

Spin-orbitronics (spin-orbit torques) in ferromagnets and antiferromagnets and beyond

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I. Spin-Transfer Torque

- Phenomenology
- Anatomy of STT (no spin-orbit)
- Complex anatomy of STT with spin-orbit coupling

II. SHE and Inverse spin galvanic effect

- SHE and Inverse spin galvanic effect phenomenology

III. Spin-Orbit Torques in Ferromagnets:

- Spin-Orbit Torques:
 - Bilayer geometry: SOT vs SHE+STTT
 - Intrinsic and Field like SOTs in ferromagnets

IV. Antiferromagnetic Spin-orbitronics: Néel SOTs

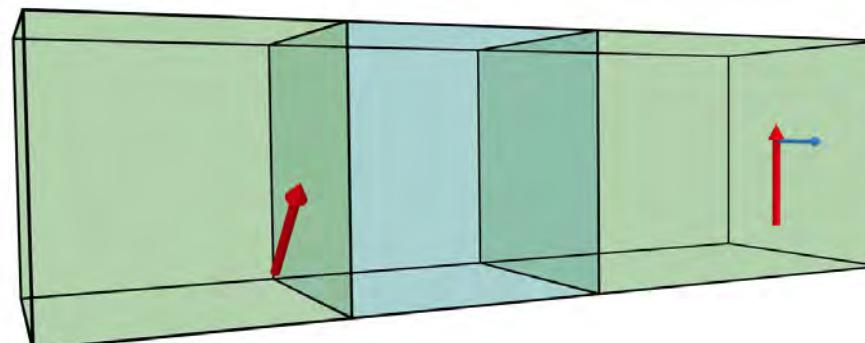
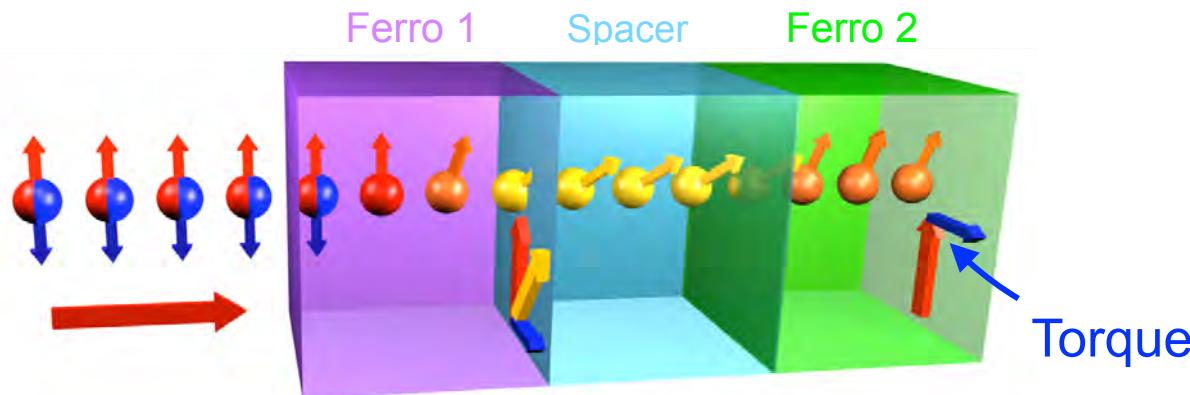
- Active manipulation of Néel order by currents: Néel spin-orbit torque

V. Topological Dirac Fermion + Antiferromagnets + Néel SOTs

Magnetization dynamics and Spin Transfer Torque

$$\frac{d\hat{M}}{dt} = -\gamma \hat{M} \times \vec{H}_{eff} + \alpha \hat{M} \times \frac{d\hat{M}}{dt} + \frac{\hbar P J}{2e} (\hat{M} \times \hat{M}_0) \times \hat{M}$$

Spin Transfer Torque



(proposed by Slonczewski, Berger 1996)

$$H_{sd} = -J_{sd} \hat{\mathbf{m}} \cdot \hat{\mathbf{M}}$$

J_{sd} exchange coupling constant [energy]

Effective exchange field acting on \mathbf{m} :

$$\mathbf{B} = \frac{J_{sd}}{m} \hat{\mathbf{M}} \rightarrow$$

Torque: $\mathbf{T} = J_{sd} \hat{\mathbf{m}} \times \hat{\mathbf{M}}$

Effective exchange field acting on \mathbf{M} :

$$\mathbf{B} = \frac{J_{sd}}{M} \hat{\mathbf{m}} \rightarrow$$

Torque: $\mathbf{T} = J_{sd} \hat{\mathbf{M}} \times \hat{\mathbf{m}}$

Changes of \mathbf{m} and \mathbf{M} are related by

$$\frac{d\mathbf{m}}{dt} = -\frac{d\mathbf{M}}{dt}$$

Action = Reaction !

Conservation of angular momentum

Note: This is exact if spin relaxation and spin-orbit coupling are neglected, i.e., assuming weak spin-lattice interactions compared to electron-electron interactions

Torques due to non equilibrium spin accumulation



$$\mathbf{T} = J_{sd} \hat{\mathbf{M}} \times \hat{\mathbf{m}}$$

Torque on \mathbf{M} due to the sd exchange interaction

$$\mathbf{m} = \mathbf{m}_0 + \delta\mathbf{m}$$

\mathbf{m}_0 equilibrium magnetization of conduction electrons, $\mathbf{m}_0 \parallel \mathbf{M}$

$$\delta\mathbf{m} = -DOS(E_F)\mu_B \boldsymbol{\mu}_s \quad \text{nonequilibrium magnetization}$$

Assuming $|\mathbf{M}| = \text{const.}$, the only component of \mathbf{m} that gives a torque is $\delta\mathbf{m}_\perp$

$$\delta\mathbf{m}_\perp = a_j \mathbf{M} \times \mathbf{m} + b_j (\mathbf{M} \times \mathbf{m}) \times \mathbf{M}$$

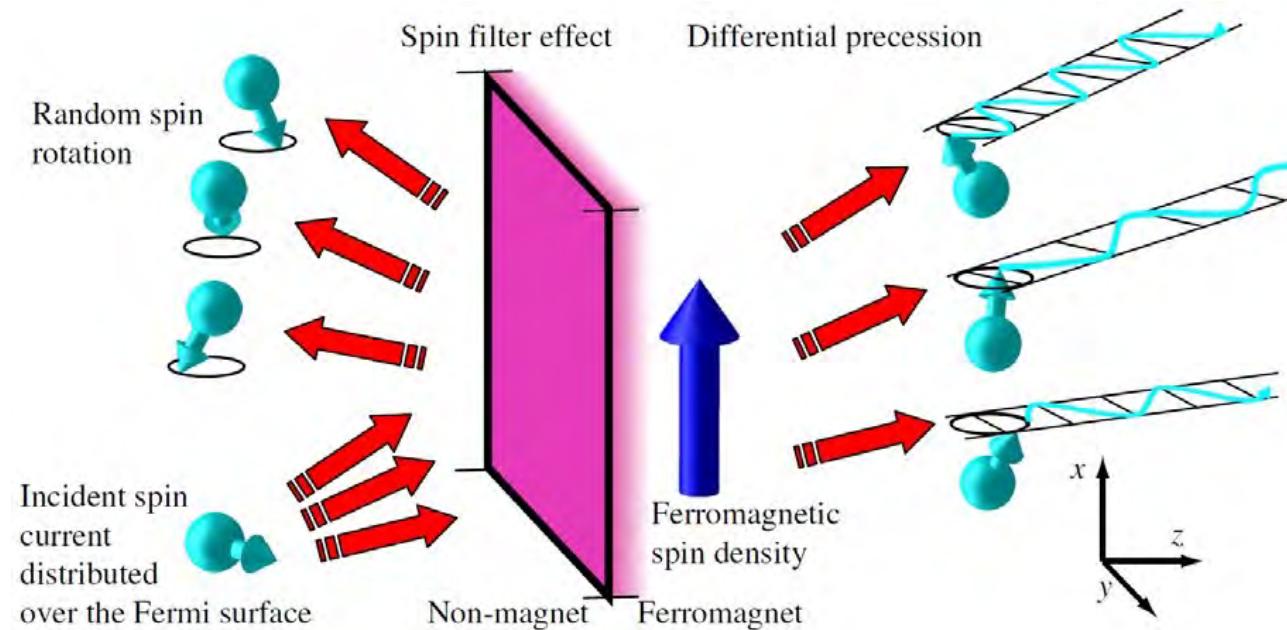
a_j, b_j parameters that depend on the current, magnetization, NM/FM geometry and materials

$$\mathbf{T} \sim \mathbf{M} \times \delta\mathbf{m}_\perp = a_j \mathbf{M} \times (\mathbf{M} \times \mathbf{m}) + b_j \mathbf{M} \times \mathbf{m}$$

- | | |
|------------------------|-------------------------|
| "In-plane torque" | "Out-of-plane torque" |
| "Spin transfer torque" | "Perpendicular torque " |
| "Slonczewski torque" | "Effective field" |
| "Antidamping torque" | "Field-like torque" |

S. Zhang, P.M. Levy, and A. Fert, PRL 88 236601 (2002); A. Shapiro et al., PRB 67, 104430 (2003).

Anatomy of spin-transfer torque: general case

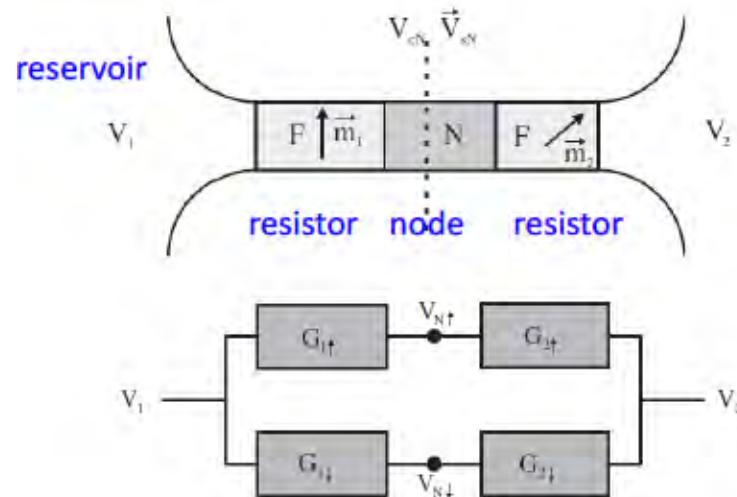


M. D. Stiles and J. Miltat,
Topics in App. Phys. 101,
225 (2006).

1. **Spin filter effect:** spin-dependent reflection and transmission at NM/FM interface, reduces the transverse spin components of reflected and transmitted electrons.
2. **The spin rotates upon reflection:** $r_{\uparrow}r_{\downarrow}^* = |r_{\uparrow}r_{\downarrow}^*|e^{i\Delta\phi}$. The relative phase $\Delta\phi$ of the reflected transverse components varies significantly over the Fermi surface. The reflected transverse spin averages out when summing over the electron distribution (classical dephasing).
3. **Spatial precession of the transmitted spins in the FM.** Spin-up and spin-down components have the same total energy E_F , but different kinetic energy $\Rightarrow k_{\uparrow} \neq k_{\downarrow}$, leading to a space-dependent phase difference $e^{i(k_{\uparrow}-k_{\downarrow})z}$ as the electron penetrates into the FM. The precession frequency is different for electrons from different portions of the Fermi surface, hence complete cancellation of the transverse spin occurs after propagation into the FM by a few lattice constants.

Courtesy of P. Gambardella

Anatomy of spin-transfer torque: circuit theory



- Generalization of the two-channel series resistor model to multilayer structures and noncollinear magnetization
- Similar to drift-diffusion theory but neglects the spatial dependence of the chemical potential within the layers (nodes).
- Practical for treating interface effects and complex device structures.

A. Brataas, Yu. V. Nazarov, and G. E. W. Bauer, PRL 84, 2481 (2000).
A. Brataas, G.E.W. Bauer, and P.J. Kelly, Phys. Rep. 427, 157 (2006).

$$\mathbf{j}_s = (j_{\uparrow} - j_{\downarrow}) \hat{\mathbf{M}} - \frac{2}{e} \operatorname{Re}\{G_{\uparrow\downarrow}\} \hat{\mathbf{M}} \times (\hat{\mathbf{M}} \times \boldsymbol{\mu}_s) - \frac{2}{e} \operatorname{Im}\{G_{\uparrow\downarrow}\} \hat{\mathbf{M}} \times \boldsymbol{\mu}_s$$

Bare spin current
determined by spin dep.
conductivity

Spin current absorbed by the ferromagnet

$$G_{\uparrow\downarrow} = \frac{e^2}{h} \sum_{n \in NM} \left[1 - \sum_{m \in NM} r_{\uparrow}^{nm} (r_{\downarrow}^{nm})^* \right]$$

- Spin mixing conductance: relevant for transport at interfaces when the spin accumulation \mathbf{m} and magnetization \mathbf{M} are not collinear

Courtesy of P. Gambardella

Anatomy of spin-transfer torque: 1D toy model



$$G_{\uparrow} = \frac{e^2}{h} \sum_{n \in NM} \sum_{m \in FM} |t_{\uparrow}^{nm}|^2$$

$$G_{\downarrow} = \frac{e^2}{h} \sum_{n \in NM} \sum_{m \in FM} |t_{\downarrow}^{nm}|^2$$

Majority and minority conductances describe electrons going from one material to another

$$G_{\uparrow\downarrow} = \frac{e^2}{h} \sum_{n \in NM} \left[1 - \sum_{m \in NM} r_{\uparrow}^{nm} (r_{\downarrow}^{nm})^* \right]$$

Describes a spin current absorbed by the FM, hence the behavior of the spins in the NM that are perpendicular to the magnetization of the FM

$Re\{G_{\uparrow\downarrow}\}$ Spin current aligned with the transverse part of μ_s in the NM

$Im\{G_{\uparrow\downarrow}\}$ Spin current perpendicular to both μ_s and M

Both spin current components $Re\{G_{\uparrow\downarrow}\}$ and $Im\{G_{\uparrow\downarrow}\}$ are absorbed in the FM, leading to the spin torque

$$\tau_{ST} = \frac{\hbar}{2e} \mathbf{j}_s^{abs} = \frac{\hbar}{e^2} [Re\{G_{\uparrow\downarrow}\} \widehat{\mathbf{M}} \times (\widehat{\mathbf{M}} \times \boldsymbol{\mu}_s) + Im\{G_{\uparrow\downarrow}\} \widehat{\mathbf{M}} \times \boldsymbol{\mu}_s]$$

[torque / unit area]

A. Braatas, G.E.W. Bauer, and P.J. Kelly, Phys. Rep. 427, 157 (2006)

Courtesy of P. Gambardella

Anatomy of SOT in Bilayers: revisiting $G_{\uparrow\downarrow}$

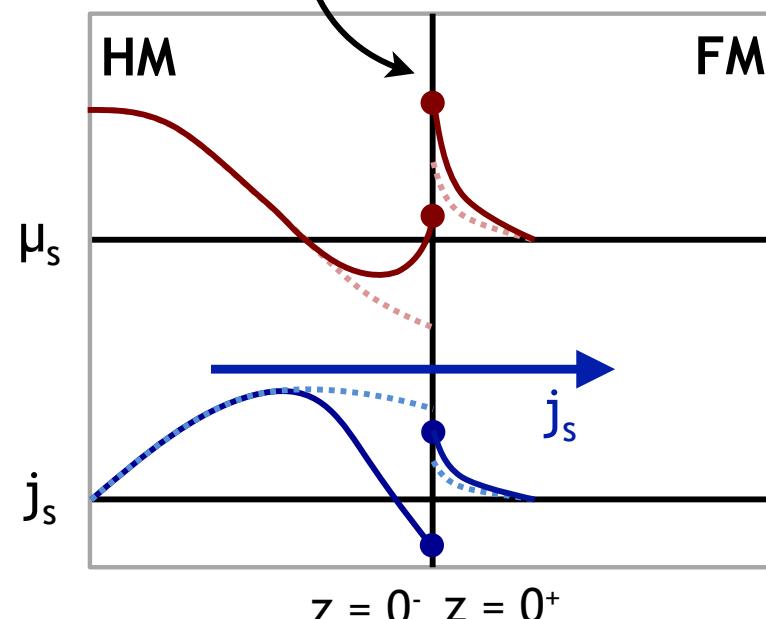


“Anatomy” of Spin-Orbit Torque in Bilayers

Spin transport **with** interfacial spin-orbit coupling

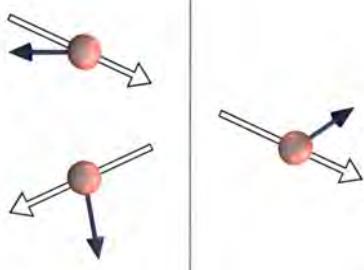
- Interfacial spin-orbit scattering creates a non-equilibrium spin polarization **and spin currents!**
- Interfacial spin current sources also determine ratio of damping-like and field-like torques
- Magneto-electric circuit theory (**Arne Brataas, et al. PRL 84, 11, 2000**) must be generalized!
Amin, et al. PRB 94, 104419 (2016)
Amin, et al. PRB 94, 104420 (2016)

Rashba SOC at interface

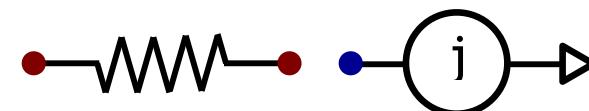


Vivek Amin

Interfacial spin-orbit scattering

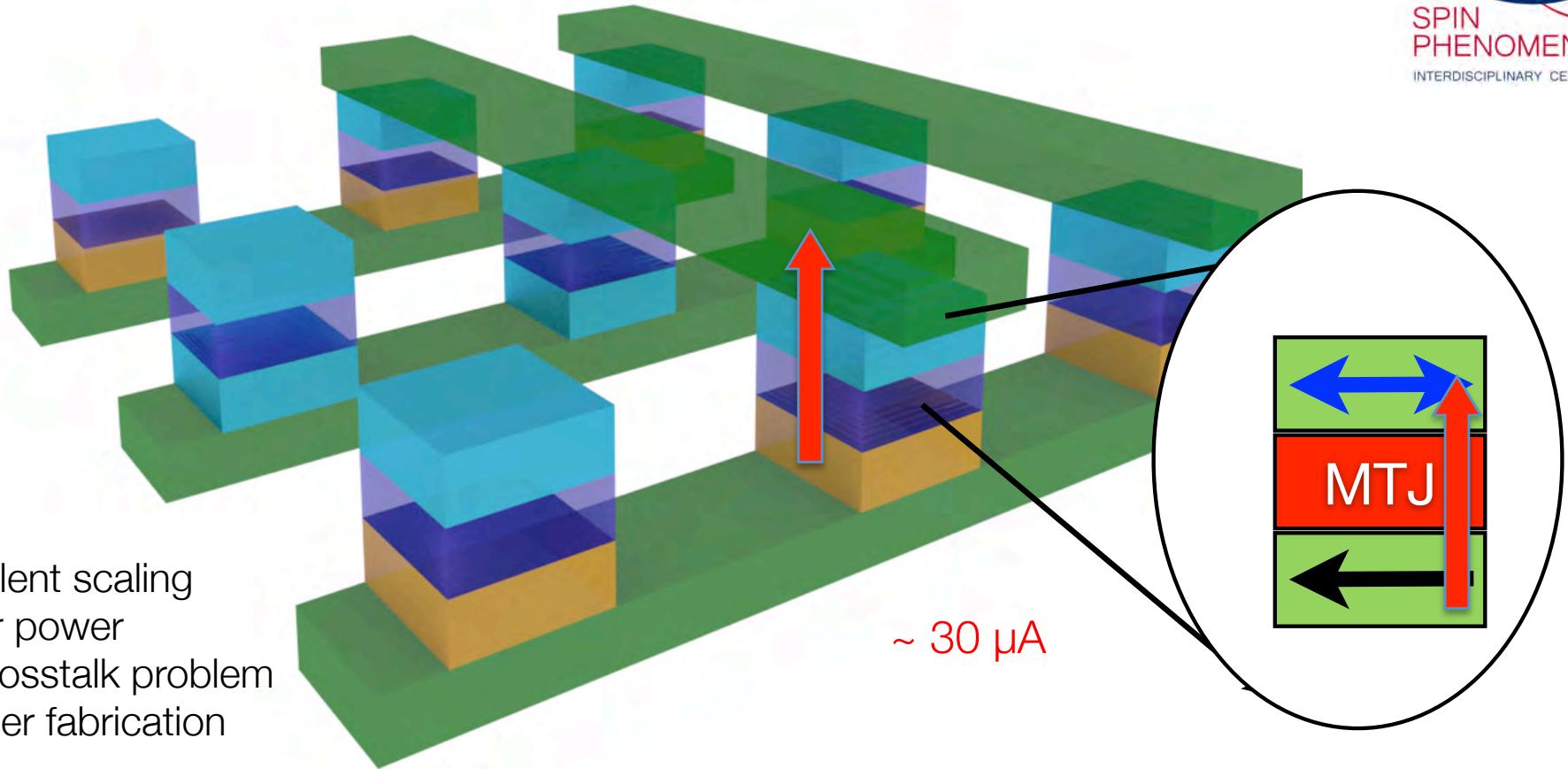


MCT w/ SOC



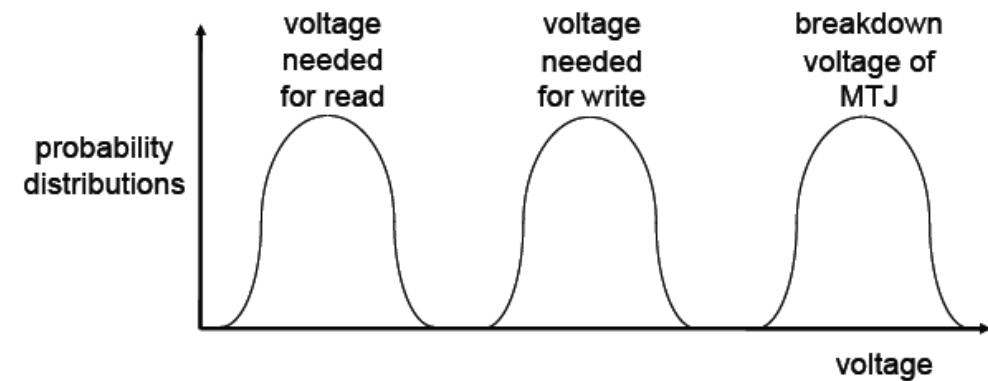
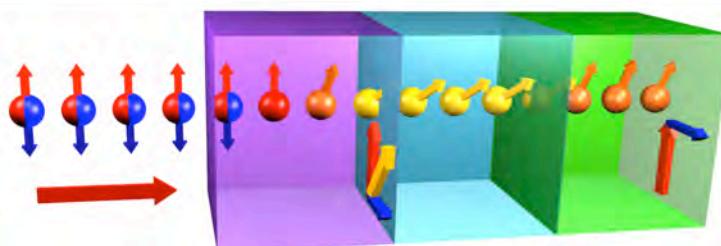
$$j_\alpha = G_{i\alpha\beta} \mu_\beta + \sigma_{i\alpha} E$$

