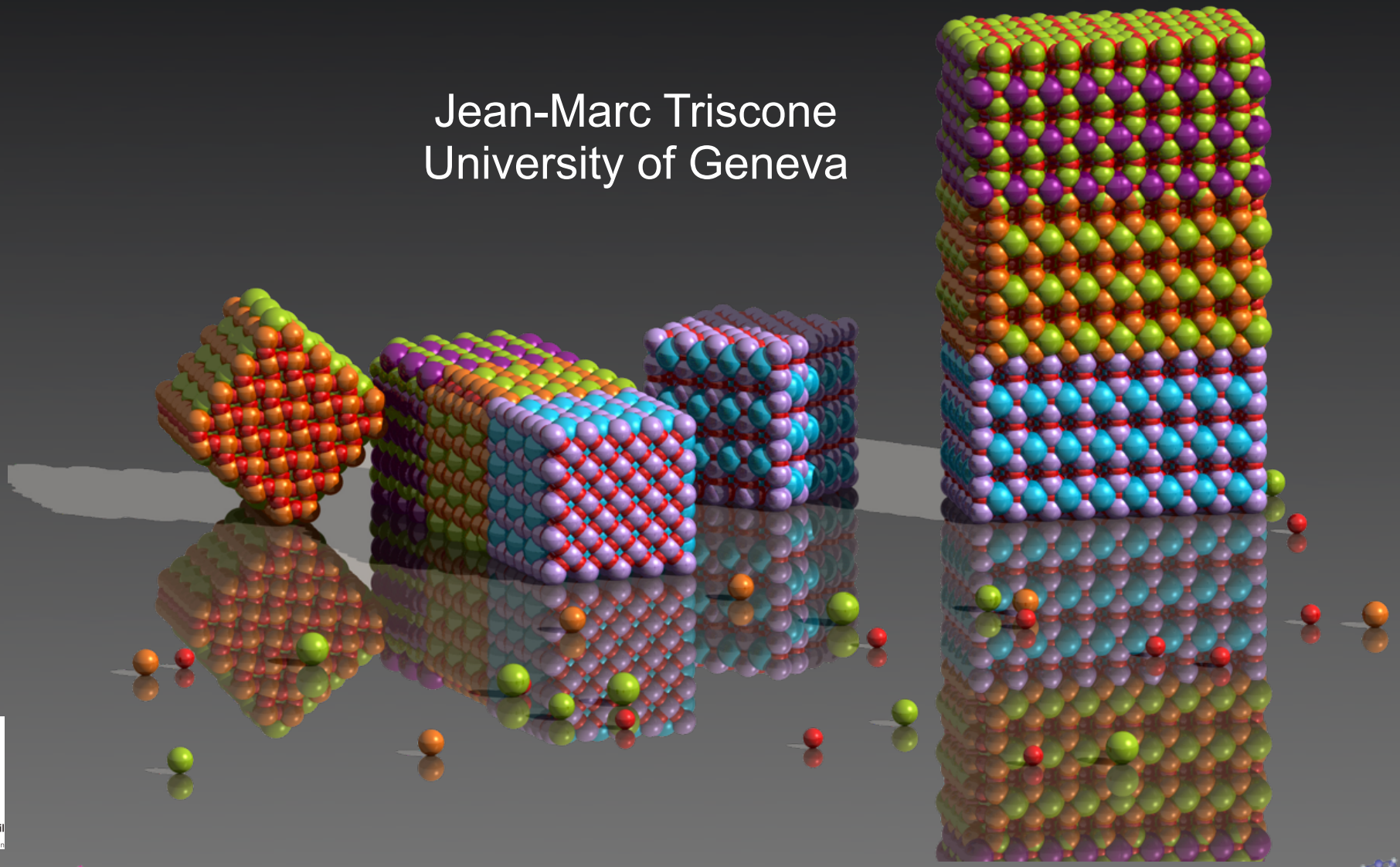
2-D Superconductivity at Oxide Interfaces

Jean-Marc Triscone
University of Geneva



Joerg Harms, MPI Hamburg

European Research Council
Established by the European Commission

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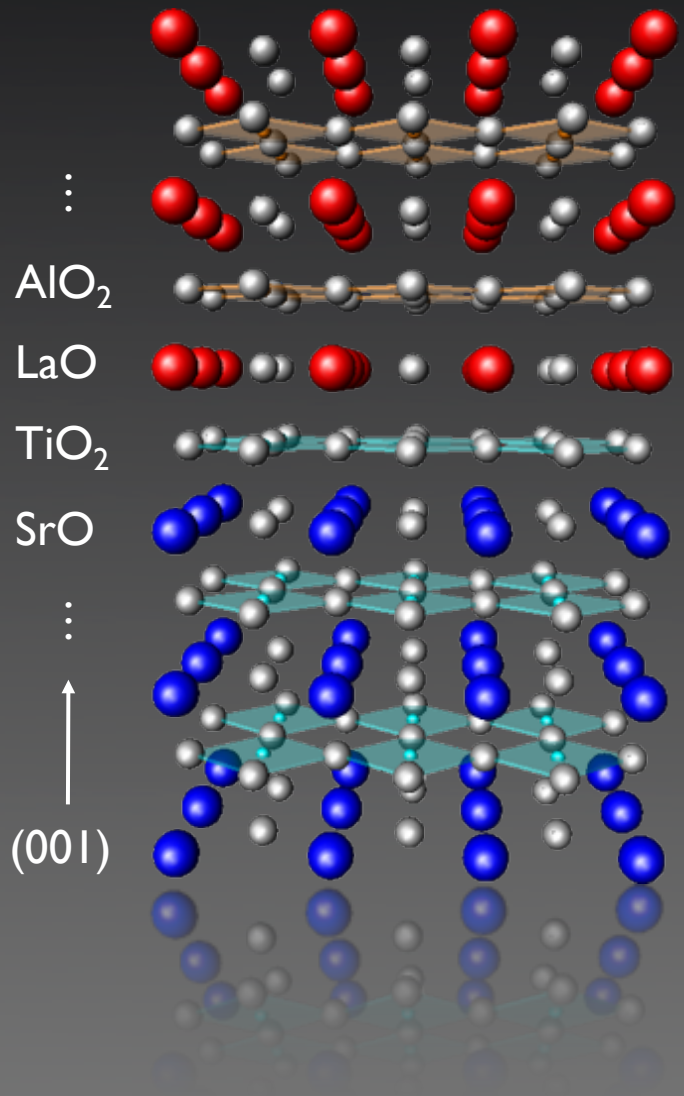
The $LaAlO_3/SrTiO_3$ Interface



$LaAlO_3$:

band insulator

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

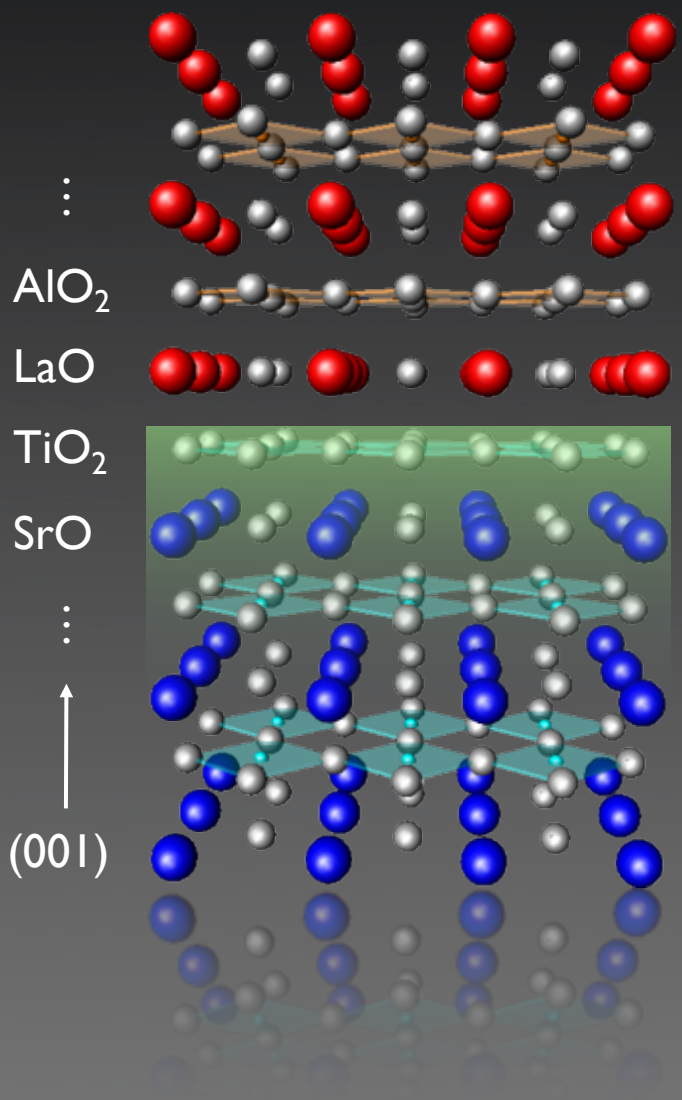
$SrTiO_3$:

