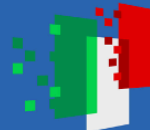




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# Oxide 2D-electron gas with engineered functional properties for quantum physics and applications

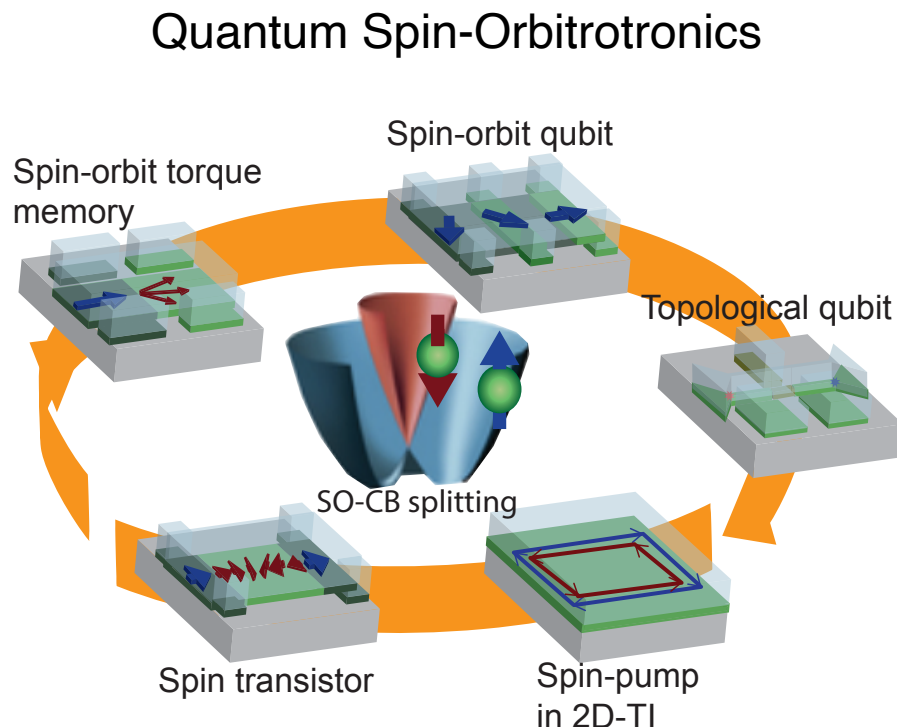
Marco Salluzzo— Research Director at CNR-SPIN  
(resp. for CNR of SPOKE 6 activities)



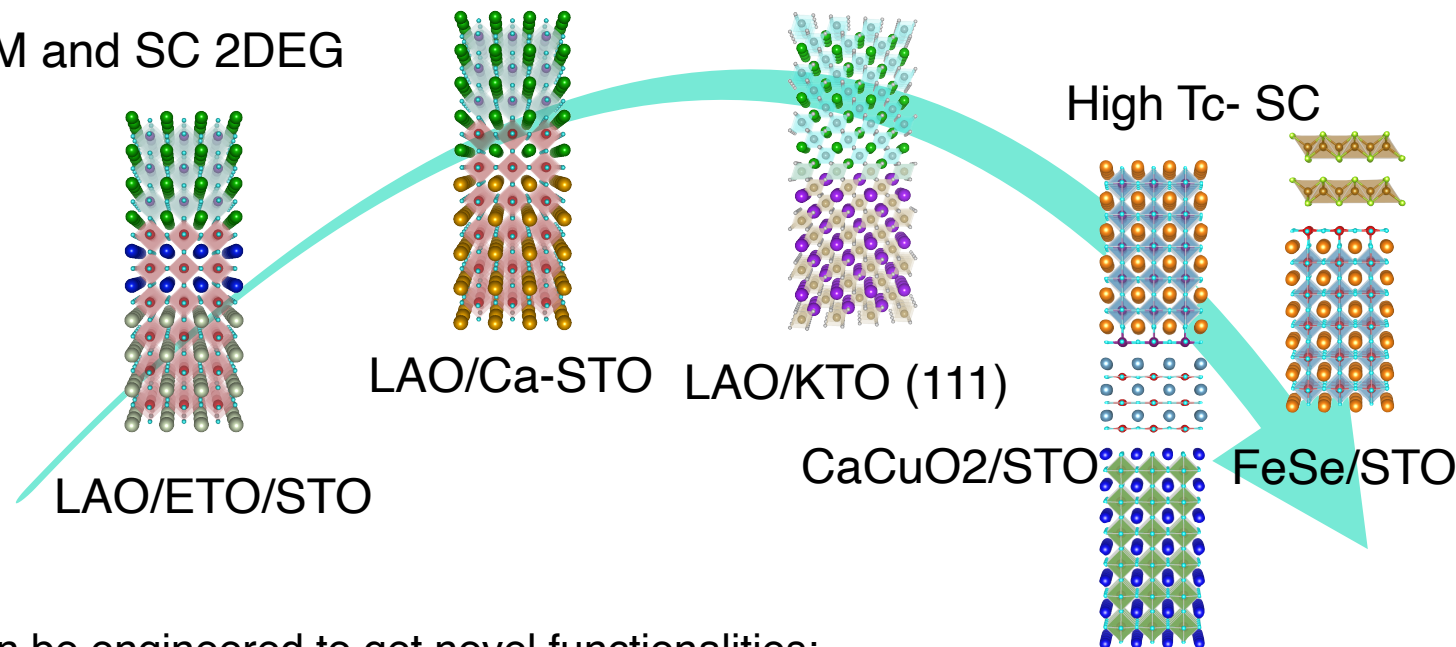
Consiglio Nazionale delle Ricerche  
Istituto SPIN - Napoli

