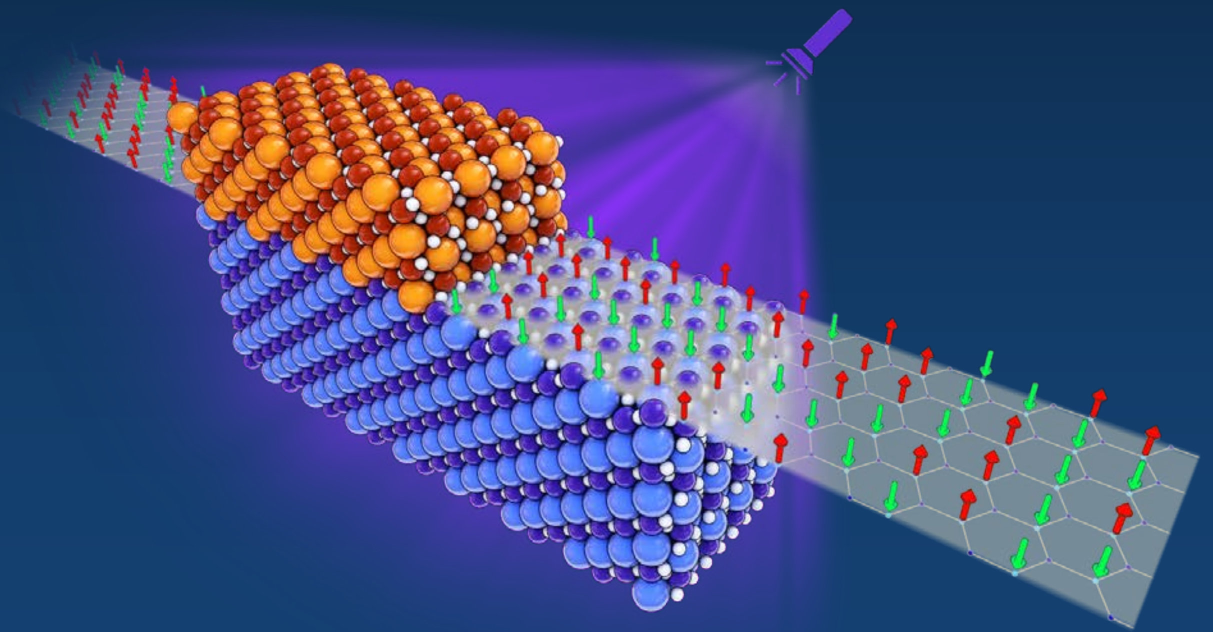
Resonant ultrafast optical control of oxide interfaces

Caviglia Lab
Department of Quantum Matter Physics
University of Geneva



Collaborators and funding

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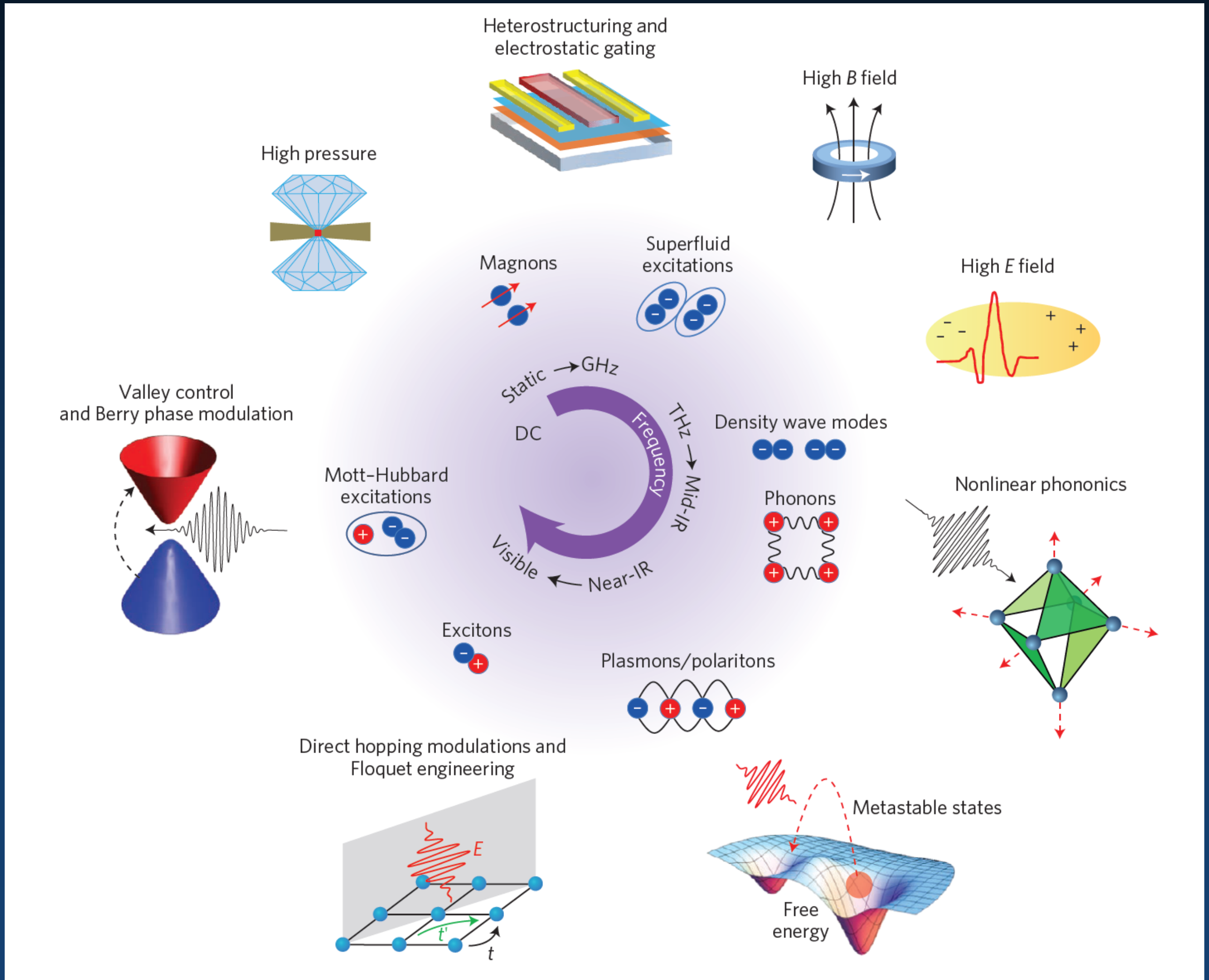
Eric Bousquet, Alireza Sazani
Uni Liege
Marc Gabay
Uni Paris Sud
Raffaele Battilomo, Carmine Ortix
Uni Utrecht

European Research Council
Established by the European Commission
NanoFront
Netherlands Organisation for Scientific Research

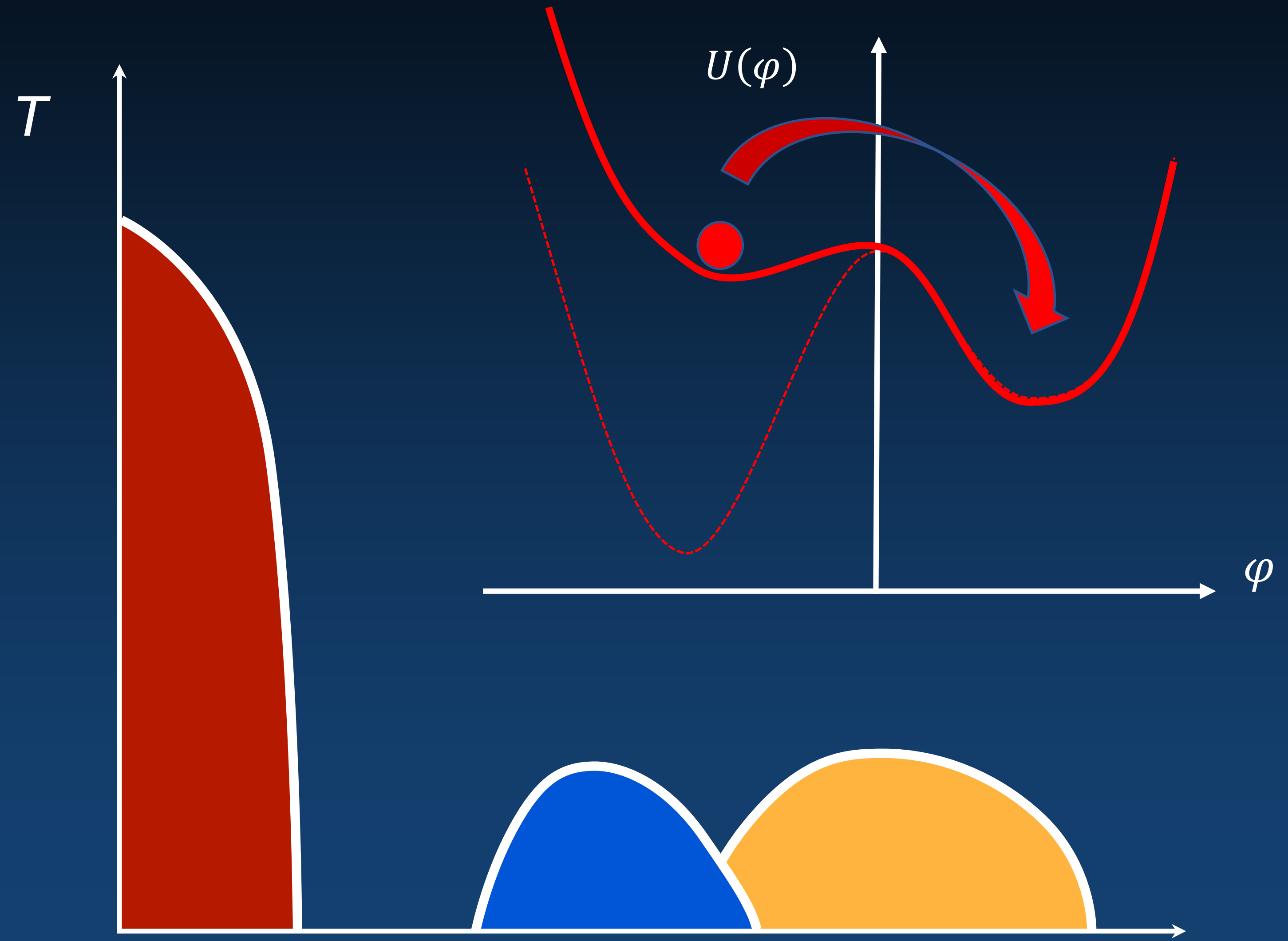
Controlling quantum materials with light

Electrons act collectively



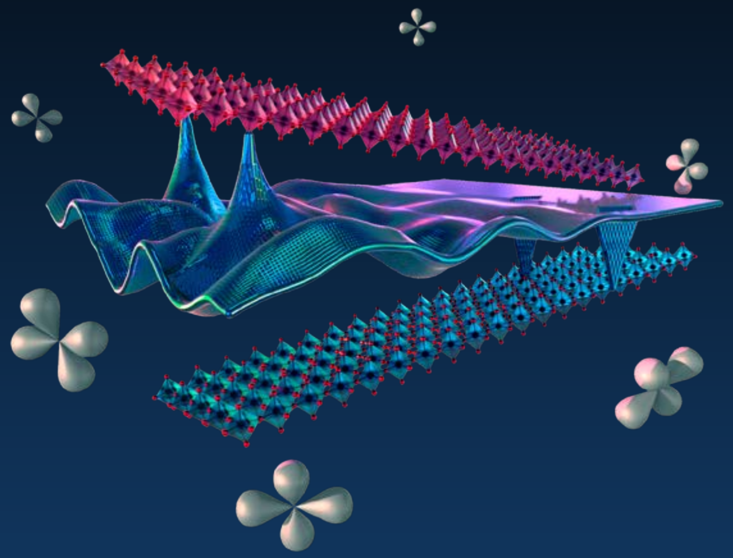
Basov et al. Nature Materials **16**, 1077 (2017)

Dynamical stability: stimulating order



Control parameter (doping, strain, etc.)

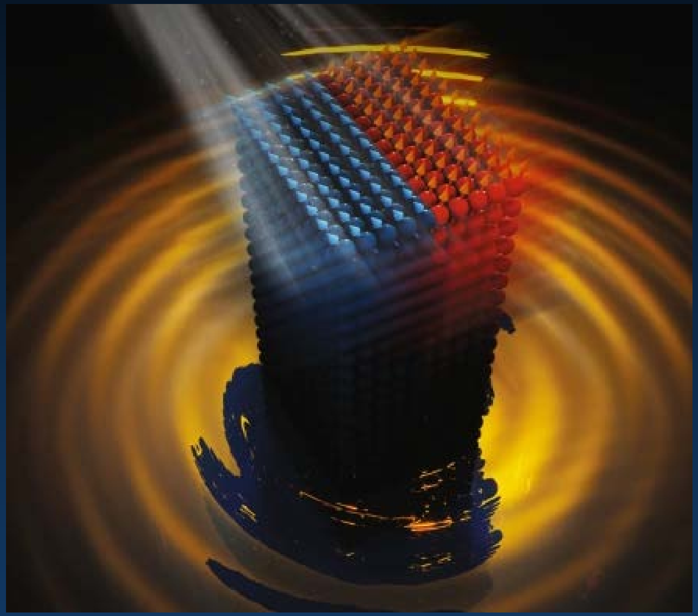
Outline



Phonon resonances

Ultrafast strain engineering

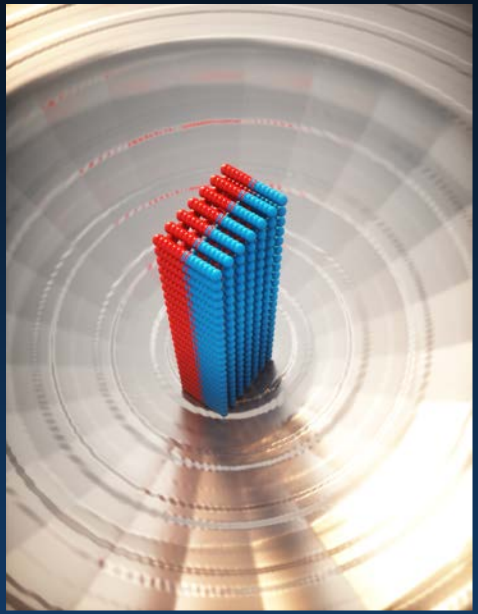
LaAlO3



Phonon resonances

Lattice control of magnetic interactions

DyFeO3
Magnetic transitions

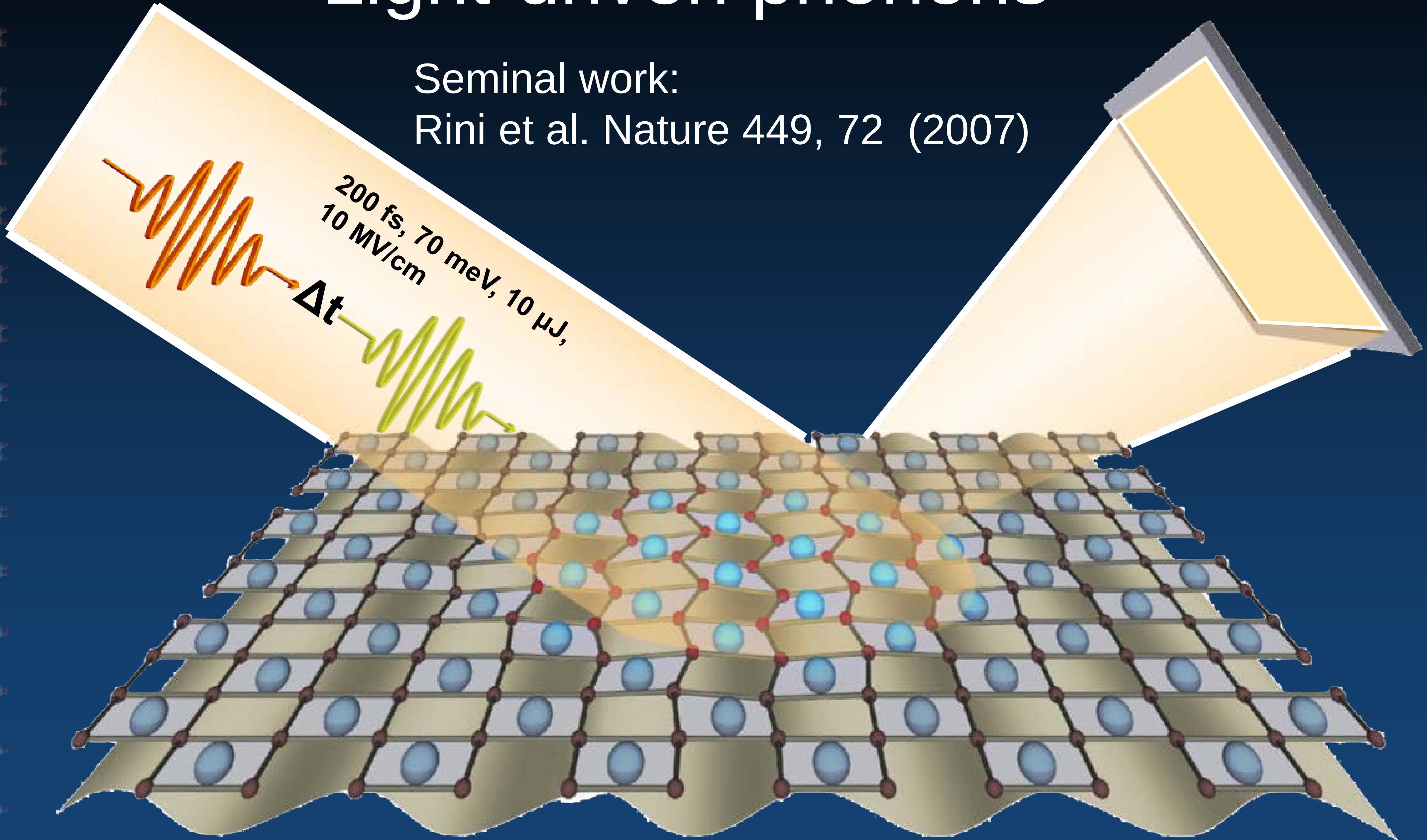


Charge resonances

Coherent spin-wave transport in antiferromagnets

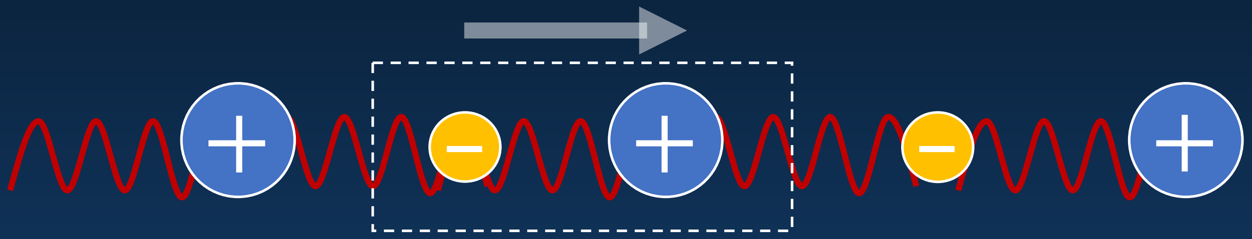
Light-driven phonons

Seminal work:
Rini et al. Nature 449, 72 (2007)

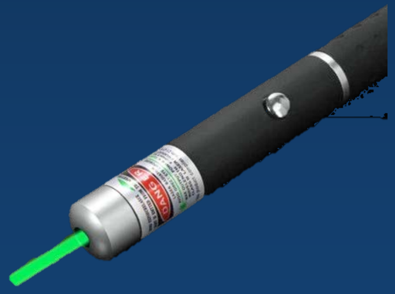


Electric fields in solids

E ~ 100 MV/cm

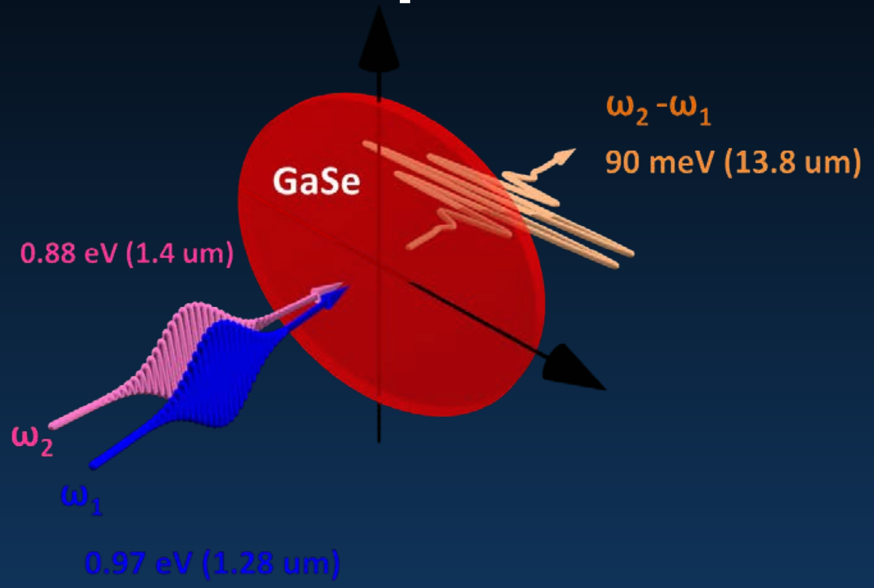


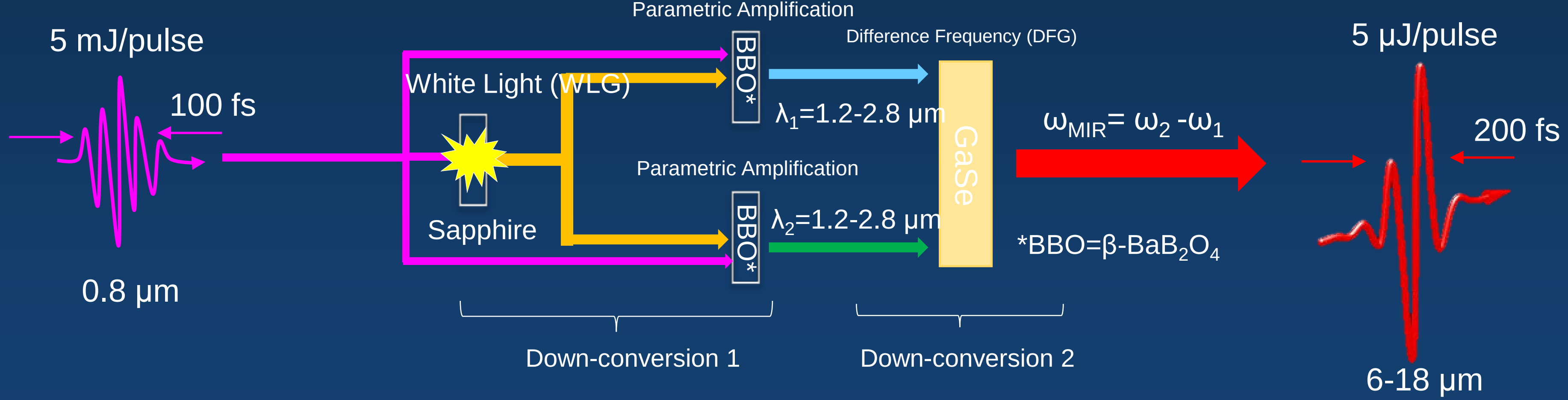
Electric field of a laser pointer is 100 V/cm



