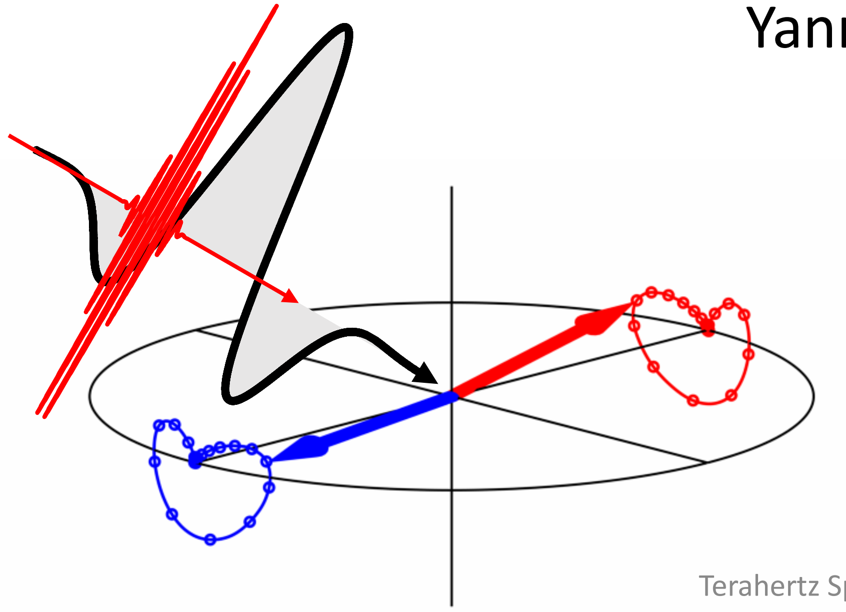
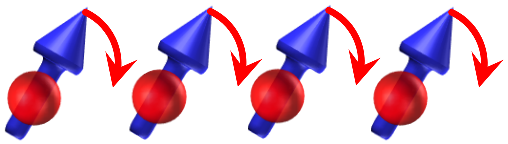
Terahertz Néel spin-orbit torques drive nonlinear spin dynamics in antiferromagnetic Mn_2Au

Yannic Behovits, FU Berlin



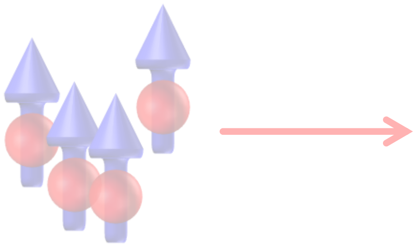
Terahertz spintronics: Basic operations

1. **Turn spins around**

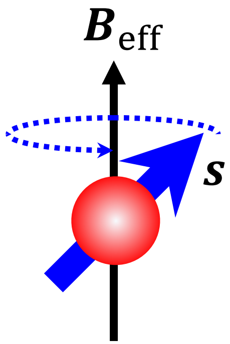


$\rightarrow$ Torque

2. **Transport spins**



3. **Detect spin dynamics**



Dynamic equation: $\partial_t \boldsymbol{s} = \boldsymbol{T} = \gamma \boldsymbol{s} \times \boldsymbol{B}_{\text{eff}}(t)$ ← Effective magnetic field

Contributions to $\boldsymbol{B}_{\text{eff}}$:

1. Applied field
2. Spin-orbit
3. Exchange

Applied field, Spin-orbit: Typically $\leq 1\,\mathrm{T}$

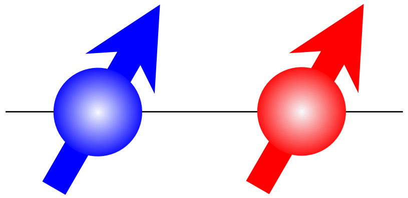
Exchange: $100 - 1000\,\mathrm{T}$

Exchange fields greatly enhance spin dynamics

Can we exploit them?

Exchange torques

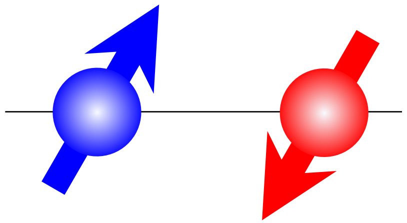
Ferromagnet



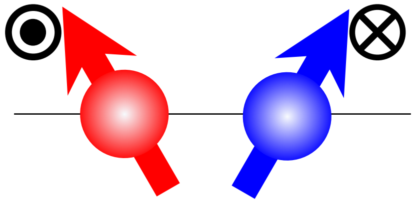
$\boldsymbol{T}_{\mathrm{ex}} = 0$

Spins parallel → No exchange torques

Antiferromagnet

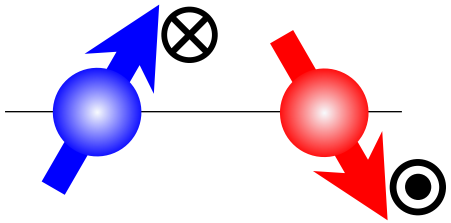


$\boldsymbol{T}_{\mathrm{ex}} = 0$



$\boldsymbol{T}_{\mathrm{ex}} \neq 0$

Spin canted → Exchange torques

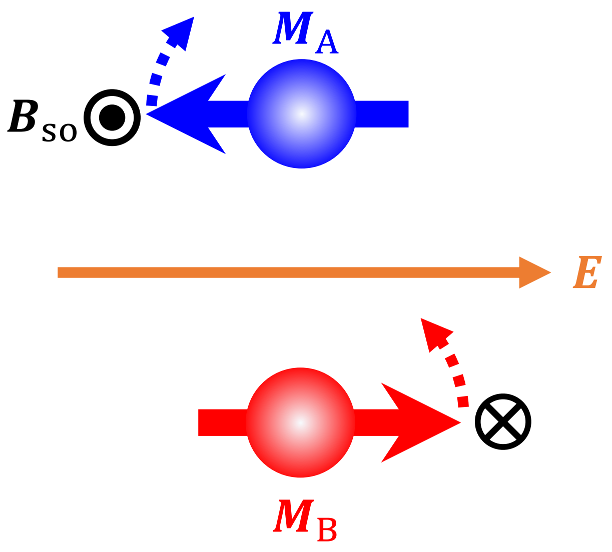


$\boldsymbol{T}_{\mathrm{ex}} \neq 0$

How to cant the spins in the first place?

