Scanning magneto-thermoelectric detection of spin-orbit torque switching in antiferromagnetic films

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[4] *Nottingham University, Germany*

[5] *Hitachi Cambridge Lab, Cavendish Lab, UK*

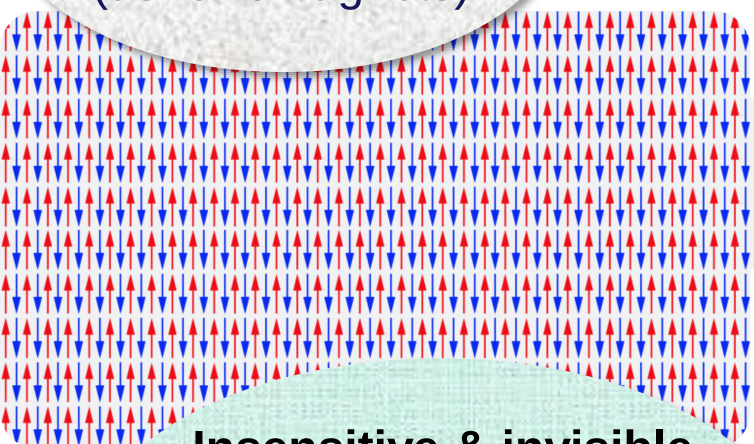
[6] *University of Regensburg, Germany*

ANTIFERROMAGNETS

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

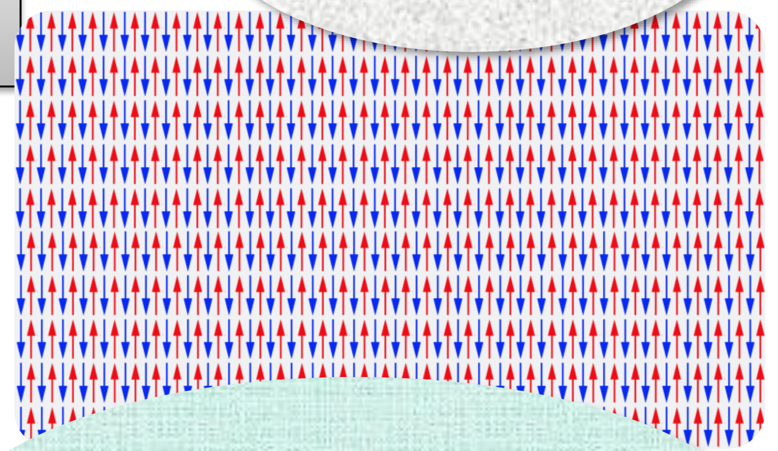
Radiation-hard
Spin not charge based
(as ferromagnets)

Non-volatile
Magnetic order
(as ferromagnets)



BUT what about

electrical DETECTION via Magneto-transport



Insensitive & invisible to magnetic fields

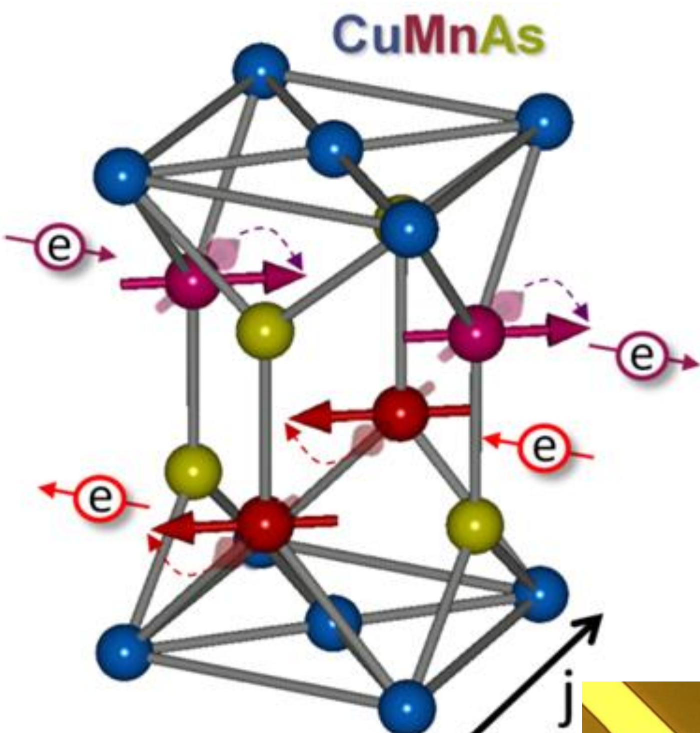
No stray field cross-talks
No net moment

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

Electrical DETECTION: Anisotropic Magnetoresistance (AMR)

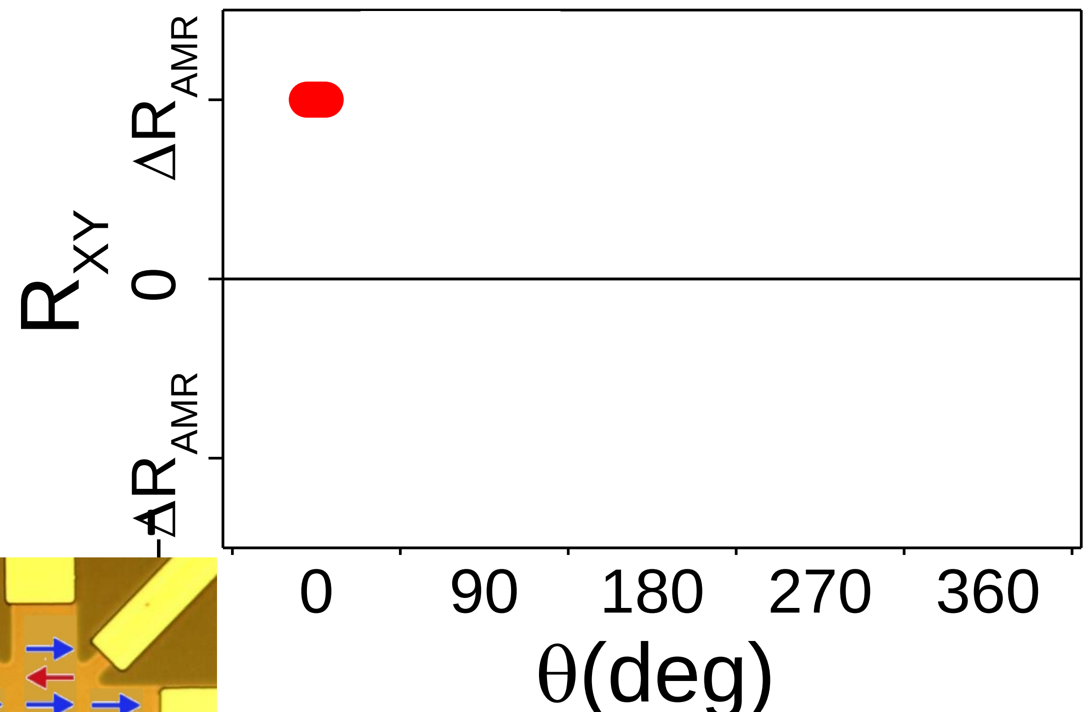
→ CuMnAs / Mn_2Au: **Electrical <u>switching between AF states</u> by SOT**

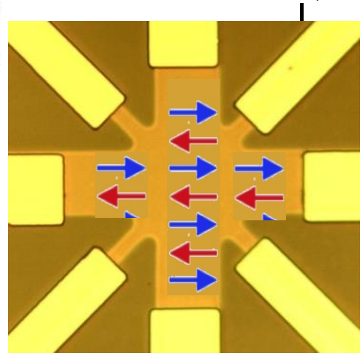
(Locally broken inversion symmetry)



biaxial switching

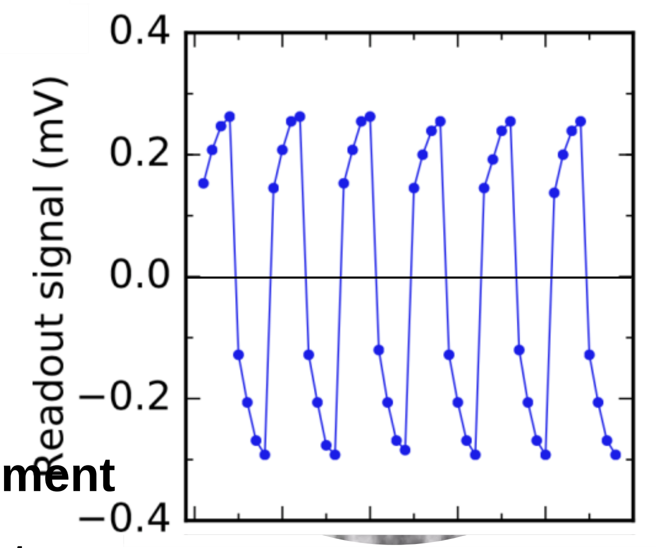
AMR for detection





Optical DETECTION: Magnetic Linear Dichroism

→ **Electrical pulse experiment in Biaxial CuMnAs**



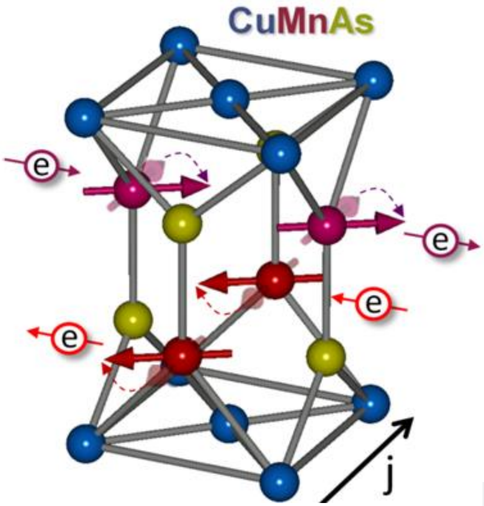
Small multi-magnetic domain states

K. Olejnik, Nat. Comm. 8, 15434 (2017)

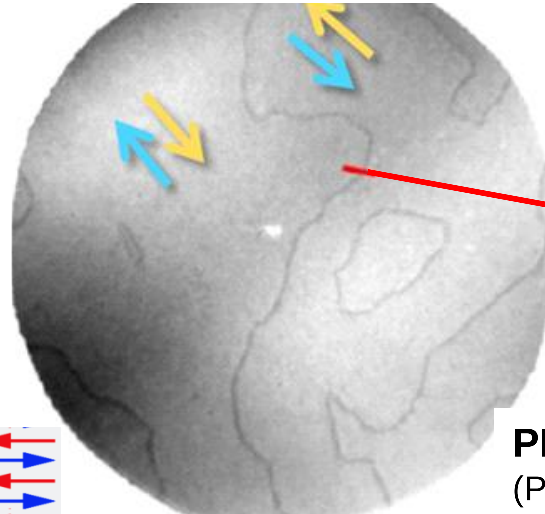
→ **requires large scale equipment**

Synchrotron Light sources

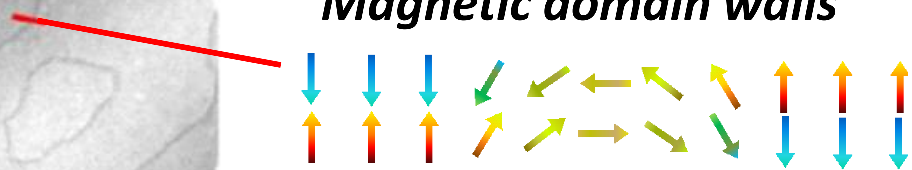
DETECTION: **Uniaxial Switching** (180° Néel vector reversal)



