Spin-orbit torque switching between **reversed antiferromagnetic state** and its **electrical detection**

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Z. Soban (2), V. Novak (2), K. Olejnik (2), T. Jungwirth (2), P. Nemec (3), ...,

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ANTIFERROMAGNETS
useful for applications?

Fast (THz) dynamics:
switching, domain wall motion
GHz in ferromagnets

Radiation-hard
Spin not charge based
(as ferromagnets)

MERITS ?

Non-volatile
Magnetic order
(as ferromagnets)

Spin-polarized band-structure coupled to magn. order
(Altermagnets, non-col. AFs)

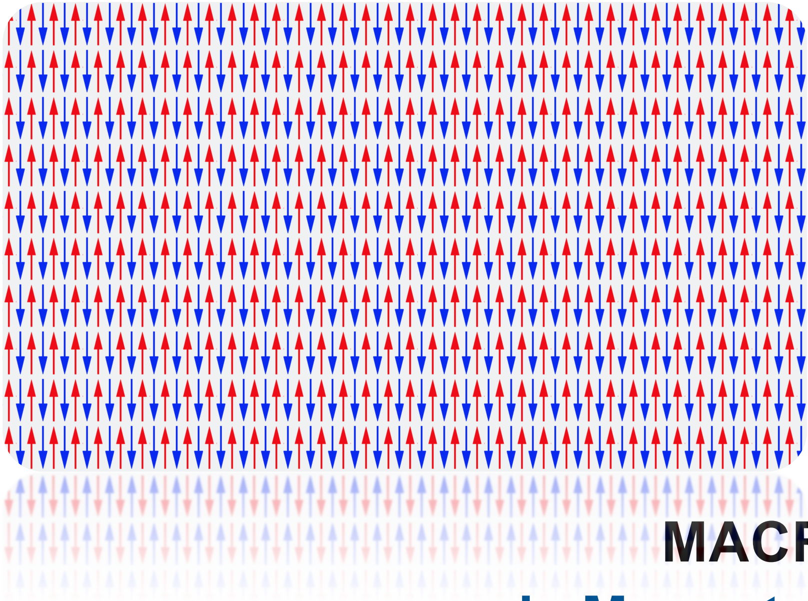
Insensitive & invisible to magnetic fields

No stray field cross-talks
No (small) net moment

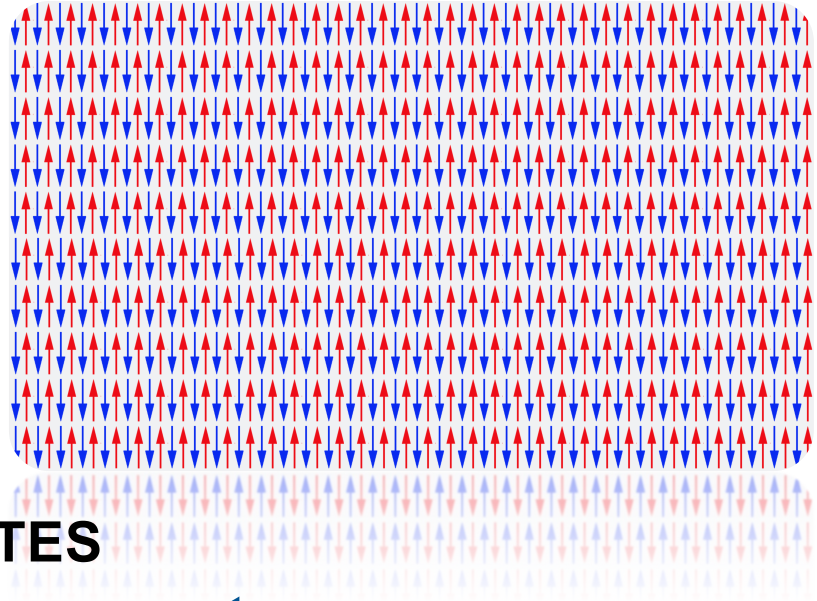
Insulators, topol. ins., semiconductors, semimetals, metals, …
Ferromagnets mostly metals

ANTIFERROMAGNETS

Anisotropic Magnetoresistance



and optical equivalents



Electrical

DETECTION of MACROSCOPIC STATES

via Magneto-transport measurements

Insensitive & invisible to magnetic fields

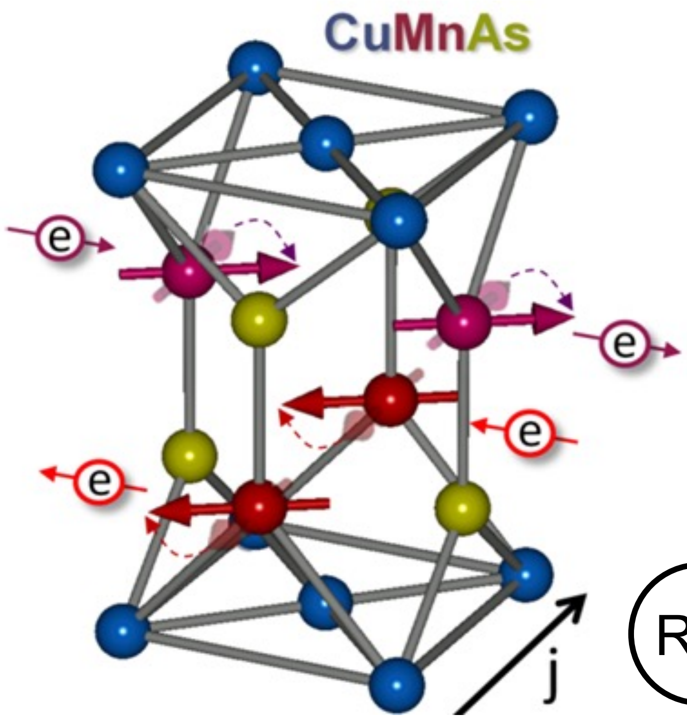
No stray field cross-talks
No net moment

ANTIFERROMAGNETS

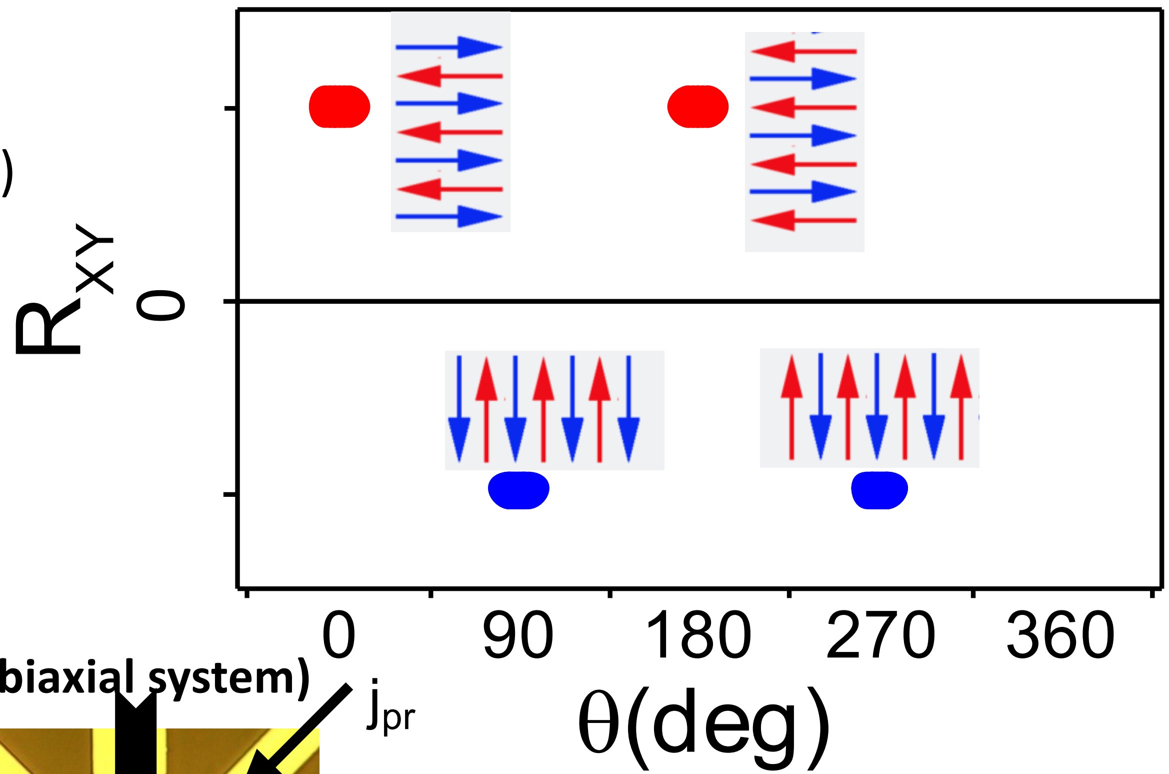
Electrical Writing
by Spin-Orbit Torque

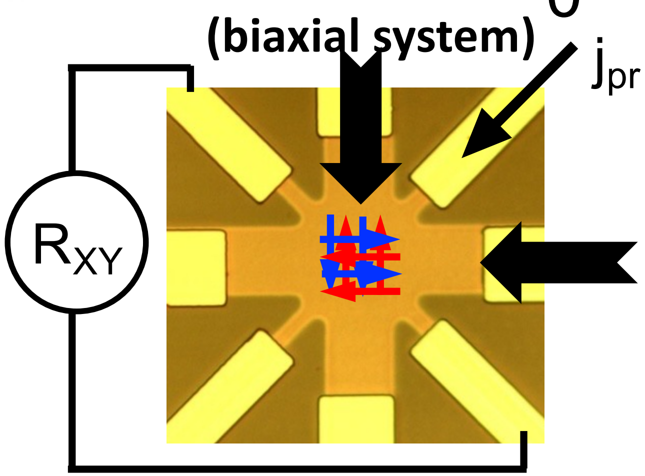
Anisotropic Magnetoresistance

CuMnAs (and also Mn_2Au)
(Locally broken inversion symmetry)



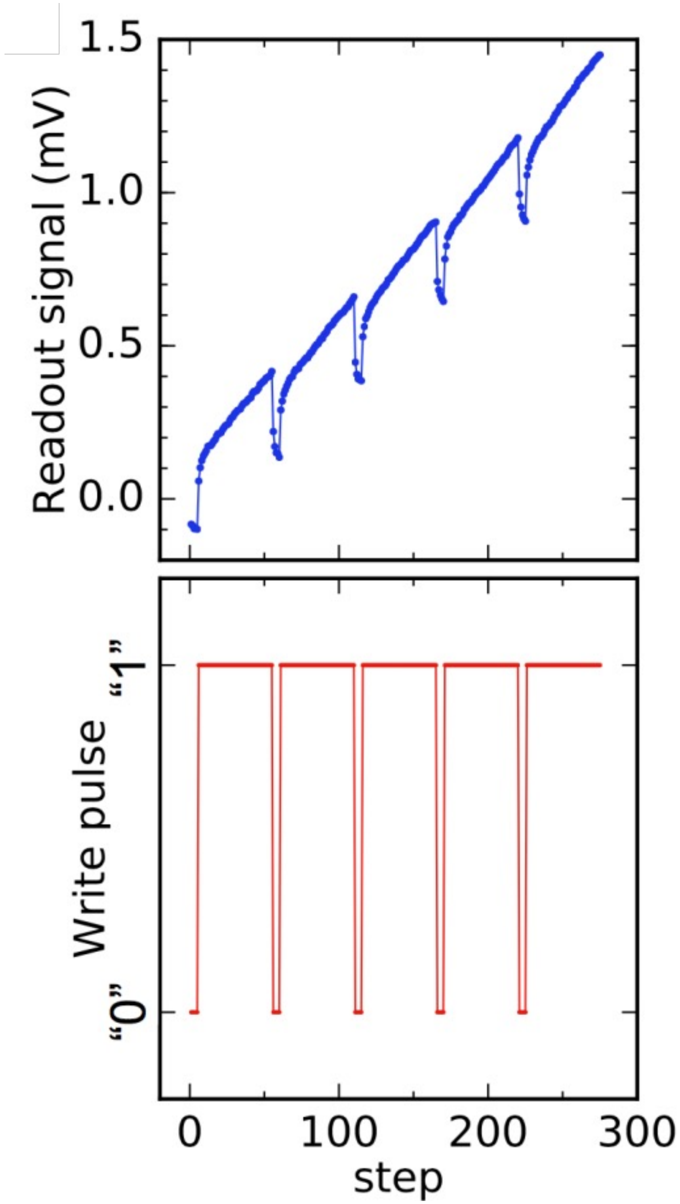
THEORY: J. Železný, et al.,
PRL 113, 157201 (2014)





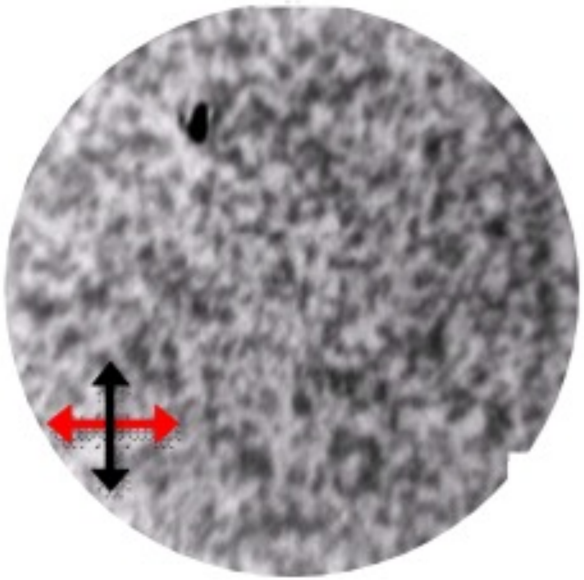
Biaxial Switching in CuMnAs

→ **Short electrical pulses**

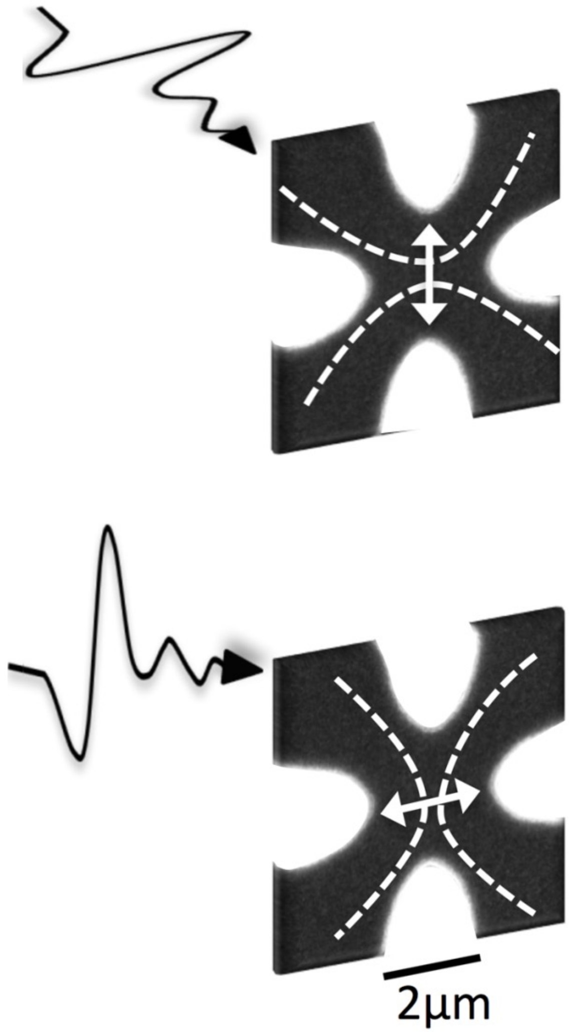


(K. Olejnik, et al., Nat. Comm. 2017)

