Writing, reading and transporting spin in antiferromagnets

M. Kläui[1,2]

[1]Institute of Physics & Materials Science in Mainz
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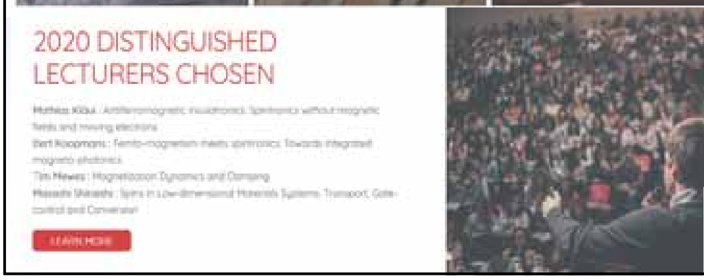
[2]QuSpin, NTNU, Trondheim, Norway

- **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**

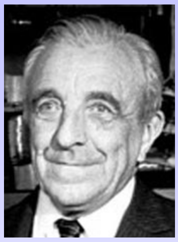


Around the Clock –
Around the Globe
Virtual Conference 27.8.2020
www.ieeemagnetics.org

https://www.ieeemagnetics.org/index.php?option=com_content&view=article&id=305&Itemid=206

Why antiferromagnets?

FM ⇒ AFM

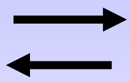


Louis Néel's Nobel Lecture 1970
"Antiferromagnets: Interesting but **useless**"

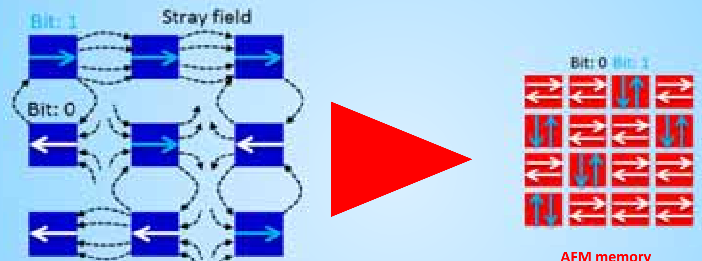
1. Introduction to Antiferromagnets – what is different?

Ferromagnets

Antiferromagnets



Close packed memory bits



FM memory
Bit interference
due to stray field

AFM memory
No stray field allows 100 times more packed bits*

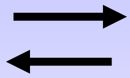
*S. Loth *et al.*, *Science* **335**, 196 (2012).

Courtesy of T. Moriyama & H. Gomonay

1. Introduction to Antiferromagnets – what is different?

Ferromagnets

Antiferromagnets



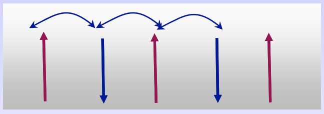
	Ferromagnet	Antiferomagnet
Magnetic Susceptibility	~ 10^{3} * (typical for Fe)	~ 10^{-2} ** (typical for MnF_2)

Reviews: Rev. Mod. Phys. **90**, 15005 (‘18); Nat. Phys. **14**, 200-242 (‘18); Adv. Mater. **32**, 1905603 (‘20)

1. Introduction to Antiferromagnets – what is different?

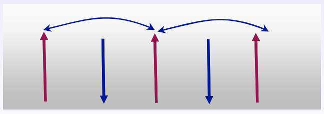
Hierarchy of Energy Scales

H, T



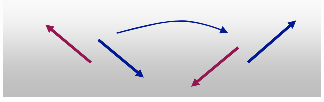
1000 T

$$H_{ex} \propto 1/\chi_{\perp}$$



100 T

$$J_{intra} \Leftrightarrow T_N$$



1 T

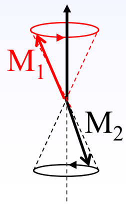
$$H_{s-f} = \sqrt{H_{ex} H_{an}}$$

1. Introduction to Antiferromagnets – what is different?

Ferromagnets →

Antiferromagnets → ←

	Ferromagnet	Antiferromagnet
Magnetic Susceptibility	~ 10^3 * (typical for Fe)	~ 10^{-2} ** (typical for MnF_2)
Eigenfrequencies	GHz	THz



Courtesy of T. Moriyama & H. Gomonay

1. Introduction to Antiferromagnets – what is different?

Ferromagnets →

Antiferromagnets → ←

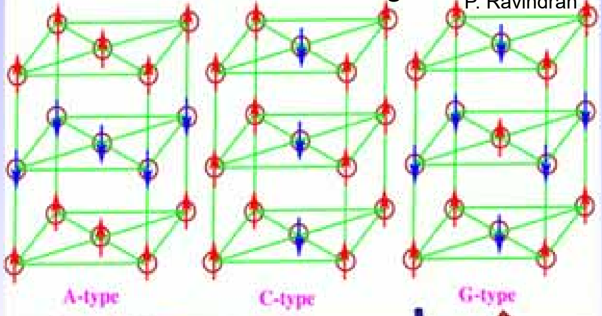
	Ferromagnet	Antiferromagnet
Magnetic Susceptibility	~ 10^3 * (typical for Fe)	~ 10^{-2} ** (typical for MnF_2)
Eigenfrequencies	GHz	THz
Abundance	Low (mostly metallic)	High (metallic and insulating)

Courtesy of T. Moriyama & H. Gomonay

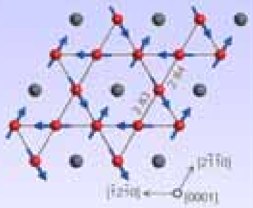
1. Antiferromagnets – there is lots of them

Collinear Antiferromagnets

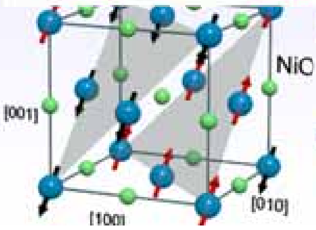
P. Ravindran



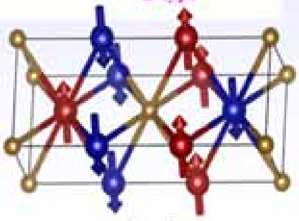
Non-collinear Antiferromagnets



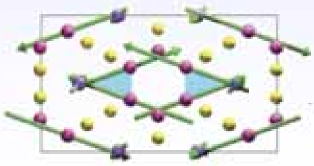
Mn_3Sn
Nature **527**, 212 (2015)



NiO PRB **98**, 024422 (2018)



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



Mn_5Si_3
Nat. Commun. **5**, 3400 (2014)

1. Introduction to Antiferromagnets – what is different?

Ferromagnets Antiferromagnets

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Eigenfrequencies	GHz	THz
Abundance	Low	High
Magnetoelastic coupling	Often weak	Mostly strong

Mathias Kläui — SPICE/Spin+X Seminar, Mainz, 19.8.2020

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Magnetoelastic coupling	Often weak	Mostly strong
Exchange	Usually simple Heisenberg	Often complex
Useful	Yes (easy to measure, easy to control)	Yes (passive elements ok / hard to measure, hard to control)

Antiferromagnets: definately interesting and possibly useful even as active elements!

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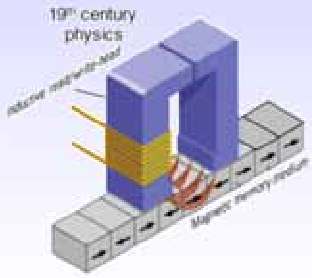
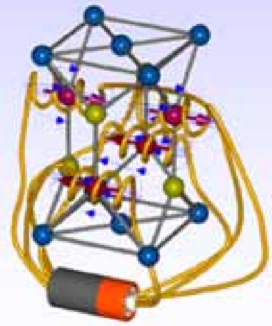
Ferromagnets → | Antiferromagnets → ←





19th century physics → 21st century physics

Courtesy of T. Moriyama & H. Gomonay

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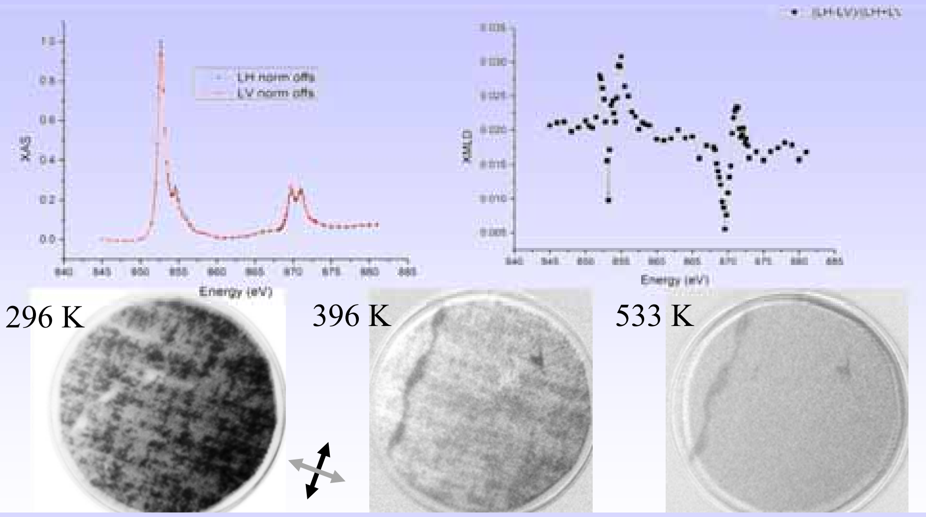
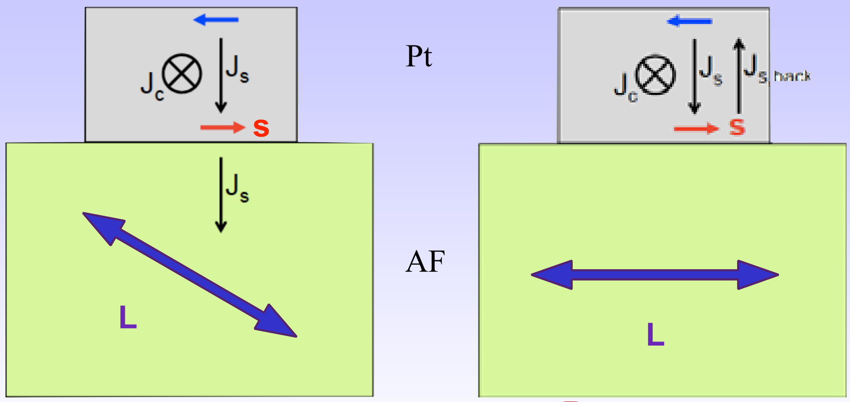
1. Reading Antiferromagnets (I) – XMLD of NiO



- 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]A. Scholl et al., Science **287**, 5455 (2000); N. Weber et al., PRL **91**, 237205 (2003); [2]L. Baldrati et al., PRB **98**, 024422 (2018).

