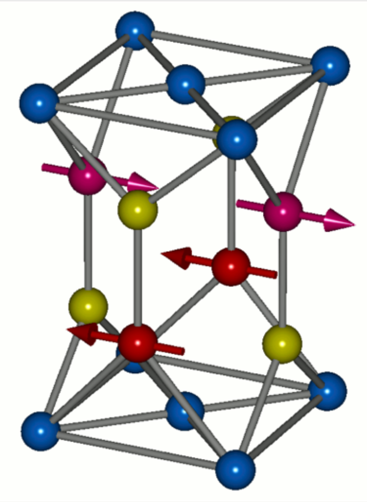
Antiferromagnetic spintronics: From memories to topological transport and ultra-fast optics

Tomas Jungwirth
Institute of Physics, Czech Academy of Sciences
University of Nottingham, United Kingdom



nature physics Focus I March 2018

Antiferromagnetic spintronics

The multiple directions of antiferromagnetic spintronics — T. Jungwirth, J. Sinova, A. Manchon, X. Marti, J. Wunderlich & C. Felser

Spin transport and spin torque in antiferromagnetic devices — J. Železný, P. Wadley, K. Olejník, A. Hoffmann & H. Ohno

Antiferromagnetic spin textures and dynamics — O. Gomonay, V. Baltz, A. Brataas & Y. Tserkovnyak

Antiferromagnetic opto-spintronics — P. Němec, M. Fiebig, T. Kampfrath & A. V. Kimel

Topological antiferromagnetic spintronics — Libor Šmejkal, Yuriy Mokrousov, Binghai Yan & Allan H. MacDonald

Synthetic antiferromagnetic spintronics — R. A. Duine, Kyung-Jin Lee, Stuart S. P. Parkin & M. D. Stiles

IOP Nanotechnology **Topical Review** 2018

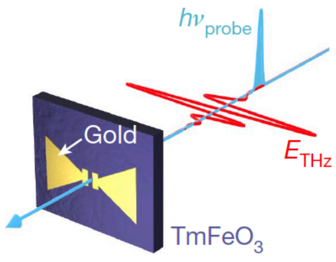
How to manipulate magnetic states of antiferromagnets — Cheng Song, Yunfeng You, Xianzhe Chen, Xiaofeng Zhou, Yuyan Wang and Feng Pan

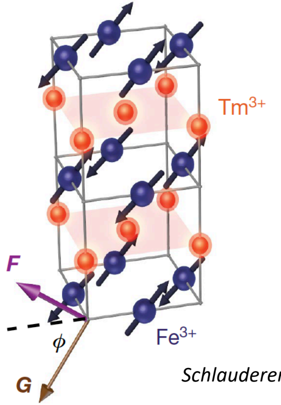
REVIEWS OF MODERN PHYSICS 2018

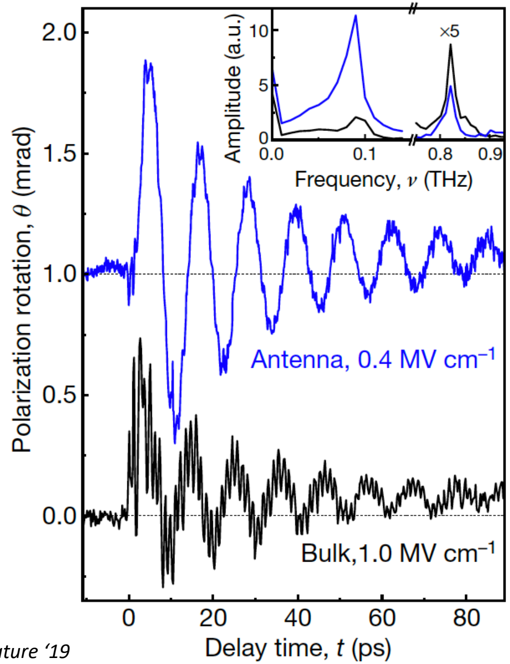
Antiferromagnetic spintronics — V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, and Y. Tserkovnyak

Insulating antiferromagnets

Ultrafast optical (THz) control of spins

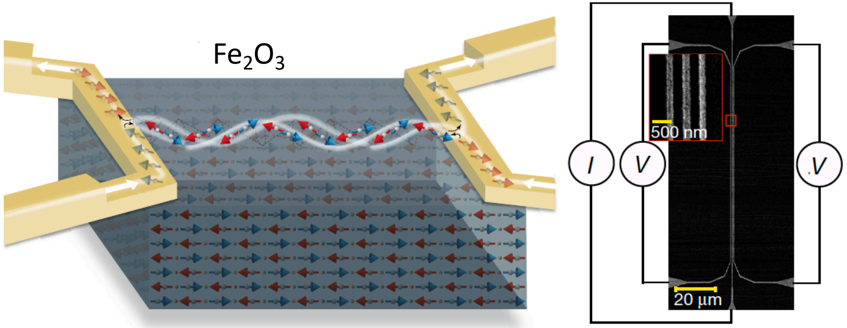






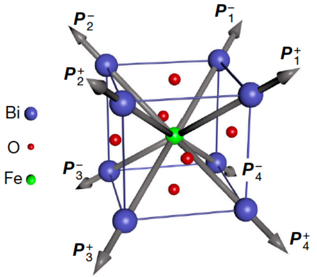
Schlauderer et al., Nature '19

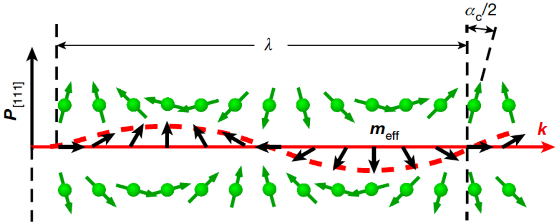
Long-distance magnon spin transport



Lebrun et al., Nature '18

Multiferroics



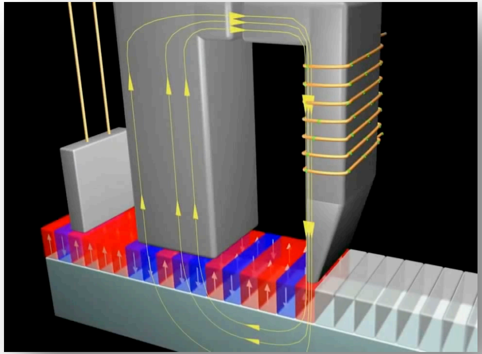


Gross et al., Nature '17

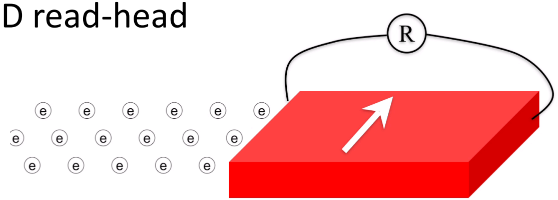
We will focus here on conducting antiferromagnets & spin-electronics

Review: Siddiqui et al., arXiv '20

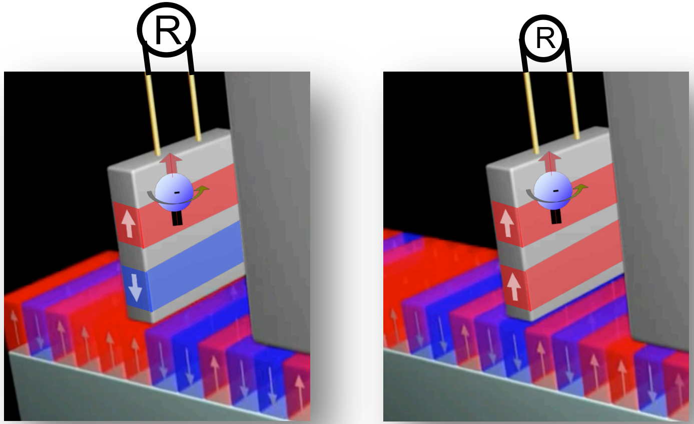
Readout: cf. ferromagnetic spintronics



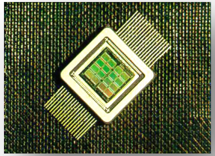
1857 **Anisotropic magnetoresistance: ~1%**
1975 Magnetic stripe reader
1984 Magnetic tape read-head
1990 HDD read-head