High field mid-infrared pulses

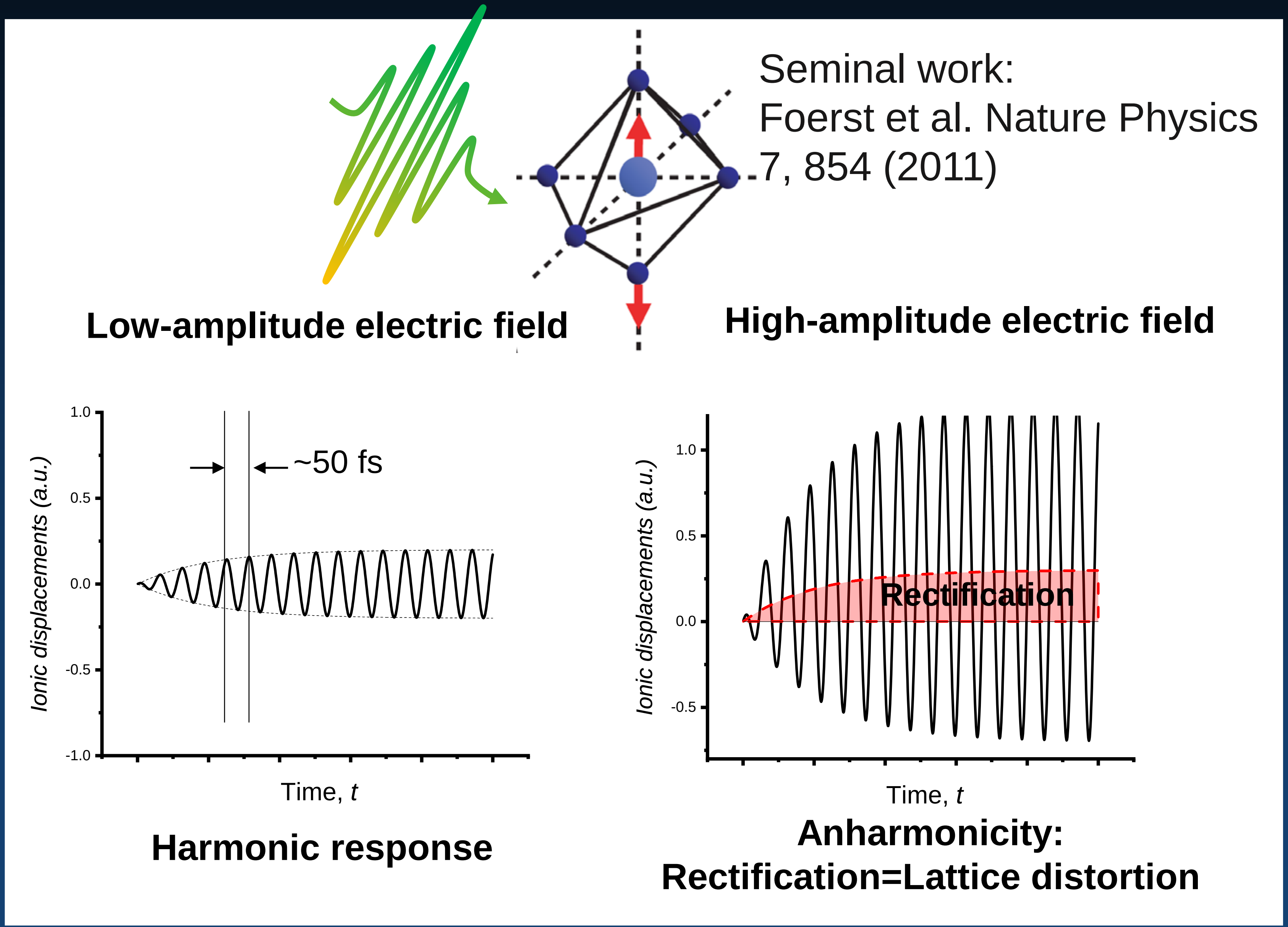
Dmytro Afanasiev



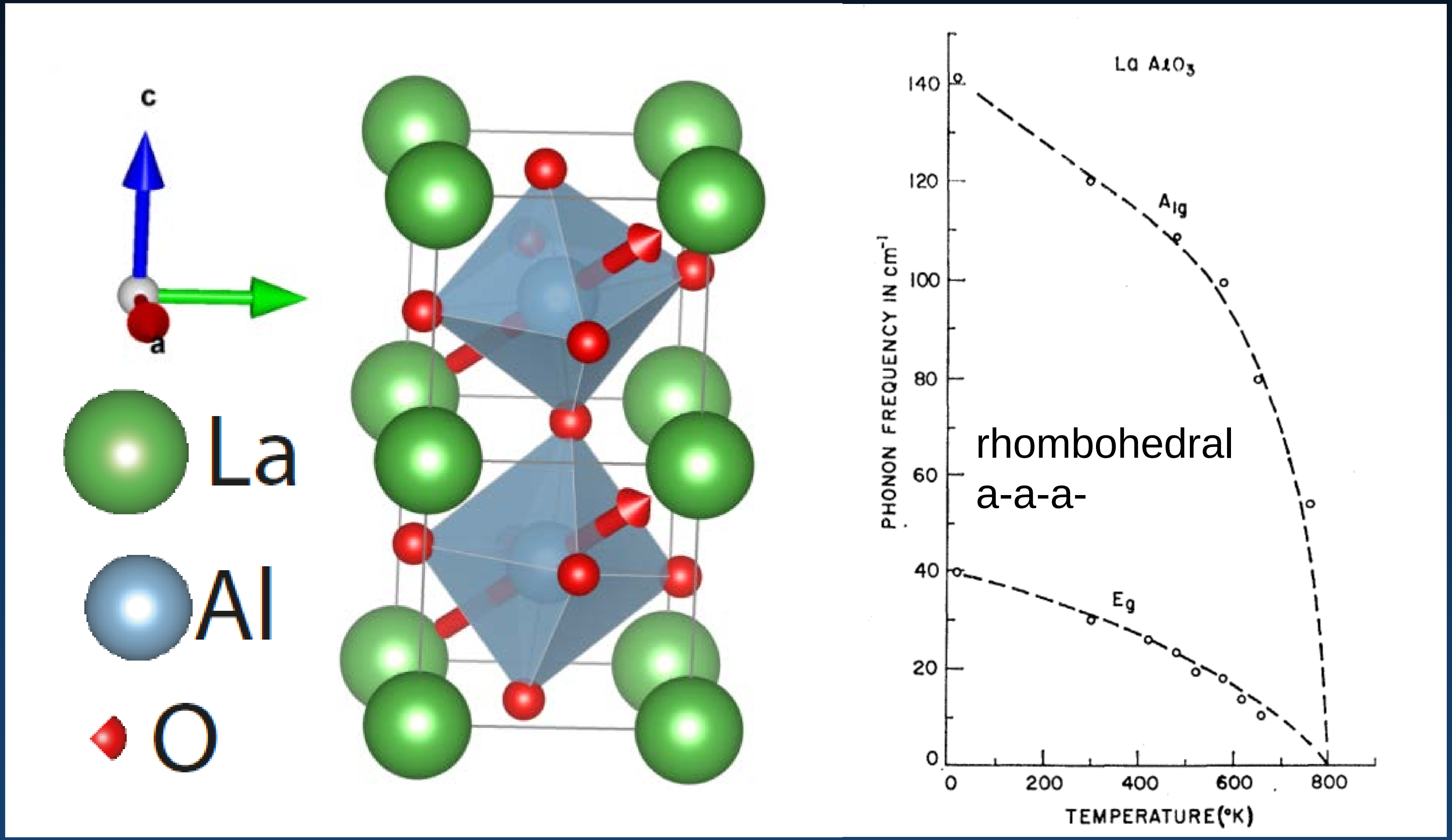


$E \sim 10$ MV/cm

Dynamically induced lattice distortions

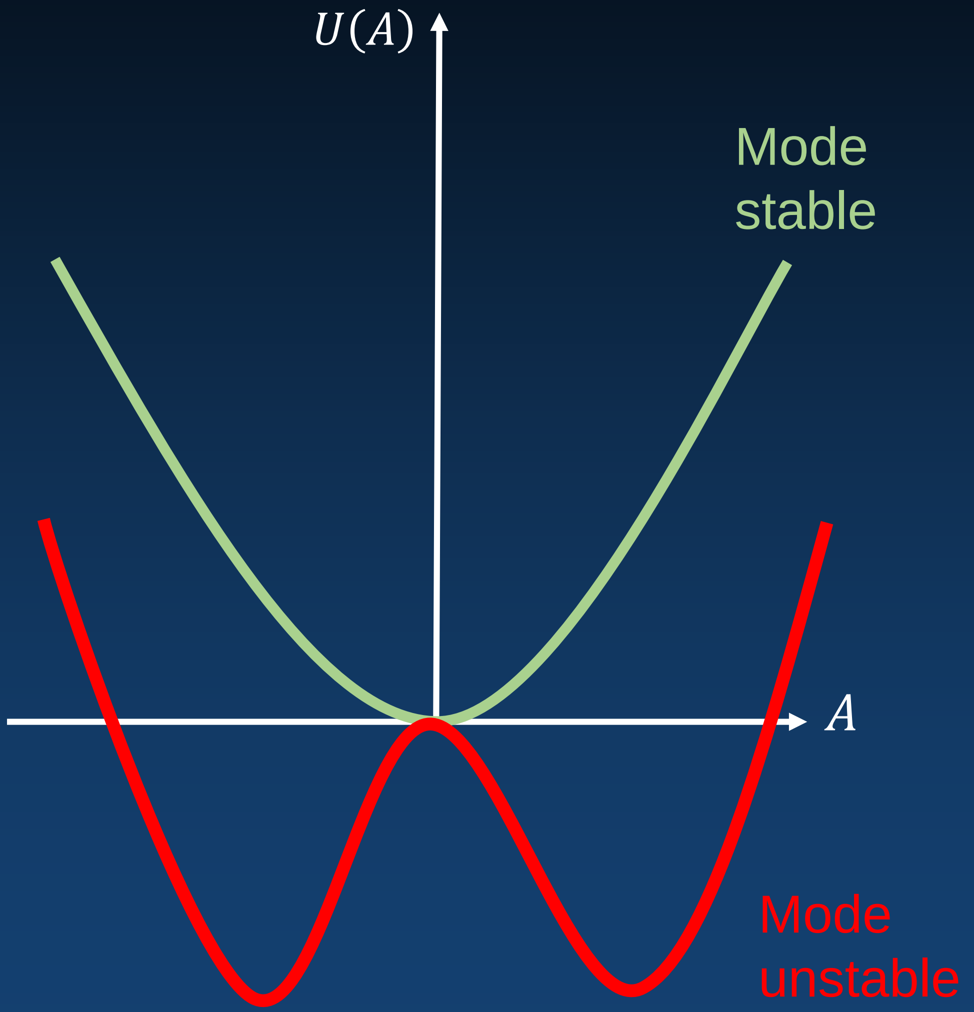


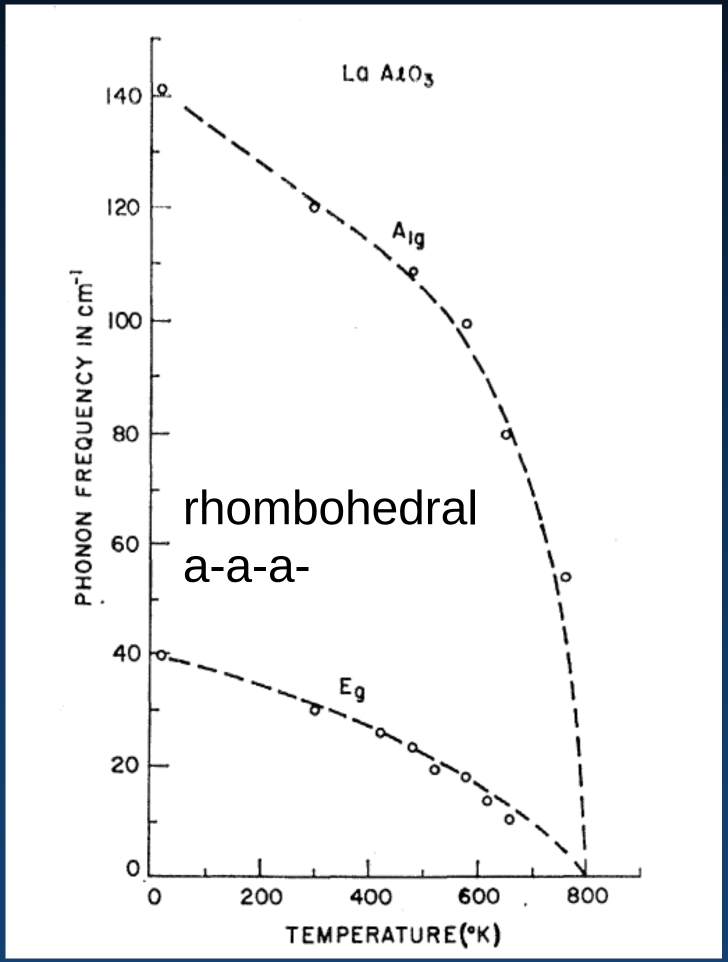
Lattice instabilities $LaAlO_3$



J.F. Scott, *Phys. Rev*, **137** 823 (1969)

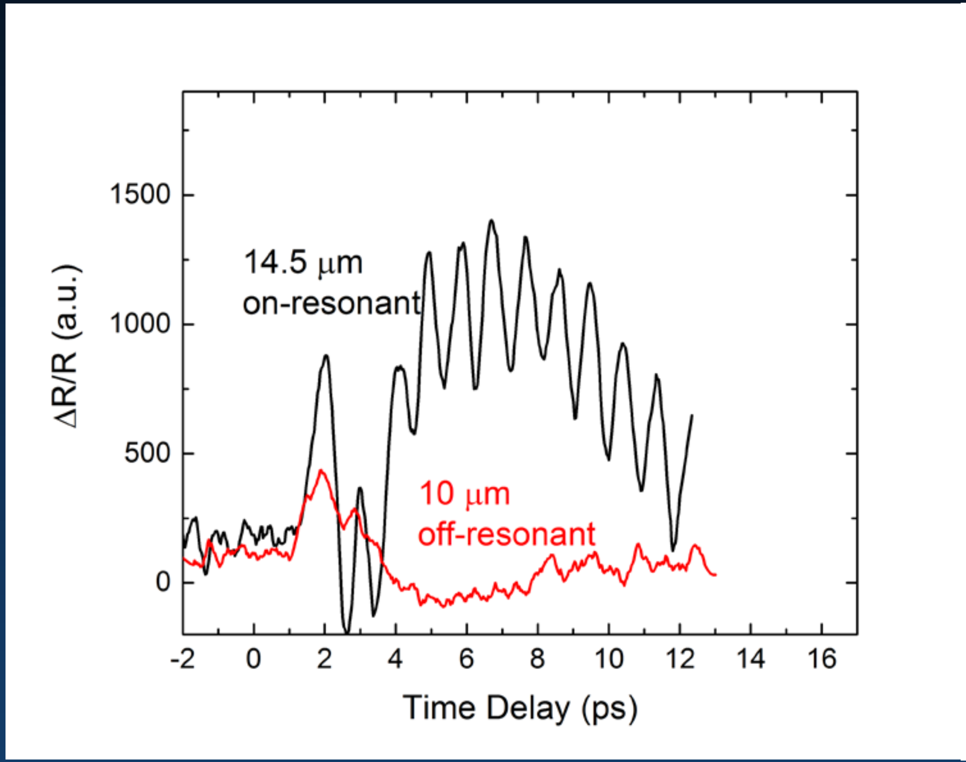
Lattice instabilities $LaAlO_3$

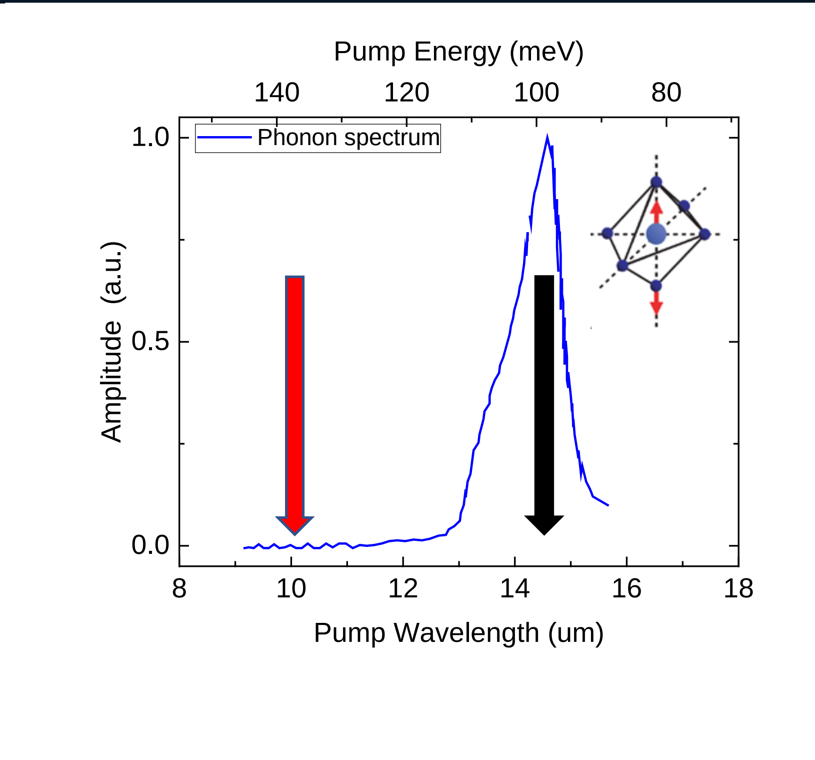




J.F. Scott, *Phys. Rev*, **137** 823 (1969)

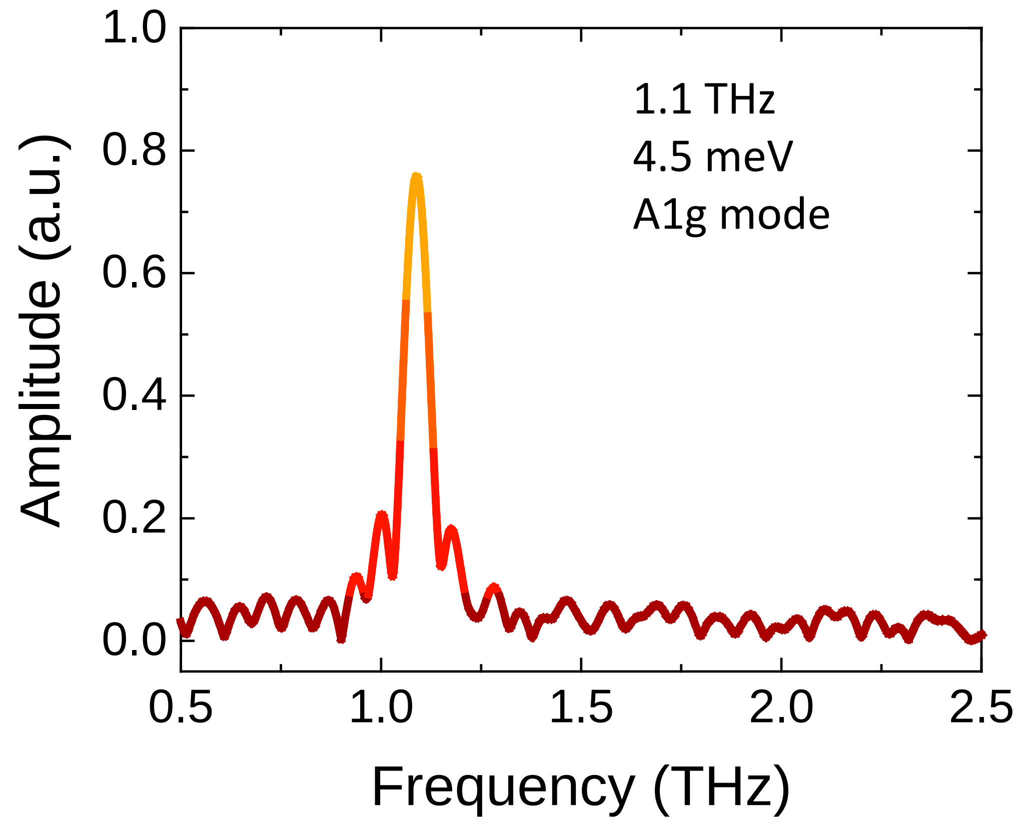
Coupling to octahedral rotations

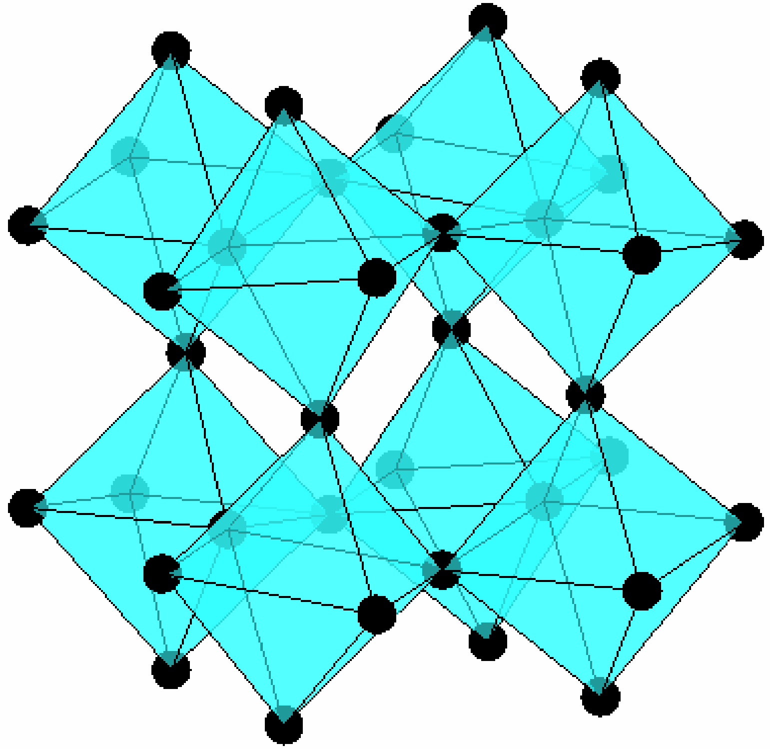




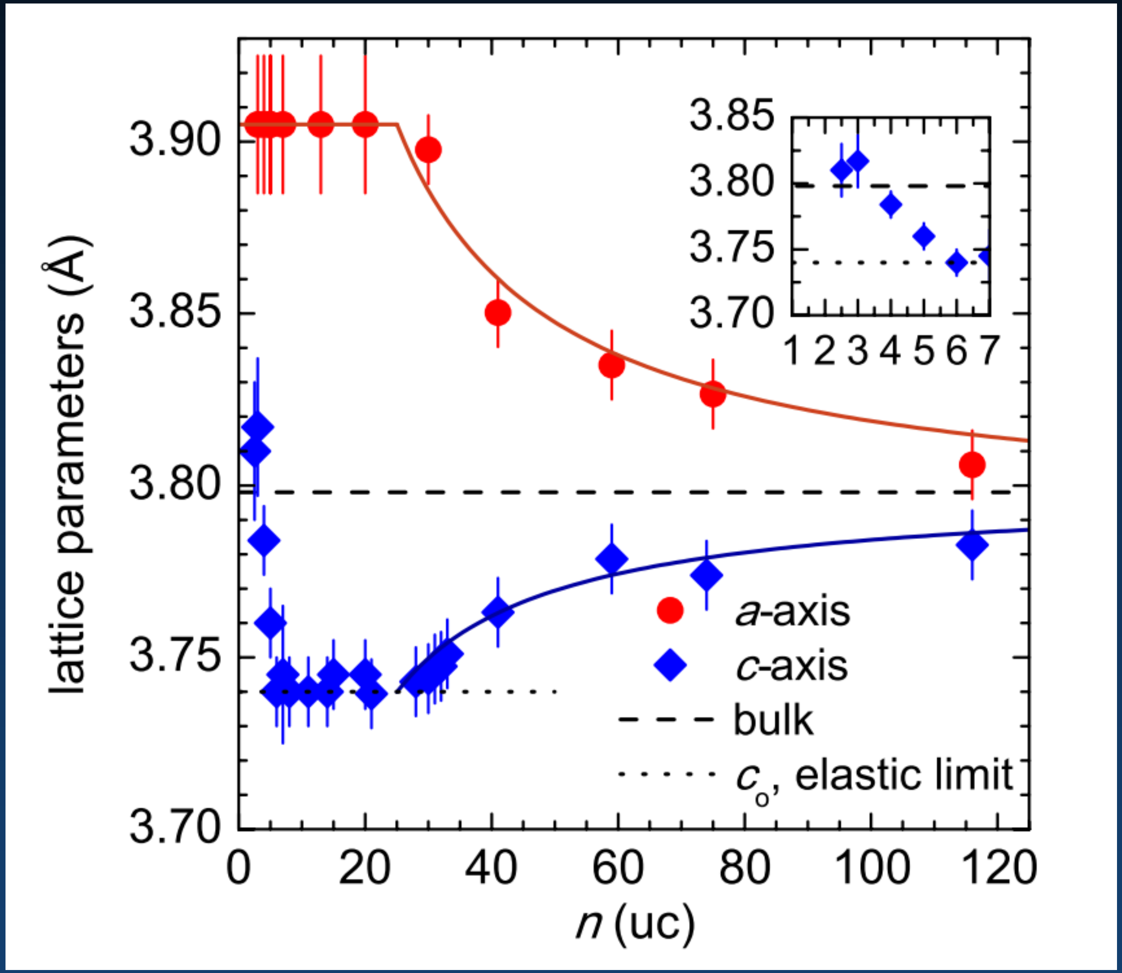
Jorrit Hortensius

Coupling to octahedral rotations





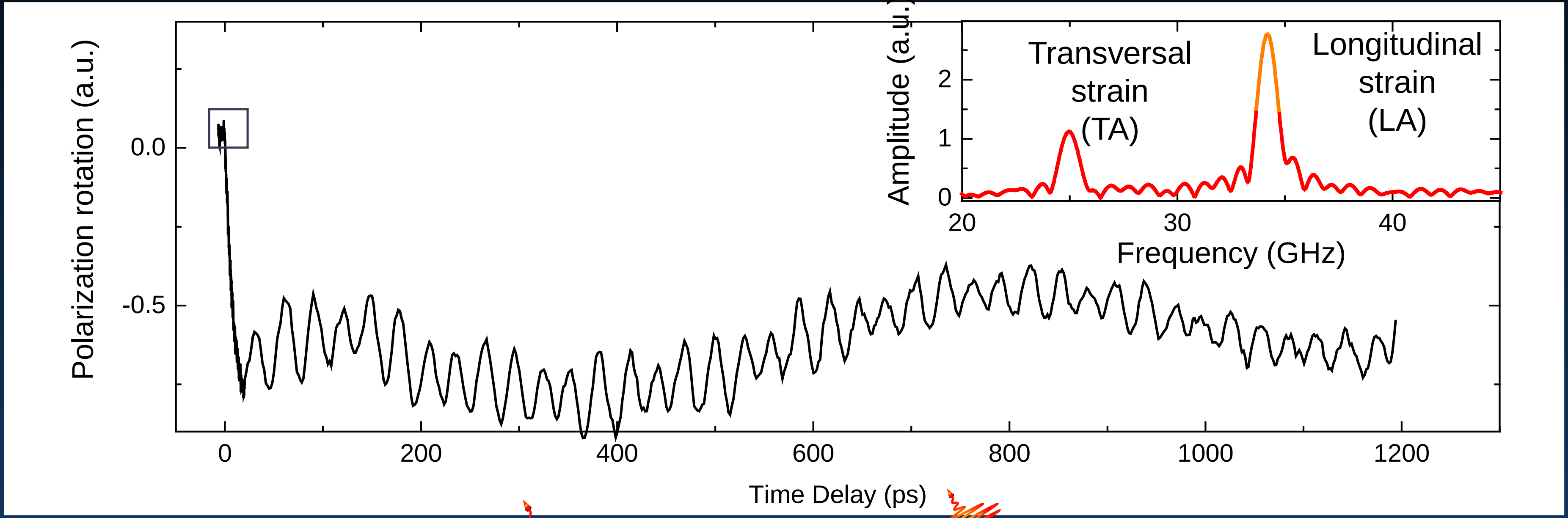
Electrostriction in $LaAlO_3$

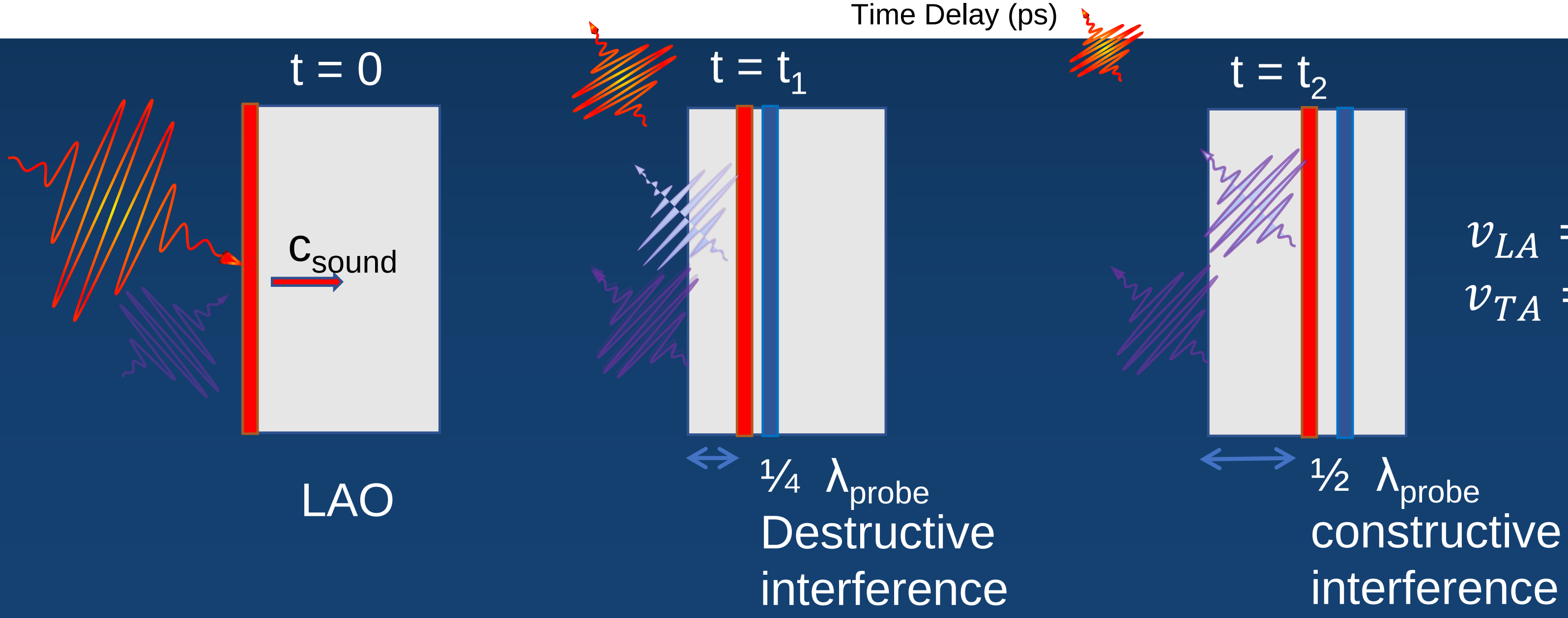


2% c-axis expansion
for 20 MV/cm electric field

Cancellieri et al. PRL 107, 056102 (2011)

