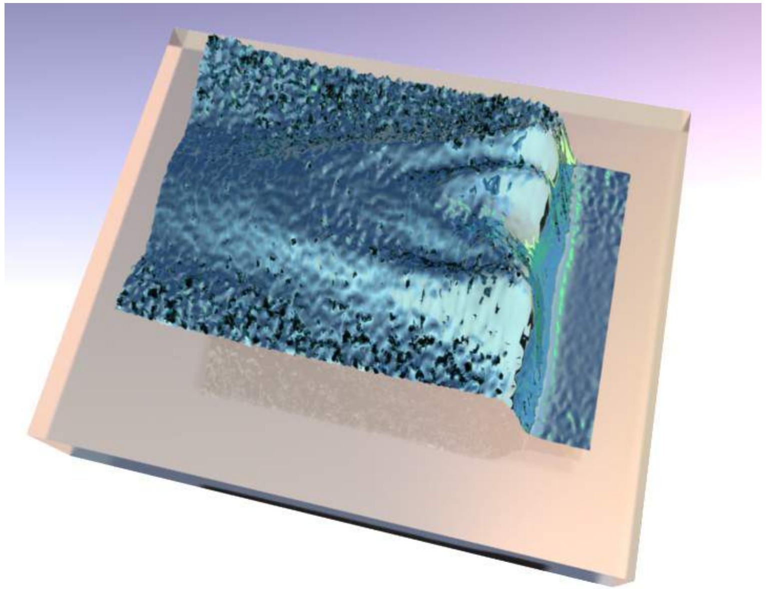
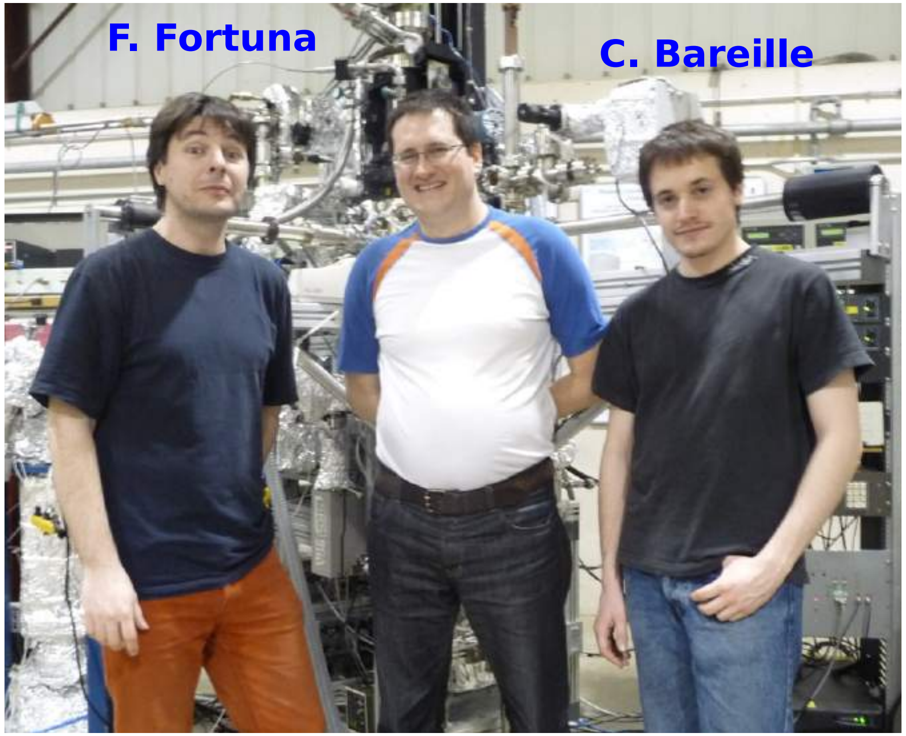
Novel 2D electron gases at the surface of transition-metal oxides



Andrés F. Santander-Syro

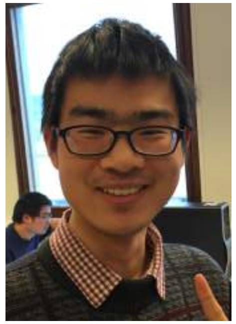
- Nature **469**, 189-193 (2011)
- Phys. Rev. B **86**, 121107(R) (2012)
- Sci. Rep. **4**, 3586 (2014)
- Phys. Rev. App. **1**, 51002 (2014)
- Nature Mater. DOI: 10.1030/NMAT4107
- Phys. Rev. B **92**, 041106(R) (2015)
- Adv. Mater. DOI: 10.1002/adma.201505021 (2016).
- Nat. Commun. 7, 11781 (2016).

"Strongly correlated electrons and exotic states of matter" @ CSNSM



T. Rödel

D.-H. Tsai



Ji Dai

F. Bertran
@ SOLEIL

P. Le Fèvre
@ SOLEIL

E. Frantzeskakis

S. Sengupta

LPS ORSAY

THALES

SOLEIL SYNCHROTRON

Oxygen vacancies in oxides:

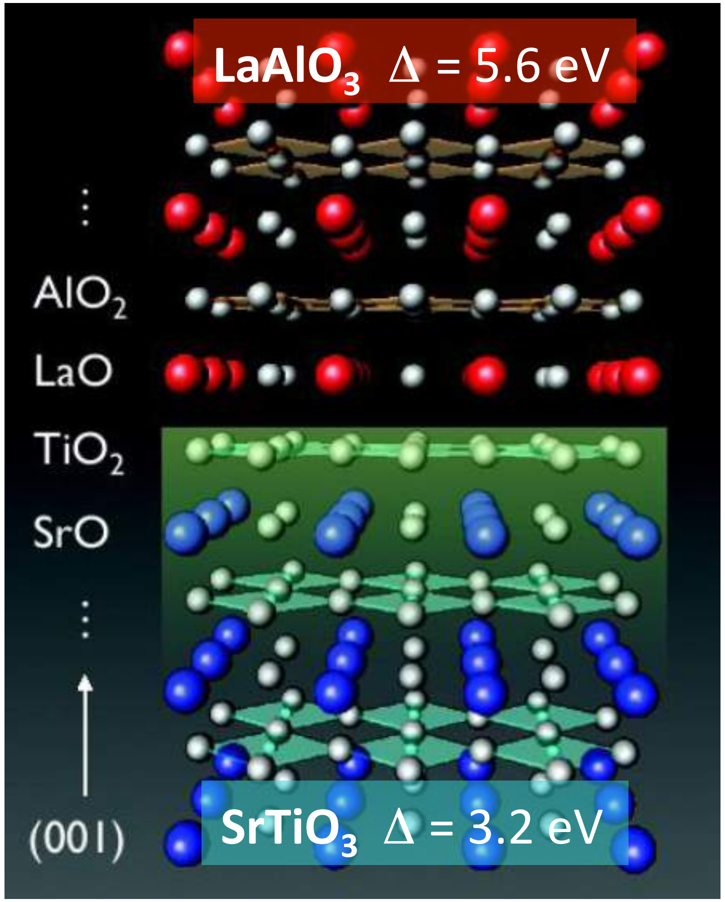
- Electron doping
- 2D confinement (electronics!)
- Tailoring of electronic structure
- Magnetism (and other exotic phenomena ?)

Universal knob to realize novel 2D electron systems and control their functionalities

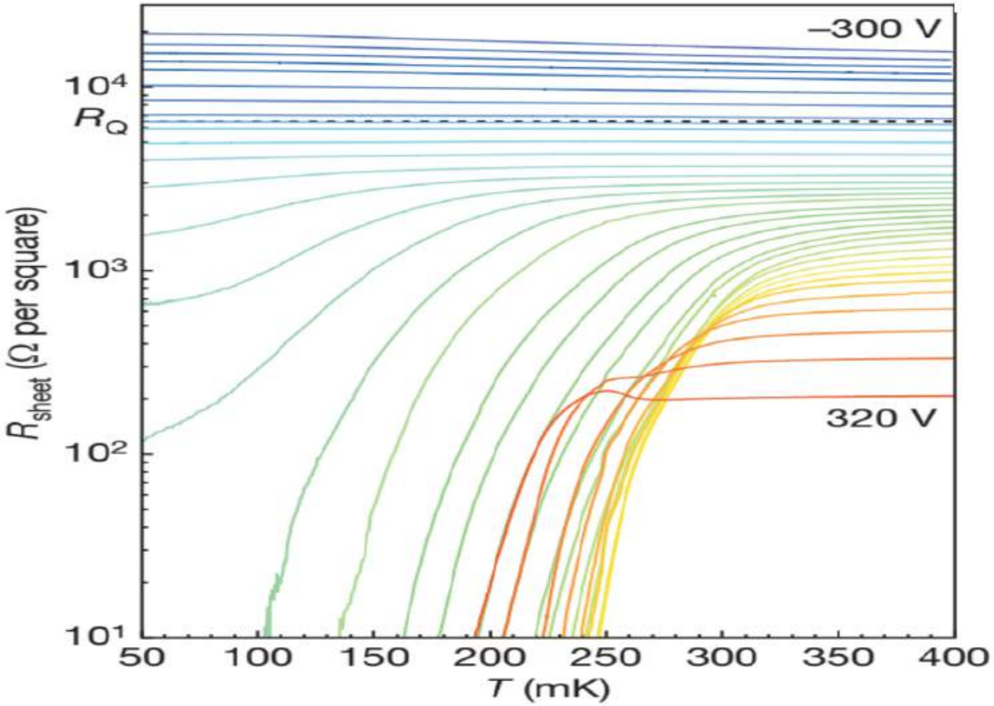
→ OXITRONICS

2DEG at the $LaAlO_3/SrTiO_3$ interface

Ohtomo and Hwang, Nature **427**, 423 (2004).



A. D. Caviglia *et al.*, Nature **456**, 624 (2008).



→ **Microscopic origin ?**
→ **Epitaxial growth €€€**

- **2DEGs**: Building blocks for **e-devices**.
- **Correlated oxides → remarkable properties**
- **$SrTiO_3$**: elementary brick for oxide heterostructures.
- Controllable ground state → **Applications**

Surprise!

