(Jun 26, 2019)

Tunable Large Magnetic Anisotropy

due to Spin-Polarized Quantum-Well Resonances in Transition Metal Oxide

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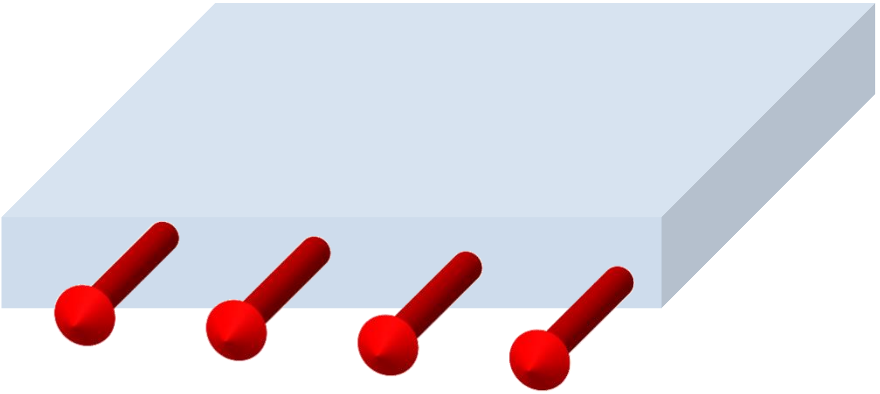
Outline

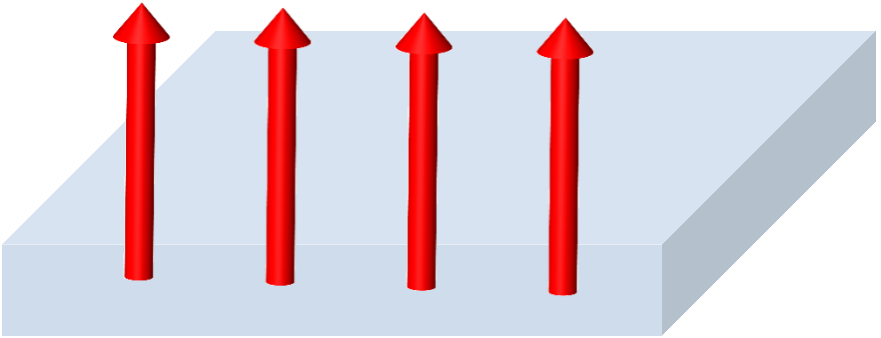
- What is the Magnetic Anisotropy?
- Mirror symmetry and magnetic anisotropy
- MA in $SrRuO_3$ quantum well state

What is Magnetic Anisotropy (MA)?

$$\mathrm{MAE} = E_{\rightarrow} - E_{\uparrow}$$

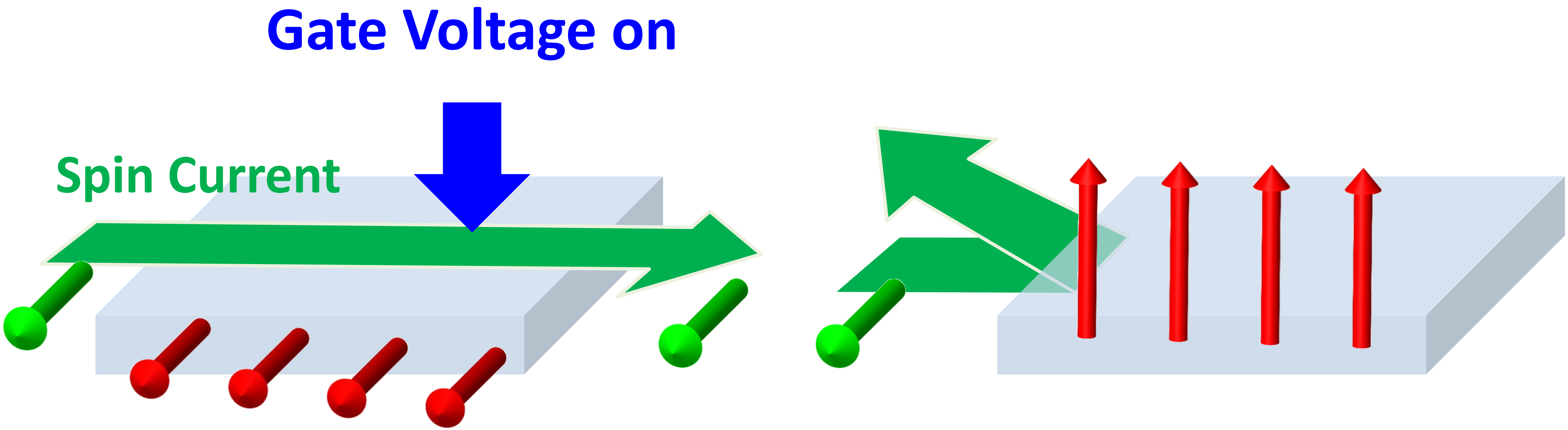


Magnetism of ion

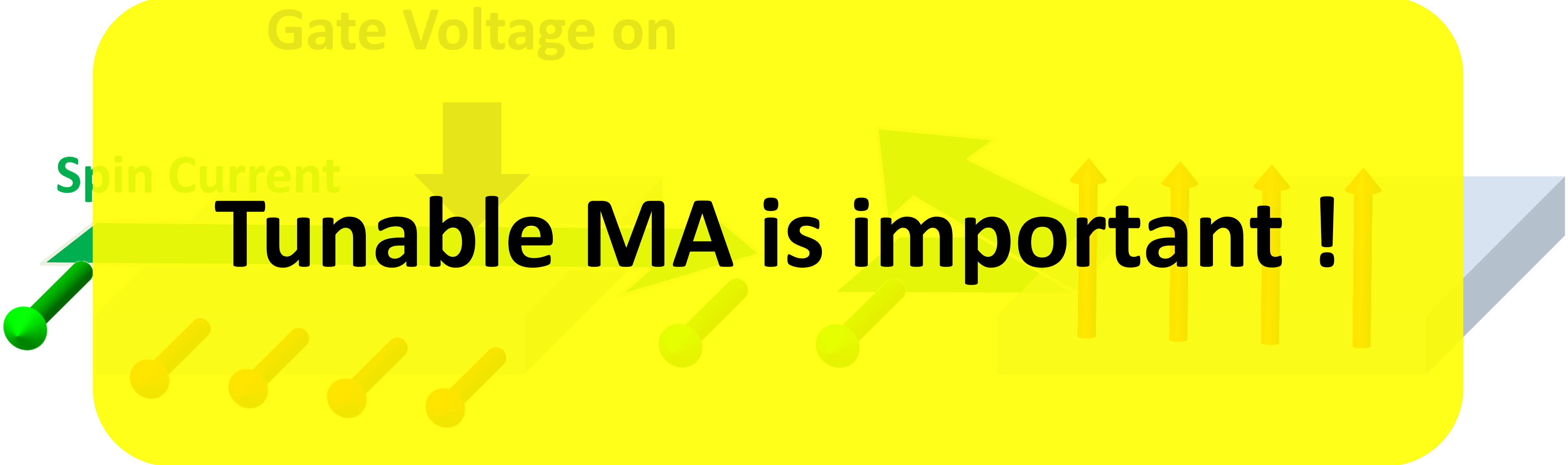


Magnetism of ion

Device of Spintronics by MA

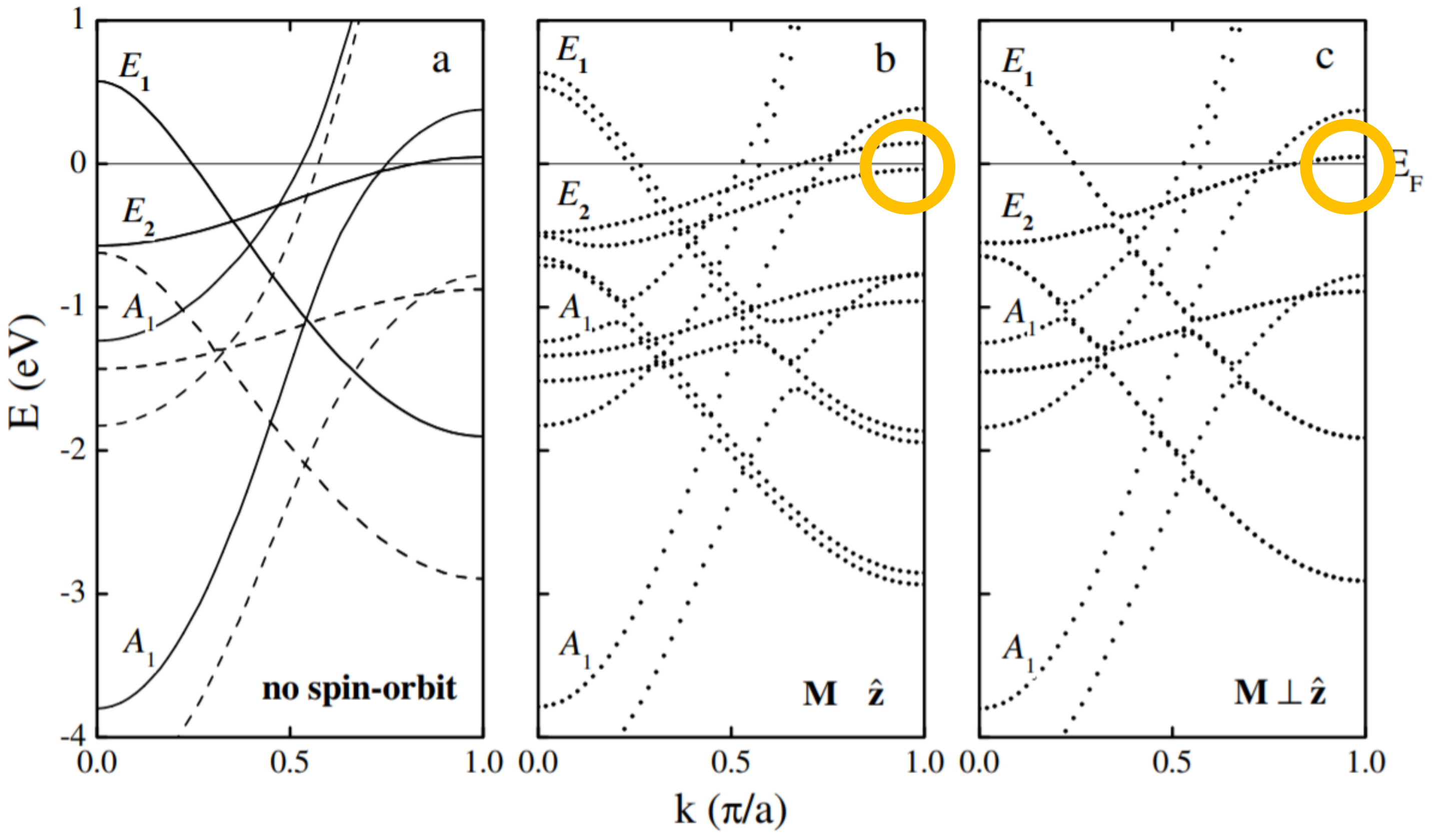


Device of Spintronics by MA



Tunable MA is important !

