Efficient spin excitation via ultrafast damping torques in antiferromagnets

CHRISTIAN TZSCHASCHEL, HARVARD UNIVERSITY

SPICE WORKSHOP: ULTRAFAST ANTIFERROMAGNETIC WRITING

MAY 9, 2022

Acknowledgment

ETH Zurich

Switzerland

Manfred Fiebig

Tokyo Tech

Japan

Takuya Satoh

Harvard

USA

Suyang Xu

must

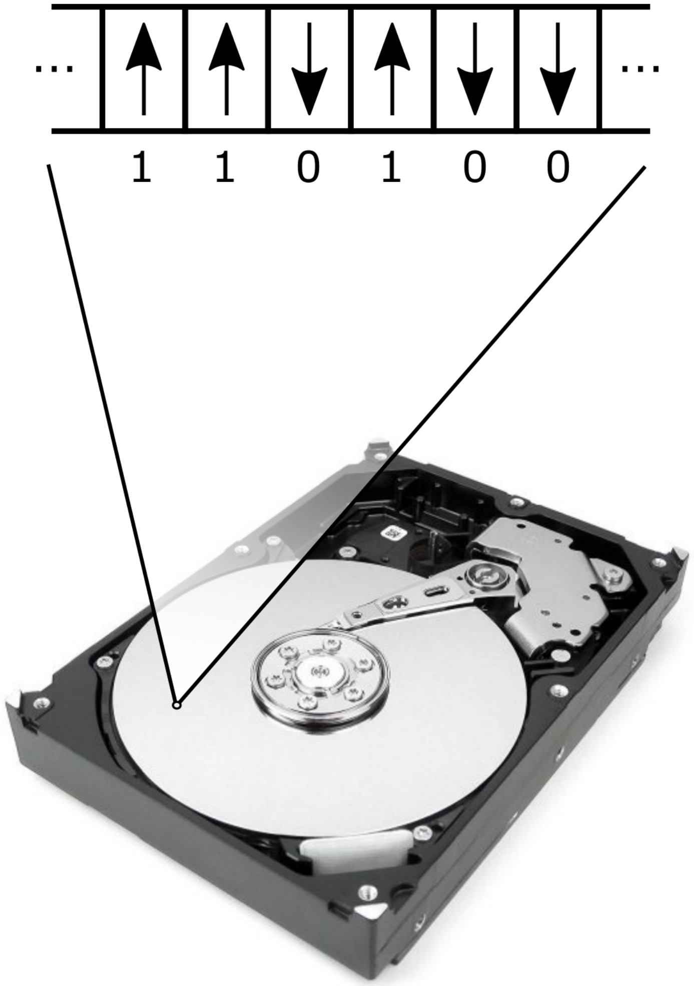
Swiss National Science Foundation

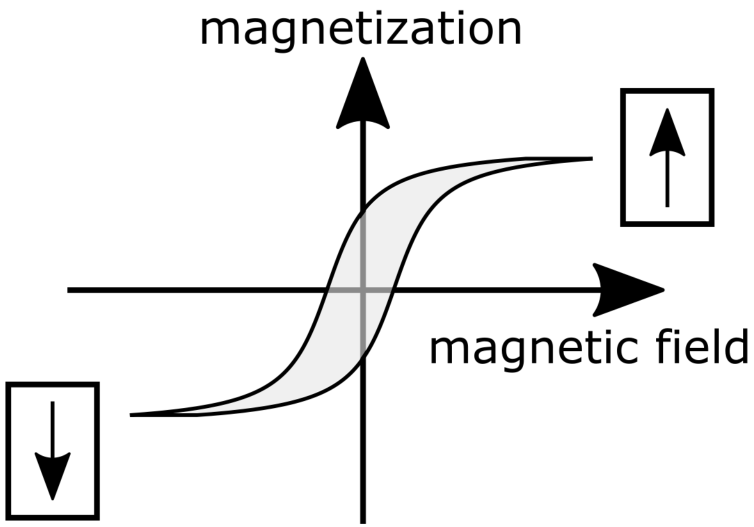
Early Postdoc.Mobility

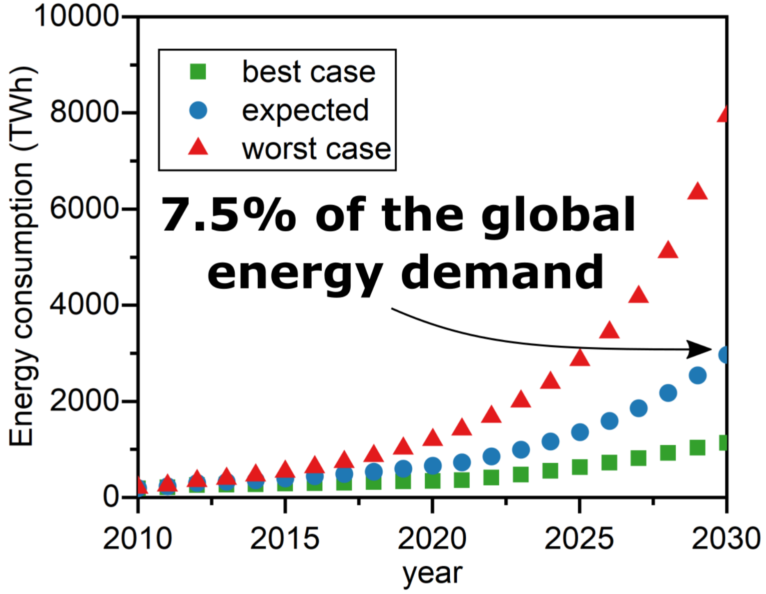
HARVARD UNIVERSITY
Office of the Vice Provost for Research

