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National Quantum Science
and Technology Institute

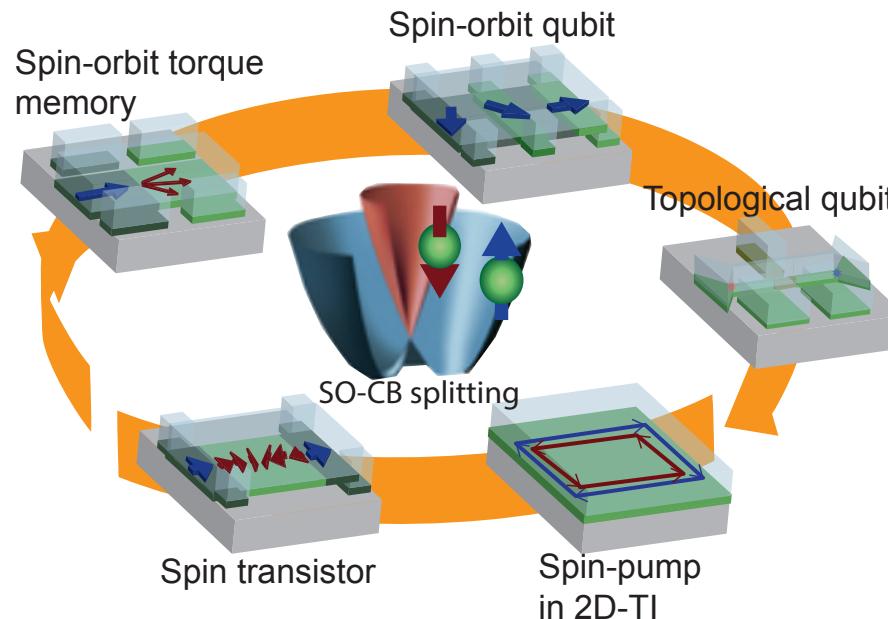
Oxide 2D-electron gas with engineered functional properties for quantum physics and applications

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



Consiglio Nazionale delle Ricerche
Istituto SPIN - Napoli

Quantum Spin-Orbitronics



Topological Quantum electronics

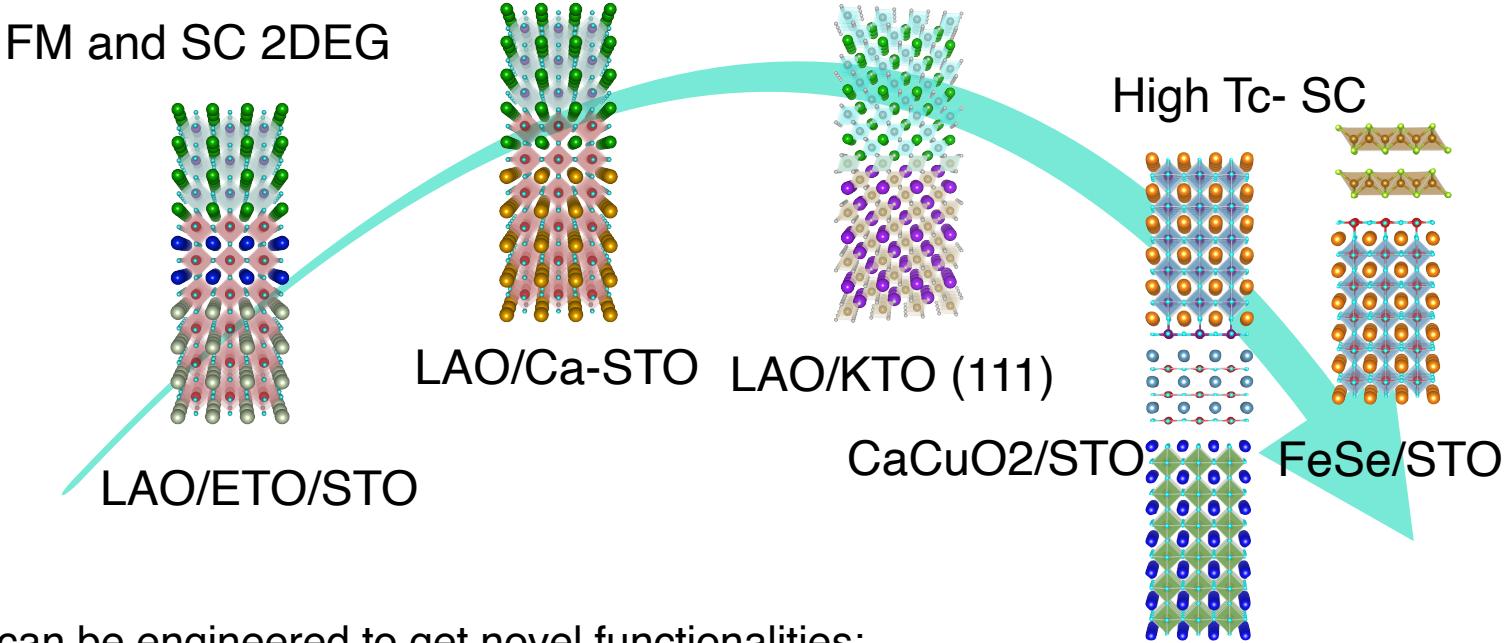
The interplay between inversion and time reversal symmetry breaking gives rise to novel quantum phenomena and novel quantum devices concepts

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. T_c, J_c, SOC, ground-state)
- Integration with Silicon at the hand



