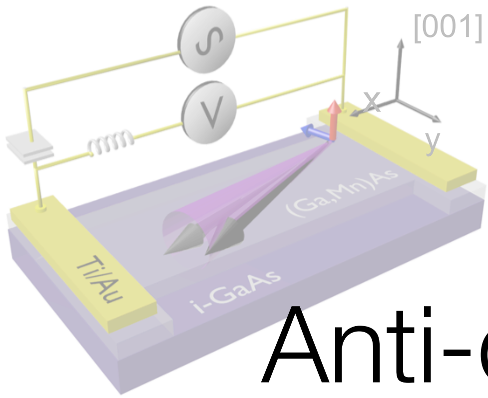
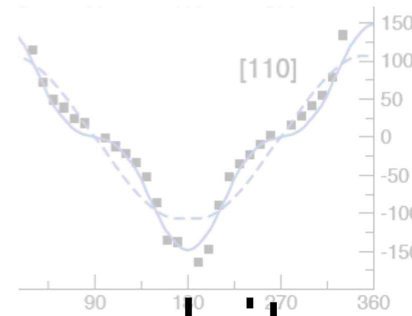




Anti-damping intrinsic spin-orbit torque arising from Berry phase

Jairo Sinova

4^{th} July 2013
16^{th} International Conference on Modulated Semiconductor Structures
Wroclaw, Poland

Hide Kurebayashi, D. Fang, A. C. Irvine, J. Wunderlich, V. Novak, R. P. Campion, B. L. Gallagher, E. K. Vehstedt, L. P. Zarbo, K. Vyborny, A. J. Ferguson, and T. Jungwirth





Institute of Physics ASCR Prague
Charles Univ. Prague, Czech Rep.

Univ. of Nottingham, UK

Hitachi and Univ. of Cambridge, UK

Texas A&M Univ. USA

Outline

1) Introduction

- Interest in spin-orbit torques: in-plane-current magnetization switching for MRAM technology
- In-plane current magnetization switching experiments and interpretations: SHE+STT vs. Spin-orbit torque

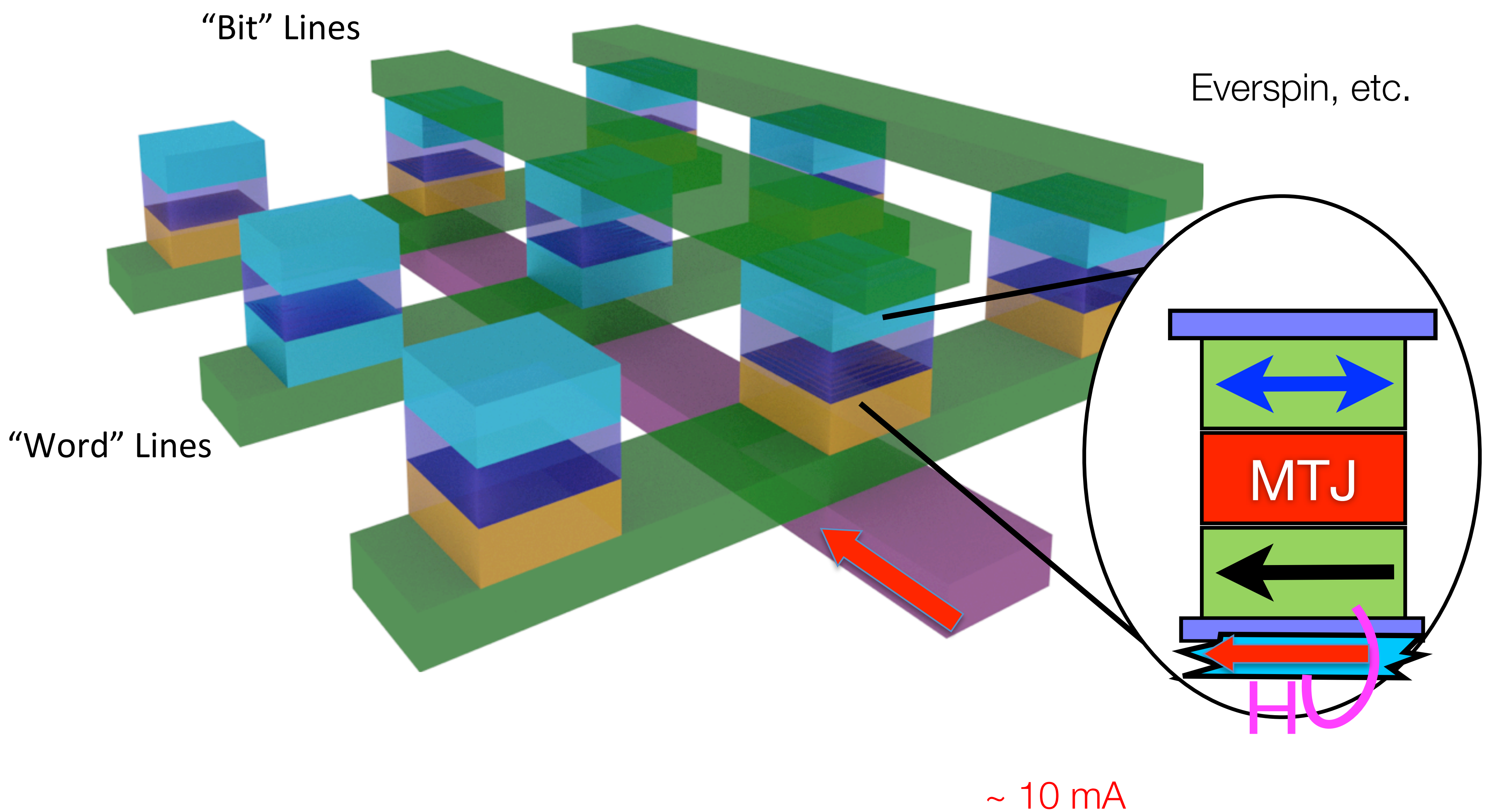
2) Theory of spin-orbit torque

- Linear response: extrinsic and intrinsic mechanisms
- Heuristic picture of Berry's phase anti-damping SOT

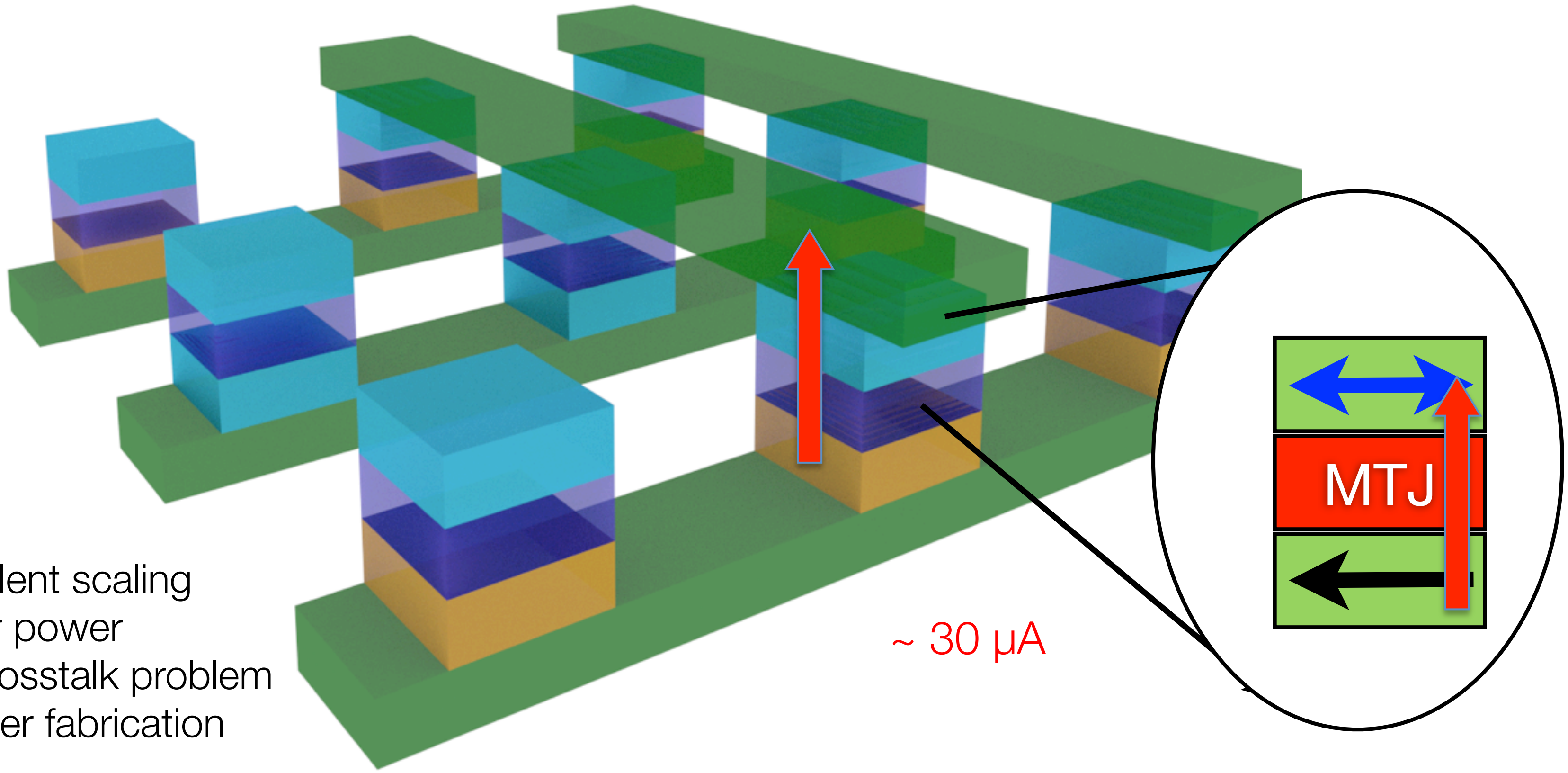
3) Experimental technique, results and modeling

- Spin-orbit-field FMR experiments
- In-plane (field-like) and out-of-plane (anti-damping-like)
- Comparison to theory predictions

Older architecture of field-driven-MRAM

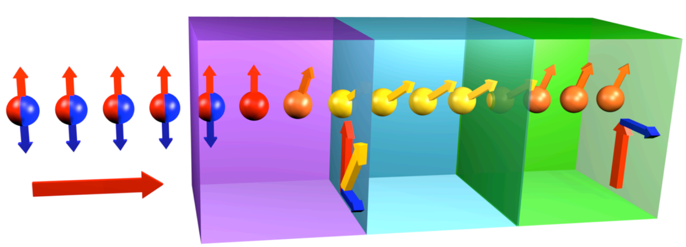


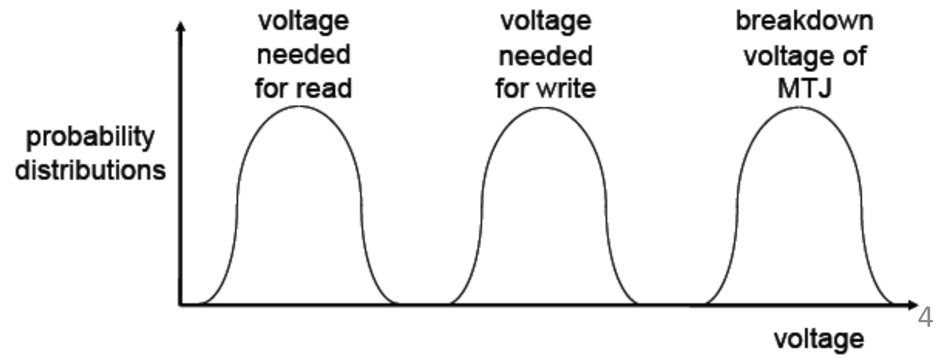
Spin-Transfer-Torque MRAM



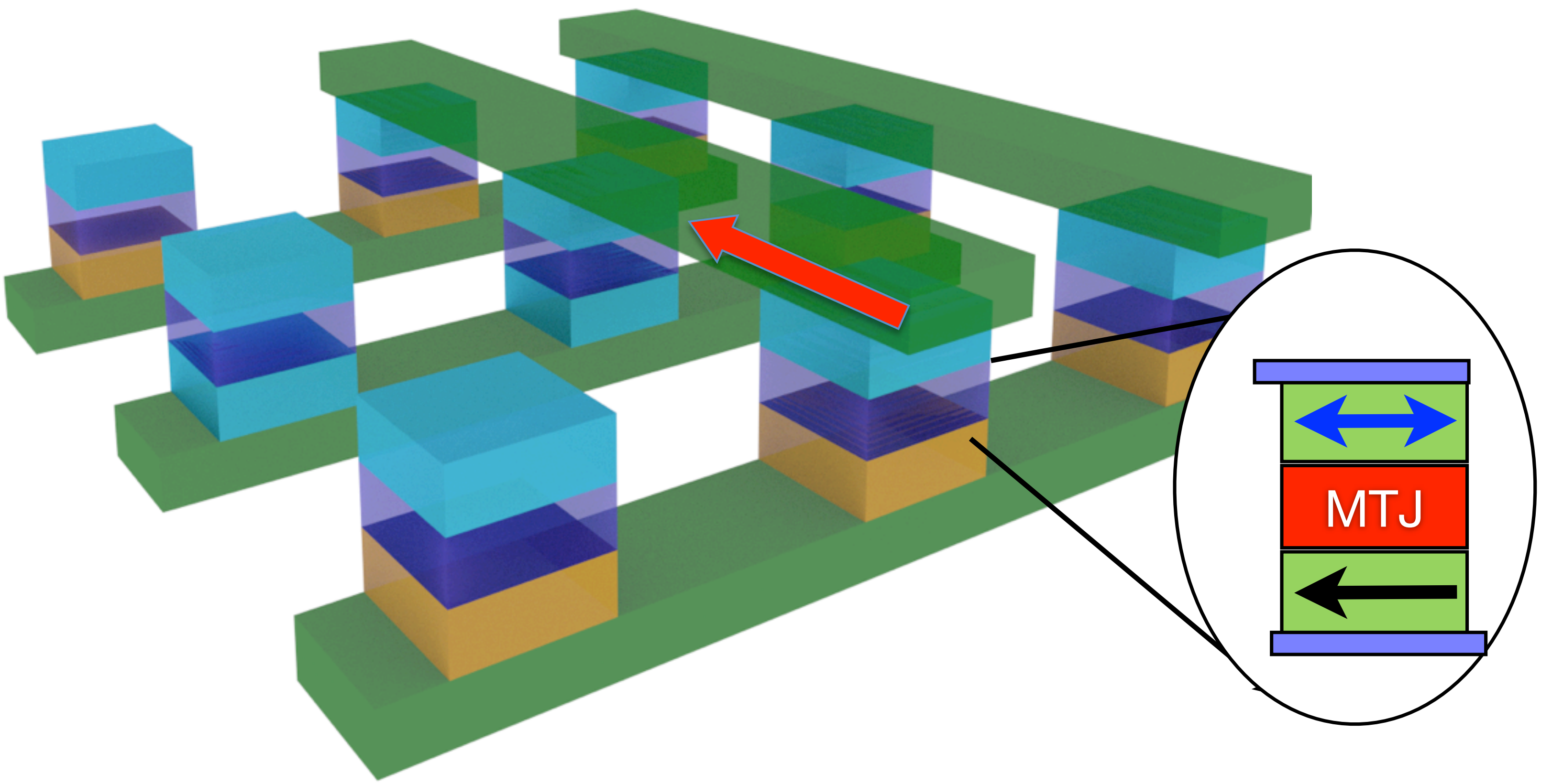
- excellent scaling
- lower power
- no crosstalk problem
- simpler fabrication

