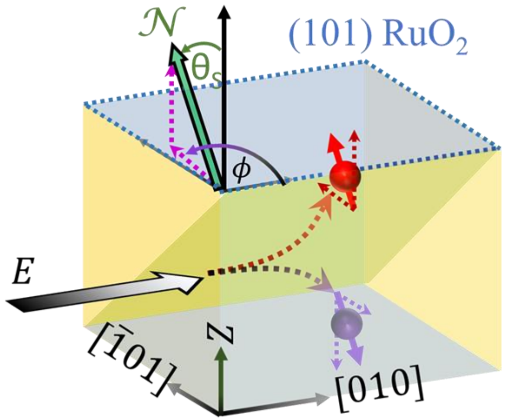
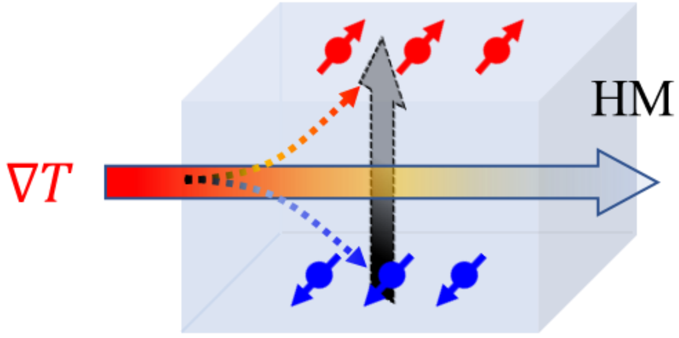
Generation of electric field induced unconventional spin-current





Arnab Bose

Johannes Gutenberg Universität Mainz, Germany

(M. Klaeui group)

Cornell University, NY, US

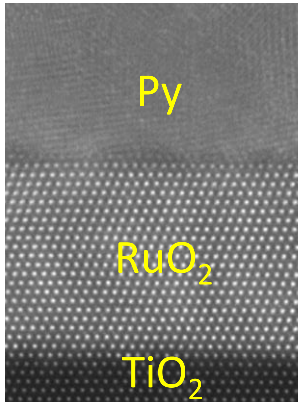
(R. Buhrman and D. Ralph group)

Outline

A. Tilted spin current generation by RuO_2

Ref: A. Bose et. al. Nature Electronics 5, 267 (2022)

A.1

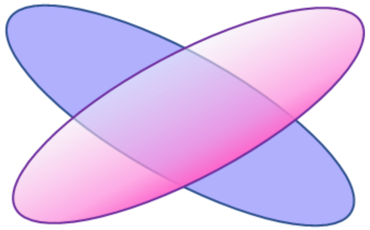


A.2

Measurement Techniques

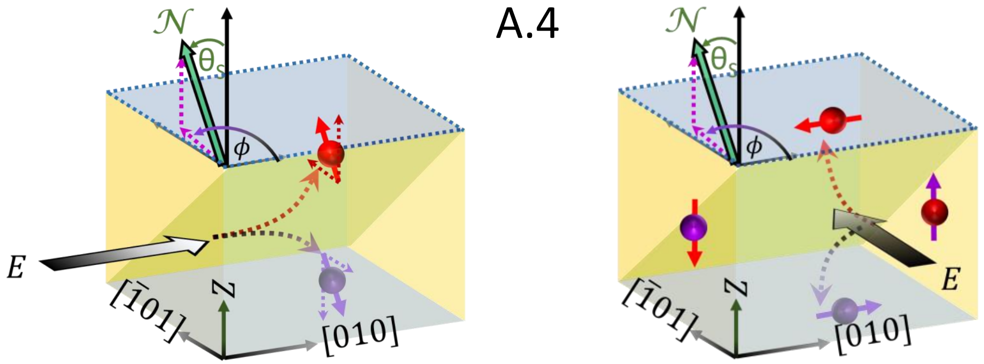
- ST-FMR
- 2^{nd} harmonics

A.3



Band-structure

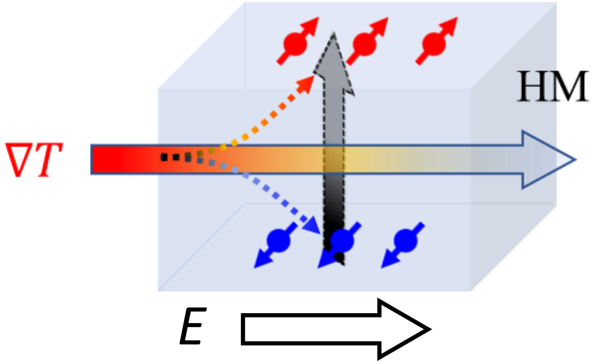
A.4

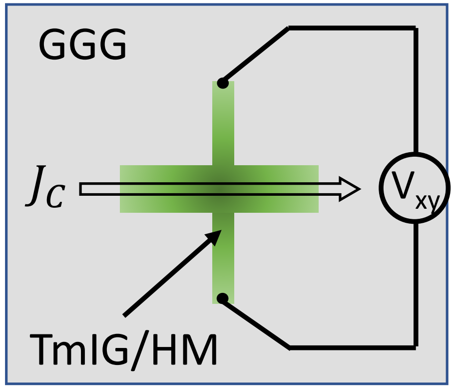


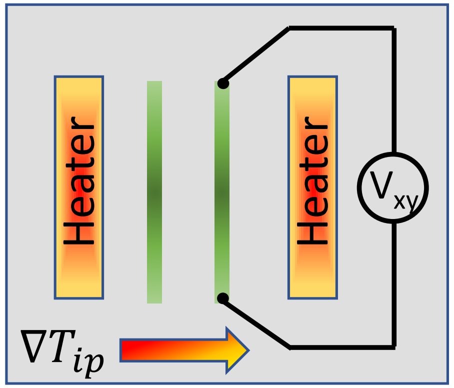
Strong crystal axis dependence

B. Spin Nernst effect and transverse magnetoresistance in TmIG/W (Pt)

Ref: A. Bose et. al. PRB L100408 (2022)







B_ϕ and B_Z

$$\left| \frac{\left(\Delta R^{\phi}_{xy} / \Delta R^{z}_{xy}\right)_{J_c}}{\left(\Delta V^{\phi}_{xy} / \Delta V^{z}_{xy}\right)_{\nabla T}} \right|$$

Origins

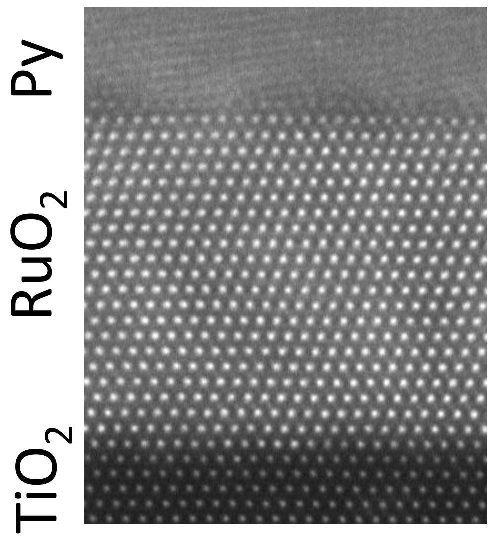
1) SHE, SNE

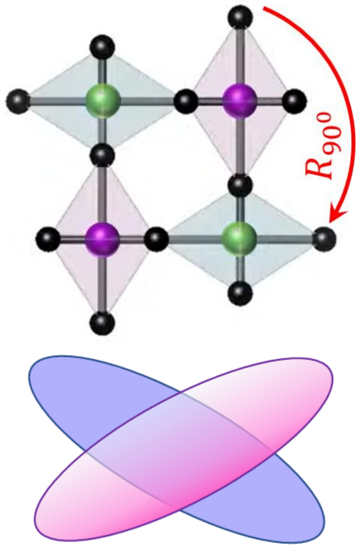
2) Proximity effect

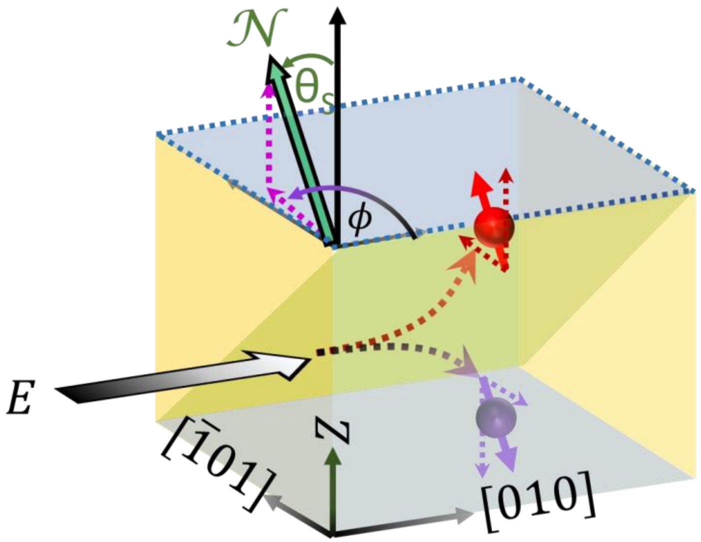
Tilted spin-current generated by the altermagnet RuO_2

A. Bose et. al. Nature Elecltronics 5,267 (2022)

A. Bose & D. C. Ralph. Research Briefings
www.nature.com/articles/s41928-022-00758-2



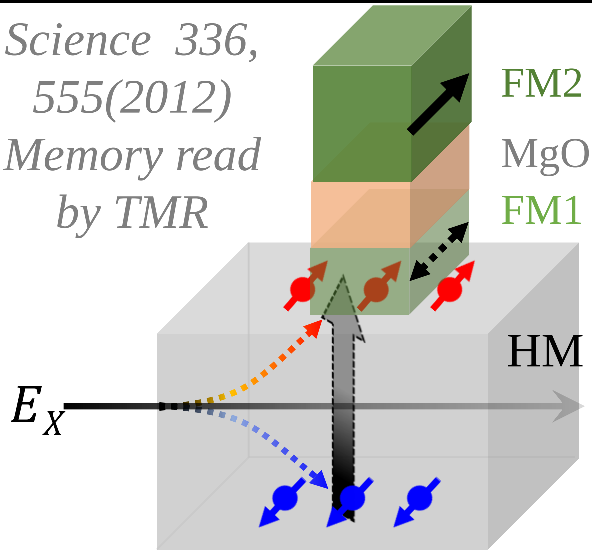




Spin-orbit torques

Science 336, 555(2012)

Memory read by TMR

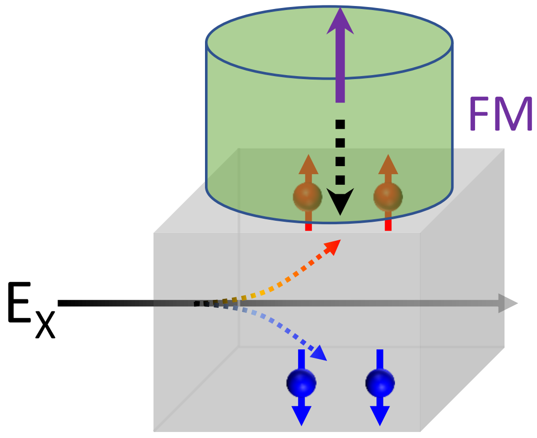


Spin Hall effect (SHE)

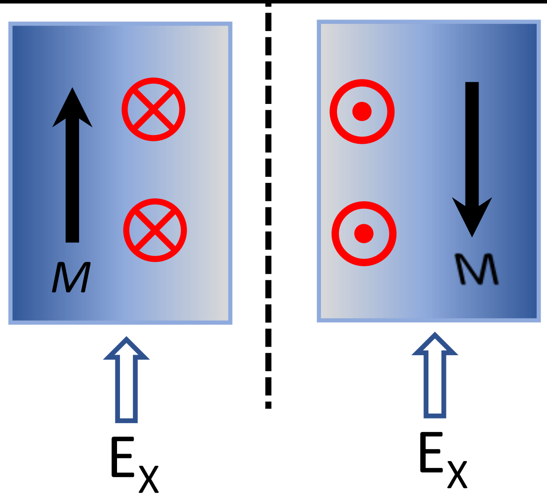
LLGS Equation

(JMMM 159, L1 (1996))

$$\frac{d\hat{m}}{dt} = -\gamma(\hat{m}\times\vec{H}_{net}) + \alpha\gamma(\hat{m}\times\vec{H}_{net}\times\hat{m}) + \Gamma_{FL}(\hat{m}\times\sigma_y) + \Gamma_{DL}(\hat{m}\times(\sigma_y\times\hat{m}))$$



Unconventional spin-current (op-DL)

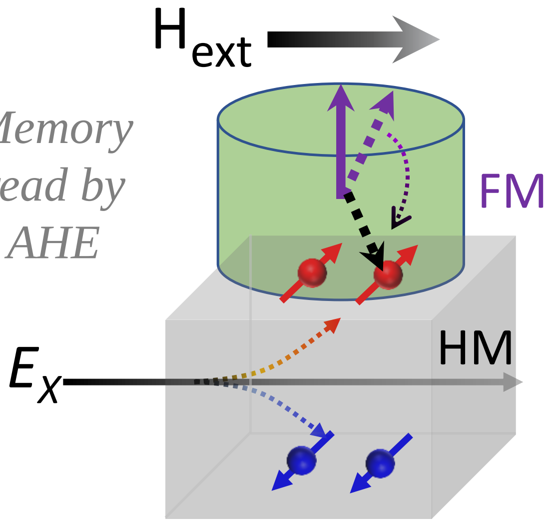


Mirror symmetry ⊥ to E_X to be broken

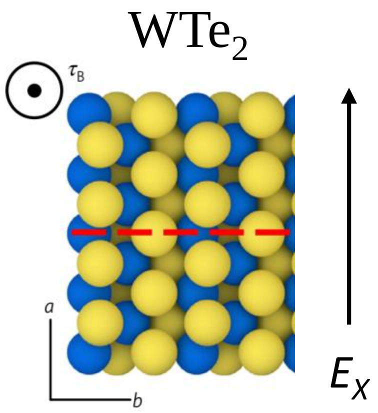
M-dependent SHE / Magnetic SHE/ Interface generated J_S

(RMP 91, 035004 (2019))