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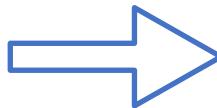
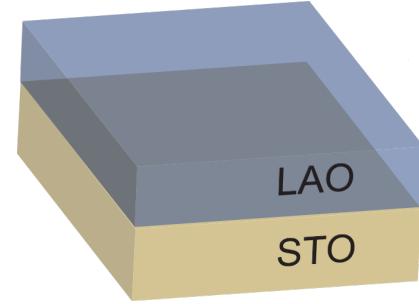
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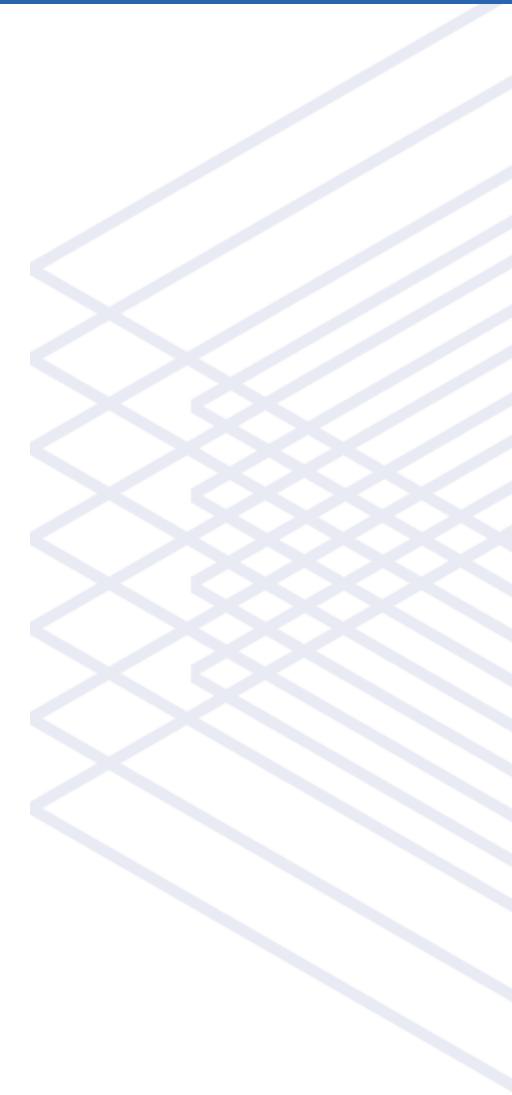
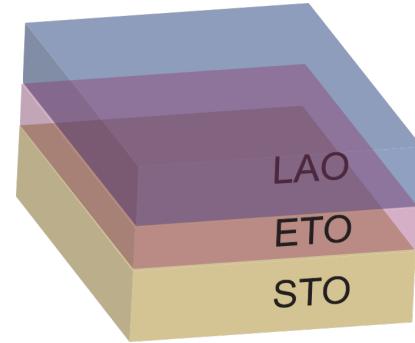
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Examples of Novel Oxide 2DEGs by Interface Engineering

SC+RSOC q2DEG

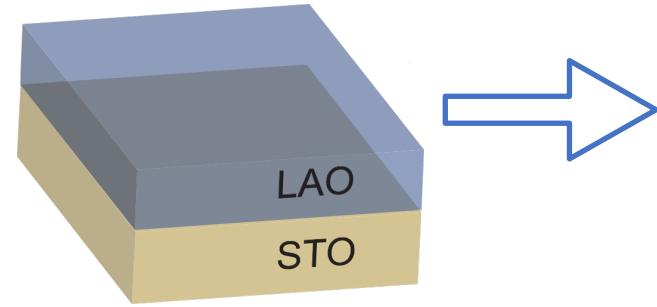


SC+RSOC +FM
q2DEG

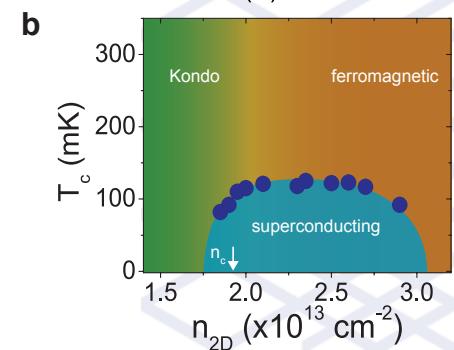
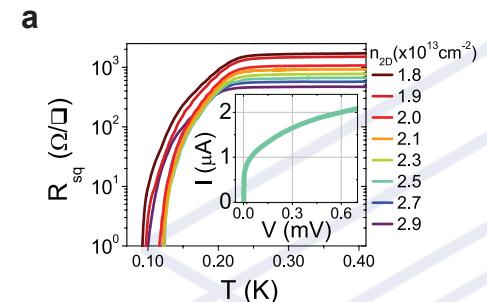
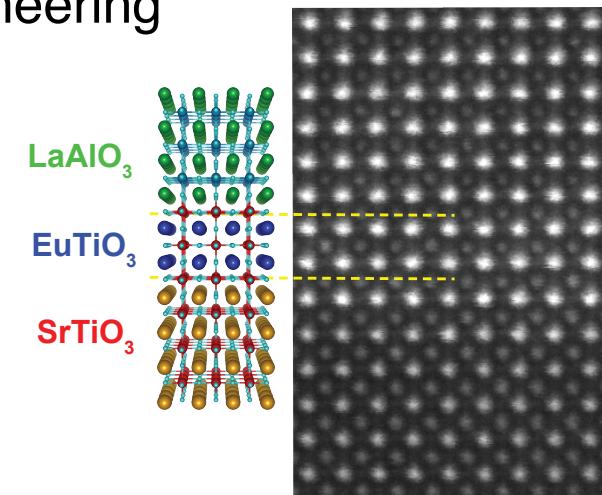
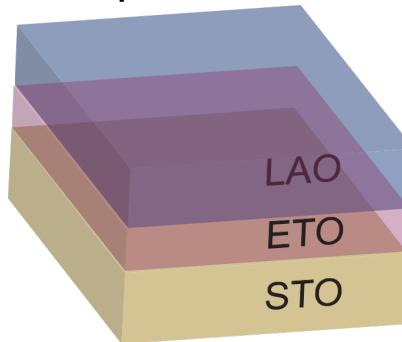


