



# The magnon creation-annihilation magnetoresistances, a new set of magnetoresistance to study the current-induced changes of the magnon population

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# Experiments performed at the magnetism and interface physics group (Pr. Pietro Gambardella)

Emir Karadža

Dr. Richard Schlitz



Swiss National Science foundation  
ETH Zürich postdoctoral fellowship



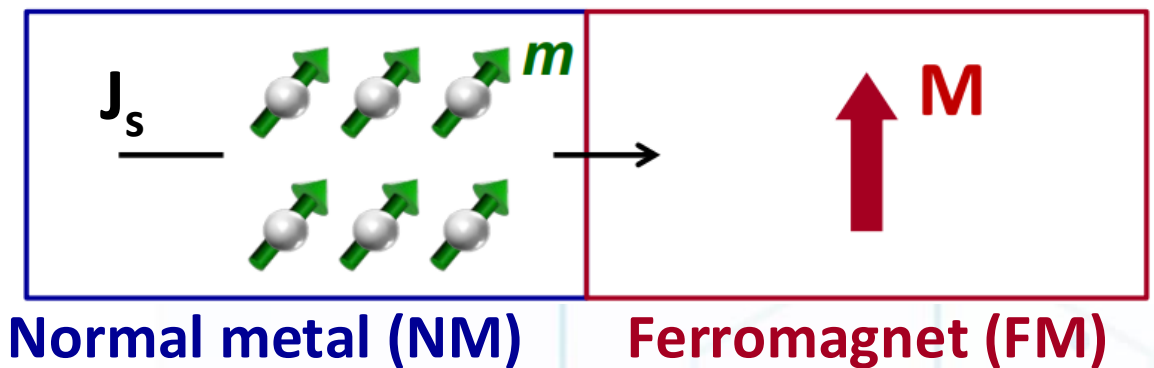
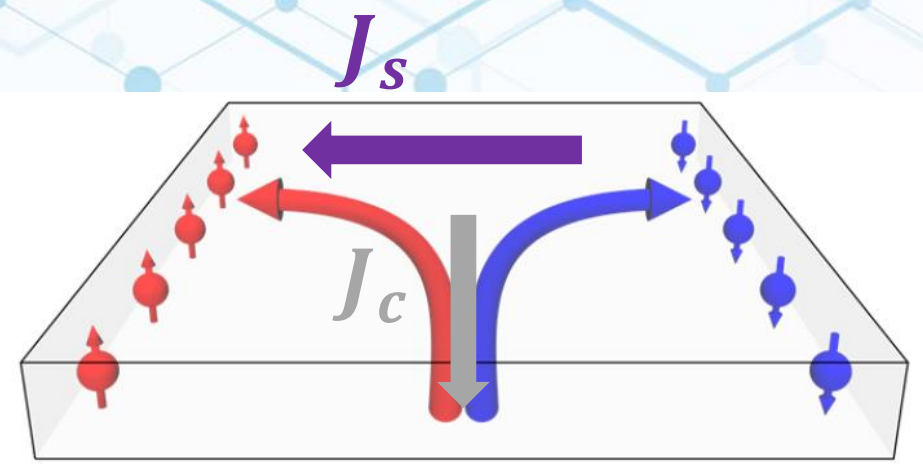
**ETH** zürich

**DMATL**

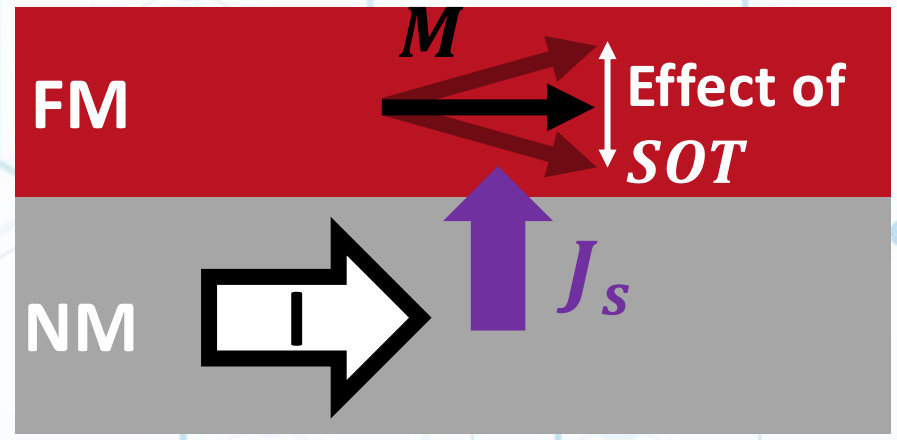
# The spin-(orbit) torques (SOT)

- An injected spin current  $J_s$  is like an entering magnetization  $m$
- Spin torque acting on the magnetization  $M$  of the ferromagnetic material via SHE

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



Tutorial spin orbit torque, P. Gambardella



- Possibility to manipulate the magnetic state with electrical current: **SOT to tune the magnetic state**

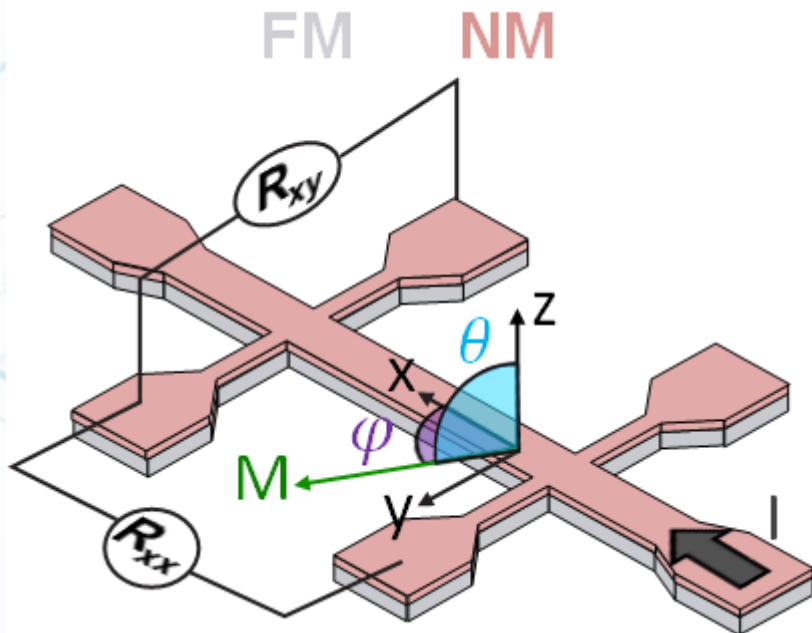
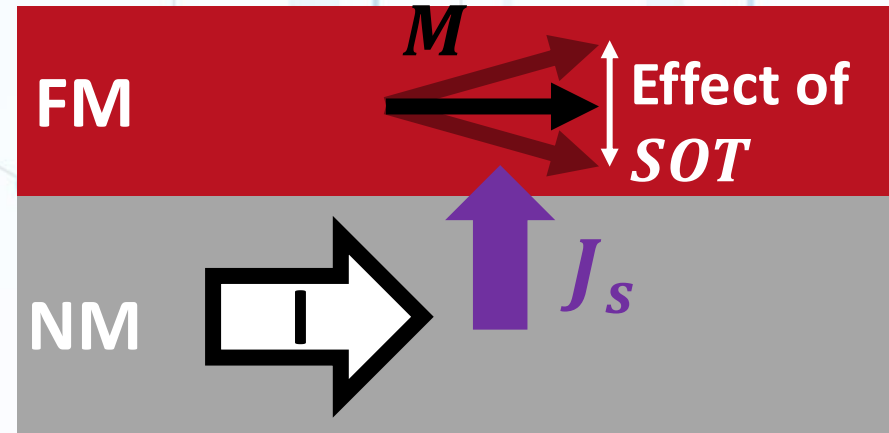
# How to measure the SOT?

Measure the change of the magnetoresistance associated with the change of the magnetization direction:

$$R = f(M)$$

$$M = f(I)$$

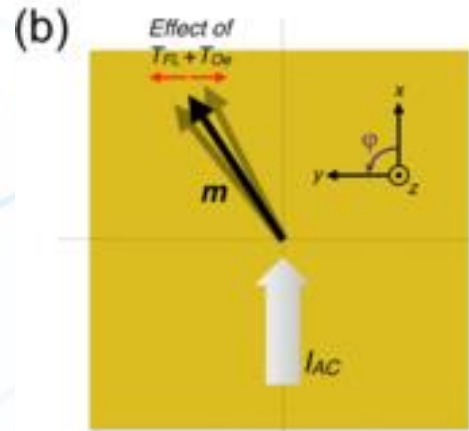
$$V = f(I^2)$$



Using AC current and lock-in detection to detect and measure the second harmonic Hall voltage/resistance in (double) Hall bar devices

# The (second) harmonic Hall technique

Many described the Harmonic Hall techniques (in 2013-2015) in different configurations, I will focus on in plane magnetized samples described by Avci et al. in 2014:



## Field like torque (FL):

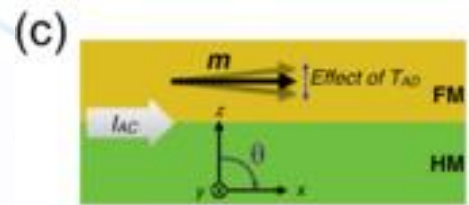
Oscillation of the magnetization in the plane, change of the planar Hall effect

$$1) R_{FL,xy}^{2\omega} = \frac{1}{2} \frac{R_{PHE}^{1\omega}}{\mu_0 H} B_{FL}$$

## Damping like torque (DL):

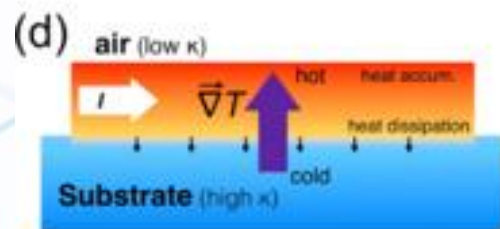
Oscillation of the magnetization out of the plane, change of the anomalous Hall effect

$$2) R_{DL,xy}^{2\omega} + R_{\nabla T,xy}^{2\omega} = \frac{R_{AHE}^{1\omega}}{\mu_0 H_{eff}} B_{DL} + R_{\nabla T,xy}^{2\omega}$$



