Writing, reading and transporting spin in antiferromagnets

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[1]Institute of Physics & Materials Science in Mainz
Johannes Gutenberg-Universität Mainz, Germany
[2]QuSpin, NTNU, Trondheim, Norway

- **Reading Antiferromagnetic systems:**
  - **Imaging and electrical read-out of bulk, thin film and 2D antiferromagnets**
- **Writing Antiferromagnetic systems:**
  - **Field- and Strain-induced switching in AFMs**
  - **Bulk spin orbit torque-induced switching in AFMs**
  - **Interfacial spin orbit torque switching in AFMs**
- **Long distance Spin Transport in antiferromagnets**

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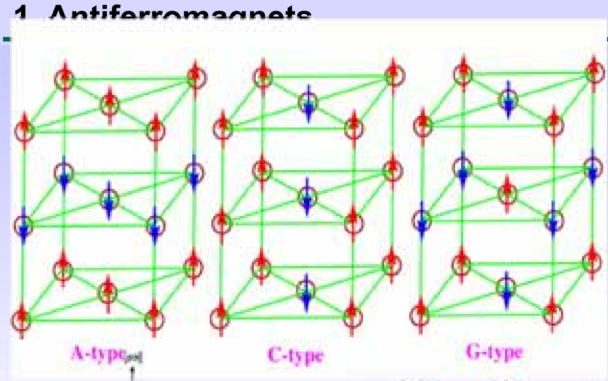
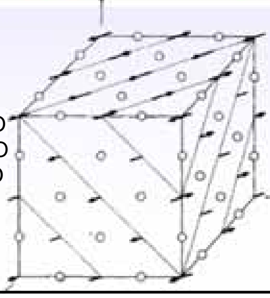
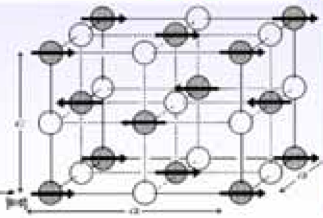
1. Antiferromagnets



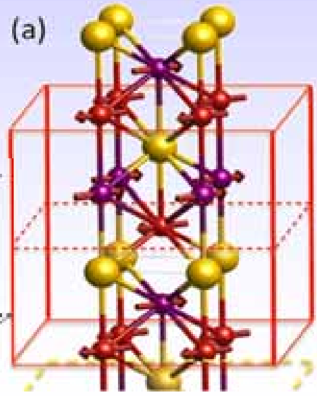
P. Ravindran
University of Oslo

NiO
CoO
MnO
FeO



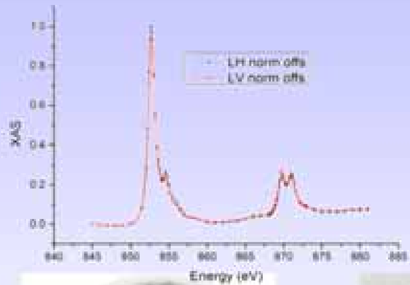


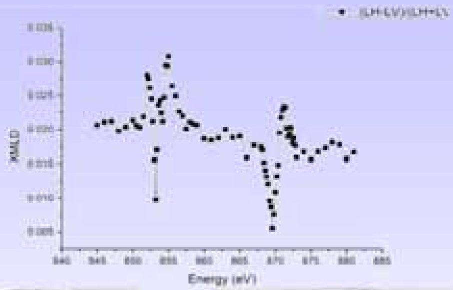
MnTe
(Nat. Commun. 7:11623)

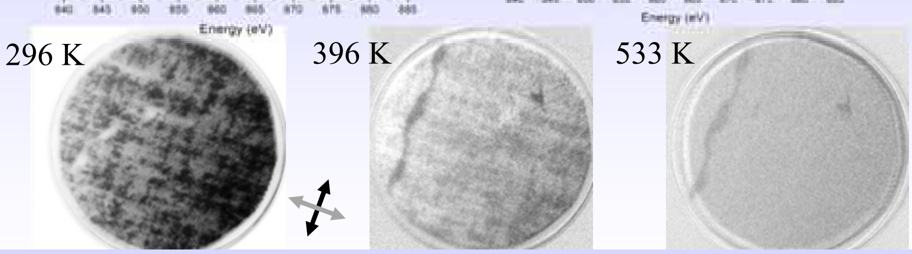


Mn_2Au
Nat. Commun. **9**, 348 (2018)

1. Reading Antiferromagnets (I) – XMLD of NiO







- XMLD imaging of NiO[1] allows for the identification of domains (field of view 20 µm).
- Temperature dependent measurements confirm Néel temperature of ~520K.[2]

[1]H. Ohldag, PhD Thesis; J. Stoehr et al., Phys. Rev. Lett. 83, 1862 (1999); [2]L. Baldrati et al., PRB **98**, 024422 (2018)

Mathias Kläui SPICE Workshop, Mainz, 8.10.2019

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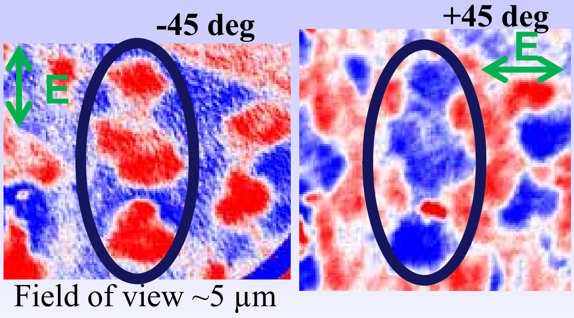
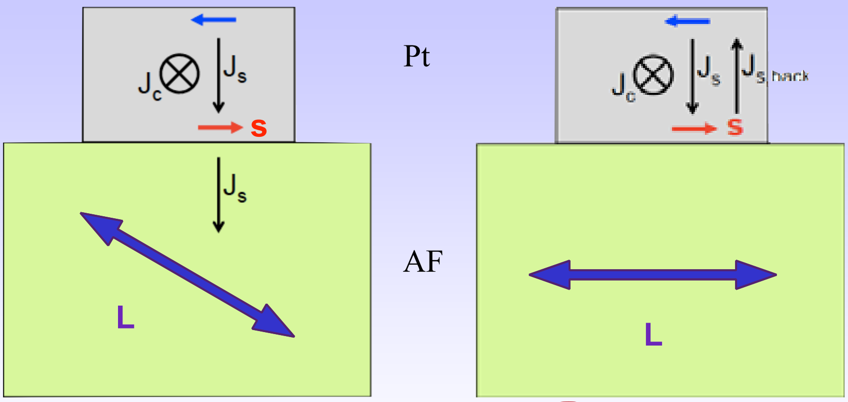