Ballistic magnetic anisotropy

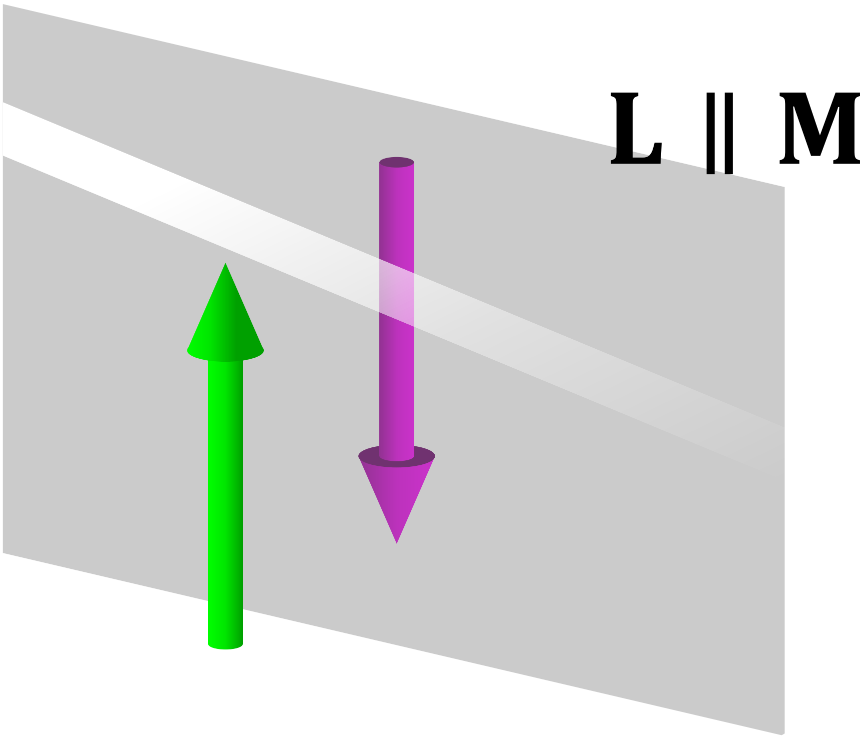


monoatomic Ni wire

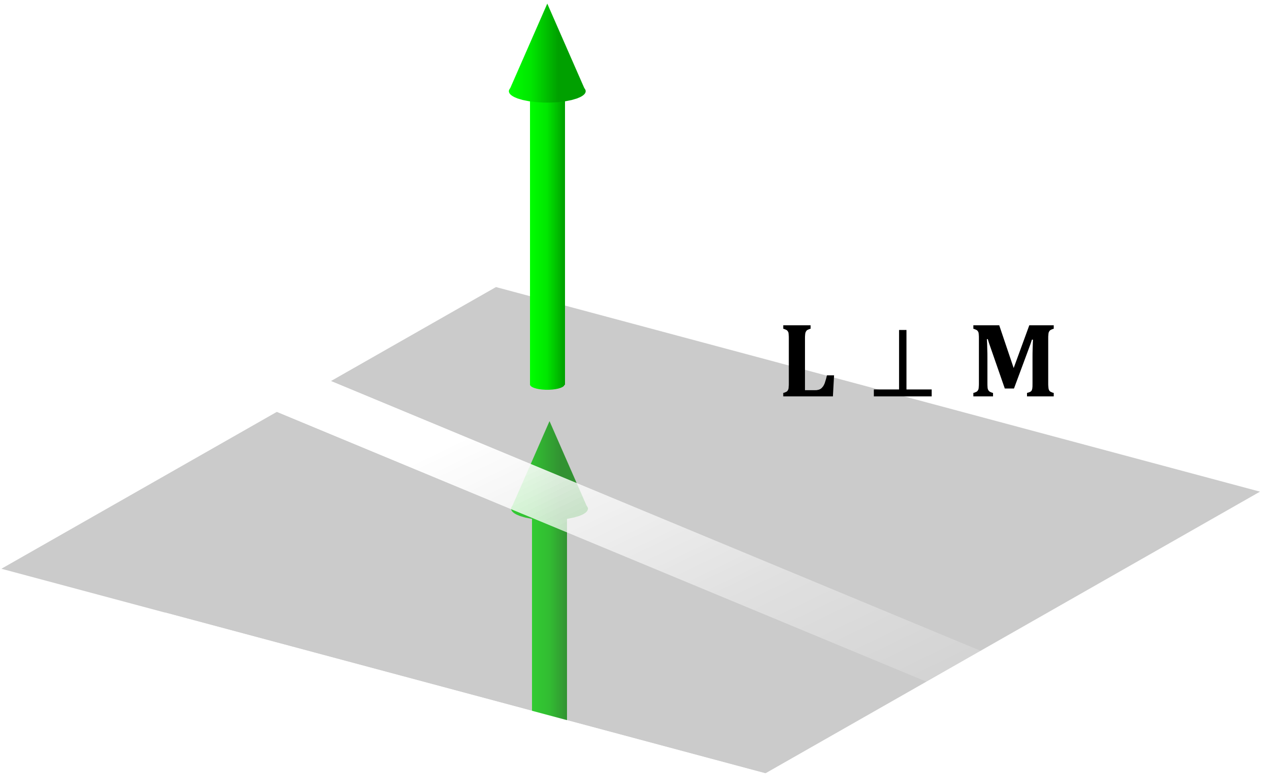
J. Velev *et al.*, *Phys. Rev. Lett.* **94**, 127203 (2005)

Review: Pseudovector (axial vector)

(a) Vertical mirror symmetry work like effective time reversal symmetry

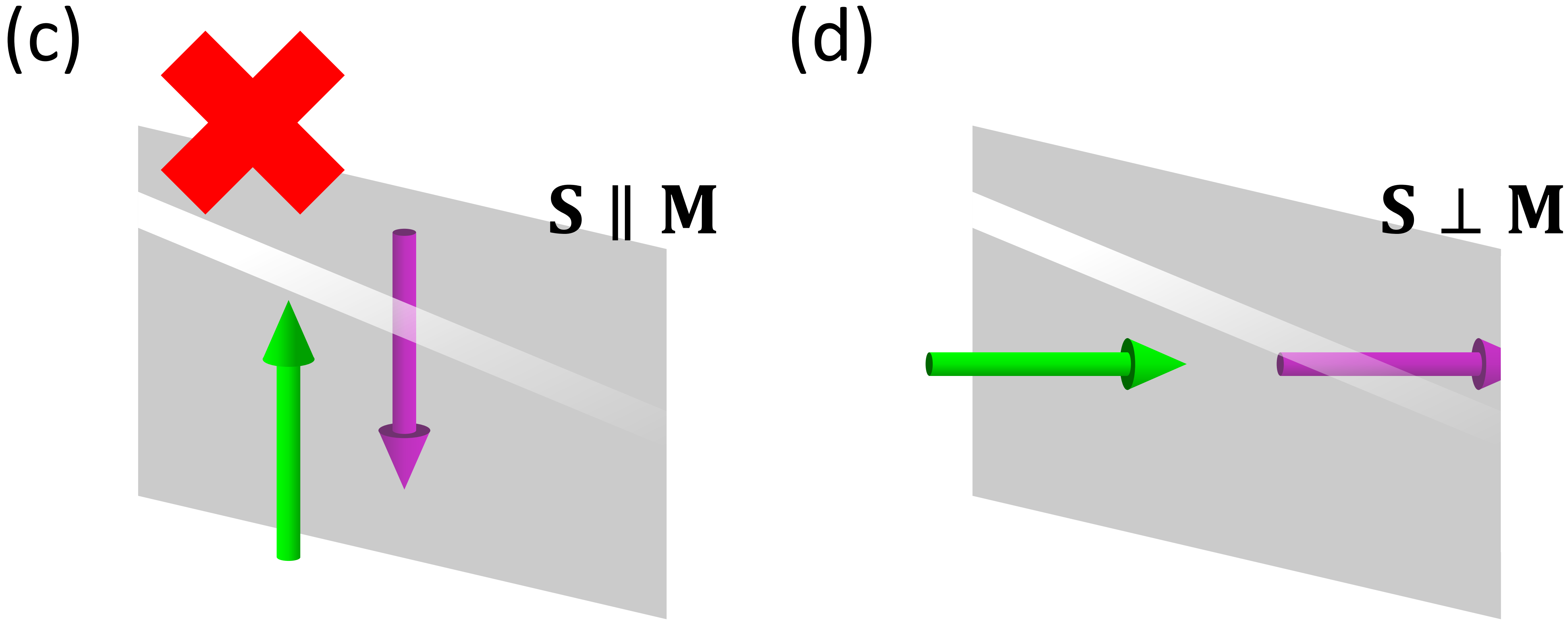


(b)

