Spin- polarized current and magnetic spin Hall effect in non-collinear antiferromagnets

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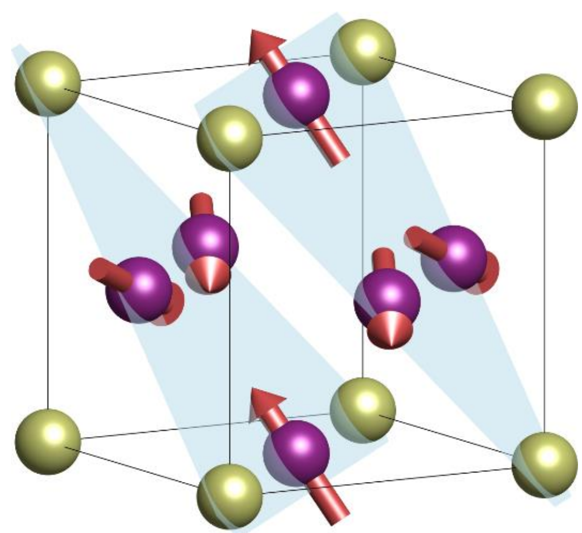


Antiferromagnetic spintronics

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

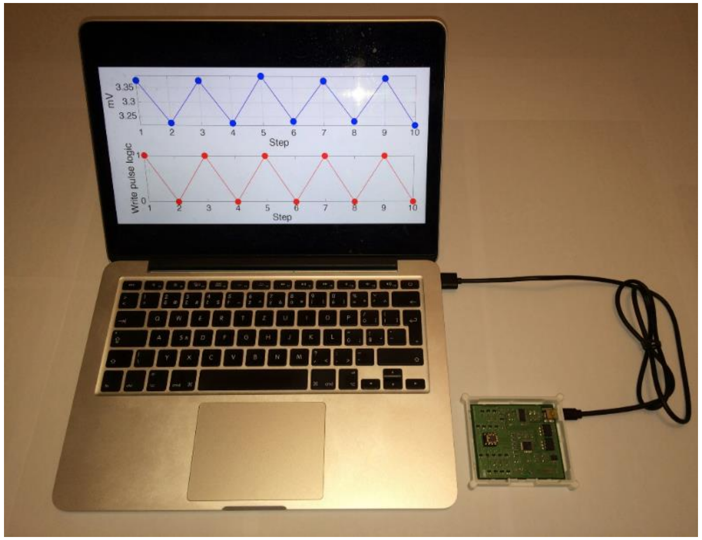
The antiferromagnetic order is difficult to control and manipulate

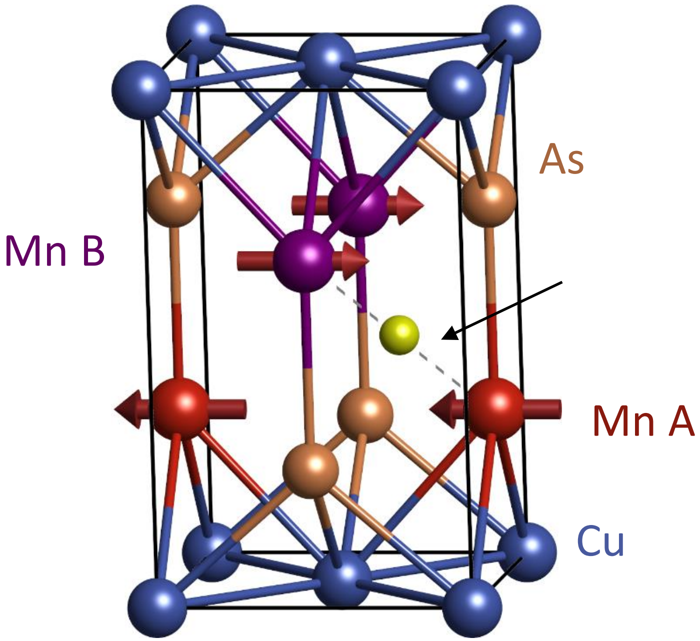
Spin-orbit torques in antiferromagnets

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

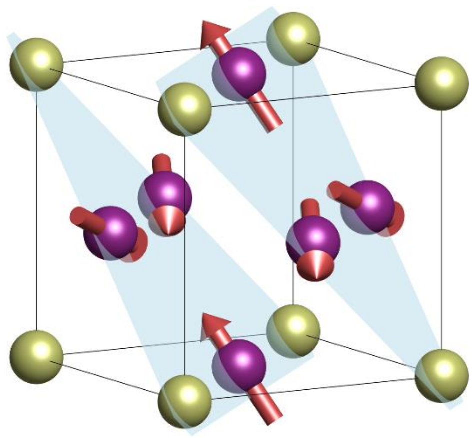
Zelezny et al., PRL 113, 157201 (2014)
Wadley et al., Science 351, 587–590 (2016)
Bodnar et al., arXiv:1706.02482
Meinert et al., arXiv:1706.06983

Non-collinear antiferromagnets

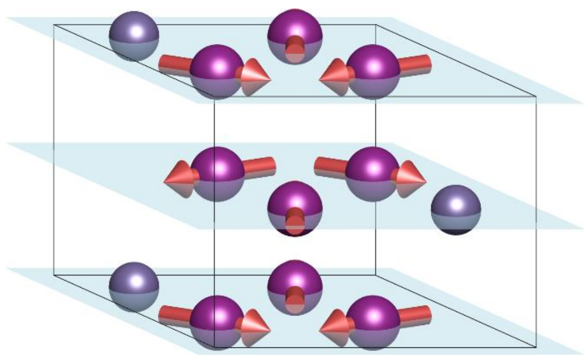
Non-collinear order is common in antiferromagnets

The most commonly used antiferromagnets are non-collinear alloys of Mn-Ir

Triangular antiferromagnets Mn3X



Mn_3Rh, Mn_3Pt, Mn_3Ir



Mn_3Ga, Mn_3Ge, Mn_3Sn

- Experimentally studied and relevant for technology
- Simplest example of a non-collinear magnetic order

Triangular antiferromagnets

- Néel temperatures above room temperature

- Large anomalous Hall effect -> also XMCD, Kerr effect, Anomalous Nernst effect

Chen et al., PRL 112, 017205 (2014) *Kubler et al., EPL 108, 67001 (2014)* *Feng et al., PRB 92, 144426 (2015)*

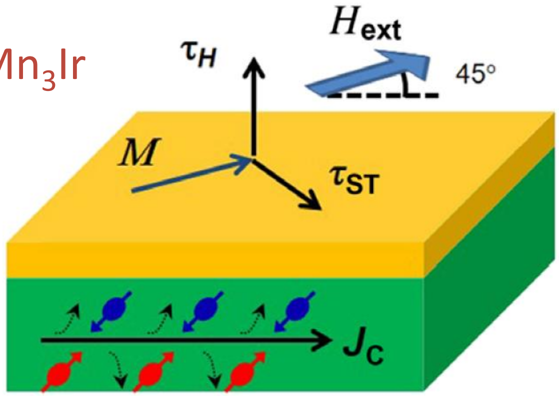
Nayak et al. Sci. Adv. 2016;2:e1501870 *Naktsuji et al. Nature 527, 212 (2015)* *Ikhlas et al., Nature Physics 13, 1085–1090 (2017)*

- Large spin-orbit torque generated by spin-Hall effect in Mn_3Ir

Zhang et al. Sci. Adv. 2016;2:e1600759

Thsitoyan et al., Phys. Rev. B 92, 214406 (2015)

Young-Wang Oh et al., Nature Nanotech. 11, (2016)



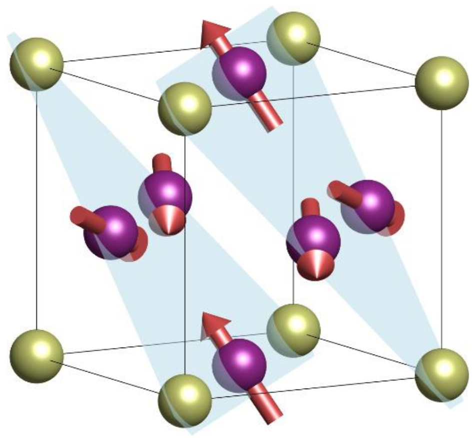
- Cancellation of anisotropy in the hexagonal antiferromagnets

