Inertial spin dynamics in ferromagnets

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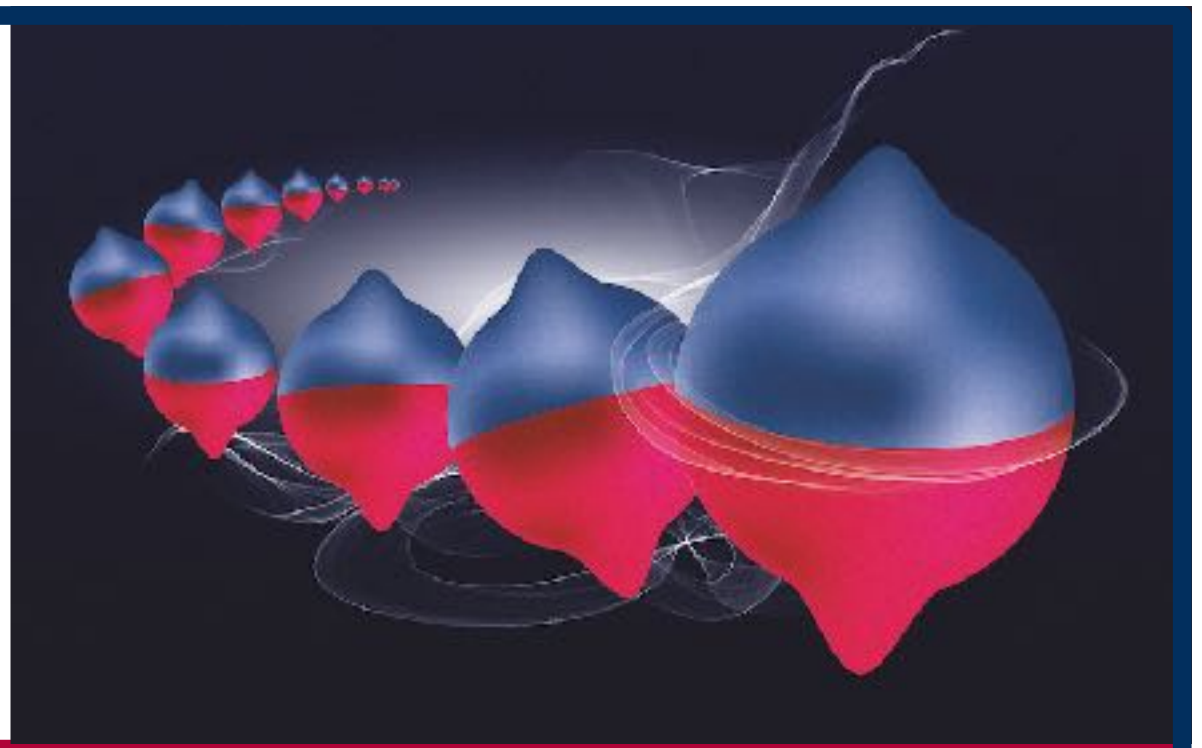

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Knut och Alice Wallenbergs Stiftelse

Vetenskapsrådet


Trends in Magnetism 2022
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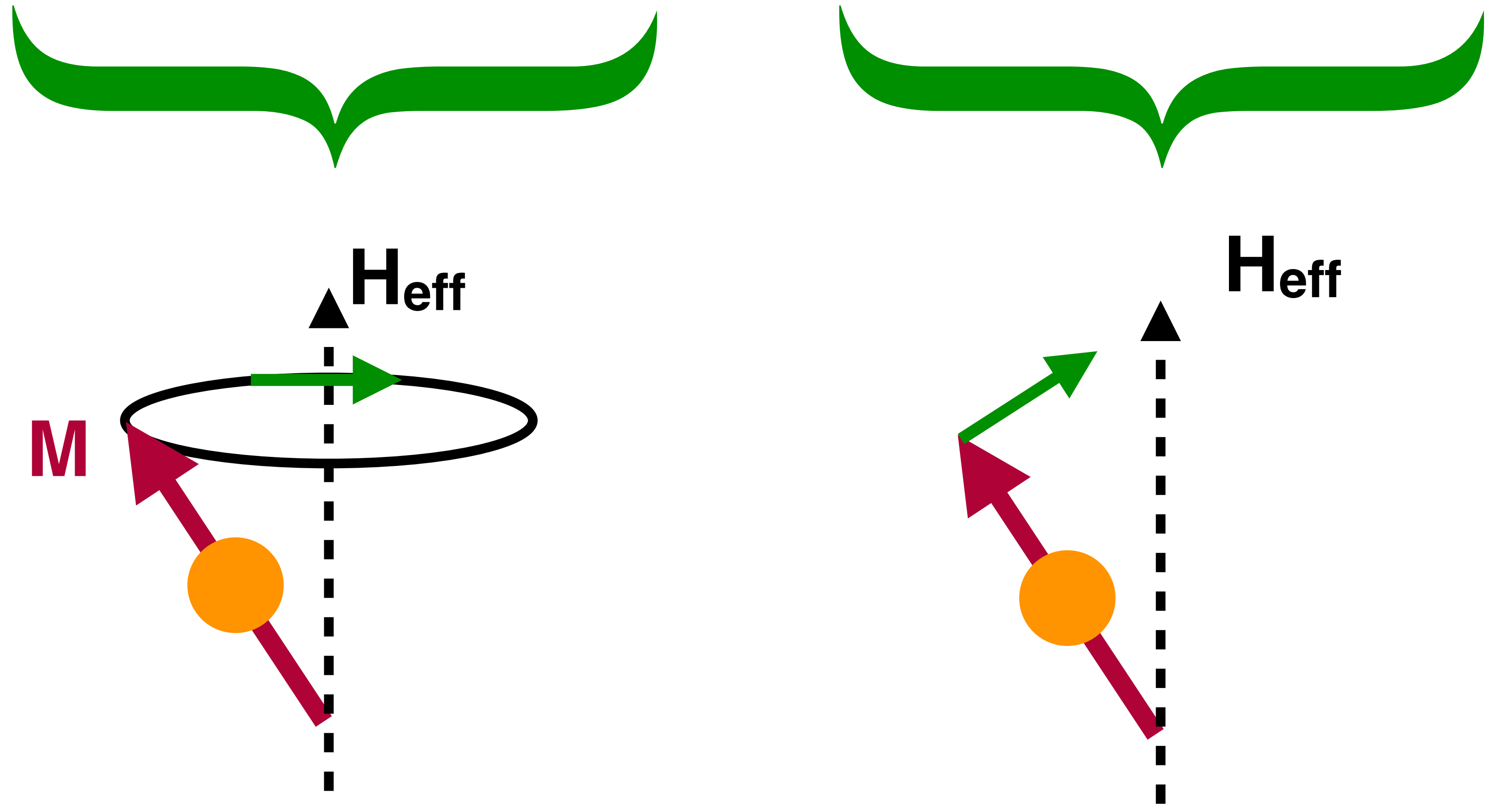
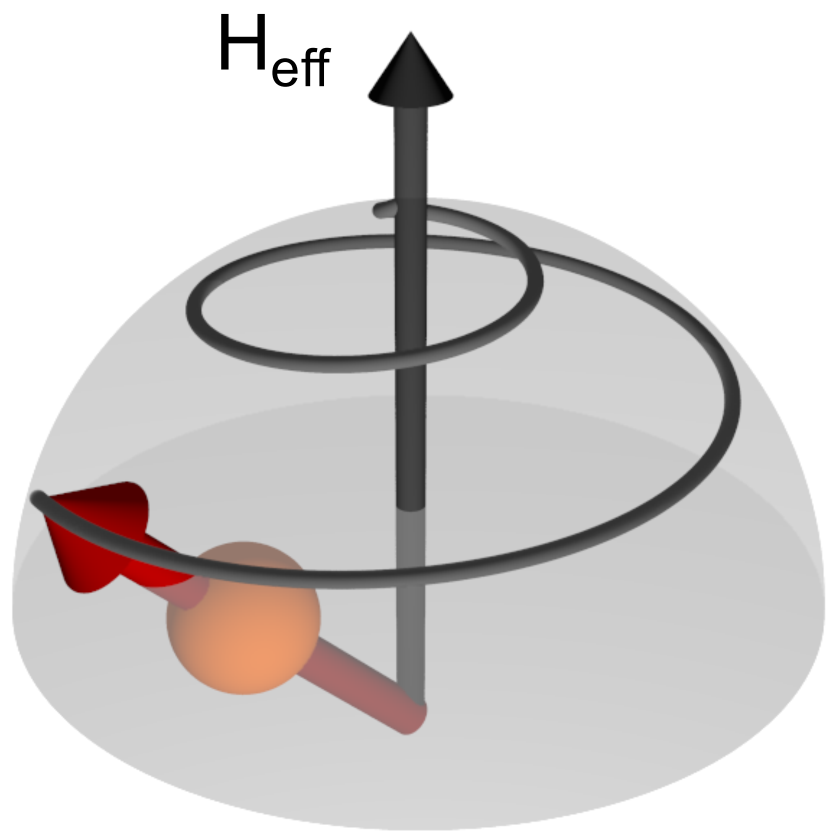
- Landau-Lifshitz-Gilbert equation

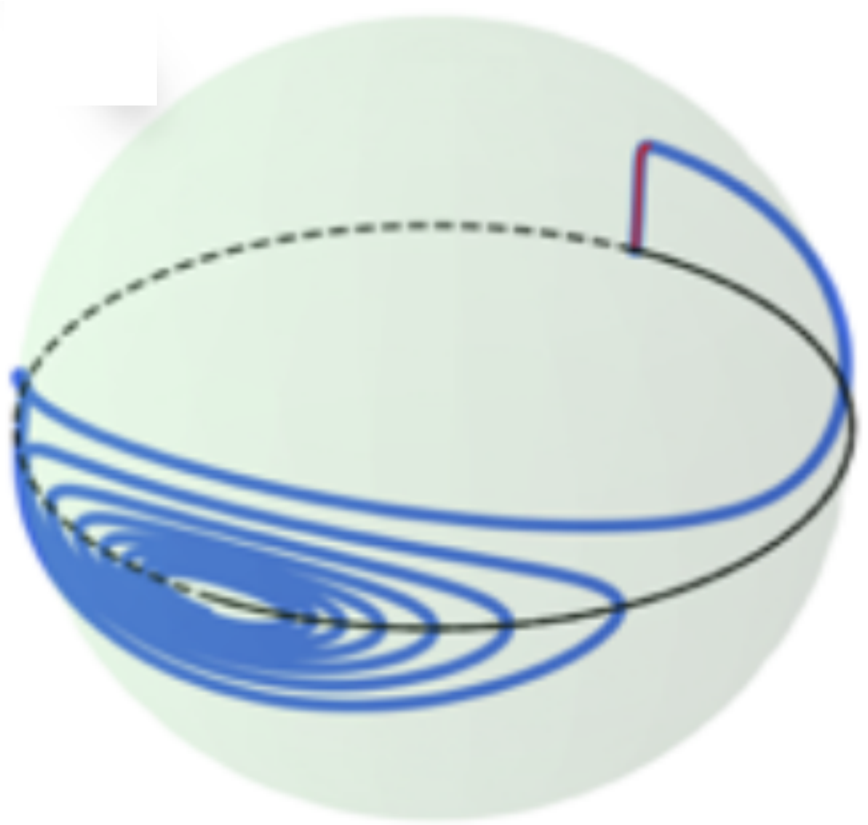
$$\frac{dM}{dt} = -|\gamma| M \times H_{eff} + \alpha M \times \frac{dM}{dt}$$



Precession



Switching

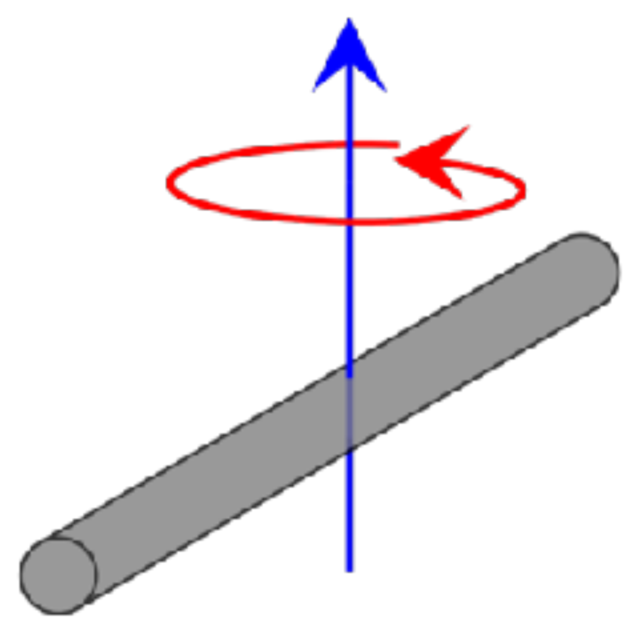


LLG is wrong!

