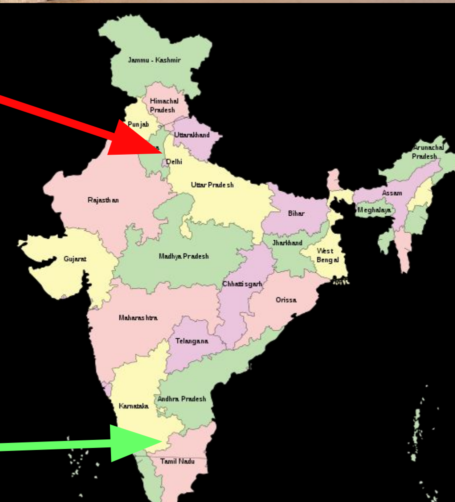
Institute of Nano Science and Technology, India

Suvankar Chakraverty

Dept. of Science and Technology
Govt. of India

~2,500Km



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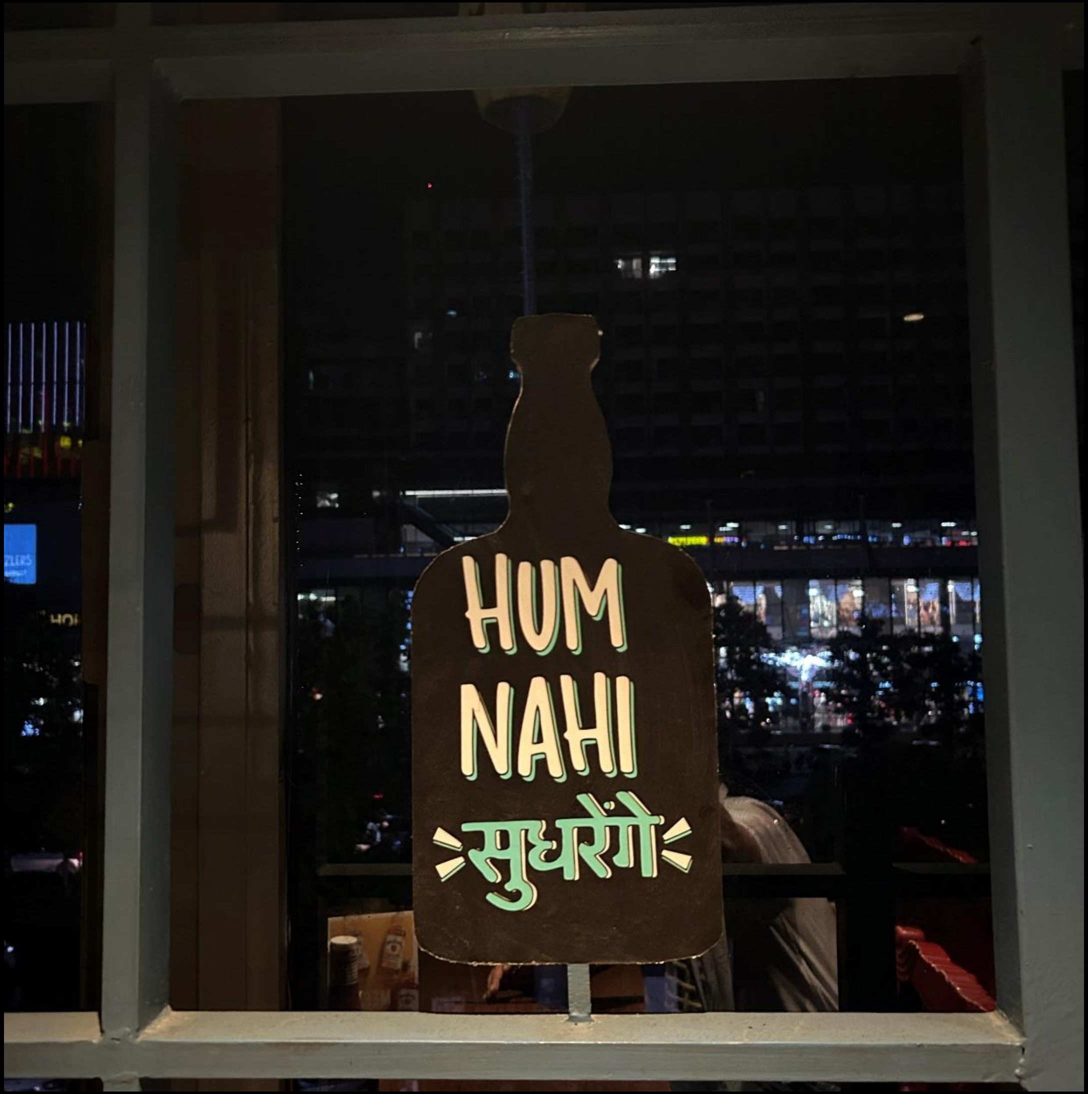
HUM
NAHI
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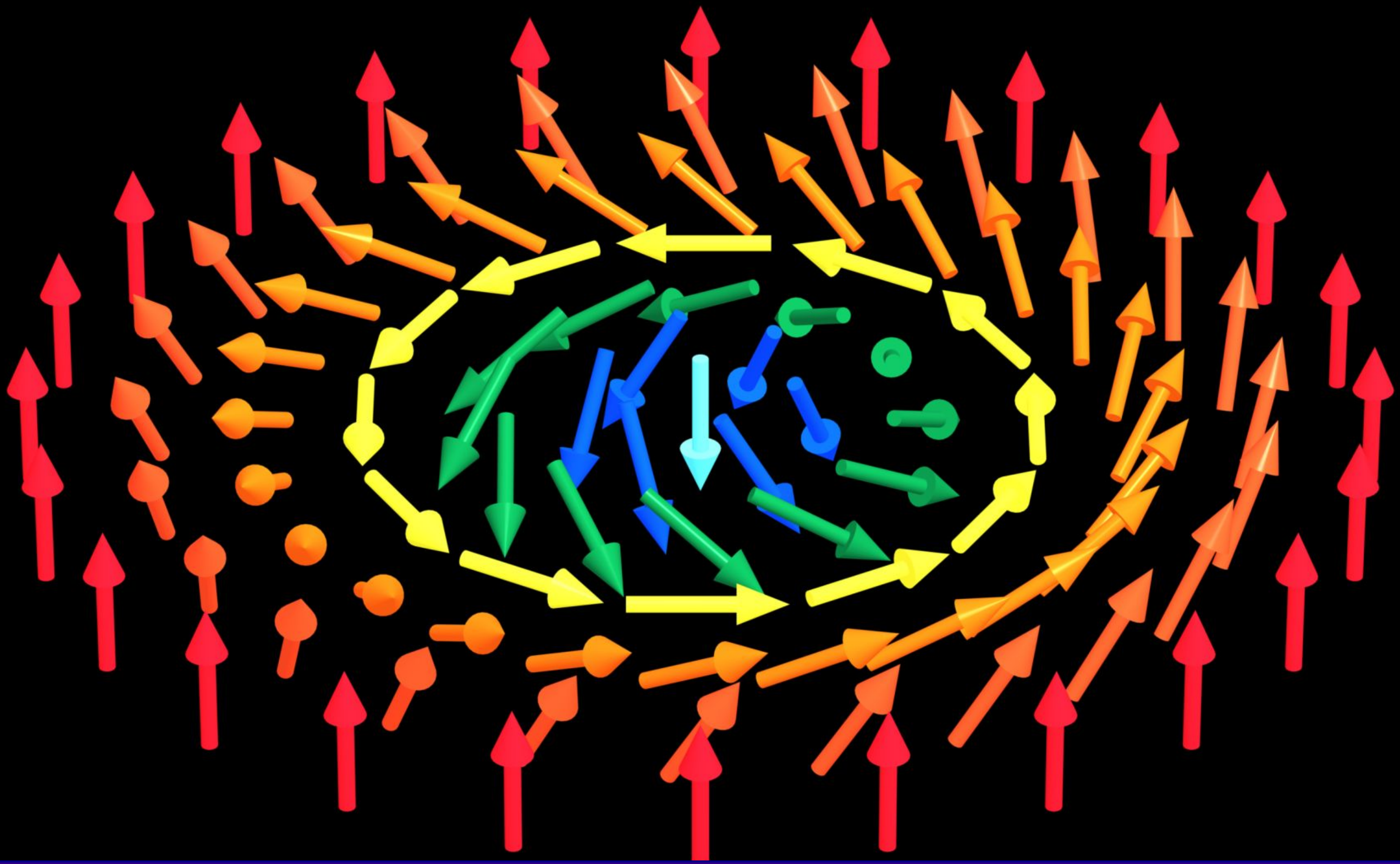
Spin polarization and topological Hall effect: Oxide interfaces and thin films



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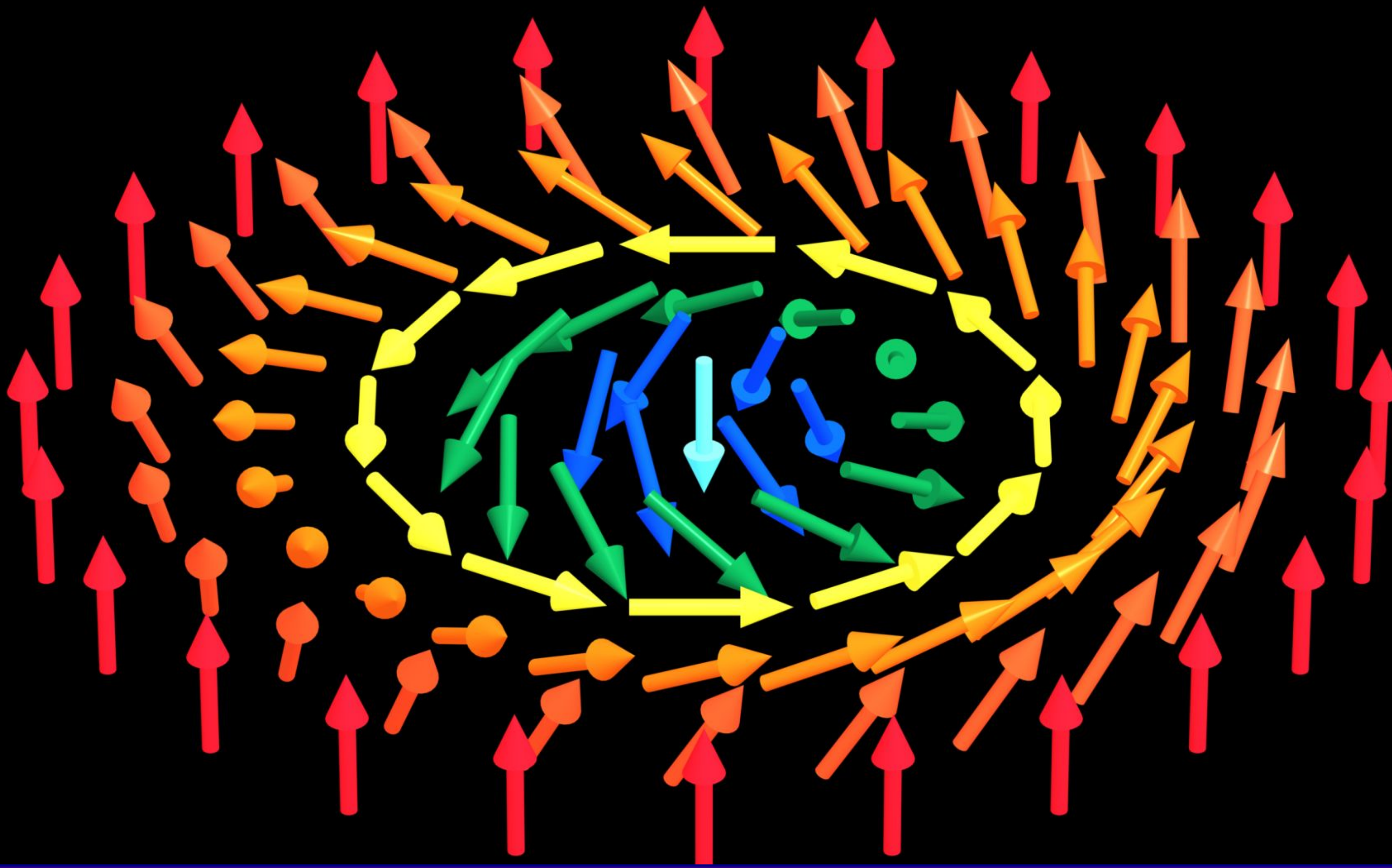
Topological effect: Oxide interfaces and thin films



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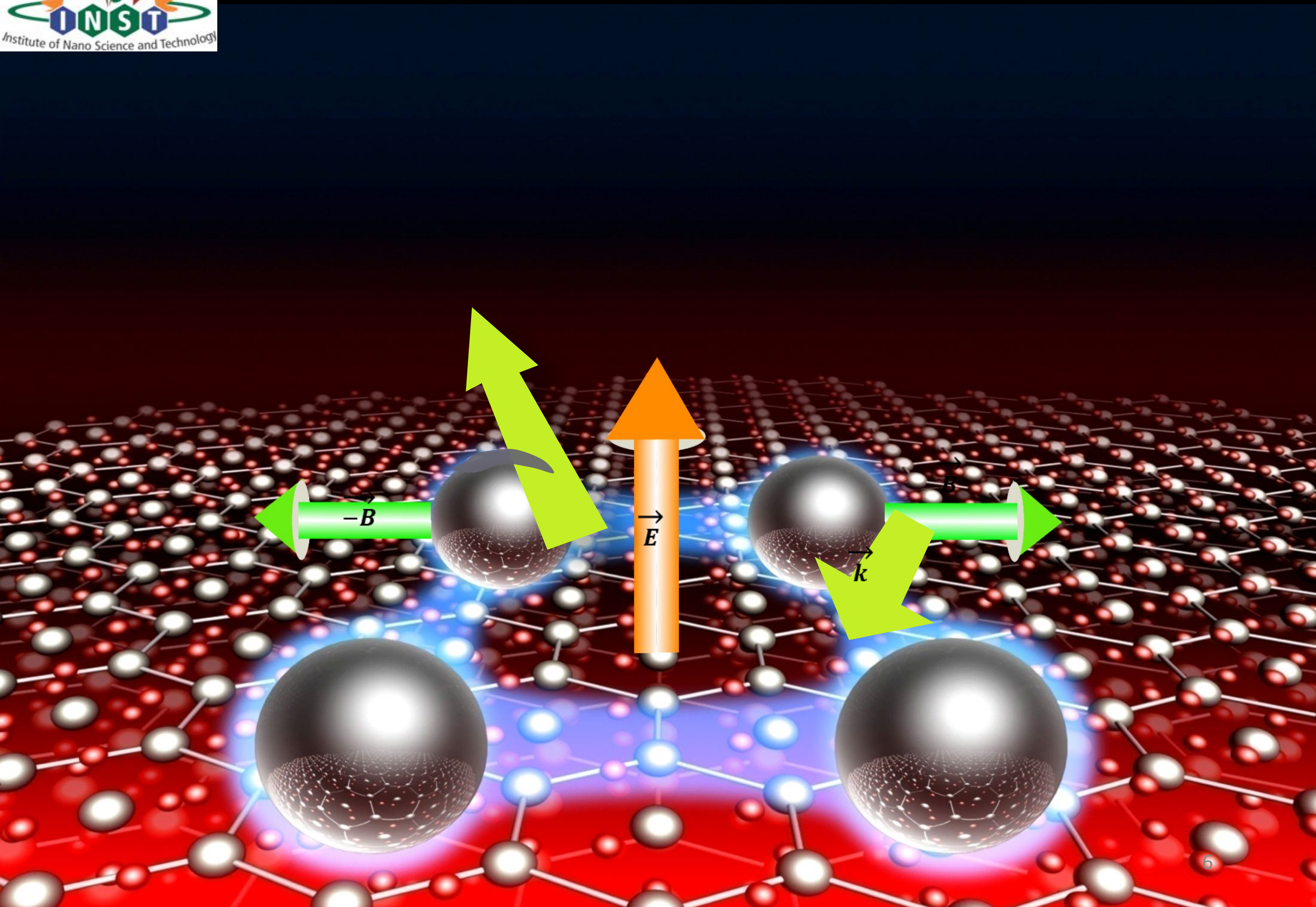
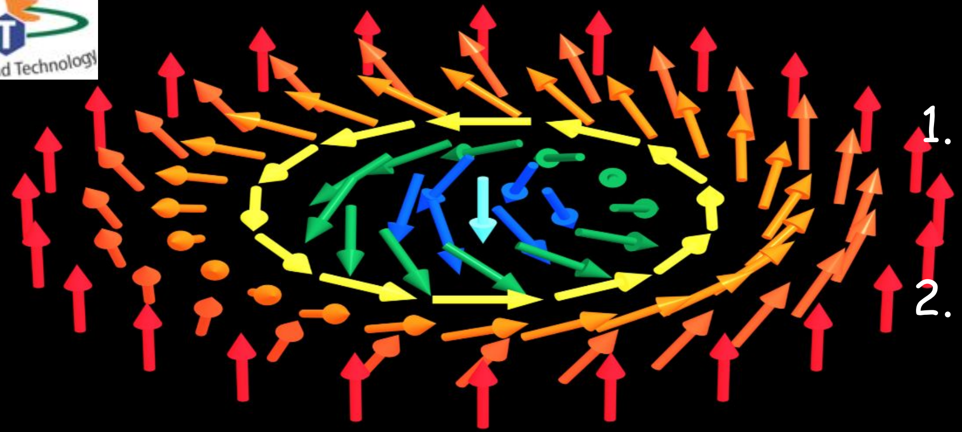
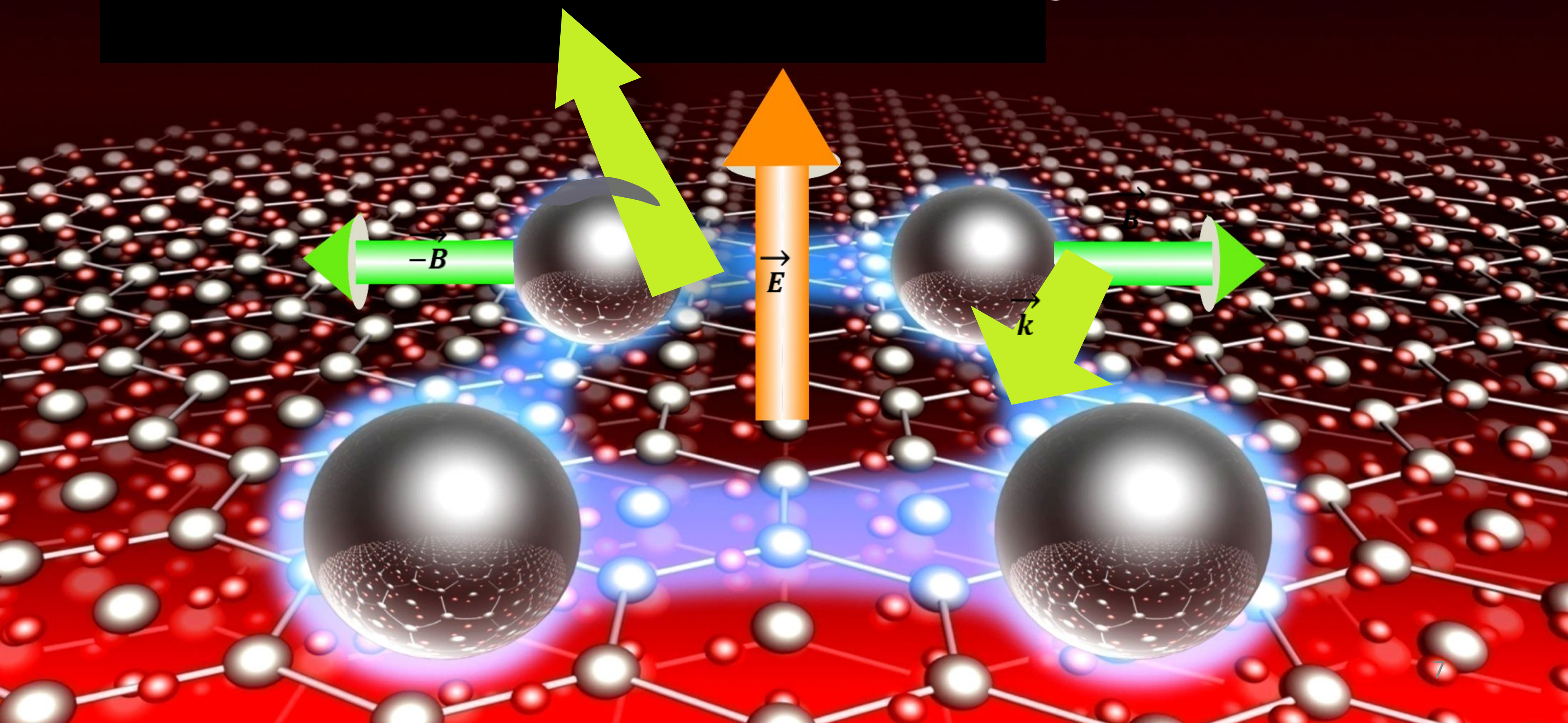
नैनो विज्ञान एवं प्रौद्योगिकी संस्थान
INST
Institute of Nano Science and Technology





1. If this spin texture is in the real space: Signature in transverse-resistance (Hall)
2. If this spin texture is in the momentum space: Signature in longitudinal-resistance (MR)



Acknowledgements

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IISc Bangalore

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- Prof. Sushanta Dattagupta

IIT Kanpur

- Amit Agarwal

BARC

- Prof. S. Singh

IIT Roorkee

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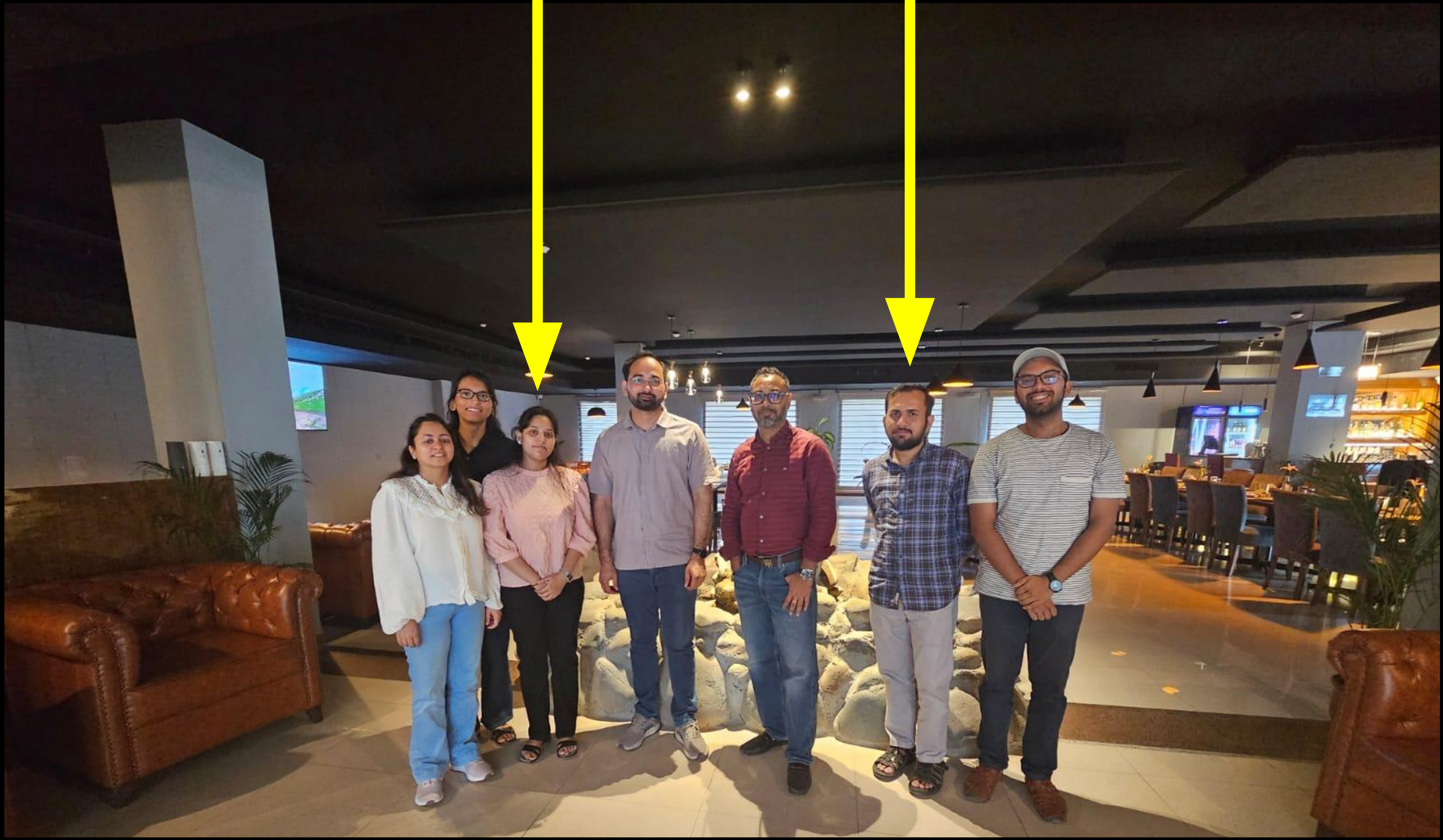
MPI
Stuart Parkin

Nand Kumar
University of Naples

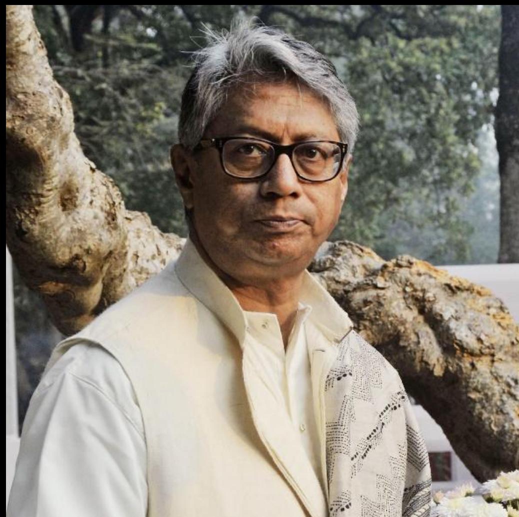
Manish
TIFR

Harsha

Bibek



Theory



Sushanta Dattagupta

Sanjeev Kumar and his group members

Amit Agarwal and his group member

Priya Mahadevan and her group member

Out line of the talk

Grow a oxide thin film using pulsed laser deposition system: Effect of laser fluence

Materials : 1. $LaVO_3$-$SrTiO_3$ interface
2. Sr_2FeMoO_6 thin films

Unusual Quantum oscillation in resistance : Non-trivial spin texture in momentum space

Material : $LaVO_3$ – $KTaO_3$ interface

Looking at longitudinal conductivity ?

Unusual magneto-transport: negative MR, Anomalous Hall, Topological Hall

Material : 1. $LaFeO_3$ – $SrTiO_3$ interface
2. W: SFMO

Grow a oxide thin film using pulsed laser deposition system: Effect of laser fluence

FULL PAPER

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Conducting $LaVO_3/SrTiO_3$ Interface: Is Cationic Stoichiometry Mandatory?

Ruchi Tomar, Rahul Mahavir Varma, Nand Kumar, D. D. Sarma, Denis Maryenko, and Suvankar Chakraverty**

ACS APPLIED ELECTRONIC MATERIALS

pubs.acs.org/acsaelm Letter

B-Site Stoichiometry Control of the Magnetotransport Properties of Epitaxial Sr_2FeMoO_6 Thin Film

Nand Kumar, Raveena Gupta, Ripudaman Kaur, Daichi Oka, Sonali Kakkar, Sanjeev Kumar, Surendra Singh, Tomoteru Fukumura, Chandan Bera, and Suvankar Chakraverty*

Unusual Quantum oscillation in resistance : Non-trivial spin texture in momentum space

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-14689-z OPEN

Check for updates

Planar Hall effect and anisotropic magnetoresistance in polar-polar interface of $LaVO_3$-$KTaO_3$ with strong spin-orbit coupling

Neha Wadehra[1], Ruchi Tomar[1], Rahul Mahavir Varma[2], R.K. Gopal[3], Yogesh Singh[3], Sushanta Dattagupta[4] & S. Chakraverty[1]✉

PHYSICAL REVIEW B **104**, L081111 (2021)

Letter

Probing conducting interfaces by combined photoluminescence and transport measurements: $LaVO_3$ and $SrTiO_3$ interface as a case study

Anamika Kumari,[1] Joydip De,[2] Sushanta Dattagupta,[3] Hirendra N. Ghosh,[4] Santanu Kumar Pal,[2] and S. Chakraverty[1,*]

A few more And Struggling

Unusual magneto-transport: negative MR, Anomalous Hall, Topological Hall

PHYSICAL REVIEW B
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Letter

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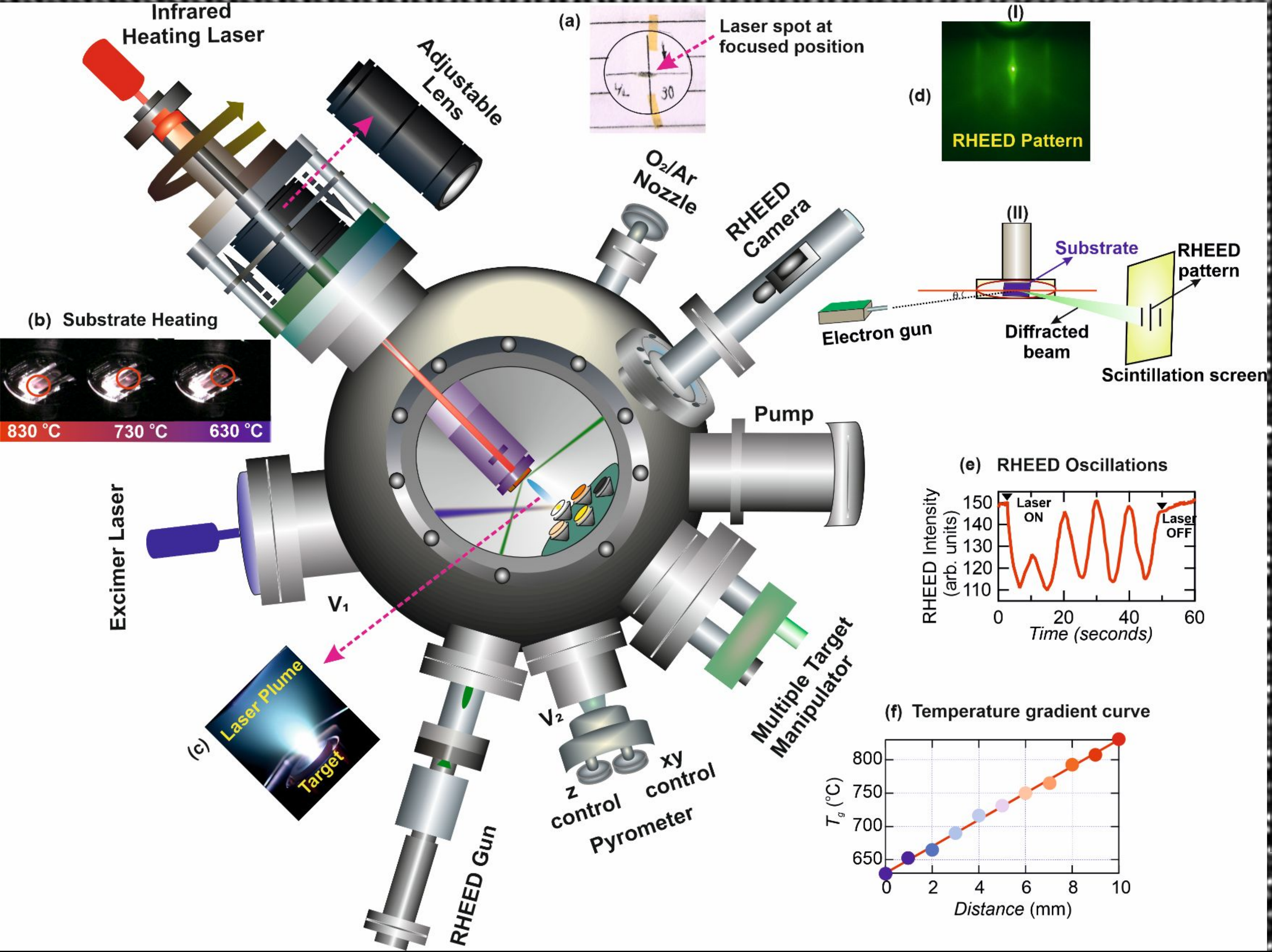
Room-temperature transparent oxide spin electronics: A conducting interface in $LaFeO_3-SrTiO_3$

Ripudaman Kaur, Anamika Kumari, Shinjini Paul, Mohd Anas, Bibek Ranjan Satapathy, Sanjeev Kumar, V. K. Malik, P. Mahadevan, D. D. Sarma, and Suvankar Chakraverty
Phys. Rev. B **109**, L201114 – Published 14 May 2024

To motivate my young research scholars towards PLD



Story by a 93.2% thin film grower

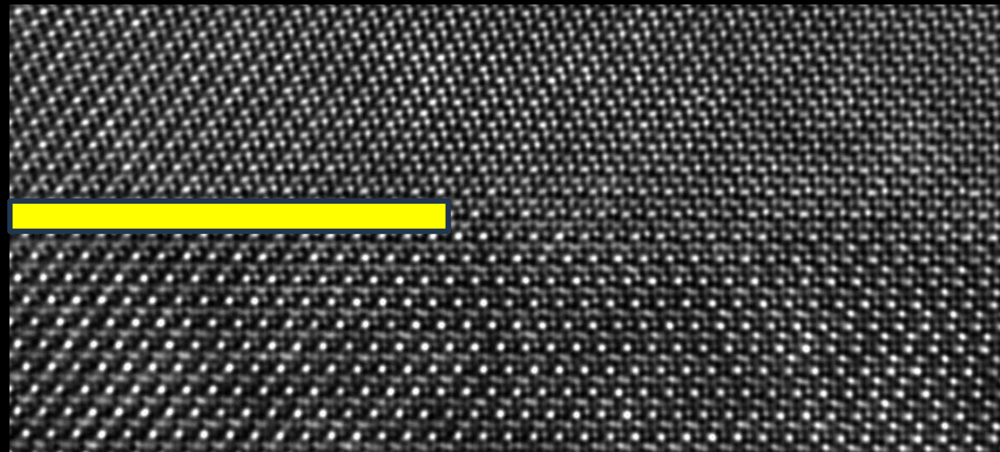
1000 thin film grown = 100% thin film grower

Advantage:

1. Epitaxy
2. Growth kinetics
3. Thermodynamics

Film

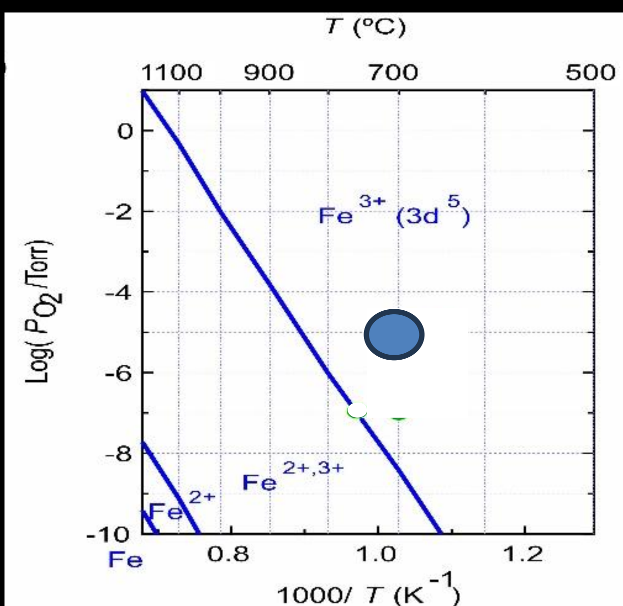
Substrate



Grow an Oxide thin film:

Thermodynamics

Ellingham Diagram



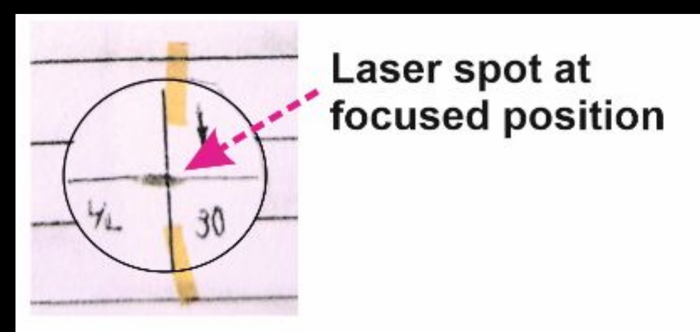
LaFeO3

Fe+3

Prescription:
Pressure ~E-5 Torr
Tg ~ 700C

Kinetics

Laser fluence



What and Why Perovskite Oxide?

General Formula:
ABO_3

A: Alkali- or rare-earth ion
B: Transition metal-ion

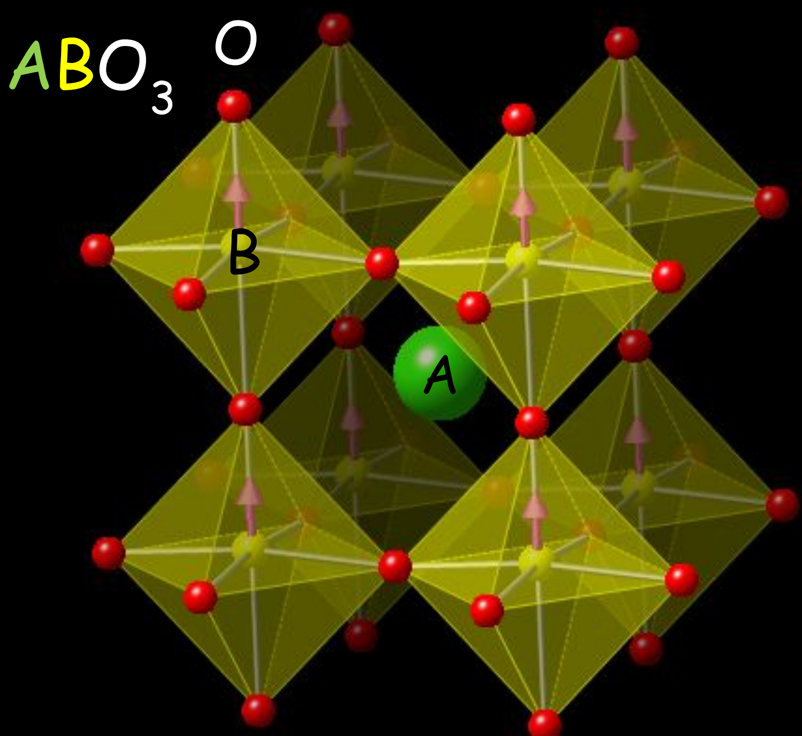
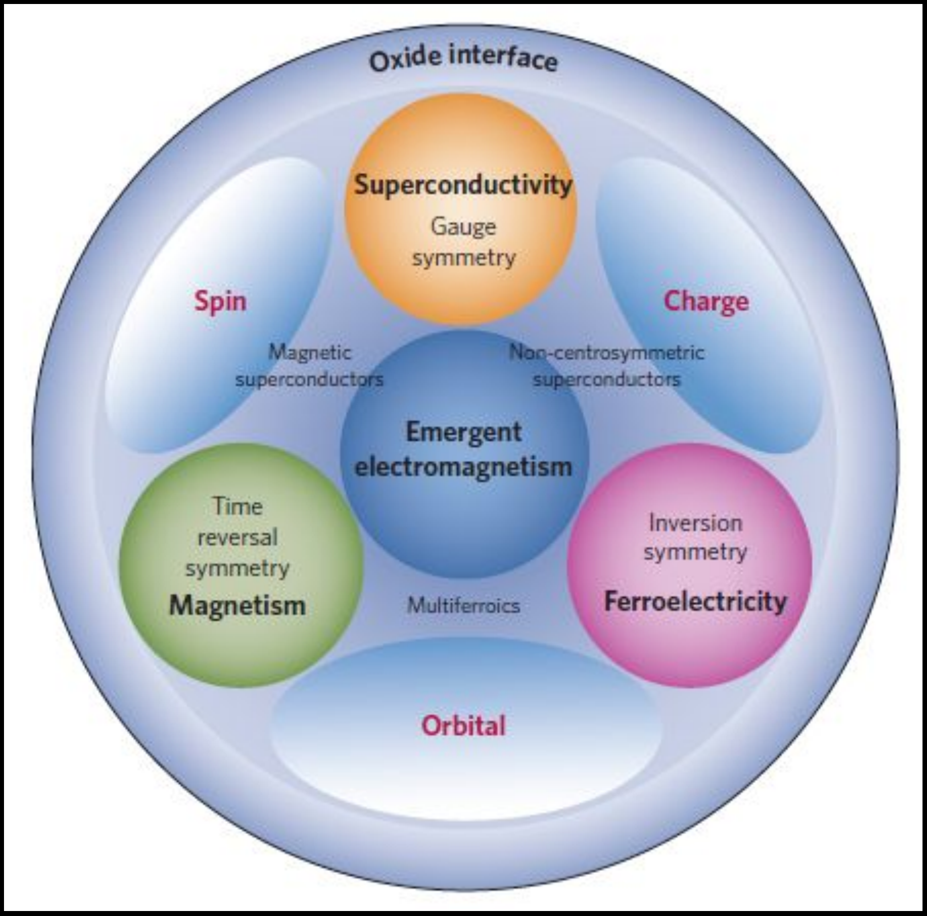


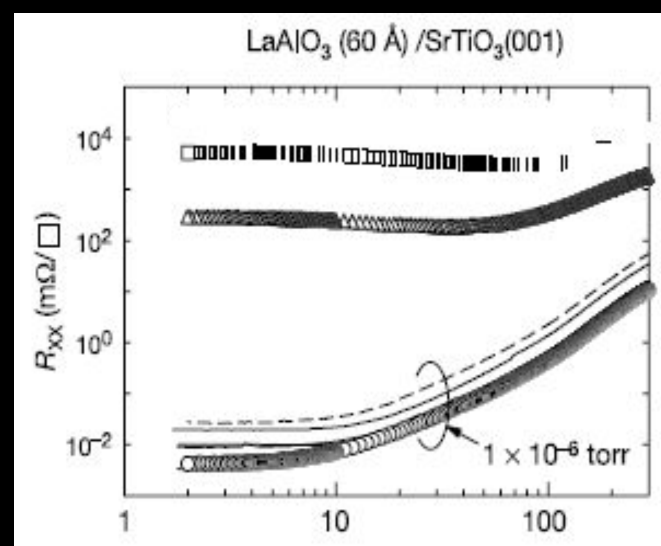
Exhibit the full spectrum of electronic, optical and magnetic properties