- Photoemission Electron Microscopy with linear dichroism contrast (XMLD-PEEM).
- Contrast is observed and by rotating the sample by 90° magnetic origin of µm sized domain signal can be confirmed.[1]

[1] A. Sapozhnik, M. Jourdan, M. Kläui et al., Phys. Rev. B **97**, 134429 (2018)

Mathias Kläui SPICE Workshop, Mainz, 8.10.2019

1. Reading Antiferromagnets electrically (II) - SMR



enhanced dissipation in Pt **reduced dissipation in Pt**

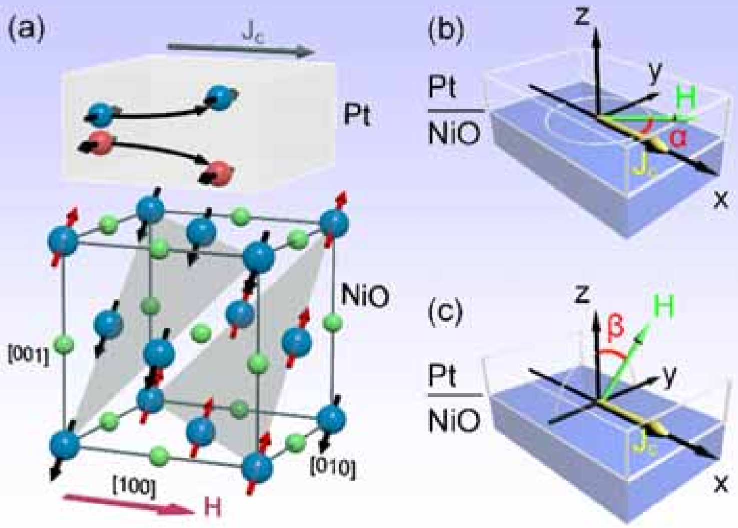
$$R = R_0 - \Delta R(\mathbf{Ls})^2$$

S. Gönnenwein

- Resistance is predicted to vary in a AFM/Pt bilayer for Néel vector parallel and perpendicular to current flow[1] → Spin Hall Magnetoresistance[2]

[1]A. Manchon, Phys. Stat. Sol. – Rap. Res. Lett. **11**, 1600409 (2017); [2]H. Nakayama et al., PRL **110**, 206601 (2013).

1. Reading Antiferromagnets by SMR (NiO)



[1] L. Baldrati, MK et al., Phys. Rev. B **98**, 024422 (2018); G. Hoogeboom et al., Appl. Phys. Lett. **111**, 052409 (2017)

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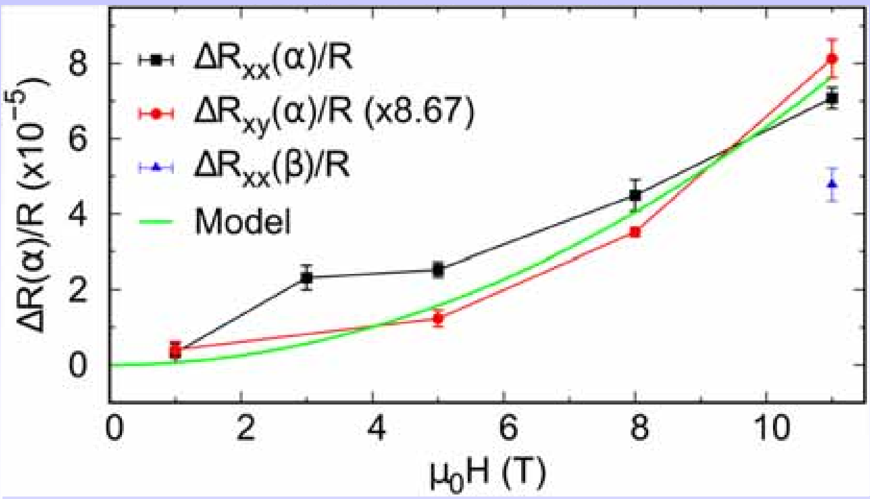
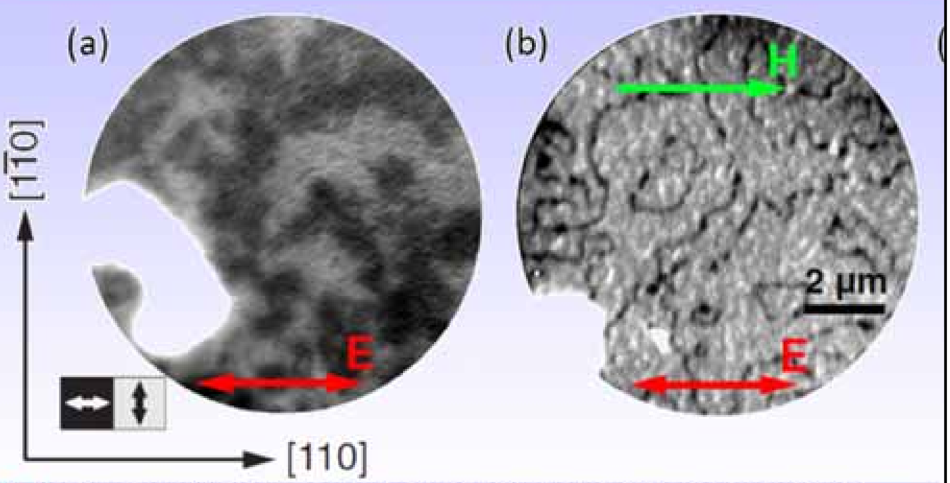