1988 **Giant magnetoresistance readout: ~ 10%**
1998 HDD read-head

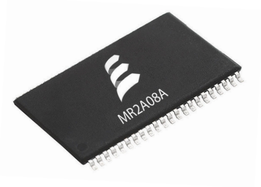


Review: Chappert, Fert, Van Dau, Nature Mater. '07



1980's ~ 100 kb AMR-MRAM

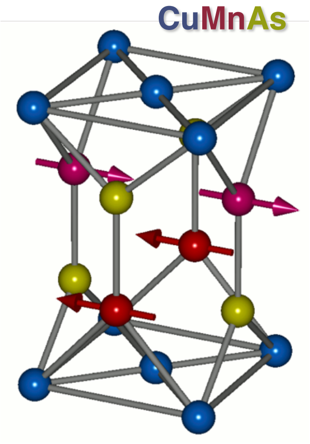
Review: Daughton, Thin Sol. Films '92

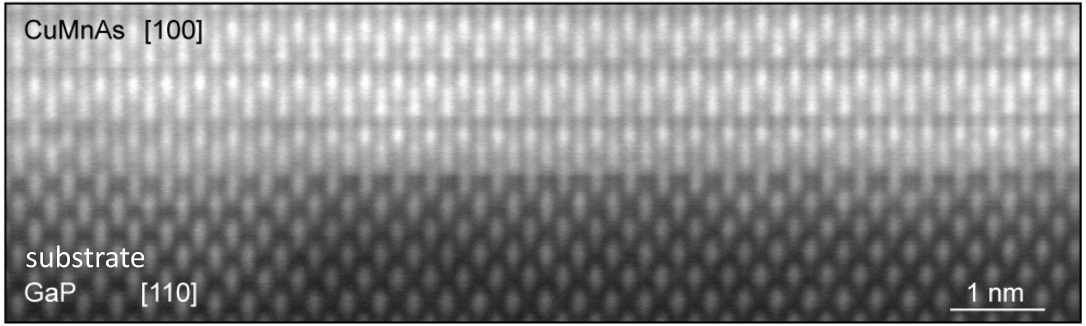


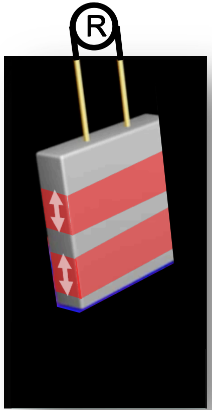
1995 **Tunneling magnetoresistance: ~ 100%**
2006 ~ 10 Mb TMR-MRAM

Readout: antiferromagnetic spintronics

No realization of GMR/TMR antiferromagnetic multilayers

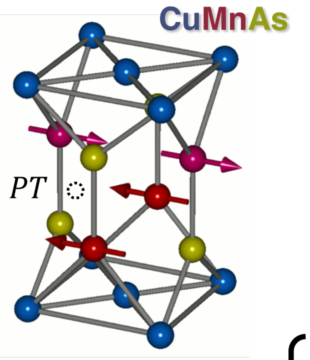




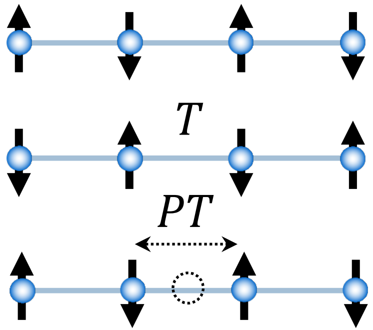


We will focus here on simple antiferromagnetic films

Review: TJ et al., Nature Nanotech. '16



Readout: antiferromagnetic spintronics



$$\vec{j} = \overleftrightarrow{\sigma}\,\vec{E}$$

Onsager relations:

$$\sigma_{ij}(\vec{s}) = \sigma_{ji}(-\vec{s})$$

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} = \begin{bmatrix} \sigma^{\mathrm{s}}_{xx} & \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{xz} \\ \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{yy} & \sigma^{\mathrm{s}}_{yz} \\ \sigma^{\mathrm{s}}_{xz} & \sigma^{\mathrm{s}}_{yz} & \sigma^{\mathrm{s}}_{zz} \end{bmatrix} + \begin{bmatrix} 0 & \sigma^{\mathrm{a}}_{xy} & \sigma^{\mathrm{a}}_{xz} \\ -\sigma^{\mathrm{a}}_{xy} & 0 & \sigma^{\mathrm{a}}_{yz} \\ -\sigma^{\mathrm{a}}_{xz} & -\sigma^{\mathrm{a}}_{yz} & 0 \end{bmatrix}$$

Anisotropic magnetoresistance

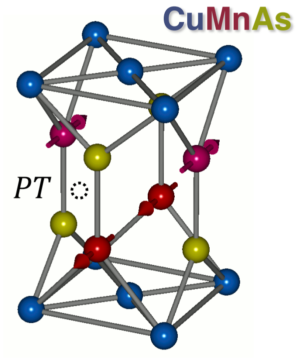
$$T\overleftrightarrow{\sigma^{\mathrm{s}}}(\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{s}}}(-\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{s}}}(\vec{s})$$

Even under time (spin)-reversal

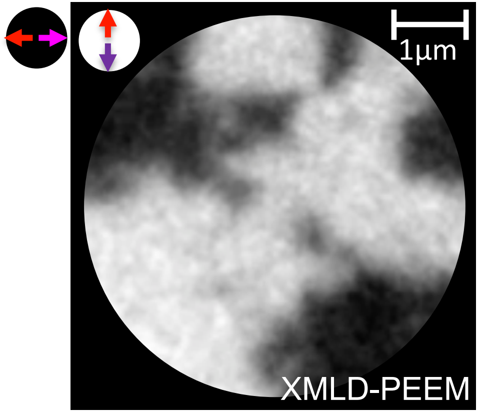
Spontaneous Hall effect

$$T\overleftrightarrow{\sigma^{\mathrm{a}}}(\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{a}}}(-\vec{s}) = \overleftrightarrow{-\sigma^{\mathrm{a}}}(\vec{s})$$

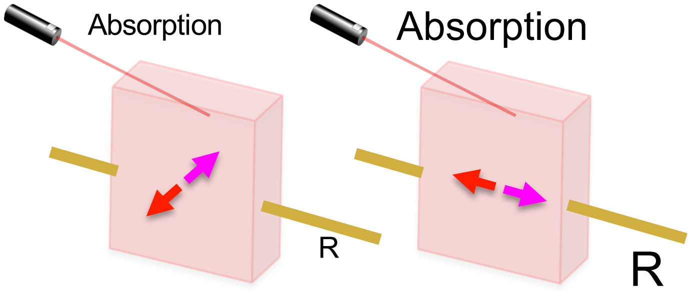
Odd under time (spin)-reversal



Readout: antiferromagnetic spintronics

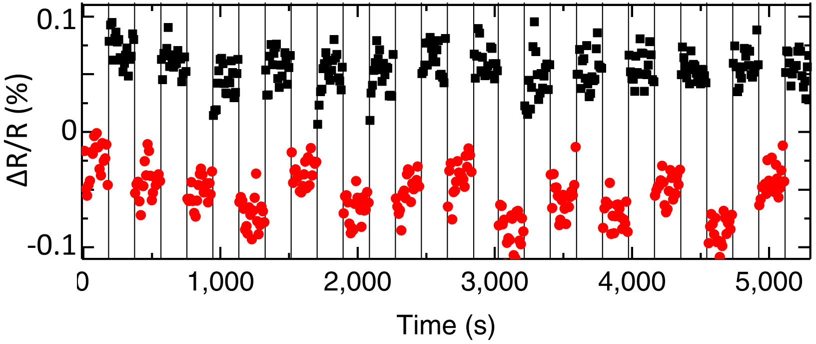


Wadley, TJ et al., Nature Nanotech. '18



Optical/X-ray magnetic linear dichroism

Anisotropic magnetoresistance

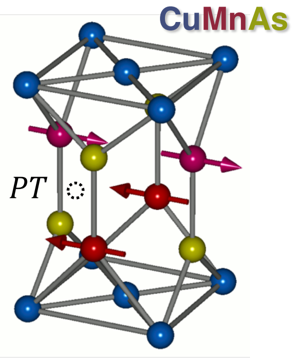


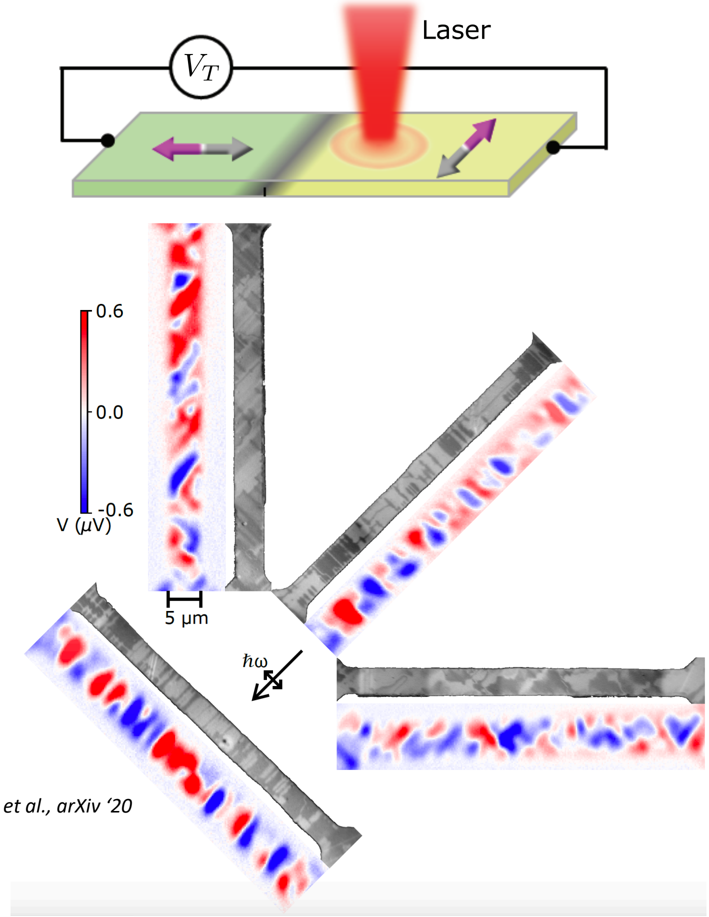
Other antiferromagnets:

Theory IrMn, Mn_2Au: Shick, TJ et al. PRB '10
Exp. IrMn: Park, TJ et al. Nature Mater '11, Wang et al. Phys. Rev. Lett. '12
Exp. FeRh: Marti, TJ et al. Nature Mater. '14, Moriyama et al. Appl. Phys. Lett. '15
Exp. MnTe: Kriegner, TJ et al. Nature Commun. '16

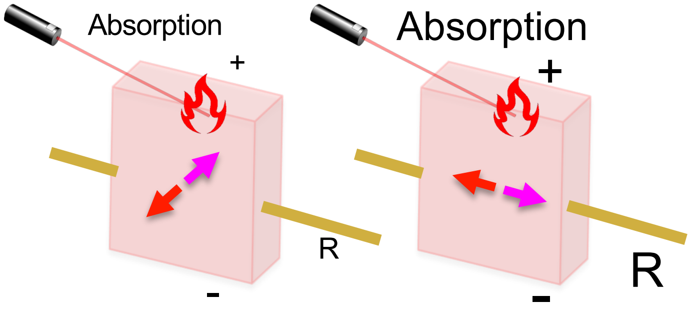
Reviews: Zelezny et al.; Nemec et al., Nature Phys. '18

Readout: antiferromagnetic spintronics





Janda, TJ et al., arXiv '20



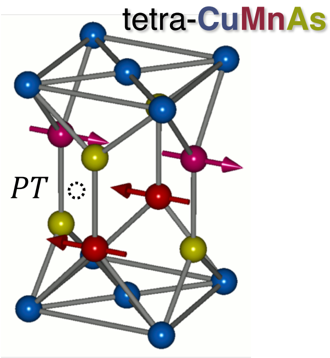
Thermoelectric magneto-Seebeck effect

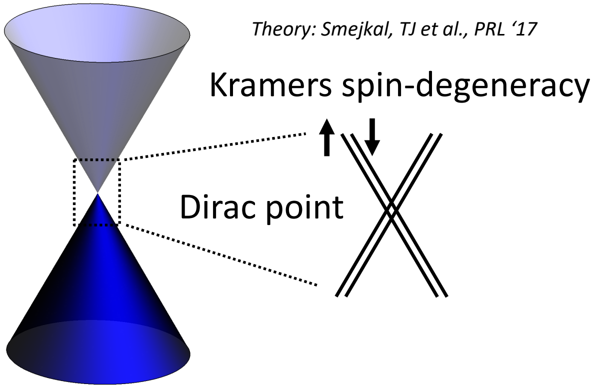
Optical/X-ray magnetic linear dichroism

Anisotropic magnetoresistance

Reviews: Zelezny et al.; Nemec et al., Nature Phys. '18

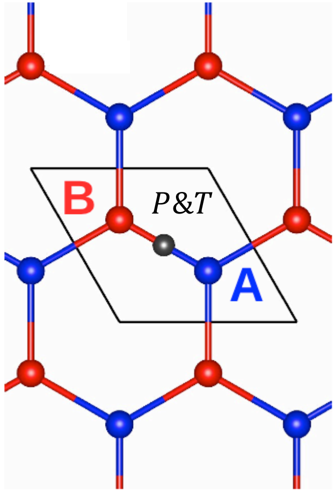
Readout: antiferromagnetic spintronics

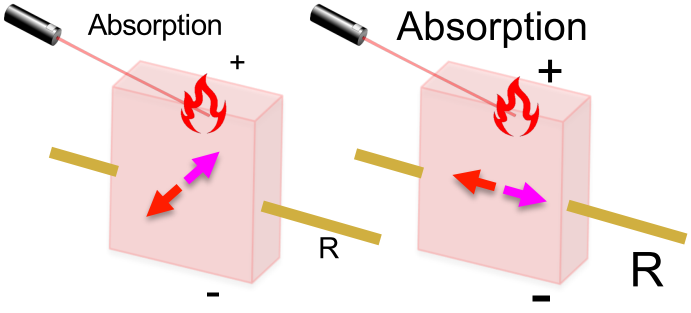




Theory: Smejkal, TJ et al., PRL '17

cf. graphene





Thermoelectric magneto-Seebeck effect

Optical/X-ray magnetic linear dichroism

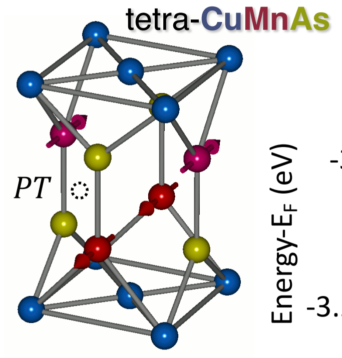
Anisotropic magnetoresistance

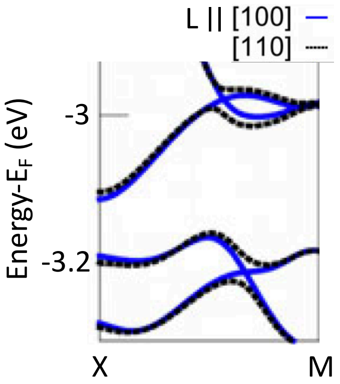
Remark:
AFs in all 122 MPGs
FMs only in 31 MPGs (all break PT)

Review: Smejkal et al., Nature Phys. '18

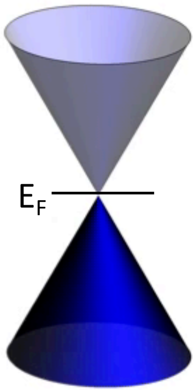
Reviews: Zelezny et al.; Nemec et al., Nature Phys. '18

Readout: antiferromagnetic spintronics



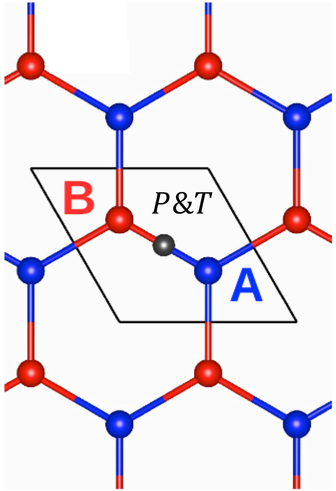


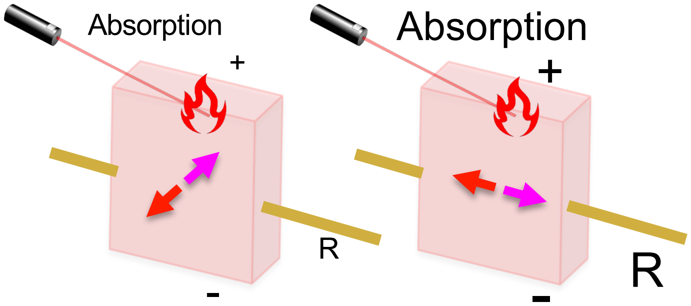
Theory: Smejkal, TJ et al., PRL '17



ortho-CuMnAs:
- Dirac semimetal
- topological MIT/AMR

cf. graphene





Thermoelectric magneto-Seebeck effect

Optical/X-ray magnetic linear dichroism

Anisotropic magnetoresistance

Review: Smejkal et al., Nature Phys. '18

Reviews: Zelezny et al.; Nemec et al., Nature Phys. '18

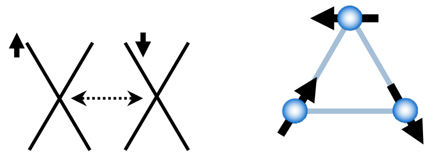
Readout: antiferromagnetic spintronics

Broken $T, PT, \ldots$

$$\vec{j} = \overleftrightarrow{\sigma}\,\vec{E}$$

Onsager relations:

$$\sigma_{ij}(\vec{s}) = \sigma_{ji}(-\vec{s})$$



(Weyl) non-collinear antiferromagnets

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} = \underbrace{\begin{bmatrix} \sigma^{\mathrm{s}}_{xx} & \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{xz} \\ \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{yy} & \sigma^{\mathrm{s}}_{yz} \\ \sigma^{\mathrm{s}}_{xz} & \sigma^{\mathrm{s}}_{yz} & \sigma^{\mathrm{s}}_{zz} \end{bmatrix}} + \underbrace{\begin{bmatrix} 0 & \sigma^{\mathrm{a}}_{xy} & \sigma^{\mathrm{a}}_{xz} \\ -\sigma^{\mathrm{a}}_{xy} & 0 & \sigma^{\mathrm{a}}_{yz} \\ -\sigma^{\mathrm{a}}_{xz} & -\sigma^{\mathrm{a}}_{yz} & 0 \end{bmatrix}}$$

Anisotropic magnetoresistance

$$T\overleftrightarrow{\sigma^{\mathrm{s}}}(\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{s}}}(-\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{s}}}(\vec{s})$$

Even under time (spin)-reversal

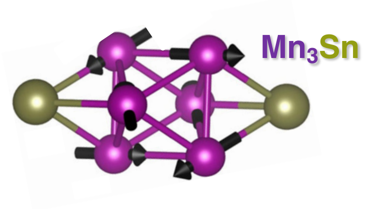
Spontaneous Hall effect

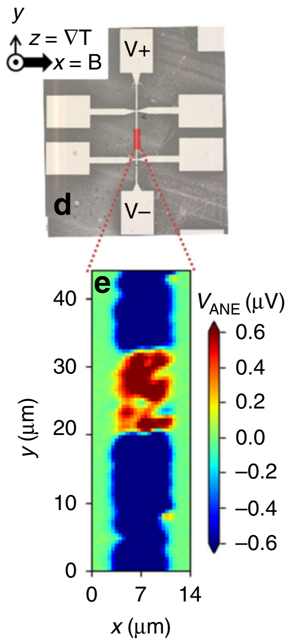
$$T\overleftrightarrow{\sigma^{\mathrm{a}}}(\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{a}}}(-\vec{s}) = \overleftrightarrow{-\sigma^{\mathrm{a}}}(\vec{s})$$