band insulator

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

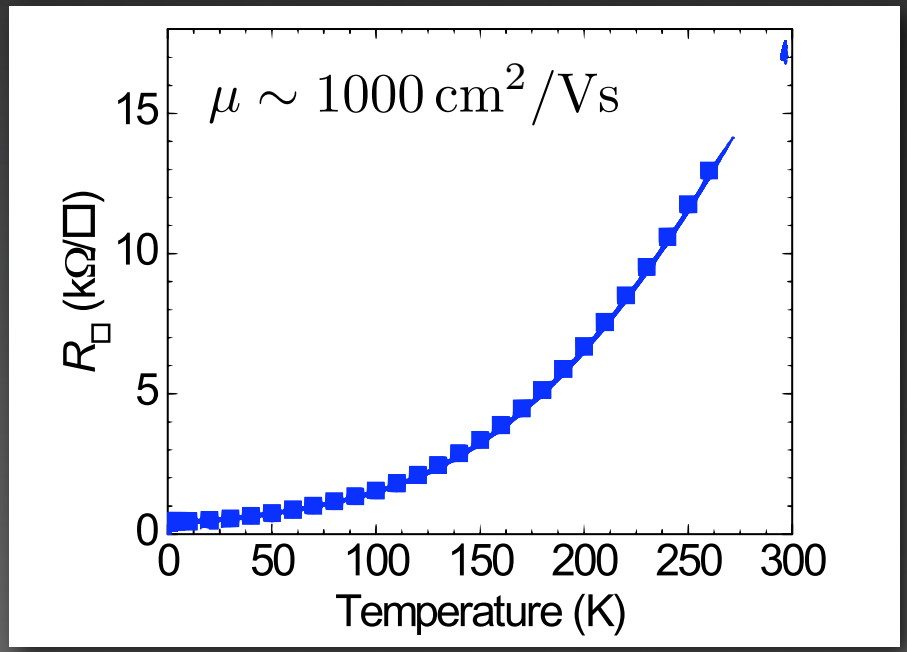
quantum paraelectric

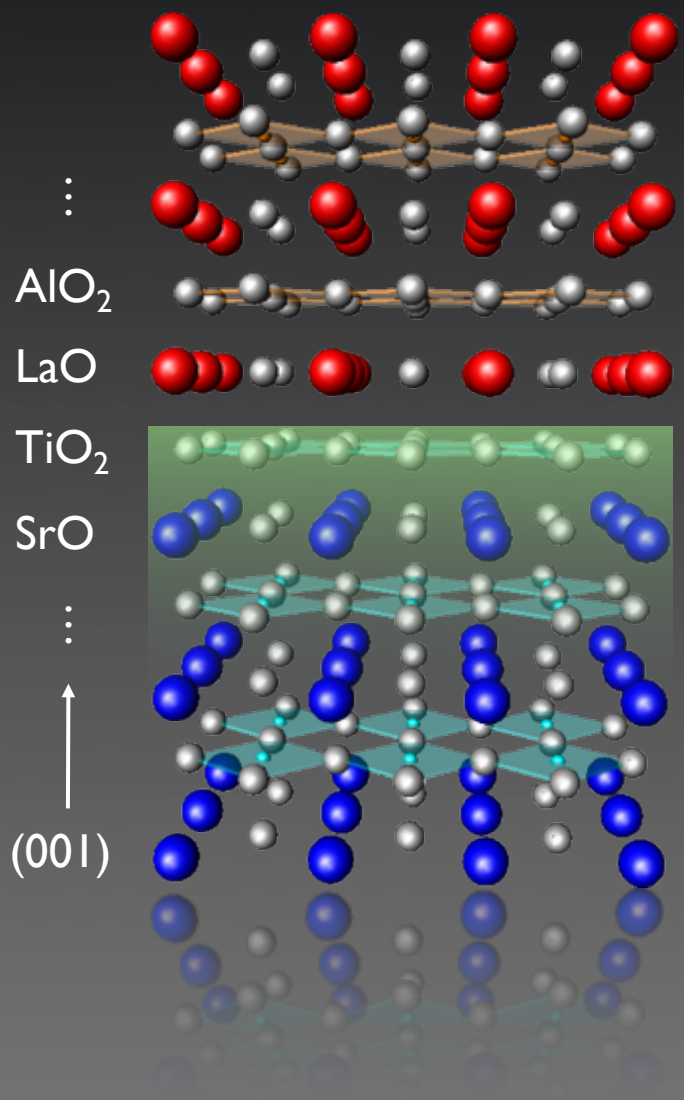
2D Electron Gas



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

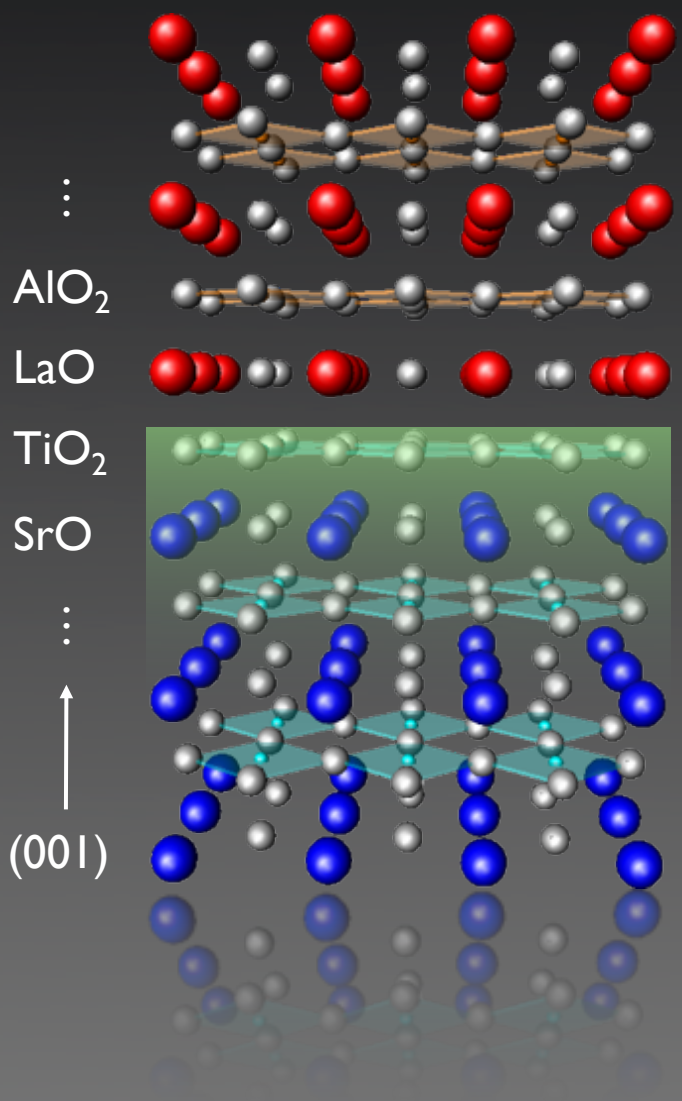
A. Ohtomo[1,2,3] **& H. Y. Hwang**[1,3,4] *Nature* **427**, 423 (2004)





A. Ohtomo, H. Hwang, *Nature* **427**, 423 (2004)
S. Okamoto, A.J. Millis, *Nature* **428**, 630 (2004)
S. Thiel *et al., Science* **313**, 1942 (2006)
N. Nakagawa *et al., Nature Materials* **5**, 204 (2006)
M. Huijben *et al., Nature Materials* **5**, 556 (2006)
C.W. Schneider, *APL* **89**, 122101 (2006)
A. Brinkman *et al., Nature Materials* **6**, 493 (2007)
G. Herranz *et al., PRL* **98**, 216803 (2007)
W. Siemons *et al., PRL* **98**, 196802 (2007)
P.R. Willmott *et al., PRL* **99**, 155502 (2007)
A. Kalabukov *et al., PRB* **75**, 121404(R) (2007)
Z. Popovic *et al., PRL* **101**, 256801 (2008)
M. Basletic *et al., Nature Materials* **7**, 621 (2008)
C. Cen *et al., Nature Materials* **7**, 298 (2008)
S. Thiel *et al., PRL* **102**, 046809 (2009)
R. Pentcheva*et al., PRL* **102**, 107602 (2009)
M. Salluzzo *et al., PRL* **102**, 166804 (2009)
O. Copie *et al., PRL* **102**, 216804 (2009)
M. Sing *et al., PRL* **102**, 176805 (2009)
C. Bell *et al., APL* **94**, 222111 (2009)
C. Bell *et al., PRL* **103**, 226802 (2009)
C. Cen *et al., Science* **323**, 1026 (2009)
C.L. Jia *et al., PRB* **79**, 081405(R) (2009)
W. Son *et al.*, PRB **79**, 245411 (2009)
G. Singh-Bhalla *et al., Nature Physics* (2010)
A. D. Caviglia *et al. PRL* **105**, 236802 (2010)
M. Ben Shalom *et al.* PRL **105**, 206401 (2010)
A. D. Caviglia *et al.* PRL **104**, 126803 (2010)
A. Dubroka *et al.* PRL **104**, 156807 (2010)
M. Ben Shalom *et al.* PRL **104**, 126802 (2010)
M. Breitschaft *et al.*, PRB **81**, 153414 (2010)
M. R. Fitzsimmons *et al.* PRL **107**, 217201 (2011)
C. Cancellieri *et al.* PRL **107**, 056102 (2011)
R. Yamamoto *et al.* PRL **107**, 036104 (2011)
P. Delugas *et al.* PRL **106**, 166807 (2011)
S. A. Pauli *et al.* PRL **106**, 036101 (2011)
L. Li *et al.*, *Nature Physics* (2011)
J.A. Bert *et al.*, *Nature Physics* (2011)
D.A. Dikin *et al.*, *PRL* **107**, 56802 (2011)
L. Li *et al.* Science (2011)
Ariando *et al.* Nature Comm. (2011)
H. J Gardner *et al.* Nature Physics (2011)
M. Stengel PRL **106**, 136803 (2011)
H. W. Jang *et al.* Science (2011)
J. W. Park *et al.* Nature Comm (2011)

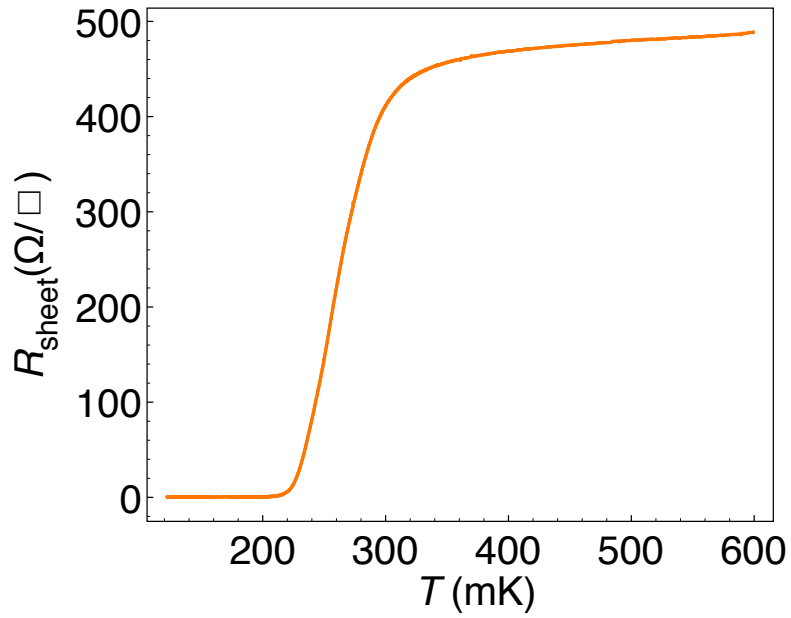
Superconductivity at Low T



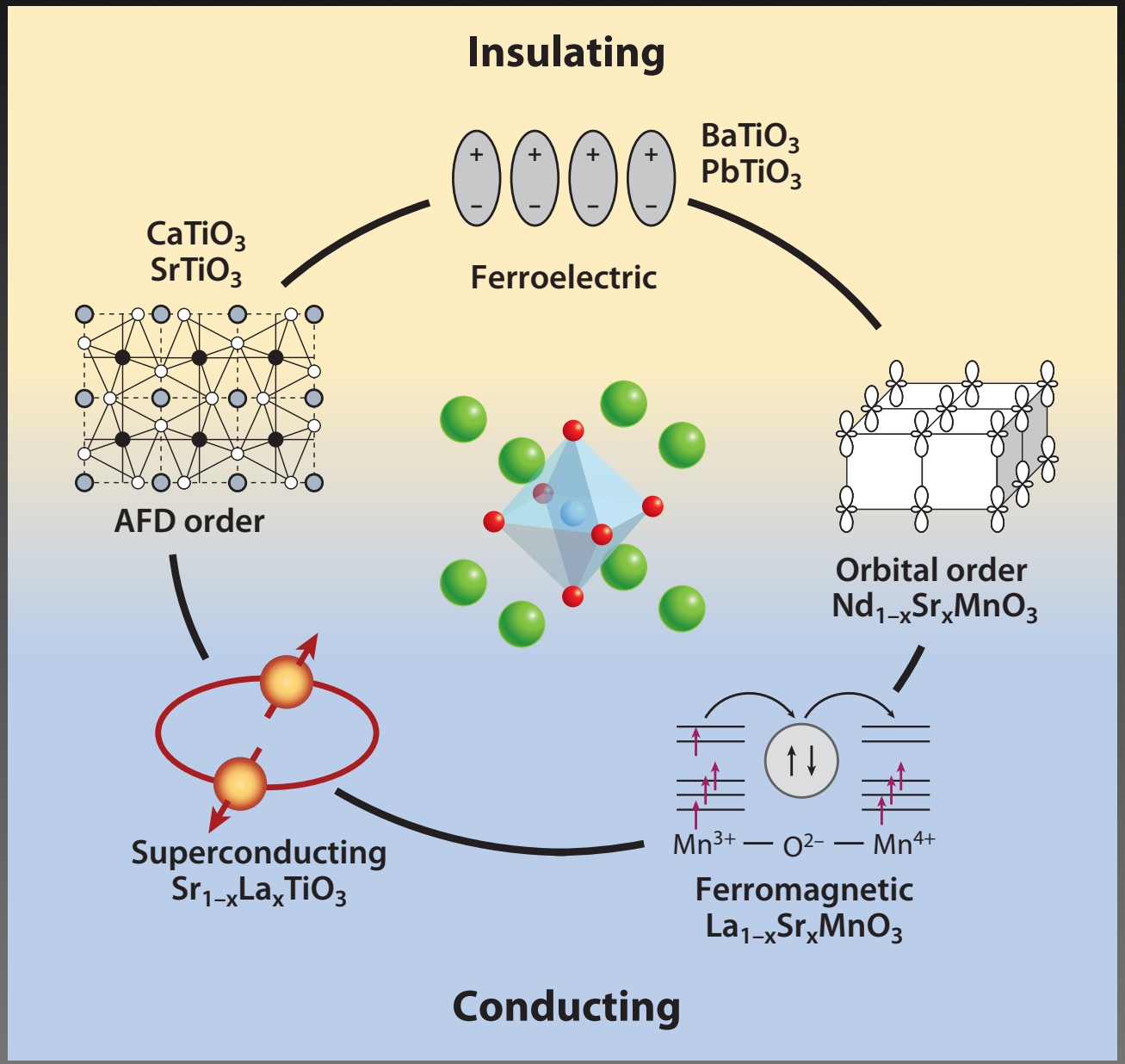
Superconducting Interfaces Between Insulating Oxides

