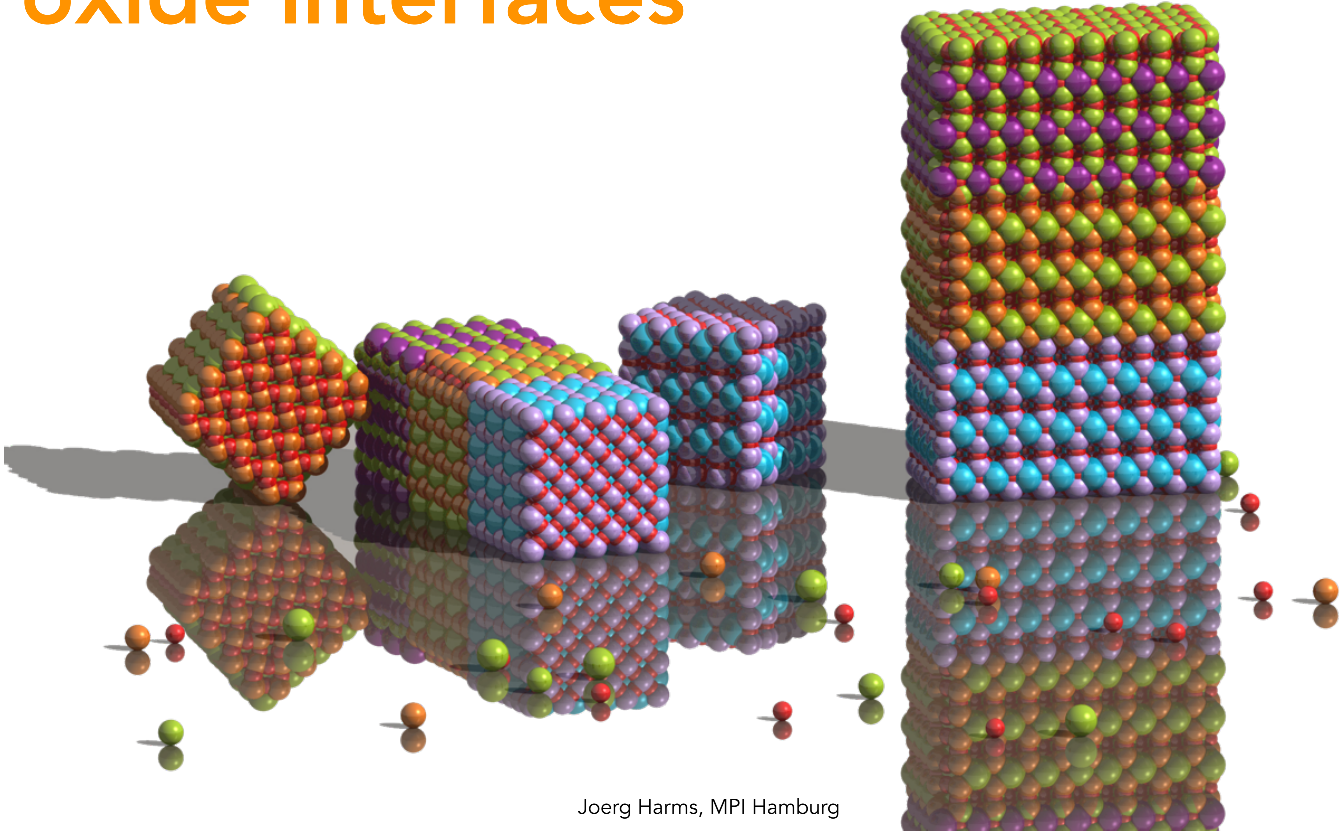
2D systems at oxide interfaces

Jean-Marc Triscone
University of Geneva



Joerg Harms, MPI Hamburg

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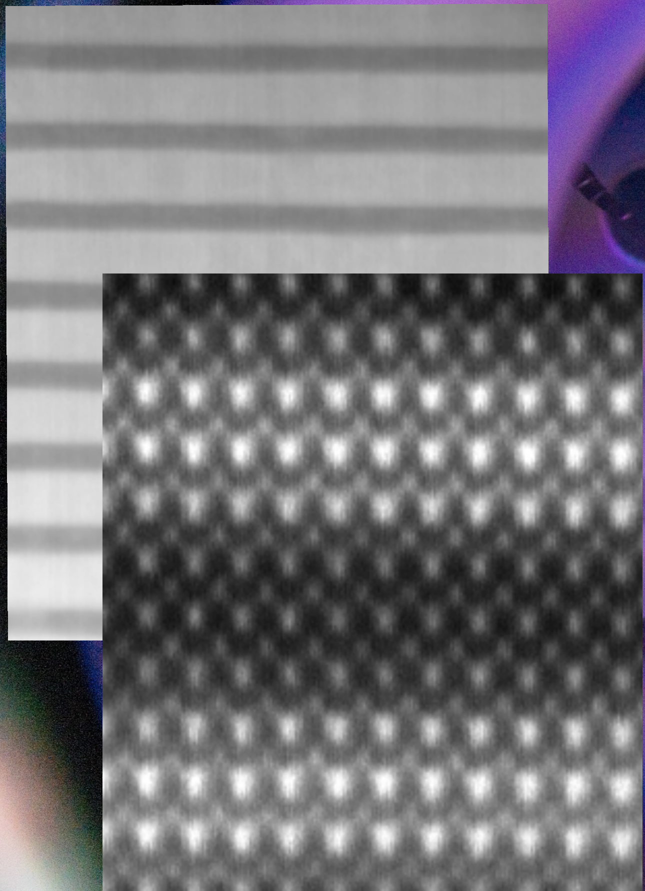
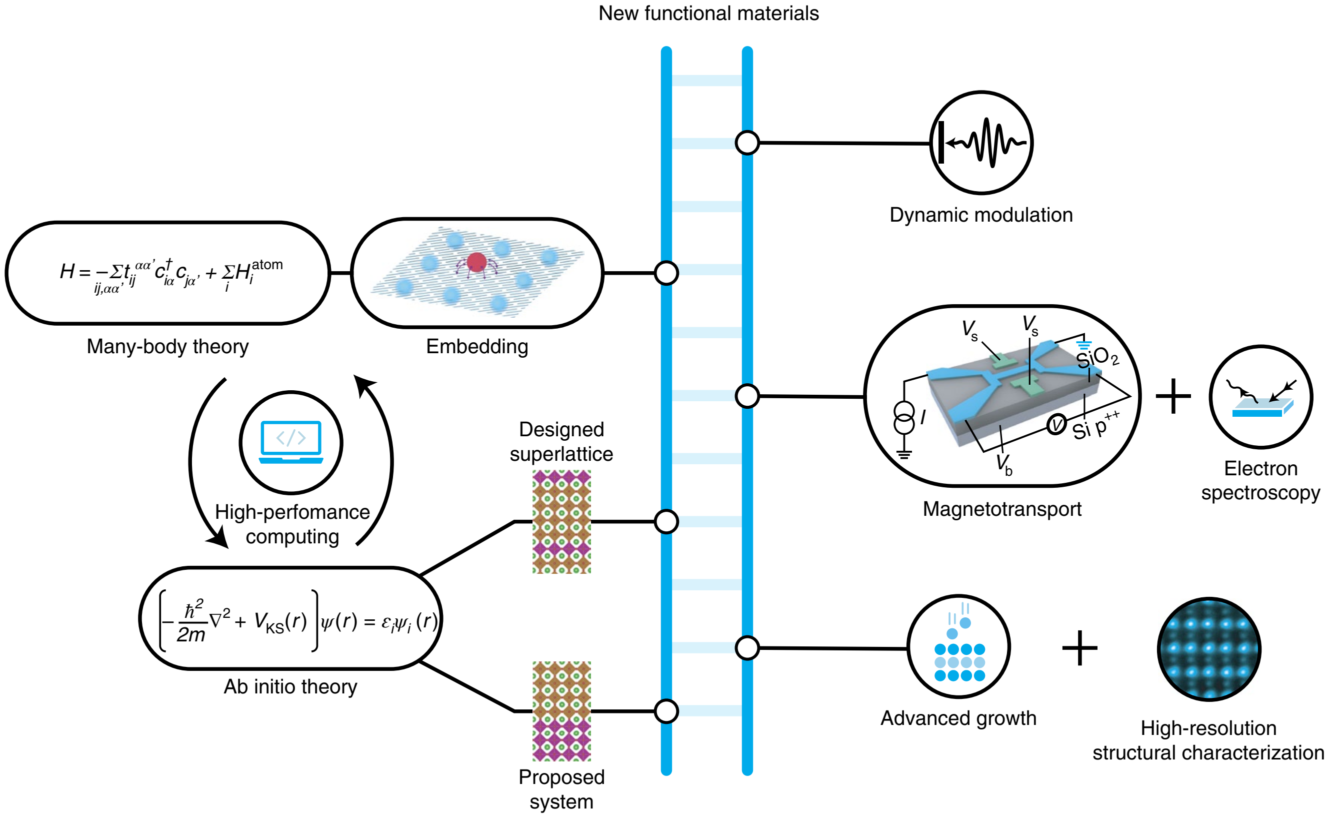
What are we doing?



A. Torres, O. Stephan, Orsay

Assemble artificial / synthetic materials
Search for novel properties and/or functionalities

Not an easy task



Amazing progress in
- advanced growth techniques
- advanced characterisation
- sophisticated calculations

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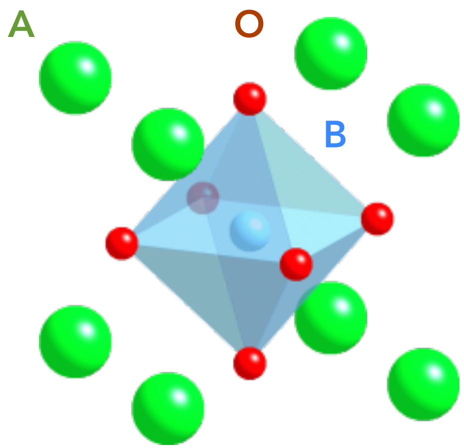
Designing and controlling the properties of transition metal oxide quantum materials
C.H. Ahn, A. Cavalleri, A. Georges, S. Ismail-Beigi, A. Millis, J.-M. Triscone
Nature Materials **20**, 1462 (2021)

Using transition metal perovskites as building blocks



ABO_3

Perovskite - $CaTiO_3$

Perovskite structure - a very common structure on Earth

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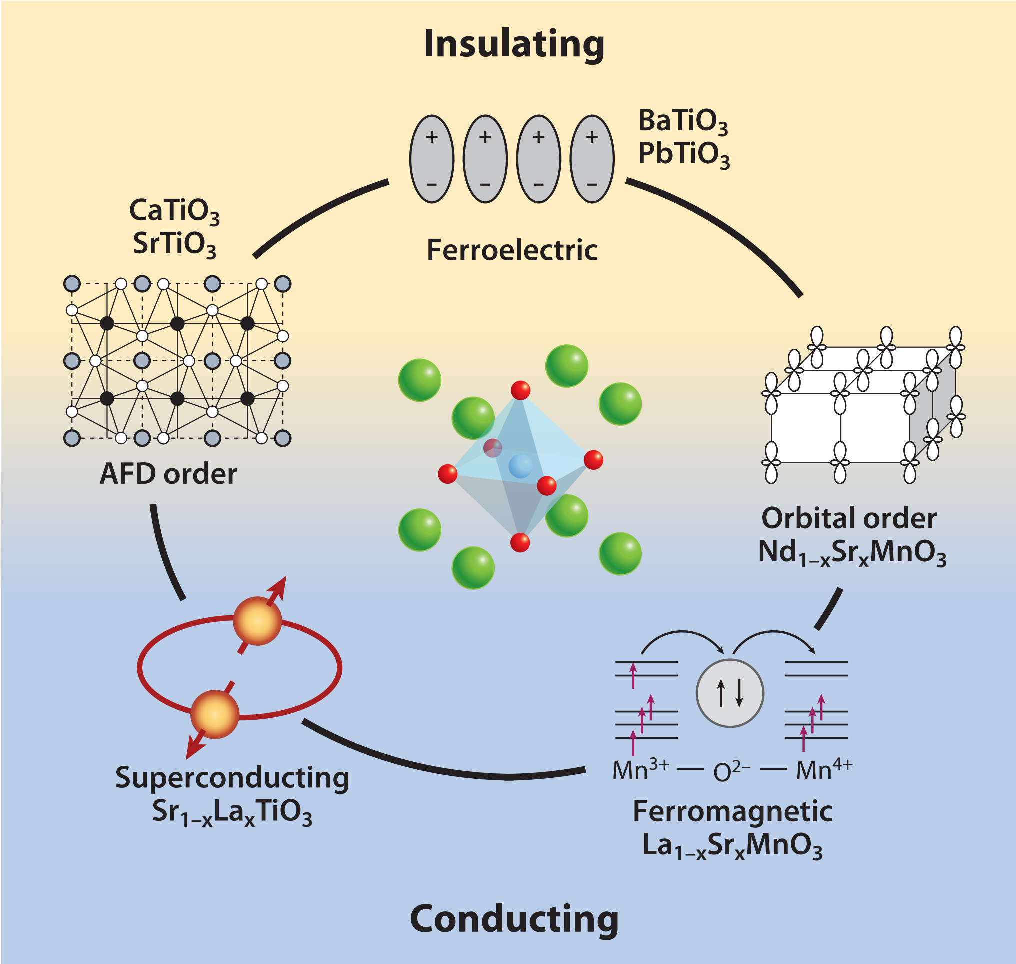
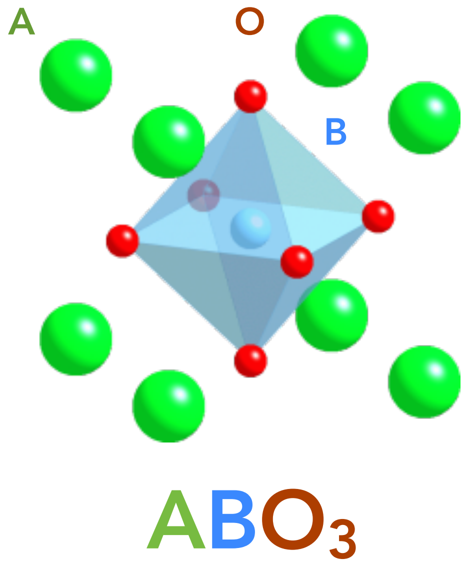
TMO perovskites display a variety of properties





P. Zubko et al., *Ann. Rev. Cond. Matter Phys.* **2**, 141 (2011)

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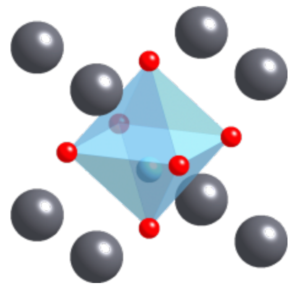
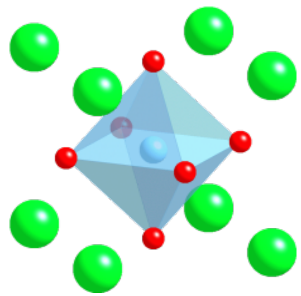
TM-oxides - Lego bricks



$PbTiO_3$ ferroelectric $T<T_C$
Tetragonal and ferroelectric
(a=b=**3.904Å**, c=4.152Å)



$SrTiO_3$ paraelectric at all temperatures
(a=b=c=**3.905Å**)