Biaxial CuMnAs



→ **Polarized THz Laser Pulses**

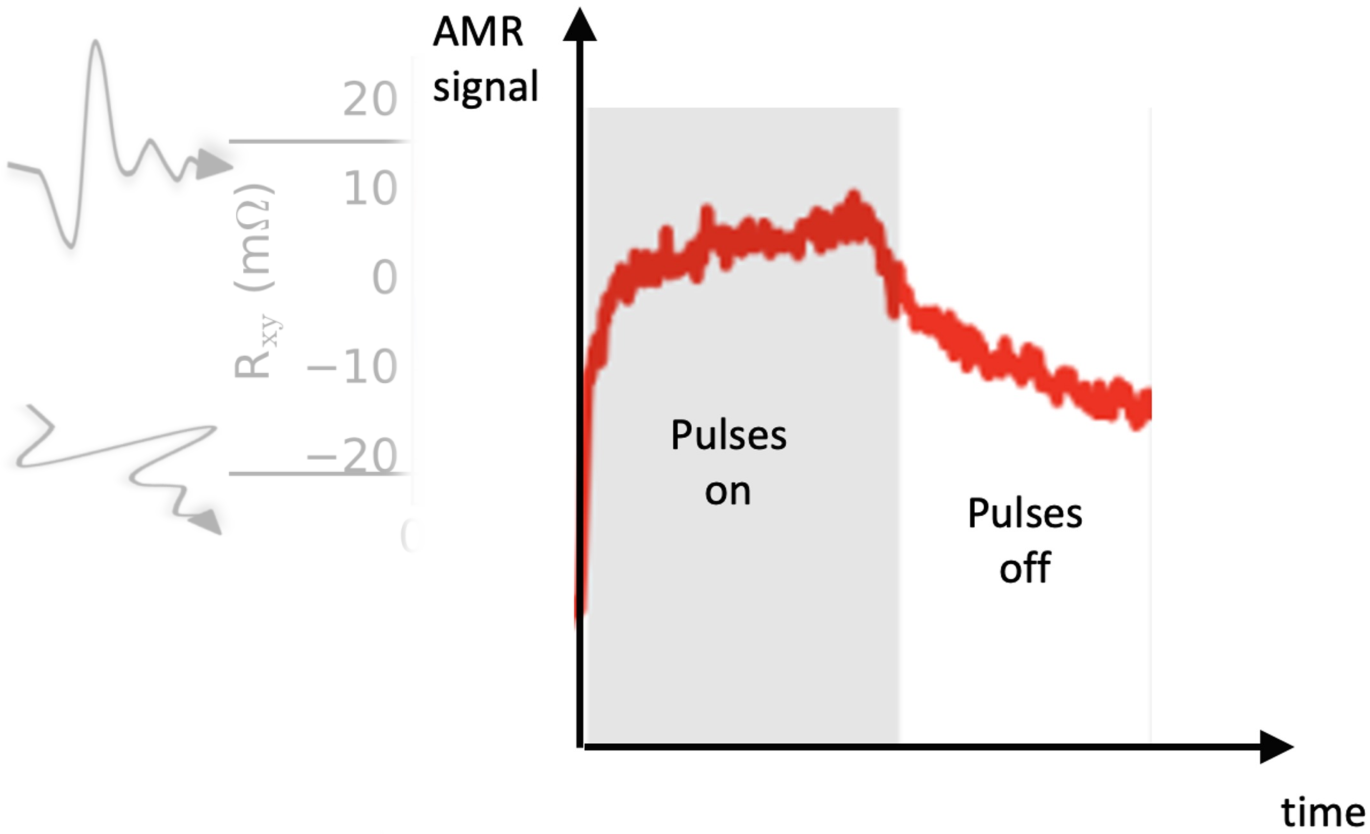


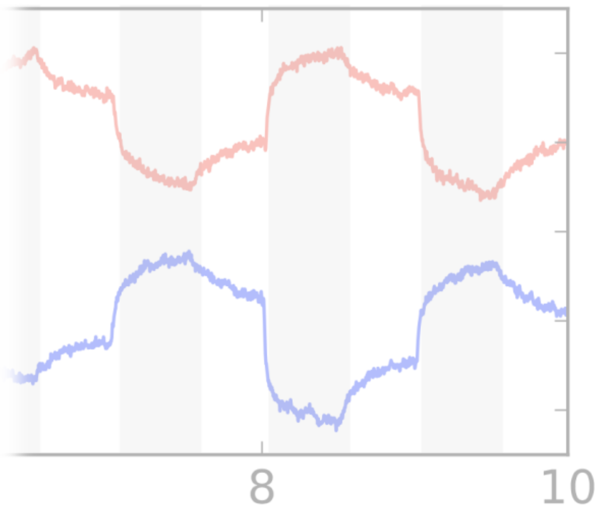
(K. Olejnik, et al., Sci. Adv. 2018;4:eaar356)

Biaxial Switching in CuMnAs

→ **Electrical pulses**

→ **Polarized THz Laser Pulses**



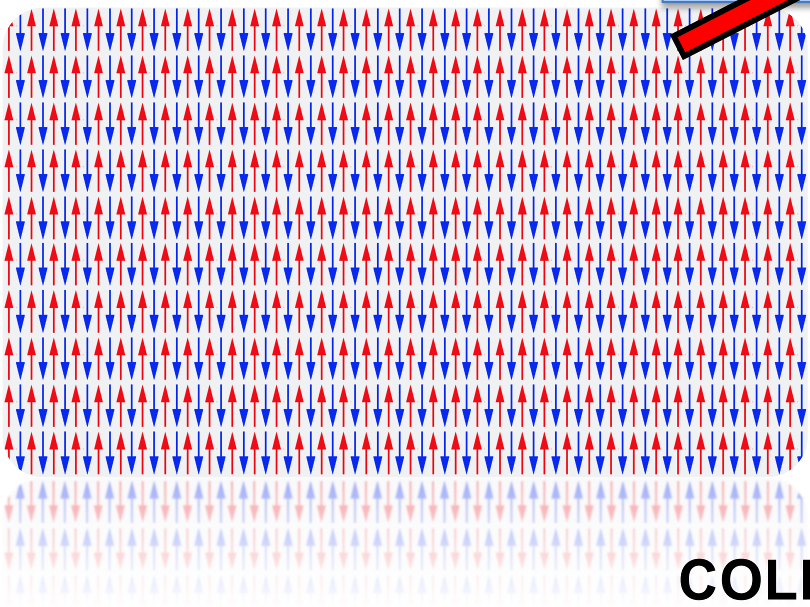


→ **NON-VOLATILE ???**

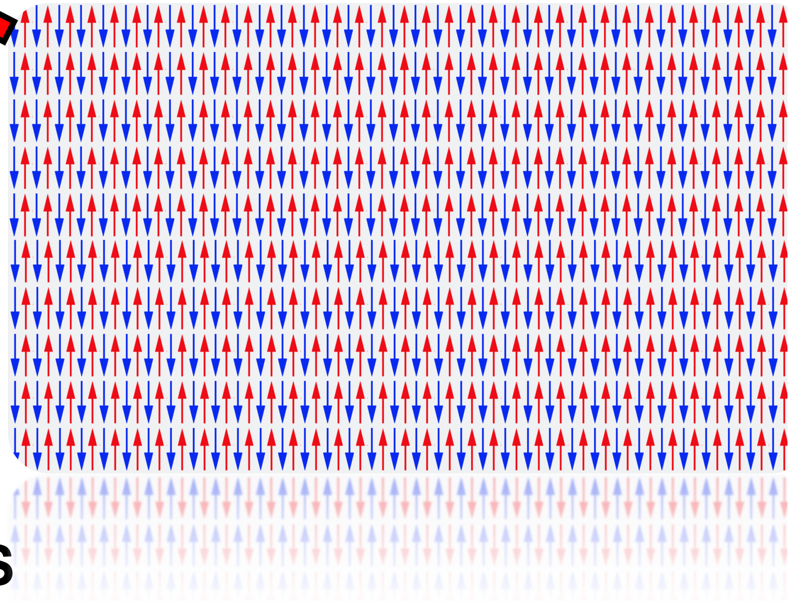
(K. Olejnik, et al., Sci. Adv. 2018;4:eaar356)

Collinear antiferromagnetic states

~~Anisotropic Magnetoresistance linear response~~



Electrical **DETECTION** of reversed **COLLINEAR STATES** ?

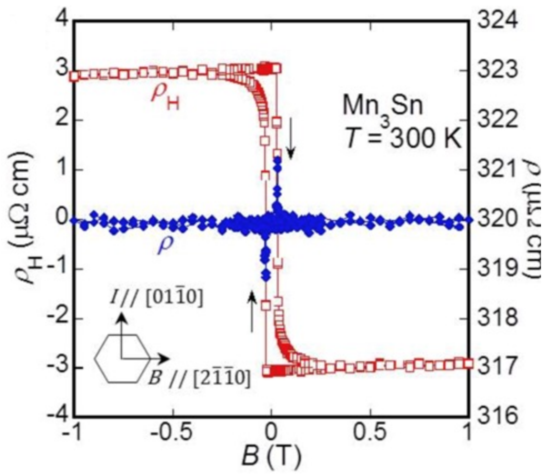


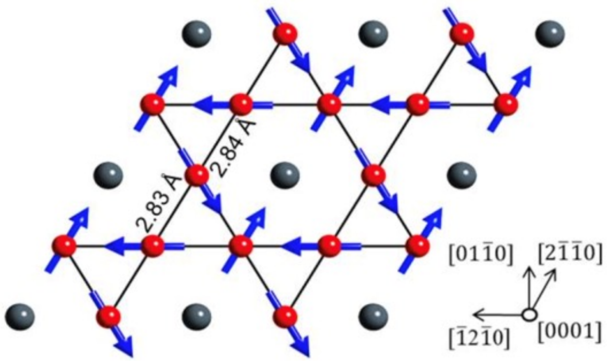
Electrical detection of 180° spin reversal

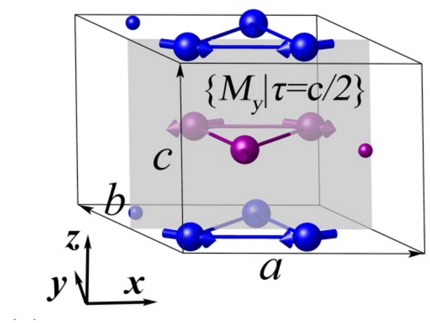
Anomalous Hall effect (AHE) in non-collinear AFs

that crystallize in ferromagn. symmetry groups, able to develop magnetic moment

(**Mn_3Ir**, **Mn_3Ge**, **Mn_3Sn**, **…**)







Chen et al., PRL 112, 017205 (2014)
Nakatsuji, et al., Nature 527, 212 (2015)
Nayak, et al., Sci. Adv. 2, e1501870 (2016)
…

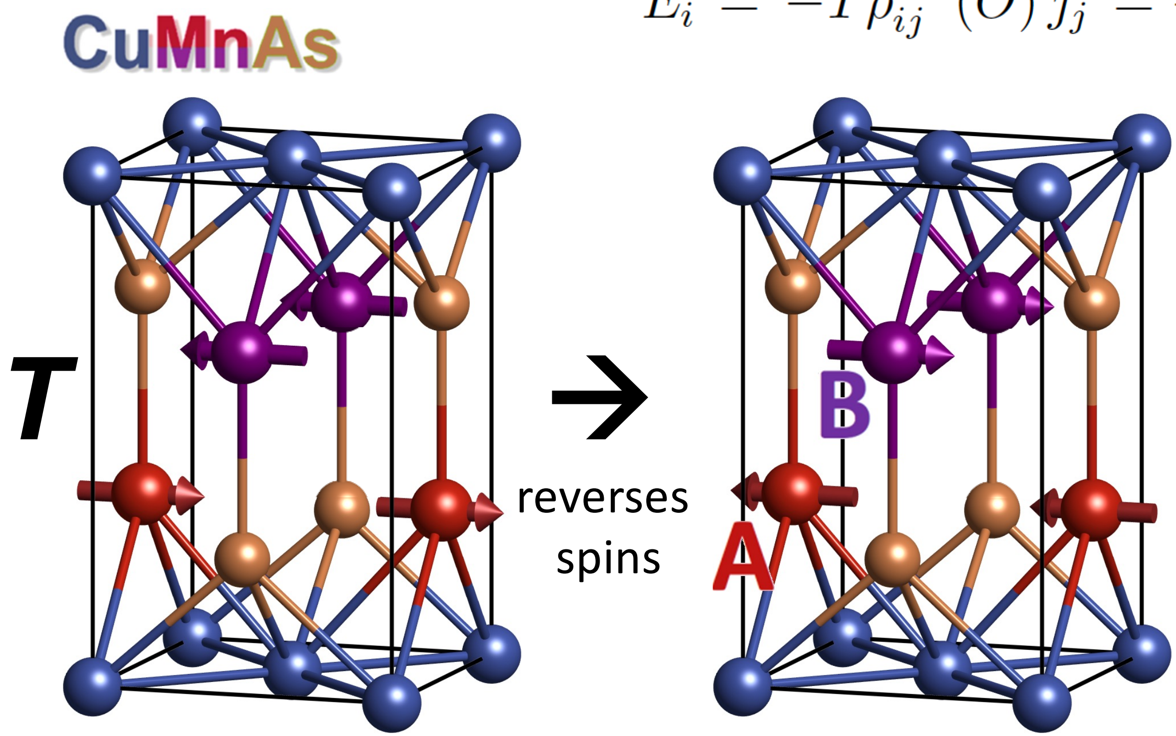
Electrical detection of 180° spin reversal

Anomalous Hall effect (AHE)

linear response: **E** = (ρ + ξj + . . .) **j**

AHE (odd under time reversal): $E_i = \rho_{ij}^{odd}(\vec{O})\, j_j$

$$E_i = -T\rho_{ij}^{odd}(\vec{O})\, j_j = -\rho_{ij}^{odd}(-\vec{O})\, j_j$$



Broken time reversal symmetry

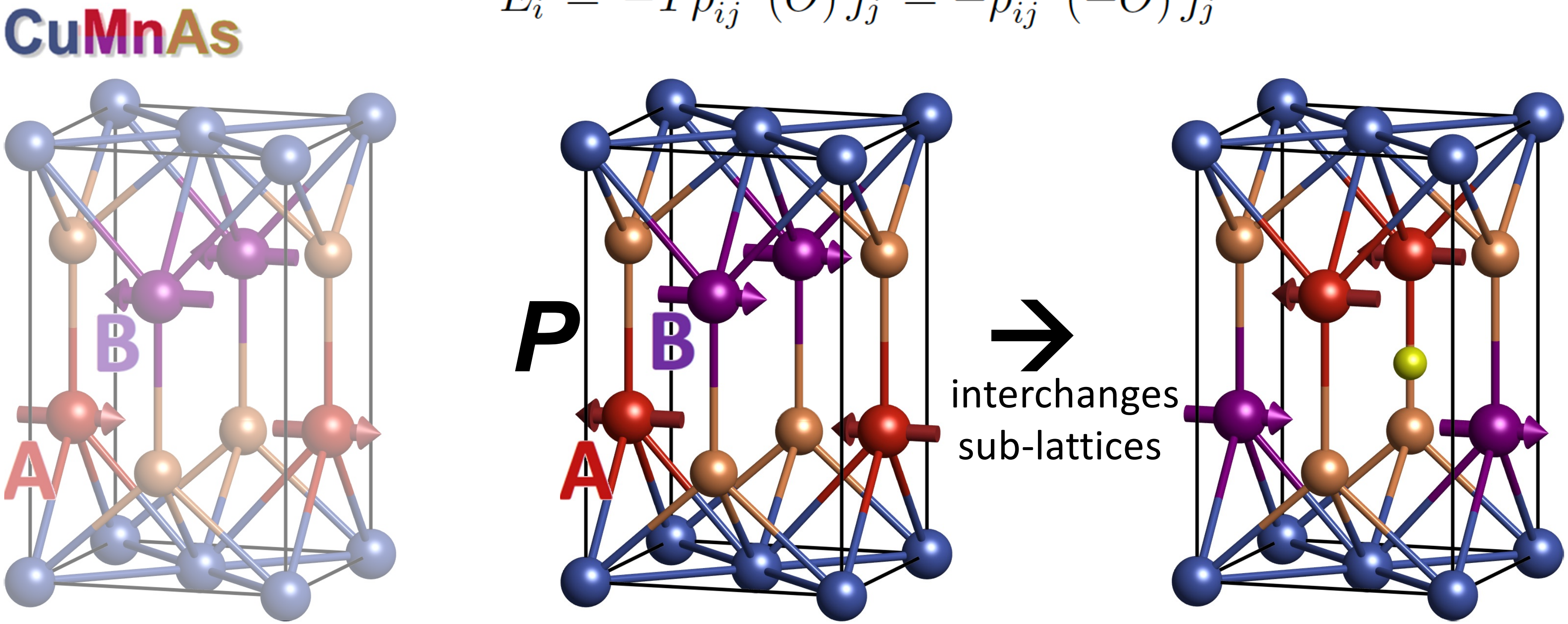
Electrical detection of 180° spin reversal

