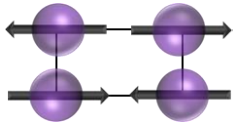
Helena Reichlova
IFMP Technische Universität Dresden

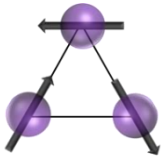
Imaging non-collinear antiferromagnetism by Scanning Thermal Gradient Microscopy

- Richard Schlitz, Sebastian Goennenwein (TU Dresden)
- Joerg Wunderlich, Joao Godinho, Jakub Zelezny, Tomas Jungwirth (FZU Prague)
- Tomas Janda, Petr Nemec (Matfyz, Charles University Prague)
- Dominik Kriegner, Anastasios Markou, Claudia Felser (CPfS MPI Dresden)
- Jay Koo, Philipp Zilske, Günter Reiss (Uni Bielefeld)

https://arxiv.org/abs/1905.13504

Collinear vs. Non-Collinear Antiferromagnets





- key experiments (CuMnAs…)
- including imaging (XMLD-PEEM…)
- STT predicted weak…

- anomalous Hall Effect demonstrated
[Nakatsuji et al., Nature (2015)]
- anomalous Nersnt effect demonstrated
[Nakatsuji et al., Nat.Phys. (2017)]
- theoretically predicted STT and GMR
[Zelezny et al., PRL (2017)]

STT/GMR/domain movement experimentally…?

- **thin epitaxial films** [Markou et al., PRM (2018)]
- tool to image ***non-collinear antiferromagnetism***

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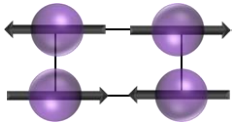

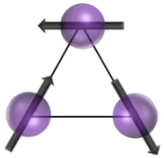

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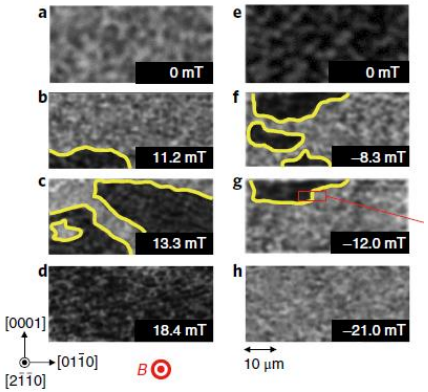
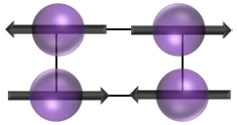


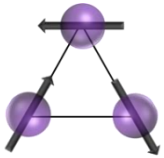
MOKE ?? [Higo et al., Nat.Phot. (2018)]

..but:

x MOKE is surface sensitive
x MOKE is spectrally dependent
(comparing materials/thicknesses…)
x Geometry of MOKE and STGM experiment for films
x Resolution limit of wavelenght..

Collinear vs. Non-Collinear Antiferromagnets





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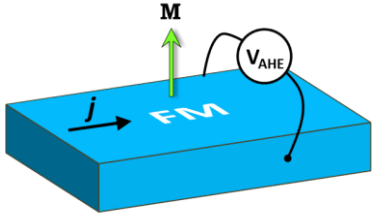
→ **Scanning Thermal Gradient Microscopy**

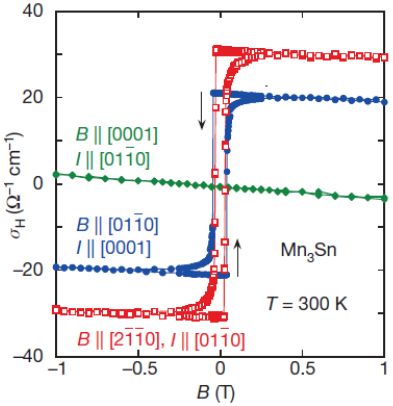
- including *buried* layers
- including domain writing

Reminder: Anomalous Nernst Effect

Anomalous Hall Effect (AHE)

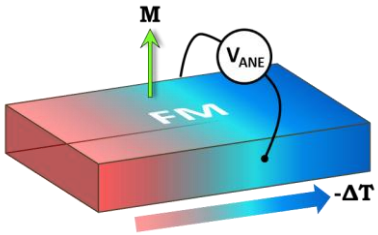


$$V_{AHE} \sim \mathbf{m} \times \mathbf{j}$$

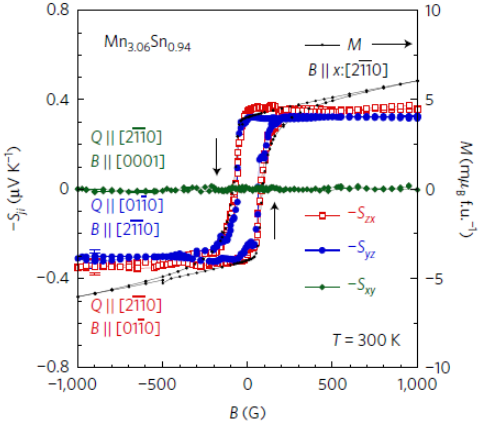


Bulk Mn_3Sn
Nakatsuji et al., Nature (2015)

Anomalous Nersnt Effect (ANE)



$$\frac{V_{ANE}}{\text{contacts distance}} = -N_{ANE}\,\mathbf{m} \times \nabla \mathbf{T}$$

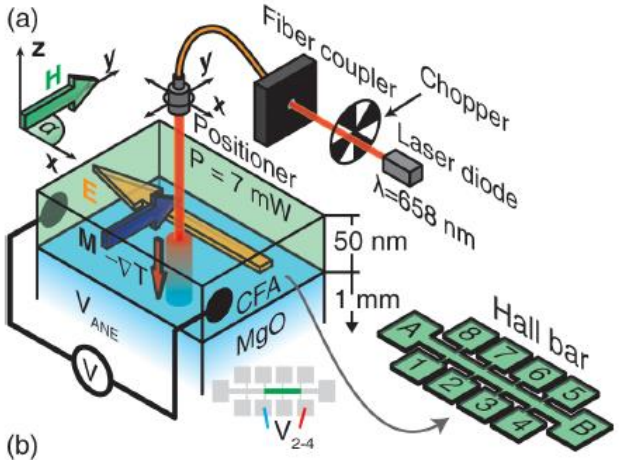


Bulk Mn_3Sn
Ikhlas et al., Nat.Phys. (2017)

- Bulk Mn_3Sn: **strong anisotropy!**
- Epitaxial Mn_3Sn thin films: [0001] out of film plane
  => uneasy AHE geometry
  => great for out of plane ∇T geometry

Idea of the Scanning Thermal Gradient Microscopy (STGM)

Known in **ferromagnets**...



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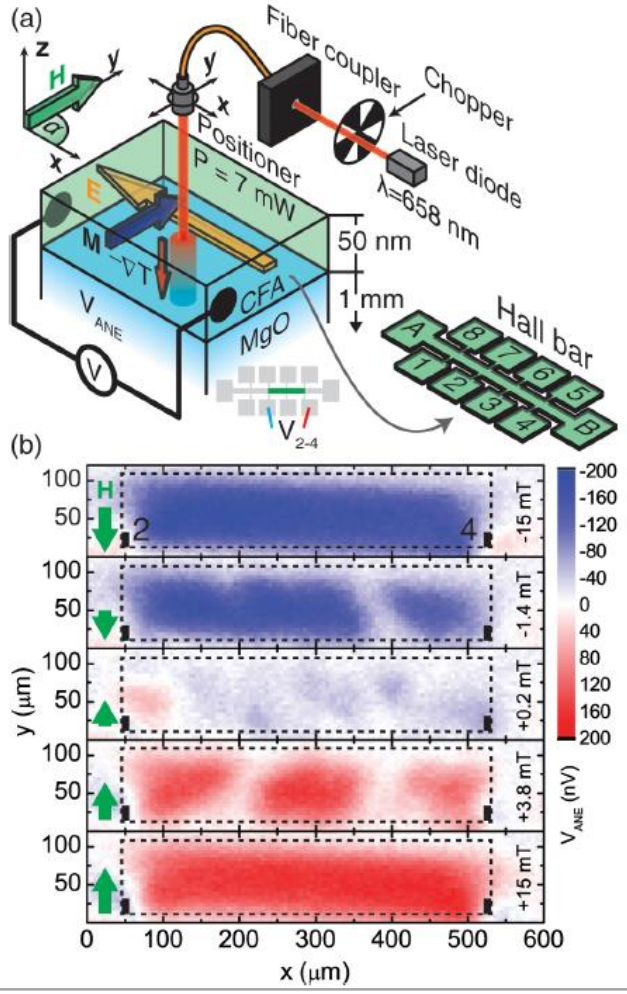