## Why oxide 2D-electron systems ?

FE and SC 2DEG SC 2DEG+large SO



FM and SC 2DEG

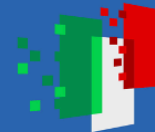


- can be engineered to get novel functionalities:  
Superconductivity+ Spin-orbit-Coupling + ferromagnetism +ferroelectricity

- Top-down device engineering using conventional e-beam lithography  
- Electric field effect large tunability of the electronic properties (e.g. Tc, Jc, SOC, ground-state)

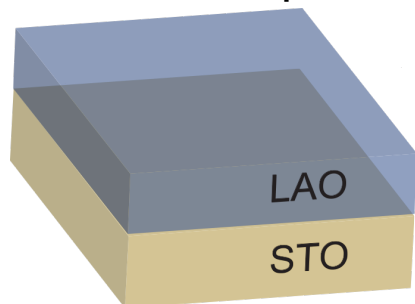
-Integration with Silicon at the hand

The interplay between inversion and time reversal symmetry breaking gives rise to novel quantum phenomena and novel quantum devices concepts

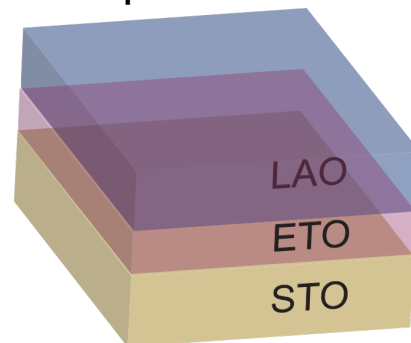


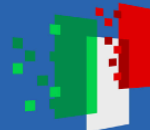
## Examples of Novel Oxide 2DEGs by Interface Engineering

SC+RSOC q2DEG



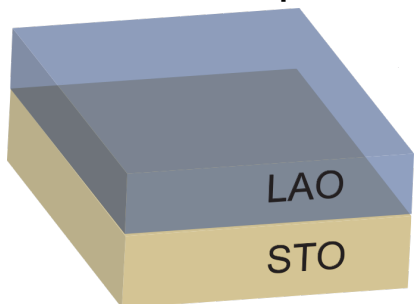
SC+RSOC +FM  
q2DEG



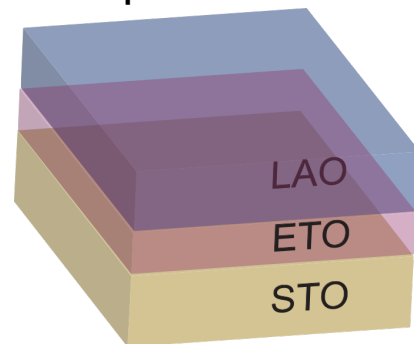


## Examples of Novel Oxide 2DEGs by Interface Engineering

SC+RSOC q2DEG



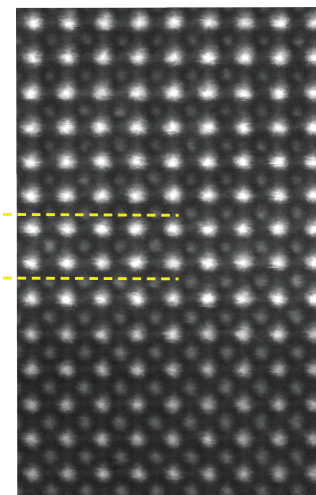
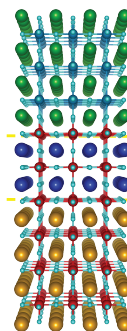
SC+RSOC +FM  
q2DEG



