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

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Fyzikální ústav
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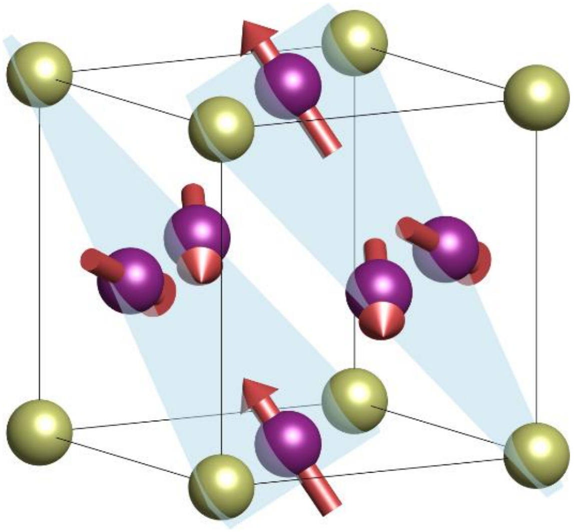
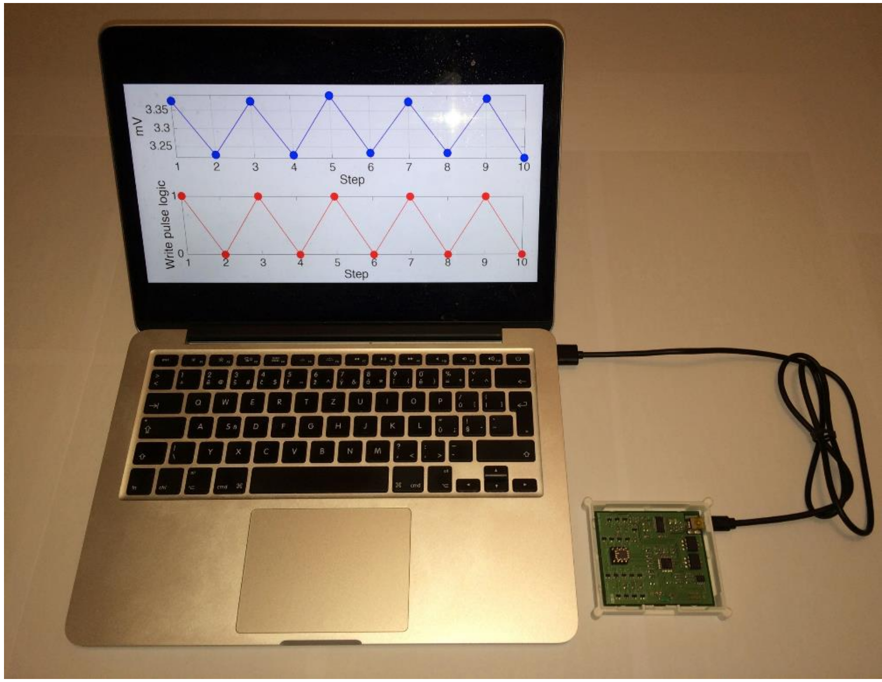


Antiferromagnetic spintronics

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…



Electrical control and detection of the antiferromagnetic order has been demonstrated

Wadley et al., Science 351, 587–590 (2016)
Bodnar et al., arXiv:1706.02482
Meinert et al., arXiv:1706.06983

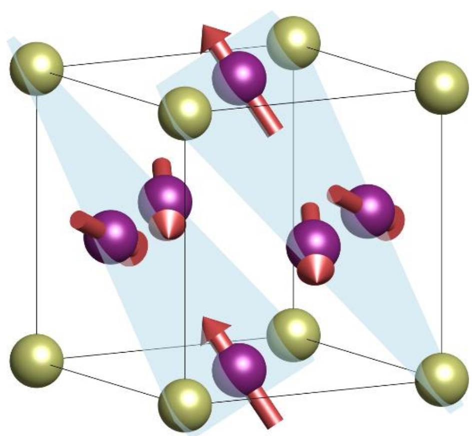
All-electrical antiferromagnetic memory functionality

Non-collinear antiferromagnets

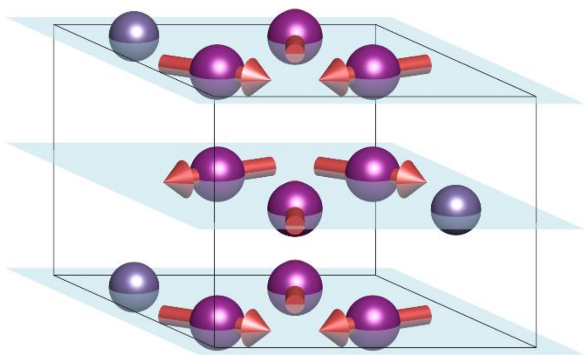
Non-collinear order is common in antiferromagnets

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

Triangular antiferromagnets Mn_3X



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

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

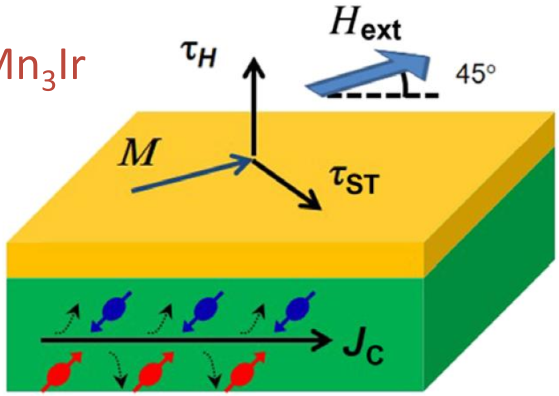
Nayak et al. Sci. Adv. 2016;2:e1501870 *Naktsuji et al. Nature 527, 212 (2015)*

- 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)



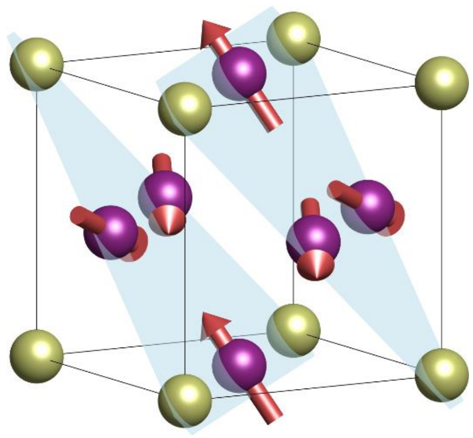
- Cubic and hexagonal compounds have very different sensitivities to magnetic fields