- By rotating a strong field, the Néel vector is rotated (spin – flop) → negative SMR
- The SMR amplitude as a function of magnetic field shows the distribution of the magnetic fields needed to align the Néel vector in different domains.[1]

[1] L. Baldrati, MK et al., Phys. Rev. B **98**, 024422 (2018); J. Fischer et al., Phys. Rev. B **97**, 014417 (2018)

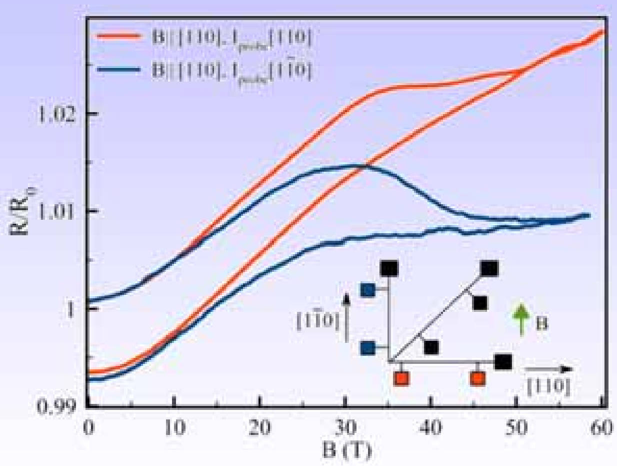
2. Reading Antiferromagnets – identifying AMR in Mn_2Au



- As grown, Mn_2Au comprises man domains with no net Néel vector orientation.
- When applying a field along along one of the cubic easy axes above the spin-flop (50T): → orientation of Néel vector perpendicular to the field.

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., arxiv:1909.12606 (2019)

2. Reading Antiferromagnets – identifying AMR in Mn_2Au



- By applying a strong field, the Néel vector is rotated (> 30T)
- Between 0 field and 50 T → large change > 3%
- Remanent persistant difference much smaller : MR of ~0.1% → Origin?

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., arxiv:1909.12606 (2019)

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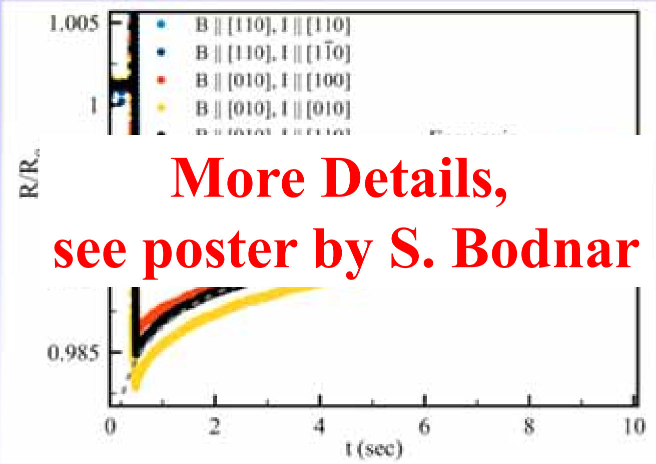

- Relaxation of the spin configuration on second timescales → thermal activation
  Current explanation: Remanent/persistent change is AMR of the domains: 0.1%
- MR during field application of 3% due to Domain Wall Magnetoresistance!

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., arxiv:1909.12606 (2019)

2. Summary of Read-Out:

- 1. Electrical read-out:
  - Insulators: Spin Hall Magnetoresistance (SMR)
  - Metals:
    - Anisotropic magnetoresistance (domains)
    - Domain Wall magnetoresistances (DWs)
- 2. Imaging read-out:
  - Metals&Insulators: X-ray magnetic linear dichroism as contrast mechanism combined with x-ray microscopy (PEEM, STXM)

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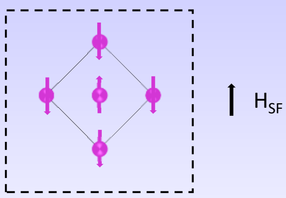
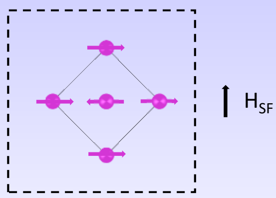
3. Magnetic field-induced reorientation in Mn_2Au probed by XMLD

Two AFM domains with different orientation of moments





- Switching from one easy axis to the other upon applying a high magnetic field
- Moments preserve their initial orientation

- By applying a strong field, a spin-flop transition can be induced and the Néel vector aligns perpendicularly to the field direction

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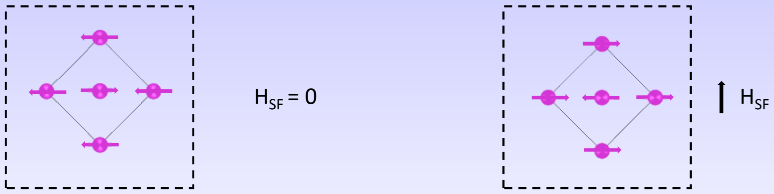

- Switching from one easy axis to the other upon applying a high magnetic field
- Moments preserve their initial orientation

However fast pulses can lead to Domain Wall motion in AFMs

H. Gomonay, MK et al., APL 109, 142404 (2016)

- By applying a strong field, a spin-flop transition can be induced and the Néel vector aligns perpendicularly to the field direction.
- For the Néel vector perpendicular to the field, only small transient canting occurs.