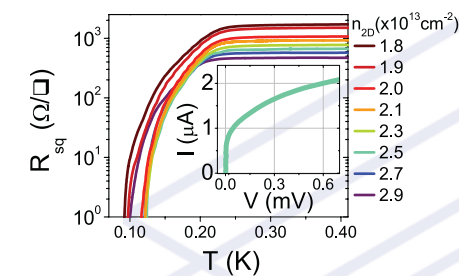
LaAlO<sub>3</sub>

EuTiO<sub>3</sub>

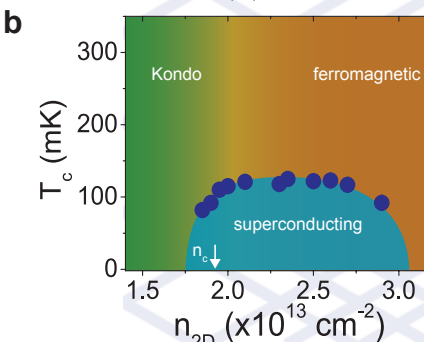
SrTiO<sub>3</sub>



a



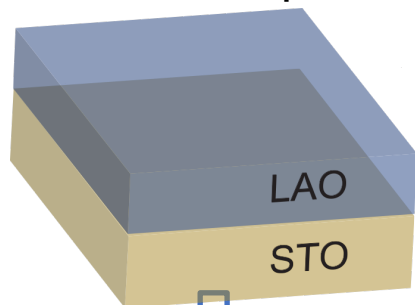
b



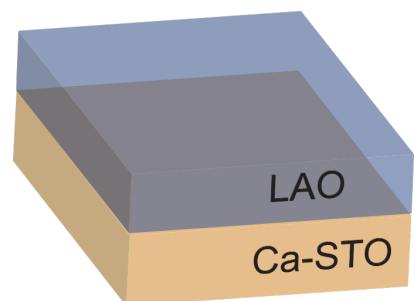


## Examples of Novel Oxide 2DEGs by Interface Engineering

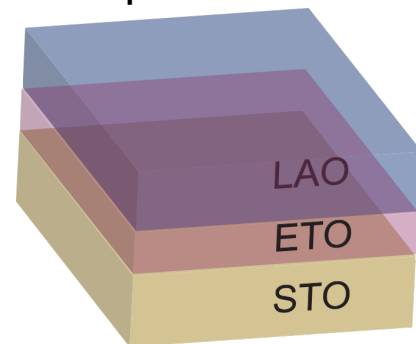
SC+RSOC q2DEG



SC+RSOC+FE  
q2DEG



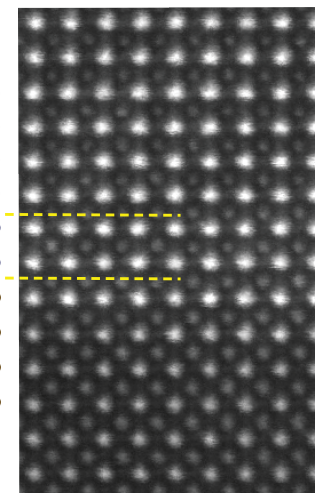
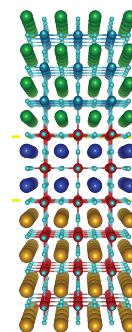
SC+RSOC +FM  
q2DEG



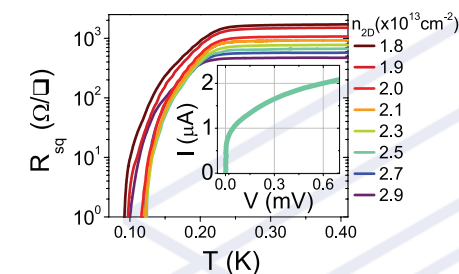
LaAlO<sub>3</sub>

EuTiO<sub>3</sub>

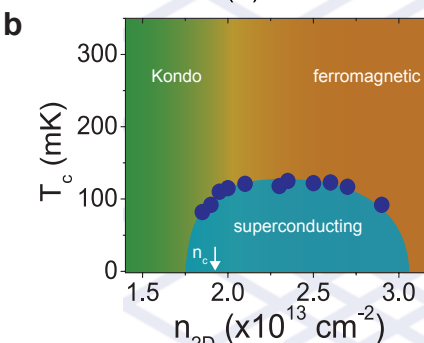
SrTiO<sub>3</sub>



a

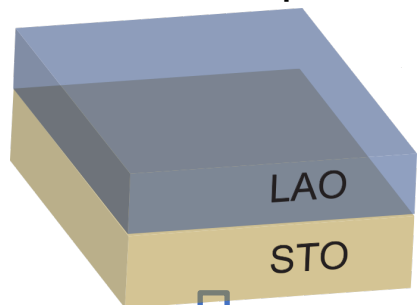


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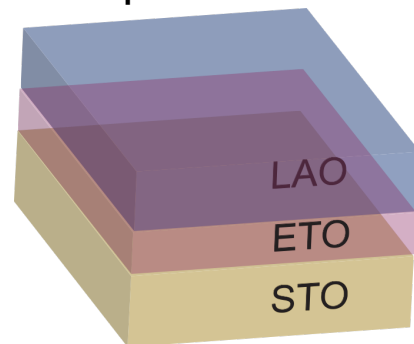


