Analytic and *ab initio* theory of magnetization dynamics

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SPICE – SPIN+X Seminar, November 3, 2021

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Outline

- The Landau-Lifshitz-Gilbert equation: a derivation from fundamental principles
- Relativistic field-derivative torque, inertia, and optical spin-orbit torque

$$T^{FDT} \propto M \times \frac{\partial H}{\partial t} \qquad T^{inert} = M \times \left[I \cdot \frac{\partial^2 M}{\partial t^2} \right] \qquad T^{OSOT} = -\frac{e^2}{2m^2 c^2 \varepsilon_0} M \times j_s$$

- *Ab initio* theory of SOTs & spin & orbital accumulation in Pt/3d-metal bilayers

$$\mathcal{T}_{\mathrm{o}} = +2\mu_B |\boldsymbol{B}_{\mathrm{XC}}|\, |\boldsymbol{E}|\, \underline{\chi^S_{yx}}\, \boldsymbol{u}_x \qquad \mathcal{T}_{\mathrm{e}} = -2\mu_B |\boldsymbol{B}_{\mathrm{XC}}|\, |\boldsymbol{E}|\, \underline{\chi^S_{xx}}\, \boldsymbol{u}_y$$

(FL SOT) (DL SOT)

- *Ab initio* theory of field-induced spin & orbital Rashba-Edelstein effects in noncentrosymmetric CuMnAs and Mn_2Au antiferromagnets

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Thanks to

Ritwik Mondal

Marco Berritta

Ashis Nandy

Leandro Salemi

Ulrike Ritzmann, Andreas Donges, Ulrich Nowak

Universität Konstanz

Vetenskapsrådet

Knut and Alice Wallenberg Foundation

SEVENTH FRAMEWORK PROGRAMME

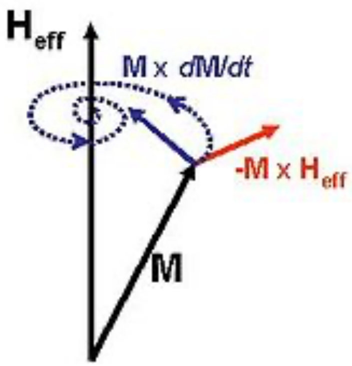
femtoSpin

S·NEBULA

Motivation: How to derive relativistic torques ?!

Landau-Lifshitz-Gilbert equation:

$$\boxed{\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} + \alpha\, \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial t}}$$



Semi-empirical, dissipative, microscopic level, continuous description, long timescale ~ns

Torques added ***ad hoc***

Dirac-Kohn-Sham theory:

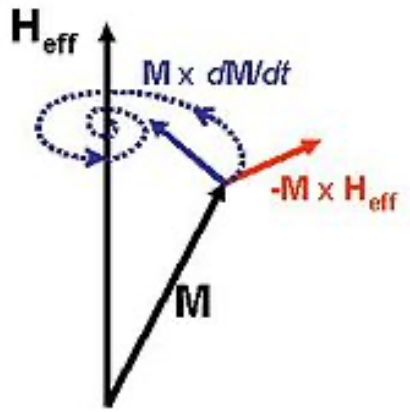
$$\boxed{\mathcal{H} = c\,\boldsymbol{\alpha}\cdot(\boldsymbol{p} - e\boldsymbol{A}) + (\beta - \mathcal{I})\,mc^2 + V}$$

Fundamental, Hermitian (non-dissipative), electronic level, quantized, short timescale ~atto-femto sec.

- Any relation between the equations?
- Expressions for relativistic torques & Gilbert damping?

Relativistic theory of Gilbert damping

Origin of Gilbert damping:



$$\alpha\, \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial t}$$

Spin-orbit coupling related

Theories of damping

Kamberský, Can. J. Phys. **48**, 2906 (1970)	Breathing Fermi surface model
Kamberský, Phys. Rev B **76**, 134416 (2007)	Torque-torque correlation model
Gilmore et al, PRL **99**, 027204 (2007)	
Brataas et al, PRL **101**, 037207 (2008)	Scattering theory formulation
Ebert et al, PRL **107**, 066603 (2011)	Linear resp. theory, CPA
Fähnle & Illg, JPCM **23**, 493201 (2011)	Effective field theory
Hickey, Moodera, PRL **102**, 137601 (2009)	Derivation from Pauli equation

→ Start from general Dirac-Kohn-Sham Hamiltonian

Most general relativistic Hamiltonian

Dirac KS hamiltonian: $H = c\boldsymbol{\alpha}\cdot(\boldsymbol{p} - e\boldsymbol{A}) + (\beta - \mathbb{1})mc^2 + V - \mu_B \beta\, \boldsymbol{\Sigma}\cdot \boldsymbol{B}^{\mathrm{xc}}$

external E-M field

$$\boldsymbol{\alpha} = \begin{pmatrix} 0 & \boldsymbol{\sigma} \\ \boldsymbol{\sigma} & 0 \end{pmatrix} \quad \beta = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & -\mathbf{1} \end{pmatrix}$$

$$\boldsymbol{\Sigma} = \mathbb{1} \otimes \boldsymbol{\sigma}$$

Foldy-Wouthuysen transformation with B^{xc}:

$$\begin{aligned} H_{\mathrm{FW}} = {} & \frac{(\boldsymbol{p} - e\boldsymbol{A})^2}{2m} + V - \mu_B\, \boldsymbol{\sigma}\cdot \boldsymbol{B}^{\mathrm{xc}} - \mu_B\, \boldsymbol{\sigma}\cdot\boldsymbol{B} - \frac{(\boldsymbol{p} - e\boldsymbol{A})^4}{8m^3c^2} - \frac{1}{8m^2c^2}(p^2V) - \frac{e\hbar^2}{8m^2c^2}\boldsymbol{\nabla}\cdot\boldsymbol{E} \\ & \boxed{+ \frac{i}{4m^2c^2}\boldsymbol{\sigma}\cdot(\boldsymbol{p}V)\times(\boldsymbol{p} - e\boldsymbol{A}) - \frac{e\hbar}{8m^2c^2}\boldsymbol{\sigma}\cdot\{\boldsymbol{E}\times(\boldsymbol{p} - e\boldsymbol{A}) - (\boldsymbol{p} - e\boldsymbol{A})\times\boldsymbol{E}\}} \\ & \boxed{+ \frac{\mu_B}{8m^2c^2}\{[p^2(\boldsymbol{\sigma}\cdot\boldsymbol{B}^{\mathrm{xc}})] + 2\boldsymbol{\sigma}\cdot(\boldsymbol{p}\boldsymbol{B}^{\mathrm{xc}})\cdot(\boldsymbol{p} - e\boldsymbol{A}) + 2(\boldsymbol{p}\cdot\boldsymbol{B}^{\mathrm{xc}})\boldsymbol{\sigma}\cdot(\boldsymbol{p} - e\boldsymbol{A}) + 4[\boldsymbol{B}^{\mathrm{xc}}\cdot(\boldsymbol{p} - e\boldsymbol{A})]\boldsymbol{\sigma}\cdot(\boldsymbol{p} - e\boldsymbol{A})\}} \\ & + \frac{i\mu_B}{4m^2c^2}[(\boldsymbol{p}\times\boldsymbol{B}^{\mathrm{xc}})\cdot(\boldsymbol{p} - e\boldsymbol{A})]. \end{aligned}$$

- Relativistic correction to exchange field $\quad \boldsymbol{B}^{\mathrm{xc}}_{\mathrm{eff}} \equiv \boldsymbol{B}^{\mathrm{xc}} + \boldsymbol{B}^{\mathrm{xc}}_{\mathrm{corr}}$
- Full expression for SO with external E-M fields (new terms)
- Gauge invariant and Hermitian Hamiltonian

Mondal, Berritta, PMO, Phys. Rev. B **94**, 144419 (2016)