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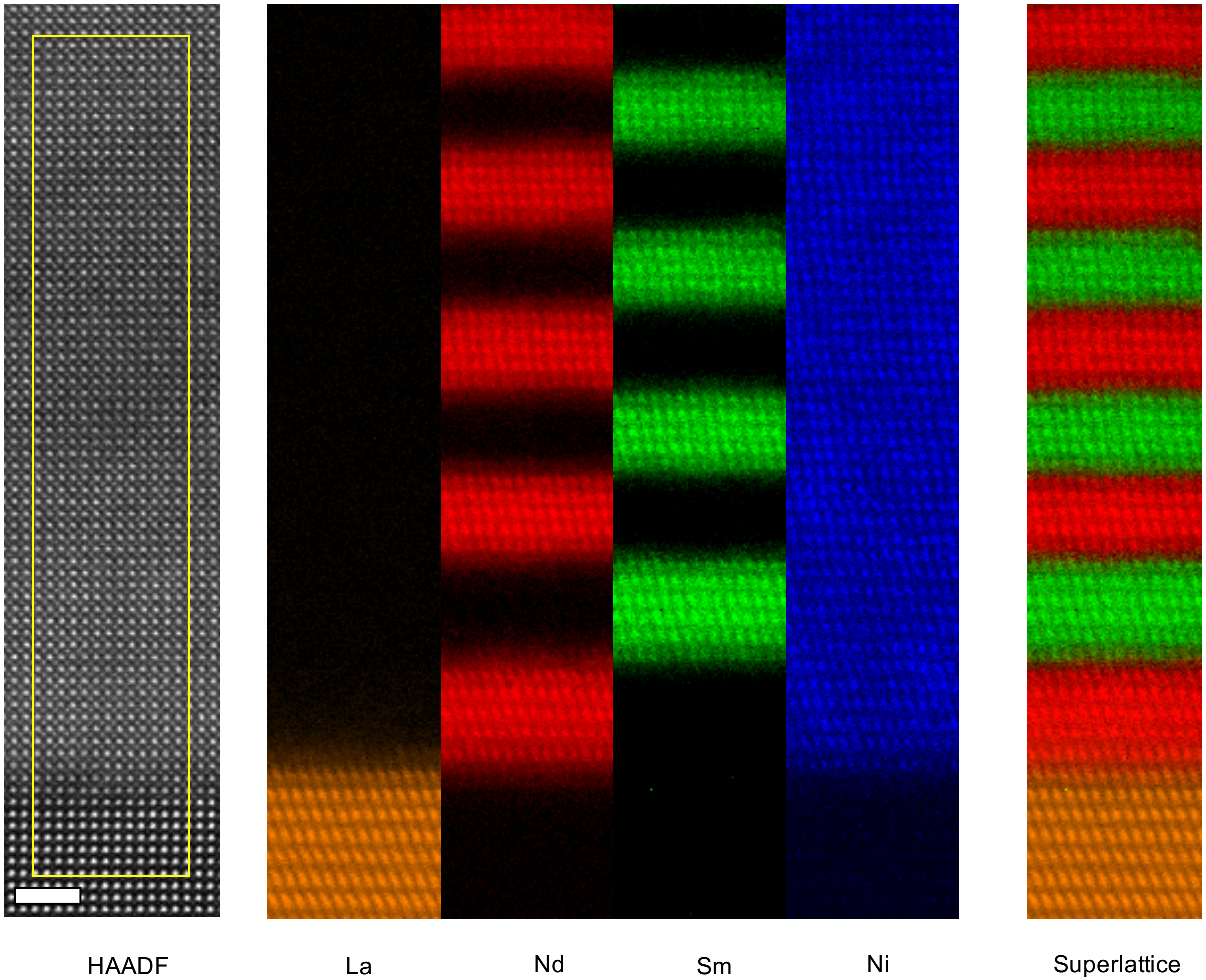
Epitaxial oxide heterostructures



$NdNiO_3/SmNiO_3$ superlattices

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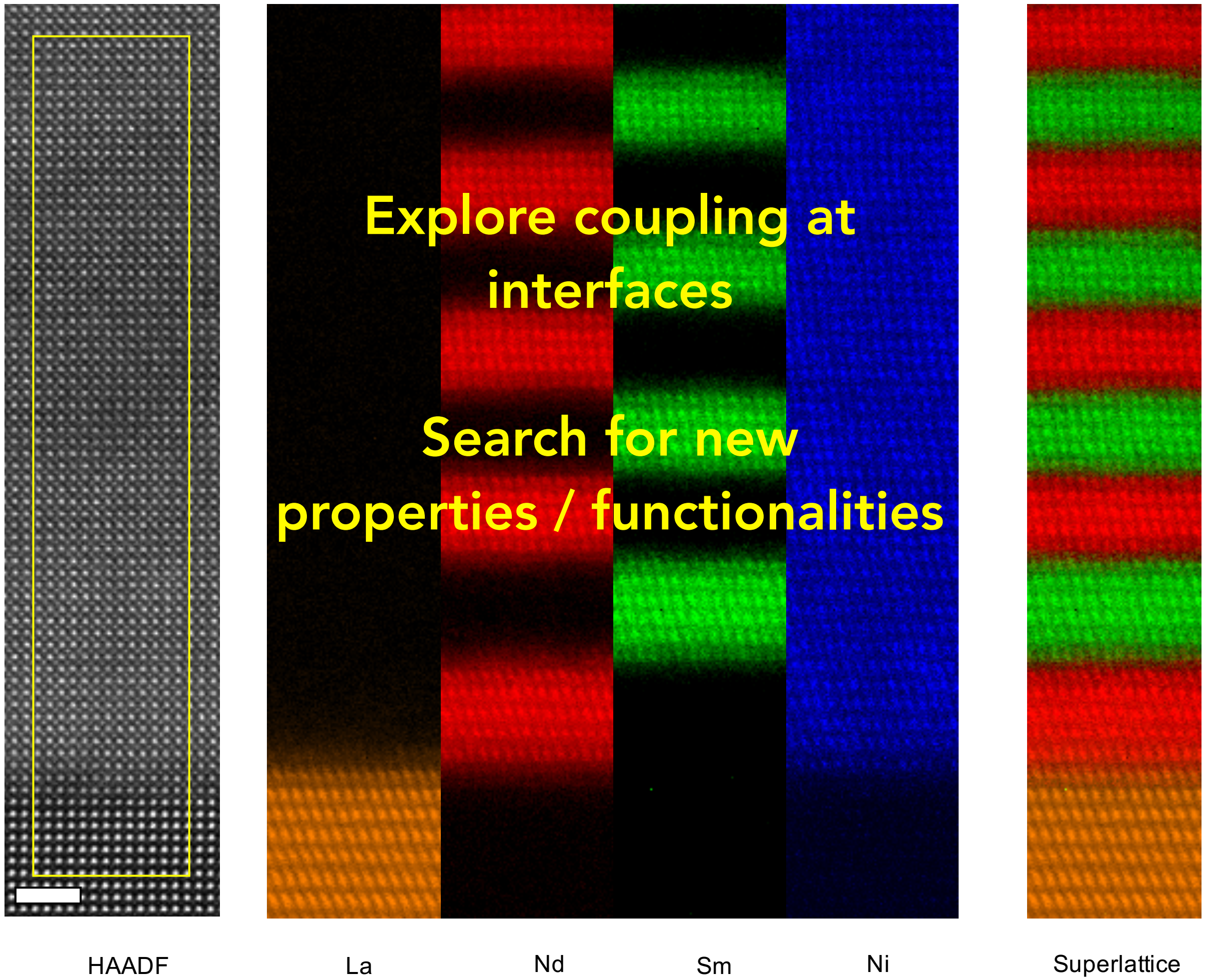
Epitaxial oxide heterostructures



$NdNiO_3/SmNiO_3$ superlattices

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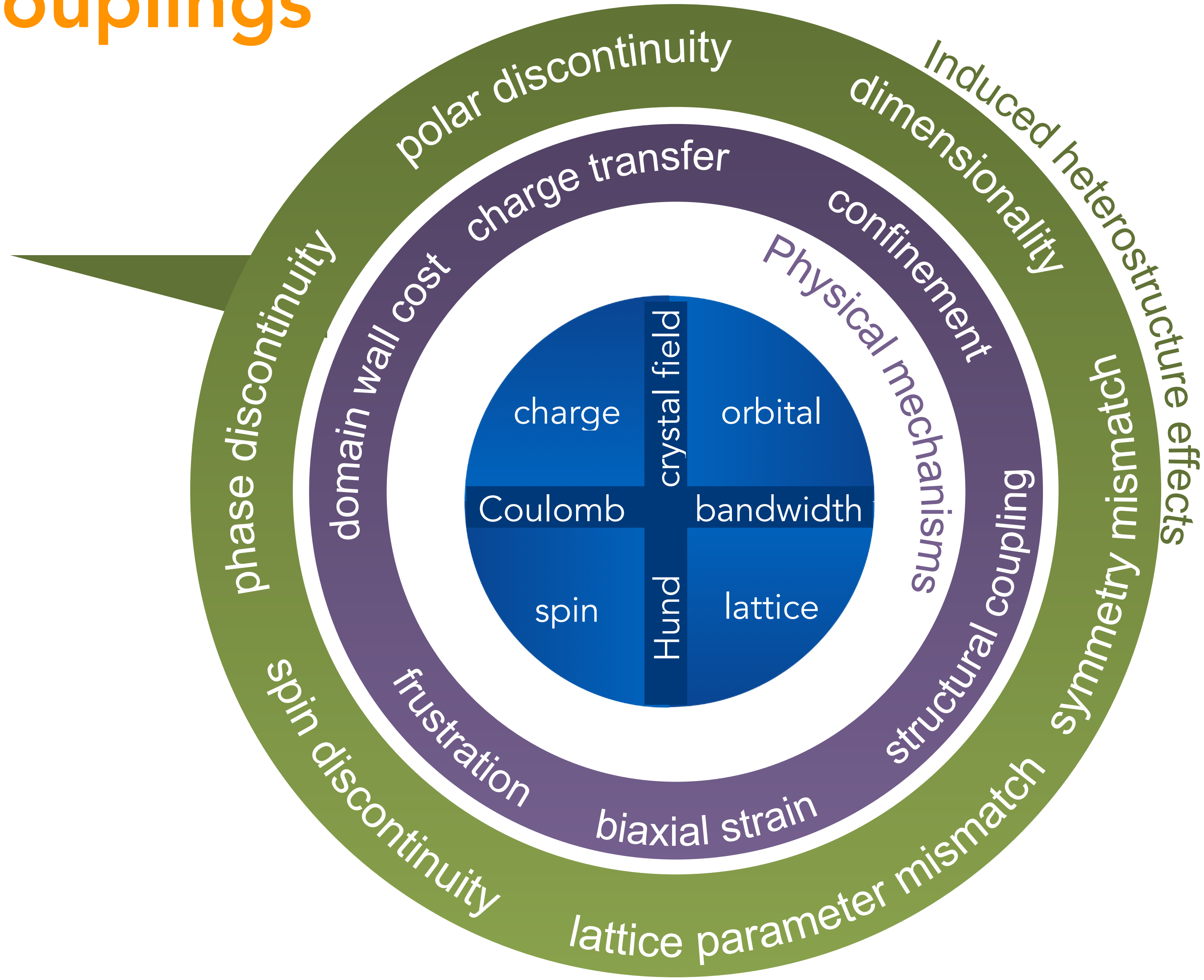
Some possible couplings in TMO's

Heterostructure
⟶ Chemical discontinuity



Interface physics in complex oxide heterostructures

P. Zubko et al., Annual Review of Condensed Matter Physics **2**, 141 (2011)

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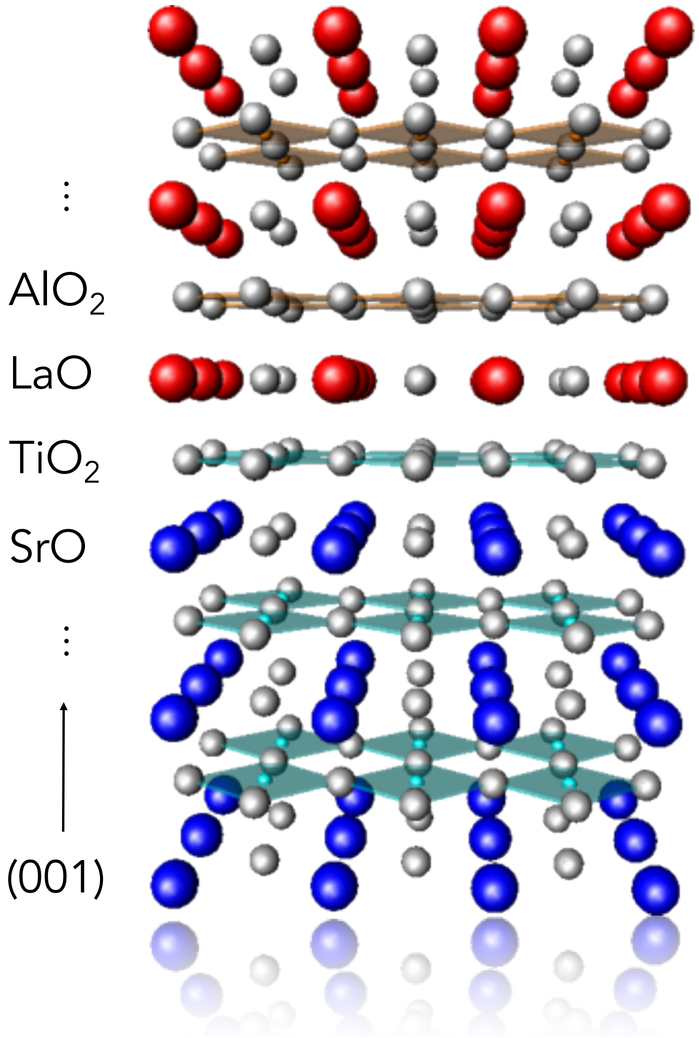
Two examples

1. The $LaAlO_3/SrTiO_3$ interface - a 2D electron system

2. Vanadate based heterostructures - possibly a new path to realise 2D structures

The $LaAlO_3$/$SrTiO_3$ system



$LaAlO_3$:

band insulator Δ=5.6eV

$SrTiO_3$:

band insulator Δ=3.2 eV

quantum paraelectric

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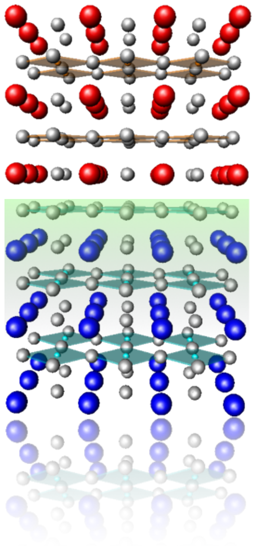
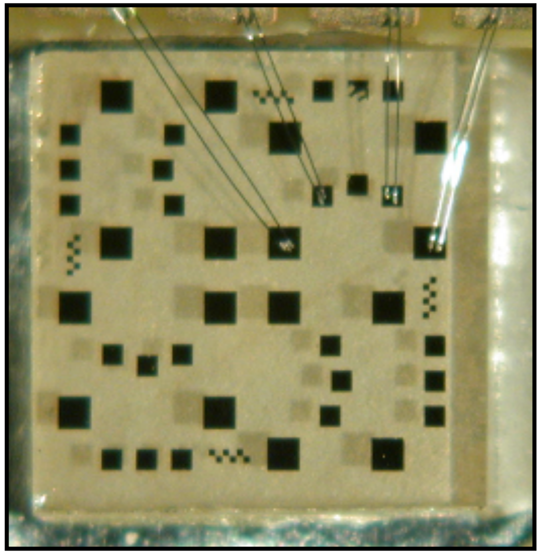