## Examples of Novel Oxide 2DEGs by Interface Engineering

SC+RSOC q2DEG

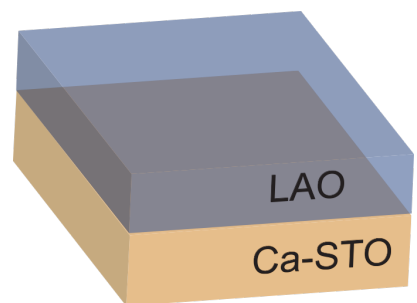


SC+RSOC +FM  
q2DEG

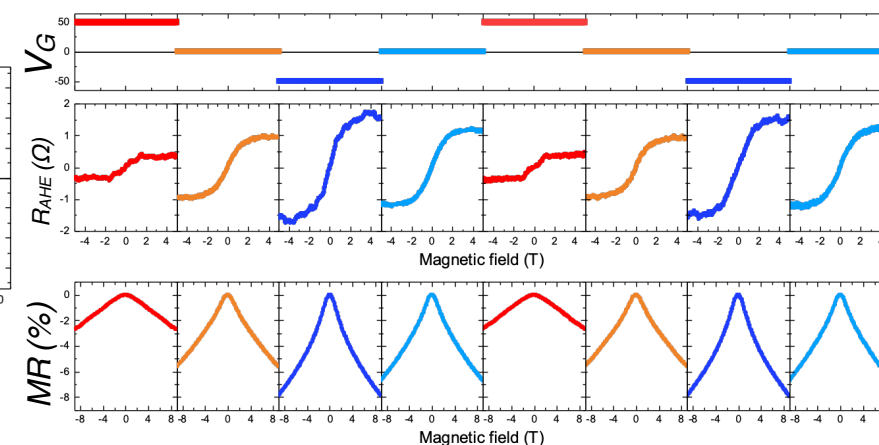
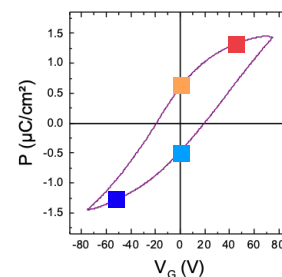
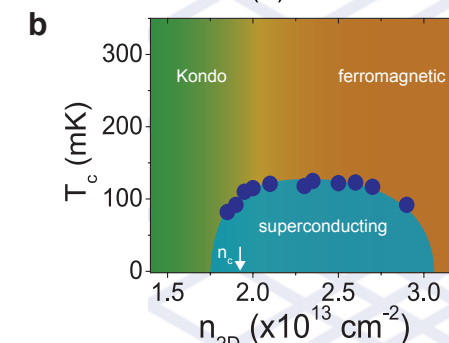
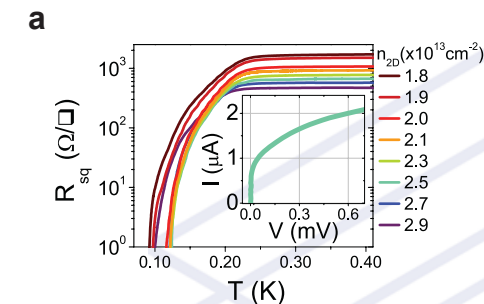
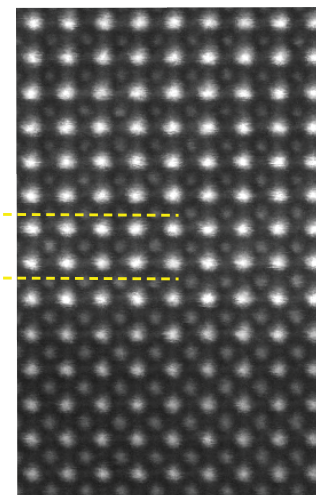
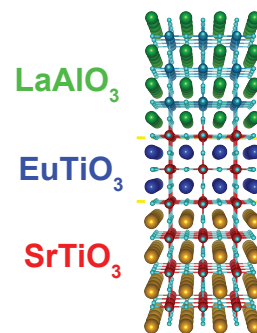
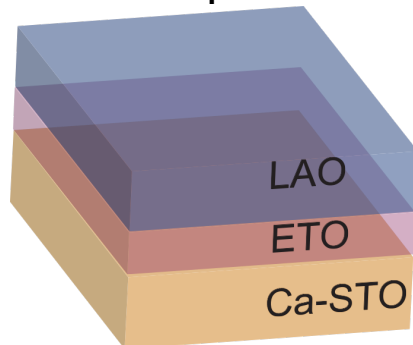


J. Bréhin, et al., *Coexistence and Coupling of Ferroelectricity and Magnetism in an Oxide Two-Dimensional Electron Gas*, Nat. Phys. **19**, 823 (2023).

SC+RSOC+FE  
q2DEG

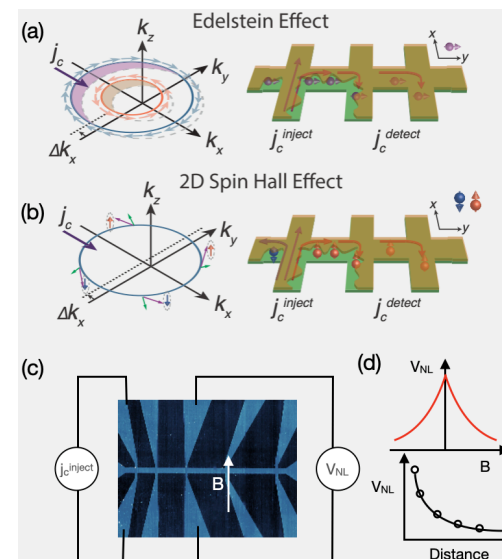
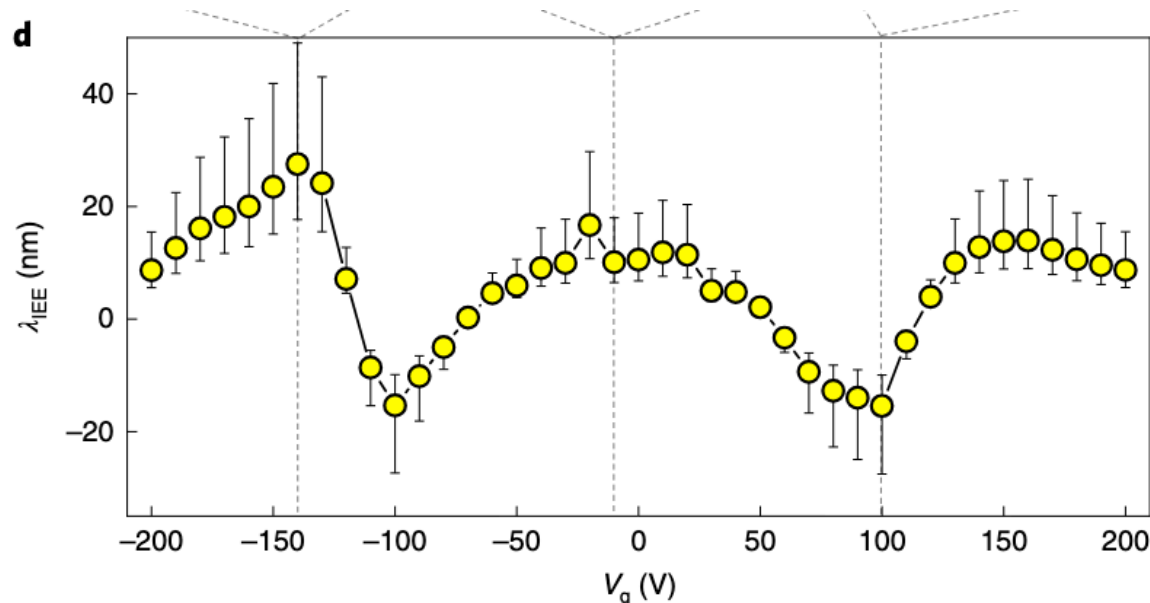