Odd under time (spin)-reversal

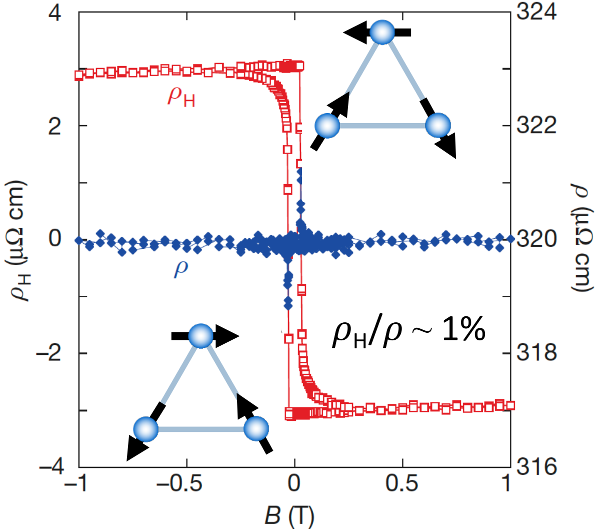
Chen, Niu, MacDonald, PRL ’14
Kubler, Felser, EPL ‘14
Nakatsuji, Kiyohara, Higo, Nature ’15
Nayak et al. Science Adv. ‘16
Higo et al. Nature Phot. ‘18

Readout: antiferromagnetic spintronics



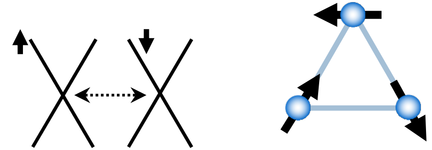


Reichlova, TJ et al., Nature Commun. '19

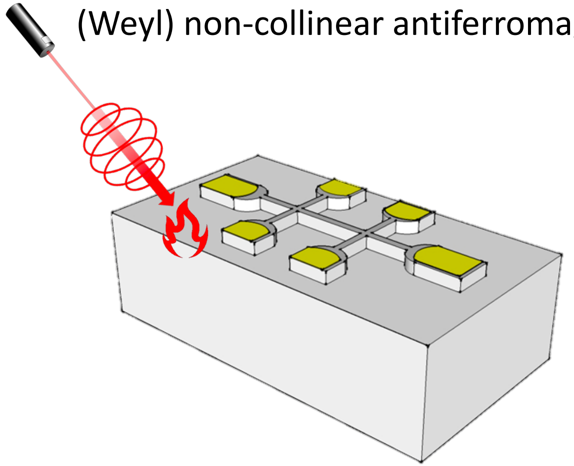


Nakatsuji, Kiyohara, Higo, Nature '15

broken PT



(Weyl) non-collinear antiferromagnets



Thermoelectric anomalous Nernst effect

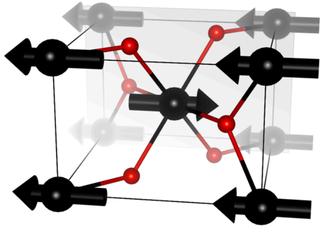
Optical/X-ray magnetic circular dichroism

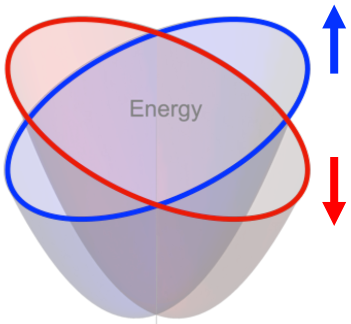
Spontaneous Hall effect

Chen, Niu, MacDonald, PRL '14
Kubler, Felser, EPL '14
Nakatsuji, Kiyohara, Higo, Nature '15
Nayak et al. Science Adv. '16
Higo et al. Nature Phot. '18

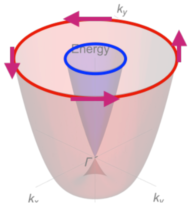
Readout: antiferromagnetic spintronics

RuO_2

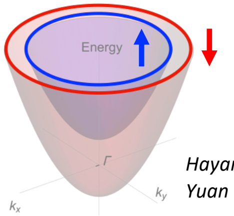




Antiferromagnetic splitting
with no SO & no M



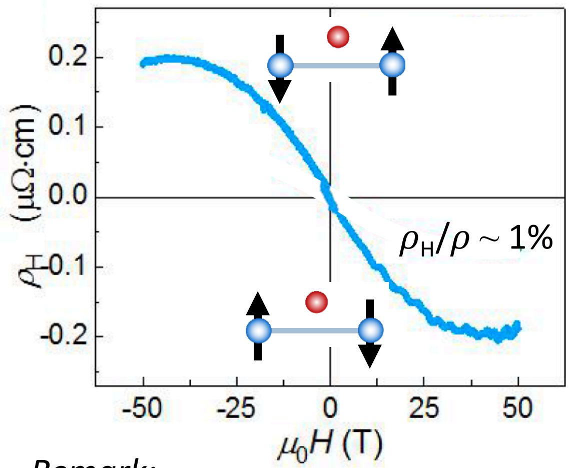
cf. SO splitting



cf. FM splitting

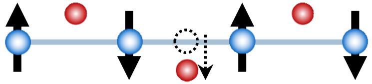
Hayami et al., J. Phys. Soc. Jap ‘19
Yuan et al., arXiv ‘19

Theory: Smejkal, TJ et al., arXiv ,‘19, Science Adv. In press
Experiment: Feng, TJ et al., arXiv ‘20

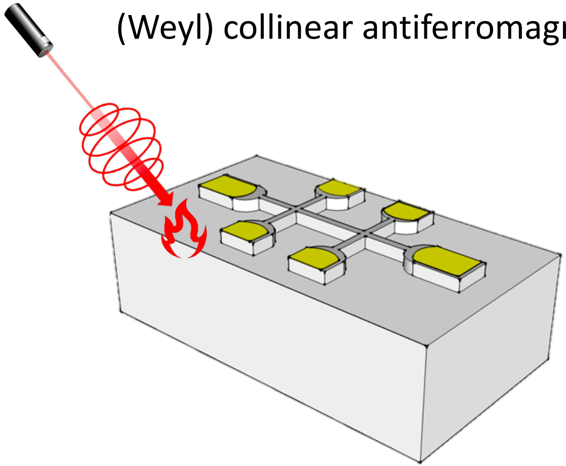


Remark:
~10% of magnets from MAGNDATA
are collinear AFs with spontaneous Hall

broken PT



(Weyl) collinear antiferromagnets



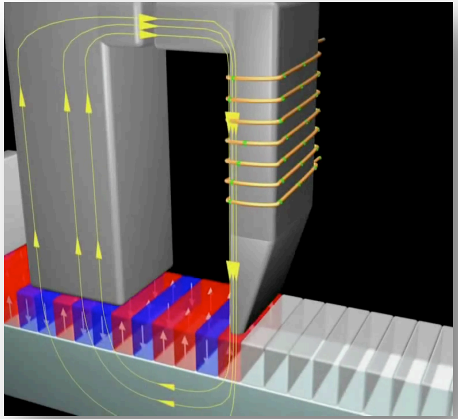
Thermoelectric anomalous Nernst effect

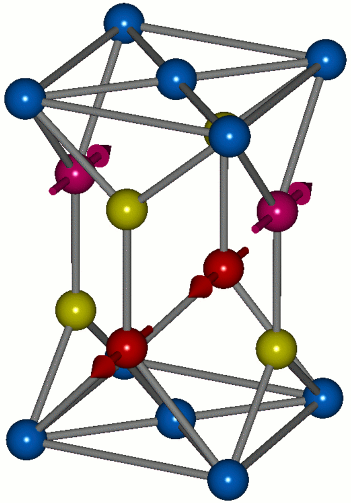
Optical/X-ray magnetic circular dichroism

Spontaneous Hall effect

Writing: magneto-recording

cf. ferromagnetic hard-drive



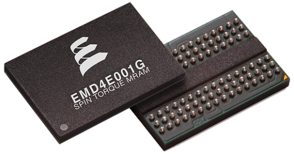


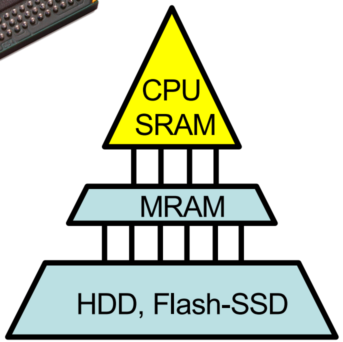
Louis Néel 1970 Nobel Prize lecture:

"**Antiferromagnets** are interesting and useless"

