Detection of antiferromagnetic states and spin-orbit torque switching in antiferromagnetic films


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[3] *Physikalisch-Technische Bundesanstalt, Berlin, Germany*

[4] *University of Nottinghgam, Germany*

[5] *University of Regensburg, Germany*

ANTIFERROMAGNETS

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

Radiation-hard
Spin not charge based
(as ferromagnets)

Non-volatile
Magnetic order
(as ferromagnets)

MERITS

Insensitive & invisible to magnetic fields

No stray field cross-talks
No net moment

Insulators, semiconductors, semimetals, metals, …
Ferromagnets mostly metals

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semimetals, metals, …
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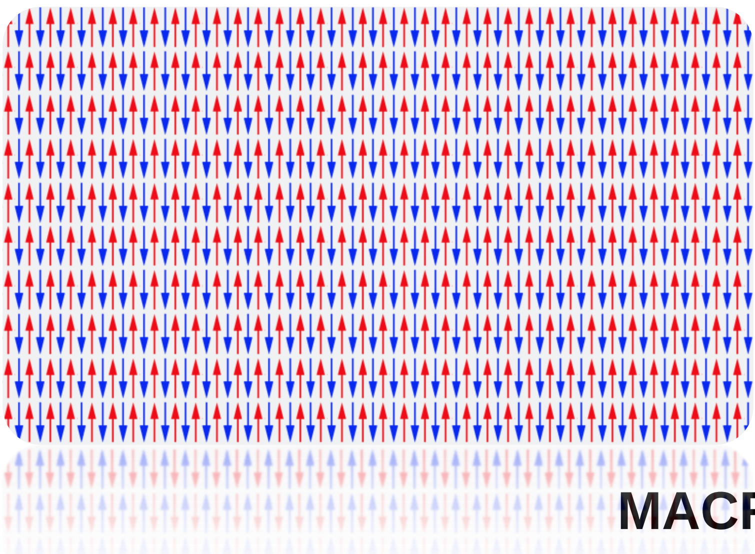
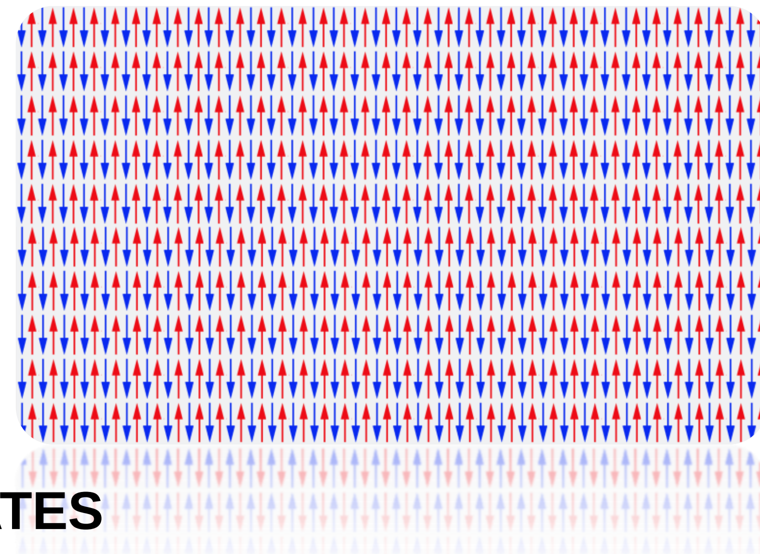
Anisotropic Magnetoresistance





Electrical

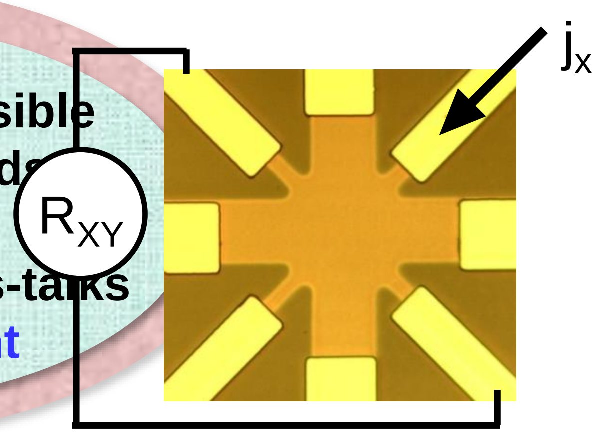
DETECTION of MACROSCOPIC STATES

via Magneto-transport measurements

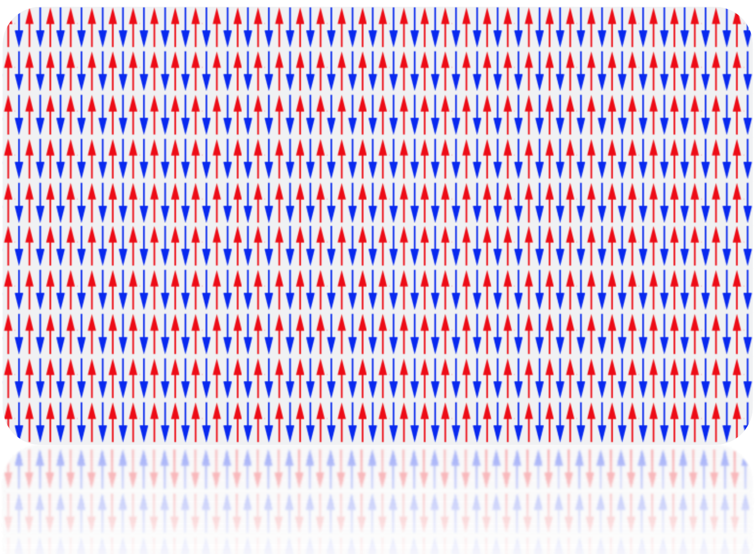
Insensitive & invisible to magnetic fields

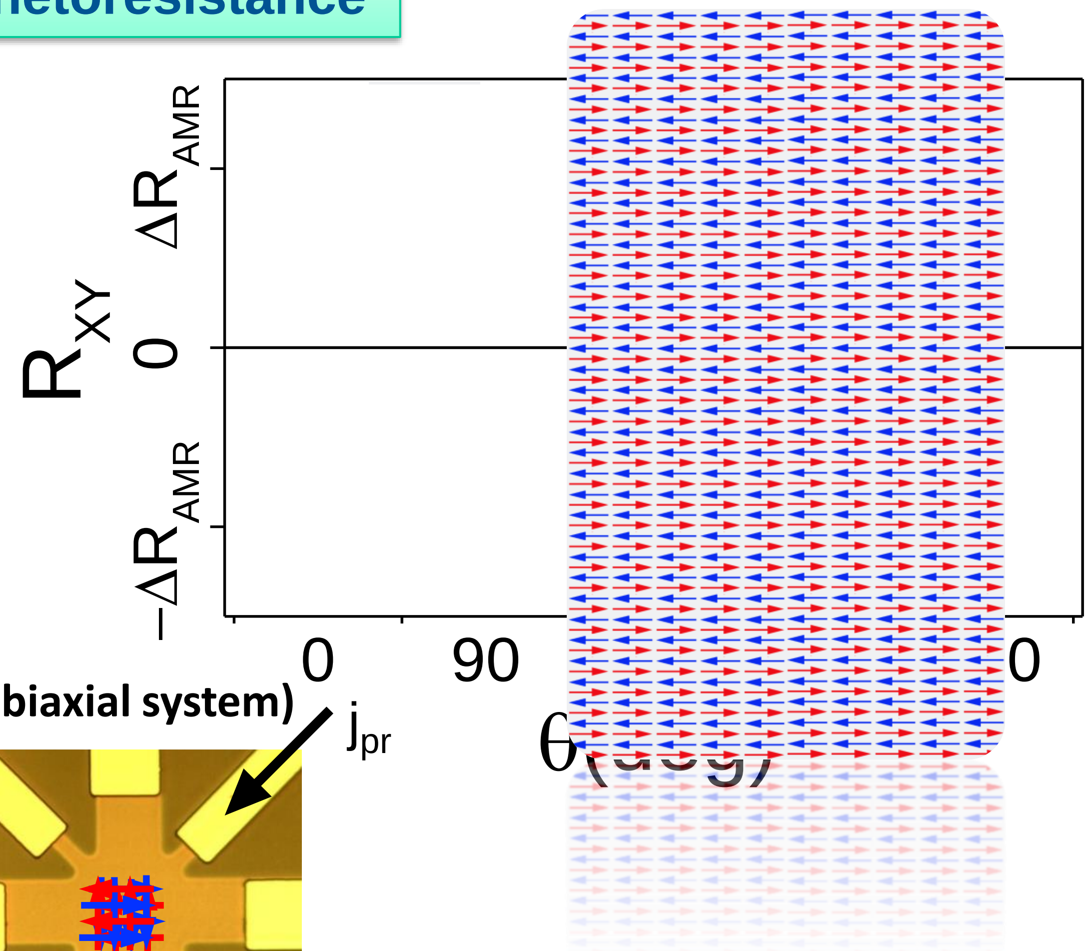
No stray field cross-talks

No net moment

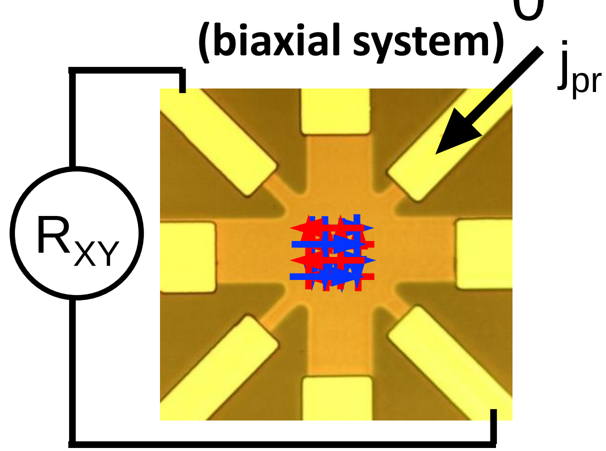


Anisotropic Magnetoresistance



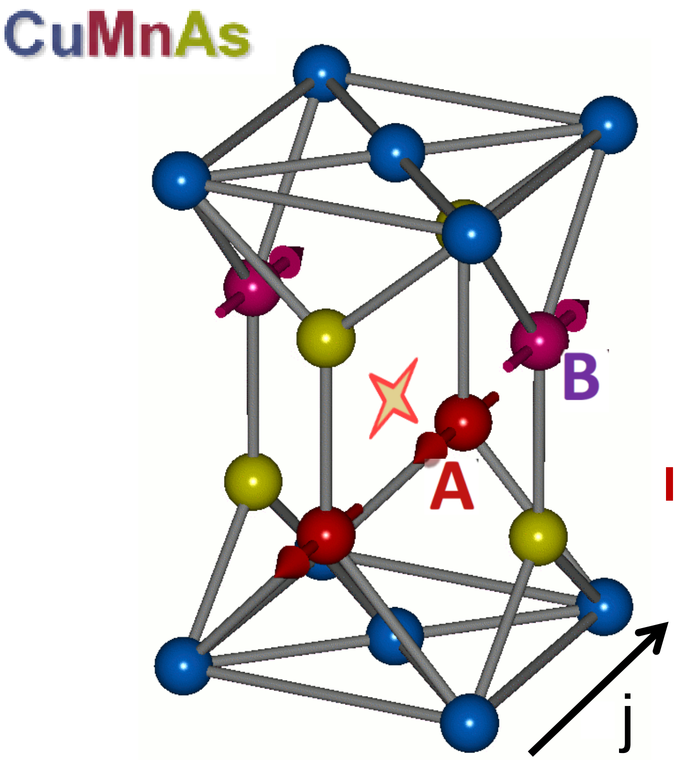


transverse AMR
"planar Hall effect"



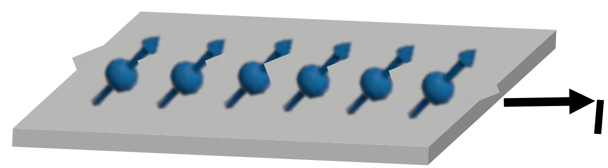
Antiferromagnet

‘Locally’ broken inversion symmetry

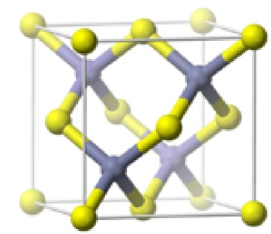


charge current

inverse spin-galvanic Effect
(Edelstein Effect)



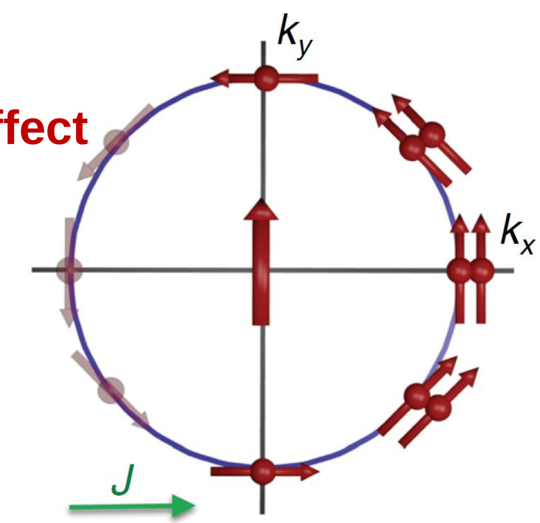
$\hat{H} = c\vec{p}\cdot\vec{\sigma}$



Inversion asymmetry

Inverse spin-galvanic effect

Inverse spin-galvanic effect



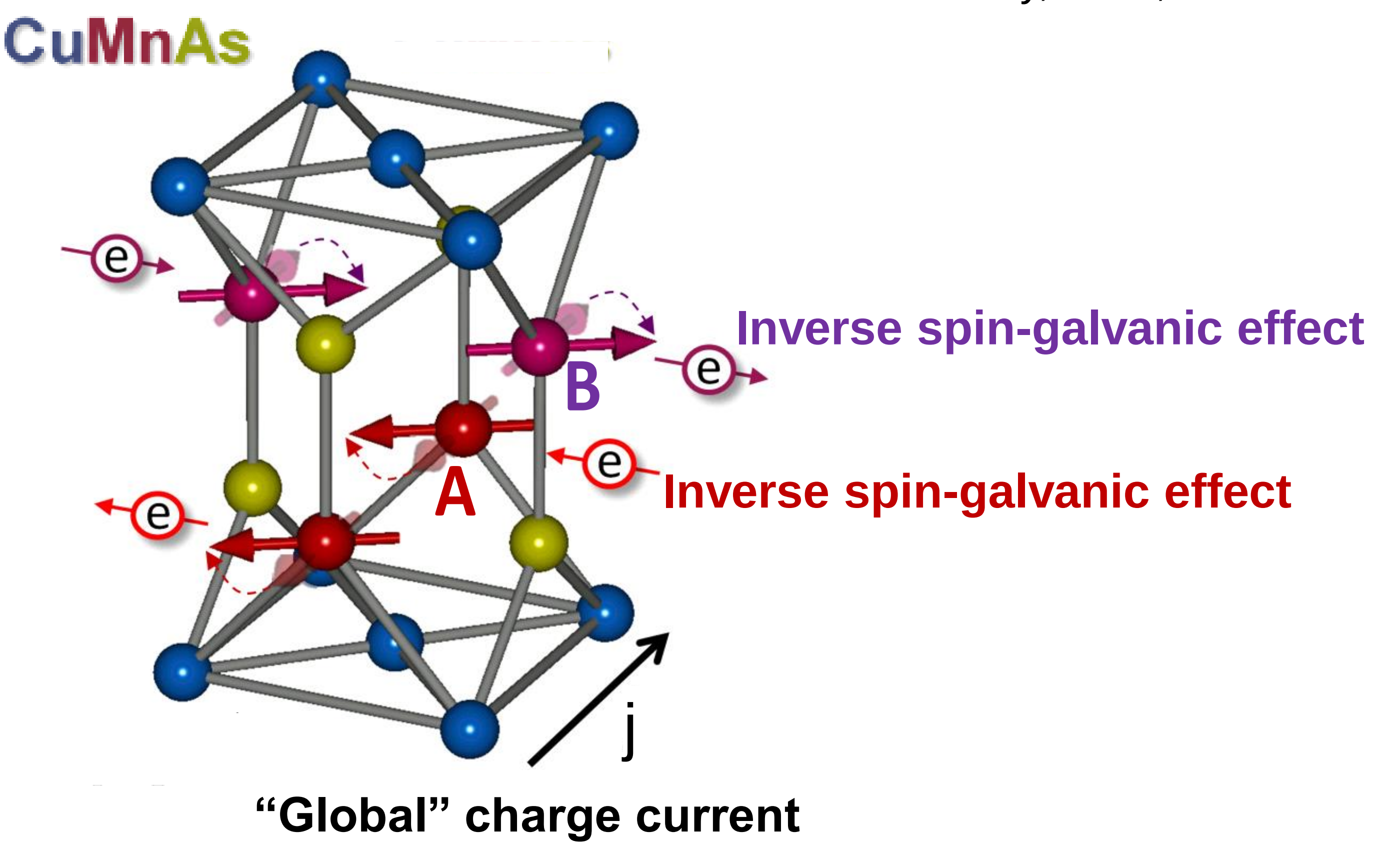
(intuitive picture for iSGE)

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).