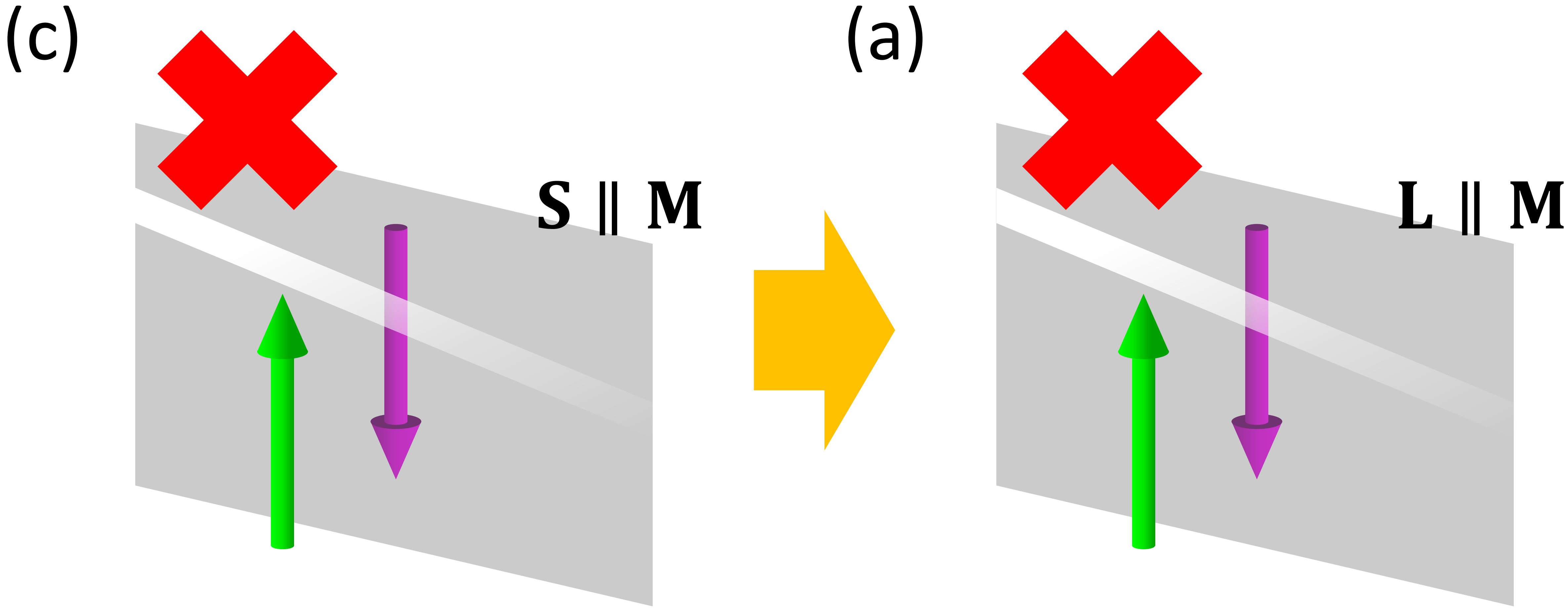


Breaking mirror symmetry by Magnetism

Spin can break some mirror plane



Use the direction of mag. Break effective TR

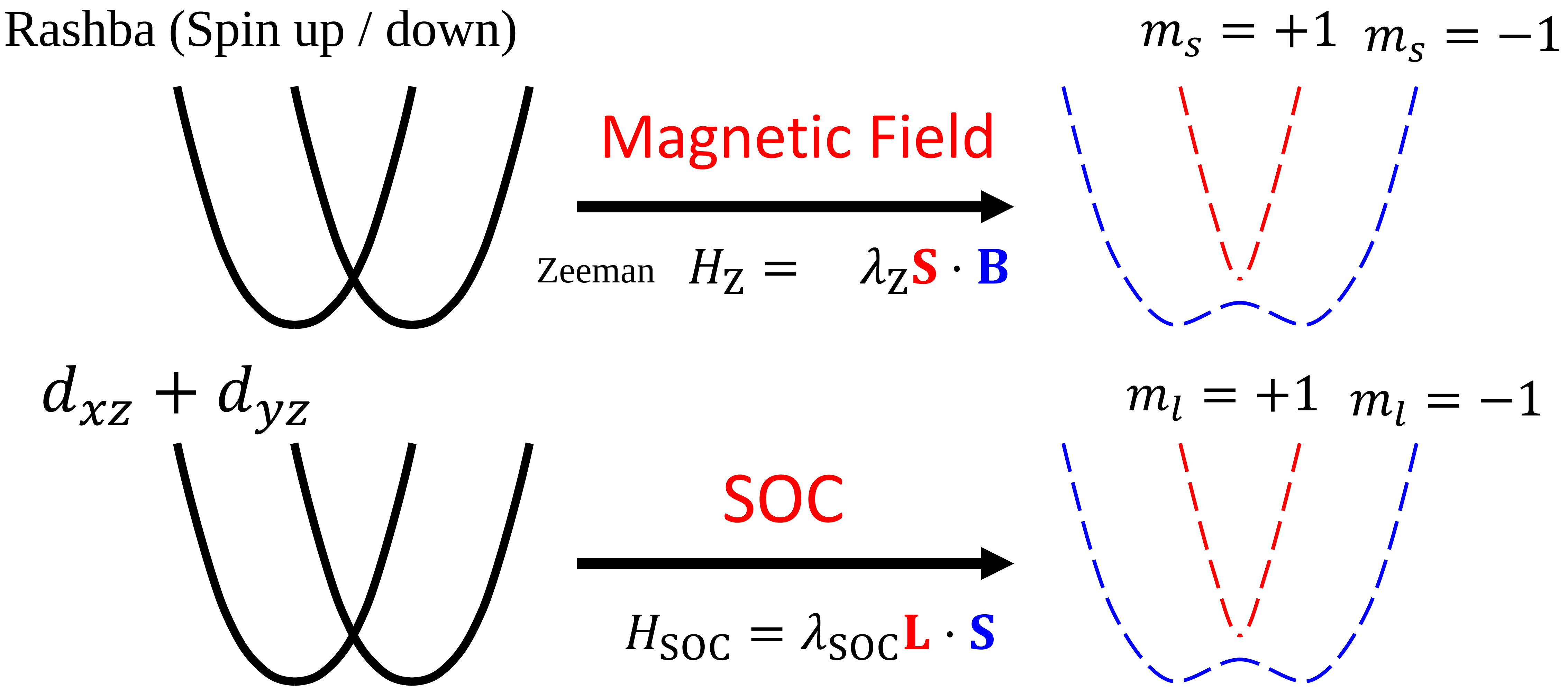


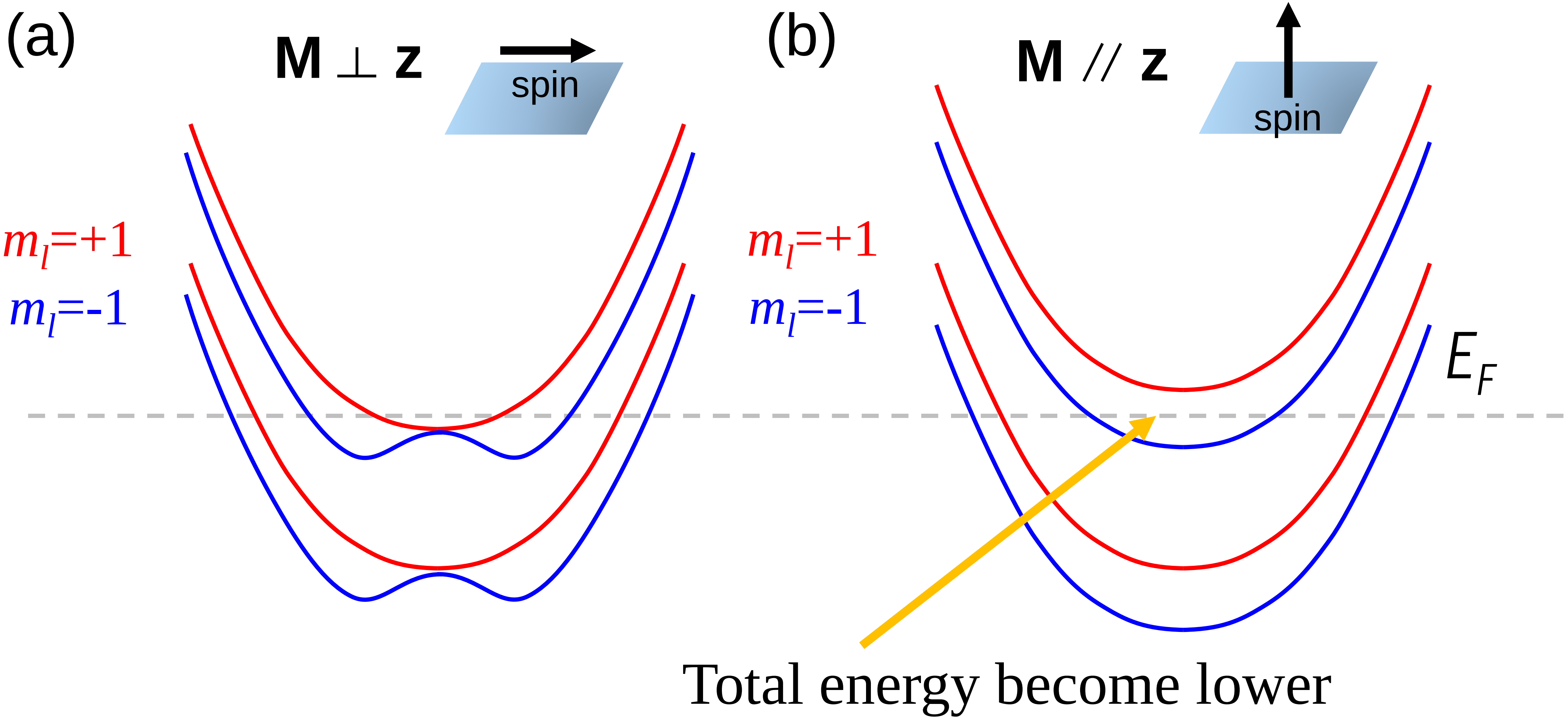
Spin-orbital coupling vs. Zeeman Term

Zeeman $$H_{\mathrm{Z}} = \lambda_{\mathrm{Z}} \mathbf{S} \cdot \mathbf{B}$$

SOC
(Leading order term) $$H_{\mathrm{SOC}} = \lambda_{\mathrm{SOC}} \mathbf{L} \cdot \mathbf{S}$$