SC+RSOC+FE  
+FM q2DEG



## The extraordinary properties of oxide 2DEGs of interest for quantum electronics

Extremely large charge-spin conversion efficiency: Oxide-2DEGs are characterized by the largest spin-charge conversion efficiency to date (much larger than topological insulators) ( $\lambda_{IEE} = J_c^{2D} / J_s^{3D}$  exceeding 20 nm at 10 K)

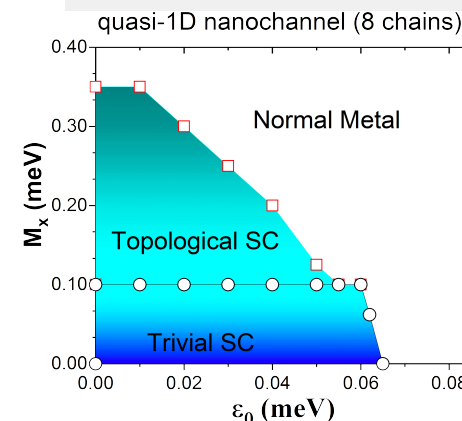
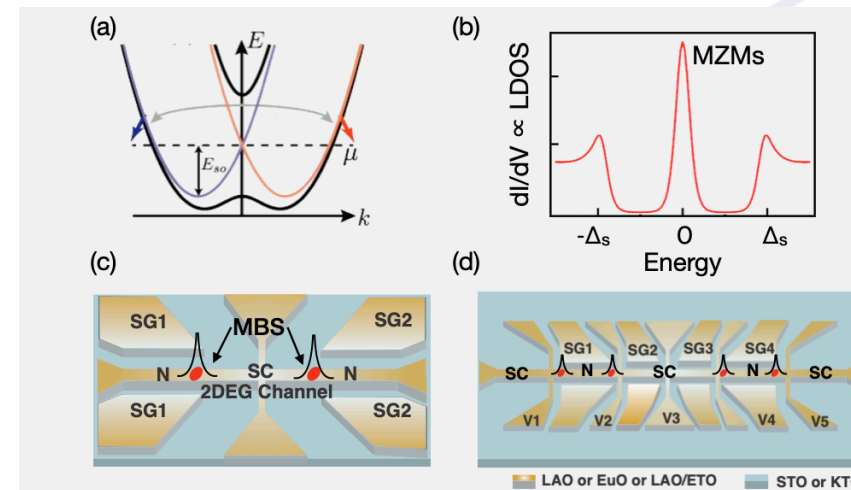
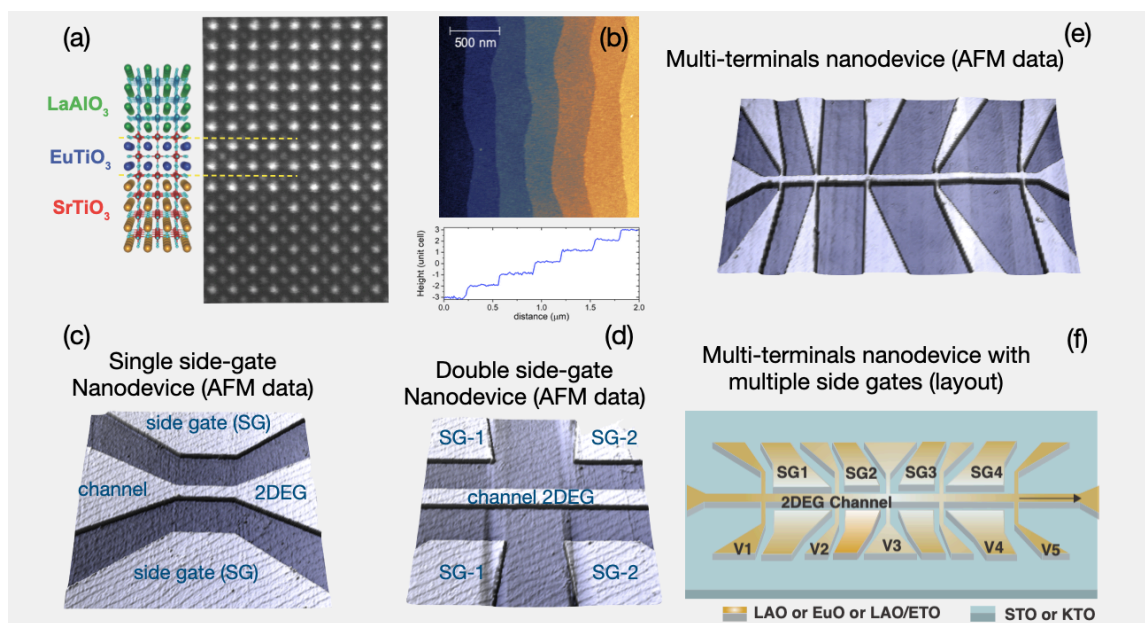