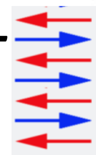
Uniaxial CuMnAs



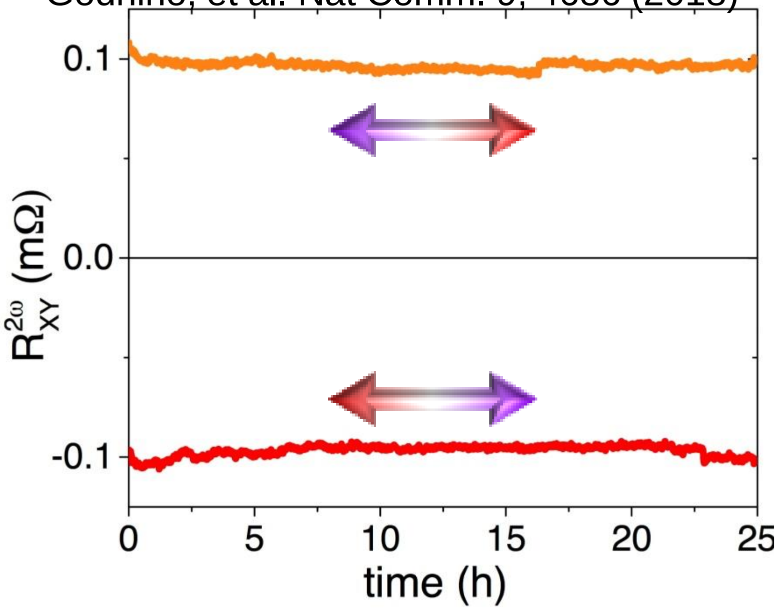
Magnetic domain walls



broken P and broken T **symmetries**



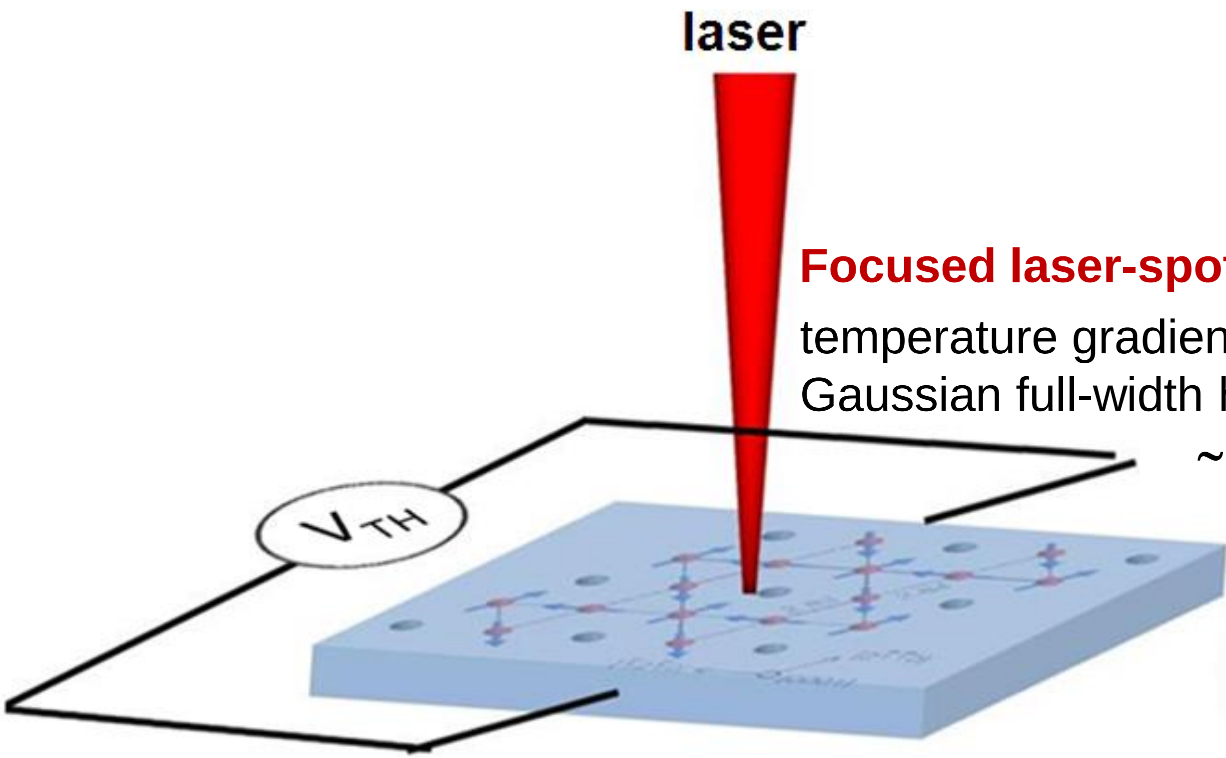
Godhino, et al. Nat Comm. 9, 4686 (2018)



PEEM – XMLD
(P. Wadley et al.)

WANTED: ALTERNATIVE (cheap) table-top DETECTION METHOD

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

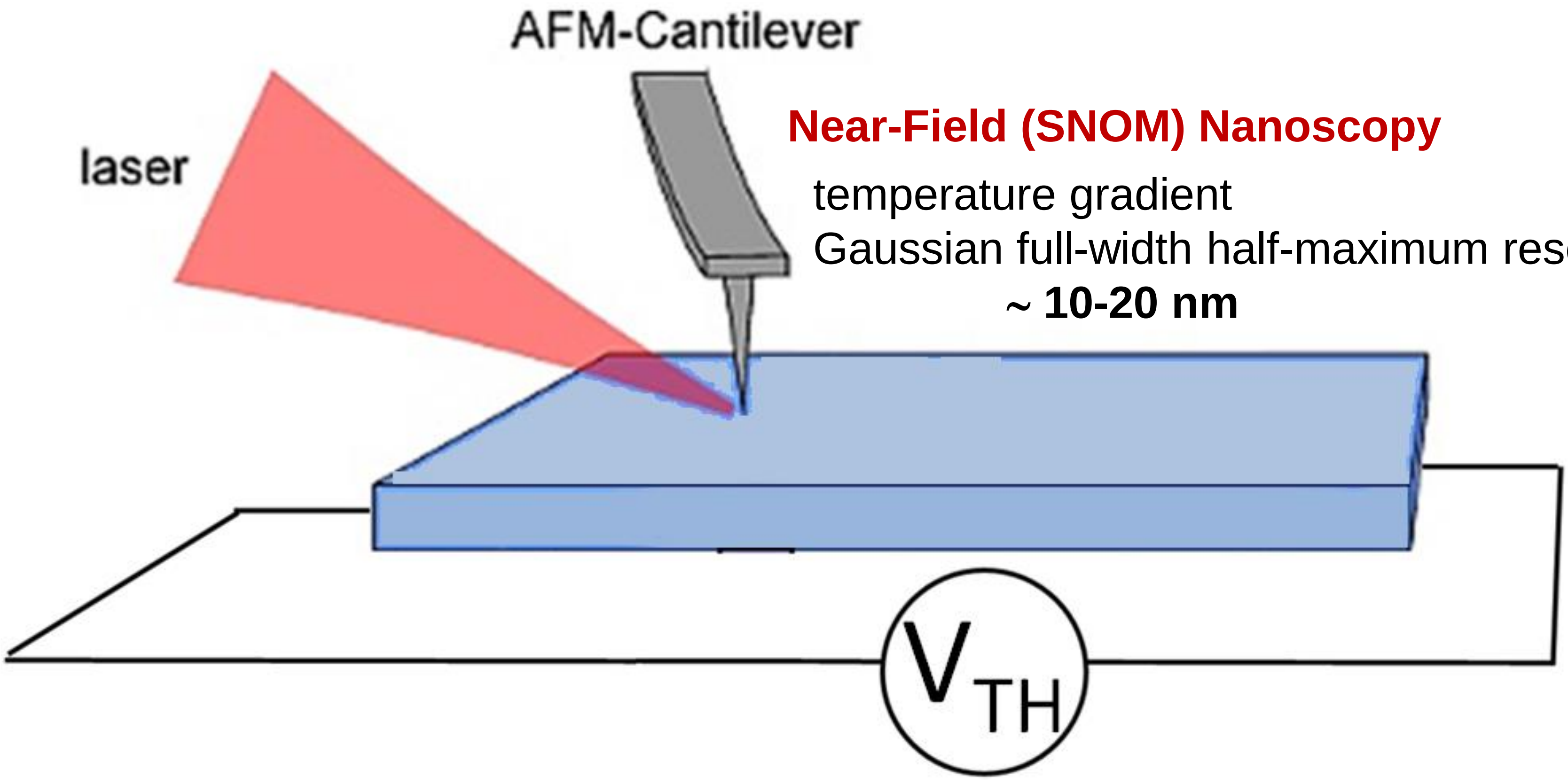


Focused laser-spot heating

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

ALTERNATIVE table-top DETECTION METHOD

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

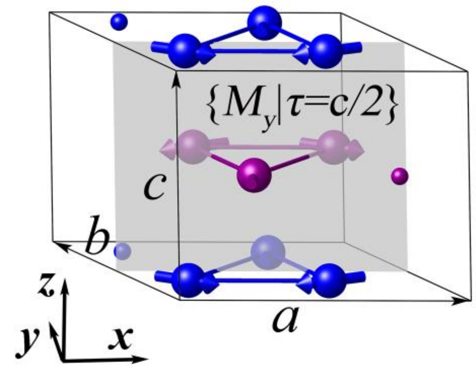


Near-Field (SNOM) Nanoscopy

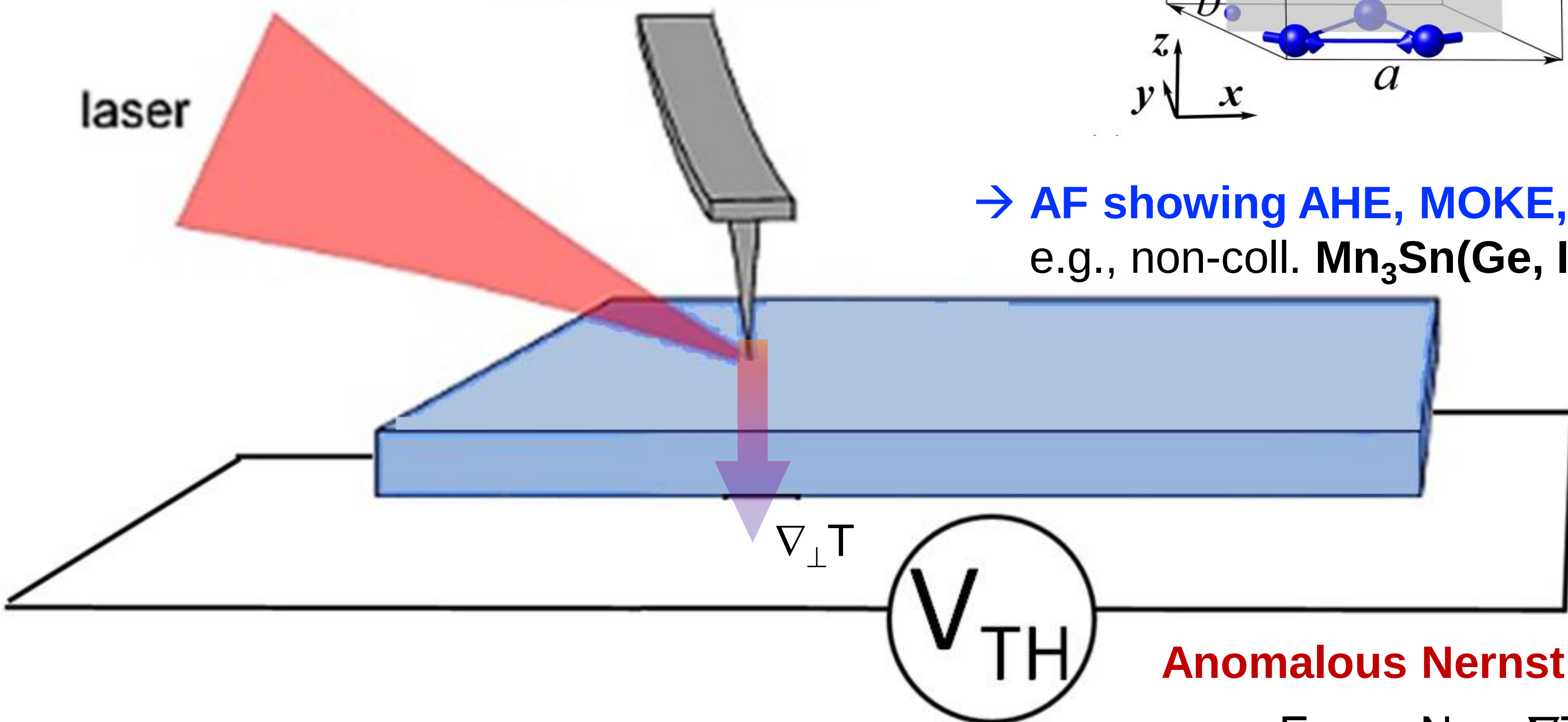
temperature gradient
Gaussian full-width half-maximum resolution:
~ **10-20 nm**

ALTERNATIVE table-top DETECTION METHOD

Generate <u>*locally*</u> **temperature gradient** *and*
measure <u>*globally*</u> **electric response**.