Field which can orient the domains: $Mn_3Ir \sim 200$ T

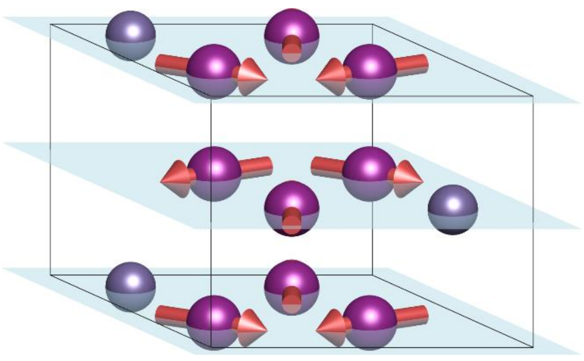
Mn_3Sn: 0.03 T

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

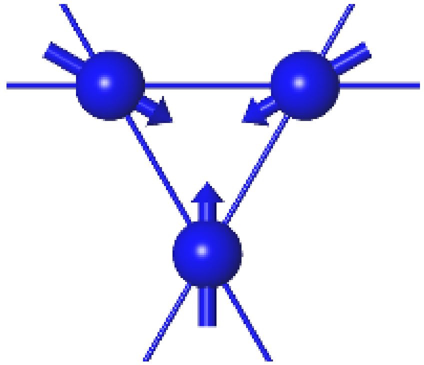
Anisotropy

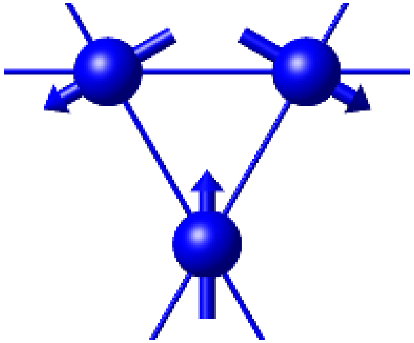


Mn_3Ir



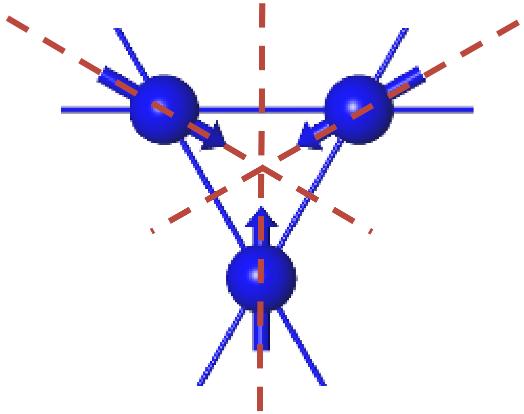
Mn_3Sn

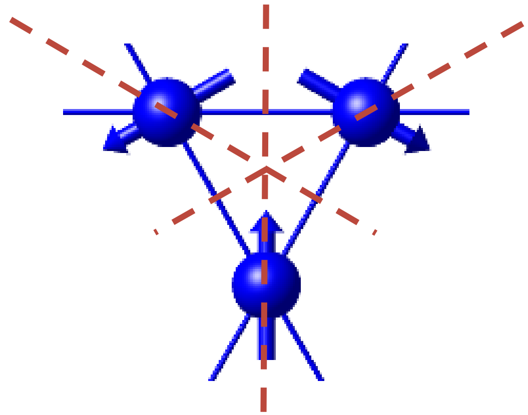




Inverted structure

Anisotropy





The inverted structure is stabilized by Dzyaloshinksi-Moria interaction

Only present in the hexagonal compounds

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

Second and fourth order anisotropy cancel for the inverted structure

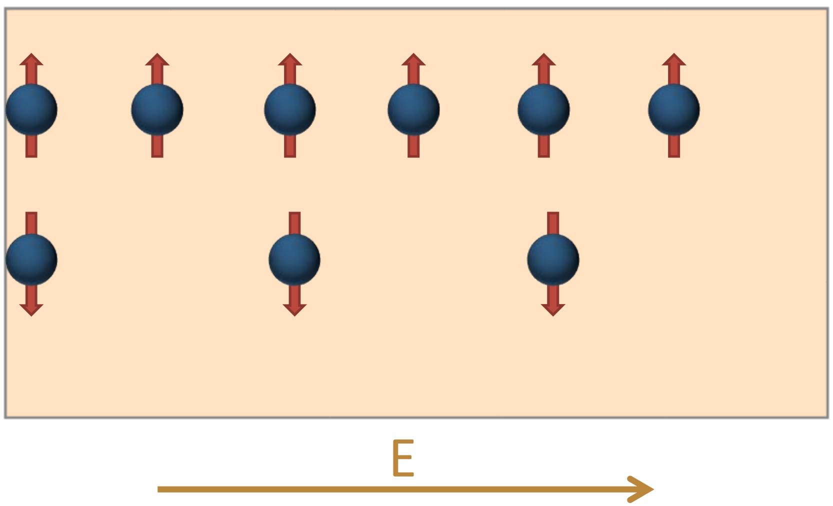
$$H_{sf} \sim \sqrt{H_E H_A}$$

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

Tomiyoshi, J. Phys. Soc. Japan, 1981

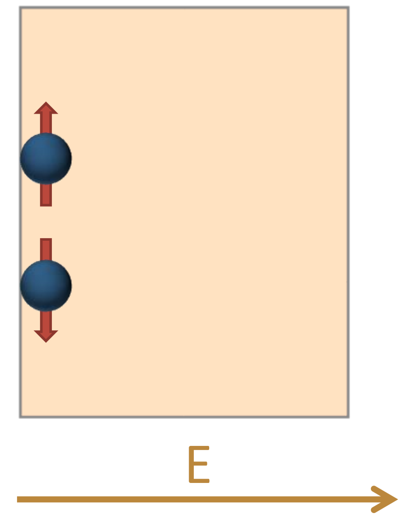
Spin currents

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

Definition of spin current

But it's a well defined physical quantity!

Alternative definitions:

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

$$\hat{\mathcal{J}}_s = \frac{d(\hat{\mathbf{r}}\hat{s}_z)}{dt}$$

Satisfies continuity equation

Only for systems with inversion symmetry

- *An et al., Scientific Reports 2, 388 (2012)*

Use instead a current of total angular momentum

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

Linear response

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

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

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

These two parts have precisely opposite transformation under time-reversal

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

Conductivity: $\hat{A} = -e\hat{\mathbf{v}}$

χ^I Even - ordinary conductivity

χ^{II} Odd - Anomalous Hall effect

Spin-orbit torque: $\hat{A} = \hat{\mathbf{T}}$

χ^I odd- Field-like torque

χ^{II} Even – Antidamping-like torque

Linear response

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

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

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

Spin current: $\hat{A} = \frac{1}{2}\{\hat{\mathbf{s}}, \hat{\mathbf{v}}\}$

χ^I Odd – In ferromagnets, it is a spin-polarized current

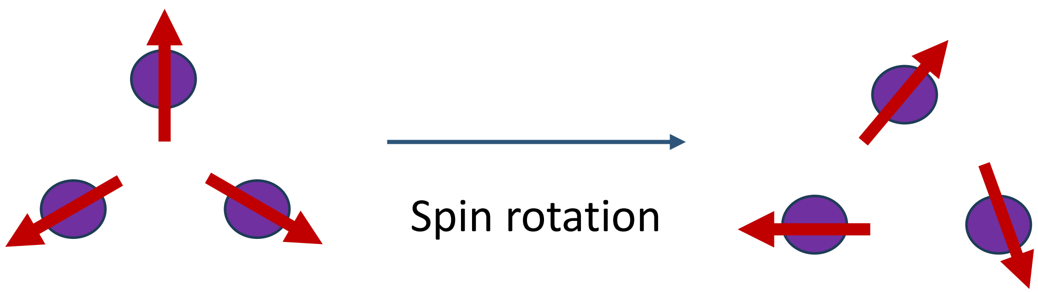
χ^{II} Even - Spin Hall effect

In FM without SOC, spin is a good quantum number $\chi^I = \frac{\hbar}{2e}(\sigma^\uparrow - \sigma^\downarrow)$

