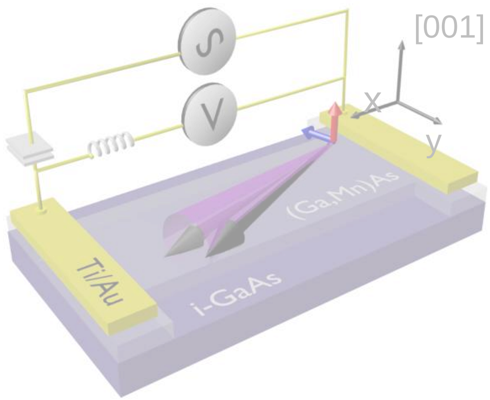
# Anti-damping intrinsic spin-orbit torque arising from Berry phase

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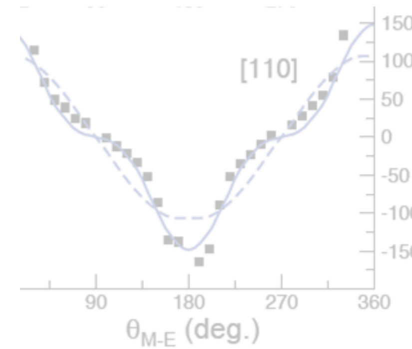


2nd October 2013
Concepts in Spintronics
KITP Conference, Santa Barbara

**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

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# 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

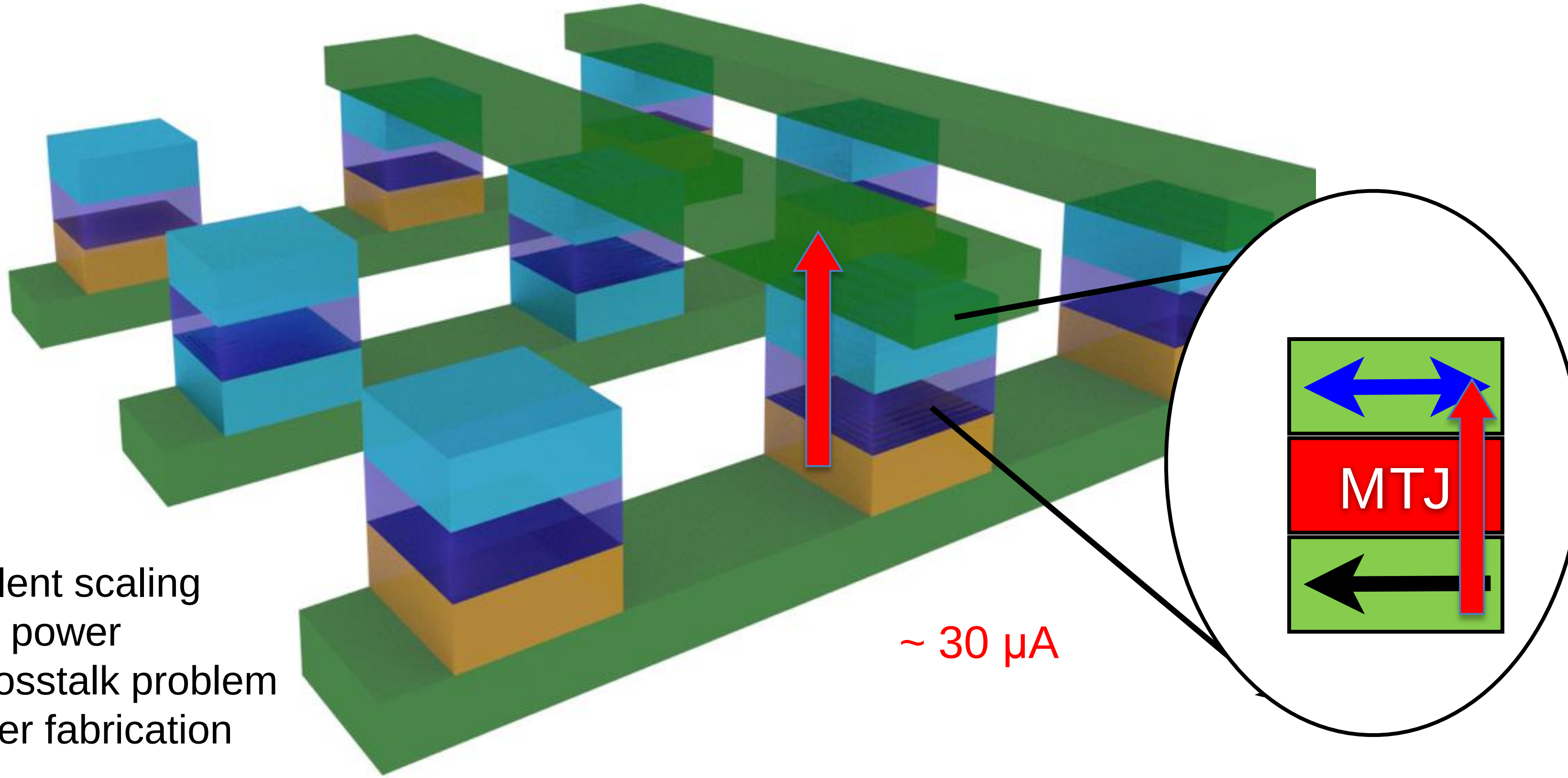
- Linear response: extrinsic and intrinsic mechanisms
- Heuristic picture of Berry's phase anti-damping SOT

## 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

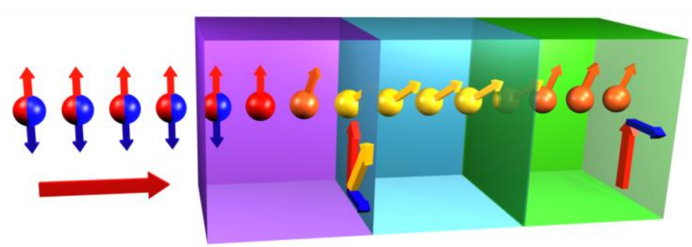
## 4) Comments

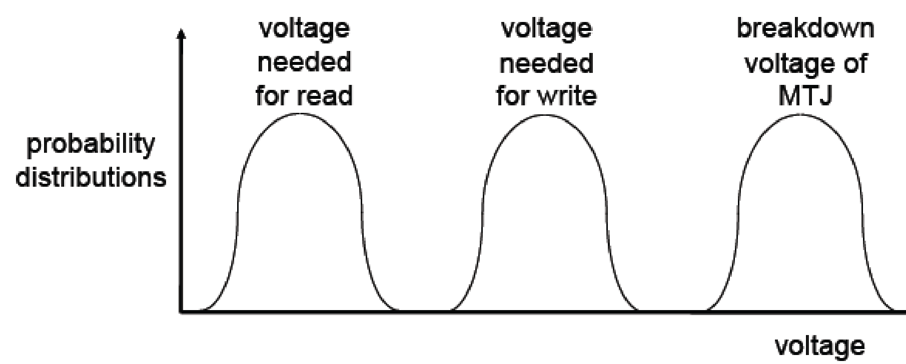
# Spin-Transfer-Torque MRAM



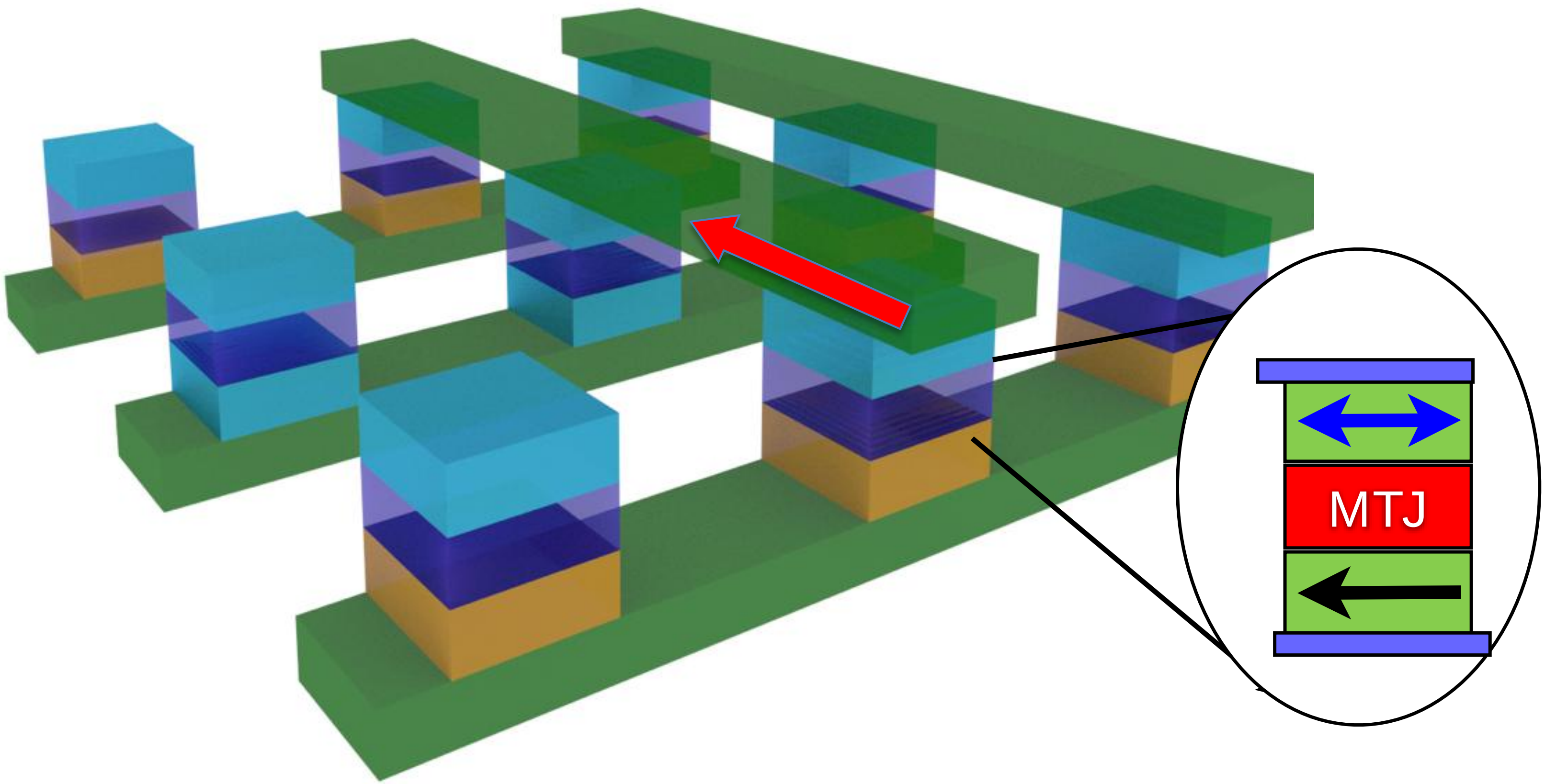

- excellent scaling
- lower power
- no crosstalk problem
- simpler fabrication

STT mechanism:

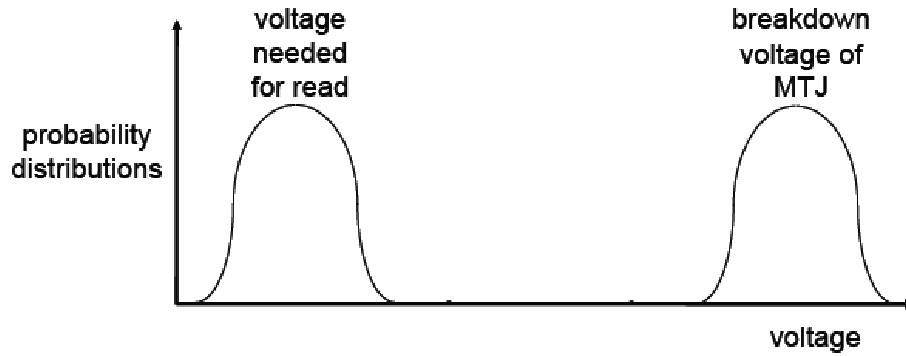




# In-plane-current-switching MRAM

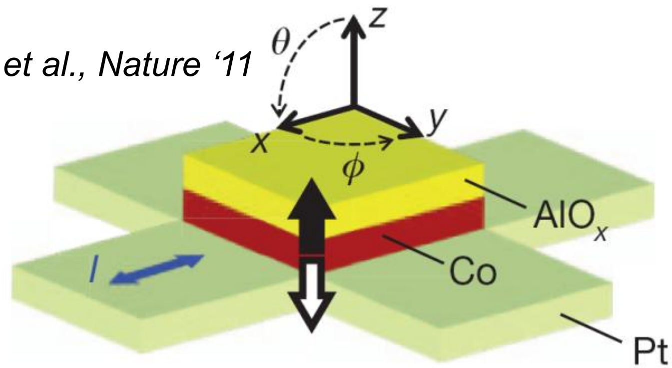


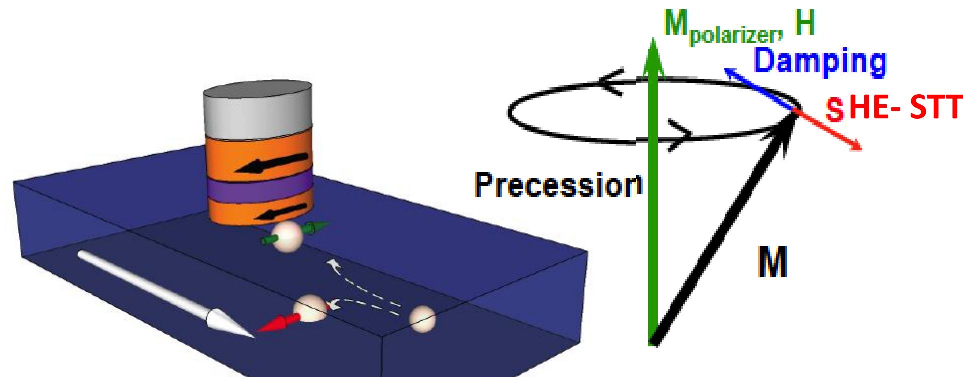

If switching can be done by an in-plane current then a key issue in STT-MRAM is resolved



# Experiments of in-plane current switching

*Miron et al., Nature '11*



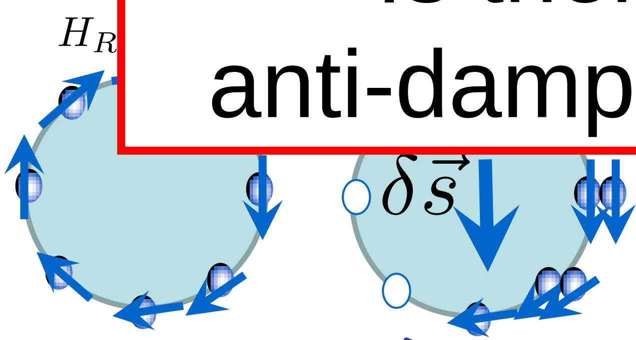




spin-orb

*ience '12*

+ STT

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

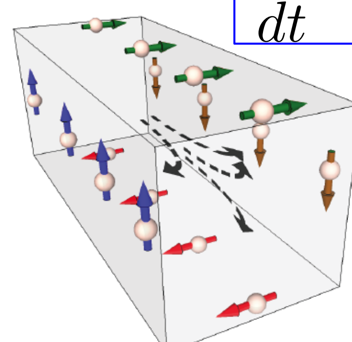



Ta,W)

&

anti-damping STT in ferromagnet (CoFeB)

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



**Intrinsic SHE** in paramagnet acts as the external polarizer

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

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

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

Scattering related and field-like SOT
Extrinsic anti-damping SOT is weak

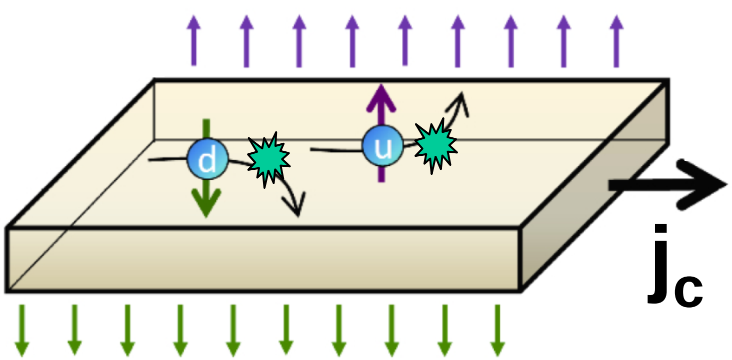
*Bernevig & Vafek PRB '05,*
*Manchon & Zhang, PRB '08, '09*

# Linear response I. (condensed matter class)

Boltzmann theory: non-equilibrium distribution function and equilibrium states

**Extrinsic (skew-scattering) SHE**

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

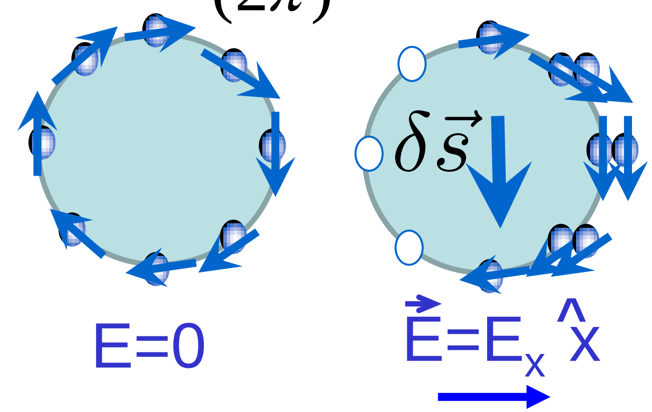



*Dyakonov and Perel 1971*
*Hirsch PRL'99*

*Kato et al., Science '04*

**Field-like SOT**

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




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

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

*Bernevig & Vafek PRB ,05*
*Manchon & Zhang, PRB '08*

*Chernyshev et al. Nature Phys.'09,*

*Miron et al. Nature Mat.'09,*

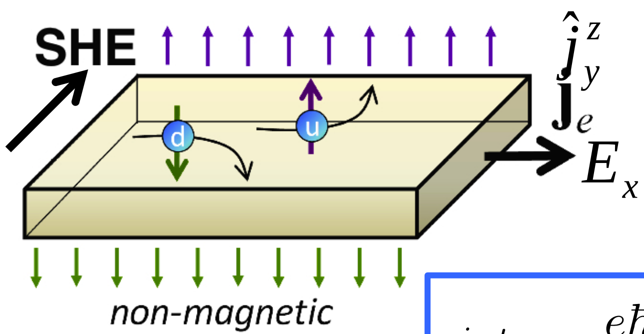
$$g_{n,\vec{k}} = f_{n,\vec{k}} - f_0(E_{n,\vec{k}})$$

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

# Linear response II. (condensed matter class)

## Perturbation theory: equilibrium distribution function and non-equilibrium states

### Intrinsic SHE from linear response II




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

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

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

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

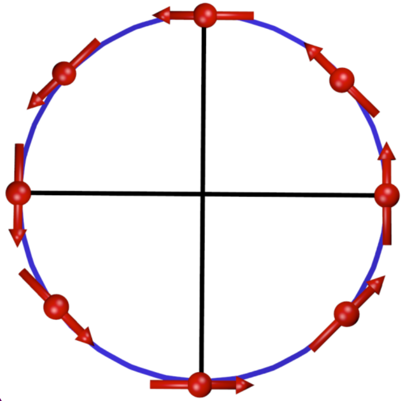
*Wunderlich et al. Phys. Rev. Lett. '05*
*Werake et al., PRL'11*

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

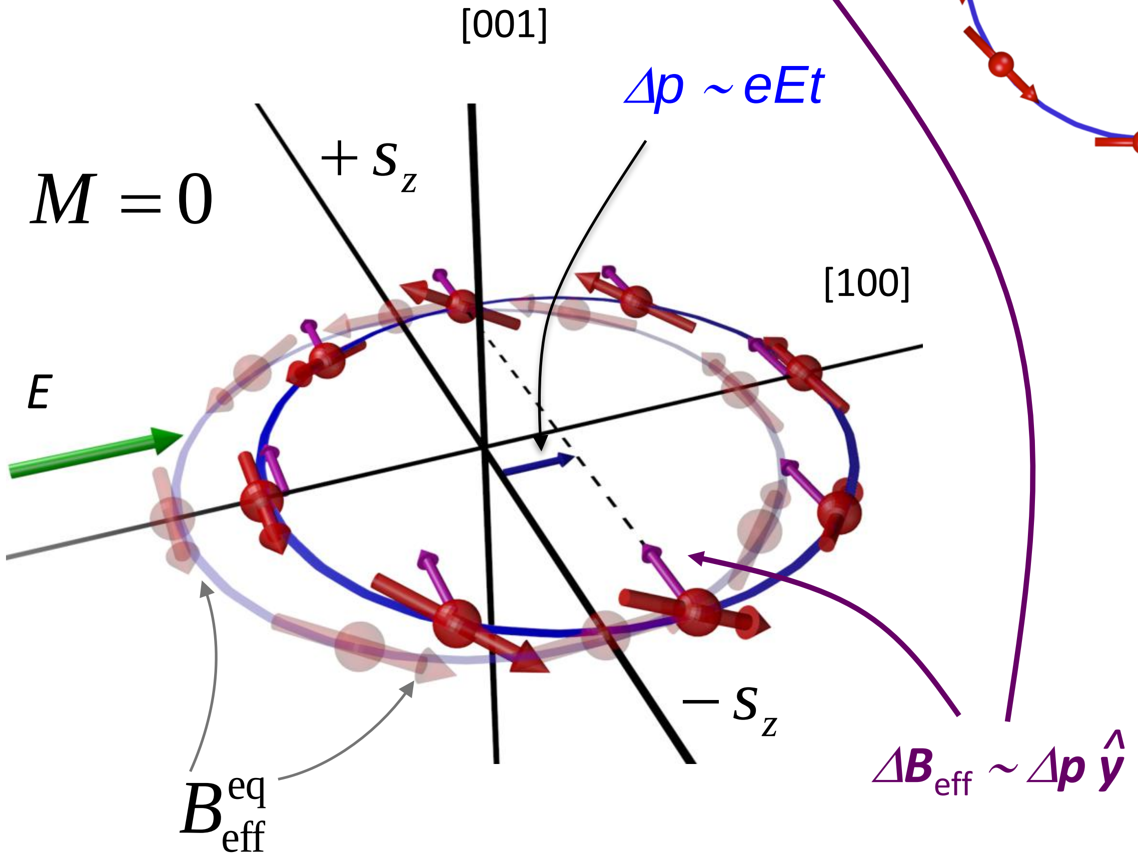
$$S^{int}_z = \frac{e\hbar}{V} \sum_{\vec{k},n\neq n'} (f^0_{\vec{k},n'} - f^0_{\vec{k},n}) \frac{\mathrm{Im}[\langle \vec{k},n'|s_z|\langle \vec{k},n\rangle \langle \vec{k},n'|\vec{v}\cdot\vec{E}|\vec{k},n'\rangle}{(E_{\vec{k},n'} - E_{\vec{k},n})^2}$$

