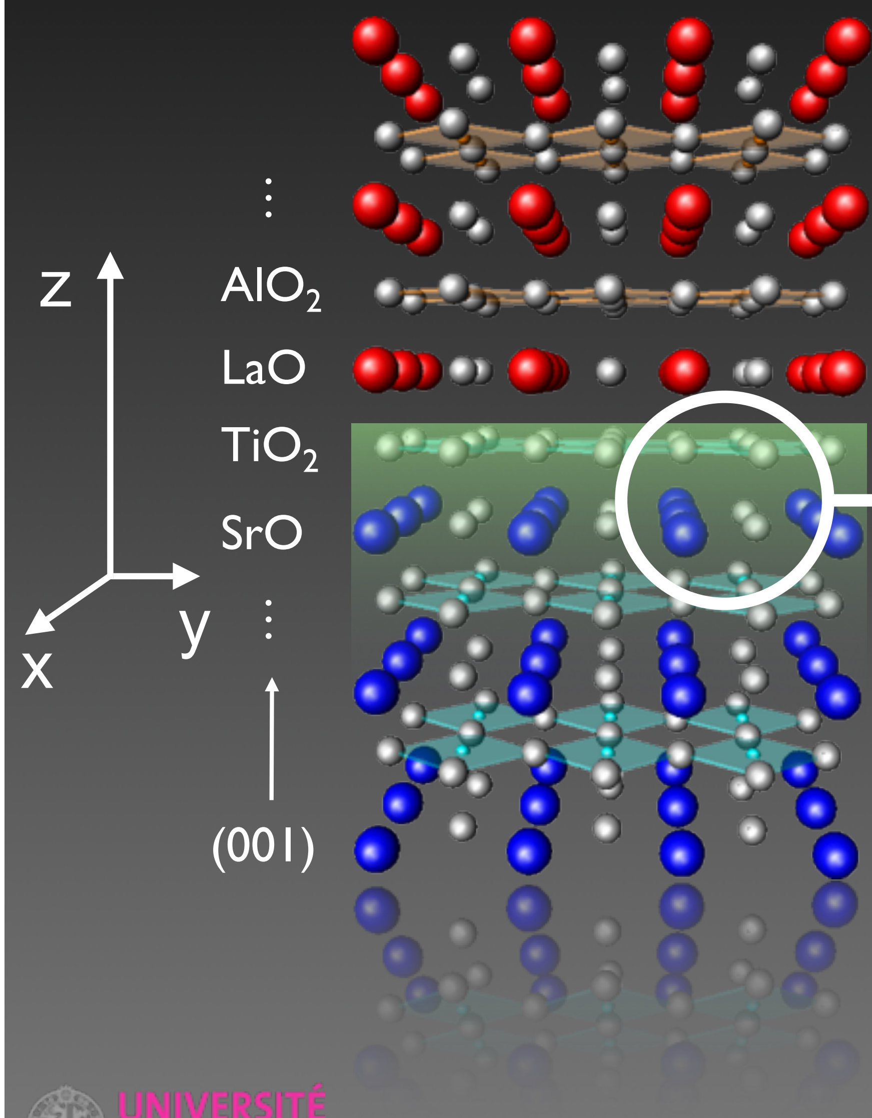


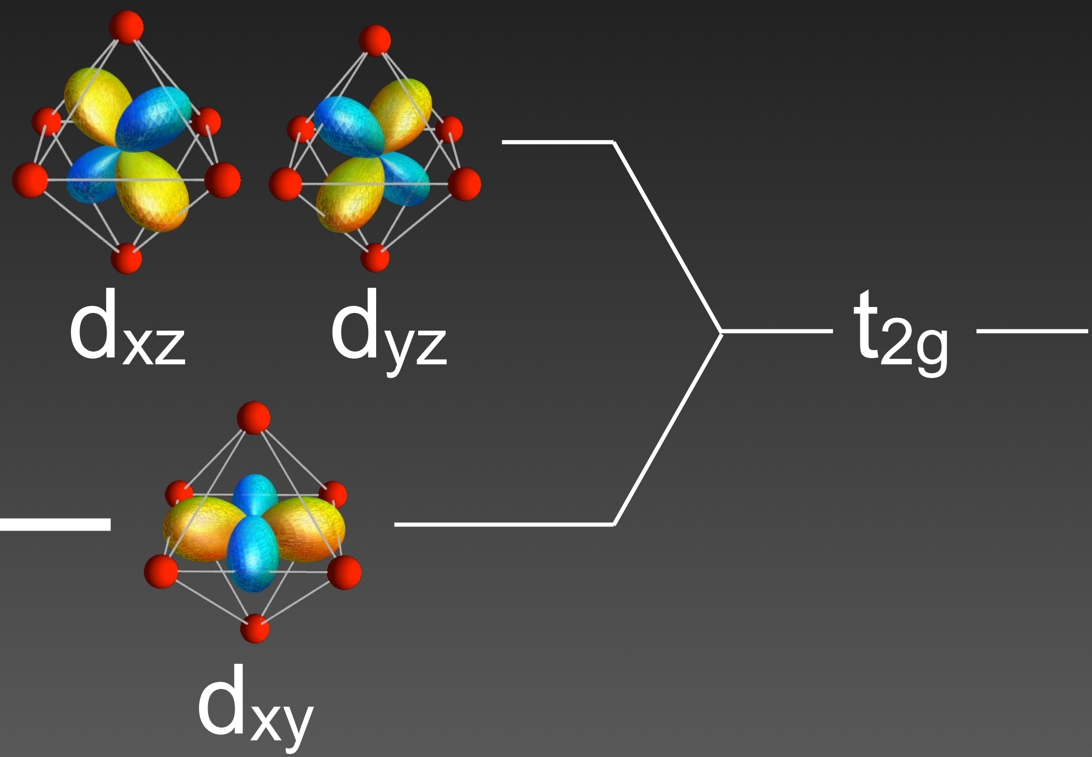
At the interface, the electrons are on the $SrTiO_3$ side, in the Ti 3d band



Electrons are in t_{2g} orbitals

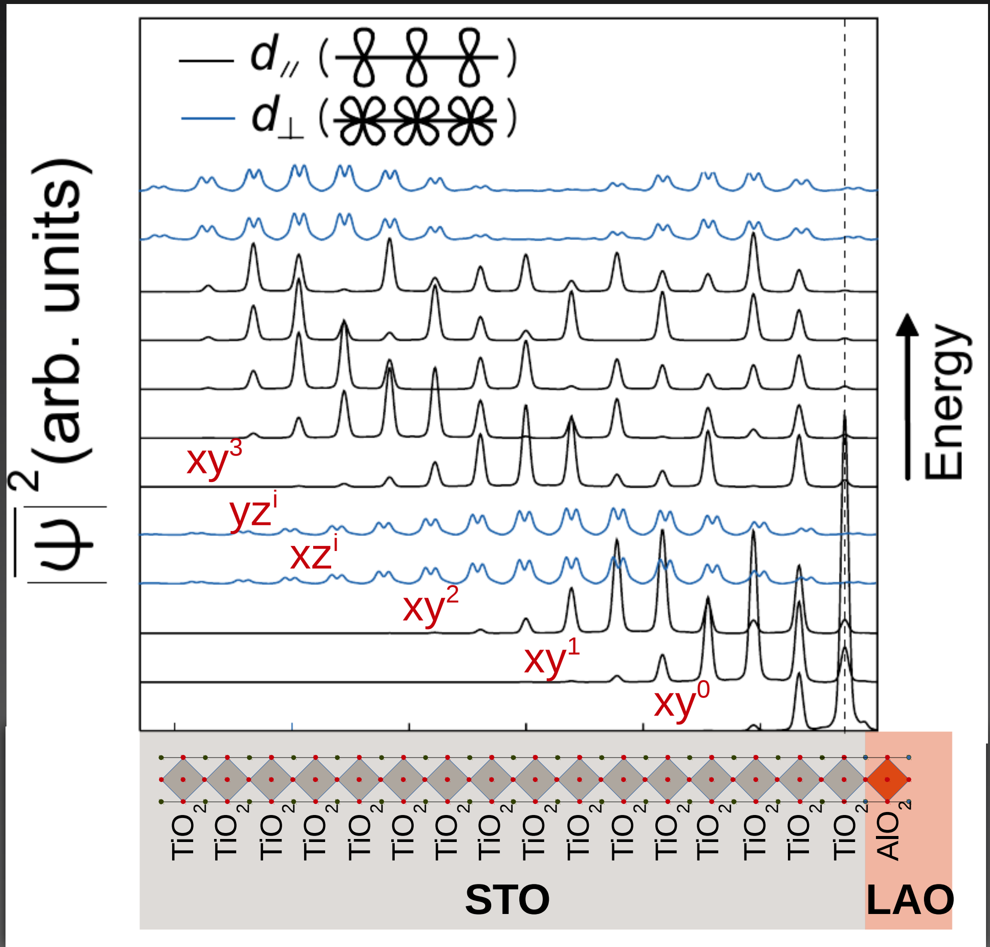
Confinement and electronic structure



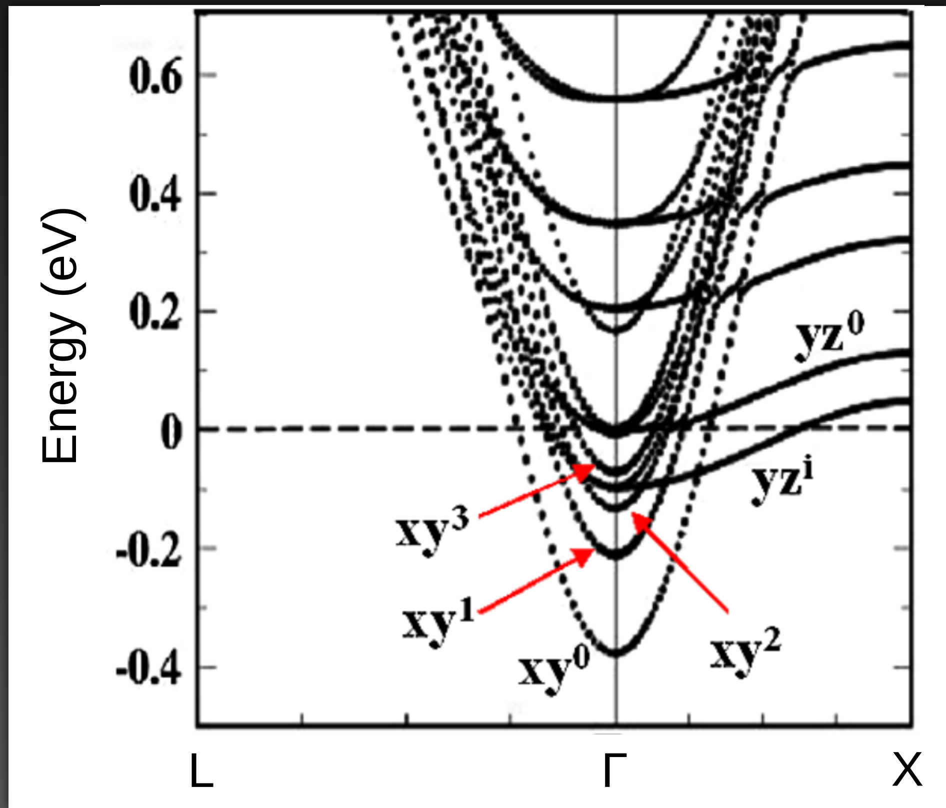


M. Salluzzo *et al.*, *PRL* **102**, 166804 (2009)

Confinement and electronic structure



Son *et al.*, PRB **79**, 245411



n_S=3.3 10 ^{14} cm^{-2}

Delugas *et al.*, PRL **106**, 166807 (2011)

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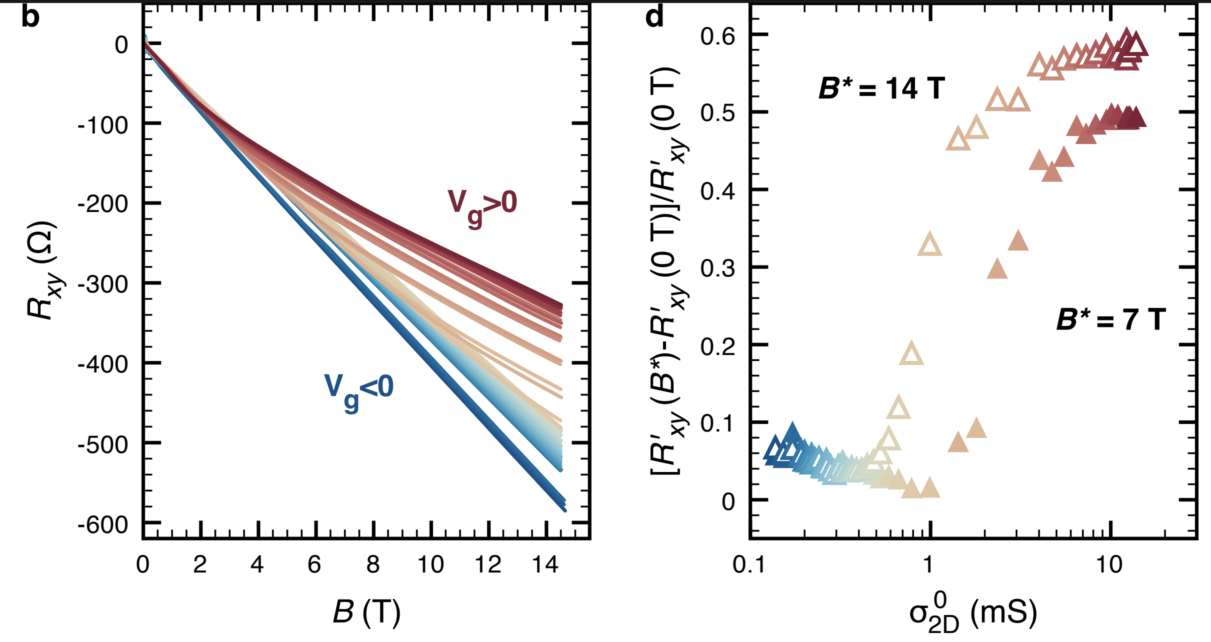
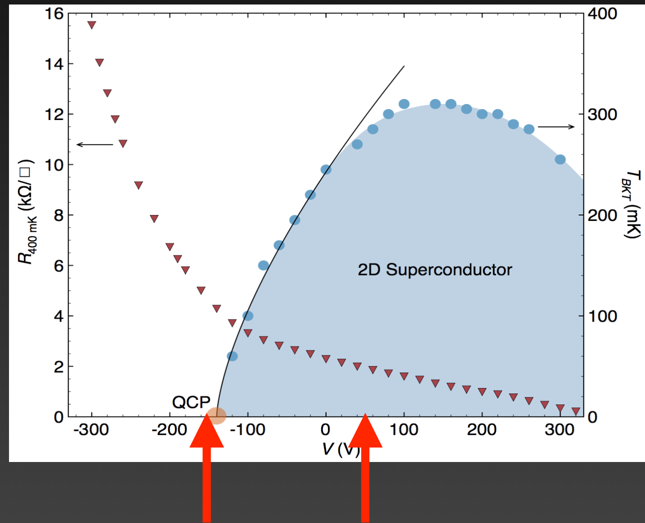
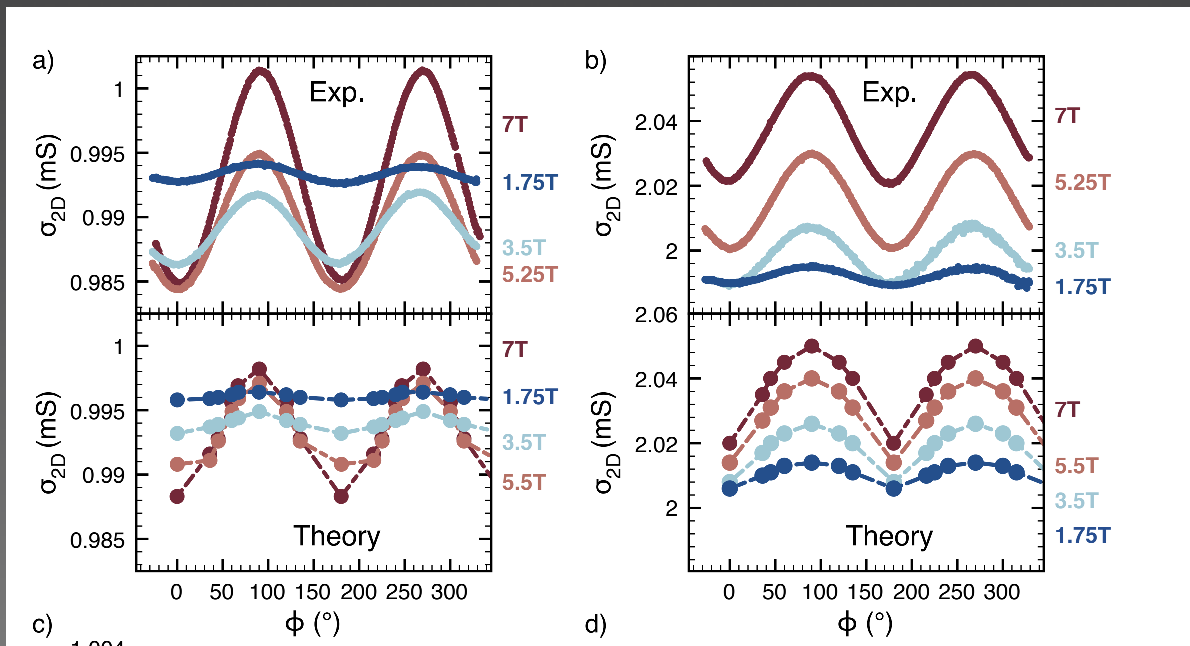
Hall response and parallel field measurements