New terms in SO Hamiltonian

Relativistic Hamiltonian couples *angular momentum of light j* with electron spin σ

$$\boxed{\mathcal{H}_{\mathrm{SOC}} = \frac{i}{4m^2c^2}\boldsymbol{\sigma}\cdot(\boldsymbol{p}V)\times(\boldsymbol{p}-e\boldsymbol{A}) - \frac{e\hbar}{8m^2c^2}\boldsymbol{\sigma}\cdot\{\boldsymbol{E}_{\mathrm{ext}}\times(\boldsymbol{p}-e\boldsymbol{A})-(\boldsymbol{p}-e\boldsymbol{A})\times\boldsymbol{E}_{\mathrm{ext}}\}}$$

Unusual coupling: $\mathcal{H} = \dfrac{e^2\hbar}{4m^2c^2}\boldsymbol{\sigma}\cdot(\boldsymbol{E}\times\boldsymbol{A}) \rightarrow \boxed{\xi\,\boldsymbol{\sigma}\cdot\boldsymbol{j}_s}$

$$\boldsymbol{j}_s = -2\boldsymbol{E}\times\boldsymbol{A}\ (\epsilon_0 = 1)$$

Spin-photon ang. moment coupling $\mathcal{H}^{\mathrm{ext}}_{\mathrm{light-spin}} = \dfrac{e^2}{2m^2c^2\epsilon_0}\boldsymbol{S}\cdot\boldsymbol{j}_s$

Optical spin-orbit torque:

$$\left.\frac{\partial \boldsymbol{M}}{\partial t}\right|^{\mathrm{ext}}_{\mathrm{light-spin}} = -\frac{e^2}{2m^2c^2\epsilon_0}\boldsymbol{M}\times\boldsymbol{j}_s$$

$$B_{opt} \propto \frac{e^2}{2m^2c^2\mu_B\omega}E_0^2$$

"inverse Faraday effect"

cf. Tesarova et al., Nat. Phot. **7**, 492 (2013)

$B_{opt} \sim 0.3 - 4$ mT

$$\boldsymbol{T} = -\gamma\boldsymbol{M}\times\boldsymbol{B}_{opt}$$

Mondal, Berritta, Paillard et al, PRB **92**, 100402R (2015)
Mondal, Berritta, PMO, JPCM **29**, 194002 (2017)

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Equation of motion for spin dynamics

Full *spin* Hamiltonian: $\mathcal{H}^S(t) = \mathcal{H}^0 + \mathcal{H}^{\rm int}_{\rm soc} + \mathcal{H}^{\rm ext}_{\rm soc}$

Spin operator dynamics: $\partial\vec{S}/\partial t = -i[\vec{S}, H^S]/\hbar$

Magnetization element $\boldsymbol{M} = \sum_j \frac{g\mu_B}{\mathcal{V}} \mathrm{Tr}\{\rho \boldsymbol{S}^j\}$

Magnetization Dynamics $\frac{\partial \boldsymbol{M}}{\partial t} = \frac{g\mu_B}{\mathcal{V}} \frac{1}{i\hbar} \sum_j \mathrm{Tr}\{\rho[\boldsymbol{S}^j, \mathcal{H}^S(t)]\}$

$$\boxed{\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma \boldsymbol{M} \times \boldsymbol{B}_{\rm eff} + \underbrace{\boldsymbol{M} \times \left[\mathrm{A} \cdot \frac{\partial \boldsymbol{M}}{\partial t}\right]}_{\mathcal{H}^{\rm ext}_{\rm soc}}}$$

(Without spin-photon term and currents!)

Mondal, Berritta, PMO, Phys. Rev. B **94**, 144419 (2016)

With *currents*: Mondal, Berritta, PMO, PRB **98**, 214429 (2018)

Intrinsic spin damping contributions

Gilbert damping $\mathbf{A}$ for *harmonic* fields: $\left.\frac{\partial \boldsymbol{M}}{\partial t}\right|_{\text{soc}}^{\text{ext}} = \boldsymbol{M} \times \left[\mathrm{A} \cdot \frac{\partial \boldsymbol{M}}{\partial t} \right]$

$$\mathrm{A}_{ij} = -\frac{e\mu_0}{8m^2c^2} \sum_{n,k} \underbrace{\left[\langle r_i p_k + p_k r_i \rangle - \langle r_n p_n + p_n r_n \rangle \delta_{ik} \right]}_{\text{Electronic damping}} (\mathbb{1} + \underbrace{\chi^{-1}}_{\text{Spin-spin corr.*}})_{kj}$$

$$\langle r_\alpha p_\beta \rangle = -\frac{i\hbar}{2m} \sum_{n,n',k} \frac{f(E_{nk}) - f(E_{n'k})}{E_{nk} - E_{n'k}} p^{\alpha}_{nn'} p^{\beta}_{n'n}$$

*Garate & MacDonald, PRB **79**, 064403 (2009)

Damping for *general time*-dependent magn. fields:

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma_0 \boldsymbol{M} \times \boldsymbol{H}_{\text{eff}} + \boldsymbol{M} \times \left[\bar{\mathrm{A}} \cdot \left(\frac{\partial \boldsymbol{M}}{\partial t} + \frac{\partial \boldsymbol{H}}{\partial t} \right) \right]$$

- New expression for spin dynamics in presence of time-dep. fields

Field-derivative torque

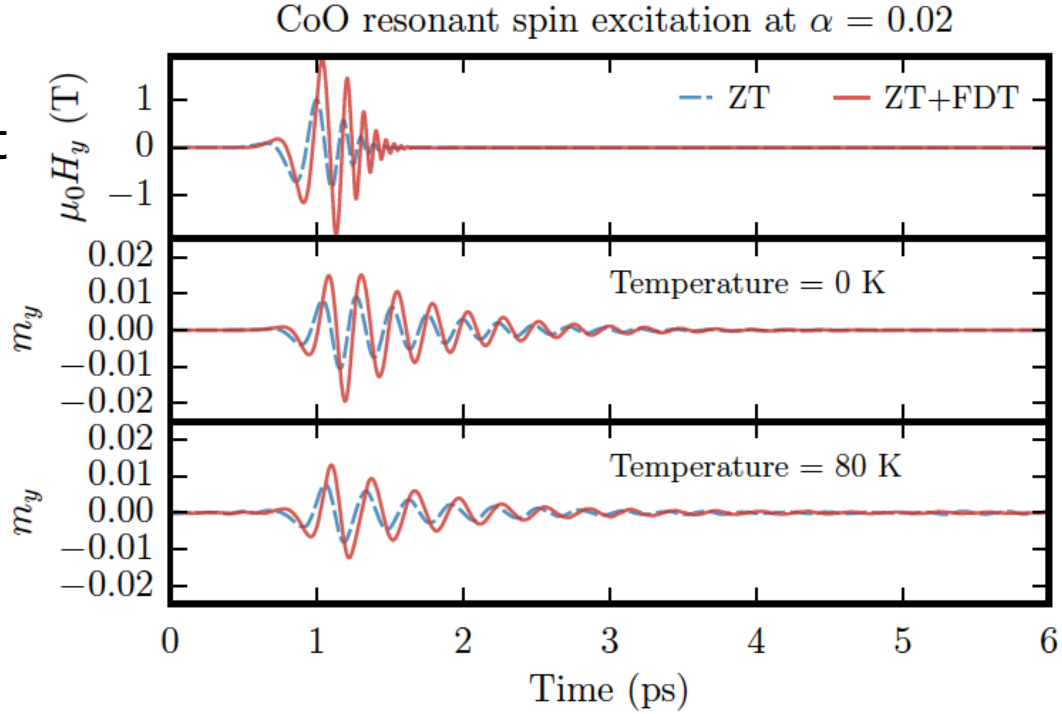
$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma_0 \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} + \boldsymbol{M} \times \left[\bar{\mathrm{A}} \cdot \left(\frac{\partial \boldsymbol{M}}{\partial t} + \frac{\partial \boldsymbol{H}}{\partial t}\right)\right] \qquad \text{(LLG)}$$

$$\boxed{\frac{\partial \boldsymbol{m}_i(t)}{\partial t} = -\frac{\gamma}{(1+\alpha^2)\mu_s} \boldsymbol{m}_i(t) \times \left[\left(\underbrace{\boldsymbol{H}_i^{\mathrm{eff}}}_{\text{Zeeman ZT}} - \frac{\alpha a^3}{\gamma}\frac{\partial \boldsymbol{H}}{\partial t}\right) + \alpha \boldsymbol{m}_i(t) \times \left(\boldsymbol{H}_i^{\mathrm{eff}} - \frac{\alpha a^3}{\gamma}\frac{\partial \boldsymbol{H}}{\partial t}\right)\right]}$$

FDT

(LL)

- for THz pulses FDT could be important
- phase difference between ZT and FDT
- at high damping, FDT can be large
- No experimental observation so far !