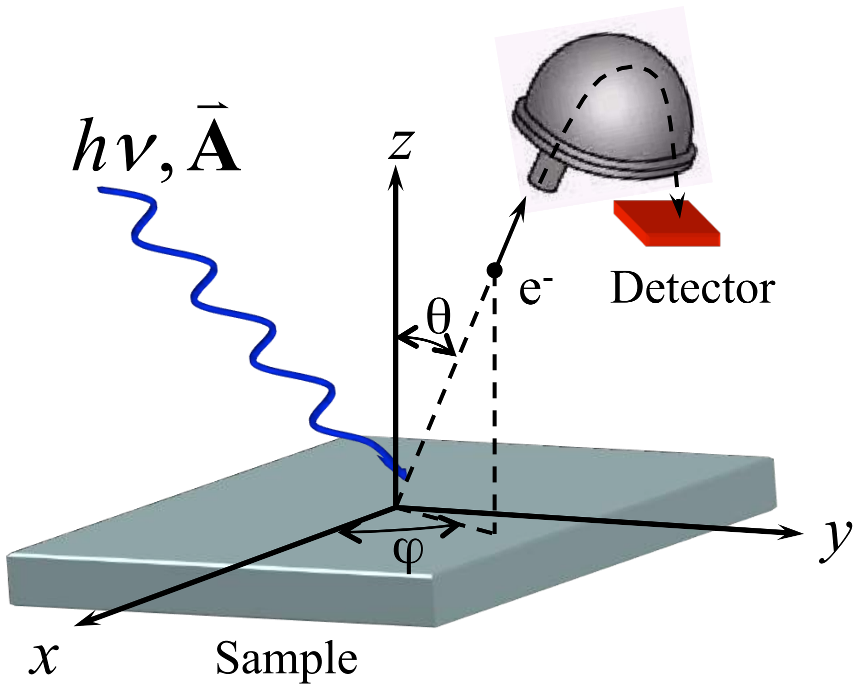
→ A 2DEG forms in vacuum at the **bare** surface of $SrTiO_3$ (cleaved/UV-irradiated)

→ Subband structure, confinement size similar to other STO interfaces

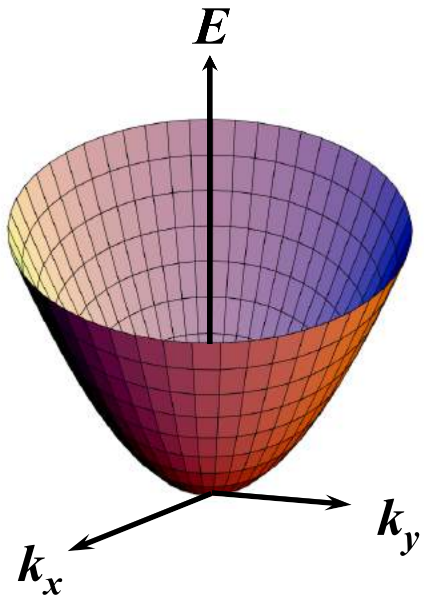
→ Mechanism well understood:
Oxygen vacancies

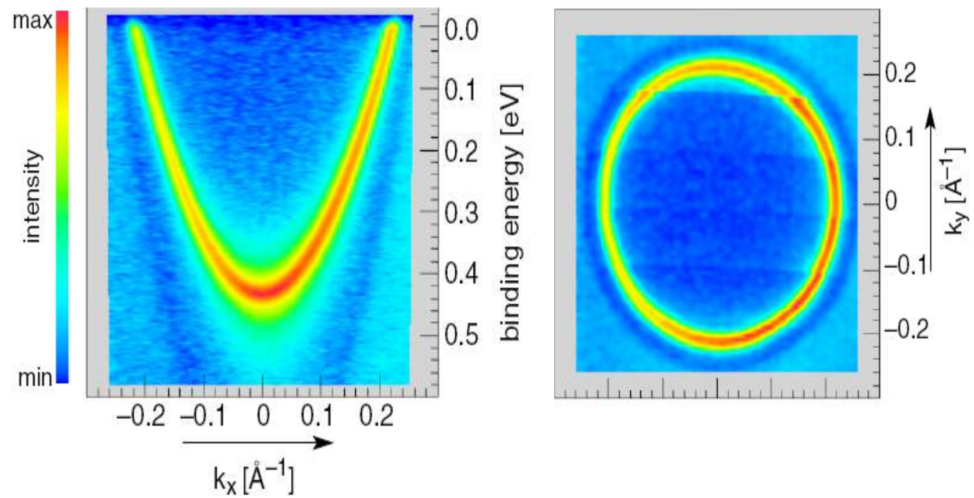
→ **Door open to generate novel 2DEGs in other oxides!**

ARPES principle



Simple example:
Cu(111) surface-state



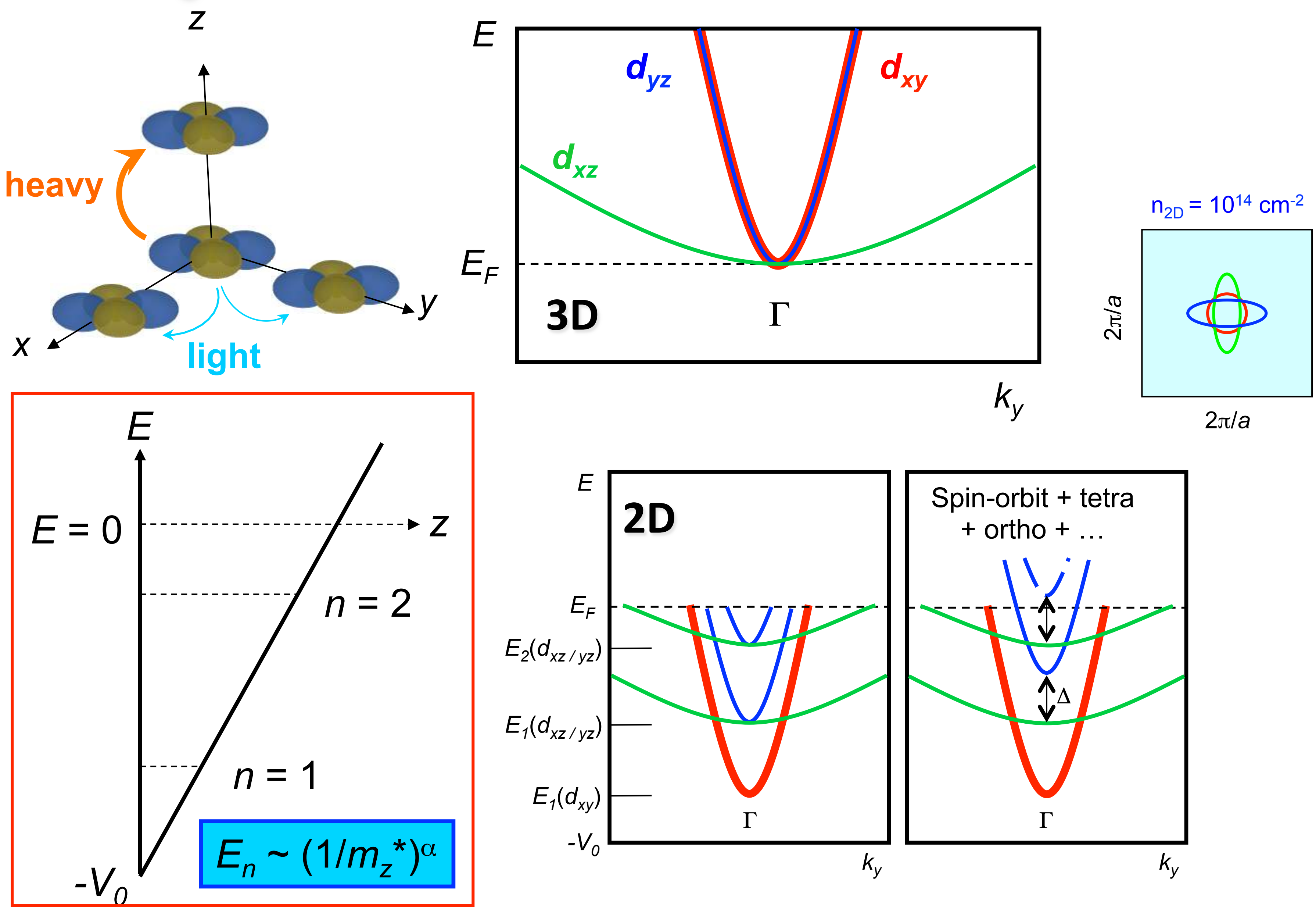


F. Reinert and S. Hüfner, *New Journal of Physics* **7**, 97 (2005)

PES $E_{kin} = h\nu - W - |E_B|$

ARPES $\hbar \mathbf{k}_{\parallel} = \sqrt{2mE_{kin}}\,\sin\theta$

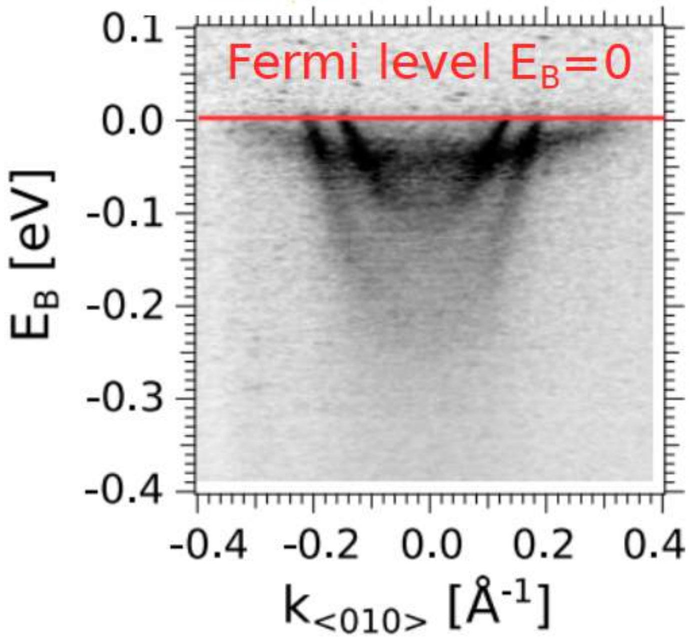
$SrTiO_3$: bulk *vs* 2D-confined electronic structure

