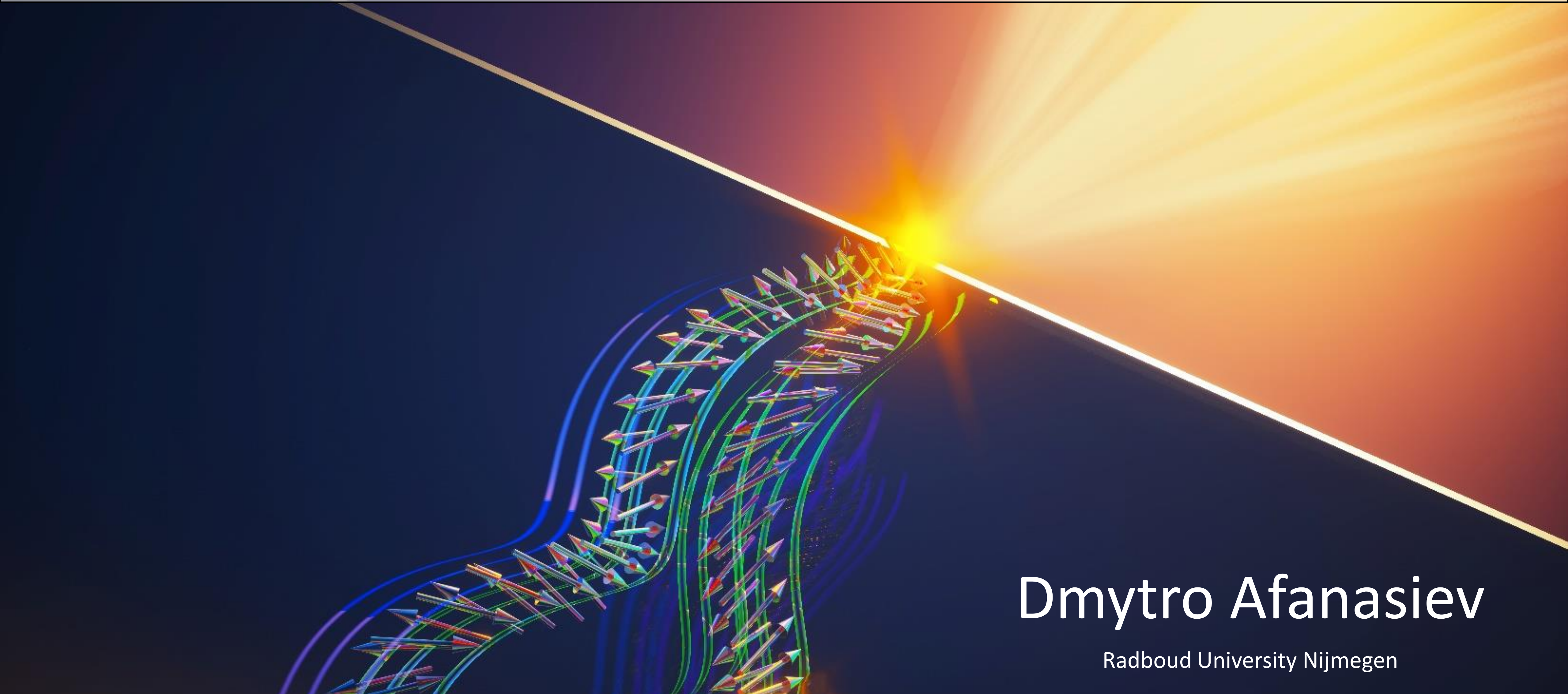
Light-driven antiferromagnetic magnonics

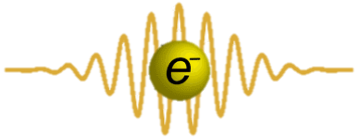


Dmytro Afanasiev

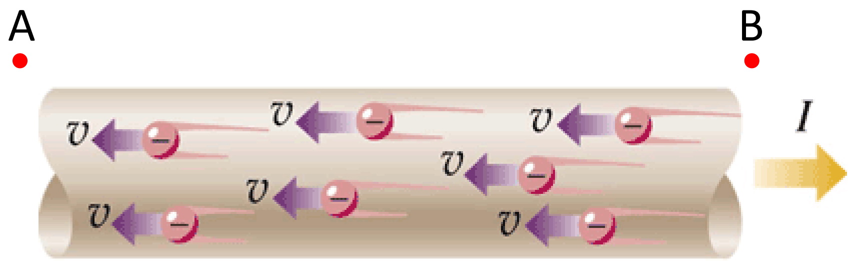
Radboud University Nijmegen

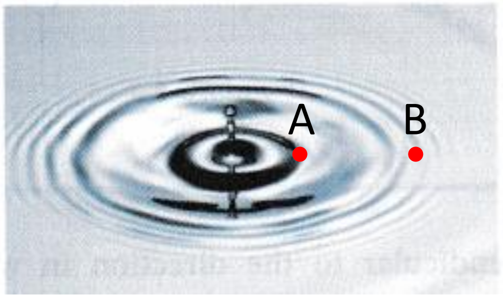
Electron as a data carrier

Particle



Wave





Particle-like transport

- mass, charge, velocity

- collisions

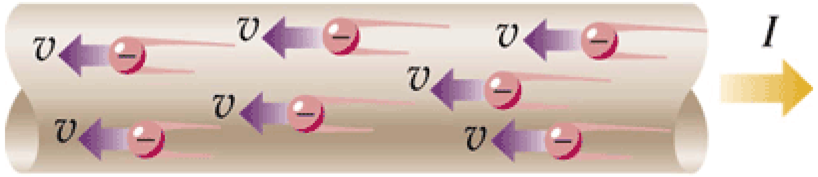
Wave-like transport

- Wavelength, frequency, dispersion
- Group and phase velocity

- Interference, diffraction

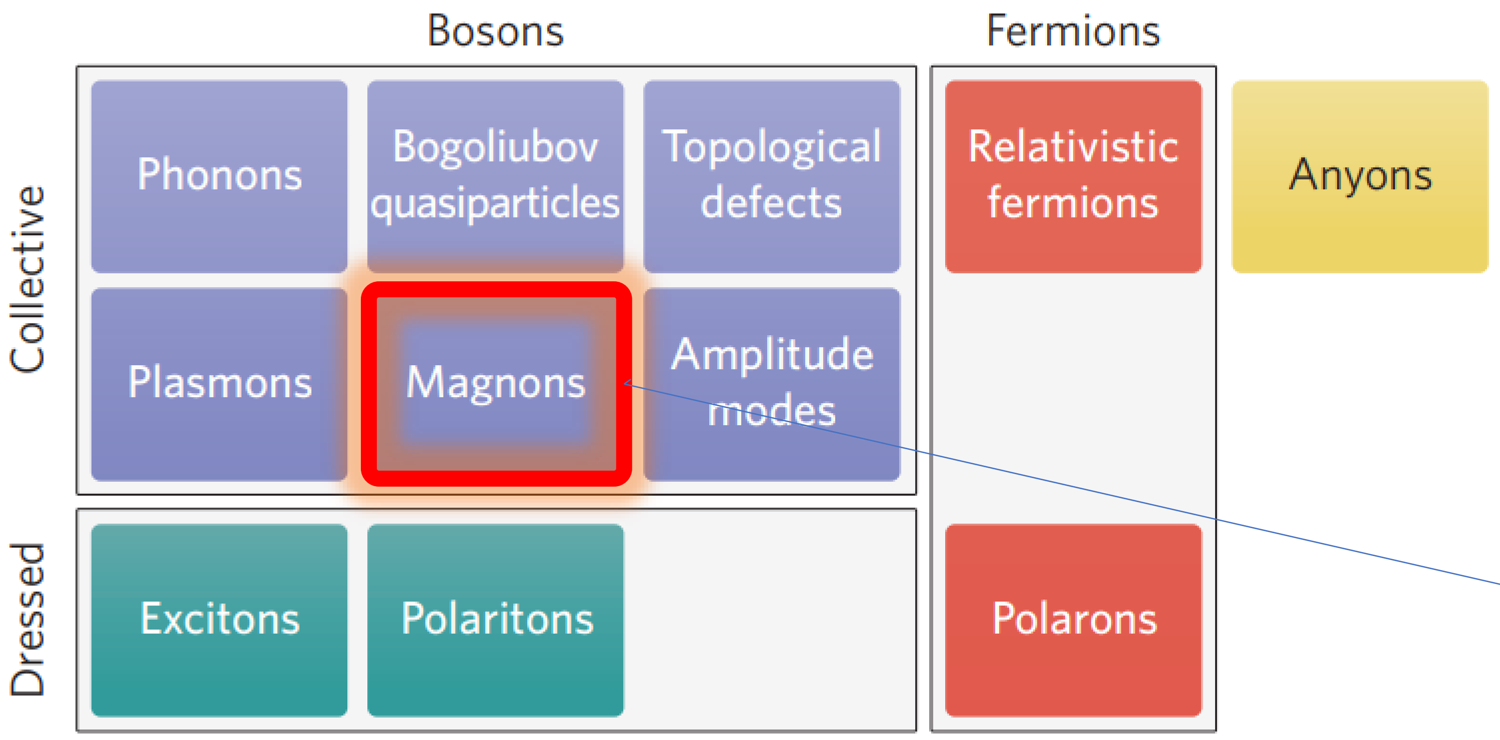
Low coherence of electrons

Limited manifestation of the wave-like nature of electron



- Typical momentum scattering time: τ_k=10-20 fs
- Short-range electron mean free propagation path: l_c~10 nm
- Enhanced dissipation/heating

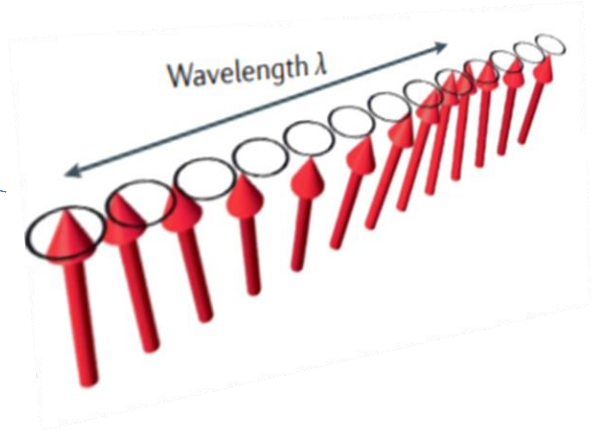
Quasiparticles zoo



	Bosons			Fermions	
Collective	Phonons	Bogoliubov quasiparticles	Topological defects	Relativistic fermions	Anyons
	Plasmons	Magnons	Amplitude modes		
Dressed	Excitons	Polaritons		Polarons	

Schematic depiction of a selection of quasiparticles.