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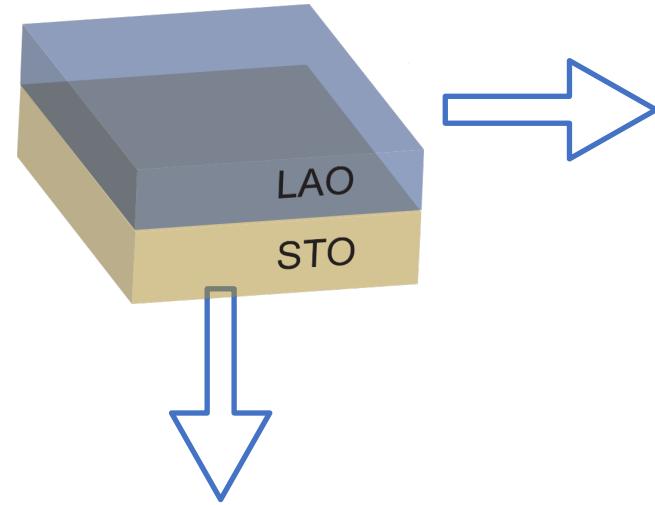


SC+RSOC +FM
q2DEG

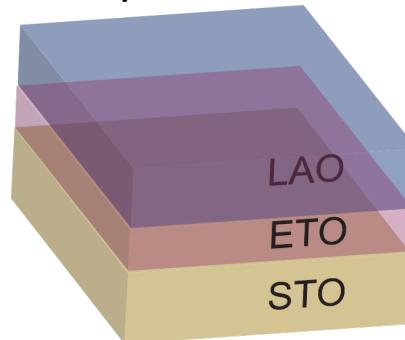


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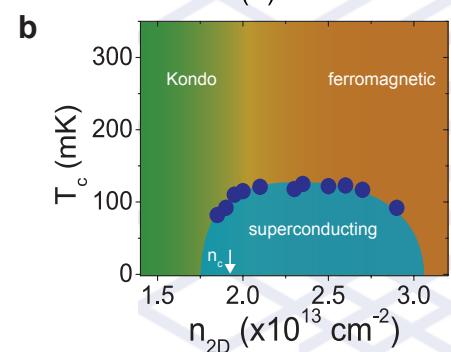
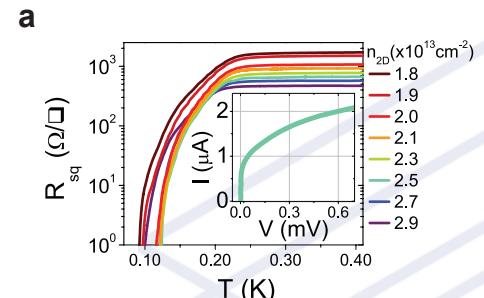
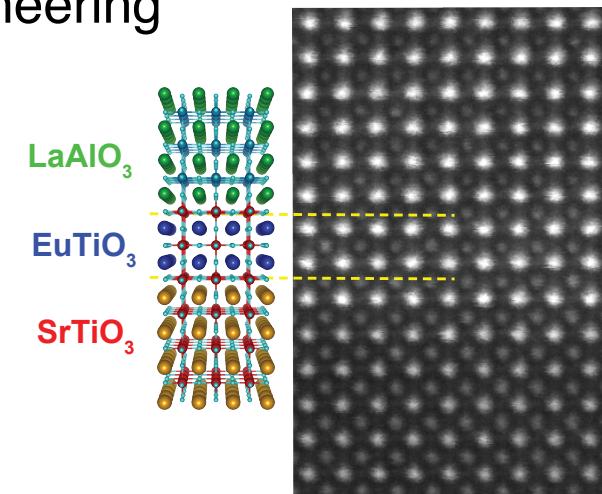
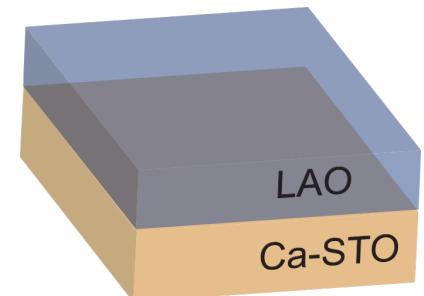
SC+RSOC q2DEG



SC+RSOC +FM
q2DEG

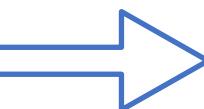
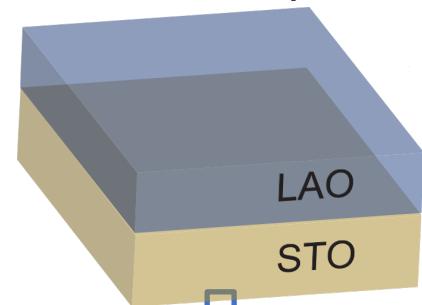