Field which can orient the domains: Mn_3Ir: > 60 T

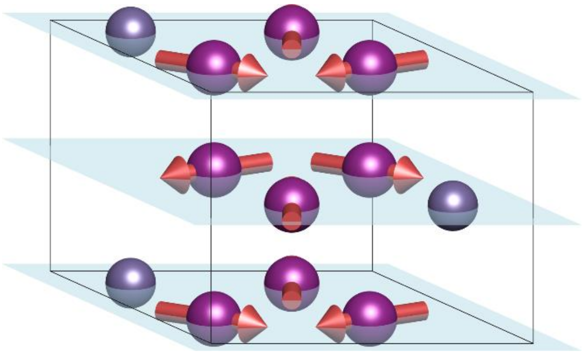
Mn_3Sn: 0.03 T

Tomiyoshi et al., J. Phys. Soc. Japan 51, 2478 (1981)

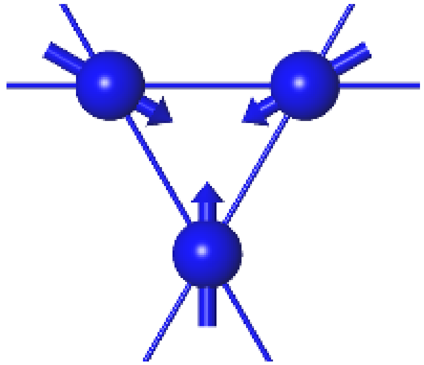
Anisotropy

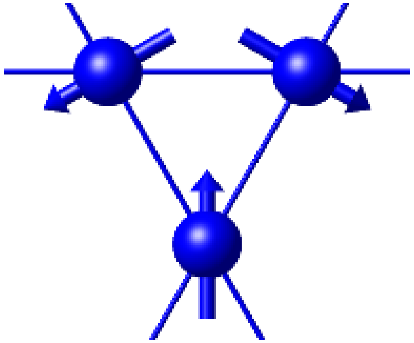


Mn_3Ir



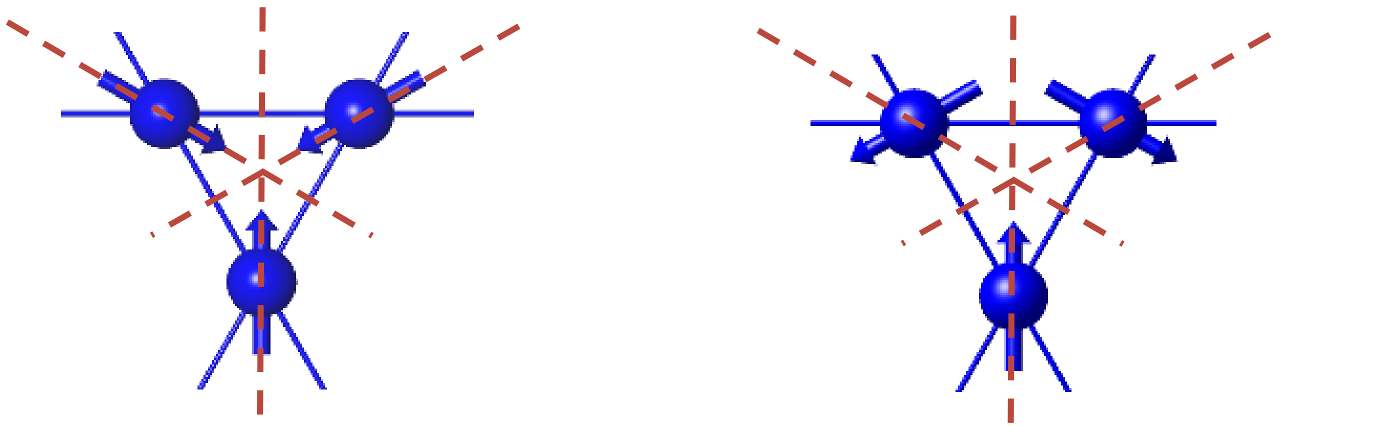
Mn_3Sn





Inverted structure

Anisotropy



The inverted structure is stabilized by Dzyaloshinksi-Moria interaction

Only present in the hexagonal compounds

$$E_{\text{ani}} = E_1(\mathbf{M}_1) + E_2(\mathbf{M}_2) + E_3(\mathbf{M}_3) \approx 0$$

Second and fourth order anisotropy cancel for the inverted structure

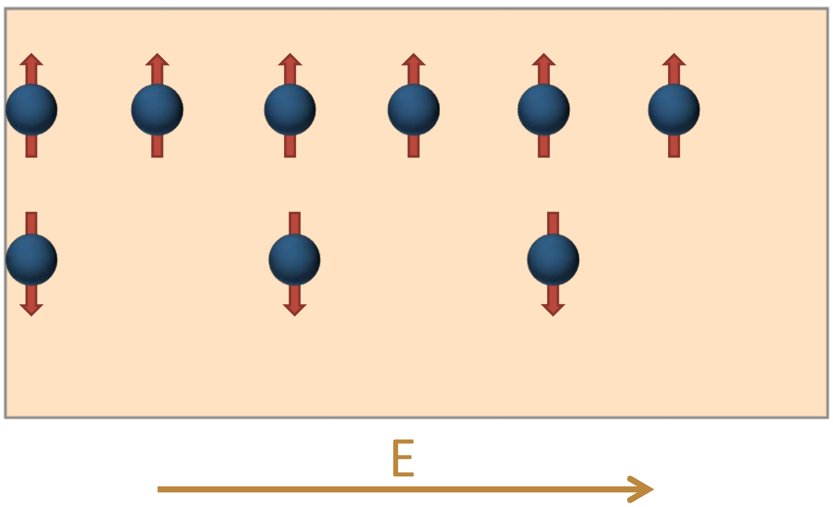
$$H_{sf} \sim \sqrt{H_E H_A}$$

This is why anomalous Hall effect was only measured in the hexagonal compound

Tomiyoshi, J. Phys. Soc. Japan, 1981

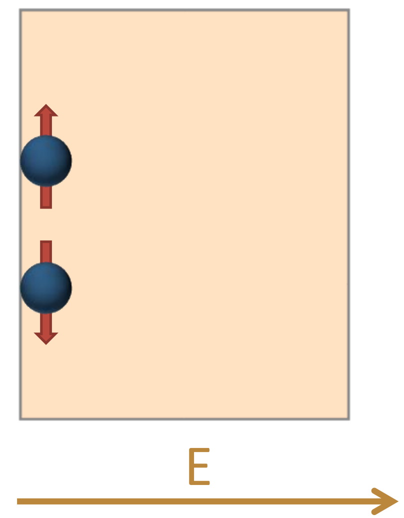
Spin currents

Spin-polarized current in ferromagnets



Odd under time-reversal

Spin-Hall effect



Even under time-reversal

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…

Linear response

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

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

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

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 in ferromagnets	even - spin Hall effect

Odd components can only exist in magnetic materials

Odd spin currents in ferromagnets

Spin current longitudinal with the charge current -> spin-polarized current

Symmetry of the spin currents in Bcc Fe with M || x:

$$\sigma^x = \begin{pmatrix} \sigma_{xxx} & 0 & 0 \\ 0 & \sigma_{xxx} & 0 \\ 0 & 0 & \sigma_{xxx} \end{pmatrix} \qquad \sigma^x = \begin{pmatrix} \sigma_{xxx} & 0 & 0 \\ 0 & \sigma_{xyy} & 0 \\ 0 & 0 & \sigma_{xyy} \end{pmatrix}$$

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

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

Without spin-orbit coupling

With spin-orbit coupling

Transverse spin currents with magnetic origin: **Magnetic spin Hall effect**

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

Not necessarily a spin-polarized transverse charge current:
can also be a pure spin current

conductivity

$$\begin{pmatrix} \sigma_{xx} & 0 & 0 \\ 0 & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{yy} \end{pmatrix}$$