Spin-Transfer-Torque MRAM

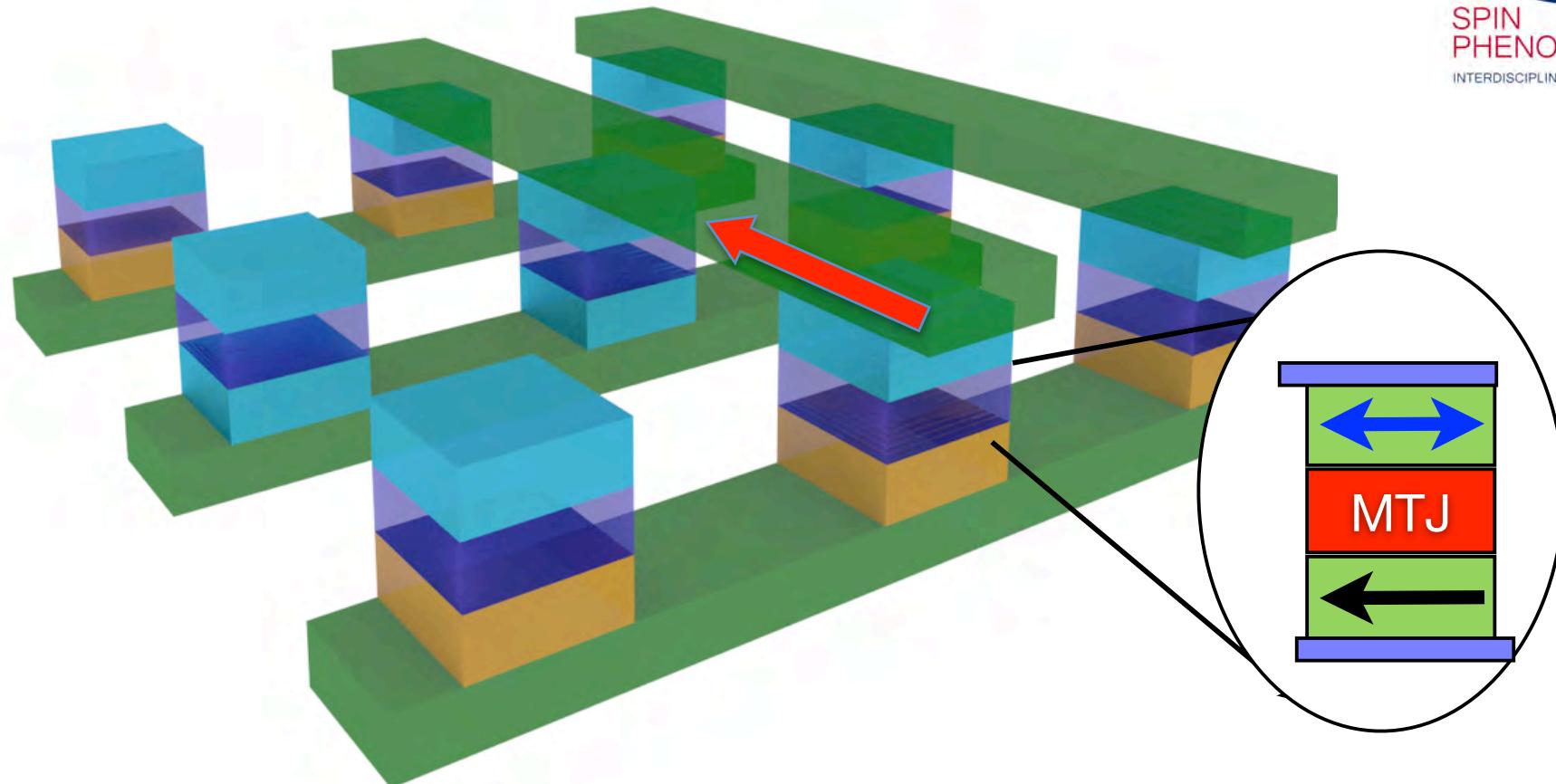


- excellent scaling
- lower power
- no crosstalk problem
- simpler fabrication

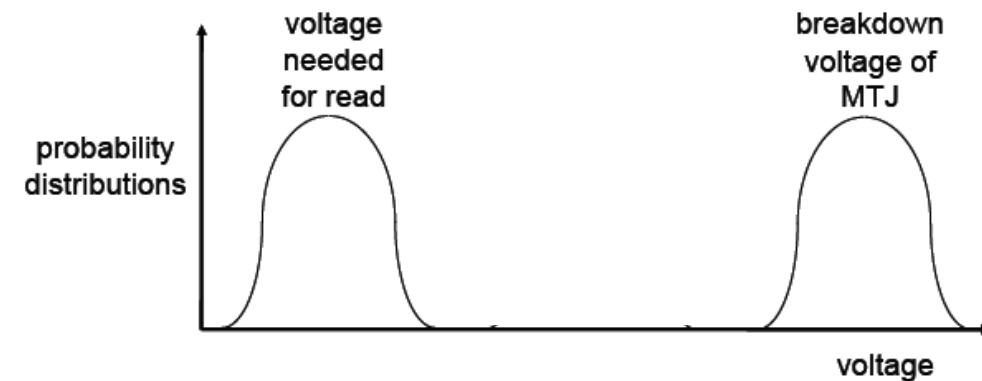
STT mechanism:



in-plane-current switching MRAM



If switching can be done by an in-plane current then a key issue in STT-MRAM is resolved



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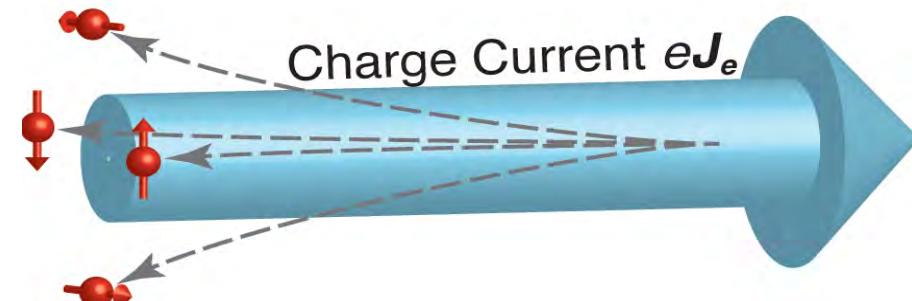
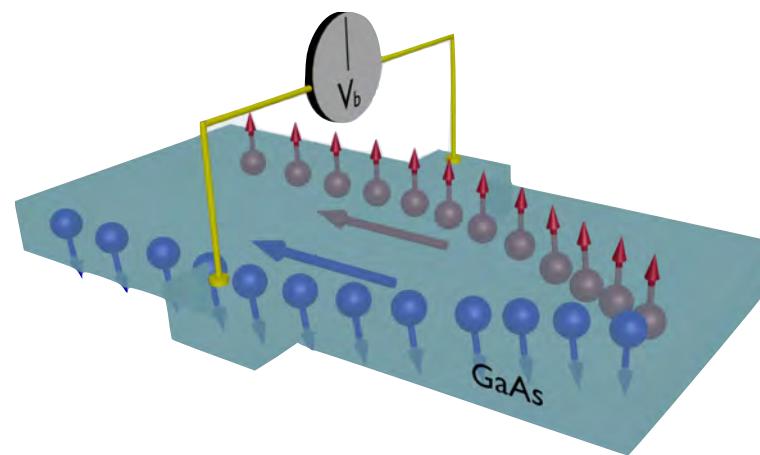
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Spin Hall effect

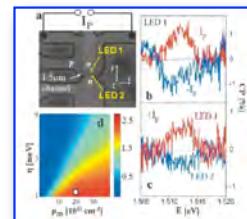


Transverse spin-current generation in paramagnets

Sinova et al RMP **87**, 1213 (2015)

Intrinsic

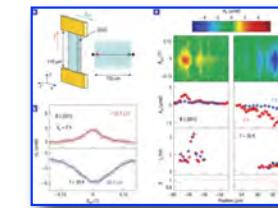
'Berry Phase', interband coherence
[Murakami et al, Sinova et al 2003]



Wunderlich, PRL 05

Extrinsic

'Skew Scattering', Occupation # Response
[Dyakonov 1971, Hirsch, S.F. Zhang 2000]

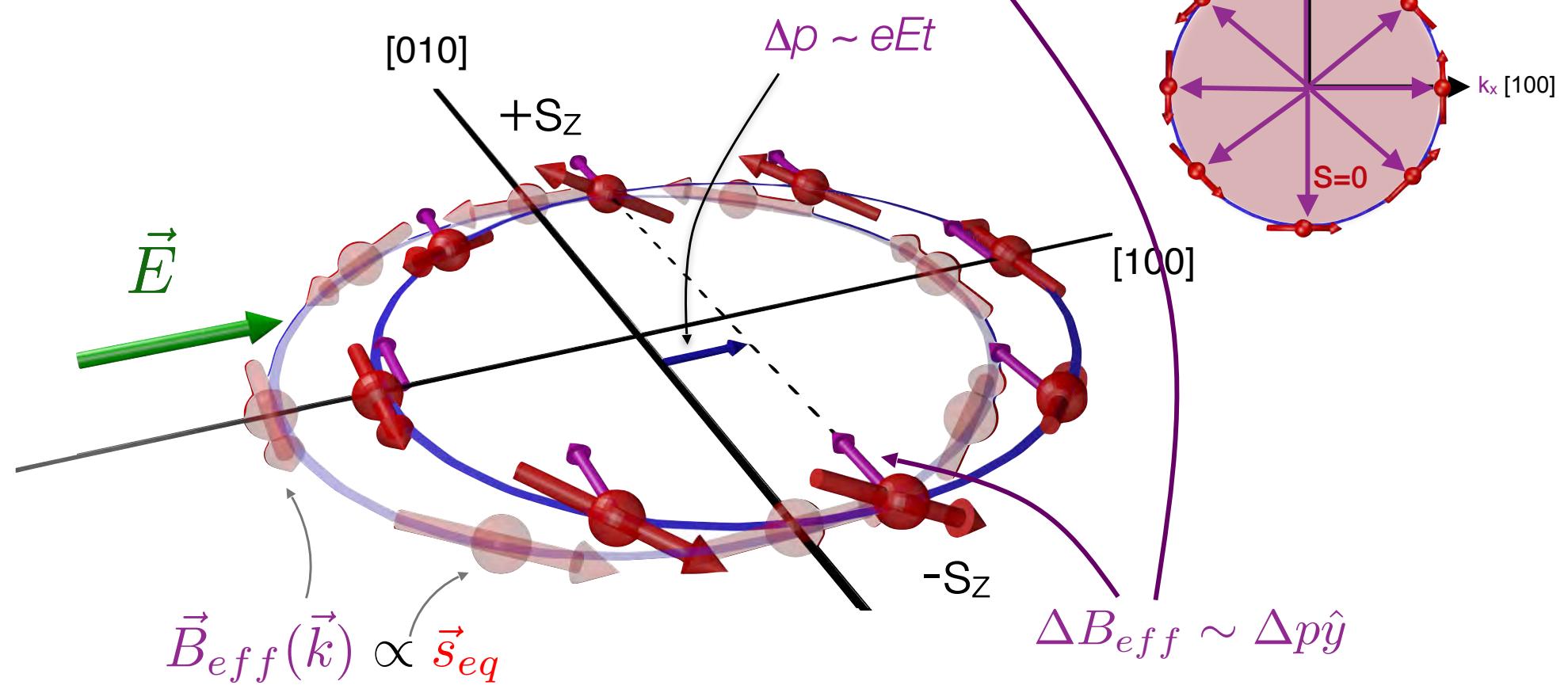


Kato,et al Science Nov 04

Intrinsic spin-Hall effect: the Rashba SOC example



$$\begin{aligned}
 H_R &= \frac{\hbar^2 k^2}{2m} - \mu_B \vec{\sigma} \cdot \vec{B}_{eff}(\vec{k}) \\
 &= \frac{\hbar^2 k^2}{2m} + \alpha_R (\sigma_x k_y - \sigma_y k_x)
 \end{aligned}$$

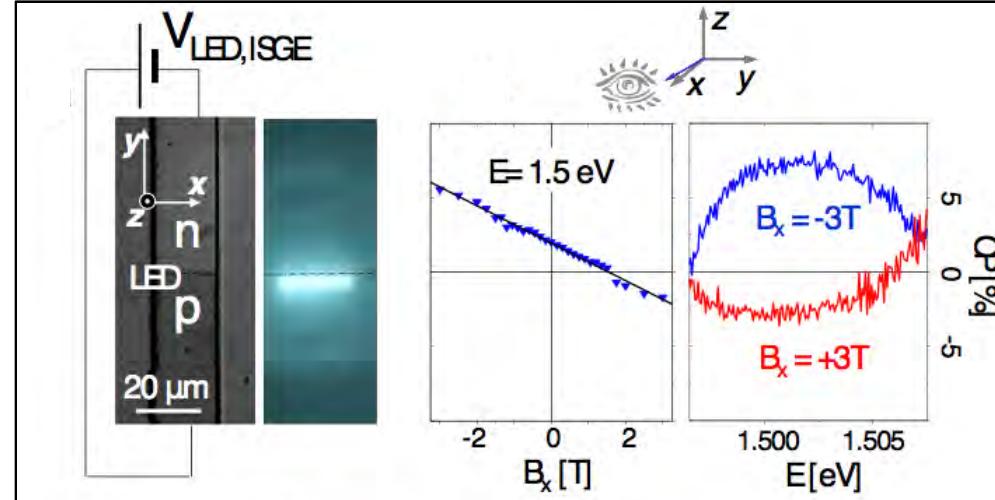
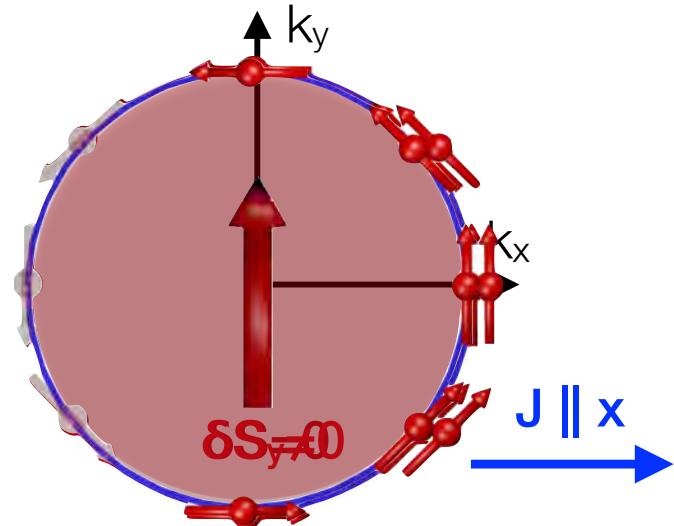


Another way to create current induced polarization

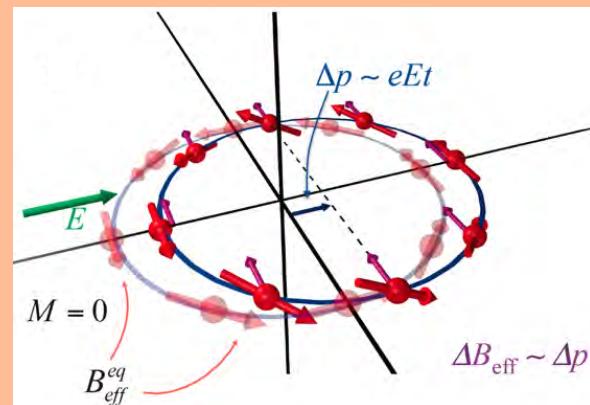


Inverse Spin Galvanic Effect or Edelstein Effect

(Reverse process of circular photo-galvanic effect, Ganichev et al., 2001)

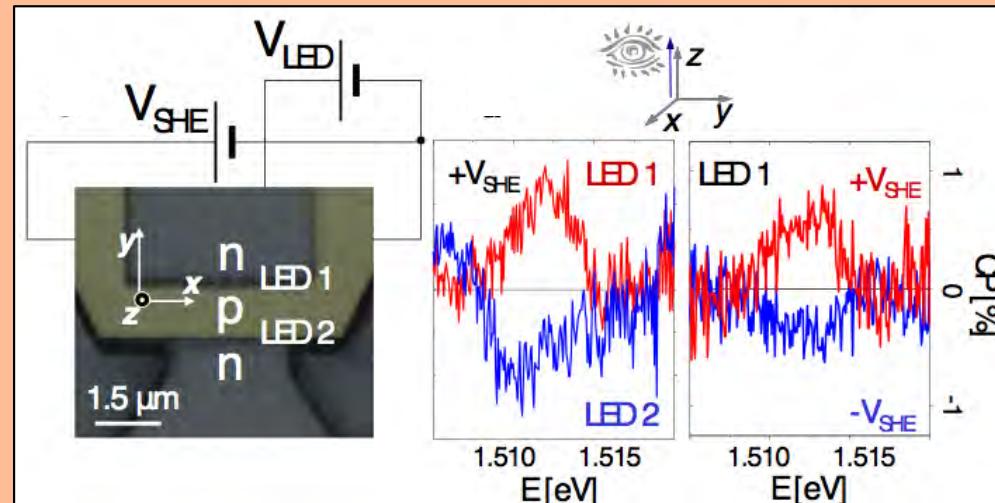


Spin Hall Effect in p-GaAs



Effective fields $\sim 1-10$ T

Spin polarizations $\sim 1-10\%$



Wunderlich et al. arXiv '04, PRL '05

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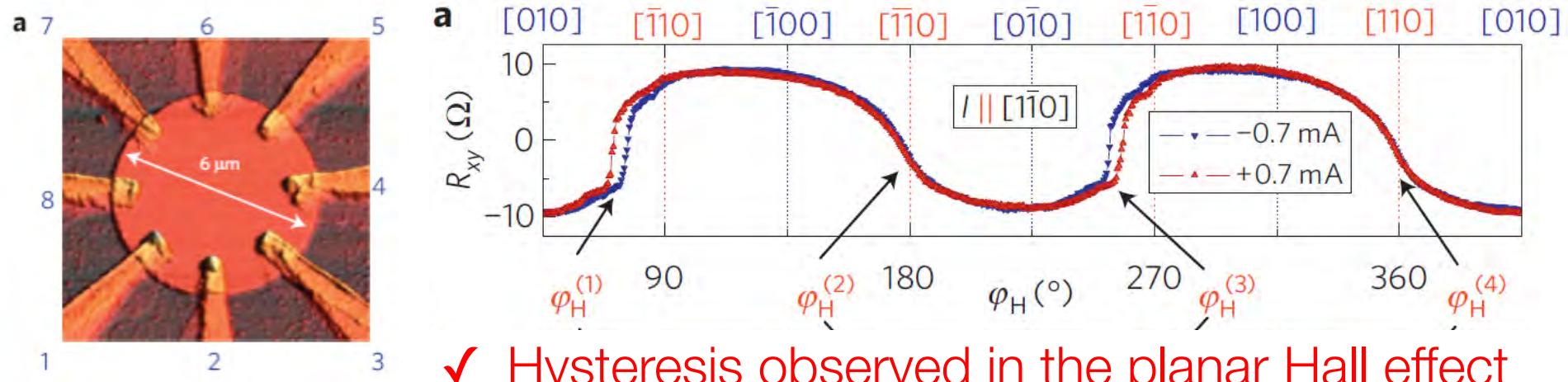
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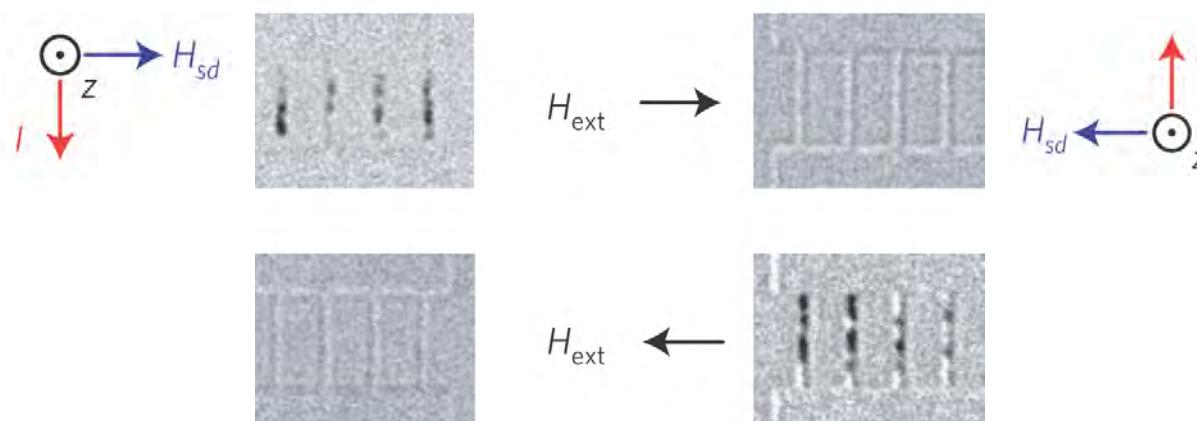
V. Topological Dirac Fermion + Antiferromagnets + Néel SOTs

Effective spin-orbit (SO) field by dc current

GaMnAs: bulk broken symmetry, Chernyshov, Rokhinson, et al, Nature Phys., 5, 656 (2009)



AlOx/Co/Pt: interface broken symmetry, Miron, Nature Mater. 9, 230 (2010)

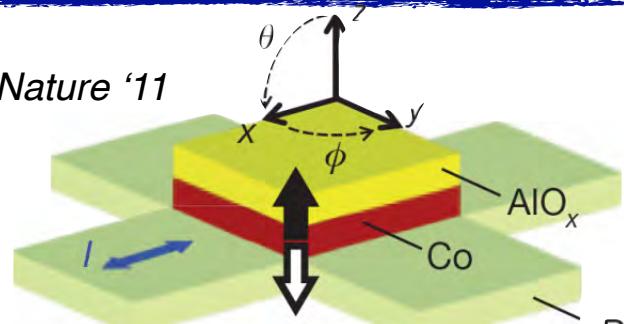


DW nucleation difference in the perpendicularly magnetised system

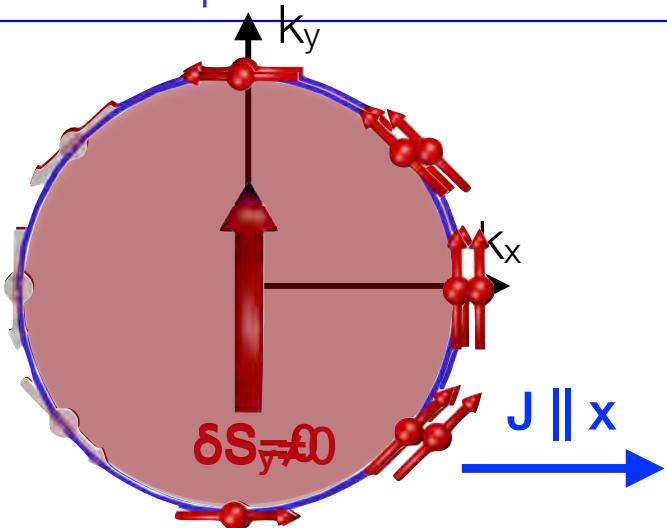
Experiments of in-plane current switching in bilayers