- LLG equation: unphysical inertia tensor. Gilbert, the “G” in the equation, noticed it:

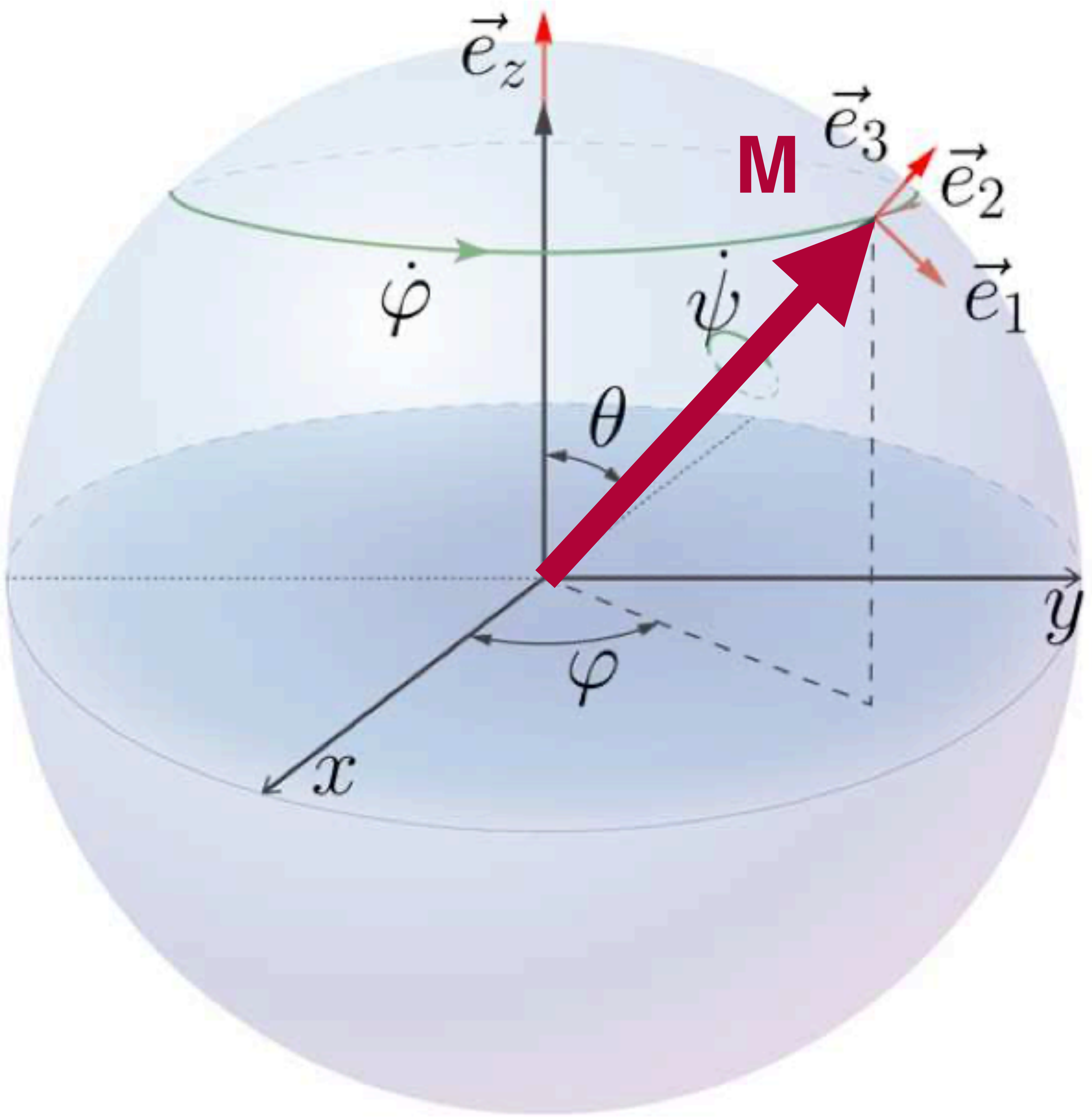
> Gilbert (2004): “I was unable to conceive of a physical object with an inertial tensor of this kind”

$$I = \begin{pmatrix} \cancelto{0}{I_1} & 0 & 0 \\ 0 & \cancelto{0}{I_2} & 0 \\ 0 & 0 & I_3 \end{pmatrix} \qquad I = \begin{pmatrix} ml^2/12 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & ml^2/12 \end{pmatrix}$$



- How can it be wrong if it is being used every day in data centers?

- Degrees of freedom separated by energy scales orders of magnitude apart



J.-E. Wegrowe and M.-C. Ciornei, “Magnetization dynamics, gyromagnetic relation, and inertial effects”, *American Journal of Physics* **80**, 607 (2012)

$$\vec{\Omega} = \frac{\vec{M}}{M_s^2} \times \frac{d\vec{M}}{dt} + \Omega_3 \vec{e}_3$$

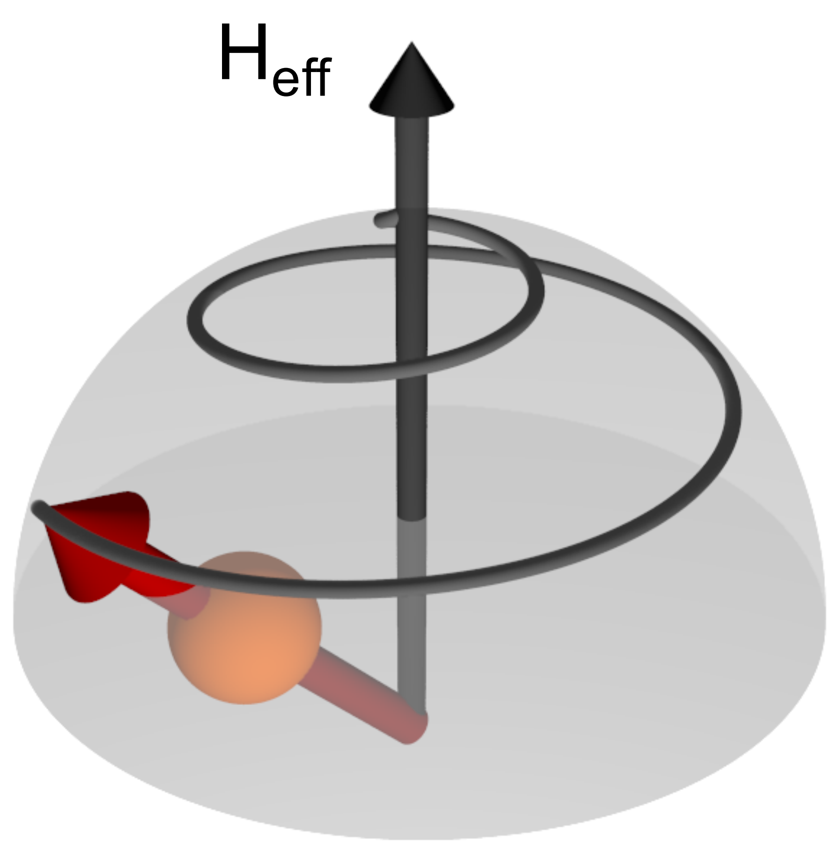
$$\vec{L} = \frac{I_1}{M_s^2}\left(\vec{M} \times \frac{d\vec{M}}{dt}\right) + \frac{M_s}{\gamma}\vec{e}_3$$

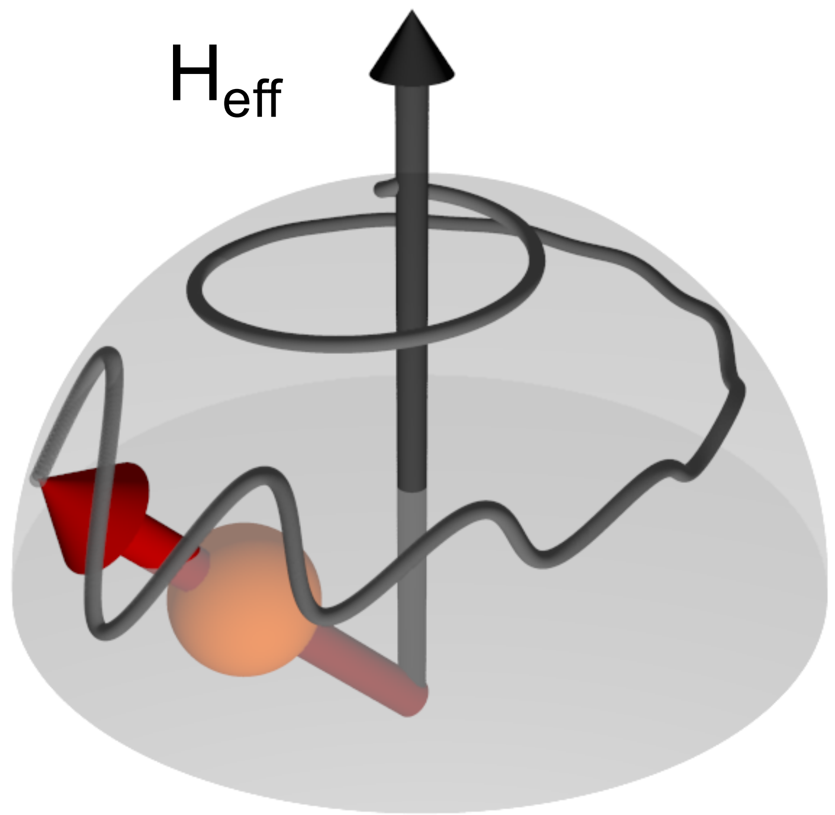
Solve Lagrangian with
Rayleigh dissipative function

Angular momentum relaxation time

$$\frac{d\mathbf{M}}{dt} = -|\gamma|\mathbf{M}\times\mathbf{H}_{\mathrm{eff}} + \alpha\,\mathbf{M}\times\left(\frac{d\mathbf{M}}{dt} + \tau\frac{d^2\mathbf{M}}{dt^2}\right)$$

J.-E. Wegrowe and M.-C. Ciornei, "Magnetization dynamics, gyromagnetic relation, and inertial effects", *American Journal of Physics* **80**, 607 (2012)





K. Neeraj et al., "Inertial spin dynamics in ferromagnets", *Nature Physics* **17**, 245 (2020)

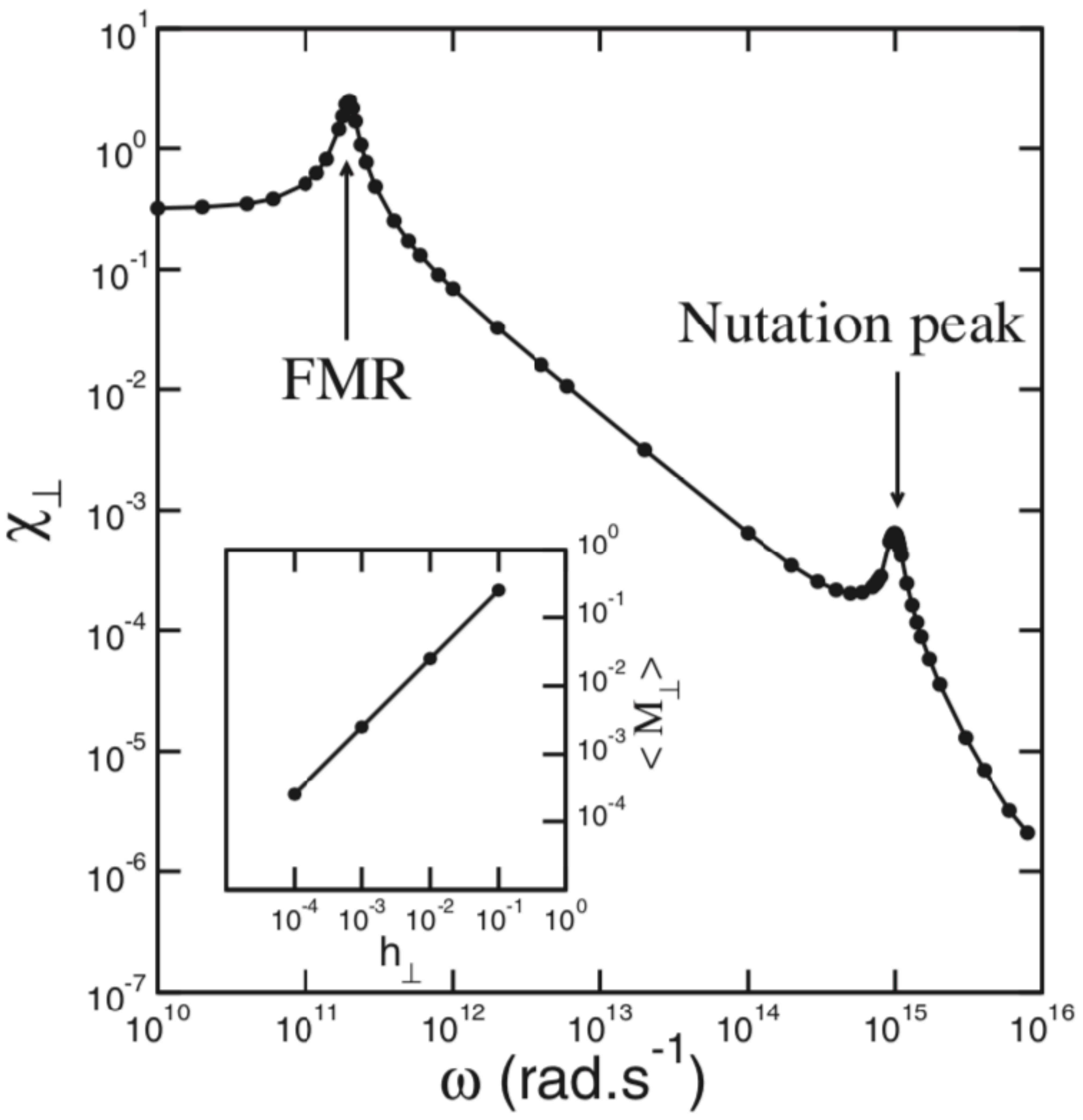
Inertial LLG - better convention

$$\frac{d\mathbf{M}}{dt} = -|\gamma|\mathbf{M}\times\mathbf{H}_{\text{eff}} + \alpha\mathbf{M}\times\frac{d\mathbf{M}}{dt} + \eta\mathbf{M}\times\frac{d^2\mathbf{M}}{dt^2}$$

Ritwik Mondal, Marco Berritta, Ashis K. Nandy, and Peter M. Oppeneer, *Phys. Rev. B* **96**, 024425 (2017)

