GFMC
Grupo de Física de Materiales Complejos

Oxitronics, VdW and beyond…..

Jacobo Santamaria

Universidad Complutense de Madrid

Outline

- Interest of TM oxides. GFMC
- PART I. ferromagnetic superconducting proximity effect:. Long range Josephson effect.
- PART II. 3d/5d oxide heterostructures. Topological spin textures.
- PART III. 2D freestanding oxides: oxide twistronics.

Mixt Unit (Unidad Asociada) UCM-ICMM CSIC

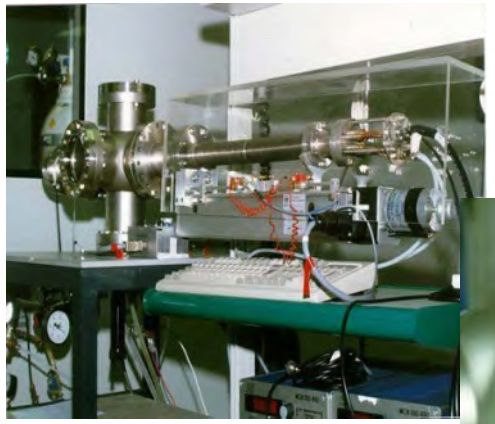
Laboratory for materials and heterostructures for spintronics

GFMC

What we can do

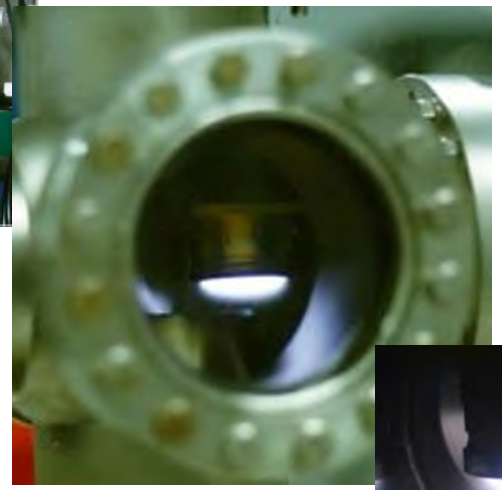
Oxide heterostructures with atomically sharp oxide interfaces .
quantum matter, spintronics, magnetism superconductivity

3- high pressure O sputtering system
in a clean room environment

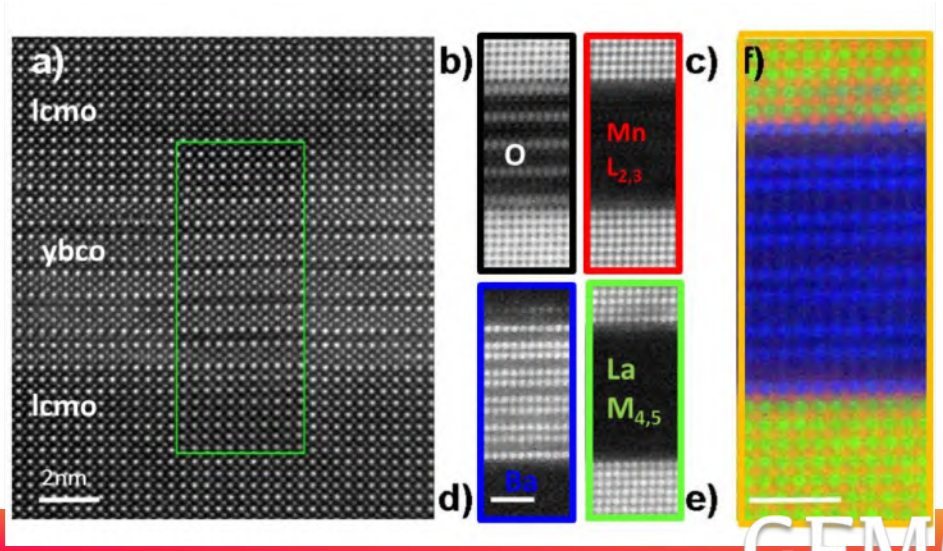


Ts = 900 ºC

P = 3 mbar oxygen plasma



State of the art HRTEM-EELS



Phys. Rev. Lett. **113**, 189902 (2014)

Oxides have always been there…..

But are they interesting??

- L. de Broglie – Nature 112, 540 (1923).

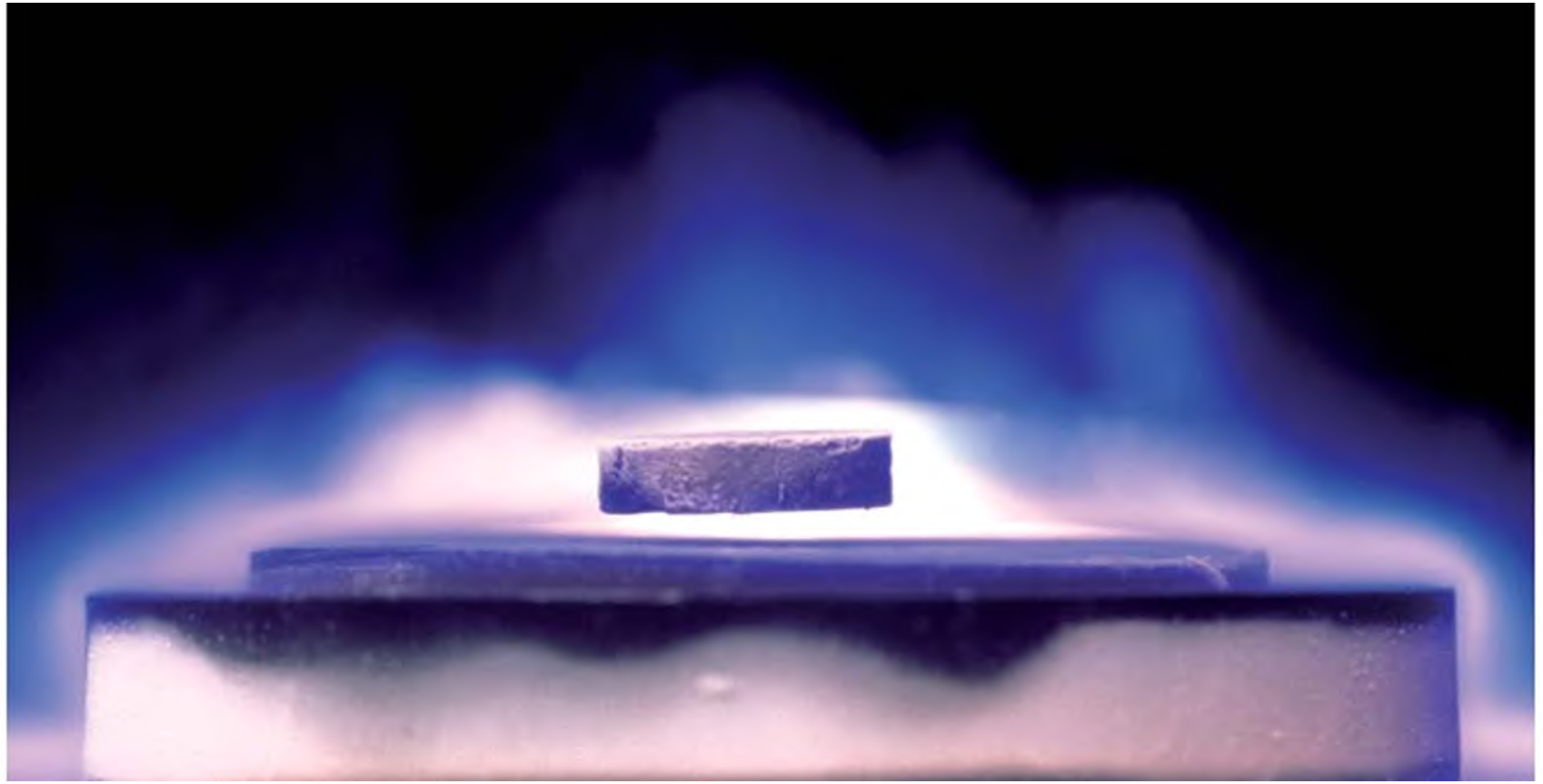
- E. Schrodinger – 1925, ….

- Pauli exclusion Principle - 1925
- Fermi statistics - 1926
- Thomas-Fermi approximation – 1927
- Dirac equation – relativistic quantum mechanics - 1928

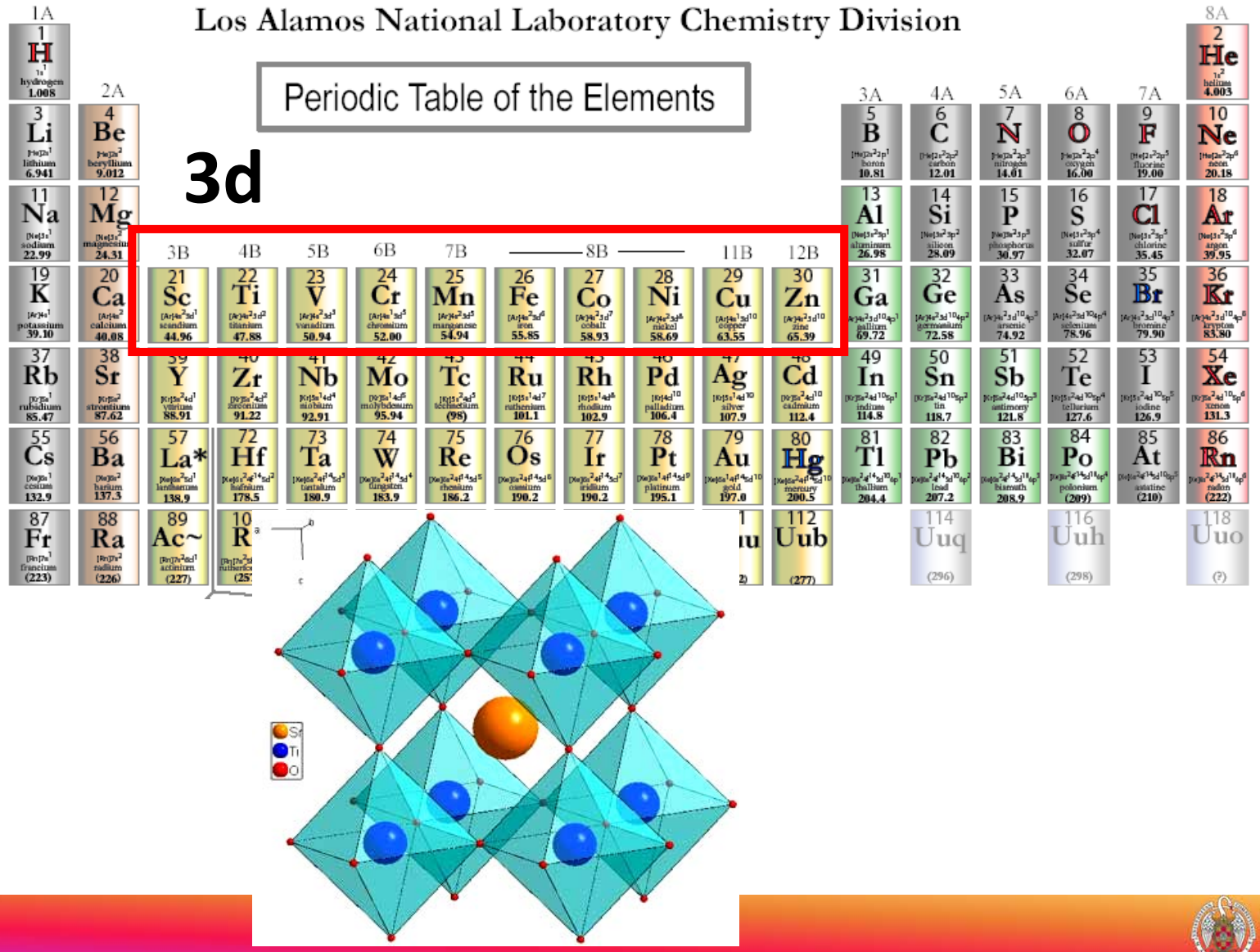
1987J. G. Bednorz and K. A. Mueller (High Tc)
2010 Andre Geim, Konstantin Novoselov (GRAPHENE)
2016 David J. Thouless, F. Duncan M. Haldane and J. **Michael Kosterlitz**
"topological phases of matter".

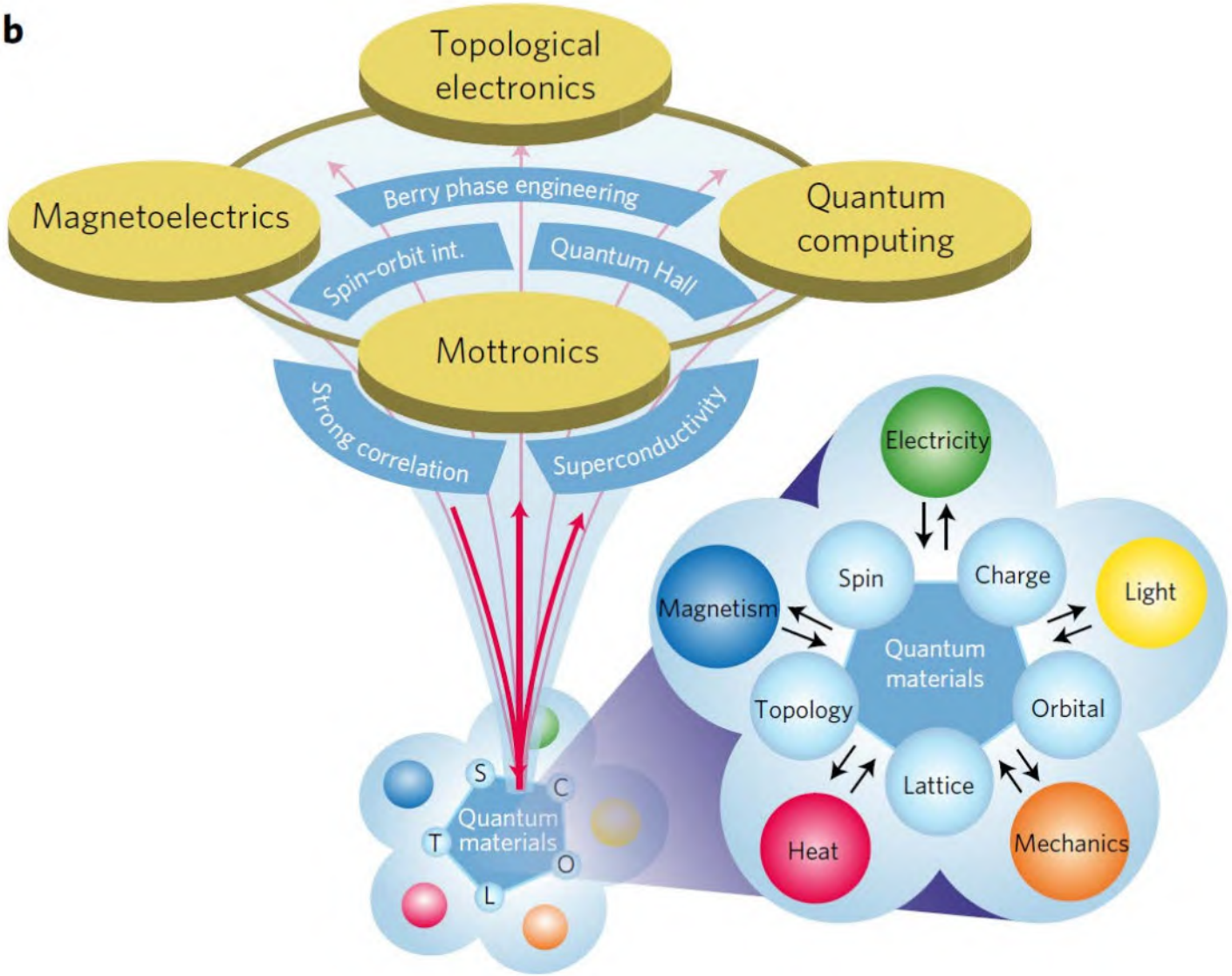
Focus point 1…..

correlated electrons feel each other: Tunability

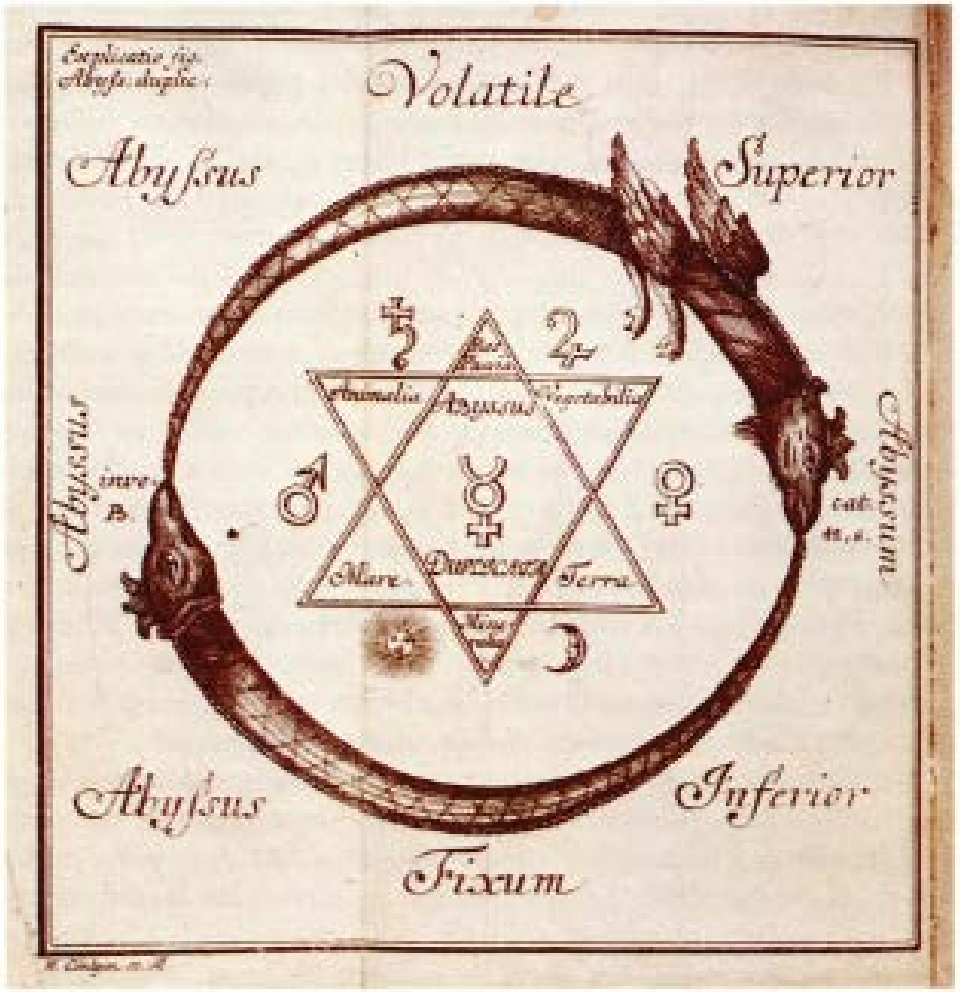


3d TRANSITION METAL OXIDES: correlated electrons



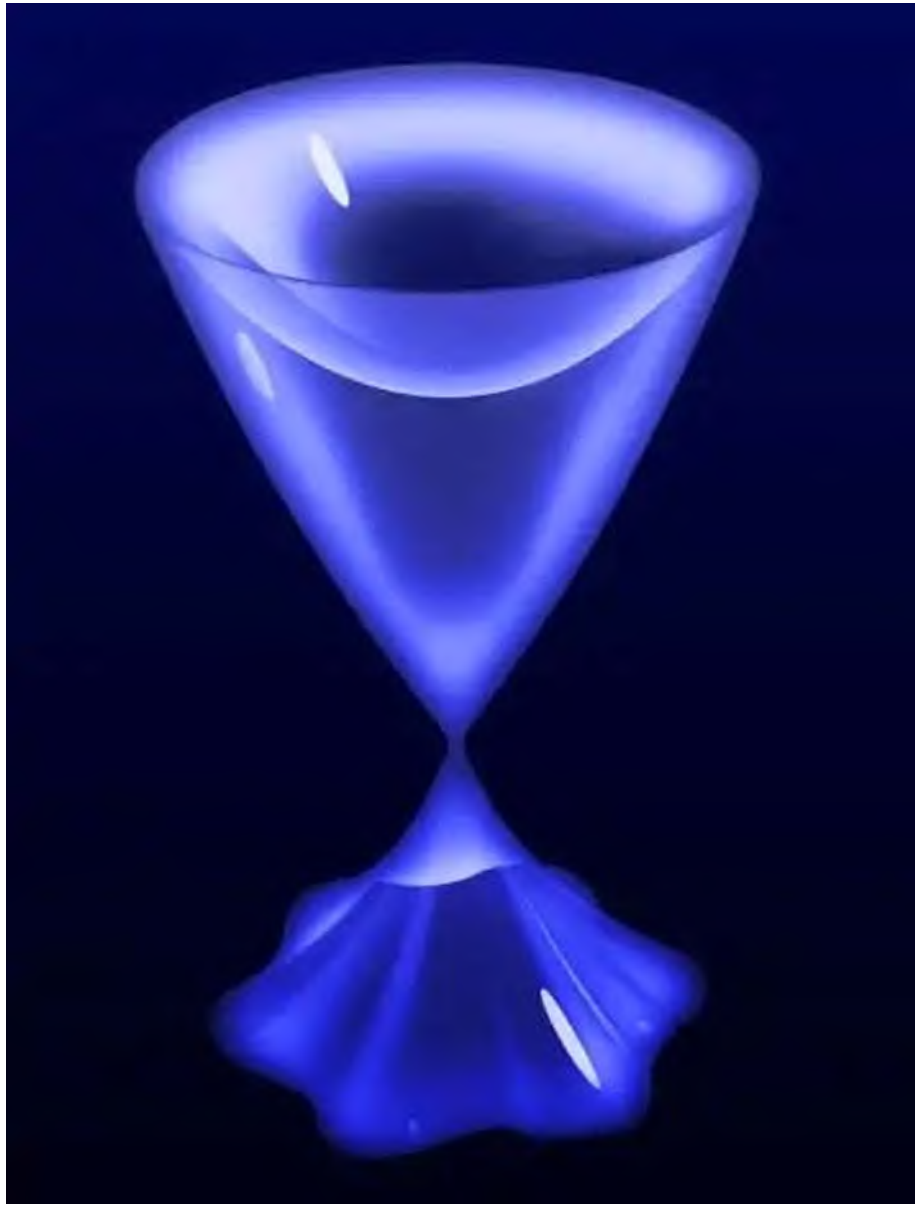


adapted from Y. Tokura. Nature Physics 13 (2017)



Adapted from oxide course by Antoine Georges

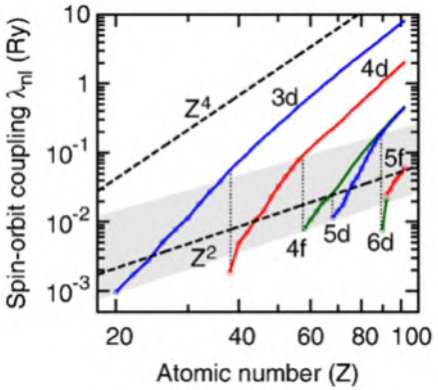
Focus point 2…..



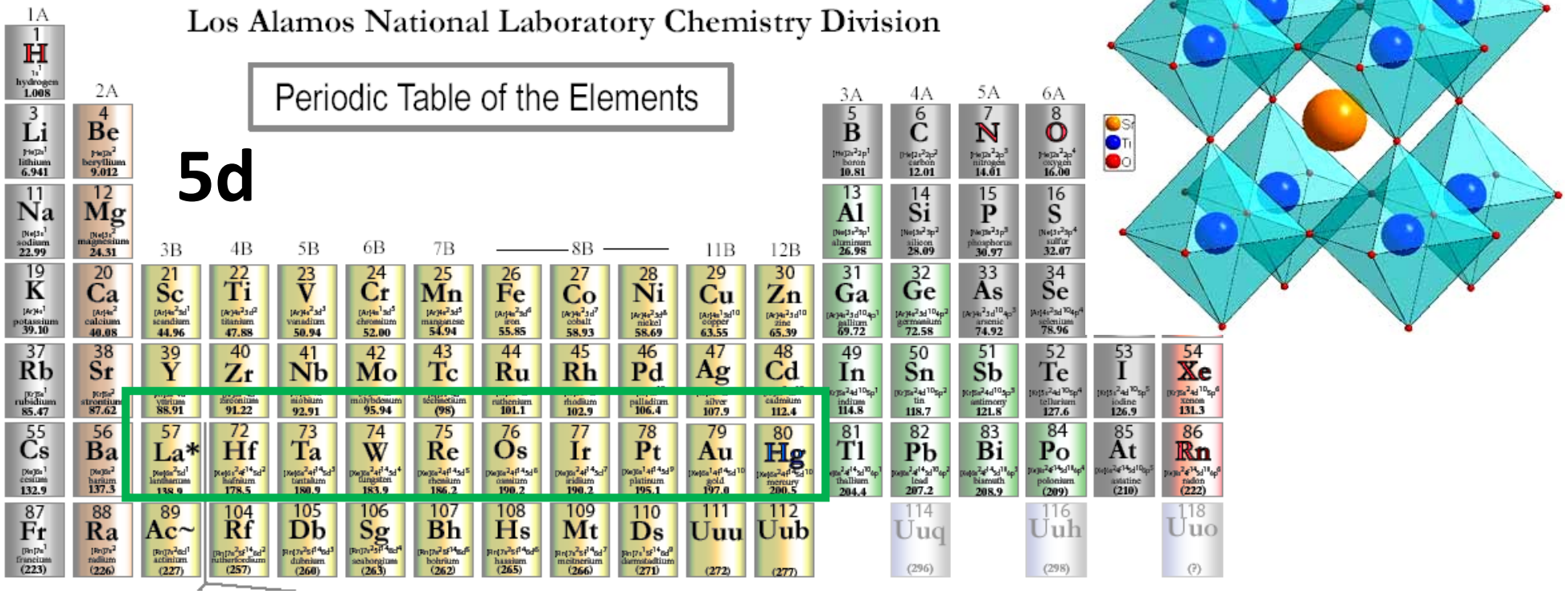
spin orbit int.: Topology **Robustness**

$$\mathcal{H}_{SO} = \frac{\xi}{\hbar}\hat{\boldsymbol{\sigma}}(\boldsymbol{\nabla}\phi \times \boldsymbol{p})$$

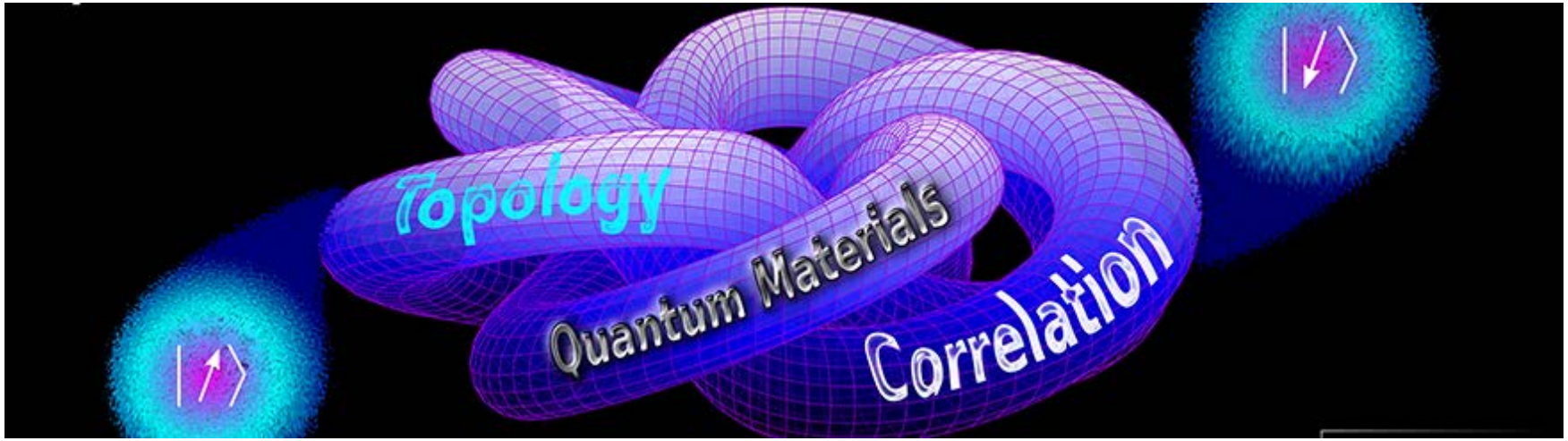
$$\boldsymbol{B} = -\frac{\boldsymbol{v} \times \boldsymbol{E}}{c^2}$$



5d TRANSITION METAL OXIDES: strong spin orbit



Why do we care?.....



ENTANGLEMENT: quantum state of a system expressed in terms of the states of its parts

$$\Psi = \left| \text{  } \right\rangle + \left| \text{  } \right\rangle$$

1) Knowledge of the system does not imply knowledge of its parts

2) Trivial entanglement can be smoothly transformed in a product state. Independent parts.
3) Non trivial entanglement resulting from manybody effects friven by Coulomb interaction

<Q|C|B>
QUANTUM COMPUTING BUSINESS
CONFERENCE 2019

The Quantum Revolution

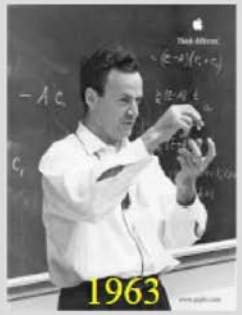
Alain ASPECT

Professor at Institut d'Optique Graduate School and Ecole Polytechnique, France

Member of the French Academy of Science and Academy of Technologies

Member of several Science and Technology Academies

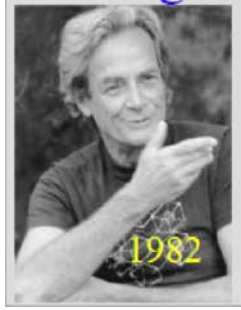
Wave-particle duality: single particle interference



- A particle (an electron) also behaves as a wave
- A wave (light) can also behave as a particle (single photon effects)

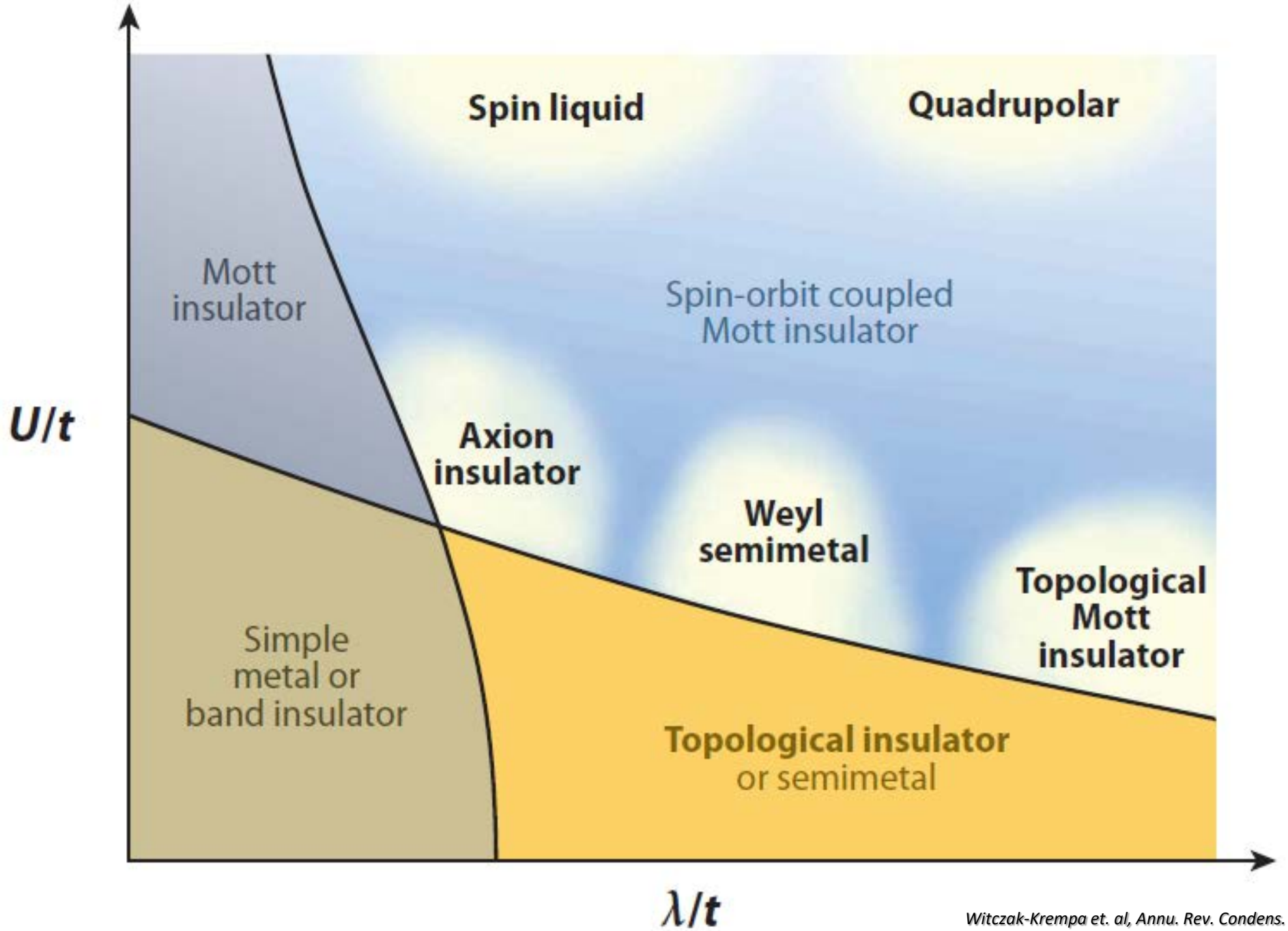
Classical models, (local realism *à la* Einstein) in ordinary space-time

Entanglement: interference between two-particles amplitudes



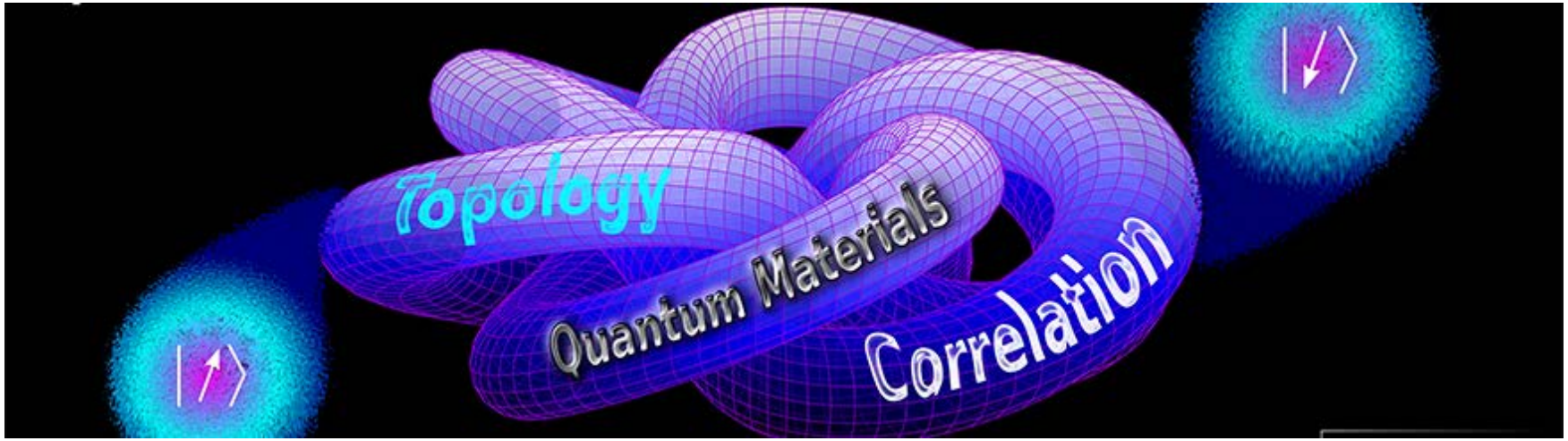
- Hanbury Brown-Twiss effect for particles
- Hong-Ou-Mandel effect
- Bell's inequalities violation

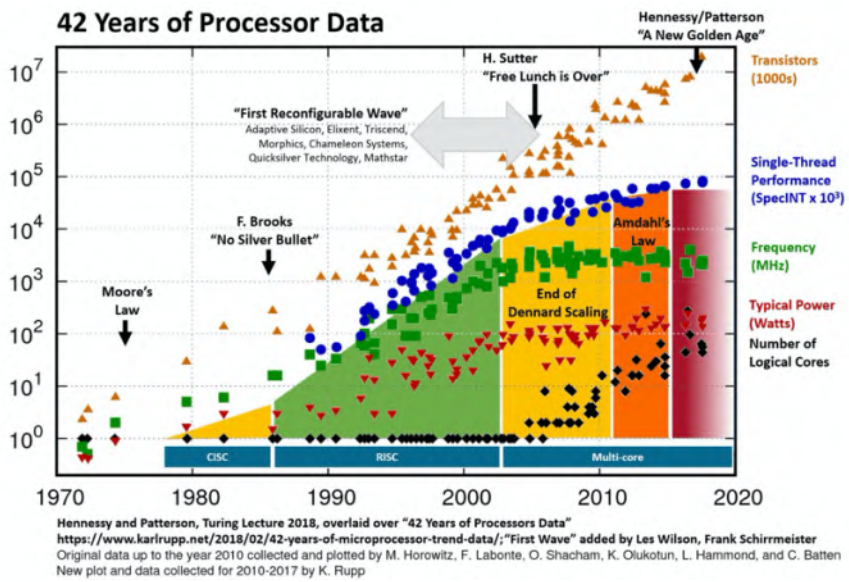
Interference in Hilbert space. No classical model in ordinary space-time

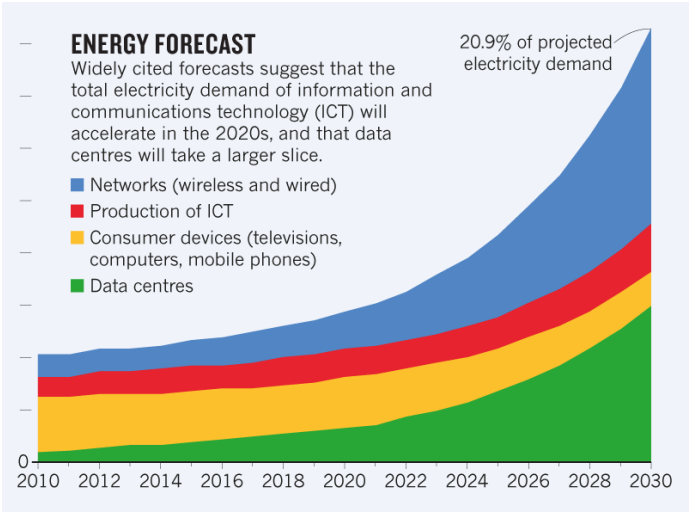


Witczak-Krempa et. al, Annu. Rev. Condens. Matter Phys. 5, 57–82 (2014).

Why do we care?.....