Magnons

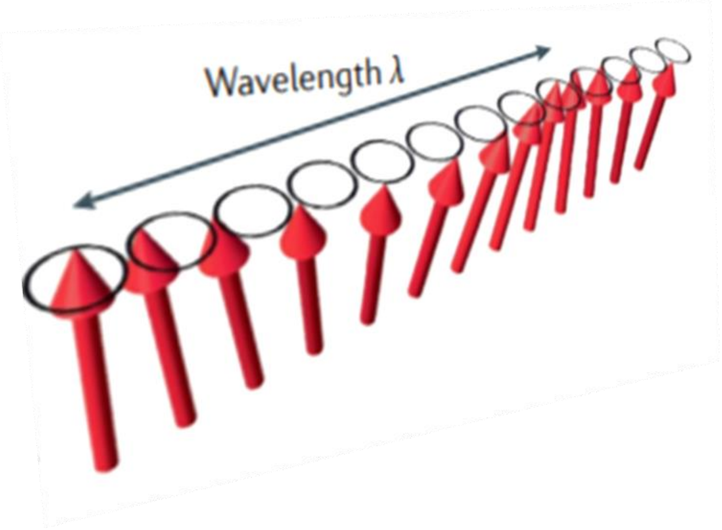


Highly coherent quasiparticles

C. Beenakker *Science*, **353** 539(2016)

Wave-based transport and data processing with magnons

Spin wave

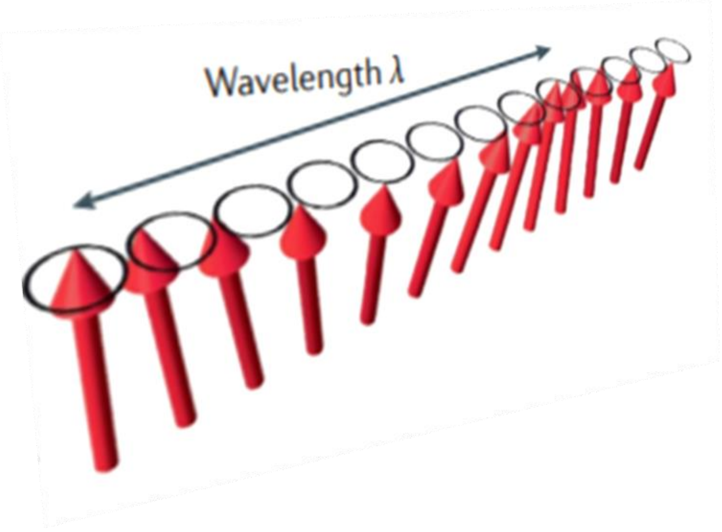


Waves of spin angular momentum

- Long coherence times: > 1 ms
- Low dissipative: maintain spatial coherence > 1 mm
- Highly nonlinear

Wave-based transport and data processing with magnons

Spin wave



Waves of spin angular momentum

- Long coherence times: > 1 ms
- Low dissipative: maintain spatial coherence > 1 mm
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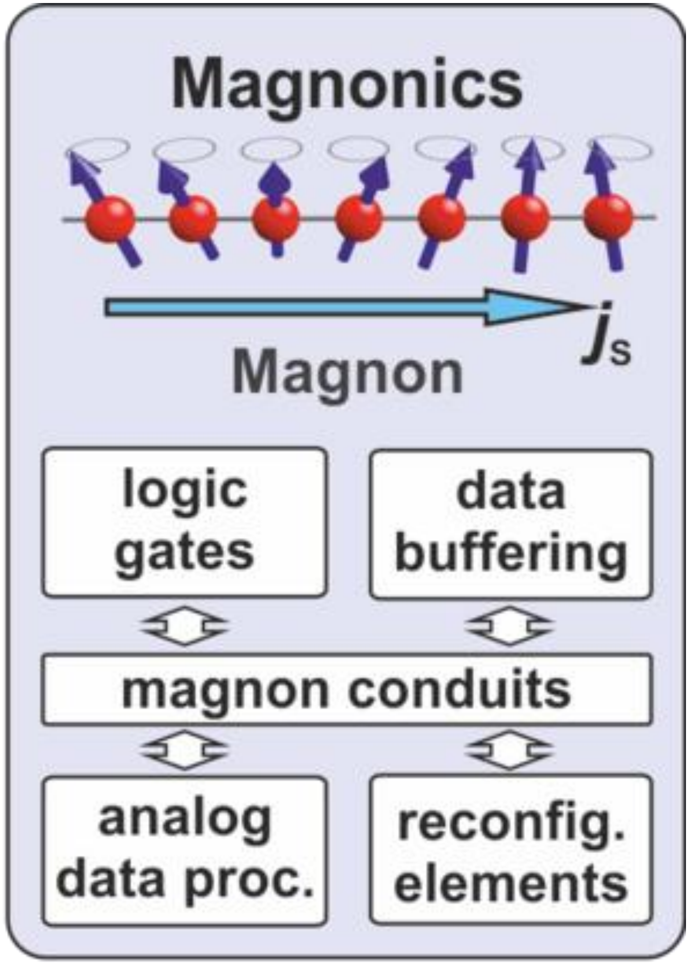


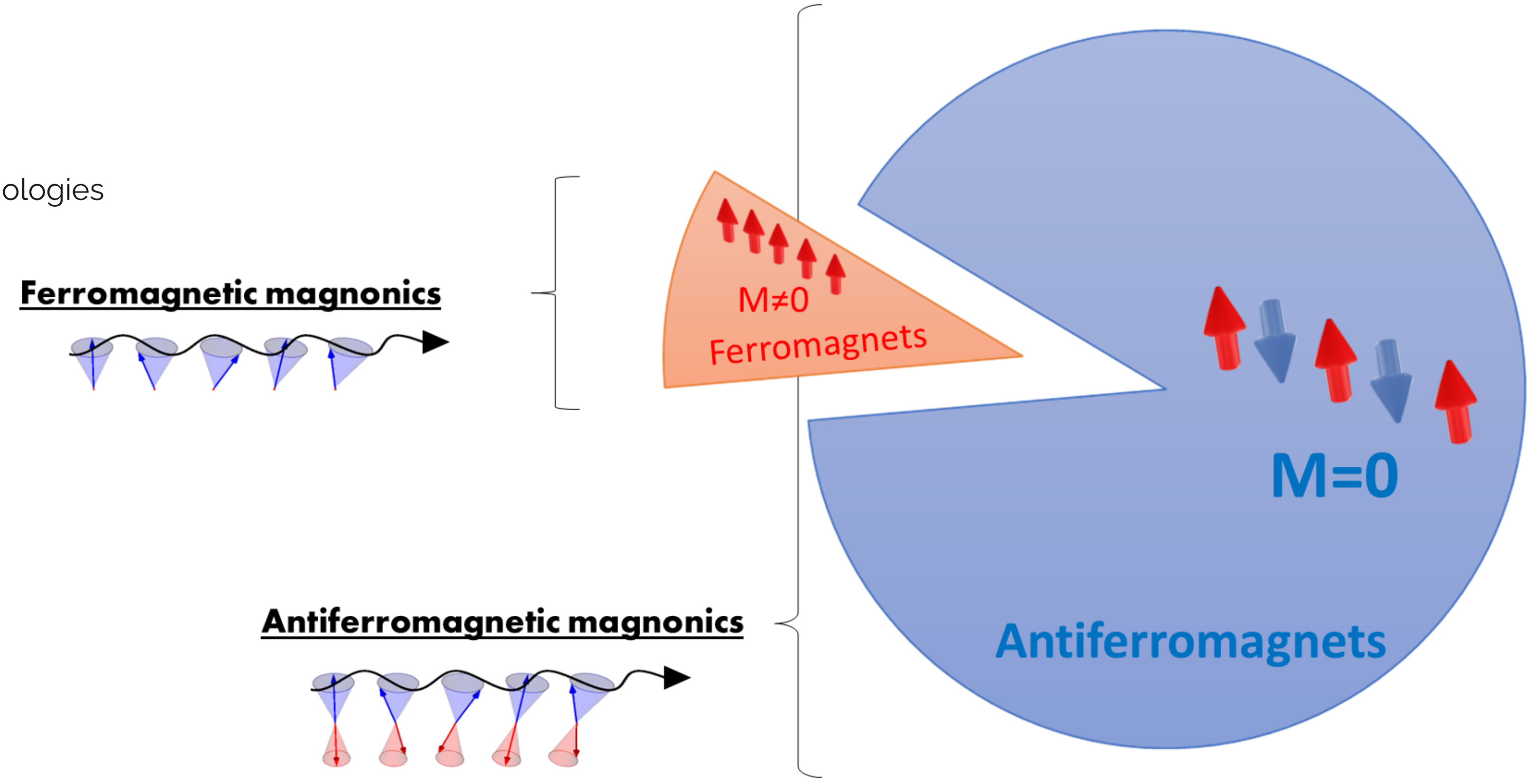
Barman *et al J. Phys.: Condens. Matter* **33,** 413001 (2021)

Present and future of magnonics

Spin insulatoronics

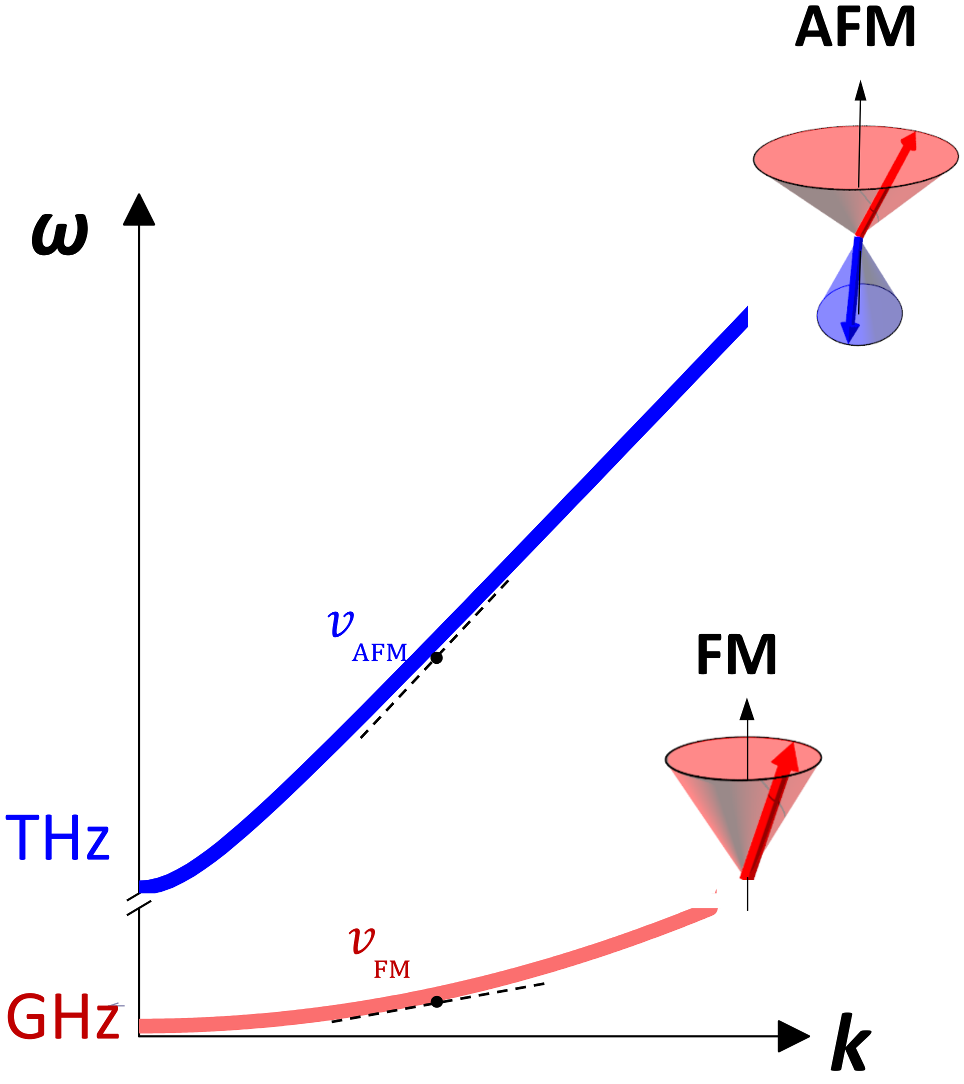
*A. Brataas, et al. Physics Reports, **885** (2020)*

