Spin currents in non-collinear antiferromagnets

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Antiferromagnetic spintronics

Rising interest in antiferromagnets for spintronics applications

Some advantages over ferromagnets:

- ✓ Fast dynamics
- ✓ No stray fields, insensitive to magnetic fields
- ✓ Wide range of antiferromagnetic materials including metals, semiconductors, insulators, multiferroics, superconductors…

but

The antiferromagnetic order is difficult to manipulate and detect

Many spintronics effects, which exist in ferromagnets are prohibited by symmetry in most antiferromagnets

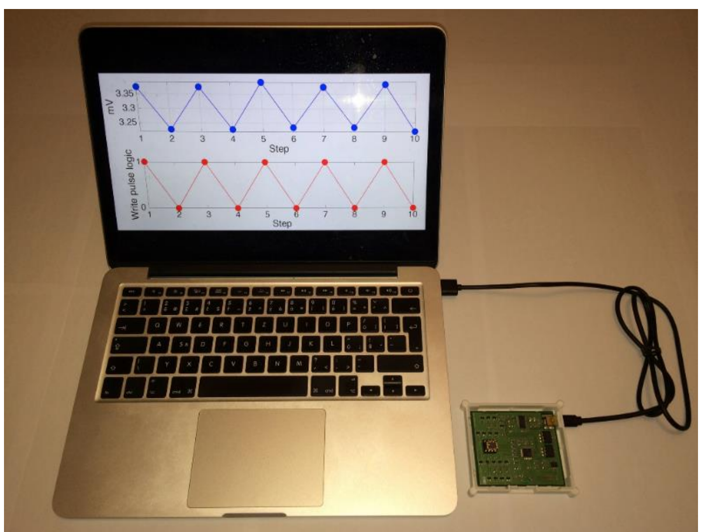
Spin-orbit torques in antiferromagnets

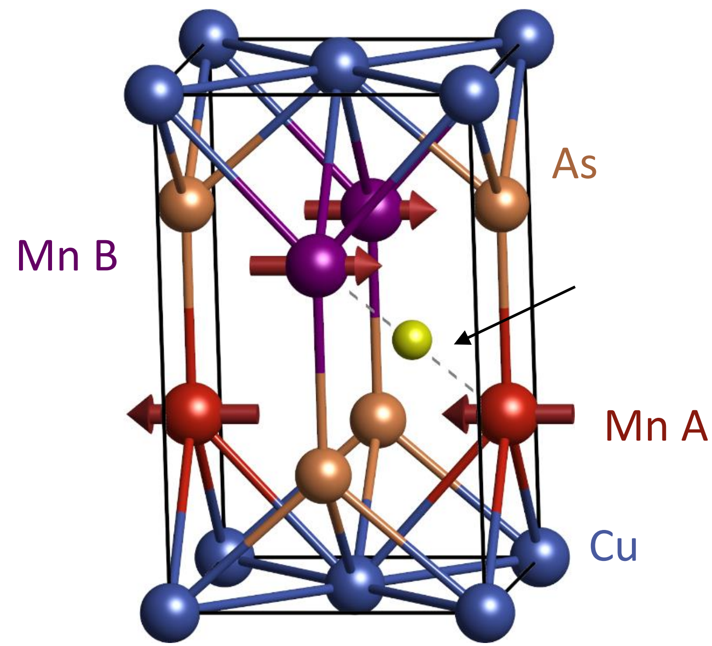
Electrical control and detection of the antiferromagnetic order has been demonstrated

A key to efficient manipulation of the antiferromagnetic order is using a **staggered magnetic field**

↓

Can be generated by spin-orbit torque

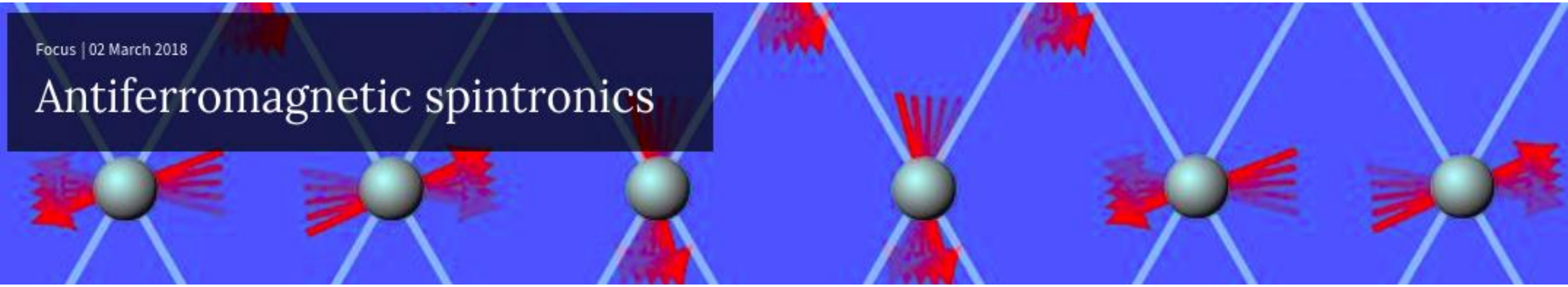




CuMnAs

Zelezny et al., PRL 113, 157201 (2014)
Wadley et al., Science 351, 587–590 (2016)
Bodnar et al., arXiv:1706.02482
Meinert et al., arXiv:1706.06983

Nature physics focused issue on antiferromagnetic spintronics



Overview - *T. Jungwirth et al., Nature Physics* ***14****, 200–203 (2018)*

Transport - *J. Železný et al., Nature Physics* ***14****, 220-228 (2018)*

Opto-spintronics - *P. Němec et al., Nature Physics* ***14****, 229-241 (2018)*

Spin textures and dynamics - *O. Gomonay et al., Nature Physics* ***14****, 213-216 (2018)*

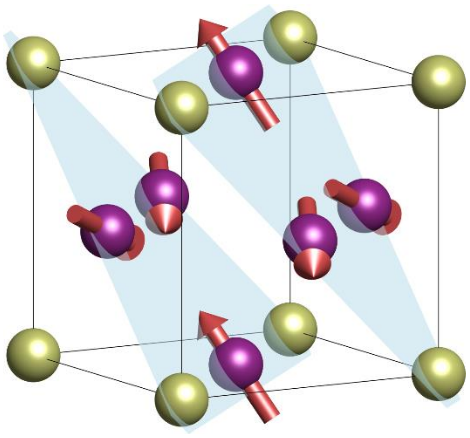
Topology - *L. Šmejkal et al., Nature Physics* ***14****, 242-251 (2018)*

Synthetic antiferromagnets - *R. A. Duine et al., Nature Physics* ***14****, 217-219 (2018)*