Symmetry without spin-orbit coupling

SHE exists in the non-collinear antiferromagnets even without SOC

How to understand the symmetry without SOC?



Without the SOC the rotated state is physically equivalent

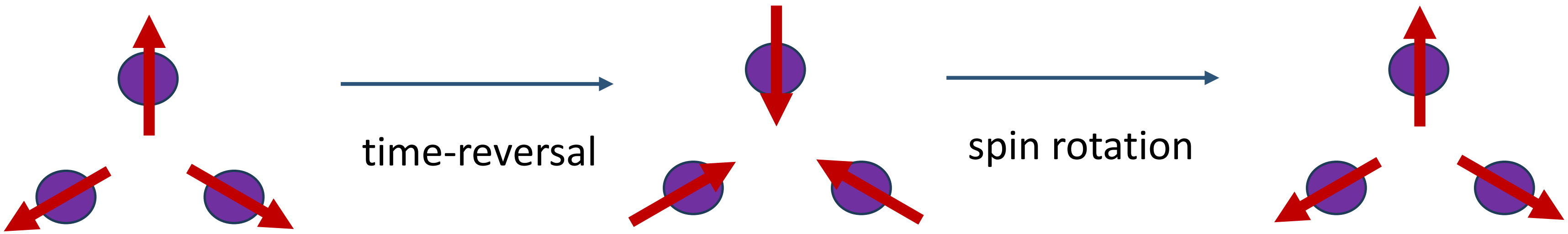
$$H(\mathbf{M}_1, \mathbf{M}_2, \dots) = t \sum_{<ij>\alpha} c^\dagger_{i\alpha} c_{j_\alpha} - J \sum_{i\alpha\beta} (\boldsymbol{\sigma} \cdot \boldsymbol{M}_i)_{\alpha\beta} c^\dagger_{i\alpha} c_{i\beta}$$

$$SH(\mathbf{M}_1, \mathbf{M}_2, \dots)S^{-1} = H(S\mathbf{M}_1, S\mathbf{M}_2, \dots)$$

S is generally not a symmetry of the Hamiltonian

Spin Hall effect in non-collinear antiferromagnets

Symmetry operation + spin rotation which leave the system invariant are symmetries of the system



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)

General symmetry rules

Anomalous Hall effect

Nonmagnetic system with or without SOC: T No AHE

Coplanar magnetic system without SOC: TS No AHE

Coplanar magnetic system with SOC AHE allowed

Sometimes referred to as the Topological Hall effect

Collinear Antiferromagnet with SOC: PT or T+translation No AHE

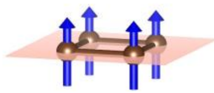
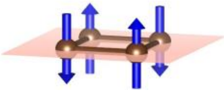
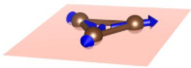
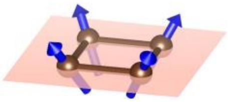
Spin Hall Effect

The TS symmetry does not prohibit the spin-Hall effect

$$\sigma^x \to -\sigma^x \qquad \sigma^y \to -\sigma^y \qquad \sigma^z \to \sigma^z$$

Yang Zhang et al., arxiv:1704.03917

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

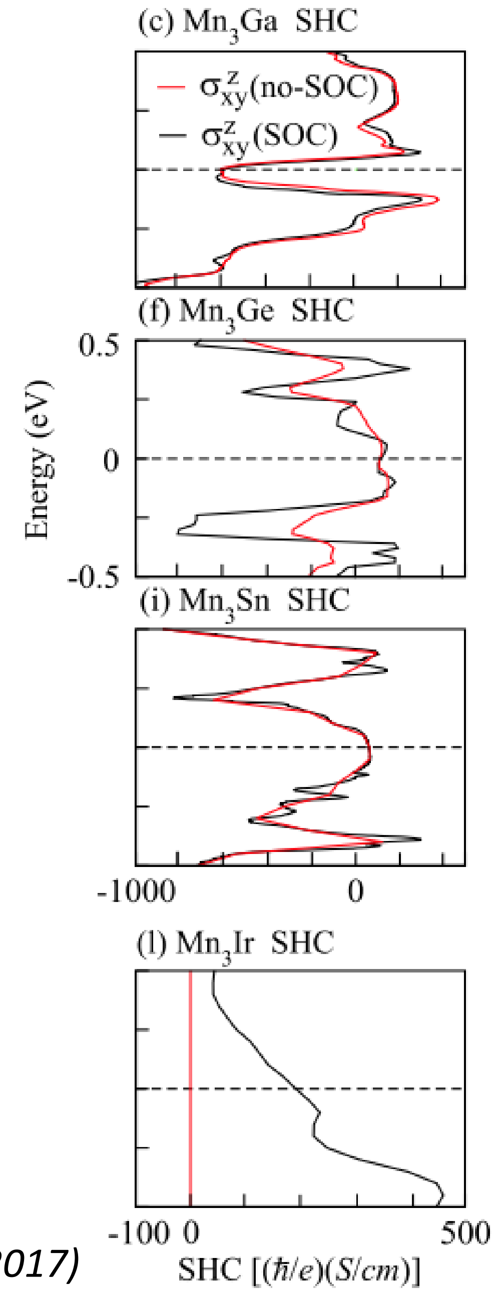
Non-collinear magnetic order plays the same role as spin-orbit coupling

