Anomalous magneto-transport of Dirac-like fermions in a spin-polarized oxide two-dimensional electron system

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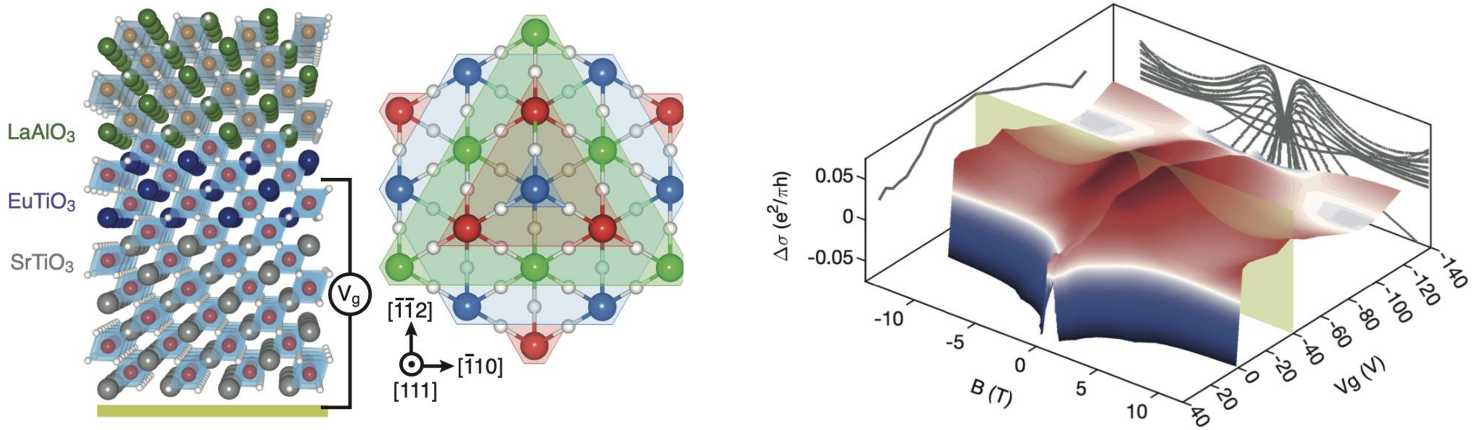

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Outline

1. Background: Oxide 2DES and weak (anti)localization

2. Anomalous magnetotransport

3. Nontrivial Berry curvature effect

4. Conclusions and Perspectives

Thank all the coauthors:
Maria D'Antuono, Mattia Trama, Daniele Preziosi, Benoit Jouault, Frédéric Teppe, Christophe Consejo, Carmine A. Perroni, Roberta Citro, Daniela Stornaiuolo*, Marco Salluzzo*

ADVANCED MATERIALS

Y. Chen, et al., Adv. Mater. **37**, 2410354 (2025).

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Dirac-Like Fermions Anomalous Magneto-Transport in a Spin-Polarized Oxide 2D Electron System

Yu Chen, Maria D'Antuono, Mattia Trama, Daniele Preziosi, Benoit Jouault, Frédéric Teppe, Christophe Consejo, Carmine A. Perroni, Roberta Citro, Daniela Stornaiuolo, Marco Salluzzo

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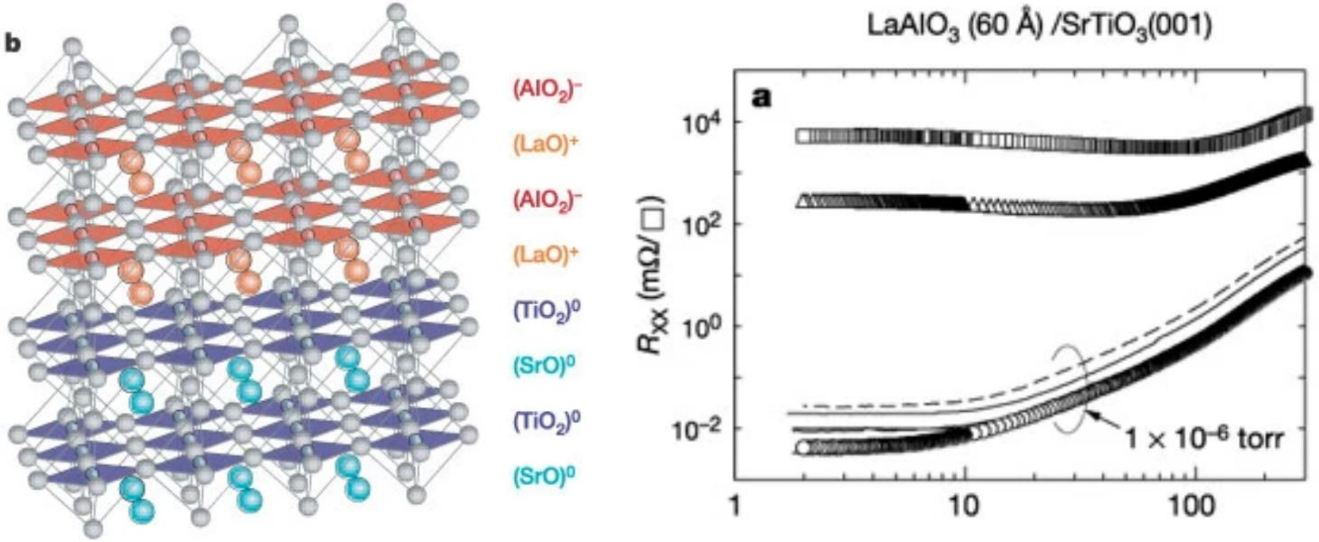
Background: Oxide 2DES and weak (anti)localization

Letter | Published: 29 January 2004

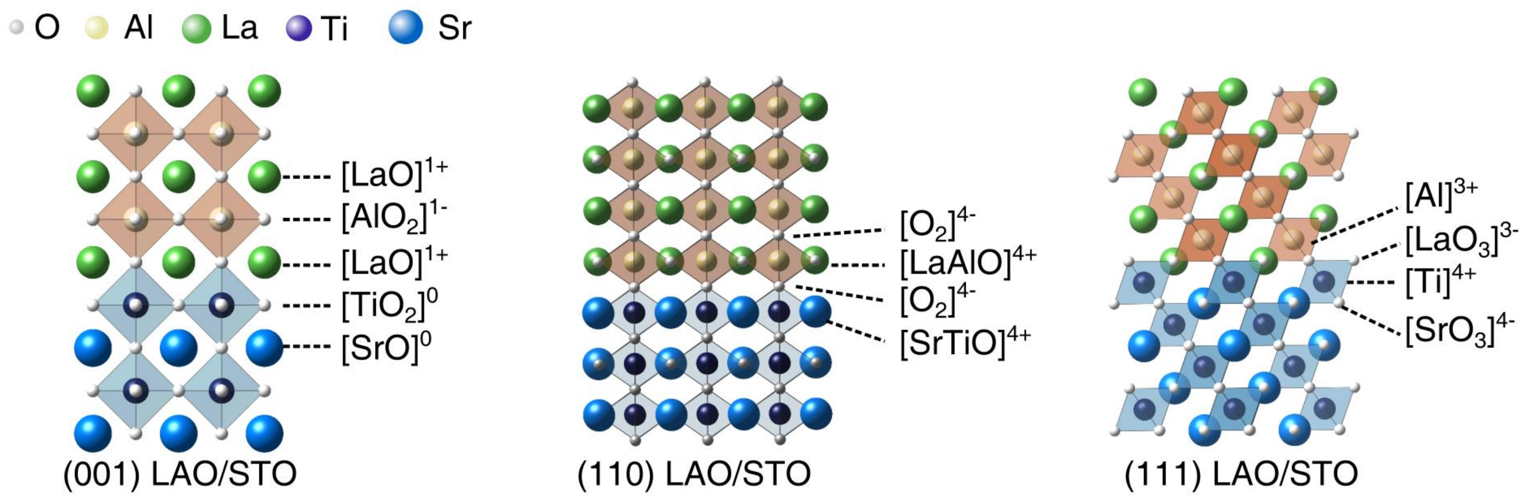
A high-mobility electron gas at the $LaAlO_3/SrTiO_3$ heterointerface