N. Jones, Nature 561, 163 (2018)

Nature 24 October 2019

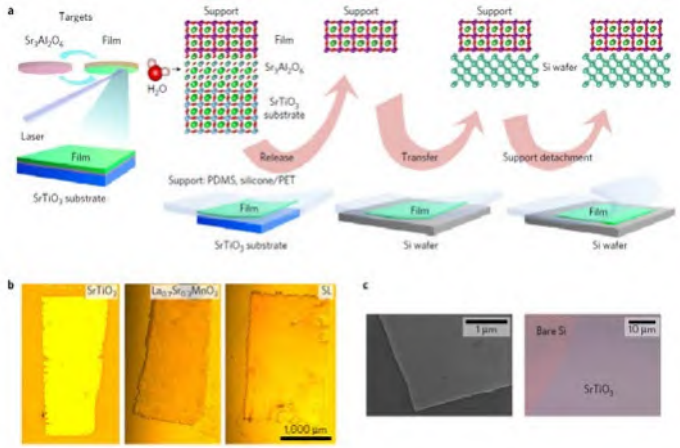
Focus point 3…..

“graphene-like oxides”, we call them oxide-membranes

nature materials
LETTERS
PUBLISHED ONLINE: 12 SEPTEMBER 2016 | DOI: 10.1038/NMAT4749

Synthesis of freestanding single-crystal perovskite films and heterostructures by etching of sacrificial water-soluble layers

Di Lu[1,2], David J. Baek[3], Seung Sae Hong[2,4], Lena F. Kourkoutis[5,6], Yasuyuki Hikita[2]* and Harold Y. Hwang[2,4]*

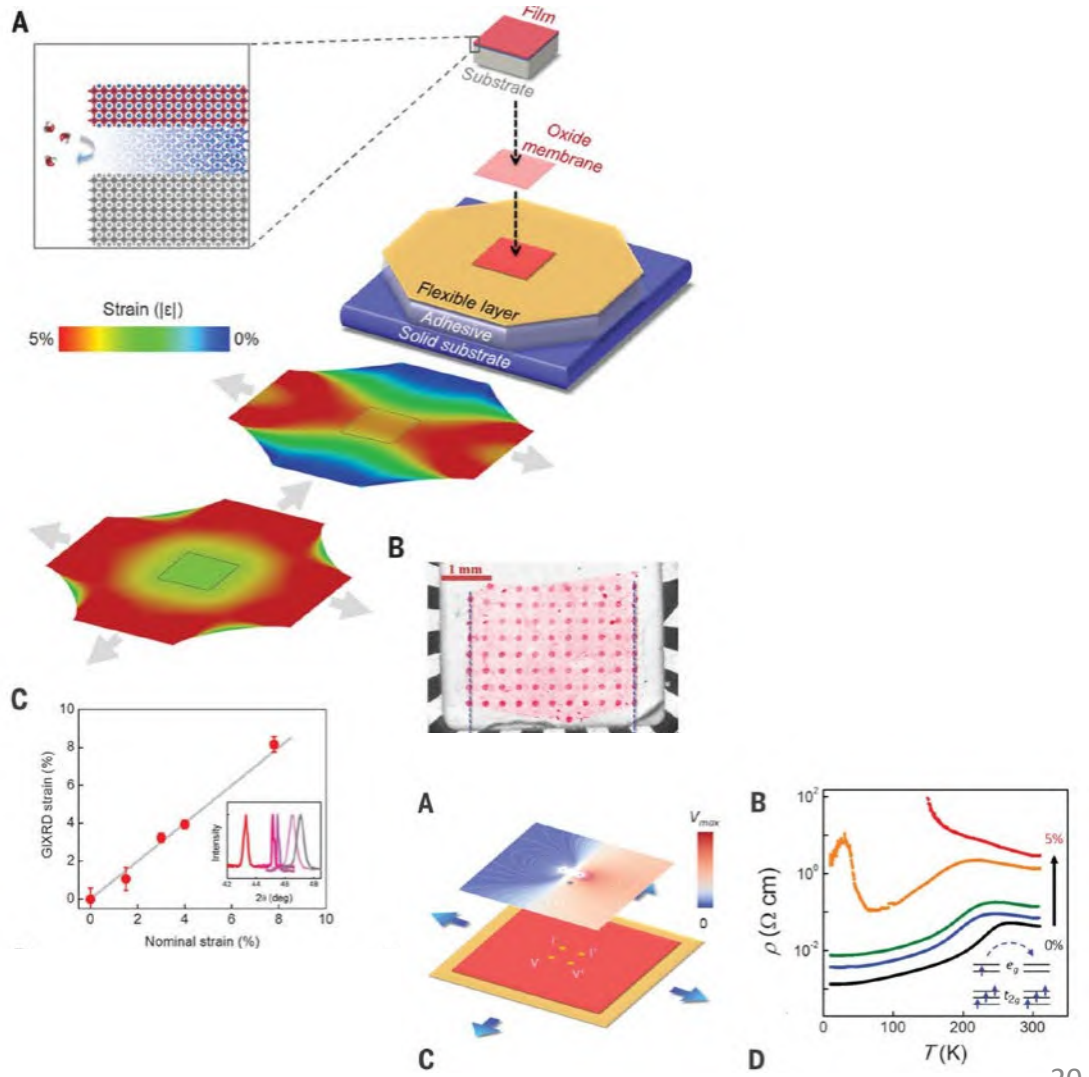


Lu et al. Nature Mater 15, 1255 (2016).

COMPLEX OXIDES

Extreme tensile strain states in $La_{0.7}Ca_{0.3}MnO_3$ membranes

Seung Sae Hong[1,2,3]*, Mingqiang Gu[4,5], Manish Verma[6], Varun Harbola[2,7], Bai Yang Wang[2,7], Di Lu[2,4,7], Arturas Vailionis[8,9], Yasuyuki Hikita[2], Rossitza Pentcheva[6], James M. Rondinelli[4], Harold Y. Hwang[1,2]



Lu et al. Science 368, 71 (2020).

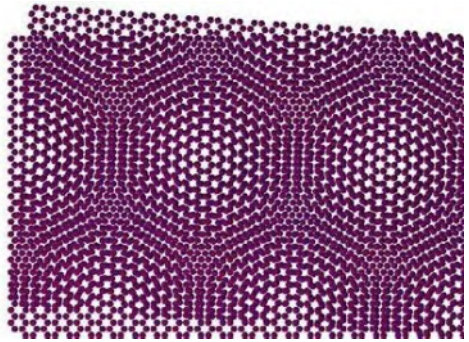
We aim at …oxide twistronics

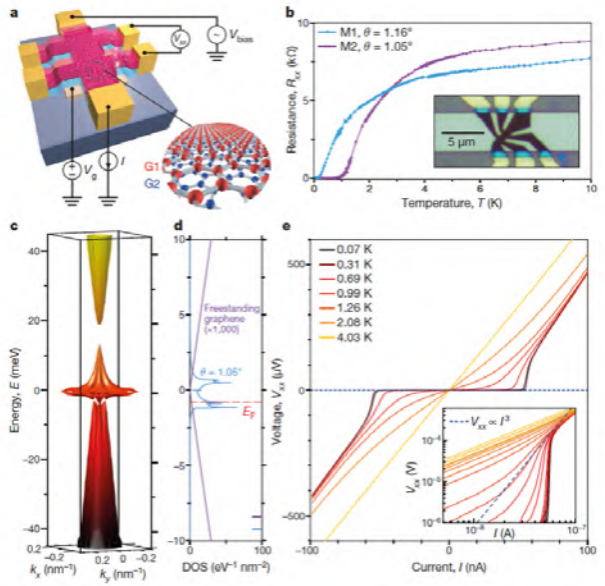
ARTICLE

doi:10.1038/nature26160

Unconventional superconductivity in magic-angle graphene superlattices

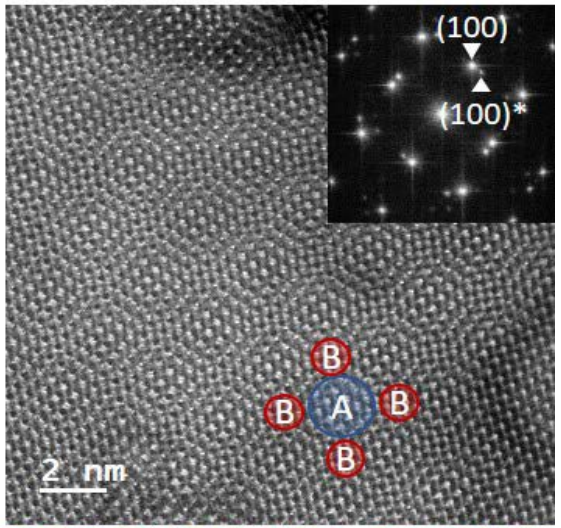
Yuan Cao[1], Valla Fatemi[1], Shiang Fang[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4] & Pablo Jarillo-Herrero[1]

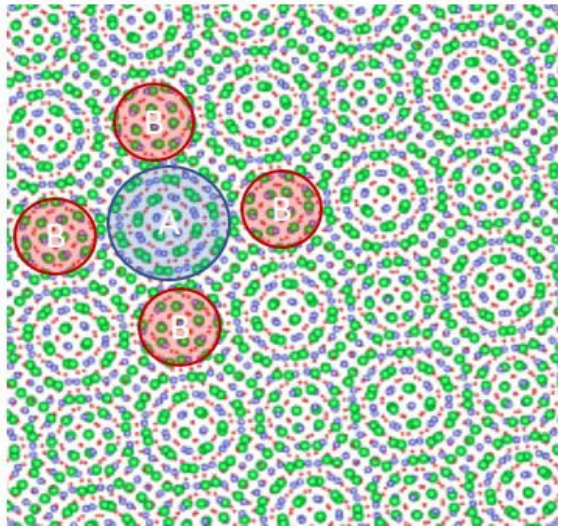




Y. Cao, Nature 556, 43 (2018).

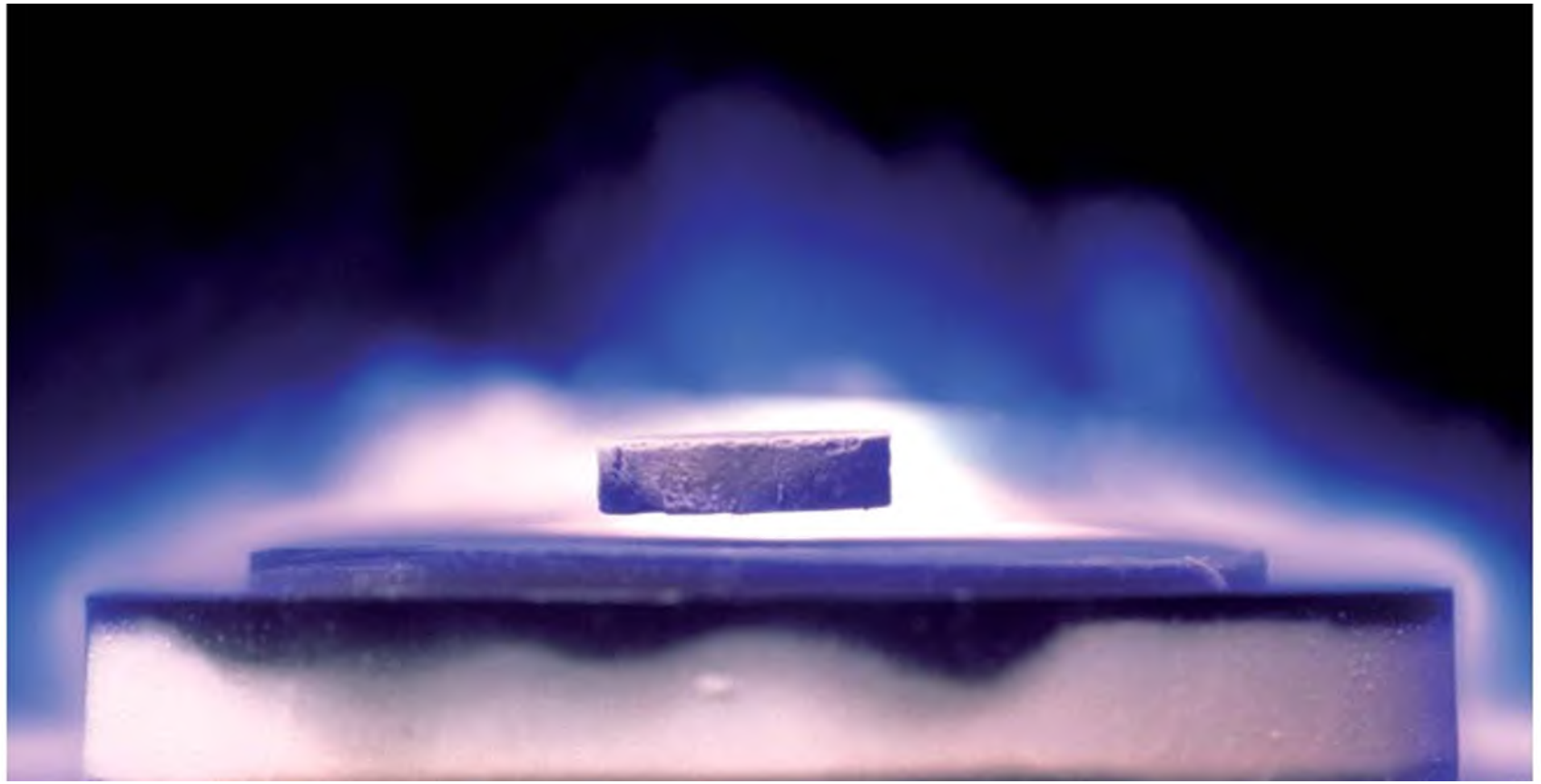
Freestanding $BaTiO_3$ twisted bilayers .



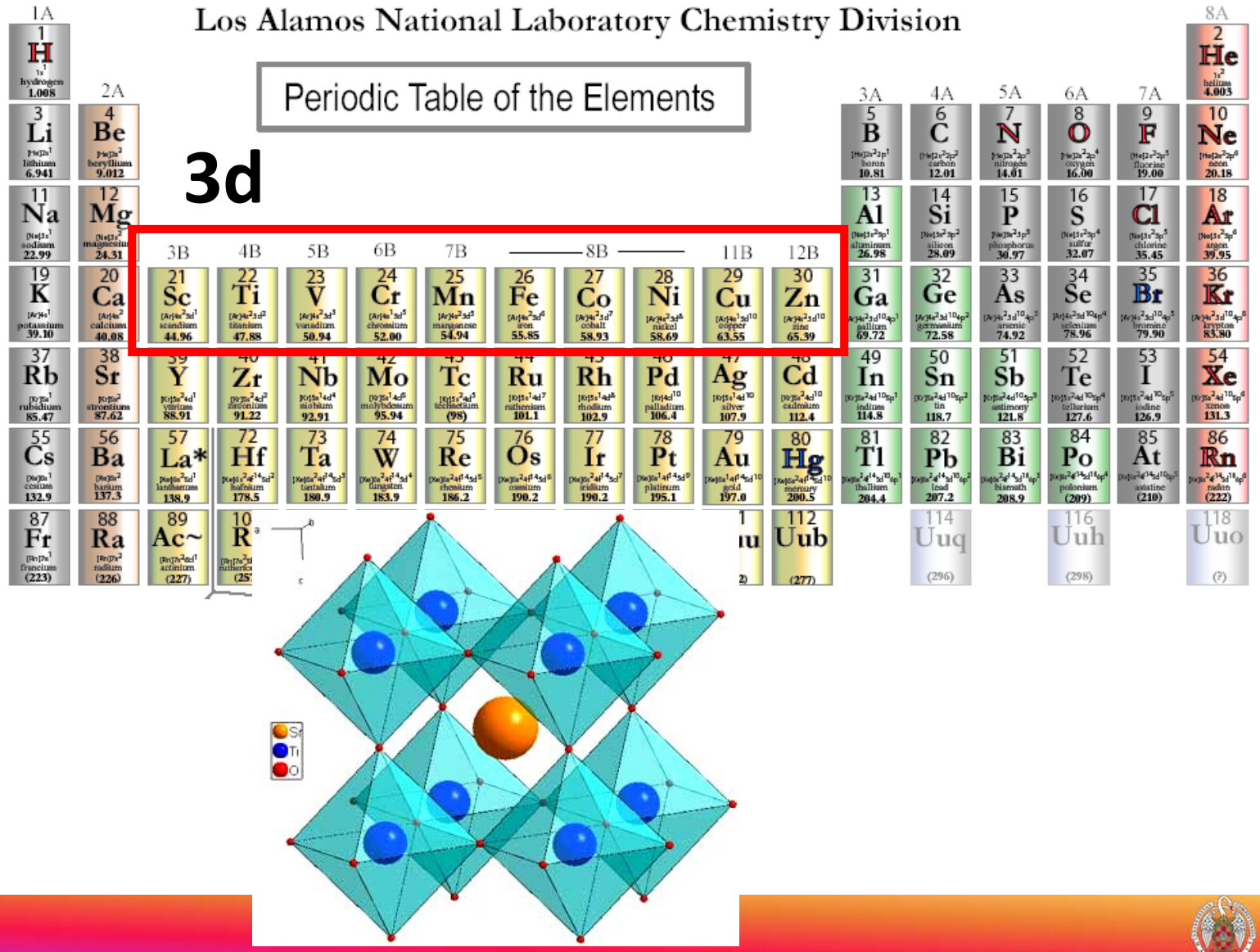


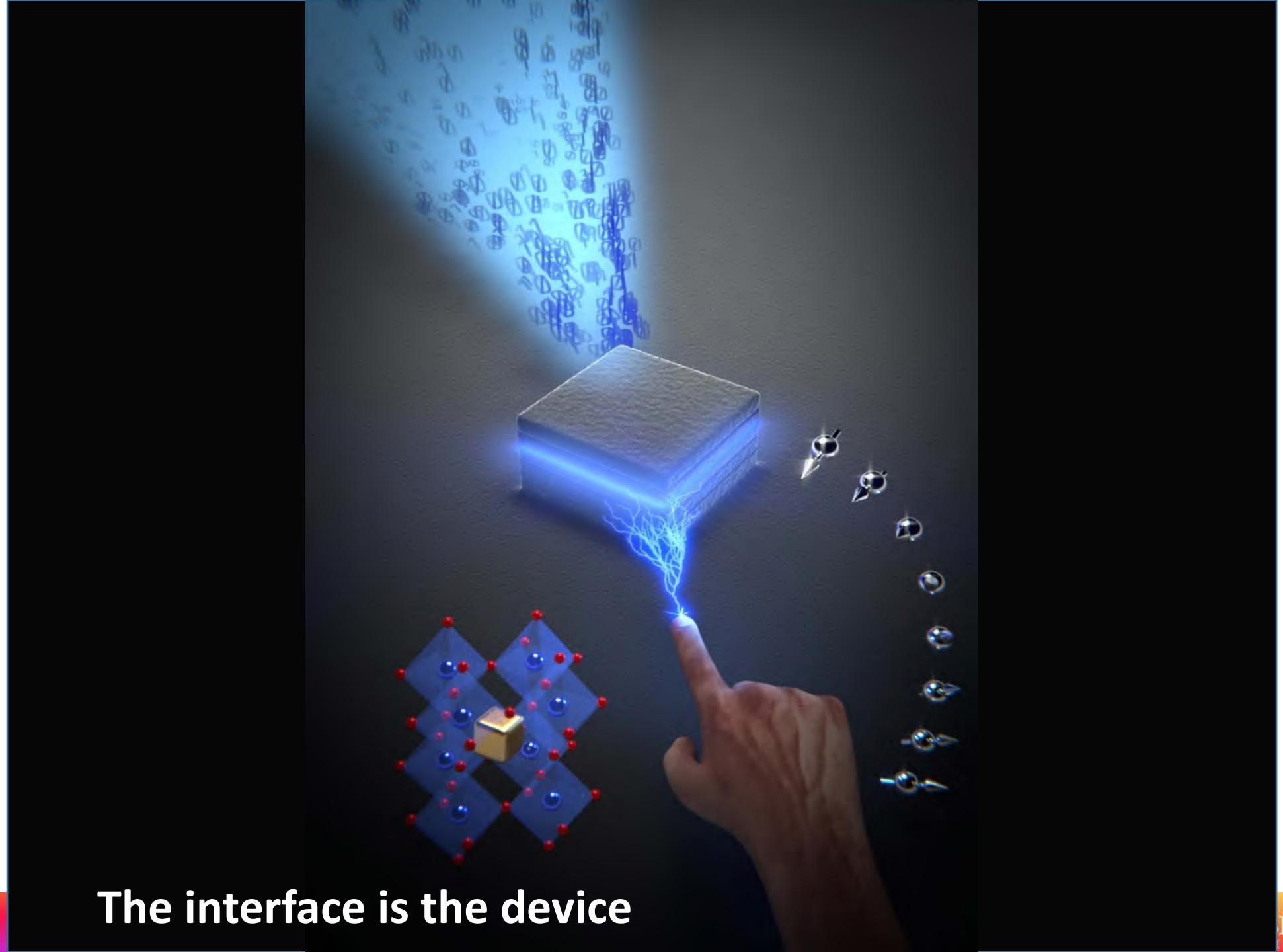
Focus point 1…..

correlated electrons feel each other: Tunability



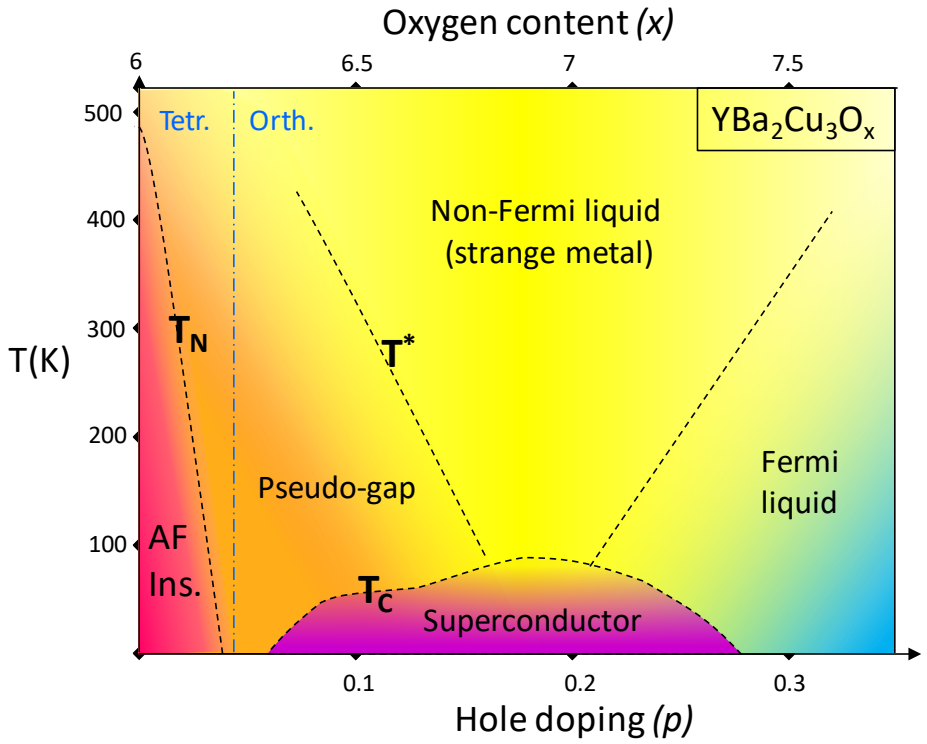
3d TRANSITION METAL OXIDES: correlated electrons



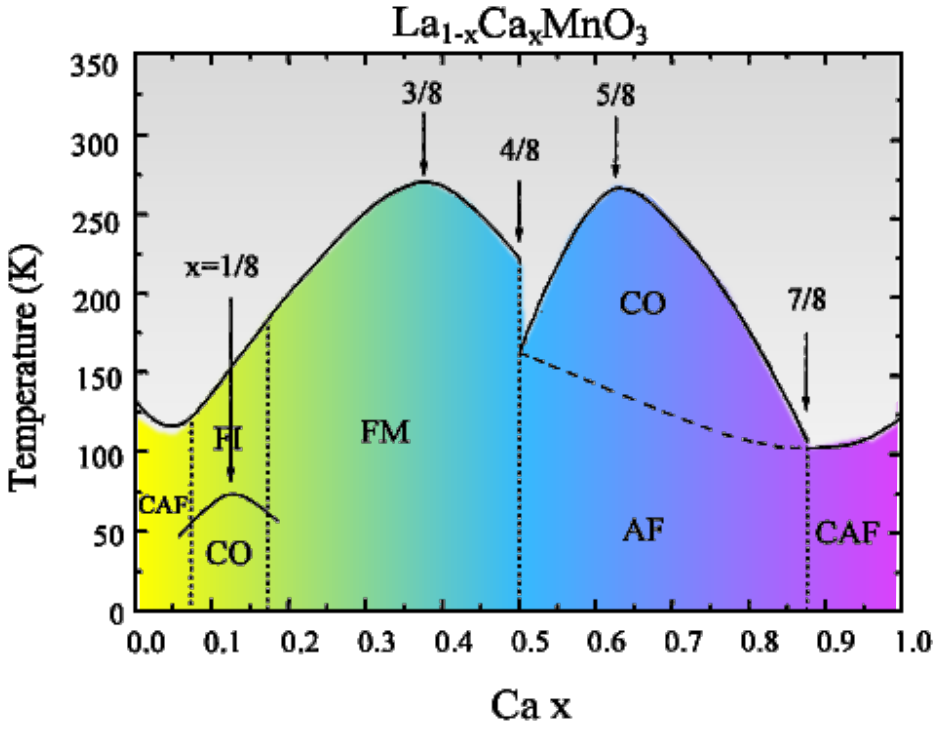


The interface is the device

Different ground states. Complex phase diagrams

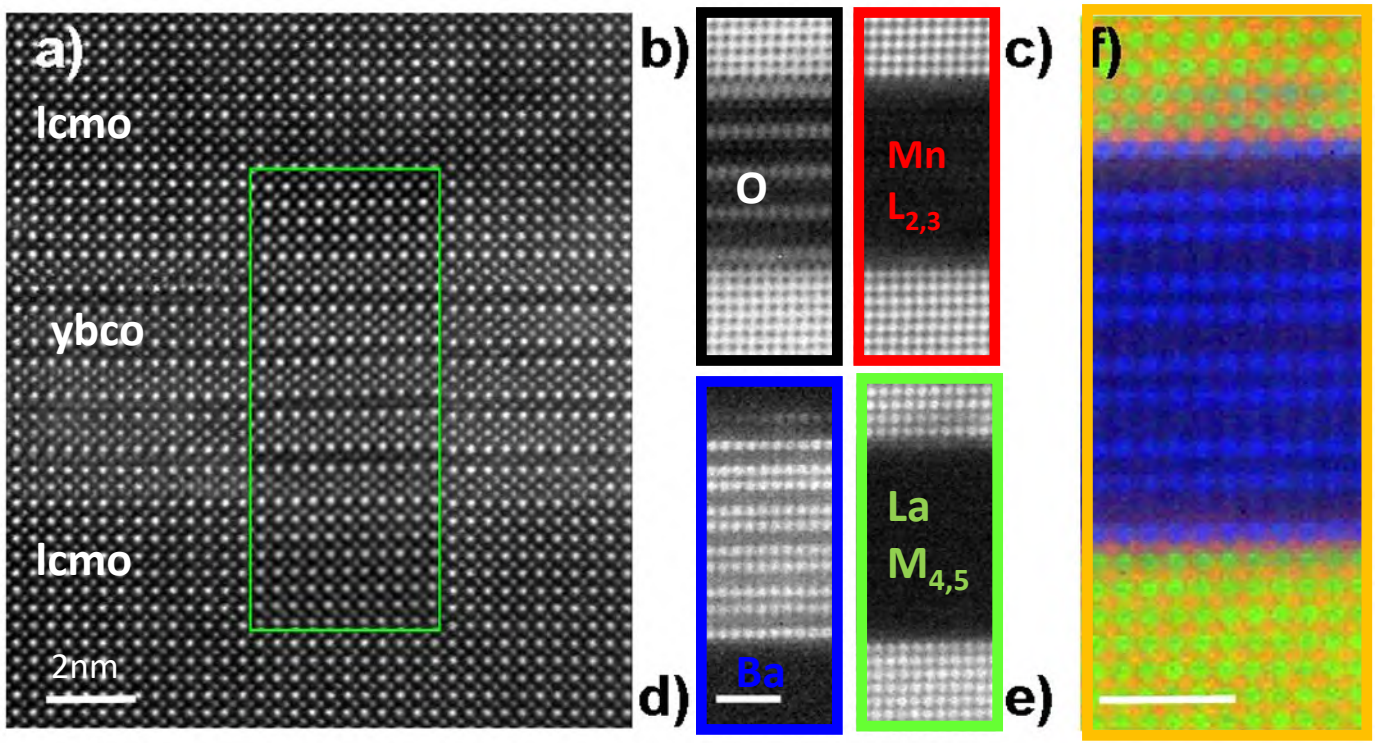


cuprates



manganites

$[La_{0.7}Ca_{0.3}MnO_3$ / $YBa_2Cu_3O_7]$ Interface



Phys. Rev. Lett. **113**, 189902 (2014)

Thanks to collaborators

• **D. Sanchez-Manzano, F. Cuellar, V. Rouco, G. Orfila, M. Rocci *, J. Garcia-Barriocanal#, F. Gallego, J. Tornos, A. Rivera, Z. Sefrioui, C. Leon**, (*GFMC-U. Complutense de Madrid)*

•**M. Cabero, J. Gonzalez-Calbet** (*CNME Luis Bru. U. Complutense de Madrid)*

•**F. Mompean, M. Garcia-Hernandez** (*Instituto de Ciencia de Materiales ICMM- CSIC)*

• **S. Mesoraca, X. Palermo, A. Balan, A. Sander, J. Villegas**, *Unité Mixte de Physique CNRS/Thales,*

• **Cheryl Feuillet-Palma, N. Bergeal, J. Lesueur**, *Laboratoire de Physique et d'Etude des Matériaux, CNRS, ESPCI Paris, PSL Research University*

• **A. Buzdin**. *Université Bordeaux, CNRS, LOMA, UMR 5798, F-33405 Talence, France*

• **L. Marcano, S. Valencia**, *Helmholtz-Zentrum Berlin für Materialien und Energie, Albert-Einstein-Strasse 15, D-12489, Berlin, Germany*

* now at Thales Alenia # now at U. of Minnesota

In this talk…..

- We examine the FM/SC proximity effect in cuprate/manganite planar nanostructures.

- We demonstrate an extremely long range (ONE MICRON) Josephson effect across a HM ferromagnet

F/S INTERPLAY. EFFECT OF AN EXCHANGE FIELD ON SUPERCONDUCTIVITY

FM SC Stolyarov, V. S. *et al. Sci. Adv.* **4**, eaat1061 (2018).

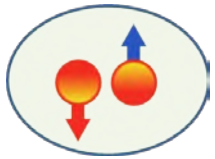
Orbital effect

$$H_O = \frac{1}{2m}(p - qA)^2$$

Ginzburg V L 1957 Ferromagnetic superconductors *Sov Phys.—JETP* ***4 153 (Engl. transl.)***

Superconductivity in Gd

Exchange effect



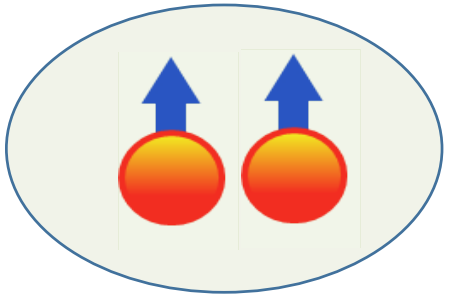
$$H_s = \varepsilon(p) - J\sigma \qquad B_{eff} = \frac{J}{\mu}$$

Matthias B T, Suhl H and Corenzwitz C 1958 Spin exchange in superconductors *Phys. Rev. Lett.* ***1 92–4***

Effect of Gd impurities on La superconductivity

Clogston A M 1962 Upper limit for the critical field in hard superconductors *Phys. Rev. Lett.* ***9 266–7***

Equal spin TRIPLETS



Aoki, D. & Jaques Flouquet. Ferromagnetism and Superconductivity in Uranium Compounds. *J. Appl. Phys.* **81**, 1–11 (2012).

NORMAL / SUPERCONDUCTOR PROXIMITY EFFECT

Boundary Effects in Superconductors

P. G. DE GENNES

Faculté des Sciences, Orsay (S & O) France

P. G. De Gennes Rev. Mod Phys, 36, 225 (1964)

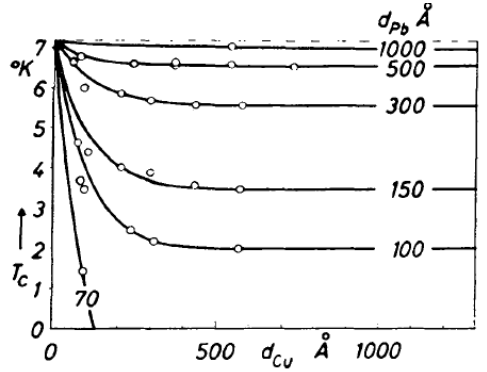


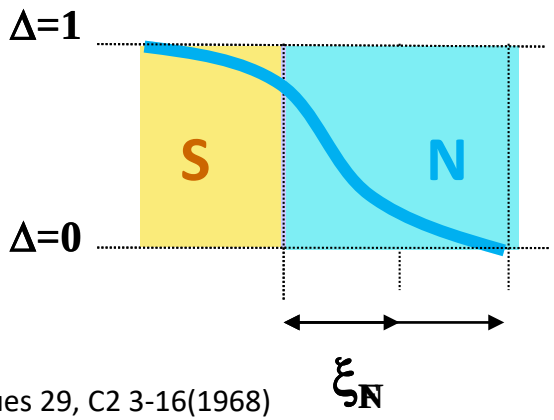
FIG. 2. — Transition temperature (T_c) of Pb/Cu sandwiches as a function of Cu thickness (d_{Cu}) for various thicknesses of Pb. (Reproduced from Hilsch et al. [11].)

JOURNAL DE PHYSIQUE *Colloque C 2, supplément au n° 2-3, Tome 29, Février-Mars 1968, page* C 2 - 3

THE PROXIMITY EFFECT BETWEEN SUPERCONDUCTING AND NORMAL THIN FILMS IN ZERO FIELD

JOHN CLARKE

Cavendish Laboratory, Cambridge, England



$$\xi_N = \left(\frac{\hbar D}{2\pi k_B T} \right)^{1/2}$$

Journal de Physique Colloques 29, C2 3-16(1968)

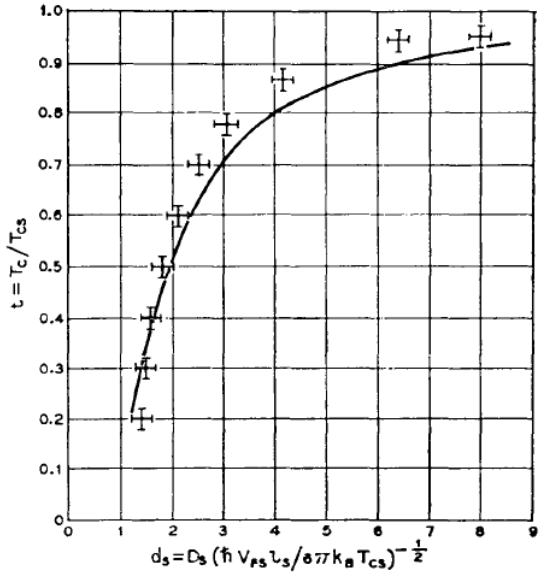
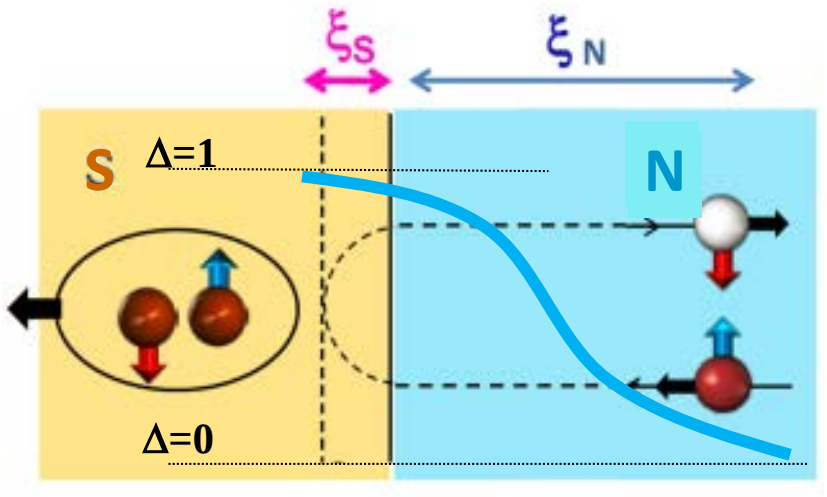


FIG. 4. — Reduced transition temperature (t) of Pb/Cu sandwiches as a function of reduced lead thickness (d_s) as predicted by the Werthamer theory (solid curve). Data points are from Hilsch's data [9, 11]. (Reproduced from Werthamer [69].)

