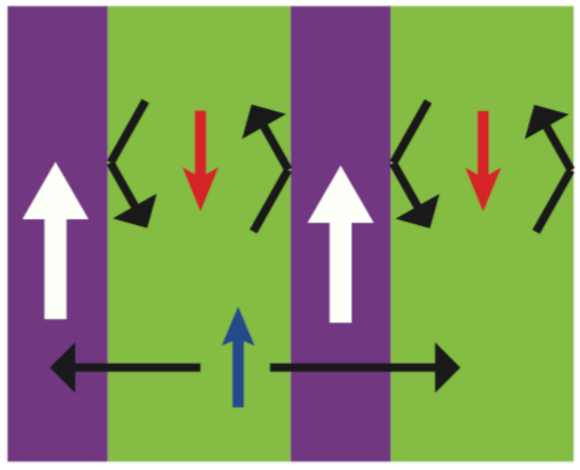
Carrier driven coupling in ferromagnetic oxide heterostructures

Ching-Hao Chang

National Cheng Kung University, Taiwan



Phys. Rev. B **96**, 184408 (2017),
arXiv:1802.05869

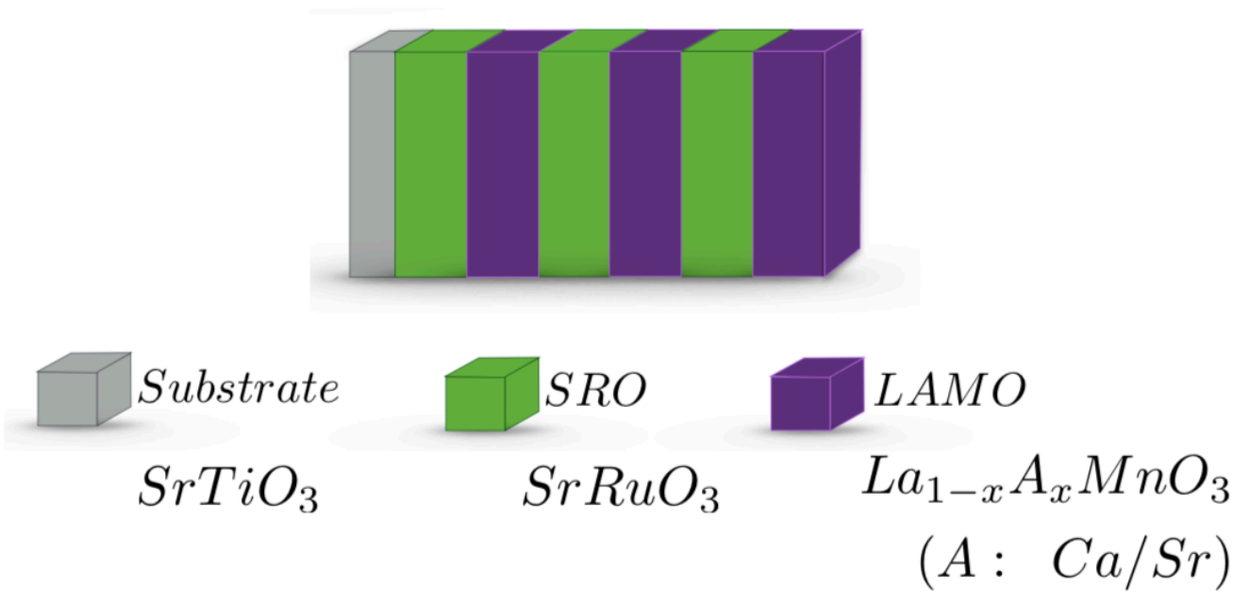
R Ganesh
IMSc Chennai, India

Sujit Das
MLU Halle & IFW Dresden, Germany

Sanjeev Kumar
IISER Mohali, India

Angus Huang,
Horng-Tay Jeng
NTHU, Taiwan

Outline

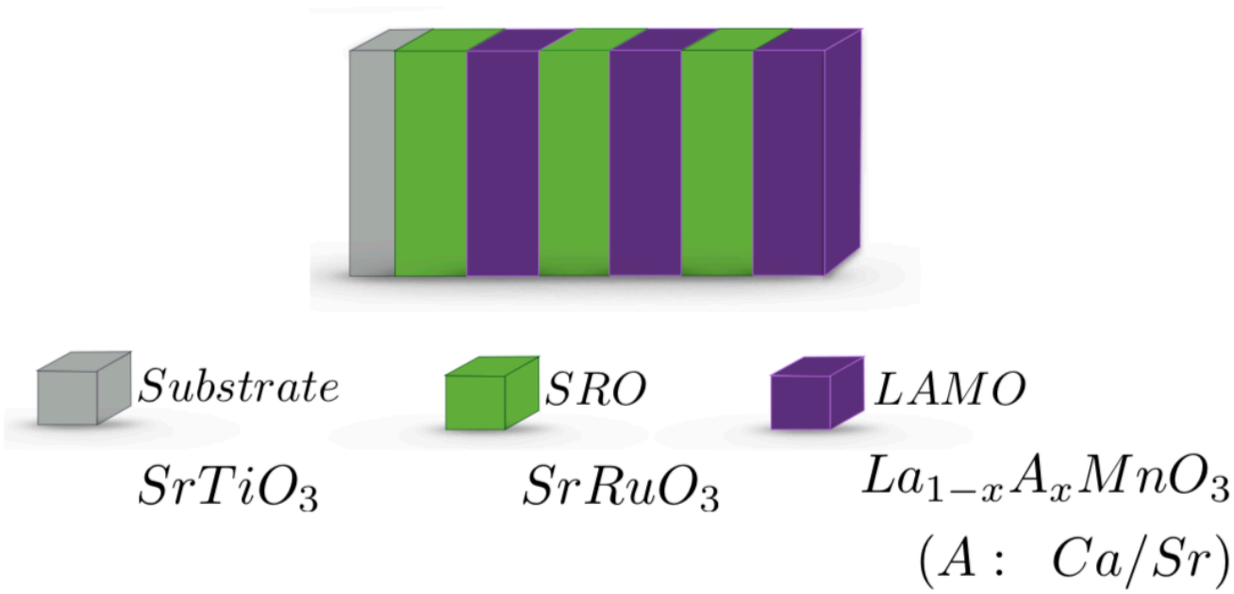


Magnetic properties due to spin-polarized carriers:

1. SRO/LAMO superlattice: Antiferromagnetic coupling.
2. SRO/LAMO bilayer: Oscillatory magnetic coupling.
3. SRO ultra-thin layer: Oscillatory magnetic anisotropy.

Outline

Search for new materials for developing spintronics !



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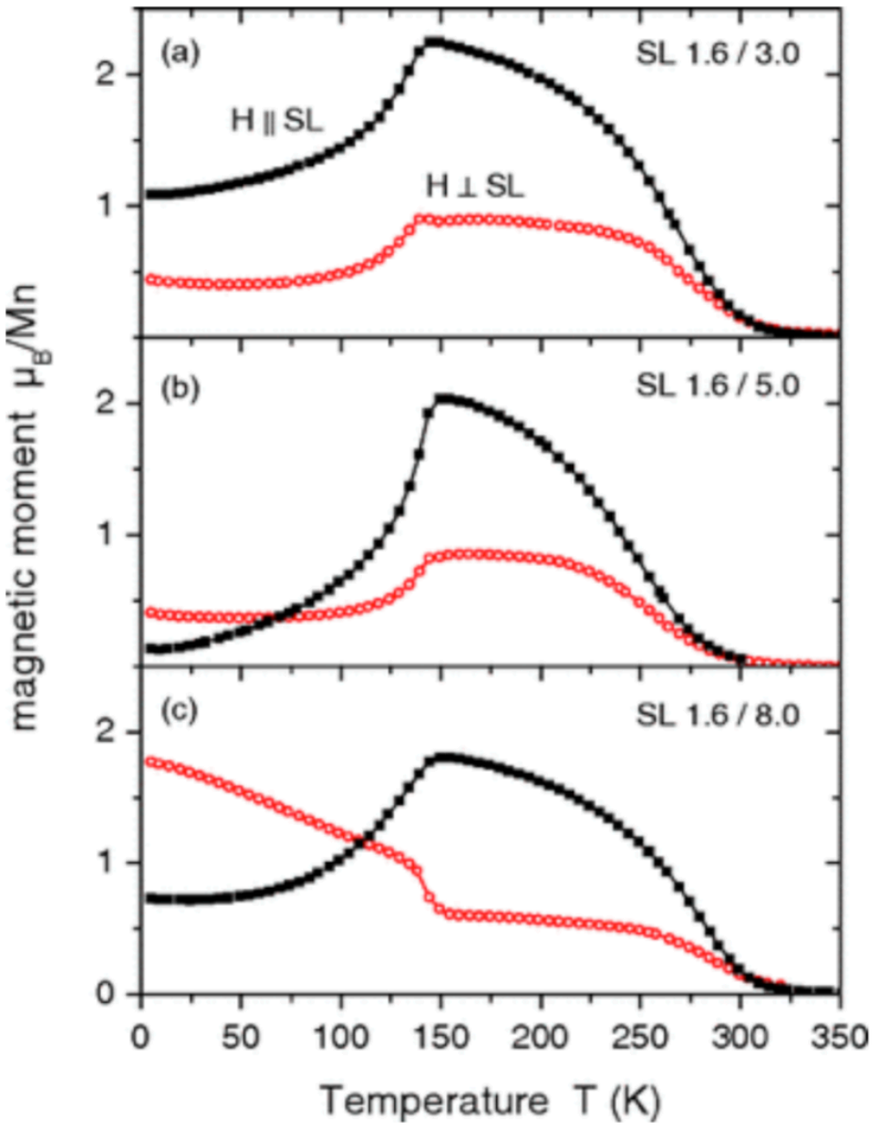
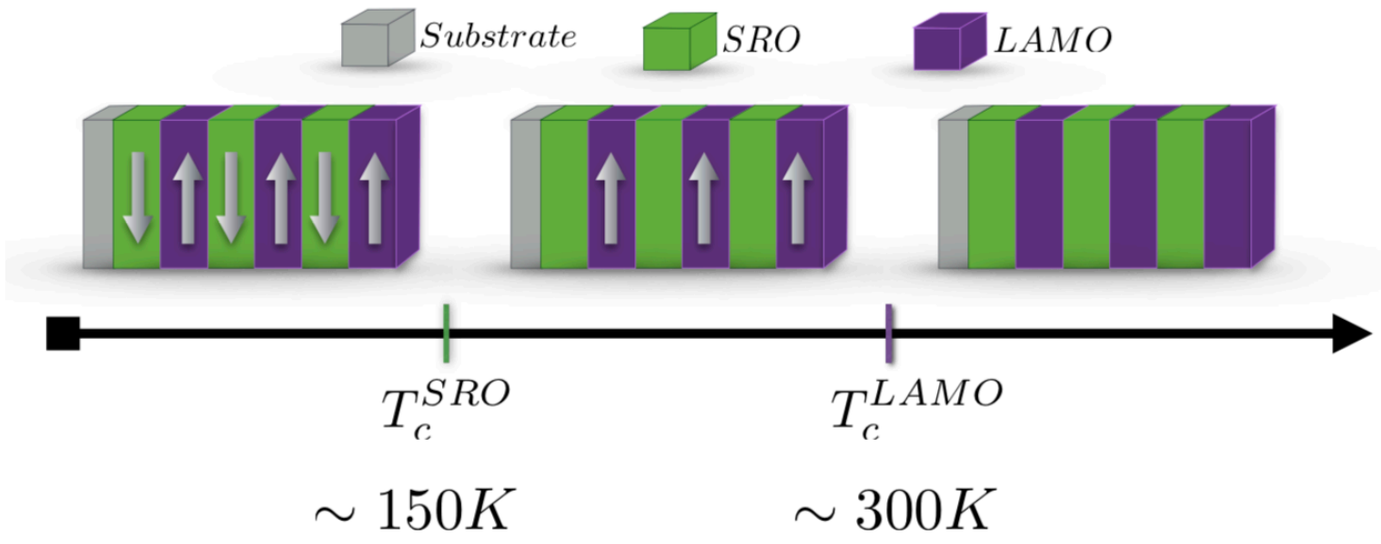
Magnetic properties of SRO/LAMO superlattice



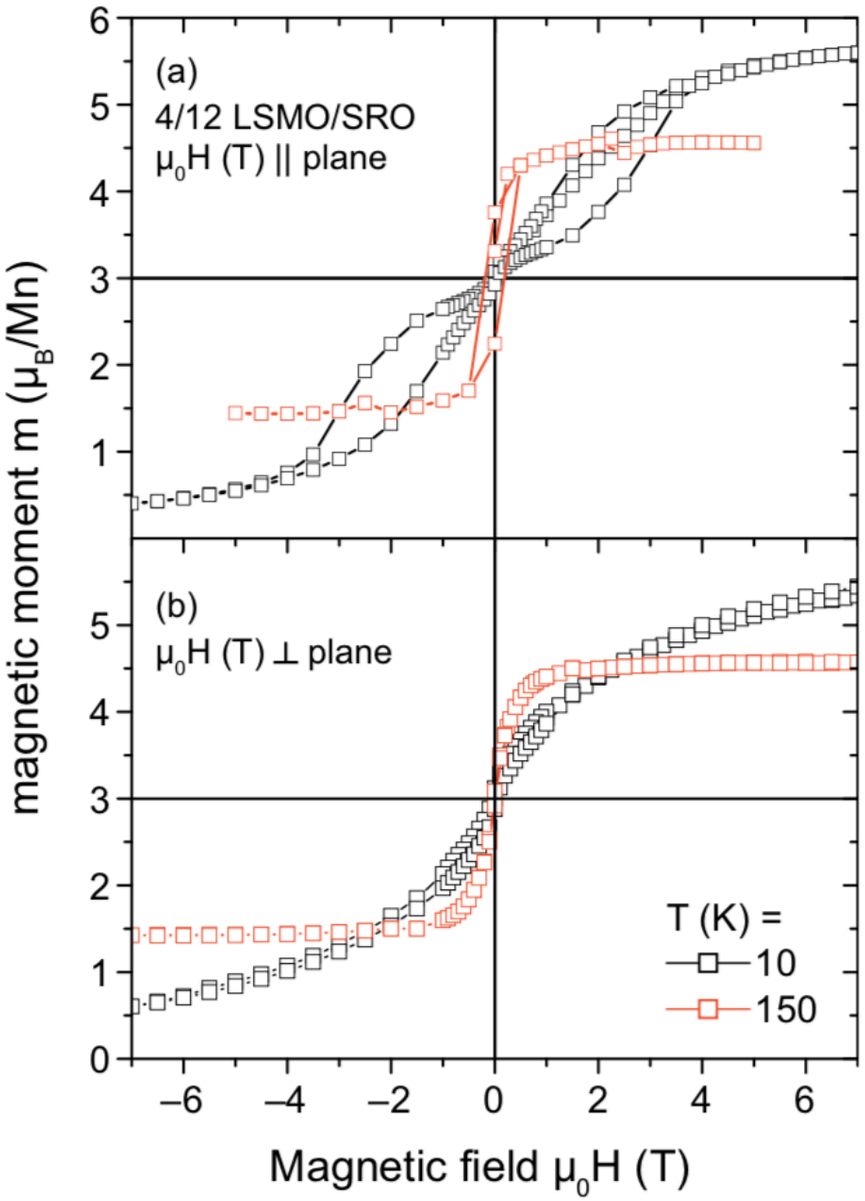


=> Each layer orders ferromagnetically

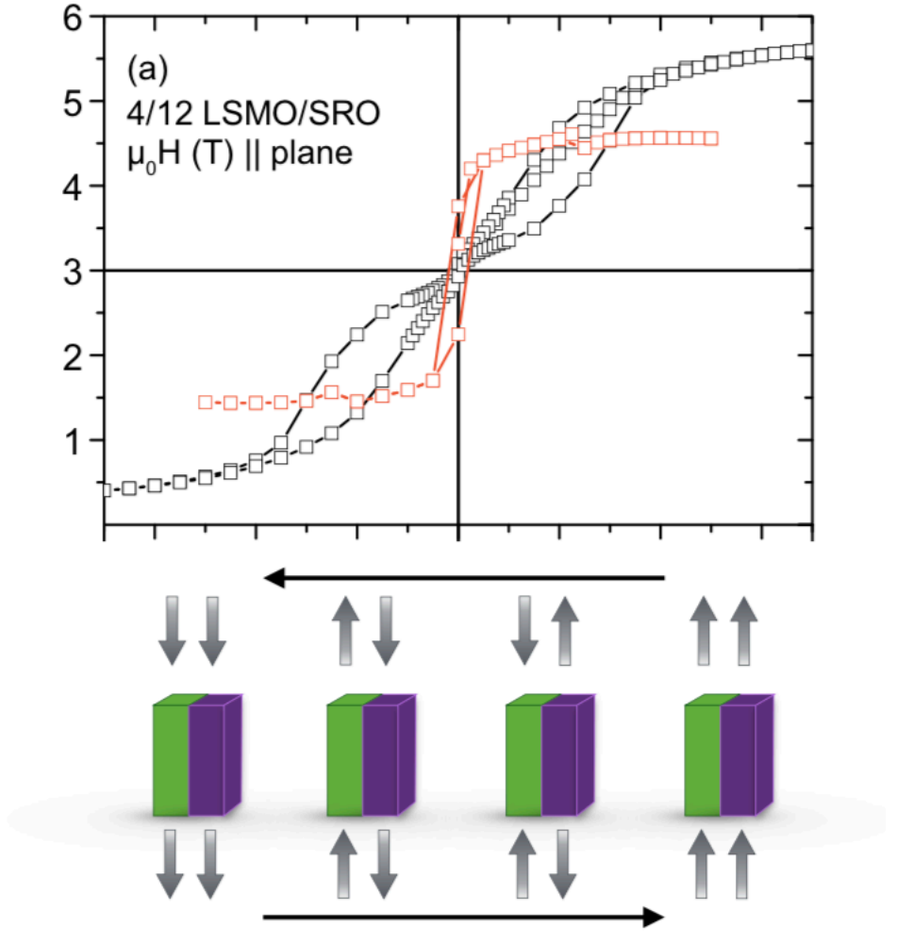
=> Layers couple antiferromagnetically

Review: Ziese and Vrejoiu, Phys. Status Solidi (2013).

Typical characteristics of SRO/LAMO superlattice



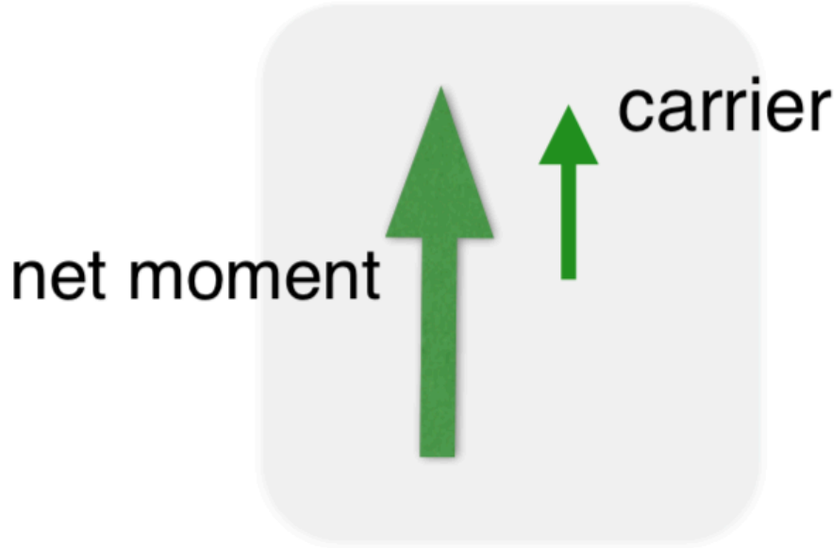
- Strong easy plane anisotropy
- Three regimes in M-H curve

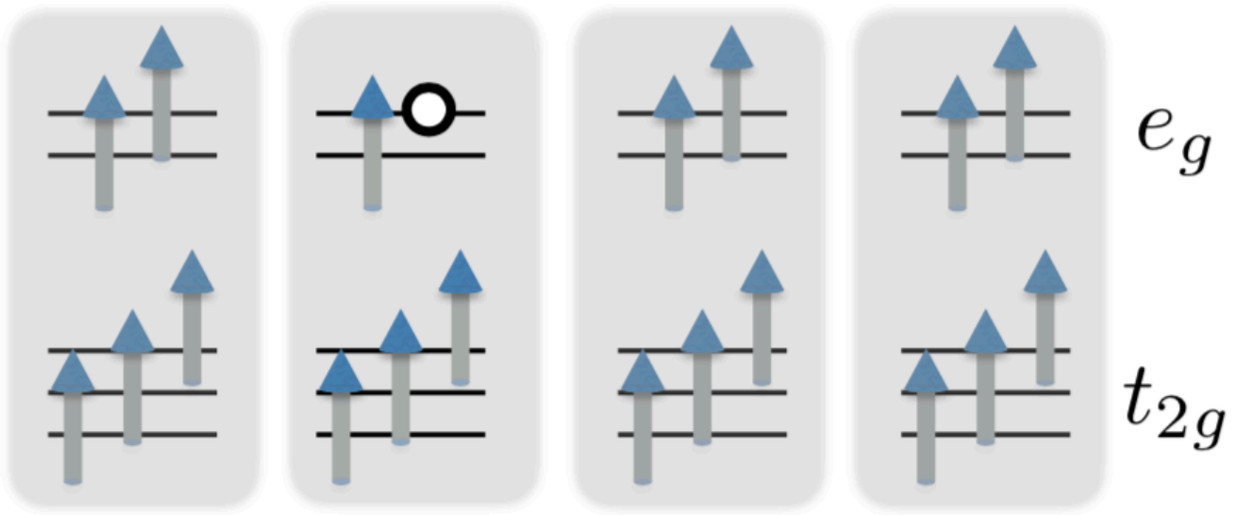


Review: Ziese and Vrejoiu, Phys. Status Solidi (2013).