Mondal, Donges, Ritzmann, PMO, Nowak, PRB **100**, 060409R (2019)

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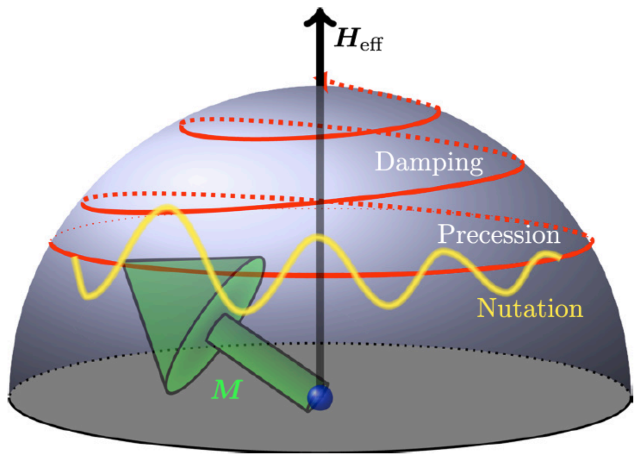
Origin of **inertial** spin dynamics?



Inertial dynamics:

$$\frac{\partial \boldsymbol{M}}{\partial t} = \boldsymbol{M} \times \left(-\gamma_0 \boldsymbol{H} + \Gamma \cdot \frac{\partial \boldsymbol{M}}{\partial t} + \underline{\mathcal{I} \cdot \frac{\partial^2 \boldsymbol{M}}{\partial t^2}} \right)$$

Earlier work:

Kimel et al, Nat. Phys. **5**, 727 (2009)
Ciornei et al, PRB **83**, 020410R (2011)
Fähnle et al, PRB **84**, 172403 (2011)
Bhattacharjee et al, PRL **108,** 057204 (2012)
Böttcher & Henk, PRB **86**, 020404 (2012)

Can inertial dynamics (nutation) be a higher order relativistic effect?

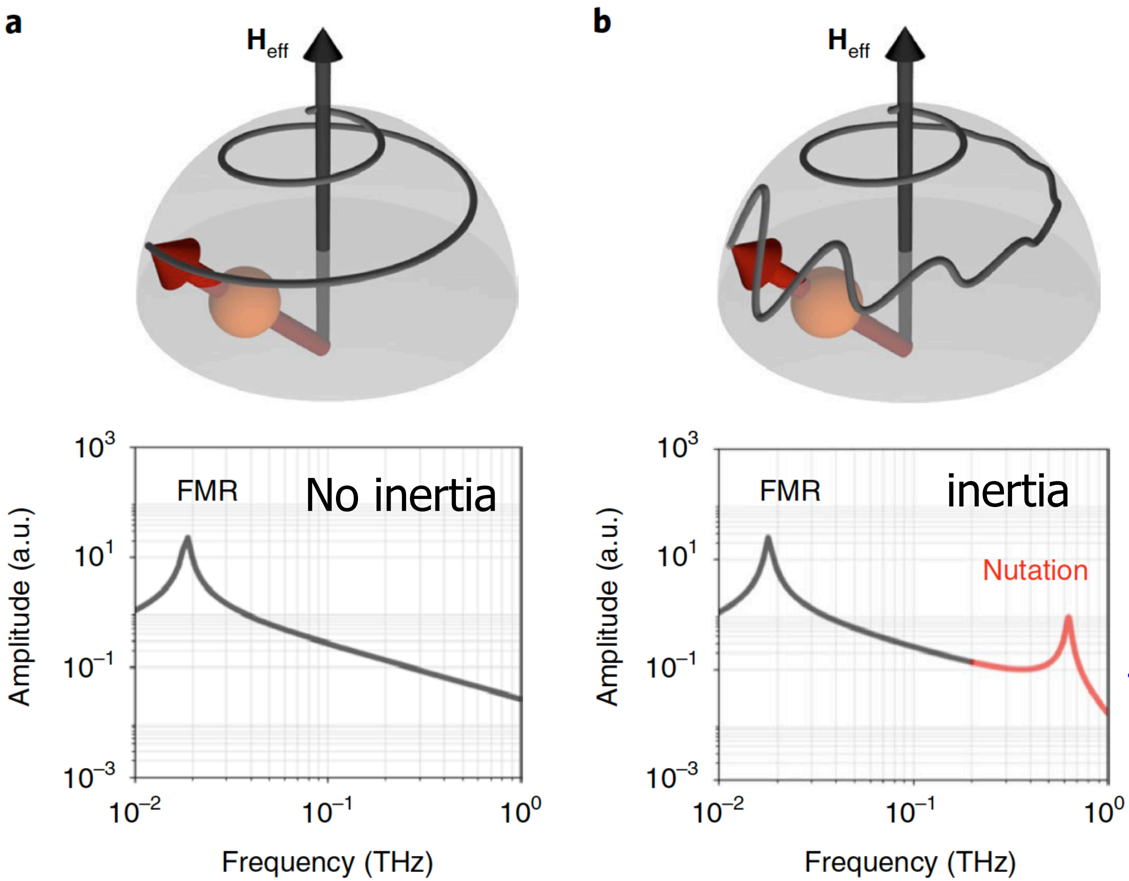
FW transformation for all terms up to order $1/c^4$ (higher order terms in SO Ham.)

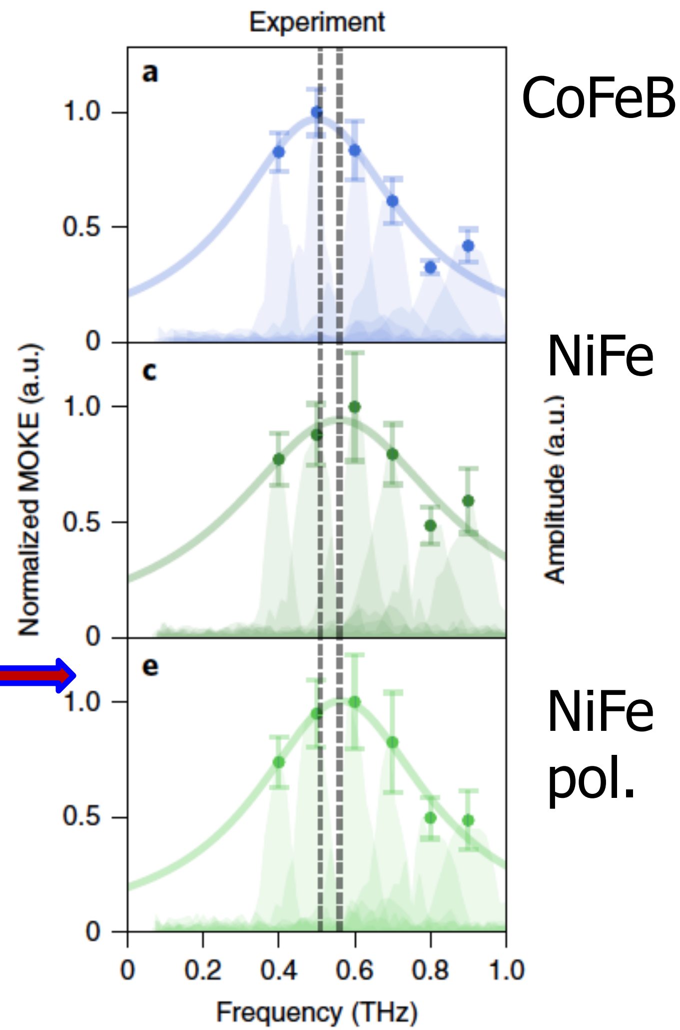
$$\begin{aligned} \mathcal{H} &= -\frac{ie\hbar^2}{16m^3c^4}\boldsymbol{\sigma}\cdot\left[\partial_t \boldsymbol{E}_{\mathrm{tot}} \times (\boldsymbol{p} - e\boldsymbol{A}) + (\boldsymbol{p} - e\boldsymbol{A}) \times \partial_t \boldsymbol{E}_{\mathrm{tot}}\right] \\ &= \frac{e\hbar^2}{8m^3c^4}\boldsymbol{S}\cdot\partial_{tt}\boldsymbol{B} \end{aligned}$$

$$\Longrightarrow \quad \left.\frac{\partial \boldsymbol{M}}{\partial t}\right|_{\mathrm{iner.}} = \boldsymbol{M} \times \left[\mathrm{I}\cdot\frac{\partial^2 \boldsymbol{M}}{\partial t^2}\right]$$