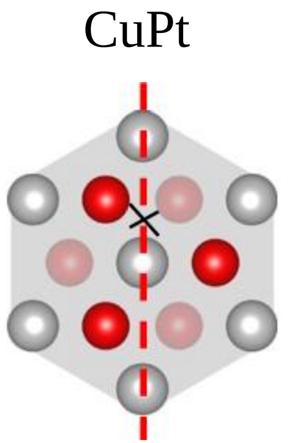
Memory read by AHE



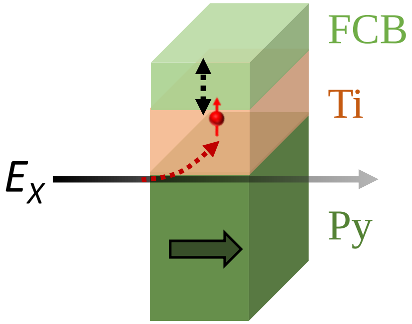
Nature 476, 189 (2011), PRL 109, 096602 (2012)



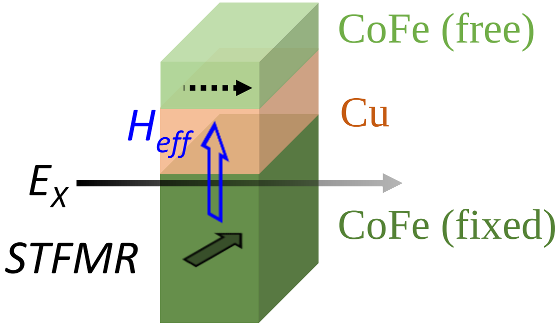
Nat. Phys. 13, 300 (2017)



Nat. Nano. 16, 277 (2021)

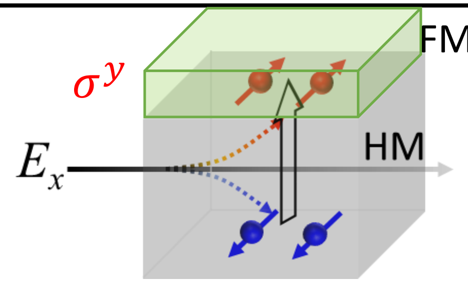


Nat. Mater. 17, 509 (2018)

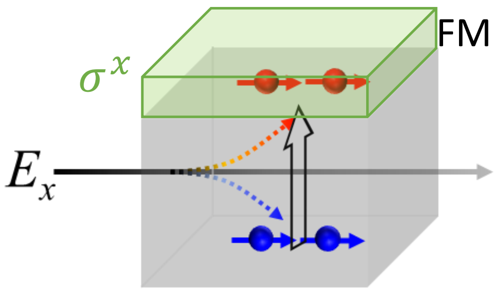


A. Bose et. al. PRAppl 9, 064026 (2018)

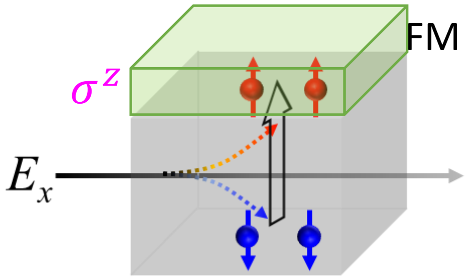
Types of SOT and measurement techniques



SHE, REE etc.



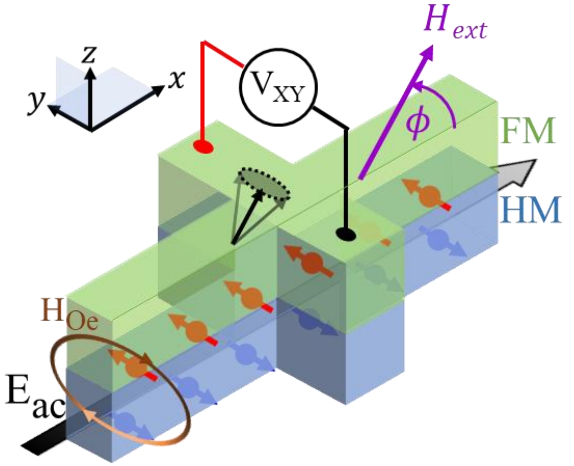
(Dresselhaus etc.)



(Unconventional, WTe_2, RuO_2)

$$\Gamma_{DL} \rightarrow \left(m \times \sigma_{z,x}^{X,Y,Z} \times m\right)$$
$$\Gamma_{FL} \rightarrow \left(m \times \sigma_{z,x}^{X,Y,Z}\right)$$

In-plane 2nd Harmonic Hall



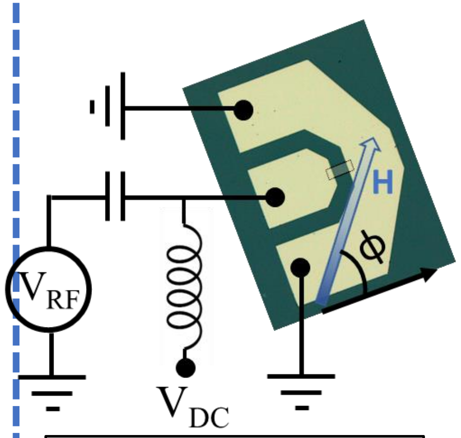
$$\tau_{ip} \rightarrow \overrightarrow{R_{AHE}(t)} \rightarrow \overrightarrow{M(t)} \times \overrightarrow{H_{eff}(t)}$$
$$\tau_{op} \rightarrow : \overrightarrow{E_{PHE}(t)} \rightarrow \overrightarrow{M(t)} \times \overrightarrow{H_{eff}(t)} \times \overrightarrow{M(t)}$$

$$V_{XY}^{2\omega} \rightarrow \begin{cases} D_{DL}^{Y} \cos\phi + F_{FL}^{Y} \cos\phi \cos 2\phi \\ + D_{DL}^{X} \sin\phi + F_{FL}^{X} \sin\phi \cos 2\phi \\ + D_{DL}^{Z} \cos 2\phi + F_{FL}^{Z} \end{cases}$$

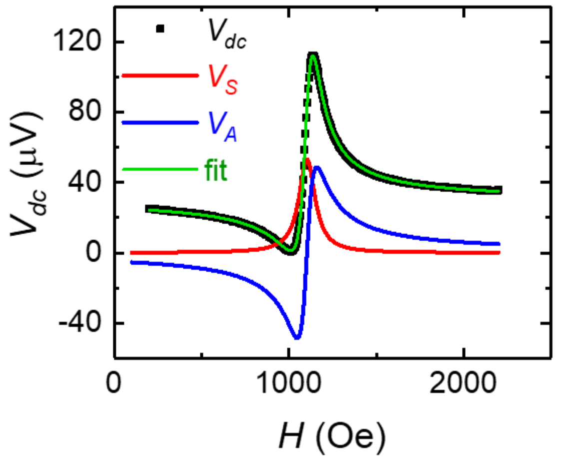
Constants D and F depend on H_{ext}

[PRB **89**, 144425 (2014), arXiv:2108.09150 (2021)]

ST-FMR



$V_{dc} \rightarrow \langle I_{rf}(t) . R_{rf}^{amr}(t) \rangle$



$$V_S = S\left(\frac{\Delta^2}{(H - H_0)^2 + \Delta^2}\right) \qquad V_A = A\left(\frac{(H - H_0)\Delta}{(H - H_0)^2 + \Delta^2}\right)$$

In-plane torques — Out-plane torques

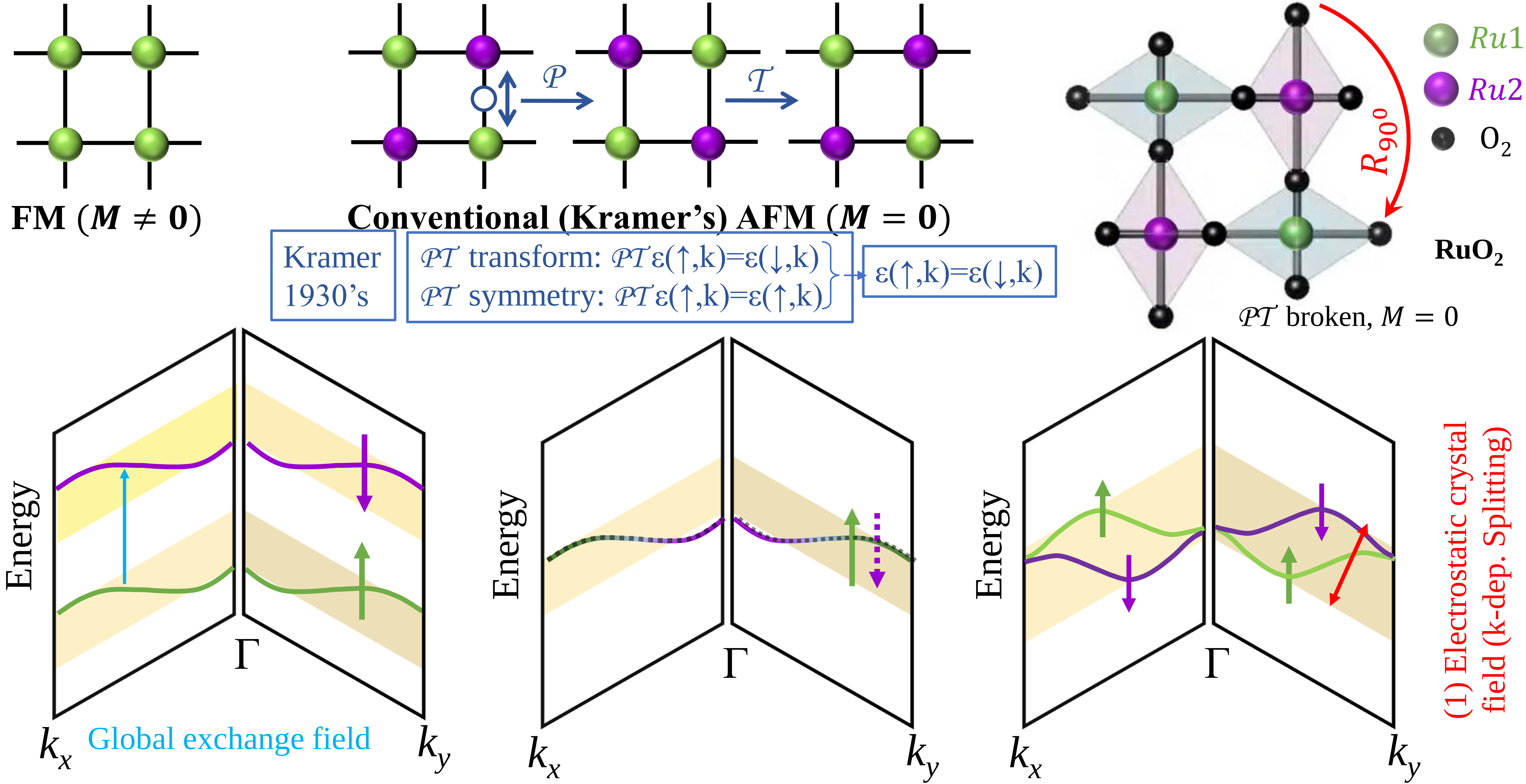
$\{m \times (\sigma_{z,x}^{Y} \times m)\}$ $\{m \times (\sigma_{z,x}^{X} \times m)\}$ $\{m \times \sigma_{z,x}^{Z}\}$

$$S = S_{DL}^{Y} \cos\phi \sin 2\phi + S_{DL}^{X} \sin\phi \sin 2\phi + S_{FL}^{Z} \sin 2\phi$$
$$A = A_{FL}^{Y} \cos\phi \sin 2\phi + A_{FL}^{X} \sin\phi \sin 2\phi + A_{DL}^{Z} \sin 2\phi$$

$\{m \times \sigma_{z,x}^{Y}\}$ $\{m \times \sigma_{z,x}^{X}\}$ $\{m \times (\sigma_{z,x}^{Z} \times m)\}$

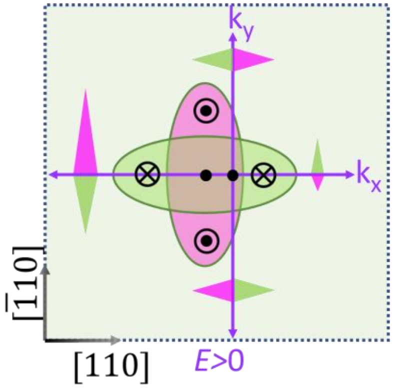
[PRL106, 036601 (2011)]

RuO_2: spin-split bands (*arXiv:2105.05820*)

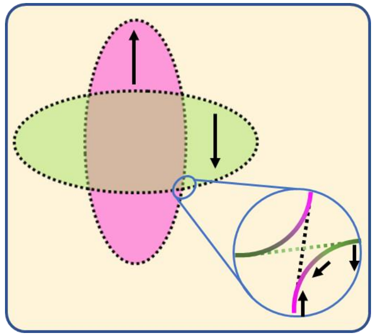


Electronics with the altermagnet (RuO_2) (Šmejkal et. al. arXiv:2204.10844)

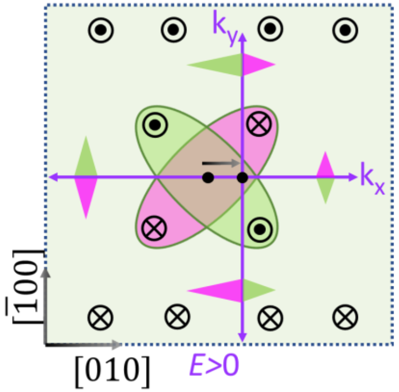
(1) Longitudinal time odd spin-polarized current by the real space collinear AFM
(strongly crystal axis dependent)
Theory: Phys Rev X 12, 011028 (2021)