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

Yang Zhang et al., arxiv:1704.03917

SHE calculations

	no SOC	SOC
Mn_3Sn	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma^x_{yz} \\ 0 & \sigma^x_{zy} & 0 \end{pmatrix}$
	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & \sigma^y_{xz} \\ 0 & 0 & 0 \\ \sigma^y_{zx} & 0 & 0 \end{pmatrix}$
	$\begin{pmatrix} 0 & \sigma^z_{xy} & 0 \\ -\sigma^z_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \sigma^z_{xy} & 0 \\ \sigma^z_{yx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
Mn_3Ir	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -\sigma^x_{xy} & \sigma^x_{xy} \\ \sigma^x_{yx} & -\sigma^x_{yy} & -\sigma^x_{yz} \\ -\sigma^x_{yx} & \sigma^x_{yz} & \sigma^x_{yy} \end{pmatrix}$
	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} \sigma^x_{yy} & -\sigma^x_{yx} & \sigma^x_{yz} \\ \sigma^x_{xy} & 0 & -\sigma^x_{xy} \\ -\sigma^x_{yz} & \sigma^x_{yx} & -\sigma^x_{yy} \end{pmatrix}$
	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} -\sigma^x_{yy} & -\sigma^x_{yz} & \sigma^x_{yx} \\ \sigma^x_{yz} & \sigma^x_{yy} & -\sigma^x_{yx} \\ -\sigma^x_{xy} & \sigma^x_{xy} & 0 \end{pmatrix}$



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

Spin currents in ferromagnets

Odd

Bcc Fe   M || x

$$\begin{array}{ll}
\sigma^x & \begin{pmatrix} \sigma_{xxx} & 0 & 0 \\ 0 & \sigma_{xyy} & 0 \\ 0 & 0 & \sigma_{xyy} \end{pmatrix} \\
\sigma^y & \begin{pmatrix} 0 & \sigma_{yxy} & 0 \\ \sigma_{yyx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\
\sigma^z & \begin{pmatrix} 0 & 0 & \sigma_{yxy} \\ 0 & 0 & 0 \\ \sigma_{yyx} & 0 & 0 \end{pmatrix}
\end{array}$$

Spin-polarized current

Magnetic spin Hall effect

Without spin-orbit coupling

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

Even - spin Hall effect

$$\begin{array}{ll}
\sigma^x & \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\sigma_{xzy} \\ 0 & \sigma_{xzy} & 0 \end{pmatrix} \\
\sigma^y & \begin{pmatrix} 0 & 0 & -\sigma_{zxy} \\ 0 & 0 & 0 \\ \sigma_{zyx} & 0 & 0 \end{pmatrix} \\
\sigma^z & \begin{pmatrix} 0 & \sigma_{zxy} & 0 \\ \sigma_{zyx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}
\end{array}$$

conductivity

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

Anomalous Hall effect

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma_{yz} \\ 0 & -\sigma_{yz} & 0 \end{pmatrix}$$

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

Zelezny et al., arXiv:1702.00295

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., arXiv:1702.00295

Calculations

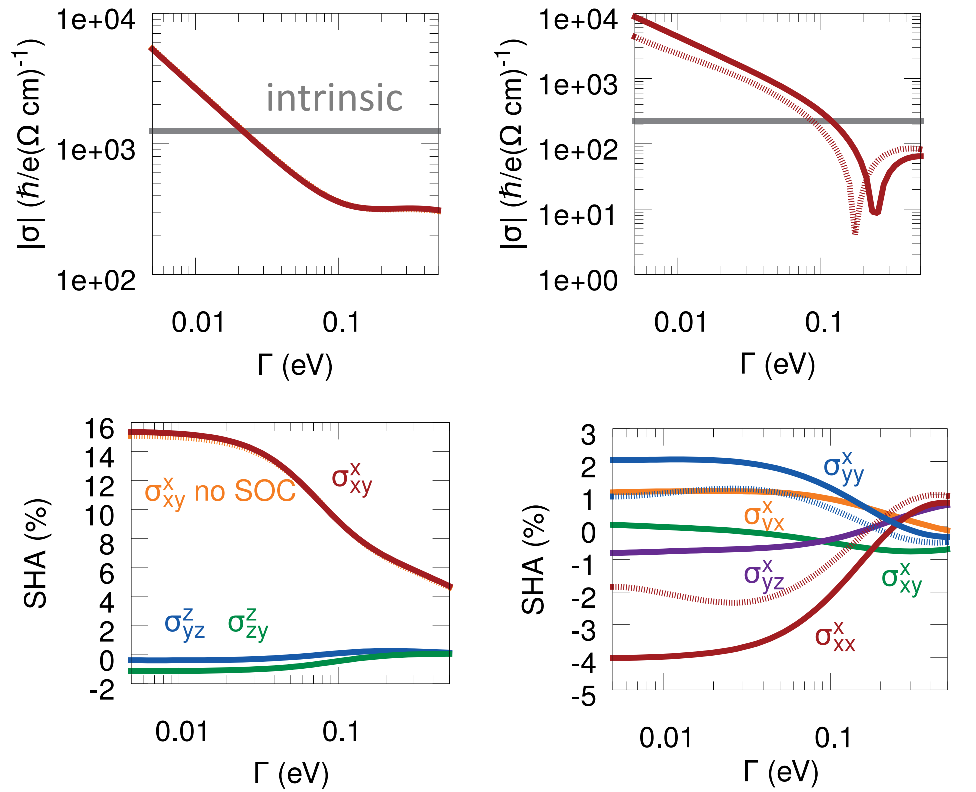
Constant Γ approximation

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

	$\boldsymbol{\alpha_{||}}$ **(%)**	$\boldsymbol{\alpha_{\perp}}$ **(%)**
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