In antiferromagnets: **Néel spin-orbit torques**

Néel spin-orbit torques (NSOTs)



Néel vector $\boldsymbol{L} = \boldsymbol{M}_\mathrm{A} - \boldsymbol{M}_\mathrm{B}$

Metallic antiferromagnets Mn_2Au and CuMnAs

Apply electric field $\boldsymbol{E}$ → Effective spin-orbit field $\boldsymbol{B}_\mathrm{so}$

Locally broken inversion symmetry:

- Opposite $\boldsymbol{B}_\mathrm{so}$ for A and B
- Torques induce spin canting

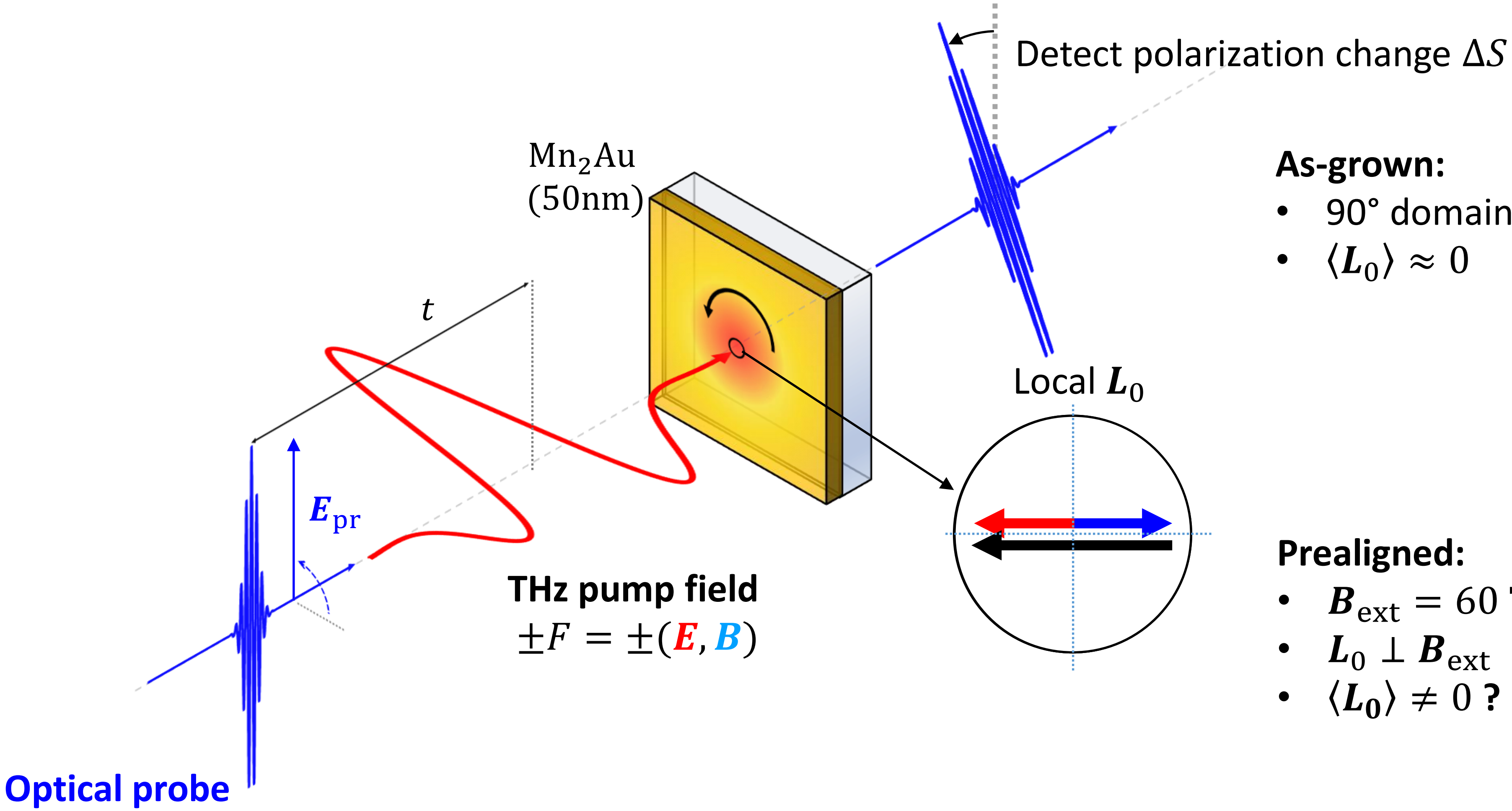
Leads to exchange-enhanced dynamics

Zelezny et al, PRB (2014)
Wadley et al., Science (2016)

1. Can NSOTs launch THz magnons?
2. Ultimately, can they switch antiferromagnetic bits?

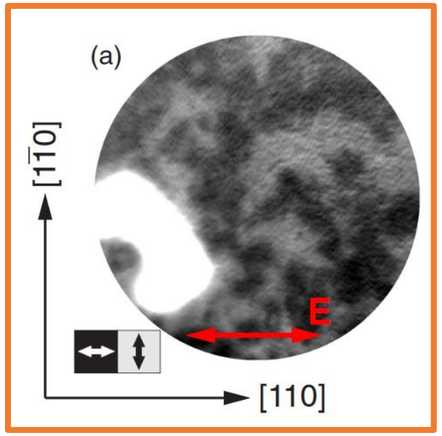
Requires ultrafast experiments

THz pump, magneto-optic probe



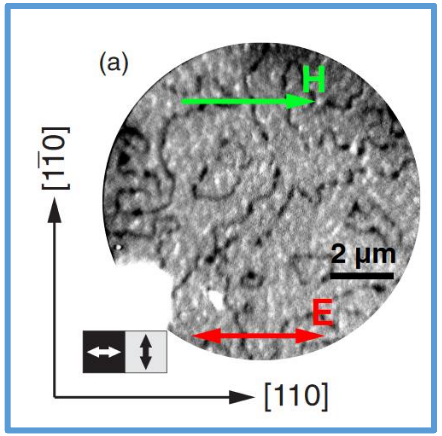
As-grown:

- 90° domains
- $\langle \boldsymbol{L}_0 \rangle \approx 0$



Prealigned:

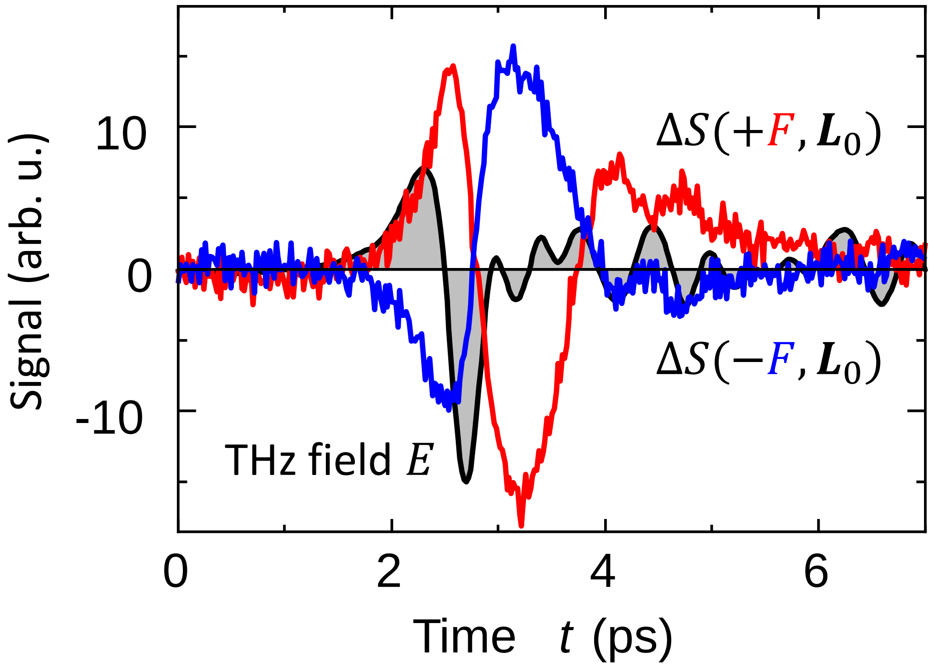
- $\boldsymbol{B}_{\mathrm{ext}} = 60\ \mathrm{T}$
- $\boldsymbol{L}_0 \perp \boldsymbol{B}_{\mathrm{ext}}$
- $\langle \boldsymbol{L}_0 \rangle \neq 0$ **?**

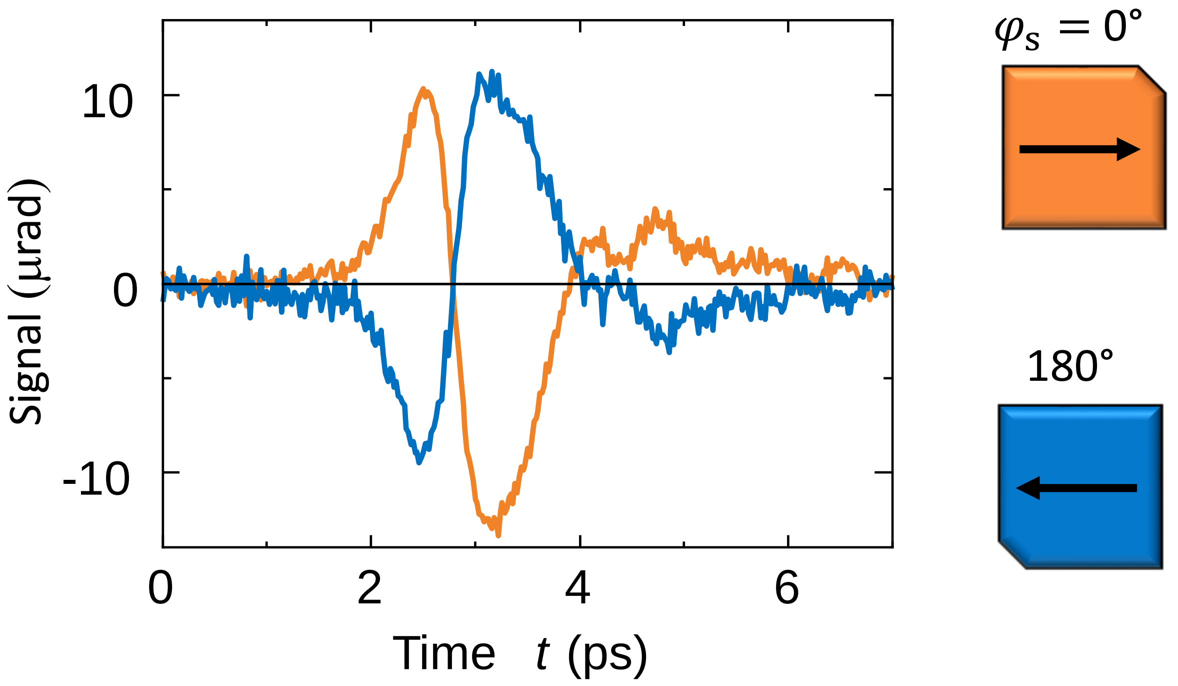


Sapozhnik et al. PRB **97**, 134429 (2018)

Let us look at the signals from the prealigned sample

Raw signals: Prealigned sample





- Response slower than $F(t)$
- Signal is mostly odd in THz field F
- Focus on:

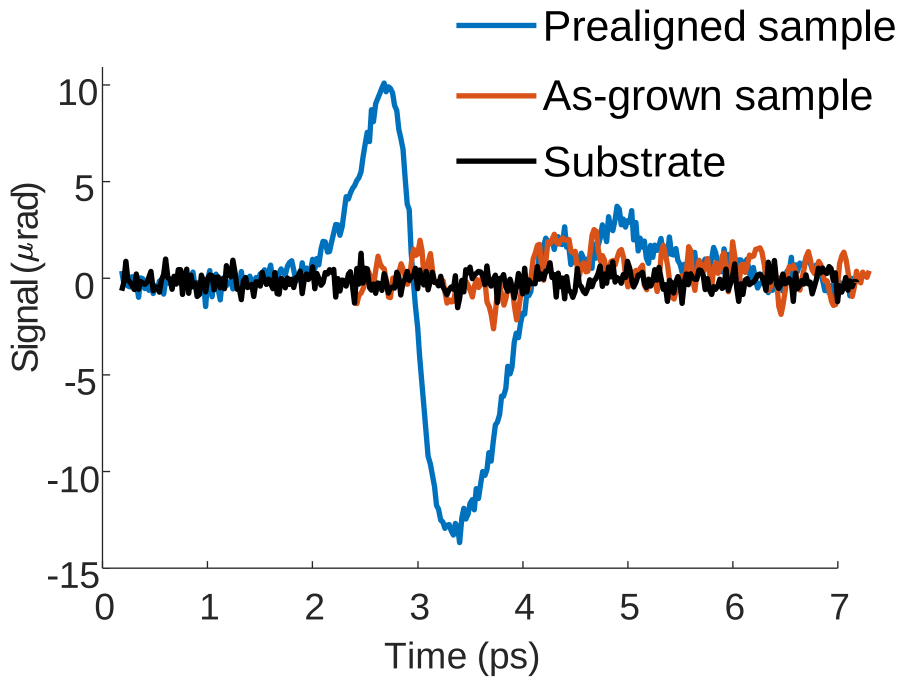
$$\Delta S(\boldsymbol{L}_0) = \frac{\Delta S(+F, \boldsymbol{L}_0) - \Delta S(-F, \boldsymbol{L}_0)}{2}$$