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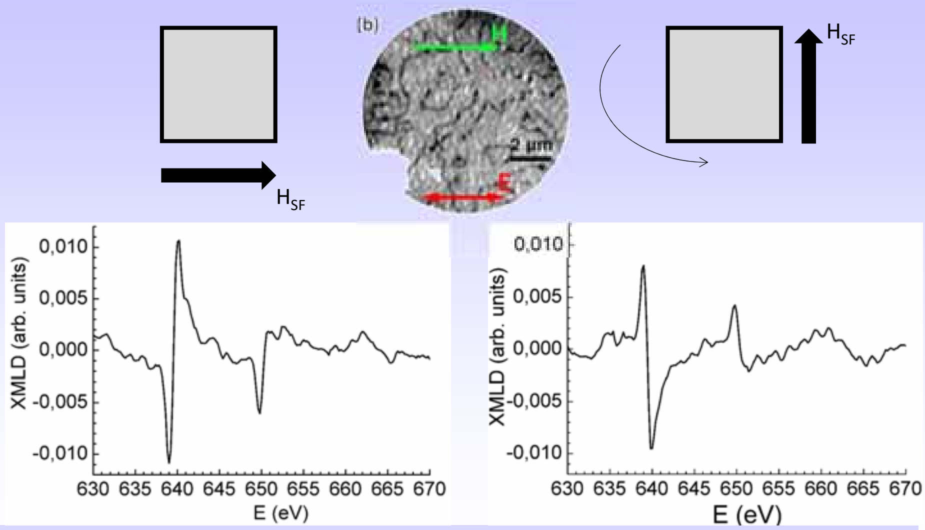

- XMLD-imaging shows clear dichroism due to the alignment of the Néel vector.

A. Sapozhnik, M. Jourdan, MK et al., Phys. Status Solidi RRL **11**, 1600438 (2017).

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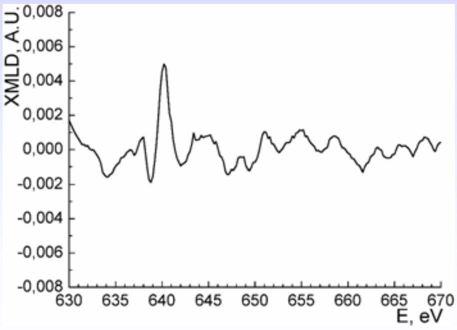

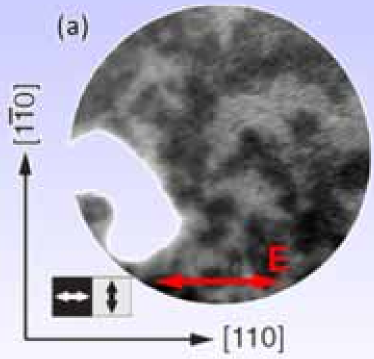

- Reference sample – same structure not exposed to strong field shows no XMLD!

A. Sapozhnik, M. Jourdan, MK et al., Phys. Status Solidi RRL **11**, 1600438 (2017).

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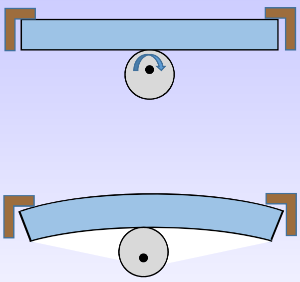
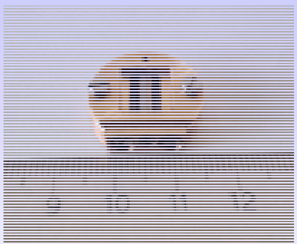
3. Strain-induced writing of Mn_2Au





- Compatibility with UHV conditions
- Controllable value of strain
- Monitoring of strain with a strain gauge

- Expected strain-induced uniaxial anisotropy → apply strain to the sample!

A. Sapozhnik, M. Jourdan, MK et al., Phys. Status Solidi RRL **11**, 1600438 (2017).

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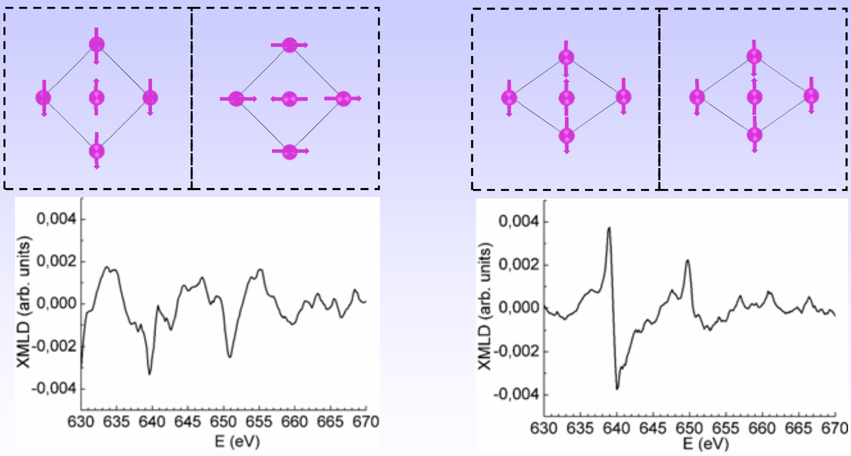
3. Engineering the spin structure of Mn_2Au by strain

Unstrained sample | Strained sample (elongation ~0,1%)



- Application of strain (0,1%) leads to alignment of Néel vector visible from XMLD!
- Spin structure can be controlled by strain → preparation of desired spin state!