N. Reyren,[1] S. Thiel,[2] A. D. Caviglia,[1] L. Fitting Kourkoutis,[3] G. Hammerl,[2] C. Richter,[2] C. W. Schneider,[2] T. Kopp,[2] A.-S. Rüetschi,[1] D. Jaccard,[1] M. Gabay,[4] D. A. Muller,[3] J.-M. Triscone,[1] J. Mannhart[2]*

Science **317**, 1196 (2007)



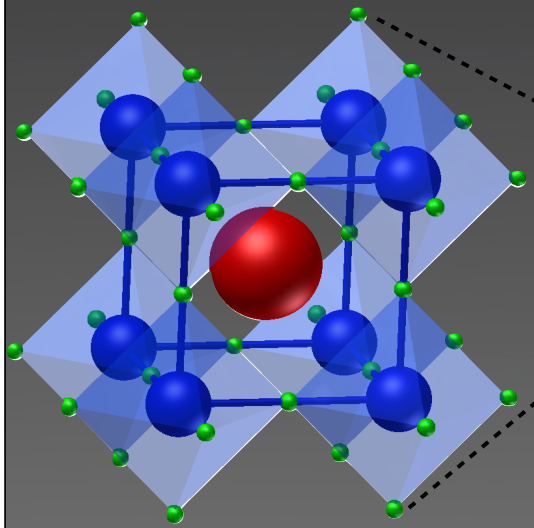
Oxides - Various Instabilities

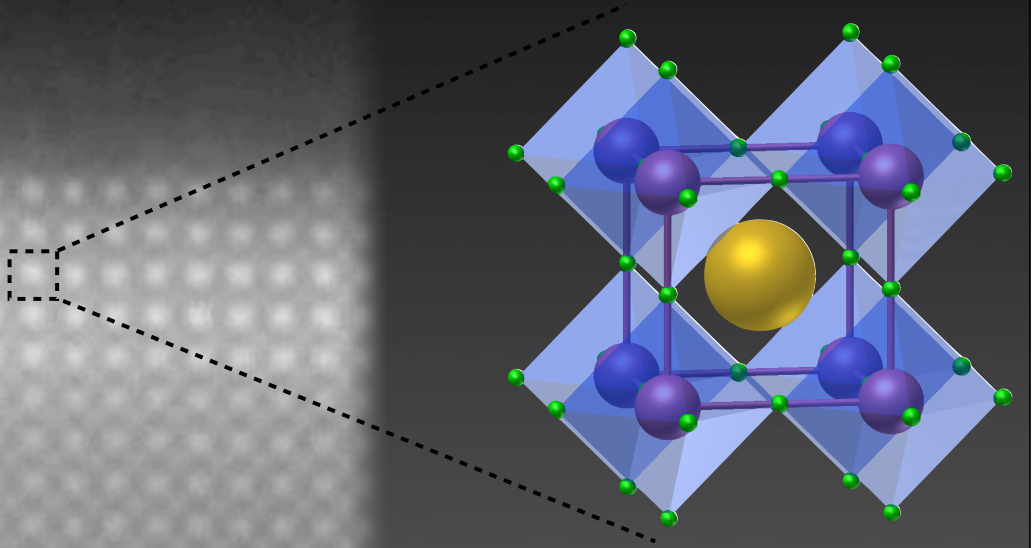


Combining Oxides

Charge and
orbital order

Polar and
AFD instabilities





20 Å

Superconductivity
Ferromagnetism
Ferroelectricity

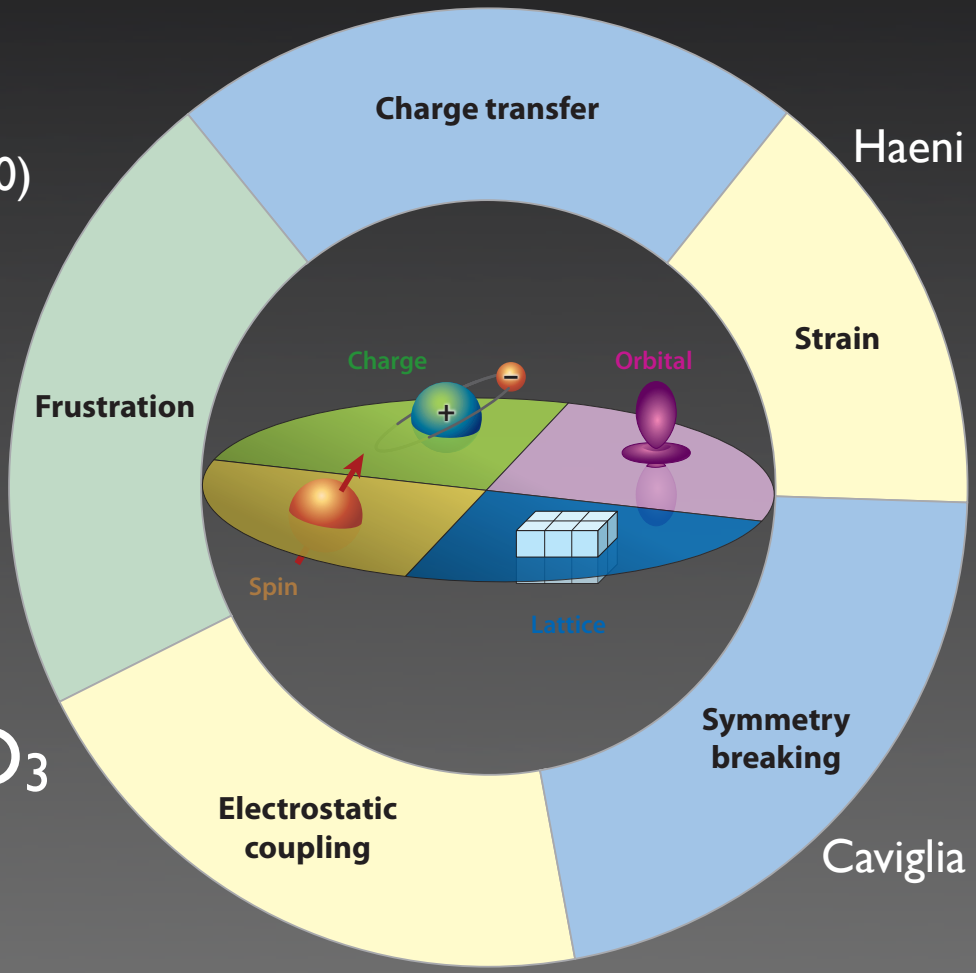
**Oxides with very diverse properties
can be combined**

Oxide Interfaces

$ZnO/(Mg,Zn)O$ Tsukazaki et al. Science **315**, 1388 (2007)
Ohtomo and Hwang Nature **427**, 423 (2004) $LaAlO_3/SrTiO_3$

Tokura and Nagaosa
Science **288**, 462 (2000)

$DyScO_3/SrTiO_3$
Haeni et al. Nature **430**, 758 (2004)



$PbTiO_3/SrTiO_3$
Bousquet et al. Nature
452, 732 (2008)

$LaAlO_3/SrTiO_3$
Caviglia et al. PRL **104**, 126803 (2010)

Interface physics in complex oxide heterostructures
P. Zubko et al., Annual Review of Condensed Matter Physics **2**, 141 (2011)

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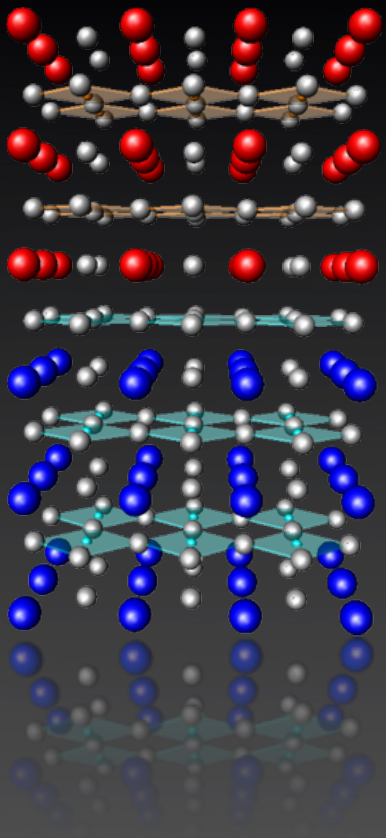
Outline



The $LaAlO_3/SrTiO_3$ system

-Origin

-Confinement of the gas

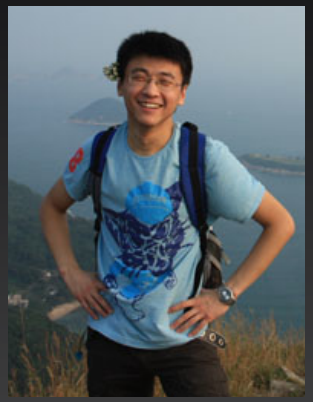
-Superconductivity - interface and bulk SC

-Recent developments

The «Geneva» $LaAlO_3/SrTiO_3$ Team

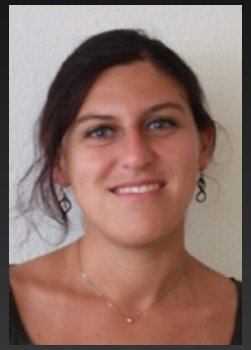
Stefano Gariglio

Daniela Stornaiuolo



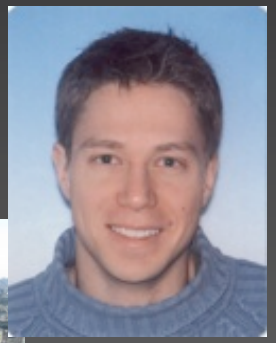
Denver Li

Andrea Caviglia
(now in Delft)

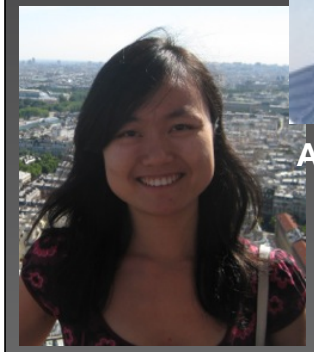


Claudia Cancellieri
(now at PSI)

Nicolas Reyren
(CNRS Paris)



Alexandre Fête



Wei Liu

Marc Gabay
(University of Paris-Sud)

in collaboration with

University of Geneva

- Alberto Morpurgo
  Benjamin Sacépé
- Didier Jaccard
  Gabriel Seyfarth
- Christophe Berthod

and:

- Philippe Ghosez (Liège)
- Phil Willmott (PSI)
  Mathilde Reinle-Schmitt
- Jochen Mannhart (Stuttgart)

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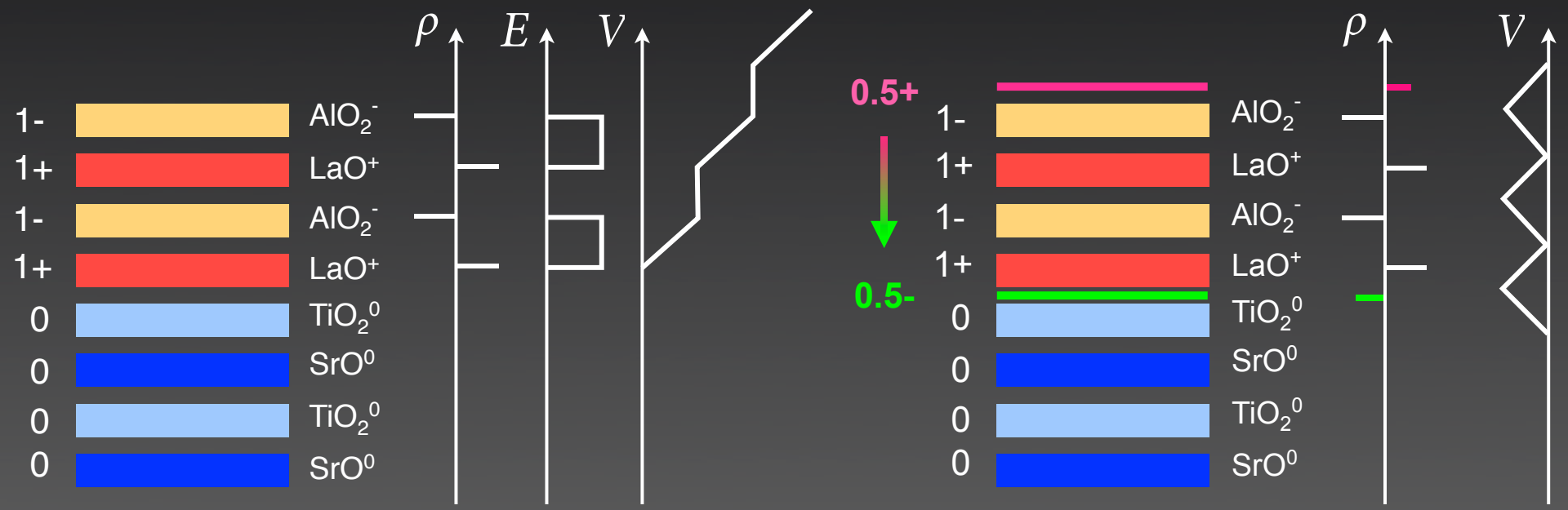
The Polar Catastrophe Scenario