N. R. Werthamer, Phys. Rev. 132, 2440 (1963)

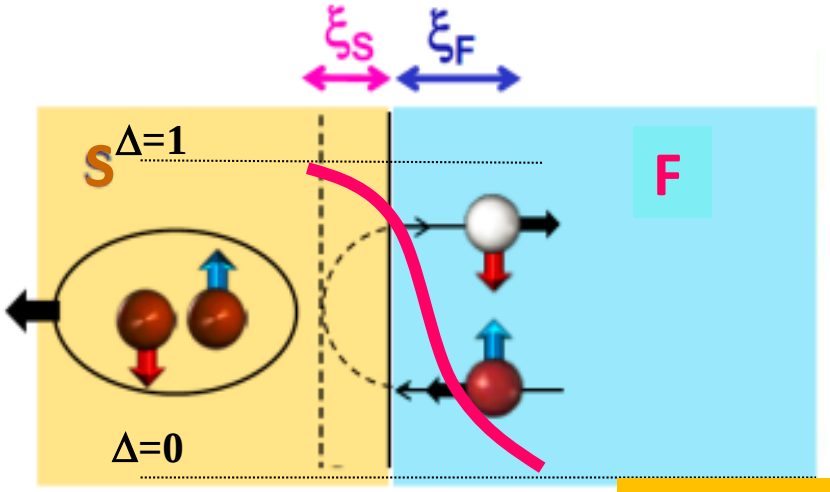
ANDREEV REFLECTION AT N/S and F/S INTERFACE



Sketch courtesy of J. Villegas

$$\xi_N = \left(\frac{\hbar D}{2\pi k_B T}\right)^{1/2}$$

Andreev A F 1964 *Sov. Phys.—JETP* ***19 1228–3***
De Gennes P G and Saint-James D 1963 *Phys. Lett.* ***4 151–2***

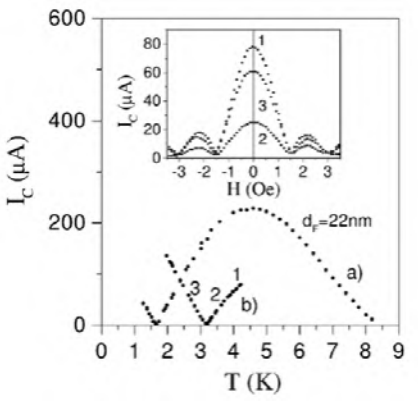


$$\xi_N = \left(\frac{\hbar D}{J}\right)^{1/2}$$

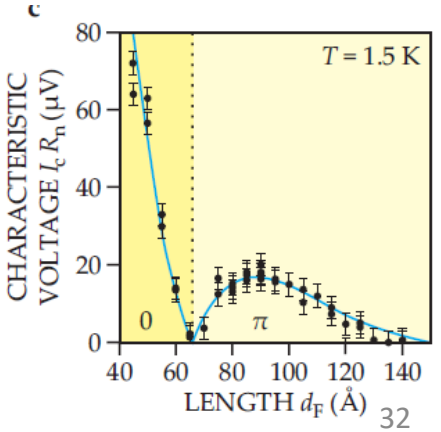
Spin mixing

$$\langle\Psi| = \frac{1}{\sqrt{2}}\left[\langle\uparrow\downarrow|e^{iQx} - \langle\downarrow\uparrow|e^{-iQx}\right] =$$

$$= \frac{1}{\sqrt{2}}[\langle\uparrow\downarrow| - \langle\downarrow\uparrow|]\cos Qx + i\frac{1}{\sqrt{2}}[\langle\uparrow\downarrow| + \langle\downarrow\uparrow|]senQx$$



PRL 86, 2428 (2001)



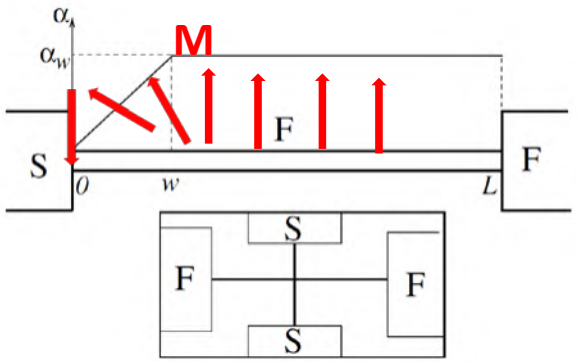
PRL 89, 137002, (2002)

Theoretical scenario I: ((helical) magnetic inhomogeneities

Long-Range Proximity Effects in Superconductor-Ferromagnet Structures

F. S. Bergeret,[1] A. F. Volkov,[1,2] and K. B. Efetov[1,3]
[1]*Theoretische Physik III, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[2]*Institute of Radioengineering and Electronics of the Russian Academy of Sciences, 103907 Moscow, Russia*
[3]*L. D. Landau Institute for Theoretical Physics, 117940 Moscow, Russia*
(Received 24 November 2000)

We analyze the proximity effect in a superconductor/ferromagnet (S/F) structure with a local inhomogeneity of the magnetization in the ferromagnet near the S/F interface. We demonstrate that not only the singlet but also the triplet component of the superconducting condensate is induced in the ferromagnet due to the proximity effect. The singlet component penetrates into the ferromagnet over a short length $\xi_h = \sqrt{D/h}$ (h is the exchange field and D the diffusion coefficient), whereas the triplet component penetrates over a long length $\sqrt{D/\epsilon}$ and leads to a significant increase of the ferromagnet conductance below the superconducting critical temperature T_c.



F. S. Bergeret et al PRL 86, 4096 (2001)

Odd frequency triplets

Spin active=Spin mixing + spin rotation

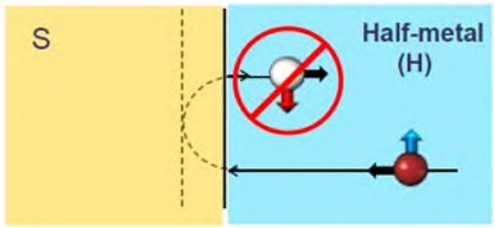
Theoretical scenario II: Spin flip scattering

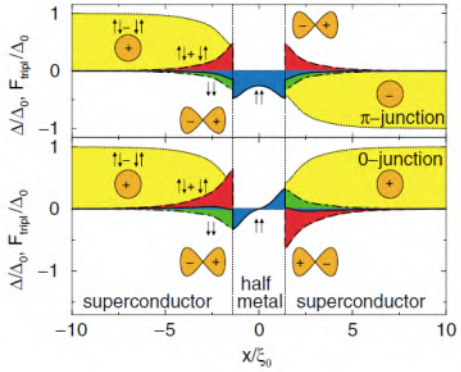
VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Theory of Half-Metal/Superconductor Heterostructures

M. Eschrig,[1] J. Kopu,[1] J. C. Cuevas,[1] and Gerd Schön[1,2]
[1]*Institut für Theoretische Festkörperphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[2]*Forschungszentrum Karlsruhe, Institut für Nanotechnologie, 76021 Karlsruhe, Germany*
(Received 17 June 2002; published 3 April 2003)

We investigate the Josephson coupling between two singlet superconductors separated by a half-metallic magnet. The mechanism behind the coupling is provided by the rotation of the quasiparticle spin in the superconductor during reflection events at the interface with the half metal. Spin rotation induces triplet correlations in the superconductor which, in the presence of surface spin-flip scattering, results in an indirect Josephson effect between the superconductors. We present a theory appropriate for studying this phenomenon and calculate physical properties for a superconductor/half-metal/superconductor heterostructure.





p-wave triplets

M. Eschrig et al PRL 90, 137003 (2003)

Odd frequency triplets

Magnetic inhomogeneity in momentum space

See also Asano, Y., Tanaka, Y. & Golubov, A. A. *Phys. Rev. Lett.* **98**, 107002 (2007).Eschrig, M. & Löfwander, *Nat. Phys.* **4**, 138–143 (2008).

Bergeret, F. S. & Tokatly, I. V.. Phys. Rev. Lett. 110, 1–6 (2013).

Spin rotation

LONG RANGE FM PROXIMITY: Equal spin $S_z=\pm1$ TRIPLETS

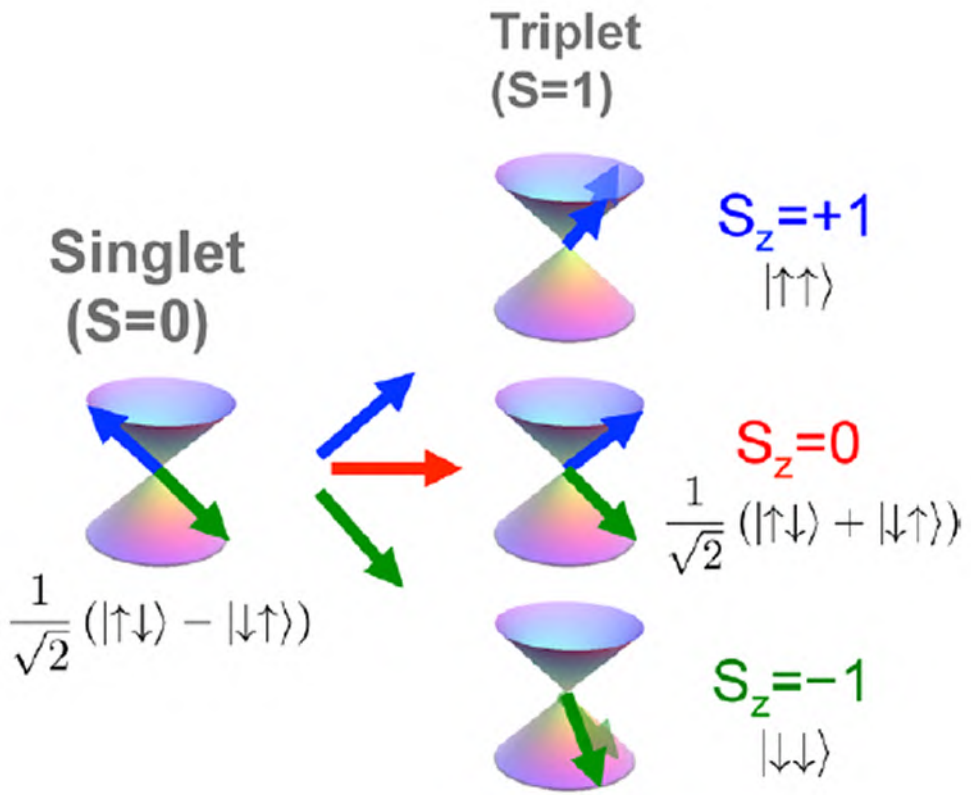
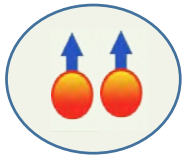


Figure adapted from M. Eschrig Rep. Prog. Phys. 78, 104501 (2015)

Spin rotation



Buzdin, A. I. Proximity effects in superconductor-ferromagnet heterostructures. *Rev. Mod. Phys.* **77**, 935–976 (2005).

Bergeret, F. S., Volkov, A. F. & Efetov, K. B., Rev. Mod. Phys. **77**, 1321 2005.

Linder, J. & Robinson, J. W. A. Superconducting spintronics. *Nature Physics* **11**, 307–315 (2015).

Eschrig, M. Spin-polarized supercurrents for spintronics: a review of current progress. *Rep. Prog. Phys.* **78**, 104501 (2015).

SYMMETRY CLASIFICATION OF PAIRING STATES

Spin	Frequency	Momentum	Overall	Type
Singlet (odd)	Even	Even (s, d)	Odd	A
	Odd	Odd (p, f)	Odd	B
Triplet (even)	Even	Odd (p, f)	Odd	C
	Odd	Even (s, d)	Odd	D

M. Eschrig and T. Lofwander Nature Physics 4, 138 (2008)

EXPERIMENTAL EVIDENCES OF F/S LONG RANGE PROXIMITY EFFECT

M. Giroud, H. Courtois, K. Hasselbach, D. Mailly, and B. Pannetier Phys. Rev. B **58**, R11872(R)

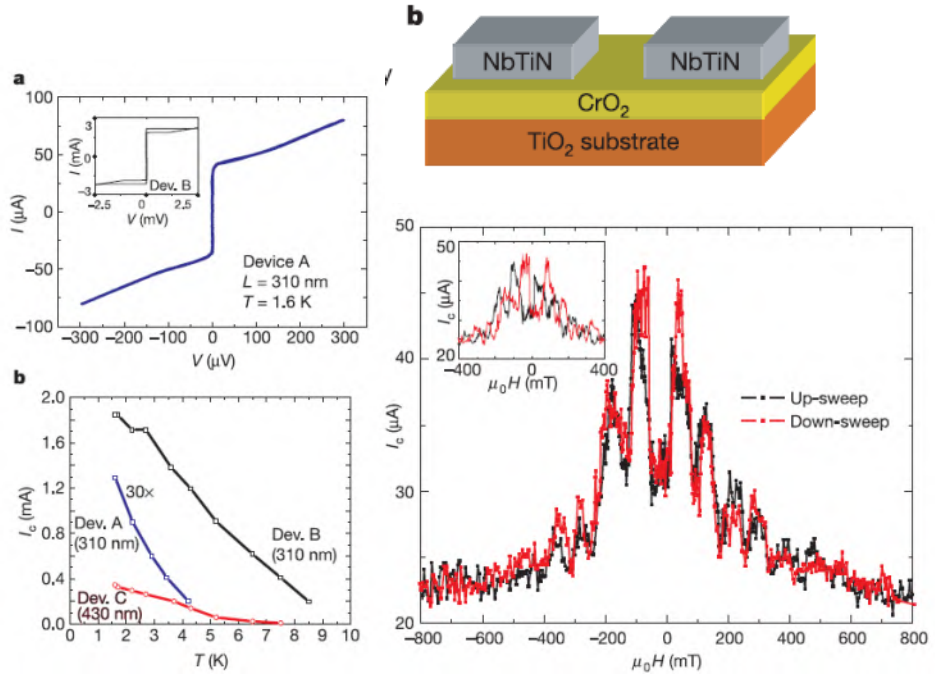
LETTERS

A spin triplet supercurrent through the half-metallic ferromagnet CrO_2

R. S. Keizer[1], S. T. B. Goennenwein[1]†, T. M. Klapwijk[1], G. Miao[2,3], G. Xiao[3] & A. Gupta[2]

Nature 438, 836 (2006)

CrO_2, HM FM T_c =390 K
NbTi contacts separated **300 nm!!**



See also Anwar, M. S., Czeschka, F., Hesselberth, M., Porcu, M. & Aarts, *Phys. Rev. B* **82**, 100501 (2010).

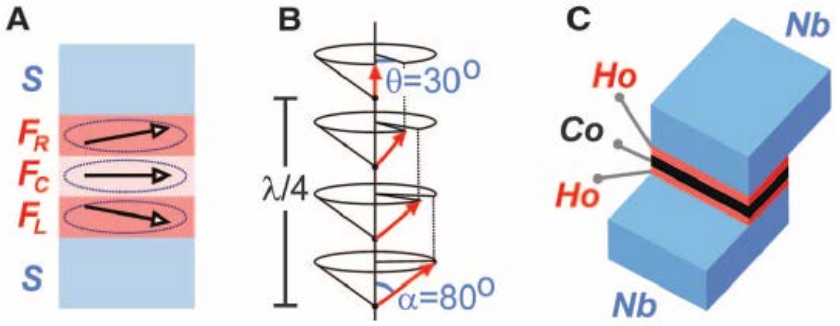
Controlled Injection of Spin-Triplet Supercurrents into a Strong Ferromagnet

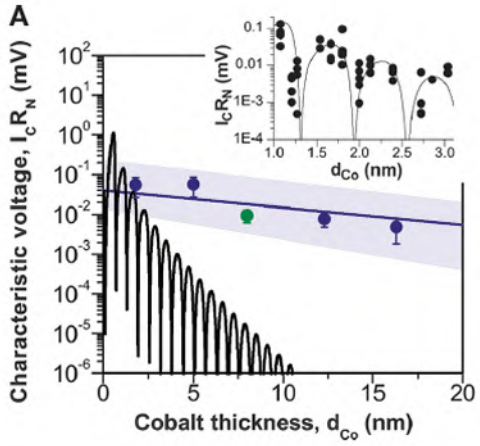
Science AAAS

J. W. A. Robinson,* J. D. S. Witt, M. G. Blamire

Science **329**, 59 (2010);

The superconductor-ferromagnet proximity effect describes the fast decay of a spin-singlet supercurrent originating from the superconductor upon entering the neighboring ferromagnet.



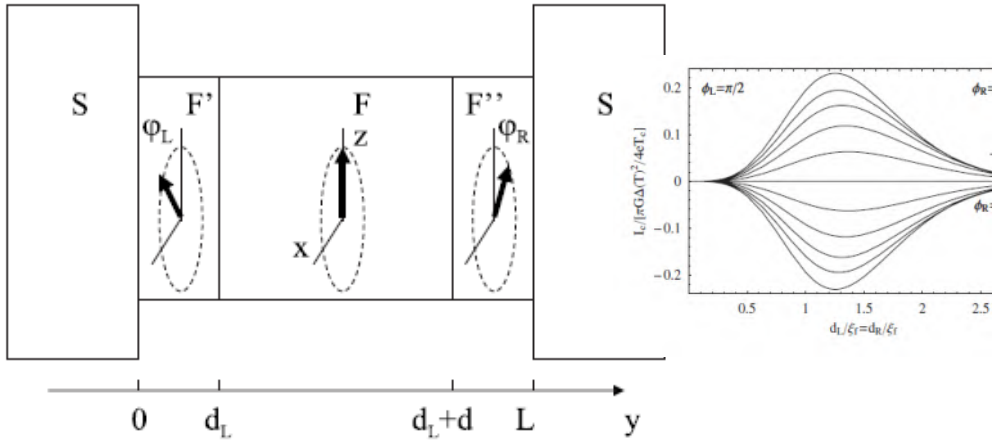


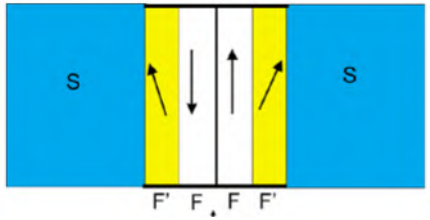
MAGNETIC MULTILAYERS WITH NON COLINEAR MOMENTS

PHYSICAL REVIEW B 76, 060504(R) (2007)

Long range triplet Josephson effect through a ferromagnetic trilayer

M. Houzet[1] and A. I. Buzdin[2]
[1]*DRFMC/SPSMS, CEA Grenoble, 17, rue des Martyrs, 38054 Grenoble Cedex 9, France*
[2]*Institut Universitaire de France and Université Bordeaux I, CPMOH, UMR 5798, 33405 Talence, France*
(Received 16 July 2007; published 15 August 2007)



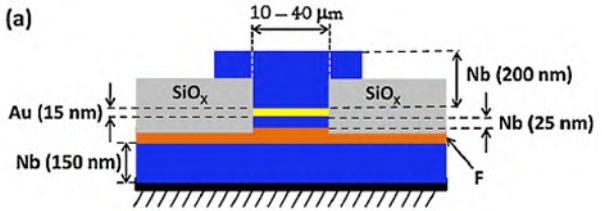


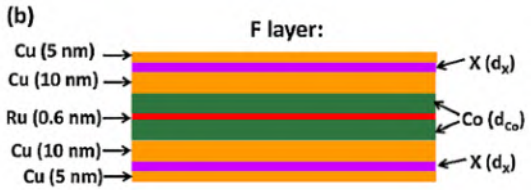
PRL 104, 137002 (2010) PHYSICAL REVIEW LETTERS week ending 2 APRIL 2010

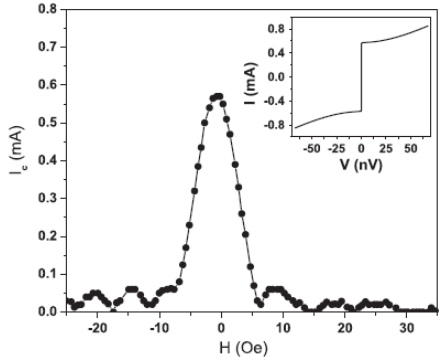
Observation of Spin-Triplet Superconductivity in Co-Based Josephson Junctions

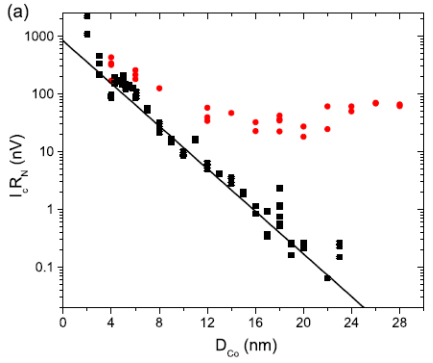
Trupti S. Khaire, Mazin A. Khasawneh, W. P. Pratt, Jr., and Norman O. Birge*
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-2320, USA
(Received 1 December 2009; published 29 March 2010)

We have measured a long-range supercurrent in Josephson junctions containing Co (a strong ferromagnetic material) when we insert thin layers of either PdNi or CuNi weakly ferromagnetic alloys between the Co and the two superconducting Nb electrodes. The critical current in such junctions hardly



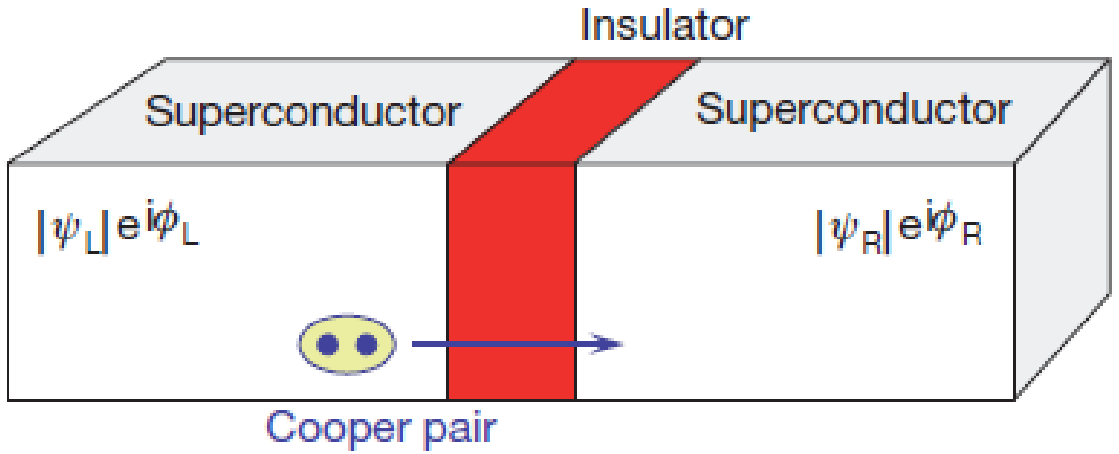






Sperstad, I. B., Linder, J. & Sudbø, A. *Phys. Rev. B* **78**, 104509 (2008).
Halterman, K., Valls, O. & Barsic, P. *Phys. Rev. B* **77**, 174511 (2008).
A. F. Volkov and K. B. Efetov, *Phys. Rev. B* **81**, 144522 (2010)

LONG RANGE TRIPLET JOSEPHSON EFFECT HAS REMAINED ELUSIVE



Phase-coherent quantum state

Josephson equations in SC

by Leggett

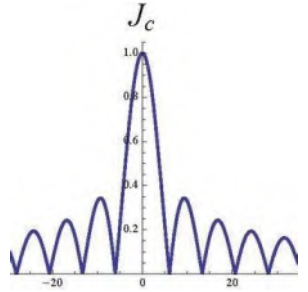
$$\begin{cases} I = I_c \sin\phi & \text{; Josephson current} \\ & \rightarrow \text{"charge current"} \\ \frac{d}{dt}\phi(t) = \frac{2eV(t)}{\hbar} = \frac{2\pi V}{\Phi_0}, \ \Phi_0 = h/2e & \text{(quantized magnetic flux)} \end{cases}$$

✓ dc Josephson effect; $\frac{d}{dt}\phi(t) \propto V(t) = 0$

→ Relative phase is time-independent; $\frac{d}{dt}\phi(t) = 0$

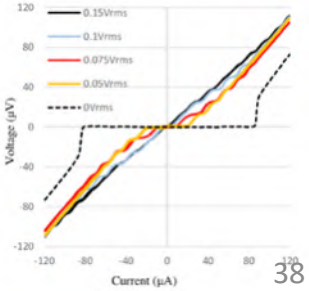
Space-domain interference

Fraunhofer pattern

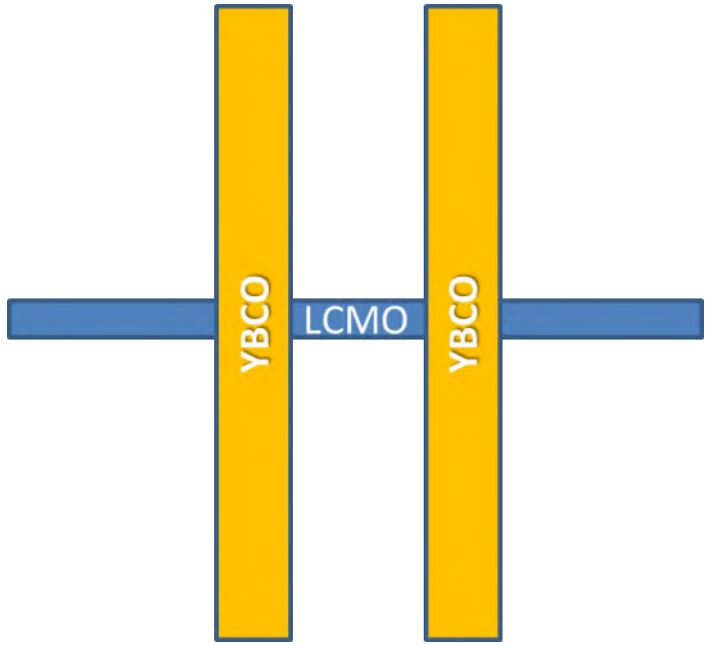


Time-domain interference

Shapiro steps



microwires
YBCO/LSMO



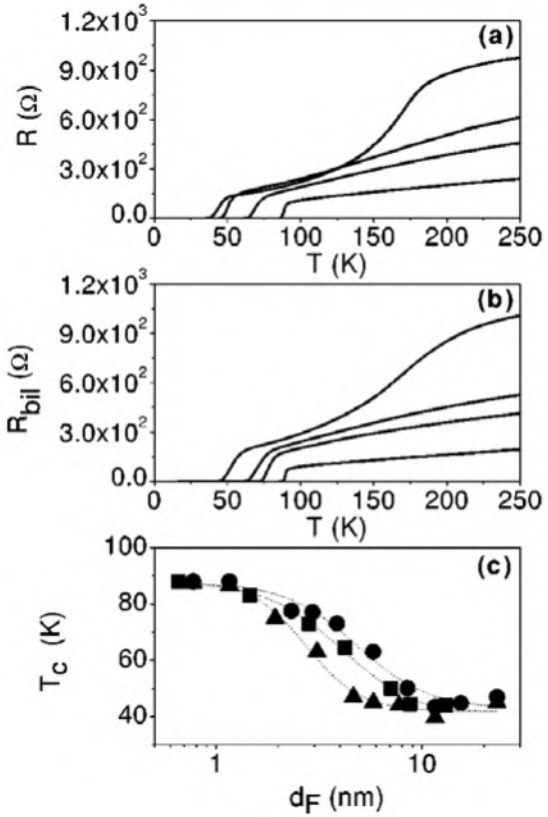
- **Well defined current geometry and magnetic state**

D. Sanchez-Manzano Nat Mater **21**, 188 (2022)

TRIPLET PAIRING IN $YBa_2Cu_3O_7$/ $La_{0.7}Ca_{0.3}MnO_3$ heterostructures

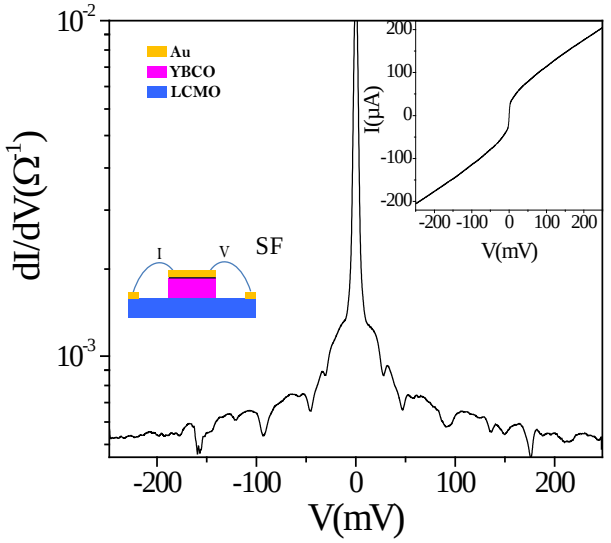
PHYSICAL REVIEW B **69**, 224502 (2004)

Coupling of superconductors through a half-metallic ferromagnet: Evidence for a long-range proximity effect



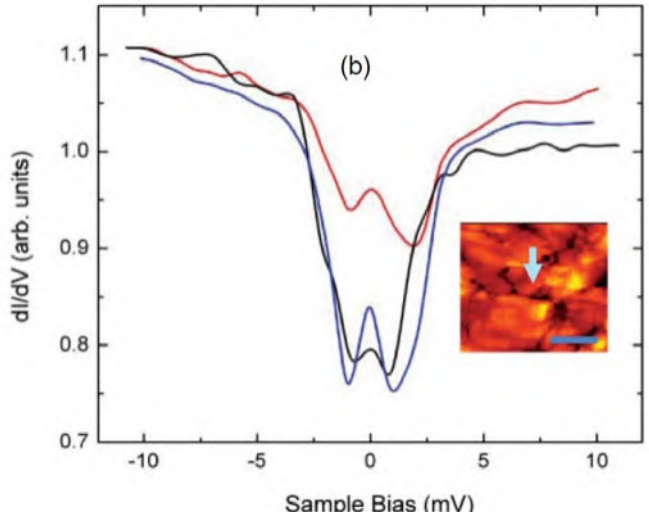
V. Peña et al Phys. Rev. B 69, 224502 (2004)

Equal-spin Andreev reflection and long-range coherent transport in high-temperature superconductor/half-metallic ferromagnet junctions



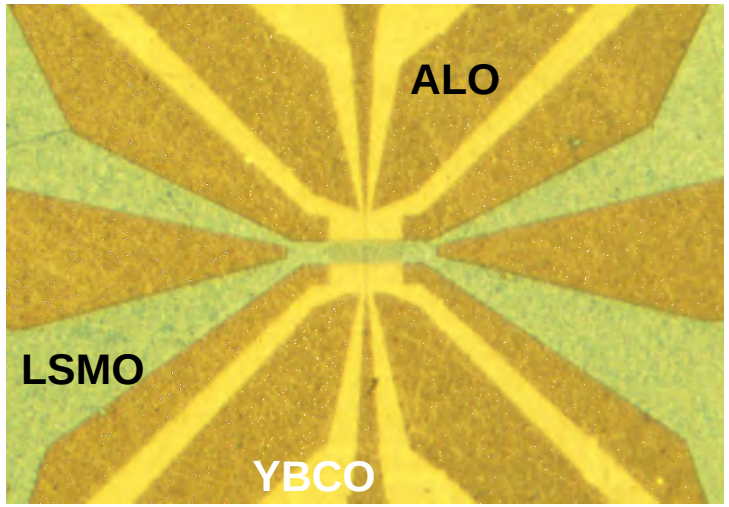
C. Visani et al. Nature Physics, 8, 539 (2012)

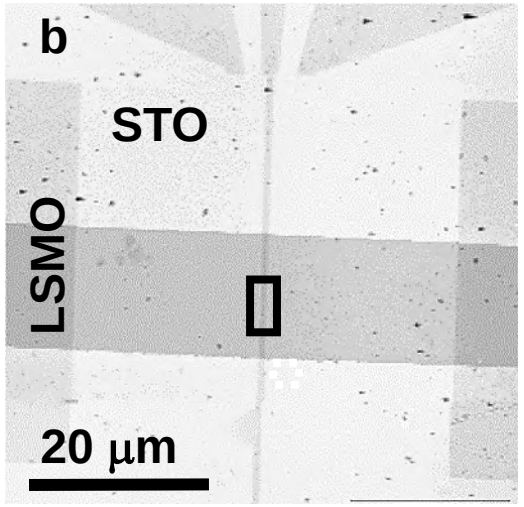
Evidence for anisotropic triplet superconductor order parameter in half-metallic ferromagnetic $La_{0.7}Ca_{0.3}Mn_3O$ proximity coupled to superconducting $Pr_{1.85}Ce_{0.15}CuO_4$

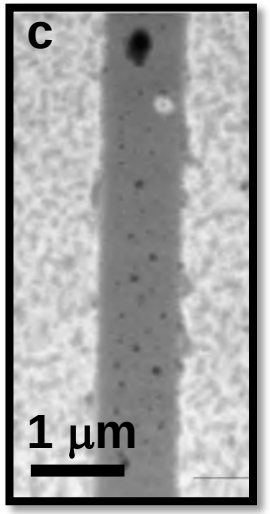


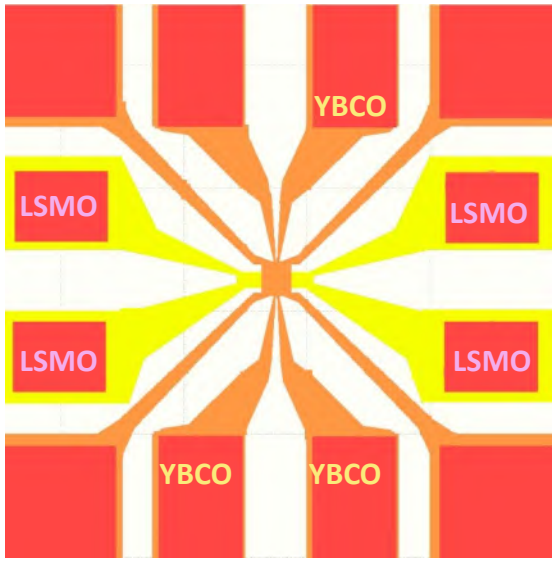
Kalcheim, Millo et al. et al. Phys. Rev. B Egilmez, Robinson and Blamire Phys. Rev. B , 85, 104504 (2012)

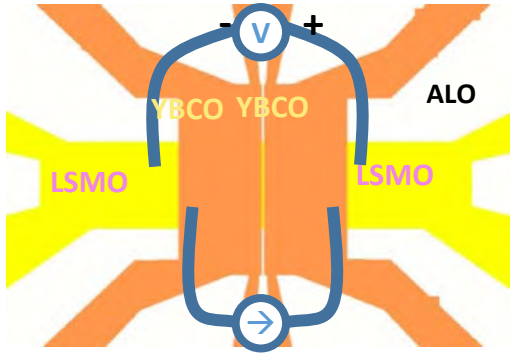
DEVICE FABRICATION (III). Actual device's structure

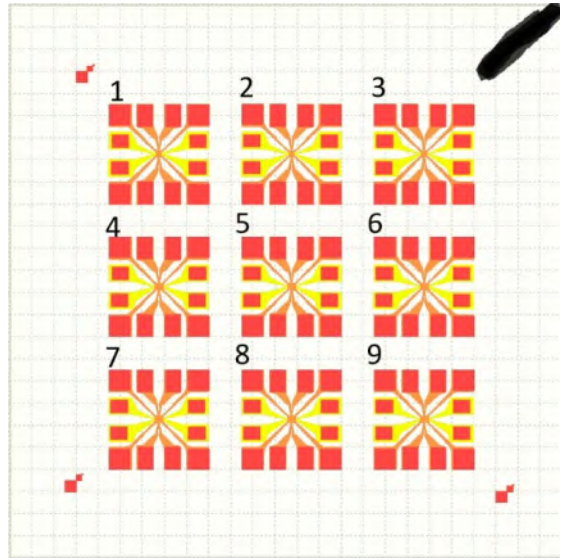


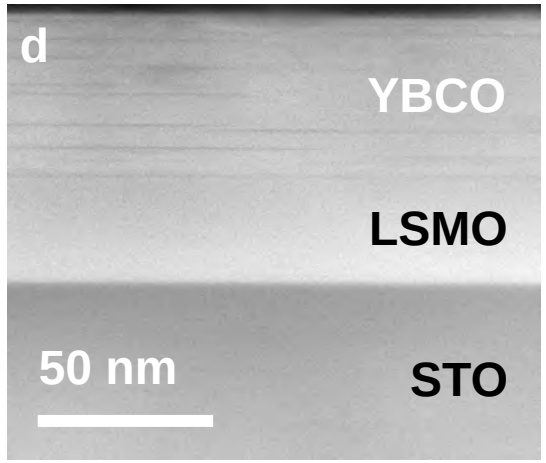


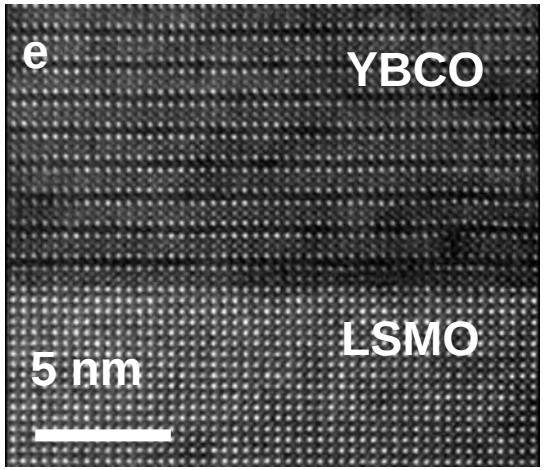


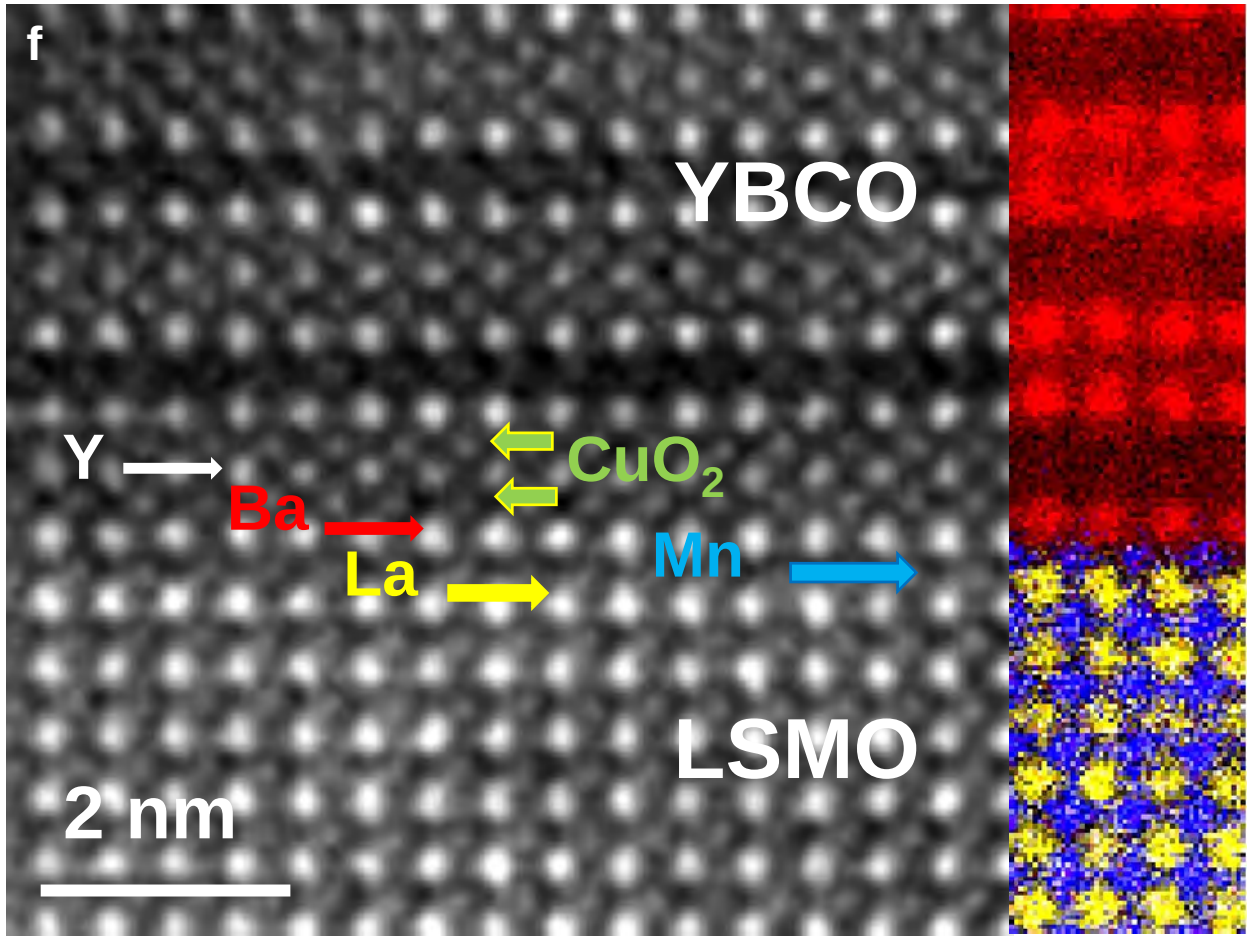






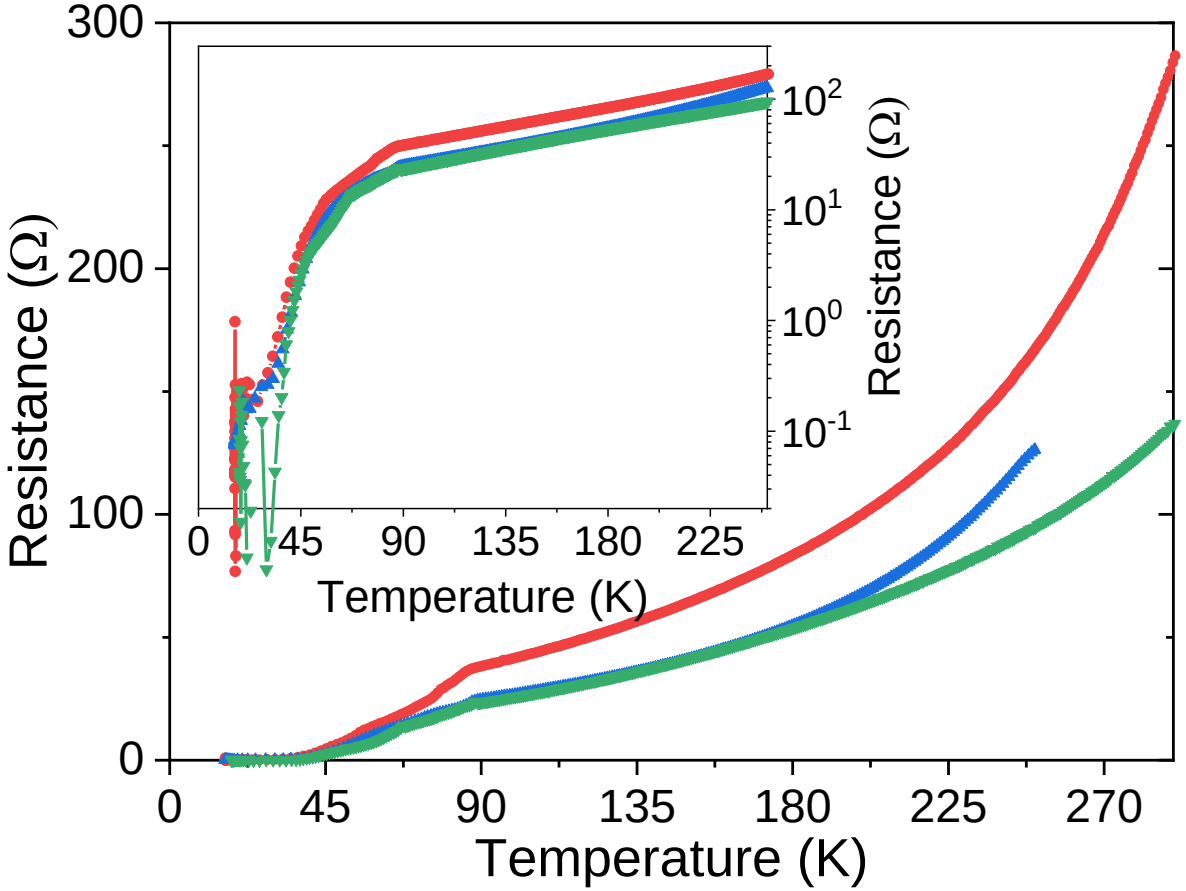


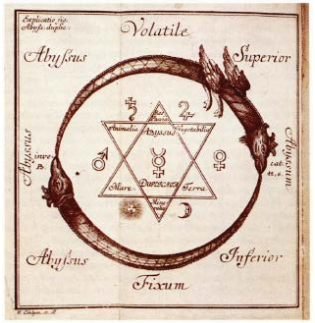


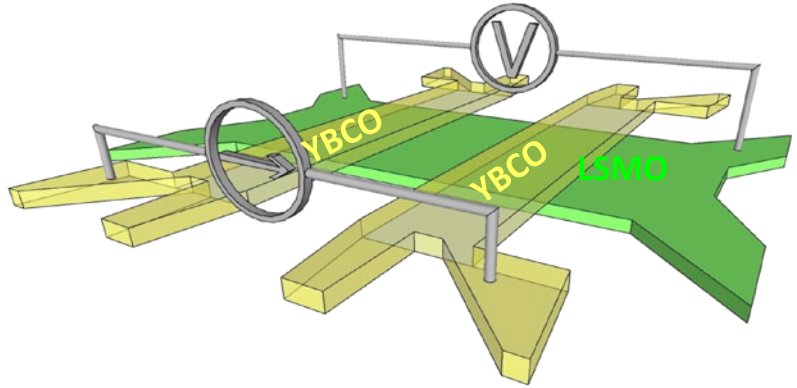


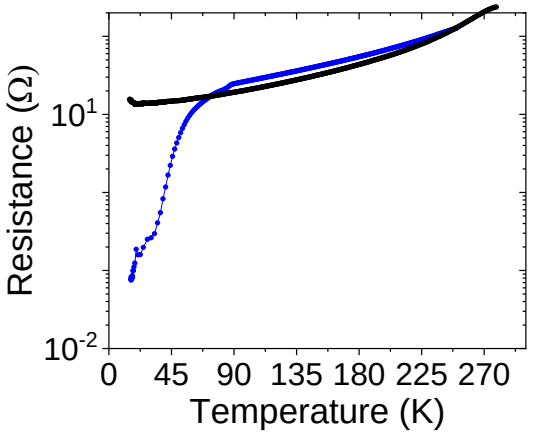
Microscopy by M. Cabero & J. M. González-Calbet