Nature of $La_{1-x}A_xMnO_3$

- Metal with partially filled e_g levels.
- Double exchange: Ferromagnetism driven by kinetic energy of holes.

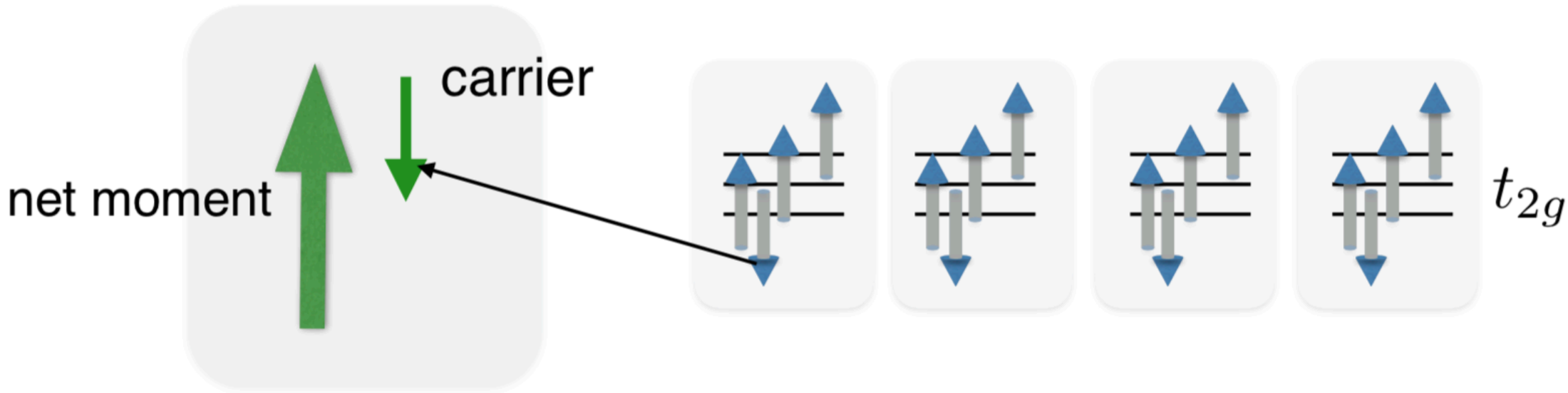




Anderson and Hasegawa, Phys. Rev. (1955)

Nature of $SrRuO_3$

- Metallic, conducting t2g carrier.
- Minority carrier ferromagnet — current is carried by electrons with spins opposite to net magnetization



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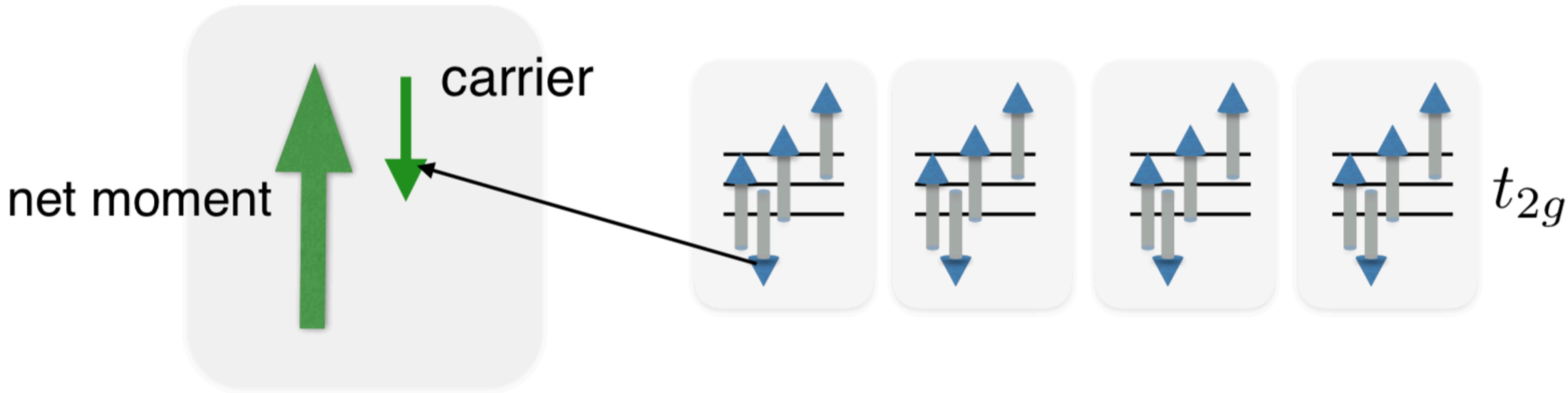
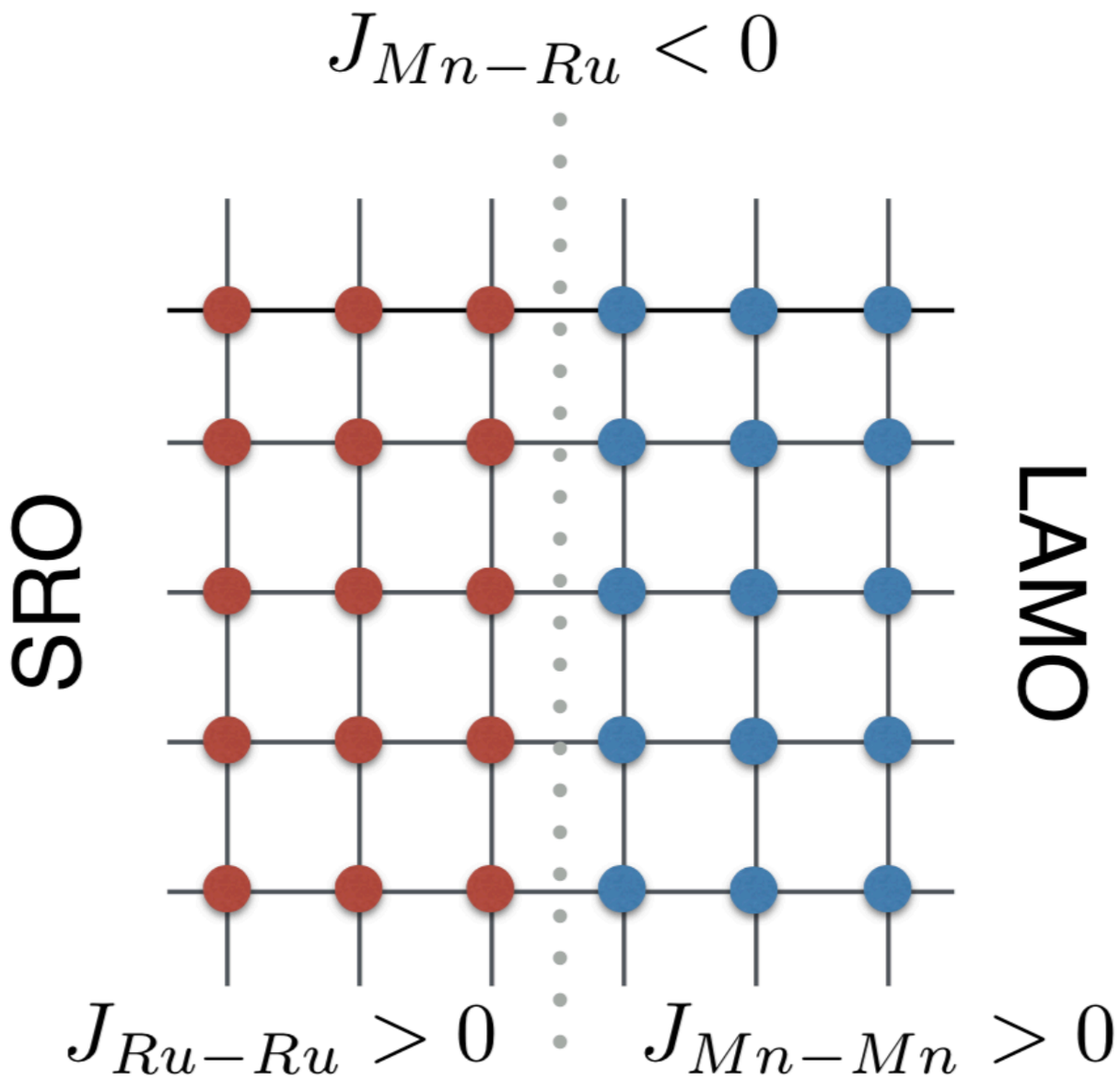


Magnetism in both materials are mediated by the carriers !

Theoretical understanding

- Ab-initio study supports anti-ferromagnetic and attribute it to interfacial coupling

Y. Lee et al., Journal of Alloys and Compounds **450**, 1 (2008).



$$H = -\sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

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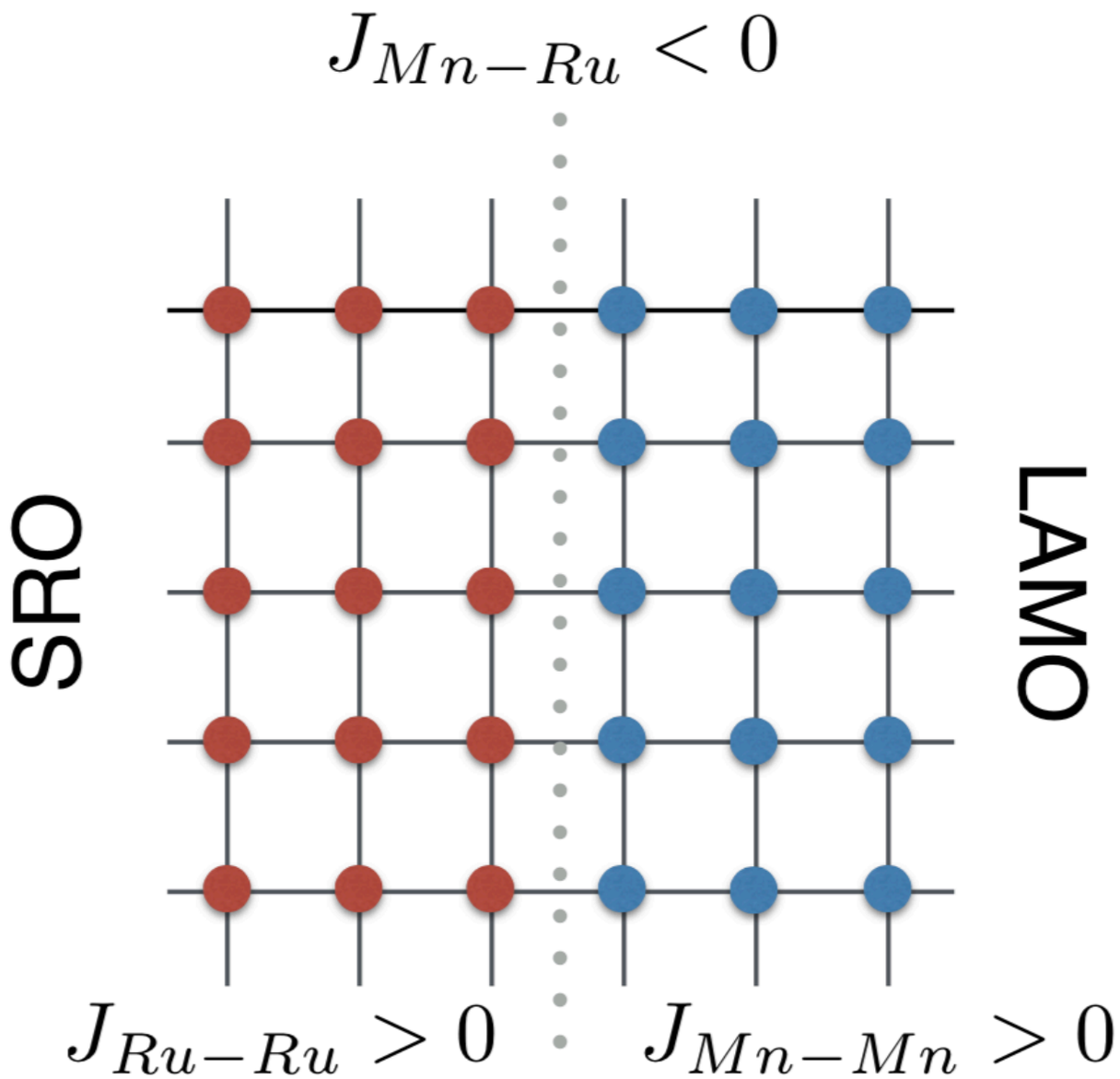


$$H = -\sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

- Local interactions.
- Metallic nature of system ?

Carrier-driven magnetic coupling ?

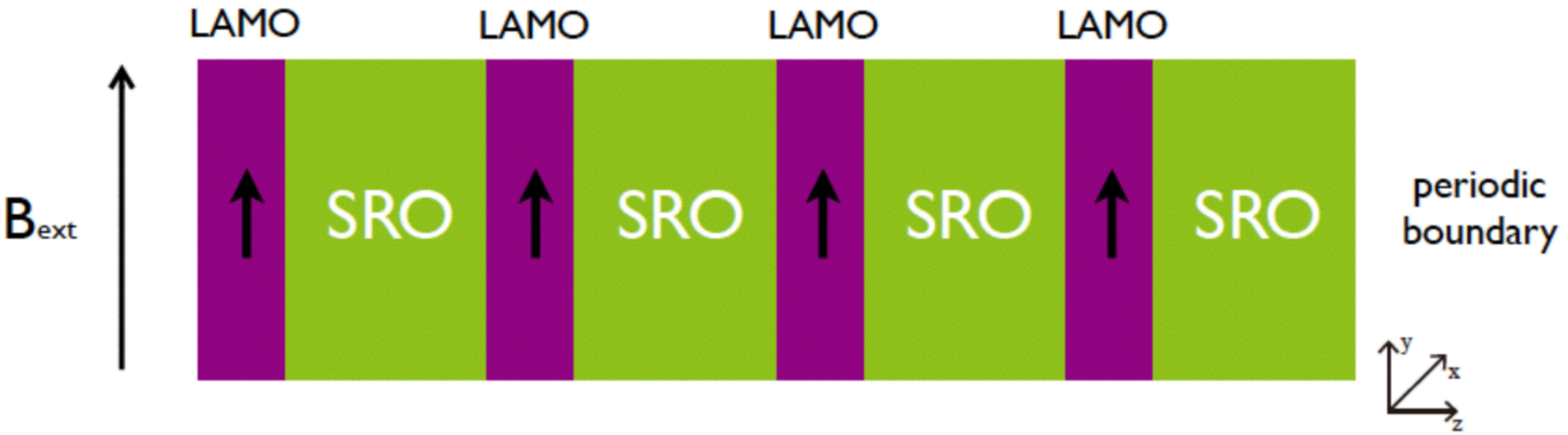
- When $T = T_c^{LAMO}$, moments of LAMO layers are align to the applied field direction.

- Carriers in SRO are spin-polarized by the aligned LAMO moments.

- When $T < T_c^{SRO}$, the carrier-spin polarization decides the moment direction of SRO layers.

LAMO/SRO superlattice

$$T_c^{SRO} < T < T_c^{LAMO}$$



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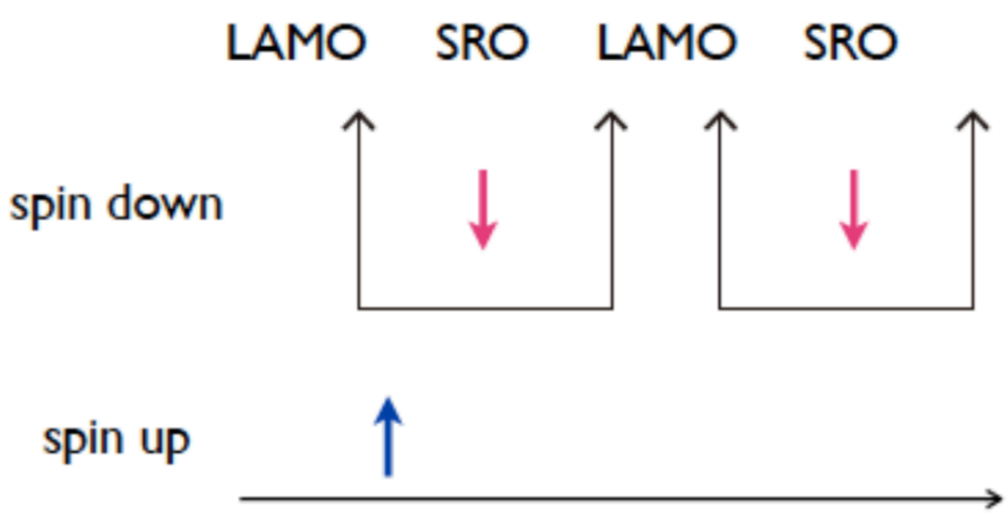

2D system with QWSs along z axis

3D system

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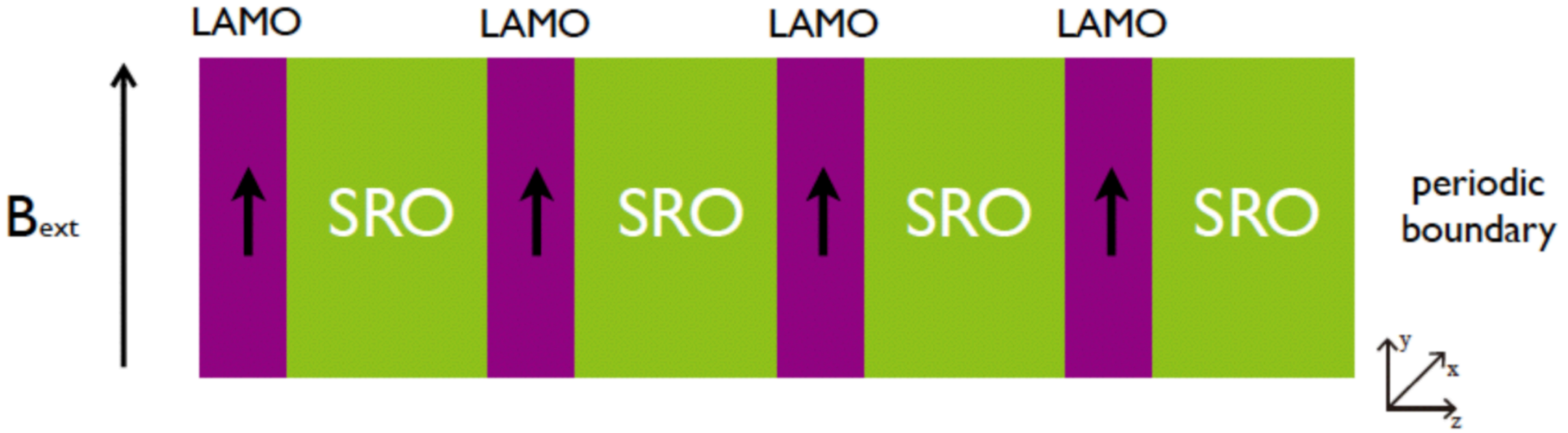