STT mechanism:

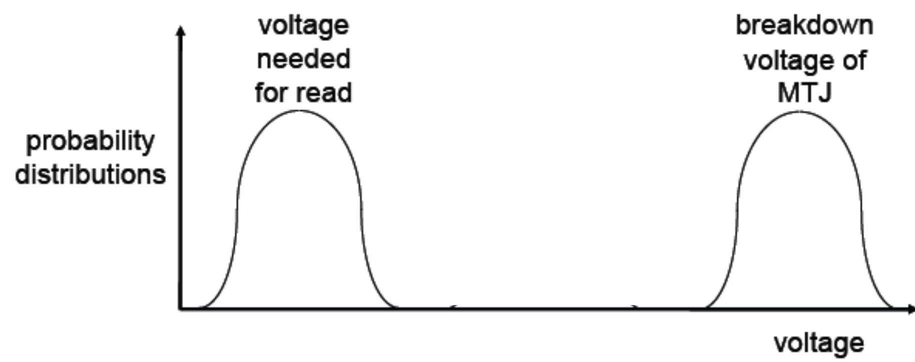




In-plane-current-switching MRAM

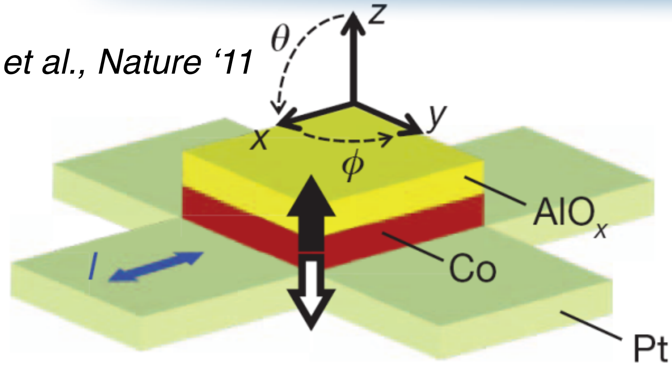


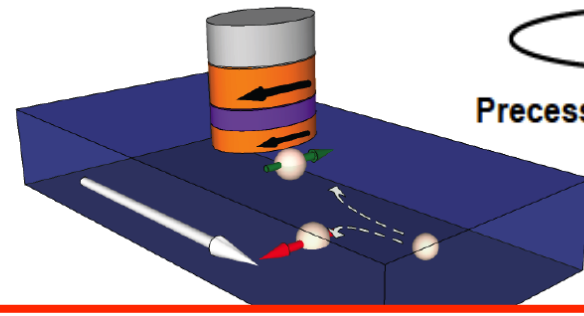
If switching can be done by an in-plane current then a key issue in STT-MRAM is resolved

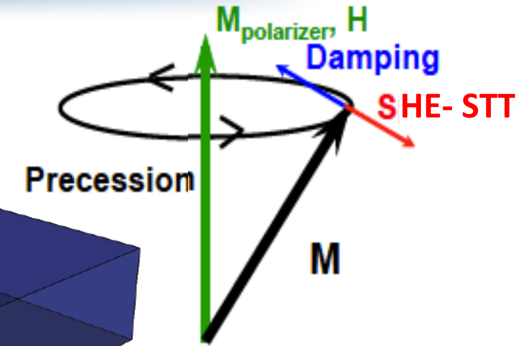


Experiments of in-plane current switching

Miron et al., Nature '11







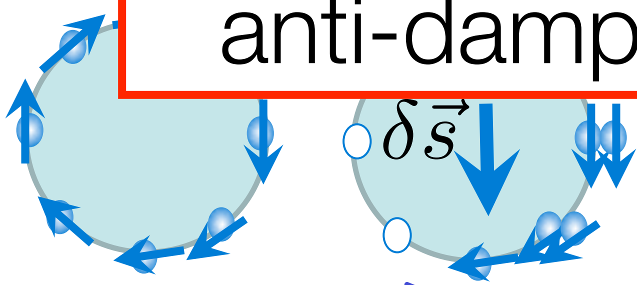
ience '12

spin-orb

STT

Is there a large intrinsic anti-damping spin-orbit torque?

H_R



E=0

$\vec{E}=E_x\hat{x}$

a,W)

&

anti-damping STT in ferromagnet (CoFeB)

$$H_{ex} = J_{ex}\vec{M}\cdot\delta\vec{s}$$

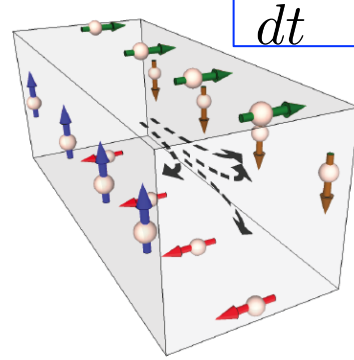
$$\frac{d\vec{M}}{dt} = \frac{J_{ex}}{\hbar}\vec{M}\times\delta\vec{s}$$

Scattering related and field-like SOT

Extrinsic anti-damping SOT is weak

Manchon & Zhang, PRB '08, '09

$$\frac{d\vec{M}}{dt} = P\hat{M}\times(\hat{n}\times\hat{M})$$



Intrinsic SHE in paramagnet acts as the external polarizer

Murakami, et al, Science'03

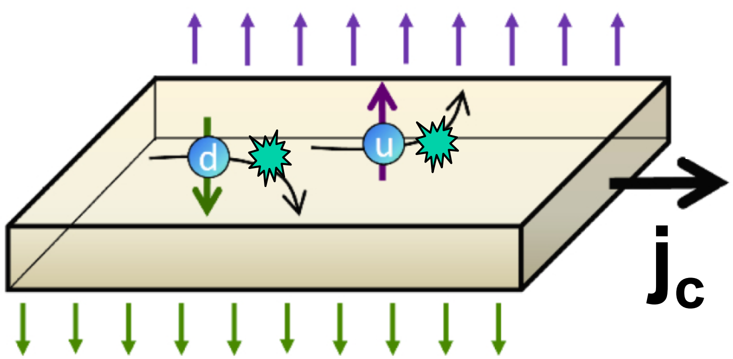
Sinova, et al. PRL'04

Linear response I. (condensed matter class)

Boltzmann theory: non-equilibrium distribution function and equilibrium states

Extrinsic (skew-scattering) SHE

$$J_i^s = e\sum_n \int \frac{d^d\vec{k}}{(2\pi)^d} j^{s,i}_{0n,\vec{k}} g_{n,\vec{k}}(E_j)$$

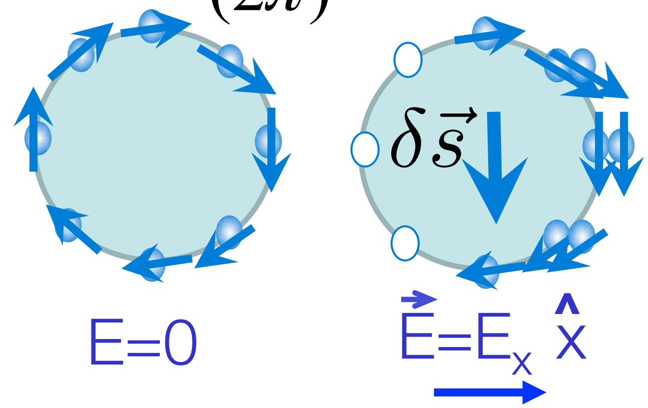


Dyakonov and Perel 1971
Hirsch PRL'99

Kato et al., Science '04

Field-like SOT

$$\delta s_i = \sum_n \int \frac{d^d\vec{k}}{(2\pi)^d} \sigma^i_{0n,\vec{k}} g_{n,\vec{k}}(E_j)$$



$$\boxed{H_{ex} = J_{ex}\vec{M}\cdot\delta\vec{s}} \quad \boxed{\frac{d\vec{M}}{dt} = \frac{J_{ex}}{\hbar}\vec{M}\times\delta\vec{s}}$$

Manchon & Zhang, PRB '08

Chernyshev et al. Nature Phys.'09,

Miron et al. Nature Mat.'09,

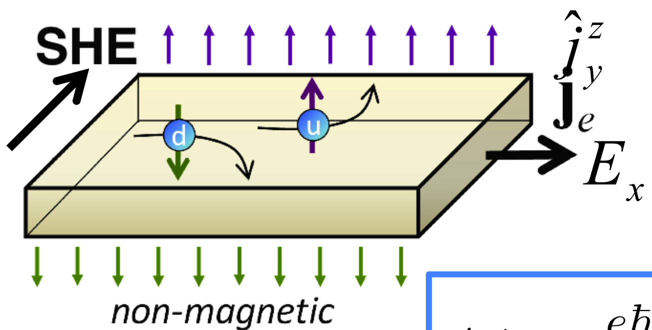
$$g_{n,\vec{k}} = f_{n,\vec{k}} - f_0(E_{n,\vec{k}})$$

$$e\vec{E}\cdot\vec{v}_{0n,\vec{k}}\frac{\partial f_0(E_{n,\vec{k}})}{\partial E_{n,\vec{k}}} = -\sum_n \int \frac{d^d\vec{k}}{(2\pi)^d} W_{n,\vec{k},n',\vec{k}'}(f_{n,\vec{k}} - f_{n',\vec{k}'})$$

Linear response II. (condensed matter class)

Perturbation theory: equilibrium distribution function and non-equilibrium states

Intrinsic SHE from linear response II



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

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

$$\boxed{J^{int}_{\vec{E}\times\hat{z}} = \frac{e\hbar}{V} \sum_{\vec{k},n\neq n'} (f^0_{\vec{k},n'} - f^0_{\vec{k},n}) \frac{\mathrm{Im}[\langle \vec{k},n' | j^z_{\vec{E}\times\hat{z}} | \langle \vec{k},n\rangle \langle \vec{k},n' | \vec{v}\cdot\vec{E} | \vec{k},n'\rangle}{(E_{\vec{k},n'} - E_{\vec{k},n})^2}}$$

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

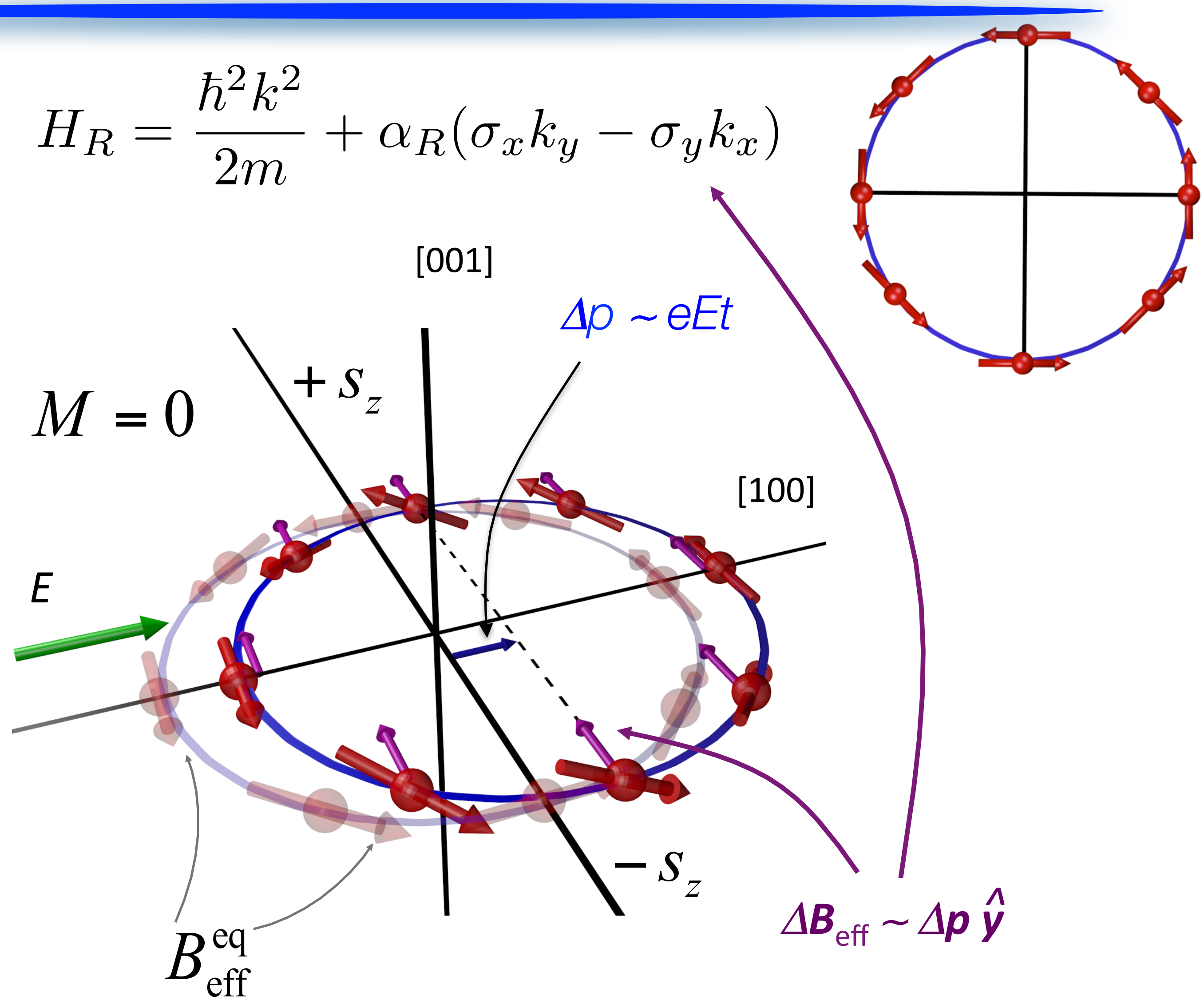
Wunderlich et al. Phys. Rev. Lett. '05
Werake et al., PRL'11