Mondal, Berritta, Nandy, PMO, PRB **96**, 024425 (2017)
Mondal, Berritta, PMO, JPCM **30**, 265801 (2018)

Recent observation of inertial dynamics





$\mathcal{I} \propto 300$ fs x M^{-1}

Kerr amplitude of magn. dynamics

Neeraj et al, Nat. Phys. **17**, 245 (2021)

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Size of *intrinsic* inertia

For ac magn. field - inertia tensor: $\mathcal{I}_{ij} = \frac{\mu_0 \gamma \hbar^2}{8m^2c^4}\left[\mathbb{1} + \mathrm{Re}\left(\chi_m^{-1}\right)_{ij}\right]$

Gilbert damping tensor: Imaginary part of susceptibility, inertia tensor real part, *but smaller because of pre-factor*

$$\Gamma_{ij} = -\frac{\mu_0 \gamma \hbar}{4mc^2} \sum_{n,k} \left[\frac{\langle r_i p_k + p_k r_i \rangle - \langle r_n p_n + p_n r_n \rangle \delta_{ik}}{i\hbar}\right] \mathrm{Im}\left(\chi_m^{-1}\right)_{kj}$$

$$\mathcal{I} \propto -\Gamma \bar{\tau}$$

- Inertial dynamics important at *short time scales* (1 fs – 1 ps)
- Offers options for THz spin dynamics

$$\bar{\tau} = 746 \pm 46 \text{ fs}$$

for 3 different Co films

Unikandanunni et al, arXiv 2109.03076

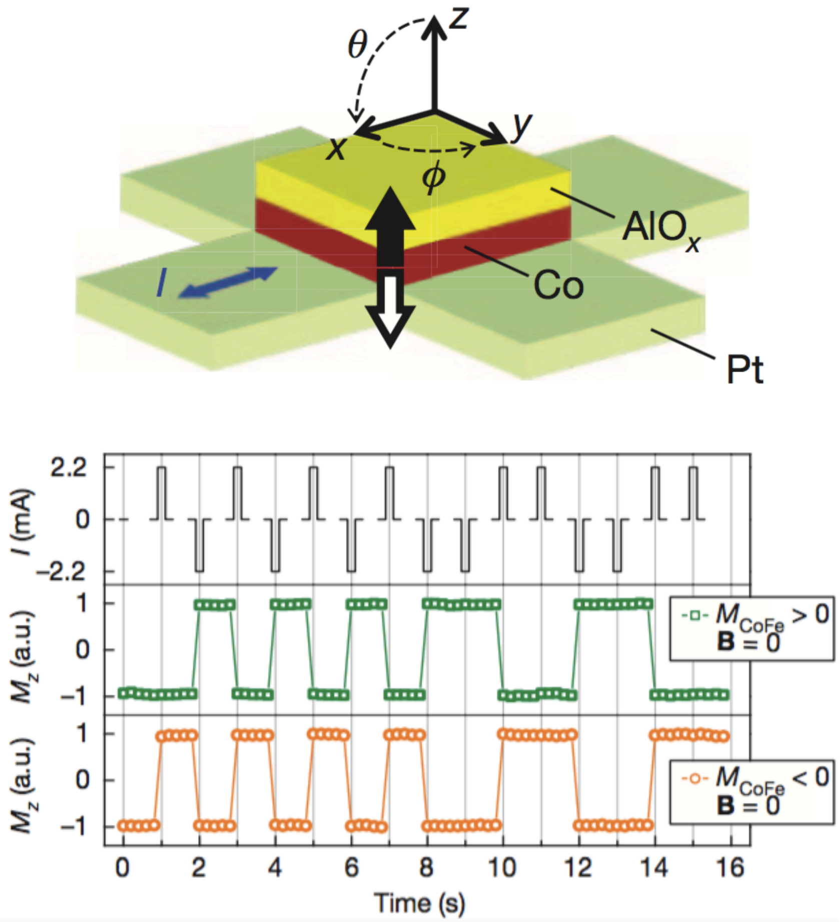
Perhaps consistent with relativistic theory

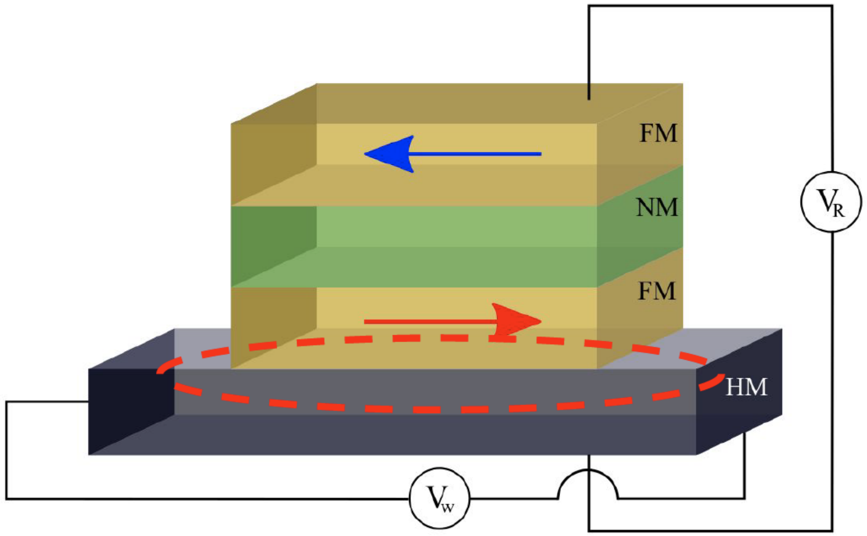
<u>Recent theories</u>

Bajpai, Nikolic, PRB **99**, 134409 (2019)
Makhfudz, Olive, Nicolis, APL **117**, 132403 (2020)
Cherkasskii et al, PRB **102**, 184432 (2020)
Titov et al, PRB **103**, 144433 (2021)
Mondal et al, PRB **103**, 104404 (2021)
Thibaudeau, Nicolis, arXiv 2103.04787

Mondal, Berritta, Nandy, PMO, PRB **96**, 024425 (2017)

II. Spin-orbit torque - Magnetization switching with SHE





Switching due to large SHE of heavy metals (Pt, W, Ta) and interfacial effect

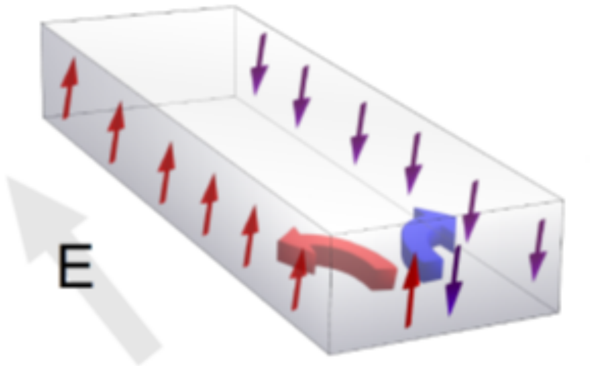
Miron et al, Nature **476**, 189 (2011)
Liu et al, Science **336**, 555 (2012)

Sinova, Valenzuela, Wunderlich, Back, Jungwirth, Rev.Mod.Phys. **87**, 1213 (2015)