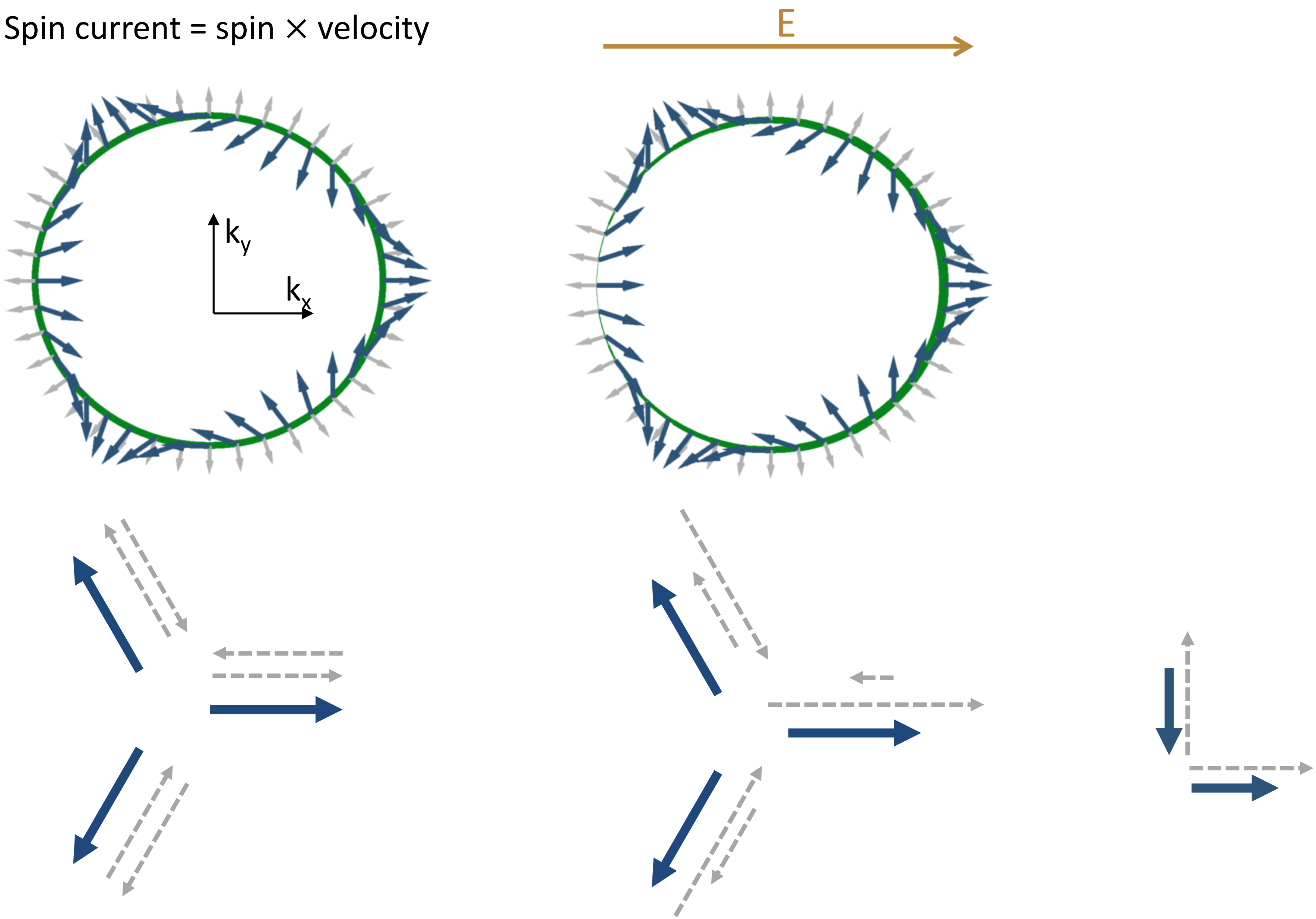
In BCC Fe $\boldsymbol{\alpha_{||}} \sim 18\%$