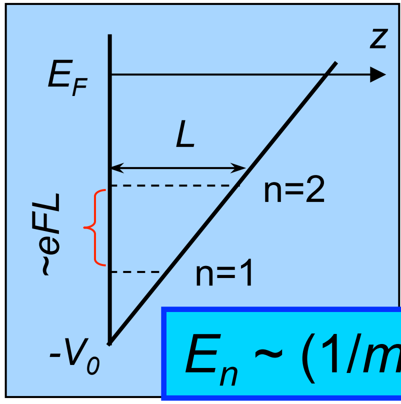


Metallic 2DEG at the surface of **insulating** $SrTiO_3$

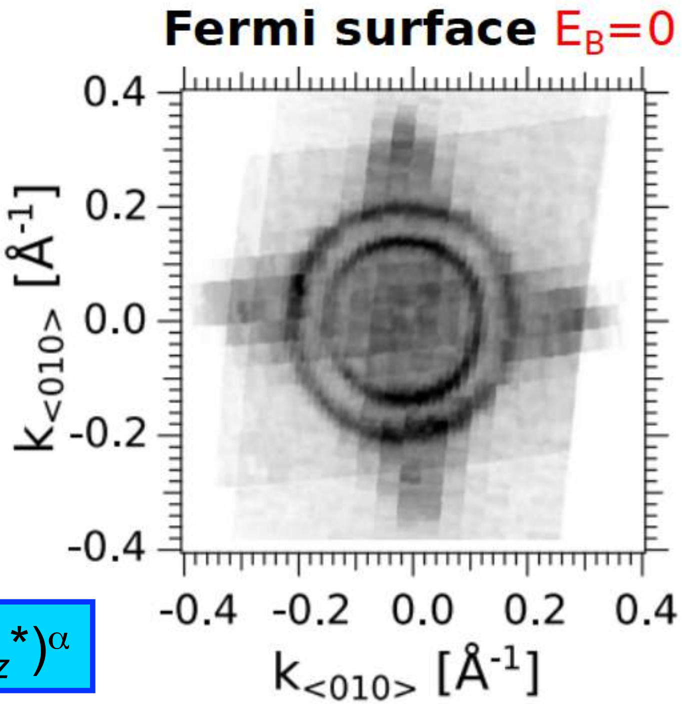
$n_{3D} < 10^{13}$ cm^{-3}

$m_{light} = 0.7m_e$ **$m_{heavy} \approx 10m_e$**





$E_n \sim (1/m_z^*)^\alpha$



→ The subbands are **ordered** by the **symmetries of their wave-fns**

$F \approx 83$ MV/m

$V_0 \approx 260$ meV

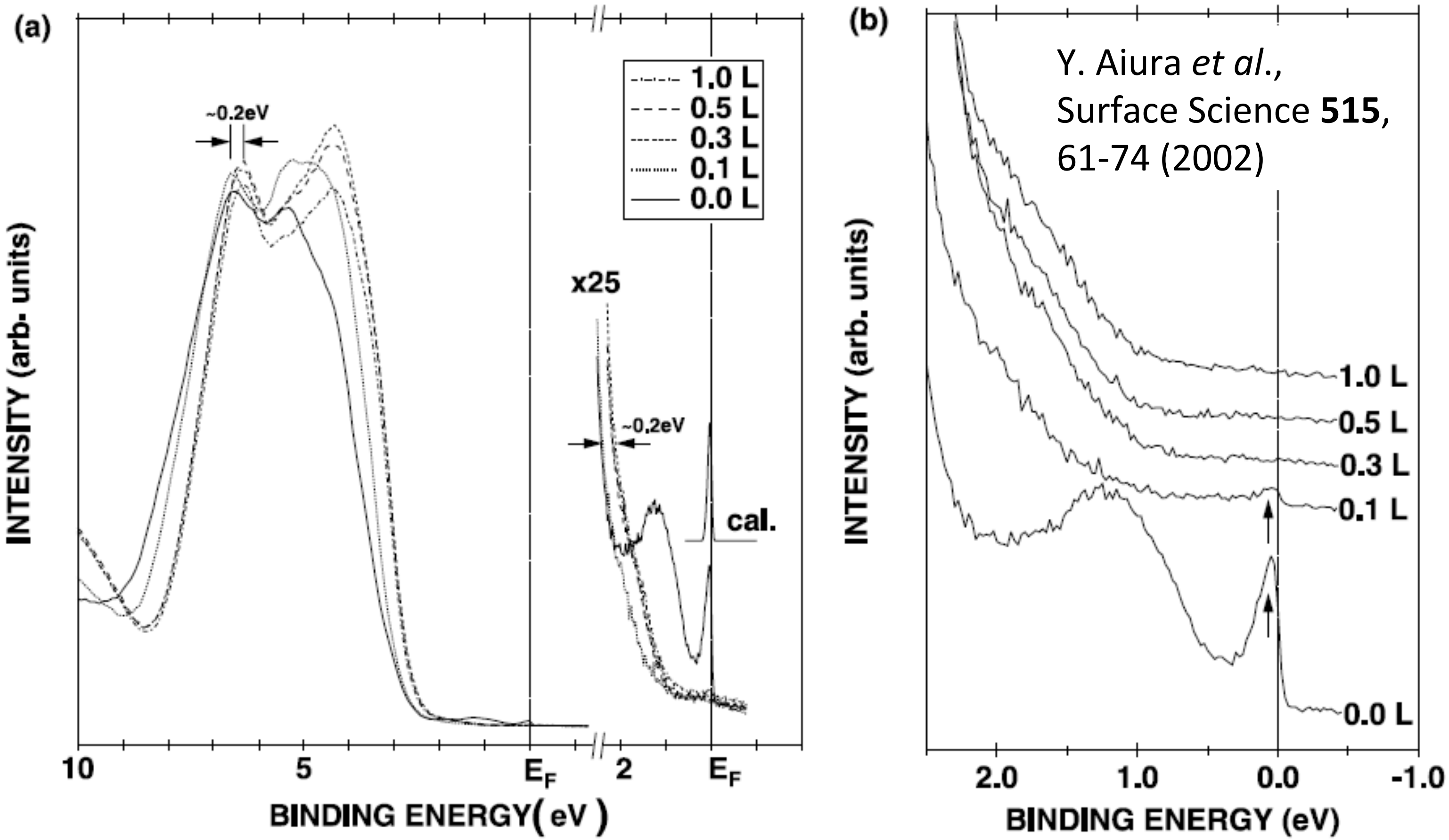
$eFL \approx \Delta E \rightarrow L \approx 14.5$ Å ≈ 4 u.c.

- AFSS *et al.*, Nature **469**, 189-193 (2011)
- T. C. Rödel et al., Adv. Mater. **28**, 1976 (2016)

See also:

- W. Meevasana *et al.*, Nat. Mat. **10**, 114 (2011)

Band bending due to O-vacancies at the cleaved/irradiated surface of STO



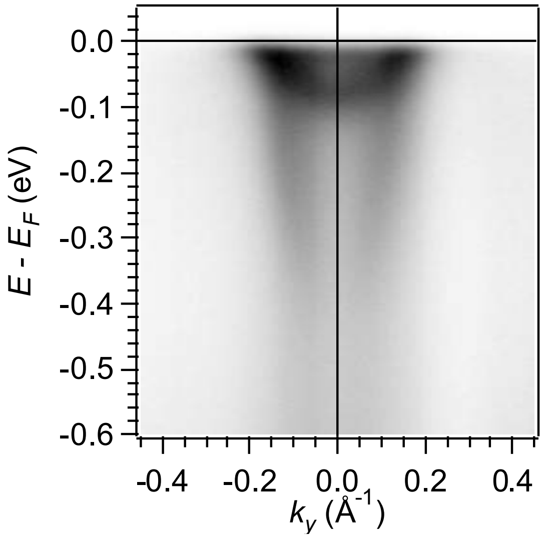
UV + PO_2 control of the 2DEG carrier density:

- S. McKeown Walker *et al.*, Adv. Mater. **2015**, DOI: 10.1002/adma.201501556
- L. Dudy *et al.*, Adv. Mater. **2016**, DOI:10.1002/adma.201600046

Can this mechanism be generalized to other oxides?

2DEG on $KTaO_3$

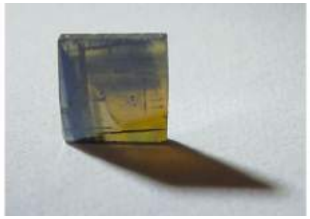
→ Reconstruction of the orbital character

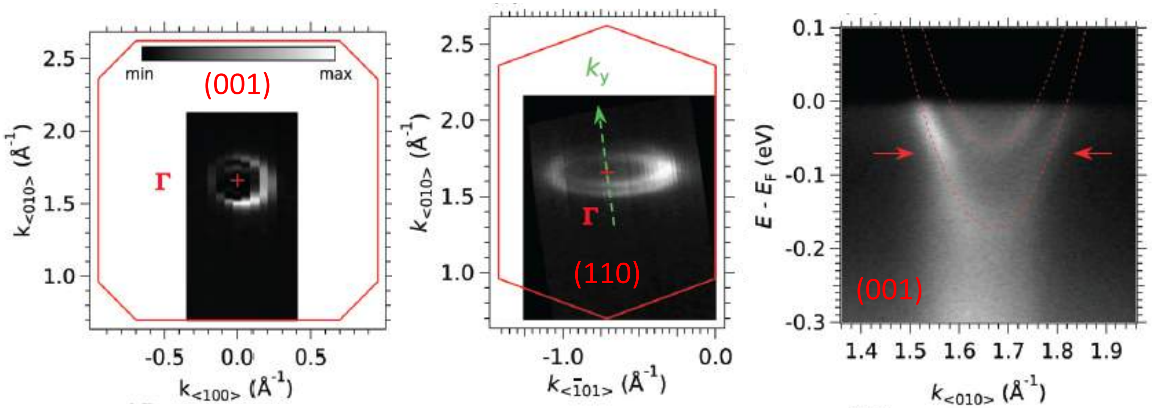


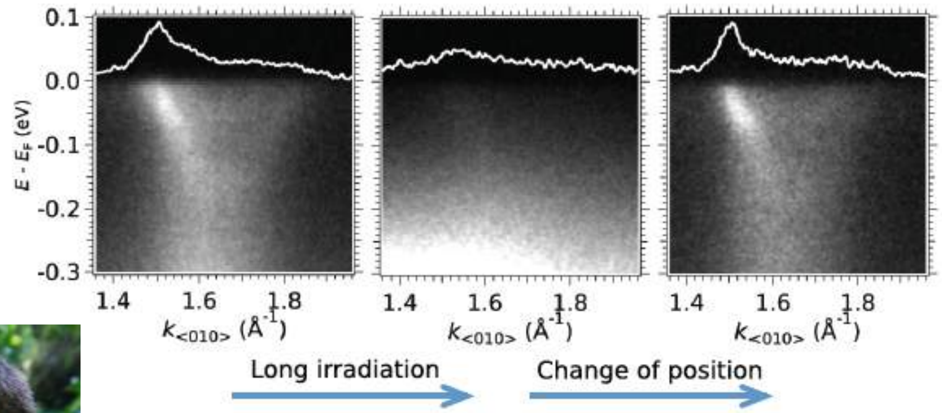
- AFSS *et al.*, PRB **86**, 121107(R) (2012)
- P. D. C. King *et al.*, PRL **108**, 117602 (2012)