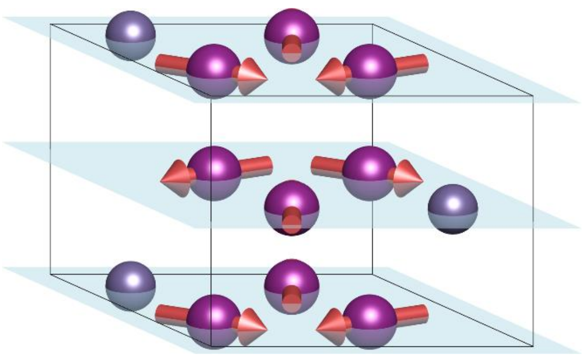
Non-collinear antiferromagnets

Non-collinear order is common in antiferromagnets

Triangular antiferromagnets Mn3X



Mn_3Rh, Mn_3Pt, Mn_3Ir

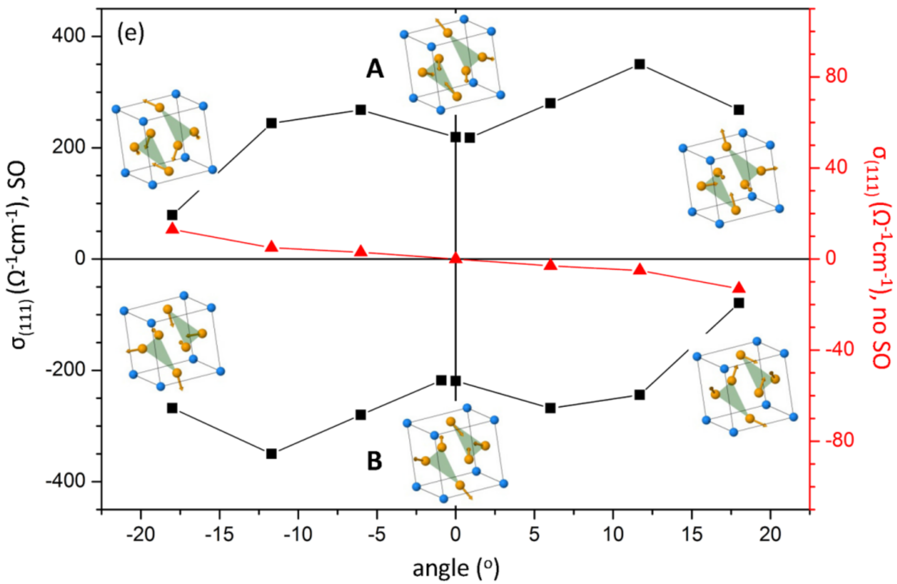


Mn_3Ga, Mn_3Ge, Mn_3Sn

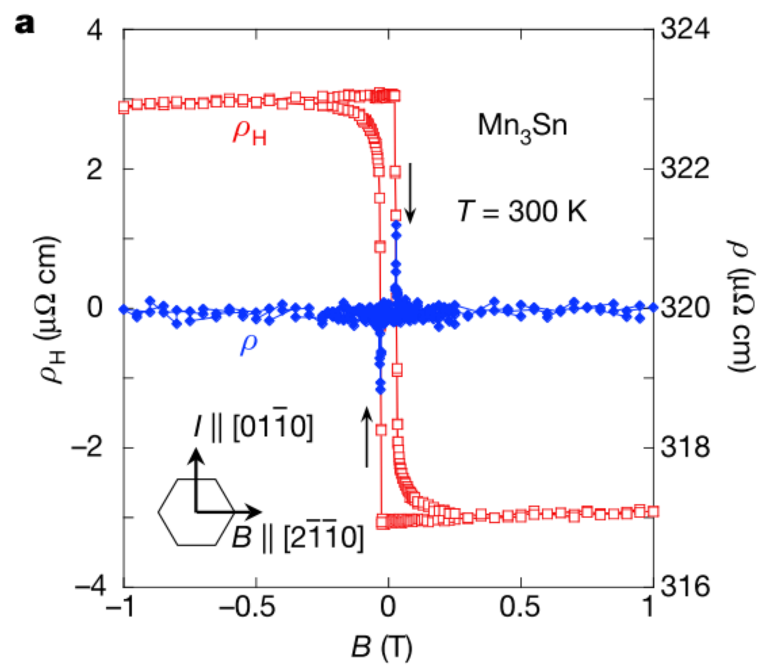
- Simplest example of a non-collinear magnetic system

Anomalous Hall effect

A large anomalous Hall effect exist in the non-collinear antiferromagnets



Chen et al., PRL 112, 017205 (2014)



Naktsuji et al. Nature 527, 212 (2015)

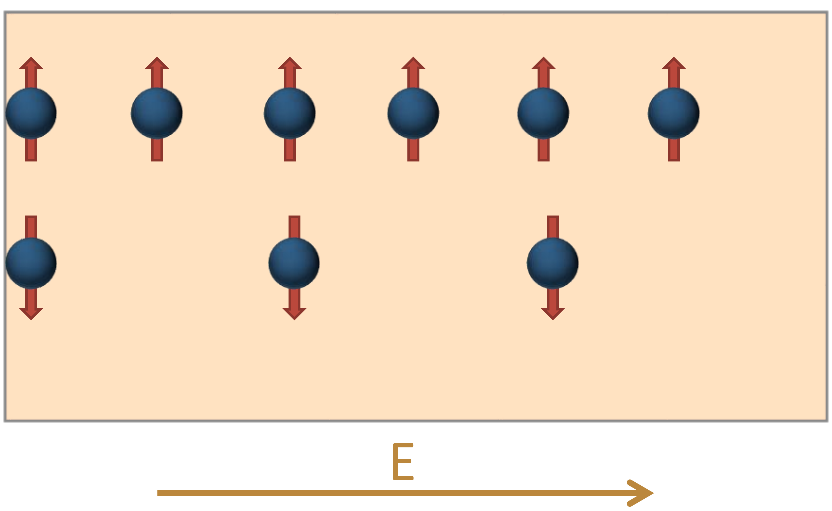
Small magnetic moment present, but is not the origin of the AHE

The AHE exists because the magnetic order breaks symmetry

Kubler et al., EPL 108, 67001 (2014)
Nayak et al. Sci. Adv. 2016;2:e1501870
Feng et al., PRB 92, 144426 (2015)

Spin currents

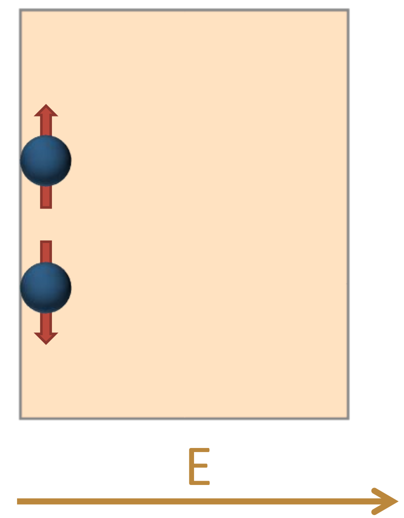
Spin-polarized current in ferromagnets



Odd under time-reversal

Non-relativistic origin

Spin-Hall effect



Even under time-reversal

Relativistic origin

Spin currents are responsible for giant and tunneling magnetoresistance, spin-transfer torque, spin-orbit torque,…

Definition of spin current

Spin current operator is normally defined as: $\hat{j}^{s}_{ij} = \frac{1}{2}\{\hat{s}_i, \hat{v}_j\}$

Issues with this definition:

1. Spin is not conserved so the spin current does not satisfy the continuity equation

$$\frac{\partial S_z}{\partial t} + \nabla \cdot \mathbf{J}_s = \mathcal{T}_z$$

Shi et al., PRL 96, 076604 (2006)