SC+RSOC+FE
q2DEG

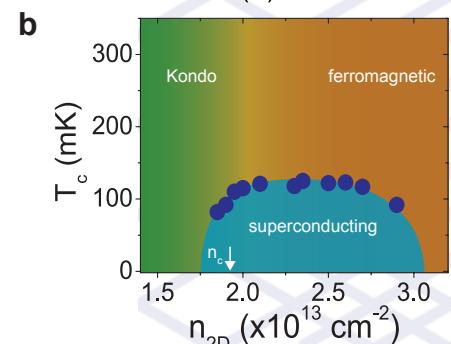
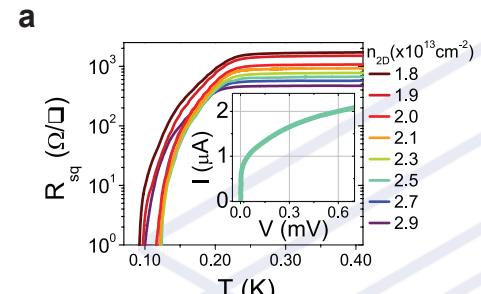
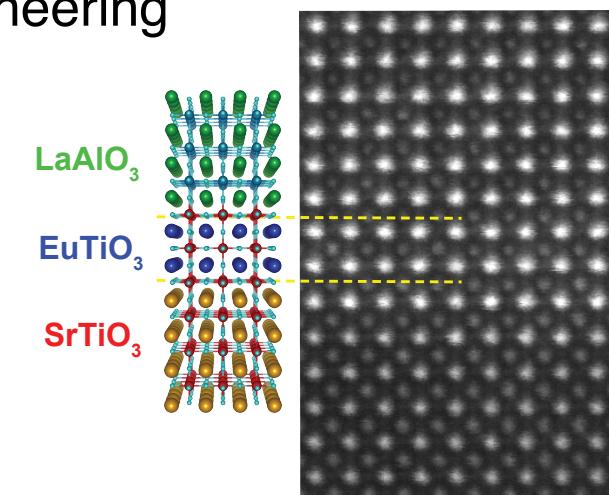
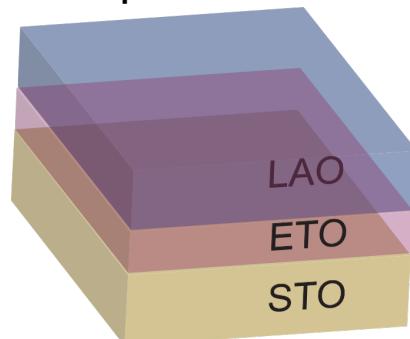


Examples of Novel Oxide 2DEGs by Interface Engineering

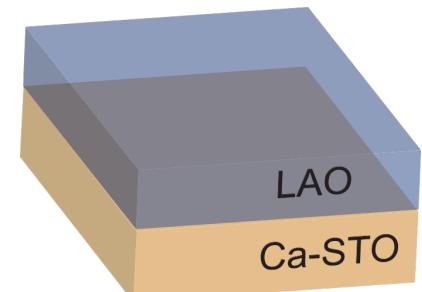
SC+RSOC q2DEG



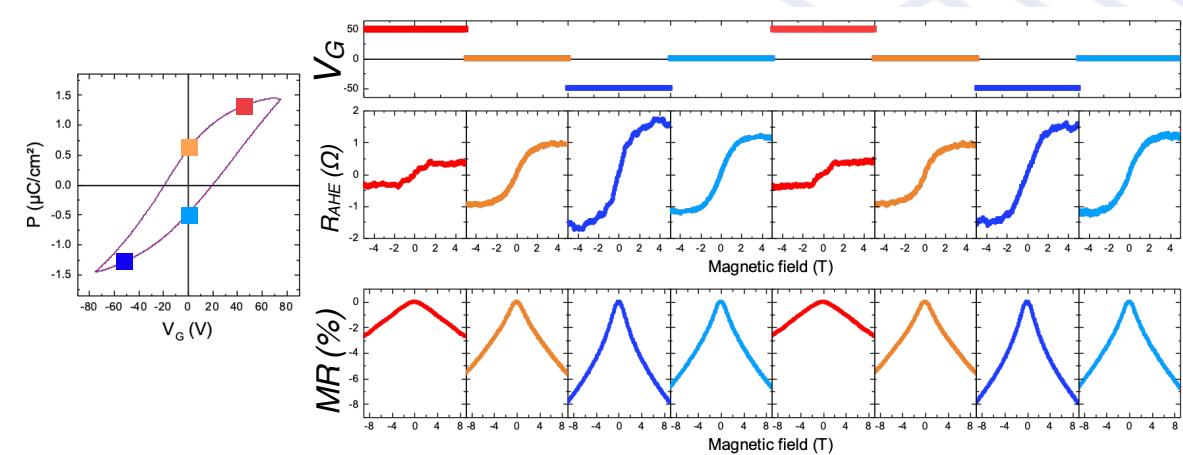
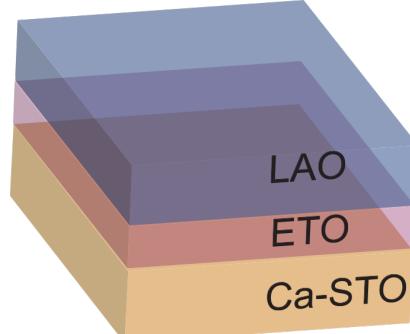
SC+RSOC +FM
q2DEG



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)