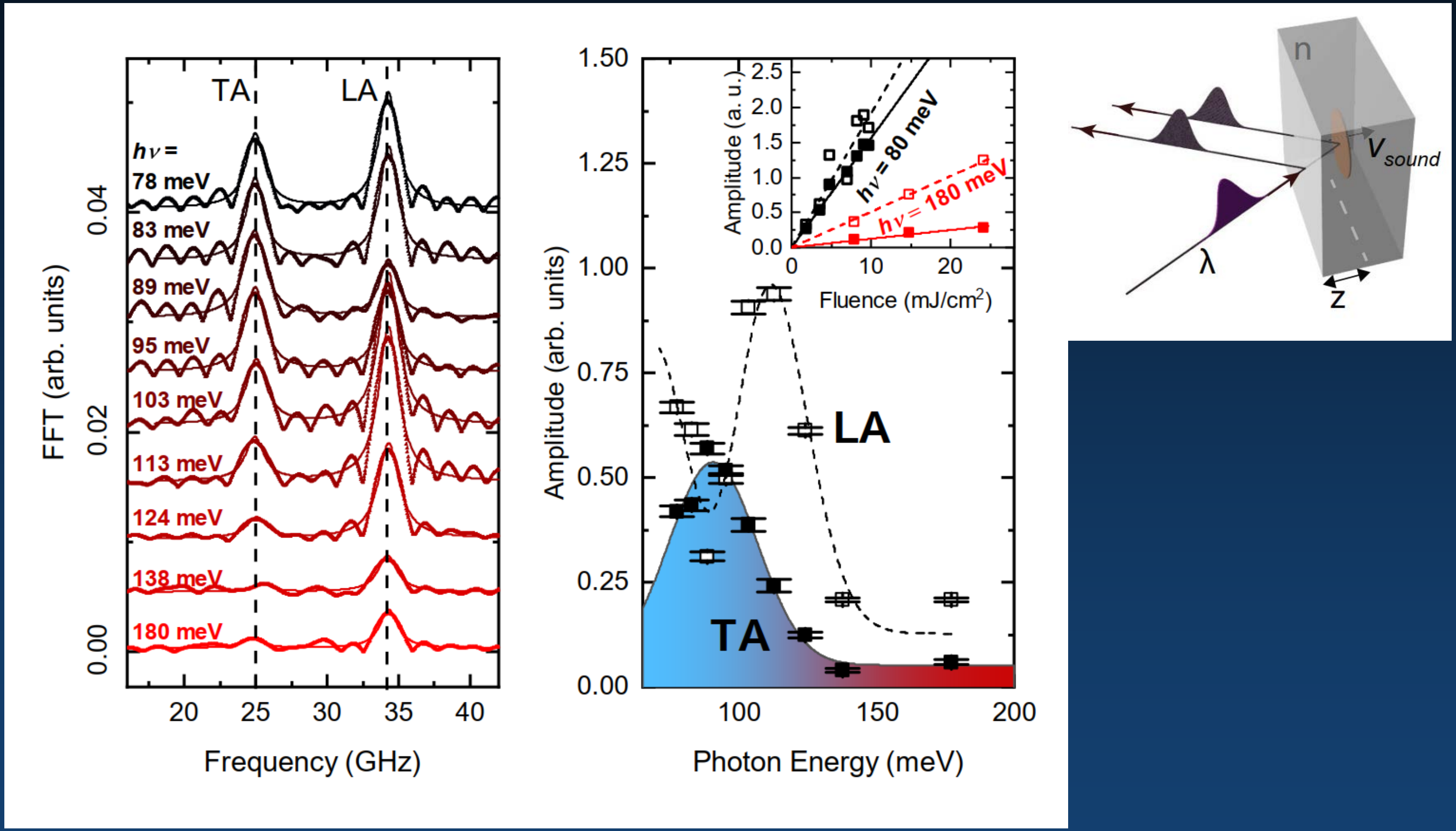
Ultrafast strain generation





$$v_{LA} = 4.8\ \text{km/s}$$
$$v_{TA} = 6.7\ \text{km/s}$$

Tunable longitudinal and shear strain



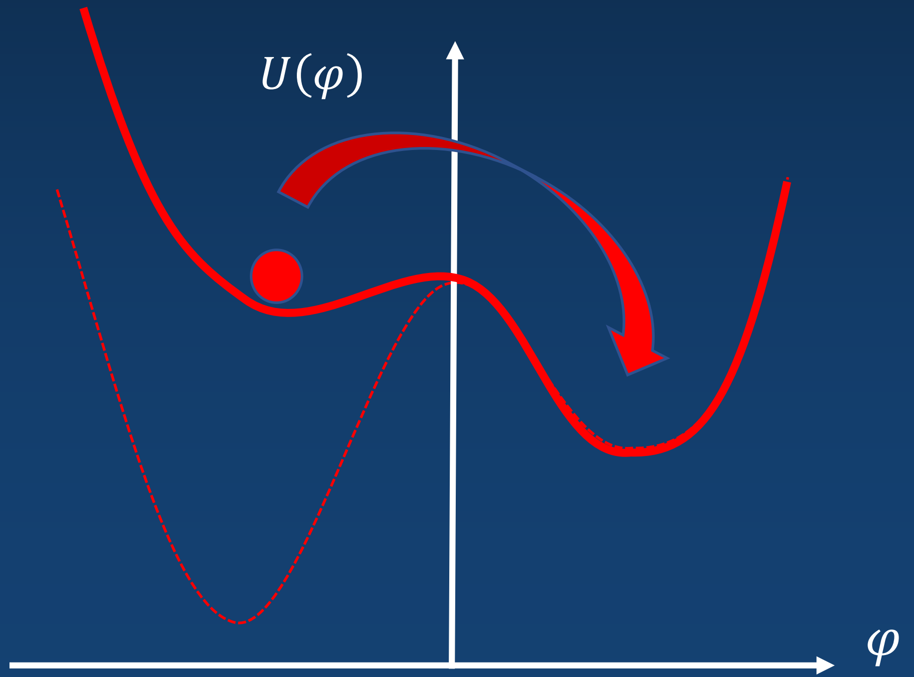
Hortensius et al. npj Quantum Materials 5, 95 (2020)

Ultrafast strain generation

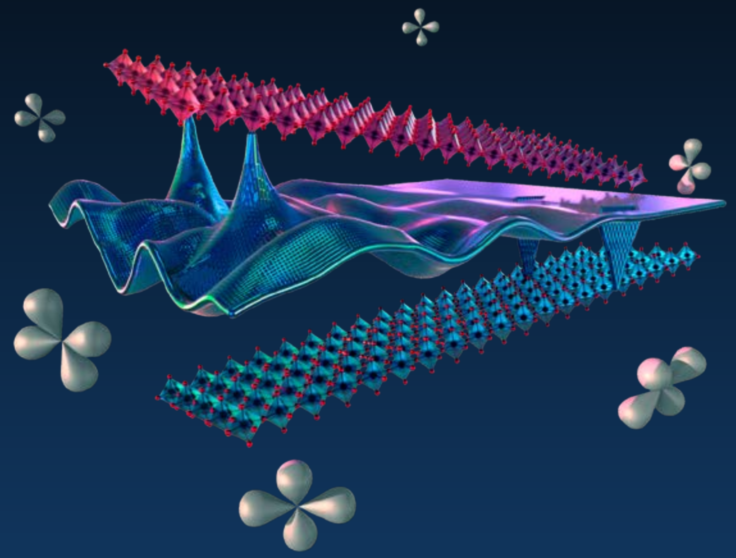
- Two types of strain generated at the surface
- Anisotropy of $LaAlO_3$ responsible for transverse strain
- Shear strain generation in optically transparent material

Hortensius et al. npj Quantum Materials 5, 95 (2020)

Can we control transitions between ordered states?



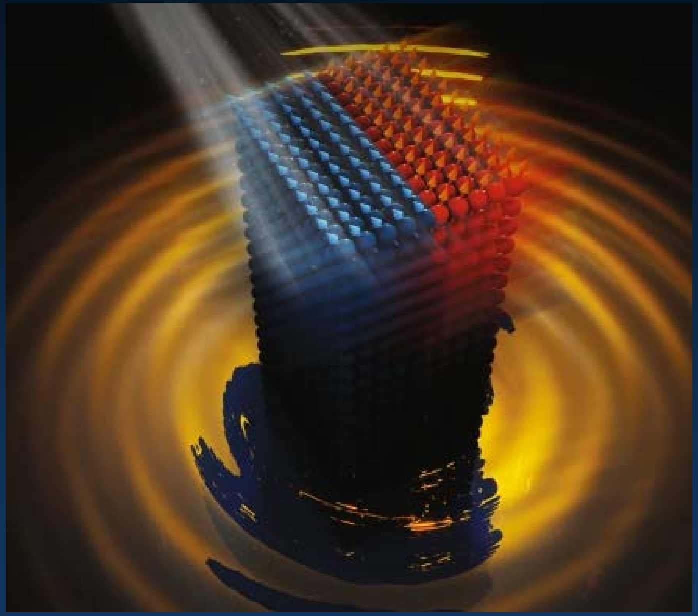
Outline



Phonon resonances

Ultrafast strain engineering

LaAlO3

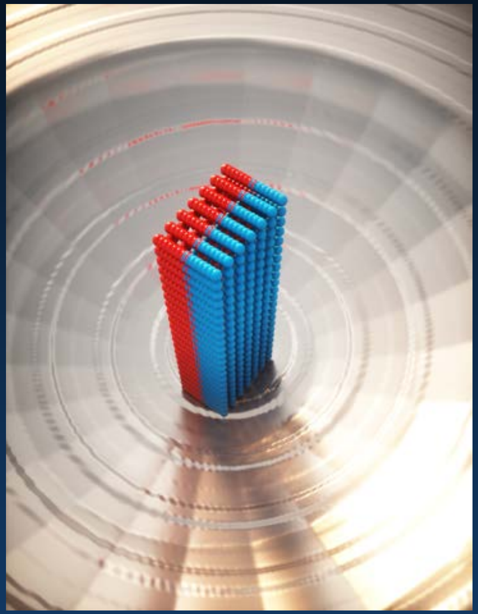


Phonon resonances

Lattice control of magnetic interactions

DyFeO3

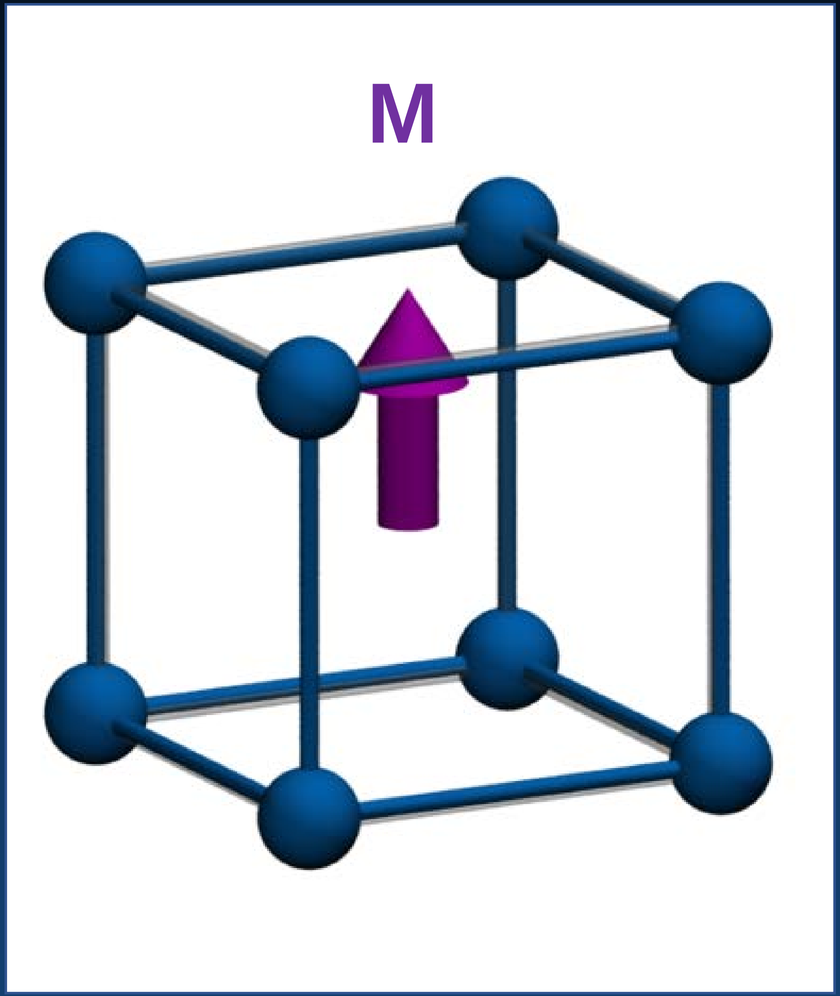
Magnetic transitions



Charge resonances

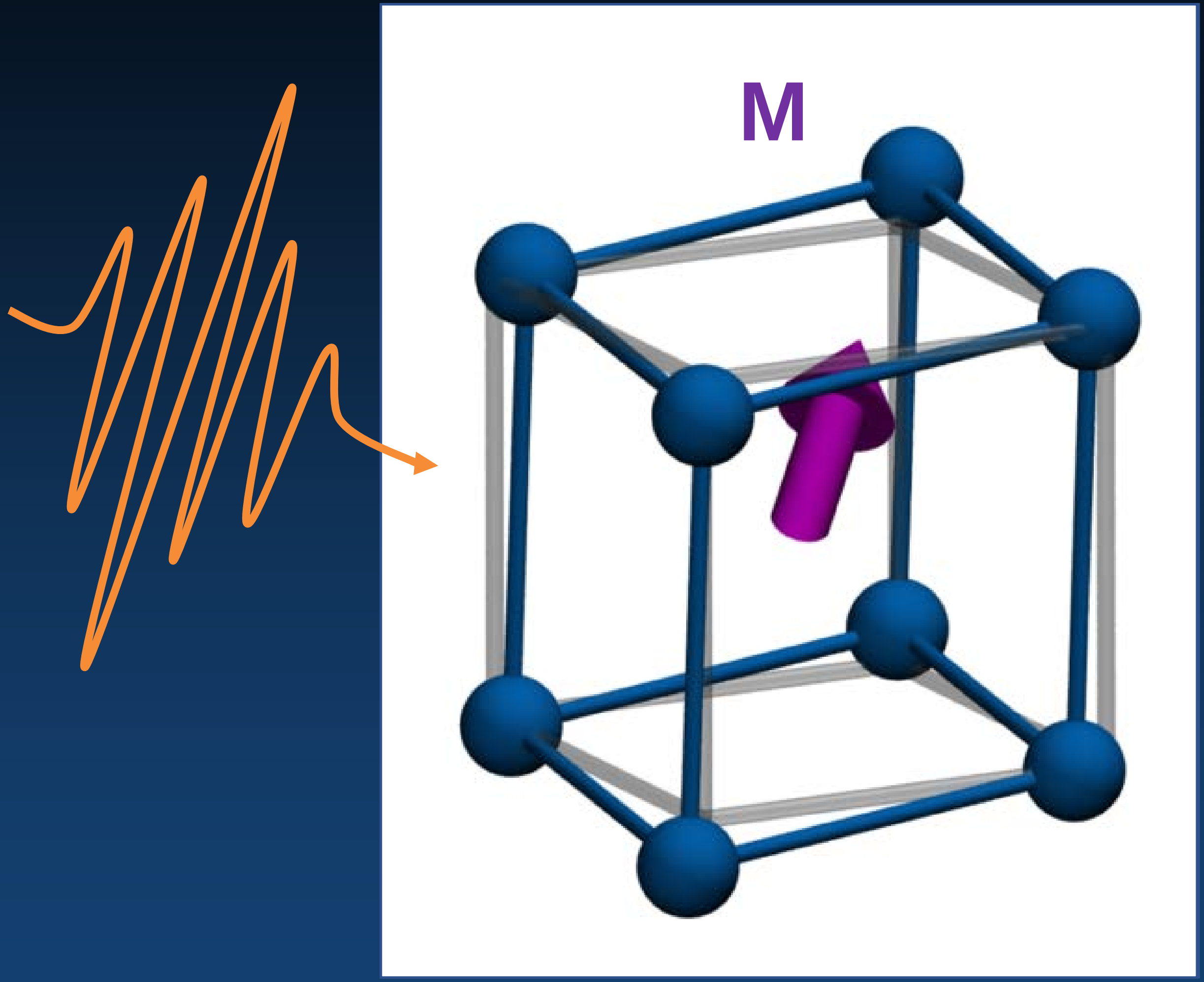
Coherent spin-wave transport in antiferromagnets

Lattice control of magnetism



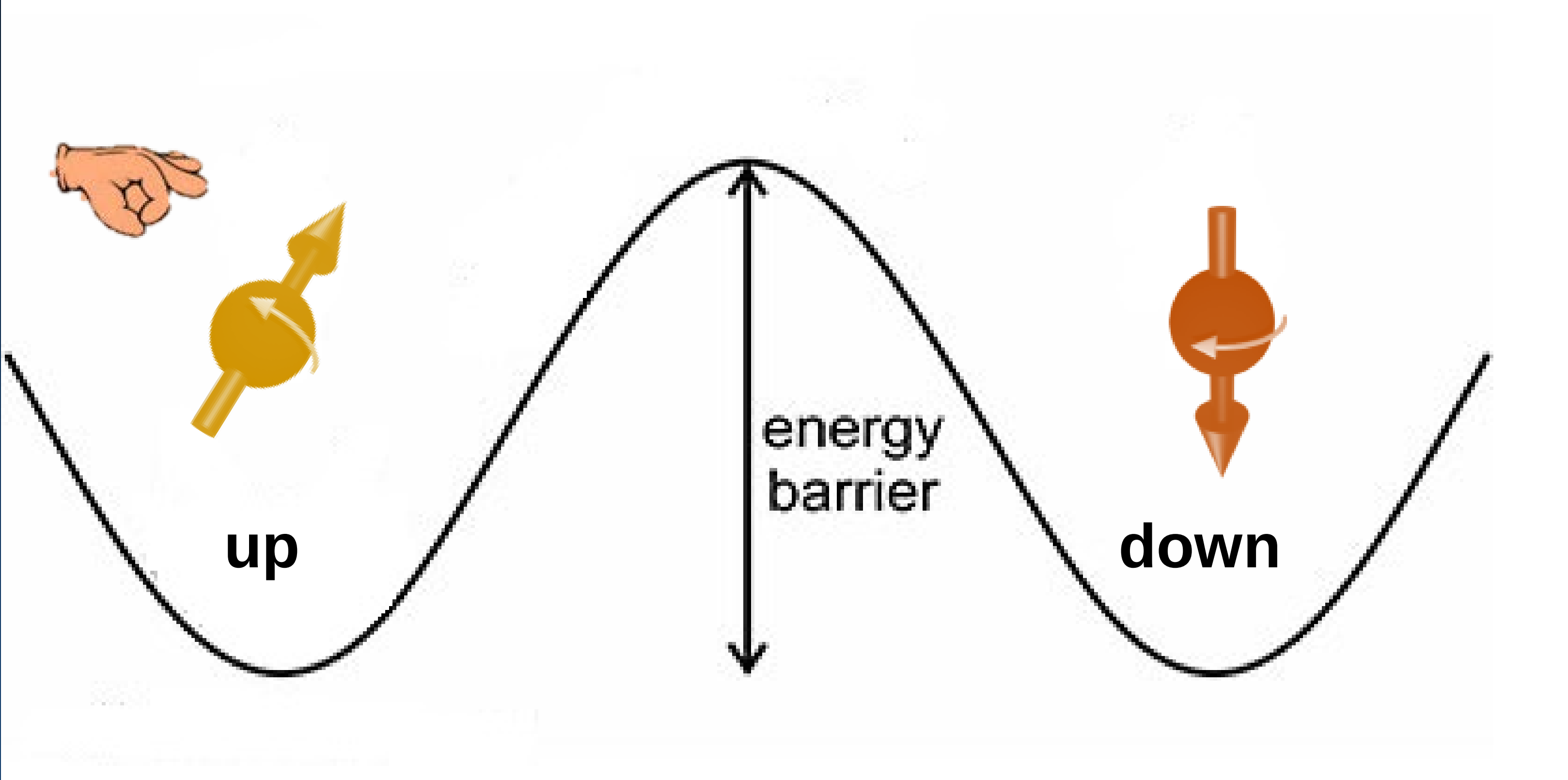
Magnetization is locked with lattice via spin-orbit coupling