**Fig.4 Spin-transport in 2DEGs:** The Rashba SOC lifts the spin-degeneracy, leading to concentric Fermi contours with opposite spin chirality, and to an electron spin-momentum locking. (a) Through the direct Edelstein effect, an injected charge current ( $j_c^{inject}$ ) along x will generate a transverse spin accumulation that will diffuse along y in the channel. (b) Additionally, after displacing the Fermi contours by  $\Delta k_x$ , the spins will not be exactly perpendicular to  $k$  and will start to precess (Hanle spin precession) around to local Rashba field and the spin will acquire a net spin polarization along z. This is the 2D spin Hall effect, will leads to a spin current in the y-direction. Both the Edelstein and the 2D-spin Hall generated spin current are then reconverted into a detectable charge current ( $j_c^{detect}$ ) along x at neighbouring Hall probes through the inverse- Edelstein and 2D spin Hall effect. The non-local voltage  $V_{NL}$  (c) is a measure of the spin-generation/conversion. By performing measurements as function of ((d)-upper panel) an external magnetic field ((d)-bottom panel) and as function of the distance, one can get precise info about the dominant mechanism and about the spin-scattering length and main orientation.

Large spin-momentum locking : Read-out of the quantum state through Direct Edelstein effect ( rather than charge detection)

# The extraordinary properties of oxide 2DEGs of interest for quantum electronics

Tunable ground-state by electric field effect: Metal/superconducting to Insulating transition achievable by local gating : GATE DEFINED NANODEVICES



Topological Phase diagram  
of LAO/STO 2DEG

Simultaneous inversion and time symmetry breaking, and large Rashba-Like SOC: TOPOLOGICAL SC

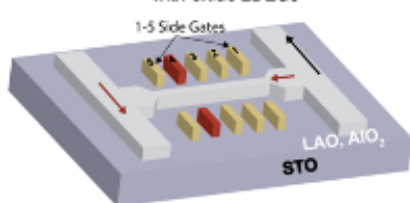


## SPIN-ORBIT QUBITS BASED ON OXIDE 2DEGS

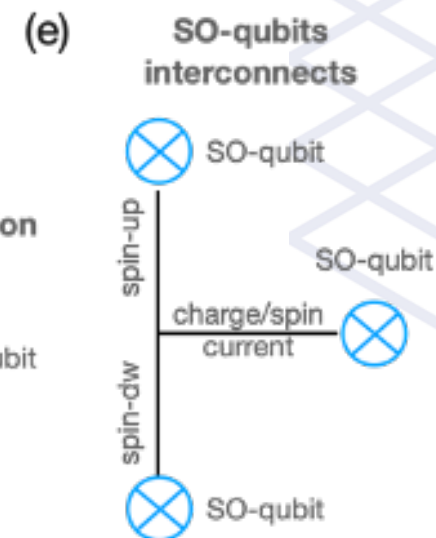
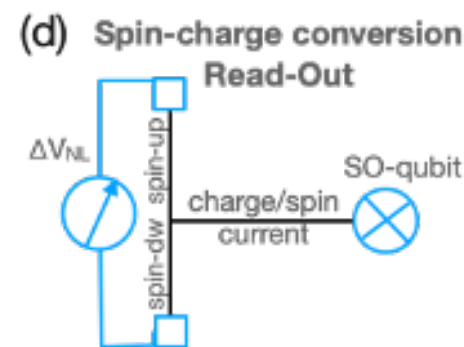
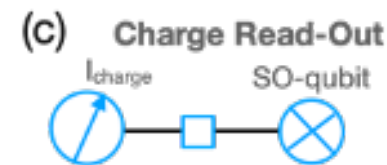
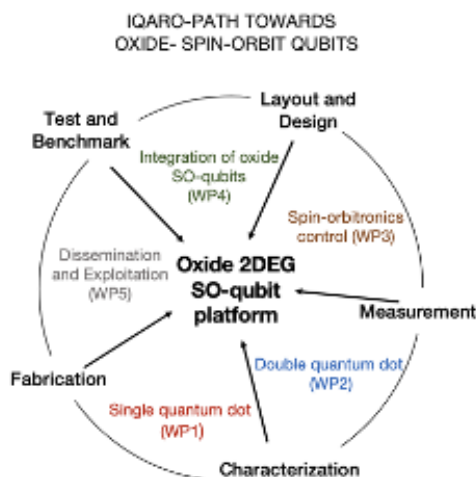
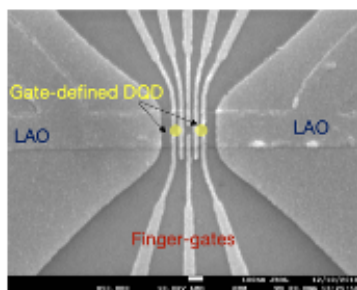
**Realization of a prototype of SO-qubit with oxide 2DEGs** with fast control of spin quantum states through tunable spin-orbit coupling (TRL4). In particular we aim a reduction of of direct and indirect sources of decoherence with respect to state of art SO-qubits due to:

- intrinsic properties of oxide materials, in particular the reduced nuclear hyperfine interaction due to carriers characterized by  $3d$ - orbital wavefunctions and small intrinsic inner nuclear field;
- large tunability of the Rashba SOC and of the giant STO dielectric screening, for the reduction of charge noise;

Sketch of a (side) gate-defined double quantum dot with oxide 2DEGs



SEM image of gate-defined double quantum dot with oxide 2DEG realized by our Consortium



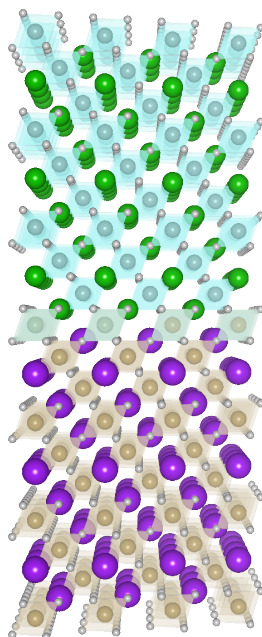
IQARO:Pathfinder EU Horizon Project 2023



# TOPOLOGICAL SUPERCONDUCTIVITY AND TOPOLOGICAL QUBITS BASED ON (111) KTO 2DEGs

*Oxide-2DEGs have all the properties needed to realize topological superconductivity  
IN ONE SINGLE MATERIAL*

LaAlO<sub>3</sub>



(111) KTaO<sub>3</sub>

Multi-band transport from  
Transition metal (Ta) d-bands  
2D superconductor

$t=6\text{nm}$

$\xi=20\text{nm}$

$T_c \approx 2.2\text{ K}!!!!$

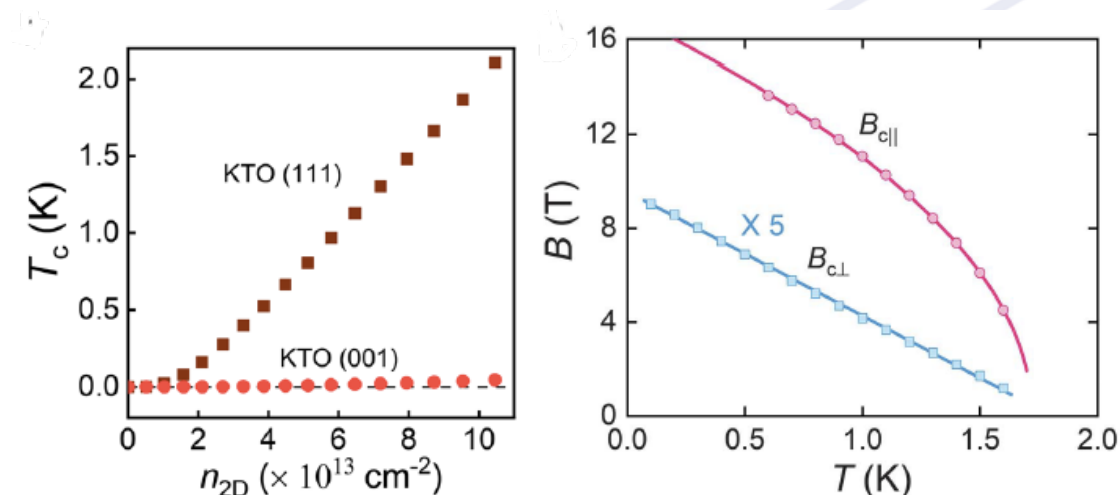
$H_{c2//} (10\text{ mK}) > 10\text{ T}$

Large SO coupling (tunable)

$\Delta_{so} > 200\text{mV}$

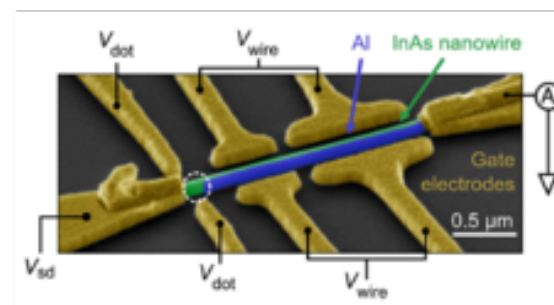
S-I transition via electric field effect