Pure spin-based information and communication technologies



Magnetic insulators

Antiferromagnetic magnonics

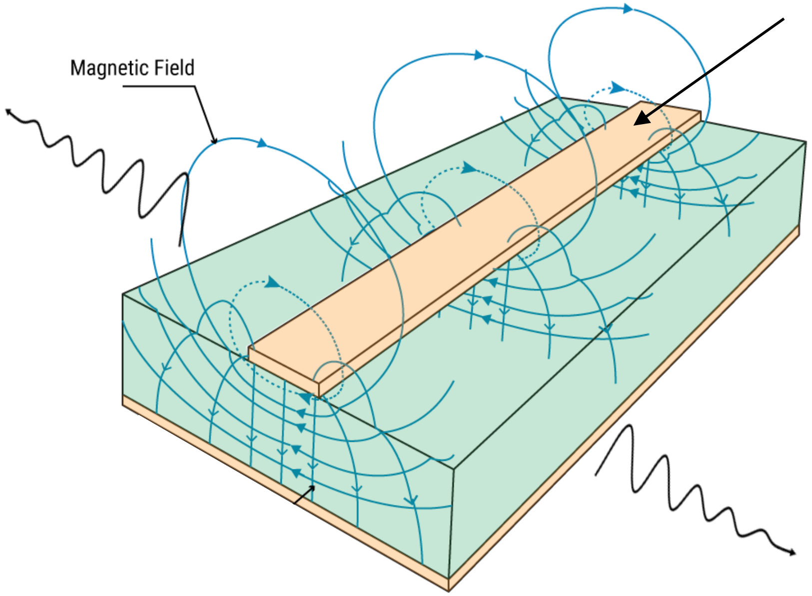


AFM $vs.$ FMs

- Higher operational frequencies $\omega_{\text{AFM}} > \omega_{\text{FM}}$
- Higher spin-wave group velocities $v_{\text{AFM}} > v_{\text{FM}}$
- Non-dispersive propagation

(Linear “light-like” dispersion at large *k*)

Traditional sources of spin wave emission



AC current

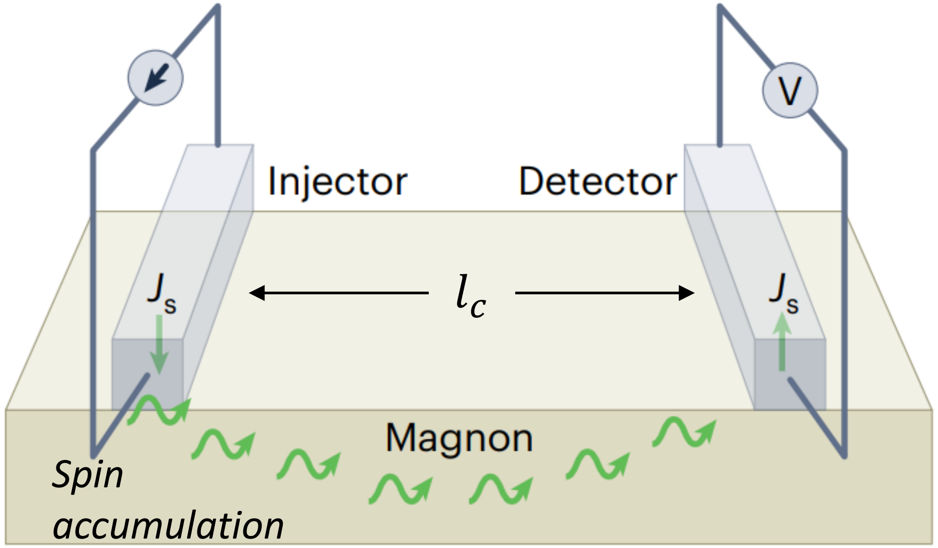
Spin-wave emissions

$\Delta\nu < 50$ GHz

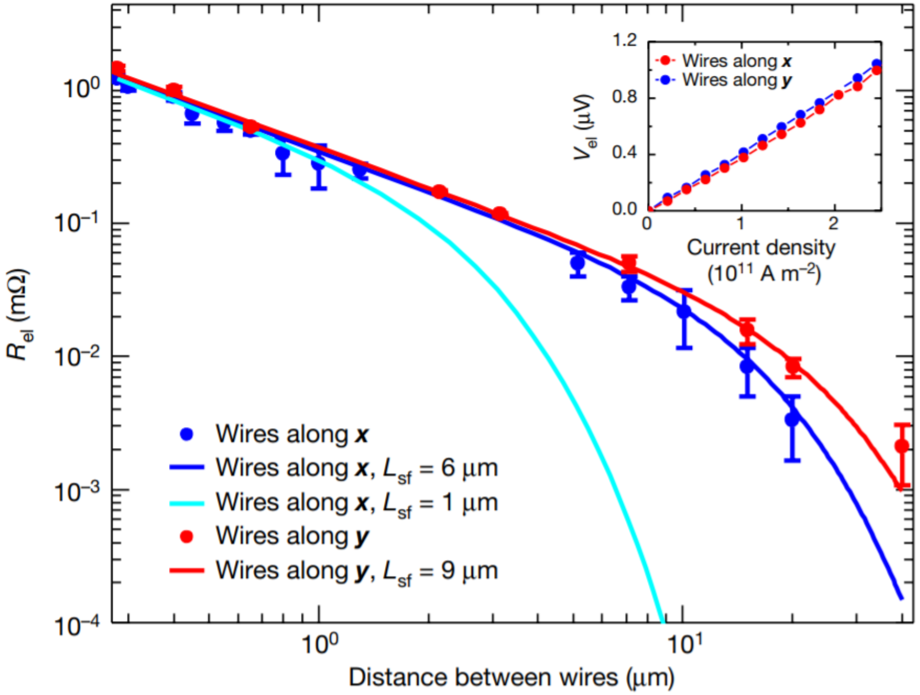
(radiative losses, etc.)

Not well applicable to antiferromagnets ($\nu \sim 1$ THz)

Universal way to excite spin waves



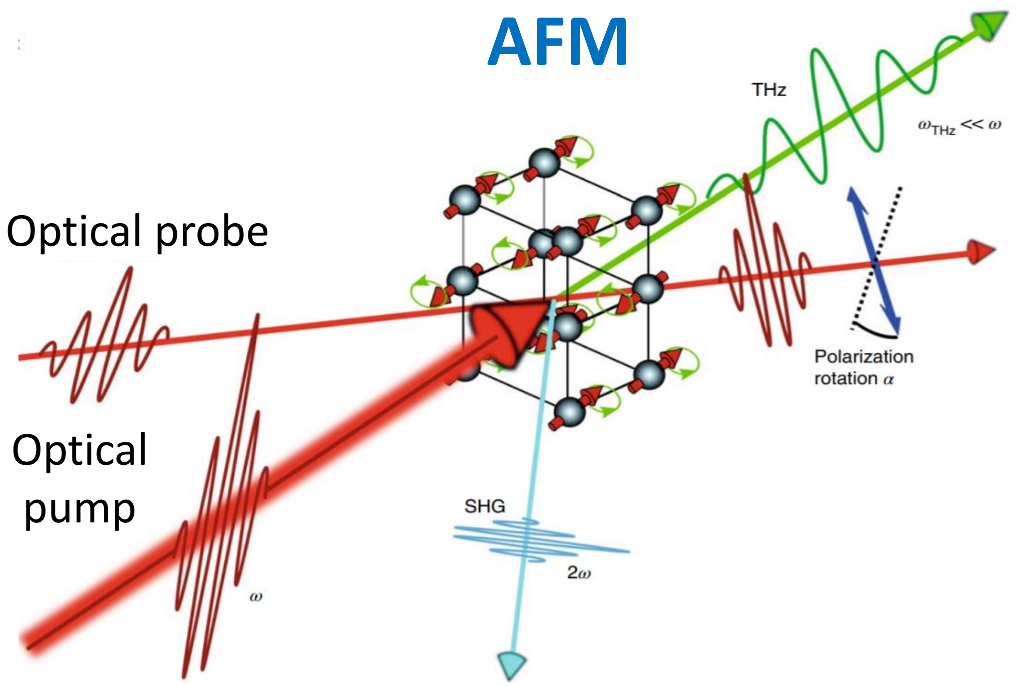
$l_c > 10$ µm



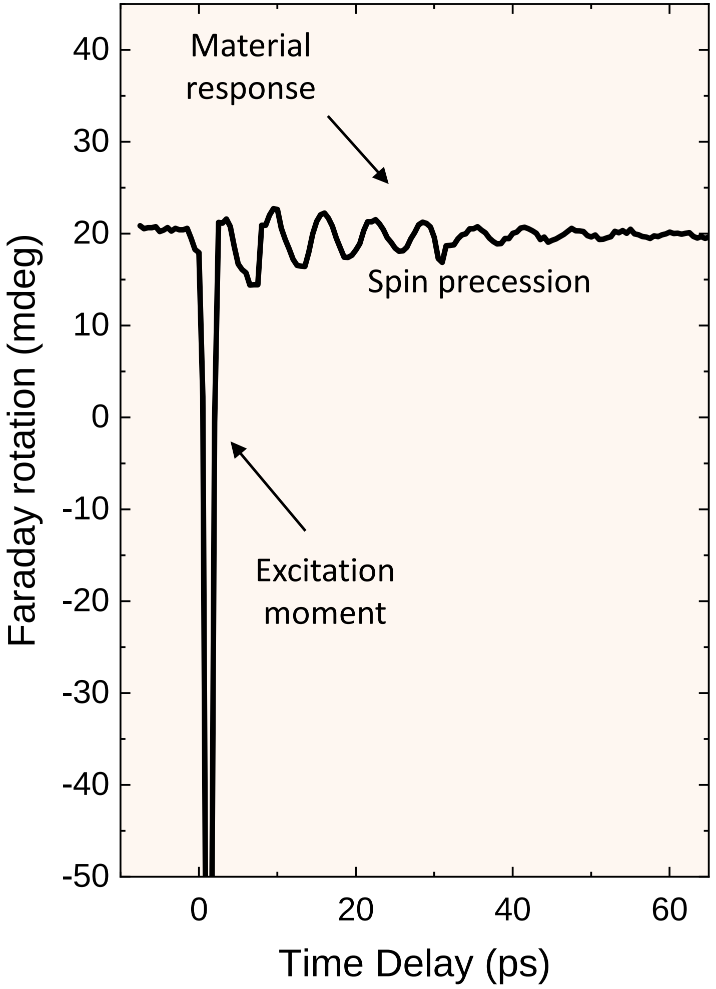
R. Lebrun et al., *Nature* **561,** 222 (2018)
J. Li et al., *Nature* **578,** 70 (2020)
P. Vaidya et al., *Science* **368,** 160 (2020)