Miron et al., Nature '11

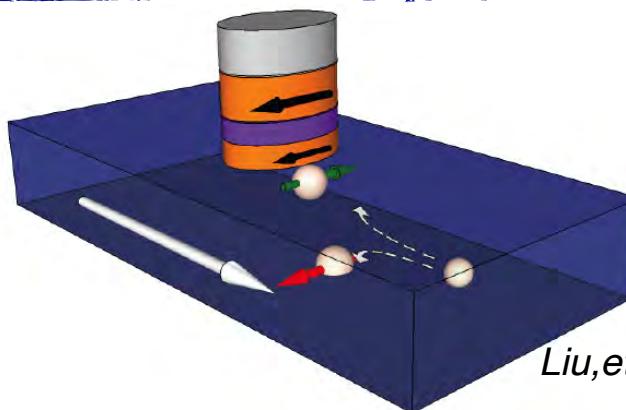
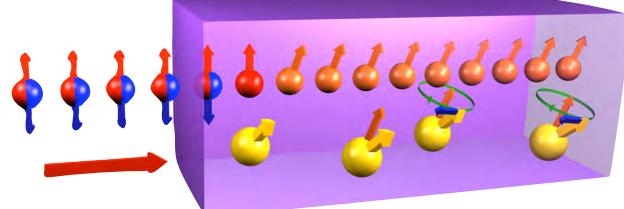


spin-orbit torque at PM/FM interface



$$H_{ex} = J_{ex} \vec{M} \cdot \delta \vec{s} \quad \left(\frac{d\vec{M}}{dt} \right)_{SOT} = \frac{J_{ex}}{\hbar} \vec{M} \times \delta \vec{s}$$

$h_{\text{SOT}} \parallel z \times J$

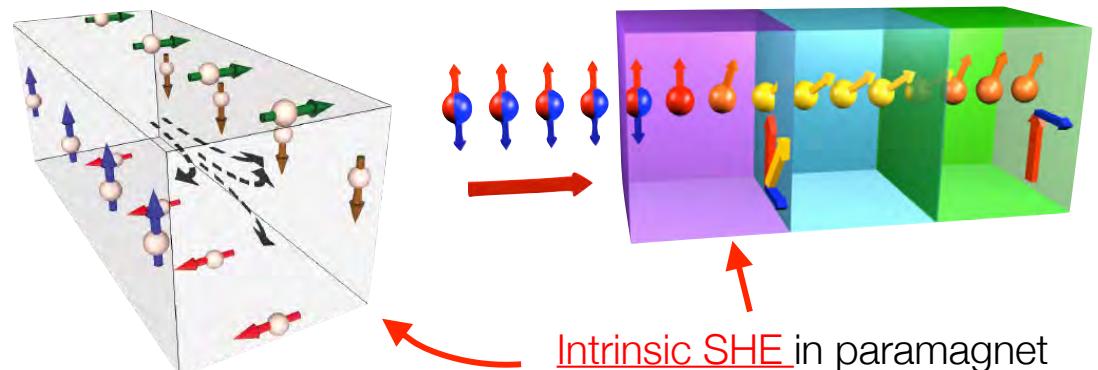


Liu, et al., Science '12

SHE as spin-current generator + STT

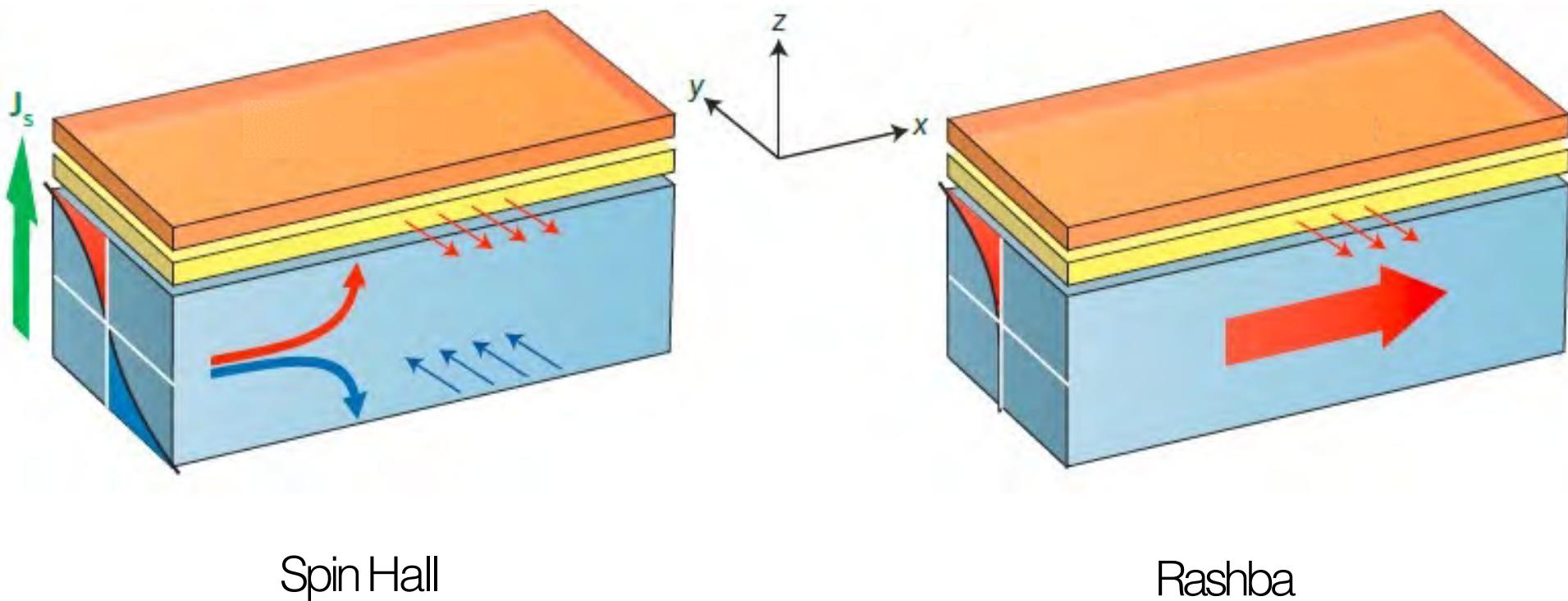
intrinsic SHE + STT

$$\left(\frac{d\vec{M}}{dt} \right)_{SHE-STT} = P \hat{M} \times (\hat{n} \times \hat{M})$$



Intrinsic SHE in paramagnet acts as the external polarizer

Spin-orbit induced spin accumulation in bilayer systems

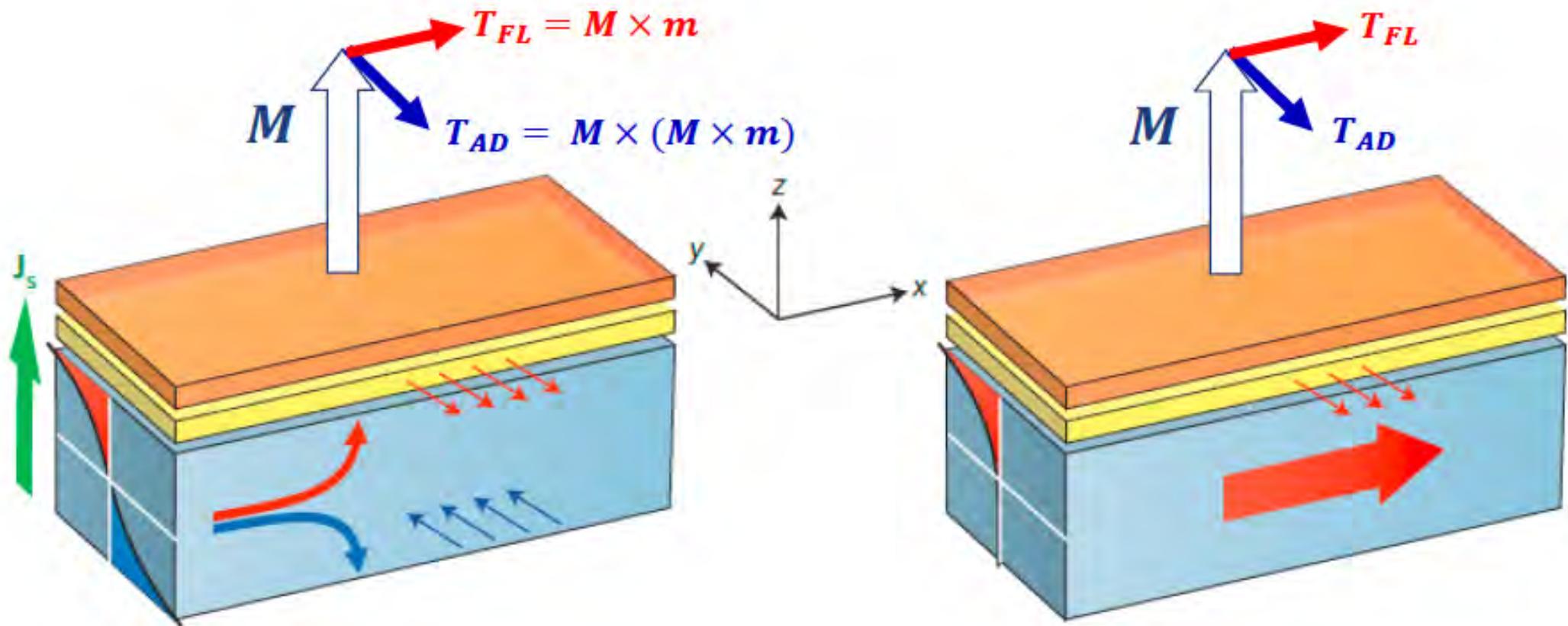


Spin Hall

Rashba

Courtesy of P. Gambardella

Spin-orbit Torques in Bilayer Systems



Courtesy of P. Gambardella

"You like potato and I like potato ...



$$\mathbf{T}_{AD} = \mathbf{M} \times (\mathbf{M} \times \mathbf{m})$$

"Spin Hall torque"

"Spin transfer torque"

"Slonczewski torque"

$$\mathbf{T}_{FL} = \mathbf{M} \times \mathbf{m}$$

"Spin orbit torque"

"Spin orbit field"

"Rashba torque"

Antidamping and field-like spin-orbit torques (SOT)

Courtesy of P. Gambardella

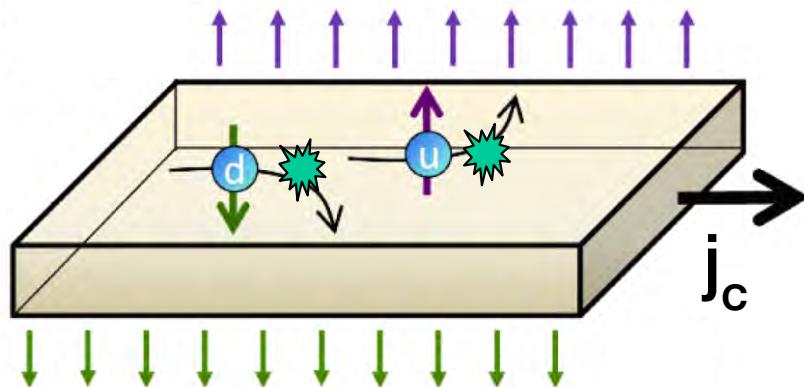
Linear response I. (condensed matter class)



Boltzmann theory: non-equilibrium distribution function and equilibrium states

Extrinsic (skew-scattering) SHE

$$\delta \vec{j}_s = \frac{1}{V} \sum_{\vec{k}} \vec{j}_s(\vec{k}) g_{\vec{k}}$$

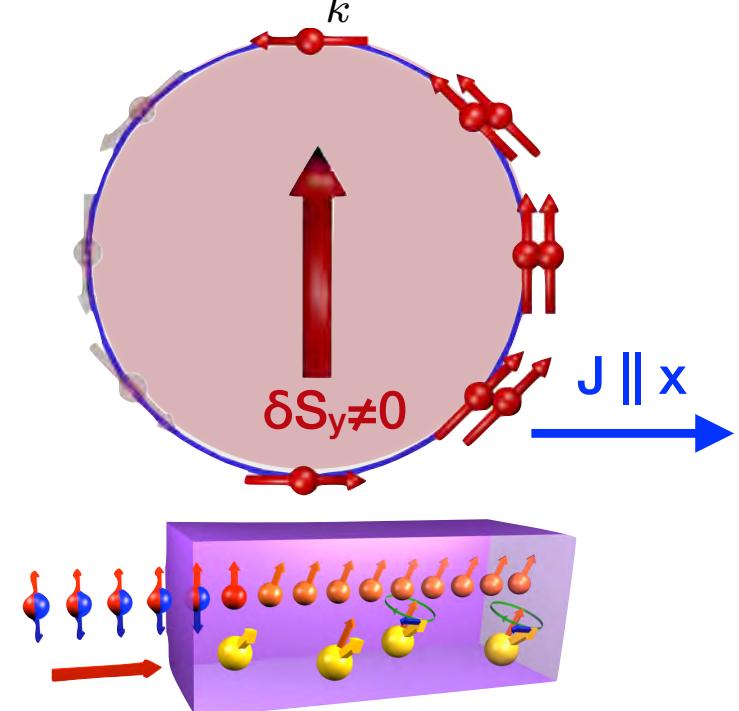


Dyakonov and Perel 1971
Hirsch PRL '99

Kato et al., Science '04

Field-like SOT

$$\delta \vec{s} = \frac{1}{V} \sum_{\vec{k}} \vec{s}(\vec{k}) g_{\vec{k}}$$



$$g_{n,\vec{k}} = f_{n,\vec{k}} - f_0(E_{n,\vec{k}})$$

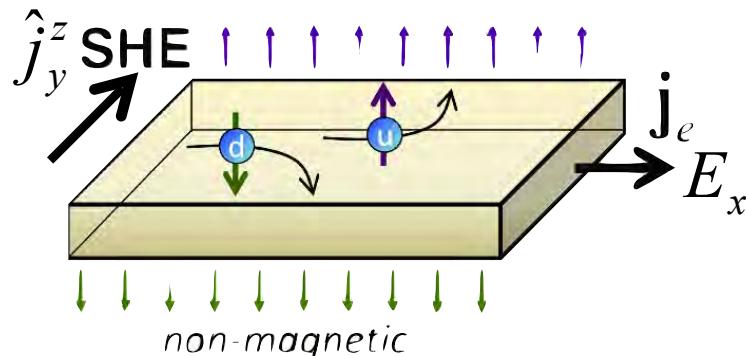
$$\left(\frac{d\vec{M}}{dt} \right)_{SOT} = \frac{J_{ex}}{\hbar} \vec{M} \times \delta \vec{s}$$

Linear response II. (condensed matter class)



Perturbation theory: equilibrium distribution function and non-equilibrium states

Intrinsic SHE from linear response II



$$\hat{j}_y^z = \sum_{\vec{k}} \langle \psi_{\vec{k}}(t) | \hat{j}_y^z | \psi_{\vec{k}} \rangle f_0(E_{\vec{k}})$$

$$|\psi_{\vec{k}}\rangle = |\vec{k}\rangle e^{-iE_{\vec{k}}t} + \frac{e}{i\omega} \sum_{\vec{k}n \neq n'} |\vec{k}n'\rangle \frac{\langle \vec{k}n' | \vec{E} \cdot \hat{v} | \vec{k}n \rangle}{E_{\vec{k}n} - E_{\vec{k}n'} + \hbar\omega} e^{-i(E_{\vec{k}n} + \omega)t} + \dots$$

$$J_{\vec{E} \times \hat{z}}^{int} = \frac{e\hbar}{V} \sum_{\vec{k}, n \neq n'} (f_{\vec{k}, n'}^0 - f_{\vec{k}, n}^0) \frac{\text{Im}[\langle \vec{k}, n' | j_{\vec{E} \times \hat{z}}^z | \langle \vec{k}, n \rangle \langle \vec{k}, n' | \vec{v} \cdot \vec{E} | \vec{k}, n' \rangle]}{(E_{\vec{k}, n'} - E_{\vec{k}, n})^2}$$

Murakami, et al, Science '03
Sinova, et al, PRL '04

Wunderlich et al. Phys. Rev. Lett. '05
Werake et al., PRL '11

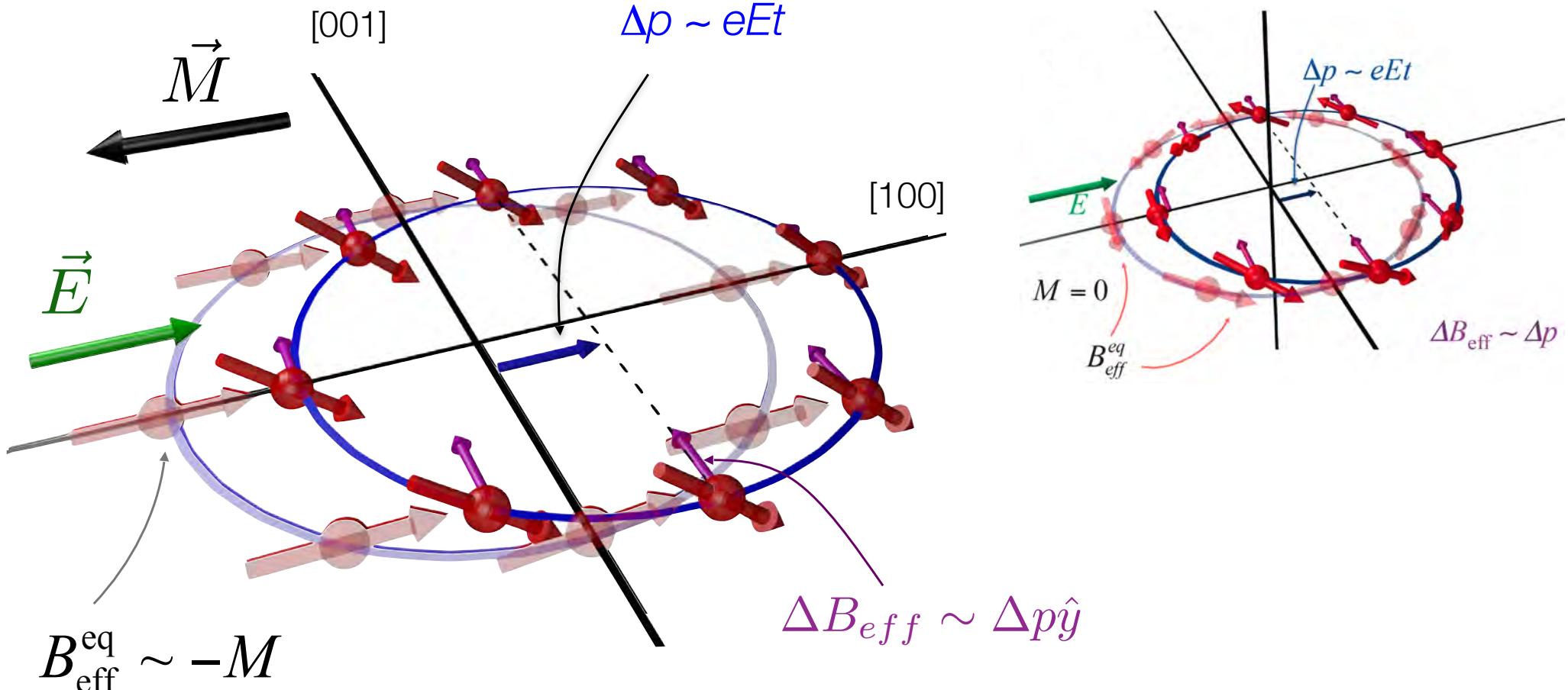
Scattering-independent anti-damping SOT from linear response II.

$$S_z^{int} = \frac{e\hbar}{V} \sum_{\vec{k}, n \neq n'} (f_{\vec{k}, n'}^0 - f_{\vec{k}, n}^0) \frac{\text{Im}[\langle \vec{k}, n' | s_z | \langle \vec{k}, n \rangle \langle \vec{k}, n' | \vec{v} \cdot \vec{E} | \vec{k}, n' \rangle]}{(E_{\vec{k}, n'} - E_{\vec{k}, n})^2}$$

Intrinsic (Berry phase) spin-orbit torque from Bloch eq.



Large exchange limit and Rashba SOC



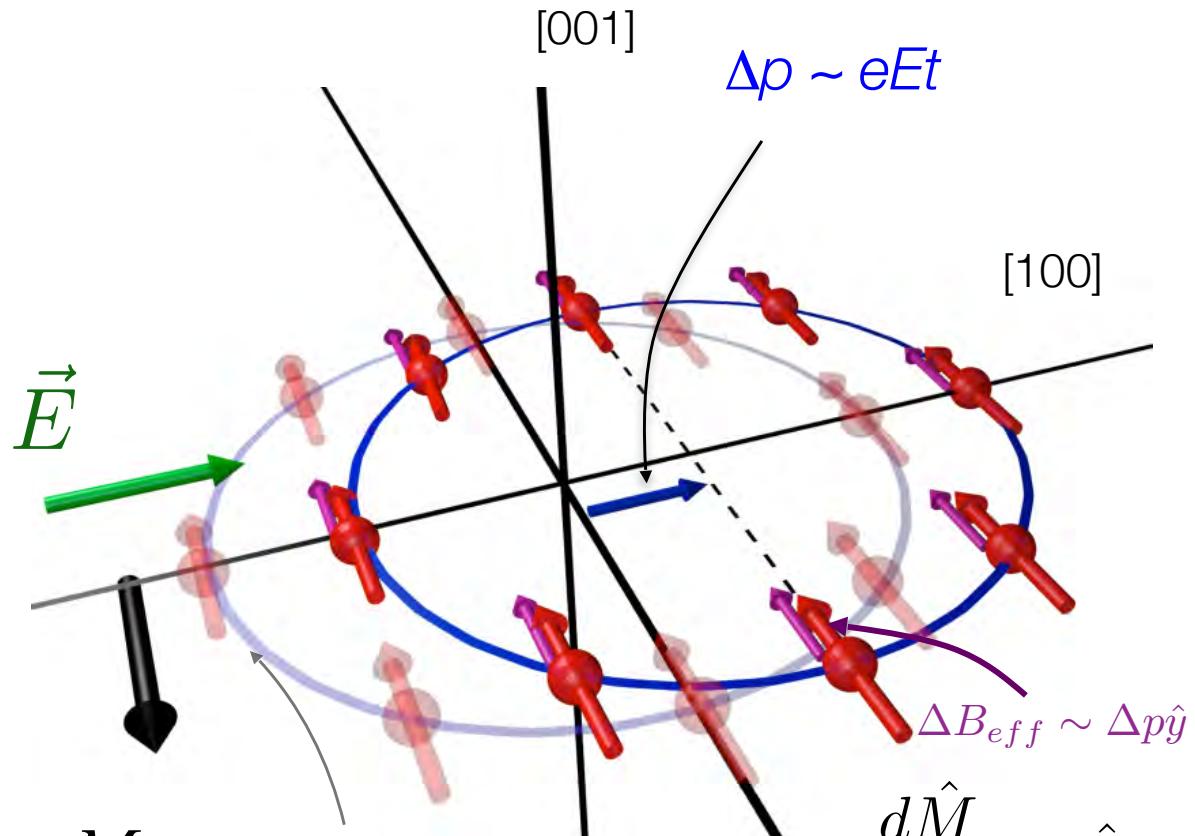
$$\frac{d\hat{M}}{dt} \sim \hat{M} \times \delta s_z \hat{z}$$

maximum $\delta s_z \hat{z}$ for $\vec{M} \parallel \vec{E}$

Intrinsic (Berry phase) spin-orbit torque from Bloch eq.