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

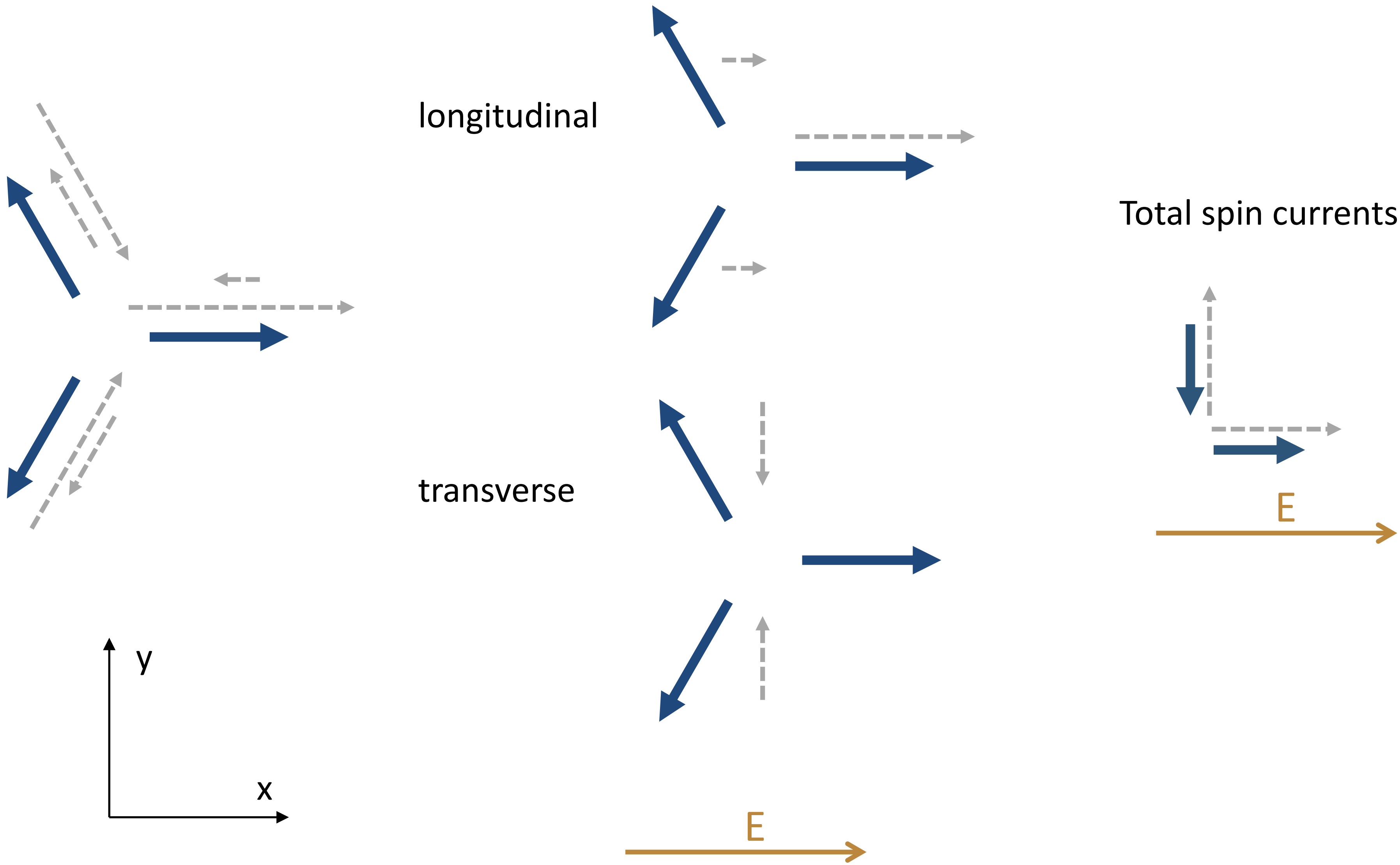
Zelezny et al., arXiv:1702.00295

Origin of the odd spin currents

Spin current = spin × velocity

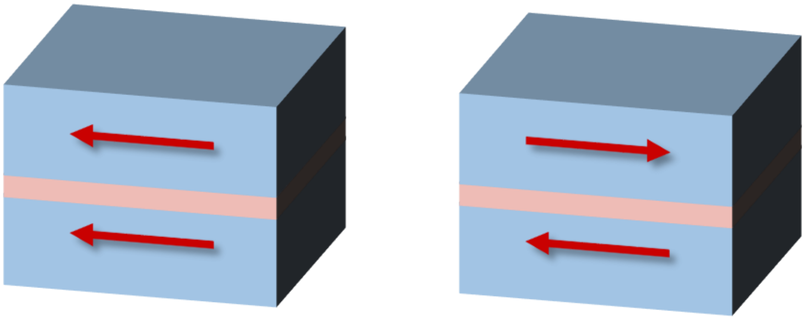


Origin of the odd spin currents



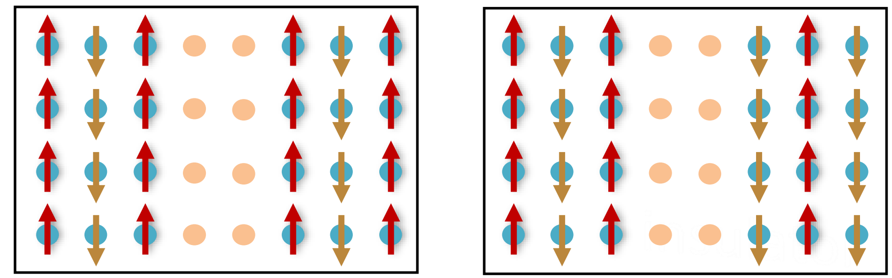
Two current model does not apply

Spin-polarized current



“1” “0”

FM junction



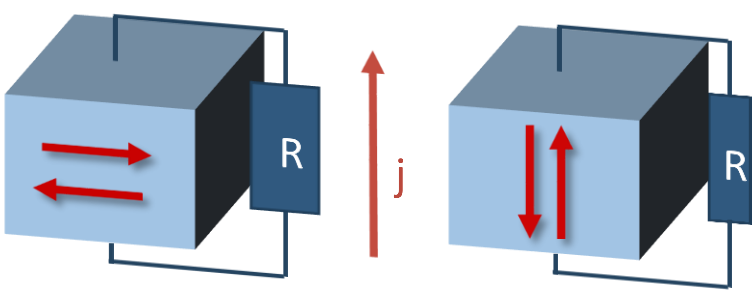
“1” “0”

AFM junction

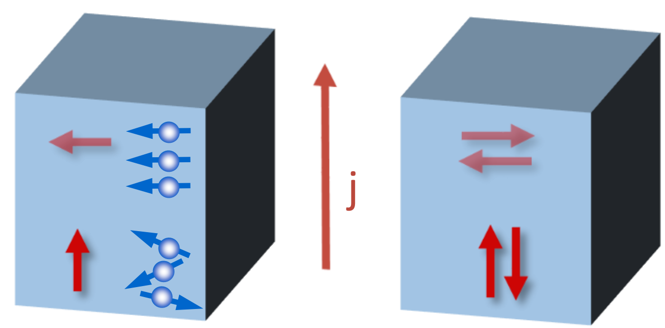
Theoretically proposed but strongly sensitive to disorder and never observed experimentally

Instead, relativistic effects are used

AMR



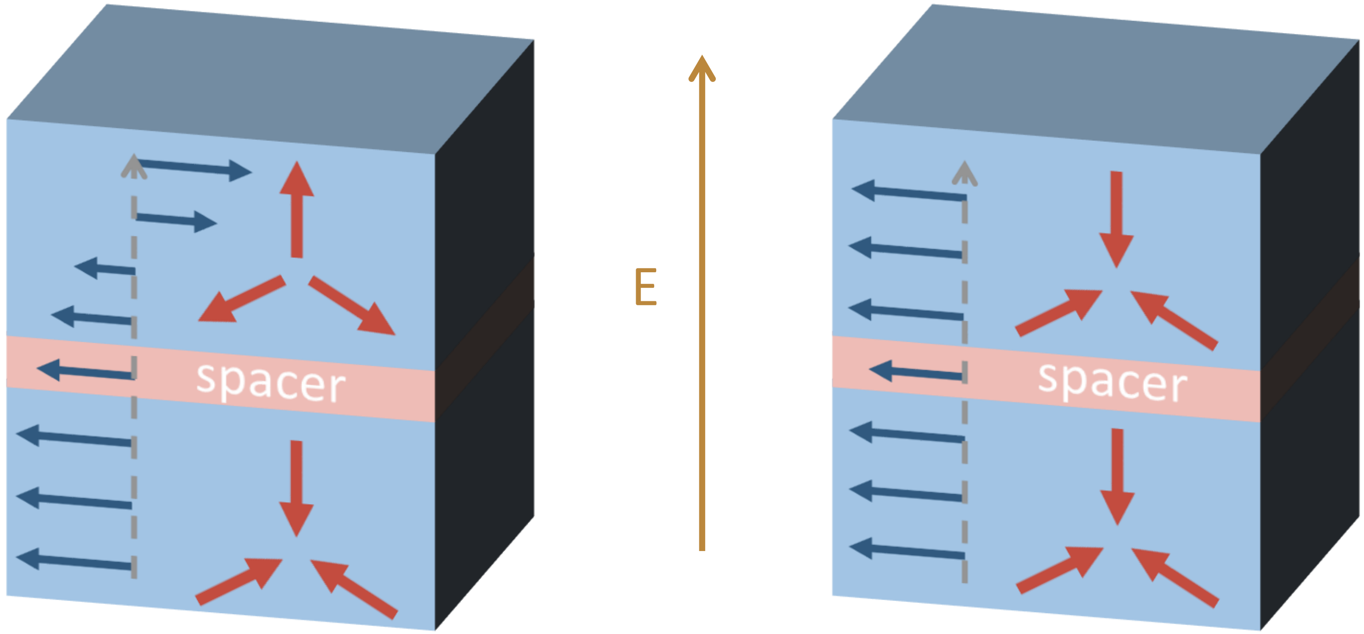
Edelstein spin-orbit torque



Spin-polarized current

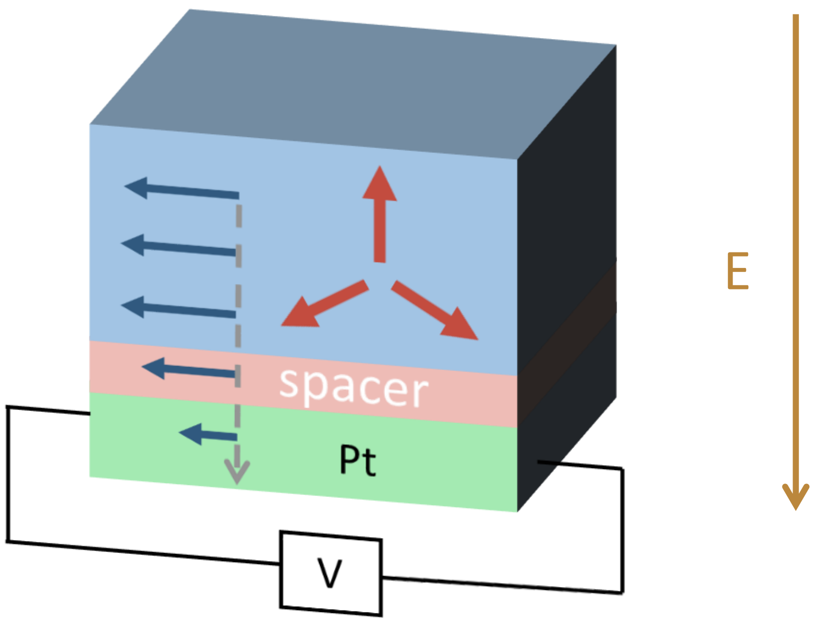
In non-collinear antiferromagnets, current is spin-polarized and thus same approach can be used as in ferromagnets