1. Reading Antiferromagnets electrically (II) - SMR



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

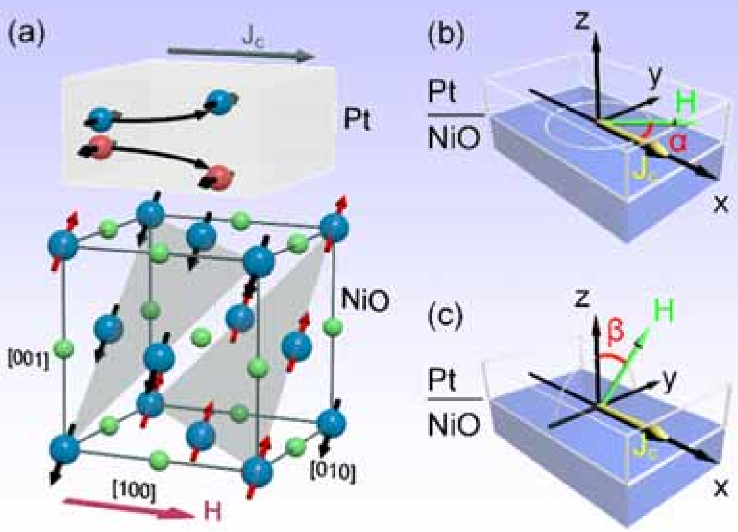
$$R = R_0 - \Delta R(\mathbf{L}\mathbf{s})^2$$

courtesy 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 Insulating 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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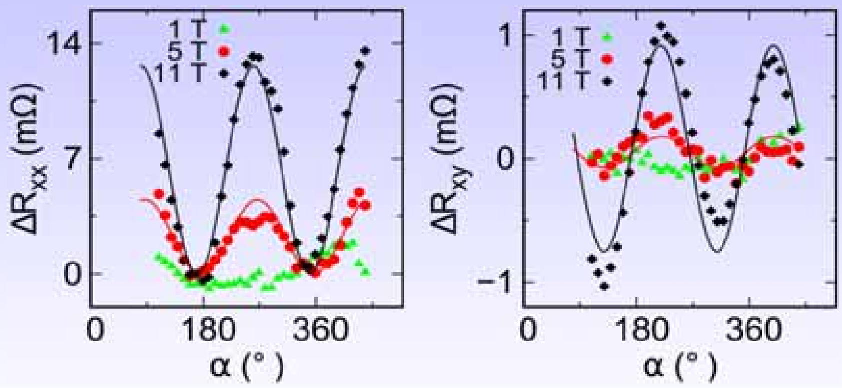

- By rotating a strong field, the Néel vector is rotated (spin – flop) → negative SMR

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

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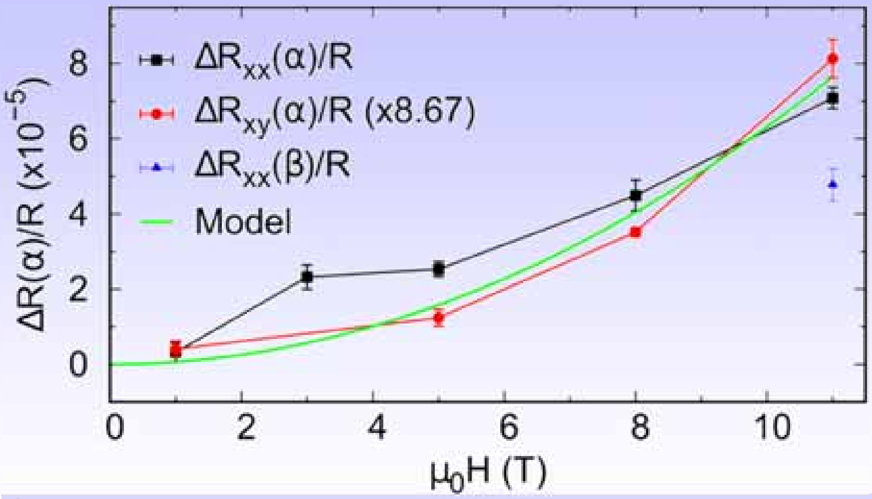
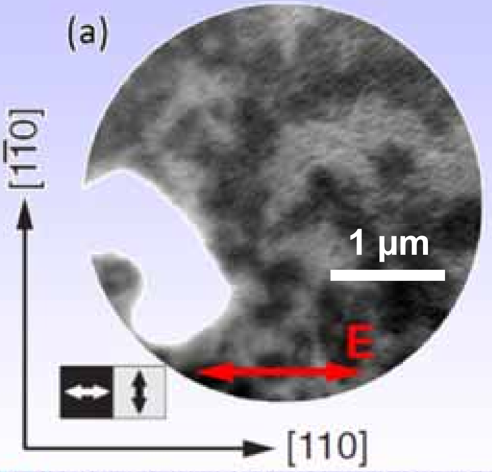


- By rotating a strong field, the Néel vector is rotated (spin – flop) → negative SMR
- The SMR amplitude as a function of magnetic field shows the distribution of the magnetic fields needed to align the Néel vector in different domains.[1]

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

2. Reading metallic Antiferromagnets – MR effects in Mn_2Au



- As grown, Mn_2Au comprises man domains with no net Néel vector orientation.

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., Phys. Rev. Appl. **14**, 014004 (2020) + new results

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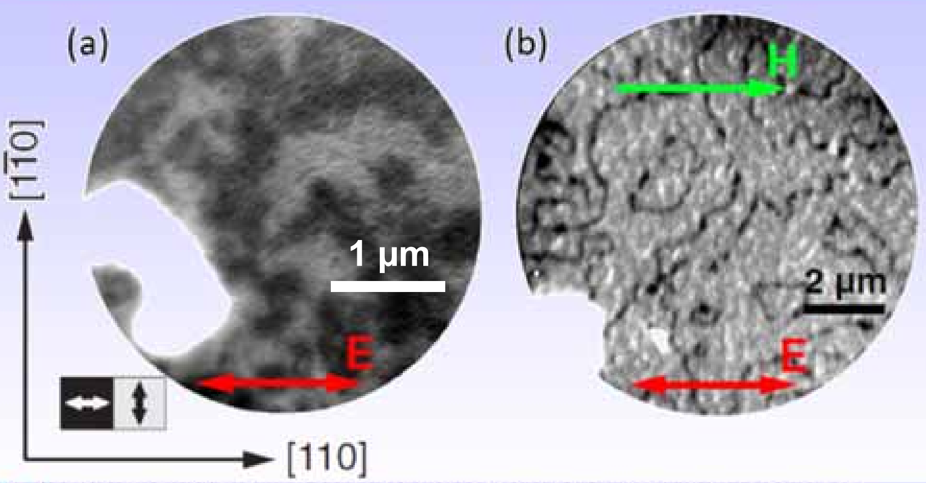
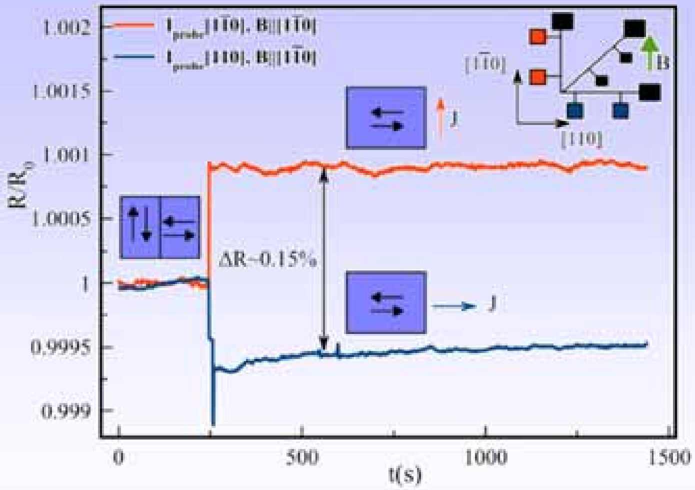


- As grown, Mn_2Au comprises man domains with no net Néel vector orientation.
- Apply field along along one of the cubic easy axes above the spin-flop (50T):
  → orientation of Néel vector perpendicular to field → fewer domains and DWs.

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., Phys. Rev. Appl. **14**, 014004 (2020) + new results

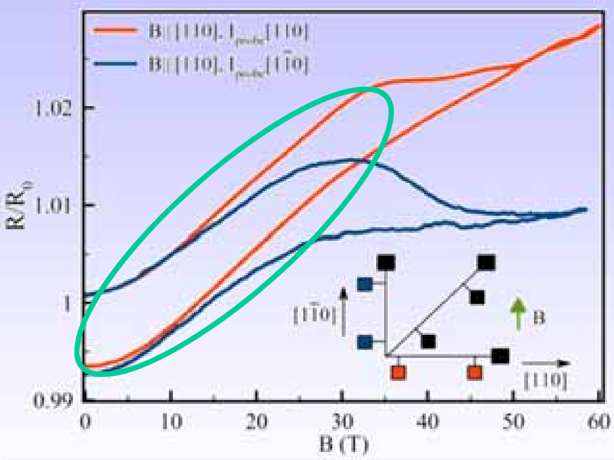
2. Reading metallic Antiferromagnets – MR effects in Mn_2Au



- Measurement of anisotropic magnetoresistance (AMR) amplitude:
- Measurement of resistance in multidomain state and after spin-flop in aligned state: ΔR = 0.15% (AMR!)

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., Phys. Rev. Appl. **14**, 014004 (2020) + new results

2. Reading metallic Antiferromagnets – MR effects in Mn_2Au



- Apply 60T field pulse: up to 30T pure OMR and no switching of the Neel vector.