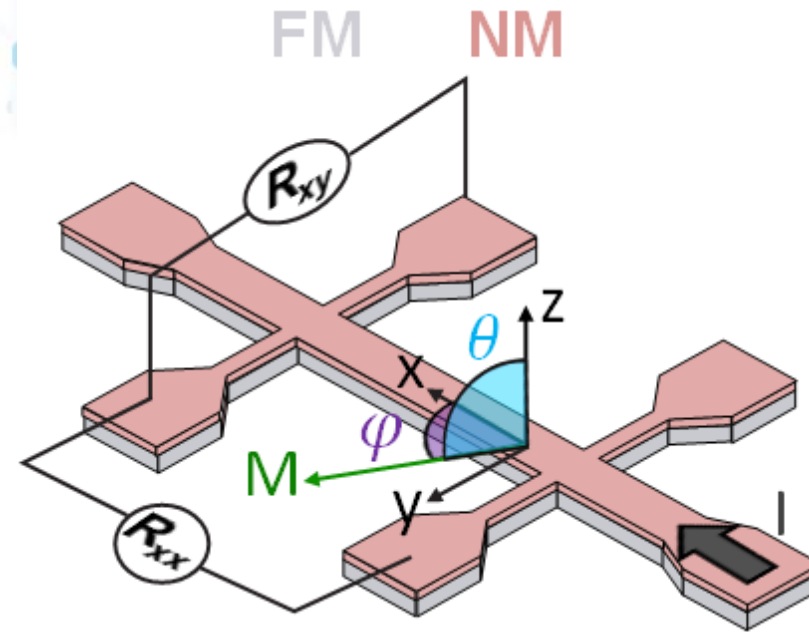
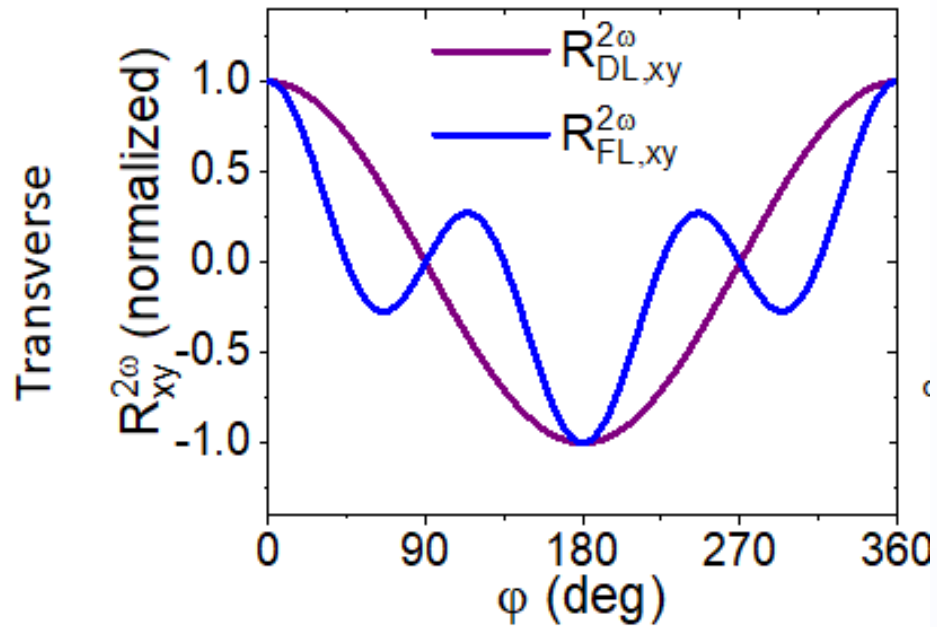
## Thermoelectric contributions ( $\nabla T$ ):

Associated with Joule heating, anomalous and ordinary Nernst effect, spin Seebeck effect



Avci, C. O. et al. *Phys. Rev. B* 90, 224427 (2014)

# The harmonic Hall measurement

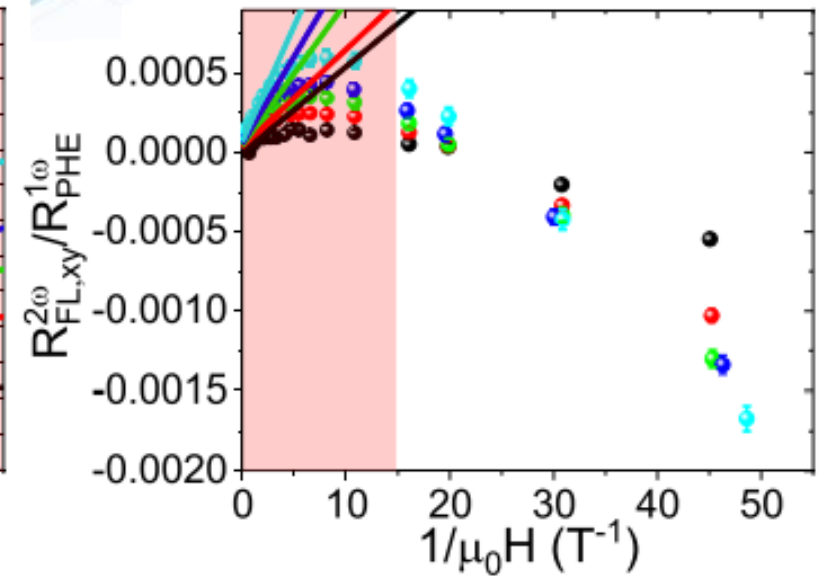
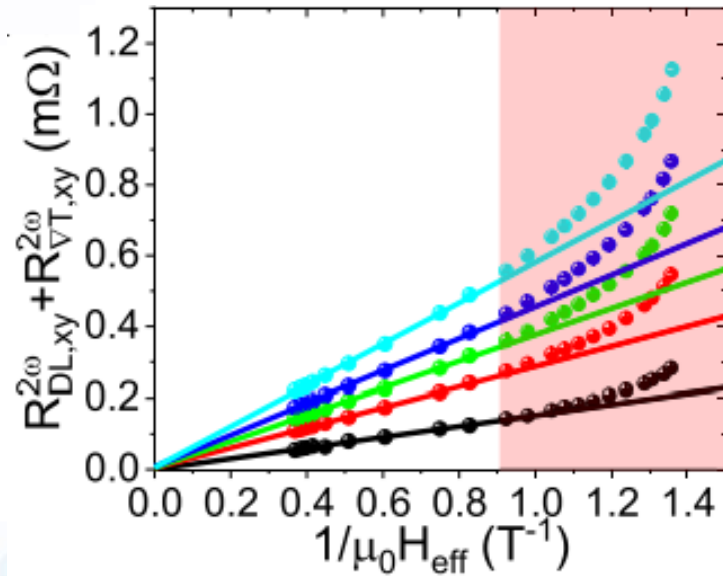
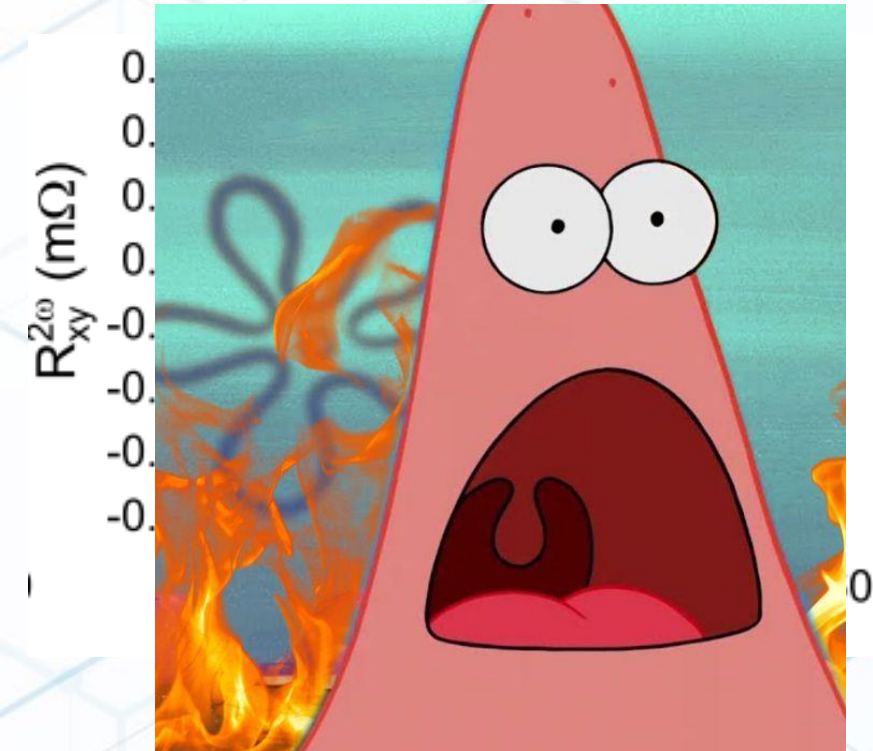


Performing angular dependent measurements at different fields to determine the torque efficiency

$$3) \quad R_{xy}^{2\omega} = \left( -R_{FL,xy}^{2\omega} + R_{\nabla T,xy}^{2\omega} - \frac{1}{2}R_{DL,xy}^{2\omega} \right) \cos \varphi + (2R_{FL,xy}^{2\omega}) \cos^3 \varphi,$$

# Is it describing well the experiments ?

We used a very studied system Pt(5 nm)/Co<sub>40</sub>Fe<sub>40</sub>B<sub>20</sub>(2.5 nm) in 10 μm Hall bars



What the heeeeeeeelllllll???



# Current-induced modification of the magnon density using the spin orbit torque at heavy metal/ferromagnet Interfaces

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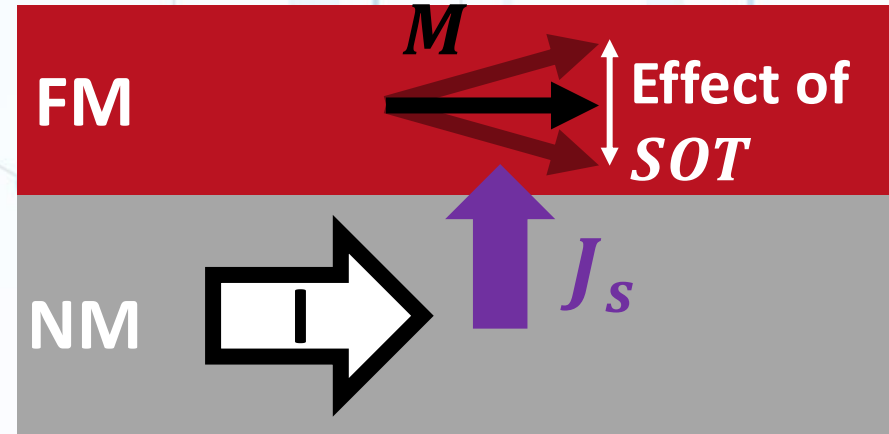
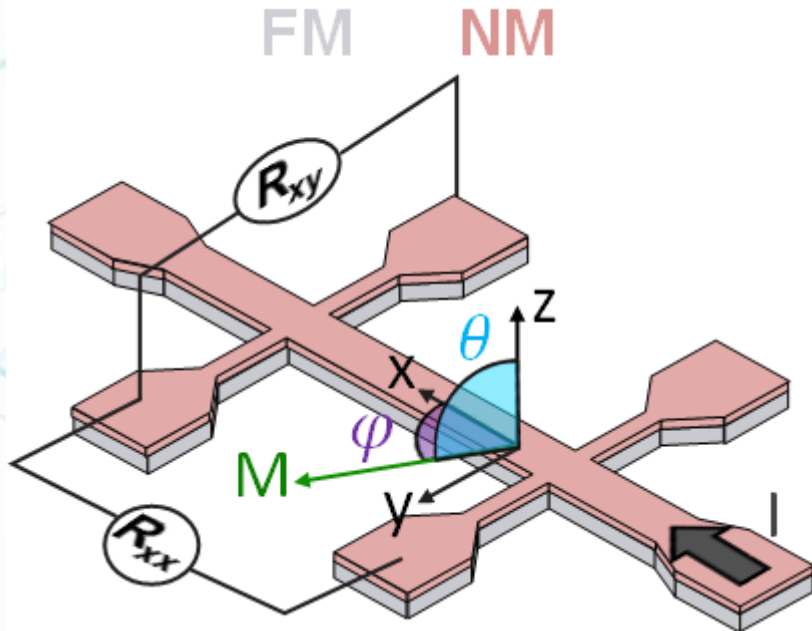
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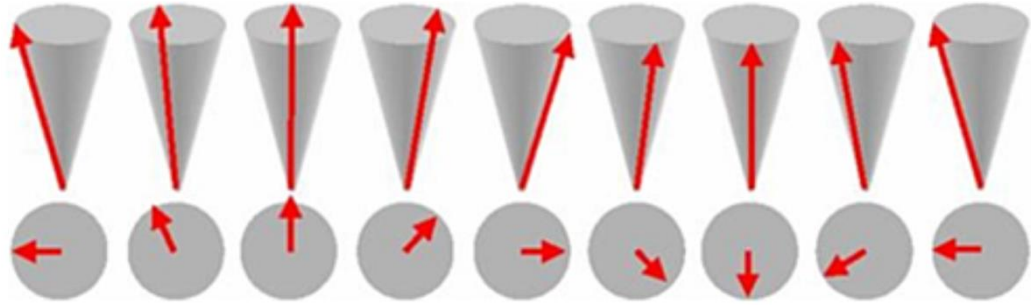
$$M = f(I)$$