→ **AF showing AHE, MOKE, …,**
e.g., non-coll. **Mn_3Sn(Ge, Ir, …)**



Anomalous Nernst effect

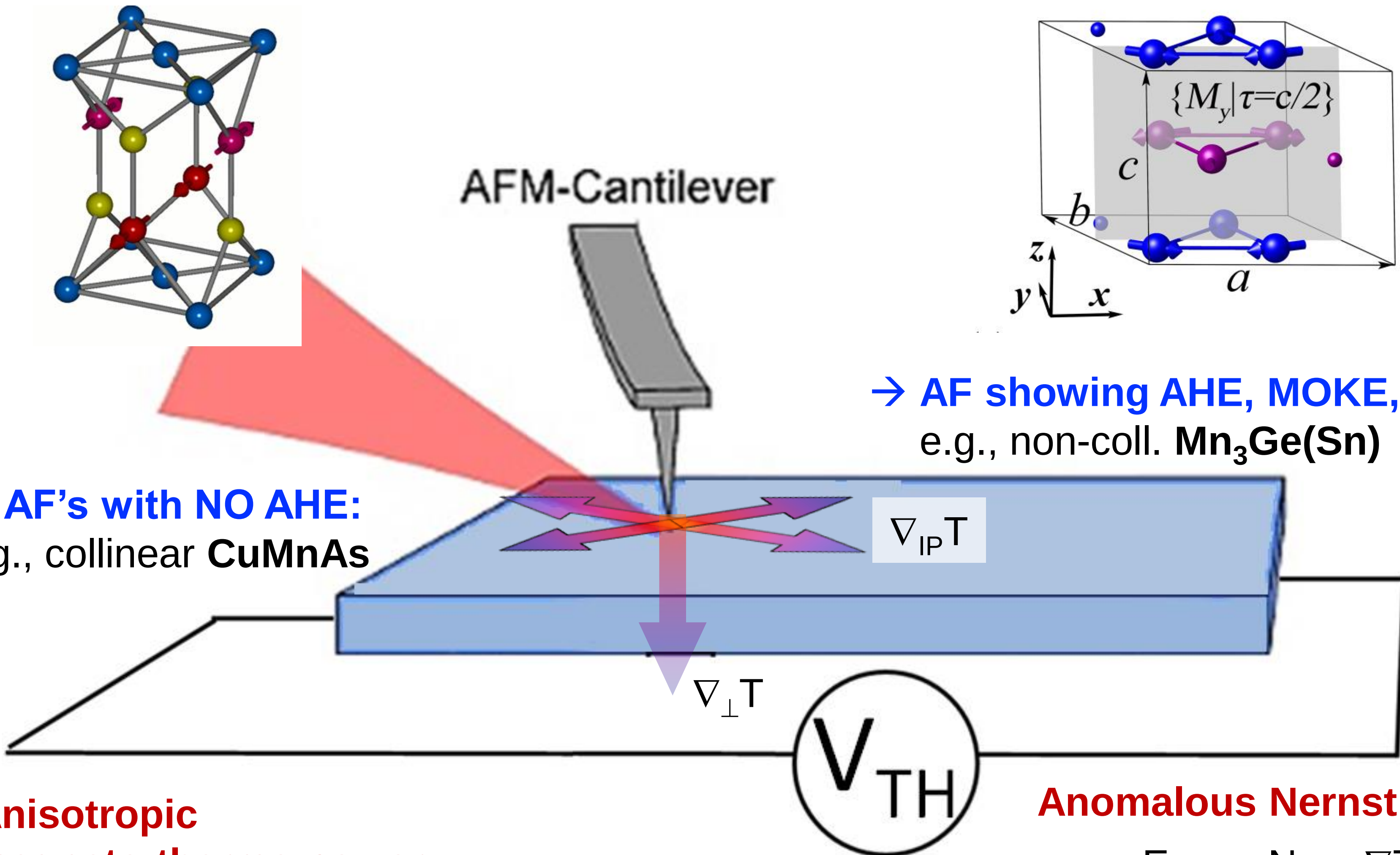
$$E_{bar} = -N_{ANE}\, \nabla T \times \mathbf{M}$$

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

H. Reichlova, et al., 3rd talk of this session,
arXiv:1905.13504 (2019)

ALTERNATIVE table-top DETECTION METHOD

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



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

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

Anisotropic magneto-thermo power

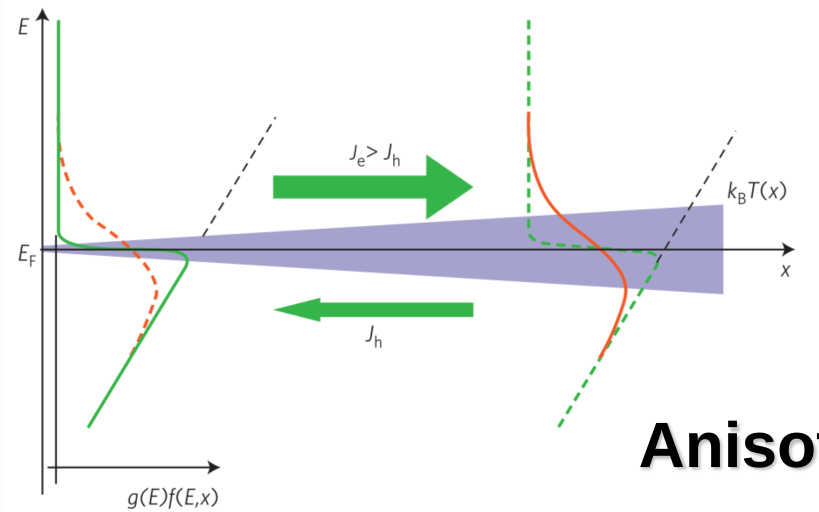
(thermoelectric equivalent to the **AMR**)

Anomalous Nernst effect

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

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

SEEBECK Effect

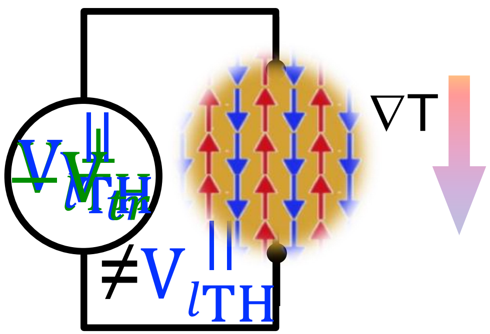


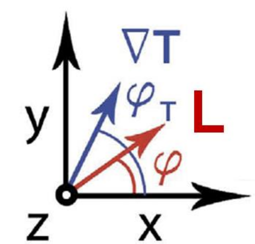
$$\begin{pmatrix}J_c\\ J_s\\ Q\end{pmatrix} = \sigma(\varepsilon_F)\begin{pmatrix}1 & P & ST\\ P & 1 & P'ST\\ ST & P'ST & \kappa T/\sigma\end{pmatrix}\begin{pmatrix}\nabla\mu_c/e\\ \nabla\mu_s/2e\\ -\nabla T/T\end{pmatrix}$$

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

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

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





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

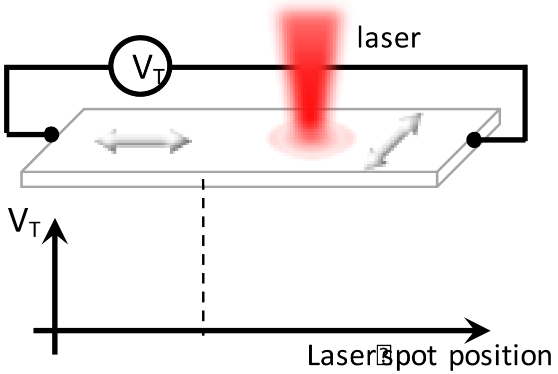
(response to the longitudinal temp. gradient)

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

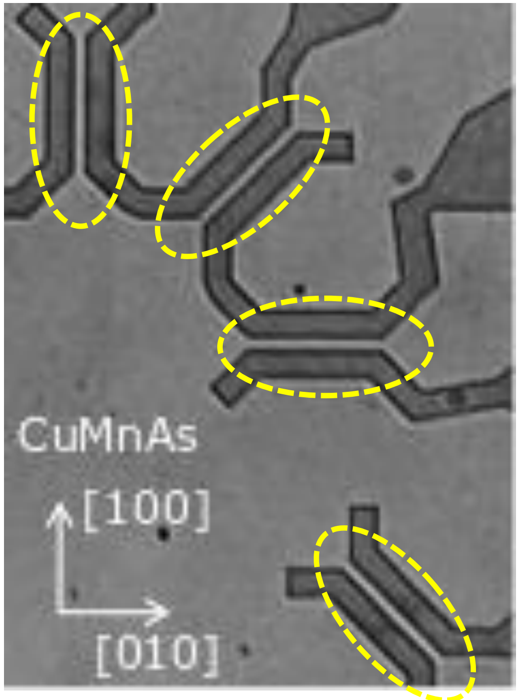
(response to the transverse temp. gradient)

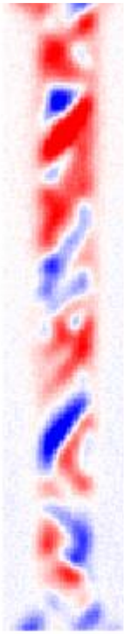
Thermoelectric signal in CuMnAs bars

Resulting thermoelectric signal

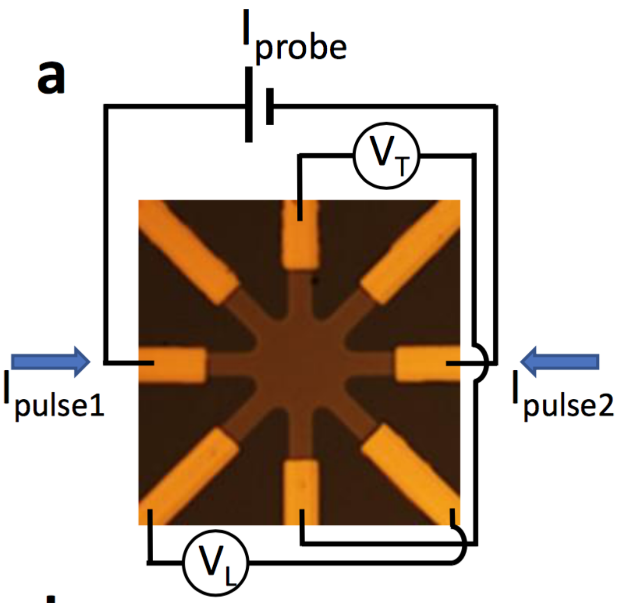


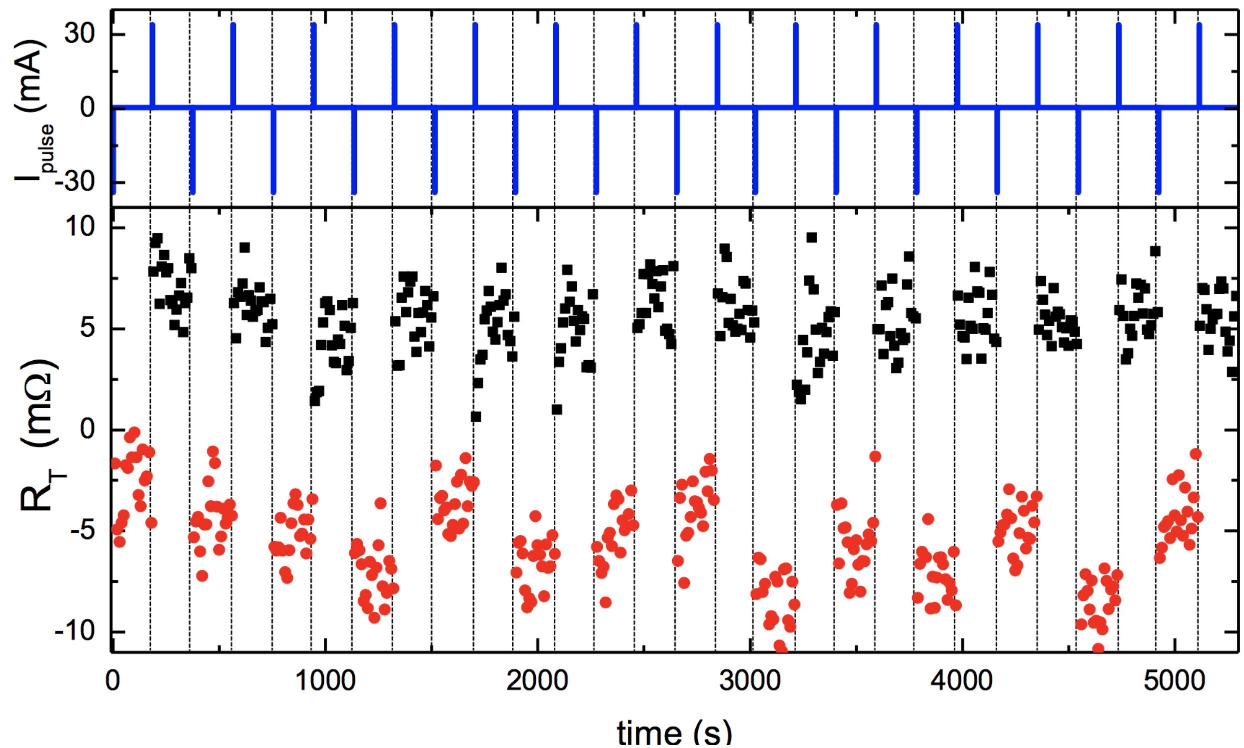
5 µm wide bars (45 nm thick CumnAs film)