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Bulk and Interface Superconductivity

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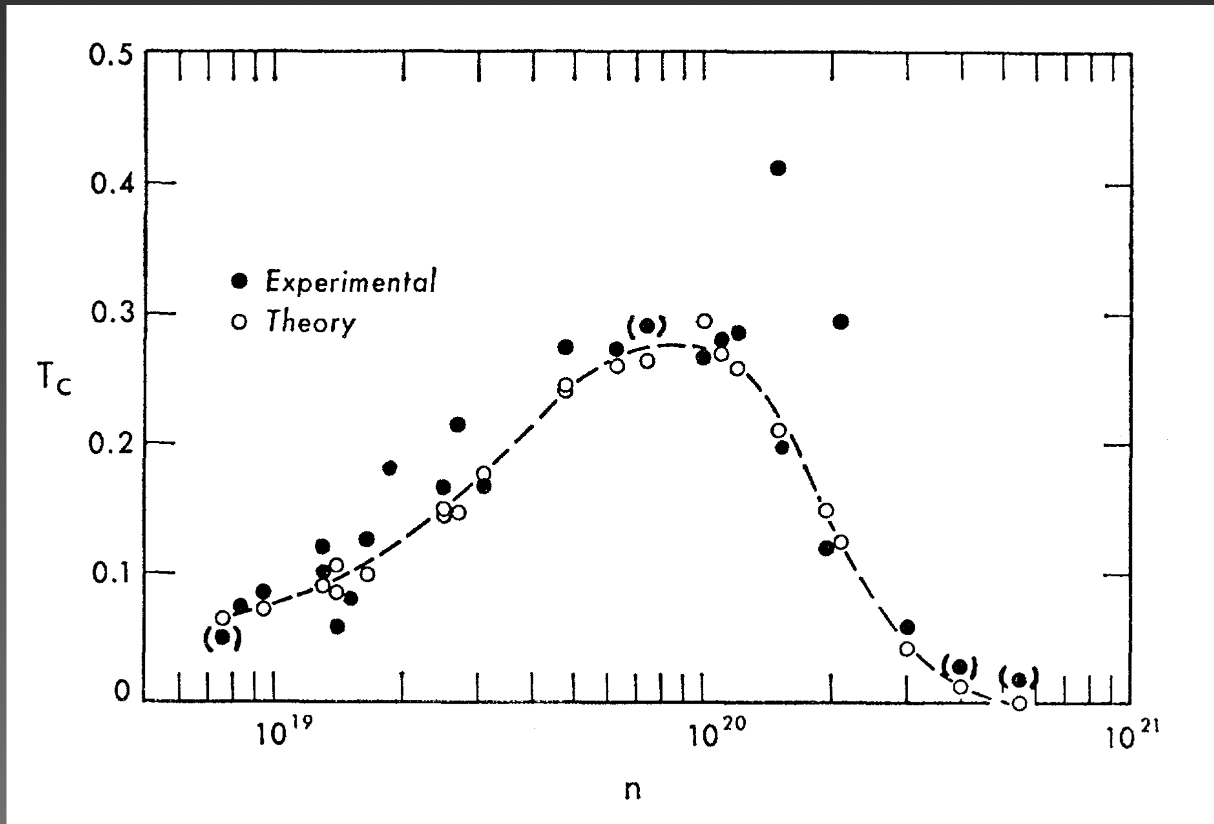
Superconductivity in bulk $SrTiO_3$

PHYSICAL REVIEW VOLUME 163, NUMBER 2 10 NOVEMBER 1967

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)



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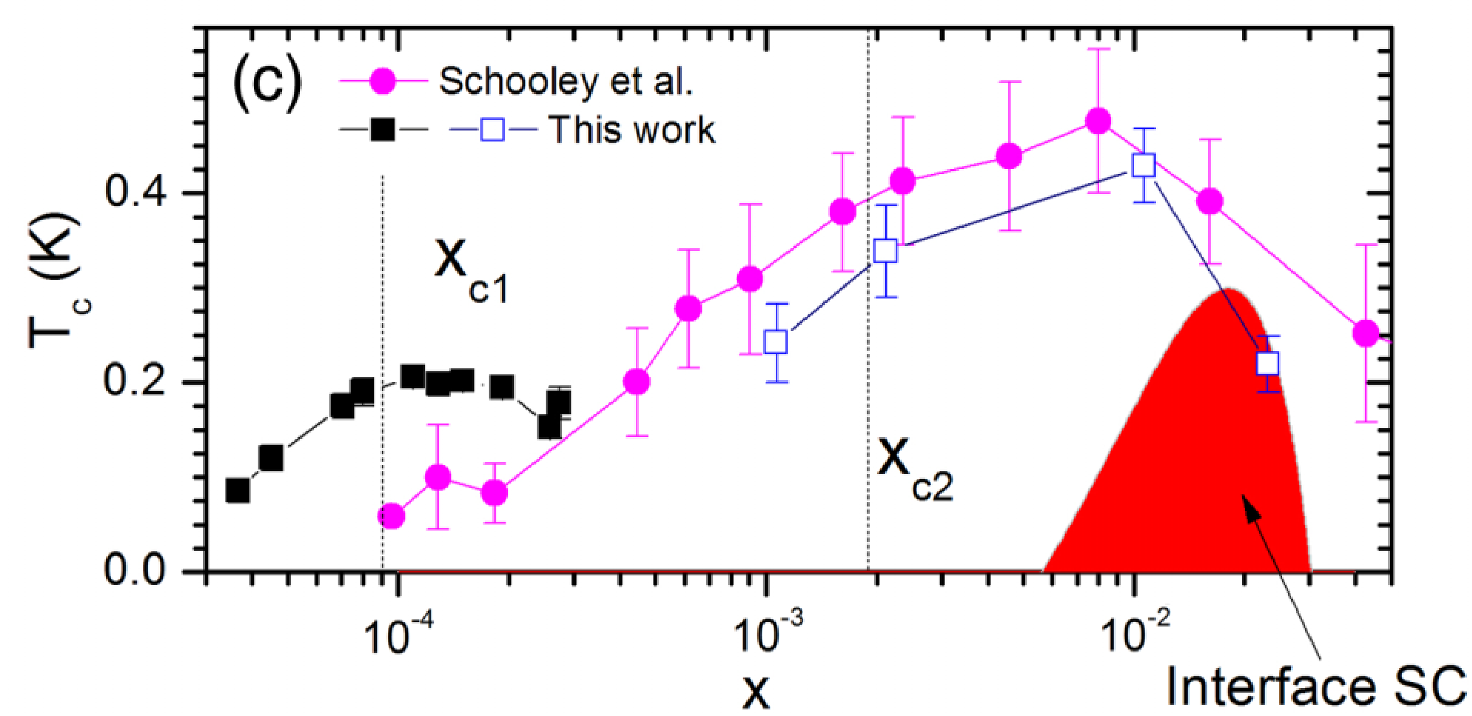
Superconductivity in bulk $SrTiO_3$



X. Lin et al. PRL **112**, 207002 (2014)

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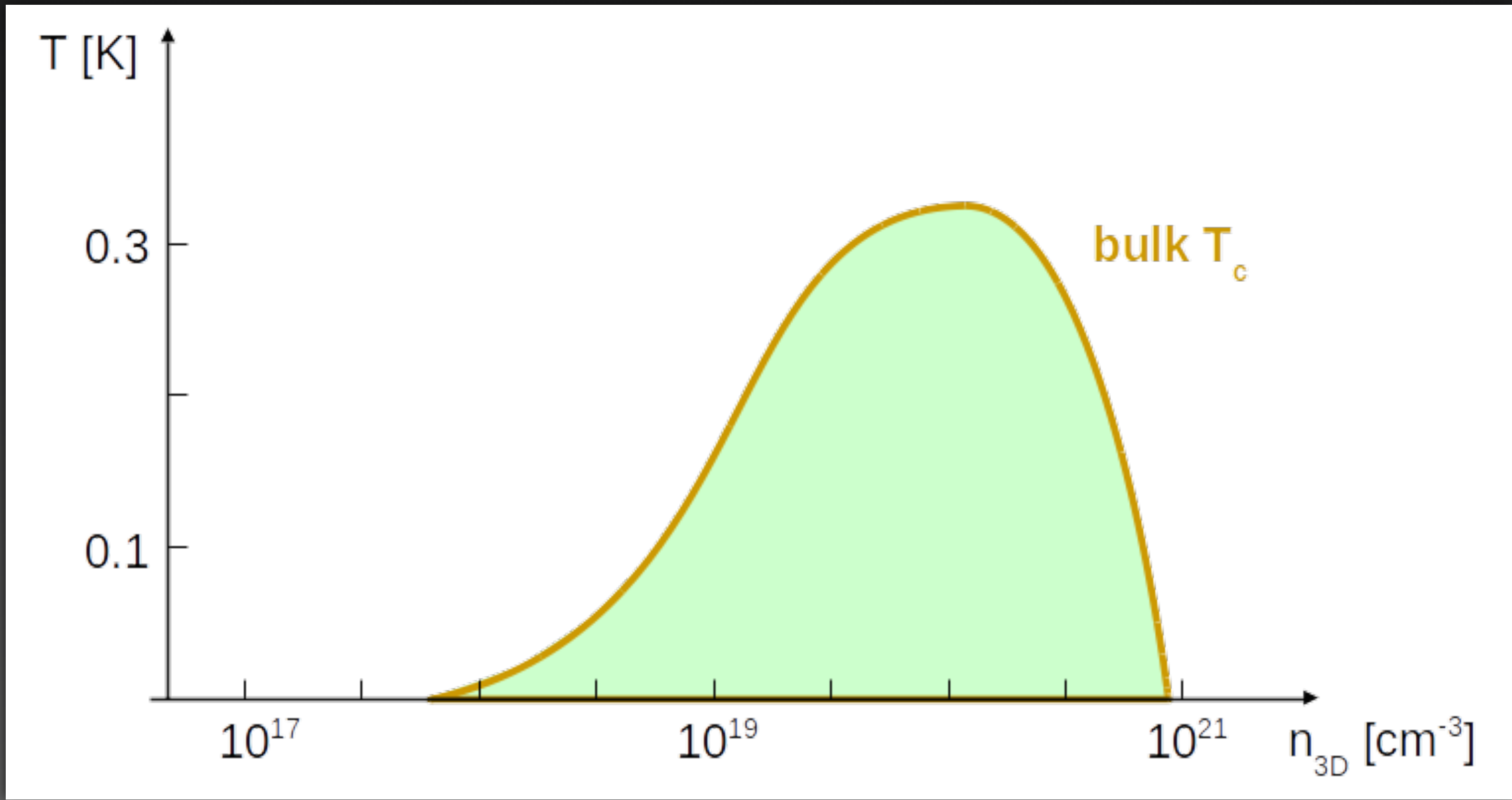
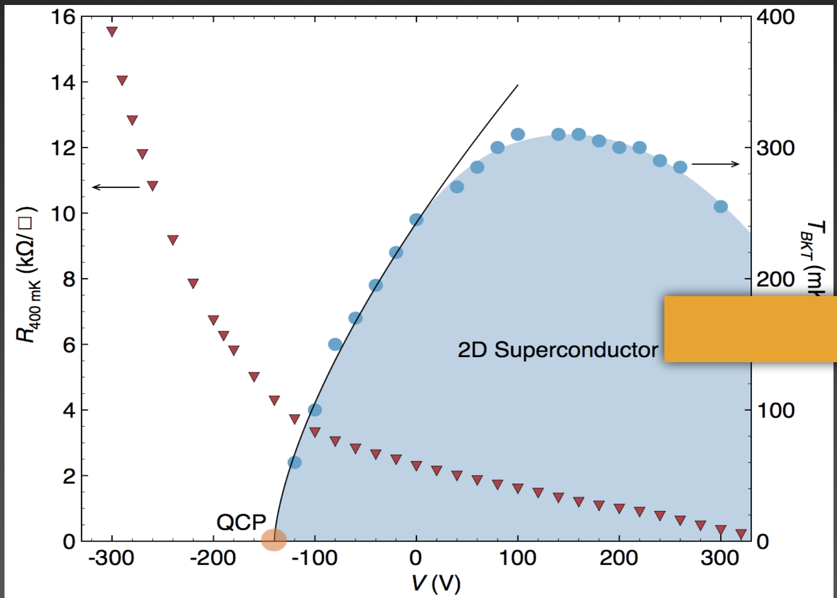
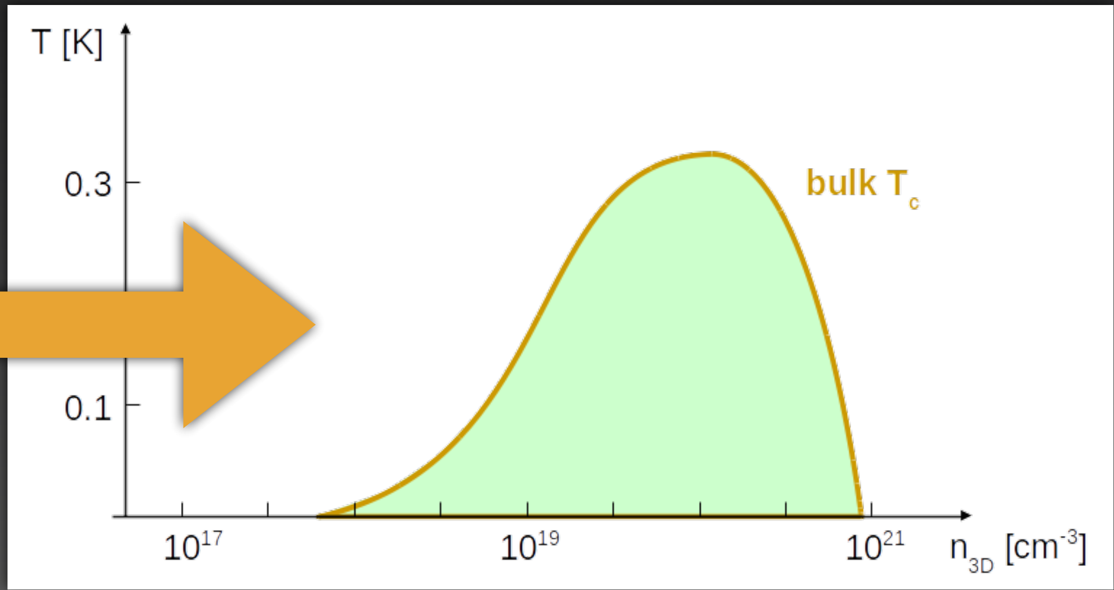
Bulk and interface SC