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



Spin-polarized current

Many other possibilities



Transverse spin currents

- The odd transverse spin currents are similar to the spin Hall effect, but have different origin and symmetry

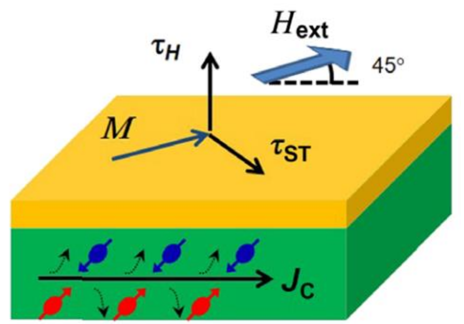
		no SOC	SOC
Mn3Sn	σ^x	$\begin{pmatrix} 0 & \sigma^x_{xy} & 0 \\ \sigma^x_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \sigma^x_{xy} & 0 \\ \sigma^x_{yx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
	σ^y	$\begin{pmatrix} -\sigma^x_{xy} & 0 & 0 \\ 0 & \sigma^x_{xy} & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} \sigma^y_{xx} & 0 & 0 \\ 0 & \sigma^y_{yy} & 0 \\ 0 & 0 & \sigma^y_{zz} \end{pmatrix}$
	σ^z	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma^z_{yz} \\ 0 & \sigma^z_{zy} & 0 \end{pmatrix}$
Mn3Ir	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	$\begin{pmatrix} -\frac{\sigma^x_{xx}}{2} & 0 & 0 \\ 0 & -\frac{\sigma^x_{xx}}{2} & 0 \\ 0 & 0 & \sigma^x_{xx} \end{pmatrix}$	$\begin{pmatrix} \sigma^x_{yy} & \sigma^x_{yz} & \sigma^x_{yx} \\ \sigma^x_{yz} & \sigma^x_{yy} & \sigma^x_{yx} \\ \sigma^x_{xy} & \sigma^x_{xy} & \sigma^x_{xx} \end{pmatrix}$

Magnetic spin Hall effect

no SOC	SOC
$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma^x_{yz} \\ 0 & \sigma^x_{zy} & 0 \end{pmatrix}$
$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & \sigma^y_{xz} \\ 0 & 0 & 0 \\ \sigma^y_{zx} & 0 & 0 \end{pmatrix}$
$\begin{pmatrix} 0 & \sigma^z_{xy} & 0 \\ -\sigma^z_{xy} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & \sigma^z_{xy} & 0 \\ \sigma^z_{yx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -\sigma^x_{xy} & \sigma^x_{xy} \\ \sigma^x_{yx} & -\sigma^x_{yy} & -\sigma^x_{yz} \\ -\sigma^x_{yx} & \sigma^x_{yz} & \sigma^x_{yy} \end{pmatrix}$
$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} \sigma^x_{yy} & -\sigma^x_{yx} & \sigma^x_{yz} \\ \sigma^x_{xy} & 0 & -\sigma^x_{xy} \\ -\sigma^x_{yz} & \sigma^x_{yx} & -\sigma^x_{yy} \end{pmatrix}$
$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} -\sigma^x_{yy} & -\sigma^x_{yz} & \sigma^x_{yx} \\ \sigma^x_{yz} & \sigma^x_{yy} & -\sigma^x_{yx} \\ -\sigma^x_{xy} & \sigma^x_{xy} & 0 \end{pmatrix}$

Spin Hall effect

Symmetry of the spin Hall effect



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

SHE normally has in-plane spin-polarization

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

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

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

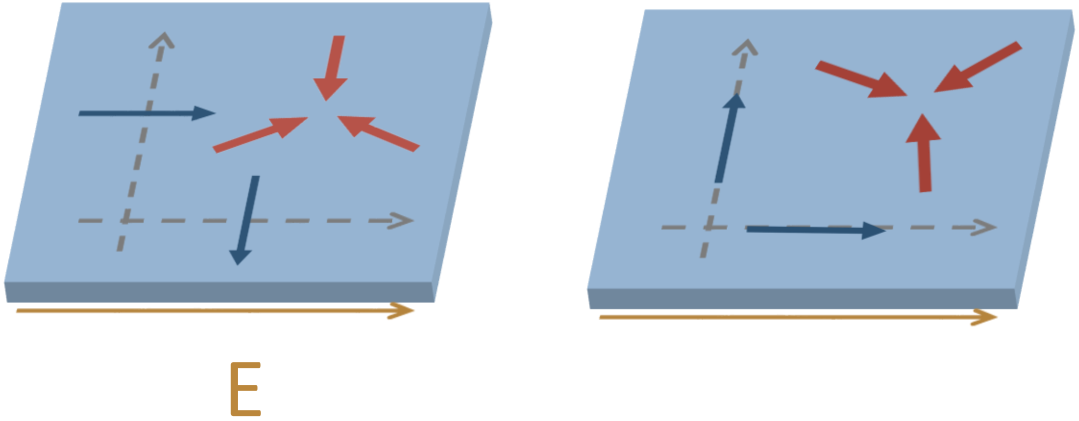
		no SOC	SOC
Mn_3Sn	σ^x	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \sigma^x_{yz} \\ 0 & \sigma^x_{zy} & 0 \end{pmatrix}$
	σ^y	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & \sigma^y_{xz} \\ 0 &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

In Mn_3Ir the SHE has out-of-plane spin-polarization

Symmetry of the spin Hall effect

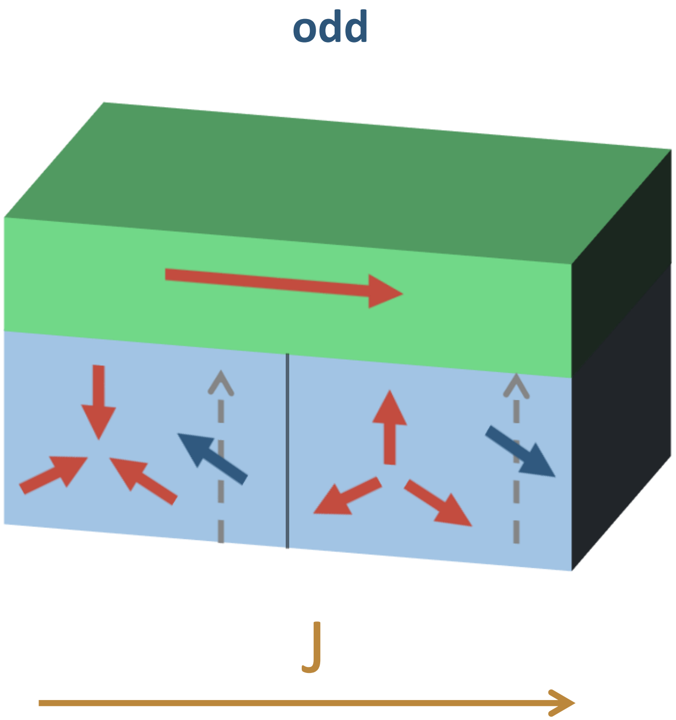
The symmetry of the (magnetic) SHE can be controlled by manipulating the magnetic order

