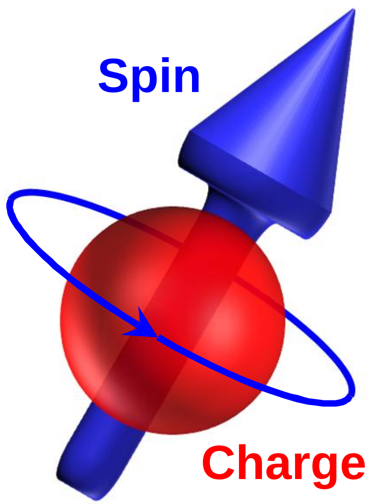
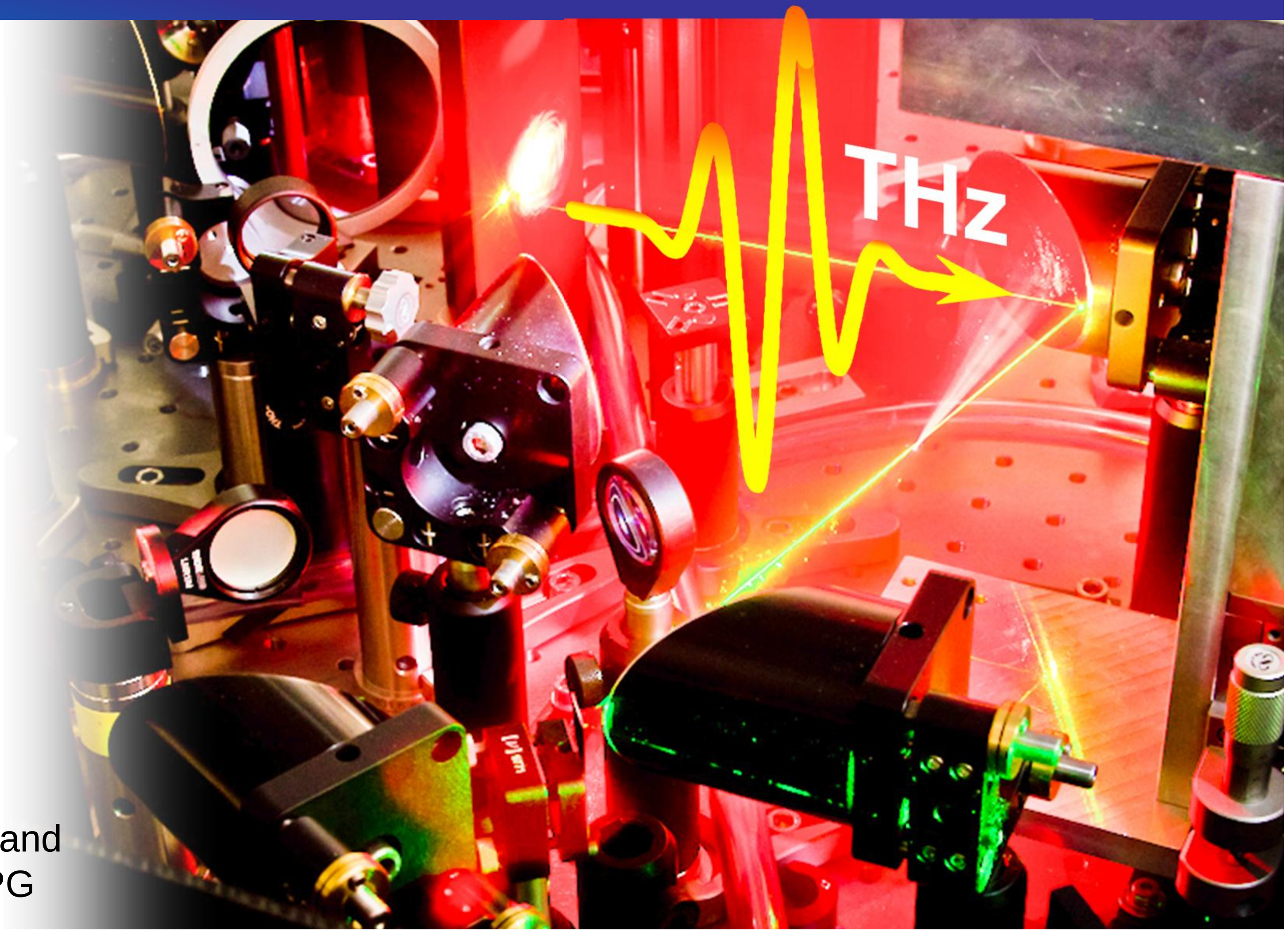
Probing and controlling THz spin dynamics in ferrimagnets





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Ultrafast Spin Dynamics

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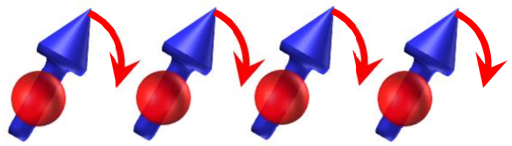
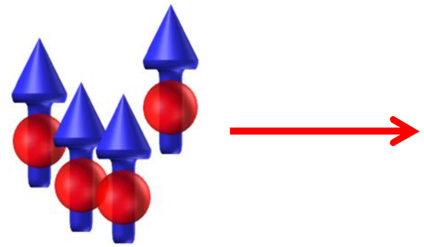
Spintronics with THz radiation

1. Turn spins around



® Torque

2. Transport spins



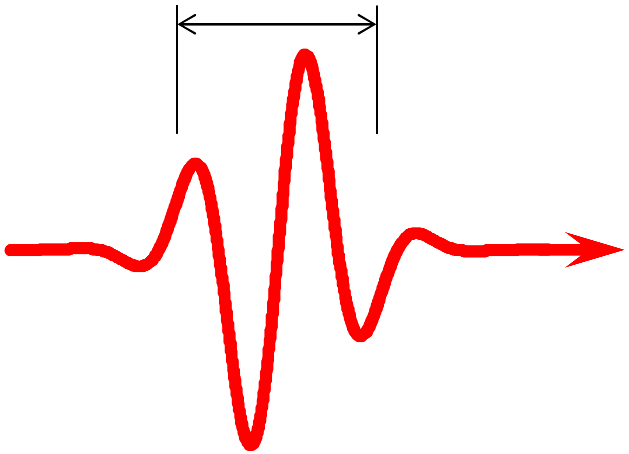
® Spin current

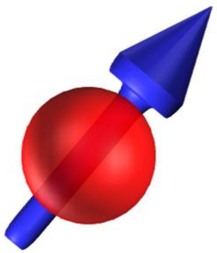
3. Detect spin dynamics

Goal: Reach speed of other information carriers, i.e. THz bandwidth

Idea: Use ultrashort THz pulses

1 ps = (1 THz)$^{-1}$ = 300 mm/*c*

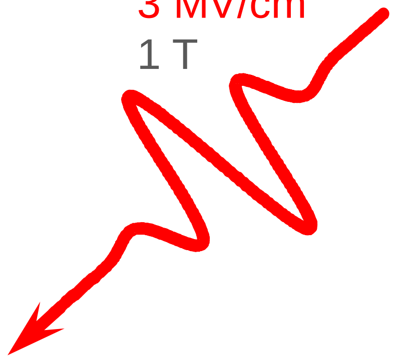




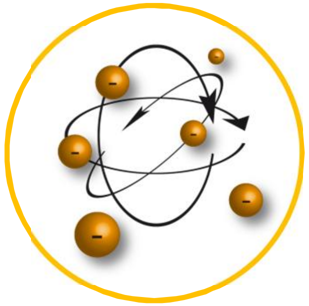
This talk:

- § Reveal spin couplings
- § Explore new pathways to spin control in e.g. antiferromagnets

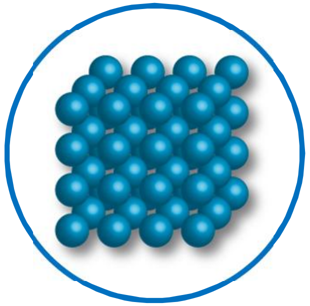
Reveal elementary spin couplings



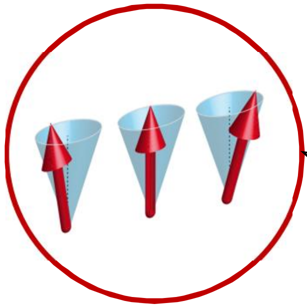
Electron orbits



Ionic lattice



Electron spins



Characterize antiferromagnetic magnons

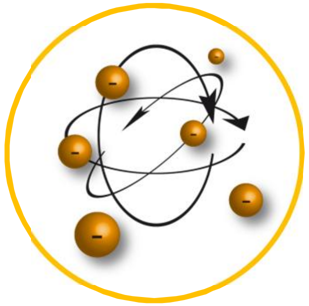
- Suemoto *et al.*, PRL (2010)
- Kampfrath, Fiebig, Huber *et al.*, Nature Phot. (2011)
- Nemec *et al.*, Nature Phys. (2018)