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

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

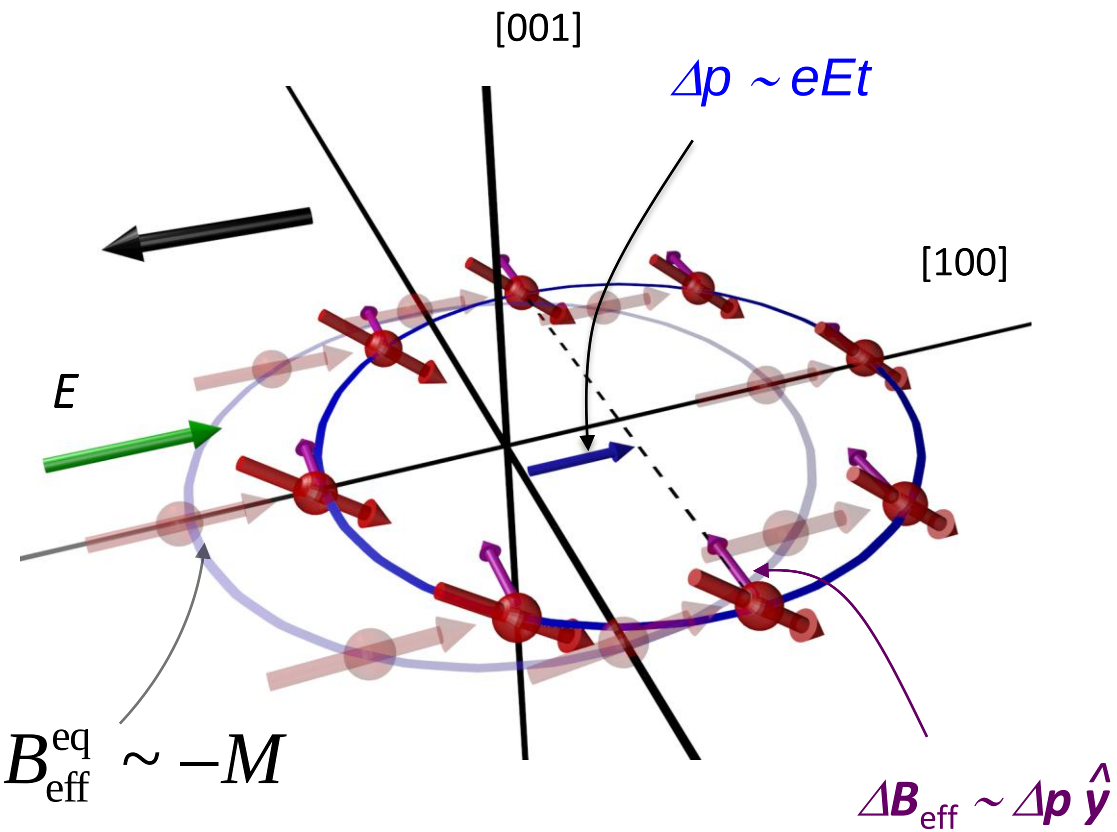


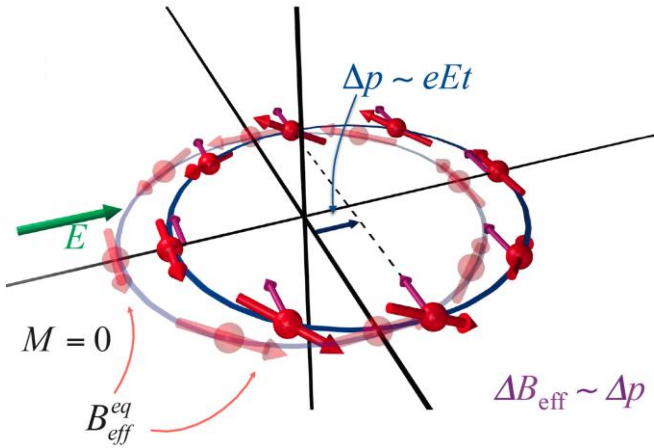
$M = 0$



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

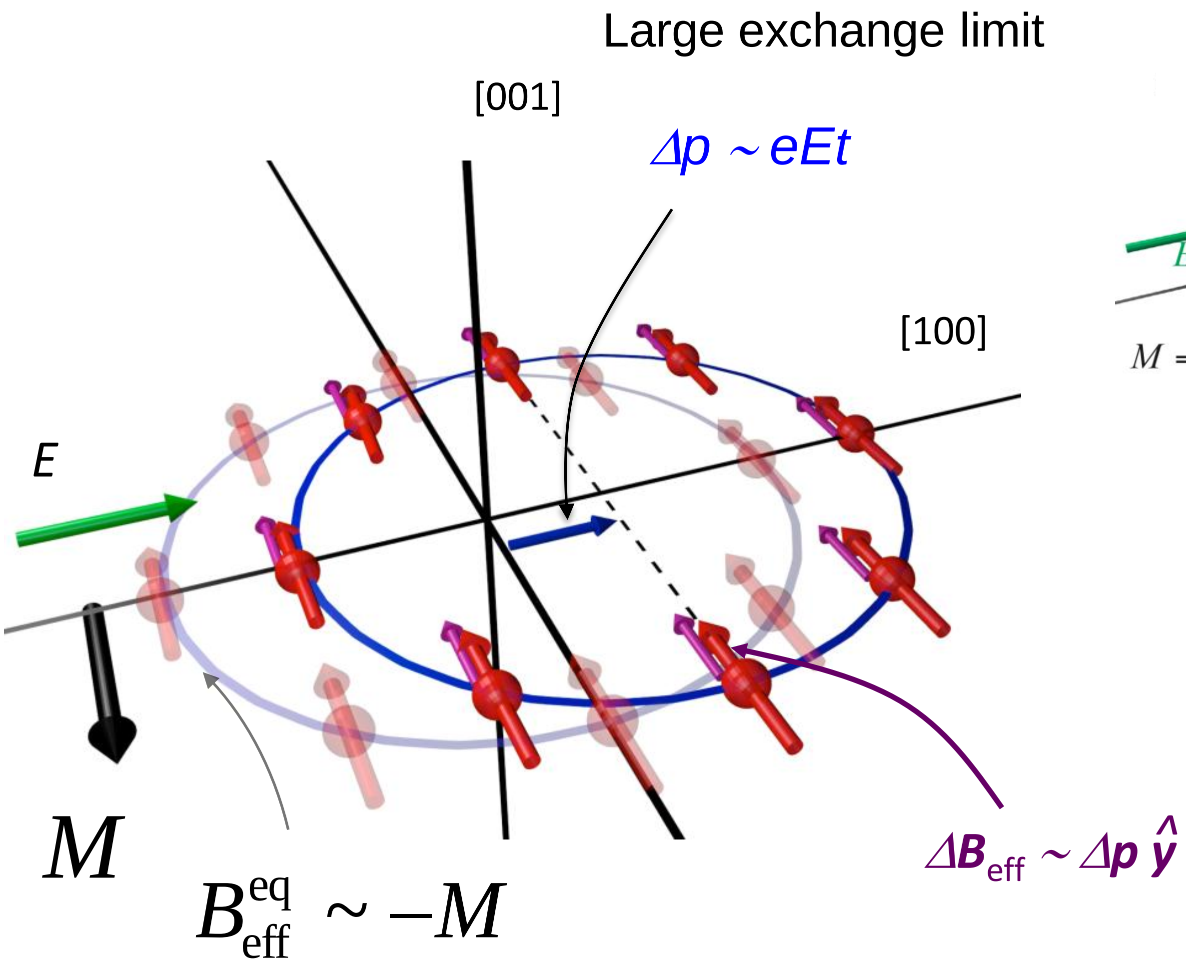
Large exchange limit

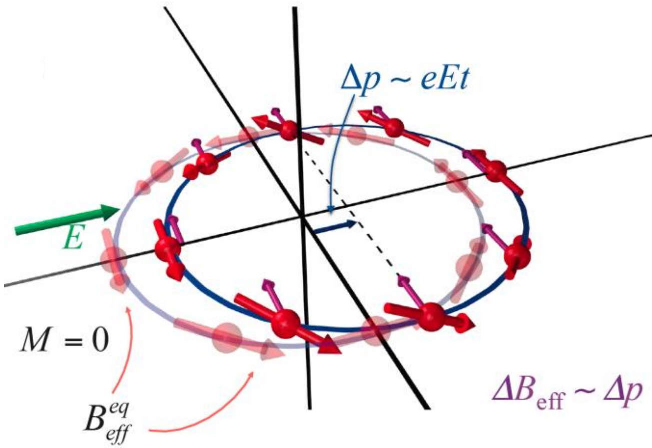



$$\frac{d\vec{M}}{dt} \sim \vec{M} \times h\hat{z}$$ maximum $h\hat{z}$ for $\vec{M} \parallel \vec{E}$