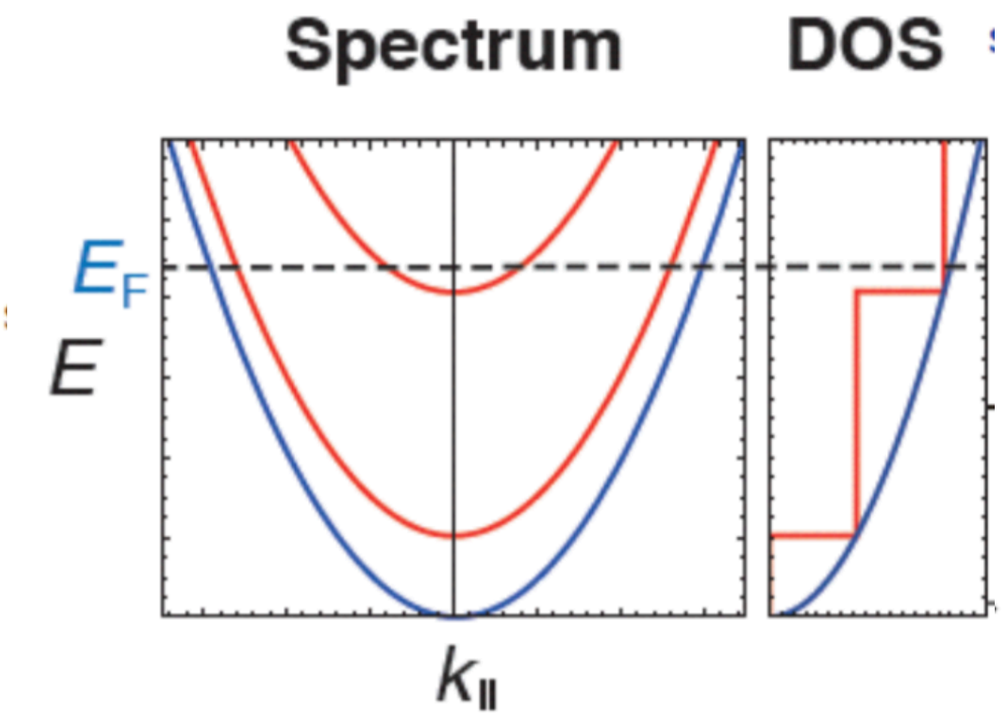

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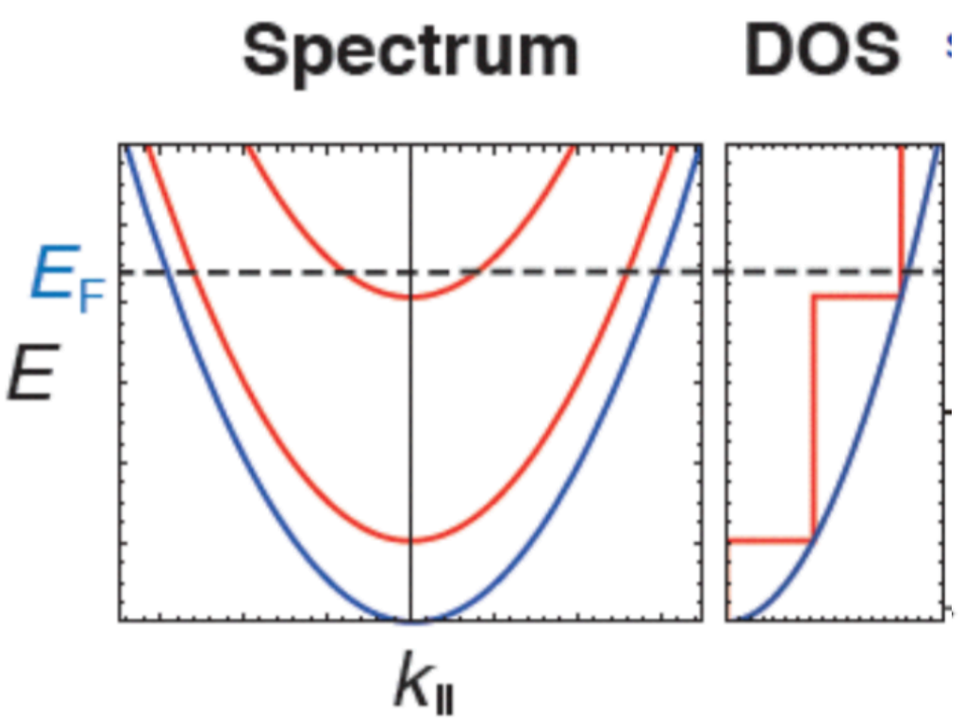
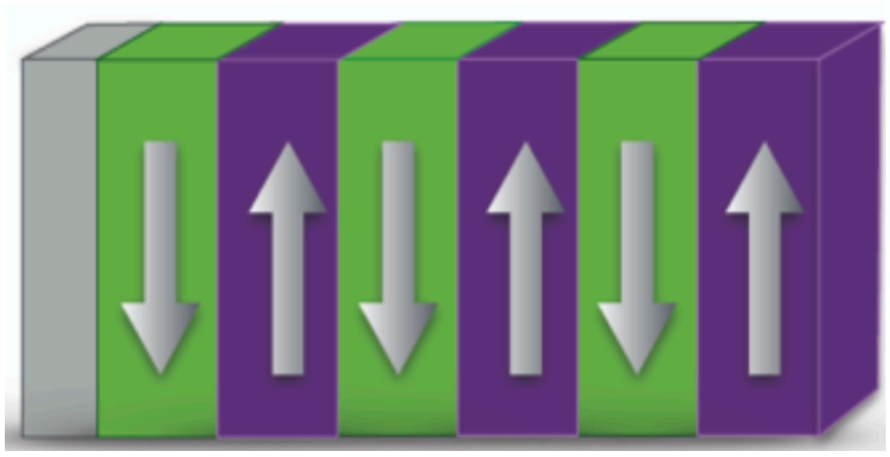
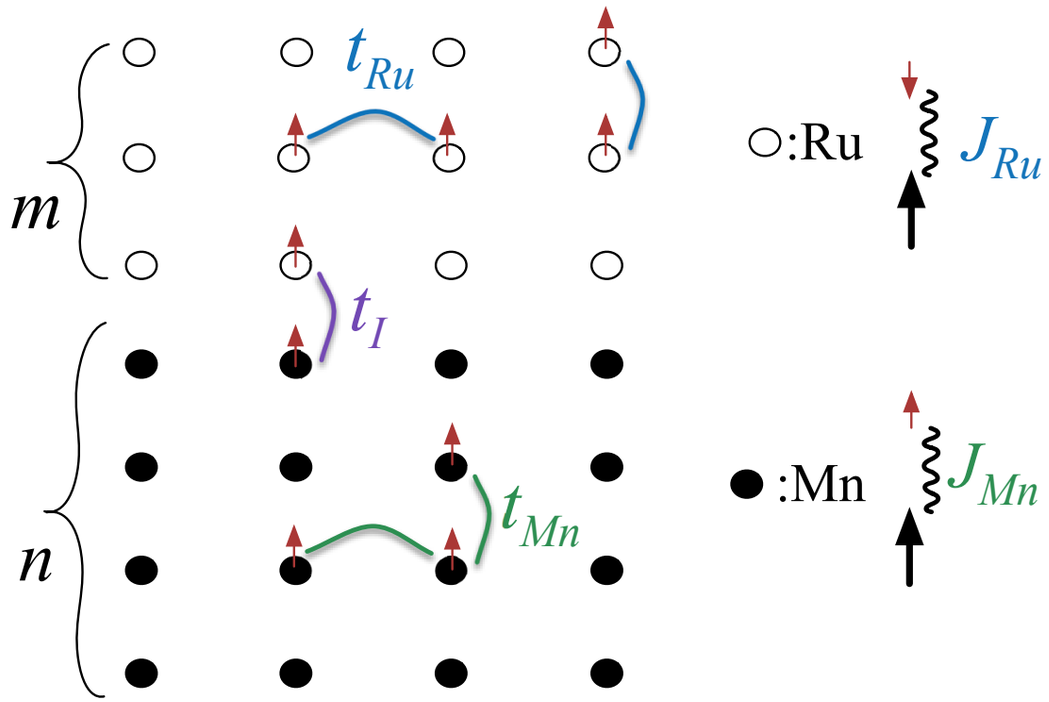


Carrier-spin polarization decides SRO antiferromagneitcally couples to LAMO !



Microscopic Model:

$$H = \sum_{i,\sigma,\sigma'} J_i \mathbf{S}_i \cdot \frac{1}{2} c^\dagger_{i,\sigma} \vec{\tau} c_{i,\sigma'} - \sum_{\langle ij \rangle,\sigma} t_{ij} c^\dagger_{i,\sigma} c_{j,\sigma} + \sum_{i,\sigma} (\epsilon_i - \mu) c^\dagger_{i,\sigma} c_{i,\sigma}$$



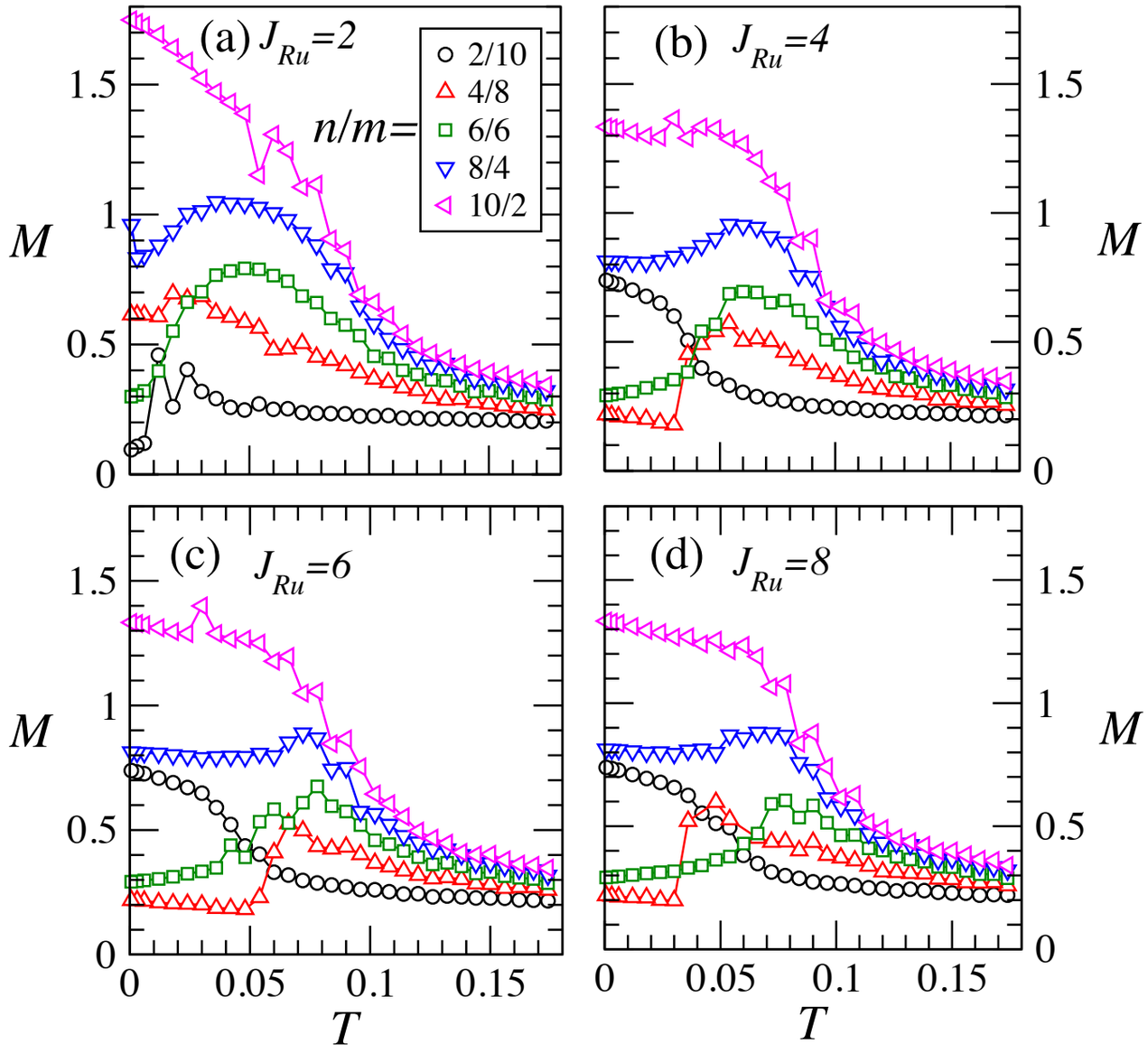
Degrees of Freedom: (i) Localized Spins, (ii) Itinerant Fermions

No direct exchange coupling in the model !

Solved M-T curve

Model Parameters

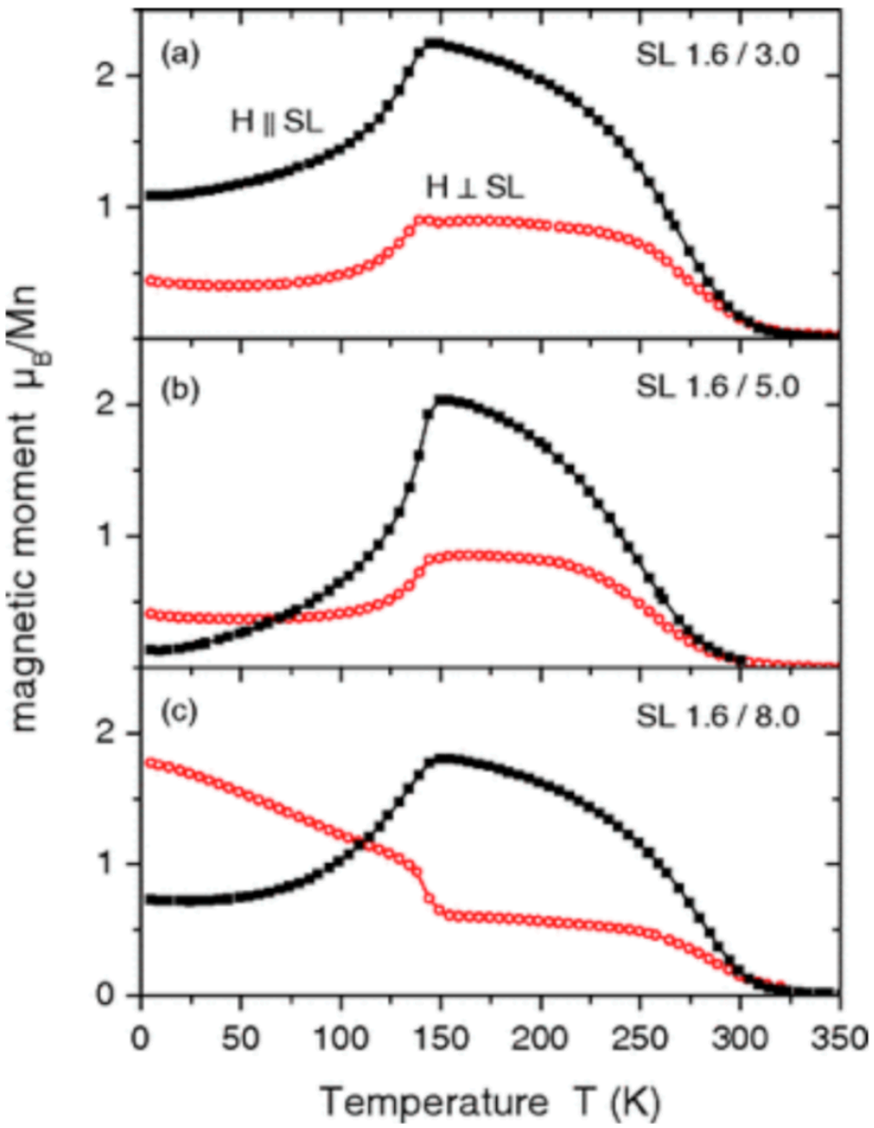
$t_{Mn} = 1.0$
$t_{Ru} = 0.5$
$t_I = 0.5$
$x_{Mn} = 0.3$
$x_{Ru} = 0.5$
$J_{Mn} = -20$

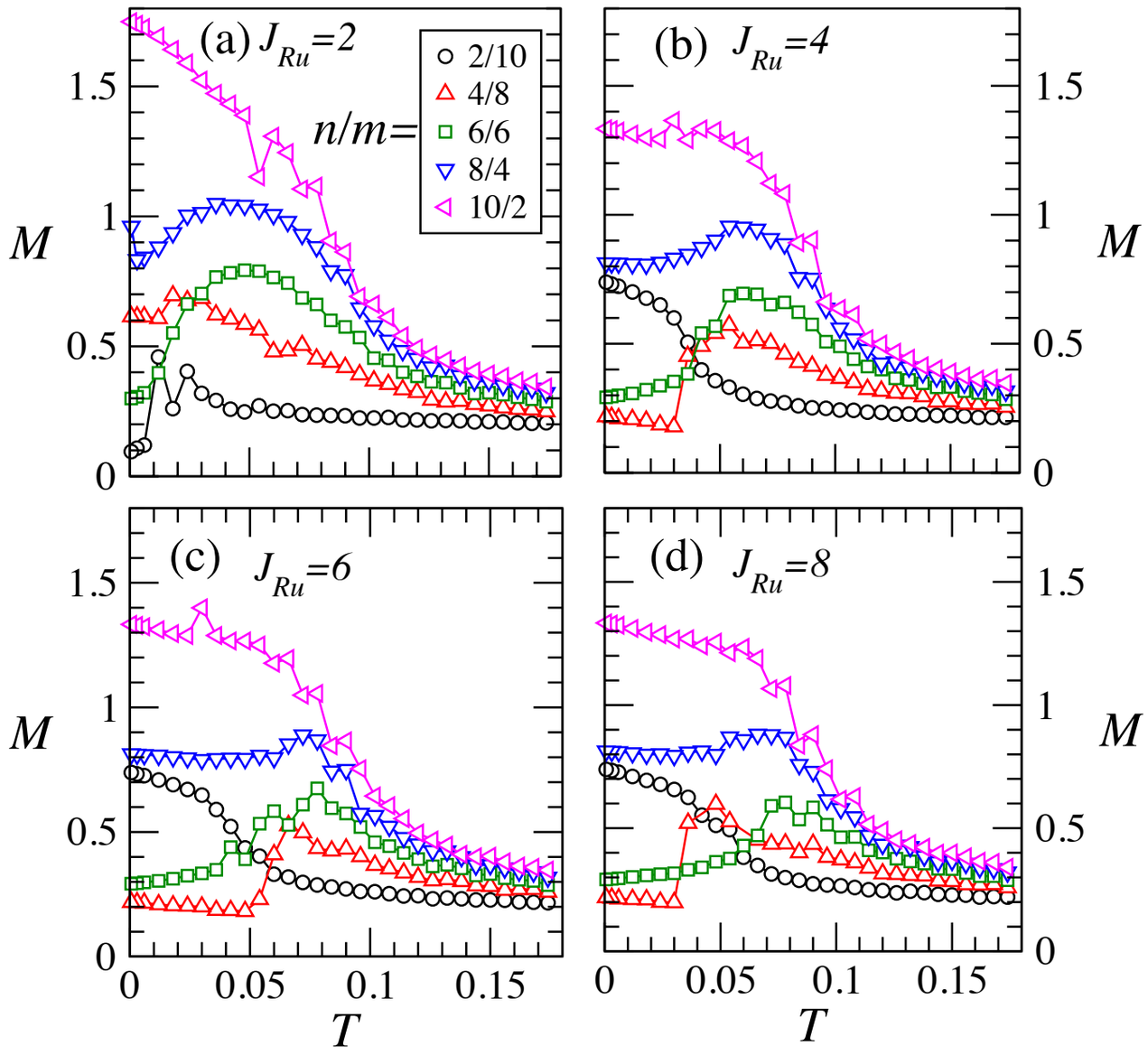


- Simulations on 2D lattice indicate AFM coupled ground states.
- The shape of M-T curve is consistent well with experimental results.