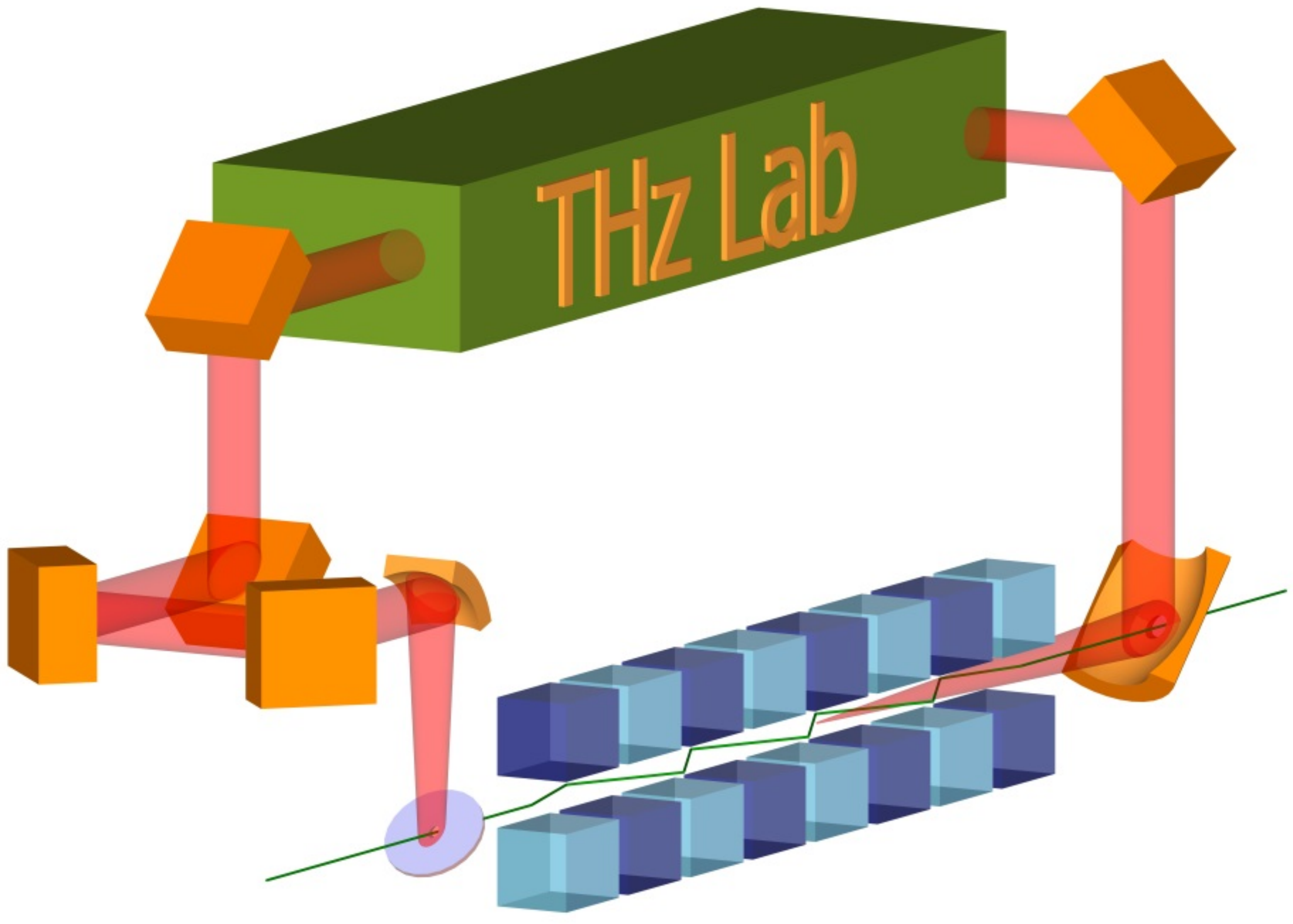
Ritwik Mondal, Sebastian Großenbach, Levente Rózsa, and Ulrich Nowak, *Phys. Rev. B* **103**, 104404 (2021)

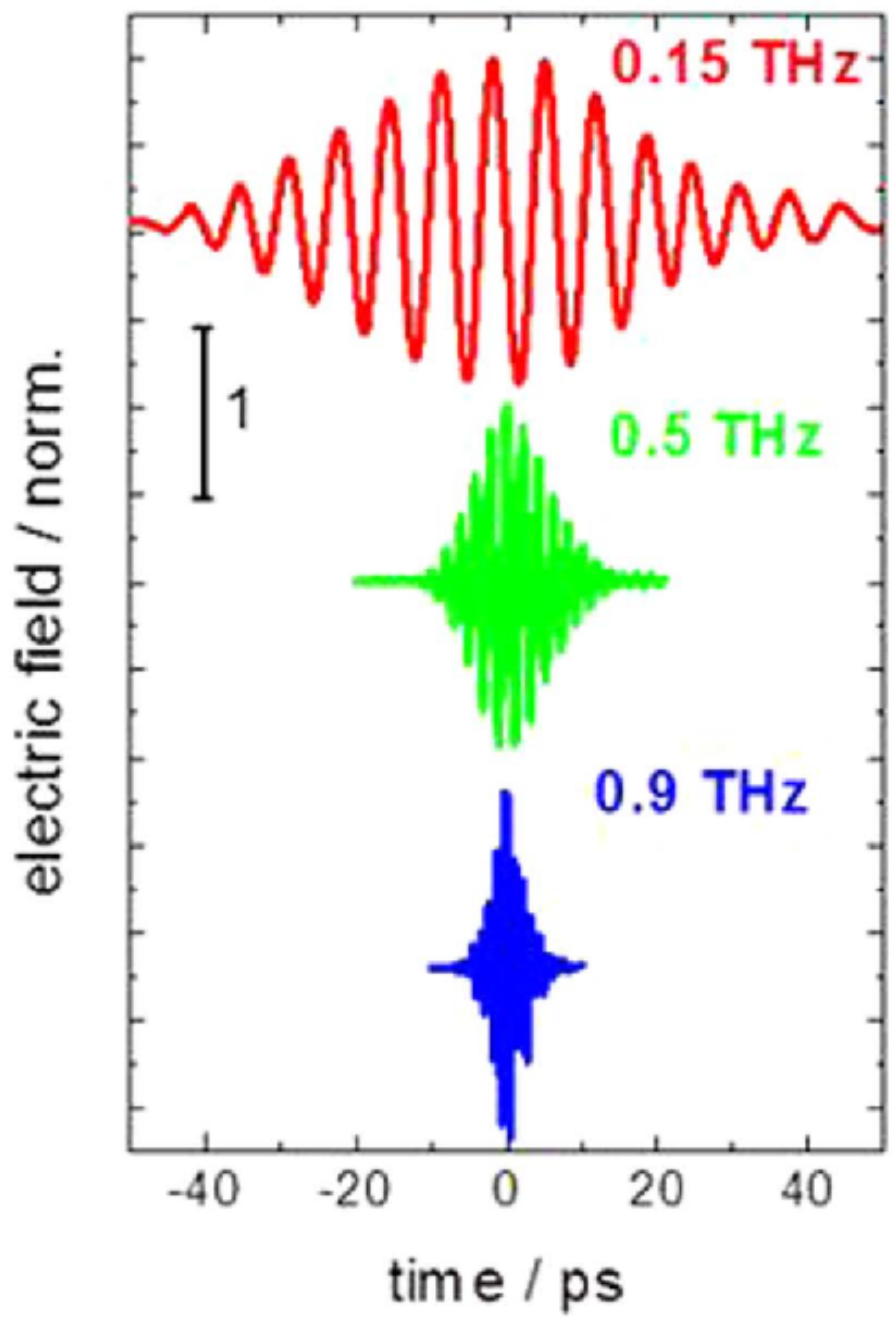
Inertial LLG equation

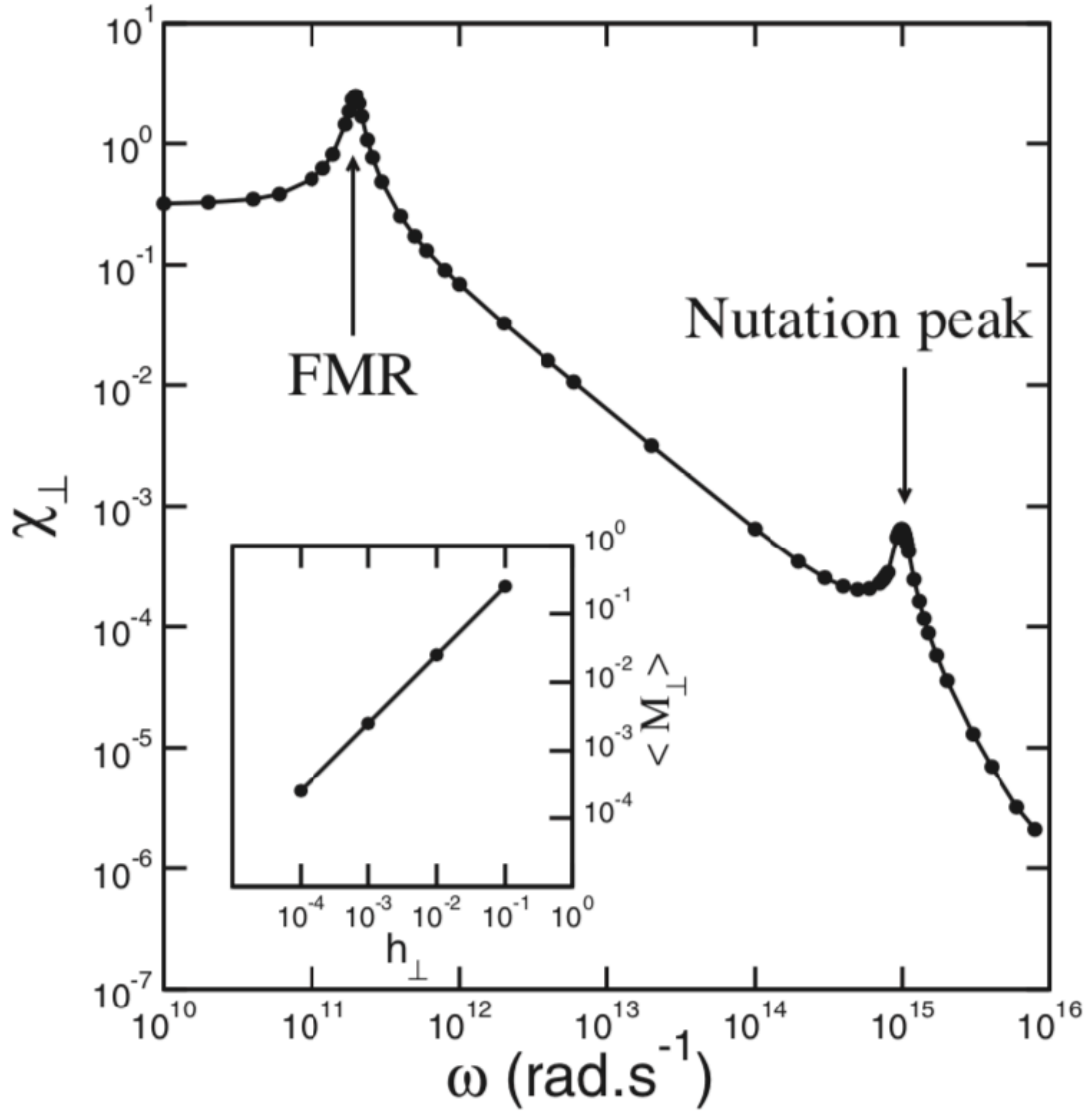


- 2017: met Jean-Eric at the Ultrafast Magnetism Conference
- In 2014 saw unexplained oscillations at 0.3 THz in a ferromagnet driven by THz fields
- Idea: ***forced oscillator experiment***. Facility TELBE was starting operation.