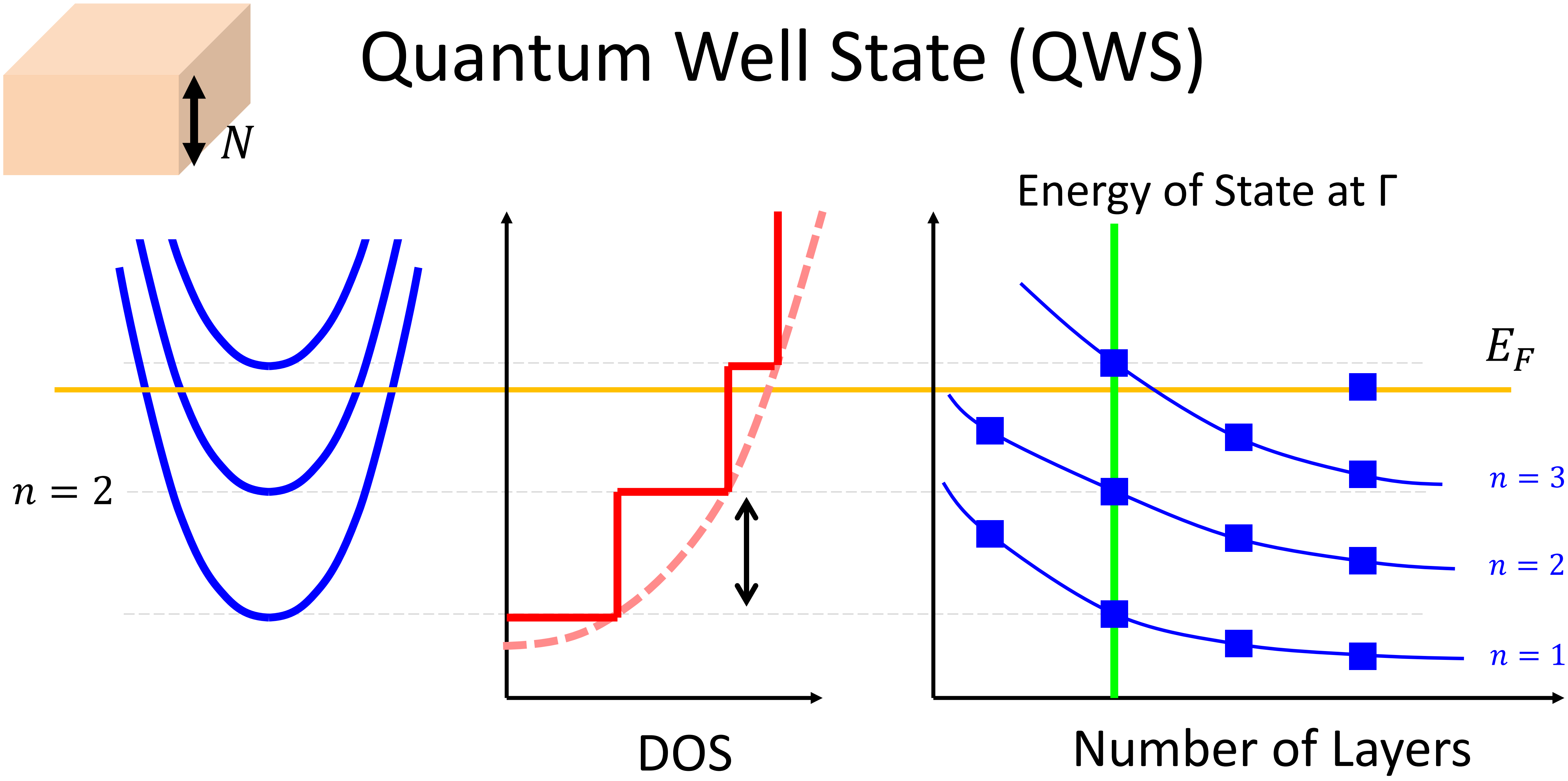
Breaking effective TR

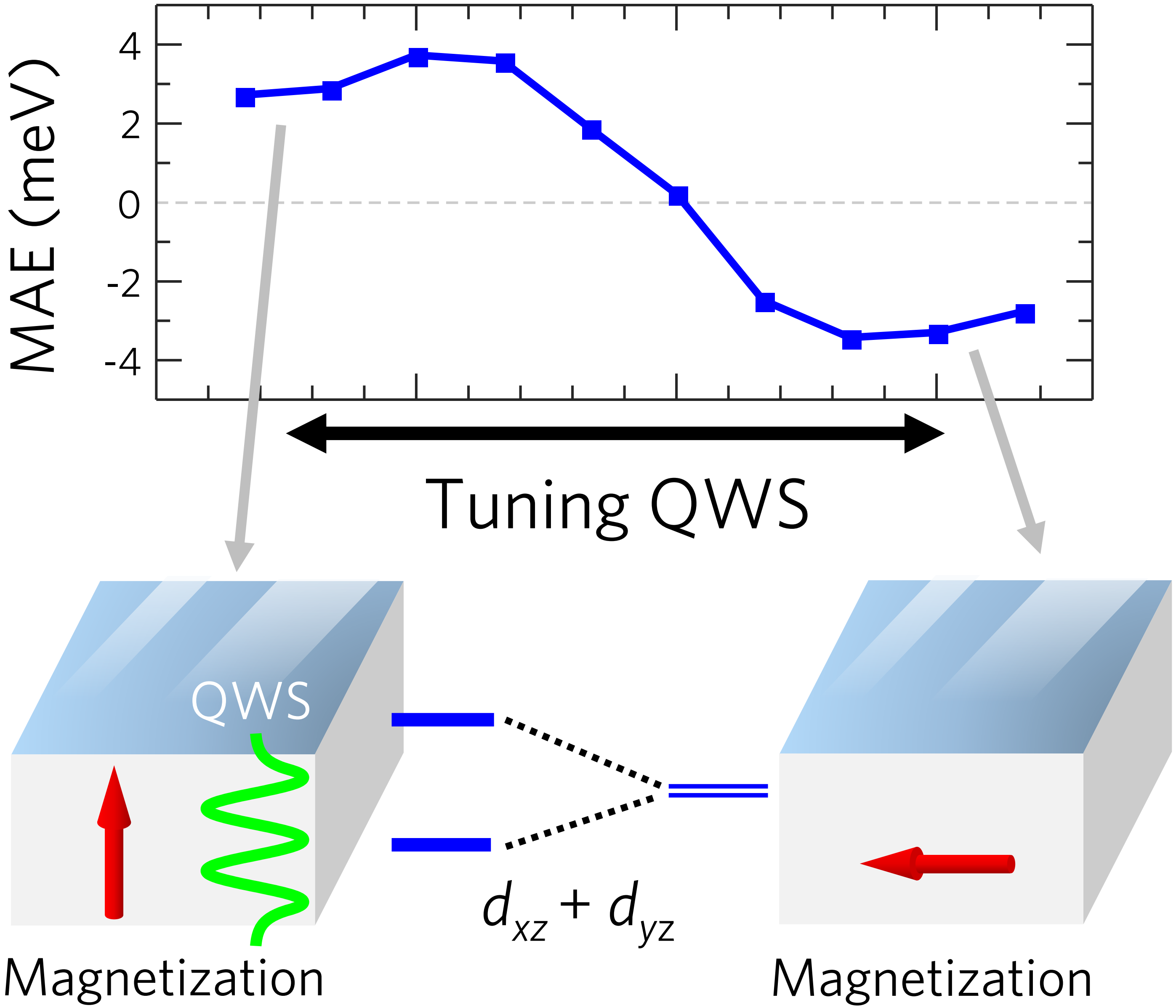




(a)
M ⊥ z
spin
m_l=+1
m_l=-1
(b)
M // z
spin
m_l=+1
m_l=-1
E_F
Total energy become lower

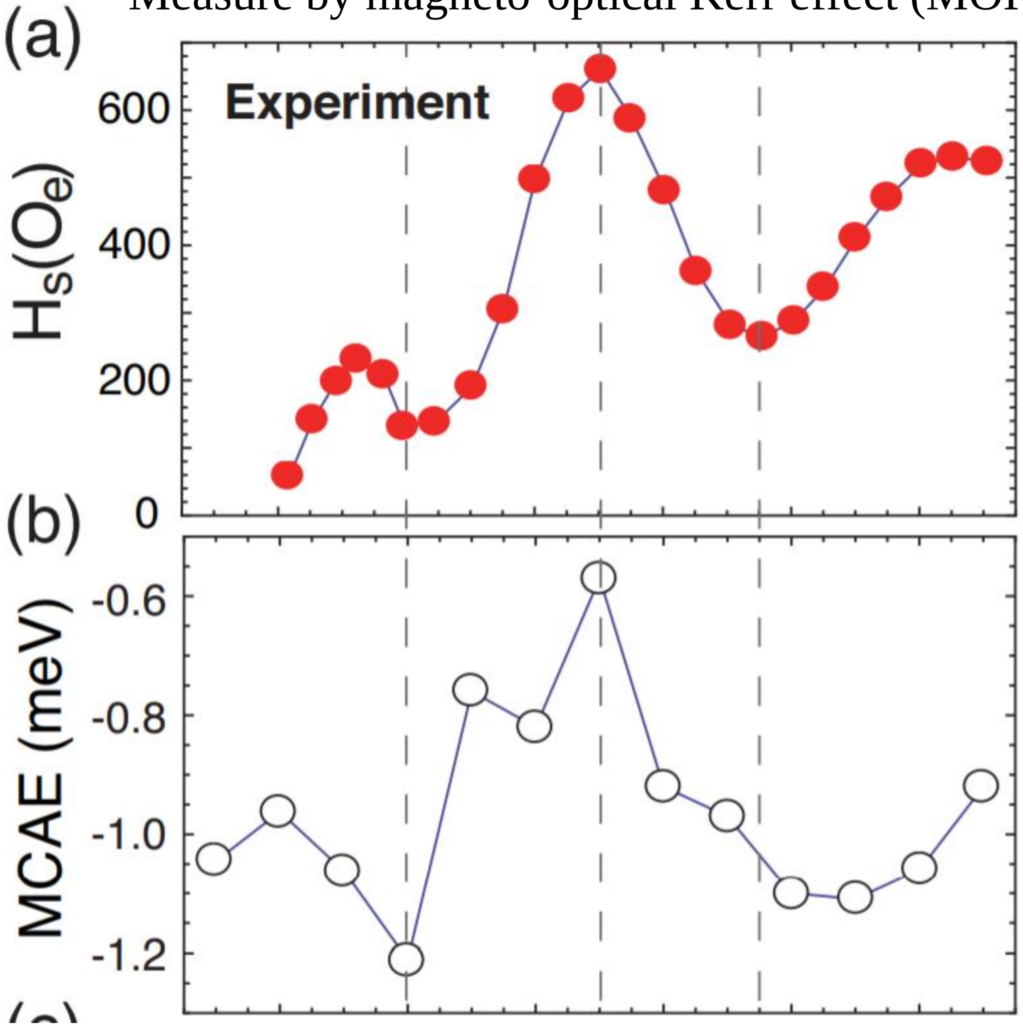
Quantum Well State (QWS)




MAE (meV)
4
2
0
-2
-4
Tuning QWS
QWS
$d_{xz} + d_{yz}$
Magnetization
Magnetization