A. Sapozhnik, M. Jourdan, MK et al., Phys. Status Solidi RRL **11**, 1600438 (2017).

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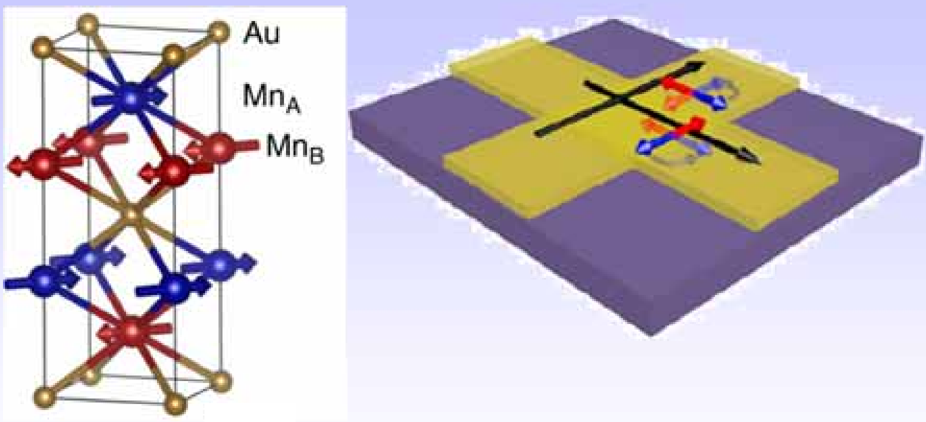
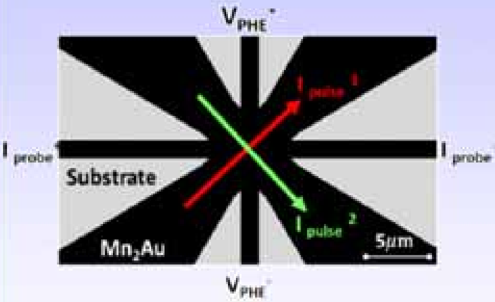
3. Spin-orbit torque switching of Mn_2Au

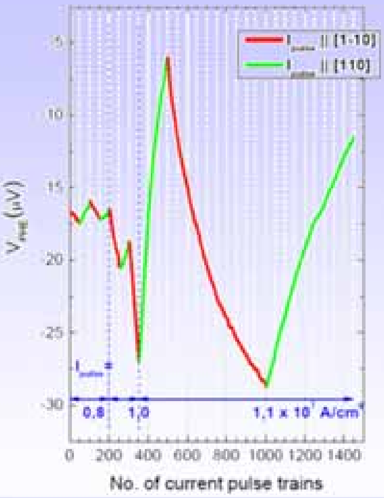


- Prediction of bulk spin orbit torques acting on the Néel order in AFM Mn_2Au[1,2,3] → manipulation of magnetization using electric currents (first observed in CuMnAs[4]).

[1]J. Zelezny, et al., PRL **113**, 157201 (2014); [2]S. Bodnar, MK et al., Nature Comms. **9**, 348 (2018)
[3]M. Meinert et al., PR Applied **9**, 064040 (2018); [4]P. Wadley et al., Science **351**, 587 (2016);

3. Bulk spin orbit torque switching in Mn_2Au

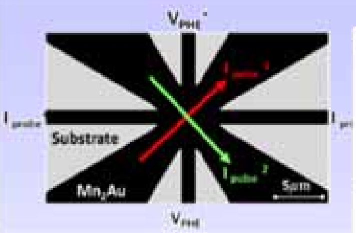


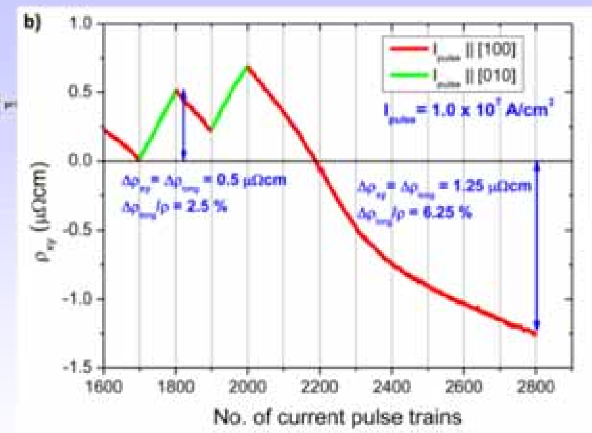


- Bulk Néel spin orbit torques have been predicted to switch the Néel vector.
- Non-linear switching as a function of current density → heating effects important!

S. Bodnar, M. Jourdan, H. Gomonay, J. Sinova, T. Jungwirth, MK et al., Nature Comms. 9, 348 (2018);

3. Bulk spin orbit torque switching in Mn_2Au

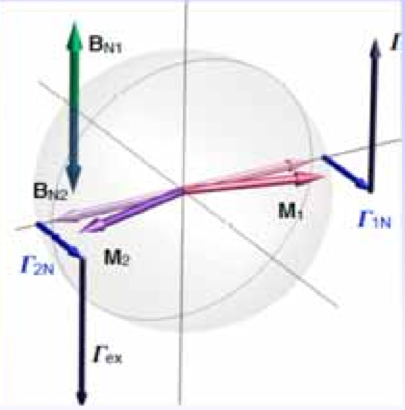


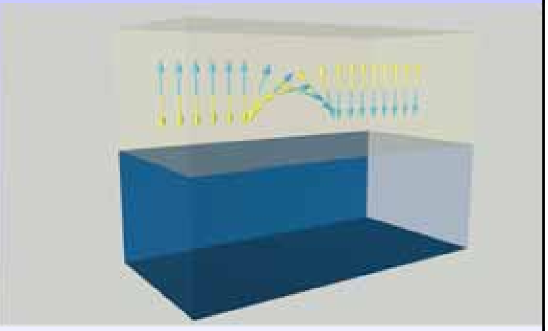


- Bi-polar switching using currents in perpendicular directions.
- Sign change of the PHE demonstrates switching of large part of domains.
- Very large PHE/AMR >6% can be reproduced by transport calculations.