Increase the THz amplitude

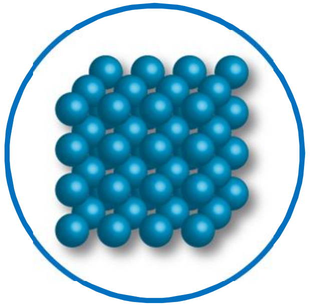
Reveal elementary spin couplings

3 MV/cm
1 T

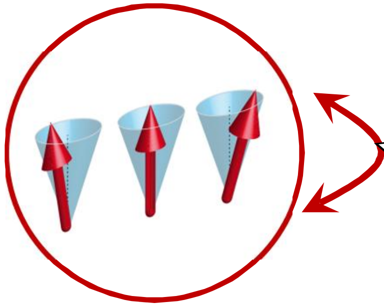
Electron orbits



Ionic lattice



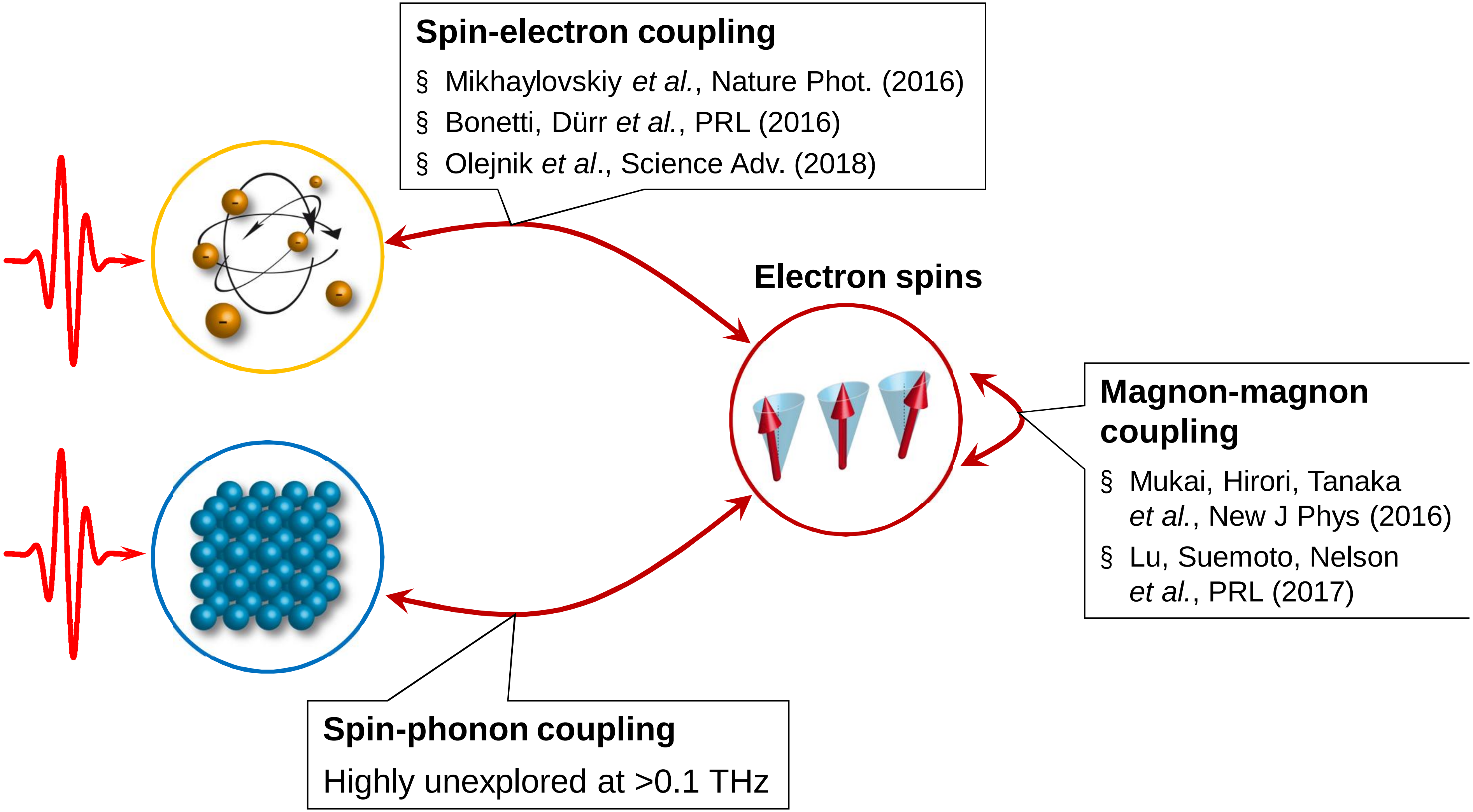
Electron spins



Magnon-magnon coupling

- Mukai, Hirori, Tanaka *et al.*, New J Phys (2016)
- Lu, Suemoto, Nelson *et al.*, PRL (2017)

Reveal elementary spin couplings



How to probe coupling of spins and phonons?

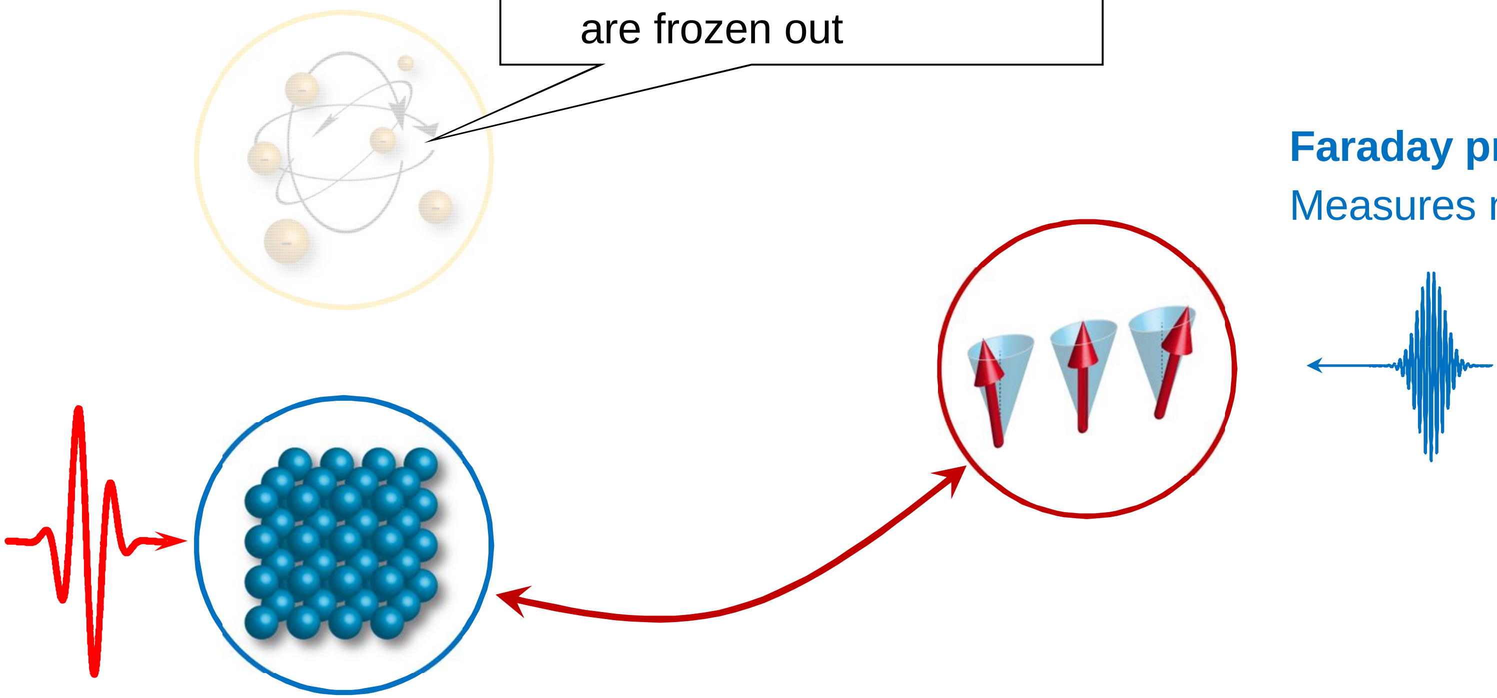
Probing spin-phonon coupling

Use an insulator

Þ Electron orbital excitations are frozen out

Faraday probe:

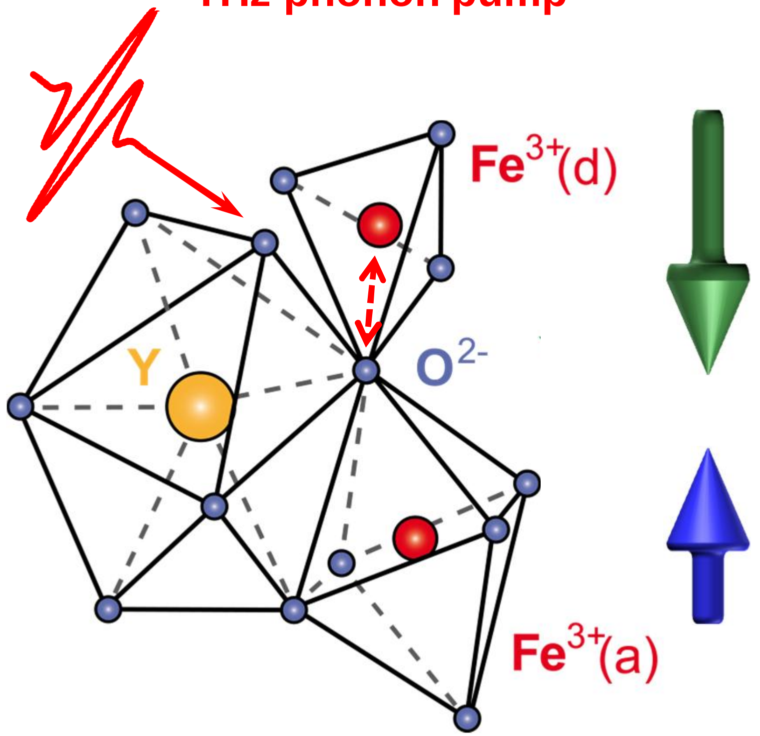
Measures magnetic state



How fast is spin-lattice equilibration?