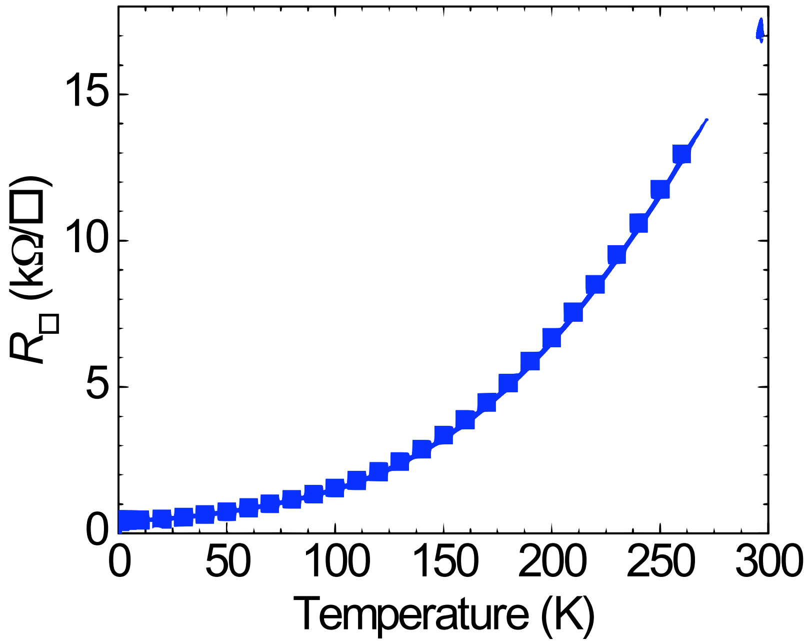
A conducting interface

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)





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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)
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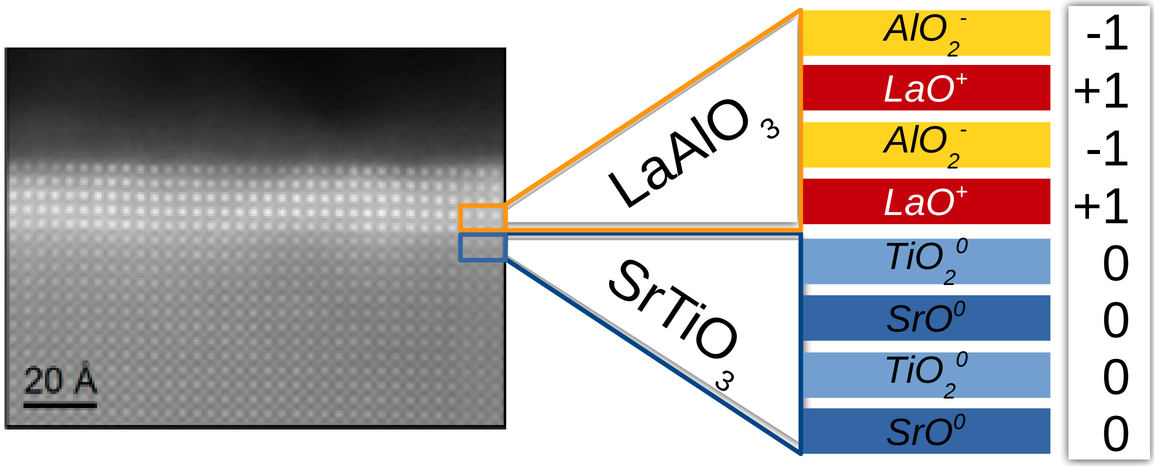
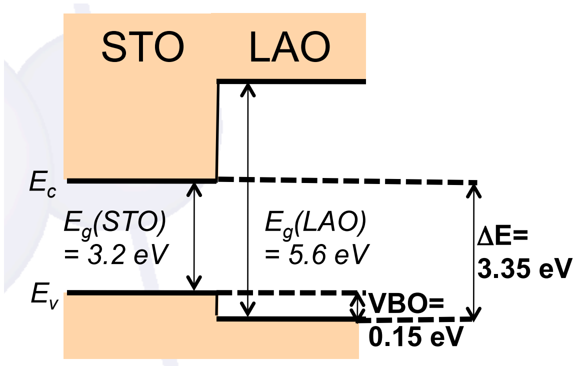
Vast literature: a review Stefano Gariglio et al. APL Mat. **4**, 060701 (2016)

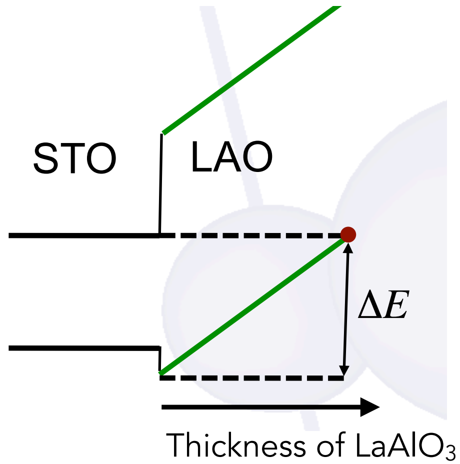
Why is this interface conducting? - Polar discontinuity





$$E=(\sigma_0 / \varepsilon_r \varepsilon_0) \Rightarrow d_c = V_c/E$$

with V_c=3.35 V, σ_0 = 3 10^{14} e/cm^2 and ε_r =25, d_c = 3.5 u.c.



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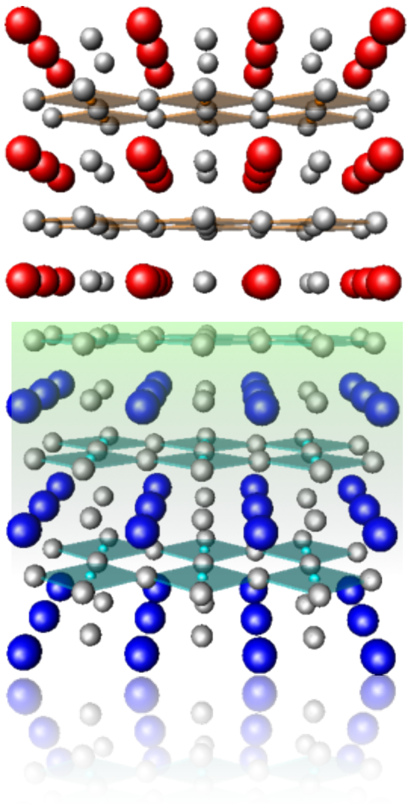
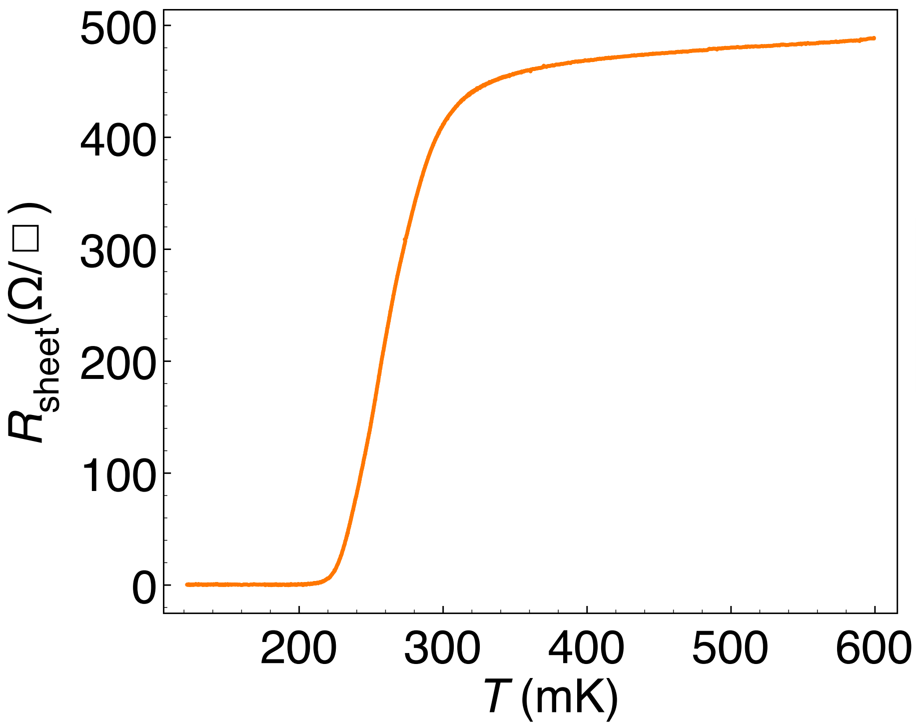
The system is superconducting





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)

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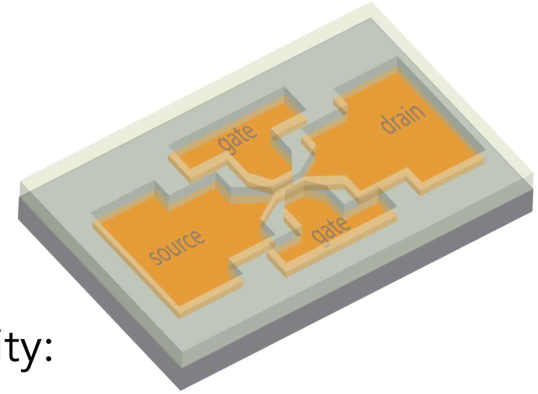
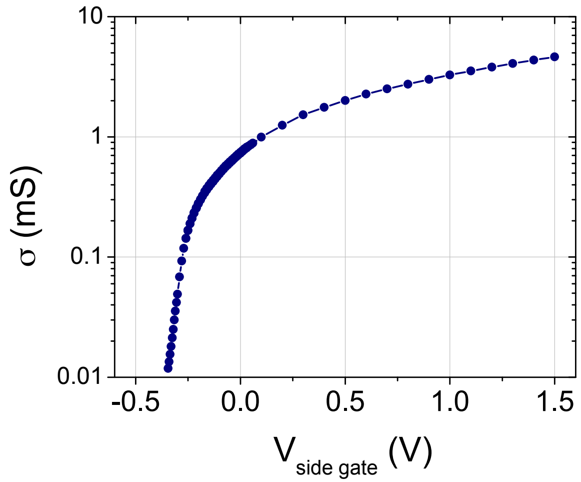
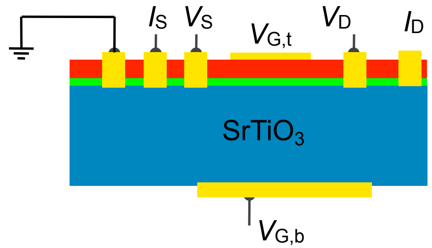
A rather unique system: Field effect control



Sheet carrier density:
2-4 10^{13} /cm^2



Side gating



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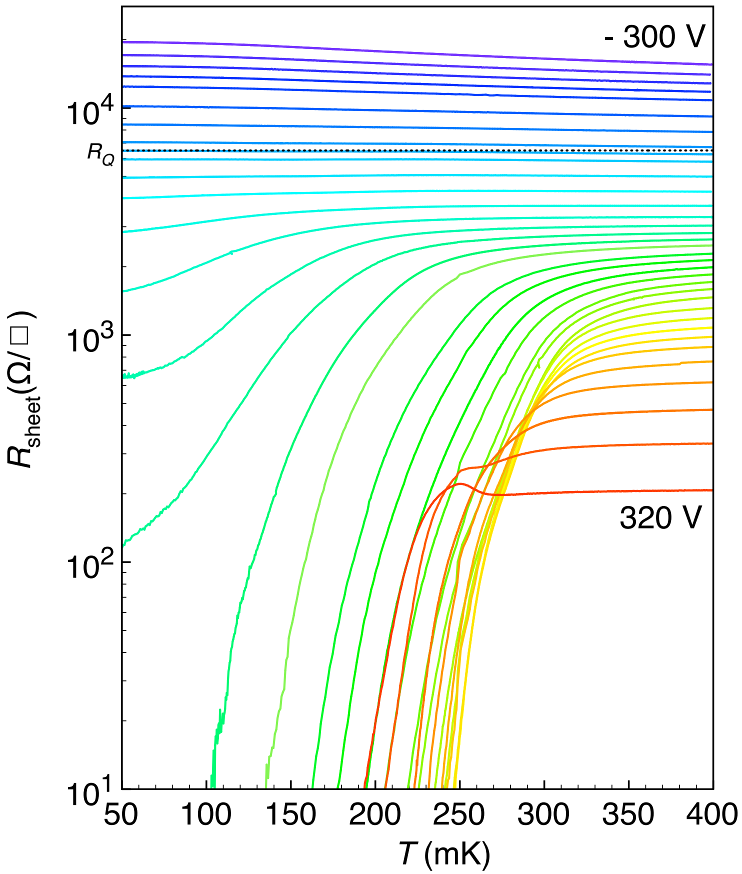
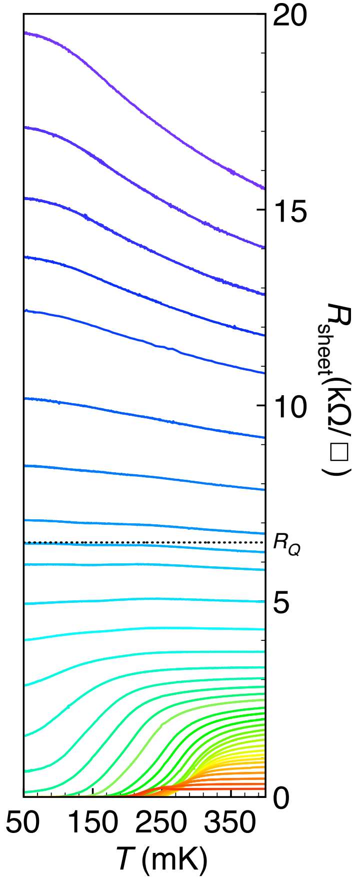
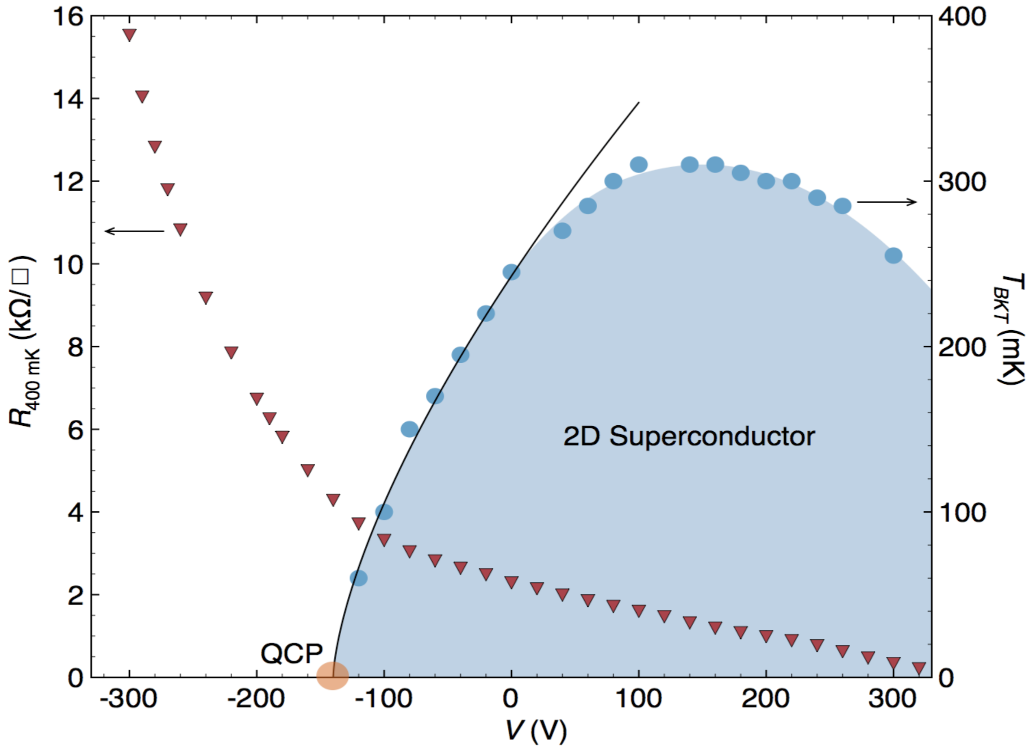
Tunable SC and phase diagram