2. Spin current can occur in equilibrium

Rashba, Phys. Rev. B 68, 241315(R) 2003

3. Spin currents also can exist in insulators
4. Spin current cannot be directly measured

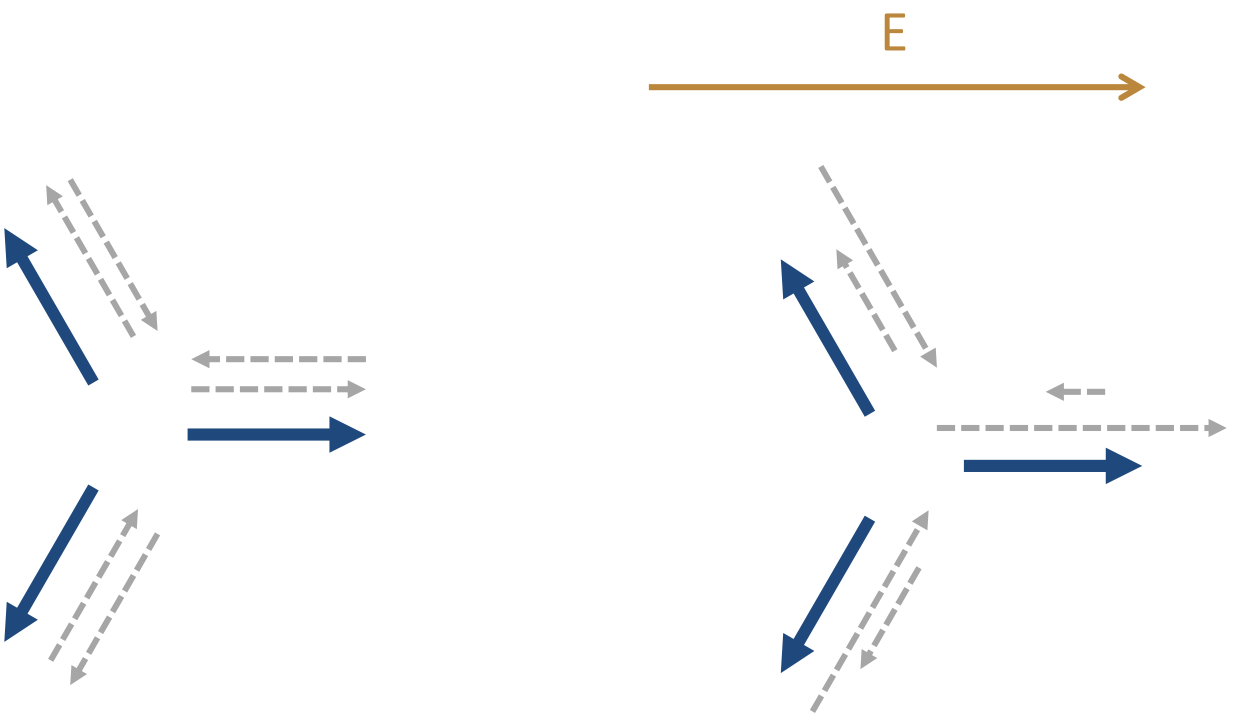
But it's a well defined (and useful) physical quantity!

For accurate estimates and comparison with experiment it's best to calculate directly spin accumulation, torque…

Spin-polarized current

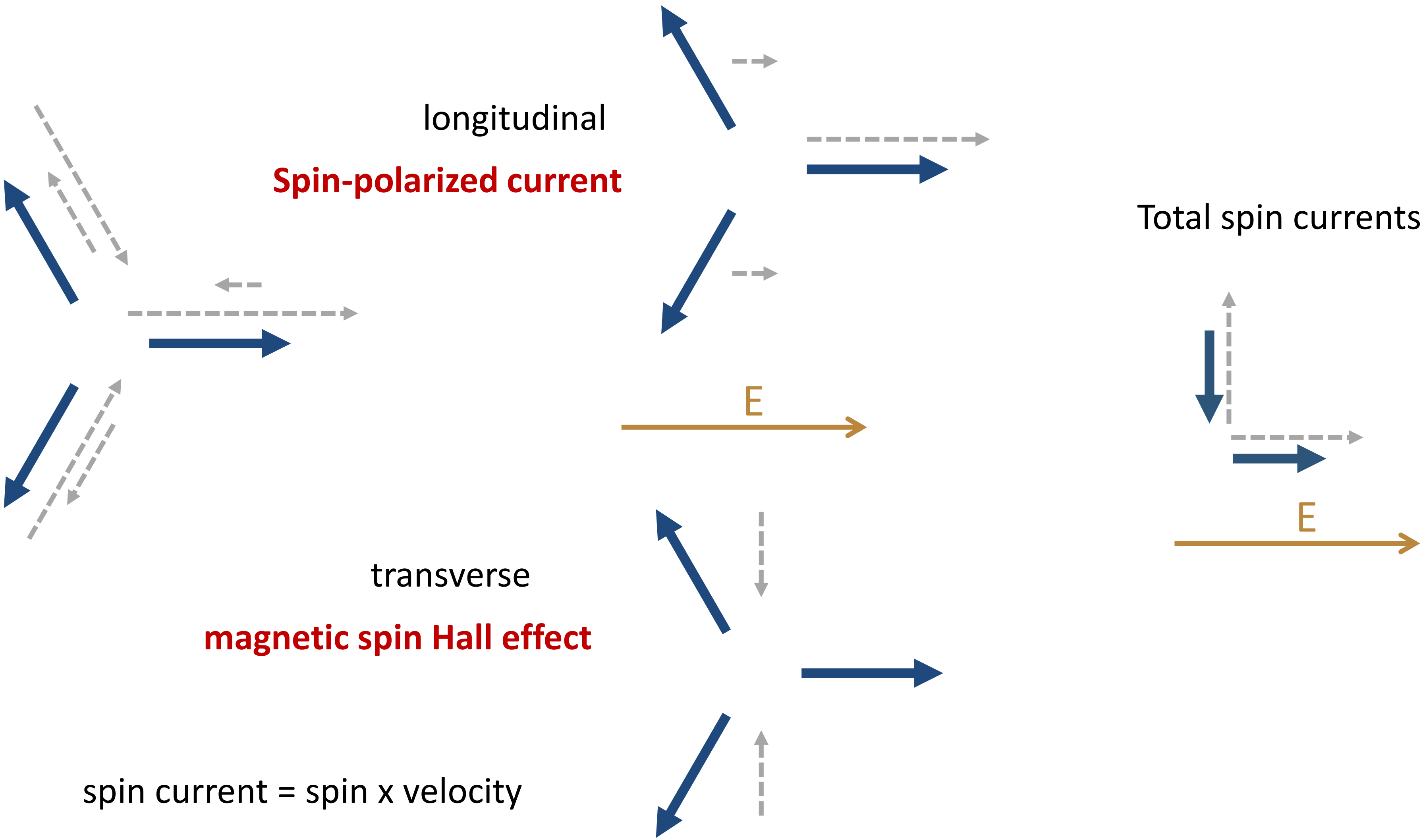
In most antiferromagnets spin-polarized current is not allowed by symmetry