A. Ohtomo & H. Y. Hwang

Nature **427**, 423–426 (2004) | Cite this article

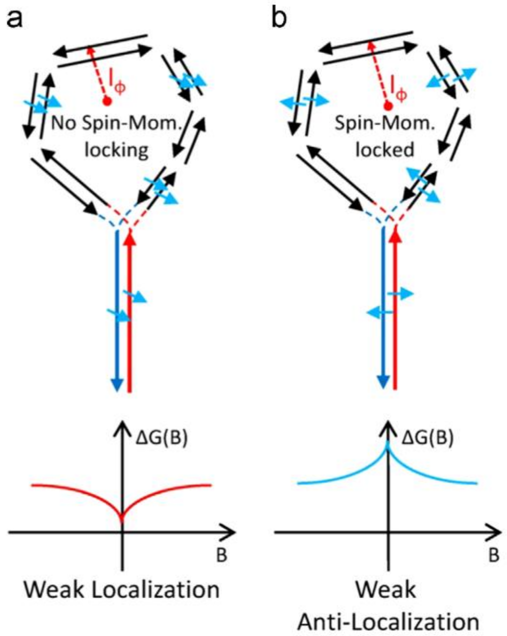


Oxide 2DES: $LaAlO_3/SrTiO_3$ (LAO/STO) interfaces

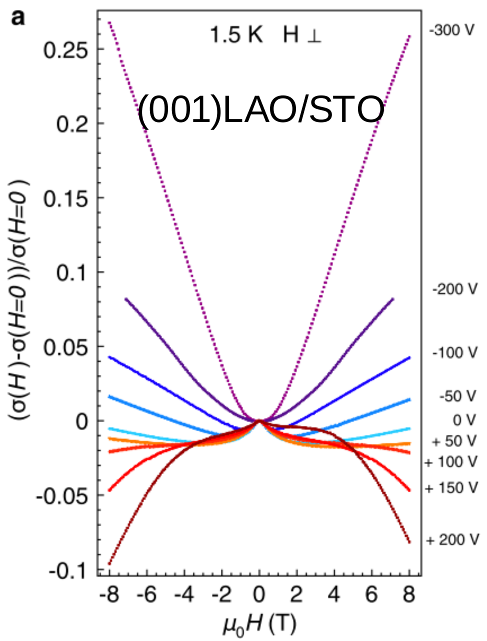


- ❑ Mechanism for 2DES: electronic reconstruction, oxygen vacancies, cation intermixing;
- ❑ Emergent properties: Superconductivity, Ferromagnetism, Strong Rashba Spin-Orbit Coupling, tunable by gate voltage.
- ❑ Other types of 2DES:
- STO-based 2DES: cleaved STO surface, Al/STO, spin-polarized 2DES at **LAO/$EuTiO_3$/STO** interfaces...
- Non-STO system: 2DES based on $KTaO_3$, LAO/Ca-STO(Ferroelectric), multi-ferroic 2DES LAO/ETO/Ca-STO...

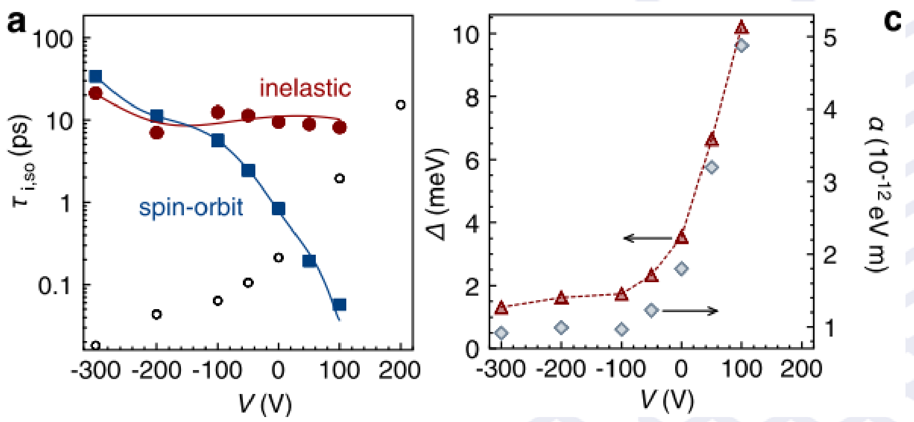
Weak localization (WL) and weak antilocalization (WAL)



Ref: Solid State Commun. 215216, 54 (2015)



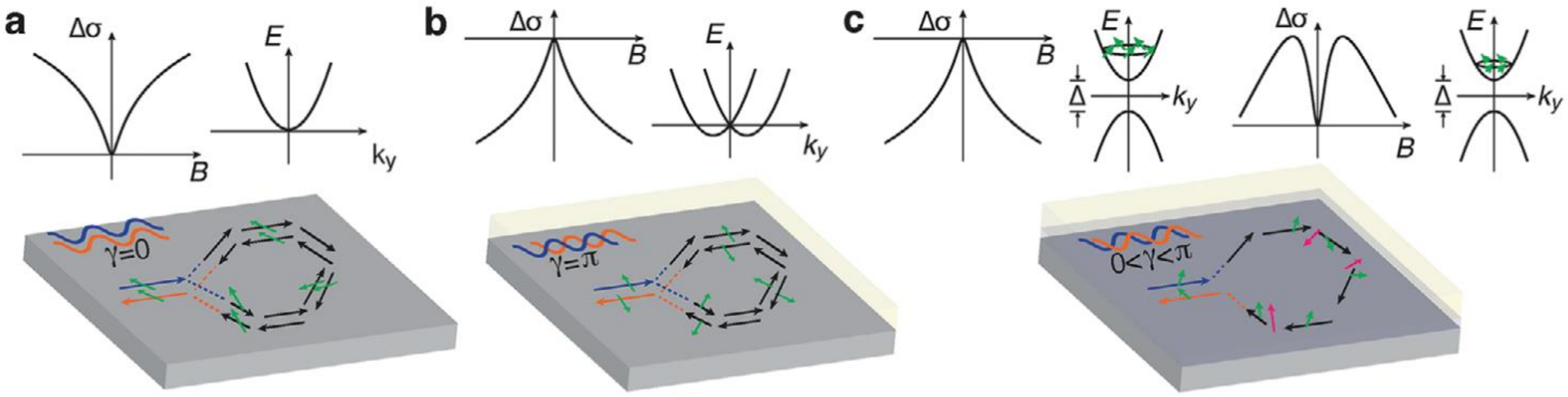
Ref: Phys. Rev. Lett. 104, 126803 (2010).