Mapping the 2D phase diagram on the 3D one





$$n_{3D}=n_{2D}/d$$

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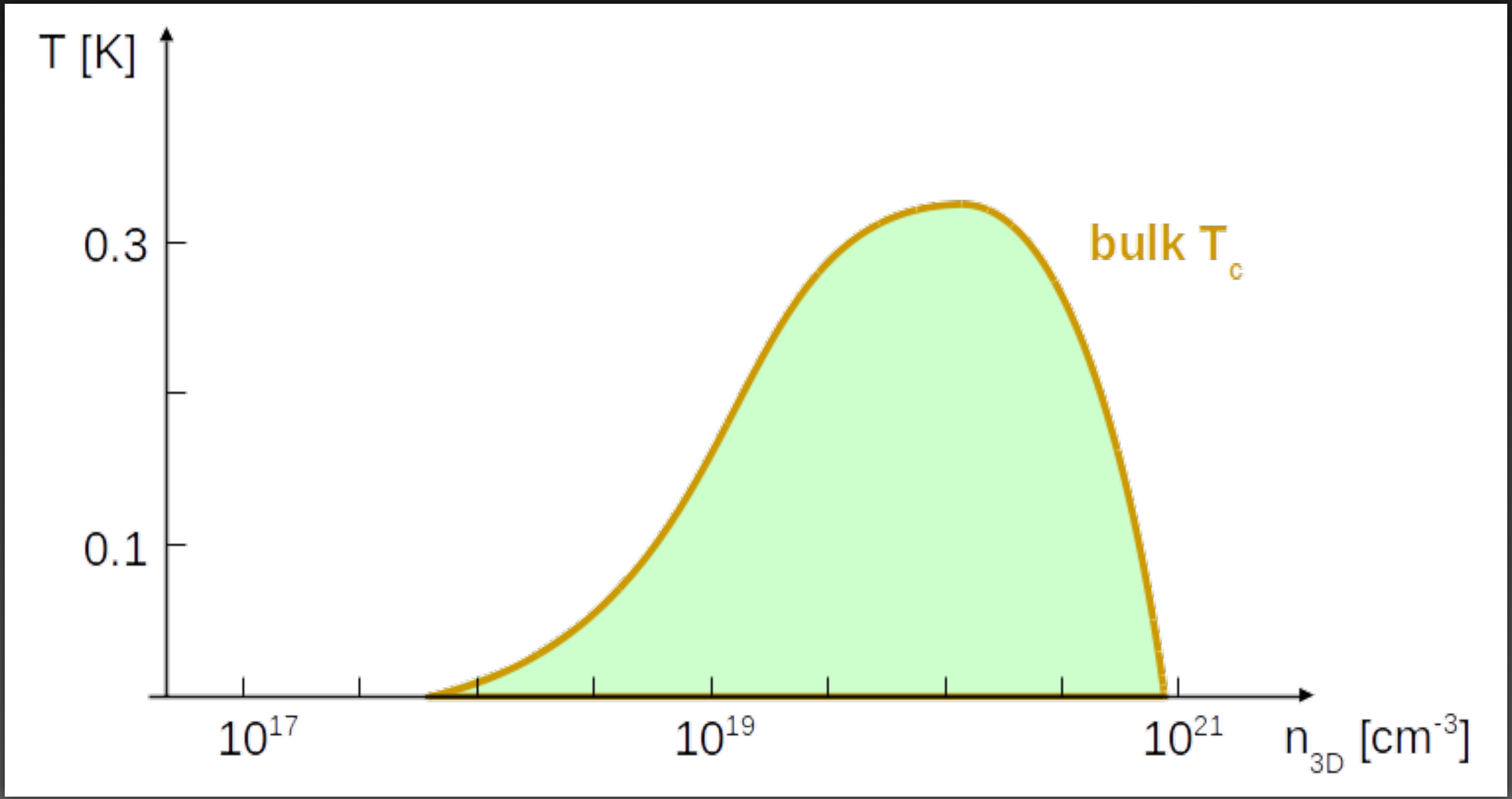
Bulk and interface SC