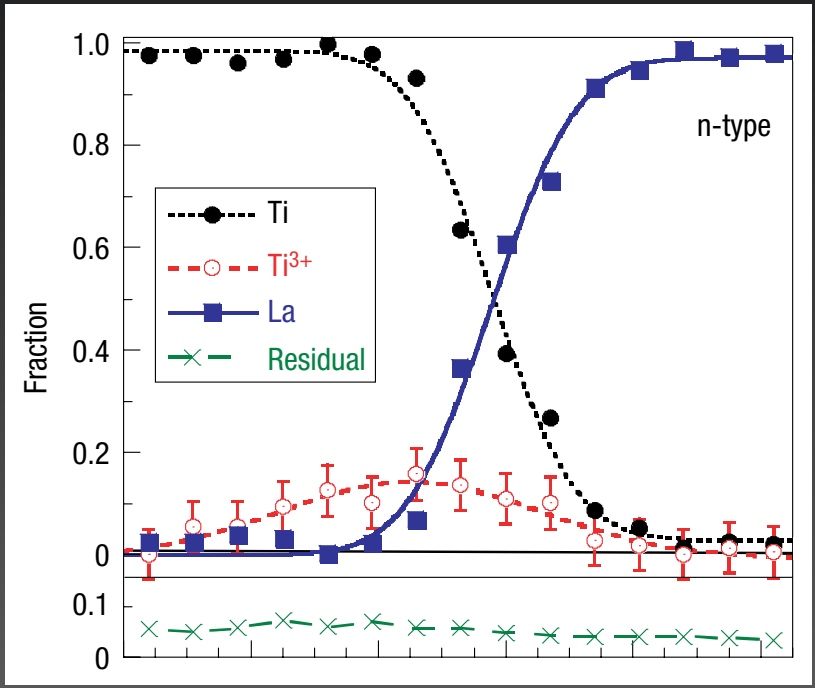


$3\ 10^{14}$ e/cm^2

N. Nakagawa *et al.*, Nature Materials (2006).

GaAs/Ge W.A. Harisson et al. PRB **18**, 4402 (1978).

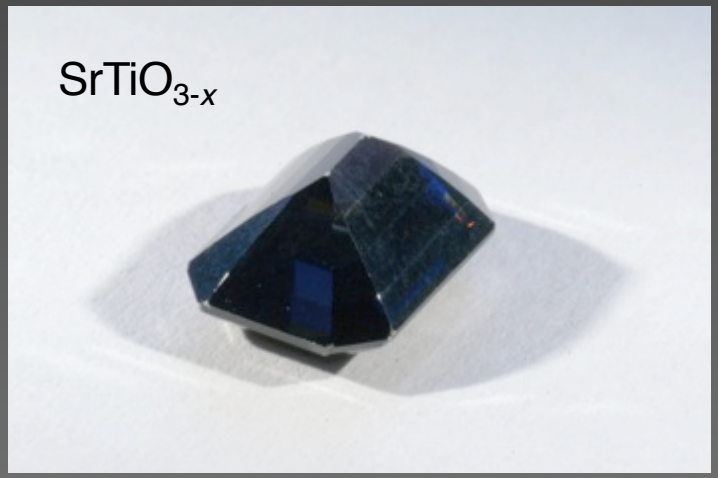
Chemical Doping



N. Nakagawa, H. Y. Hwang, and D. A. Muller, *Nat. mater.* **5**, 204 (2006)

La/Sr intermixing

P.R. Willmott et al. PRL **99**, 155502 (2007)
A.S. Kalabukhov et al. PRL **103**, 146101 (2009)

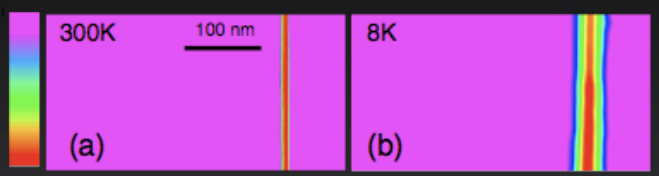


J. Mannhart, D.G. Schlom, Nature N&V **430**, 620 (2004)

Gas Thickness

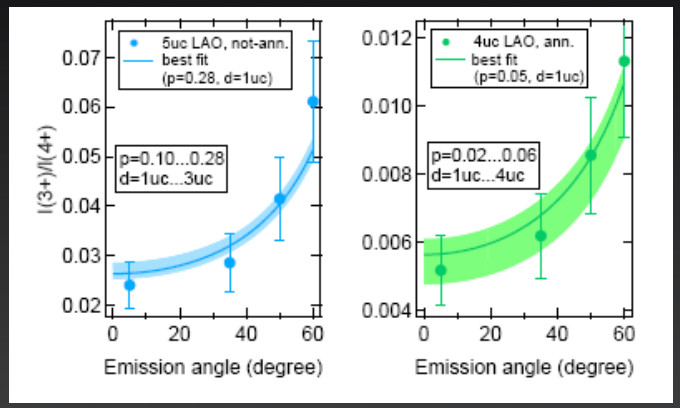
RT d<7nm

12 nm at low T



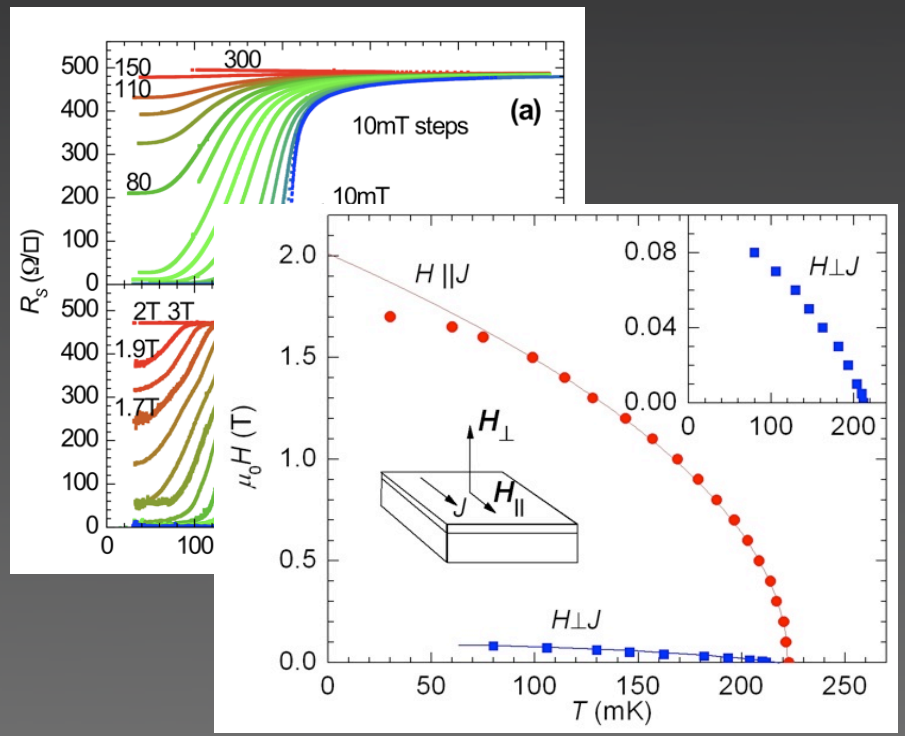
M. Basletic *et al*, Nat. Mater. 7, 621 (2008)

O. Copie *et al*, *Physical Review Letters*. **102**, 216804 (2009)



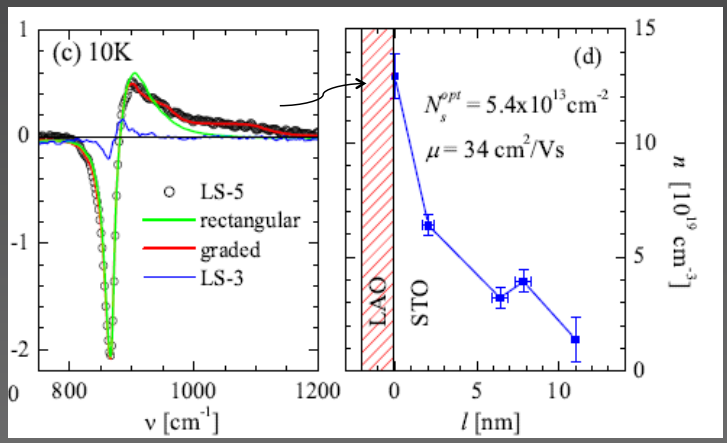
M. Sing *et al*, PRL **102**, 176805 (2009)