- Study the model ferrimagnet YIG
- Also relevant for antiferromagnets

Spin-lattice equilibration in YIG



Sample: Ferrimagnet YIG

- Has two spin sublattices (a and d)
- Band gap of 2.8 eV
- Magnonic model material: Long-lived $q = 0$ spin waves

Many open questions, e.g.:

Time scale and mechanism of spin-phonon equilibration unknown

~1 ps	~250 ps	~1 µs
Rezende *et al.*, JMMM (2016)	Schreier *et al.*, PRB (2013)	Xiao *et al.*, PRB (2010)

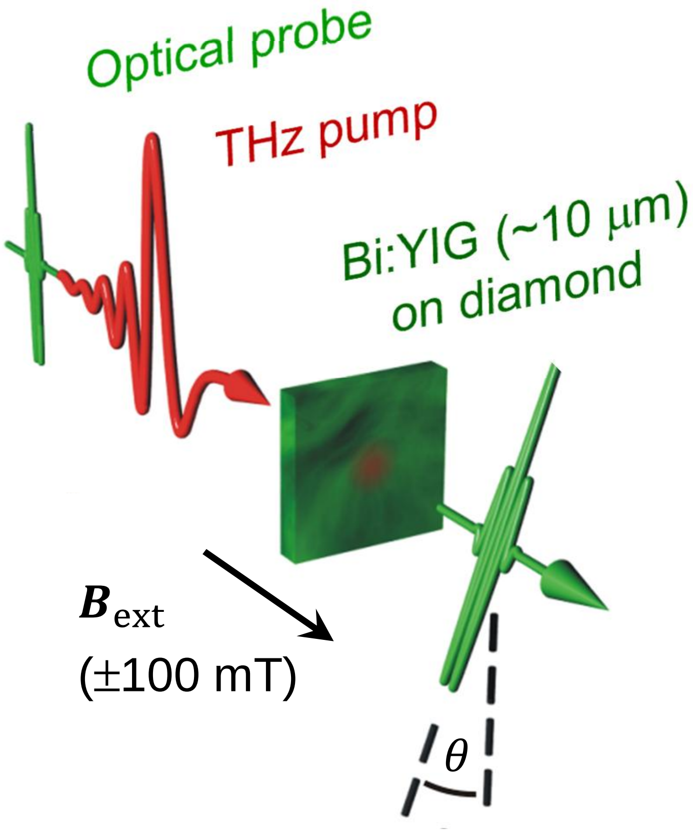
Relevant for

- Magnetization switching
- Spin Seebeck effect

Experiment

- Excite Fe-O lattice vibrations
- Probe spin dynamics from femtoseconds to microseconds

THz lattice pump–magnetooptical probe



Sell, Leitenstorfer, Huber,
Opt. Lett. (2008)

Also see:
Nova, Kimel, Cavalleri *et al.*,
Nature Phys. (2016)

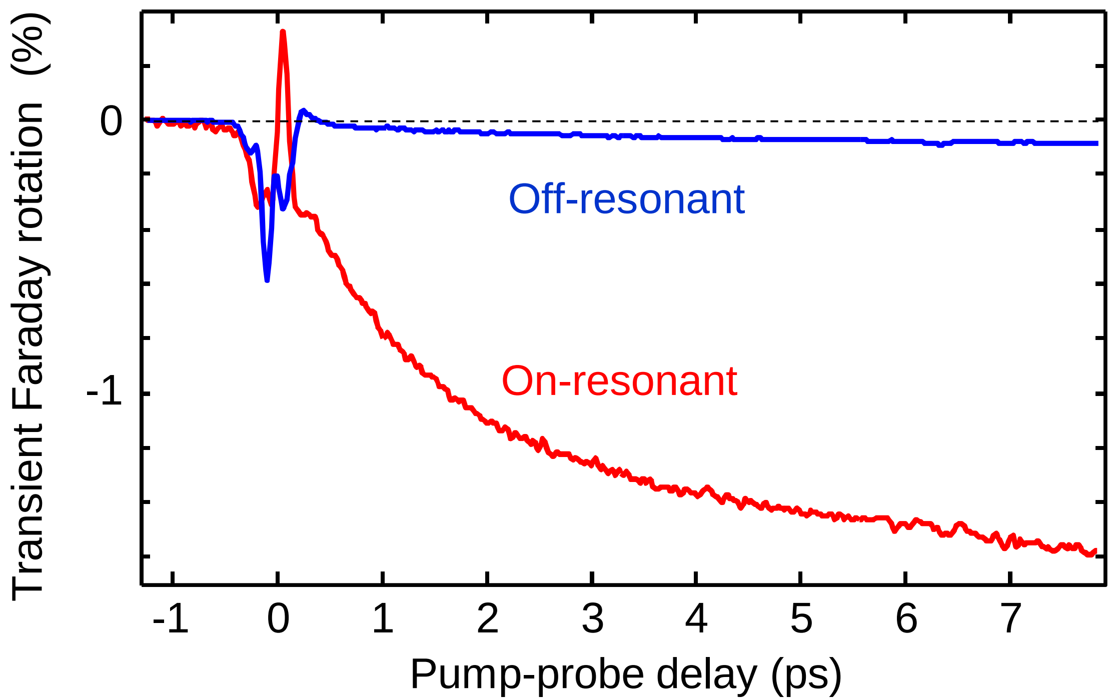
Detect Faraday rotation

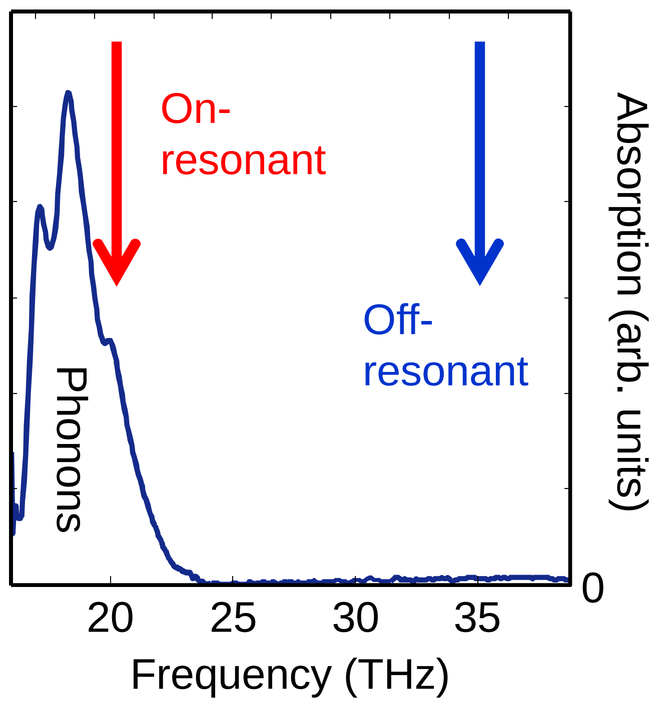
$$\theta = a_{\mathrm{d}} M_{\mathrm{d}} + a_{\mathrm{a}} M_{\mathrm{a}}$$

Krumme *et al.*,
Thin Solid Films (1984)