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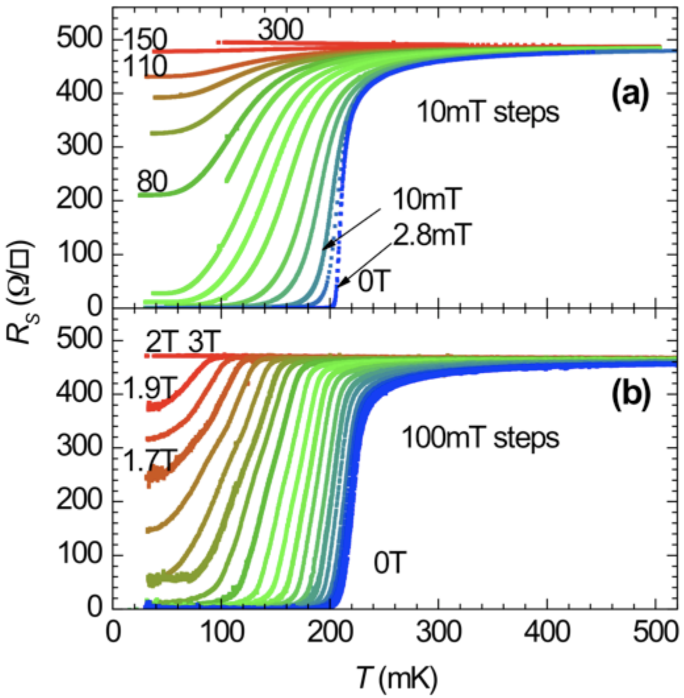
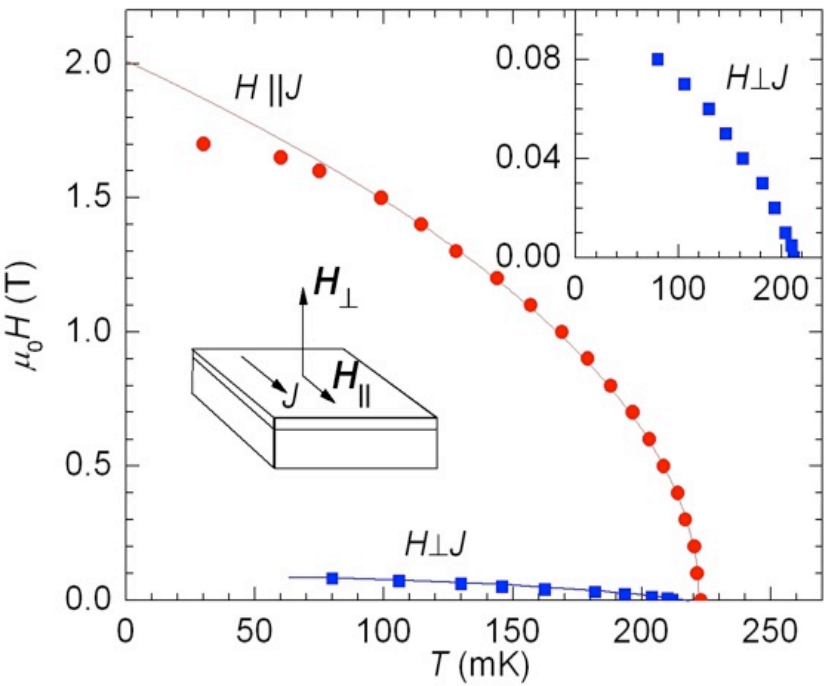
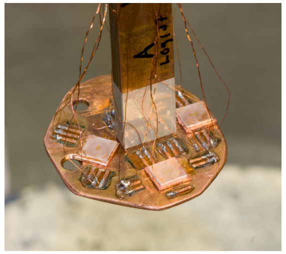
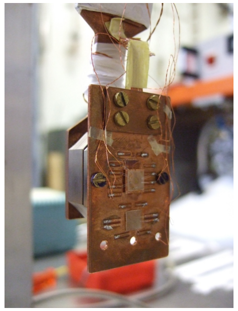
A.D. Caviglia *et al*, Nature **456**, 625 (2008)

2D superconductivity









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

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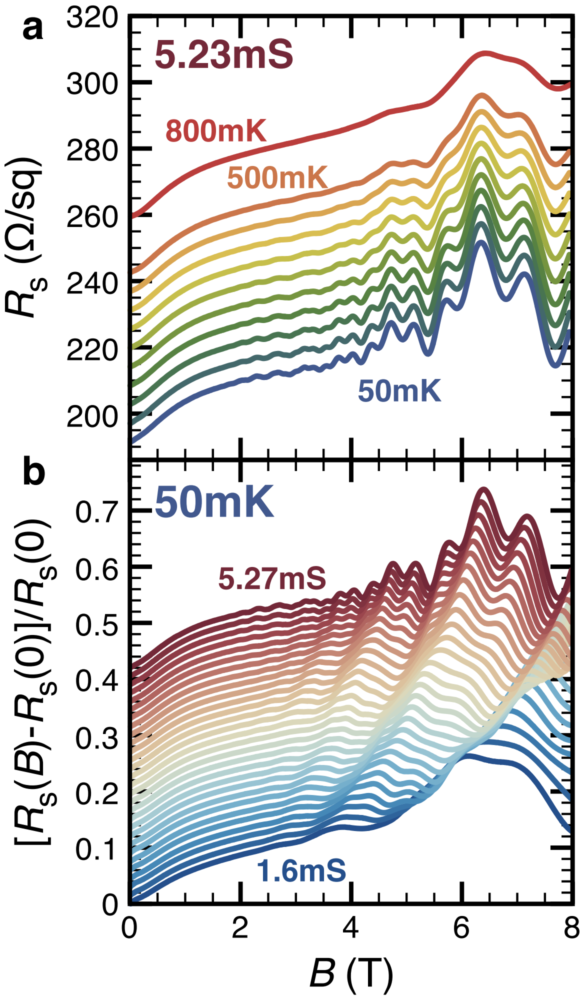
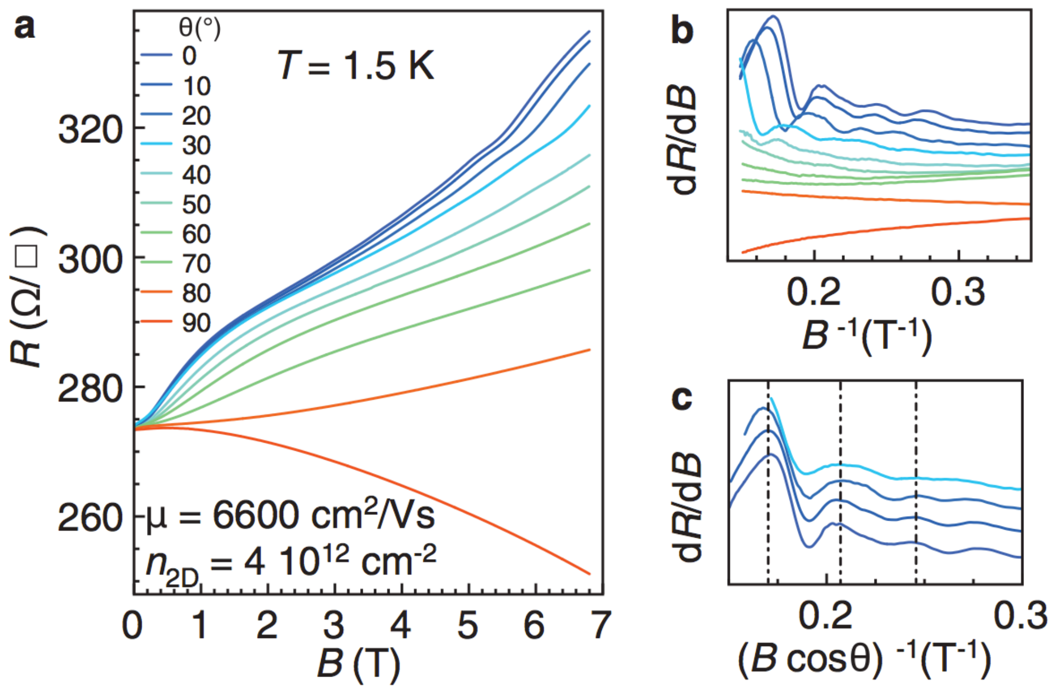
2D signatures in the normal state

A. Fête et al. New J. Phys. **16** 112002 (2014)





A. Fête PhD thesis 2014

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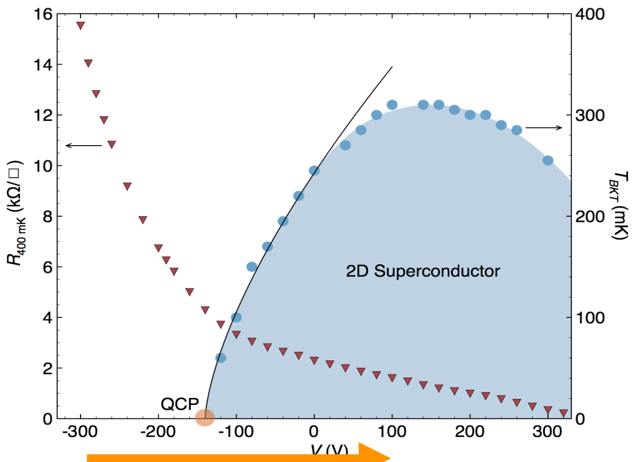
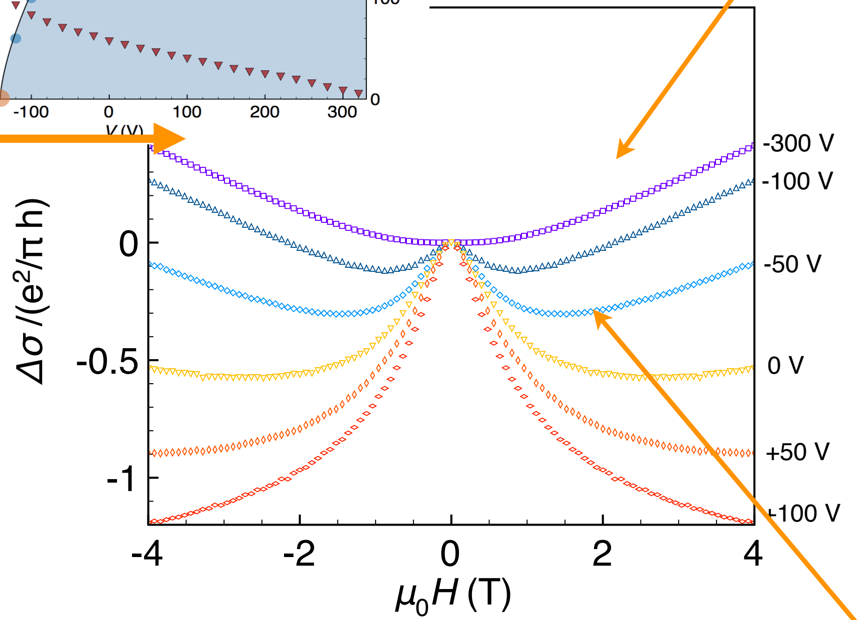
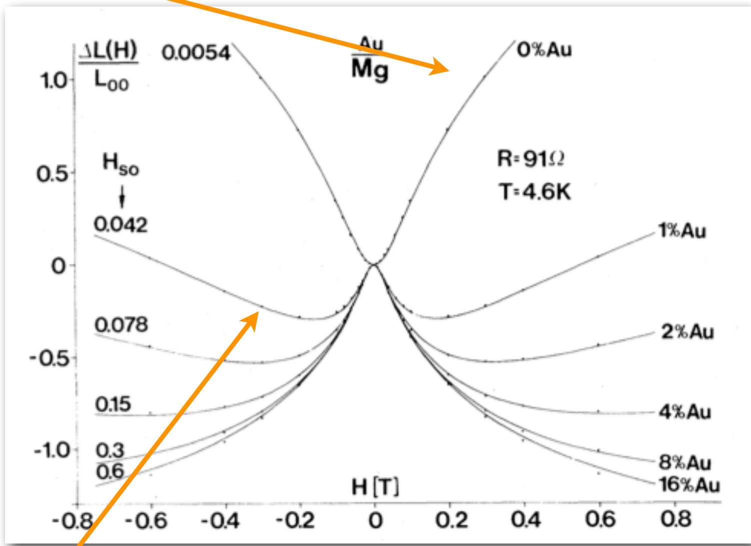
WL - WAL - spin-orbit interaction



Weak localization



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



G. Bergman, Phys Rev Lett **48**, 1046 (1982)

Weak anti-localization

Strong spin-orbit interaction

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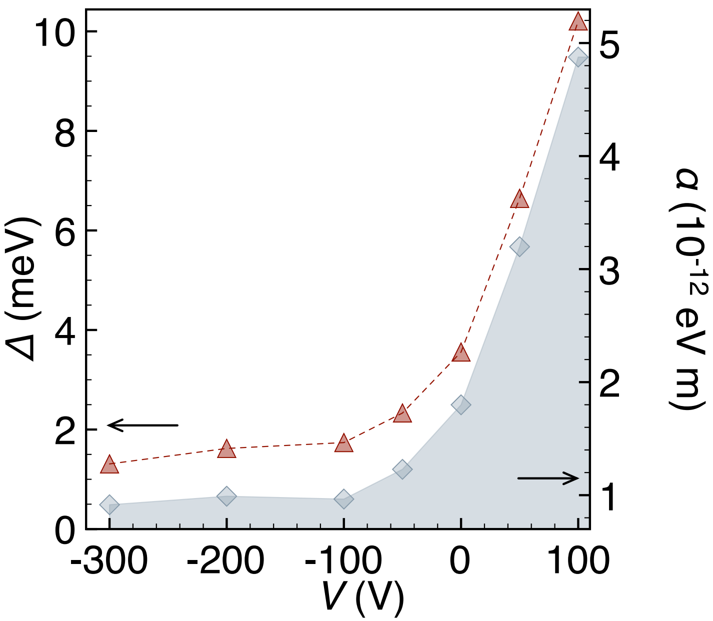
Tunable Rashba spin-orbit interaction

$$\alpha = \frac{\hbar}{m}\sqrt{\frac{\hbar e H_{so}}{2}}$$

$$\Delta = 2\alpha k_F$$



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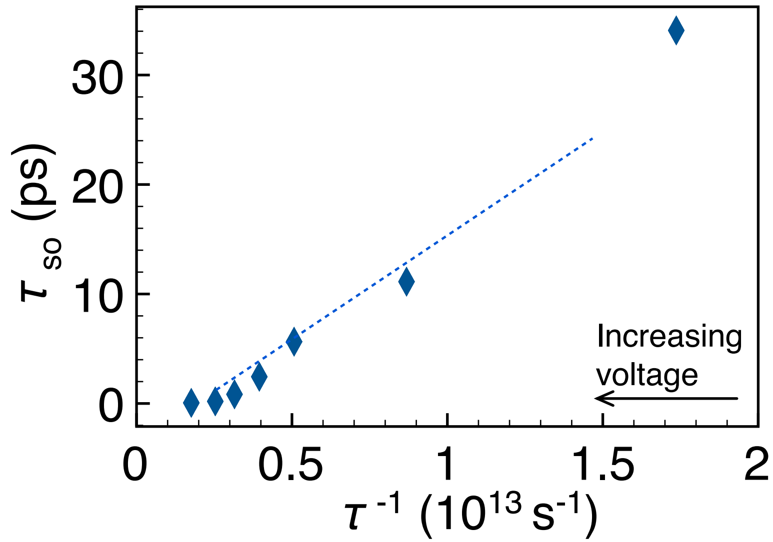