RT d = 1-3 uc



10 nm at low T

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



11 nm at 10K

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

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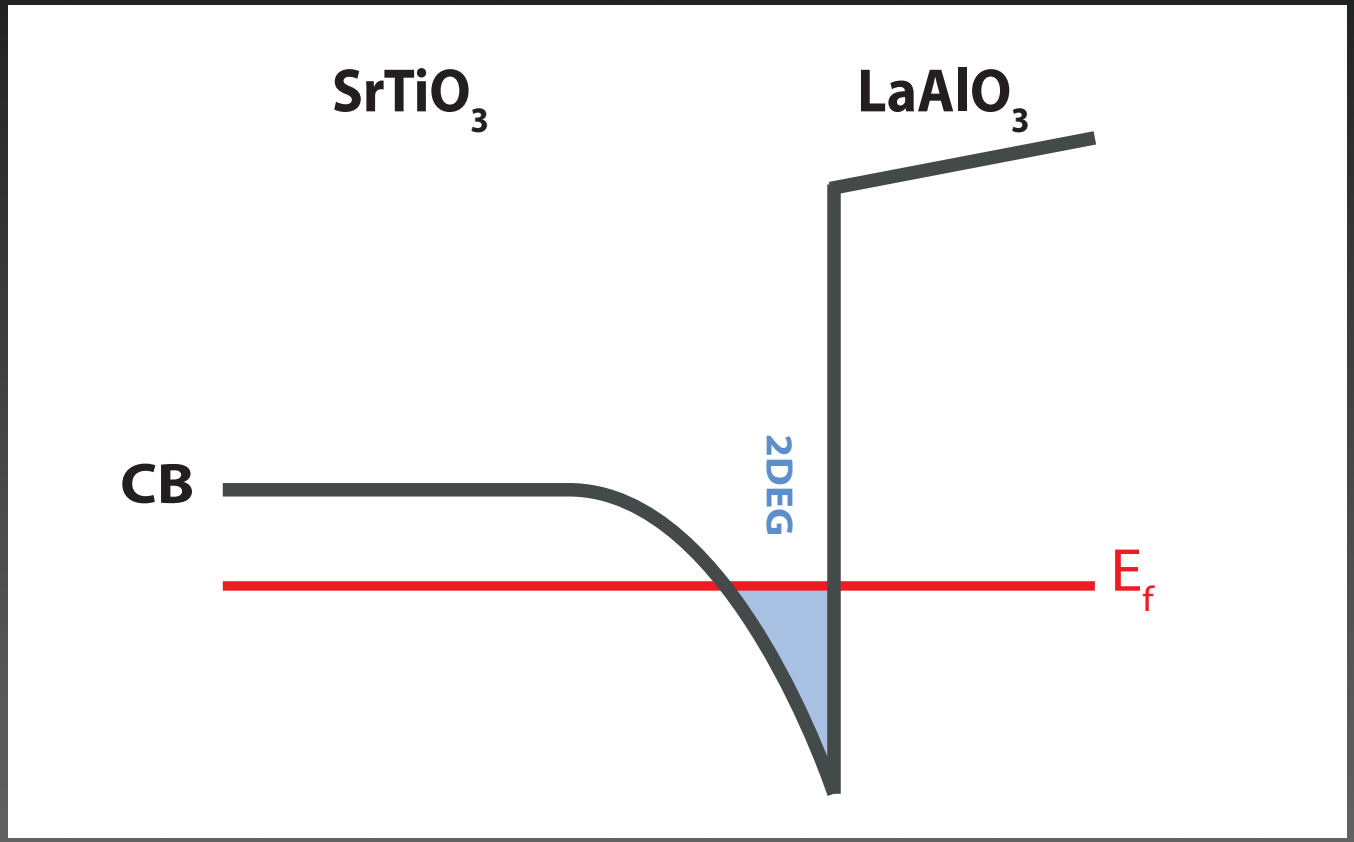
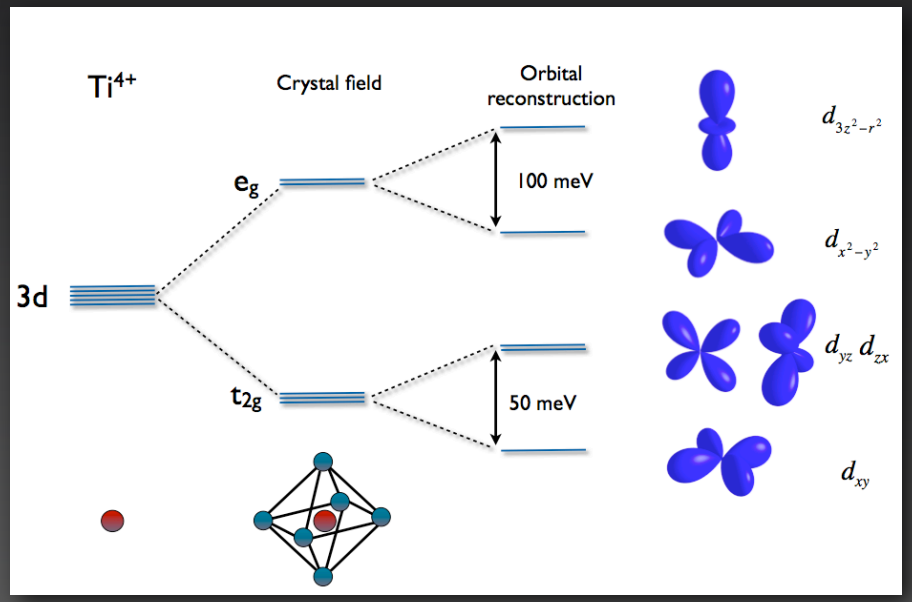
Confinement of the electron gas

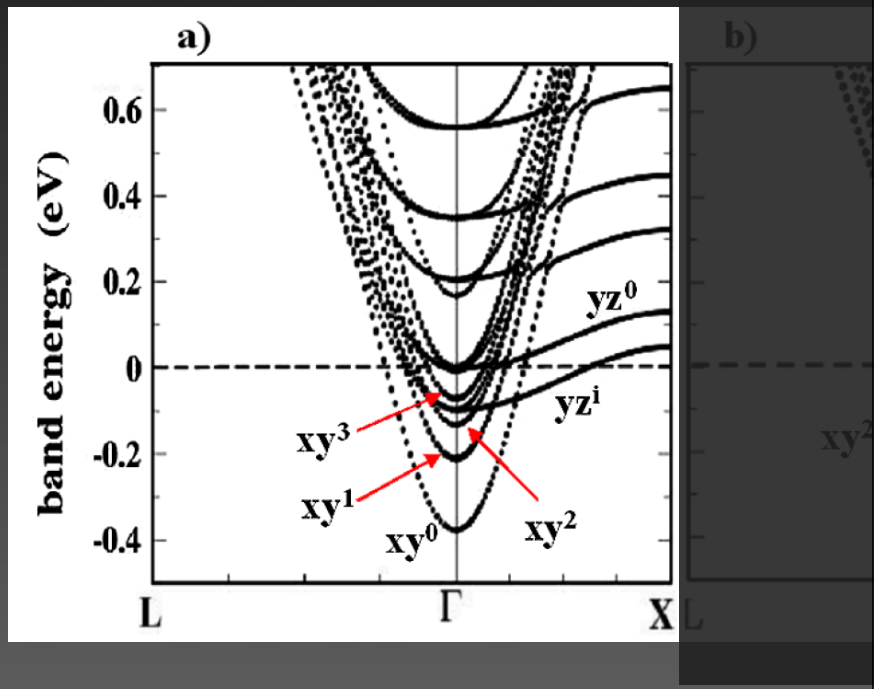


The electrons are in the Ti 3d band - in t_{2g} «orbitals»

Electronic Structure



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

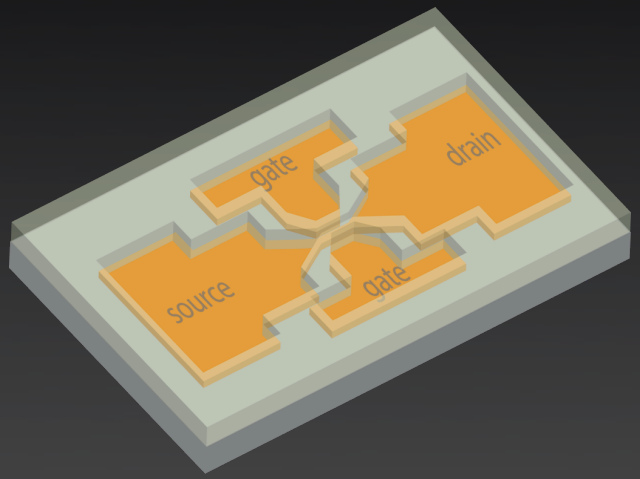


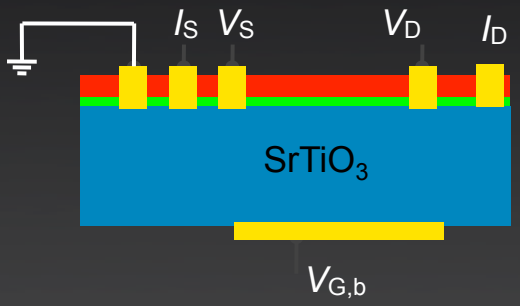
n_s=3.3 10 ^{14} cm^{-2}

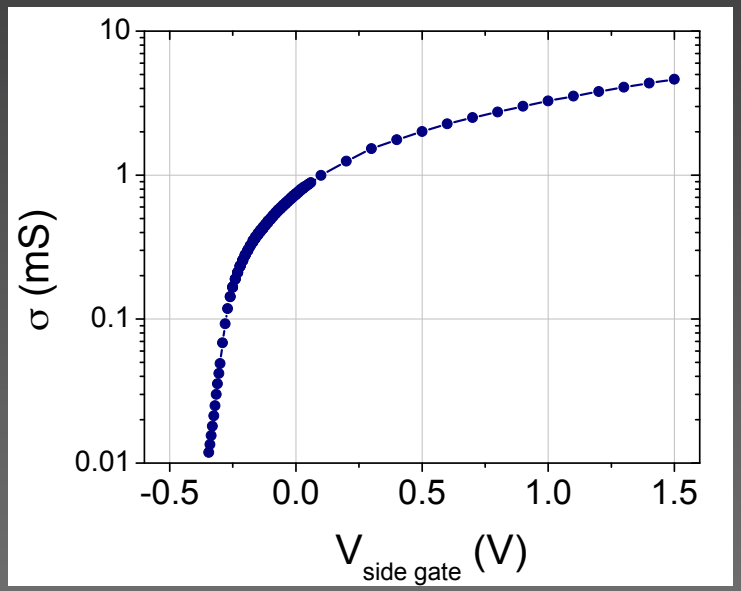
Delugas *et al.*, PRL **106**, 166807 (2011)