$$V = f(I^2)$$



**A very strong assumption:** the magnetization is constant

# Modification of the magnon population with spin current



Uni Munster, Demokritov group webpage

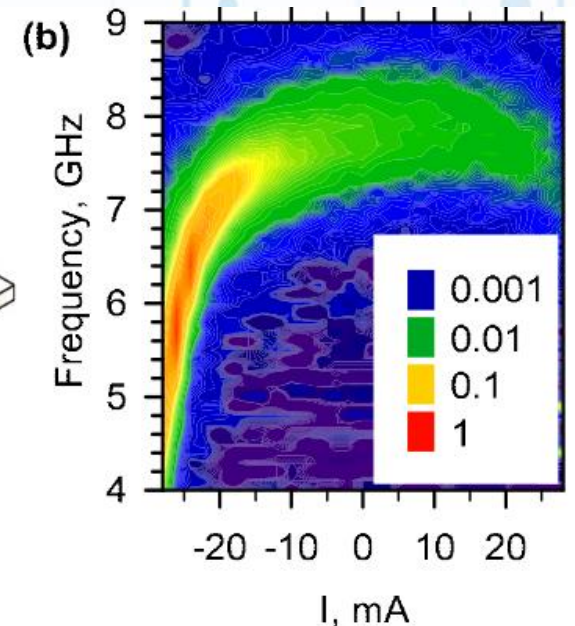
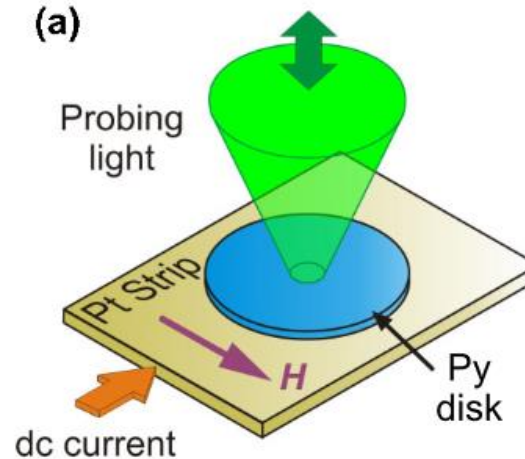
$$\mathbf{T} = J_{sd} \hat{\mathbf{M}} \times \hat{\mathbf{m}}$$

Possibility to control the magnons with spin current in ferromagnet/heavy metal bilayers.

Possibility to tune the damping with spin current

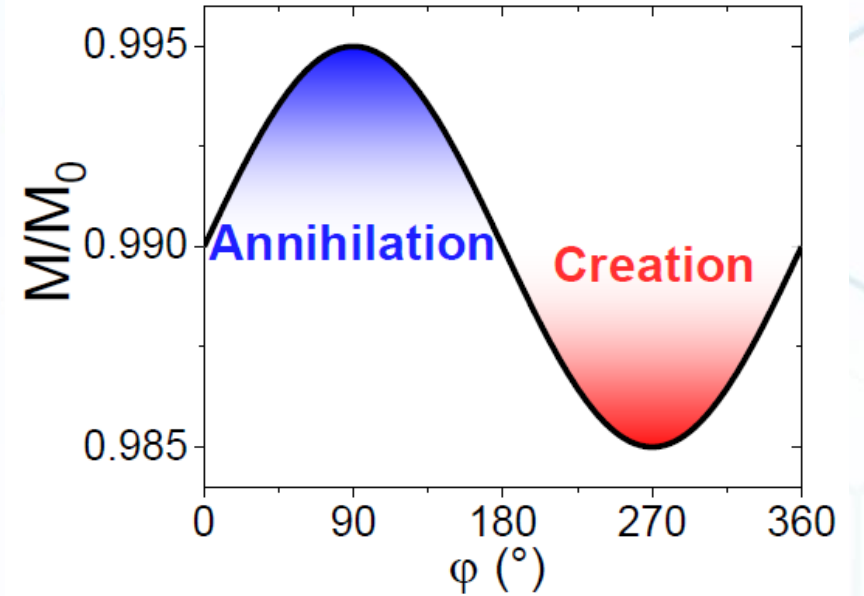
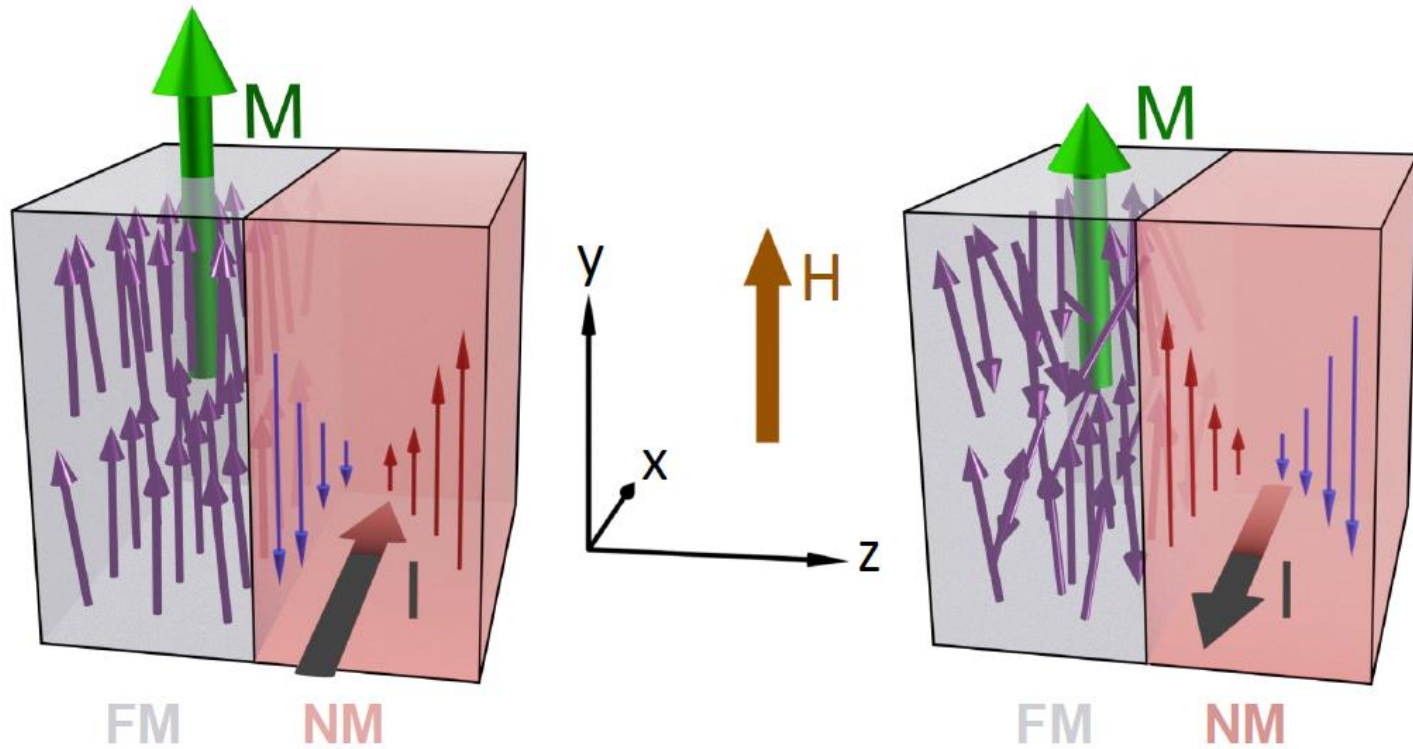
At non-zero temperature spin deviates randomly from alignment reducing the total magnetization:

magnons/spin waves



Demidov, V. E. *et al. Phys. Rev. Lett.* 107, 107204 (2011)

# Magnon creation-annihilation



Noël, P. *et al. Phys. Rev. Lett.* **134**, 146701 (2025)

**Magnetization vector is not only changing direction it is also changing length!**

# Contributions due to magnon creation-annihilation

$$M(I) = M_s + \Delta M(I) \sin \varphi.$$

All magnetization dependent magnetoresistances have a current nonlinear contribution

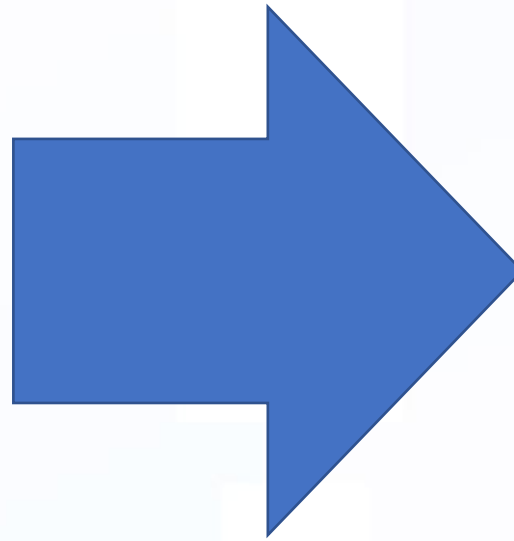
$$R_{PHE} \propto M_x M_y$$

$$R_{AHE} \propto M_z$$

$$R_{AMR} \propto M_x^2$$

$$R_{SMR} \propto -M_y^2$$

$$R_{MMR} \propto M_0 - M_s$$



$$R_{PHE}^{2\omega} = 2R_{PHE}^{1\omega} \frac{\Delta M(I)}{M_s} \sin^2 \varphi \cos \varphi,$$

$$R_{AHE}^{2\omega} = R_{AHE}^{1\omega} \frac{\Delta M(I)}{M_s} \sin \varphi \cos \theta,$$

$$R_{AMR}^{2\omega} = 2R_{AMR}^{1\omega} \frac{\Delta M(I)}{M_s} \sin \varphi \cos^2 \varphi,$$

$$R_{SMR}^{2\omega} = -2R_{SMR}^{1\omega} \frac{\Delta M(I)}{M_s} \sin^3 \varphi,$$

$$R_{MMR}^{2\omega} \propto \Delta M(I) \sin \varphi.$$

We call these current nonlinear magnetoresistive effects magnon creation annihilation magnetoresistances  $m^\dagger m$ MRs