Fe_N/Ag junction

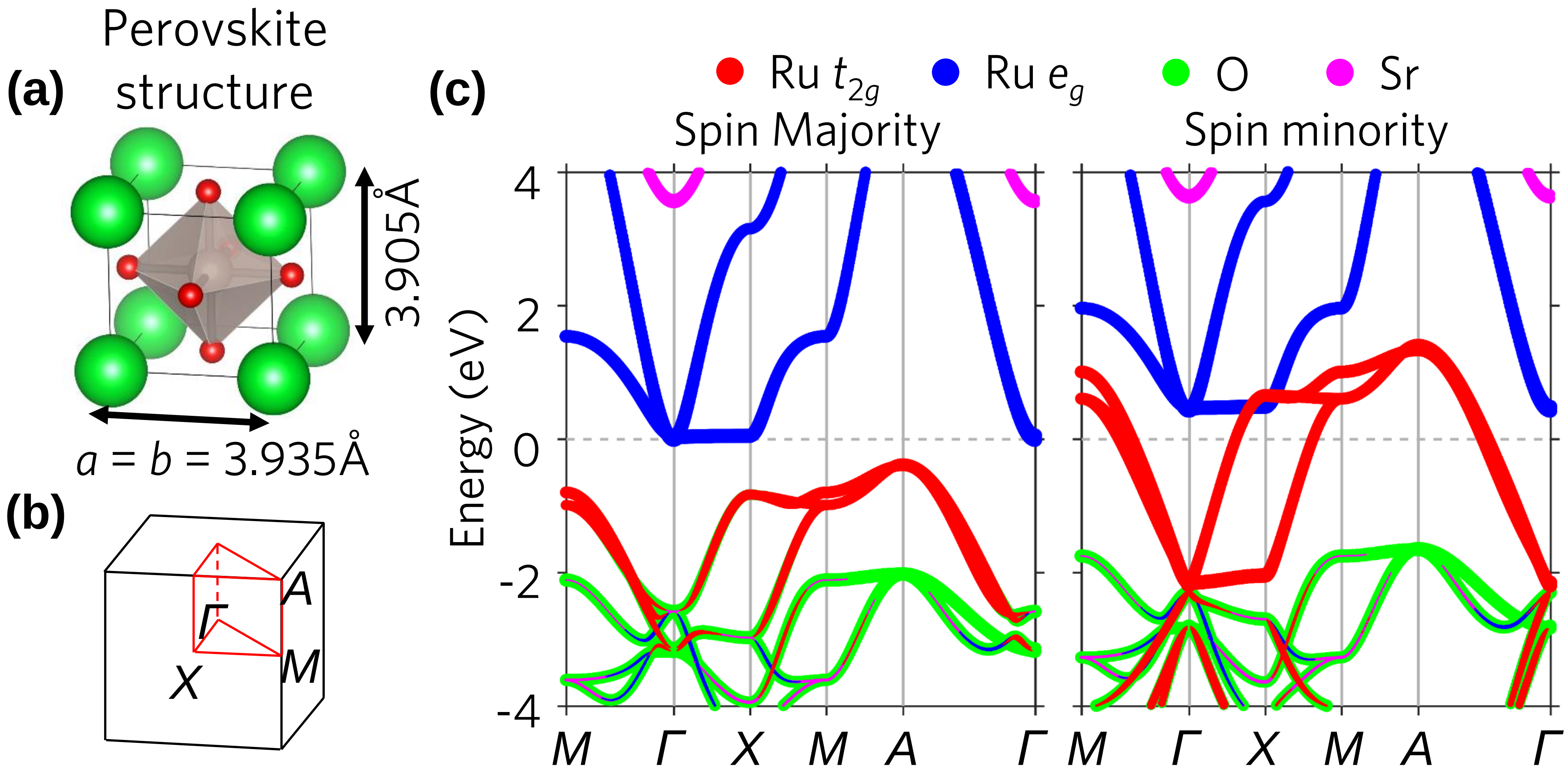
Measure by magneto-optical Kerr effect (MOKE)



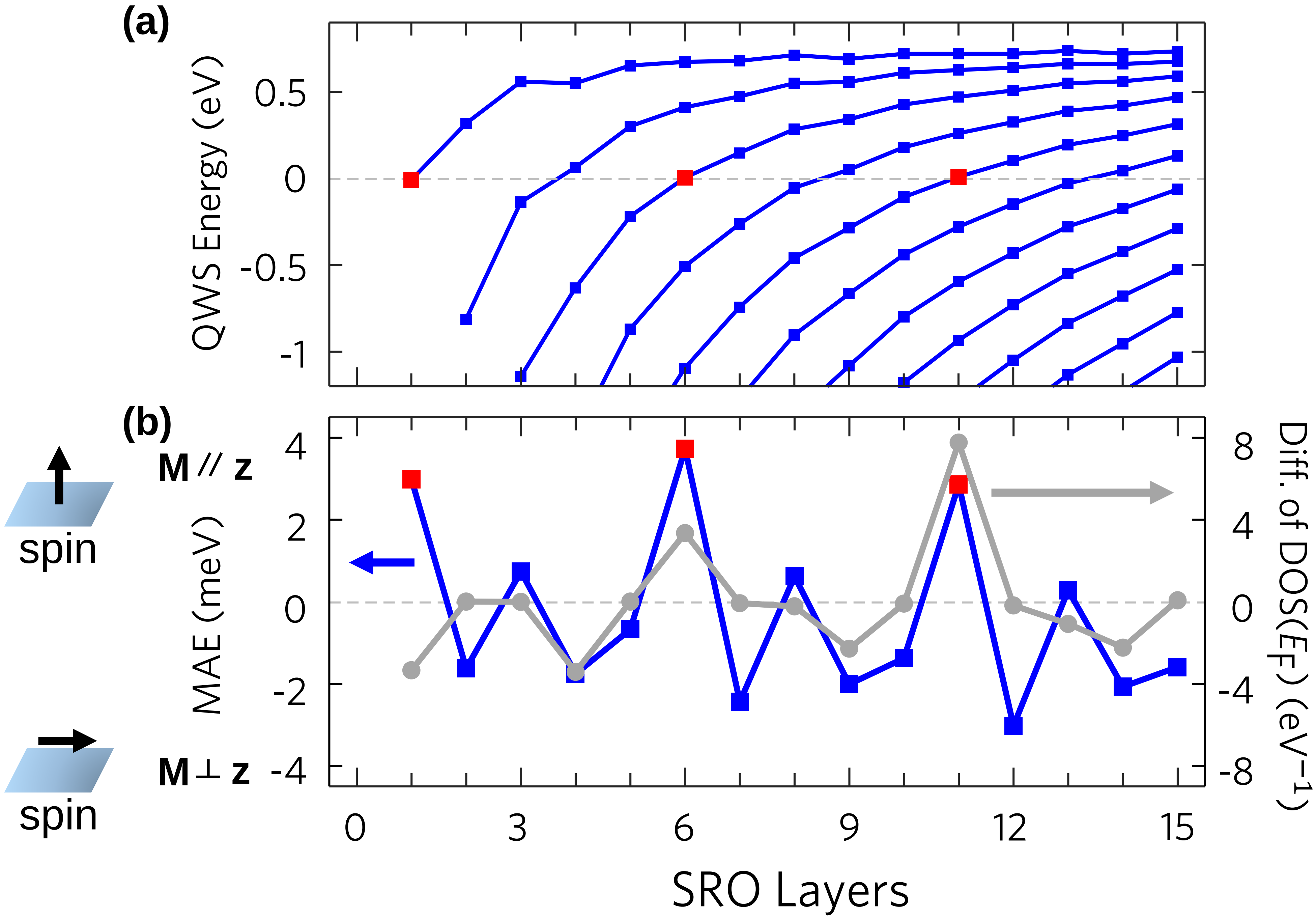
M. Dabrowski *et al.*, *Phys. Rev. Lett.* **113**, 067203 (2014)

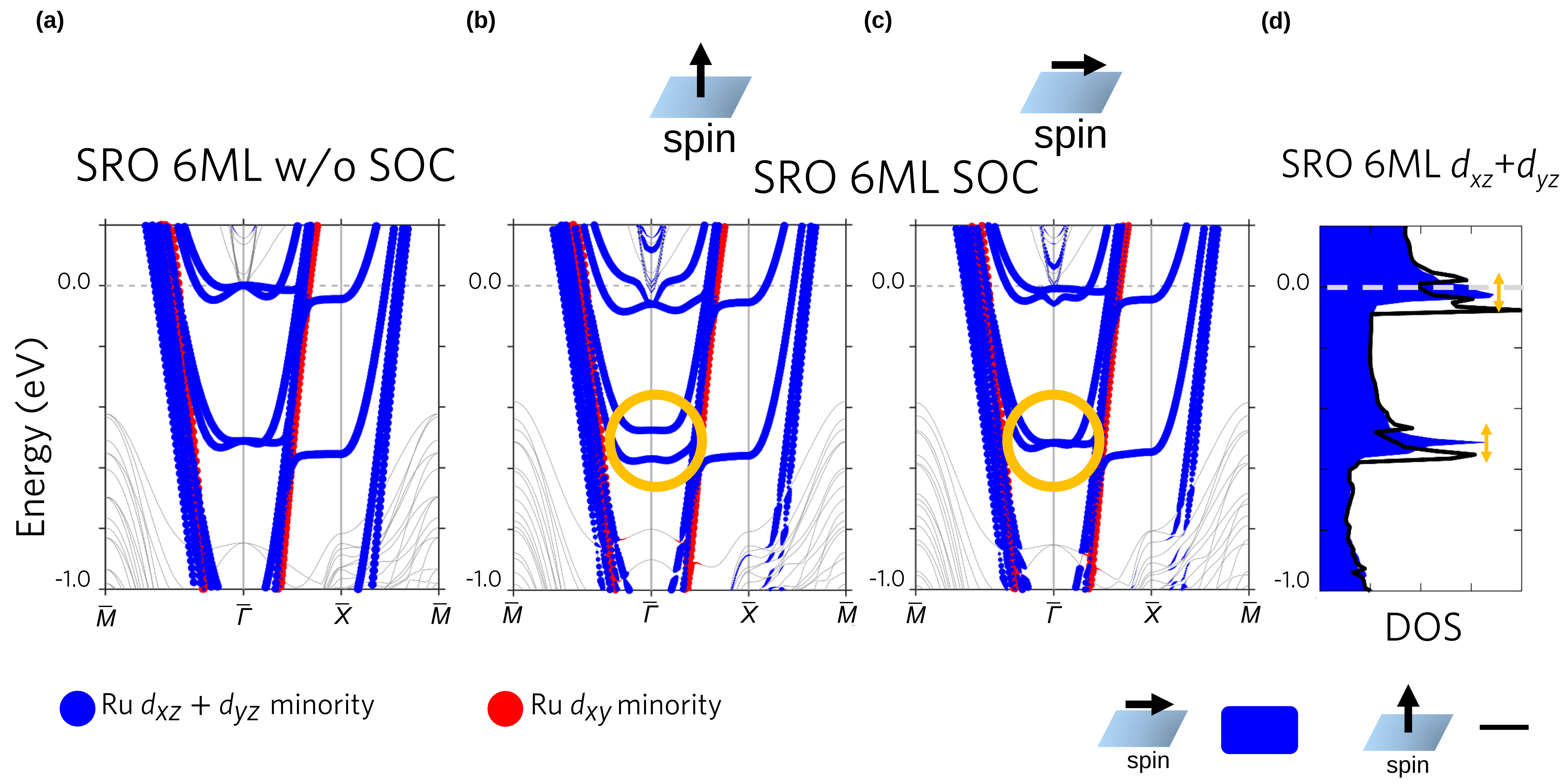
Ching-Hao Chang, Kun-Peng Dou, Guang-Yu Guo and Chao-Cheng Kaun, *NPG Asia Materials* **9**, 424 (2017)

Half metal: $SrRuO_3$ (SRO)