Diffusive (incoherent) spin-wave transport

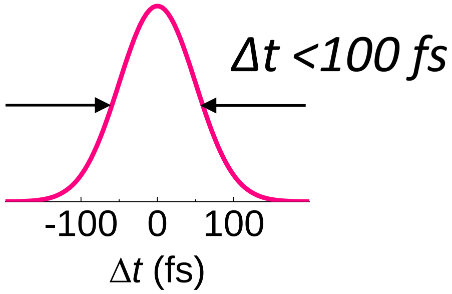
Light-driven excitation of coherent spin wave dynamics



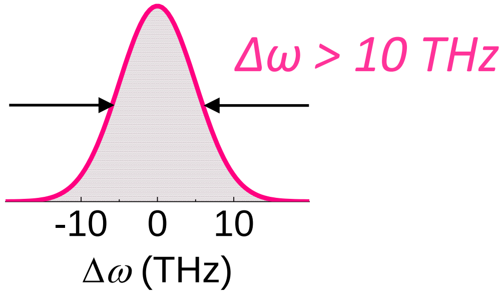
Antiferromagnetic optospintronics
Nat. Phys. **14,** 229–241 (2018)



Limitations of light

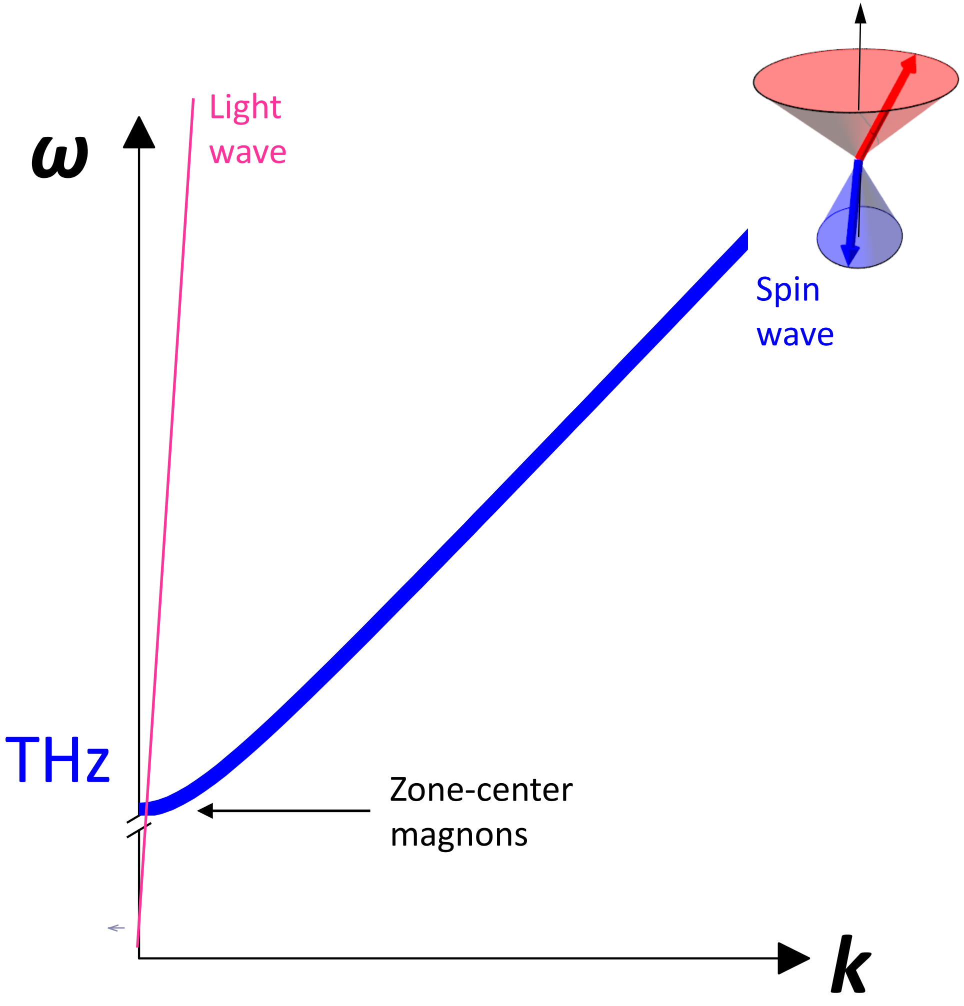


Ultrashort



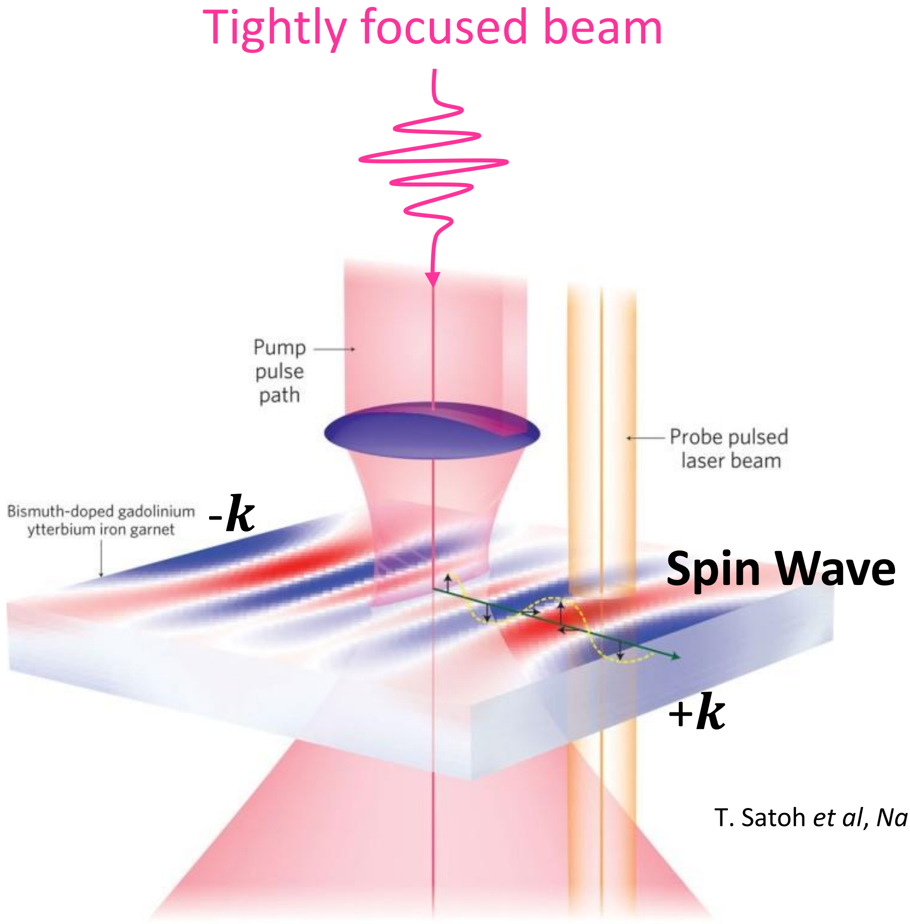
Ultrabroadband

Impulsive excitation



- Lowest frequency magnons
- No propagation

Localization of the optical excitation by focusing

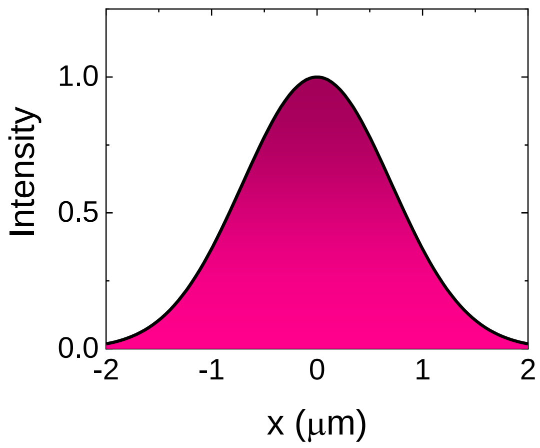


T. Satoh *et al*, *Nat. Photonics* **6**, 662 (2012)

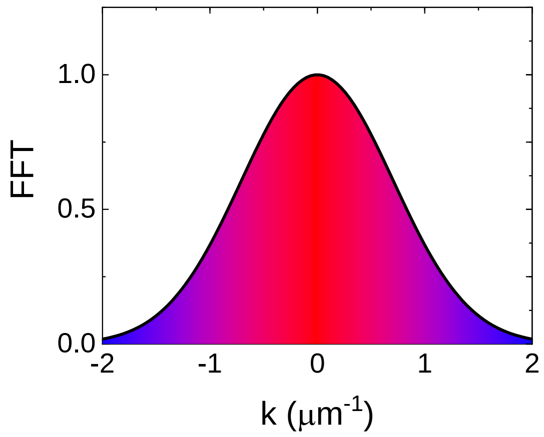
Diffraction limited ~ 1 μm

(to propagate λ_{sw} < 100 nm)

