Spin-Orbit Torque in Locally and Globally Non-Centrosymmetric Antiferromagnets

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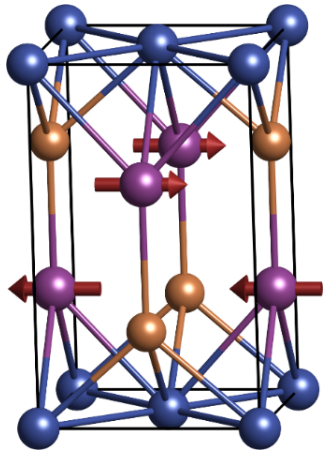
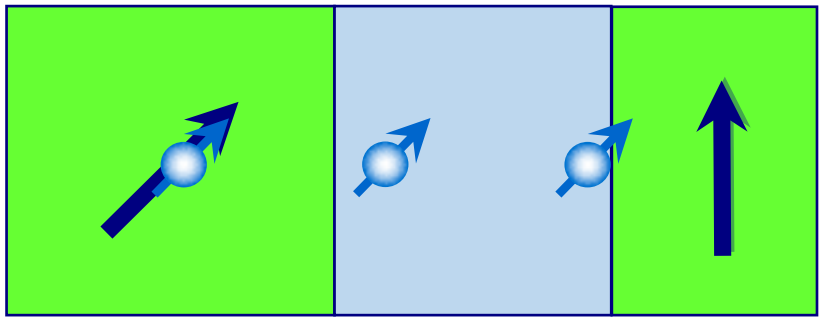
Why antiferromagnets?

Magnetic order in antiferromagnets is hard to detect and manipulate



Spintronics opens new ways for manipulating and detecting magnetic order



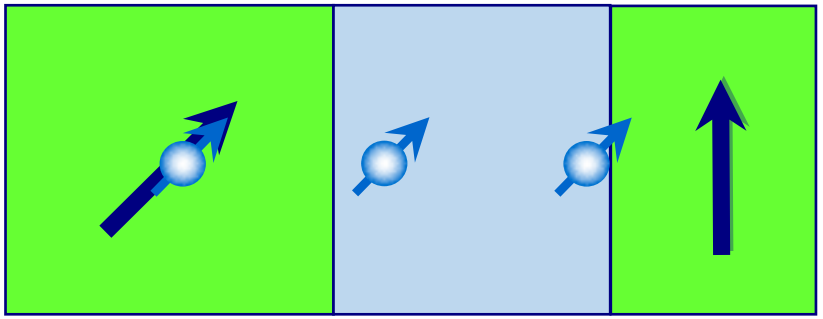
Berger PRB '96, Slonczewski JMMM '96

Advantages of antiferromagnets:

- No stray fields, insensitive to magnetic fields
- Ultrafast dynamics – switching possible on ps timescale
- Many antiferromagnets materials exist: plenty of antiferromagnetic semiconductors

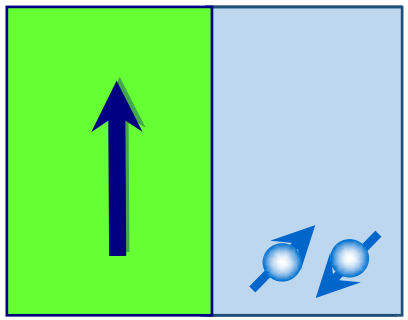
How to manipulate FM

Spin-transfer torque



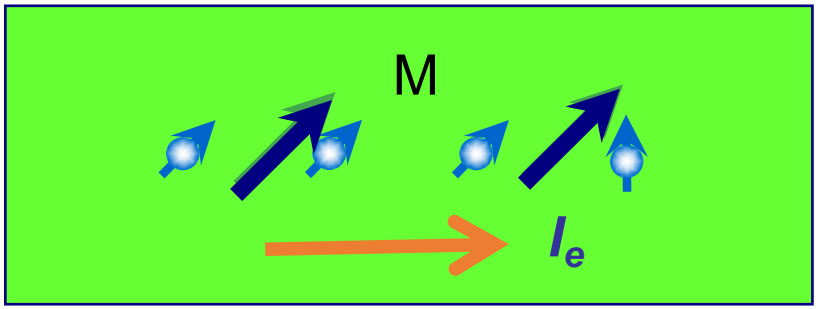
Berger PRB '96, Slonczewski JMMM '96

Spin-orbit torque



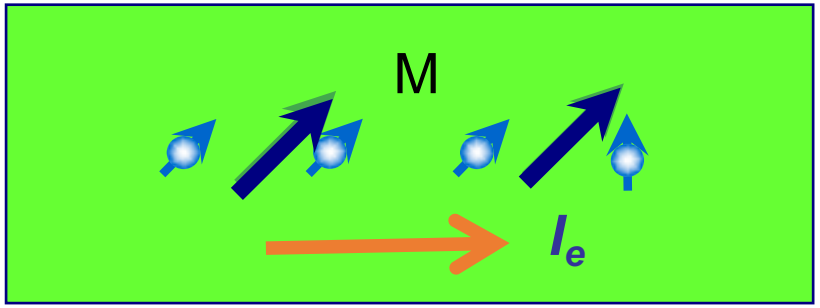
Liu, Ralph, Buhrman,et al. 2012
Miron et al., Nature '11