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., Phys. Rev. Appl. **14**, 014004 (2020) + new results

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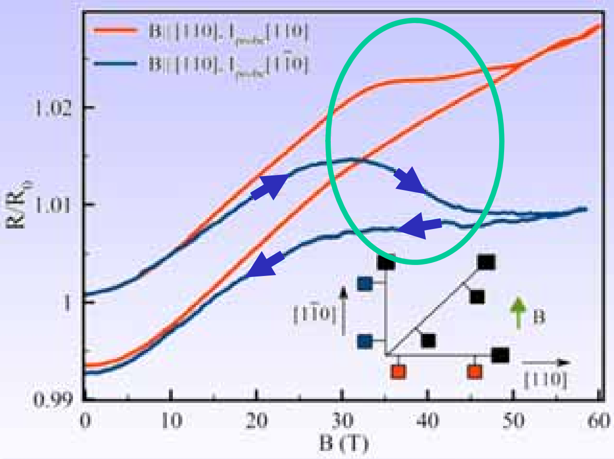

- Apply 60T field pulse: up to 30T pure OMR and no switching of the Neel vector.
- 30-50T: spin-flop → Néel vector is rotated → hysteresis with ΔR = 0.75%!

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., Phys. Rev. Appl. **14**, 014004 (2020) + new results

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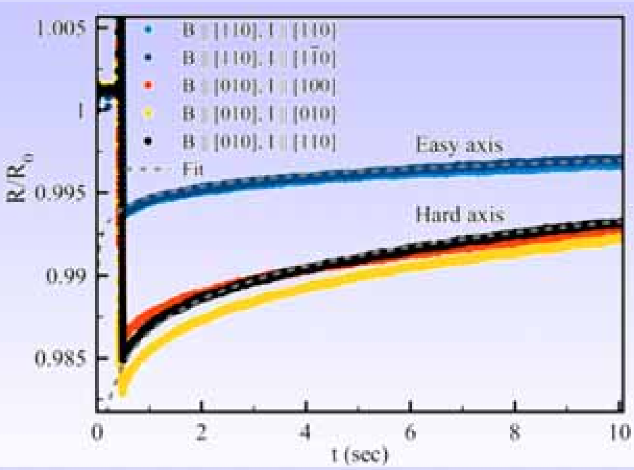
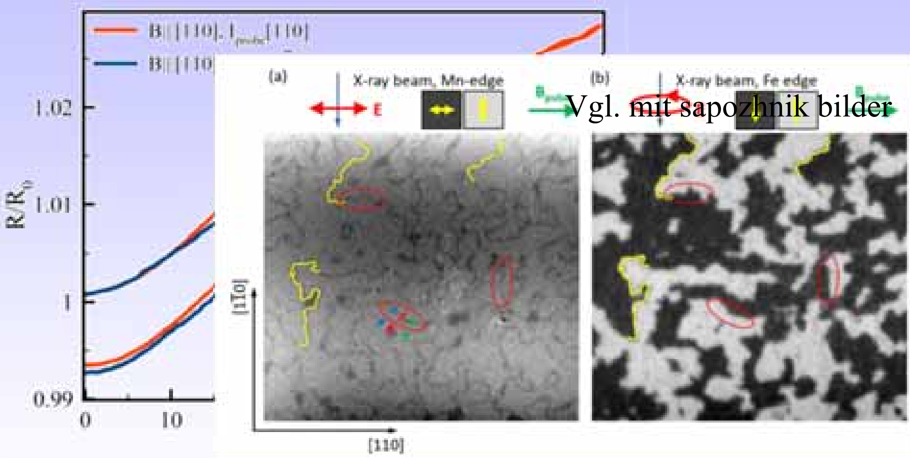


- Apply 60T field pulse: up to 30T pure OMR and no switching of the Neel vector.
- 30-50T: spin-flop → Néel vector is rotated → hysteresis with ΔR = 0.75%!
- ΔR relaxes over a few seconds to ΔR = 0.15% → AMR!
- Origin of ΔR = 0.75% is Domain Wall Magnetoresistance

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., Phys. Rev. Appl. **14**, 014004 (2020) + new results

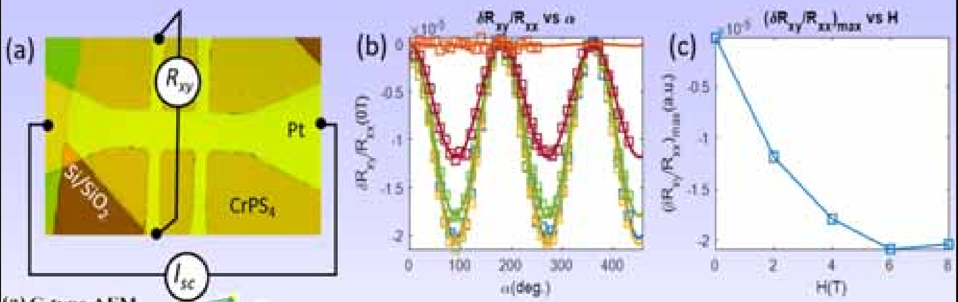
2. Reading Antiferromagnets – identifying AMR in Mn_2Au

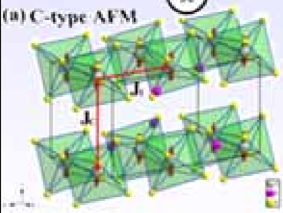


Apply 60T field pulse: up to 30T pure OMR and no switching of the Neel vector.
- 30-50T the Néel vector is rotated (> 30T)
- Between 0 field and 50 T → large change > 3%
- Remanent persistant difference much smaller : MR of ~0.1% → Origin?

[1] S. Y. Bodnar, M. Jourdan, M. Kläui et al., Phys. Rev. Appl. **14**, 014004 (2020) + new results

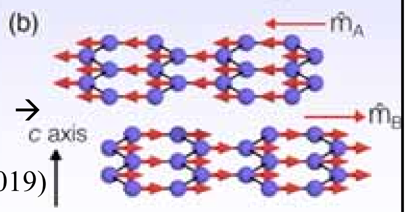
2. Reading Antiferromagnets – 2D AFMs (unpublished)





← $CrPS_4$
JAP **119**,
043902 (2016)

$CrCl_3$ →
PRL **123**,
047204 (2019)



- 2D magnetic materials: layered compounds with antiferromagnetic order: Ising-model (easy axis) or XY-model (easy plane) anisotropy
- First measurements show signals in $CrPS_4$/Pt heterostructures (R. Wu NTNU&JGU)

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2. Summary of Read-Out of Antiferromagnets:

- 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, TXM, x-ray holography,…)
- 3. Other mechanisms:
  - Thermal Seebeck Imaging PRX **9**, 041016 (2019), arxiv:2004.05460
  - Anomalous Nernst Effect Nat. Commun.**10**, 5459 (2019)
  - Imaging uncompensated moments Nature **549**, 252 (2017)
  - Second Harmonic Generation Nature Mater. **16**, 803 (2017)
  - Magneto-optical Kerr effect Phys. Rev. B **100**, 134413 (2019)
  - Exchange Bias JMMM **322**, 883 (2010); JMMM **416**, 2 (2016)

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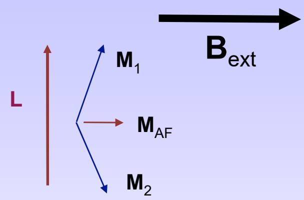
3. Magnetic field-induced switching of antiferromangets

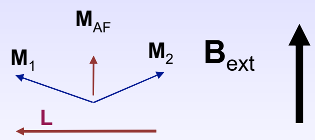
1. Susceptibility is small:

M_{AF} is usually very small for realistic fields (mrad)



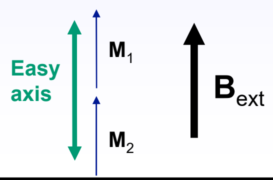
2. Spin - Flop:

For typical (small) anisotropies, the Néel vector orients perpendicular to the field B_{ext}.



2. Spin – Flip (rare, not considered here):

For very strong uniaxial anisotropy and low exchange, the two sub-lattice abruptly orient along the field direction.



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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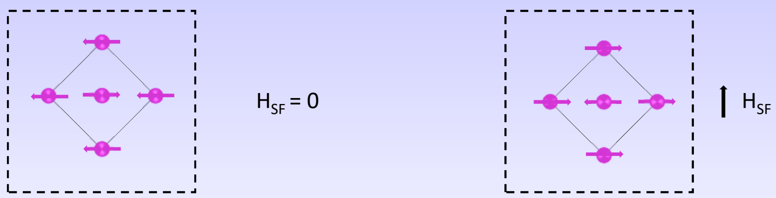

- Switching from one easy axis to the other upon applying a high magnetic field
- Moments preserve their initial orientation

- 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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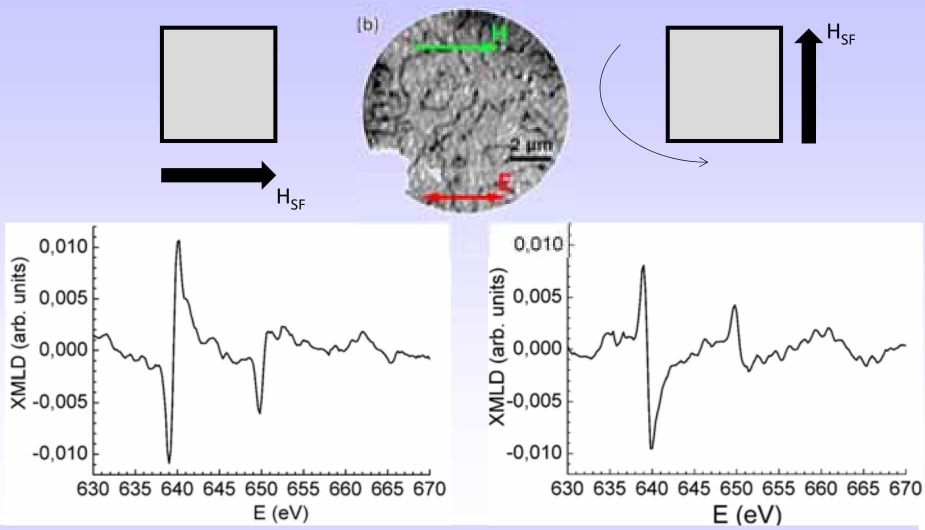

- XMLD-imaging shows clear dichroism due to the alignment of the Néel vector.