Terahertz spectroscopy at TELBE

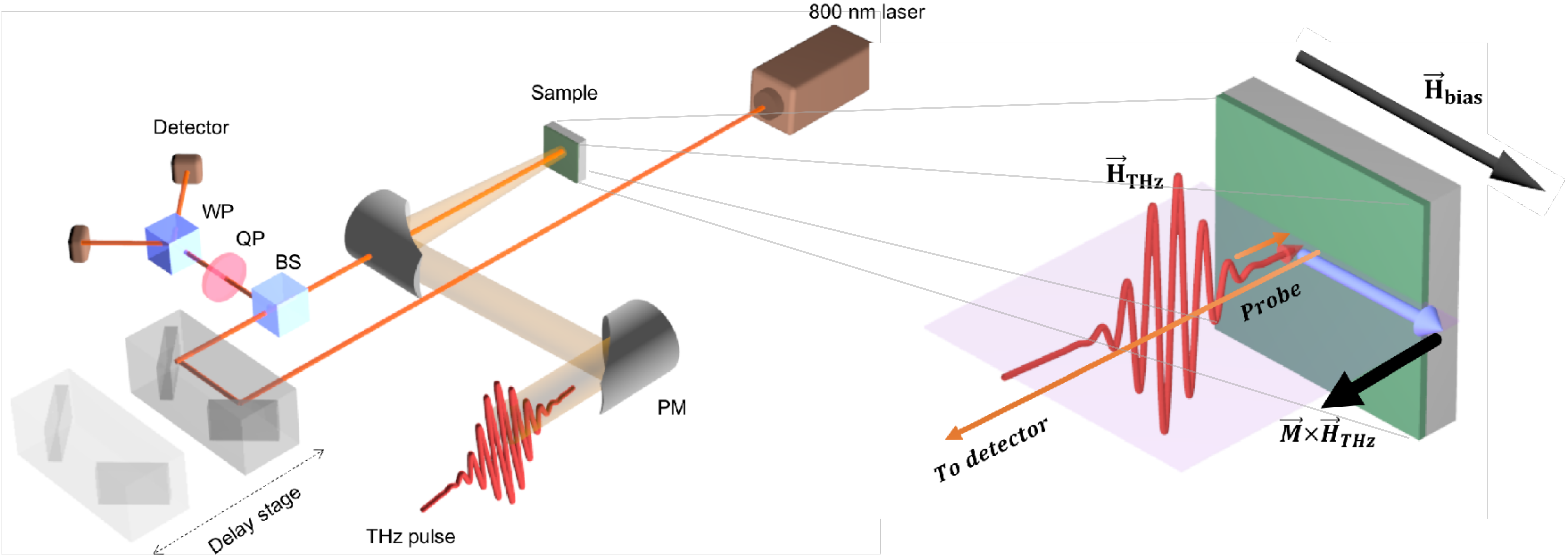




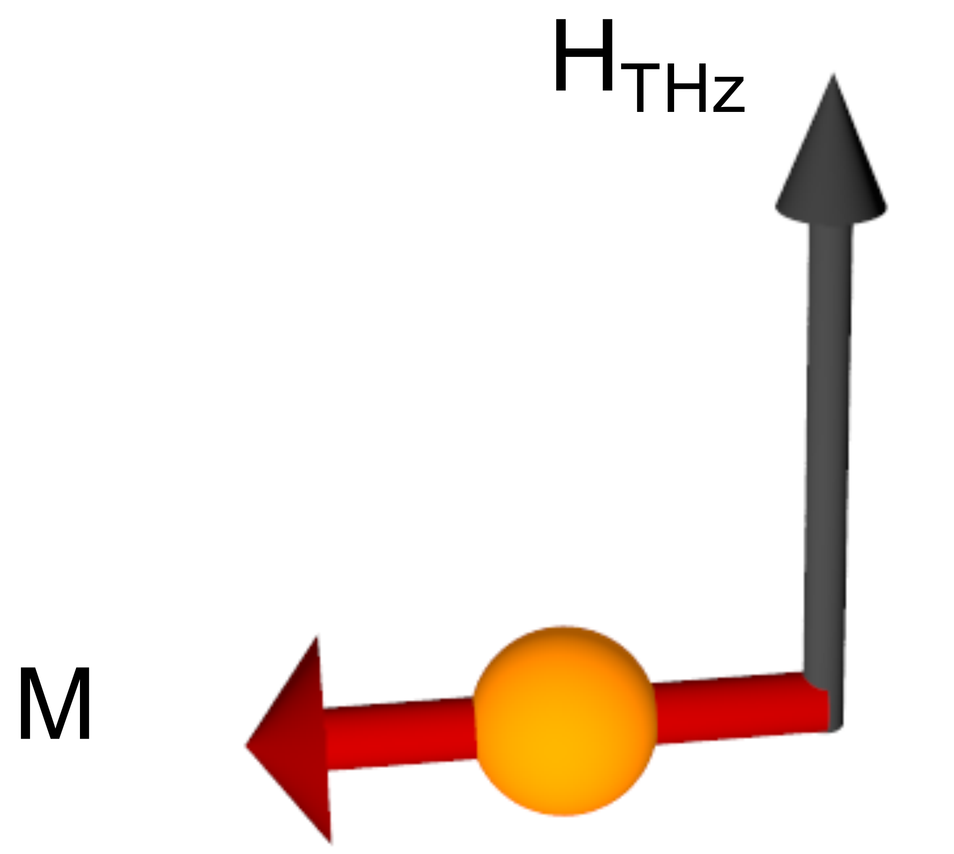


0.1 - 1.2 THz, 1 μJ

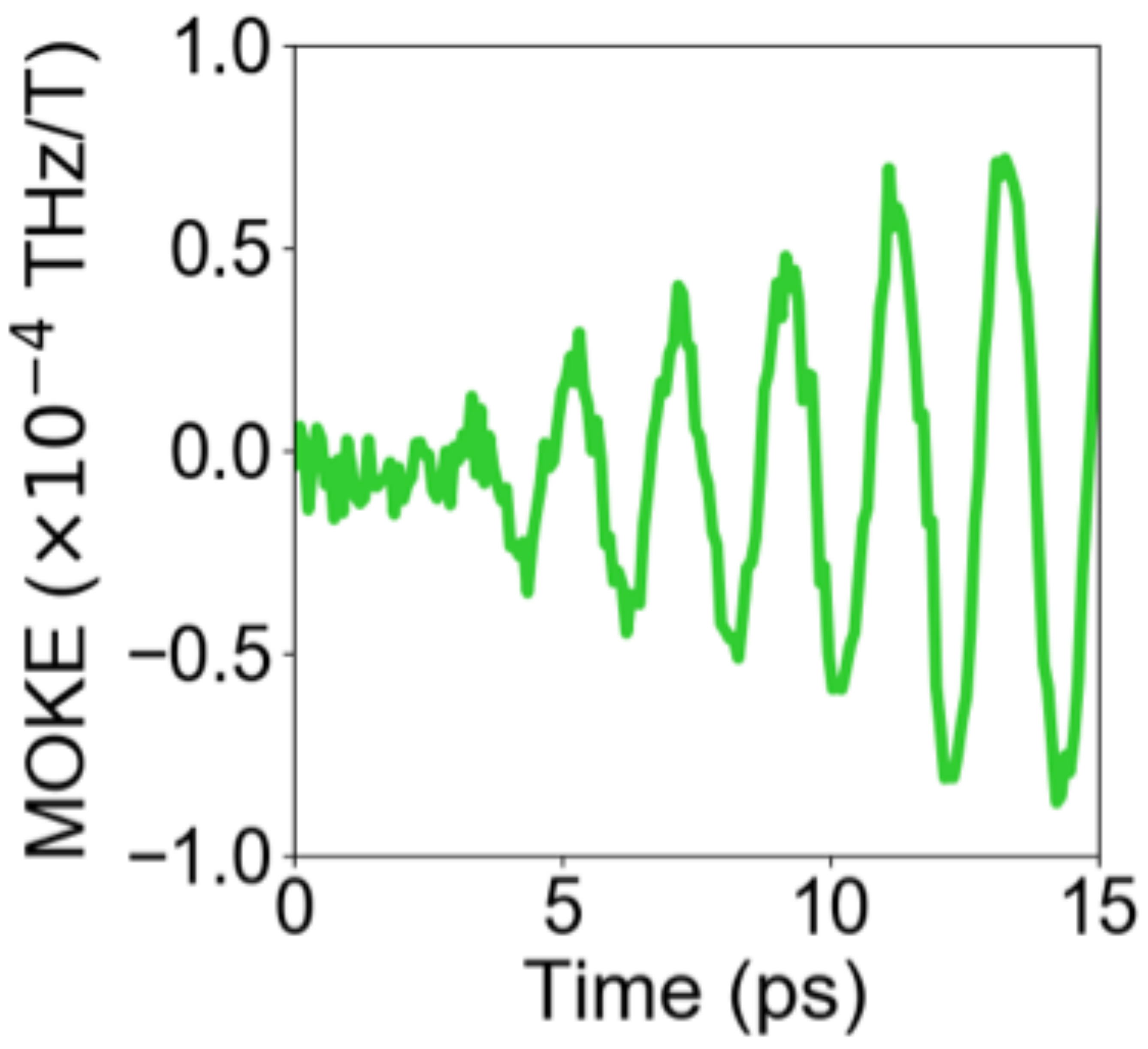
B. Green et al., “High-Field High-Repetition-Rate Sources for the Coherent THz Control of Matter”, *Scientific Reports* **6**, 22256 (2016)