# Evidence the $m^+m$ MRs in $Y_3Fe_5O_{12}/Pt$

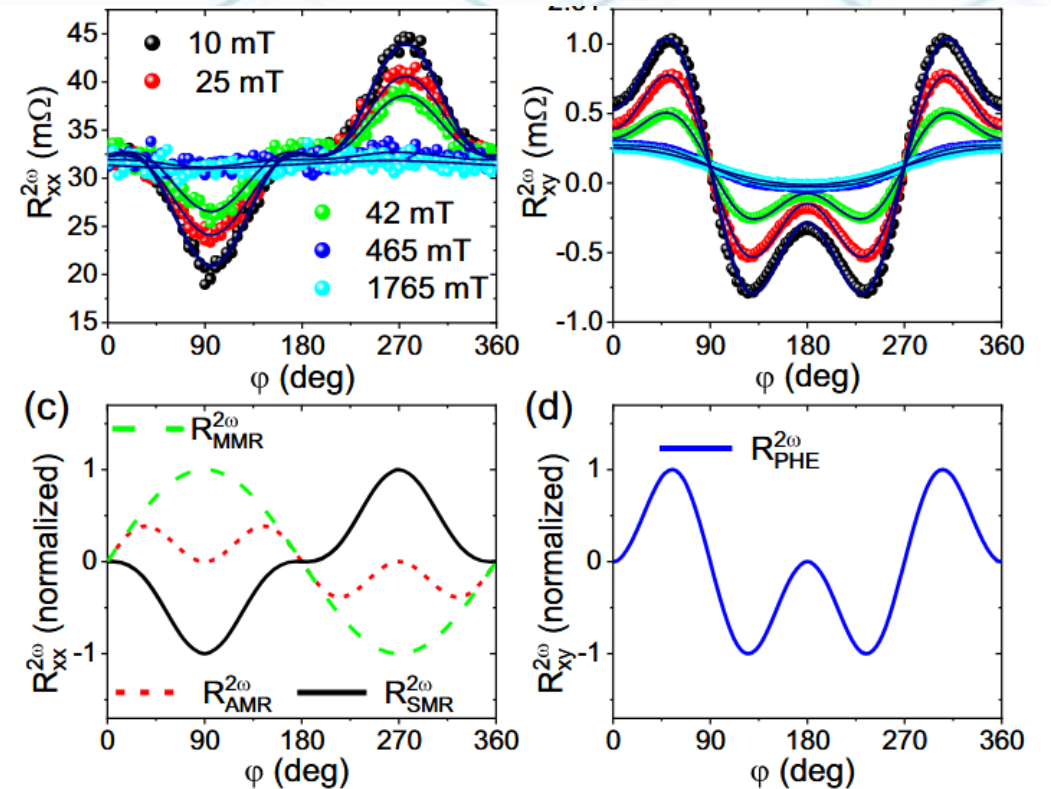
**YIG/Pt is known for the strong change of magnon population at a relatively small current density**

Ultra-thin YIG deposited by PLD (group of Pr. Morgan Trassin)  
**YIG (6.2 nm) / Pt (3 nm), 10  $\mu$ m wide Hall bar**

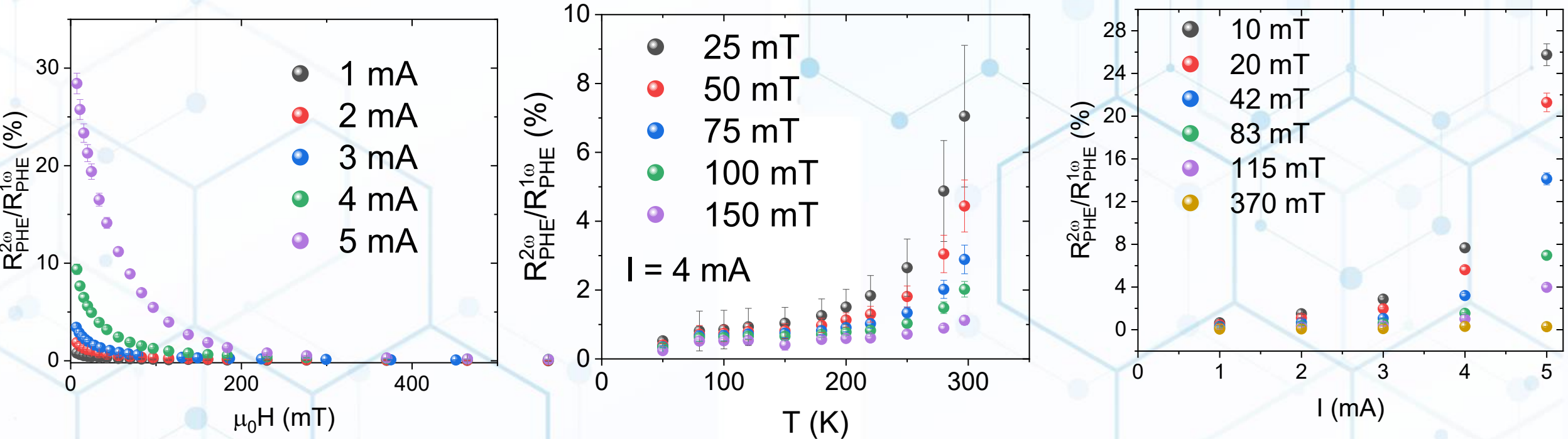
**As YIG is insulating it has no AMR, no MMR and small AHE: magnonic contributions dominates**

$$R_{SMR}^{2\omega} = -2R_{SMR}^{1\omega} \frac{\Delta M(I)}{M_s} \sin^3 \varphi,$$

$$R_{PHE}^{2\omega} = 2R_{PHE}^{1\omega} \frac{\Delta M(I)}{M_s} \sin^2 \varphi \cos \varphi,$$



# Evidence of the magnonic nature of the $m^+$ mMR



## Typical signatures of magnonic effects

- Suppressed with increasing external magnetic field (subthermal magnons)
  - Suppressed at low temperature
- Nonlinear regime at high current densities (damping compensation)

Noël, P. *et al.* *Phys. Rev. Lett.* **134**, 146701 (2025)

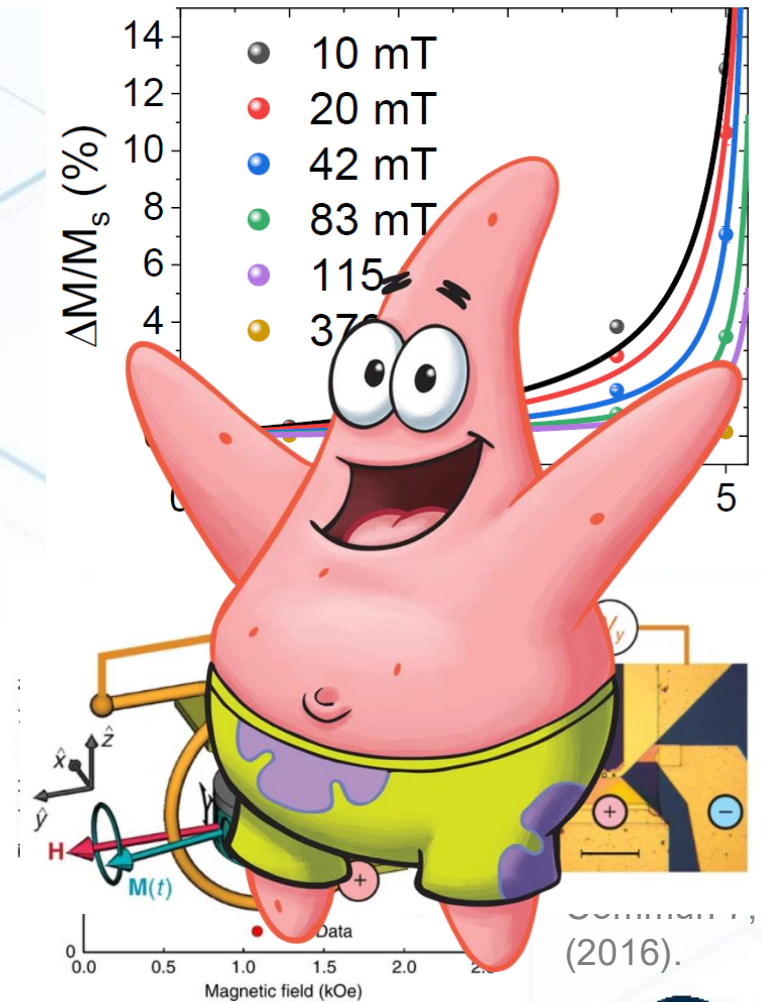
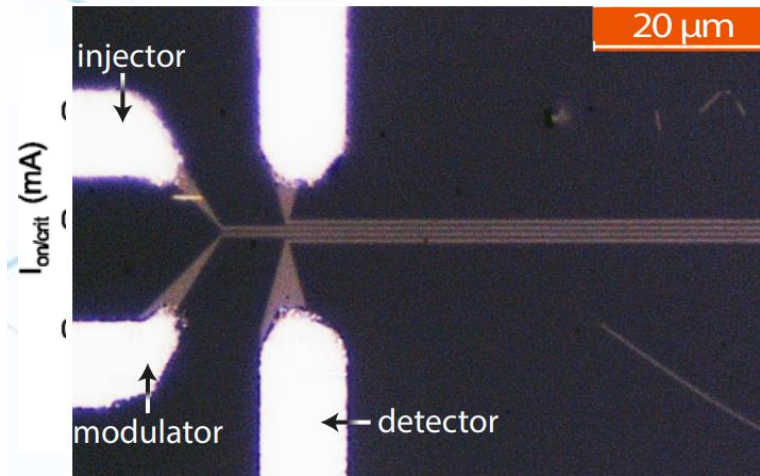
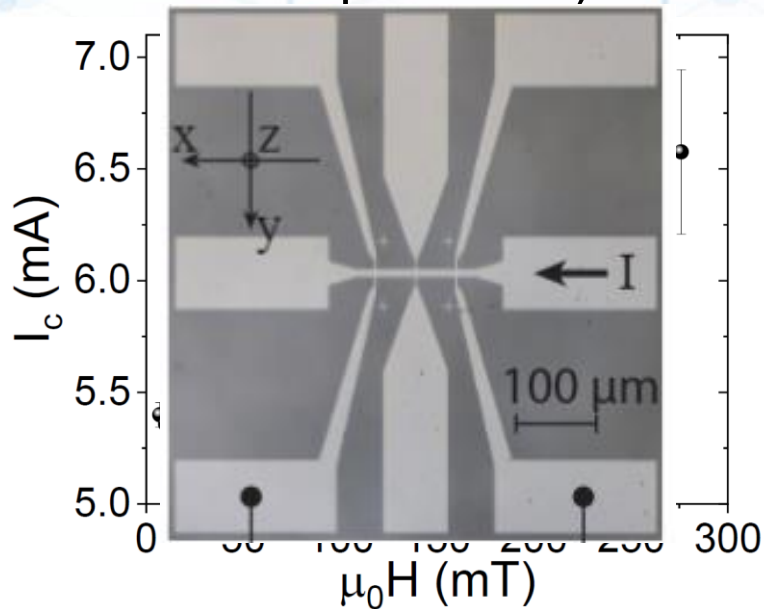
# A simple probe of damping compensation