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

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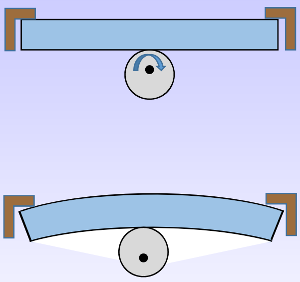
3. Strain-induced writing of Mn_2Au



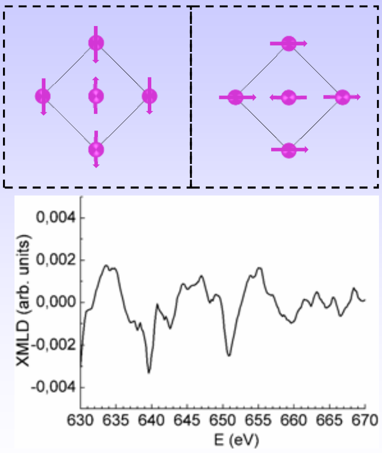
- Compatibility with UHV conditions
- Controllable value of strain
- Monitoring of strain with a strain gauge

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

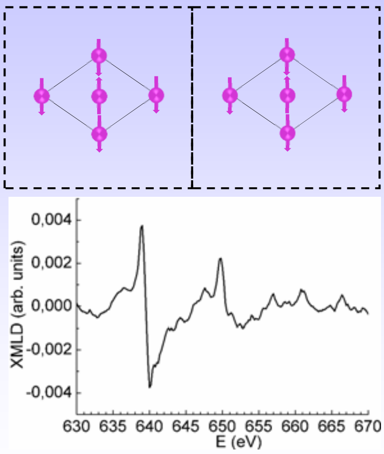
A. Sapozhnik, M. Jourdan, MK et al., Phys. Status Solidi RRL **11**, 1600438 (2017).

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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4. Spin torque switching of Antiferromagnets – spin transfer torques

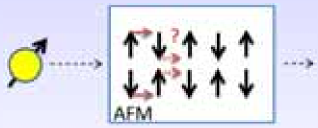
Ferromagnets

Spin Transfer Torque
for ferromagnets

Well known
J. Slonczewski, JMMM 159, L1 (1996),
D. C. Ralph et al., JMMM 320, 1190 (2008)

Antiferromagnets

Spin Transfer Torque
for antiferromagnets?



Unclear?
Will not work?

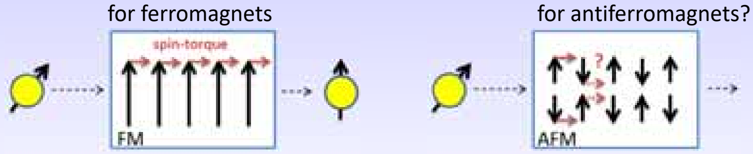
- Problem for electrical switching by spin transfer torque:
  Sub-lattices with opposite magnetization are affected by spin current in oposite directions → no net effect?!?

Courtesy T. Moriyama

4. Spin-orbit torque switching of Antiferromagnets

Ferromagnets | Antiferromagnets

Spin Transfer Torque for ferromagnets | Spin Transfer Torque for antiferromagnets?



Well known
J. Slonczewski, JMMM 159, L1 (1996),
D. C. Ralph et al., JMMM 320, 1190 (2008)

Unclear?
Will not work?

- 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);

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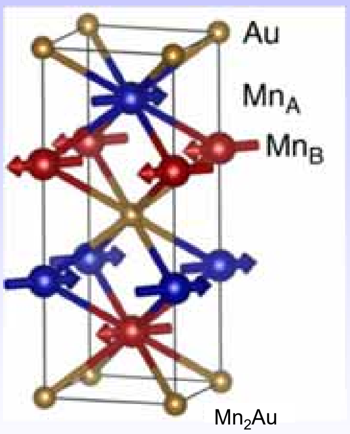
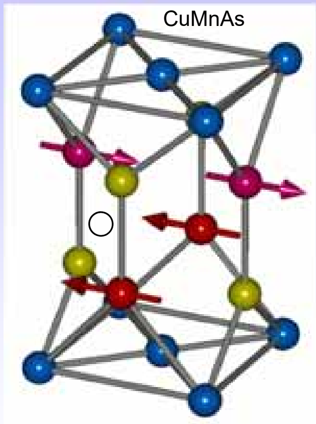
4. Spin-orbit torque switching of Mn_2Au



Effective time-reversal Symmetry because of inequivalent Mn-sites (A and B)!



J. Zelezny, F. Freimuth

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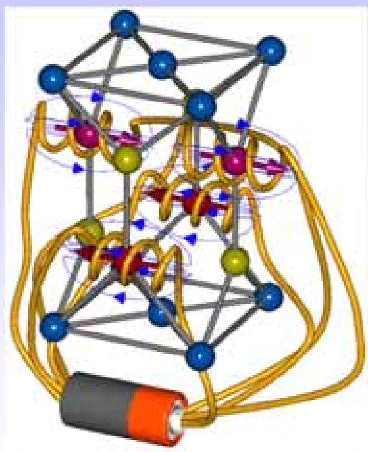
4. Spin-orbit torque switching of Mn_2Au



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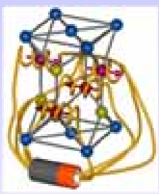
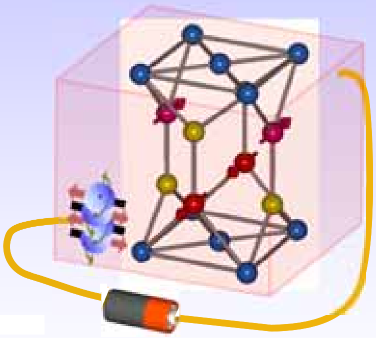
4. Spin-orbit torque switching of Mn_2Au

Antiferromagnets



Bulk Spin-orbit torque writing



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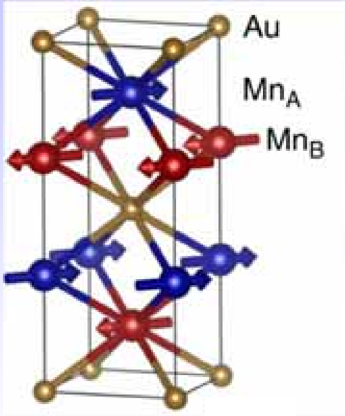
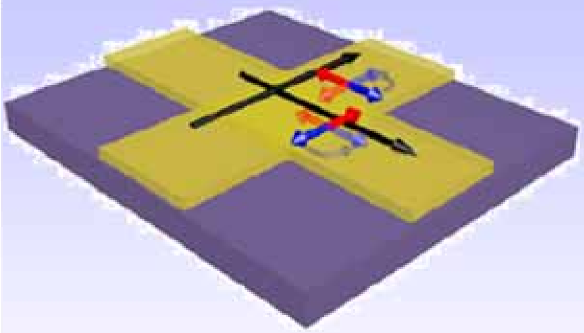
4. Spin-orbit torque switching of Mn_2Au





- Predicted effect: Néel vector orients perpendicular to the charge current flow[1-4]
  → 90° different current paths lead to 90° switching (but current polarity independent!)

[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]X. Zhou et al., Phys. Rev. Appl. **9**, 054028 (2018

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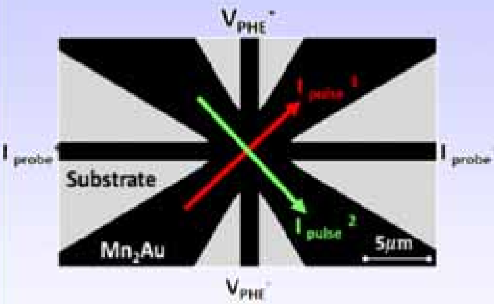
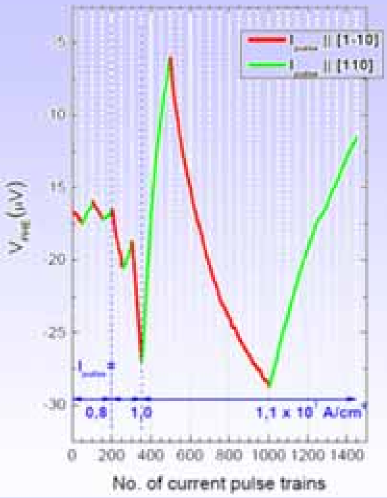
4. Bulk spin orbit torque switching in Mn_2Au

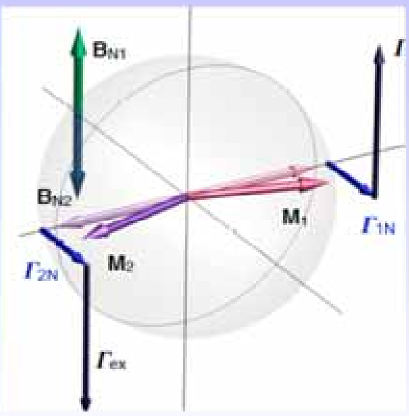


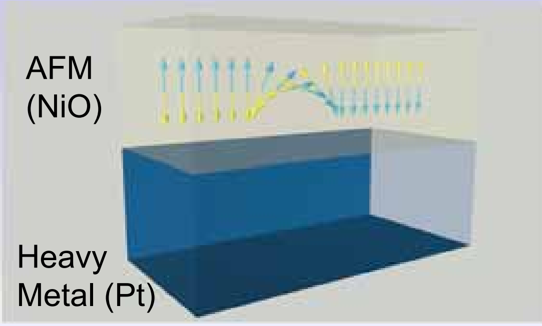


- Bulk Néel spin orbit torques have been predicted to switch the Néel vector.
- Non-linear switching as a function of current density → heating effects important!