Rotate sample by 180° → Signal changes sign

"Built-in arrow": Is it the Néel vector $\boldsymbol{L}_0$?

YB, Chekhov, Kampfrath et al. Nature Commun. **14**, 6083 (2023)

Magnetic origin?



- "Built-in arrow" is $\boldsymbol{L}_0$
- Signal ΔS odd in $F = (\boldsymbol{E}, \boldsymbol{B})$ **and** odd in $\boldsymbol{L}_0$

Which field is acting?

Symmetry analysis:

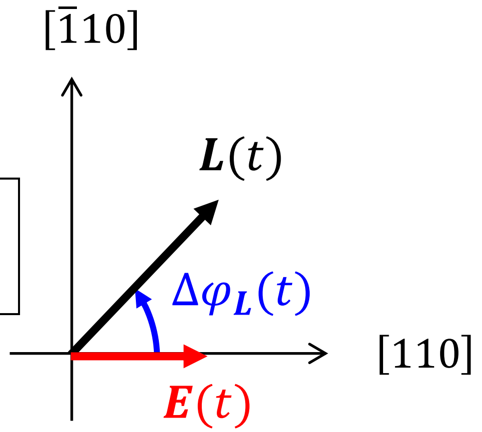
- Space inversion: $\boldsymbol{L}_0$ and THz $\boldsymbol{E}$ change sign, $\boldsymbol{B}$ does not
- Implies: $\Delta S \propto \boldsymbol{E} \Leftrightarrow \Delta S \propto \boldsymbol{L}_0$

In general: „Odd"

Further analysis (incl. probe polarization) shows:

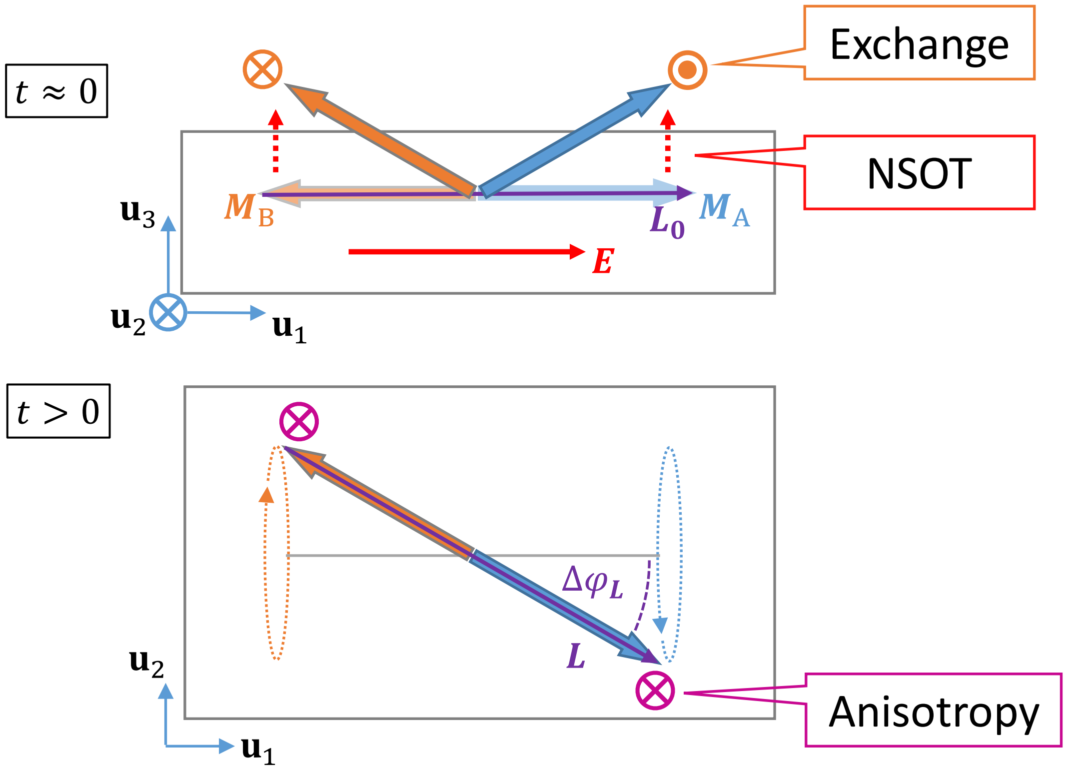
$\Delta S \propto \Delta\varphi_L(t)$

In-plane rotation of $\boldsymbol{L}$



How can we model this rotation?