Field Effect Control of the Carrier Density and Tuning of SC

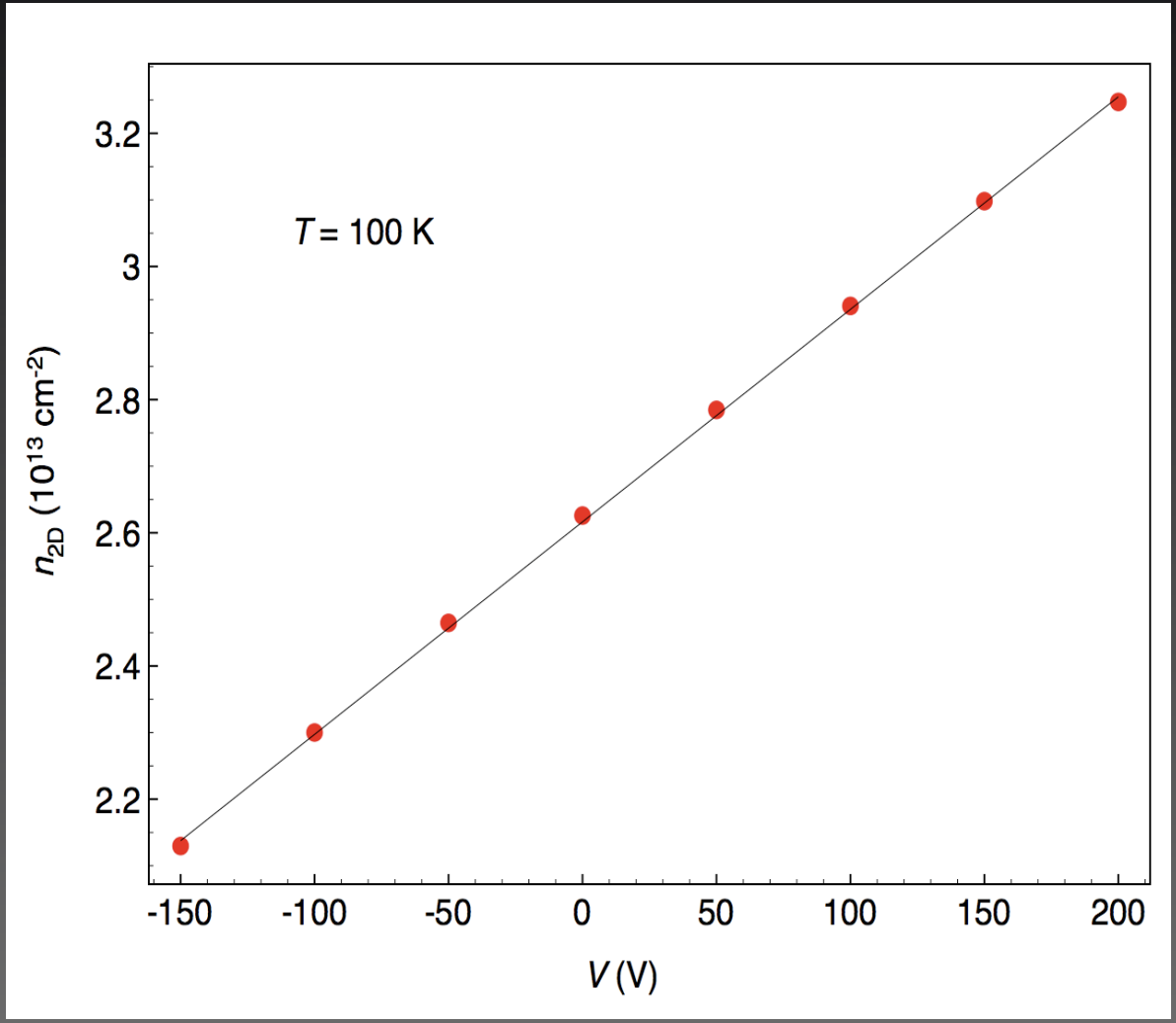
Top, side, back gating

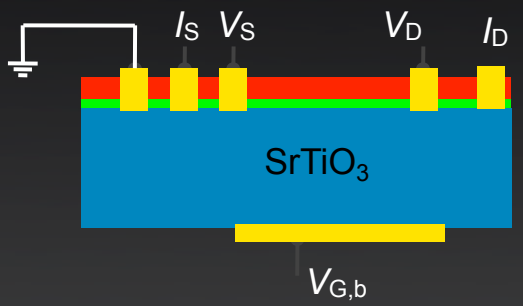




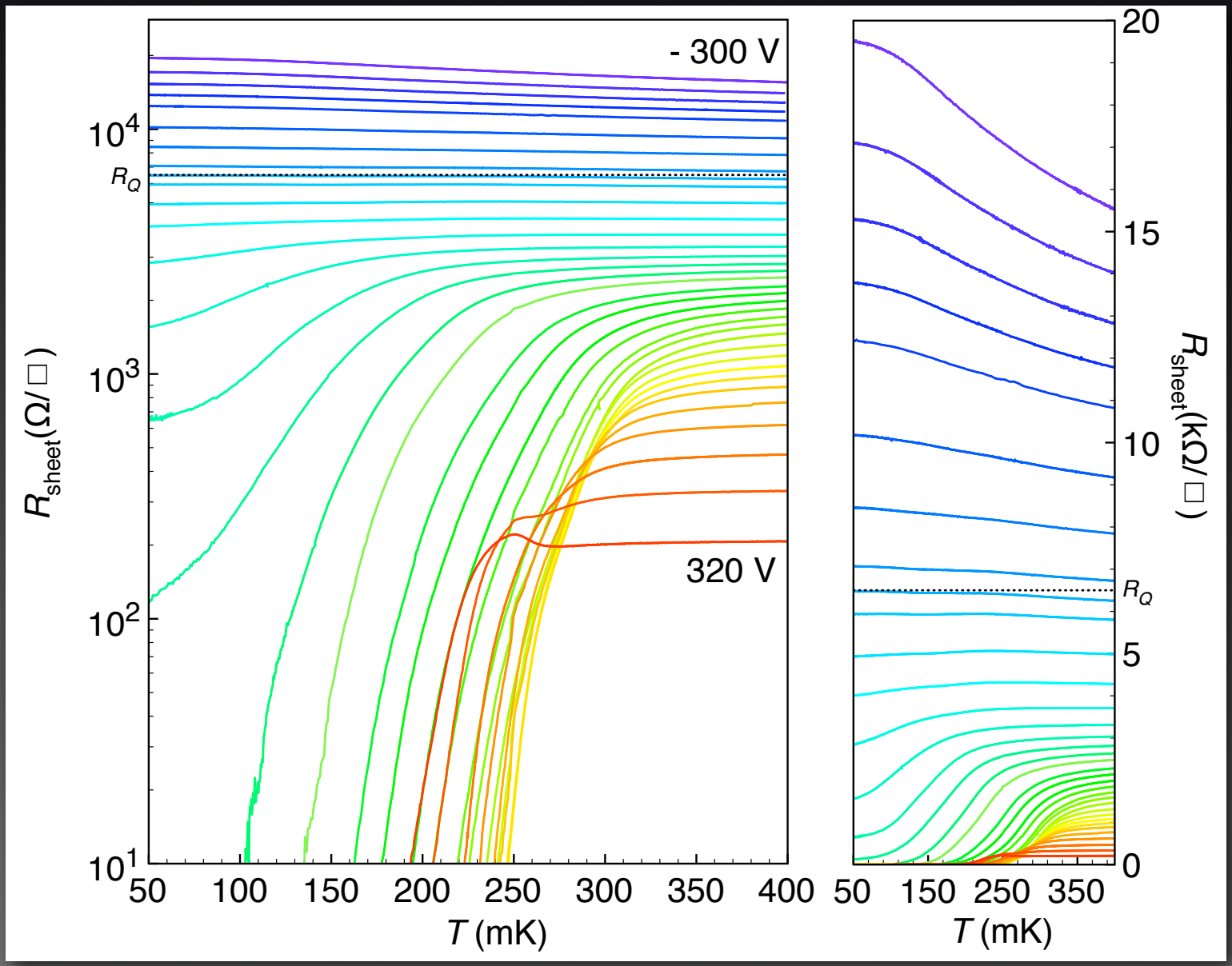


Field Effect Experiments





Modulation of SC



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

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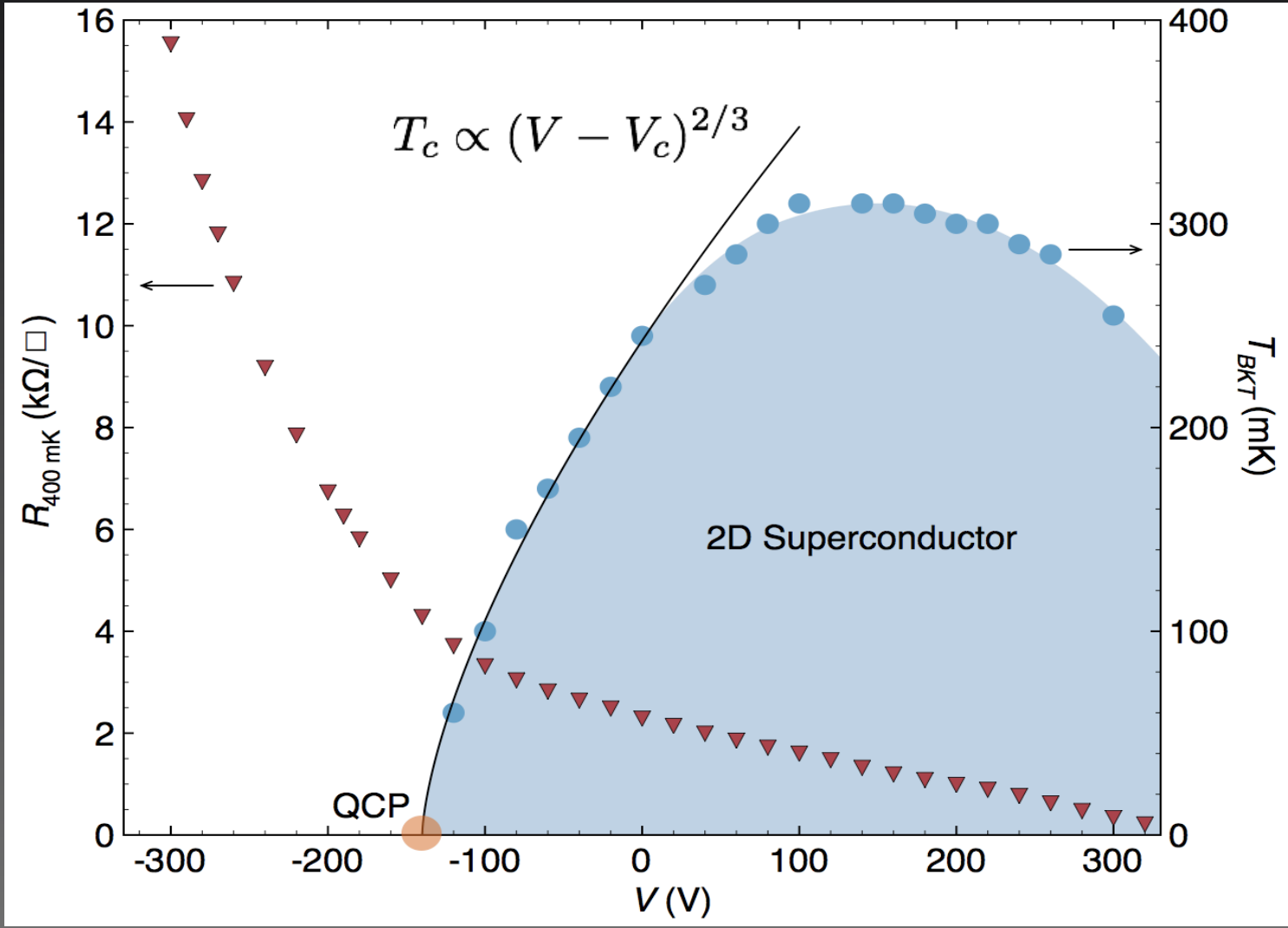
System Phase Diagram

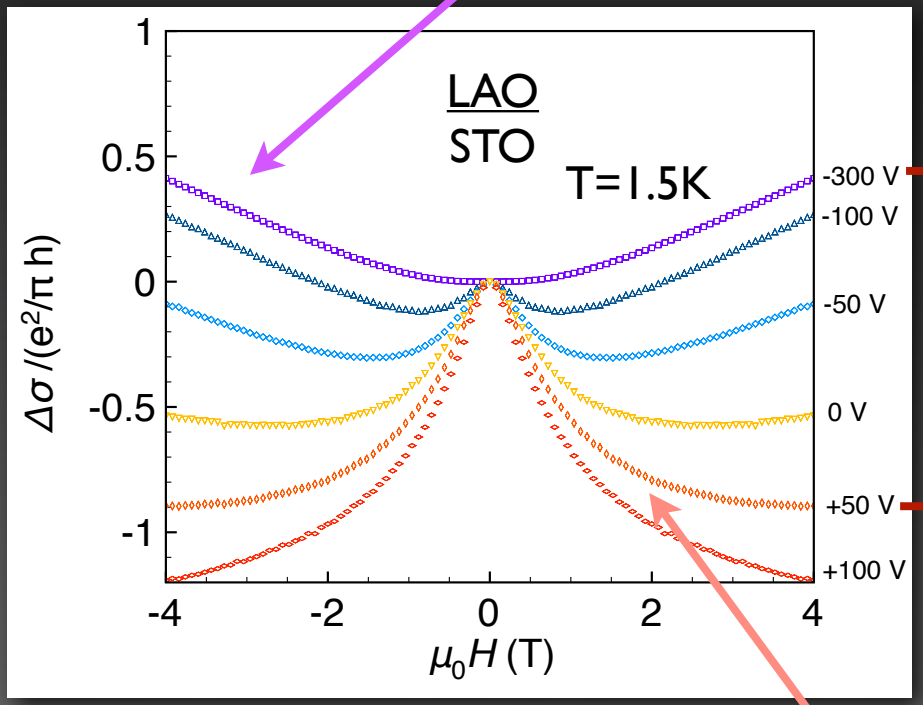


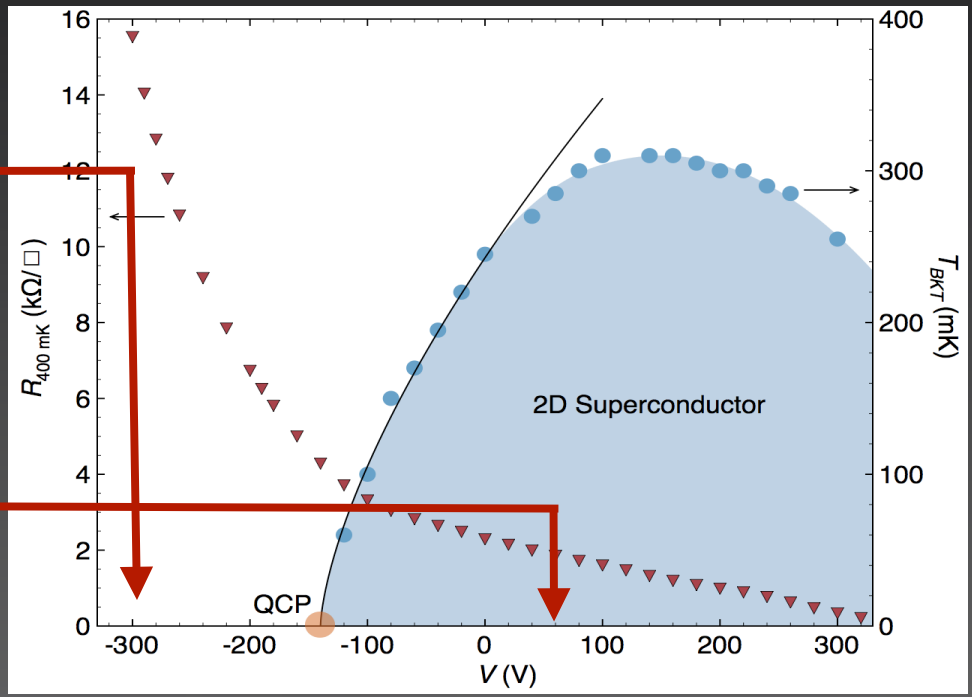
See also C. Bell et al. PRL **103**, 226802 (2009).