Manchon et al, Rev.Mod.Phys. **91**, 035004 (2019)

Origin of SOT: charge-to-spin conversion

Spin Hall effect



Transport

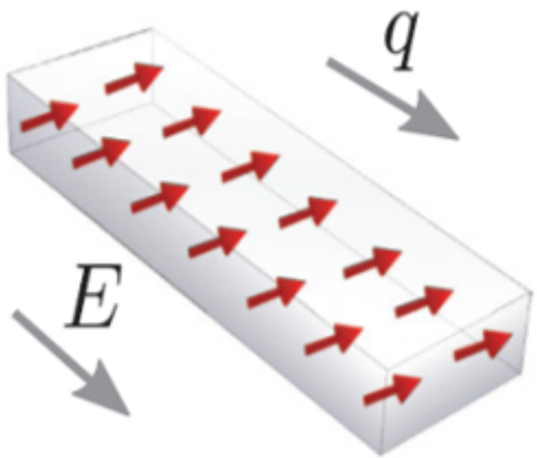
$$J_x^{s_z} = \sigma_{xy}^{S_z} \cdot E_y$$

Dyakonov & Perel, JETP Lett.**13**, 467 (1971)

Hirsch, PRL **83**, 1834 (1999)

Infinite bulk crystal

Inverse spingalvanic effect,
Rashba-Edelstein effect



Local

$$\delta S_x^{ind} = \chi_{xy} \cdot E_y$$

Edelstein, Solid State Commun. **73**, 233 (1990)

(Rashba SOC + 2D)

http://zfmezo.home.amu.edu.pl/research.php

Ab initio calculations

Rashba-Edelstein effect

$$M_i^{ind} = \chi_{ij} \cdot E_j$$

magneto-electric effect, possible
for inversion symm. breaking

Linear-response theory formulation: $\delta \boldsymbol{M} = \mu_B \delta(\boldsymbol{L} + 2\boldsymbol{S}) \longrightarrow A$

$$\chi_{ij}^A = -\frac{ie}{m_e}\int_\Omega \frac{d\boldsymbol{k}}{\Omega}\sum_{n\neq m}\frac{f_{n\boldsymbol{k}} - f_{m\boldsymbol{k}}}{\hbar\omega_{nm\boldsymbol{k}}}\frac{A^i_{mn\boldsymbol{k}}\, p^j_{nm\boldsymbol{k}}}{-\omega_{nm\boldsymbol{k}} + i\tau^{-1}_{\text{inter}}} - \frac{ie}{m_e}\int_\Omega \frac{d\boldsymbol{k}}{\Omega}\sum_{n}\frac{\partial f_{n\boldsymbol{k}}}{\partial\epsilon}\frac{A^i_{nn\boldsymbol{k}}\, p^j_{nn\boldsymbol{k}}}{i\tau^{-1}_{\text{intra}}}$$

$$\delta \boldsymbol{S} = \boldsymbol{\chi}^S \boldsymbol{E}$$

$$\delta \boldsymbol{L} = \boldsymbol{\chi}^L \boldsymbol{E}$$

Spin Hall effect $\boldsymbol{J}^{S_k} = \boldsymbol{\sigma}^{S_k} \boldsymbol{E}$

Orbital Hall effect $\boldsymbol{J}^{L_k} = \boldsymbol{\sigma}^{L_k} \boldsymbol{E}$

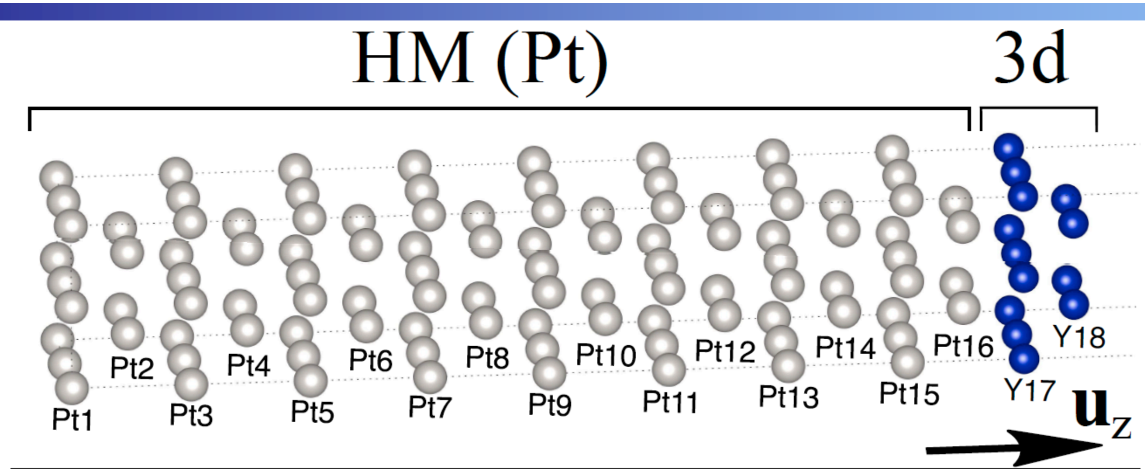
$$A = \hat{\boldsymbol{j}}^{S_k} = \frac{\{\hat{S}_k, \hat{\boldsymbol{p}}\}}{2m_e V}$$

Spin/orbital current operator

(Relativistic WIEN2k)

SHE: Guo, Yao, and Niu, PRL **94**, 226601 (2005)
OHE: Tanaka et al, Phys. Rev. B **77**, 165117 (2008)
Jo, Go, and Lee, PRB **98**, 214405 (2018)

SOTs at symmetry broken interface Pt/3d FM



n Pt / 2 Y
Y = Ni, Co, Cu or Pt

E along *x*

$$\begin{cases} \delta S_x = \chi^S_{xx} E_x \\ \delta S_y = \chi^S_{yx} E_x \end{cases}$$

Effective torques

$$\mathcal{T} = \boldsymbol{M} \times \delta \boldsymbol{B} \qquad \delta \boldsymbol{B} \approx |\boldsymbol{B}_{\mathrm{XC}}| \frac{\delta \boldsymbol{S}}{|\boldsymbol{S}|}$$