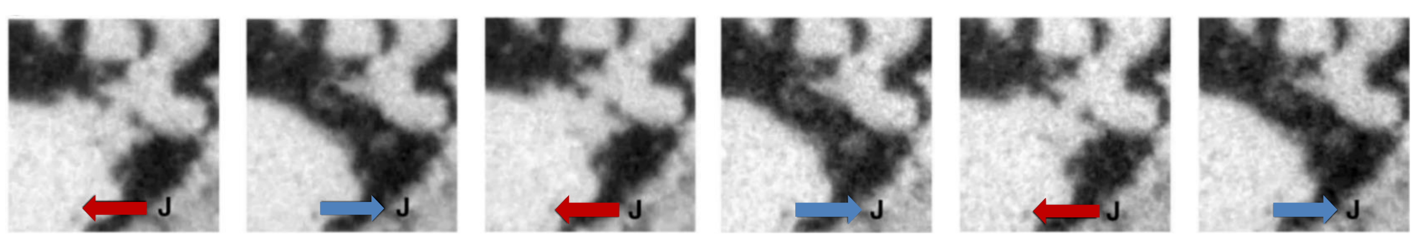


Current polarity dependent switching





XMLD-PEEM

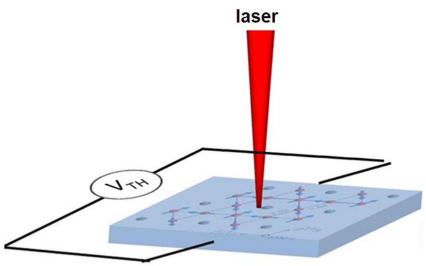


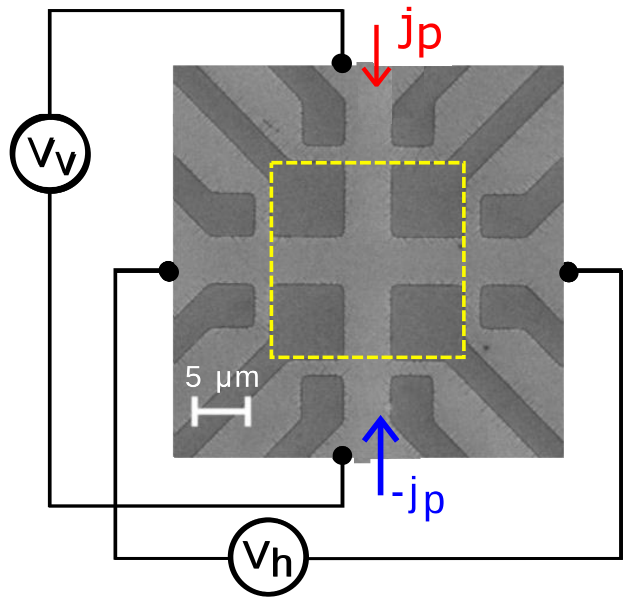
P. Wadley, et al., Nature Nano. (2018)

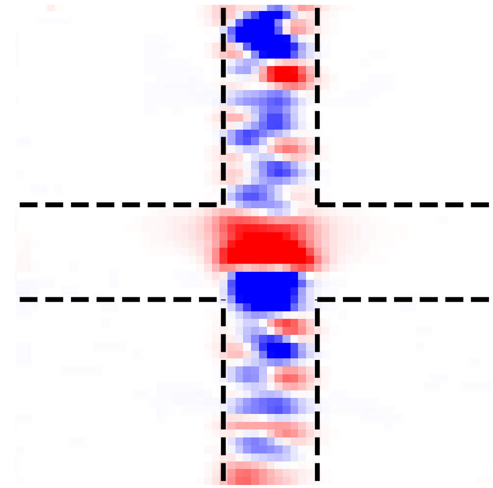
Current polarity dependent switching

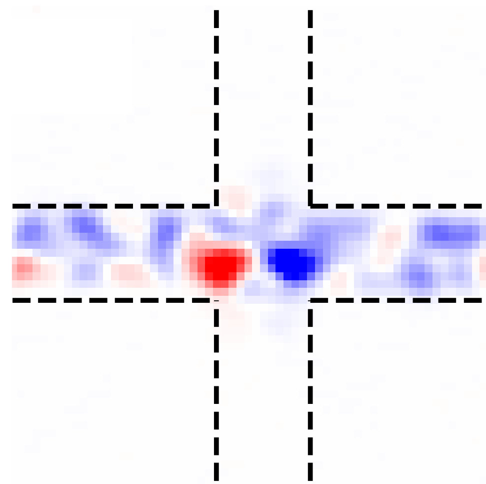
Cross bar geometry

Anisotropic magneto-thermo power

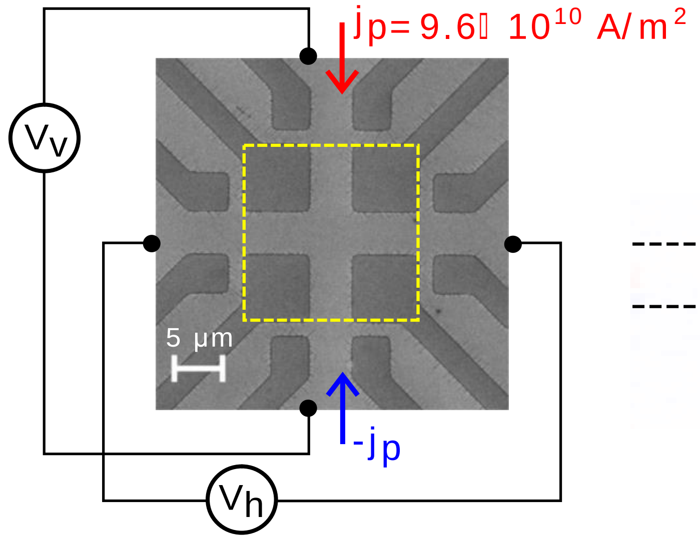


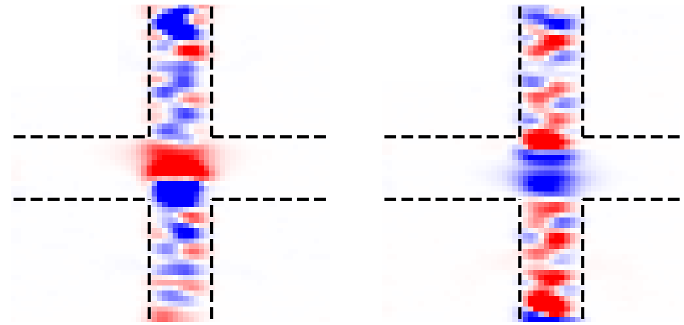




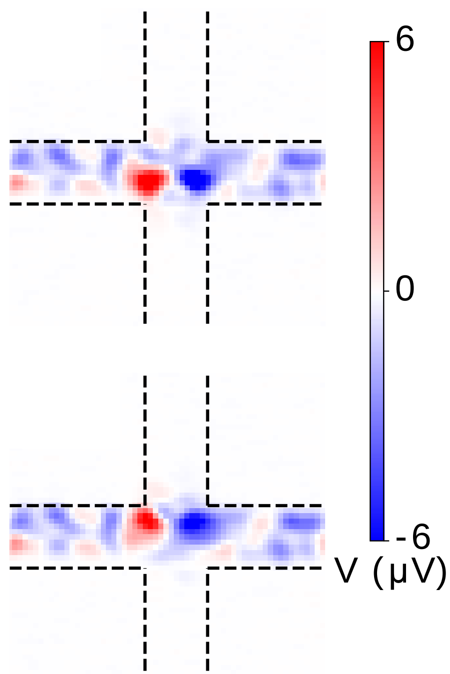


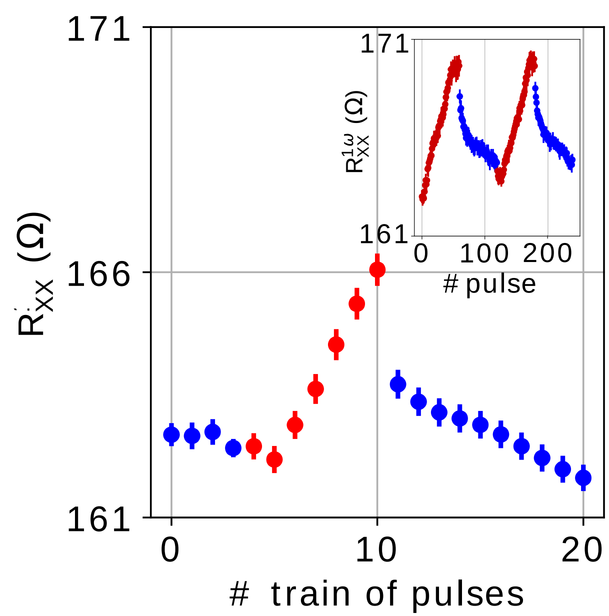
Current polarity dependent switching





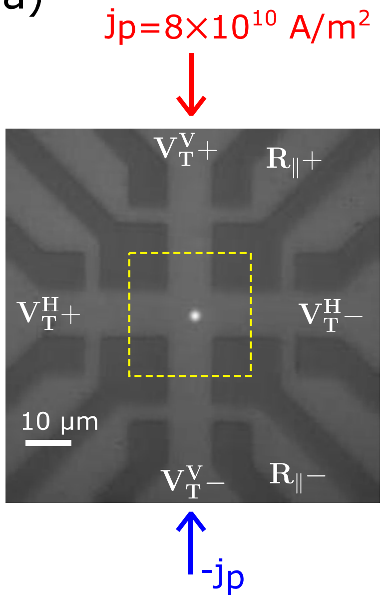
Associated resistance variation ~ 5%

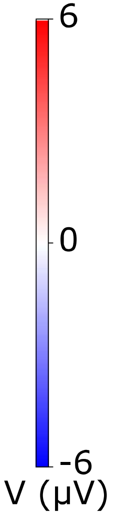




Current polarity dependent switching

(a)

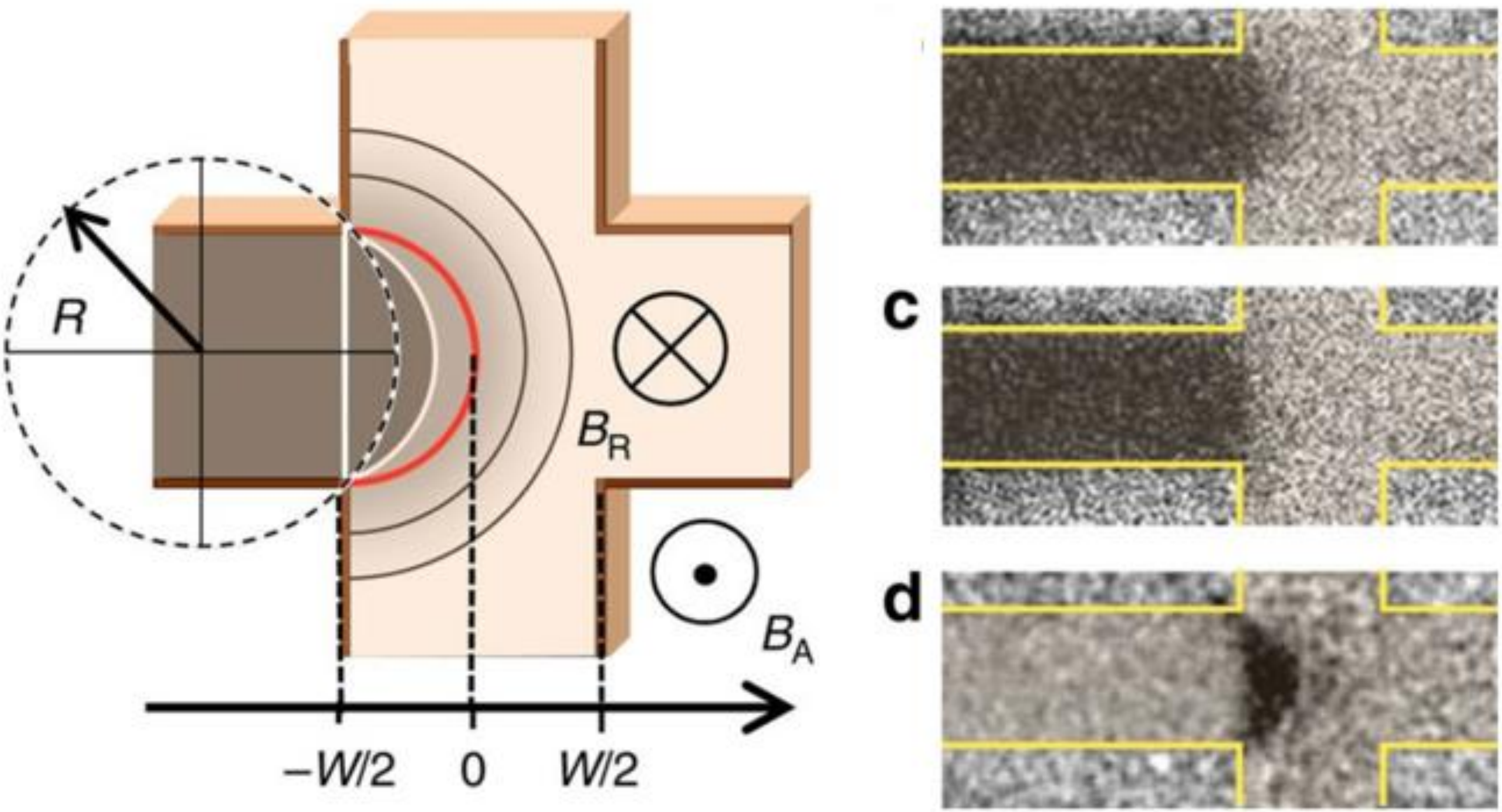




Current polarity dependent switching

Figure 2 : Soap-bubble-like domain wall expansion.