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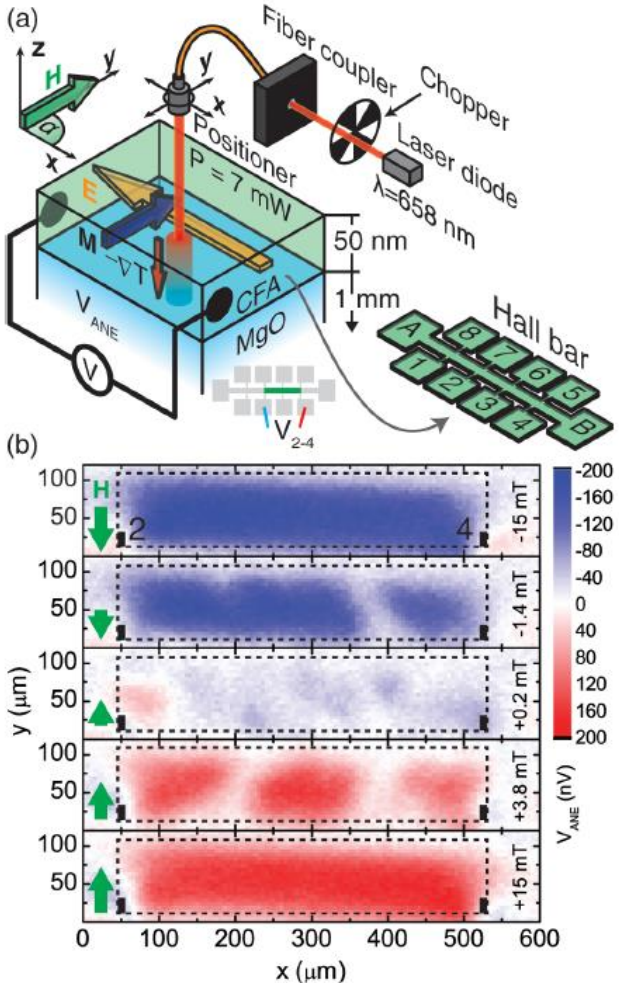

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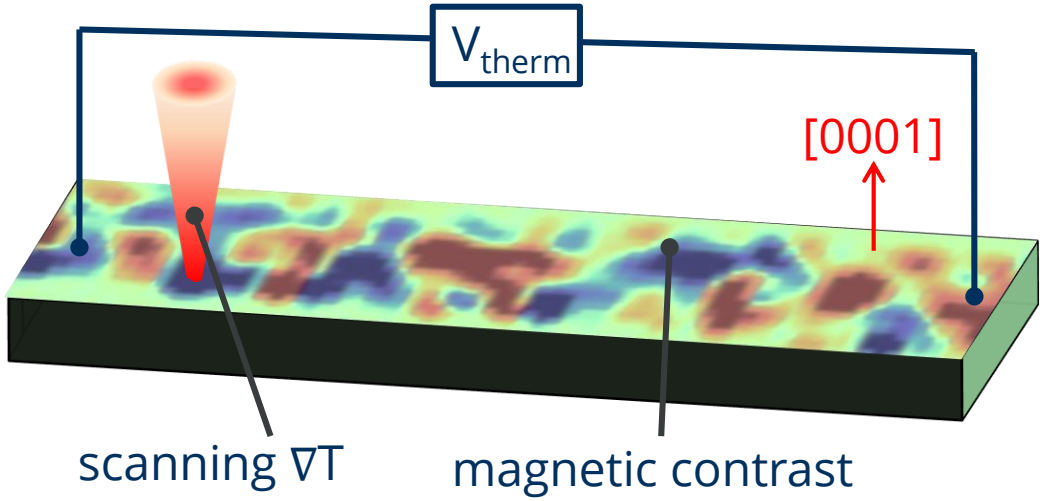
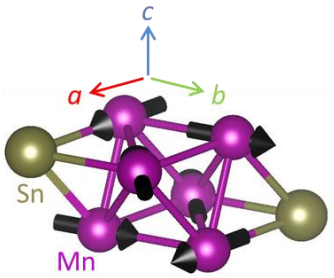


- Mn_3Sn thin film
- T_N ~ 420K
- spins in sample plane



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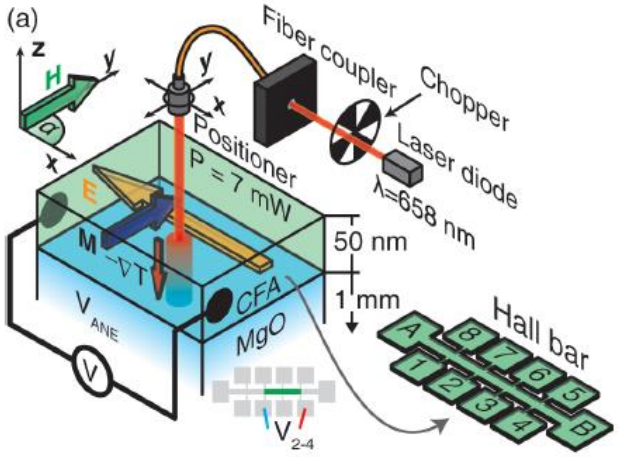

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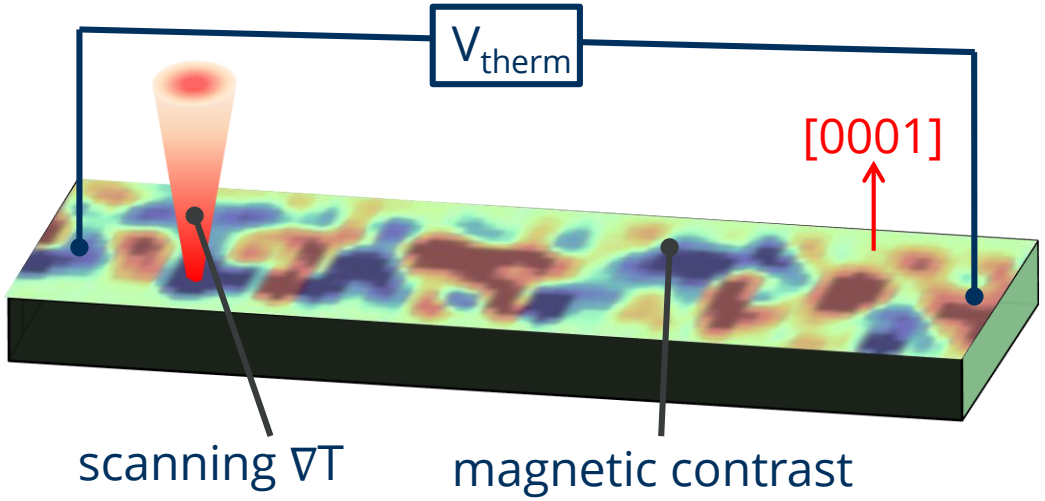
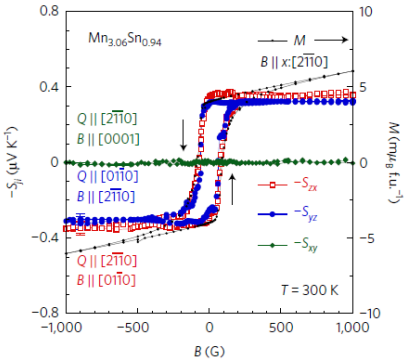
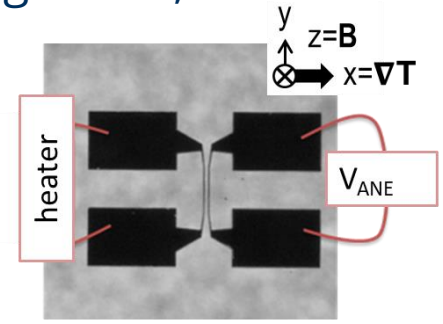
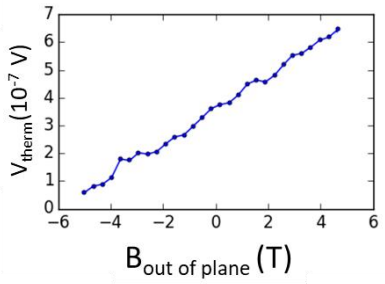


laser induced ∇T:

- in plane component averaged out; even if remains (sides): ANE not expected







quick consistency check on our thin films

Idea of the Scanning Thermal Gradient Microscopy (STGM)

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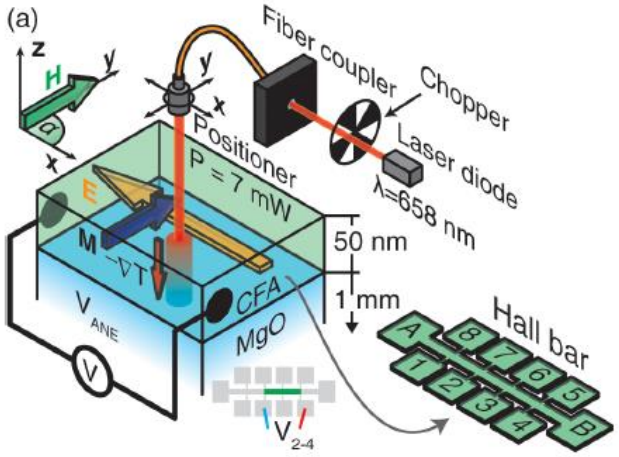

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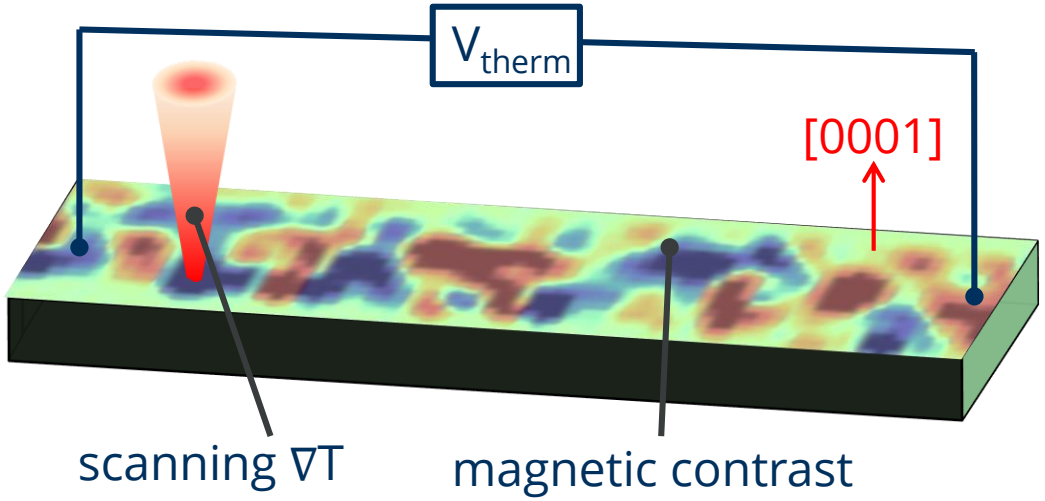

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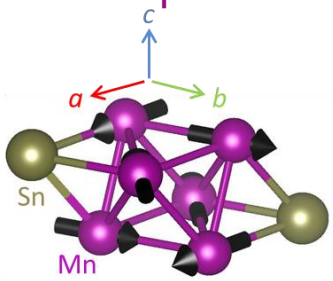
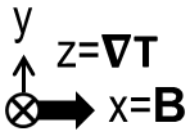
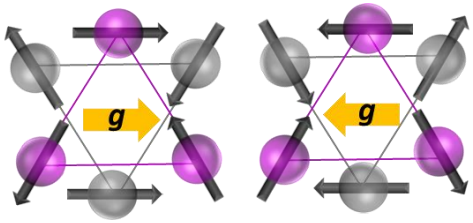
- out of plane ∇T