Due to spin-Hall effect

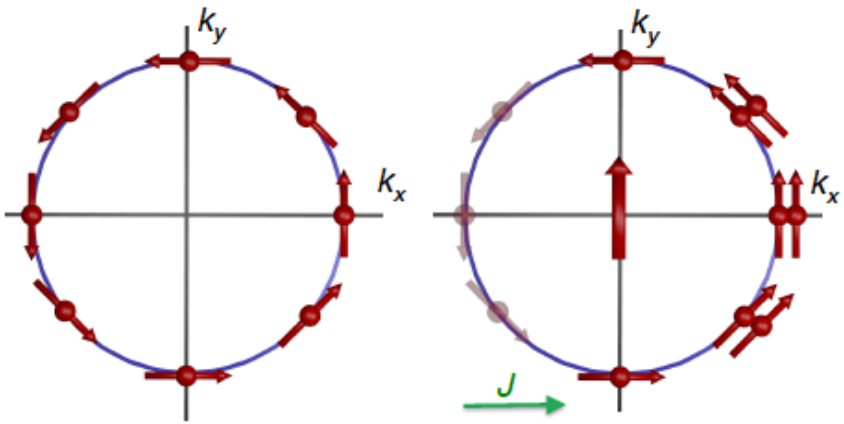


Bulk spin-orbit torque

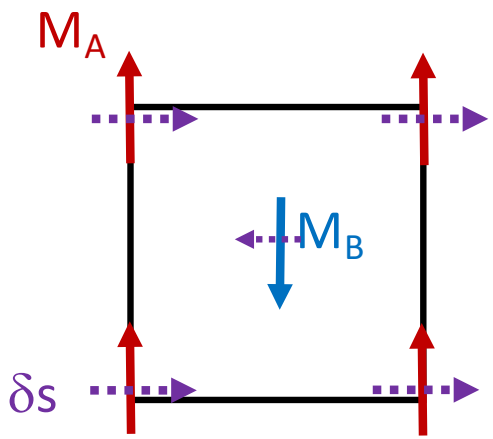
Origin of the spin-orbit torque



Spin-orbit torque is due to the inverse spin-galvanic (Edelstein) effect

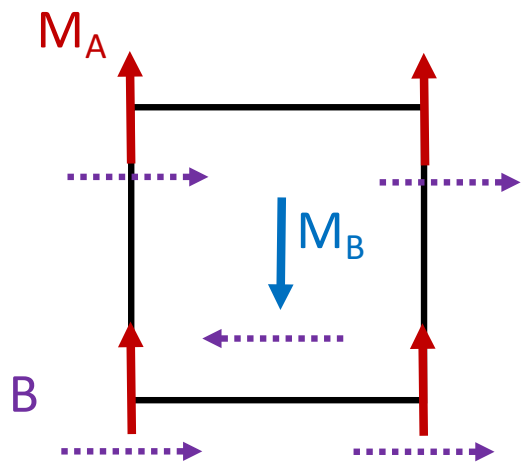


In antiferromagnets:



Néel order fields

A staggered field is necessary for efficient manipulation of collinear antiferromagnets

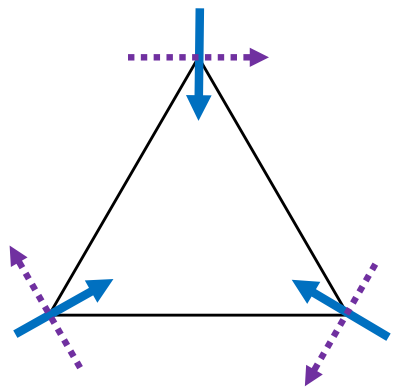


Uniform field: $B_{\mathrm{crit}} \sim \sqrt{B_{\mathrm{ani}} B_{\mathrm{ex}}}$

Staggered field: $B_{\mathrm{crit}} \sim B_{\mathrm{ani}}$

Typically: $B_{\mathrm{ex}} \gg B_{\mathrm{ani}}$

More generally, a magnetic field with same order as the magnetic order is needed: a **Néel order field**



Magnetic dynamics in antiferromagnets

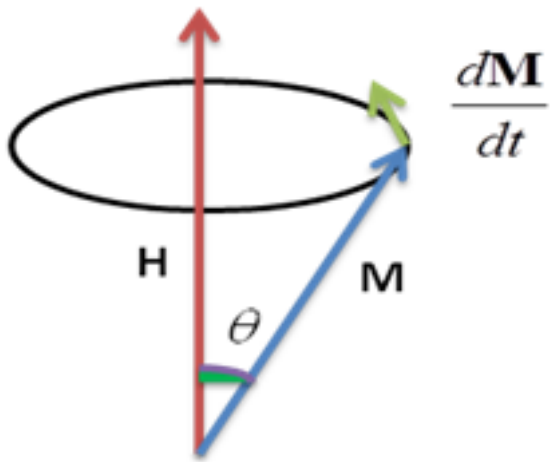
FM:

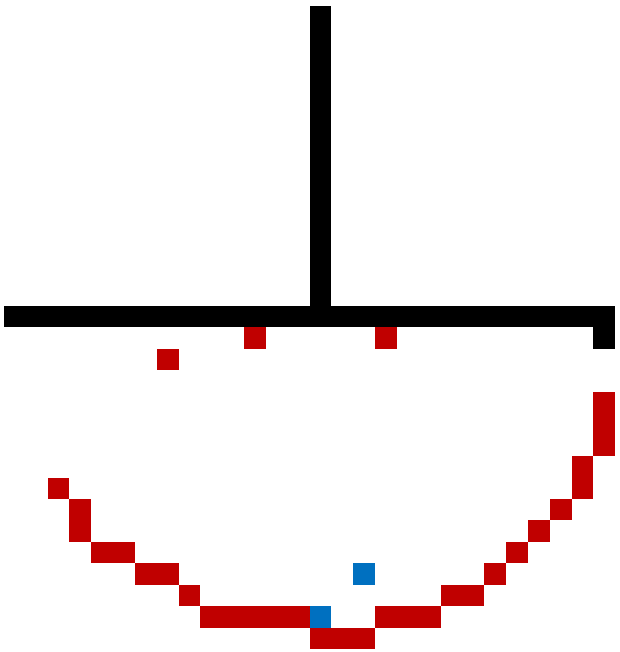
$$\frac{d\mathbf{M}}{dt} = \gamma \mathbf{M} \times \left(\mathbf{B}_{\mathrm{ani}}(\mathbf{M}) + \mathbf{B}\right).$$

AFM:

$$\frac{d^2\mathbf{L}}{dt^2} = -\frac{1}{L^2}\left[\mathbf{L}\left(\frac{d\mathbf{L}}{dt}\right)^2\right] - \gamma^2 J\left[\mathbf{L} \times \left(\mathbf{L} \times \left(\mathbf{B}_{\mathrm{ani}}(\mathbf{L}) + \mathbf{B}_{\mathrm{S}}\right)\right)\right].$$

In the limit of small anisotropy the AFM equation becomes the equation of a simple pendulum.





How to evaluate the spin-orbit torque?

$$\mathbf{T}_a = \mathbf{M}_a \times \mathbf{B}_a^{\text{eff}}$$

sublattice

$$\mathbf{B}_a^{\text{eff}} = -\frac{1}{M_a}\frac{\partial E(\mathbf{M}_1, \mathbf{M}_2, \dots)}{\partial \hat{\mathbf{M}}_a}$$

Simplest model we can consider:

$$H = J\mathbf{s}_a \cdot \hat{\mathbf{M}}_a$$

Exchange constant

Direction of the equilibrium magnetic moment

Spin-operator of conduction electrons

Energy contribution due to current-induced spin-polarization is:

$$E = J\delta\mathbf{s}_a \cdot \hat{\mathbf{M}}_a \qquad \Rightarrow \qquad \mathbf{B}_a^{\text{eff}} = -J\frac{\delta\mathbf{s}_a}{M_a}$$

Linear response theory

To actually calculate the current-induced spin-polarization we use the linear response theory

$$H = H_0 + e\mathbf{E}\hat{\mathbf{r}}$$

perturbation

We assume that the response is linear in the applied field

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

We calculate the response of spin or directly the torque

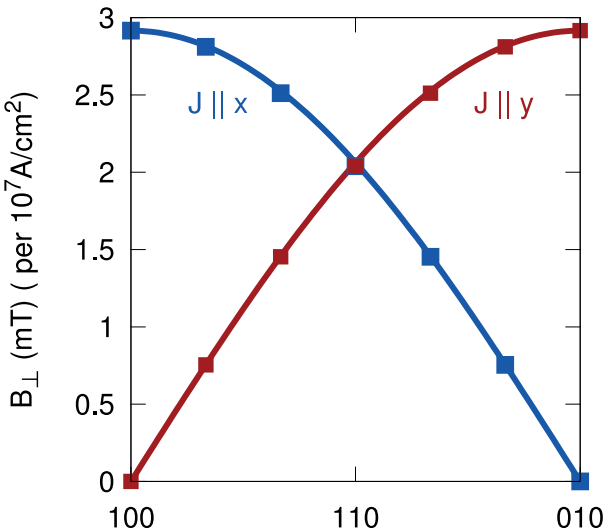
Disorder:

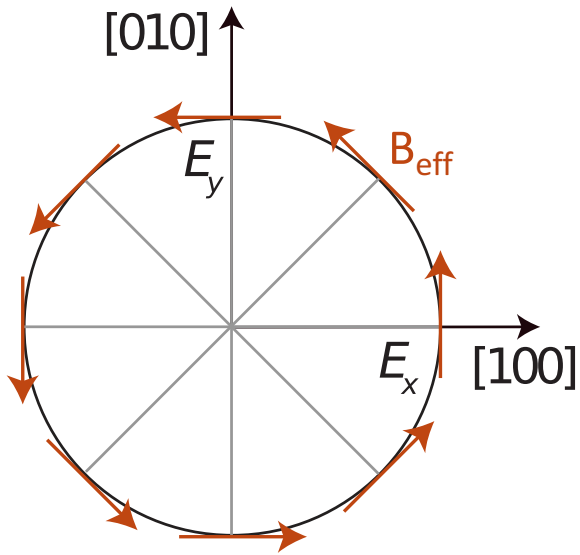
Constant Gamma broadening

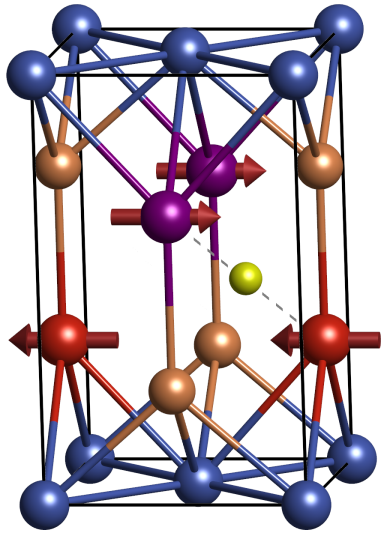
$$G^{\pm}(E) = \frac{1}{E - \hat{H} \pm i\epsilon} \longrightarrow G^{\pm}(E) = \frac{1}{E - \hat{H} \pm i\Gamma}$$

CuMnAs calculations

•Electronic structure description using DFT

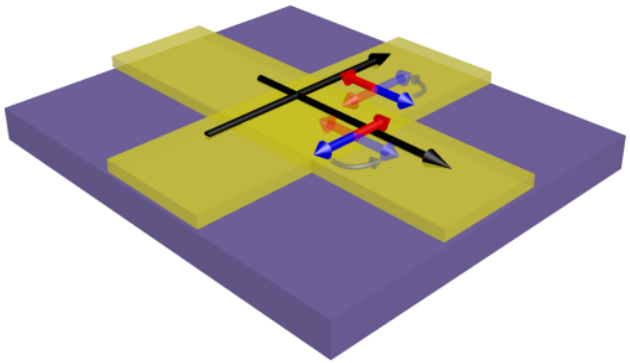






Field-like torque: $\mathbf{B}_{\text{eff}} \approx \mathbf{z} \times \mathbf{E}$

B ~ 3 mT per 10^7 Acm^{-2}



Magnitude comparable to SOT in ferromagnets!

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

Symmetry

We the effective field into **even** and **odd** parts under time reversal

$$\mathbf{B}_a^{\text{even}}(\mathbf{L}) = \frac{\mathbf{B}_a(\mathbf{L}) + \mathbf{B}_a(-\mathbf{L})}{2}$$

Typically field-like

$$\mathbf{B}_a^{\text{odd}}(\mathbf{L}) = \frac{\mathbf{B}_a(\mathbf{L}) - \mathbf{B}_a(-\mathbf{L})}{2}$$

Often antidamping-like

$$\mathbf{L} = \mathbf{M}_A - \mathbf{M}_B$$

$$\mathbf{B}_a = \chi_a \mathbf{E}$$

$$\chi_{a,ij} - \frac{\hbar e V}{\Gamma} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \sum_n \delta(E_{n\mathbf{k}} - E_F) \langle n\mathbf{k}| \hat{A}_i |n\mathbf{k}\rangle \langle n\mathbf{k}| \hat{v}_j |n\mathbf{k}\rangle$$

$$\chi_{a,ij} = i\hbar e \sum_{\mathbf{k}} \sum_{n \neq m} \frac{f(E_{n\mathbf{k}}) - f(E_{m\mathbf{k}})}{(E_{n\mathbf{k}} - E_{m\mathbf{k}})^2} \langle n\mathbf{k}| \hat{A}_i |m\mathbf{k}\rangle \langle m\mathbf{k}| \hat{v}_j |n\mathbf{k}\rangle$$

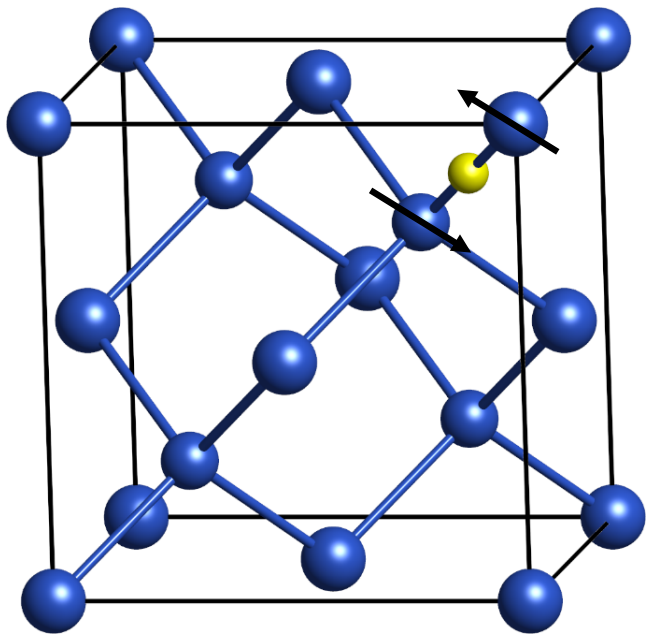
When will the spin-orbit torque exist?