Spin-orbit Coupling

Weak Localization to Weak Antilocalization

Weak localization



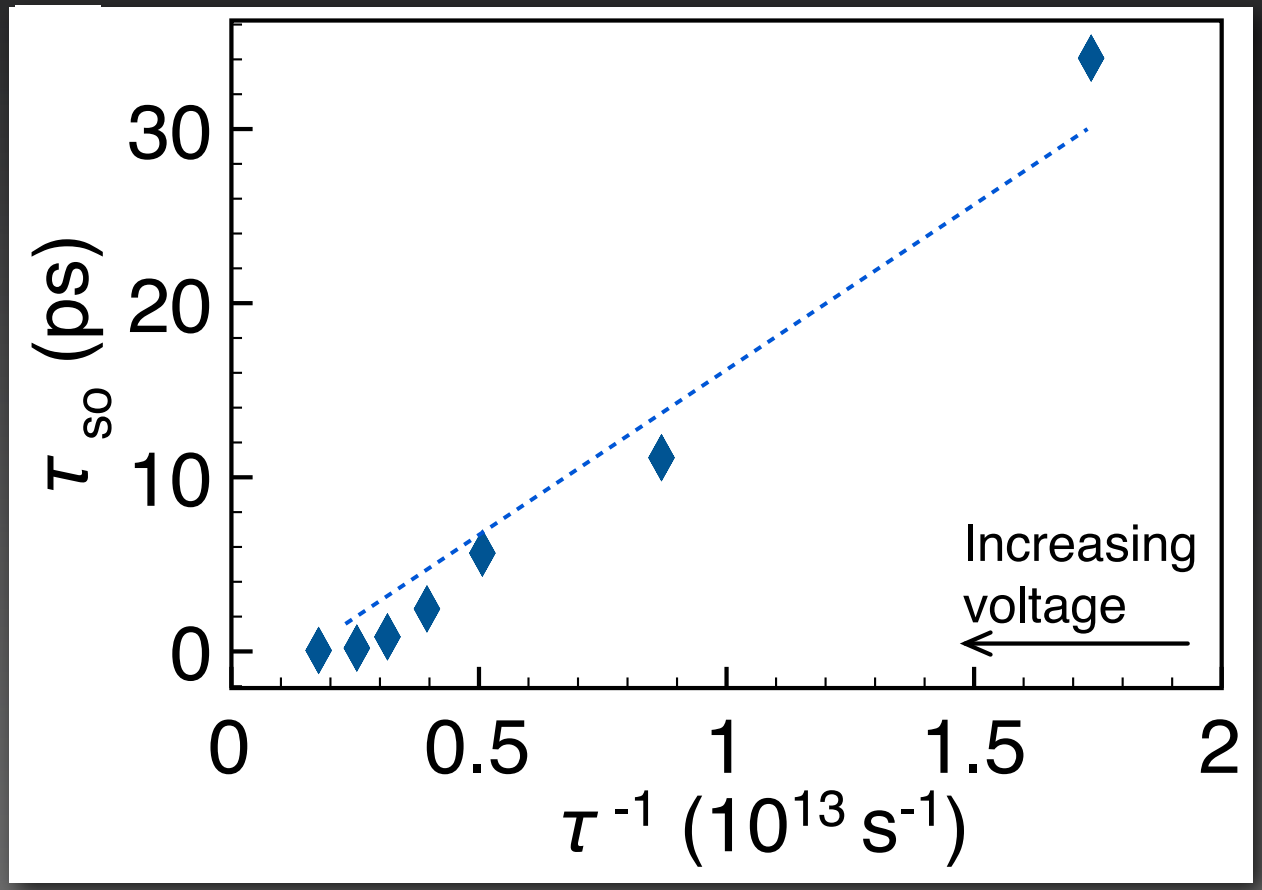


A.D. Caviglia et al., Phys. Rev. Lett. **104**, 126803 (2010)

Weak anti-localization

Strong spin-orbit interaction

Rashba Spin-Orbit Coupling

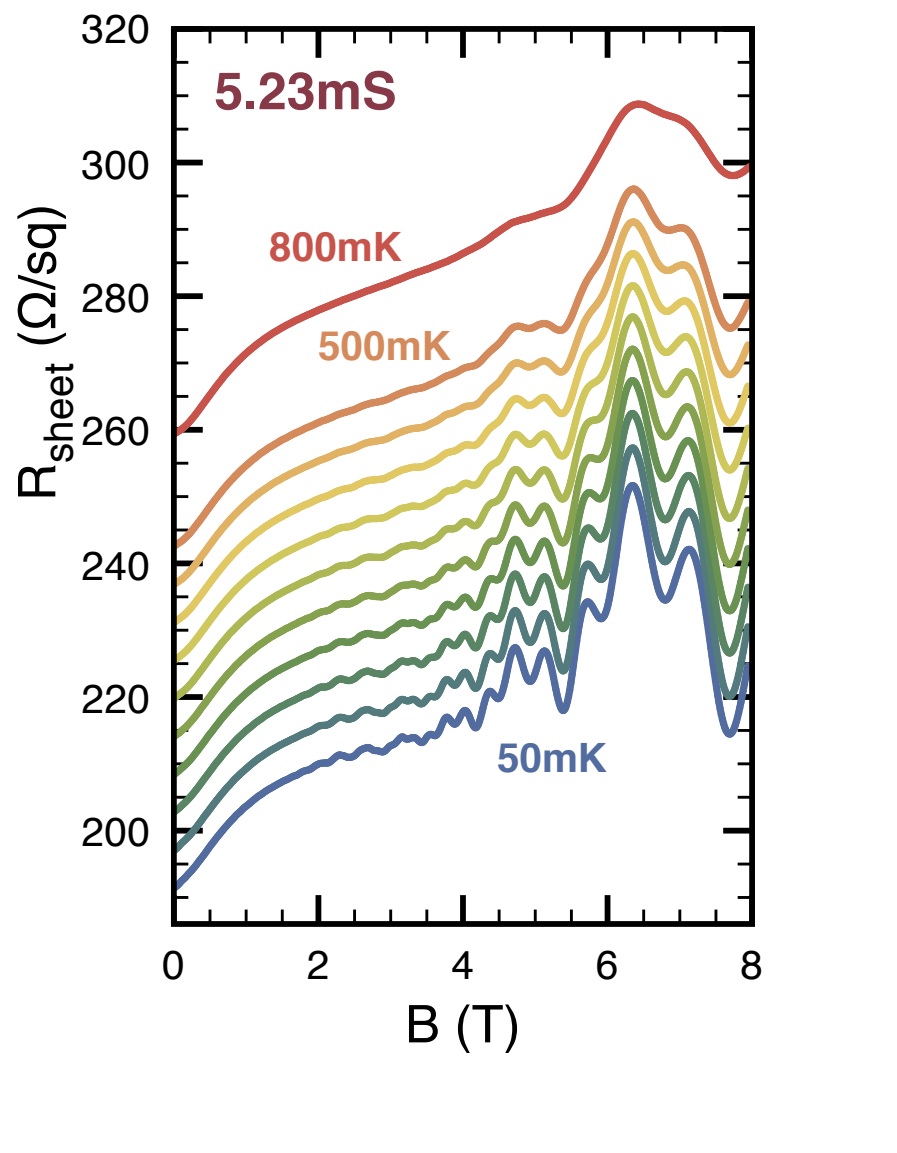


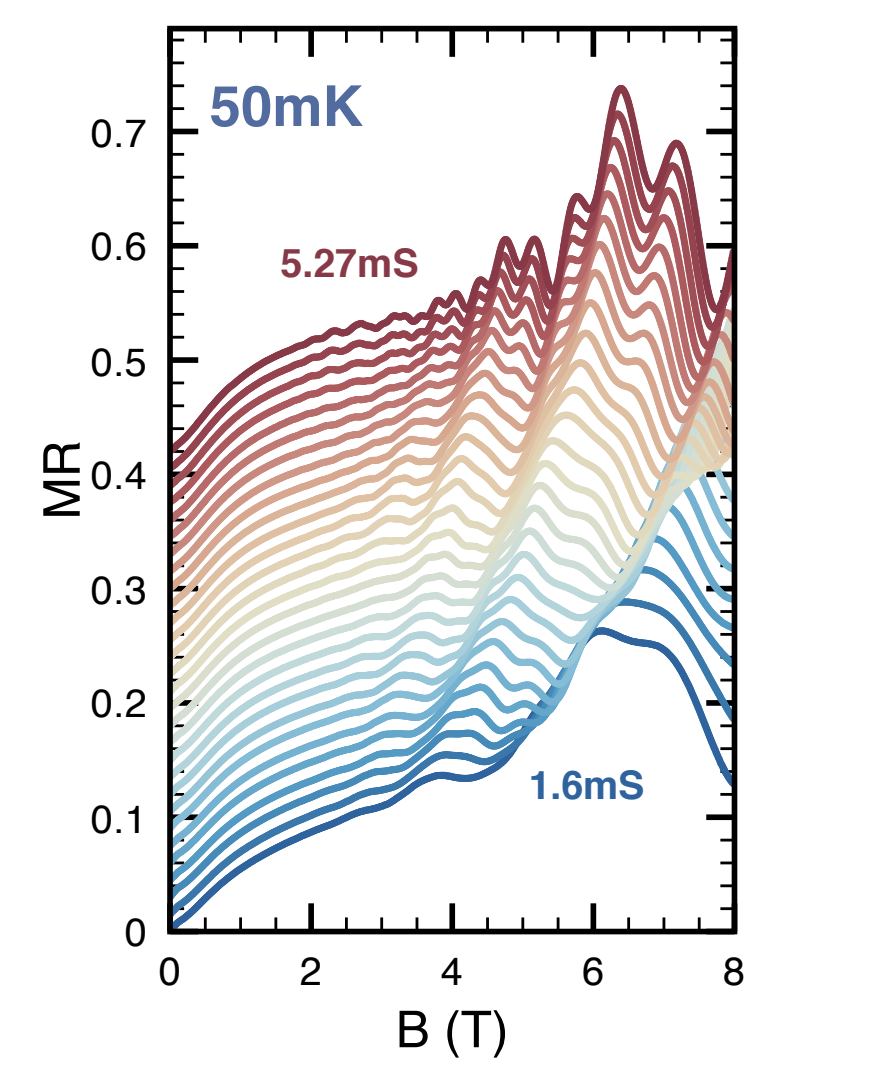
D'yakonov - Perel'