Solved M-T curve

Experiment: Phys. Status Solidi (2013)





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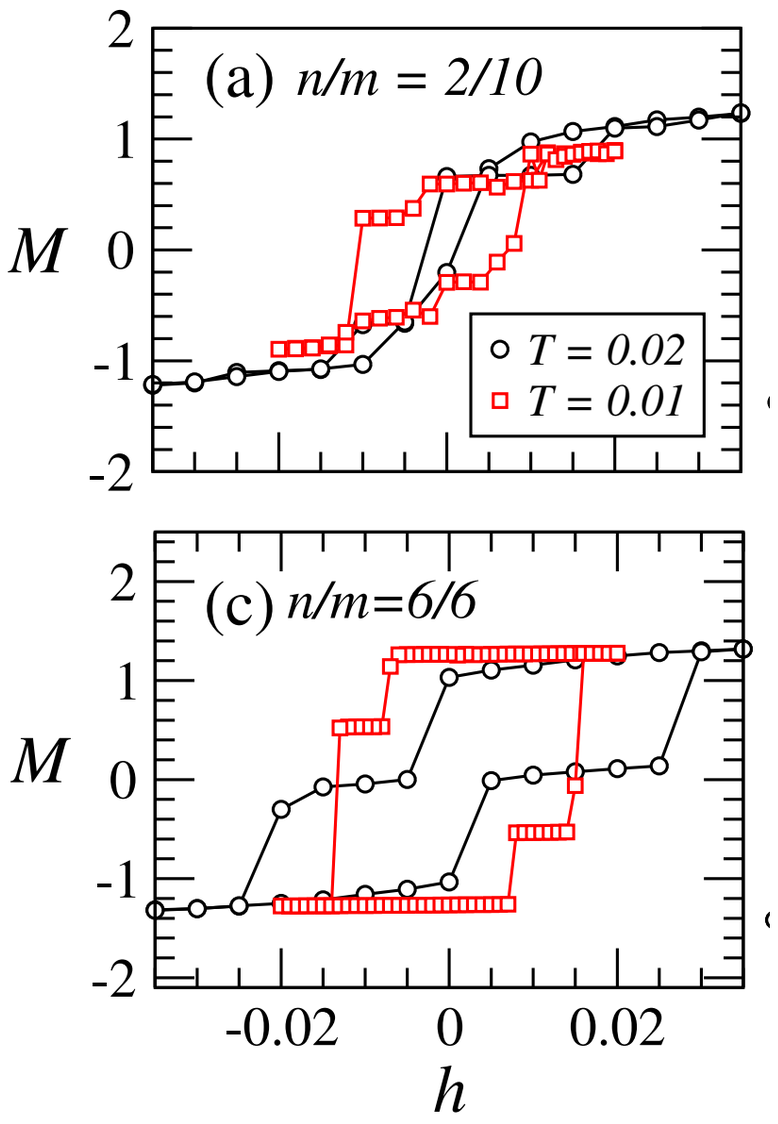
Low-temperature hysteresis loops



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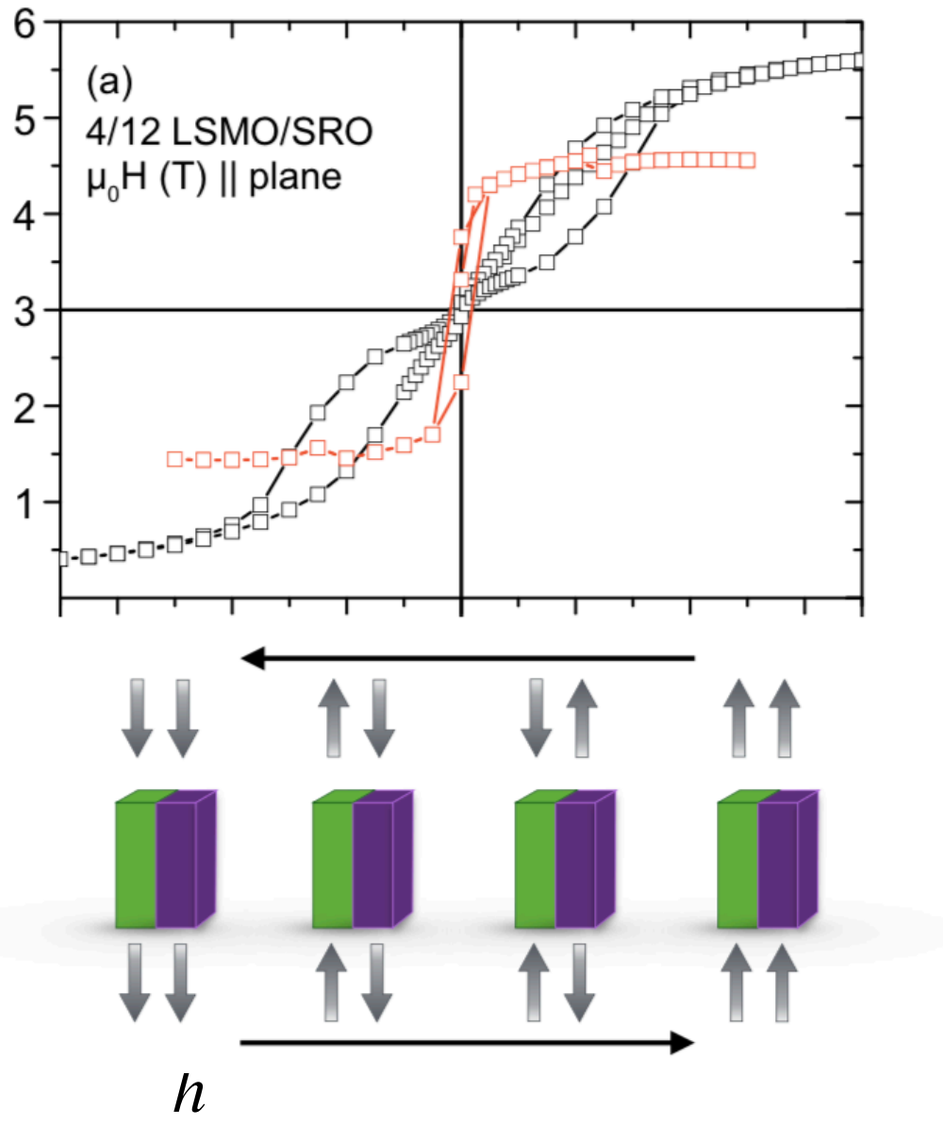
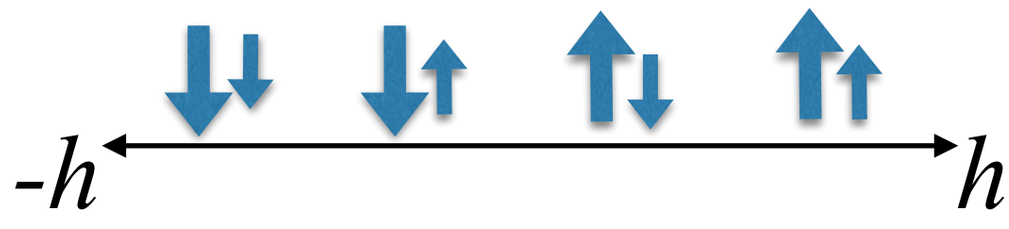


- Variety of hysteresis loops are found in simulations, depending on n/m ratio, temperature and J_{Ru}
- Can be understood as

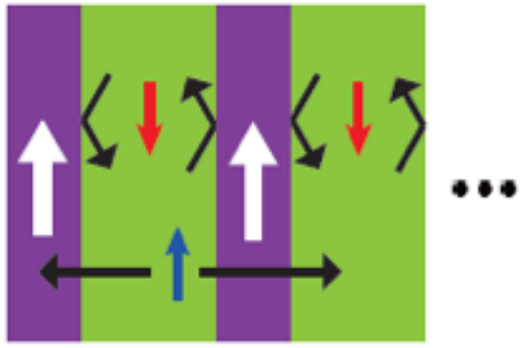


Discussions:

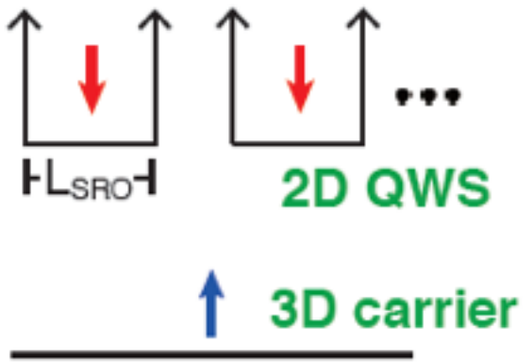
- Based the picture of carrier-driven magnetic coupling, AFM coupling, M-T curve, M-H curve can be addressed.

- Can we propose an experiment that confirms this mechanism and rules out the interfacial coupling ??

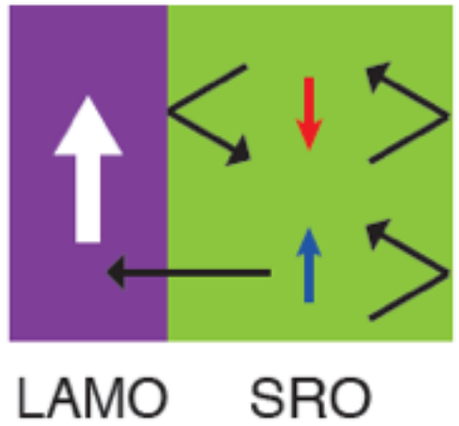
Superlattice

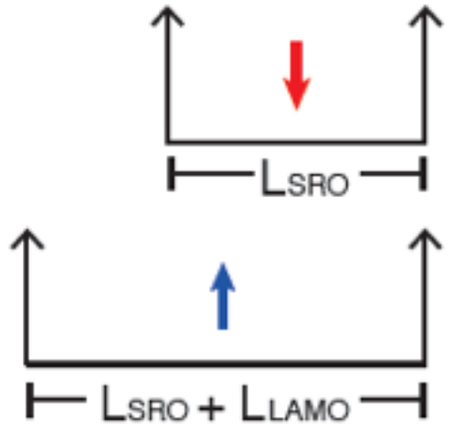


Spin confinement

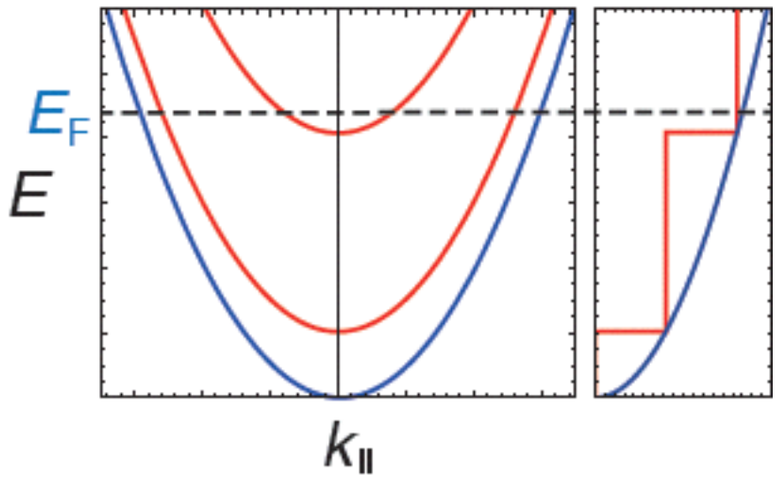


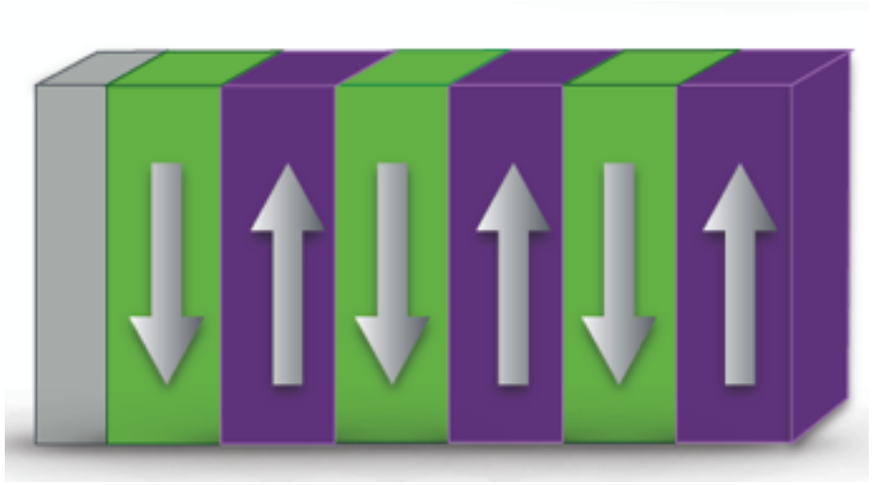
Bilayer





Spectrum DOS





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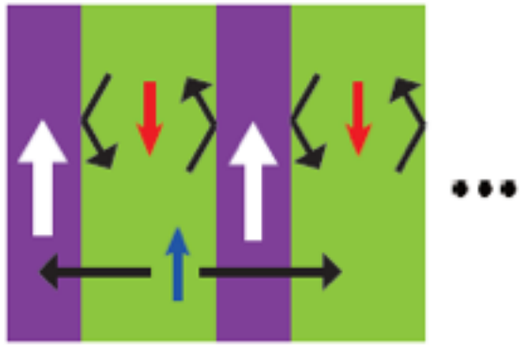
Superlattice



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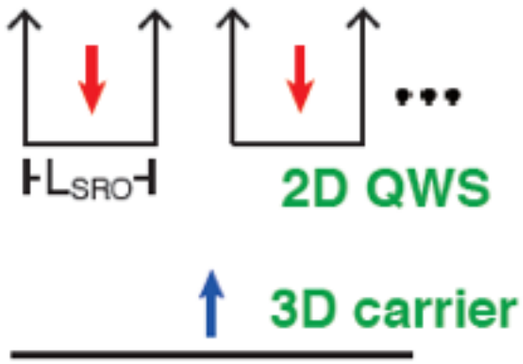

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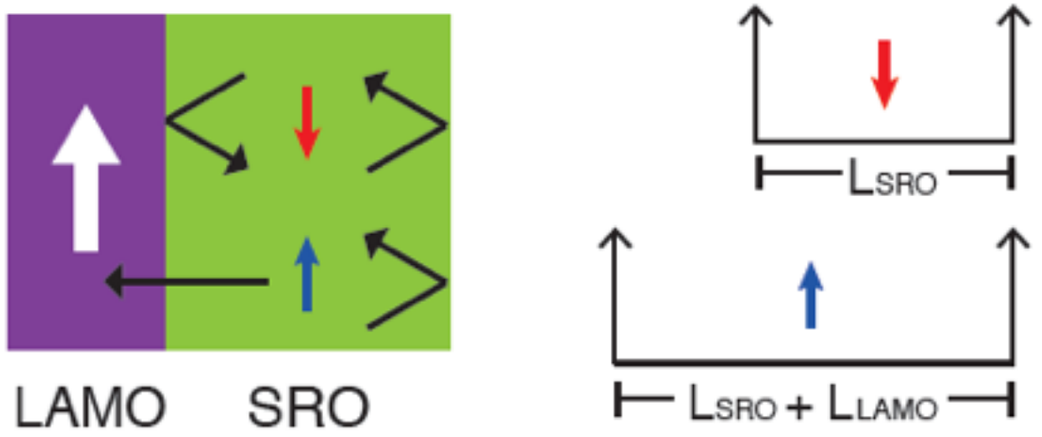

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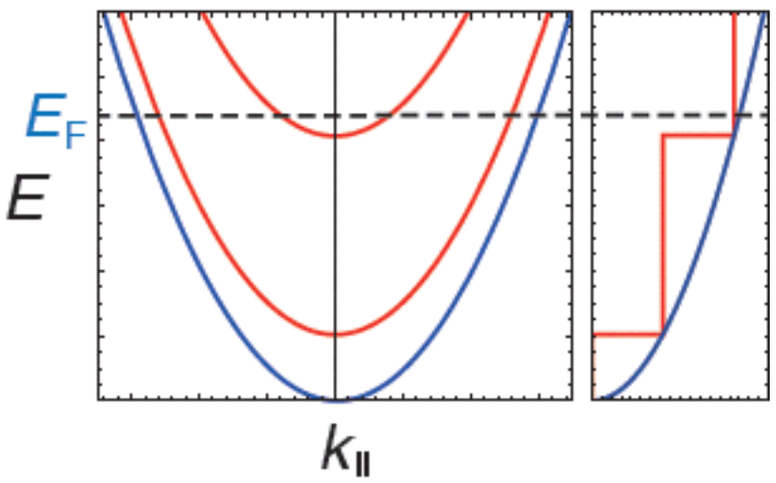