Magnon model



Response for impulse:
$E(t) \propto \delta(t)$

We expect:

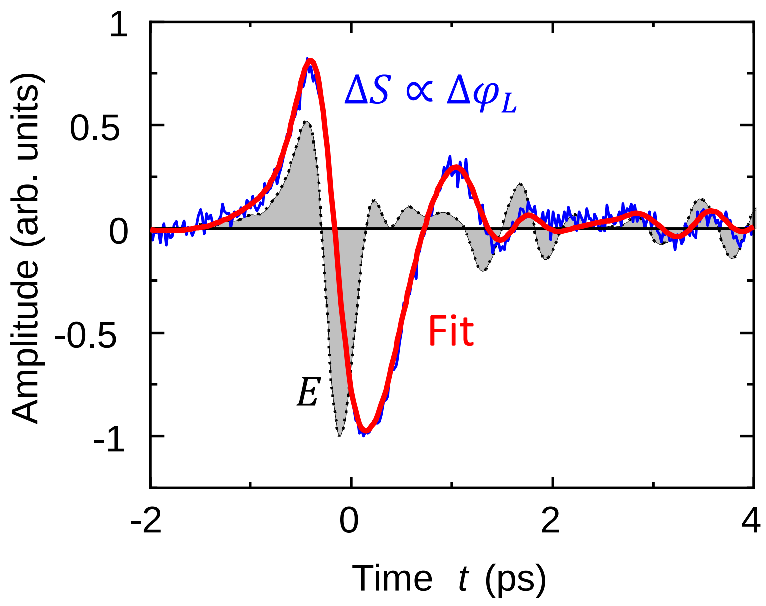
- In-plane magnon, i.e. oscillation of $\Delta\varphi_L$
- Exchange-enhanced (THz frequency)

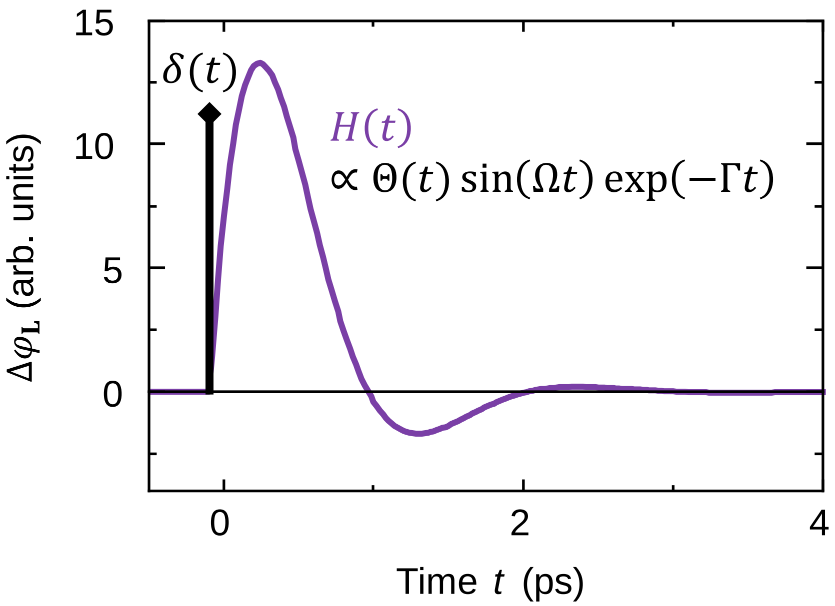
Roy *et al.*, PRB (2016); Gomonay *et al.*, PRB (2018)

Solution: $\Delta\varphi_L(t) \propto \Theta(t)\sin(\Omega t)\exp(-\Gamma t)$

Does it fit our data?

Model vs. experiment





Linear model: $\Delta\varphi_L(t) = \int H(t)E(t-\tau)\, d\tau$ — Convolution

Bare frequency: $\frac{\Omega_0}{2\pi} = \frac{\sqrt{\Omega^2+\Gamma^2}}{2\pi} = 0.6\ \mathrm{THz}$

→ Implies spin-flop field $B_{\mathrm{sf}} = \frac{\Omega_0}{\gamma} \approx 20\ \mathrm{T}$

OK with Sapozhnik et al., PRB (2018)

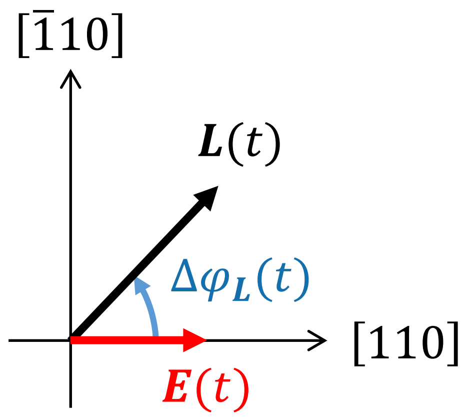
Damping: $\frac{\Gamma}{2\pi} = 0.3\ \mathrm{THz}$

→ Gilbert damping $\alpha = \frac{\Gamma}{\gamma B_{\mathrm{ex}}} \approx 10^{-2}$

OK with other AFM, e.g. IrMn (Kang et al., APL (2021))

We observe a strongly damped THz magnon

Torkance and deflection



- How strong is the coupling between electric field and spins, i.e. the **effective spin-orbit field**?
- How large is the pump-induced deflection $\Delta\varphi_L$?

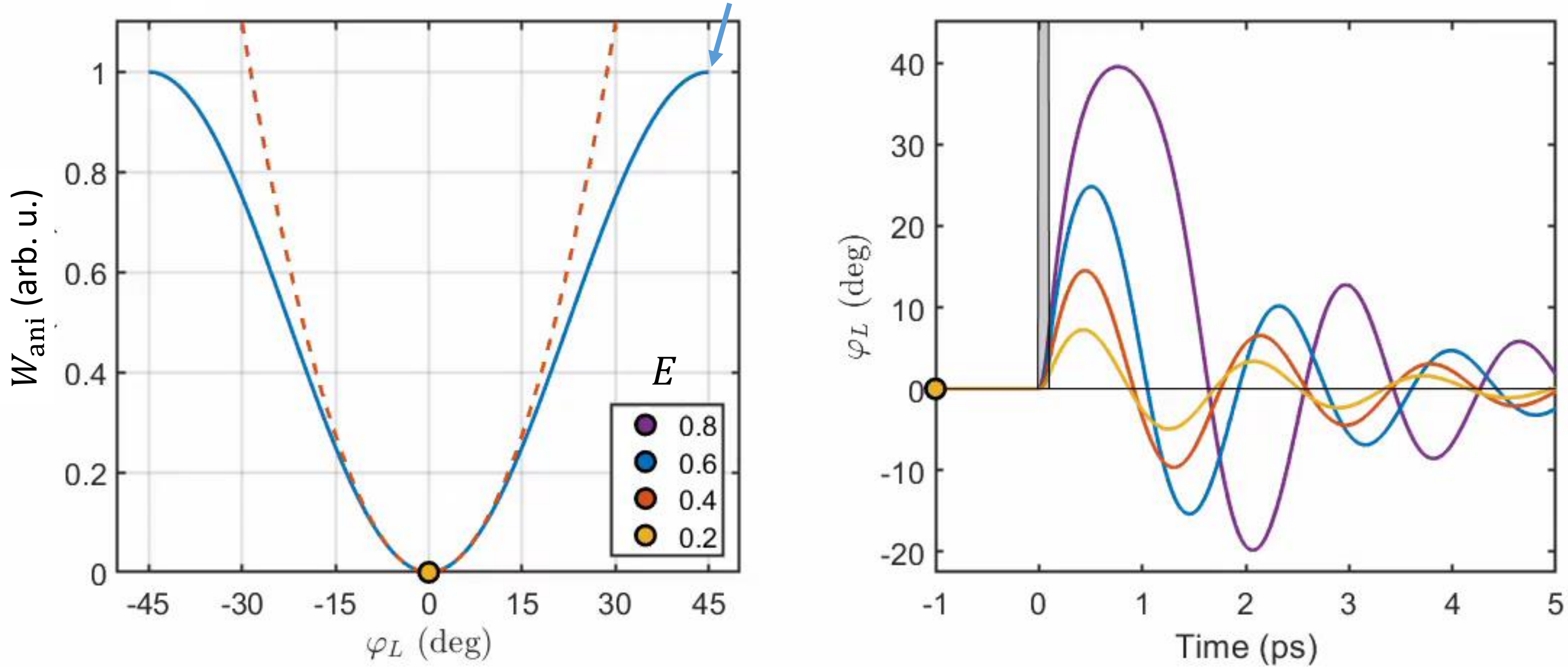
Calibration challenging in linear regime