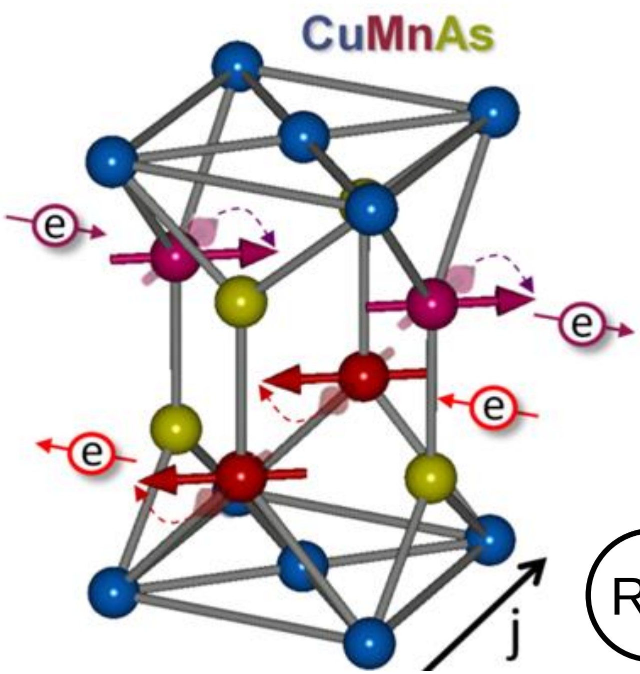


ANTIFERROMAGNETS

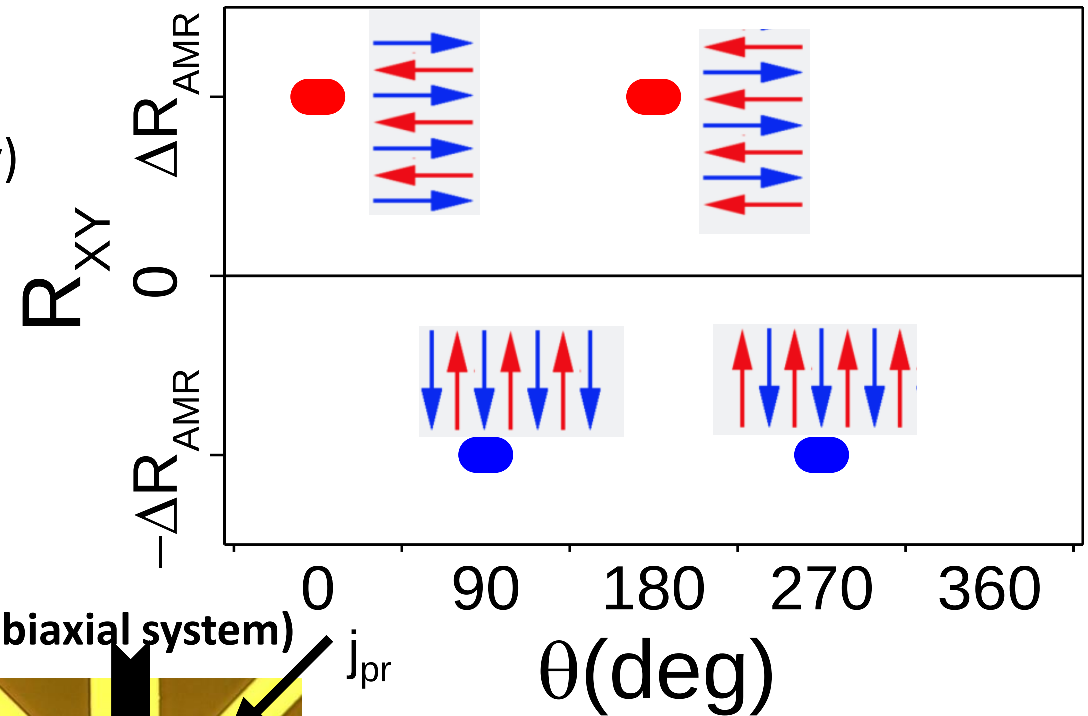
Electrical Writing
by Spin-Orbit Torque

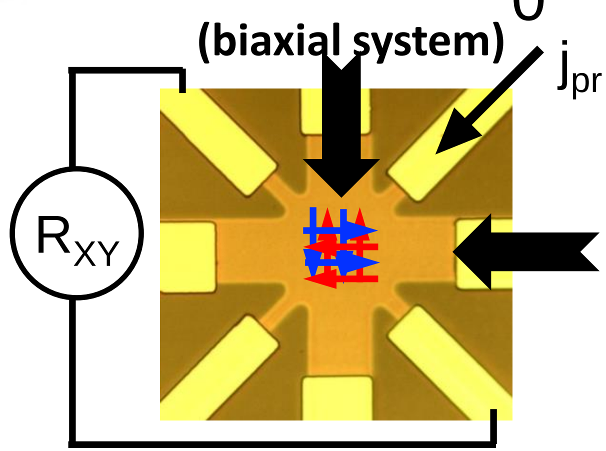
Anisotropic Magnetoresistance

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



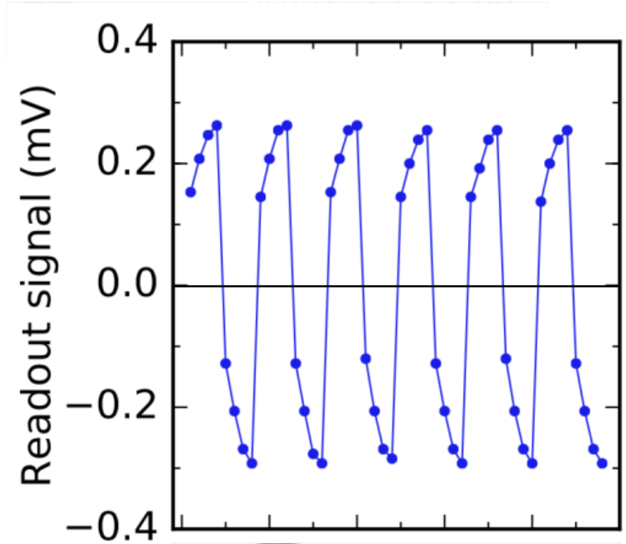
THEORY: J. Železný, et al., PRL 113, 157201 (2014)





Electrical PEEM XMLD: X-ray Magnetic Linear Dichroism (AMR)

→ **Electrical pulse experiment in Biaxial CuMnAs**



Small
ti-magnetic domain states

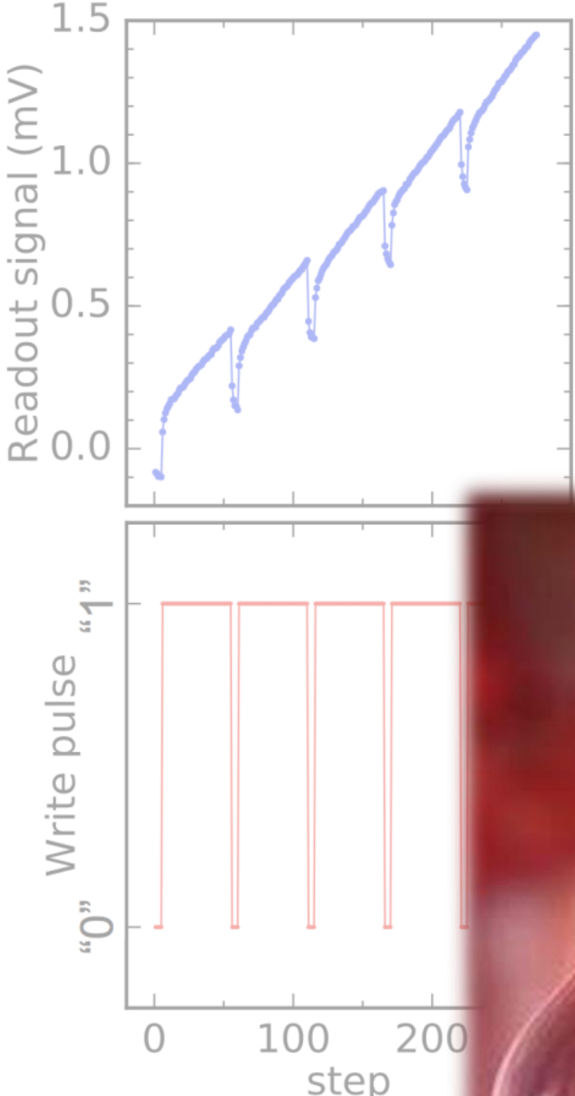
→ **requires large scale equipment**

Synchrotron Light sources

EXPERIMENT: K. Olejnik, et al., Nat. Comm. 8, 15434 (2017)

Biaxial Switching in CuMnAs

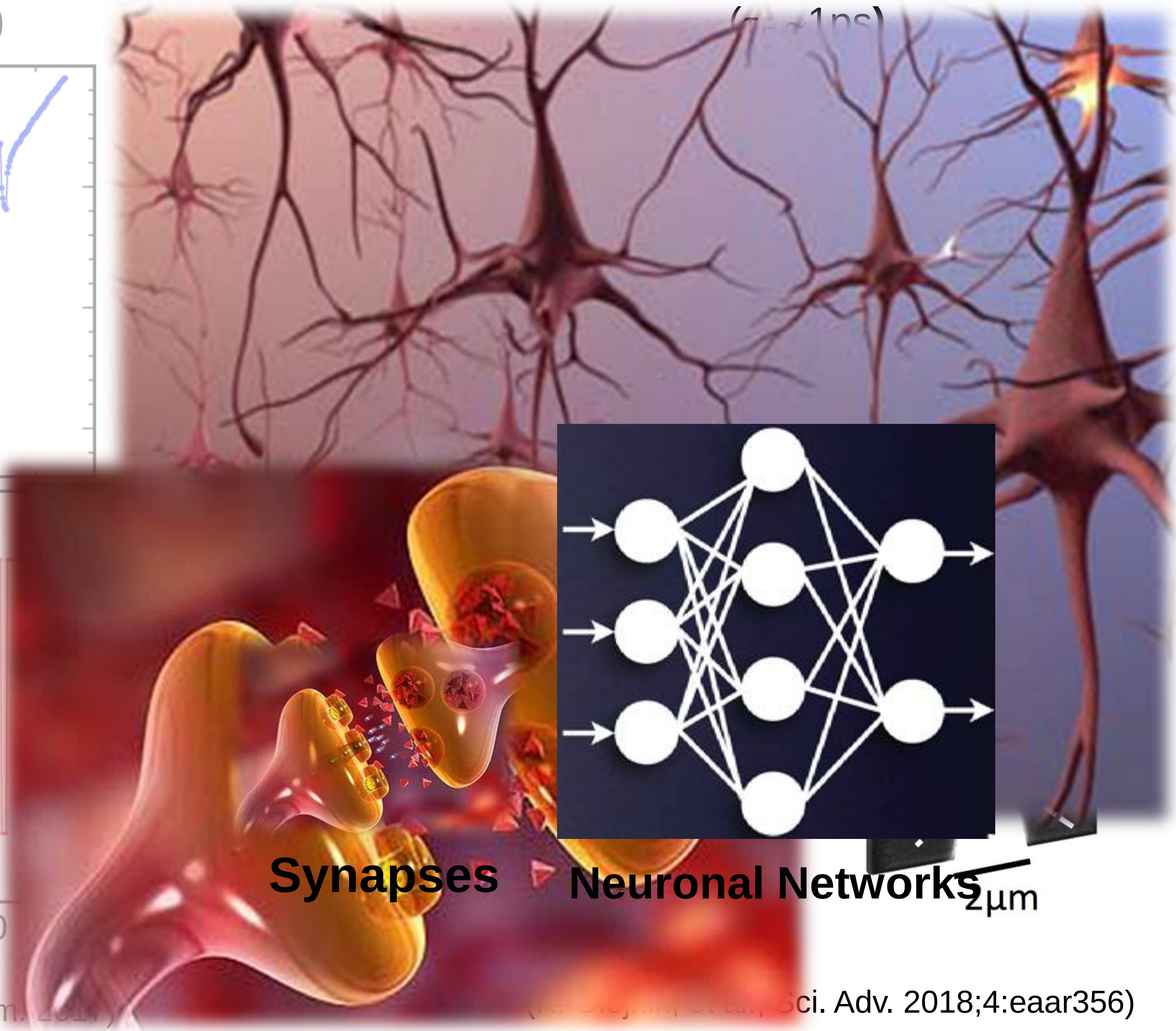
→ **Short electrical pulses**
(down to τ_P ~250ps)



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

Neuromorphic Computing

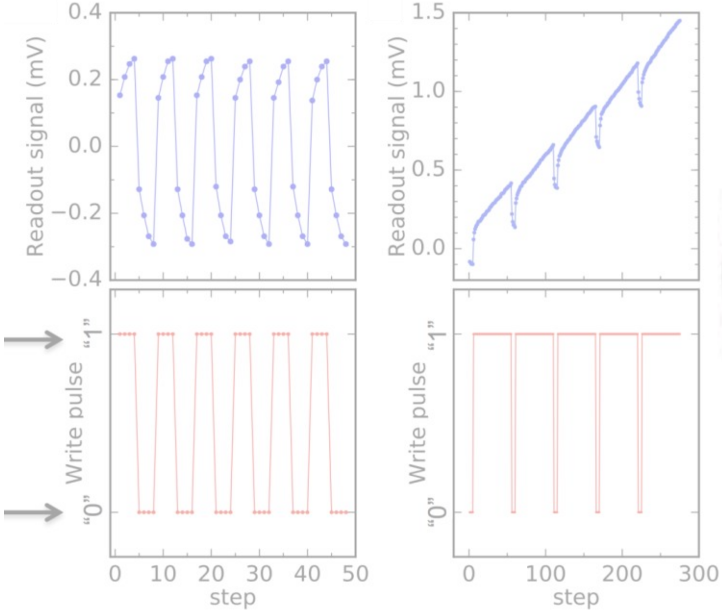
→ **Polarized THz Laser Pulses**



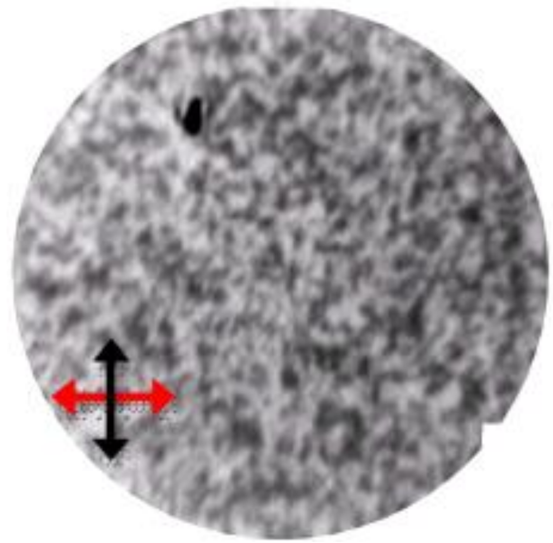
Sci. Adv. 2018;4:eaar356)

Biaxial Switching in CuMnAs

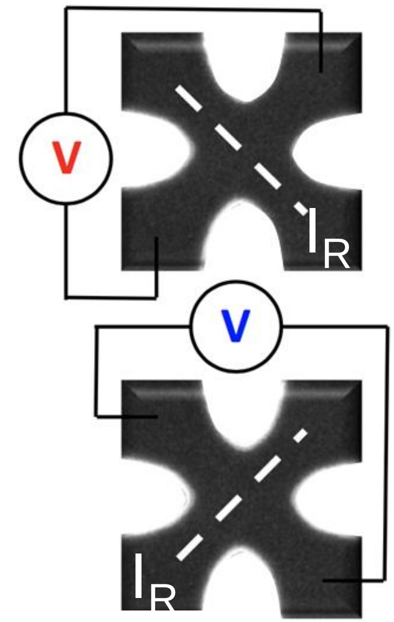
→ **Electrical pulses**
(down to τ_P ~250ps)