Anomalous Hall effect (AHE)

linear response: **E** = (ρ + ξj + …) **j**

AHE (odd under time reversal): $E_i = \rho_{ij}^{odd}(\vec{O})\, j_j$;

$$E_i = -T\rho_{ij}^{odd}(\vec{O})\, j_j = -\rho_{ij}^{odd}(-\vec{O})\, j_j$$



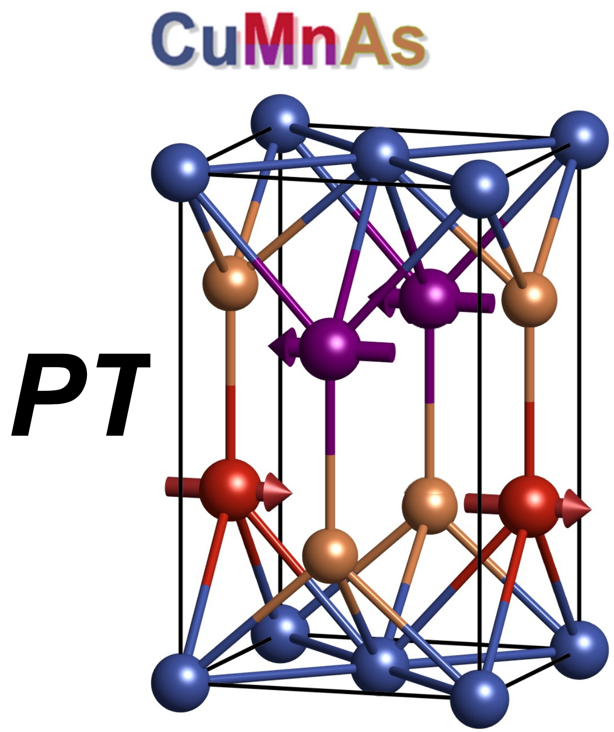
Broken space-inversion symmetry

Electrical detection of 180° spin reversal

Anomalous Hall effect (AHE) linear response: $\mathbf{E} = (\rho + \xi \mathbf{j} + \ldots)\, \mathbf{j}$

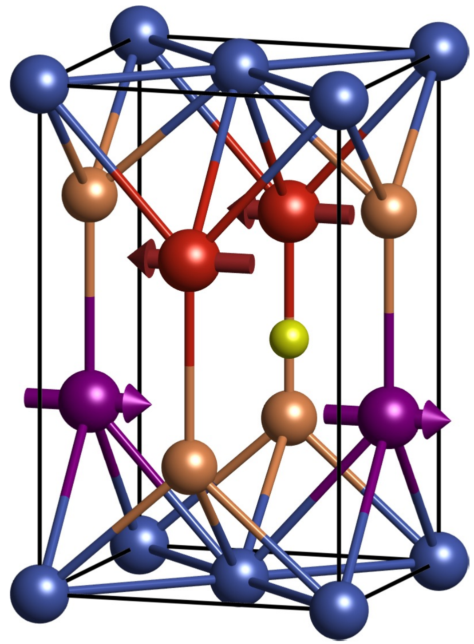
AHE (odd under time reversal): $E_i = \rho_{ij}^{odd}(\vec{O})\, j_j$

$$E_i = -T\rho_{ij}^{odd}(\vec{O})\, j_j = -\rho_{ij}^{odd}(-\vec{O})\, j_j$$



→

Combined *PT* symmetry



PT symmetry of the CuMnAs crystal: $\rho_{ij}^{odd} = PT\rho_{ij}^{odd}$

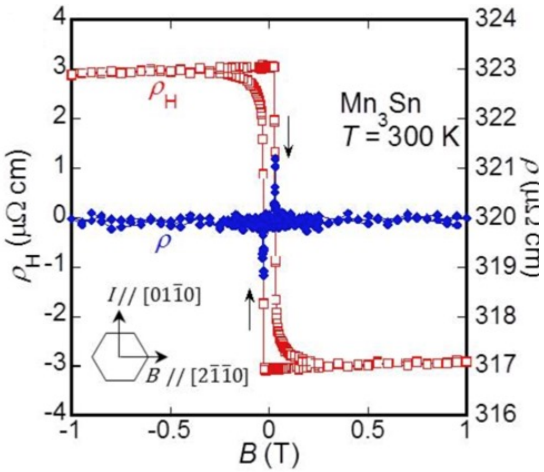
Space inversion flips sign of both electric field E_i and current j_j

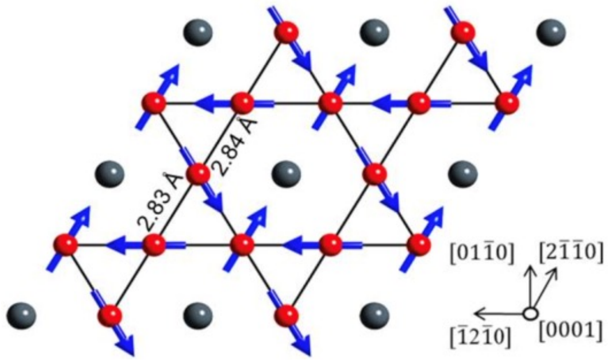
Time rev. symmetry flips sign only of current j_j: $\rho_{ij}^{odd} = -PT\rho_{ij}^{odd}$

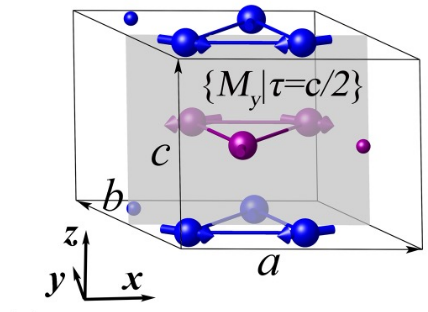
$\Longrightarrow$ $\rho_{ij}^{odd} = 0$ **(no AHE)**

Anomalous Hall effect (AHE) in **non-collinear AFs**

that crystallize in ferromagn. symmetry groups, able to develope a magnetic moment (**Mn_3Ir**, **Mn_3Ge**, **Mn_3Sn**, **…**)







Chen et al., PRL 112, 017205 (2014)
Nakatsuji, et al., Nature 527, 212 (2015)
Nayak, et al., Sci. Adv. 2, e1501870 (2016)
…

Magnetoresistance

$\mathbf{E} = (\rho + \xi\mathbf{j} + \dots)\,\mathbf{j}$ (second order response)

- allows detection of spin-reversal in **AF with broken *T* symmetry**

  but actually requires that **AF has also combined *PT* symmetry**: $E_i = \xi^{\mathrm{odd}}_{ijk}\, j_j j_k;$

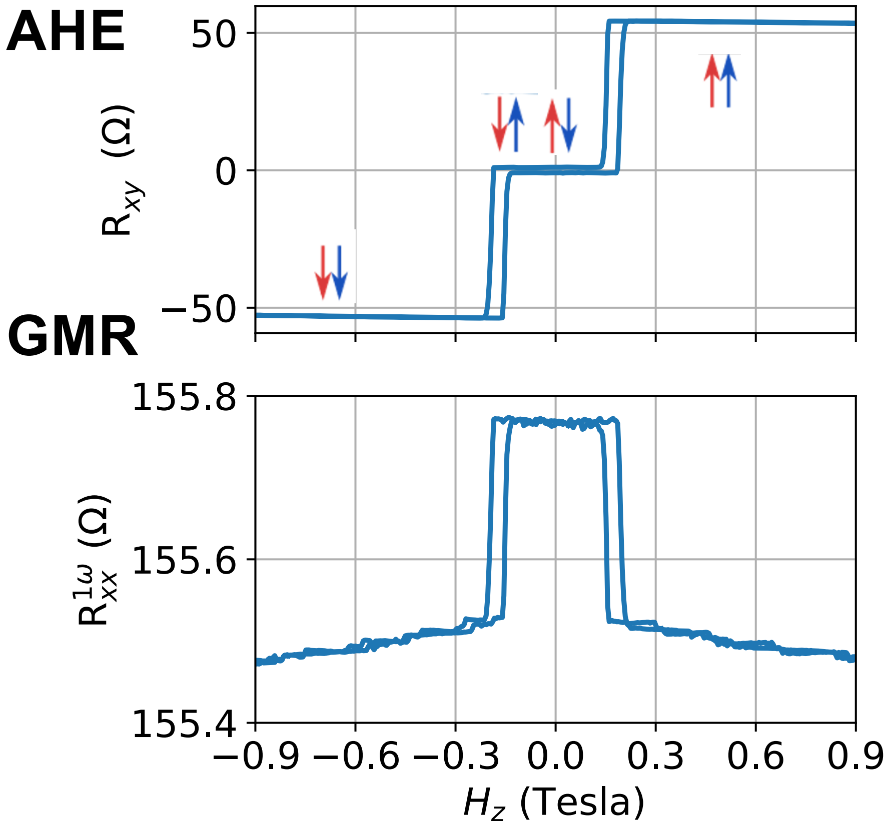
Most of the antiferromagnetic point-groups with broken ***T*** symmetry have ***PT*** symmetry

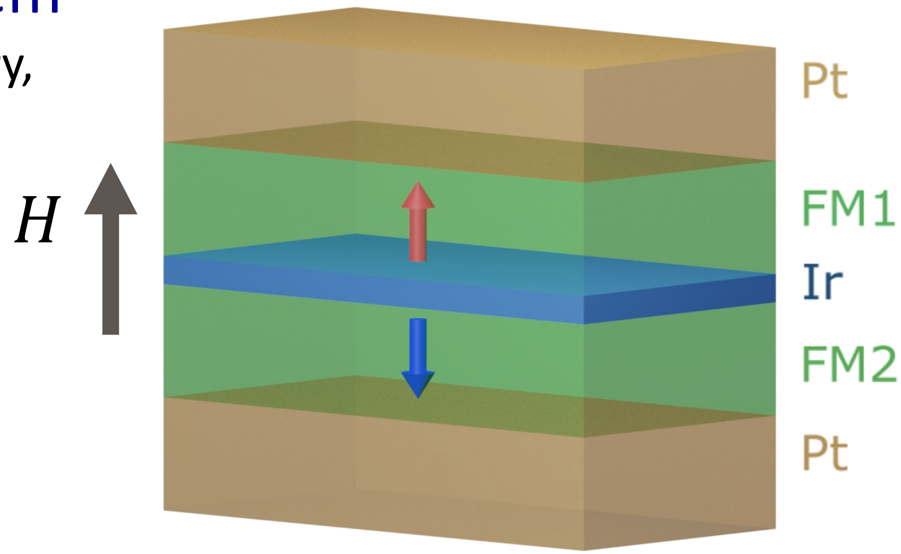
(48 out of 59) H. Grimmer, *Acta Crystallographica Section A* **49**, 763-771 (1993)

Electrical detection of 180° spin reversal

Synthetic Antiferromagnet model system

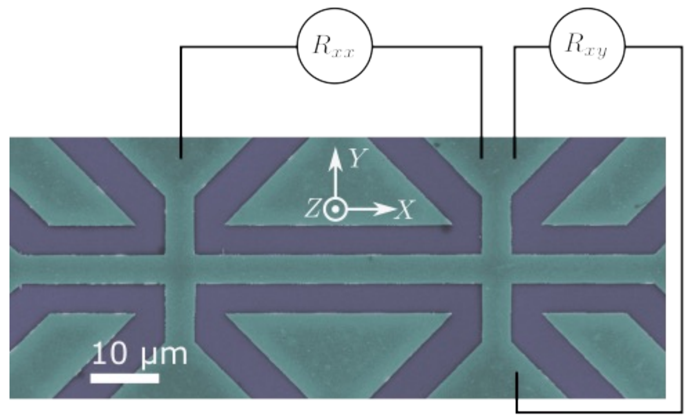
most simple AF model system with PT symmetry, and broken T symmetry





2 reversed AF states → equal AHE and **GMR** responses

… hysteresis loop enables "setting up" the two opposite AF states by the polarity of a perp. Magn. field larger than the spin flip field

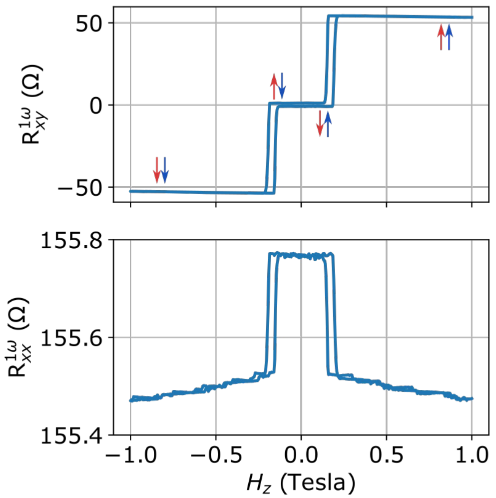


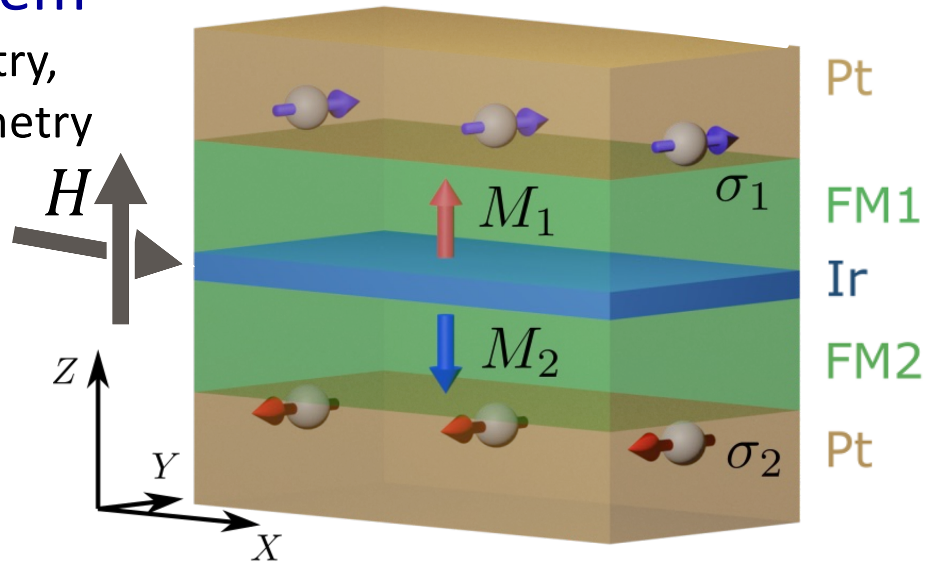
Electrical detection of 180° spin reversal

Synthetic Antiferromagnet model system

most simple AF model system with PT symmetry,
if a magn. field is applied: also broken T symmetry