Climate Change Solutions Fund

Information Technology



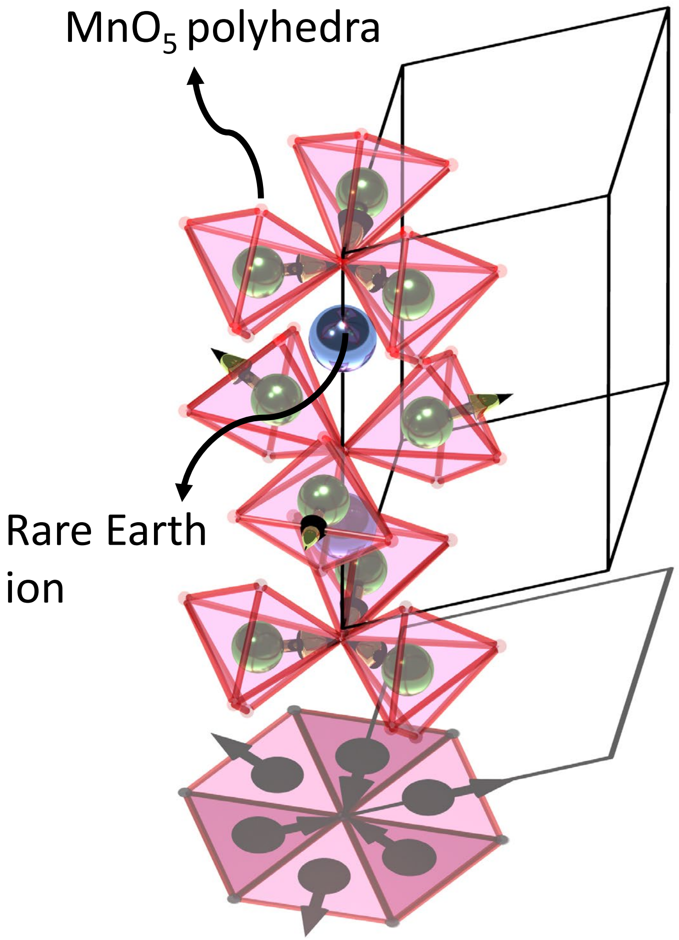


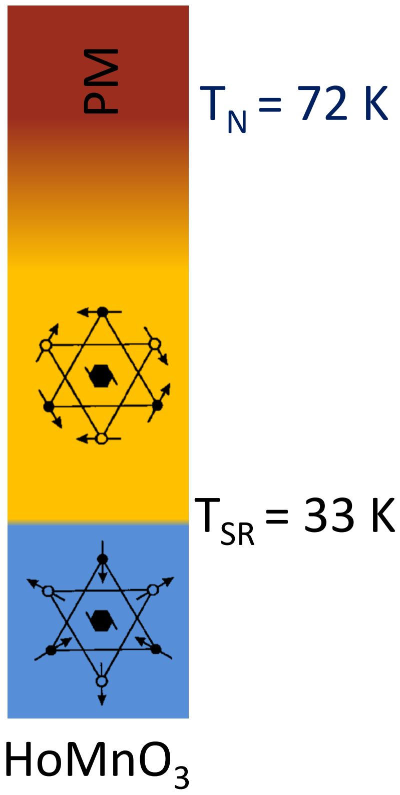


Andrae et al., *Challenges* **6,** 117 (2015)

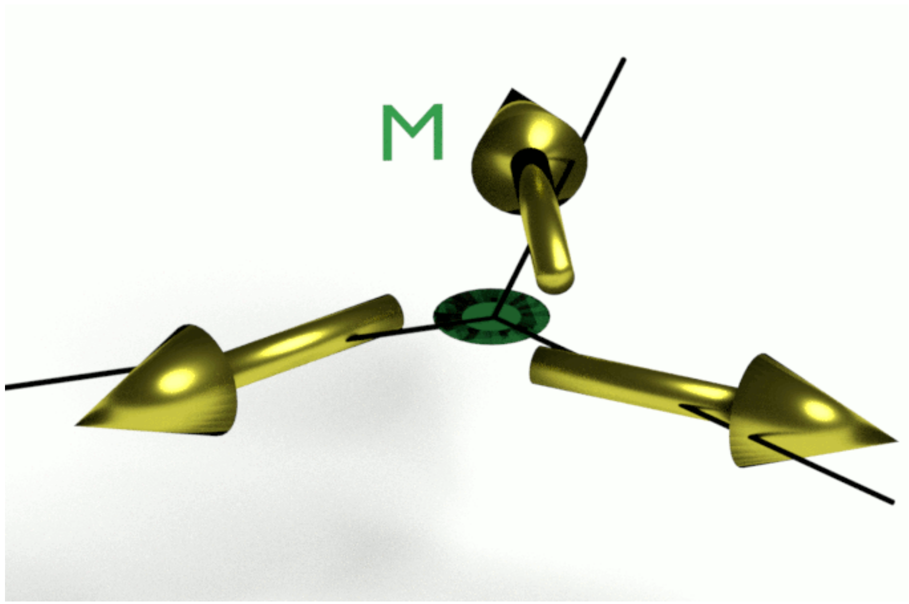
Challenge
Storing and processing data with the smallest energy and the fastest speed