Lattice control of magnetism

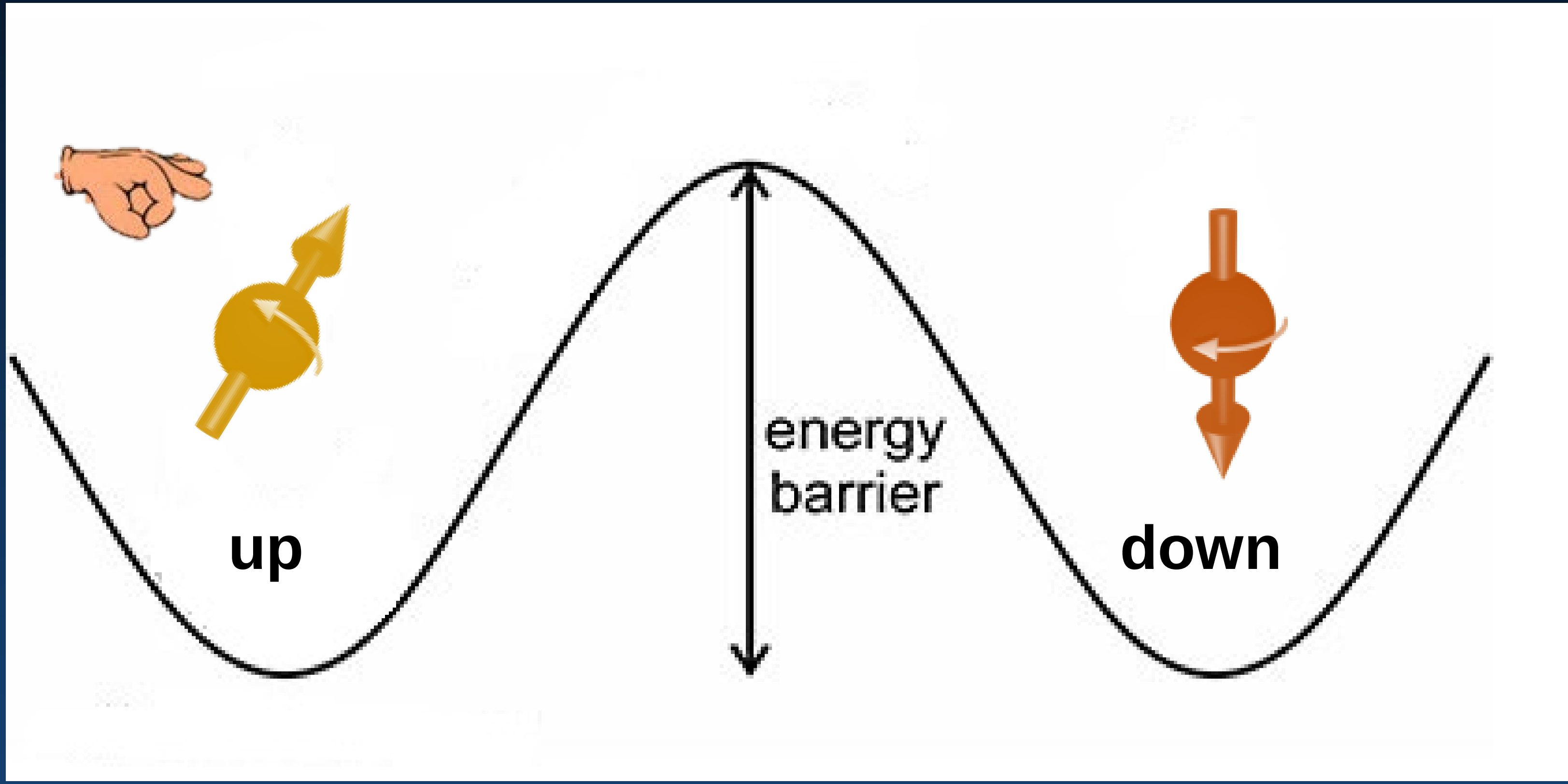


Change of the magnetic anisotropy

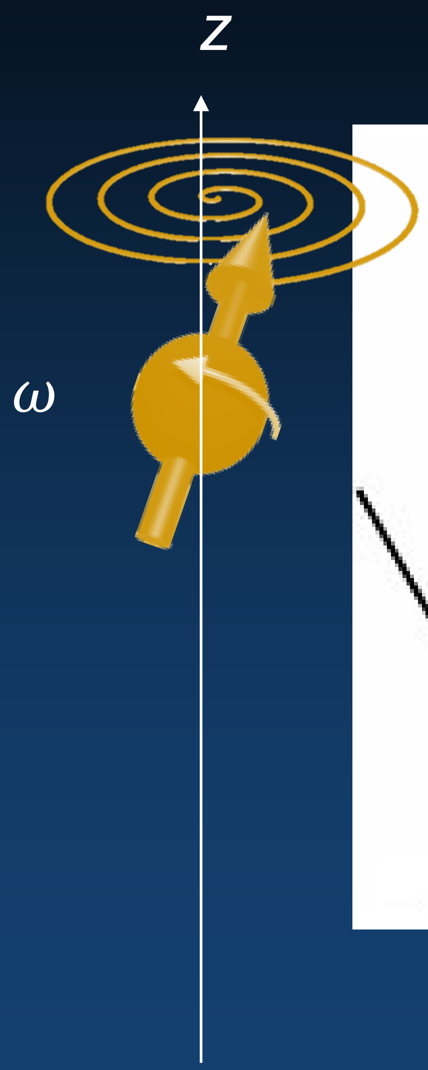
Magnetic recording



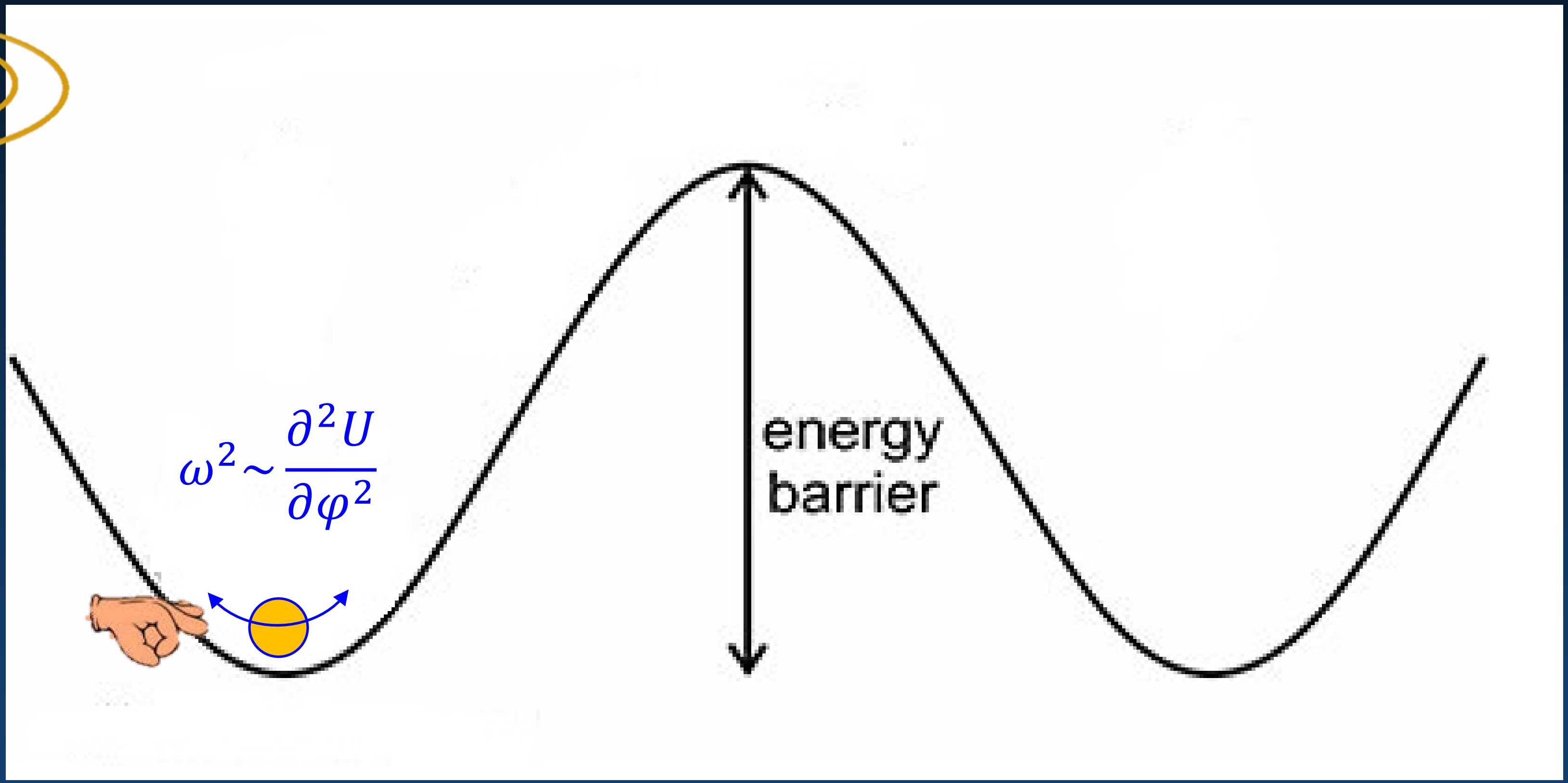
Magnetic anisotropy as energy barrier



Magnetic anisotropy as energy barrier

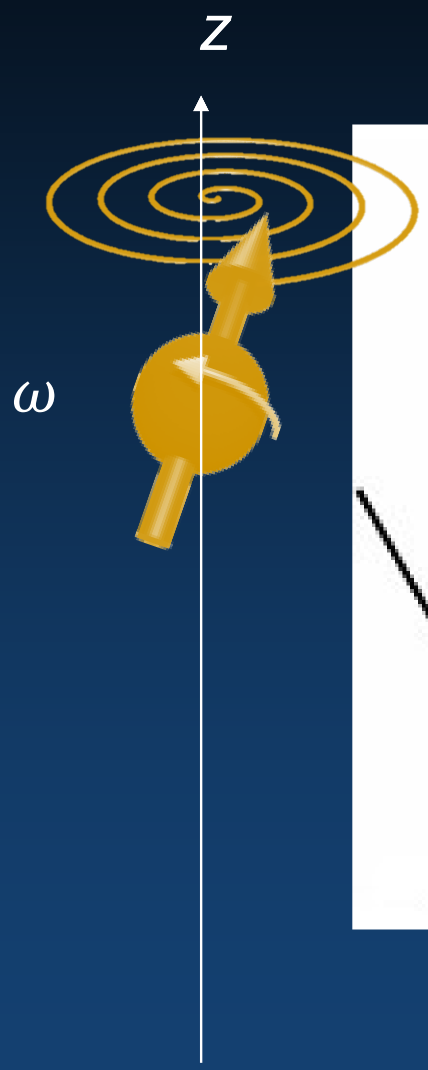


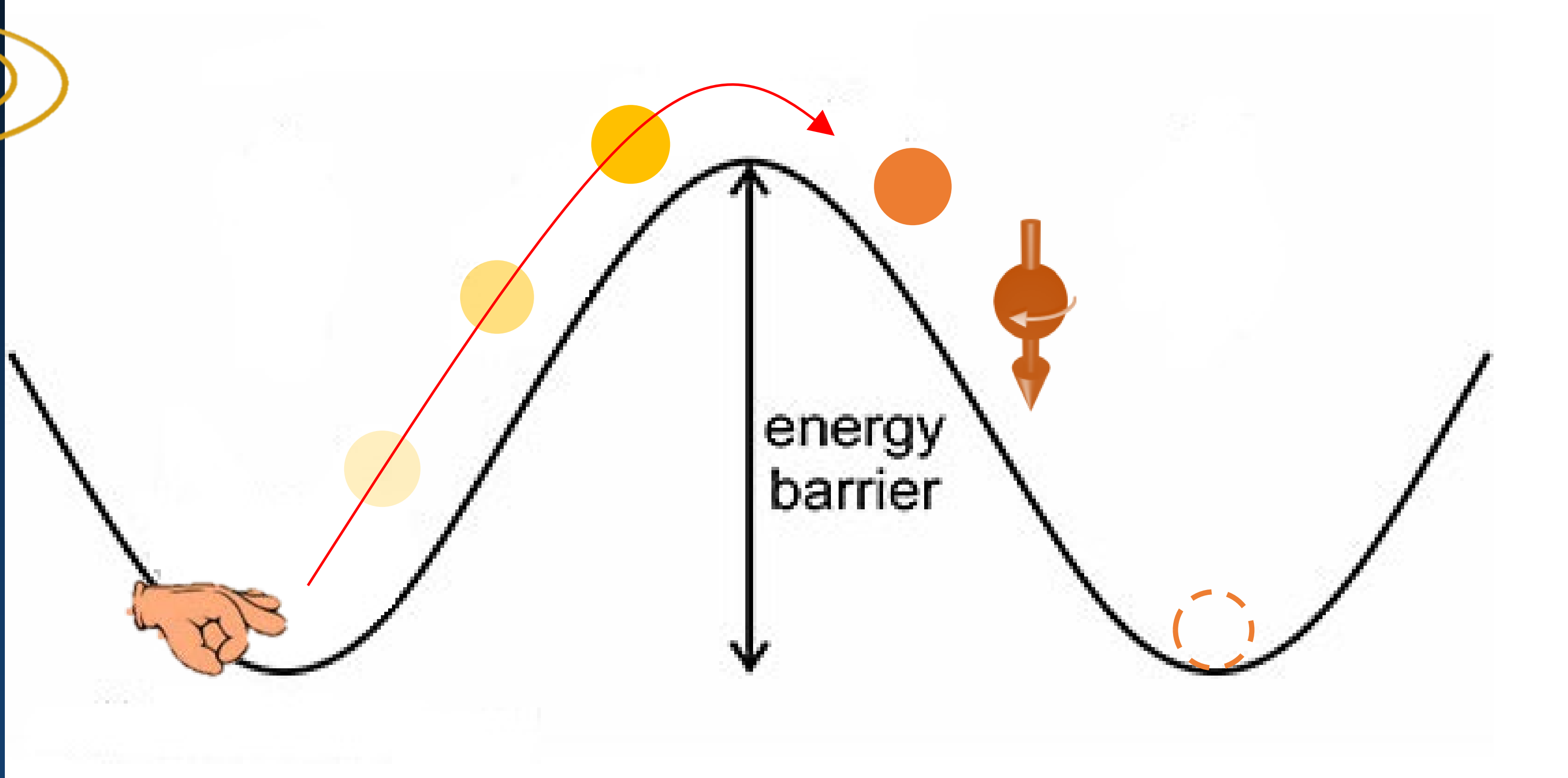
Spin precession ω



The precession frequency
reflects the local curvature of the potential

Magnetic anisotropy as energy barrier

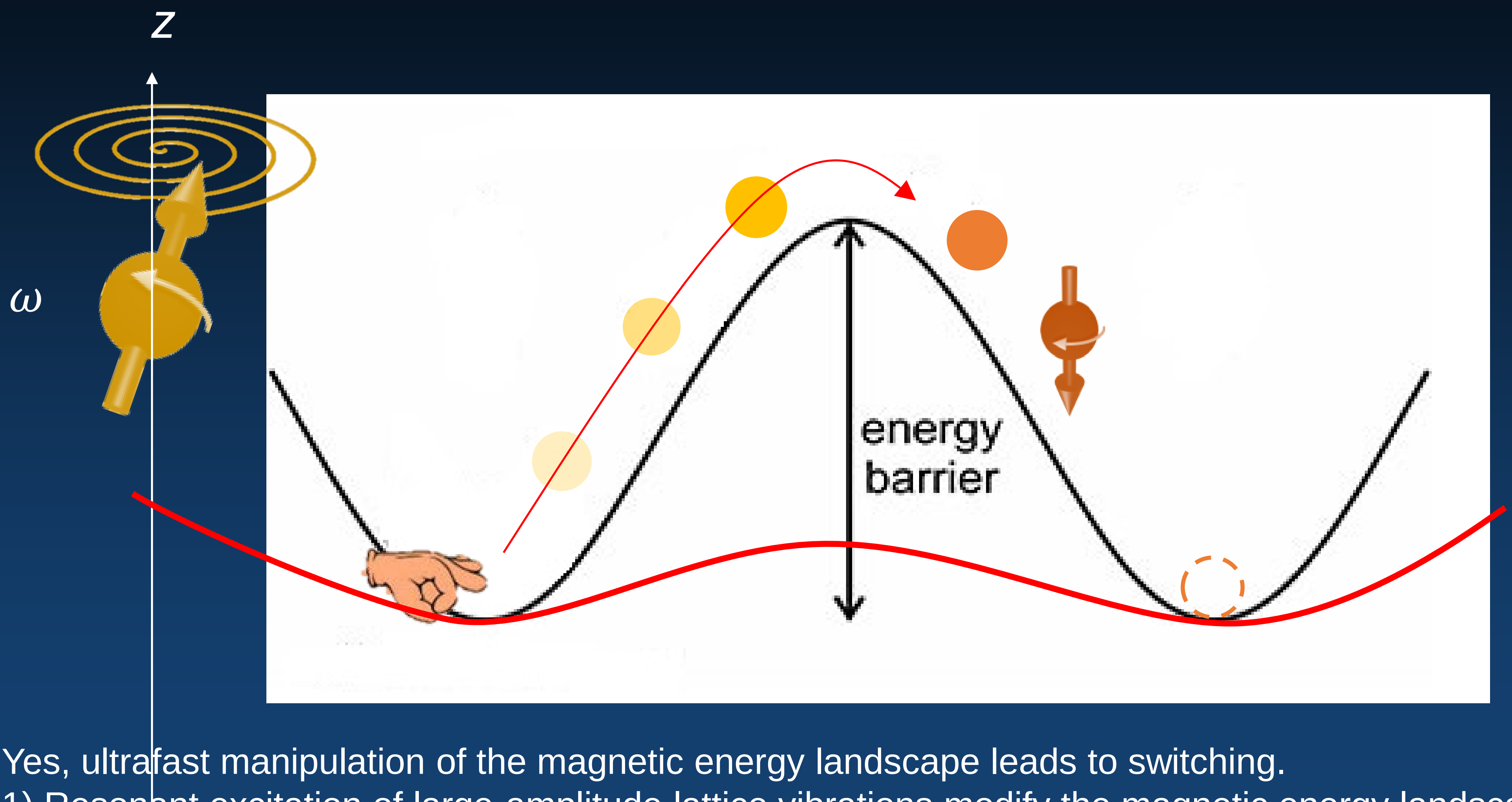




The precession frequency
reflects the local curvature of the potential

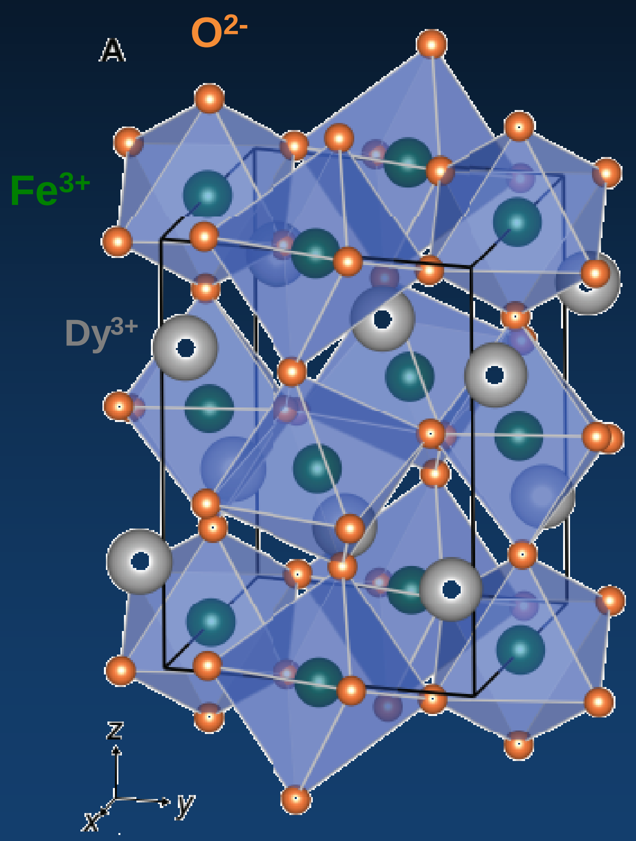
Spin precession ω

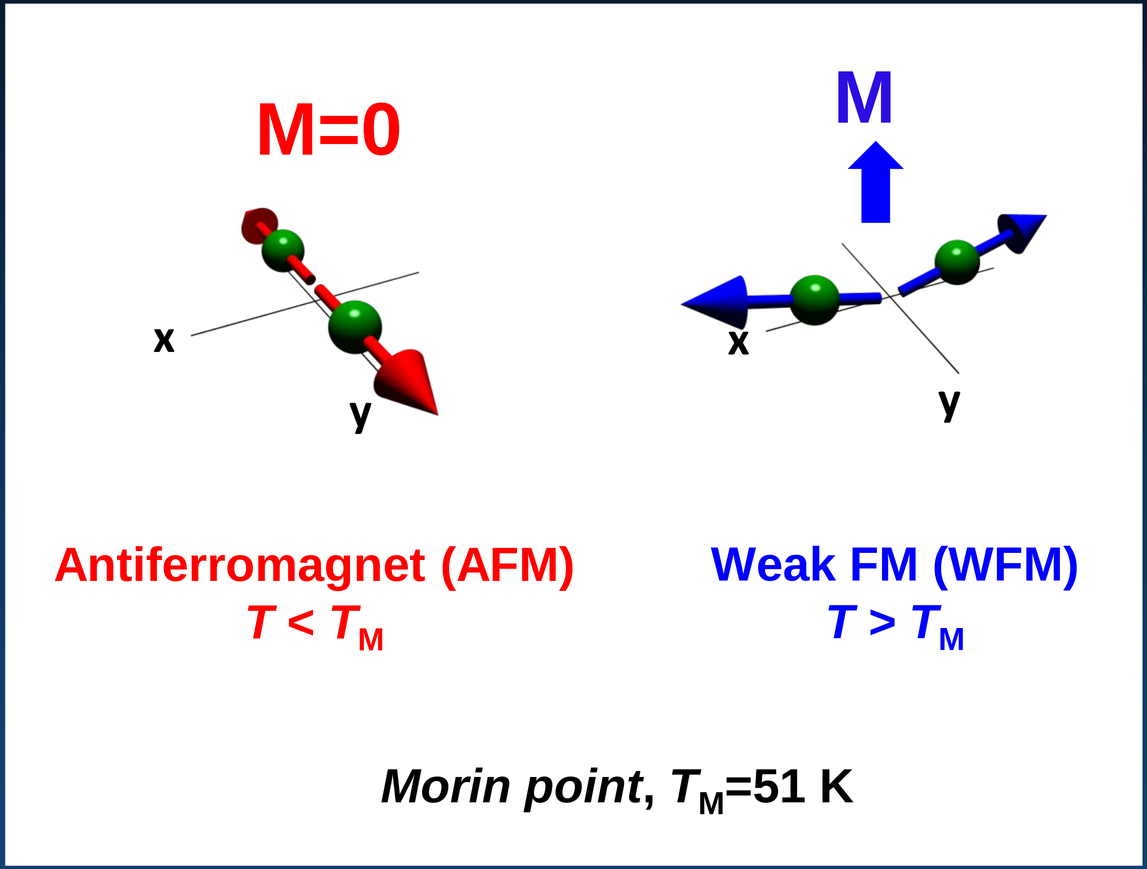
Can we manipulate the energy barrier?



Yes, ultrafast manipulation of the magnetic energy landscape leads to switching.
1) Resonant excitation of large-amplitude lattice vibrations modify the magnetic energy landscape.
2) Magnetic switching occurs during the fist periods of magnon oscillations.

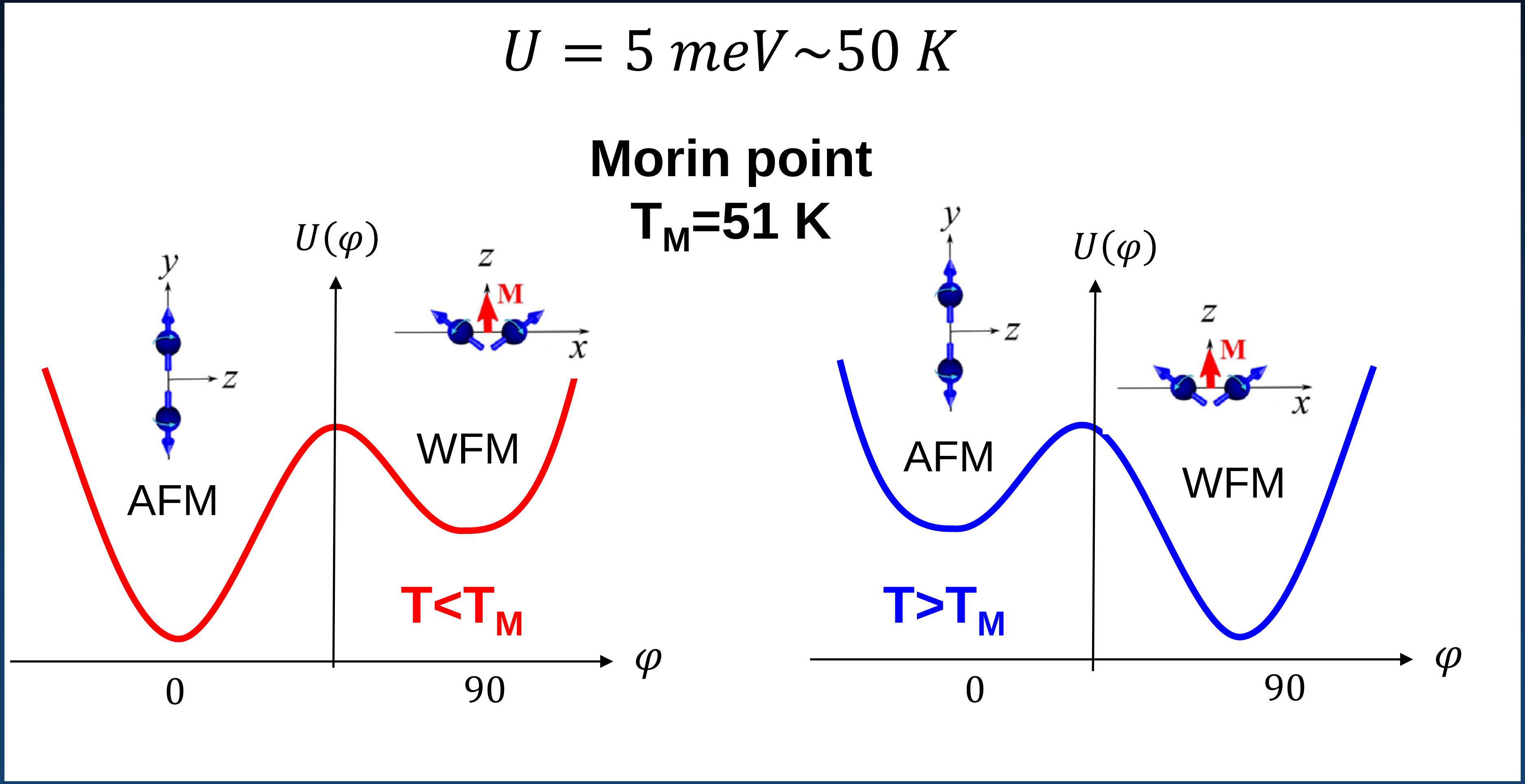
Rare earth orthoferrite $DyFeO_3$



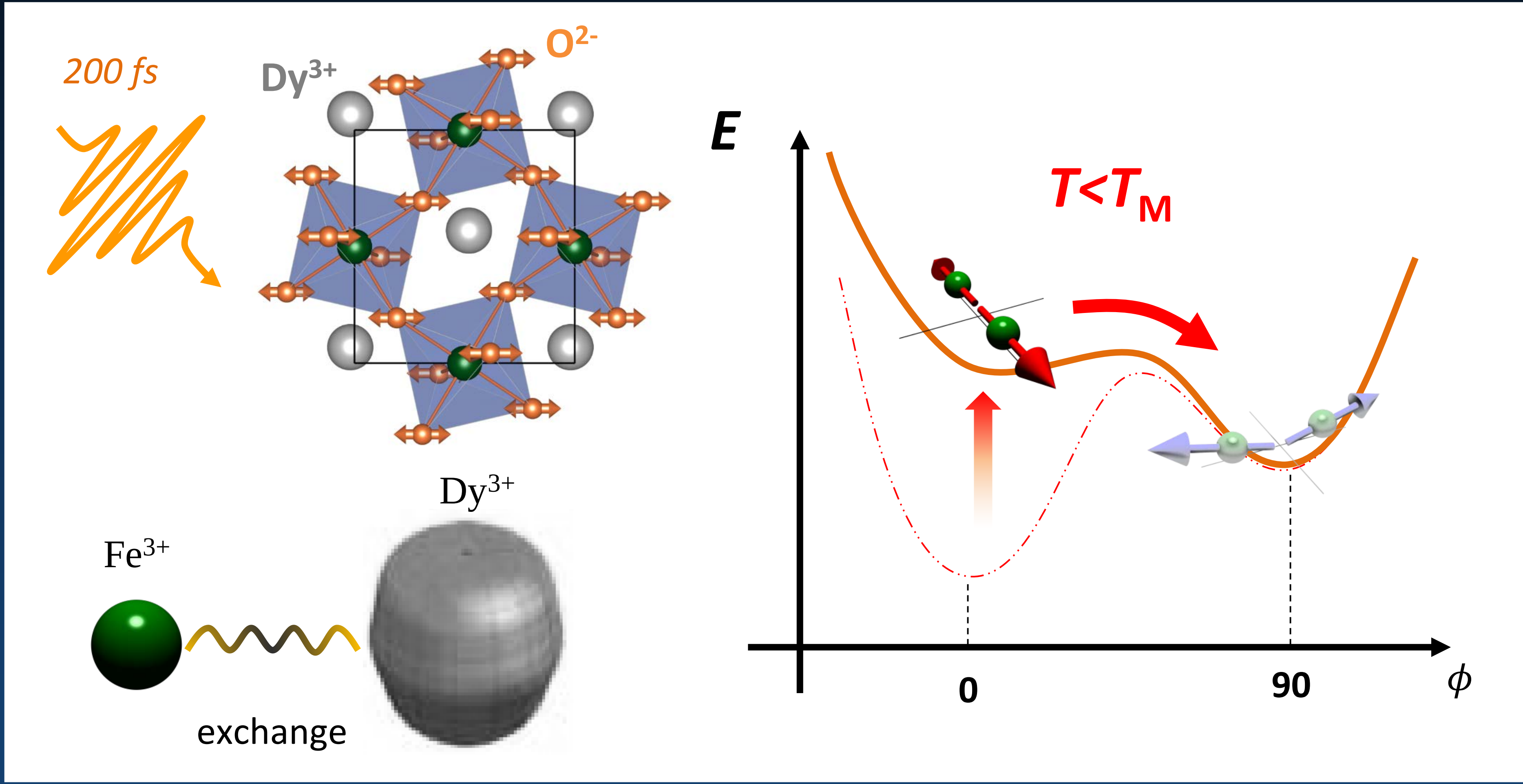


Orthorhombic perovskite (*Pnma)*
Fe^{3+} are AFM ordered (T_N=650 K)

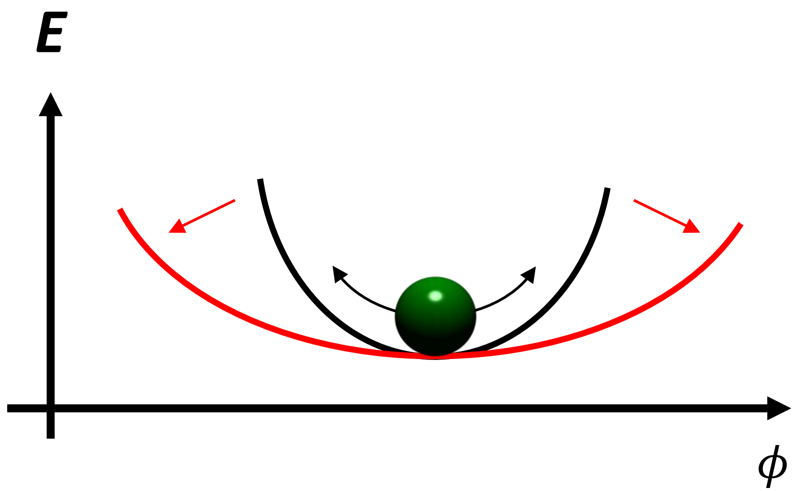
Spin reorientation transition



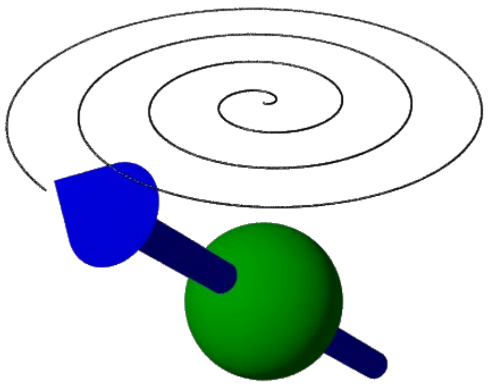
Control AFM to FM transition



How to measure potential dynamics?



$$f^2 \sim \frac{\partial^2 E}{\partial \phi^2}$$

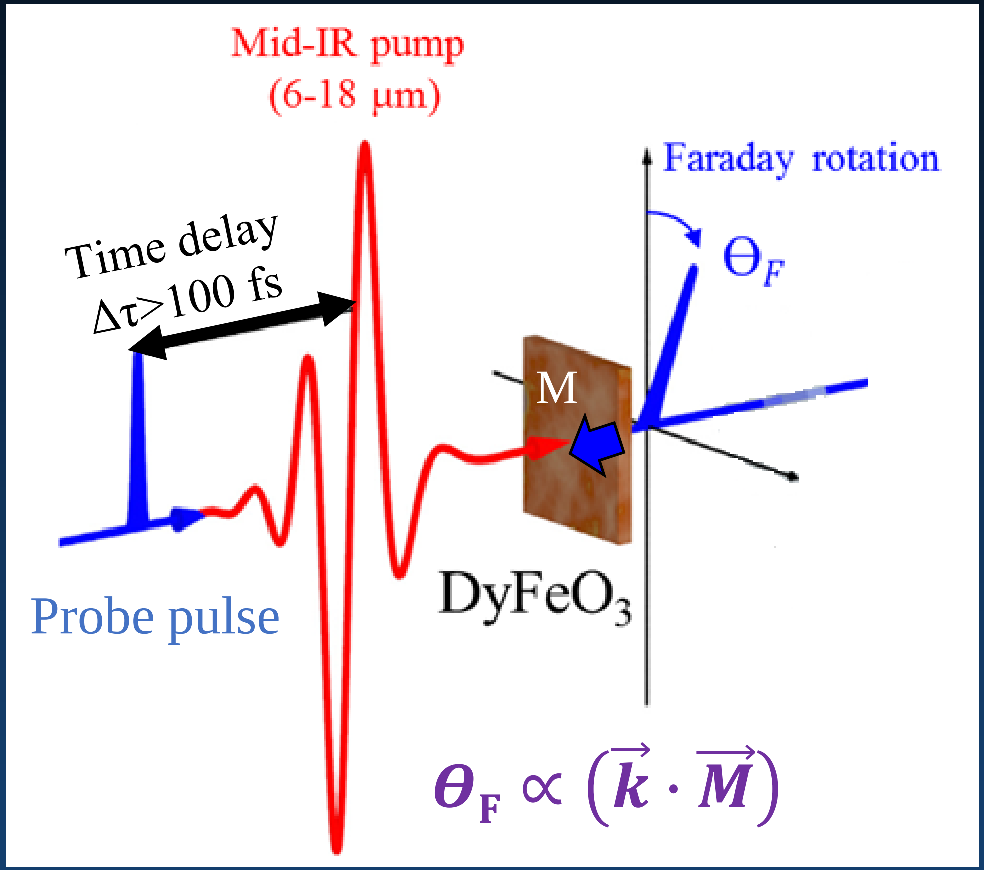


Spin precession

Measurement scheme

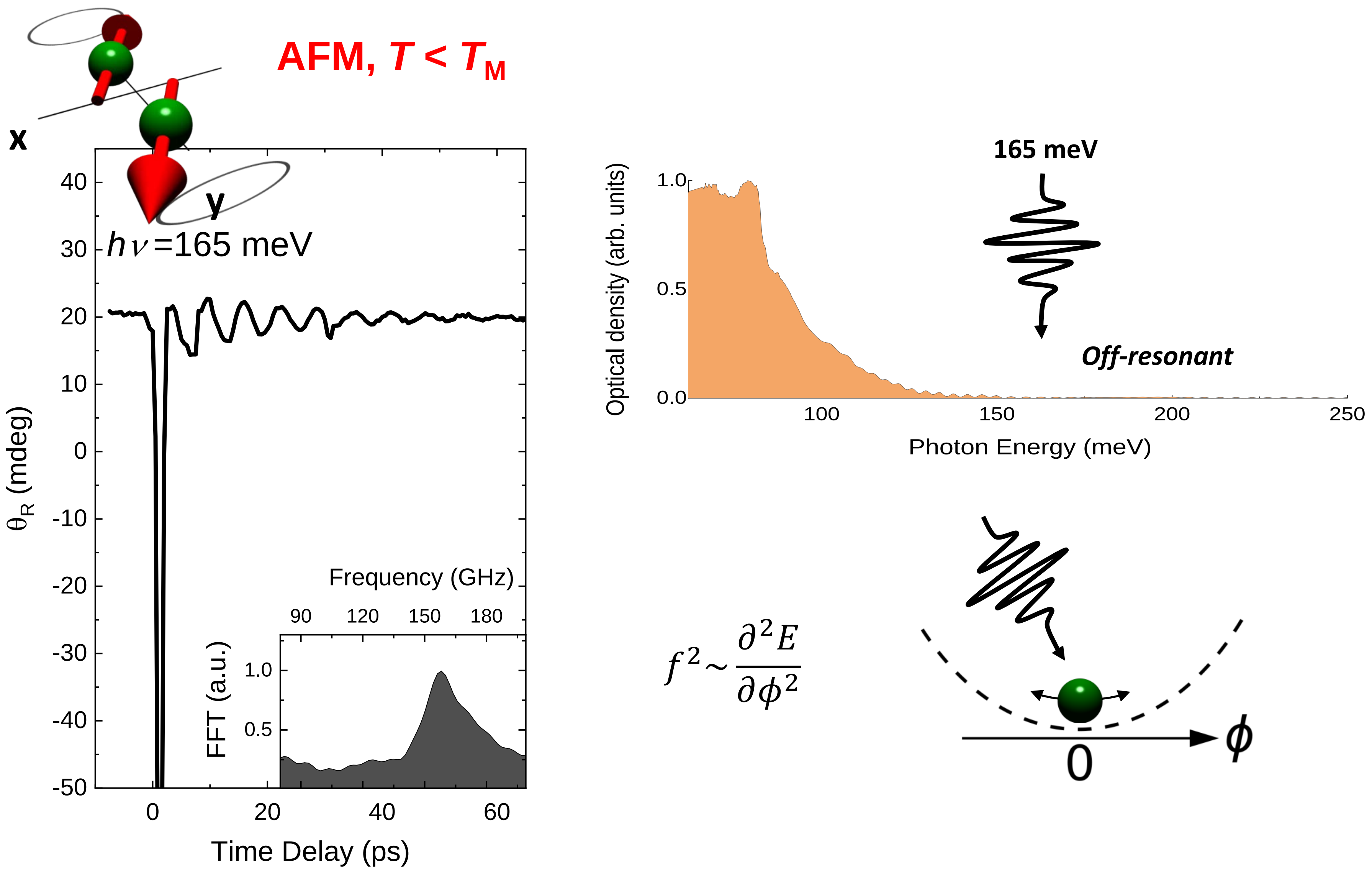
Dmytro Afanasiev

Jorrit Hortensius



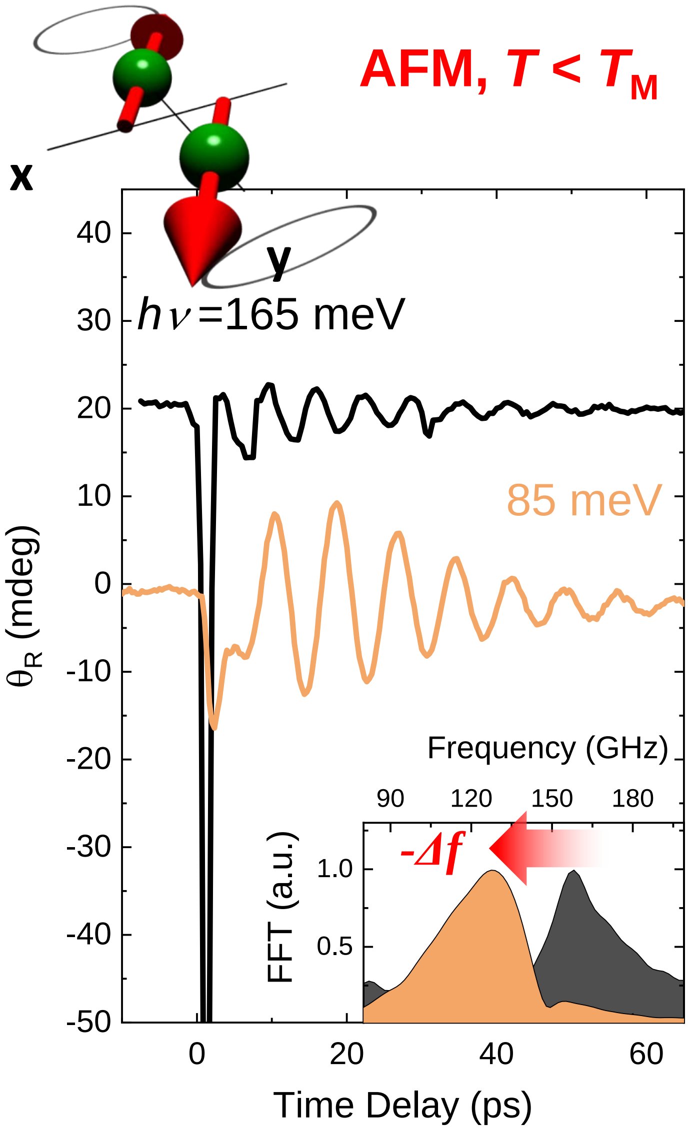
M is the magnetization of Fe^{3+}

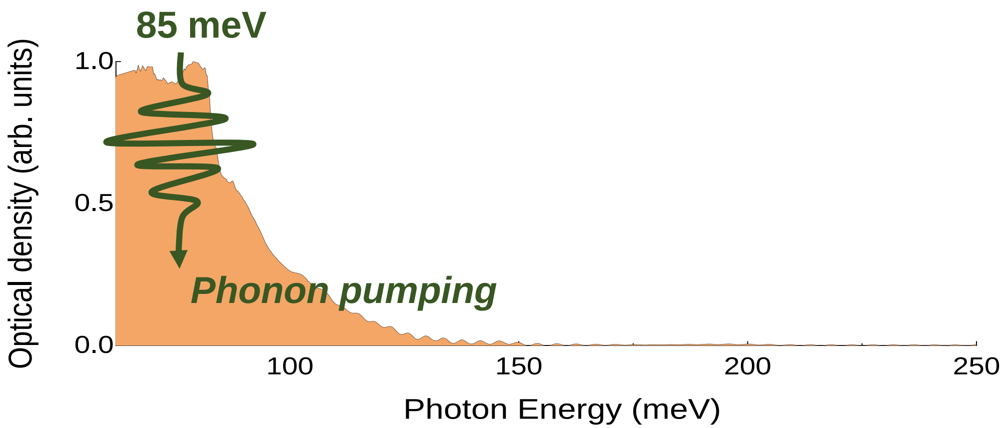
Non resonant spin precession



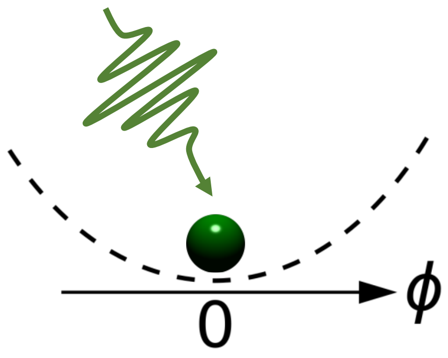
$$f^2 \sim \frac{\partial^2 E}{\partial \phi^2}$$