D'yakonov - Perel' ← Rashba SO

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

Elliott - Yafet ← Atomic SO

$$\tau_{so} \sim \tau/(\Delta g)^2$$

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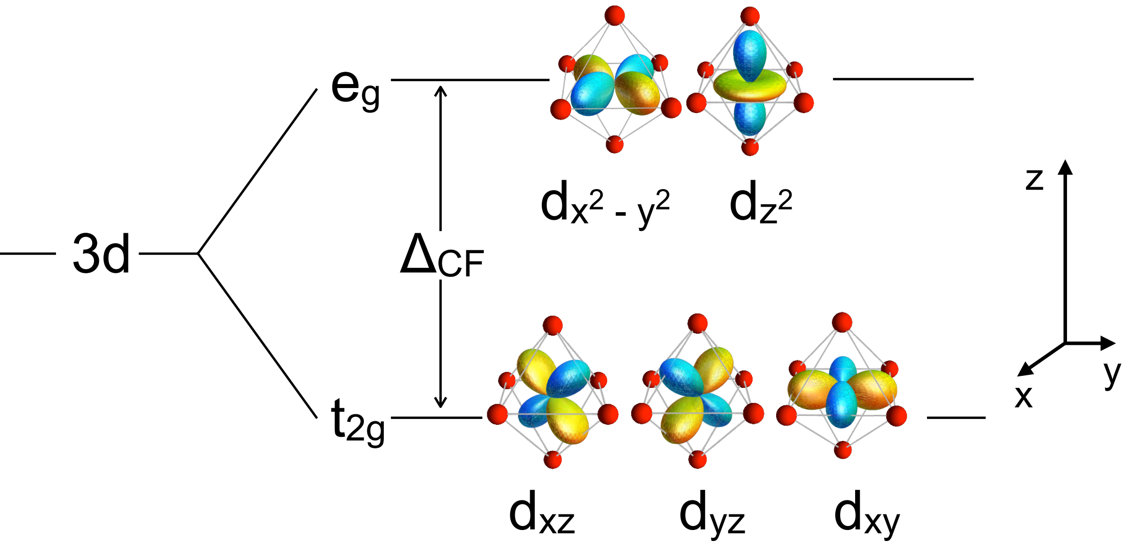
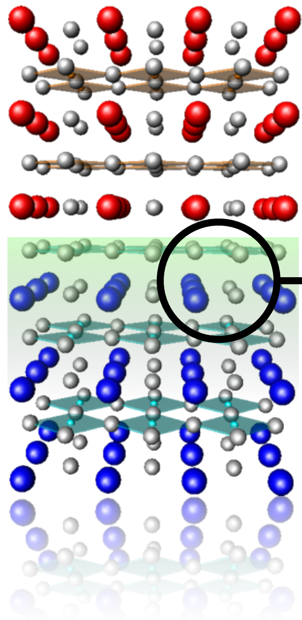
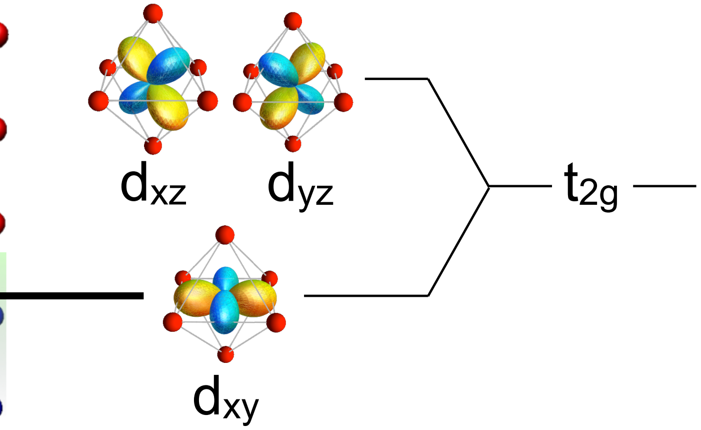
Electronic structure

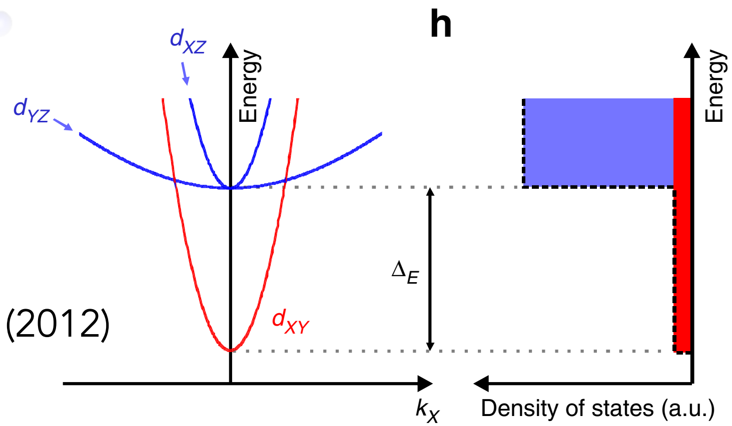






M. Salluzzo et al., PRL **102**, 166804 (2009)

Without atomic spin-orbit coupling



A. Joshua et al. Nature Com. 3, 1129 (2012)

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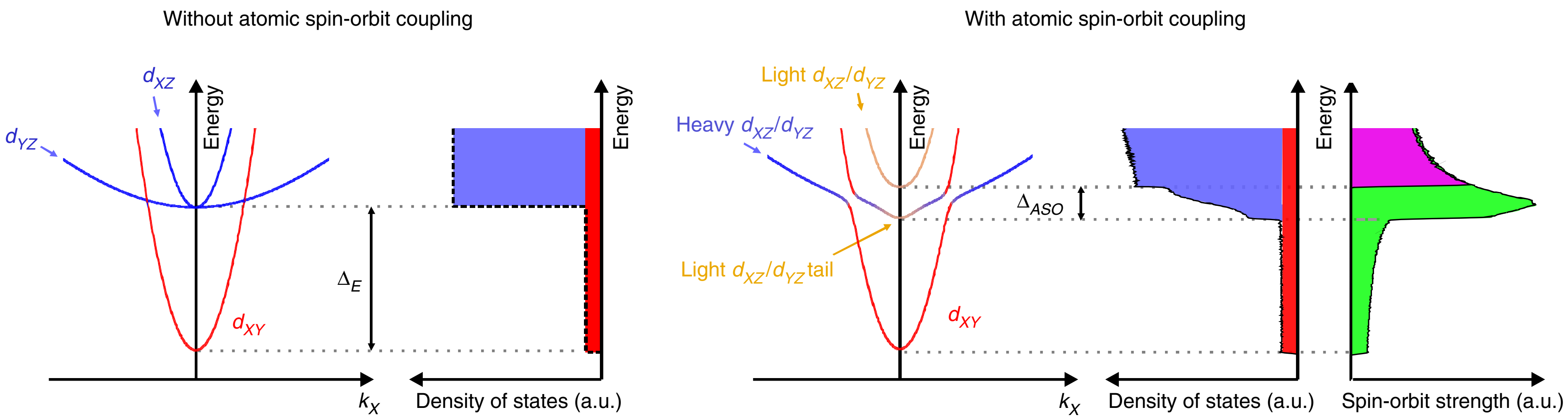
With spin-orbit



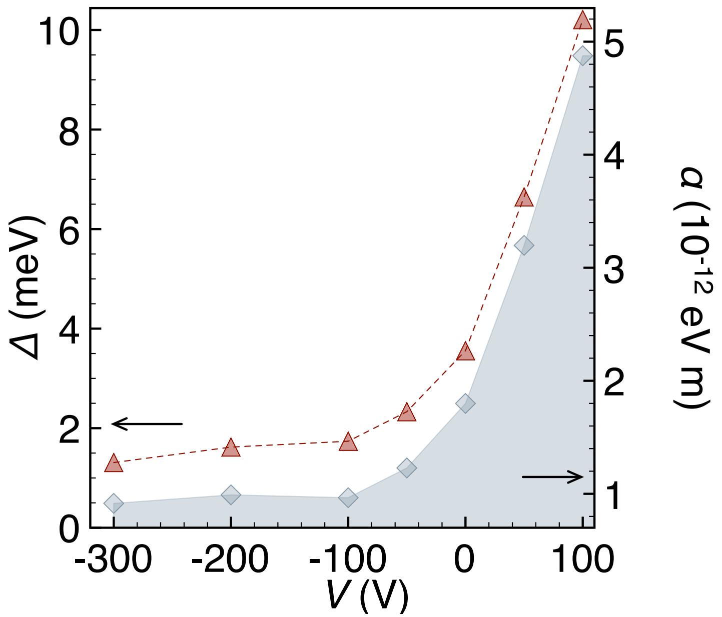
A. Joshua et al. Nature Com. 3, 1129 (2012)

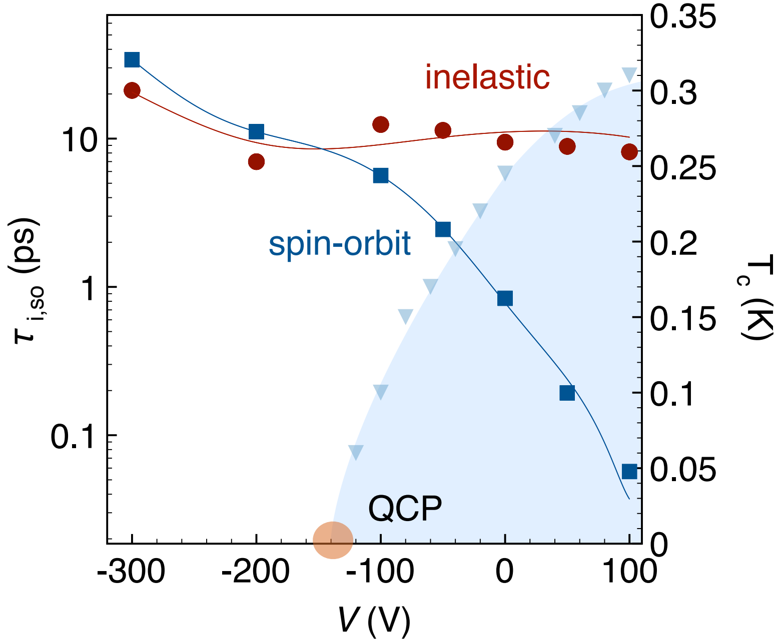
Superconductivity and spin-orbit

$$\alpha = \frac{\hbar}{m}\sqrt{\frac{\hbar e H_{so}}{2}}$$

$$\Delta = 2\alpha k_F$$

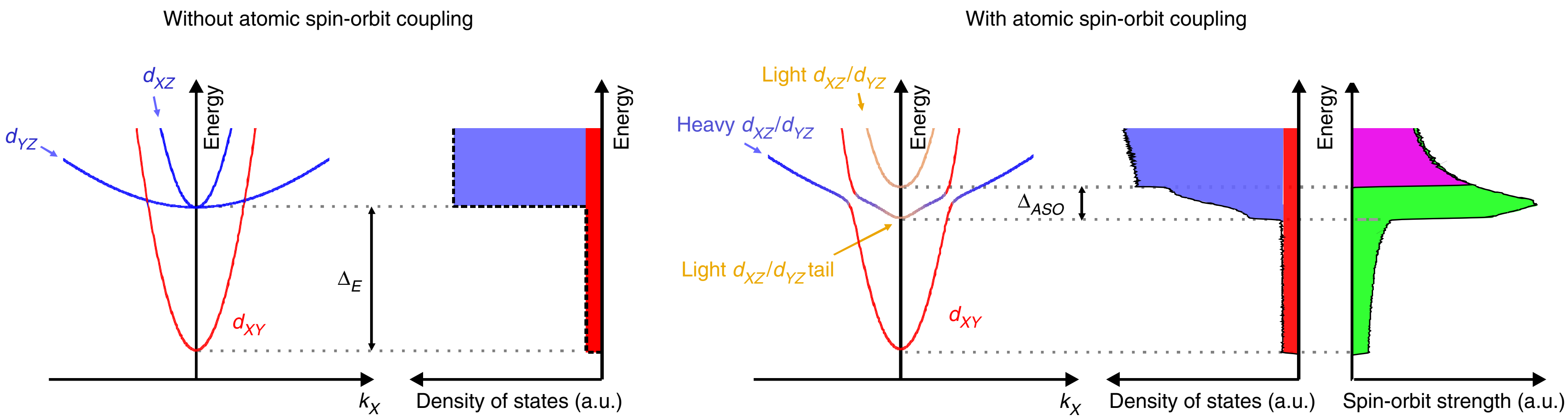
Δ=10meV is much larger than the SC gap (~40μeV)