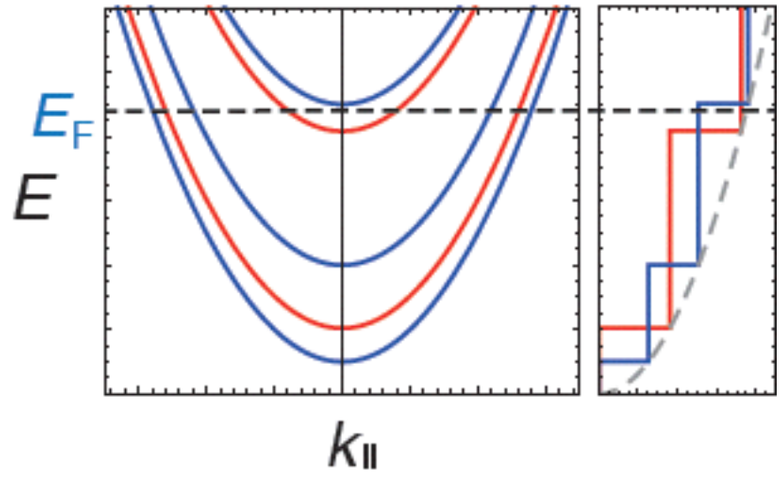

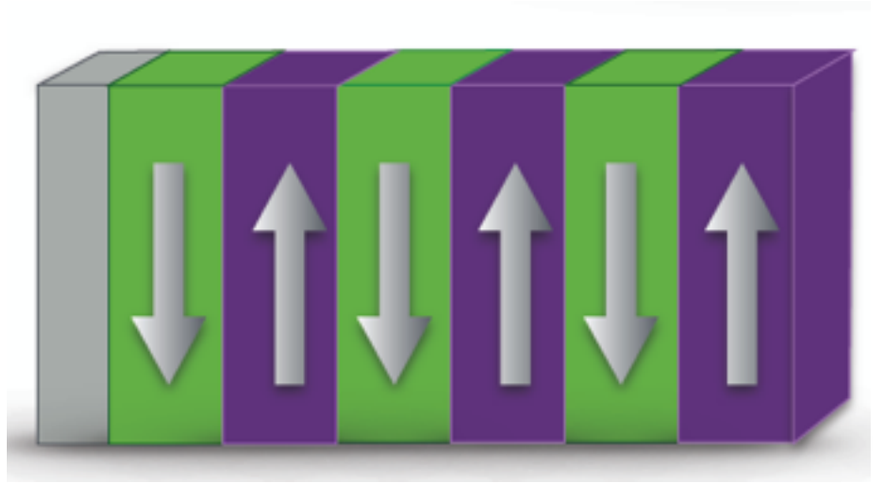

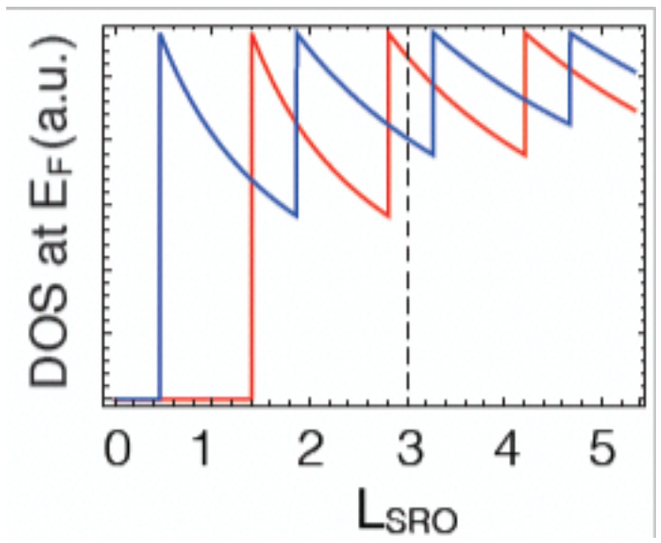

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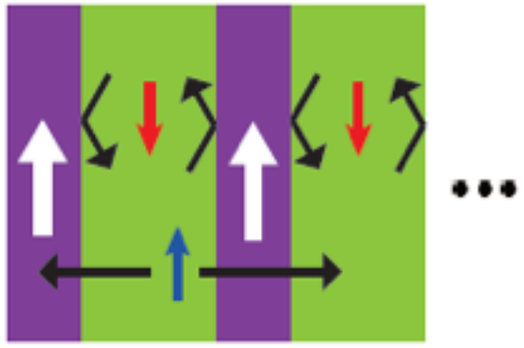
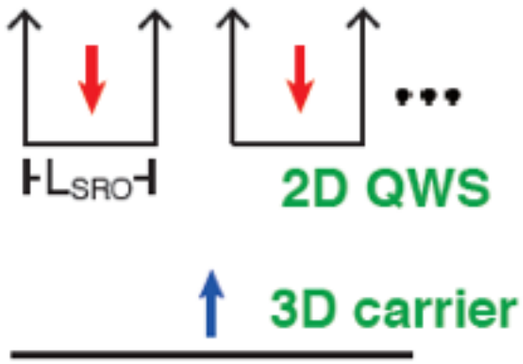
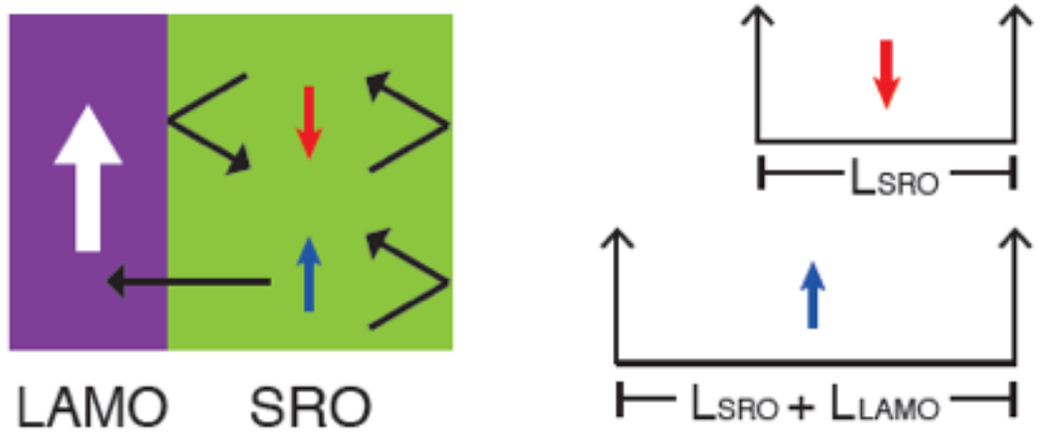
Superlattice



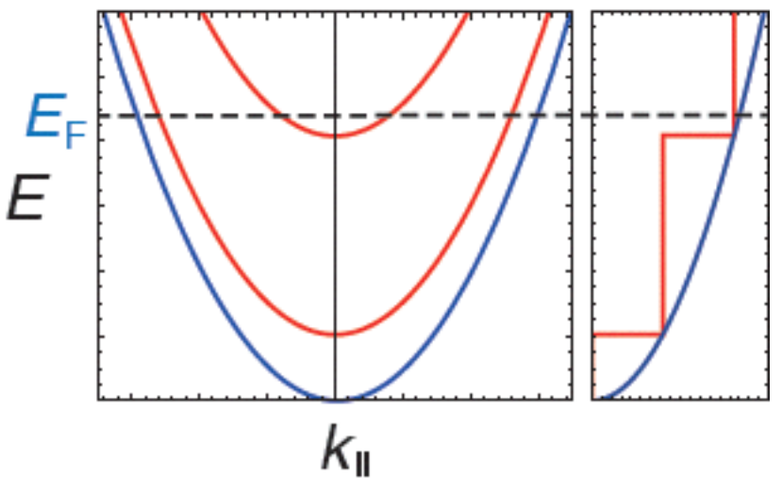
Spin confinement

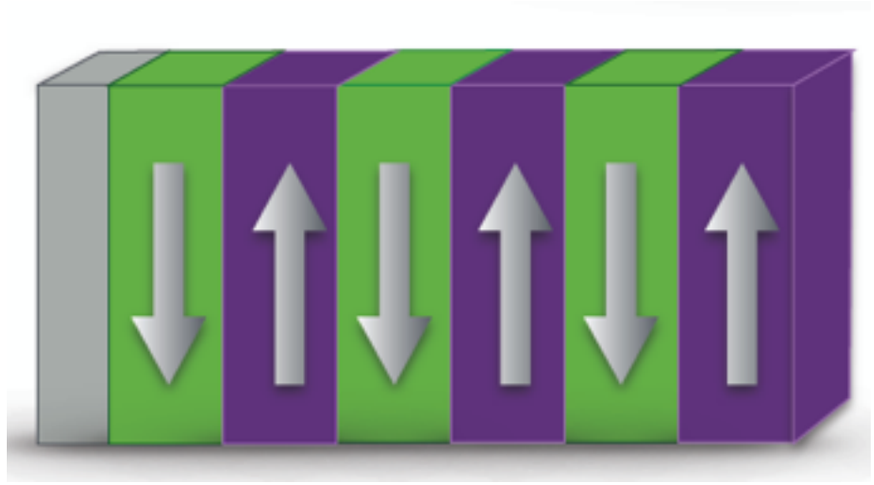


Bilayer



Spectrum DOS





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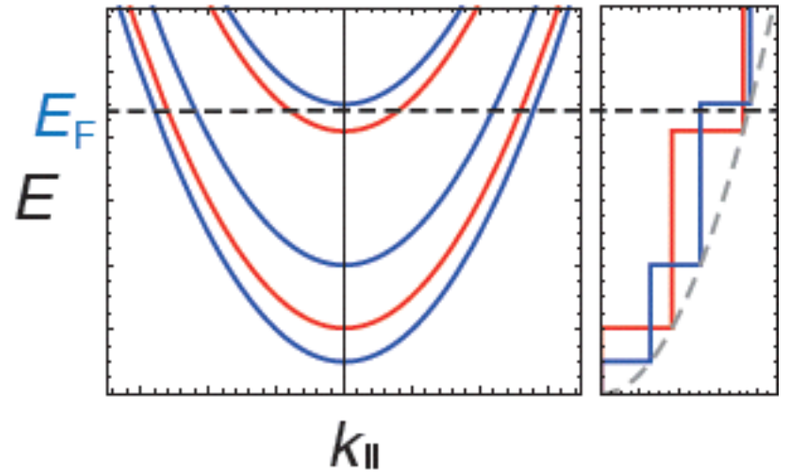
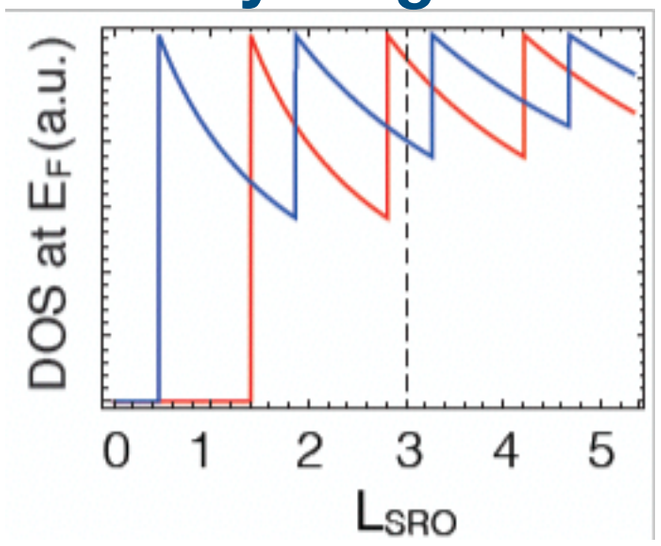
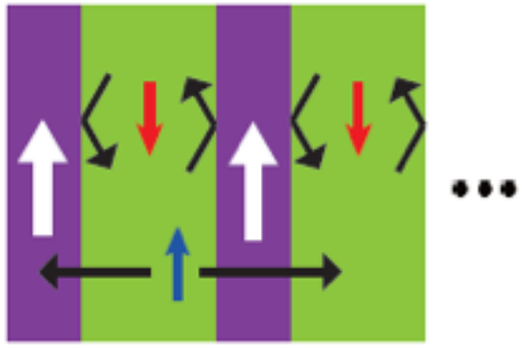


Oscillatory magnetic coupling !



Superlattice



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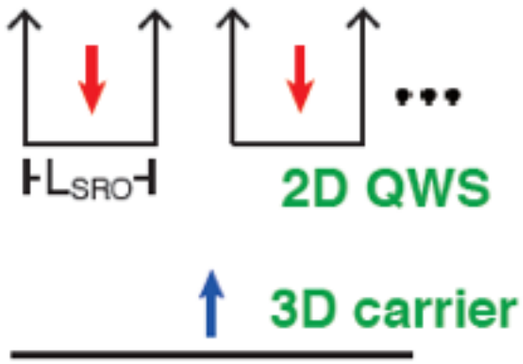

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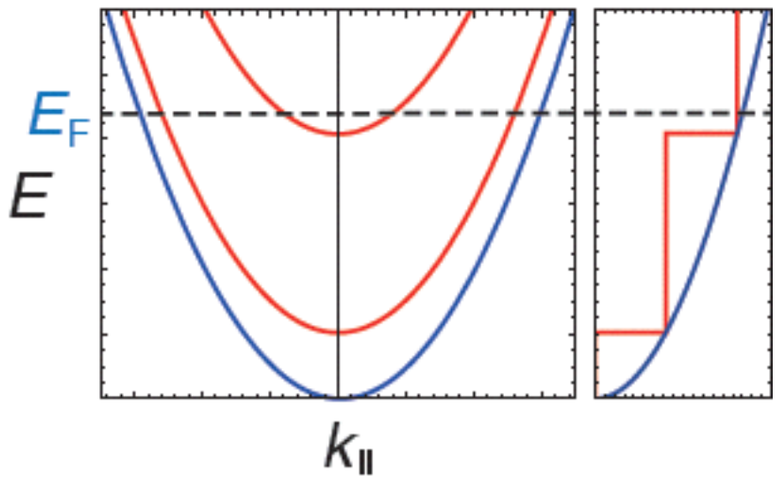

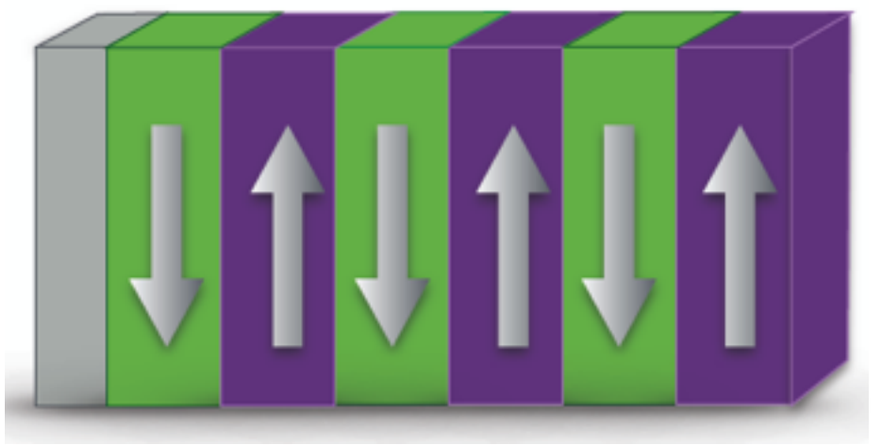

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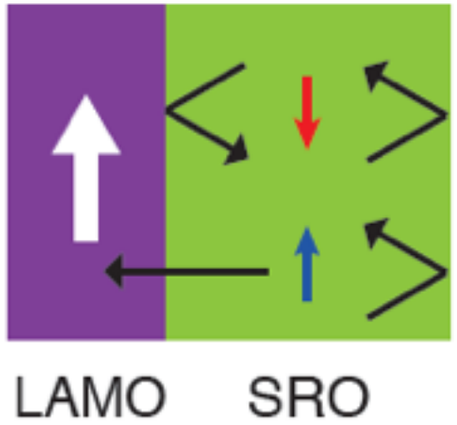
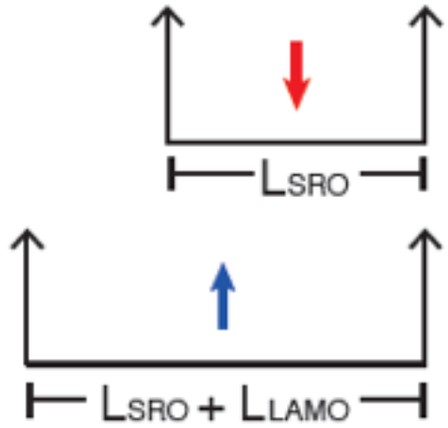
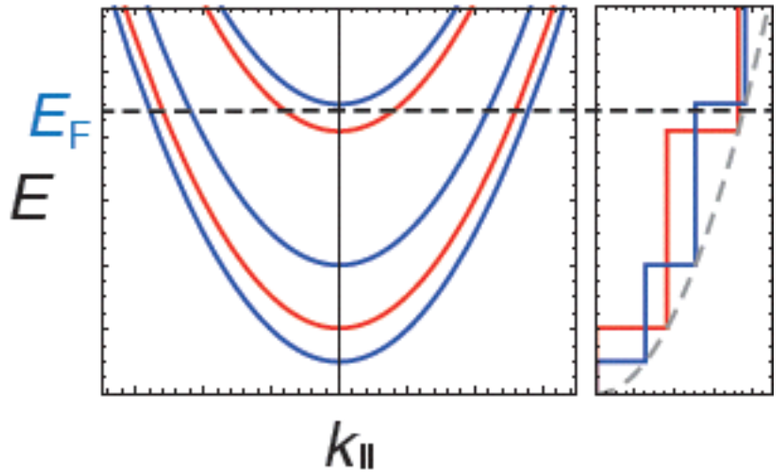
Confirmed in *ab-initio* calculation !

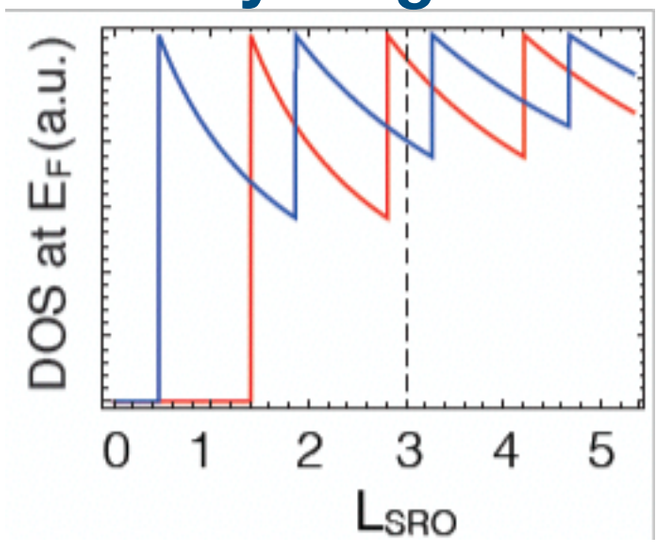
Bilayer







Oscillatory magnetic coupling !



Summary

C. H. Chang, *et al*., Phys. Rev. B **96**, 184408 (2017).

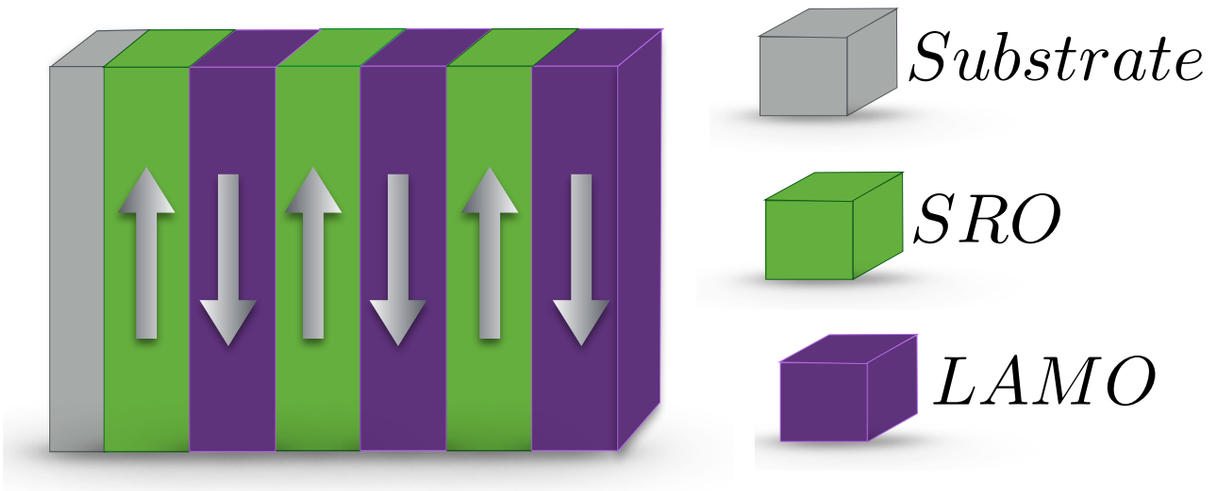
- Antiferromagnetic coupling in the LSMO/SRO superlattice due to carrier.

- The measured M-T and M-H curves can be explained.

- Prediction of oscillatory magnetic coupling in the LAMO/SRO bilayer.

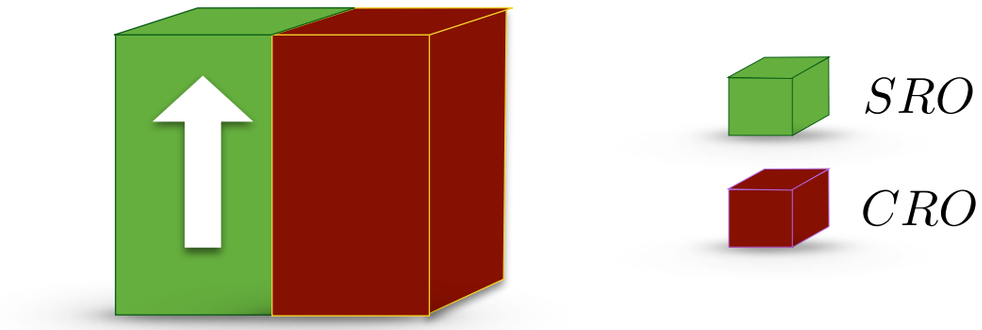
Magnetic-nonmagnetic heterostructure ?