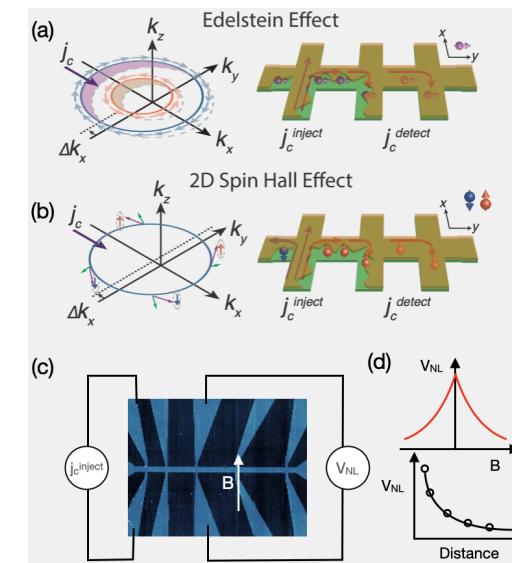
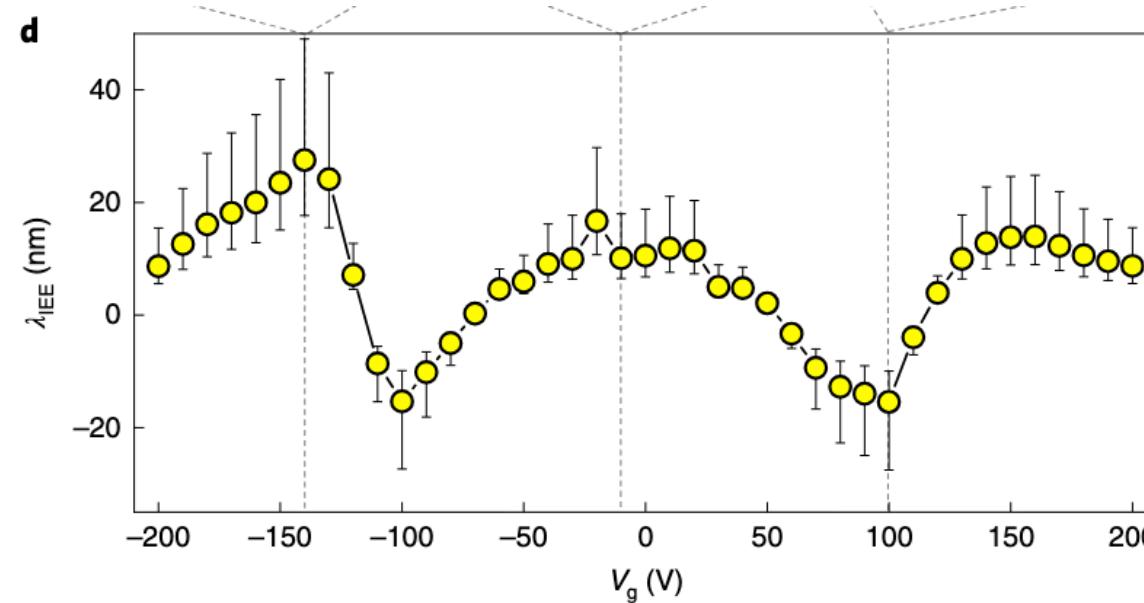
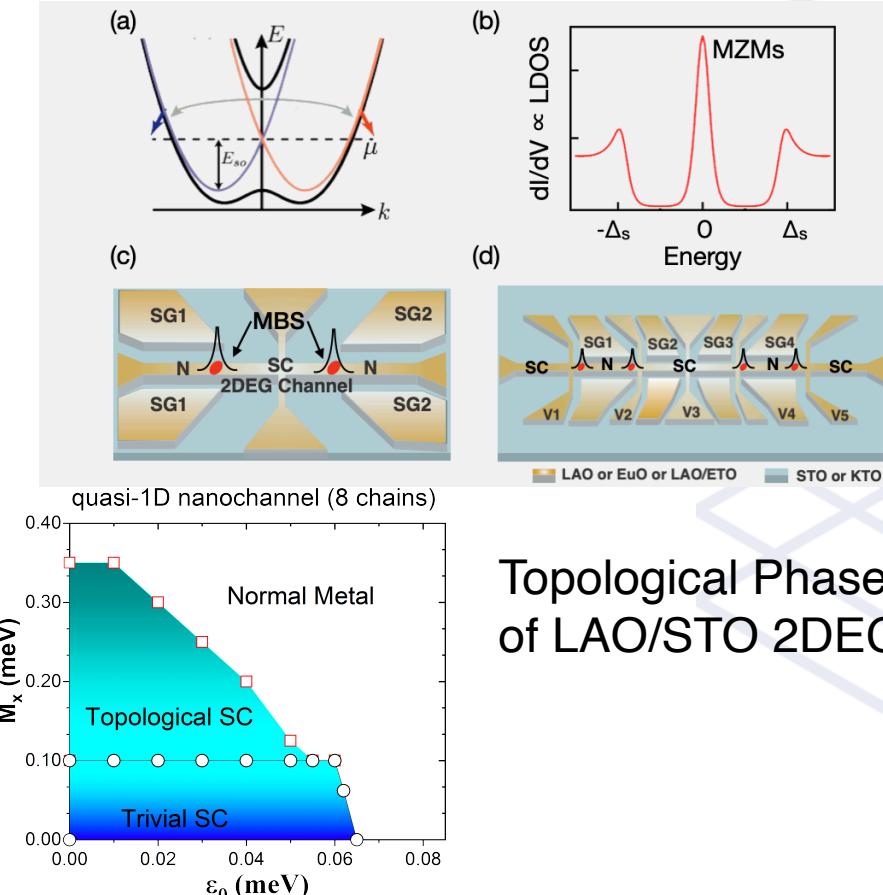
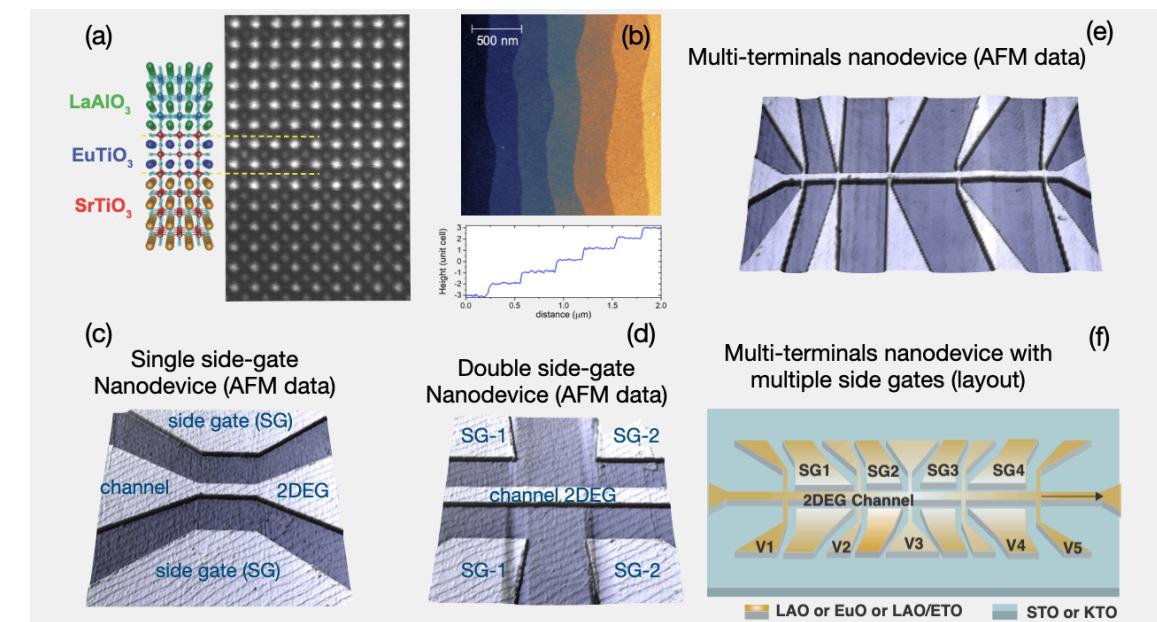