Inhomogeneous excitation

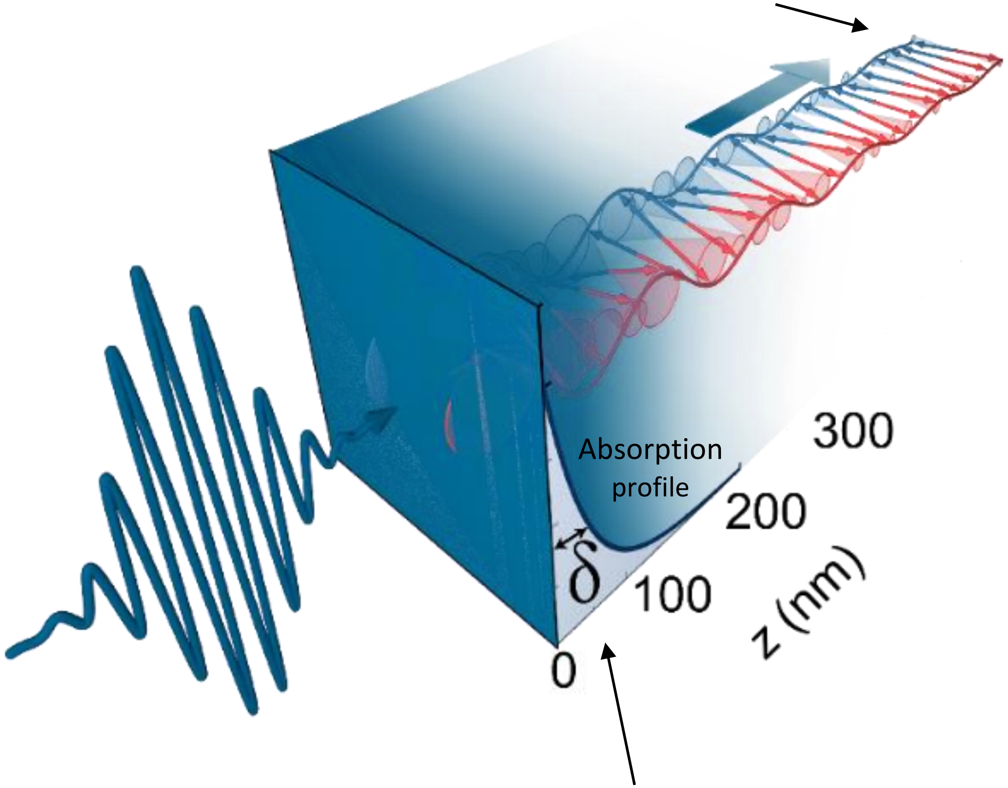


Source of finite *k*-vectors



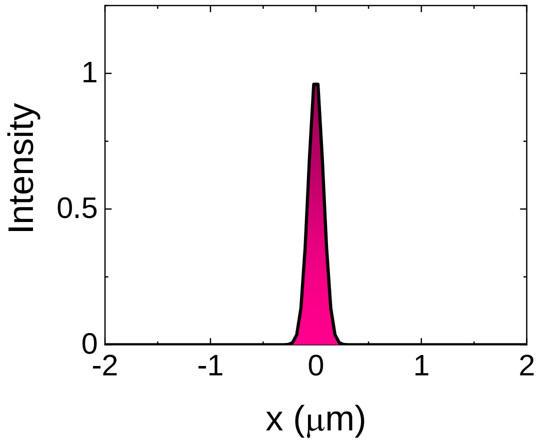
Subwavelength localization of the spin excitation

Spin-wave emission

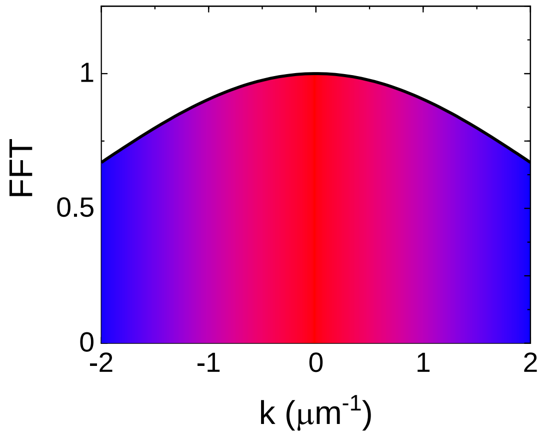


Nanoscale THz spin-wave antenna

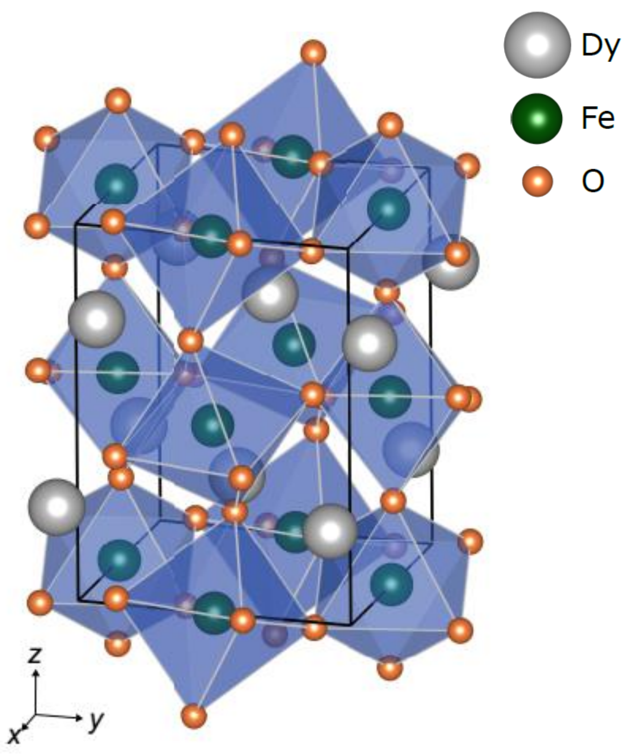
Inhomogeneous excitation



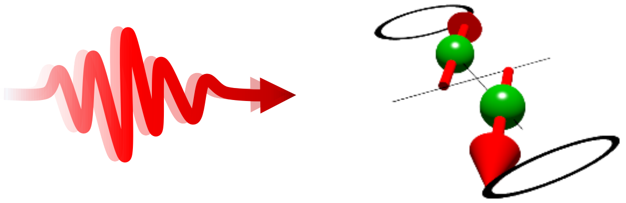
Source of finite *k*-vectors



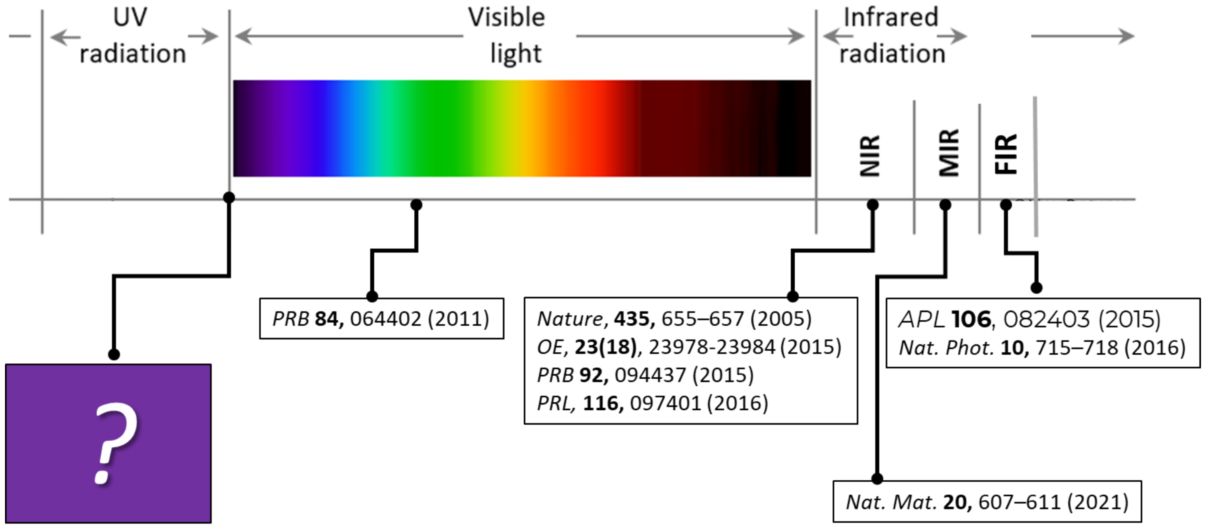
Ultrafast optomagnetism in antiferromagnetic $DyFeO_3$



T_N=650 K



Coherent spin precession



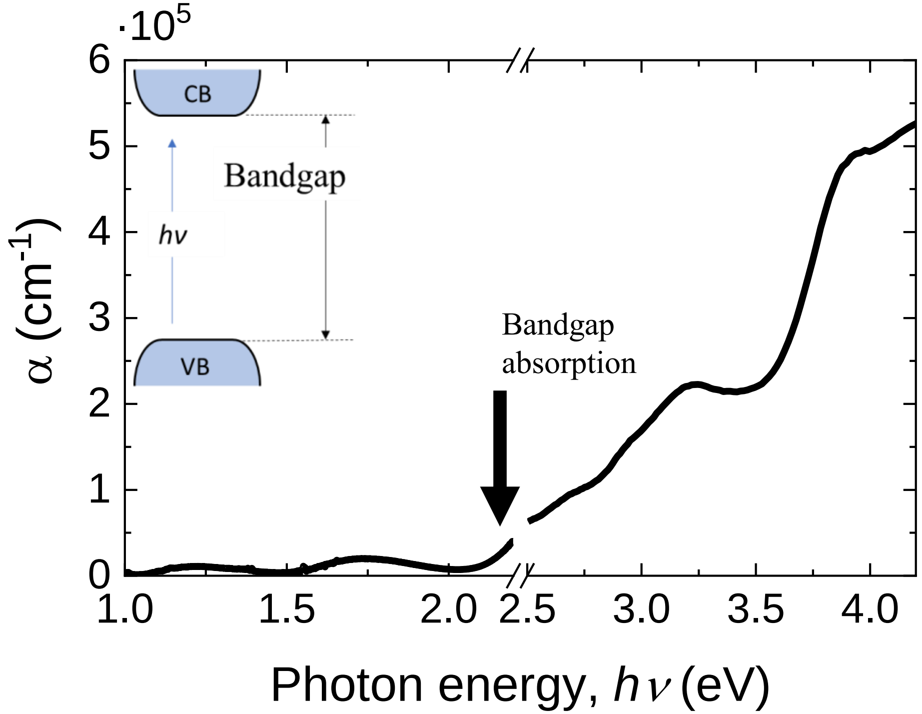
PRB **84,** 064402 (2011)

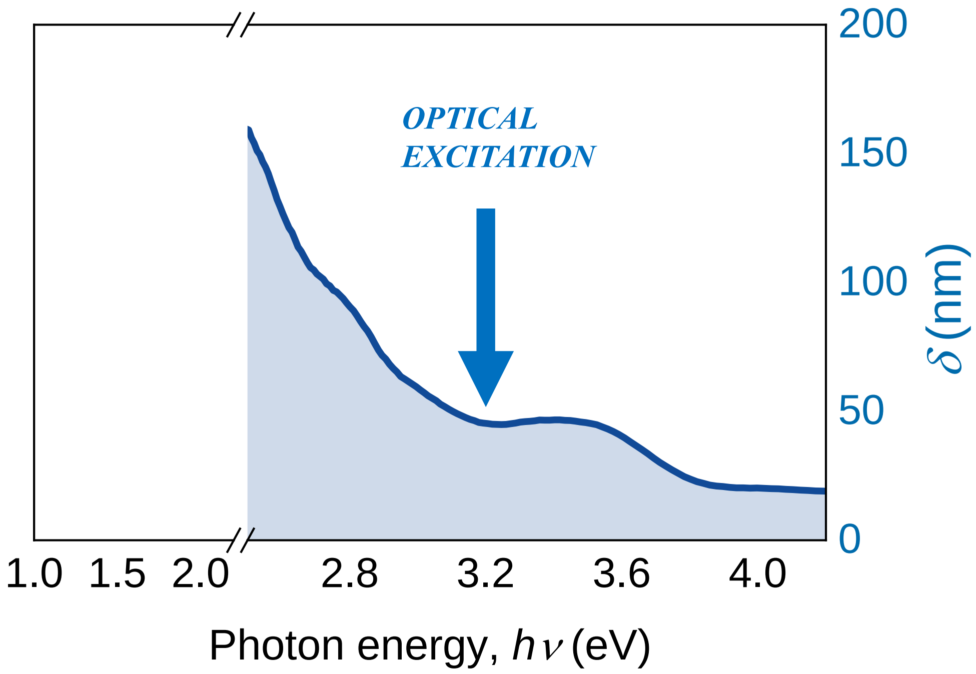
Nature, **435,** 655–657 (2005)
OE, **23(18)**, 23978-23984 (2015)
PRB **92,** 094437 (2015)
PRL, **116,** 097401 (2016)