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

$$\boxed{S^{int}_z = \frac{e\hbar}{V} \sum_{\vec{k},n\neq n'} (f^0_{\vec{k},n'} - f^0_{\vec{k},n}) \frac{\mathrm{Im}[\langle \vec{k},n' | s_z | \langle \vec{k},n\rangle \langle \vec{k},n' | \vec{v}\cdot\vec{E} | \vec{k},n'\rangle}{(E_{\vec{k},n'} - E_{\vec{k},n})^2}}$$

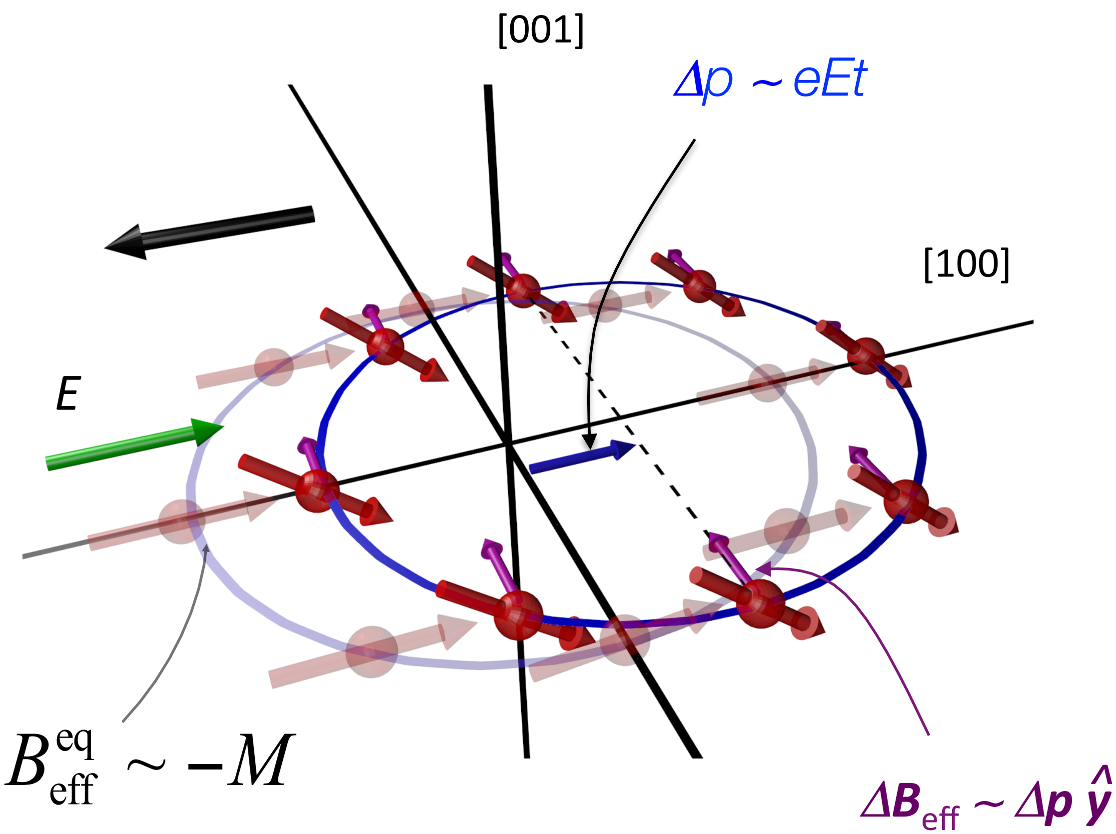
Intrinsic (Berry phase) spin-Hall effect from Bloch eq.

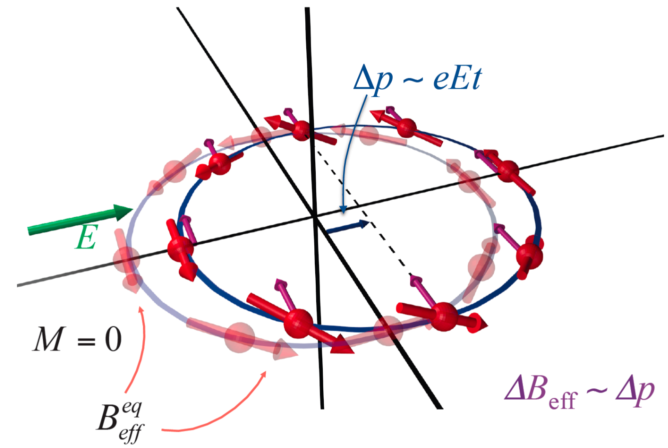
$$H_R = \frac{\hbar^2 k^2}{2m} + \alpha_R(\sigma_x k_y - \sigma_y k_x)$$



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

Large exchange limit

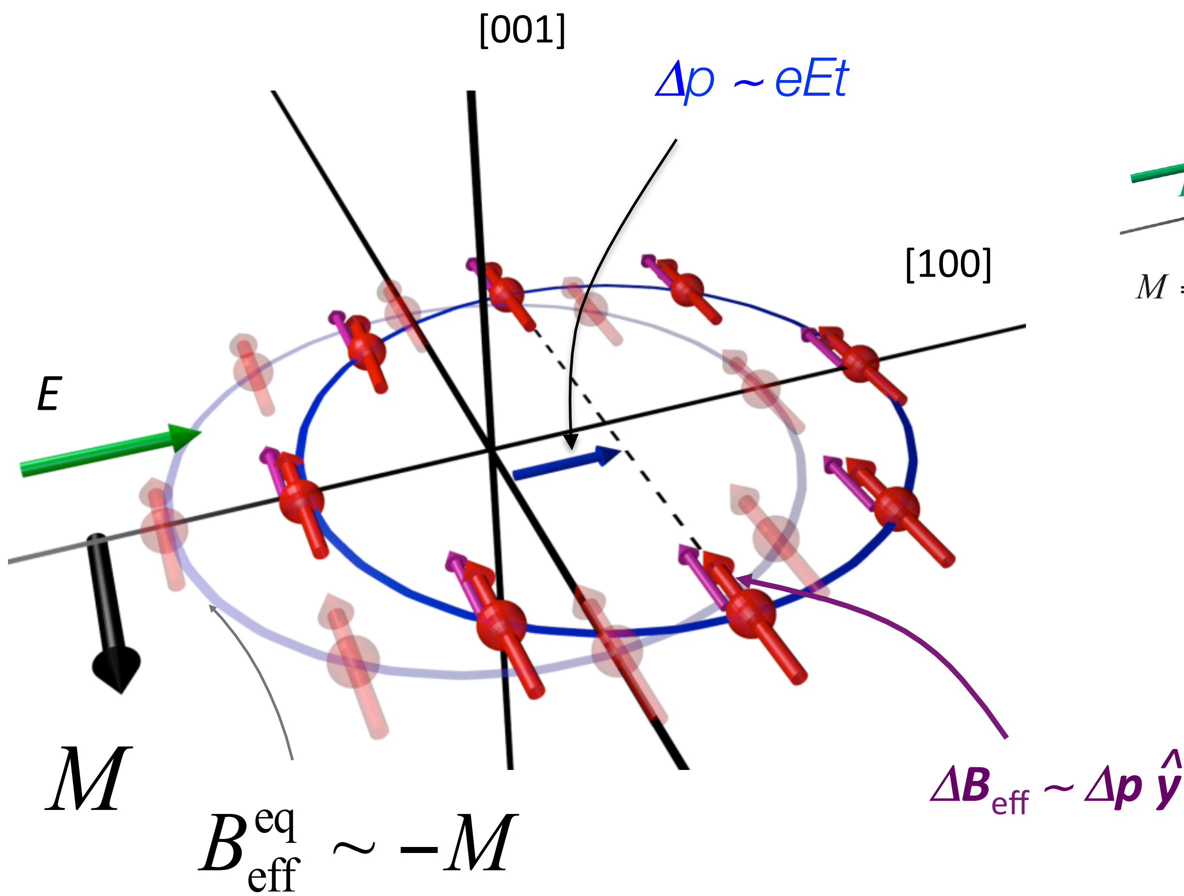


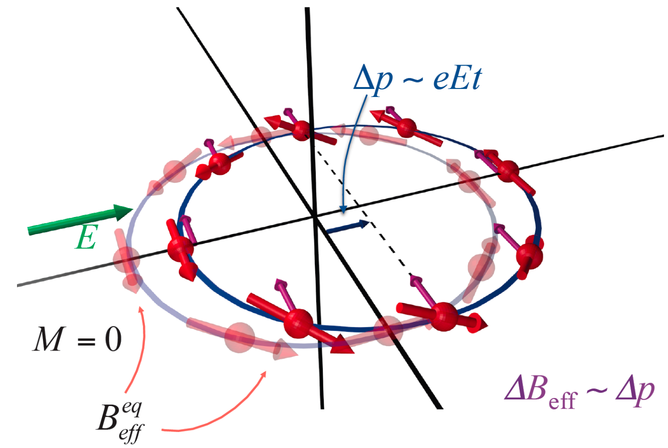


$$\frac{d\vec{M}}{dt} \sim \vec{M} \times h\hat{z} \quad \text{maximum } h\hat{z} \text{ for } \vec{M} \parallel \vec{E}$$

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

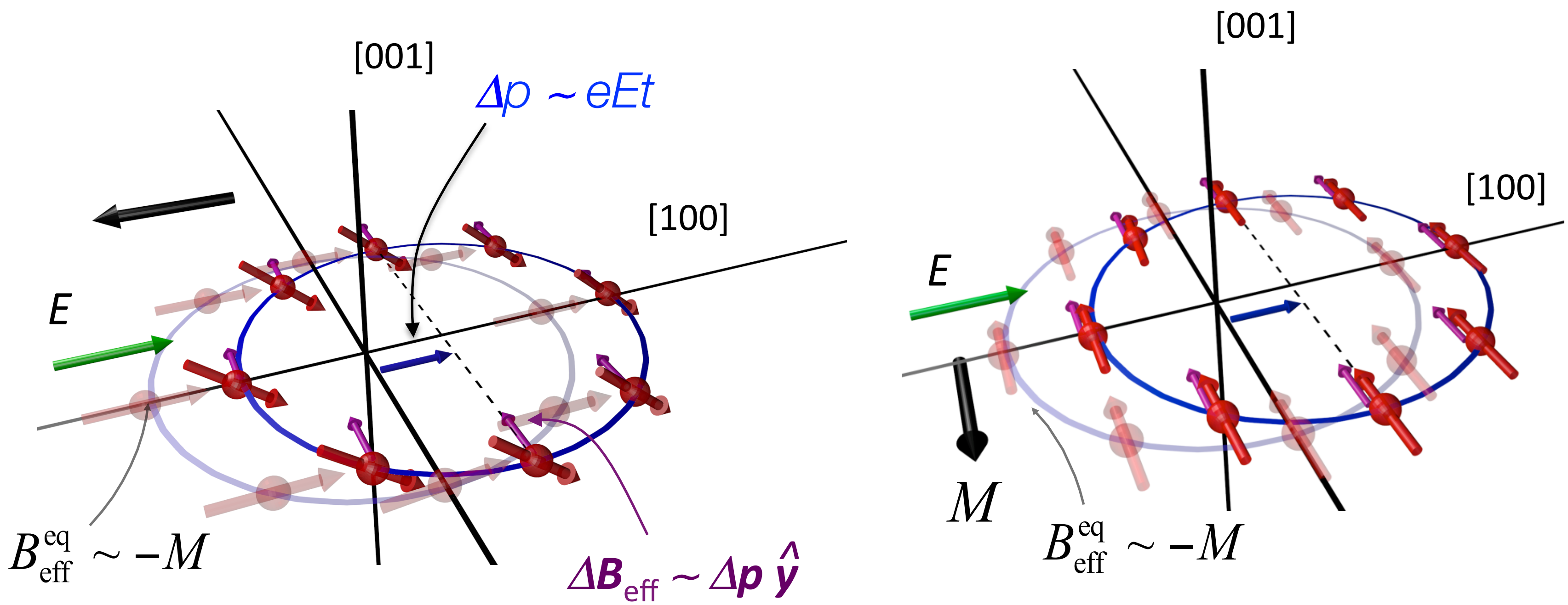
Large exchange limit





$$\frac{d\vec{M}}{dt} \sim \vec{M} \times h\hat{z} \qquad \text{zero } h\hat{z} \text{ for } \vec{M} \perp \vec{E}$$