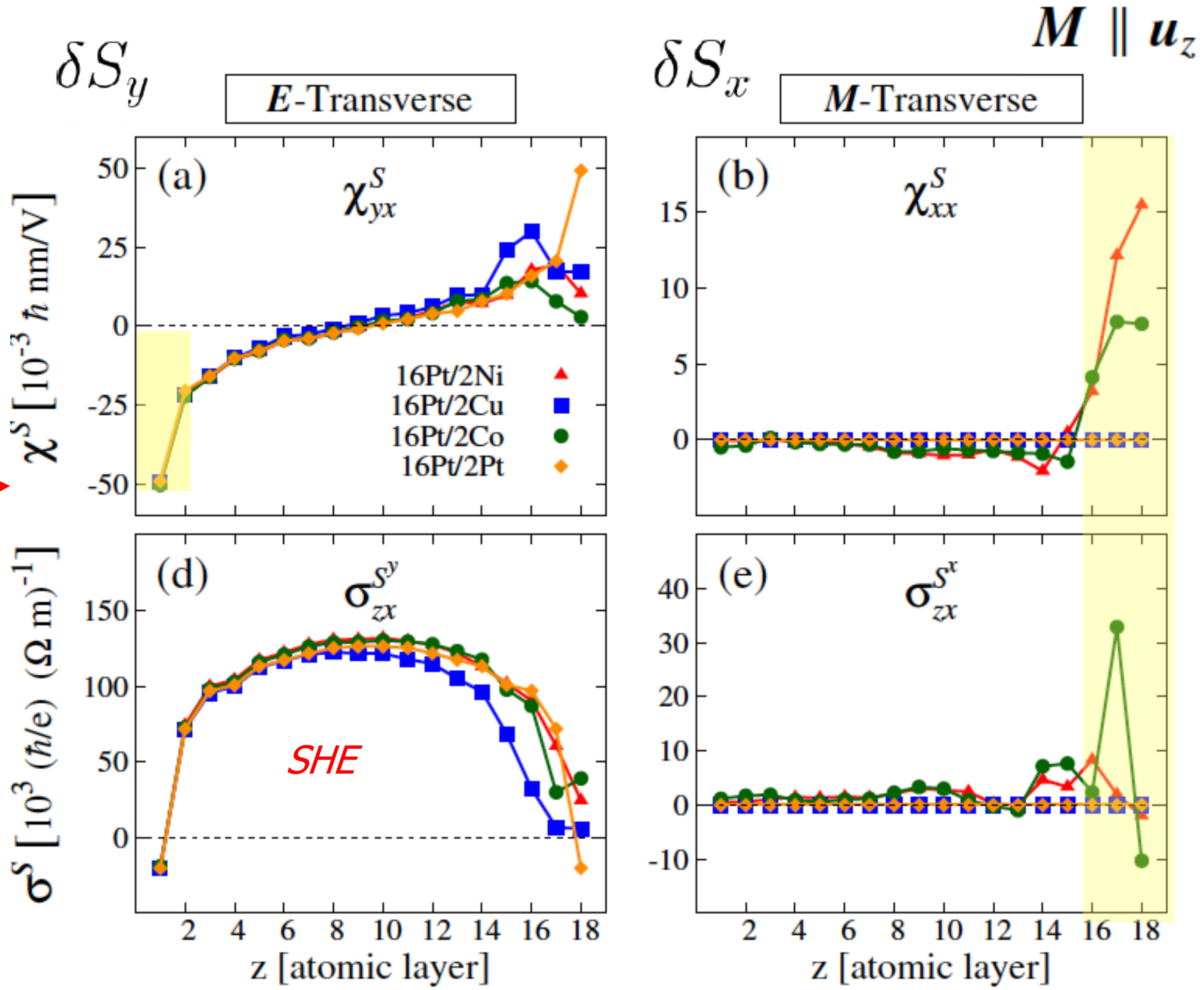
$$\mathcal{T}_{\mathrm{o}} = +2\mu_B |\boldsymbol{B}_{\mathrm{XC}}|\, |\boldsymbol{E}|\, \chi^S_{yx}\, \boldsymbol{u}_x$$ Time-rev. odd - FL

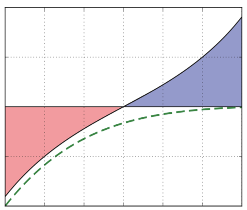
$$\mathcal{T}_{\mathrm{e}} = -2\mu_B |\boldsymbol{B}_{\mathrm{XC}}|\, |\boldsymbol{E}|\, \chi^S_{xx}\, \boldsymbol{u}_y$$ Time-rev. even - DL

Early work:

Haney, Lee, Lee, Manchon, Stiles, PRB **88**, 214417 (2013)
Freimuth, Blügel, Mokrousov, PRB **90**, 174423 (2014)

Results Pt/3d-bilayers – induced spin polarization





FL

DL

δS_y

- Typical transverse spin accumulation (stationary state)
- Modified at the interface
- M, t-even effect

δS_x

- Very local response at interface, along E_x
- Only exists for magn. material (M, t-odd)
- Same size as transv.

"Magnetic SHE"

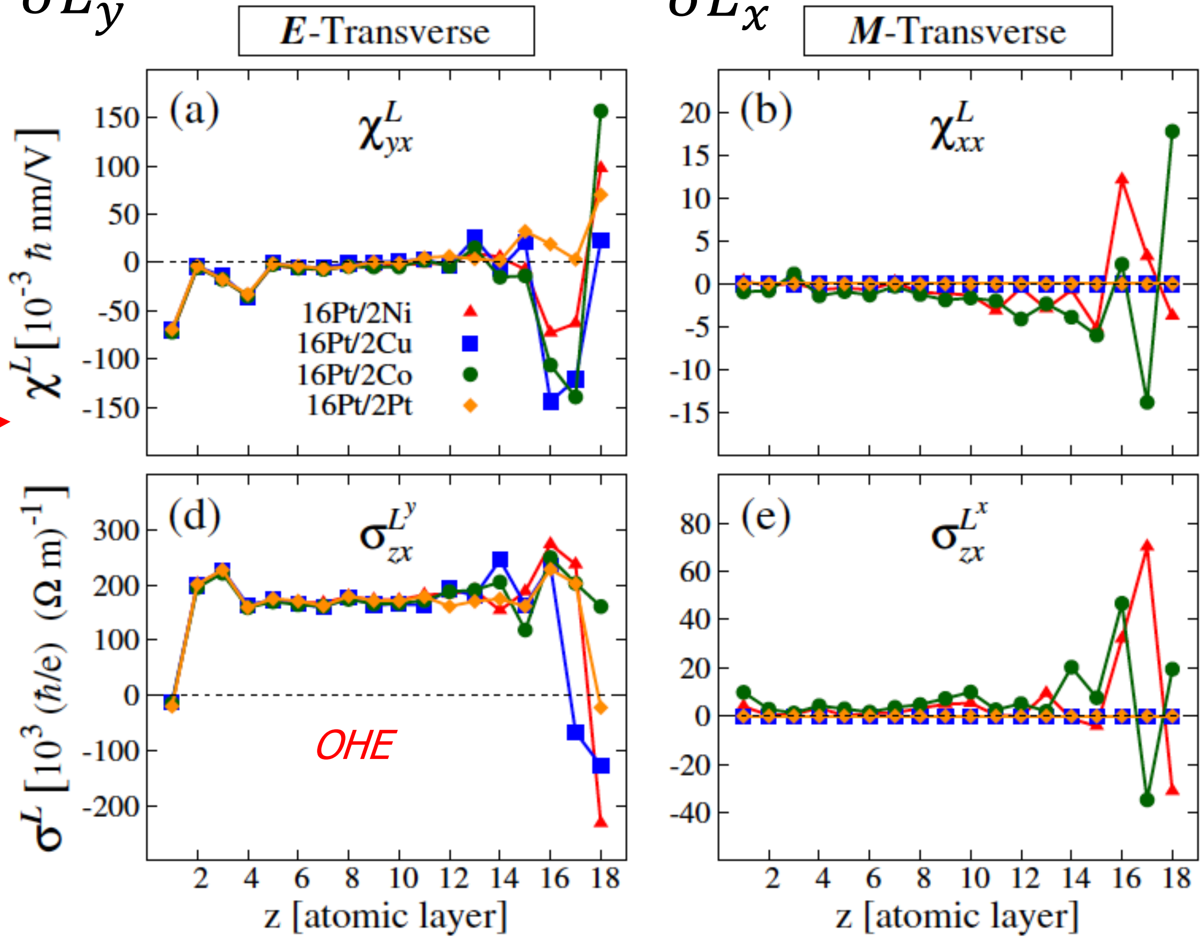
Kimata et al, Nature **565**, 627 (2019)

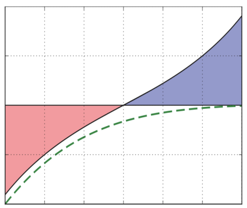
Salemi, Berritta, PMO, PRMat. **5**, 074407 (2021)

Results Pt/3d-bilayers –*orbital* polarization & current

$\boldsymbol{M} \parallel \boldsymbol{u}_z$

δL_y δL_x





δL_y

- Huge OHE
- Orb. accumulation profile quite different from spin
- Enlarged at the interface
- M, t-even effect

δL_x

- Local response at interface, along E_x
- Only exists for magn. material (M, t-odd)
- Smaller than transv.