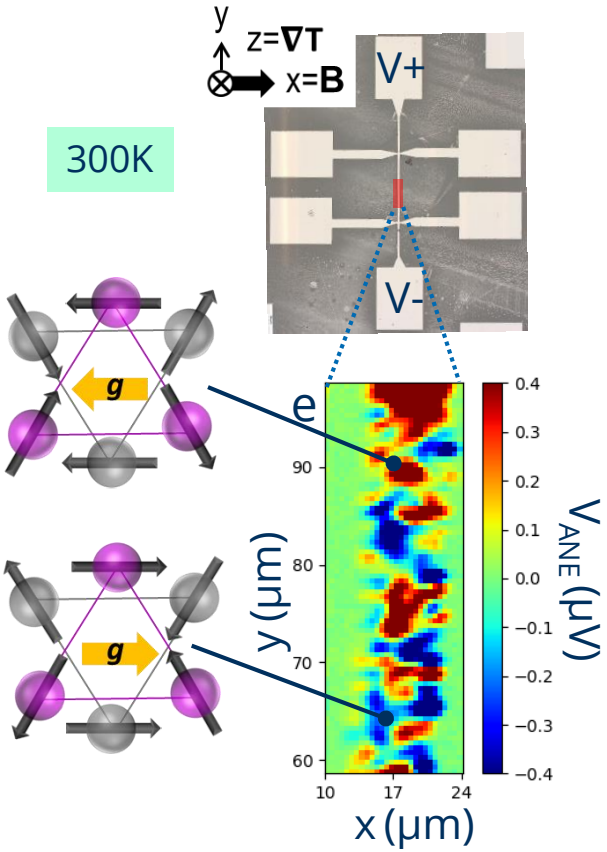






opposite Hall vector
=> opposite ANE

Results of the STGM: spatial imaging

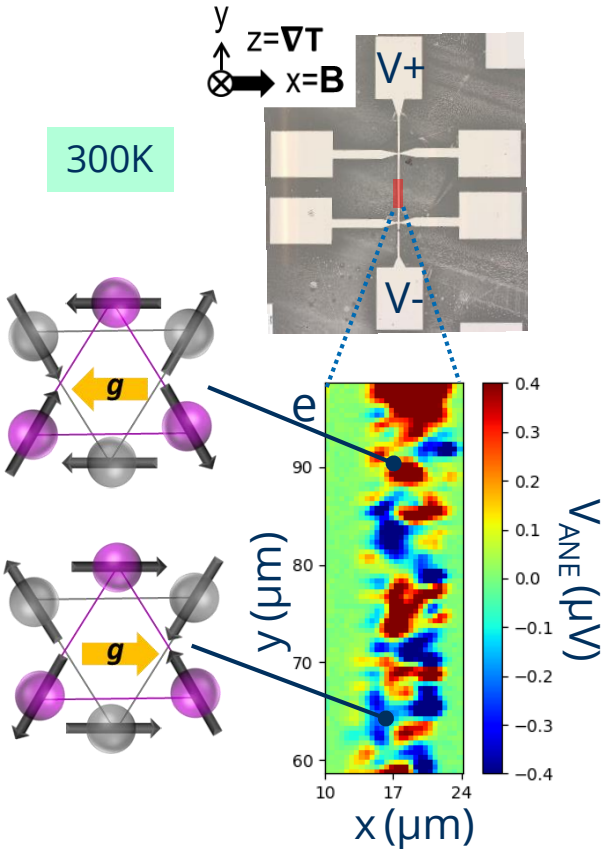


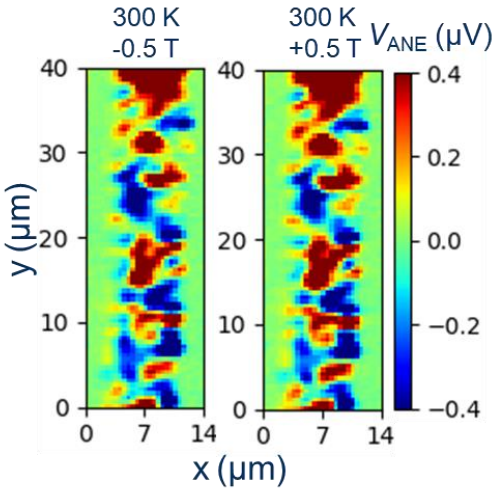
$MgO/Ru(5nm)/Mn_3Sn(50nm)/AlO_x$

✓ **spatial imaging**
??? magnetic origin

Results of the STGM: spatial imaging

Apply ∓ 0.5T and compare STGM maps





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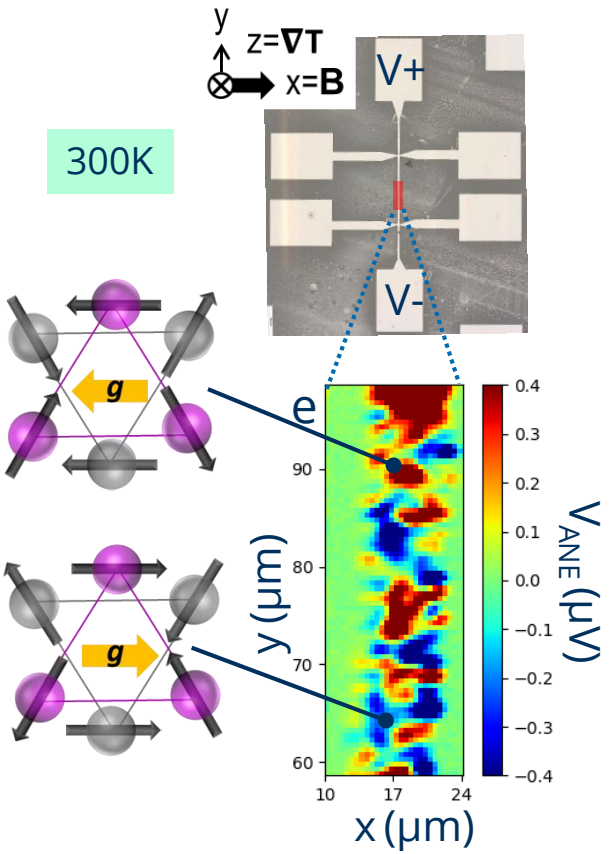

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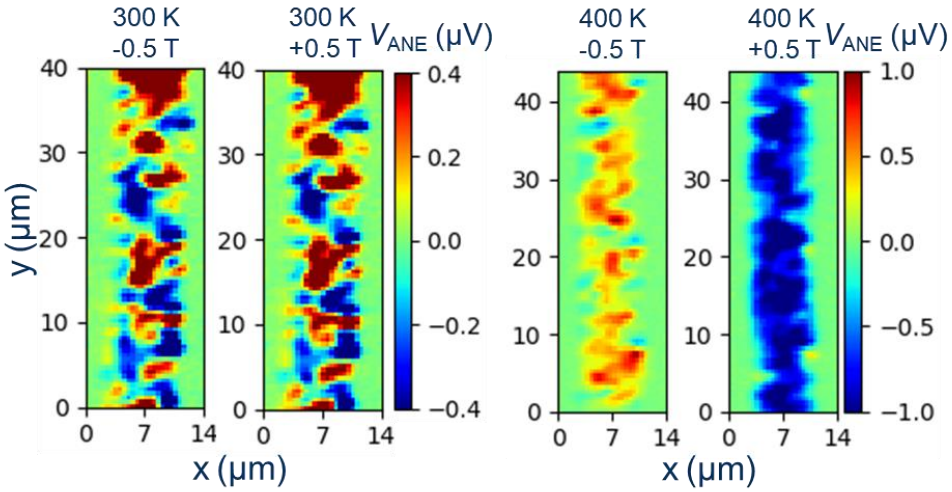
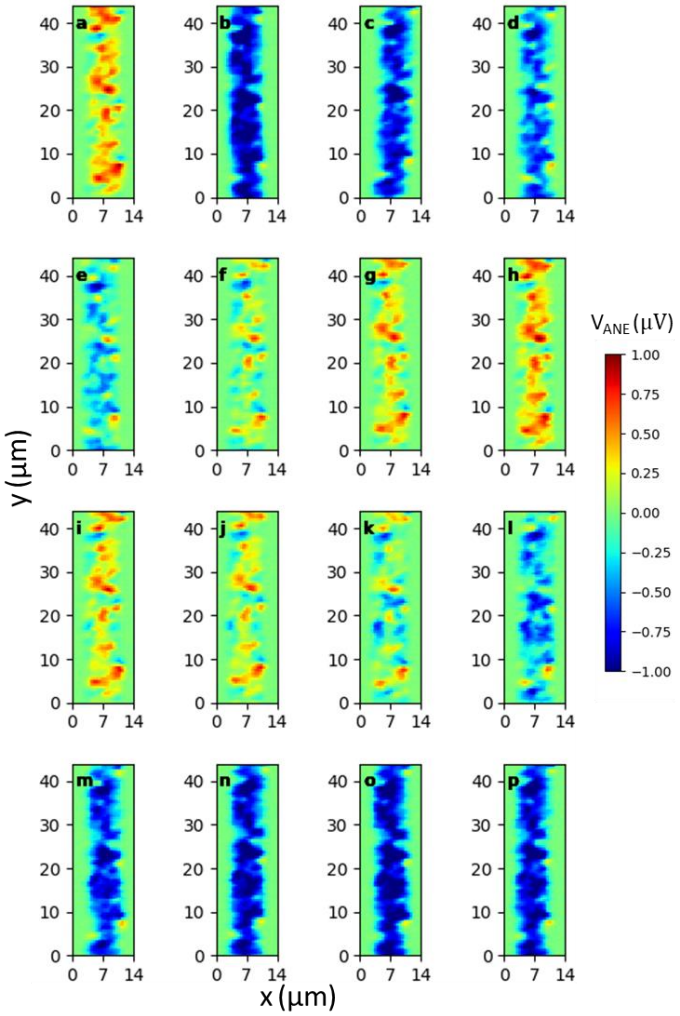
Apply ∓ 0.5T and compare STGM maps
At 400K lowered anisotropy



Ordinary Nernst?