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

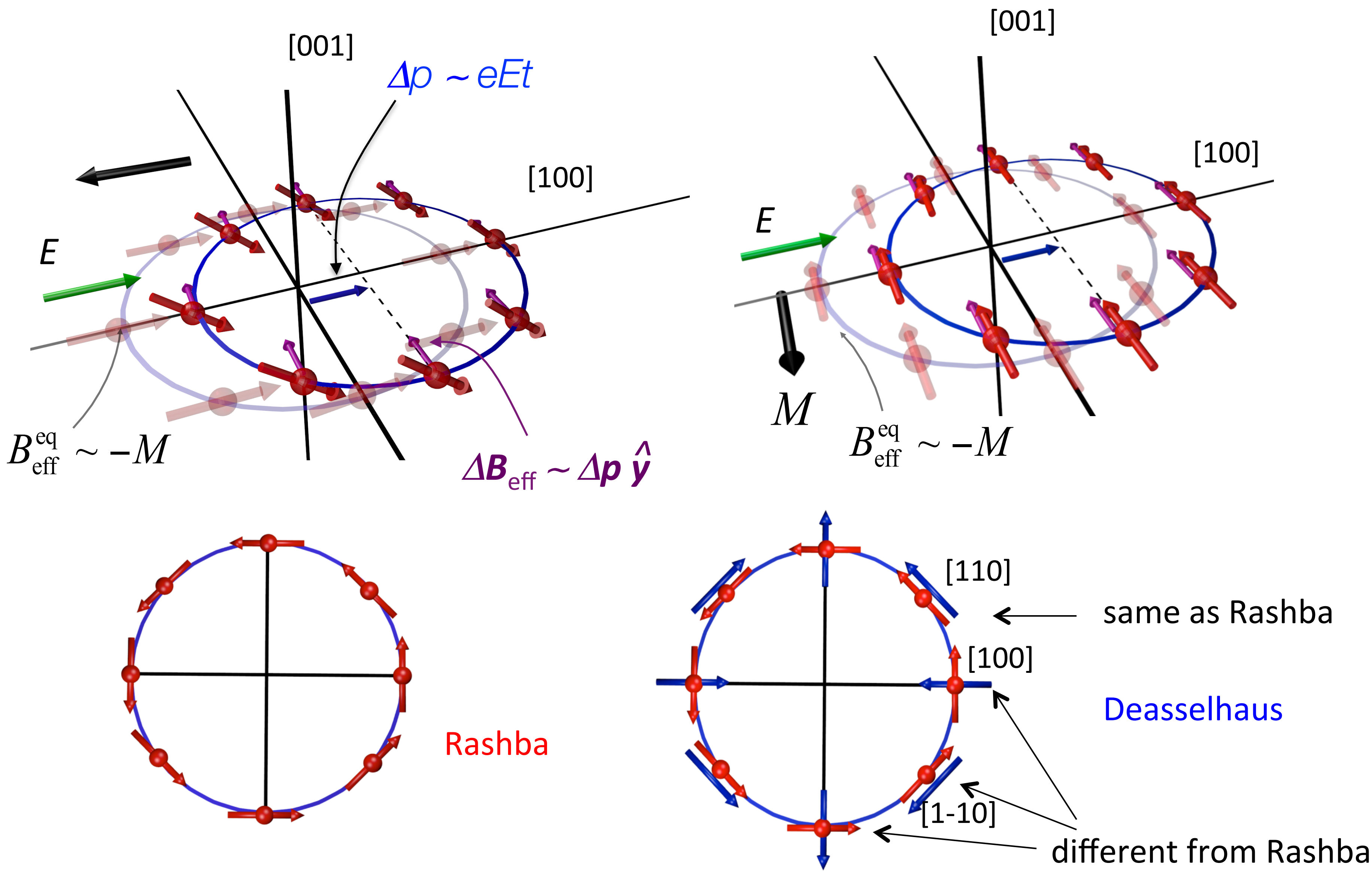


anti-damping

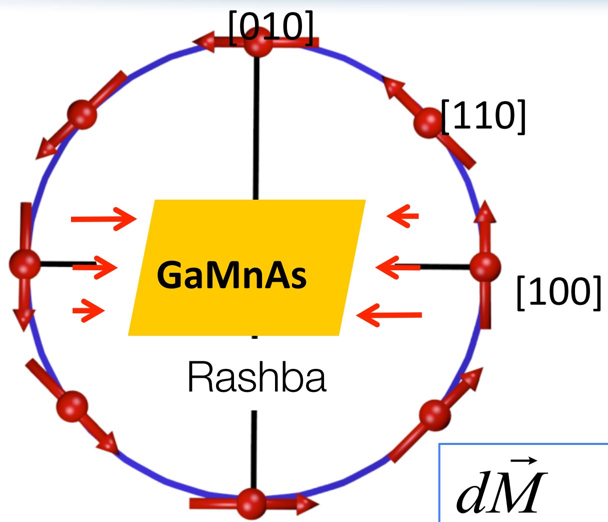
$$\frac{d\vec{M}}{dt} \sim \vec{M} \times h_z \hat{z}$$

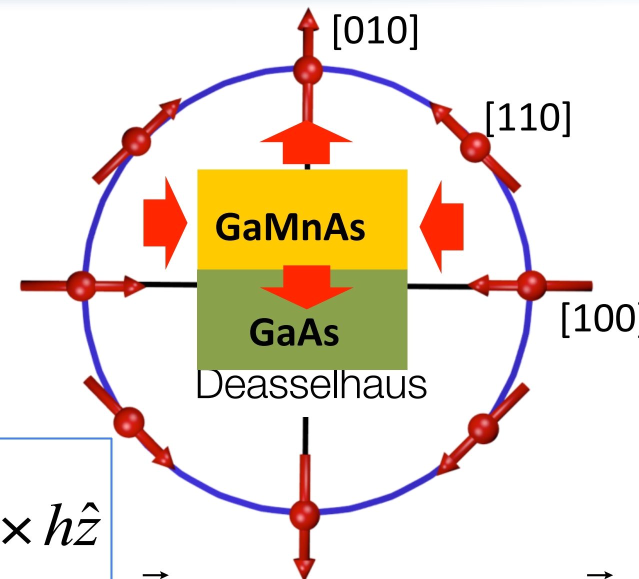
$$h_z \hat{z} \sim [\vec{E} \times \hat{z}] \times \vec{M}$$

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



Intrinsic (Berry phase) spin-orbit torque in GaMnAs





$$\boxed{\frac{d\vec{M}}{dt} \sim \vec{M} \times h\hat{z}}$$

all $\vec{E} : h\hat{z} \sim [\vec{E} \times \hat{z}] \times \vec{M}$

$\vec{E} \parallel [110]: \quad h\hat{z} \sim [\vec{E} \times \hat{z}] \times \vec{M}$

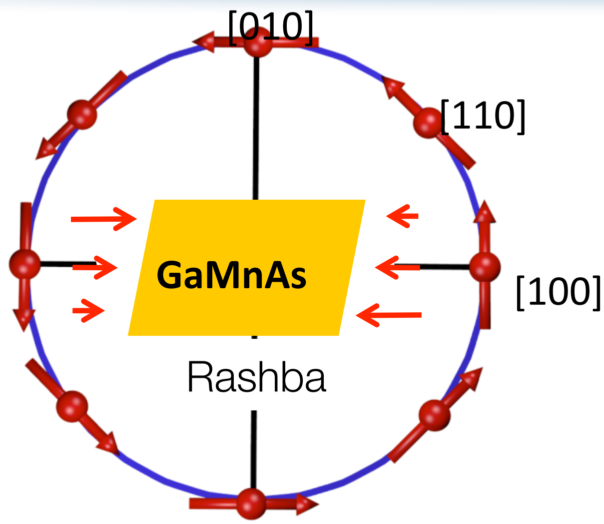
$\vec{E} \parallel [1-10]: \quad h\hat{z} \sim -[\vec{E} \times \hat{z}] \times \vec{M}$

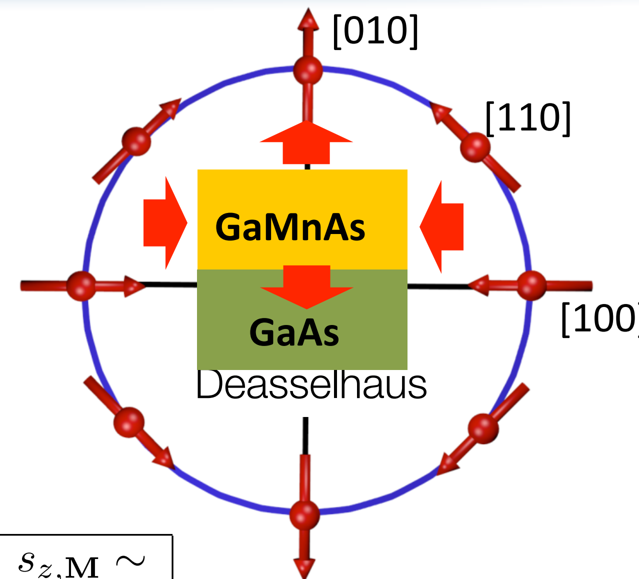
$\vec{E} \parallel [100]: \quad h\hat{z} \sim \vec{E} \times \vec{M}$

$\vec{E} \parallel [010]: \quad h\hat{z} \sim -\vec{E} \times \vec{M}$

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

Intrinsic (Berry phase) spin-orbit torque in GaMnAs





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

$$H_{\mathrm{GaAs}} = H_{\mathrm{KL}} + H_{\mathrm{strain}}$$

$$H_{\mathrm{KL}} = \frac{\hbar^2 k^2}{2m_0}\left(\gamma_1 + \frac{5}{2}\gamma 2\right)\mathbf{I}_4 - \frac{\hbar^2}{m_0}\gamma_3\left(\mathbf{k}\cdot\mathbf{J}\right)^2$$

$$H_{\mathrm{strain}} = b\left[\left(J_x^2 - \frac{\mathbf{J}^2}{3}\right)\epsilon_{xx} + \text{c.p.}\right]$$

Deasselhaus $\rightarrow$ $\boxed{-C_4\left[J_x\left(\epsilon_{yy} - \epsilon_{zz}\right)k_x + \text{c.p.}\right]}$

Rashba $\rightarrow$ $\boxed{-C_5\left[\epsilon_{xy}(k_yJ_x - k_xJ_y) + \text{c.p.}\right]}$

Competition between these terms give rise to higher harmonics

Road Map

1) ~~Introduction~~

- ~~Interest in spin-orbit torques: in-plane-current magnetization switching for MRAM technology~~
- ~~In-plane current magnetization switching experiments and interpretations: SHE+STT vs. SOT~~

2) ~~Theory of spin-orbit torque~~

- ~~Linear response: extrinsic and intrinsic mechanisms~~
- ~~Heuristic picture of Berry's phase anti-damping SOT~~

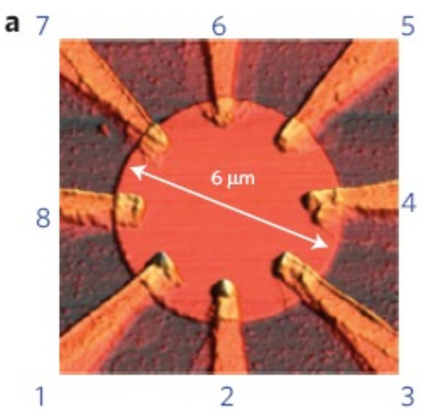
3) Experimental technique, results and modeling

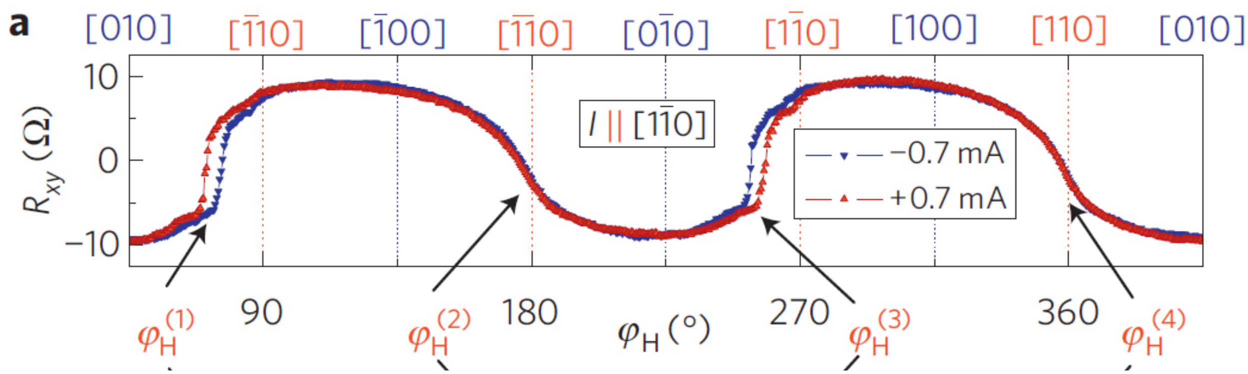
- Spin-orbit-field FMR experiments
- In-plane (field-like) and out-of-plane (anti-damping-like)
- Comparison to theory predictions