But: We can use the non-linear response instead

Anharmonic potential for calibration

Harmonic potential $\propto \varphi_L^2$

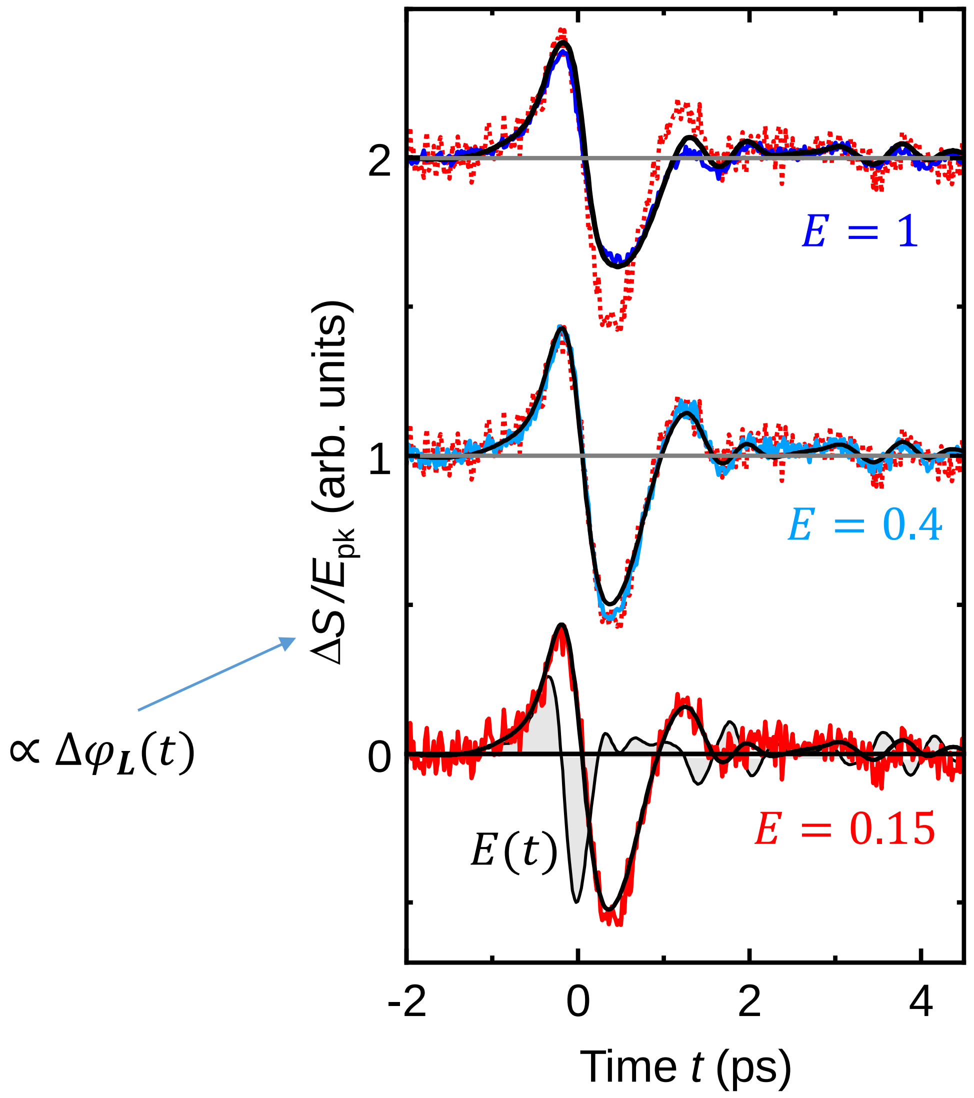
Anisotropy potential $\propto 1 - \cos(4\varphi_L)$



Beyond harmonic approximation: Size of φ_L is *uniquely* determined by waveform shape

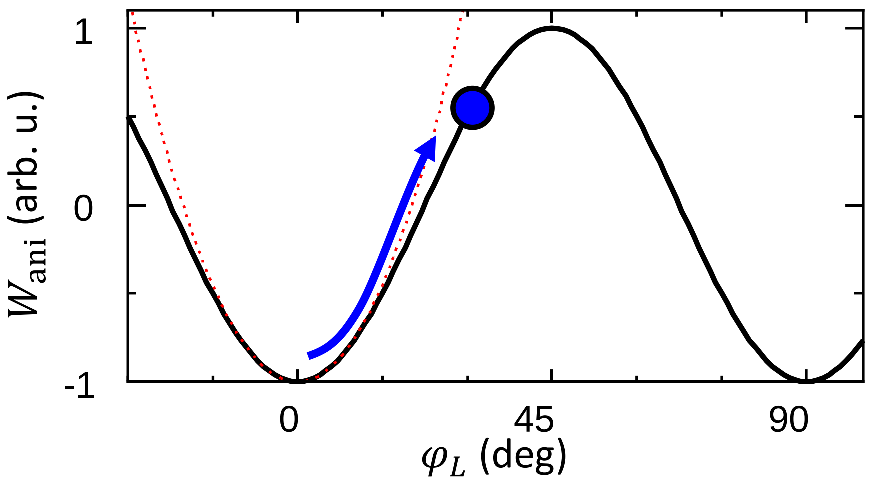
Can we observe non-linear behavior?