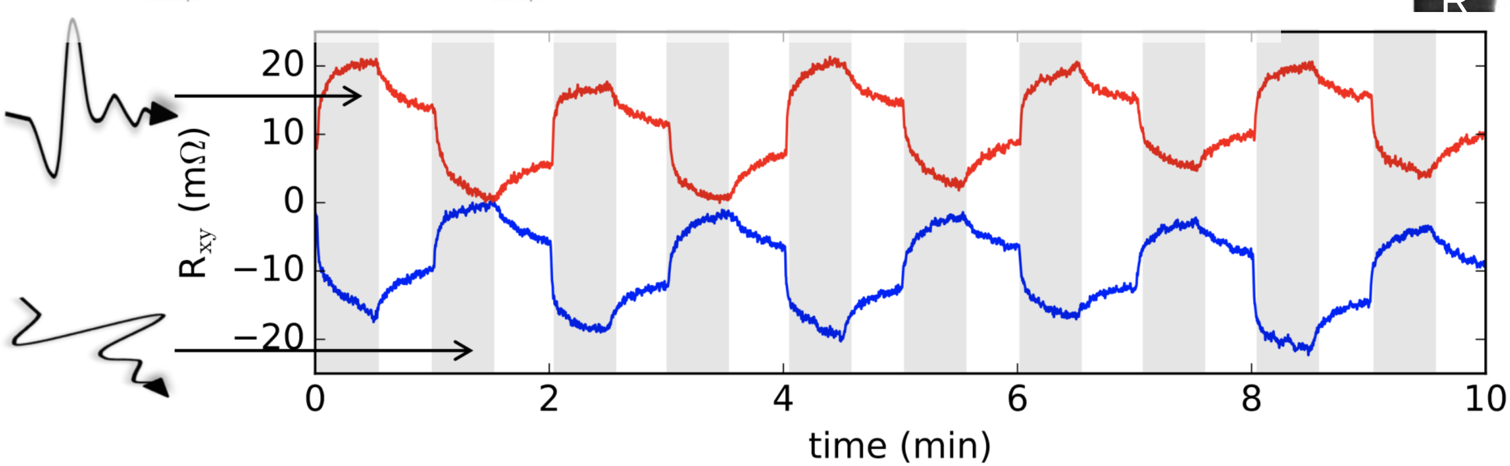


Biaxial CuMnAs



→ **Polarized THz Laser Pulses**
(τ_P ~1ps)

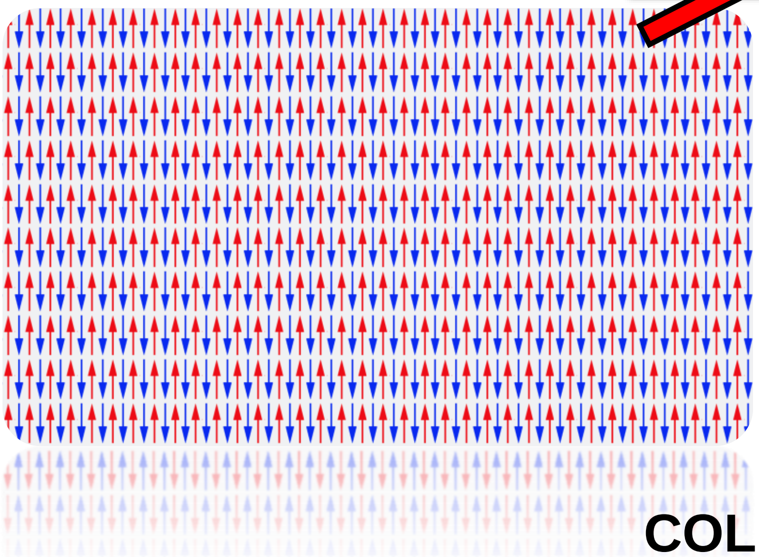




(K. Olejnik, et al., Sci. Adv. 2018;4:eaar3566)

Collinear antiferromagnetic states

~~Anisotropic Magnetoresistance linear response~~



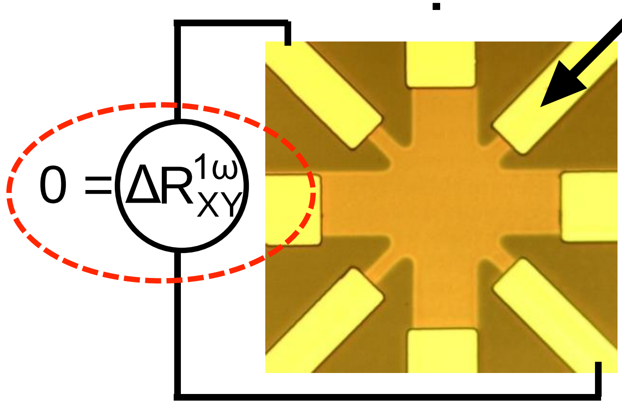
Electrical

DETECTION

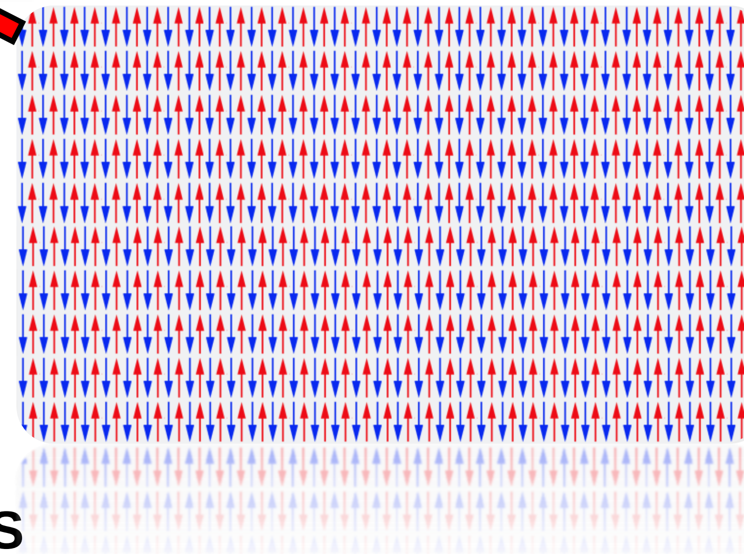
of

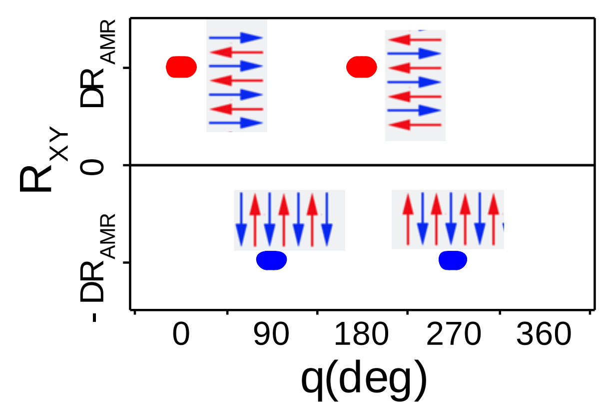
COLLINEAR STATES

?



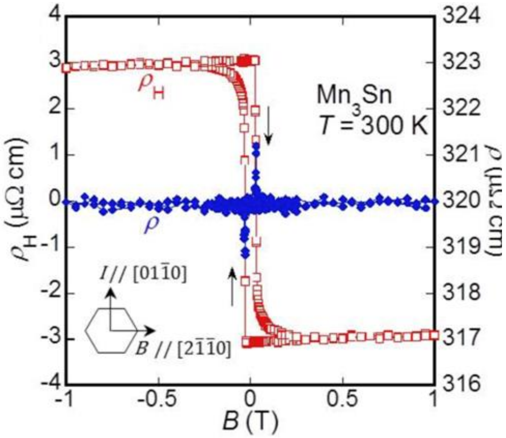
$j_x(\omega) = j_0 \sin(\omega t)$

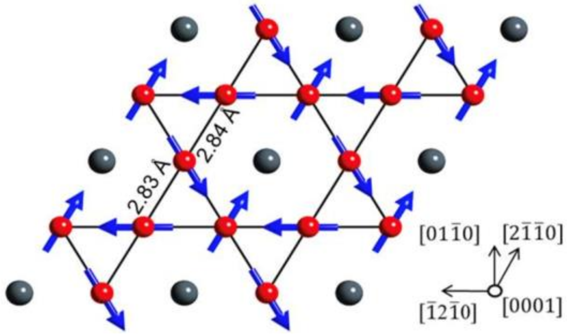


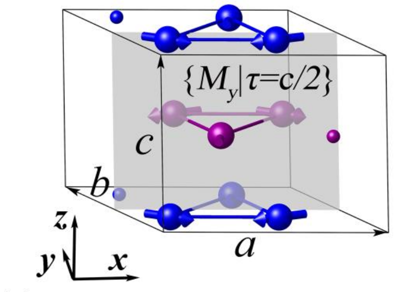


Anomalous Hall effect (AHE) in **non-collinear AFs**

that crystallize in ferromagn. symmetry groups, able to develop 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)
…

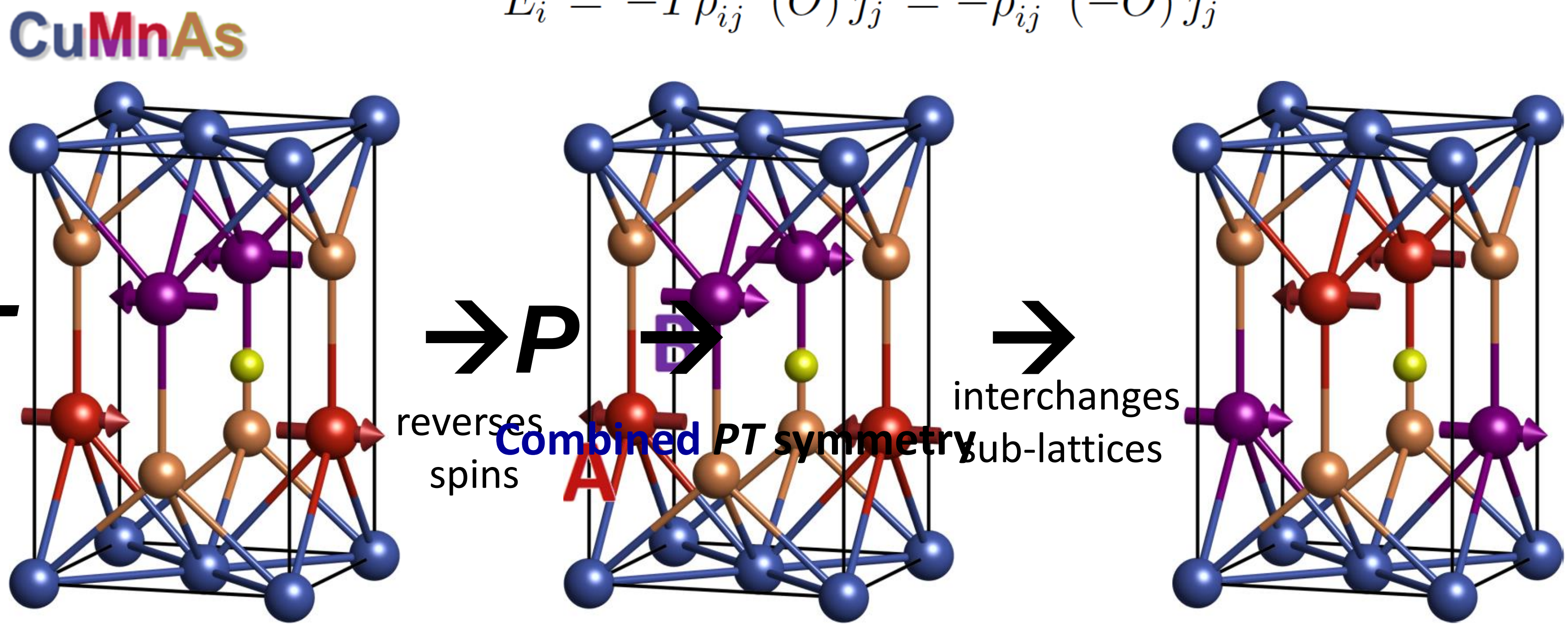
Anomalous Hall effect (AHE)

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

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

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

PT



Broken time reversal symmetry Broken space-inversion symmetry

PT symmetry of the CuMnAs crystal: $\rho^{\mathrm{odd}}_{ij} = PT\rho^{\mathrm{odd}}_{ij}$.

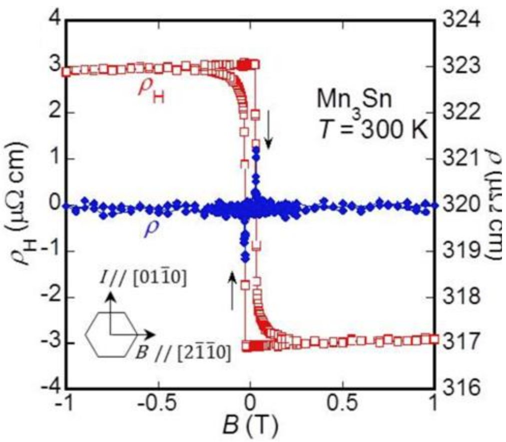
Space inversion flips sign of both electric field E_i and current j_j: $\rho^{\mathrm{odd}}_{ij} = -PT\rho^{\mathrm{odd}}_{ij}$

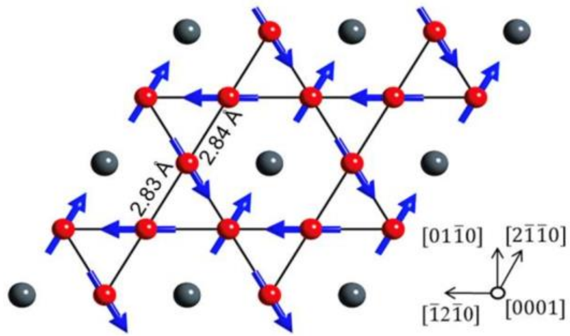
$\Longrightarrow$ $\rho^{\mathrm{odd}}_{ij} = 0$ **(no AHE)**

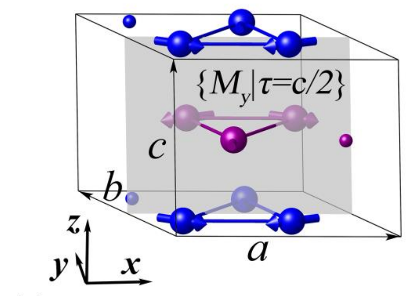
Electrical detection of collinear states (180° spin reversal)

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)
…

Anisotropic Magnetoresistance

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

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

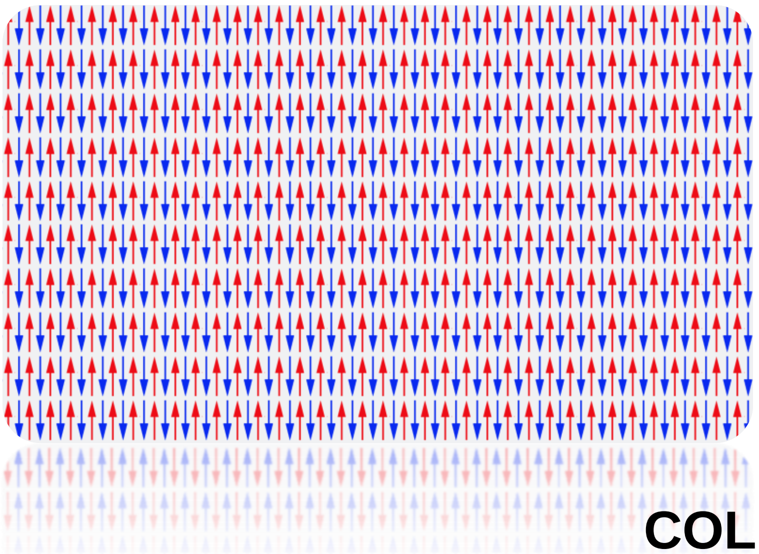
  but requires that **AF has also broken *P* symmetry**: $E_i = \xi^{\mathrm{odd}}_{ijk} j_j j_k$;