First works: current-induced SO effective fields

Effective spin-orbit (SO) field by dc current

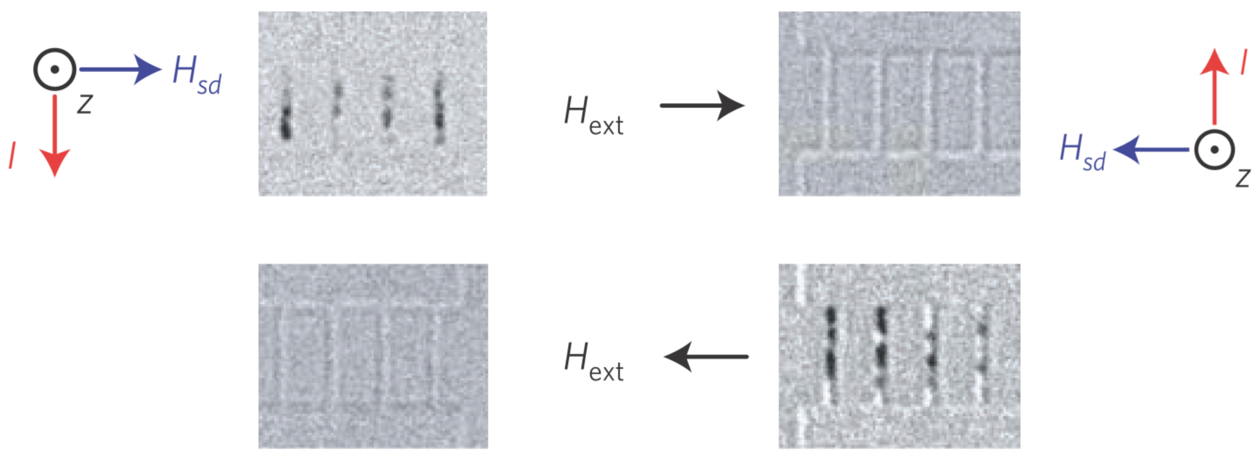
GaMnAs: bulk broken symmetry, Chernyshov, Rokhinson, et al, Nature Phys., 5, 656 (2009)





✓ Hysteresis observed in the planar Hall effect

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



✓ DW nucleation difference in the perpendicularly magnetised system

Other works and measurement techniques

Current-induced SO fields by ac current

It's all about the Ohm's law. ΔR_{ac} can be any magneto-resistances

$$V = I_{ac}\sin\omega t \times (R_0 + \Delta R_{ac}\sin\omega t)$$
$$\sim I_{ac}R_0\sin\omega t + 0.5\times(I_{ac}\Delta R_{ac} + I_{ac}\,\Delta R_{ac}\sin 2\omega t)$$

Magnetic dynamics (GHz frequency): SO field-FMR

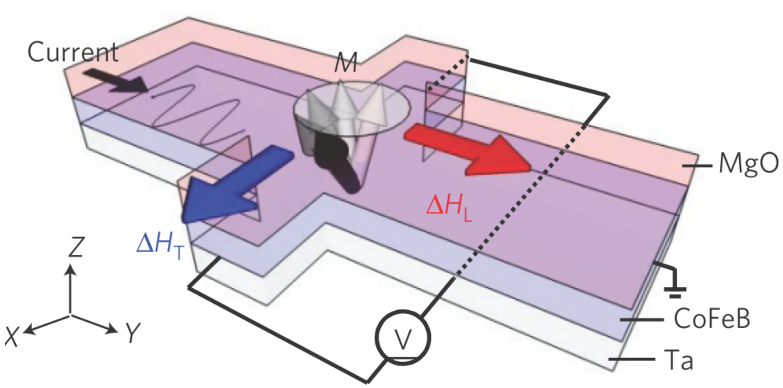
GaMnAs: Fang et al., Nature Nanotech., 6, 413 (2011).

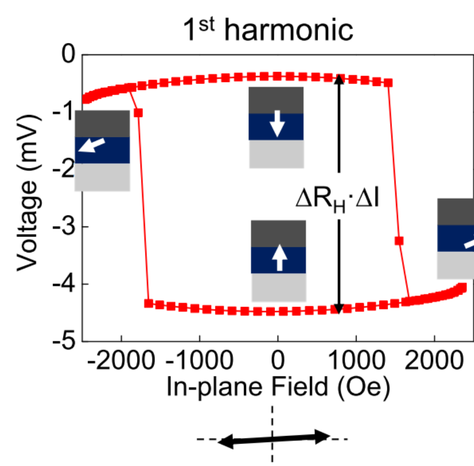
Quasi-static regime (kHz frequency)

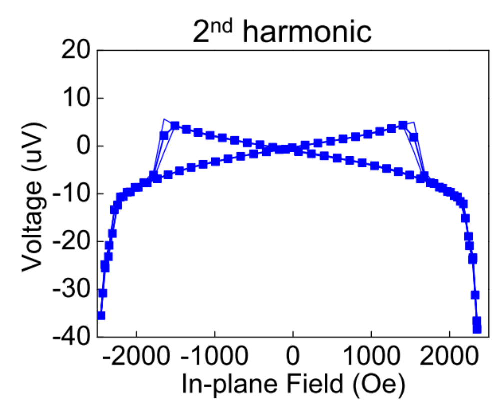
AlOx/Co/Pt: Pi et al., APL 97 162507 (2010).

AlOx/Co/Pt: Garello et al., arXiv: 1301.3573.

MgO/CoFeB/Ta: Kim et al., Nature Mater. 12 240 (2013).



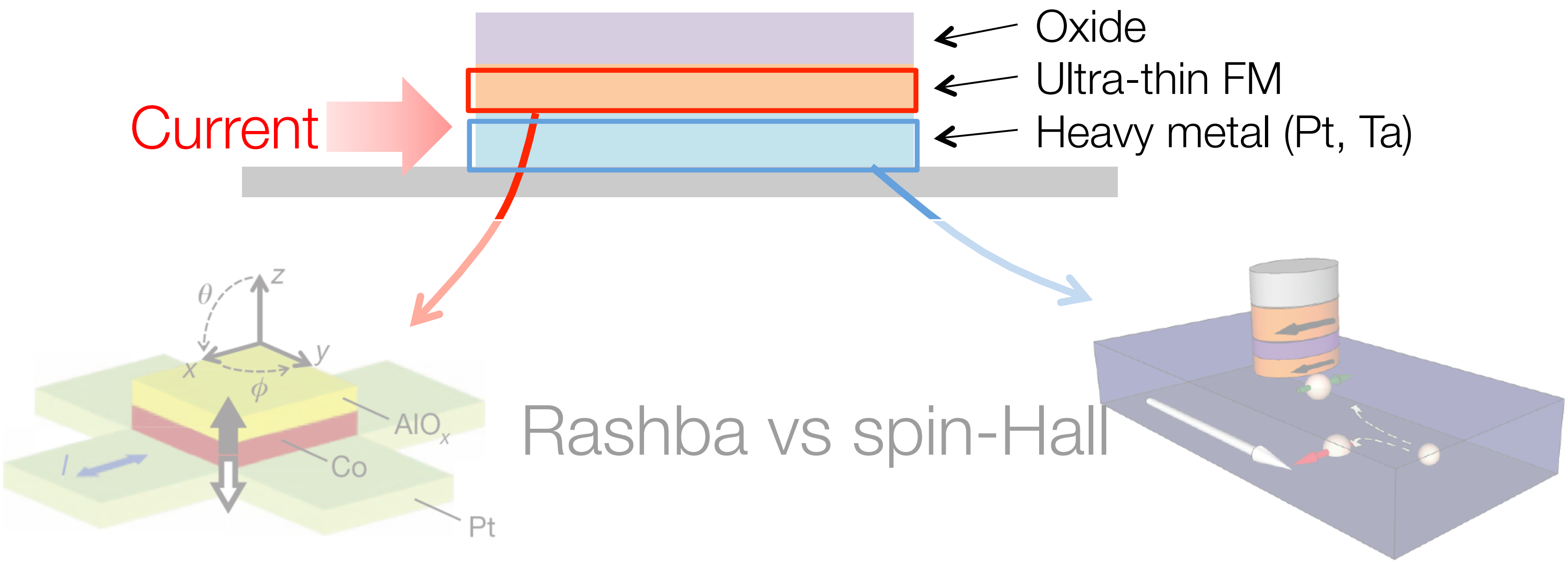




ΔH_T~60 Oe

Problems in metal multi-layers

In-plane current-induced magnetisation switching in multi-layers



Miron et al., Nature 476 189 (2011)

Liu et al., Science 336 555 (2012)

GaMnAs

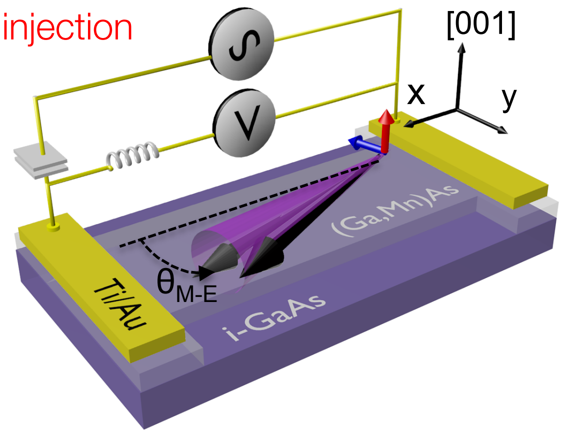
- ✓ Bulk spin-orbit effect → current flows only in GaMnAs.
- ✓ Well-known GaAs band structures and calculations.
- ✓ Allows for single thin film geometry: no SHE-STT by design

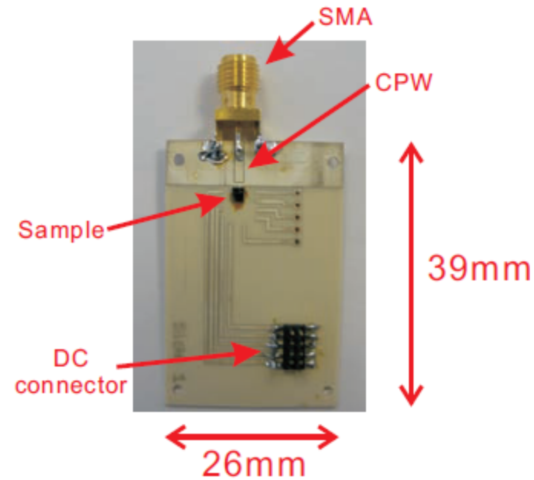
→ The ideal material for understanding spin-orbit torques

Electrical induced/detected FMR

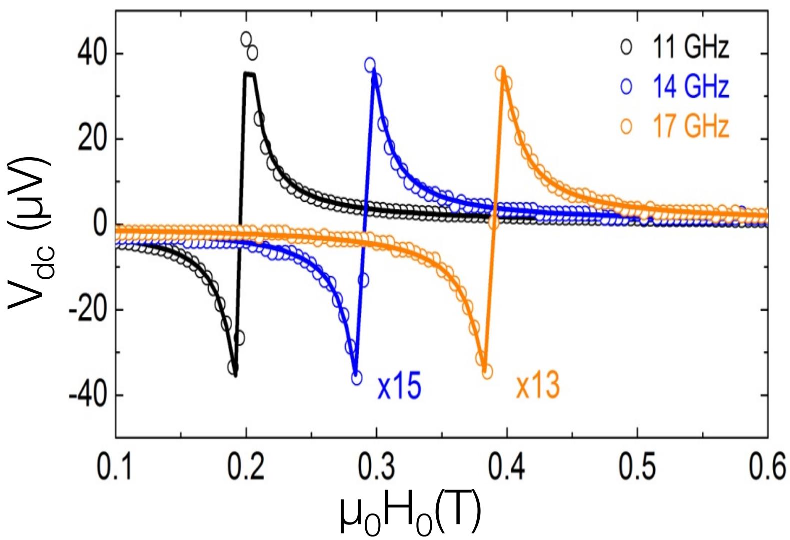
Fang, et al., Nature Nanotech. (2011)

GHz ac current injection

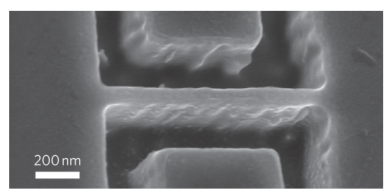




$$V = I_{ac}\sin\omega t \times (R_0 + \Delta R_{ac}\sin\omega t)$$
$$= I_{ac}R_0\sin\omega t + 0.5\times(I_{ac}\Delta R_{ac} + I_{ac}\Delta R_{ac}\sin 2\omega t)$$



SEM image



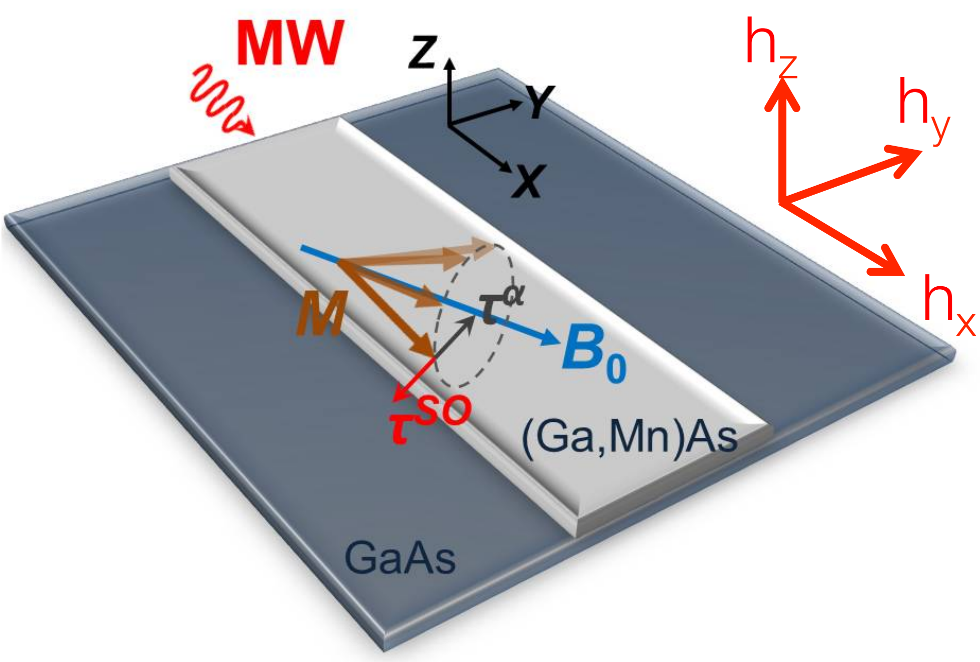
80 nm width!
(if you push hard…)