"Magnetic OHE"

OHE and transv. orbital polarization not due to SOC

Salemi, Berritta, PMO, PRMat. **5**, 074407 (2021)

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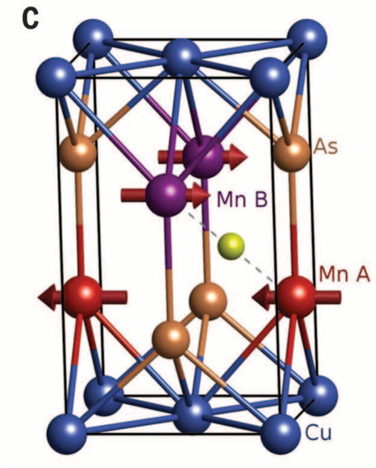
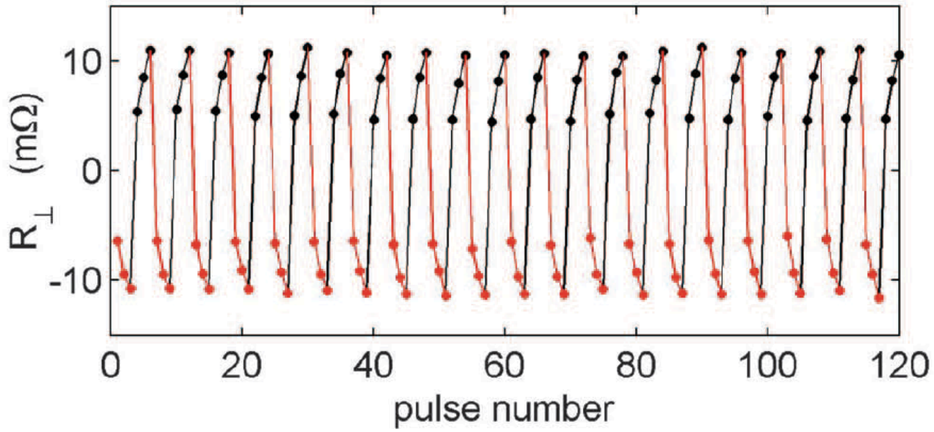
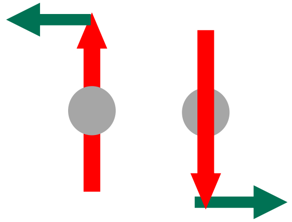
Current-induced SOT switching in AFMs

CuMnAs



Wadley et al, Science **351**, 587 (2016)



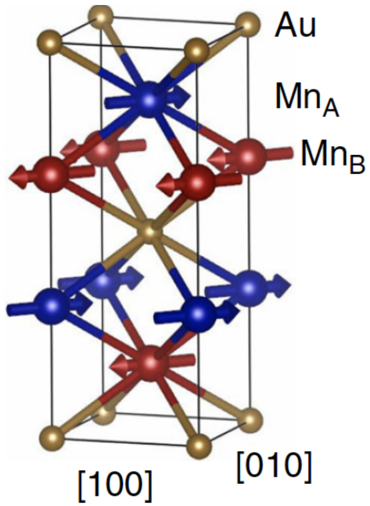


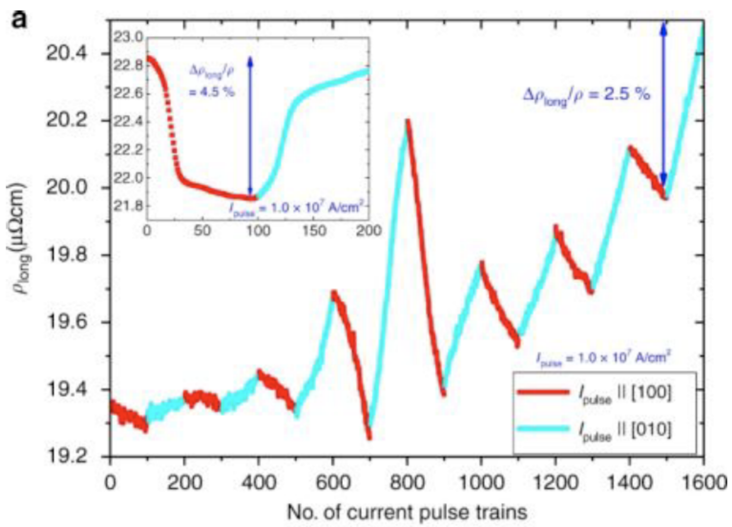
Proposed mechanism: staggered SO torque*

$$dM_{\mathrm{A,B}}/dt \sim M_{\mathrm{A,B}} \times p_{\mathrm{A,B}}$$

$$p_{\mathrm{A}} = -p_{\mathrm{B}} \quad (p^{ind} \perp j)$$

due to $M_i^{ind} = \chi_{ij} \cdot E_j$

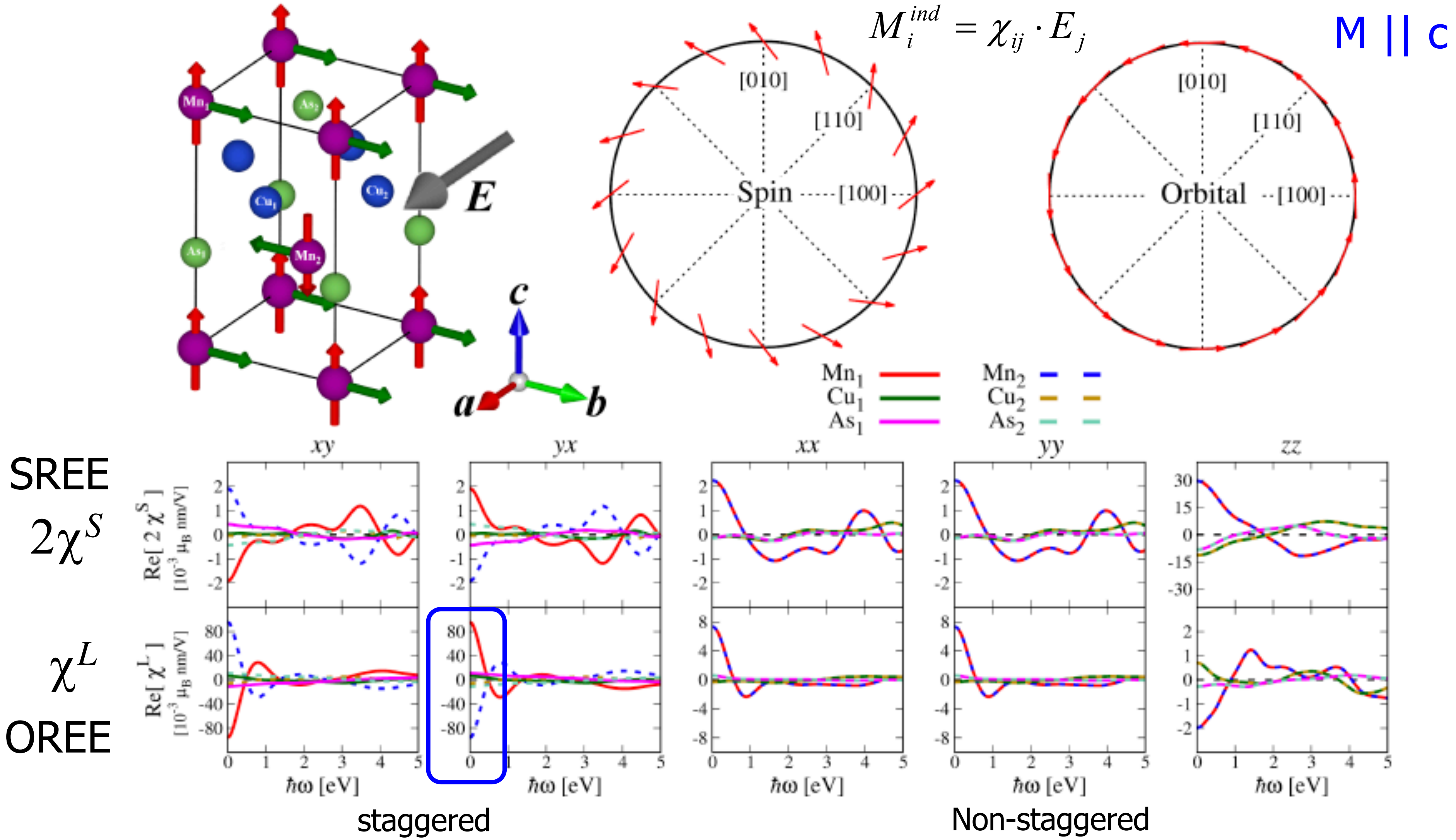




*Zelezny et al, PRL **113**, 157201 (2014)
Zelezny et al, PRB **95**, 014403 (2017)