In FMs: $\delta \mathbf{s} = \chi \mathbf{E}$ $\xrightarrow{\text{Inversion}}$ $\delta \mathbf{s} = \chi(-\mathbf{E})$

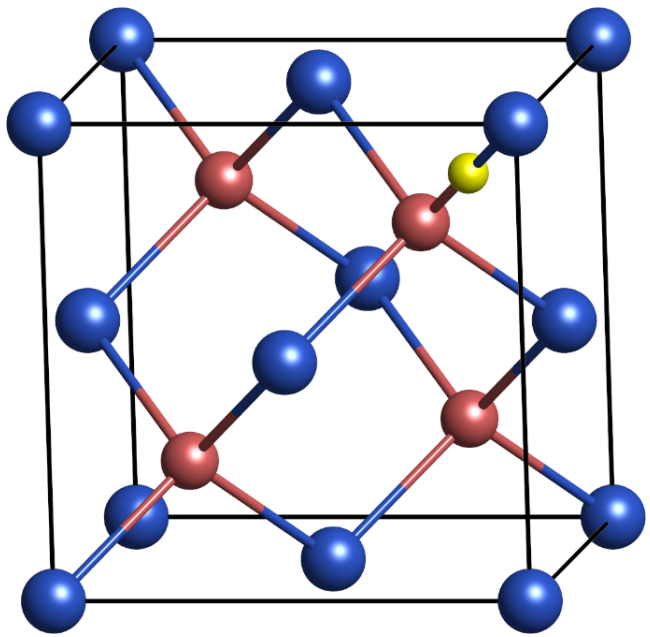
In AFMs: $\delta \mathbf{s}_a = \chi \mathbf{E}$ $\longrightarrow$ $\delta \mathbf{s}_{a'} = \chi(-\mathbf{E})$

Local inversion symmetry breaking is necessary

There must be no inversion center in the atomic site

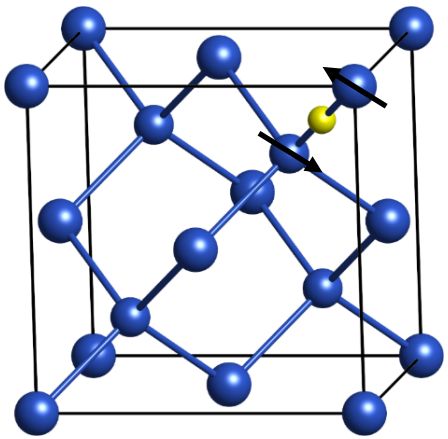


Si

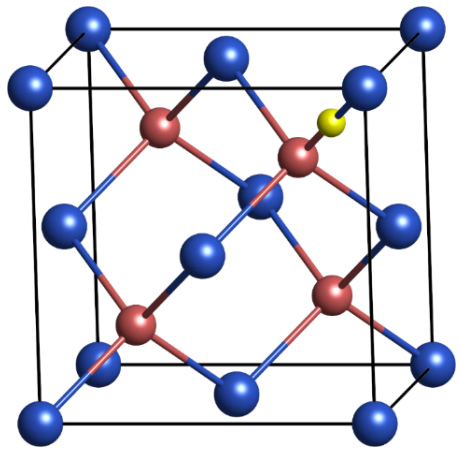


GaAs

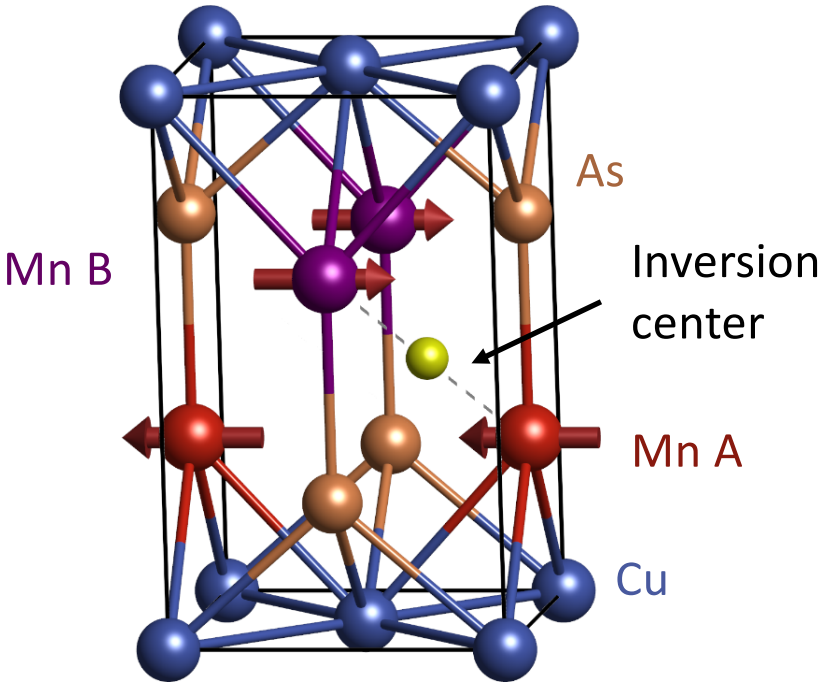
When will the spin-orbit torque exist?