Hwang et al. Nat. Mater. 2012, 11, 103

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

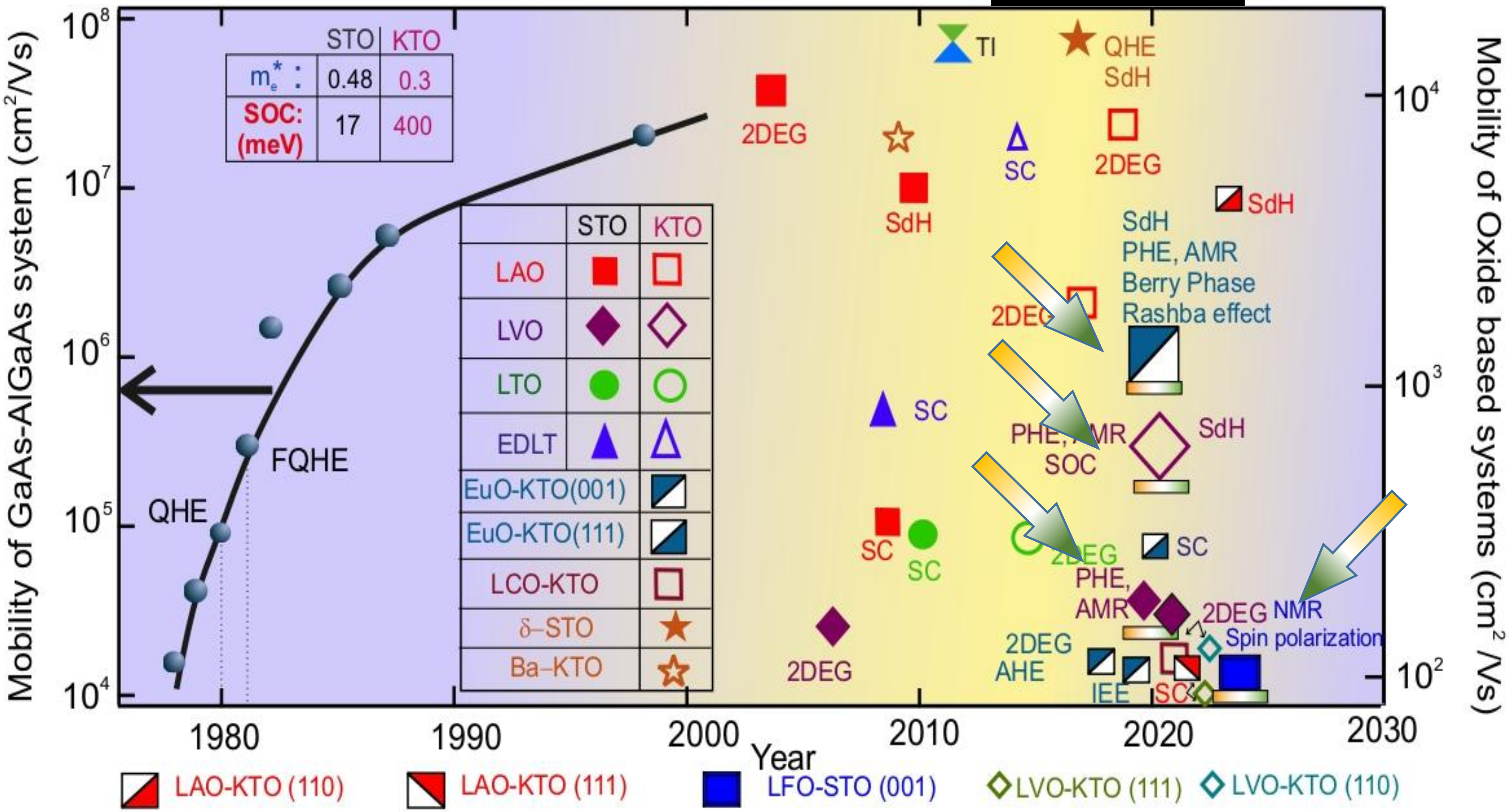
A. Ohtomo et. al. Nature 2004, 427, 423



STO Era Started

KTO Era Continue

STO Era Revised



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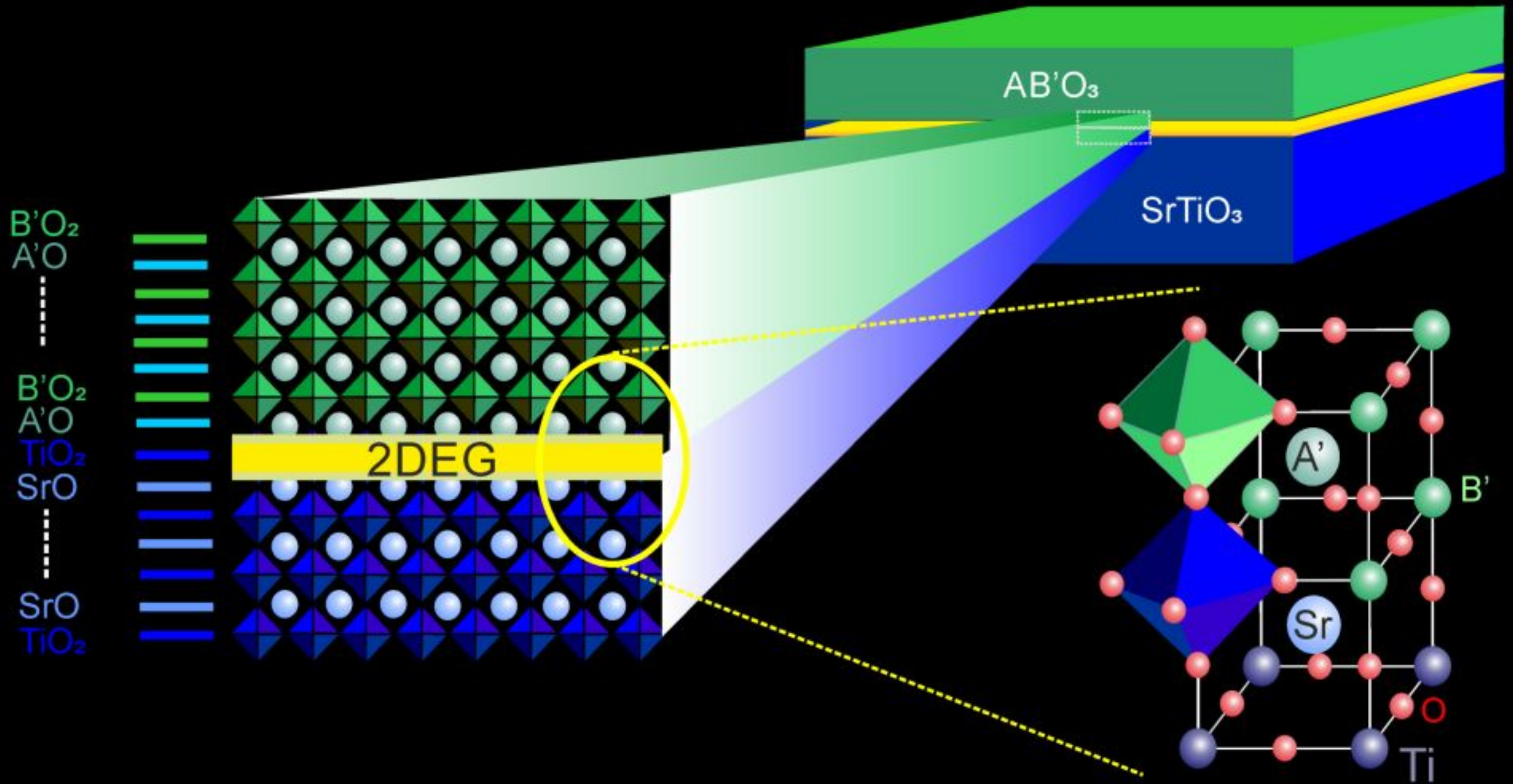
Possible mechanisms

1. Oxygen Vacancy.
2. Cation intermixing.
3. Polar Catastrophe.
4. Band alignment

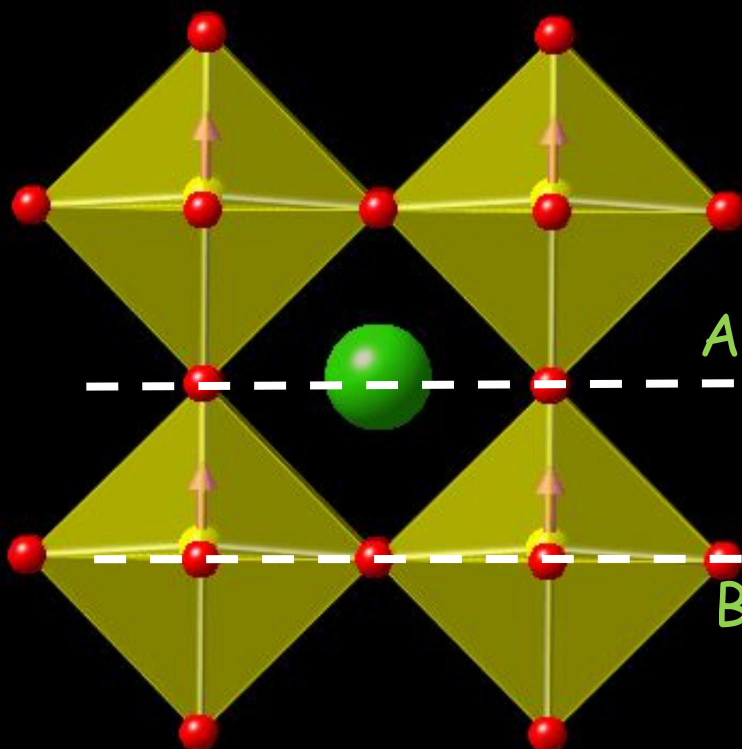
Effect of film stoichiometry?

Conducting interface of two insulating perovskite Oxides:
polar catastrophe !!!



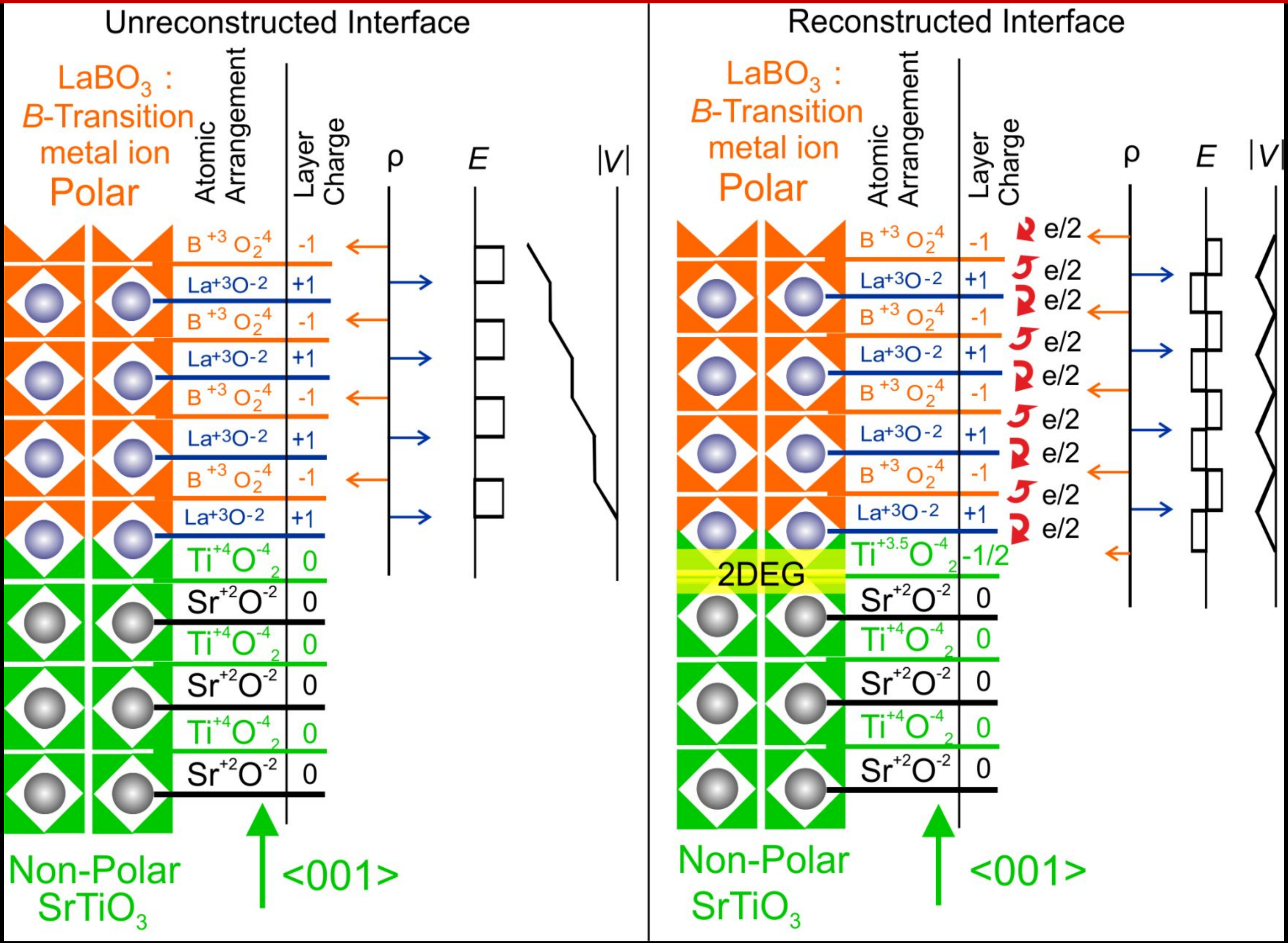
Interface of two insulating perovskite Oxides: Why Conducting???

ABO_3



	Non-Polar $A^{+2}B^{+4}O_3$ ($SrTiO_3$)		Polar $A^{+3}B^{+3}O_3$ ($LaAlO_3$)	
	Atomic Arrangement	Layer Charge	Atomic Arrangement	Layer Charge
AO	$Sr^{+2}O^{-2}$	0	$La^{+3}O^{-2}$	+1
BO_2	$Ti^{+4}O^{-4}$	0	$Al^{+3}O^{-4}$	-1

Conducting interface of two insulating perovskite Oxides: polar catastrophe !!!



Polar Catastrophe : 1. ½ electron per unit cell at the interface
2. A critical thickness of film is needed

0. Why Such interfaces are conducting???

FULL PAPER

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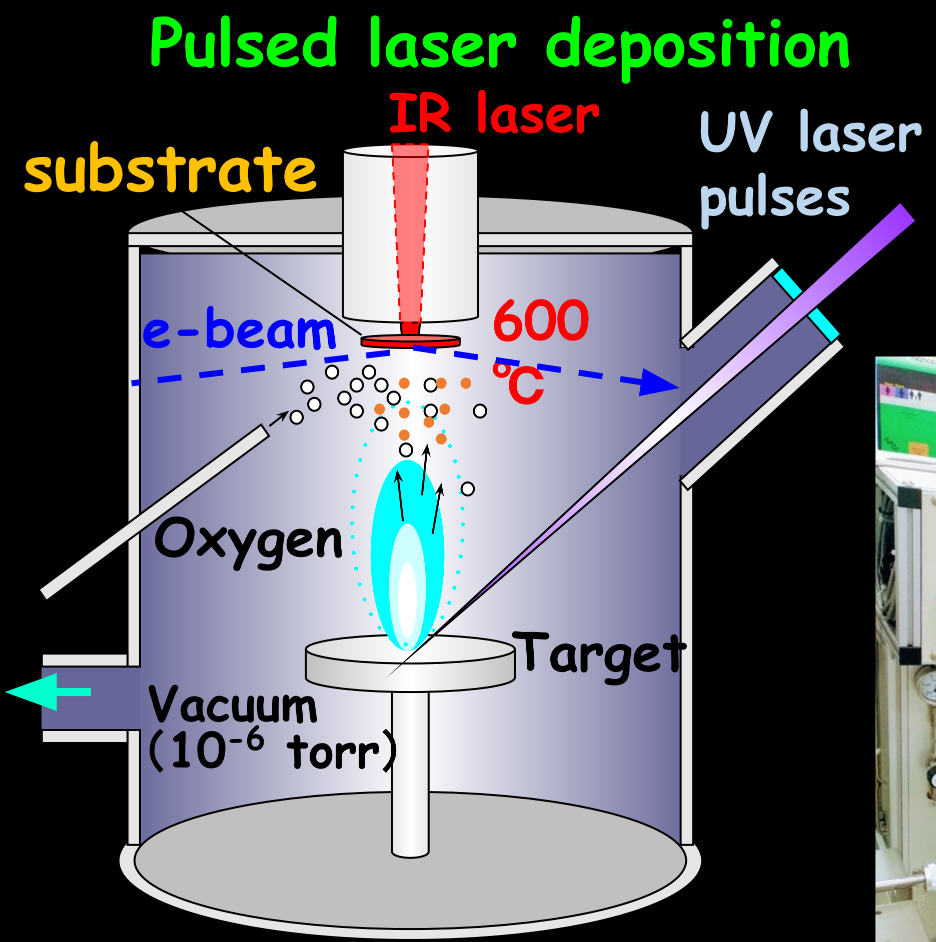
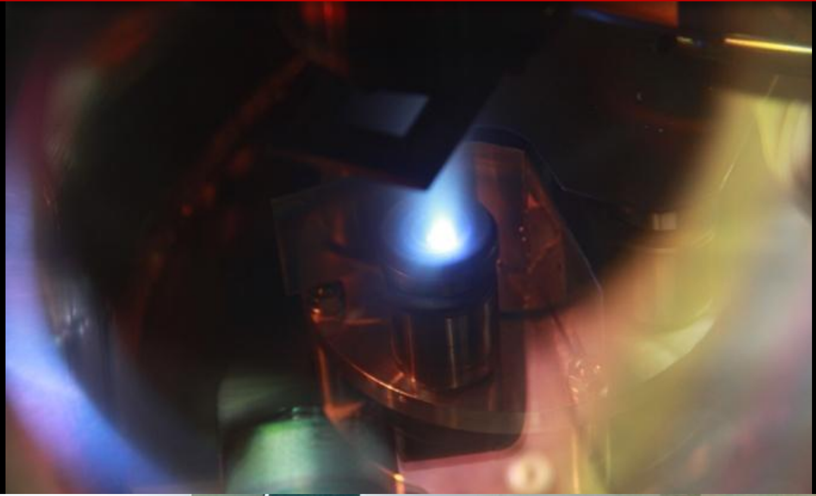
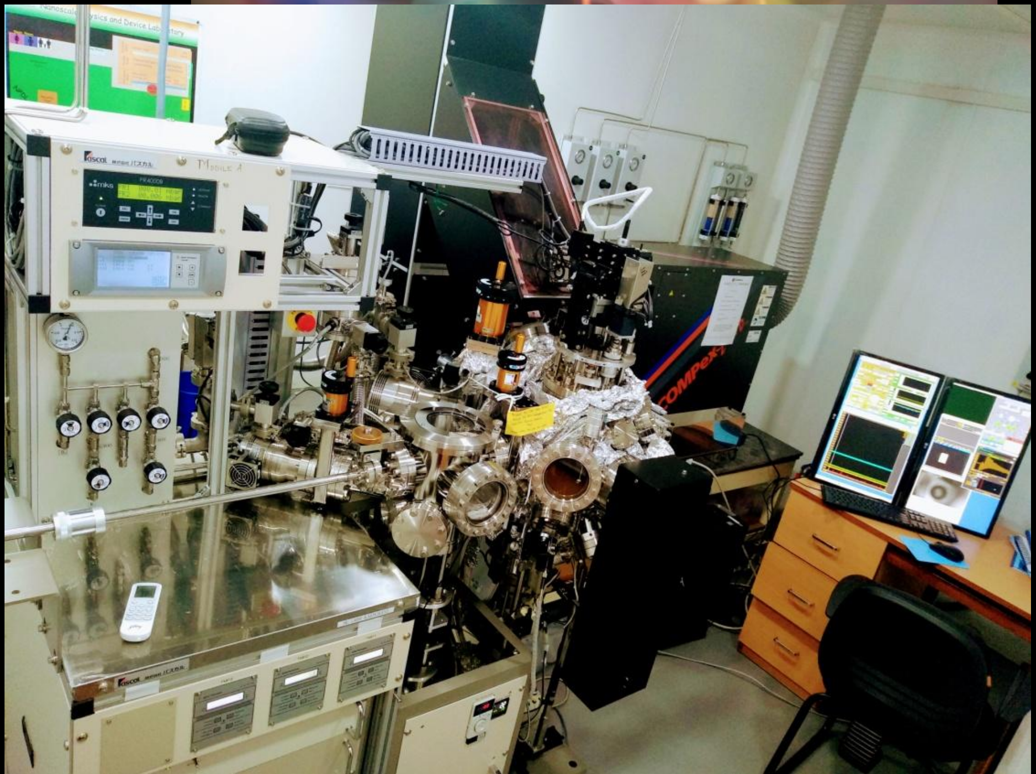
Conducting $LaVO_3/SrTiO_3$ Interface: Is Cationic Stoichiometry Mandatory?

Ruchi Tomar, Rahul Mahavir Varma, Nand Kumar, D. D. Sarma, Denis Maryenko, and Suvankar Chakraverty**

Thin film growth using Pulse Laser Deposition

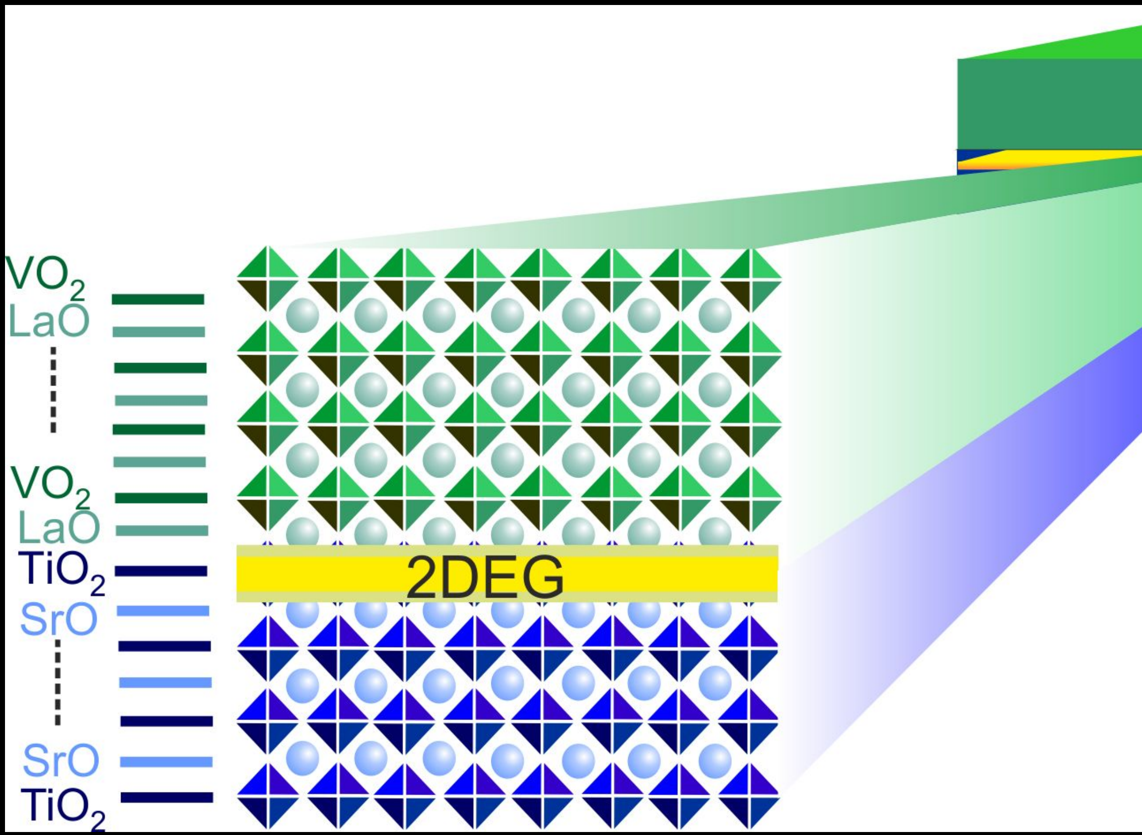






What have we done?

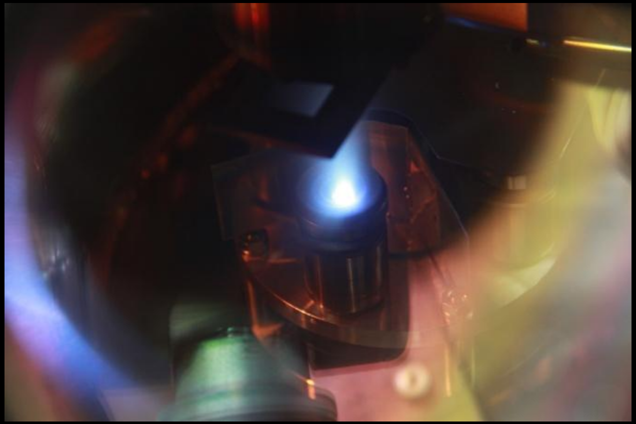
We have prepared several samples: Several LaVO3 thin films on SrTiO3 substrate: kept all growth parameter same for all samples only laser energy (laser fluence) was varied.

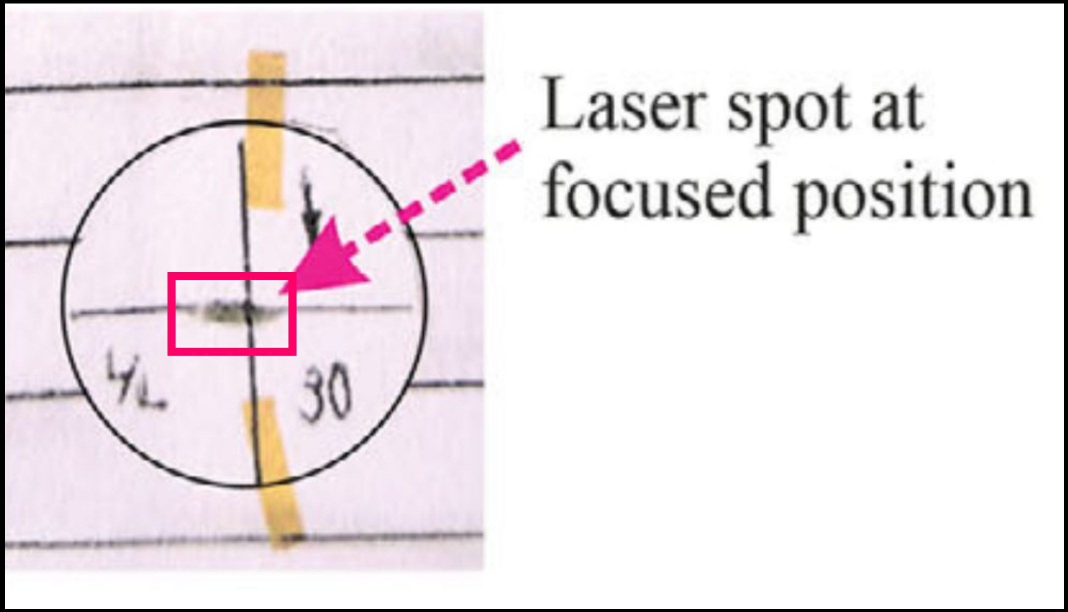


- **Mott Insulator with band gap ~1.1eV**
- **Lattice mismatch<0.4%**

Less possibility of oxygen vacancies in STO of LVO/STO heterostruture as compared to LAO-STO

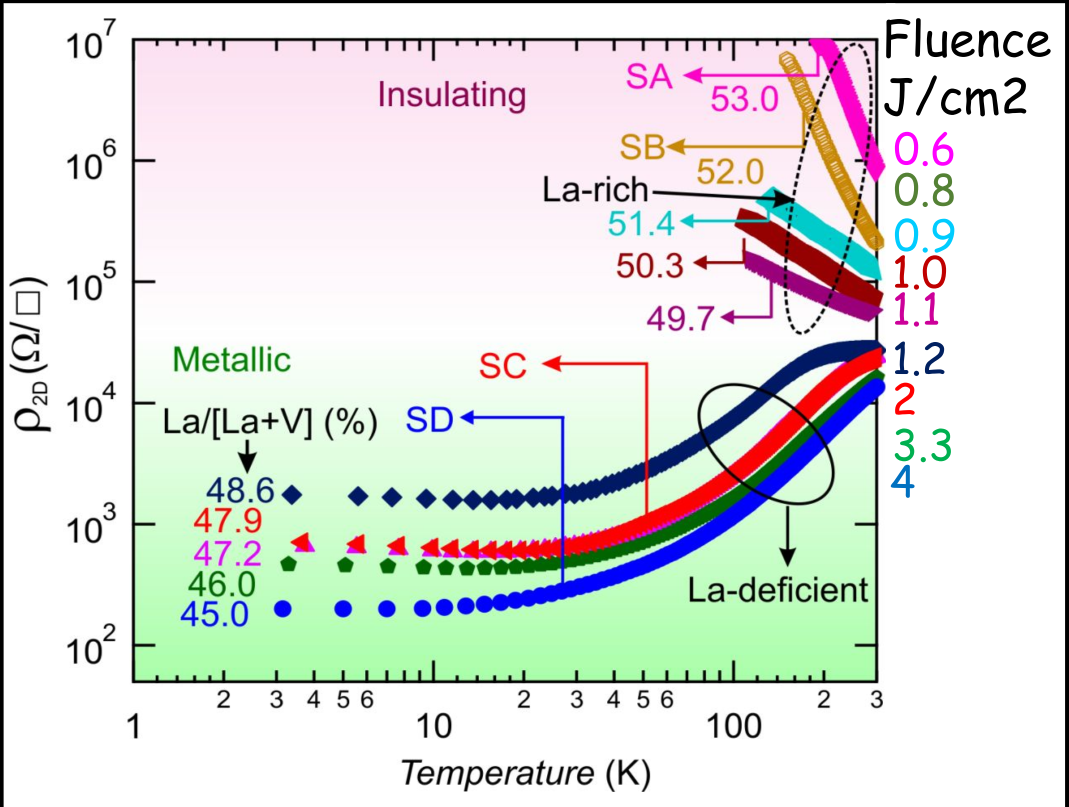
Laser Fluence: Laser energy per unit area on the target





Effect of Laser Fluence:

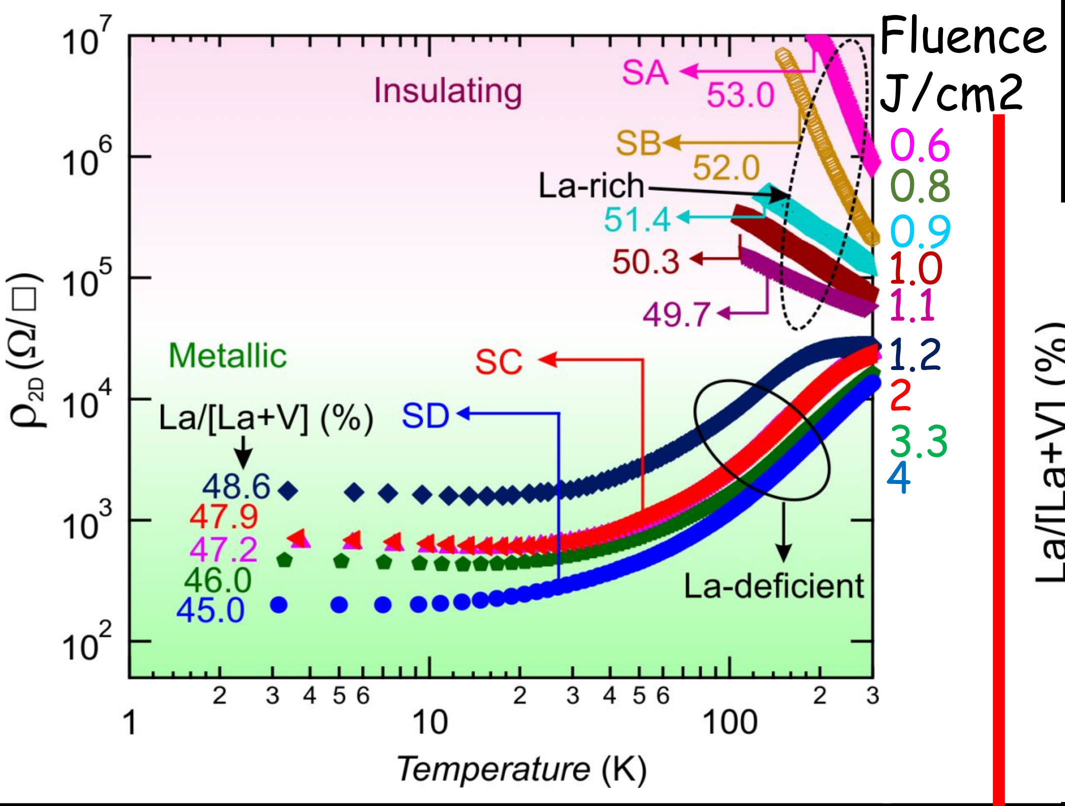
On conducting property of the interface



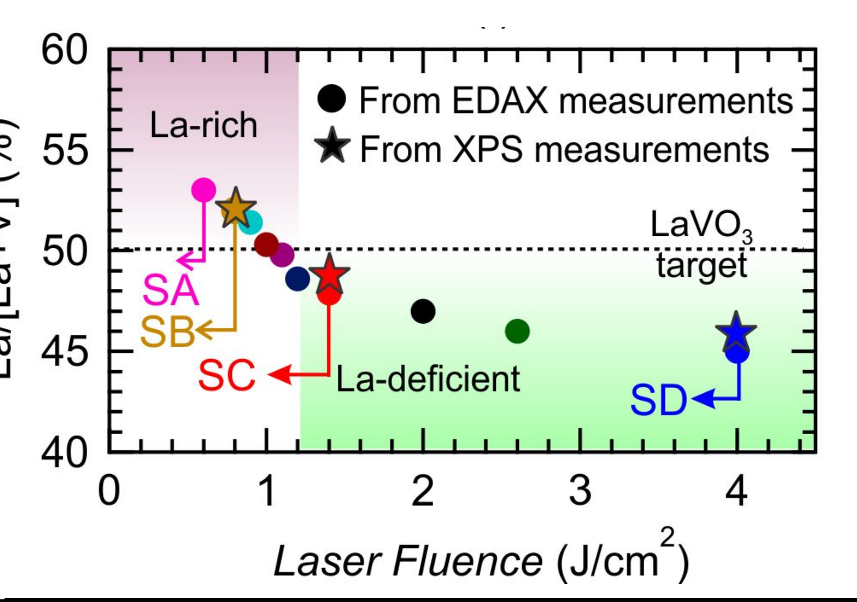
Conducting above 1.1J/cm2

Effect of Laser Fluence:

On conducting property of the interface



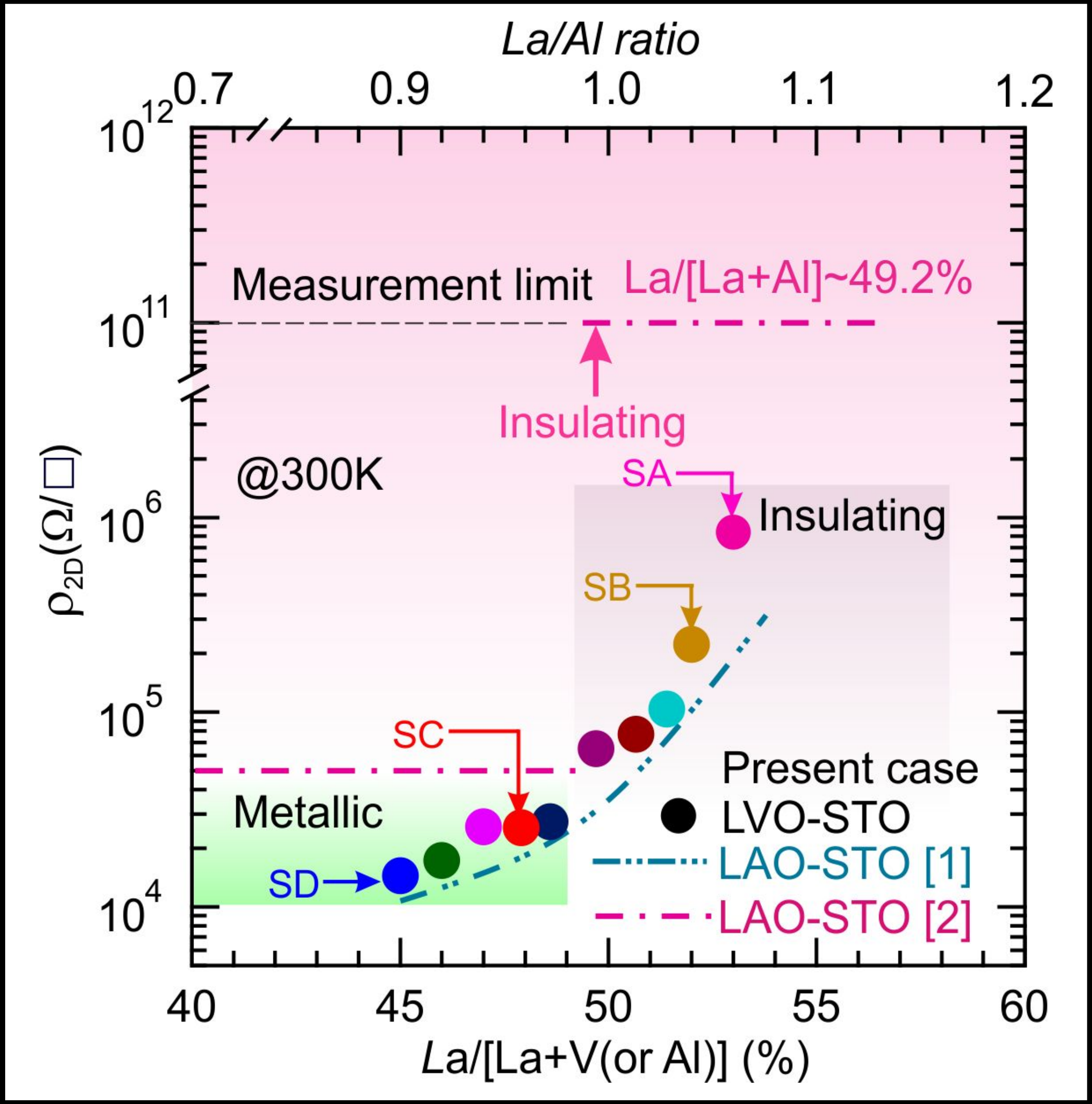
On film stoichiometry



Conducting above 1.1J/cm2

Below 1J/cm2 La-rich
Above La-deficient

Film stoichiometry: La-deficiency is needed for interface conductivity



1. PRL 2013, 110, 196804

2. Nat. Comm. 2013, 4, 2351

What about other mechanisms are they meaningless???

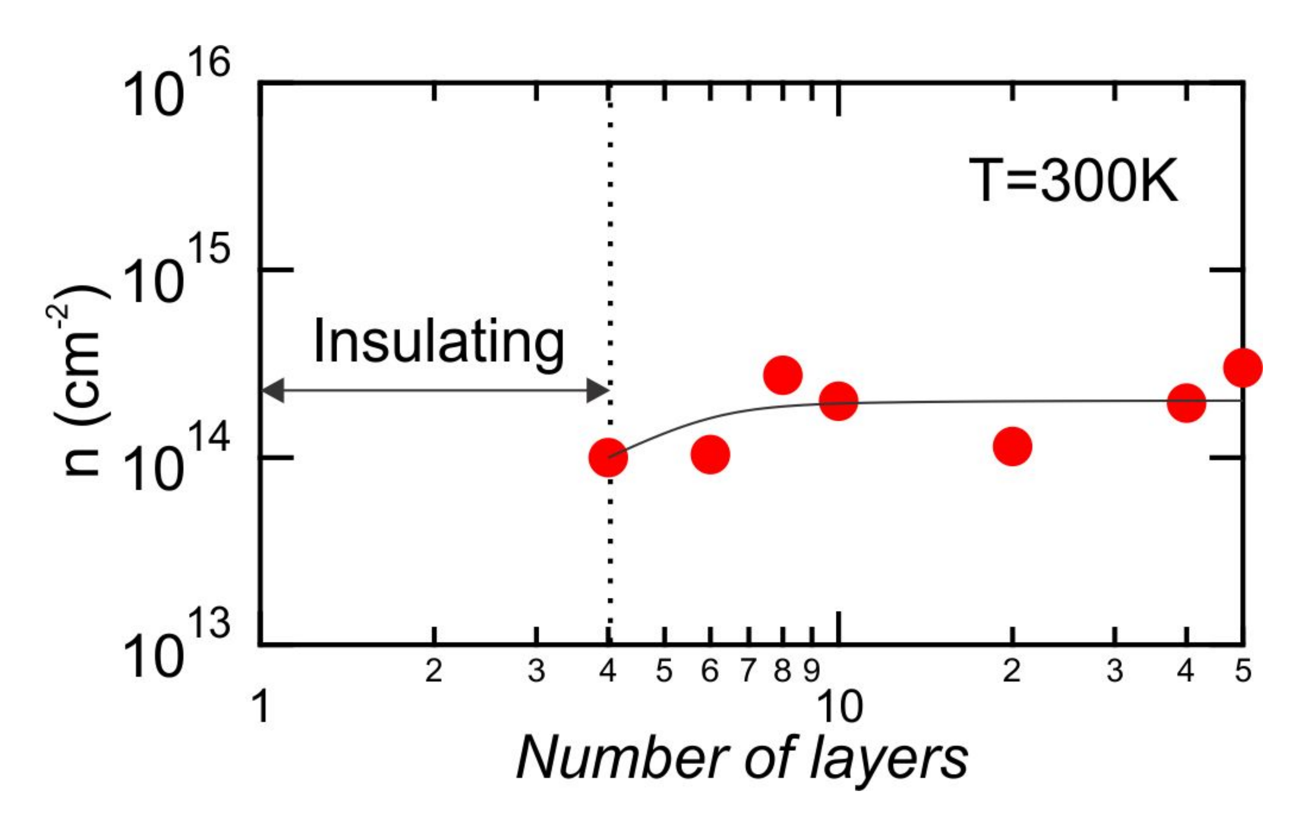
1. Oxygen Vacancy. : Annealing under oxygen

2. Cation intermixing. : No critical thickness of the flim is needed

3. Polar Catastrophe. : A critical thickness of the film is needed

Film thickness dependent transport measurements

Laser Fluence kept constant (2J/cm2) and grow film with different thicknesses



LVO films < 4ML, Insulating

LVO films ≥ 4ML, Conducting

Conclusion:

Both A-site deficient film and a critical thickness of the film is needed to realize a conducting interface of two insulating perovskite oxide

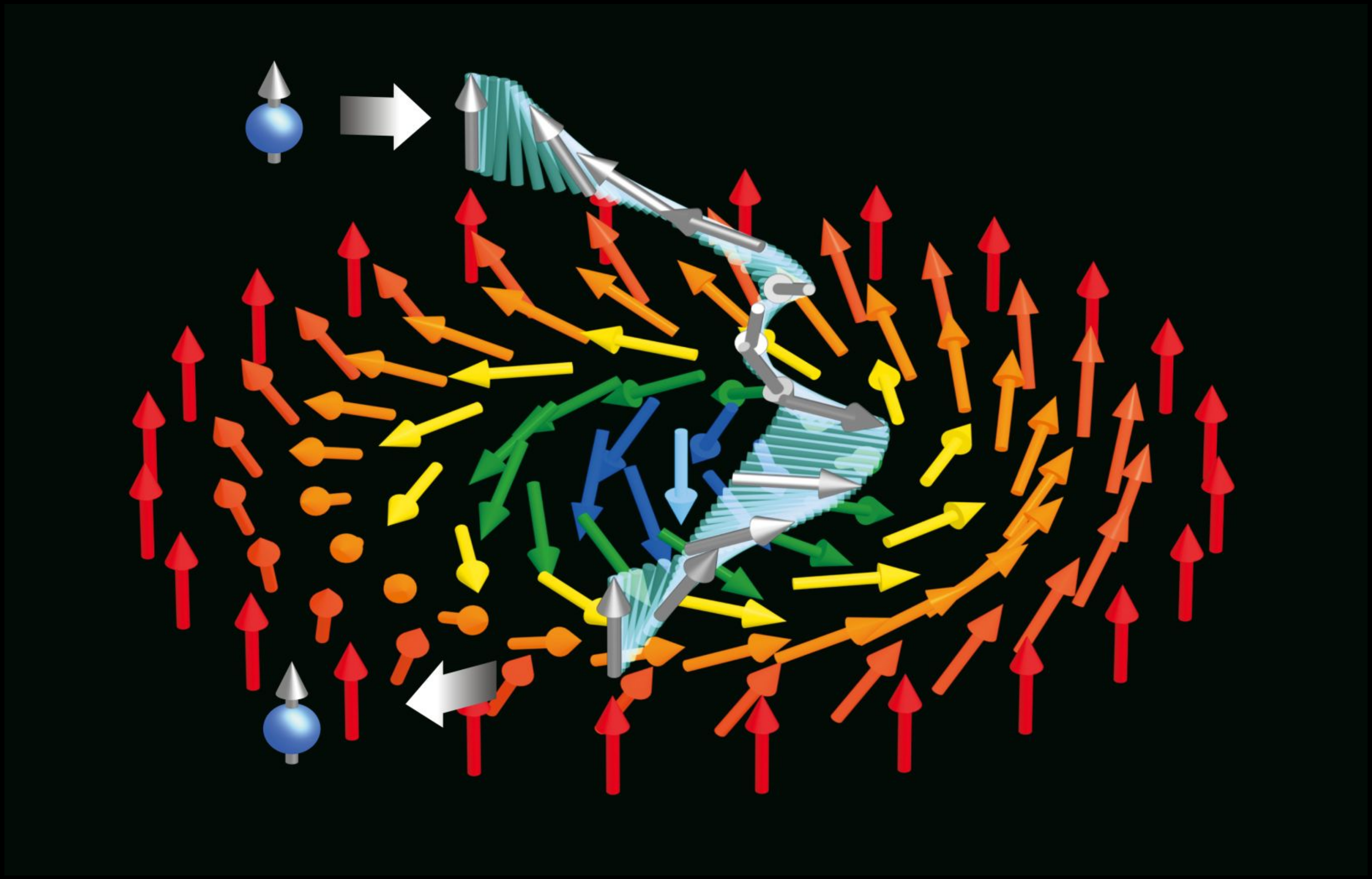
A-site deficient film triggers polar catastrophe!!!