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

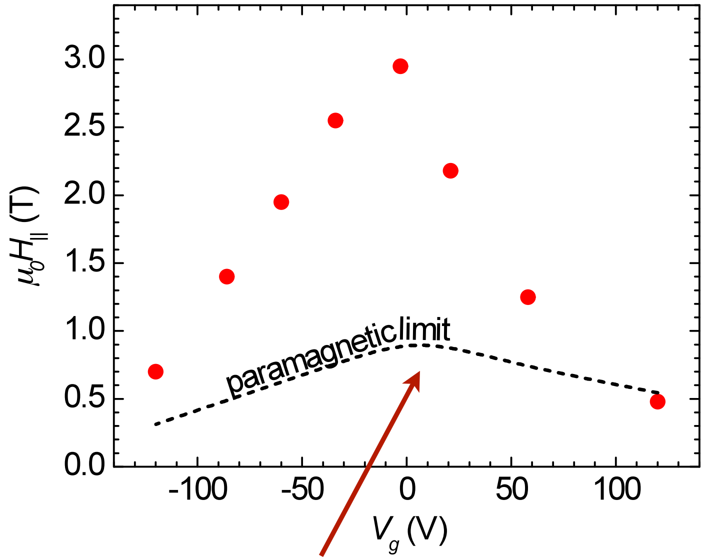
Superconductivity and spin-orbit



T_c goes as $\exp(-1/(N(E_F)V))$

A. Joshua et al. Nature Com. 3, 1129 (2012)

Signatures of spin-orbit in the SC state

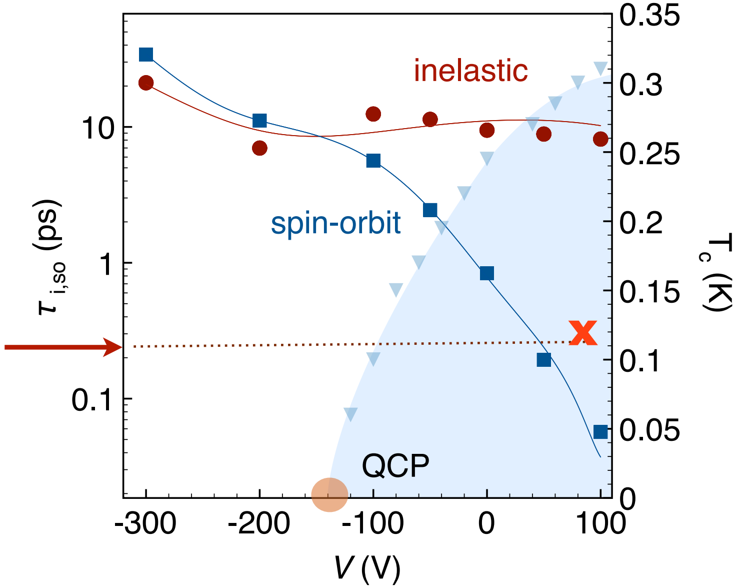


$$\mu_0 H_p = \frac{\Delta(0)}{\sqrt{2}\mu_B} = 1.84 T_c$$

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

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

τ_{s0} = 2.4 10^{-13} s



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

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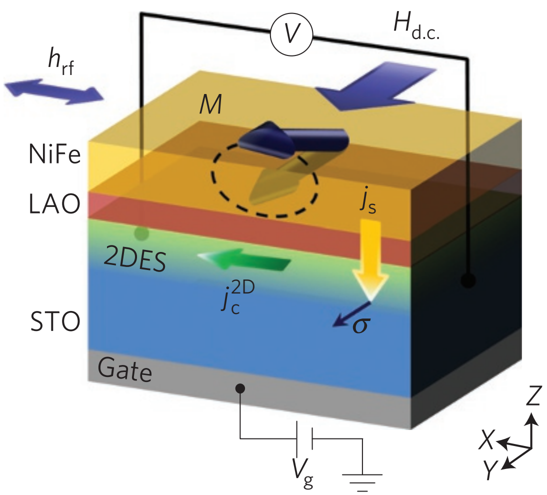
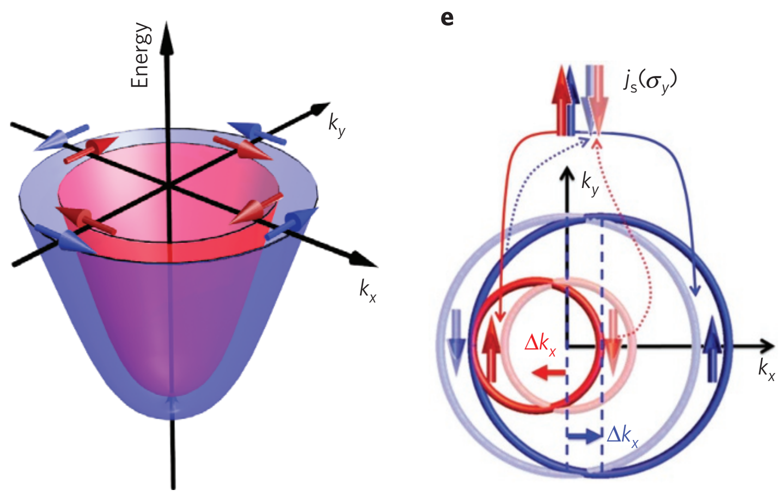
The inverse Edelstein effect

Spin pumping



A pure spin current is injected through the $LaAlO_3$ layer that generates a charge current in the 2DES



Allows a spin current to charge current conversion

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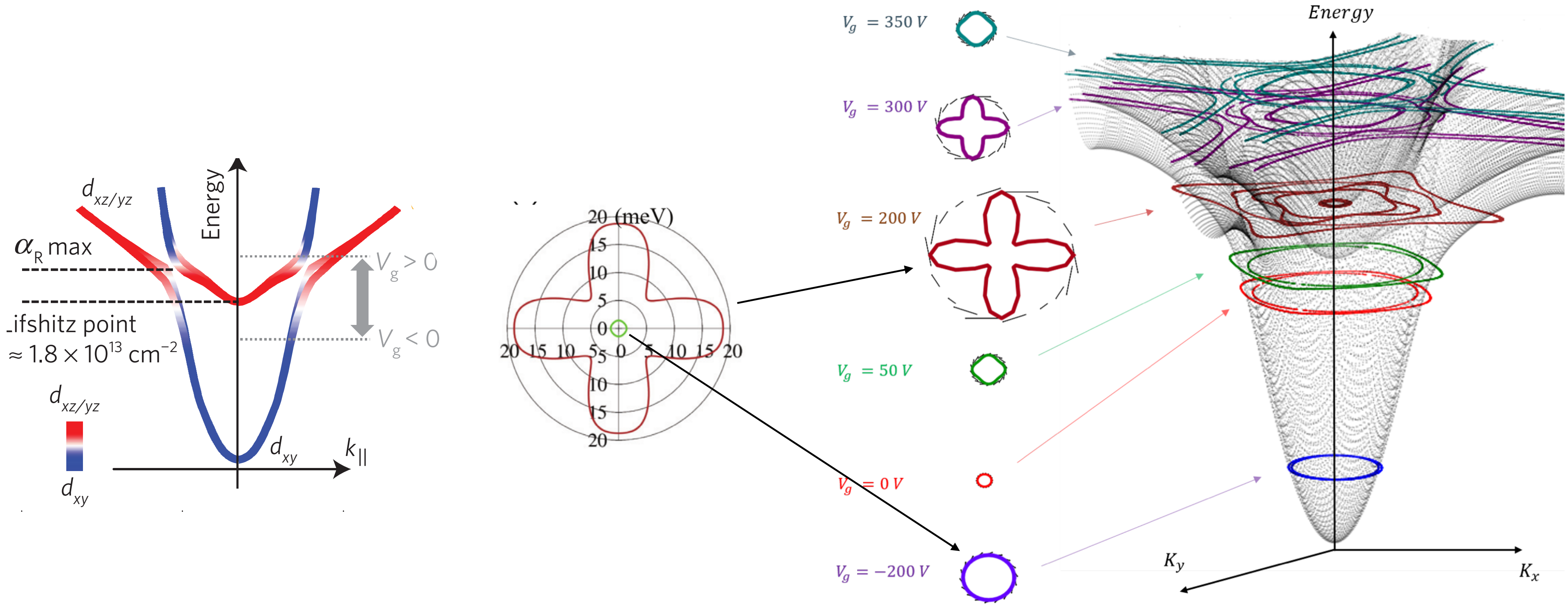
From E. Lesne et al. Nat. Mater. **15**, 1261 (2016)

Predicted angular dependence



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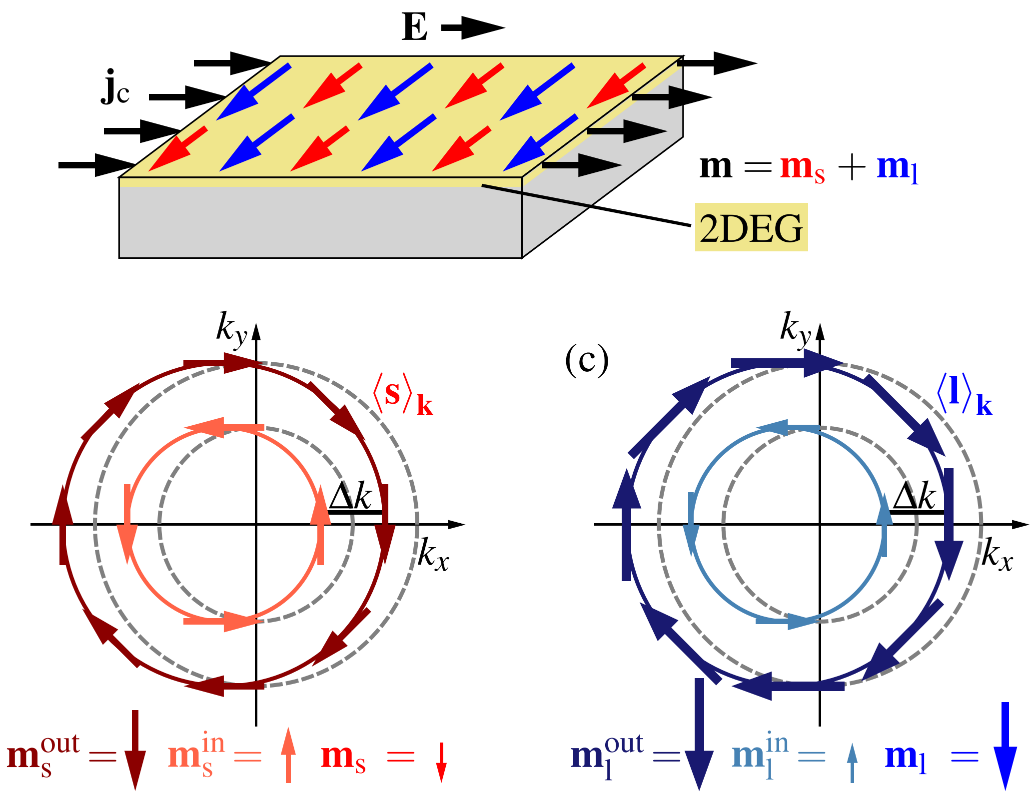
Prediction: Z. Zhong et al. PRB**87** 161102 (2013)
Experiments: A. El Hamdi et al. to appear in Nature Physics

Spin and orbital Rashba effect



Along with the spin Rashba effect, one can have an orbital contribution

The orbital Rashba effect is linear and is not predicted to change sign - it may play an important role at the $LaAlO_3$/ $SrTiO_3$ interface

A . Johansson et al. PRR **3**, 013275 (2021)

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A different « mix » of orbital and spin injection - possibly linked to the barrier - could explain the difference between the results of Lesne et al. and ours

Open / interesting questions

Spin-orbit and superconductivity

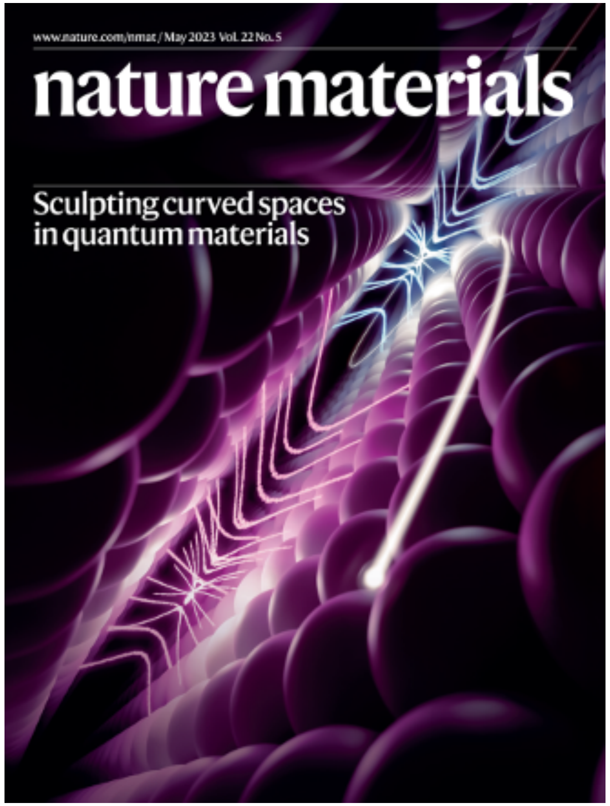
Physics in the under doped superconducting regime

Spin and orbital Rashba effect

Recent studies in [111] direction

Recent studies at the interface with $KTaO_3$

(111) $LaAlO_3/SrTiO_3$



The cover shows the curvature of the space fabric due to the superposition of spin and orbital states at the interface between lanthanum aluminate ($LaAlO_3$) and strontium titanate ($SrTiO_3$). © Xavier Ravinet – UNIGE

Article https://doi.org/10.1038/s41563-023-01498-0

Designing spin and orbital sources of Berry curvature at oxide interfaces

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Edouard Lesne[1,6], Yildiz G. Sağlam[1], Raffaele Battilomo[2], Maria Teresa Mercaldo[3], Thierry C. van Thiel[1], Ulderico Filippozzi[1], Canio Noce[3], Mario Cuoco[4], Gary A. Steele[1], Carmine Ortix[2,3] & Andrea D. Caviglia[5]

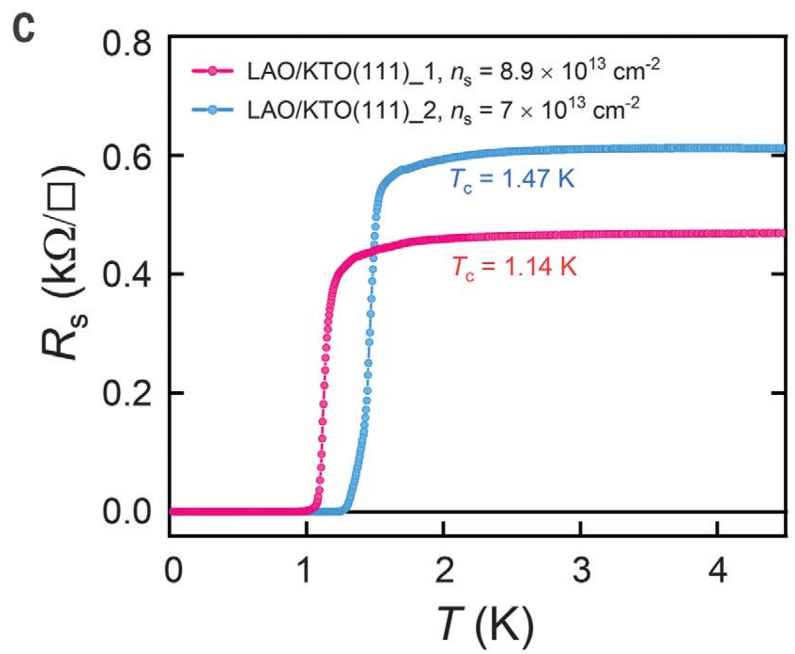
(111) $KTaO_3$ interface

SUPERCONDUCTIVITY

Two-dimensional superconductivity and anisotropic transport at $KTaO_3$ (111) interfaces

Changjiang Liu[1]*†, Xi Yan[1,2,3]†, Dafei Jin[4], Yang Ma[5], Haw-Wen Hsiao[6], Yulin Lin[4], Terence M. Bretz-Sullivan[1], Xianjing Zhou[4], John Pearson[1], Brandon Fisher[4], J. Samuel Jiang[1], Wei Han[5], Jian-Min Zuo[6], Jianguo Wen[4], Dillon D. Fong[1], Jirong Sun[3,7], Hua Zhou[2], Anand Bhattacharya[1]*

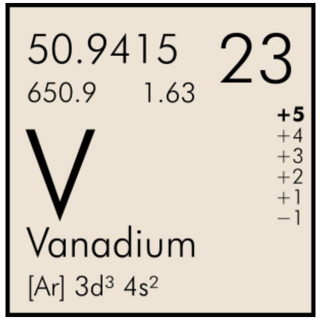
The distinctive electronic structure found at interfaces between materials can allow unconventional quantum states to emerge. Here we report on the discovery of superconductivity in electron gases formed at interfaces between (111)-oriented $KTaO_3$ and insulating overlayers of either EuO or $LaAlO_3$. The superconducting transition temperature, as high as 2.2 kelvin, is about one order of magnitude higher than that of the $LaAlO_3/SrTiO_3$ system. Notably, similar electron gases at $KTaO_3$ (001) interfaces remain normal down to 25 millikelvin. The critical field and current-voltage measurements indicate that the superconductivity is two-dimensional. In EuO/$KTaO_3$ (111) samples, a spontaneous in-plane transport anisotropy is observed before the onset of superconductivity, suggesting the emergence of a distinct "stripe"-like phase, which is also revealed near the critical field.