Pump on and off the phonon resonances

Phonon-driven magnetization dynamics





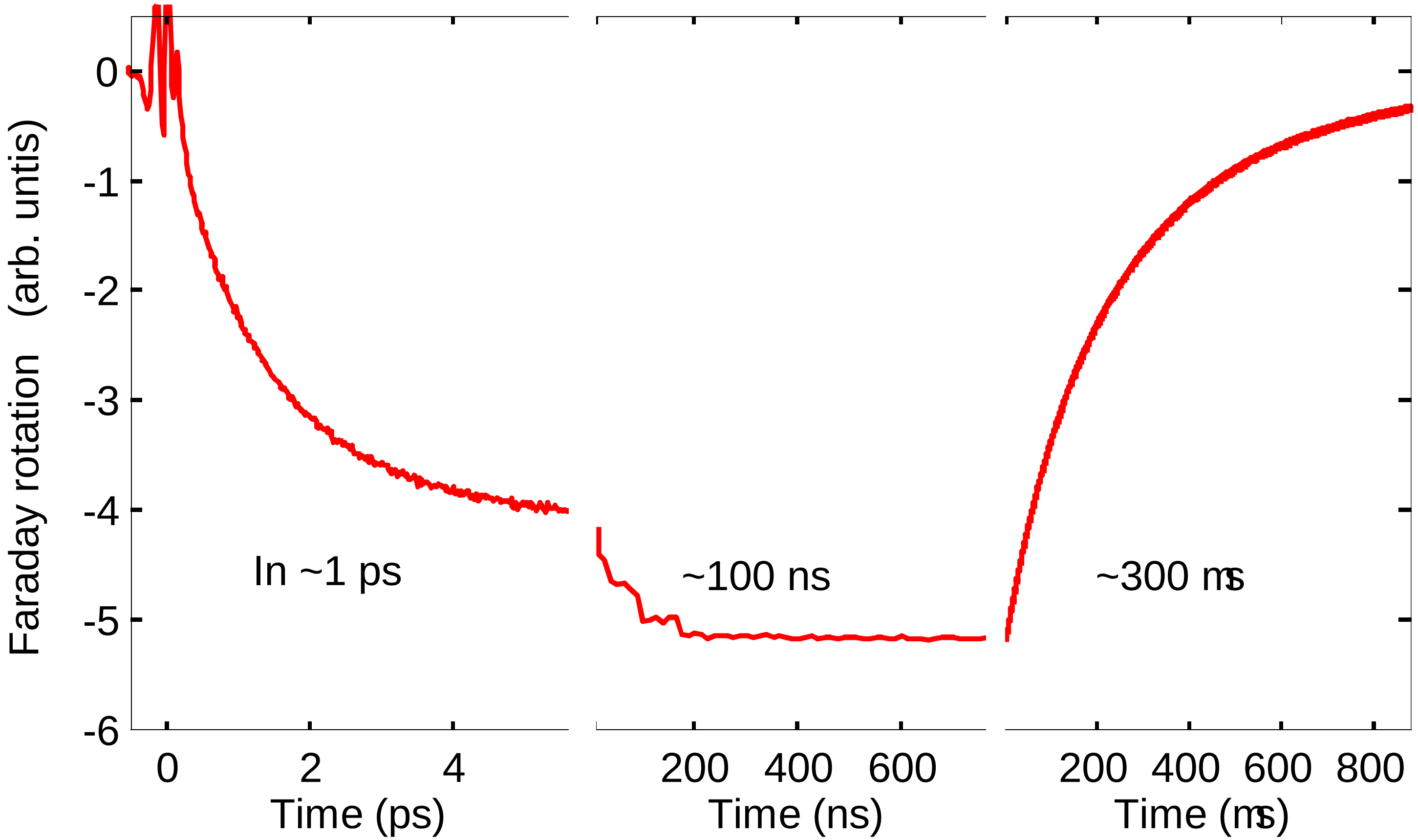
Surprisingly fast loss of magnetic order within ~1 ps:

- ~10^5 faster than lifetime of YIG's $\boldsymbol{q} = 0$ magnons (FMR)
- Response speed is comparable to laser-excited metals

Behavior on longer time scales?

Maehrlein *et al.*, Science Advances (2018)

From femtoseconds to milliseconds



Ultrafast magnetic-order quenching

What is the mechanism?

Full equilibration:

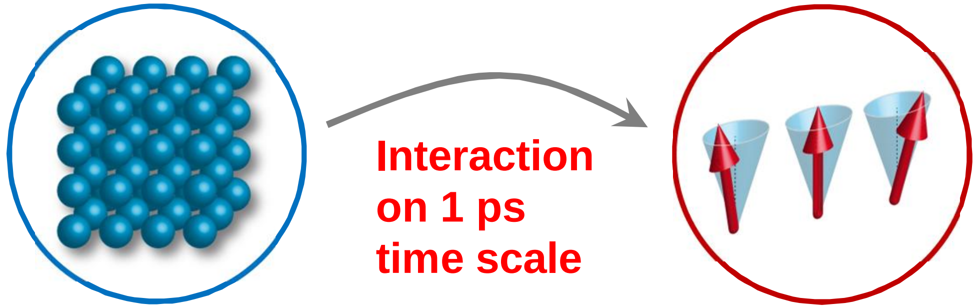
Deduced from temp.-dependence

Heat flow to substrate:

From simulations, different substrates

Maehrlein *et al.*, Science Advances (2018)

Microscopic spin-lattice interactions



Can arise from only 4 fundamental spin couplings

1. Spin-orbit coupling **NO**

In YIG ~10 times smaller than in Fe, and no electronic scattering channels

Þ Would yield much slower dynamics than in Fe (~0.1 ps)

2. Spin-spin magnetic-dipole coupling **NO**

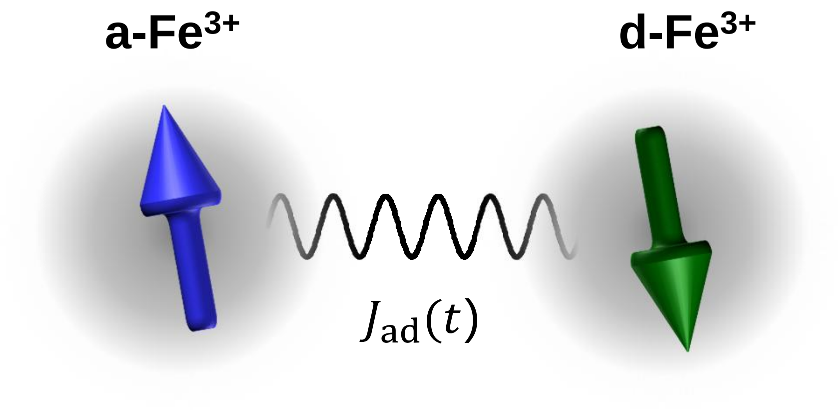
Strength comparable to spin-orbit coupling

3. Oersted fields induced by infrared-active phonons **NO**

Kumar *et al.*, Physica **36** (1967): Yes, but extreme over-estimation

Just one coupling mechanism left…

Microscopic spin-lattice interactions



4. Isotropic exchange interaction

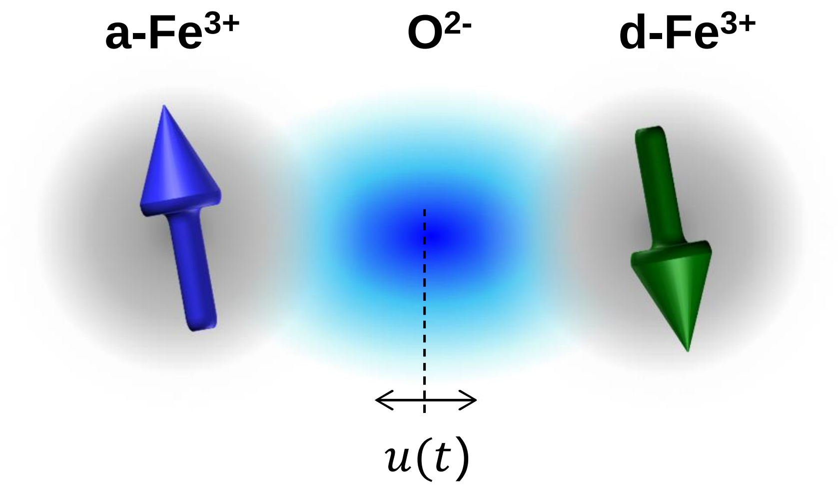
Seems possible

- Intrinsically fast: YIG has magnon frequencies up to 20 THz
- Constraint: Conserves total spin, $\Delta M_a = -\Delta M_d$
- Yet yields a nonzero Faraday signal:

$$\Delta\theta = a_d \Delta M_d + a_a \Delta M_a = (a_d - a_a)\Delta M_d$$

How can phonons modulate the exchange coupling J_{ad}?

Model for modulation of J_{ad}



Pump-heated lattice:

Randomly modulates exchange coupling by

$$\Delta J_{\mathrm{ad}}(t) = \frac{\partial J_{\mathrm{ad}}}{\partial u} \Delta u(t)$$

Model implementation:

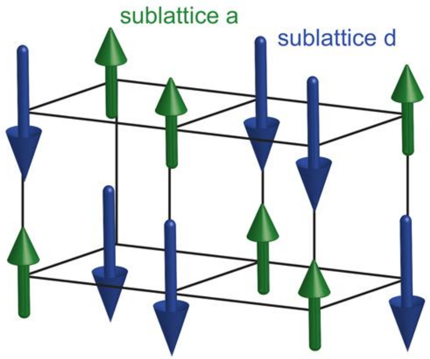
Include fluctuating J_{ad} in atomistic spin-dynamics simulations