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

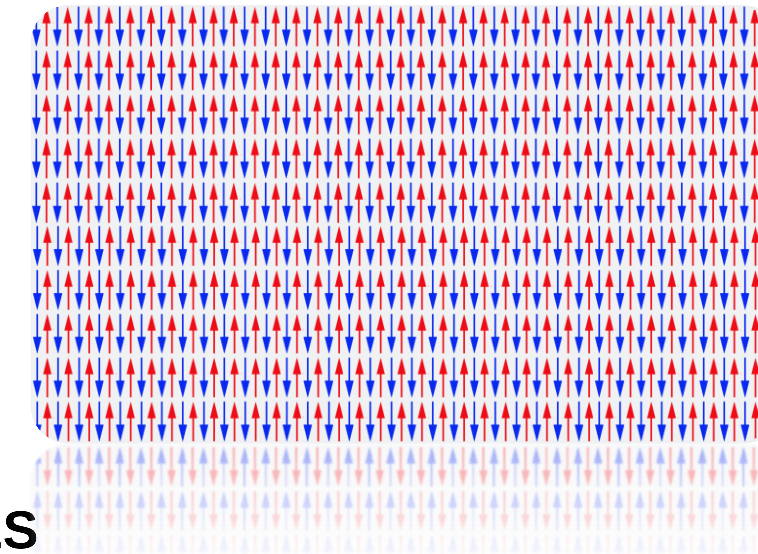
(**48** out of **59**) H. Grimmer, *Acta Crystallographica Section A* **49**, 763-771 (1993)

Electrical detection of collinear states (180° spin reversal)

Anisotropic Magnetoresistance
2nd ORDER

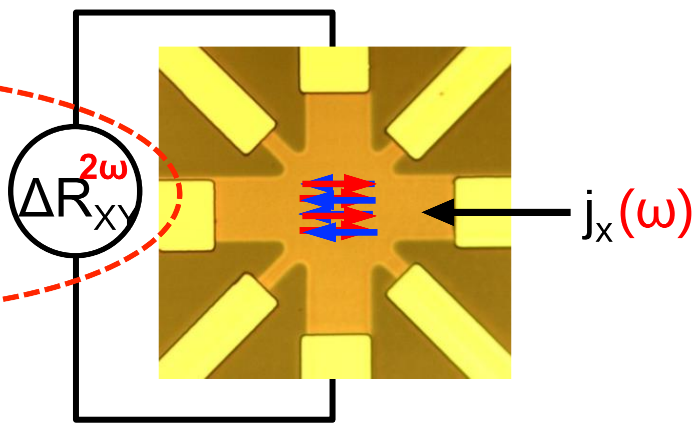


Electrical DETECTION of COLLINEAR STATES

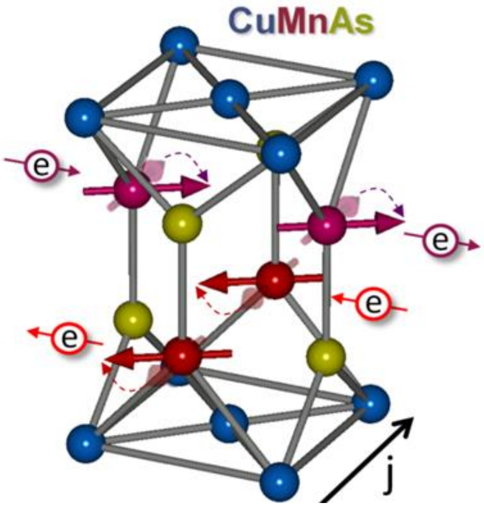


Spin-Orbit torque ~ $\Delta R_{xy}^{2\omega}$
~ $p_S \times m_i$

$\lessgtr 0$

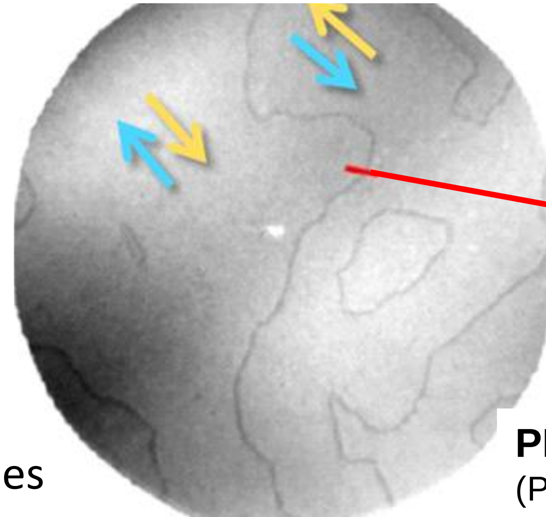


Electrical detection of collinear states (180° spin reversal)

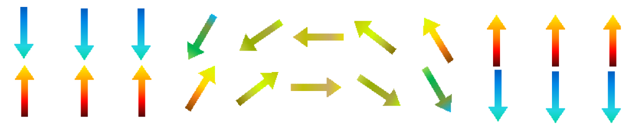


broken T and P symmetries
and combined PT symmetry

Uniaxial CuMnAs

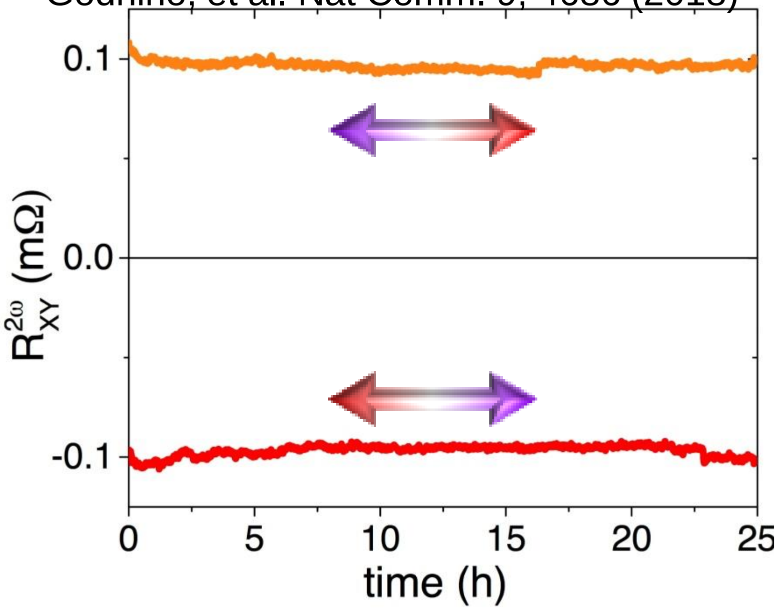


Magnetic domain walls



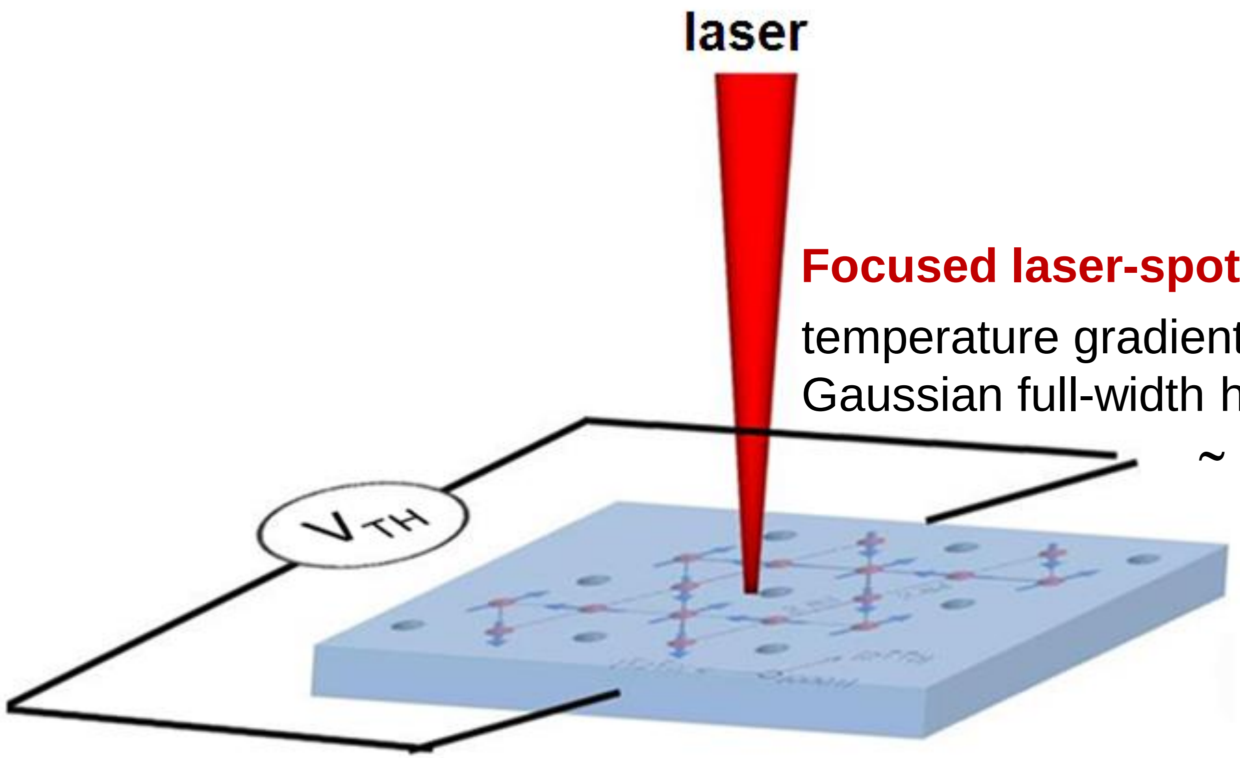
PEEM – XMLD
(P. Wadley et al.)

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



ALTERNATIVE magneto-thermal DETECTION METHOD

Generate locally **temperature gradient** *and*
measure globally **electric response**.

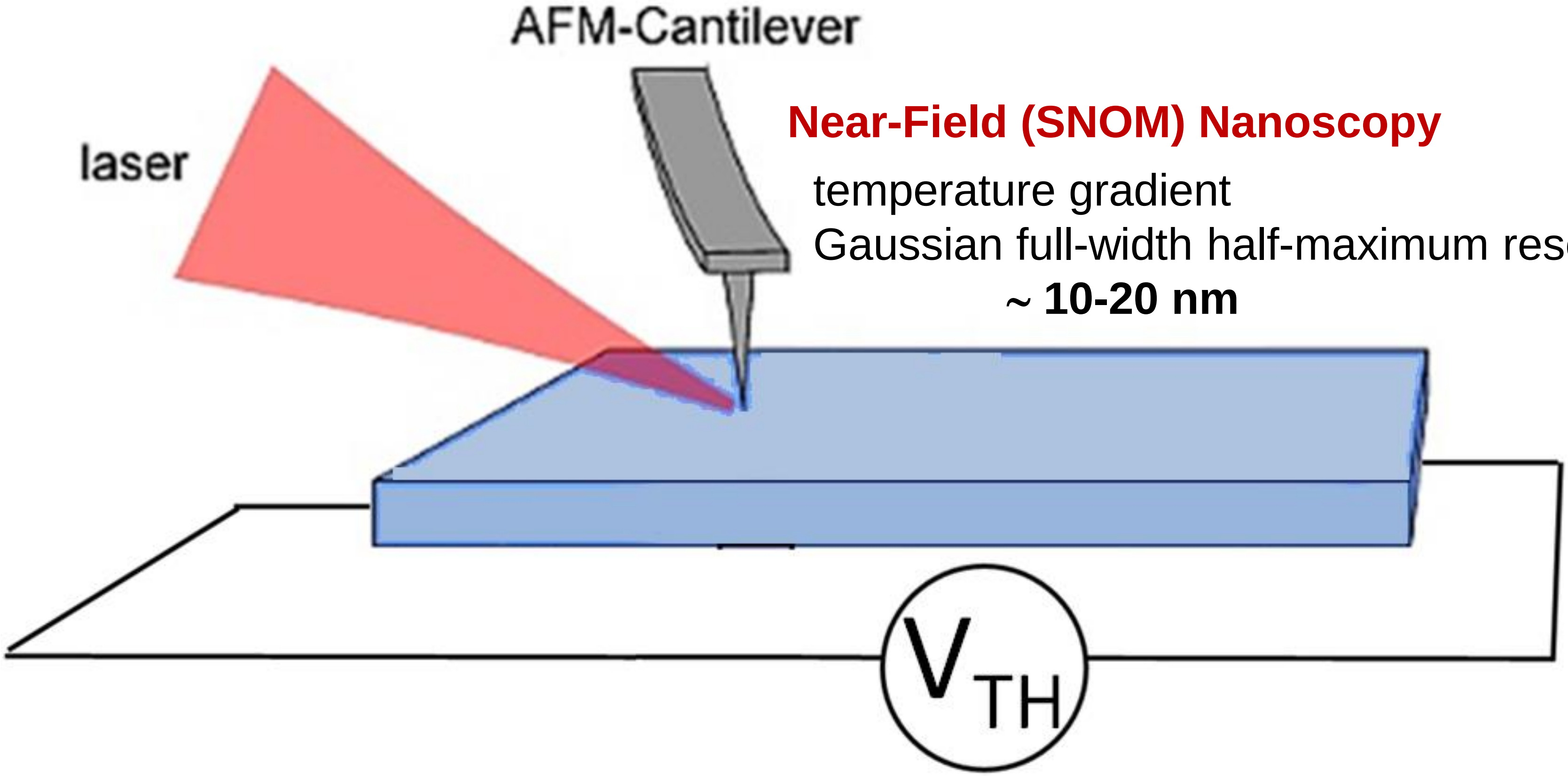


Focused laser-spot heating

temperature gradient
Gaussian full-width half-maximum resolution:
~ 1-2 μm

ALTERNATIVE magneto-thermal DETECTION METHOD

Generate locally **temperature gradient** *and*
measure globally **electric response**.

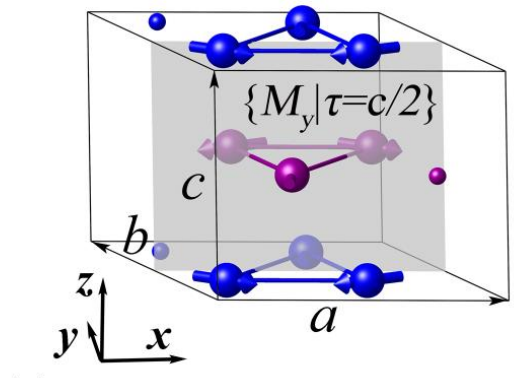


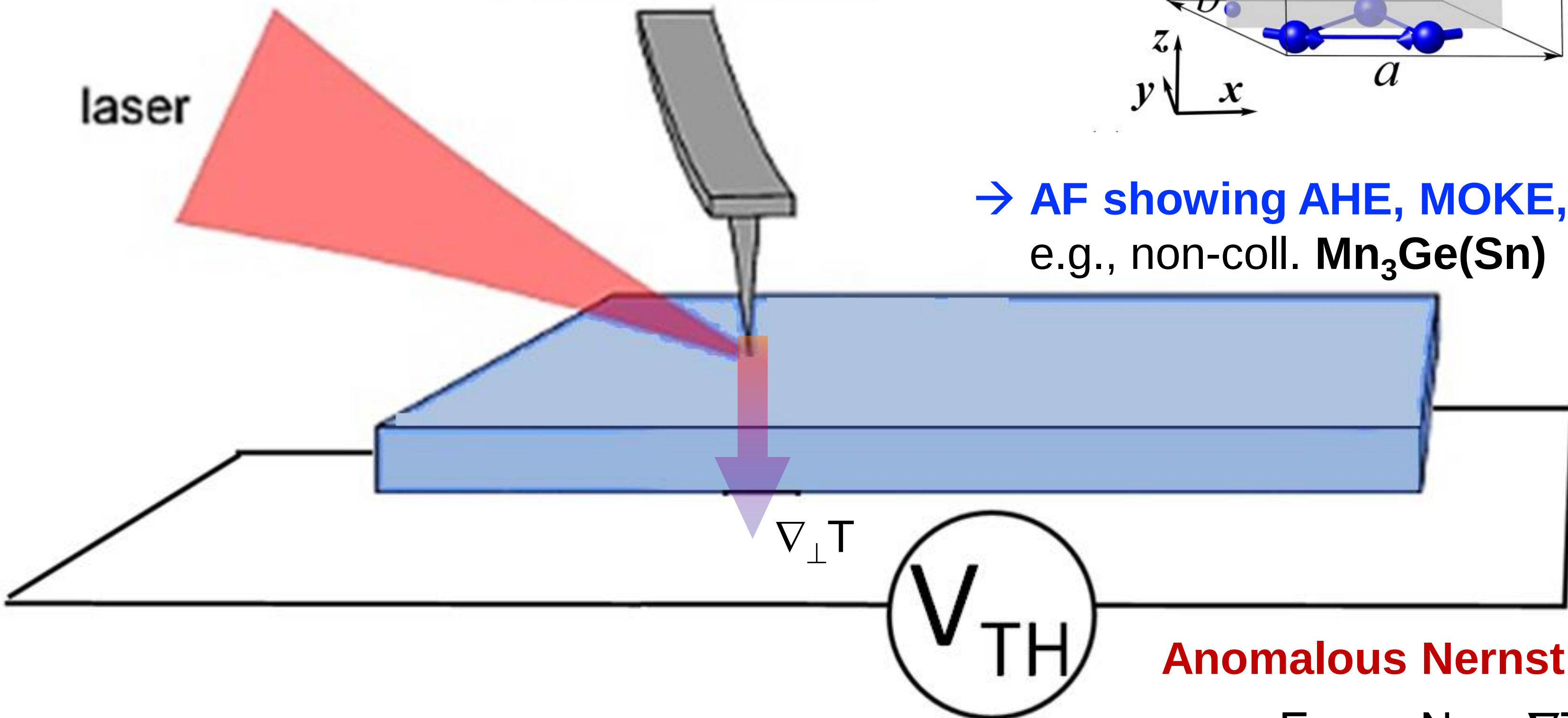
Near-Field (SNOM) Nanoscopy

temperature gradient
Gaussian full-width half-maximum resolution:
~ 10-20 nm

ALTERNATIVE magneto-thermal DETECTION METHOD

Generate locally **temperature gradient** *and measure globally* **electric response**.