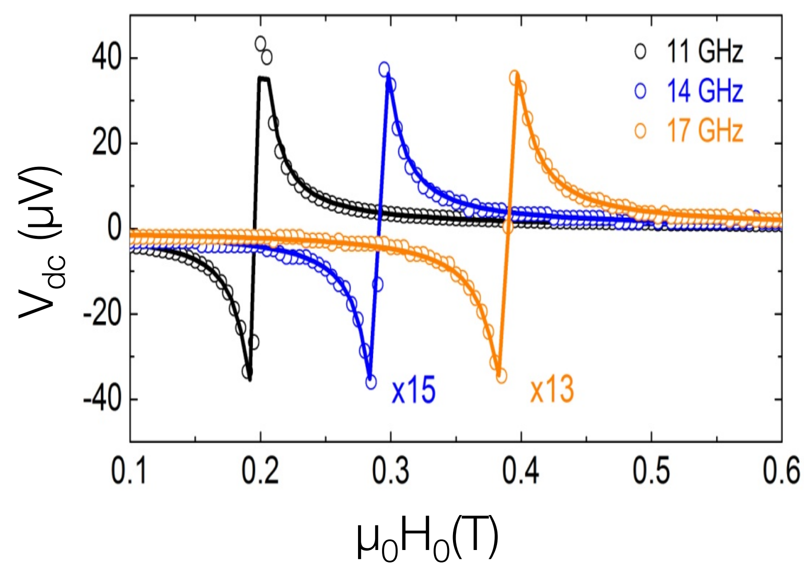
✓ Nanoscale on-chip FMR measurements

Magnetic dynamics phenomenology

Landau-Lifshitz-Gilbert equation

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

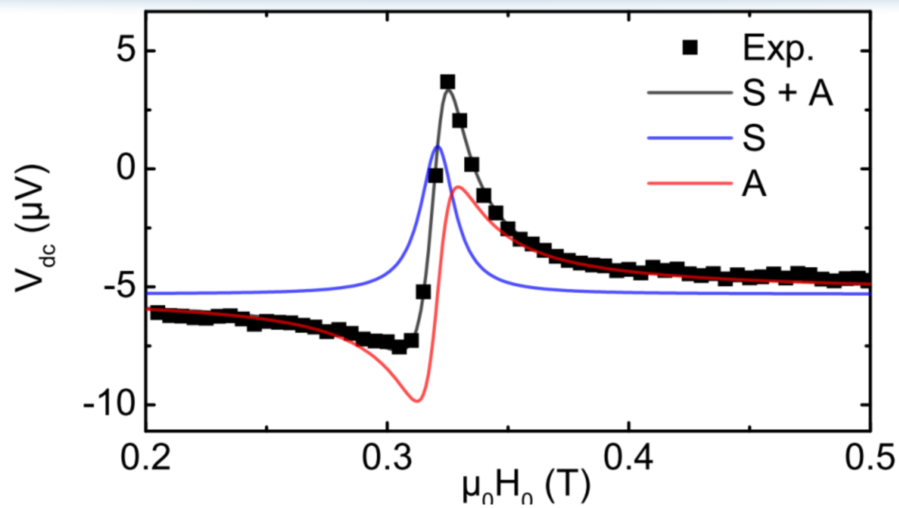




Because $h_{so}=-J_{pd}\,\Delta s$

the V amplitudes contain SO information.

Torque types and line-shapes



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

$$V_{\text{sym}} \frac{\Delta H^2}{(H_0 - H_{\text{res}})^2 + \Delta H^2}$$

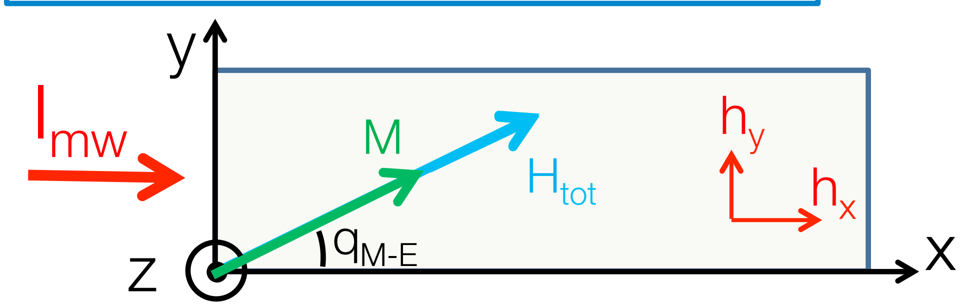
$$V_{\text{sym}} = C_1 \times h_z \sin(2\theta)$$

$+$

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

$$V_{\text{asy}} \frac{\Delta H (H_0 - H_{\text{res}})}{(H_0 - H_{\text{res}})^2 + \Delta H^2}$$

$$V_{\text{asy}} = C_2 \times \sin(2\theta) \times (-h_x \sin(\theta) + h_y \cos(\theta))$$



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

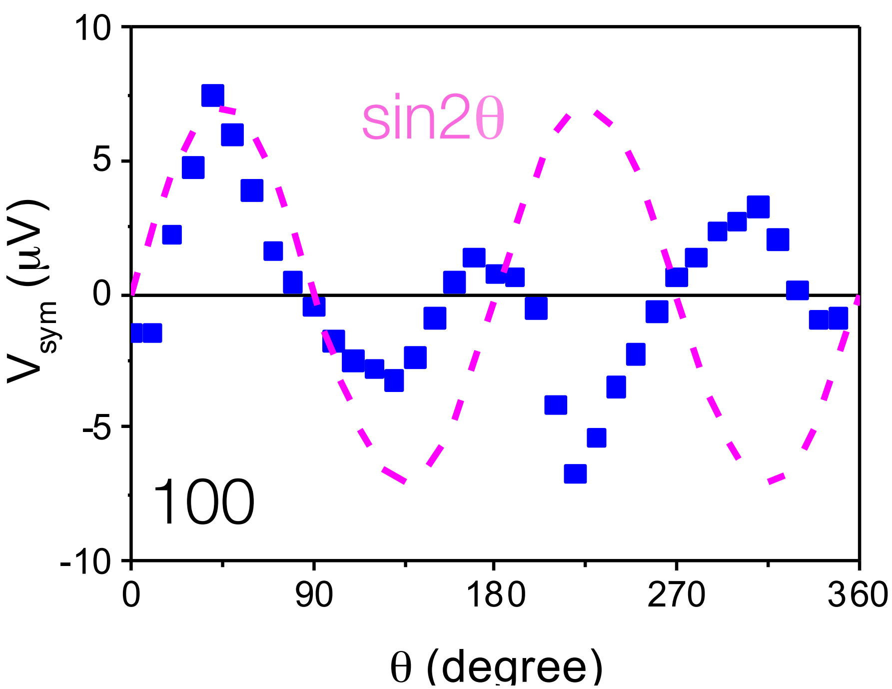
Kurebayashi, Sinova et al., arXiv:1306.1893
Fang et al., Nature Nanotech. (2011)

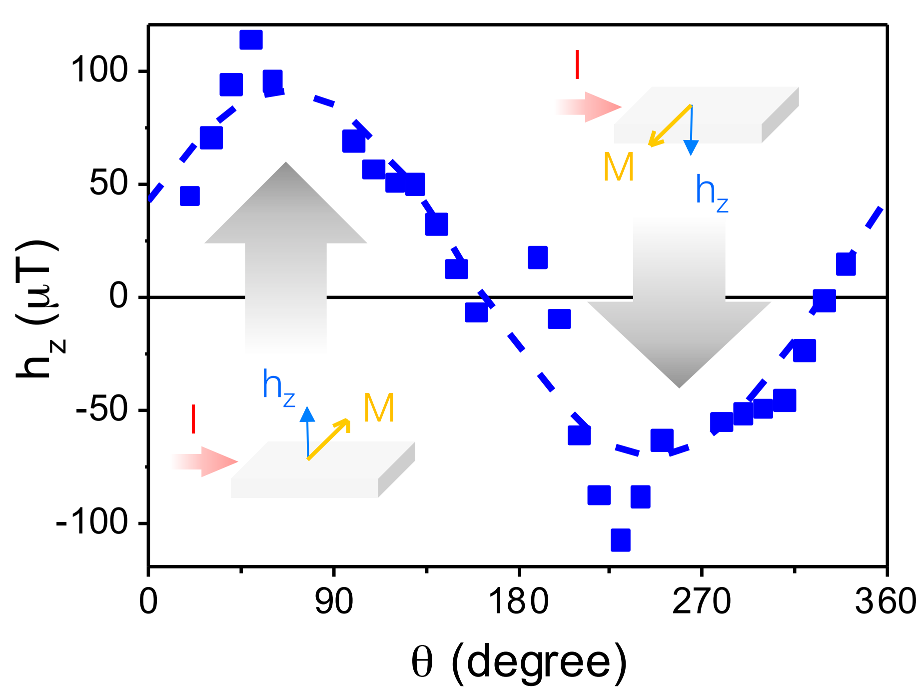
The out-of-plane SO field

the out-of-plane field ⟷ the symmetric line-shape

$$V_{\mathrm{sym}}(\theta_{\mathbf{M-E}}) = \frac{I\Delta R\omega}{2\gamma\Delta H(2H_{\mathrm{res}}+H_1+H_2)}\sin(2\theta_{\mathbf{M-E}})h_z$$

$$h_z(\theta)=h_{z0} + h_{z1}\sin\theta + h_{z2}\cos\theta$$

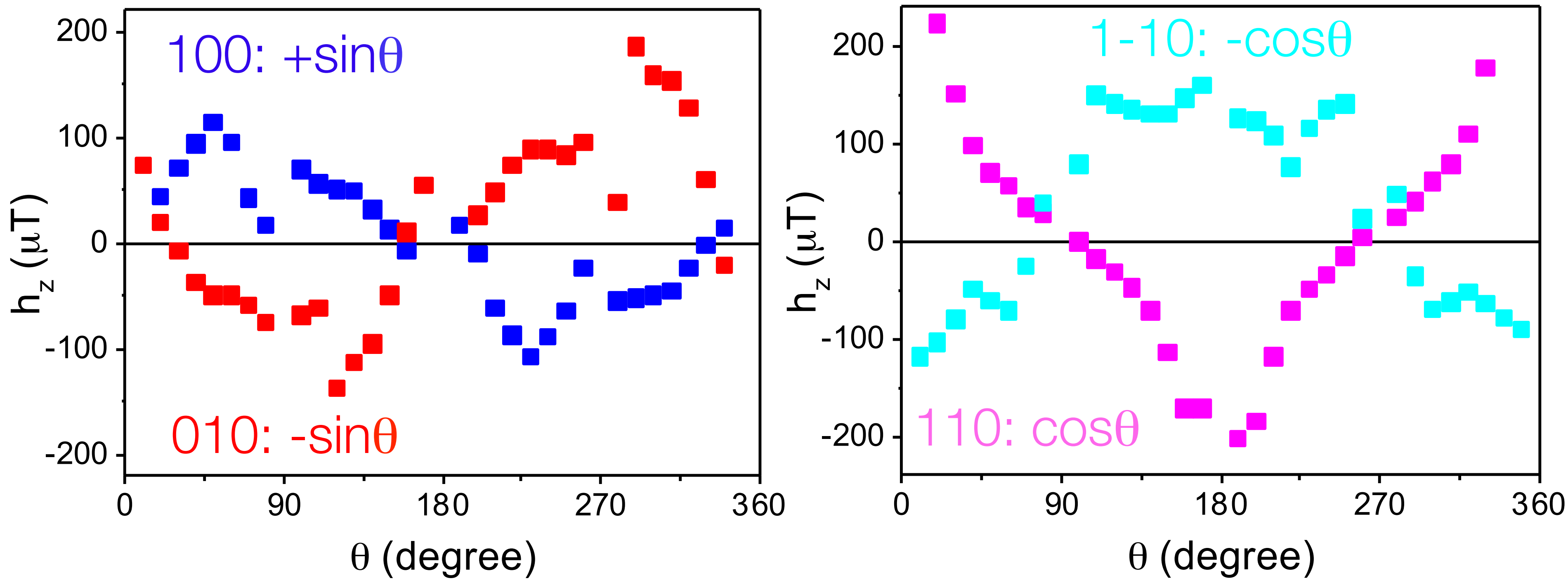




✓ M-dependent h_z

✓ The sinθ symmetry for 100 direction.