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

4. Interfacial spin-orbit torque switching of Antiferromagnets



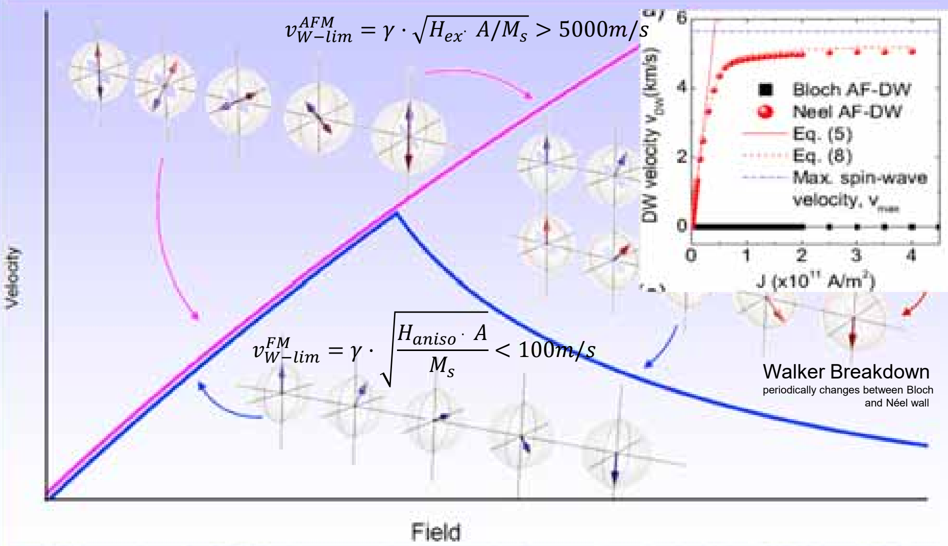


H. Gomonay, J. Sinova et al.,
Phys. Rev. Lett. **117**, 017202 ('16)

- Different switching mechanisms:
  Domain Wall motion[1]

[1]T. Shiino et al., Phys. Rev. Lett. **117**, 087203 ('16); [2]L. Baldrati, MK et al., Phys. Rev. Lett. **123**, 177201 ('19)

4. Interfacial spin-orbit torque switching of Antiferromagnets



- DW motion in AFMs is potentially much faster (not limited by Walker-field)

H. Gomonay, J. Sinova et al., PRL **117**, 017202 (2016); H. Gomonay, MK et al., APL **109**, 142404 (2016)

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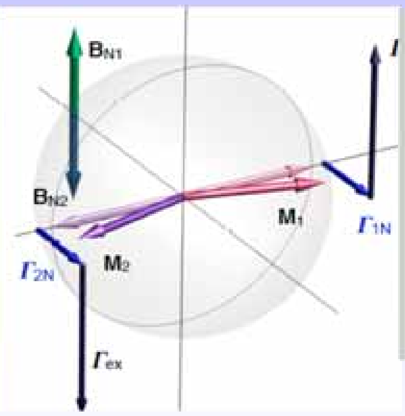
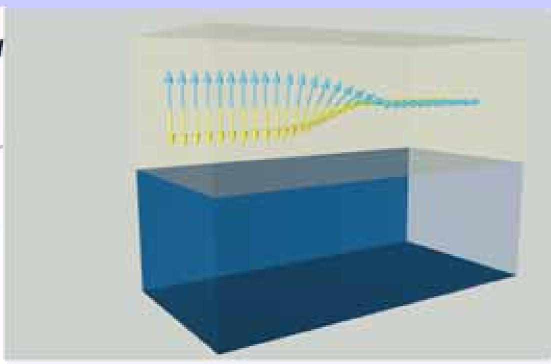
4. Interfacial spin-orbit torque switching of Antiferromagnets





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

- Different switching spin-based mechanisms:
  Domain Wall motion[1]
  Ponderomotive force[2]

[1]T. Shiino et al., Phys. Rev. Lett. **117**, 087203 (‘16); [2]L. Baldrati, MK et al., Phys. Rev. Lett. **123**, 177201 (‘19)

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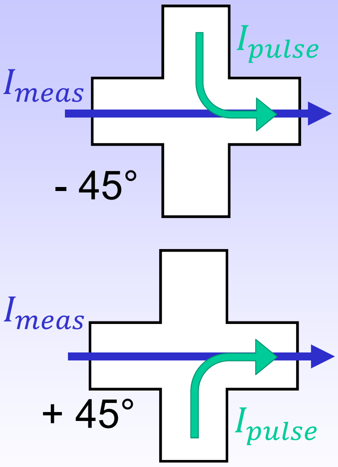
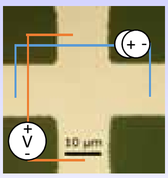
4. Combining reading and writing: interfacial SOT switching of NiO





Geometry for switching of MgO(001)/NiO(5-50 nm)/Pt(2-5nm)

[1]L. Baldrati, MK et al.,
Phys. Rev. Lett. **123**, 177201 (‘19)

- In combination with Pt layer: (i) possible damping-like non-staggered SOTs[1] (ii) joule heating & associated thermal strain, (iii) pure charge current effects.

See also Cheng et al., PRL **124**, 27202 (2020); Chen et al., PRL **120**, 207204 (2018); Gray et al., PRX **9**, 41016 (2019

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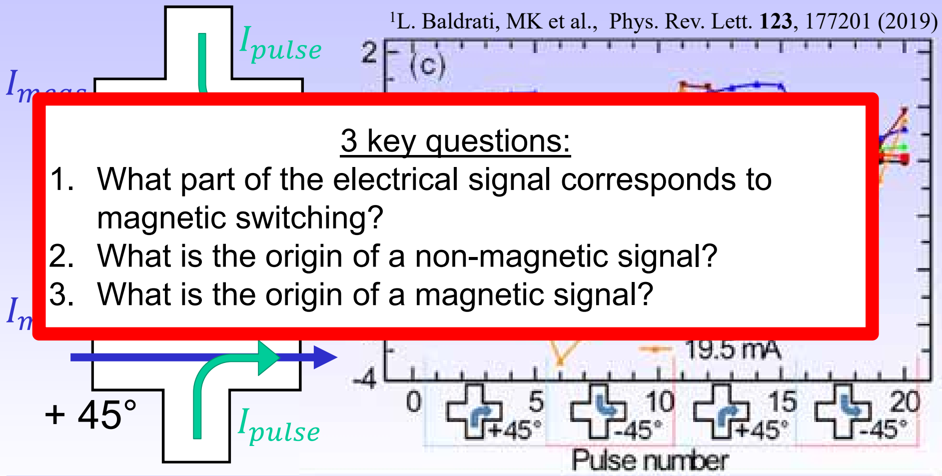
4. Combining reading and writing: interfacial SOT switching of NiO

[1]L. Baldrati, MK et al., Phys. Rev. Lett. **123**, 177201 (2019)



3 key questions:
1. What part of the electrical signal corresponds to magnetic switching?
2. What is the origin of a non-magnetic signal?
3. What is the origin of a magnetic signal?

- In combination with Pt layer: (i) possible damping-like non-staggered SOTs[1] (ii) joule heating & associated thermal strain, (iii) pure charge current effects. →2 effects: Néel vector change+structural changes in Pt due to charge current?

See also Cheng et al., PRL **124**, 27202 (2020); Chen et al., PRL **120**, 207204 (2018); Gray et al., PRX **9**, 41016 (2019

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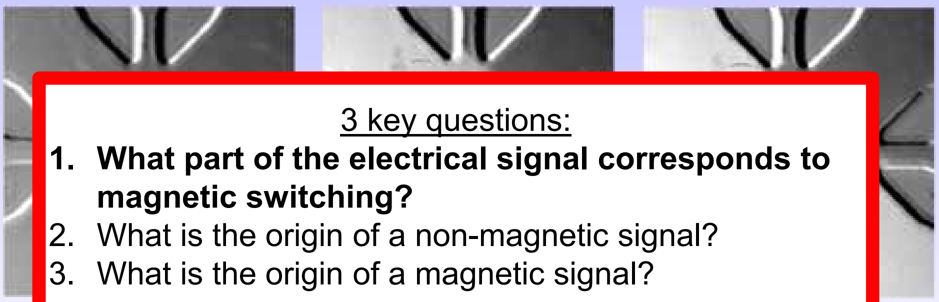


3 key questions:
1. **What part of the electrical signal corresponds to magnetic switching?**
2. What is the origin of a non-magnetic signal?
3. What is the origin of a magnetic signal?

before pulse after pulse ↘ after pulse ↗

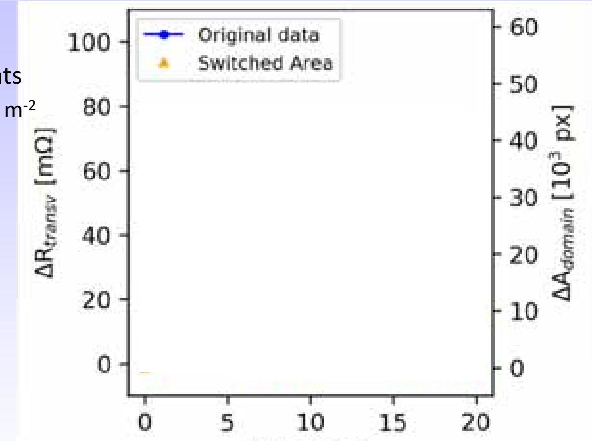
Full switching of area where current is flowing: $j_P = 1.5 \times 10^{12}$ A m^{-2}
F. Schreiber et al., Appl. Phys. Lett. **117**, 082401 (2020)

- In combination with Pt layer, damping-like non-staggered SOTs generate 90° switching in NiO: Néel vector is rotated **parallel** to electron flow![1]
- Direct imaging shows 90° switching of Néel vector upon pulse injection

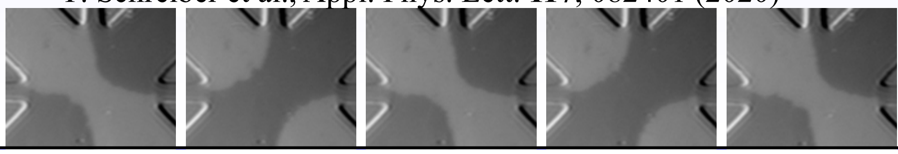
See also Cheng et al., PRL **124**, 27202 (2020); Chen et al., PRL **120**, 207204 (2018); Gray et al., PRX **9**, 41016 (2019