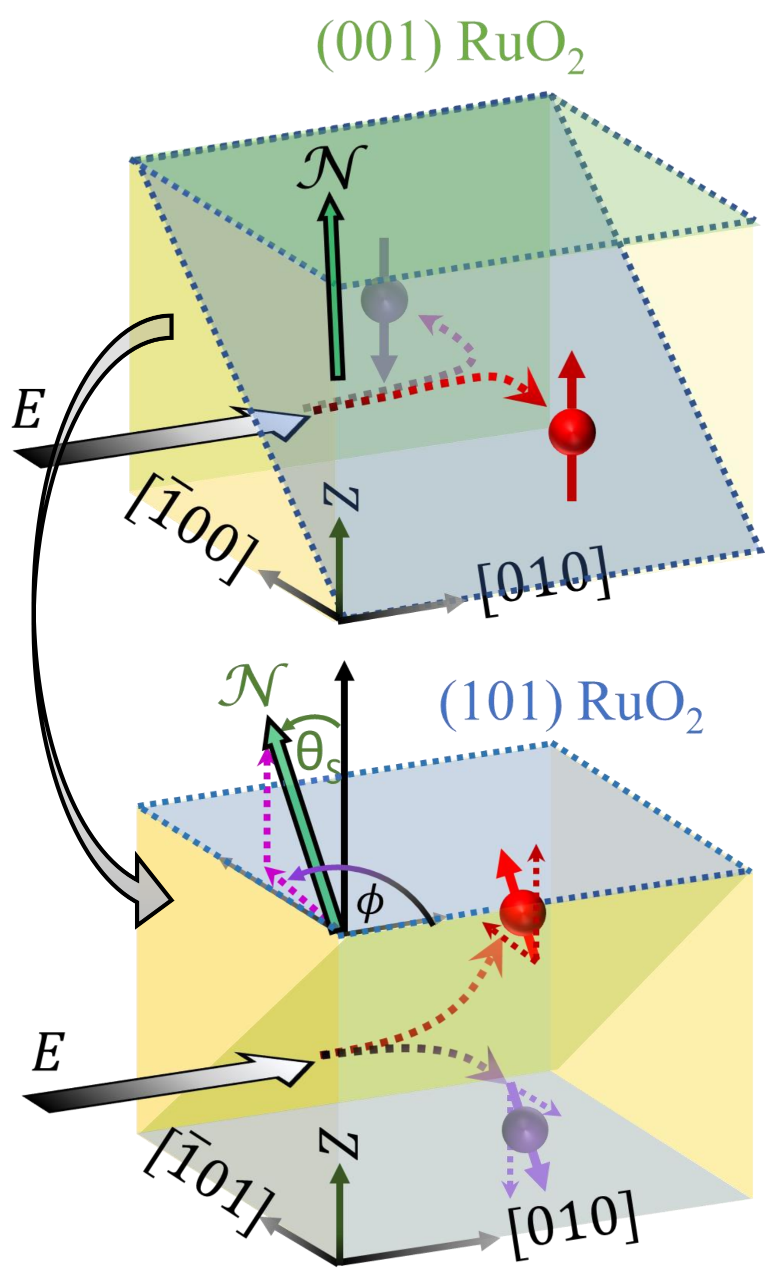
(2) Anomalous Hall effect by the real space collinear AFM
(strongly crystal axis dependent)
Theory: Sci Adv. 6, eaaz8809 (2020)

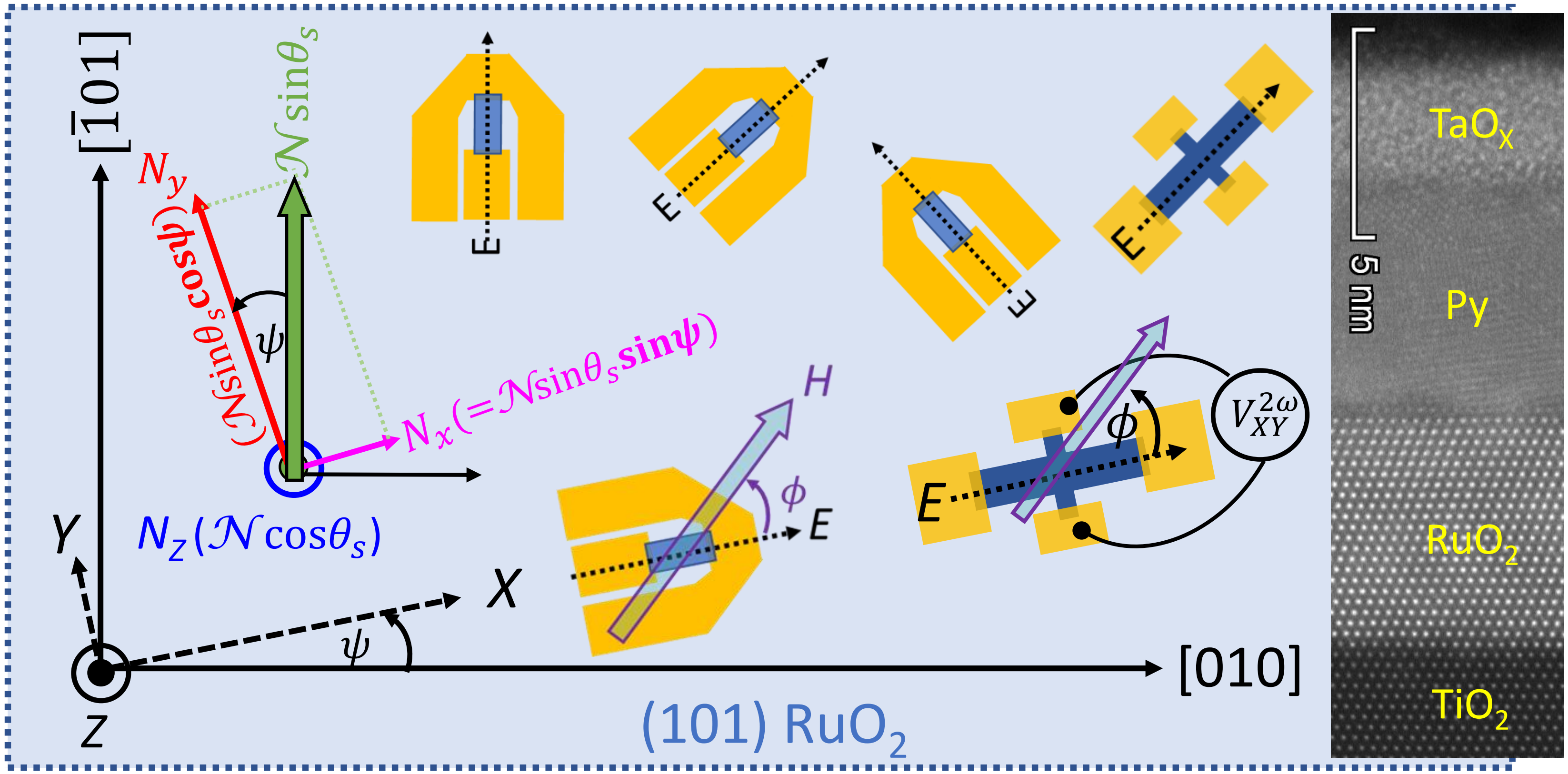


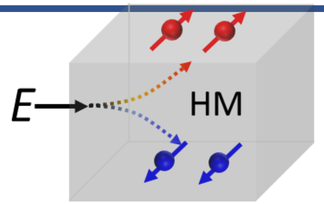
(3) Unconventional time-odd spin-Hall current even in the absence of SOC determined by *N*-vector (strongly crystal axis dependent)
Theory: PRL 126, 127701 (2021)
Exp: A. Bose. et. al. Nat. Electron. 5, 267 (2022)



Tilted spin-current generated by RuO_2 (*A. Bose et. al. Nat. Elecl.5, 267 (2022)*)

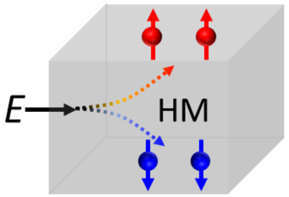


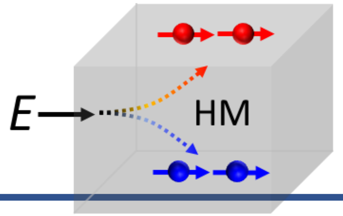




$$\xi^{Y}_{DL,E} = C_1.\ \sin\theta_s(\sin\theta_s\,\boldsymbol{\cos\psi})\,\boldsymbol{\cos\psi} + C_0$$

$$\xi^{Z}_{DL,E} = C_1.\ \sin\theta_s\ (\cos\theta_s)\,\boldsymbol{\cos\psi}$$

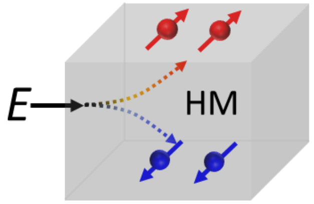




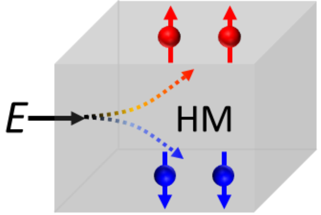
$$\xi^{X}_{DL,E} = C_1.\ \sin\theta_s(\sin\theta_s\,\boldsymbol{\sin\psi})\,\boldsymbol{\cos\psi}$$

Time even vs time odd transverse spin currents

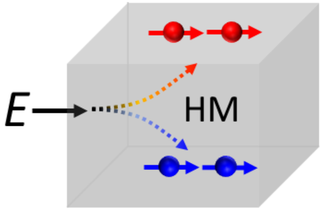
$\xi_{DL}^{Y} \propto \cos^2 \psi$

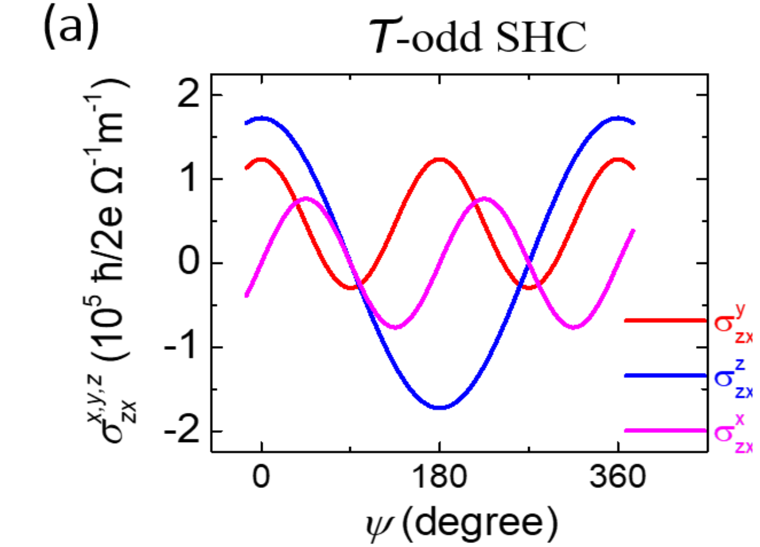


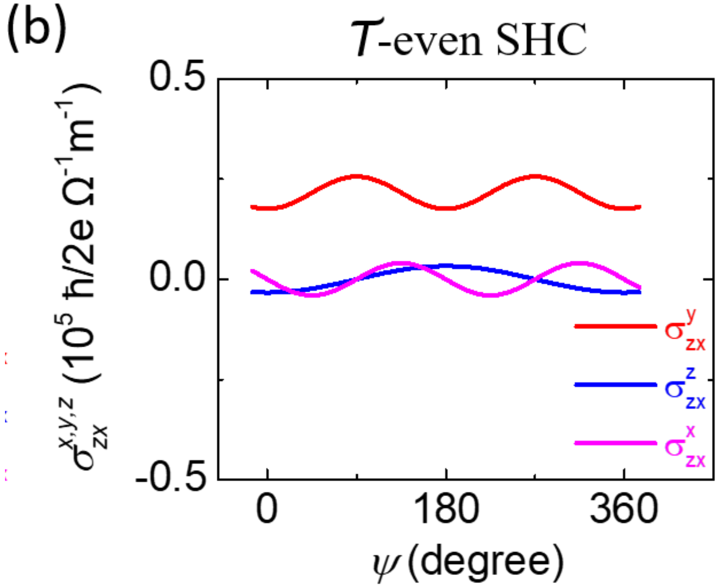
$\xi_{DL}^{Z} \propto \cos \psi$



$\xi_{DL}^{X} \propto \sin \psi \cos \psi$







$$\sigma_{ij}^{k} = -\frac{e\hbar}{\pi}\int \frac{d^3\vec{k}}{(2\pi)^3}\sum_{n,m}\frac{\Gamma^2 \mathrm{Re}\left(\langle n\vec{k}|J_i^k|m\vec{k}\rangle\langle m\vec{k}|v_j|n\vec{k}\rangle\right)}{\left[\left(E_F - E_{n\vec{k}}\right)^2 + \Gamma^2\right]\left[\left(E_F - E_{m\vec{k}}\right)^2 + \Gamma^2\right]}$$

$\Gamma \approx 50\ eV$ for $\rho = 270\ \mu\Omega - cm$

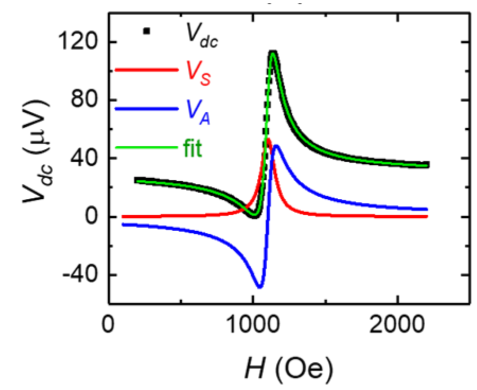
$\Gamma \approx 25\ eV$ for $\rho = 140\ \mu\Omega - cm$

$\sigma_{ij}^{k}(\Gamma \approx 25) \approx 2\sigma_{ij}^{k}(\Gamma \approx 50)$

Strong temperature dependence

$$\sigma_{ij}^{k} = -\frac{2e}{\hbar}\int \frac{d^3\vec{k}}{(2\pi)^3}\sum_{n' \neq n}\frac{\mathrm{Im}\left(\langle n\vec{k}|J_i^k|n'\vec{k}\rangle\langle n'\vec{k}|v_j|n\vec{k}\rangle\right)}{\left(E_{n\vec{k}} - E_{n'\vec{k}}\right)^2}$$

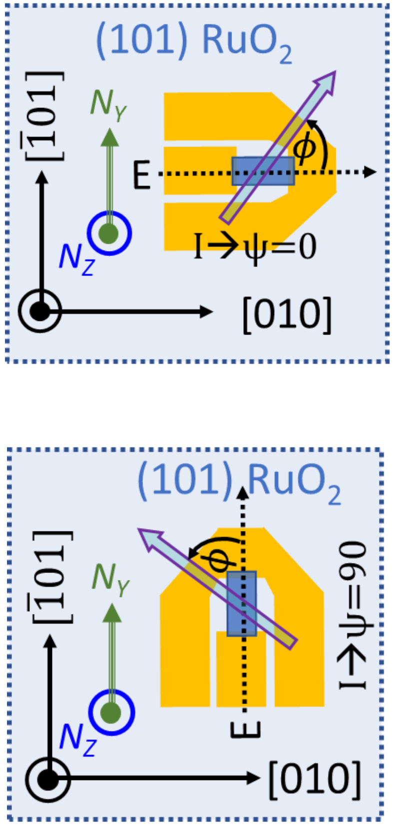
Spin-torque measurements by ST-FMR and SHH