Magnetization change :

$$\frac{\Delta M(I)}{M_s} = \frac{R_{\text{PHE}}^{2w}}{2R_{\text{PHE}}^{1w}} = \frac{R_{\text{SMR}}^{2w}}{2R_{\text{SMR}}^{1w}}$$

Critical current (damping compensation):

$$\frac{\Delta M(I)}{M_s} \propto \frac{I/I_c}{1 - (I/I_c)^2}$$



Noël, P. et al. *Phys. Rev. Lett.* **134**, 146701 (2025)

*Phys. Rev. Lett.* **123**, 257201 (2019)

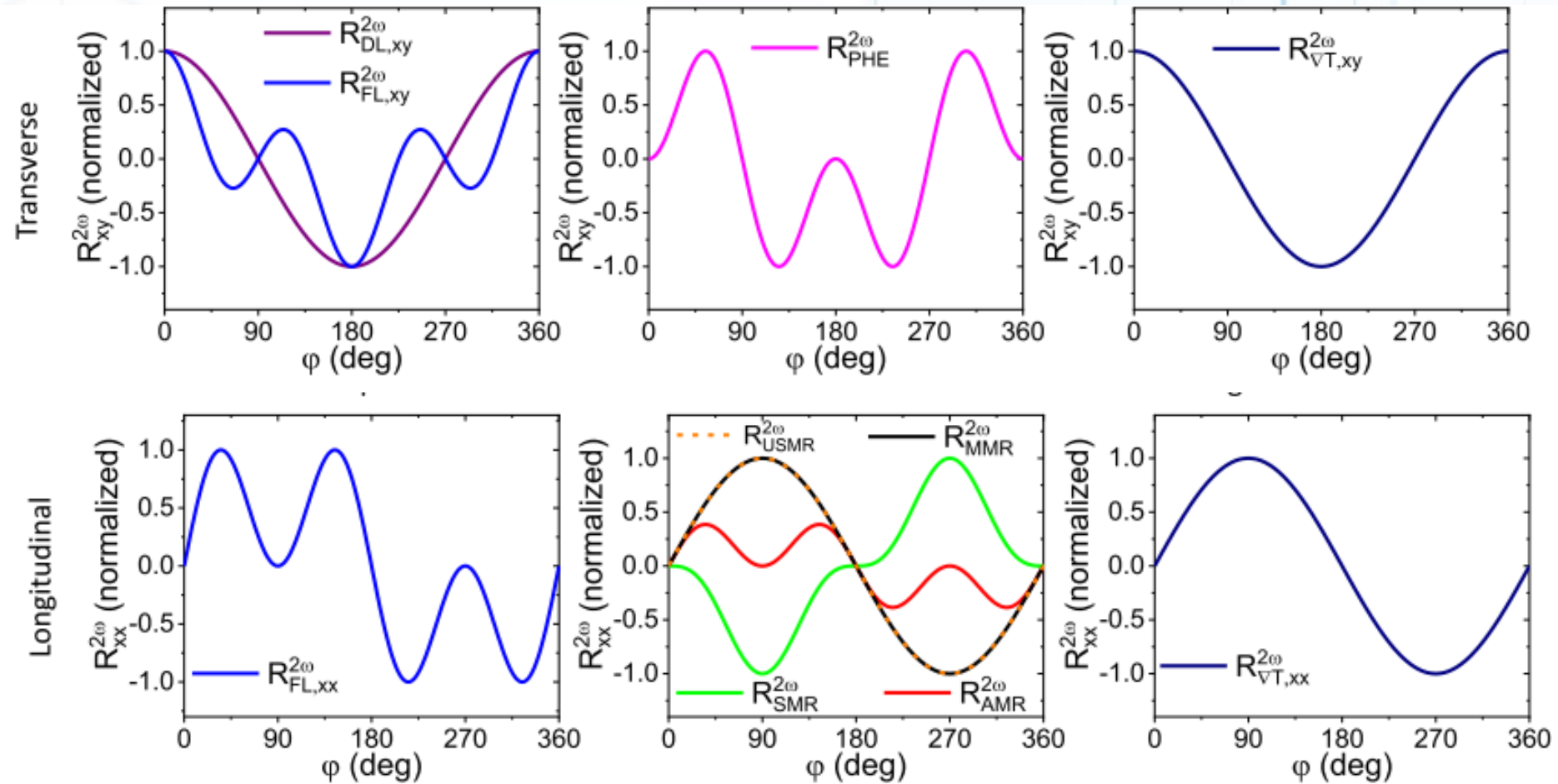
*Science*, **351**, 10377 (2016).

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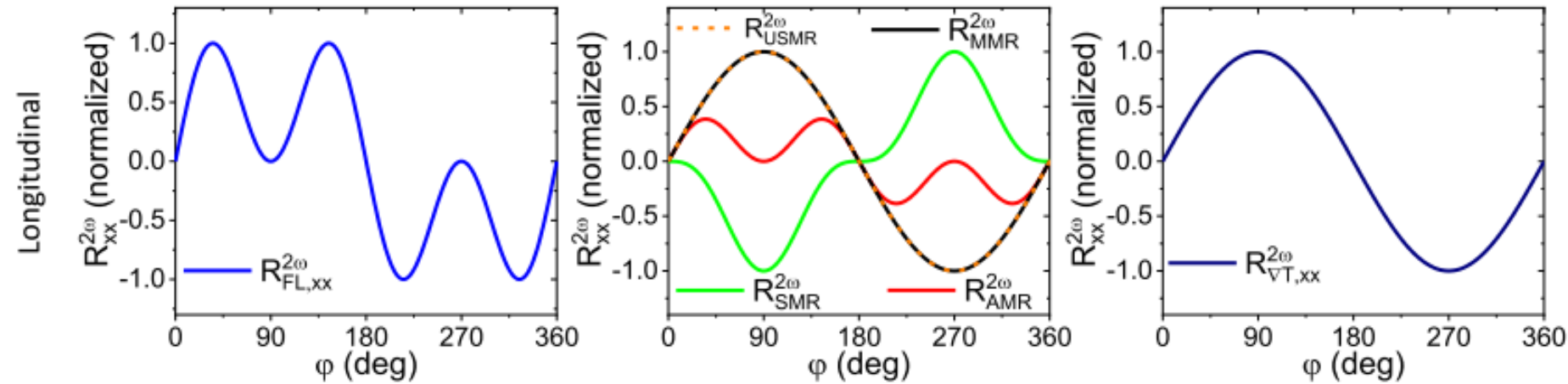
# Why didn't we notice this earlier?



**The  $m^{\dagger}mMR$  cannot be distinguished from torque contributions purely based on the angular dependence.**

# Let's use the field dependence then

$$R_{xx}^{2\omega} = R_{\sin}^{2\omega} \sin \varphi + R_{\sin^3}^{2\omega} \sin^3 \varphi$$



$$R_{\text{magnon}} = R_{\sin}^{2\omega} + R_{\sin^3}^{2\omega} = \underbrace{R_{USMR}^{2\omega} + R_{VT,xx}^{2\omega}}_{\text{Field independent}} + \underbrace{R_{MMR}^{2\omega} + R_{SMR}^{2\omega}}_{\text{Magnonic contribution}}$$