S. Bodnar, M. Jourdan, H. Gomonay, J. Sinova, T. Jungwirth, MK et al., Nature Comms. 9, 348 (2018);

3. Combining reading and writing: interfacial SOT switching of NiO





H. Gomonay, J. Sinova et al.,
Phys. Rev. Lett. **117**, 017202 ('16)

- Different switching mechanisms:
  Domain Wall motion[1]

[1]T. Shiino et al., Phys. Rev. Lett. **117**, 087203 (2016); [2]L. Baldrati, MK et al., arxiv:1810.11326 (PRL in press)

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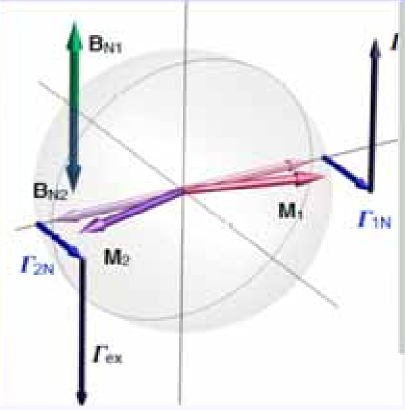

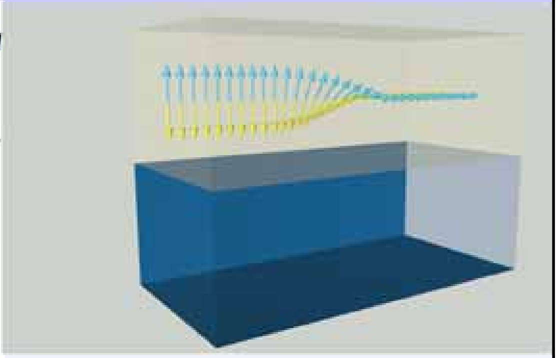

H. Gomonay, J. Sinova et al.,
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- Different switching mechanisms:
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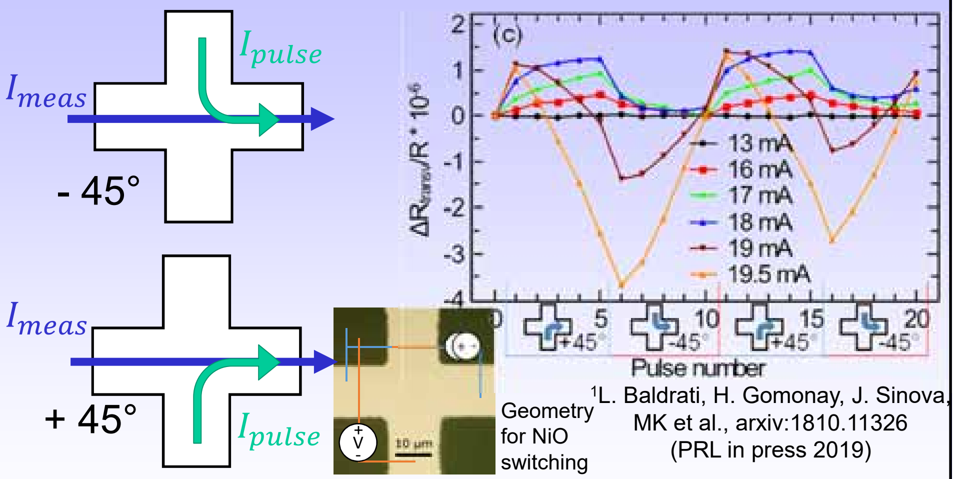

[1]L. Baldrati, H. Gomonay, J. Sinova, MK et al., arxiv:1810.11326 (PRL in press 2019)

- In combination with Pt layer, damping-like non-staggered SOTs generate 90° switching in NiO: Néel vector is rotated **parallel** to electron flow![1]
  → 2 effects: Néel vector change + structural changes in Pt layer?

See also Y. Cheng et al., arxiv:1906.04694 (2019); X. Chen et al., Phys. Rev. Lett. **120**, 207204 (2018)

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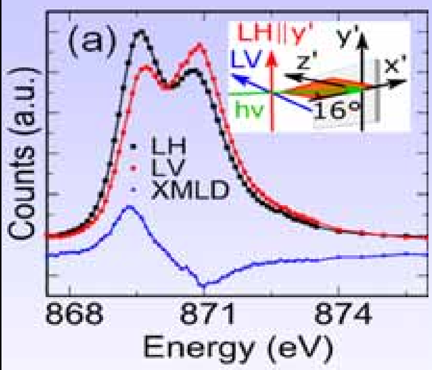
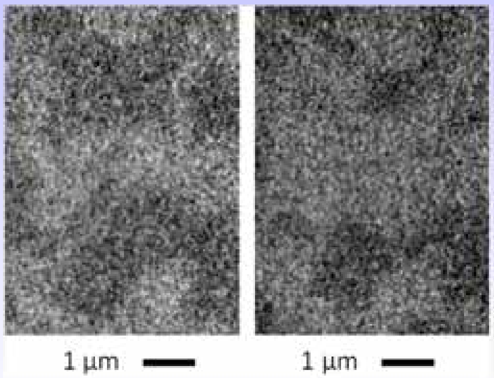


L. Baldrati, MK et al. arxiv:1810.11326 (2018), PRL in press



before pulse after pulse

- In combination with Pt layer, damping-like non-staggered SOTs generate 90° switching in NiO: Néel vector is rotated **parallel** to electron flow![1]
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See also Y. Cheng et al., arxiv:1906.04694 (2019); X. Chen et al., Phys. Rev. Lett. **120**, 207204 (2018)

3. Summary of Writing:

- 1. Writing by magnetic fields:
  Spin-flop
- 2. Writing by strain:
  Magneto-elastic coupling
- 3. Writing by spin-orbit torques:
  -Bulk Néel staggered spin-orbit torques in metallic antiferromagnets with appropriate symmetry (Mn2Au, CuMnAs)
  -Interfacial non-staggered spin-orbit torques in insulating AFM / Pt bilayer