→ **AF showing AHE, MOKE, …,**
e.g., non-coll. **$Mn_3Ge(Sn)$**

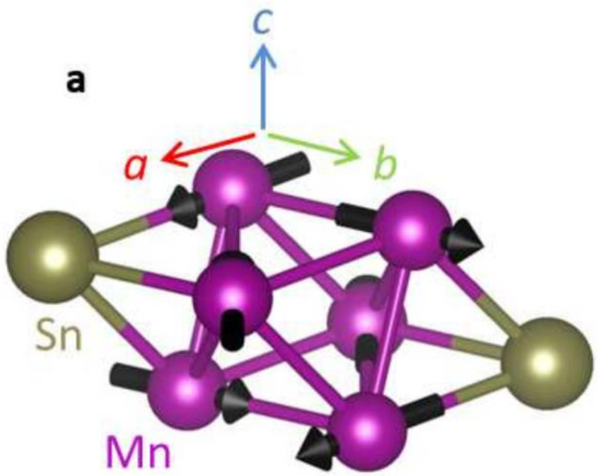
Anomalous Nernst effect

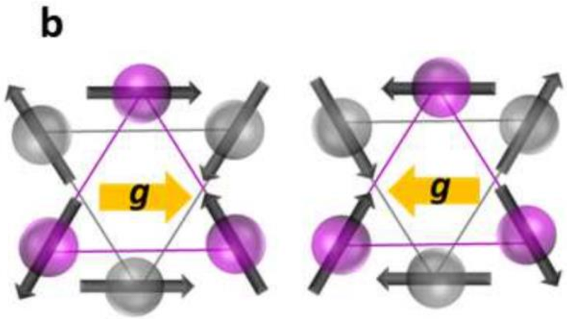
$E_{bar} = -N_{ANE} \nabla T \times \mathbf{M}$

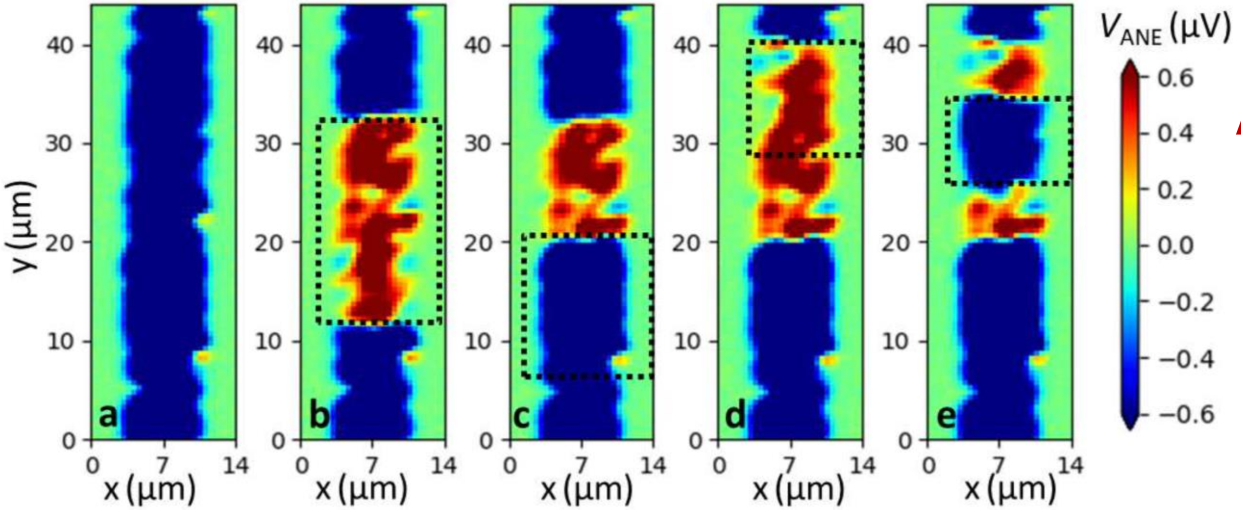
Thermal gradient detetction

Anomalous Nernst effect in non-collinear Mn_3Sn

H. Reichlova, et al., 10, 5459 (2019)





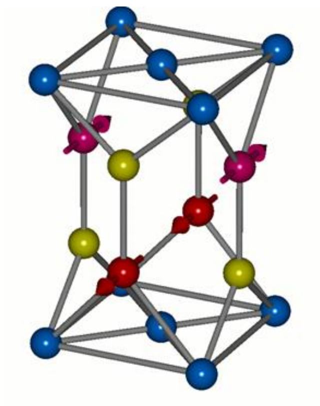


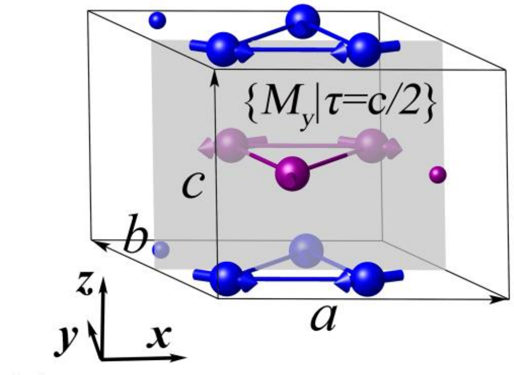
Anomalous Nernst effect

$$\mathbf{E}_{bar} \sim \nabla_z T \times \mathbf{g}$$

ALTERNATIVE table-top DETECTION METHOD

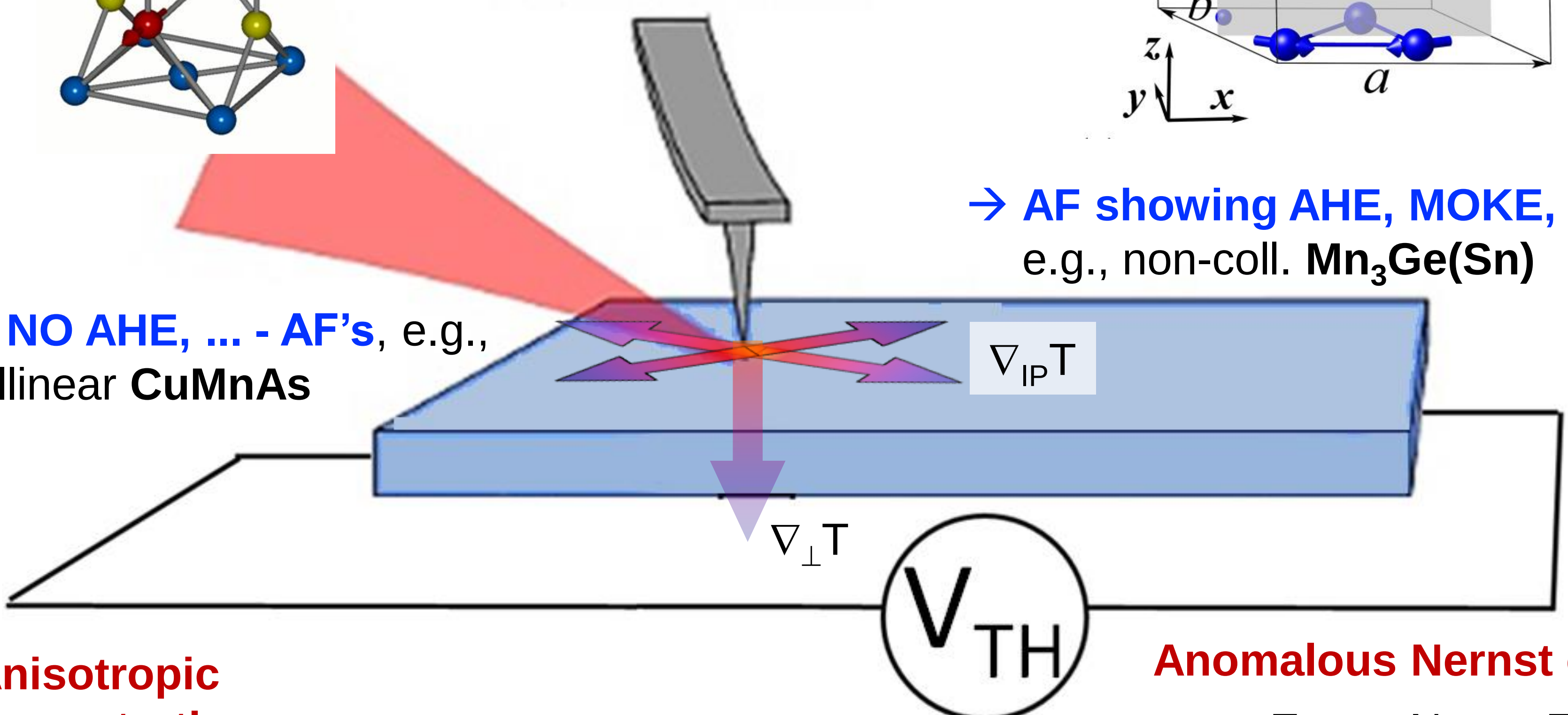
Generate locally **temperature gradient** *and measure globally* **electric response**.





→ **AF showing AHE, MOKE, …,**
e.g., non-coll. **$Mn_3Ge(Sn)$**

→ **NO AHE, ... - AF's**, e.g.,
collinear **CuMnAs**



Anisotropic magneto-thermo power

(thermoelectric equivalent to the **AMR**)

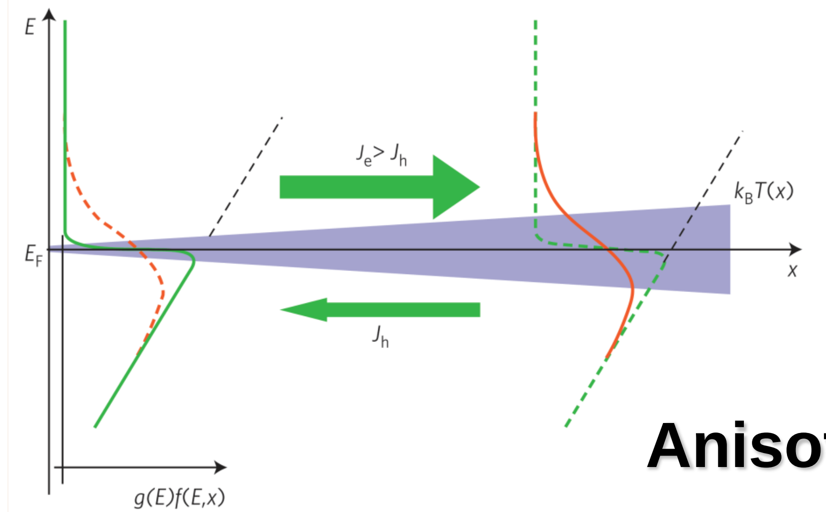
Anomalous Nernst effect

$$E_{bar} = -N_{ANE}\, \nabla T \times p$$

(thermoelectric equivalent to the **anomalous Hall effect**)

ANISOTROPIC MAGNETOTHERMAL POWER

ANISOTROPIC MAGNETO SEEBECK Effect

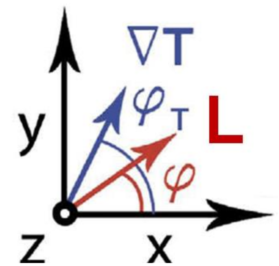


$$\begin{pmatrix} J_c \\ J_s \\ Q \end{pmatrix} = \sigma(\varepsilon_F) \begin{pmatrix} 1 & P & ST \\ P & 1 & P'ST \\ ST & P'ST & \kappa T/\sigma \end{pmatrix} \begin{pmatrix} \nabla\mu_c / e \\ \nabla\mu_s / 2e \\ -\nabla T / T \end{pmatrix}$$

Anisotropic: $S_{\parallel} \neq S_{\perp}$

$S_{\parallel} : \boldsymbol{L} \parallel \nabla T$

$S_{\perp} : \boldsymbol{L} \perp \nabla T$



Anisotropic-Magnetothermopower: $E_y = -(S_+ - S_- \cos 2\varphi) \, |\nabla T| \sin \varphi_T$

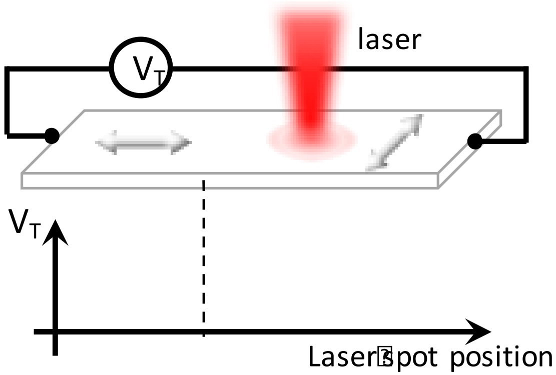
(response to the longitudinal temp. gradient)

“Planar Nernst” effect: $E_y = -S_- \sin 2\varphi |\nabla T| \cos \varphi_T$

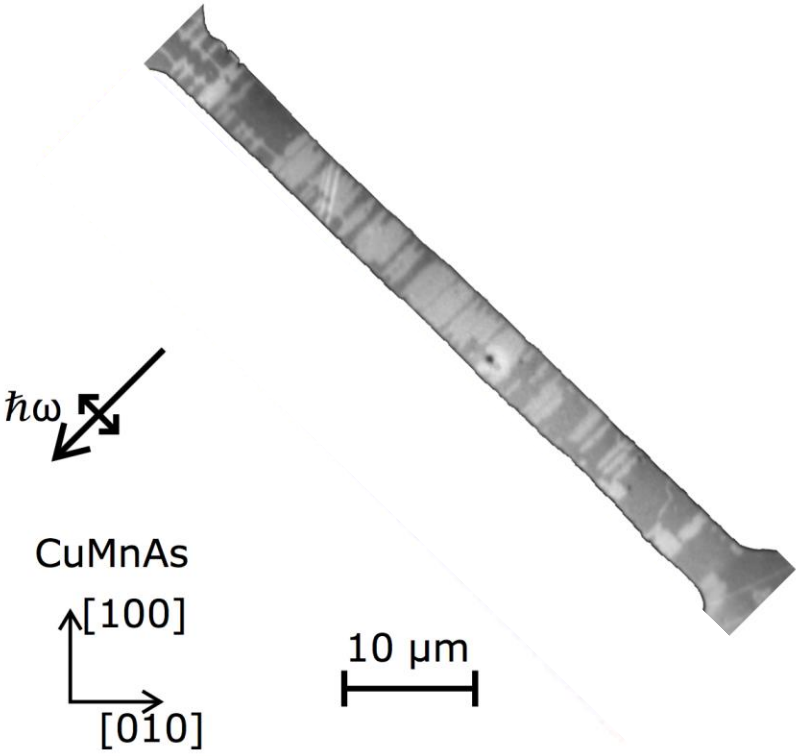
(response to the transverse temp. gradient)