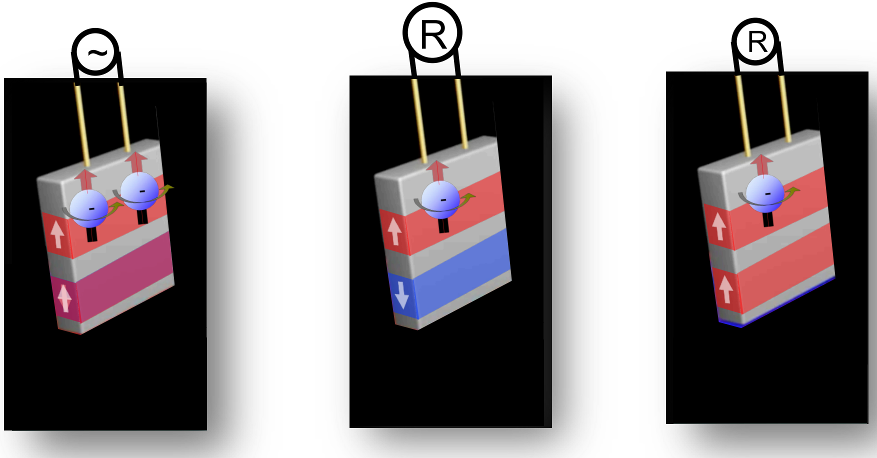
Writing: cf. ferromagnetic spintronics

1998 **Spin transfer torque writing**
2016 ~ 1 Gb STT-MRAM





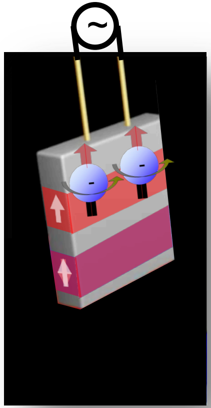
Reversible by
current-polarity

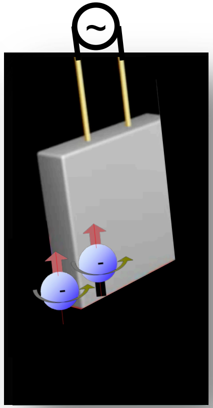


Review: Ralph and Stiles, JMMM '08

Writing: cf. ferromagnetic spintronics

2004 **Spin Hall effect**



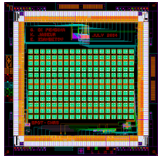


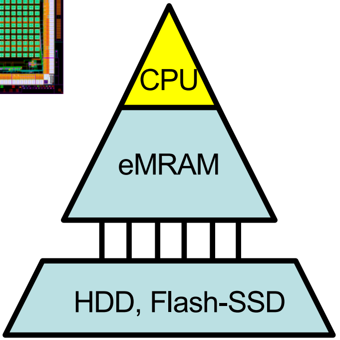
Review: Sinova, TJ et al., RMP '15

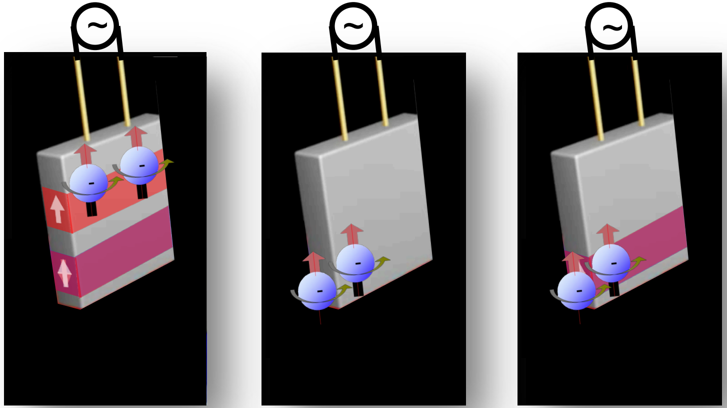
- Relativistic spin-orbit coupling
- Inversion asymmetry
- Spin polarization flips for opposite currents

Writing: cf. ferromagnetic spintronics

2004 **Spin Hall effect**
2011 **Spin orbit torque**
2016 Experimental chip (SPINTEC)







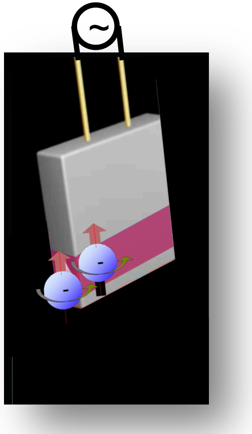
Reversible by current-polarity

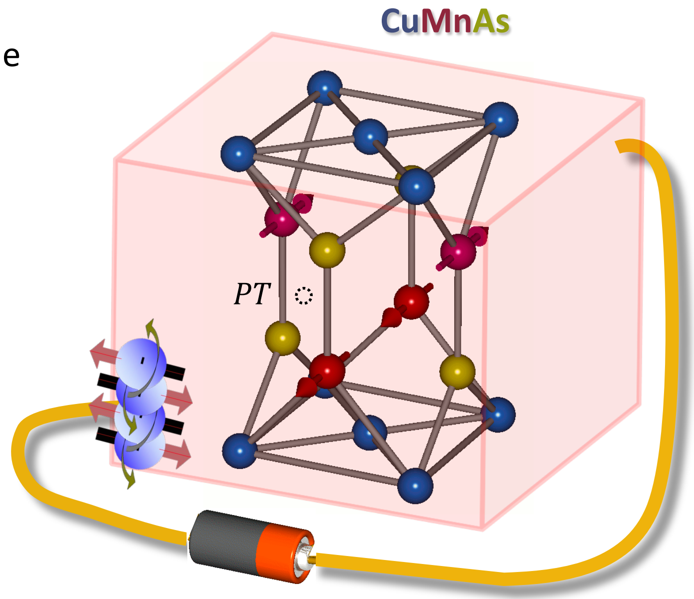
Review: Sinova, TJ et al., RMP ’15   *Review: Manchon, TJ et al., RMP ‘19*

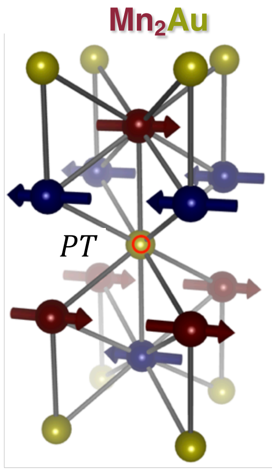
Writing: antiferromagnetic spintronics

Antiferromagnetic spin-orbit torque

cf. ferromagnetic spin-orbit torque







Zelezny, TJ et al., PRL '14
Wadley, TJ et al., Science '16
Bodnar, TJ et al., Nature Commun. '18
Meinert et al. Phys. Rev. Appl. '18,
Zhou et al. Phys. Rev. Appl. '18

Again focus here on simple AF films

cf. Other works on multilayers:

- NM/(insulating)AF bilayers

Overview: Zink, Physics '19

- FM/AF bilayers

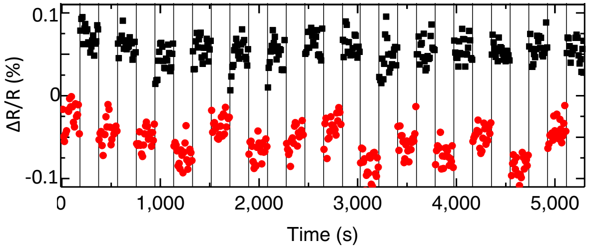
Fukami et al, Nature Mater. '16

Global inversion asymmetry

Local inversion asymmetry

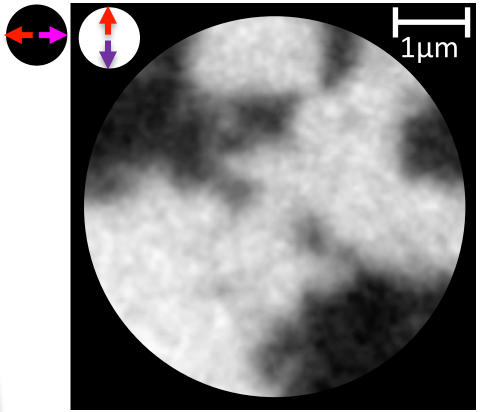
Reviews: Manchon, TJ et al., RMP '19; Zelezny et al., Nature Phys. '18