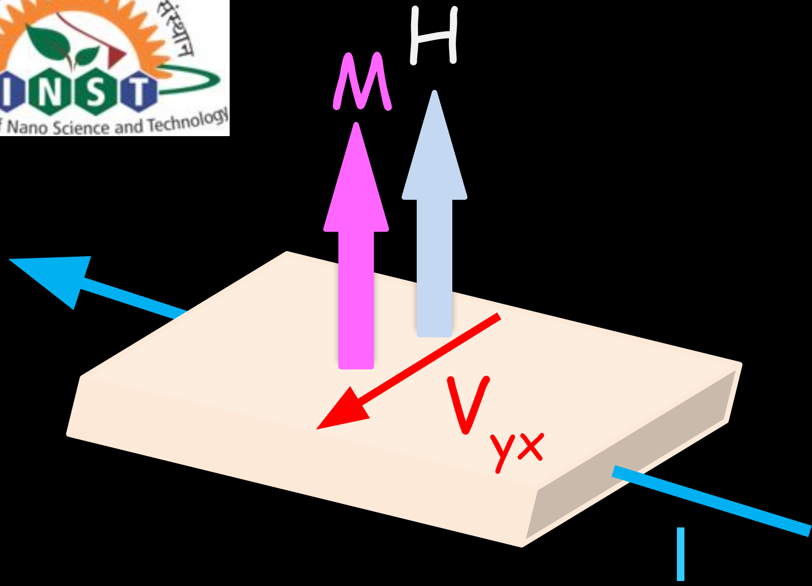
Non-trivial spin texture in momentum space

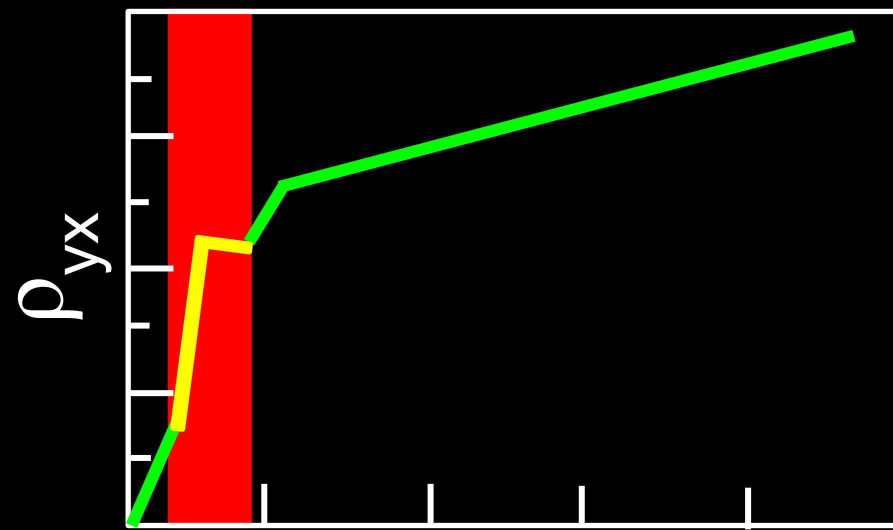
Material : $LaVO_3$ – $KTaO_3$ interface

Looking at **longitudinal** conductivity

Signature of non-trivial spin texture in real space: Topological Hall Effect







Empirical relation

$$\rho_{yx} = \boxed{R_o B_z} + \boxed{R_s M} + \boxed{R B_z^{eff}}$$

Normal Hall	Anomalous Hall	Topological Hall
Lorentz force	Proportional to M	Berry phase in real space

What if there is non-trivial spin texture in "Momentum -Space"

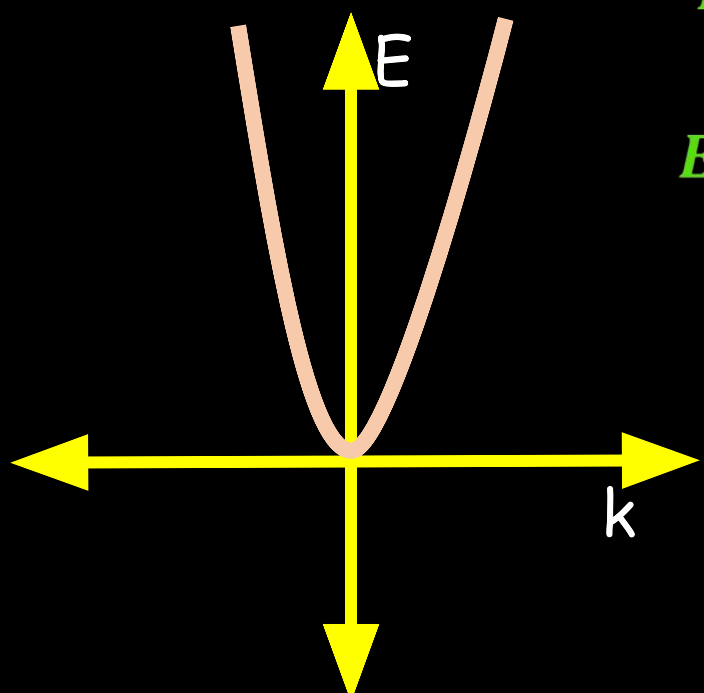
Possible Non-trivial spin texture in momentum space: Rashba

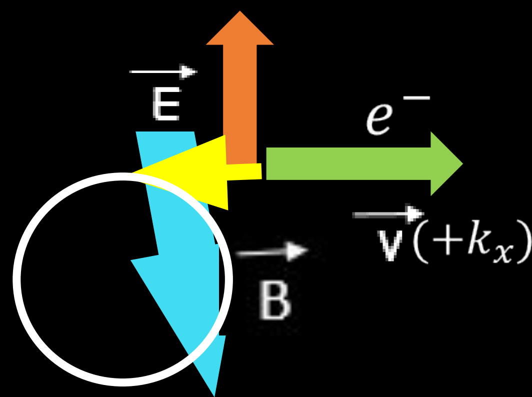
Rashba Effect

Free Electron Model

$$H_F = \frac{p^2}{2m}$$

$$E = \frac{\hbar^2 k^2}{2m}$$

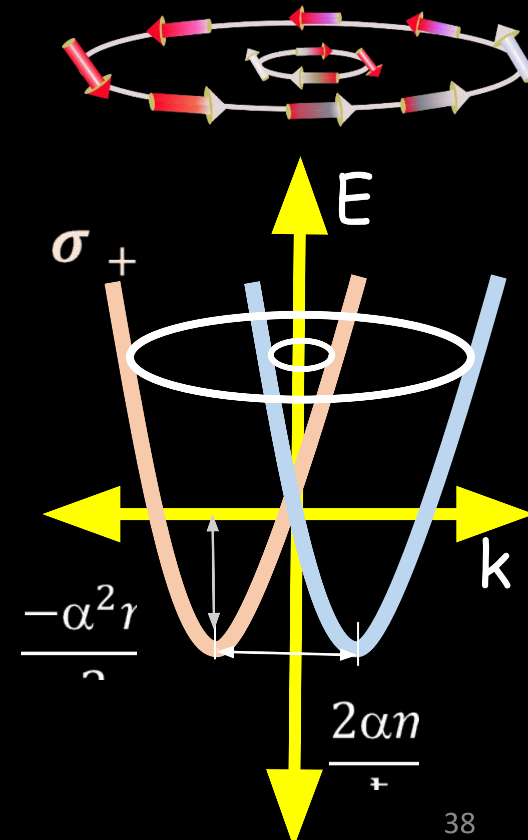




$$H_{tot} = H_F - \mu_B \cdot B$$

$$E_\pm = \frac{\hbar^2 k^2}{2m} \mp \alpha\hbar k$$

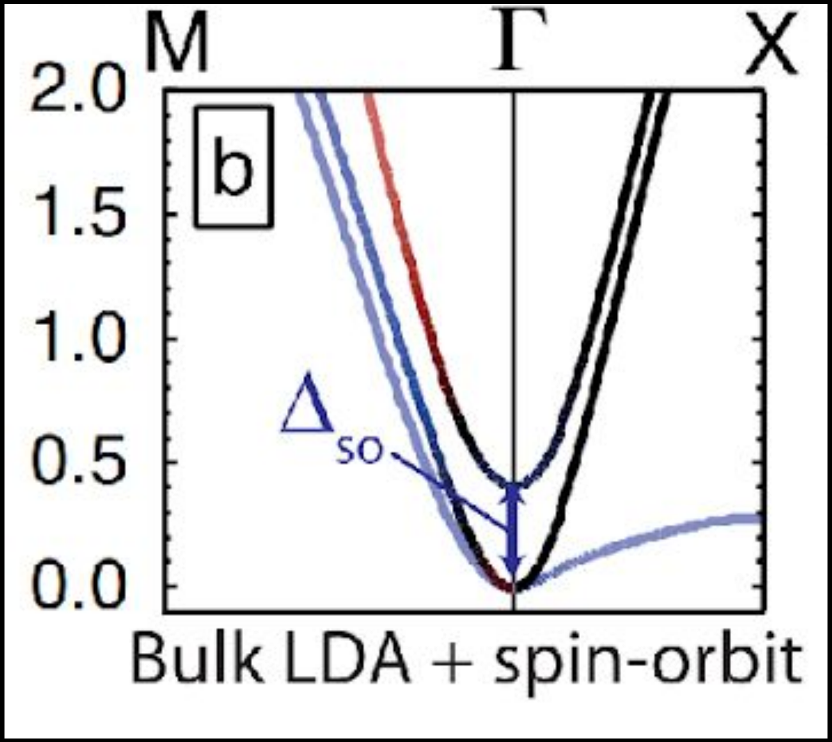
Strong SOC + Electric field



Possible perovskite oxide with strond spin-orbit coupling: KTaO3

Possible Strong Spin Orbit Coupled perovskite oxides

KTaO3(001) Single crystal: SOC ~ 300mEv



Phys. Rev. Lett. **108**, 117602 (2012)

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-14689-z OPEN

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Planar Hall effect and anisotropic magnetoresistance in polar-polar interface of $LaVO_3$-$KTaO_3$ with strong spin-orbit coupling

Neha Wadehra[1], Ruchi Tomar[1], Rahul Mahavir Varma[2], R.K. Gopal[3], Yogesh Singh[3], Sushanta Dattagupta[4] & S. Chakraverty[1]✉

PHYSICAL REVIEW B **104**, L081111 (2021)

Letter

Probing conducting interfaces by combined photoluminescence and transport measurements: $LaVO_3$ and $SrTiO_3$ interface as a case study

Anamika Kumari,[1] Joydip De,[2] Sushanta Dattagupta,[3] Hirendra N. Ghosh,[4] Santanu Kumar Pal,[2] and S. Chakraverty[1,*]

COMMUNICATION

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Observation of Shubnikov–de Haas Oscillations, Planar Hall Effect, and Anisotropic Magnetoresistance at the Conducting Interface of EuO–$KTaO_3$

*Nand Kumar, Neha Wadehra, Ruchi Tomar, Shama, Sanjeev Kumar, Yogesh Singh, Sushanta Dattagupta, and Suvankar Chakraverty**

Chec

ADVANCED MATERIALS

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$KTaO_3$—The New Kid on the Spintronics Block

Anshu Gupta, Harsha Silotia, Anamika Kumari, Manish Dumen, Saveena Goyal, Ruchi Tomar, Neha Wadehra, Pushan Ayyub, and Suvankar Chakraverty**

RESEARCH ARTICLE

ADVANCED ELECTRONIC MATERIALS

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Possible Signatures of Chiral Anomaly in the Magnetoresistance of a Quasi-2-Dimensional Electron Gas at the Interface of $LaVO_3$ and $KTaO_3$

*Harsha Silotia, Anamika Kumari, Anshu Gupta, Joydip De, Santanu Kumar Pal, Ruchi Tomar, and Suvankar Chakraverty**

PHYSICAL REVIEW B

covering condensed matter and materials physics

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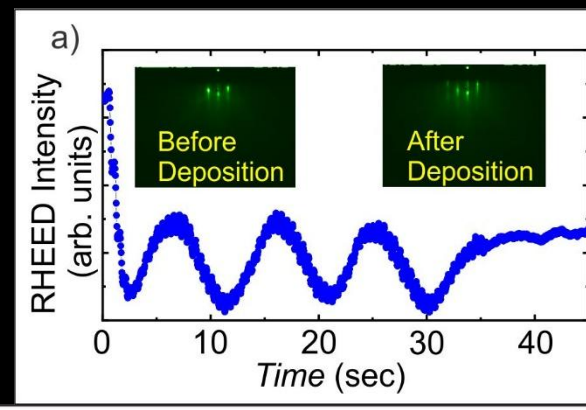
Linear magnetoresistance and weak antilocalization in a $LaVO_3$/$KTaO_3$ heterostructure

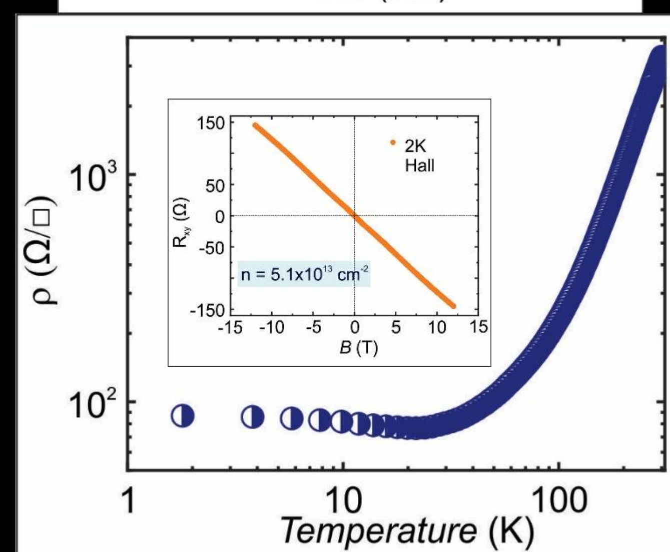
Harsha Silotia, Anamika Kumari, Amit Vashist, and S. Chakraverty

Phys. Rev. B **109**, 245405 – Published 5 June 2024

Systems to be discussed

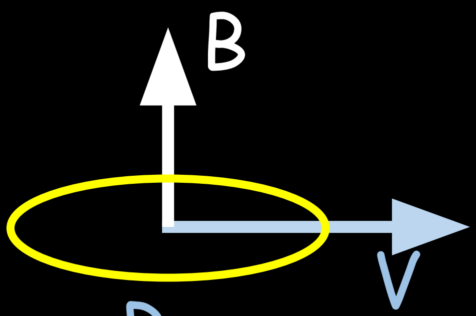
Present sample 4ml LVO on KTO
carrier density ~ 5E13 cm-^{2}



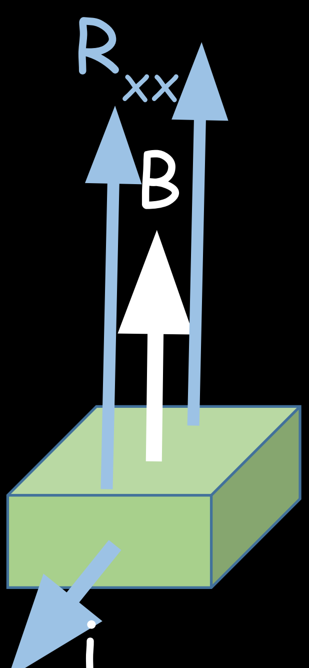


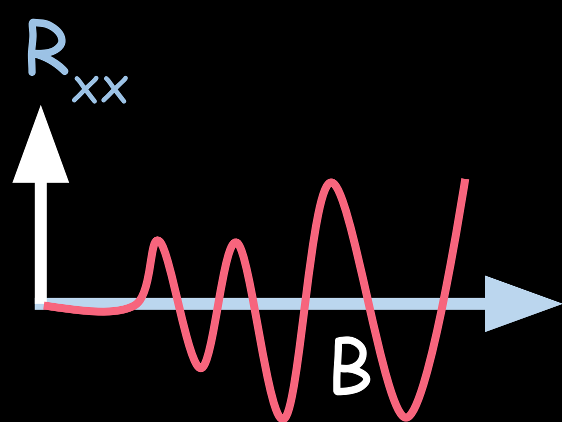
B_{so} ~ 4.4T : Rashba!!!
Non Trivial spin texture in "Momentum Space"

Towards the observation of quantum oscillation in the magneto-resistance: Shubnikov-de Hass oscillation



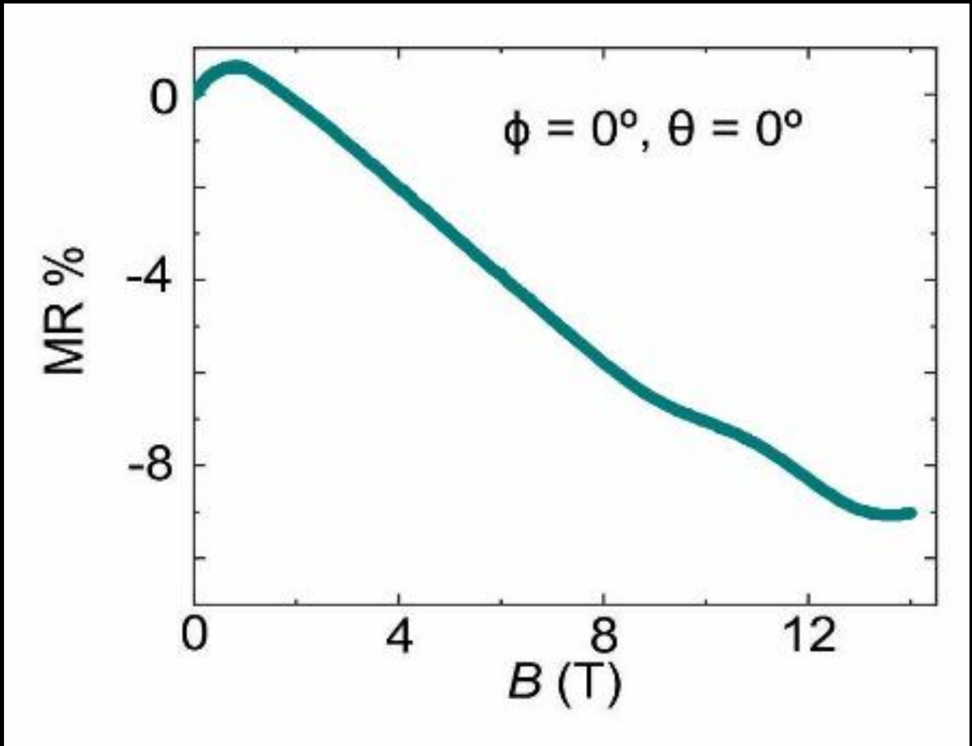
Classical	**Quantum**
1. Orbit size not-quantized	1. Orbit size quantized $\oint P.dr = \hbar\pi N$
2. Energy not-quantized	2. Energy quantized $E_n = \hbar\omega_c (n+1/2)$: $\omega_c = qB/m$



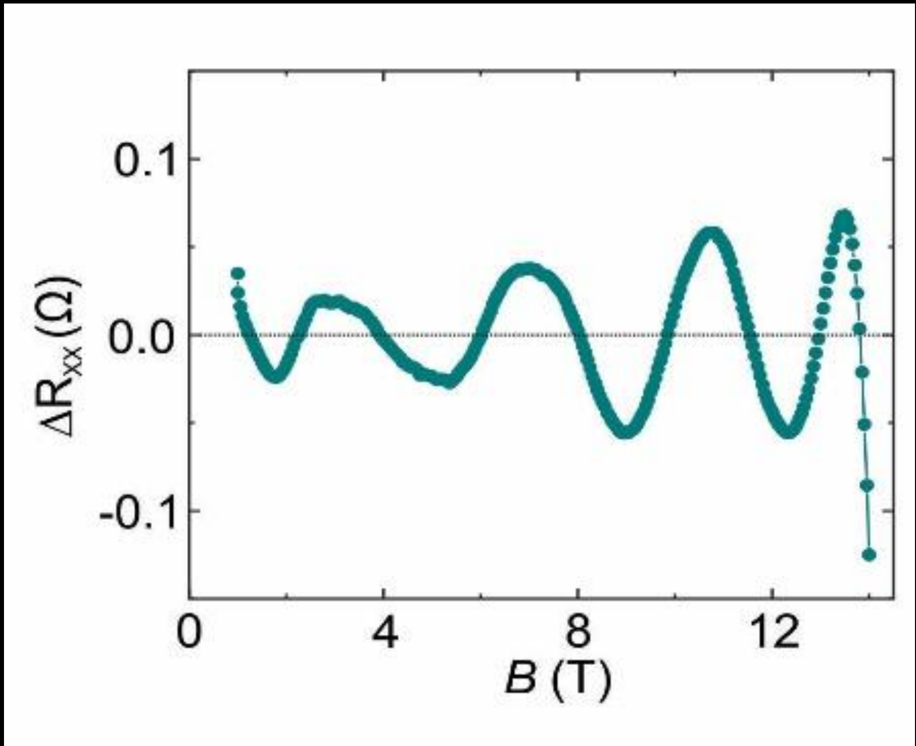


1. Shape of the Fermi Surface : Nature of the charge carrier, 2D/3D
2. Effective mass
3. Nature of the band: Trivial/Non-trivial

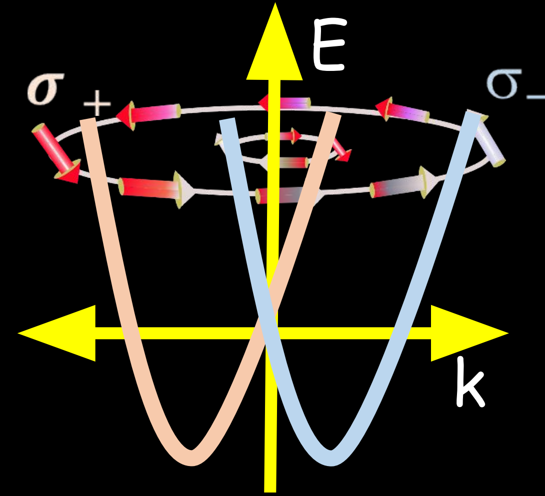
Raw data



Background subtracted data



Lifshitz-Onsager equation



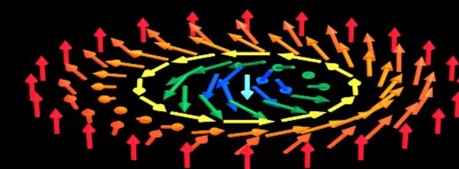
For a Trivial Parabolic band

$$n=\left(\frac{A\hbar}{2\pi e}\right)\frac{1}{B}$$

For a non-Trivial band: Say with Dirac point

Berry's Phase

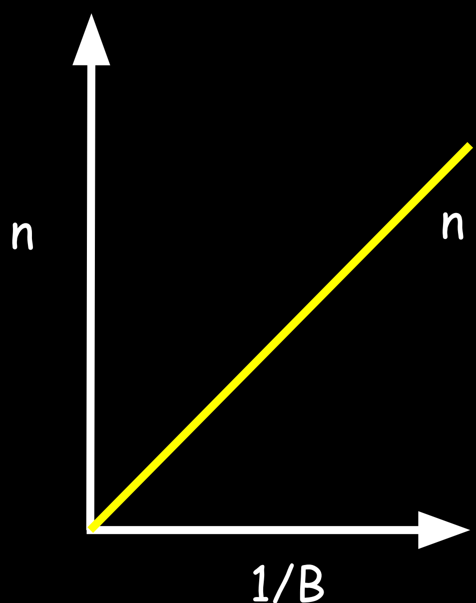
$$n=\left(\frac{A\hbar}{2\pi e}\right)\frac{1}{B}+\left(\frac{\phi_B}{2\pi}\right)$$

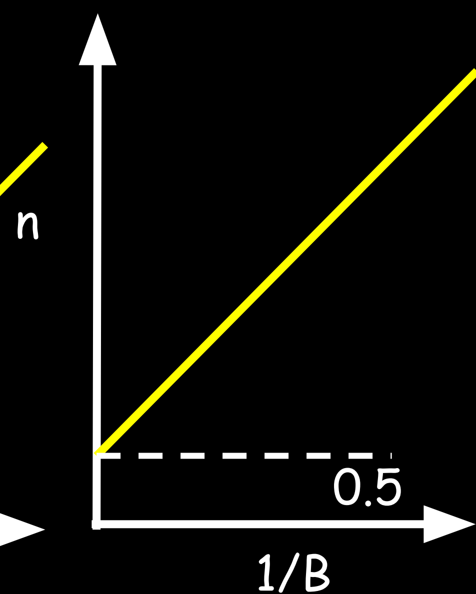


Non-trivial spin texture in K-space???

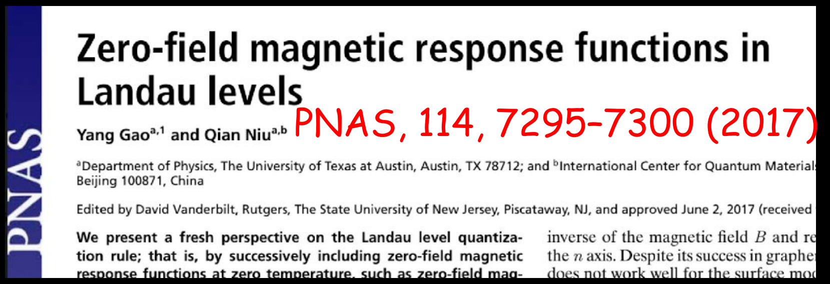
n linear to 1/B???

$$N=\frac{F}{B}-\gamma+CB,\delta=0$$





n linear to 1/B!!!



Zero-field magnetic response functions in Landau levels

Yang Gao[a,1] and Qian Niu[a,b]

PNAS, 114, 7295–7300 (2017)

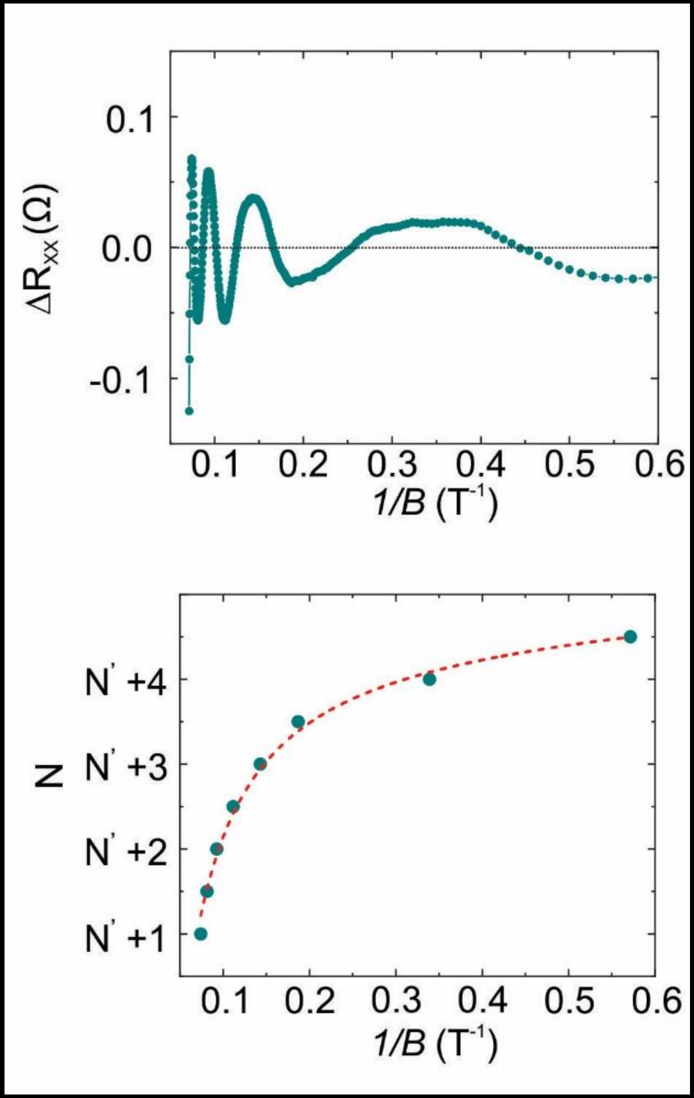
[a]Department of Physics, The University of Texas at Austin, Austin, TX 78712; and [b]International Center for Quantum Material
Beijing 100871, China

Edited by David Vanderbilt, Rutgers, The State University of New Jersey, Piscataway, NJ, and approved June 2, 2017 (received

We present a fresh perspective on the Landau level quantization rule; that is, by successively including zero-field magnetic response functions at zero temperature, such as zero-field mag-

inverse of the magnetic field B and re the n axis. Despite its success in graphe does not work well for the surface mod

Lifshitz-Onsager equation



N = $\frac{F}{B} - \gamma + CB$, : This fits our Landau plot with Berry's Phase $\gamma = \pi$

Non-trevial electronic state + Non-trivial spin texture at k-space (???)

Unusual Quantum oscillation in resistance : Non-trivial spin texture in momentum space

Material : $LaVO_3$ – $KTaO_3$ interface

Looking at **longitudinal** conductivity

?

Interface conductivity: Non-stoichiometry triggers the conductivity

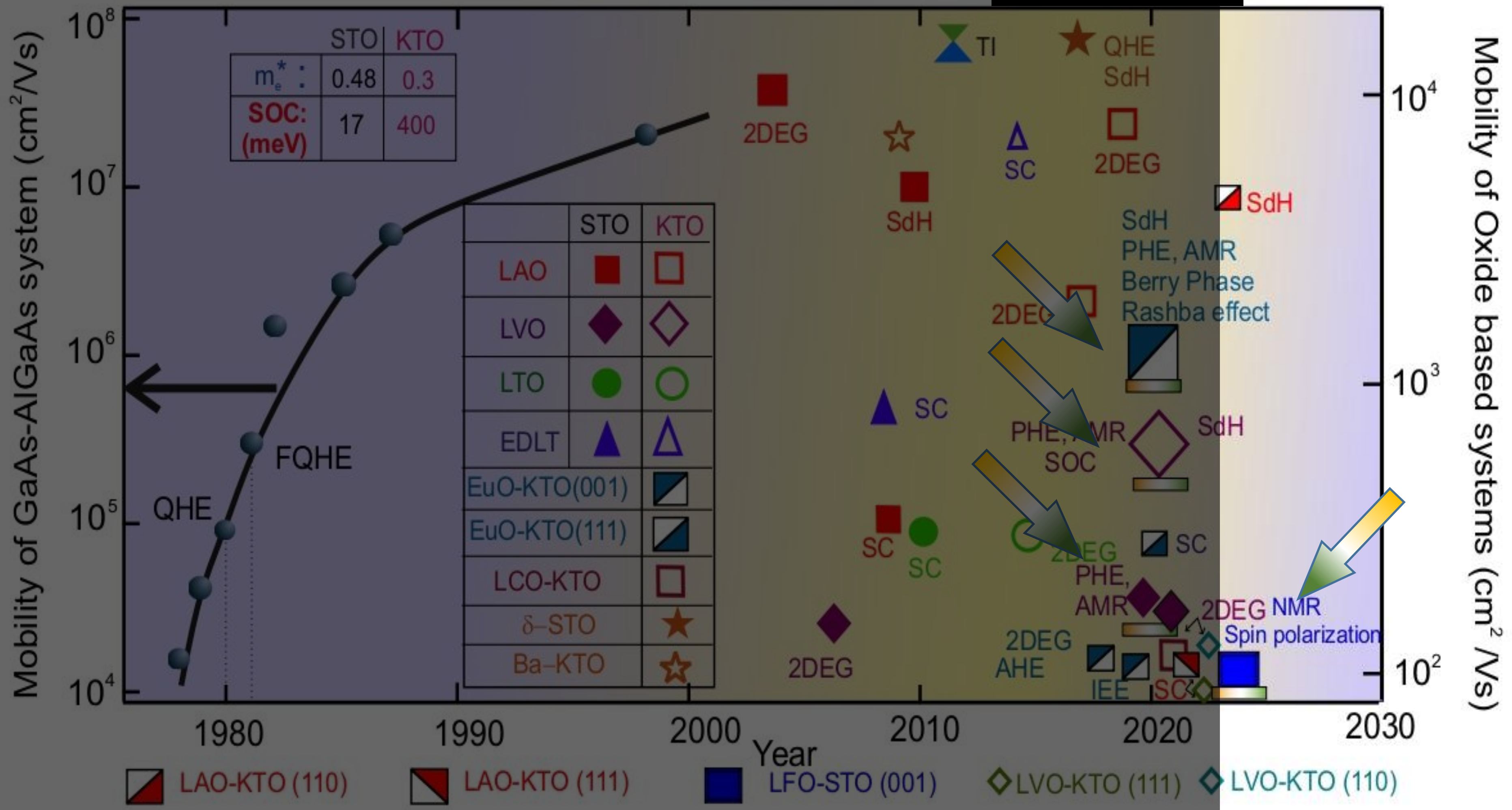
Real space non-trivial spin texture: Transverse resistance as Topological Hall

Momentum space non-trivial spin texture: longitudinal resistance unusual SdH

STO Era Started

KTO Era Continue

STO Era Revised



Conducting interface of LaFeO3 and SrTiO3

PHYSICAL REVIEW B
covering condensed matter and materials physics

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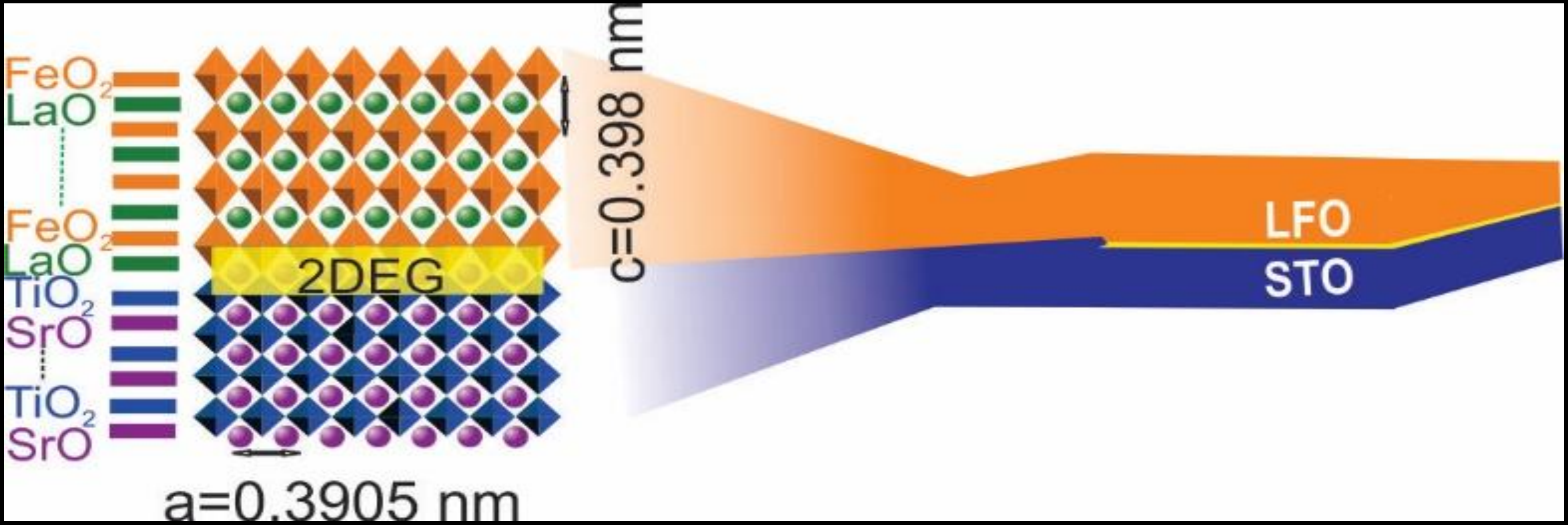
Letter

Access by Institute of Nano Science and Technology (INST)

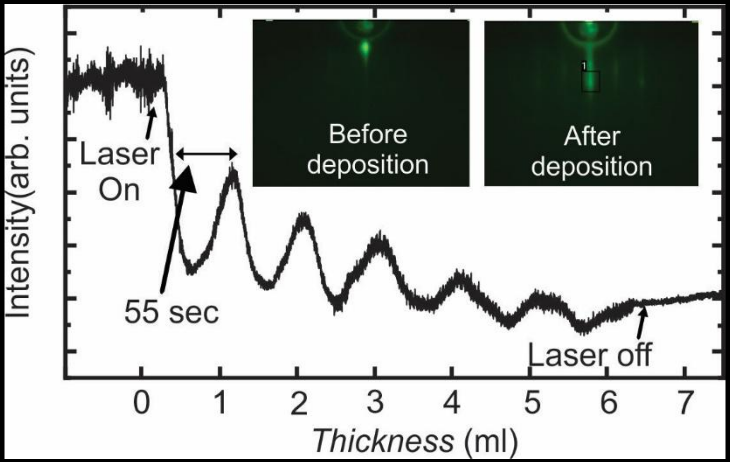
Room-temperature transparent oxide spin electronics: A conducting interface in $LaFeO_3 - SrTiO_3$

Ripudaman Kaur, Anamika Kumari, Shinjini Paul, Mohd Anas, Bibek Ranjan Satapathy, Sanjeev Kumar, V. K. Malik, P. Mahadevan, D. D. Sarma, and Suvankar Chakraverty

Phys. Rev. B **109**, L201114 – Published 14 May 2024



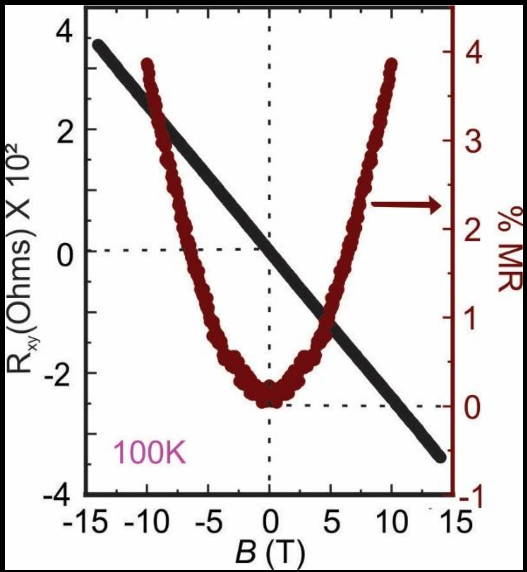
Sample preparation: RHEED

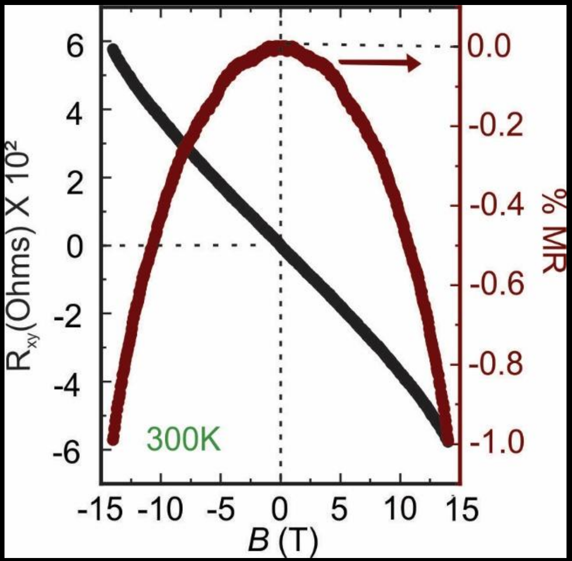


Hall and Magnetoresistance

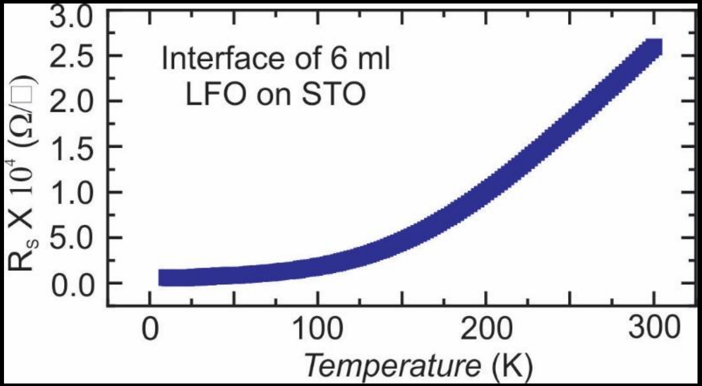
100K

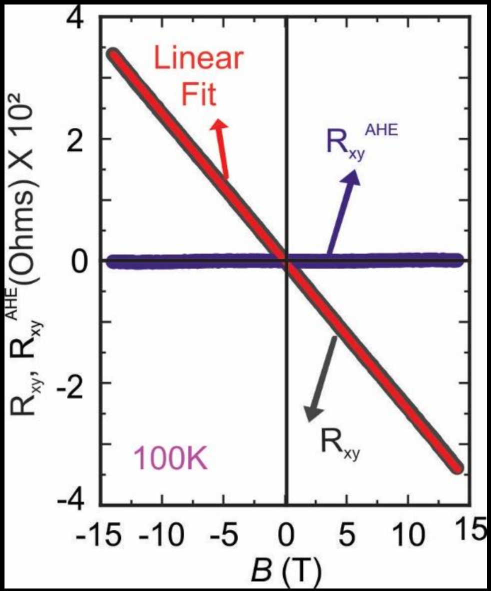
300K

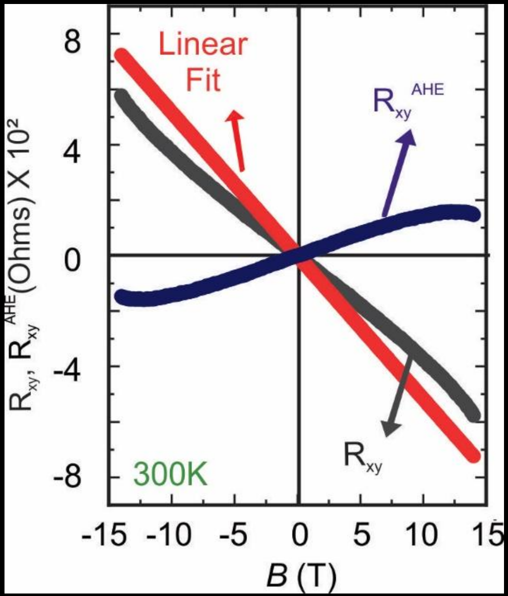


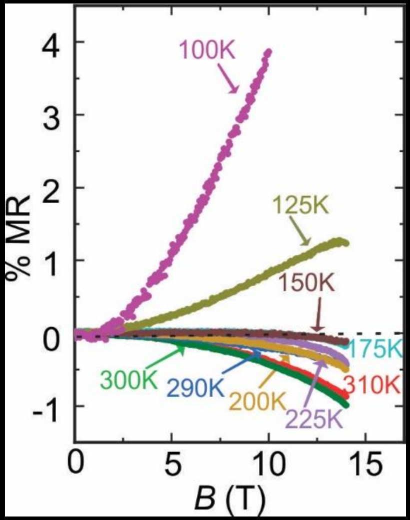


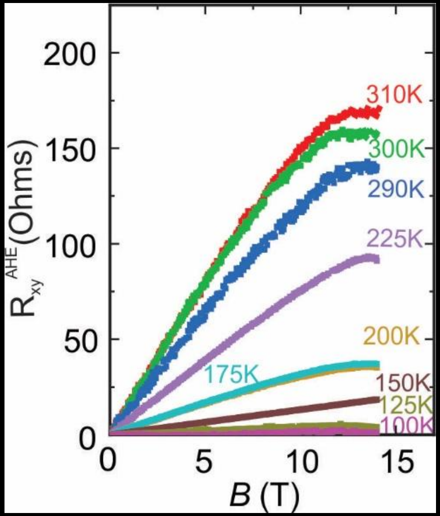
Resistivity vs temperature: conducting interface



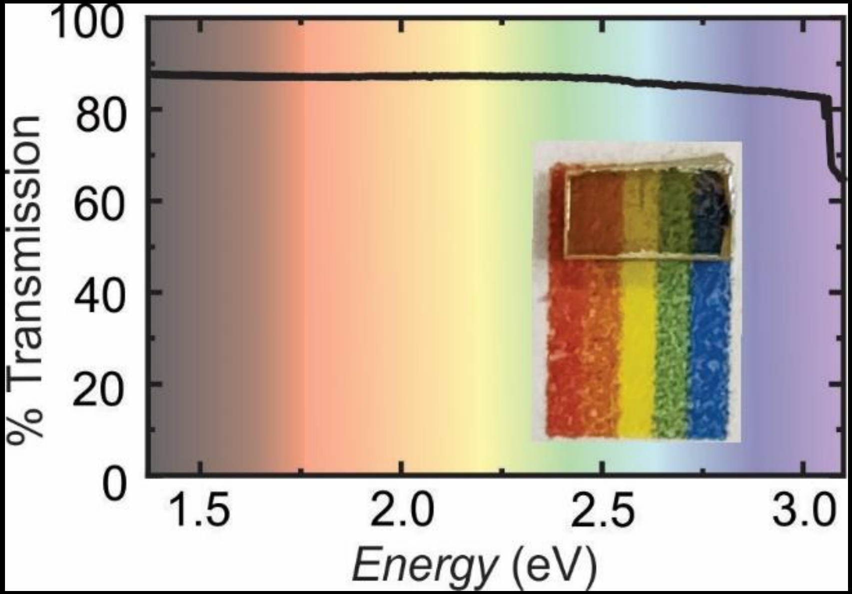




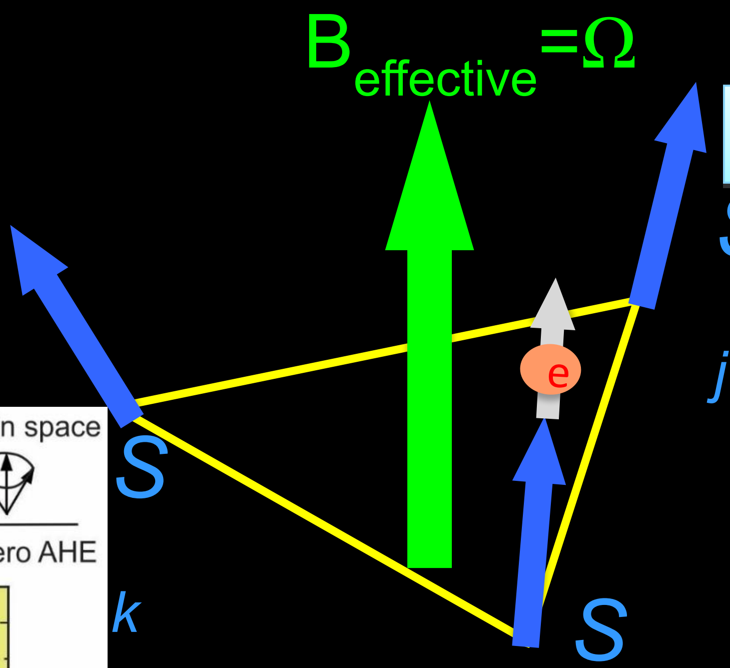




Transparent Oxide electronics!!!