Non-linear dynamics



- Clear signs of non-linear dynamics
- Fit by model:
  - Effective field $B_{so} = 8\ \mathrm{mT}$ per $10^{11}\mathrm{A/m^2}$
  - Maximum deflection $\Delta\varphi_L \approx 30°$

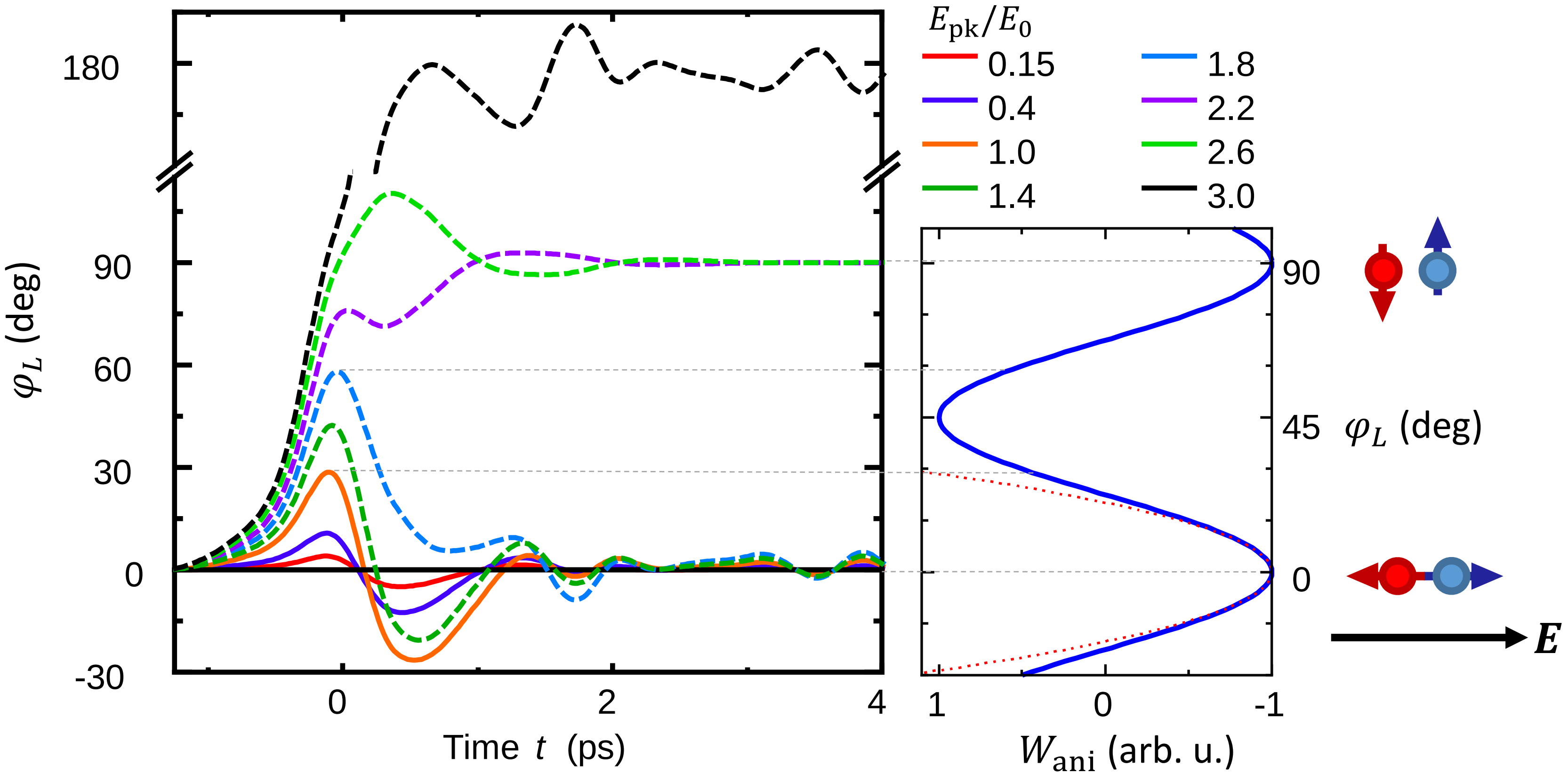
DFT: 2 mT
Zelezny et al.,
2017 (PRB)