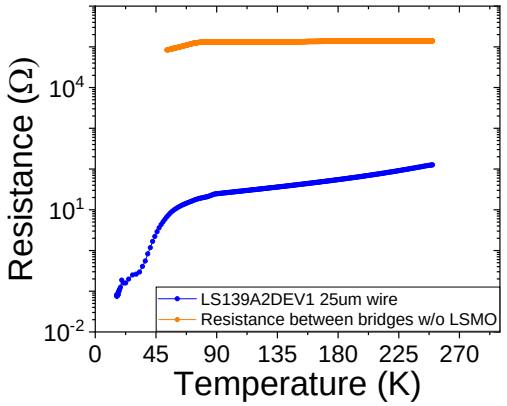
SUPERCONDUCTING (zero resistance) STATE IN THE LSMO



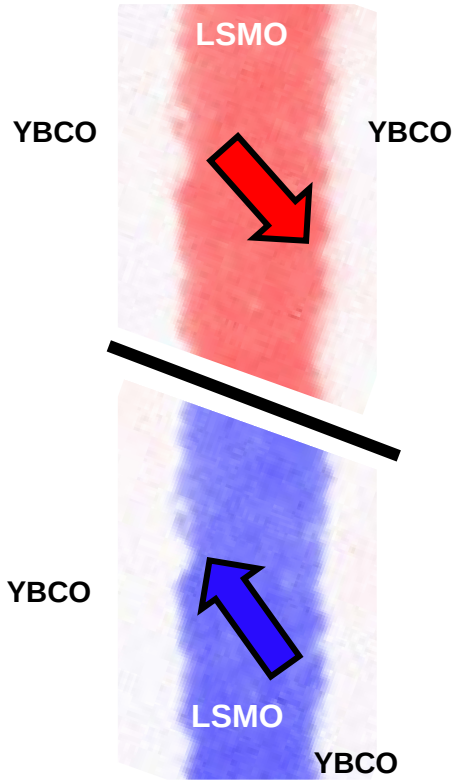


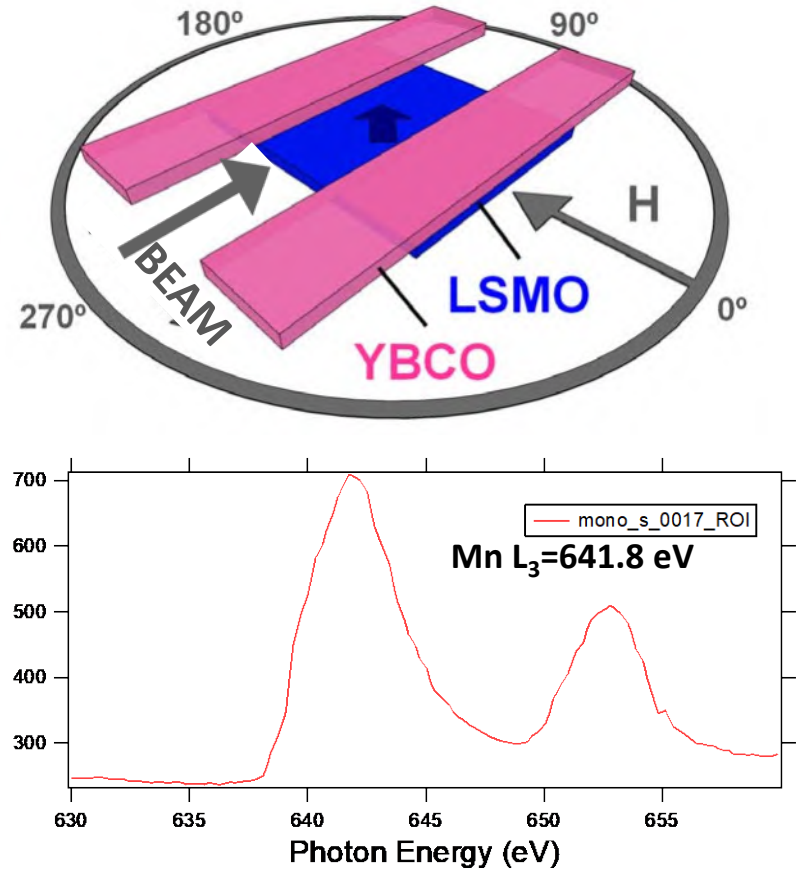


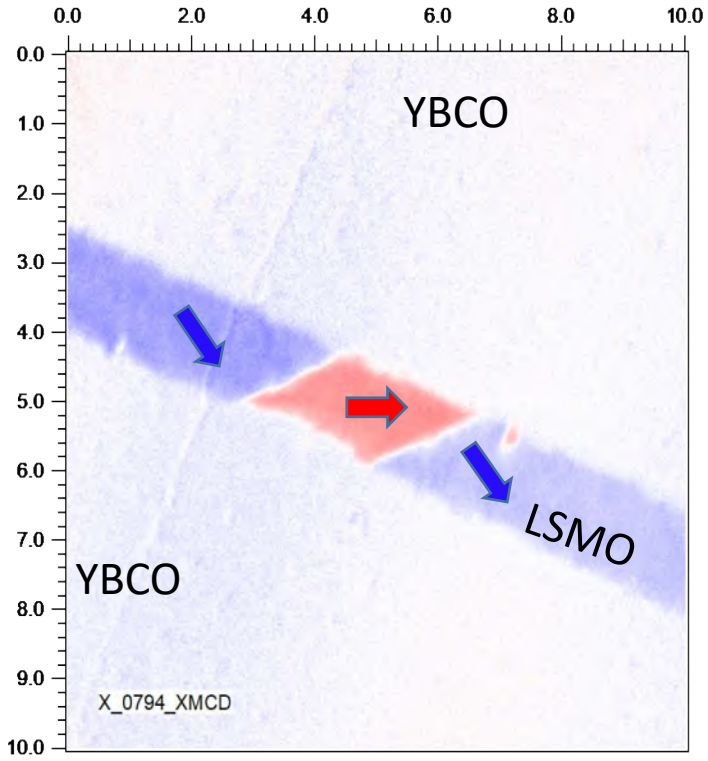




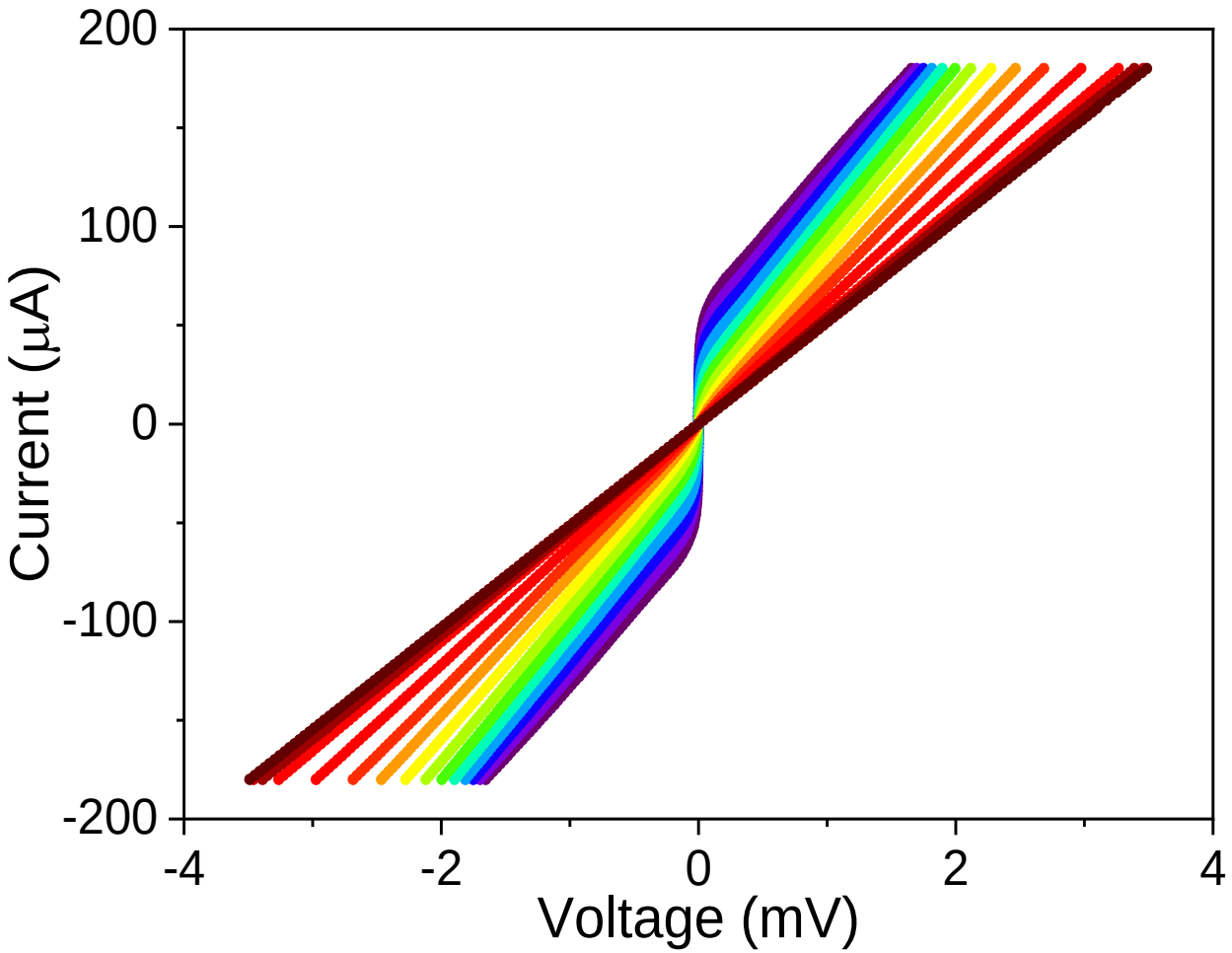
MAGNETIC STRUCTURE. X-ray absorption (PEEM)

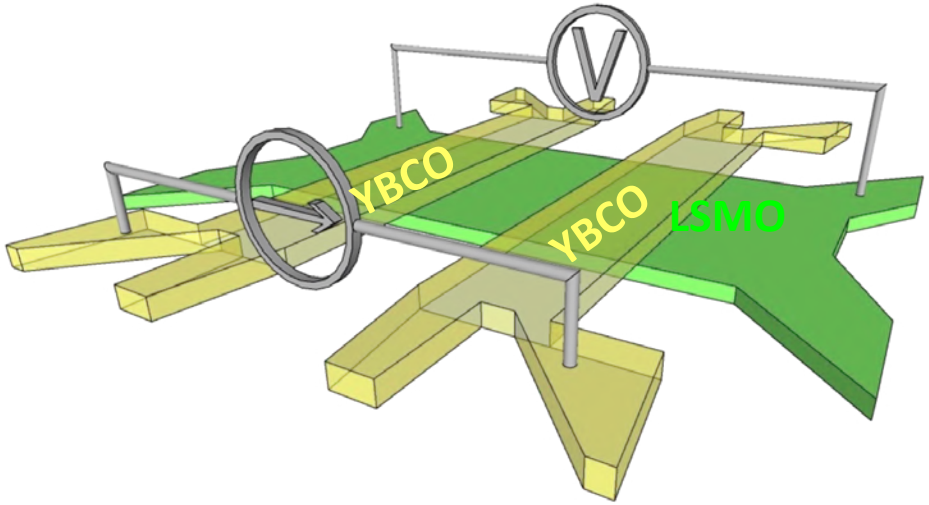


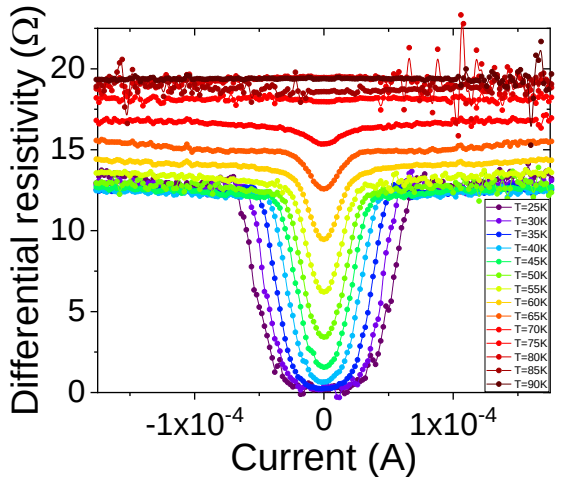




CRITICAL CURRENT in the LSMO wire

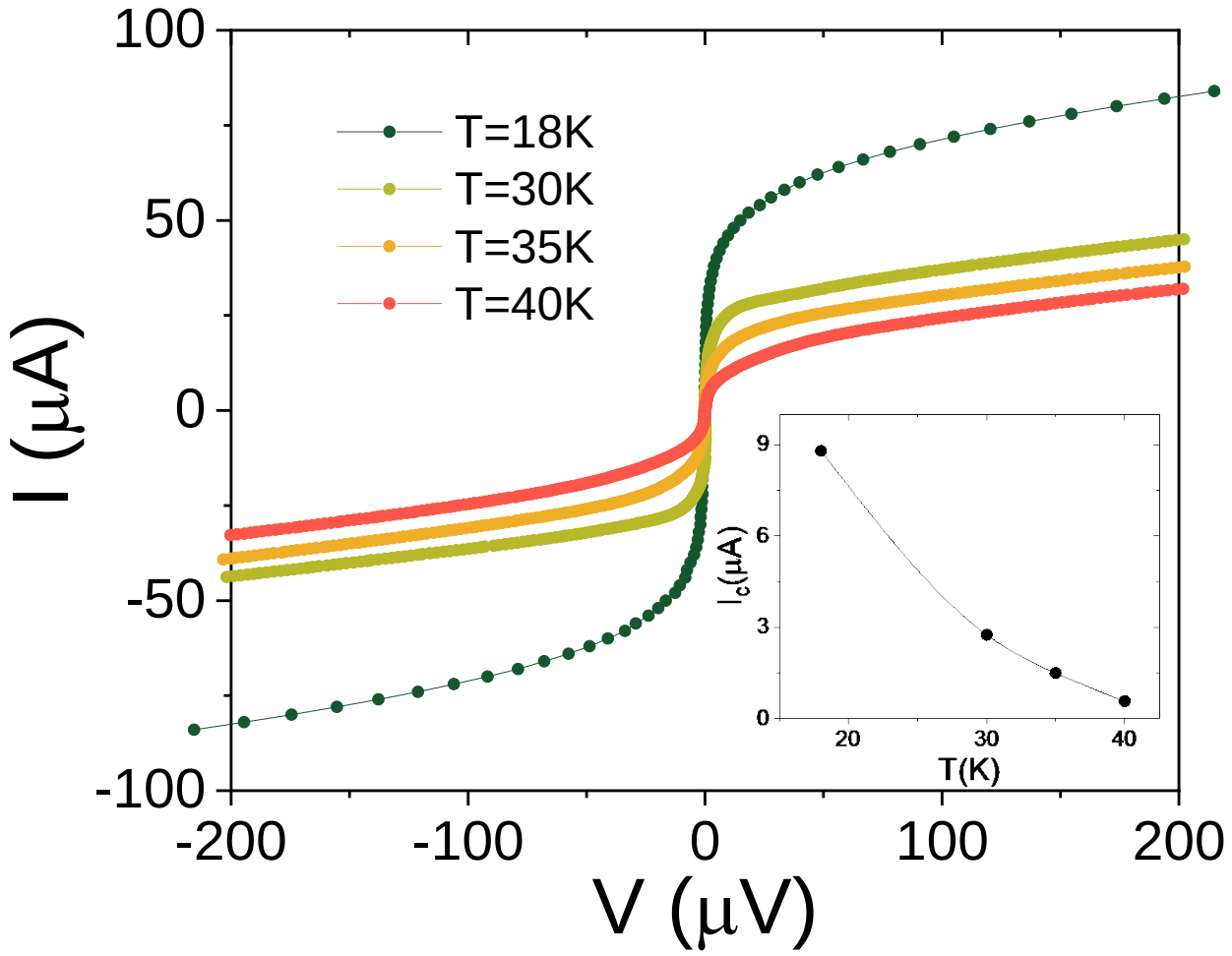


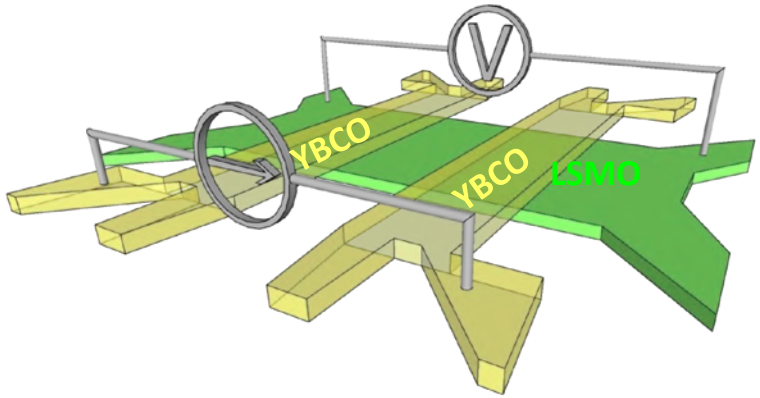


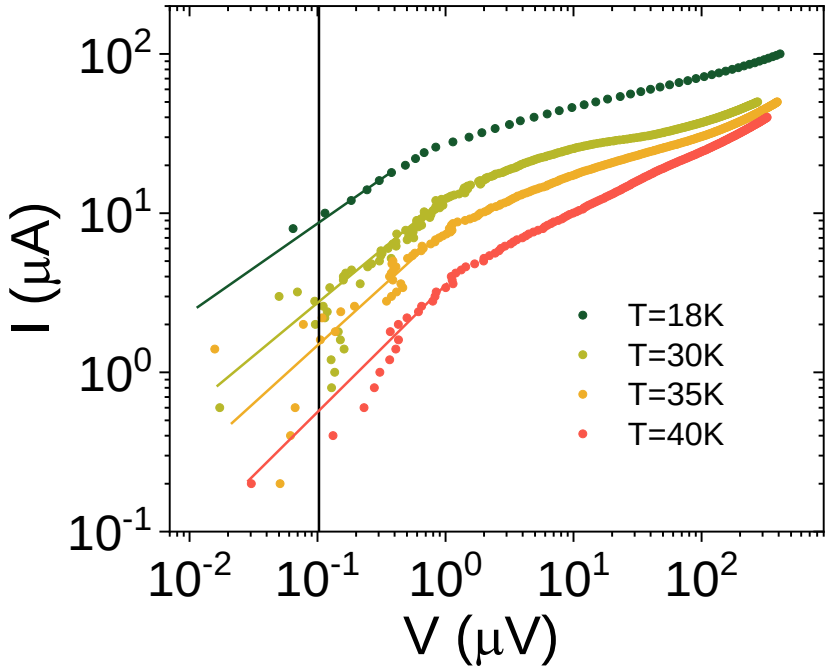


D. Sanchez-Manzano Nat Mater **21**, 188 (2022)

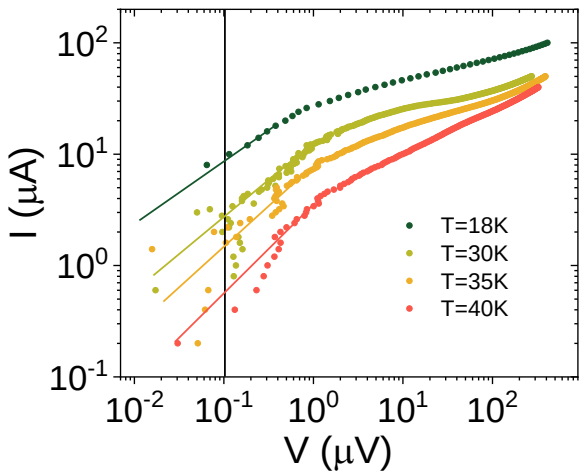
CRITICAL CURRENT in the LSMO wire

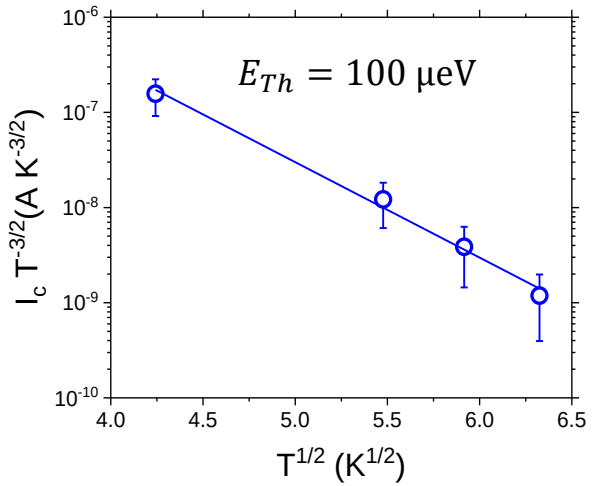




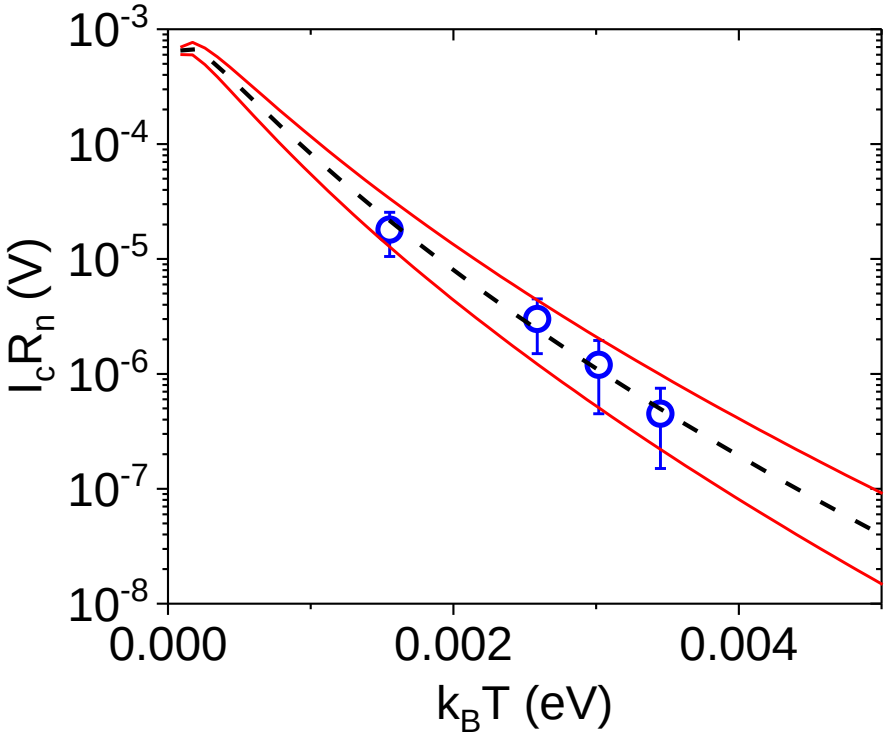


CRITICAL CURRENT in the LSMO wire: Temperature dependence





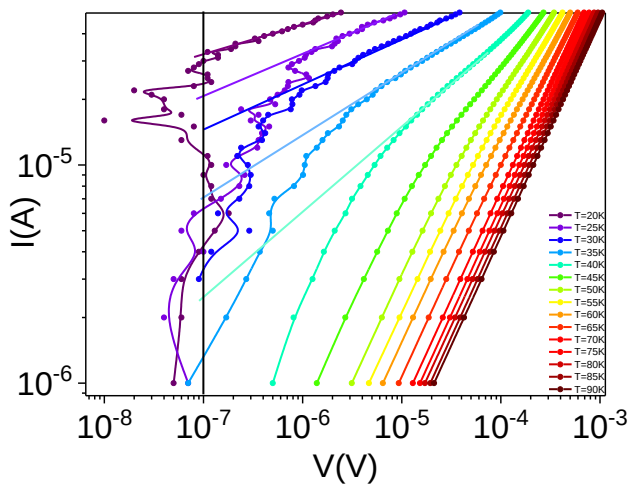
Anwar, M. S., Veldhorst, M., Brinkman, A. & Aarts, J. *Appl. Phys. Lett.* **100**, 052602 (2012).

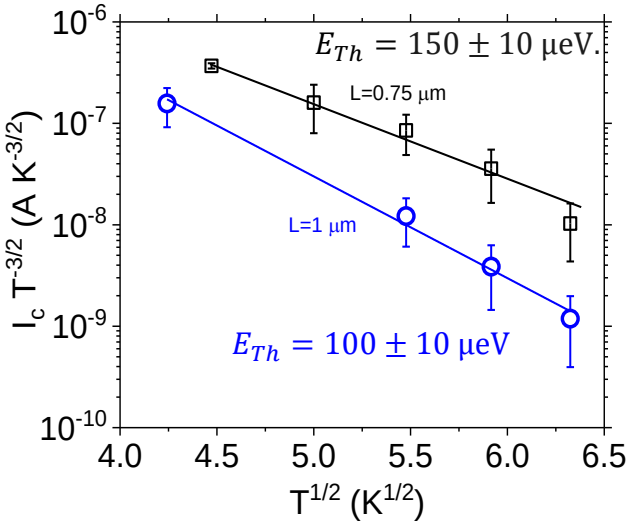


$$eI_cR_n = \frac{32}{3+2\sqrt{2}} E_{Th} \left[\frac{2\pi k_B T}{E_{Th}}\right]^{3/2} e^{-[2\pi k_B T/E_{Th}]^{1/2}}$$

Dubos, P. *et al.* Josephson critical current in a long mesoscopic S-N-S junction. *Phys. Rev. B* **63**, 1–5 (2001)

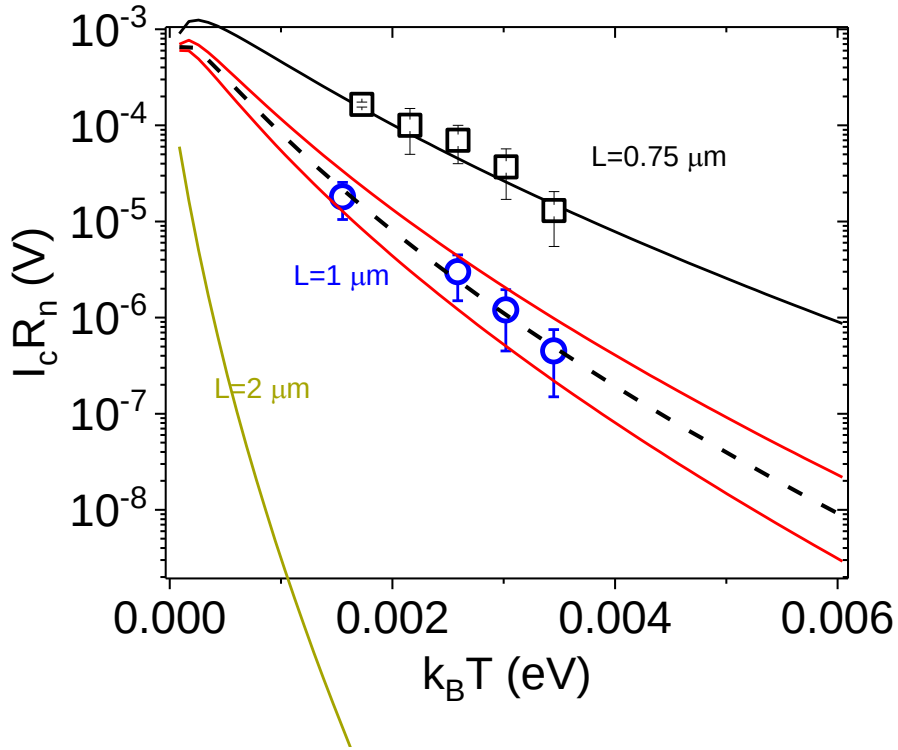
CRITICAL CURRENT in the LSMO wire: length dependence





Anwar, M. S., Veldhorst, M., Brinkman, A. & Aarts, J. *Appl. Phys. Lett.* **100**, 052602 (2012).

$$E_{TH} = \frac{\hbar D}{L^2}$$

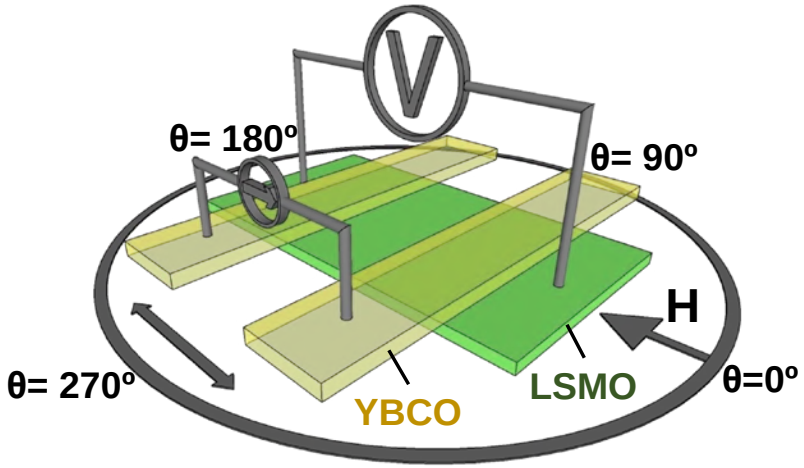


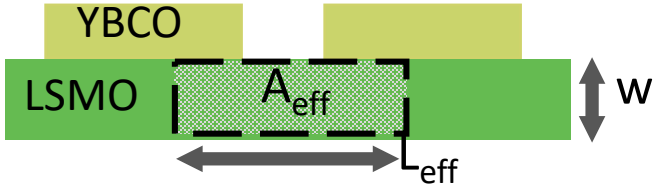
$$eI_cR_n = \frac{32}{3+2\sqrt{2}} E_{Th} \left[\frac{2\pi k_B T}{E_{Th}}\right]^{3/2} e^{-[2\pi k_B T/E_{Th}]^{1/2}}$$

Dubos, P. *et al.* Josephson critical current in a long mesoscopic S-N-S junction. *Phys. Rev. B* **63**, 1–5 (2001)

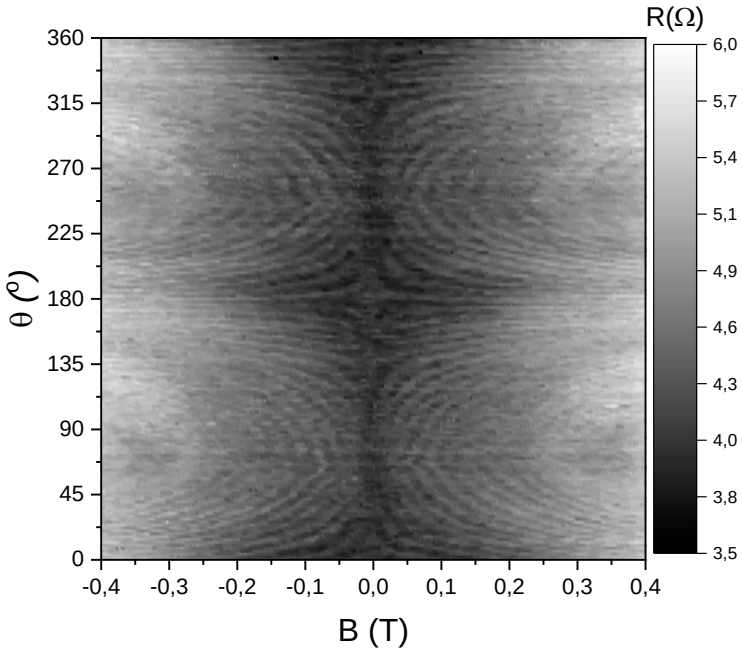
$$I_c(H,\theta) = I_{c0}\left|\frac{sin\pi\frac{\Phi}{\Phi_0}}{\pi\frac{\Phi}{\Phi_0}}\right|$$

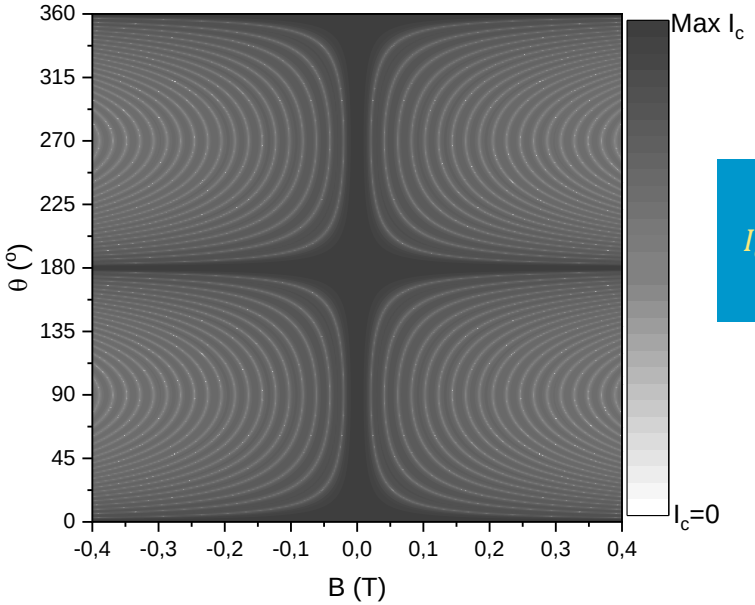
CURRENT INTERFERENCE: FRAUNHOFER PATTERN