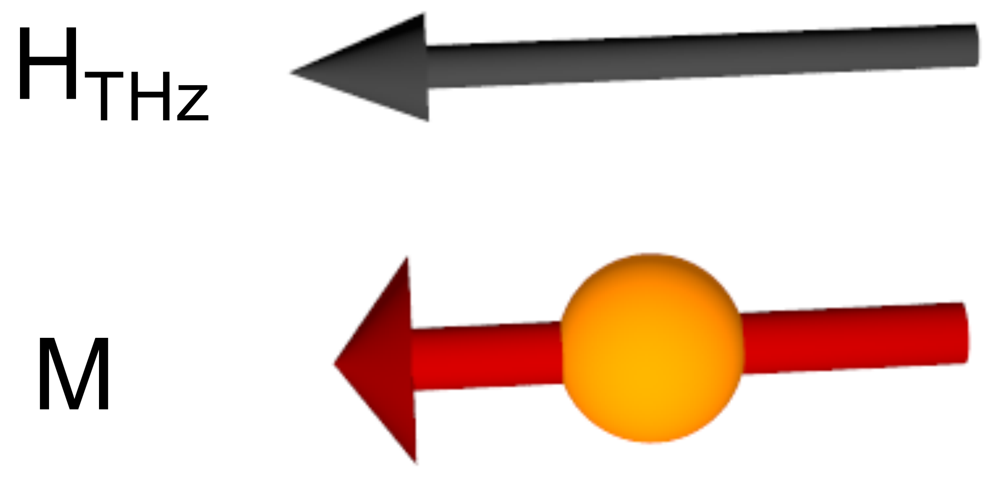


K. Neeraj et al., "Inertial spin dynamics in ferromagnets", *Nature Physics* **17**, 245 (2020)

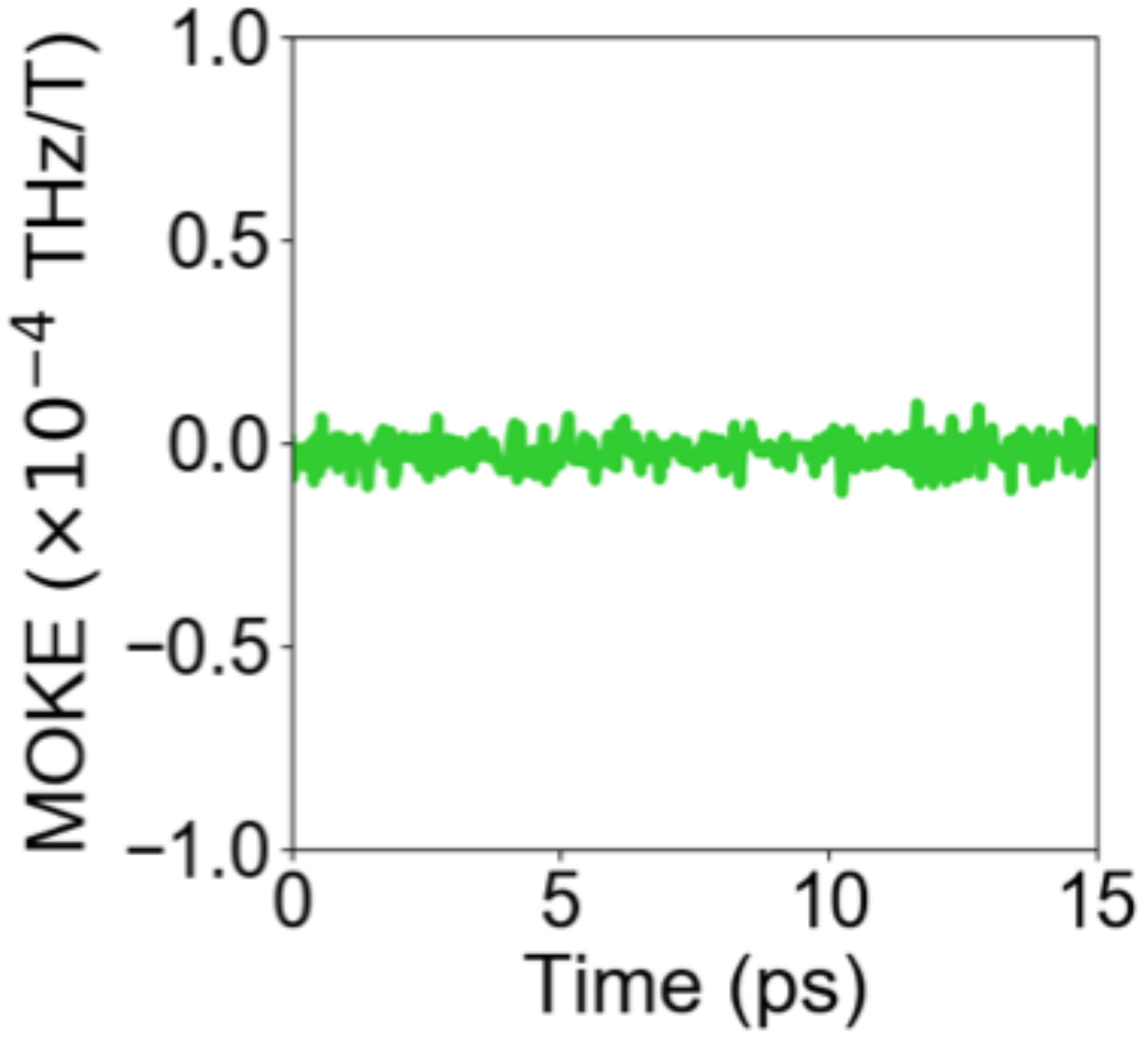


M x H_{THz} = max





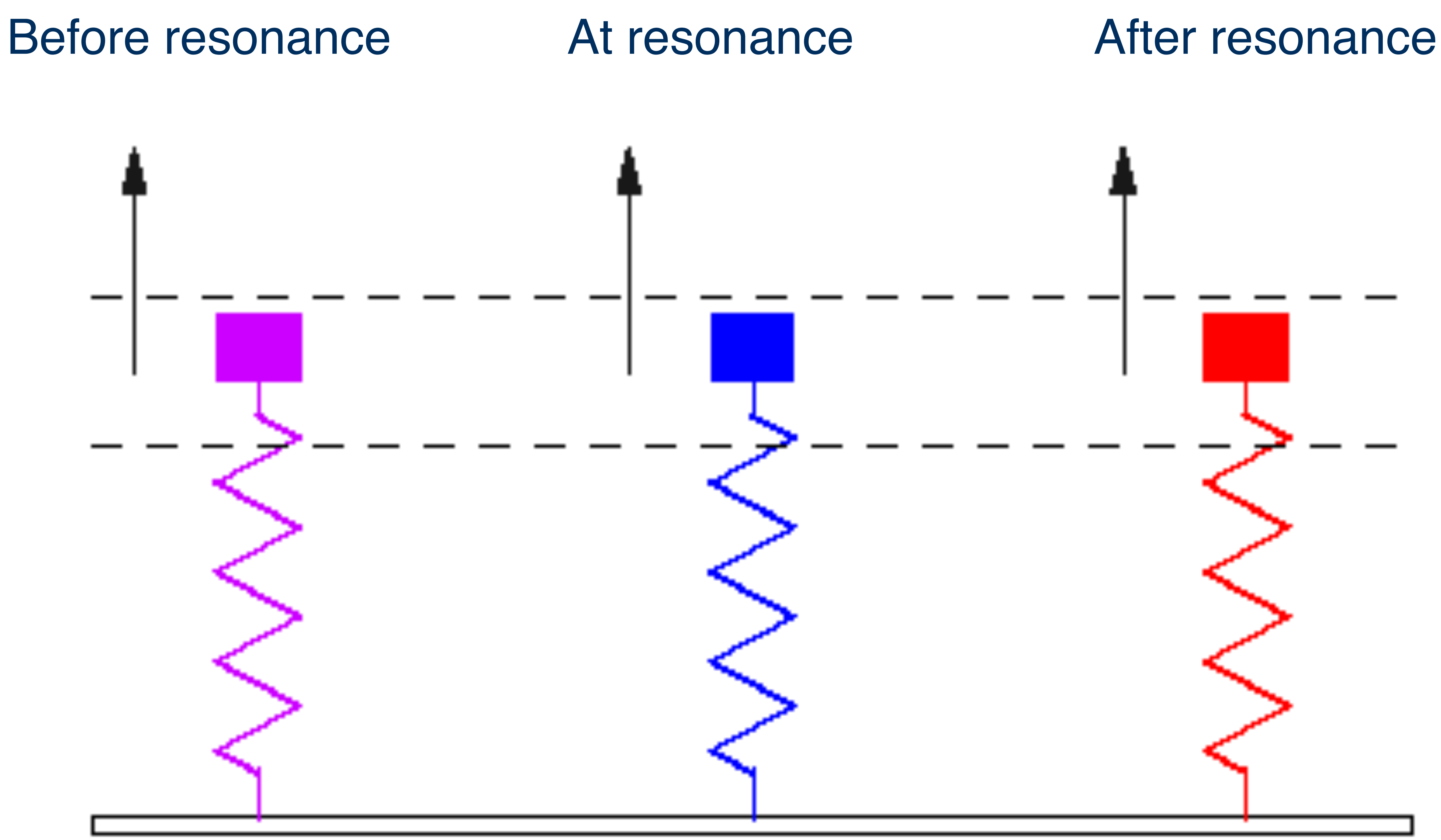
M x H_{THz} = 0



K. Neeraj et al., "Inertial spin dynamics in ferromagnets", *Nature Physics* **17**, 245 (2020)

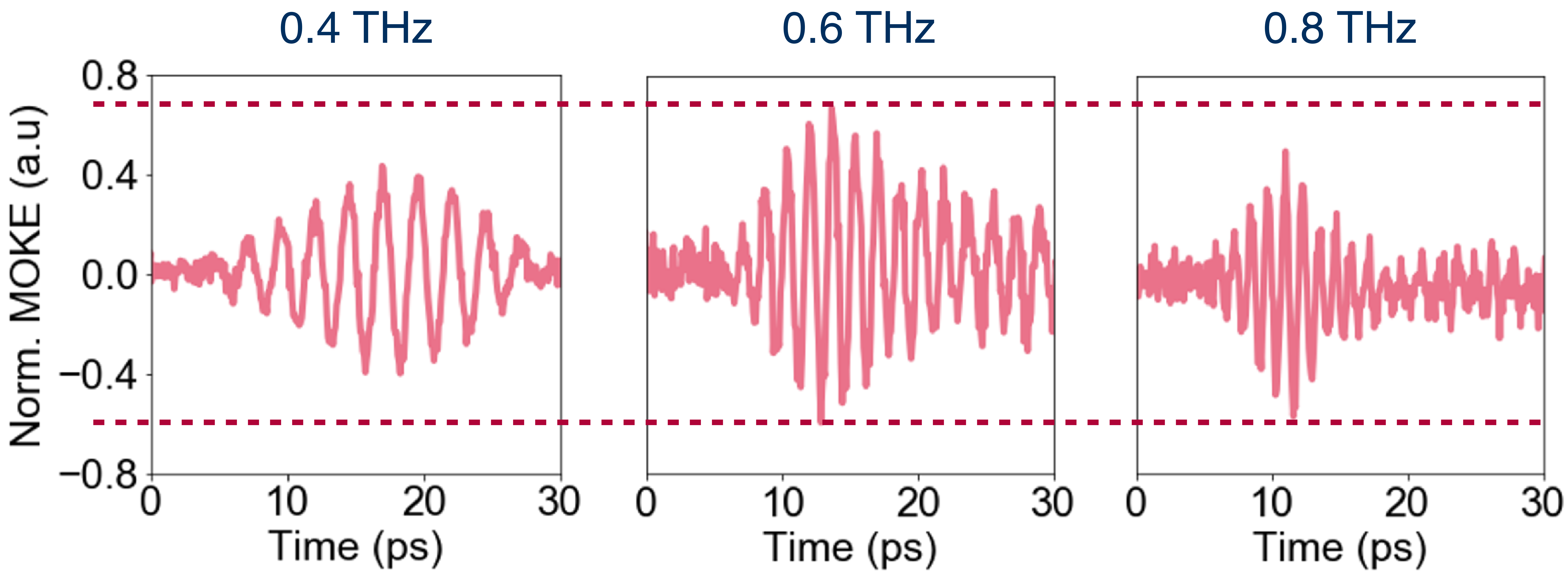
- Largest ***amplitude*** of response when driving force has same frequency of intrinsic resonance

- ***Phase*** shift between driving force and oscillator varies monotonously with frequency (90 degrees at resonance)



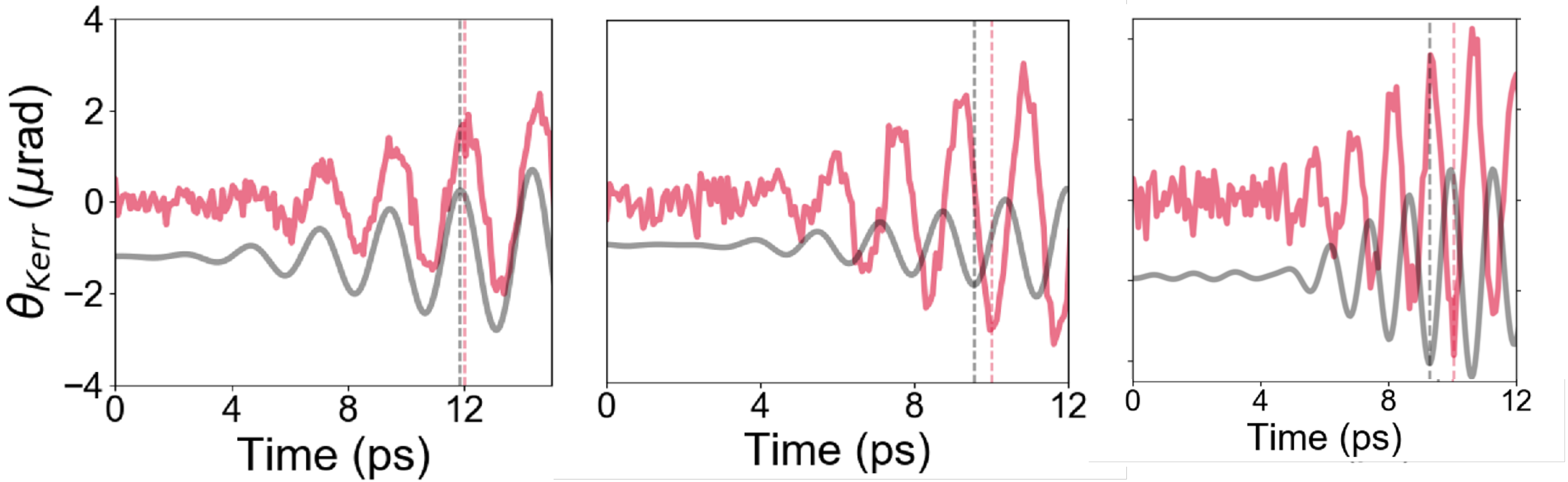
https://www.acs.psu.edu/drussell/Demos/SHO/mass-force.html

Amplitude response



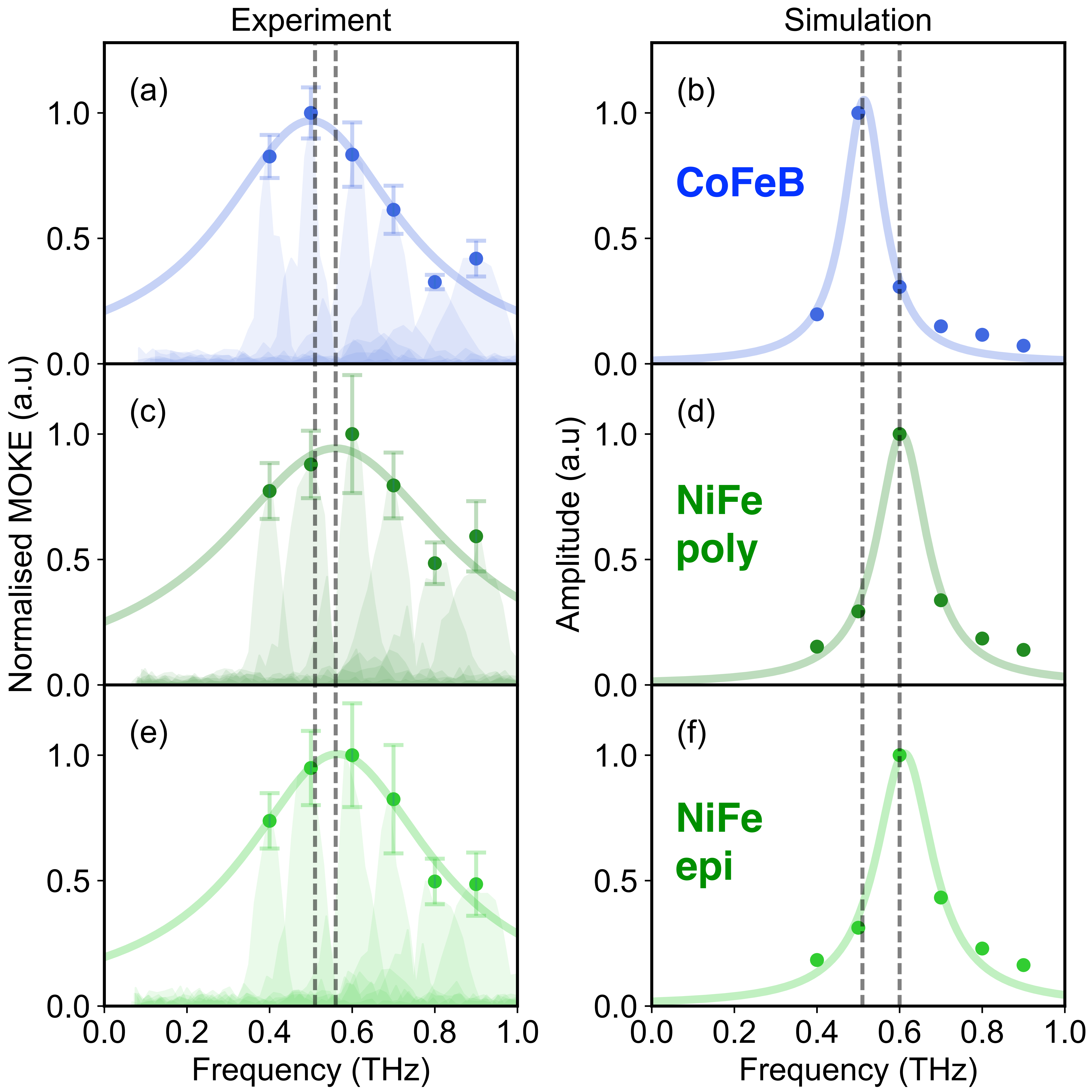
K. Neeraj et al., “Inertial spin dynamics in ferromagnets”, *Nature Physics* **17**, 245 (2020)

0.4 THz   0.6 THz   0.8 THz



K. Neeraj et al., “Inertial spin dynamics in ferromagnets”, *Nature Physics* **17**, 245 (2020)

FFT summary for three samples



- Forced resonance at 100-1000x higher frequency than FMR
- Peak shifts (slightly) for different materials
- Peak frequency and phase shift reproduced by inertial LLG, not linewidth

K. Neeraj et al., "Inertial spin dynamics in ferromagnets", *Nature Physics* **17**, 245 (2020)

Open issues

- Free nutation oscillations not yet observed
- Damping appears to be one order of magnitude larger than expected
- Relatively weak (~20%) material-dependent nutation frequency

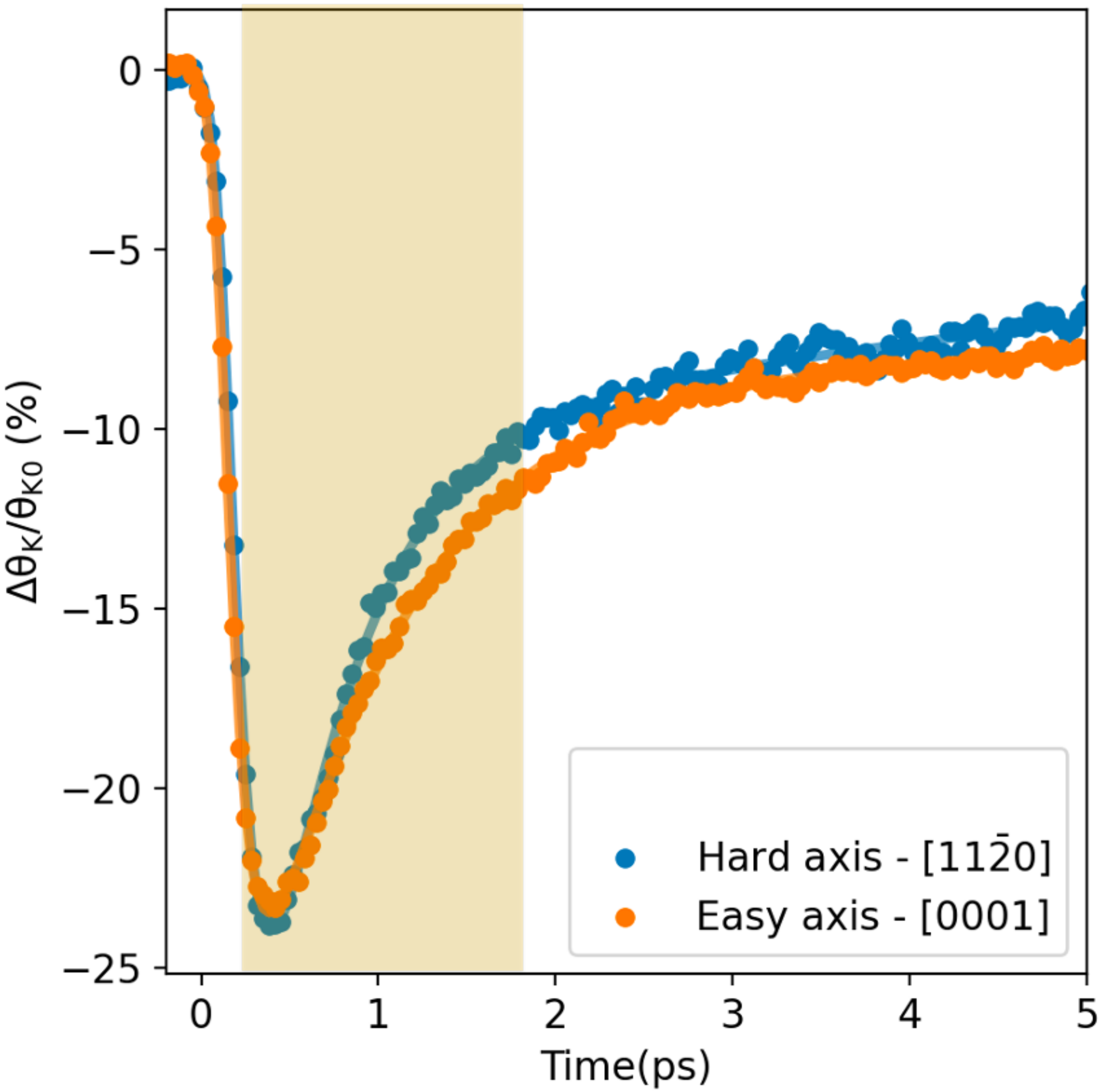
Next step

- Microscopically, inertial effects found when including higher-order spin-orbit terms in Dirac Hamiltonian