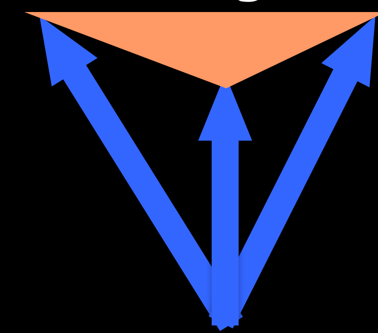


Solid angle by spins acting as a Fictitious magnetic field



scalar spin chirality

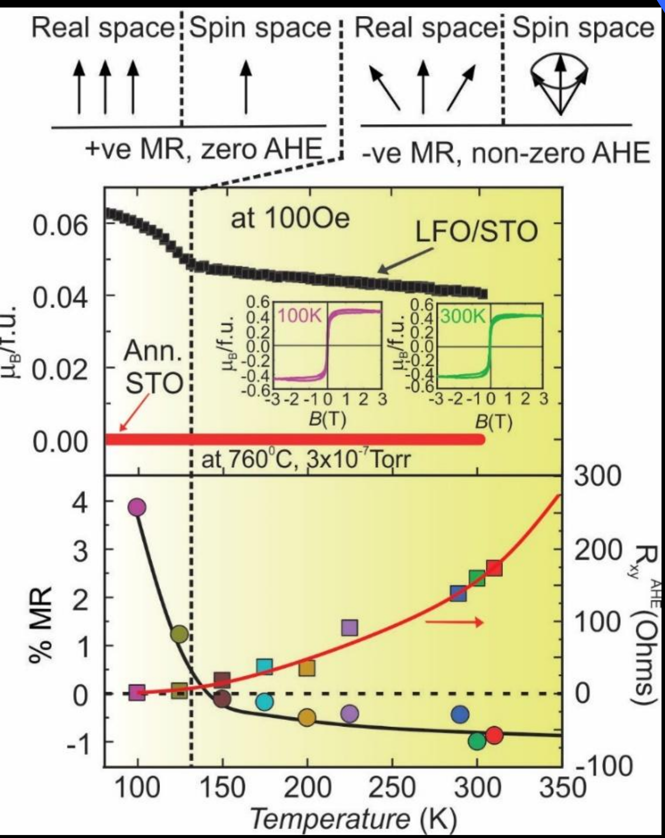
S Solid angle : Ω



Fictitious flux (in a continuum limit)

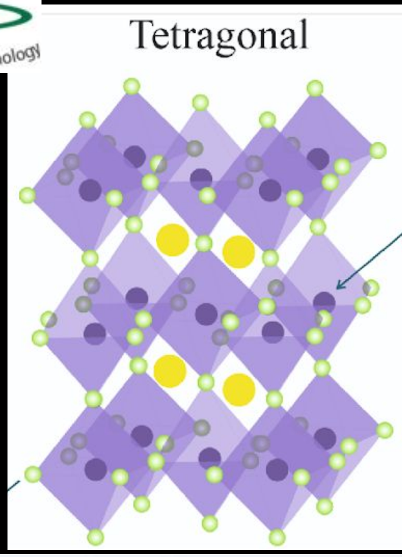
$$\Phi \propto \frac{\mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)}{2} = \frac{\Omega}{2}$$

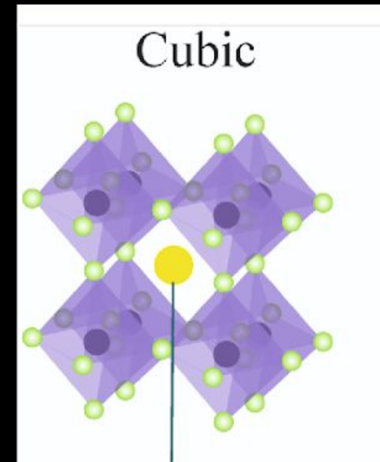
$$\Phi = (\Omega/4\pi)\varphi_0 : \quad \varphi_0 = h/e$$

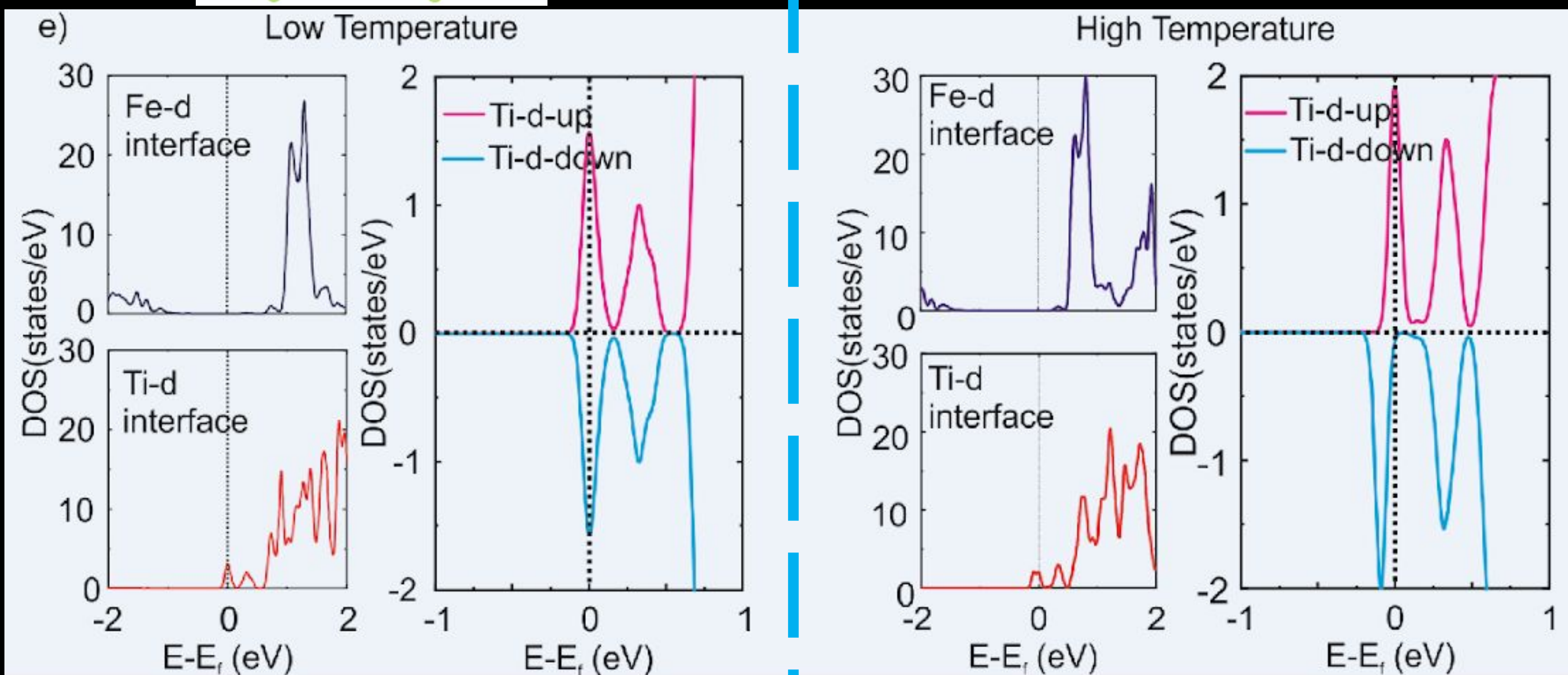


Institute of Nano Science and Technology

Structural phase transition of STO around 120K



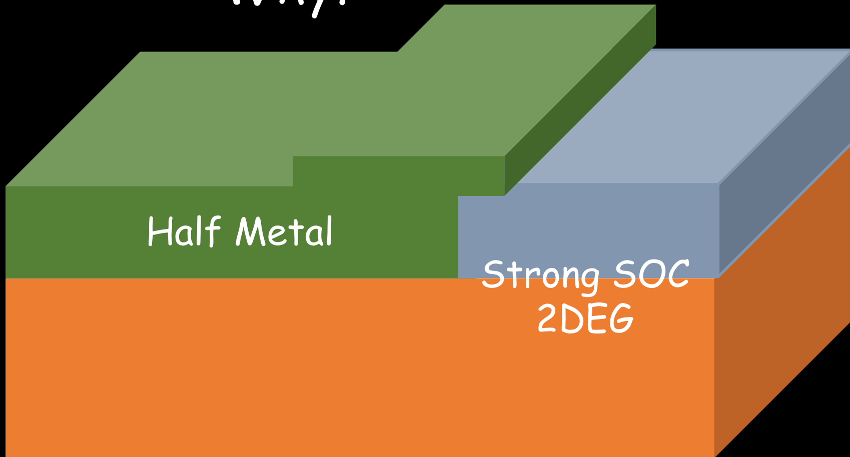


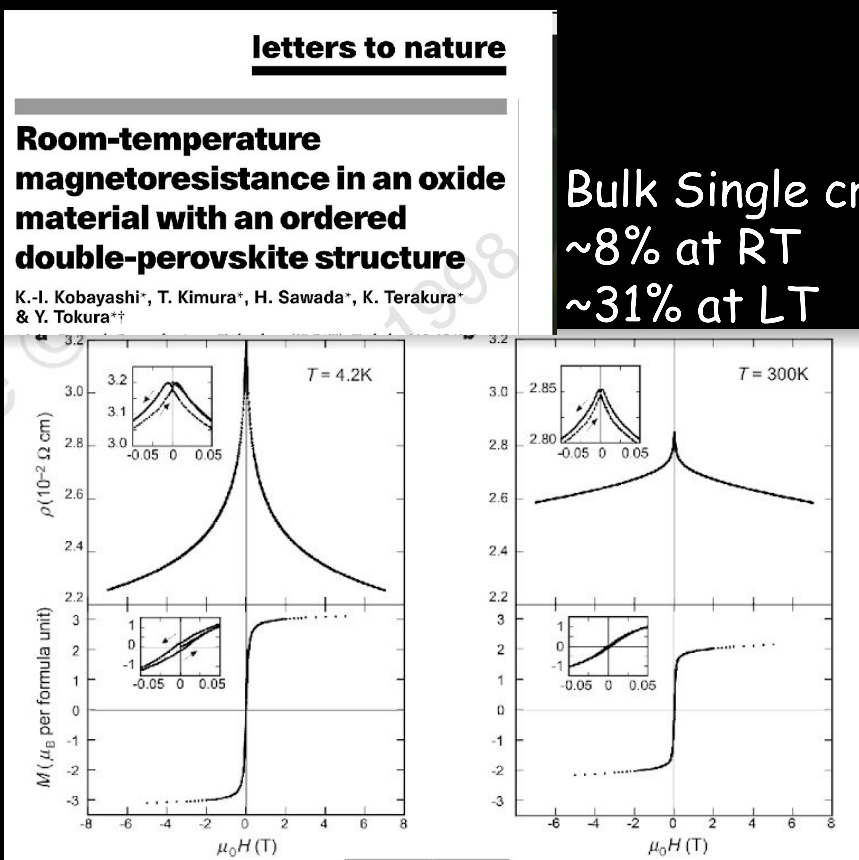


Spin polarized interface to spin-polarized thin film

Sr2FeMoO6

Why?



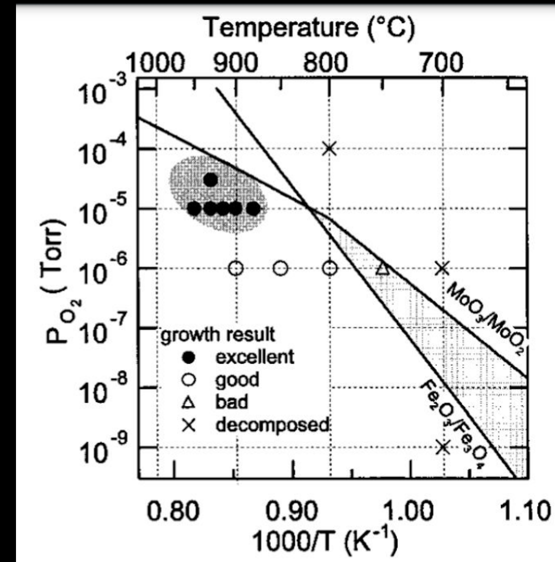

letters to nature

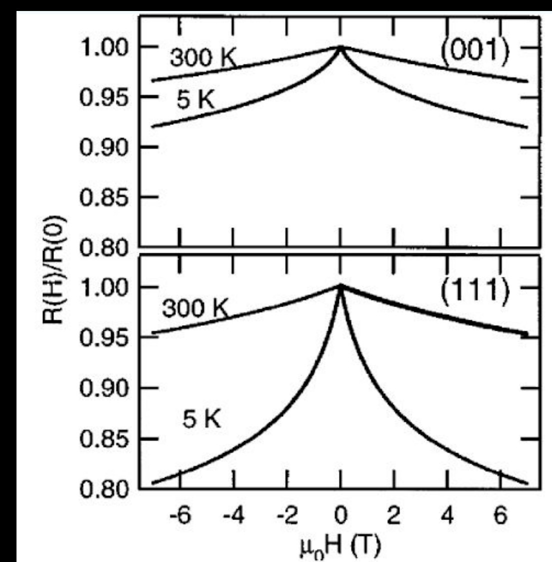
Room-temperature magnetoresistance in an oxide material with an ordered double-perovskite structure

K.-I. Kobayashi*, T. Kimura*, H. Sawada*, K. Terakura* & Y. Tokura*†

Bulk Single crystal
~8% at RT
~31% at LT

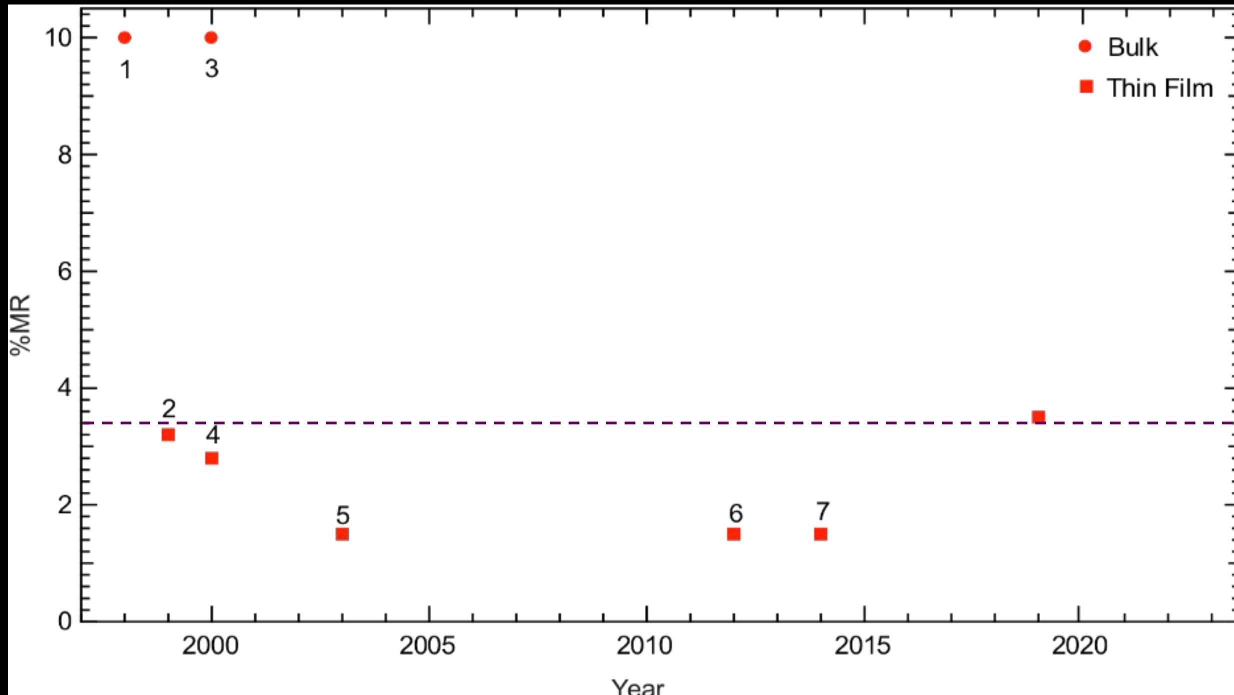
Thin films





~2.5 % at RT
~ 10% at LT

Summary



Question:
Can we increase this in thin film

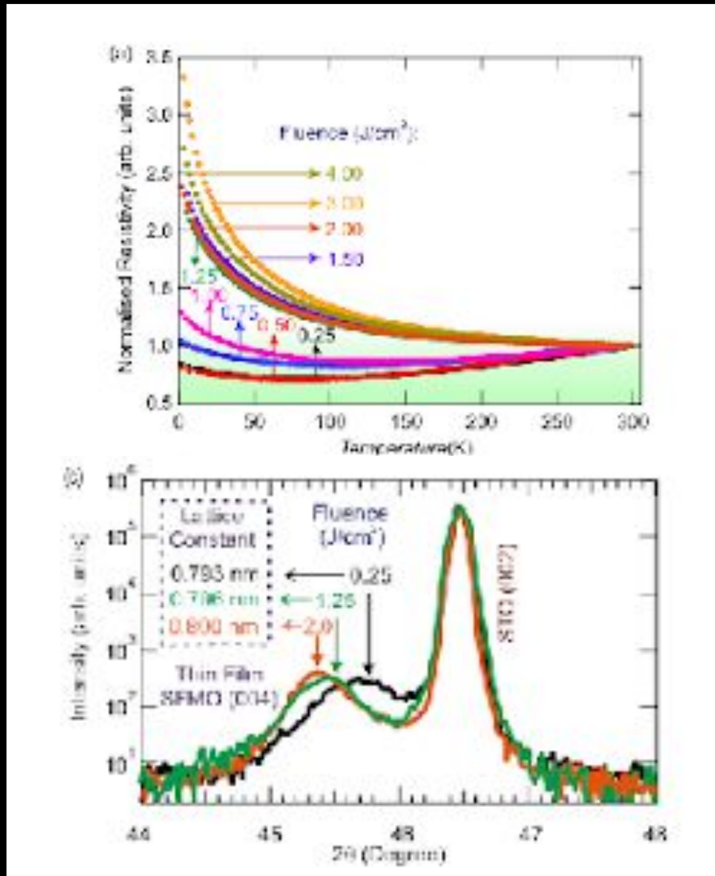
ACS APPLIED ELECTRONIC MATERIALS

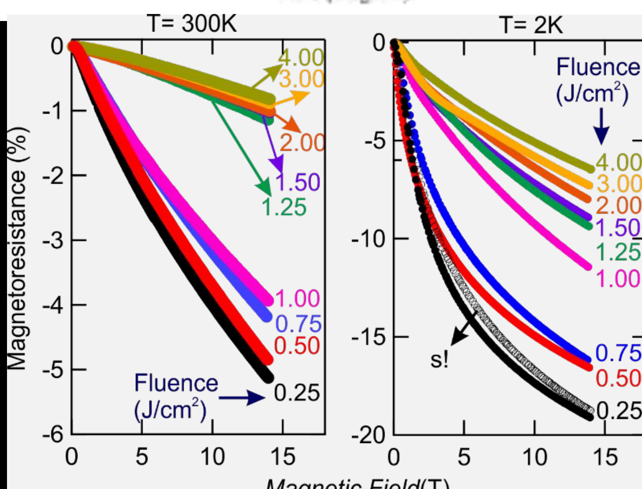
pubs.acs.org/acsaelm Letter

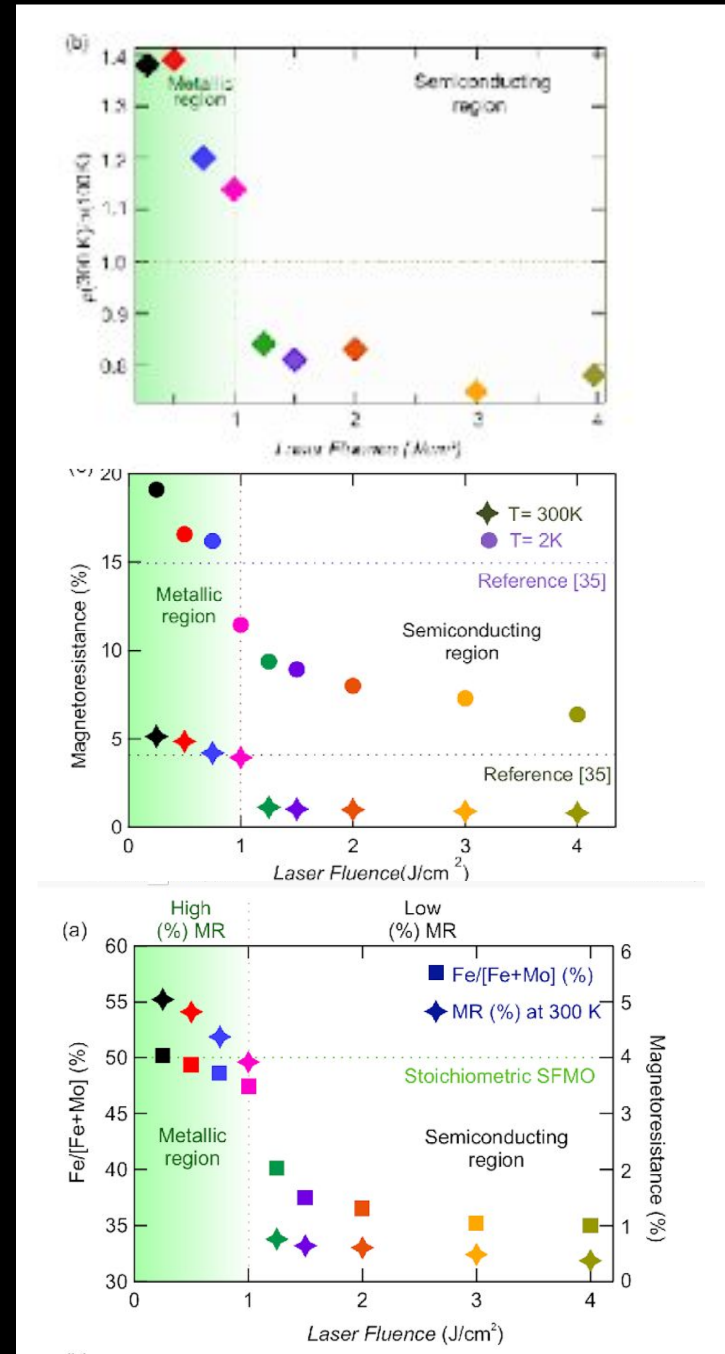
B-Site Stoichiometry Control of the Magnetotransport Properties of Epitaxial Sr_2FeMoO_6 Thin Film

Nand Kumar, Raveena Gupta, Ripudaman Kaur, Daichi Oka, Sonali Kakkar, Sanjeev Kumar, Surendra Singh, Tomoteru Fukumura, Chandan Bera, and Suvankar Chakraverty*

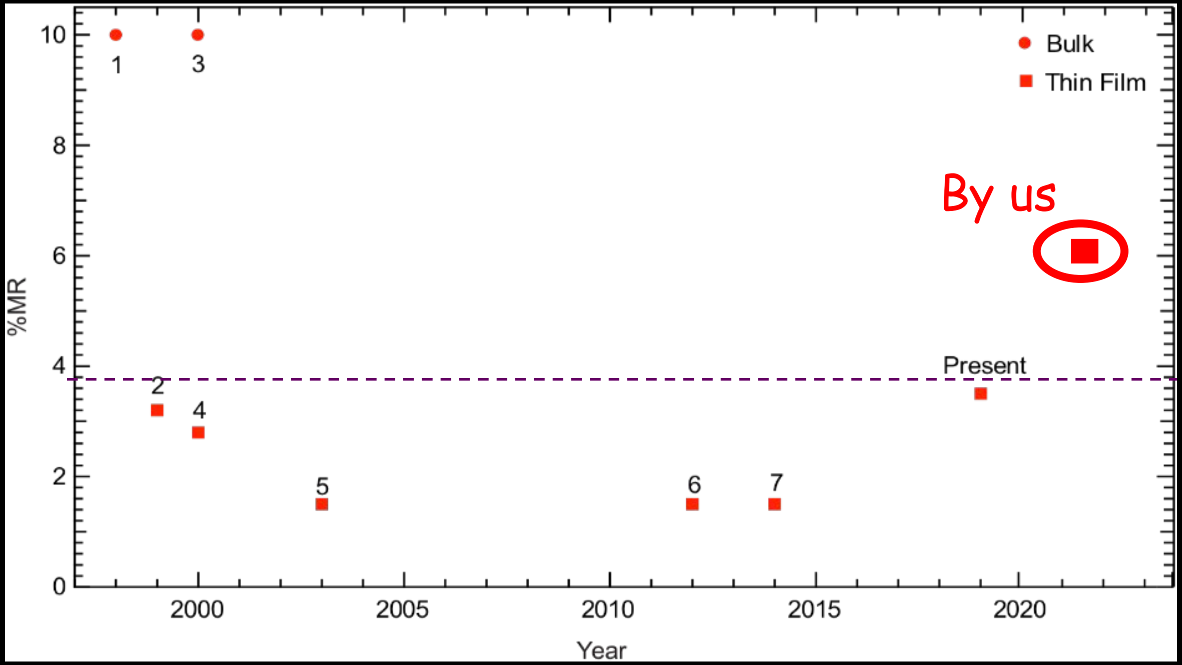
Changing the laser fluence







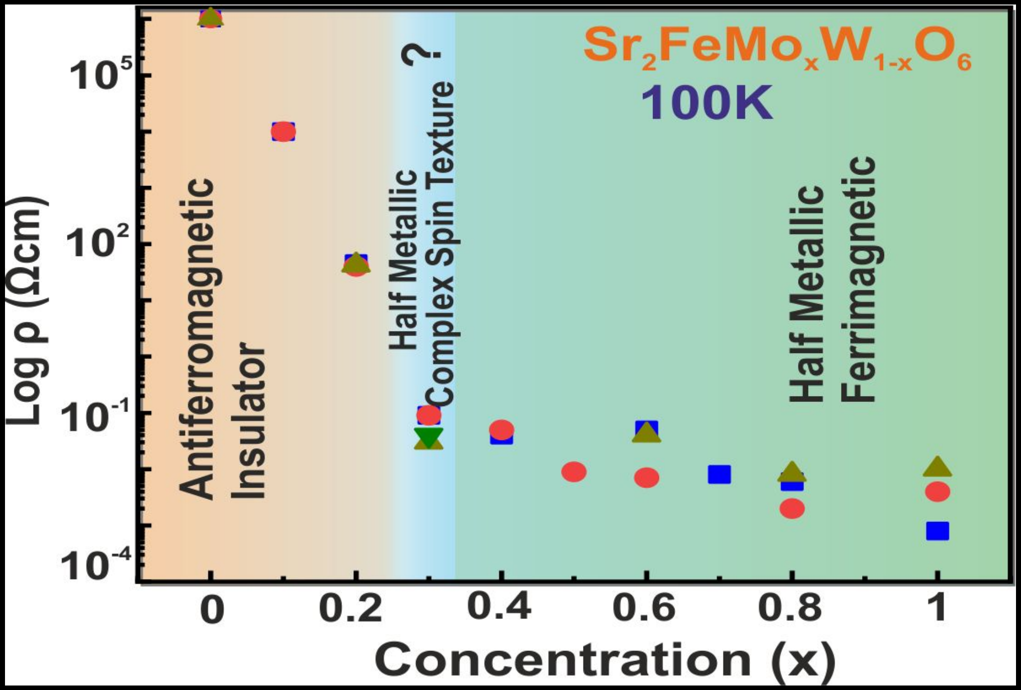
Summary

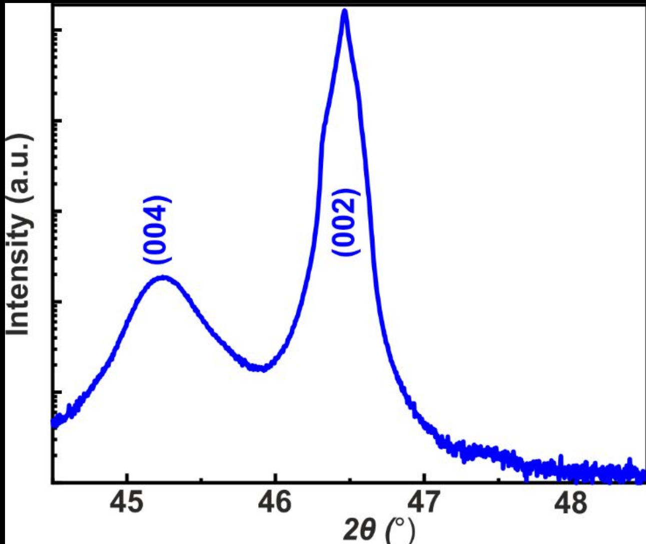


Laser fluence can play a vital role !!!

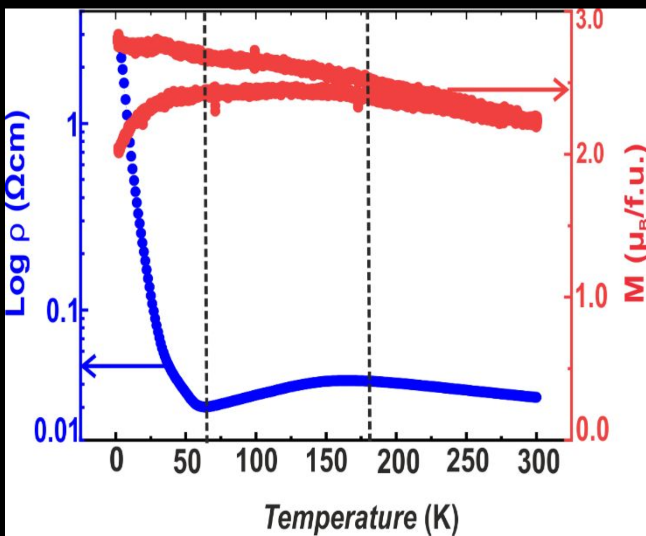
Problem with SFMO

W: SFMO Thin Film

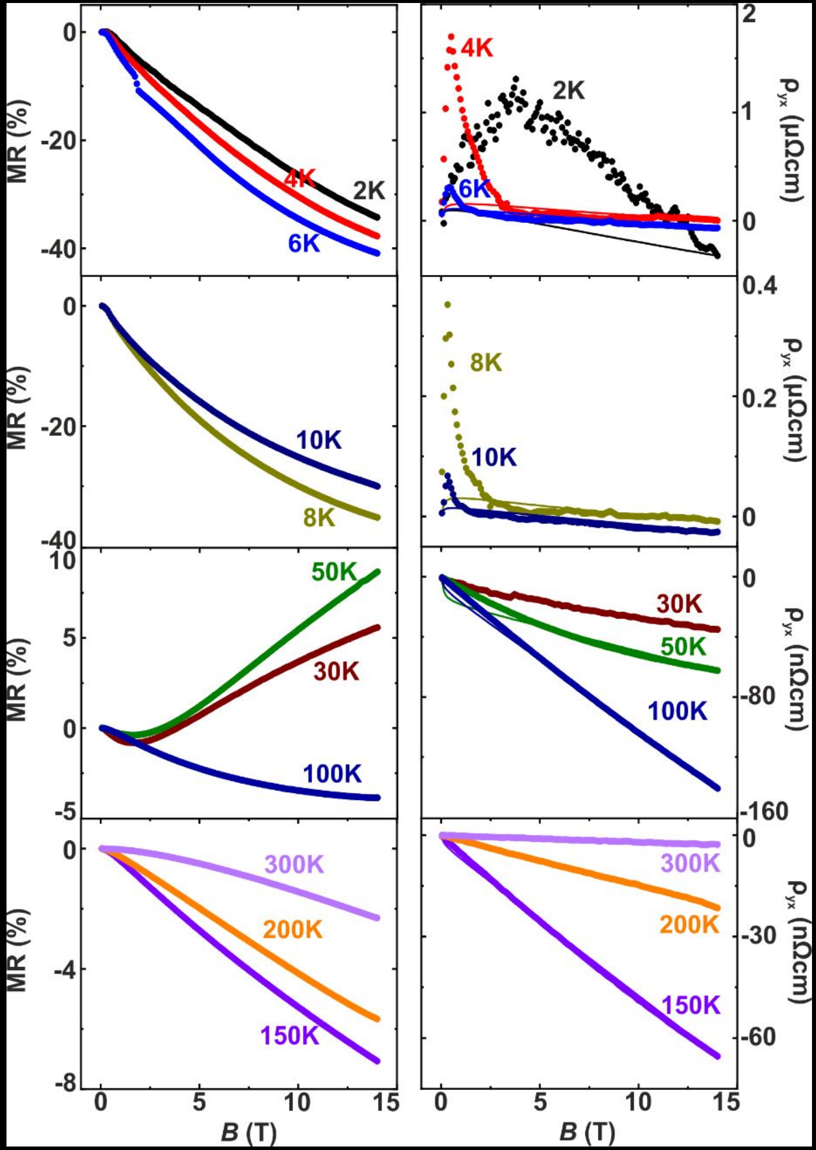




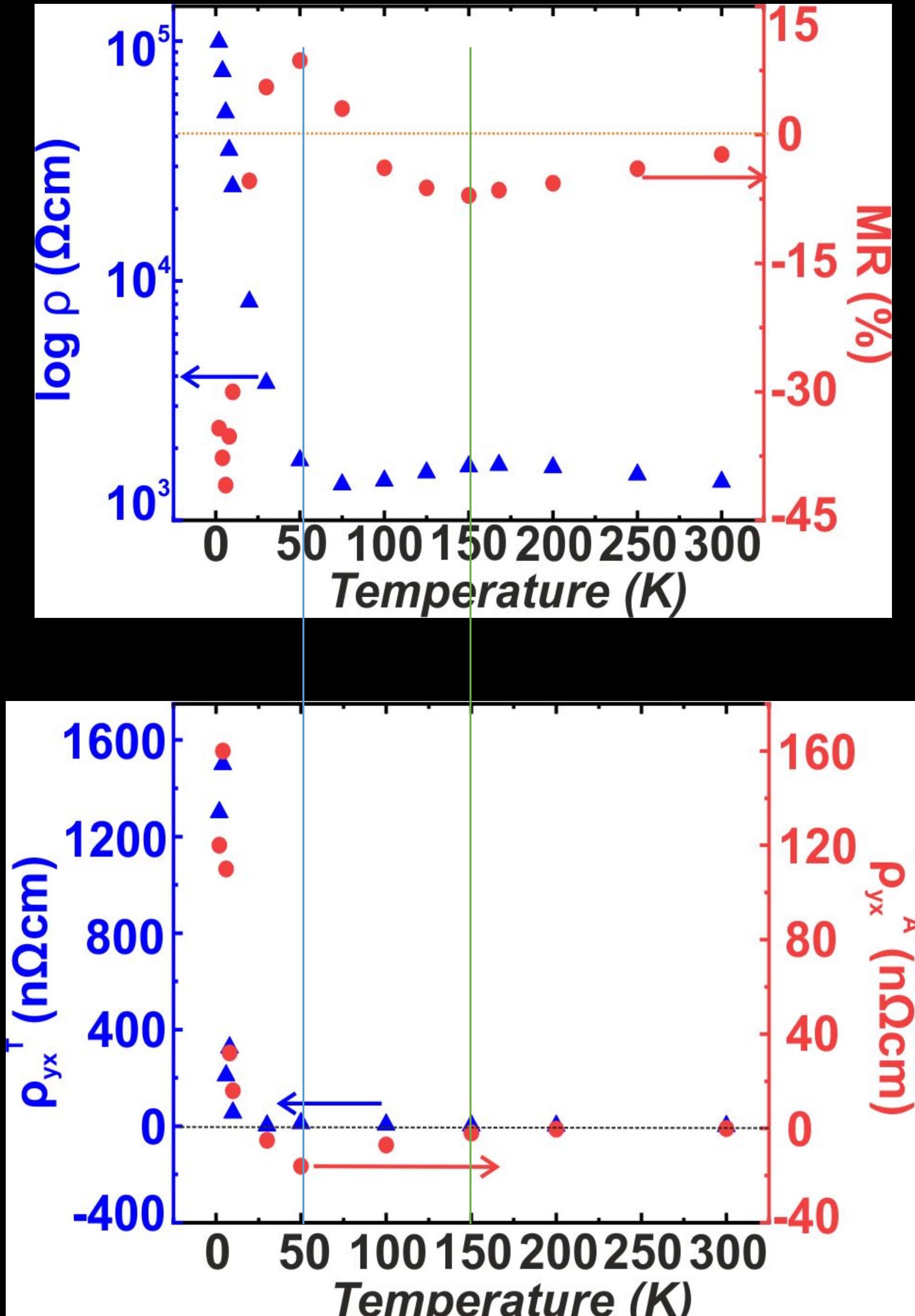
Intensity (a.u.)
(004)
(002)
45
46
47
48
2θ (°)



Log ρ (Ωcm)
M (μB/f.u.)
1
0.1
0.01
3.0
2.0
1.0
0.0
0
50
100
150
200
250
300
Temperature (K)



MR (%)
ρyx (μΩcm)
ρyx (nΩcm)
2K
4K
6K
8K
10K
30K
50K
100K
150K
200K
300K
B (T)



Several magneto-electronic Phases???

Conclusion

Grow a oxide thin film using pulsed laser deposition system: Effect of laser fluence

Materials : 1. LaVO3-SrTiO3 interface
2. Sr2FeMoO6 thin films

Crucial role of film stoichiometry

Unusual Quantum oscillation in resistance : Non-trivial spin texture in momentum space

Material : LaVO3 – KTaO3 interface

Looking at **longitudinal** conductivity

Non-linear Landau Fan diagram

Unusual magneto-transport: negative MR, Anomalous Hall, Topological Hall

Material : 1. LaFeO3 – SrTiO3 interface
2. W: SFMO

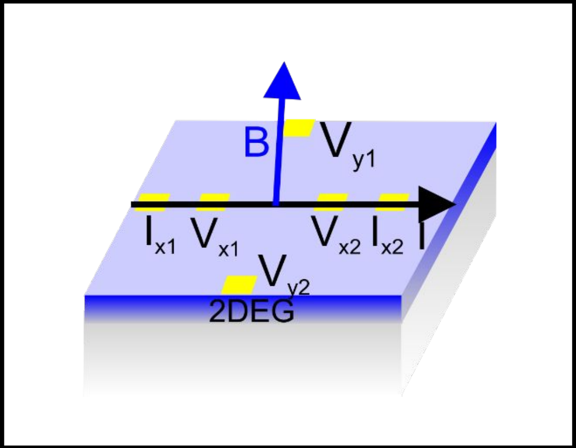
Crystal structure driven spin polarization transition

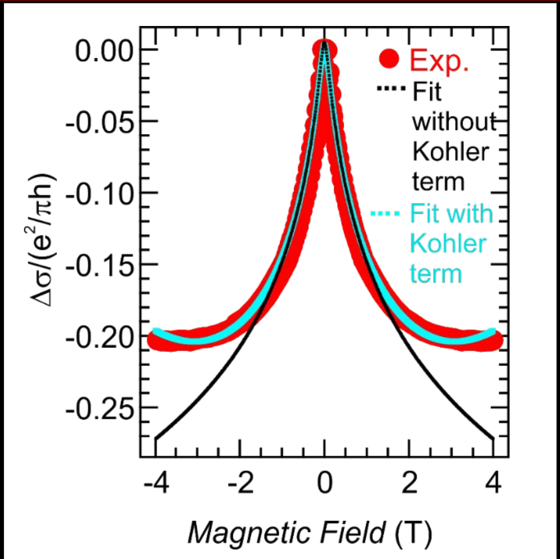
Our recent setected publications relevant for this talk:

1. Phys. Rev. B 109, 245405 (2024)
2. Phys. Rev. B (Lett.) 109, L201114 (2024)
3. Advanced Electronic Materials 8 (9), 2200195 (2023).
4. Adv. Quantum Technol, 2100105 (2022).
5. Adv, Mat. 34, 2106481 (2022).
6. Phys. Rev. B (Lett.) 104, L081111 (2021).
7. Adv. Quantum Technol. 2000081 (2020).
8. Advanced Materials Interfaces, 000: 2000646 (2020).
9. Nature communication, 11: 874(1-7) (2020).
10. Applied Surface Science, 509: 145214 (2020).
11. Advanced Material Interfaces, 1900941(1-6) (2019).
12. Journal of Applied Physics, 126: 35303 (2019).