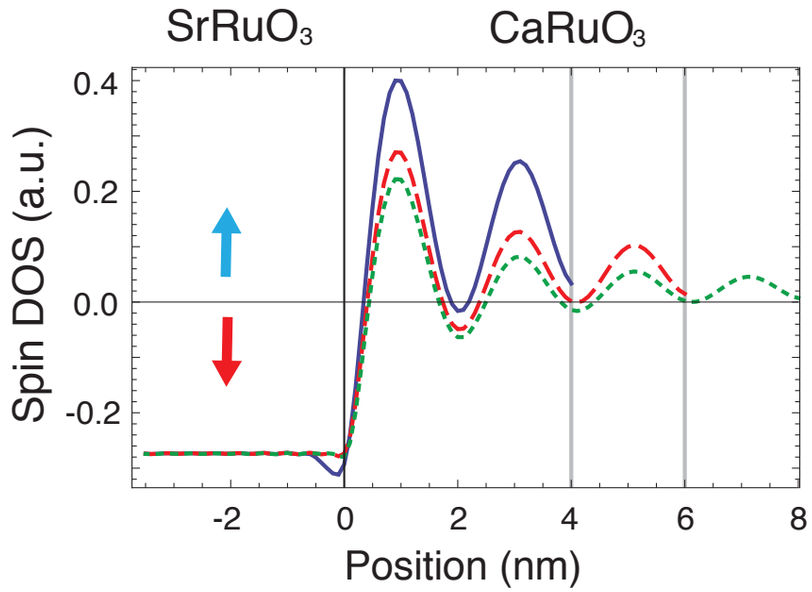
Magnetic ordering due to spin-polarized carriers



- Carriers leads to antiferromagnetic alignment
- Explains observed M-H and M-T curves

Phys. Rev. B 96, 184408 (2017)





arXiv:1802.05869

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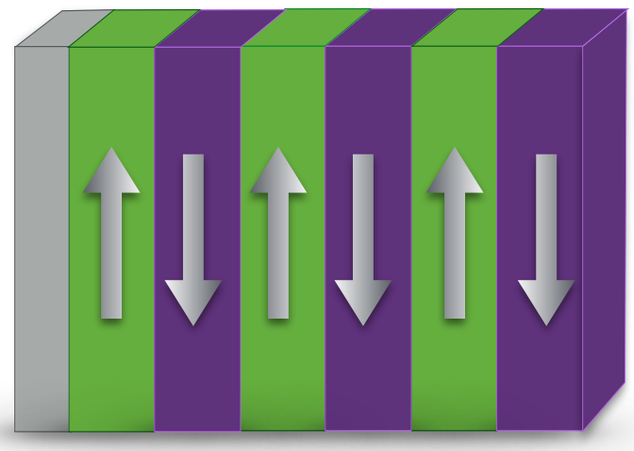

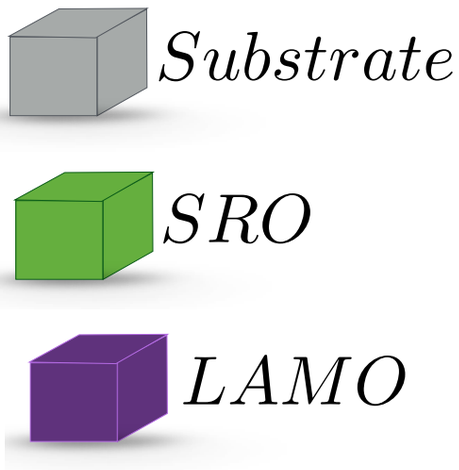

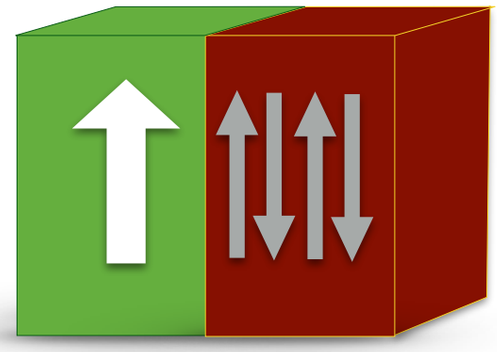

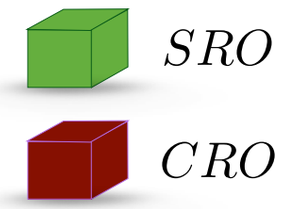

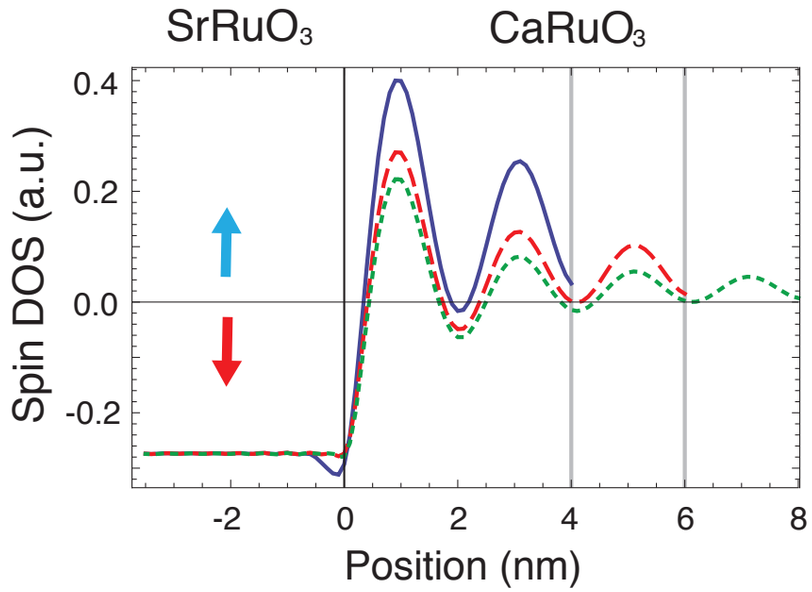

- Carriers leads to antiferromagnetic alignment
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Phys. Rev. B 96, 184408 (2017)

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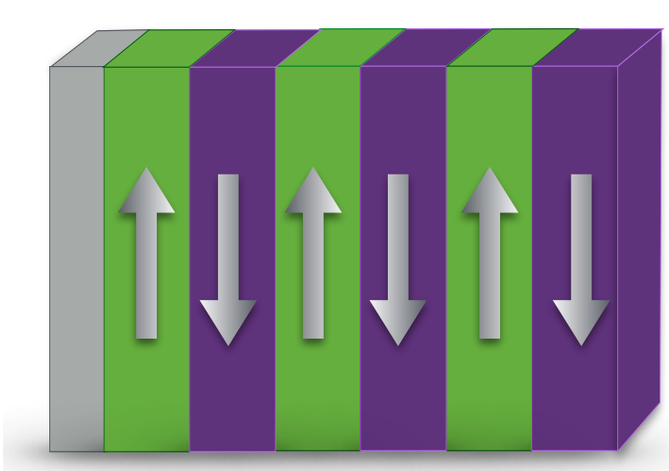

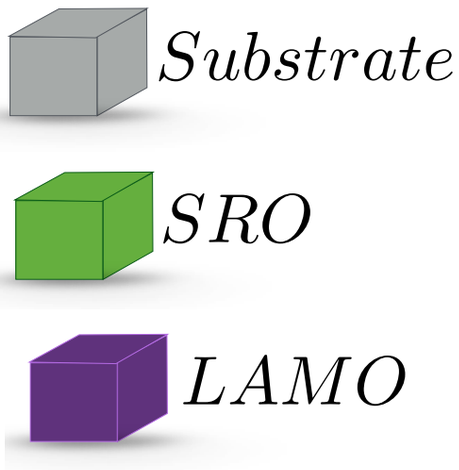

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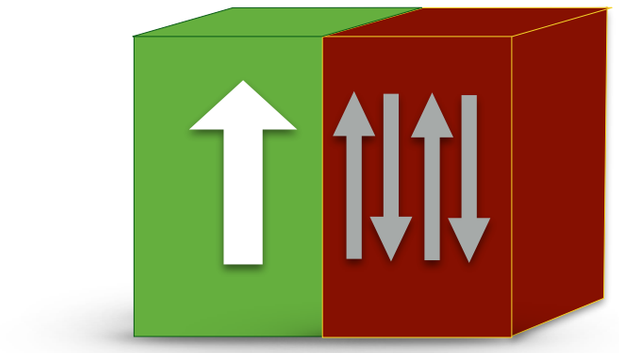
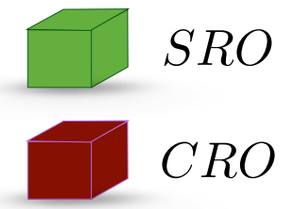
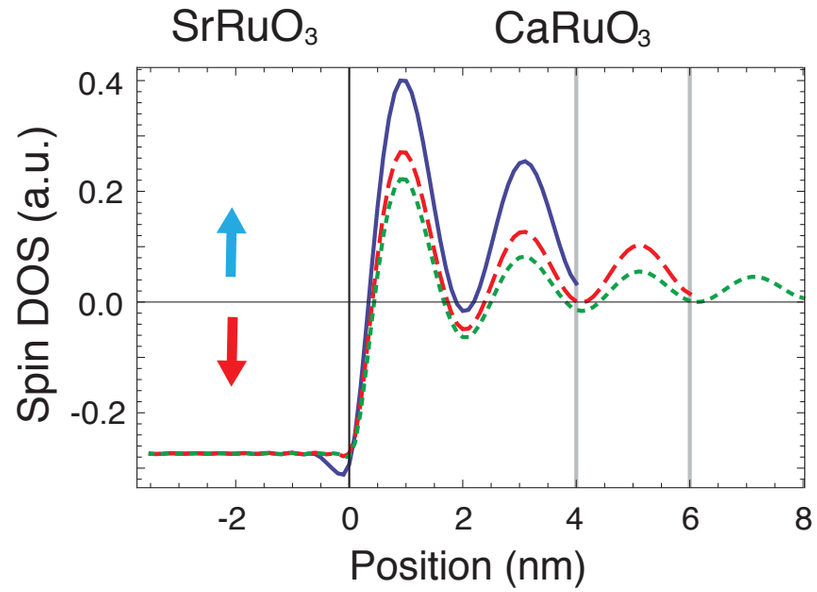
Phys. Rev. B 96, 184408 (2017)







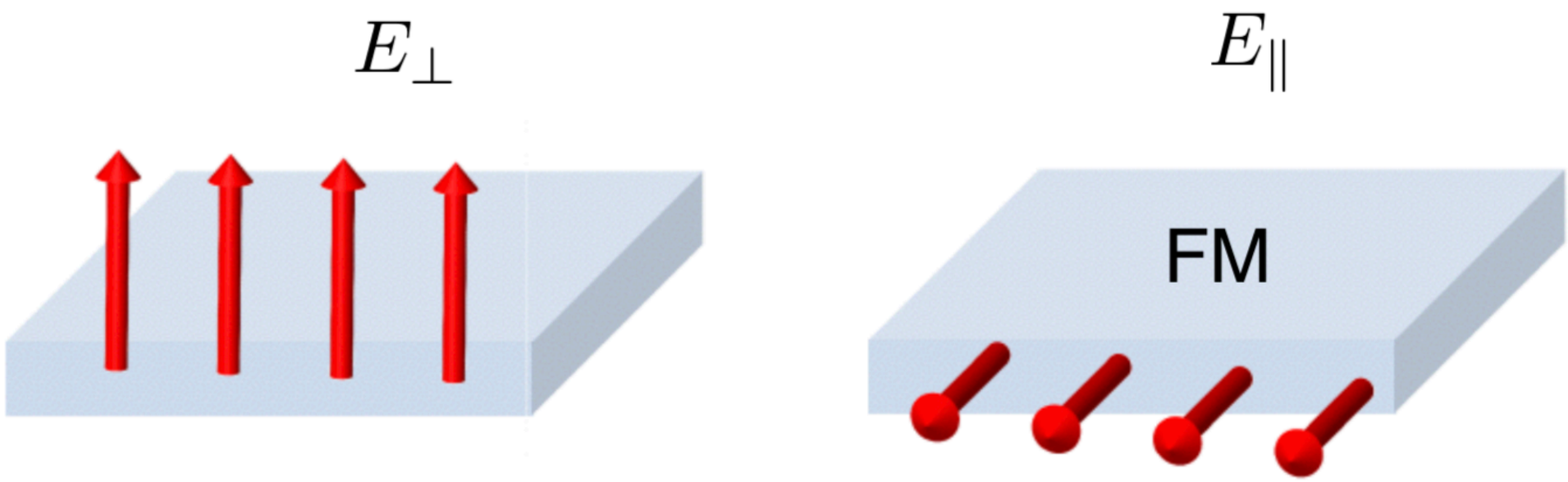
- Friedel-like oscillations of majority carrier in CRO !
- Consequences for magnetic moment and exchange bias

arXiv:1802.05869

Magnetic anisotropy in a SrRuO3 layer

Magnetic anisotropy energy (MAE)

$$\mathrm{MAE} = E_{\perp} - E_{\parallel}$$



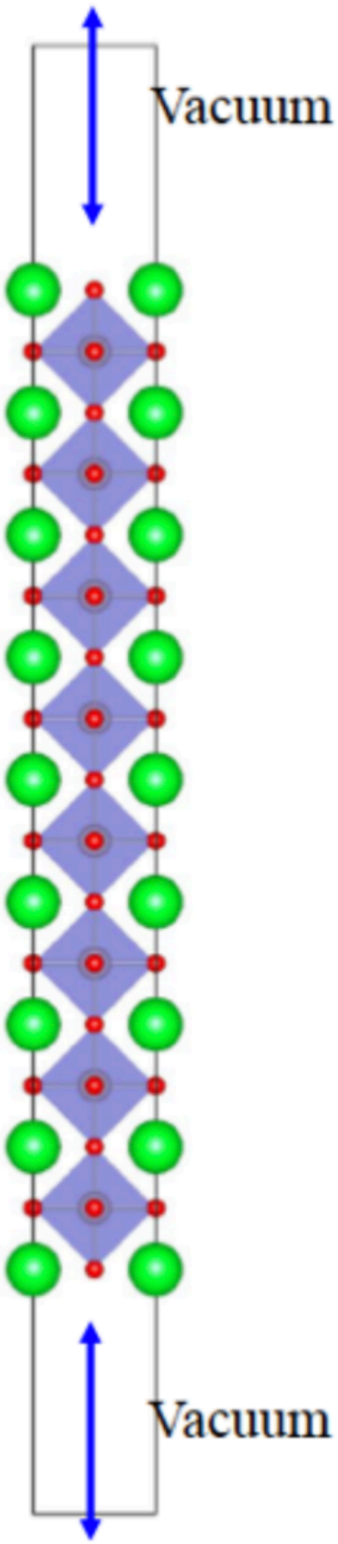
- Spin orbital coupling (SOC) dominates MAE in nanoscale.
- Understanding the origin of SOC-induced MAE is a challenge due to the complex band structure.

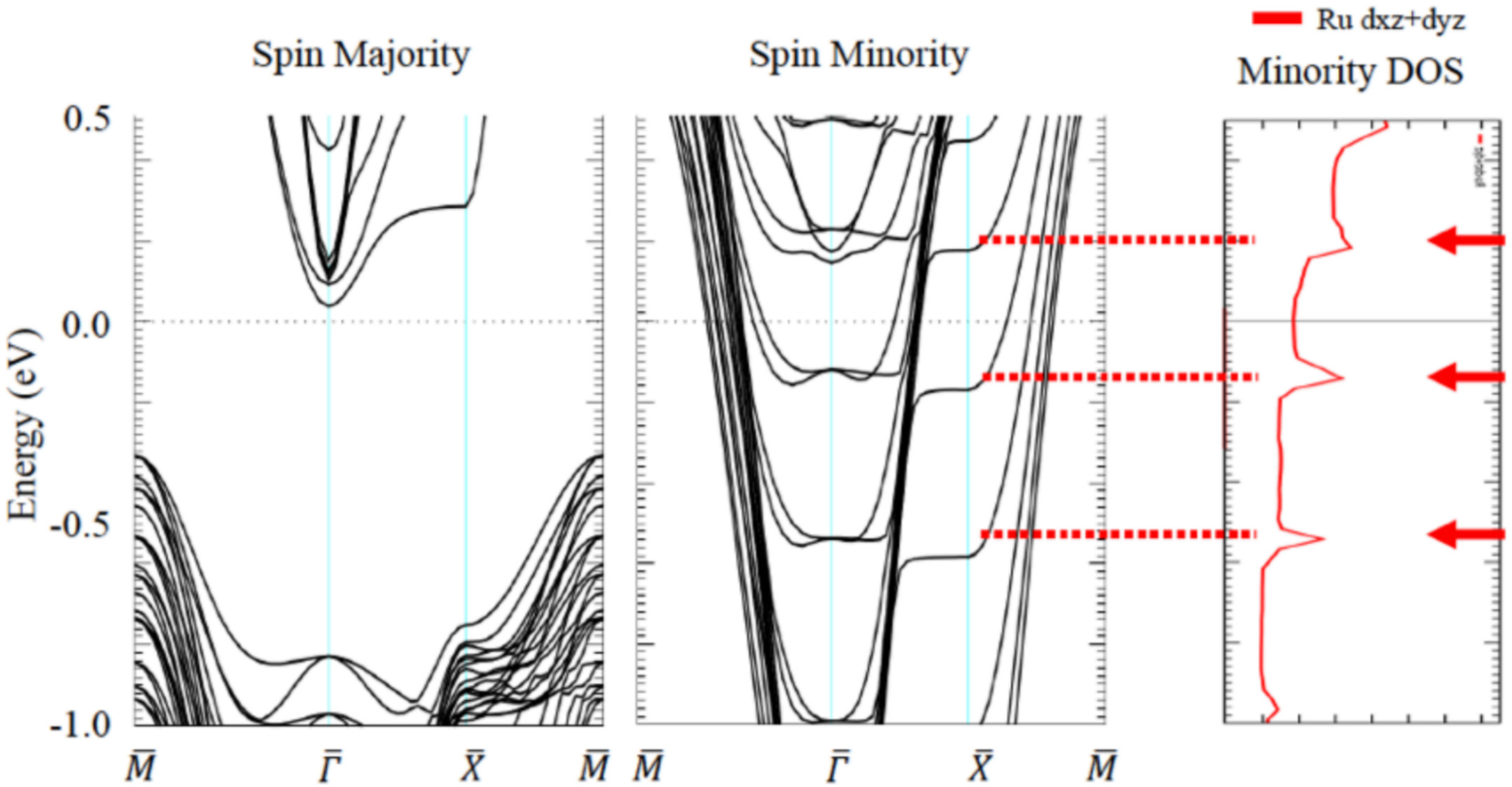
The SRO layer

- The SRO layer has only minority t2g-orbital states at Fermi level.

- The SRO layer is a best system to explore the origin of MAE to control the MAE.