In the Mn_3X non-collinear antiferromagnets spin-polarized current is present



Zelezny et al., PRL 119, 187204 (2017)

Origin of the odd spin currents



Zelezny et al., PRL 119, 187204 (2017)

Linear response

$$\delta A = \chi^I \mathbf{E} + \chi^{II} \mathbf{E}$$

$$\chi^I = -\frac{e\hbar}{\pi} \sum_{\mathbf{k},n,m} \frac{\Gamma^2 \mathrm{Re}\left(\langle n\mathbf{k}| \hat{A} |m\mathbf{k}\rangle \langle m\mathbf{k}| \hat{\mathbf{v}} \cdot \hat{\mathbf{E}} |n\mathbf{k}\rangle \right)}{[(E_F - \varepsilon_{n\mathbf{k}})^2 + \Gamma^2][E_F - \varepsilon_{m\mathbf{k}})^2 + \Gamma^2]},$$

$$\chi^{II} = -2\hbar e \sum_{\mathbf{k},n \neq m}^{\substack{n \text{ occ.} \\ m \text{ unocc.}}} \frac{\mathrm{Im}\left(\langle n\mathbf{k}| \hat{A} |m\mathbf{k}\rangle \langle m\mathbf{k}| \hat{\mathbf{v}} \cdot \hat{\mathbf{E}} |n\mathbf{k}\rangle \right)}{(\varepsilon_{n\mathbf{k}} - \varepsilon_{m\mathbf{k}})^2},$$

These two parts have precisely opposite transformation under time-reversal

Under time-reversal: $\langle n\mathbf{k}| \hat{A} |m\mathbf{k}\rangle \rightarrow \langle n\mathbf{k}| T^{-1} \hat{A} T |m\mathbf{k}\rangle^*$

We use a constant band broadening to simulate disorder

Linear response

		"Real" part	"Imaginary" part
Conductivity:	$\hat{A} = -e\hat{\mathbf{v}}$	even - ordinary conductivity	odd - Anomalous Hall effect
Spin-orbit torque:	$\hat{A} = \hat{\mathbf{T}}$	Odd - field-like torque	even – antidamping-like torque
Spin current:	$\hat{A} = \frac{1}{2}\{\hat{\mathbf{s}}, \hat{\mathbf{v}}\}$	odd – spin-polarized current	even - spin Hall effect

Odd components can only exist in magnetic materials

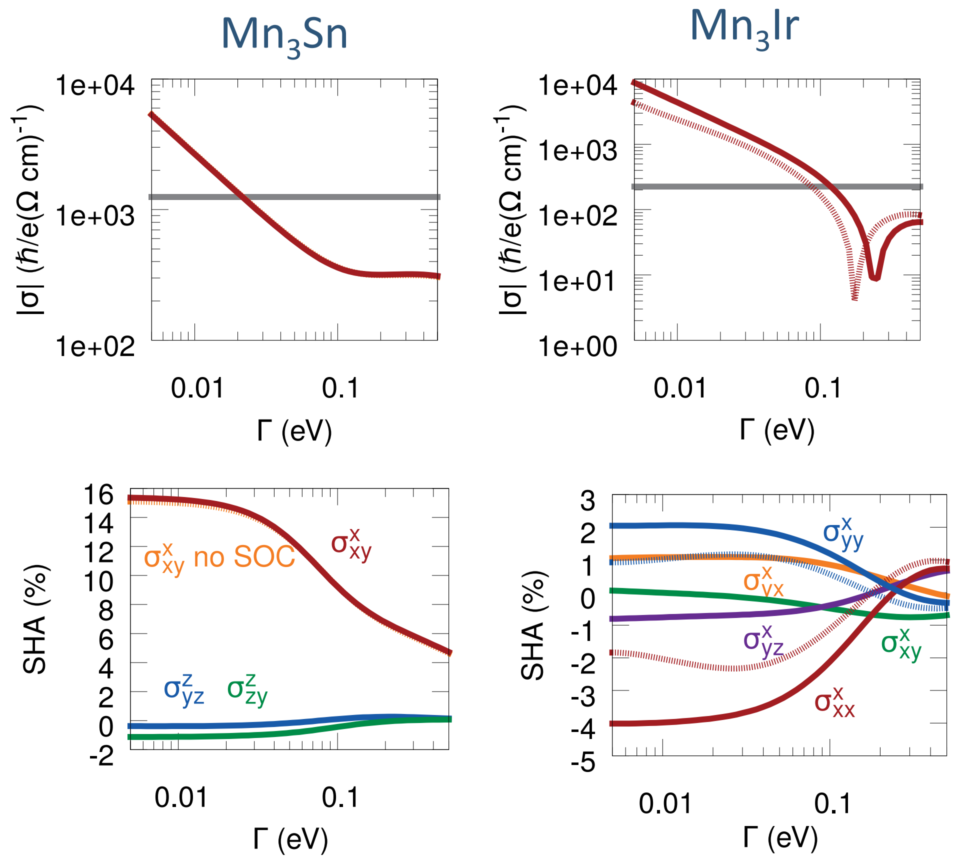
Calculations

The odd spin currents **depend strongly on disorder** unlike the intrinsic spin Hall effect

Spin current angle: $\alpha = \frac{e}{\hbar}\frac{\sigma^{i}_{jk}}{\sigma_{kk}}$

Both large longitudinal and transverse spin currents present

	$\boldsymbol{\alpha_{\|\|}}$ **(%)**	$\boldsymbol{\alpha_{\perp}}$ **(%)**
Mn_3Ga	13.7	13.5
Mn_3Ge	5.1	5.0
Mn_3Sn	12.4	12.4
Mn_3Rh	1.1	0.7
Mn_3Ir	3.5	1.9
Mn_3Pt	4.2	1.9



Spin currents are smaller than typically in ferromagnets, but still relatively large

In BCC Fe $\boldsymbol{\alpha_{||}} \sim 18\%$

$\boldsymbol{\alpha_{\perp}} \sim 1\%$

Zelezny et al., PRL 119, 187204 (2017)

Magnetic spin Hall effect

Odd – magnetic spin Hall effect

$$\sigma^x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\sigma^y = \begin{pmatrix} 0 & \sigma_{yxy} & 0 \\ \sigma_{yyx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\sigma^z = \begin{pmatrix} 0 & 0 & \sigma_{yxy} \\ 0 & 0 & 0 \\ \sigma_{yyx} & 0 & 0 \end{pmatrix}$$

Even - spin Hall effect

$$\sigma^x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\sigma_{xzy} \\ 0 & \sigma_{xzy} & 0 \end{pmatrix}$$

$$\sigma^y = \begin{pmatrix} 0 & 0 & -\sigma_{zxy} \\ 0 & 0 & 0 \\ \sigma_{zyx} & 0 & 0 \end{pmatrix}$$

$$\sigma^z = \begin{pmatrix} 0 & \sigma_{zxy} & 0 \\ \sigma_{zyx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