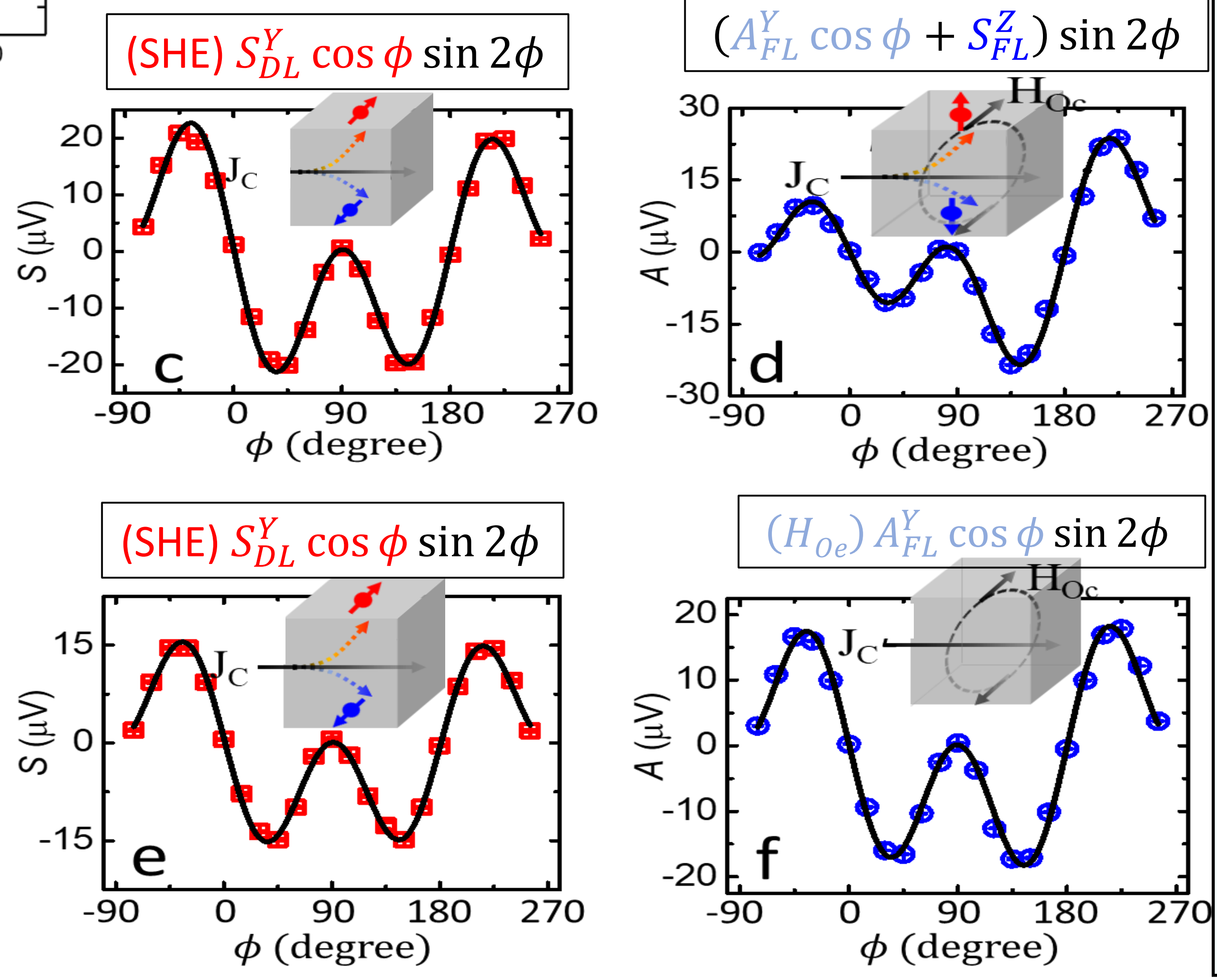


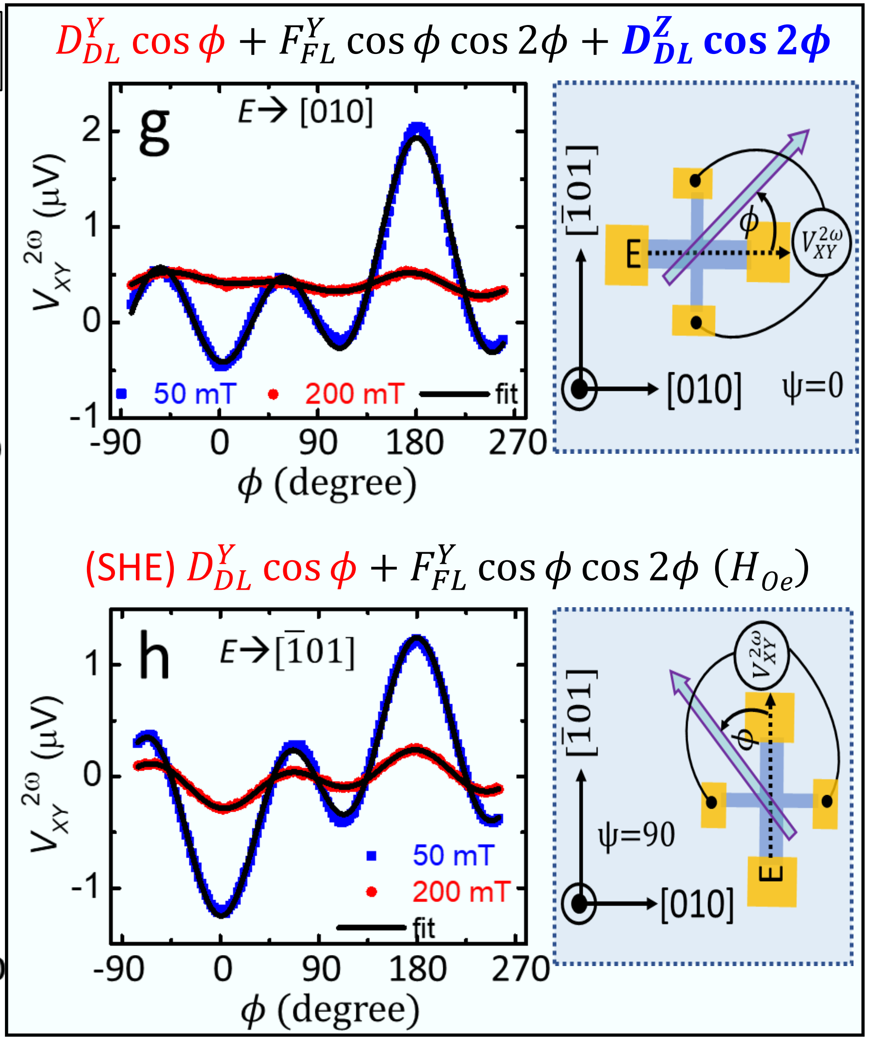
$$V_S = S\left(\frac{\Delta^2}{(H-H_0)^2+\Delta^2}\right) \qquad S = (S_{DL}^{Y}\cos\phi + S_{DL}^{X}\sin\phi + S_{FL}^{Z})\sin 2\phi$$

$$V_A = A\left(\frac{(H-H_0)\Delta}{(H-H_0)^2+\Delta^2}\right) \qquad A = (A_{FL}^{Y}\cos\phi + A_{FL}^{X}\sin\phi + S_{FL}^{Z})\sin 2\phi$$

$$V_{XY}^{2\omega} = C + D_{DL}^{Y}\cos\phi + F_{FL}^{Y}\cos\phi\cos 2\phi + D_{DL}^{Z}\cos 2\phi + F_{FL}^{X}\sin\phi\cos 2\phi + D_{DL}^{Y}\sin\phi$$

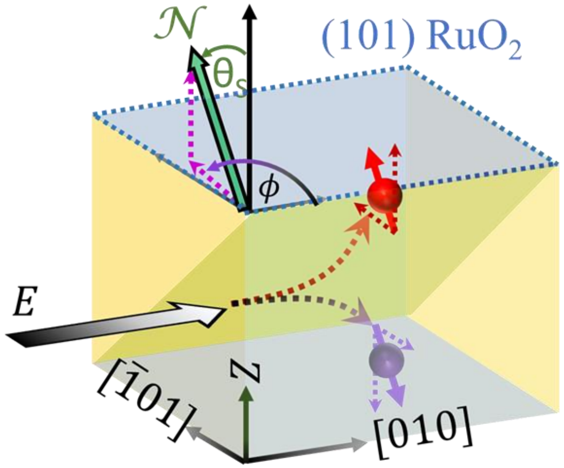


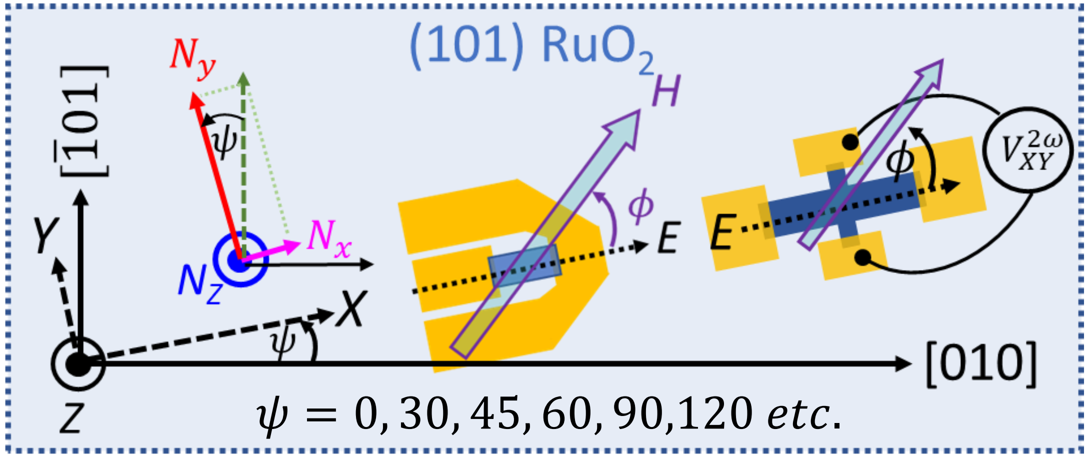




Detection of the tilted spin current in RuO_2

(A. Bose et. al. Nat. Electron. 5, 267 (2022))

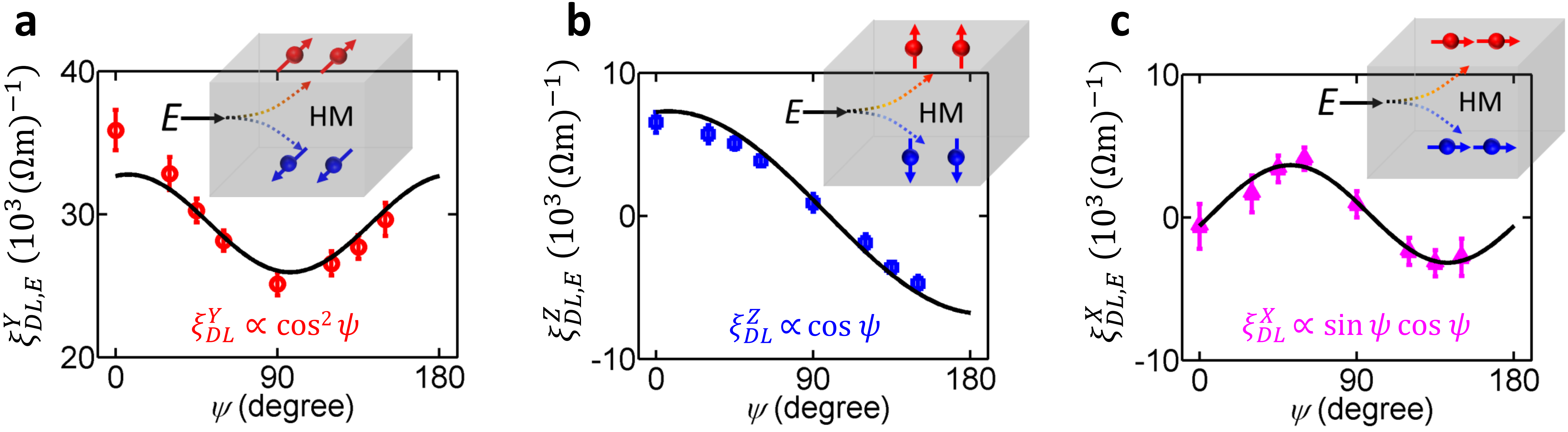




S. Karube, et. al. PRL 129, 137201 (2022)

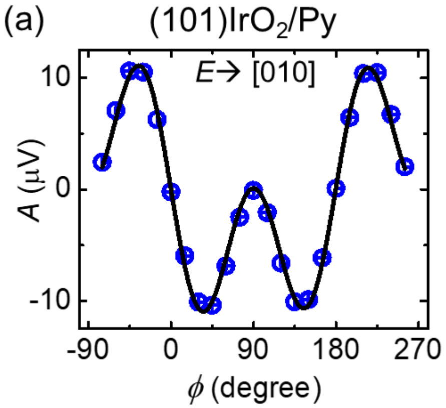
H. Bai, et. al. PRL 128, 197202 (2022)

X. Chen et. al. Nat. Mat. 20, 800 (2021)



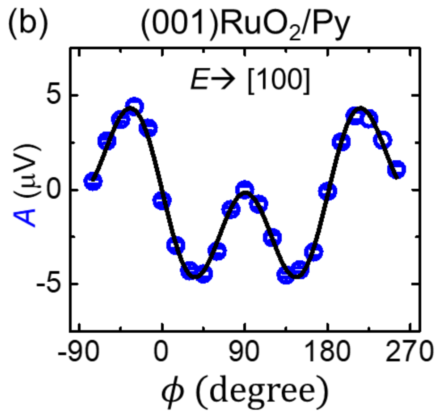
The tilted spin-current is a consequence of the novel spin-split bands of the emerging new type of anti-ferromagnet