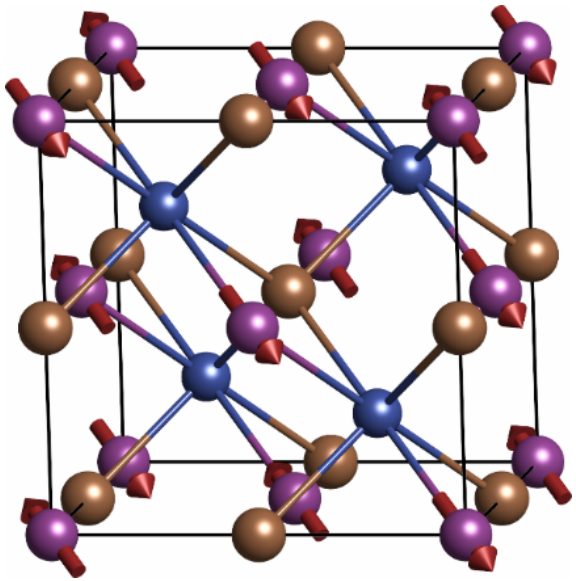
Si



GaAs



CuMnAs

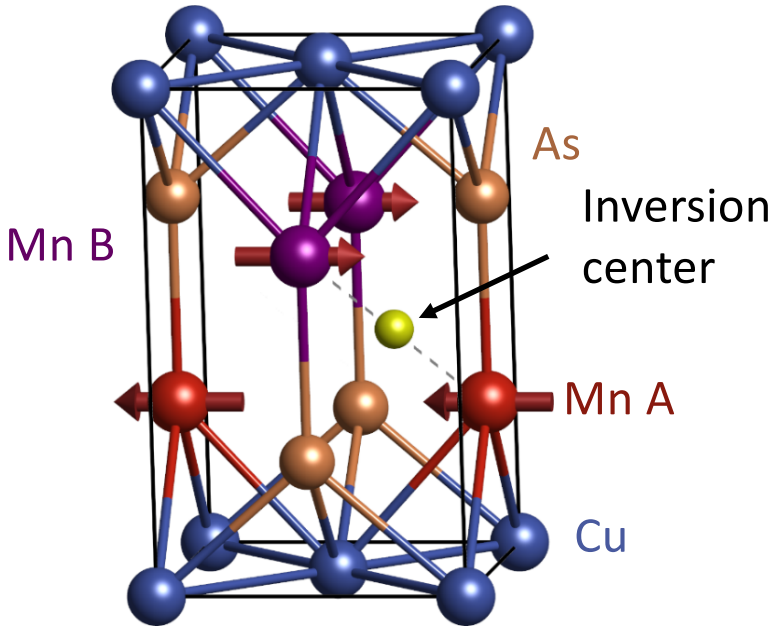


CuMnSb

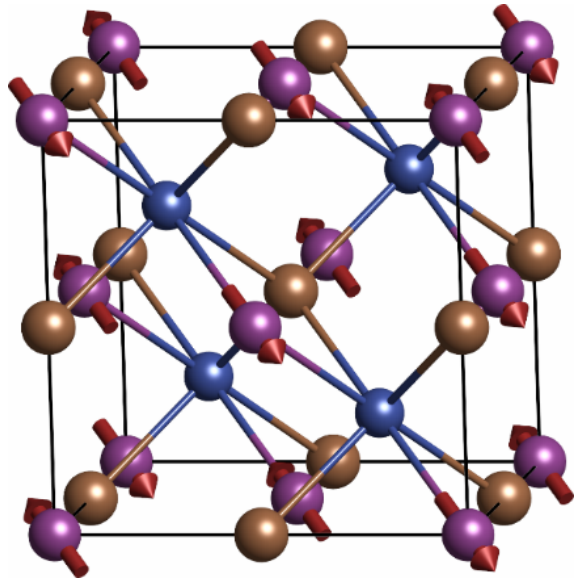
When will the spin-orbit torque be efficient?

$$\mathbf{T}_a = \mathbf{M}_a \times \mathbf{B}_a^{\mathrm{eff}}$$

We need a staggered effective field



CuMnAs



CuMnSb

Sublattices connected by inversion

$$\chi_A^{\mathrm{even}} = -\chi_B^{\mathrm{even}}$$
$$\chi_A^{\mathrm{odd}} = \chi_B^{\mathrm{odd}}$$

Even part of the field is staggered

Sublattices connected by translation

$$\chi_A^{\mathrm{even}} = \chi_B^{\mathrm{even}}$$
$$\chi_A^{\mathrm{odd}} = -\chi_B^{\mathrm{odd}}$$

Odd part of the field is staggered

How does the effective field depend on direction of magnetic moments?

The dependence on magnetic moments is largely controlled by symmetry

We expand the tensor χ in powers of the Neel vector

$$\hat{\mathbf{L}} = \mathbf{M}_A - \mathbf{M}_B$$

$$\chi_{a,ij}(\hat{\mathbf{L}}) = \chi^{(0)}_{a,ij} + \chi^{(1)}_{a,ij,k}\hat{L}_k + \chi^{(2)}_{a,ij,kl}\hat{L}_k\hat{L}_l + \dots$$

Only the lowest order terms are typically needed

$\chi^{(0)}_a$ Field-like term: **B** independent of **L**

$\chi^{(1)}_a$ Lowest order odd term

Can be antidamping-like: $\mathbf{B} \sim \mathbf{L} \times \mathbf{p}$

Zelezny et al., arXiv:1604.07590

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Only the lowest order terms are typically needed

Symmetry of this expansion determined by the local nonmagnetic point group

Only 21 groups with broken inversion symmetry

Zelezny et al., arXiv:1604.07590

Symmetry tables

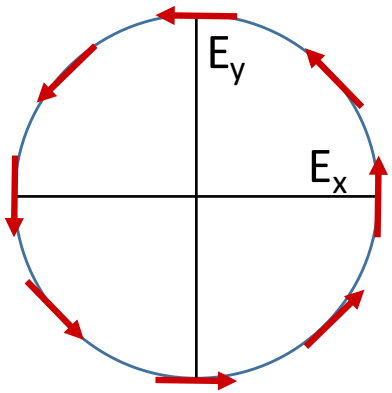
Symmetry of this expansion determined by the local nonmagnetic point group

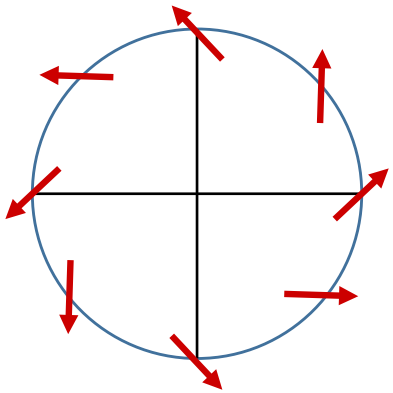
Only 21 groups with broken inversion symmetry

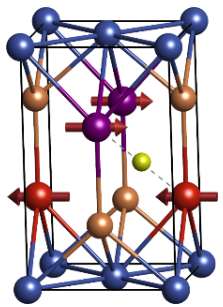
point group	field-like χ	point group	field-like χ
2	$\begin{pmatrix} x_{11} & 0 & x_{13} \\ 0 & x_{22} & 0 \\ x_{31} & 0 & x_{33} \end{pmatrix}$	312	$\begin{pmatrix} x_{11} & 0 & 0 \\ 0 & x_{11} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$
m	$\begin{pmatrix} 0 & x_{12} & 0 \\ x_{21} & 0 & x_{23} \\ 0 & x_{32} & 0 \end{pmatrix}$	3m1	$\begin{pmatrix} 0 & -x_{21} & 0 \\ x_{21} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
222	$\begin{pmatrix} x_{11} & 0 & 0 \\ 0 & x_{22} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$	6	$\begin{pmatrix} x_{11} & -x_{21} & 0 \\ x_{21} & x_{11} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$
mm2	$\begin{pmatrix} 0 & x_{12} & 0 \\ x_{21} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	-6	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
4	$\begin{pmatrix} x_{11} & -x_{21} & 0 \\ x_{21} & x_{11} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$	622	$\begin{pmatrix} x_{11} & 0 & 0 \\ 0 & x_{11} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$
-4	$\begin{pmatrix} x_{11} & x_{21} & 0 \\ x_{21} & -x_{11} & 0 \\ 0 & 0 & 0 \end{pmatrix}$	6mm	$\begin{pmatrix} 0 & -x_{21} & 0 \\ x_{21} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
422	$\begin{pmatrix} x_{11} & 0 & 0 \\ 0 & x_{11} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$	-6m2	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
4mm	$\begin{pmatrix} 0 & -x_{21} & 0 \\ x_{21} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$	23	$\begin{pmatrix} x_{11} & 0 & 0 \\ 0 & x_{11} & 0 \\ 0 & 0 & x_{11} \end{pmatrix}$
-42m	$\begin{pmatrix} x_{11} & 0 & 0 \\ 0 & -x_{11} & 0 \\ 0 & 0 & 0 \end{pmatrix}$	432	$\begin{pmatrix} x_{11} & 0 & 0 \\ 0 & x_{11} & 0 \\ 0 & 0 & x_{11} \end{pmatrix}$
3	$\begin{pmatrix} x_{11} & -x_{21} & 0 \\ x_{21} & x_{11} & 0 \\ 0 & 0 & x_{33} \end{pmatrix}$	-43m	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Field-like terms