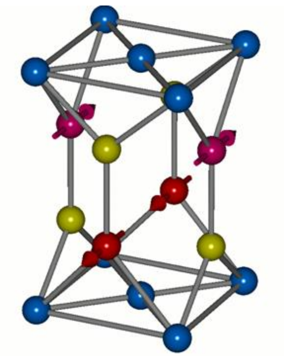
From: Inertial displacement of a domain wall excited by ultra-short circularly polarized laser pulses



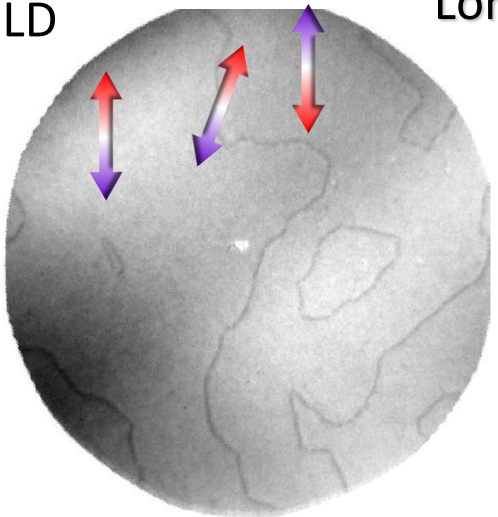
T. Janda, et al, Nat. Comm. 8, 15226 (2017)

CuMnAs with uniaxial anisotropy: 180° Néel magnetic DWs

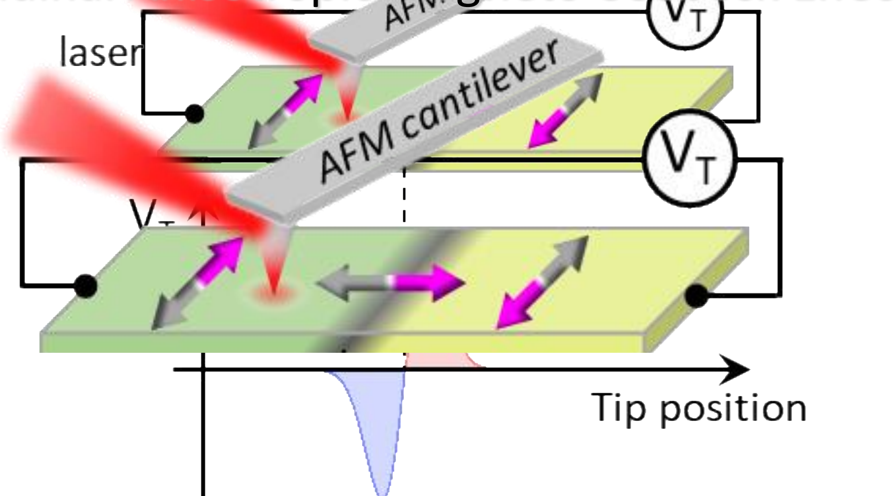
PEEM XMLD



CuMnAs



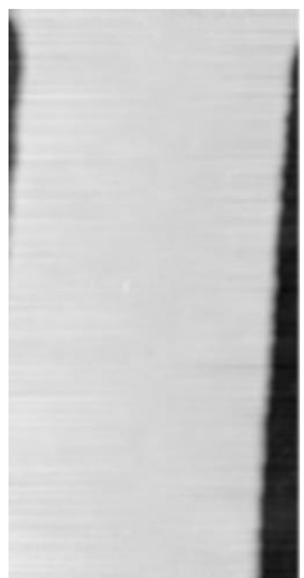
Longitudinal Anisotropic Magneto-Seebeck Effect



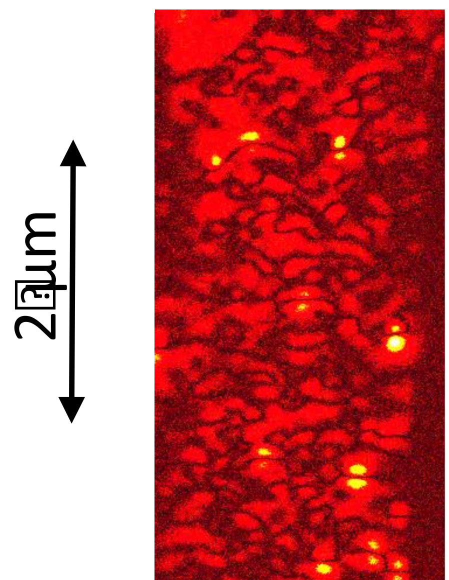
Near-field Nanoscopy:
AFM + thermal voltage

thin 20nm CuMnAs (wafer O 049)

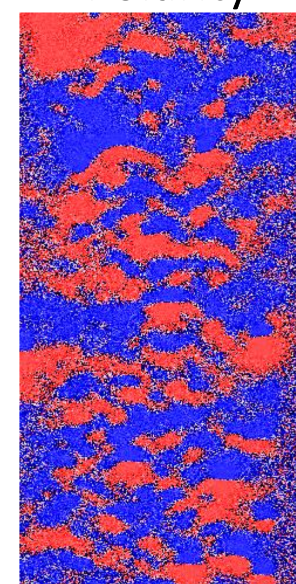
AFM (~1nm res.)
(2 µm wide stripe)



Thermovoltage
Magnitude



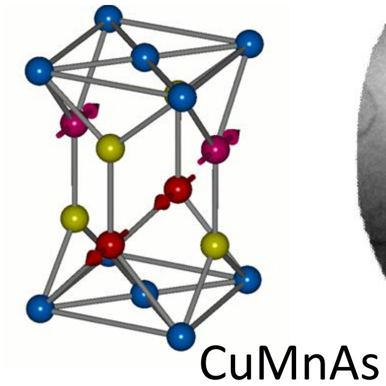
Thermovoltage
Polarity

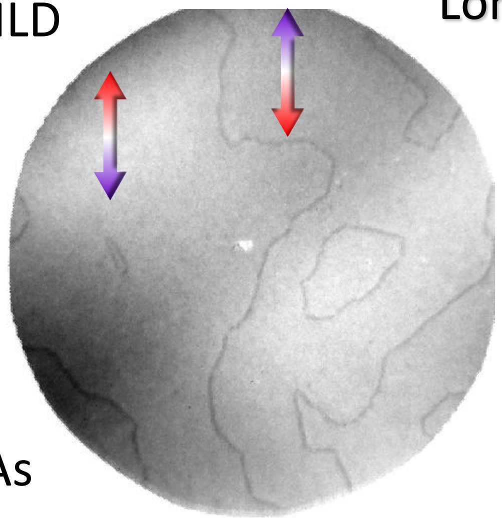


(~20 nV amplitude, 0.01 GW/m^2 power density)

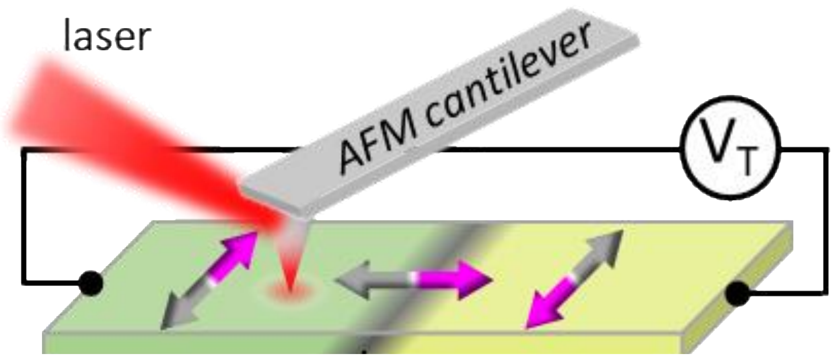
AF with uniaxial anisotropy: 180° Néel magnetic DWs

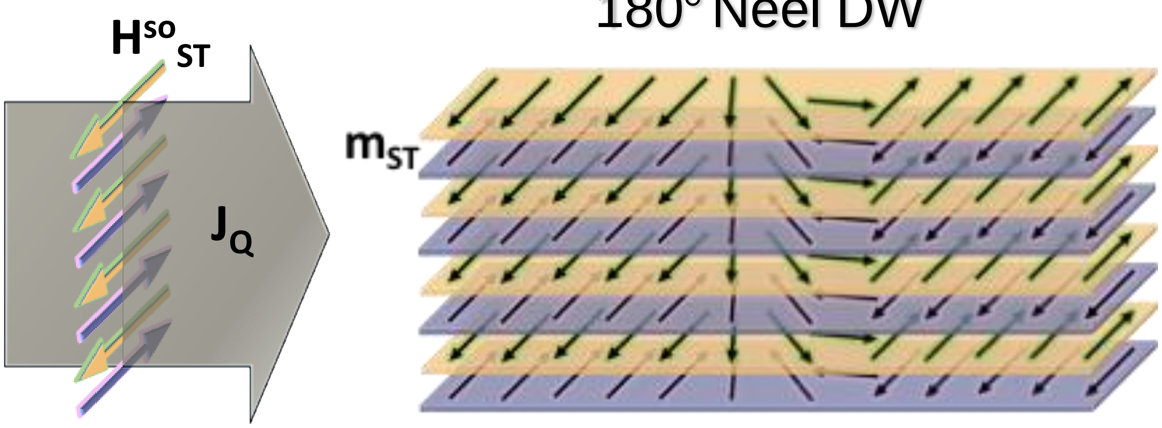
PEEM XMLD





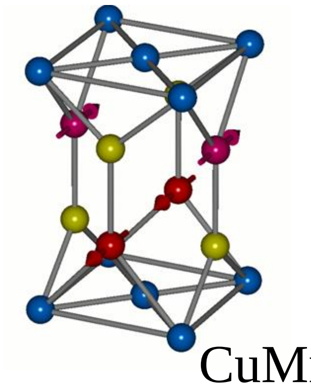
Longitudinal Anisotropic Magneto-Seebeck Effect