Resonant spin precession

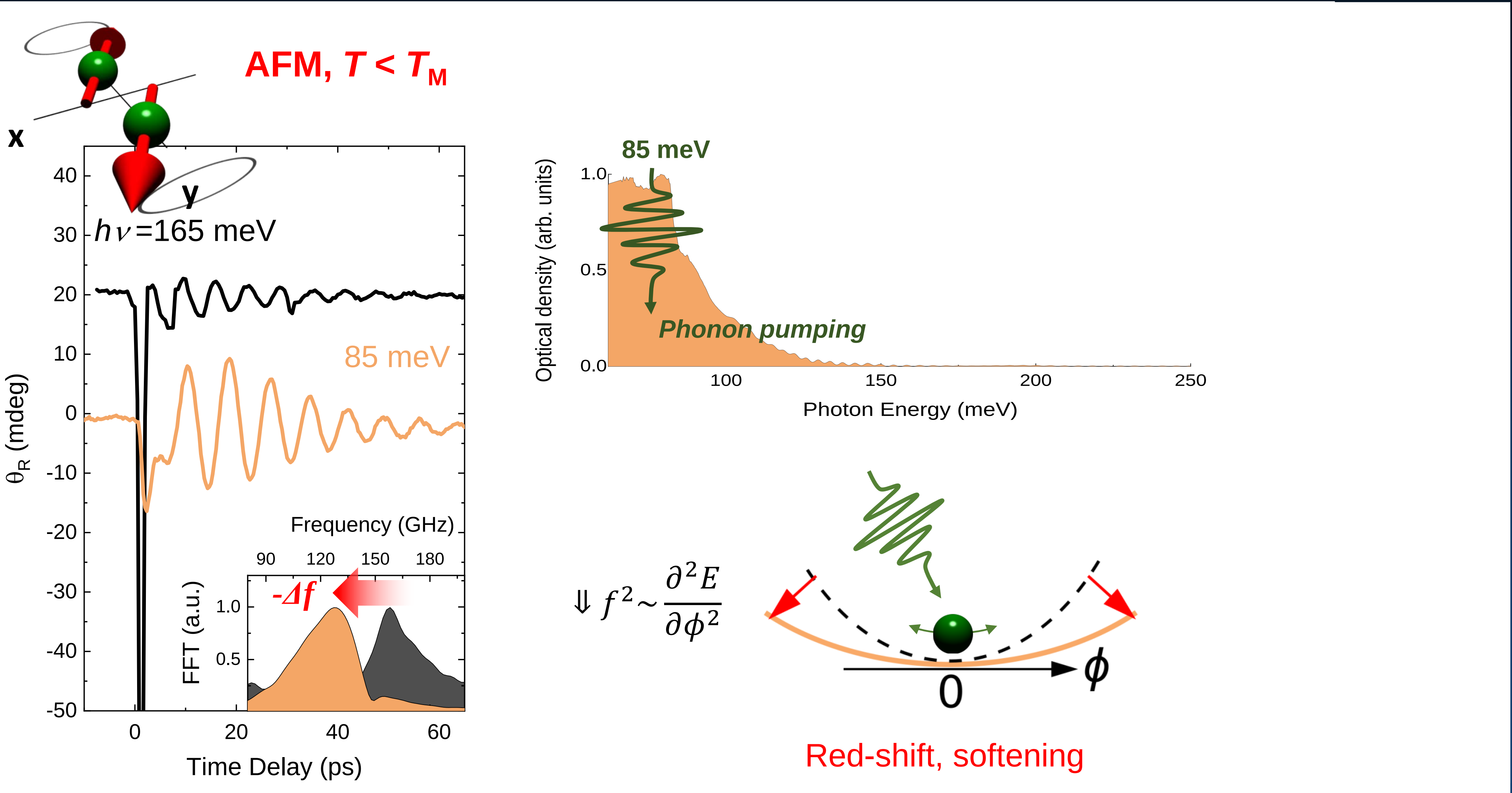




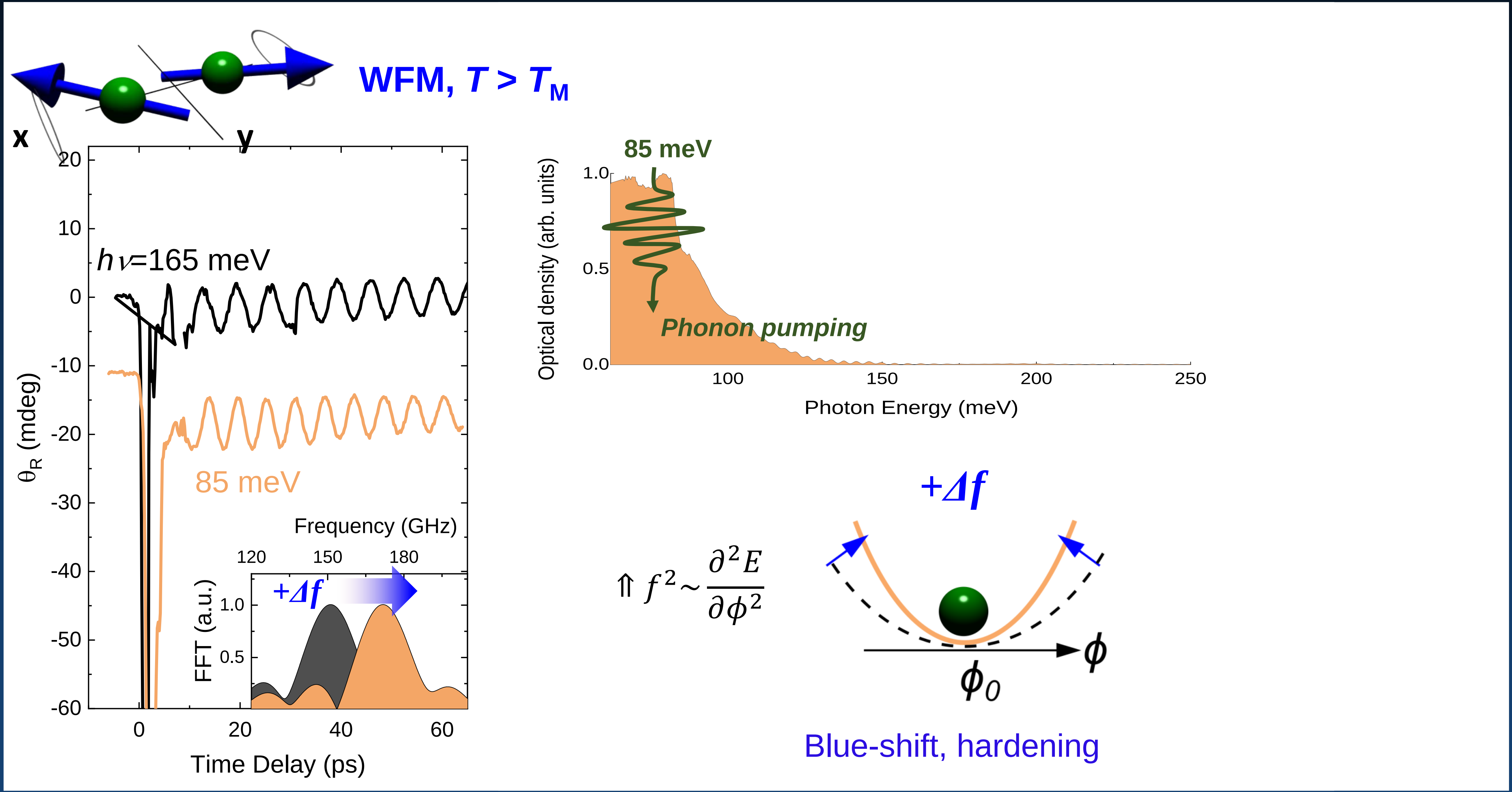
$$f^2 \sim \frac{\partial^2 E}{\partial \phi^2}$$



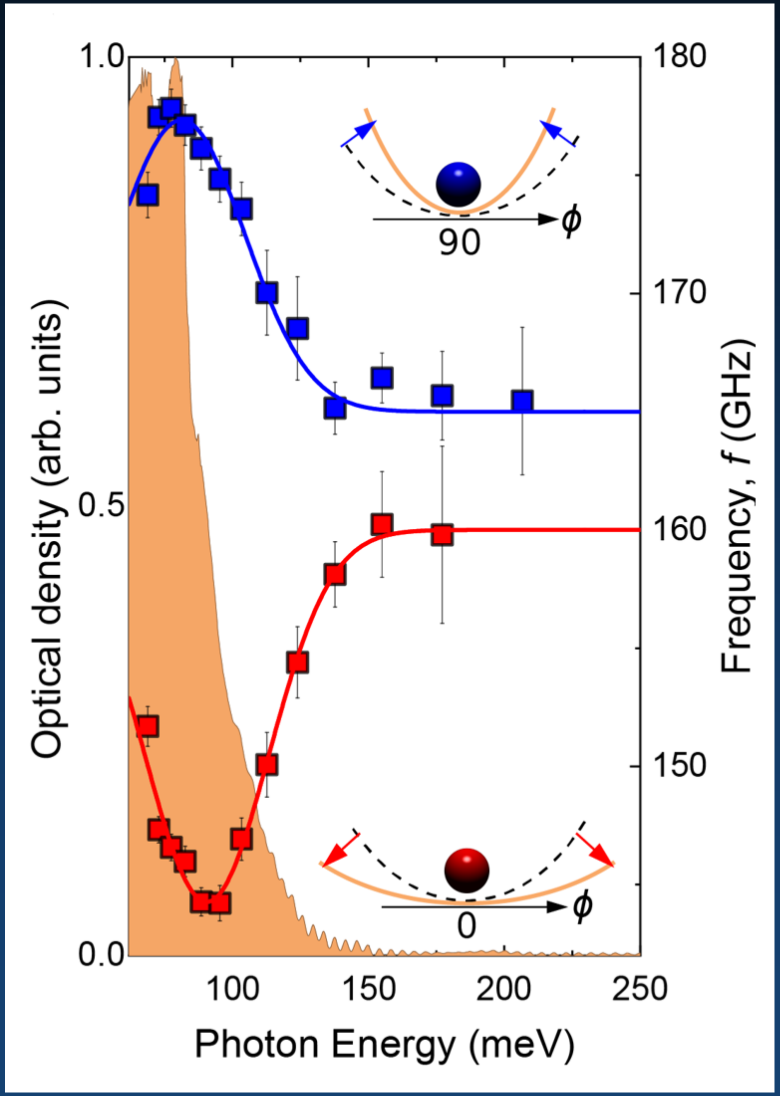
Resonant spin precession



Resonant spin precession

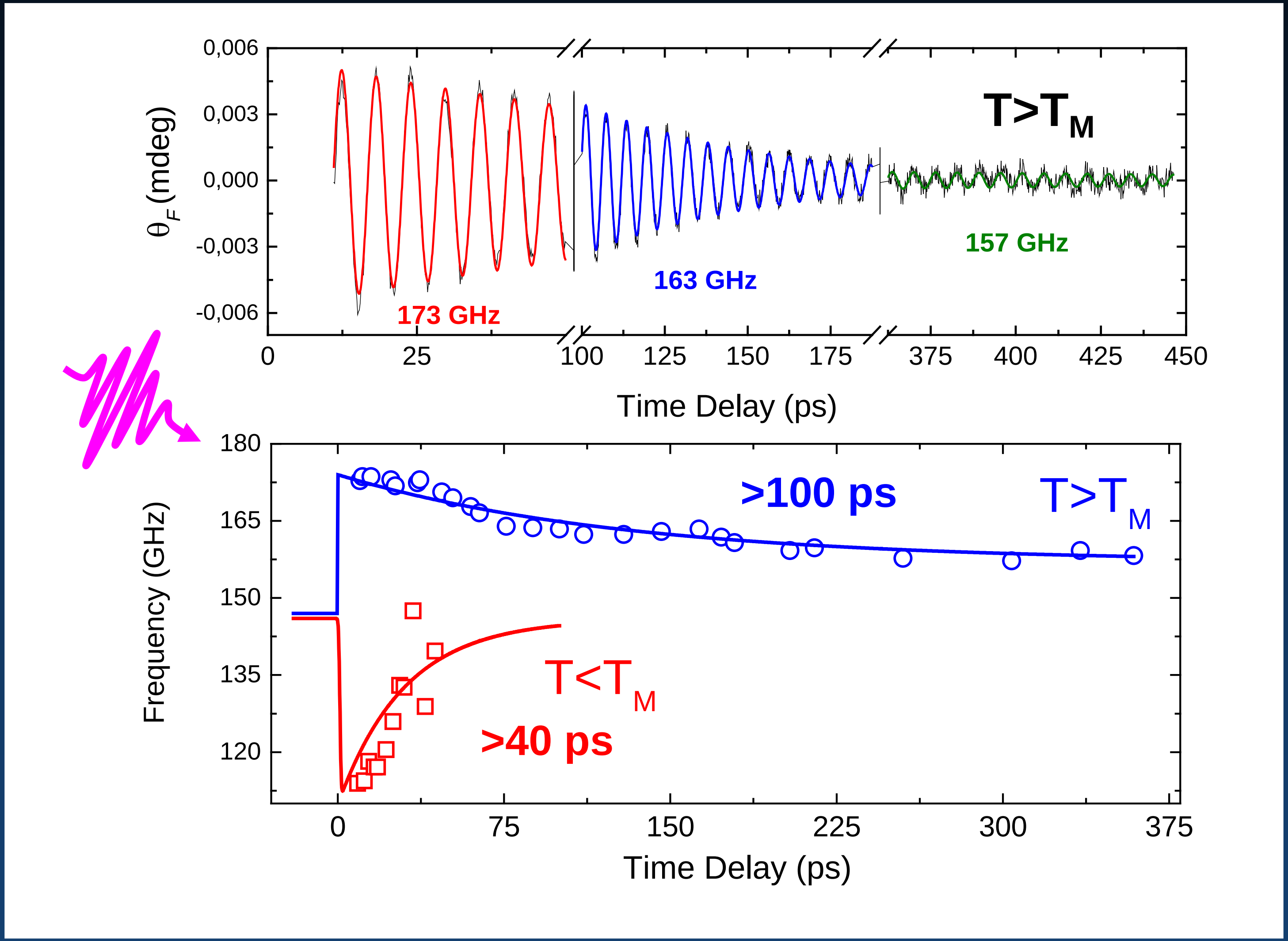


Resonant spin precession



Resonant change of the spin precession frequency

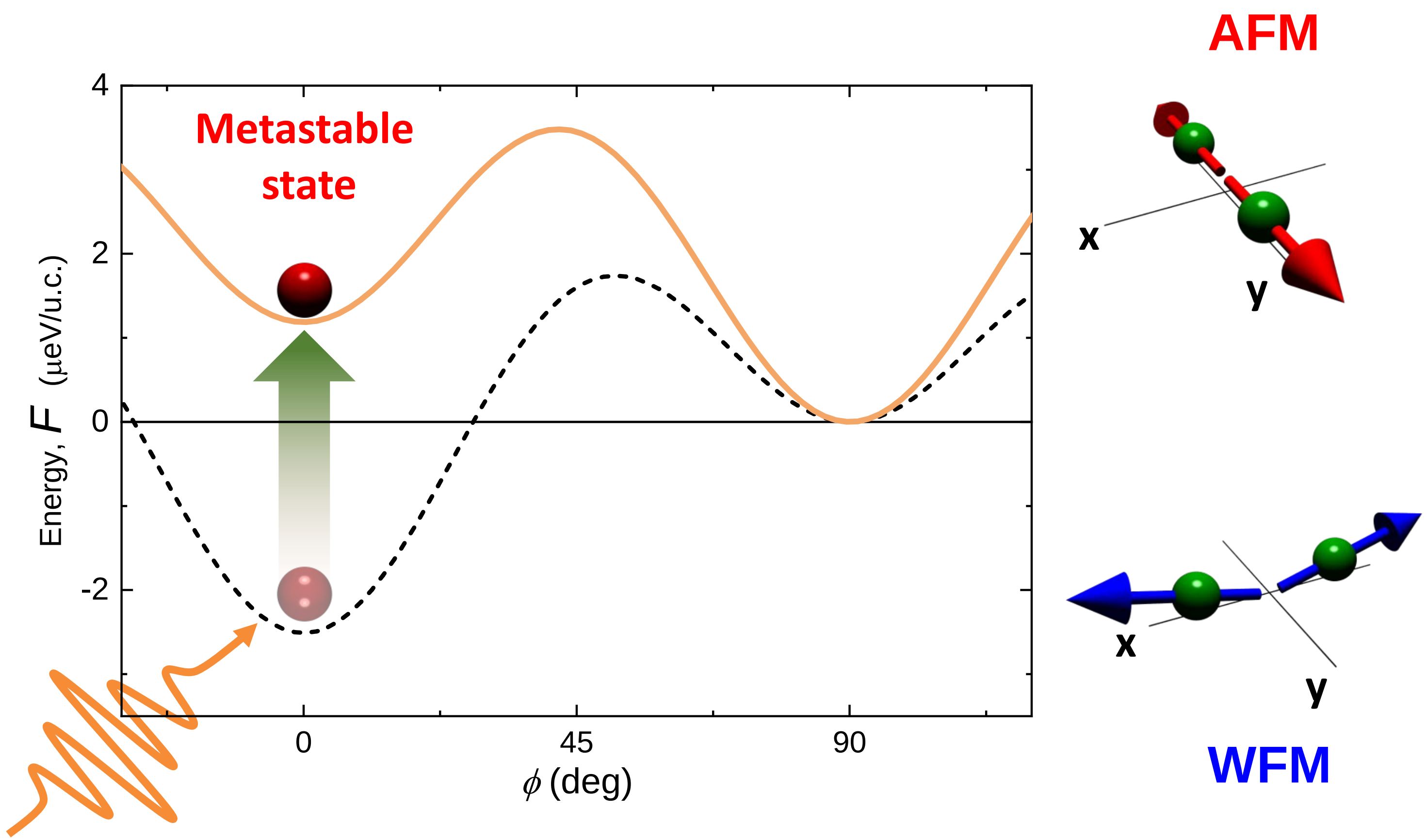
Magnetic energy landscape



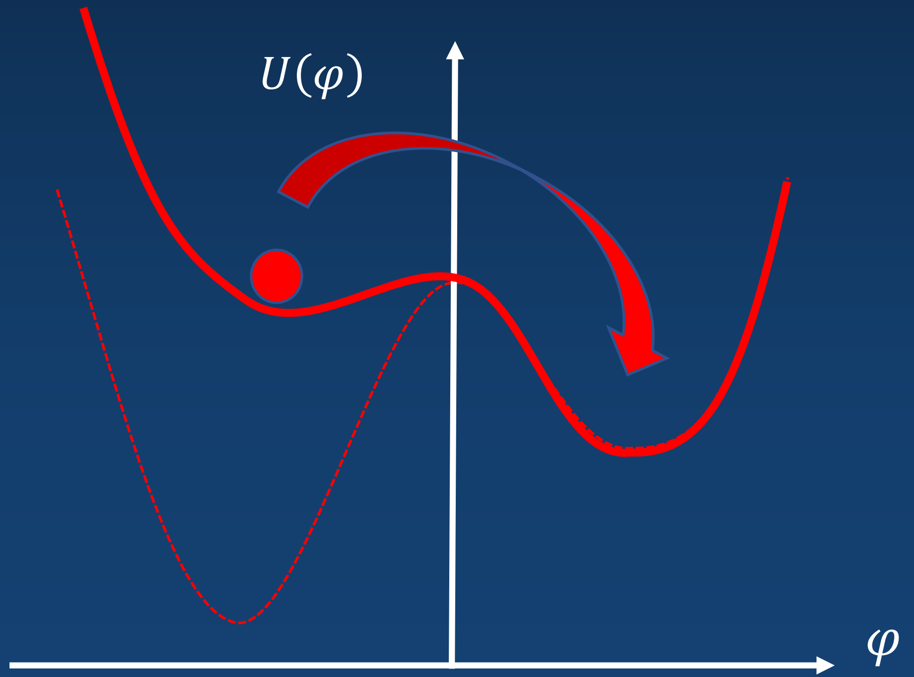
Fast settling (<5 ps) and long-lifetimes (>100 ps) of the new magnetic potential

Out of equilibrium state

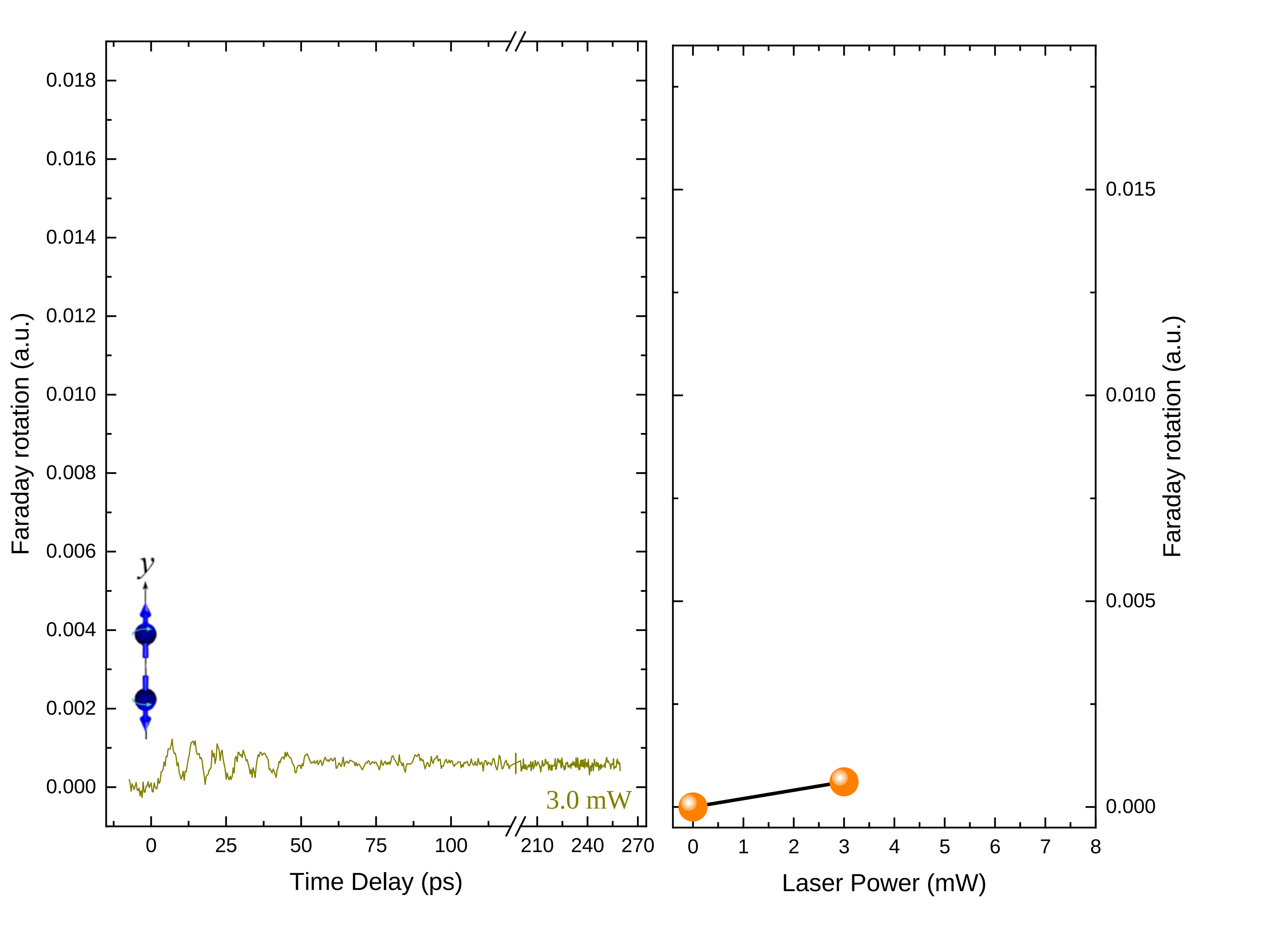
$$E(\phi) = (K_2(T) + \Delta K_2)\sin^2\phi - K_4\sin^4\phi$$



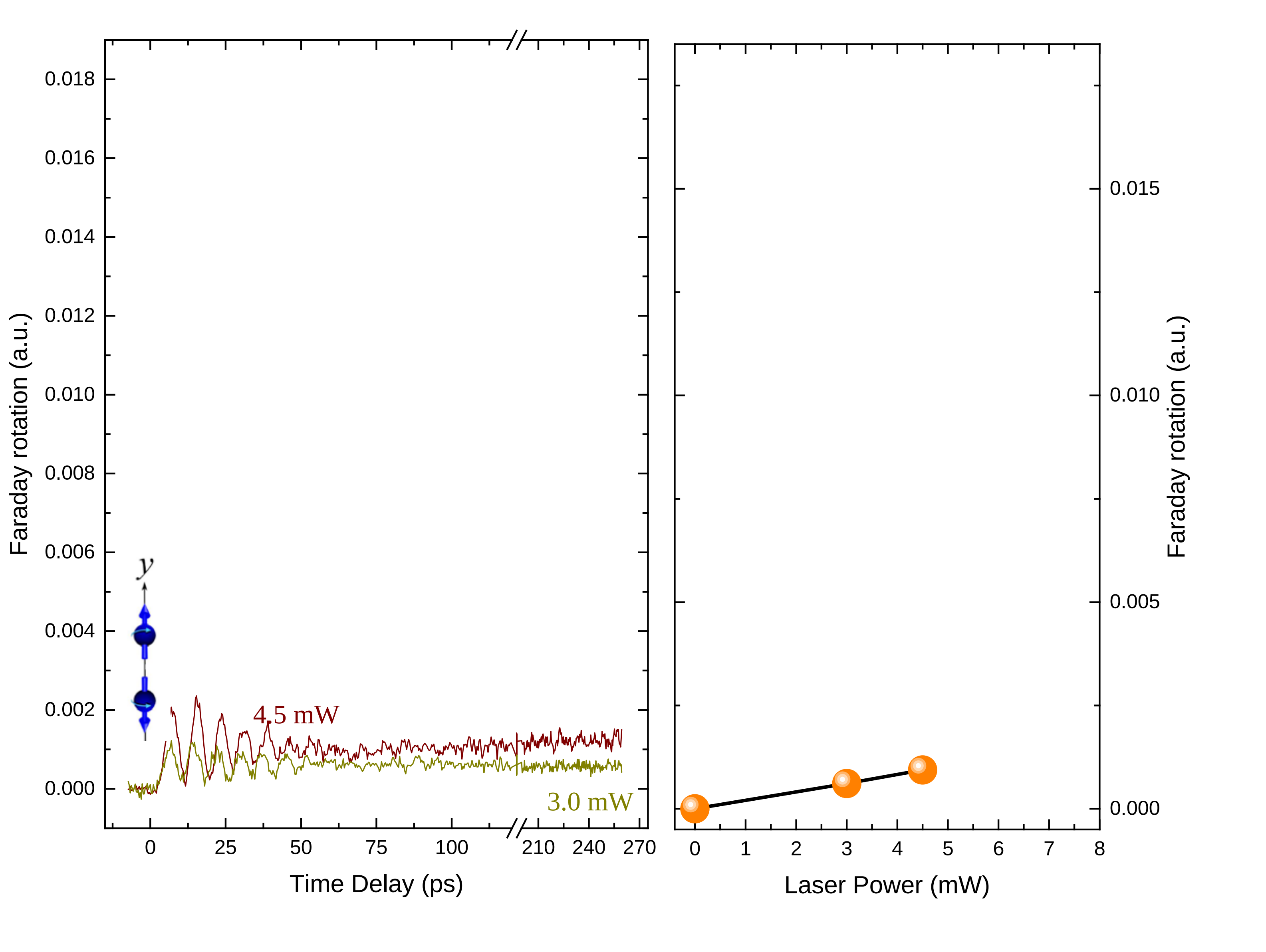
Can we control transitions between ordered states?