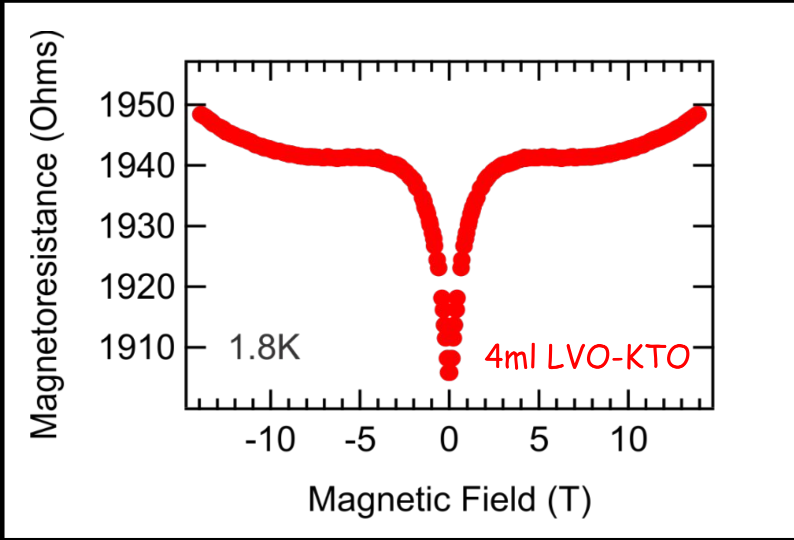
Thank you !!

Conventional magnetoresistance measurements





Signature of weak-antilocalization ! $\Delta\sigma = \frac{e^2}{2\pi^2\hbar}\left[\ln\left(\frac{B_\phi}{B}\right) - \psi\left(\frac{1}{2}+\frac{B_\phi}{B}\right) + \ln\left(\frac{\boldsymbol{B_{SO}}}{\boldsymbol{B}}\right) - \psi\left(\frac{1}{2}+\frac{B_{SO}}{B}\right) - A_k B^2\right]$



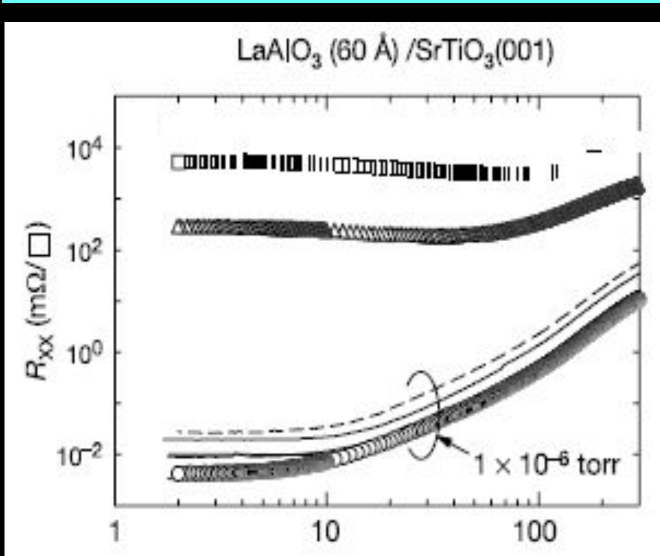
B_{so} ~ 4.4T : Rashba!!!
Non Trivial spin texture in "Momentum Space"

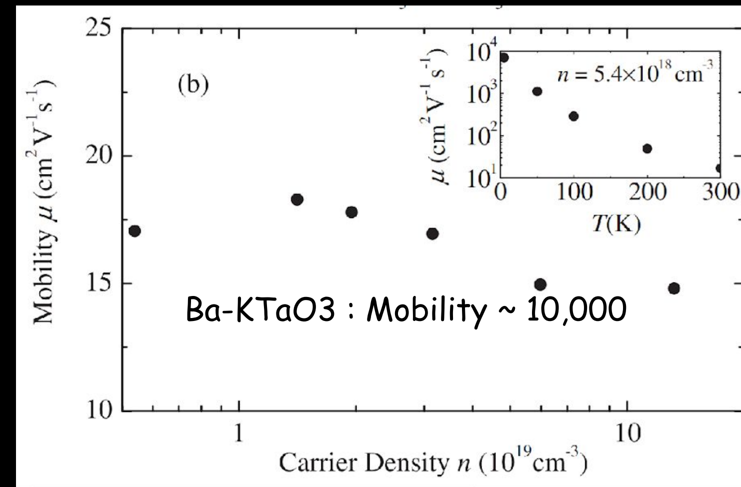
A high mobility electron gas at $LaAlO_3$/ $SrTiO_3$ heterointerface

KTaO3

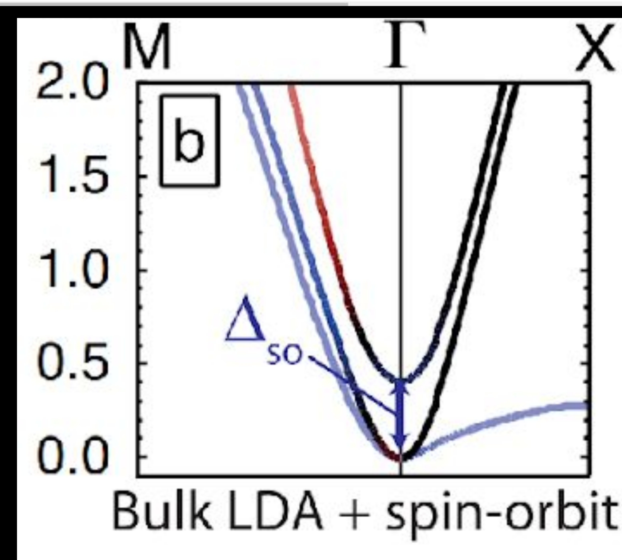
A. Ohtomo et. al. Nature 2004, 427, 423

Jpn J Appl Phys, 48(9R):097002, (2009)



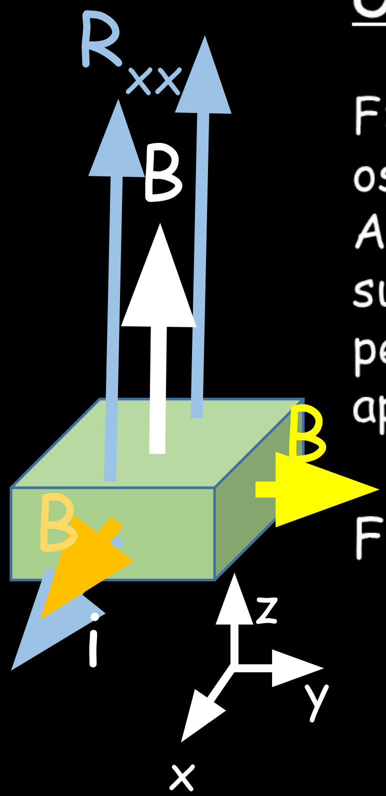


Possible Strong Spin Orbit Coupled perovskite oxides



KTaO3(001)
Single crystal:
SOC ~ 300mEv

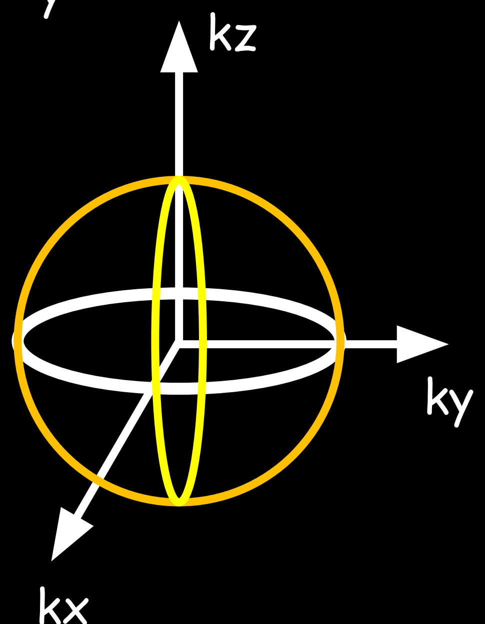
Phys. Rev. Lett. **108**, 117602 (2012)



Onsagar relation:

F: Frequency of oscillation
A: Area of the Fermi surface perpendicular to the applied field

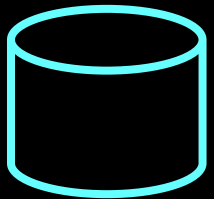
$$F = \frac{\hbar}{2\pi e} A\ (\varepsilon_F)$$



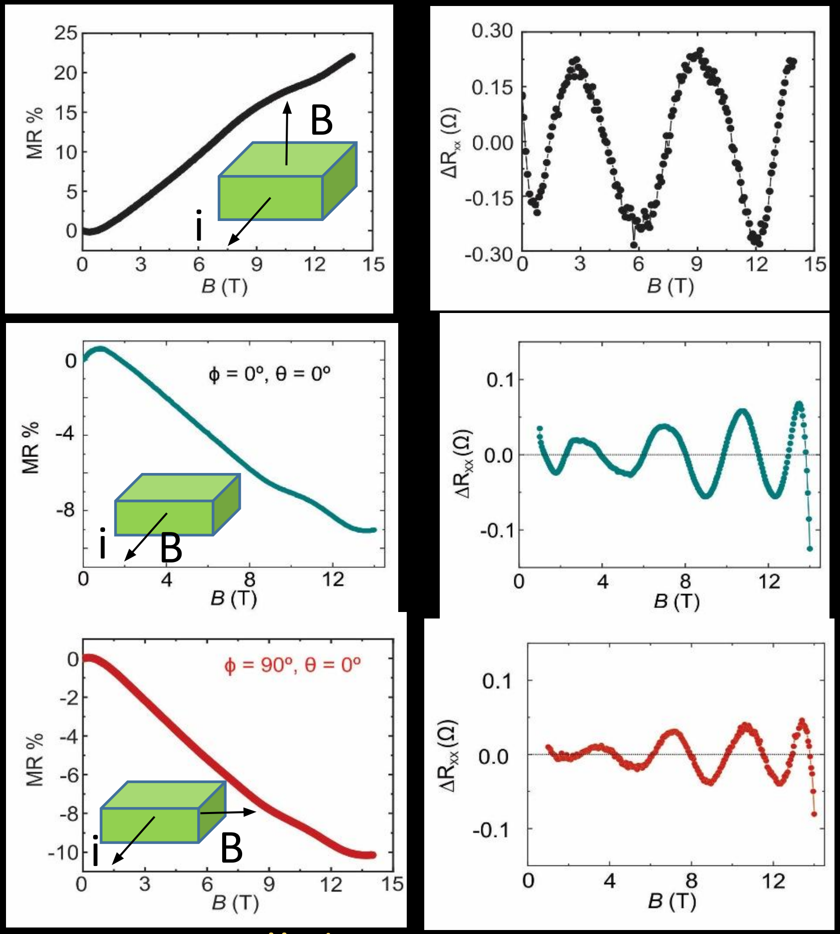
Finite frequency in all direction

Closed Fermi surface: 3D type carrier

Finite frequency in only one direction

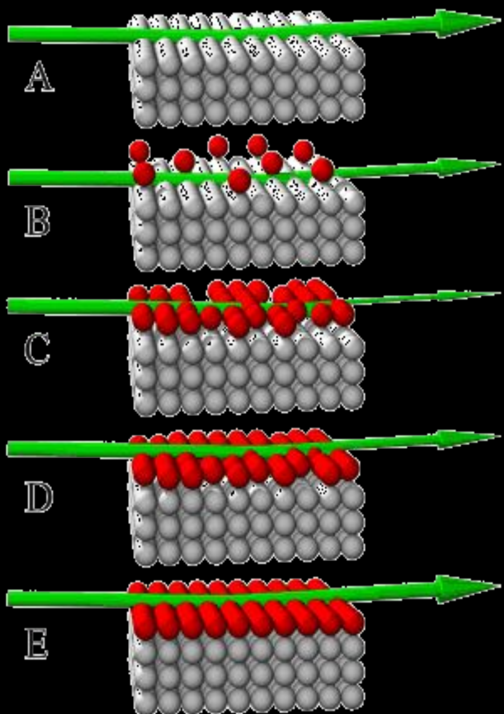


Open Fermi surface: 2D type carrier

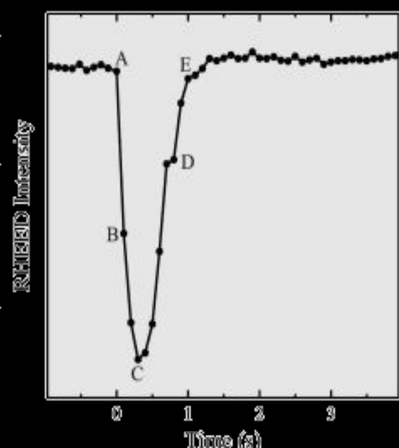


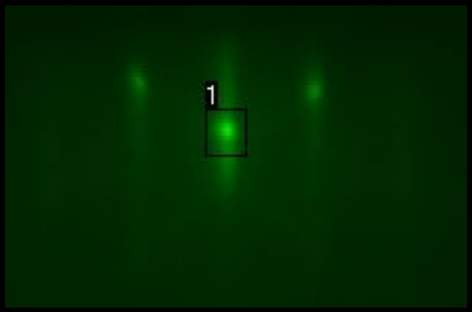
Finite frequency in all direction :3D type carrier

Reflection High Energy Electron beam diffraction (RHEED) technique

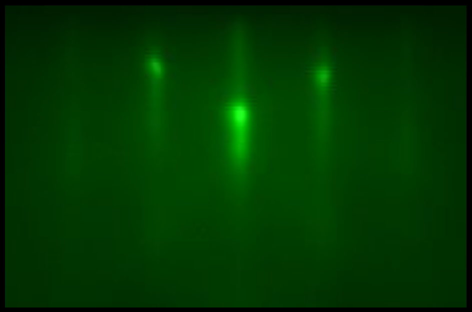


RHEED

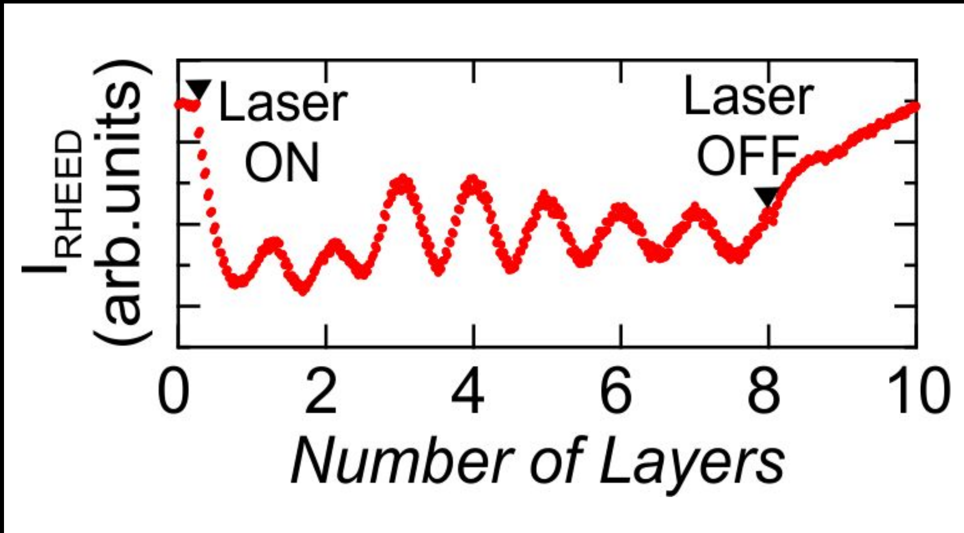




RHEED before deposition



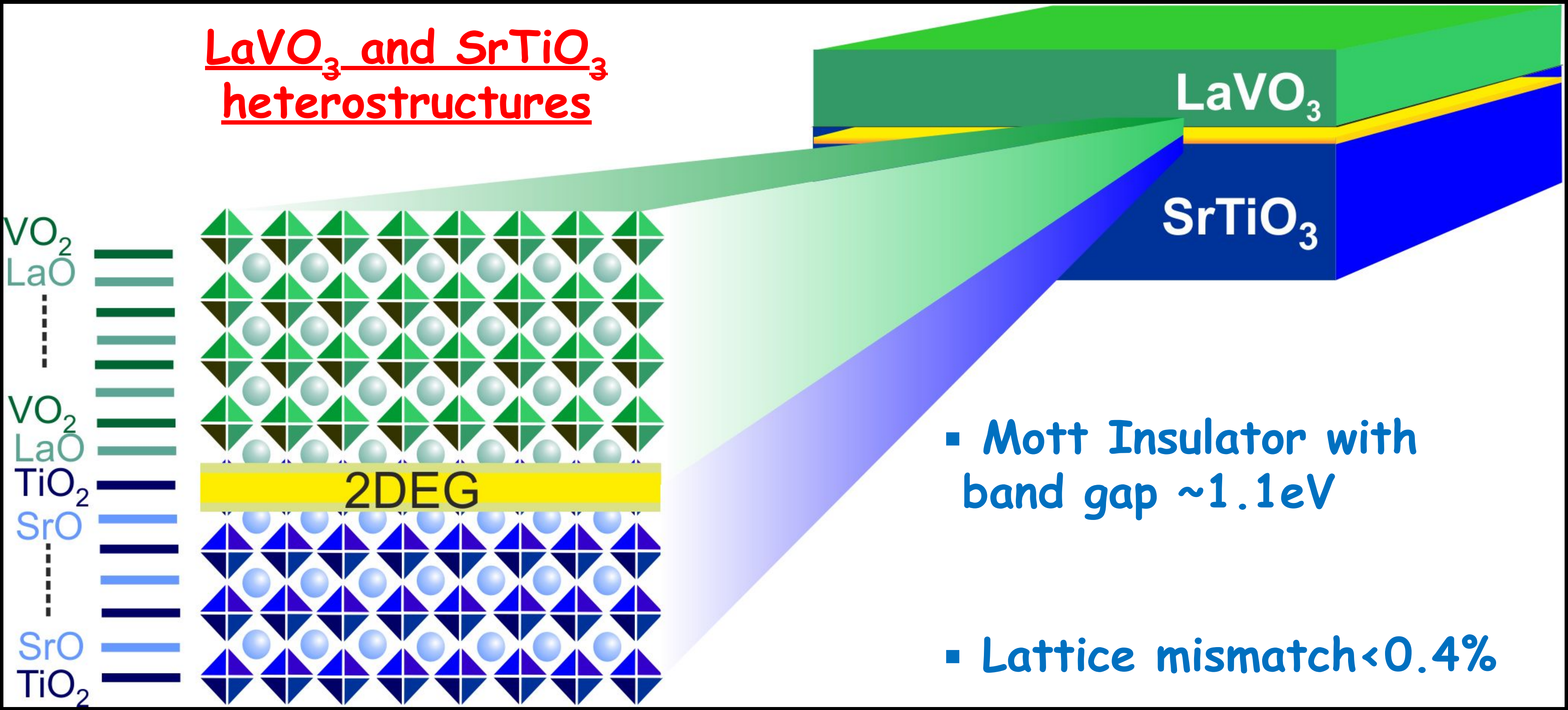
RHEED after deposition



Precise film thickness control by RHEED technique

Is cationic stoichiometry mandatory to produce conductivity at oxide interface?

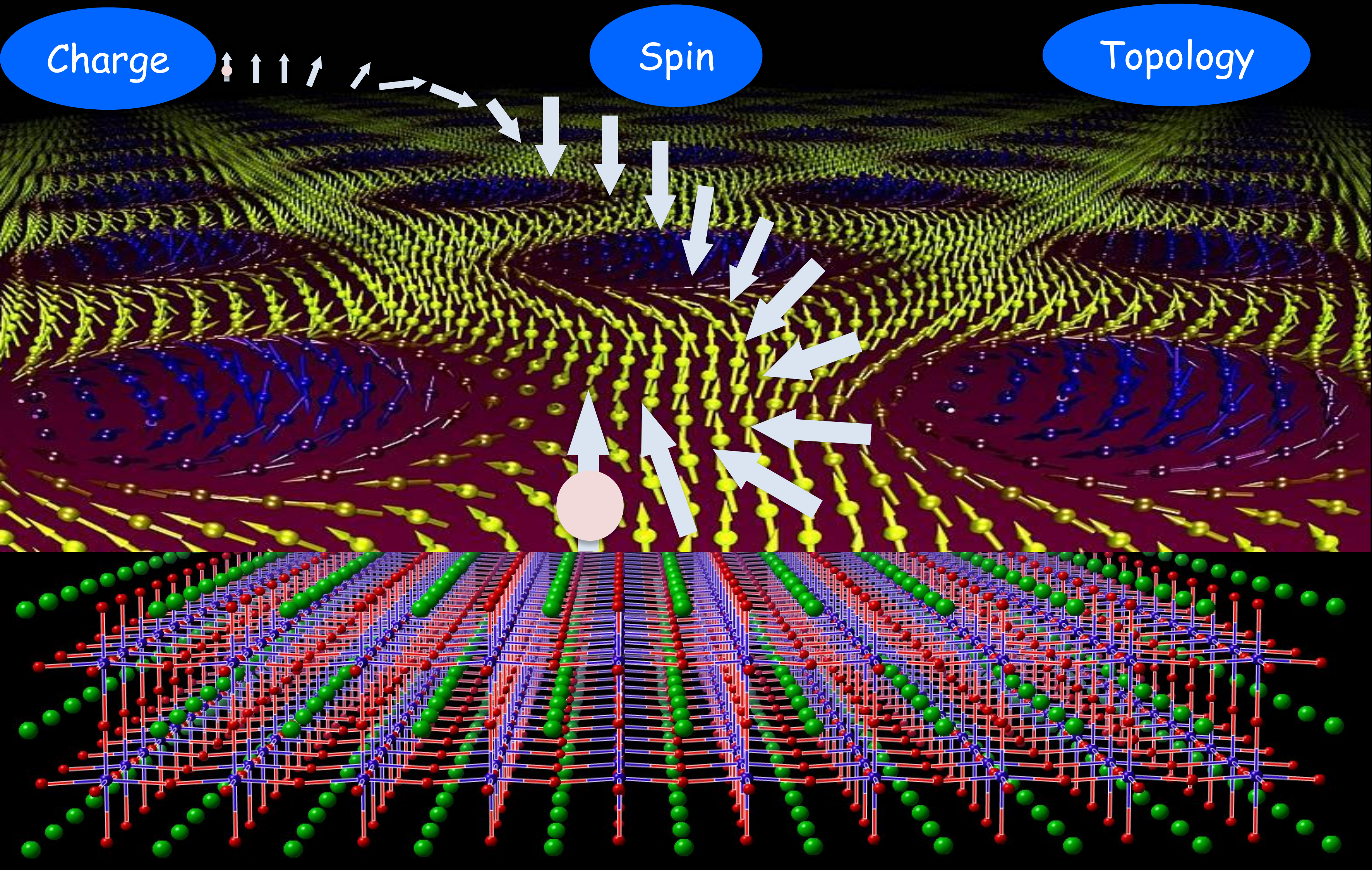
Ruchi et. al. Adv. Mater. Interfaces 2019, 1900941



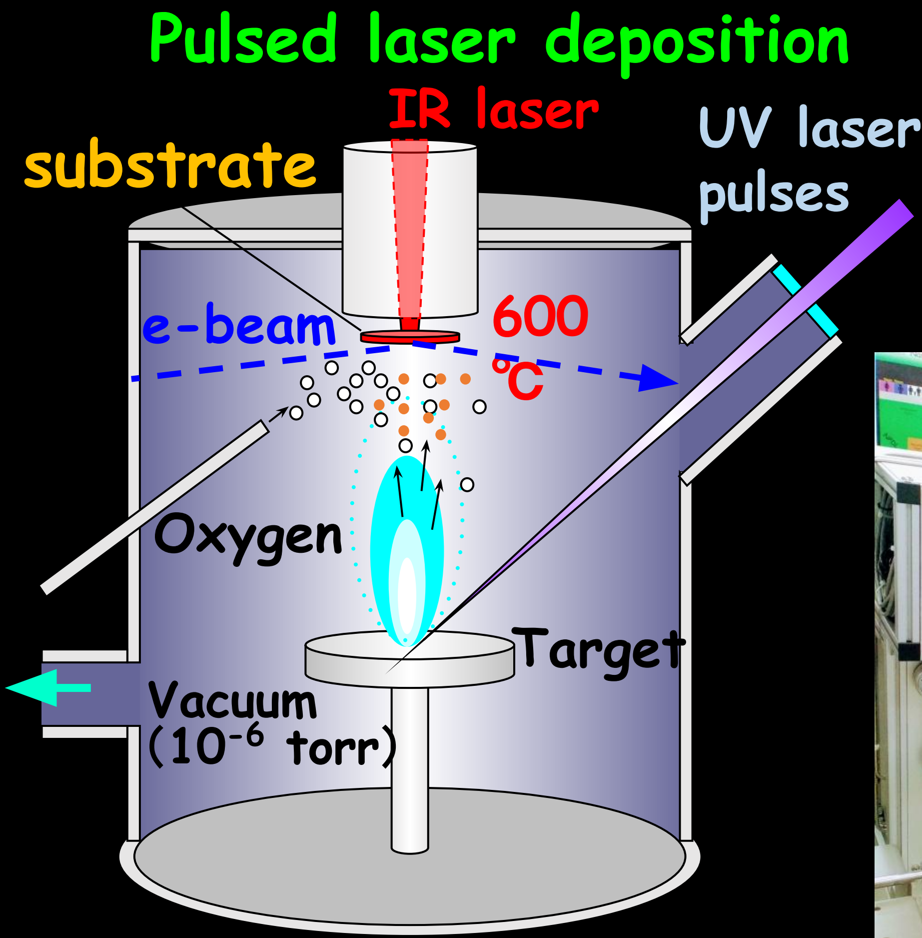
- Mott Insulator with band gap ~1.1eV
- Lattice mismatch<0.4%

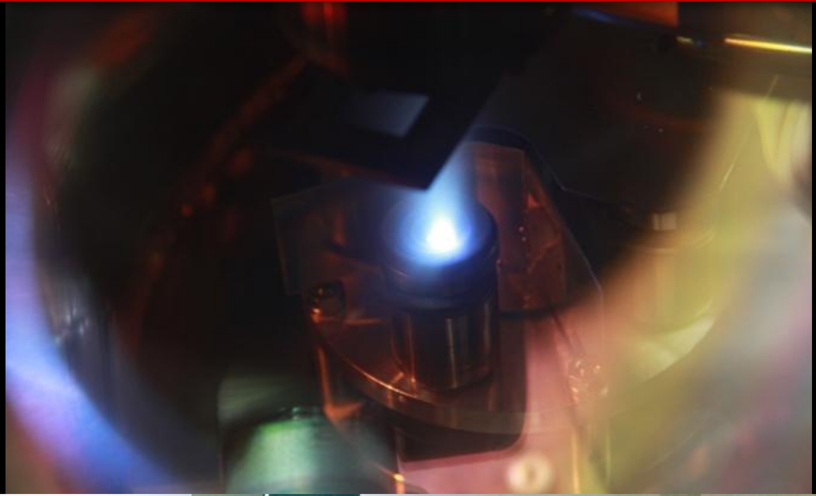
Less possibility of oxygen vacancies in STO of LVO/STO heterostruture as compared to LAO-STO

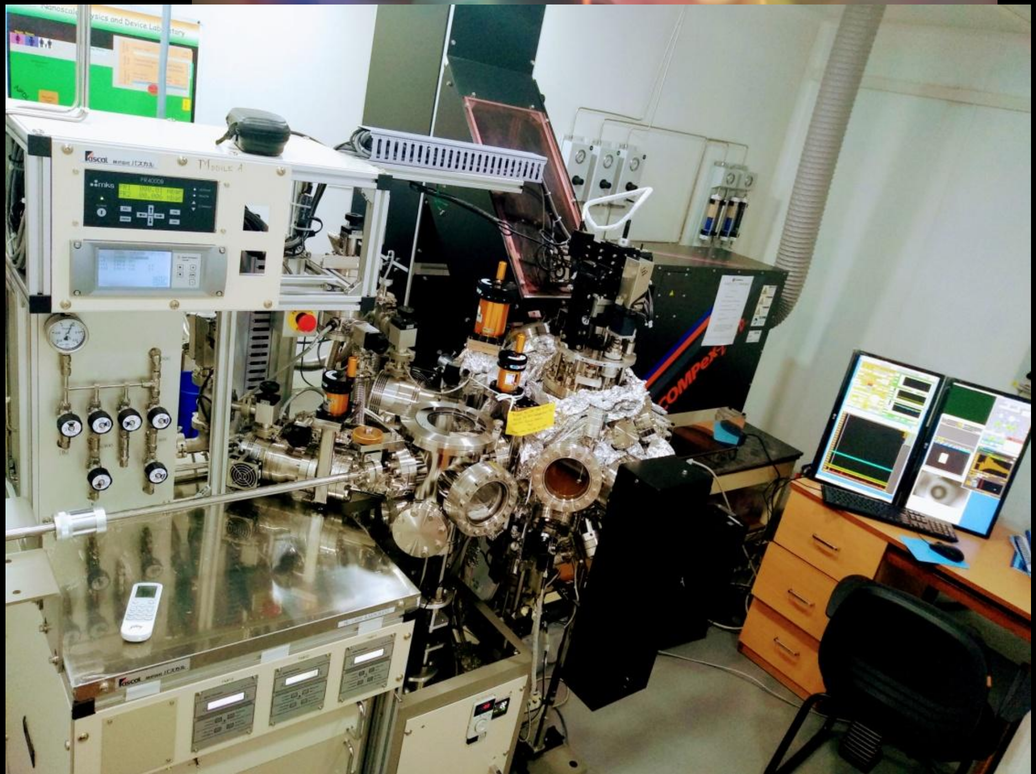
Electron Motion through a non-trivial spin texture



Thin film growth using Pulse Laser Deposition







$LaVO_3$-$SrTiO_3$ (001) heterostructures

Deposition parameters:

- ❑ Oxygen partial pressure (1×10^{-6} Torr)
- ❑ Growth temperature (T_g = 600°C)
- ❑ Laser spot area (A=0.03 cm^2)
- ❑ Frequency (2Hz)
- ❑ Laser fluence (Laser energy/area)

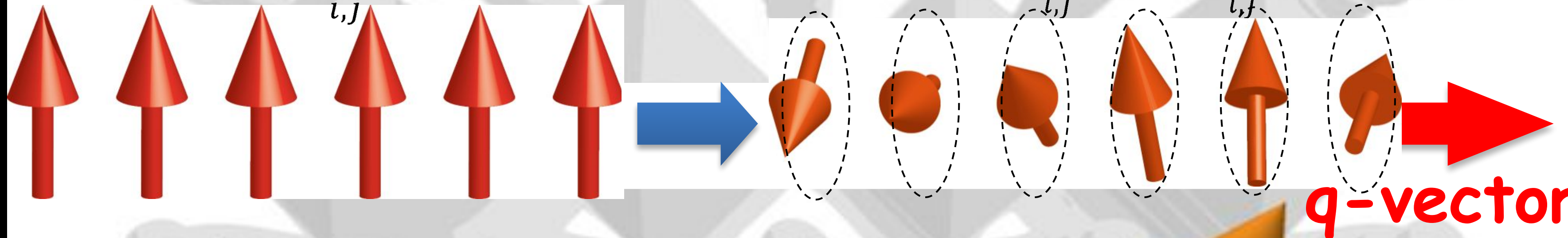
Laser fluence is varied

Non-trivial spin texture in real space

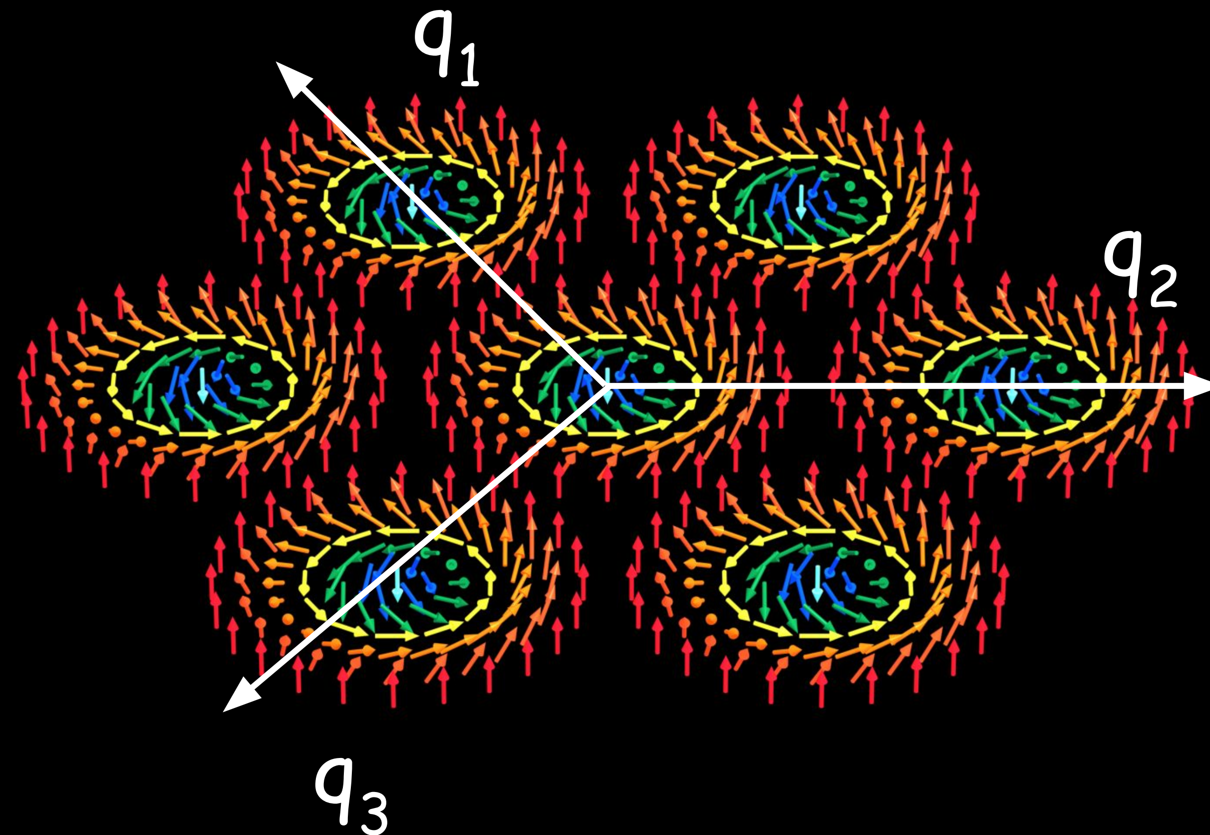
skyrmion crystal formation

$$\mathcal{H} = -J\sum_{i,j}\vec{S}_i\cdot\vec{S}_j$$

$$\mathcal{H} = -J\sum_{i,j}\vec{S}_i\cdot\vec{S}_j - \sum_{i,j}\vec{D}_{i,j}\cdot(\vec{S}_i\times\vec{S}_j)$$



Multiple q-vectors

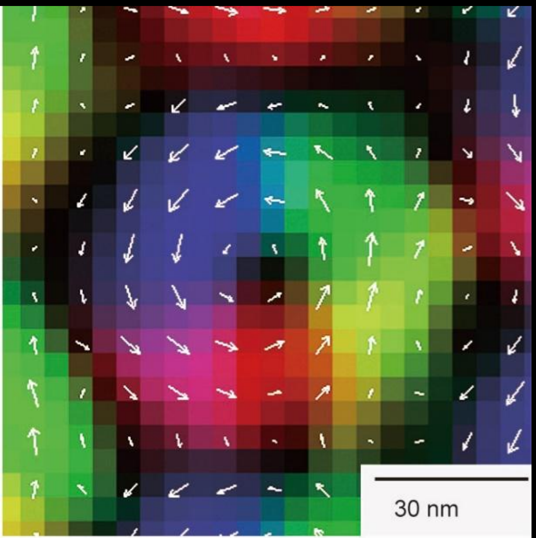


skyrmion crystal

Mühlbauer *et al*,
Science (2009)

Detection techniques :

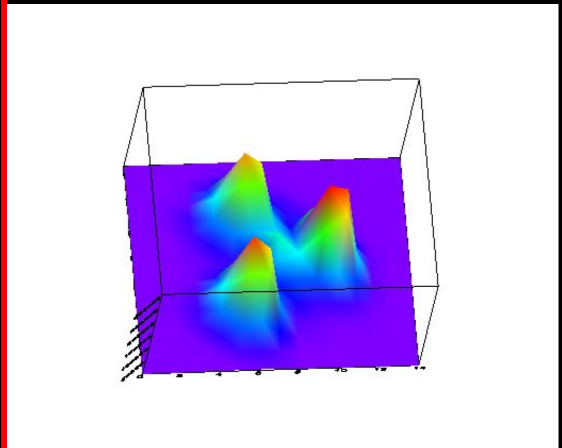
By Lorentz TEM



Limitation :

1. The resolution is ~ 3nm.
2. Difficult for thin films (?)

Neutron diffraction

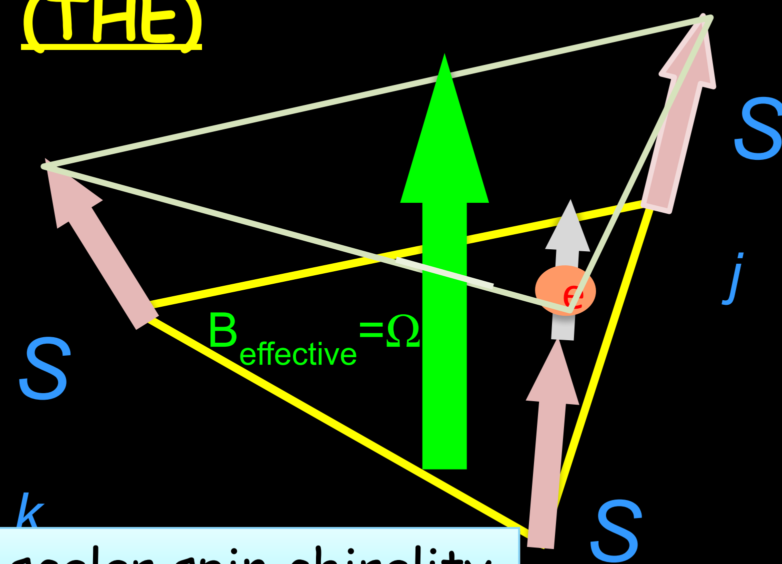


Limitation :

1. Needs large volume.

Resonant soft x-ray diffraction

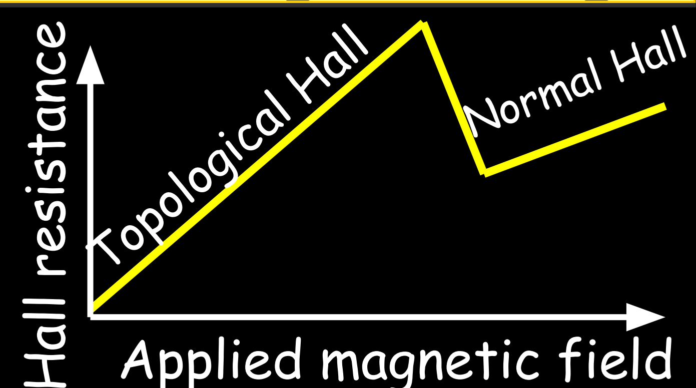
Topological Hall Effect (THE)



scalar spin chirality

Fictitious flux (in a continuum limit)

$$\Phi \propto \frac{\mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)}{2} = \frac{\Omega}{2}$$



Skyrmion : magnetic mono pole !!!

Solid angle $\Omega = 4\pi$

$$\Phi = (\Omega/4\pi)\varphi_0 : \quad \varphi_0 = h/e$$

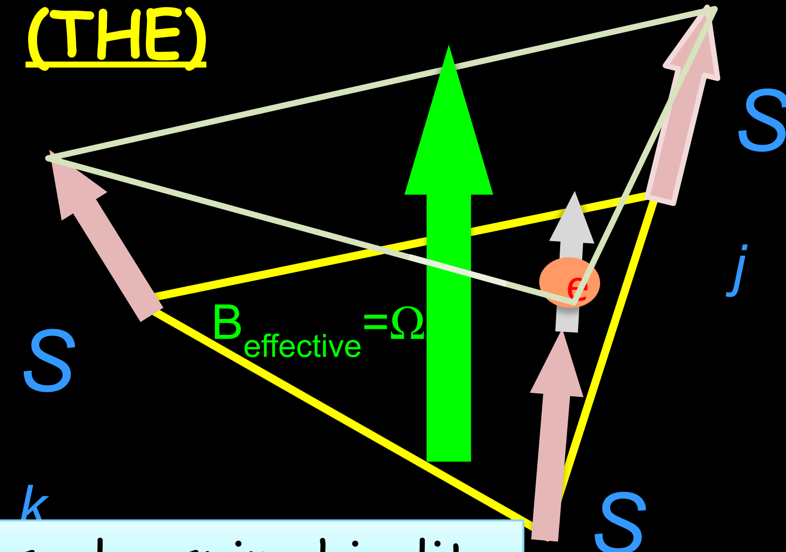
One Skyrmion ↔ One magnetic flux

$$\Phi = \varphi_0 = h/e$$

Magnetic mono pole !!!