Results of the STGM: sweep magnetic field

At various magnetic fields measured a STGM map



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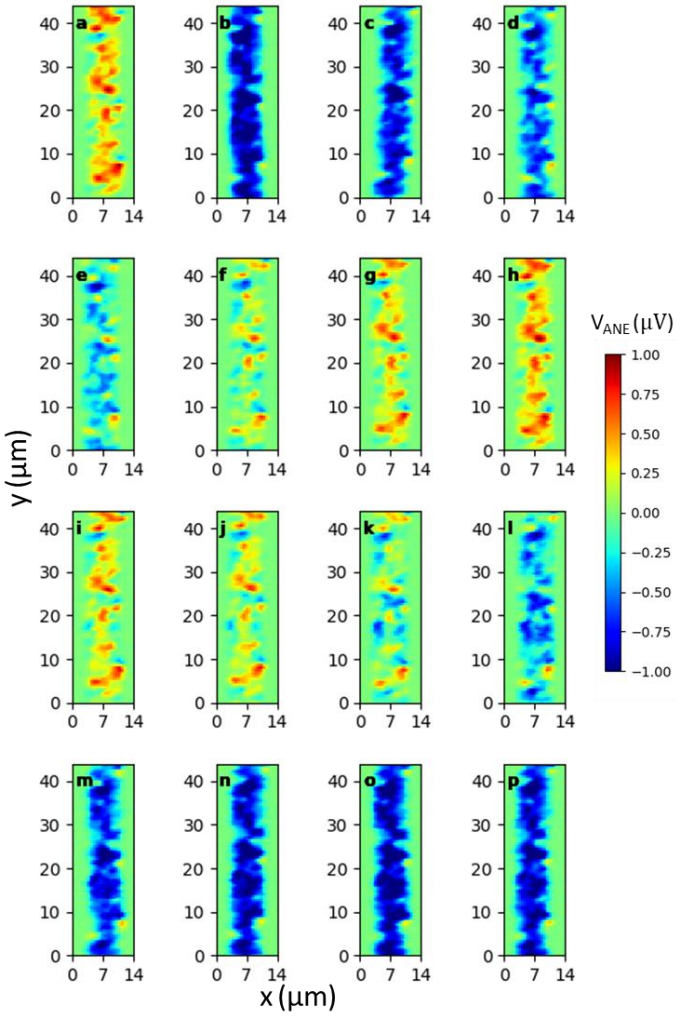
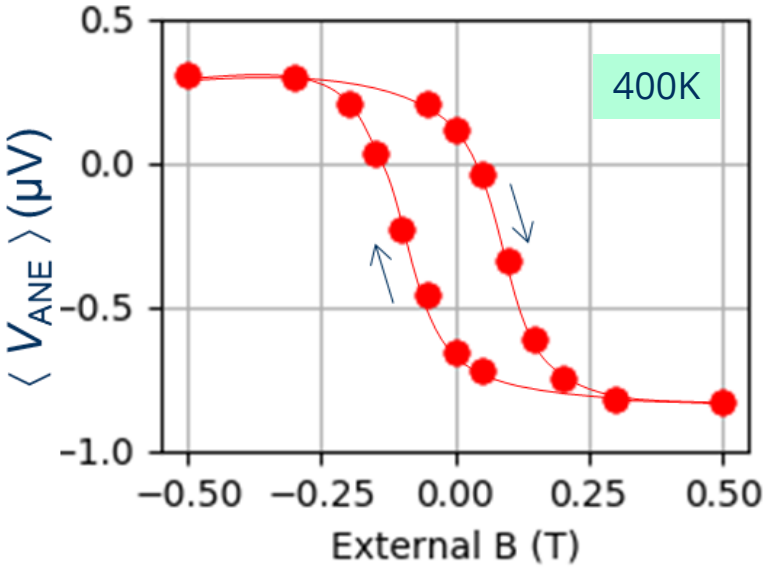


STGM averaged over full maps $\langle V_{ANE} \rangle$ (µV)



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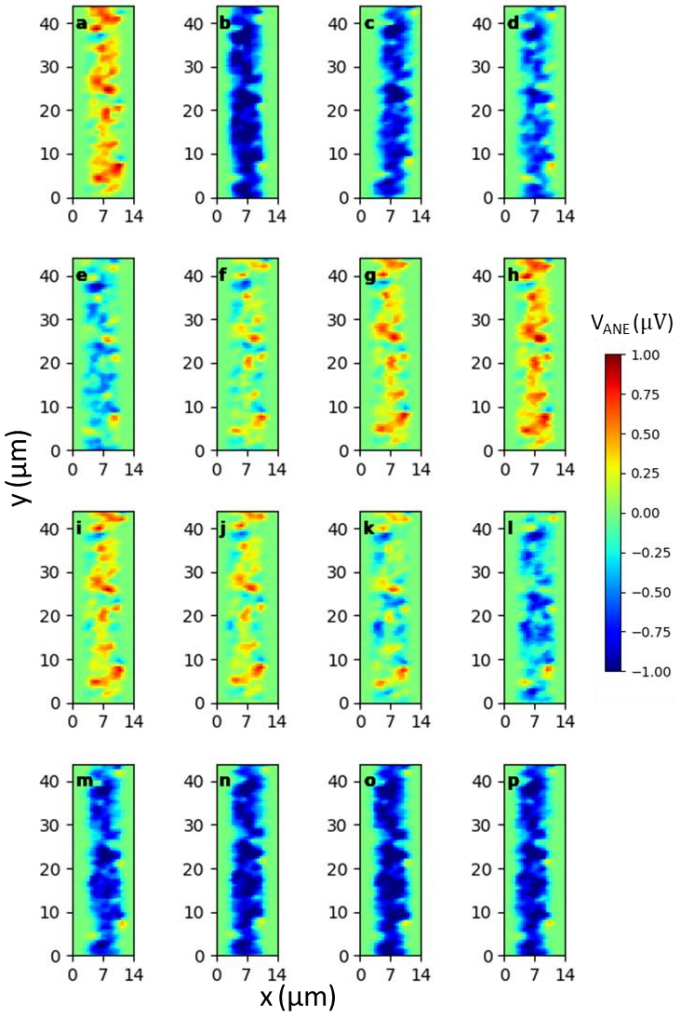

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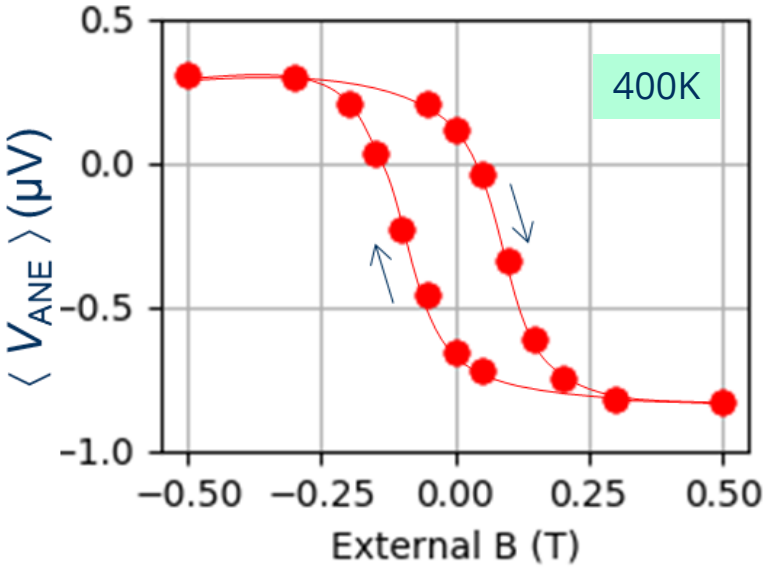
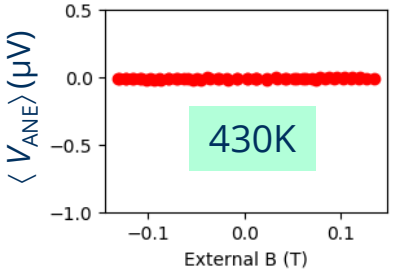
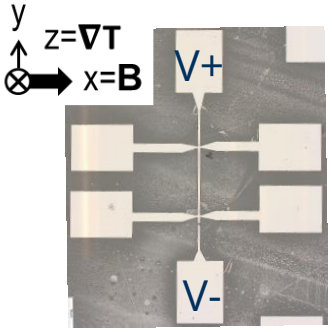


same experiment at 430K (above T_N)