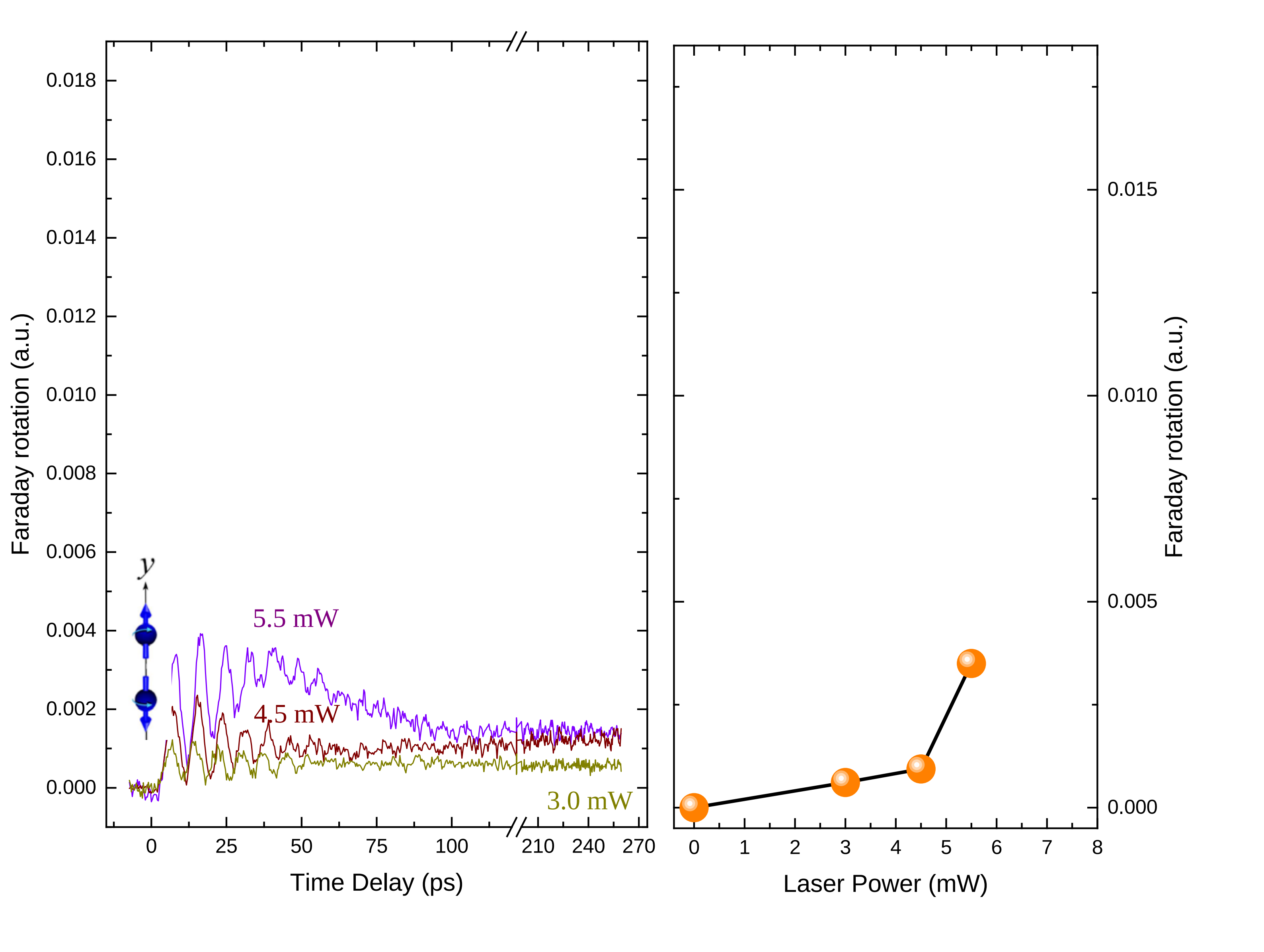
Harmonic spin dynamics



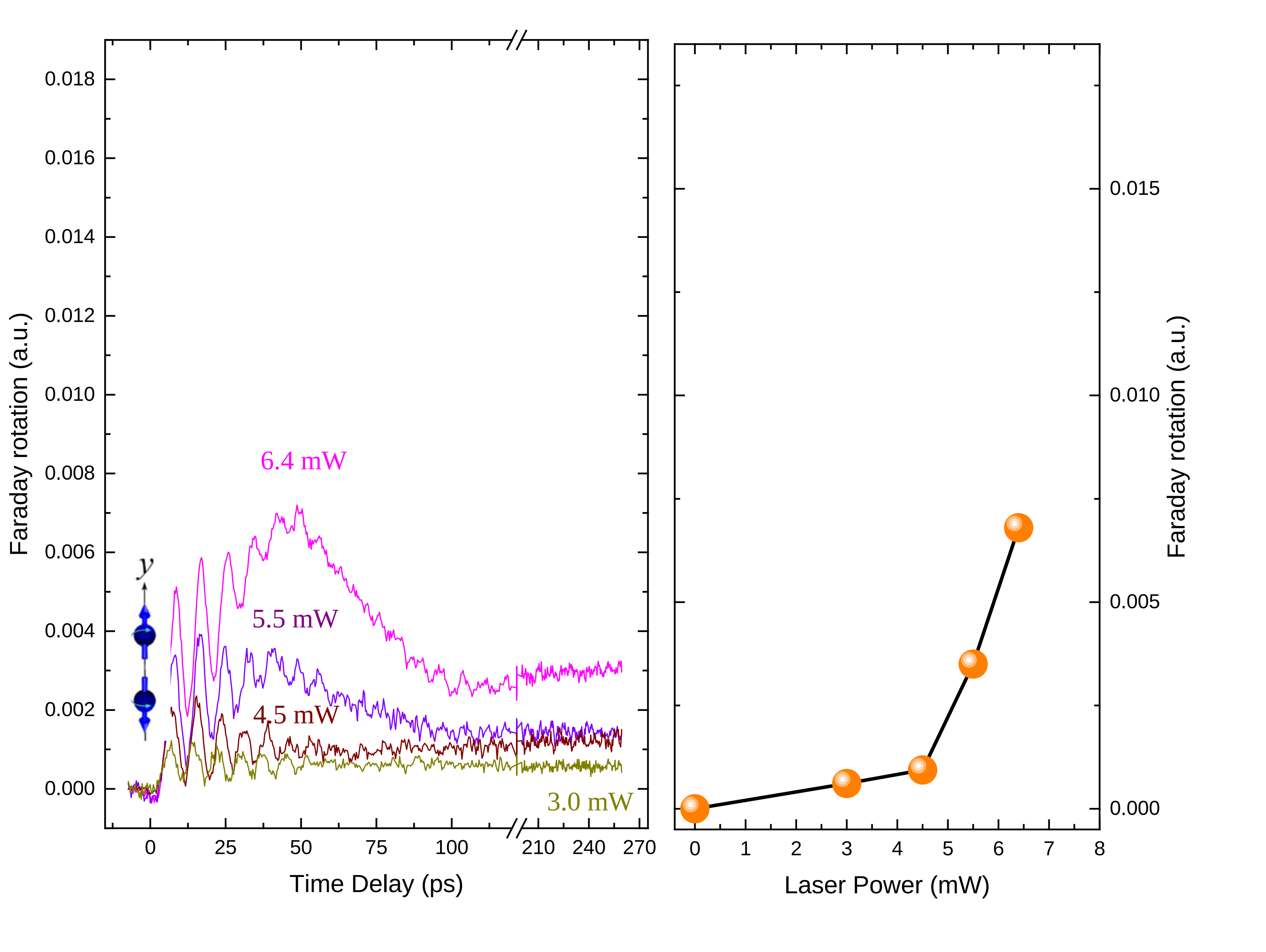
Harmonic spin dynamics



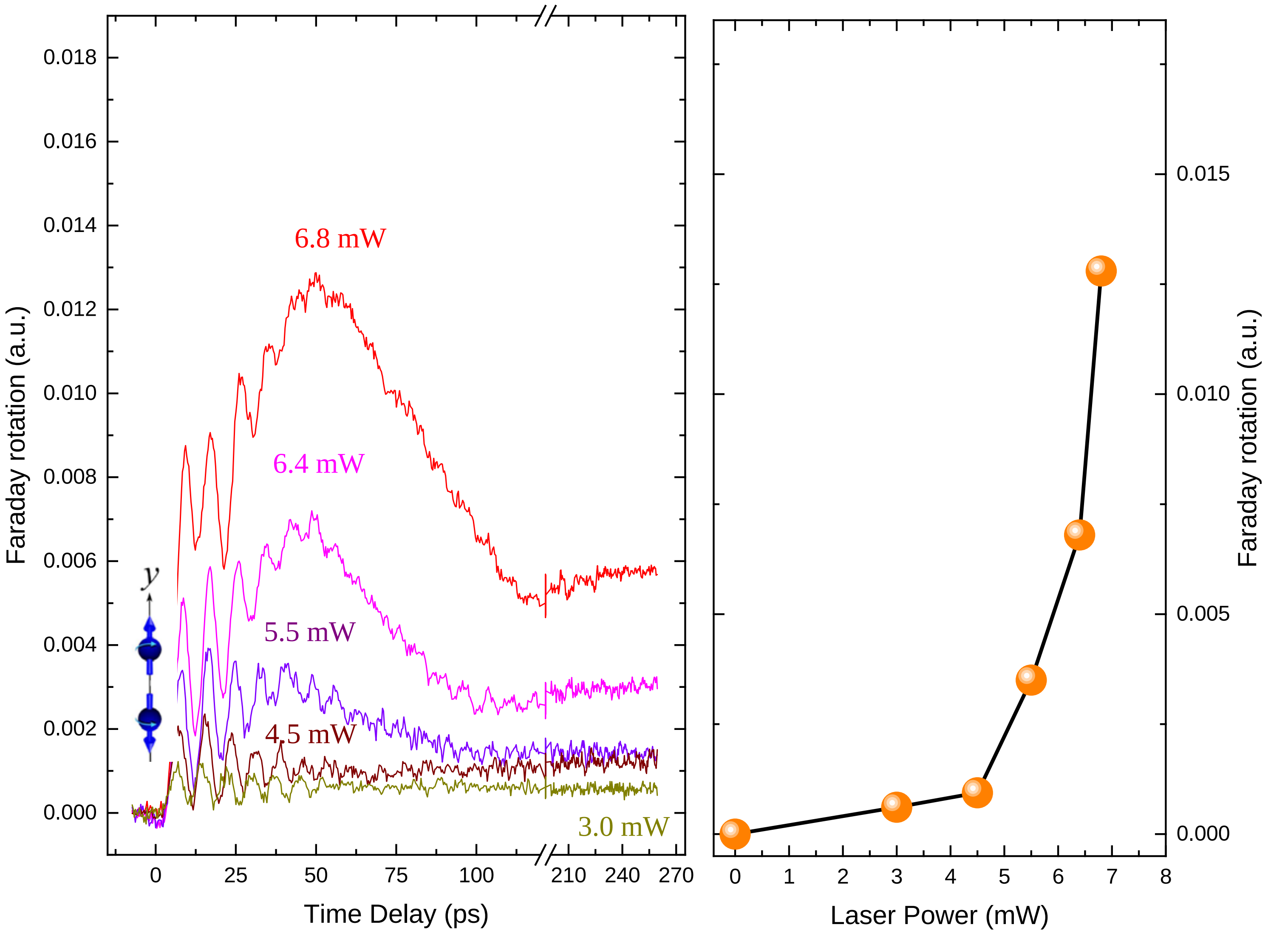
Non-linear spin dynamics. Switching



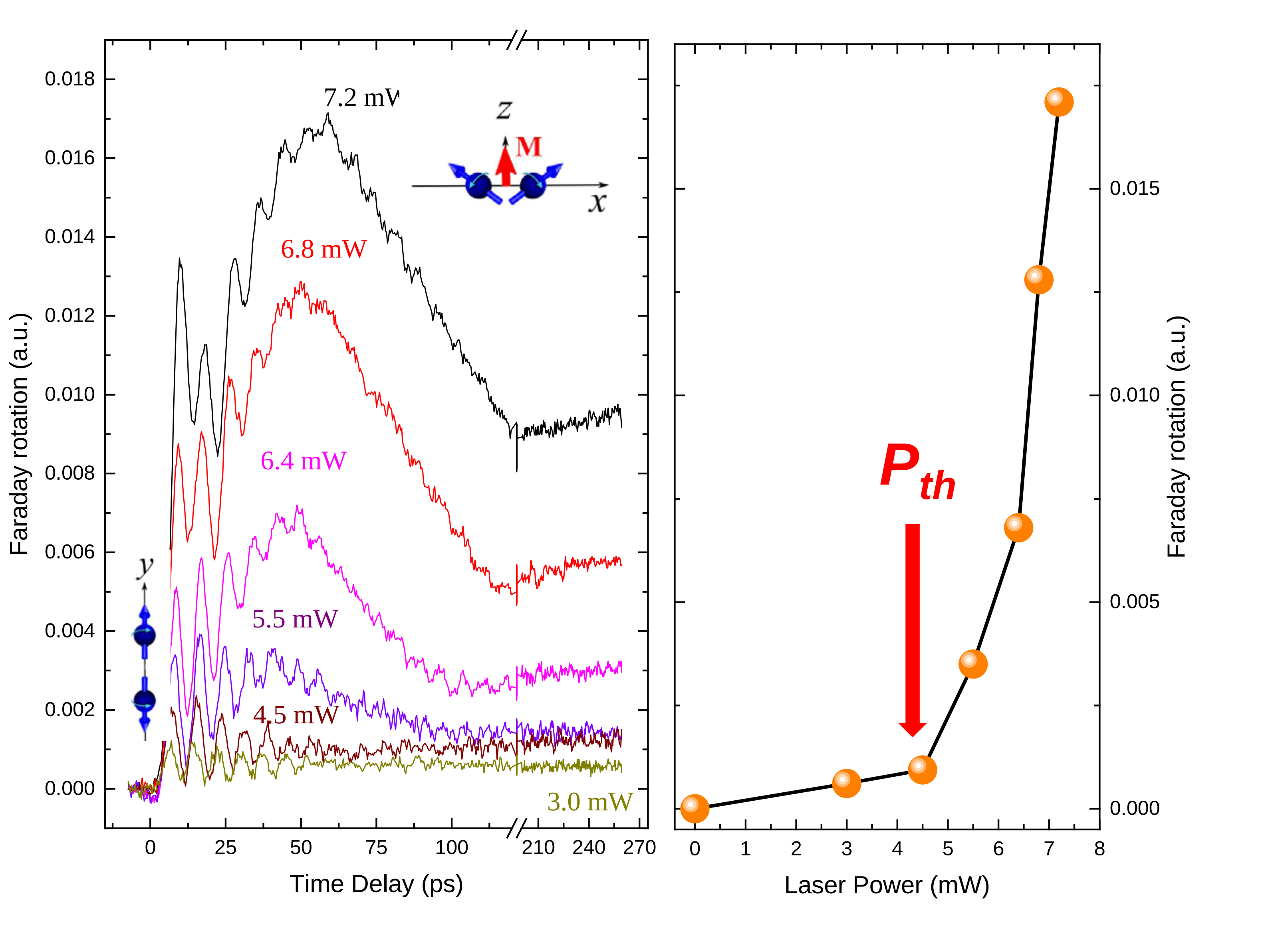
Non-linear spin dynamics. Switching



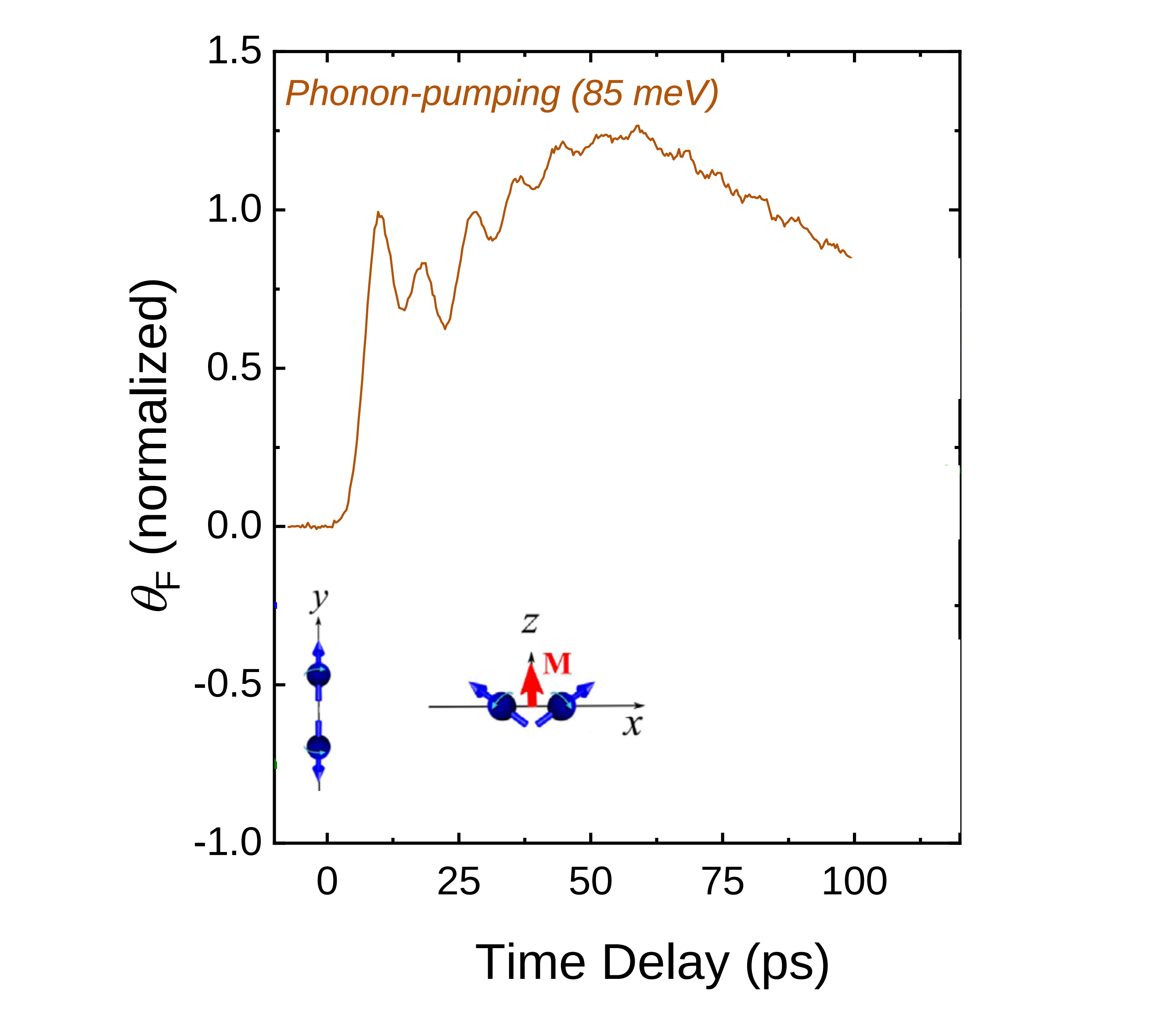
Non-linear spin dynamics. Switching



Non-linear spin dynamics. Switching

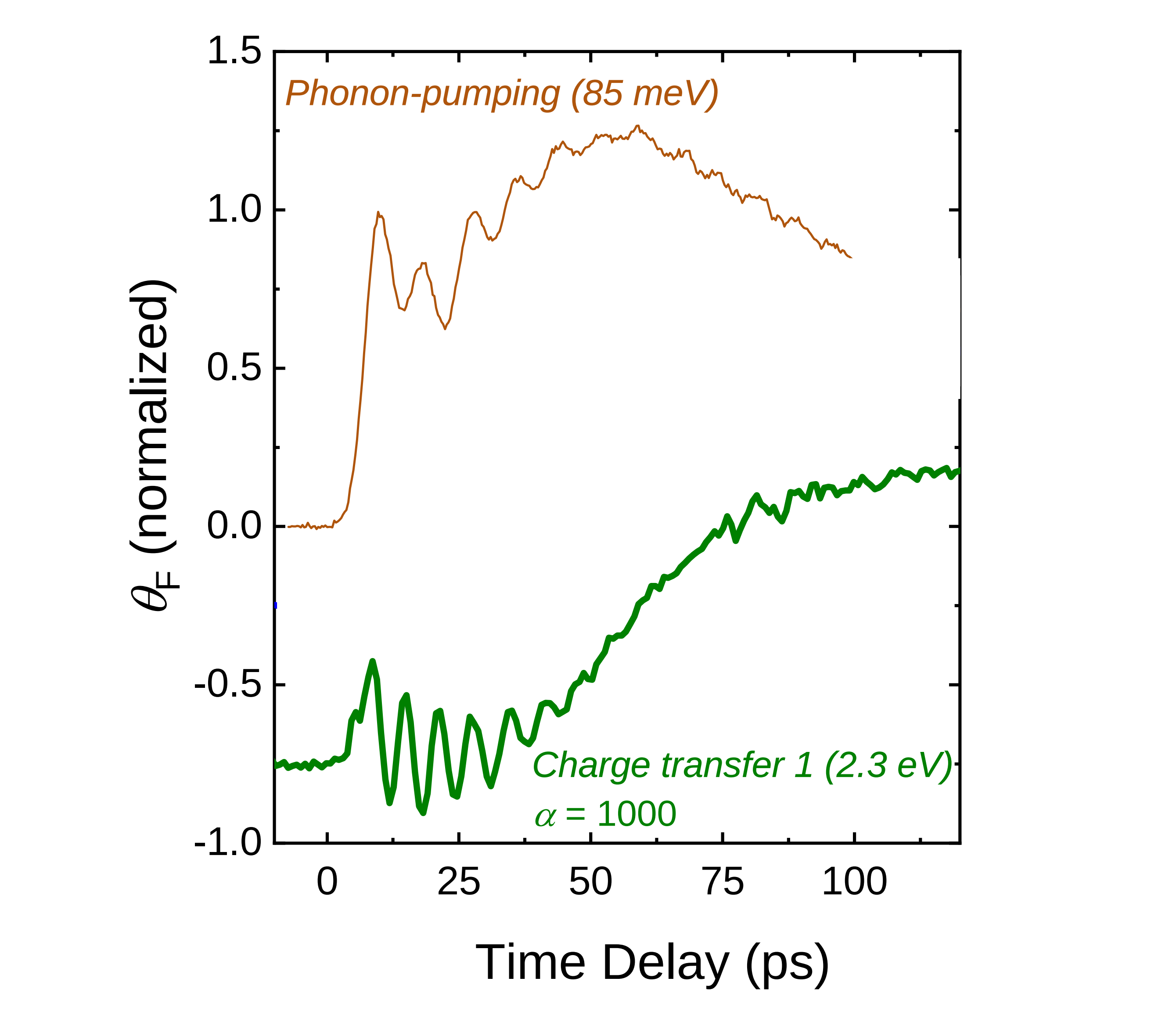


Phono-magnetism



Afanasiev et al. Nature Materials 20, 607 (2021)

Phono-magnetism



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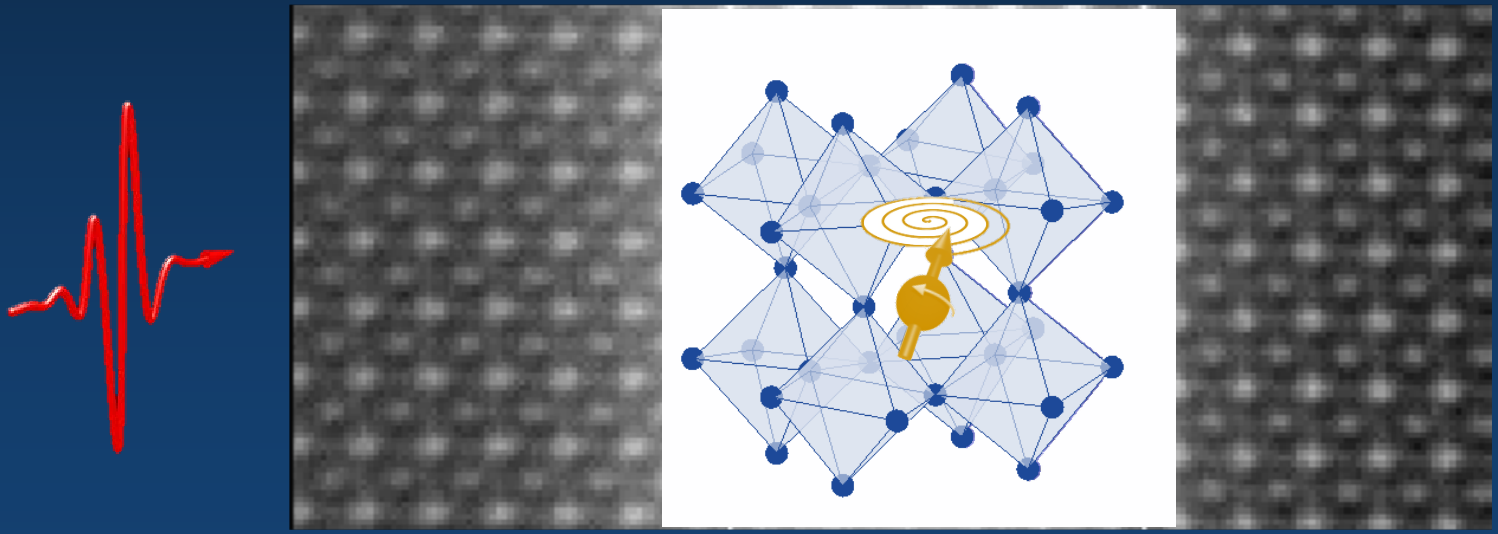
Ultrafast phono-magnetism

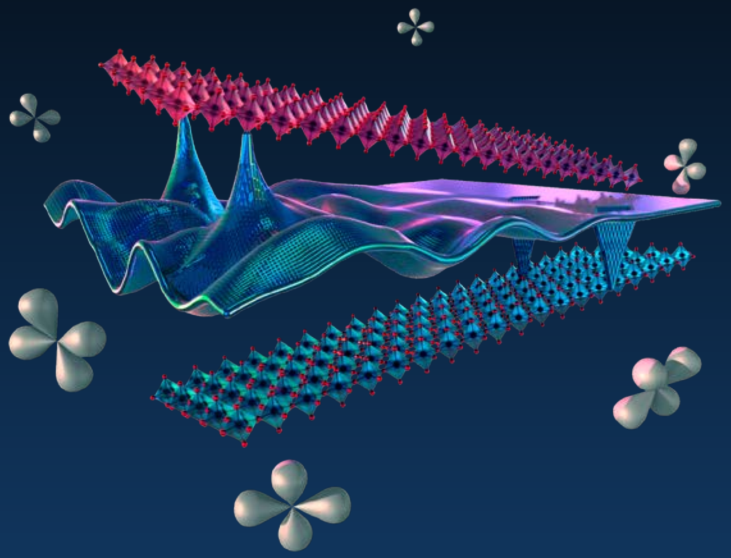
Ultrafast lattice excitation results in ultrafast long-living modification of the magnetic interactions.