$\Phi(H,\theta)=\mu_0 H A_{eff}|\sin(\theta)|$



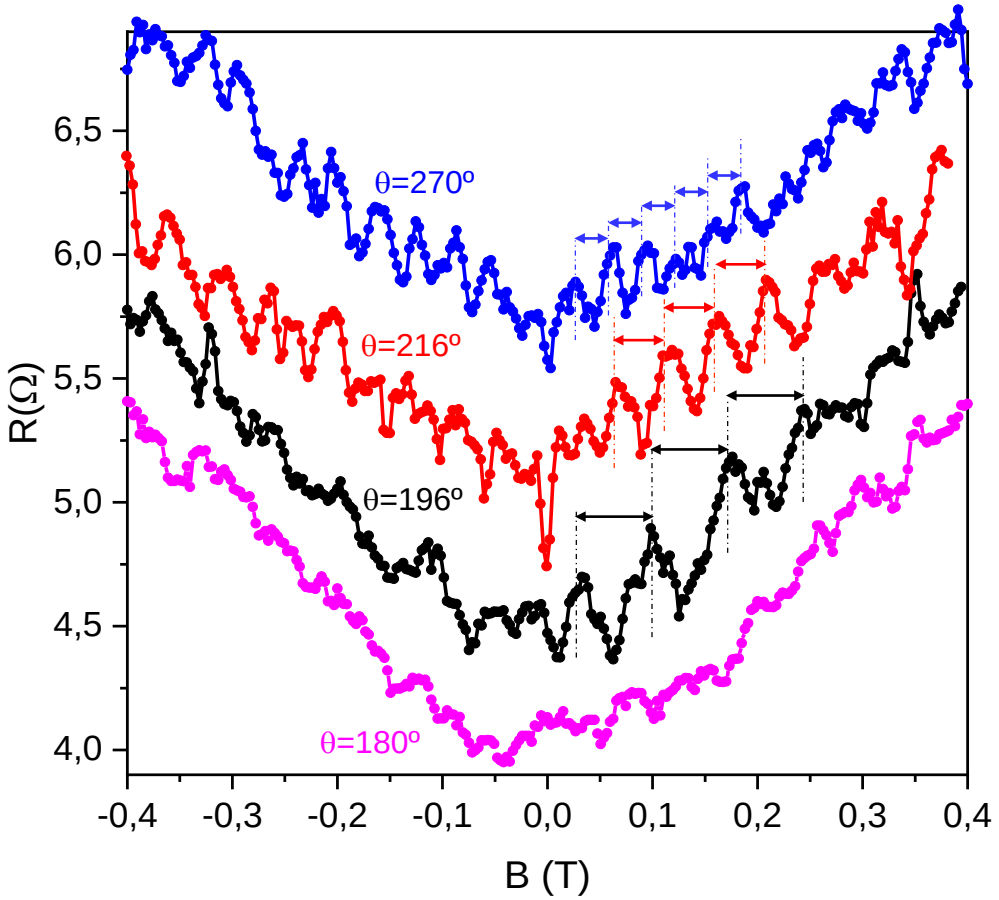


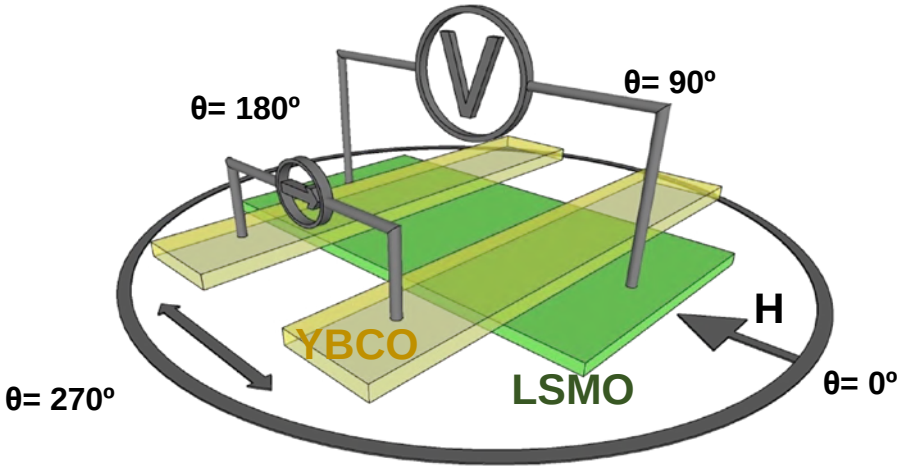
$$I_c(H,\theta) = I_{c0}\left|\frac{sin\pi\frac{\Phi}{\Phi_0}}{\pi\frac{\Phi}{\Phi_0}}\right|$$

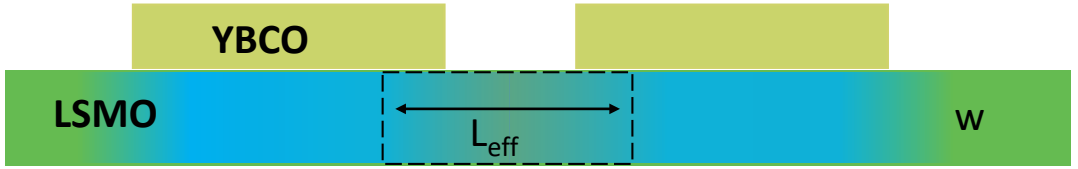
L_{eff}= 3 μm

D. Sanchez-Manzano Nat Mater **21**, 188 (2022)

CURRENT INTERFERENCE: FRAUNHOFER PATTERN







$$I_c(H,\theta) = I_{c0}\left|\frac{sin\pi\frac{\Phi}{\Phi_0}}{\pi\frac{\Phi}{\Phi_0}}\right|$$

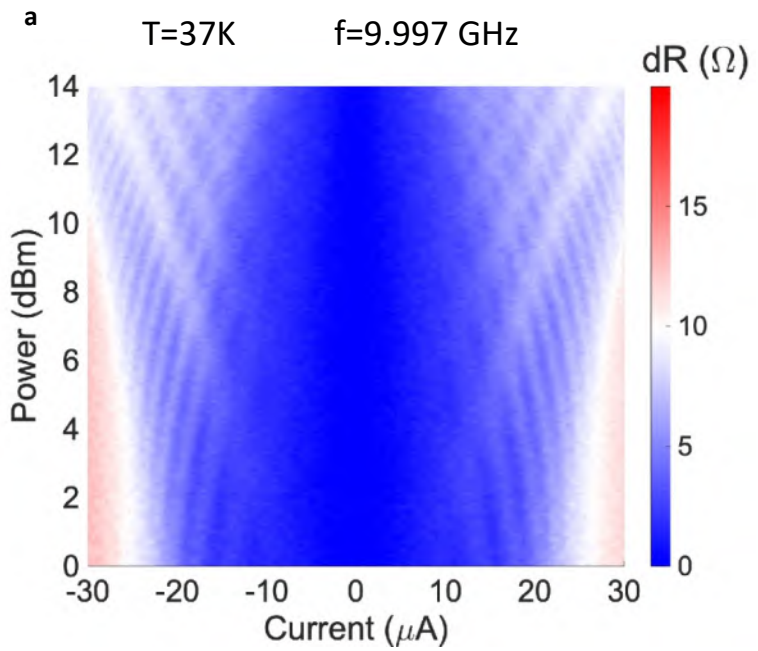
$$\Phi(H,\theta)=\mu_0 H A_{eff}\,|\sin(\theta)|$$

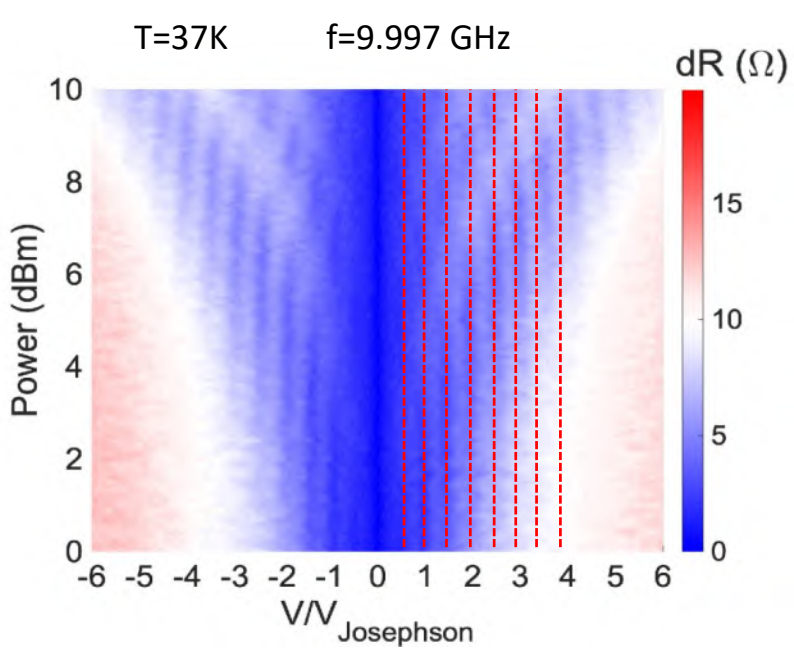
$$\frac{d\varphi}{dt} = 2\pi \frac{V}{\Phi_0}$$

$$\frac{V}{\Phi_0} = n f_{MW} \rightarrow \frac{V}{f_{MW}\Phi_0} = n$$

V_J

PHASE LOCKING: (fractional) SHAPIRO STEPS





$$V_{Josephson} = \Phi_0 f$$

$$j_s = j_{c1} \sin(\phi),$$

S/F/S

$$j_s(\phi) = j_{c1} \sin(\phi) + j_{c2} \sin(2\phi)$$

A. A. Golubov, M. Y. Kupriyanov, and E. Il'ichev, Rev. Mod. Phys. **76**, 411 (2004).

S. Kashiwaya, and Y. Tanaka, Rep. Prog. Phys. **63**, 1641 (2000).
E. Goldobin *et al.*, Phys. Rev. B **76**, 224523 (2007).

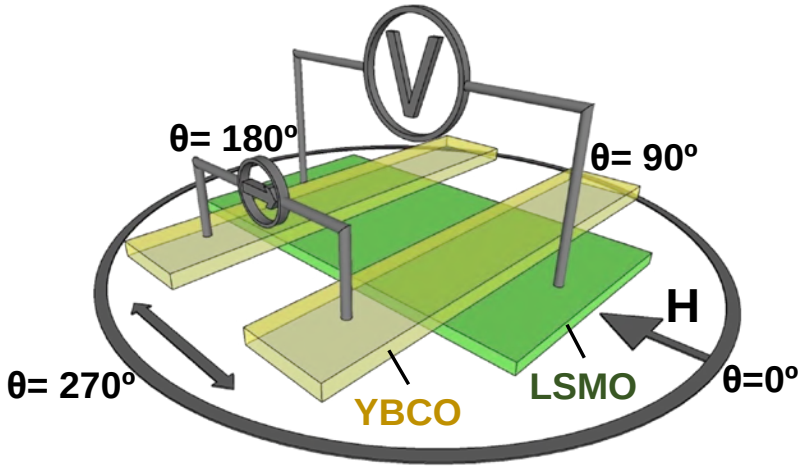
→ Junctions with dominant second harmonic term in the CPR

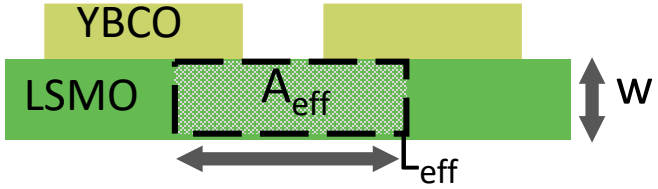
→ (Triplet) junctions with spin flip scattering at interfaces
CPR anomalous

Asano, Y., Sawa, Y., Tanaka, Y. & Golubov, A. A. Phys. Rev. B **76,** 224525 (2007).

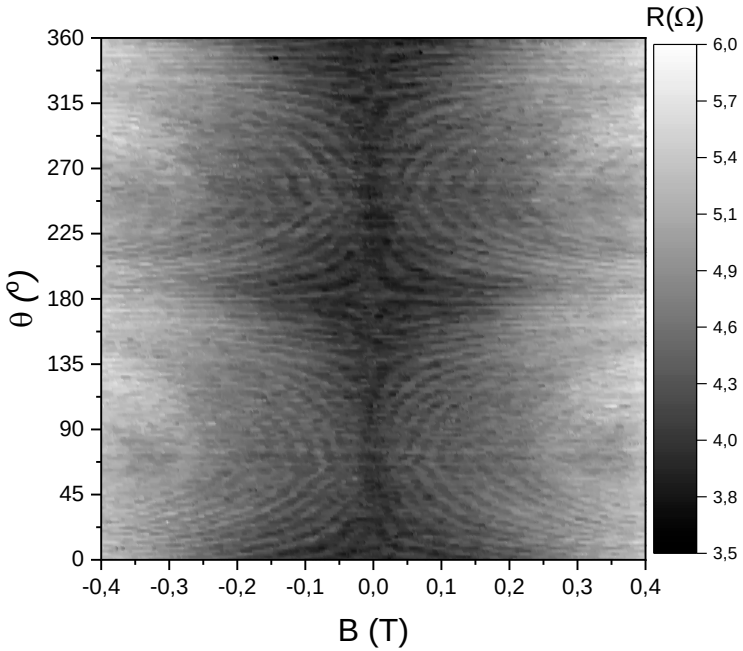
D. Sanchez-Manzano Nat Mater **21**, 188 (2022)

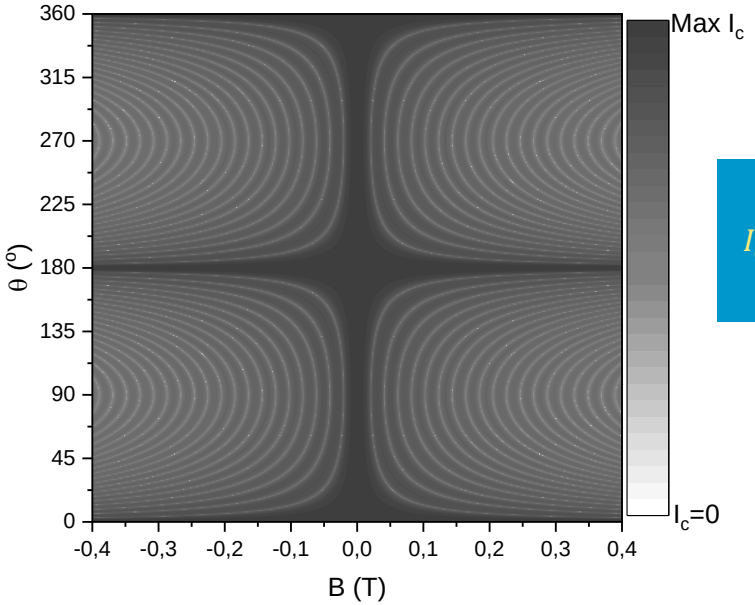
CURRENT INTERFERENCE: FRAUNHOFER PATTERN





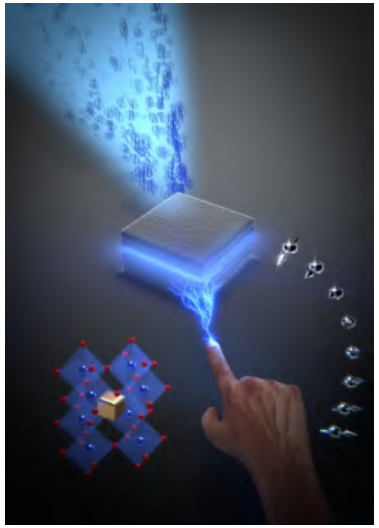
$\Phi(H,\theta)=\mu_0 H A_{eff}|\sin(\theta)|$





$$I_c(H,\theta) = I_{c0}\left|\frac{sin\pi\frac{\Phi}{\Phi_0}}{\pi\frac{\Phi}{\Phi_0}}\right|$$

L_{eff}= 1.5 μm



- **Triplet unconventional Josephson effect** d-wave SC/HM

- Non-harmonic CPR (twice-shorter period Fraunhofer oscillations half-period super-harmonic Shapiro steps).

- Calls for theory on the d-wave/HM triplet proximity effect

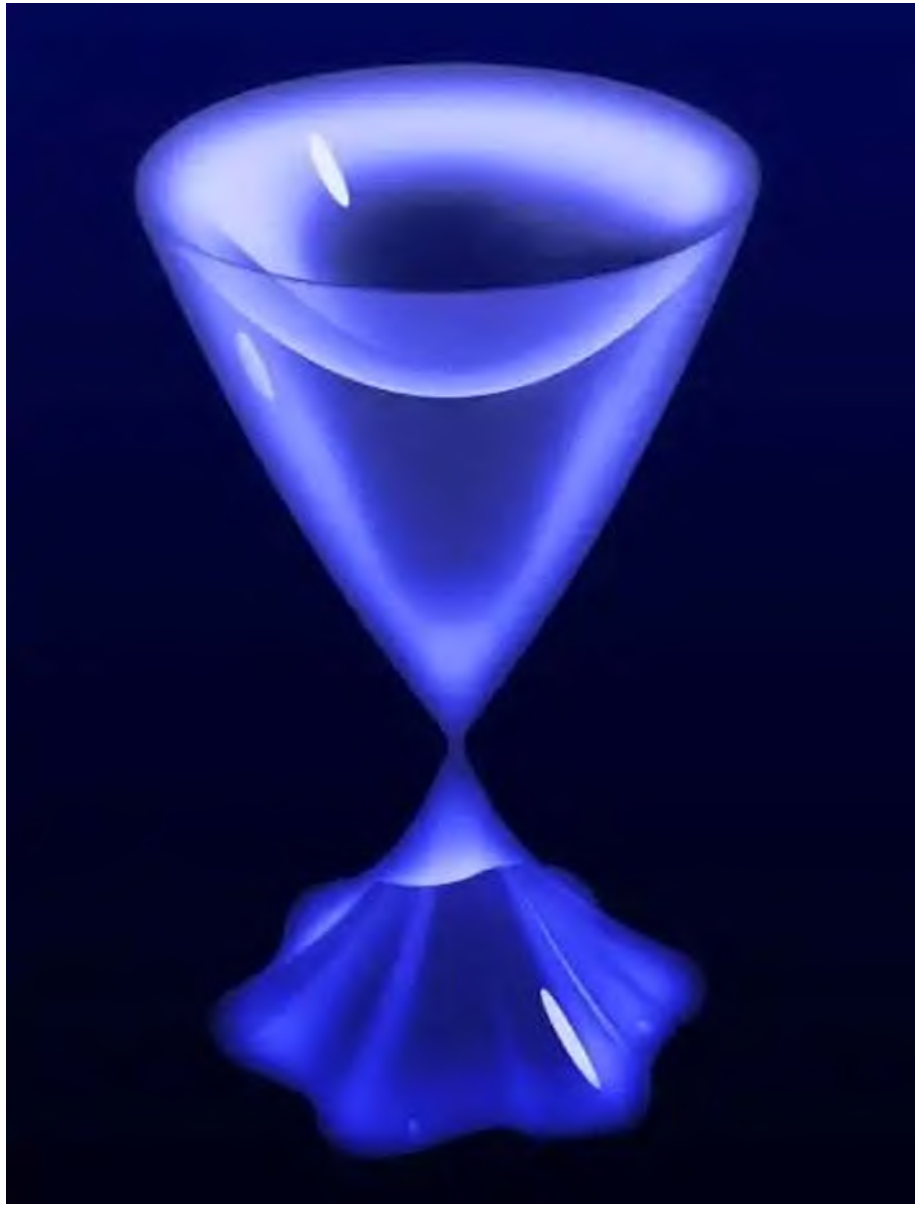
- **φ_0-junction**

- **Outlook**.

-magnetic information is stored in the phase, allowing for a completely new spintronic quantum logic.

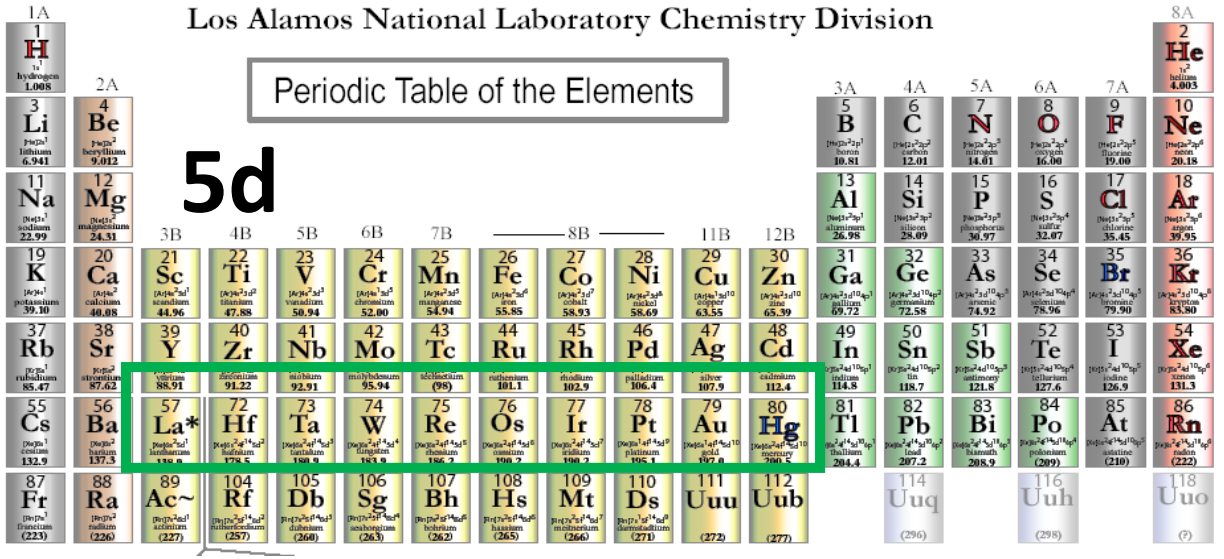
-non-dissipative phase batteries (theoretically proposed) important to reduce decoherence in quantum circuits

Part 2..... spin orbit int.: Topology Robustness



$$\mathcal{H}_{SO} = \frac{\xi}{\hbar}\hat{\boldsymbol{\sigma}}(\boldsymbol{\nabla}\phi \times \boldsymbol{p})$$

5d TRANSITION METAL OXIDES: strong spin orbit

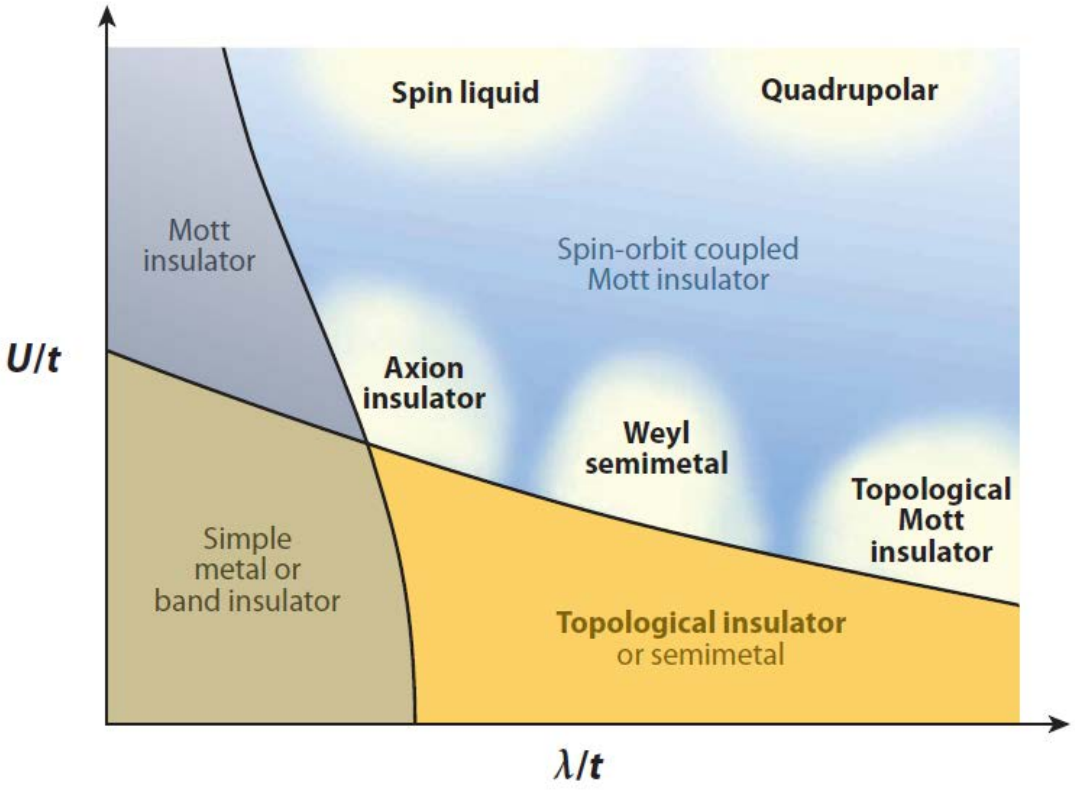


Electric fieldcontrol of symmetry breaking in $SrIrO_3$ ultrathin layers

F. Gallego[1,2], A. Peralta[1], J. Tornos[1], J. I. Beltran[1], Javier Garcia-Barriocanal[3], Guichuan Yu[3,4], Geoffrey Rojas[3], C. Munuera[2,5], M. Cabero[6,7], D. Sanchez-Manzano[1], F. Cuellar[1], G. Sanchez-Santolino[1,2], Z. Sefrioui[1,5], A. Rivera-Calzada[1,5], F. J. Mompean[2,5], M. Garcia-Hernandez[2,5], C. Leon[1,5], M. C. Muñoz[8] and J. Santamaria[1,5]

F. Gallego et al. Communications Materials 4 (1), 36 (2023)

5d oxides



Witczak-Krempa et. al, Annu. Rev. Condens. Matter Phys. 5, 57–82 (2014).

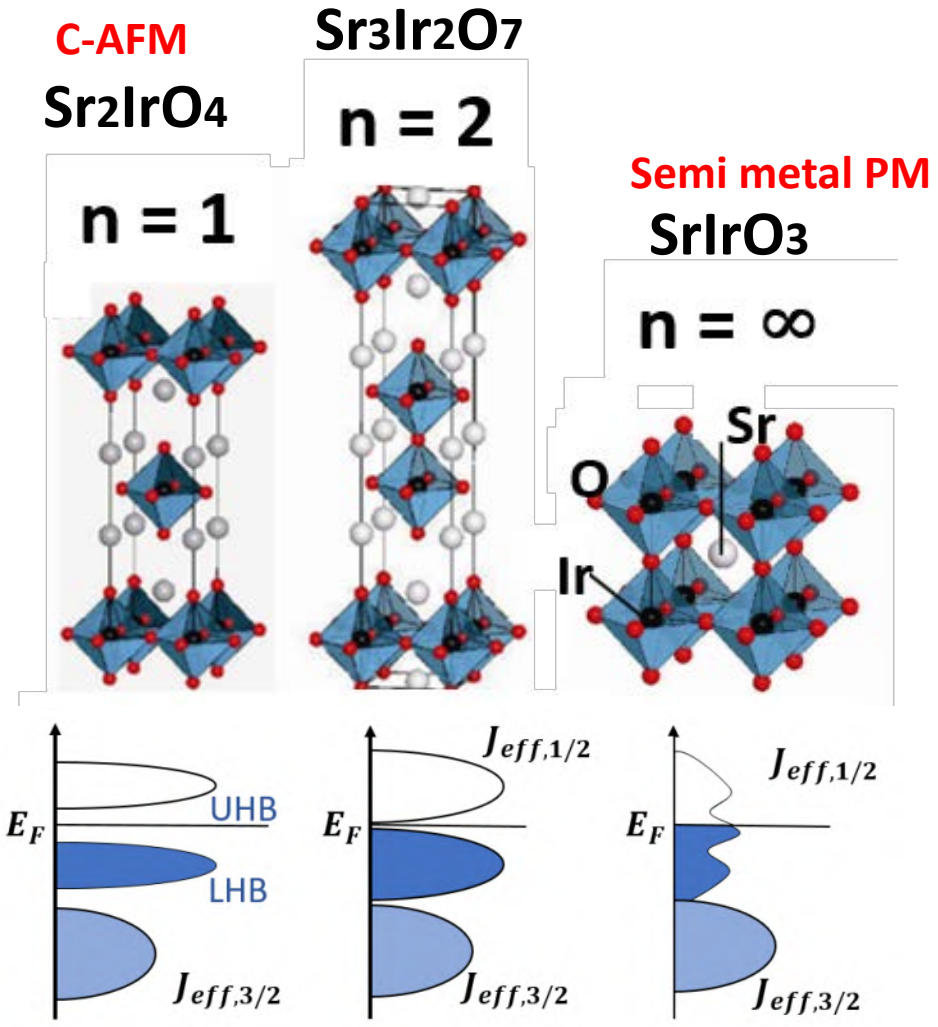
B. J. Kim et. al, Phys. Rev. Lett., 101, 076402 (2008)

S. J. Moon et al. Phys. Rev. Lett. 101, 226402 (2008)

Y. Okada et al. Nat.Mater.12,707 (2013)

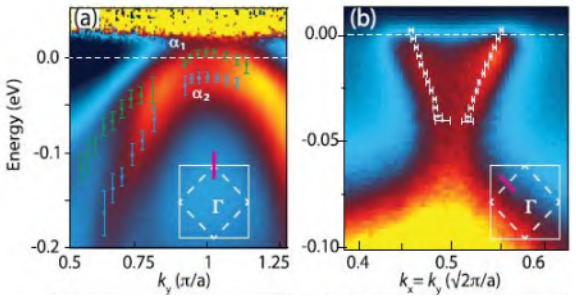
Ruddlesen-Popper series:

$Sr_{n+1}Ir_nO_{3n+1}$ (n=1, 2… ∞)



$SrIrO_3$

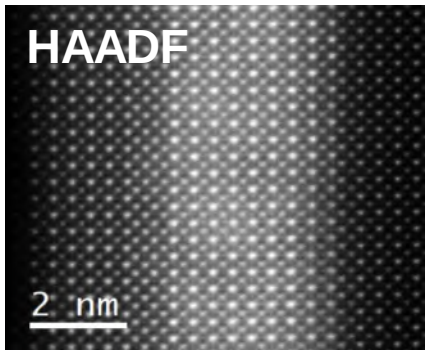
Narrow band semimetal



Y. F. Nie et al. Phys. Rev. Lett. 114, 016401 (2015)

Spin-orbit coupling
+
Strong Correlations

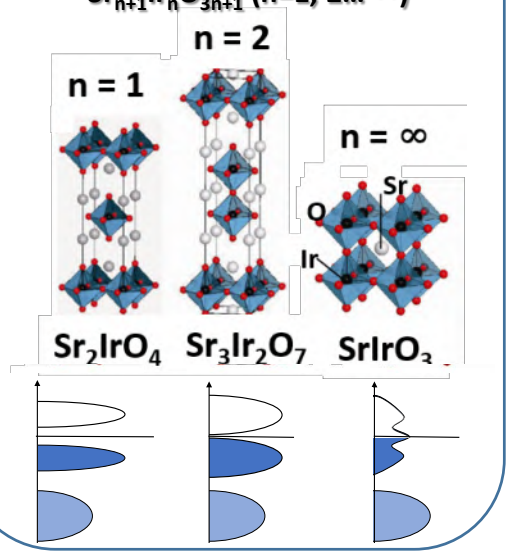
Epitaxial ultra-thin layers

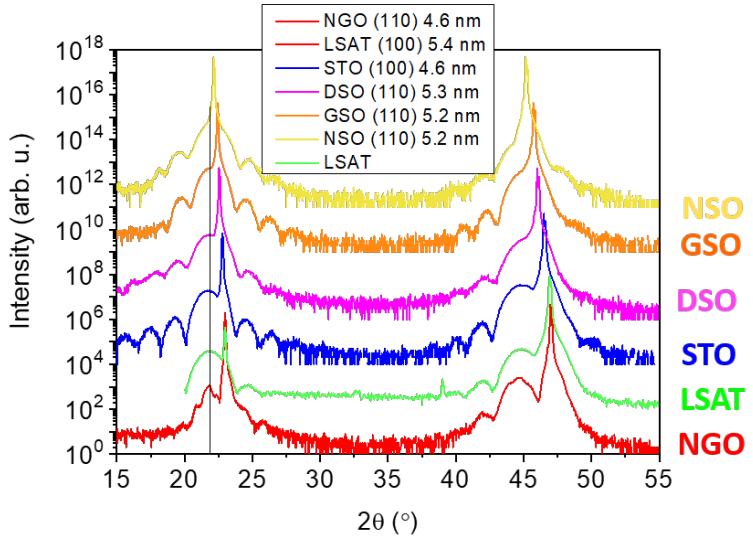


$La_{0.7}Sr_{0.3}MnO_3$ ⋮ $SrIrO_3$ ⋮ $SrTiO_3$

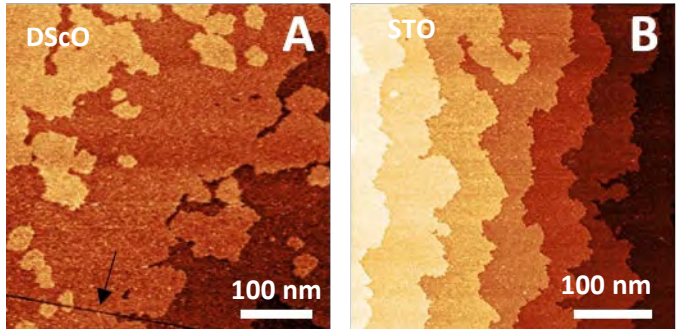
Ruddlesen-Popper series:

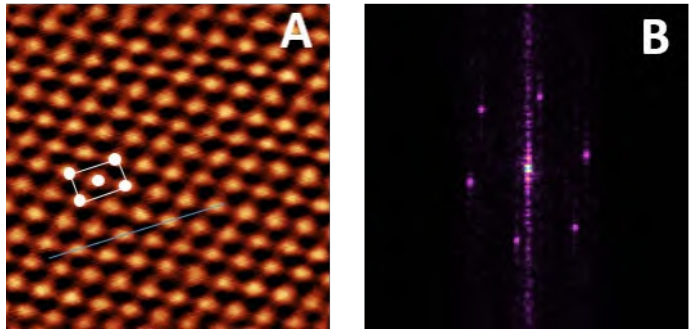
$Sr_{n+1}Ir_nO_{3n+1}$ (n=1, 2… ∞)

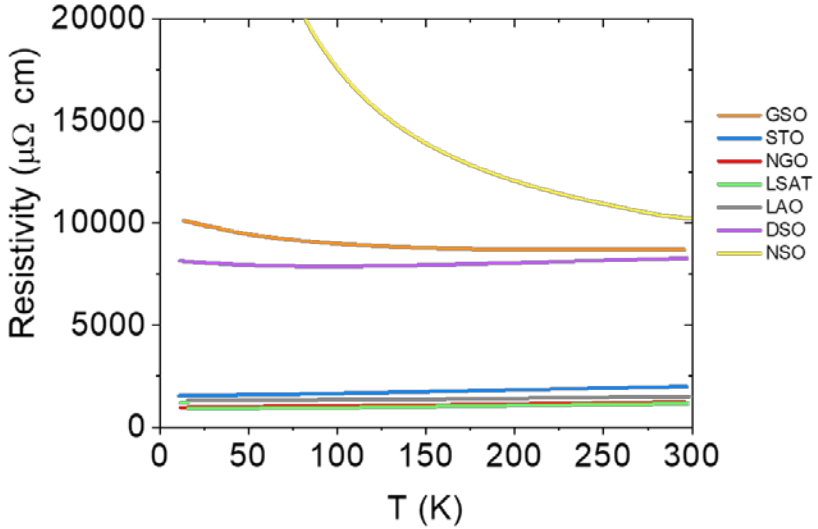




STM @ Char. Fac. U. Minesotta

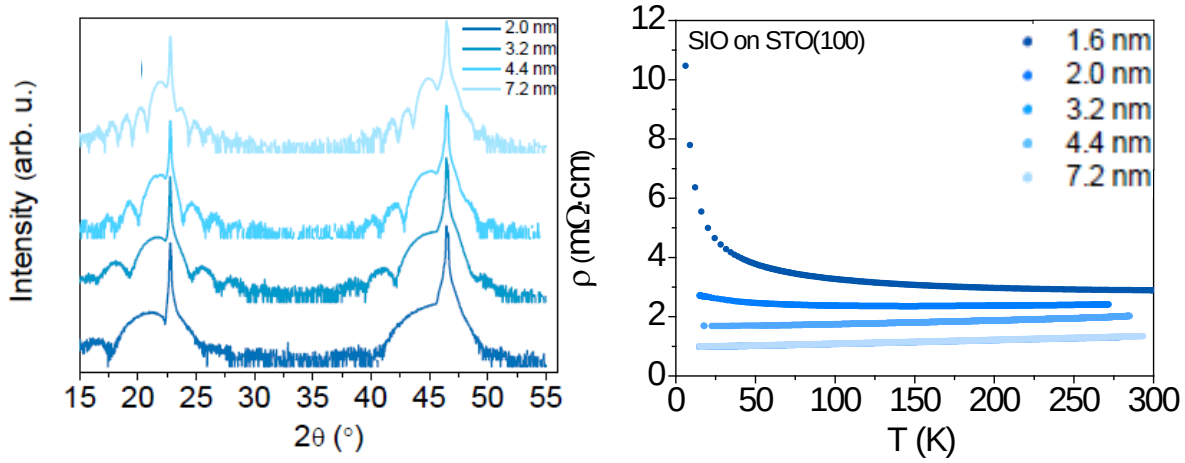


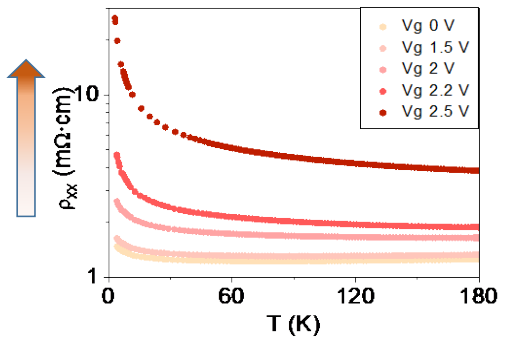


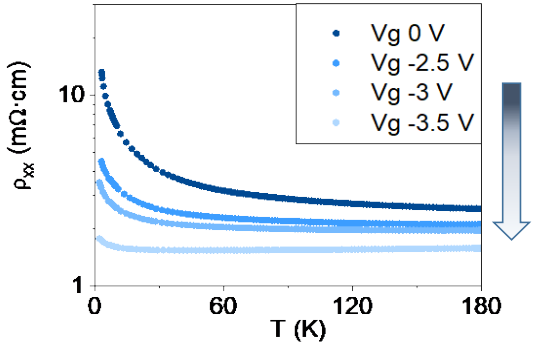


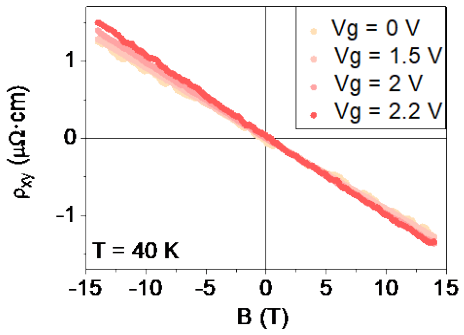
Structure and transport of $SrIrO_3$ ultrathin films. Epitaxial strain