- WAL to WL with decreasing Vg in (001) LAO/STO
- Fit using Maekawa-Fukuyama (MF) formula
- Characteristic field/time/length. The extracted Rashba coefficient α_R is around $10 - 50\ meV$Å
- SOC is strongly tunable by gate voltage

- ❑ WL/WAL are the effect that conductance is suppressed/enhanced due to constructive/destructive interference between time-reversed electron self-intersecting paths.
- ❑ Dephased by magnetic field, interference is suppressed, causing positive magnetoconductance for WL while negative for WAL.

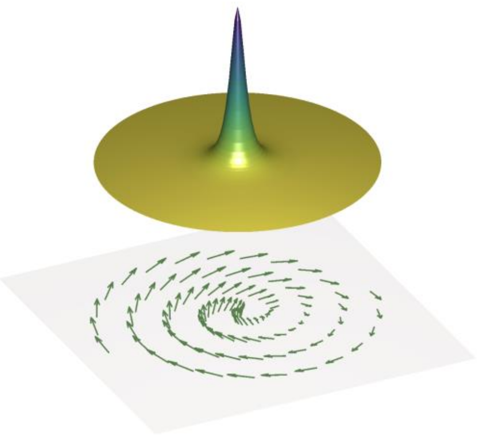
WL, WAL and beyond (competing WL and WAL)



No Spin-orbit coupling
Berry Phase $\gamma = 0$

Spin-orbit coupling
Berry Phase $\gamma = \pi$

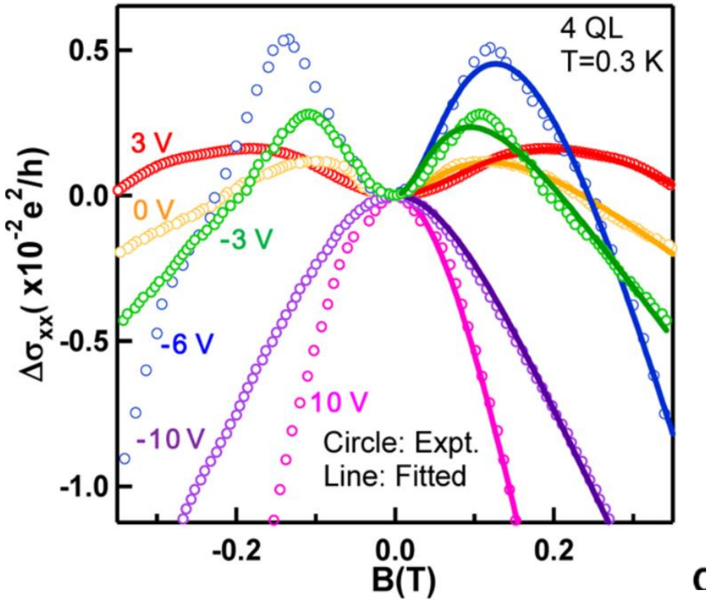
Spin-orbit coupling
+ Magnetic gap or surface gap opening in thin 3D-toplocial insulator
Berry Phase $0 < \gamma = \pi(1 - \frac{\Delta}{2E_F}) < \pi$

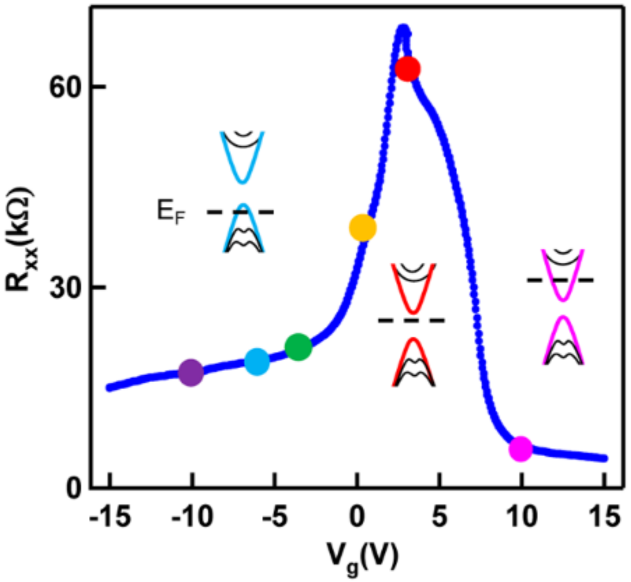


Non-trivial
Berry curvature
and spin texture

Competing effect of WL and WAL

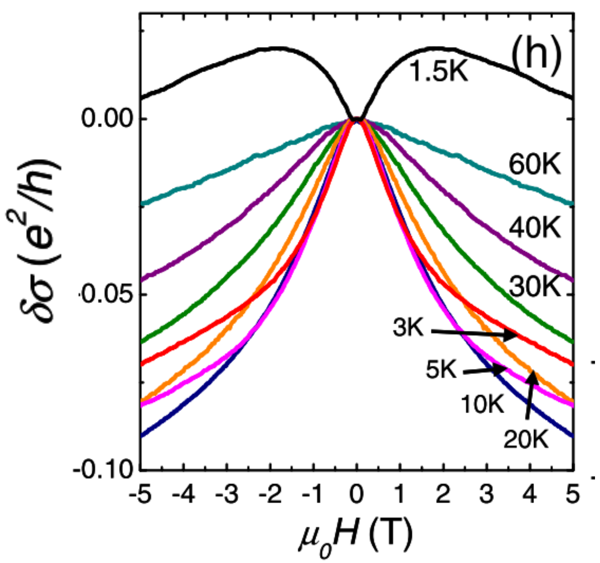
Surface gap opening in topological insulator
4 quintuple layers $(Bi_{0.57}Sb_{0.43})_2Te_3$





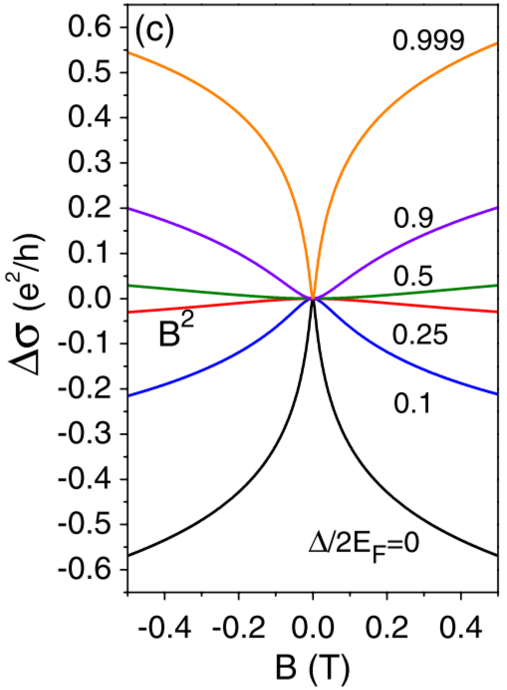
Ref: M. Lang, et al., Nano Lett. **13**, 48 (2013).

Magnetically Doped Topological Insulator $Bi_{2-x}Cr_xSe_3$ (x = 0.07)



Ref: M. Liu, et al., Phys. Rev. Lett. **108**, 036805 (2012).