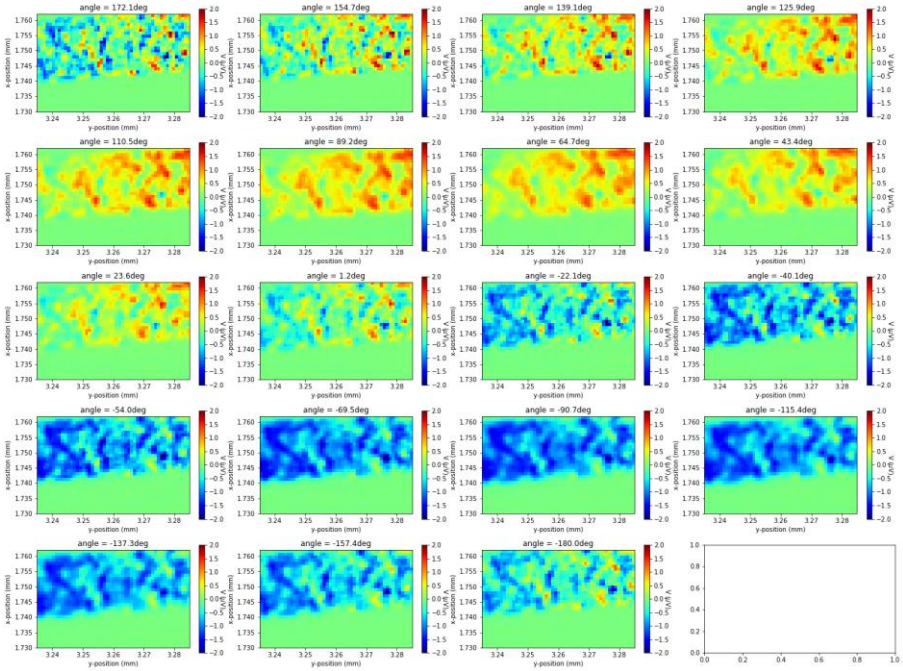


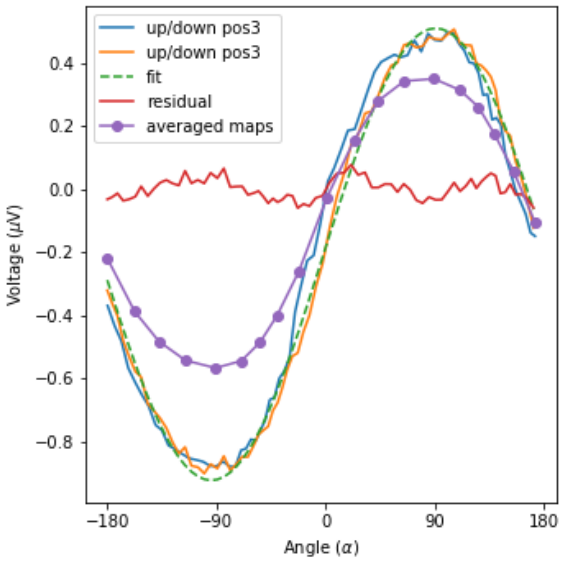
Results of the STGM: rotate magnetic field

Vary angle voltage detection vs. magnetic field 200 mT



- easiest expected picture (“easy plane anisotropy”):
  variation of *g vector projection* – shades of blue/yellow
- reality: breaking into islands/domains
- likely dominated by pinning centers
  higher resolution STGM in progress…



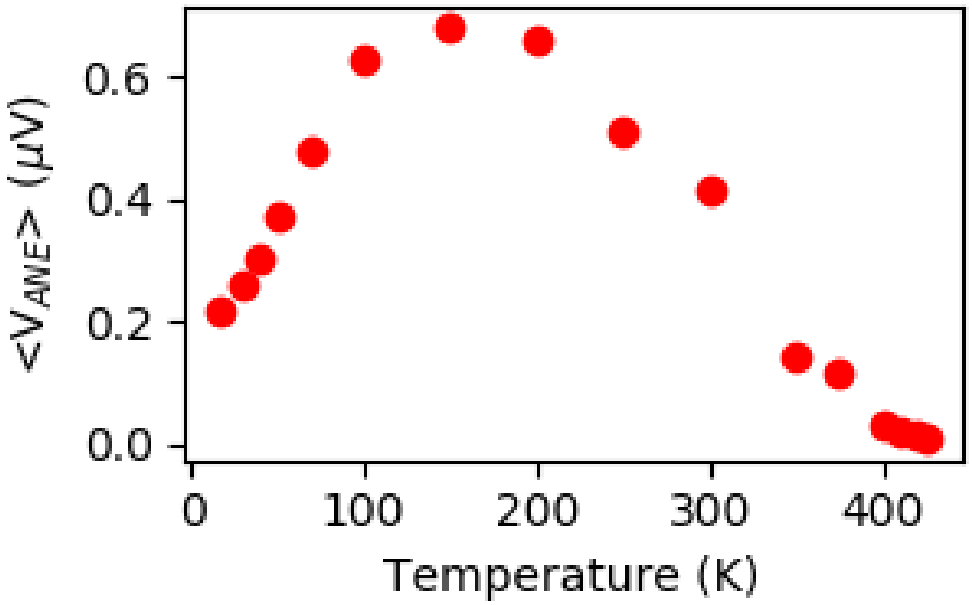


STGM averaged over full maps $\langle V_{ANE} \rangle$ (μV)

Results of the STGM: temperature dependency

Anomalous Nernst effect – expected to be temperature dependent
→ 0 at low temperatures
→ 0 at T_N

Map at every temperature and plot average $\langle V_{ANE} \rangle$ (μV)



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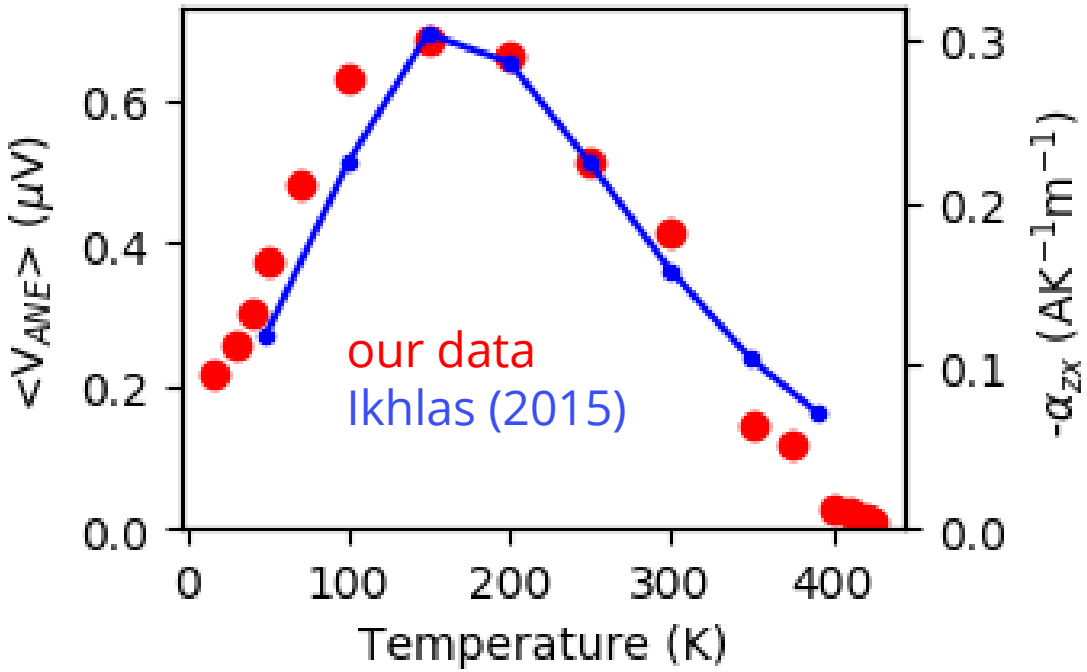
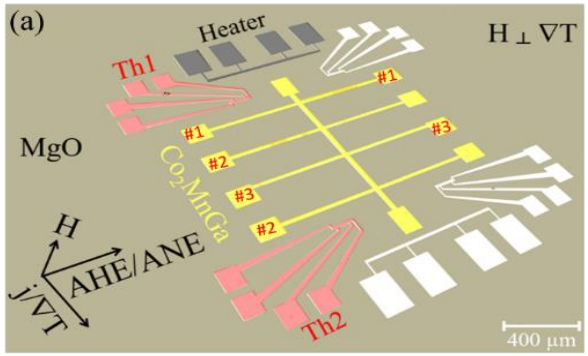
Compared with bulk Mn3Sn ANE [Ikhlas, Nat.Phys.(2015)]



Results of the STGM: Nernst coefficient estimation

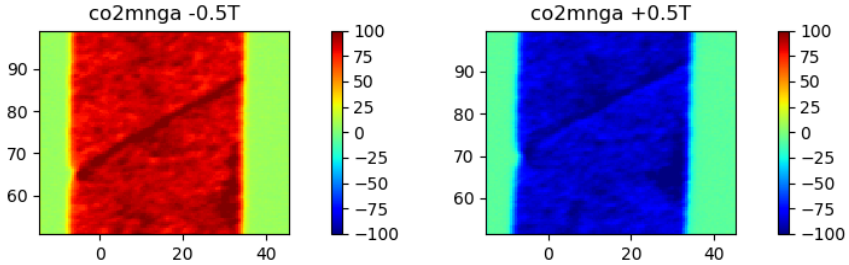
How we calibrate laser induced ∇T ?