Linear
AHE and **GMR**





Nonlinear
(2nd order) MR

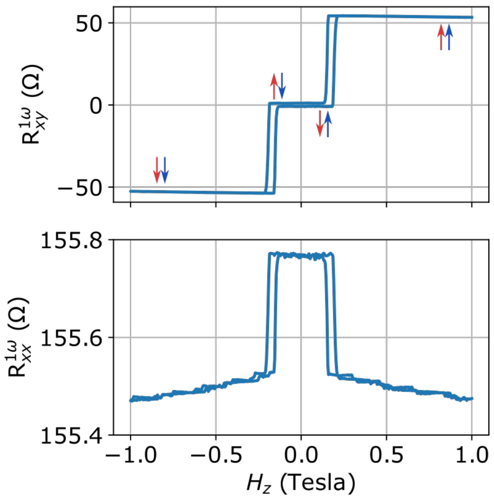
~ **Spin-Orbit torque** (due to staggered SO field)

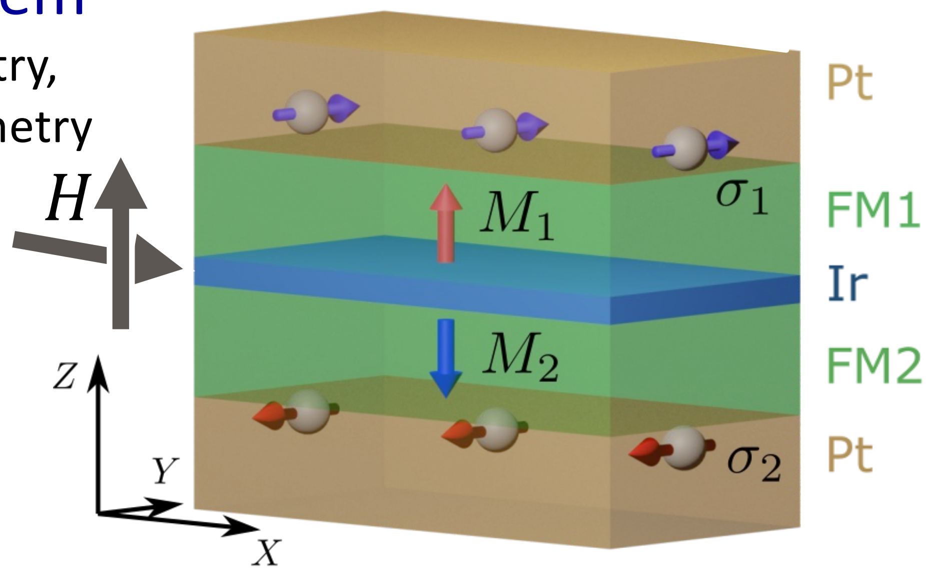
Synthetic Antiferromagnet model system

most simple AF model system with PT symmetry,
if a magn. field is applied: also broken T symmetry

Linear

AHE and **GMR**





Nonlinear

(2nd order) MR

~ **Spin-Orbit torque** (due to staggered SO field)

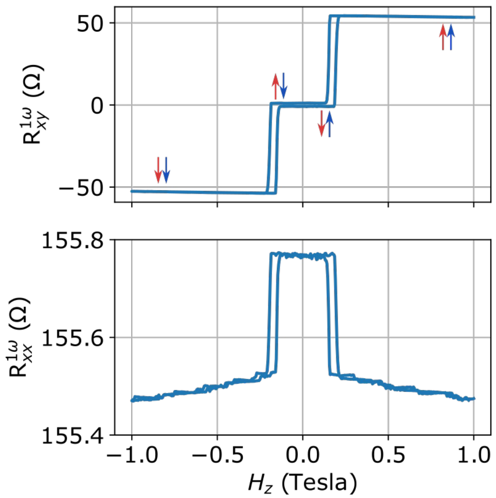
< 0 (depending on Néel vector orientation ↑↓)

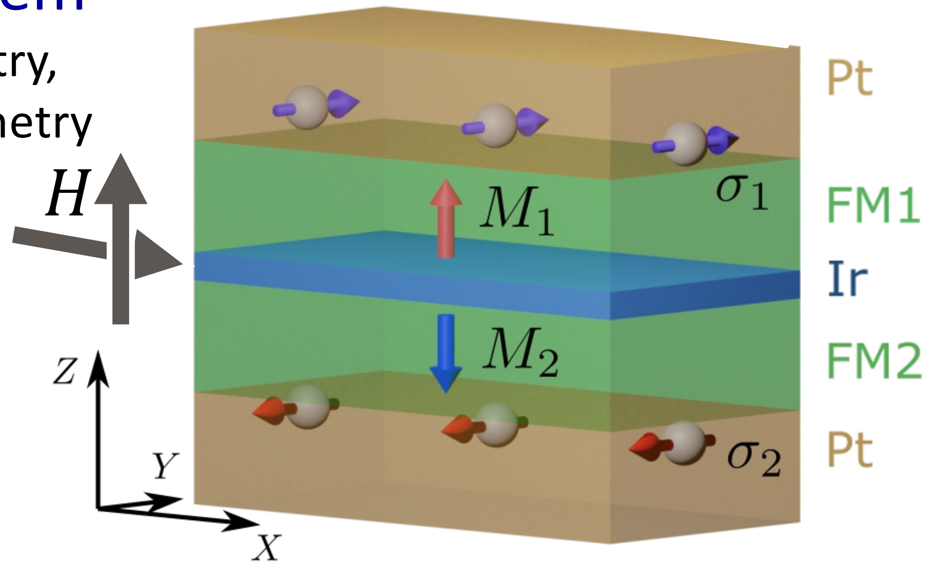
Electrical detection of 180° spin reversal

Synthetic Antiferromagnet model system

most simple AF model system with PT symmetry,
if a magn. field is applied: also broken T symmetry

Linear
AHE and **GMR**





Nonlinear
(2nd order) MR

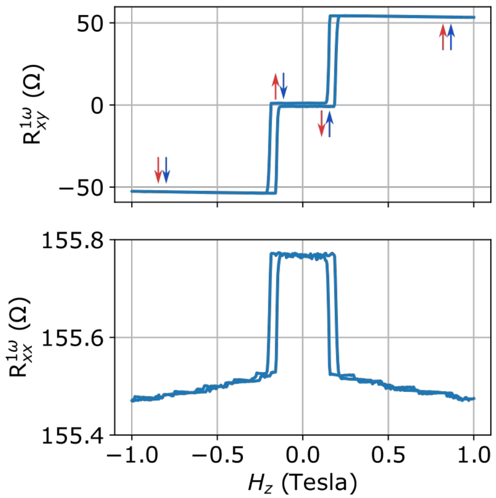
~ **Spin-Orbit torque** (due to staggered SO field)
> 0 (depending on Néel vector orientation ↓↑)

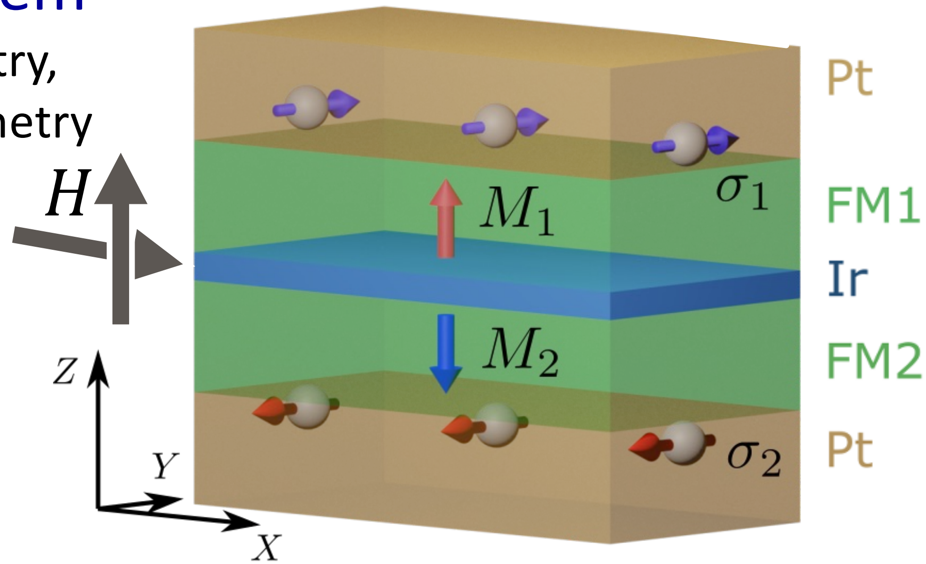
Electrical detection of 180° spin reversal

Synthetic Antiferromagnet model system

most simple AF model system with PT symmetry,
if a magn. field is applied: also broken T symmetry

Linear
AHE and **GMR**





Nonlinear
(2^nd^ order) MR

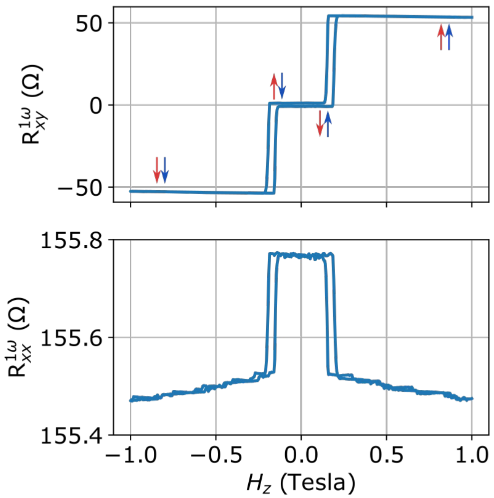
~ **Spin-Orbit torque** (due to staggered SO field)
× d**MR**$/d\theta$ $= 0$ in case of perpendicular magnetic anisotropy 🙁

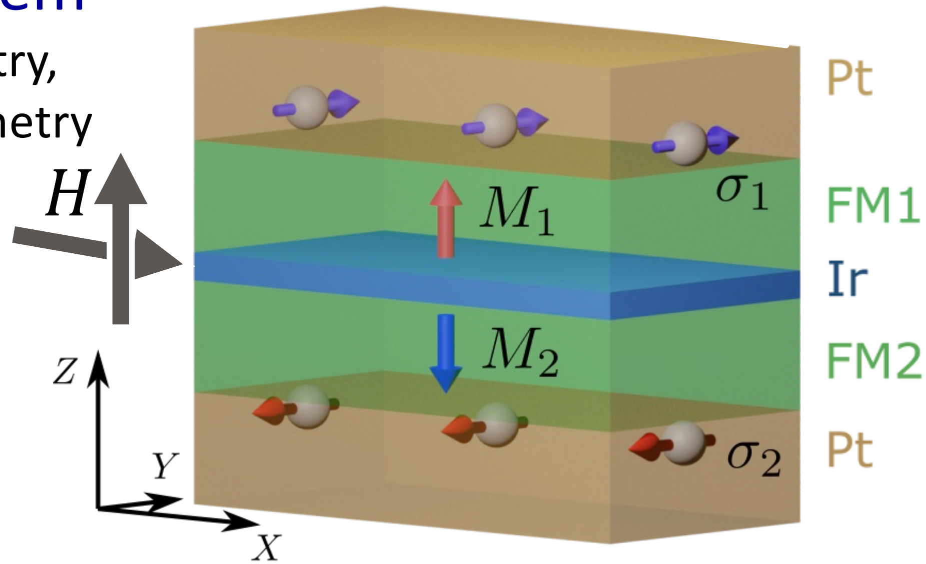
Electrical detection of 180° spin reversal

Synthetic Antiferromagnet model system

most simple AF model system with PT symmetry,
if a magn. field is applied: also broken T symmetry

Linear
AHE and **GMR**





Nonlinear
(2nd order) MR

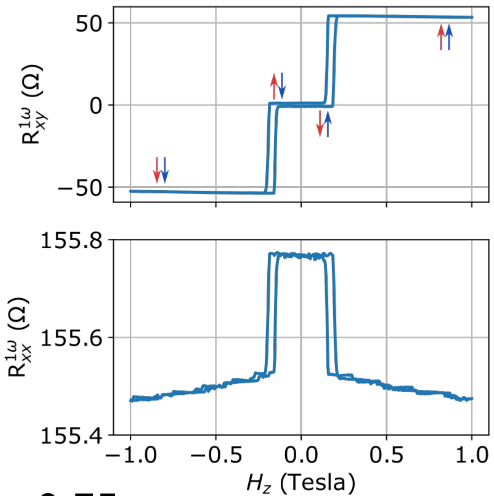
~ **Spin-Orbit torque** (due to staggered SO field)
× d**MR**$/d\theta$ $\neq 0$ by applying a small perturbation, e.g., an inplane magnetic field

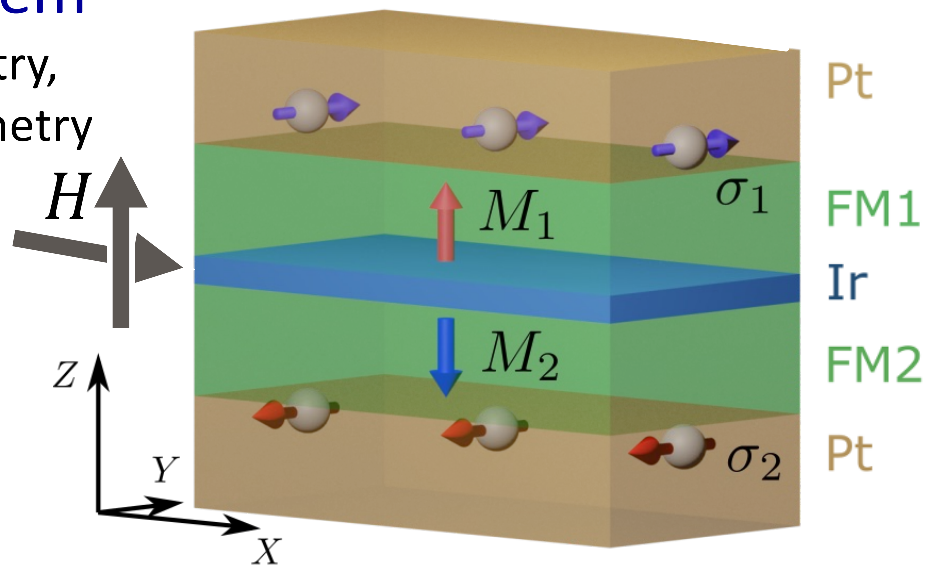
Electrical detection of 180° spin reversal

Synthetic Antiferromagnet model system

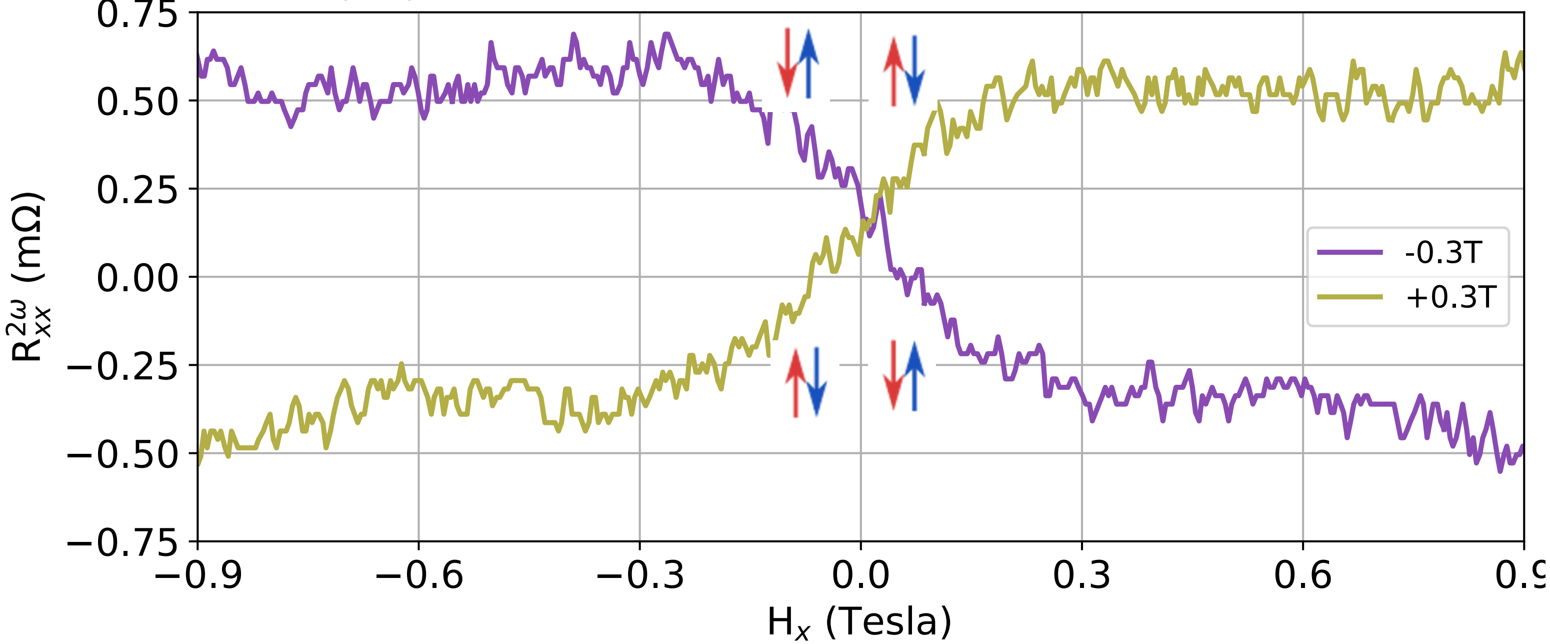
most simple AF model system with PT symmetry,
if a magn. field is applied: also broken T symmetry