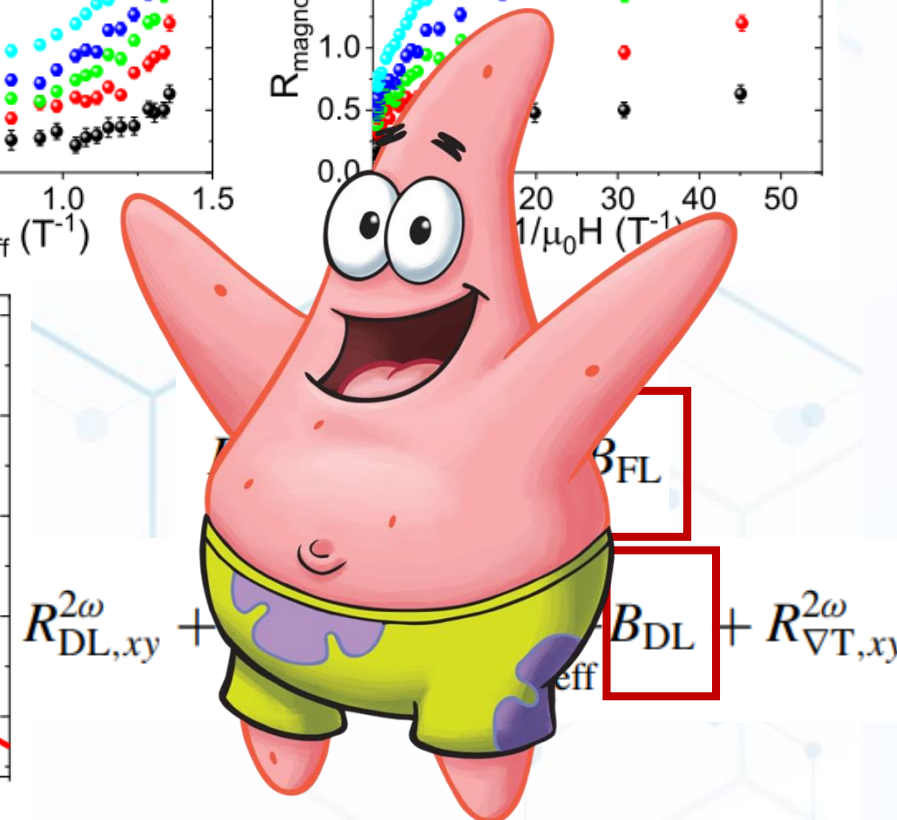
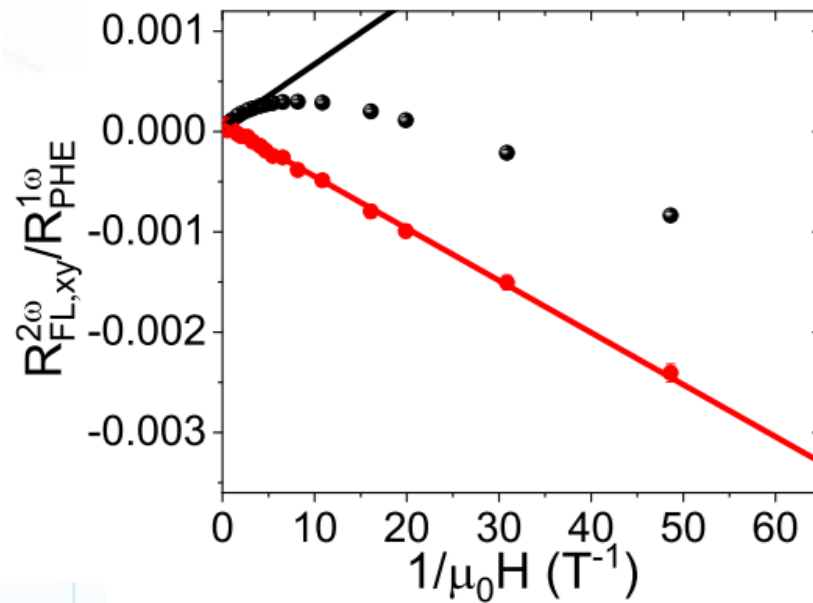
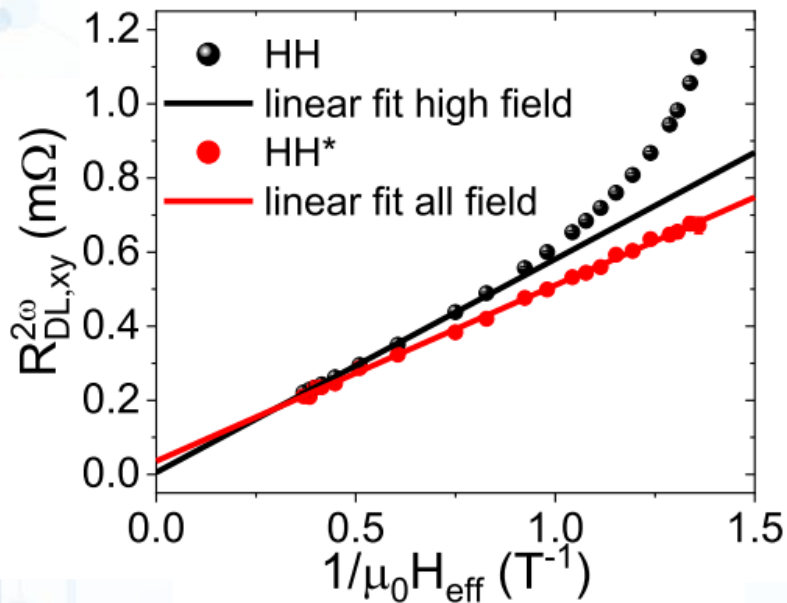
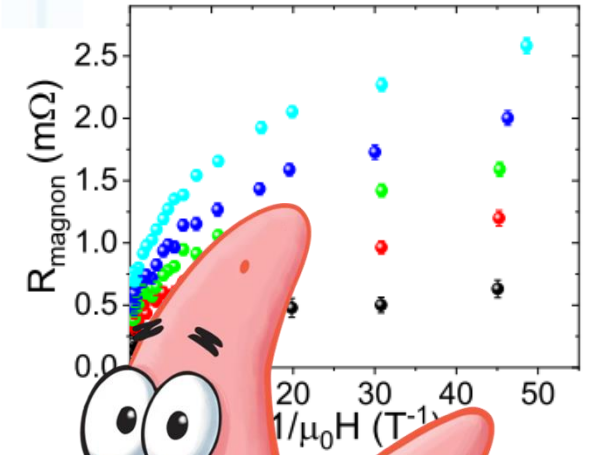
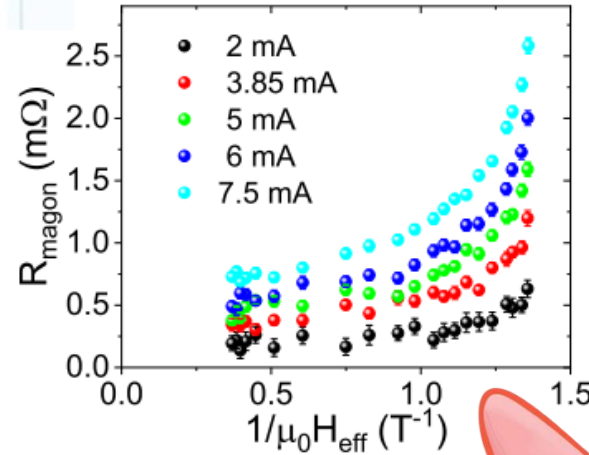
**With longitudinal second harmonic measurements it is possible to obtain the field dependence of the magnonic contribution**

# Can we measure SOT properly?

$$R_{DLcorr,xy}^{2\omega} = R_{DL,xy}^{2\omega} - C_{mag}(R_{magnon} - R_{off}),$$

$$R_{FLcorr,xy}^{2\omega} = R_{FL,xy}^{2\omega} - \frac{C_{mag}}{2}(R_{magnon} - R_{off}),$$

Pt(5 nm)/Co<sub>40</sub>Fe<sub>40</sub>B<sub>20</sub>(2.5 nm)



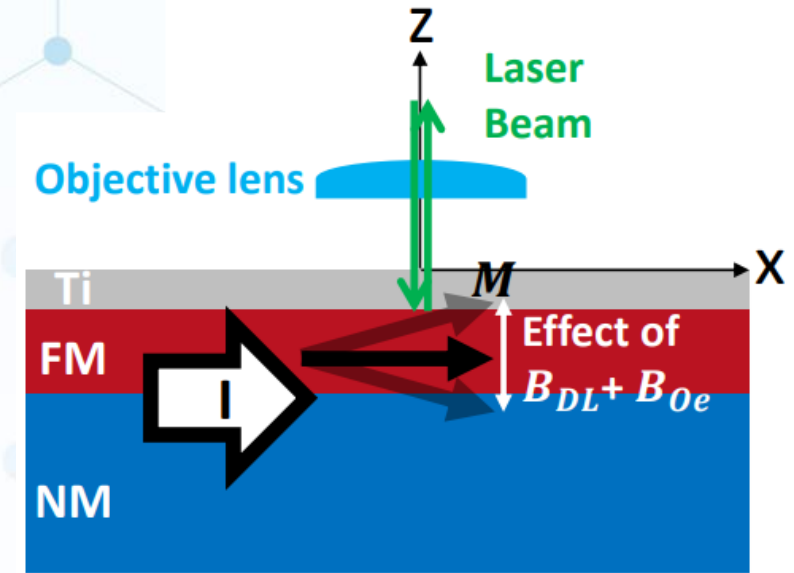
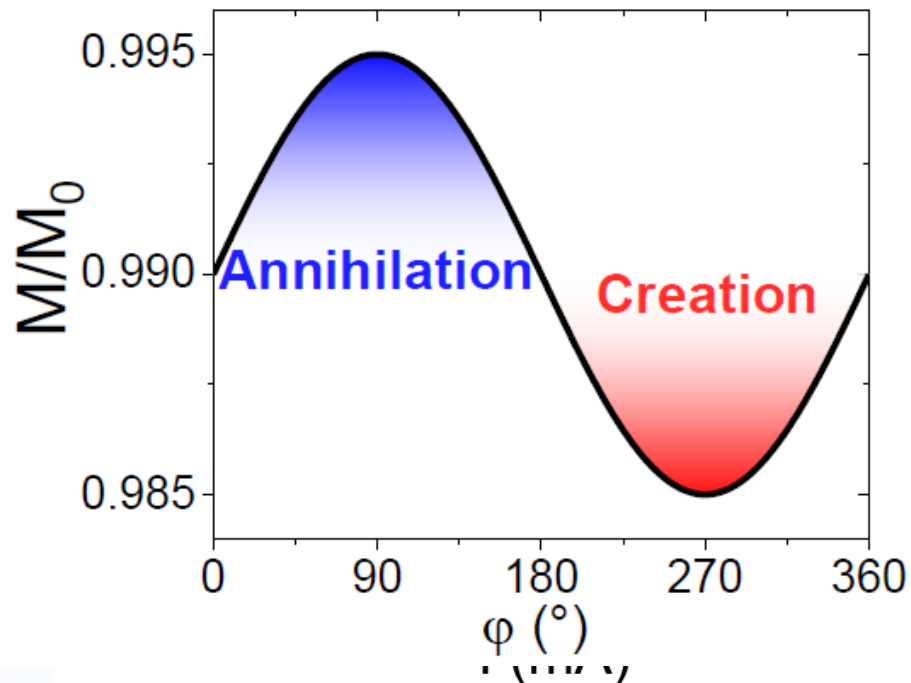
# Comparison with optical detection of the torque

➤ Detect the change of the magnetization optically: from the change of the light polarization (Magneto-optical Kerr effect)

➤ Magneto-optical Kerr effect (MOKE) allows to detect the torques free of magnonic contributions