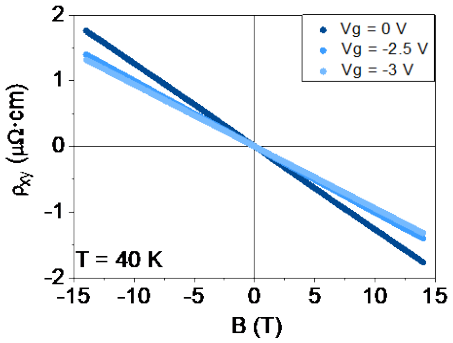
$SrIrO_3$ grown on STO

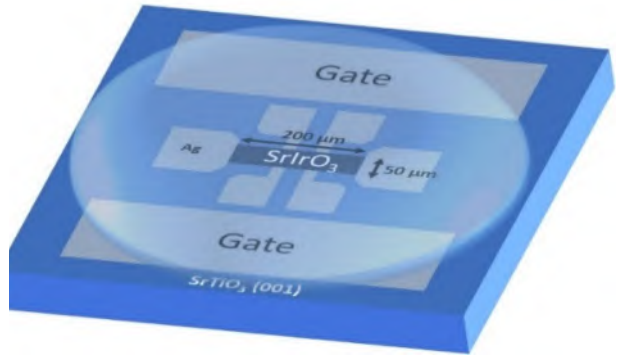








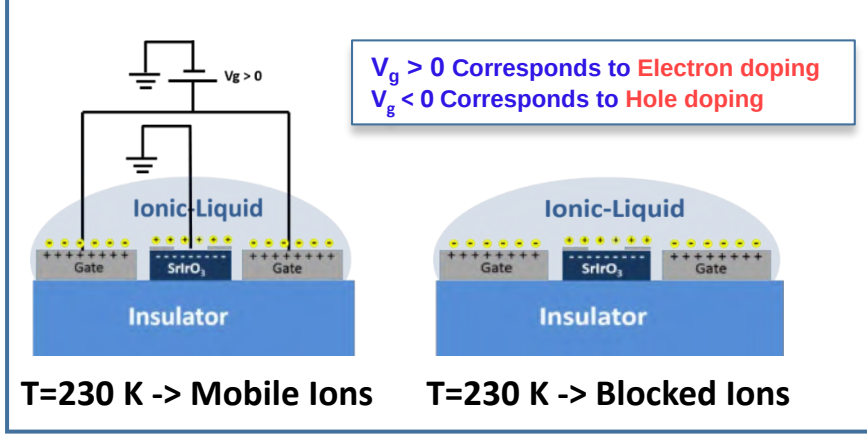


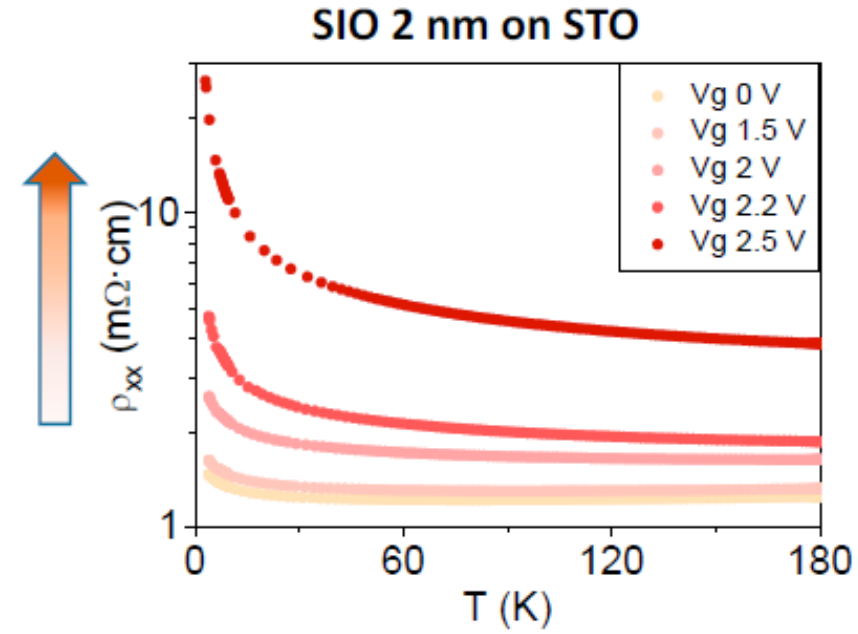


$SrIrO_3$ ultrathin films on STO. Field effect experiments to tune the MIT

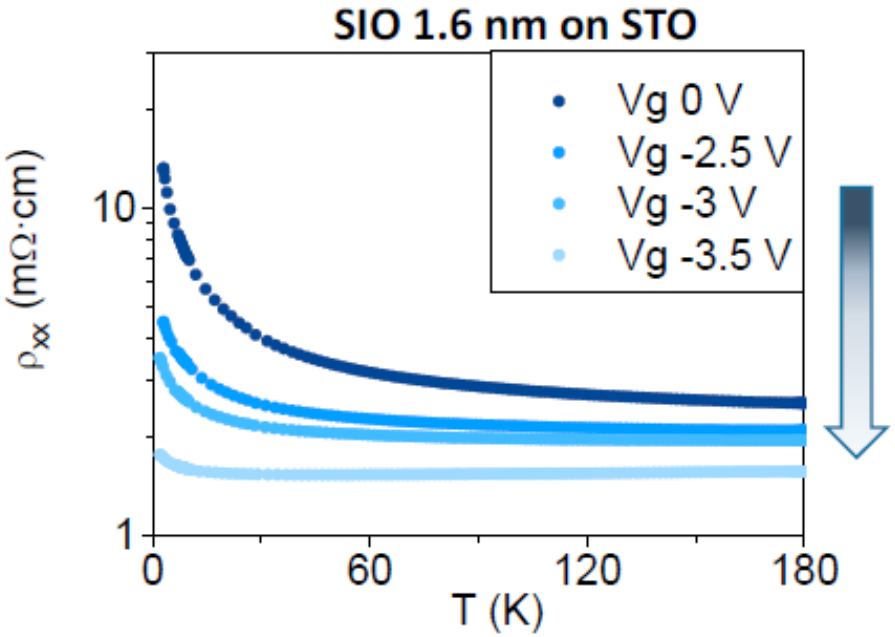
Resistivity measurements

Unexpected electric field effect **beyond** electrostatic doping





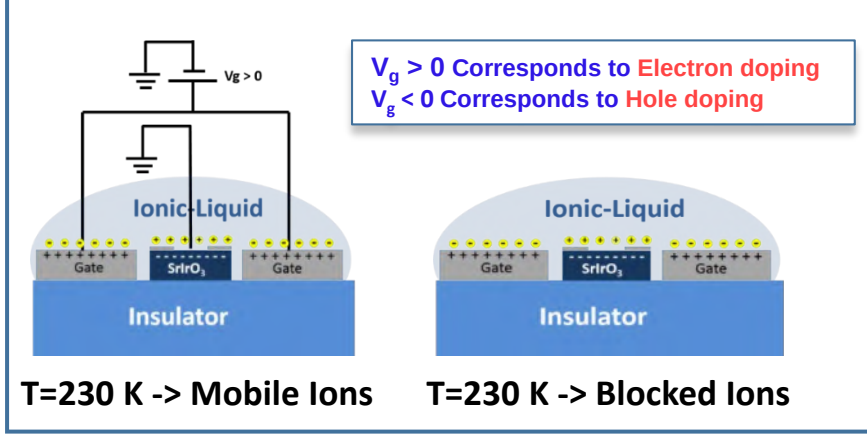
Expected electron doping ➡ Insulating state

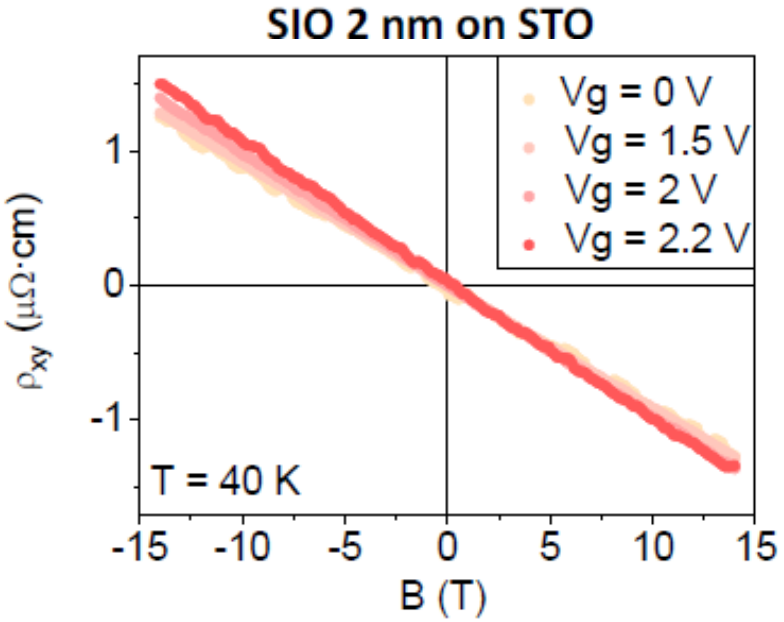


Expected hole doping ➡ Metallic state

Hall effect measurements

Unexpected electric field effect **beyond** electrostatic doping

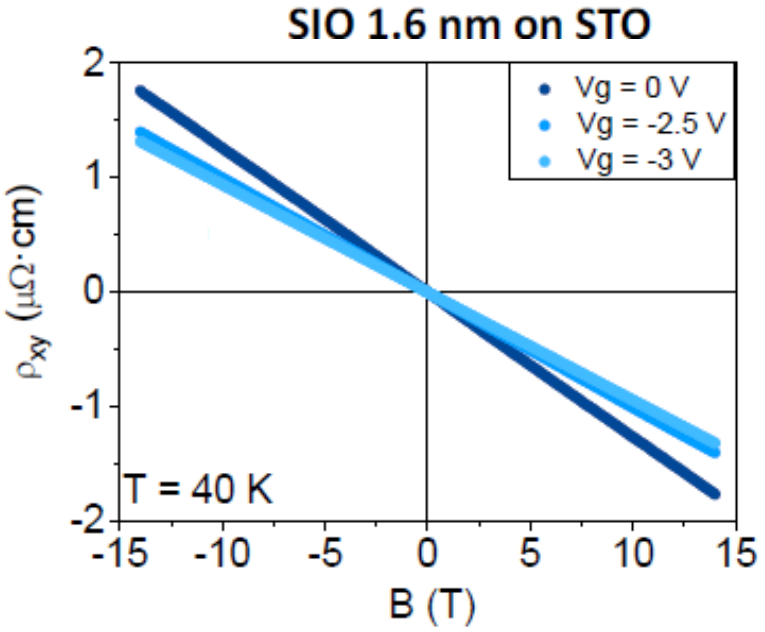




Expected electron doping

↓

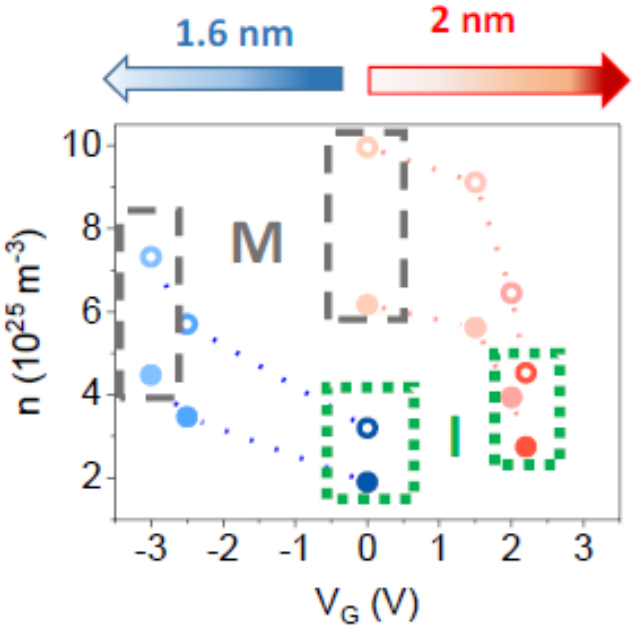
Reduce electron densities



Expected hole doping

↓

Increase electron densities

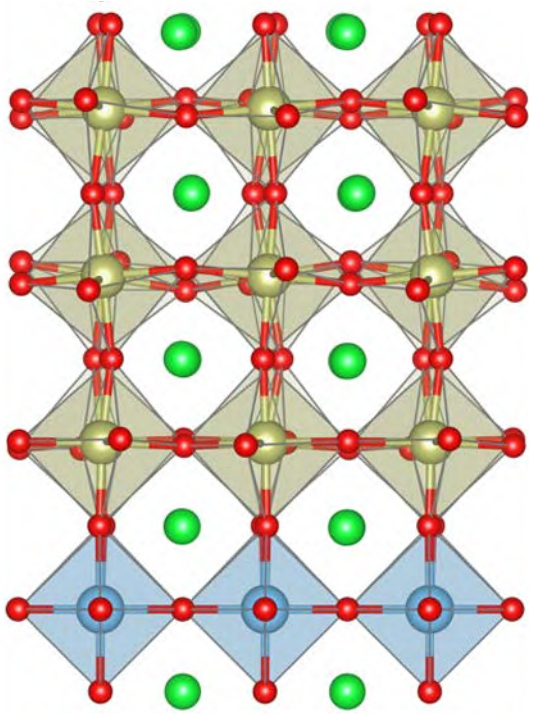


As the result of the reduced carrier density, screening effects on the charge density are less important

DFT calculations

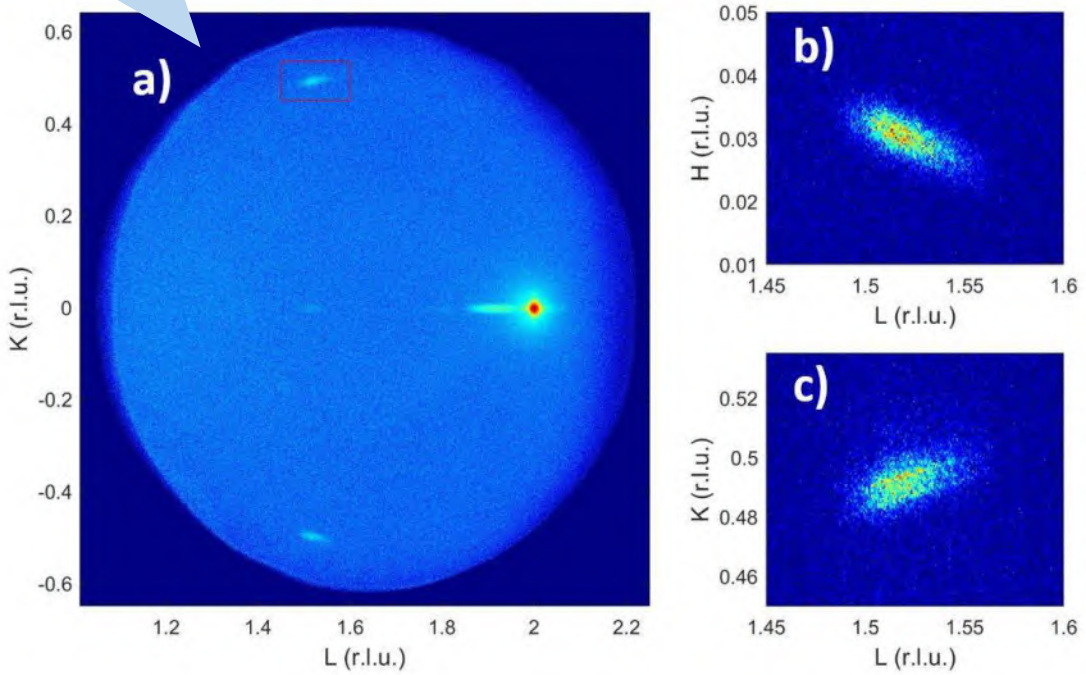
Juan Beltrán M.C. Muñoz @IMM-CSIC

$a^-a^-c^+$



Octahedral rotations

X-ray reciprocal space maps



Asymmetric (001) SIO*m*/STO slabs with two free SrO surfaces

The external electric field is added via a sawtoothlike potential, and conventional dipole corrections are used

For m ≤ 2 the films are insulators and a MIT occurs for *m* = 3

In plane rotations $a^0a^0c^-$ below 1 nm

Bulk --> $a^-a^-c^+$ octahedral rotations

DFT calculations

The external electric field is added via a sawtoothlike potential, and conventional dipole corrections are used

Meyer, B. & Vanderbilt *Phys. Rev. B* (2001)

Negative electric field increase film asymmetry

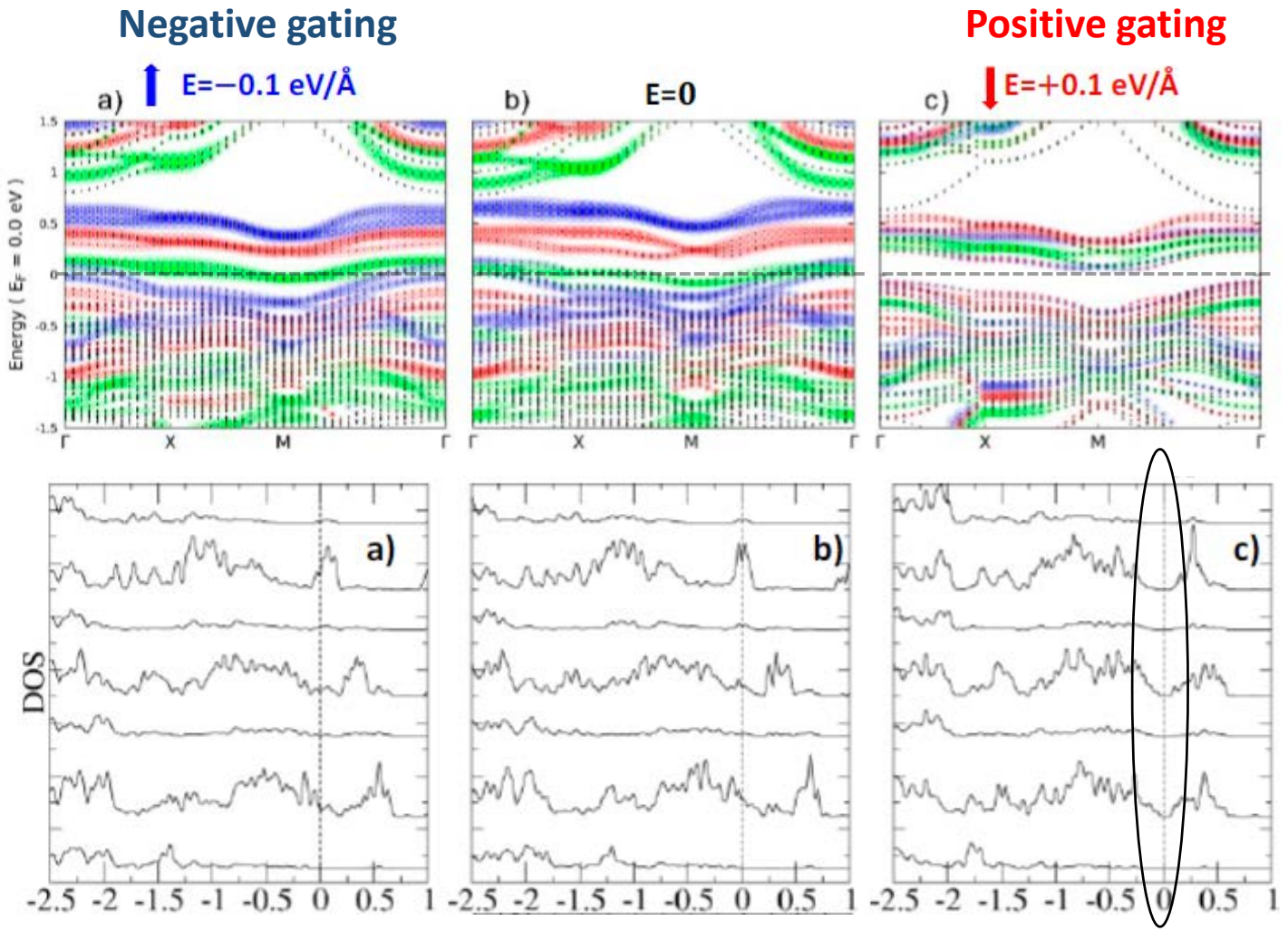
Positive electric field reduce film asymmetry

↓

Compensation of the intrinsic asymmetry field of the film grown on STO

↓

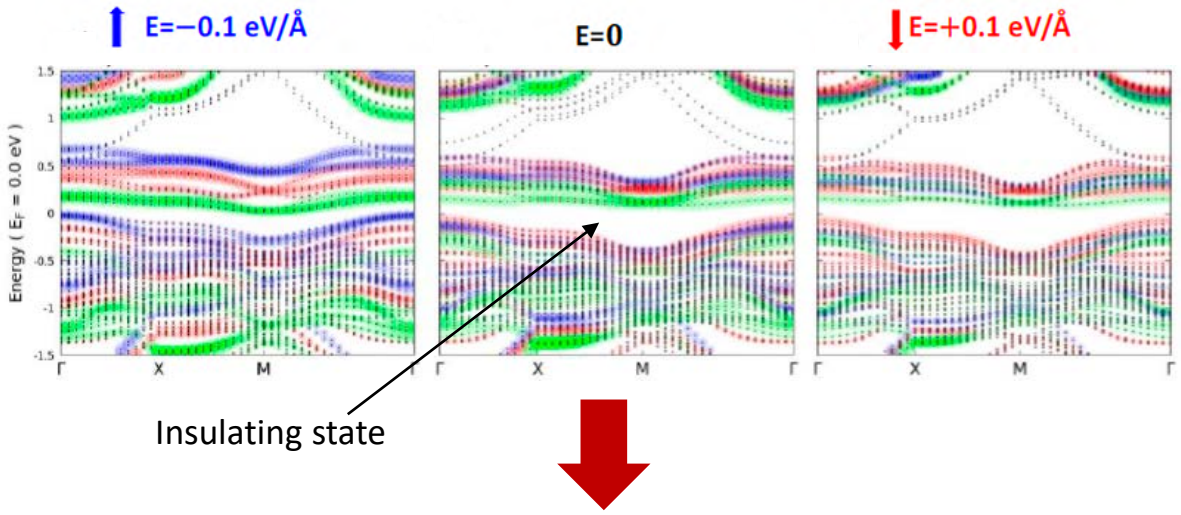
GAP opening



F. Gallego et al. Communications Materials 4 (1), 36 (2023)

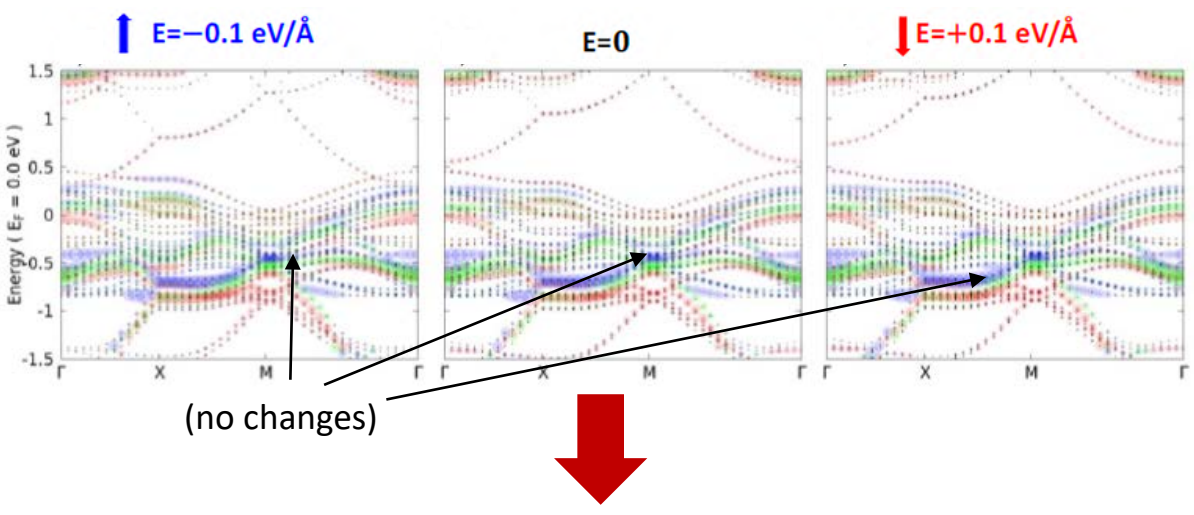
DFT calculations

DFT simulations without STO layers



Symmetry breaking introduced by STO is similar to a negative electric field

DFT simulations not including spin-orbit interaction



Spin orbit interaction required for the coupling between the electronic structure and the electric field

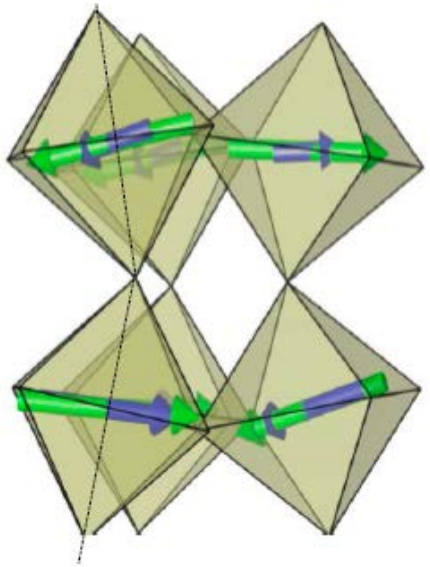
Fundametal interplay:

symmetry breaking + spin orbit coupling + electric field

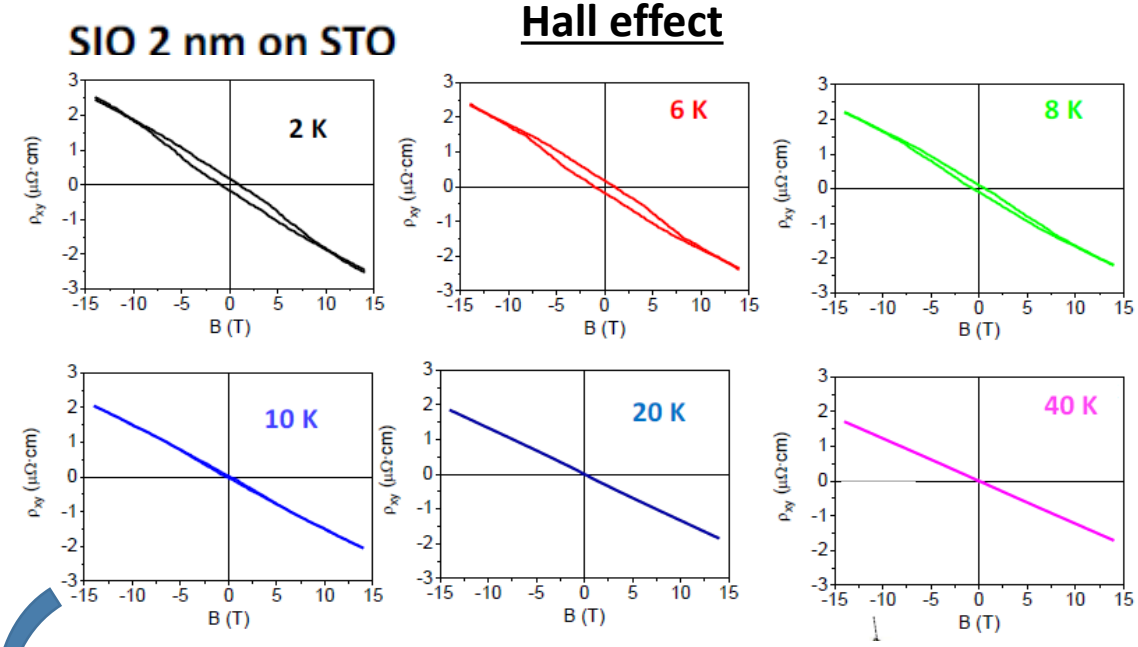
Anomalous Hall effect

Insulator phase under positive field presents canted orbital (0.26 μ_B) and spin (0.17 μ_B) moments yielding out of plane components of 0.04 μ_B and 0.02 μ_B respectively.

Canting of the magnetic moments associated with the rotation and tilting of the IrO_6 octahedra

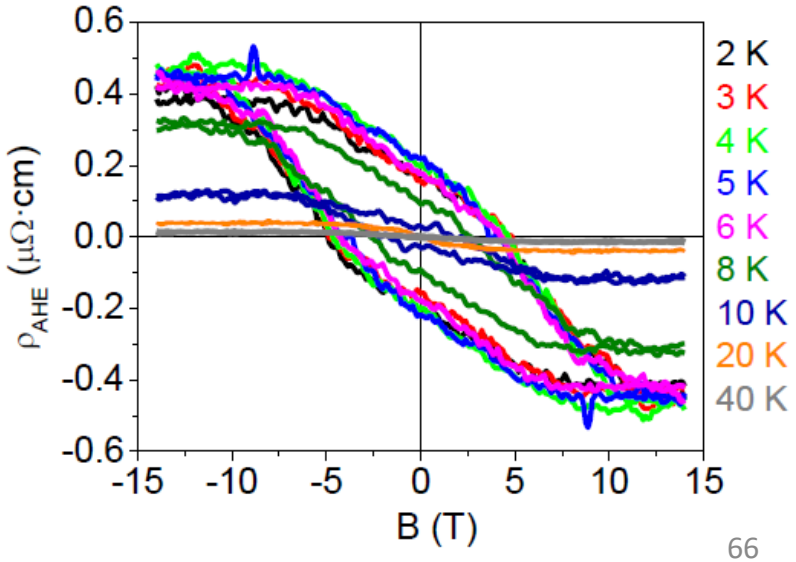


Hall effect



Substraction of the linear component

Anomalous Hall effect



Conclusions

- **We have shown a new perspective of ionic liquid gating producing effects on the electronic structure beyond doping**

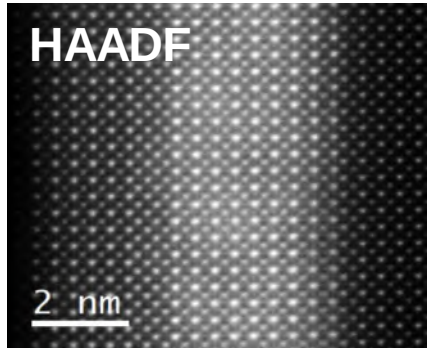
- **Large electric fields couple strongly to the electronic structure producing deep modifications in $SrIrO_3$ ultrathin films.**

- **Electric field controlled symmetry breaking provides an effective knob to modulate the effective strength of the correlations yielding the MIT transition.**

Large topological Hall effect and spin textures in $La_{0.7}Sr_{0.3}MnO_3$ / $SrIrO_3$ bilayers

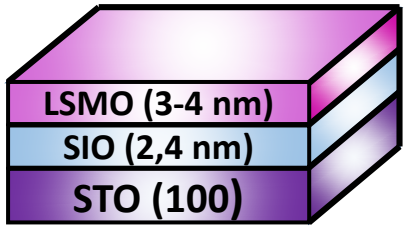
A. Peralta-Somoza , S. López , J.J. Riquelme, J. Tornos , Víctor Zamora, I. Barbero, D. Sánchez-Manzano, F. A. Cuellar, Sergio Valencia, C. Munuera, F. Mompeán, M. GarcíaHernández, C. León and Jacobo Santamaría

Epitaxial ultra-thin layers

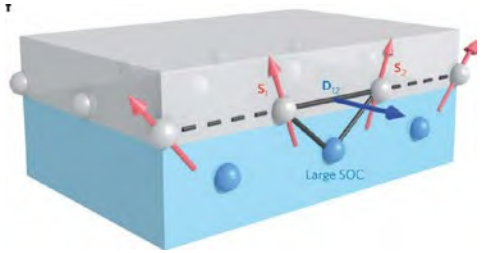


$La_{0.7}Sr_{0.3}MnO_3$ | $SrIrO_3$ | $SrTiO_3$

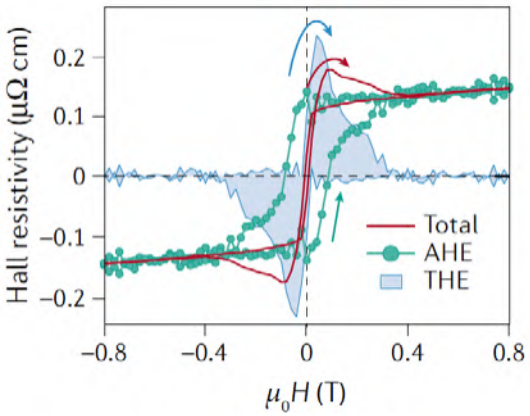
Experiment proposed to generate spin textures



Spin textures



*Fert, A. et al. Skyrmions on the track. Nature Nanotech **8**, 152–156 (2013).*



J. Matsuno et al., Sci. Adv. 2, (2016).

Dzyaloshinskii-Moriya Interaction (DMI)

- ✓ Strong Spin-Orbit Coupling
- ✓ Breaking of inversion Symmetry

$$H_{DM} = \vec{D}_{ij} \cdot (S_i \times S_j)$$

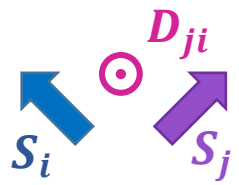
Observation of spin textures in $La_{0.7}Sr_{0.3}MnO_3$ / $SrIrO_3$ bilayers

Magnetic textures

Interfaces 5d/3d

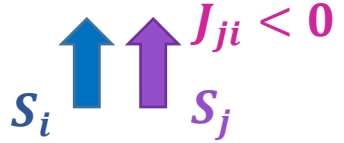
Spin-orbit coupling ✚ **Symmetry breaking**

Dzyaloshinskii Moriya interaction (DMI)



$$E_{\mathrm{DM}} = \sum_{i,j} \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

Heisenberg exchange



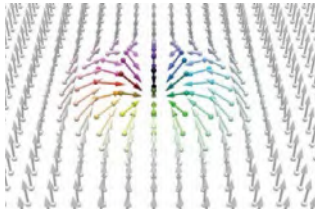
$$E_{\mathrm{H}} = \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

I. Dzyaloshinsky, «A thermodynamic theory of "weak" ferromagnetism of antiferromagnetics», *J. Phys. Chem. Sol* 4, 241 (1958)

T. Moriya, «Anisotropic Superexchange Interaction and Weak Ferromagnetism», *Phys. Rev.*, 120, 91 (1960)

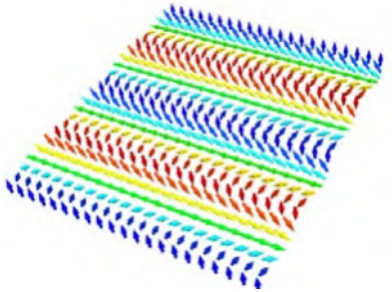
A. Fert y P. M. Levy, «Role of anisotropic exchange interactions in determining the properties of spin-glasses», *PRL*, 44, 1538 (1980).

Skyrmions



Trier, F., Noël, P., Kim, JV. *et al.* *Nat Rev Mater* **7**, 258–274 (2022).

Spirals



Wang, S. et al. J Low Temp Phys 197, 321–336 (2019)

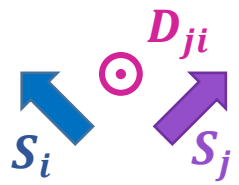
M. Bode *et al.*, «Chiral magnetic order at surfaces driven by inversion asymmetry», *Nature*, 447, 190 (2007)

Magnetic textures

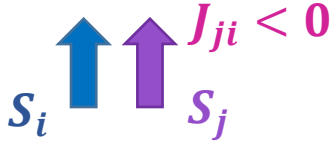
Interfaces 5d/3d

Spin-orbit coupling ✚ Symmetry breaking

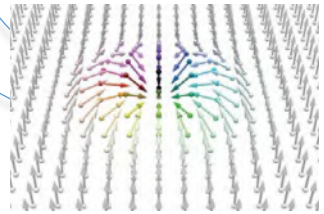
Dzyaloshinskii Moriya interaction (DMI)



Heisenberg exchange

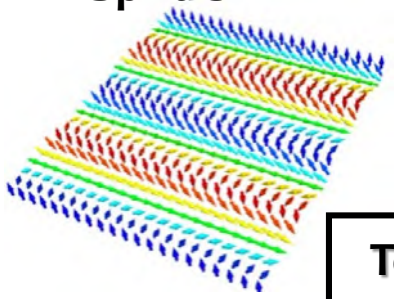


Skyrmions



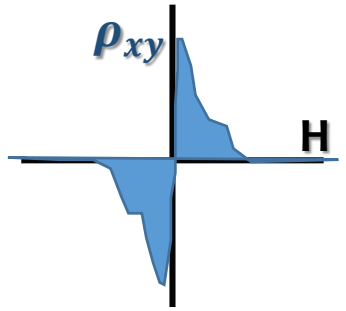
Trier, F., Noël, P., Kim, JV. *et al. Nat Rev Mater* **7**, 258–274 (2022).

Spirals



Wang, S. et al. J Low Temp Phys 197, 321–336 (2019)

Topological Hall Effect (THE)

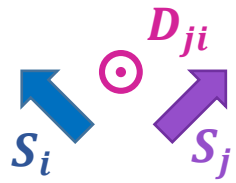


Magnetic textures

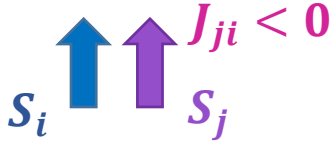
Interfaces 5d/3d

Spin-orbit coupling ✚ Symmetry breaking

Dzyaloshinskii Moriya interaction (DMI)

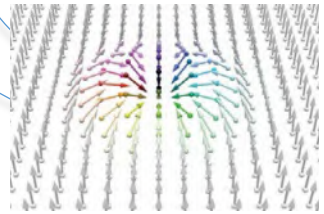


Heisenberg exchange



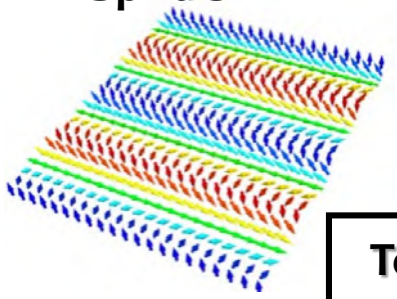
Dipolar interaction

Skyrmions



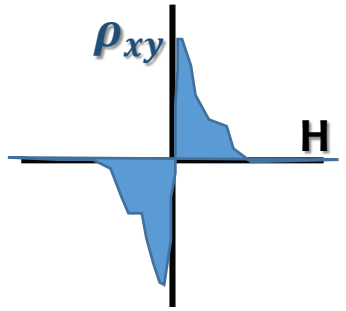
Trier, F., Noël, P., Kim, JV. *et al.* *Nat Rev Mater* **7**, 258–274 (2022).

Spirals

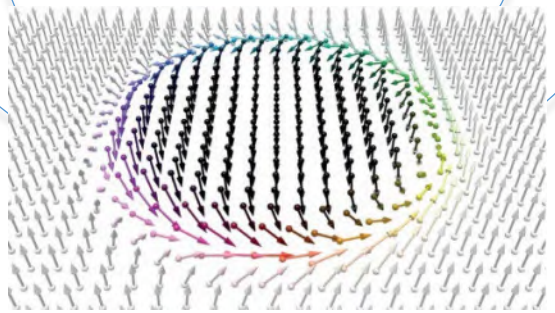


Wang, S. et al. J Low Temp Phys 197, 321–336 (2019)

Topological Hall Effect (THE)



Bubbles



Trier, F., Noël, P., Kim, JV. *et al.* *Nat Rev Mater* **7**, 258–274 (2022).

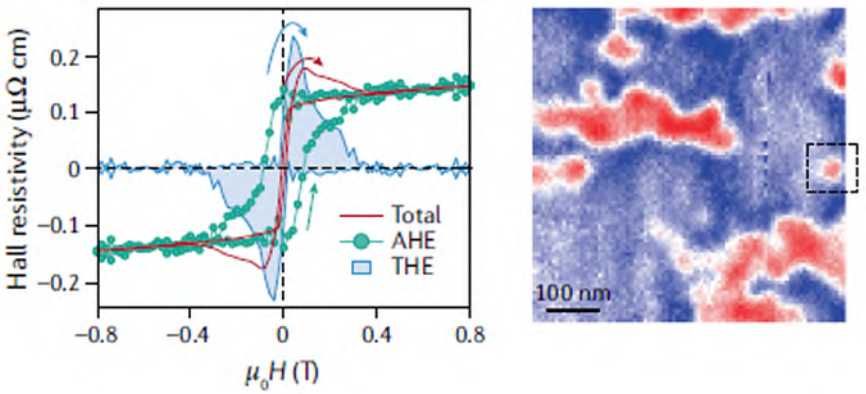
A. Fert, N. Reyren, y V. Cros, «Magnetic skyrmions: advances in physics and potential applications», *Nature Reviews Materials*, 2, 7 (2017)

N. Nagaosa y Y. Tokura, «Topological properties and dynamics of magnetic skyrmions», *Nature nanotechnology*, 8, 12 (2013)

A.P. Malozemoff y J. C. Slonczewski, «Magnetic Domain Walls in Bubble Materials (Academic», *New York*, 1979.
W. Jiang *et al.*, «Blowing magnetic skyrmion bubbles», *Science* 349, 6245 (2015).