Linear
AHE and **GMR**





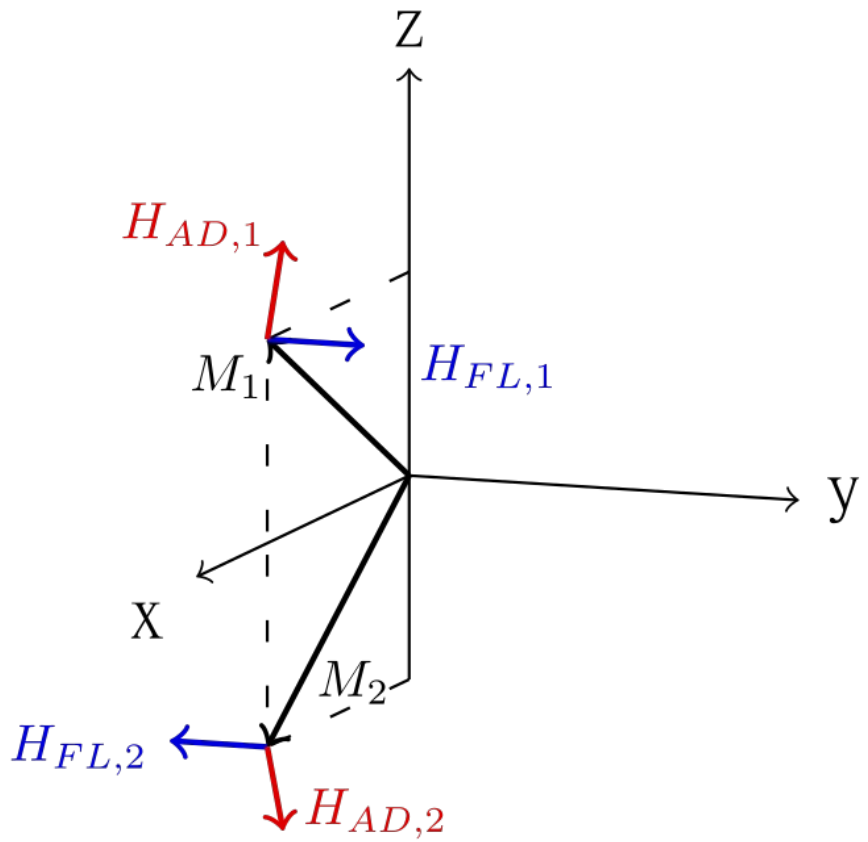
Nonlinear
(2[nd] order) MR



Synthetic Antiferromagnet model system with perpendicular magn. anisotropy

Nonlinear MR

generated by torque of the *staggered component* of the *damping like* SO field



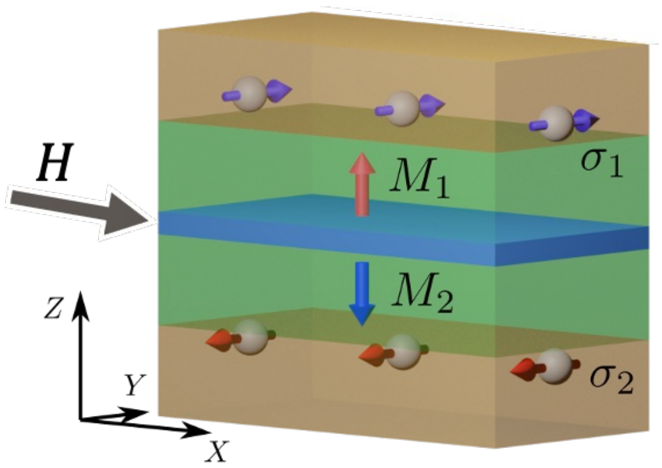
SO effective fields (current $\boldsymbol{j}$ and inplane field $\boldsymbol{H}$ along x)