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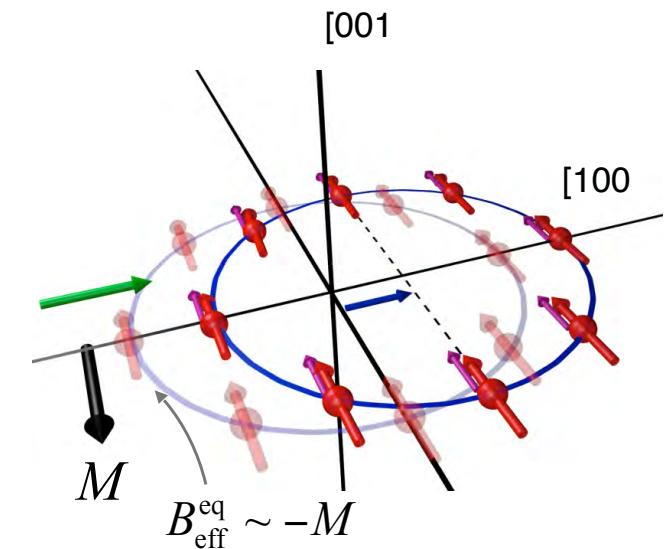


$$\frac{d\hat{M}}{dt} \sim \hat{M} \times \delta s_z \hat{z}$$

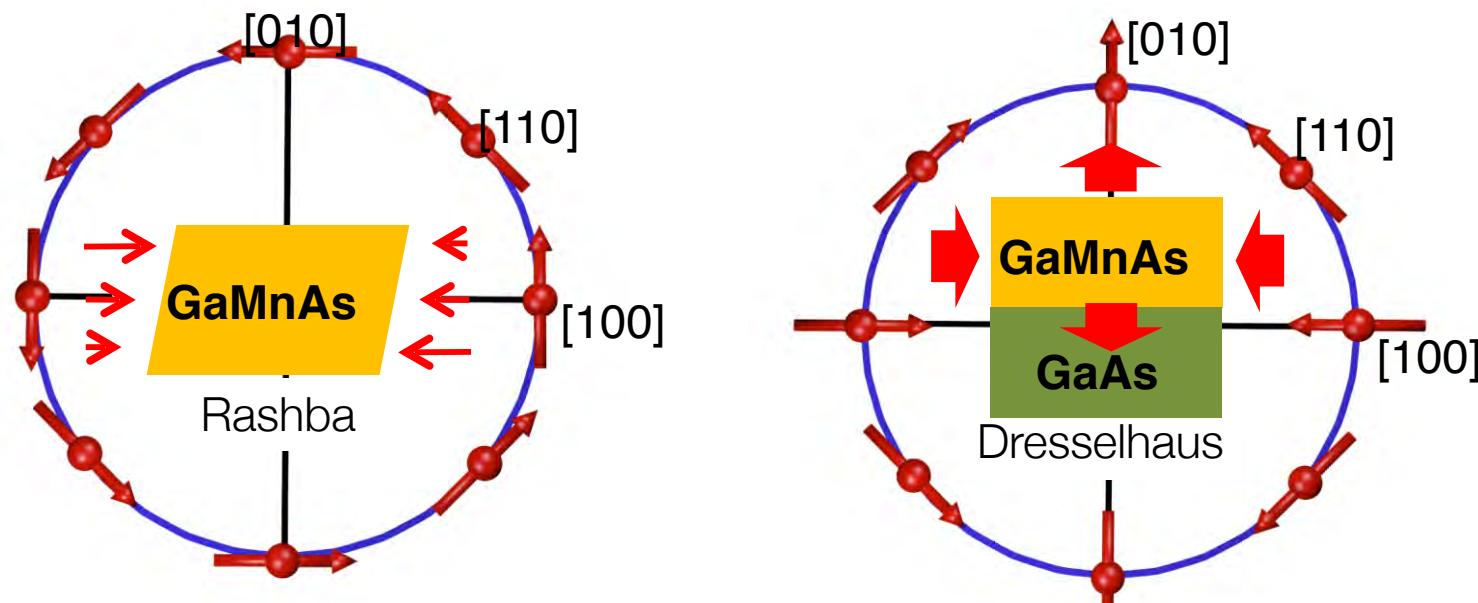
anti-damping

$$\boxed{\frac{d\hat{M}}{dt} \sim \hat{M} \times \delta s_z \hat{z}}$$

$$\delta s_z \hat{z} \sim (\vec{E} \times \hat{z}) \times \hat{M} \sim \cos(\theta_{\mathbf{M}-\mathbf{E}})$$



Intrinsic (Berry phase) spin-orbit torque in GaMnAs



$$\left(\frac{d\hat{M}}{dt} \right)_{SOT} = \hat{M} \times \delta s_z(\theta_{\mathbf{M}-\mathbf{E}}) \hat{z}$$

angle between \mathbf{M} and current direction

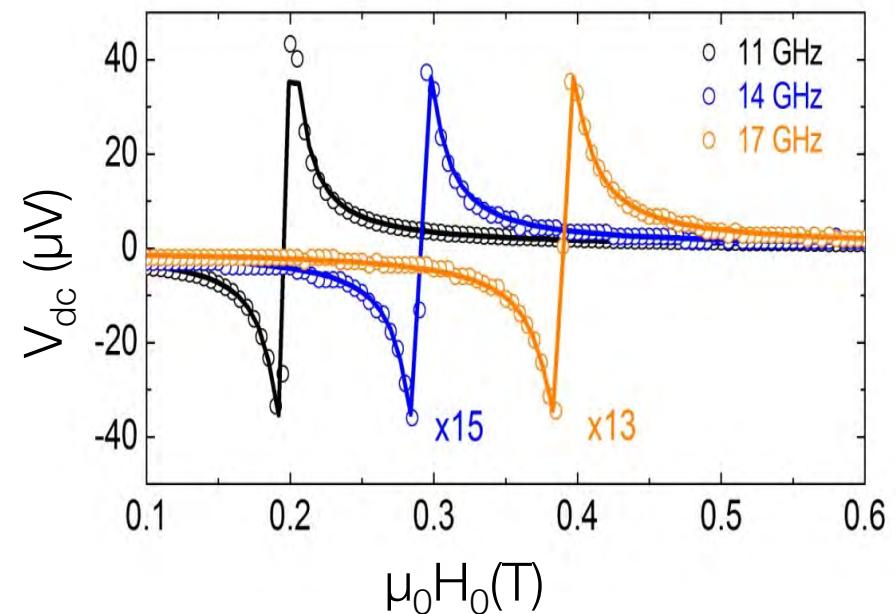
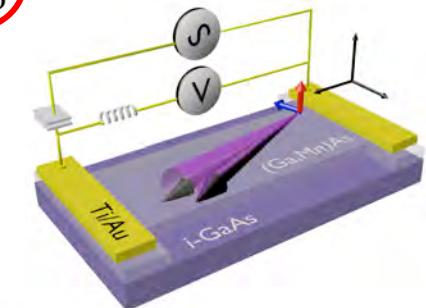
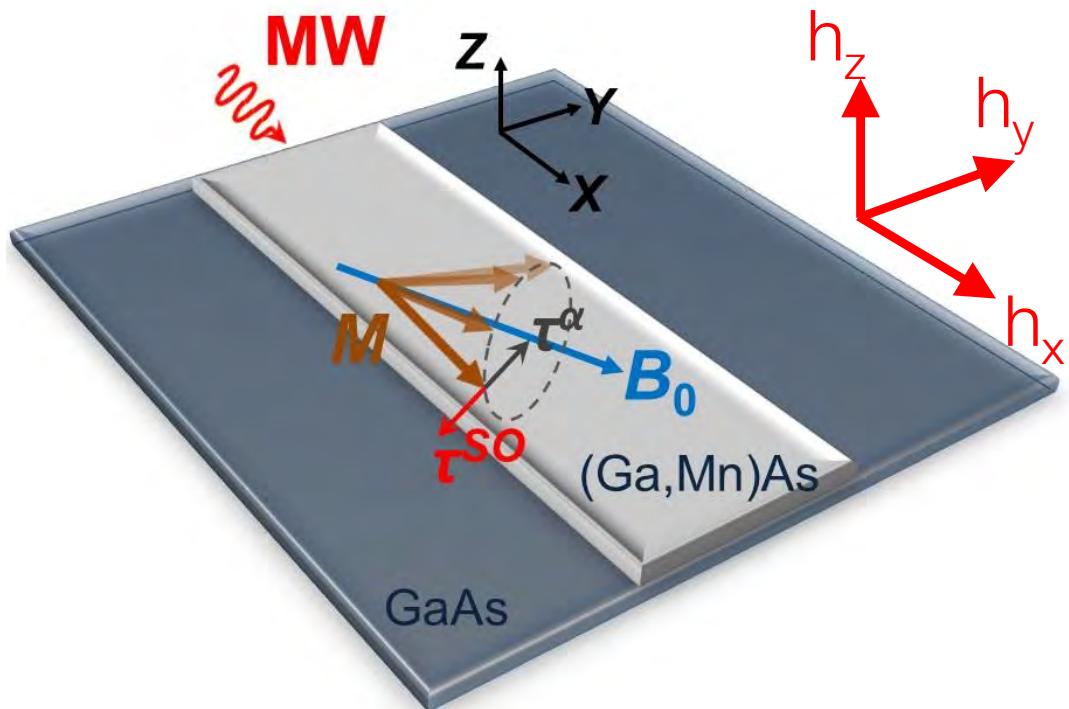
current direction	Rashba: $\delta s_{z,\mathbf{M}} \sim$	Dresselhaus: $\delta s_{z,\mathbf{M}} \sim$
$\mathbf{E} \parallel [100]$	$\cos \theta_{\mathbf{M}-\mathbf{E}}$	$\sin \theta_{\mathbf{M}-\mathbf{E}}$
$\mathbf{E} \parallel [010]$	$\cos \theta_{\mathbf{M}-\mathbf{E}}$	$-\sin \theta_{\mathbf{M}-\mathbf{E}}$
$\mathbf{E} \parallel [110]$	$\cos \theta_{\mathbf{M}-\mathbf{E}}$	$\cos \theta_{\mathbf{M}-\mathbf{E}}$
$\mathbf{E} \parallel [1-10]$	$\cos \theta_{\mathbf{M}-\mathbf{E}}$	$-\cos \theta_{\mathbf{M}-\mathbf{E}}$

Measuring spin-orbit fields: electrical induced/detected FMR



Landau-Lifshitz-Gilbert equation

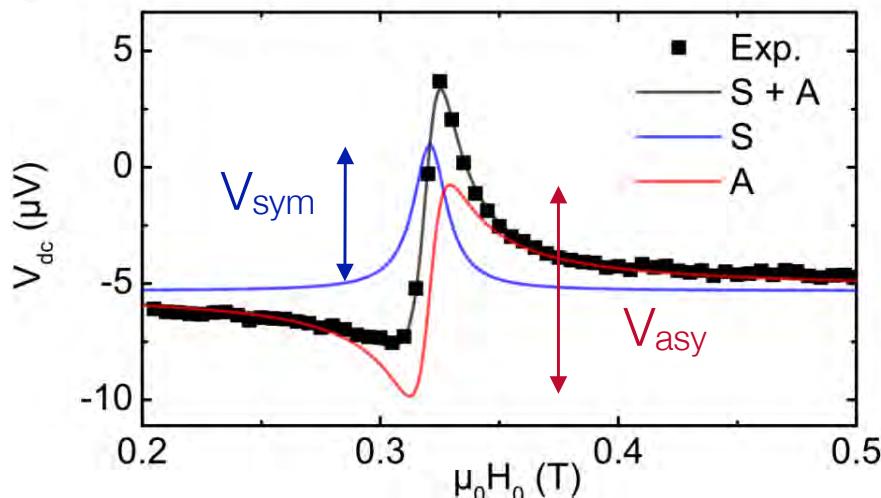
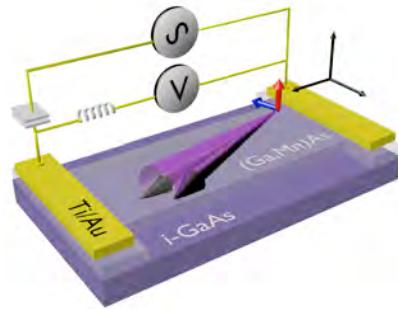
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{tot}} + \frac{\alpha}{M_s} \left(\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right) - \gamma \mathbf{M} \times \mathbf{h}_{\text{so}}$$



Because $h_{\text{so}} = -J_{\text{pd}} \Delta s$

the V amplitudes contain spin-orbit fields information.

Torque types and line-shapes



Anti-damping torque

$T_{in-plane}$ (or h_z)

$$V_{sym} = C_1 \times h_z(\theta_{M-E}) \sin(2\theta_{M-E})$$

+

Field-like/Rashba torque

$T_{out-of-plane}$ (h_x & h_y)

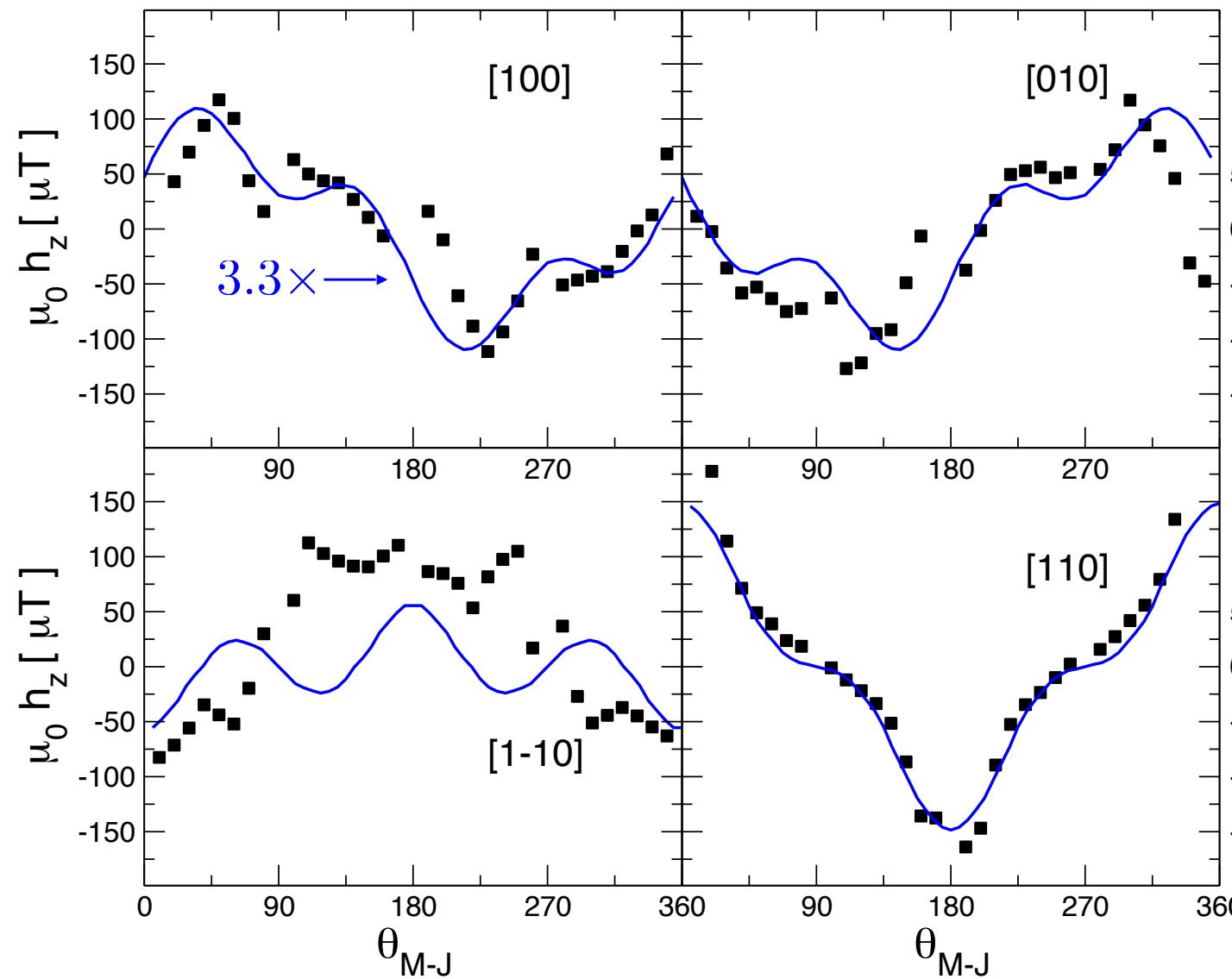
$$V_{asy} = C_2 \times \sin(2\theta_{M-E}) \times (-h_x(\theta_{M-E}) \sin(\theta_{M-E}) + h_y(\theta_{M-E}) \cos(\theta_{M-E}))$$

Kurebayashi, Sinova et al., Nature Nanotech. (2014)
Fang et al., Nature Nanotech. (2011)

Sample:
18 or 25 nm-thick GaMnAs 4 mm-wide

Comparison of Experiment - Theory

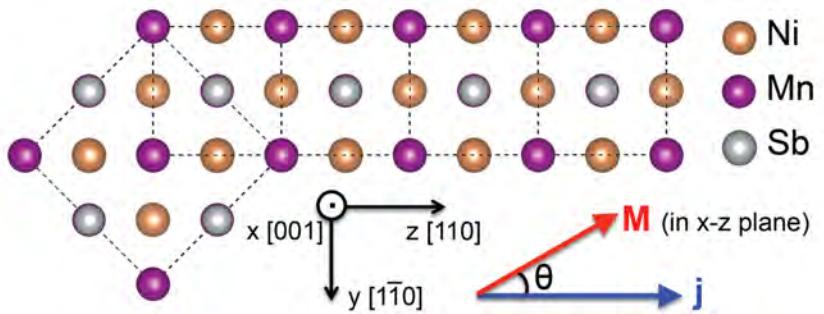
Solid line: Calculations with H_{KL} (captures higher harmonics)



Kurebayashi, et al., Nature Nanotech (2014)

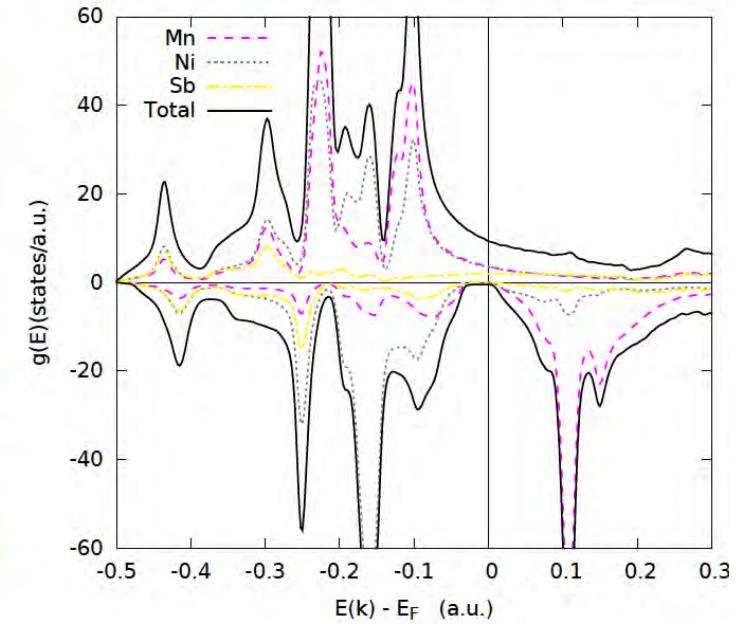
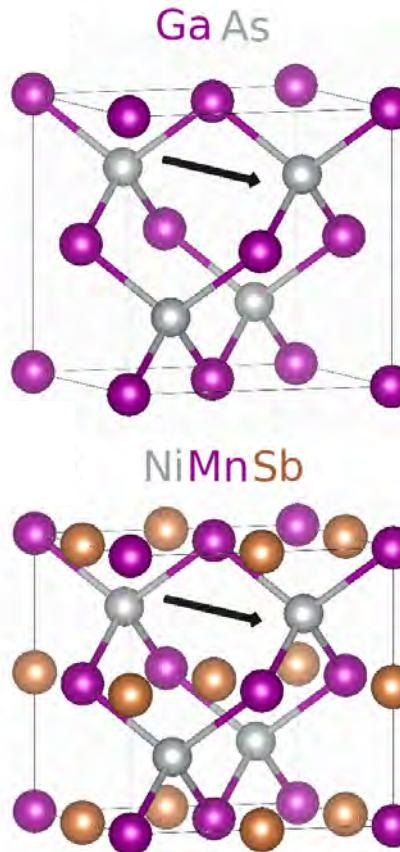


Other Materials: Half Heuslers



NiMnSb

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	$\begin{pmatrix} x_{21} & 0 & x_{23} \\ 0 & x_{12} & 0 \\ 0 & x_{32} & 0 \end{pmatrix}$	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	$\begin{pmatrix} x_{21} & 0 & 0 \\ 0 & x_{12} & 0 \\ 0 & 0 & 0 \end{pmatrix}$	-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	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$