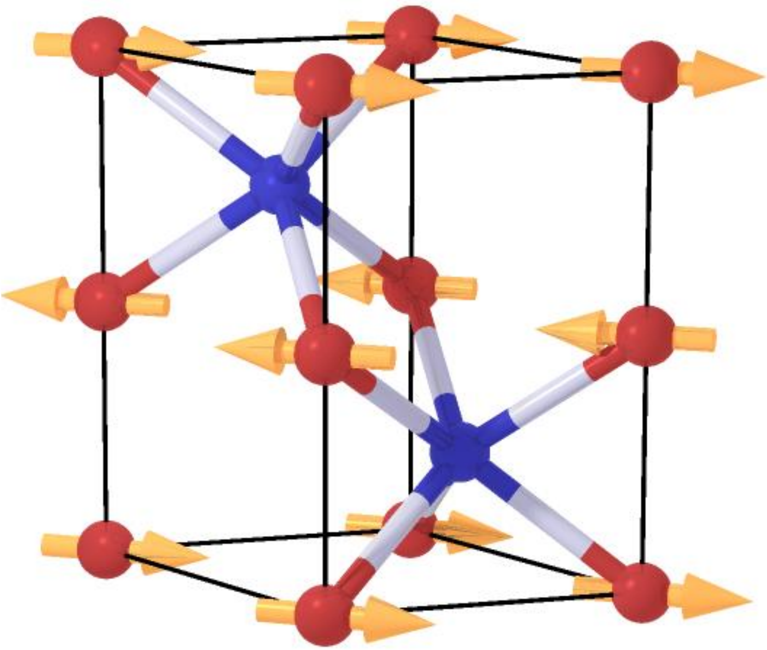
Symmetry and origin distinct from the conventional spin Hall effect

Odd: $\sigma(\mathbf{M}) = -\sigma(-\mathbf{M})$

Even: $\sigma(\mathbf{M}) = \sigma(-\mathbf{M})$

No experimental evidence so far

Spin-polarized current in a collinear system

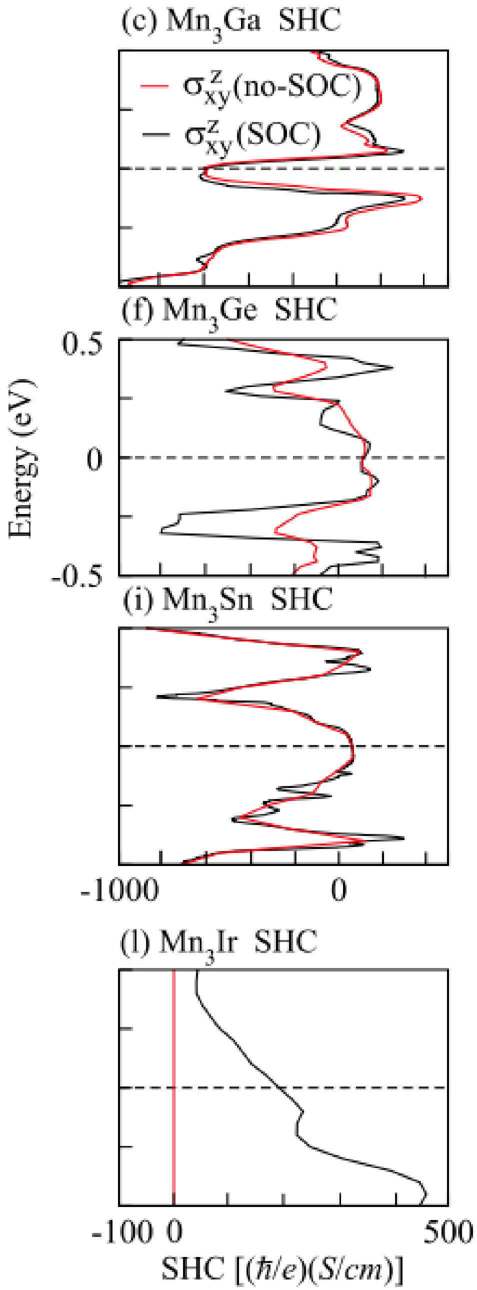


MnTe

The two sublattices are not connected **by T + inversion** or **T + translation**

Spin current angle for spin-polarized current and the magnetic SHE ~1%

SHE calculations



Spin Hall effect exist in these materials even without spin-orbit coupling!

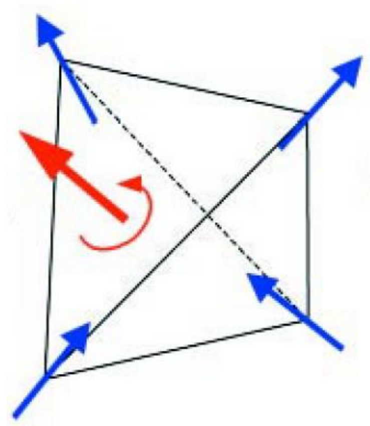
(No spin-orbit coupling = no relativistic effects)

Yang Zhang et al., Phys. Rev. B 95, 075128 (2017)
Yang Zhang et al., New J. Phys. 20 073028 (2018)

What is the origin of the SHE?

Originates from the magnetic order instead of spin-orbit coupling

Similar to AHE or orbital magnetic moment in non-coplanar magnetic systems



Taguchi et al., Science 291, 2573 (2001)

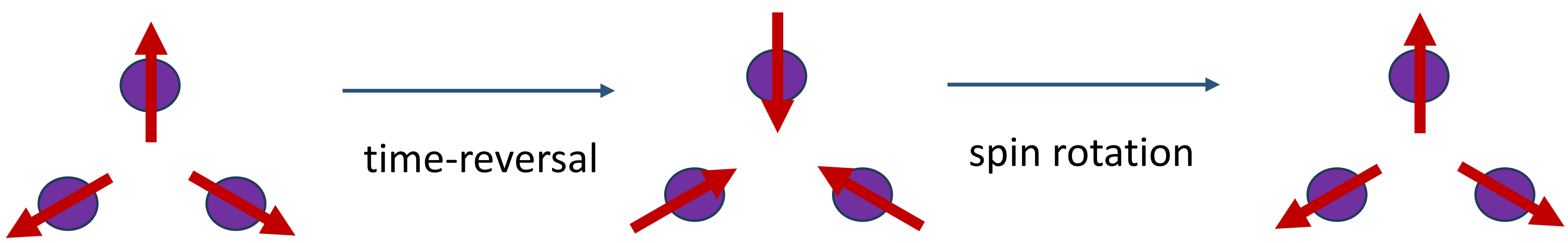
What is the origin of the SHE?