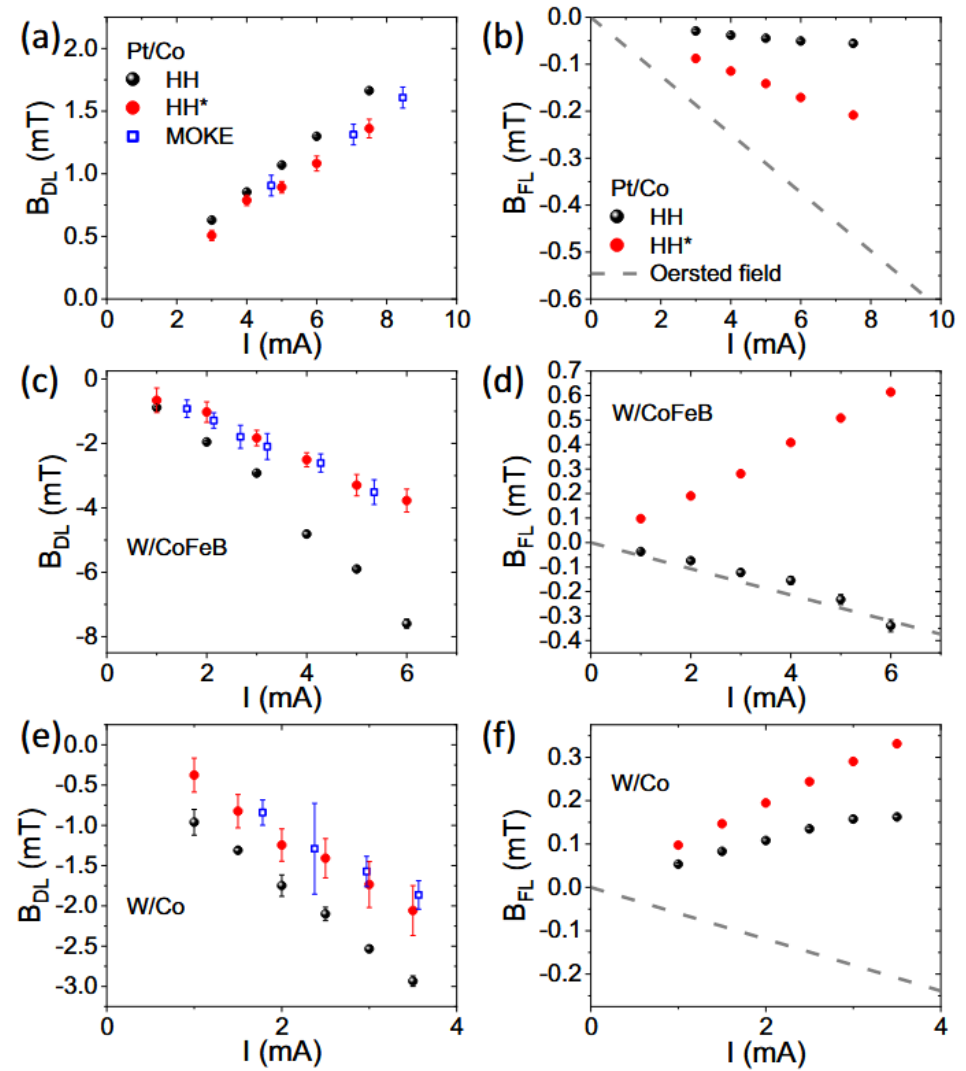
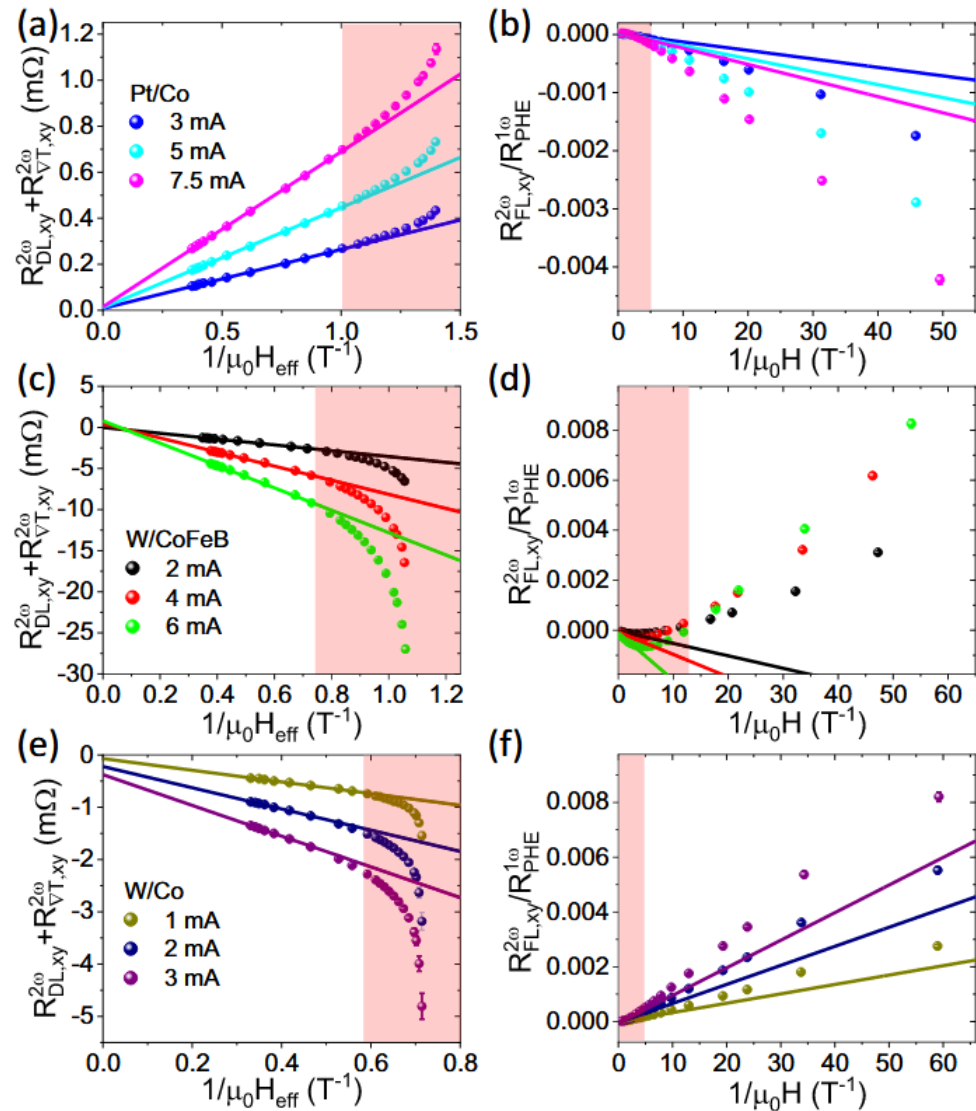


Emir Karadža



These results can explain long standing discrepancy between different measurement methods of the SOT

# A “universal” contribution



Noel, P. et al. *Phys. Rev. B* **111**, 144409 (2025)

# Misestimation of the SOT efficiency

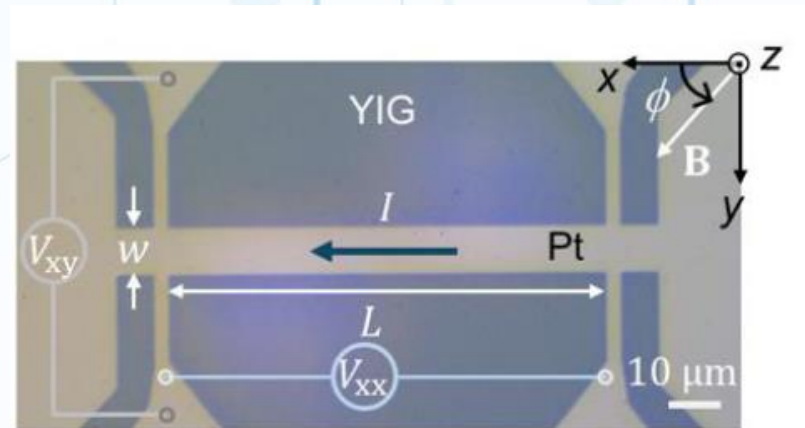
Sample	$R$ ( $\Omega$ )	$M_s$ (kA/m)	$\xi_{DL,HH}^j$ (%)	$\xi_{DL,HH}^{j*}$ (%)	$\xi_{DL,MOKE}^j$ (%)	$\xi_{FL}^j$ (%)	$\xi_{FL,HH}^{j*}$ (%)
Pt(5)/CoFeB(2.5)	501	$939 \pm 6$	$9.8 \pm 0.2$	$8.3 \pm 0.3$	$7.7 \pm 0.3$	$3.0 \pm 0.2$	$1.7 \pm 0.1$
Pt(5)/Co(2.5)	552	$1082 \pm 10$	$8.9 \pm 0.2$	$7.4 \pm 0.5$	$7.9 \pm 0.1$	$2.2 \pm 0.1$	$1.4 \pm 0.1$
W(5)/CoFeB(2.5)	2405	$876 \pm 6$	$-42 \pm 6$	$-24 \pm 2$	$-25 \pm 2$	$0.4 \pm 0.3$	$6.0 \pm 0.1$
W(5)/Co(2.5)	2076	$954 \pm 4$	$-33 \pm 2$	$-21 \pm 3$	$-20 \pm 1$	$4.3 \pm 0.1$	$6.0 \pm 0.1$
YIG(6.2)/Pt(3)	924	$116 \pm 12$	$-118 \pm 7$	$8 \pm 9$	—	$1.5 \pm 0.1$	$0.1 \pm 0.1$

The misestimation depends on both the FM and the normal metal and can reach more than 100%

The larger the SOT the larger the misestimation

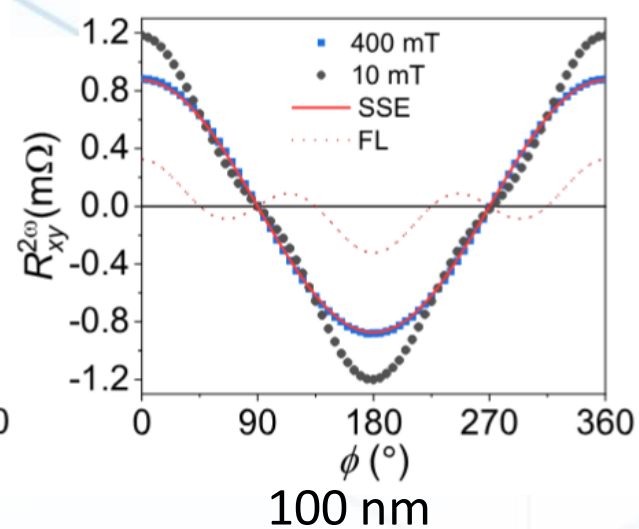
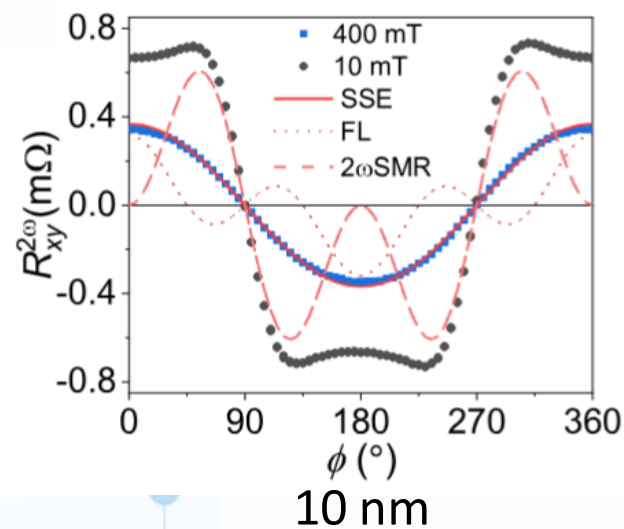
The larger the PHE compared to the AHE the larger the misestimation

# A simpler probe, more samples, more physics



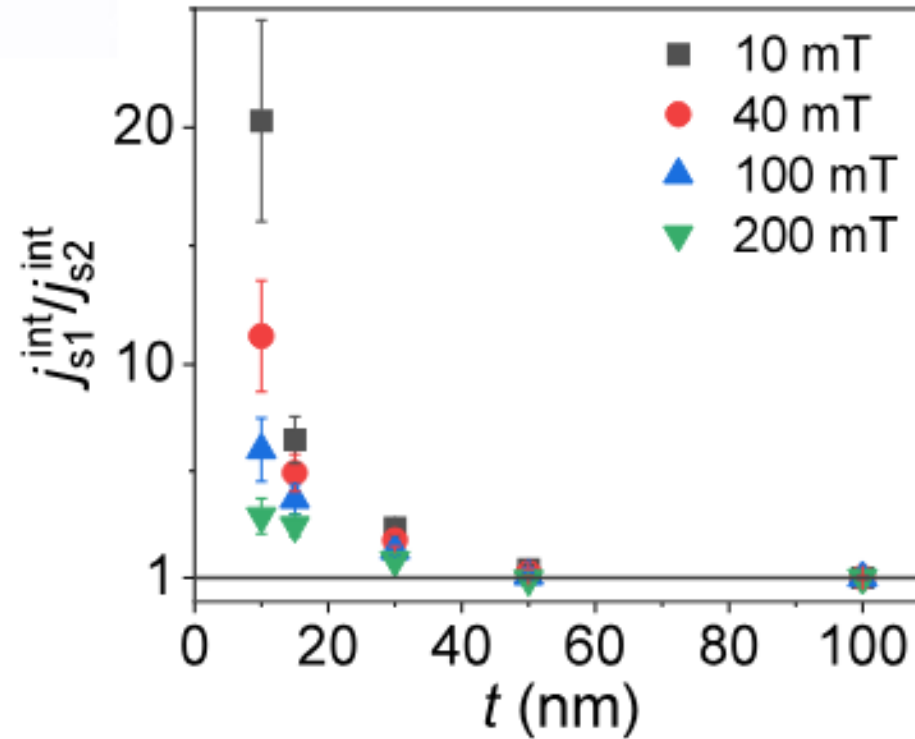
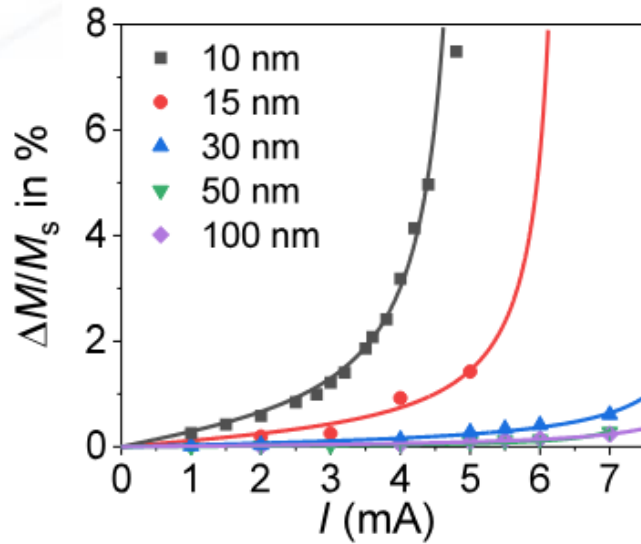
Haripriya Madathil Pranav Pradeep Pr. Saul Velez