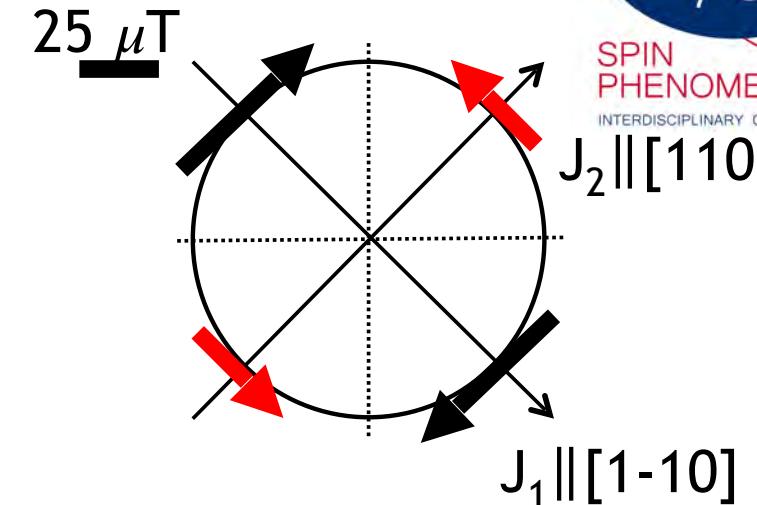
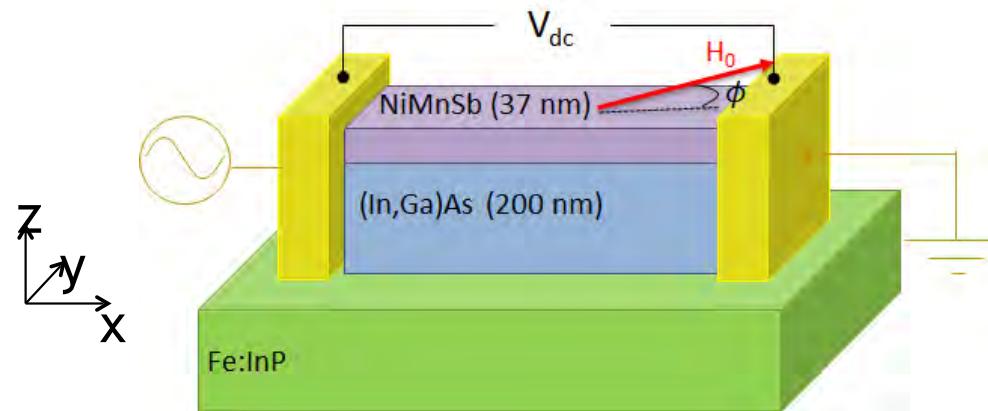
$T_c = 730$ K in bulk

Room-temperature SOT in NiMnSb

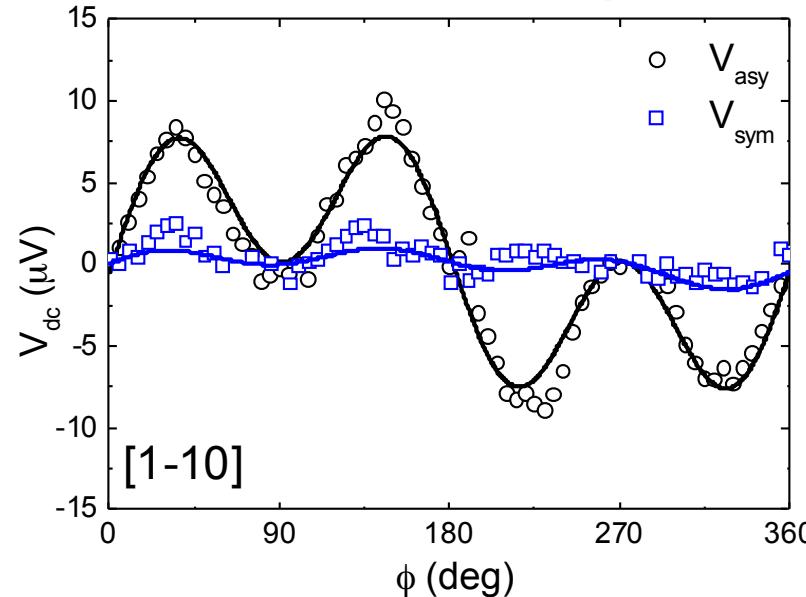


SPIN
PHENOMENA
INTERDISCIPLINARY CENTER

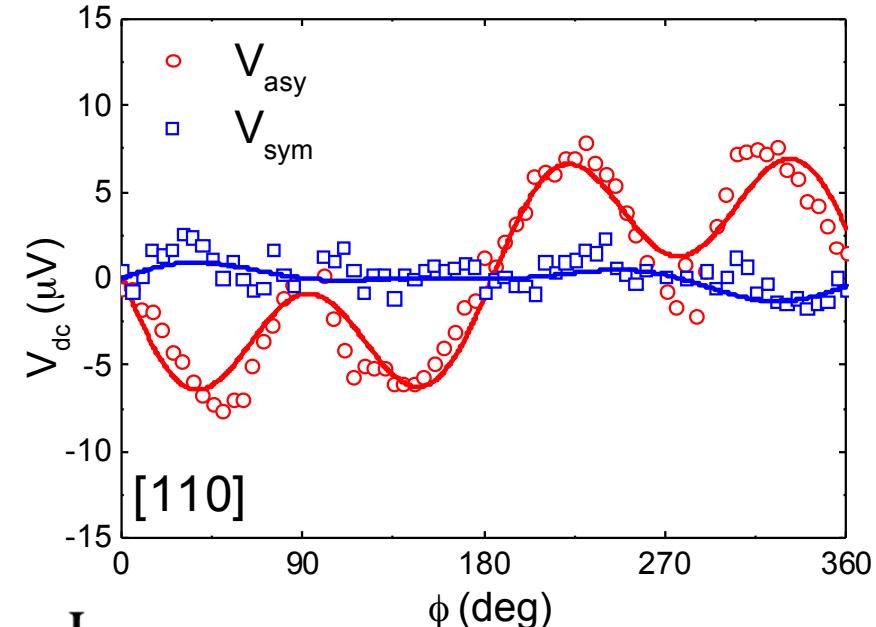
Ciccarelli, et al., Nature Physics (2016)



$$V_{\text{asy}}^{[1-10]}(\theta) \propto -B_x \sin 2\theta \sin \theta + B_y \sin 2\theta \cos \theta$$



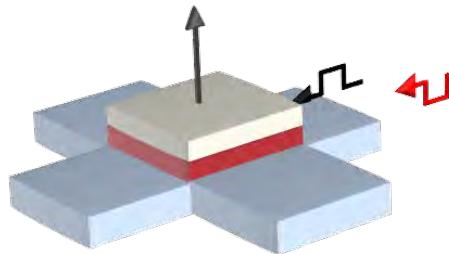
$$V_{\text{asy}}^{[110]}(\theta) \propto -B_x \sin 2\theta \sin \theta - B_y \sin 2\theta \cos \theta$$



The driving field is linear in current: $B_{\text{SO}} \sim J$

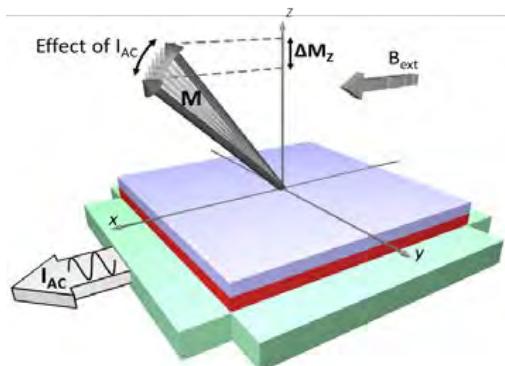
Measurement Techniques

Magnetization switching:



Miron et al.,
Nat. Mater. 2010; Nature 2011

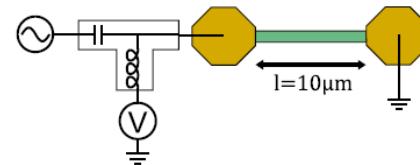
AC Hall voltage and AMR modulation



Piet et al., APL 2010;
Garello et al., Nat. Nanotech. 2013;
Kim et al., Nat. Mater. 2013

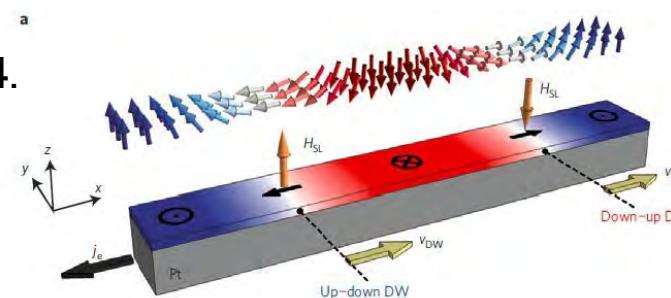
...

Spin-torque FMR:
(Resonant AC current excitation
AMR readout)



Liu et al., PRL 2011
Fang et al., Nat. Nanotech. 2011
Kurebayashi et al. Nat. Nanot. 2014

MOKE Fan et al., Nat. Comm. 2014.
Domain wall motion



Emori et al., Nat. Mater. 2013
Ryu et al., Nat. Nanotech. 2013
Haazen et al., Nat. Mater. 2013

Courtesy of P. Gambardella

Spin-orbitronics (spin-orbit torques) in ferromagnets and antiferromagnets



I. Spin Transfer Torque

- Phenomenology
- Anatomy of STT (no spin-orbit)
- Complex anatomy of STT with spin-orbit coupling

II. SHE and Inverse spin galvanic effect

- SHE and Inverse spin galvanic effect phenomenology

III. Spin-Orbit Torques in Ferromagnets:

- Spin-Orbit Torques:
 - Bilayer geometry: SOT vs SHE + STT
 - Intrinsic and Field like SOTs in ferromagnets

IV. Antiferromagnetic Spin-orbitronics: Néel SOTs

- Active manipulation of Néel order by currents: Néel spin-orbit torque

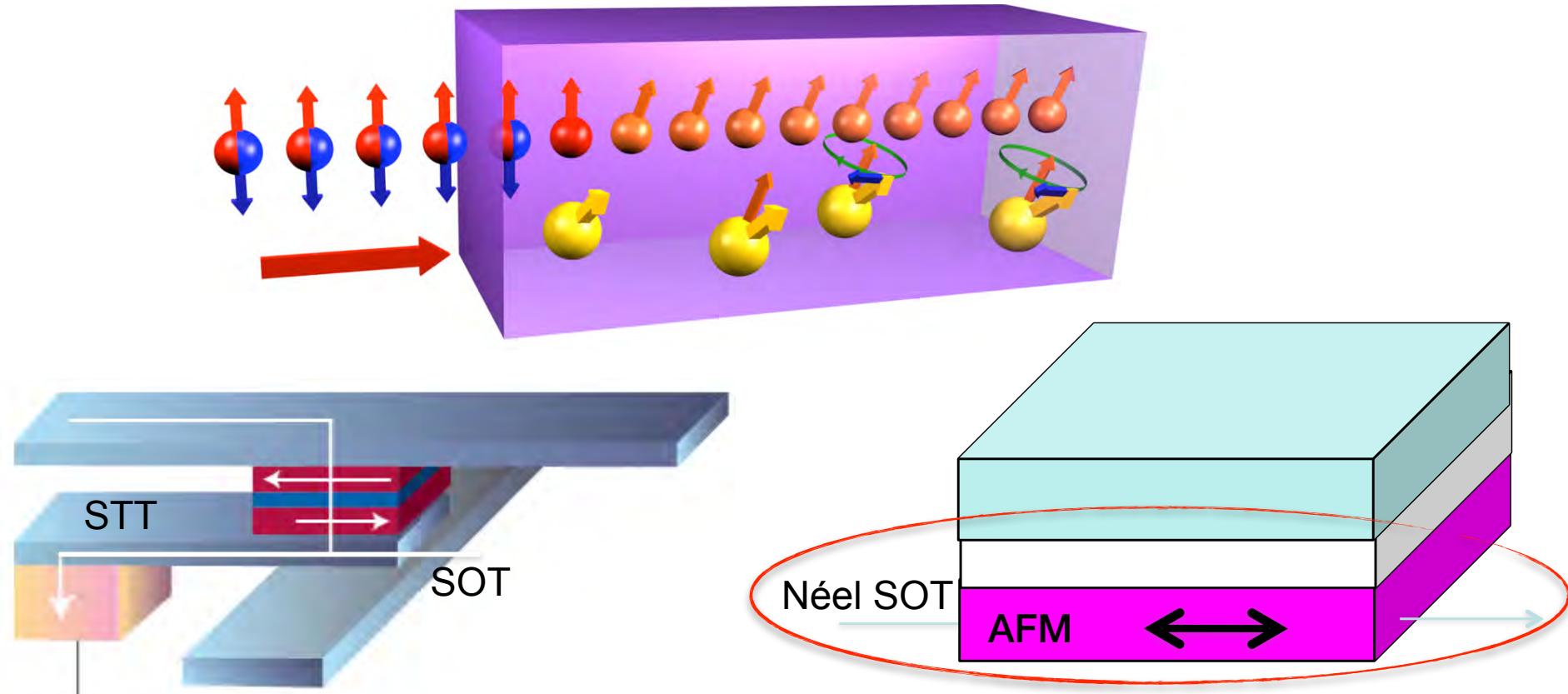
V. Topological Dirac Fermion + Antiferromagnets + Néel SOTs

Antiferromagnetic Spin-orbitronics



Writing by spin-orbit torque in a single-layer ferromagnet

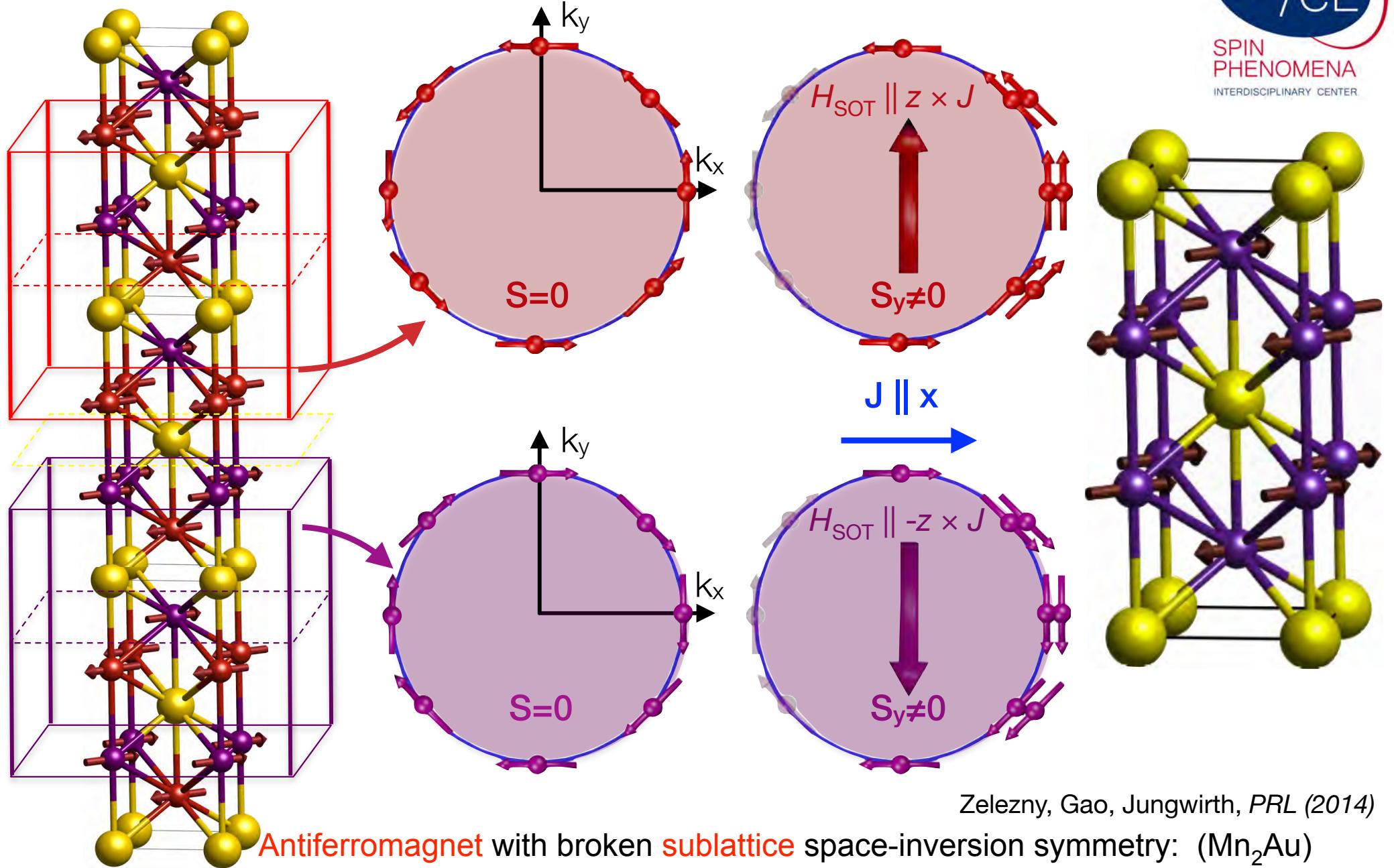
Magnet reversing itself : SOT



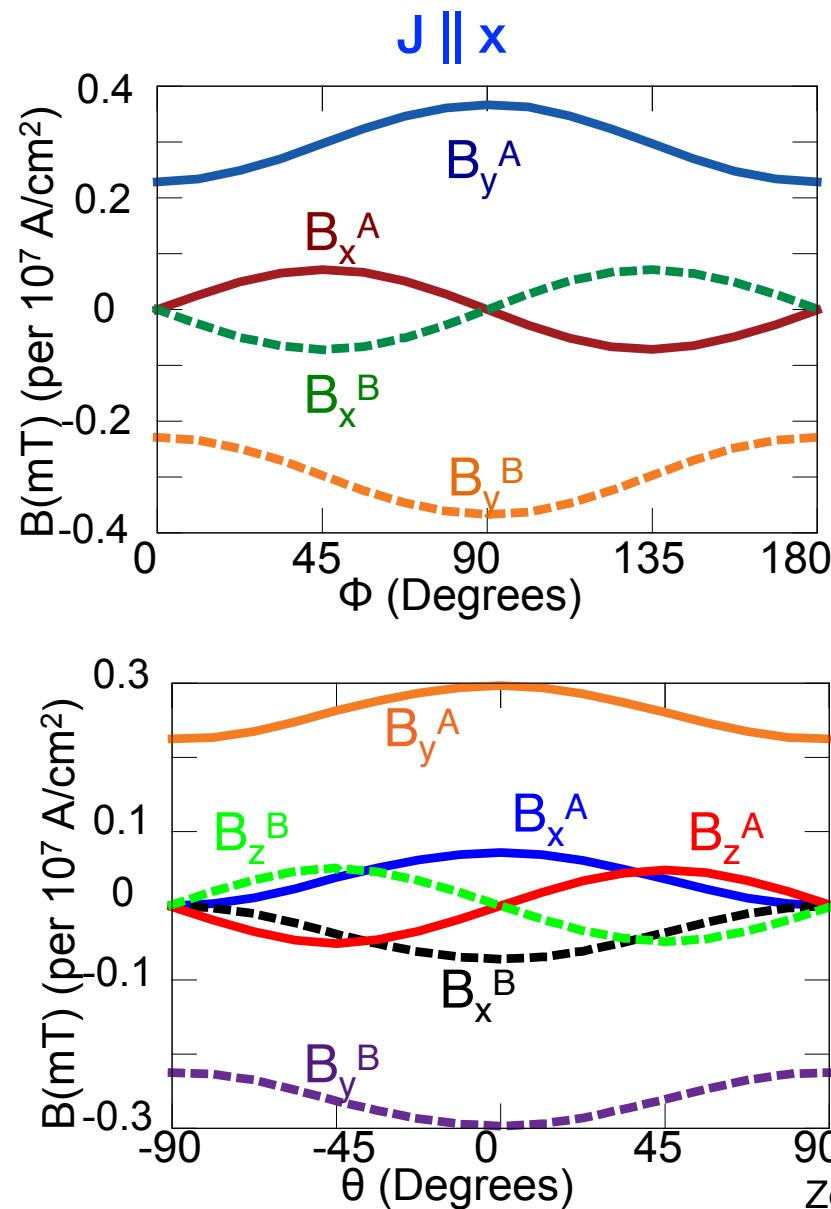
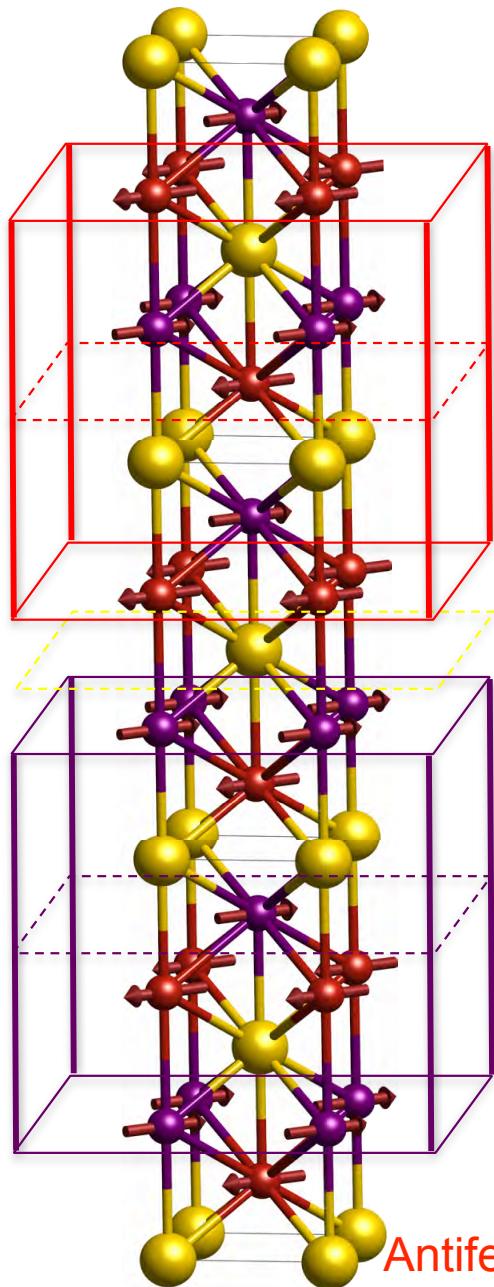
J. Zelezny, et al, *PRL* (2014)

What type of current-induced polarisation can we generate?