Rashba

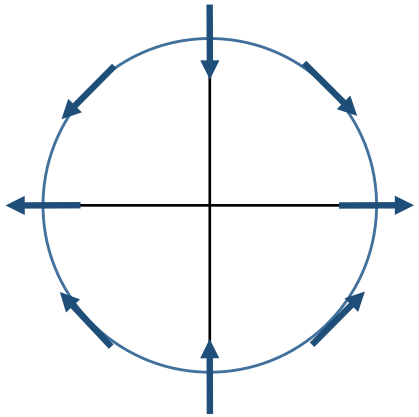


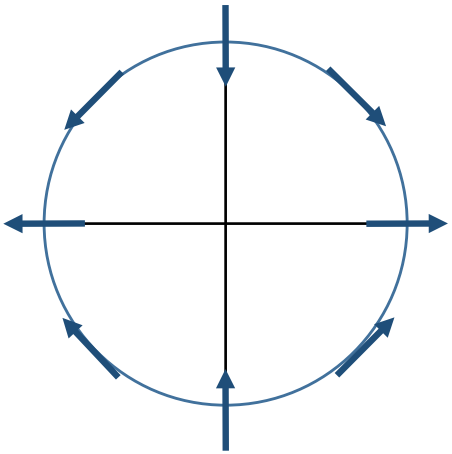


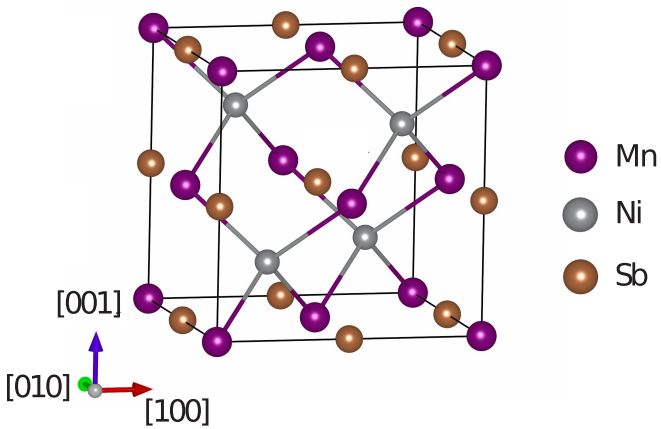


CuMnAs

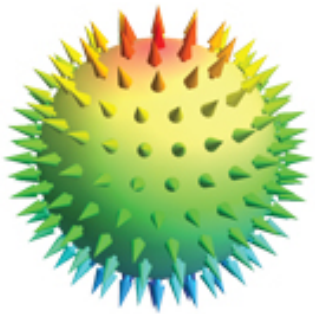
Dresselhaus







"Weyl"

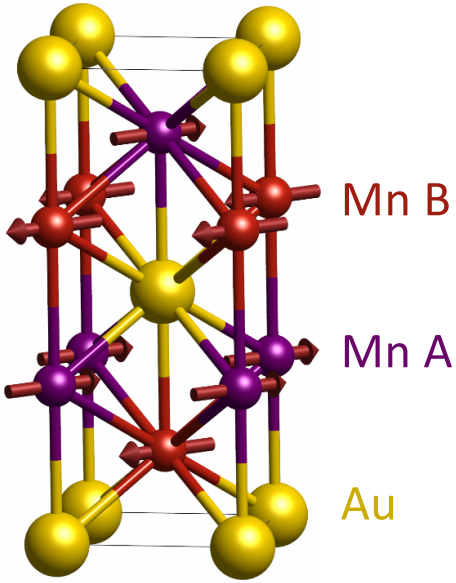


$$\delta \mathbf{s} \sim \mathbf{E}$$

Taiki Yoda et al., Scientific Reports (2015)

Tight-binding calculations

Mn2Au

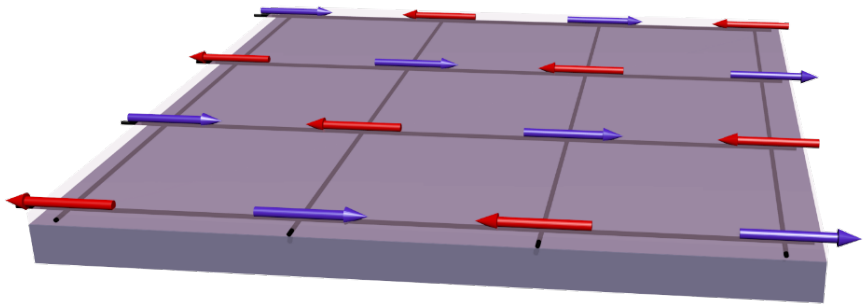


Symmetry analogous to CuMnAs

Sublattices connected by **inversion**

Even part of the field is staggered

A simple toy model



A 2D lattice with Rashba spin-orbit coupling

Sublattices connected by **translation**

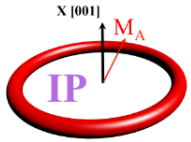
Odd part of the field is staggered

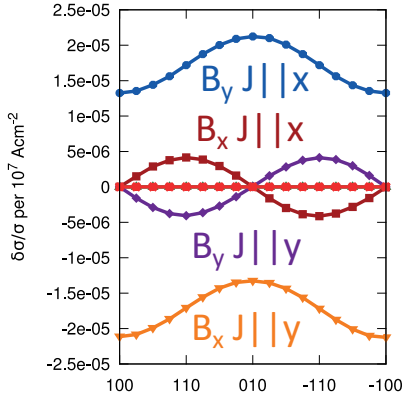
Site point group is *4mm* in both cases

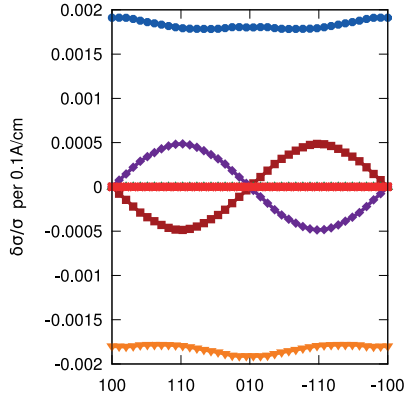
Microscopic calculations

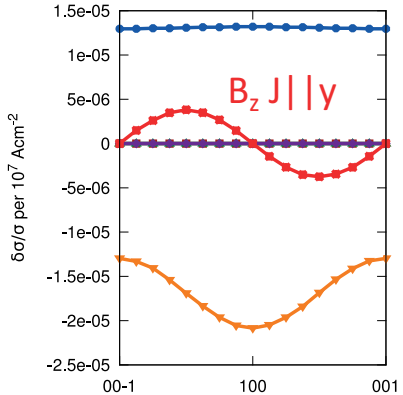
Even

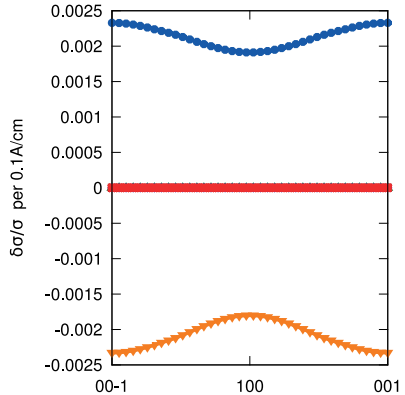
$$\mathbf{B}_{\text{eff}} \sim \mathbf{z} \times \mathbf{E}$$