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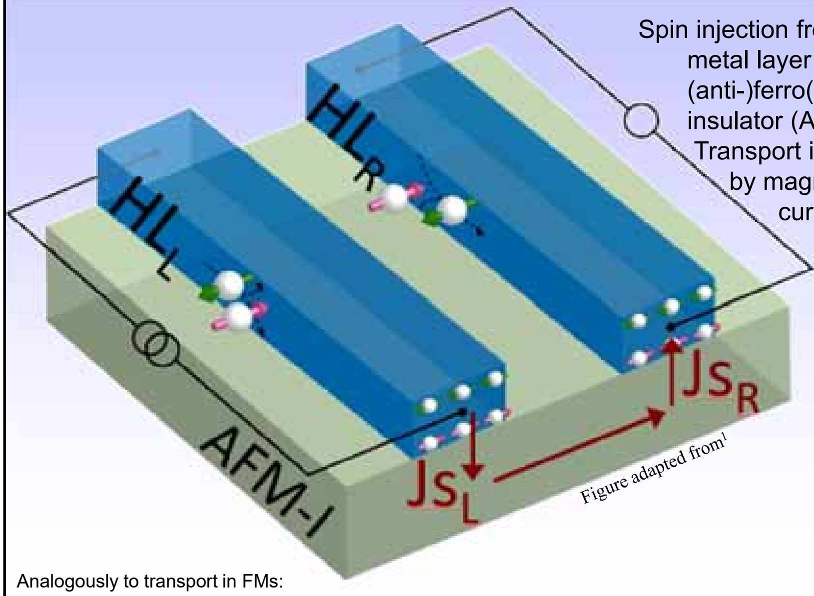
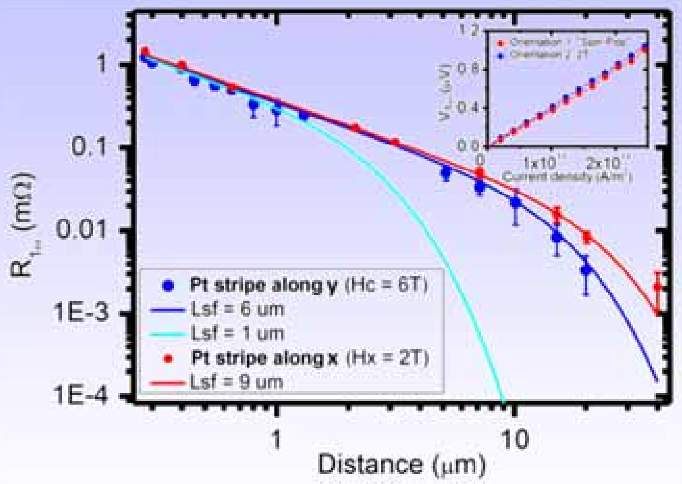
5. Lateral spin transport in antiferromagnetic insulators



Spin injection from a heavy metal layer (HM) into a (anti-)ferro(i)magnetic insulator (AFM-I)[1,2]. Transport in the AFMI-I by magnonic spin currents.

Analogously to transport in FMs:
L. Cornelissen et al., Nature Phys. **11**, 1022 (2015); K. Ganzhorn, MK et al., AIP Adv. **7**, 085102 (2017)

5. Quantifying spin transport & dissipation in bulk hematite



- Distance dependence: exponential decay → diffusive spin transport
- Largest ever reported spin diffusion lengths for a magnetic insulator: 5-10 μm depending on applied field and transport over 40 μm observed!

R. Lebrun, A. Ross, S. Bender, A. Qaiumzadeh, A. Brataas, R. A. Duine, M. Kläui et al., Nature **561**, 222 (2018)

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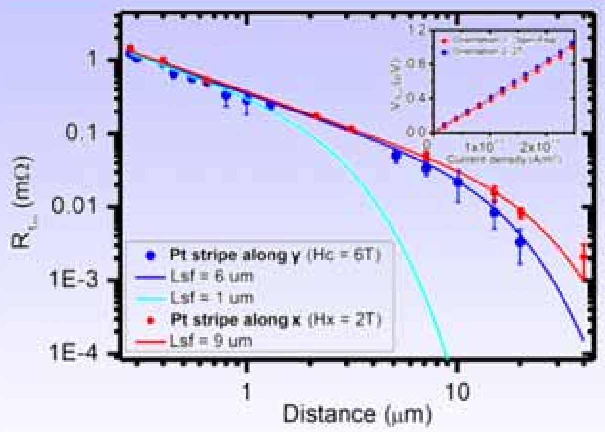

- No threshold
- Visible at high temperature
- Exponential decay
  → Diffusive transport over tens of microns in easy axis AFM![1]
- Previous transport in insulator AFMs only over few nm![2]

[1]R. Lebrun, A. Ross, S. Bender, A. Brataas, R. A. Duine, and M. Kläui Nature **561**, 222 (2018)
[2]PRL 113, 97202 (2014); Nat. Comm. **9**, 1089; PRB **98**, 014409

	Experiments	Spin superfluid	Diffusive transport
Threshold	No	X	✓
Temperature	200 K	X	✓
Decay	Exponential (visible for large D)	X	✓

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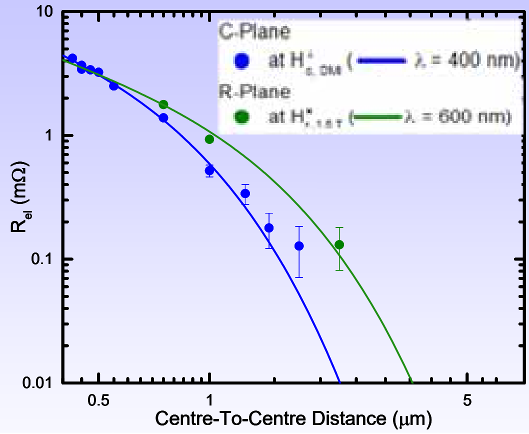
5. Quantifying spin transport in thin film hematite