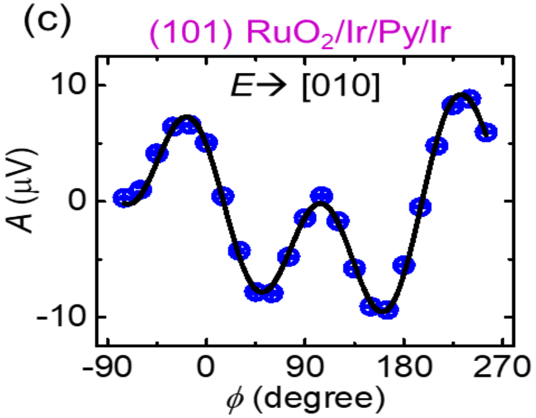
Additional experiments

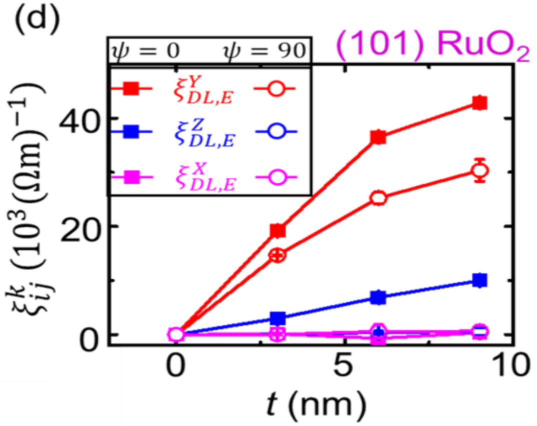


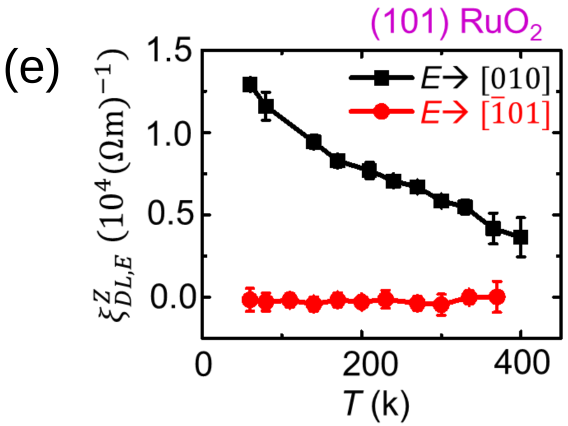
Isostructural

	RuO$_2$	IrO$_2$
a	4.543	4.545
b	4.543	4.545
c	3.140	3.190









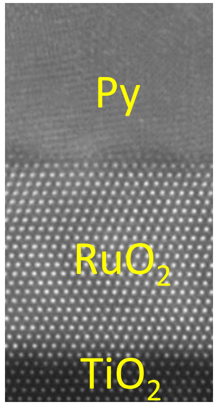
Summary

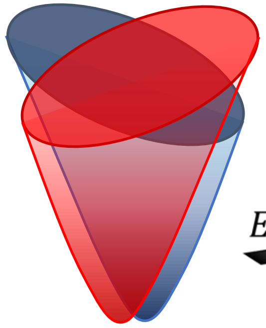
1. Isostructural (101) IrO$_2$ cannot produce op-DLT that (101) RuO$_2$ exhibits suggesting the importance of AF-ordering.

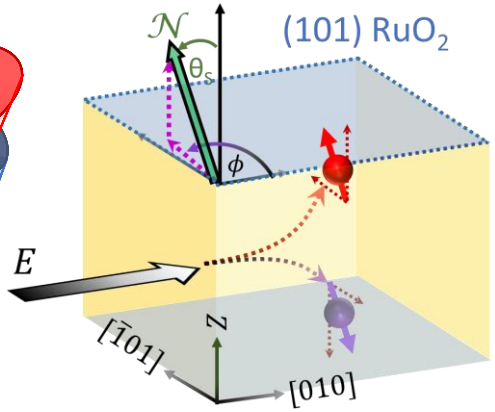
2. Strong dependence of OP-DLT with crystal axis and crystal planes.

3. Bulk origin of the spin current from RuO2 thickness dependence and Ir spacer insertion.

4. Signature of T-odd spin current from strong temperature dependence of op-DLT.

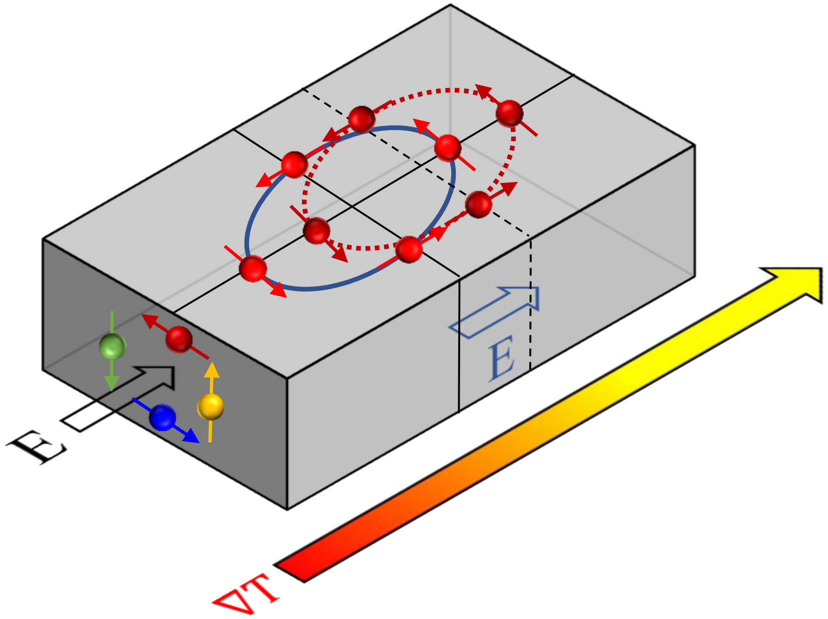




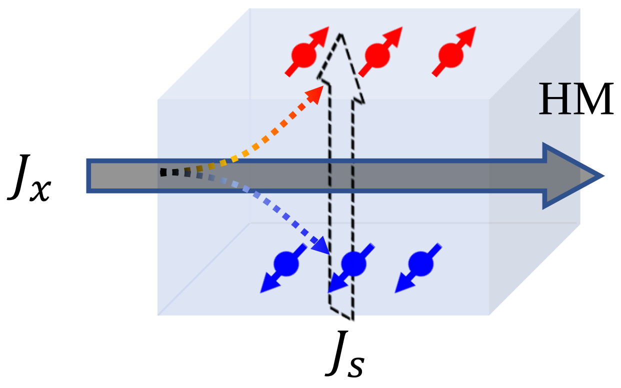


Spin Nernst effect (SNE) detected by comparing transverse MR driven by electric current and thermal gradient

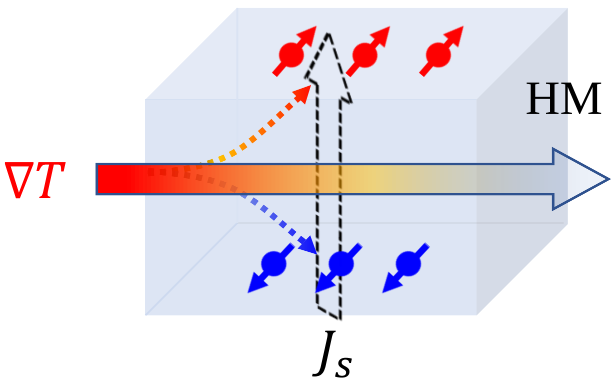
A. Bose et. al. Phys. Rev. B 105, L100408 (2022)



What is spin Nernst effect (SNE)?



Spin Hall effect (SHE)
J. Sinova et. al. RMP: 87, 1213 (2015)



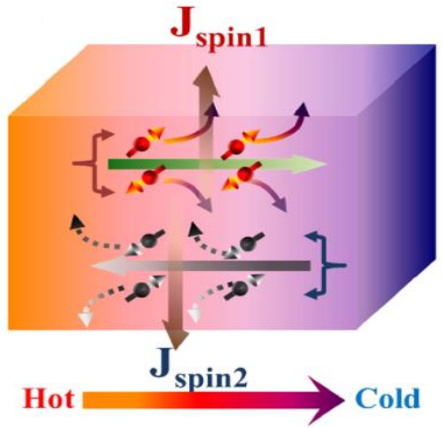
Spin Nernst effect (SNE)
A. Bose & A. Tulapurkar. JMMM 491 (2019)

1) Hall effect (*Am. J. Math. 2, 287 (1879)*)
2) Anomalous Hall effect (*Philos. Mag. 12, 157 (1881)*)
3) Nernst effect (thermal Hall effect) (*Ann. Phys. 265, 343 (1886)*)
4) Quantum Hall effect (*Phys. Rev. Lett. 45, 494 (1980)*)
5) Spin Hall effect (*Science 306, 1910 (2004), Nature 176, 442 (2005)*)
6) Magnon Hall effect (*Science 329, 297 (2010)*)
7) Photonic spin Hall effect (*Science 1405, 339 (2013)*)
8) Valley Hall effect (*Science 344, 6191 (2014)*)
9) Etc.…
10) Thermal spin Hall effect (Spin Nernst effect)

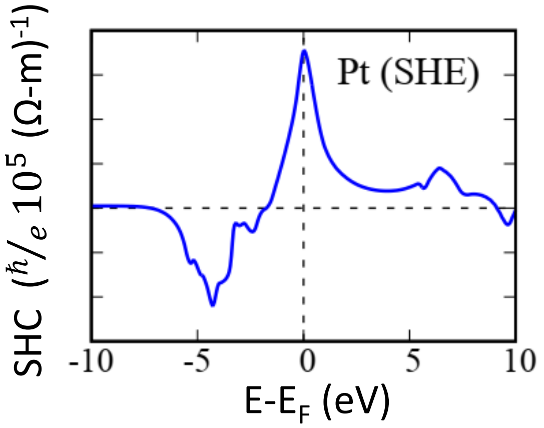
(*Nat Mat. 16, 978 (2017),*
Sci. Adv. 3, e1701503 (2017),
Nat. Comm. Nov. 8L1400 2017),
A. Bose et. al. APL 112, 162401 (2018), PRB 98 (184412) (2018), PRB 105, L100408 (2022))

Origins of SNE

Energy dependent scattering



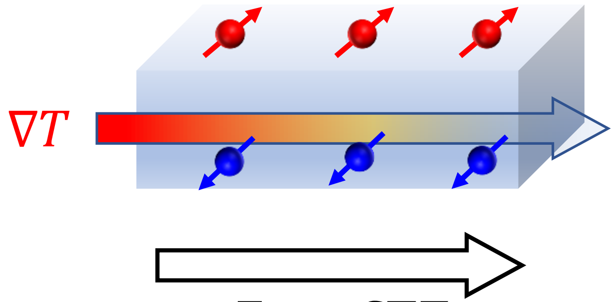
A. Bose et. al. APL 112,162401 (2018)



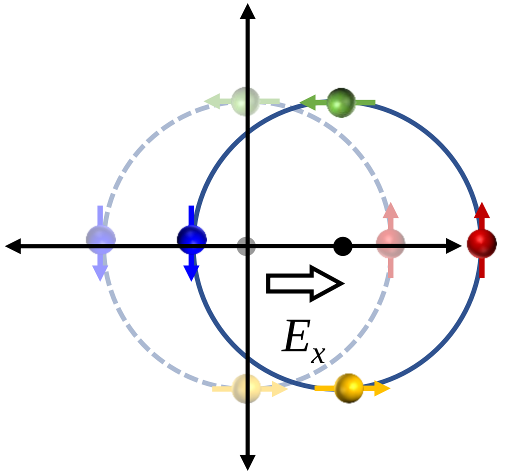
arXv:2203.17037v1

$$\sigma_{SN} \equiv -\frac{\pi^2 k_B^2 T}{e}\left(\frac{d}{dE}\sigma_{SH}\right)_{E=E_F}$$