Can be understood in terms of symmetry and is not necessarily related to topology

Non-collinear magnetic order breaks symmetry similarly to spin-orbit coupling

Example:

In a coplanar system time-reversal + 180° spin rotation is a symmetry without SOC



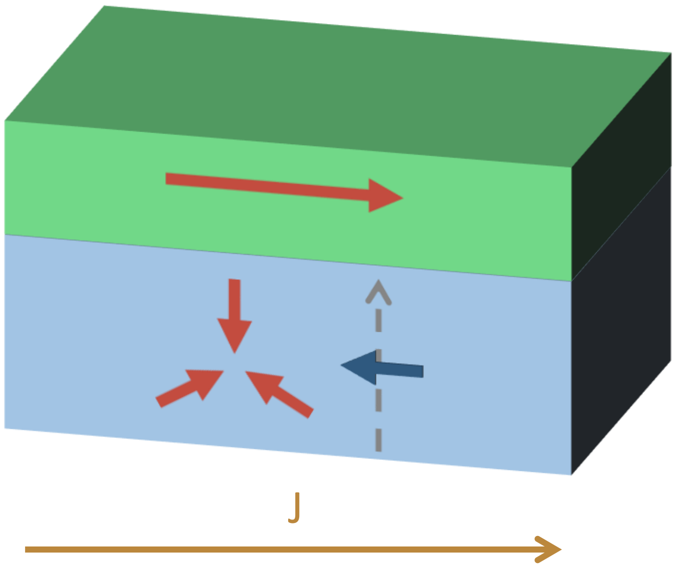
No AHE in a coplanar magnetic system

Brinkman et al., Proc. Royal Soc. London A, 294, 343-358 (1966)

Litvin et al., Physica 76, 538-554 (1974)

SOT in bilayer systems

- SHE and the magnetic SHE will generate a **spin-orbit torque** in FM/AFM bilayer systems
- The spin-orbit torque has been experimentally studied in a number of systems



The SHE and the magnetic SHE exist even without spin-orbit coupling

The spin-orbit torque does not necessarily originate from spin-orbit coupling

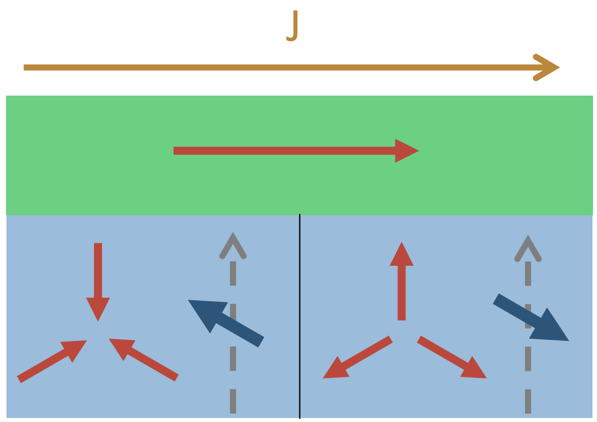
Thsitoyan et al., PRB 92, 214406 (2016)

Zhang et al., Science Advances 2, (2016)

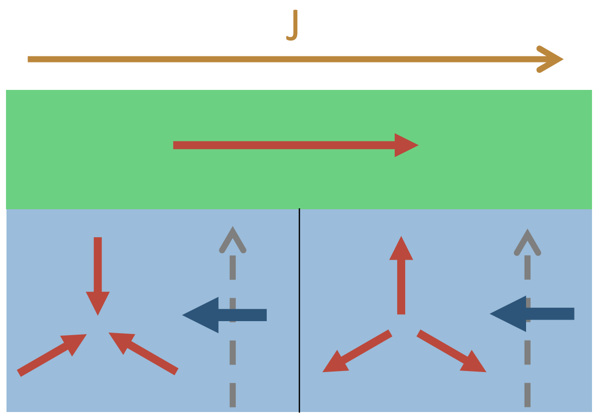
Young-Wan oh et al., Nature Nanotech., (2016)

Transverse spin currents

Magnetic and conventional spin Hall effect will depend differently on presence of magnetic domains and have different symmetry



odd

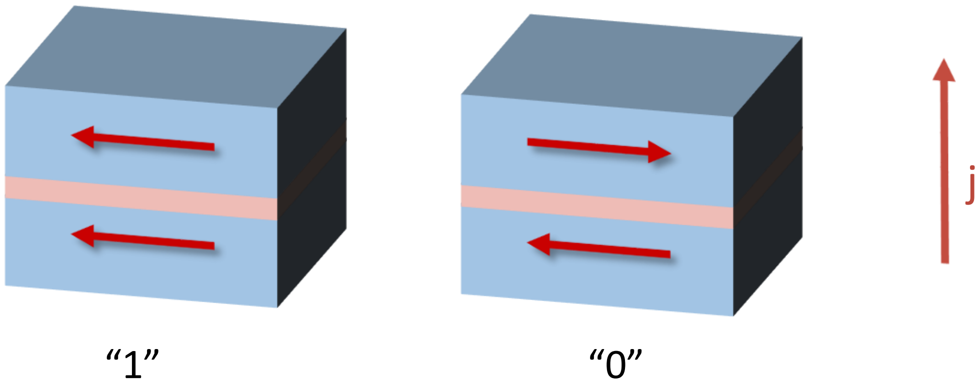


even

Sensitive to the antiferromagnetic order and presence of domains

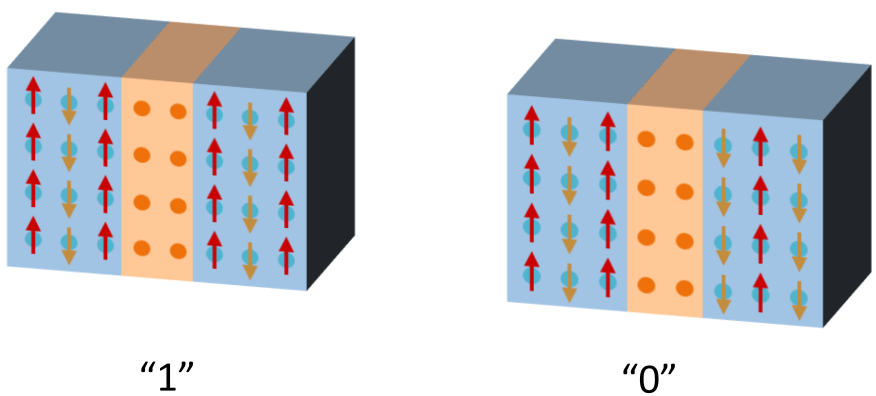
Spin current with spin-polarization along the spin current flow is possible

Antiferromagnetic junctions



Spin-transfer torque and giant or tunneling magnetoresistance

FM junction



Similar effects were theoretically predicted, but are very sensitive to disorder and have never been observed experimentally