By Joe Barker, Tohoku University

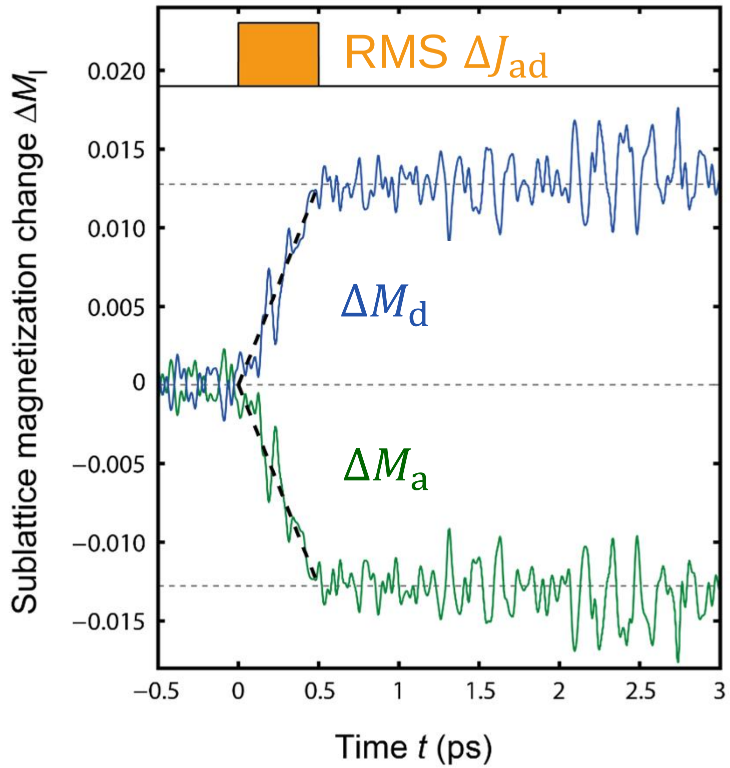
See J. Barker *et al.*, PRL (2016)

Atomistic spin-dynamics simulations

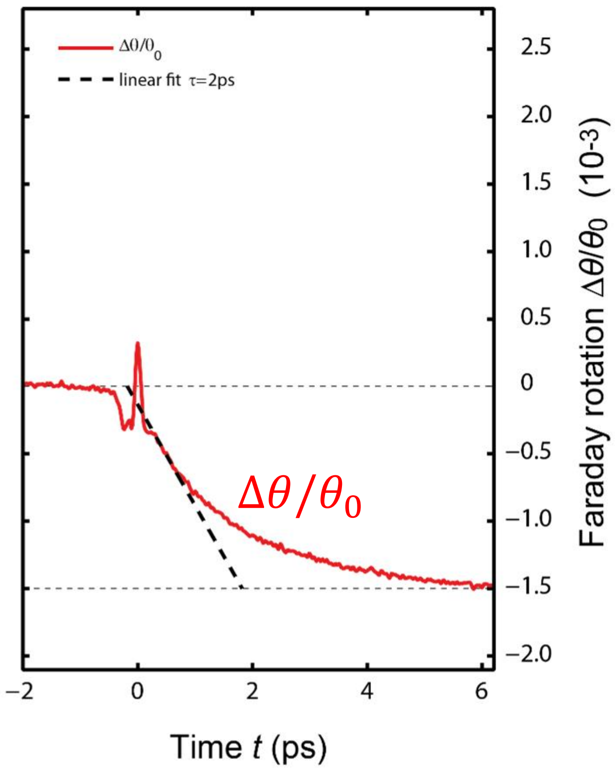
Joe Barker,
Tohoku University



Simulations



Experiment



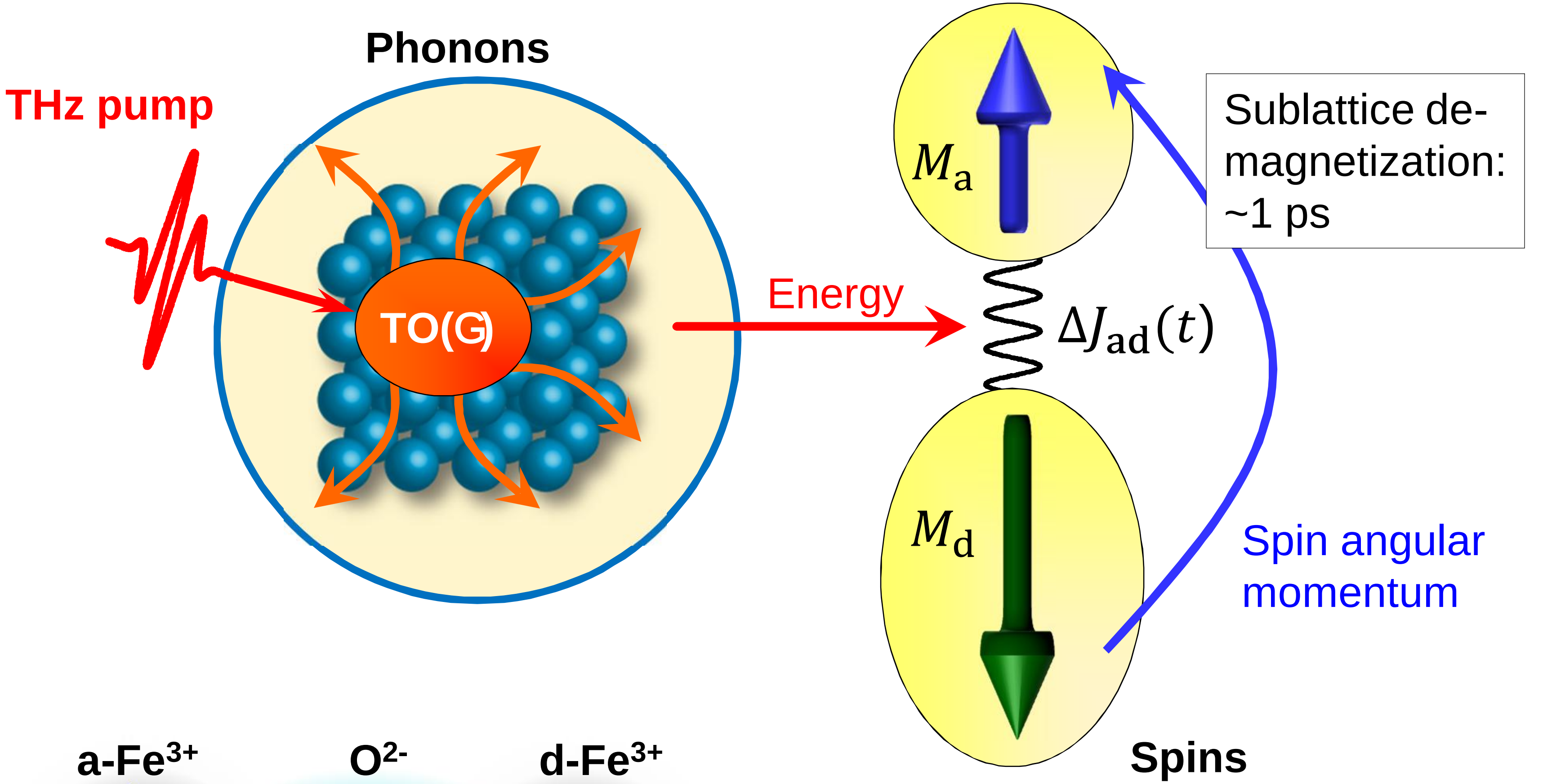
- Simulations reproduce ultrafast loss of M_a and M_d
- Compare calculated $\Delta M_a / M_{a0}$ and measured $\Delta\theta/\theta_0$
- Agrees well with DFT calculations

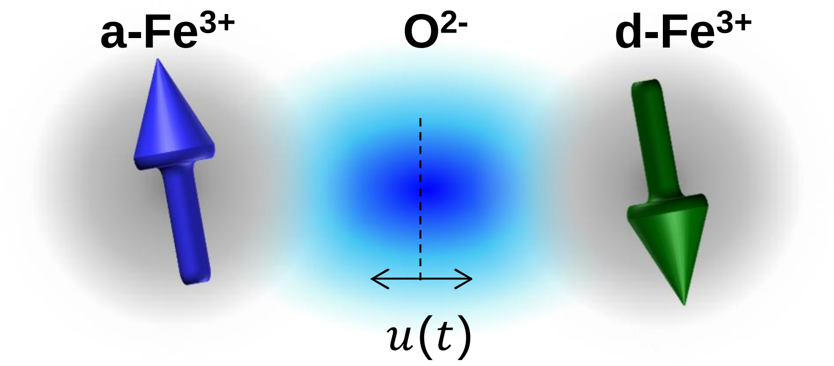
  Xia *et al*., PRB **96**, 174416 (2017)

$$\Rightarrow \frac{\partial J_{ad}}{\partial u} \sim \frac{10\, J_{ad}}{1\ \text{Å}}$$