Scattering independent

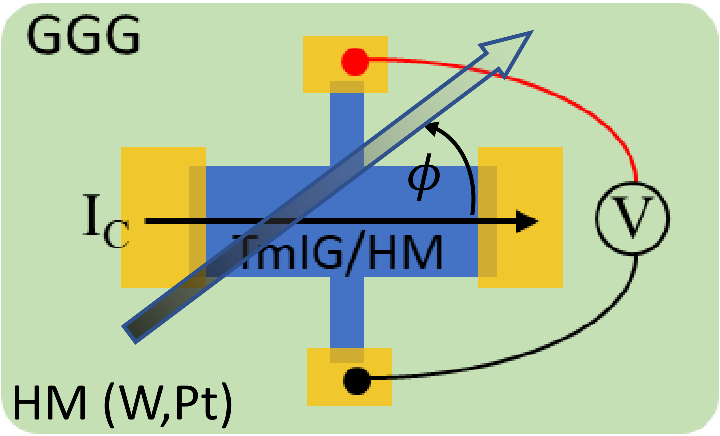


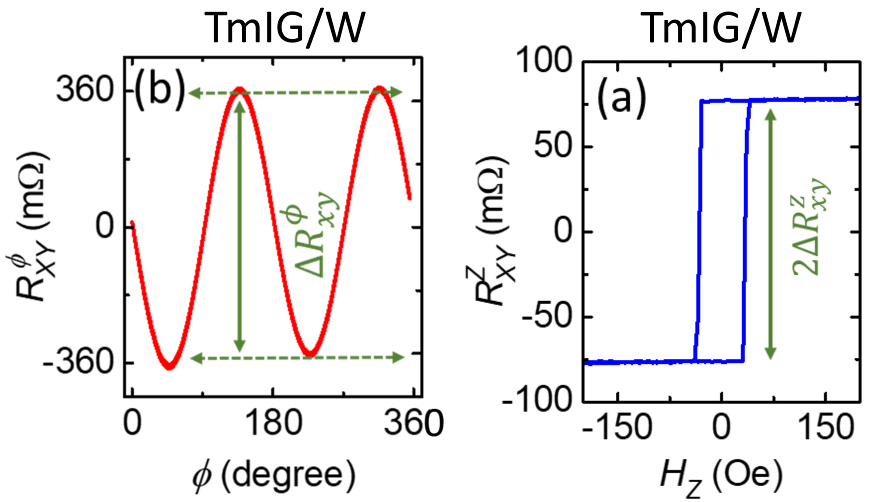
$$E_x = S\nabla T$$

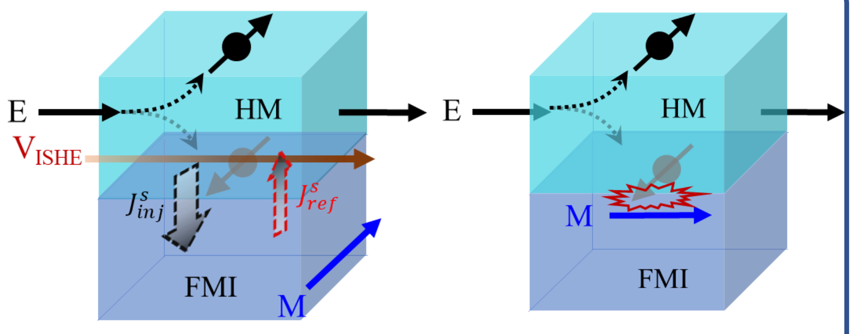


$$J^s_{z,x} = \sigma^s_{z,x} E_x$$

Experimental detection of SNE via SMR



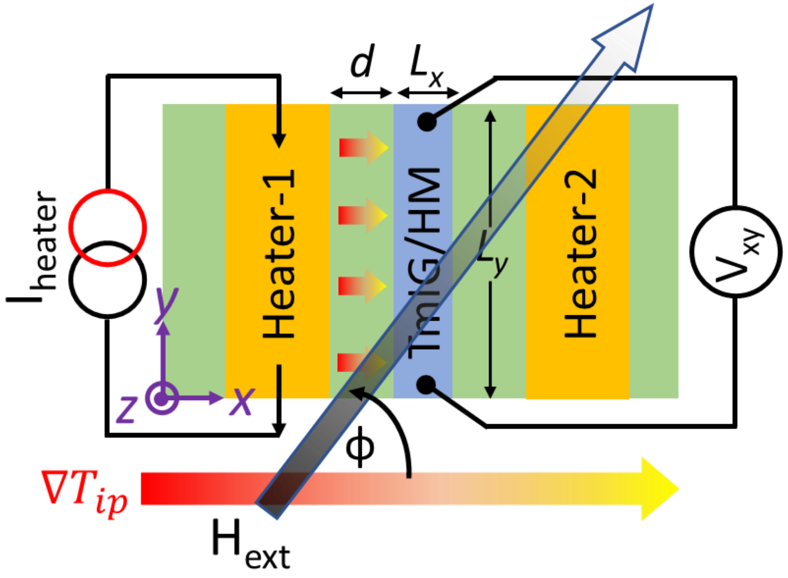


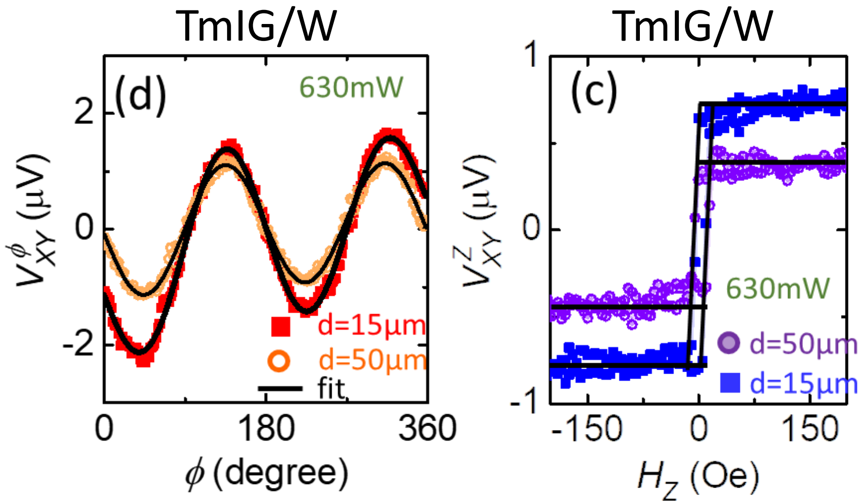


SMR (*PRL 110, 206601 (2013)*)

$$\frac{V_{xx}}{L_x} = -\left(V_0 + \Delta V_{xy}^{\phi,SMR} m_y^2\right) E$$

$$\frac{V_{xy}}{L_y} = -\left(\Delta V_{xy}^{z,SMR} m_z + \Delta V_{xy}^{\phi,SMR} m_x m_y\right) E$$





$$V_{\nabla T_x} \sin 2\phi + V_{\nabla T_z} \cos\phi$$

$$\eta = \left| \frac{\left(\Delta R_{xy}^{\Phi} / \Delta R_{xy}^{z}\right)_{Electric}}{\left(\Delta V_{xy}^{\Phi} / \Delta V_{xy}^{z}\right)_{thermal}} \right|$$

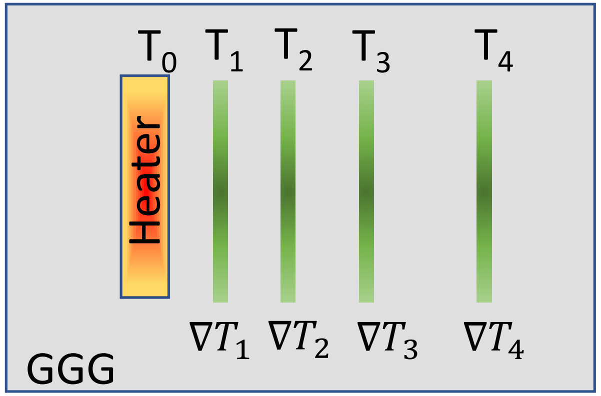
$\eta = 1$ → SHE, SNE (SMR)

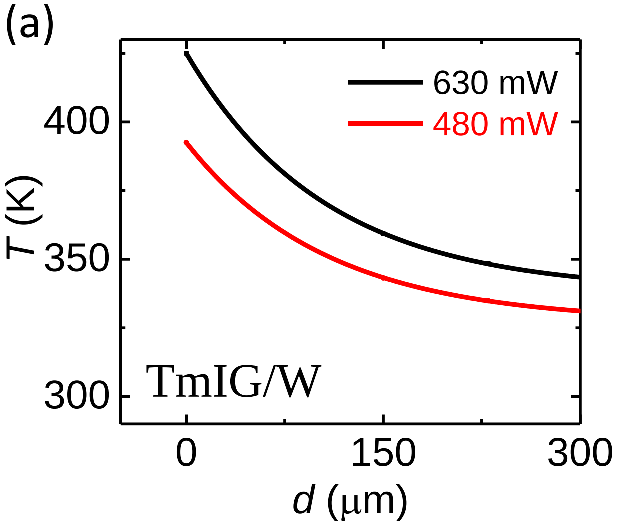
$\eta \neq 1$ MPE /+ TSD

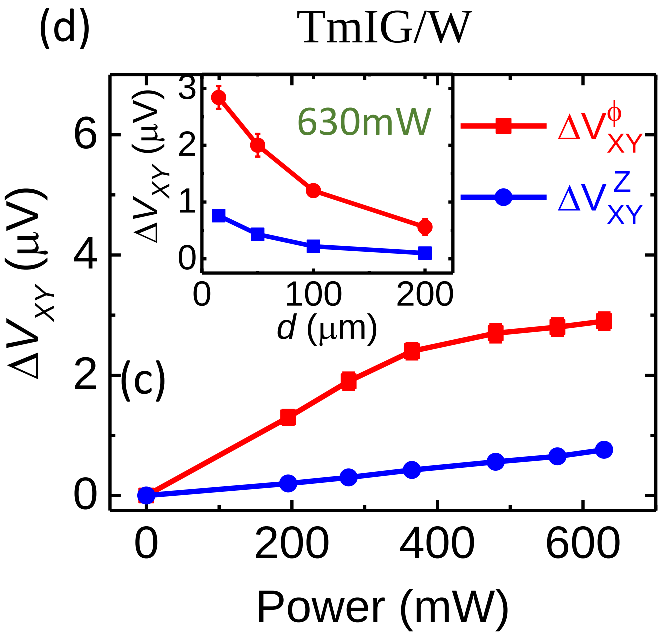
Origins of transverse thermal MR in TmIG/HM (Bose et. al. *PRB (2022)*)

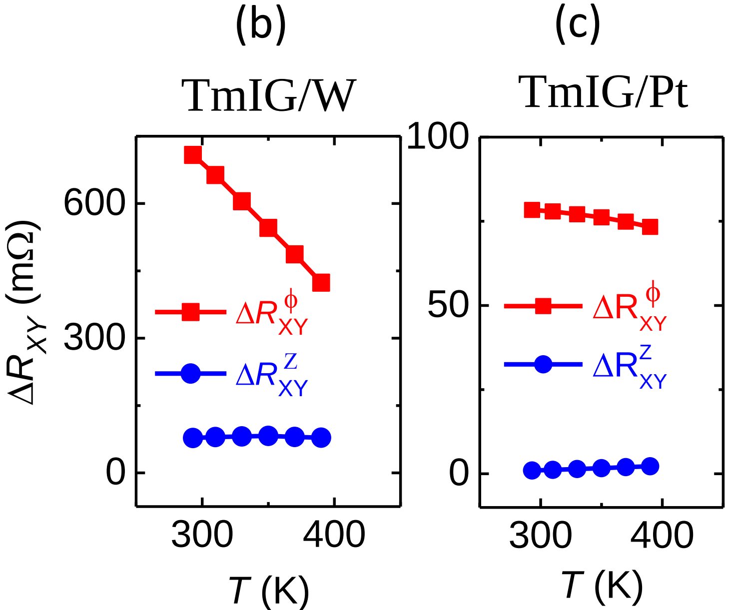
$$\eta = \left| \frac{\left(\Delta R_{xy}^{\phi} / \Delta R_{xy}^{z}\right)_{Electric}}{\left(\Delta V_{xy}^{\phi} / \Delta V_{xy}^{z}\right)_{thermal}} \right|_{T}$$

$$P_{heater} \Uparrow \longrightarrow \nabla T_x \Uparrow, T_{avg} \Uparrow$$

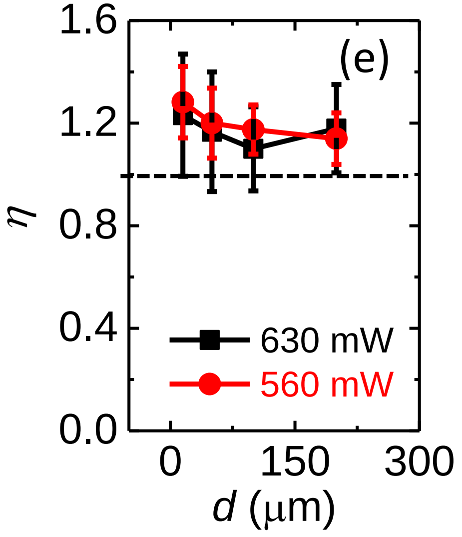




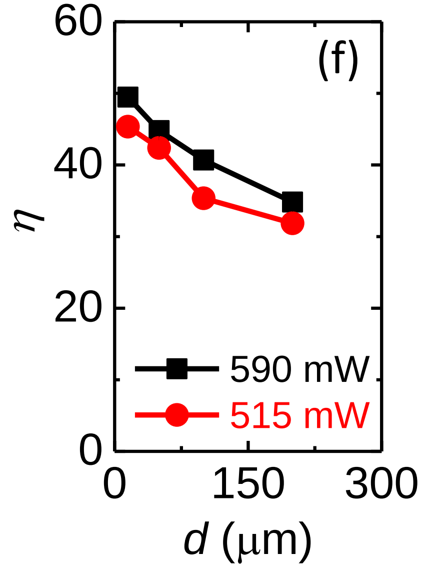


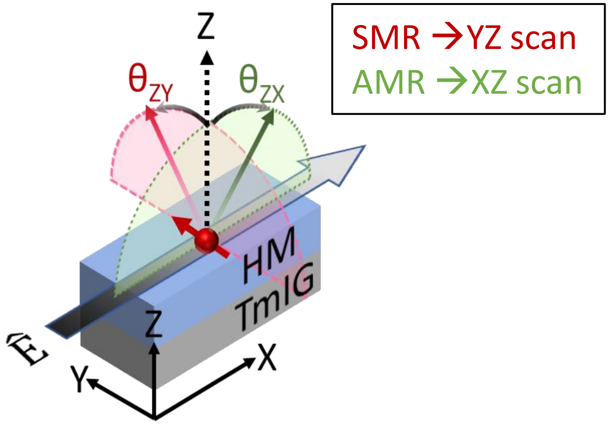


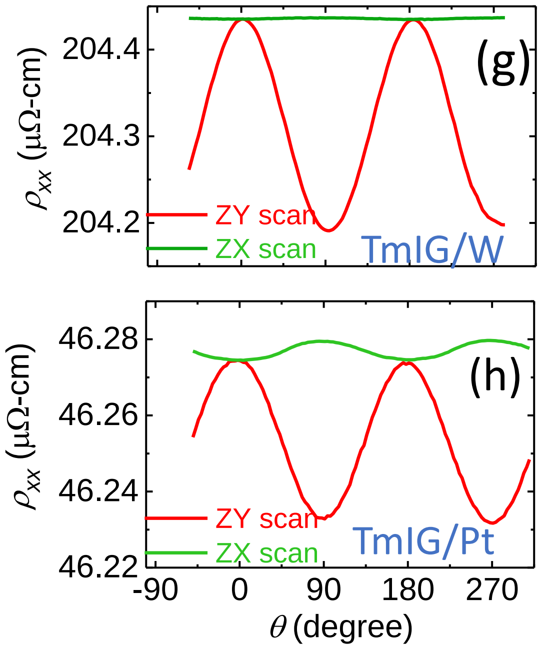
TmIG/W (SHE+SNE)



TmIG/Pt (Origin?)