4. Identifying electrical signals of switching of NiO

Electrical measurements
$j_P = 1.27 \times 10^{12}$ A m^{-2}

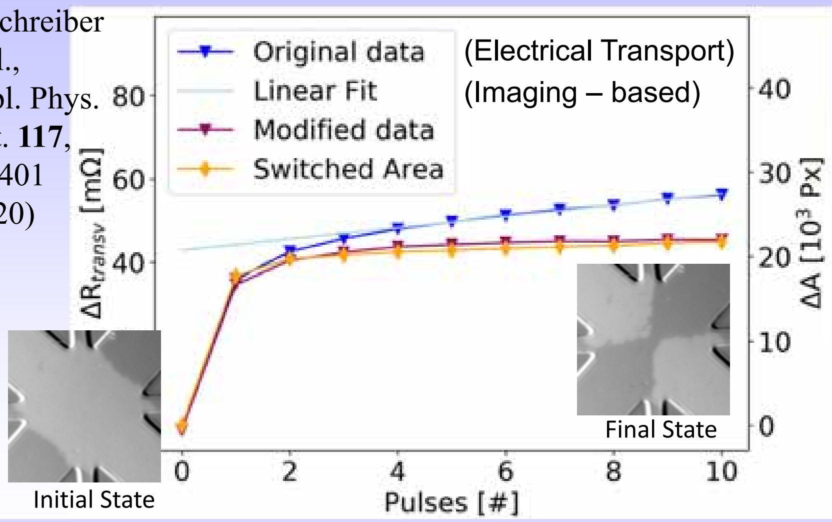


F. Schreiber et al., Appl. Phys. Lett. **117**, 082401 (2020)



4. Identifying electrical signals of switching of NiO

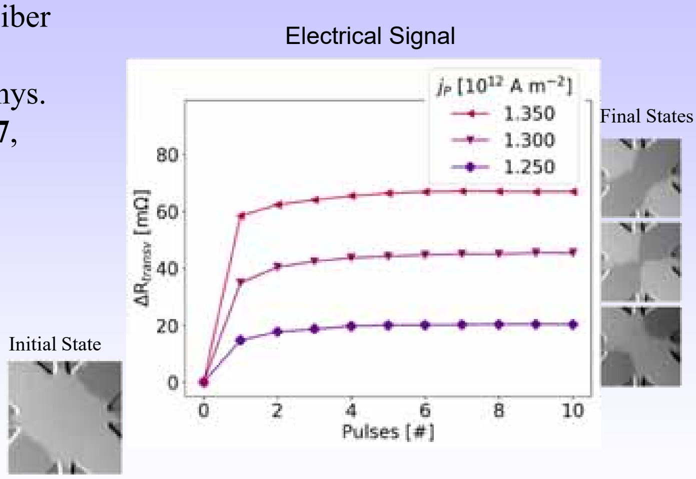
F. Schreiber et al., Appl. Phys. Lett. **117**, 082401 (2020)



- The switched area saturates after a few pulses but electrical signal increases
  Subtracting linear increase → excellent agreement of imaging and transport!

4. Identifying electrical signals of switching of NiO

F. Schreiber et al., Appl. Phys. Lett. **117**, 082401 (2020)



- Increasing current density increases the amount of switched area!

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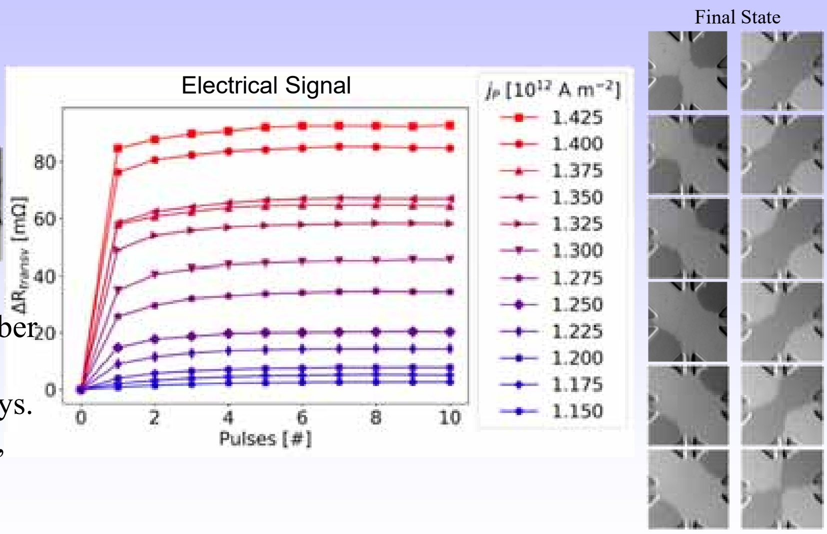
4. Identifying electrical signals of switching of NiO

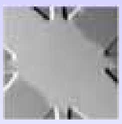


F. Schreiber et al., Appl. Phys. Lett. **117**, 082401 (2020)

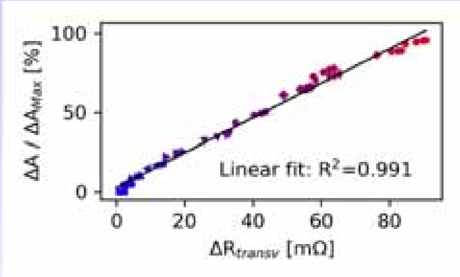
- Increasing current density increases the amount of switched area!

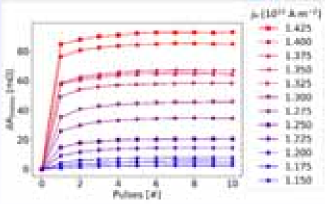
4. Identifying electrical signals of switching of NiO

Initial State

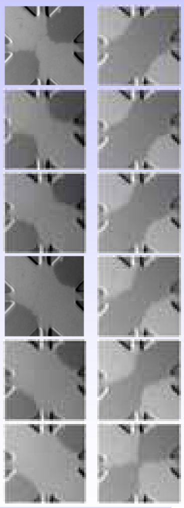


F. Schreiber et al., Appl. Phys. Lett. **117**, 082401 (2020)





Final State



- Correlation between electrical signal amplitude & switched area from imaging → robust electrical measurement of the area that is switched!

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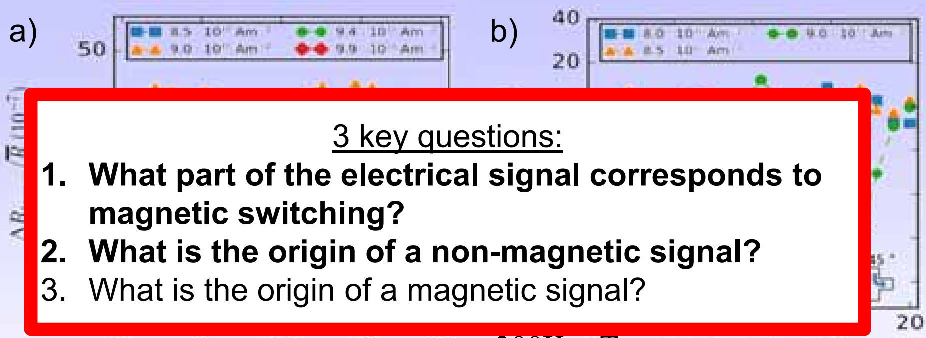
4. Electrical switching of CoO/Pt: identifying non-magnetic signals



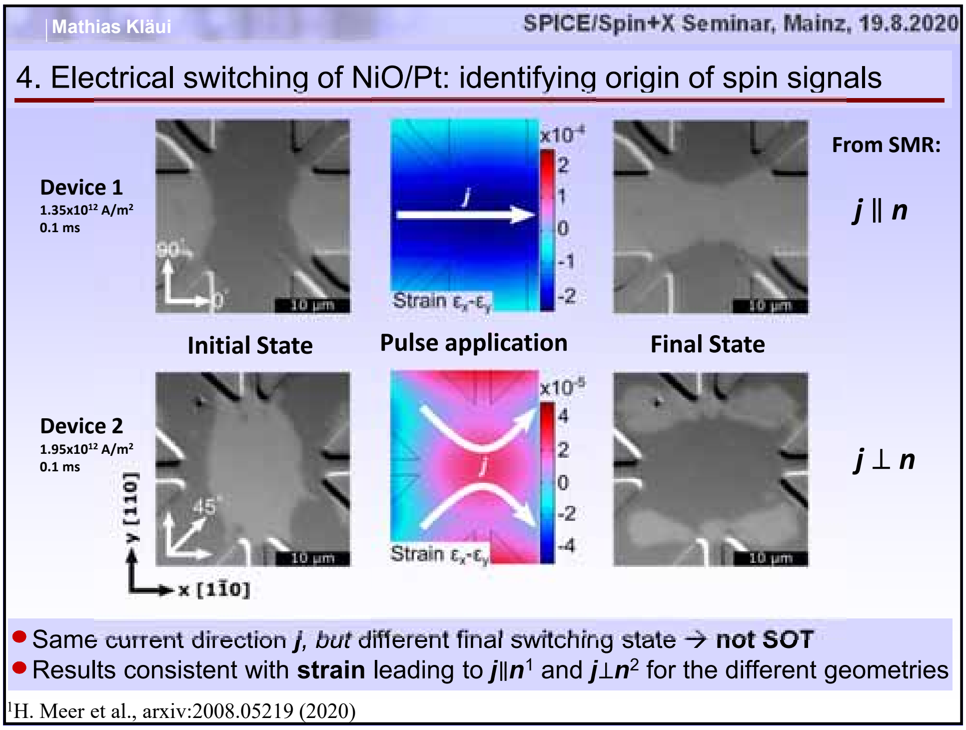
3 key questions:

1. **What part of the electrical signal corresponds to magnetic switching?**
2. **What is the origin of a non-magnetic signal?**
3. What is the origin of a magnetic signal?

254K < $T_{Néel}$ *Number of pulses* 300K > $T_{Néel}$ *Number of pulses*

- $T<T_{Néel}$: (i) rectangular switching at low j & (ii) saw-tooth switching at high j[1]
- $T>T_{Néel}$: only saw-tooth switching signal → electromigration effects[1,2,3,4]!!!