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

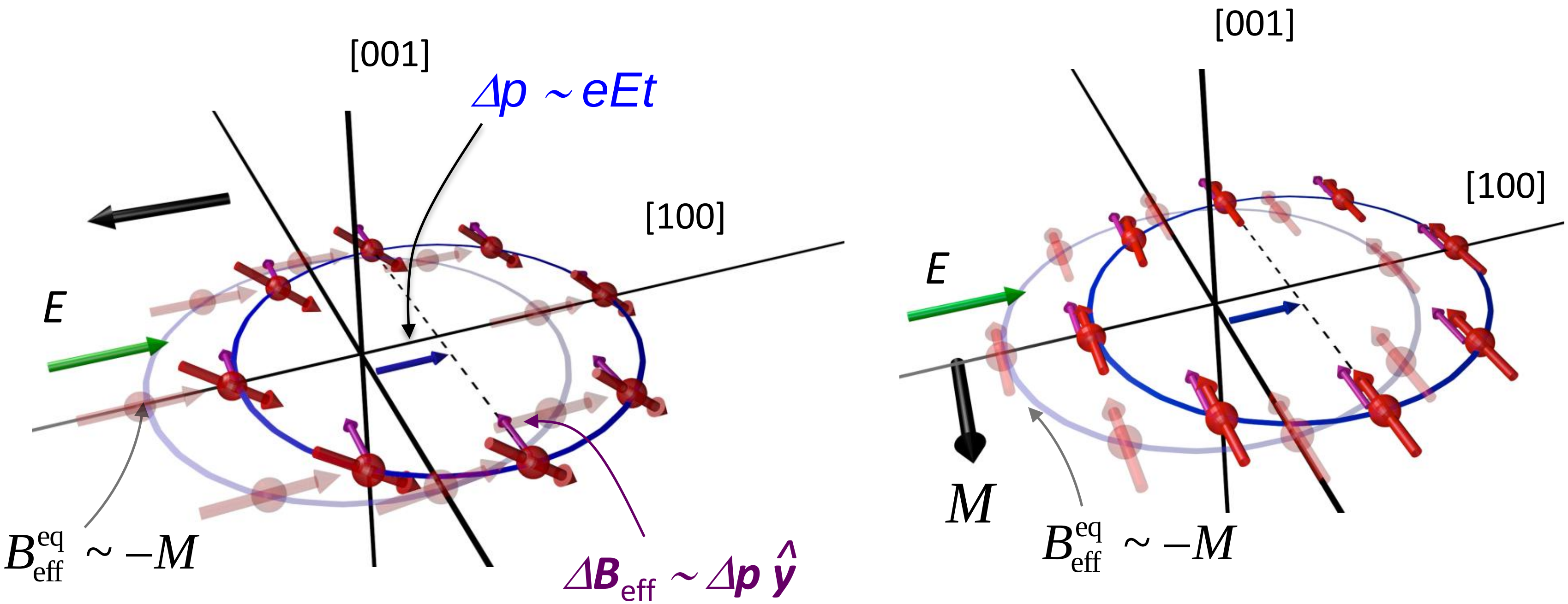



$$\frac{d\vec{M}}{dt} \sim \vec{M} \times h\hat{z}$$

zero $h\hat{z}$ for $\vec{M} \perp \vec{E}$

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

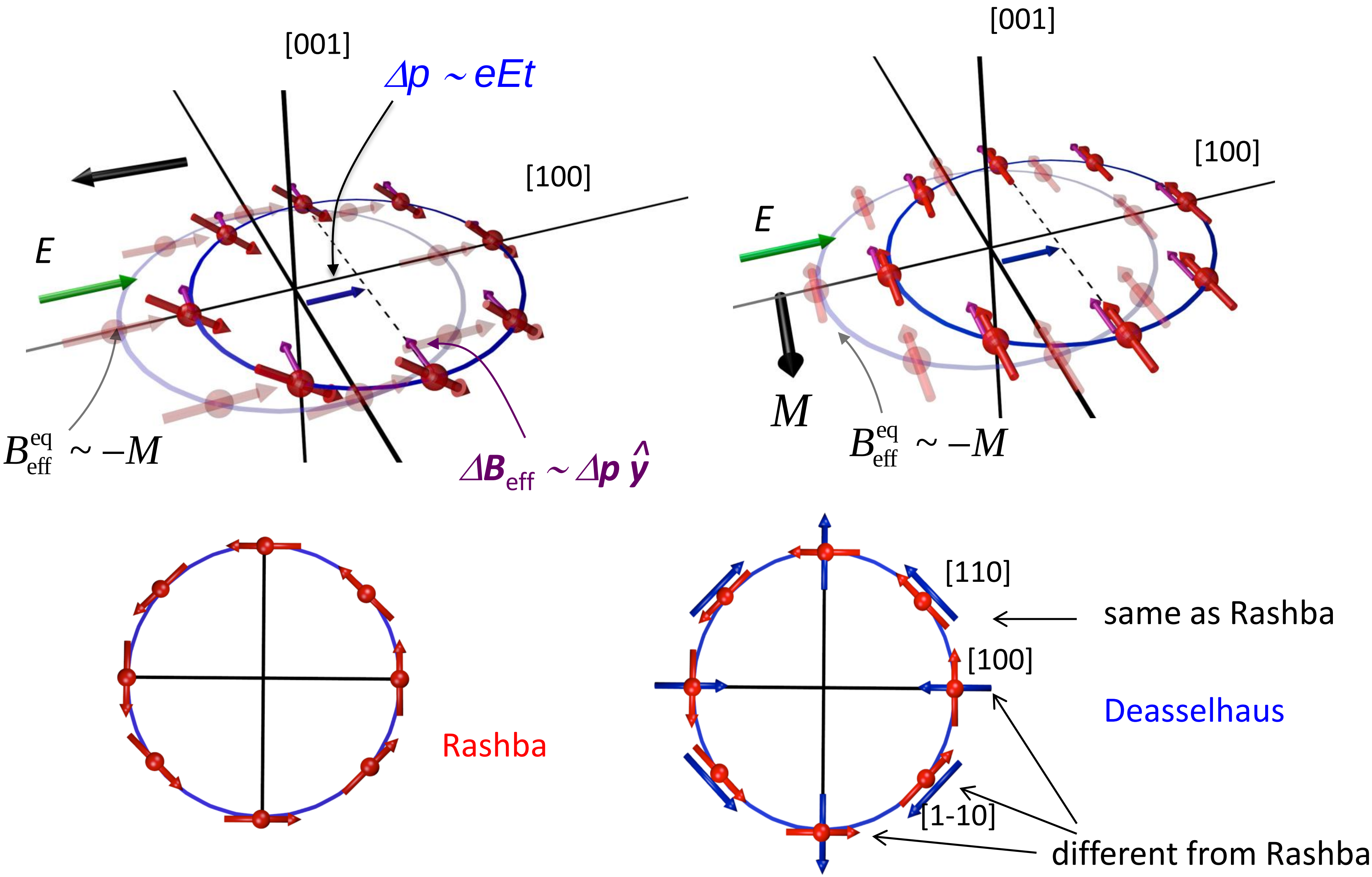



anti-damping

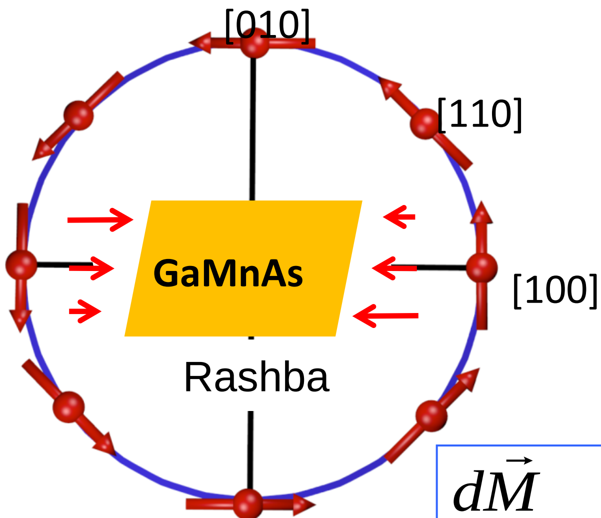
$$\frac{d\vec{M}}{dt} \sim \vec{M} \times h_z \hat{z}$$

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

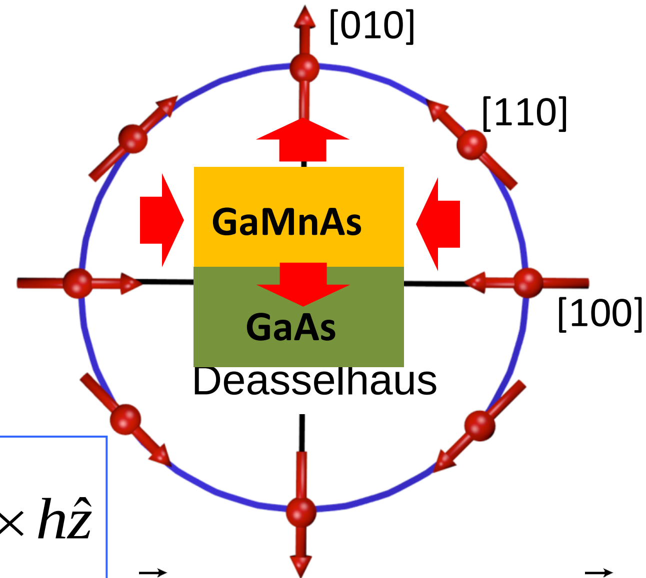
# Intrinsic (Berry phase) spin-orbit torque from Bloch eq.



# Intrinsic (Berry phase) spin-orbit torque in GaMnAs




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




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

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

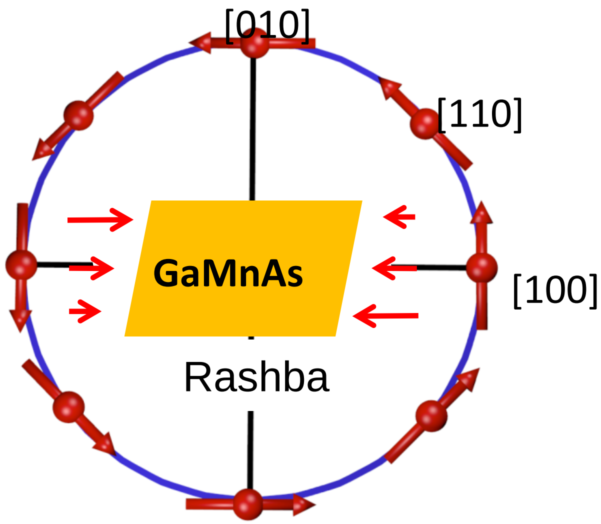
$\vec{E} \parallel [1-10]: \quad h\hat{z} \sim -[\vec{E} \times \hat{z}] \times \vec{M}$

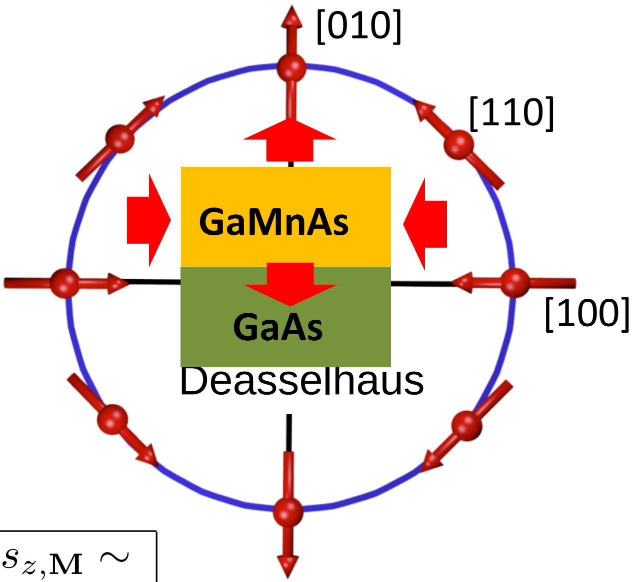
$\vec{E} \parallel [100]: \quad h\hat{z} \sim \vec{E} \times \vec{M}$

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

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

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

$$H_{\mathrm{KL}} = \frac{\hbar^2 k^2}{2m_0}\left(\gamma_1 + \frac{5}{2}\gamma_2\right)\mathbf{I}_4 - \frac{\hbar^2}{m_0}\gamma_3\left(\mathbf{k}\cdot\mathbf{J}\right)^2$$

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

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

Rashba → $-C_5\left[\epsilon_{xy}(k_y J_x - k_x J_y) + \mathrm{c.p.}\right]$

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~~

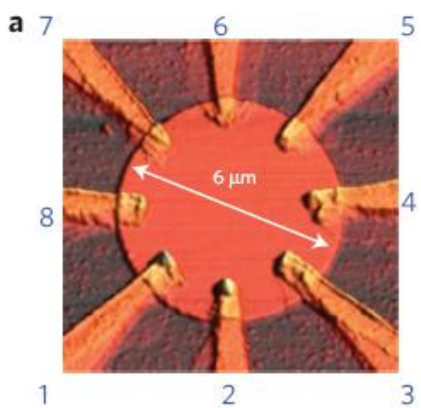
## 3) Experimental technique, results and modeling

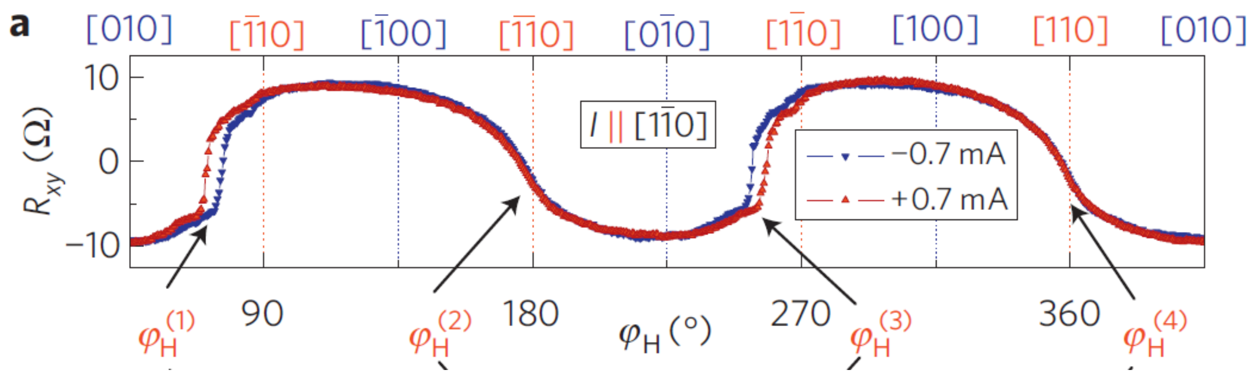
- Spin-orbit-field FMR experiments
- In-plane (field-like) and out-of-plane (anti-damping-like)
- Comparison to theory predictions

# First works: current-induced SO effective fields

## Effective spin-orbit (SO) field by dc current

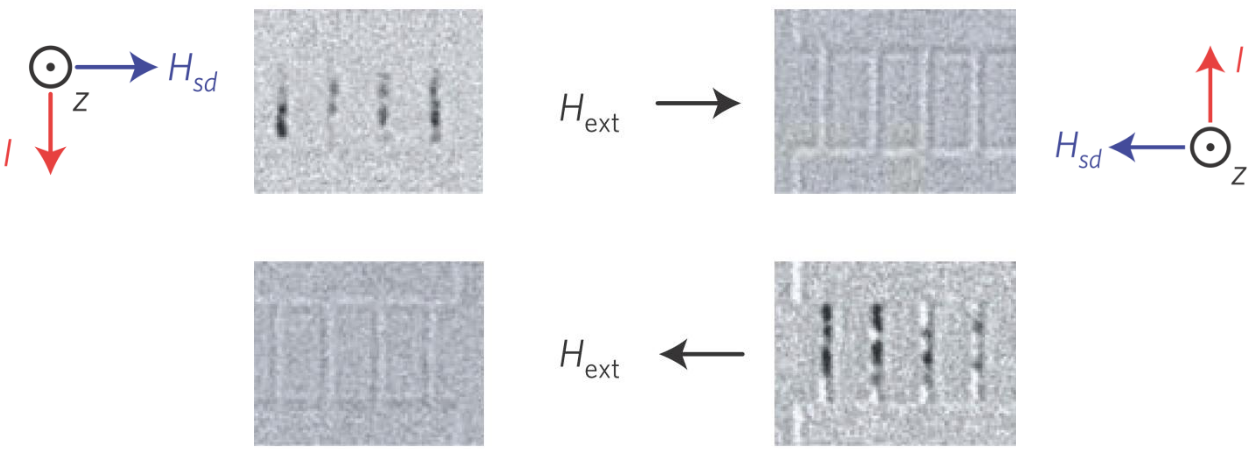
GaMnAs: bulk broken symmetry, Chernyshov, Rokhinson, et al, Nature Phys., 5, 656 (2009)




✓ 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 syst

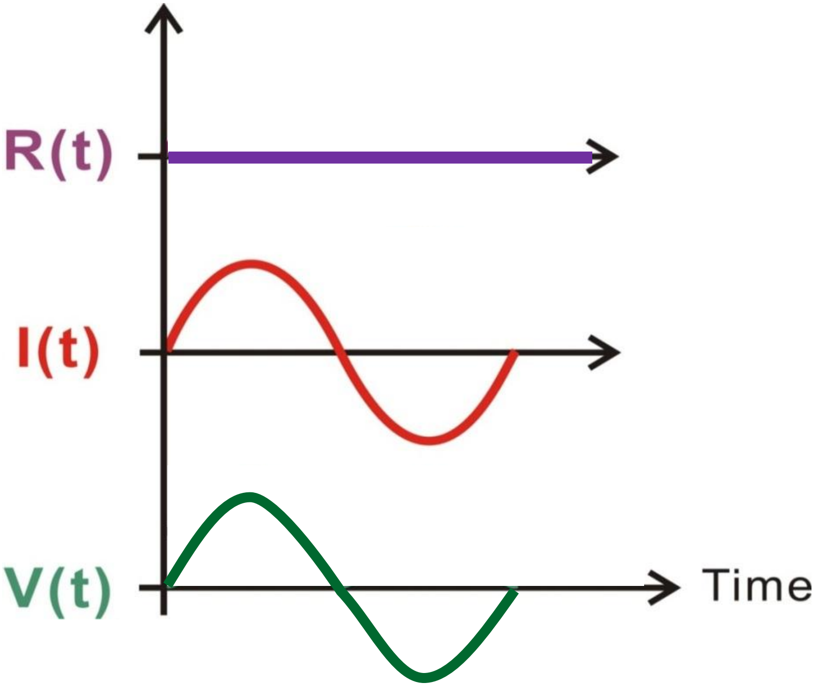
# Measuring SOT by ac-currents

Current-induced SO fields by ac current

It's all about the Ohm's law.