APL **106**, 082403 (2015)
Nat. Phot. **10,** 715–718 (2016)

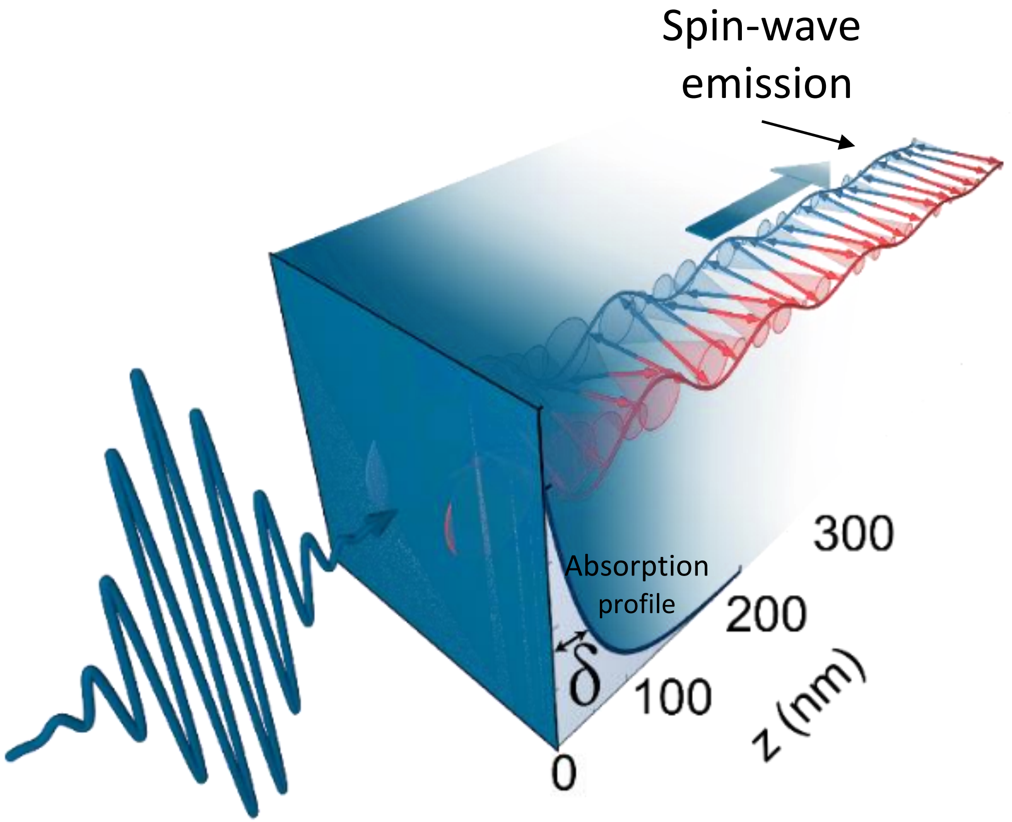
Nat. Mat. **20,** 607–611 (2021)

Optical absorption in $DyFeO_3$

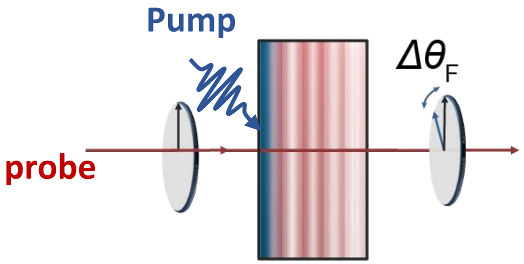




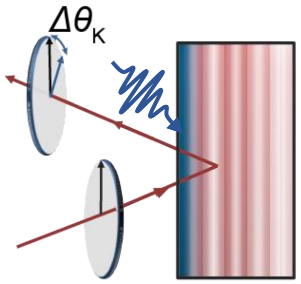
Experimental geometry



Ultrashort light pulse
@3.1 eV, δ=50 nm

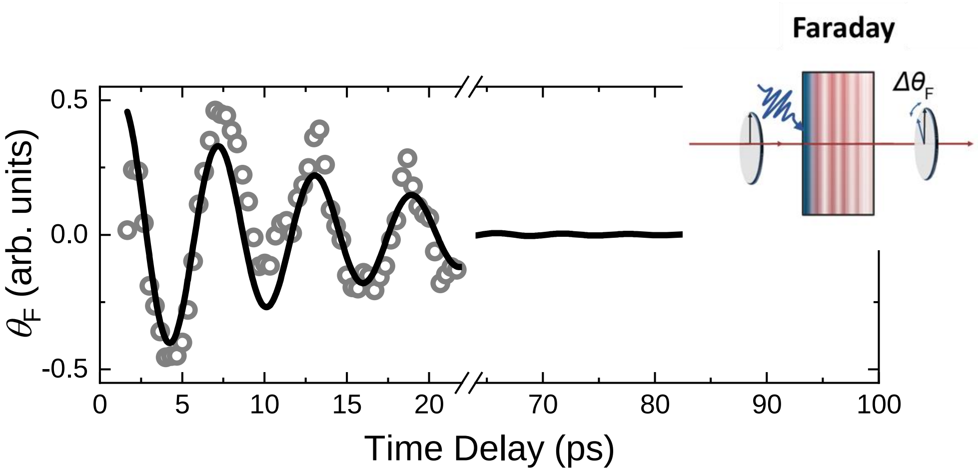


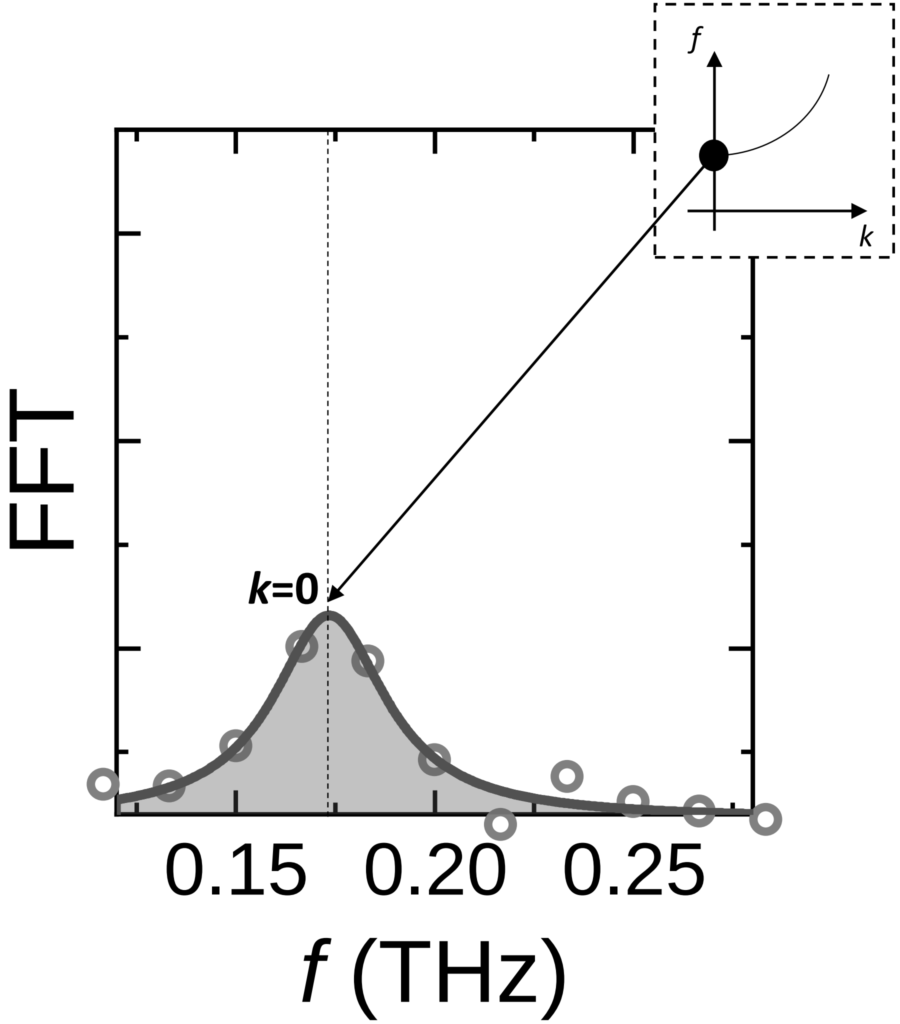
Magneto-optical Faraday effect
(bulk sensitive)



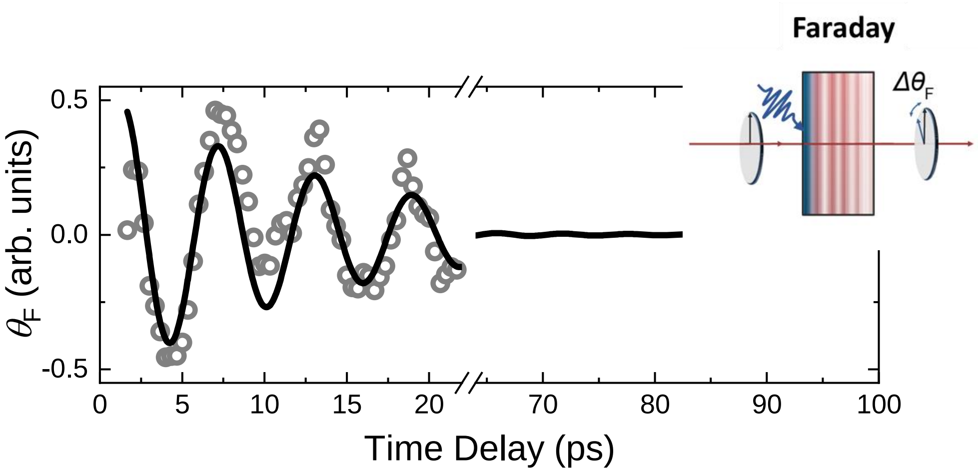
Magneto-optical Kerr effect (MOKE)
(surface sensitive)