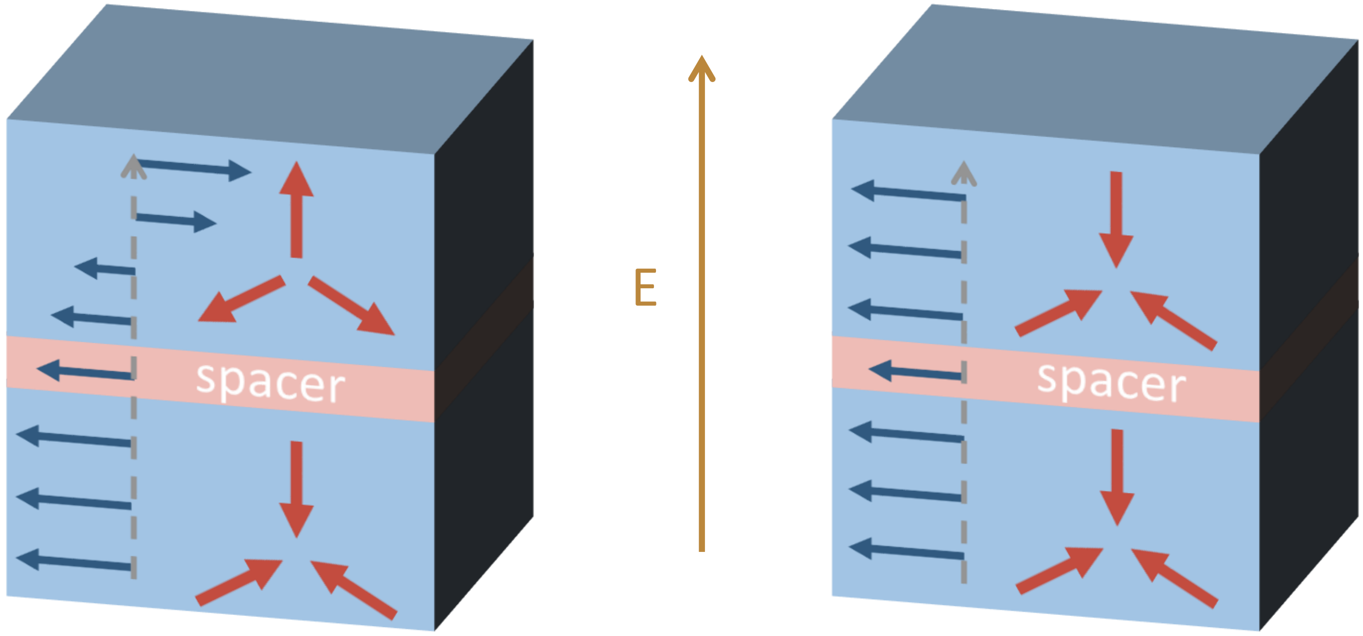
AFM junction

J. Železný, Nature Phys. 14, 220–228 (2018)

Spin-polarized current

In non-collinear antiferromagnets, current is spin-polarized and thus same approach can be used as in ferromagnets

Robust giant or tunneling magnetoresistance and spin-transfer torque should be present



180^o reversal

Significance of the AHE and the spin-polarized current is in part because they allow to detect **180^o reversal** of all magnetic moments

180^o reversal is equivalent to time-reversal

$$\mathbf{j} = \sigma \mathbf{E} \qquad\qquad \mathbf{j_s} = \sigma_s \mathbf{E}$$

$$\sigma^{\text{even}} = \sigma(\mathbf{M}_1, \mathbf{M}_2, \ldots) + \sigma(-\mathbf{M}_1, -\mathbf{M}_2, \ldots) \qquad \sigma_s{}^{\text{even}} = \sigma_s(\mathbf{M}_1, \mathbf{M}_2, \ldots) + \sigma_s(-\mathbf{M}_1, -\mathbf{M}_2, \ldots)$$

$$\sigma^{\text{odd}} = \sigma(\mathbf{M}_1, \mathbf{M}_2, \ldots) - \sigma(-\mathbf{M}_1, -\mathbf{M}_2, \ldots) \qquad \sigma_s{}^{\text{odd}} = \sigma_s(\mathbf{M}_1, \mathbf{M}_2, \ldots) - \sigma_s(-\mathbf{M}_1, -\mathbf{M}_2, \ldots)$$

$\sigma^{\text{odd}} =$ AHE

$\sigma_s{}^{\text{odd}} =$ spin-polarized current and magnetic SHE

In AFM with T + inversion or T + translation symmetry both σ^{odd} and $\sigma_s{}^{\text{od}}$ vanish

Second-order effects

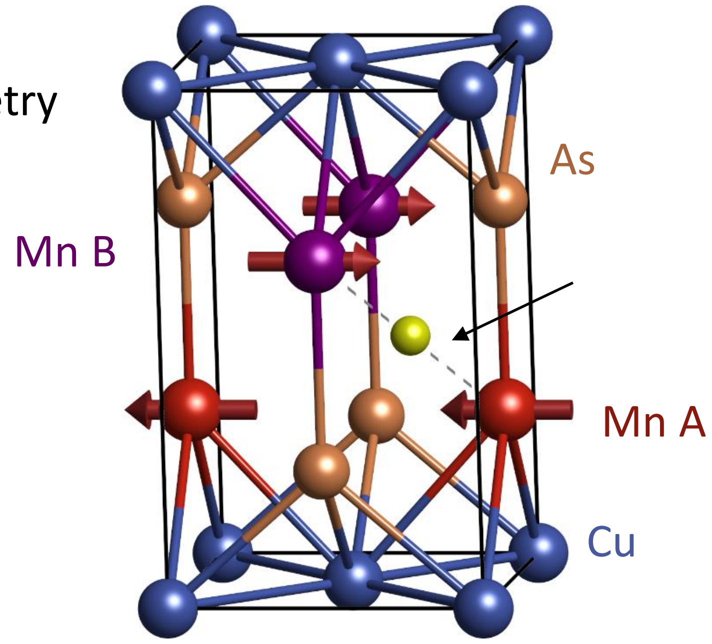
In AFM with T + inversion or T + translation 180° reversal cannot be detected with **linear transport effects**

Possible with second order, however!

$$j_i = \sigma^{(2)}_{ijk} E_j E_k$$

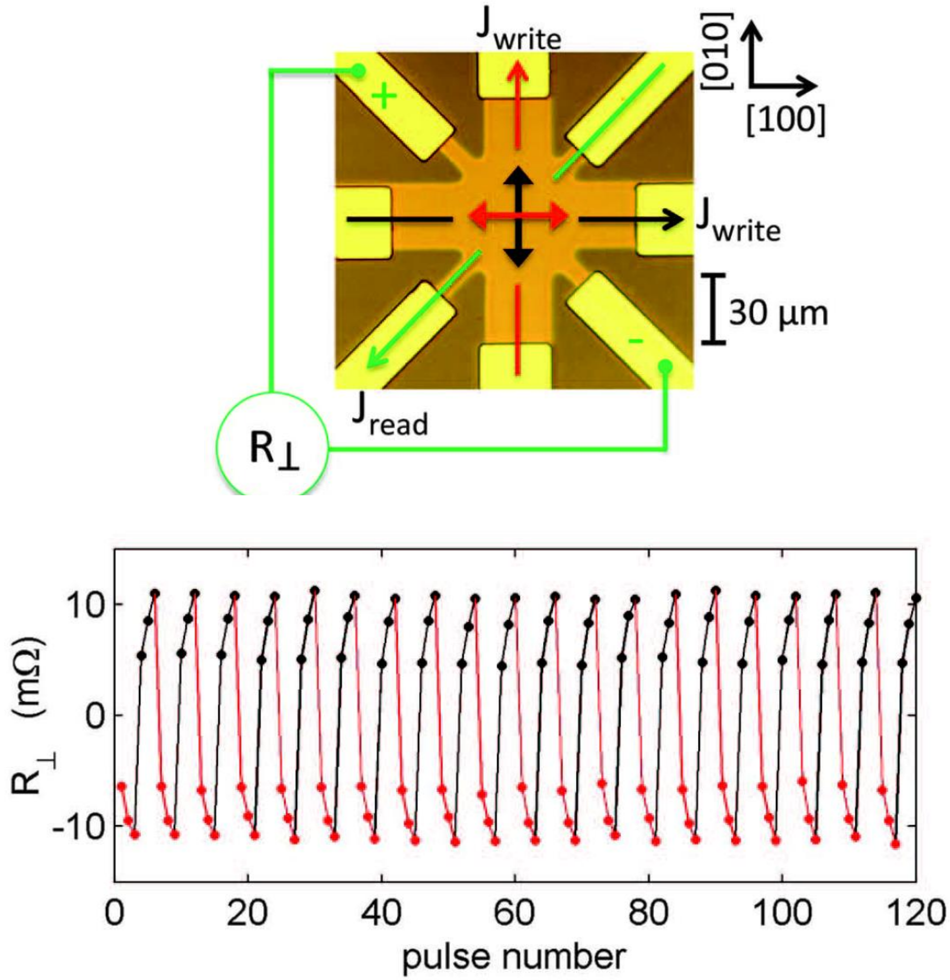
$\sigma^{(2)}$, allowed in systems with broken inversion symmetry