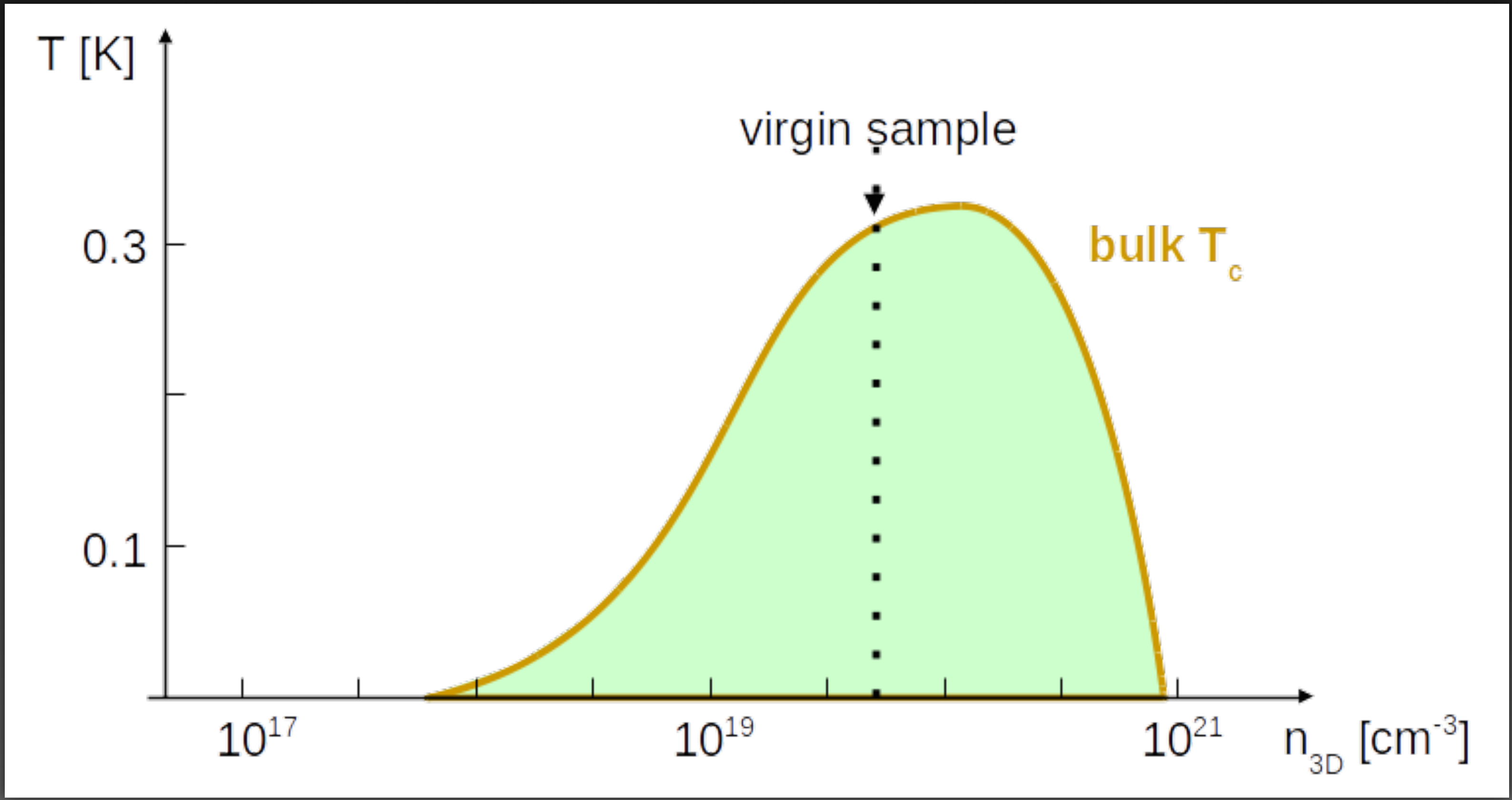


$n_{3D}=n_{2D}/d$

Virgin: $n_{2D}=3\ 10^{13}\ cm^{-2}$

d=10nm

Bulk and interface SC

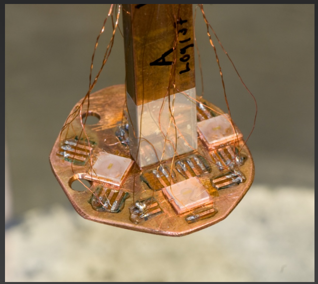


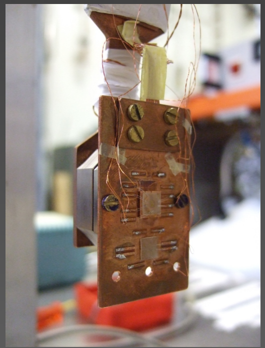
$n_{3D}=n_{2D}/d$

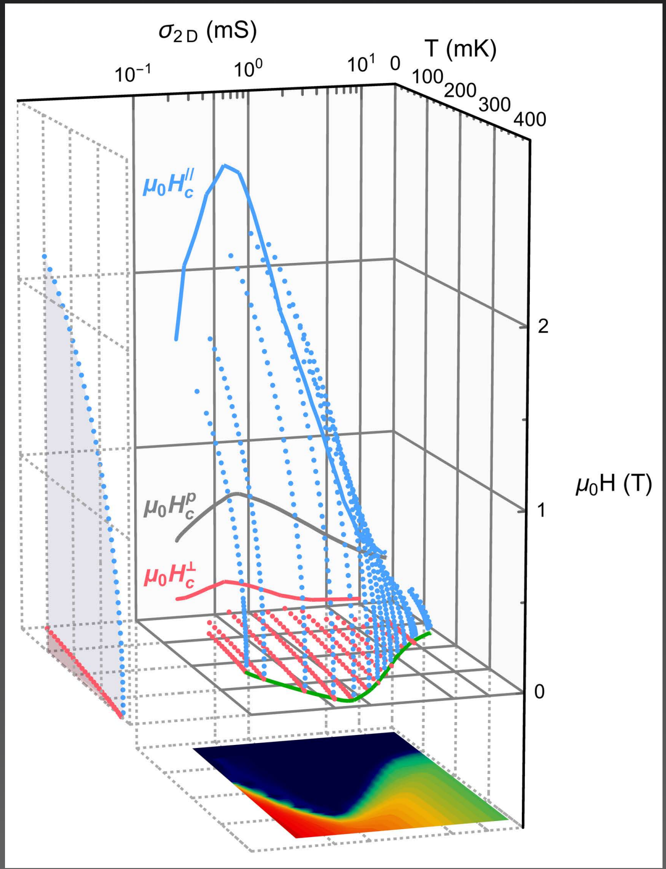
Virgin: $n_{2D}=3\ 10^{13}\ cm^{-2}$

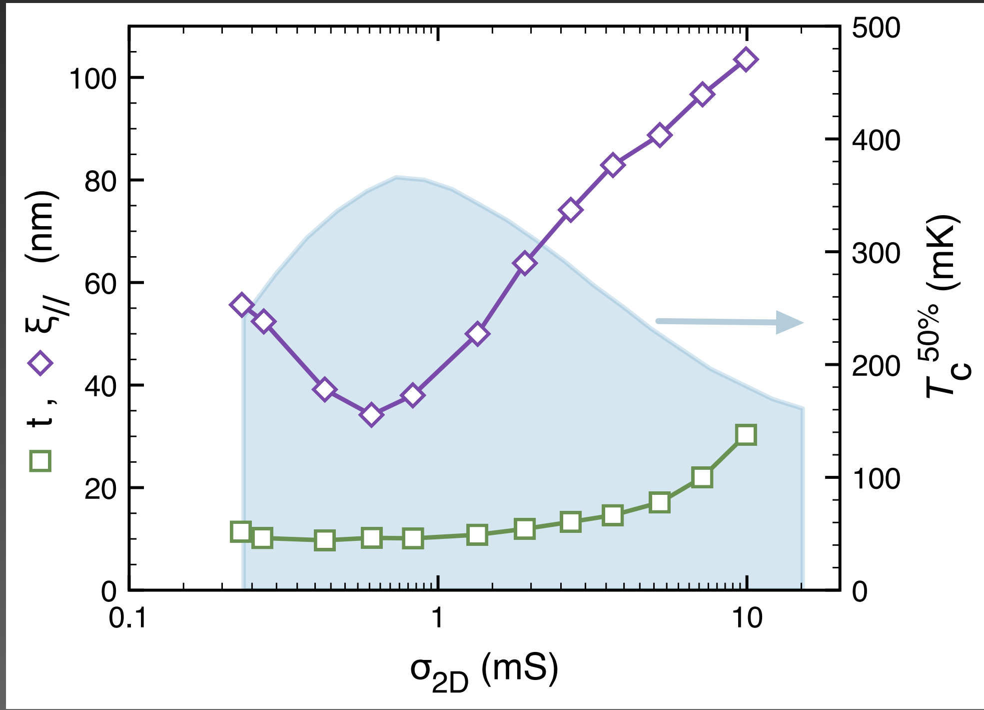
d=10nm

Determination of the SC thickness



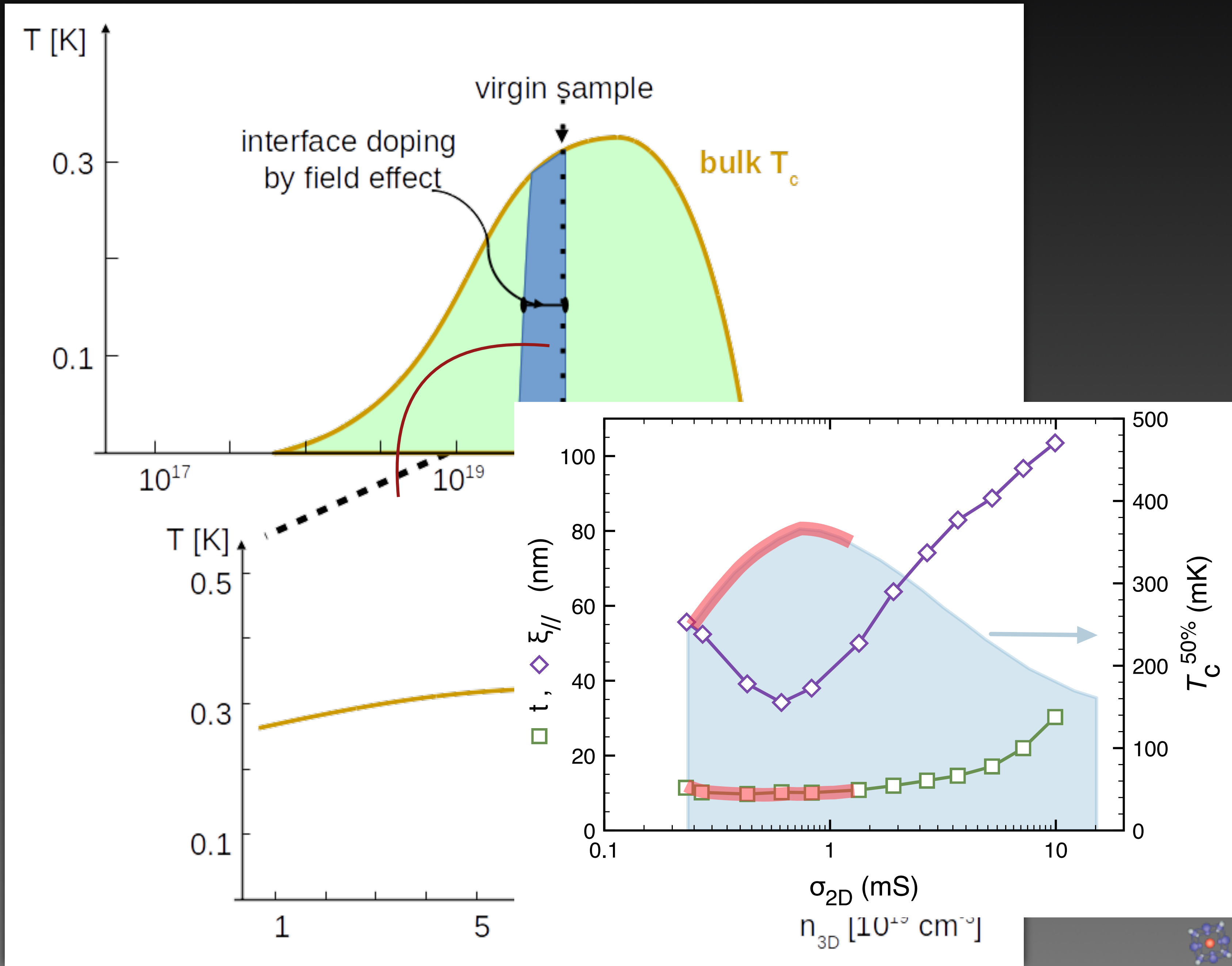






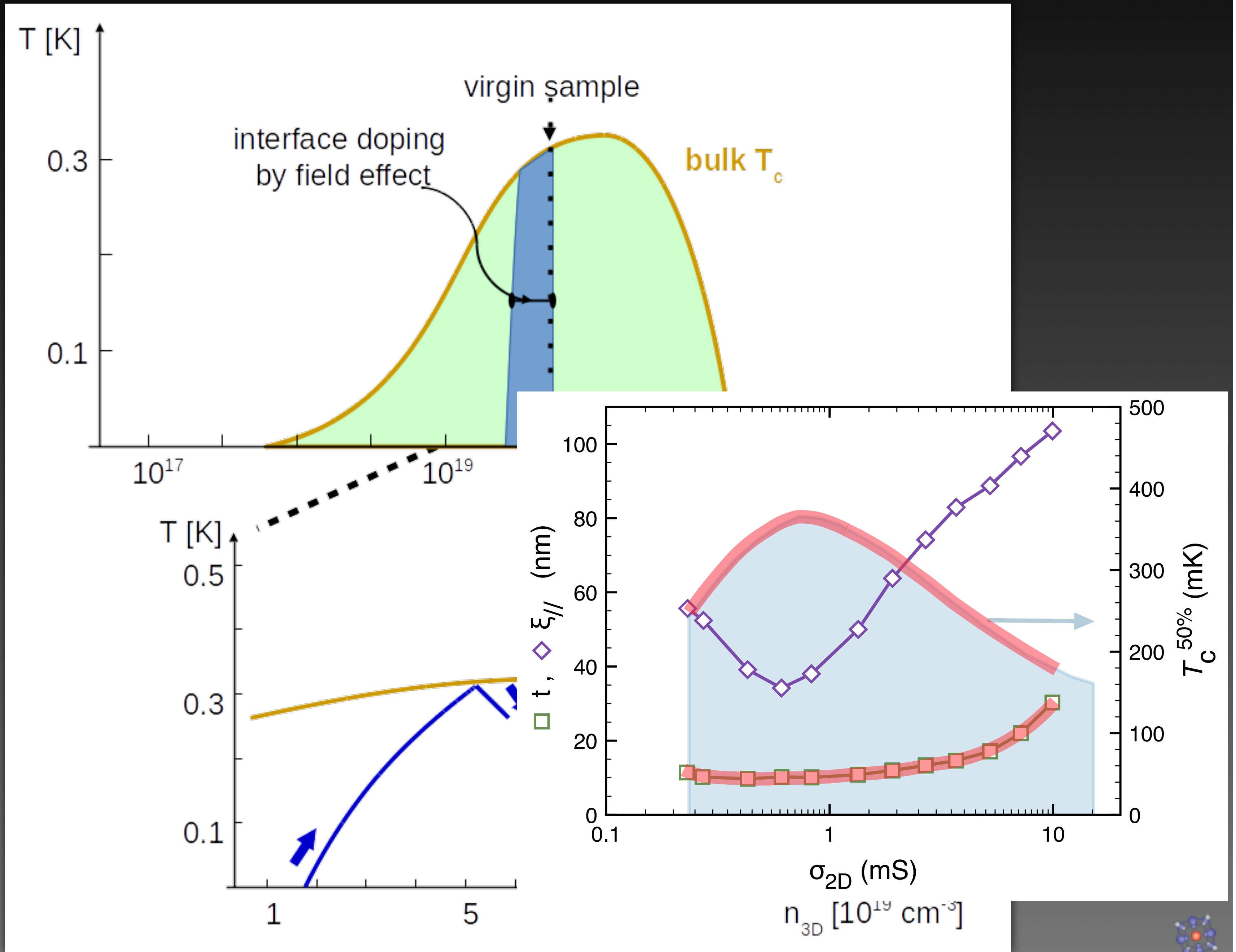
N. Reyren et al. APL **94**, 112506 (2009)
M. Ben Shalom et al. PRL **104**, 126802 (2010)

Zoom bulk T_c



T [K]
virgin sample
interface doping
by field effect
bulk T_c
0.3
0.1
10^{17}
10^{19}
T [K]
0.5
0.3
0.1
1
5
n_{3D} [10^{19} cm^{-3}]
□ t , ◇ $\xi_{//}$ (nm)
100
80
60
40
20
0
0.1
1
10
σ_{2D} (mS)
$T_c^{50\%}$ (mK)
500
400
300
200
100
0

The underdoped regime



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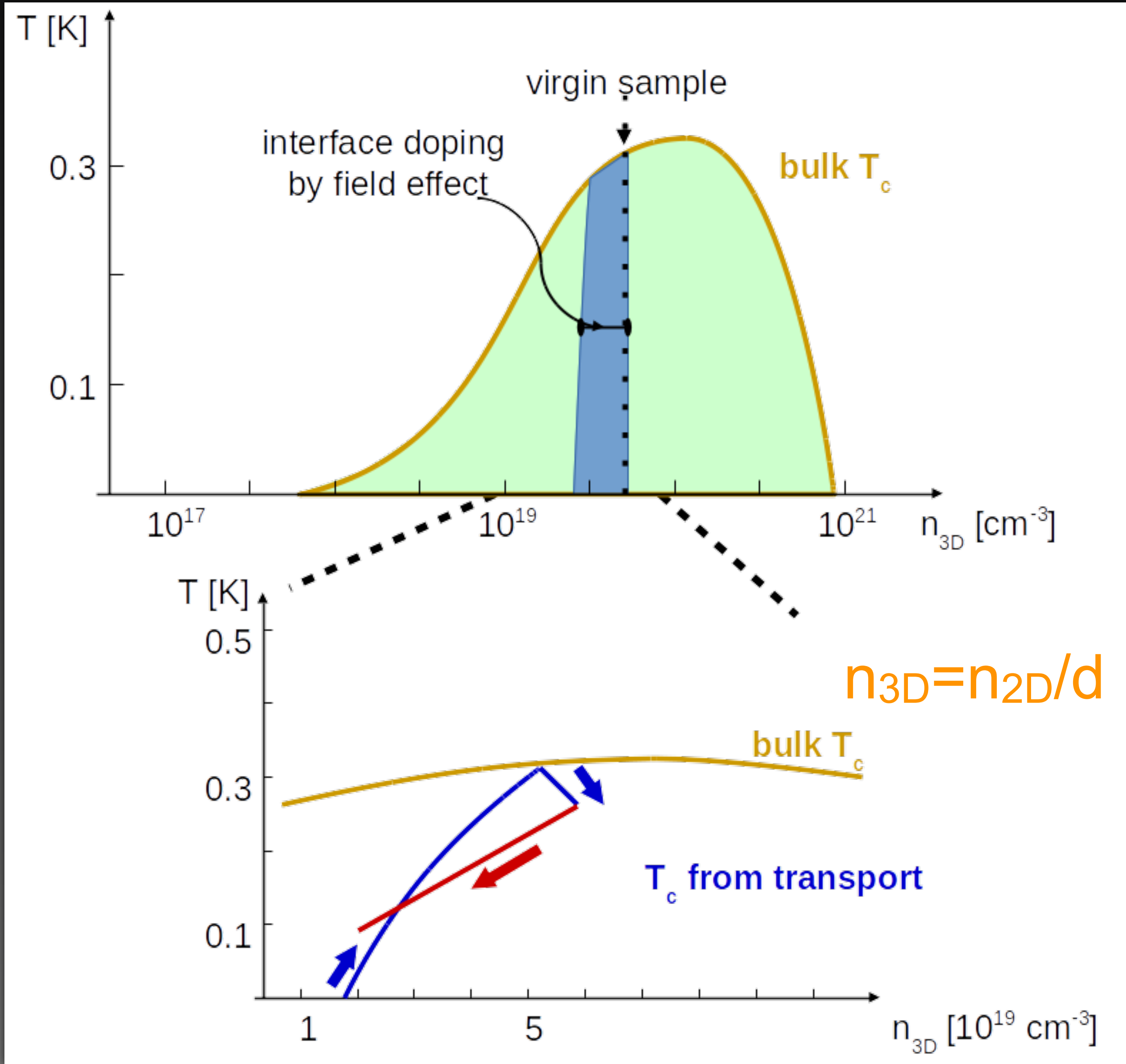
The « overdoped » regime



$n_{3D}=n_{2D}/d$

S. Gariglio et al.
review
APL Mat. 4,
0601701 (2016)

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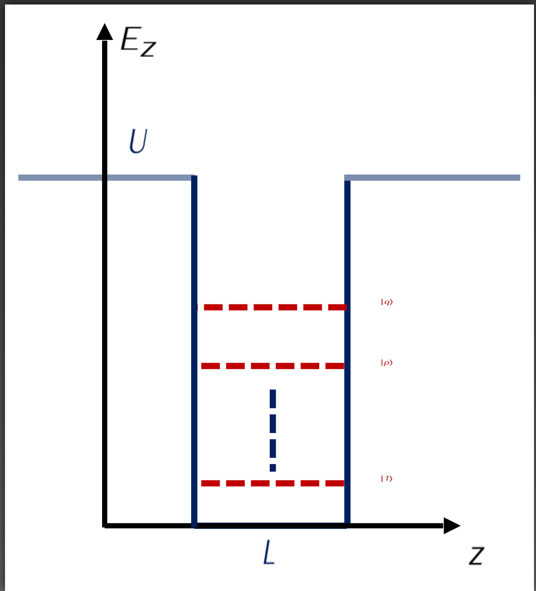
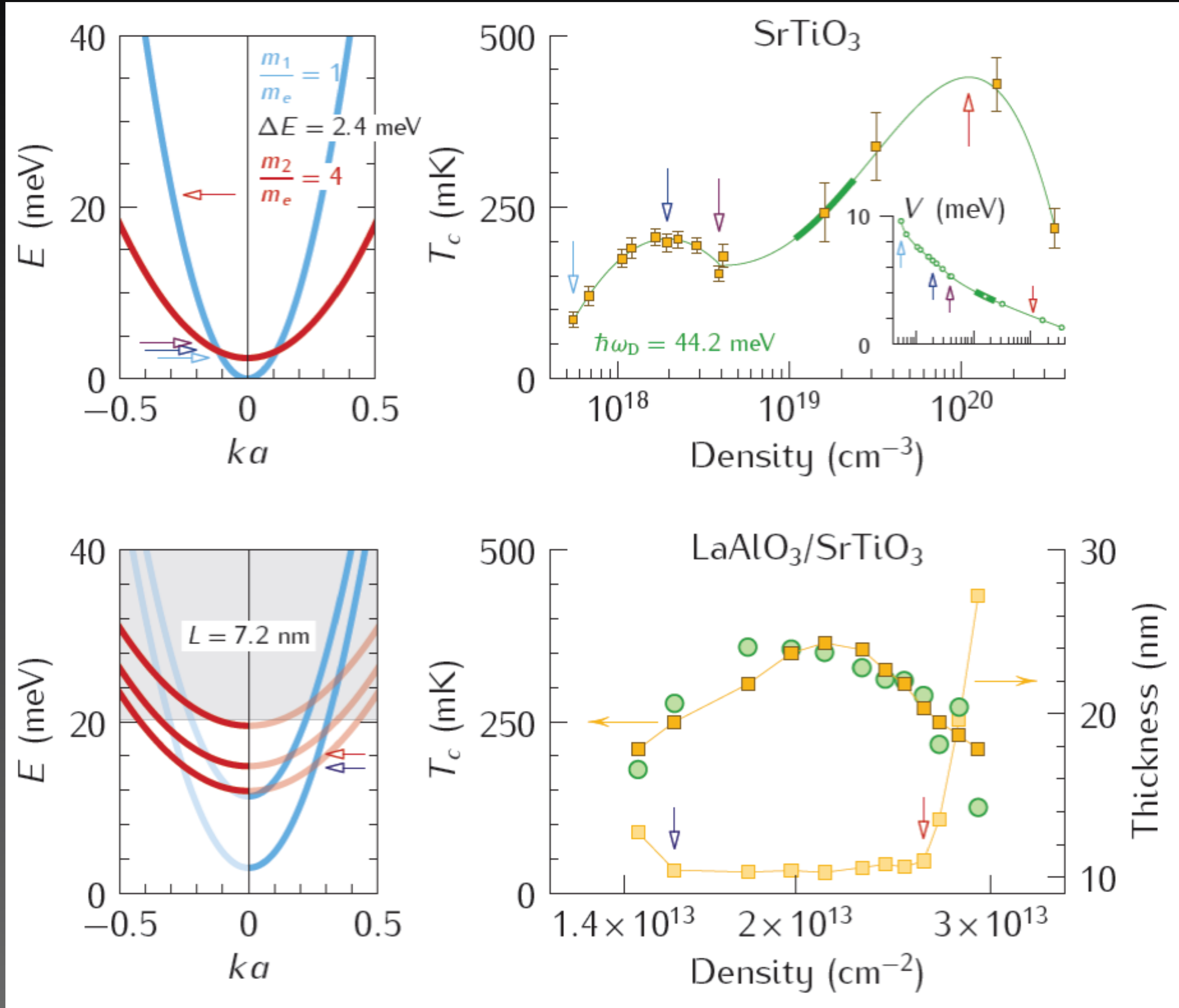
Bulk and interface SC