Fig.4 Spin-transport in 2DEGs: The Rashba SOC lifts the spin-degeneracy, leading to concentric Fermi contours with opposite spin chirality, and to an electron spin-momentum locking. (a) Through the direct Edelstein effect, an injected charge current (j_c^{inject}) along x will generate a transverse spin accumulation that will diffuse along y in the channel. (b) Additionally, after displacing the Fermi contours by Δk_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

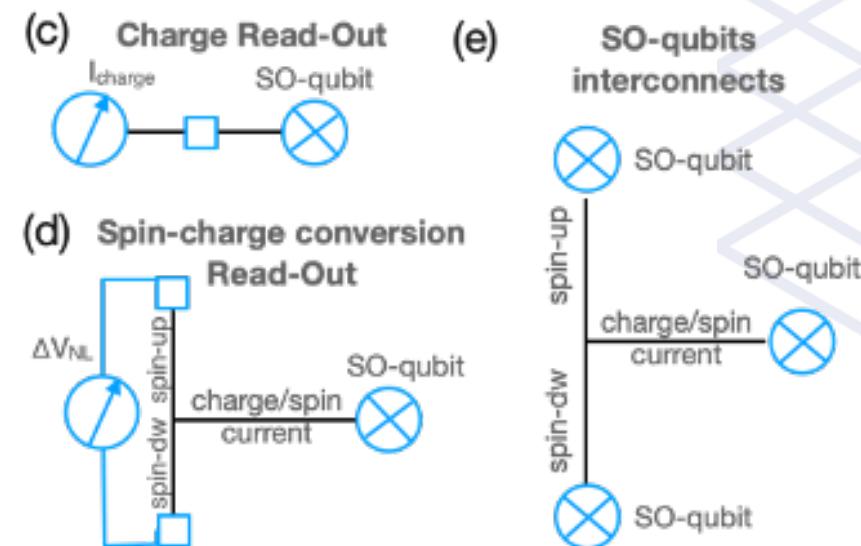
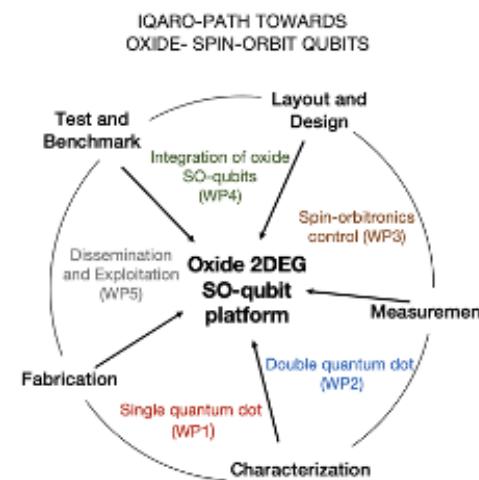
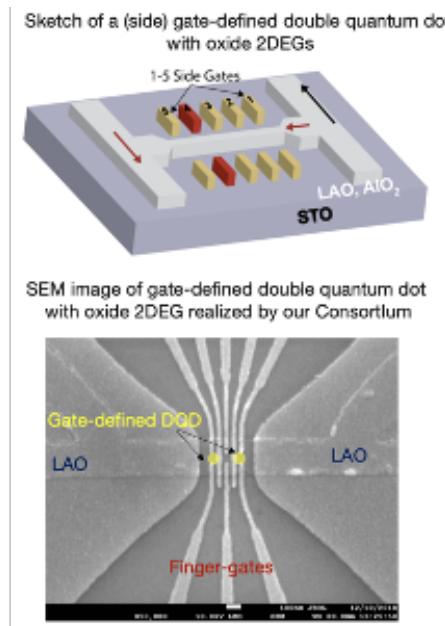