Mn_2Au
Bodnar et al, Nat. Commun. **9**, 348 (2018)

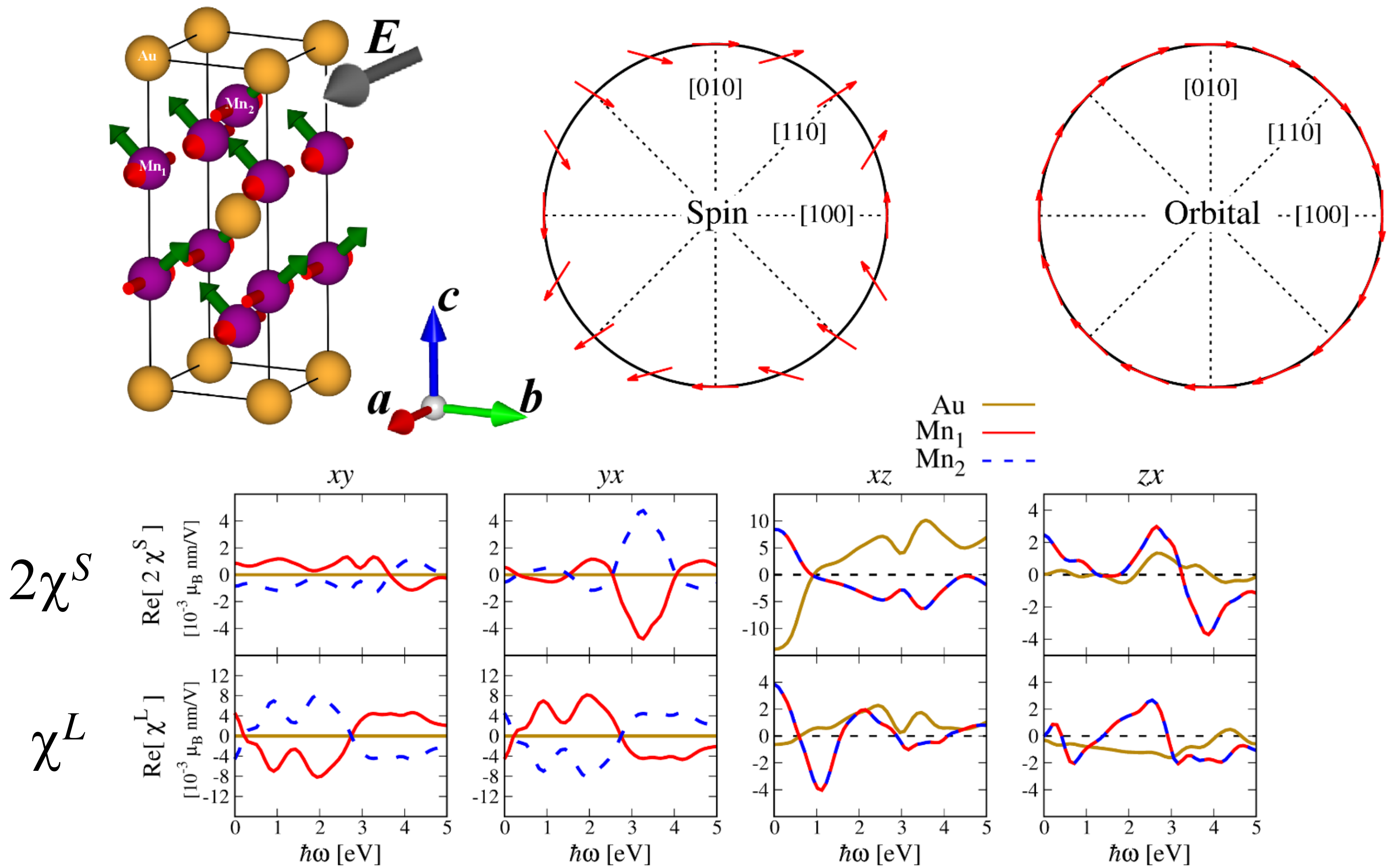
Results for CuMnAs



- Dominant staggered induced *orb*. polarization (40 x larger) – not due to SOC
- Frequency dependent and *non-staggered* χ elements also present

Mn_2Au – moments in basal plane

M || a



- Dresselhaus-like spin response, Rashba-type orbital response $\mathcal{PT}\{L^{\text{ind}}_{\text{Mn}_1}\} = -L^{\text{ind}}_{\text{Mn}_2}$
- Large *non-staggered* χ elements present, give out-of-plane direction

Salemi, Beritta, Nandy, PMO, Nat. Commun. **10**, 5381 (2019)

Possible recent observation

nature materials

LETTERS

https://doi.org/10.1038/s41563-021-00946-z

Check for updates

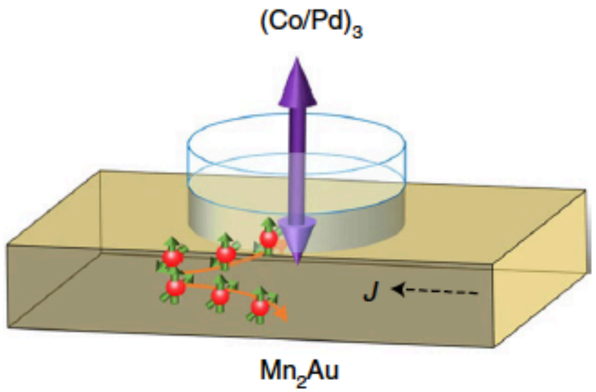
Observation of the antiferromagnetic spin Hall effect

Xianzhe Chen[1,9], Shuyuan Shi[2,9], Guoyi Shi[2,3,9], Xiaolong Fan[4], Cheng Song[1]✉, Xiaofeng Zhou[1], Hua Bai[1], Liyang Liao[1], Yongjian Zhou[1], Hanwen Zhang[4], Ang Li[5], Yanhui Chen[5], Xiaodong Han[5], Shan Jiang[6], Zengwei Zhu[6], Huaqiang Wu[7], Xiangrong Wang[8], Desheng Xue[4], Hyunsoo Yang[2,3]✉ and Feng Pan[1]✉

Nat. Mater. **20**, 800 (2021)

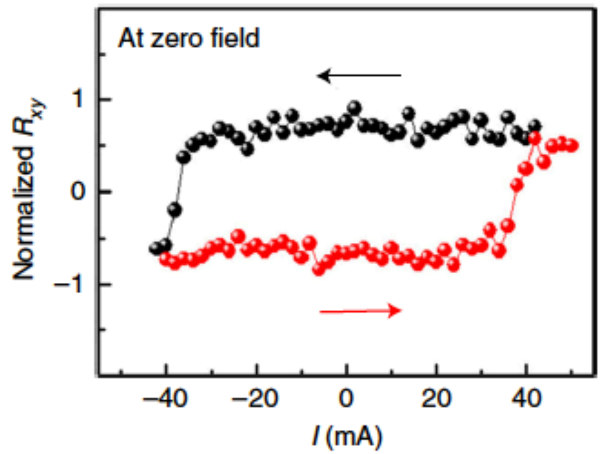
- Non-staggered element zx that gives an induced spin polarization in z-direction for a charge current in x-direction
- Can be used for so-called field free switching

g



Unusual spin polarization normal to layer; not normal SHE

h



Can switch the magnetization of Co/Pd layer

Summarizing ...

- LLG can be derived from and is consistent with Dirac-Kohn-Sham theory
- New relativistic SOT: optical SOT, field-derivative torque for time-dep. fields
- Intrinsic inertial torque can be due to relativistic effects
- Additional torques important and can extend LLG to shorter time scales

- Orbital Rashba-Edelstein effect huge (much larger than SREE) AFMs
- OREE staggered, not due to SOC, in symm.-broken AFMs
- SREE: large non-staggered elements

- Magn. SHE/OHE with induced spin/orbital pol. along E-field in Pt/3d layers
- Orbital accumulation *different* from spin accumulation
- Both δS_x and δS_y terms relevant for torques (dep. on magn. direction)