Taniguchi et al., Phys. Rev. Applied 3, 044001 (2015)

Odd spin currents in non-collinear antiferromagnets

- The odd spin currents are present in the Mn3X antiferromagnets, unlike in collinear antiferromagnets
- longitudinal spin current – **spin-polarized current**
- Transverse spin current – **magnetic spin Hall effect**

		no SOC	SOC
Mn_3Sn	σ^x	$\begin{pmatrix} 0 & \sigma^x_{xy} & 0 \\ \sigma^x_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \sigma^x_{xy} & 0 \\ \sigma^x_{yx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
	σ^y	$\begin{pmatrix} -\sigma^x_{xy} & 0 & 0 \\ 0 & \sigma^x_{xy} & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} \sigma^y_{xx} & 0 & 0 \\ 0 & \sigma^y_{yy} & 0 \\ 0 & 0 & \sigma^y_{zz} \end{pmatrix}$
	σ^z	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma^z_{yz} \\ 0 & \sigma^z_{zy} & 0 \end{pmatrix}$
Mn_3Ir	σ^x	$\begin{pmatrix} \sigma^x_{xx} & 0 & 0 \\ 0 & -\frac{\sigma^x_{xx}}{2} & 0 \\ 0 & 0 & -\frac{\sigma^x_{xx}}{2} \end{pmatrix}$	$\begin{pmatrix} \sigma^x_{xx} & \sigma^x_{xy} & \sigma^x_{xy} \\ \sigma^x_{yx} & \sigma^x_{yy} & \sigma^x_{yz} \\ \sigma^x_{yx} & \sigma^x_{yz} & \sigma^x_{yy} \end{pmatrix}$
	σ^y	$\begin{pmatrix} -\frac{\sigma^x_{xx}}{2} & 0 & 0 \\ 0 & \sigma^x_{xx} & 0 \\ 0 & 0 & -\frac{\sigma^x_{xx}}{2} \end{pmatrix}$	$\begin{pmatrix} \sigma^x_{yy} & \sigma^x_{yx} & \sigma^x_{yz} \\ \sigma^x_{xy} & \sigma^x_{xx} & \sigma^x_{xy} \\ \sigma^x_{yz} & \sigma^x_{yx} & \sigma^x_{yy} \end{pmatrix}$
	σ^z	$\begin{pmatrix} -\frac{\sigma^x_{xx}}{2} & 0 & 0 \\ 0 & -\frac{\sigma^x_{xx}}{2} & 0 \\ 0 & 0 & \sigma^x_{xx} \end{pmatrix}$	$\begin{pmatrix} \sigma^x_{yy} & \sigma^x_{yz} & \sigma^x_{yx} \\ \sigma^x_{yz} & \sigma^x_{yy} & \sigma^x_{yx} \\ \sigma^x_{xy} & \sigma^x_{xy} & \sigma^x_{xx} \end{pmatrix}$

In FM without SOC with magnetization along *z*

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

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

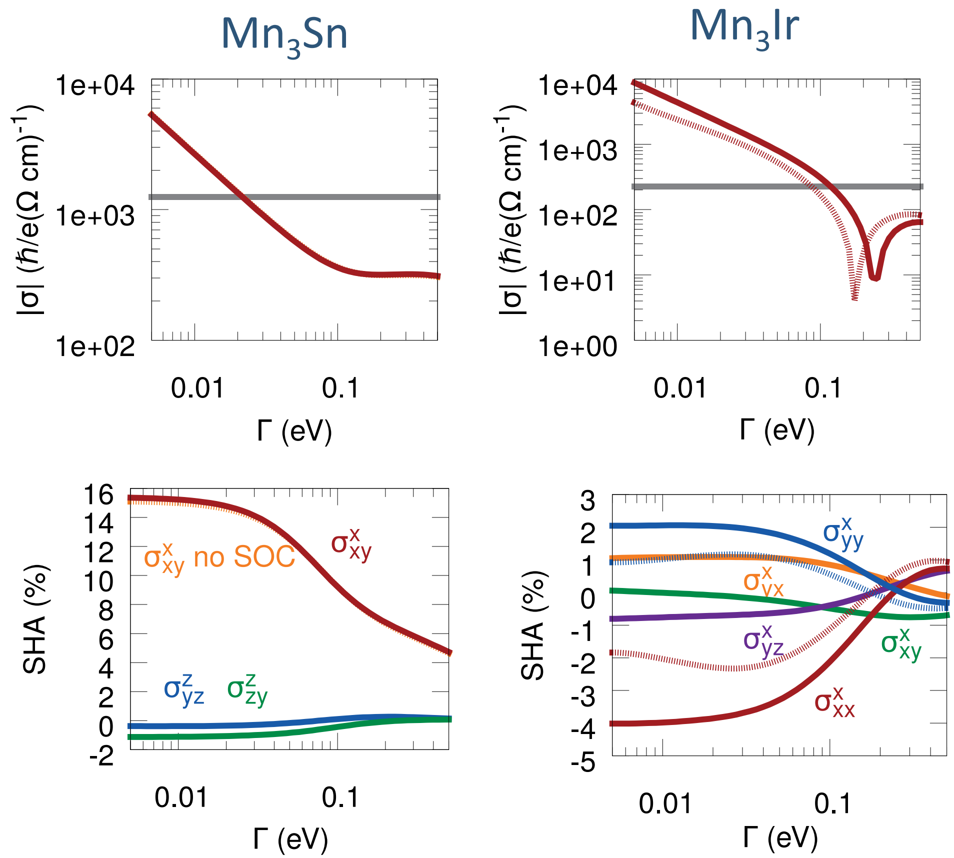
Calculations

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

	$\alpha_{\parallel}$ (%)	$\alpha_{\perp}$ (%)
Mn3Ga	13.7	13.5
Mn3Ge	5.1	5.0
Mn3Sn	12.4	12.4
Mn3Rh	1.1	0.7
Mn3Ir	3.5	1.9
Mn3Pt	4.2	1.9