$$V = I_{ac}\sin\omega t \times (R_{(}$$

$$= \underline{I_{ac}R_0\sin\omega t}$$



# Other works and measurement techniques

## Current-induced SO fields by ac current

It's all about the Ohm's law. $\Delta R_{ac}$ 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)

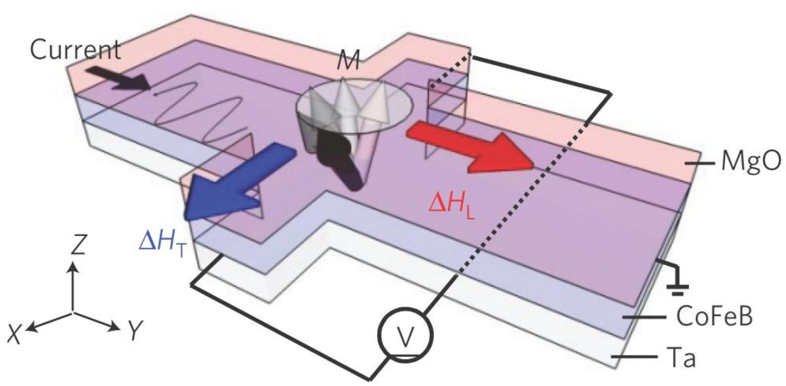
Py/Pt: Fan, et al J. Q. Xiao, Nature Comm. 4, 1799 (2013)

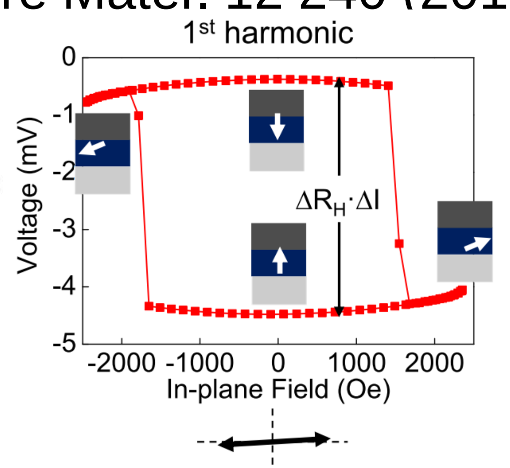
Quasi-static regime (kHz frequency)

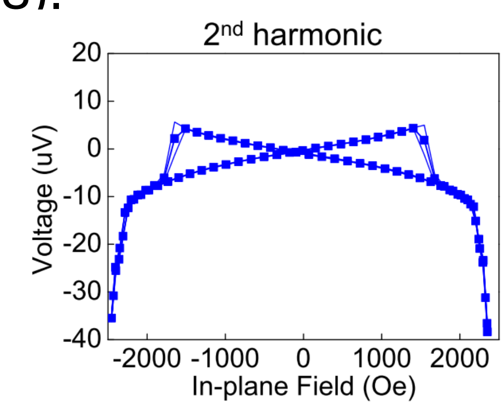
AlOx/Co/Pt: Pi et al., APL 97 162507 (2010).

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

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



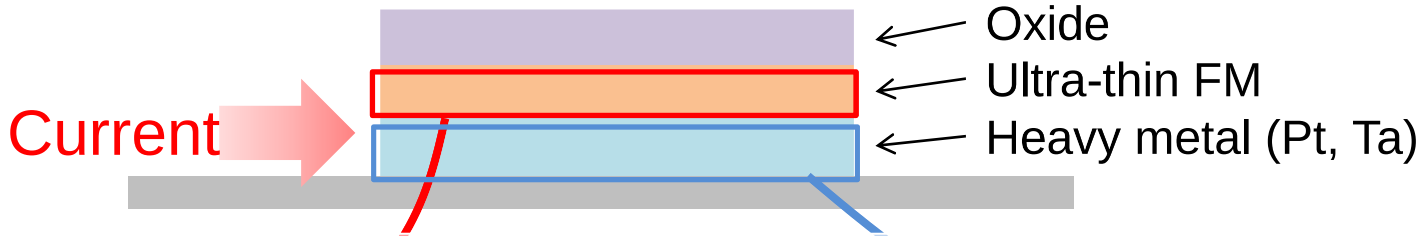



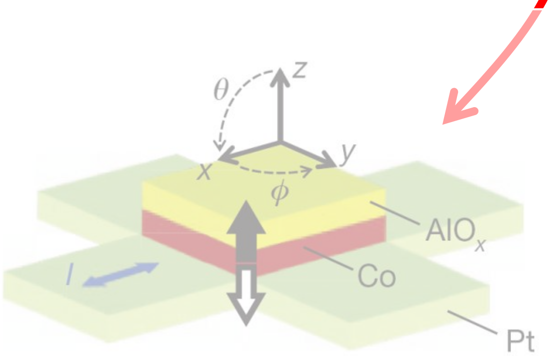




$\Delta H_T$~60 Oe

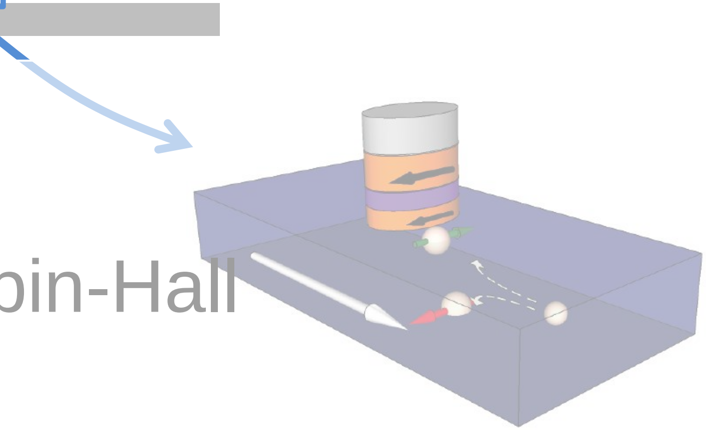
# Problems in metal multi-layers

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




Rashba vs spin-Hall



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.

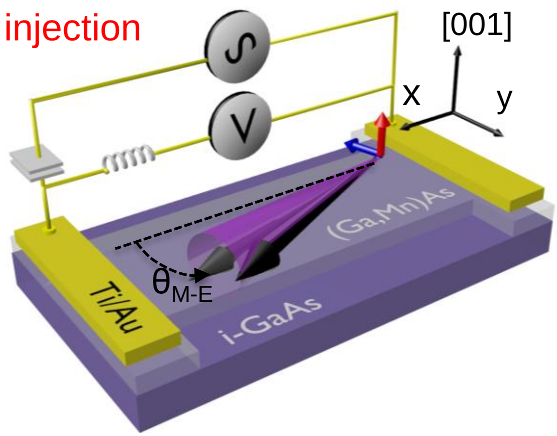
✓ Allows for single thin film geometry: no SHE-STT by desig

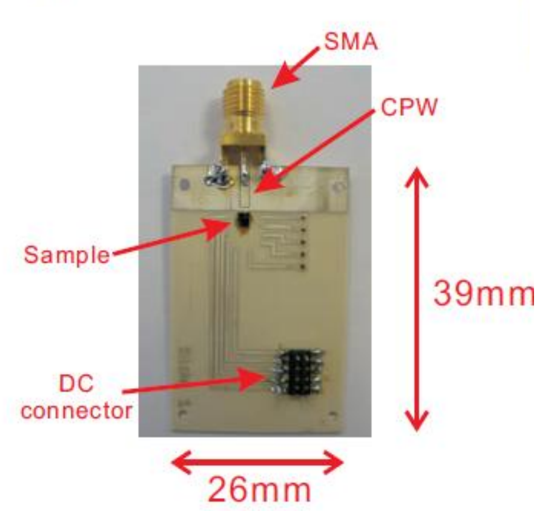
➡ The ideal material for understanding spin-orbit torques

# Electrical induced/detected FMR

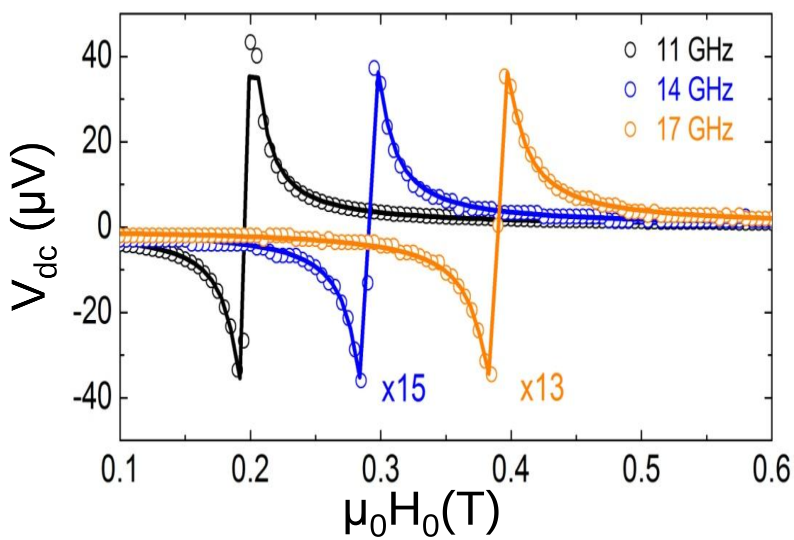
Fang, et al., Nature Nanotech. (2011)

GHz ac current injection

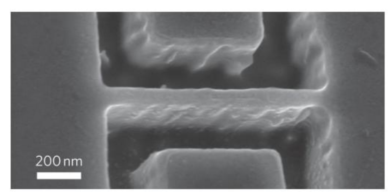



$$V = I_{ac}\sin\omega t \times (R_0 + \Delta R_{ac}\sin\omega t)$$
$$= I_{ac}R_0\sin\omega t + 0.5\times(I_{ac}\Delta R_{ac} + I_{ac}\Delta R_{ac}\sin 2\omega t)$$




SEM image



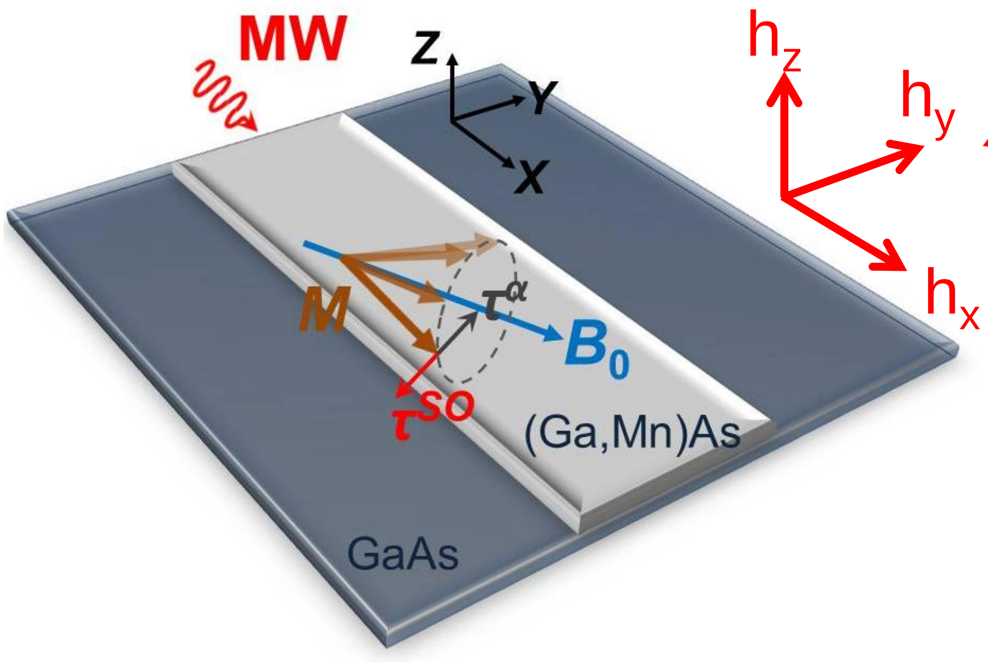

80 nm width!
(if you push hard…)