MPE in TIG/Pt at and above 300K unlike TIG/W

ANE and PNE from Mott's expression

Mott relation

$$S_{yx} = \frac{1}{\sigma_{xx}}(\alpha_{yx} - \sigma_{yx}S_{xx})$$

$$\alpha_{xy} = \frac{\pi^2 k_B^2 T}{3e}\left(\frac{\partial \sigma_{xy}}{\partial E}\right)_{E_F}$$

AHE →ANE ($Ga_xMn_{1-x}As$) PRL 101, 117208 (2008)
*SHE →SNE PRB (R) **98**, 081401(R) (2018)*
arXv:2203.17037v1

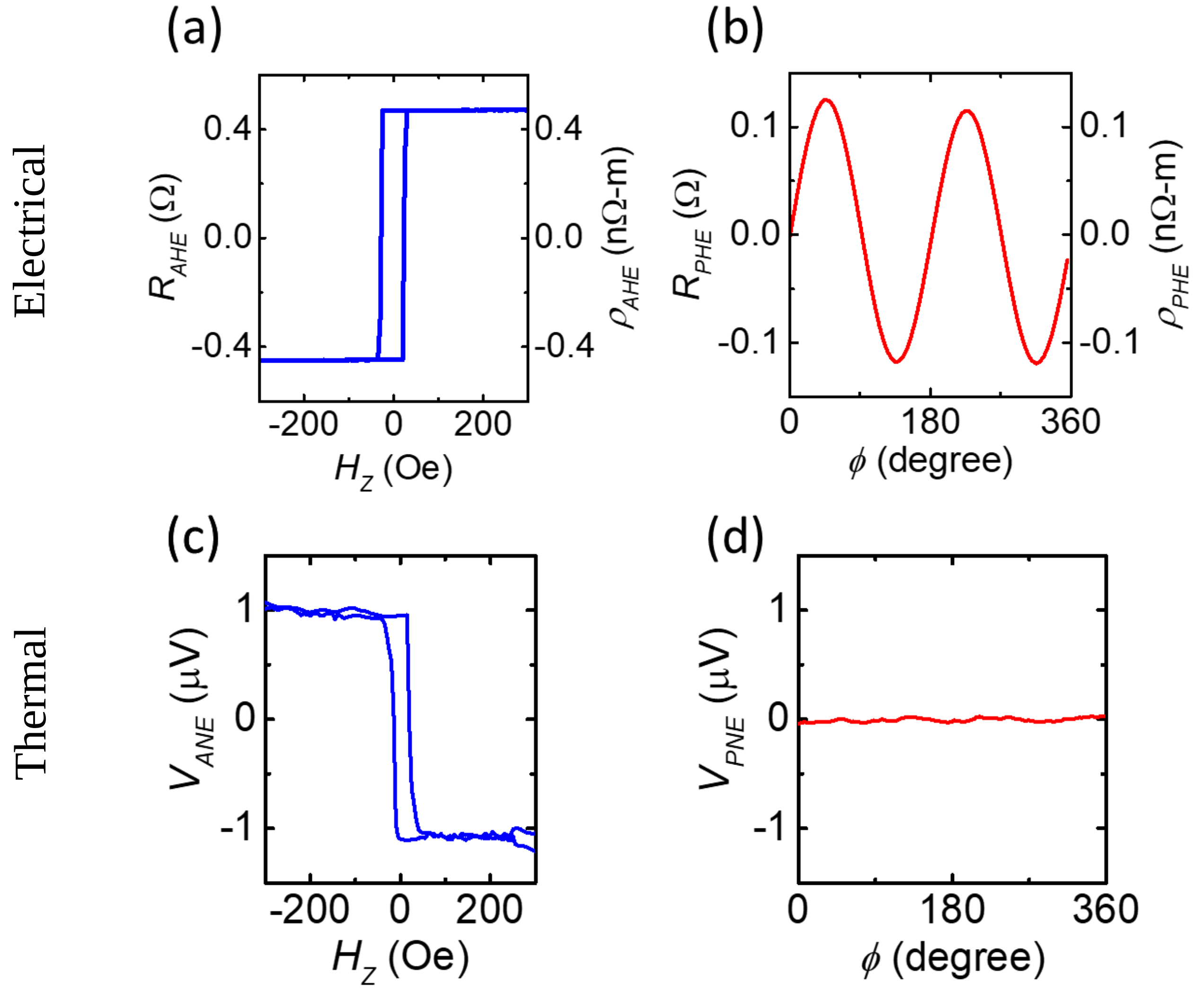
$$\rho_{xy}^{AH} = \lambda M_Z \rho_{xx}^{n} \qquad \rho_{xy}^{PHE} = \gamma M_x M_y \rho_{xx}^{m}$$

$$S_{yx}^{AHE} = \frac{\rho_{xy}^{AHE}}{\rho_{xx}}\left(T\frac{\pi^2 k_B^2}{3e}\frac{\lambda'}{\lambda} - (n-1)S_{xx}\right)$$

$$S_{yx}^{PHE} = \frac{\rho_{xy}^{PHE}}{\rho_{xx}}\left(T\frac{\pi^2 k_B^2}{3e}\frac{\gamma'}{\gamma} - (m-1)S_{xx}\right)$$

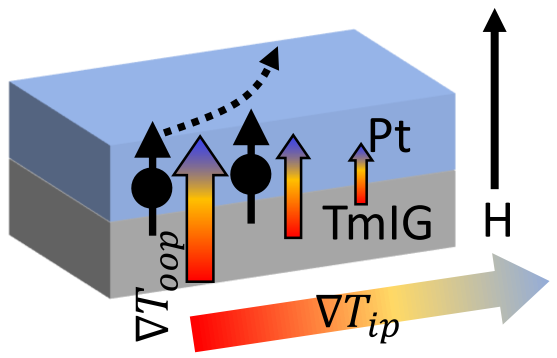
$$\frac{\rho_{AHE}}{\rho_{PHE}} \neq \frac{S_{yx}^{AHE}}{S_{yx}^{PHE}} \rightarrow \eta \neq 1$$

$\eta \neq 1$ for Ti/$Fe_{60}Co_{20}B_{20}$(1)/MgO/Ta (PMA)

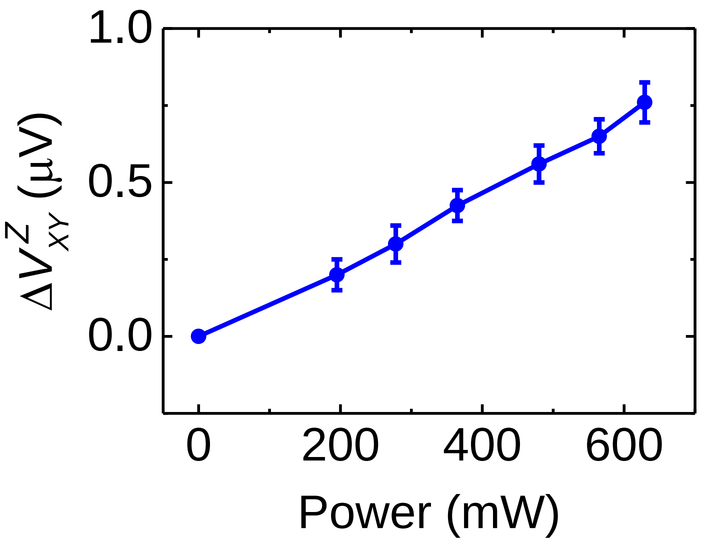


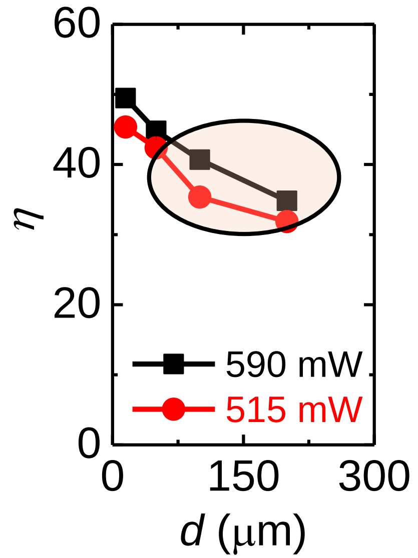
Role of thermal spin drag

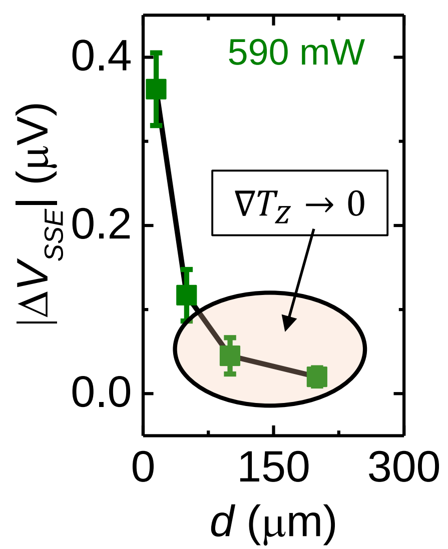
Thermal spin drag (TSD)
[C. Avci et. al. PRL, 124, 027701 (2020)→η~10 – 15]



$V_{xy}^{z,drag} \rightarrow \nabla T_{ip} \nabla T_{oop} \rightarrow P_{heater}^2$



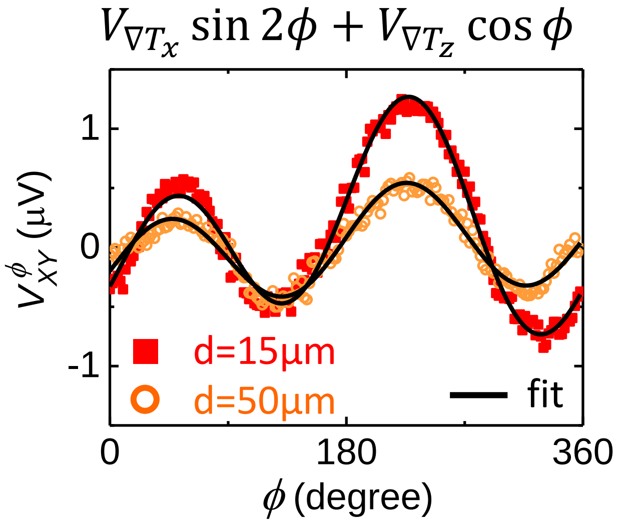




Negligible effect from thermal spin drag

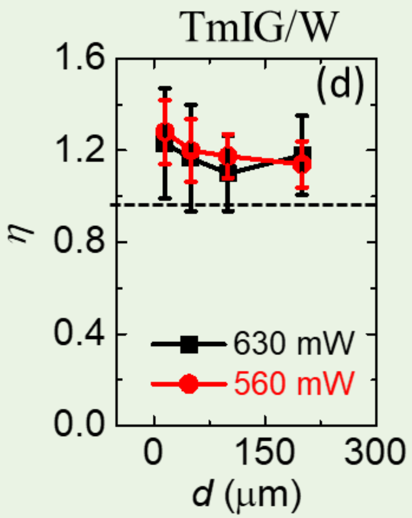
(1) In our exp. $\Delta V_{xy}^{z} \propto P_{power}$

(2) For d>100, ∇T_Z (hence ∇V_{SSE})→0
But still $\eta \gg 1$ (> 30)!

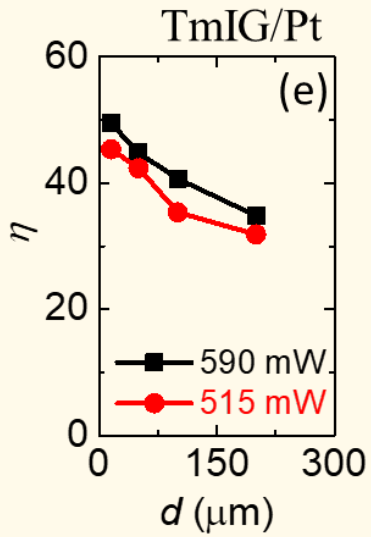


Summary

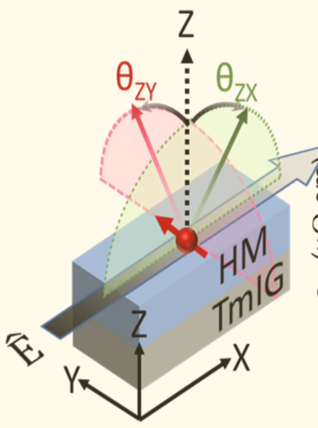
(1) TIG/W → SHE and SNE since $\eta \approx 1$

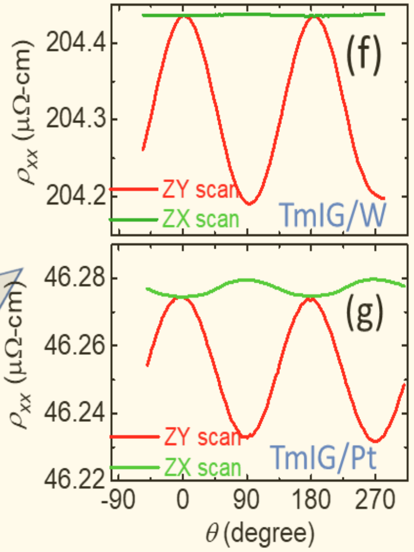


*(2) TIG/Pt → SHE+SNE+**MPE** as $\eta \gg 1$*

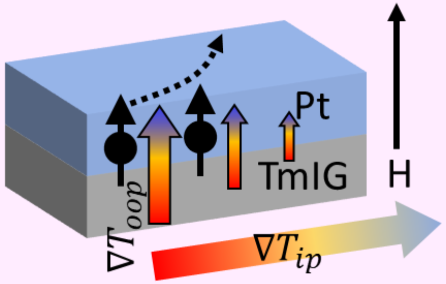


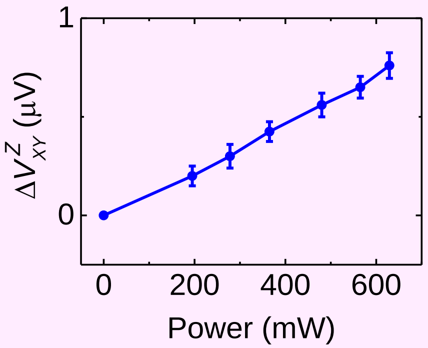
SMR ($\angle(\sigma, M)$)
AMR ($\angle(I_C, M)$)

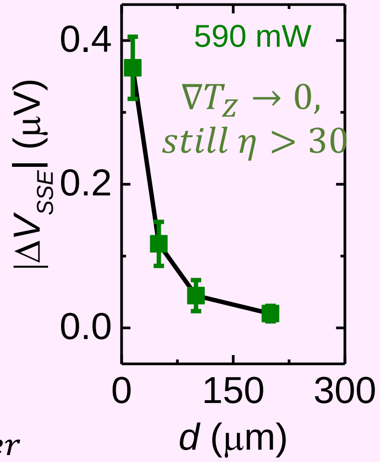




(3) TSD is negligible for TIG/Pt





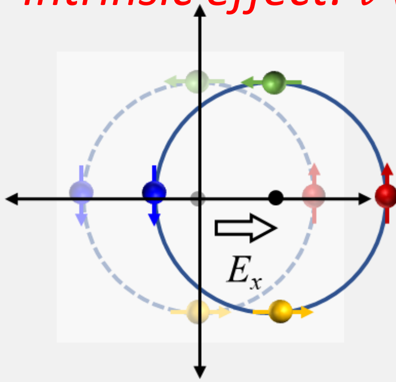


For TSD: $V_{xy}^{z,drag} \to P_{heater}^2$

In our exp. $V_{xy}^{z} \propto P_{power}$

(4) For TIG/W: $\theta_{SN}/\theta_{SH} = -2.2 \pm 0.6$

Intrinsic effect: $\vec{v}\left(\vec{k}, \vec{\sigma}\right) = e\vec{E} \times \vec{\Omega}\left(\vec{k}, \vec{\sigma}\right)$



$$J_{z,x}^{s} = \sigma_{z,x}^{s} E_x$$

$$E_x = S\nabla T$$

$$E_x = J_C/\sigma_x$$

arXiv:2210.05636 (Bi_2Se_3)