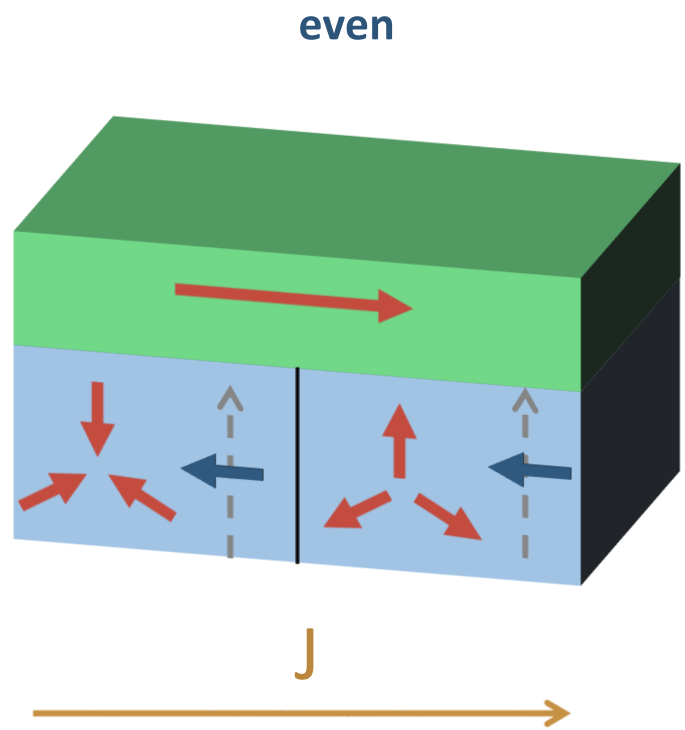
For odd spin currents in a collinear magnetic system without SOC the spin-polarization and the direction spin current flow lies in the plane of the magnetic moments



Transverse spin currents

The odd currents can also contribute to the spin-orbit torque





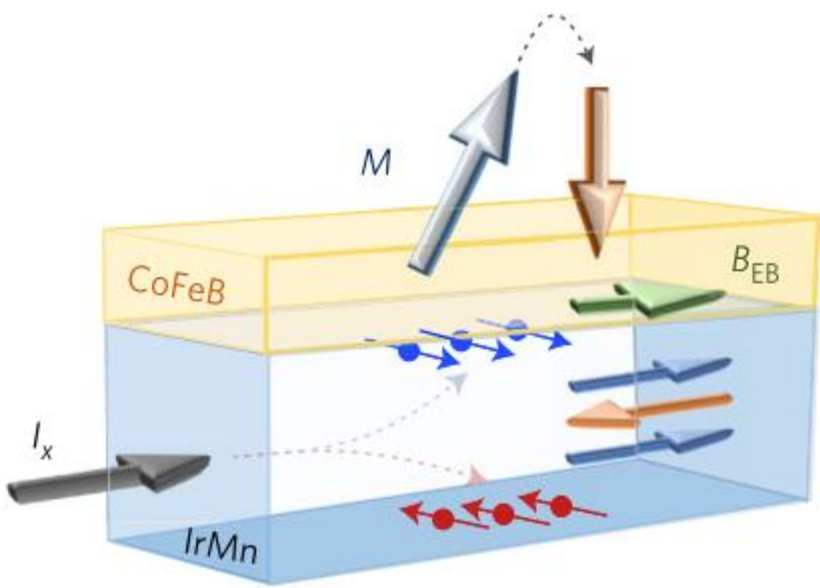
Sensitive to the antiferromagnetic order and presence of domains

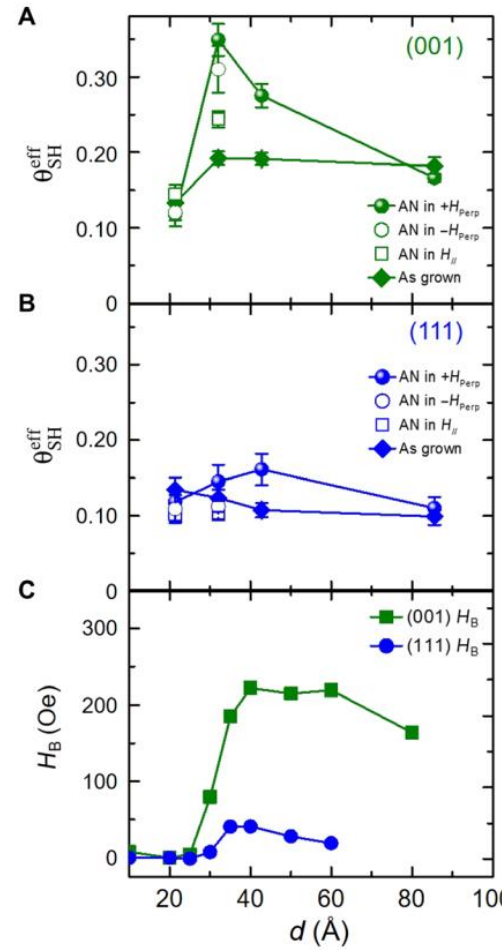
Thsitoyan et al., PRB 92, 214406 (2016)

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

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

Spin-orbit torque in AFM/FM devices





Strong increase of the torque in the presence of exchange coupling between the FM and AFM layers

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)

Symmetry code

- Symmetry of various linear response properties

$$\delta \mathbf{A} = \chi \mathbf{E}$$

  - SHE is also implemented
  - Projected quantities (useful for spin-orbit torque)
  - Expansion in magnetic moment direction

$$\chi(\mathbf{M}) = \chi^0 + \chi_i M_i + \chi_i j M_i M_j + \dots$$

- Symmetry of magnetic interactions

$$H = H_{ij} M_i M_j + H_{ijkl} M_i M_j M_k M_l + \dots$$

https://bitbucket.org/zeleznyj/linear-response-symmetry

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 Mn_3X compounds
  - 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., arXiv:1702.00295

Yang Zhan et al., arxiv:1704.03917