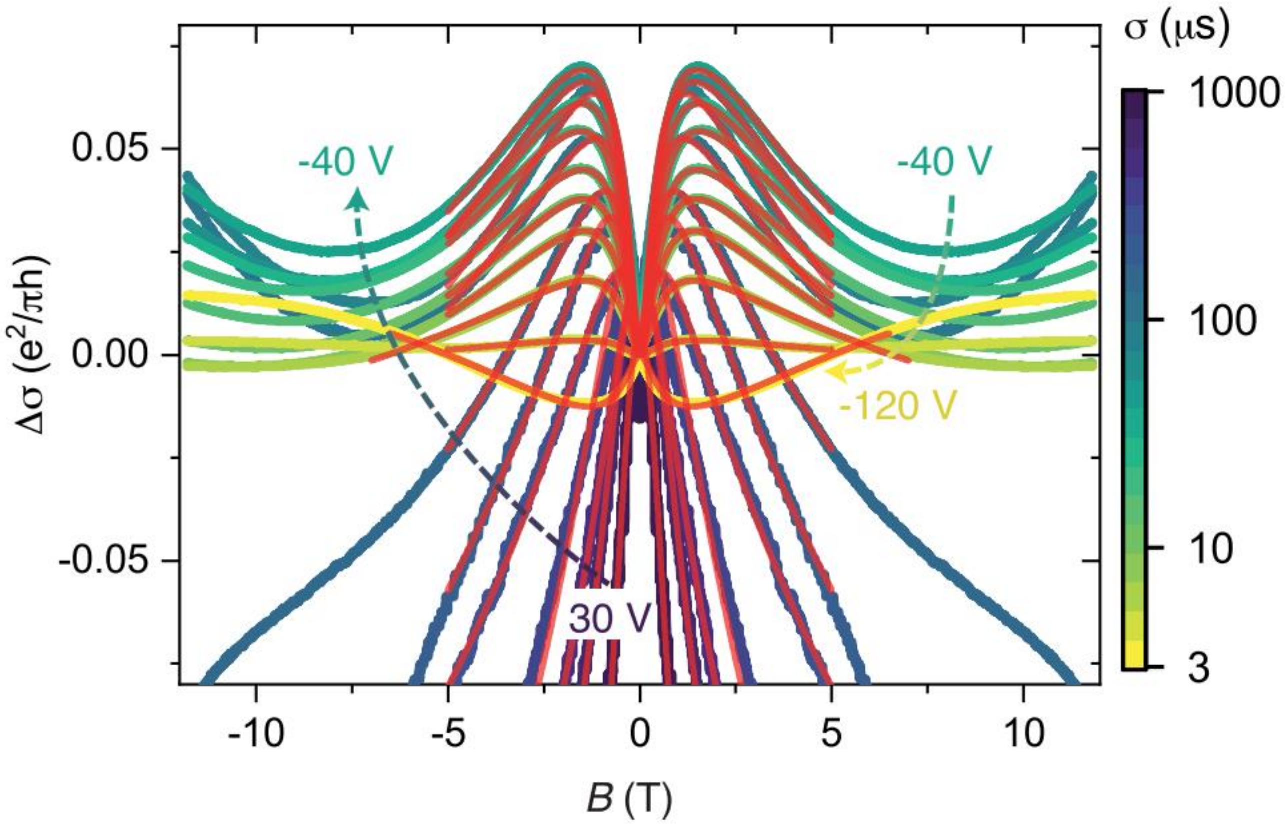
Theoretical model



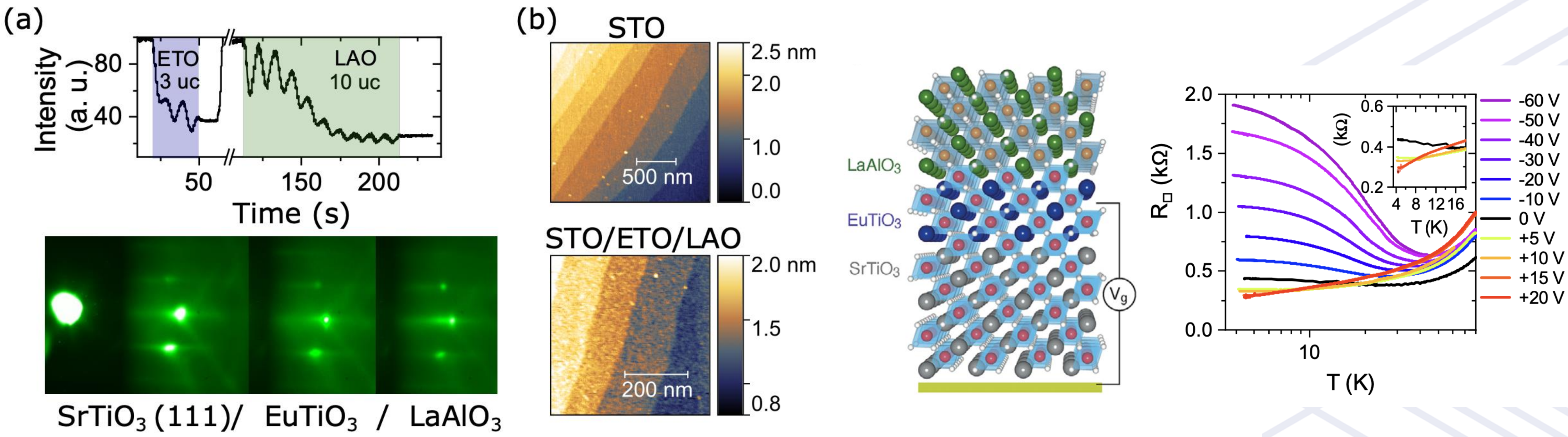
$$\delta\sigma(B) = \sum_{i=0,1} \frac{\alpha_i e^2}{\pi h} [\Psi\left(\frac{l_B^2}{l_{\phi i}^2} + \frac{1}{2}\right) - \ln(\frac{l_B^2}{l_{\phi i}^2})]$$

Ref: H. Z. Lu, et al., Phys. Rev. Lett. **107**, 076801 (2011).

Anomalous magnetotransport



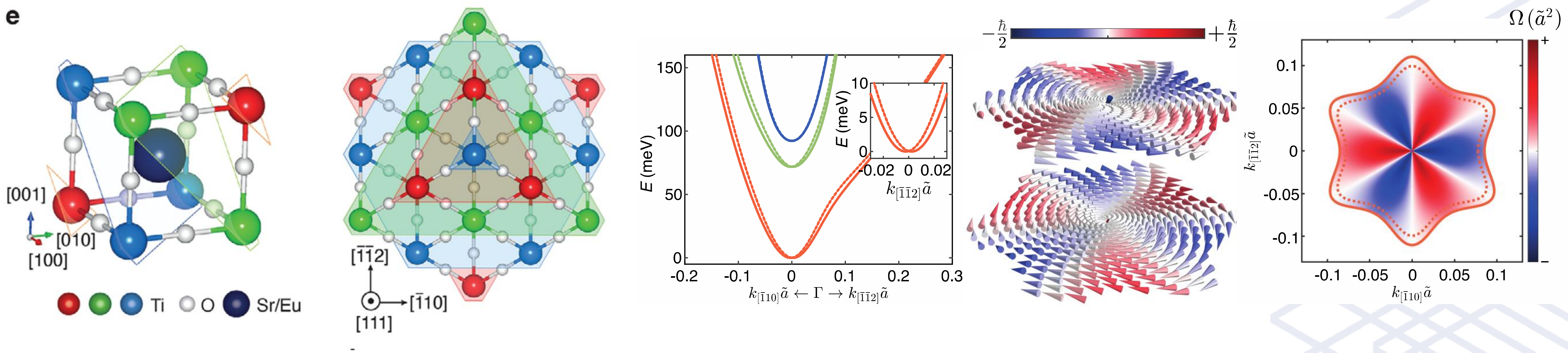
Engineering a ferromagnetic 2DES at (111)$LaAlO_3$/$EuTiO_3$/$SrTiO_3$ interfaces