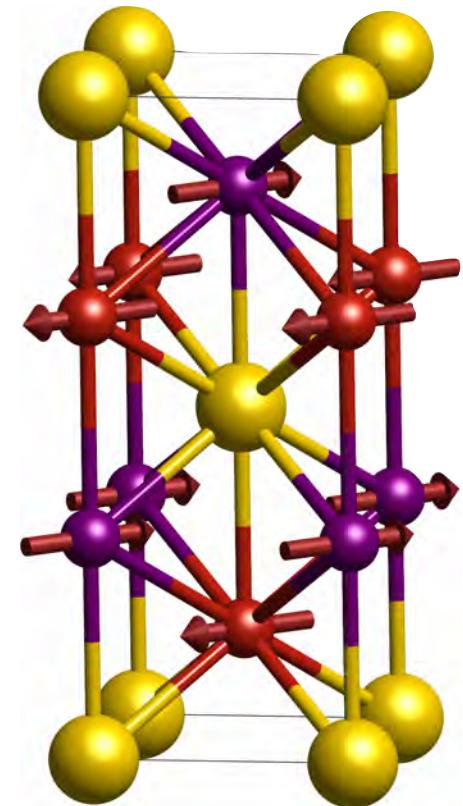
Néel spin-orbit torque in a single-layer antiferromagnet



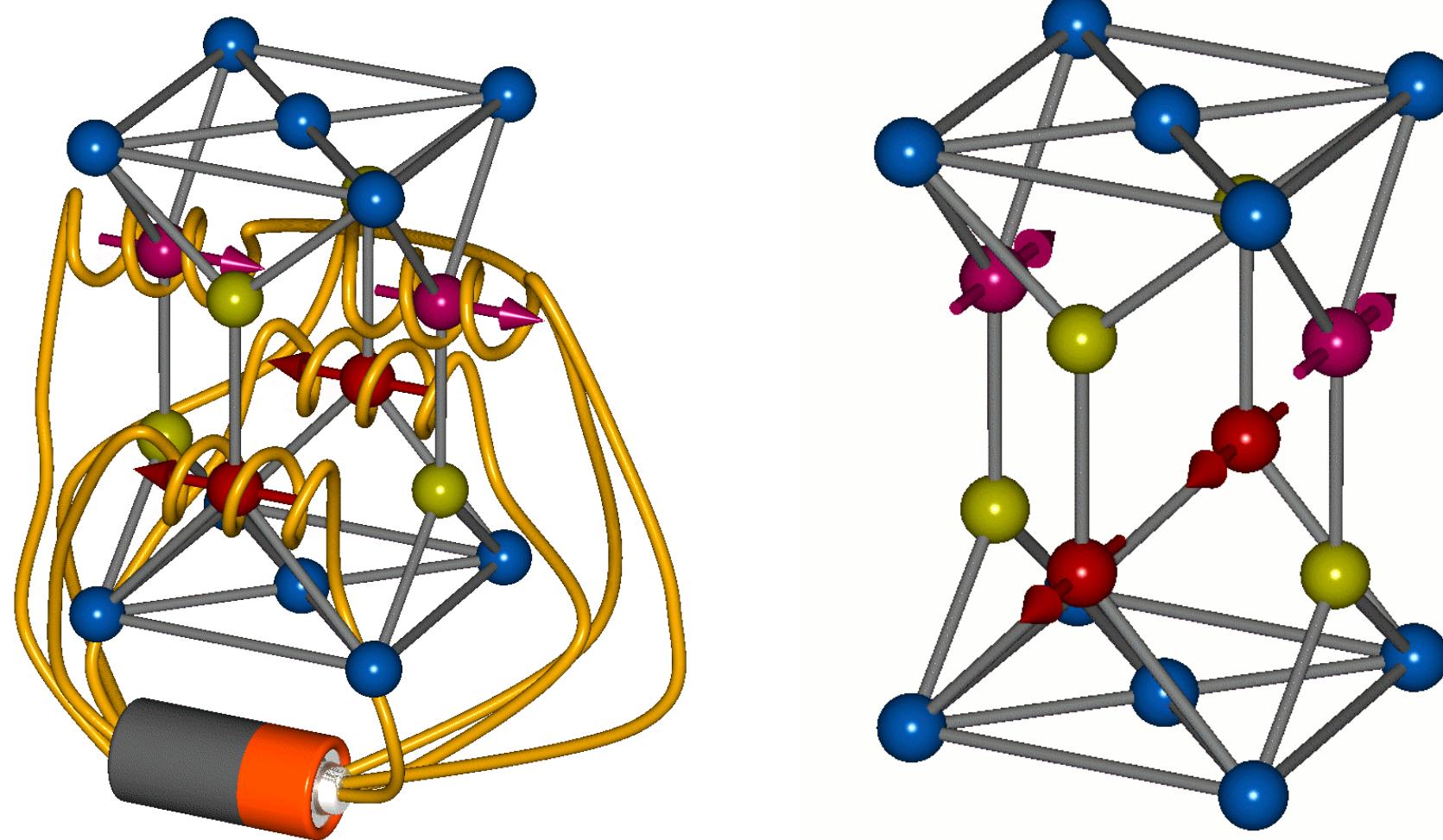
Néel spin-orbit torque in a single-layer antiferromagnet



Zelezny, Gao, Jungwirth, *PRL* (2014)



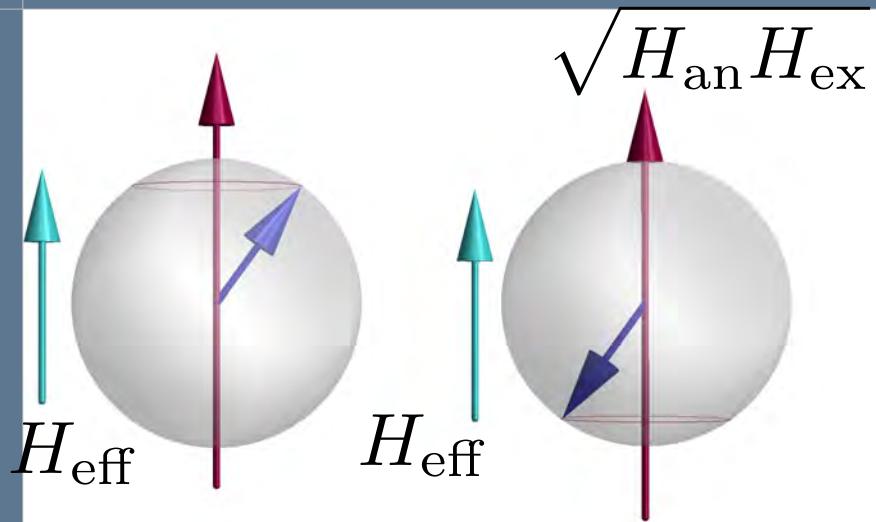
How it works - kind of



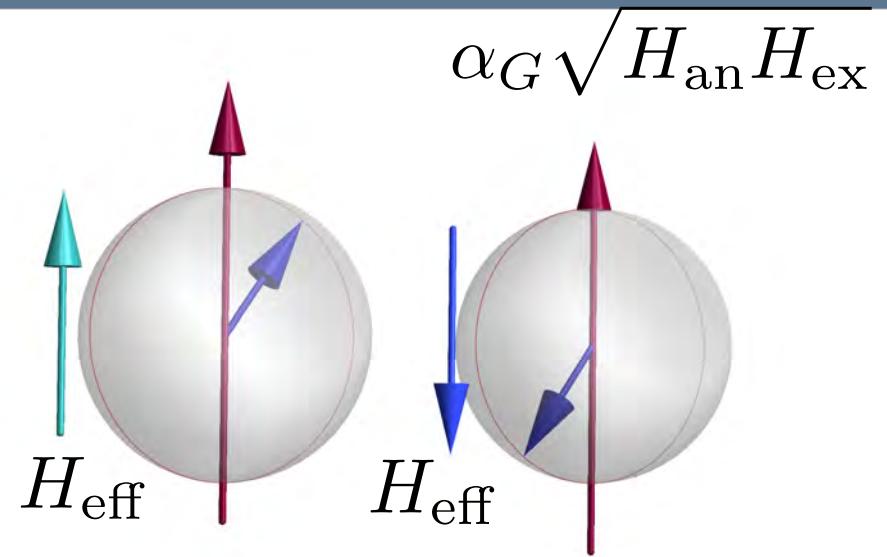
Frank Freimuth

Classification of torques

Field-like, $M \times p$

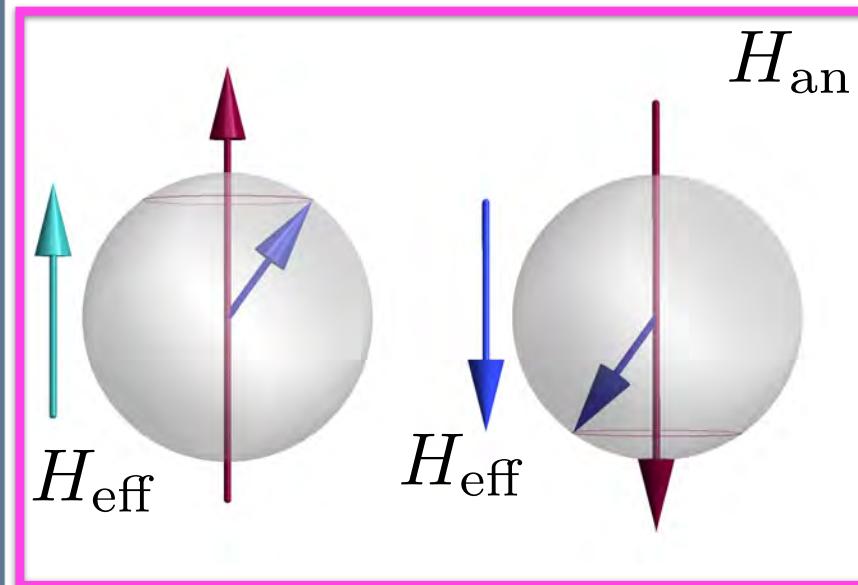


Antidamping-like, $M \times p \times M$

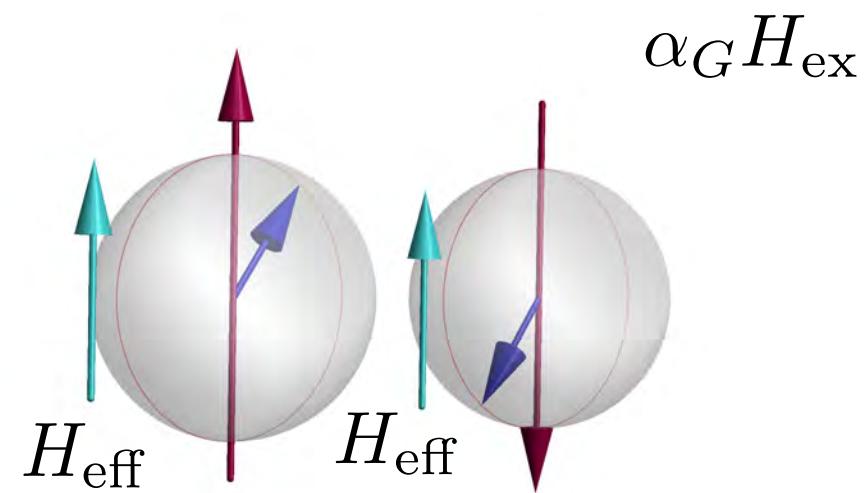


Non staggered
 $p_1 = p_2$

Staggered
 $p_1 = -p_2$



$$H_{\text{an}}$$



$$\alpha_G H_{\text{ex}}$$

How to use the Neel SOTs?

Staggering antiferromagnetic domain wall velocity in a staggered spin-orbit field

O. Gomonay,^{1,2} T. Jungwirth,^{3,4} and J. Sinova^{1,3}

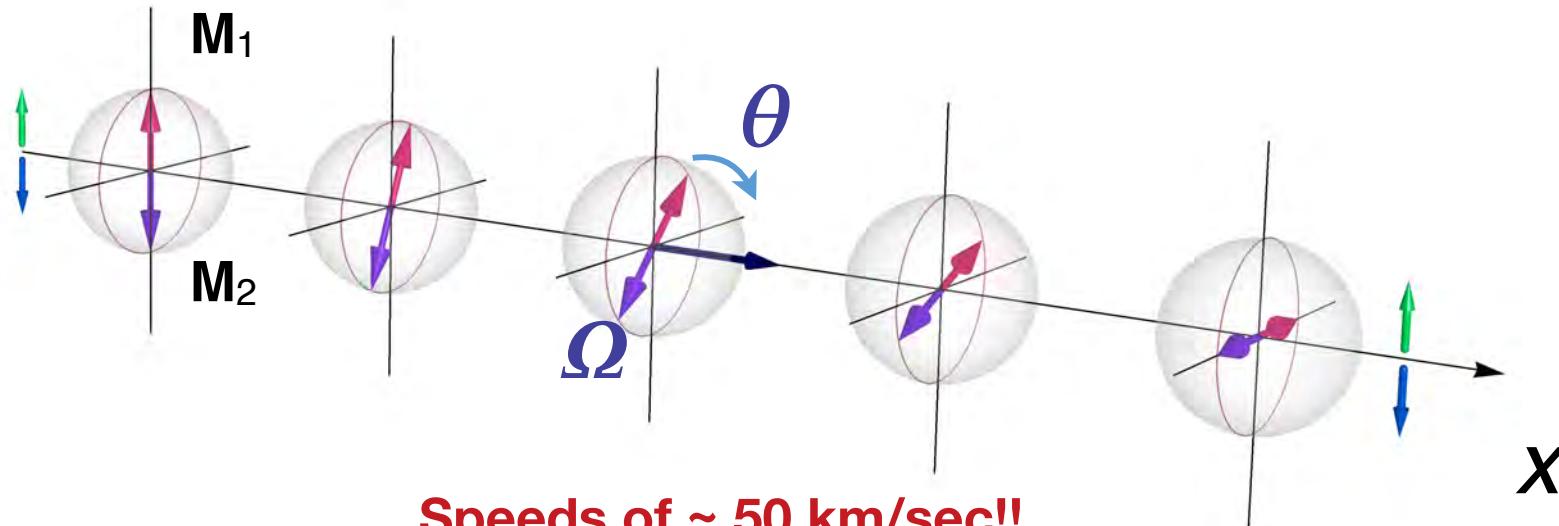
¹*Institut für Physik, Johannes Gutenberg Universität Mainz, D-55099 Mainz, Germany*

²*National Technical University of Ukraine "KPI", 03056, Kyiv, Ukraine*

³*Institute of Physics ASCR, v.v.i., Cukrovarnicka 10, 162 53 Praha 6 Czech Republic*

⁴*School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, United Kingdom*

Gomonay, Jungwirth, JS arXiv:1602.06766 (2016)



Speeds of ~ 50 km/sec!!

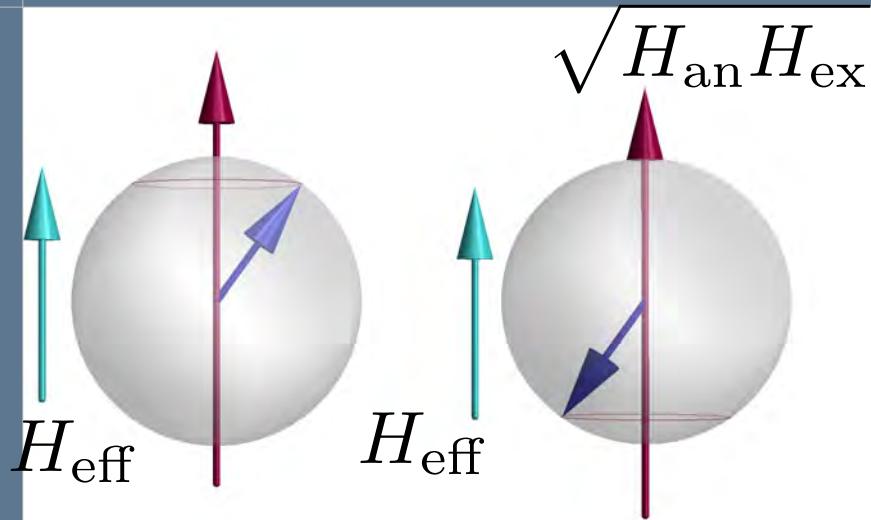
NEXT TALK

Classification of torques

Field-like, $M \times p$

Non staggered

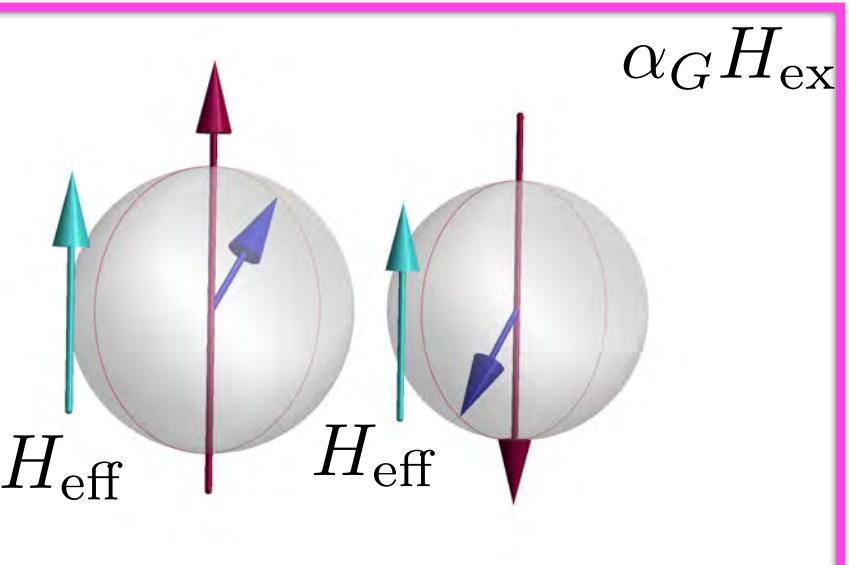
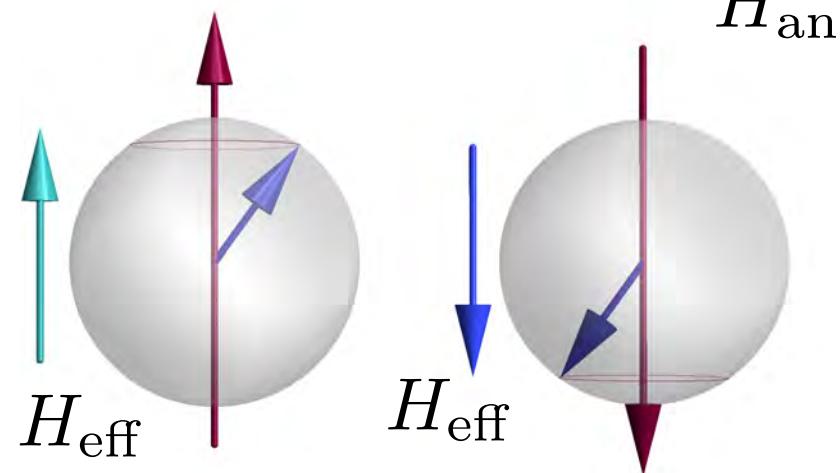
$$p_1 = p_2$$



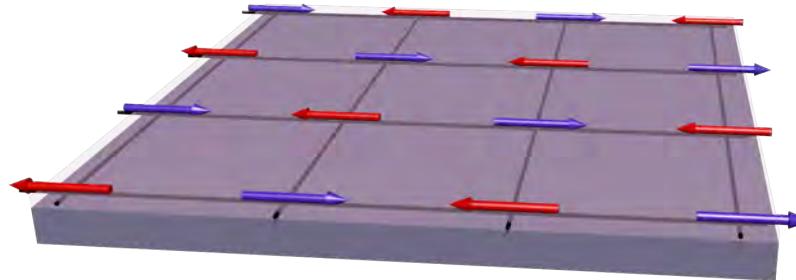
Antidamping-like, $M \times p \times M$

Staggered

$$p_1 = -p_2$$

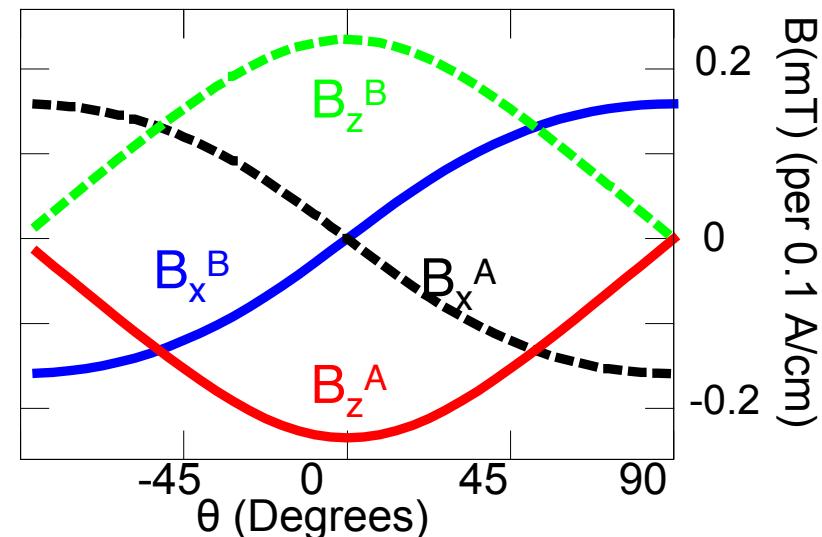
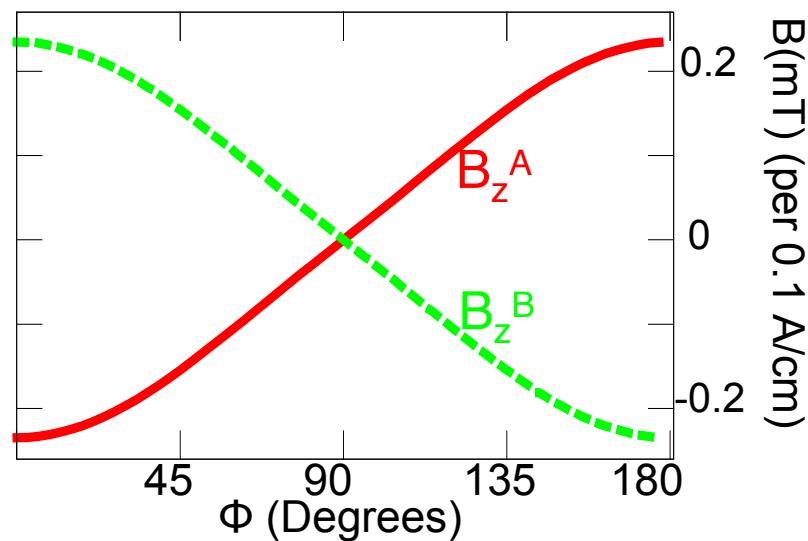


2D Antiferromagnet with Rashba SOC intrinsic Néel SOT can be much larger than FM SOTs!!