The odd component of $\sigma^{(2)}$ allowed even in AFMs with PT symmetry

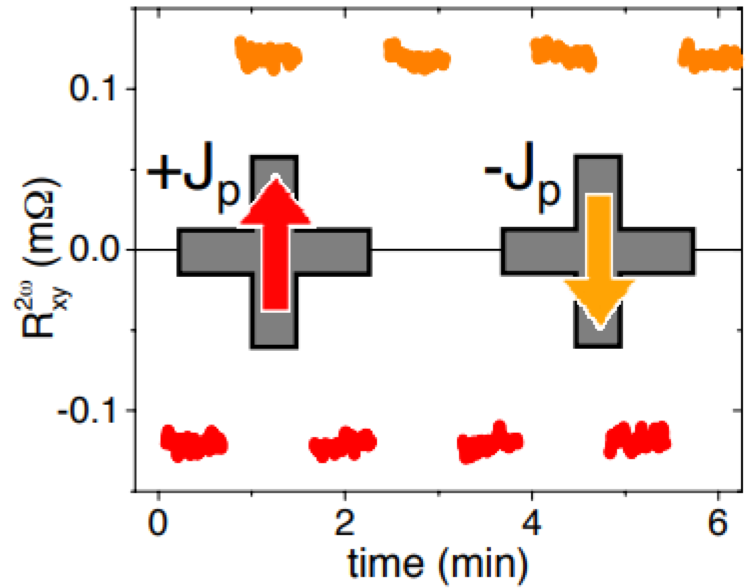


180° switching in CuMnAs

Switching in CuMnAs is normally 90° measured by AMR



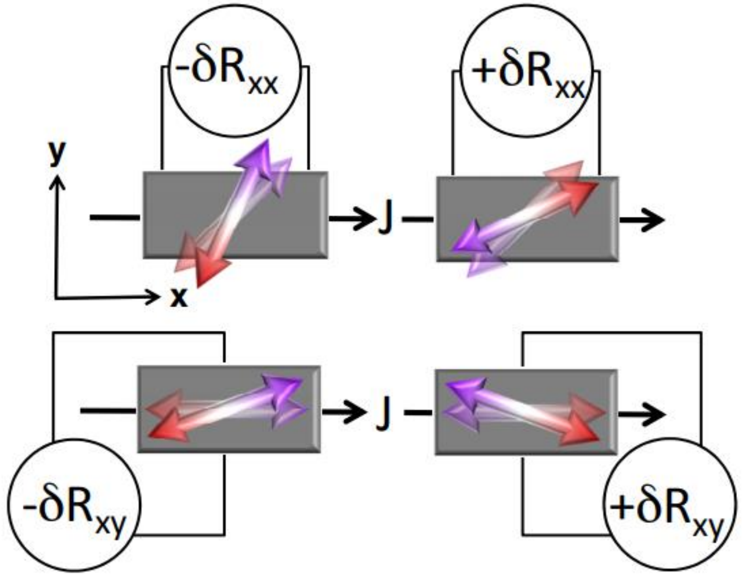
Wadley et al., Science 351, 587–590 (2016)



J. Godinho et al., arXiv:1806.02795

180° switching

Origin of the second-order signal



The original idea behind the experiment was that the second-order signal is due to tilting of the magnetic moments by the spin-orbit torque

But the second order signal could also simply be a second order conductivity, unrelated to a spin-polarization or a torque

Origin of the second-order signal

Using the Boltzmann equation within the constant relaxation time approximation:

$$\sigma_{ij}^{(1)} = -e^2\tau \int d^3k \left(v_i v_j \frac{\partial f_{\mathrm{FD}}}{\partial \varepsilon} \right)$$

$$\sigma_{ijk}^{(2)} = -e^3\tau^2 \int d^3k \left(v_i v_j v_k \frac{\partial^2 f_{\mathrm{FD}}}{\partial \varepsilon^2} + \frac{1}{\hbar} v_i \frac{\partial v_k}{\partial k_j} \frac{\partial f_{\mathrm{FD}}}{\partial \varepsilon} \right)$$

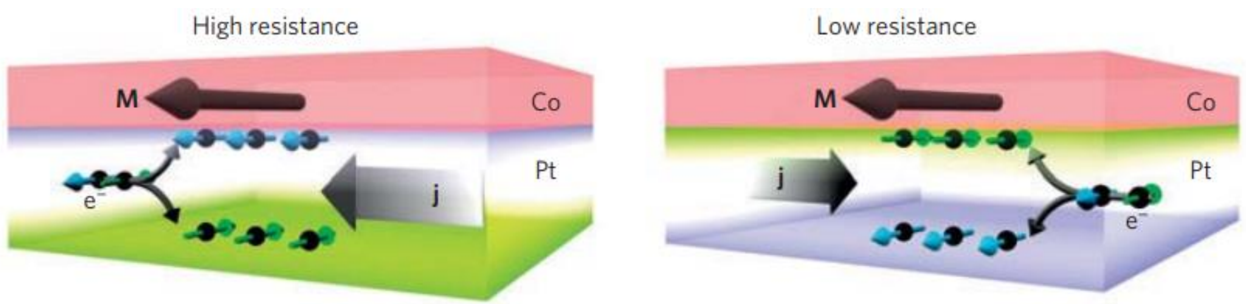
The second-order term can be understood as originating from k $\leftrightarrow -k$ band assymetry

Requires broken inversion and time-reversal + spin-orbit coupling (or non-collinear magnetic order)

Second-order measurements

Second harmonics commonly used to measure spin-orbit torques

Unidirectional magnetoresistance



Olejnik et al., Phys Rev B 91, 180402(R) (2015)
Avci et al., Nature Physics 11, 570–575 (2015)

Summary

- Noncollinear antiferromagnets are very attractive for spintronics since they **combine advantages of ferromagnets and antiferromagnets**

✓ Spin-polarized current
✓ AHE, Kerr effect
✓ spin Hall effect (without SOC)
✓ Detecting 180° switching possible

✓ Fast magnetic dynamics
✓ Insensitive to external magnetic fields
✓ No stray fields

- Spin-polarized current not limited to ferromagnets, but can exist in collinear and non-collinear antiferromagnets
- Magnetic spin Hall effect: in magnetic materials a transverse current distinct from the spin Hall effect can exist
- Spin-Hall effect can exist without SOC

Zelezny et al., PRL 119, 187204 (2017)

Yang Zhang et al., New J. Phys. 20 073028 (2018)