Consistency of theory and experiment suggests the following scenario

Summary: Spin-phonon equilibration in YIG

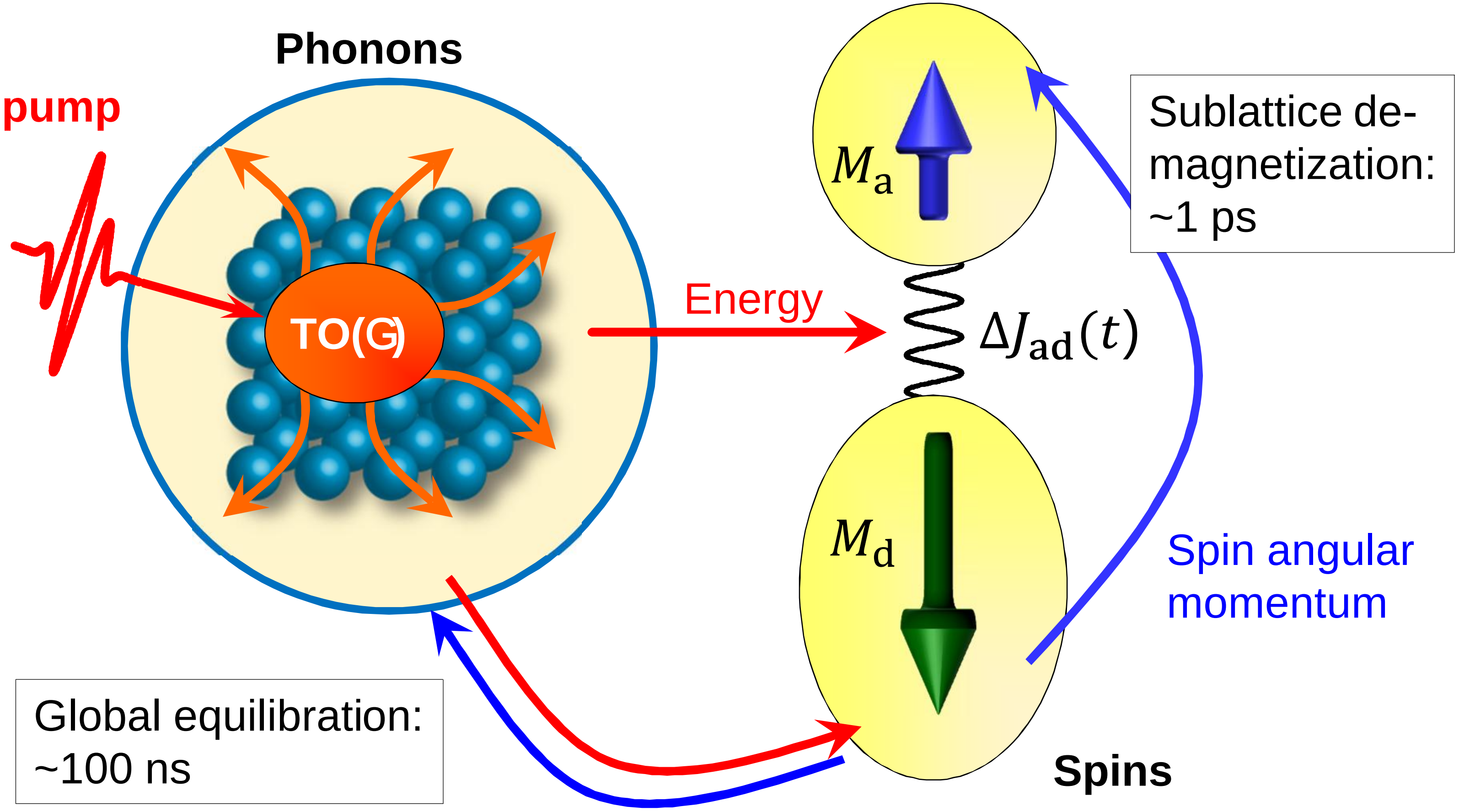




$$\Delta J_{ad}(t) = \frac{\partial J_{ad}}{\partial u} \Delta u(t)$$

Maehrlein *et al.*,
Science Advances (2018)

Summary: Spin-phonon equilibration in YIG



Reveals spin-phonon equilibration in YIG:

- Transfer of energy: in ~1 ps
- …and angular momentum: ~100 ns

Maehrlein *et al.*, Science Advances (2018)

Constrained thermal state

Equal sublattice demagnetization leads to a “hidden state”:

§ Thermal state with constraint $M_a + M_d$ = const

§ Spins are hot, but total magnetization unchanged

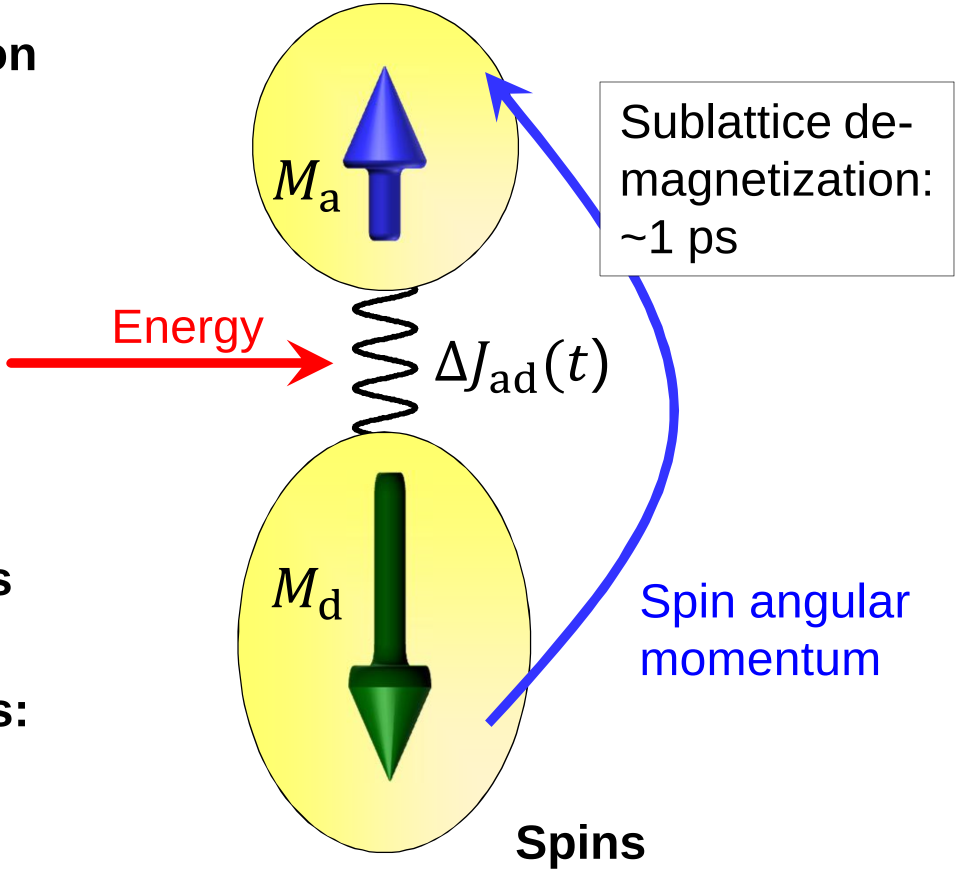
§ Lifetime ~100 ns

Accessible by ultrafast methods

Implication for antiferromagnets:

No angular-momentum transfer to lattice required

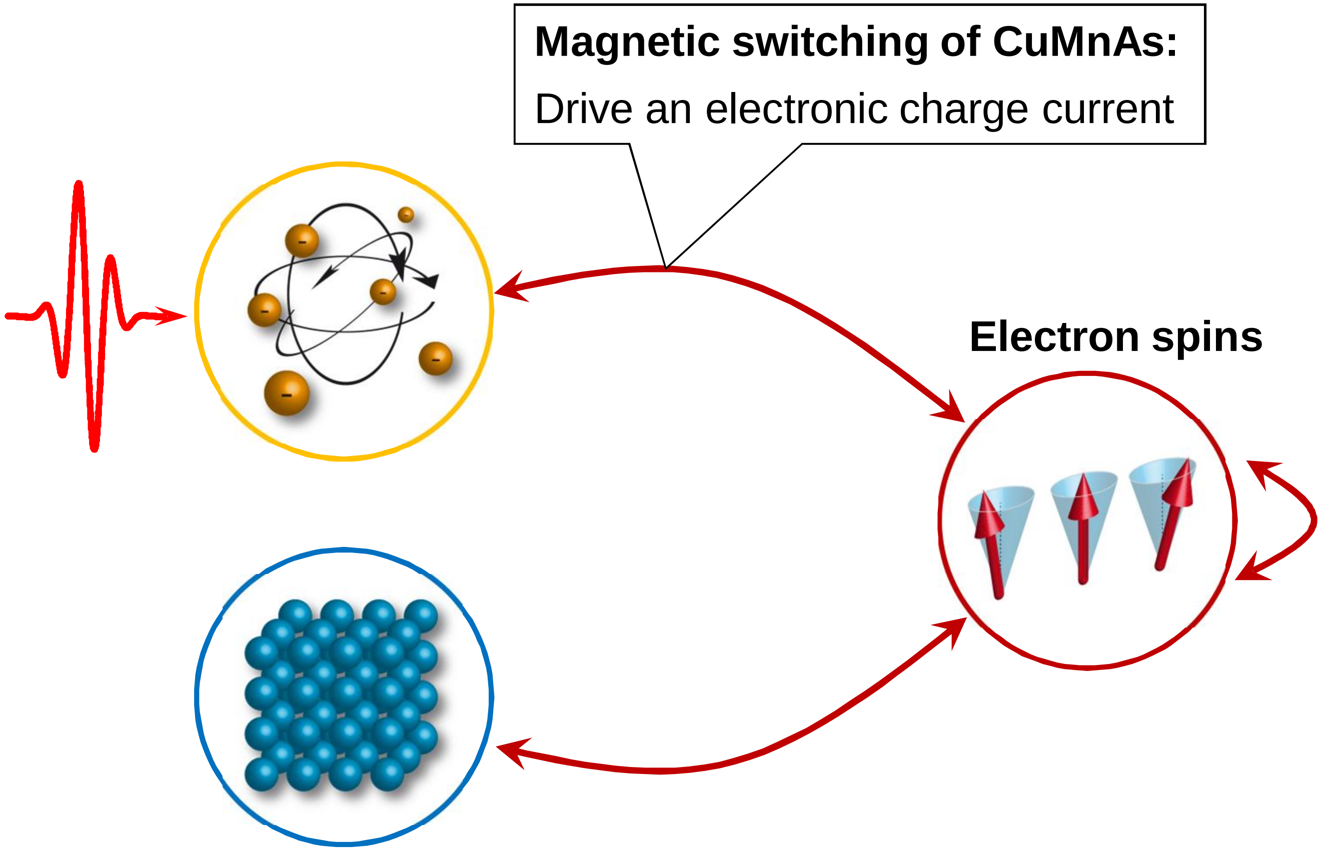
Þ Spin-phonon equilibration should proceed in ~1 ps



How to switch antiferromagnets with THz pulses?