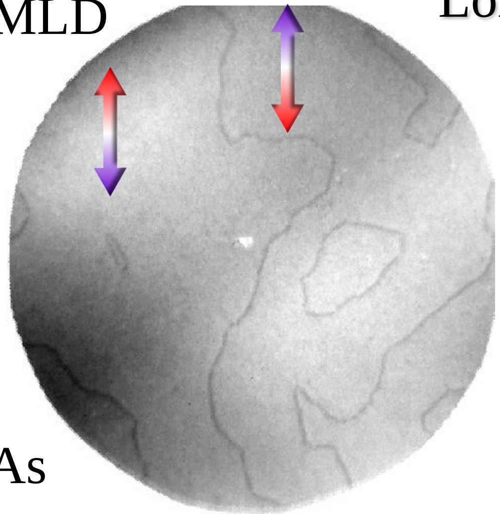


AF with uniaxial anisotropy: 180° Néel magnetic DWs

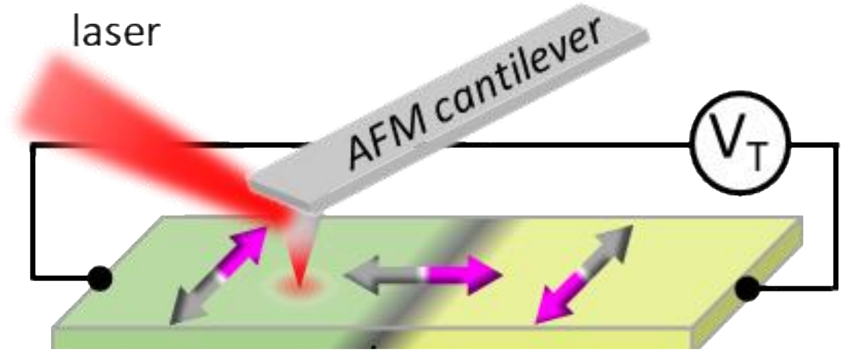
PEEM XMLD

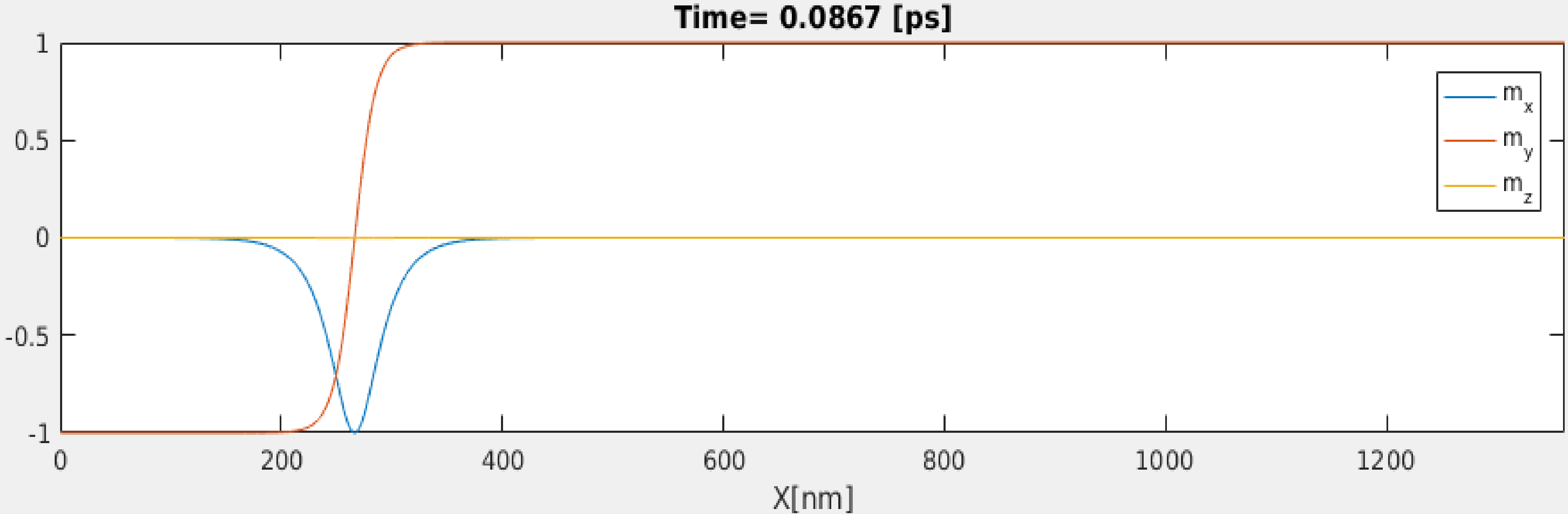


CuMnAs

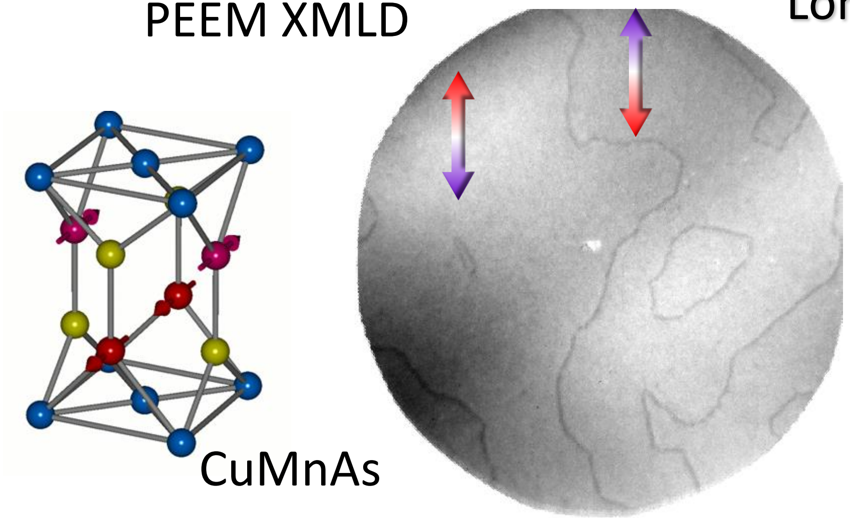


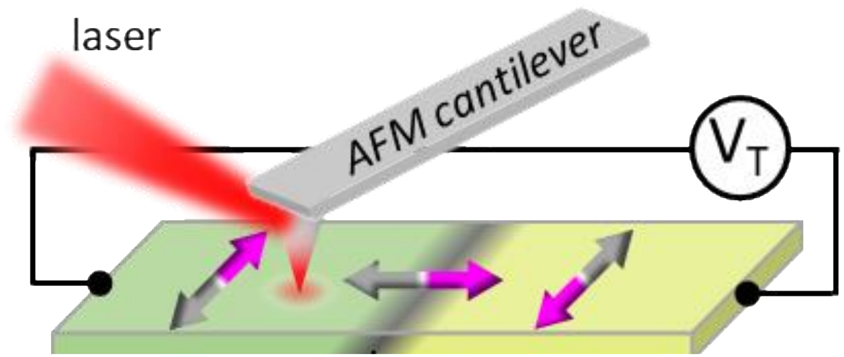
Longitudinal Anisotropic Magneto-Seebeck Effect

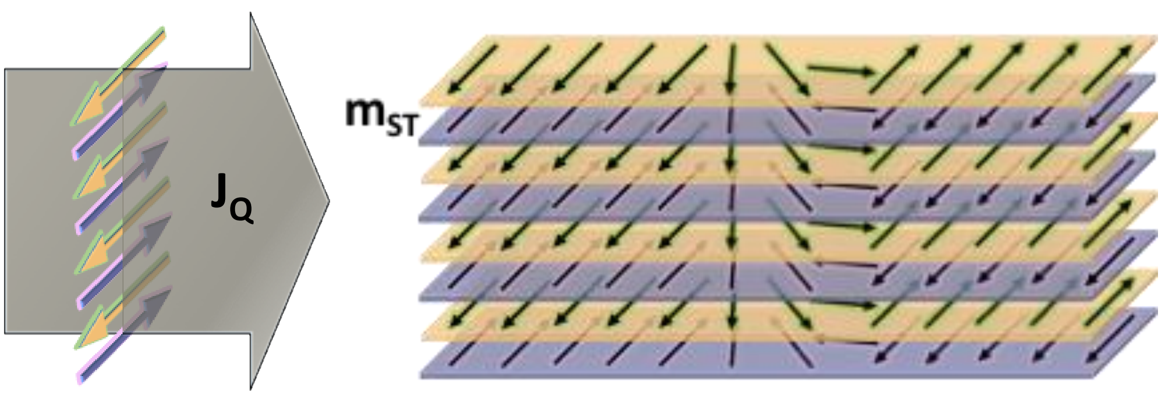


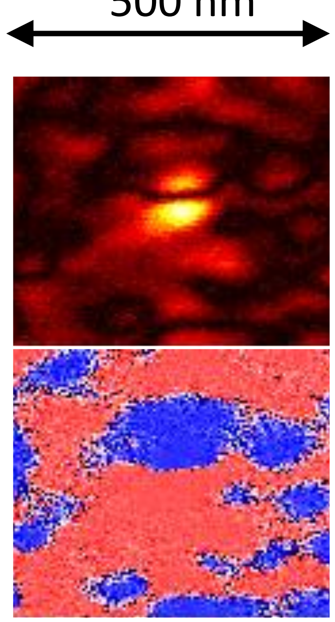


AF with uniaxial anisotropy: 180° Néel magnetic DWs





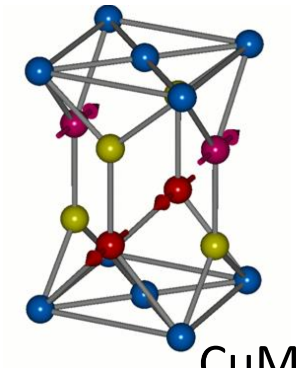


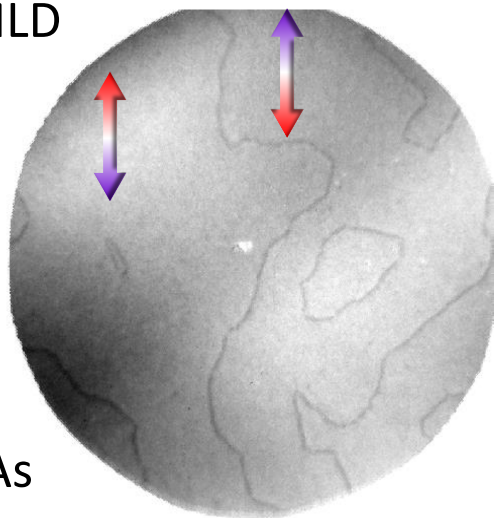


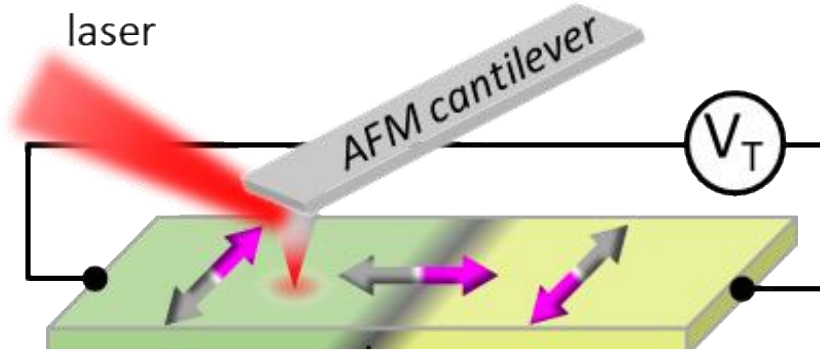
(~50 nV amplitude, 0.01 GW/m^2 power density)

AF with uniaxial anisotropy: 180° Néel magnetic DWs

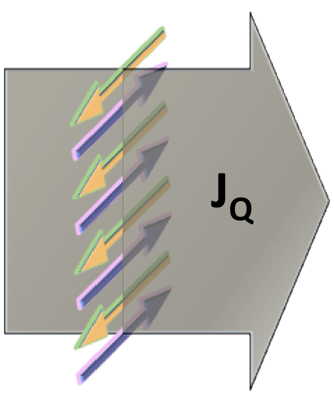
PEEM XMLD

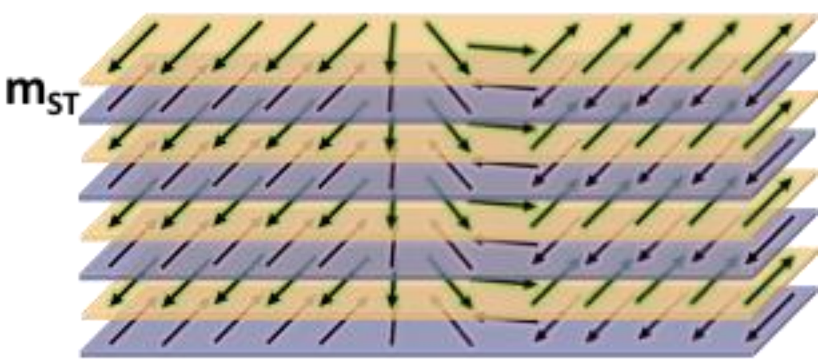


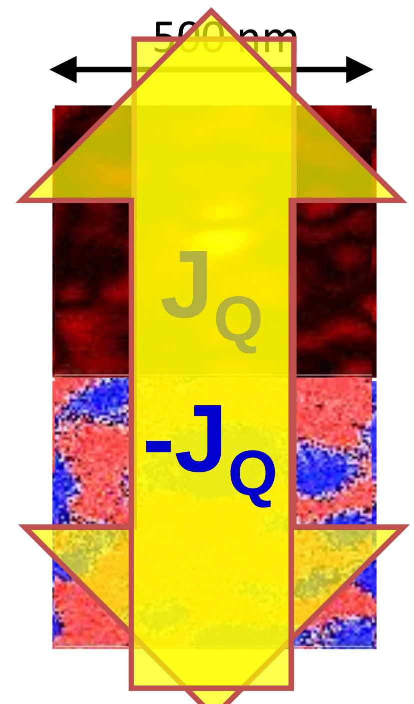




J_Q ~3 x 10^{10} A/m^2



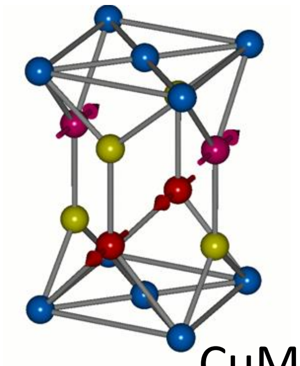




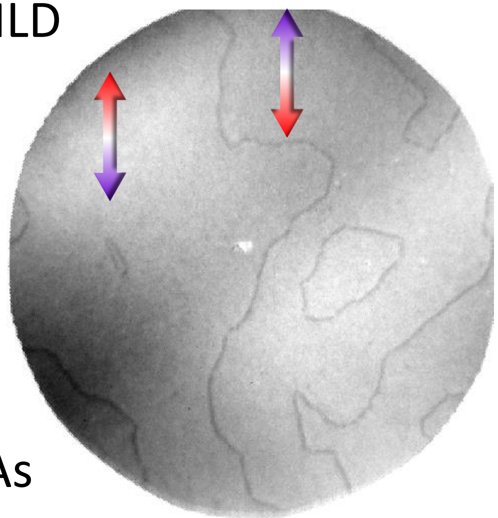
(~50 nV amplitude, 0.01 GW/m^2 power density)