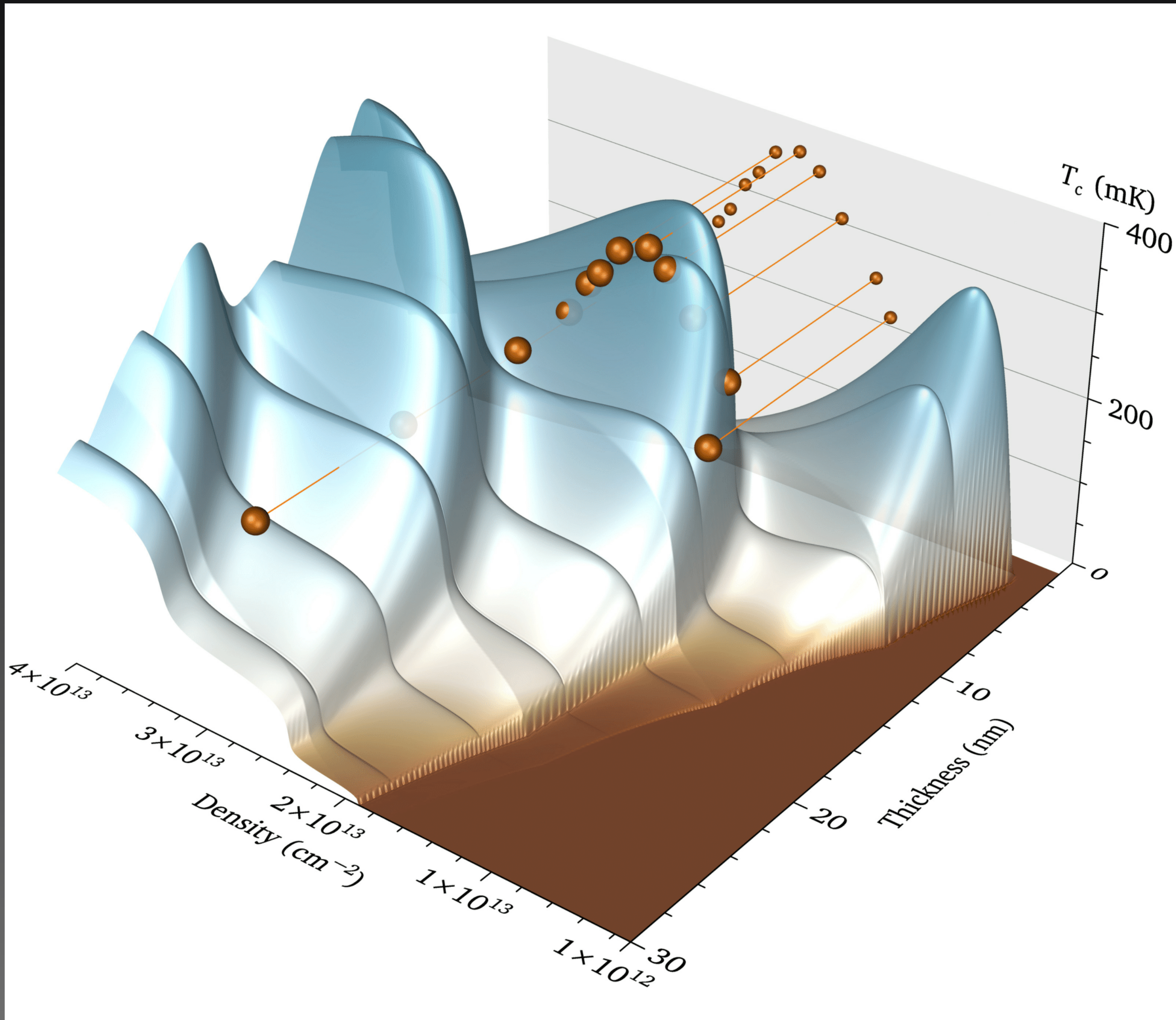




D. Valentinis et al. PRB **96**, 094518 (2017)

Bulk data from X. Lin et al. PRL **112**, 207002 (2014)

Shape resonances



D. Valentinis et al. PRB **96**, 094518 (2017)

Related systems and the role of the heavy bands

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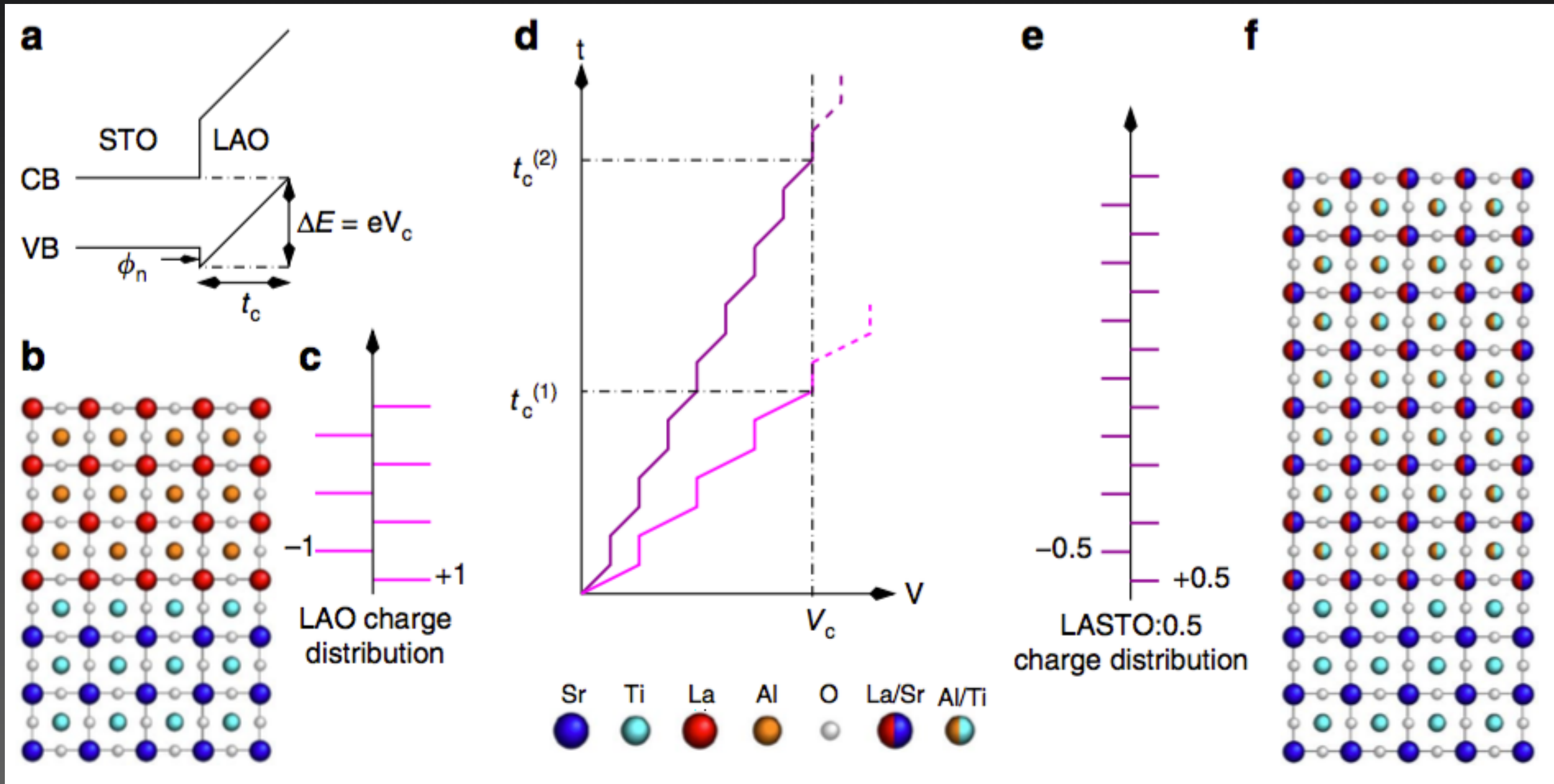
$((LaAlO_3)_{0.5}(SrTiO_3)_{0.5}) / SrTiO_3$



0.5 e^-/u.c.

0.25 e^-/u.c.

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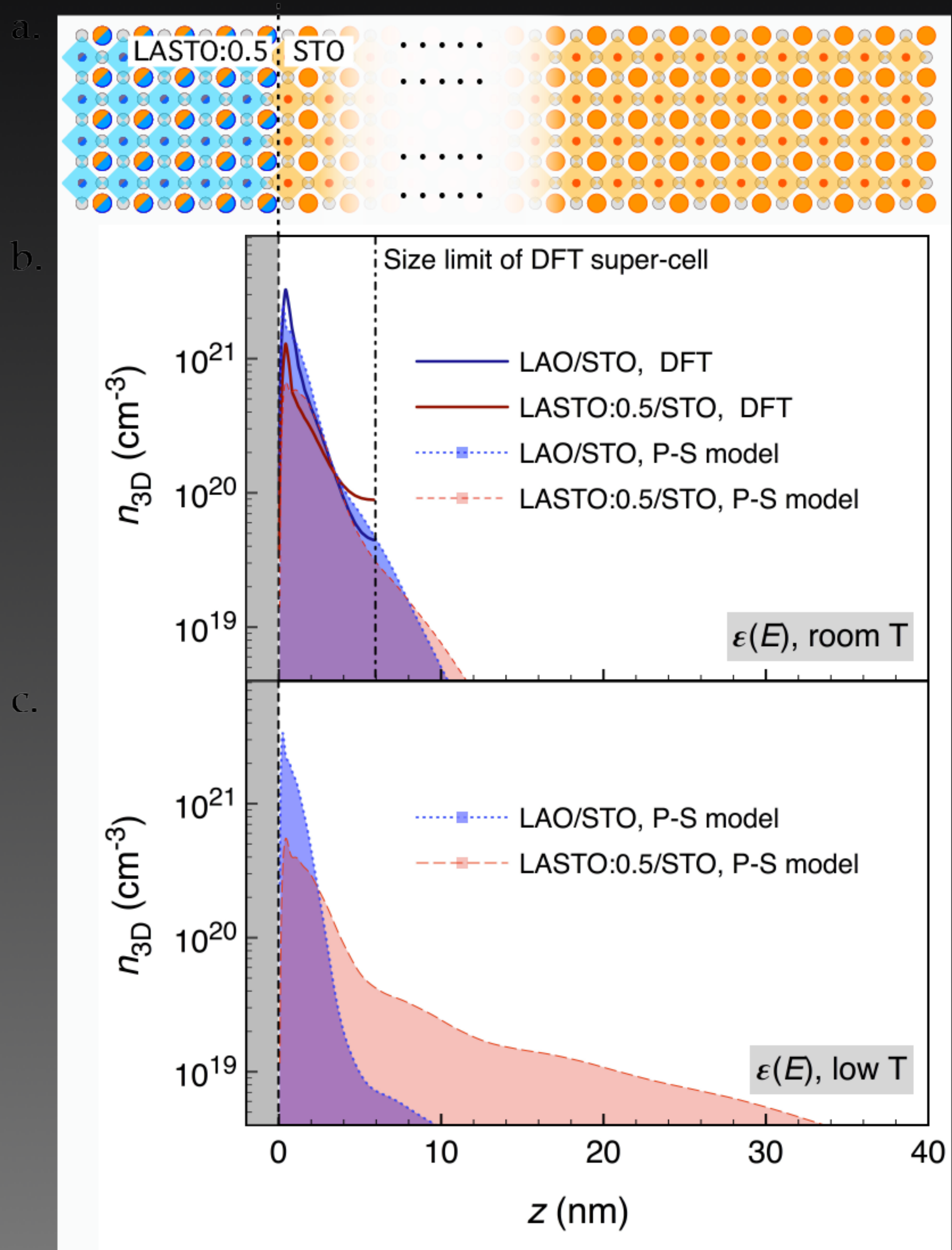
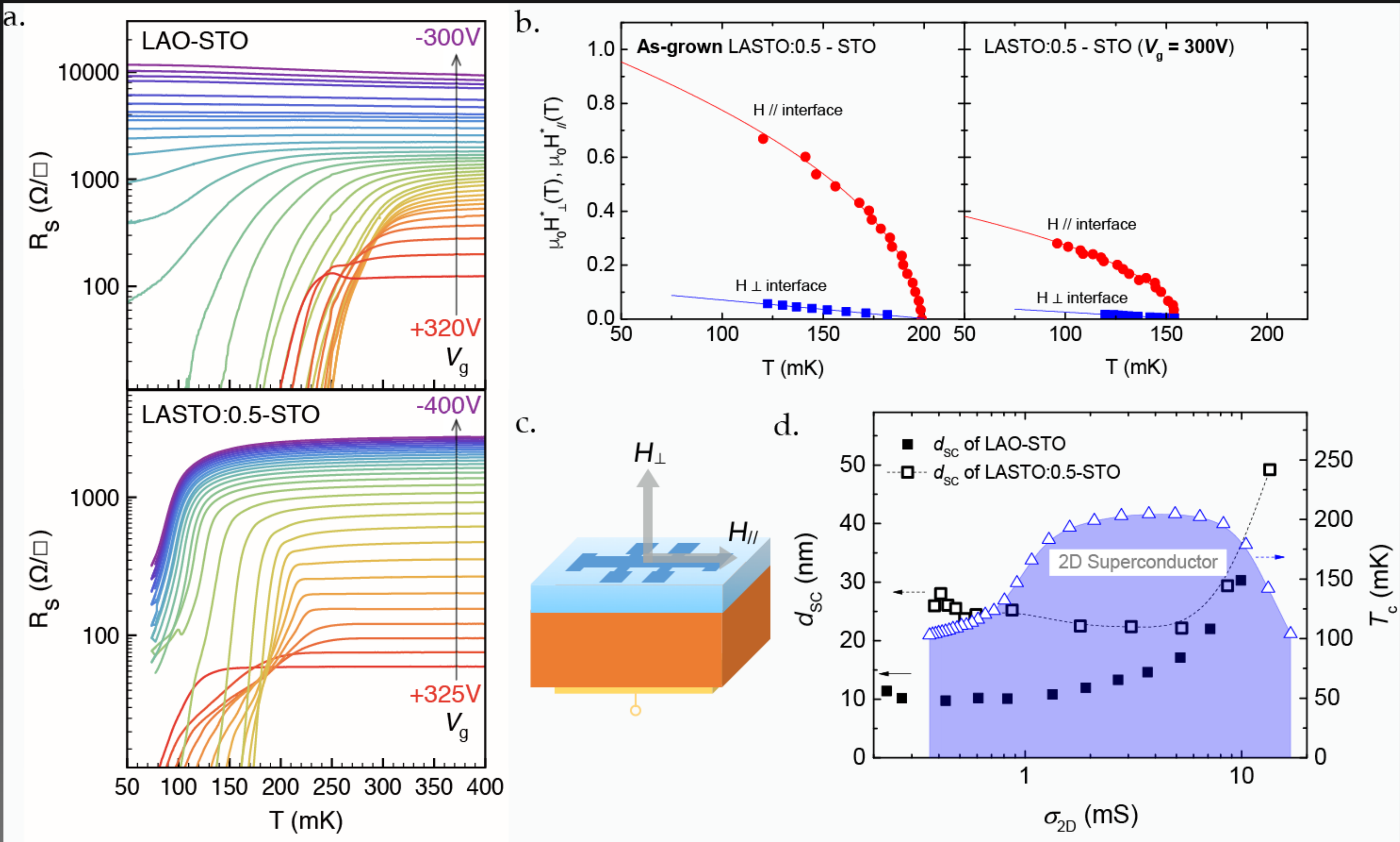
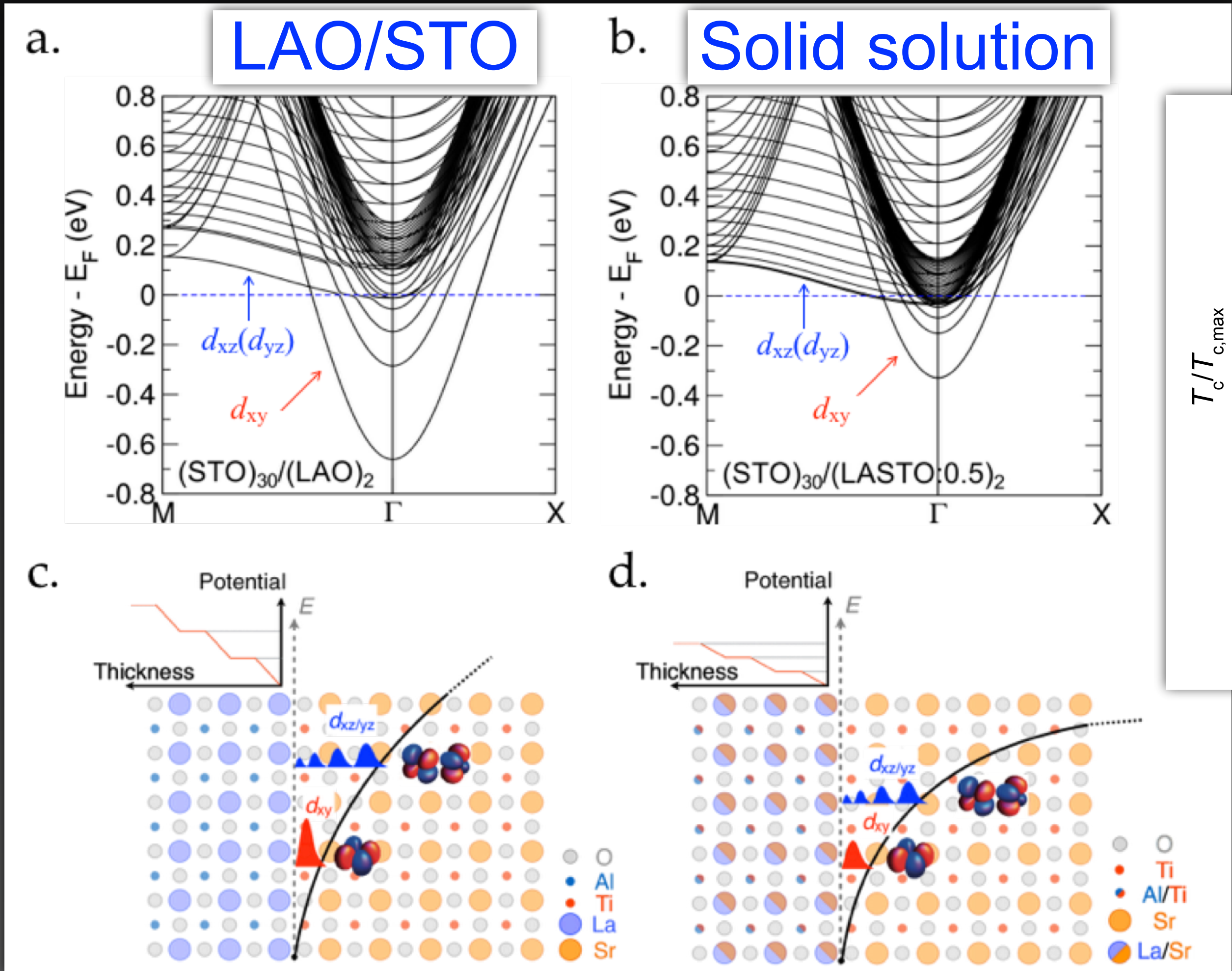
Confining potential