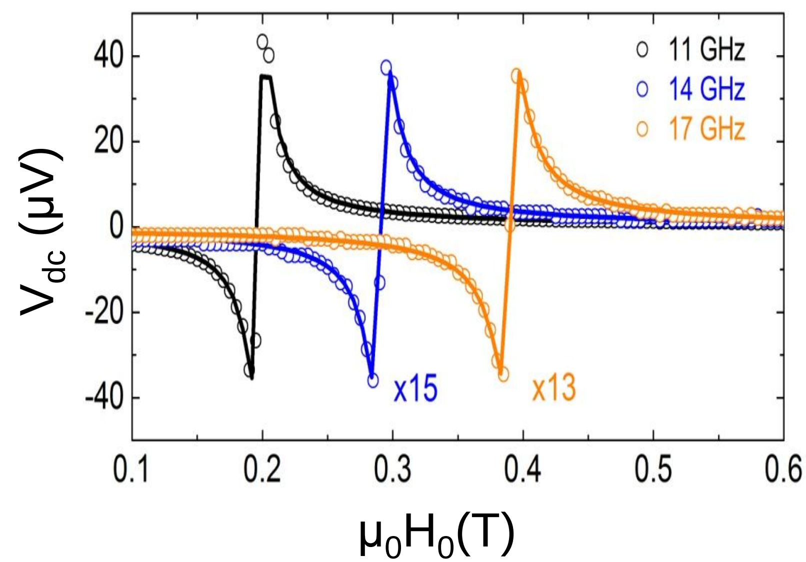
✓ Nanoscale on-chip FMR measurements

# Magnetic dynamics phenomenology

## Landau-Lifshitz-Gilbert equation

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

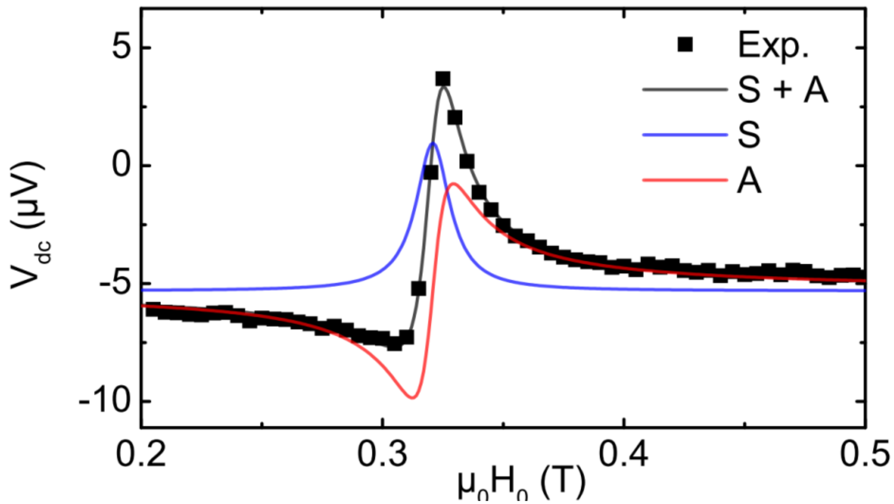



Because $h_{so}=-J_{pd}\,\Delta s$

the V amplitudes contain SO information.

# Torque types and line-shapes




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

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

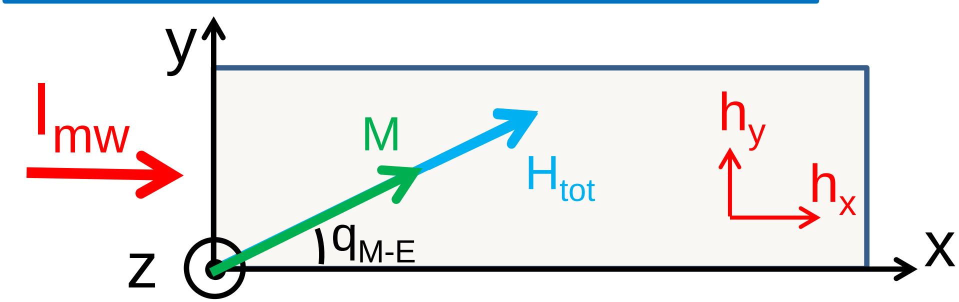
$V_{sym} = C_1 \times h_z(\theta) \sin(2\theta)$

+

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

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

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



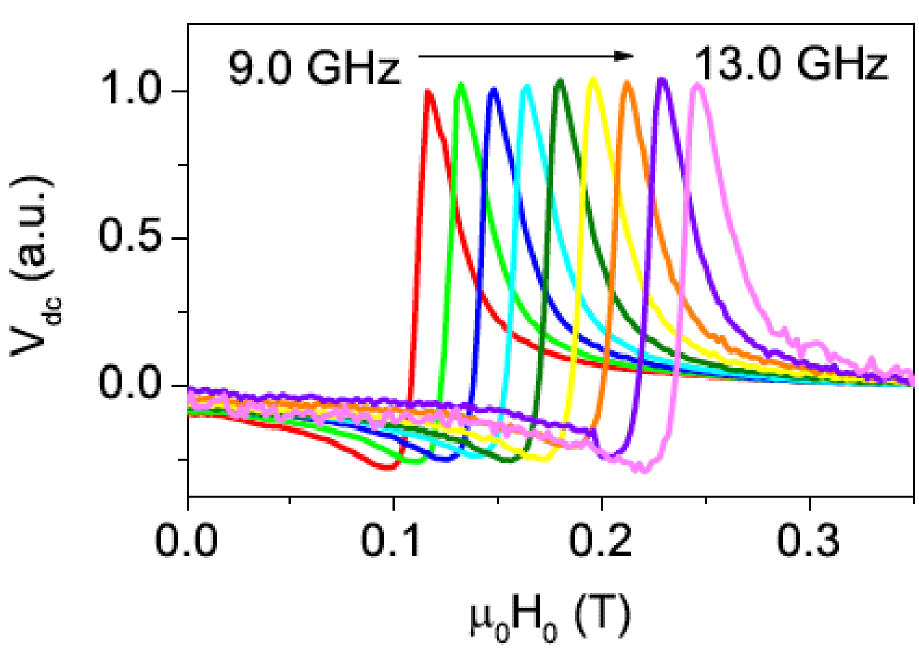

Sample:
18 or 25 nm-thick GaMnAs
4 mm-wide

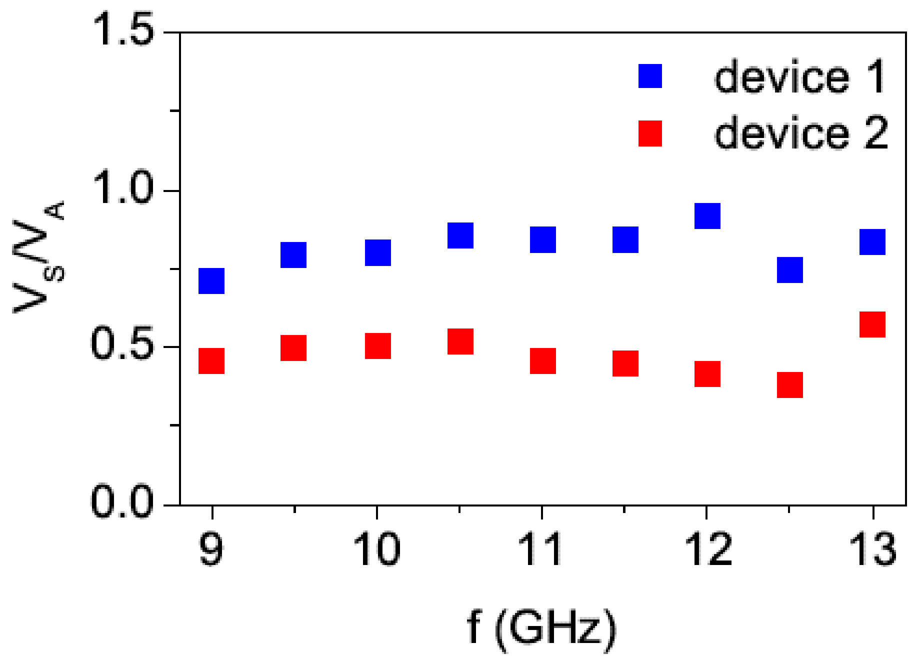
Kurebayashi, Sinova et al., arXiv:1306.1893
Fang et al., Nature Nanotech. (2011)

# Relative phase of current and induced field

Expected to be in phase since at microwave frequencies real part of conductivity dominates (omega $\omega\tau < 10^{-4}$ at GHz frequencies)

Harder, M., Cao, Z. X., Gui, Y. S., Fan, X. L. & Hu, C.-M. Analysis of the line shape of electrically detected ferromagnetic resonance. Phys. Rev. B 84, 054423 (2013):
In bi-layer systems inductive or capacitive coupling can induce a relative phase that can change the ratio of symmetric to antisymmetric signal by many orders of magnitude