- Epitaxial growth using Pulsed Laser Deposition (PLD) assisted with Reflected High Energy Electron Diffraction (RHEED).
- Back-gate voltage dependence of sheet resistance as a function of the temperature
- **Why do we need (111) interface and ferromagnetic 2DES?**

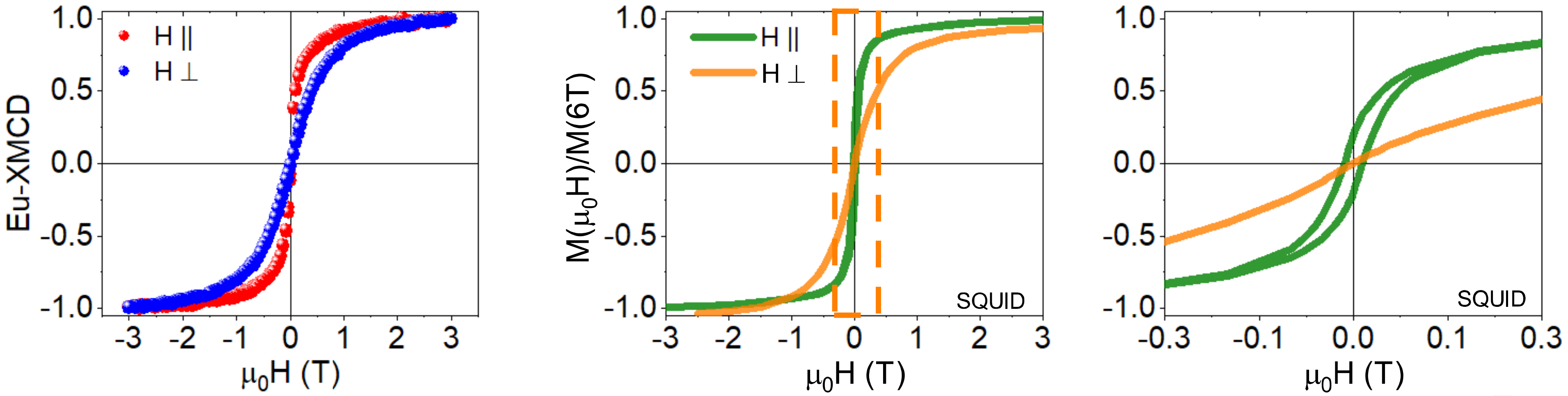
Ref: Y. Chen, at al., g, ACS Appl. Electron. Mater. 4, 3226 (2022). Y. Chen, et al., Adv. Mater. **37**, 2410354 (2025).

(111)$LaAlO_3$/（$EuTiO_3$）/$SrTiO_3$ interfaces



- Lower symmetric: trigonal crystal field gives rise to a_{1g} and e_g^{π} derived bands.
- Spin textures: hexagonal warping and out-of-plane spin alignment.
- Berry curvature with alternatively positive and negative values at the snowflake-like Fermi contour.
- The hexagonal band-warping of (111) heterostructures unveiled large and unexpected in-plane second order bi-linear magneto-resistance and anomalous Hall effect, induced by a large external in-plane magnetic field.

Magnetic Characterizations



- X-ray magnetic circular dichroism (XMCD) at Eu-$M_{4,5}$ edge
- Anisotropic XMCD and SQUID confirm in-plane magnetization
- **What is the magnetic effect on the transport behavior?**

Y. Chen, et al., Adv. Mater. **37**, 2410354 (2025)

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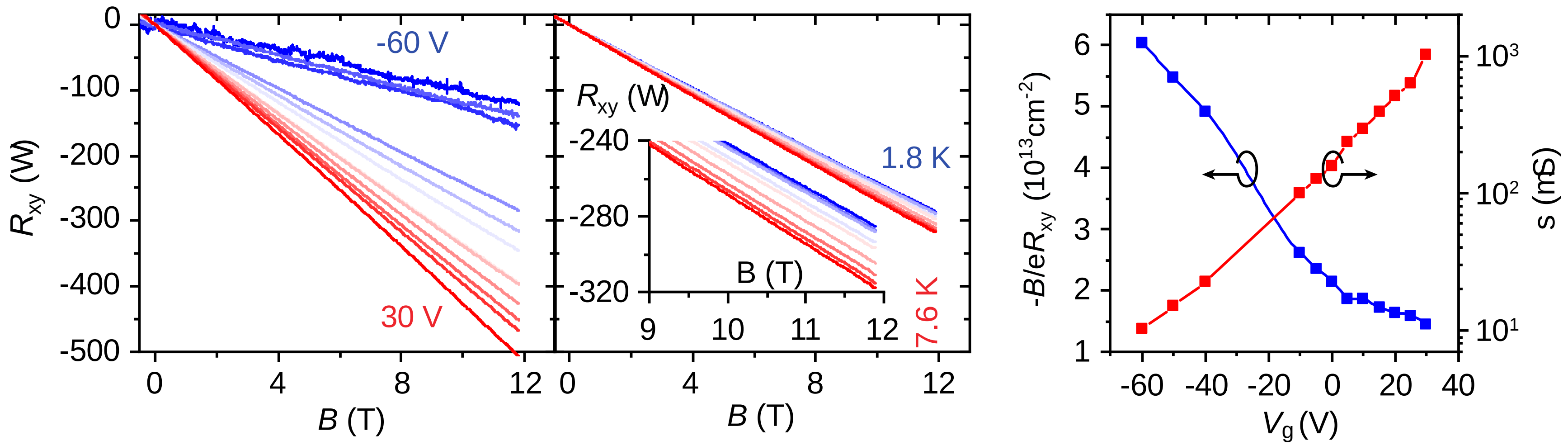
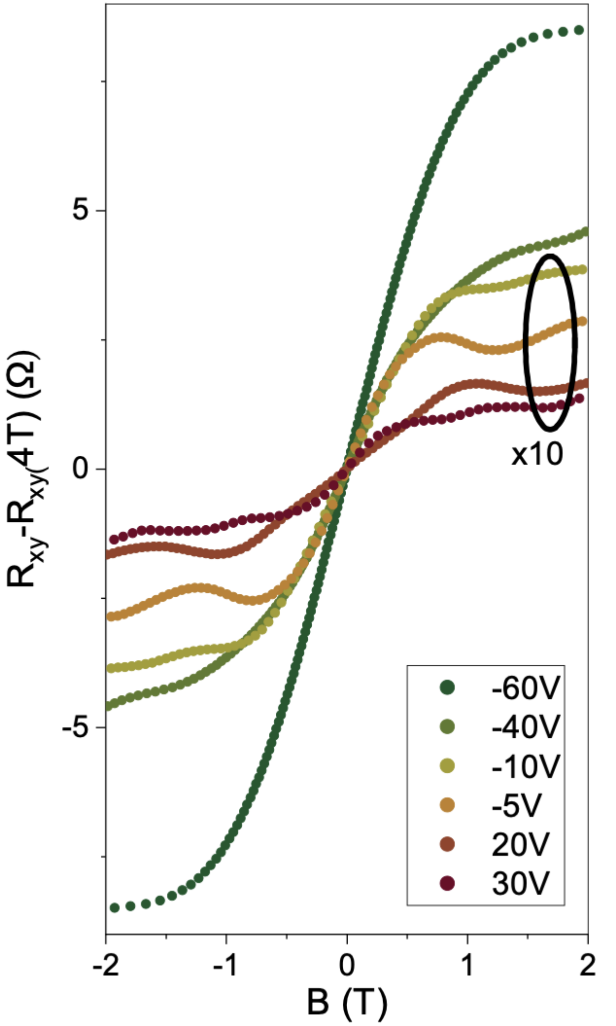
Anomalous Hall effect





- The inverse Hall coefficient decreases with increasing gate-voltage, which is opposite to the expected accumulation of electron due to the snowflake-like Fermi contour.
- Anomalous Hall effect contribution due to 2DES magnetism.