[1]L. Baldrati et al., Phys. Rev. Lett. **125**, 077201 (2020); [2]T. Matalla-Wagner et al., PR Res. **2**, 033077 (2020); [3]C. Chiang et al., Phys. Rev. Lett. **123**, 227203 (2019); [4]A. Churikova et al., Appl. Phys. Lett. **116**, 22410 (2020)



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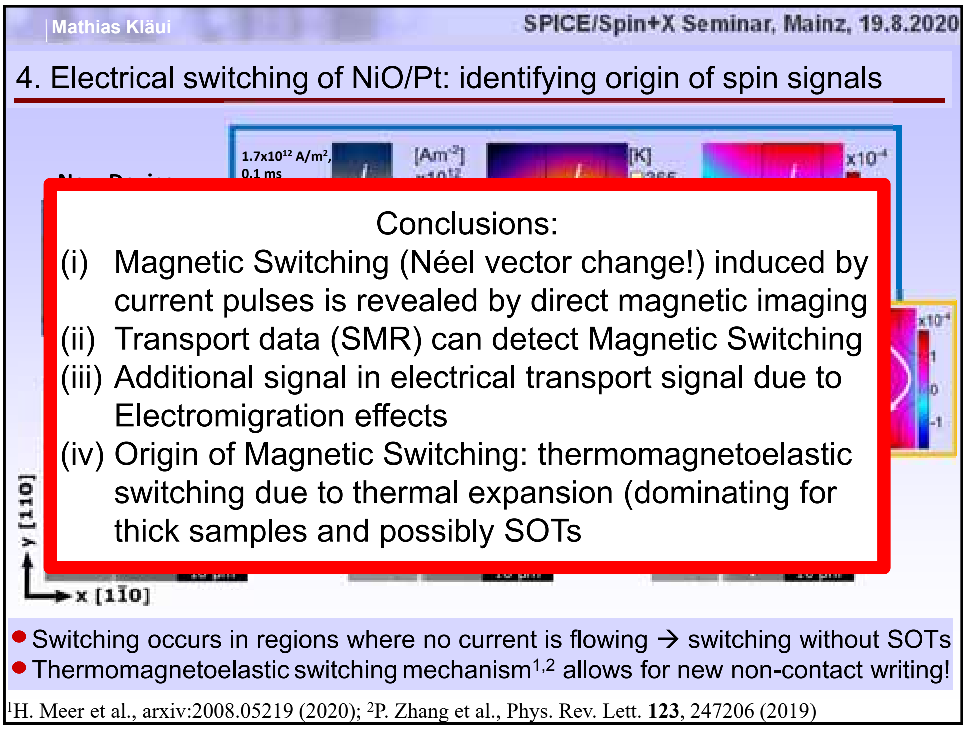
4. Electrical switching of NiO/Pt: identifying origin of spin signals
Device 1
1.35x10¹² A/m²
0.1 ms
Initial State
Pulse application
Final State
From SMR:
j ∥ n
Strain εx-εy
x10⁻⁴
10 µm
Device 2
1.95x10¹² A/m²
0.1 ms
x10⁻⁵
j ⊥ n
y [110]
x [11̄0]
Same current direction j, but different final switching state → not SOT
Results consistent with strain leading to j∥n¹ and j⊥n² for the different geometries
¹H. Meer et al., arxiv:2008.05219 (2020)



Mathias Kläui
SPICE/Spin+X Seminar, Mainz, 19.8.2020
4. Electrical switching of NiO/Pt: identifying origin of spin signals
1.7x10¹² A/m²
0.1 ms
[Am⁻²]
[K]
x10⁻⁴
Conclusions:
(i) Magnetic Switching (Néel vector change!) induced by current pulses is revealed by direct magnetic imaging
(ii) Transport data (SMR) can detect Magnetic Switching
(iii) Additional signal in electrical transport signal due to Electromigration effects
(iv) Origin of Magnetic Switching: thermomagnetoelastic switching due to thermal expansion (dominating for thick samples and possibly SOTs
y [110]
x [11̄0]
Switching occurs in regions where no current is flowing → switching without SOTs
Thermomagnetoelastic switching mechanism¹,² allows for new non-contact writing!
¹H. Meer et al., arxiv:2008.05219 (2020); ²P. Zhang et al., Phys. Rev. Lett. 123, 247206 (2019)

4. 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 (Mn_2Au, CuMnAs)
  -Interfacial non-staggered spin-orbit torques in insulating AFM / Pt bilayer
  -Thermo-magnetoelastic switching

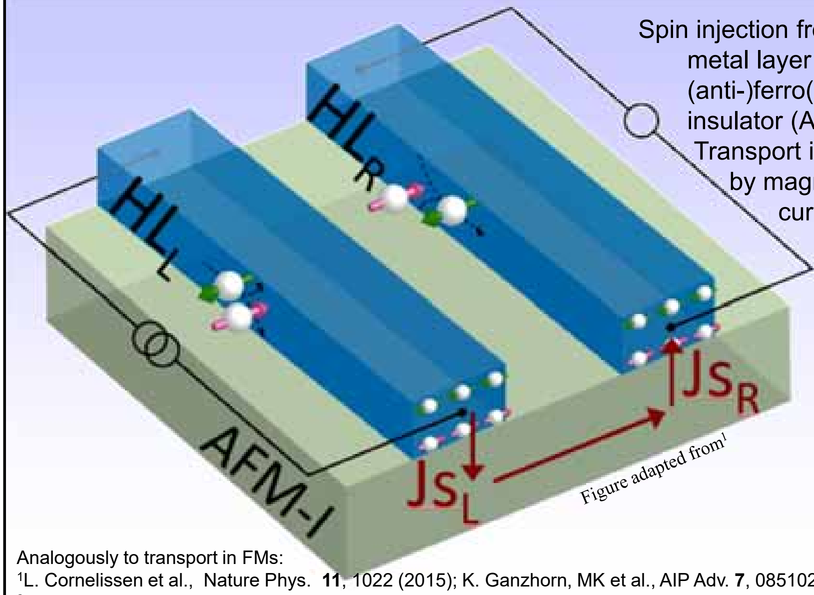
Courtesy T. Jungwirth

Writing, reading and transporting spin in antiferromagnets

M. Kläui[1,2]
[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**

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]. Transport in the AFM-I by magnonic spin currents.[2]

Analogously to transport in FMs:

[1]L. Cornelissen et al., Nature Phys. **11**, 1022 (2015); K. Ganzhorn, MK et al., AIP Adv. **7**, 085102 (2017)

[2]S. Rezende et al., J. Appl. Phys. **126**, 151101 (2019); M. Hagiwara et al., J. Infrared Millim. Waves **20**, 4 (1999)

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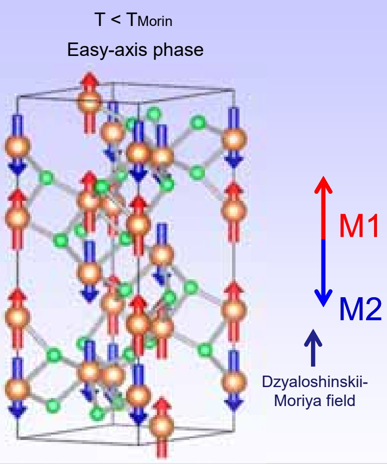
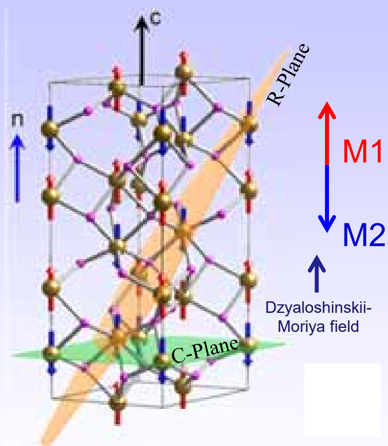
4. Hematite – R-cut bulk crystals with easy axis anisotropy





- Hematite (α-Fe_2O_3)[1] is an easy axis collinear antiferromagnet with an easy [111] axis.
- Use R-cut hematite with a (1120) surface → easy axis is at 30° to our surface[2].
- For analysis it is sufficient to consider only the projection into the surface plane.

[1] A. Sanson et al., J. Chem Phys. 140, 224504 (2014); [2]R. Lebrun, MK et al., Comm. Phys. **2**, 50 (2019)

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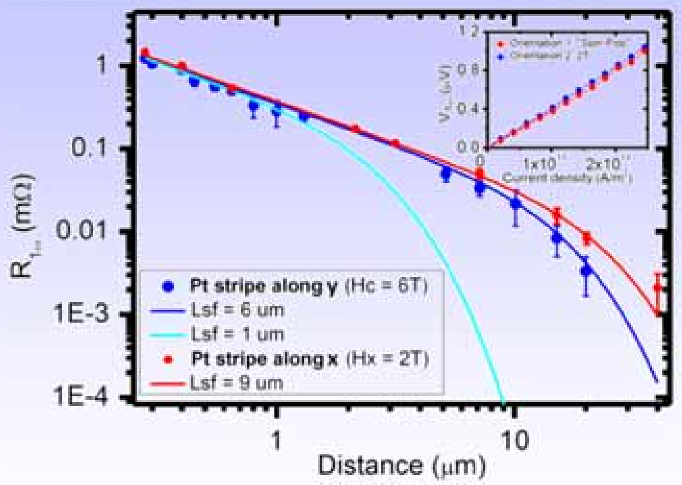
5. Quantifying spin transport & dissipation in bulk hematite

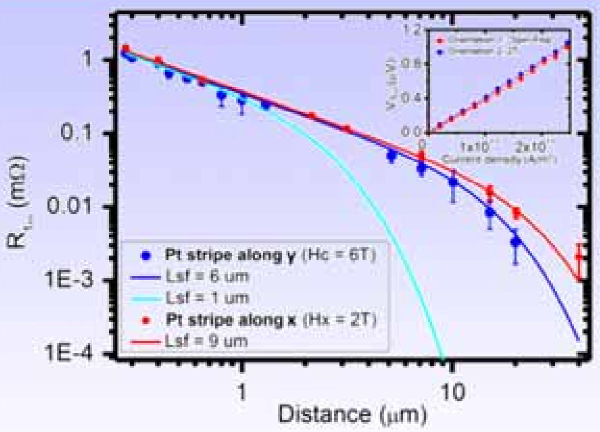


- Distance dependence: exponential decay → diffusive spin transport
- Largest ever reported spin diffusion lengths for a magnetic insulator: 5-10 μm depending on applied field and transport over 40 μm observed!