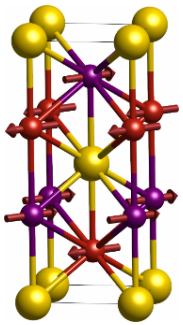


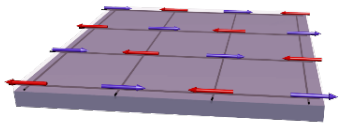








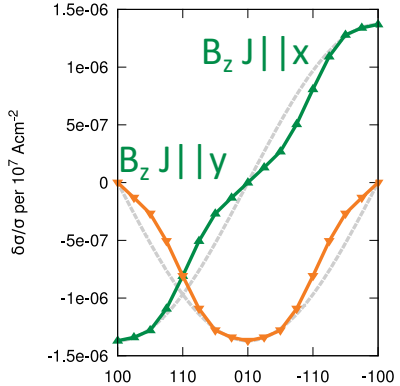


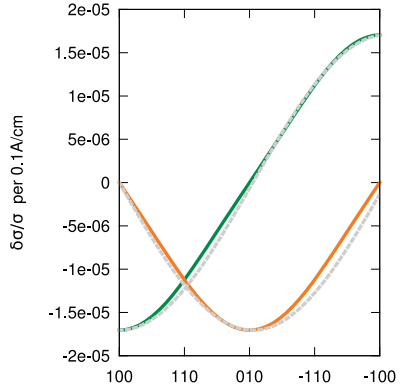


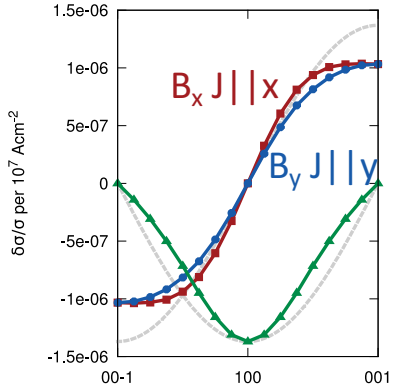
Zelezny et al., PRL 113, 157201 (2014)

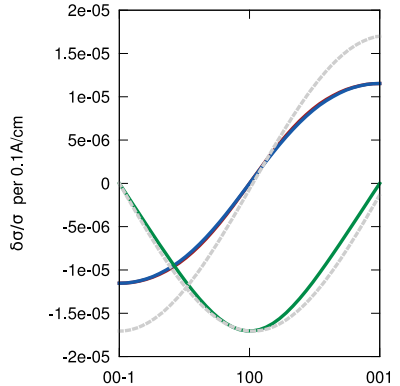
Odd

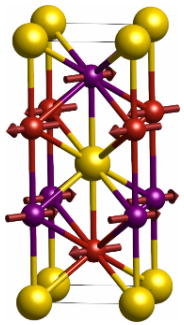
$$\mathbf{B}_{eff} \sim \mathbf{M} \times (\mathbf{z} \times \mathbf{E})$$

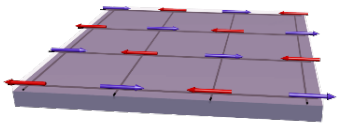










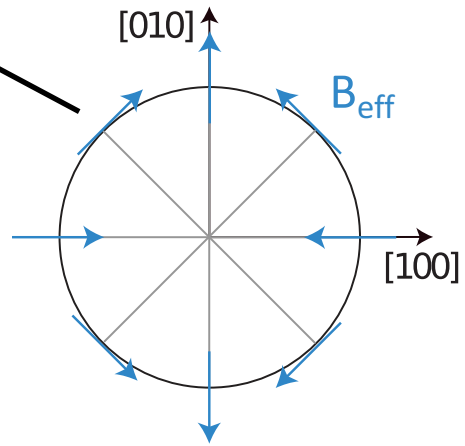


Zelezny et al., arXiv:1604.07590

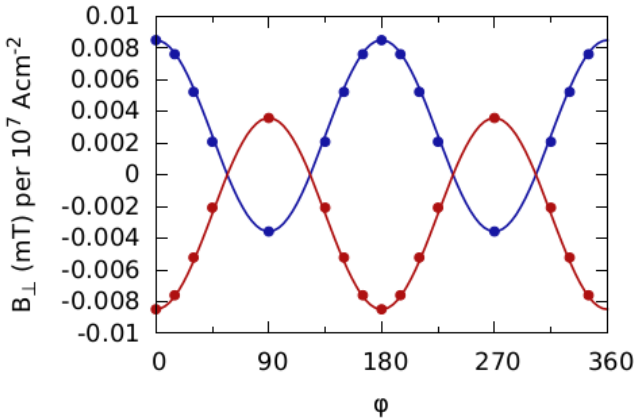
NiMnSb

Without strain: $\chi^{\text{even}} \approx \chi^{(2)}$ $\chi^{\text{odd}} \approx \chi^{(1)}$

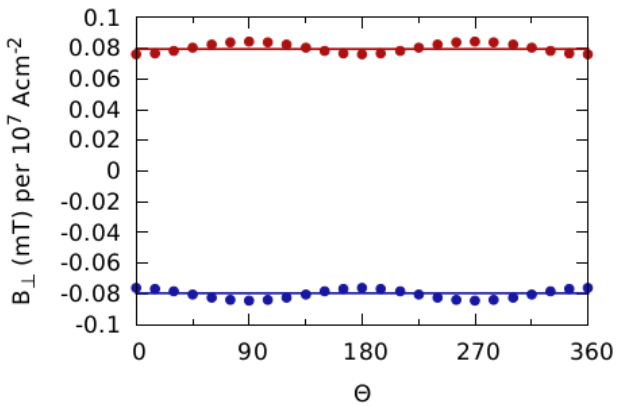
With uniaxial strain : $\chi^{\text{even}} \approx \chi^{(0)} + \chi^{(2)}$ $\chi^{\text{odd}} \approx \chi^{(1)}$