CuMnAs layer with bi-axial magnetic anisotropy

Effect of bar orientation on magnetic domain structure



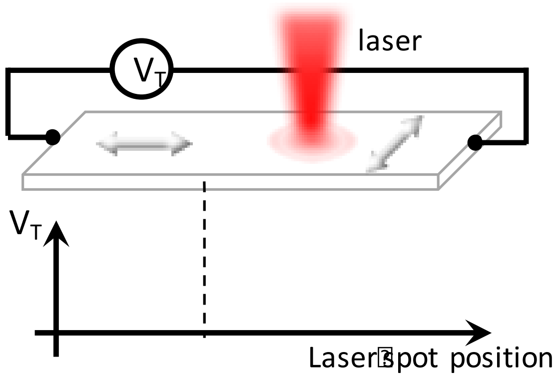
PEEM XMLD

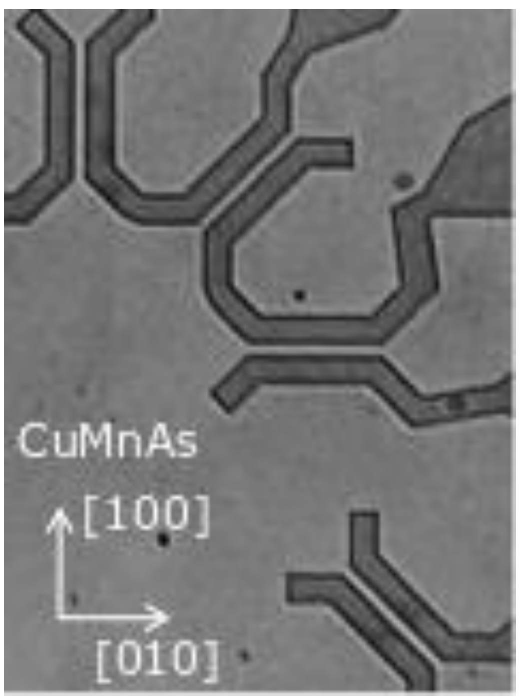


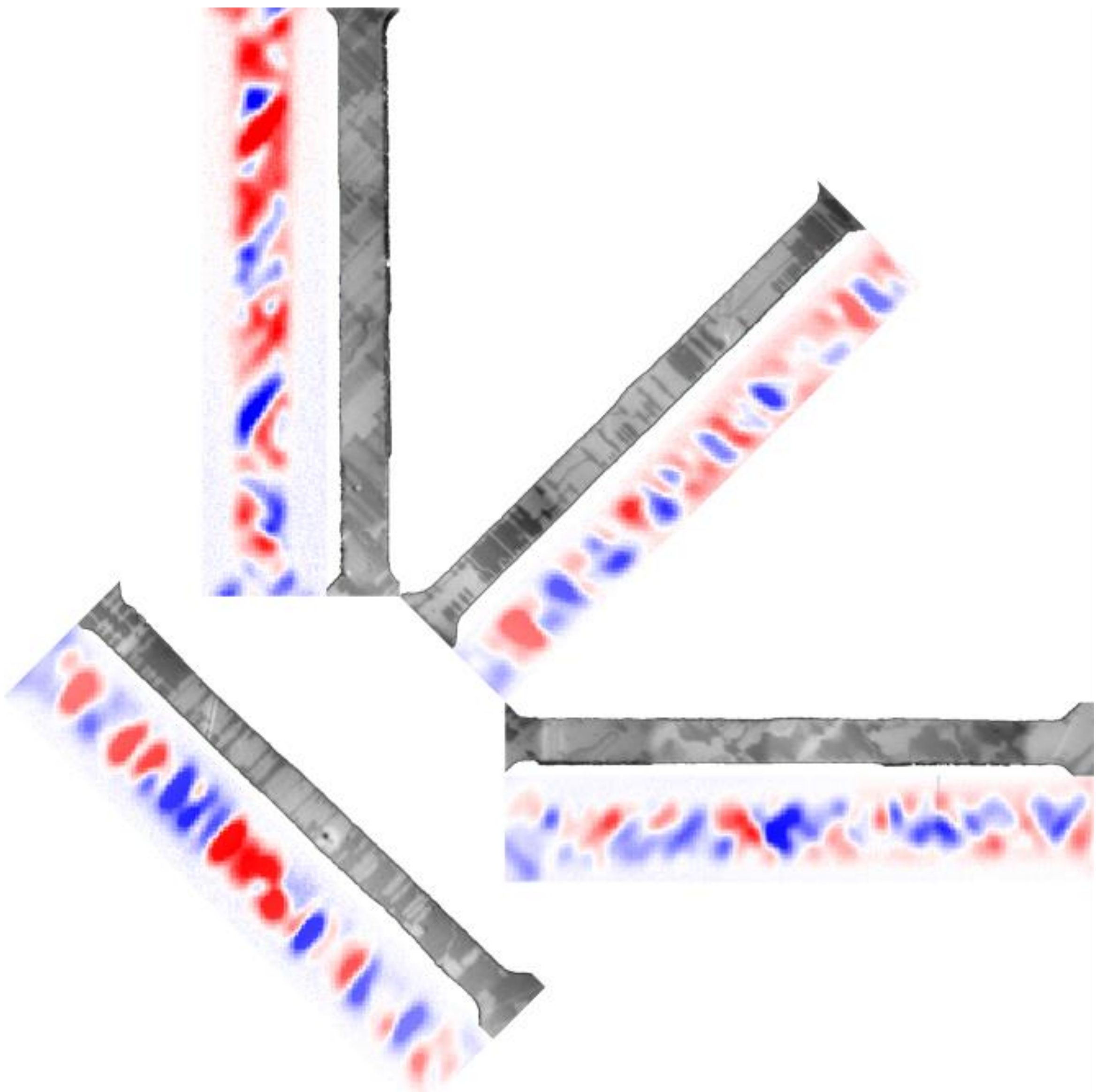
T. Janda *et al.,* Phys. Rev. Materials **4**, 094413 (2020)

CuMnAs layer with bi-axial magnetic anisotropy

Effect of bar orientation on magnetic domain structure

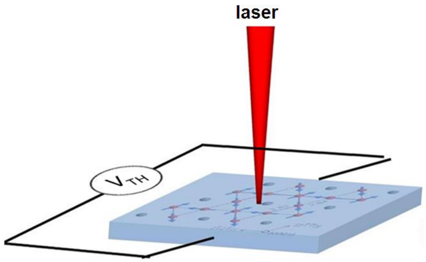




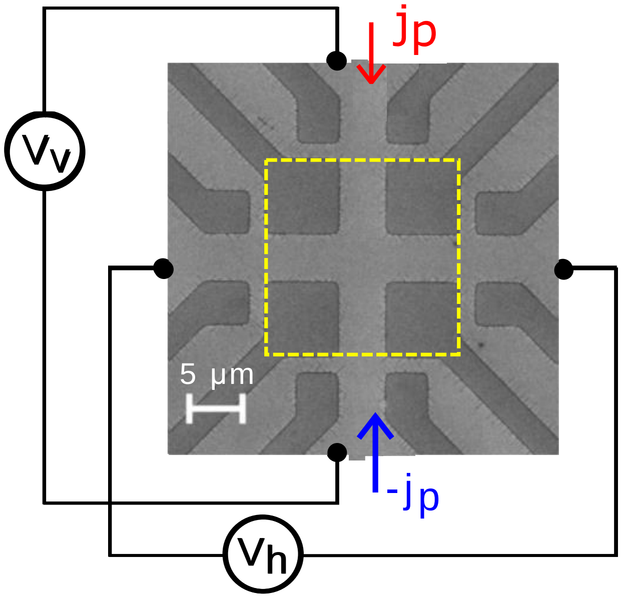


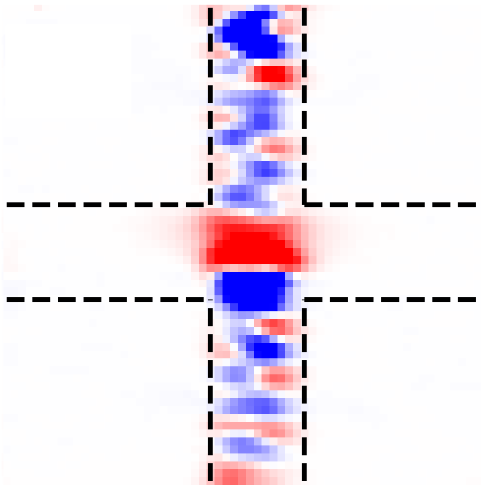
Current pulse affected domain structure

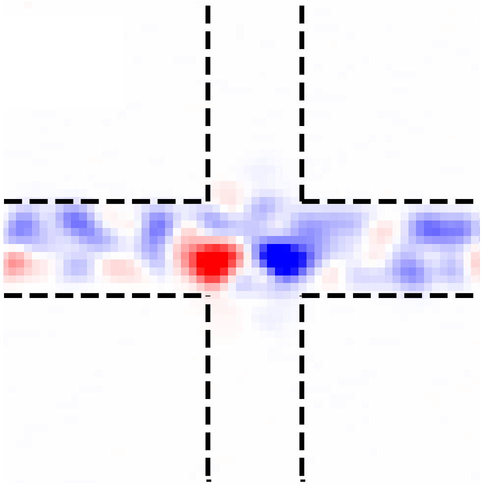
Anisotropic magneto-thermo power



Cross bar geometry

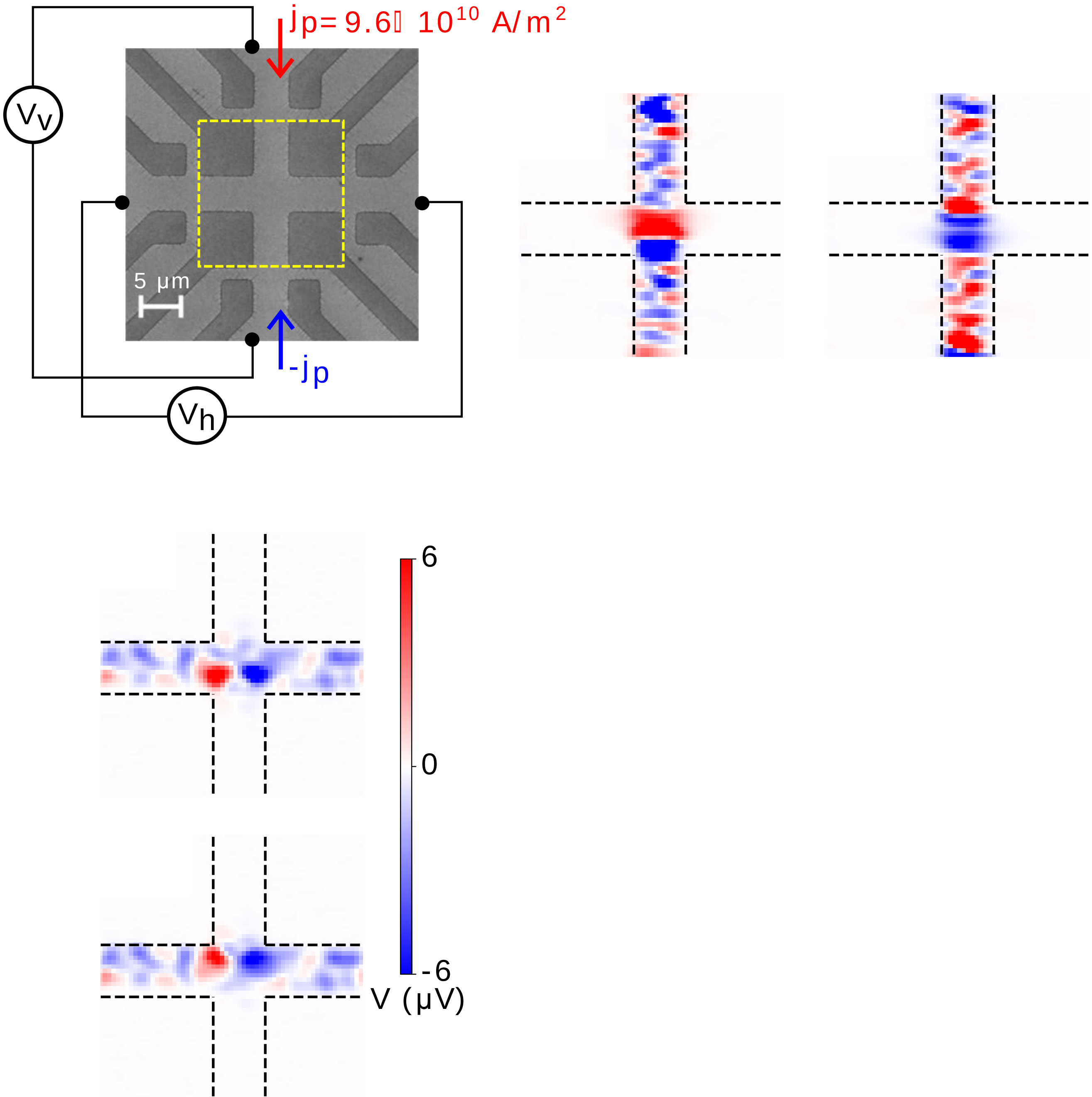




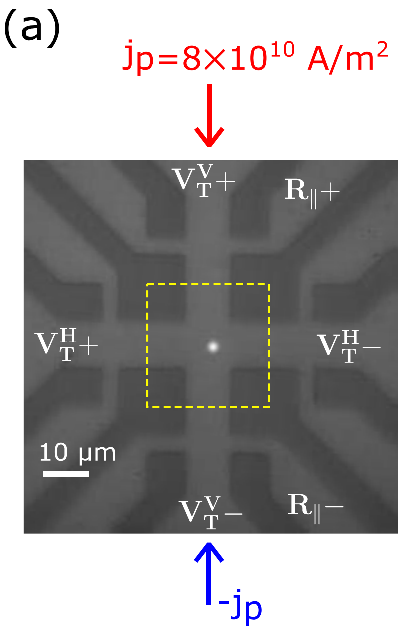


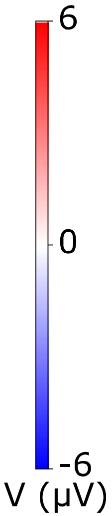
T. Janda *et al.*, Phys. Rev. Materials **4**, 094413 (2020)