Orthorhombic vanadates

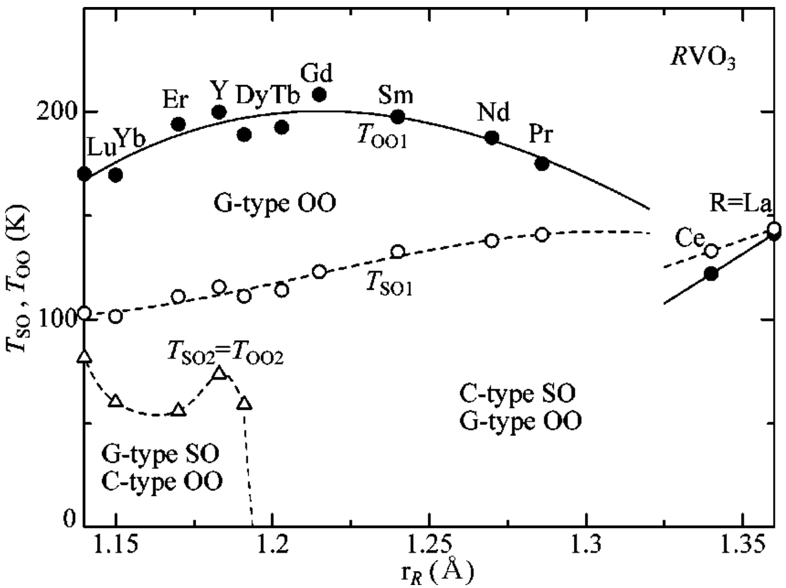
Structural coupling leads to a transition layer

Perovskite vanadates $REVO_3$

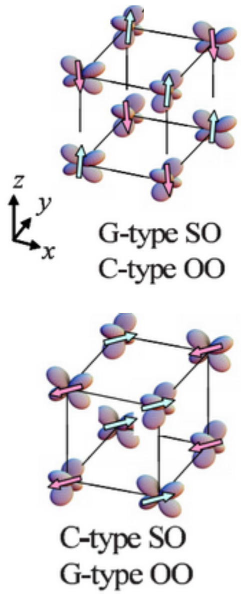


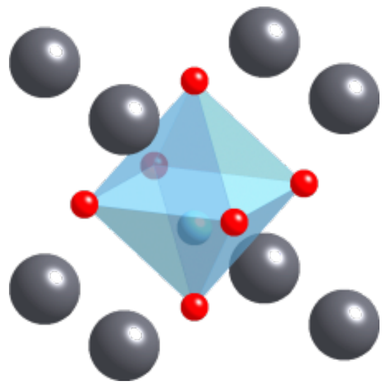
V^{4+} (d^1) : metallic (e.g. $SrVO_3$)

V^{3+} (d^2) : Mott-insulators (rare earth or Y, e.g. $LaVO_3$)



S. Miyasaka et al. PRB **68**, 100406 (2003)

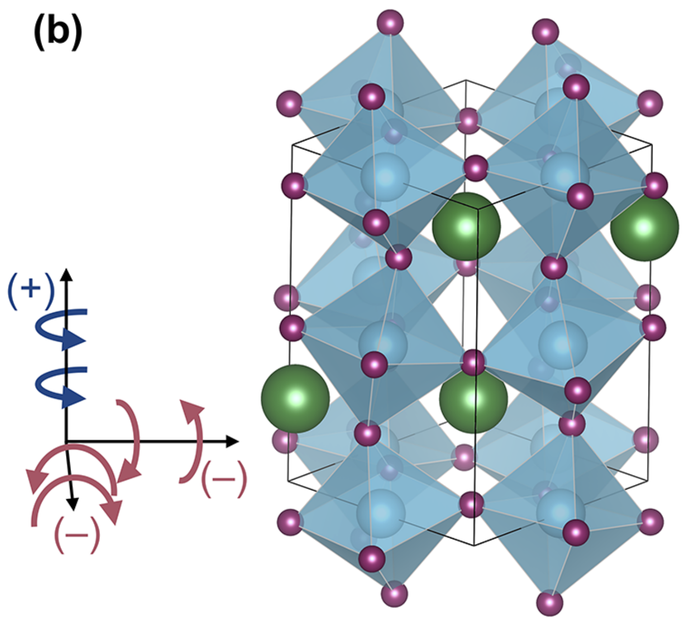




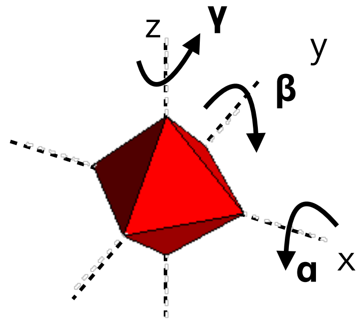
Pseudo-cubic unit-cell - a_{pc}

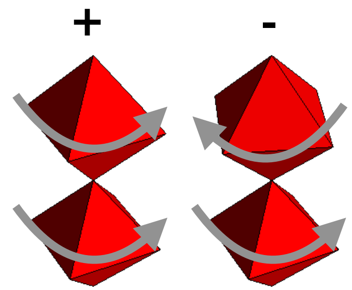
Perovskite vanadates RVO_3

Orthorhombic structure as many perovskites
Pnma with a tilt pattern $a^-b^+c^-$



Orthorhombic structure $a^-b^+c^-$

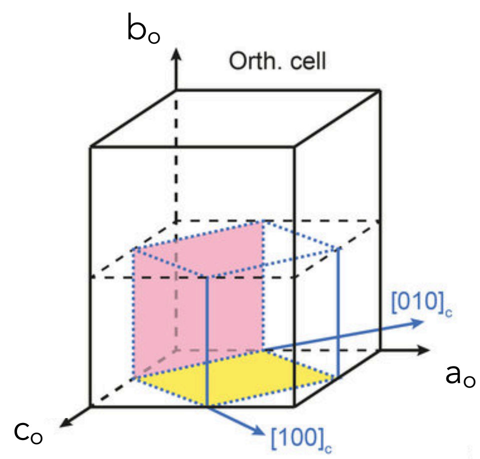




$a^-b^+c^-$

$LaVO_3$
a_o=5.555Å
b_o=7.849Å - in phase rotations
c_o=5.553Å

b_o is the orthorhombic « long-axis »



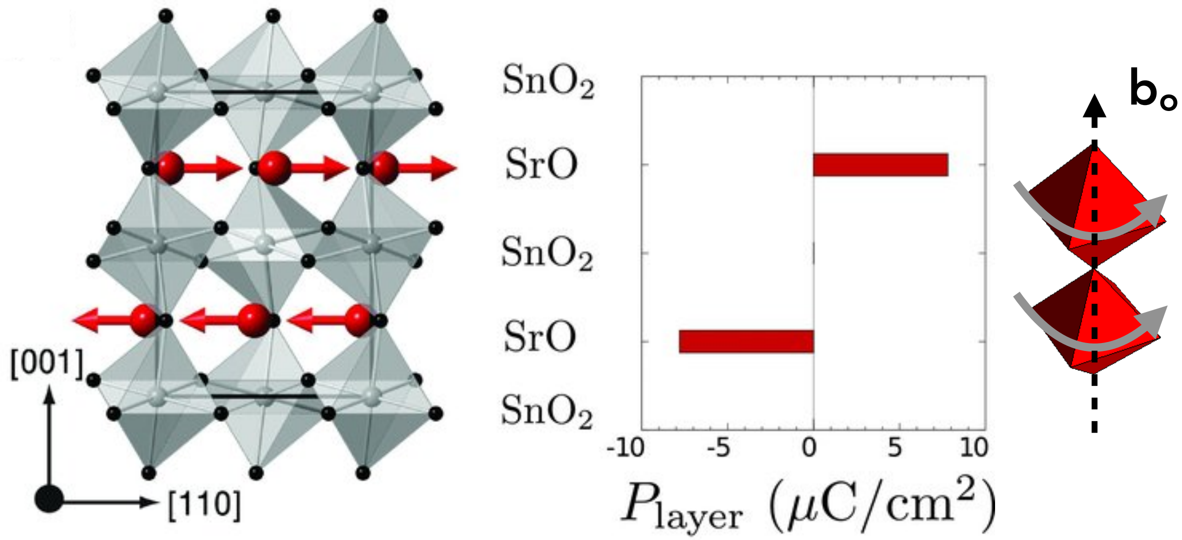
$a_{pc} \approx b_o/2 \approx (a_o^2+c_o^2)^{1/2}$

Perovskite vanadates RVO_3

These instabilities couple to an anti-polar mode (AM) X_5^-

$$F \sim \phi_{xy}^- \phi_z^+ X_5^-$$

AM - cation displacements in the [110] pseudocubic direction



J. Rondinelli and C. Fennie Adv. Func. Mat. **23**, 4810 (2013)

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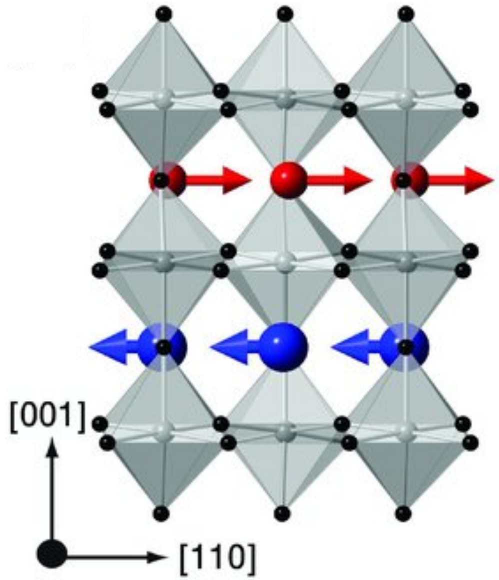
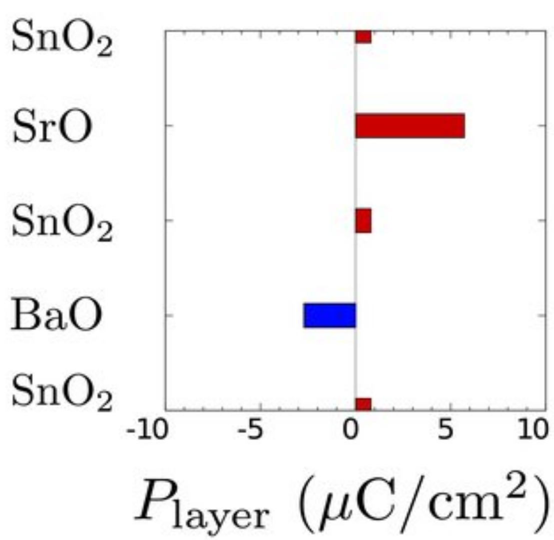
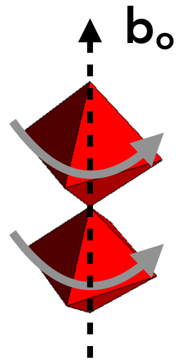
Synthetic ferroelectric
1u.c./1u.c. (odd) ABO_3/A'BO_3 superlattices







The long orthorhombic axis - in-phase rotations has to be out of plane

J. Rondinelli and C. Fennie Adv. Func. Mat. **23**, 4810 (2013)
M.J. Pitcher et al. Science **347**, 420 (2015)

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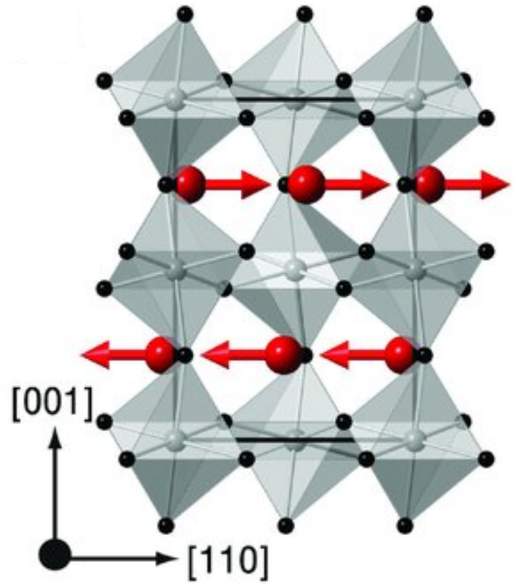
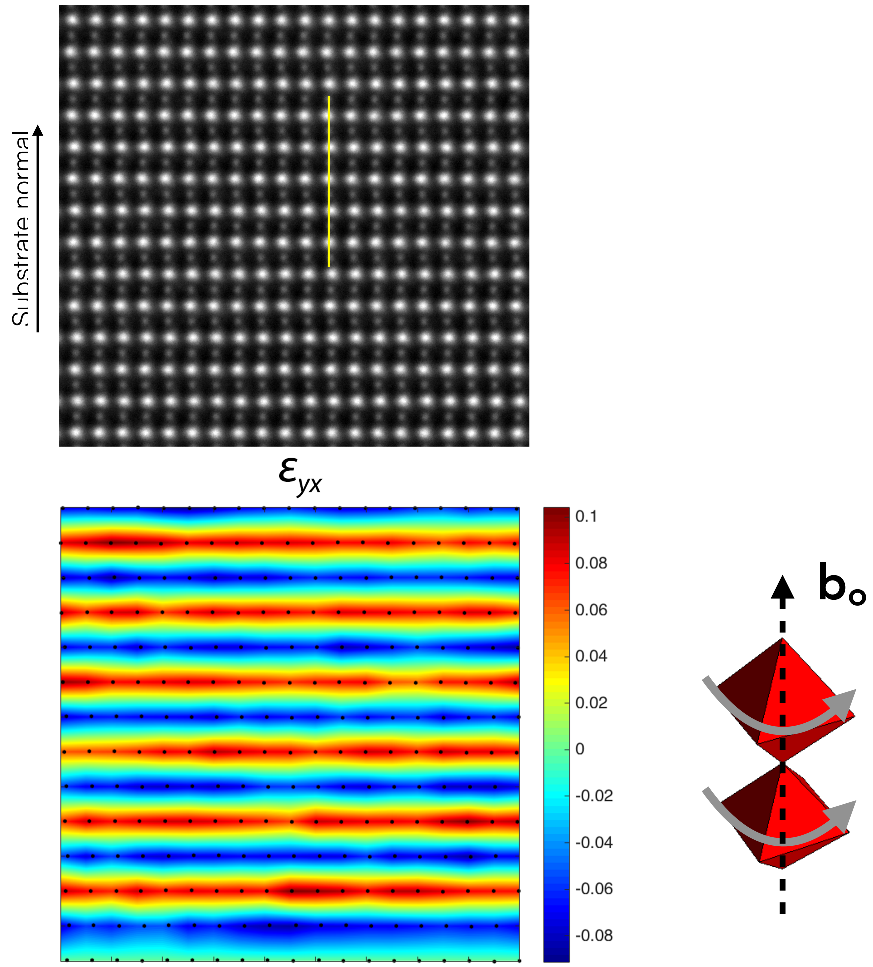
AM seen using STEM