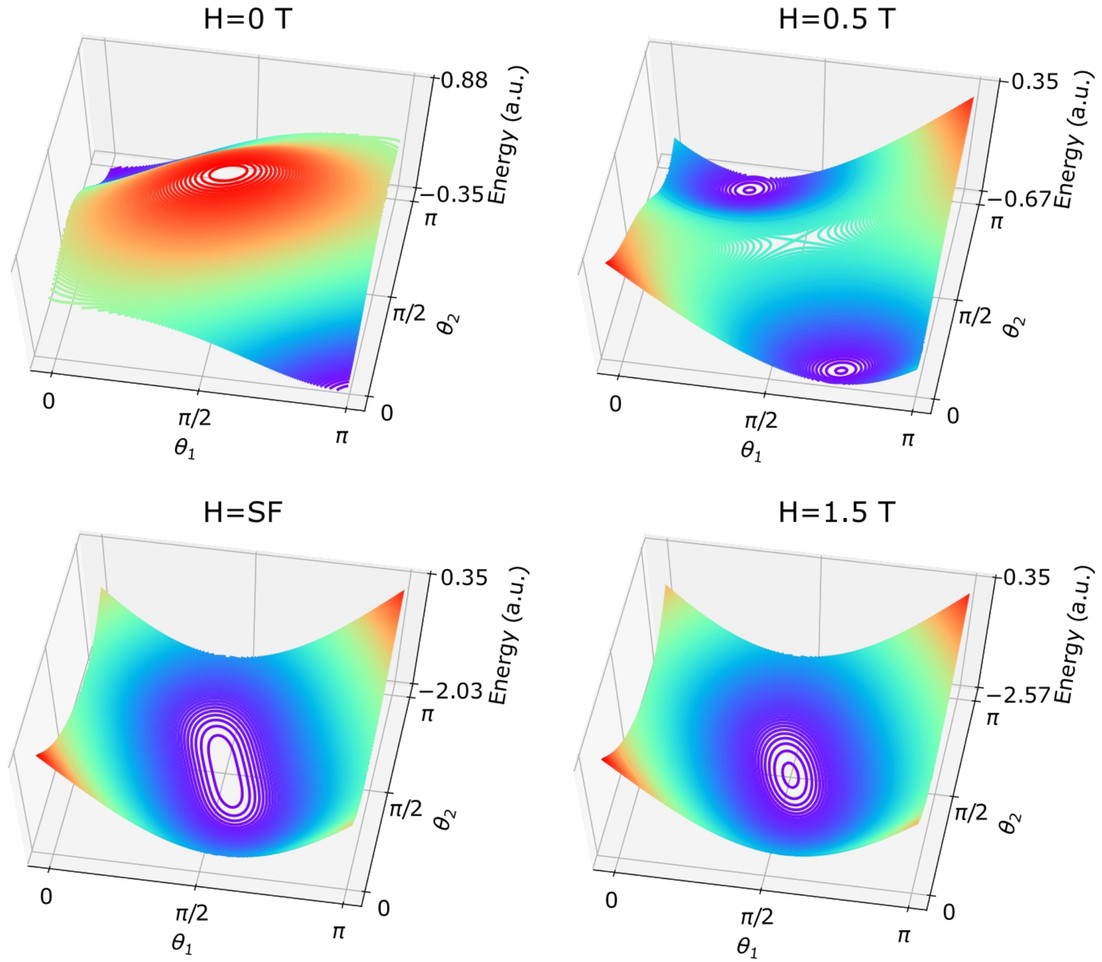
Current induced spin reversal by SOT

Synthetic Antiferromagnet model system

Electrical switching with SO Torque

facilitate switching by reducing anisotropy energy barrier

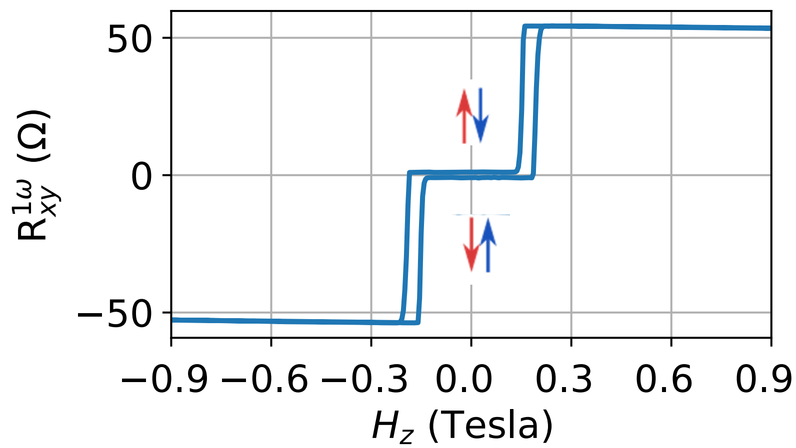




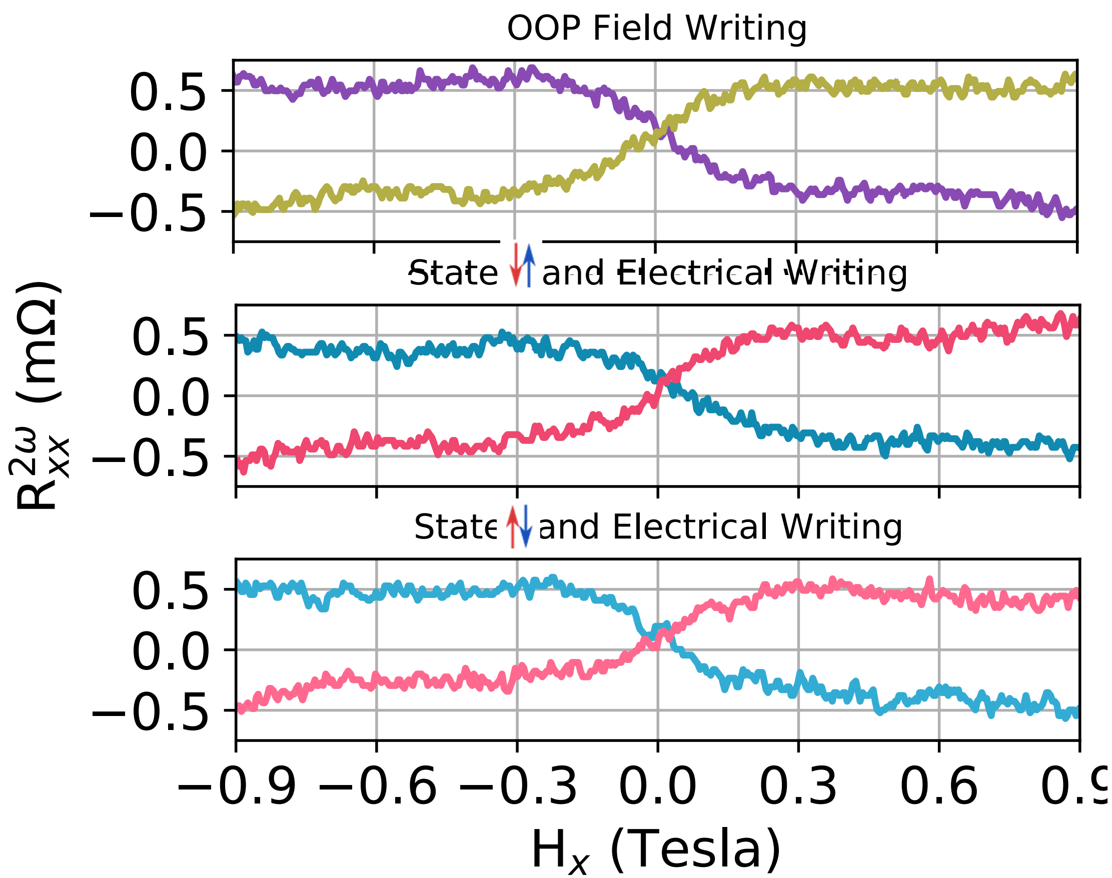
Synthetic Antiferromagnet model system

Electrical switching with SO Torque

Initializing the AF state with perp. field

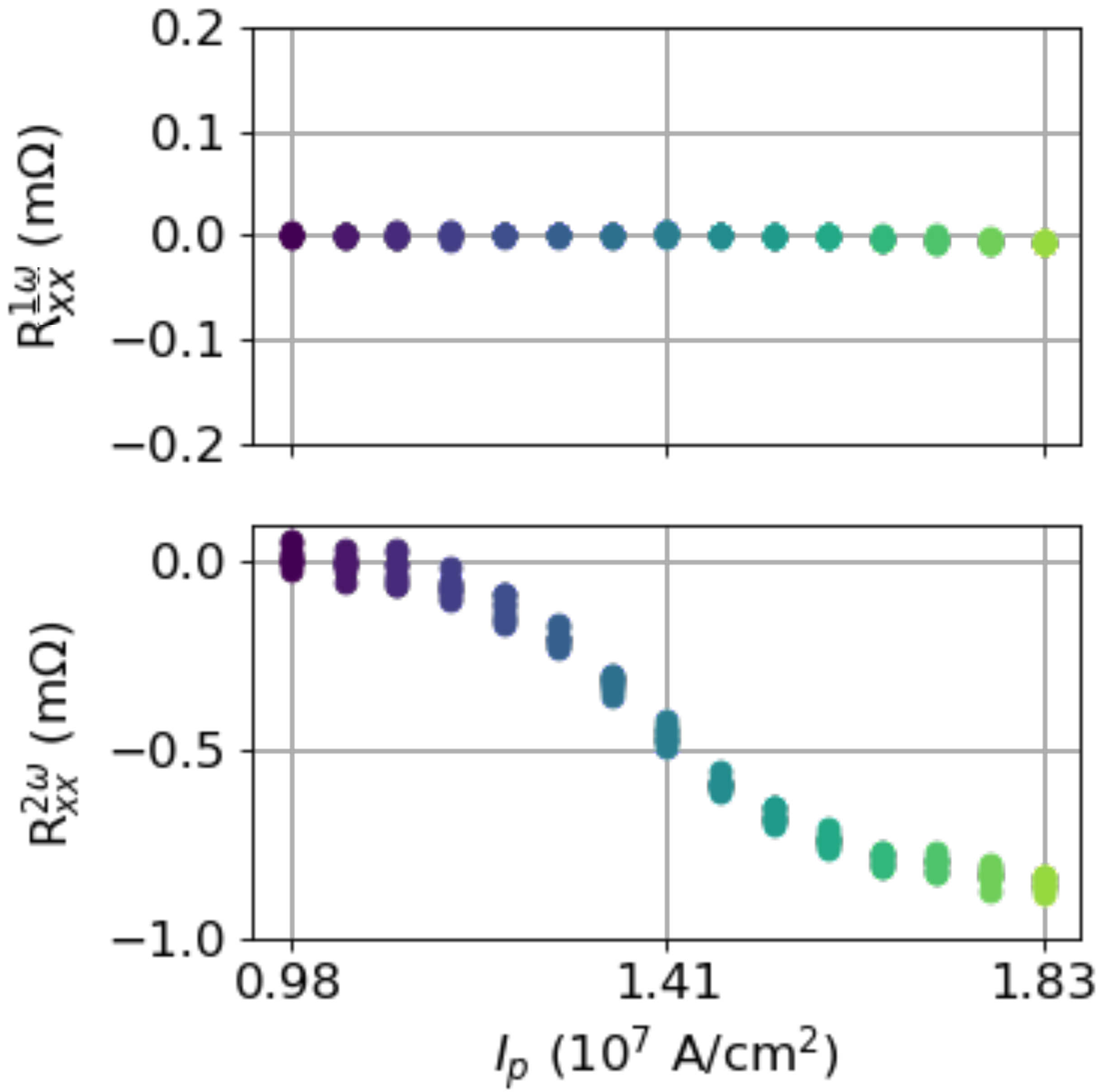


Nonlinear (2nd order) MR



Electrical writing by current pulses $\pm Ip$

Multilevel switching



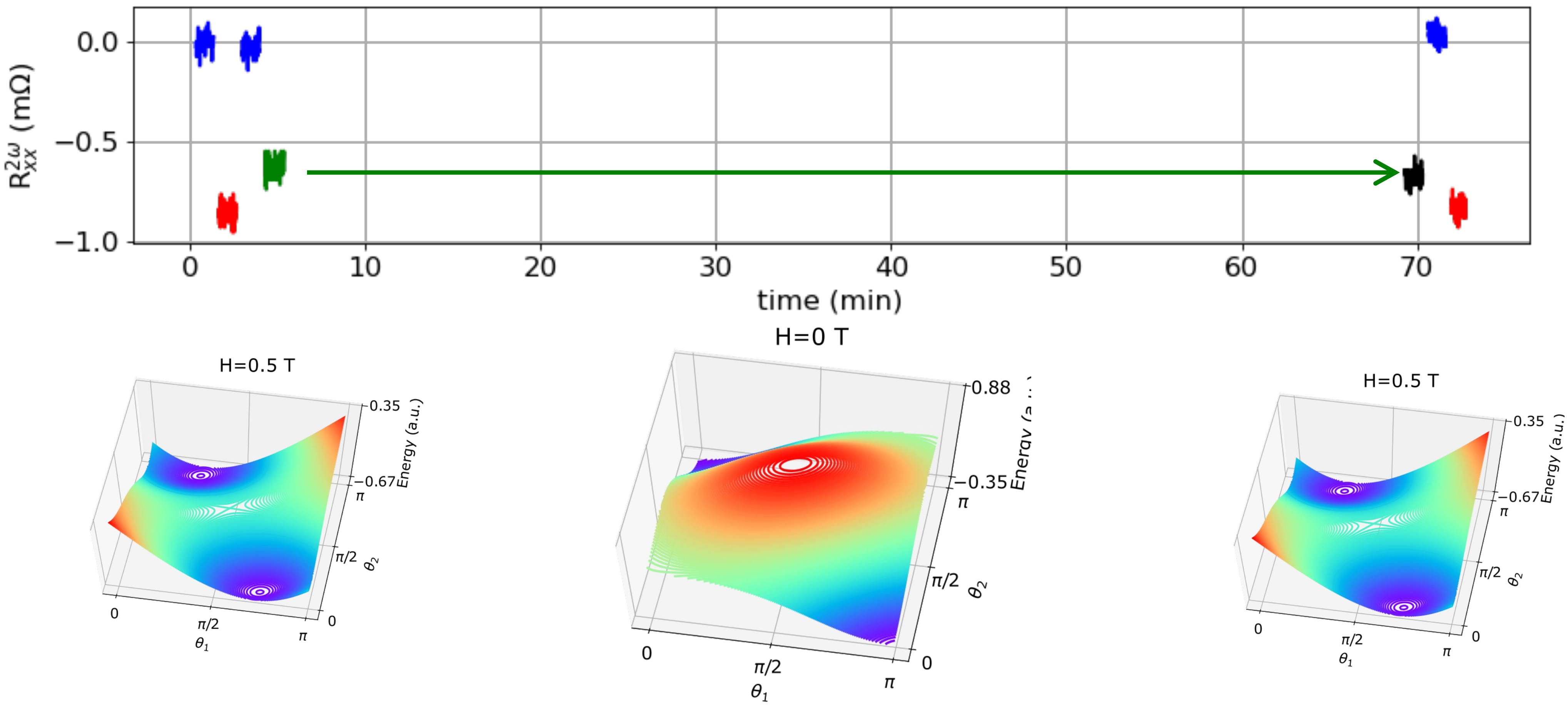
Nonvolatile Multilevel switching

Long retention times (nonvolatile)

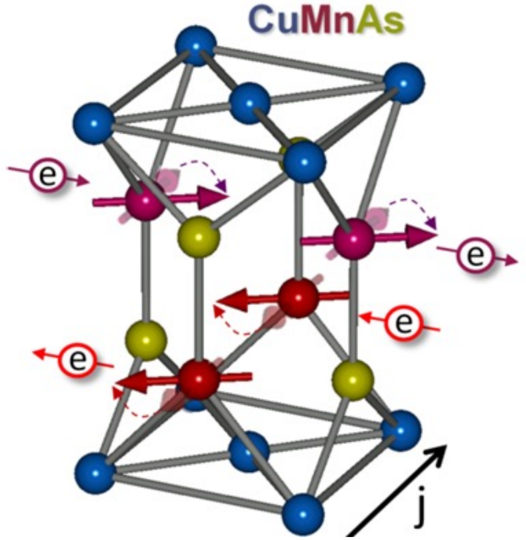
reading and writing at reduced barrier height

nonvolatile storage with full anisotropy barrier

reading and writing at reduced barrier height

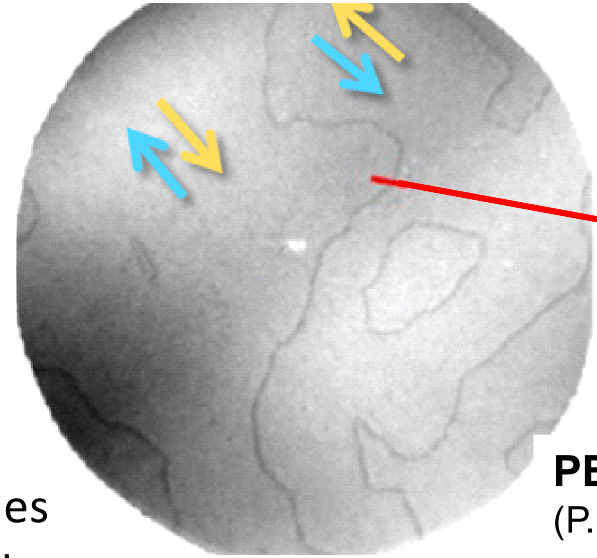


SOT switching and detection of 180° spin reversal in CuMnAs

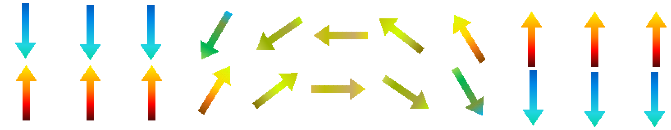


broken T and P symmetries
and combined PT symmetry

Uniaxial CuMnAs

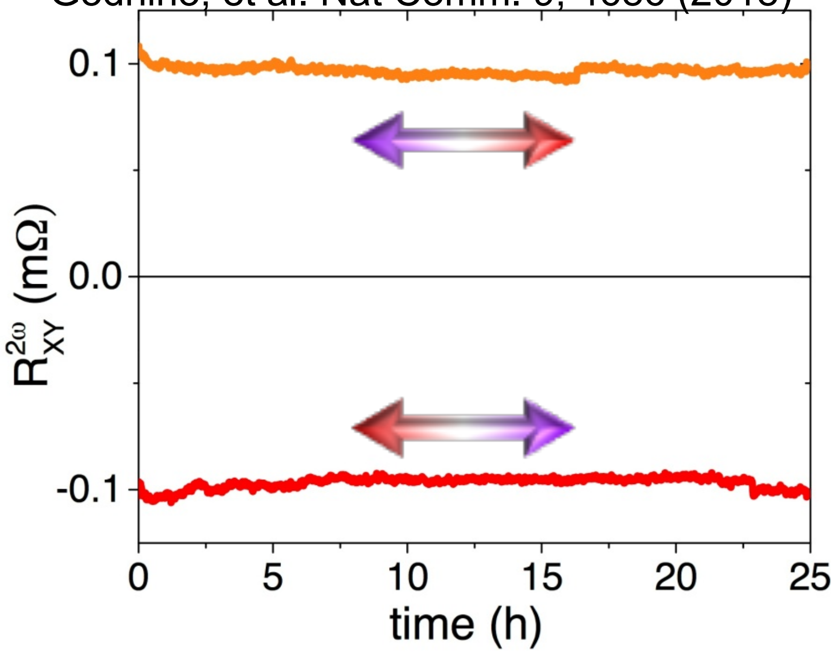


Magnetic domain walls



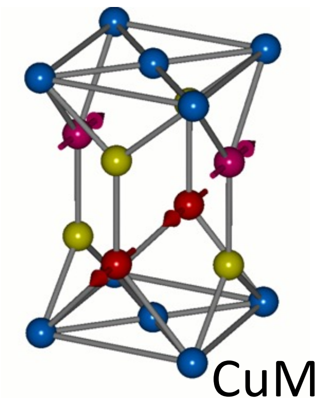
PEEM – XMLD
(P. Wadley et al.)

Godhino, et al. Nat Comm. 9, 4686 (2018)

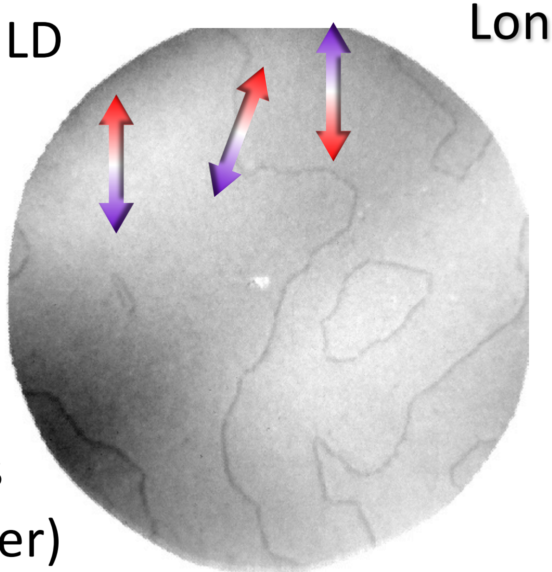


AF with uniaxial anisotropy: 180° Néel magnetic DWs

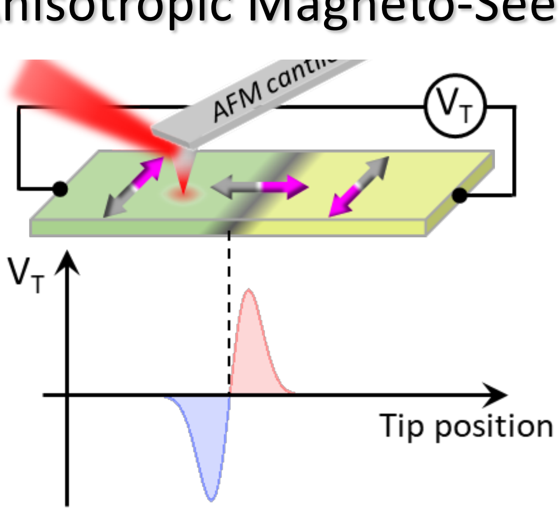
PEEM XMLD



CuMnAs
(thin layer)



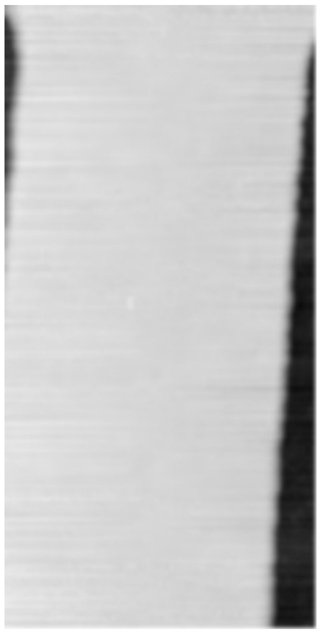
Longitudinal Anisotropic Magneto-Seebeck Effect



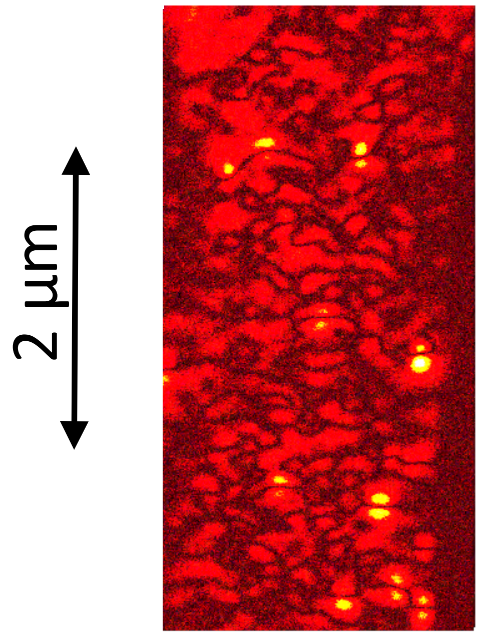
Near-field Nanoscopy:
AFM + thermal voltage

thin 20nm CuMnAs

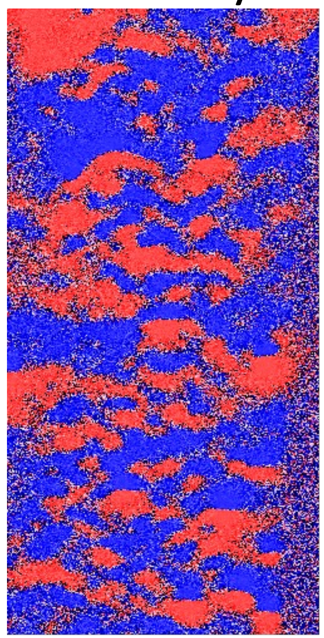
AFM (~1nm res.)
(2 µm wide stripe)