Current pulse affected domain structure



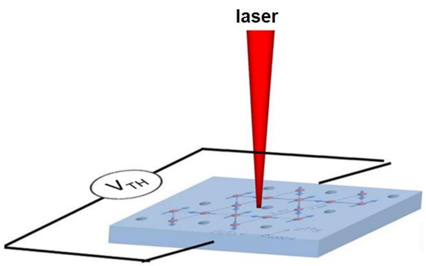
Current pulse affected domain structure

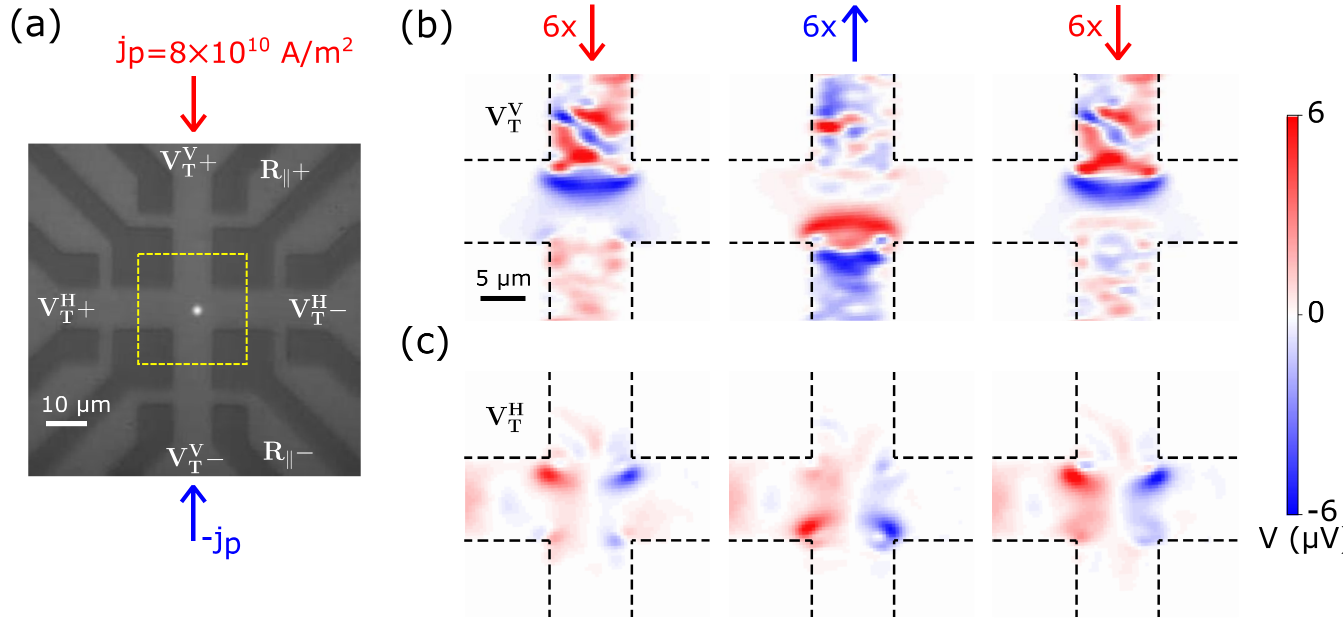




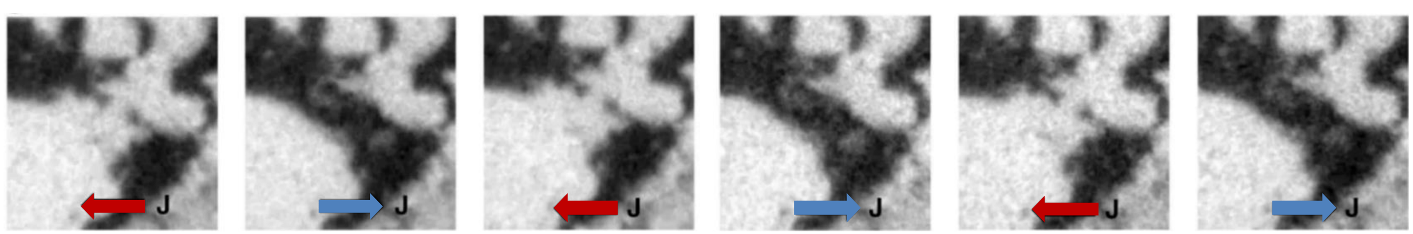
Current pulse affected domain structure

Anisotropic magneto-thermo power





XMLD-PEEM



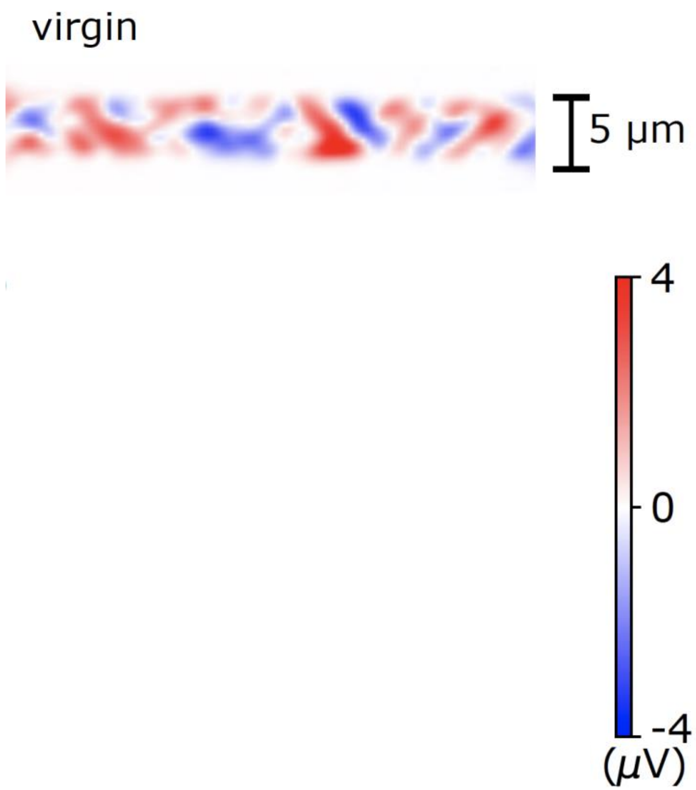
P. Wadley, et al., Nature Nano. (2018)

Current pulse affected domain structure

LARGE Amplitude CURRENT PULSES

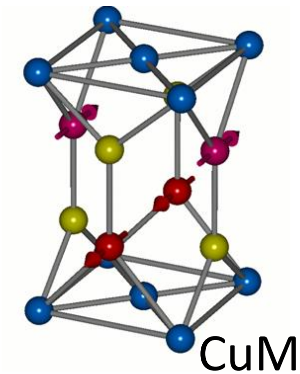
XMLD-PEEM

Focused Laser-spot AMS

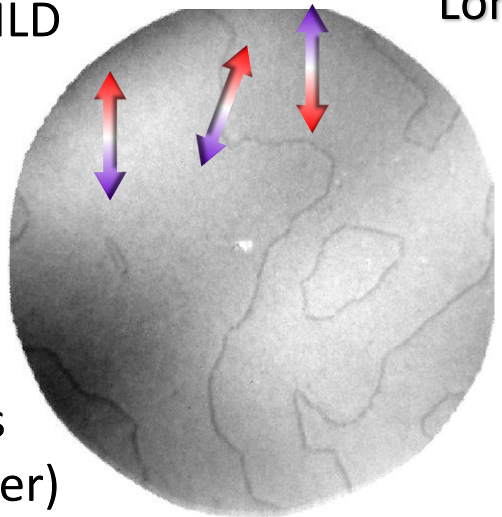


AF with uniaxial anisotropy: 180° Néel magnetic DWs

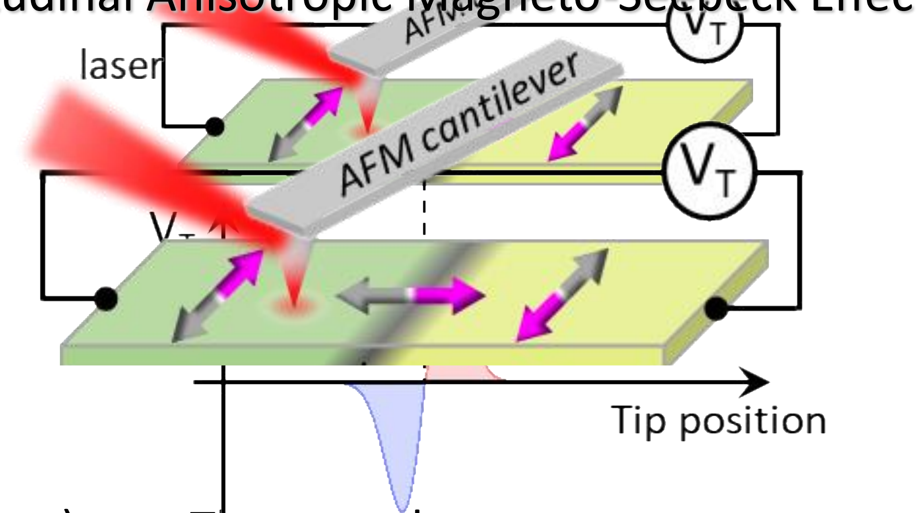
PEEM XMLD



CuMnAs
(thin layer)



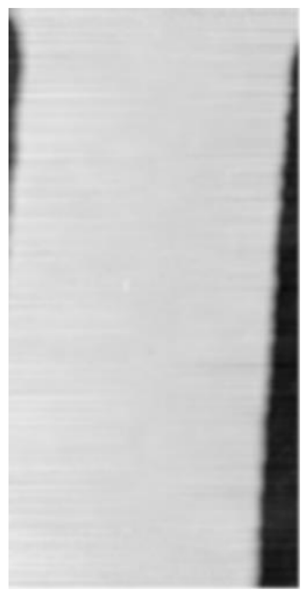
Longitudinal Anisotropic Magneto-Seebeck Effect



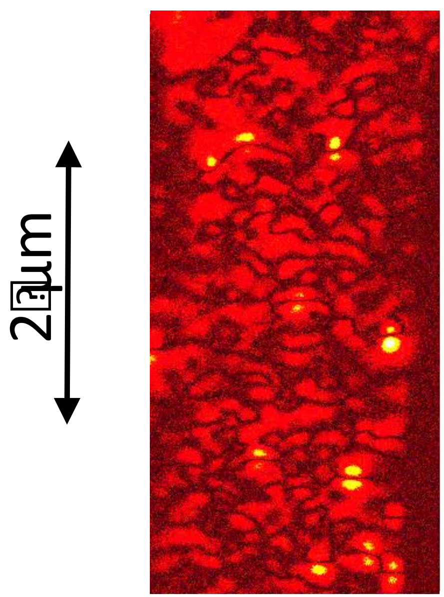
Near-field Nanoscopy:
AFM + thermal voltage

thin 20nm CuMnAs

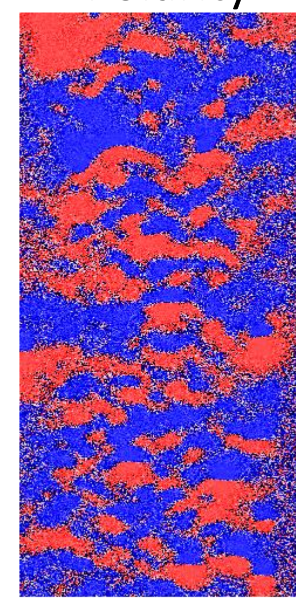
AFM (~1nm res.)
(2 µm wide stripe)



Thermovoltage
Magnitude



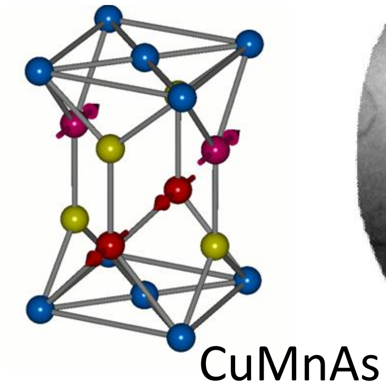
Thermovoltage
Polarity

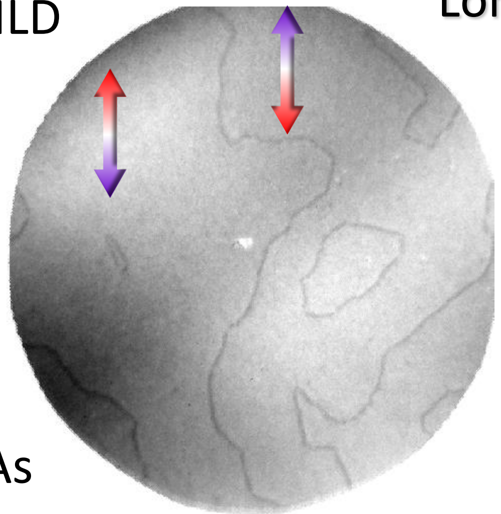


(~20 nV amplitude, 0.01 GW/m^2 power density)

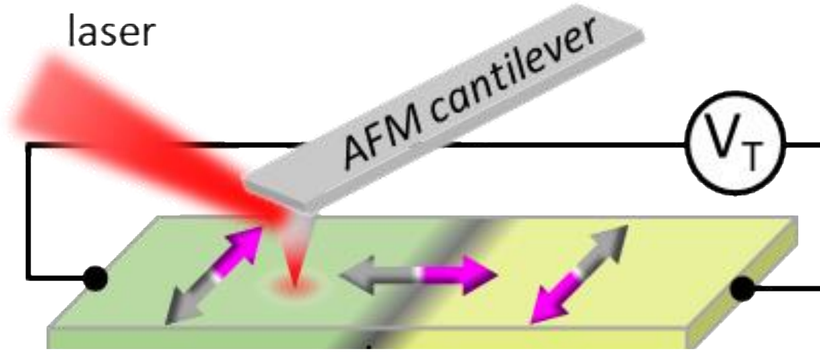
AF with uniaxial anisotropy: 180° Néel magnetic DWs