2DEG on anatase-TiO_2

→ Nano-engineering of the metal-insulator transition using light





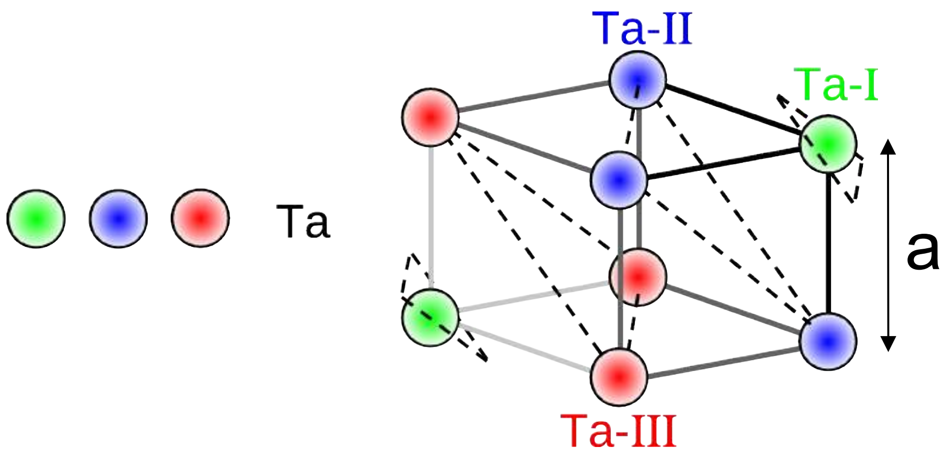


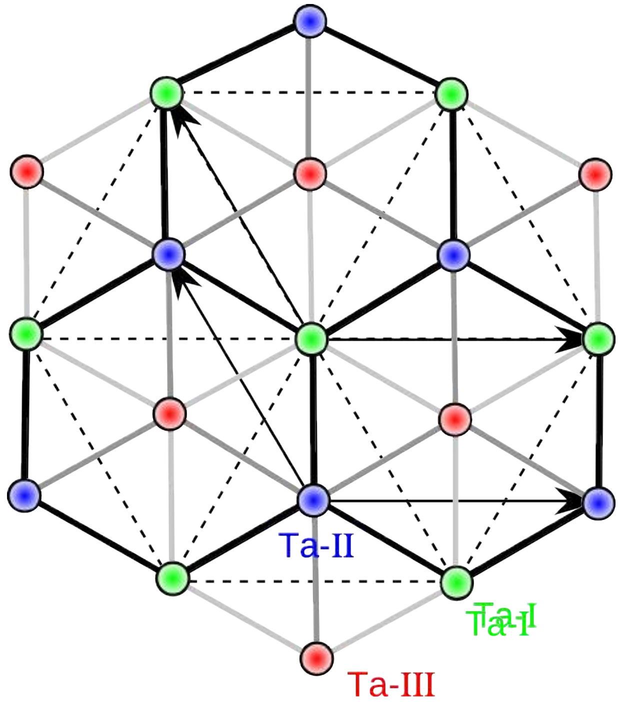
- S. Moser *et al.*, PRL **110**, 196403 (2013)
- T. C. Rödel *et al.*, PRB **92**, 041106(R) (2015)

Surface topology

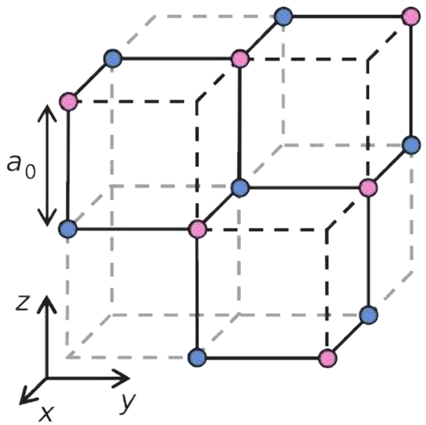
Tailoring new 2DEGs with emergent properties at oxide surfaces

Transition-metal oxides: (111) surface





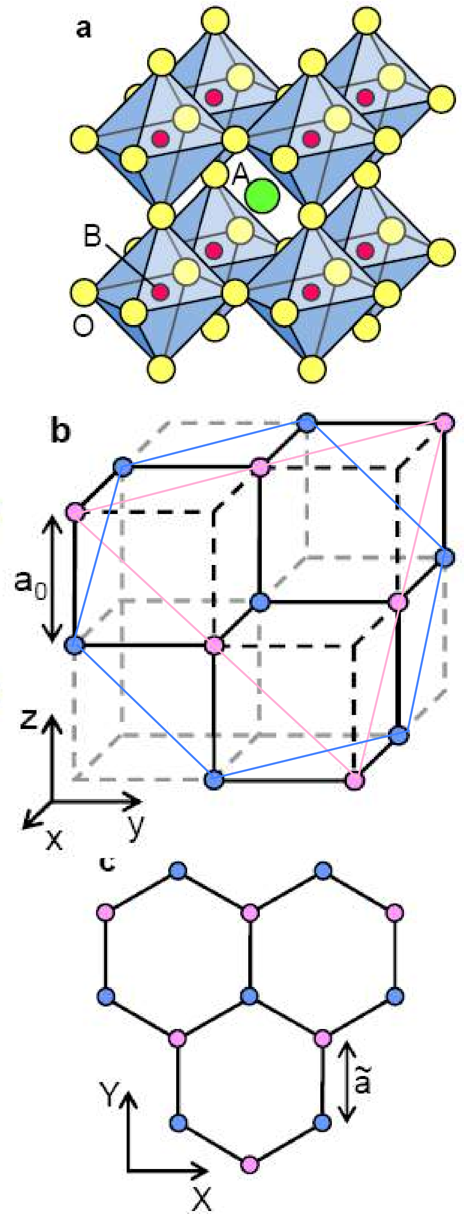
3-fold symmetry

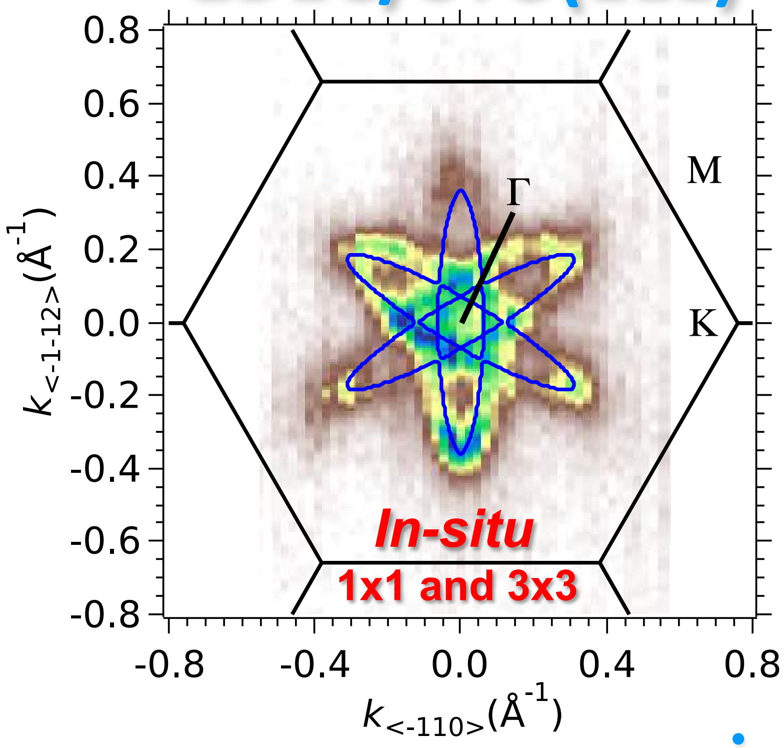


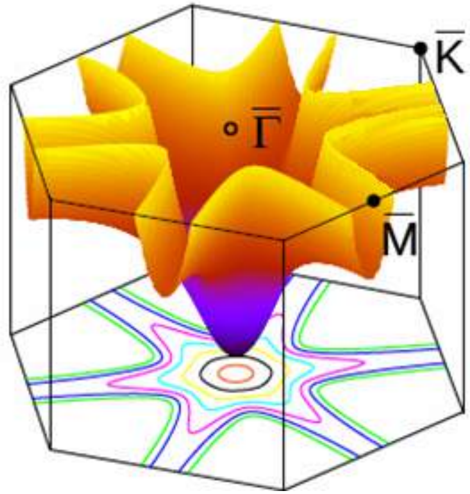
Bilayer → Honeycomb lattice

Possible non-trivial topological states
D. Xiao *et al.*, Nat. Comm. 2, 596 (2011)

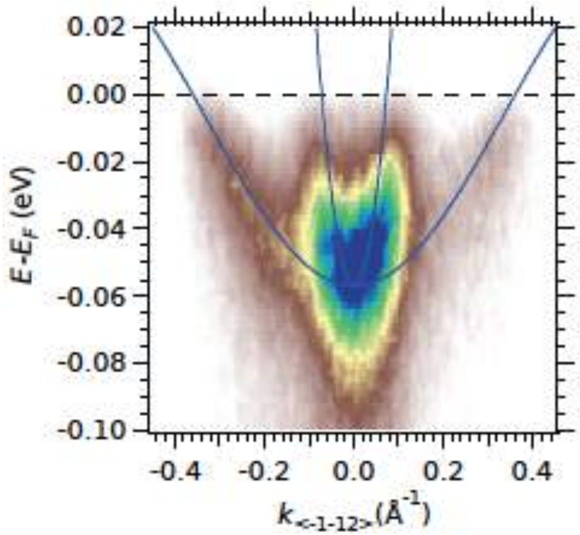
2DEG/STO(111)







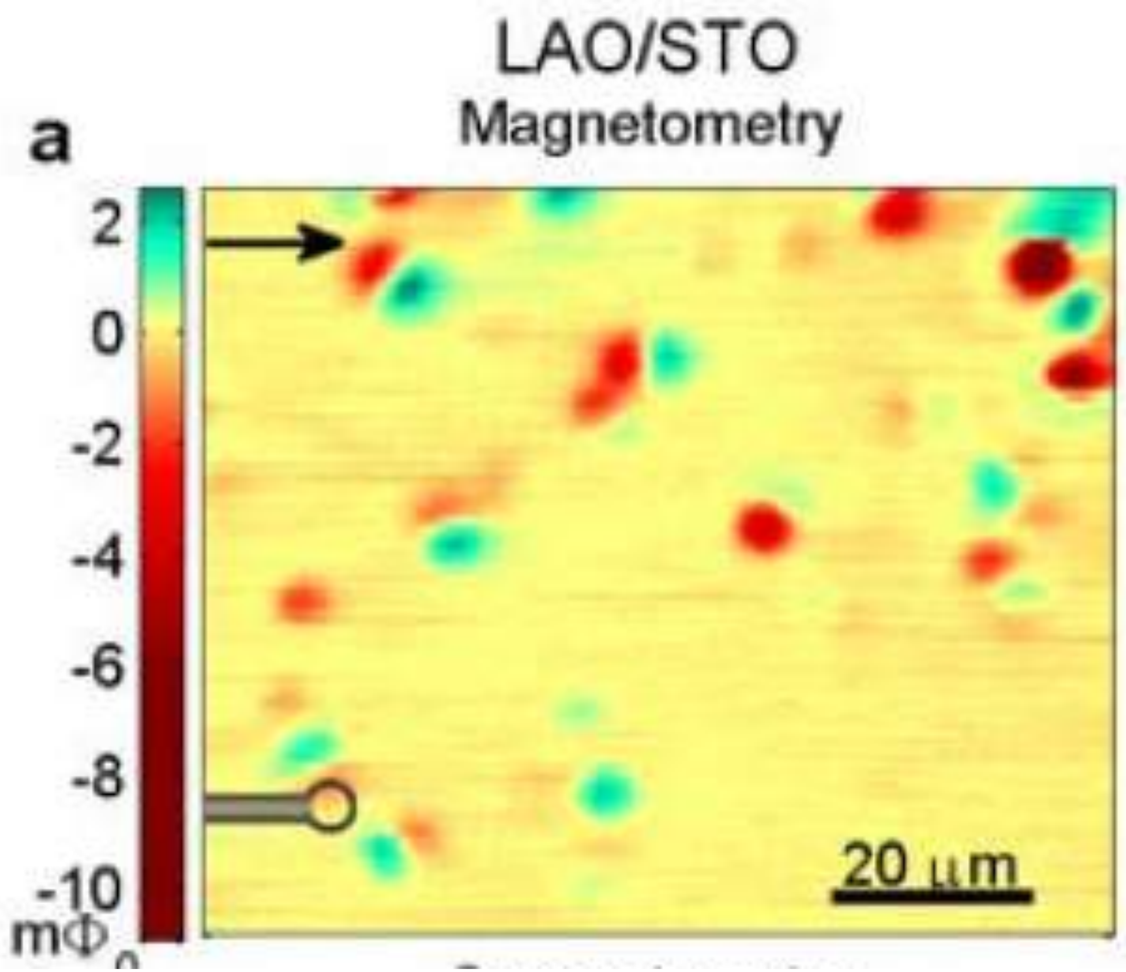
- Sci. Rep. **4**, 3586 (2014).
- Phys. Rev. App. **1**, 51002 (2014).