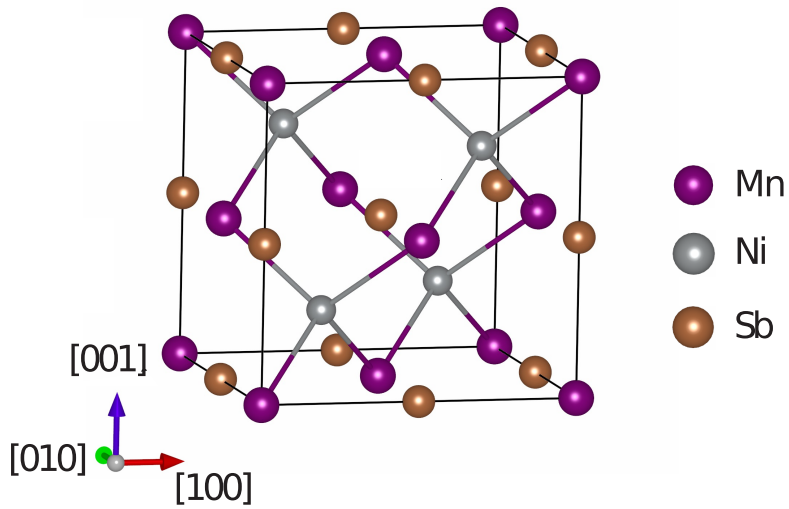
Dresselhaus field



Without strain



With uniaxial strain



Ciccarelli et al., Nature Physics (2016)

NiMnSb

Without strain: $\chi^{\text{even}} \approx \chi^{(2)}$ $\chi^{\text{odd}} \approx \chi^{(1)}$

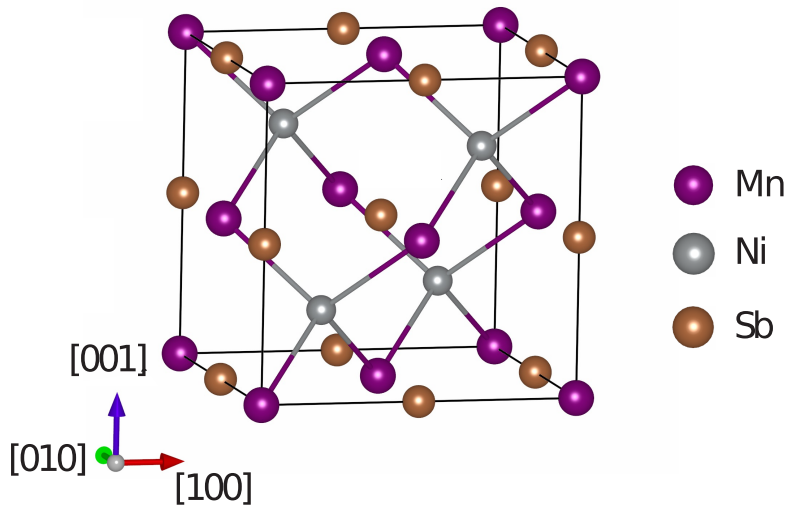
With uniaxial strain : $\chi^{\text{even}} \approx \chi^{(0)} + \chi^{(2)}$ $\chi^{\text{odd}} \approx \chi^{(1)}$

Odd field is not antidamping-like

For **E** along 110:

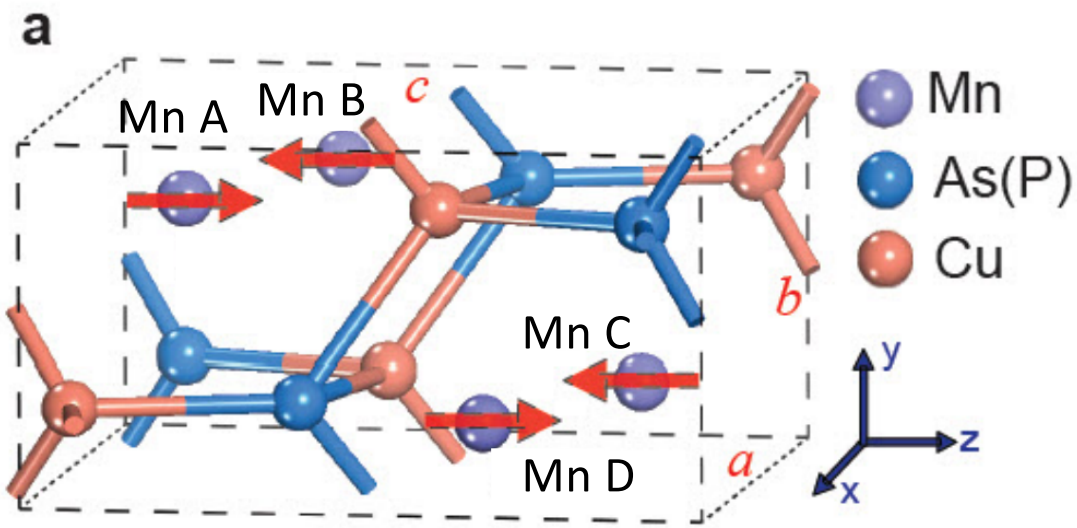
$$\mathbf{B}^{\text{odd}} \sim (M_z, M_z, (M_x + M_y))$$

Cannot be written as $\mathbf{M} \times \mathbf{p}$



Ciccarelli et al., Nature Physics (2016)

Orthorombic CuMnAs



Inversion symmetry locally broken – analogous to tetragonal CuMnAs

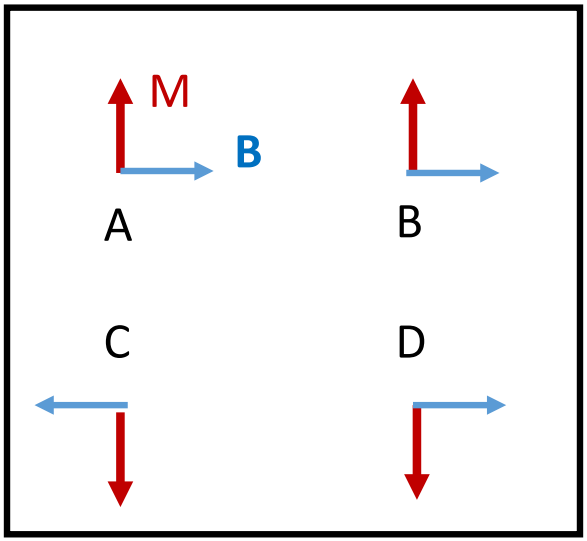
PT symmetry

Mn A → Mn C

Mn B → Mn D

Even field staggered
Odd field uniform

Field-like torque



Lowest order - field that generates the **field-like** torque

$$\chi_A^{(0)} = \begin{pmatrix} 0 & x_{12} & 0 \\ x_{21} & 0 & x_{23} \\ 0 & x_{32} & 0 \end{pmatrix}, \qquad \chi_B^{(0)} = \begin{pmatrix} 0 & x_{12} & 0 \\ x_{21} & 0 & -x_{23} \\ 0 & -x_{32} & 0 \end{pmatrix}$$

Efficient component

$$\chi_A^{(0)} = \begin{pmatrix} 0 & x_{12} & 0 \\ x_{21} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Summary

- Spin-orbit torque enables electrical control of antiferromagnets
- Symmetry is crucial for understanding the spin-orbit torque
- Spin-orbit torque can be as large in antiferromagnets as in ferromagnets
- Switching has been experimentally observed

Zelezny et al., PRL 113, 157201 (2014)
Zelezny et al., arXiv:1604.07590
Wadley et al., Science 351, 587-590 (2016)
Ciccarelli et al., Nature Physics (2016)