Simultaneous inversion and time symmetry breaking, and large Rashba-Like SOC: TOPOLOGICAL SC

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 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;

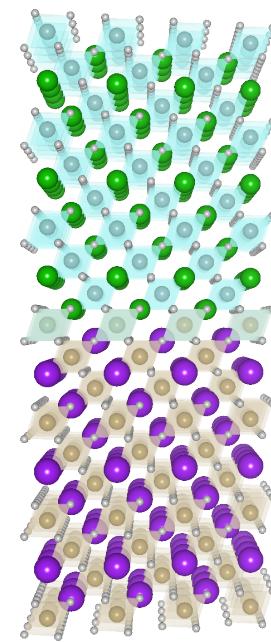


IQARO:Pathfinder EU Horizon Project 2023

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*

LaAlO₃



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

$t=6\text{ nm}$

$\xi=20\text{ nm}$

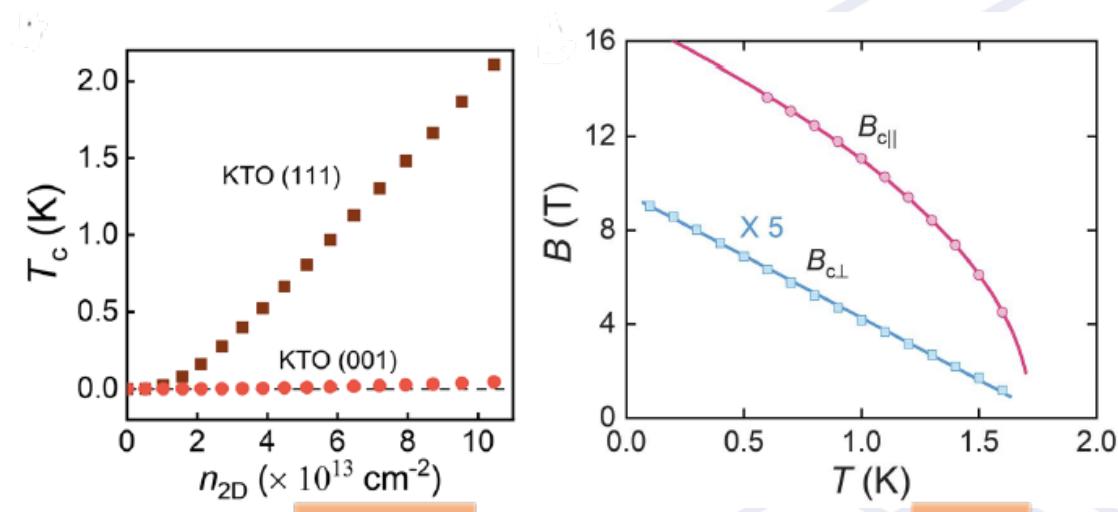
$T_c \approx 2.2\text{ K} !!!!!$

$H_{\text{c}2}/(10\text{ mK}) > 10\text{ T}$

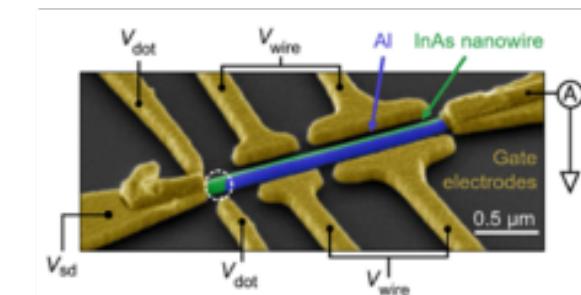
Large SO coupling (tunable)
 $\Delta_{\text{SO}} > 200\text{ mV}$

S-I transition via electric field effect

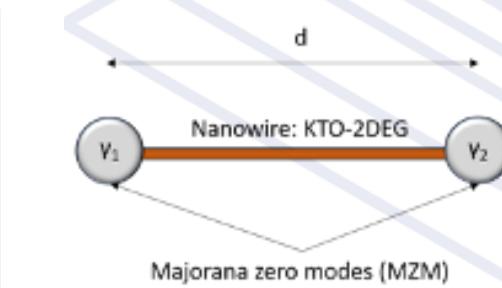
Engineered ferromagnetism coexisting with SC