h-$HoMnO_3$

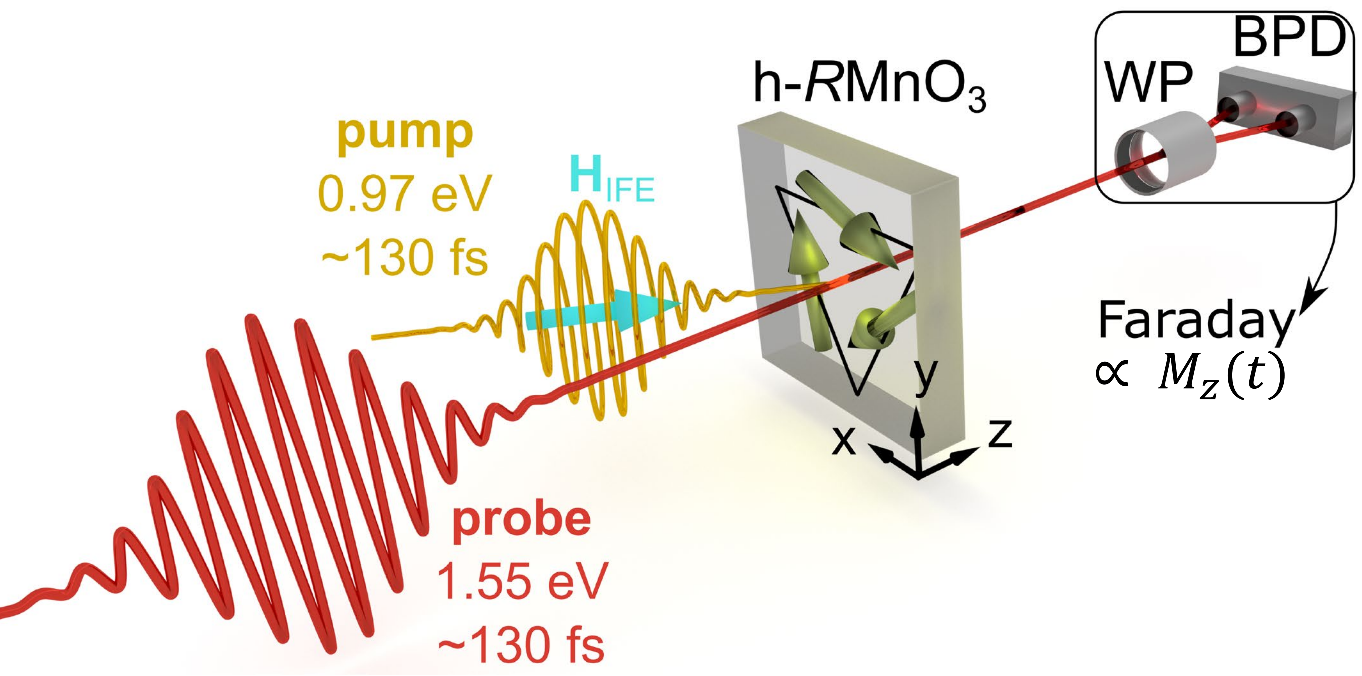




- 3 magnon modes (**X**, **Y**, **Z**)
- **X/Y** mode ~ 1.3 THz
- **Z** mode ~ 260 GHz



Setup



$$\frac{\partial \boldsymbol{m}}{\partial t} = -\mu_0\gamma\boldsymbol{m}\times\boldsymbol{H}_{\mathrm{IFE}} - \mu_0\gamma\alpha\frac{\boldsymbol{m}}{|\boldsymbol{m}|}\times(\boldsymbol{m}\times\boldsymbol{H}_{\mathrm{IFE}})$$

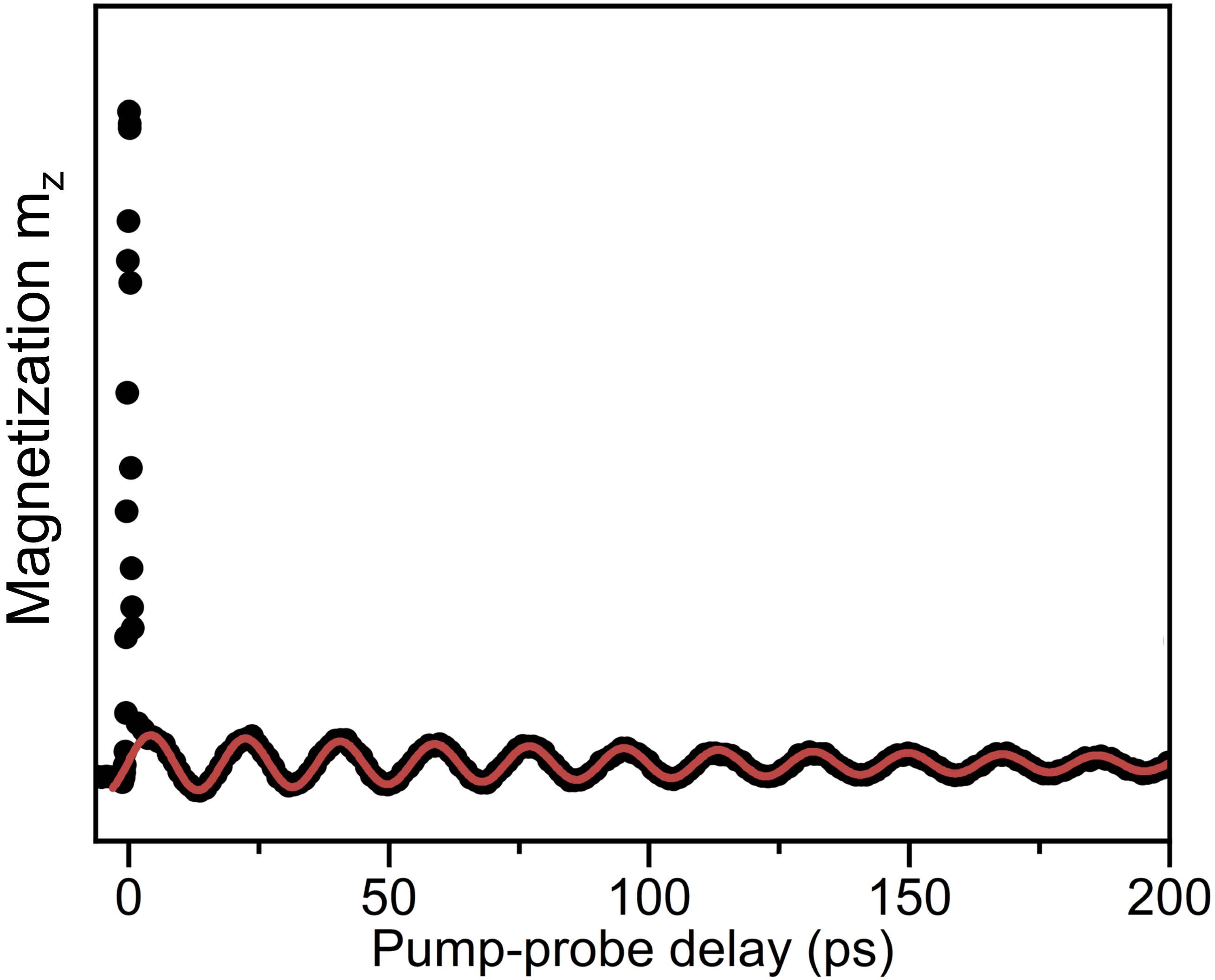
$\mu_0 H_{\mathrm{IFE}} = 1\ \mathrm{T}$

$\tau = 100\ \mathrm{fs}$

→ $\varphi = 1°$

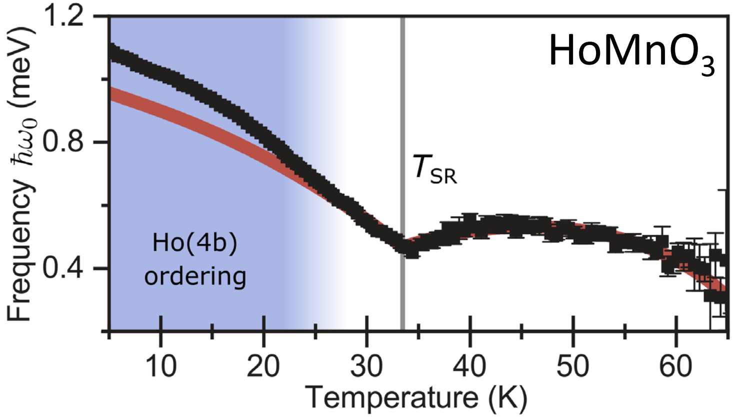
Independent of exchange/anisotropy constants