AF with uniaxial anisotropy: 180° Néel magnetic DWs

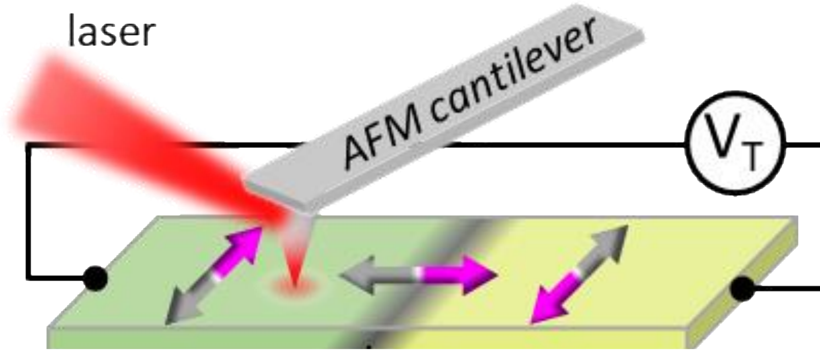
PEEM XMLD



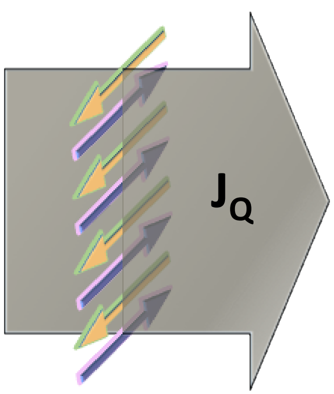
CuMnAs

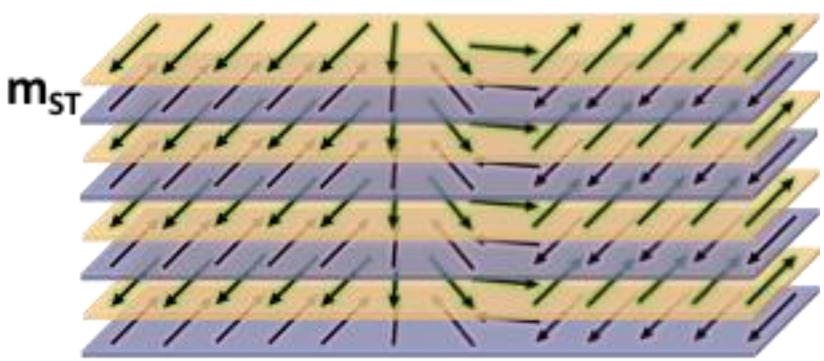


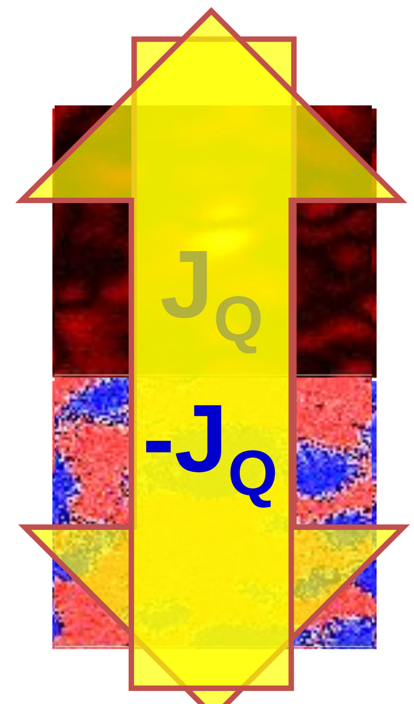
Anisotropic Magneto-Seebeck Effect



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



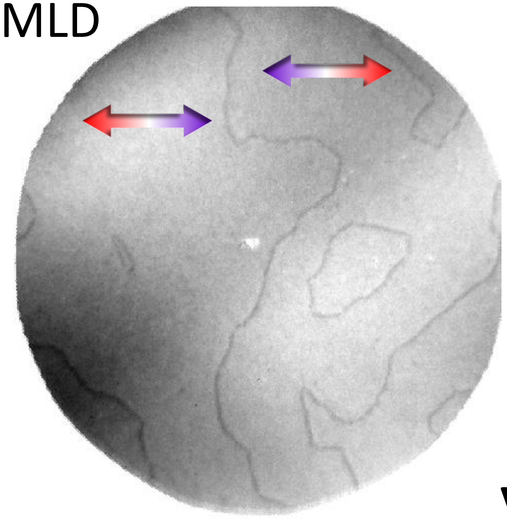


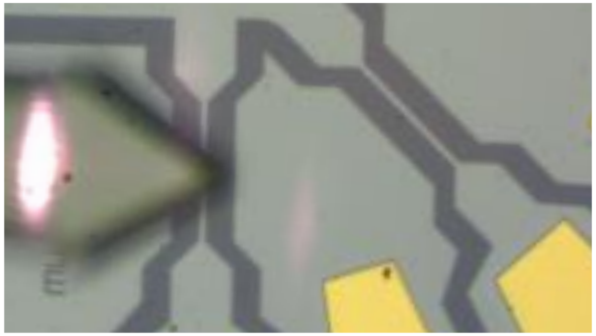


(~50 nV amplitude, 0.01 GW/m^2 power density)

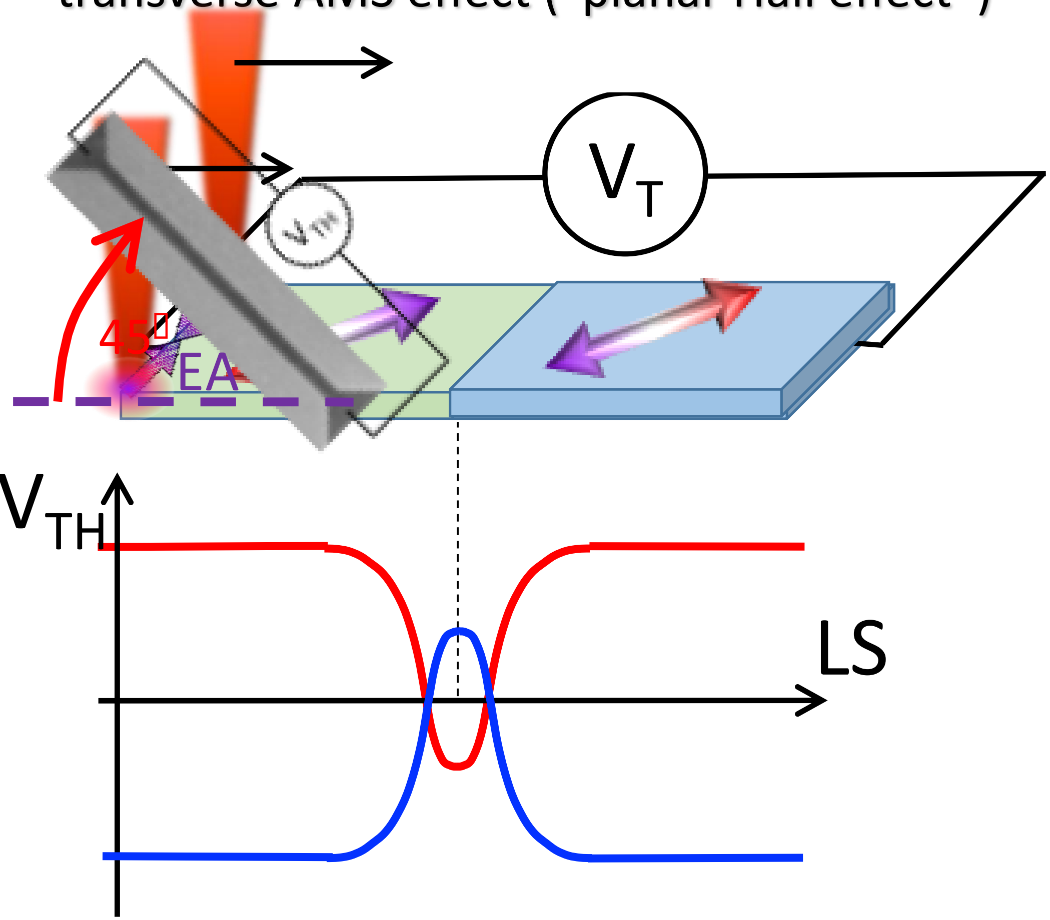
AF with uniaxial anisotropy: transversal temp. gradient

PEEM XMLD



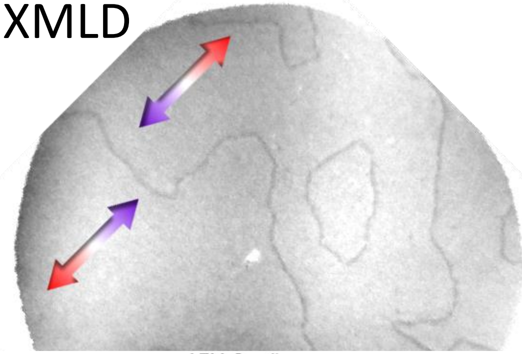


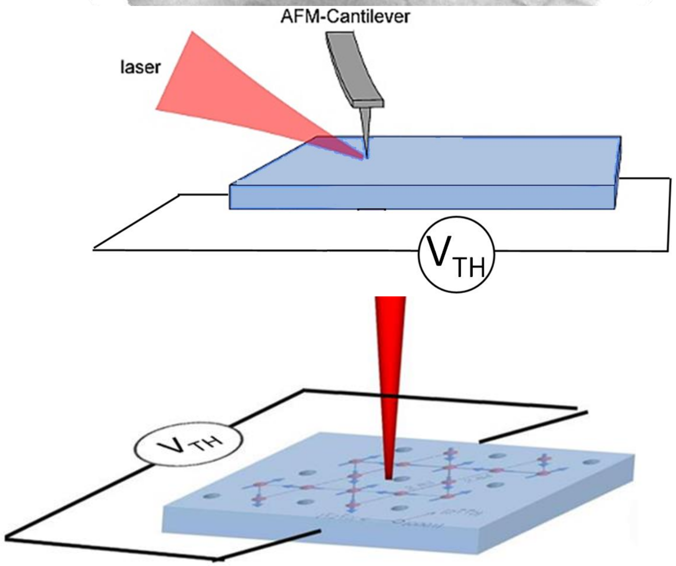
transverse AMS effect (“planar Hall effect”)



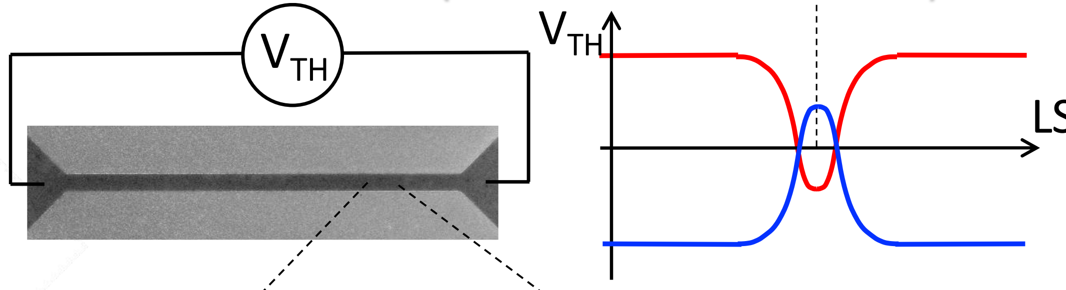
AF with uniaxial anisotropy: transversal temp. gradient

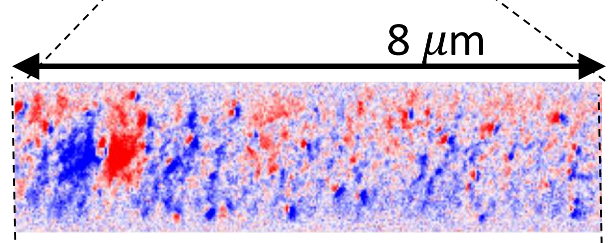
PEEM XMLD



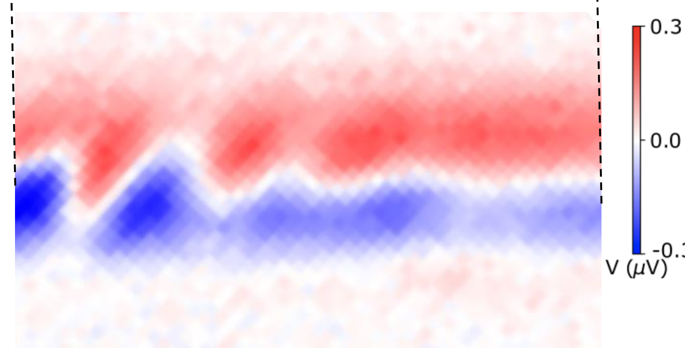


Planar Hall effect (transverse AMS effect)