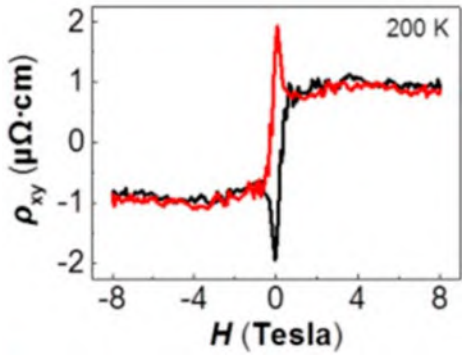
Magnetic textures in correlated oxides

$SrRuO_3$(5 u.c.)/$SrIrO_3$(2 u.c.)



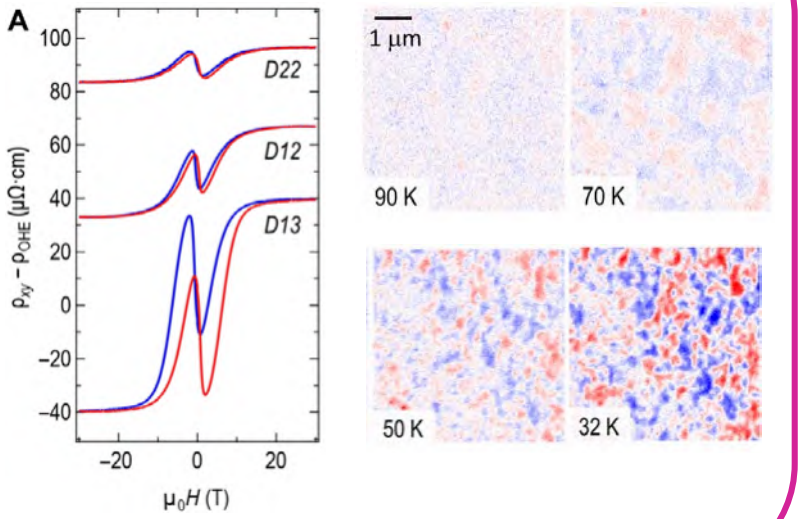
Matsuno, J. et al. Sci. Adv. ***2*** *(2016)*

$La_{0.7}Sr_{0.3}MnO_3$(8 u.c.)/$SrIrO_3$(2 u.c.)



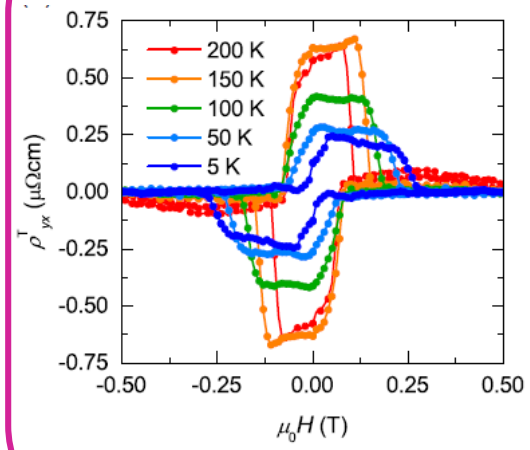
Yao Li et al. ACS Appl. Mater. Interfaces (2019), 11, 23

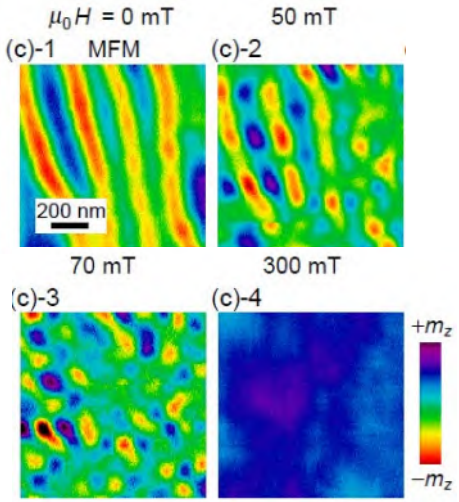
$[(LaMnO_3)_n/(SrIrO_3)_n]_m$



Skoropata E et al. Sci Adv. (2020)

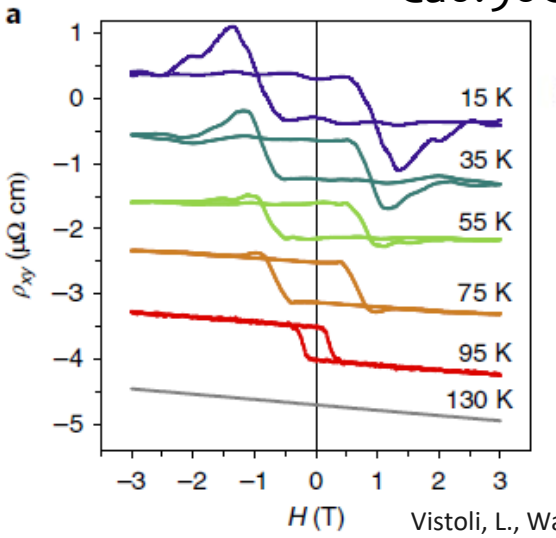
Lao.7Sro.3Mn1-yRuyO3

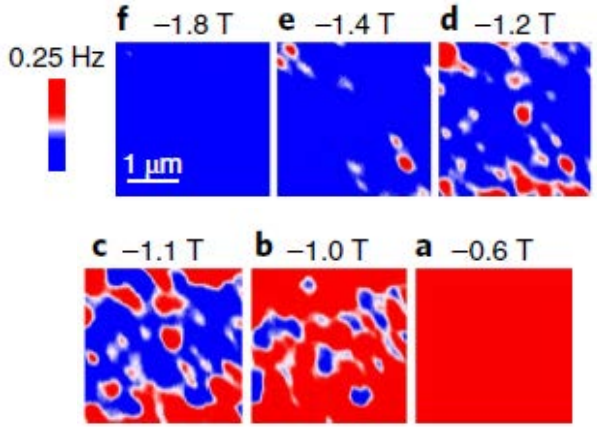




M. Nakamura et al. J. Phys. Soc. Jpn. 87, 074704 (2018)

Cao.96Ceo.04MnO3



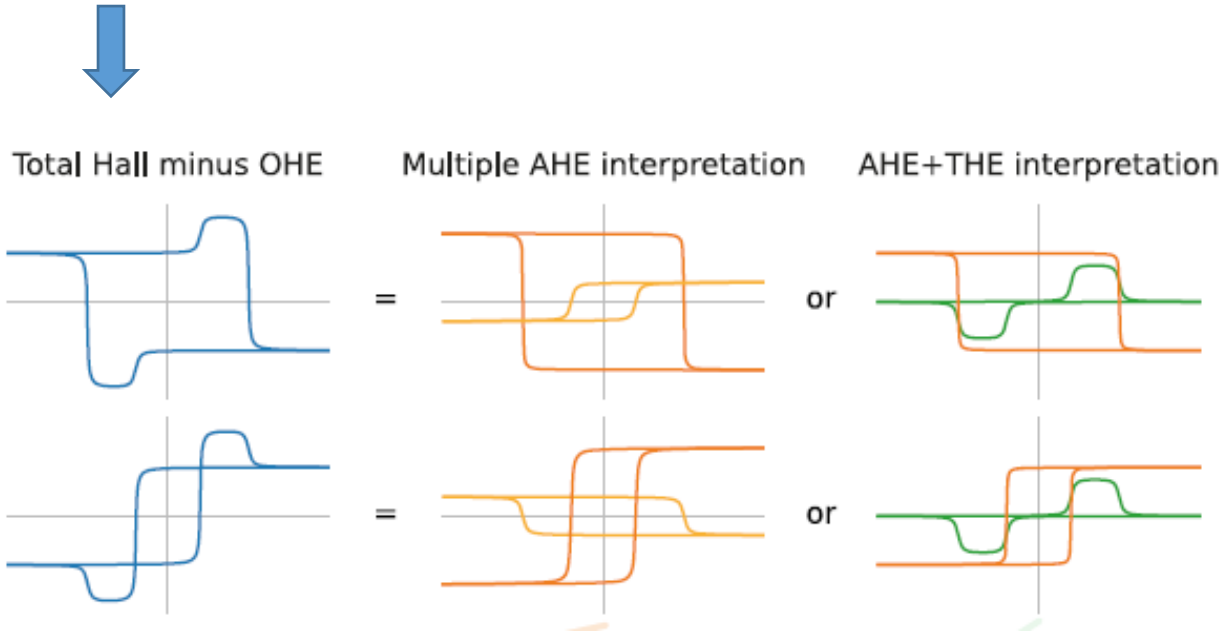


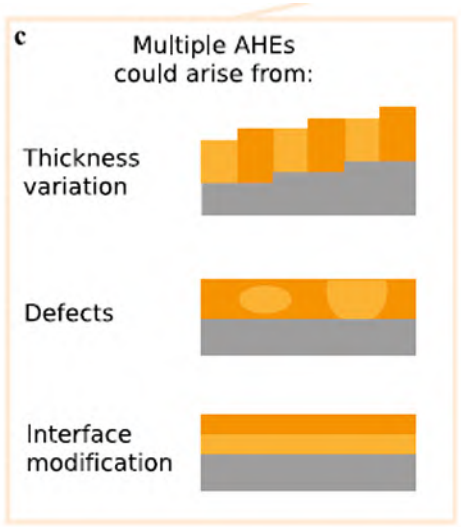
Vistoli, L., Wang, W., Sander, A. *et al. Nature Phys* **15**, 67–72 (2019)

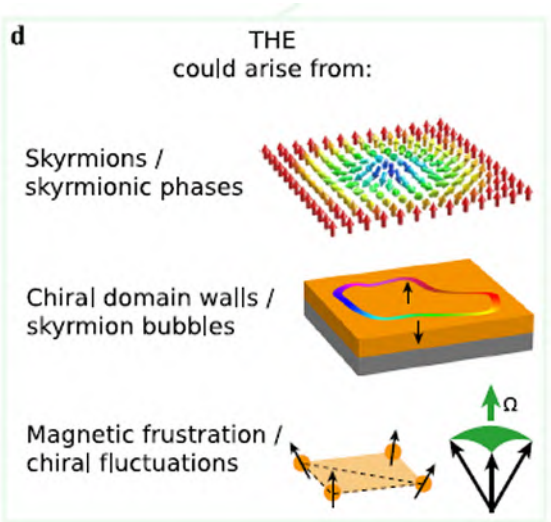
The debate

(1) Discrepancies between the skyrmion densities obtained from THE and MFM observations.

(2) Inhomogeneities may yield inhomogeneous multicomponent anomalous Hall effect which can be mistaken with THE. (TC van Thiel *et al* 2020 *J. Phys. Mater.*) (Groenendijk, D. J. et al. Phys. Rev. Res. 2, (2020))







Kimbell, G., Kim, C., Wu, W. *et al*. *Commun Mater* **3**, 19 (2022)

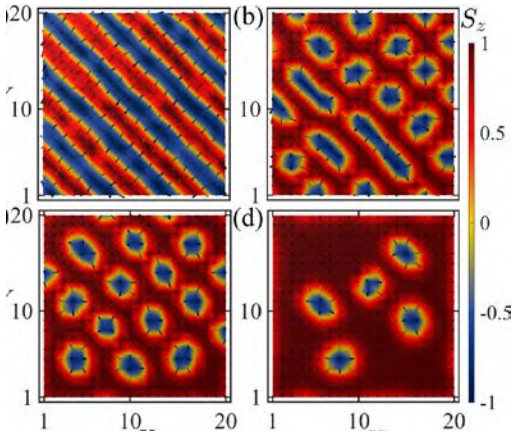
Experiment

Hall Effect ✚ MFM &PEEM

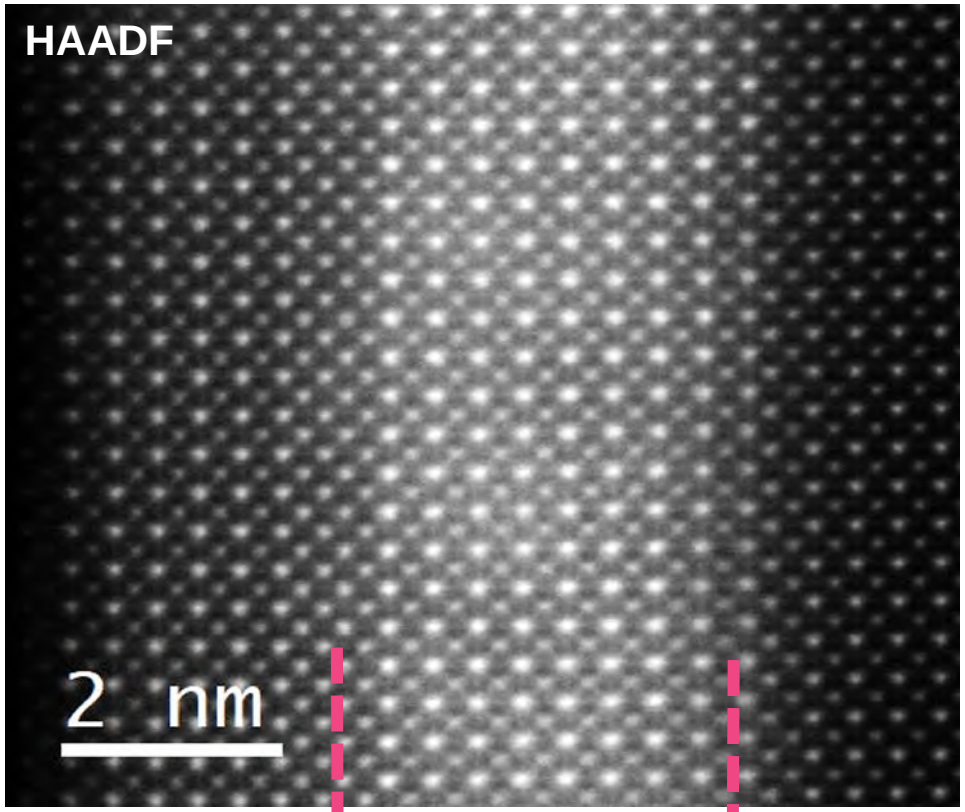
LSMO (3.5 nm)

SIO (2.4 nm)

STO (100)



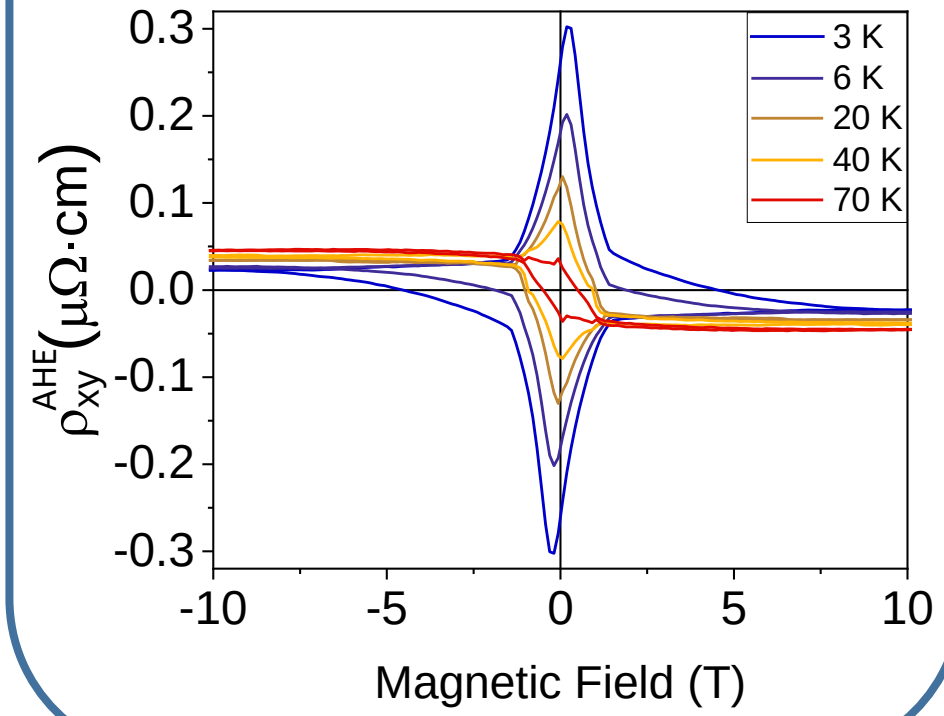
Mohanta, Dagotto, and Okamoto
Physical Review B **100**, 064429 (2019)

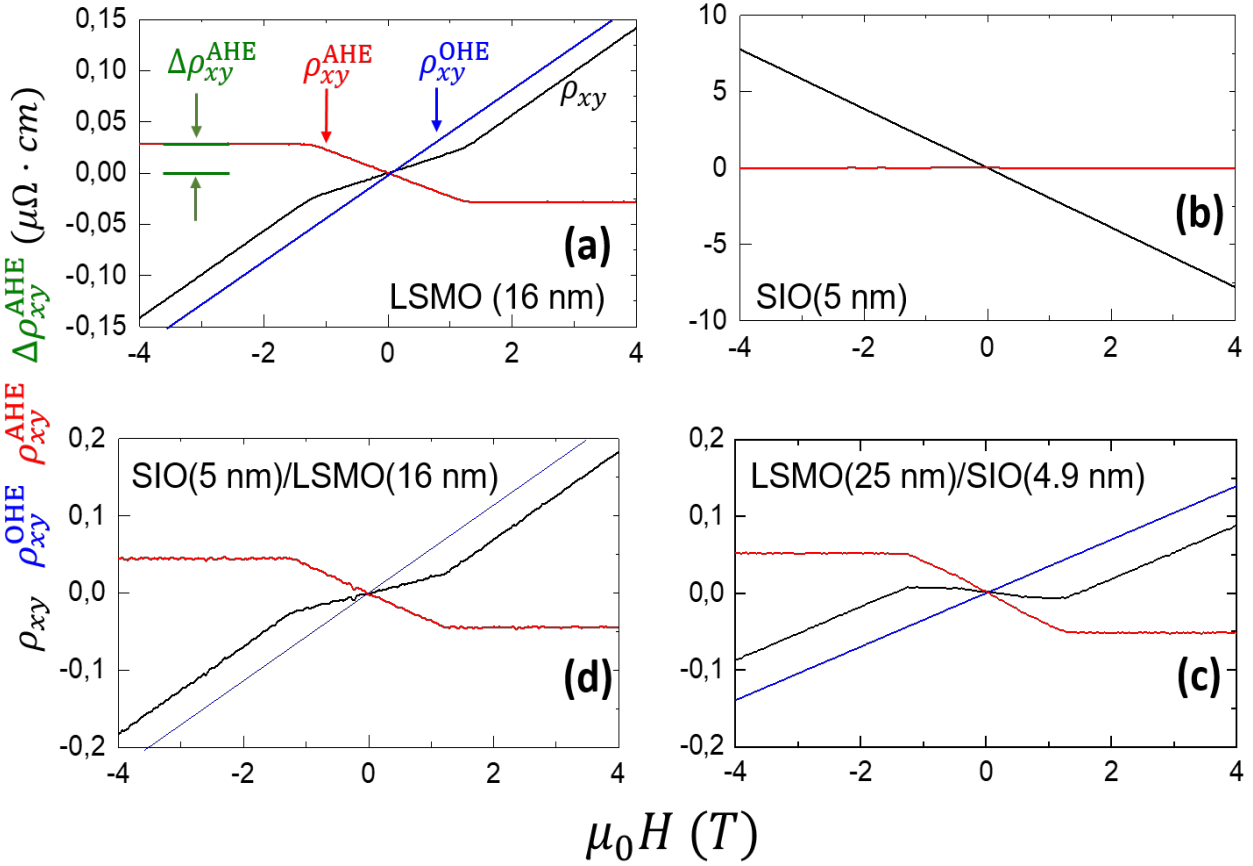


$La_{0.7}Sr_{0.3}MnO_3$ | $SrIrO_3$ | $SrTiO_3$

THE and MFM/PEEM images

Topological peak at a wide range of temperature

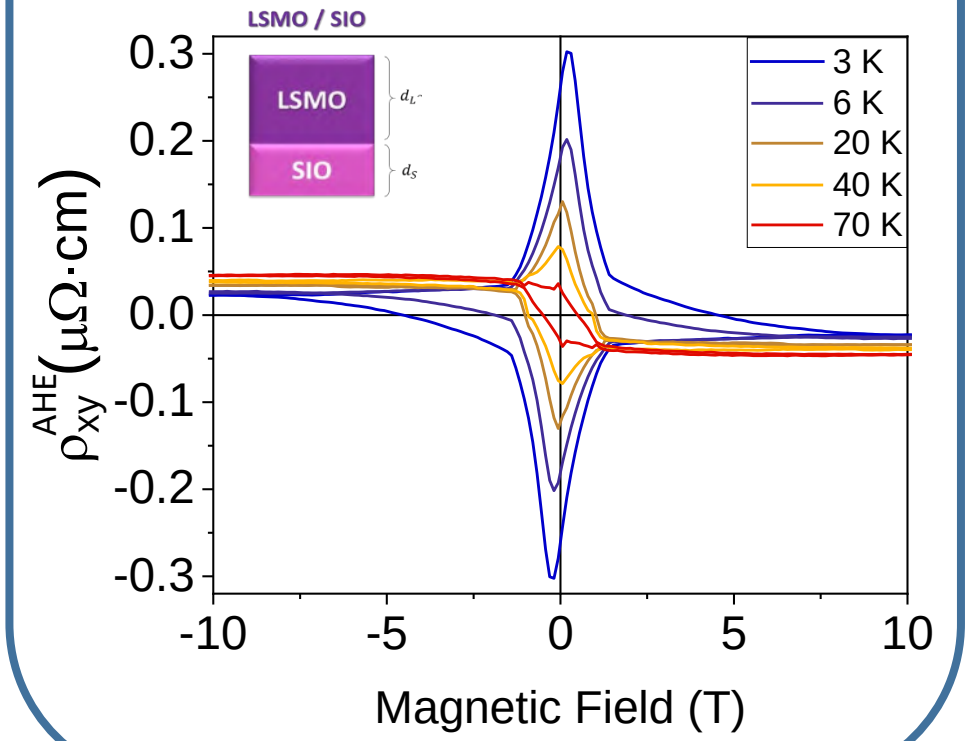




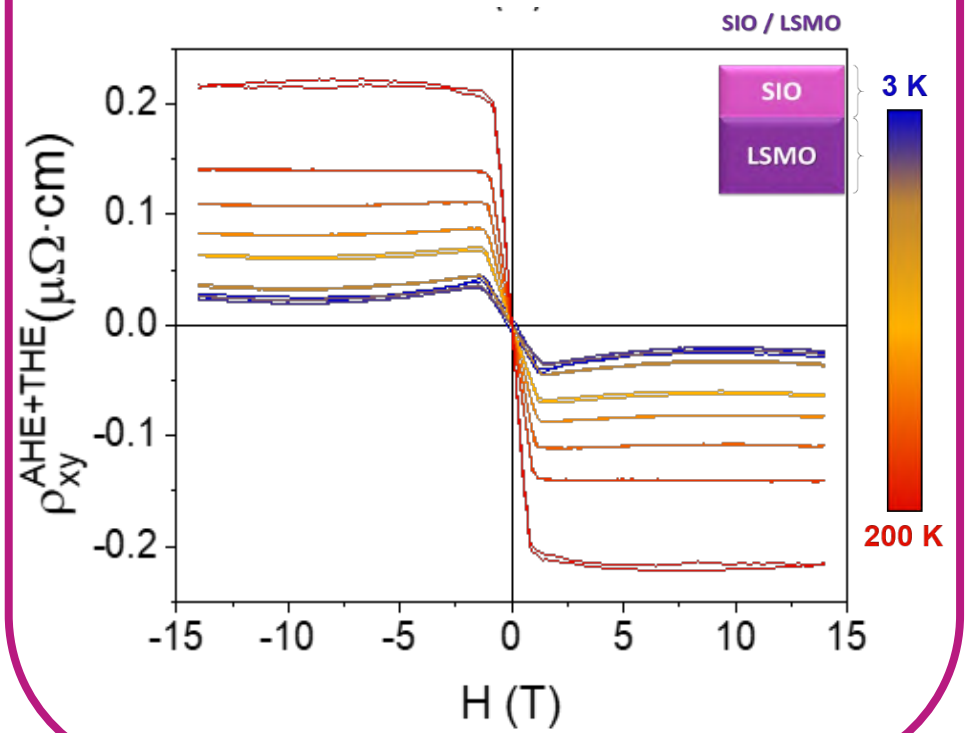
Nature Communications 12 (1), 3283 (2021)

THE is an interface effect

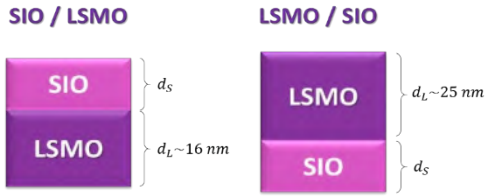
Topological peak at a wide range of temperature



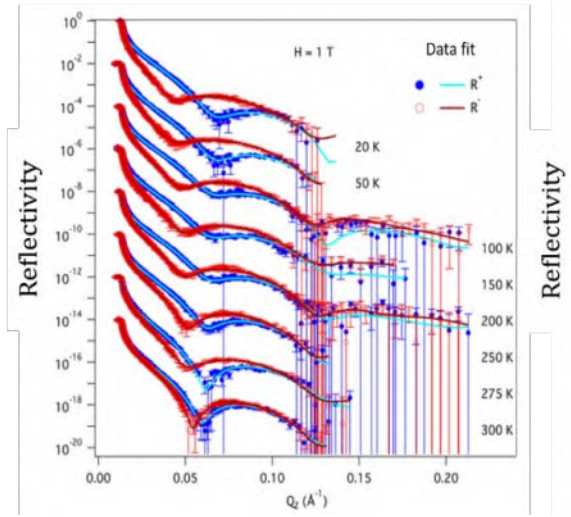
THE absent in bilayers with inverted layer sequence

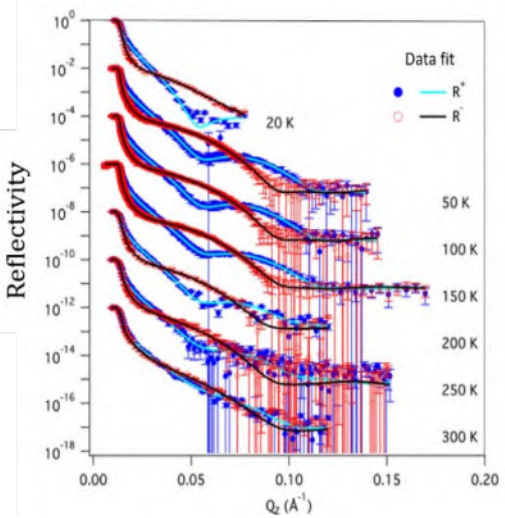


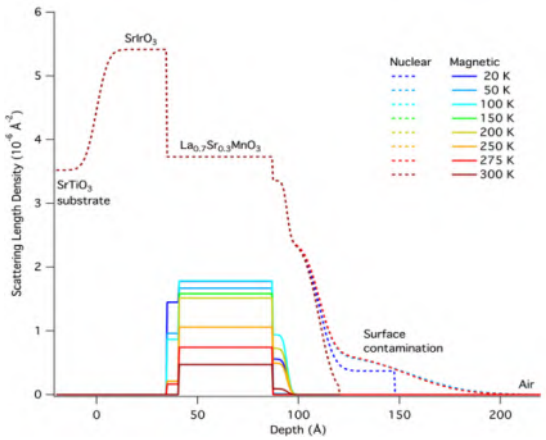
PNR@ ORNL
S. te Velthuis

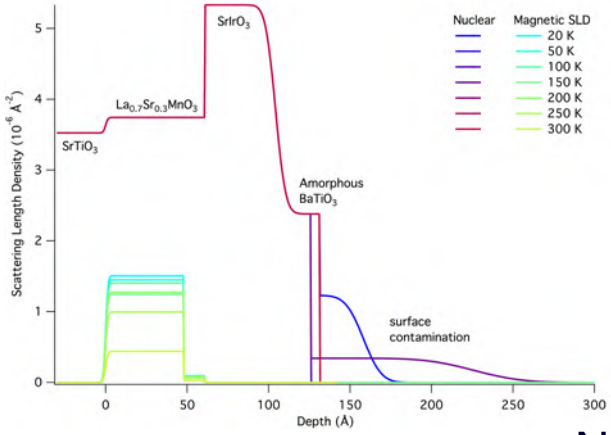


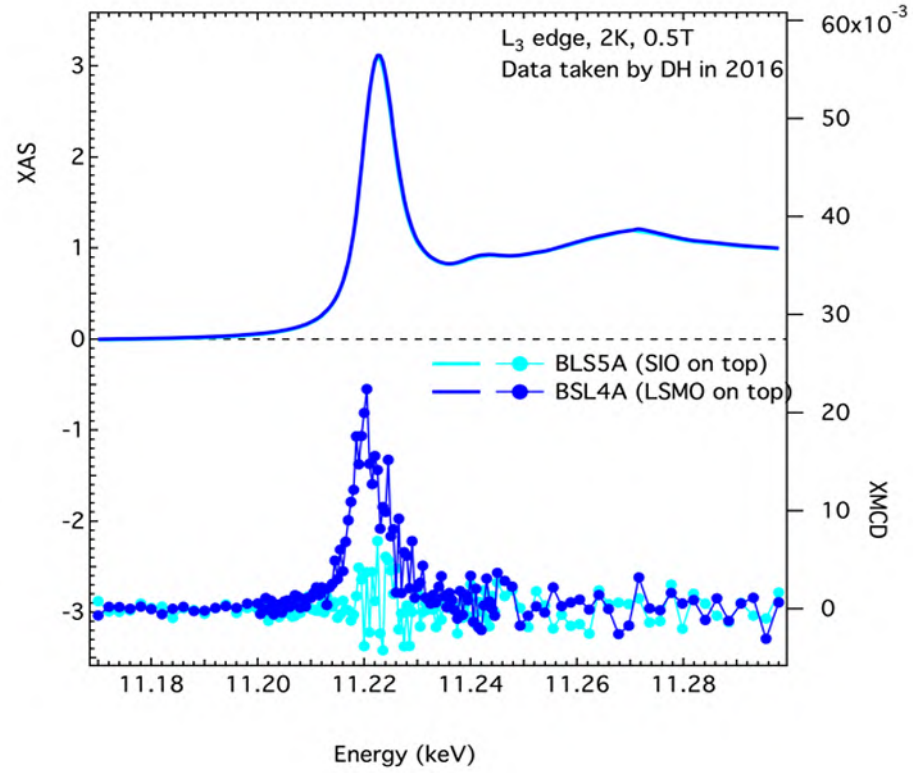
XMCD @ APS
D. Haskel





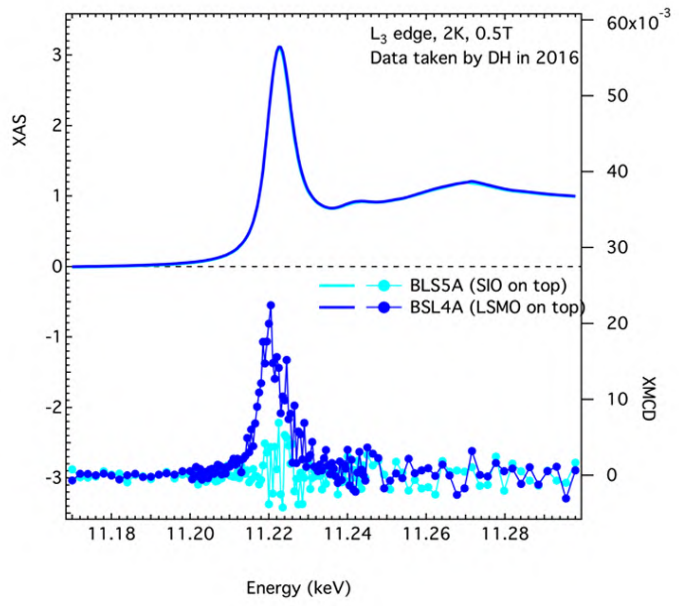


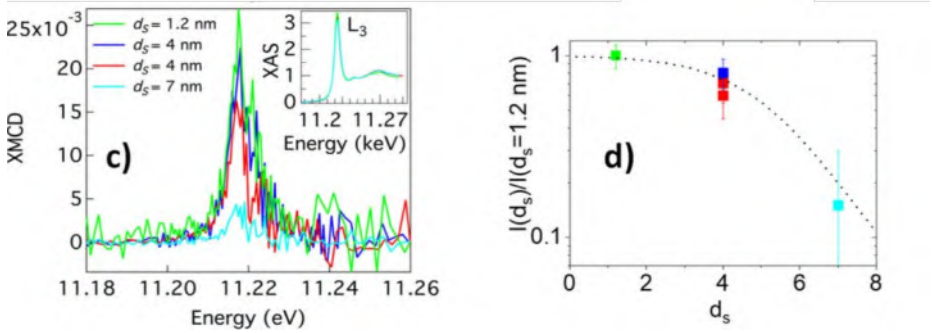


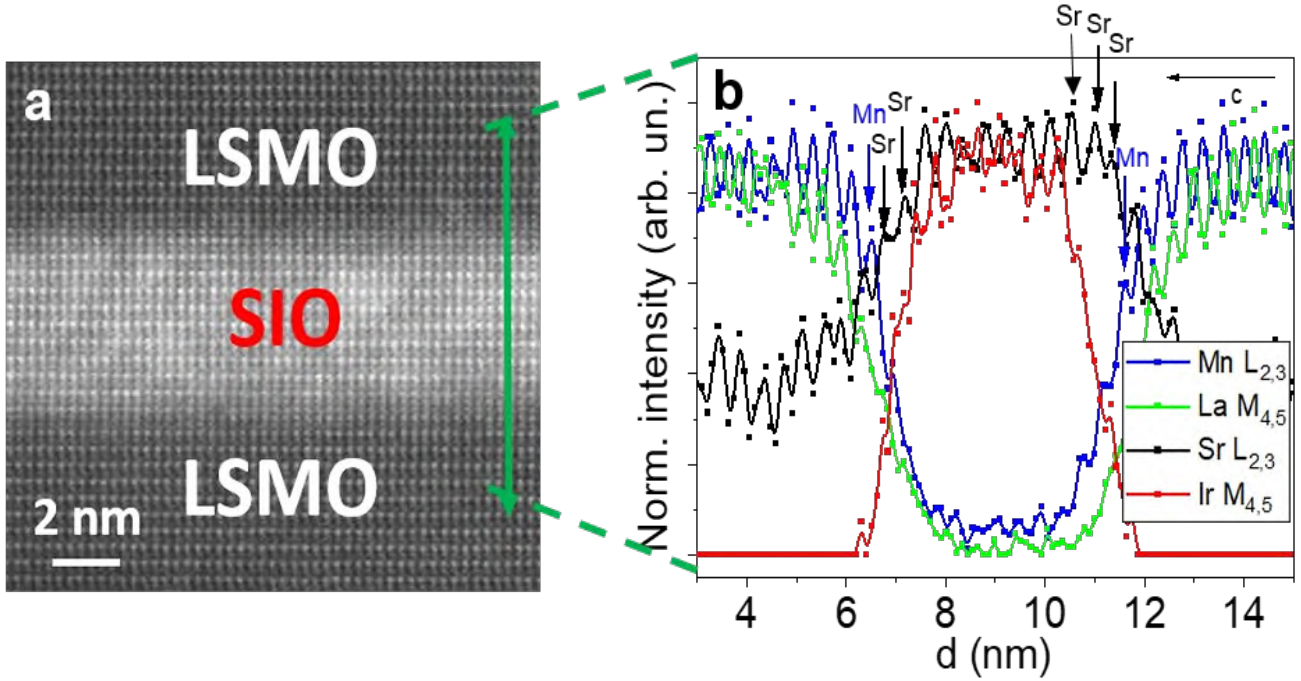


Nature Communications 12 (1), 3283 (2021)

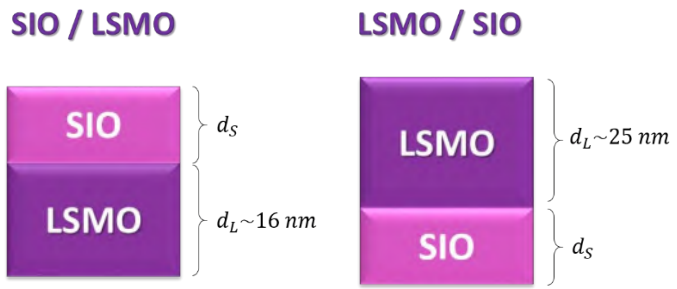
STEM EELS @ UCM
M. Cabero

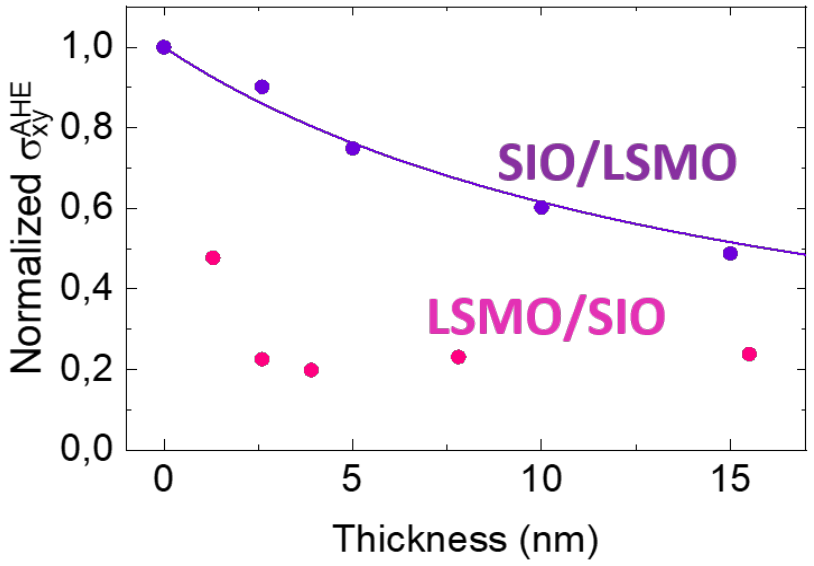




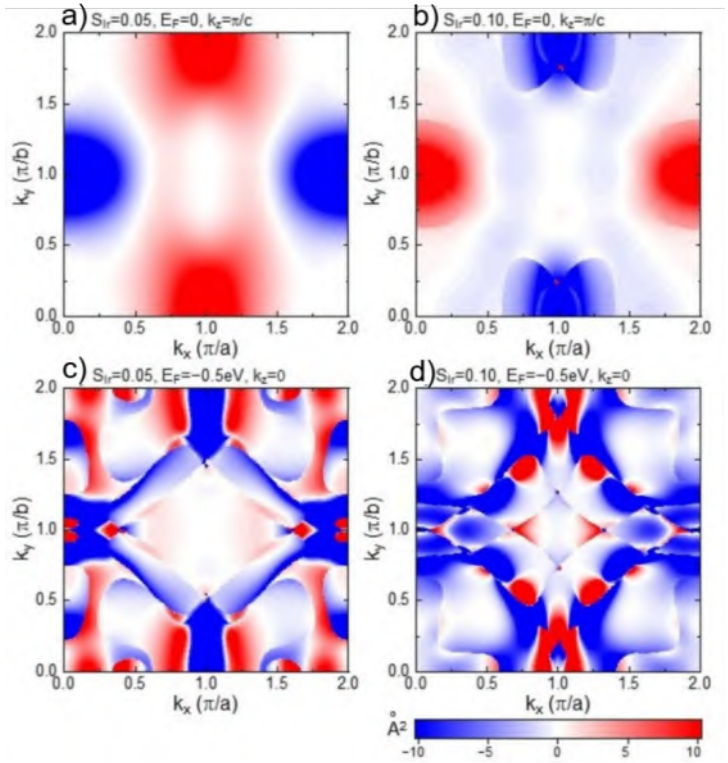


Nature Communications 12 (1), 3283 (2021)