Current direction dependence

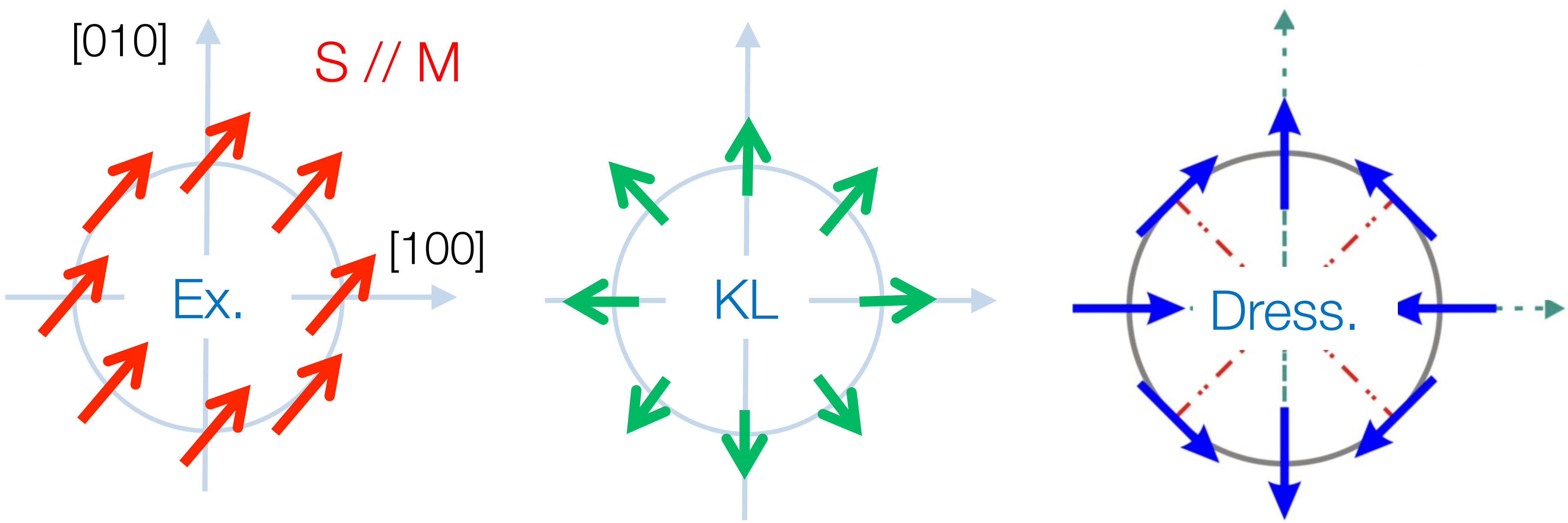


	Rashba: $s_{z,\mathbf{M}} \sim$	Dresselhaus: $s_{z,\mathbf{M}} \sim$
$\mathbf{E} \parallel [100]$	$\cos\theta_{\mathbf{M-E}}$	$\sin\theta_{\mathbf{M-E}}$
$\mathbf{E} \parallel [010]$	$\cos\theta_{\mathbf{M-E}}$	$-\sin\theta_{\mathbf{M-E}}$
$\mathbf{E} \parallel [110]$	$\cos\theta_{\mathbf{M-E}}$	$\cos\theta_{\mathbf{M-E}}$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

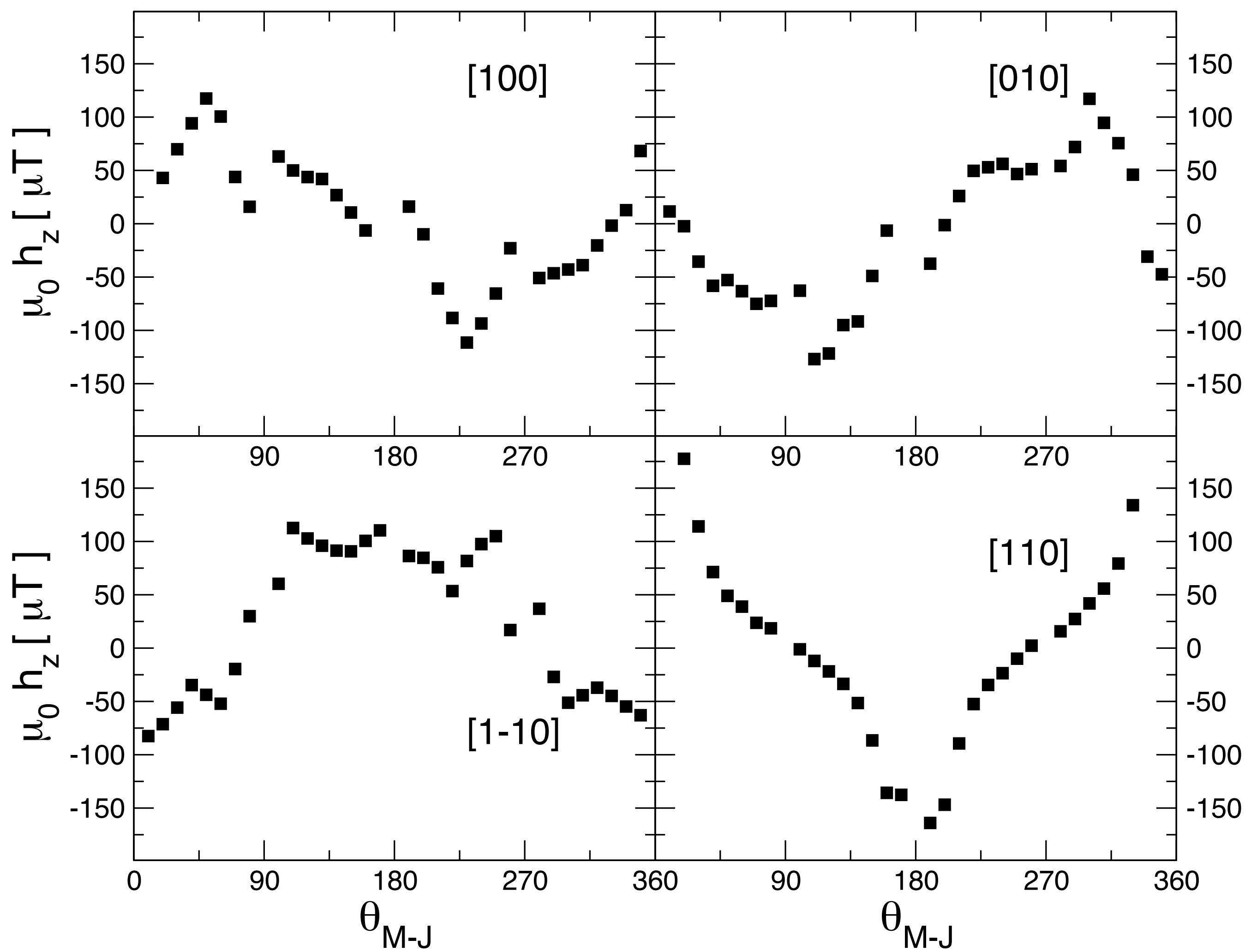
Effective Hamiltonian of GaMnAs

$$H = H_{ex} + H_{KL} + H_{so\text{-}R\text{-}D}$$

k-independent	k^2-dependent	k-linear
~100 meV	~100 meV	~1 meV

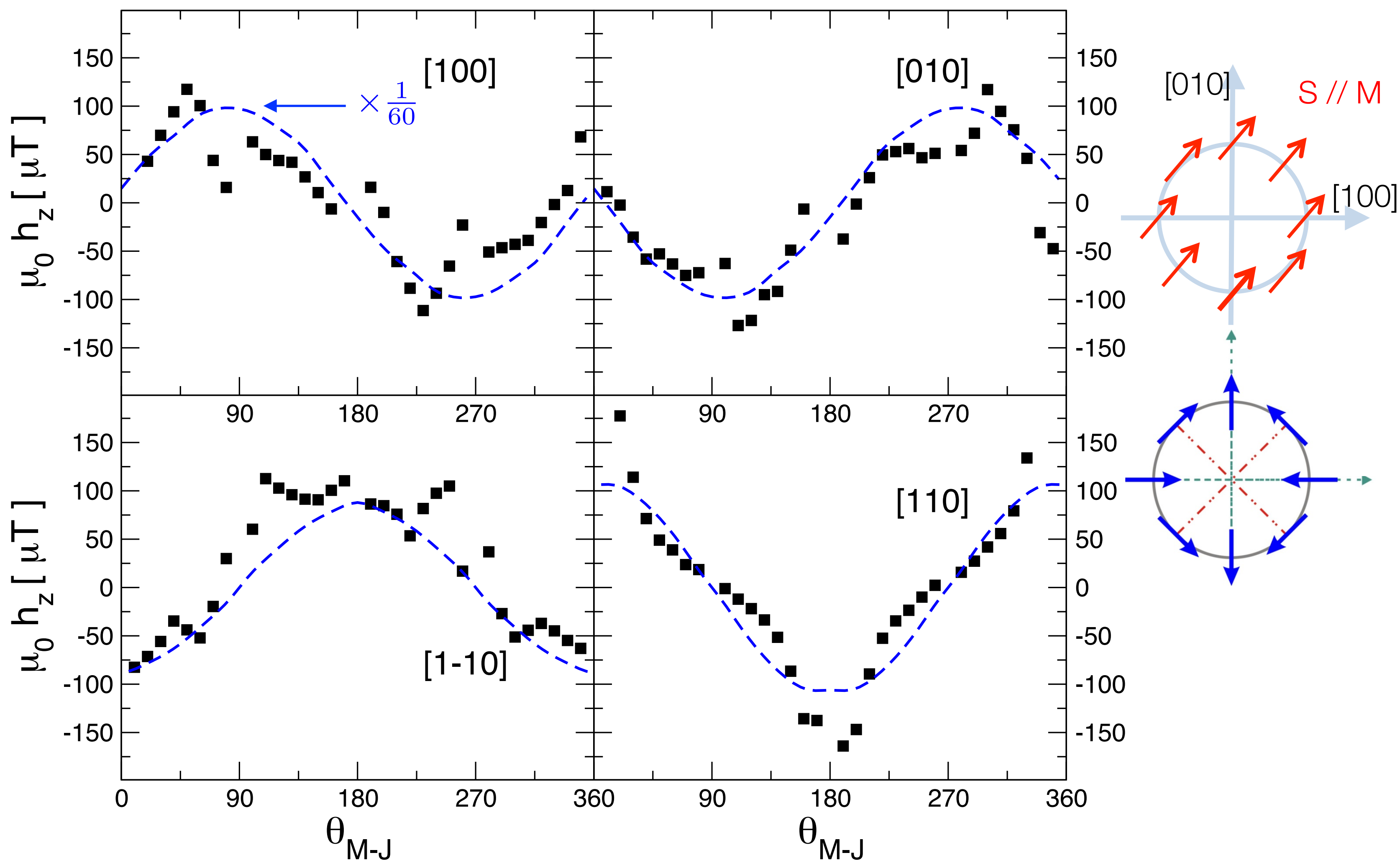


Comparison to Theory



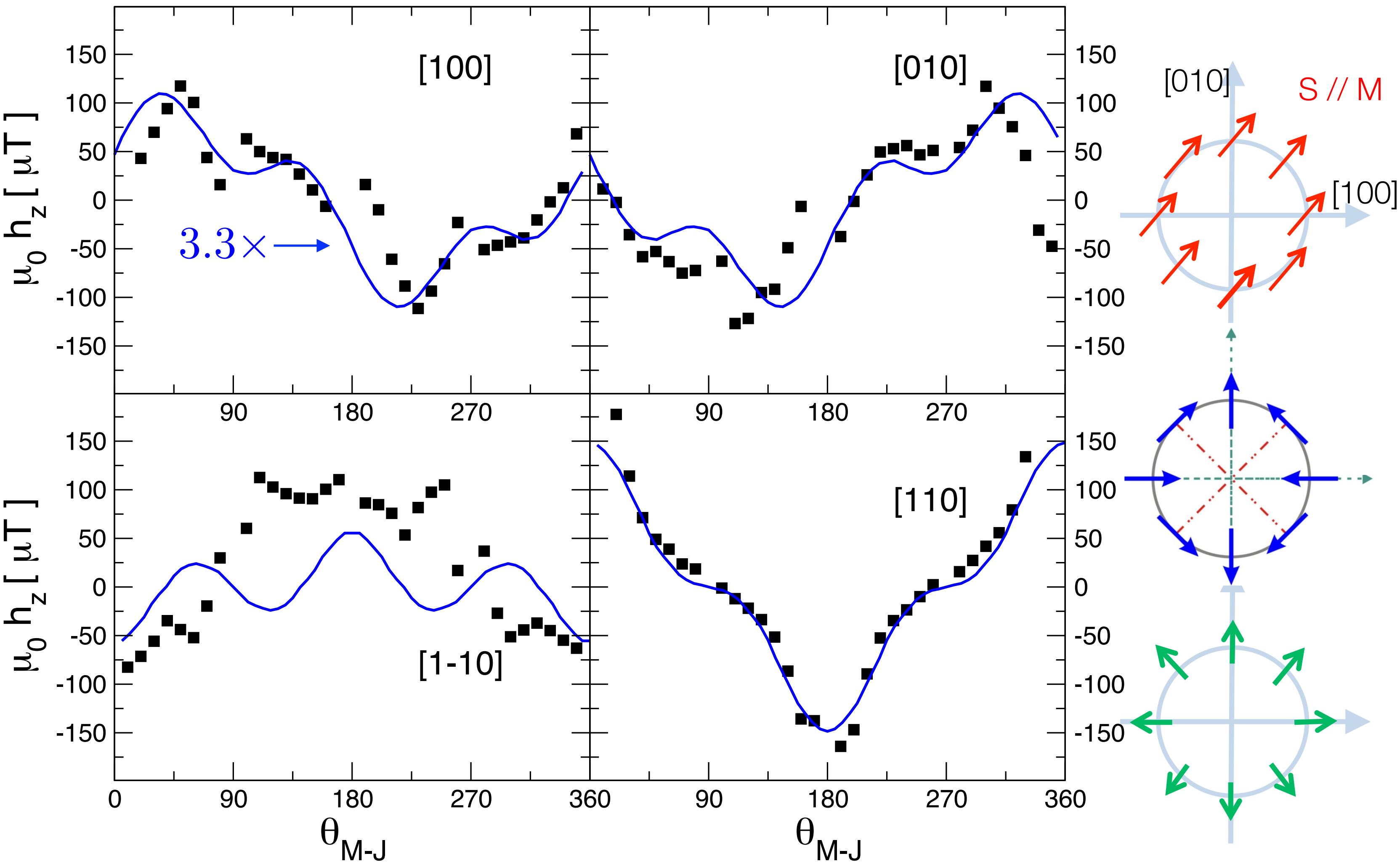
Comparison to Theory

Dash line: Calculations replacing H_{KL} with a parabolic model, i.e. no $(J.k)^2$ term