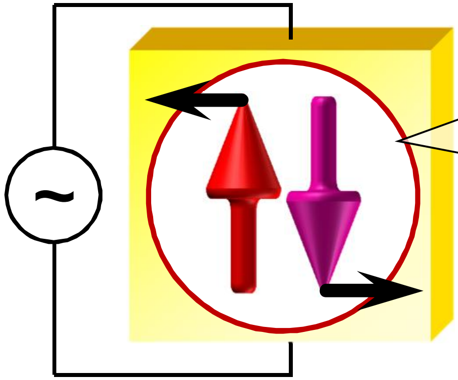
Maehrlein *et al.*, Science Advances (2018)

Current-driven magnetic switching



Outlook: switching of antiferromagnets

Electric writing with Ohmic contacts



CuMnAs

§ Antiferromagnetic metal

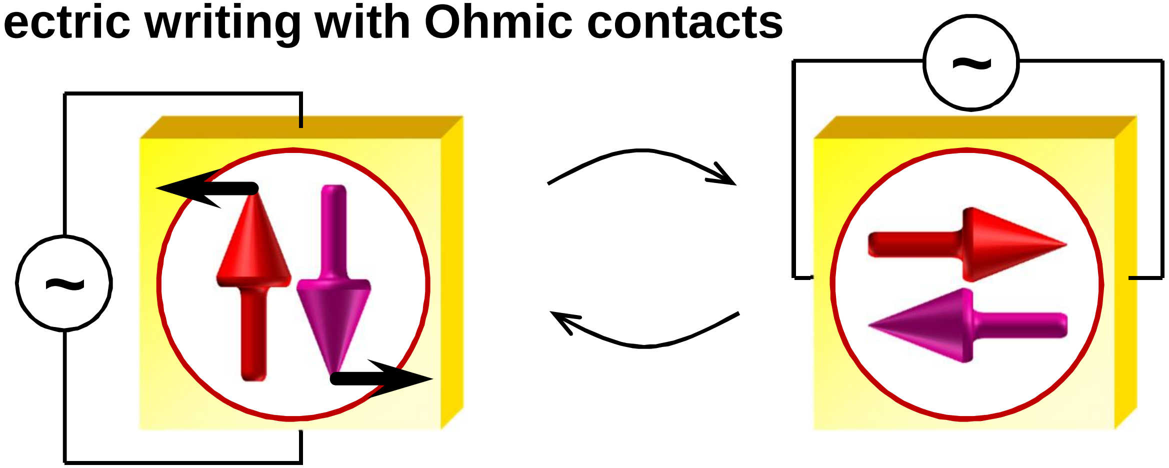
§ Locally broken inversion symmetry

Þ Current induces staggered magnetic field

Wadley, Jungwirth *et al.*, Science (2016)

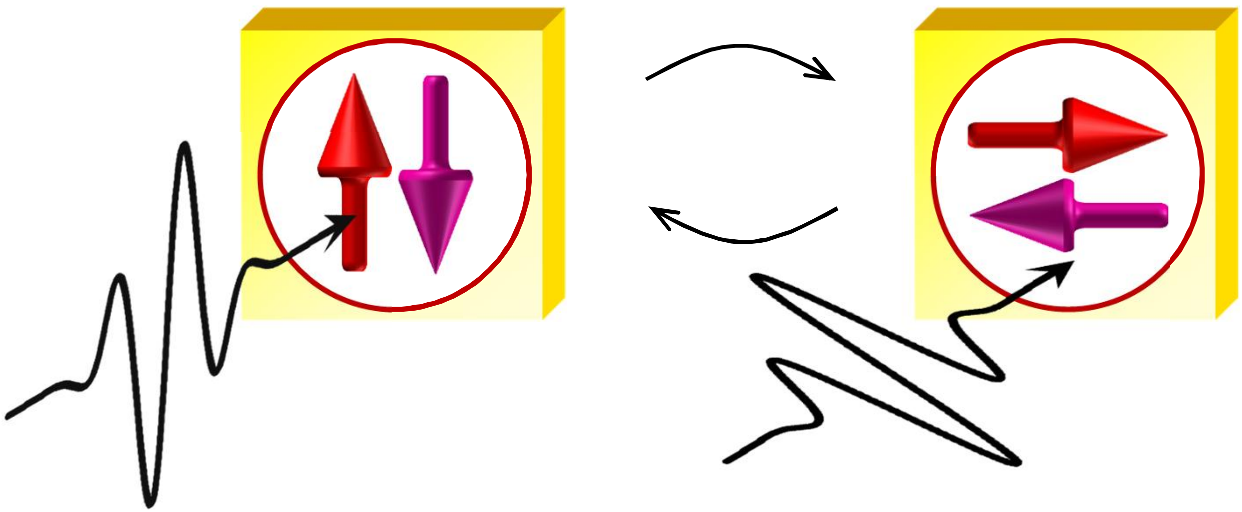
Outlook: switching of antiferromagnets

Electric writing with Ohmic contacts



Wadley, Jungwirth *et al.*, Science (2016)

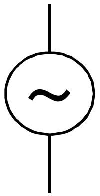
Idea: Drive a THz current, contact-free



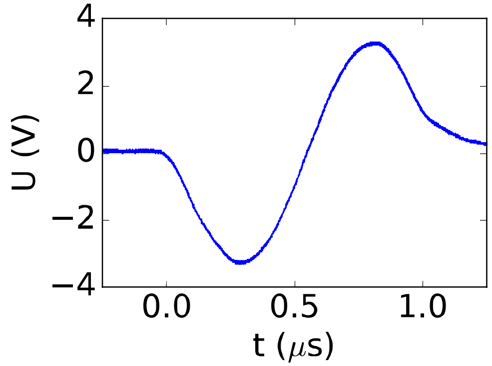
Olejnik, Seifert, Kuzel, Sinova, Kampfrath, Jungwirth *et al.*, Science Advances (2018)

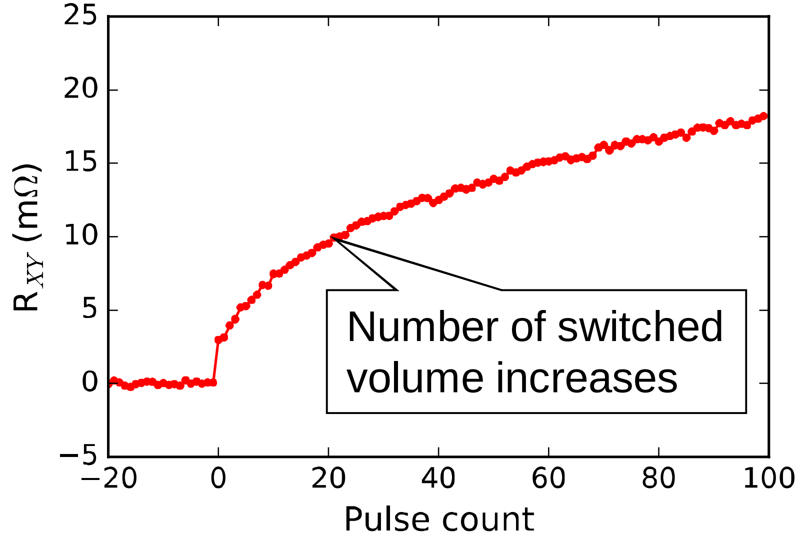
Compare DC vs THz for same sample: Probe *L* with AMR