Acknowledgement

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Cornell, Material Science (RuO_2, IrO_2)

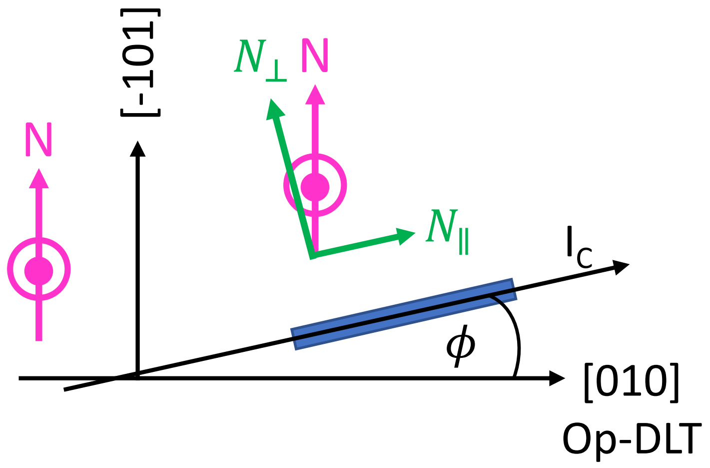
D.-F. Shao, E. Tsymbal, University of
Nebraska–Lincoln (DFT in RuO_2)

X. Zhang, D. Muller, **Cornell** AEP (STEM)

J. Bauer, C. Ross, Material Sci. **MIT** (TmIG)

R. Jain, D. C. Ralph and R. A. Buhrman
Cornell APE, Physics

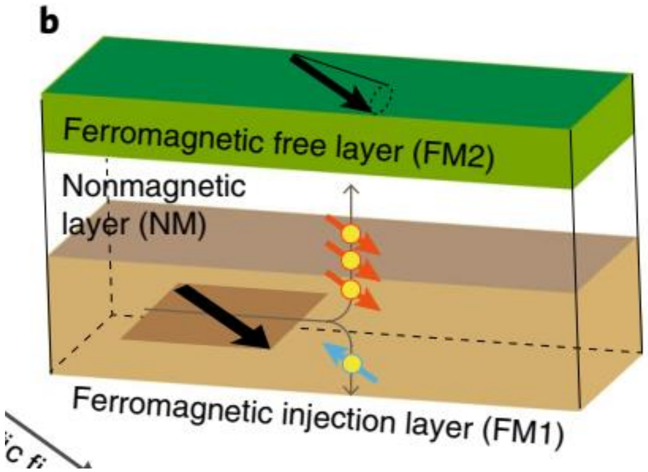
Complete probable angular of spin-torques in (101) plane



Spin-flow direction: $N \times J_C = (N_y\hat{y} + N_z\hat{z}) \times (\cos\phi\,\hat{x} + \cos\phi\,\hat{y})J_C \propto \hat{z}\cos\phi$

Spin vector: $N \times J_C = N_\parallel \sin\phi\,\widehat{\phi_\parallel} + N_\perp \cos\phi\,\widehat{\phi_\perp} + N_z\hat{z}$

Angular dependence of imparted torque:
Angular dependence of spin current x angular dependence of spin flow direction



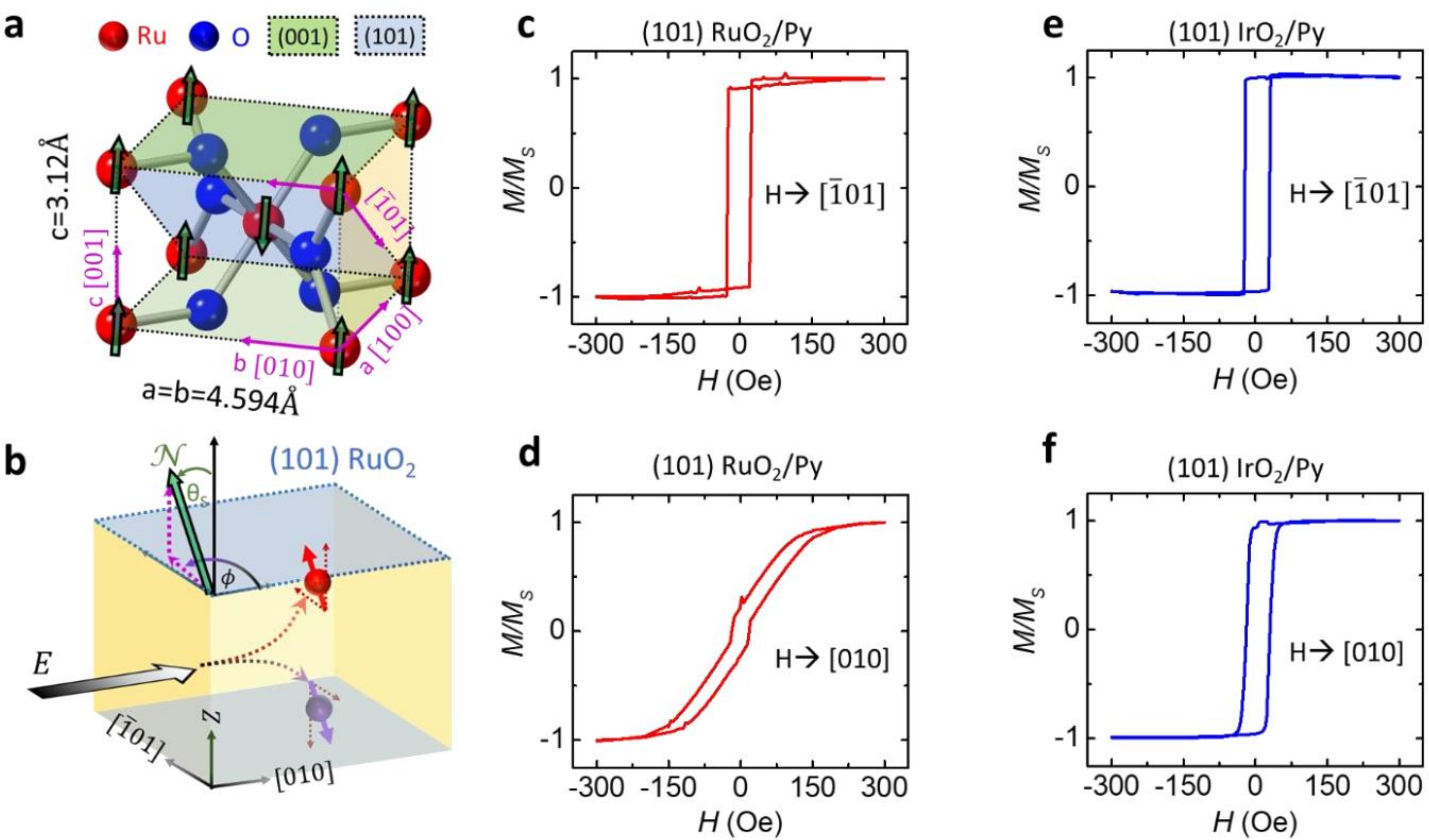
In-plane damping-like torque from m-SHE $\propto \cos^2\phi$

In-plane Dresselhaus-like torque from m-SHE $\propto \sin\phi\cos\phi$

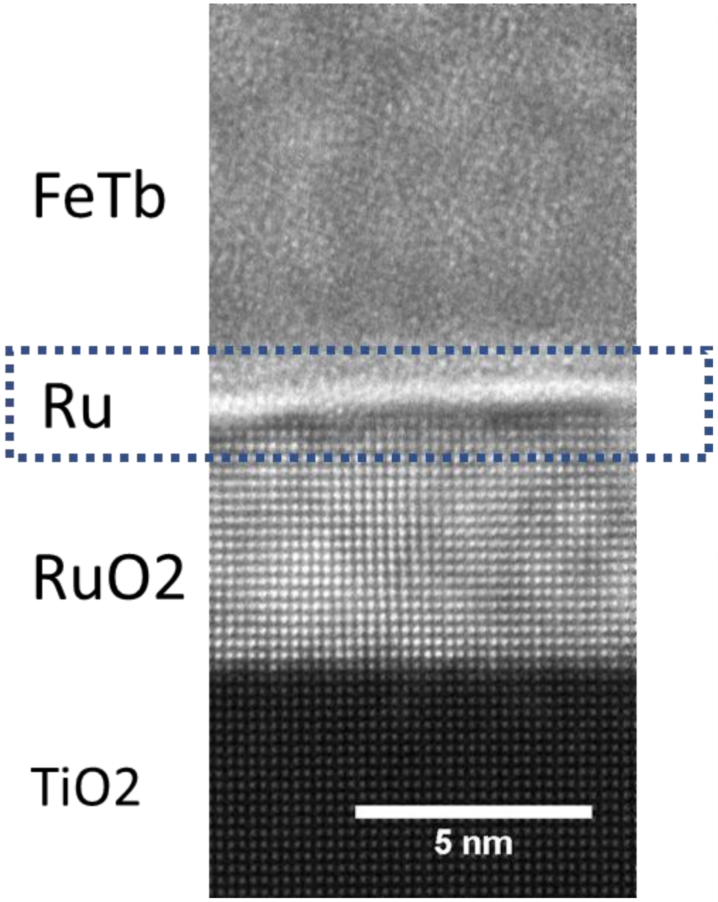
Out-of-plane damping-like torque from m-SHE $\propto \cos\phi$

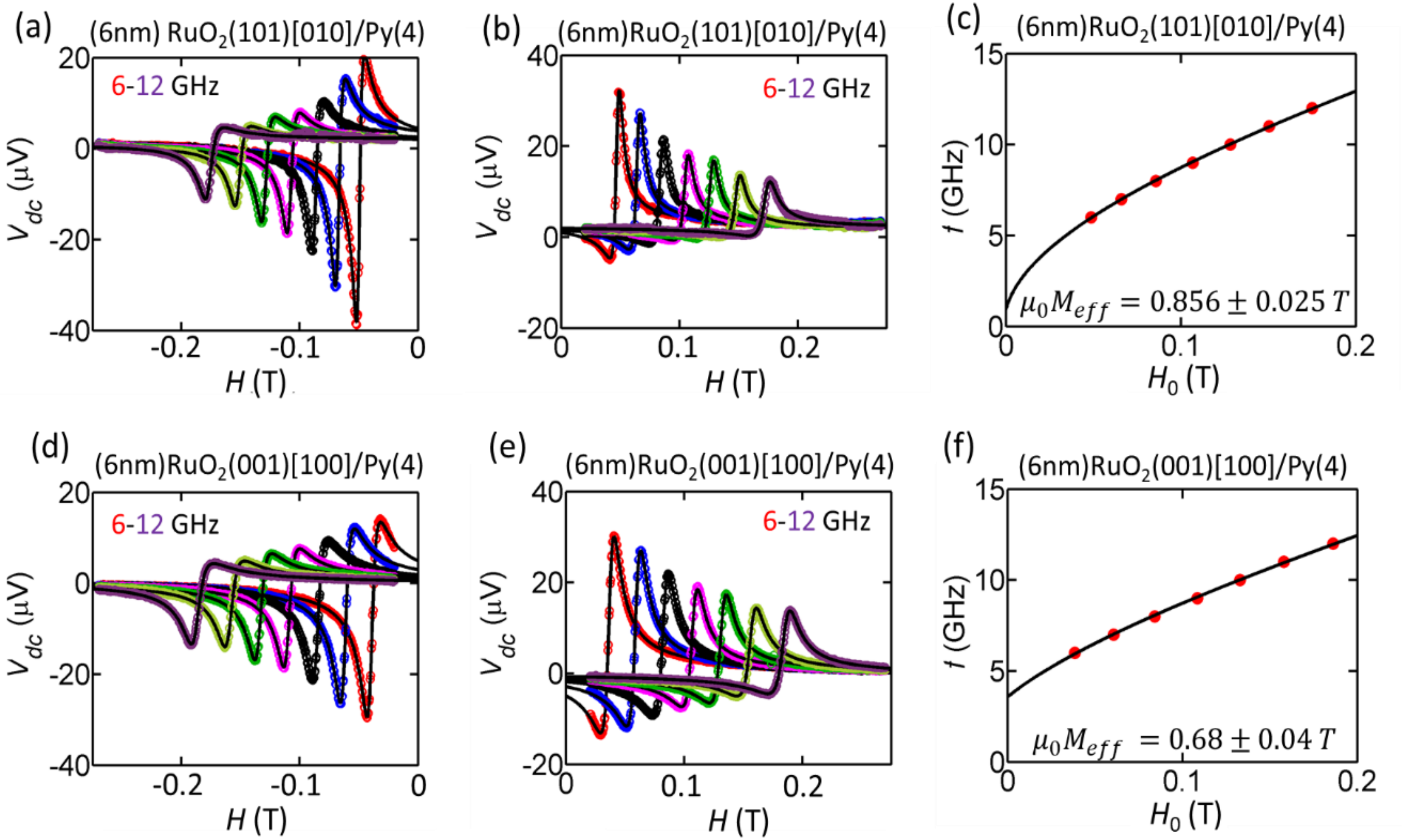
Satoshi Iihama et. al. Nature Electronics 1, 120 (2021)

Taniguchi, T., Grollier, J. & Stiles, M. D. *Phys. Rev. Applied* **3**, 044001 (2015)



a
Ru
O
(001)
(101)
c=3.12Å
c [001]
b [010]
a [100]
[$\bar{1}$01]
a=b=4.594Å
b
(101) RuO$_2$
$\mathcal{N}$
θ$_S$
ϕ
E
Z
[$\bar{1}$01]
[010]
c
(101) RuO$_2$/Py
H→ [$\bar{1}$01]
d
(101) RuO$_2$/Py
H→ [010]
e
(101) IrO$_2$/Py
H→ [$\bar{1}$01]
f
(101) IrO$_2$/Py
H→ [010]
M/M_S
H (Oe)


FeTb
Ru
RuO2
TiO2
5 nm


(a)
(6nm) RuO2(101)[010]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(b)
(6nm)RuO2(101)[010]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(c)
(6nm)RuO2(101)[010]/Py(4)
f (GHz)
H0 (T)
μ0Meff = 0.856 ± 0.025 T
(d)
(6nm)RuO2(001)[100]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(e)
(6nm)RuO2(001)[100]/Py(4)
6-12 GHz
Vdc (μV)
H (T)
(f)
(6nm)RuO2(001)[100]/Py(4)
f (GHz)
H0 (T)
μ0Meff = 0.68 ± 0.04 T