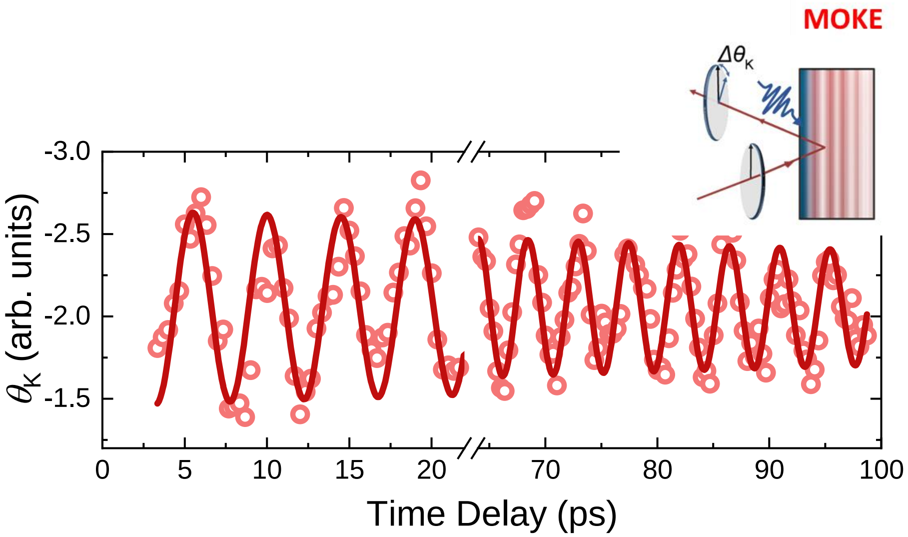
Excitation of coherent spin dynamics

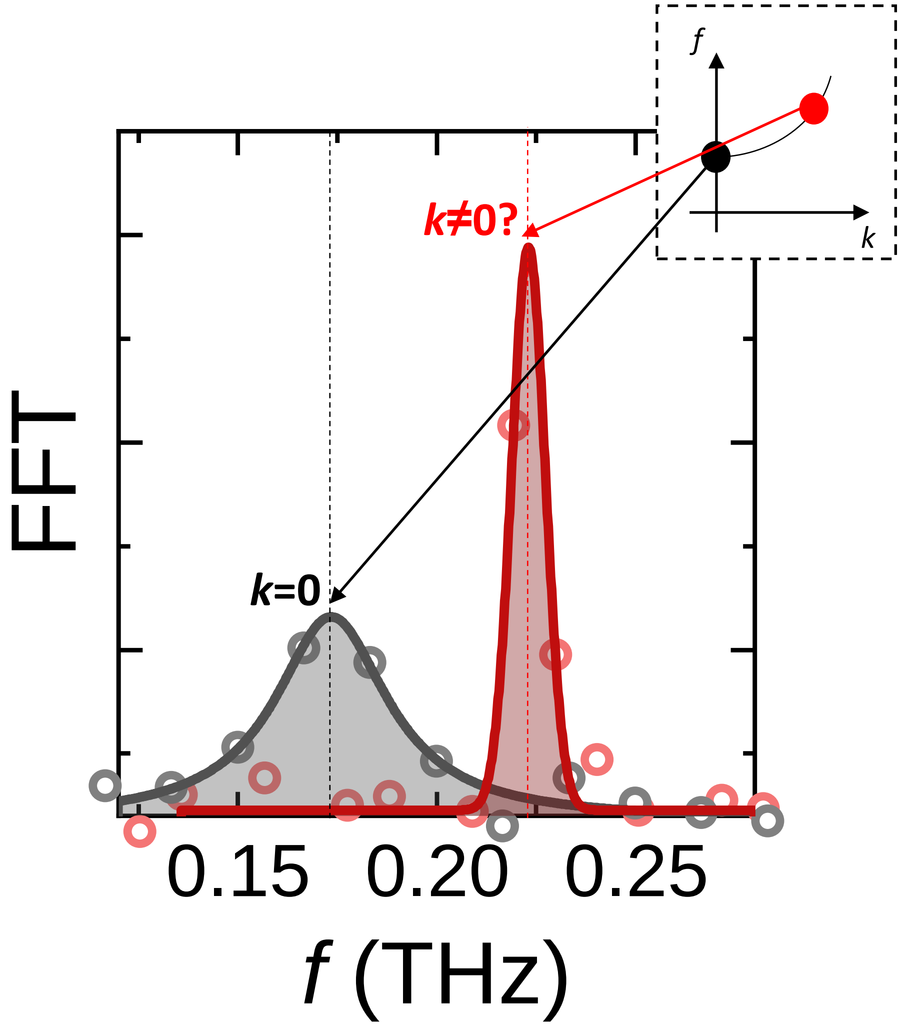




Excitation of coherent spin dynamics

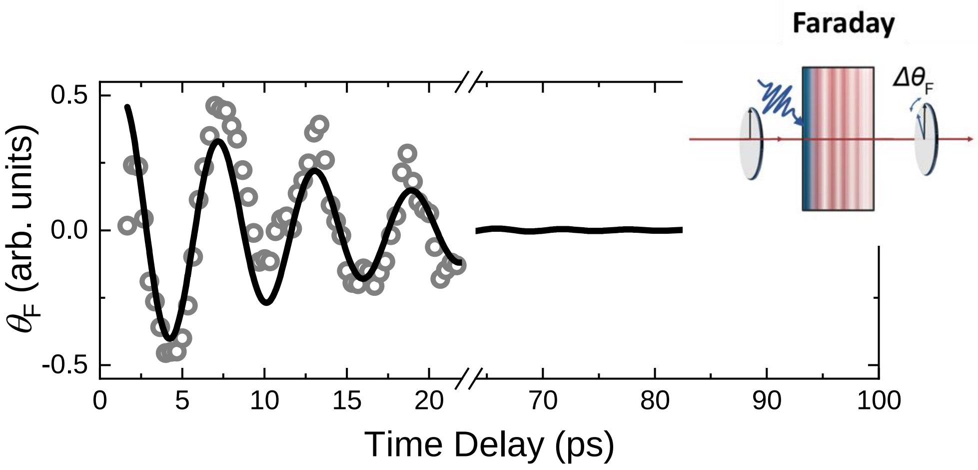


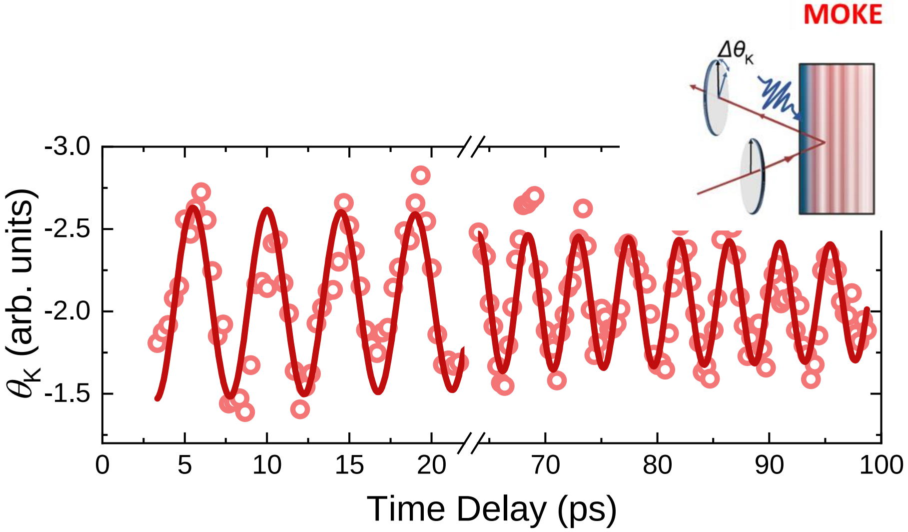


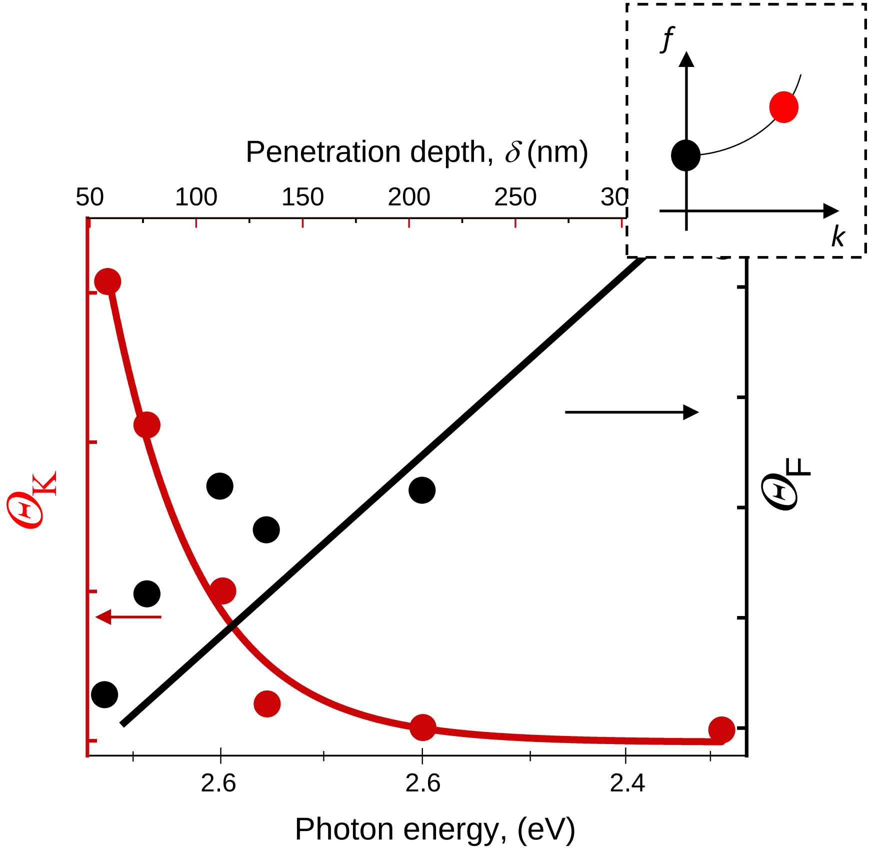


Θ_F and Θ_K probe different dynamics of spins

Excitation of coherent spin dynamics

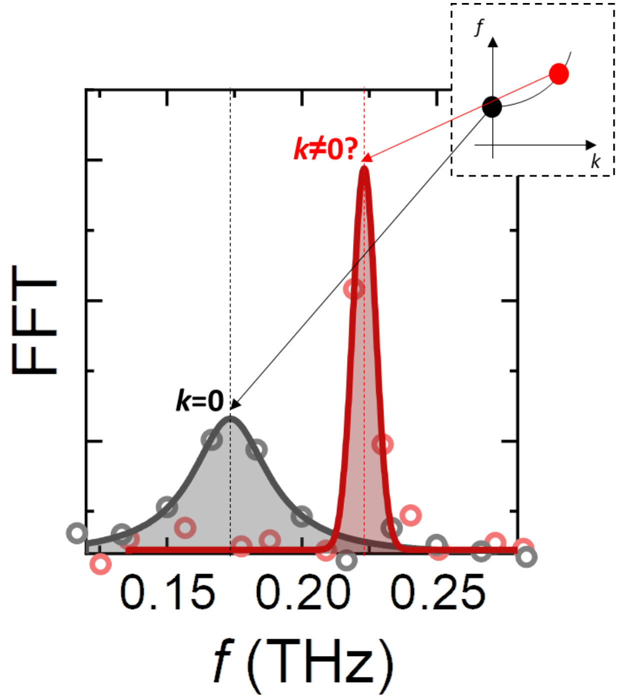




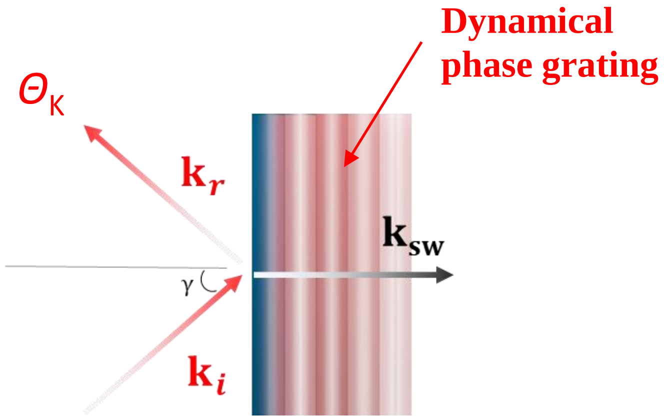


Θ_F and Θ_K show different sensitivity to the uniformity of the light excitation

What do we probe with MOKE ?