Thermovoltage
Magnitude



Thermovoltage
Polarity



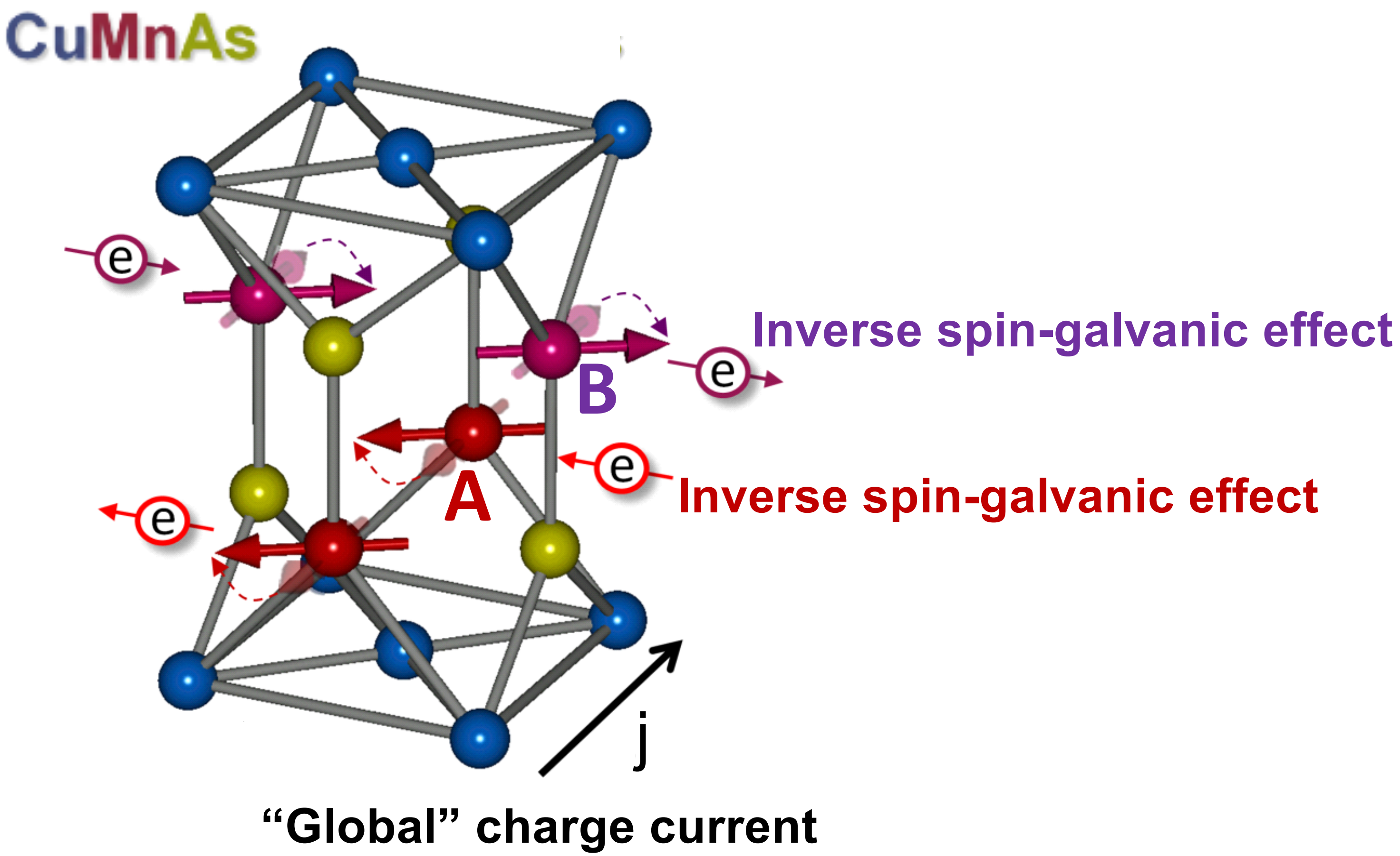
T. Janda et al, Phys. Rev. Materials 4, 094413 (2020)

Antiferromagnet

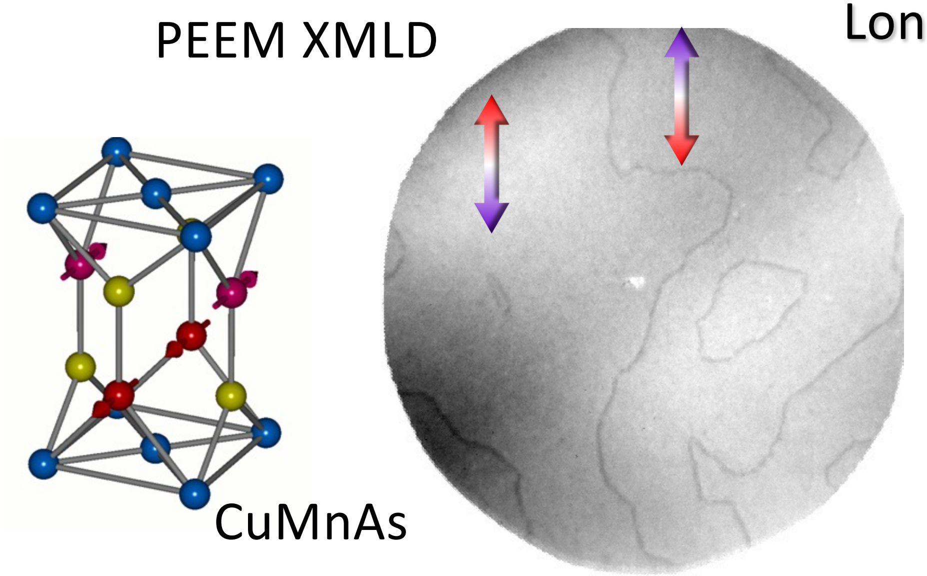
‘Locally’ broken inversion symmetry

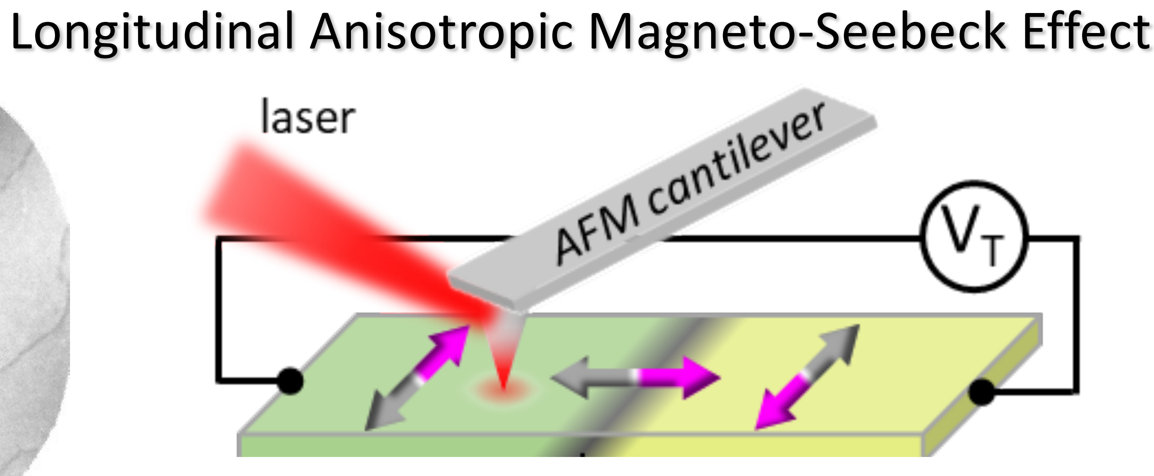
→ **Electrical excitation of ultrafast dynamics of Antiferromagents**

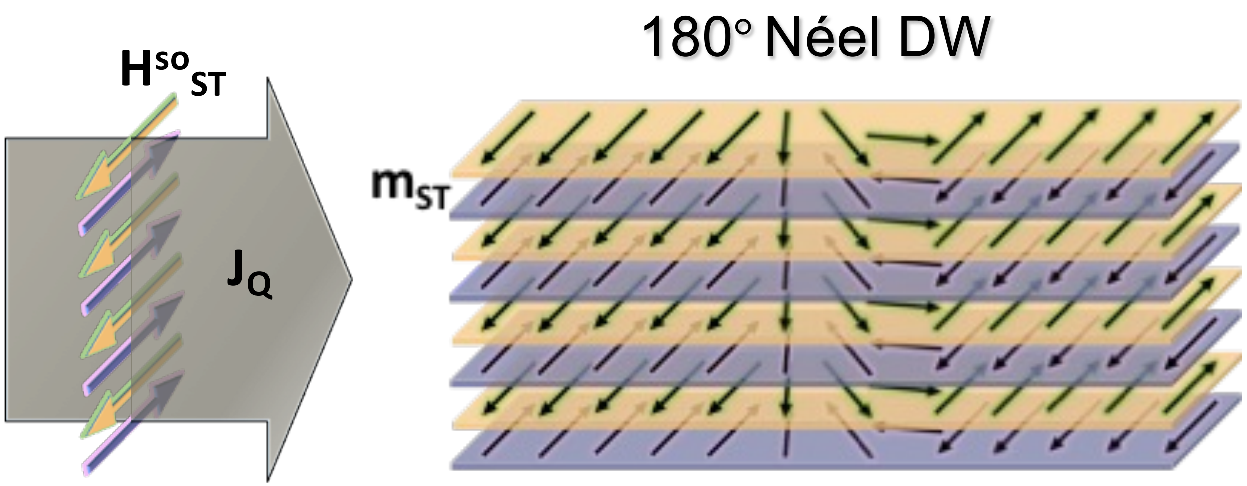
J. Železný, et al., Phys. Rev. Lett. 113, 157201 (2014).
P. Wadley, et al., Science 351, 6273, 587 (2016).



AF with uniaxial anisotropy: 180° Néel magnetic DWs

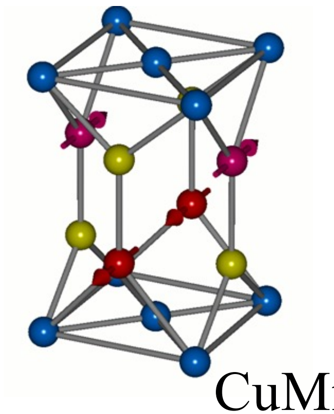


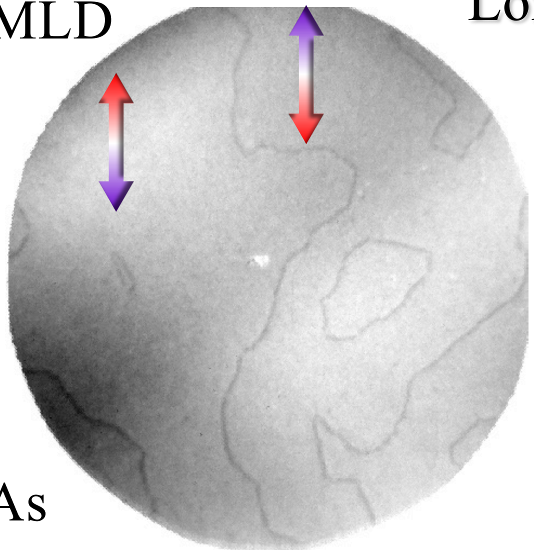




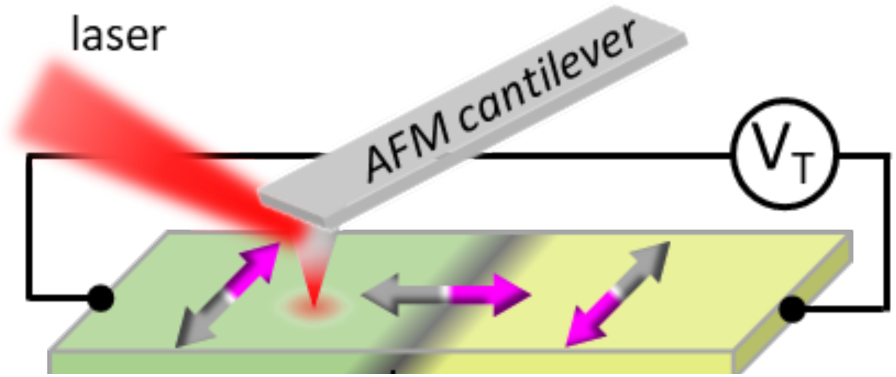
180° Néel magnetic DWs

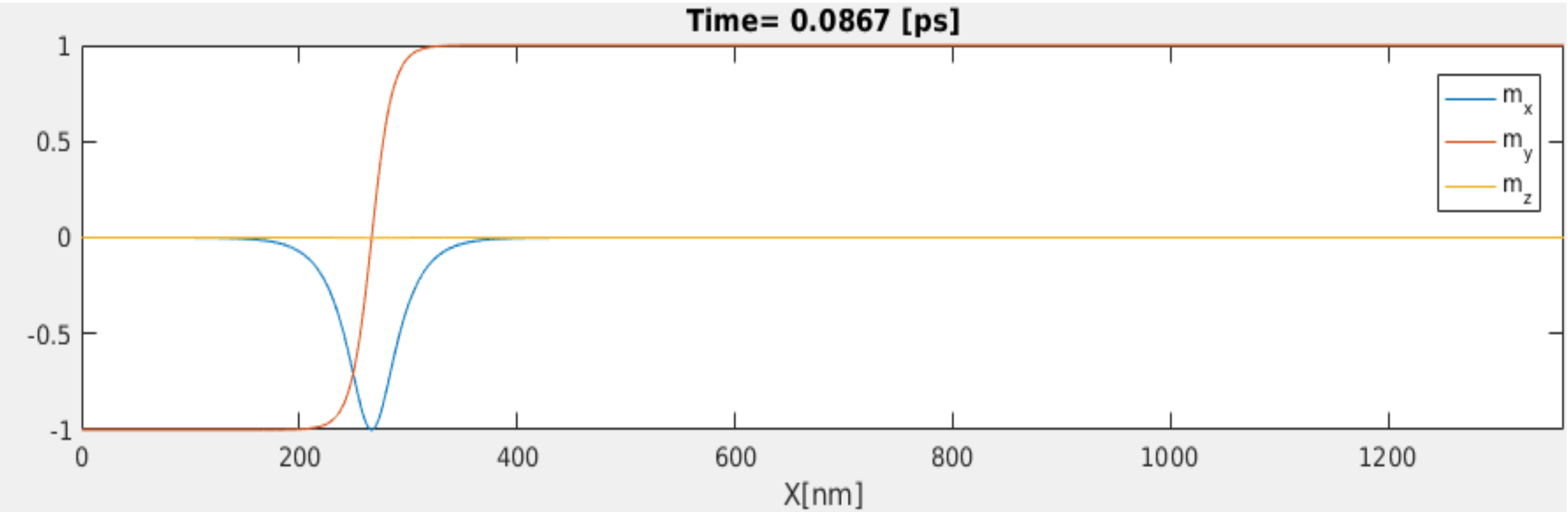
PEEM XMLD





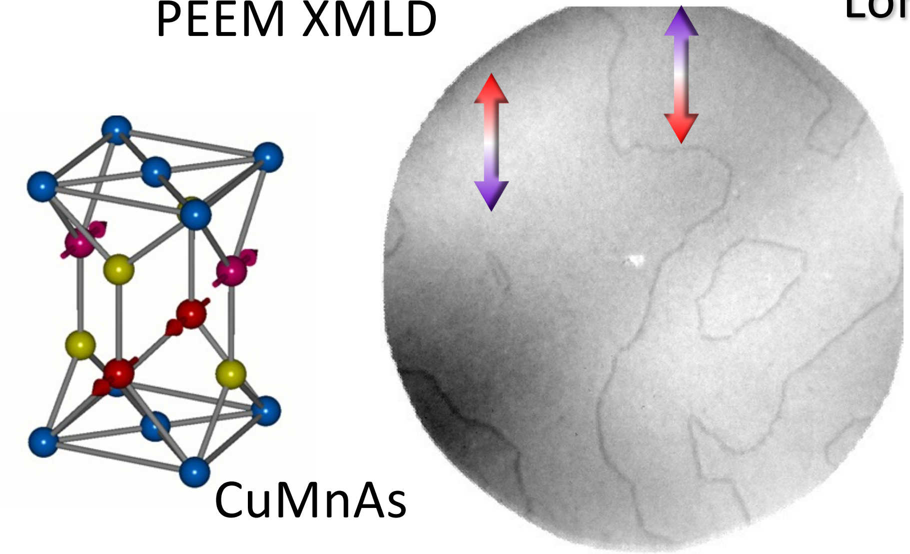
Longitudinal Anisotropic Magneto-Seebeck Effect