QWS in SRO (8uc)





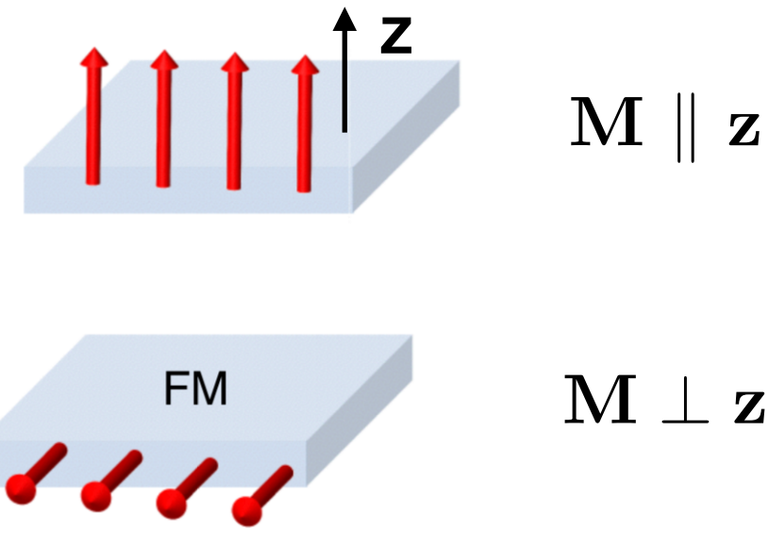
QWS and magnetization direction

The SOI Hamiltonian:

$$H_s = \lambda\Big[L_z\sigma_z + L_+\sigma_- + L_-\sigma_+\Big],$$

Magnetic Crystalline Energy

$$E(M\|z) - E(M \perp z),$$



C. H. Chang *et al.*, NPG Asia Materials **9**, e424 (2017)

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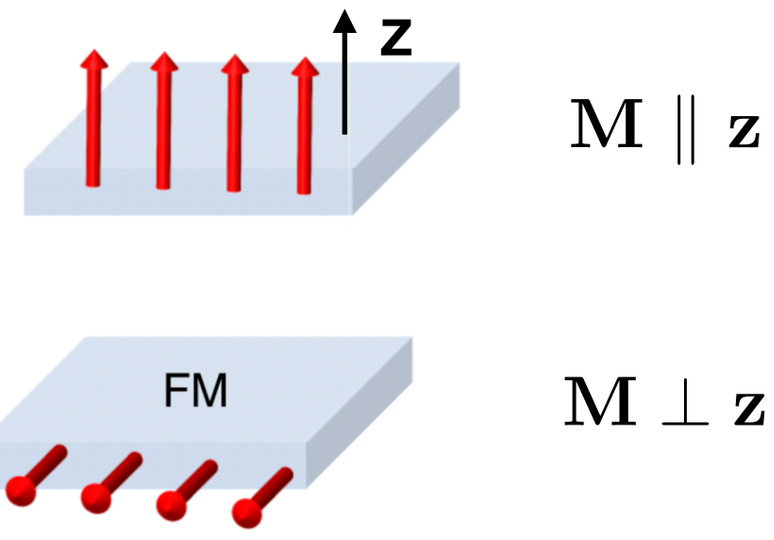

Solved band structures

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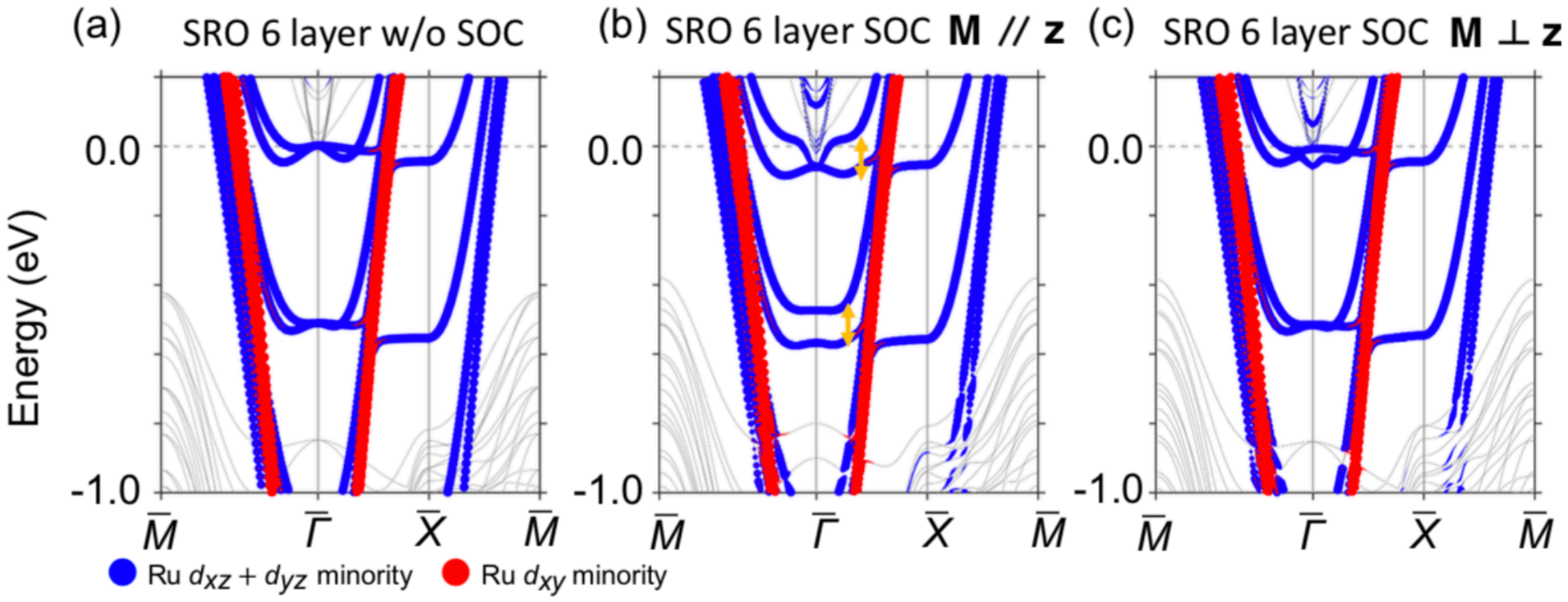

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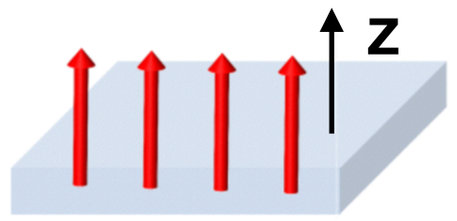
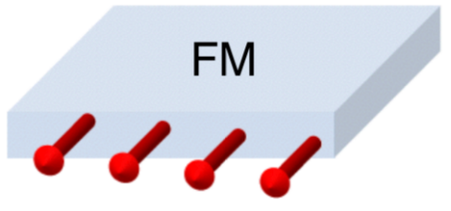


$\mathbf{M} \parallel \mathbf{z}$



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C. H. Chang *et al.*, NPG Asia Materials **9**, e424 (2017)

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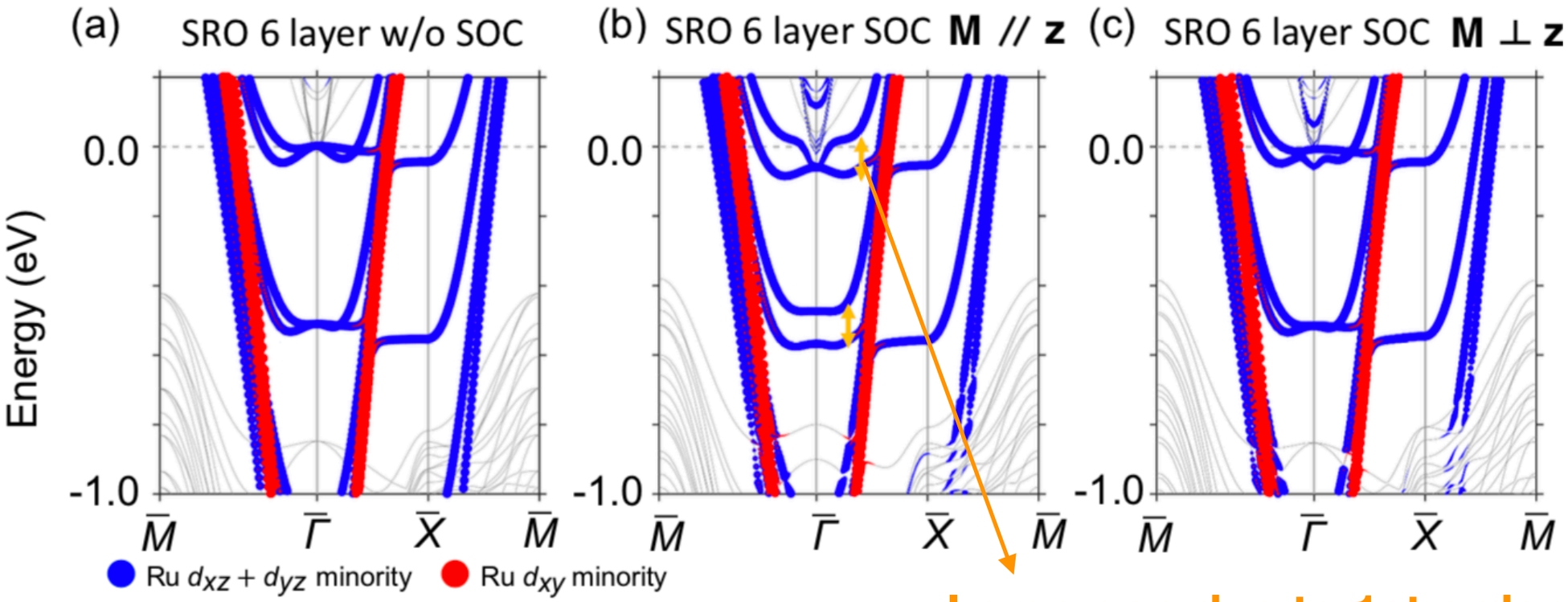

Large gap due to 1st order perturbation

QWS and magnetization direction

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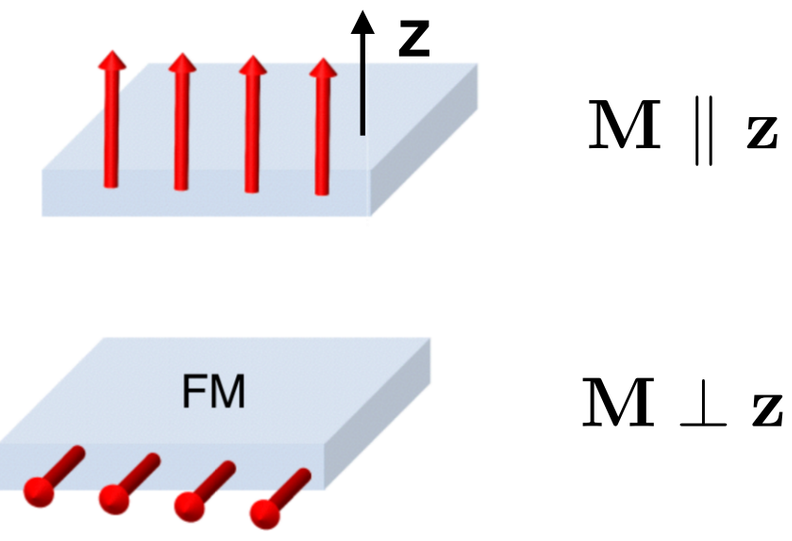
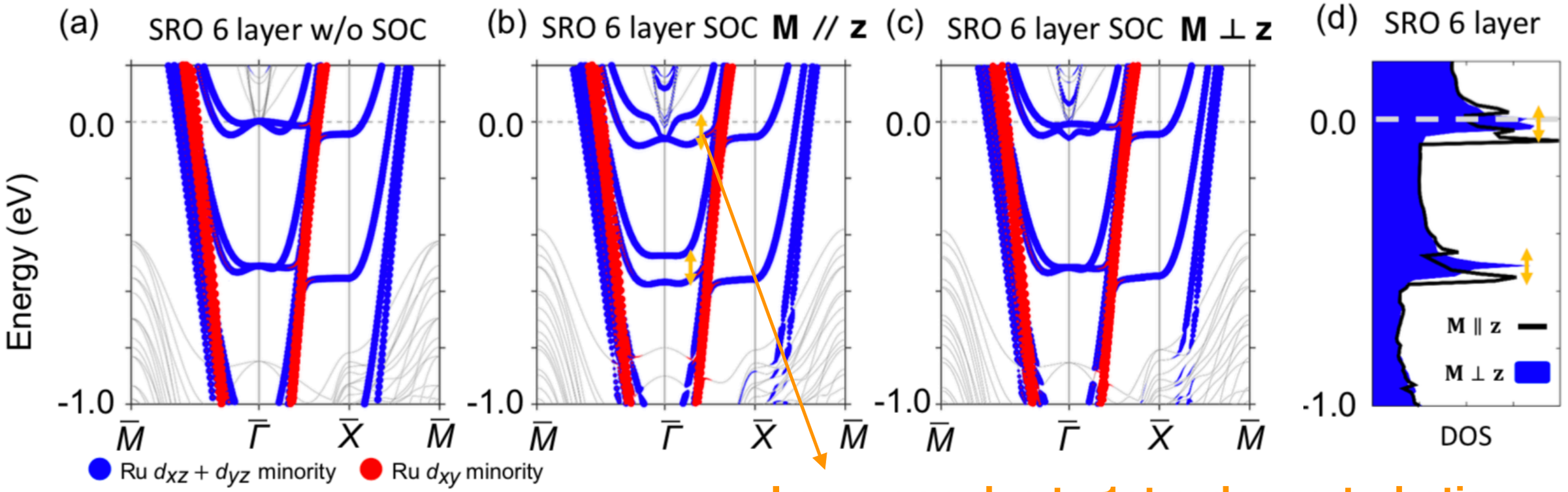


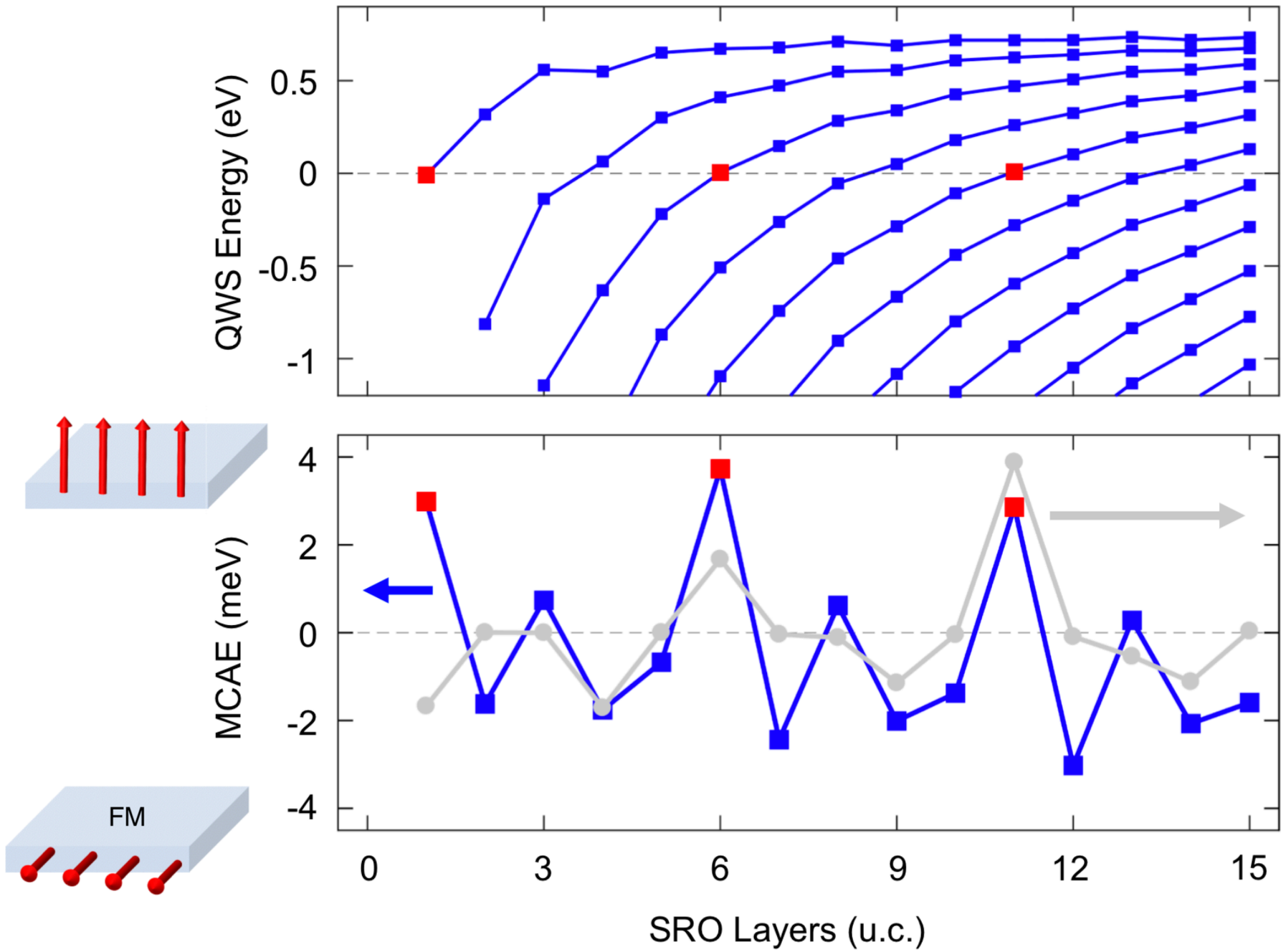
Solved band structures

C. H. Chang *et al.*, NPG Asia Materials **9**, e424 (2017)

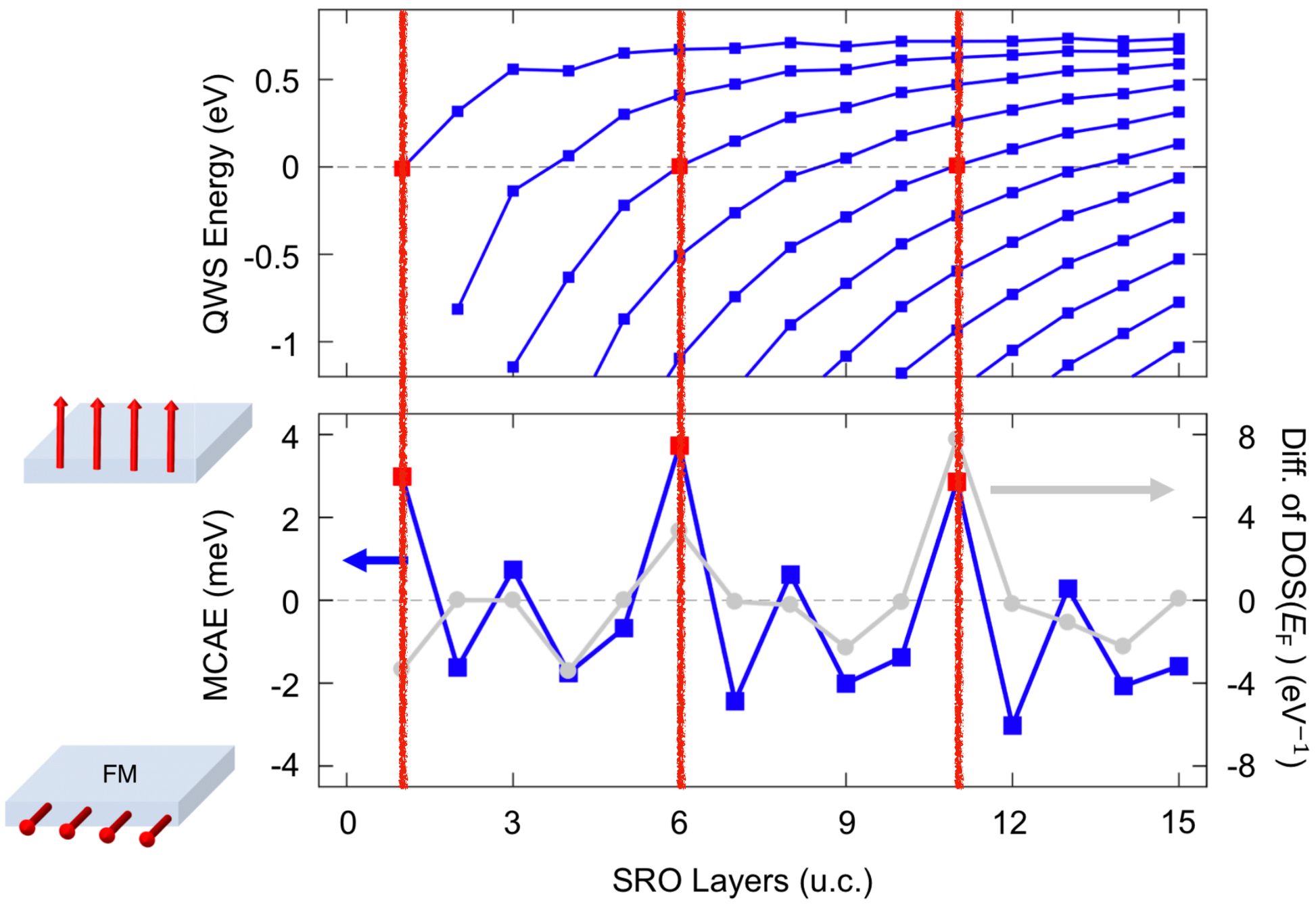


Large gap due to 1st order perturbation

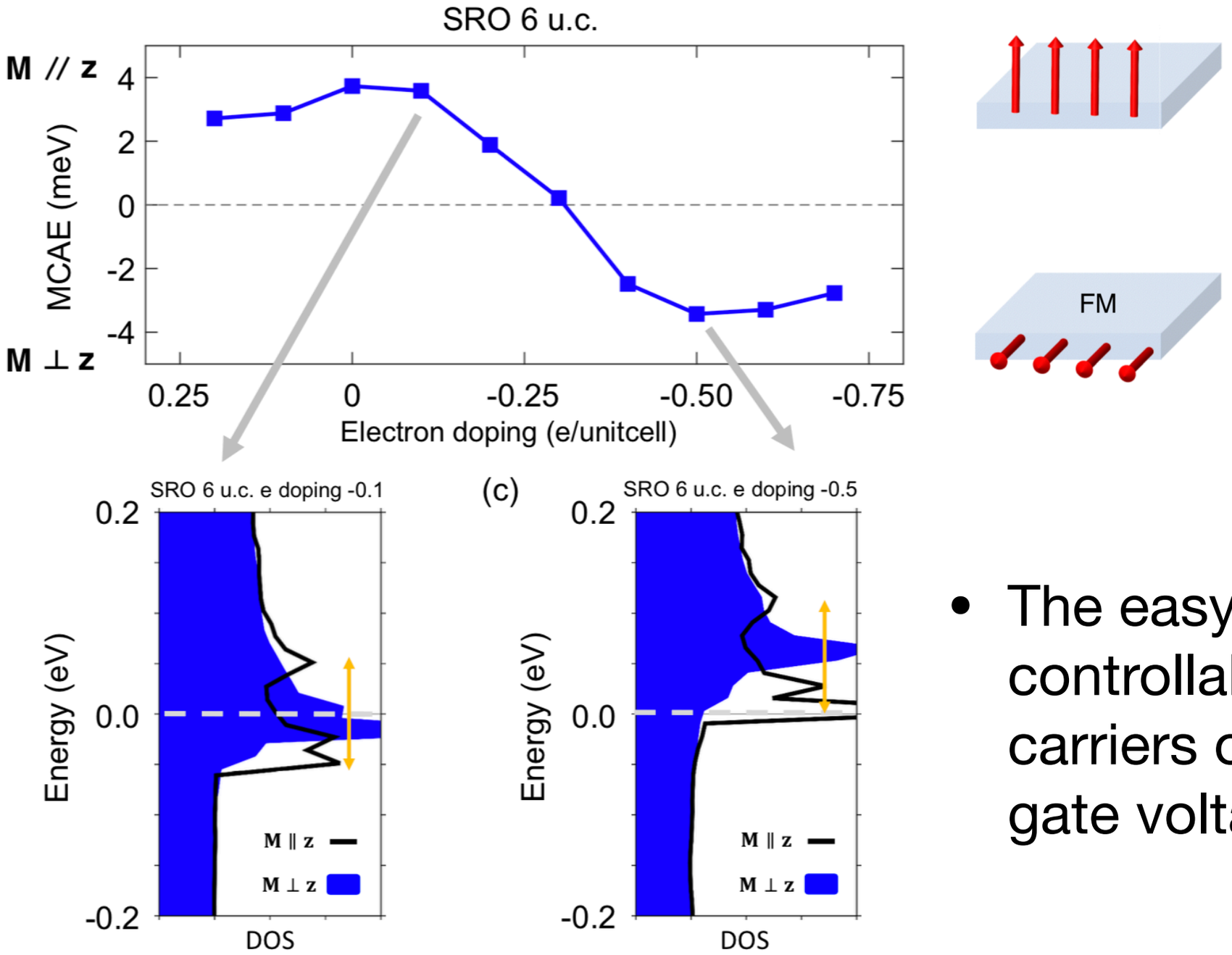
Magnetic anisotropy vs QWSs



Magnetic anisotropy vs QWSs



Electric-tunable easy axis



- The easy axis is controllable by injecting carriers or applying a gate voltage to tune Ef.