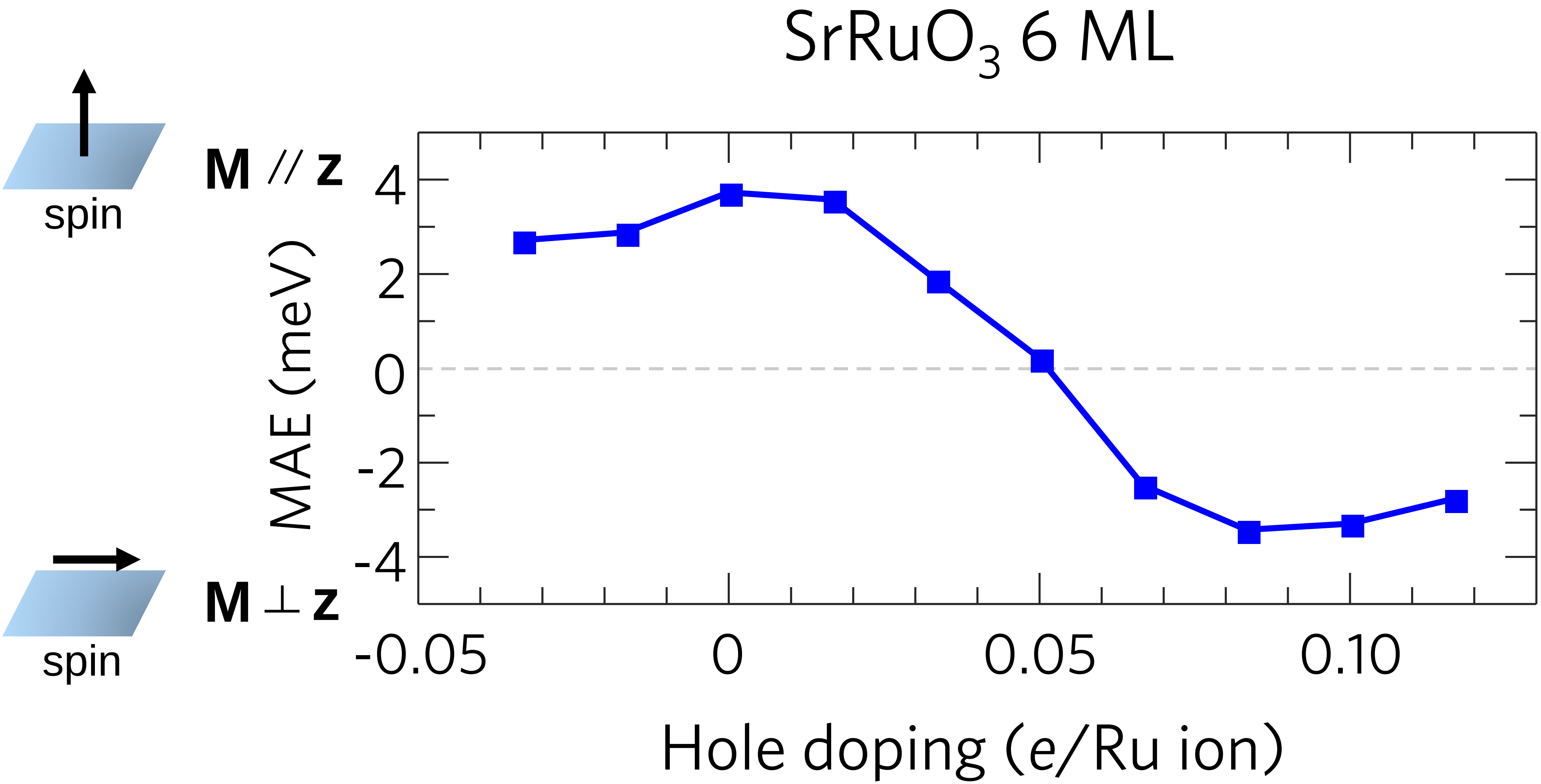


Submit to *Communication Physics*


(a)
QWS Energy (eV)
0.5
0
-0.5
-1
(b)
M // z
M ⊥ z
spin
spin
MAE (meV)
4
2
0
-2
-4
8
4
0
-4
-8
Diff. of DOS(E_F) (eV^{-1})
0
3
6
9
12
15
SRO Layers



(a)
(b)
(c)
(d)
spin
spin
SRO 6ML w/o SOC
SRO 6ML SOC
SRO 6ML $d_{xz}+d_{yz}$
Energy (eV)
0.0
-1.0
$\bar{M}$
$\bar{\Gamma}$
$\bar{X}$
$\bar{M}$
DOS
Ru $d_{xz}+d_{yz}$ minority
Ru d_{xy} minority
spin
spin



SrRuO3 6 ML
M // z
spin
M ⊥ z
spin
MAE (meV)
4
2
0
-2
-4
-0.05
0
0.05
0.10
Hole doping (e/Ru ion)

Conclusion

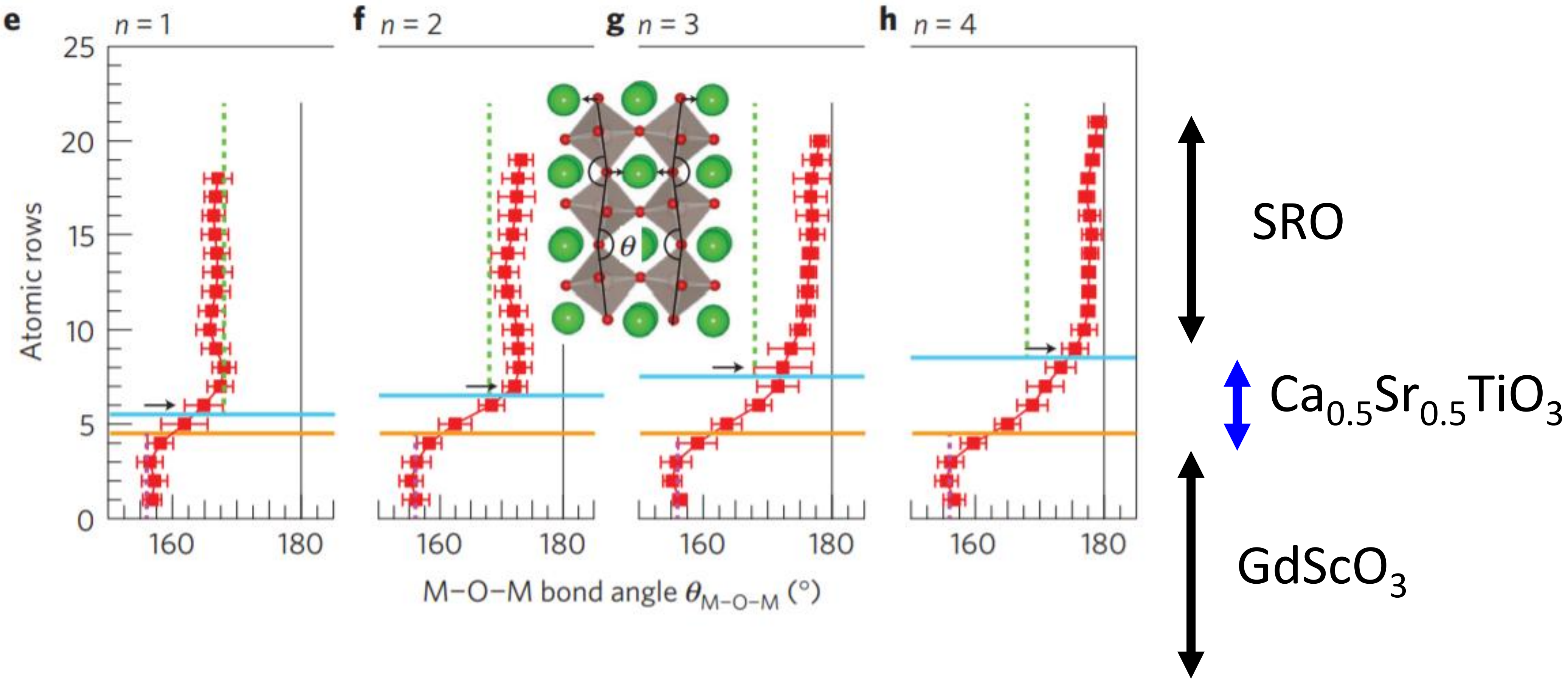
- The SOC can been seem as a effective Zeeman term in magnetic thin film with $d_{xz} + d_{yz}$ degenerate band

- We fond the SRO QWS have large MA, tunable by thickness and gate voltage

Acknowledgement

- Prof. Kun-Peng Dou, Prof. Chao-Cheng Kaun, Prof. Guang-Yu Guo, Prof. Tay-Rong Chang

SRO/CSTO/GSO



D. Kan *et al*., *Nat. Mater.* **15**, 432 (2016)

- Time Reversal symmetry

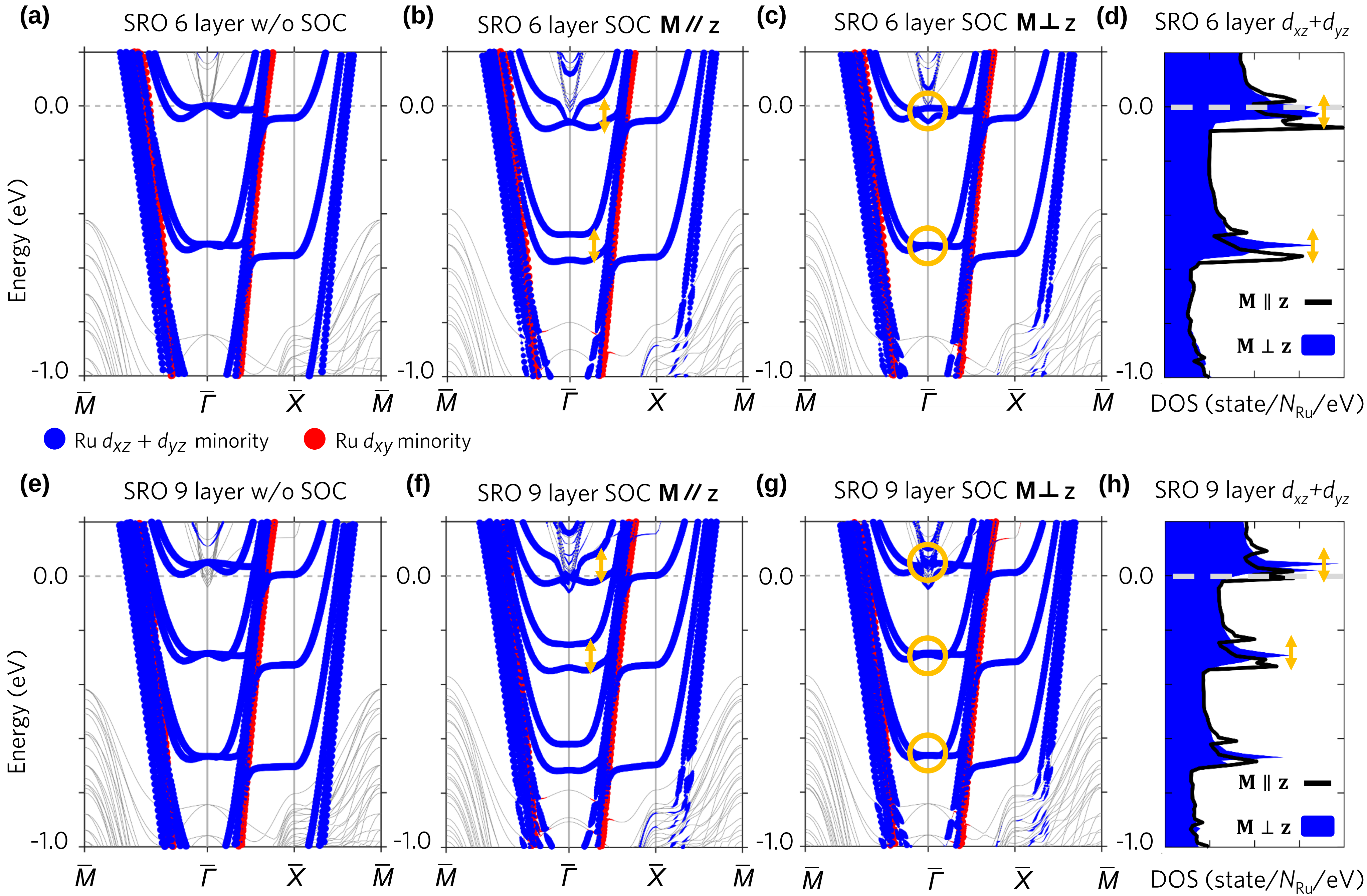
$$(k_x, k_y, k_z) \rightarrow (-k_x, -k_y, -k_z)$$