Different YIG/Pt samples,  
with YIG thickness from 10  
nm to 100 nm deposited by  
sputtering and patterned  
into Hall bars



Madathil, H., Pradeep, P., Noël, P. & Vélez, S. Nano Lett. 26, 20, 6525–6531 (2026)

# Thickness dependence of the magnon modulation



$$\frac{\Delta M}{M_s} \propto \frac{j_s^{\text{int}}}{\mu_s t \alpha M_s [1 - (I/I_c)^2]} I$$

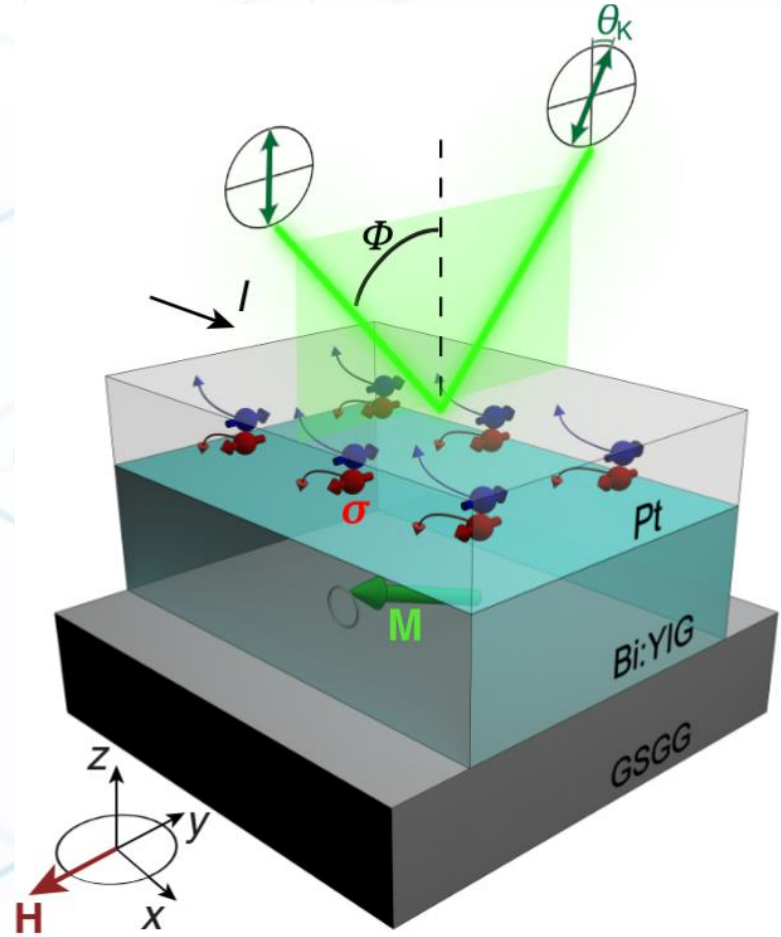
Madathil, H., Pradeep, P., Noël, P. & Vélez, S. Nano Lett. 26, 20, 6525–6531 (2026)

Damping compensation much easier to obtain in ultrathin films (10 nm) than in thick YIG (100 nm):

**Role of vertical confinement of subthermal magnons to be further understood**

# Measuring the change of magnetization optically

- Inject current and measured longitudinal MOKE
- YIG is not adapted due to its small magneto-optical constant



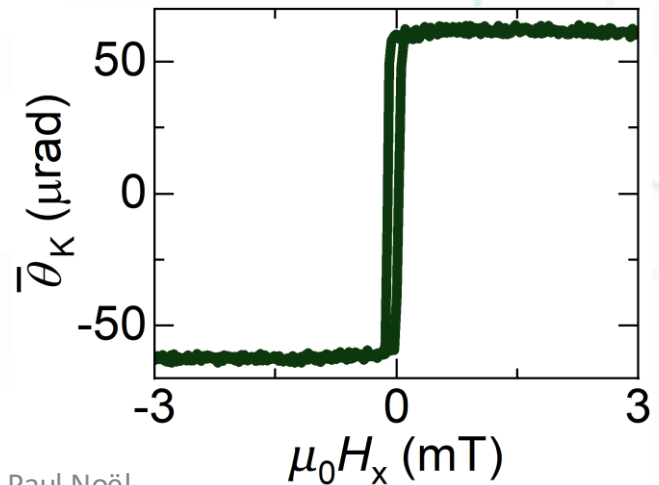
William Legrand



Emir Karadža

**BiYIG has a very large magneto-optical constant leading to easy MOKE measurements**

Legrand, W. et al. *Advanced Functional Materials* **36**, 2503644 (2026)

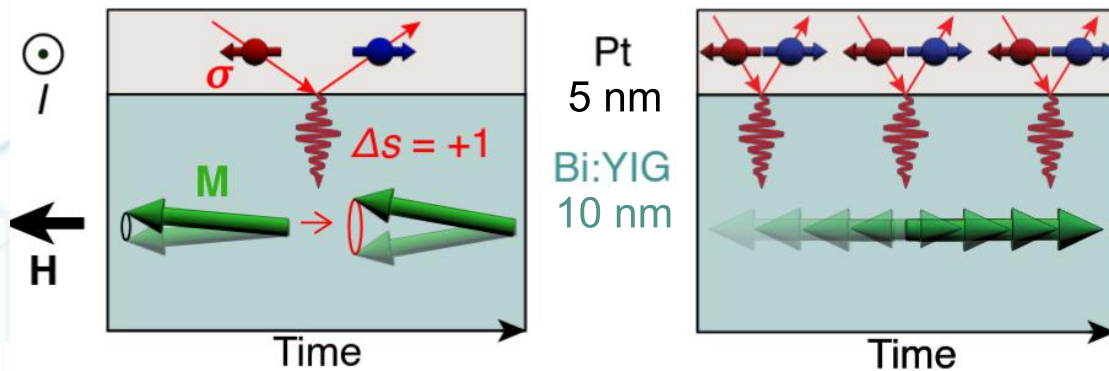
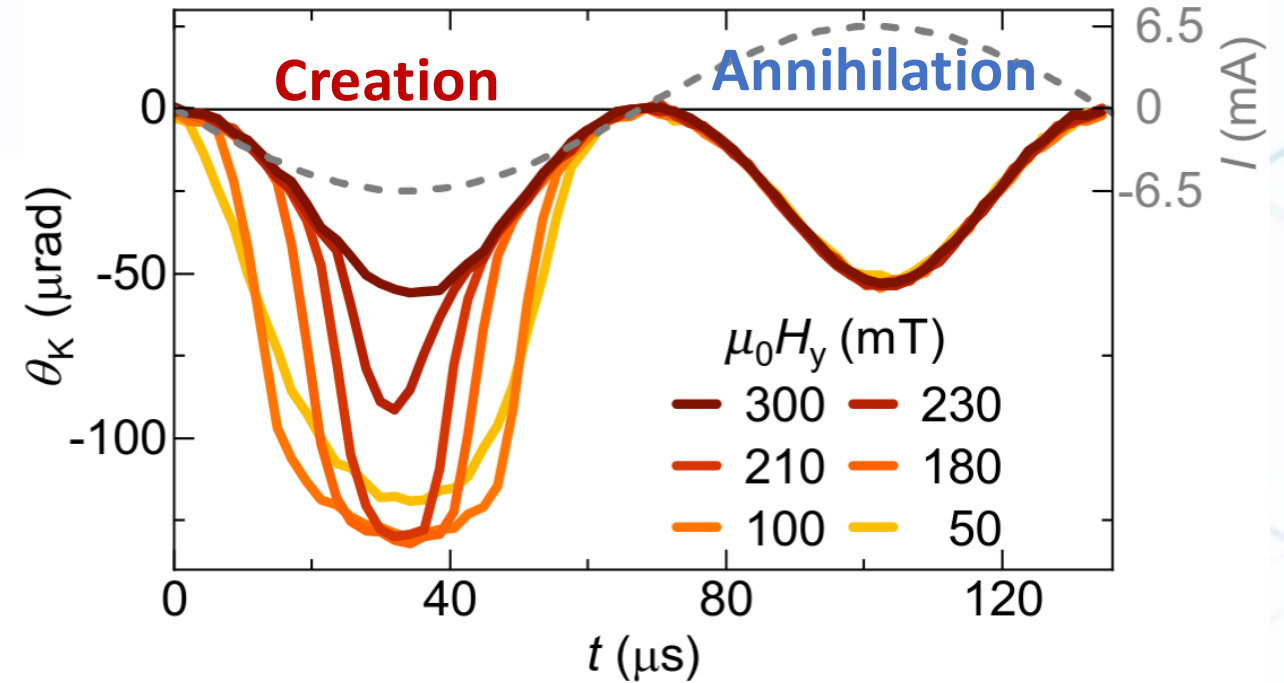


# Measuring the change of magnetization optically



- Injecting current and following the magnetic state over time
- For positive current creation of magnons, for negative current annihilation of magnons

Richard Schlitz's talk about antimagnonics  
 Karadza, E. et al. arXiv.2601.09569 (2026)



The creation of magnons is so large that the magnetization is reversed against the external magnetic field: **antimagnons**



Swiss National Science foundation  
ETH Zürich postdoctoral fellowship



PROGRAMME  
DE RECHERCHE  

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SPINTRONIQUE

# Thank you all for your attention

Noël, P. et al. Phys. Rev. Lett. **134**, 146701 (2025)

Noel, P. et al. Phys. Rev. B **111**, 144409 (2025)

Madathil, H. et al. Nano Lett. **26**, 20, 6525–6531 (2026)

Karadza, E. et al. arXiv.2601.09569 (2026)

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