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

Mathias Kläui SPICE/Spin+X Seminar, Mainz, 19.8.2020

5. Quantifying spin transport & dissipation in bulk hematite



- 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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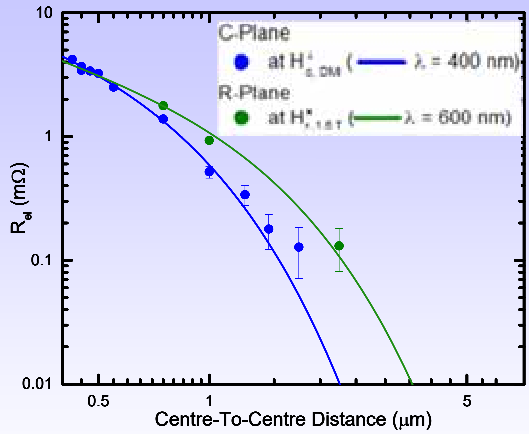
5. Quantifying spin transport in thin film hematite



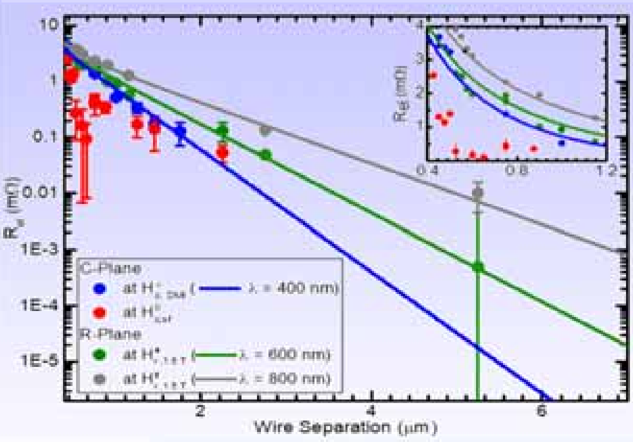
- μm diffusive transport in thin film antiferromagnet
- Origin of differences in spin diffusion lengths?:
  - -Bulk Fe_2O_3: 5-10 μm[1]
  - -Thin film Fe_2O_3:
    - c-cut: 400 nm
    - r-cut: 600 nm
  - -Thin film NiO: few nm[2]

[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	✓

Mathias Kläui SPICE/Spin+X Seminar, Mainz, 19.8.2020

5. Quantifying spin transport in thin film hematite



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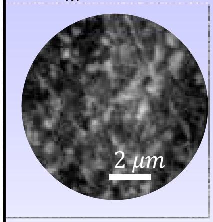
  - -Bulk Fe_2O_3: 5-10 μm[1]
  - -Thin film Fe_2O_3:
    - c-cut: 400 nm
    - r-cut: 600 nm
  - -Thin film NiO: few nm[2]
- Signal at spin-flop not simple diffusion → reason?

[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	✓

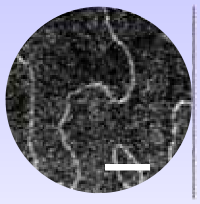
5. Correlating domain structures and spin transport lengths

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



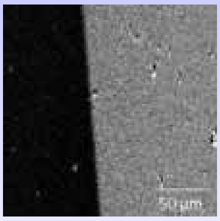
Domain size:
100 nm
λ = <100 nm

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



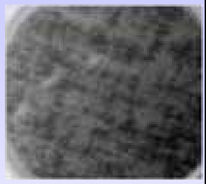
Domain size:
500 nm
λ = 600 nm

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



Domain size:
> 10 μm
λ = 5-10 μm

NiO (001) thin film[3]

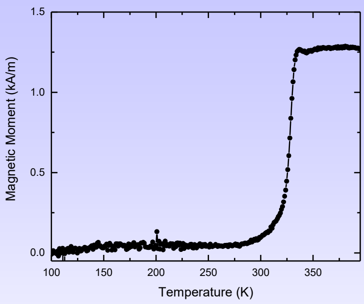


Domain size:
<100 nm
λ = few nm[2]

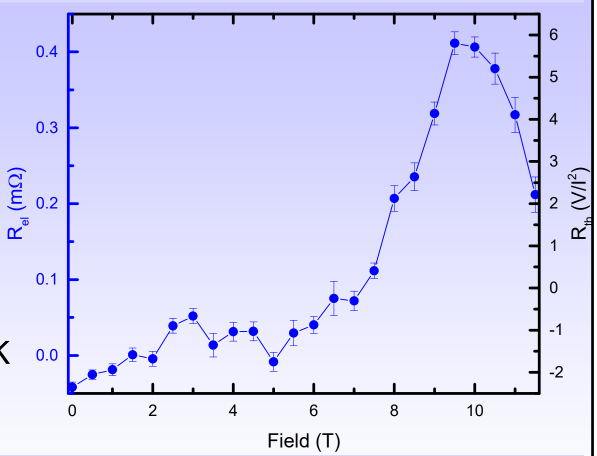
- Spin transport length scales with domain size.
- Circularly polarized magnons are predicted to be scattered from domain walls → many domain walls → scattering – magnon domain wall resistance![4]
- Domain size can govern spin transport length due to DWs![1]

[1]A. Ross, A. Qaiumzadeh, C. Ulloa, R. Duine, A. Brataas, MK et al., Nano Lett. **20**, 306 (2020);
[2]R. Lebrun, A. Qaiumzadeh, S. Bender, R. Duine, A. Brataas, MK et al., Nature **561**, 222 (2018);
[3]L. Baldrati, MK et al., Phys. Rev. B **98**, 024422 (2018); [4]E. Tveten et al., Phys. Rev. Lett. **112**, 147204 (2014)

5. Spin transport in Antiferromagnets at Room temperature



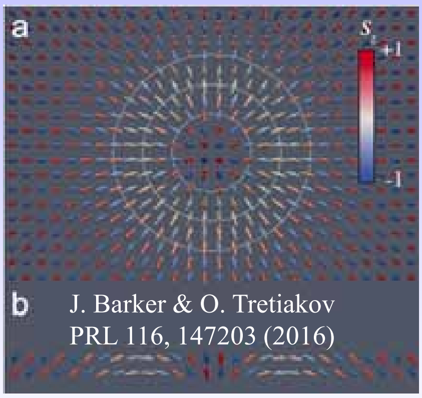
Morin transition at 310K



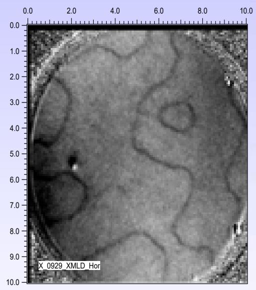
- Doping of hematite can increase or decrease the Morin transition[1]
- Transport in the easy plane phase (at room temperature) possible![2]

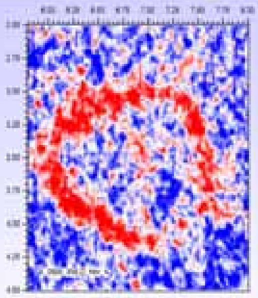
[1]F. J. Morin, Phys. Rev. **83** 5 (1951); N. Shimomura et al, J. Appl. Phys. **117**, 17C736 (2015)
[2]R. Lebrun,MK et al., arxiv:2005.14414; J. Han et al., Nature Nano. (2020)

5. Skyrmions in Antiferromagnets



Skyrmions? Sneak preview…
A. Ross, MK et al., arxiv:2001.03117v2





- Doping of hematite can increase or decrease the Morin transition[1]
- Transport in the easy plane phase (at room temperature) possible![2]
- Possible antiskyrmion structures in hematite.

[1]F. J. Morin, Phys. Rev. **83** 5 (1951); N. Shimomura et al, J. Appl. Phys. **117**, 17C736 (2015)
[2]R. Lebrun,MK et al., arxiv:2005.14414; J. Han et al., Nature Nano. (2020)

4. Summary of Spin Transport in Antiferromagnets:

- 1. Diffusive vs. Superfluid spin transport in AFMs
  Nature **561**, 222 (‘18); Phys. Rev. Lett. **119**, 187705 (2017); Sci. Adv. **4**, eaat1098 (2018); Nature Mater. 17, 577 (2018); arxiv:2005.14414 (2020); arxiv:2001.03117
- 2. Influence of domains and domain walls on spin transport in AFMs
  Nano Lett. **20**, 306 (2020)
- 3. Further Transport Studies:
  Vertical transport across AFMs
  Phys. Rev. Lett. **113**, 097202 (2014); Europhys. Lett. **108**, 57005 (2014); Appl. Phys. Lett. **106**, 162406 (2015); Phys. Rev. Lett. **116**, 186601 (2016); Nat. Comm. **7**, 12670 (‘16); Phys. Rev. B **98**, 014409 (‘18), PRB **98**, 094422 (‘18).
  Magnon Spin Valves (FM/AFM-I/FM)
  Nature Comm. **9**, 1089 (2018); Phys. Rev. Lett. **120**, 097205 (2018); Phys. Rev. Lett. **120**, 097702 (2018)

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S. Prakash, A. Rajan **H. Zabel, M. Jourdan, G. Jakob…and many former group members!**

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V. Baltz, CEA Grenoble, T. Moriyama, T. Ono, Kyoto
T. Seifert, T. Kampfrath, FHI-FUB,…

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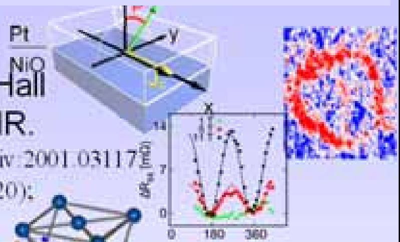
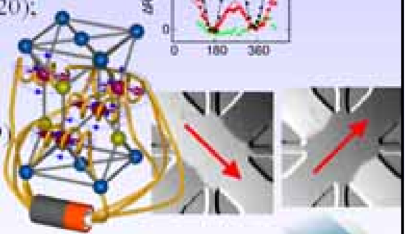
ICC-IMR Visiting Professor, Stanford-Tohoku-Mainz SpinNet, QuSpin

Summary:

- Reading AFMs: XMLD- and Kerr-microscopy and in insulators by spin Hall magnetoresistance & in metals by AMR.
  PRB **98**, 24422 (2018); PRB **99**, 140409 (2019); arxiv:2001.03117;
  Comm. Phys. **2**, 50 (2019). PR Appl. **14**, 014004 (2020);



- Writing AFM insulators and metals: current injection (e.g. SOTs) & strain
  Nature Com. **9**, 348 (2018); PRL **123**, 177201 (2019);
  PRL **125**, 077201 (2020); APL **109**, 142404 (2016);
  arxiv:2004.13374; arxiv:2008.05219



- Spin Transport in AFM insulators: Observation of long-distance diffusive transport & strong dependence on domain structure
  → spin transport can be tuned! arxiv:2005.14414 (2020)

Nano Lett. **20**, 306 (2020); Nature **561**, 222 (2018); PRL **119**, 187705 (2017);
General reviews: Rev. Mod. Phys. **90**, 15005 (2018); Nature Phys. **14**, 200, 213, 220, 229, 242 (2018);