“Graphene” with oxydes!
D. Xiao et al, Nature Comm. 2011

Magnetic effects at **<u>non-magnetic</u>** oxide **<u>surfaces</u>**

Ferromagnetic domains in LAO/STO



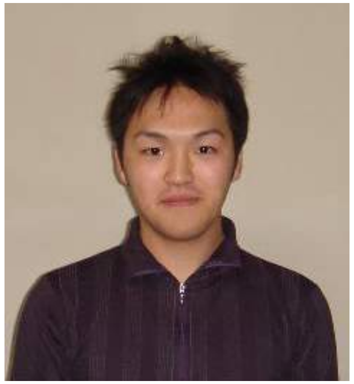
- L. Li *et al*., Nat. Phys. **7**, 762-766 (2011).
- J. Bert *et al*., Nat. Phys. **7**, 767-771 (2011).

Room-T ferromagnetic nano-domains at the oxygen-deficient $SrTiO_3$ surface

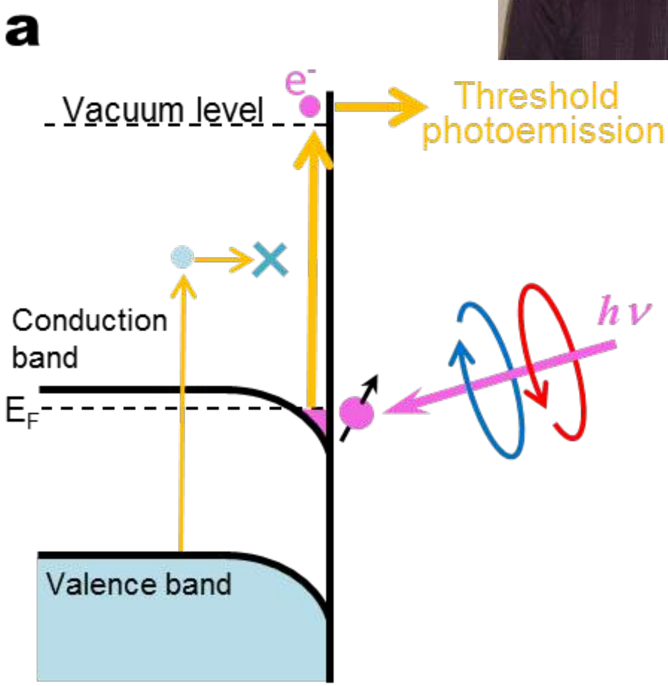
The University of Tokyo
The Institute for Solid State Physics