$$s_z \rightarrow -s_z$$

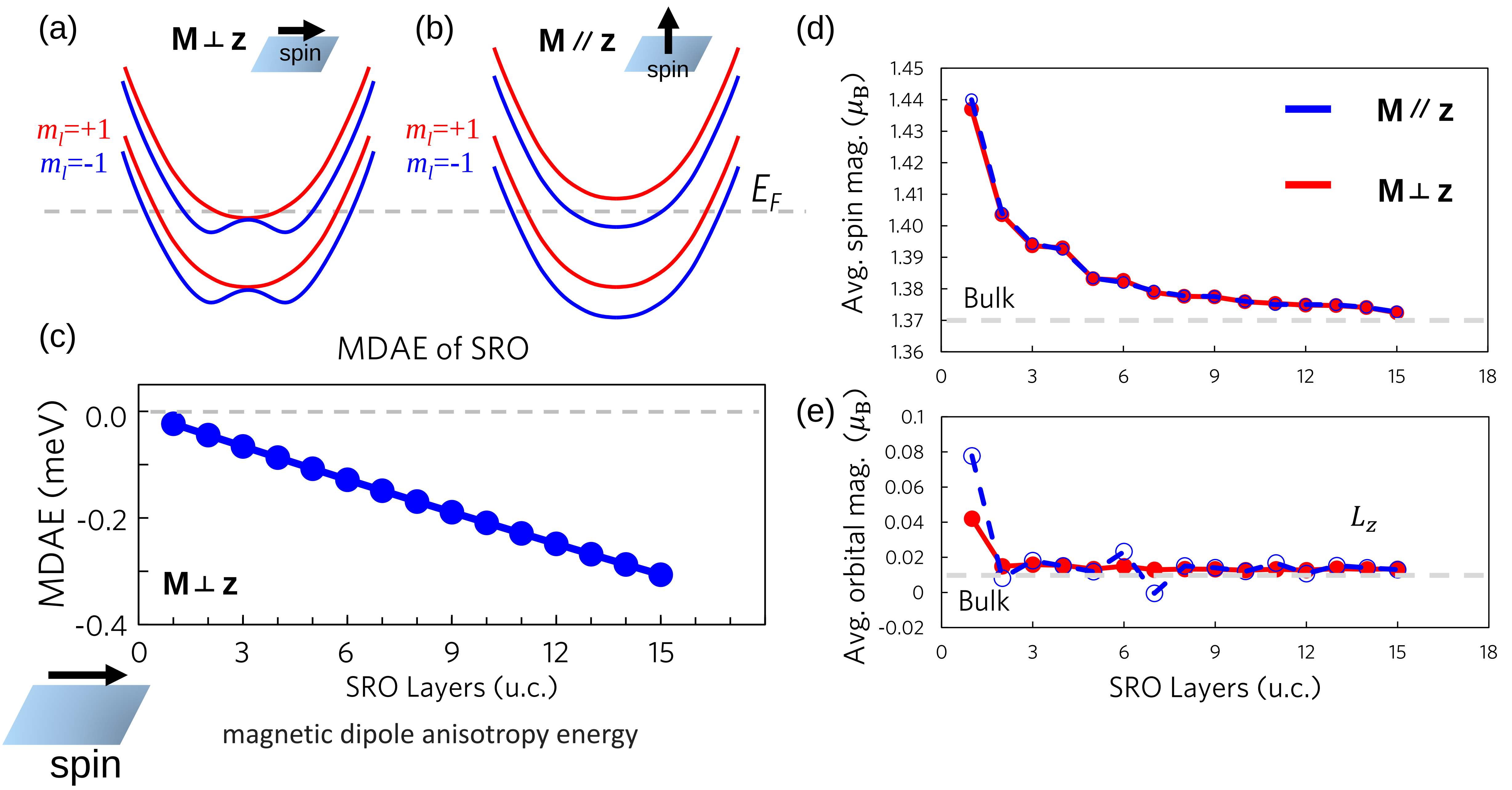
- Mirror symmetry

$$(k_x, k_y, k_z) \rightarrow (-k_x, k_y, k_z)$$

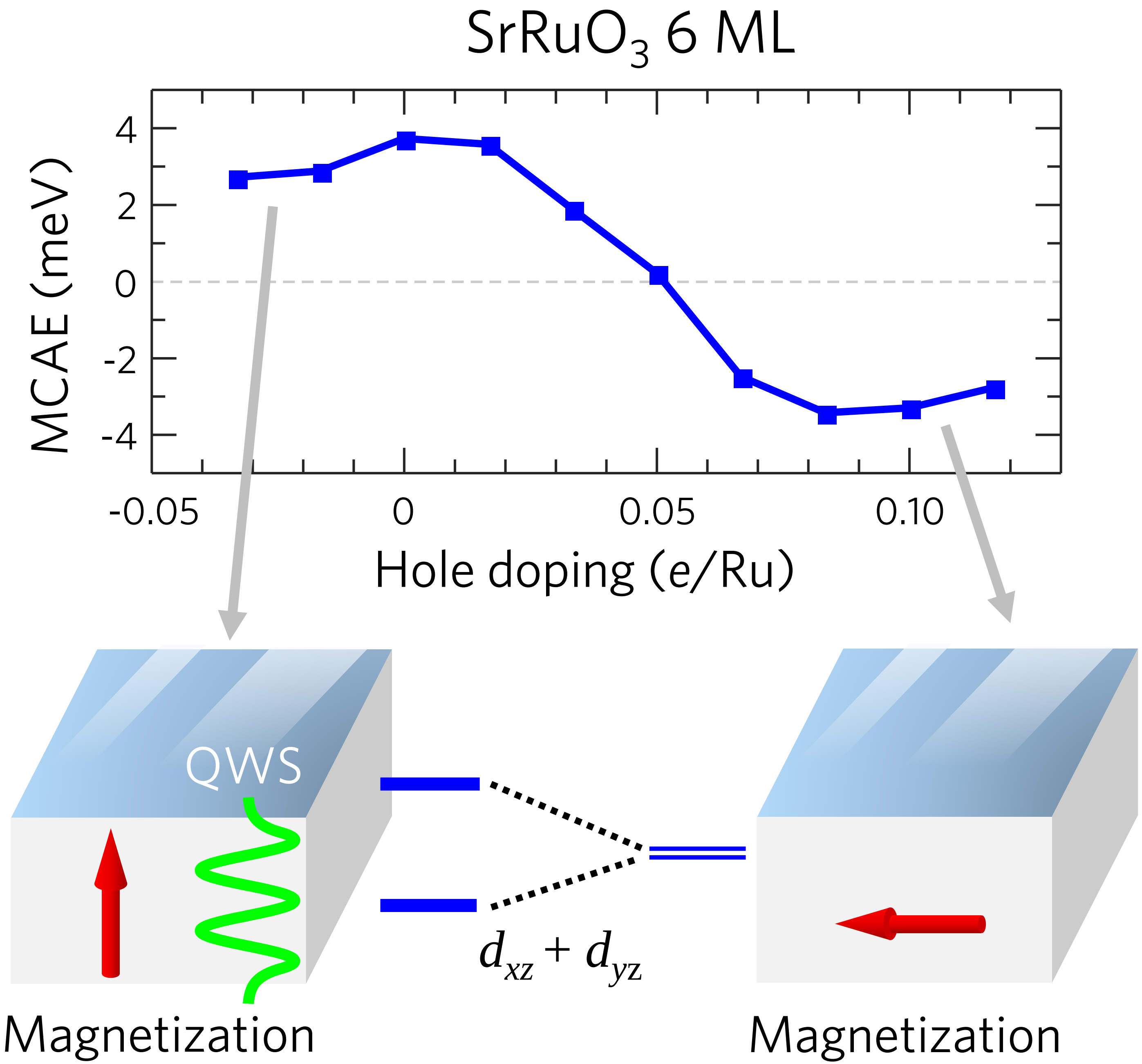
$$l_z \rightarrow -l_z$$

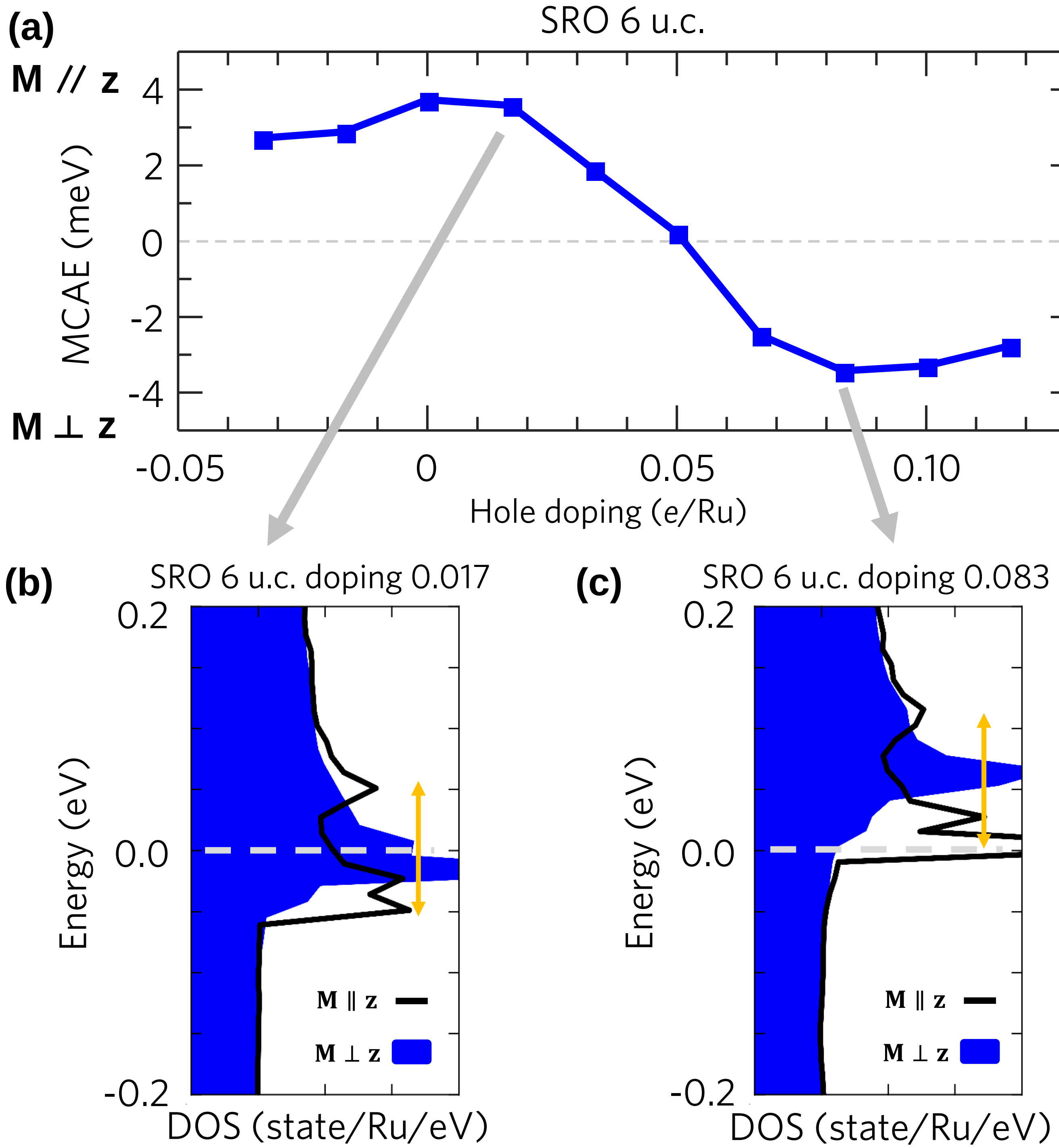


(a)
SRO 6 layer w/o SOC
(b)
SRO 6 layer SOC M // z
(c)
SRO 6 layer SOC M ⊥ z
(d)
SRO 6 layer d_{xz}+d_{yz}
Energy (eV)
0.0
-1.0
$\bar{M}$
$\bar{\Gamma}$
$\bar{X}$
M ∥ z
M ⊥ z
DOS (state/N_{Ru}/eV)
Ru $d_{xz} + d_{yz}$ minority
Ru d_{xy} minority
(e)
SRO 9 layer w/o SOC
(f)
SRO 9 layer SOC M // z
(g)
SRO 9 layer SOC M ⊥ z
(h)
SRO 9 layer d_{xz}+d_{yz}



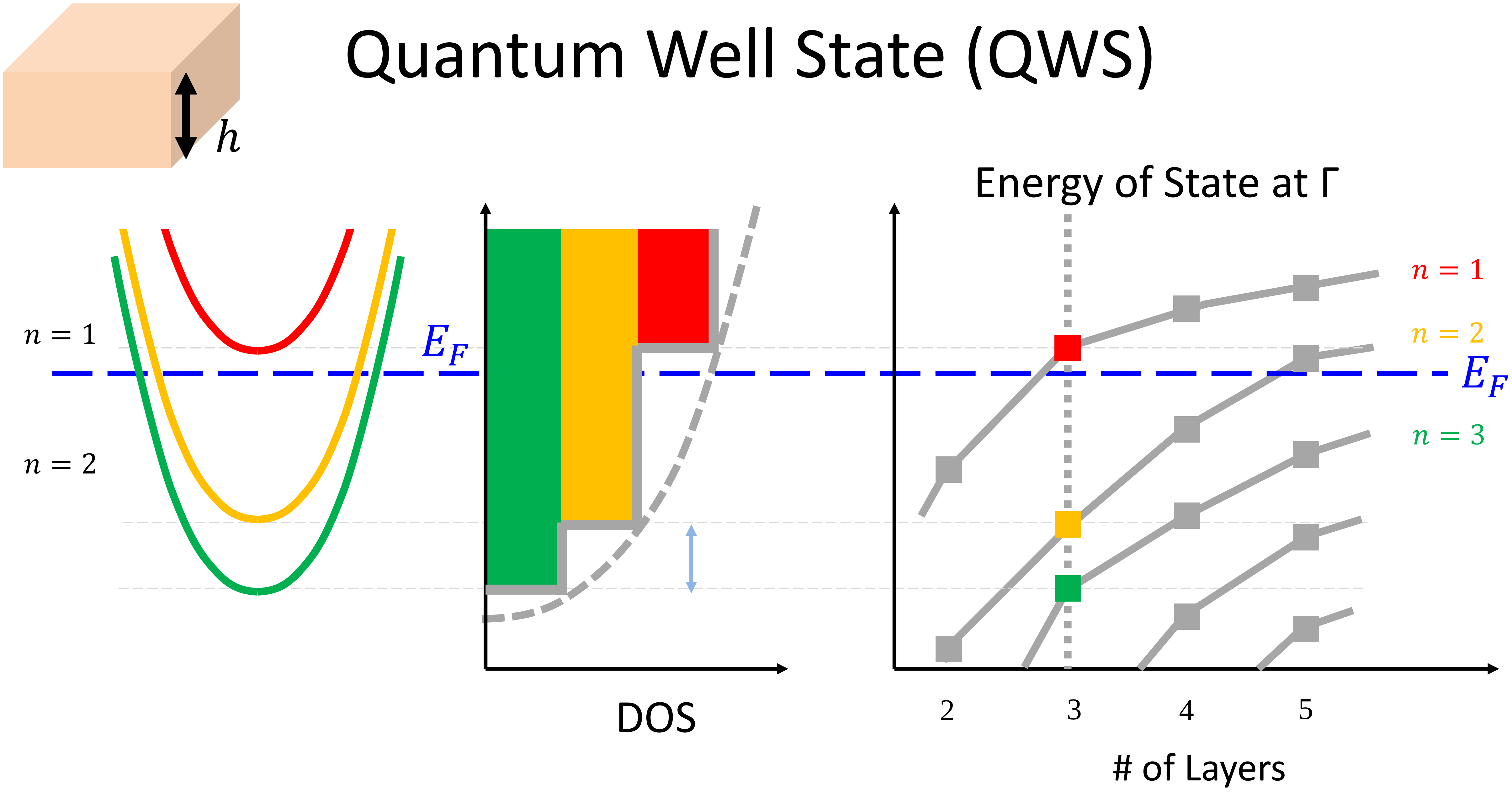
(a)
M ⊥ z
spin
m_l=+1
m_l=-1
(b)
M // z
spin
m_l=+1
m_l=-1
E_F
(c)
MDAE of SRO
MDAE (meV)
0.0
-0.2
-0.4
M ⊥ z
0
3
6
9
12
15
SRO Layers (u.c.)
spin
magnetic dipole anisotropy energy
(d)
Avg. spin mag. (μ_B)
1.45
1.44
1.43
1.42
1.41
1.40
1.39
1.38
1.37
1.36
M // z
M ⊥ z
Bulk
0
3
6
9
12
15
18
(e)
Avg. orbital mag. (μ_B)
0.1
0.08
0.06
0.04
0.02
0
-0.02
L_z
Bulk
0
3
6
9
12
15
18