Detection techniques :

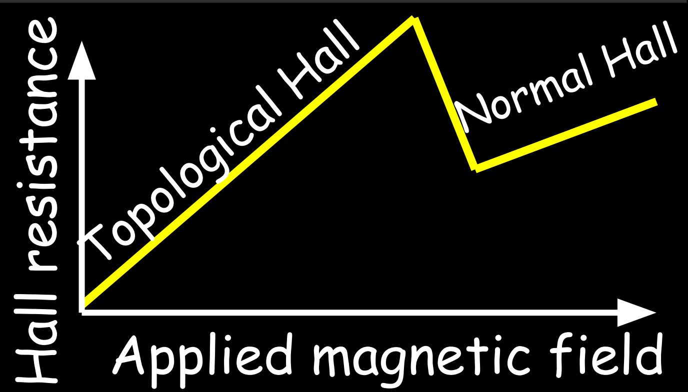
Topological Hall Effect (THE)



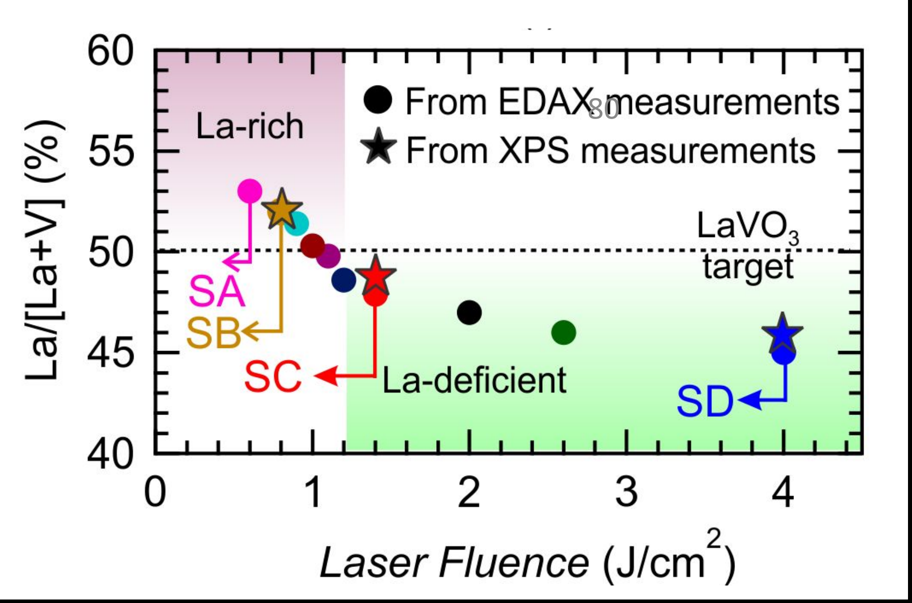
scalar spin chirality

Fictitious flux (in a continuum limit)

$$\Phi \propto \frac{\mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)}{2} = \frac{\Omega}{2}$$

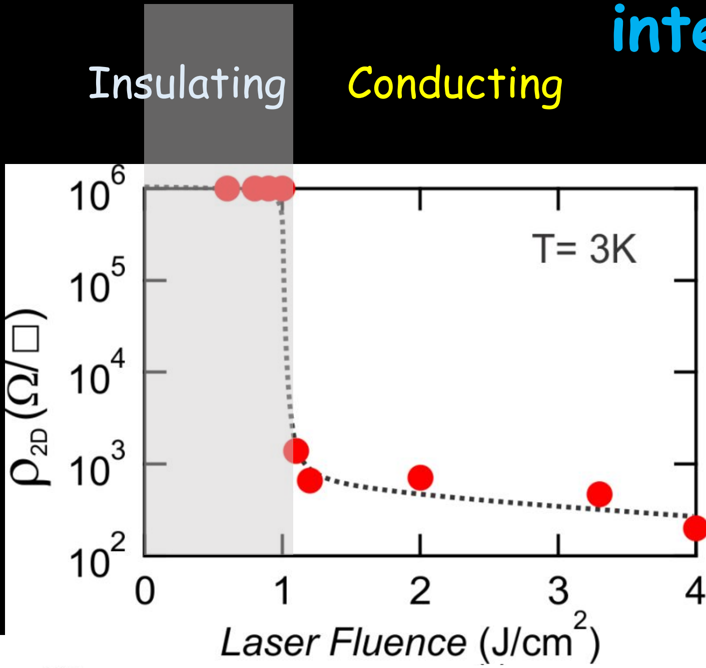


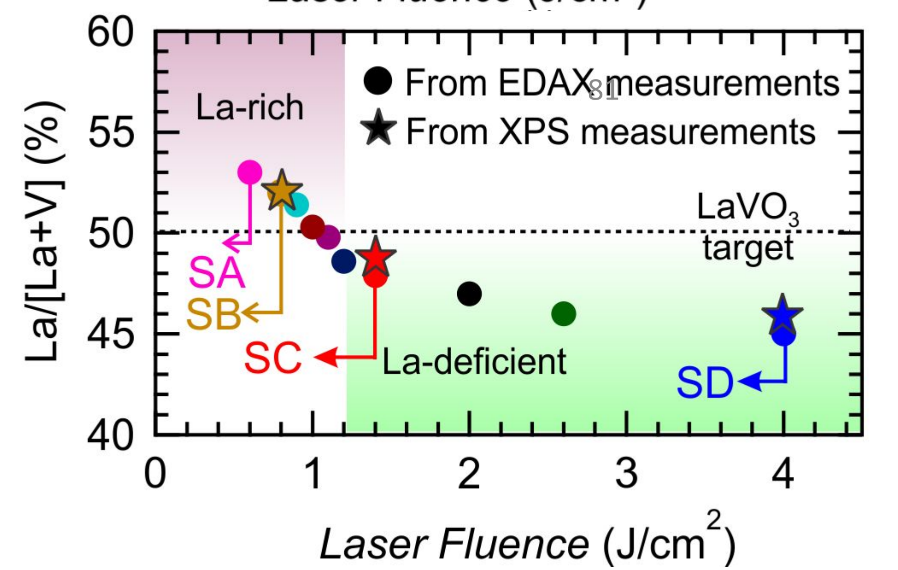
Film stoichiometry by XPS and EDX Spectroscopy

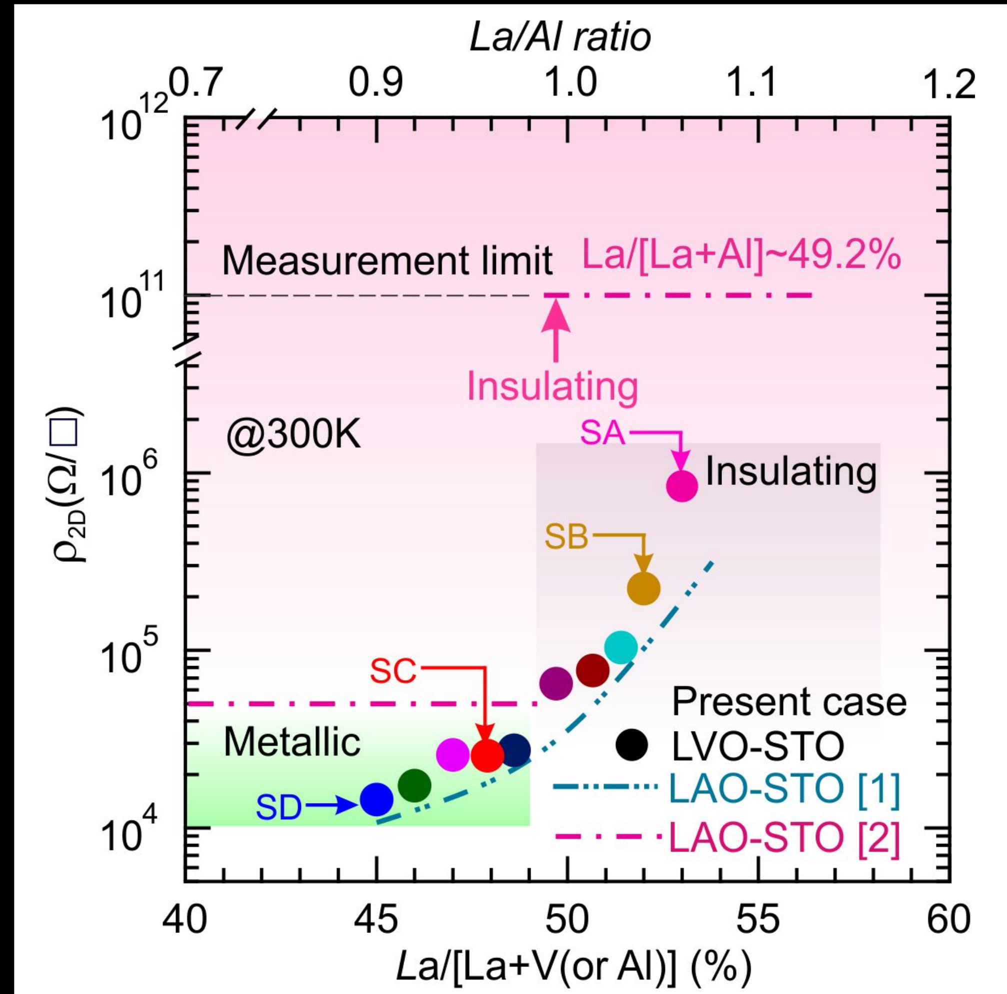


Change in film stoichiometry with laser fluence

Film stoichiometry is a key to realize conducting interface of Perovskite oxides



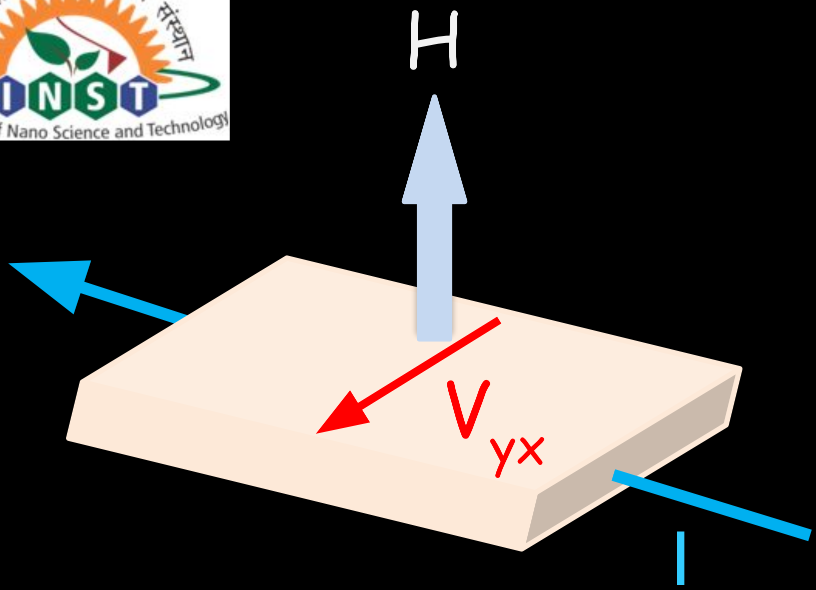




1. PRL 2013, 110, 196804

2. MNat. Comm. 2013, 4, 2351

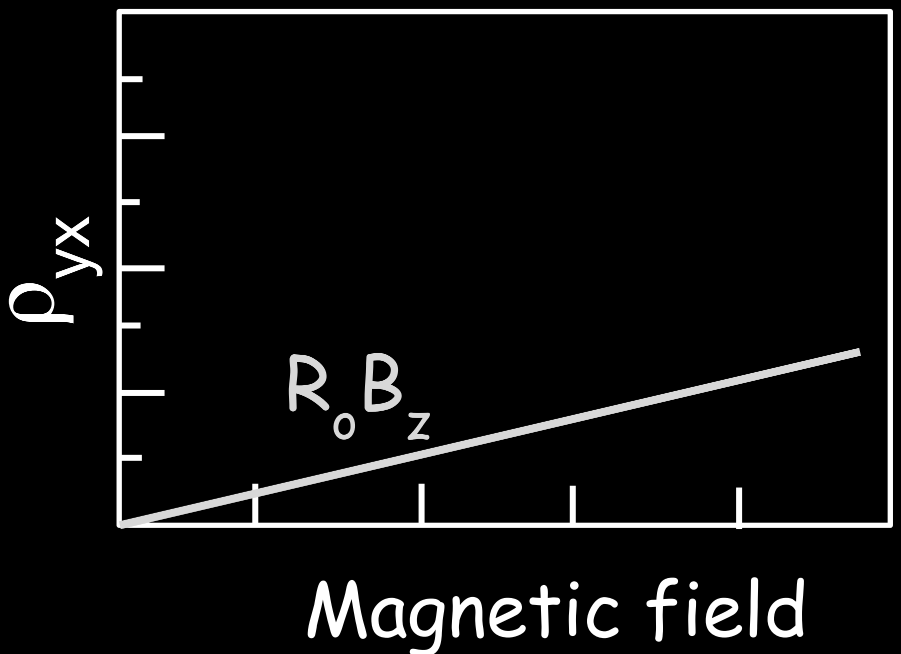
Change in film stoichiometry with laser fluence

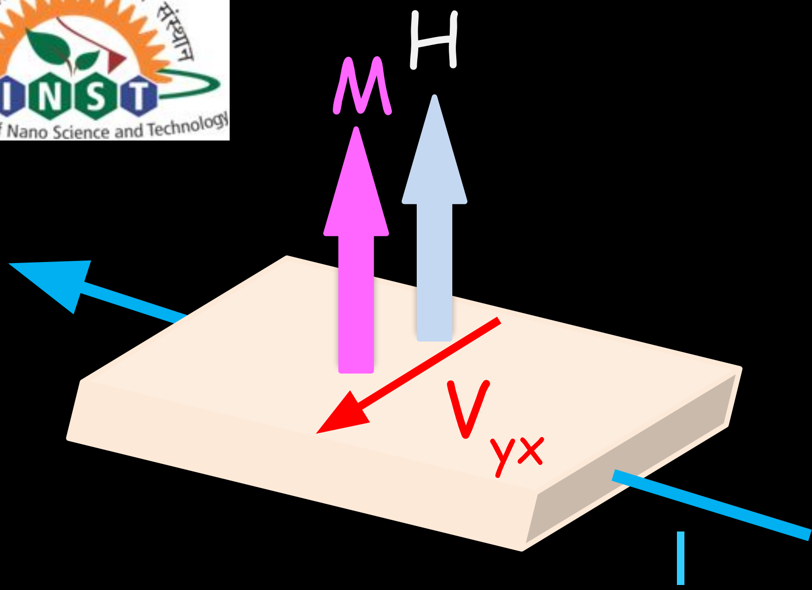


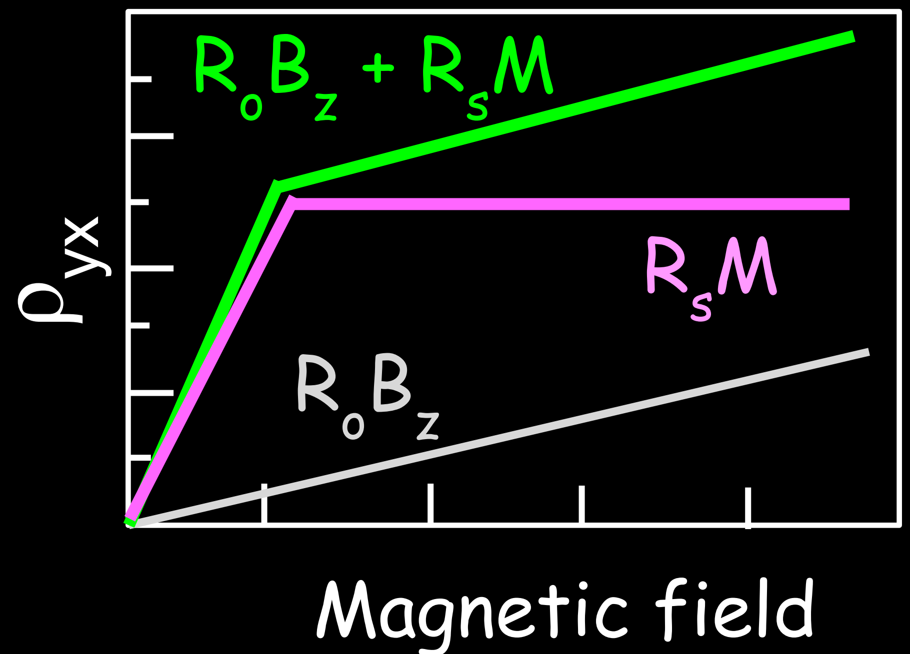
Empirical relation

$\rho_{yx} = R_o B_z$

Normal Hall
Lorentz force







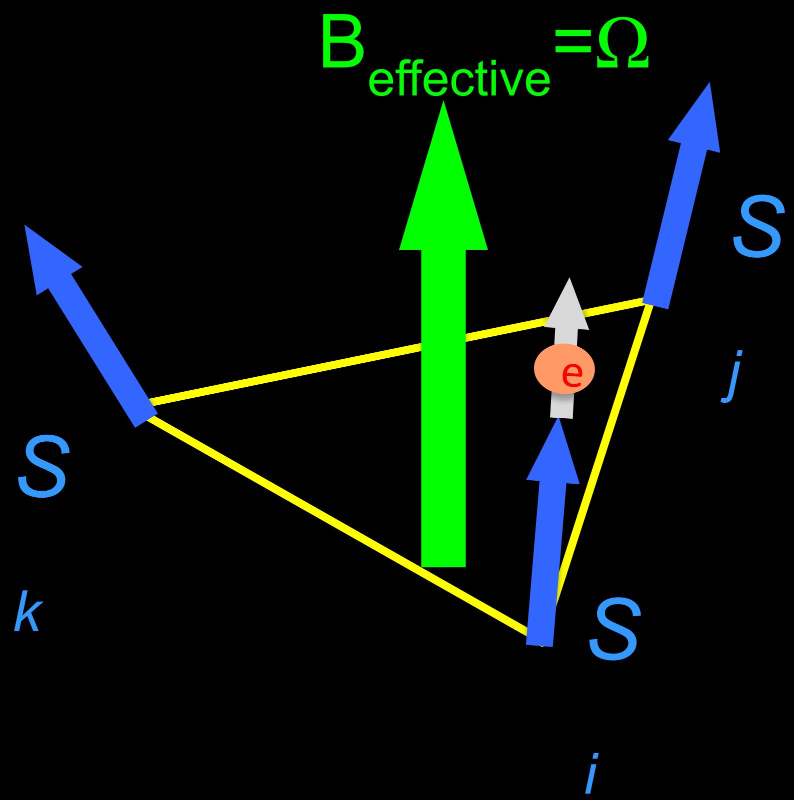
Empirical relation

$$\rho_{yx} = \boxed{R_o B_z} + \boxed{R_s M}$$

Normal Hall
Lorentz force

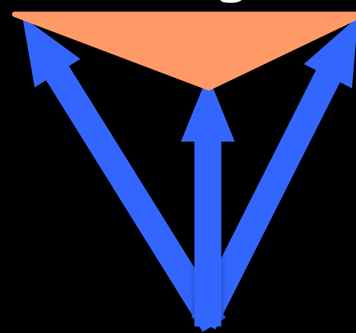
Anomalous Hall
Proportional to M

Solid angle by spins acting as a Fictitious magnetic field



scalar spin chirality

Solid angle : Ω



Fictitious flux (in a continuum limit)

$$\Phi \propto \frac{\mathbf{S}_i \cdot (\mathbf{S}_j \times \mathbf{S}_k)}{2} = \frac{\Omega}{2}$$

$\Phi = (\Omega/4\pi)\varphi_0$: $\varphi_0 = h/e$

What will be shown?

I. Fundamental Aspects

0. Why Such interfaces are conducting???

LaVO3 – KTaO3: conducting interface

1. Non-trivial quantum oscillation in magneto-transport:

a. Nonlinear Landau fan diagram
b. Angular dependent quantum mobility

LaFeO3 – SrTiO3: conducting interface

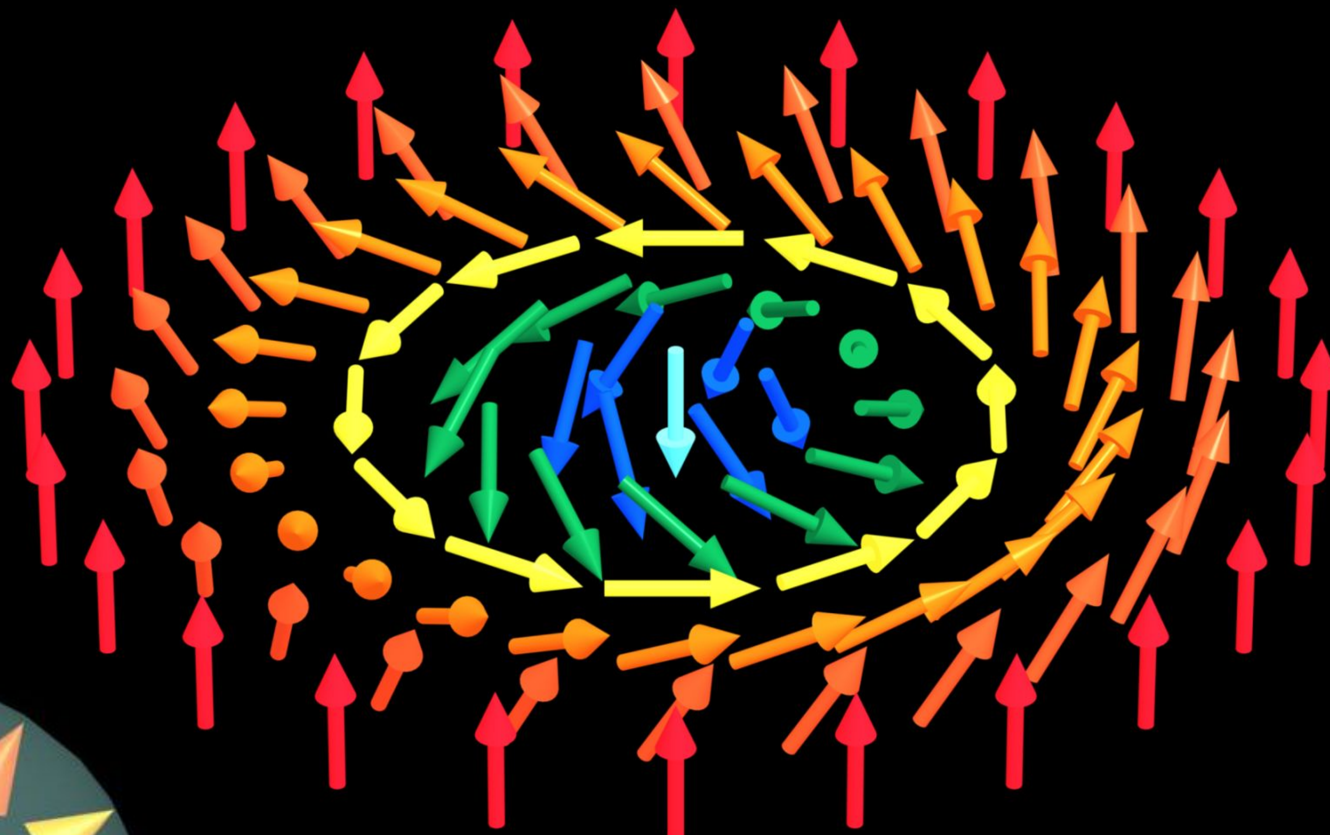
4. A step towards room temperature oxide electronics:

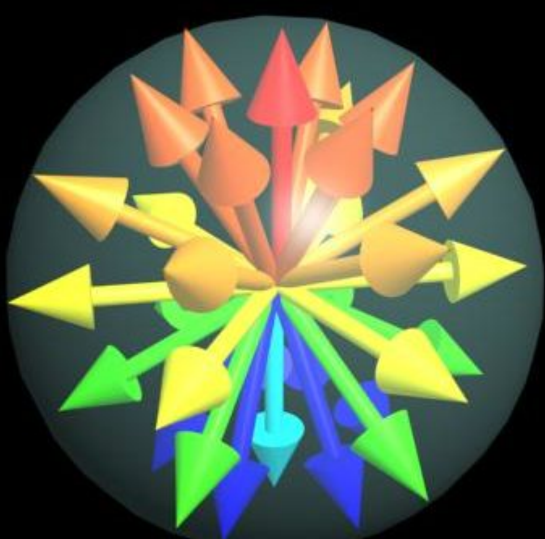
a. Room temperature anomalous Hall effect and Negative magneto resistance

II. Some Possible applications

a. Holographic Memory
b. Electrostatic Memory

Skyrmion : magnetic mono pole !!!





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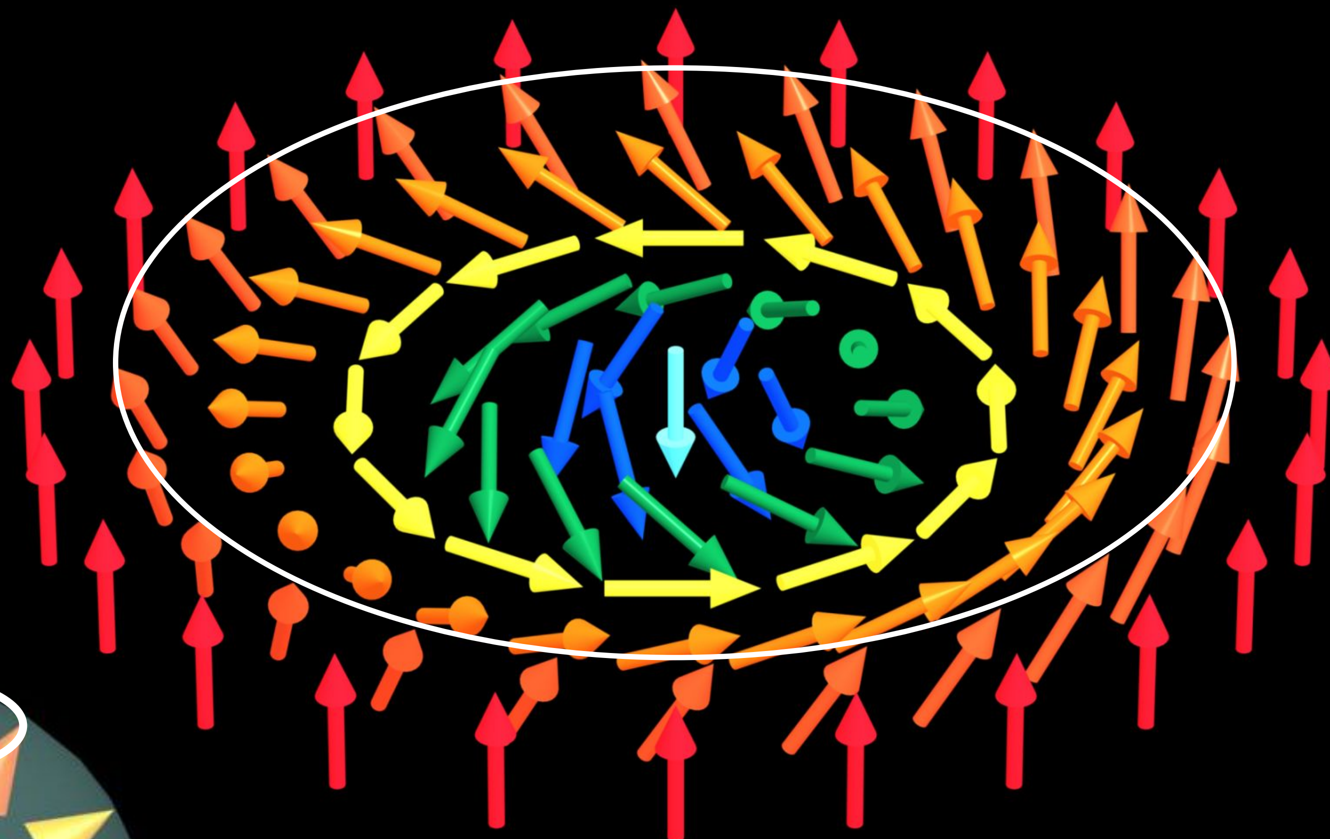
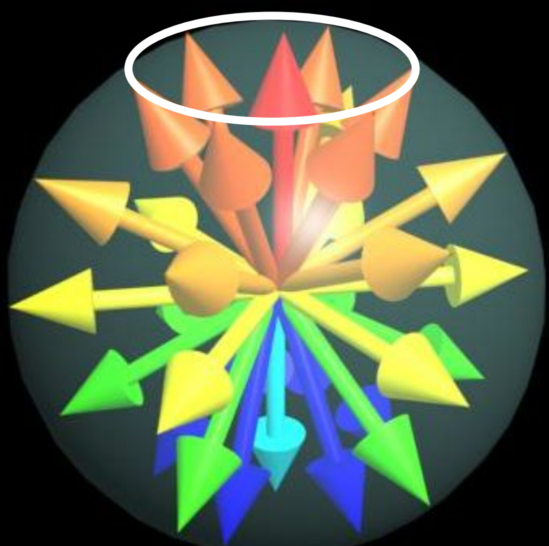
Skyrmion : magnetic mono pole !!!





RHEED and AFM analysis of the surface of the samples grown at different laser fluence

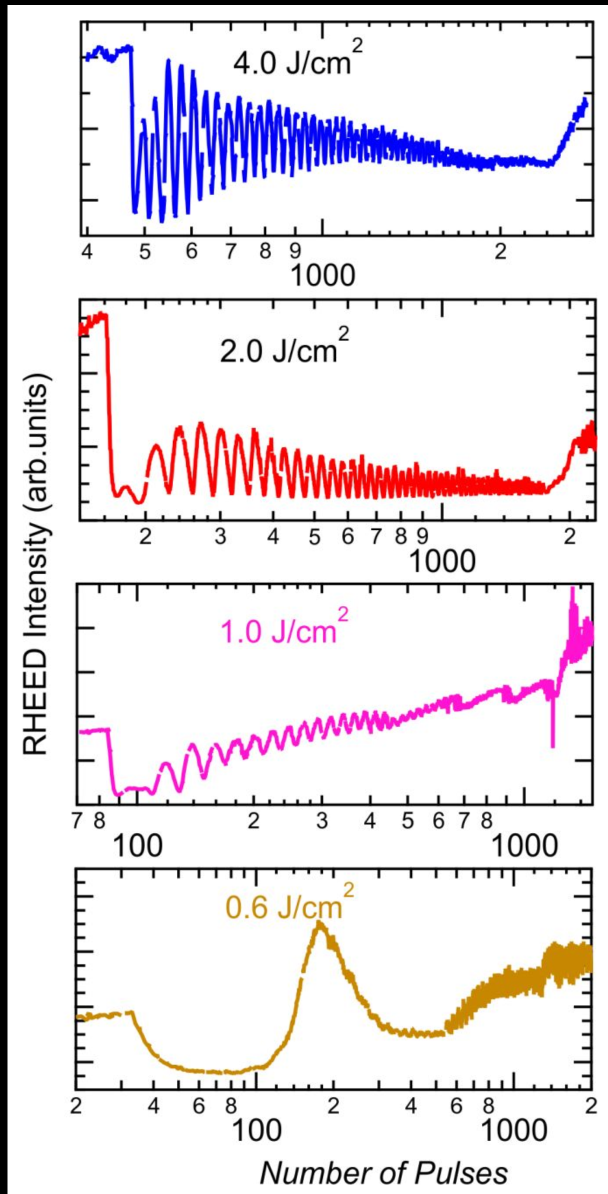
Fluence | **RHEED Oscillations** | **RHEED pattern** | **AFM images**

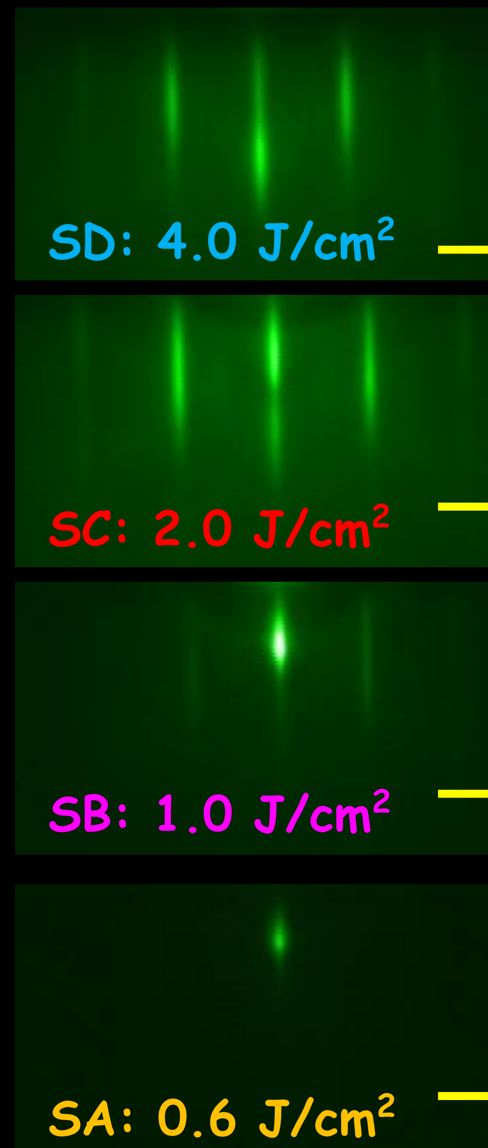
4 J/cm^2

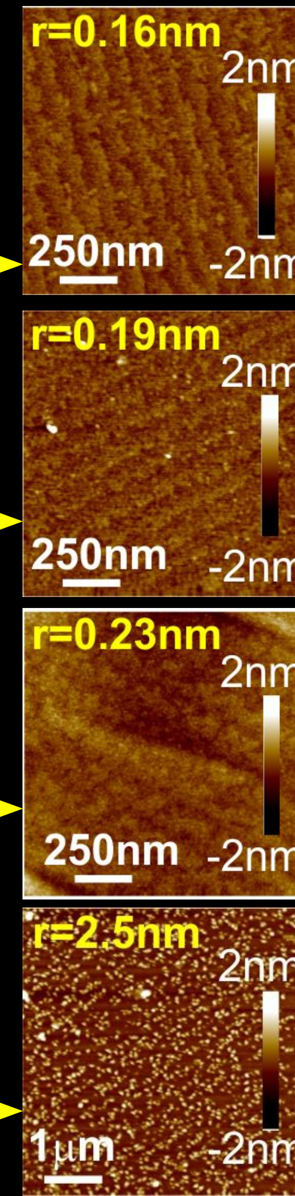
2 J/cm^2

1 J/cm^2

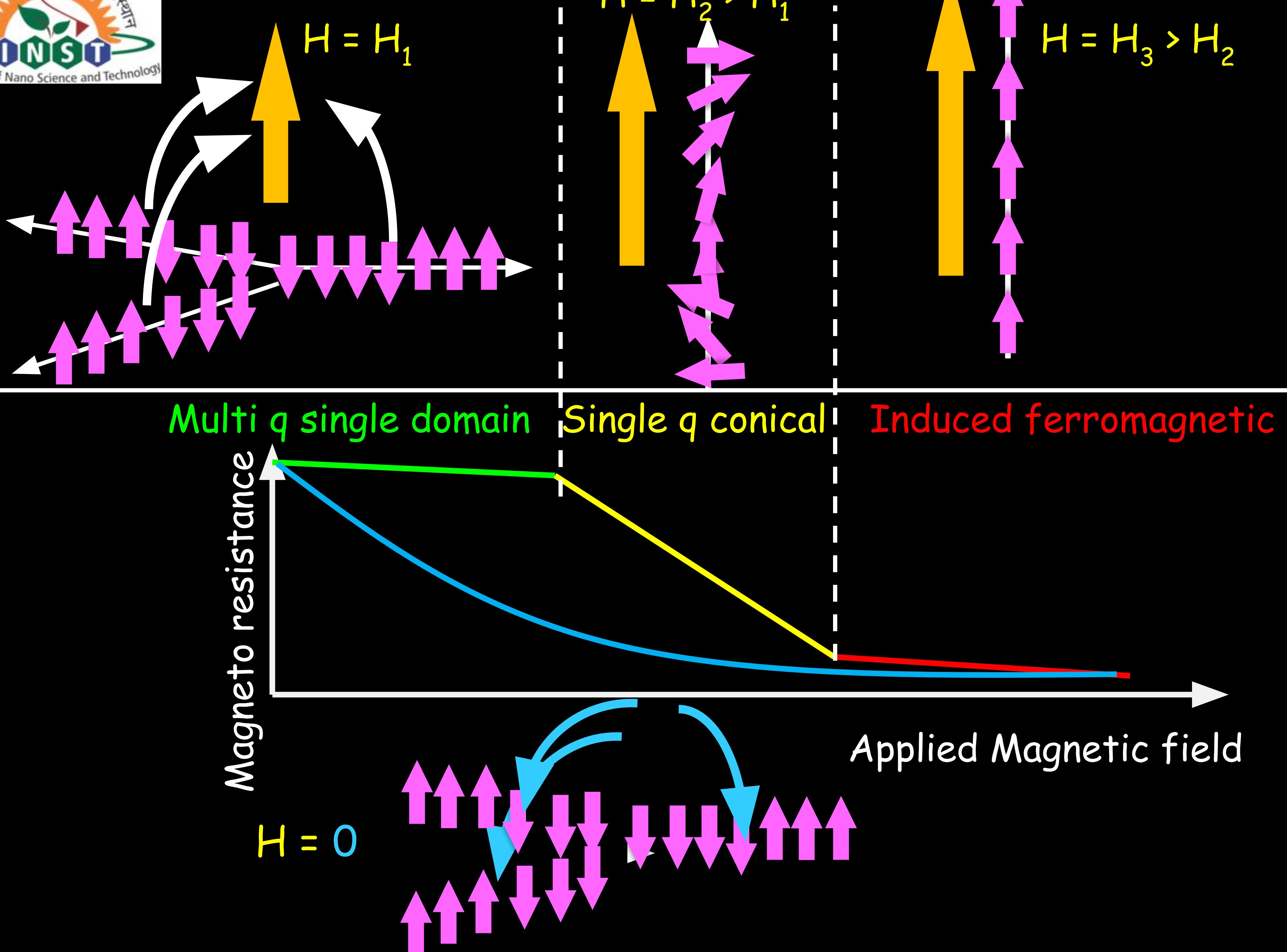
0.6 J/cm^2



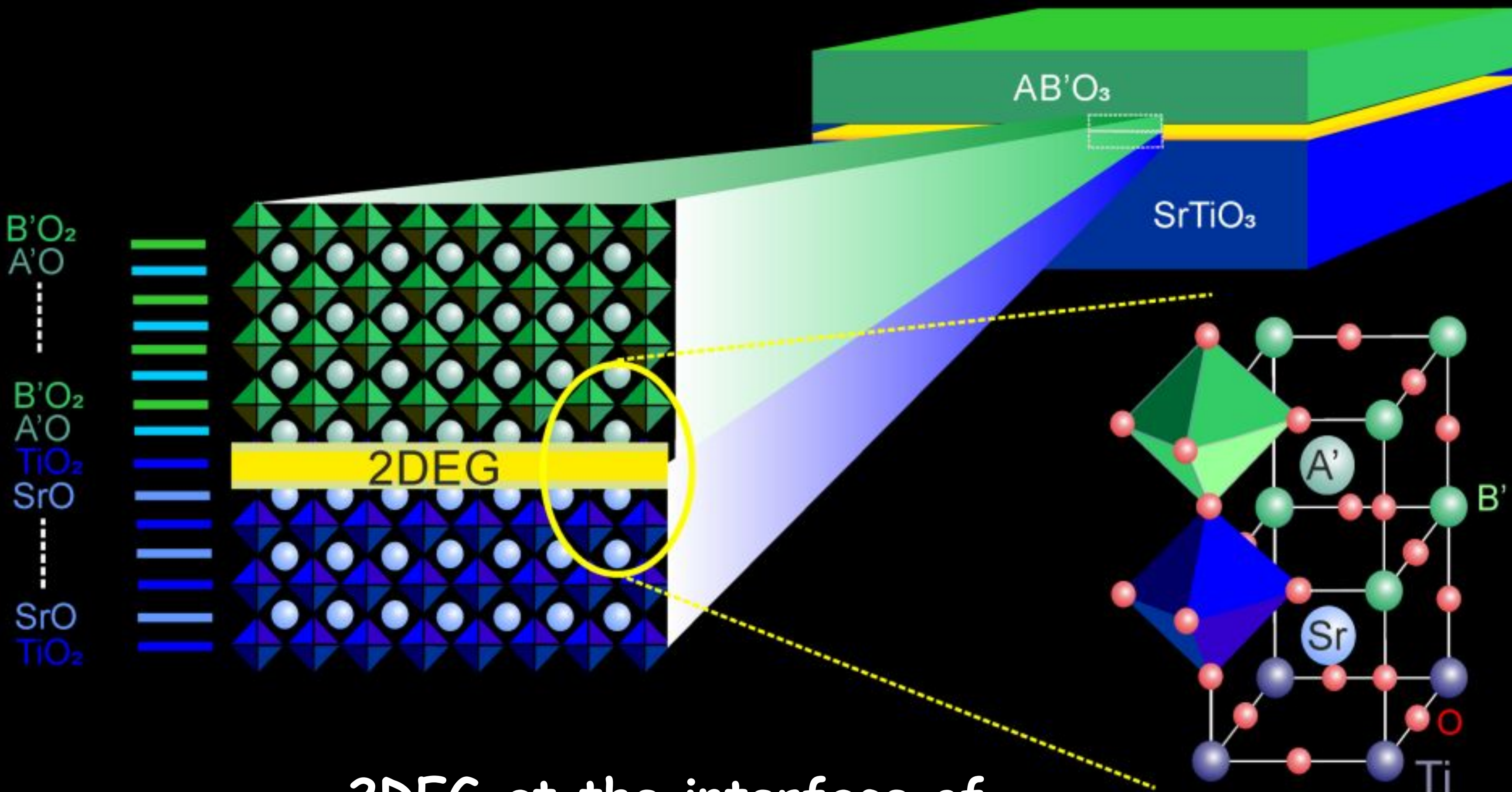




MR measurements



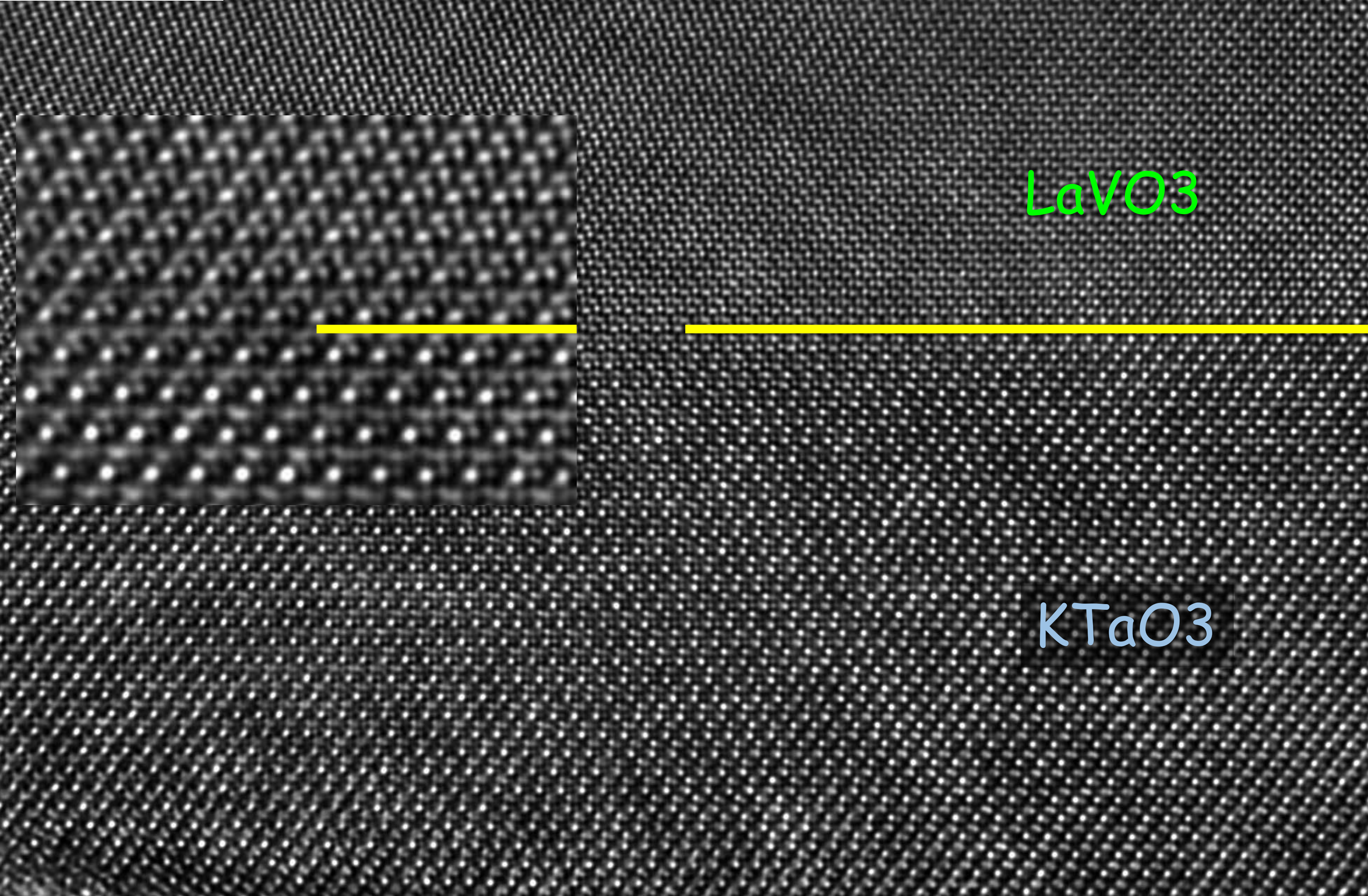
Today we are going to discuss on:



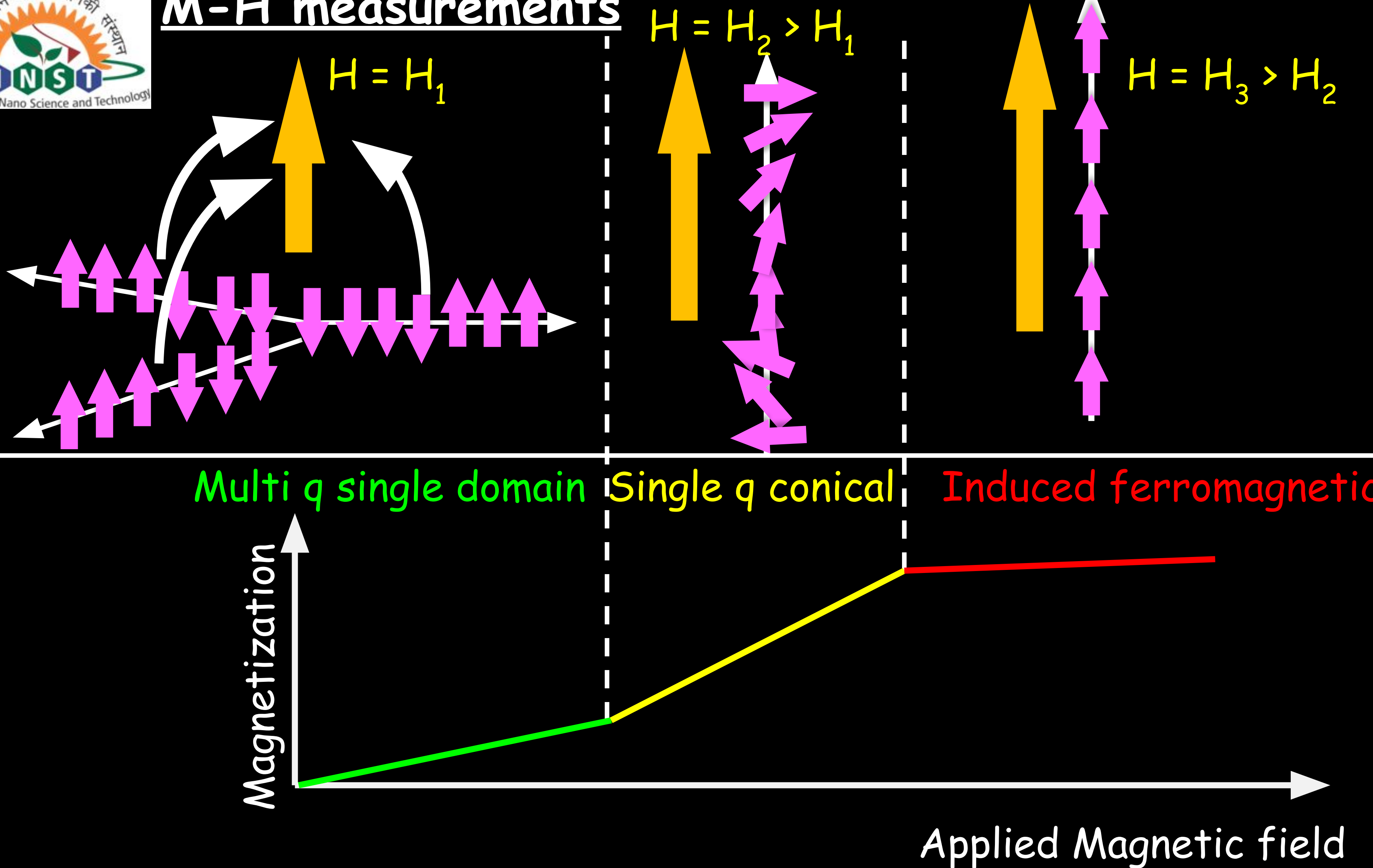
2DEG at the interface of two insulators

New aspect: Introduction of

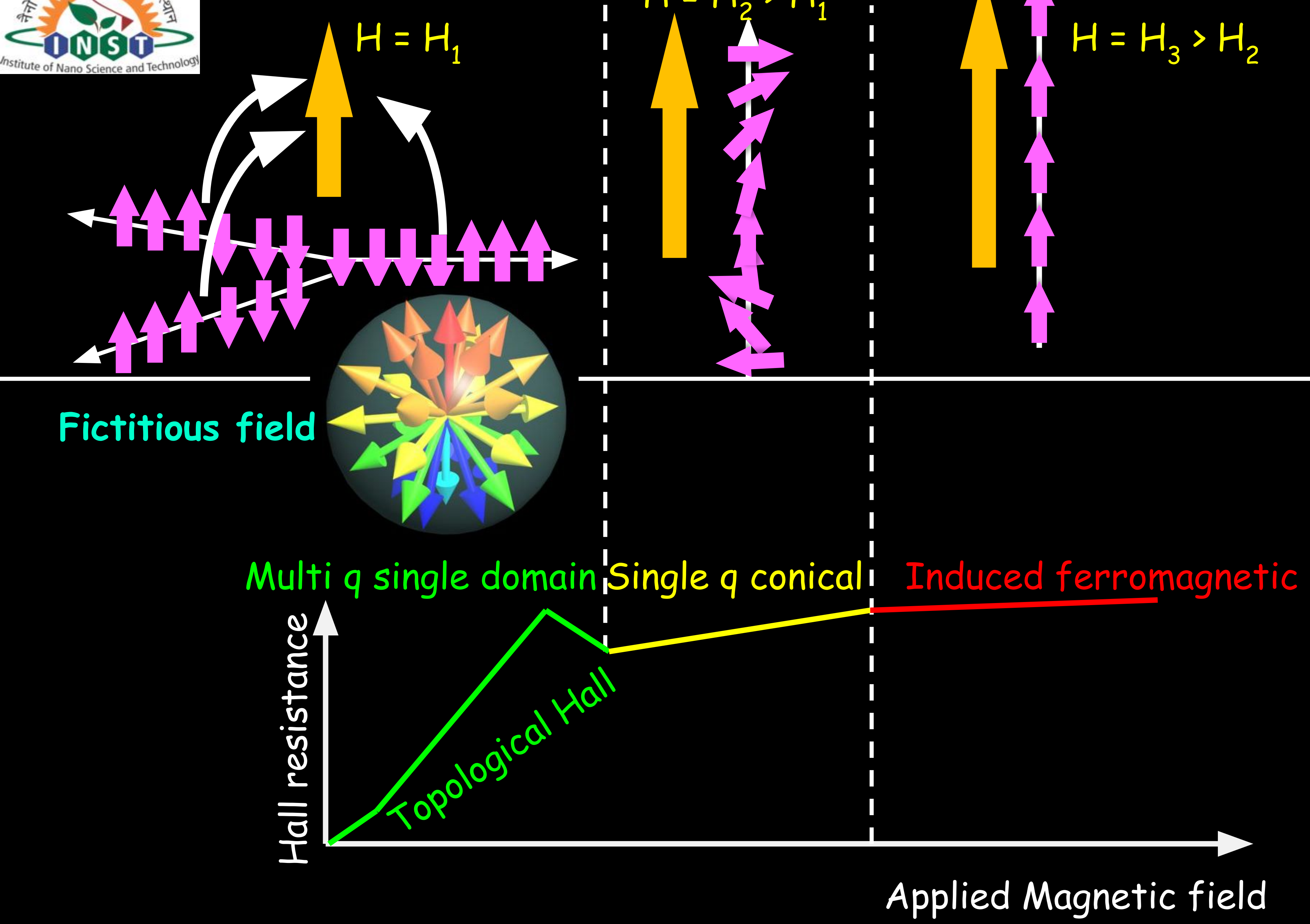
a. strong spin-orbit coupling.
b. magnetic interaction.


LaVO3
KTaO3

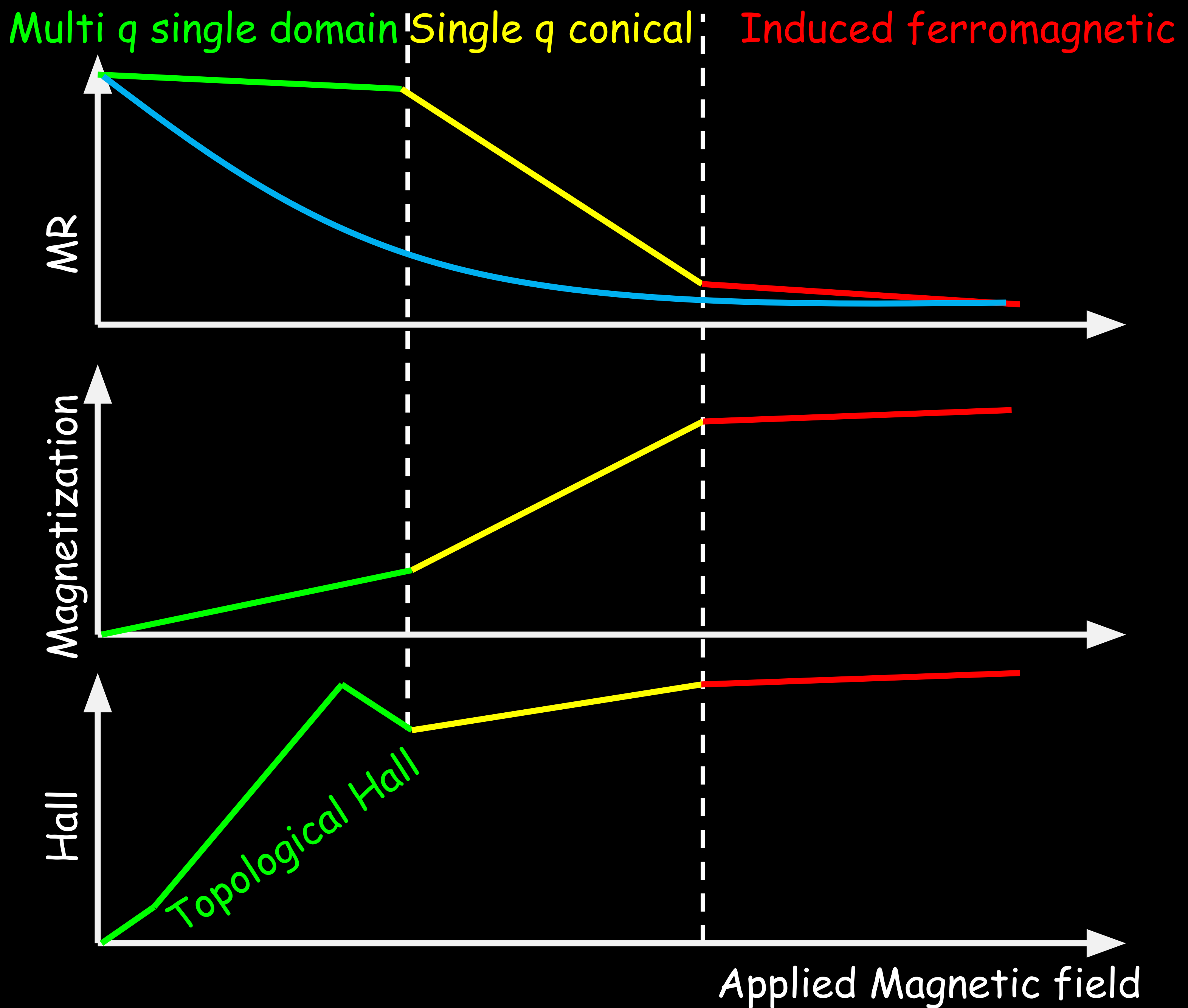
M-H measurements



Hall measurements



Measurements



SrFeO3 Thin film

Rapid Communication

Access by Institute of Nano Science

Multiple helimagnetic phases and topological Hall effect in epitaxial thin films of pristine and Co-doped $SrFeO_3$

S. Chakraverty, T. Matsuda, H. Wadati, J. Okamoto, Y. Yamasaki, H. Nakao, Y. Murakami, S. Ishiwata, M. Kawasaki, Y. Taguchi, Y. Tokura, and H. Y. Hwang

Phys. Rev. B **88**, 220405(R) – Published 5 December 2013

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Access by Institute of Nano Science and Technolog

Photoinduced Demagnetization and Insulator-to-Metal Transition in Ferromagnetic Insulating $BaFeO_3$ Thin Films

T. Tsuyama, S. Chakraverty, S. Macke, N. Pontius, C. Schüßler-Langeheine, H. Y. Hwang, Y. Tokura, and H. Wadati

Phys. Rev. Lett. **116**, 256402 – Published 21 June 2016

Such material in cubic perovskite family : $SrFeO_3$

Phys. Rev. B 88, 220405(R)

J. Mater. Chem., 2001, 11, 2235–2237

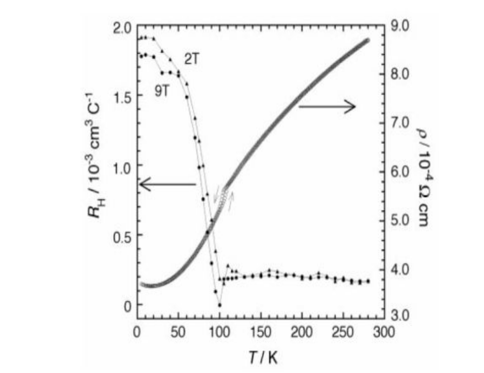
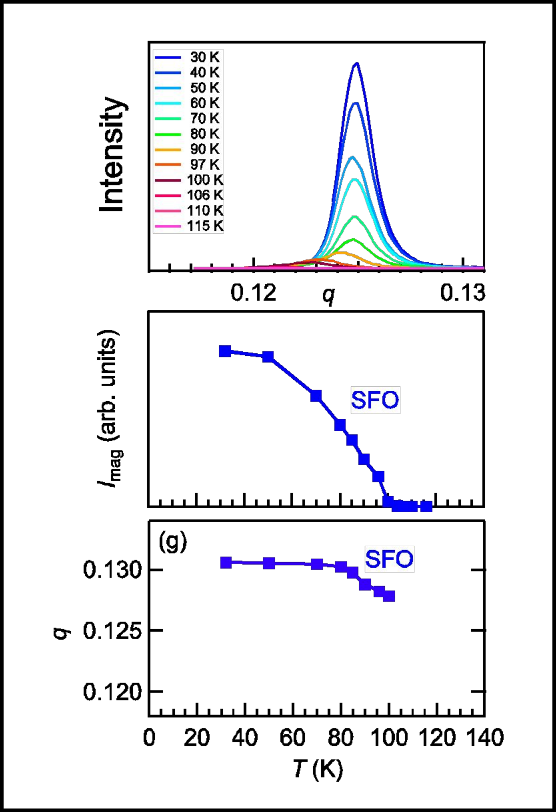


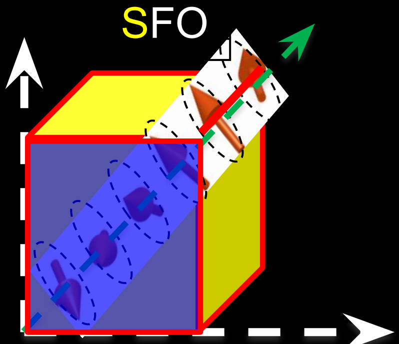
Fig. 2 Temperature dependences of resistivity and the Hall coefficient of the $SrFeO_3$/LSAT film.

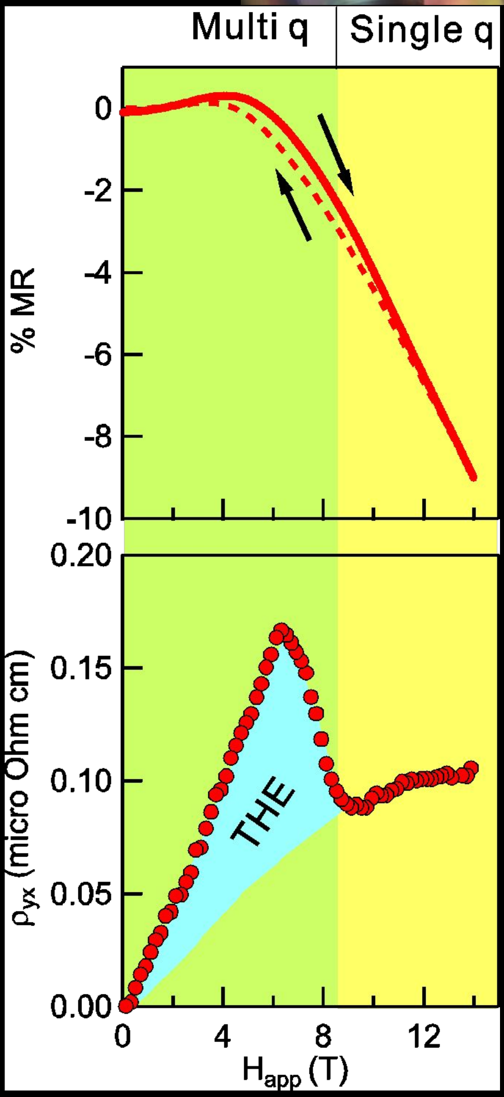
There is a dramatic change in Hall resistivity as a function of temperature.

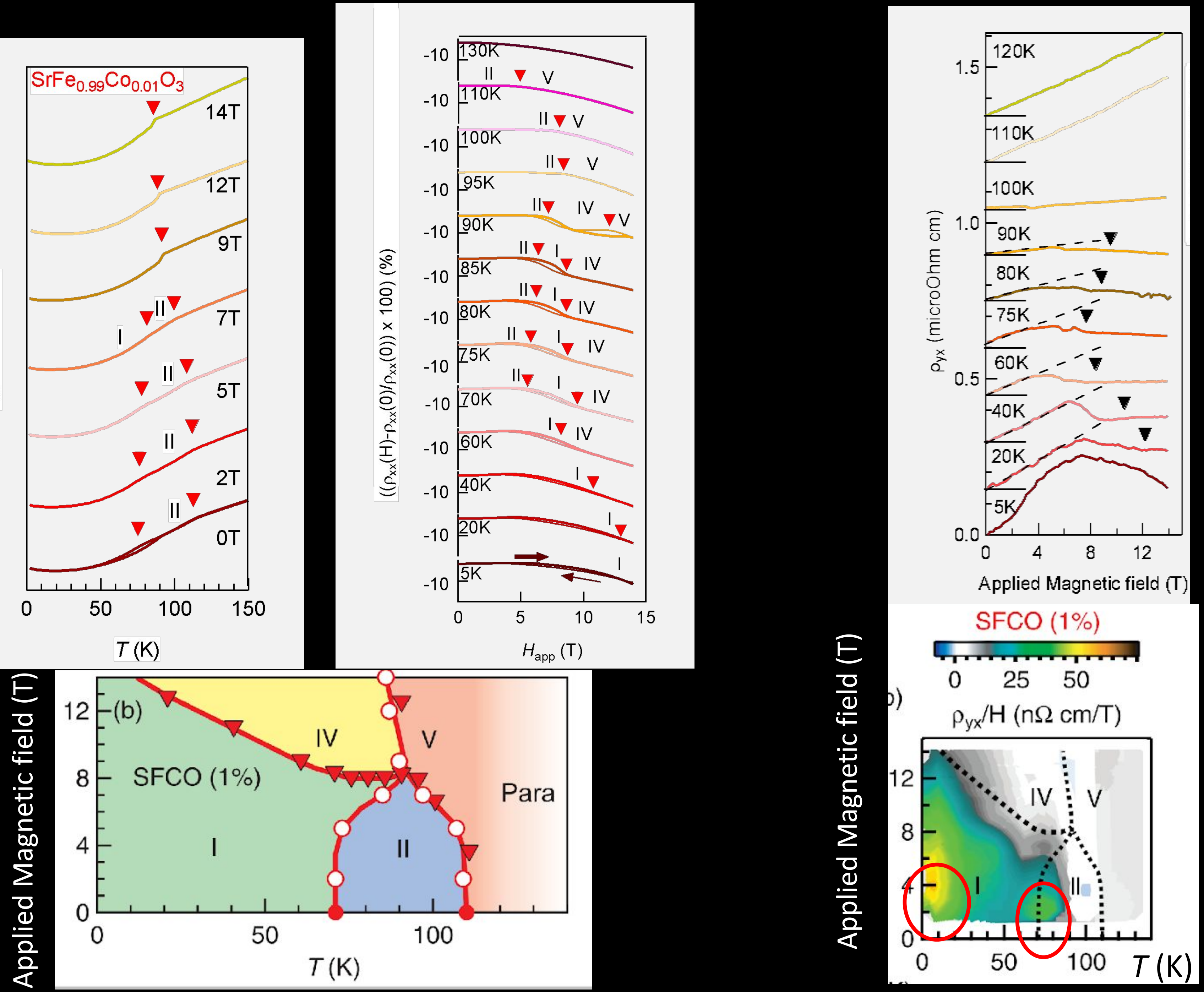
Phys. Rev. B **84**, 054427 (2011)

Bulk Single crystal: Several Magnetic Phases



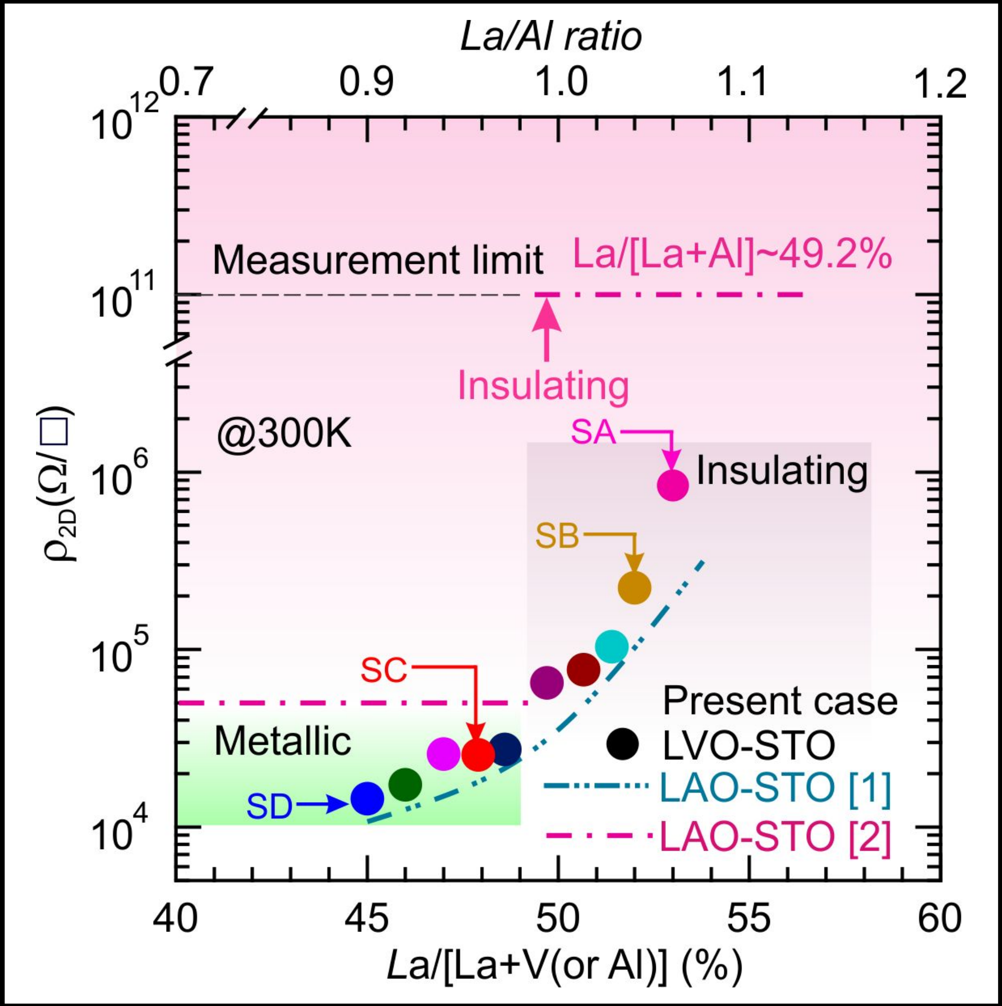






$SrFe_{0.99}Co_{0.01}O_3$
14T
12T
9T
7T
5T
2T
0T
I
II
ρ_{xx} (mOhm cm)
0
50
100
150
T (K)
$((\rho_{xx}(H)-\rho_{xx}(0)/\rho_{xx}(0)) \times 100)$ (%)
-10
130K
110K
100K
95K
90K
85K
80K
75K
70K
60K
40K
20K
5K
I
II
IV
V
0
5
10
15
H_{app} (T)
ρ_{yx} (microOhm cm)
0.0
0.5
1.0
1.5
120K
110K
100K
90K
80K
75K
60K
40K
20K
5K
0
4
8
12
Applied Magnetic field (T)
Applied Magnetic field (T)
(b)
SFCO (1%)
I
II
IV
V
Para
0
4
8
12
0
50
100
T (K)
Applied Magnetic field (T)
SFCO (1%)
0
25
50
ρ_{yx}/H (nΩ cm/T)
I
II
IV
V
0
4
8
12
0
50
100
T (K)

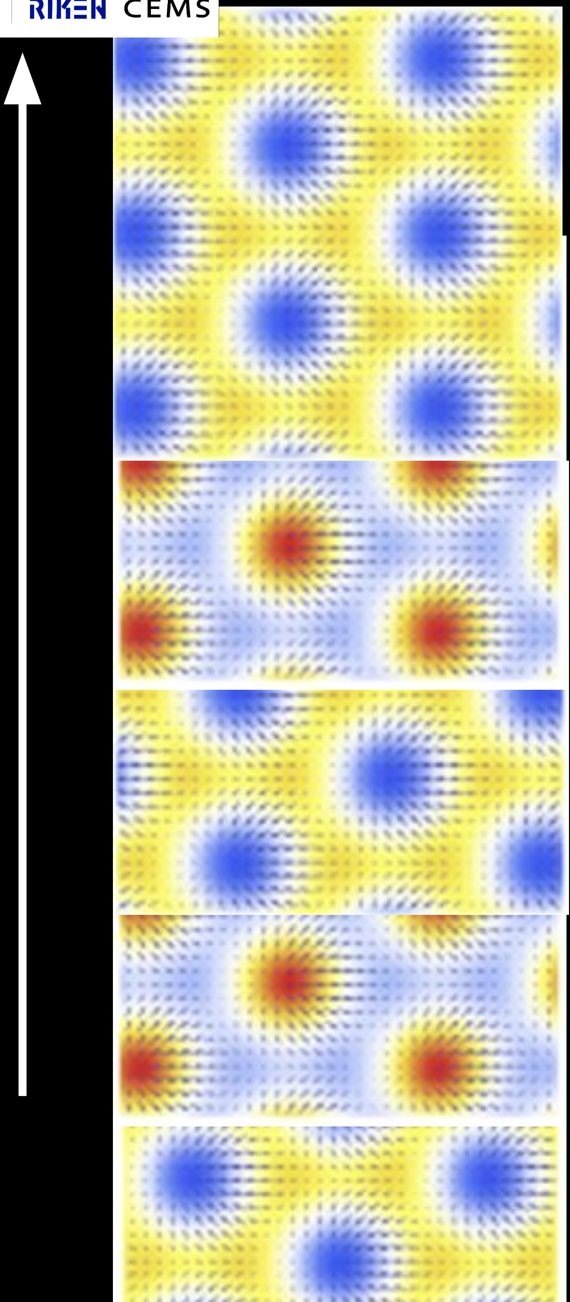
Comparison of our LVO-STO case with reported LAO-STO interface



Film stoichiometry is a key to realize conducting interface of Perovskite oxides

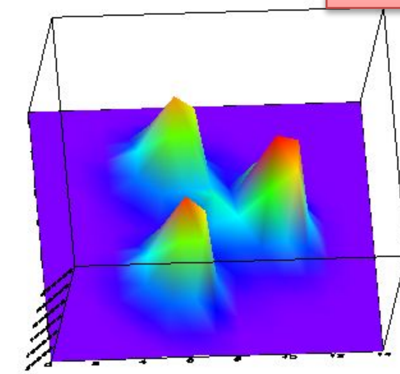
References:
1. E. Breckenfeld PRL 2013, 110, 196804
2. M. P. Warusawithana et. al. Nat. Comm. 2013, 4, 2351

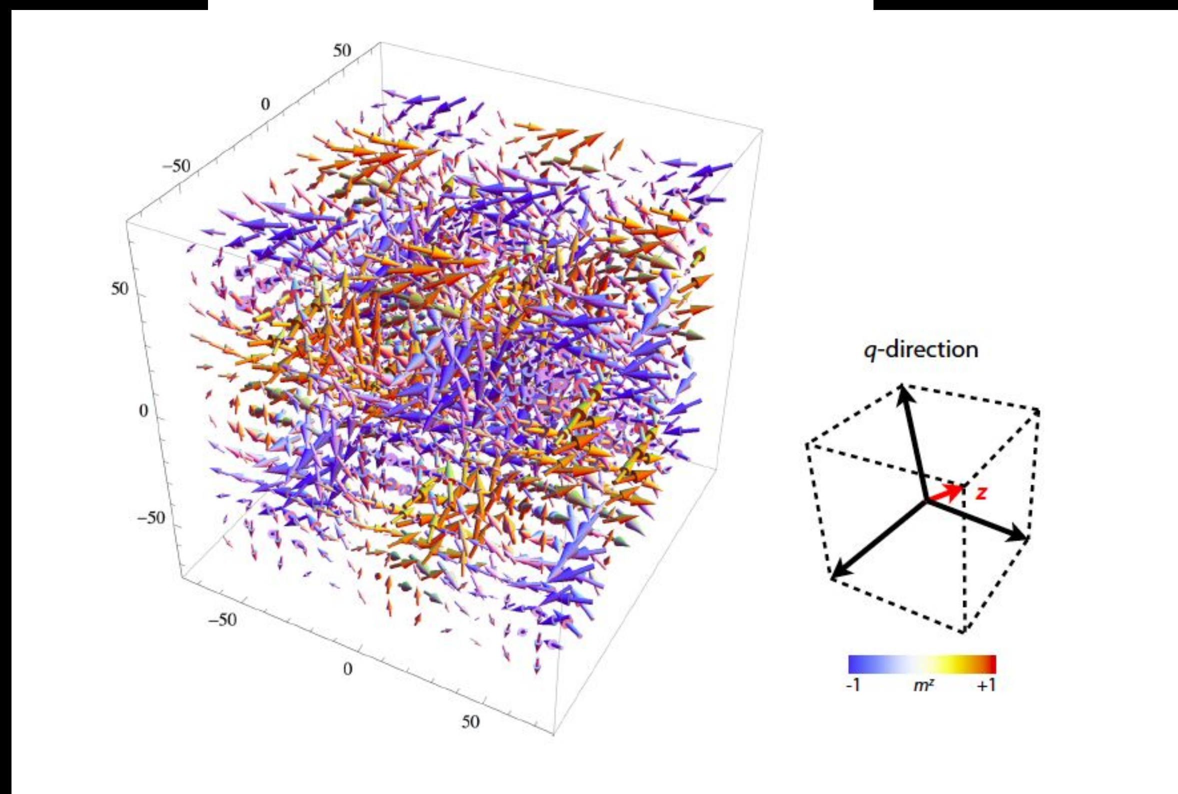
Possible structure of Skyrmions



T = 3.4 K

Phase I (multi-Q)





Non-trivial spin texture in real space

Material : $SrFeO_3$

Reflected in **<u>transverse</u>** conductivity as THE

Out line of the talk

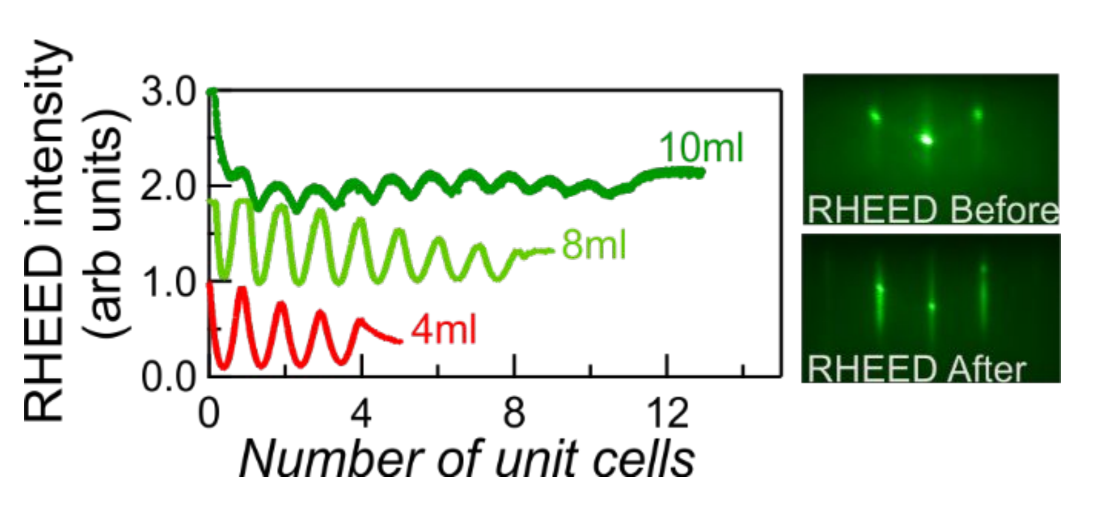
Non-trivial spin texture in real space	Non-trivial spin texture in momentum space
Material : $SrFeO_3$	Material : $LaVO_3$ – $KTaO_3$ interface
Observed in **transverse** conductivity	Observed in **longitudinal** conductivity
Topological Hall Effect	**Non-linear Fan Diagram**

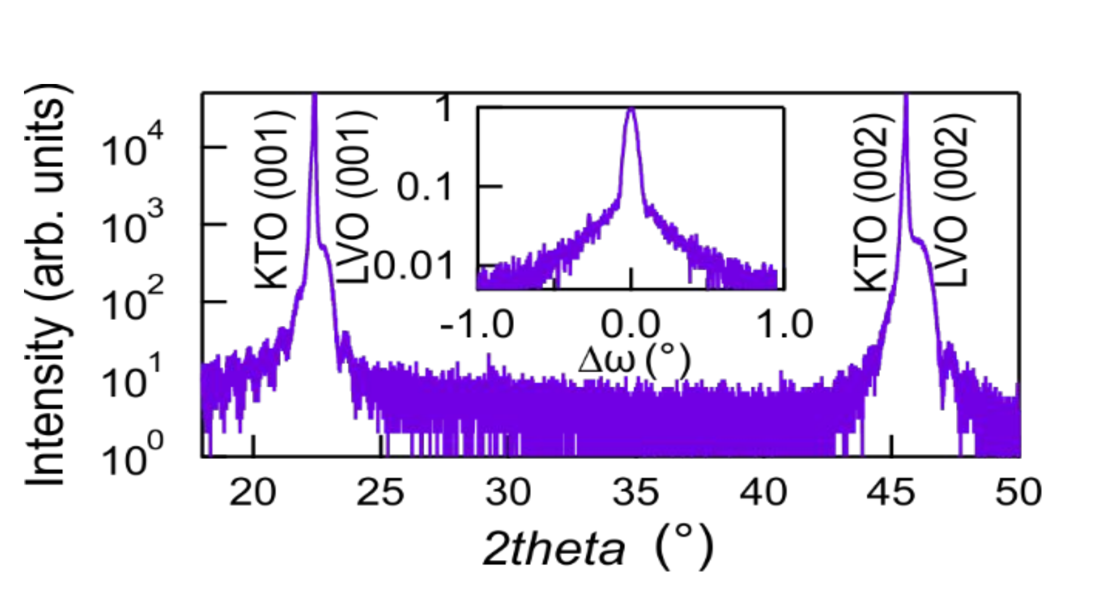
?

$LaVO_3$-$KTaO_3$ (LVO-KTO)

Growth Parameters:

- Substrate temperature : 600°C
- Oxygen partial pressure: 9.7×10^{-7} torr
- Laser fluence : $4 Jcm^{-2}$





1. Layer by Layer growth of LVO
2. Epitaxial film of LVO on KTO
3. Atomically well defined interface

Nature Communication, 1, 874 (2020).

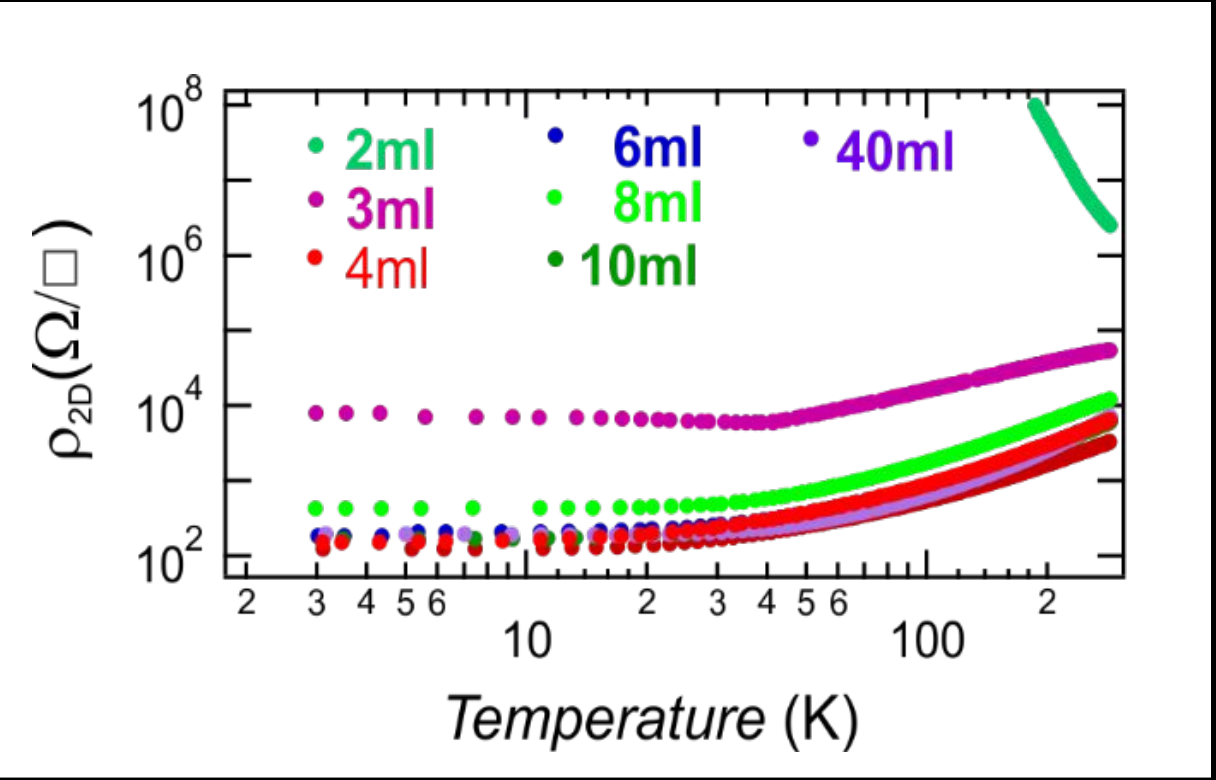
Resistance vs Temperature

Q. Is interface of LVO-KTO or LVO conducting?

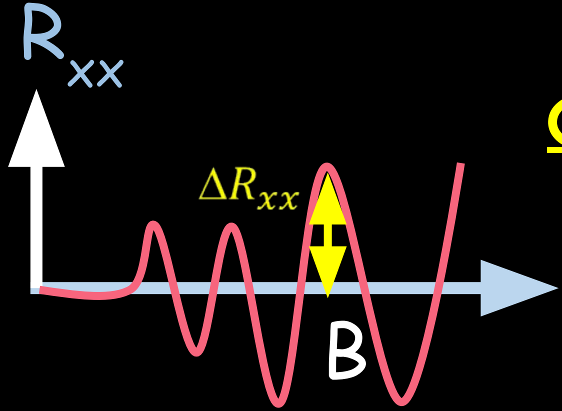
Different thickness of LVO grown

2D resistivity of the system is independent of thickness of LVO

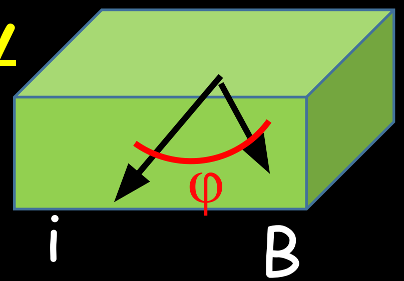
Ans: Interface conducting



Nature Communication, 1, 874 (2020).