Ultrafast spin excitation



CT et al., Nat. Commun. **11**, 6142 (2020)

Spin excitation



$$\mathcal{F} = J \sum_{<i,j>} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + D_z \sum_i S_{i,z}^2 + D_y \sum_i S_{i,y}^2 + \Delta \sum_i S_{i,x}^2 S_{i,y}^2$$

$J = 2.44\ \mathrm{meV}$ $\quad D_z = 0.38\ \mathrm{meV}$ $\quad D_y = \kappa(T_{SR} - T)$

W. Ratcliff et al., npj Quantum Mater. **1,** 16003 (2016)

<u>Fit reveals:</u>

$\kappa = 0.032\ \mathrm{\mu eV/K}$

$\Delta = 1.22\ \mathrm{\mu eV}$

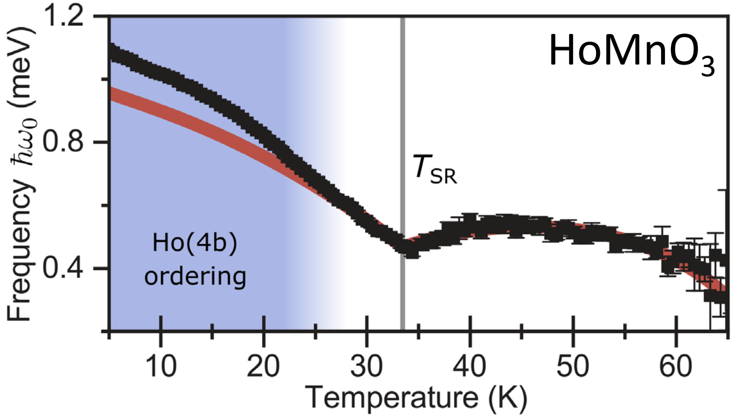
Small anisotropy parameters difficult to determine by neutron scattering, but crucial for estimating the minimal switching energy:

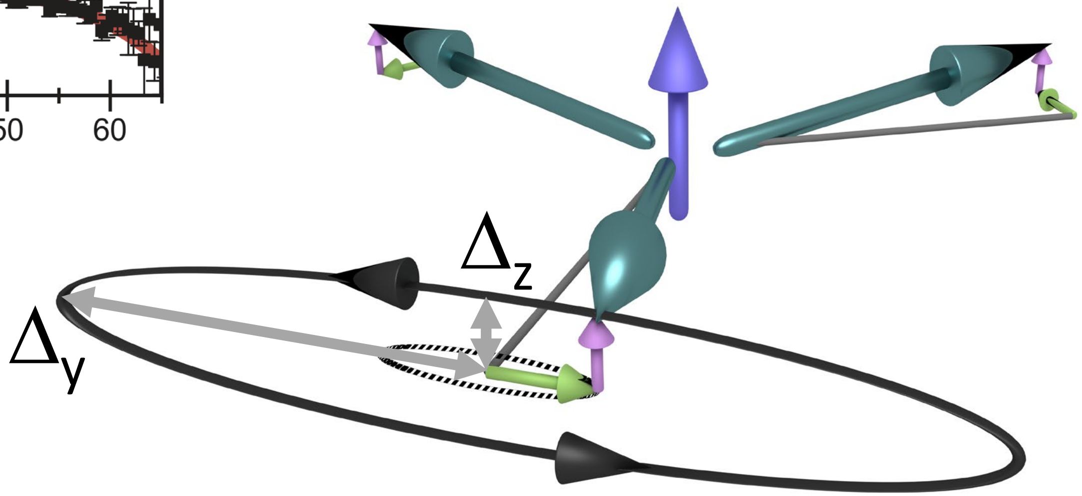
Bit volume 40x40x20 nm^3 ≅ 500.000 spins → ≈ 1 eV/bit

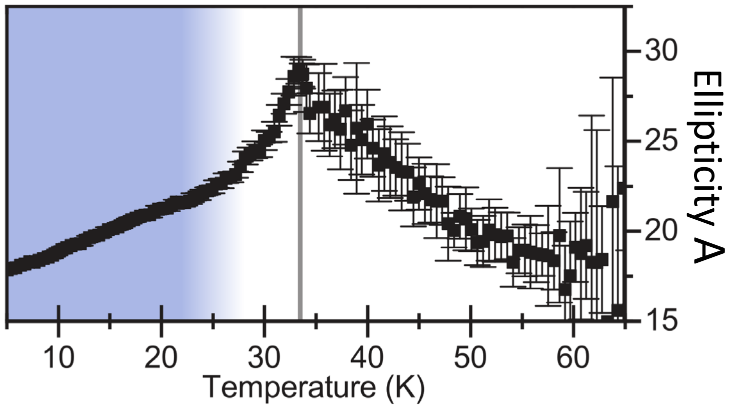
CT et al., Nat. Commun. **11**, 6142 (2020)

Spin excitation

$$\mathcal{F} = J \sum_{<i,j>} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + D_z \sum_i S_{i,z}^2 + D_y \sum_i S_{i,y}^2 + \Delta \sum_i S_{i,x}^2 S_{i,y}^2$$