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

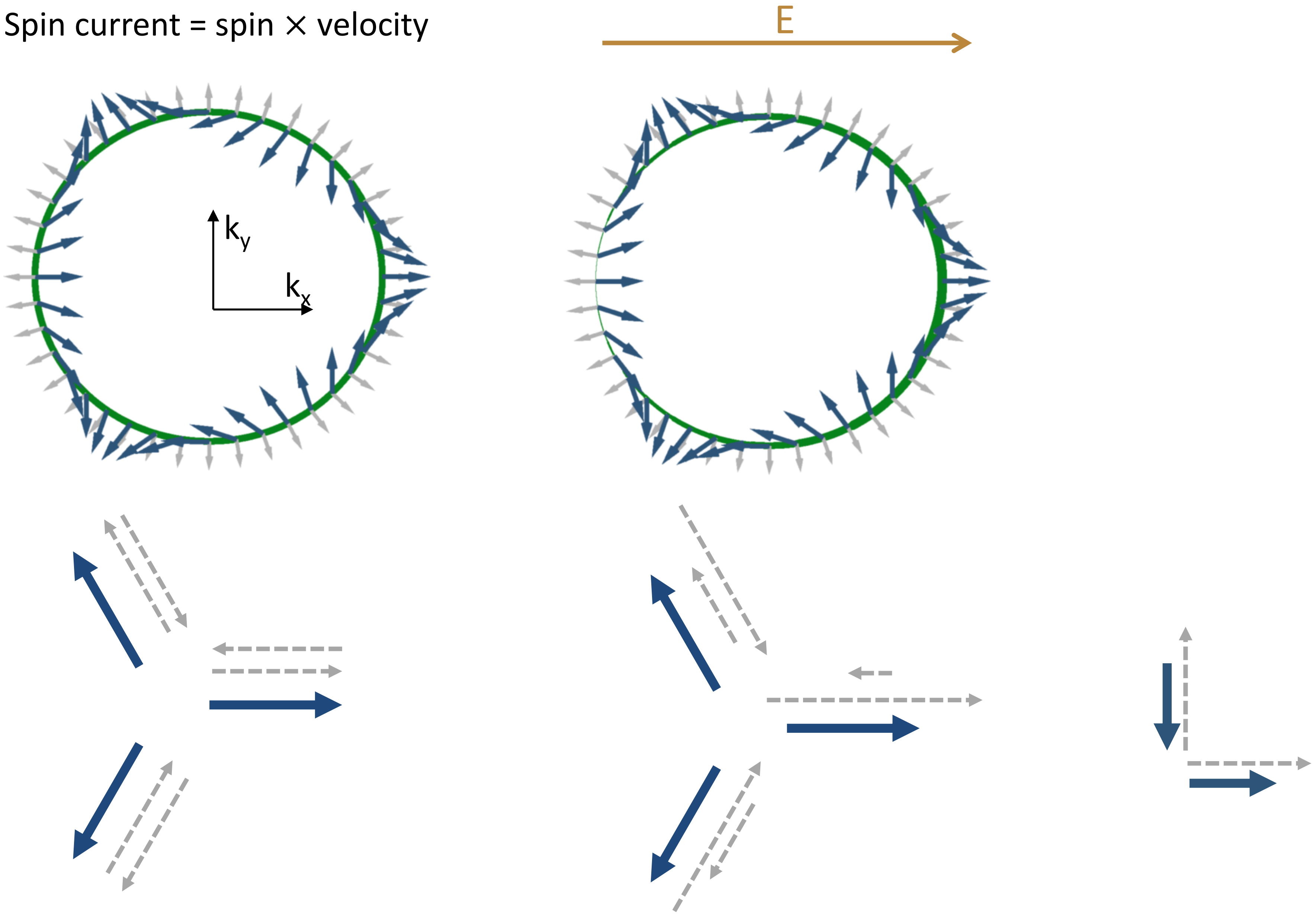
In BCC Fe $\alpha_{\parallel}$ ~ 18%

$\alpha_{\perp}$ ~ 1%

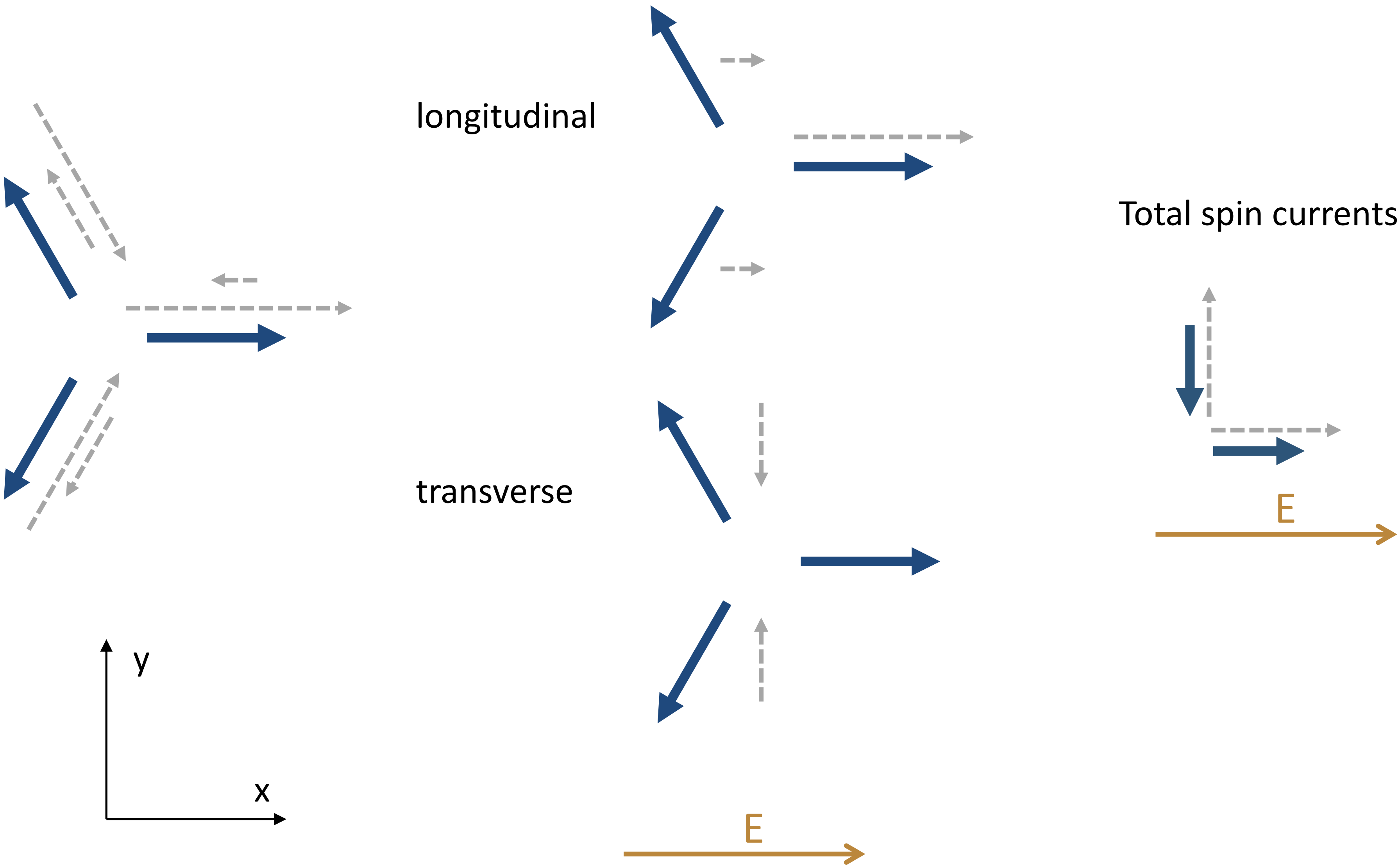
Zelezny et al., PRL 119, 187204 (2017)