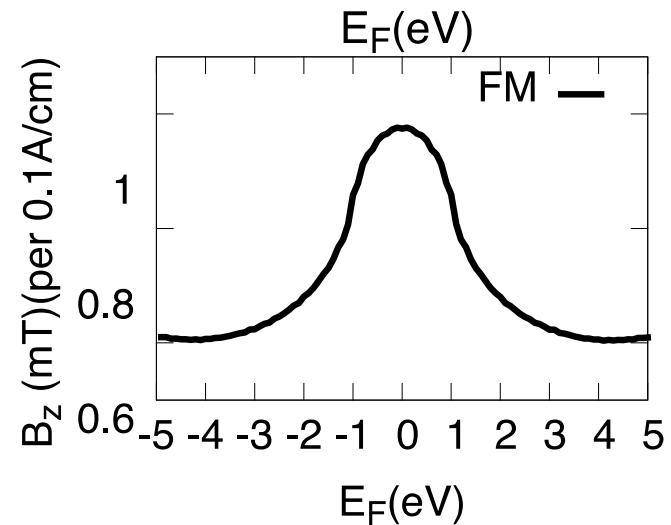
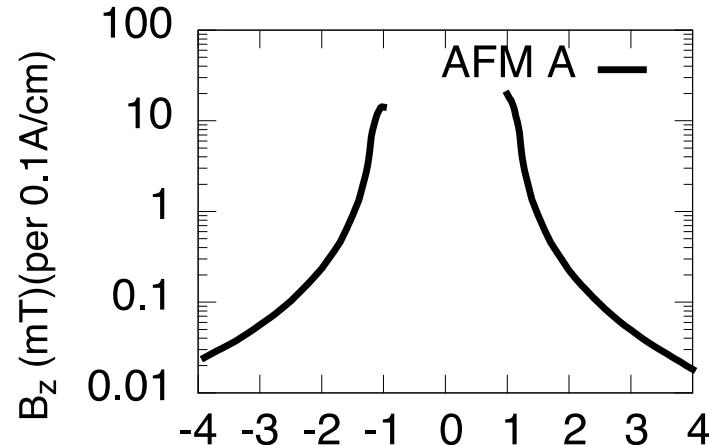
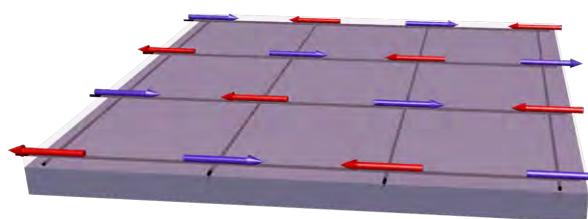
extrinsic/Rashba Néel SOT=0

BUT intrinsic Néel SOT $\neq 0$



Antiferromagnet with broken global space-inversion symmetry: 2D-AFM+Rashba

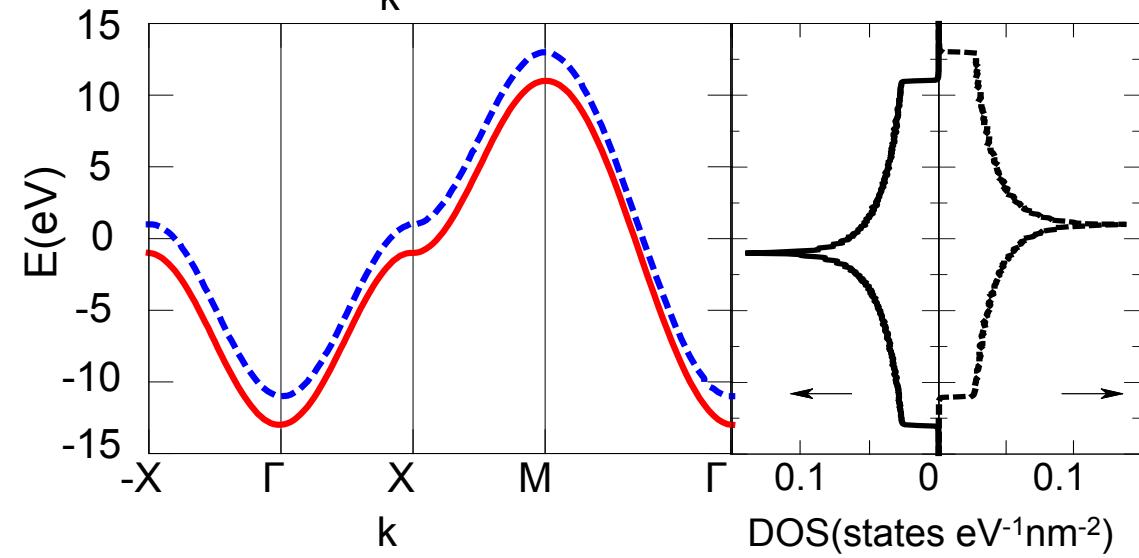
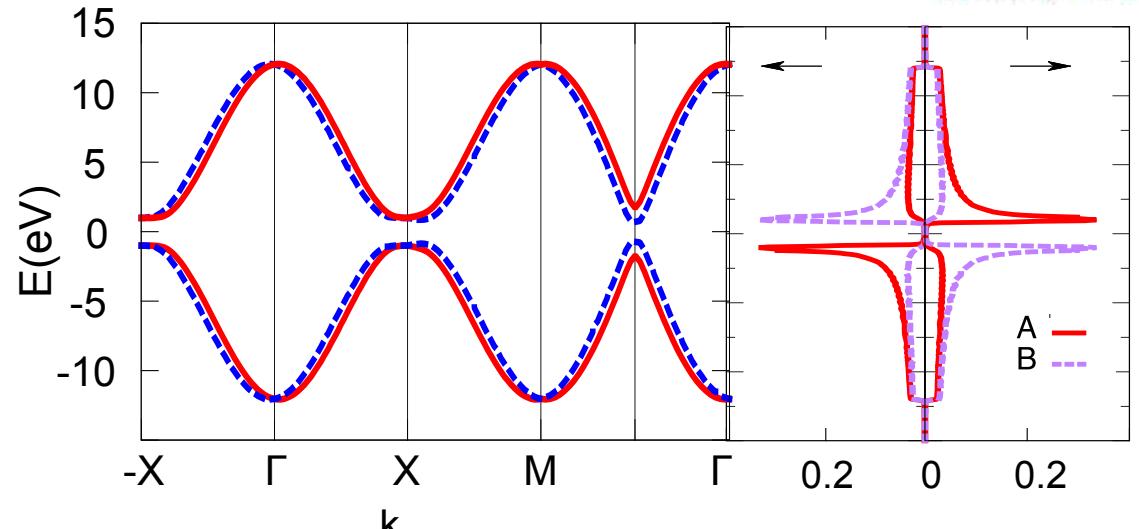
Writing by Néel spin-orbit torque in a single-layer antiferromagnet



Antiferromagnet with broken global space-inversion symmetry: 2D-AFM+Rashba

2D Antiferromagnet with Rashba SOC

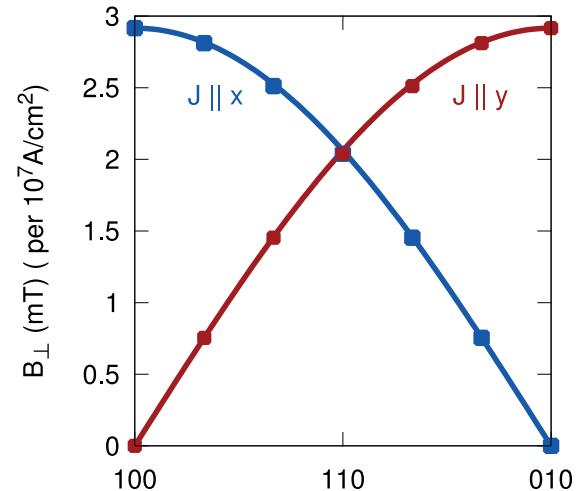
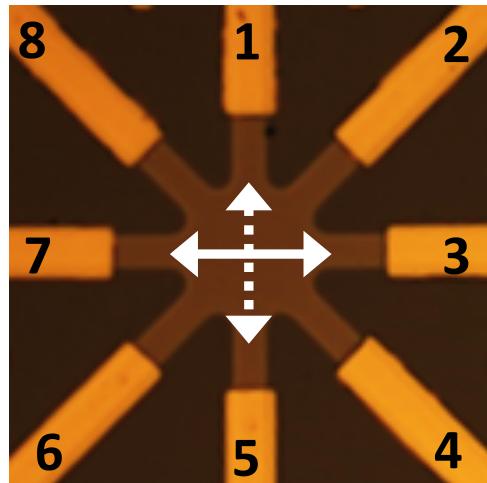
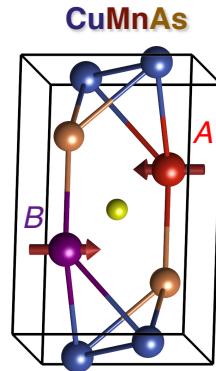
intrinsic Néel SOT can be much larger than FM SOTs!!



Experimental discovery of Néel SOT in CuMnAs

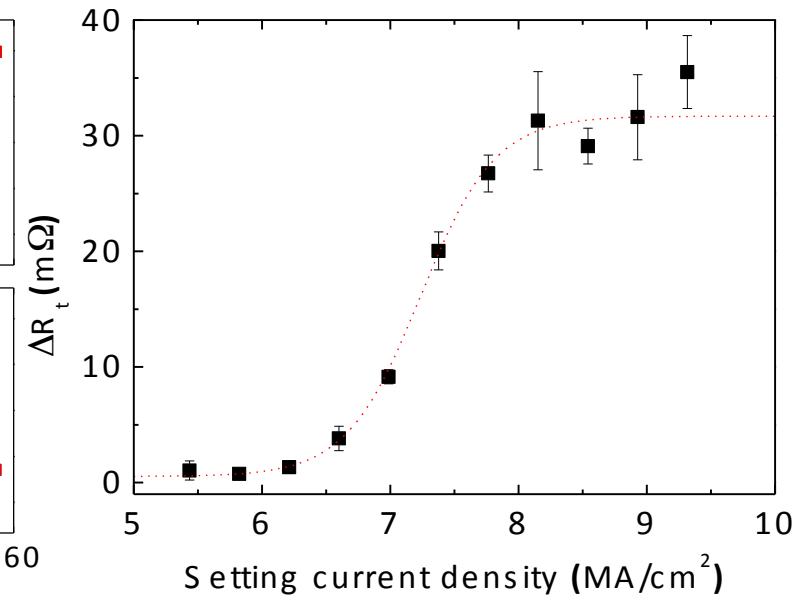
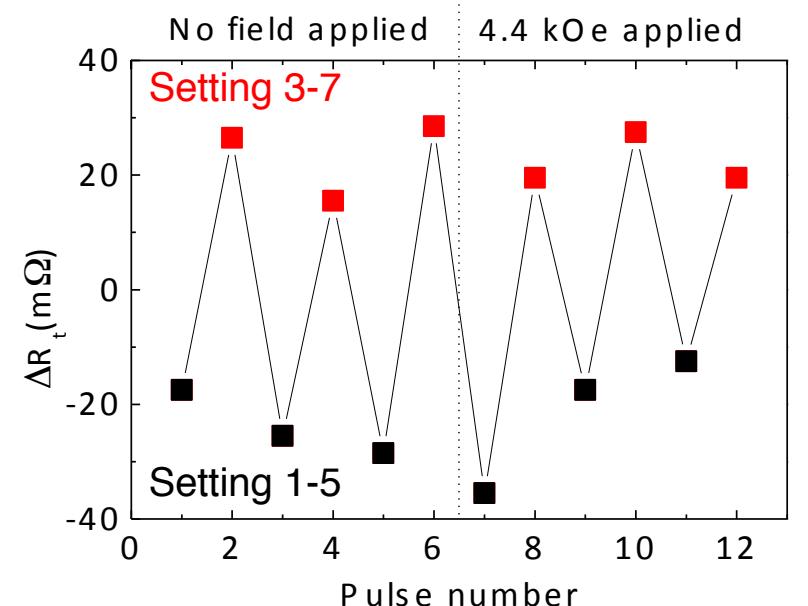
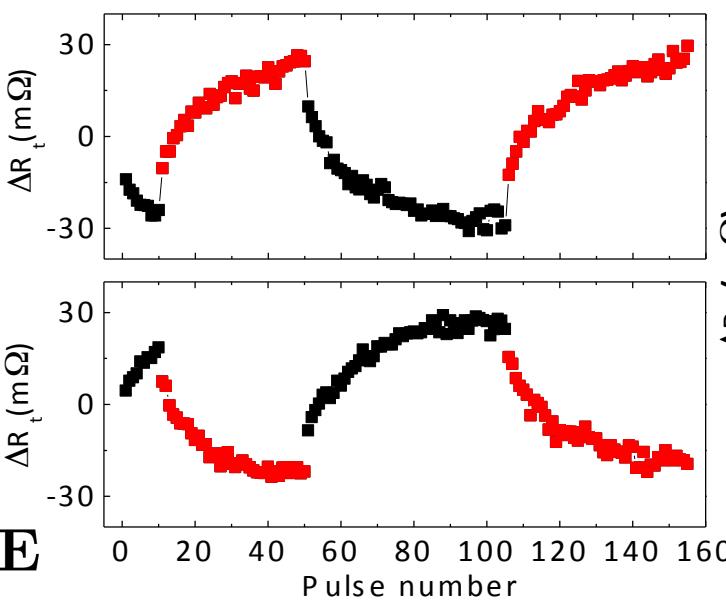


Wadley et al, Science 2016

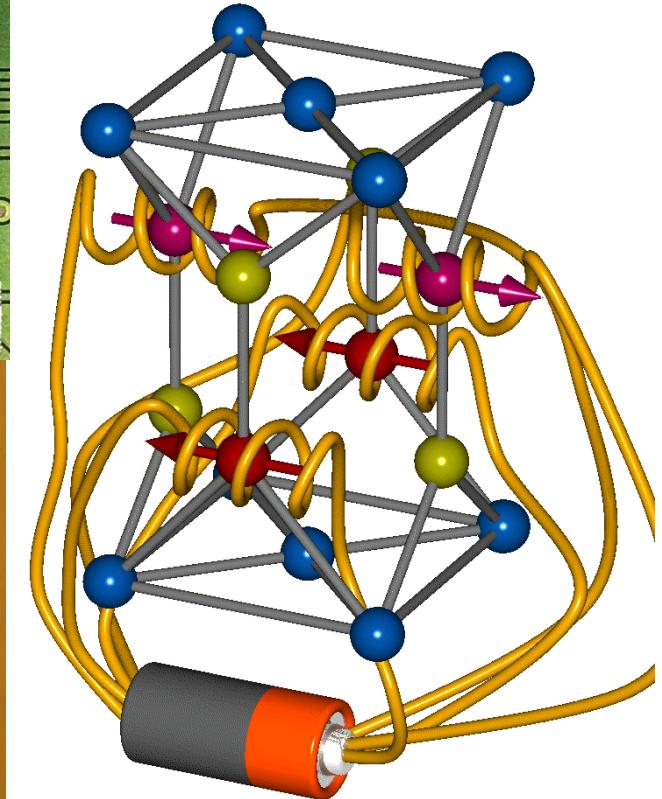
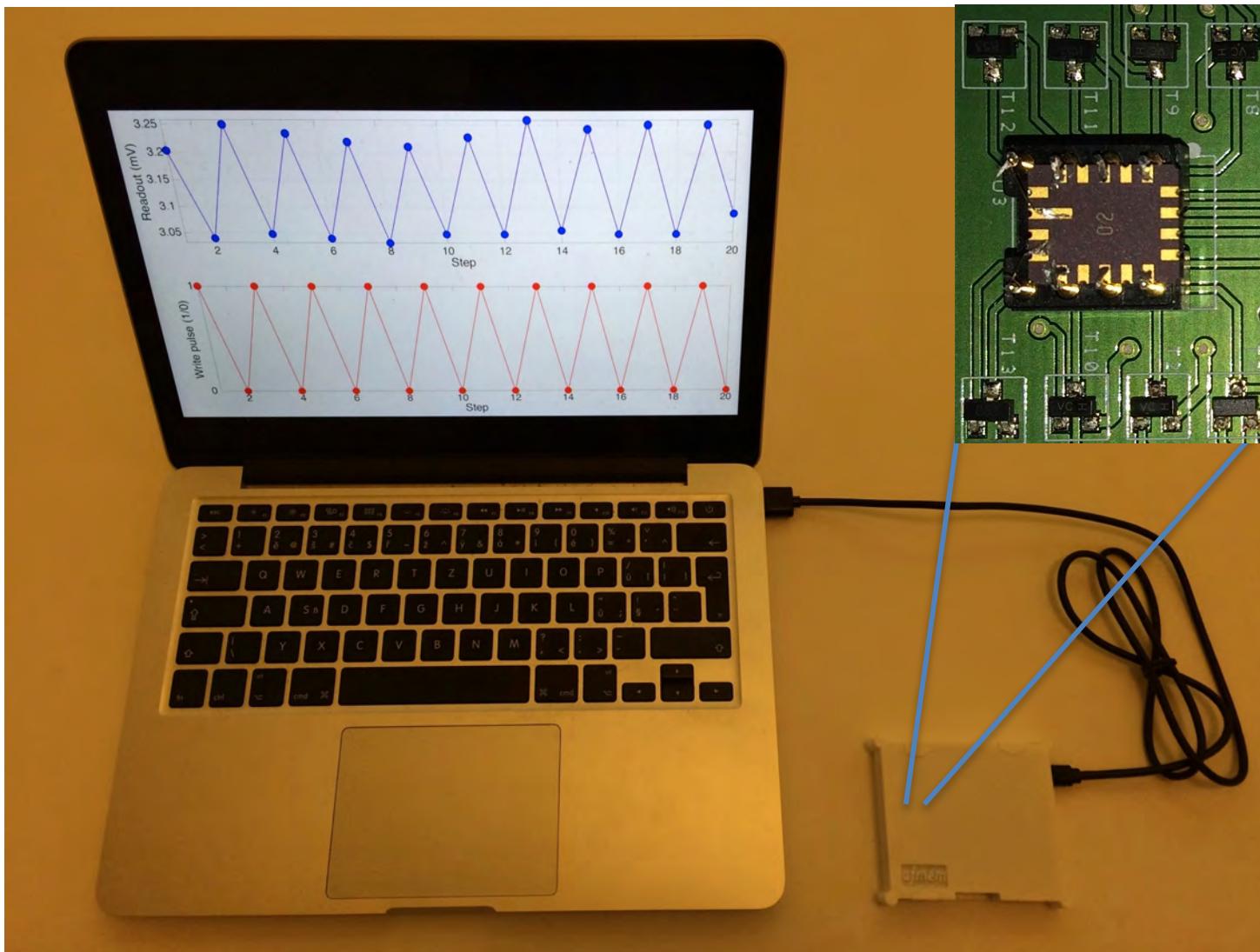


Rashba field: $B_{\text{eff}} \approx \mathbf{z} \times \mathbf{E}$

$$B \sim 3 \text{ mT per } 10^7 \text{ A cm}^{-2}$$



From prediction, to observation, to device in 1 one year!!

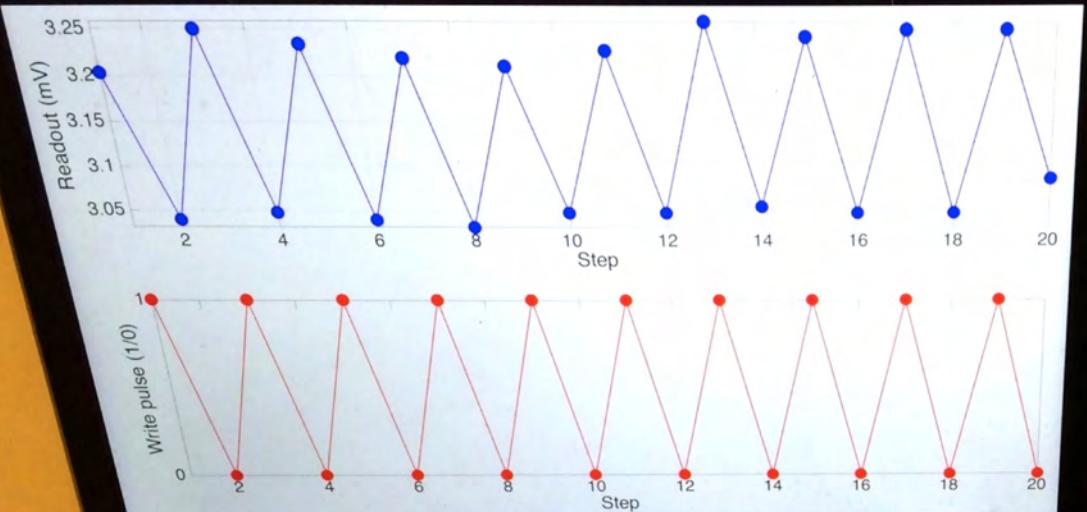


**Works like this but
not done like this**

Electrical read/write antiferromagnetic memory

Wadley, TJ et al. *Science* '16, TJ, Marti, Wadley, Wunderlich, *Nature Nanotech.* '16

Antiferromagnetic recording & spin-orbit torque

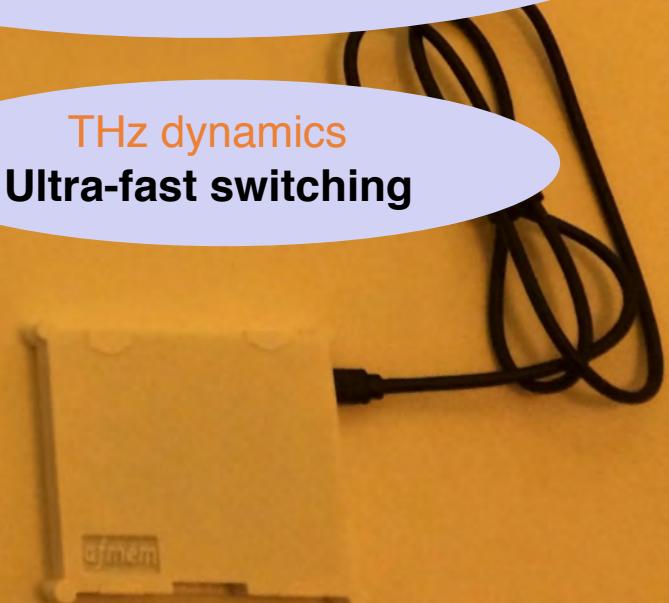


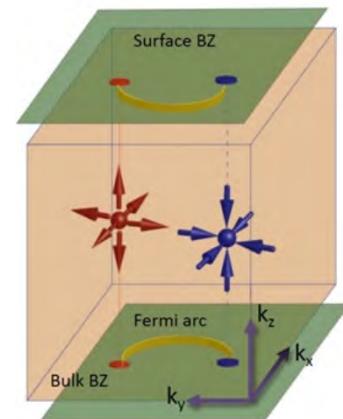
Spin; not charge based
Radiation-hard

Ordered spins
Non-volatile

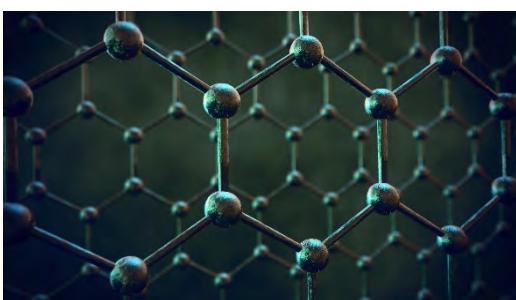
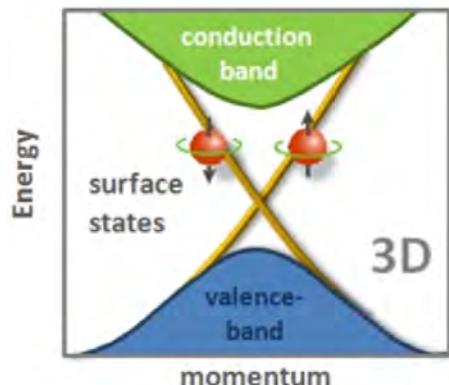
No net moment, no dipolar fields
Insensitive, invisible to magnetic fields,
no magnetic cross-talk