Writing: antiferromagnetic spintronics

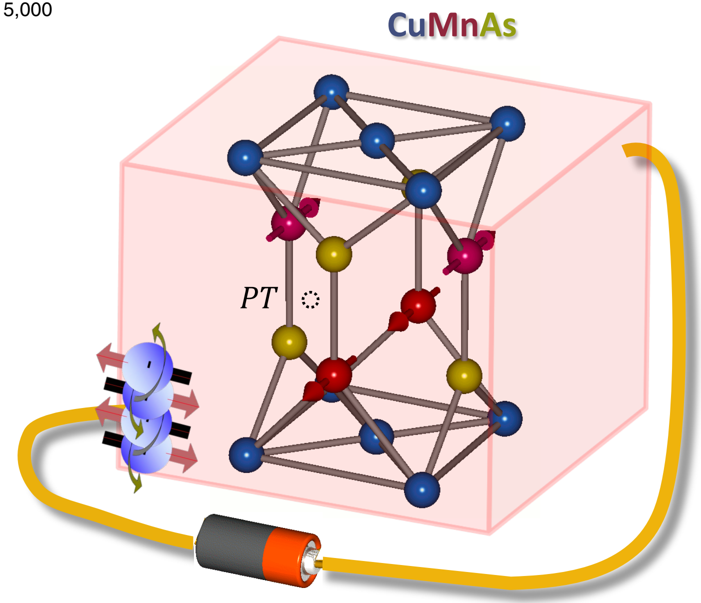


Antiferromagnetic spin-orbit torque

Wadley, TJ et al., Nature Nanotech. '18



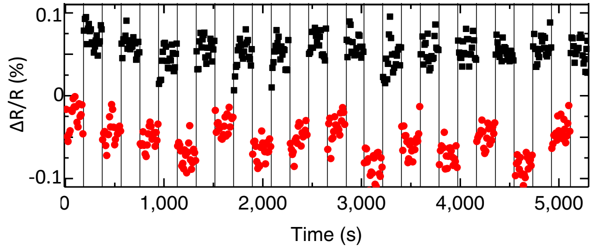
Mn-edge XMLD-PEEM



Local inversion asymmetry

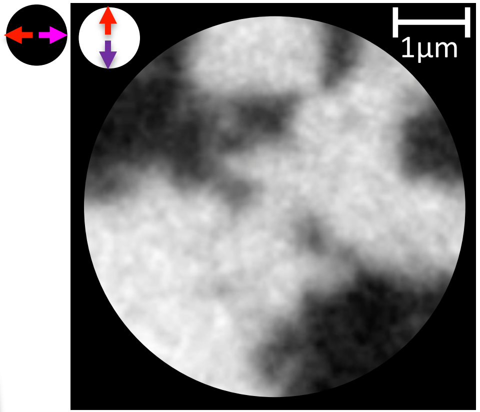
Reviews: Manchon, TJ et al., RMP '19; Zelezny et al., Nature Phys. '18

Writing: antiferromagnetic spintronics

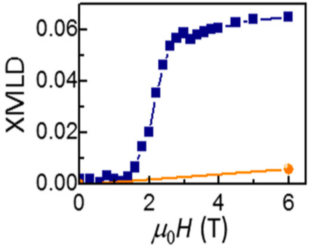


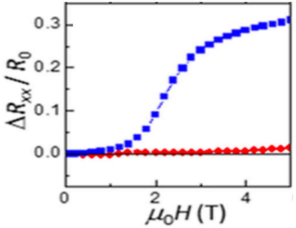
Antiferromagnetic spin-orbit torque

Wadley, TJ et al., Nature Nanotech. '18



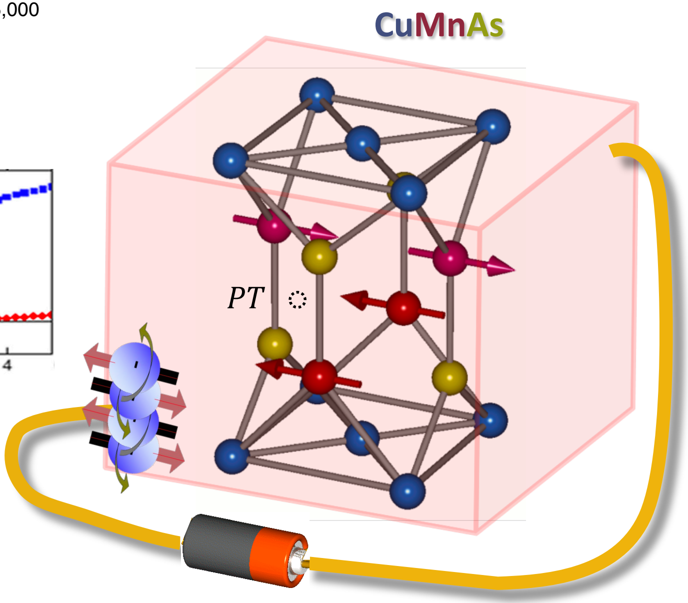
Mn-edge XMLD-PEEM
- no Mn-edge XMCD
- no Cu-edge signal





Spin-flop reorientation

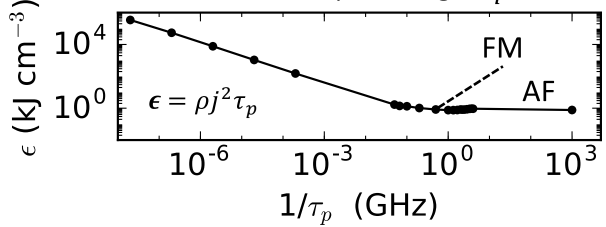
Wang, TJ et al., PRB '20



Local inversion asymmetry

From dc to THz

Electrical pulse length τ_p

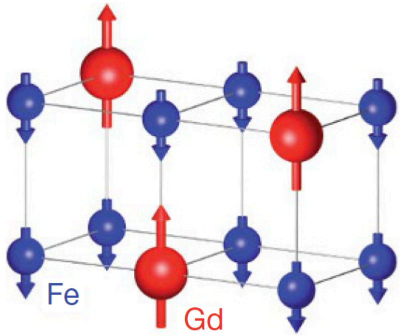


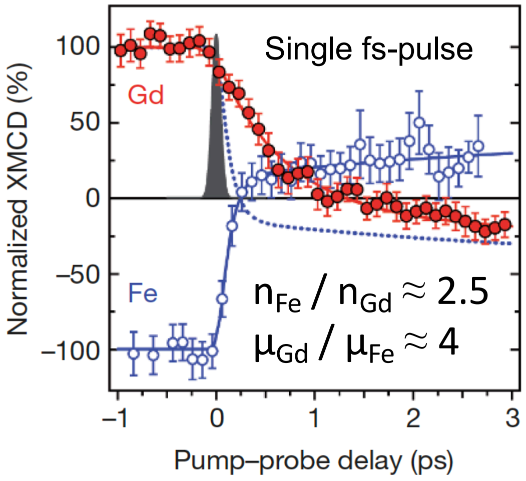
Olejnik, TJ et al., Science Adv. '18

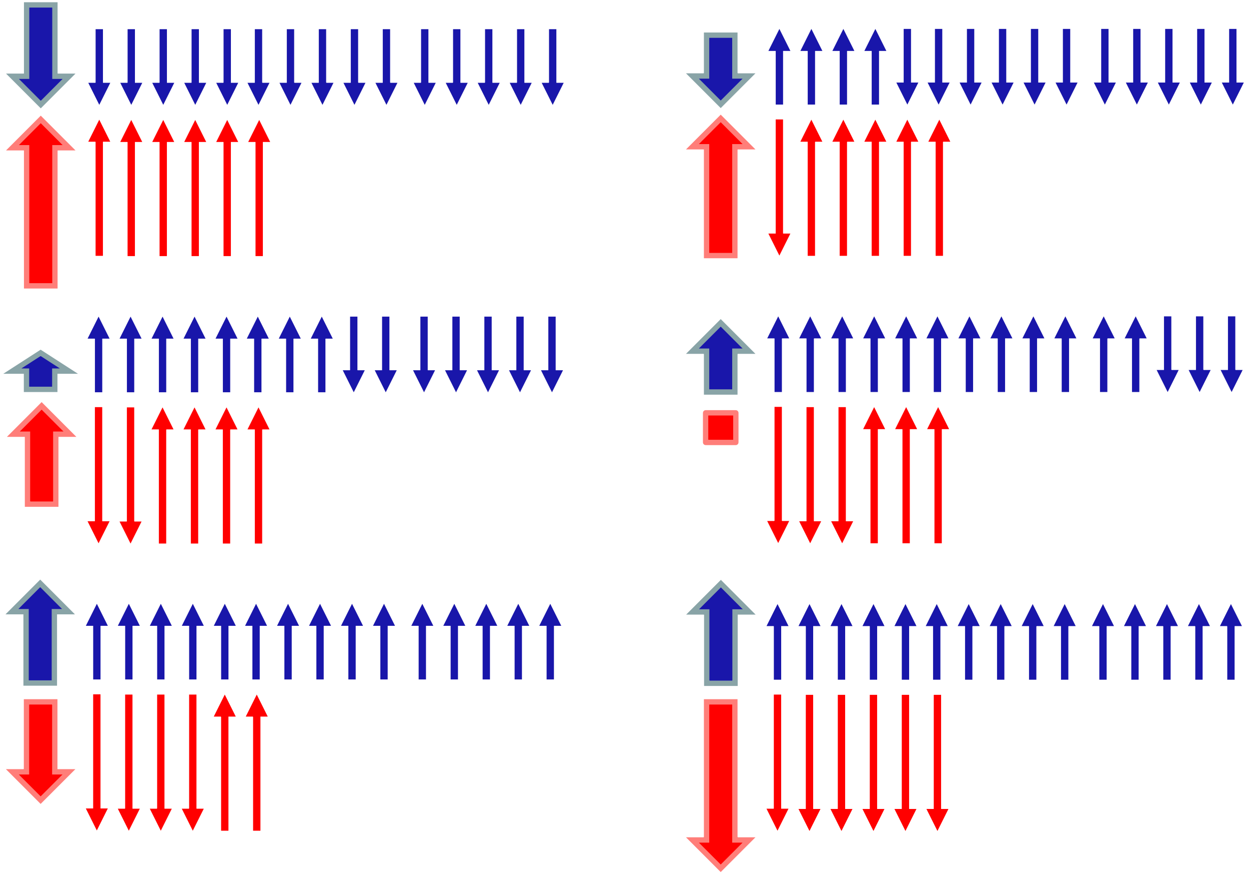
Reviews: Manchon, TJ et al., RMP '19; Zelezny et al., Nature Phys. '18

cf. Ferrimagnets: fs-optical switching by spin transfer between different sublattices