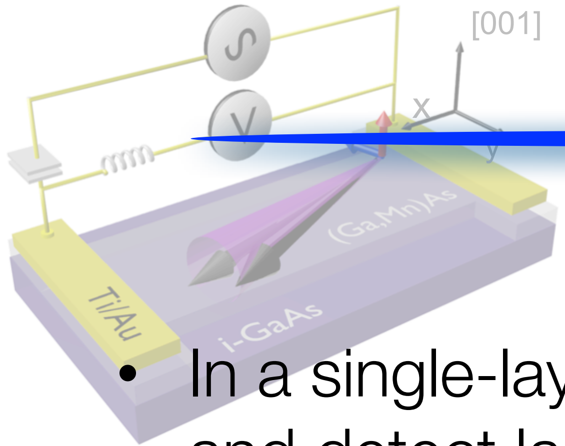


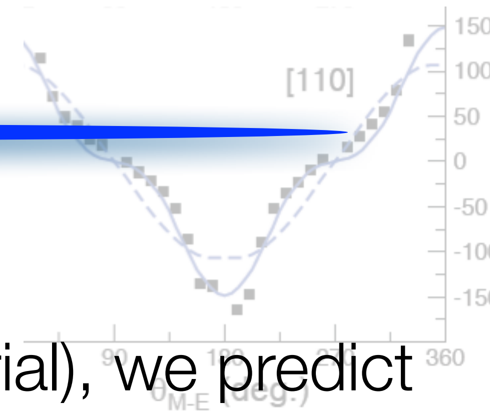
Comparison to Theory

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



Summary

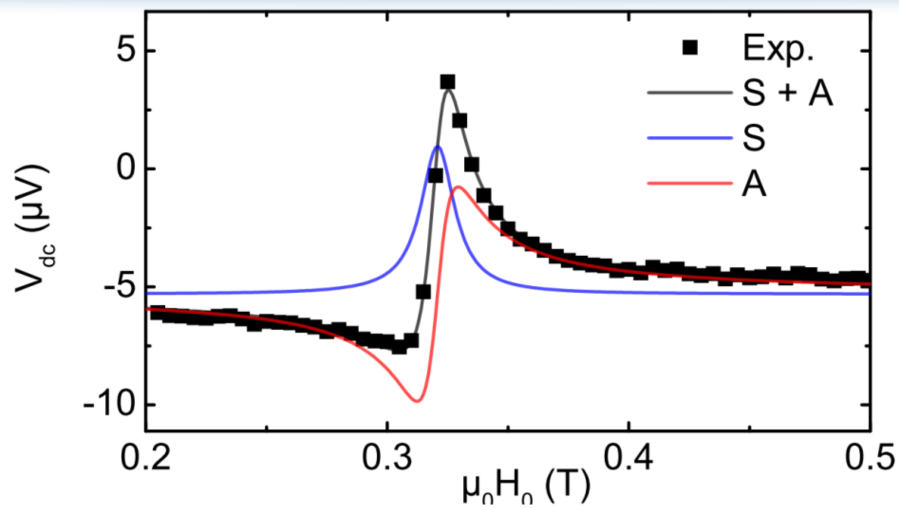




- In a single-layer GaMnAs (bulk SO material), we predict and detect large intrinsic anti-damping spin-orbit torque
- Both extrinsic field-like SOTs and anti-damping intrinsic SOTs are of similar strength
- Because of common origin intrinsic anti-damping SOT will be of comparable strength to SHE-STT in metal multi-layer structures.

More details in: Kurebayashi, Sinova et al., arXiv:1306.1893
Fang et al., Nature Nanotech. (2011)

Torque types and lineshapes



$T_{inplane}$ (or h_z)

$$V_{\rm sym}\frac{\Delta H^2}{(H_0 - H_{\rm res})^2 + \Delta H^2}$$

$V_{sym} = C_1 \times h_z \sin(2\theta)$

Anti-damping torque

Scattering-independent

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

$$V_{\rm asy}\frac{\Delta H(H_0 - H_{\rm res})}{(H_0 - H_{\rm res})^2 + \Delta H^2}$$

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

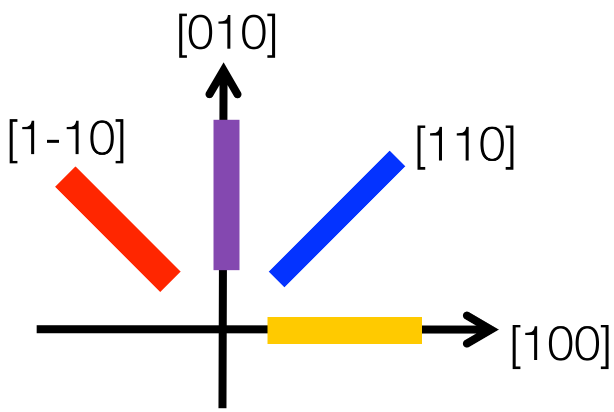
Field-like torque

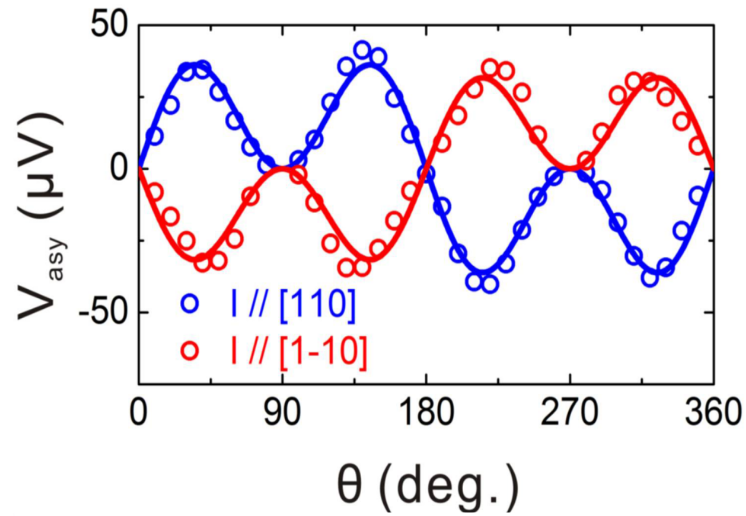
Scattering-dependent

V_{asy} analysis for in-plane SO fields

$$V_{asy} = C_2 \times \sin(2\theta) \times (h_x \sin(\theta) + h_y \cos(\theta))$$

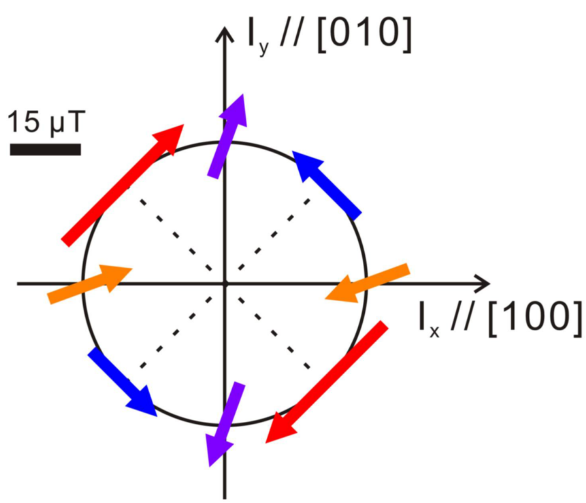
Device bar direction

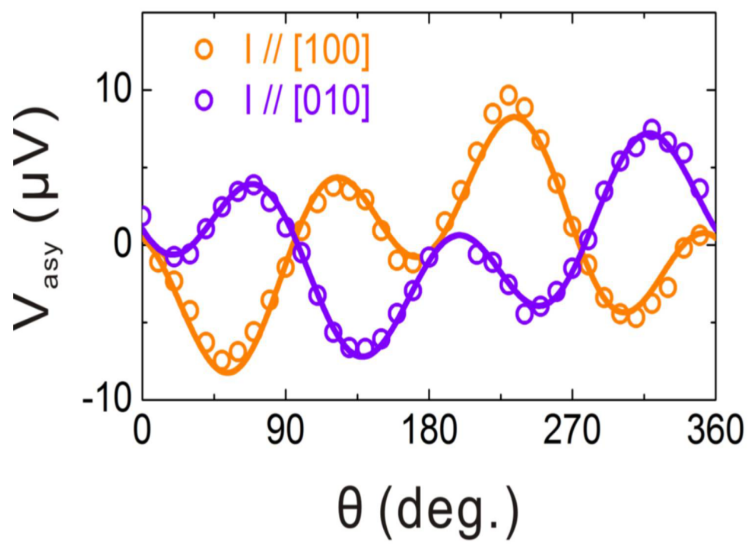




[110]
$+h_y$

[1-10]
$-h_y$





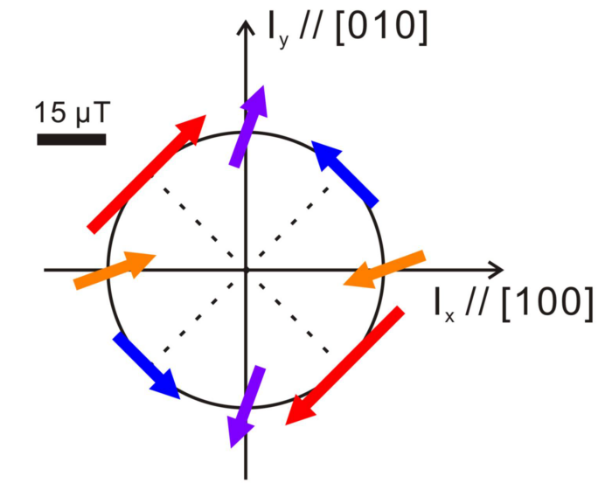
[100]
h_x+h_y

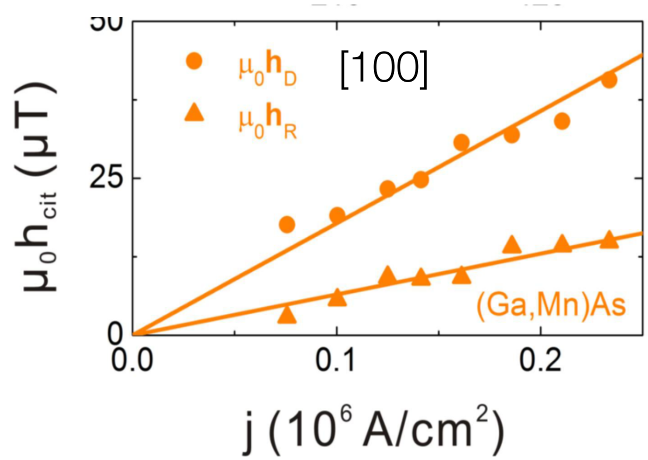
[010]
$-h_x+h_y$

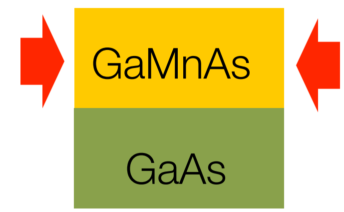
✓Fit well with constant inplane (field-like) h_{SO}

Materials with the opposite strain sign

GaMnAs

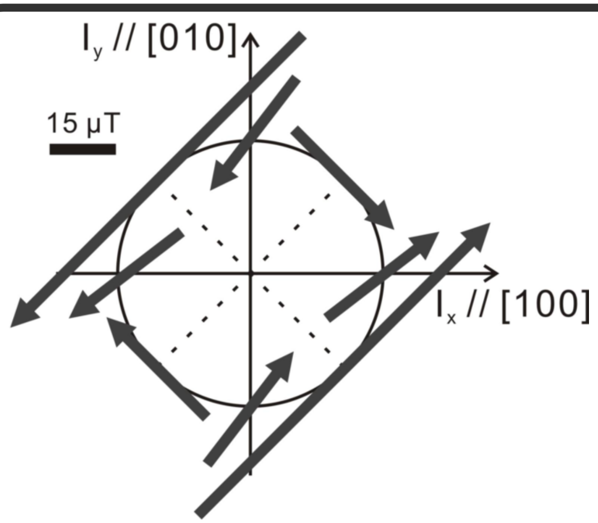


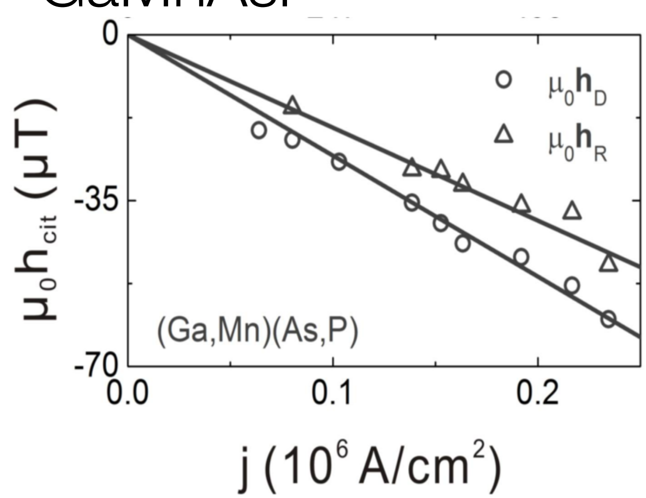




Growth-induced compressive e_{yy}

GaMnAsP





Growth-induced tensile e_{yy}

- ✓ Linear to current density (or k-vector)
- ✓ A sign change between the two materials

↔ Strain-induced h_{SO}