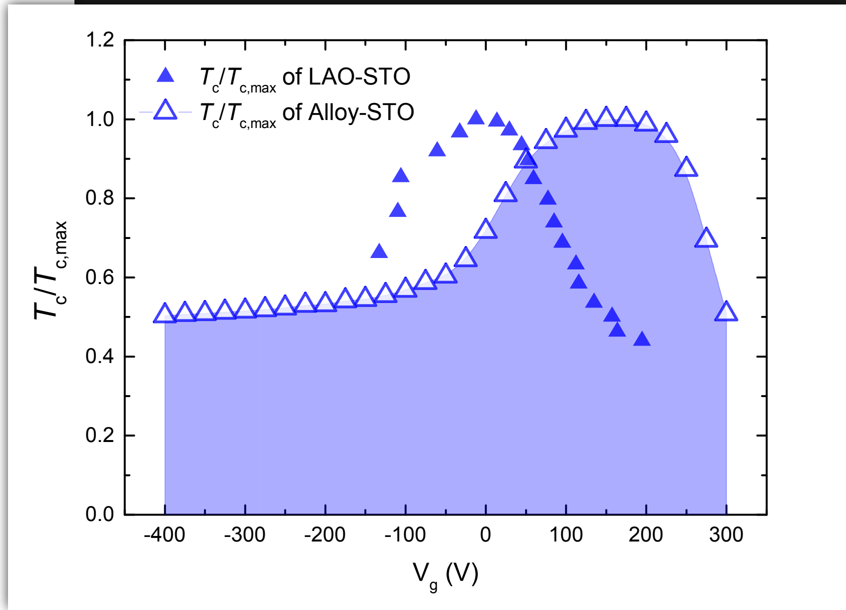


Superconducting properties



Confining potential, e-structure and SC





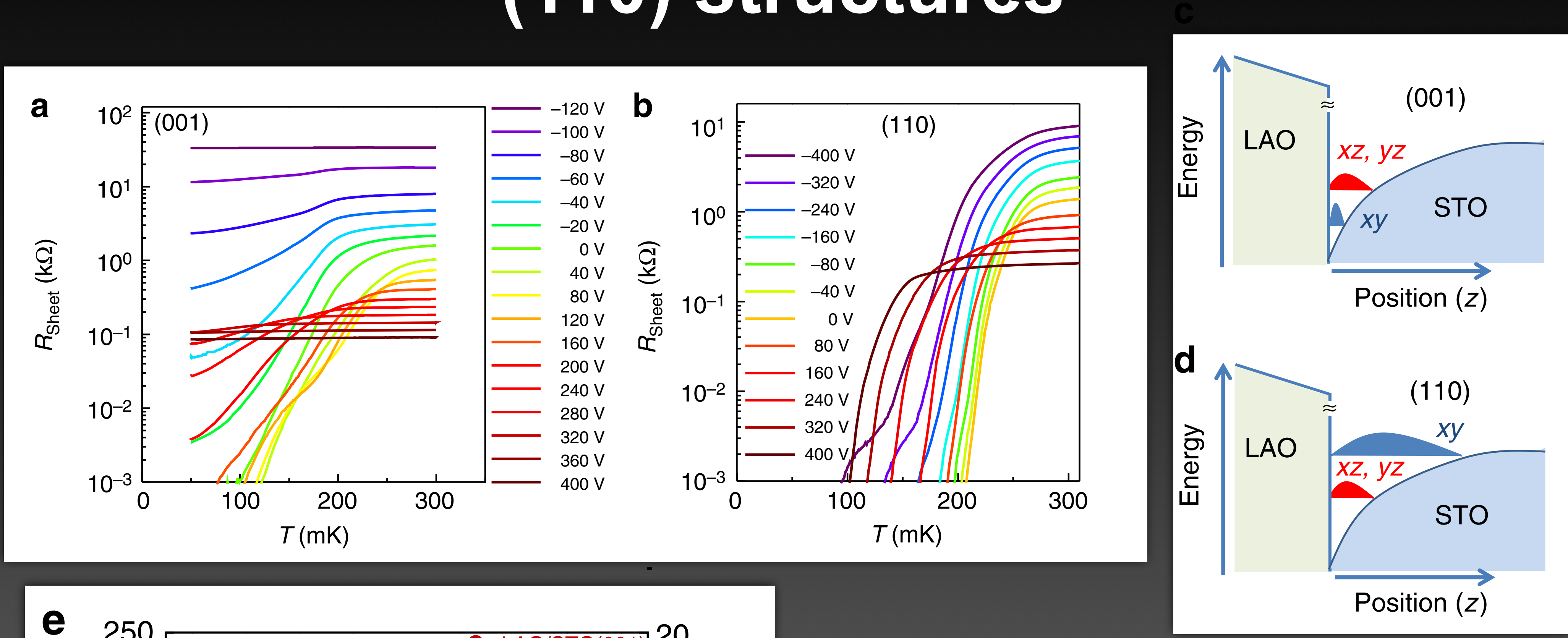
Very « robust » SC

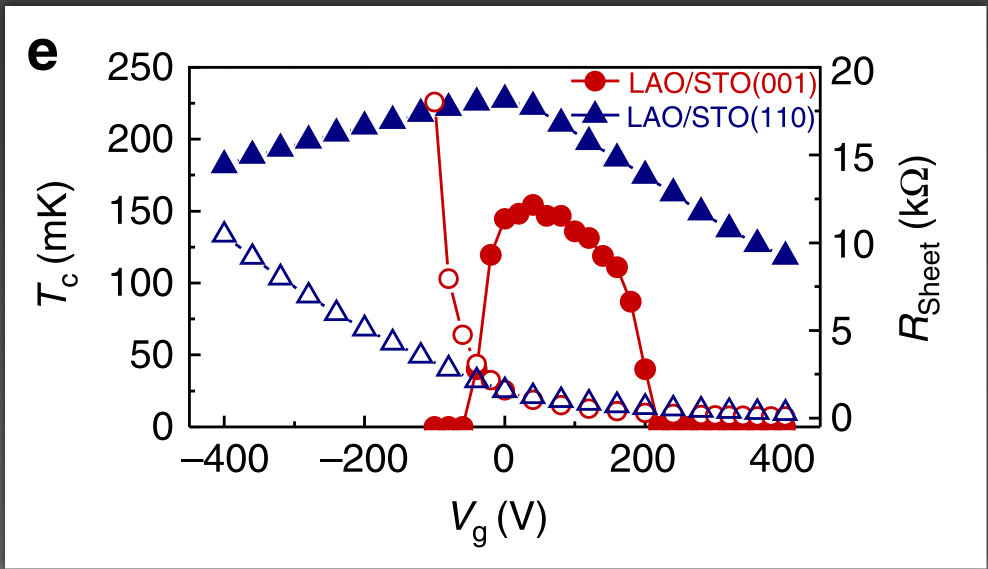
Smaller polar discontinuity

0.25e⁻/uc

Less confined 2DES

(110) structures



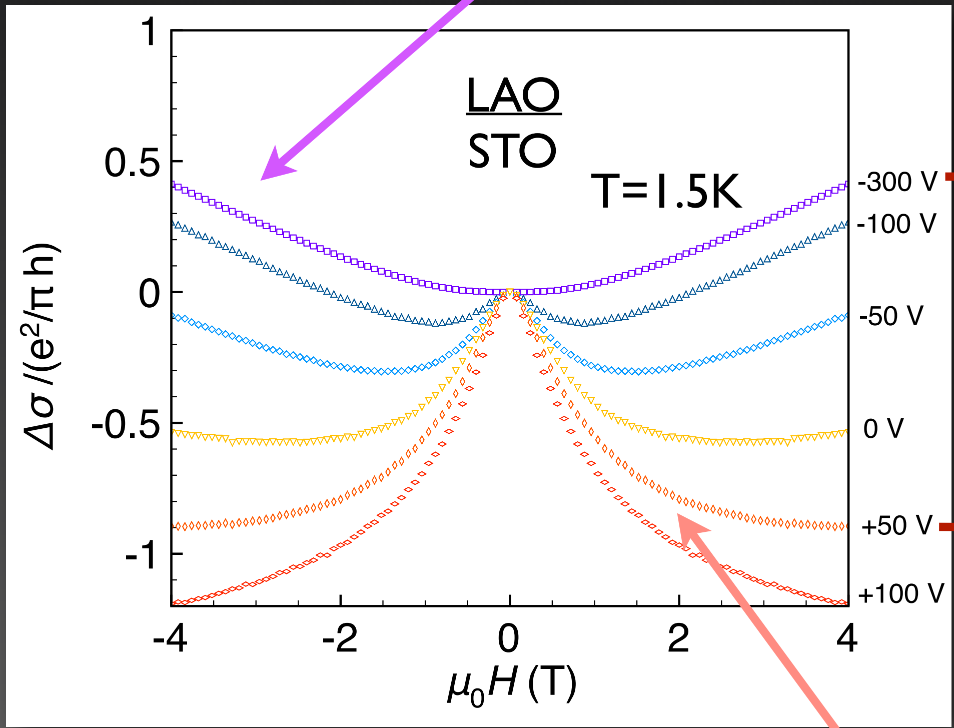


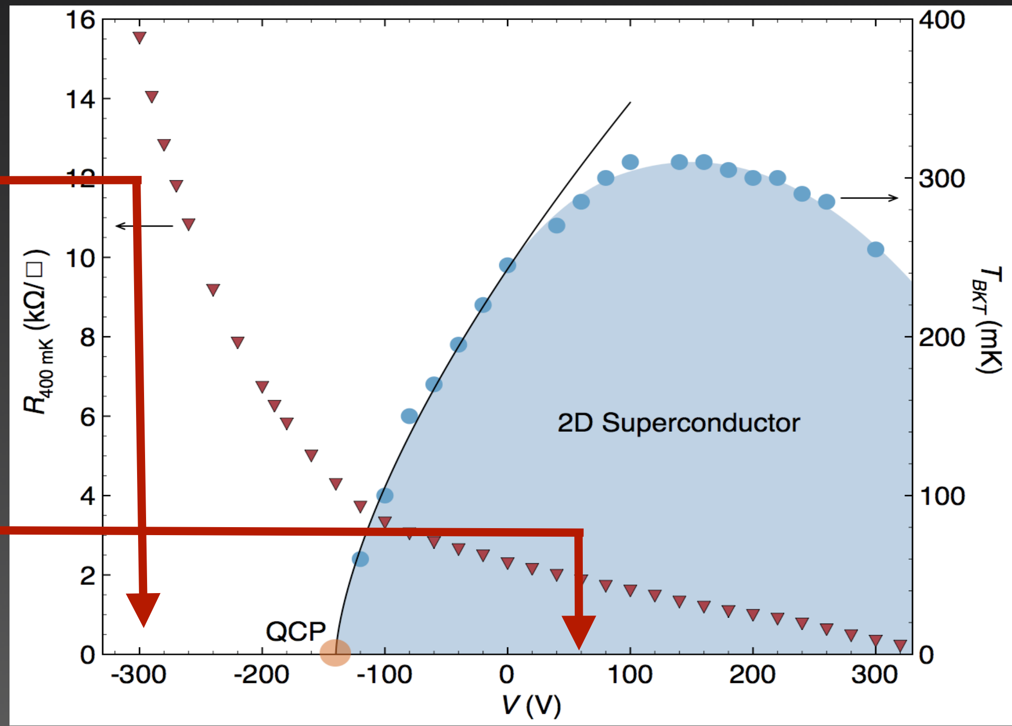
G. Herranz et al.
Nat. Com. 6, 6028 (2014)