- Idea 1: let’s measure materials where we can control the magneto-crystalline anisotropy

- Idea 2: try with single-cycle, broadband intense THz fields (~1 MV/cm)

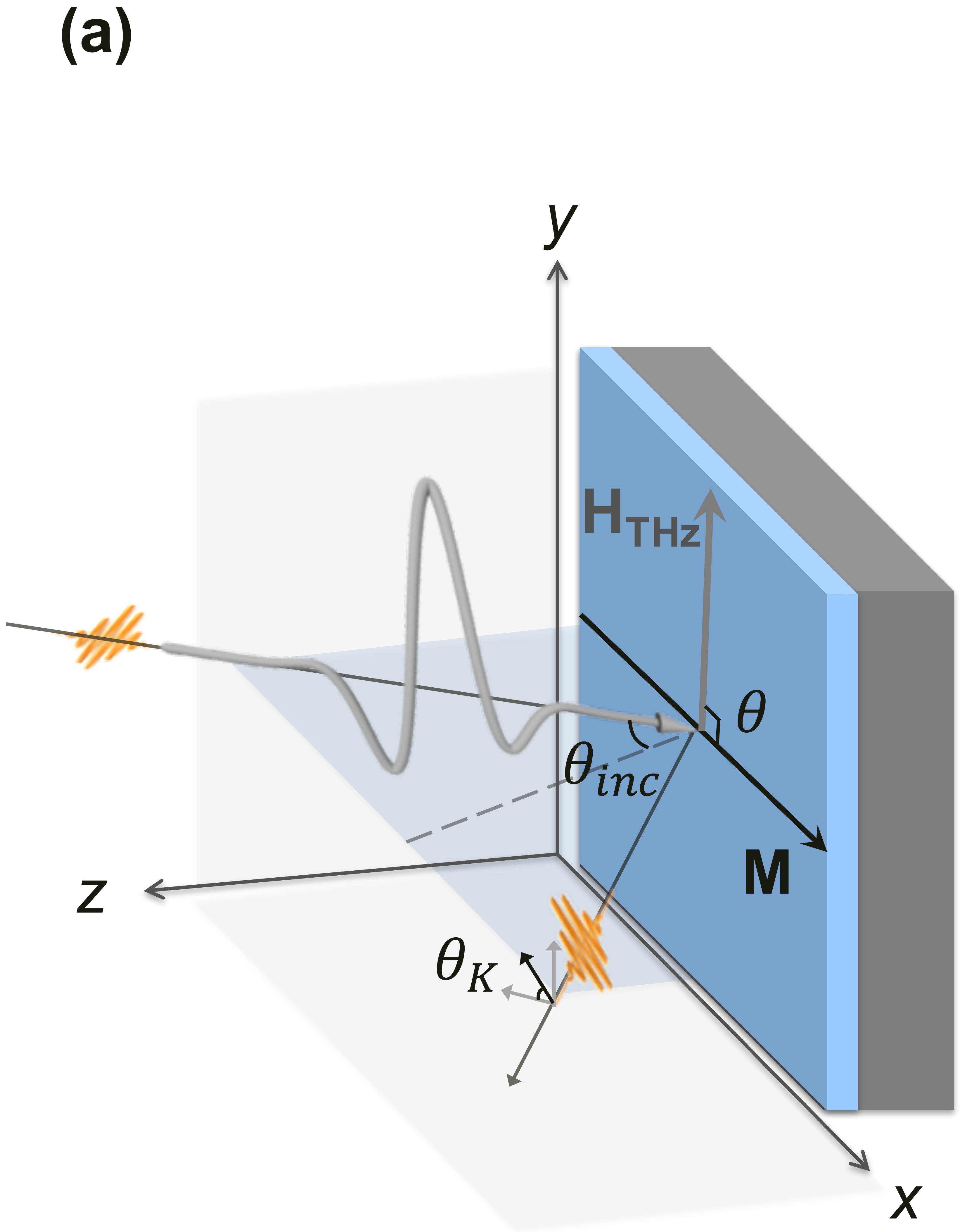
Anisotropy in ultrafast magnetism in epitaxial cobalt

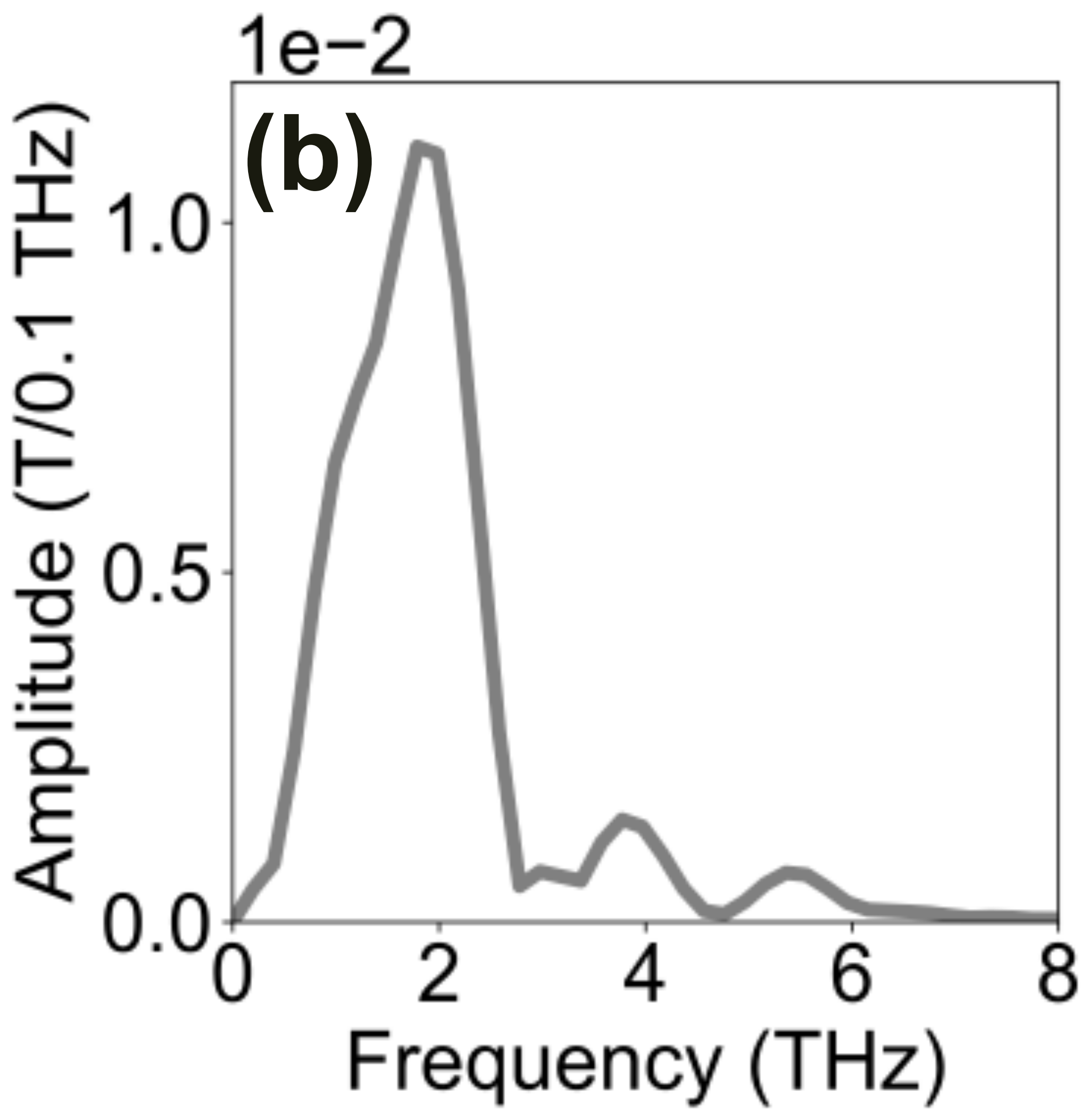


- pump hcp cobalt with NIR laser
- observe 35-40% faster magnetization dynamics along the hard axis than the easy one
- anisotropy found at demagnetization, recovery and precession time scales

V. Unikandanunni, R. Medapalli, E. E. Fullerton, K. Carva, P. M. Oppeneer, S. Bonetti, *Applied Physics Letters* **118**, 232404 (2021)

Compare three epitaxial cobalt films

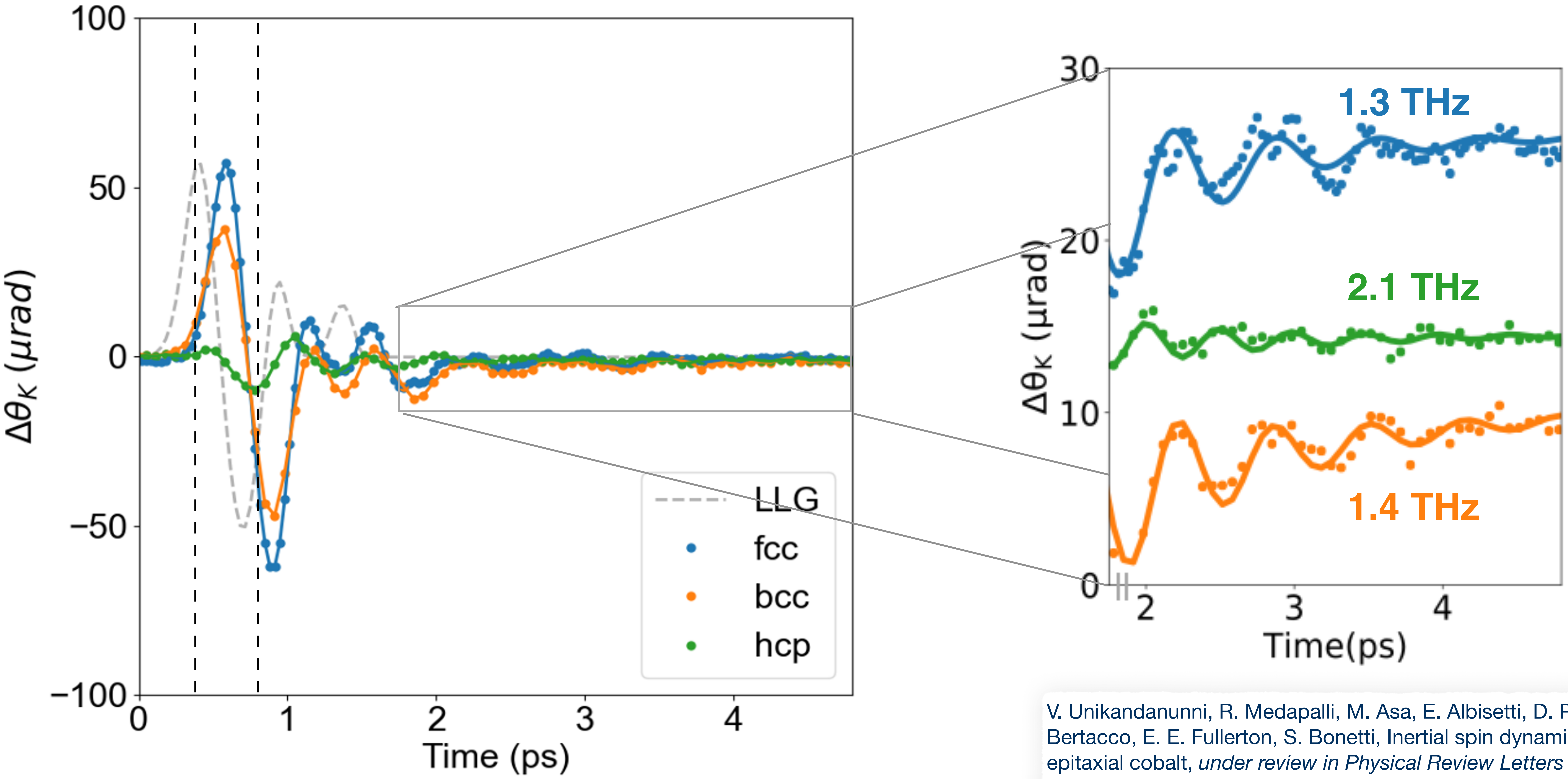




- Use broadband THz pump radiation centered at 1.5 THz
- Measure with time-resolved (~50 fs) MOKE
- Compare epitaxial fcc, bcc and hcp cobalt films