1. thin film, same substrate, same capping, large Anomalous Nernst effect
   Co2MnGa thin films [Reichlova, APL113, 212405 (2018)]
2. evaluate Anomalous Nernst coefficient N_{ANE} with known thermal gradient



N_{ANE} ~ 2 μV/K

3. Co_2MnGa device of same size as Mn_3Sn measured in laser setup

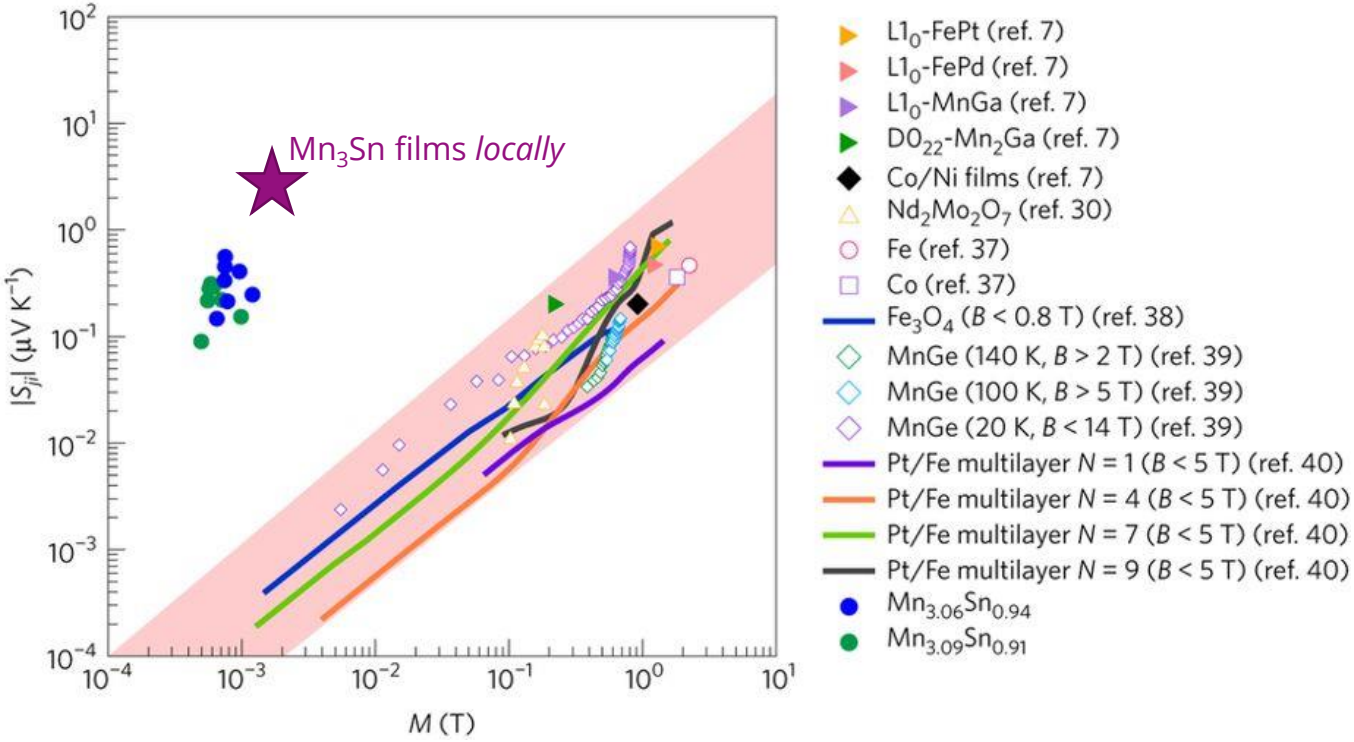


4. estimate laser induced ∇T (E = N_{ANE} ∇T) ~ 2K/μm

Results of the STGM: Nernst coefficient estimation

Evaluate Mn_3Sn films $N_{ANE} \sim 2\ \mu V/K$

Compared with bulk Mn_3Sn ANE [Ikhlas, Nat.Phys.(2015)]



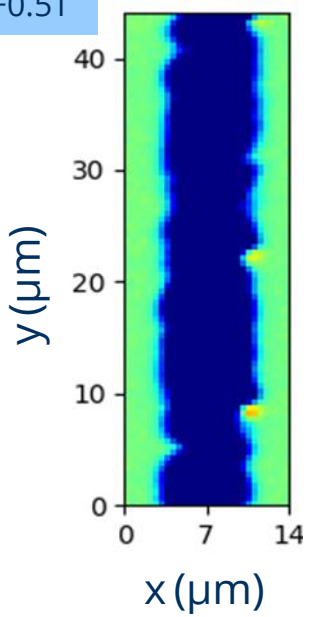
- very local measurement
- gradient estimation error (spot size etc.)
- comparing ANE measurement methods...