L gets close to the maximum of the potential barrier

Extrapolate what happens at larger fields

Extrapolation



Possibility of coherent switching for increased fields

- Switching time $1\ \text{ps}$
- $90° \times n$ – rotation possible

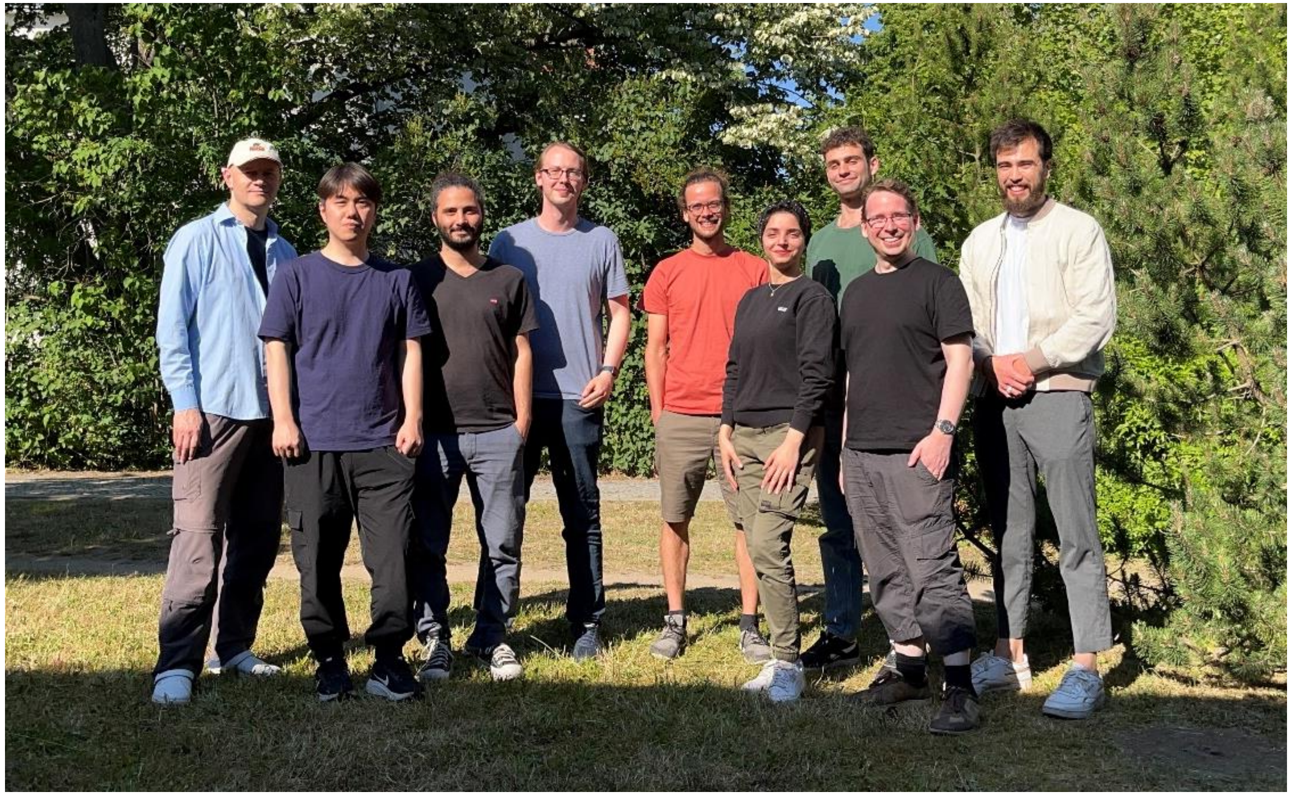
Acknowledgments

THz physics group

Afnan Alostaz
Genaro Bierhance
Alexander Chekhov
Oliver Gueckstock
Chihun In
Zdenek Kaspar
Quentin Remy
Reza Rouzegar
Amon Ruge
Bruno Serrano
Tom Seifert
Junwei Tong

Tobias Kampfrath

Freie Universität Berlin



JGU Mainz
Stanislav Bodnar
Satya Bommanaboyena
Sonka Reimers
Martin Jourdan
Mathias Kläui
Yaryna Lytvynenko

Helen Gomonay

HZDR
Yurii Skourski

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

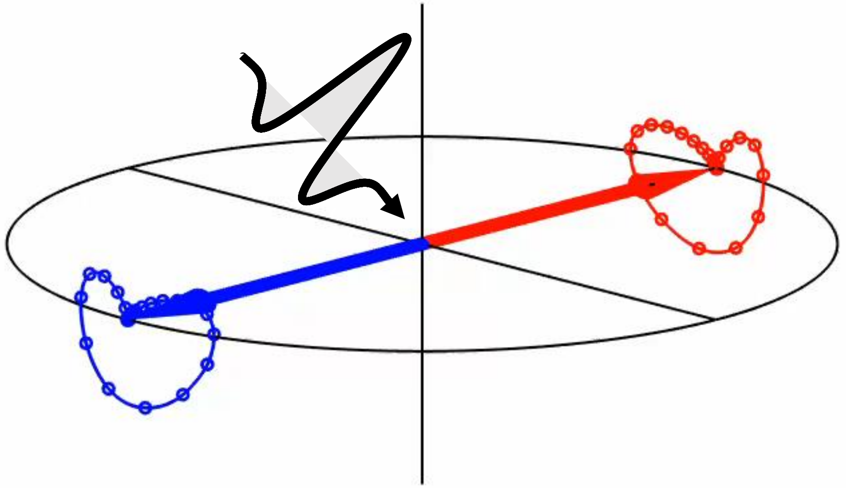
DFG

CRC / TRR 227
Ultrafast Spin Dynamics

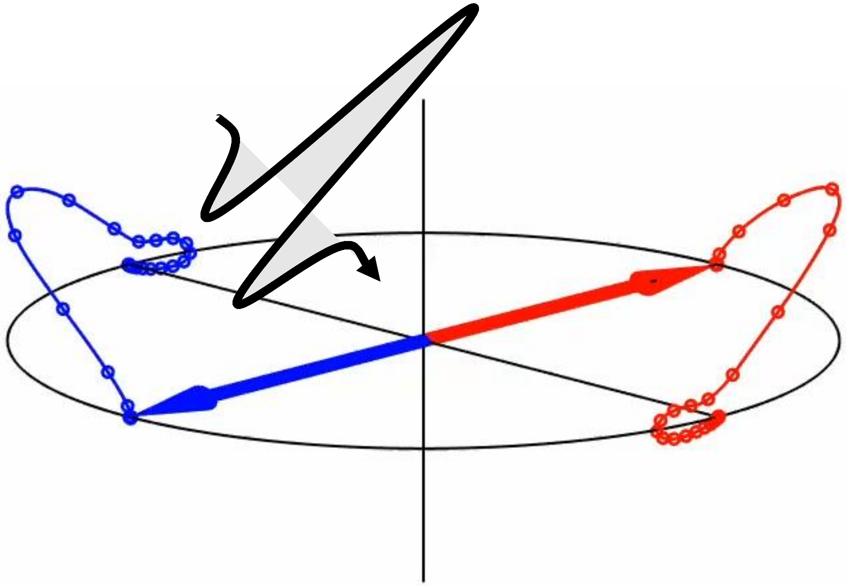
erc

Summary and outlook

- We observe signatures of Néel spin-orbit torques
- Exchange-enhanced THz magnon
- Deflection reaches non-linear regime at $\Delta\varphi_{L} \approx 30°$



- 90° switching is expected at 2-3 times higher THz fields
- For observation in our experiments, we need:
  - Signal sensitive to switched domains
  - Reinitialization by in-situ control
  - Enhanced electric field inside film



YB, Chekhov, Kampfrath et al. Nature Commun. **14**, 6083 (2023)