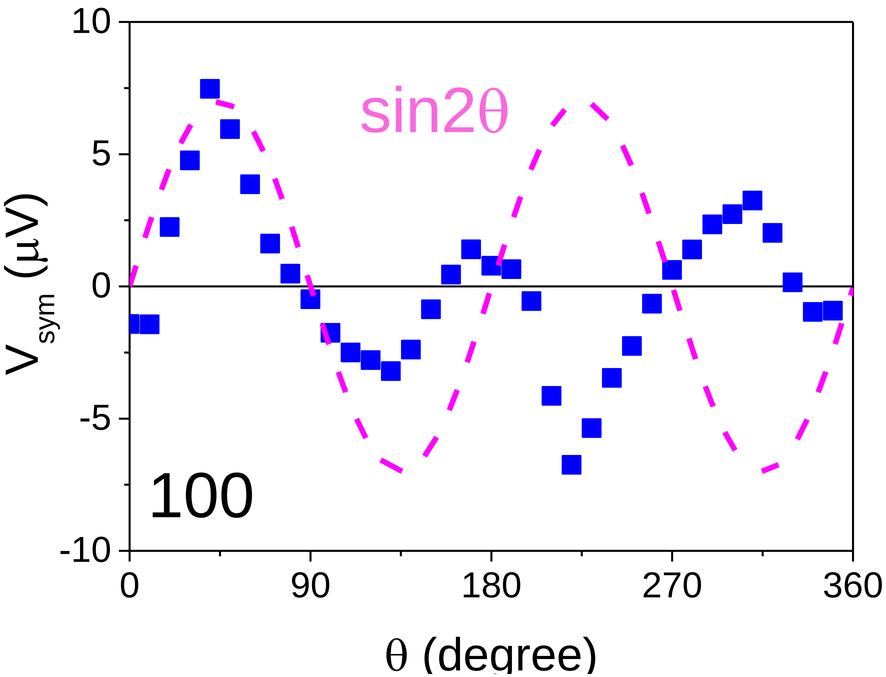

RATIO INDEPENDENT OF FREQUENCY → ZERO RELATIVE PHASE SHIFT

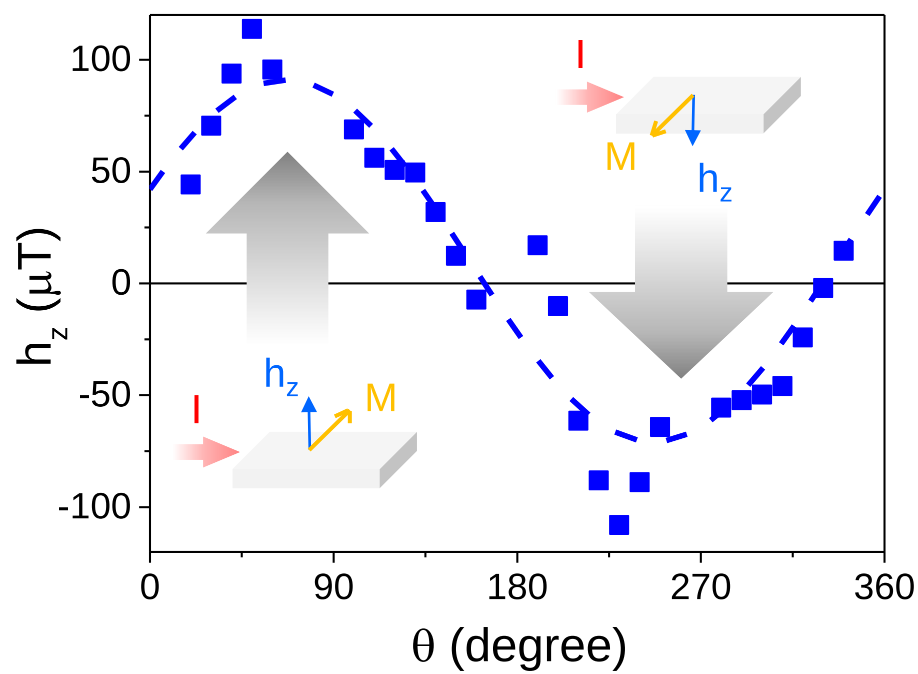
# The out-of-plane SO field

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

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

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

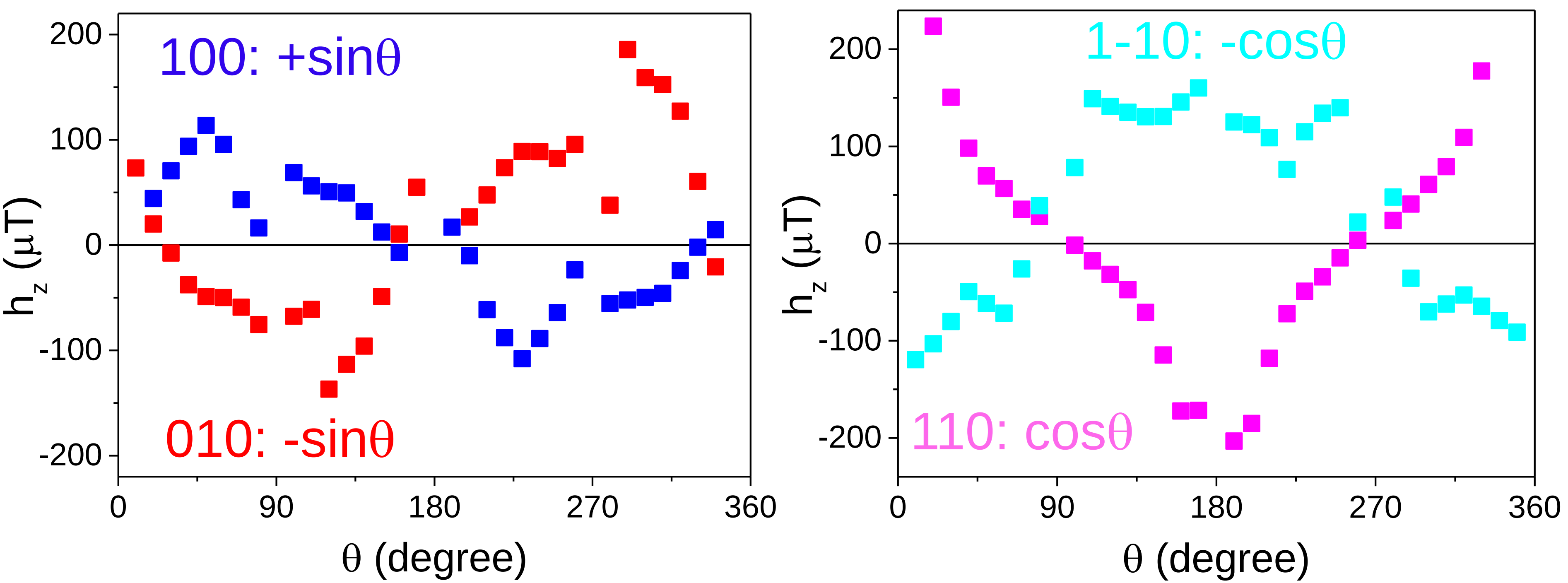



✓ M-dependent $h_z$

✓ The sinθ symmetry for 100 direction.