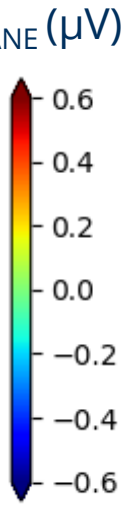
Results of the STGM: domain writing

At 300K ∓ 0.5T no effect, but **300K+laser power** = heat assisted writing

laser
50mW
+0.5T

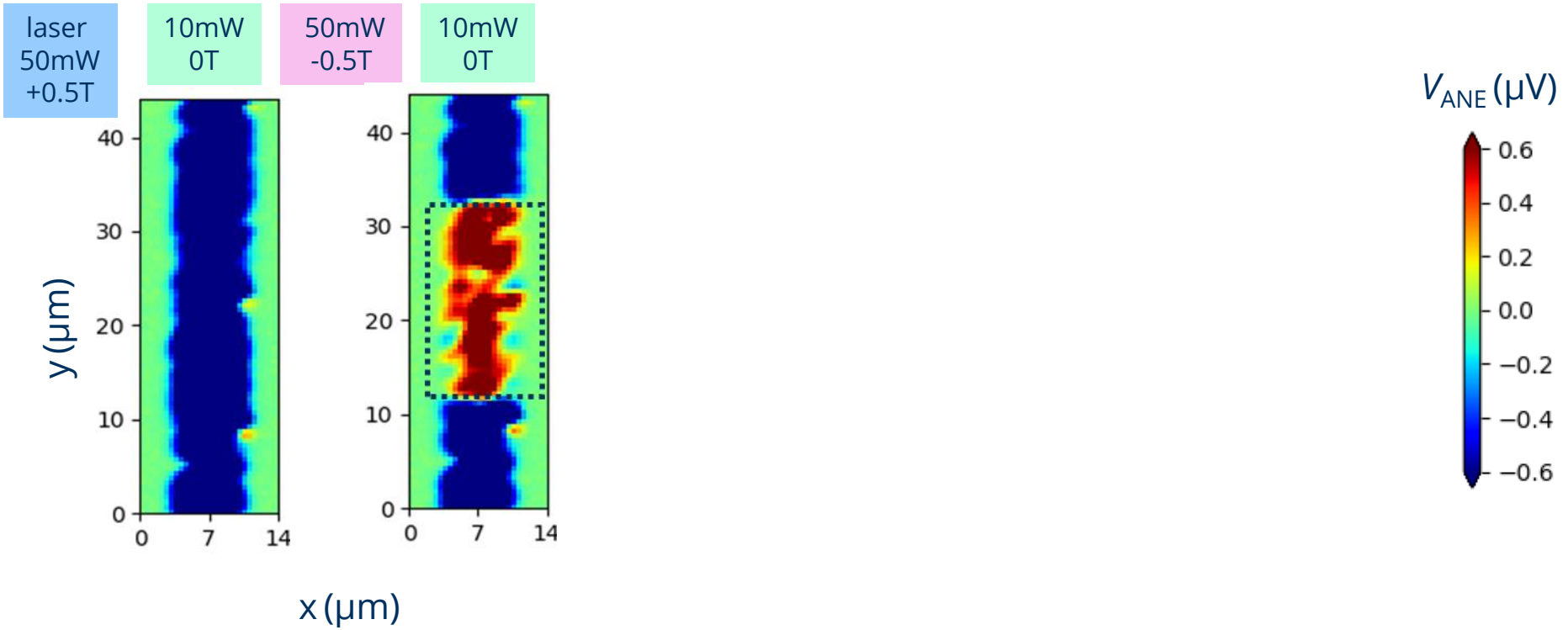
10mW
0T





Results of the STGM: domain writing

At 300K ∓ 0.5T no effect, but 300K+laser power = heat assisted writing



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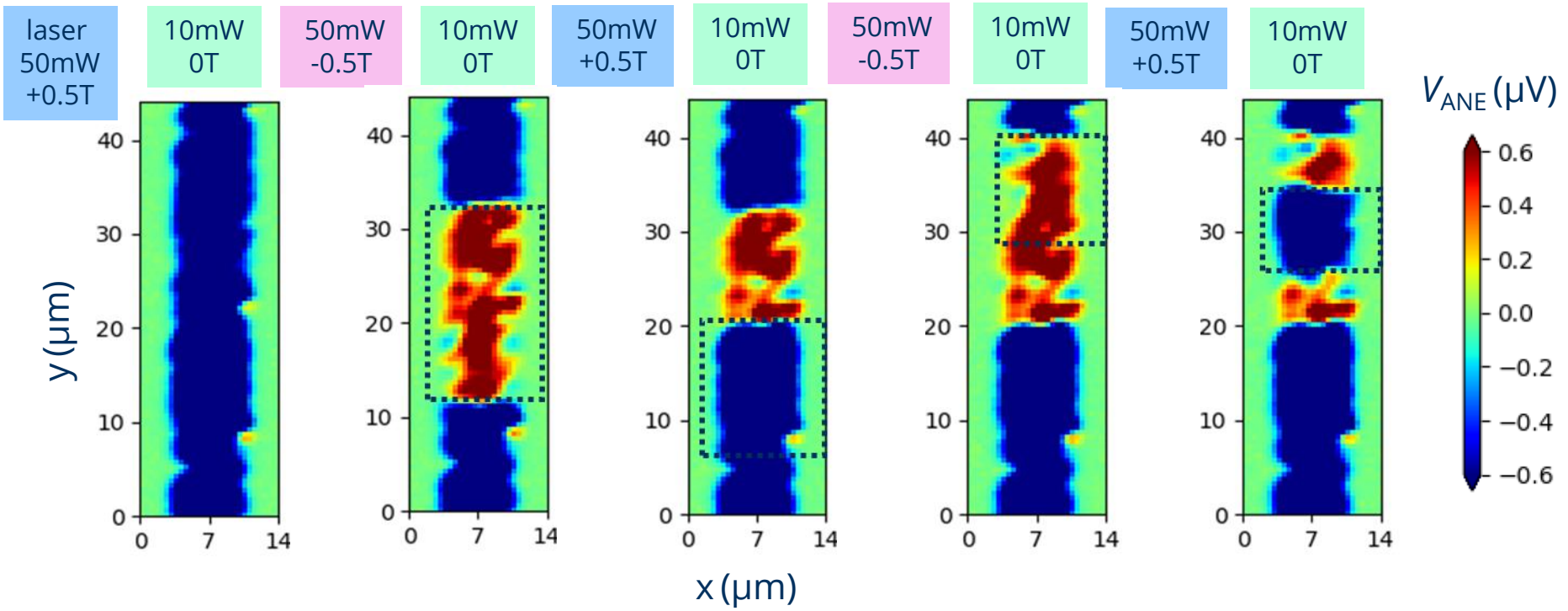

Reproducible writing and erasing of domains at 300K: impossible to erase 6T

STGM for antiferromagnets: next steps...

domains vs. *magnetic clusters* (STT observation....?)
rotation data, STGM vs. MOKE...
increase resolution:

1) SNOM in Berlin (B. Kaerstner, J. Wunderlich)
2) heated AFM tip in Milan (E. Albisetti, D. Petti)

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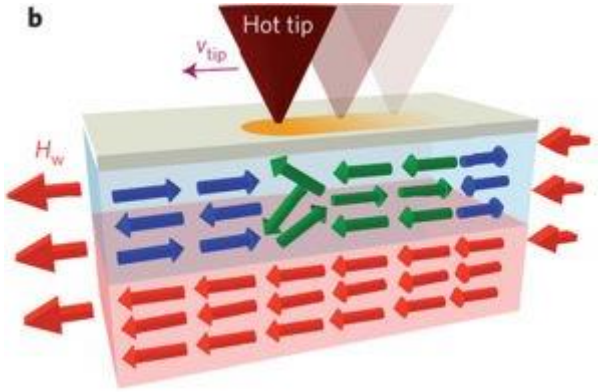
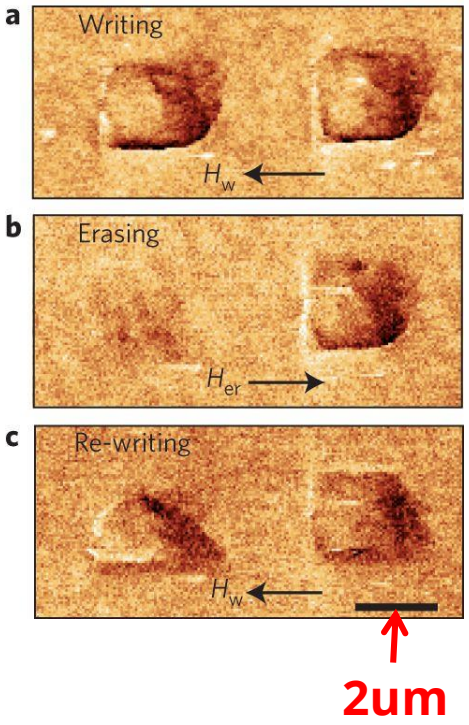
Nanopatterning reconfigurable magnetic landscapes via thermally assisted scanning probe lithography

E. Albisetti[1,2]*, D. Petti[1], M. Pancaldi[3], M. Madami[4], S. Tacchi[5], J. Curtis[2], W. P. King[6], A. Papp[7], G. Csaba[7], W. Porod[7], P. Vavassori[3,8], E. Riedo[2,9]* and R. Bertacco[1,10]*





Conclusion

- **STGM – enabling technique for imaging and writing**
- Tested on Mn_3Sn thin films:
  - ✓ **imaging of magnetic contrast in Mn_3Sn shown**
  - ✓ **writing of magnetic domains in Mn_3Sn shown**
- Pushing the resolution in progress…
  - to domain size resolution?
- Other materials in progress…
  - extraordinary versatile technique…

- Richard Schlitz, Sebastian Goennenwein (TU Dresden)
- Joerg Wunderlich, Joao Godinho, Jakub Zelezny, Tomas Jungwirth (FZU Prague)
- Tomas Janda, Petr Nemec (Matfyz, Charles University Prague)
- Dominik Kriegner, Anastasios Markou, Claudia Felser (CPfS MPI Dresden)
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https://arxiv.org/abs/1905.13504