Shin group – Laser-spectroscopy

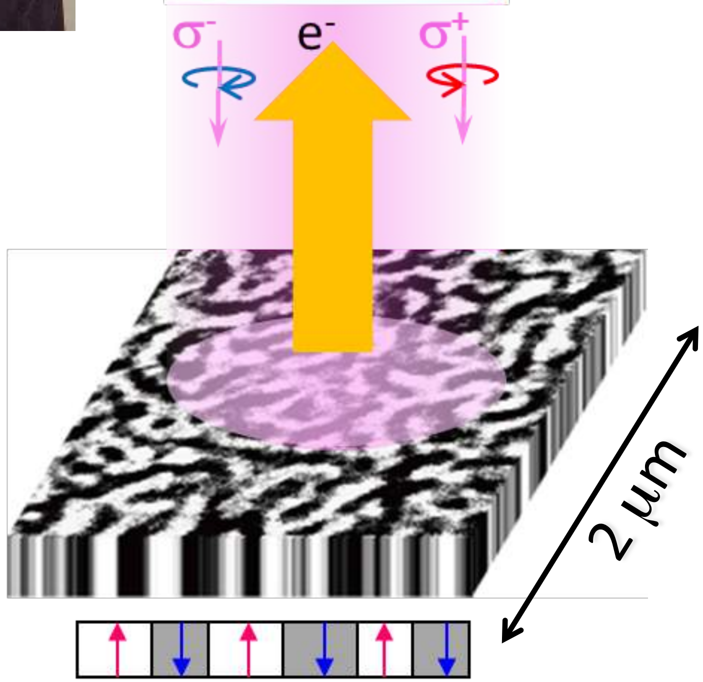
Toshiyuki Taniuchi



CSNSM

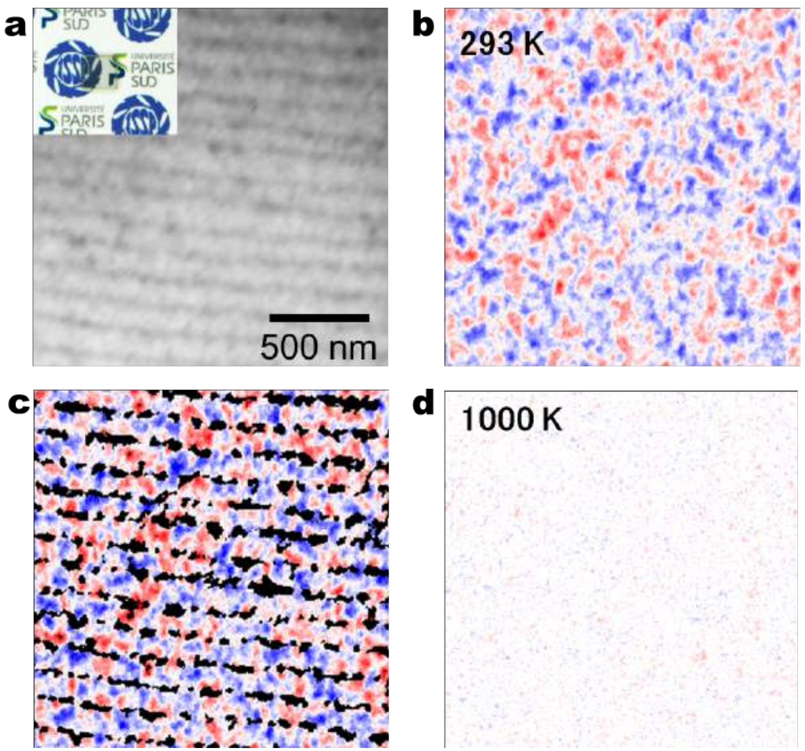


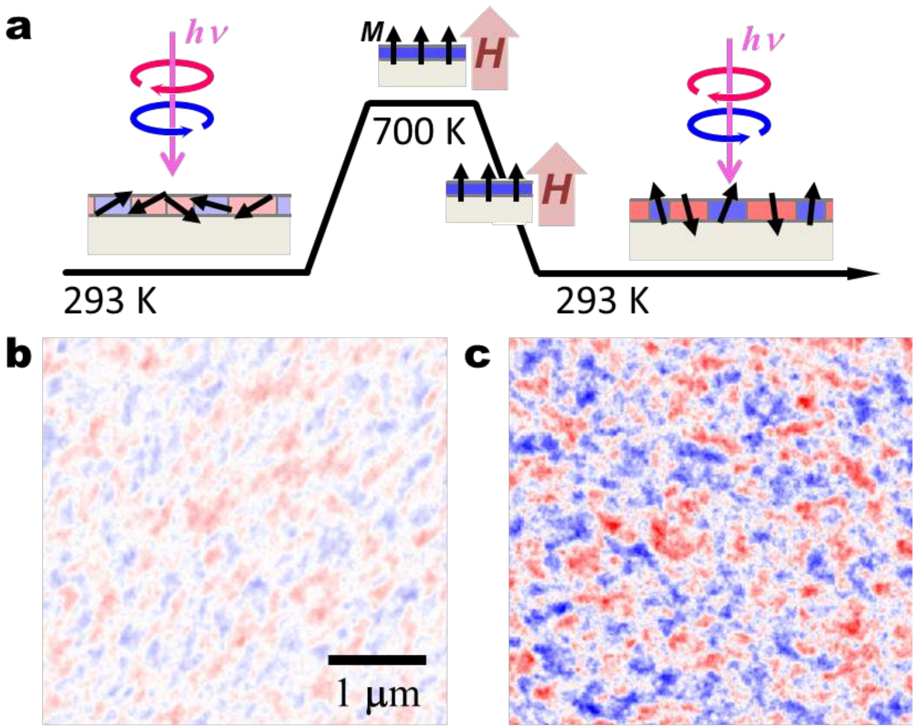
Example:
FM domains in FePt



T. Taniuchi *et al.*, Rev. Sci. Instrum. **86**, 023701 (2015).

Room-T ferromagnetic nano-domains at the oxygen-deficient $SrTiO_3$ surface

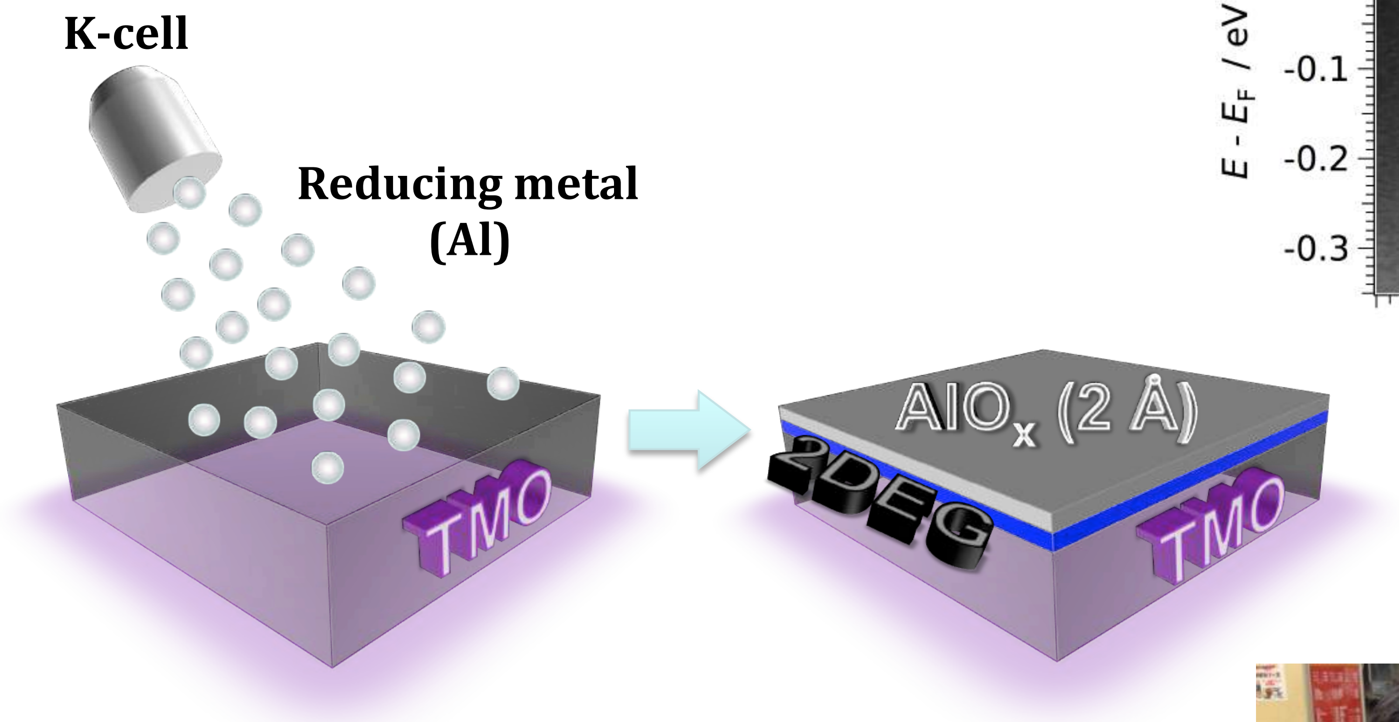


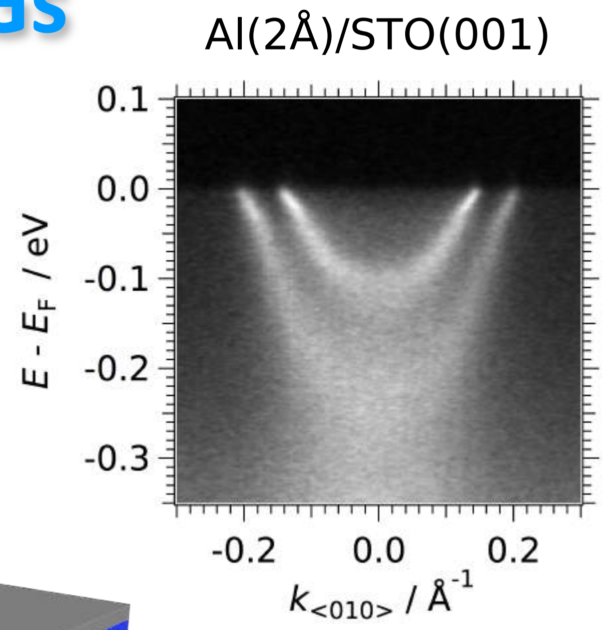


T. Taniuchi *et al.*, Nat. Commun. **7**, 11781 (2016).

Universal fabrication of 2DEGs in oxides

Universal fabrication of 2DEGs in functional oxides

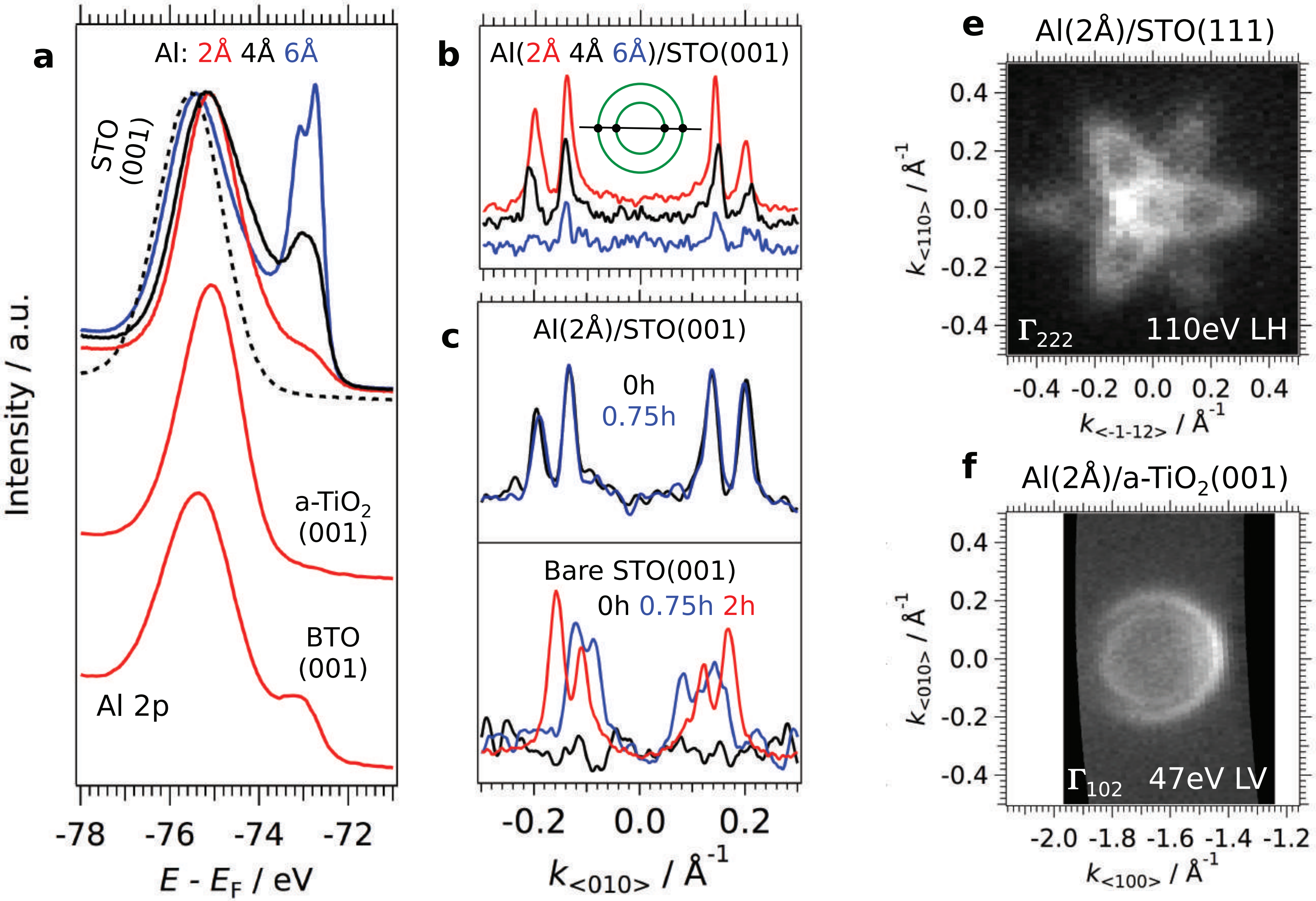




T.C. Rödel, F. Fortuna *et al.*, Adv. Mater. **28**, 1976 (2016)

Redox reaction → AlO_x + 2DEG

Universal method



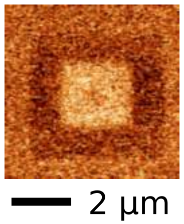
T.C. Rödel, F. Fortuna *et al*., Adv. Mater. DOI: 10.1002/adma.201505021 (2016)

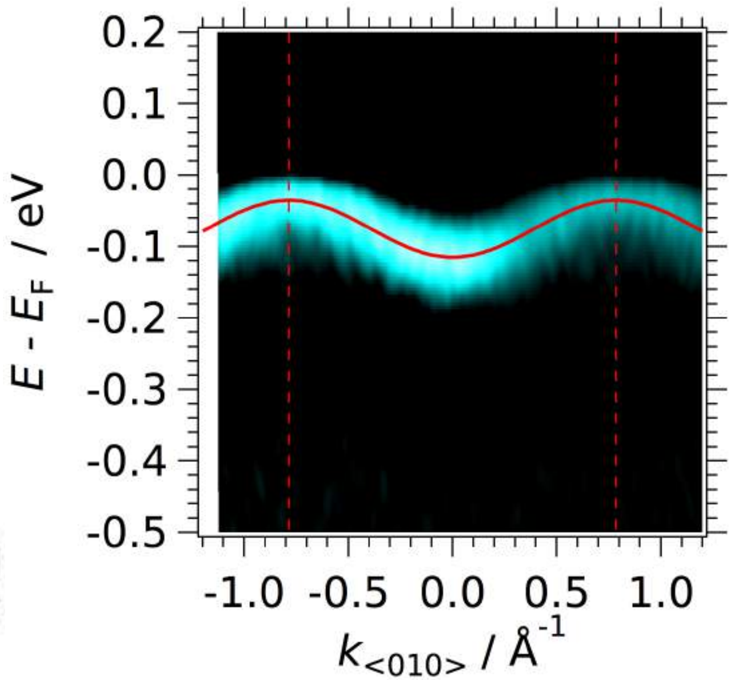
2DEG at the surface of a room-temperature ferroelectric insulator