Writing with MHz and THz fields

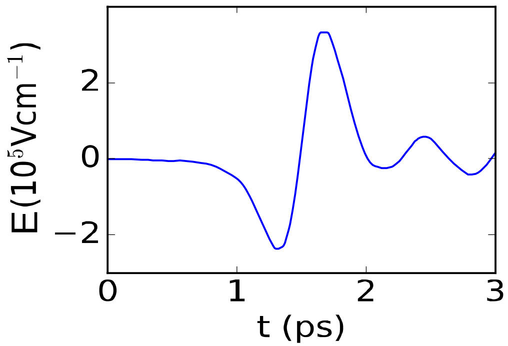


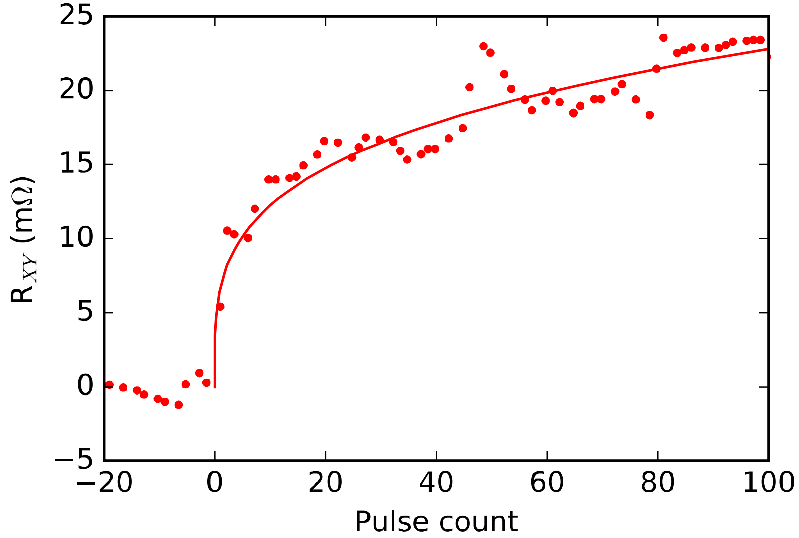
MHz voltage pulse





Free-space THz pulse

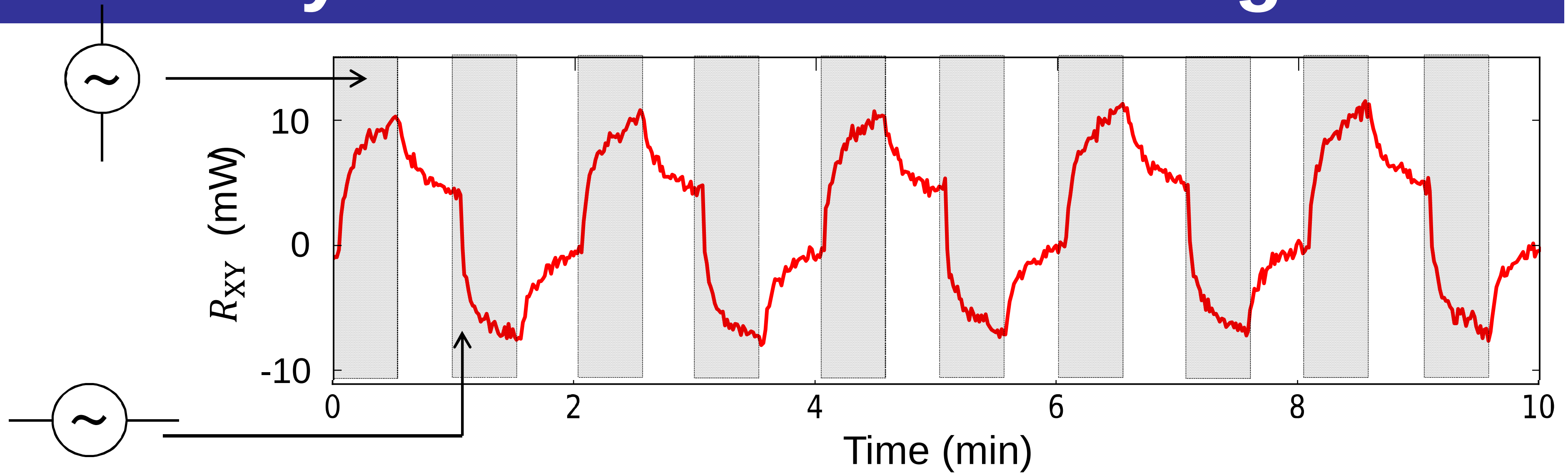


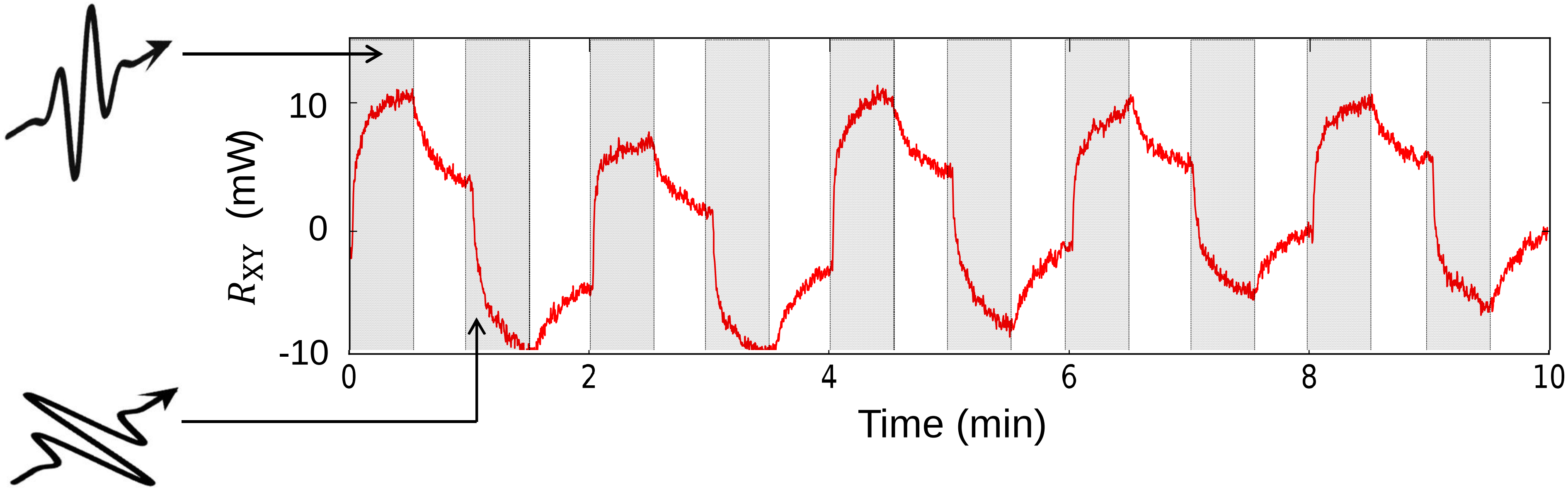


Cyclic operation also possible

Olejnik *et al.*,
Science Advances (2018)

Cyclic MHz and THz writing

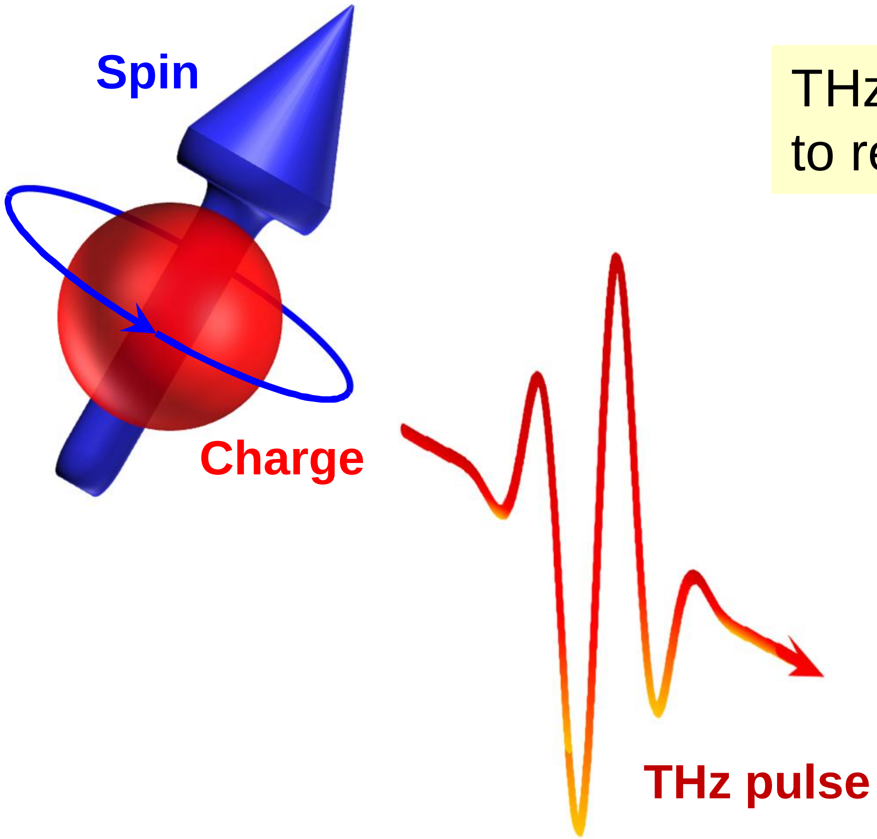




Olejnik *et al.*,
Science Advances (2018)

Summary

- THz fields can access elementary spin couplings (e.g. to phonons)
- THz spectroscopy permits new insights into physics of established spintronic effects



THz radiation is a useful tool
to reveal and control spin dynamics