THz dynamics
Ultra-fast switching





Dirac/Weyl
semimetals



graphene

2D TI

3D TI

2016

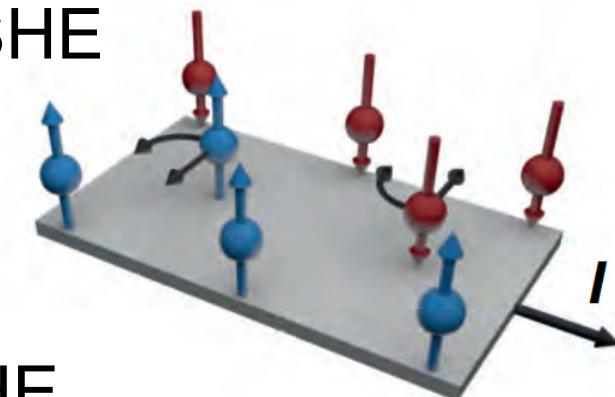
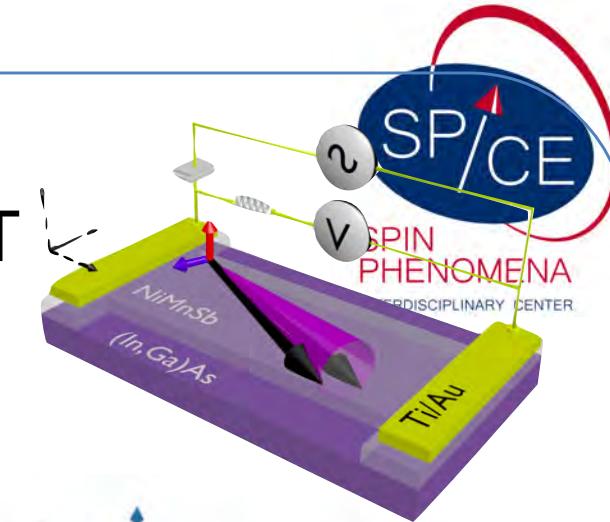
2003

Néel SOT

SOT

QSHE

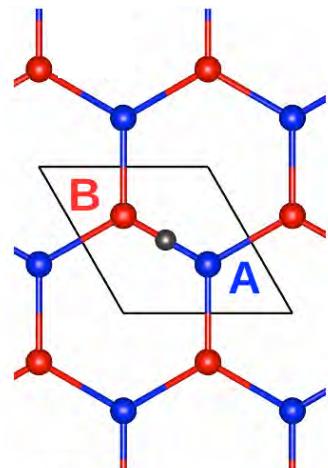
SHE



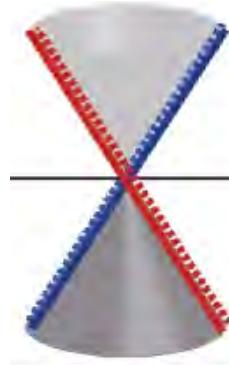
Antiferromagnetic spintronics and Dirac metals



Dirac fermions in graphene → topological insulators, semimetals, superconductors ...



Novoselov, Geim et al. 2004



Serendipitous overlap of symmetry conditions:

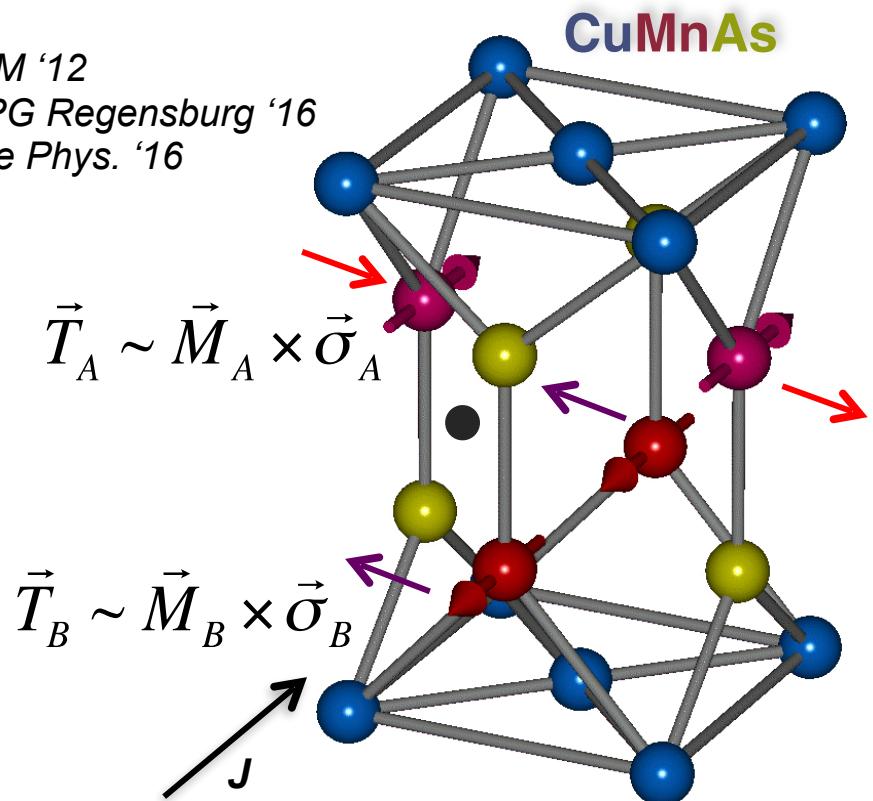
- Two sites in unit cell
- PT symmetry

Electric control of Dirac semimetal/semiconductor via AF

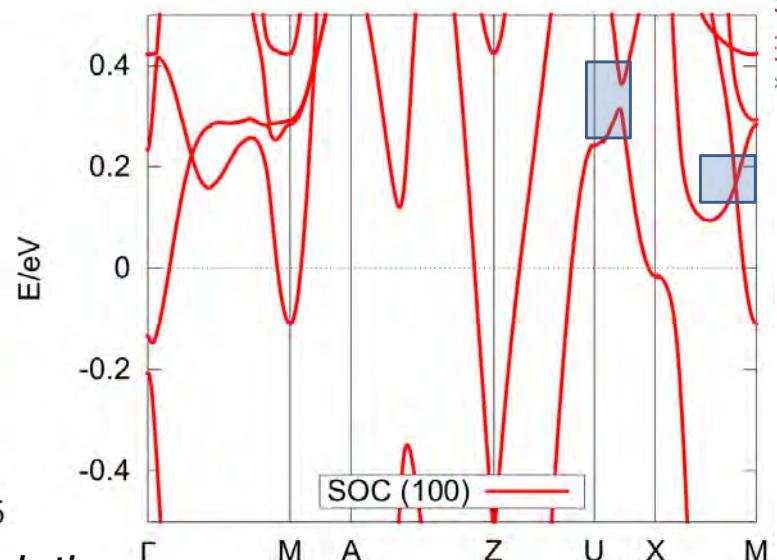
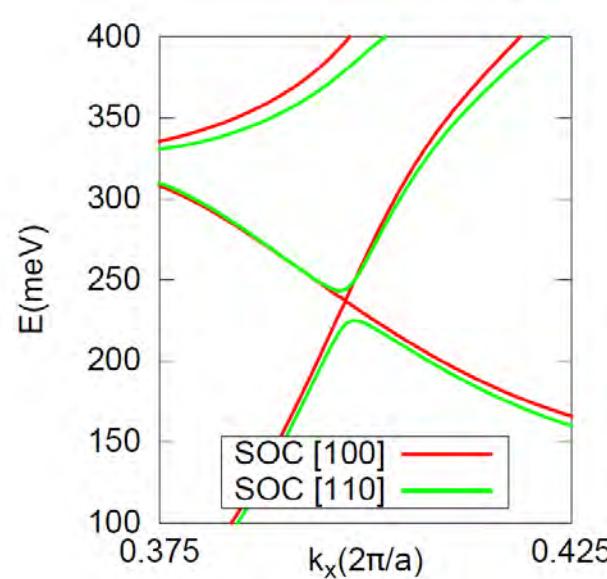
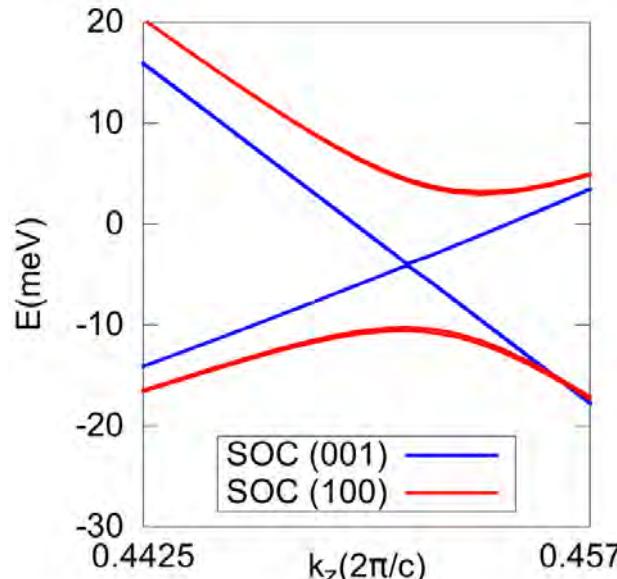
Šmejkal et al. DPG Regensburg '16

Inverse spin galvanic (Edelstein) torque
Local inversion asymmetry & antiferromagnet

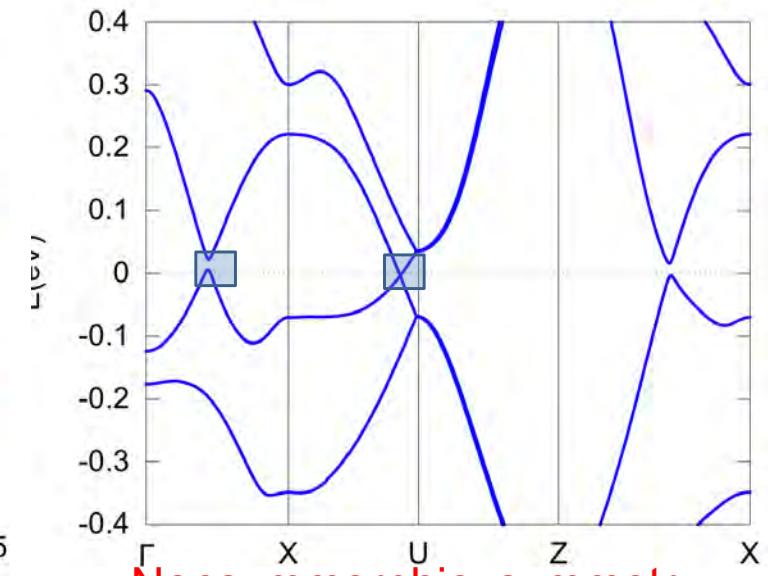
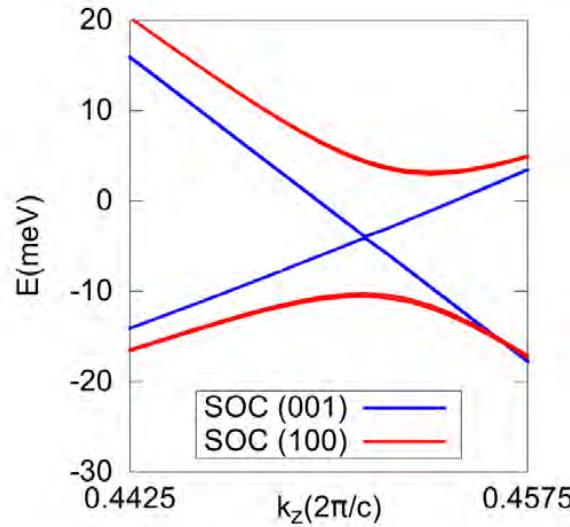
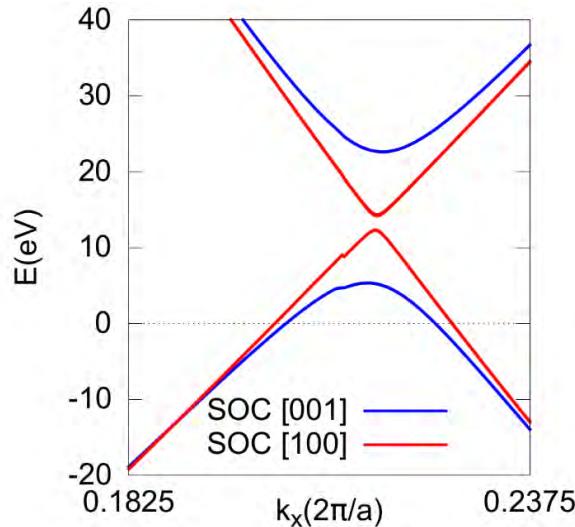
Máca et al. JMMM '12
Šmejkal et al. DPG Regensburg '16
Tang et al. Nature Phys. '16



Electrical control of Dirac fermions



Demonstration of inplane Field like torque manipulation



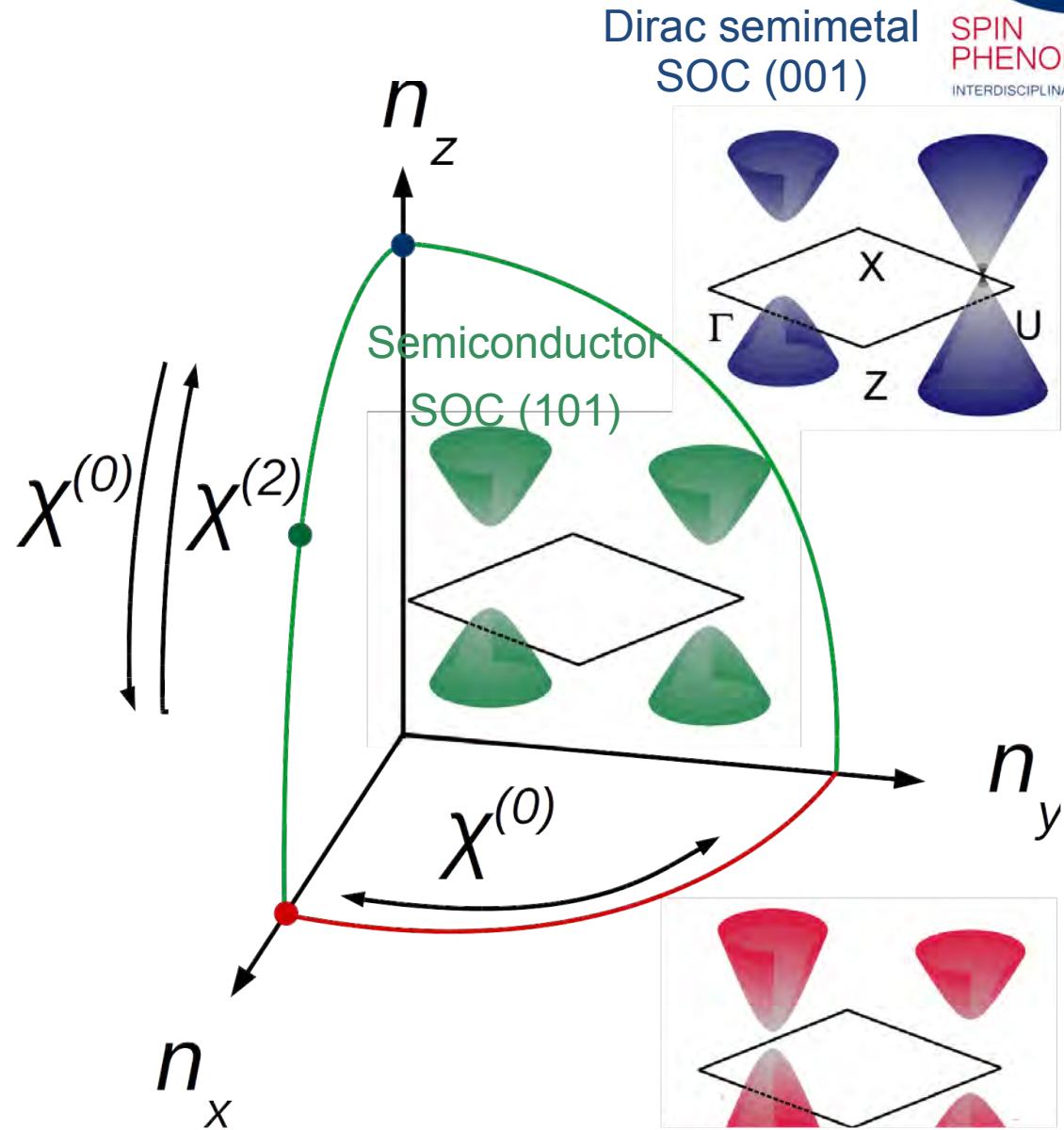
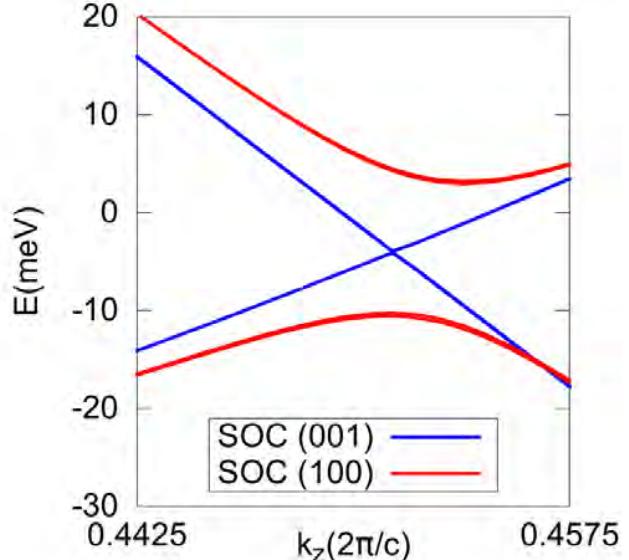
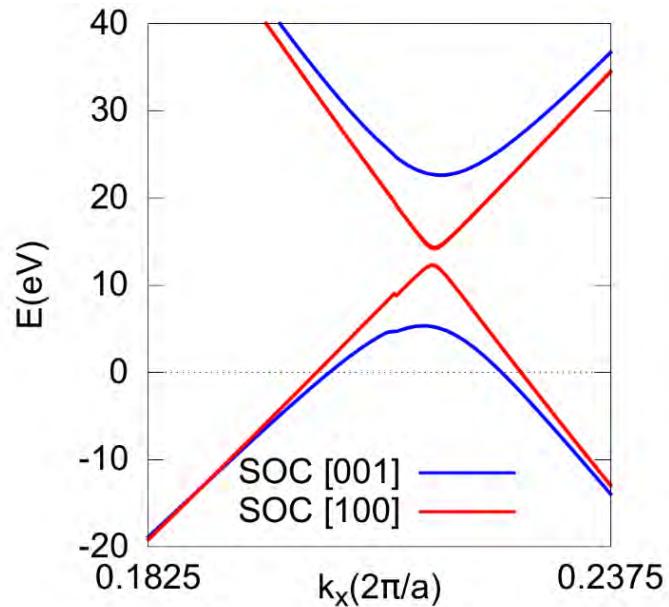
Demonstration of (001) → inplane Field like torque

Nonsymmorphic symmetry:
Screw axis+Glide plane

Electrical control of phases



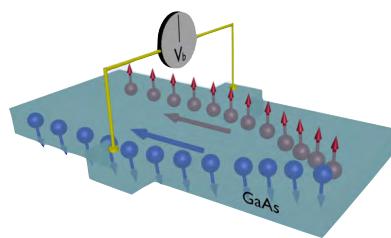
SPIN
PHENOMENA
INTERDISCIPLINARY CENTER



SUMMARY

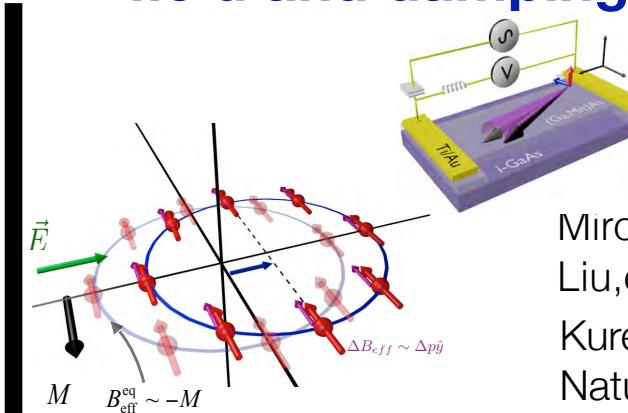


SHE and ISGE



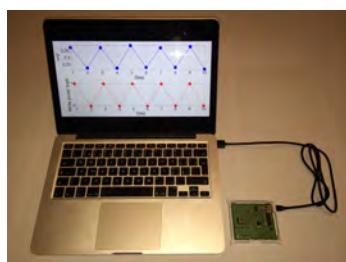
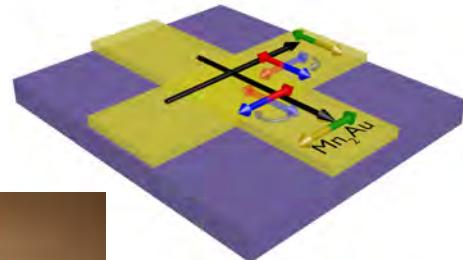
Sinova, Valenzuela, Wunderlich, Back,
Jungwirth RMP (2015)

SOTs in ferromagnet: field and damping like



Miron, et al, Nat. Mat. (2011)
Liu, et al., Science (2012)
Kurebayashi, et al.,
Nature Nanotech (2014)

Néel SOT in a single-layer antiferromagnet

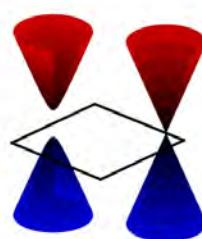


J. Zelezny, et al, PRL (2014)
J. Zelezny, et al, PRB (2016)

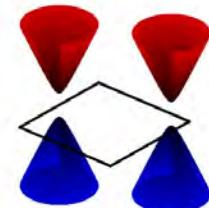
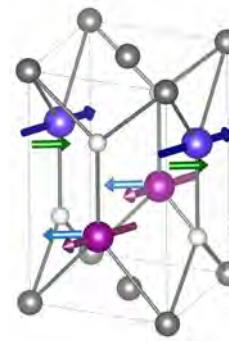
Wadley, Jungwirth et al Science (2016)

Electrical control of Dirac fermions and topological phases

Topological Dirac
Semi Metal+ AFM (i)



Neel SOT physics (ii)



Libor Smejkal, et al (2016)