The Possible Role of Spin-orbit on SC

Weak localization to weak antilocalization

Weak localization



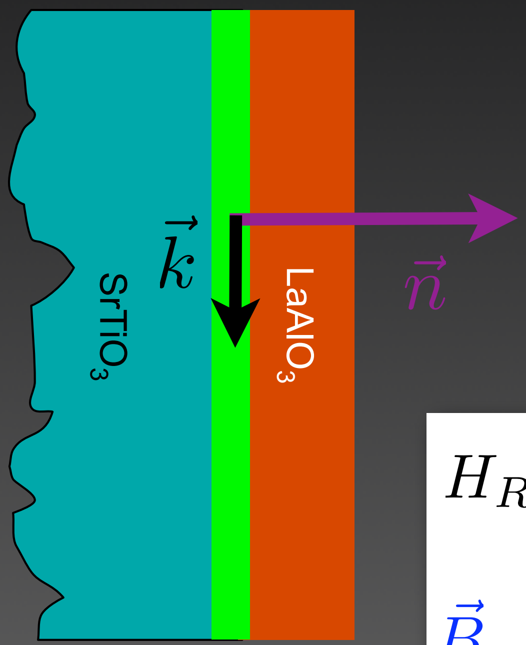


A.D. Caviglia et al., Phys. Rev. Lett. **104**, 126803 (2010)

Weak anti-localization

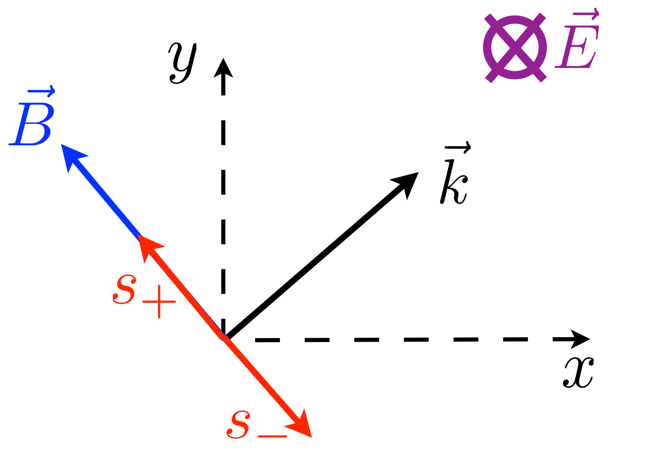
Strong spin-orbit interaction

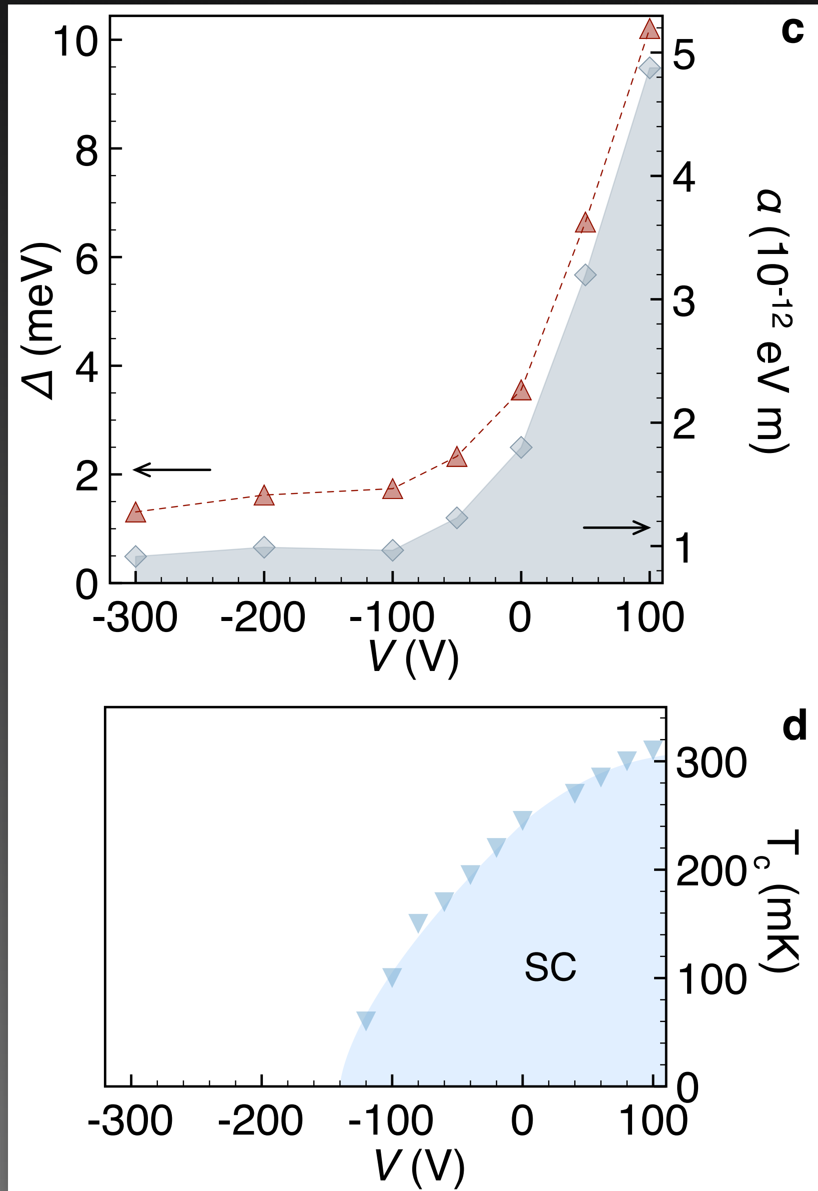
Rashba Spin-Orbit Coupling



The electrons experience an internal magnetic field oriented in the 2DEL plane

$$H_R = \alpha(\vec{k} \wedge \vec{n}) \cdot \vec{\sigma}$$





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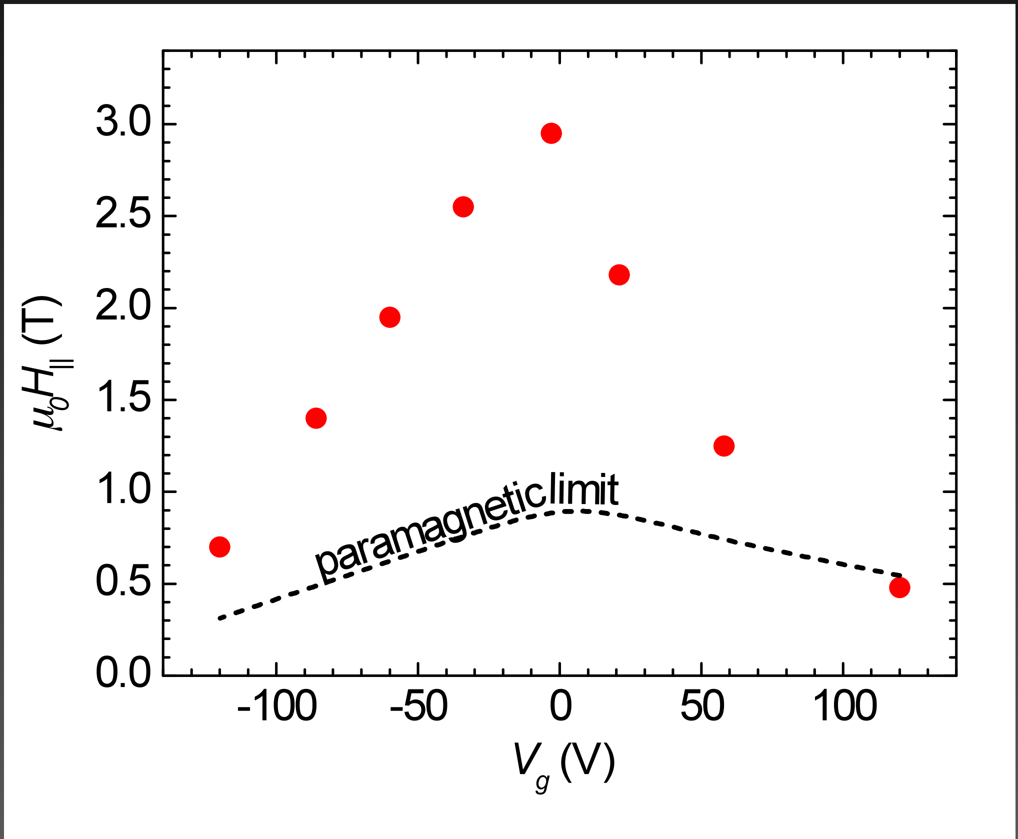
Signatures of spin-orbit coupling

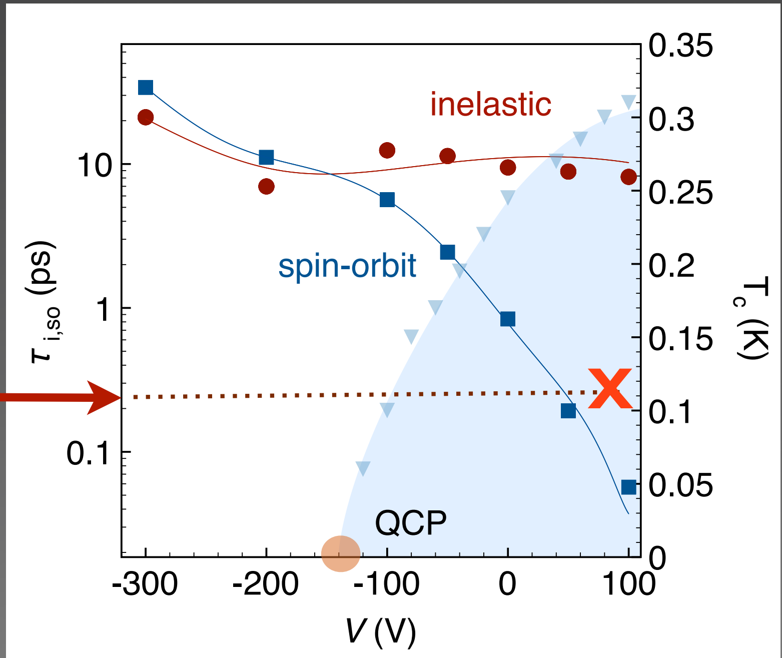


$$\mu_0 H_p = \frac{\Delta(0)}{\sqrt{2}\mu_B} = 1.84 T_c$$

$$\tau_{\rm so} = 0.602^2 \hbar^2 / (T_{co} k_B)(H_p/H_{co})^2$$

R.A. Klemm et al. PRB 12, 877 (1975)

$\tau_{s0} = 2.4\ 10^{-13}$ s



See also M. Ben Shalom et al. PRL **104**, 126802 (2010)

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Superconductivity in $SrTiO_3$

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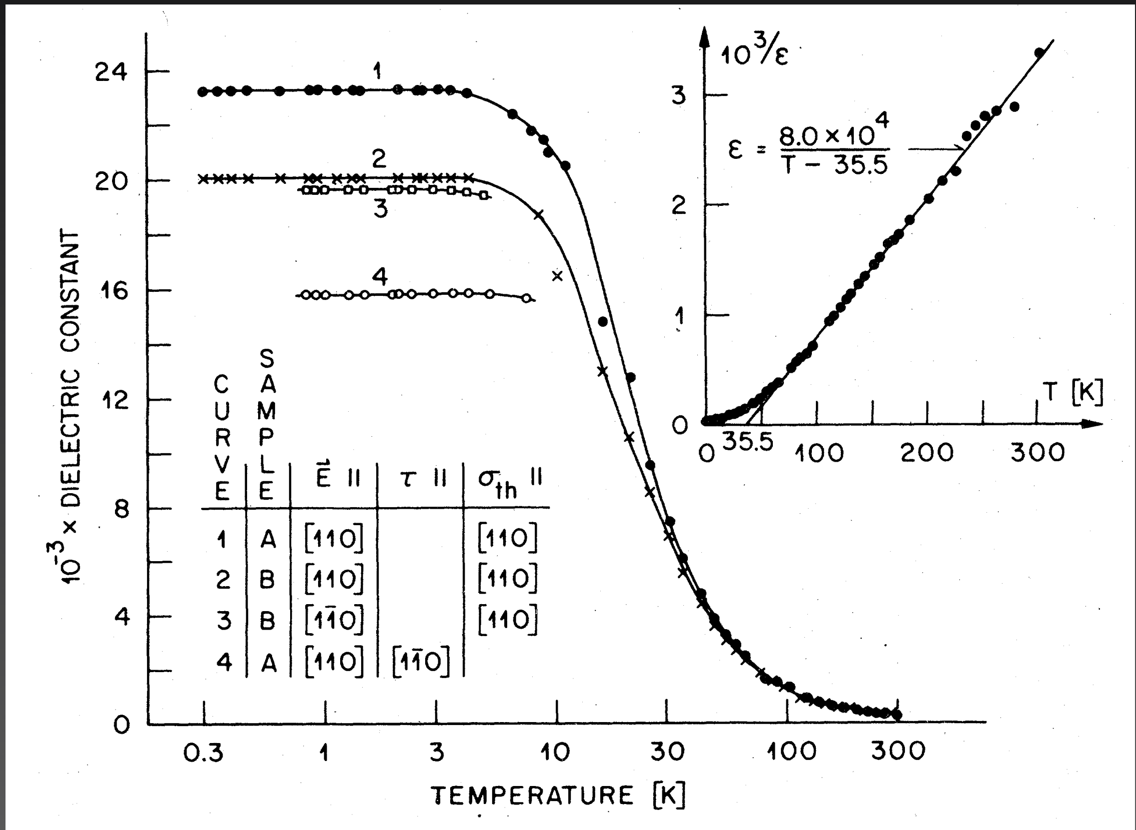
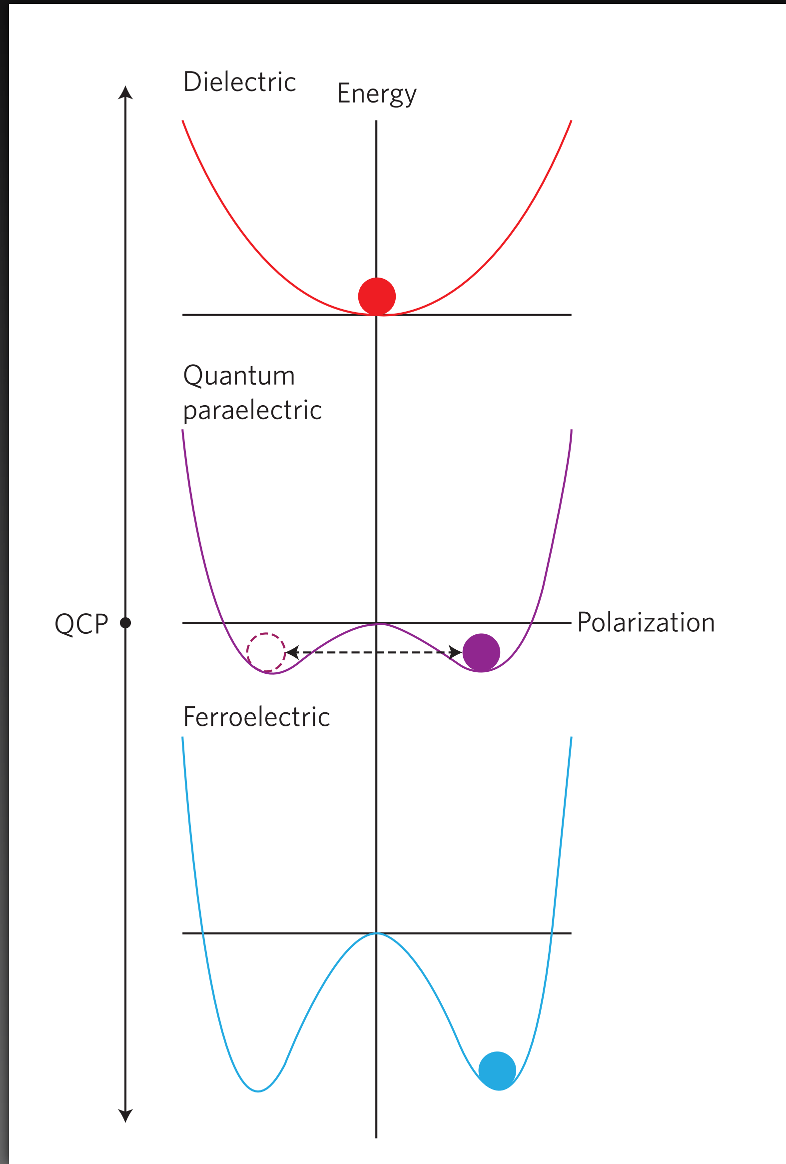
$SrTiO_3$ - a quantum paraelectric