$Gd_{25}Fe_{65}Co_{10}$



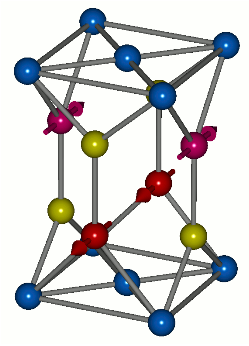


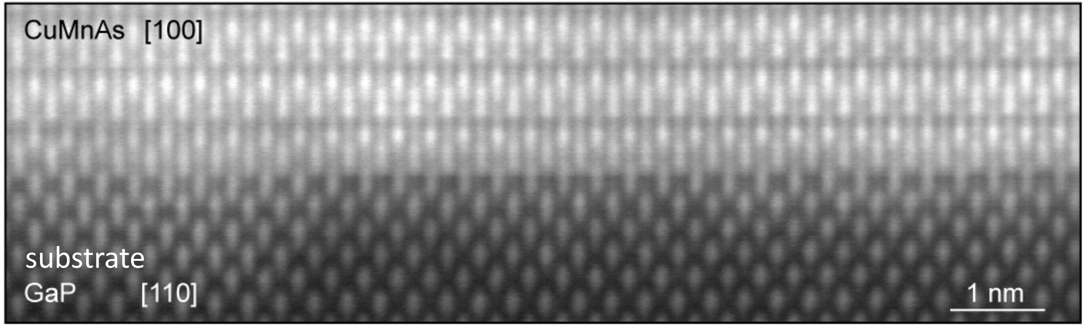


Excludes antiferromagnets

Review: Kimel & Li, Nature Rev. Mater. '19

Reorientation-switching of antiferromagnets



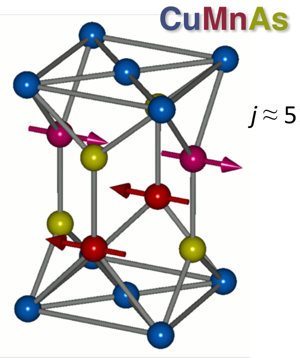


Weaknesses inherited from the adapted ferromagnetic spintronics principles

- Low resistivity readout signals in simple magnetic films

- No extension of the current-induced spin-torque to ultra-fast optical switching

Reorientation vs. quench-switching of antiferromagnets



$j \approx 5\times10^{6}$ Acm^{-2} @ $\tau_p \sim$ ms – μs

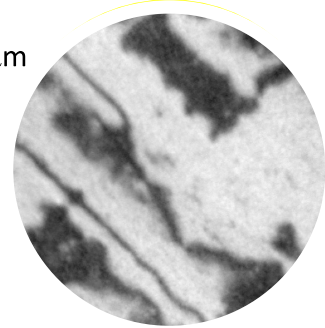
Reorienting
larger domains

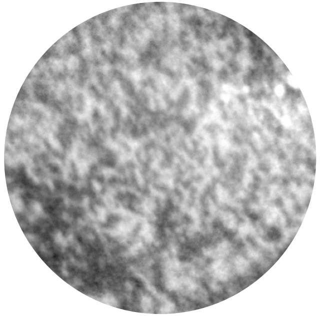
Quenching into
nano-fragmented domains

$j \approx 1\times10^{7}$ Acm^{-2} @ $\tau_p \sim$ ms – μs

2 μm

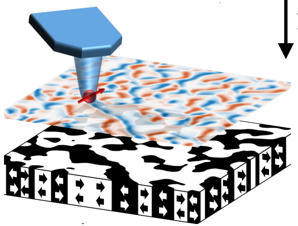
XMLD-PEEM



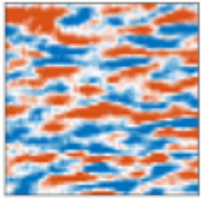


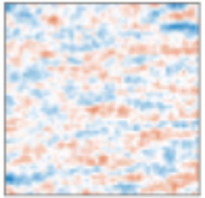
Kaspar, TJ et al., arXiv '19, Nature Electron. in press

NV-diamond

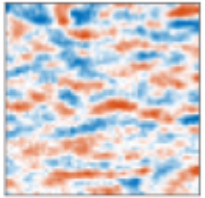


1 μm





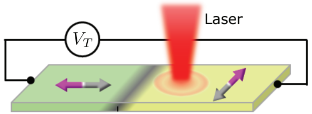
Relaxed
towards large domains



3 days

Wornle, TJ et al., arXiv '19

Magneto-Seebeck



5 μm

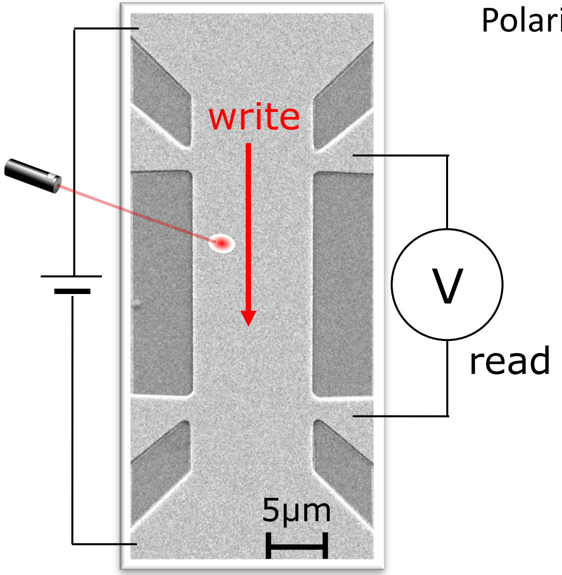
1 week

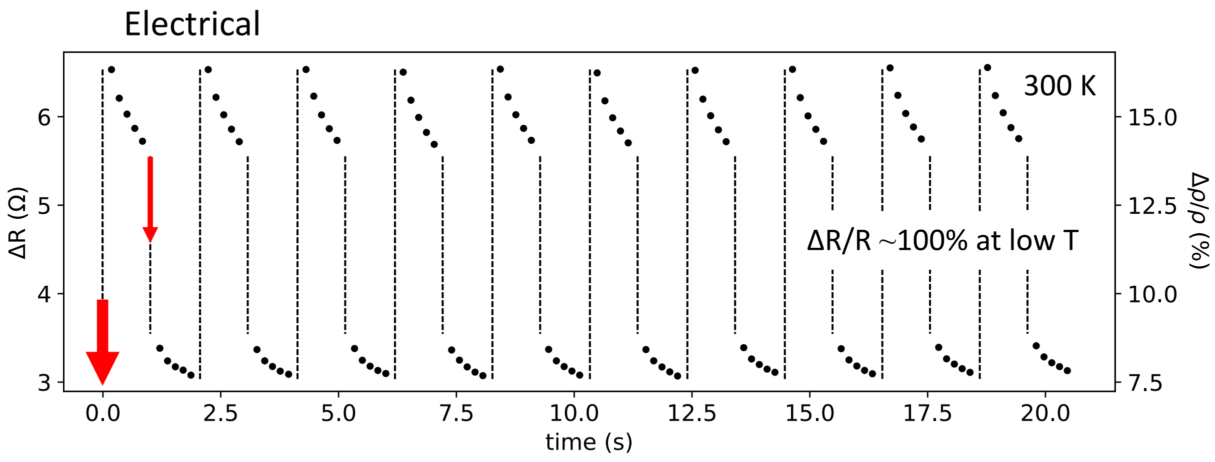
Janda, TJ et al., arXiv '20

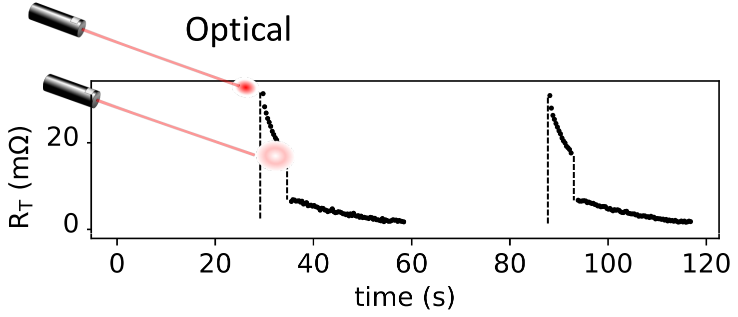
CuMnAs

Quench-switching of antiferromagnets

Polarity/polarization independent switching controlled by pulse-amplitude







Stronger pulse

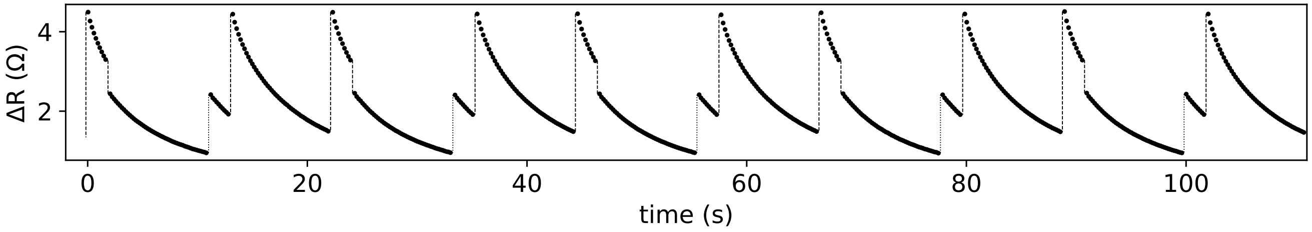
Weaker pulse
(90% of the stronger)