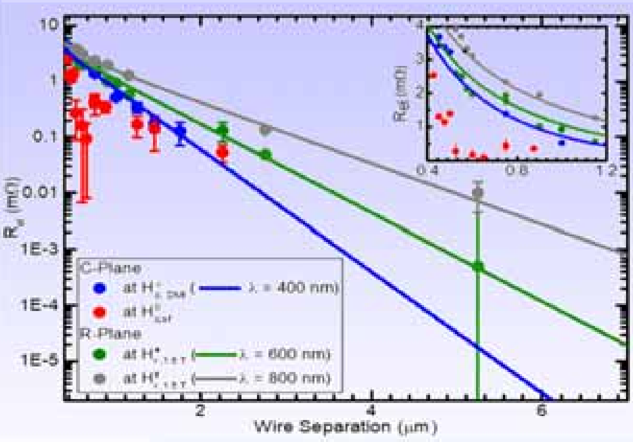


- μm diffusive transport in thin film antiferromagnet
- Origin of differences in spin diffusion lengths?:
  - -Bulk Fe_2O_3: 5-10 μm[1]
  - -Thin film Fe_2O_3:
    - c-cut: 400 nm
    - r-cut: 600 nm
  - -Thin film NiO: few nm[2]

[1]R. Lebrun, A. Ross, S. Bender, A. Brataas, R. A. Duine, and M. Kläui Nature **561**, 222 (2018)
[2]PRL 113, 97202 (2014); Nat. Comm. **9**, 1089; PRB **98**, 014409

	Experiments	Spin superfluid	Diffusive transport
Threshold	No	X	✓
Temperature	200 K	X	✓
Decay	Exponential (visible for large D)	X	✓

5. Quantifying spin transport in thin film hematite



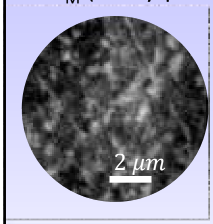
- μm diffusive transport in thin film antiferromagnet
- Origin of differences in spin diffusion lengths?:
  - -Bulk Fe_2O_3: 5-10 μm[1]
  - -Thin film Fe_2O_3:
    - c-cut: 400 nm
    - r-cut: 600 nm
  - -Thin film NiO: few nm[2]
- Signal at spin-flop not simple diffusion → reason?

[1]R. Lebrun, A. Ross, S. Bender, A. Brataas, R. A. Duine, and M. Kläui Nature **561**, 222 (2018)
[2]PRL 113, 97202 (2014); Nat. Comm. **9**, 1089; PRB **98**, 014409

	Experiments	Spin superfluid	Diffusive transport
Threshold	No	X	✓
Temperature	200 K	X	✓
Decay	Exponential (visible for large D)	X	✓

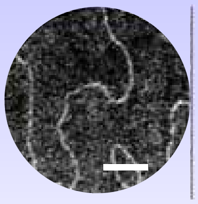
5. Correlating domain structures and spin transport lengths

C-Plane (0001) thin film[1]
$T>T_M$ (~easy-plane)



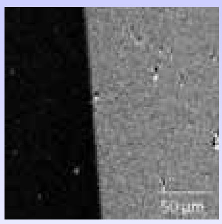
Domain size:
100 nm
λ = <100 nm

R-Plane (1102)[1]
(thin film)



Domain size:
500 nm
λ = 600 nm

R-Plane (1102)[2]
(bulk)



Domain size:
> 10 μm
λ = 5-10 μm

NiO (001) thin film[3]

Domain size:
<100 nm
λ = few nm[2]

- Spin transport length scales with domain size.
- Circularly polarized magnons are predicted to be scattered from domain walls → many domain walls → scattering – magnon domain wall resistance![4]
- Domain size can govern spin transport length due to DWs![1]

[1]A. Ross, MK et al., arxiv:1907.02751; [2]R. Lebrun, MK et al., Nature **561**, 222 (2018)
[3]L. Baldrati et al., Phys. Rev. B **98**, 024422 (2018); [4]E. Tveten et al., Phys. Rev. Lett. **112**, 147204 (2014)

Mathias Kläui SPICE Workshop, Mainz, 8.10.2019

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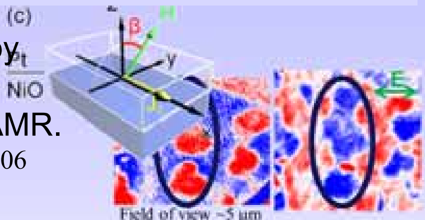
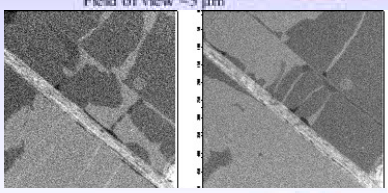
Summary:

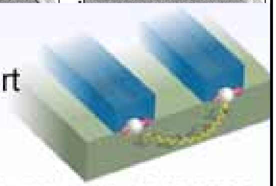
- Reading AFMs by XMLD-microscopy, and in insulators by spin Hall magnetoresistance and metals by AMR.
  Phys. Rev. B. **98**, 024422 (2018); arxiv:1909.12606



- Writing AFM insulators and metals by Spin-Orbit torques due to DW motion & ponderomotive force effects
  Nature Commun. **9**, 348 (2018); APL **109**, 142404 (2016); arxiv:1810.11326 (PRL in press 2019)



- Spin Transport in AFM insulators:
  -Observation of long-distance diffusive transport
  -Strong dependence on domain structure
  → spin transport can be tuned!



Nature **561**, 222 ('18); PRL **119**, 187705 ('17); Comm. Phys. **2**, 50 ('19); arxiv:1907.02751