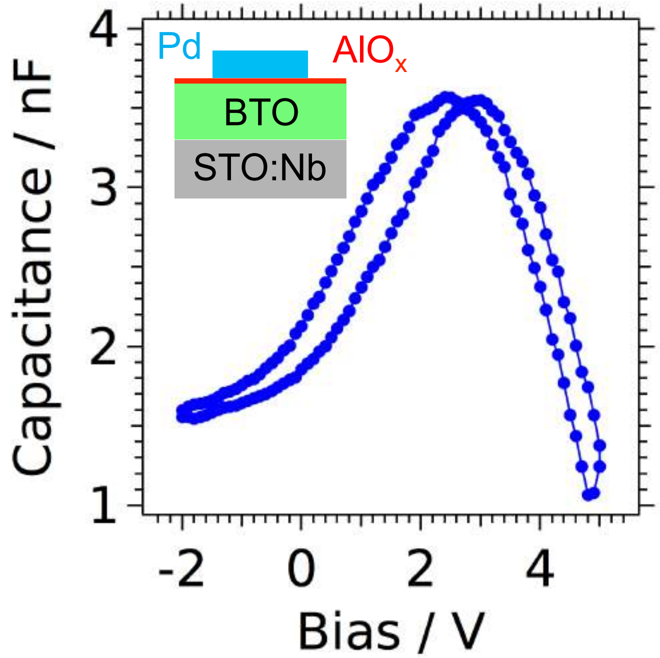
Al(2Å)/$BaTiO_3$/$SrTiO_3$

$BaTiO_3$/STO

PFM





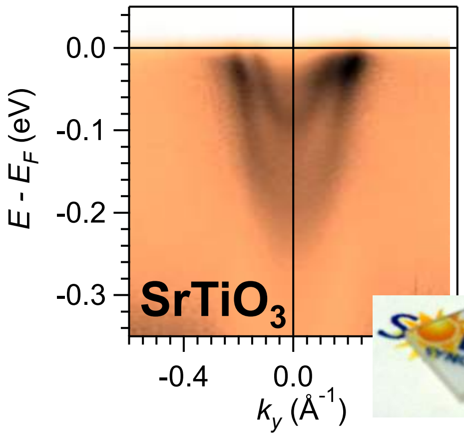


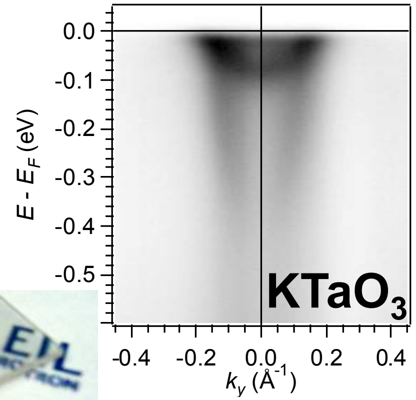
T.C. Rödel, F. Fortuna *et al.*, Adv. Mater. **28**, 1976 (2016)

"Surface Oxitronics"

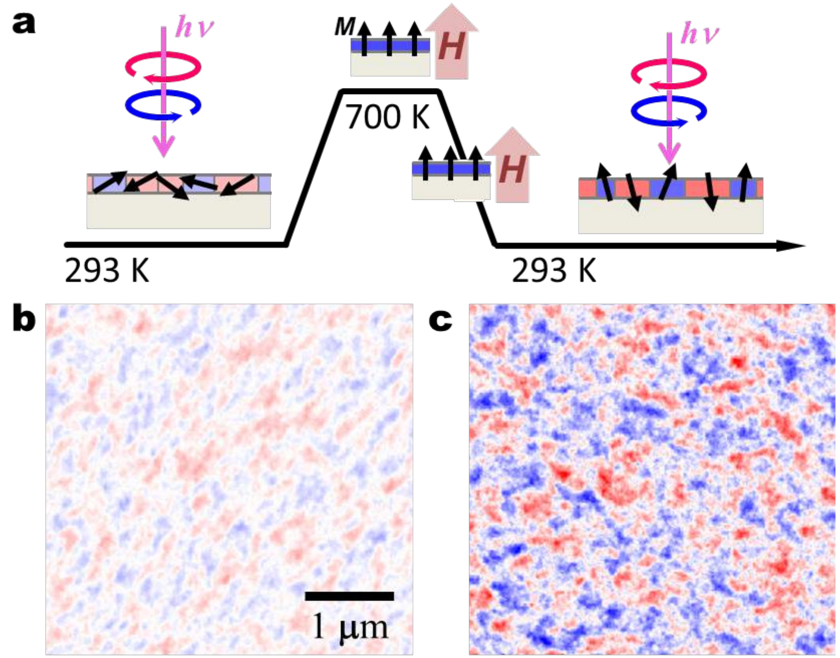
Oxide surfaces are novel materials

- Surface 2DEGs in **various TMOs**
- **New physics** not shown by the bulk



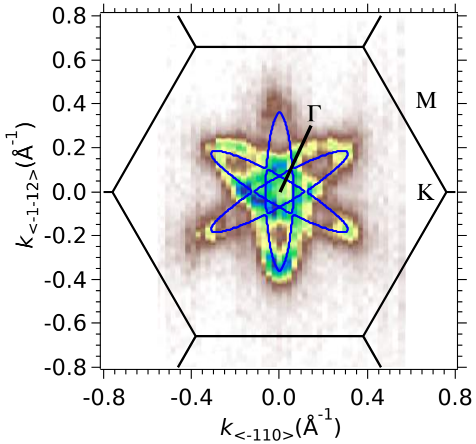


Magnetism



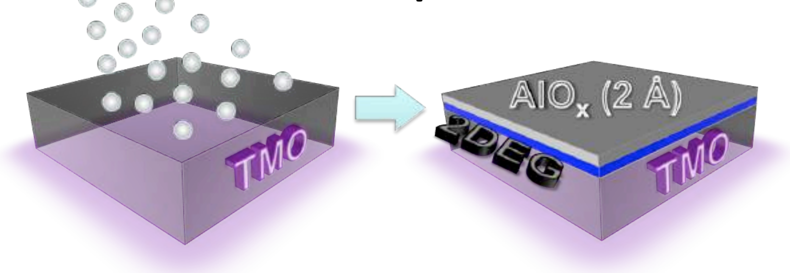
Surface **topology**

→ **Tailor novel 2DEGs**



Universal fabrication

→ **Transport & devices**



New playground for fundamental and applied physics !

Light-induced nightmares for Condensed-Matter theoreticians

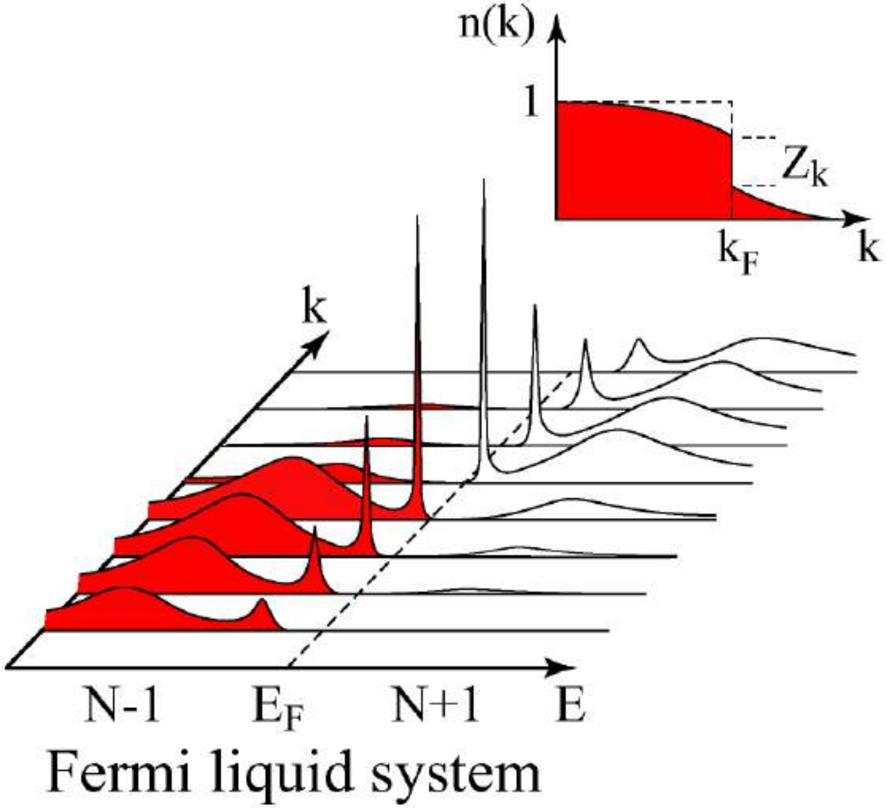
The mystery of $SrVO_3$

a paradigmatic correlated-electron metal:

Mott-Hubbard or…

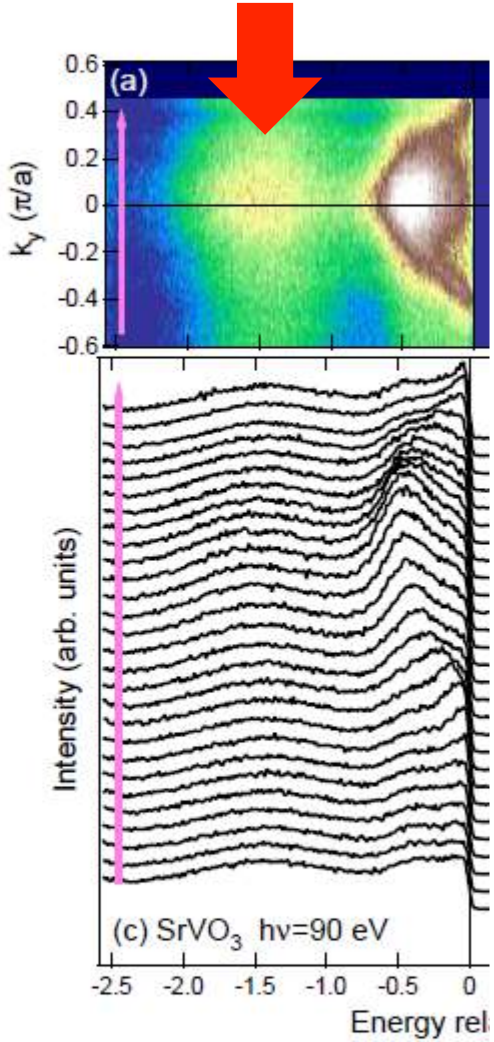
oxygen vacancies?

Many-body effects in photoemission spectra



$SrVO_3$

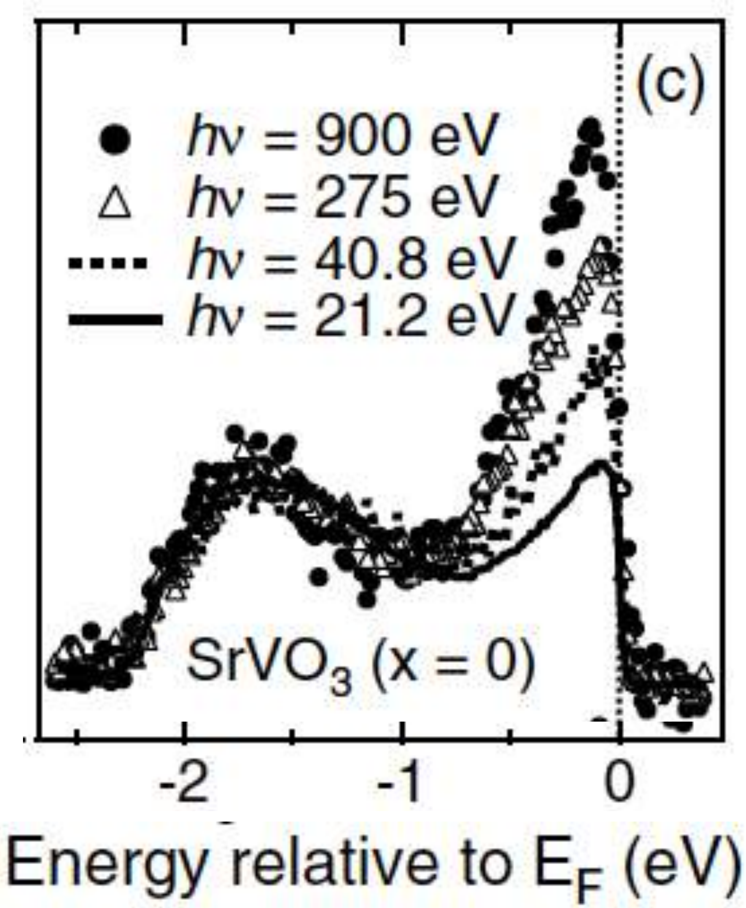
"Hubbard band"