$$\tau_{\mathrm{so}} \propto \tau^{-1}$$

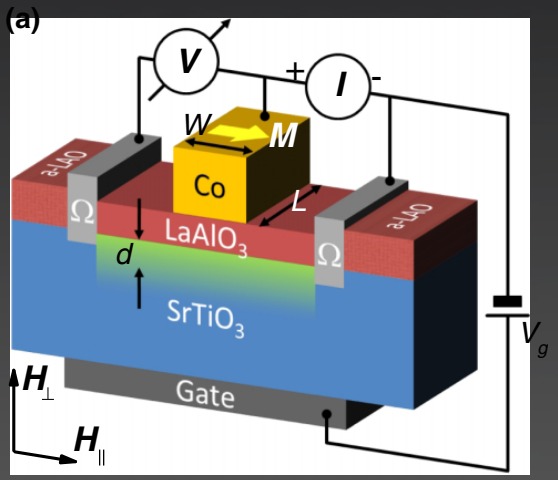
Exciting developments

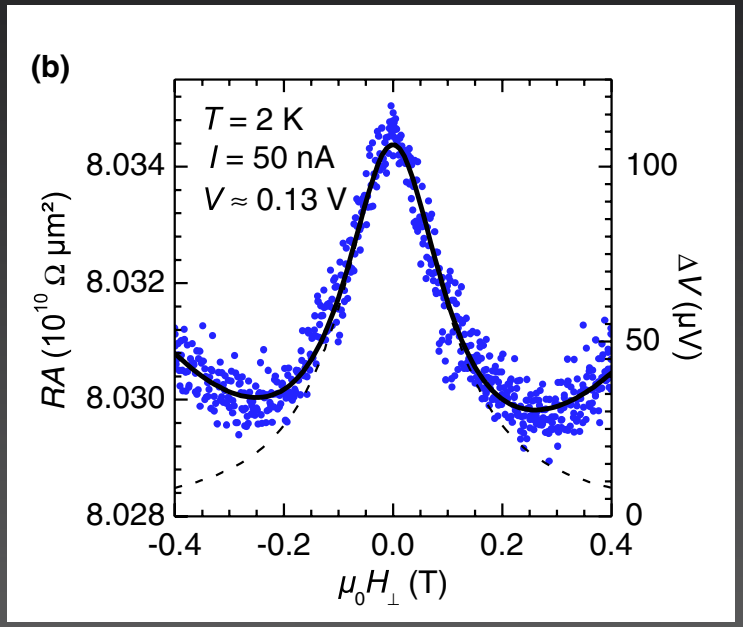
High mobility samples





Injection of spin polarized electrons

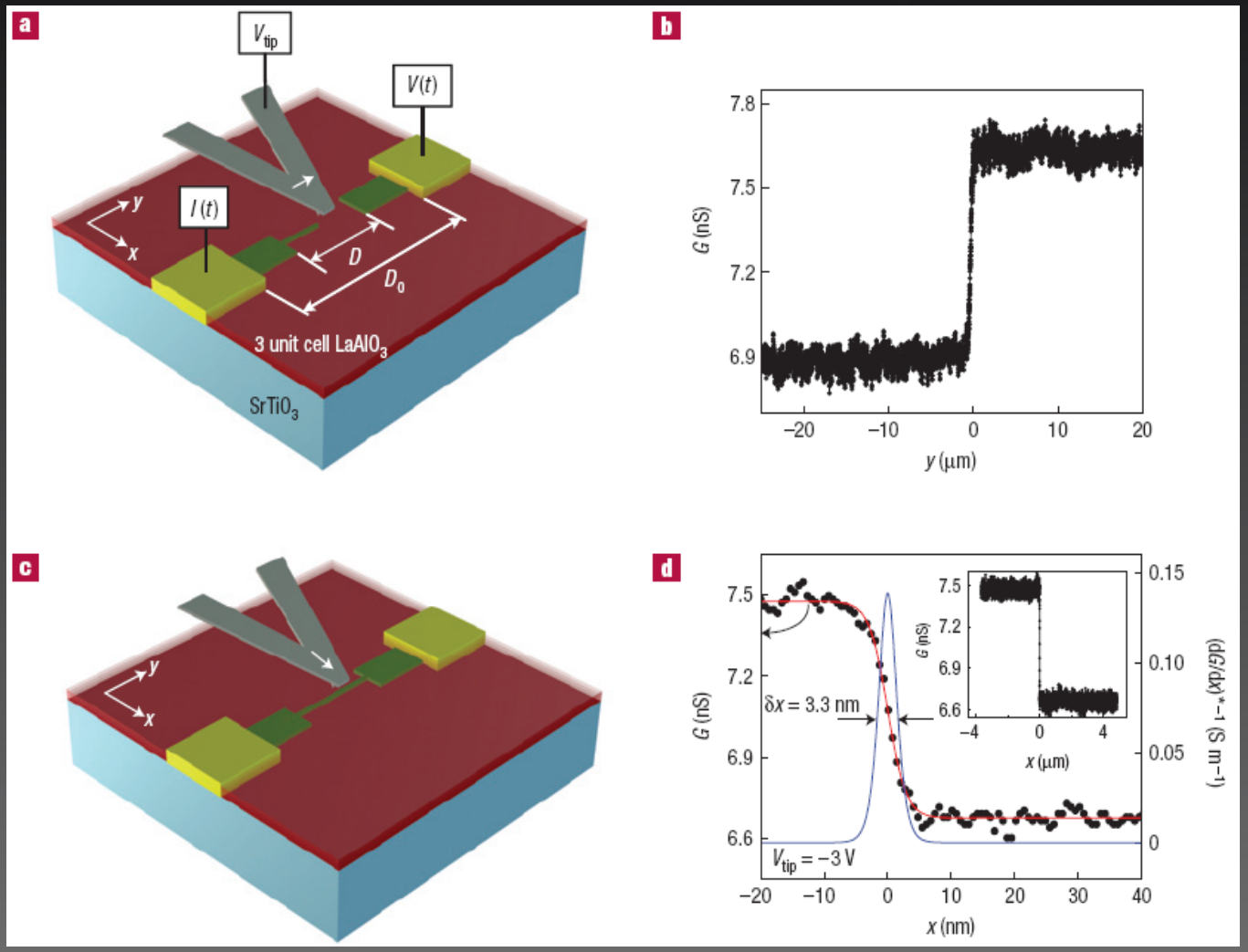


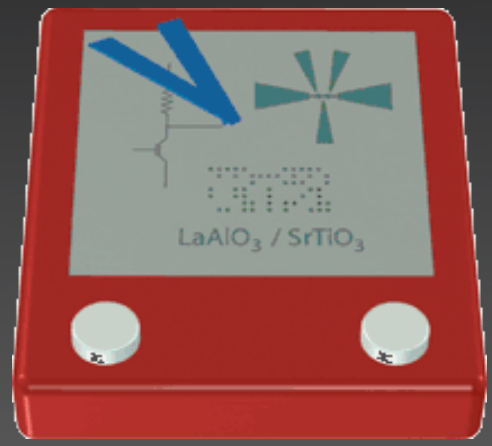


Hanle measurements

N. Reyren et al. Phys. Rev. Lett. **108**, 186802 (2012)

AFM Writing of Electronic Nanofeatures





J. Levy
Pittsburgh

C. Cen *et al*, Nat. Mater. **7**, 298 (2008)
C. Cen et al. Science **323**, 1026 (2009)

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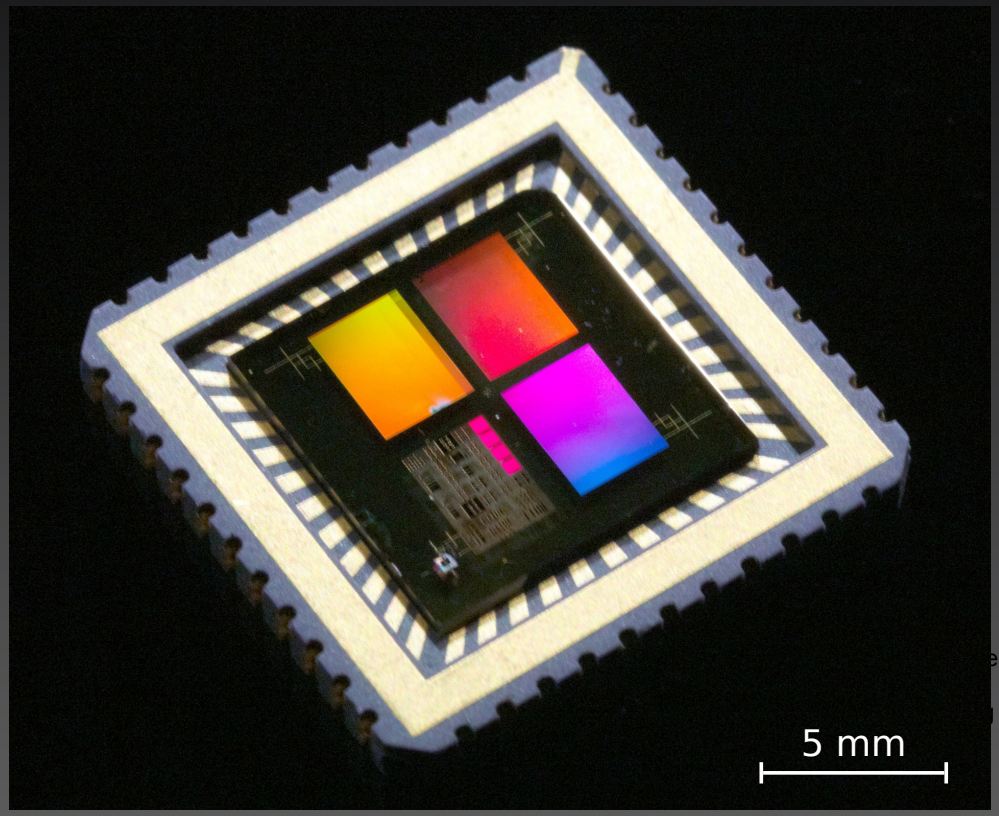
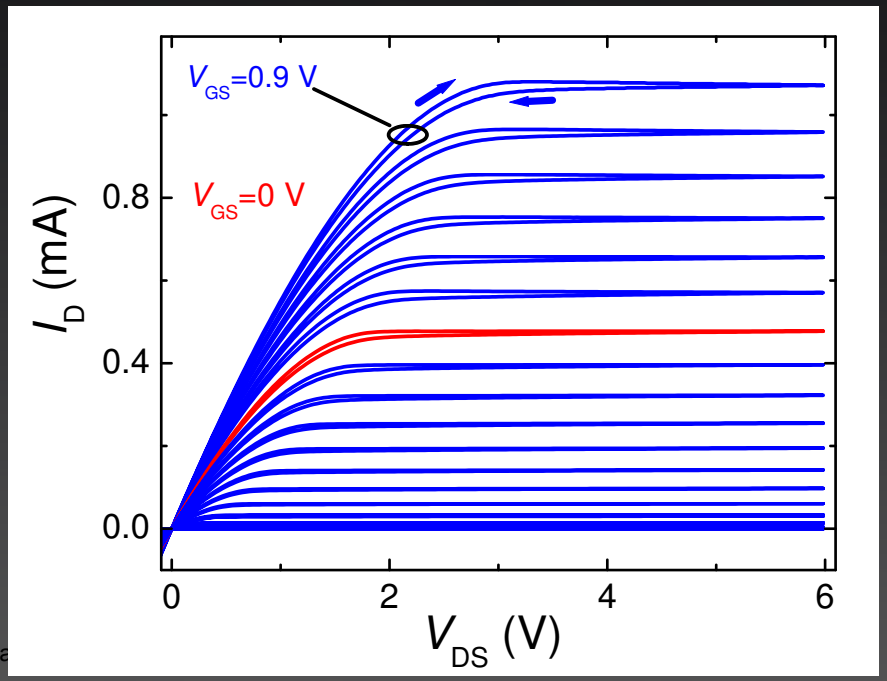
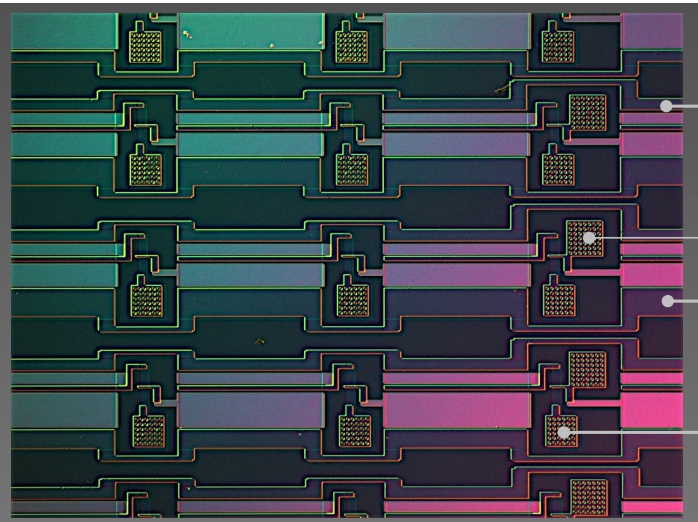
700’000 FET’s - Channel Length 350nm







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Conclusions

The $LaAlO_3/SrTiO_3$ is an amazing platform displaying tunable properties

Magneto-transport and superconductivity reveal the importance of the sub-band structure

Bulk and interface superconductivity seem different although T_{cmax} is the same

Recent developments are promising for the realization of nanostructures and possibly devices