Origin of the odd spin currents

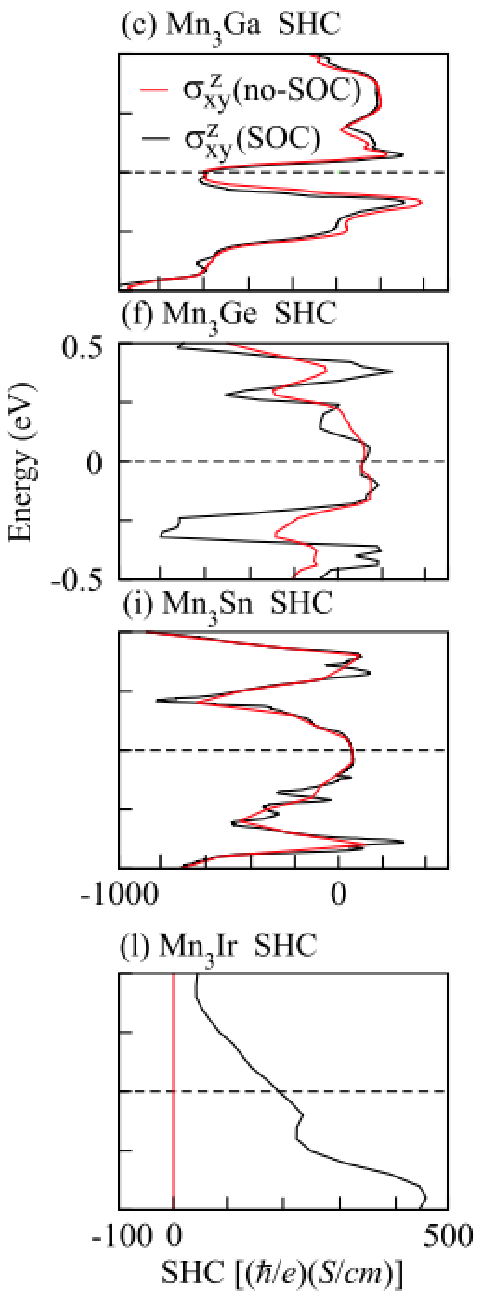
Spin current = spin × velocity



Origin of the odd spin currents



SHE calculations

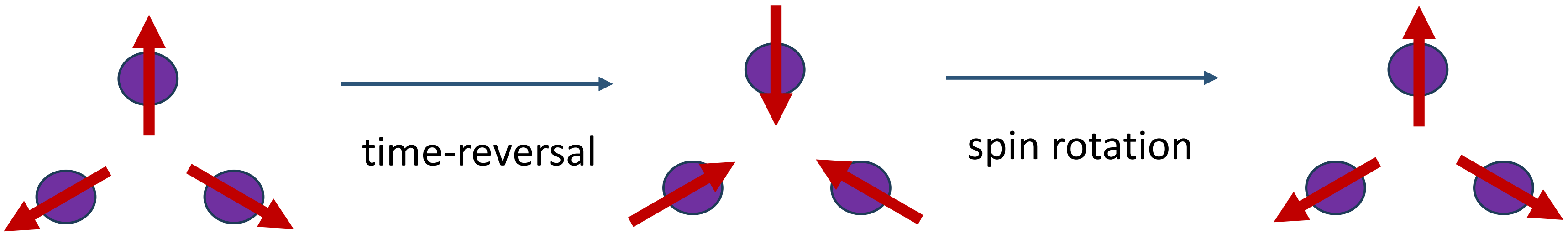


Spin Hall effect exist in these materials even without spin-orbit coupling!

Yang Zhang et al., Phys. Rev. B 95, 075128 (2017)
Yang Zhan et al., arxiv:1704.03917

Symmetry without spin-orbit coupling

Symmetry operation + spin rotation which leave the system invariant are symmetries of the system if spin-orbit coupling is neglected



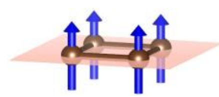
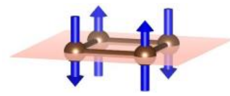
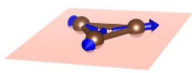
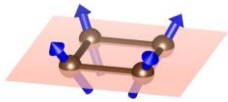
In a coplanar system time-reversal + 180° spin rotation is a symmetry without SOC

"Spin groups" or "spin-space" groups

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

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

Symmetry without spin-orbit coupling

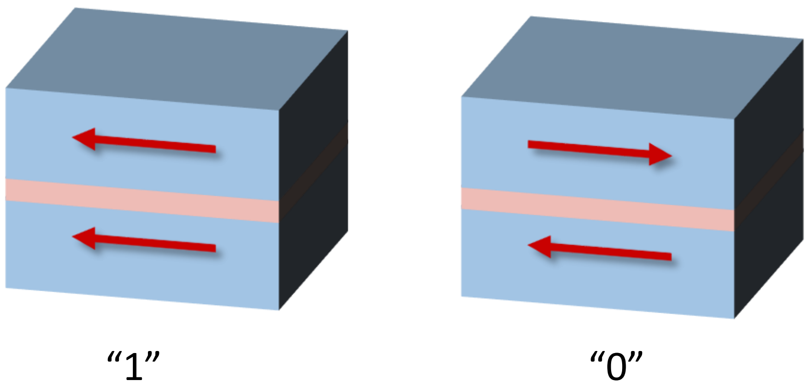
		Collinear FM	Collinear AFM	Coplanar	Non-coplanar
					
Without SOC	AHE	NO	NO	NO	YES
	SHE	NO	NO	YES	YES
With SOC	AHE	YES	NO	YES	YES
	SHE	YES	YES	YES	YES

Non-collinear magnetic order plays the same role as spin-orbit coupling

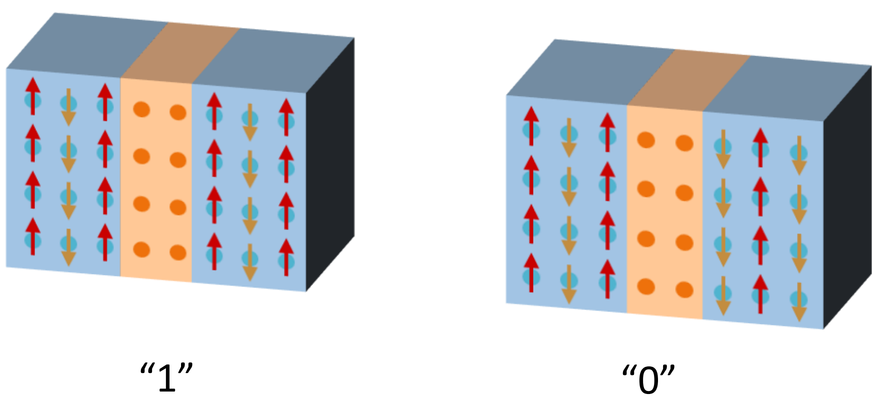
Applies also for orbital magnetic moment, Dzyaloshinskii-Moriya interaction,…

Yang Zhang et al., arxiv:1704.03917

Antiferromagnetic junctions

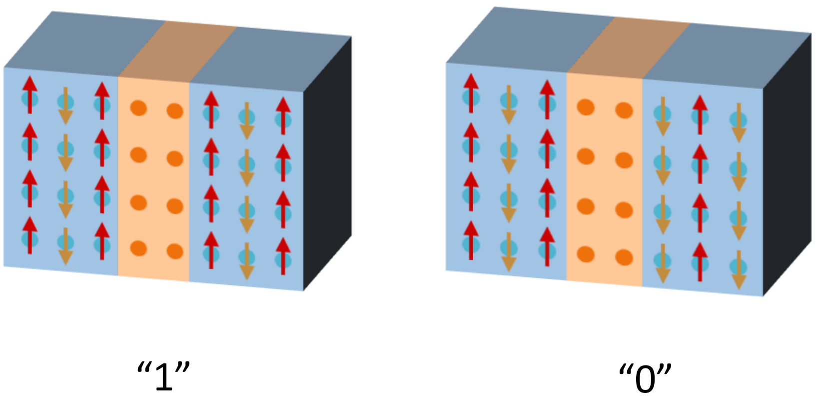


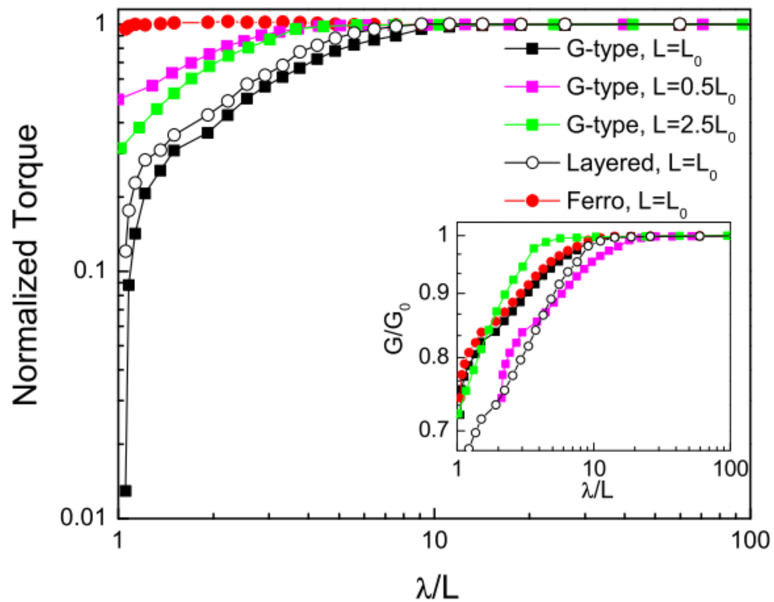
FM junction



AFM junction

Antiferromagnetic junctions





Theoretically proposed but strongly sensitive to disorder and never observed experimentally

Saidaoui et al., PRB 89, 174430 (2014)

“It is simply not possible to achieve spin transfer torque in a spin-valve composed of two antiferromagnets in the semiclassical limit.”