Aizaki *et al*., PRB 2011

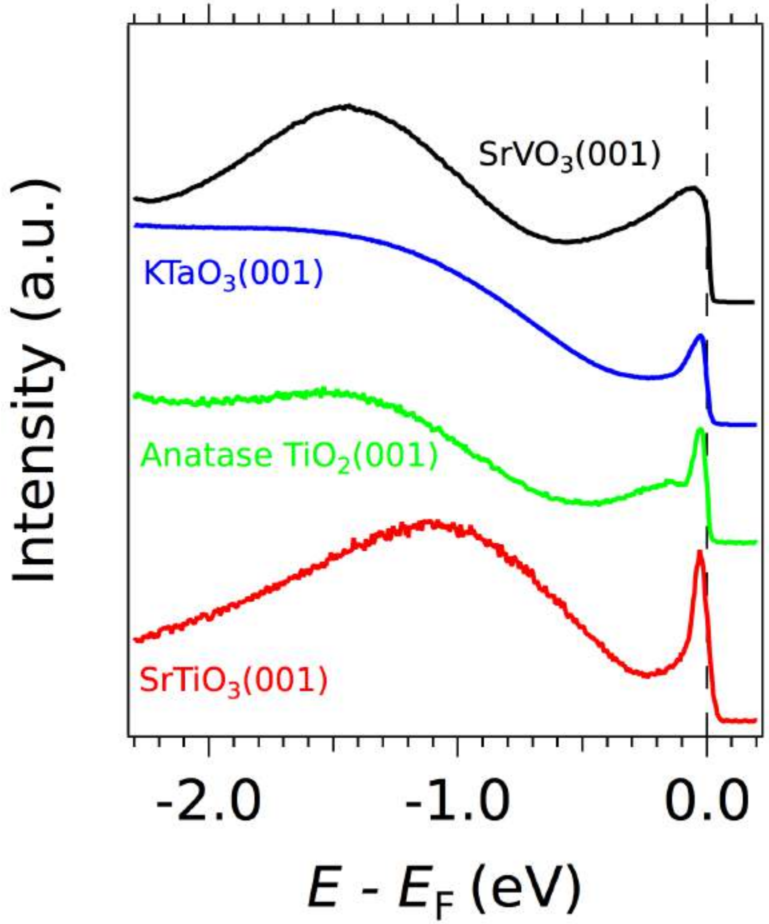
Intrinsic ratio of QP-to-Hubbard peaks?

Seikiyama *et al.*, PRL 2004

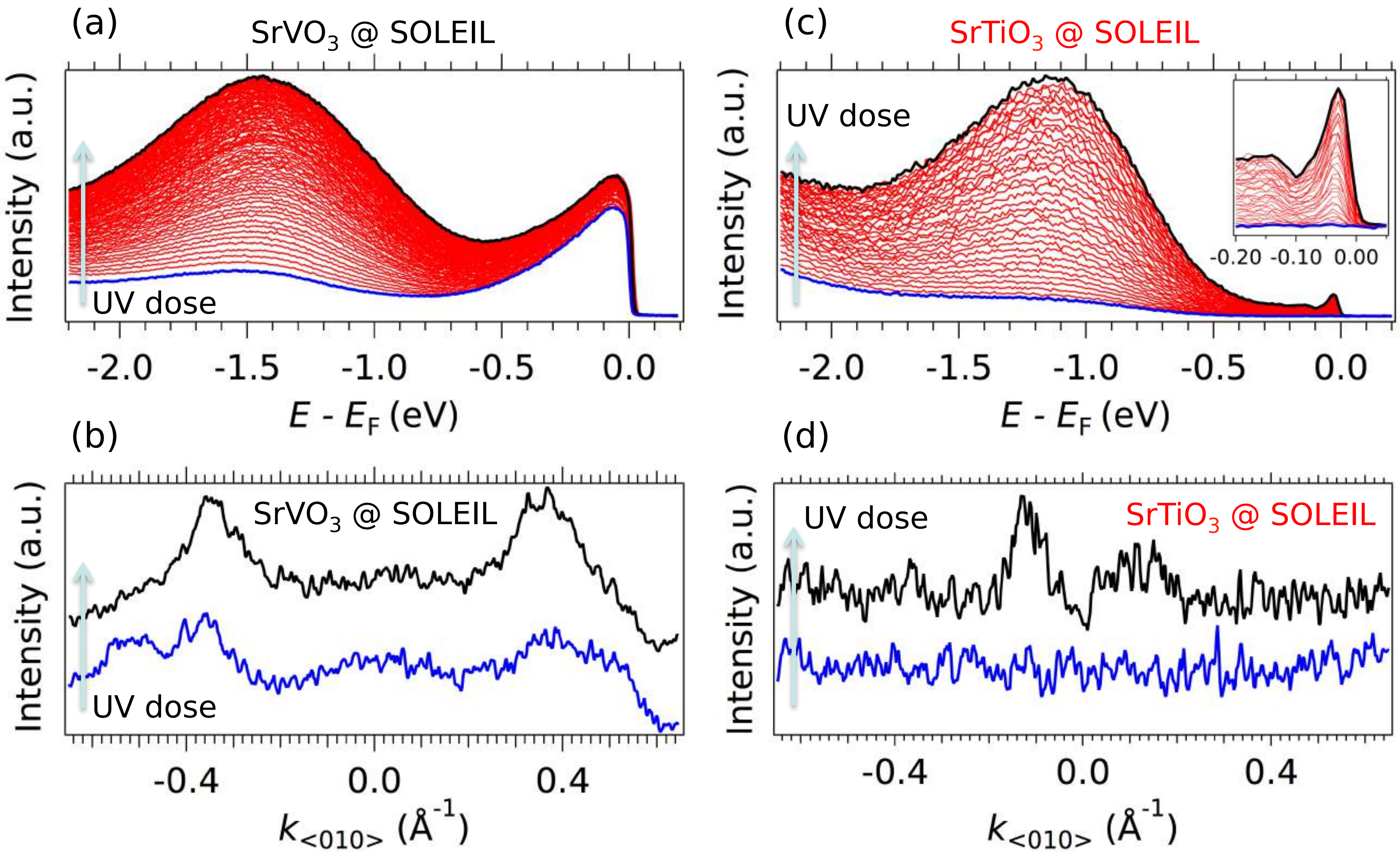


Hubbard band or … oxygen vacancies !?

S. Backes, T. C. Rödel *et al.*, PRB **94**, 241110 (2016)

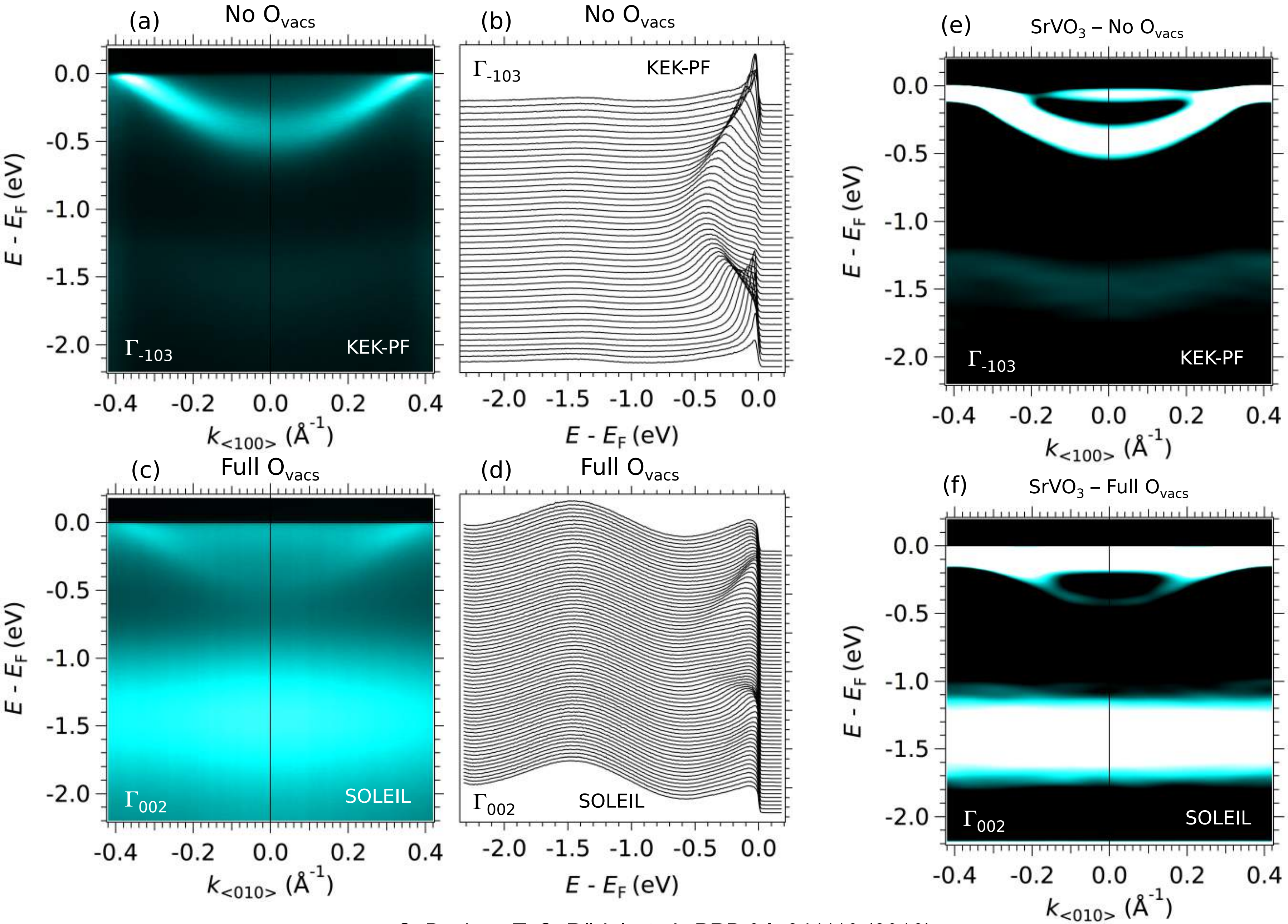


"Hubbard" peak strongly depends on UV dose!



S. Backes, T. C. Rödel *et al.*, PRB **94**, 241110 (2016)

Disentangling Hubbard and oxygen vacancies



S. Backes, T. C. Rödel *et al.*, PRB **94**, 241110 (2016)