K.A. Müller and H. Burkard PRB **19**, 3593 (1979)



M. Gabay and J.-M. Triscone
N&V Nature Physics 2017

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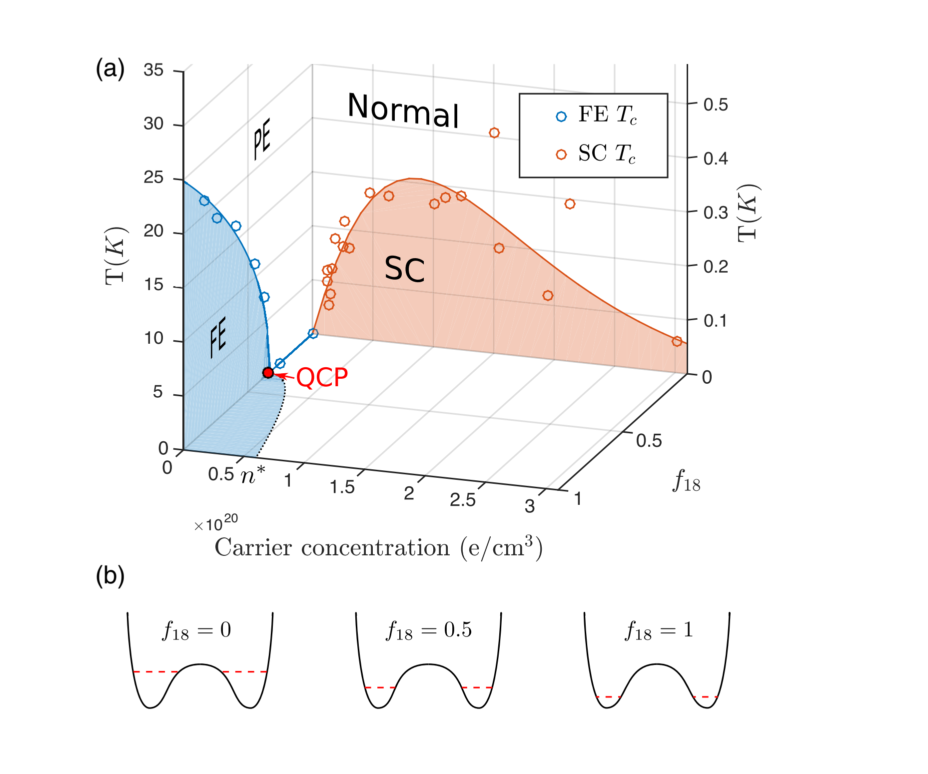
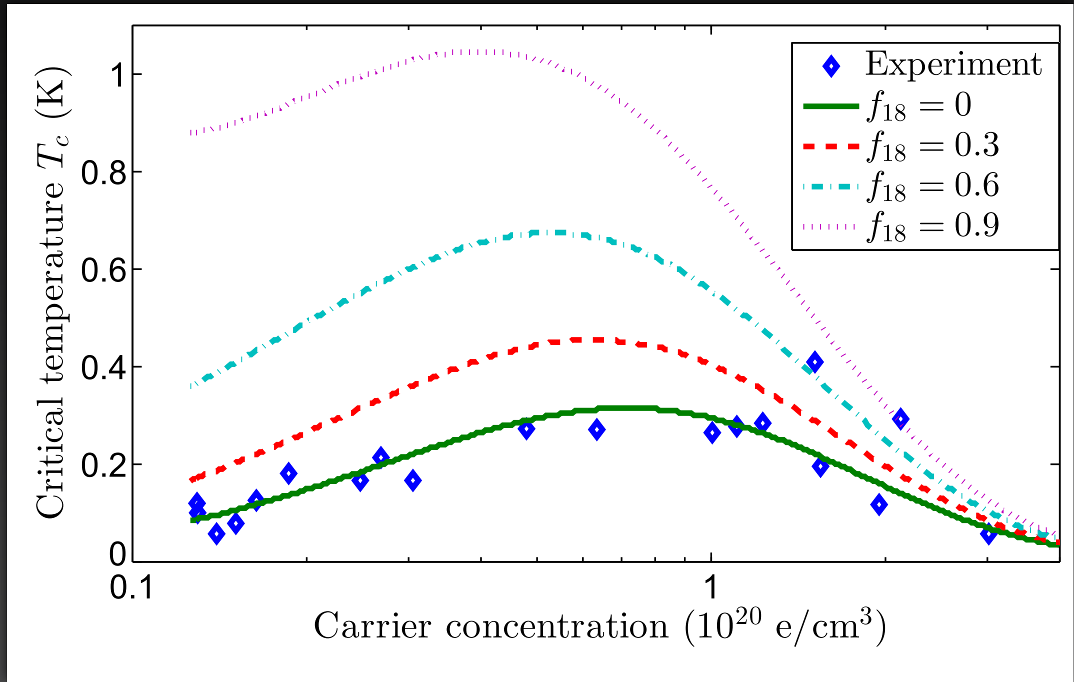
Role of the ferroelectric soft mode





O^{18} for O^{16}

$$\lambda = \int_0^\infty \alpha^2(\omega) F(\omega) \frac{d\omega}{\omega}, \quad \lambda = \alpha^2 \frac{1}{\omega_{\mathbf{q}=0}(f_{18}, E_F)},$$

J.M. Edge et al. PRL **115**, 247002 (2015)

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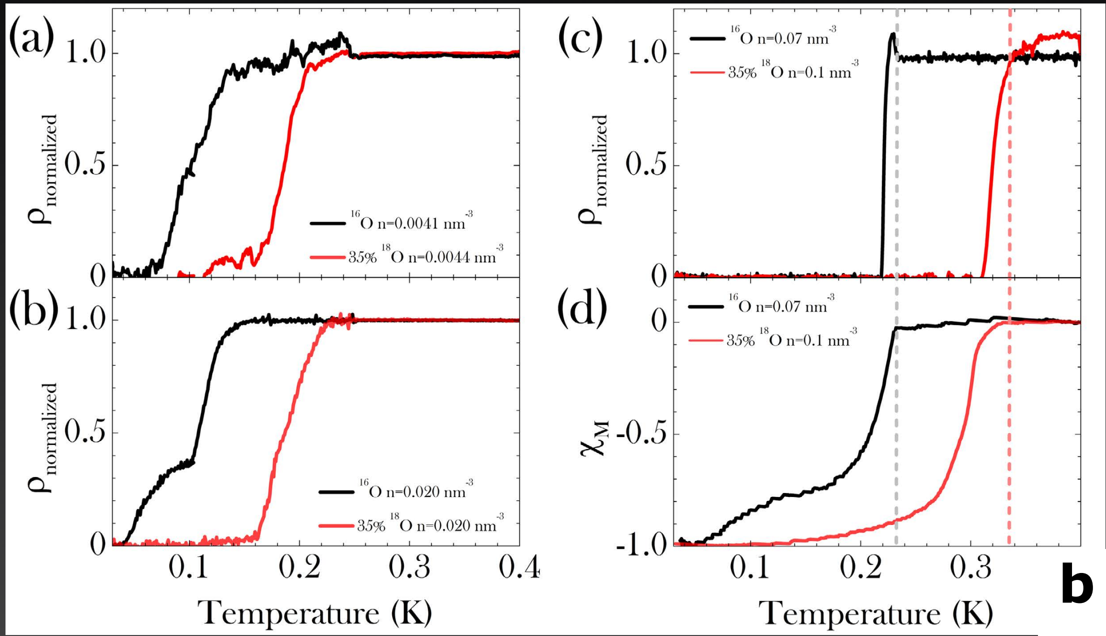
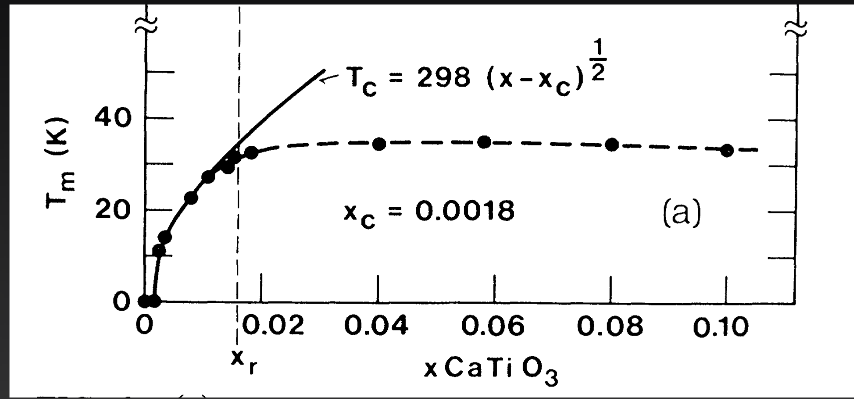
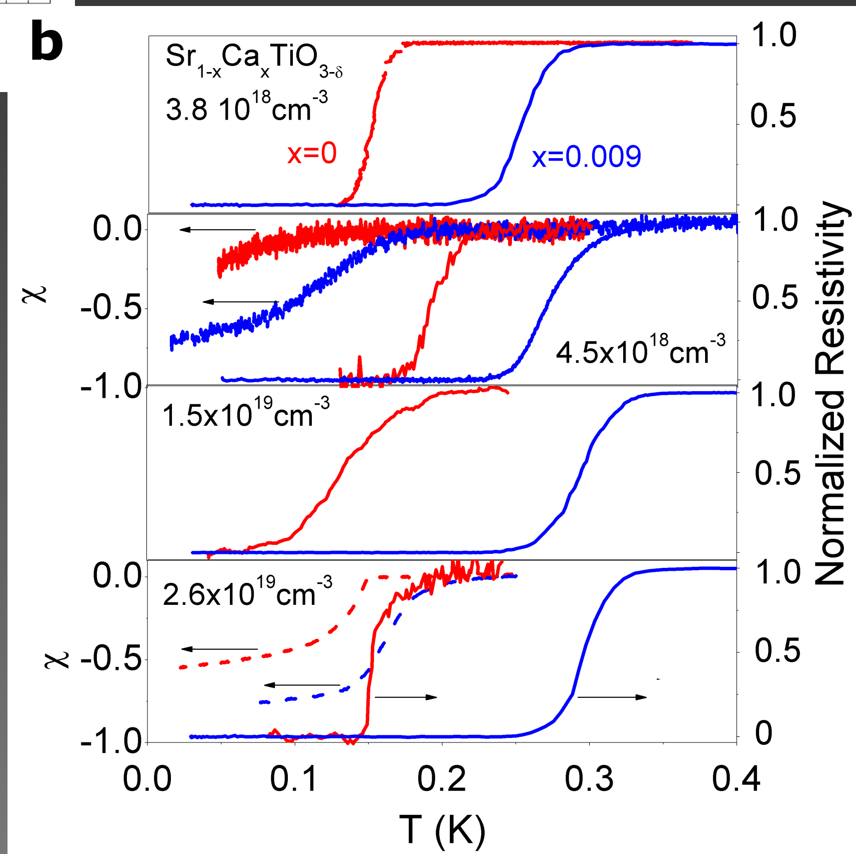
O^{18}-O^{16}

Ca-doped





J.G. Bednorz and K.A. Müller
PRL 52, 2289 (1984)



A. Stucky et al. Scientific reports **6**, 37582 (2016) - O^{18} doped $SrTiO_3$

C.W. Rischau et al. Nature Physics 2017 - Ca-doped $SrTiO_3$

M. Gabay and J.-M. Triscone
N&V Nature Physics 2017

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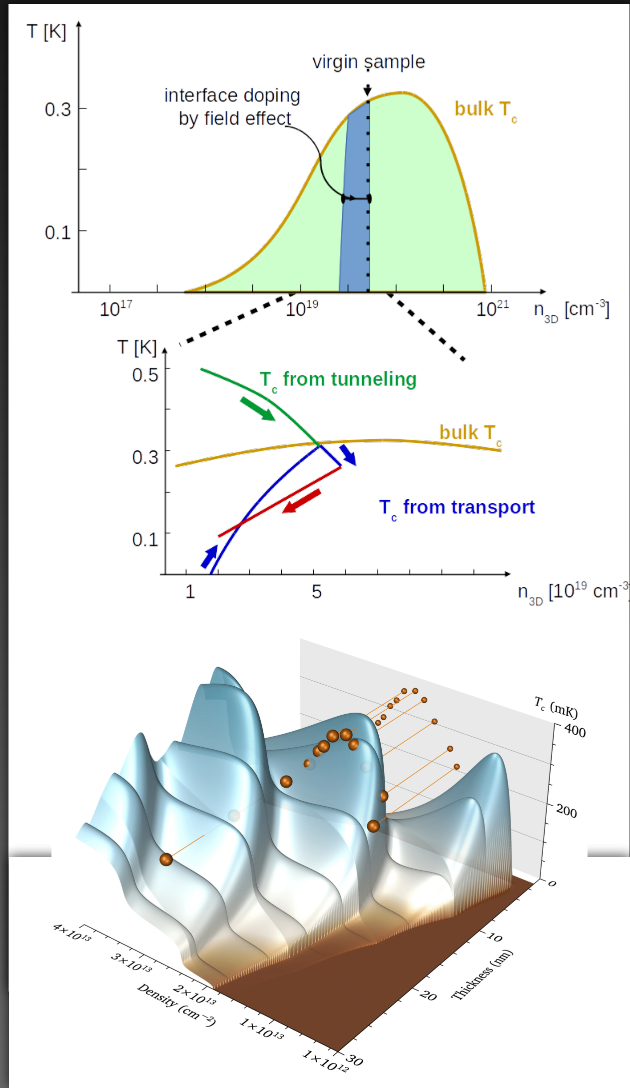
Conclusions - open questions

The bulk and interface phase diagrams are different - the modified electronic structure and the heavy bands play a key role

Impact of spin-orbit on SC?

Do ferroelectric fluctuations contribute to pairing in $SrTiO_3$?



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