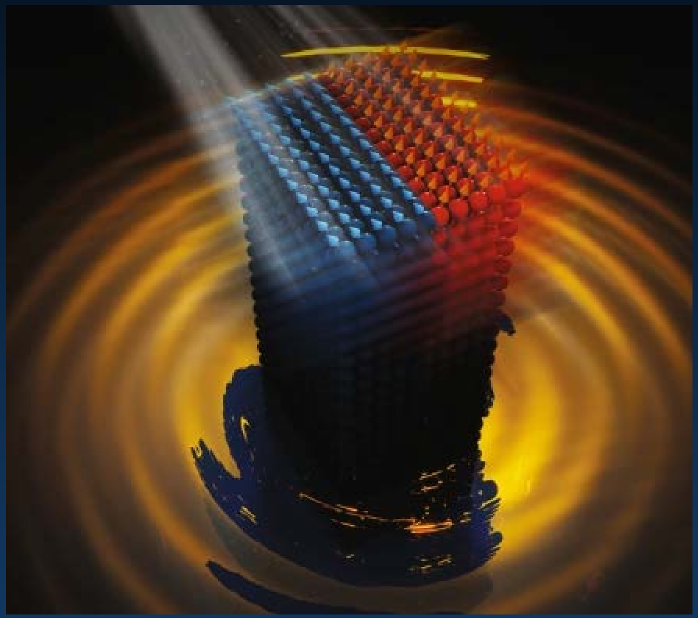
Large-amplitude lattice excitation drives ultrafast spin-reorientation transition between competing phases

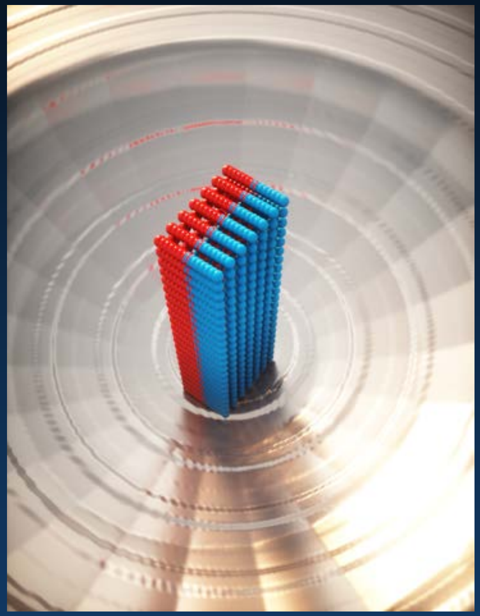


Afanasiev et al. Nature Materials 20, 607 (2021)

Outline



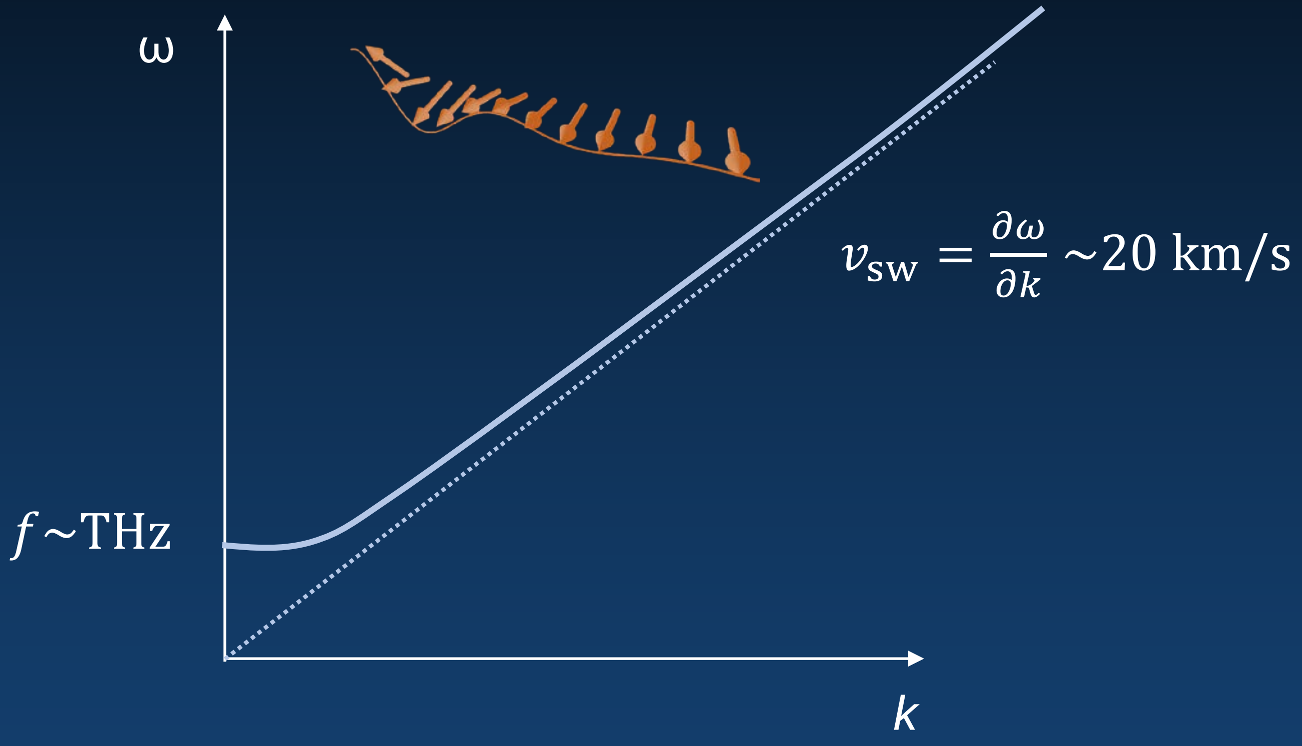




Phonon resonances	Phonon resonances	Charge resonances
Ultrafast strain engineering	Lattice control of magnetic interactions	Coherent spin-wave transport in antiferromagnets
LaAlO3	DyFeO3 Magnetic transitions	

Antiferromagnetic spin transport

- THz operation
- High-speed wave propagation
- Phase coherence
- Macroscopic ballistic propagation



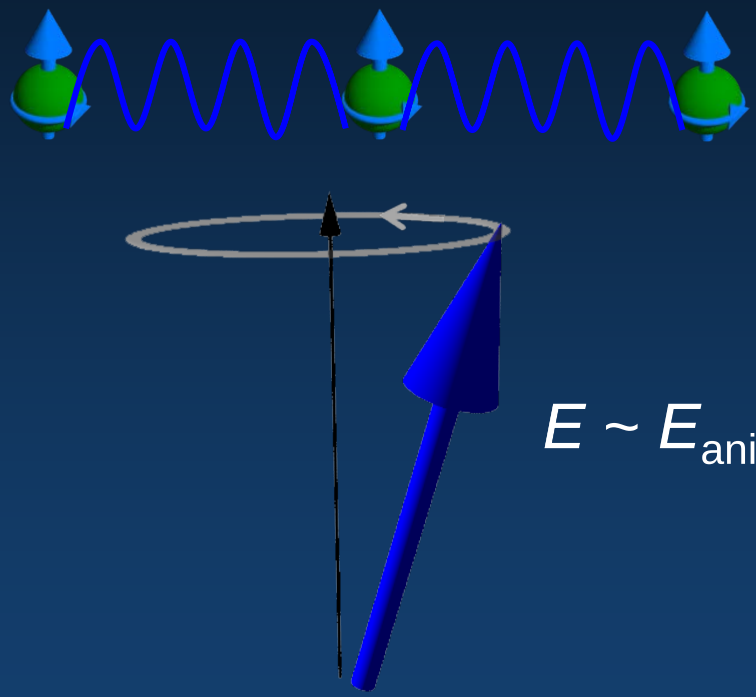
Current approaches:
spin-currents
via thermally-driven spin accumulation.

Incoherent diffusive spin transport.

R. Lebrun et al., *Nature* **561,** 222 (2018)
J. Li et al., *Nature* **578,** 70 (2020)
P. Vaidya et al., *Science* **368,** 160 (2020)

Spin waves

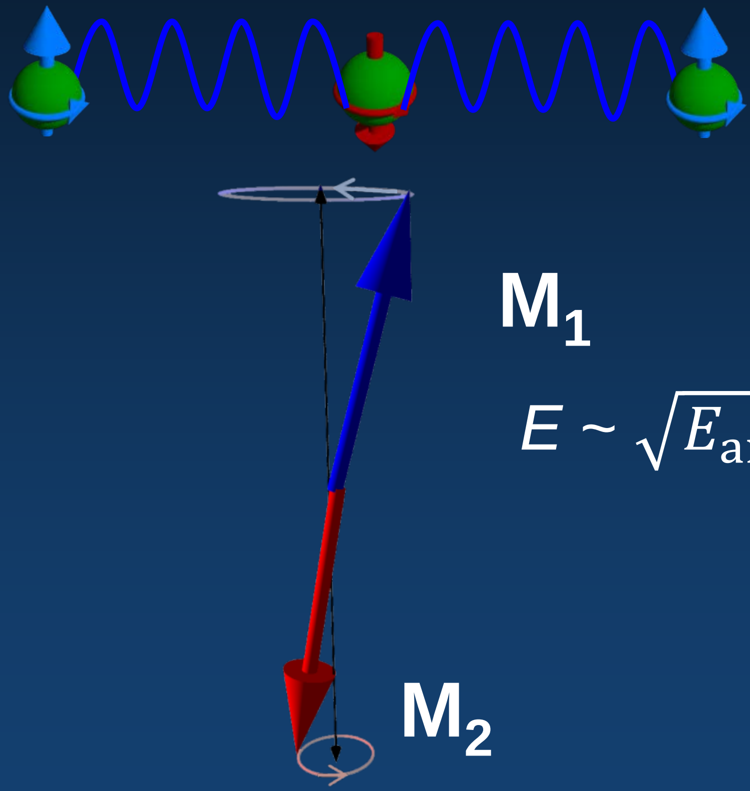
Ferromagnets



$E \sim E_{ani}$ (GHz)

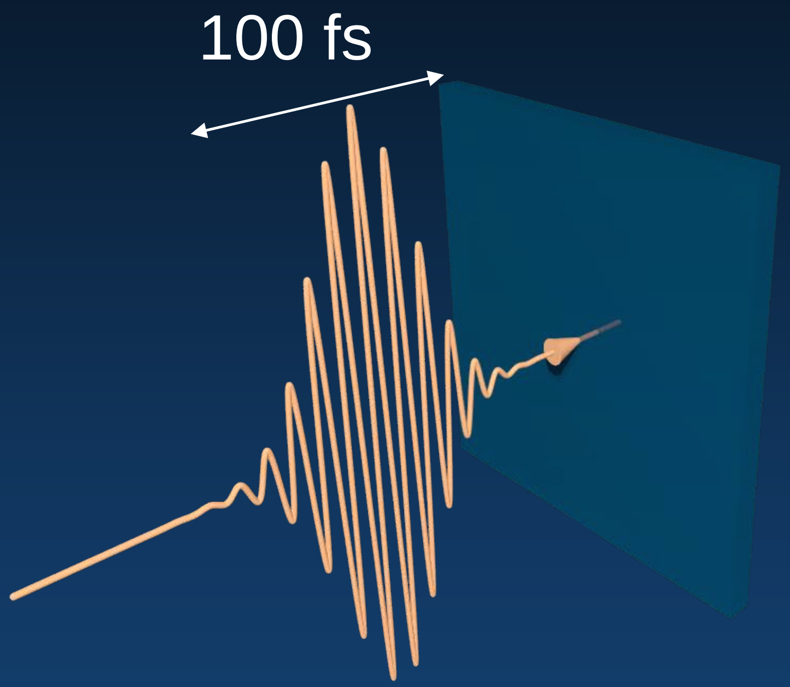
uniform precession

Antiferromagnets

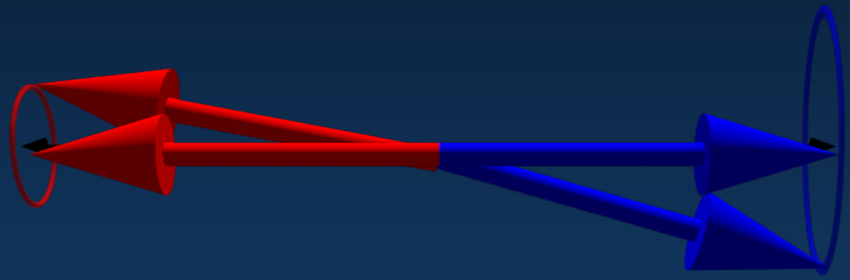


$E \sim \sqrt{E_{ani} E_{exc}}$ (THz)

Coherent AFM spin dynamics



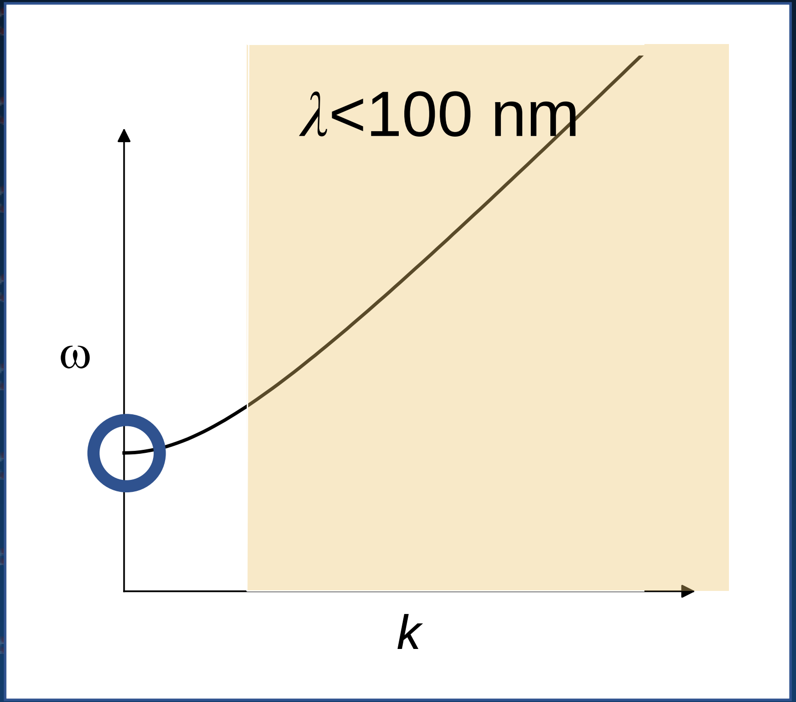
Impulsive excitation in transparent AFM

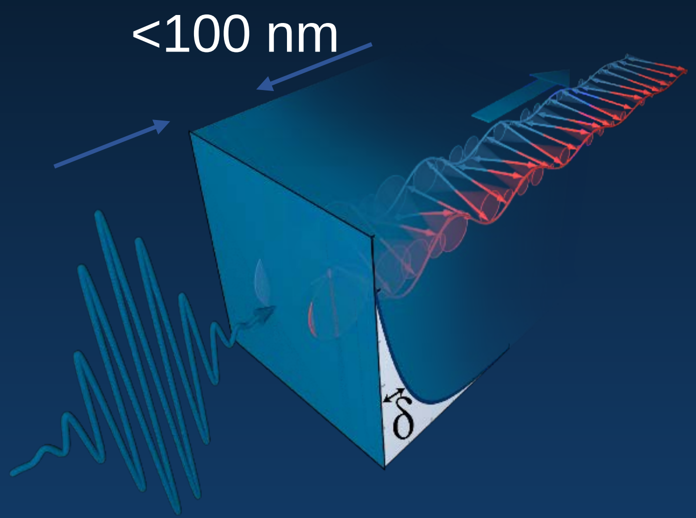


Uniform AFM spin precession
does not propagate

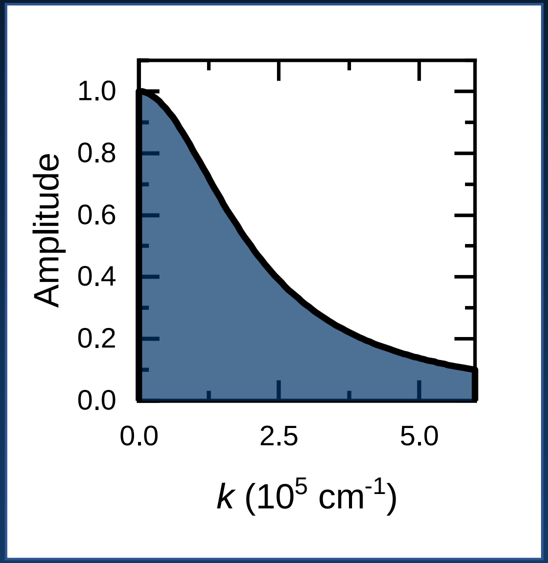
P. Němec, M. Fiebig, R. Kampfrath, A.V. Kimel. *Nat. Phys.* **14,** 229 (2018)

Propagating spin waves in AFMs





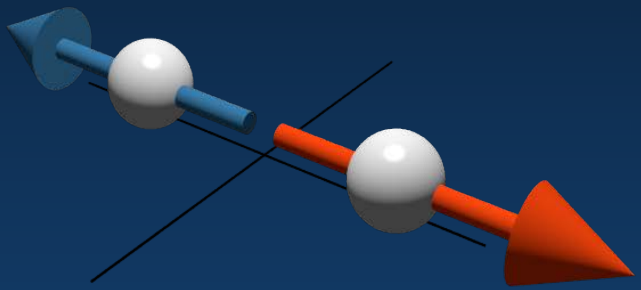
confined optical excitation



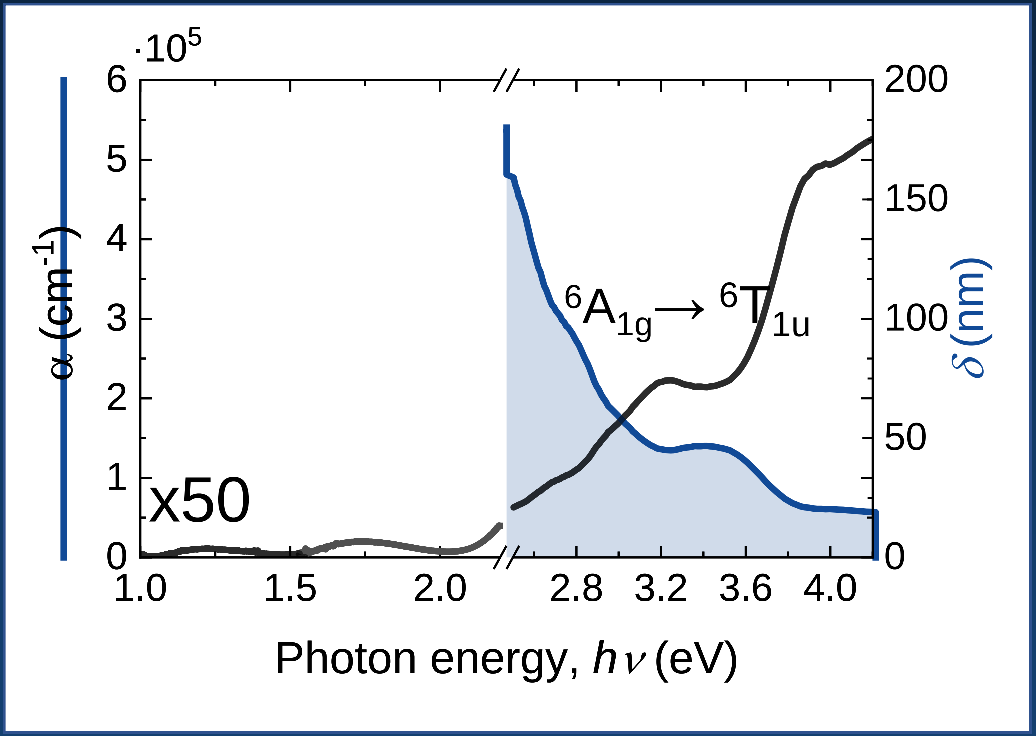
magnon
wavepacket

Hortensius et al. Nature Physics 17, 1001 (2021)

$DyFeO_3$

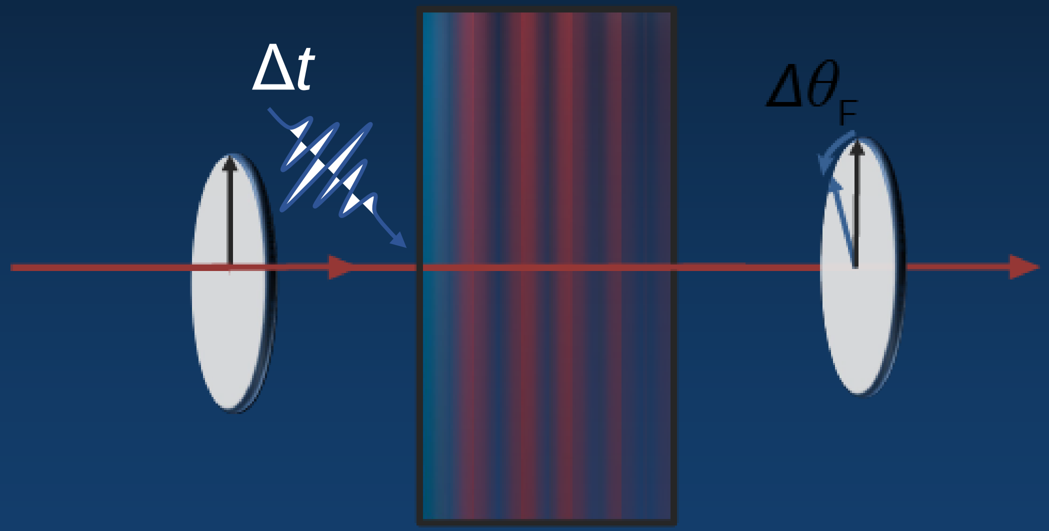


Optical absorption



Transmission: uniform spin precession

Faraday Rotation: $\theta_F \propto M$

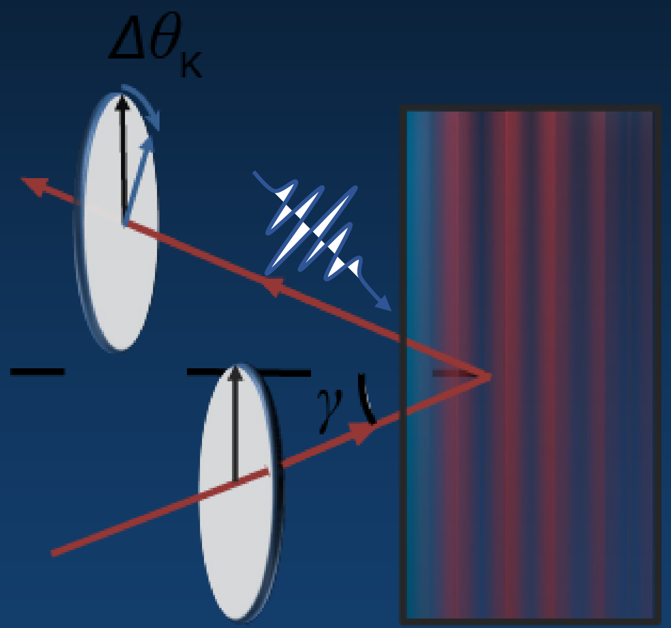


Conventional scheme

Uniform spin precession

Reflection: nonuniform spin precession

Kerr Rotation: $\theta_K \propto M$

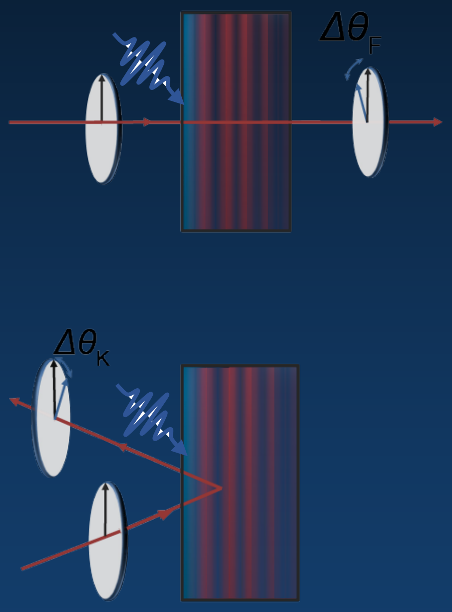


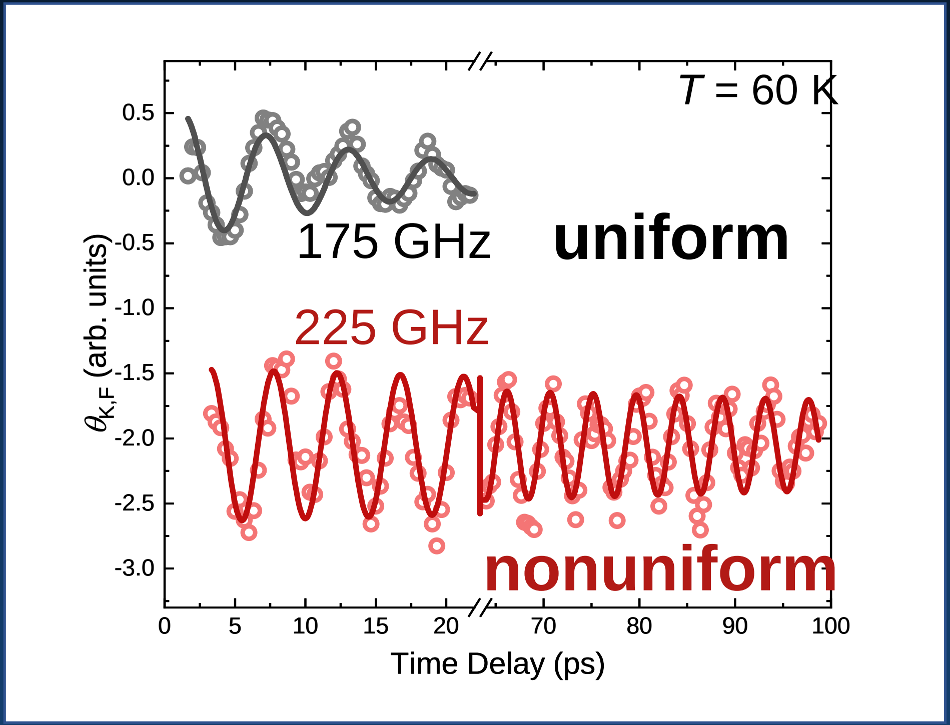
Bragg reflection:

$$k_{sw} = 2k_0 n \cos\gamma'$$

non-uniform spin precession

Results: Magnetic dynamics

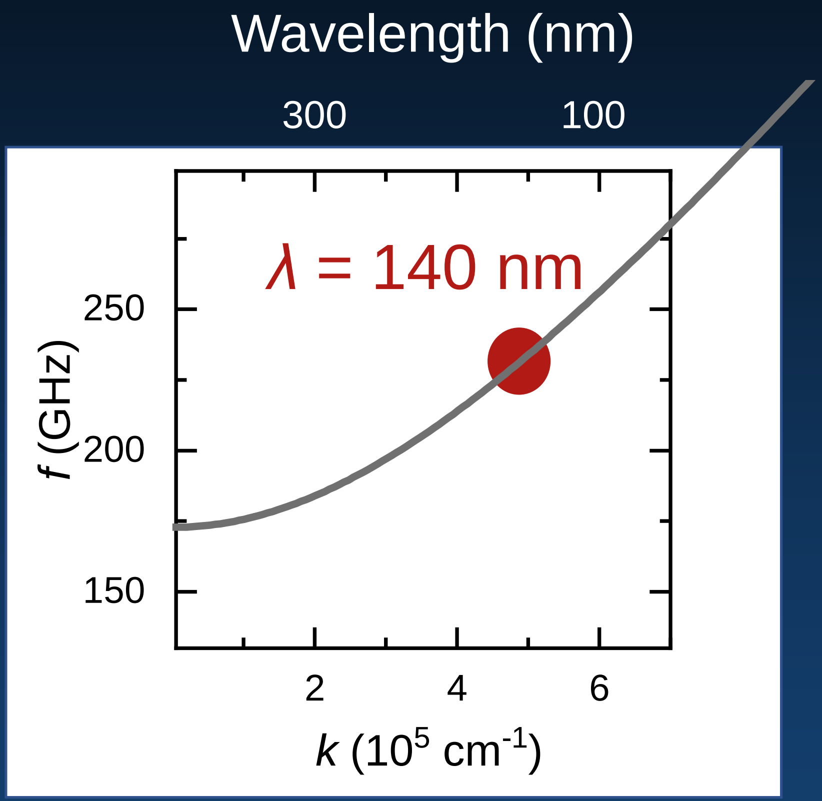




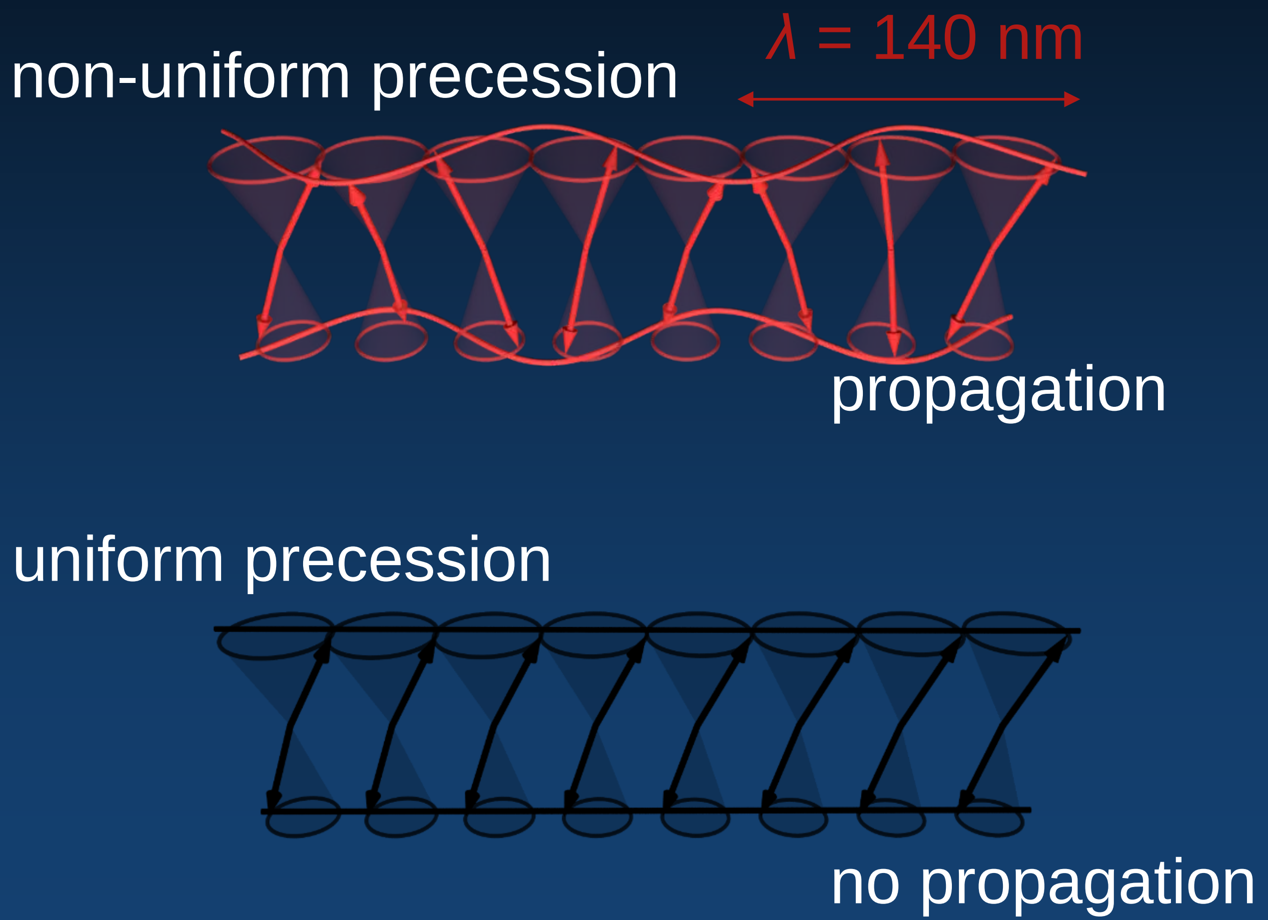
Frequencies: A.S. Balbashov et al. *Sov. Phys. JETP* **61,** 573 (1985)

Hortensius et al. Nature Physics 17, 1001 (2021)

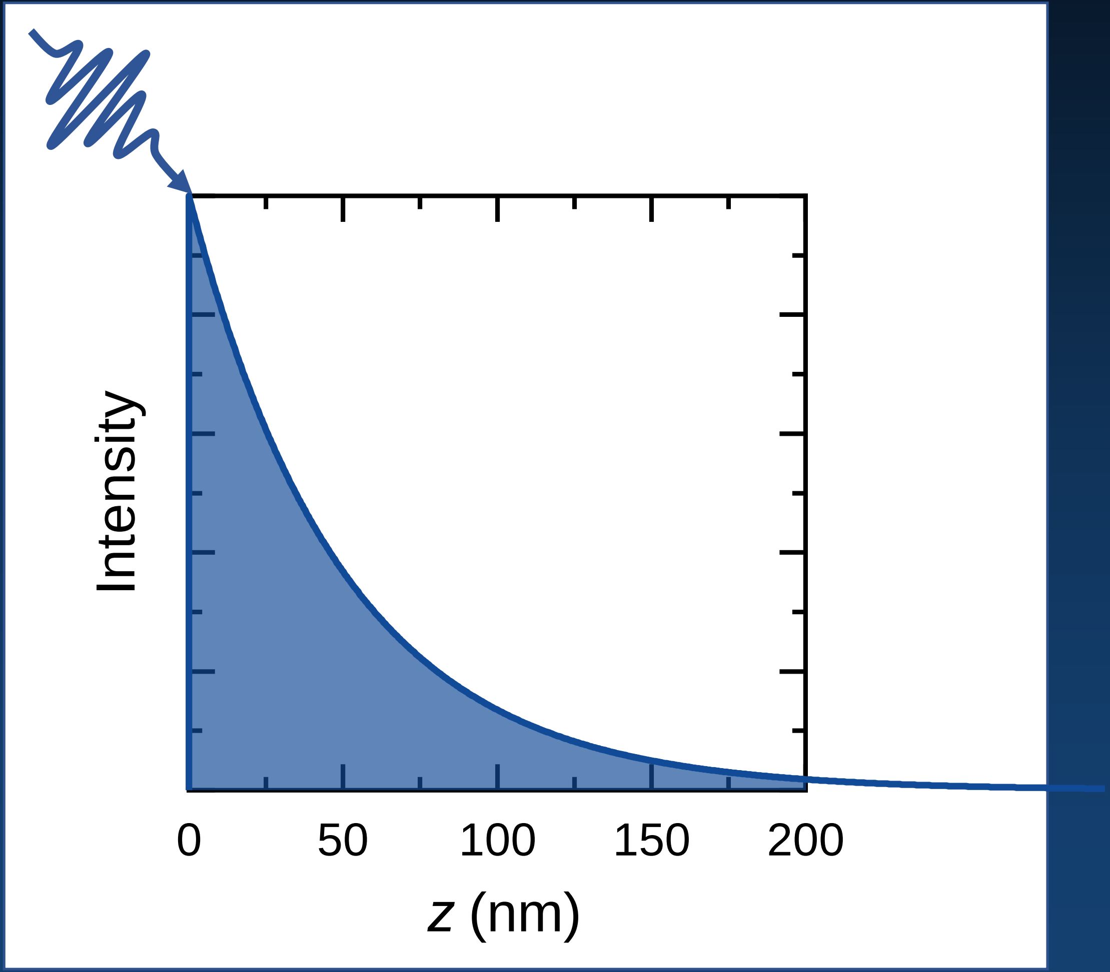
Results: Magnetic dynamics

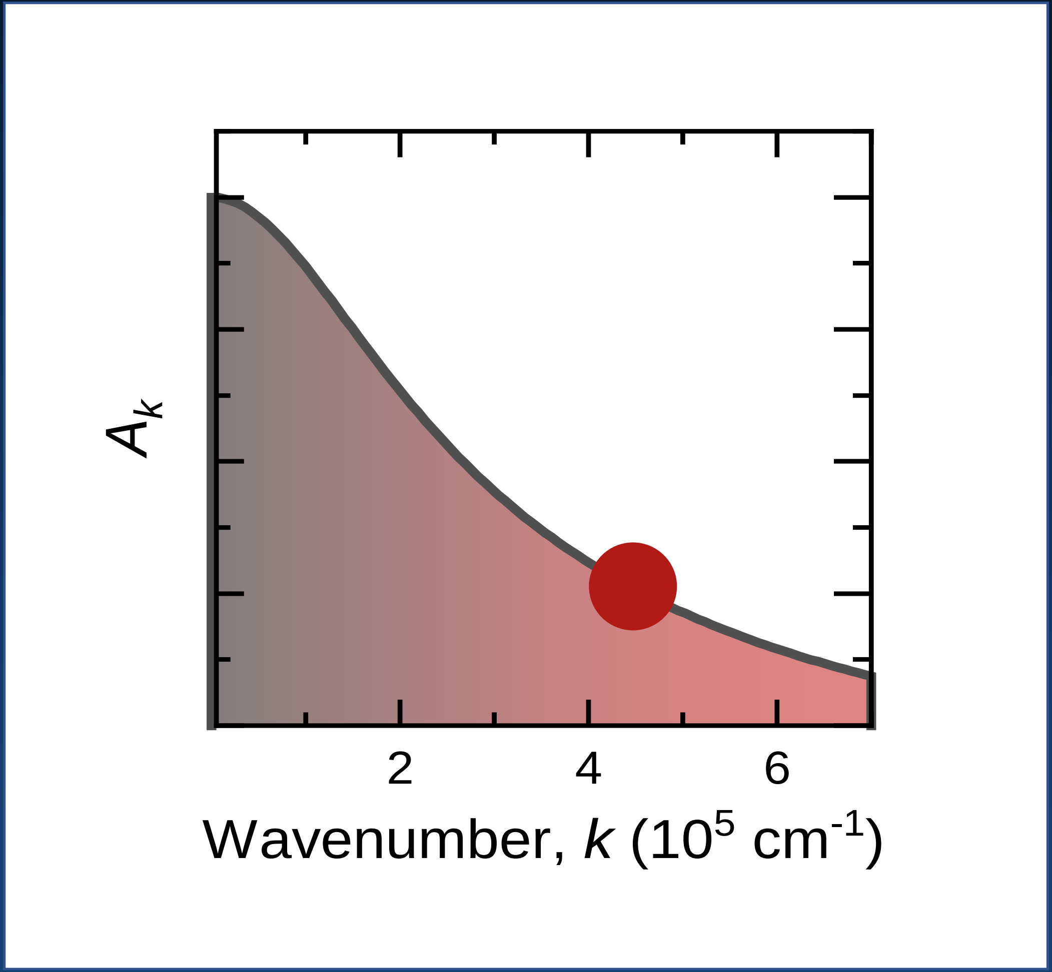


$$\omega = \sqrt{\omega_0^2 + (ck)^2}$$



Propagating spin wavepacket

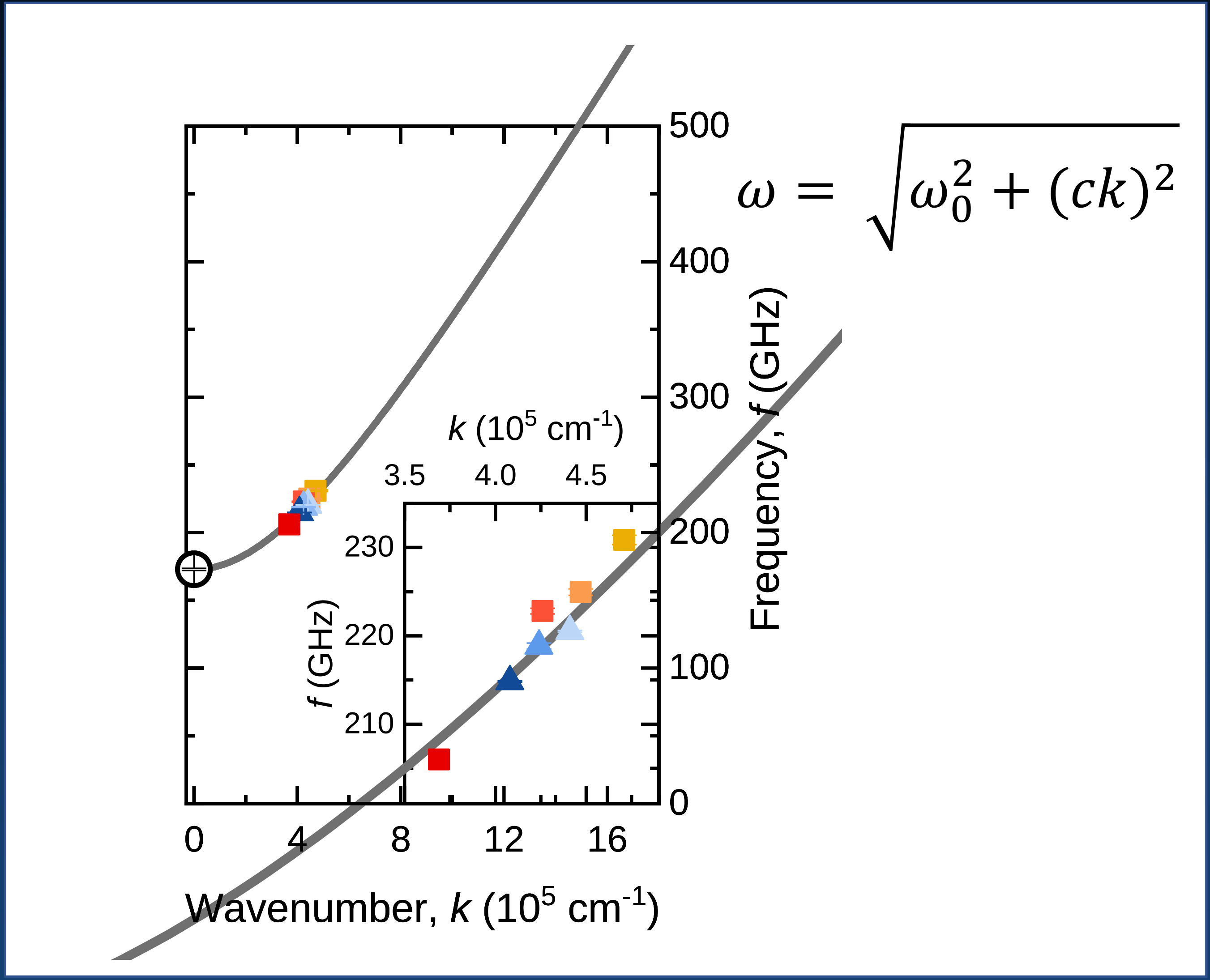




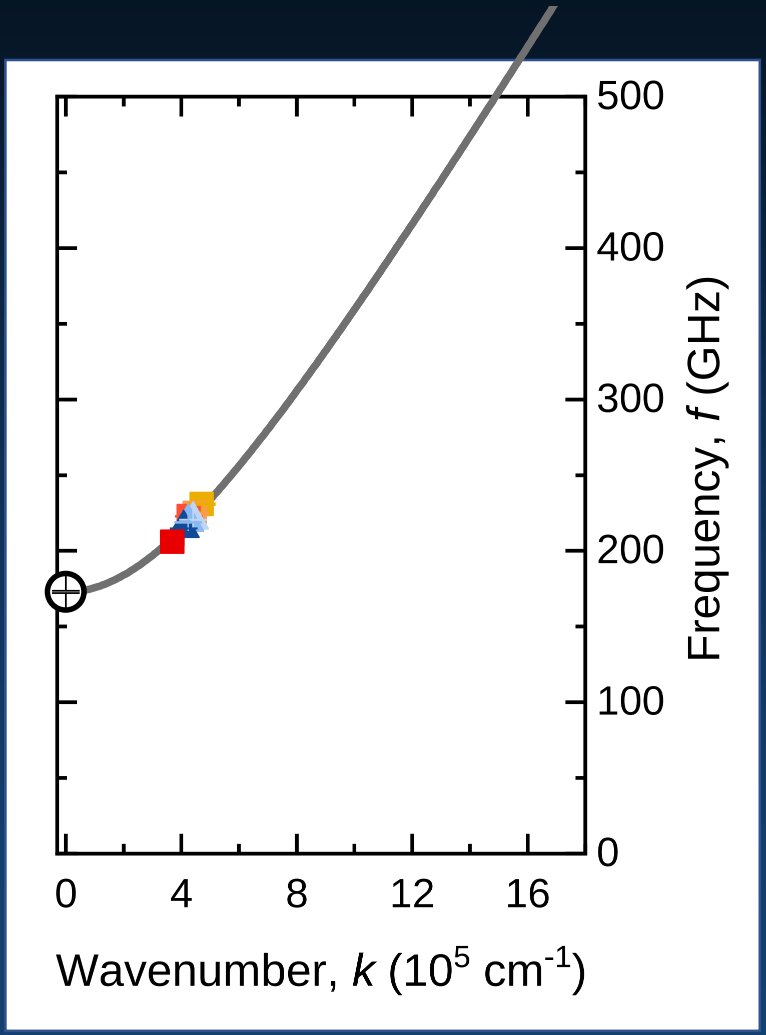
Spectral components of the magnon wavepacket

$$k_{sw} = 2k_0 n \cos\gamma'$$

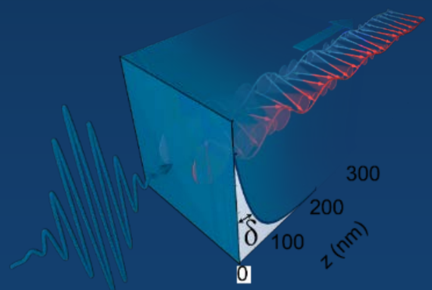
k-selective detection

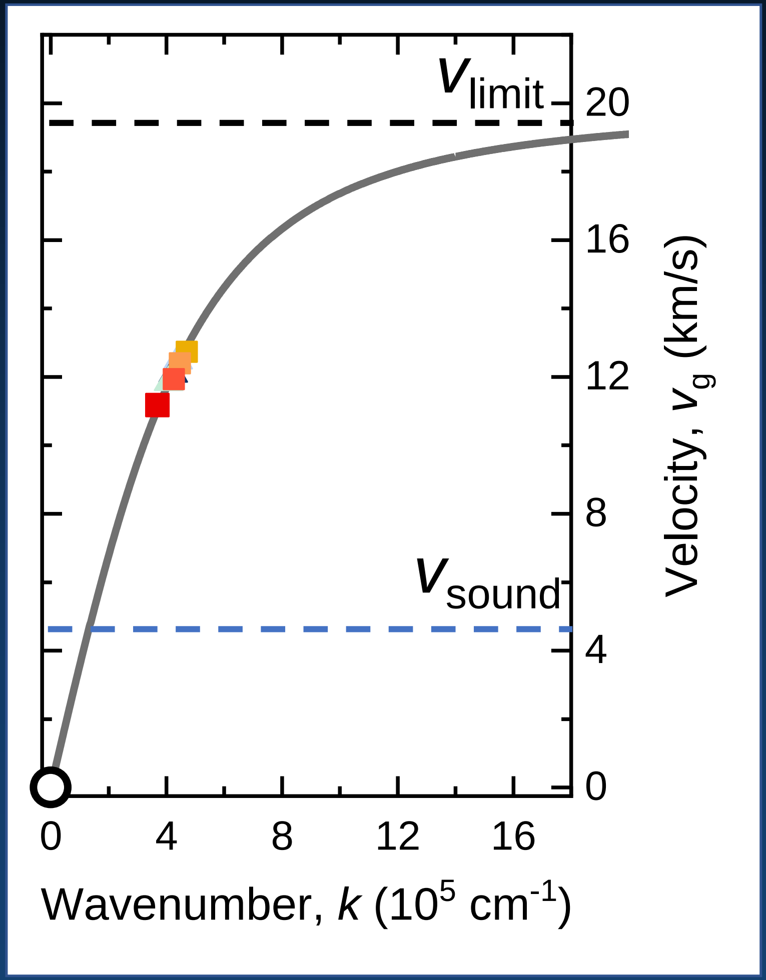


Spin wave velocity

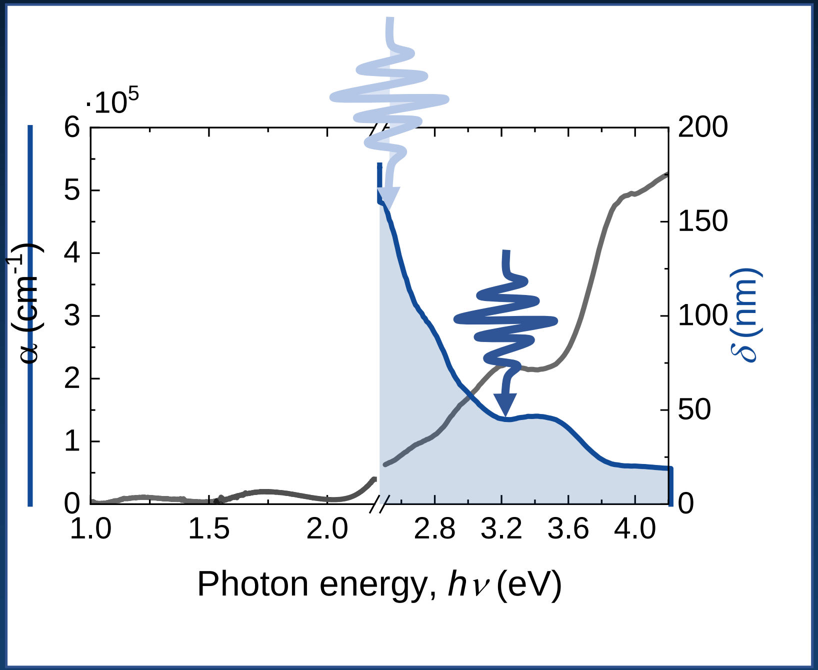


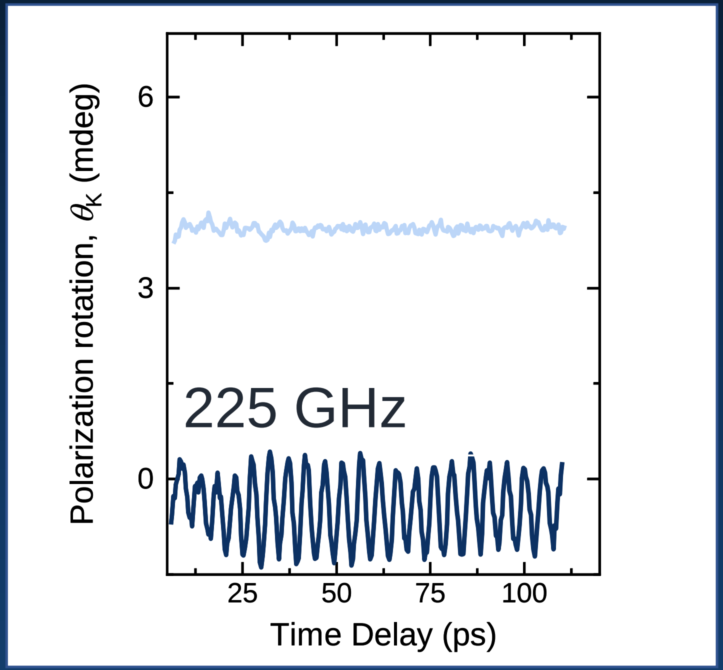
Coherence length
1 µm

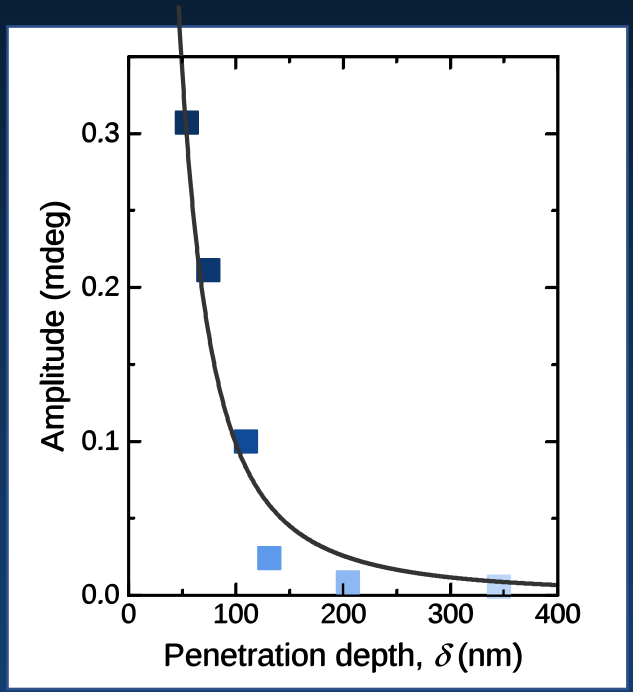




Confined excitation







propagating spin wave

crucial confinement

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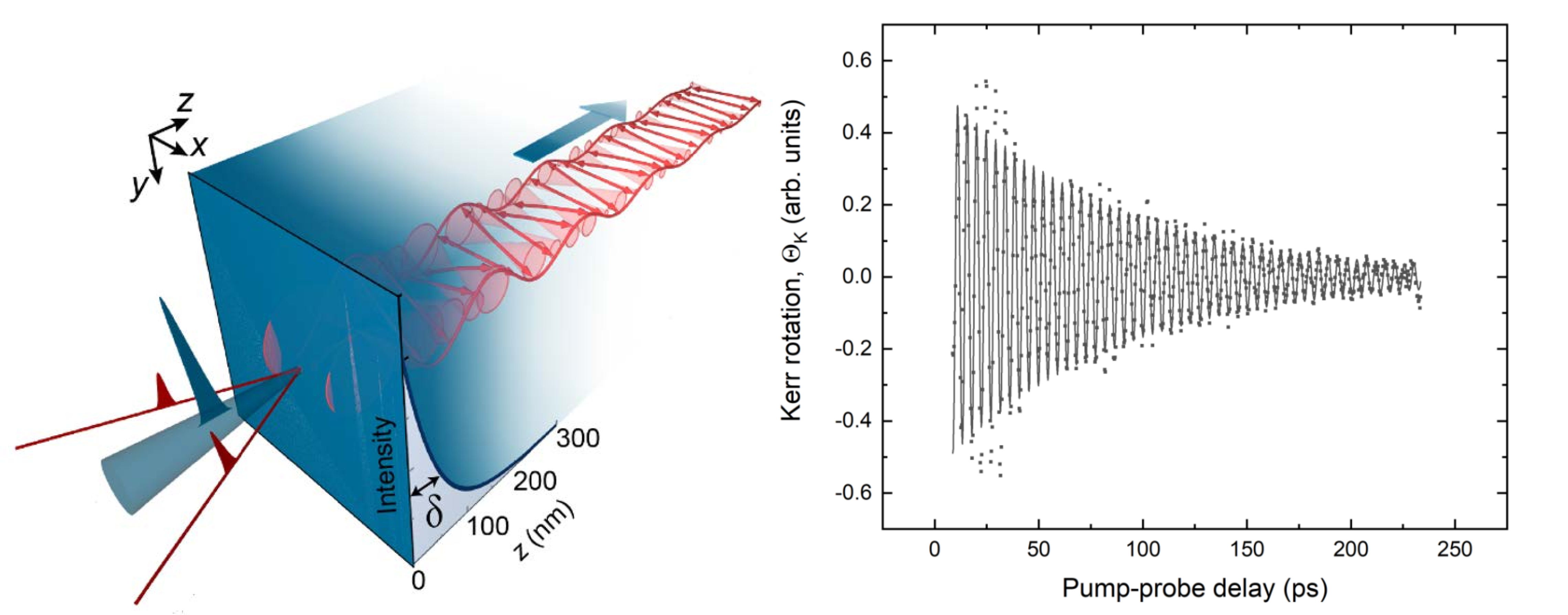
Antiferromagnetic spintronics



First ballistic antiferromagnetic spin-wave propagating at supersonic velocity (~12 km/s) and macroscopic distance (~ µm)

Hortensius et al. Nature Physics 17, 1001 (2021)

Collaborators and references

Controlling magnetic interactions with light

Nature Materials 20, 607 (2021)
Nature Physics 17, 1001 (2021)
Science Advances 7 eabf3096 (2021)
Nature Physics 17, 489 (2021)
npj Quantum Materials 5, 95 (2020)
Physical Review X 9, 021020 (2019)

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