V. Unikandanunni, R. Medapalli, M. Asa, E. Albisetti, D. Petti, R. Bertacco, E. E. Fullerton, S. Bonetti, Inertial spin dynamics in epitaxial cobalt, *under review in Physical Review Letters* (2021) arXiv:2109.03076

Broadband THz magnetic response



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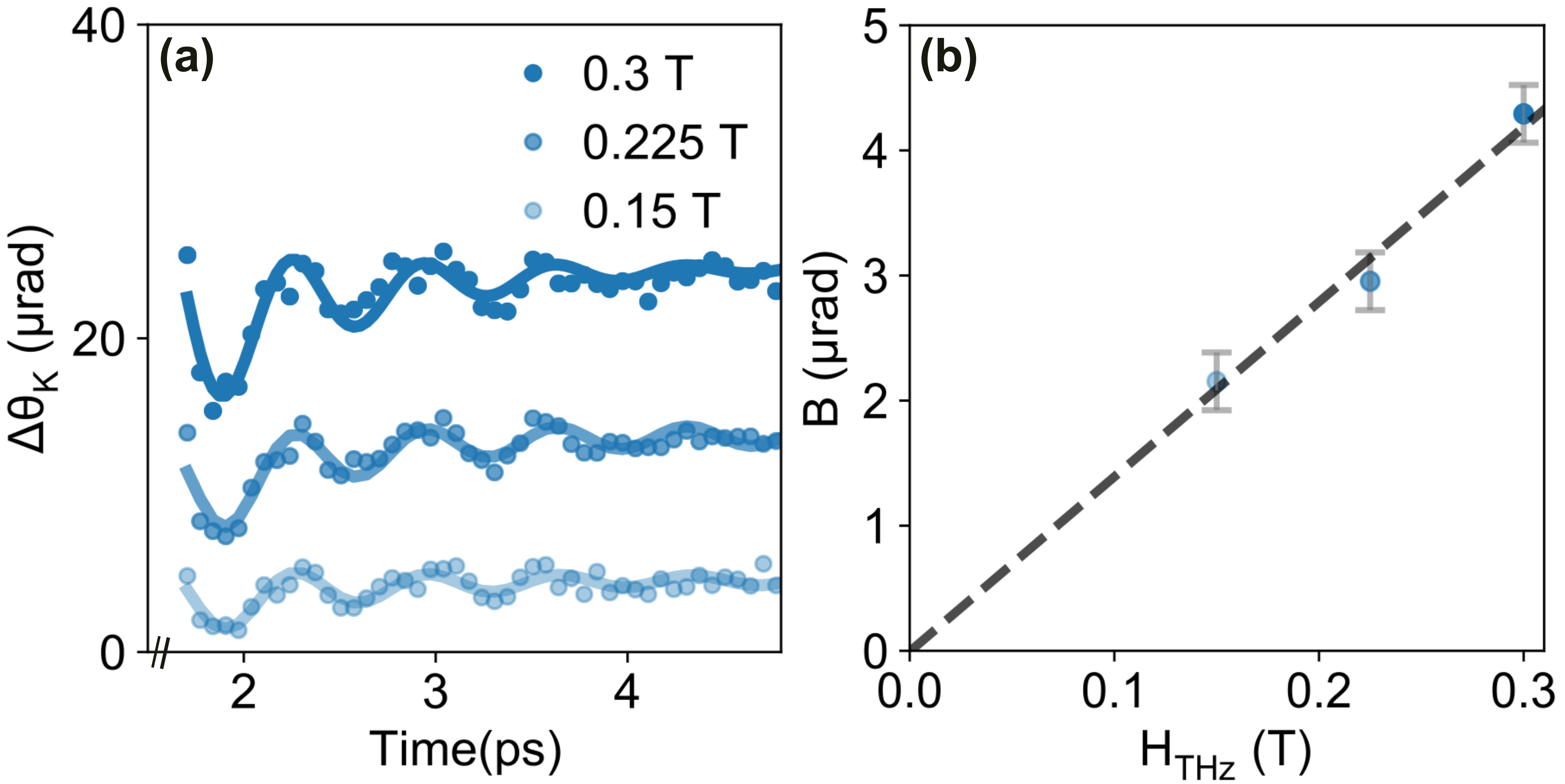
Magnetic origin, linear dependence



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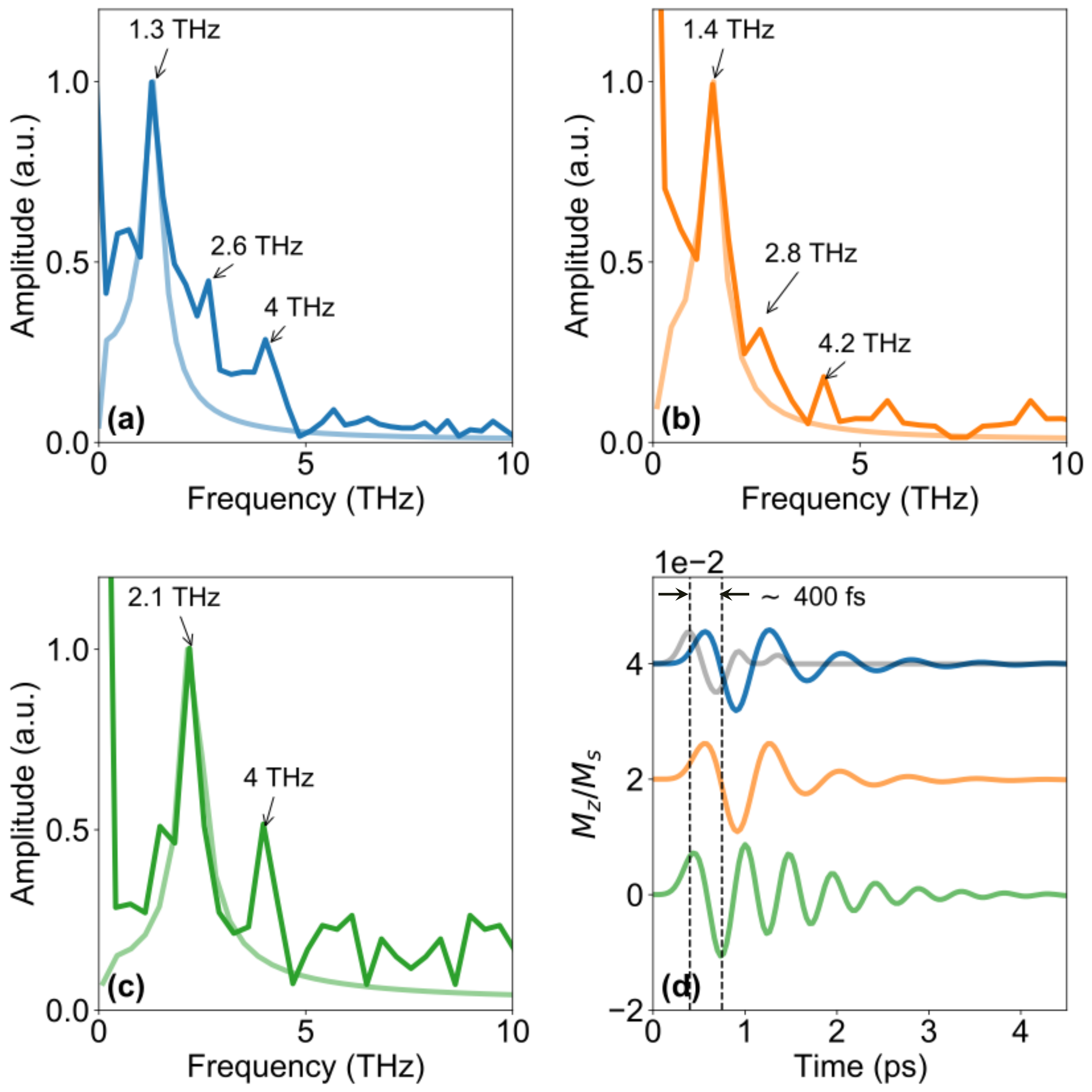
Frequency analysis



- Inertial LLG reproduces nutation frequency, linewidth and temporal shift
- Only input parameters: measured damping (10x Gilbert FMR damping) and tau
- Higher order harmonics not reproduced

V. Unikandanunni, R. Medapalli, M. Asa, E. Albisetti, D. Petti, R. Bertacco, E. E. Fullerton, S. Bonetti, Inertial spin dynamics in epitaxial cobalt, *under review in Physical Review Letters* (2021) arXiv:2109.03076

$$\mathcal{H} = c\underline{\boldsymbol{\alpha}} \cdot (\boldsymbol{p} - e\boldsymbol{A}) + (\underline{\beta} - \underline{\mathbb{1}})mc^2 + V\underline{\mathbb{1}}$$

$$\mathcal{H}^S = -\frac{e}{m}\boldsymbol{S}\cdot\boldsymbol{B} + \frac{e}{2m^3c^2}\boldsymbol{S}\cdot\boldsymbol{B}\left[p^2 - 2e\boldsymbol{A}\cdot\boldsymbol{p} + \frac{3e^2}{2}A^2\right]$$

$$- \frac{e}{2m^2c^2}\boldsymbol{S}\cdot[\boldsymbol{E}_{\text{tot}} \times (\boldsymbol{p} - e\boldsymbol{A})] + \frac{ie\hbar}{4m^2c^2}\boldsymbol{S}\cdot\partial_t\boldsymbol{B}$$

$$+ \frac{e\hbar^2}{8m^3c^4}\boldsymbol{S}\cdot\partial_{tt}\boldsymbol{B}$$

Ritwik Mondal, Marco Berritta, Ashis K. Nandy, and Peter M. Oppeneer, *Phys. Rev. B* **96**, 024425 (2017)

$$\frac{d\mathrm{M}}{dt} = \mathrm{M} \times \left(-\gamma_0 \mathrm{H}_{\mathrm{eff}} + \Gamma \frac{d\mathrm{M}}{dt} + I \frac{d^2\mathrm{M}}{dt^2} \right)$$

Dependent on magneto-crystalline anisotropy

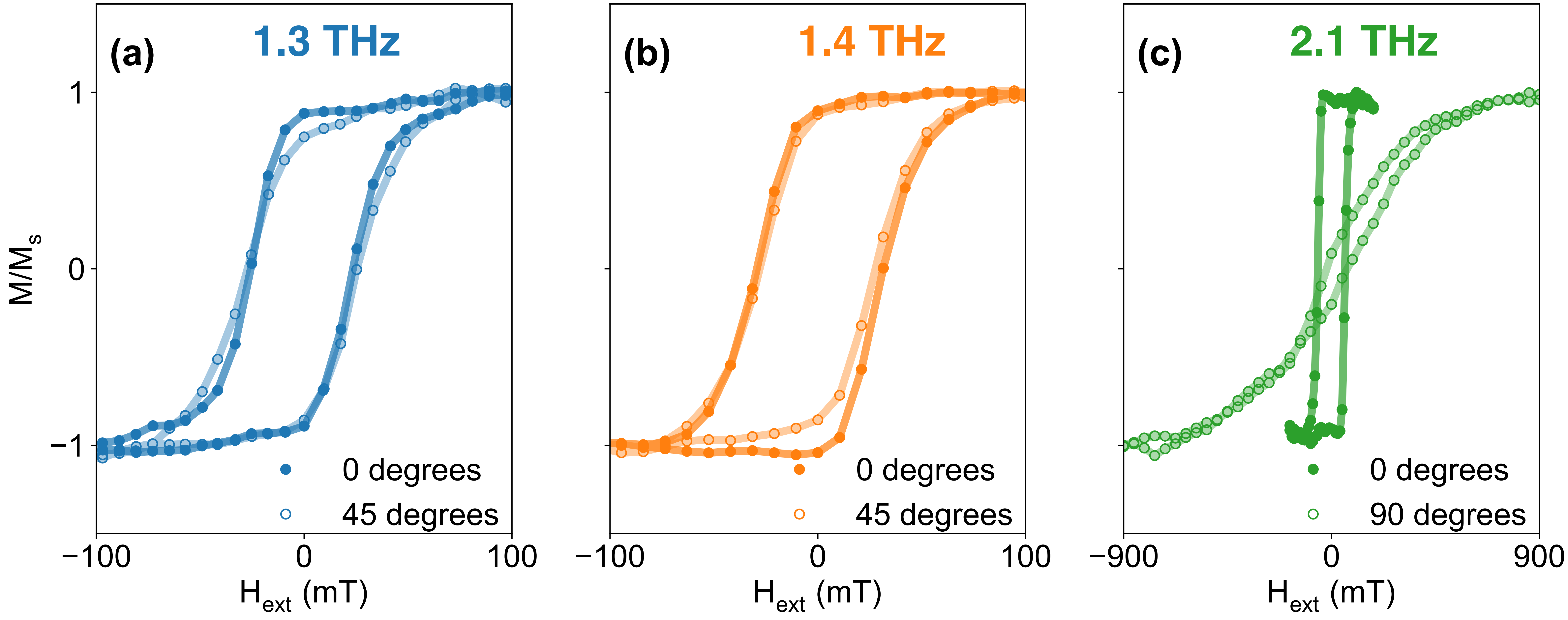
$$\Gamma_{ij} = A_{ij} + \mu_0 \delta \partial_t \left(\chi_m^{-1} \right)_{ij}$$

$$I_{ij} = \mu_0 \delta \left(1 + \chi_m^{-1} \right)_{ij}$$

$$\frac{I}{\Gamma} = 746 \pm 46 \text{ fs}$$

Only one free parameter needed for inertial LLG to reproduce experiments!