# Current direction dependence




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

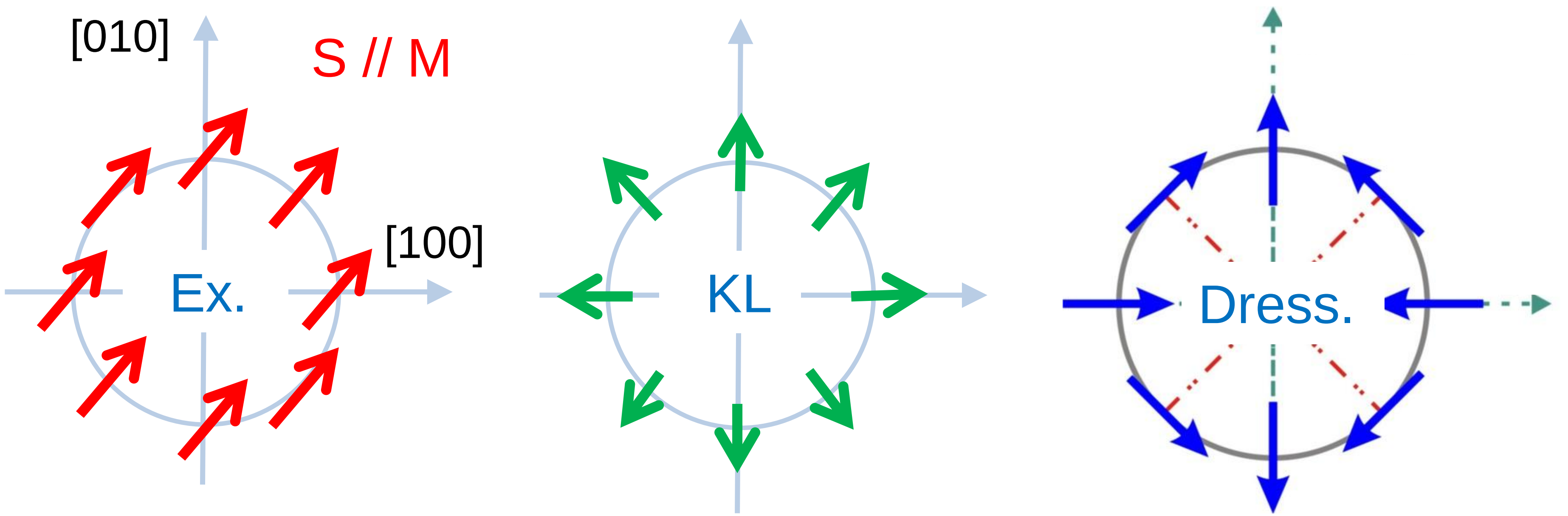
# Effective Hamiltonian of GaMnAs

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

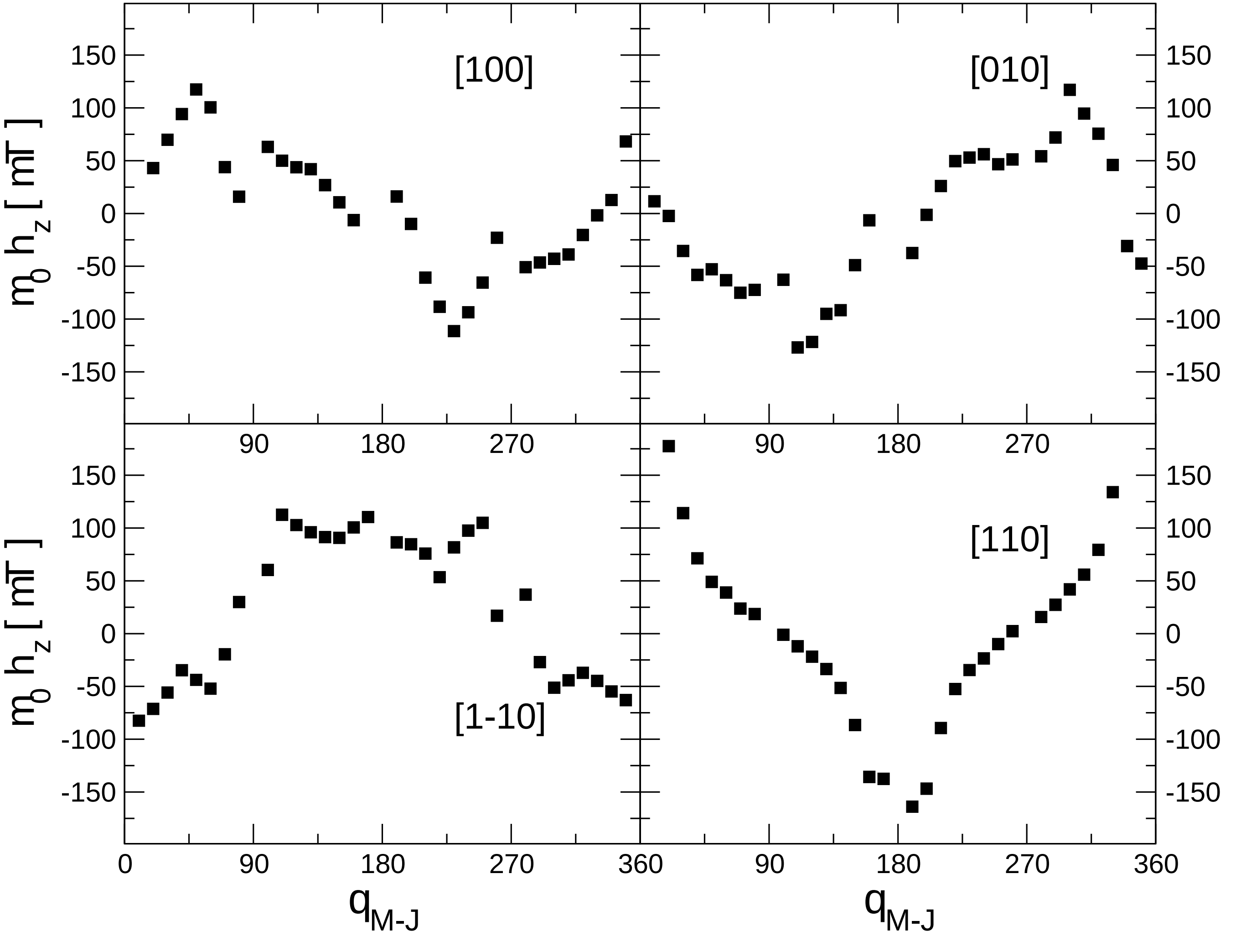
k-independent ~100 meV

$k^2$-dependent ~100 meV

k-linear ~1 meV

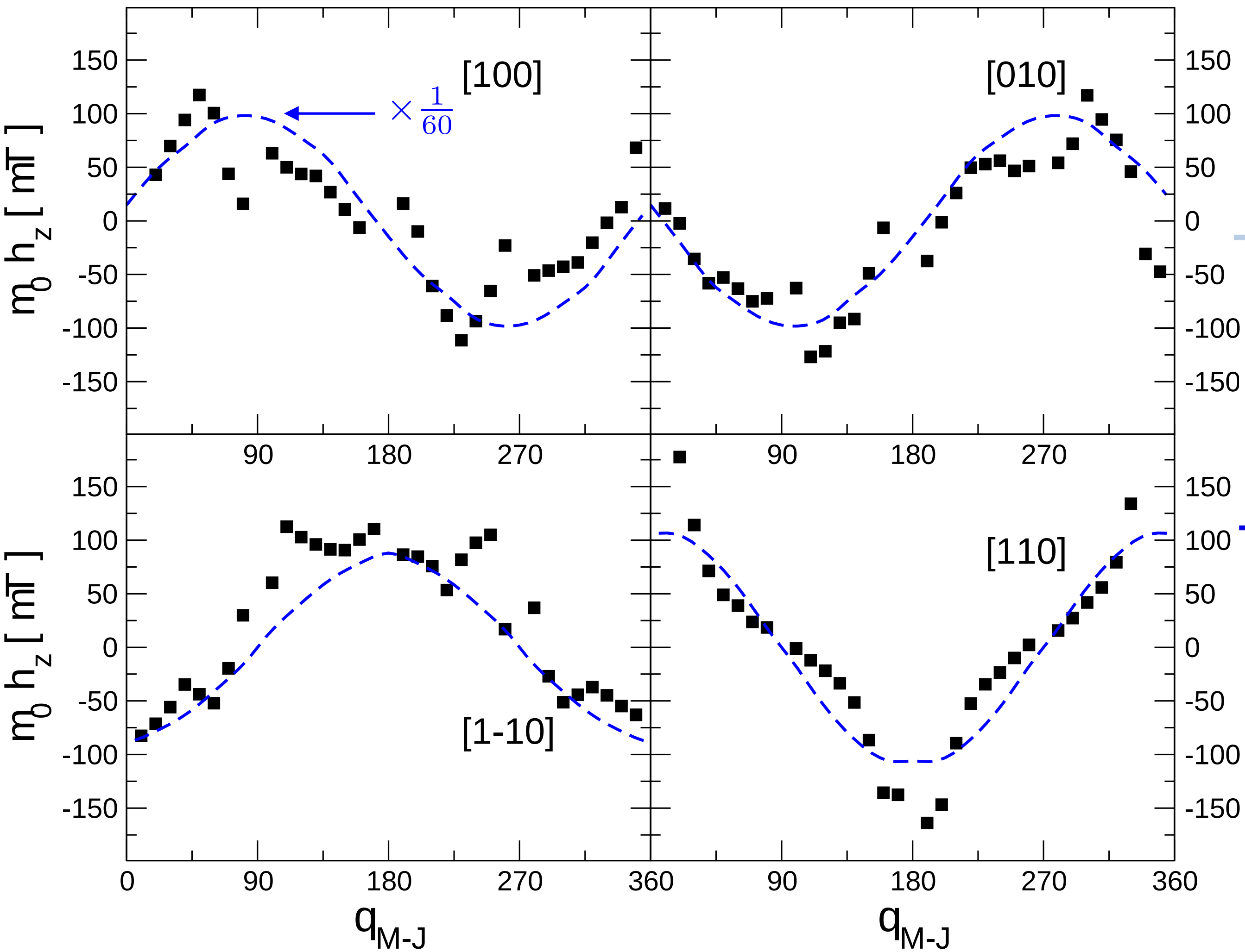


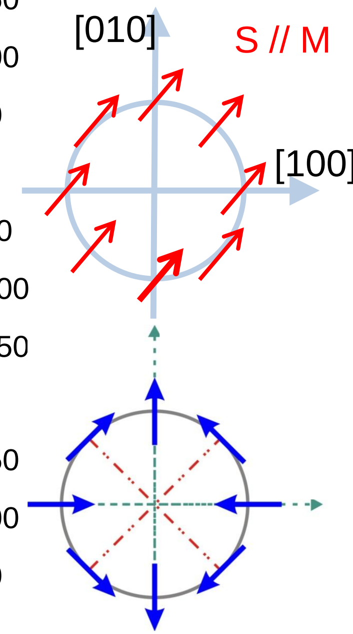
# Comparison to Theory



# Comparison to Theory

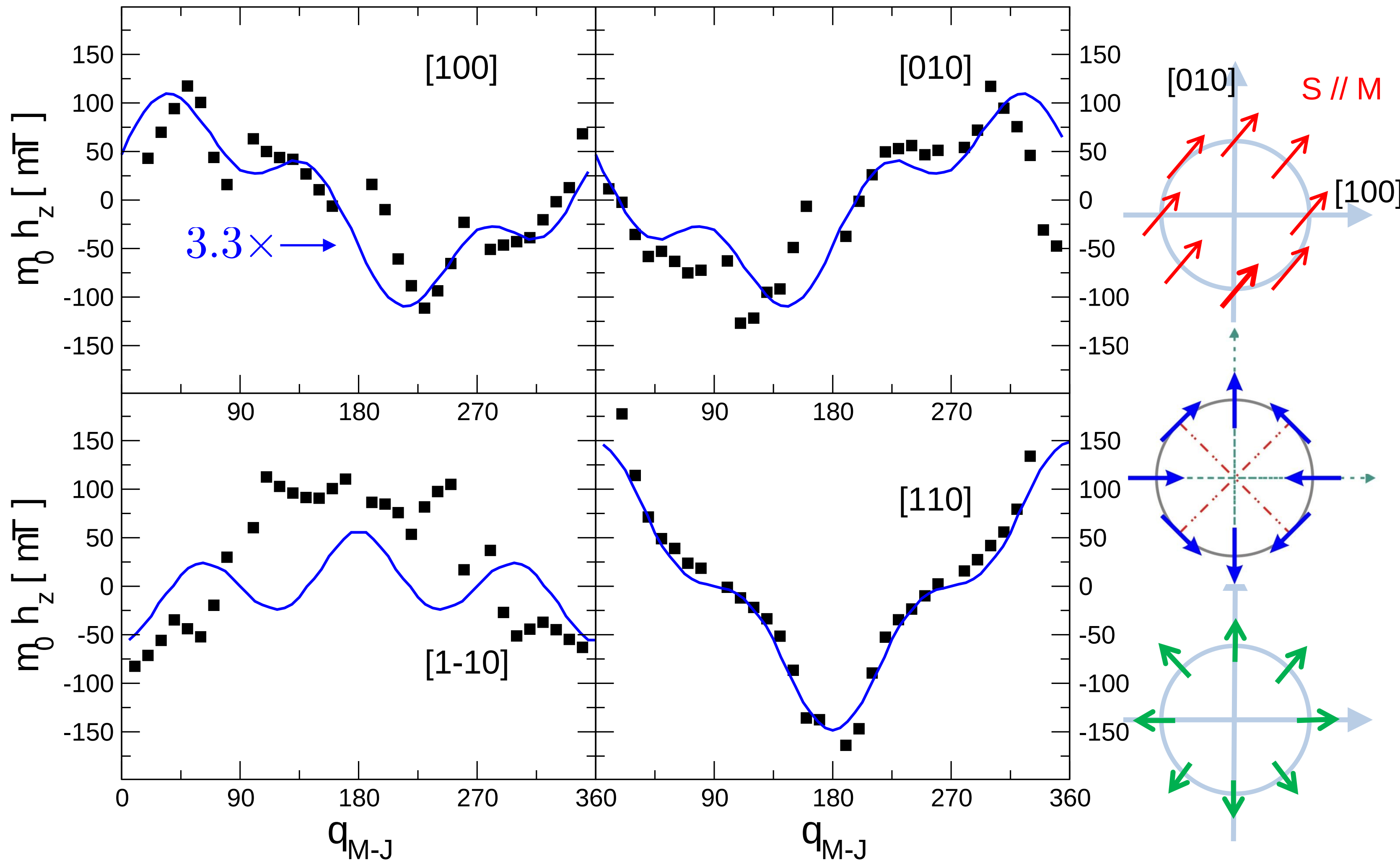
Dash line: Calculations replacing $H_{KL}$ with a parabolic model, i.e. no $(J.k)^2$ term



# Comparison to Theory

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



# 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~~

## 4) Comments

# SHE and SOT: re-examining momentum

Not mutually exclusive BUT the dominance of SHE+STT is historical!

SHE measured in bi-layers:

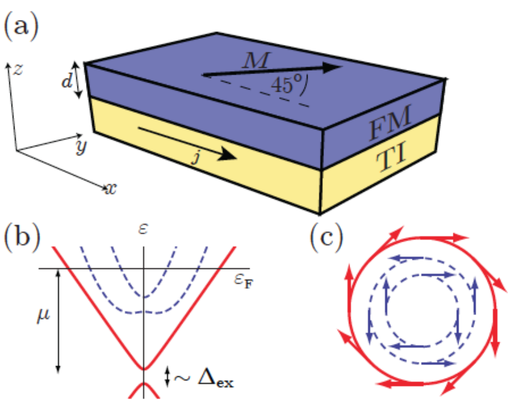
- Consistent with “expectations” of intrinsic SHE (better than AHE?) and sign changes; consistent with symmetry
- Afterward, due to consistency, no other alternative origin considered to dominate at the time (otherwise lots of re-examination needed)

“SHE” predictions in TI/F: Fischer, Manchon, et al 2013

$$\langle S_y \rangle^{\mathrm{D}}_{\mathrm{neq}} = -\frac{\hbar}{2ev_{\mathrm{F}}} j_x$$

$$\langle S_y \rangle^{\mathrm{R}}_{\mathrm{neq}} = \frac{\hbar}{2e} \frac{m\alpha j_x}{2E_{\mathrm{F}}}$$

$$\hat{\theta} = \frac{\hat{T}}{j_x} \frac{2e}{\hbar}$$




**Large Spin Torque in Topological Insulator/Ferromagnetic Metal Bilayers**

Mark H. Fischer,[1] Abolhassan Vaezi,[1] Aurelien Manchon,[2] and Eun-Ah Kim[1]

# SHE and SOT: re-examining momentum

PHYSICAL REVIEW B **88**, 085423 (2013)

**Phenomenology of current-induced spin-orbit torques**

Kjetil M. D. Hals and Arne Brataas
*Department of Physics, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway*
(Received 1 July 2013; published 20 August 2013)

## Spin-orbit torques in Pt/Co films from first principles

Frank Freimuth,* Stefan Blügel, and Yuriy Mokrousov
arXiv:1305.4873v1

$$t_{ij}^{\mathrm{I(a)}} = -\frac{e}{h}\int_{-\infty}^{\infty} d\mathcal{E}\,\frac{df(\mathcal{E})}{d\mathcal{E}}\ \mathrm{Tr}\langle \mathcal{T}_i G^{\mathrm{R}}(\mathcal{E}) v_j G^{\mathrm{A}}(\mathcal{E})\rangle$$

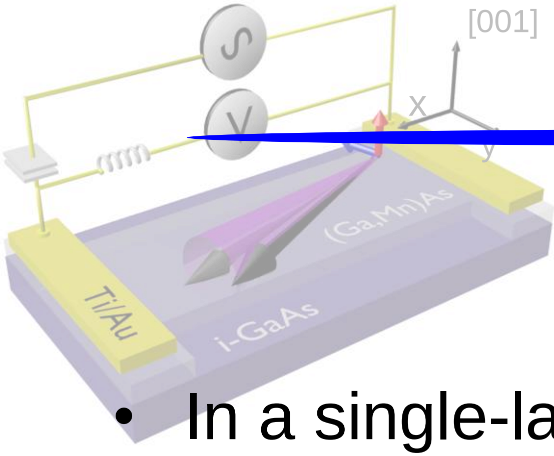
$$t_{ij}^{\mathrm{I(b)}} = \frac{e}{h}\int_{-\infty}^{\infty} d\mathcal{E}\,\frac{df(\mathcal{E})}{d\mathcal{E}}\,\Re\mathrm{Tr}\langle \mathcal{T}_i G^{\mathrm{R}}(\mathcal{E}) v_j G^{\mathrm{R}}(\mathcal{E})\rangle$$

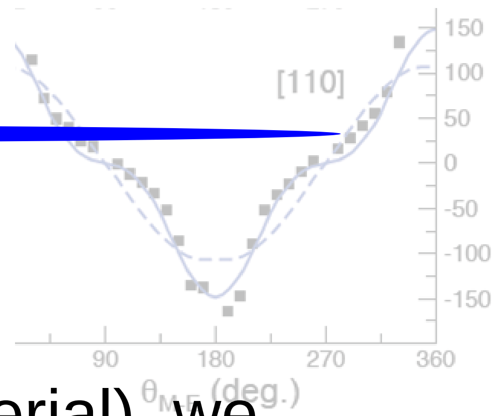
$$t_{ij}^{\mathrm{II}} = \frac{e}{h}\int_{-\infty}^{\infty} d\mathcal{E}\, f(\mathcal{E})\ \Re\mathrm{Tr}\langle \mathcal{T}_i G^{\mathrm{R}}(\mathcal{E}) v_j \frac{dG^{\mathrm{R}}(\mathcal{E})}{d\mathcal{E}} - \mathcal{T}_i \frac{dG^{\mathrm{R}}(\mathcal{E})}{d\mathcal{E}} v_j G^{\mathrm{R}}(\mathcal{E})\rangle$$

| | theor | | | expt |
|---|---|---|---|---|
| | Pt/Co | Pt/Co/O | Pt/Co/Al | Pt/Co/AlO$_x$ |
| $\frac{T_{yx}^{\mathrm{even}}}{\mu_s}$[mT] | 3.2 (4.5) | 5.1 (6.3) | 3.9 (4.9) | $5 \pm 0.2^{\mathrm{a}}$ $6.9 \pm 0.3^{\mathrm{b}}$ $1.7 \pm 0.3^{\mathrm{c}}$ $8^{\mathrm{d}}$ |
| $\frac{T_{xx}^{\mathrm{odd}}}{\mu_s}$[mT] | 0.15 (0.73) | -3.0 (-3.0) | -5.6 (-3.6) | $-3.2 \pm 0.2^{\mathrm{a}}$ $-4 \pm 0.3^{\mathrm{b}}$ $0 \pm 1.3^{\mathrm{c}}$ $-29^{\mathrm{e}}$ |

Agree on calculations and results: small disagreement of interpretation of fig. 2

# 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 in GaMnAs

- Because of common origin intrinsic anti-damping SOT can 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)