« Atomic displacement mapping » allows the anti-polar modes to be visualised and the long axis direction to be determined

H. Meley et al. APL Mat. **6**, 046102 (2018)

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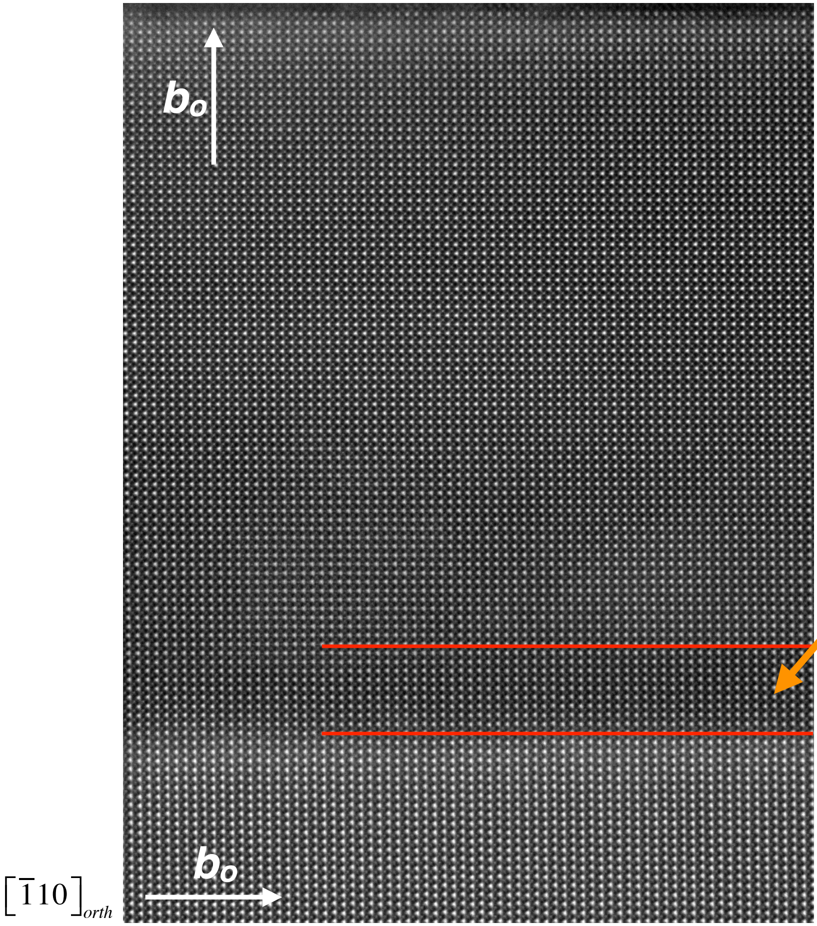
$LaVO_3$ grown on a $(101)_o$ $DyScO_3$ substrate



Strain favours a long axis in the out-of-plane direction

An unusual contrast at the interface
-no defect
-no chemical contrast

$(101)_o$ $DyScO_3$
Orthorhombic b-axis (long axis) in-plane

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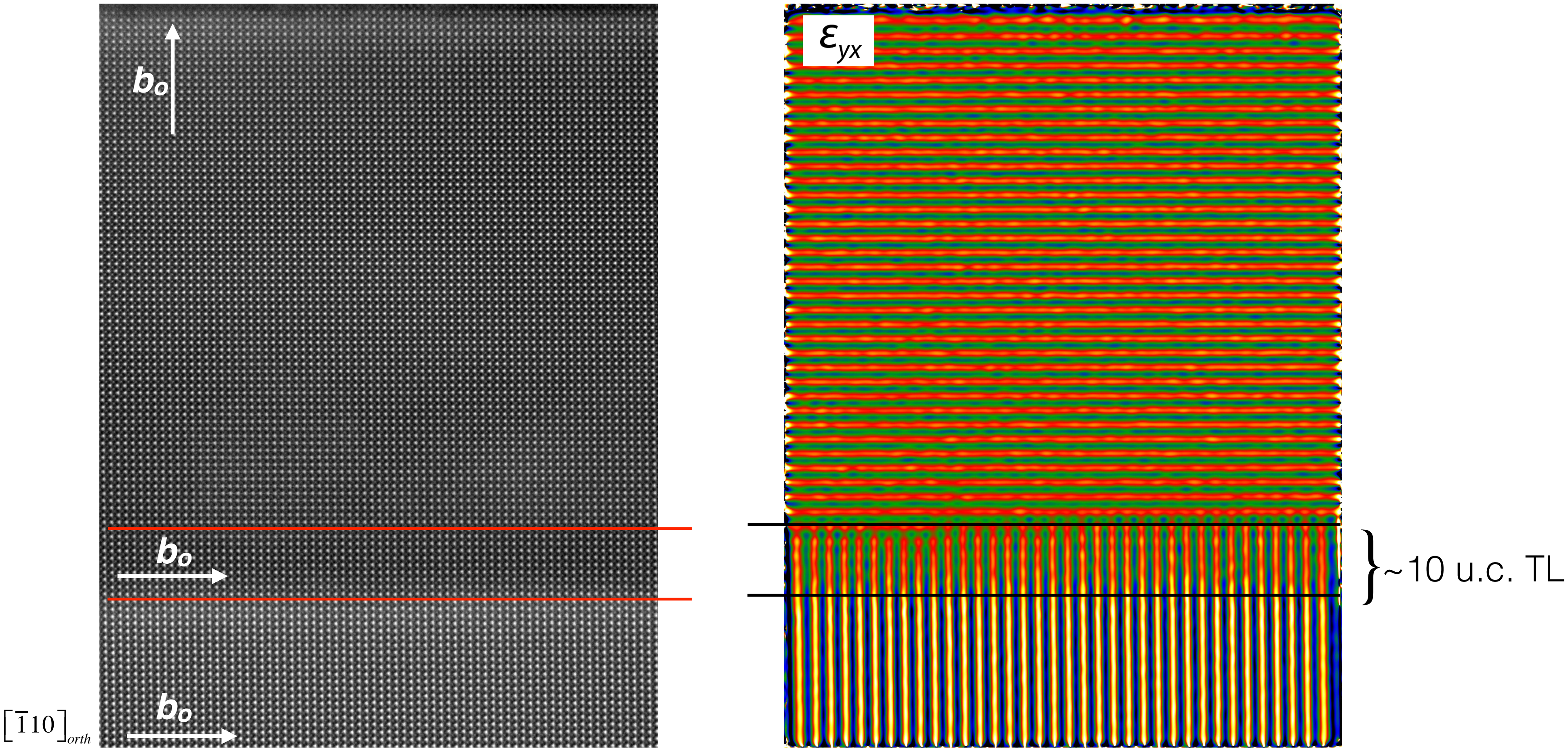
A 10 unit-cell thick transition layer with in-plane b-axis



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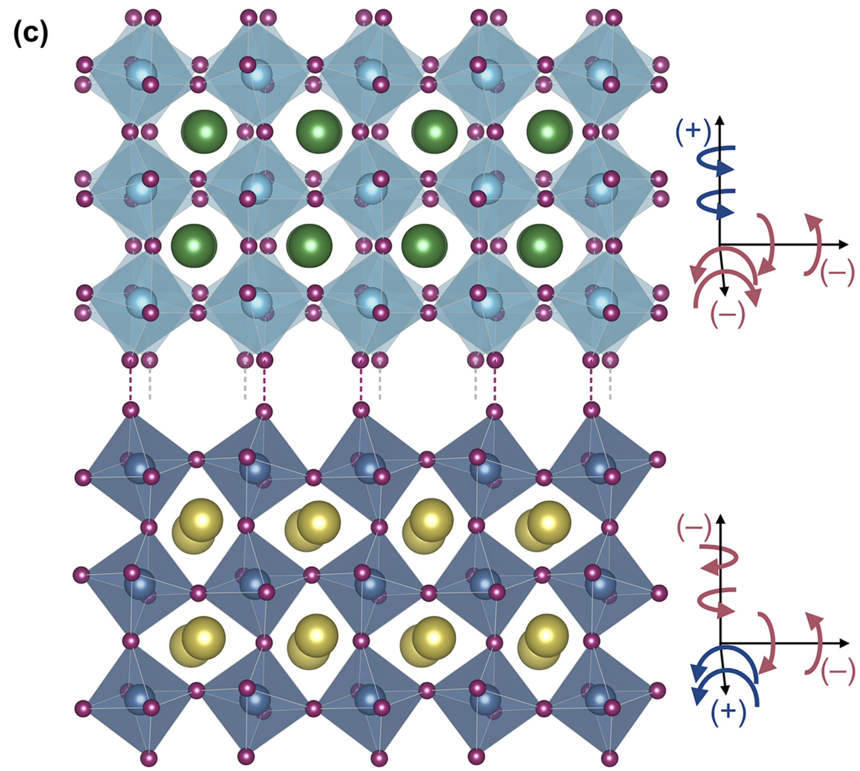
The transition layer comes from the competition between macroscopic strain and the oxygen octahedral rotations coupling energy



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A new path to create a sharp interface between two regions of the same material under distinct mechanical boundary conditions - one of them being possibly 2D

Open questions

This TL a « universal » phenomenon ?

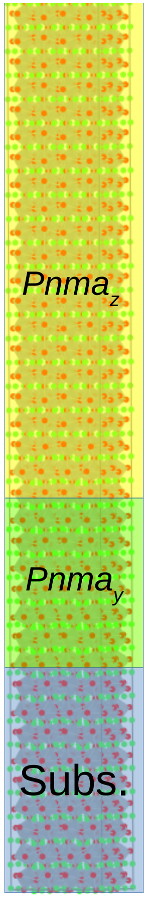
Parameters controlling the TL?

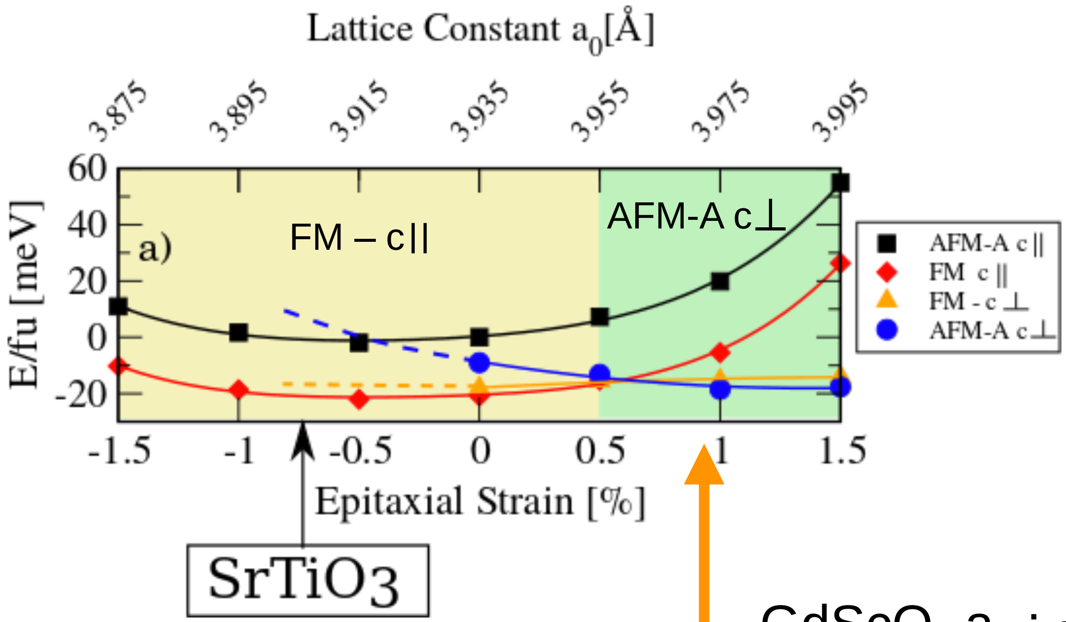
Can this be useful / become functional?

Can this be useful? $LaMnO_3$

b_o out of plane antiferro

b_o in-plane ferro



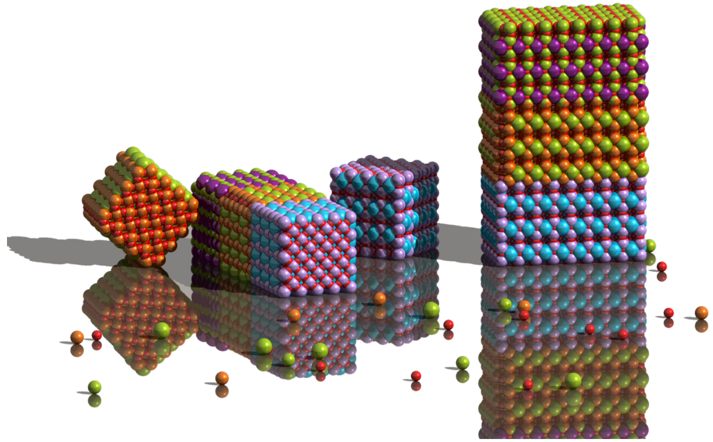


$GdScO_3$ a_{pc}: ~3.96Å

$NdScO_3$ a_{pc}: ~4.00Å

Marcus Schmitt and Philippe Ghosez (Liège)

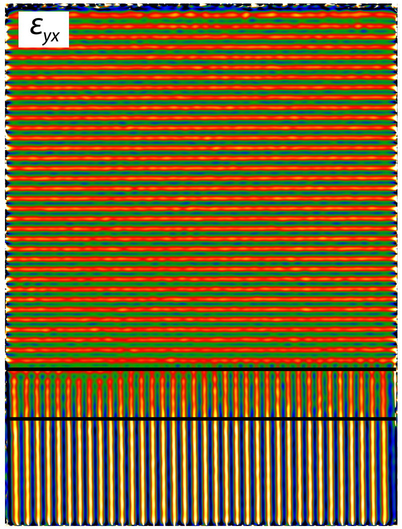
Conclusions


Joerg Harms, MPI Hamburg

Structural and electronic couplings deeply affect the properties in oxide structures

-The $LaAlO_3/SrTiO_3$ system illustrates how an interfacial coupling can lead to a 2D electron system which displays…

-In $LaVO_3$ films on $DyScO_3$ substrates, structural coupling leads to a 10 u.c. thick transition layer



…a way to create a sharp interface between two regions of the same material under distinct mechanical boundary conditions

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FNSNF

The « Geneva » $LaAlO_3/SrTiO_3$ team

and the pioneers

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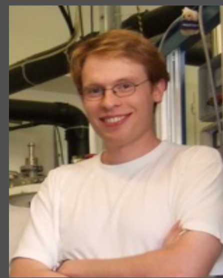
Adrien Waelchli

Stefano Gariglio



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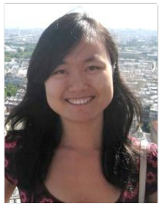

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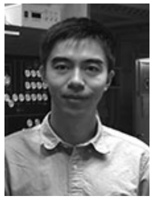

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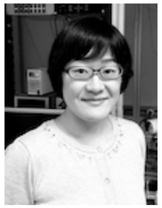

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(Okayama)

Gernot Scheerer
(CERN)

Margherita Boselli
(CERN)

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The « Geneva-EPFL » vanadate team

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Stefano Gariglio

Duncan Alexander EPFL

Hugo Meley

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