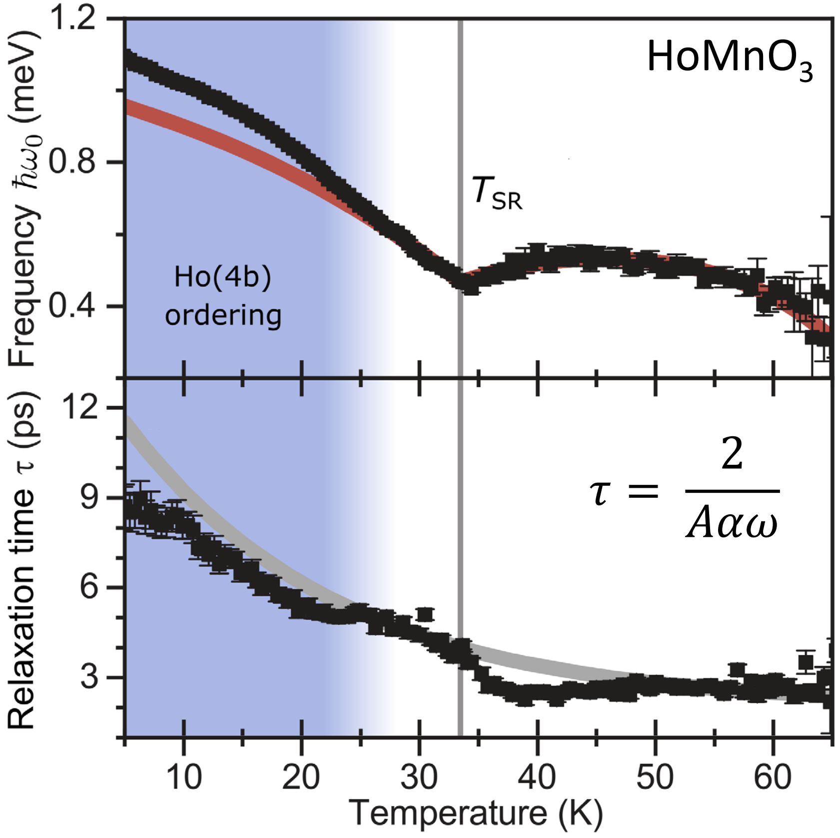




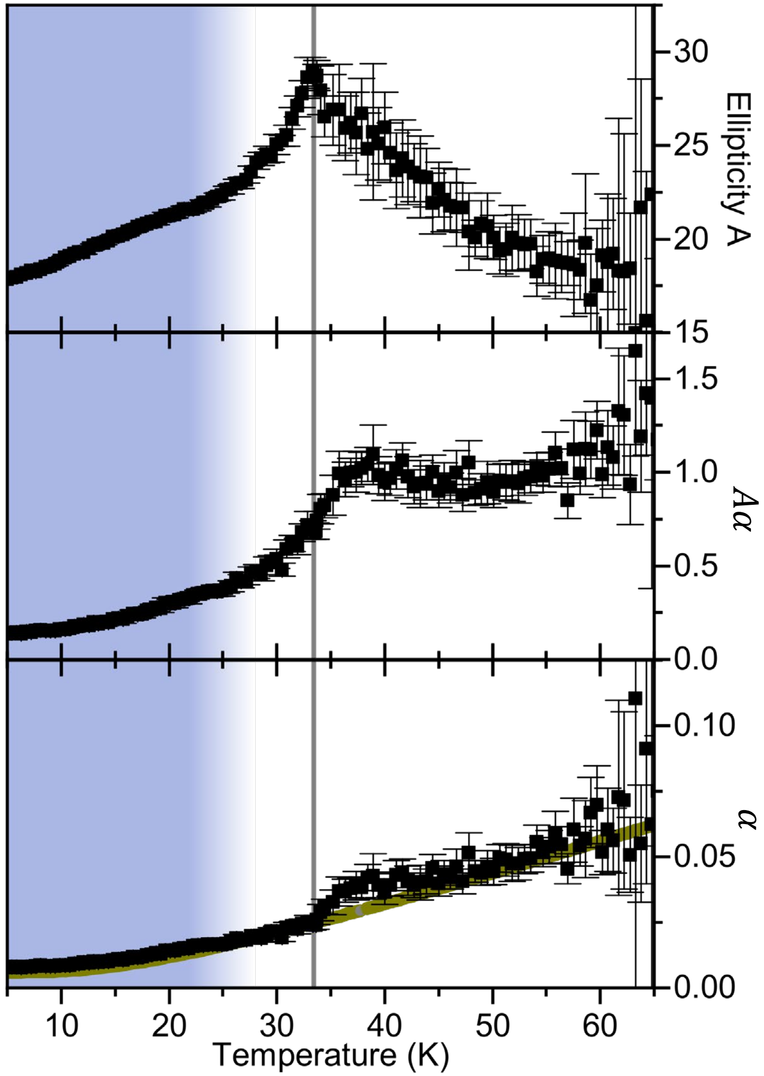
In antiferromagnets:

aspect ratio $A = \frac{\Delta_y}{\Delta_z} \gg 1$

Spin excitation



$$A\alpha = \frac{2}{\omega_0 \tau}$$

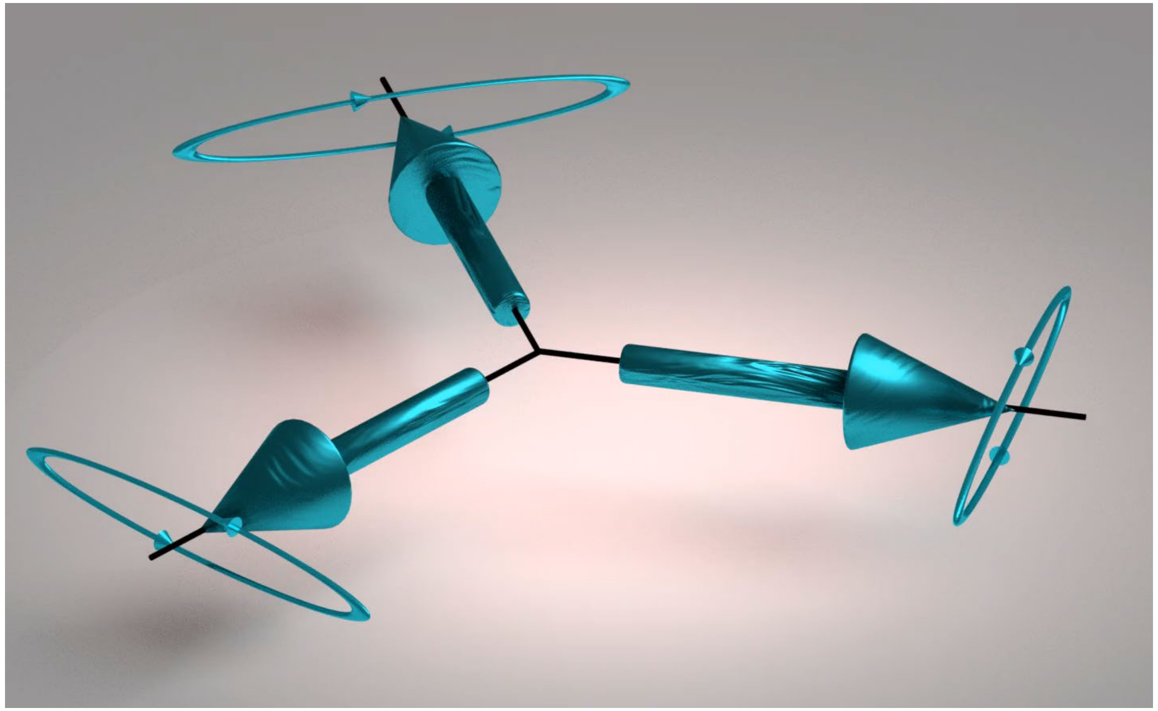


- Dissipation determined by $A\alpha$
- $A\alpha$ <u>not</u> small

→ **Reconsider excitation mechanism**

Damping-torque of the IFE

$$\frac{\partial \boldsymbol{m}}{\partial t} = -\mu_0 \gamma \boldsymbol{m} \times \boldsymbol{H}_{\text{eff}} - \mu_0 \gamma \alpha \frac{\boldsymbol{m}}{|\boldsymbol{m}|} \times (\boldsymbol{m} \times \boldsymbol{H}_{\text{eff}})$$