A. Manchon, Journal of Physics: Condensed Matter 29 (2017)

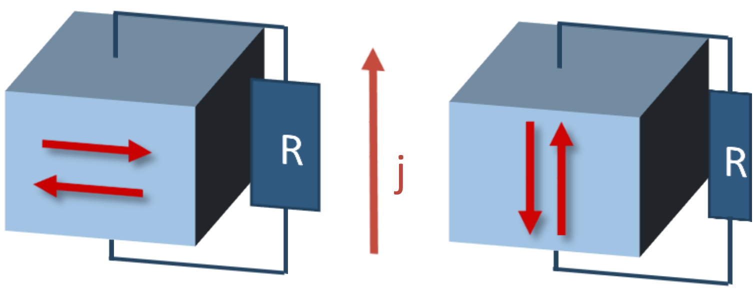
Zelezny et al., arXiv:1705.10675

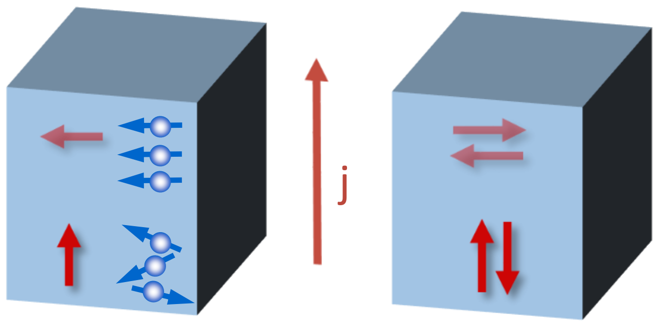
Antiferromagnetic spintronics

Instead of the junctions, relativistic effects are used

spin-orbit torque

AMR

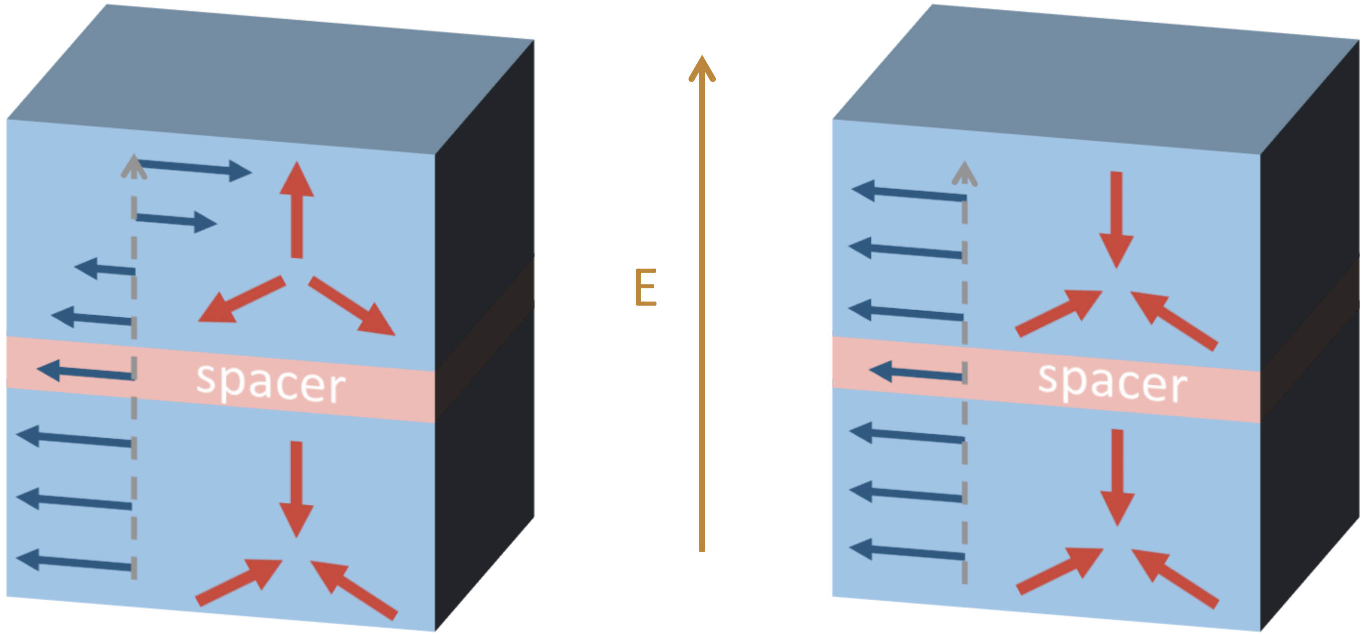




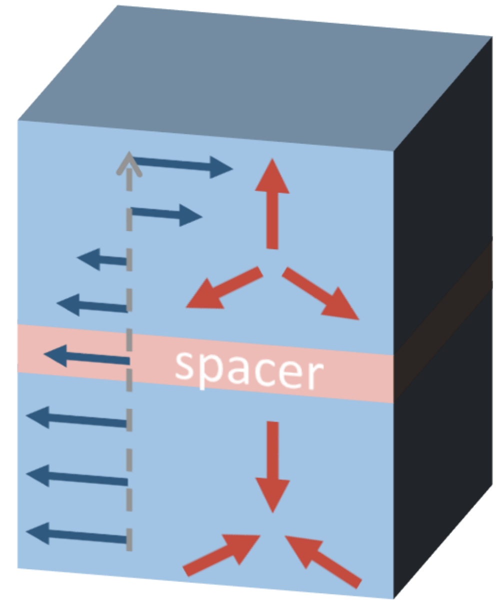
Spin-polarized current

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

Giant or tunneling magnetoresistance and spin-transfer torque should be present

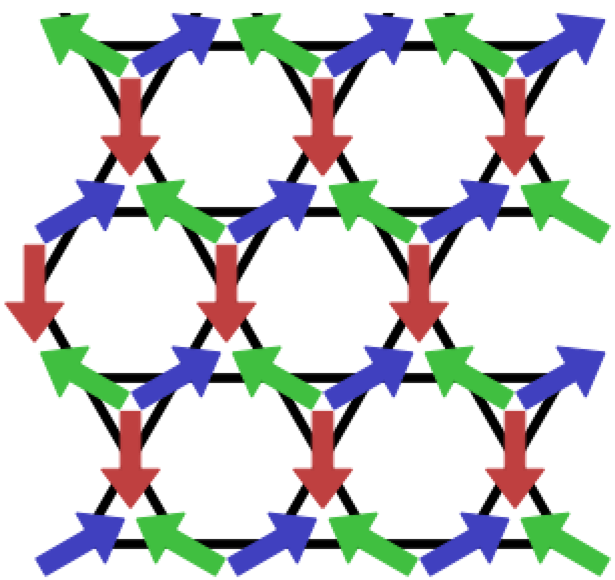


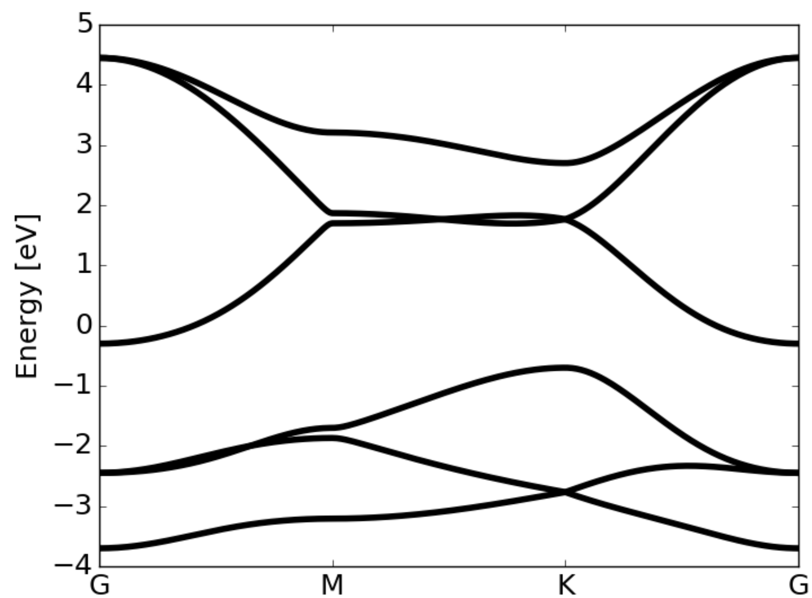
Spin valves and tunneling junctions



We use a simple tight-binding model

$$H(\mathbf{M}_1, \mathbf{M}_2, \ldots) = \sum_{i\alpha} e_{i\alpha} c^\dagger_{i\alpha} c_{i_\alpha} + t \sum_{<ij>\alpha} c^\dagger_{i\alpha} c_{j_\alpha} - J \sum_{i\alpha\beta} (\boldsymbol{\sigma} \cdot \boldsymbol{M}_i)_{\alpha\beta} c^\dagger_{i\alpha} c_{i\beta}$$