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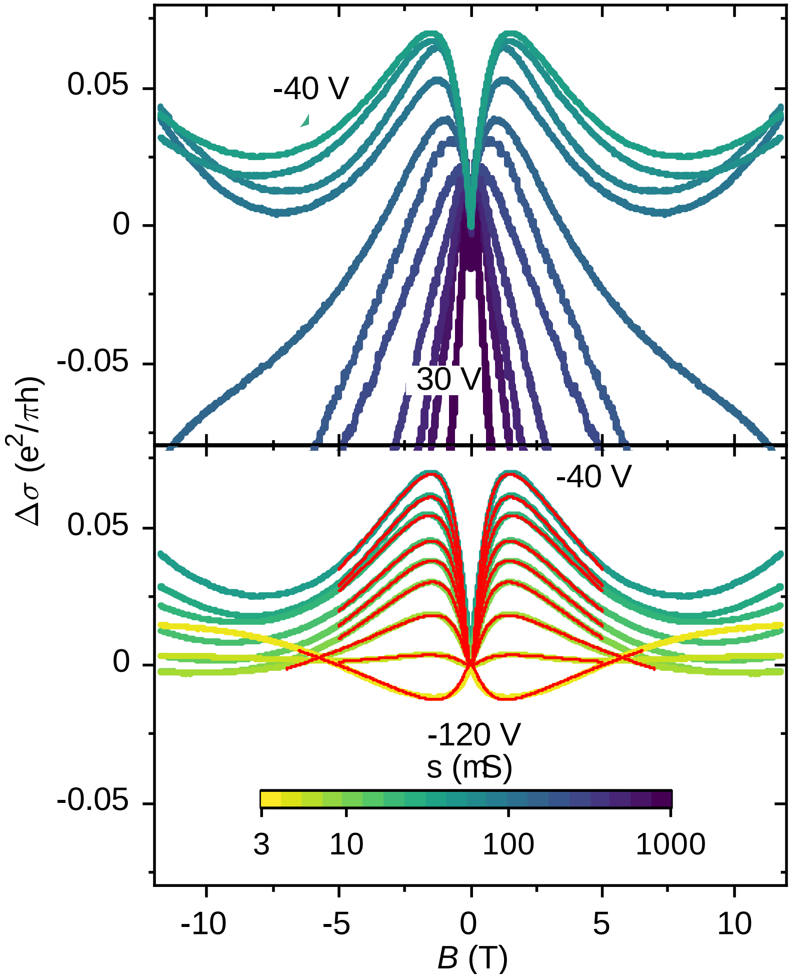
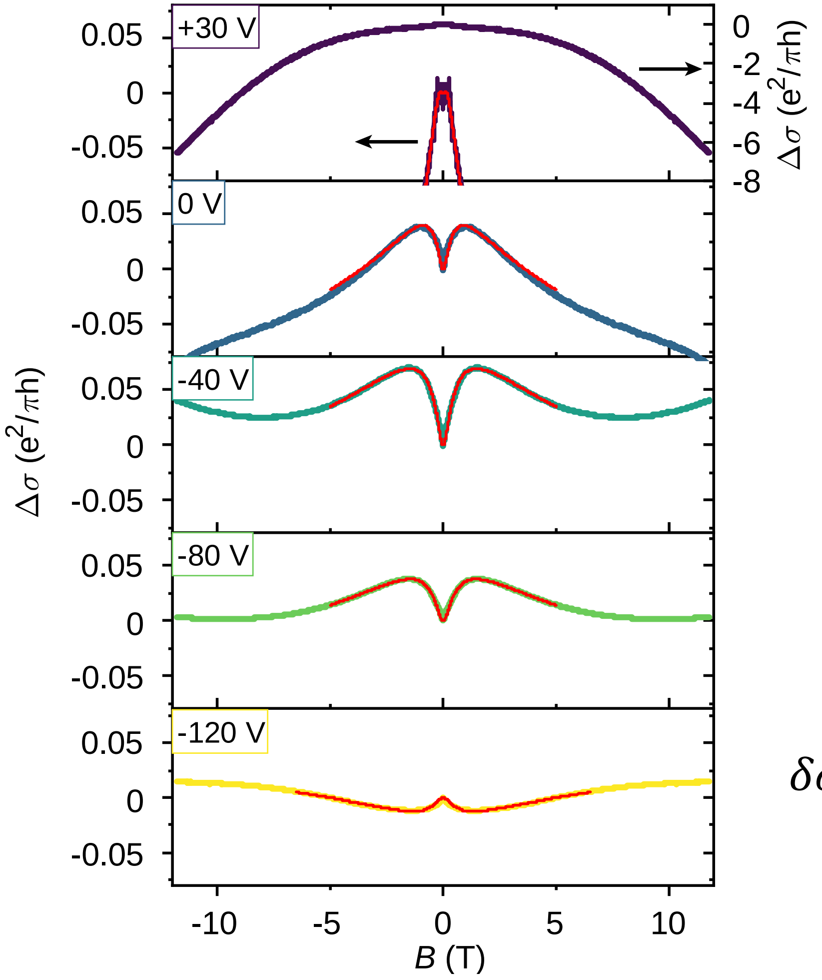
Anomalous magnetoconductance





- Anomalous shoulder-peak
- Models of Hikami-Larkin-Nagaoka, Iordanskii-Lyanda-Geller-Pikus, or Maekaewa-Fukuyama do NOT capture the MC data.
- Fitting Using formula derived in the gapped topological insulators (TIs) [Ref :*H. Z. Lu, et al, Phys. Rev. Lett. 107, 076801 (2011)*.]

$$\delta\sigma(B) = \sum_{i=0,1} \frac{\alpha_i e^2}{\pi h}[\Psi\left(\frac{l_B^2}{l_{\phi i}^2}+\frac{1}{2}\right) - \ln(\frac{l_B^2}{l_{\phi i}^2})]$$

$\alpha_0 \rightarrow$ WAL-like, $\alpha_1 \rightarrow$ WL-like

- Is it the ferromagnetic effect?