(a) Hybrid device: Superconductivity by proximity effect



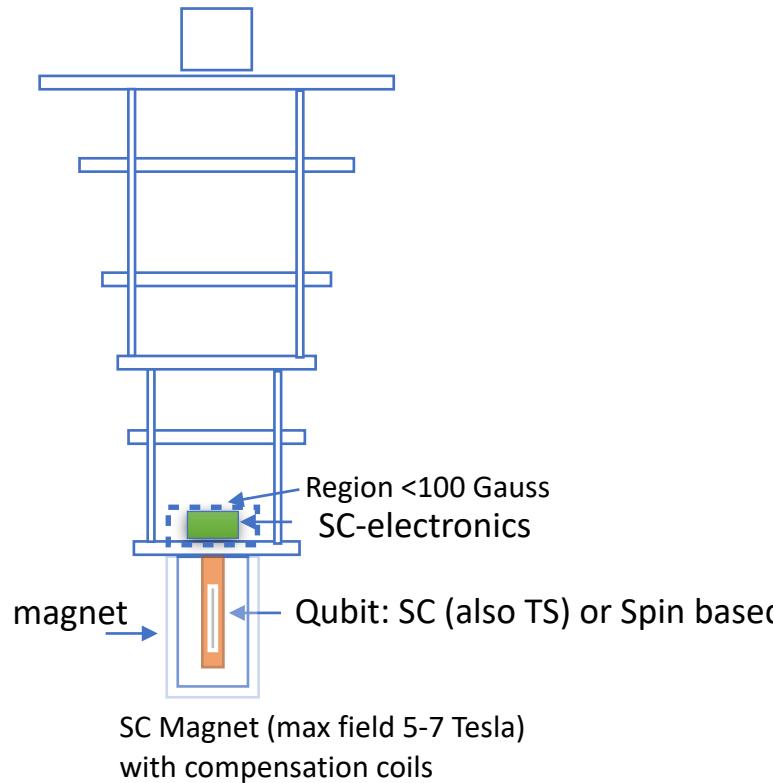
(b) Single device: Inherent superconductivity



-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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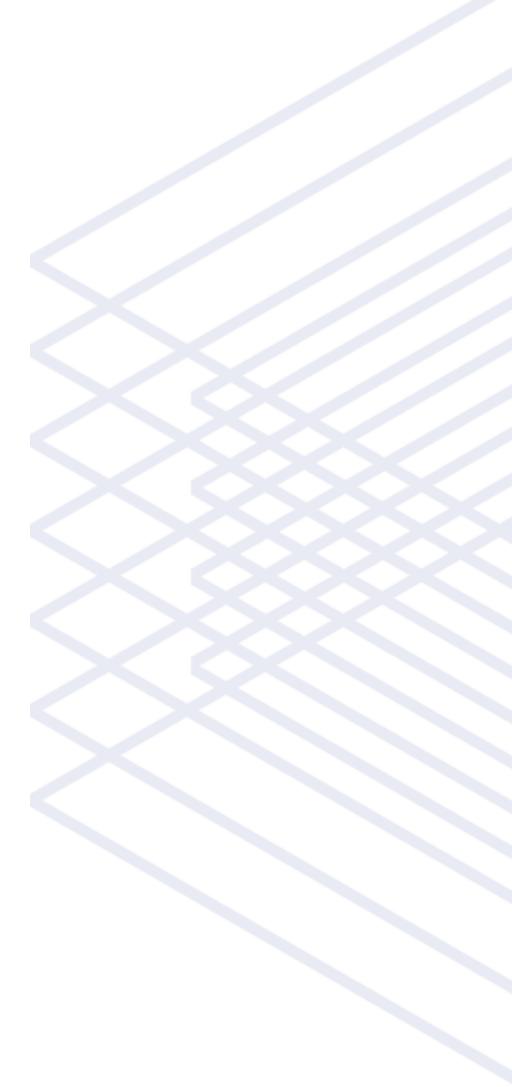


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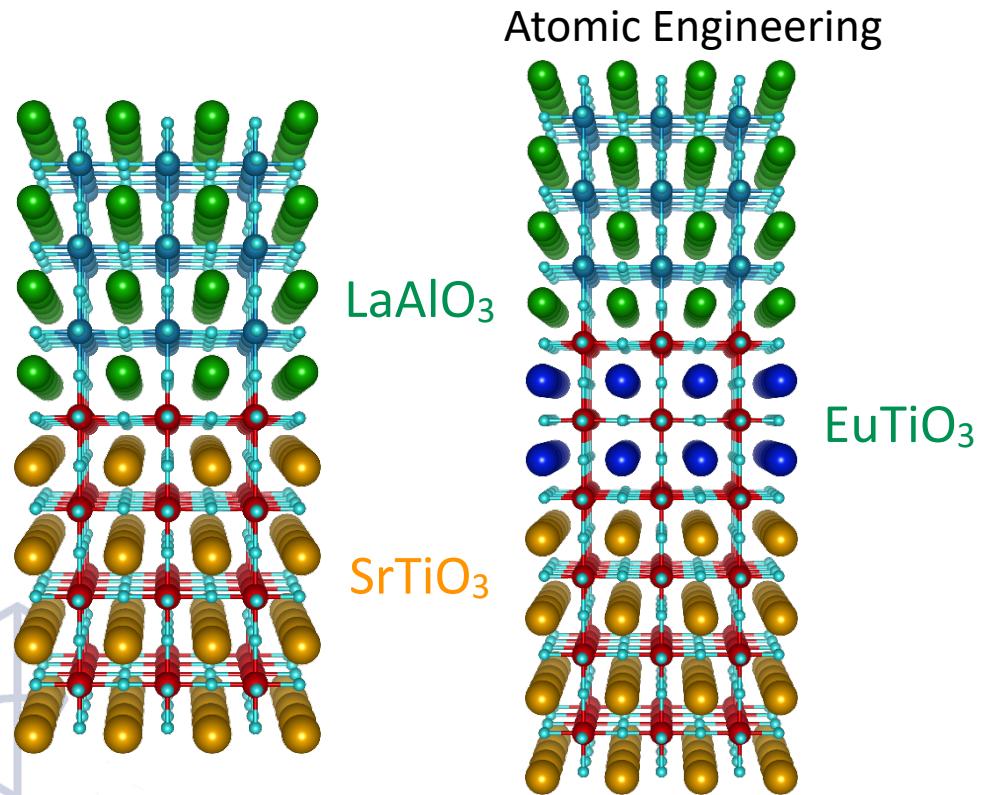
THANKS FOR YOUR ATTENTION



OXIDE 2DEGs : SrTiO₃ 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