PEEM XMLD

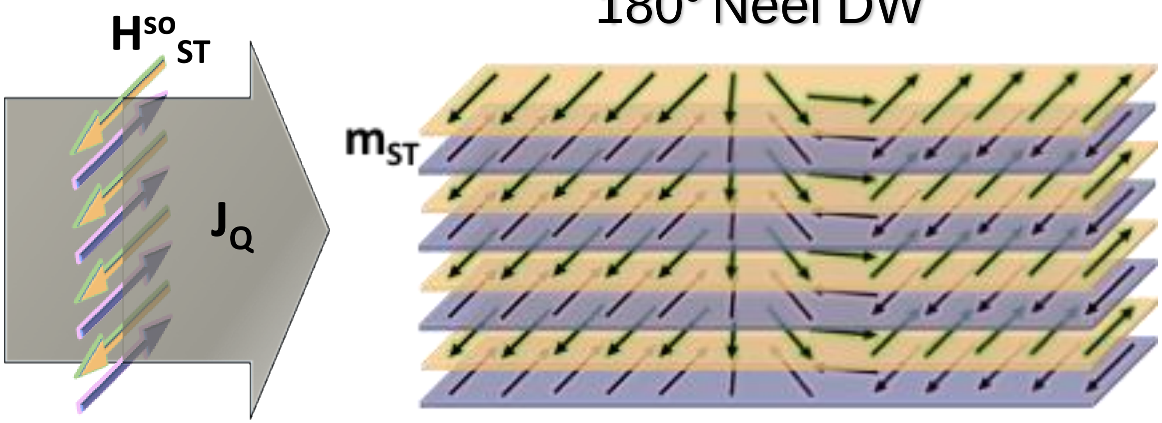




Longitudinal Anisotropic Magneto-Seebeck Effect

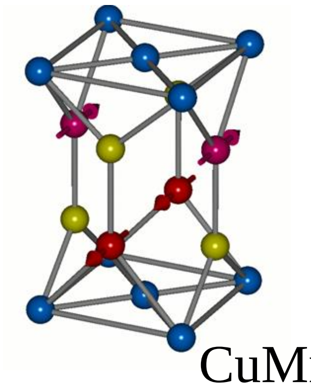


180° Néel DW

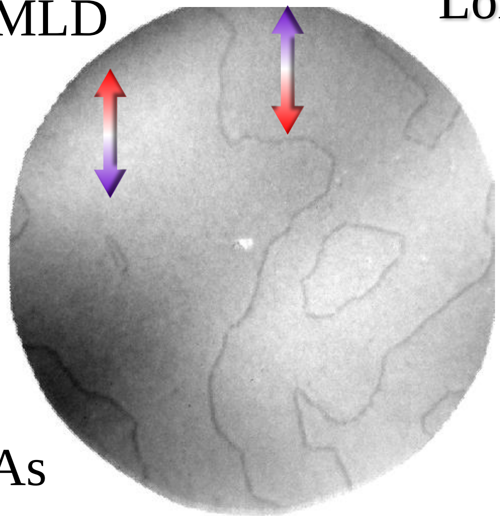


AF with uniaxial anisotropy: 180° Néel magnetic DWs

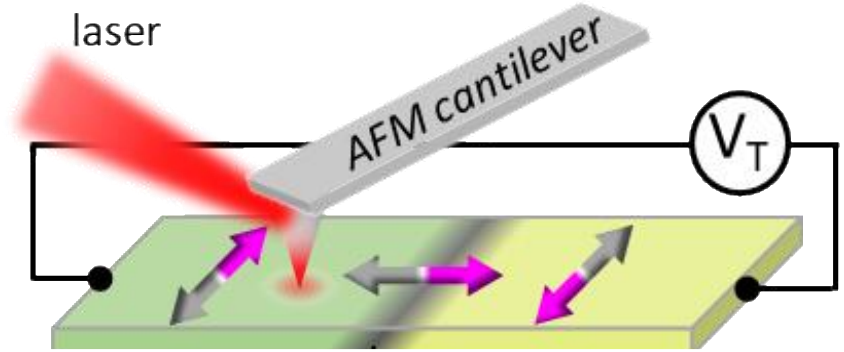
PEEM XMLD

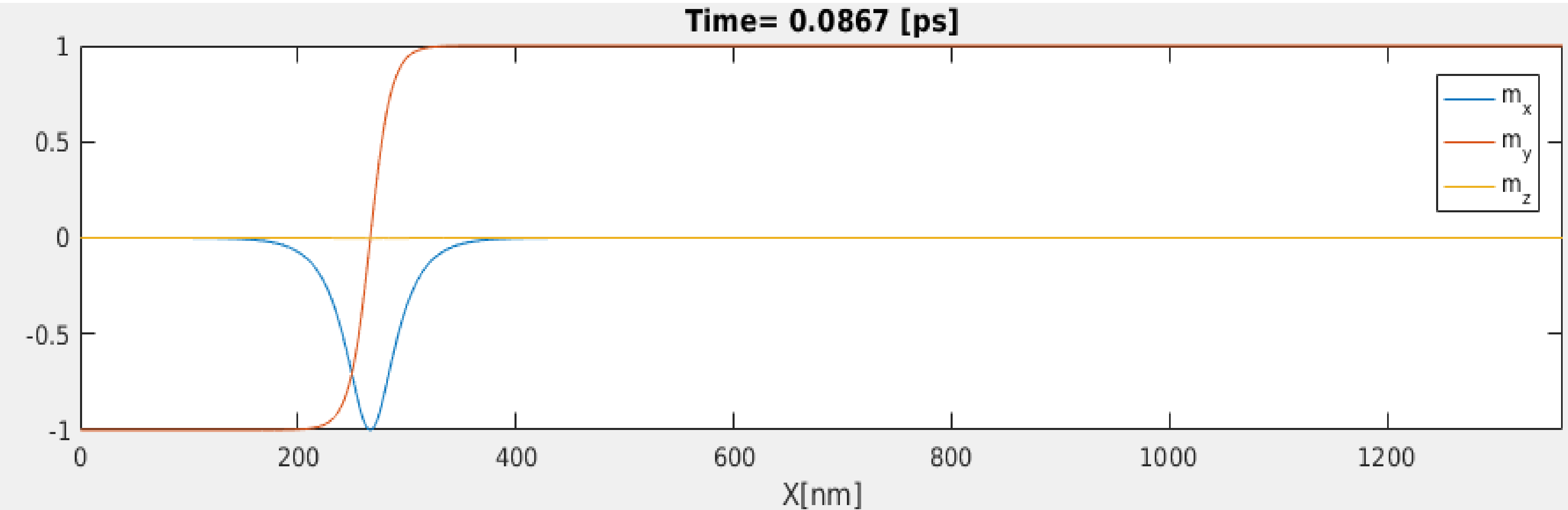


CuMnAs

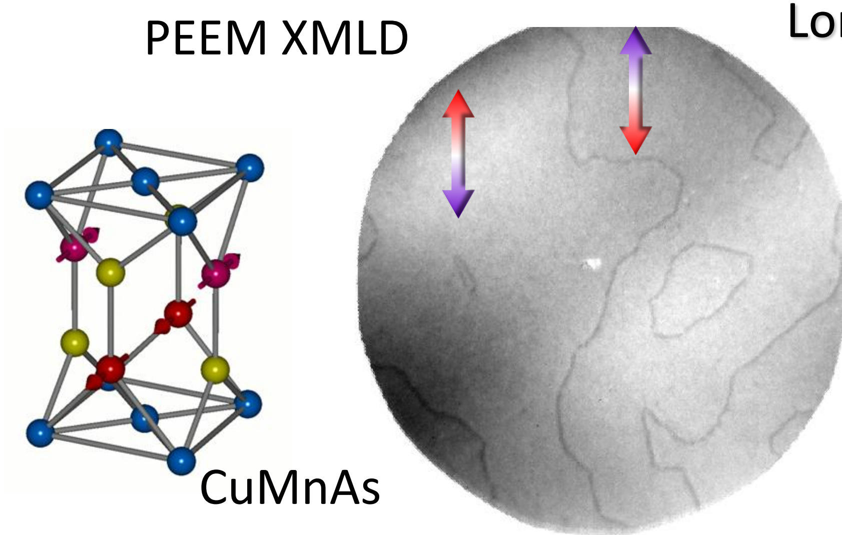


Longitudinal Anisotropic Magneto-Seebeck Effect

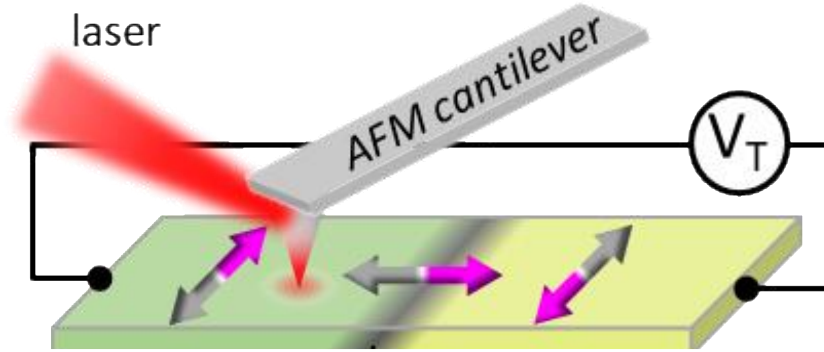


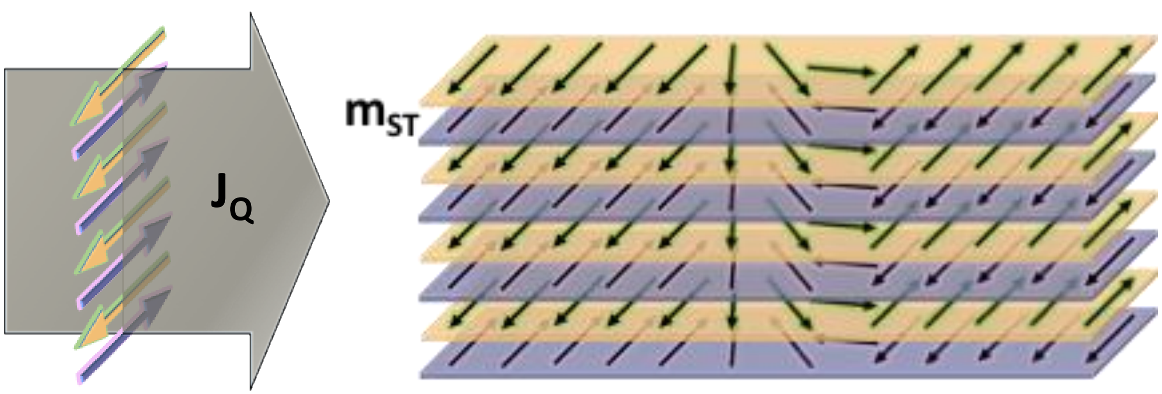


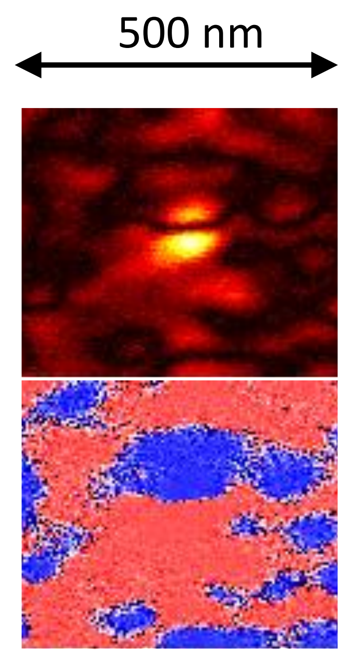
AF with uniaxial anisotropy: 180° Néel magnetic DWs



Longitudinal Anisotropic Magneto-Seebeck Effect

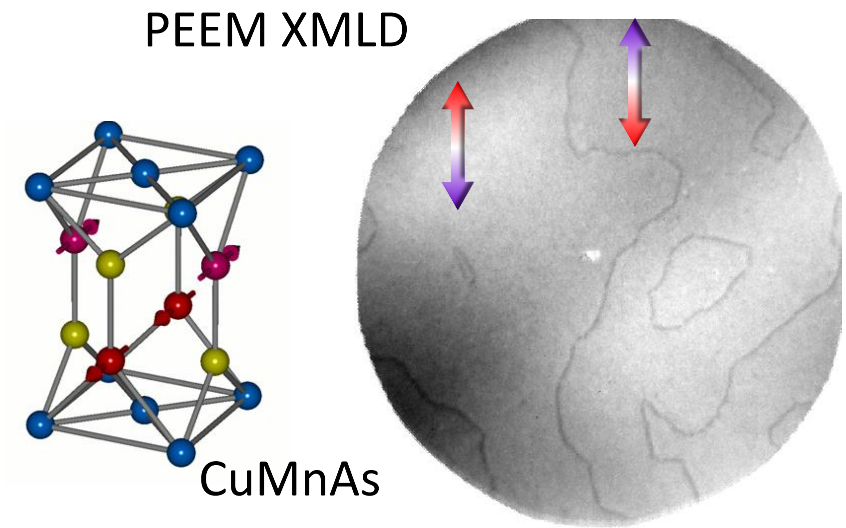


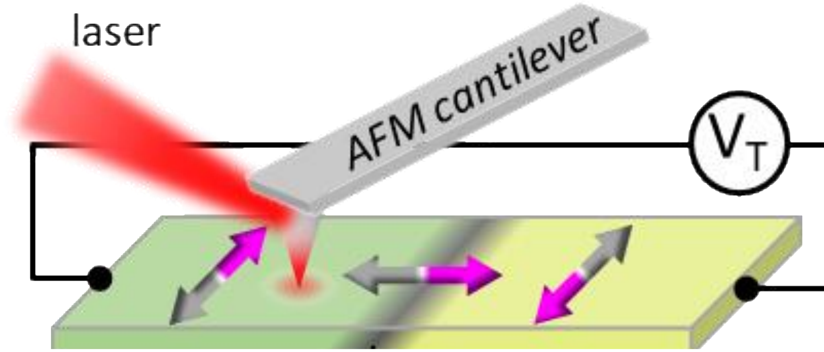




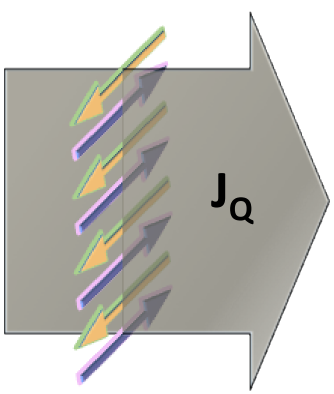
(~50 nV amplitude, 0.01 GW/m^2 power density)

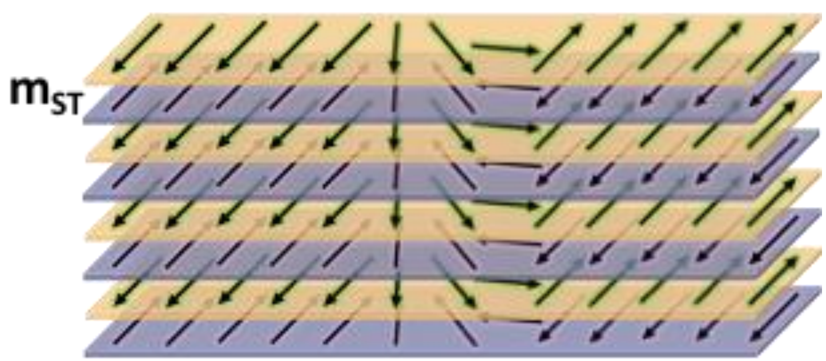
AF with uniaxial anisotropy: 180° Néel magnetic DWs

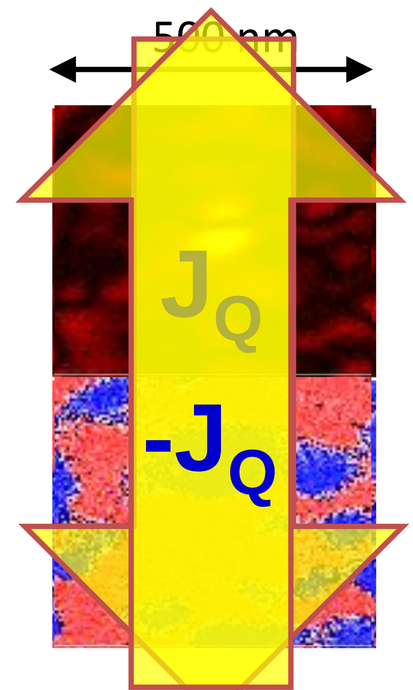




J_Q ~3 x 10^{10} A/m^2



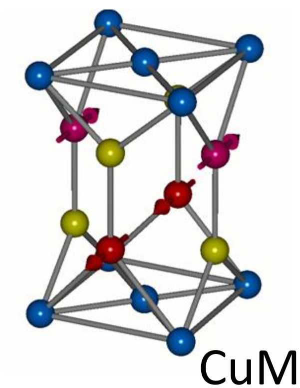


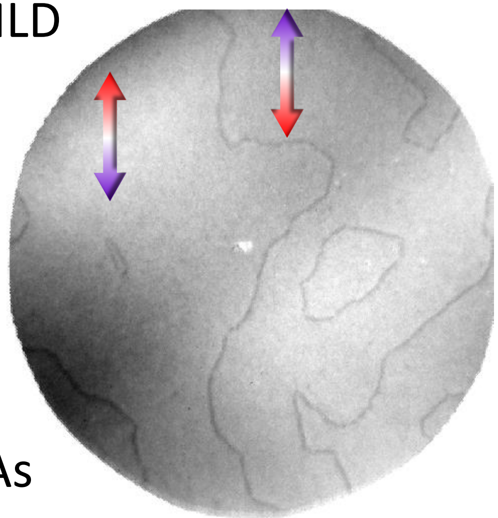


(~50 nV amplitude, 0.01 GW/m^2 power density)

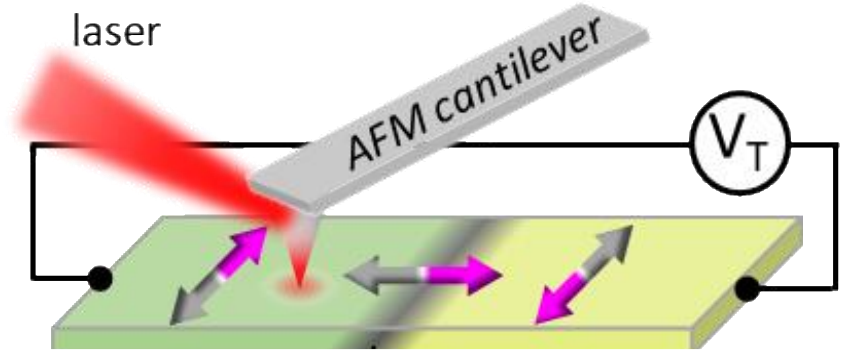
AF with uniaxial anisotropy: 180° Néel magnetic DWs

PEEM XMLD

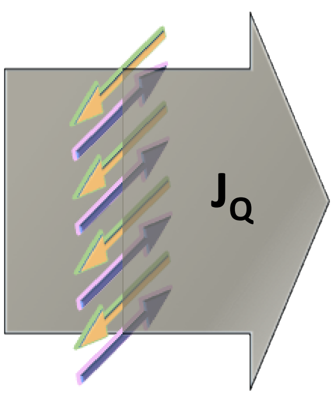


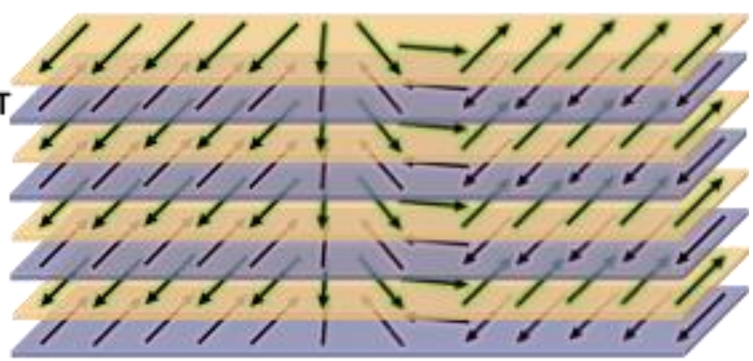


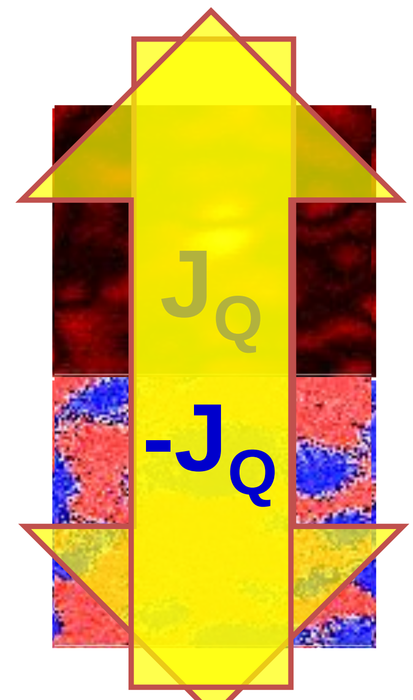
Anisotropic Magneto-Seebeck Effect



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







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

Summary

SPINTRONICS with ANTIFERROMAGNETS:

- Electrical **detection** and electrical **manipulation** of **AF states**

SCANNING MICROSCOPY for AF domains based on MAGNETOTHERMAL EFFECTS:

- Low resolution (wavelength restricted) **“far-field”** and high-resolution **“near-field”**

OBSERVATION of:

- **current induced domain switching**

  (Correlation between pulse induced AF domain structure and device resistance)

- AF **domain shattering** and **relaxation**

- **Current pulse induced DW motion of 180 deg DWs**

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Tomaš Ostatnicky

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PTB, Berlin
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Bernd Kaestner

TU Dresden
Helena Reichlova

University of Nottingham
Sonka Reimers
Richard Campion
Kevin Edmonds
Pete Wadley

Diamond Light Source
Sarnjeet Dhesi
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Hitachi Laboratory, Cambridge
Ruben Otxoa
Pierre Roy