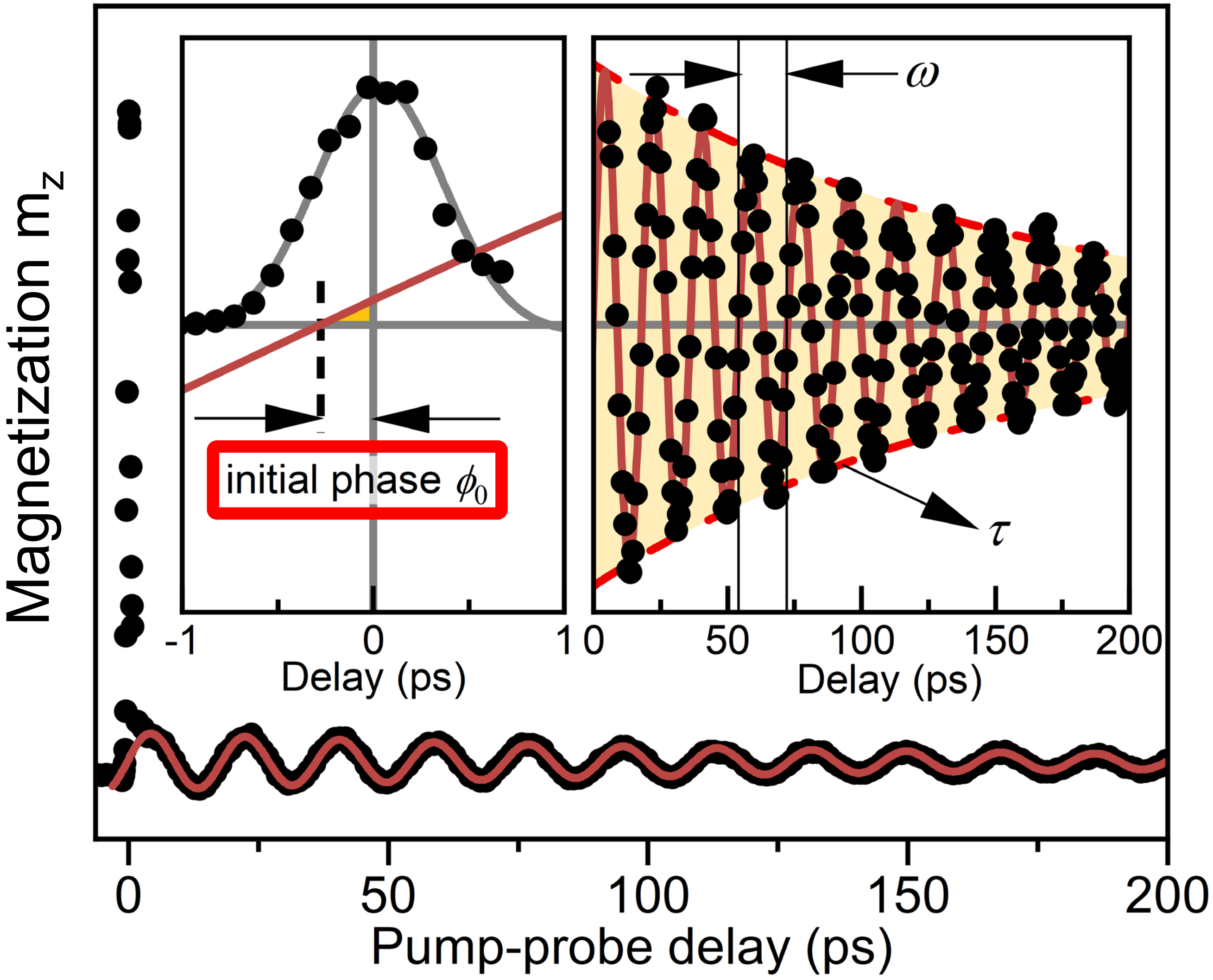


Gilbert damping α affects

Initial phase ϕ_0

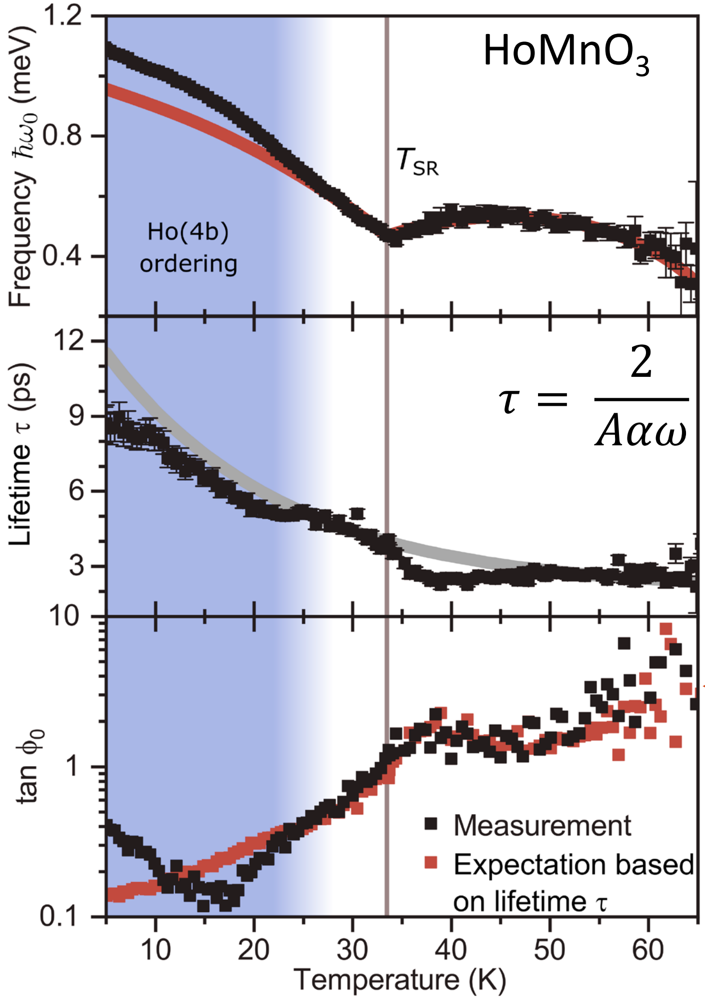
Lifetime τ

Ultrafast spin excitation

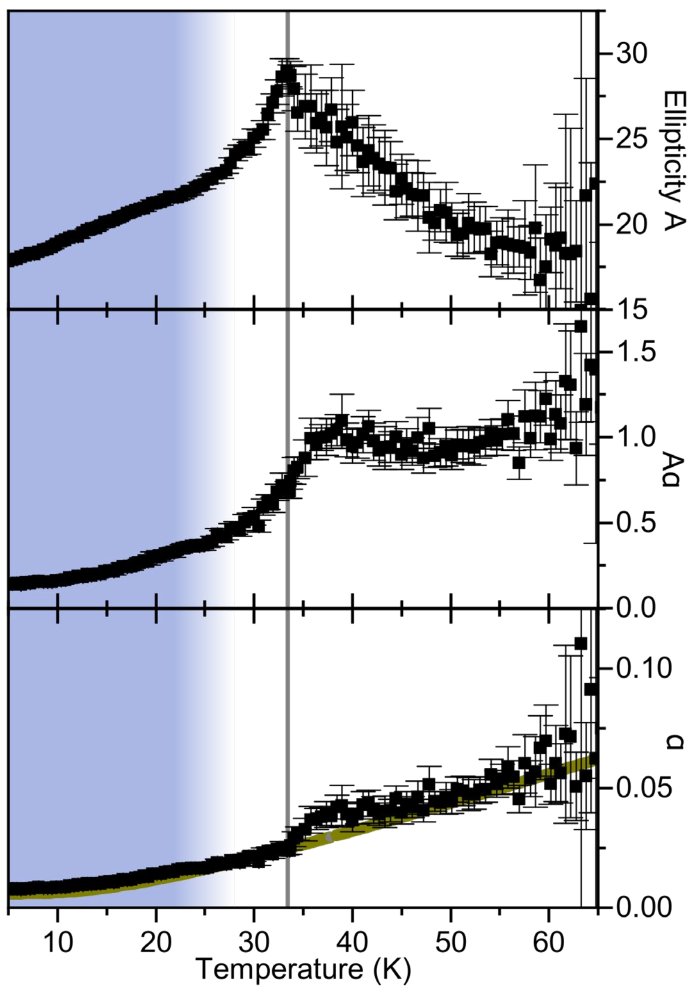


CT et al., Nat. Commun. **11**, 6142 (2020)

Ultrafast spin excitation via damping torques



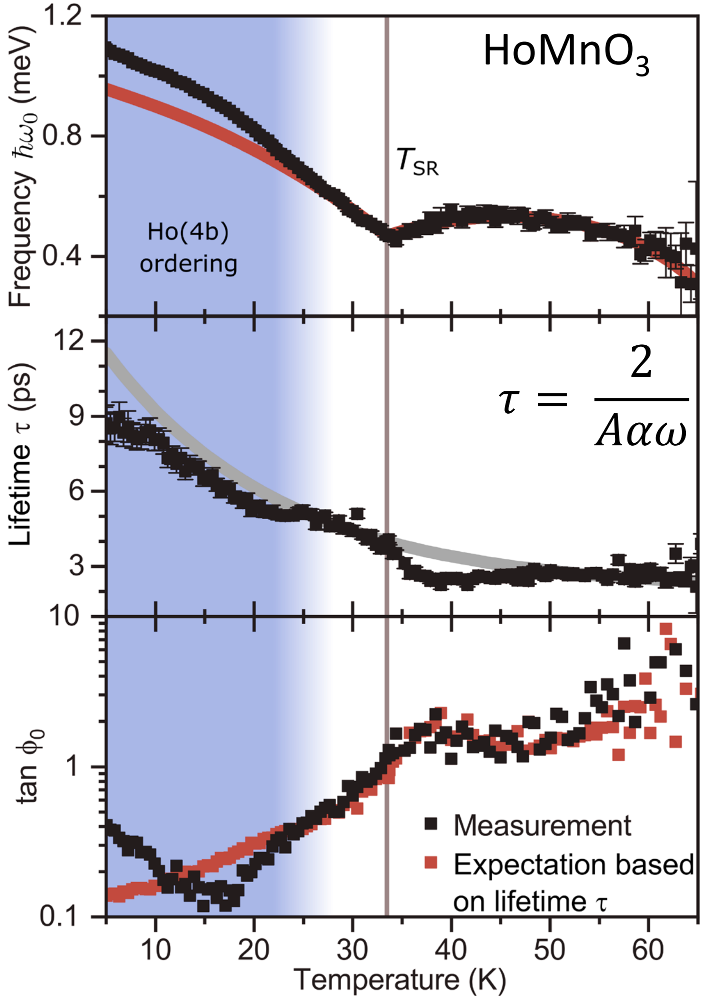
$\tan\phi_0 = f(A\alpha)$