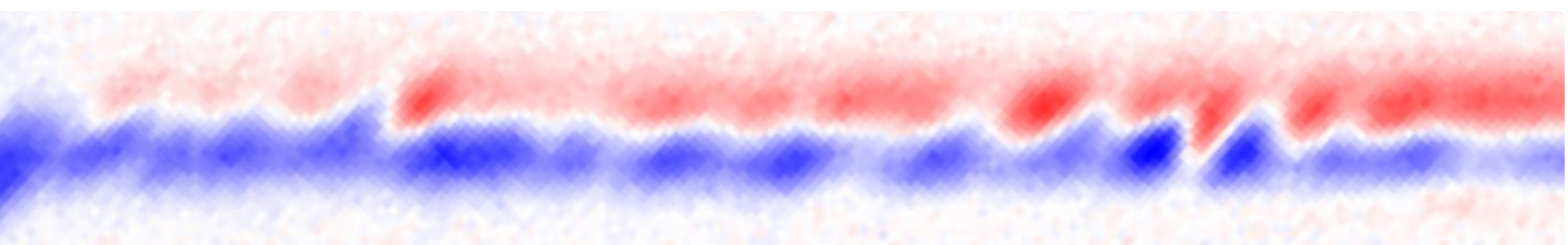




Nearfied Nanoskopy



Scanning Laser Spot

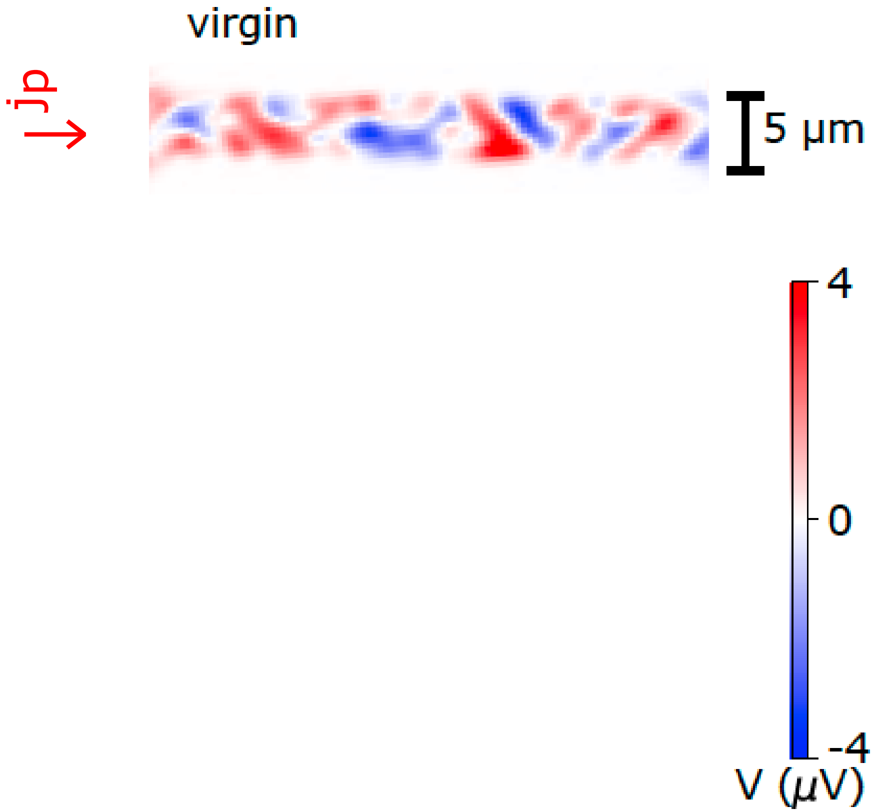


LARGE CURRENT PULSES: Shuttering large domains into multiple small domains

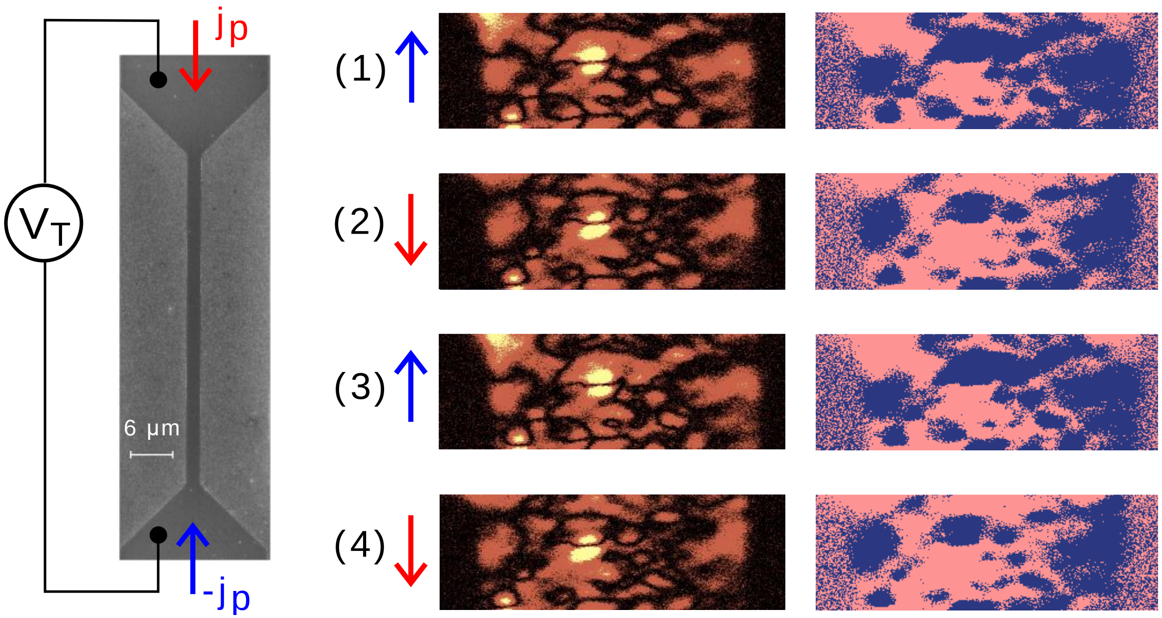
(related to talks on Monday from T. Jungwirth and K. Olejnik)

XMLD-PEEM

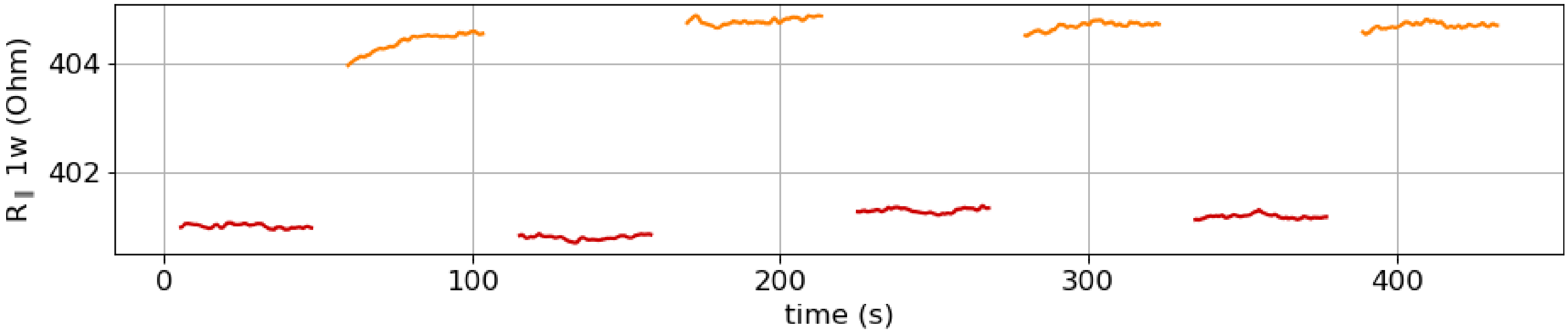
AMS effect measured with foscused Laser spot



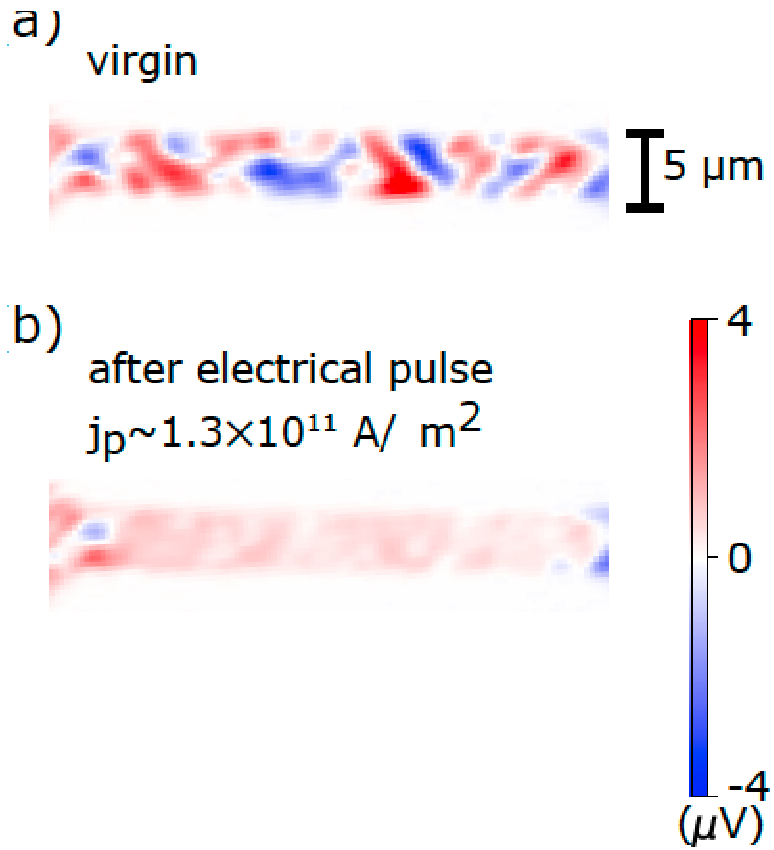
SOT bipolar switching



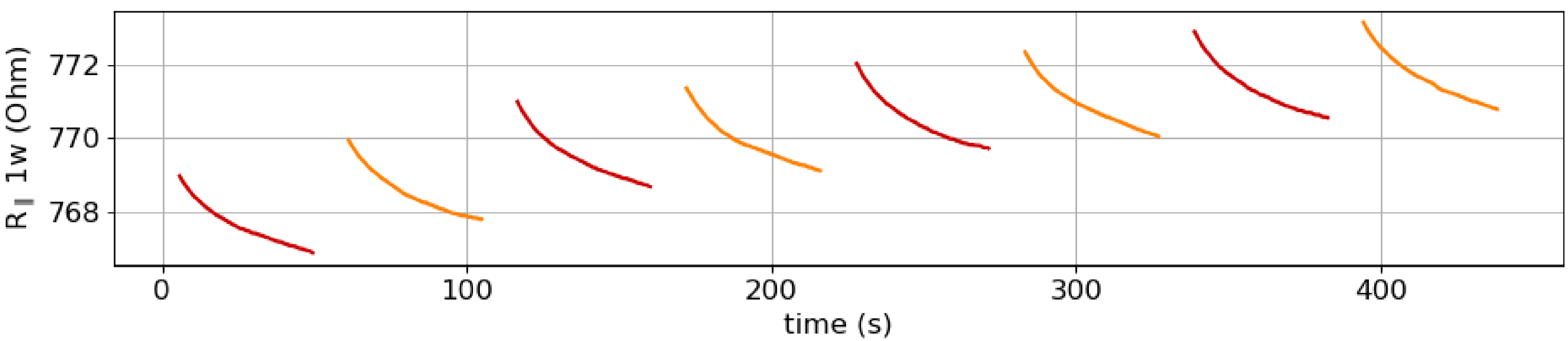
$J_P = 1.6 \times 10^7$ A/cm^2



Thermal (unipolar) switching



$J_P = 2.8 \times 10^7$ A/cm^2



Summary

SCANNING MICROSCOPY based on the magneto-anisotropic Seebeck effect

- Wavelength restricted **“far-field”** and high-resolution **“near-field”** technique

OBSERVATION:

- Effect of **patterning on the antiferromagnetic domain structure** in CuMnAs bars

- **Reversible** and **current polarity dependent SOT switching** showing **correlated resistance variations** in CuMnAs films with uniaxial and biaxial magnetic anisotropy

-

- **Shattering of large antiferromagnetic domains** by high magnitude current pulses

Thank you!