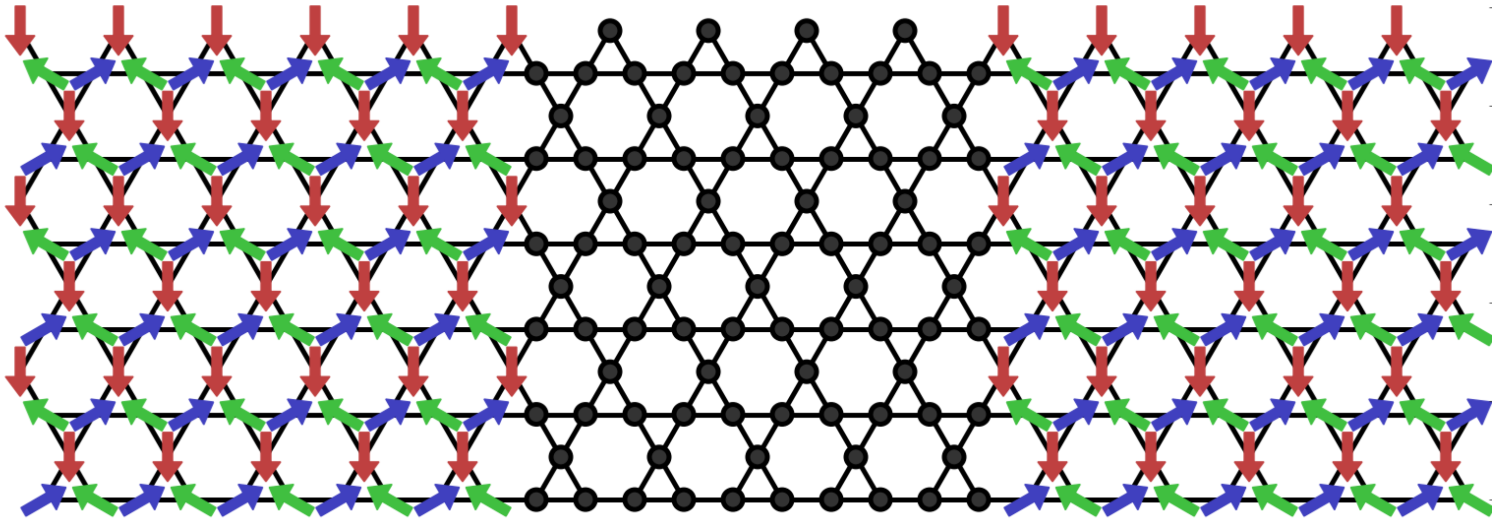




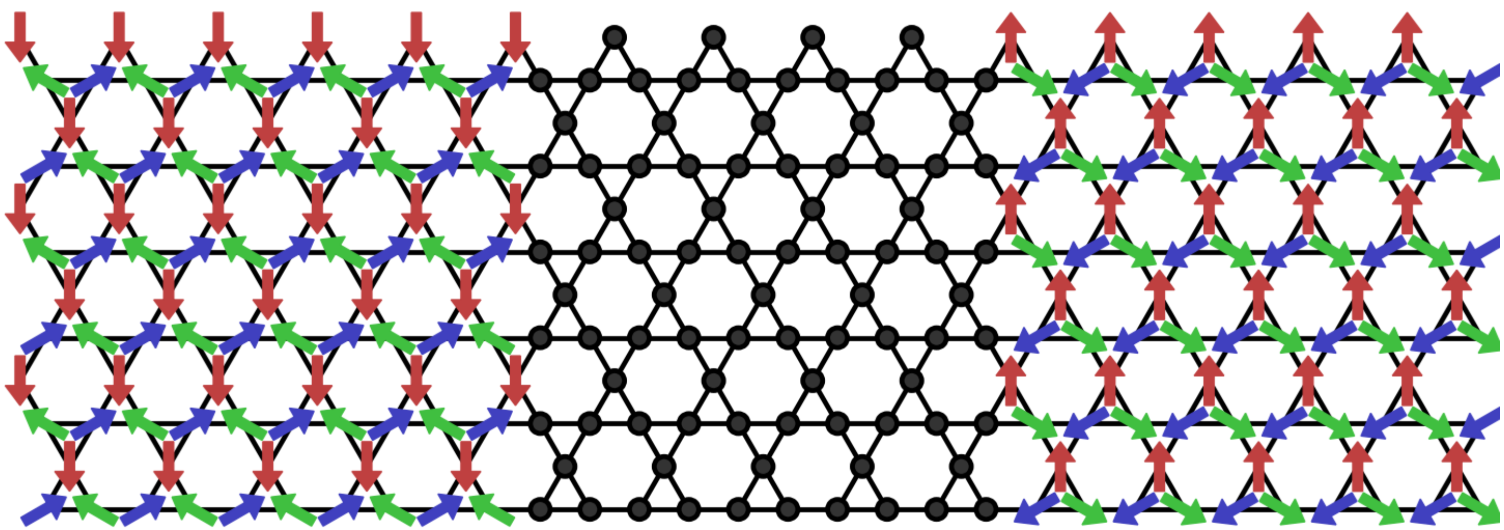
Chen et al., PRL 112, 017205 (2014)