- Damping torque of IFE determines initial phase
- same Gilbert damping during **relaxation** and **excitation**

CT et al., Nat. Commun. **11**, 6142 (2020)

Ultrafast spin excitation via damping torques



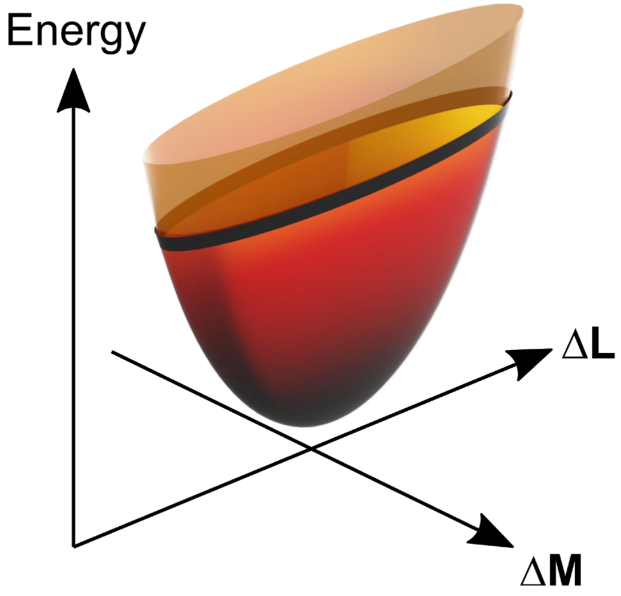
Ground state

Damping torque | Field torque

IFE excitation

$$\Delta\mathcal{F} \sim J(\Delta\boldsymbol{M})^2 + D((\Delta\boldsymbol{M})^2 + (\Delta\boldsymbol{L})^2)$$