Magneto-crystalline anisotropy and nutation frequency



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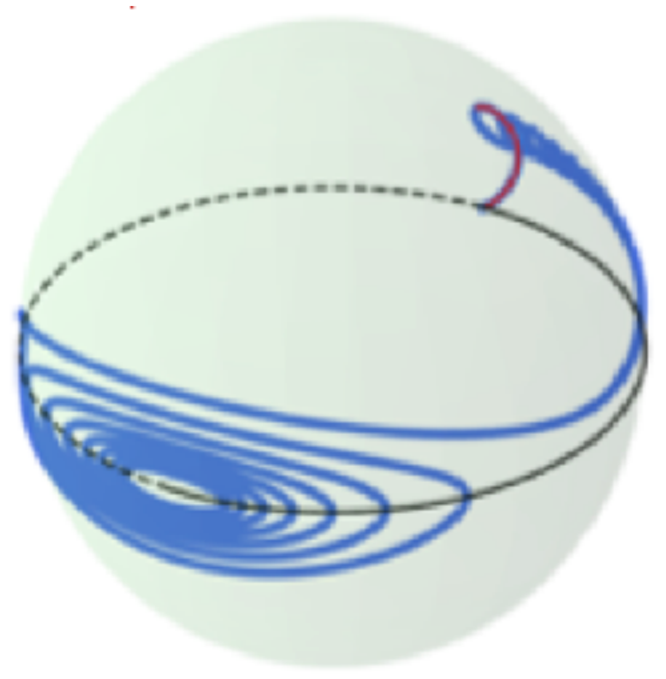
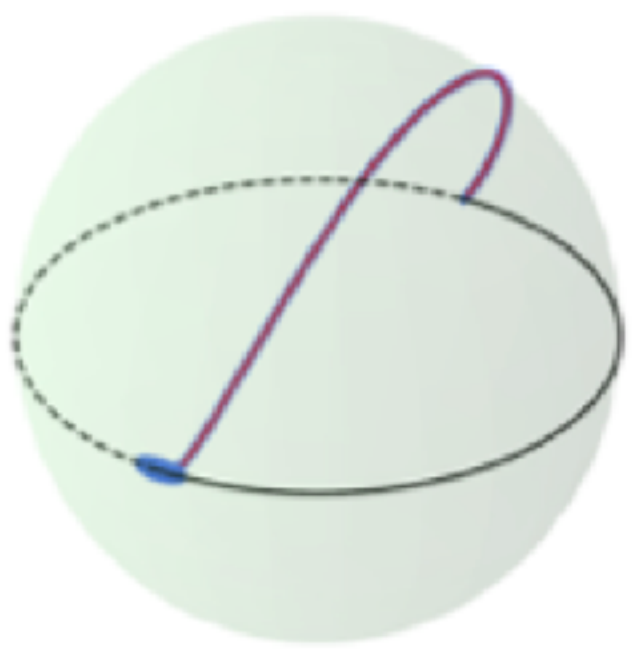
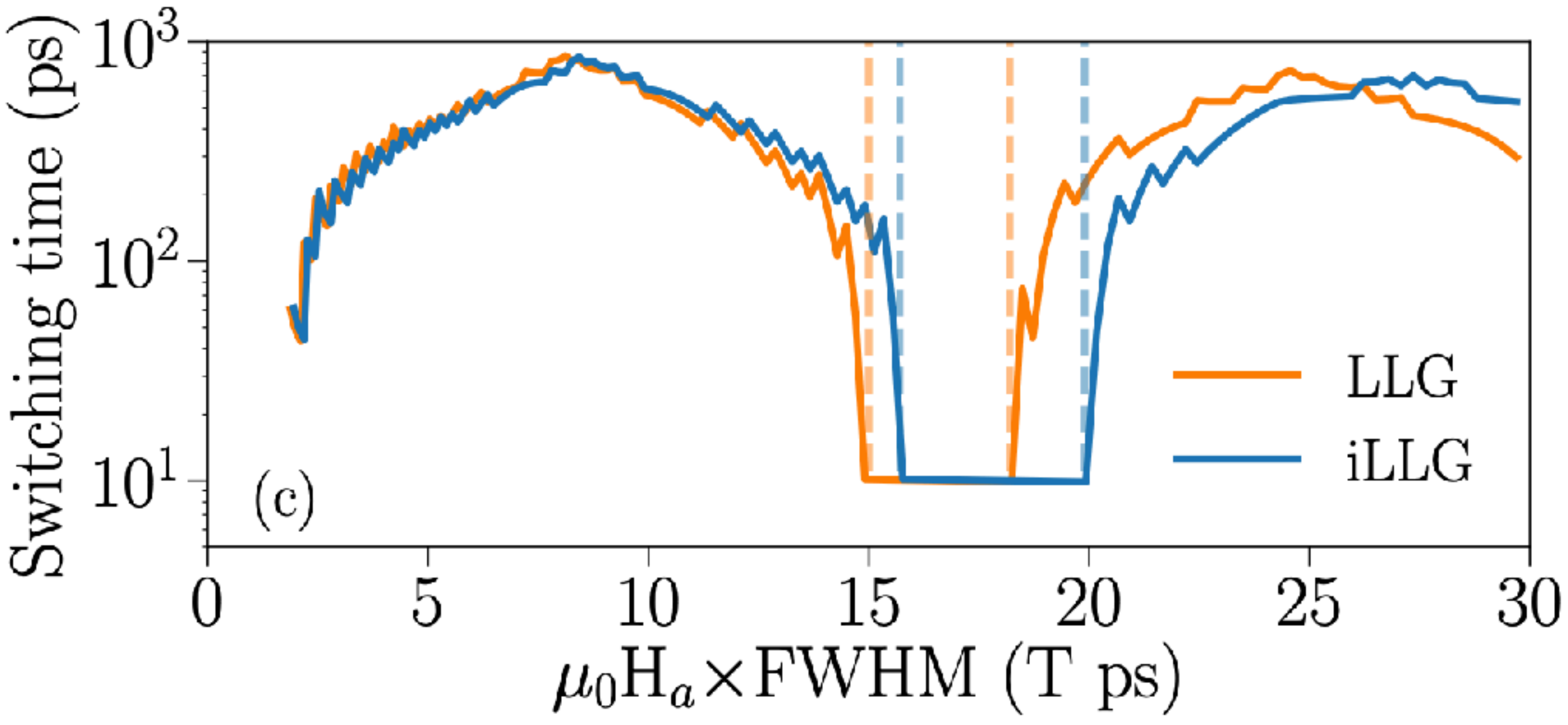


Precessional switching



Ballistic switching



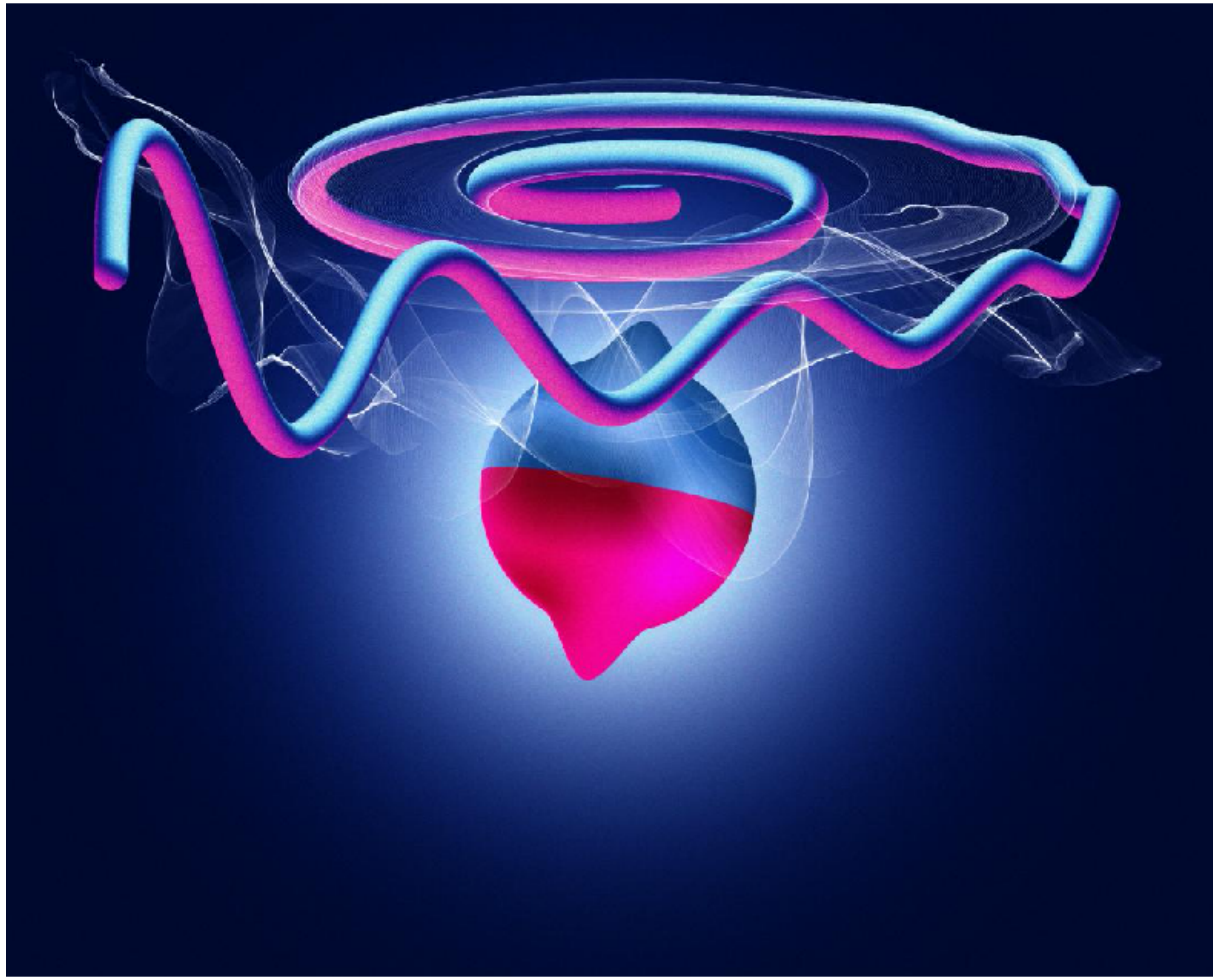
K. Neeraj et al., “Magnetization switching in the inertial regime”, under review in *Physical Review B* (2021), arXiv:2107.08234

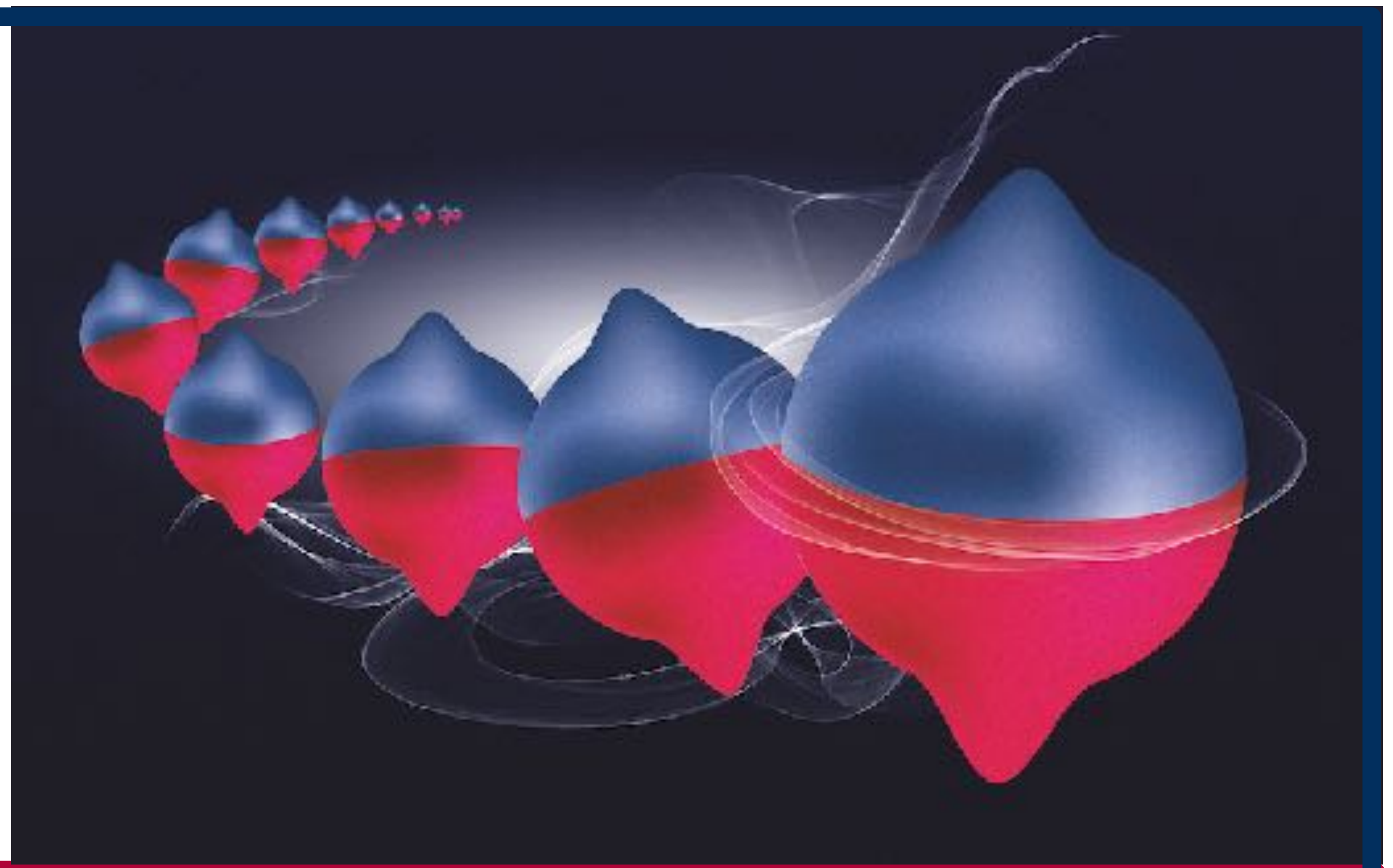
Inertia broadens the magnetic field range of ballistic switching via coherent torques

Looking forward: open questions

- Why is the nutation damping much larger than the FMR Gilbert damping?
- How do we understand the higher harmonics of the nutation?
- Can we test the magneto-crystalline hypothesis in other materials?
- Can inertial effects be controlled with sample engineering?

Thank you for listening!





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