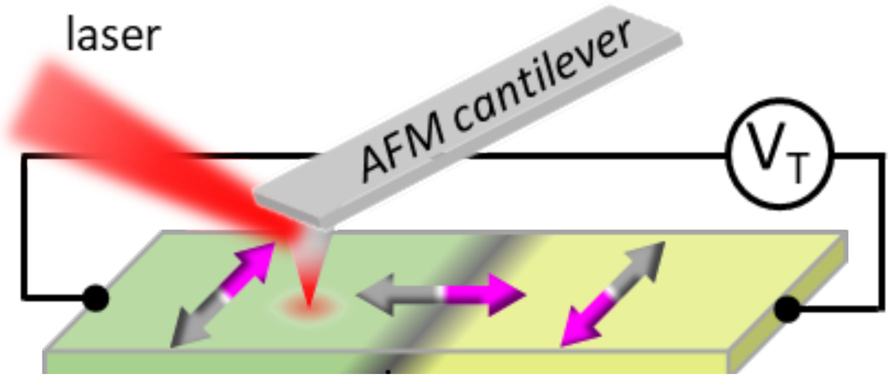


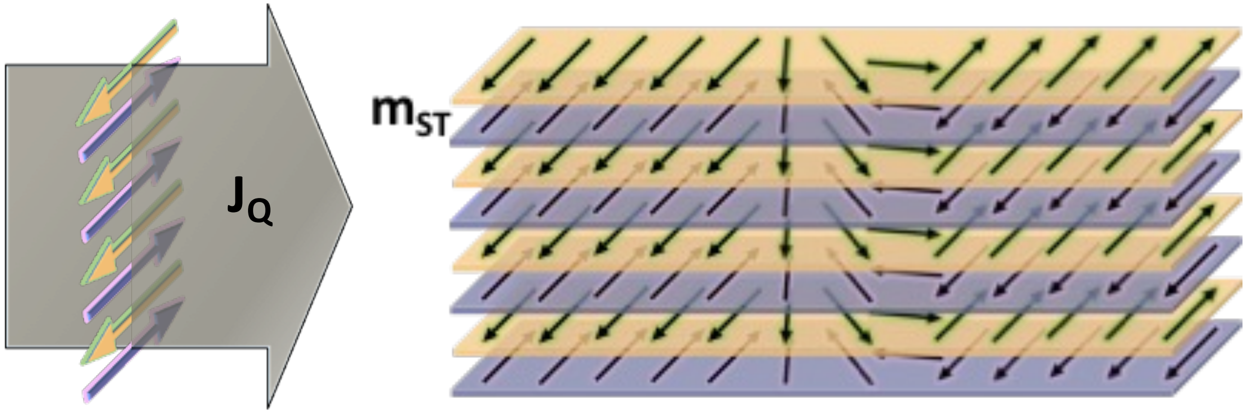
AF with uniaxial anisotropy: 180° Néel magnetic DWs

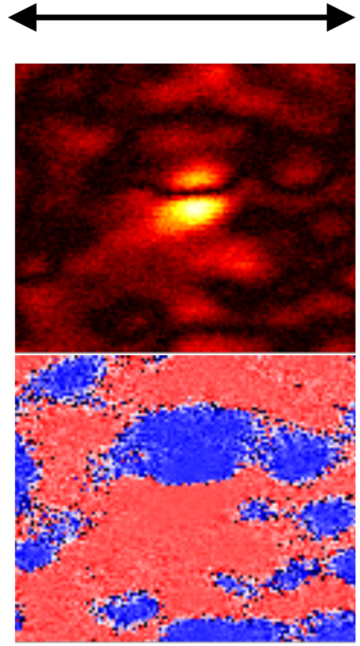
PEEM XMLD



Longitudinal Anisotropic Magneto-Seebeck Effect

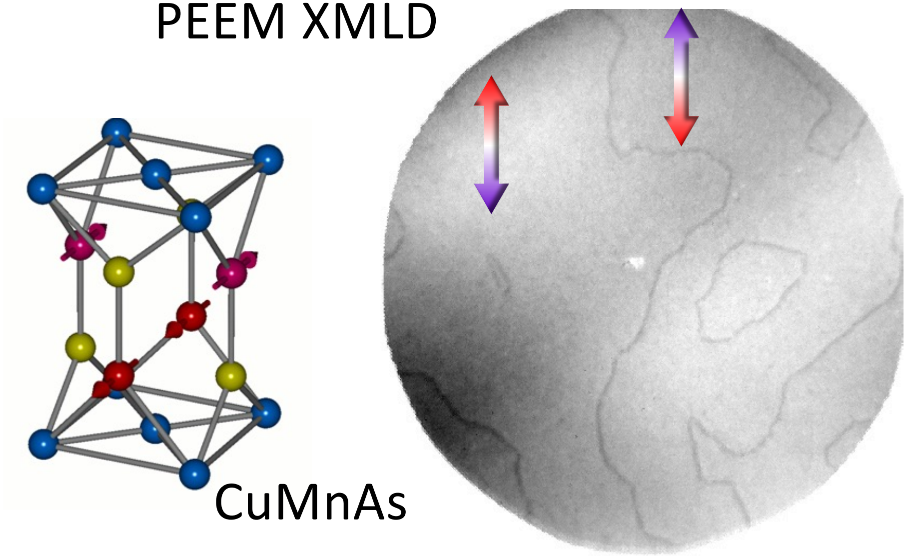


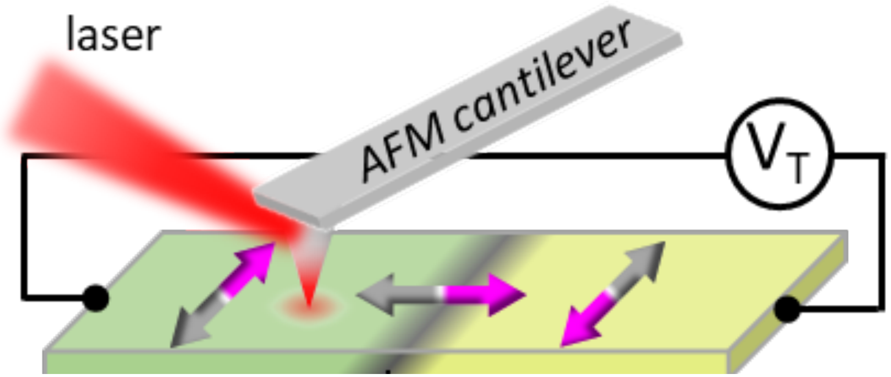


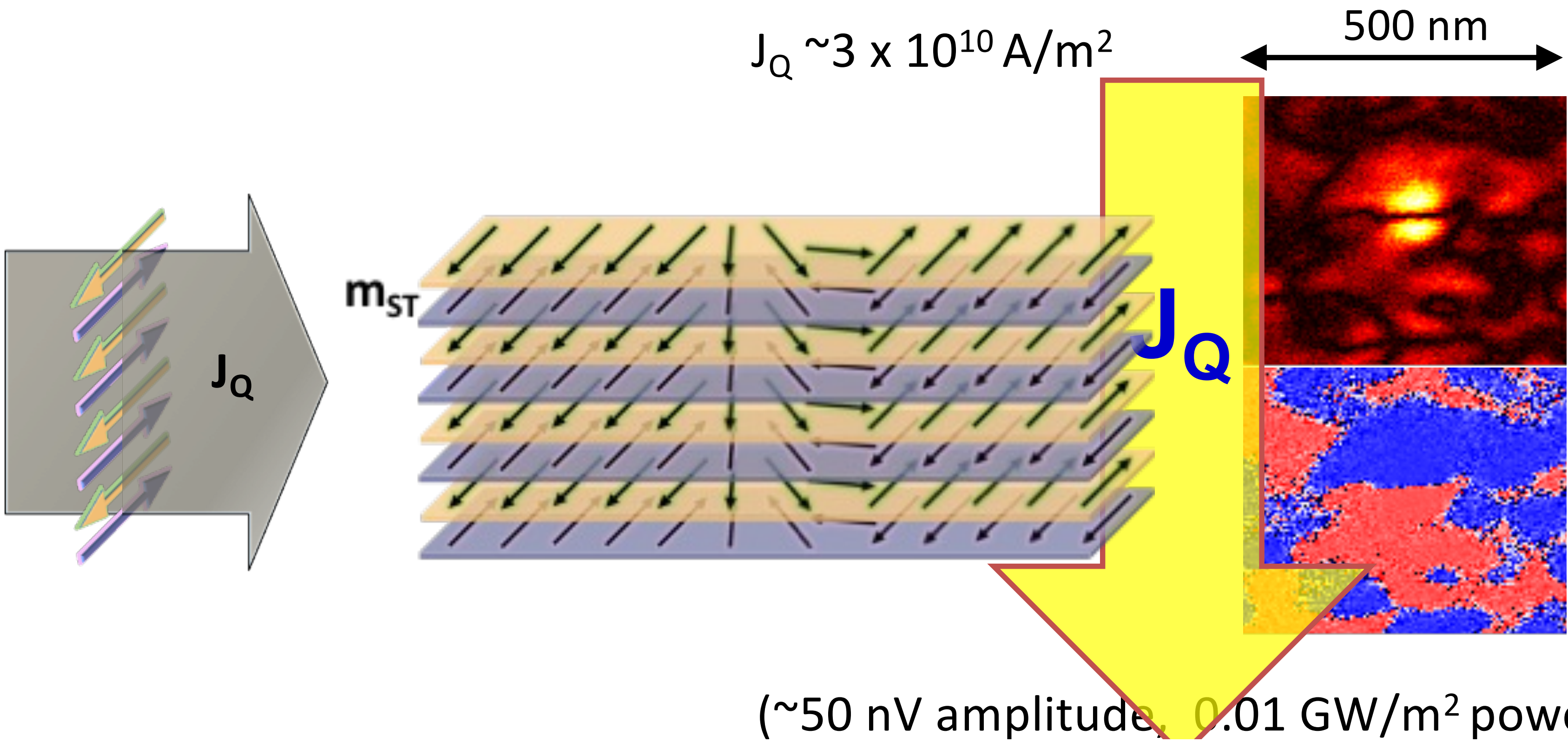


(~50 nV amplitude, 0.01 GW/m^2 power density)

AF with uniaxial anisotropy: 180° Néel magnetic DWs

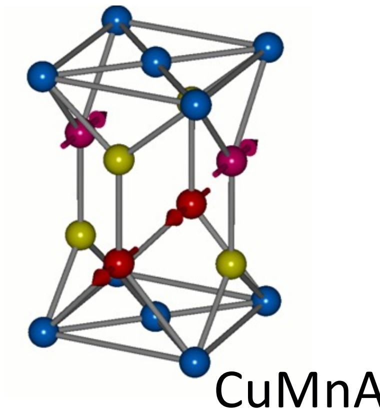


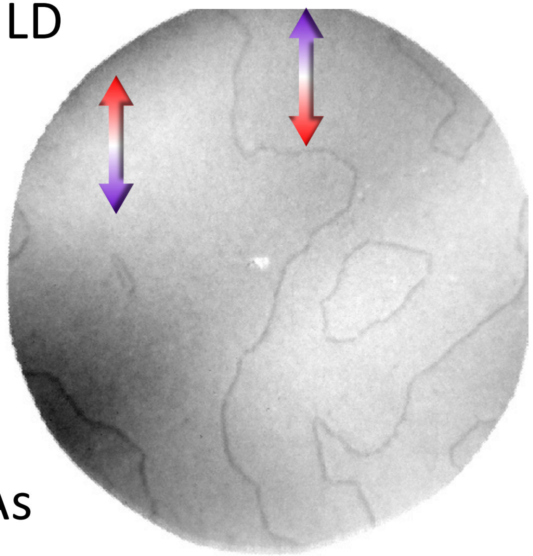


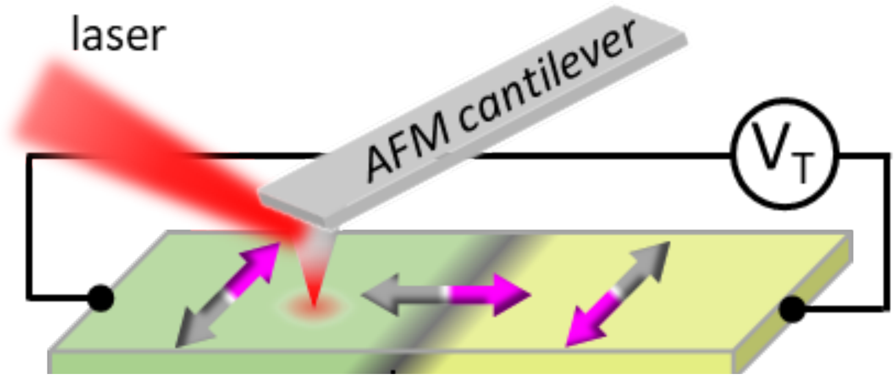


(~50 nV amplitude, 0.01 GW/m² power density)

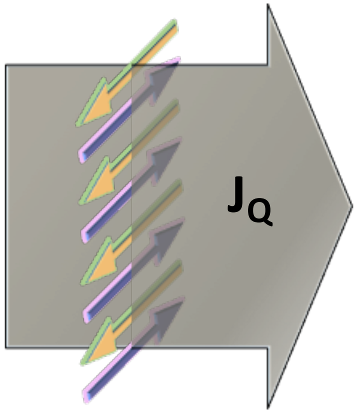
AF with uniaxial anisotropy: 180° Néel magnetic DWs

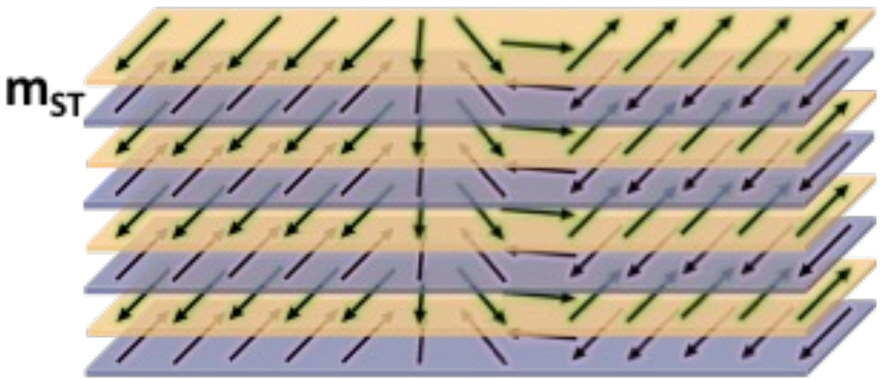


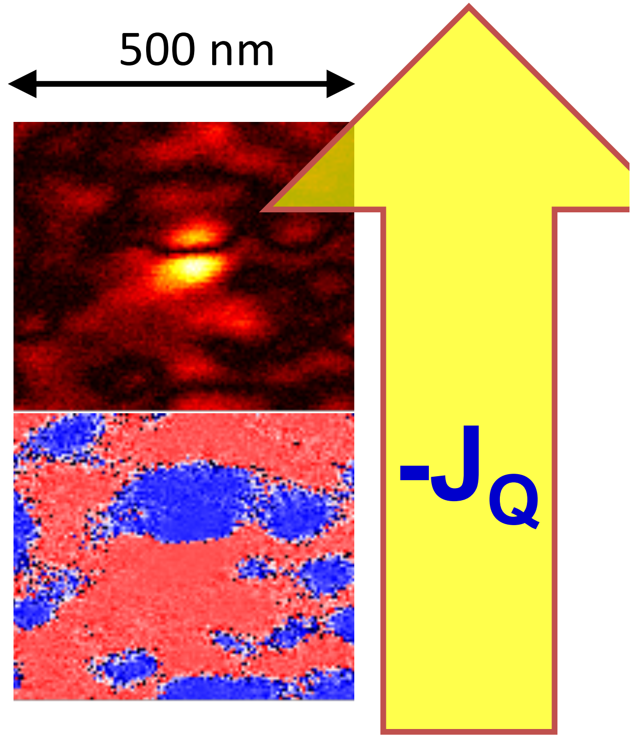




J_Q ~3 x 10^{10} A/m^2







(~50 nV amplitude, 0.01 GW/m^2 power density)

Summary

SPINTRONICS with ANTIFERROMAGNETS:

- electrical **180° spin reversal switching** and its **detection** via spin-orbit fields in synthetic + real antiferromagnets with **PT symmetry** and **uniaxial magn. anisotropy**

- writing and reading of stable **nonvolatile multidomain states**

- (potentially ultrafast) 180° switching by SOT-driven **domain wall motion**

- scanning high resolution **magneto-Seebeck microscopy** using a scattering near field microscope

THANK YOU!