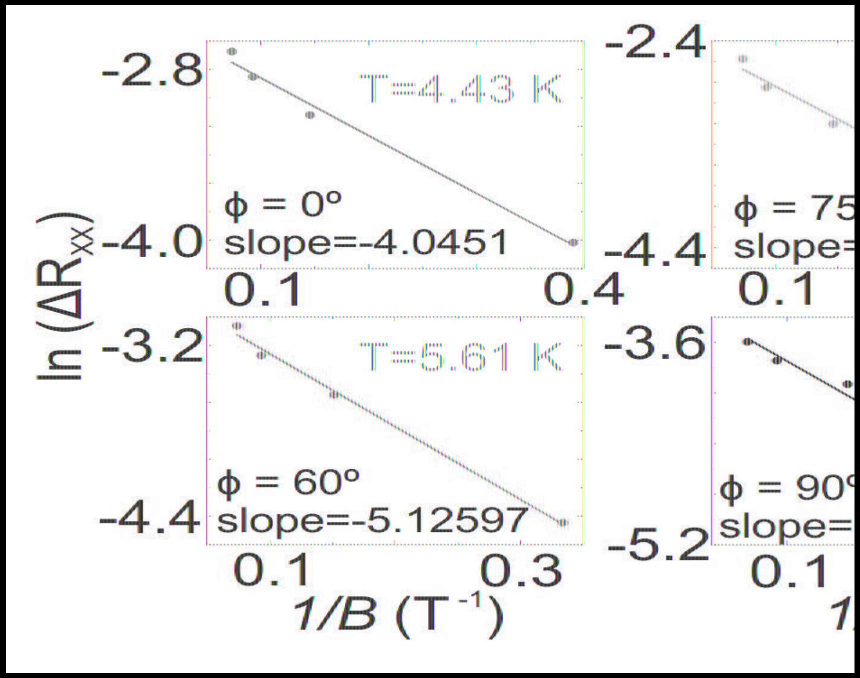


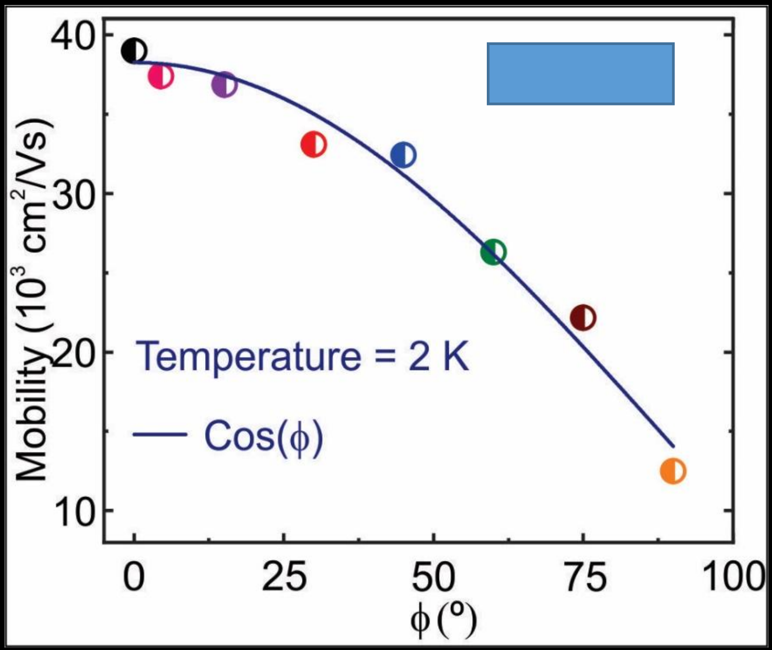
Quantum Mobility



$$\Delta R_{xx} = \exp\left(-\frac{\pi \quad m^*}{\tau e B}\right)$$

$$\ln(\Delta R_{xx}) = \quad \left(-\frac{\pi \quad m^*}{\tau e B}\right)$$

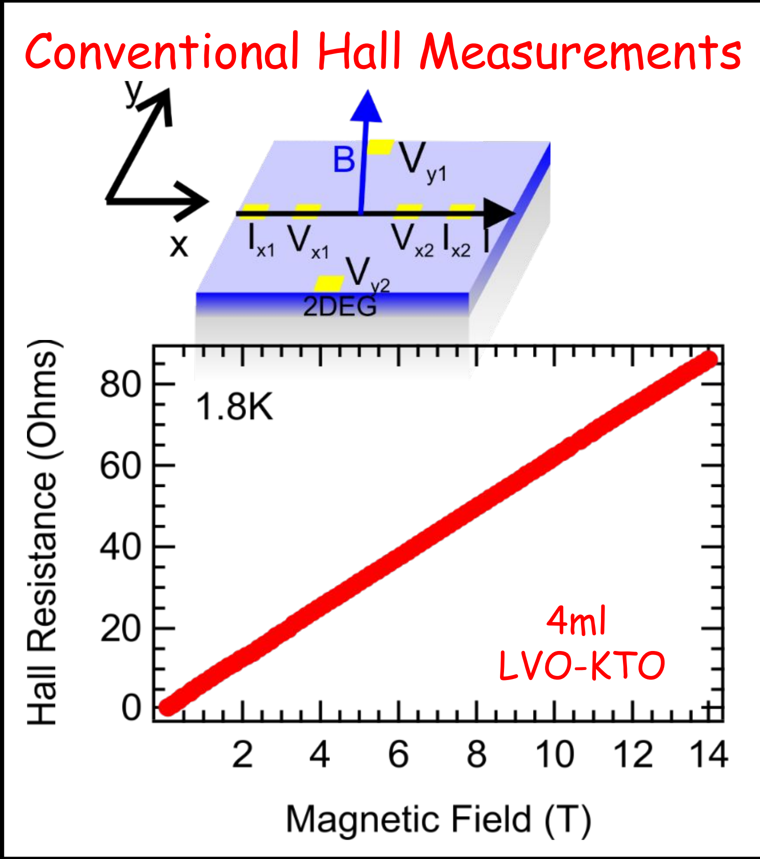


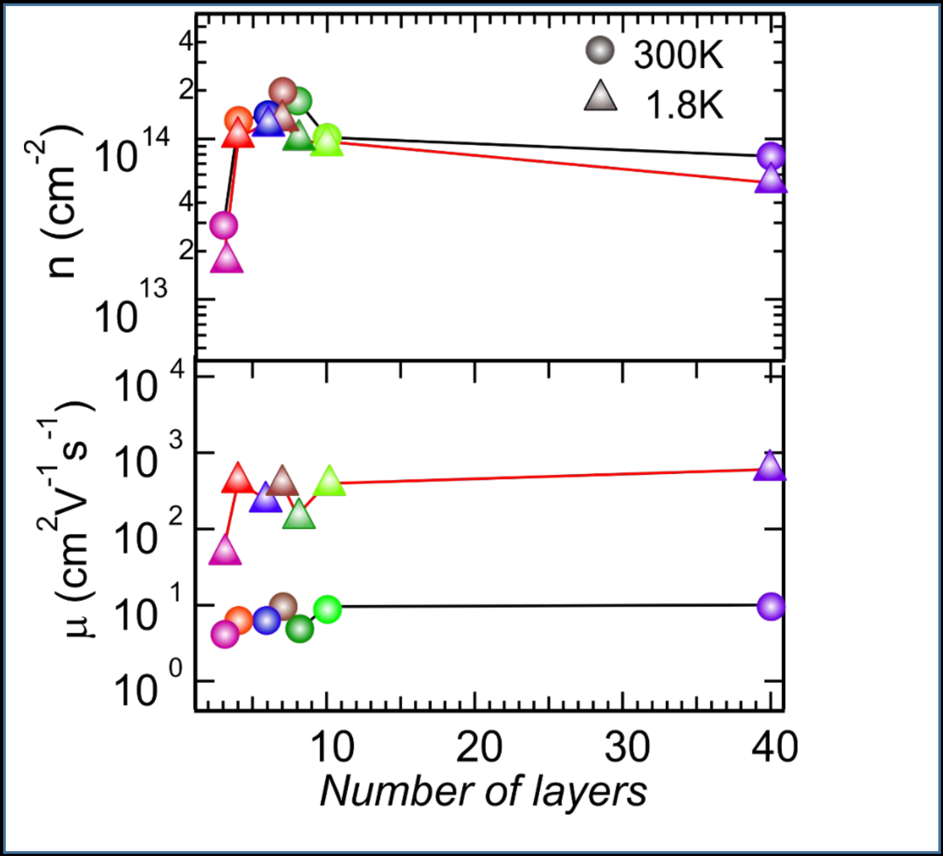


Inverse of the slop will give τ

Now $\mu = \frac{e * \tau}{m^*}$

Charge carrier density and mobility





Perfect Example of polar Catastrophe???

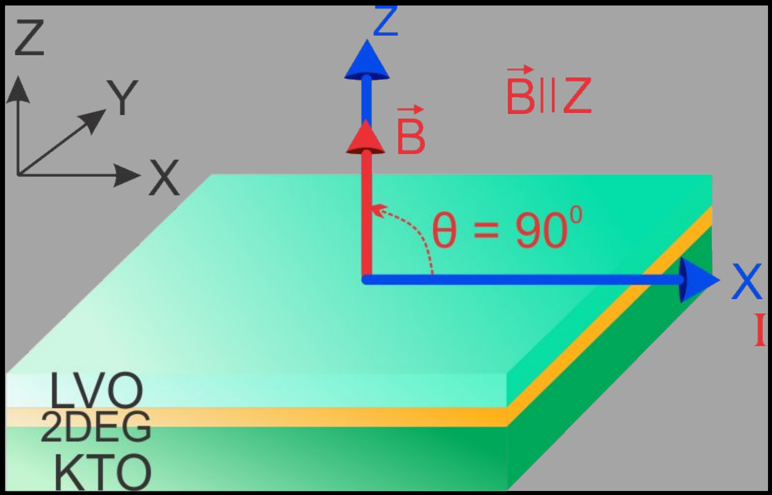
Nature Communication, **1**, 874 (2020).

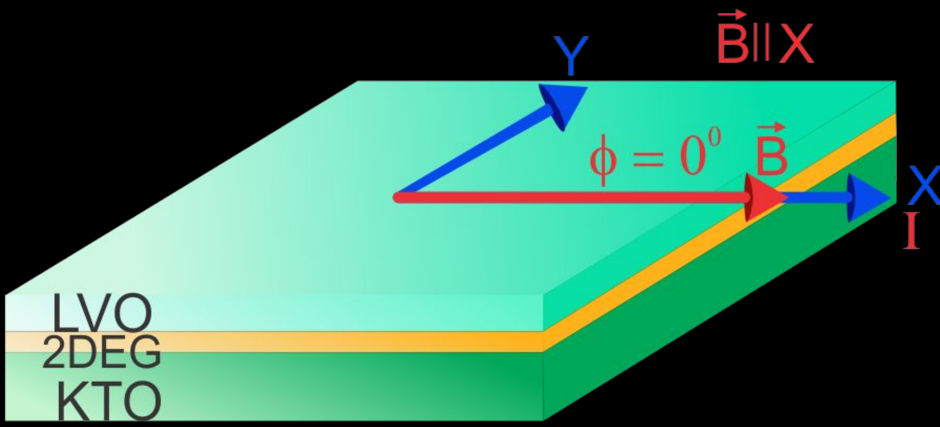
1. Carrier density ~3×10^{14} cm^{-2} : ½ electron per unit cell:
2. Critical thickness 3 monolayers of LVO on KTO.

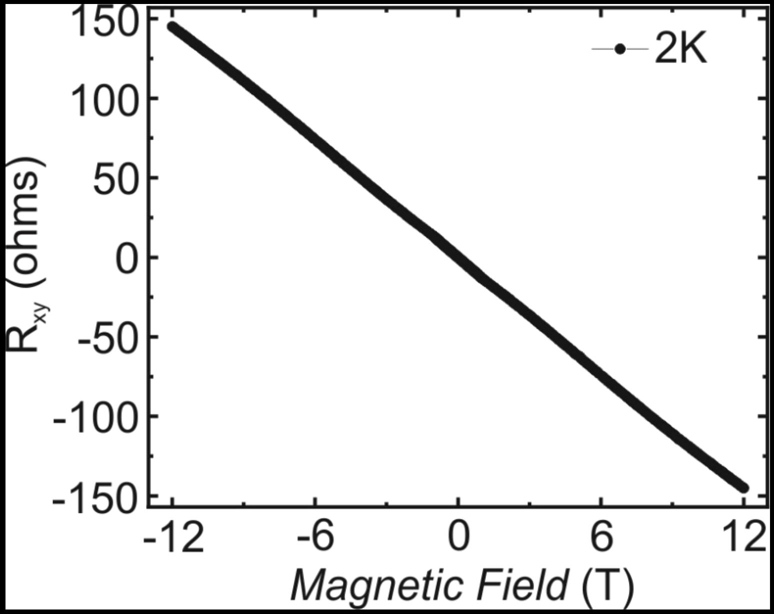
Compare:	LAO/STO	GTO/STO	LVO/KTO
Critical Thickness:	YES	No	YES
½ Carrier doping	No (Much less)	YES	YES

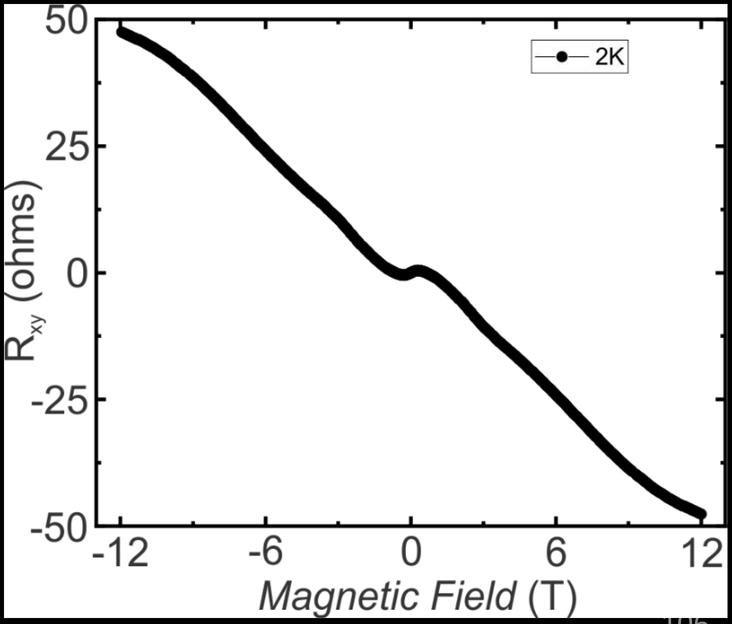
Scientific Reports | 5:18647 | DOI: 10.1038/srep18647

Normal vs Planar Hall



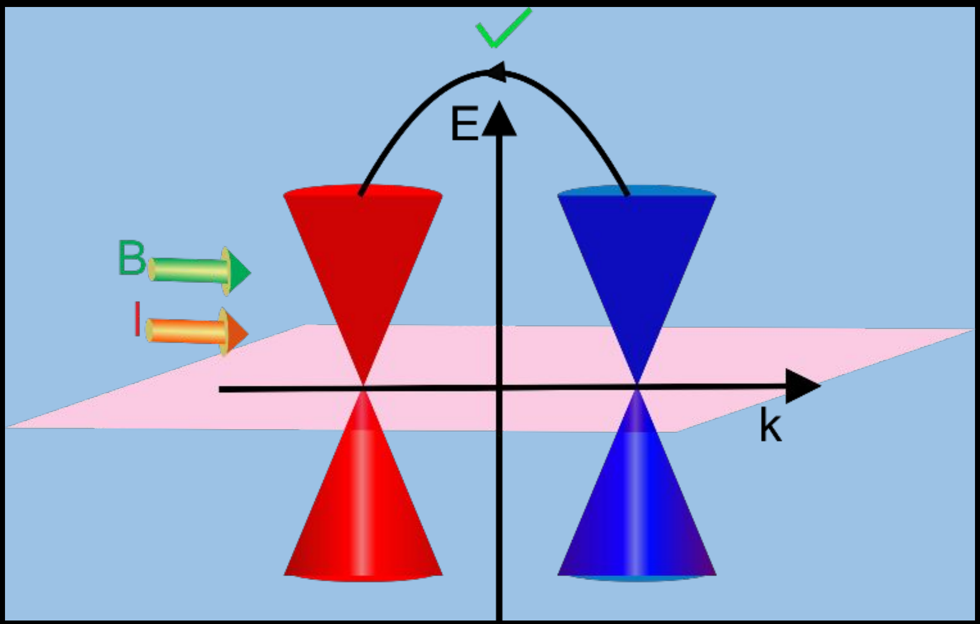




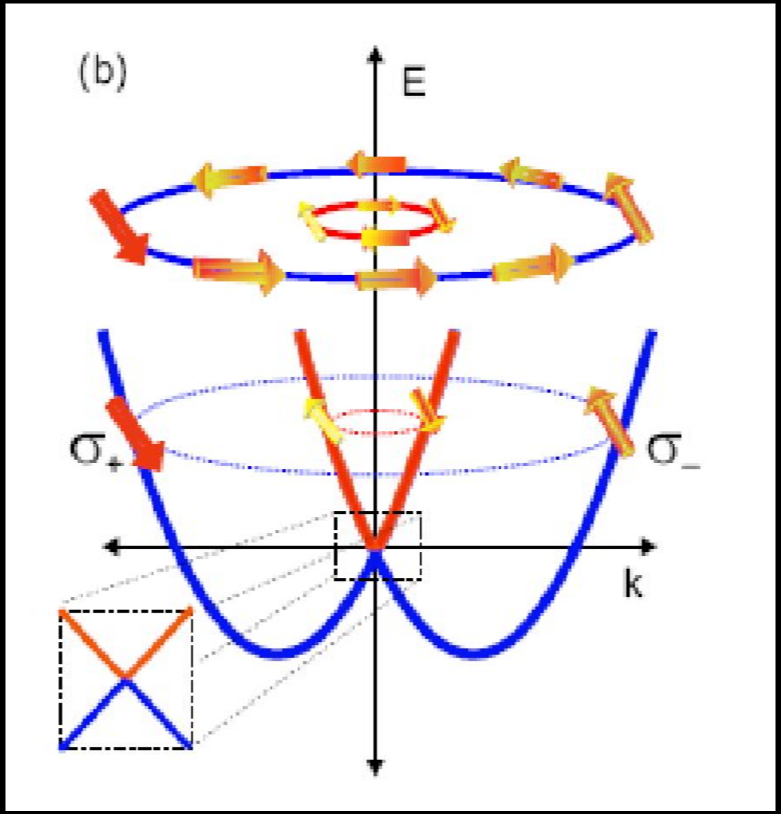


Some analogy: Motivation for further measurements

Weyl



Rashba

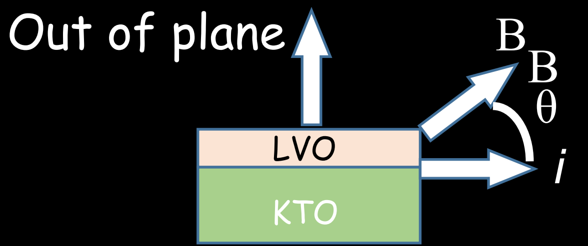


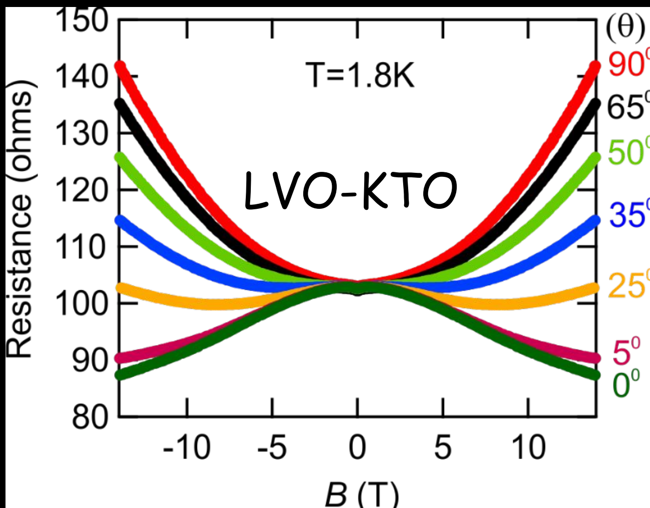
Can we see???

Signatures:

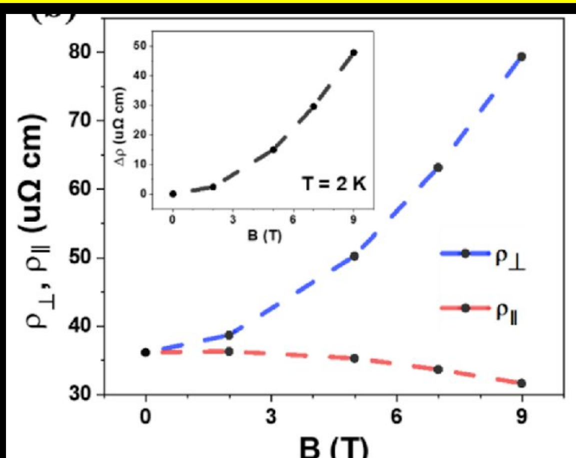
1. Negative in plane Magnetoresistance.
2. Planar Hall.
3. Anisotropic Magnetoresistance.

LVO-KTO vs reported (Weyl)





Our Sample



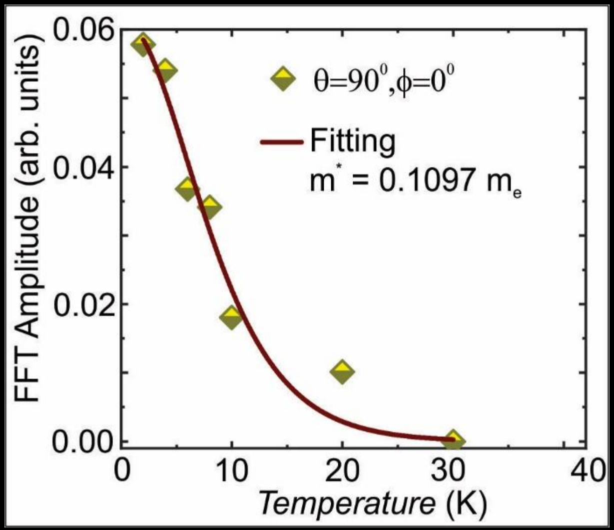
Reported Weyl

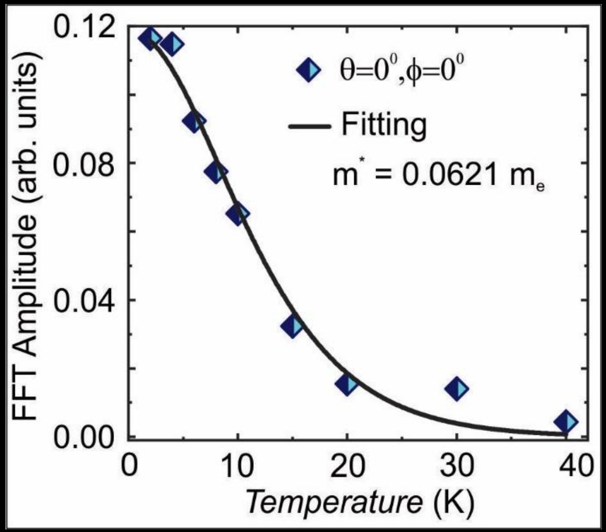
WTe_2

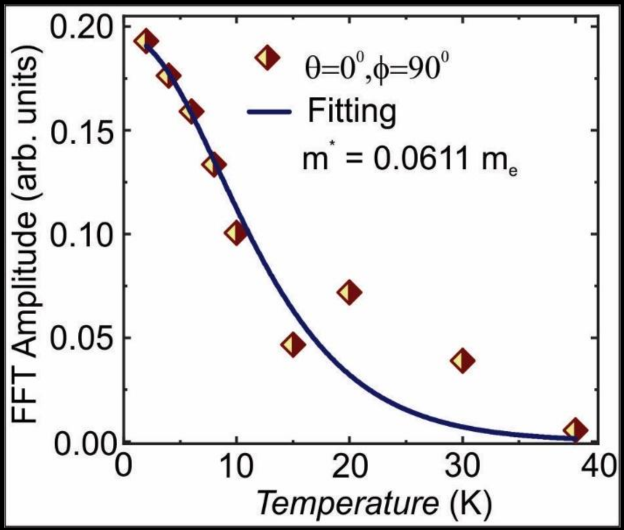
J. Phys.: Condens. Matter 32 (2020) 015702

Calculating the effective masd of the carrier

$$FFT\ Amplitude = \frac{\lambda T}{Sinh(\lambda T)} \qquad \lambda = \frac{2\pi^2 K_B m^*}{\hbar e B}$$

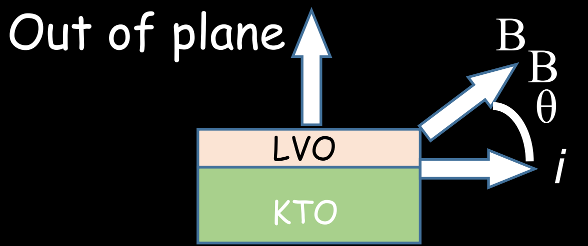




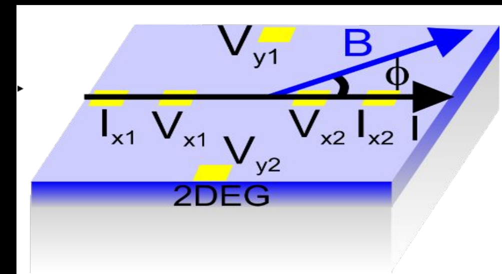


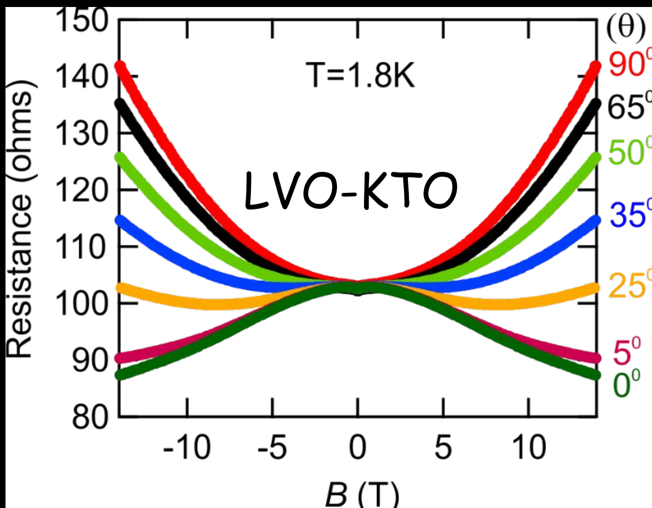
Very low effective mass

LVO-KTO vs reported (Weyl)

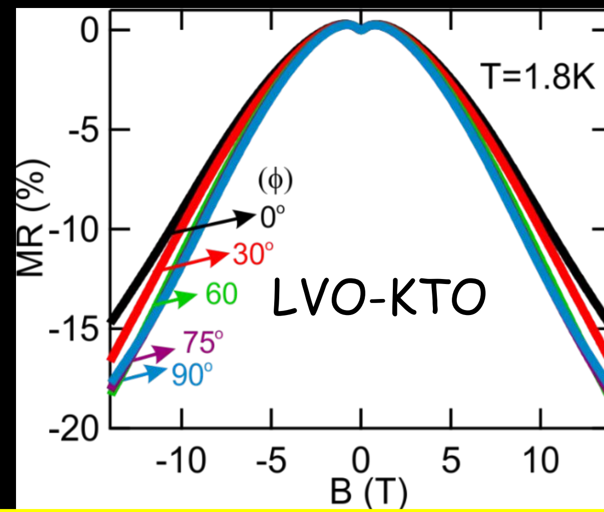


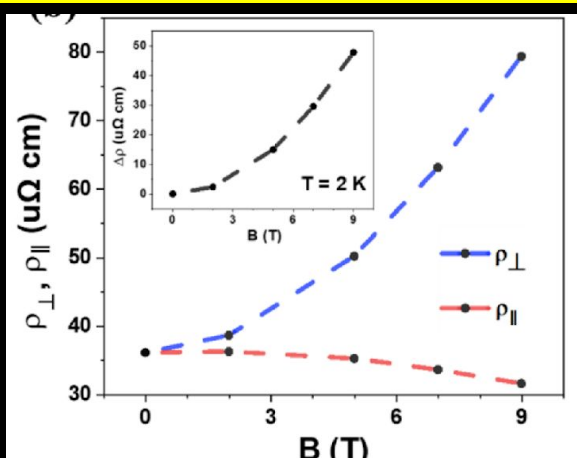
In plane



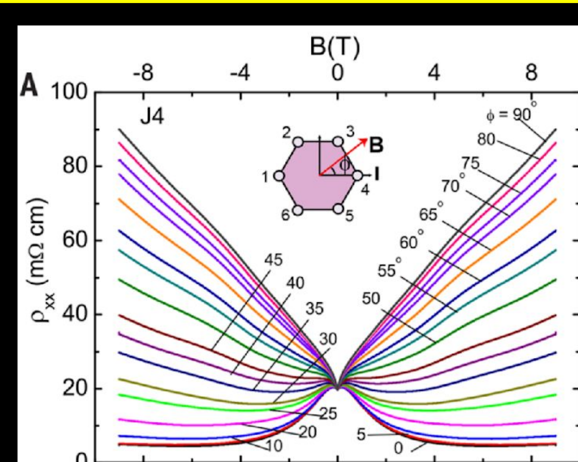


Our Sample





Reported Weyl



WTe2
J. Phys.: Condens. Matter 32 (2020) 015702

Na3Bi
Science 350 (6259), 413-416

Conclusion: Rashba – Weyl Or Something else???

RESEARCH ARTICLE

ADVANCED ELECTRONIC MATERIALS
www.advelectronicmat.de

Possible Signatures of Chiral Anomaly in the Magnetoresistance of a Quasi-2-Dimensional Electron Gas at the Interface of $LaVO_3$ and $KTaO_3$

*Harsha Silotia, Anamika Kumari, Anshu Gupta, Joydip De, Santanu Kumar Pal, Ruchi Tomar, and Suvankar Chakraverty**

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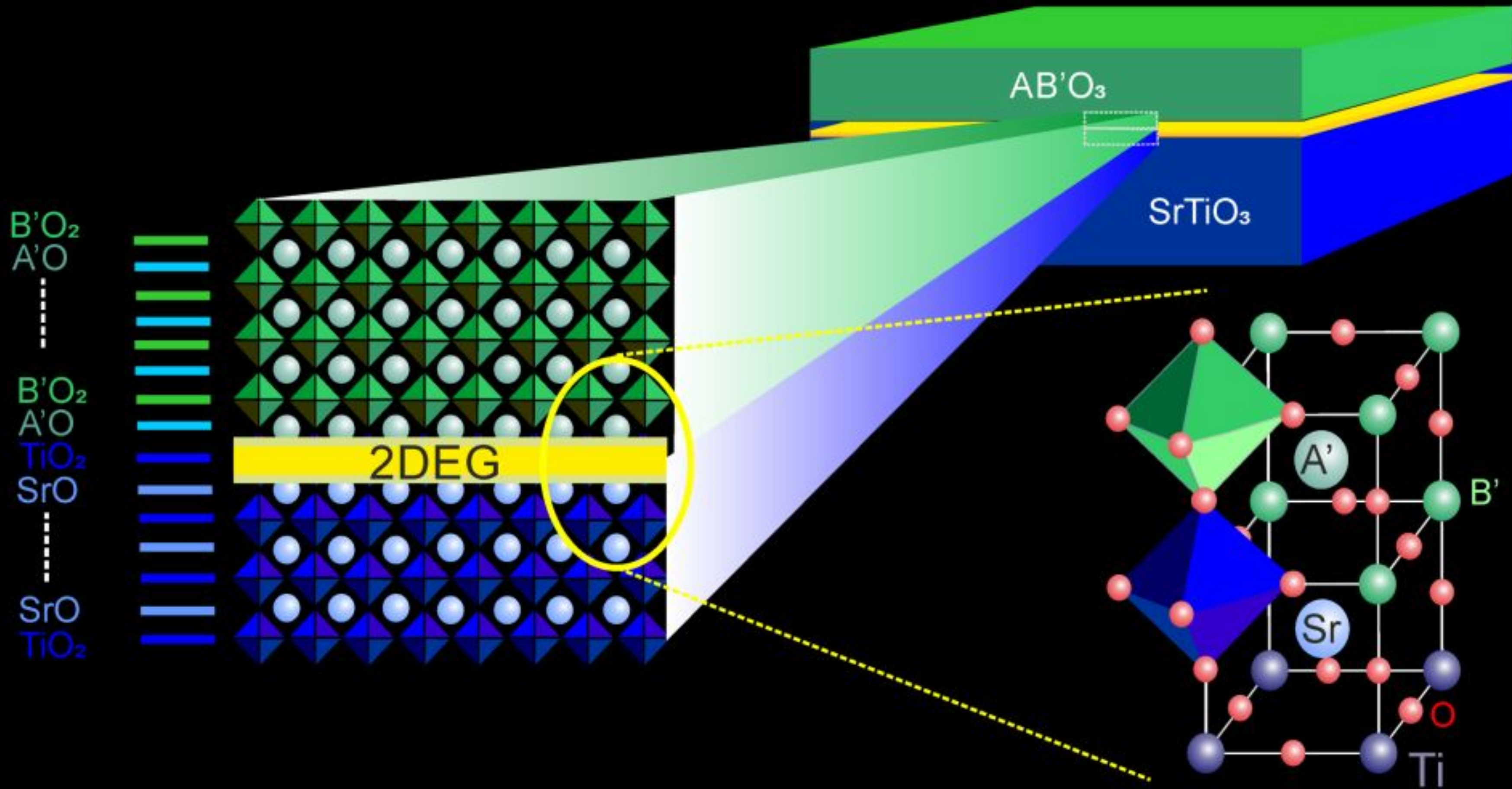
Unique Signatures of Rashba Effect in Angle Resolved Magnetoresistance

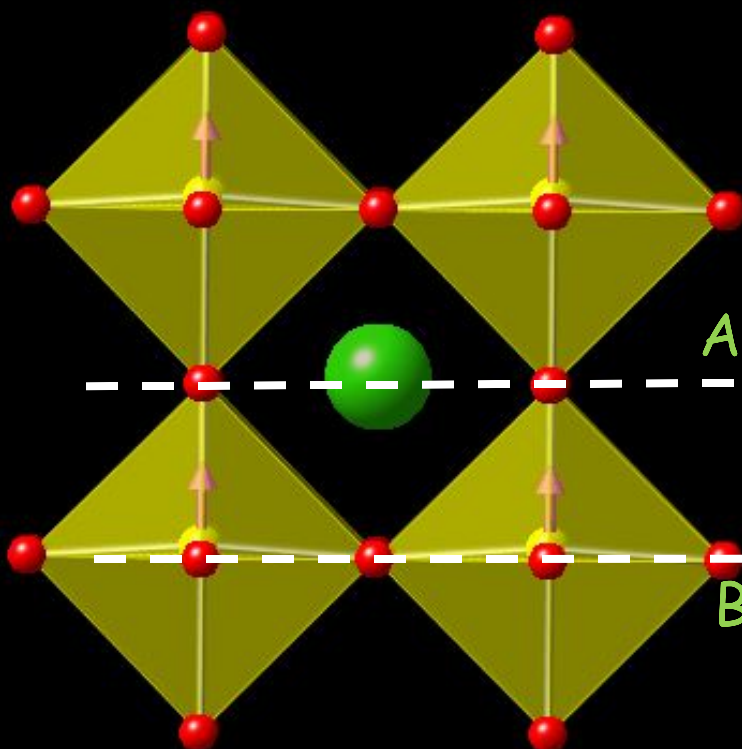
Anshu Gupta, Deepak S. Kathyat, Arnob Mukherjee, Anamika Kumari, Ruchi Tomar, Yogesh Singh, Sanjeev Kumar, and Suvankar Chakraverty**

What is the angular dependence of AMD and PHE???

Conducting interface of two insulating perovskite Oxides: polar catastrophe !!!



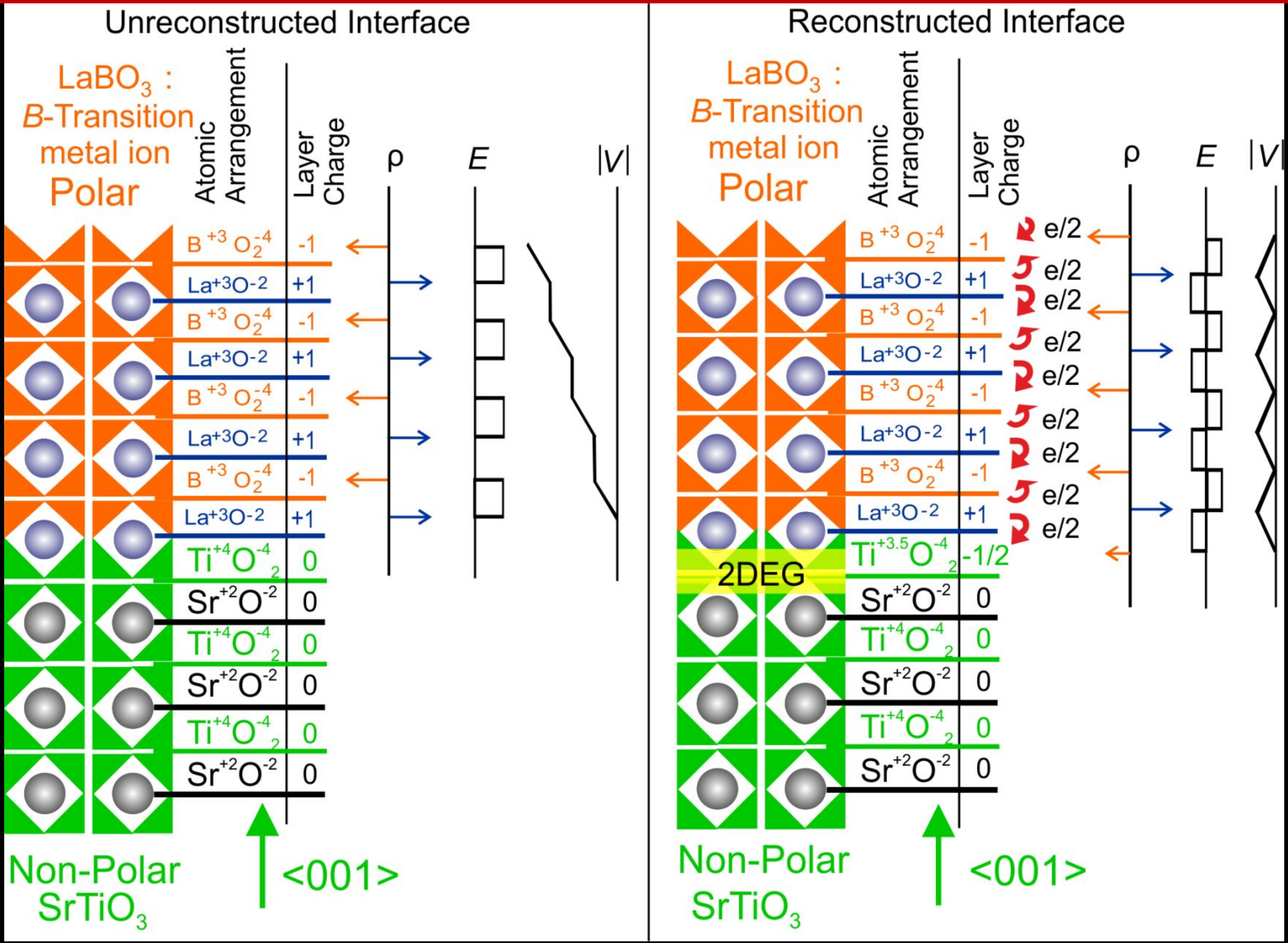
Interface of two insulating perovskite Oxides: Why Conducting???



ABO_3

	Non-Polar $A^{+2}B^{+4}O_3$ ($SrTiO_3$) Atomic Arrangement	Layer Charge	Polar $A^{+3}B^{+3}O_3$ ($LaAlO_3$) Atomic Arrangement	Layer Charge
AO	$Sr^{+2}O^{-2}$	0	$La^{+3}O^{-2}$	+1
BO_2	$Ti^{+4}O^{-4}$	0	$Al^{+3}O^{-4}$	-1

Conducting interface of two insulating perovskite Oxides: polar catastrophe !!!

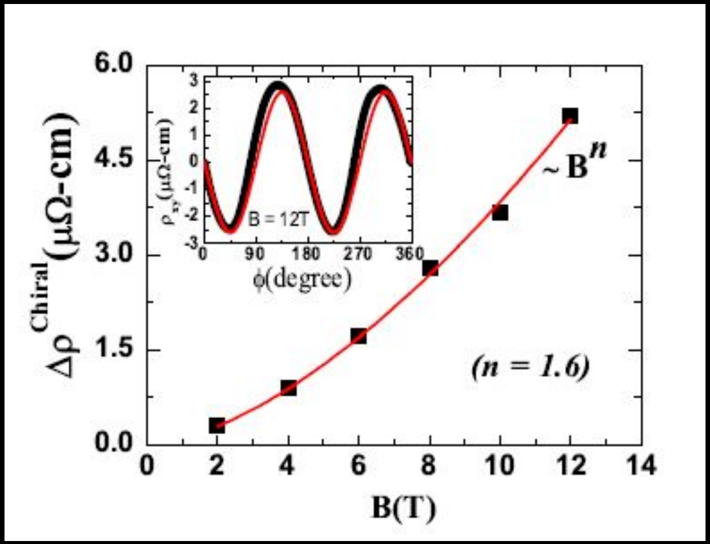


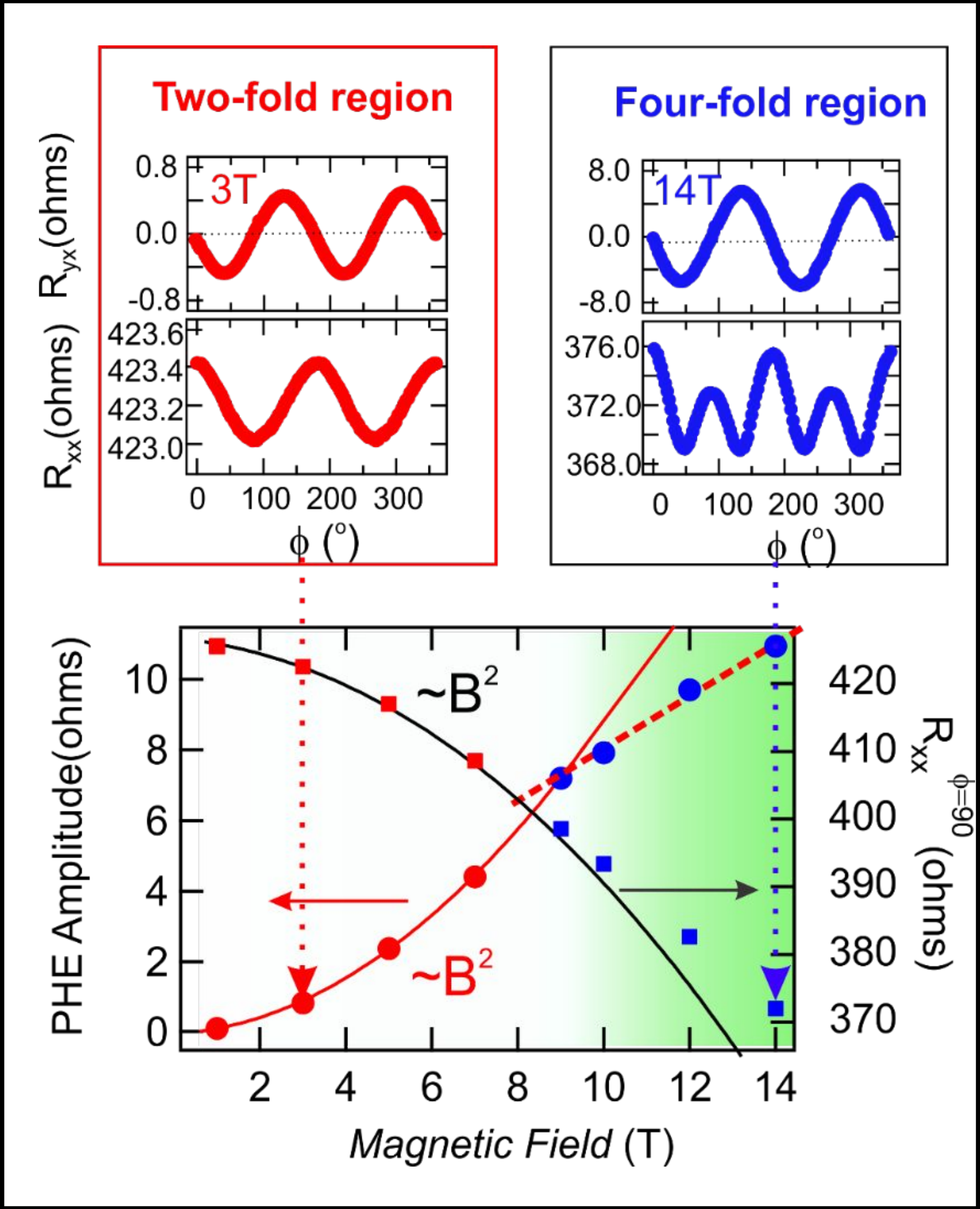
Polar Catastrophe : 1. ½ electron per unit cell at the interface

2. A critical thickness of film is needed

Planar magnetotransport measurements

Weyl semimetal $Co_3Sn_2S_2$





Nature Communication, 1, 874 (2020).

Conclusion 1

Realization of 3D like carrier, with

1. low effective mass
2. Doesn't follow linear 1/B relation in Landau fan diagram: topologically non-trivial spin texture in k-space?
3. Barry’s phase in Landau fan diagram: linear band dispersion?
4. Quantum mobility depends on the relative orientation of applied E and B field. ???

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$KTaO_3$—The New Kid on the Spintronics Block

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