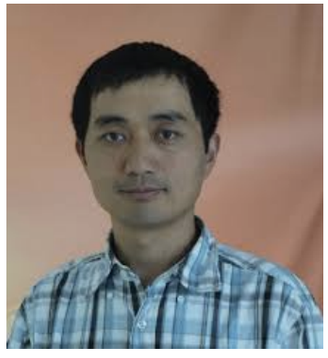
Summary

- Oscillatory magnetic anisotropy due to quantum well resonances in SRO layer.
- Electric control of easy axis in SRO layer is possible (screen effect is much small in SRO comparing to Fe and Cr).

Acknowledgement:

Prof. Ganesh Ramachandran
(IMSc, India)

Dr. Shengqiang Zhou
(HZDR, Germany)



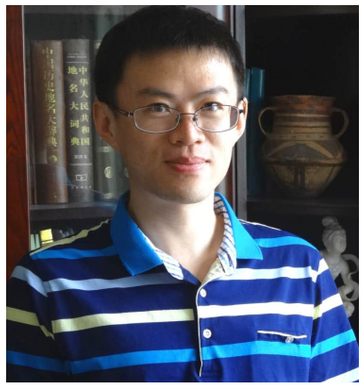
Prof. Ying Hao Chu
(NCTU, Taiwan)

Prof. Horng-Tay Jeng
(NTHU, Taiwan)

Prof. Chao-Cheng Kaun
(Academia Sinica, Taiwan)

Prof. Guang-Yu Guo
(NTU, Taiwan)

Prof. Kun-Peng Dou
(OUC, China)

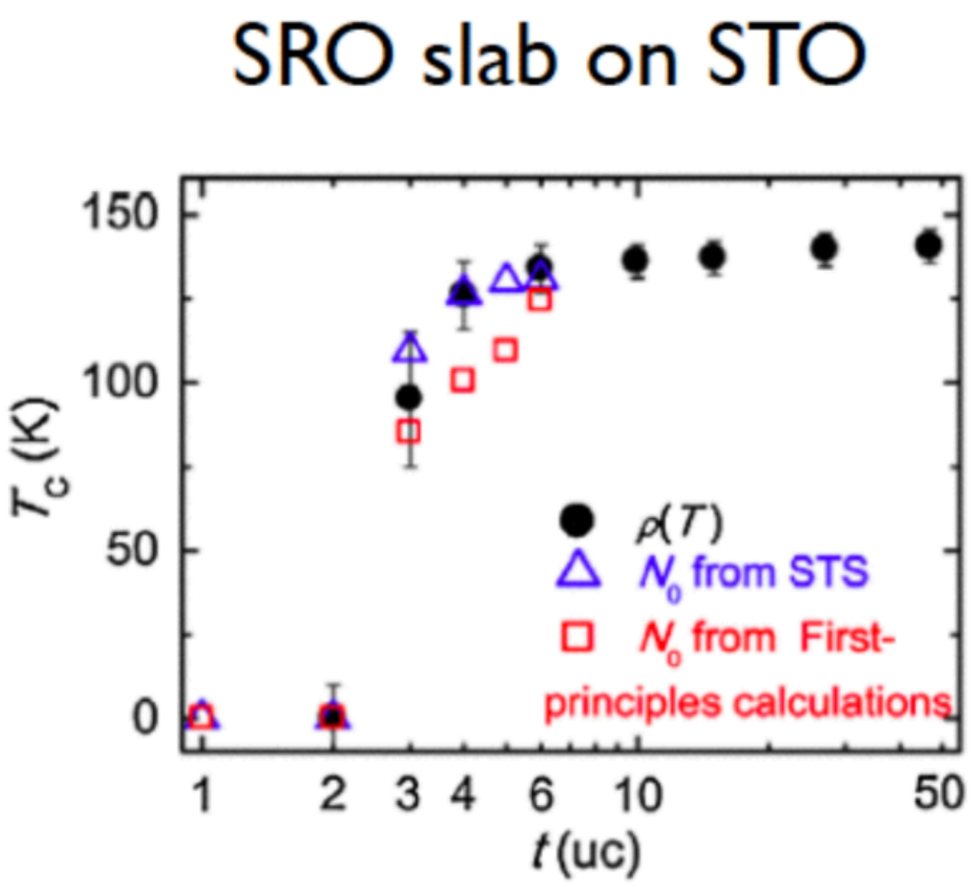


Prof. Tay-Rong Chang
(NCKU, Taiwan)

Thank you !

Nature of $SrRuO_3$

- Quantum confinement (carrier nature) crucially decides magnetism of a thin SRO layer.



PRL 103, 057201 (2009).

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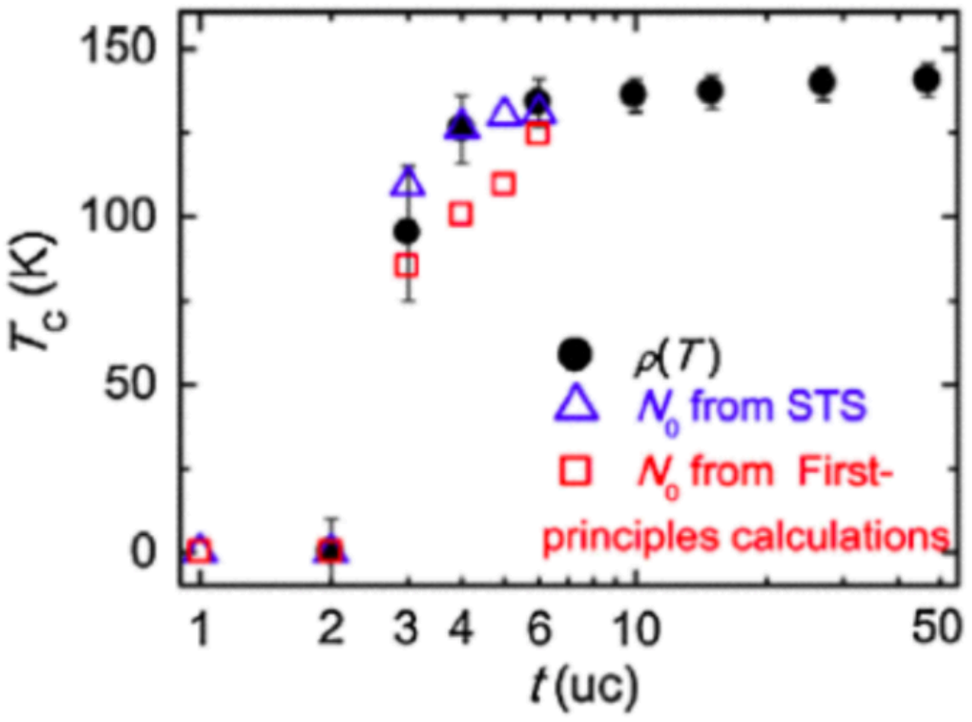
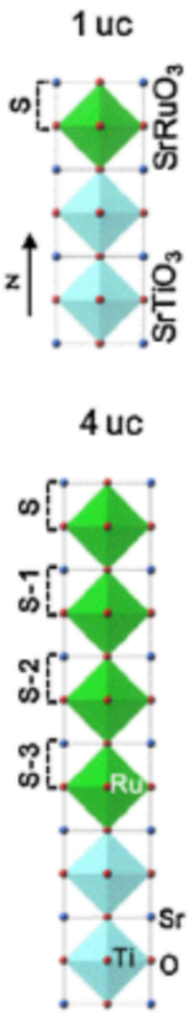
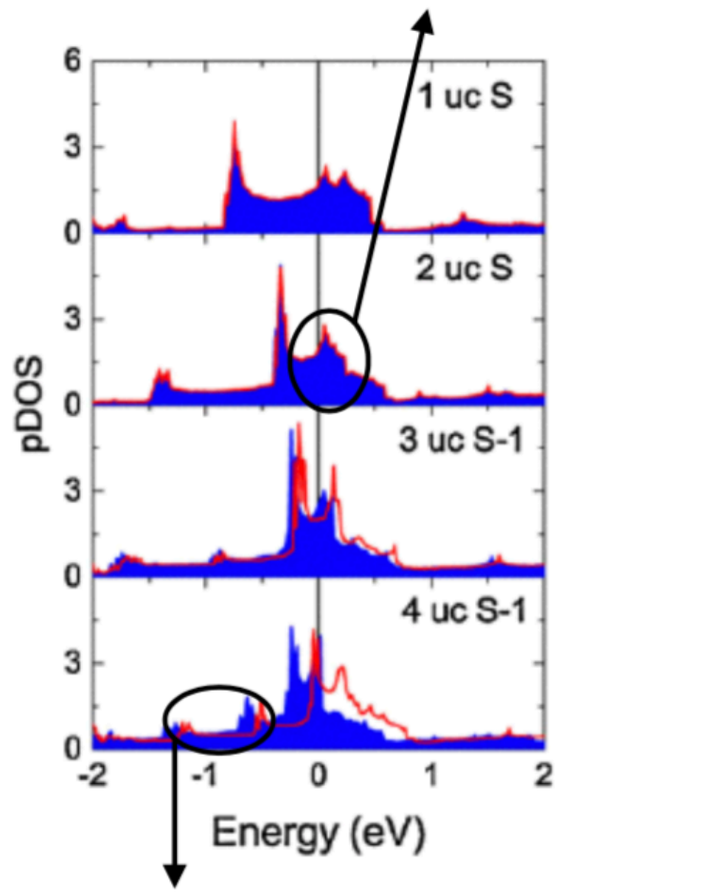
SRO slab on STO



PRL 103, 057201 (2009).

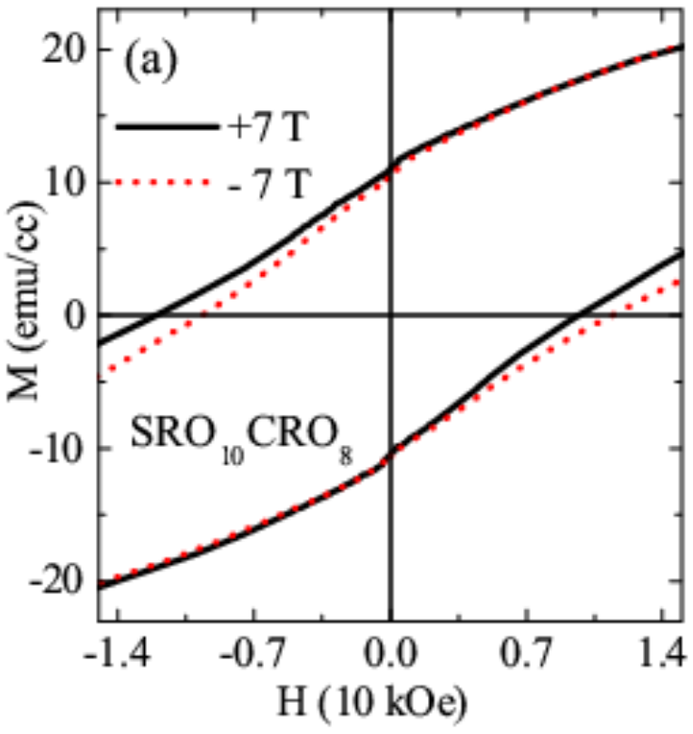


No spin polarization at Ef



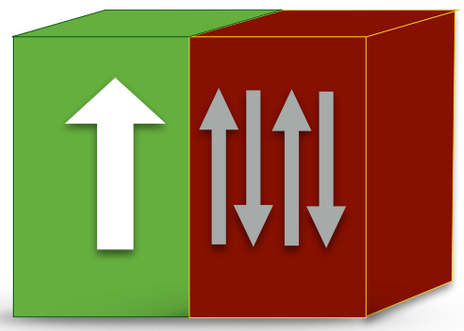
Quantum well states

Exchange bias



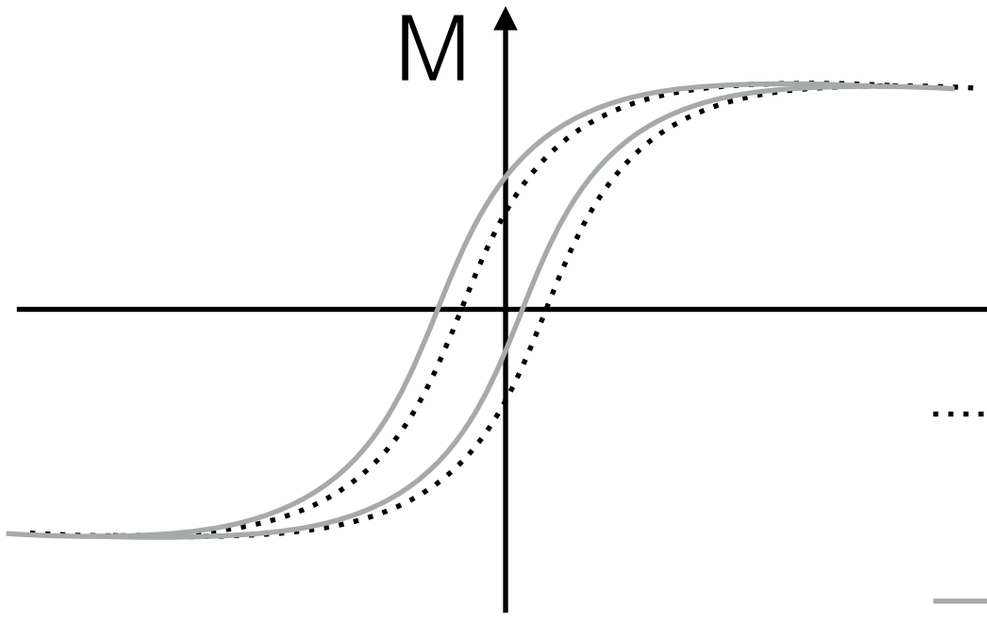
M-H curve shifts opposite to the direction of the cooling field

'negative' exchange bias



ferromagnet

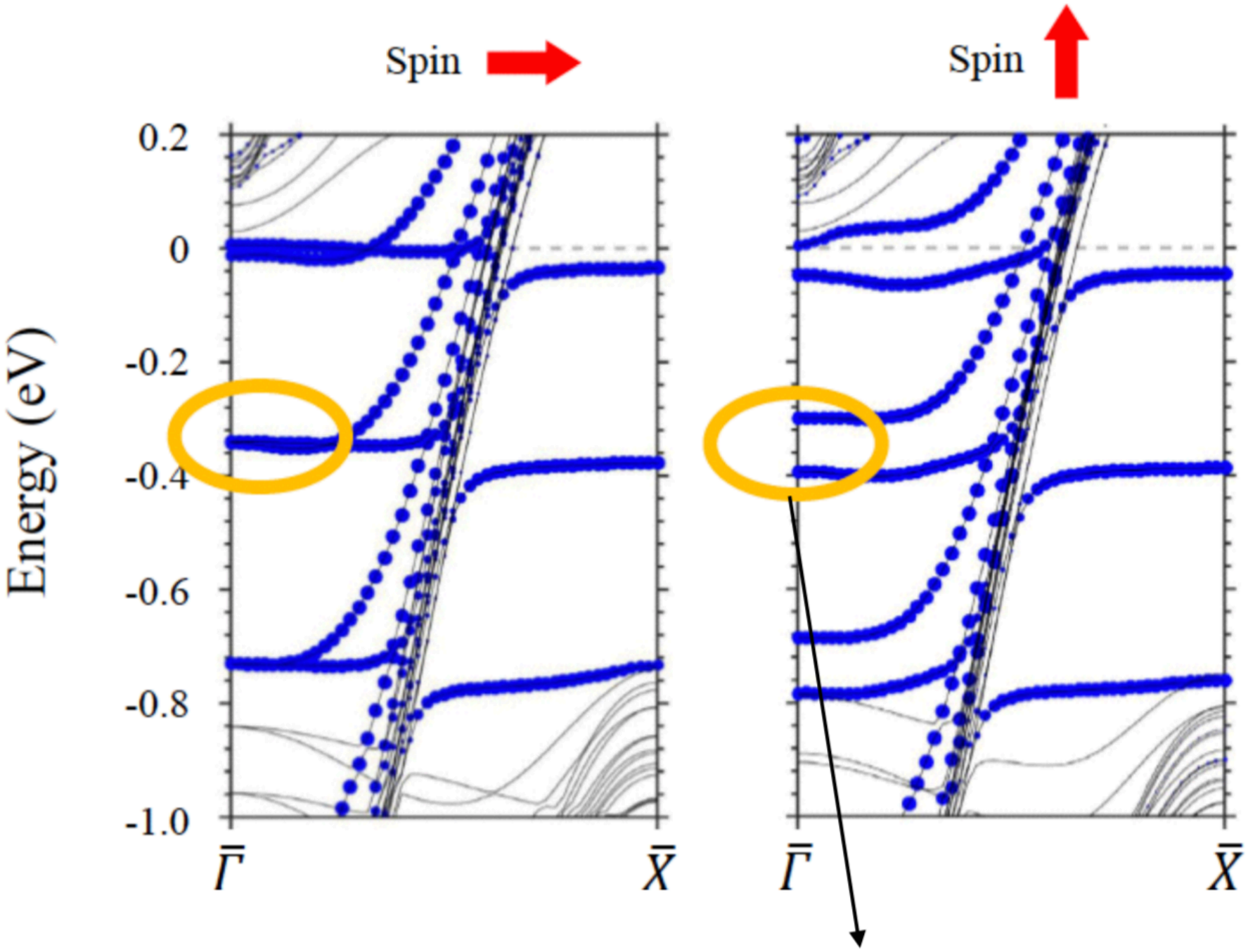
antiferromagnet



usual FM

FM adjacent to an AFM

QWS in SRO (9uc)



$E_\perp < E_\parallel,$

MAE < 0.

energy gap due to internal SOC