SRO Layers (u.c.)


SrRuO3 6 ML
MCAE (meV)
4
2
0
-2
-4
-0.05
0
0.05
0.10
Hole doping (e/Ru)
QWS
dxz + dyz
Magnetization
Magnetization



(a)
SRO 6 u.c.
M // z
M ⊥ z
MCAE (meV)
4
2
0
-2
-4
-0.05
0
0.05
0.10
Hole doping (e/Ru)
(b)
SRO 6 u.c. doping 0.017
0.2
0.0
-0.2
Energy (eV)
DOS (state/Ru/eV)
M ∥ z
M ⊥ z
(c)
SRO 6 u.c. doping 0.083
0.2
0.0
-0.2
Energy (eV)
DOS (state/Ru/eV)
M ∥ z
M ⊥ z

Quantum Well State (QWS)



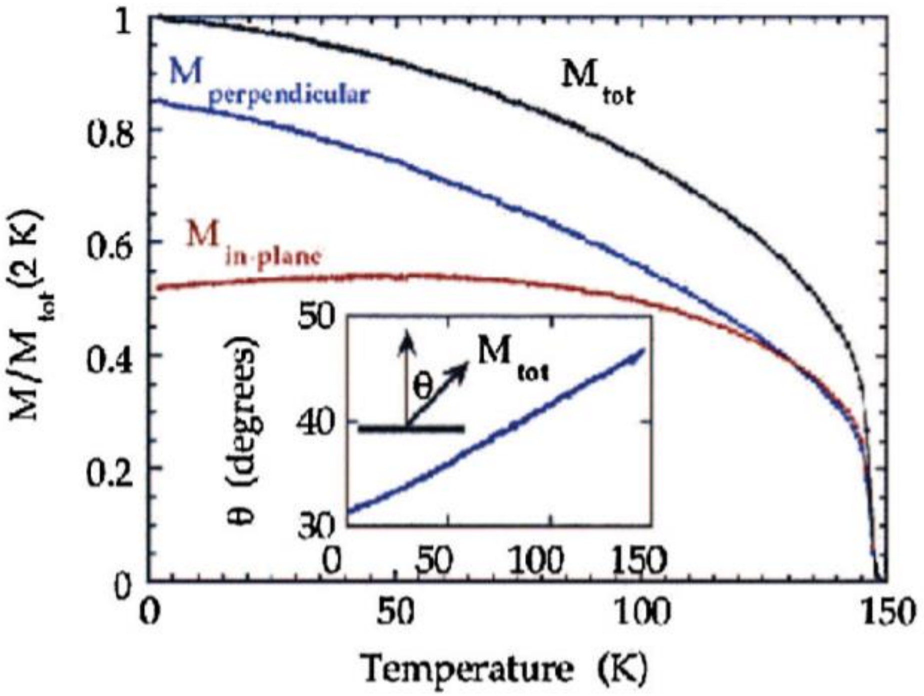


FIG. 27 (color online). Temperature dependences of the in-plane, out-of-plane, and total remanent magnetizations of a $SrRuO_3$ film. The film was cooled in a saturating field down to 5 K and the magnetization was measured upon warming after removing the applied field. The temperature dependence of the angle between the magnetic moment and the normal to the film plane is also shown. From Klein, Dodge, Ahn, Reiner *et al.*, 1996.

G. Koster *et al.*, *Rev. Mod. Phys.* **84**, 253 (2012)
L. Klein *et al.*, *J. Phys. Condens. Matter* **8**, 10111 (1996)