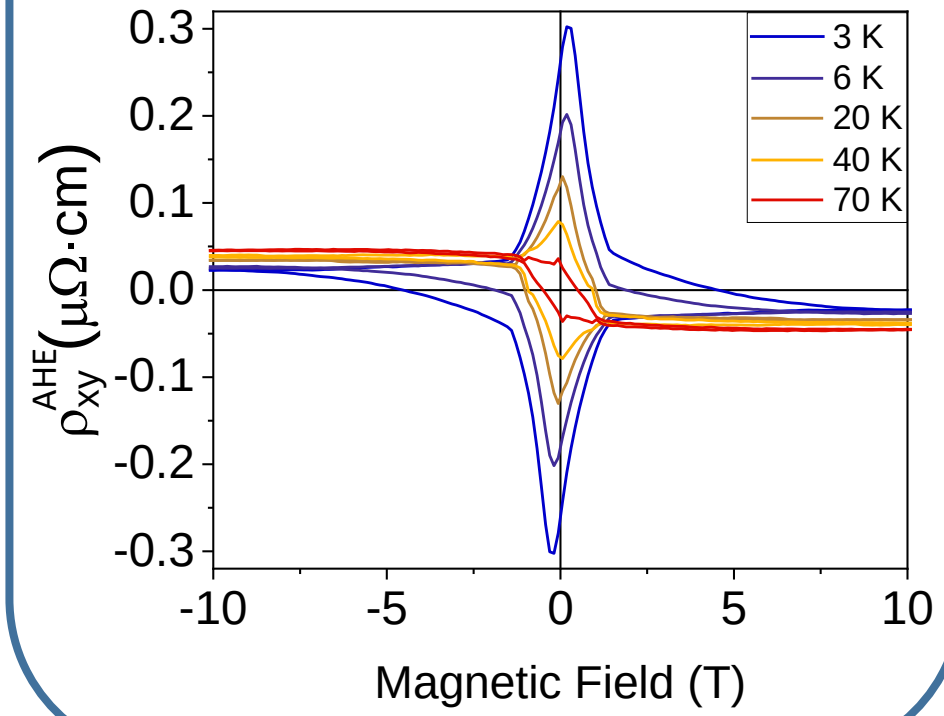
Berry curvature
S. Okamoto, E. Dagotto @ ORNL



Nature Communications 12 (1), 3283 (2021)

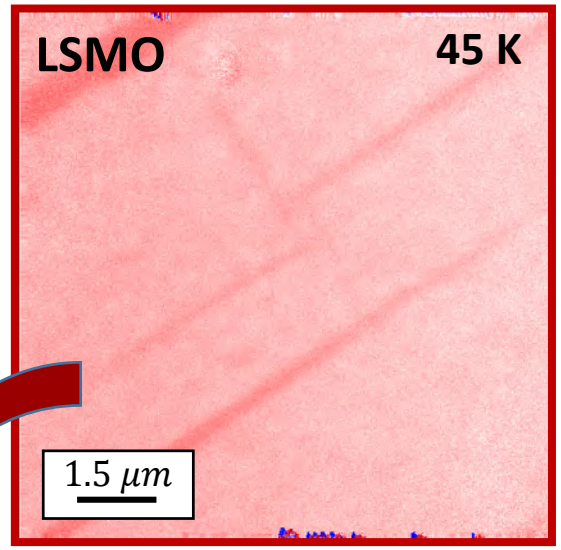
THE and MFM/PEEM images

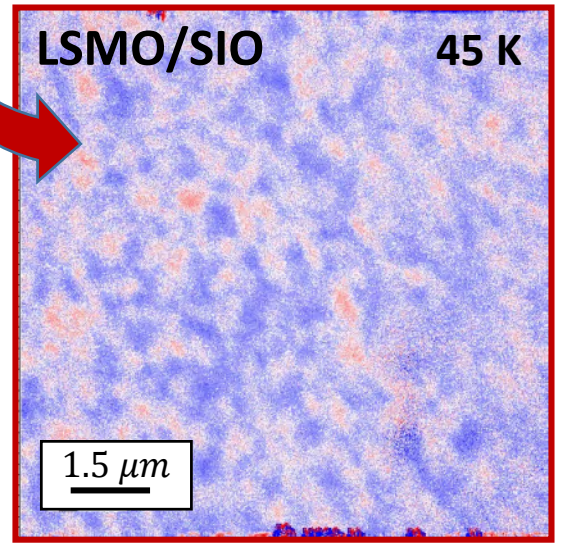
Topological peak at a wide range of temperature



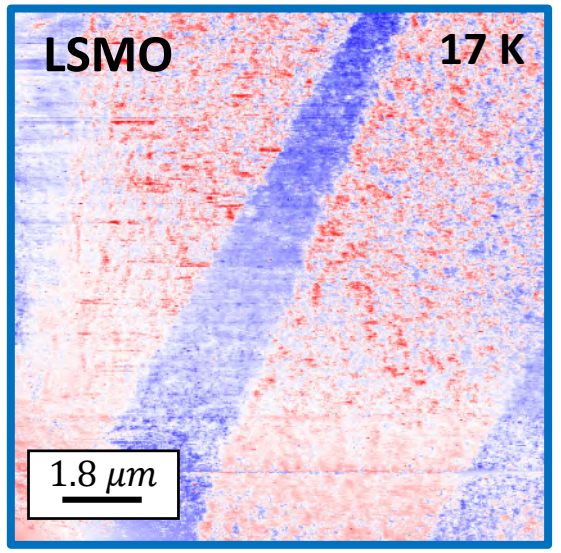
Emergence of magnetic textures

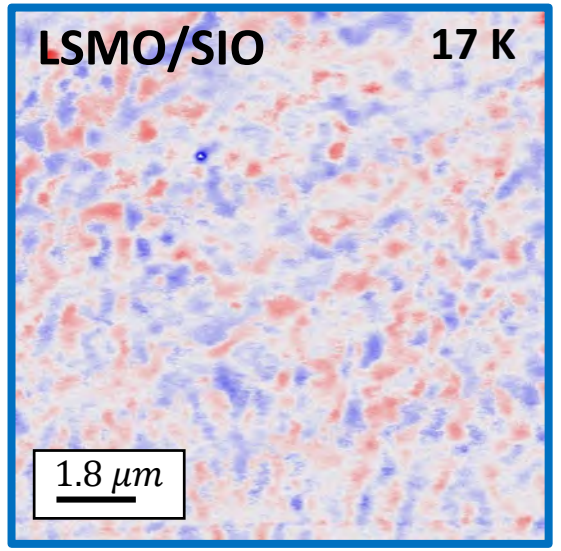
PEEM





MFM



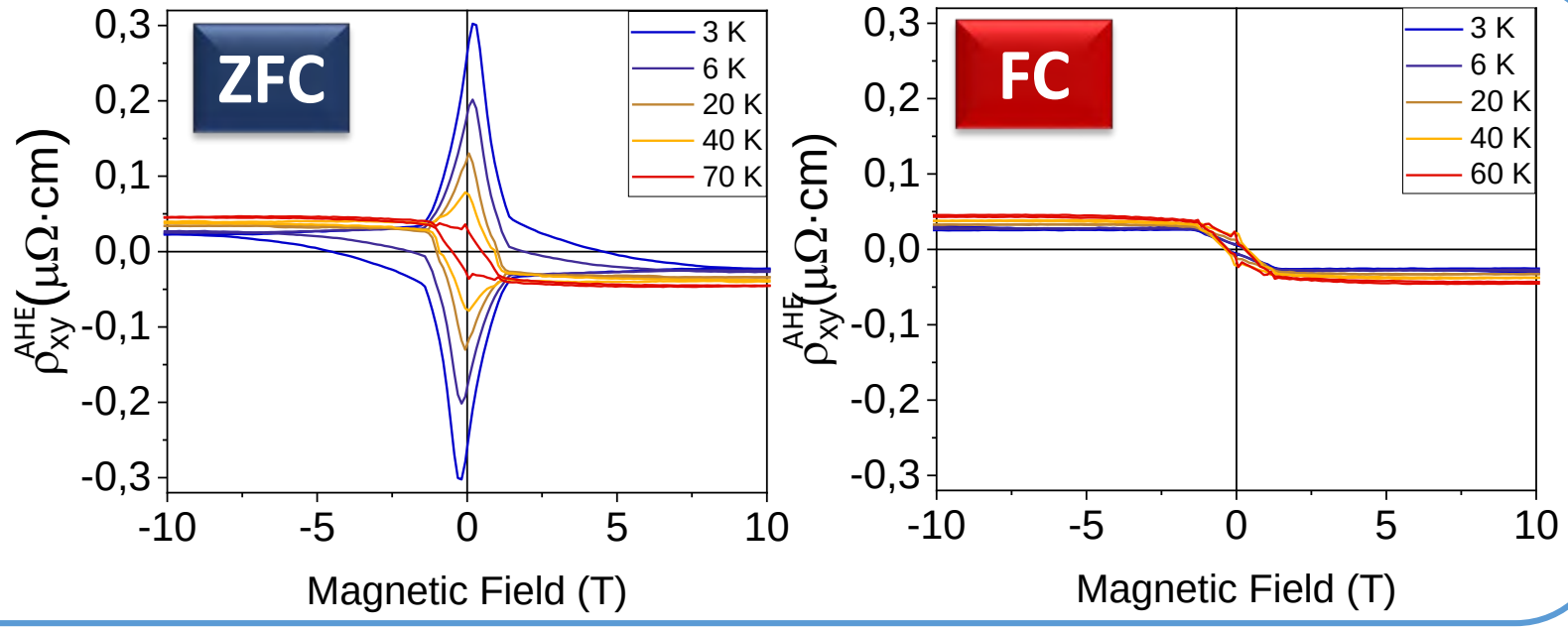


Zero Field Cool / Field Cool

(ZFC) Zero field cooling -> Cooling from 300 K to 2 K at 0T
(FC) Field cooling -> Cooling form 320 K to 2 K at 14T

The THE disappear after field cooling (FC)

FC -> Anomalous Hall effect expected in LSMO



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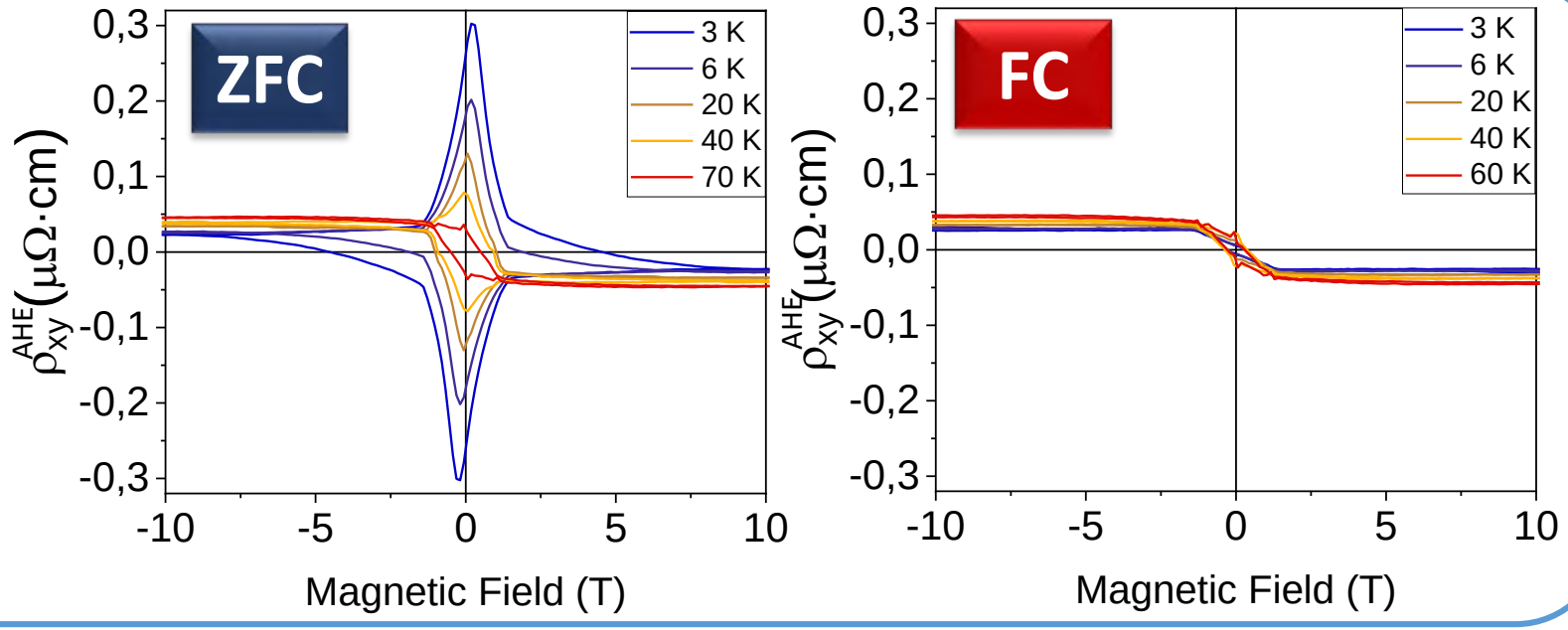
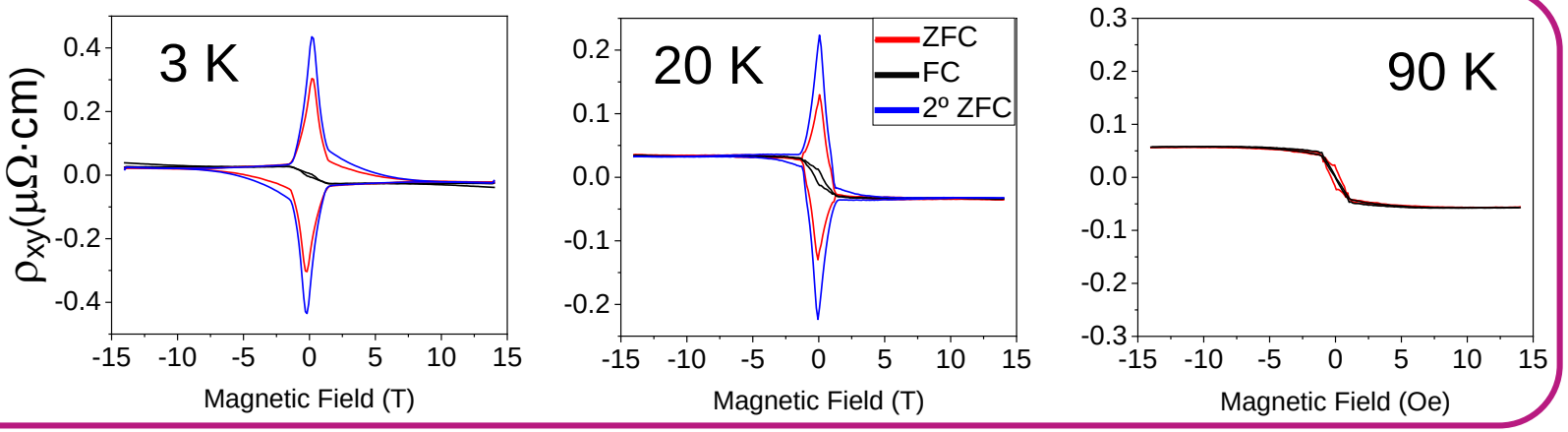
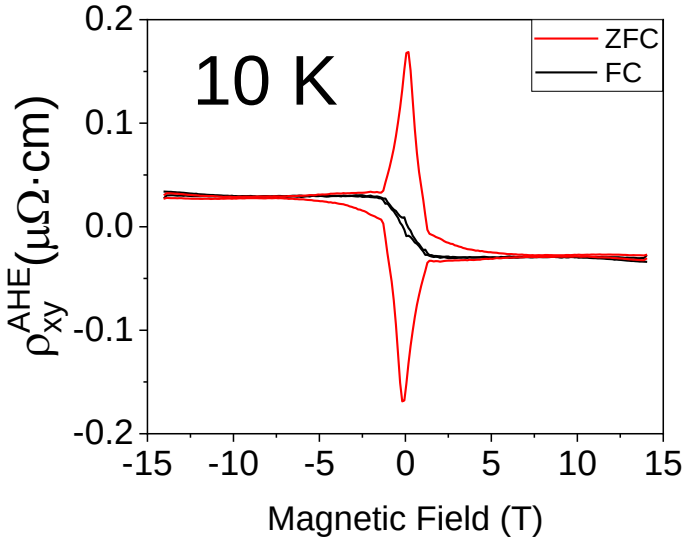
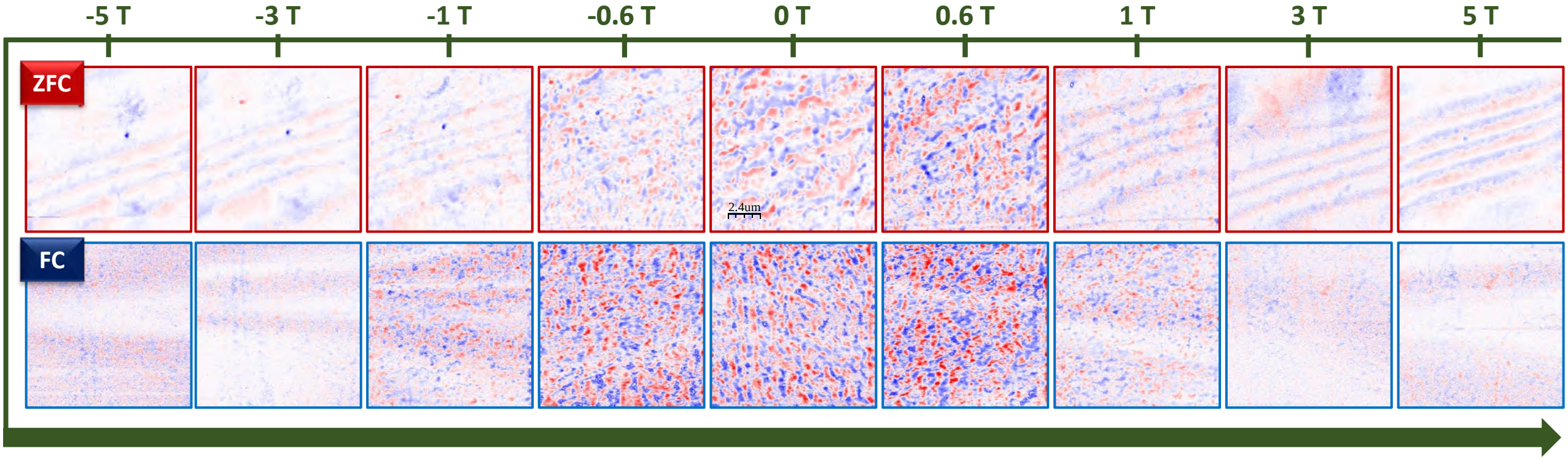


After second ZFC we recover THE

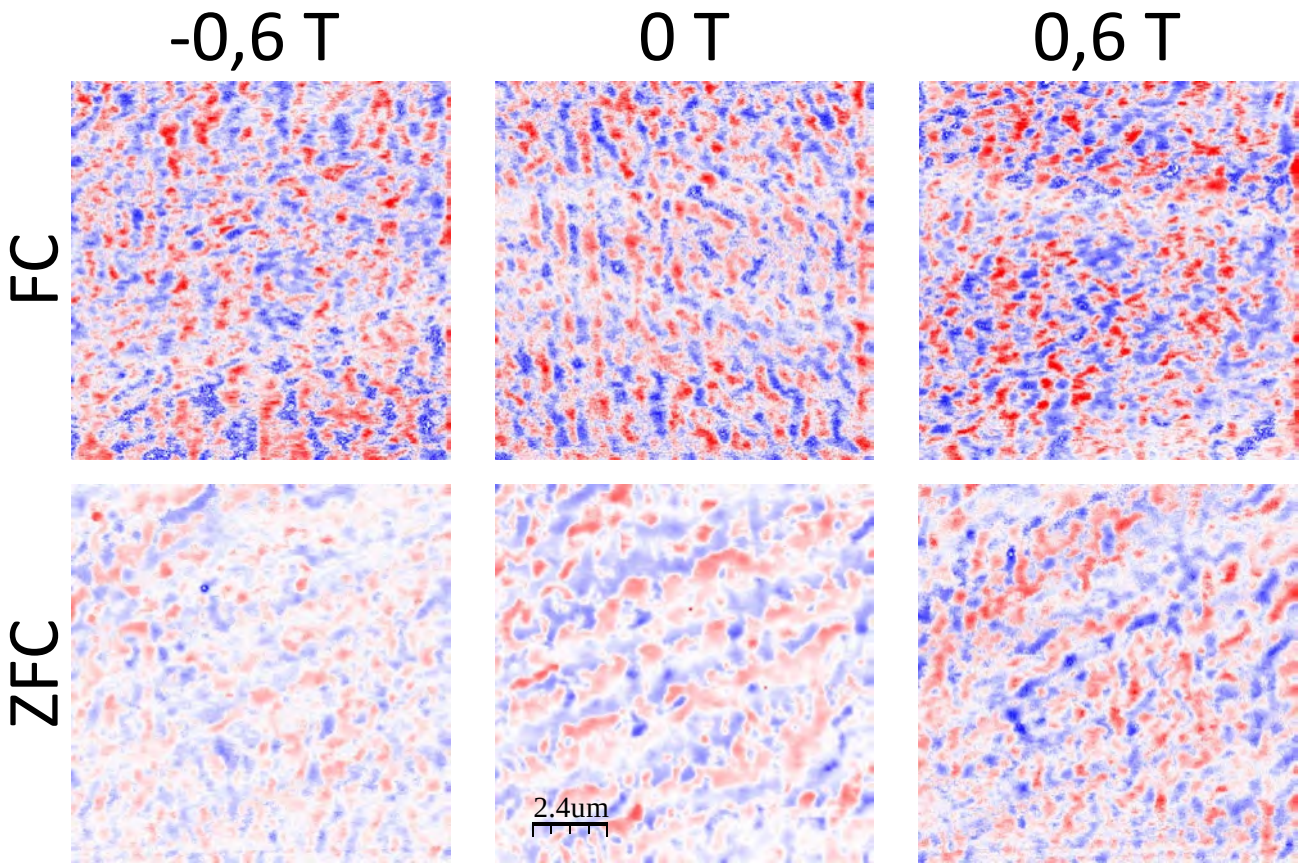


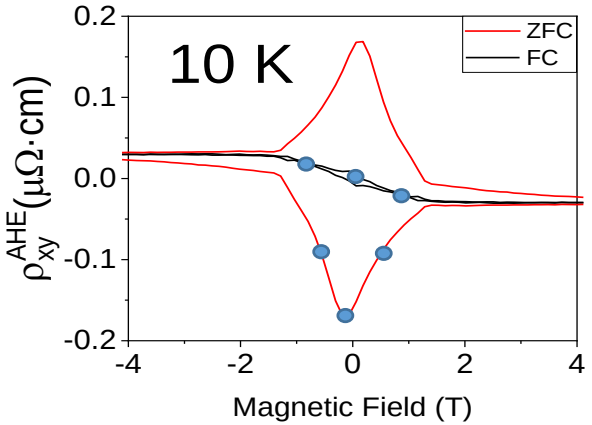
MFM study in ZFC/FC

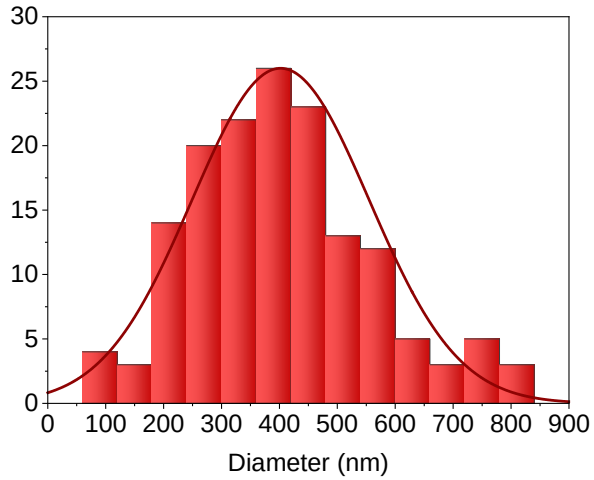




MFM study in ZFC/FC: size analysis







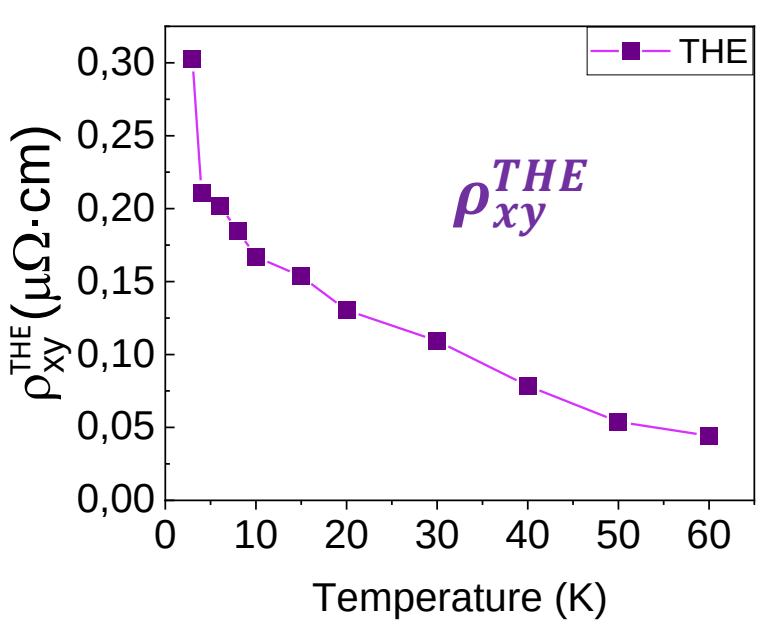
Transport measurements

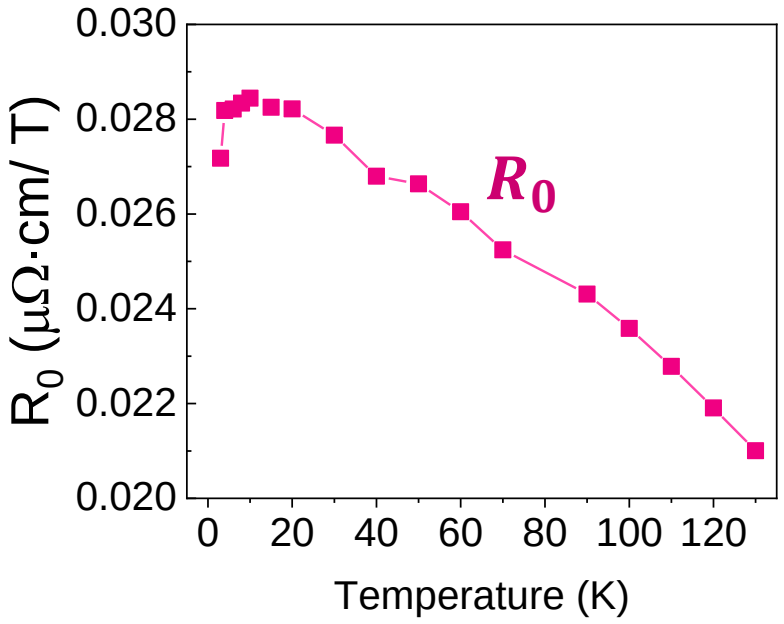
Unexpected dependence of the topological peak with the temperature

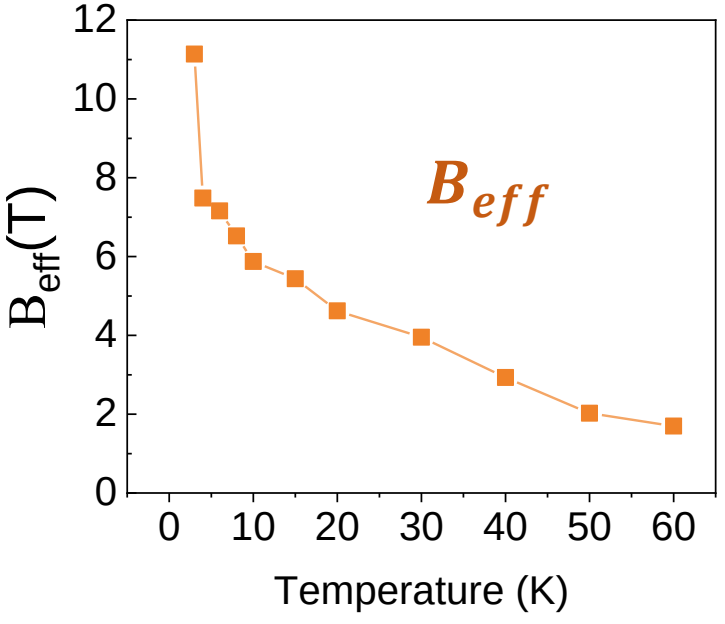
In the reported skyrmion systems, topological Hall resistivity is temperature-independent

N. Kanazawa et al. Phys. Rev. Lett. **106**, 156603 (2011)

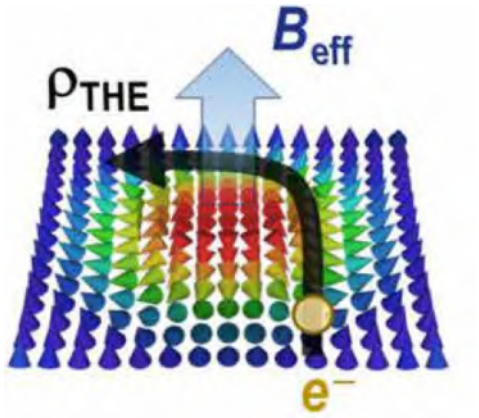
$$\rho_{xy}^{THE} = R_0 \cdot B_{eff}$$

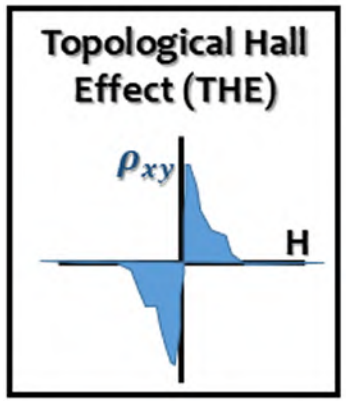






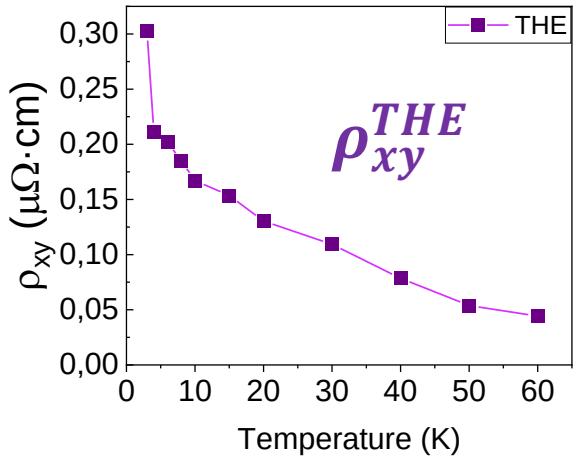
Skyrmion diameters estimated from THE smaller than actual (MFM) size

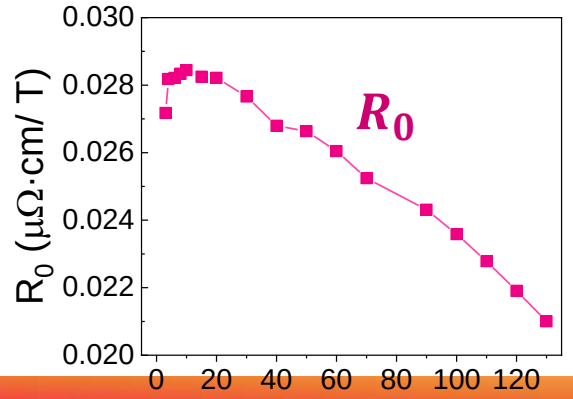




$$\rho_{xy}^{\mathrm{THE}} = PR_0B_{\mathrm{eff}} = PR_0n_{\mathrm{sk}}\Phi_0$$

P. Bruno, V. K. Dugaev, M. Taillefumier, Phys. Rev. Lett. 93, (2004)



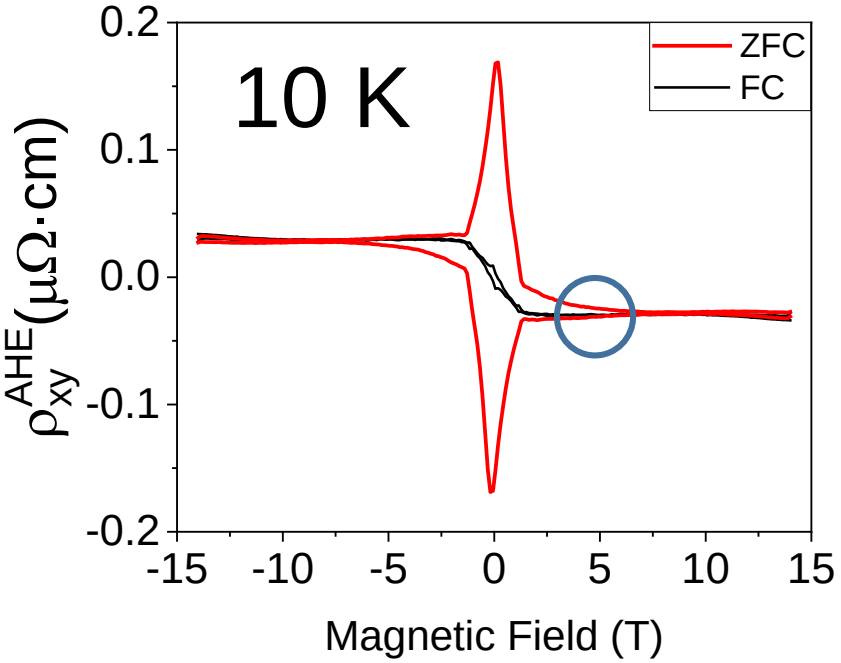


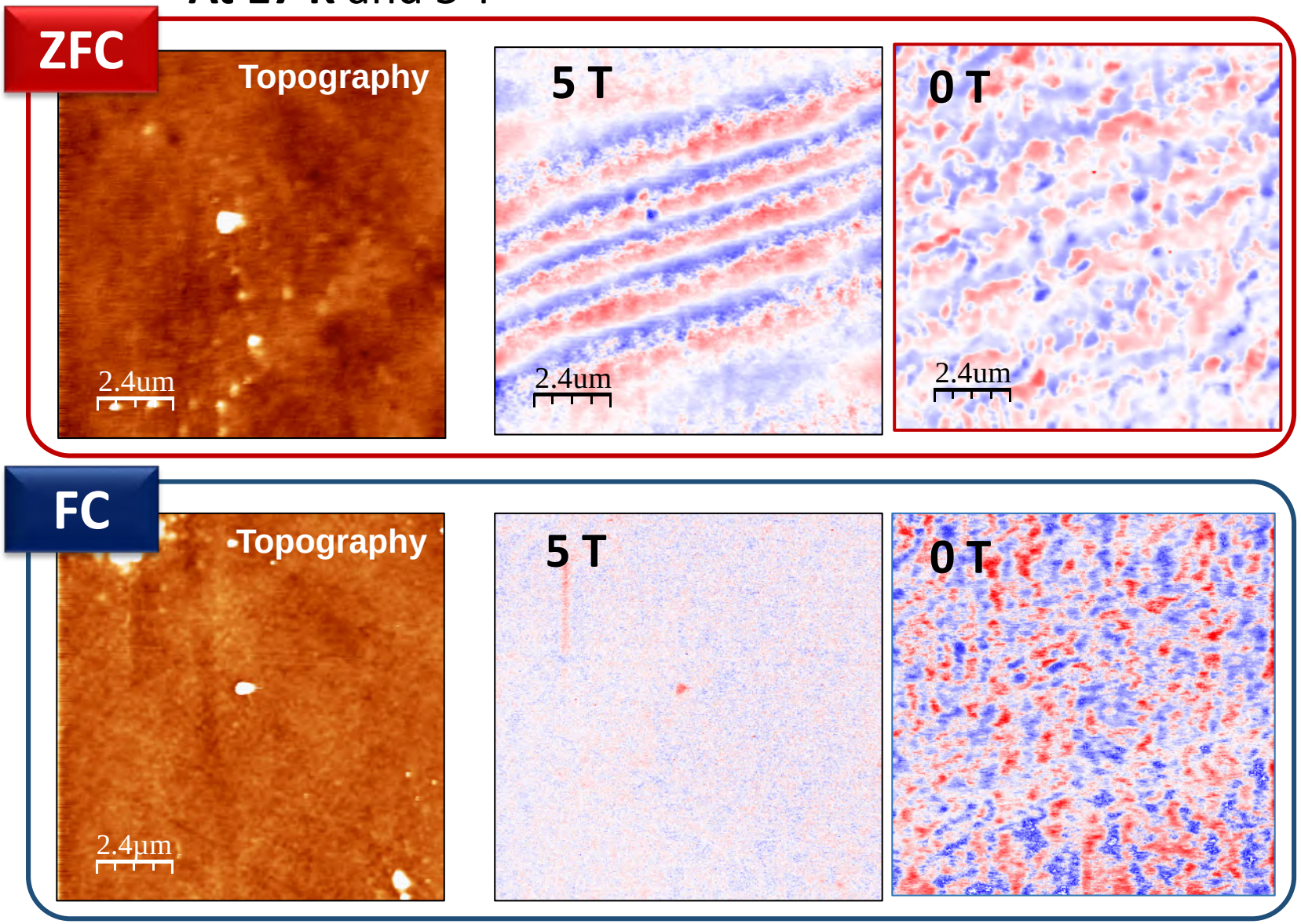
Temperature (K)	Diameter (nm)
3	18
4	22
6	23
8	24
10	25
15	26
20	28
30	31
40	36
50	43
60	47

MFM study at ZFC/FC

Spiral features at the origin of THE

At 17 K and 5 T





Conclusions

- **We have found a giant THE in LSMO/SIObilayers which is tunable with magnetic history (FC/ZFC).**

- **We propose that the origin of THE are the magnetic textures with chiral boundaries endowed by spin spirals driven by DMI.**

General Conclusions

- **TMO can be combined in highly perfect interfaces.**

- **Variety of different groundstates can be brought into direct contact (oxitronic effects): We have shown a long range Josephson effect in a half metallic ferromagnetic weak link which signals a path towards superconducting spintronics**

- **Spin orbit interaction of 5d oxides couples symmetry breaking electric fields to the electronic structure.**

- **We have shown interfacial DMI in 3d/5d heterostructures drives the nucleation of chiral domzin boundaries yielding very large THE.**