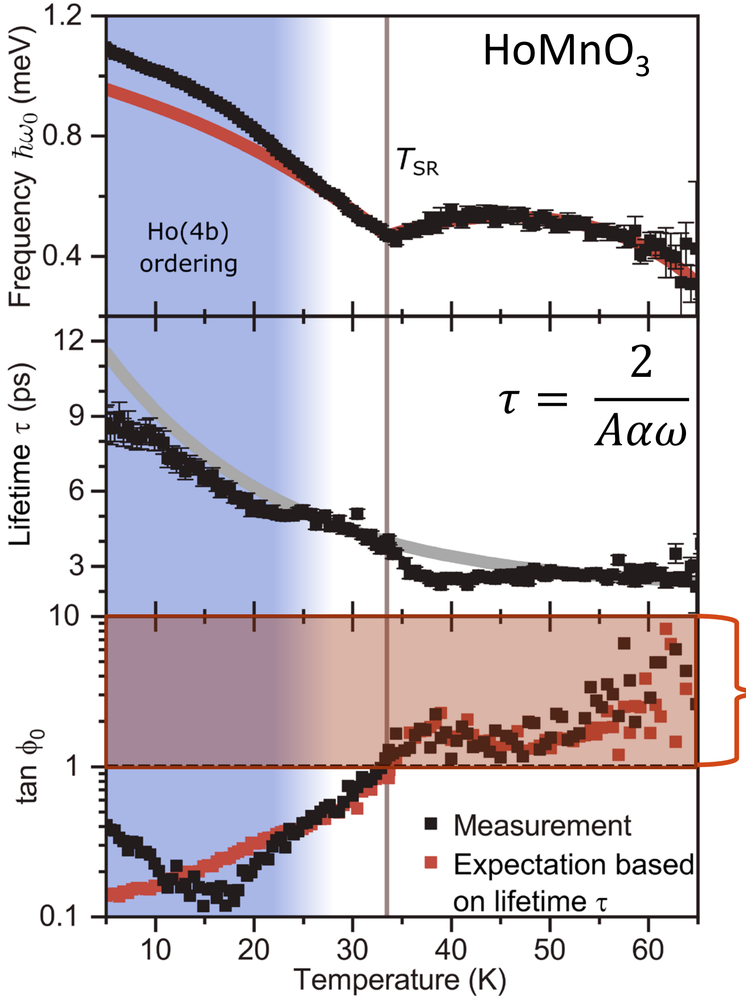
Exchange >> Anisotropy



Giant efficiency of damping torques in AFMs

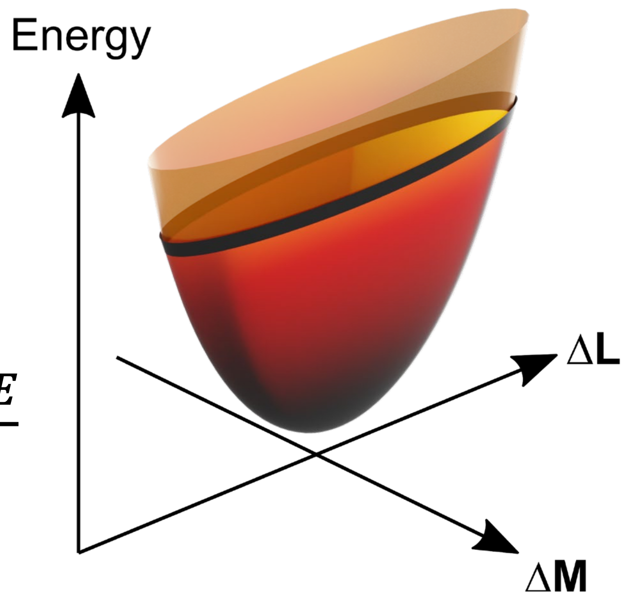
CT et al., Nat. Commun. **11**, 6142 (2020)

Ultrafast spin excitation via damping torques



$\tan(\phi_0)$ ~ corresponds to energy ratio:

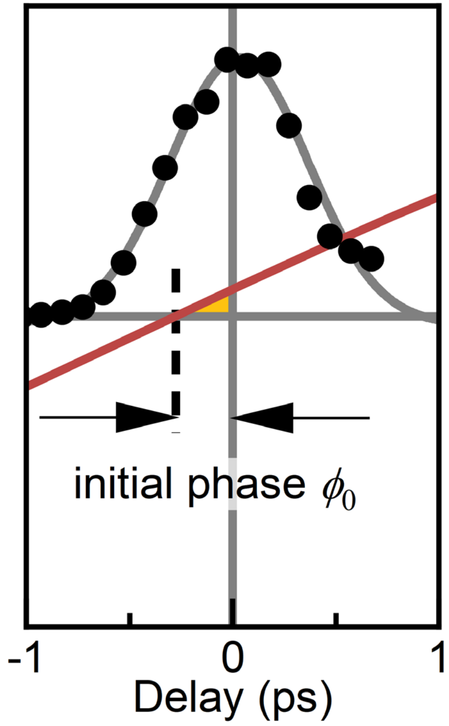
$$\frac{\textit{spin excitation via damping torque of IFE}}{\textit{spin excitation via field torque of IFE}}$$



→ $\tan(\phi_0) > 1$ implies: excitation via **damping torque dominates** despite $\alpha \ll 1$

CT et al., Nat. Commun. **11**, 6142 (2020)

Summary



Spin excitations provide valuable insights into magnetic low-energy landscape

→ **Quantification of magnetic anisotropy**

Initial phase of optically driven excitations encodes information of the excitation mechanism

→ **Ultrafast damping torque of the IFE**

Exchange enhancement dramatically boosts any excitation mechanism that generates net magnetization in an AFM

→ **Any such mechanism may enable highly efficient switching of AFM order**