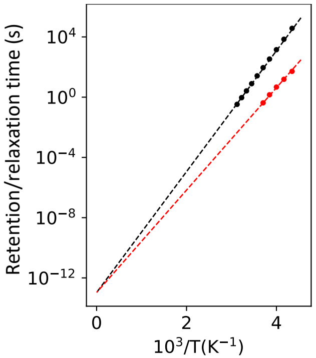
$\epsilon \sim \mathrm{kJcm}^{-3}$ @
$\tau_p \sim$1ns electrical
$\tau_p \sim$1ps THz
$\tau_p \sim$100fs optical

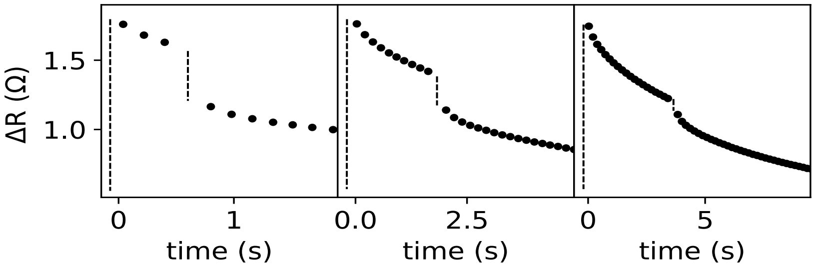
Kaspar, TJ et al., arXiv '19, Nature Electron. in press

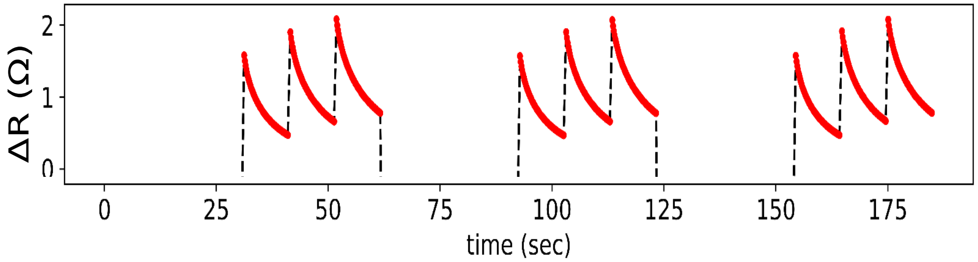
CuMnAs

Quench-switching of antiferromagnets

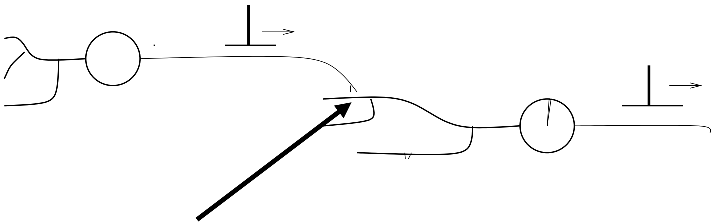






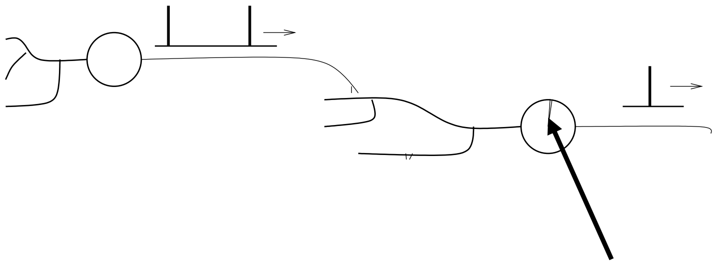


Order and delay between pulses



Synaptic strength

Leaky-sum of pulses



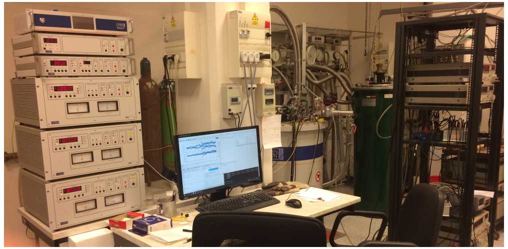
Neuron potential

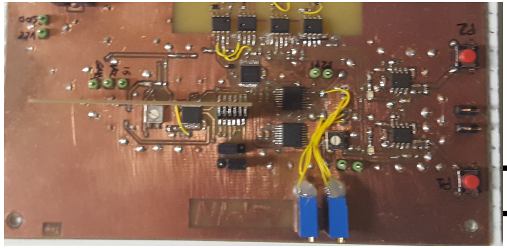
Kaspar, TJ et al., arXiv '19, Nature Electron. in press

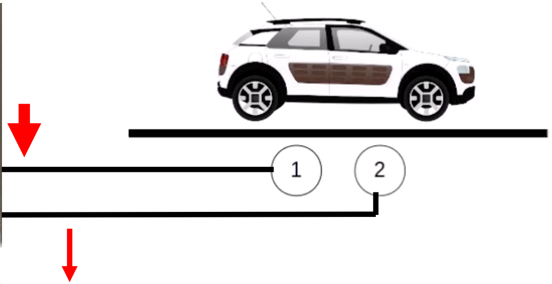
Development boards with antiferromagnetic devices

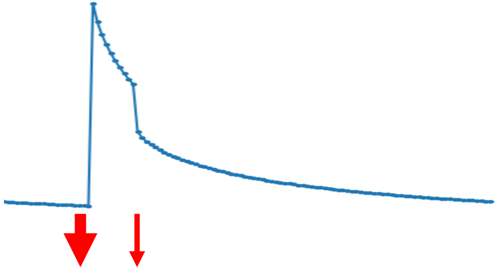
Experimental lab set-up for antiferromagnetic devices → Packed into development analog Printed Circuit Board

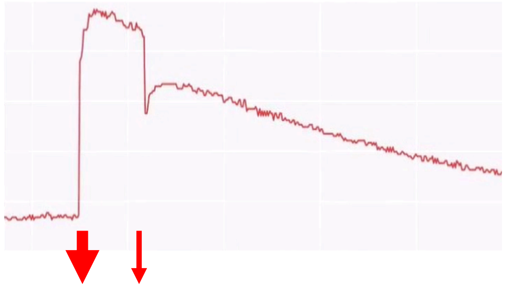
Illustrative example:
Sensors sending pulses to analog PCB with antiferromagnetic device







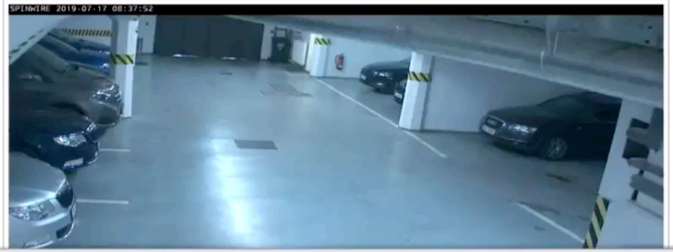


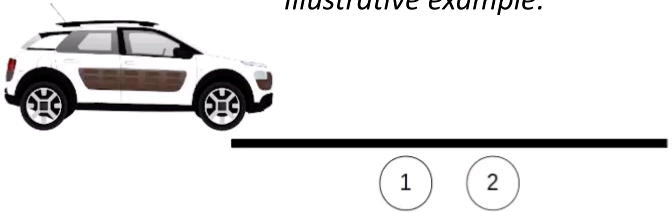


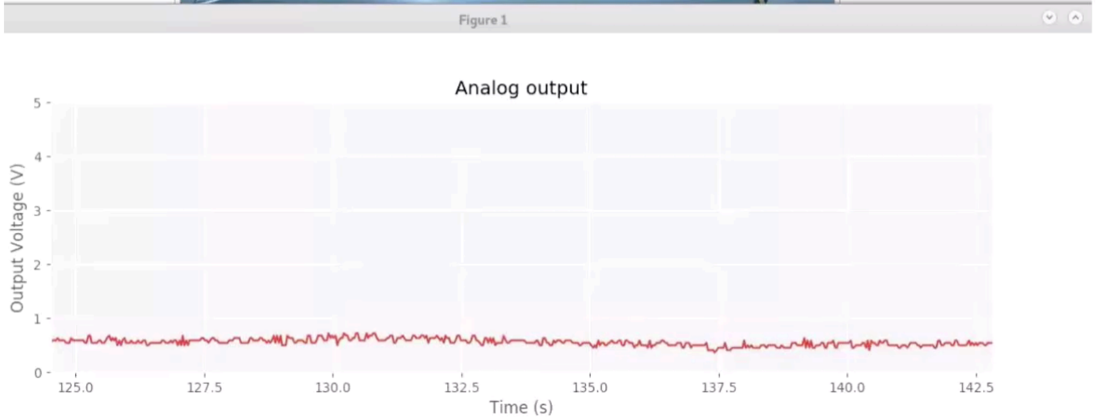
Thanks to public & private funding

Development boards with antiferromagnetic devices

Illustrative example:







Thanks to public & private funding

erc
European Research Council
Established by the European Commission

Horizon 2020 - FET Open
European Commission

GAČR
CZECH SCIENCE FOUNDATION

HITACHI

Neuron
FOND NA PODPORU VĚDY