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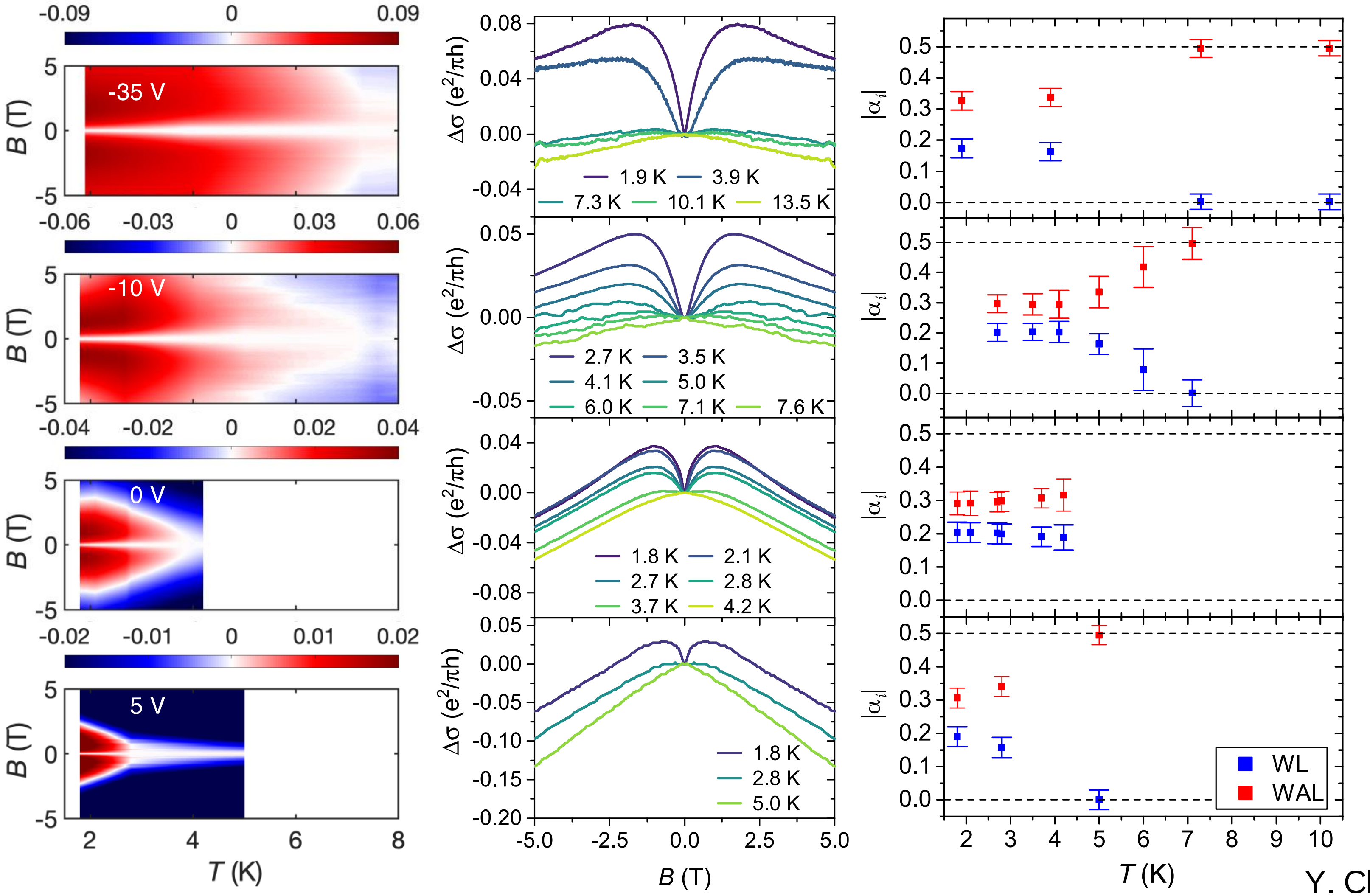
Temperature dependence of magnetoconductance



- MC data as function of the temperature at Vg= -35 V, -10 V, 0 V and 5 V shown as color map and bare MC vs B data.
- Fit parameters α_i (i =0,1) using Equation (1). The fits show that α_1 (WL-like contribution) goes to zero above 7-8 K, i.e. at a temperature similar to the FM Tc.
- The MC is associated with the gap Δ induced by ferromagnetic mangetization.

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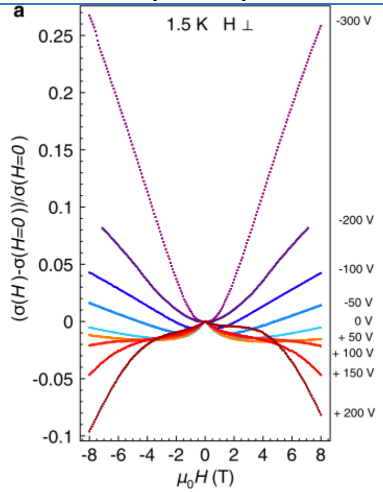
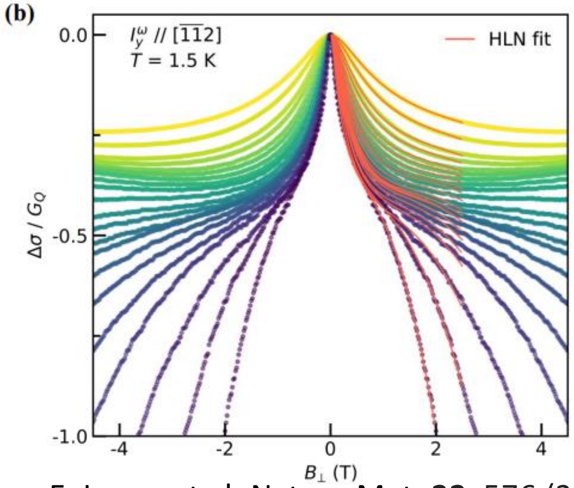
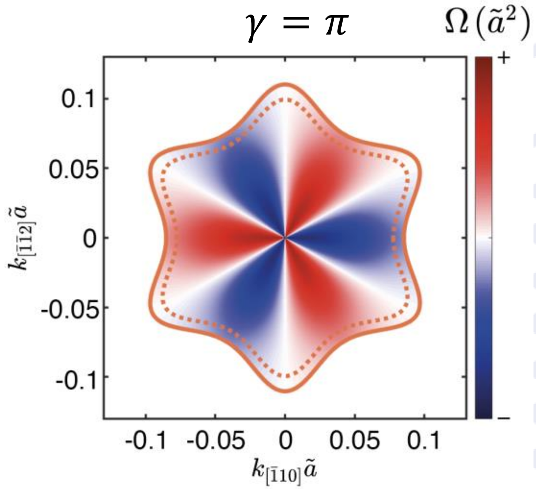
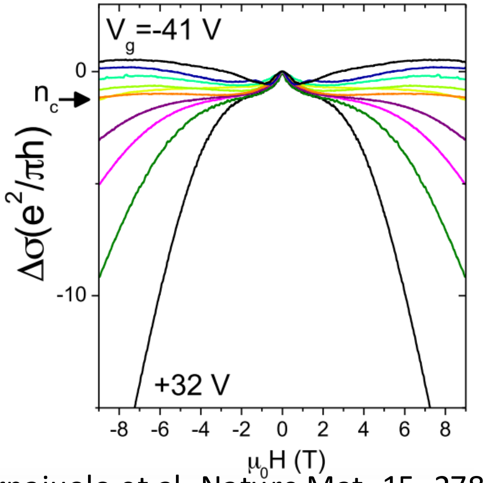
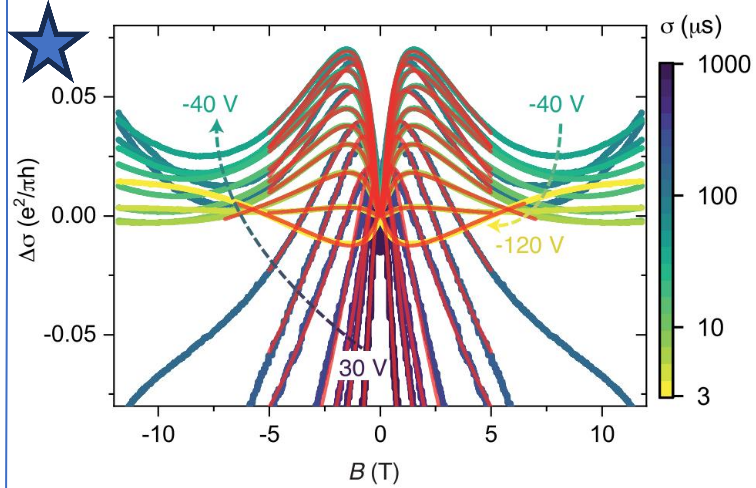
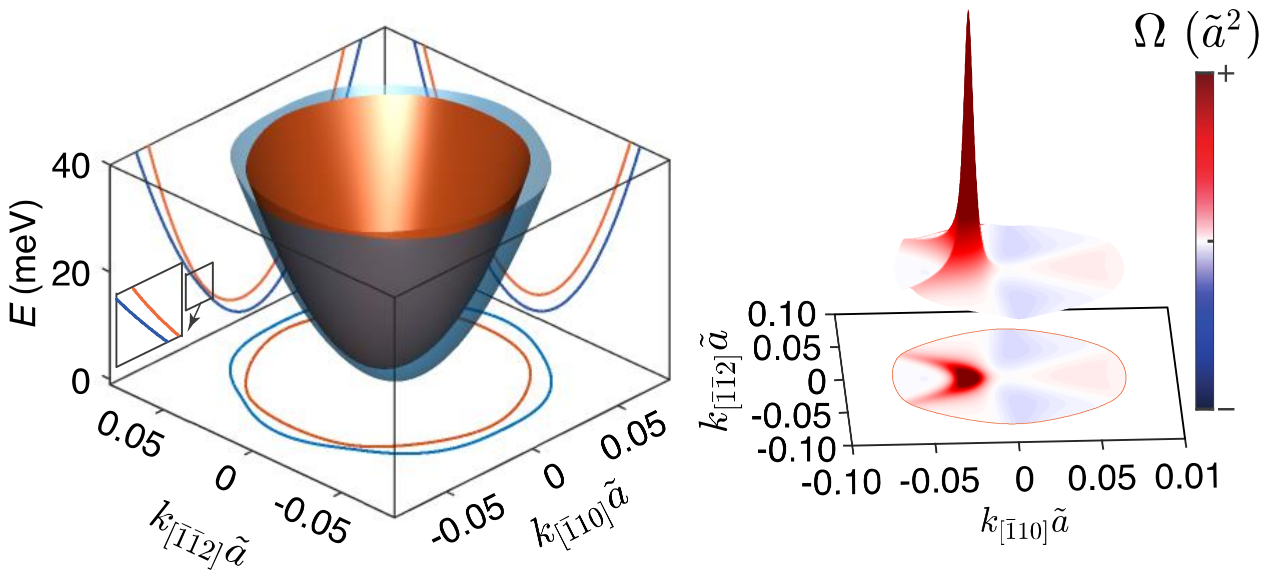
WL and WAL at oxide interfaces