Engineered ferromagnetism coexisting with SC

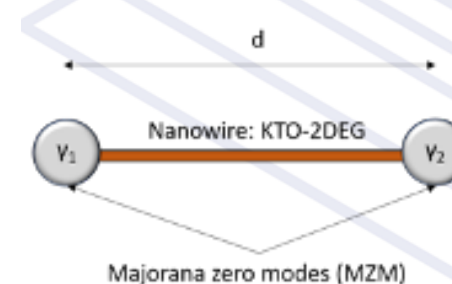


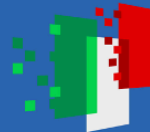
State-of-the art

(a) Hybrid device: Superconductivity by proximity effect



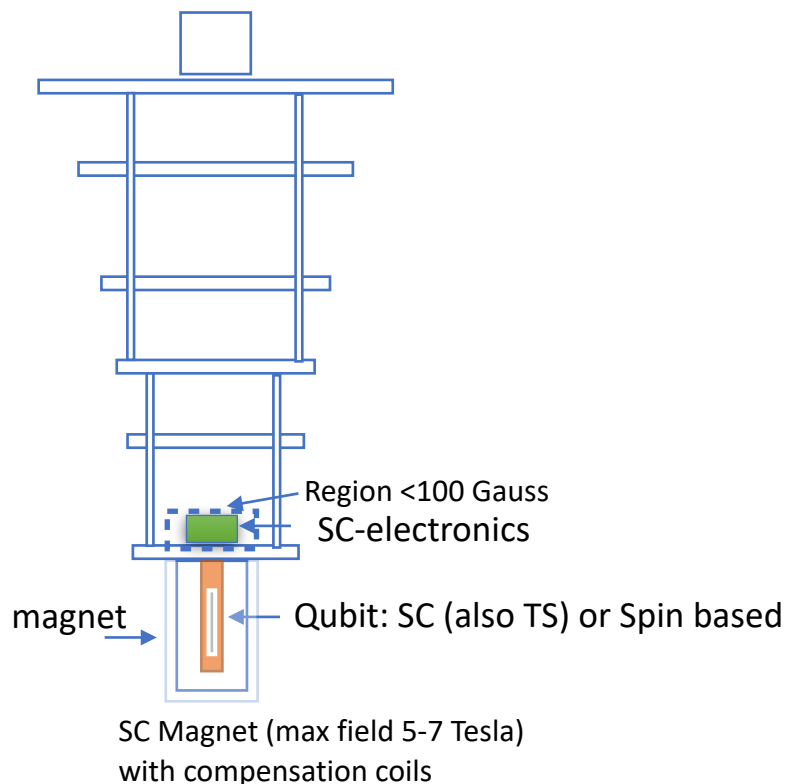
(b) Single device: Inherent superconductivity





**-CNR-SPIN has designed a new cryogen (free) dilution system for integration of spin or SC qubits operating in magnetic fields, and SC-electronics**

**Example: Spin-qubit based on single electron Semiconducting QD (i.e. oxide QD and DQD or others) and TWPA  
Topological Qubit and TWPA**



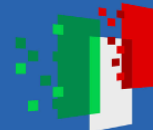
**The system will be acquired on funding from SPOKE 5 and SPOKE 6 and will be naturally bridging our activities on the two spokes**



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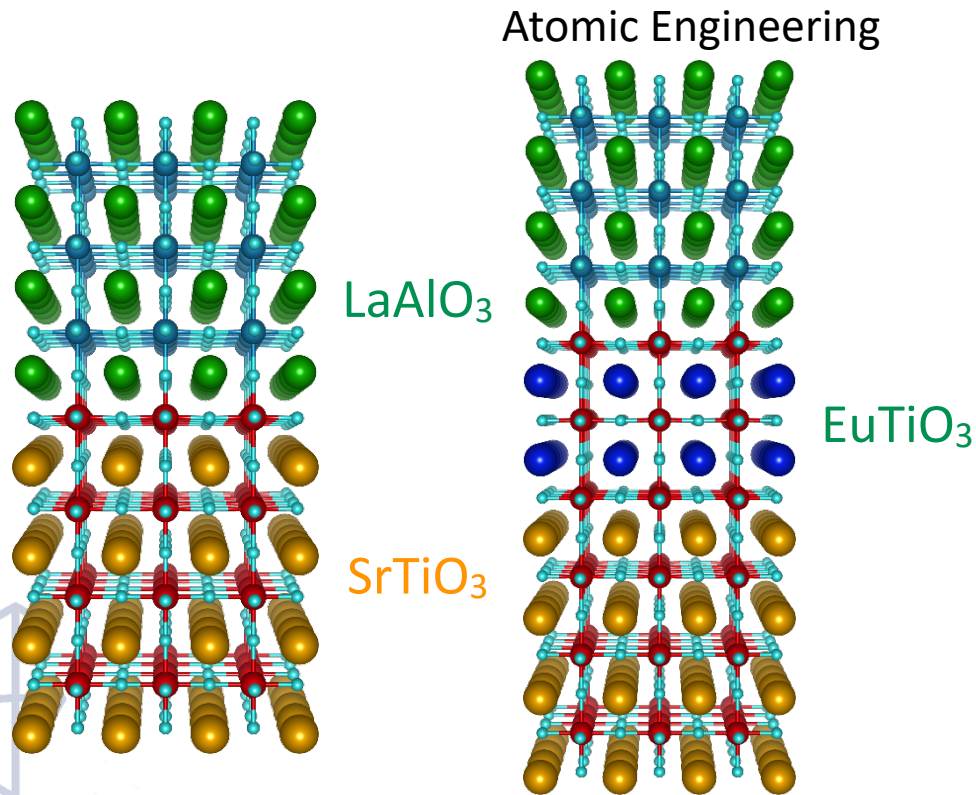


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THANKS FOR YOUR ATTENTION

# OXIDE 2DEGs : $\text{SrTiO}_3$ single crystal-based

*Oxide-2DEGs have all the properties needed to realize topological superconductivity*



Multi-band transport from  
Titanium 3d bands

2D superconductor

$t=10\text{nm}$

$\xi=70\text{nm}$

$T_c \approx 250\text{mK}$

Large SO coupling (tunable)

$\Delta_{\text{so}} \approx 8\text{mV}$

S-I transition via electric field effect

ferromagnetism