Spin valves and tunneling junctions

Parallel

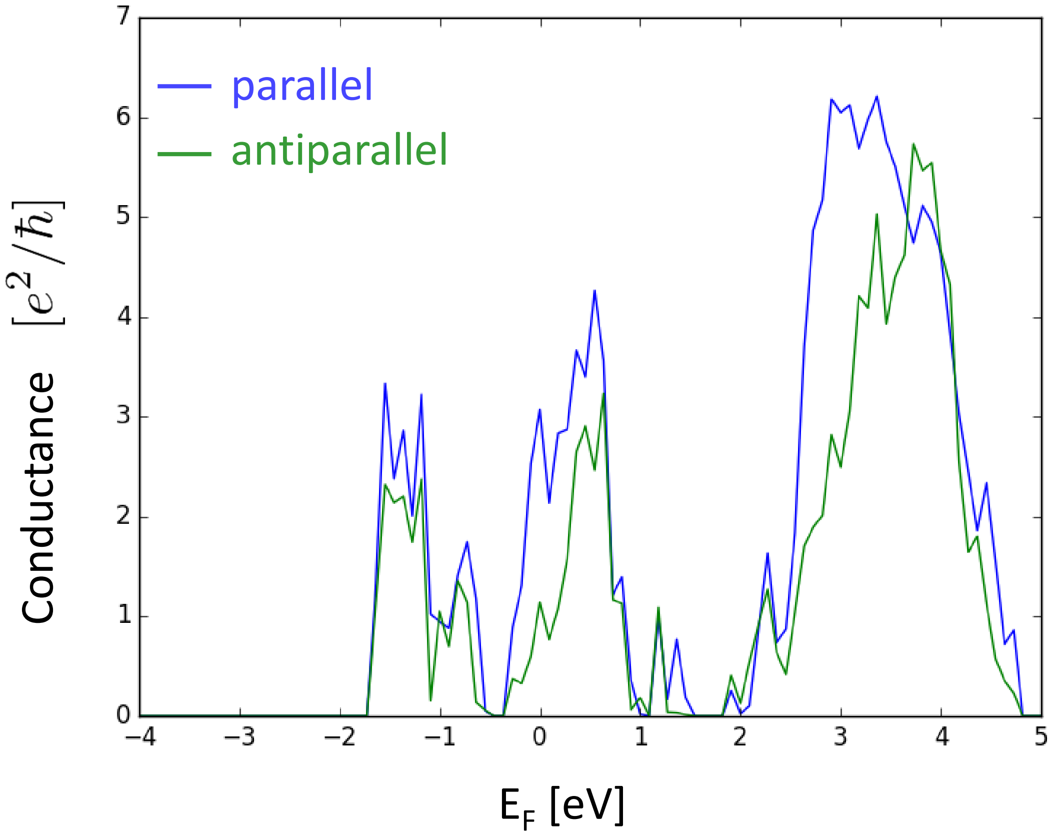


Antiparallel



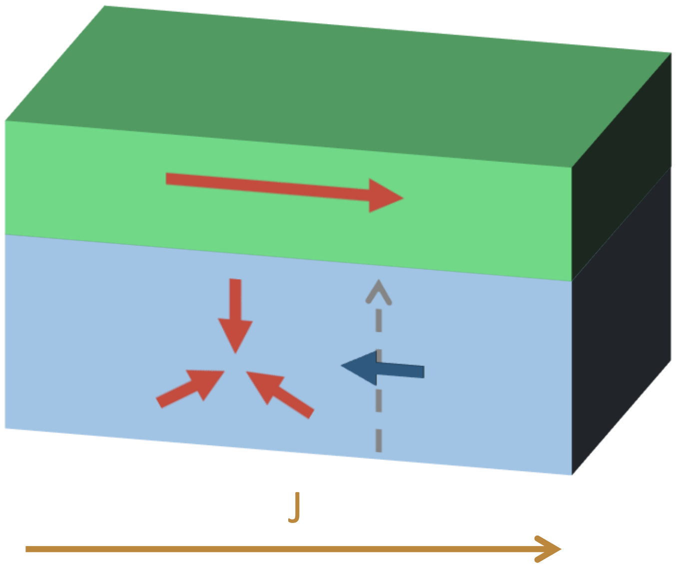
Spin valves and tunneling junctions

Large magnetoresistance is present in a metallic spin valve



Transverse spin currents

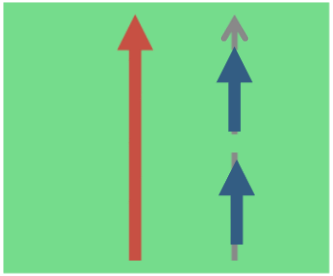
- Both magnetic and conventional spin Hall effect is present
- Both could be used for spin-orbit torques, but they have different symmetry

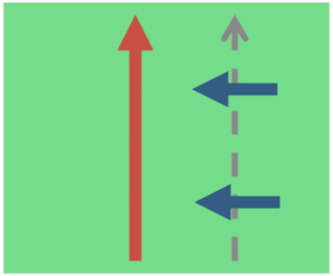


Symmetry matters for the spin-orbit torque

Spin-orbit torque switching

Two main configurations for the spin torque due to spin current:





Spin-polarization of the spin current **parallel** with the magnetization

Spin-polarization of the spin current **perpendicular to** the magnetization

No field needed

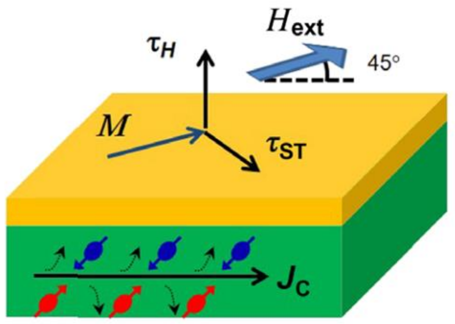
Static external magnetic field is needed for reversible switching

$$H_c = \alpha H a$$

$$H_c \sim 0.5 H_a$$

Truly antidamping switching

Symmetry of the spin Hall effect



For SOT out-of-plane spin-polarization is preferential

SHE normally has in-plane spin-polarization

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

$$\sigma^y \quad \begin{pmatrix} 0 & 0 & \sigma \\ 0 & 0 & 0 \\ -\sigma & 0 & 0 \end{pmatrix}$$

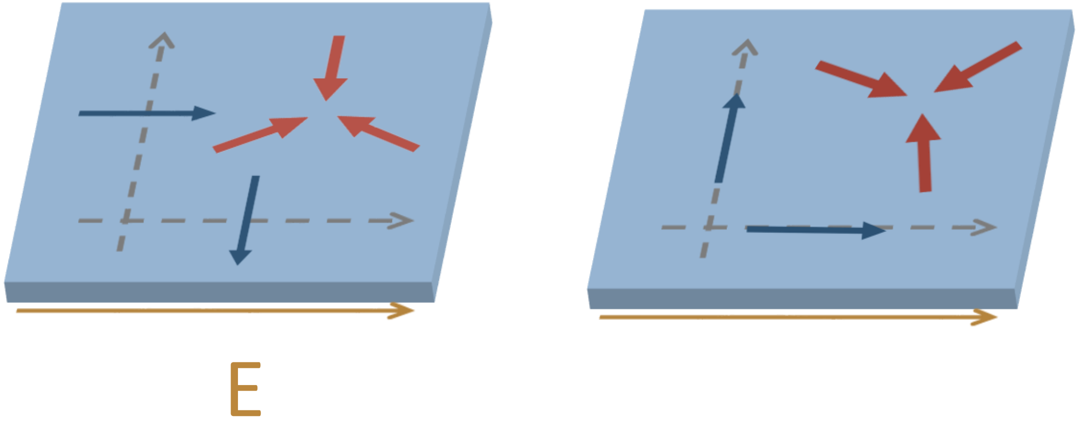
$$\sigma^z \quad \begin{pmatrix} 0 & -\sigma & 0 \\ \sigma & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Both magnetic and conventional spin Hall effect can have the out-of-plane spin-polarization in the triangular antiferromagnets

Symmetry of the spin Hall effect

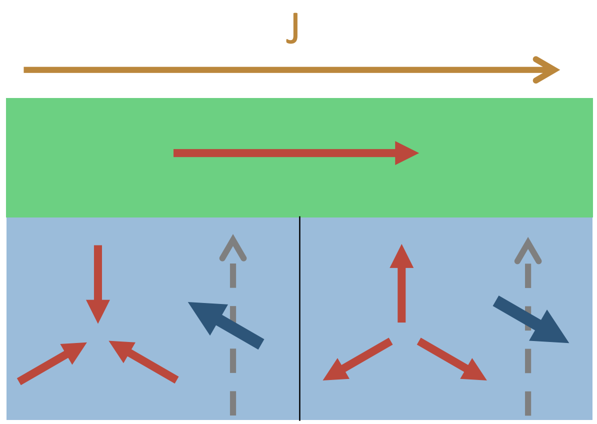
The symmetry of the (magnetic) SHE can be controlled by manipulating the magnetic order

For odd spin currents in a collinear magnetic system without SOC the spin-polarization and the direction spin current flow lies in the plane of the magnetic moments

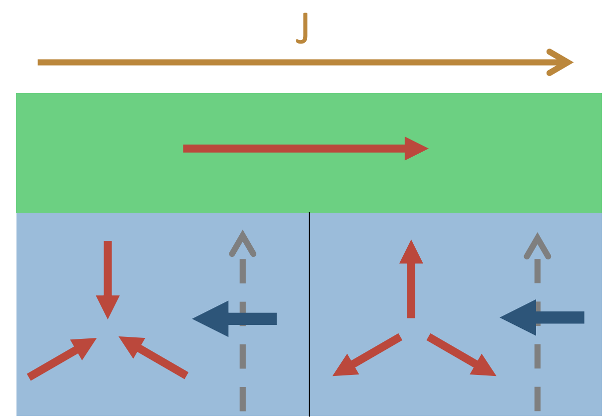


Transverse spin currents

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



odd



even

Sensitive to the antiferromagnetic order and presence of domains

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

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

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

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

- Consequences beyond non-collinear AFMs
  - Spin-polarized current not limited to ferromagnets
  - 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 Zhan et al., arxiv:1704.03917