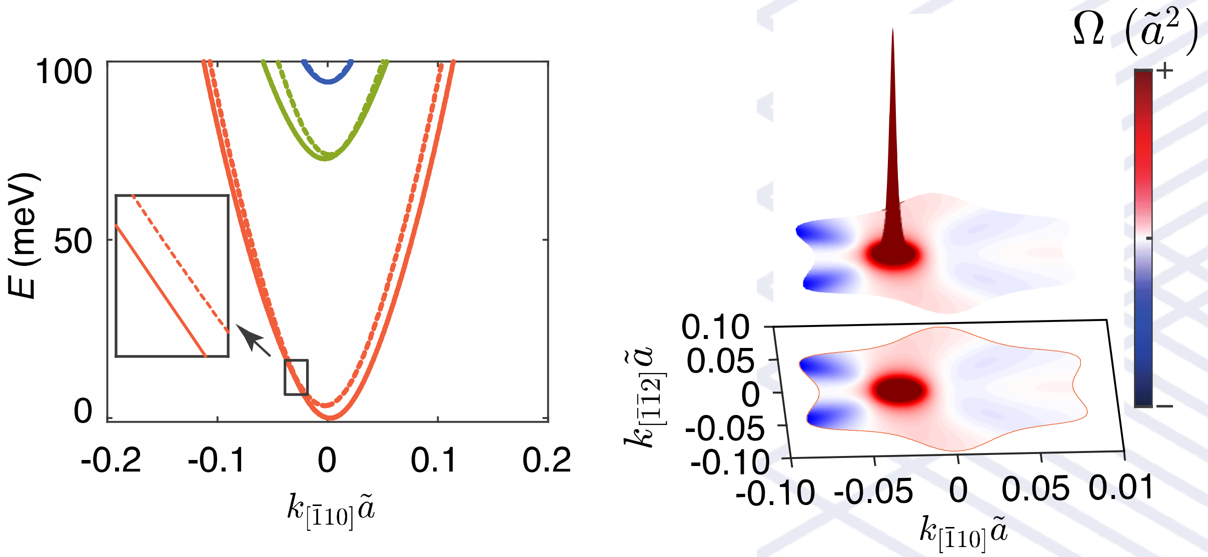
	(001)	(111)
Non-FM LAO/STO	 A.D. Caviglia et al. PRL 104,126803 (2010)	  E. Lesne et al. Nature Mat. **22**, 576 (2023)
Ferromagnetic LAO/ETO/STO	 D. Stornaiuolo et al. Nature Mat. 15, 278 (2016).	 ? Y. Chen, et al., Adv. Mater. **37**, 2410354 (2025)

Competing WL and WAL due to non-trivial Berry curvature

minimal model



Tight-binding Hamiltonian calculations

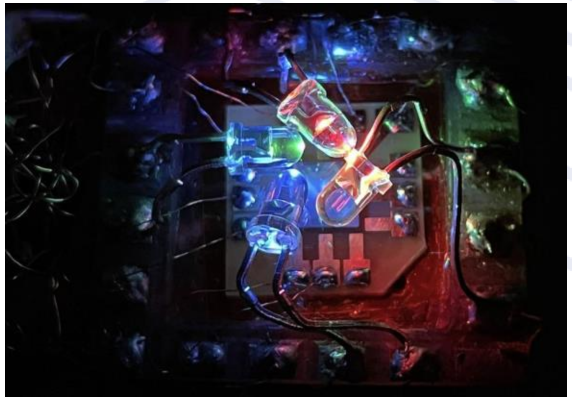


$$H = \frac{\hbar^2 \mathbf{k}^2}{2m^*} + h_w \sigma_z - \lambda(\sigma_x k_y - \sigma_y k_x) + H_M$$

Hexagonal band warping + Rashba-like split + in-plane or canted magnetization brings about a local gap, resulting in non-trivial Berry curvature with a hot spot, analog to the MC observed in gapped TIs.

Conclusions and Perspectives

- A method to create oxide 2DES characterized by anomalous transport properties mimicking those of systems hosting Dirac fermions, as in gapped 3D-TIs.
- Dirac-like point generated by the spin-split lowest energy bands in the simultaneous presence of Rashba-SOC, magnetic correlations, and the hexagonal symmetry of the system.
- Berry-curvature hot-spot without external planar magnetic field.
- To evaluate the Rashba Coefficient from quadratic and bilinear magnetoresistance response because we cannot use HLN, ILP, and MF formulas to fit the data.
- Second Harmonic Hall voltage detection scheme to study Berry curvature at (111) LAO/ETO/STO interfaces.
- Light control of the Non-trivial Berry Curvature : Magnetotransport under illumination with LEDs.
- spin-orbitronics and topological electronics based on the nontrivial berry curvature.



Thank you for your attention