Θ_F and Θ_K probe different dynamics of spins

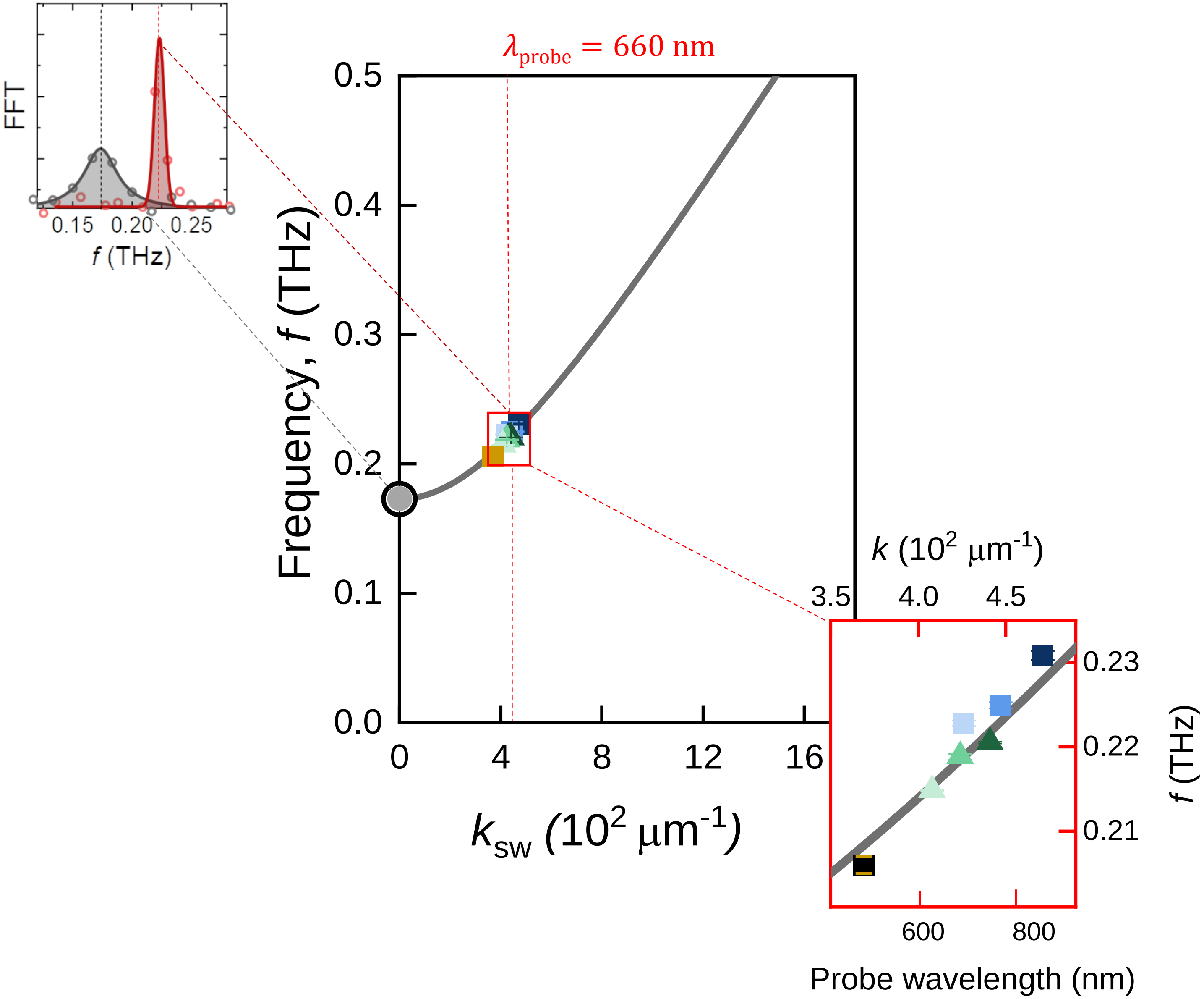


Momentum conservation

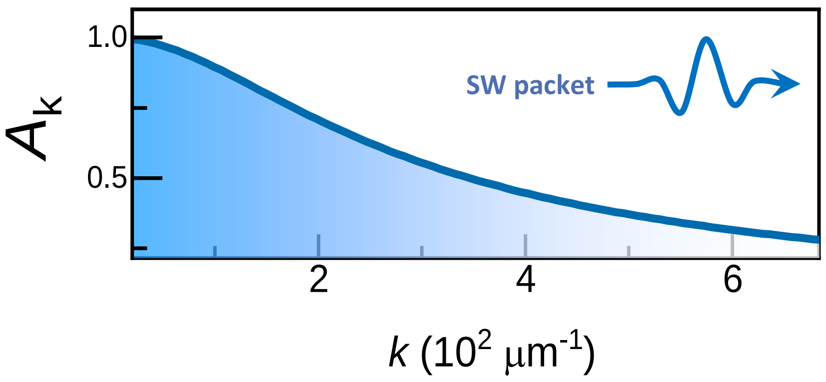
$$k_i - k_r = \pm k_{sw},$$
$$k_{i,r} = {}^{2\pi n_0}/_{\lambda_{probe}} \cos\gamma$$

Varying probe wavelength you get sensitivity
to different spectral components

Mapping components of the broadband spin-wave packet

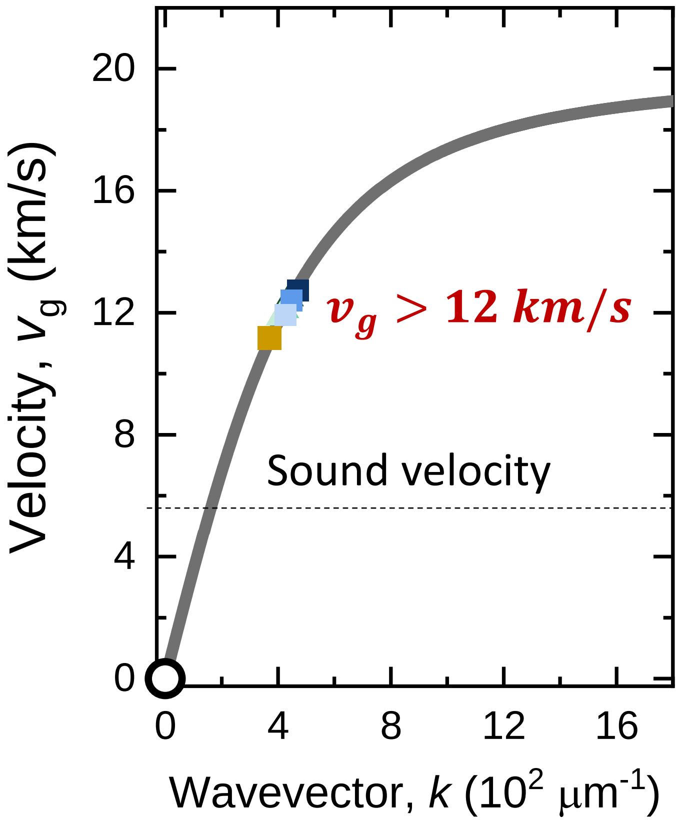


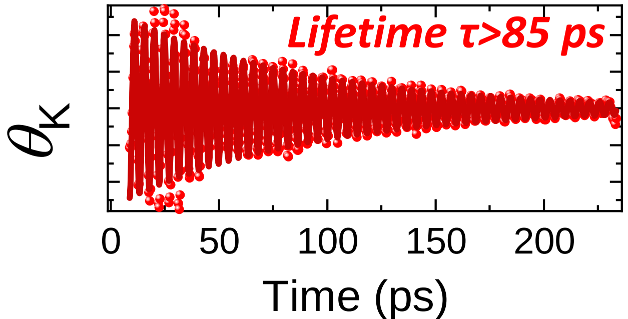
Fourier image of the spin excitation



The light-induced spin-wave packet is broadband. Its components can be mapped out by changing probe wavelength

Supersonic long-propagating waves





Coherence length:

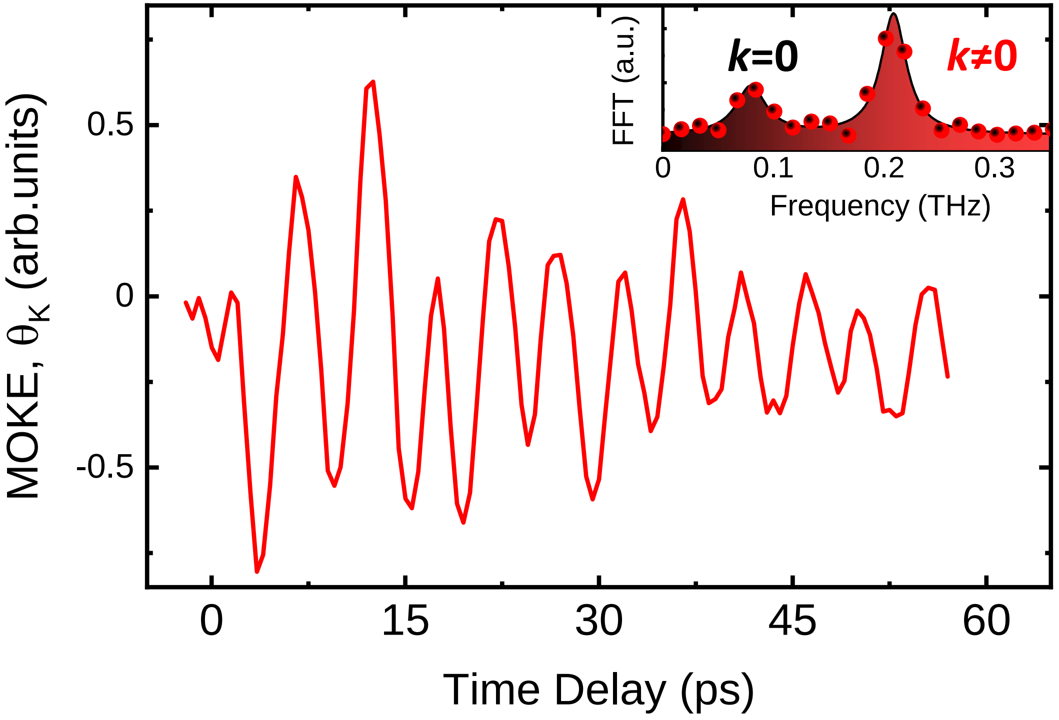
$$l_c = v_g \tau > 1\ \mu m$$

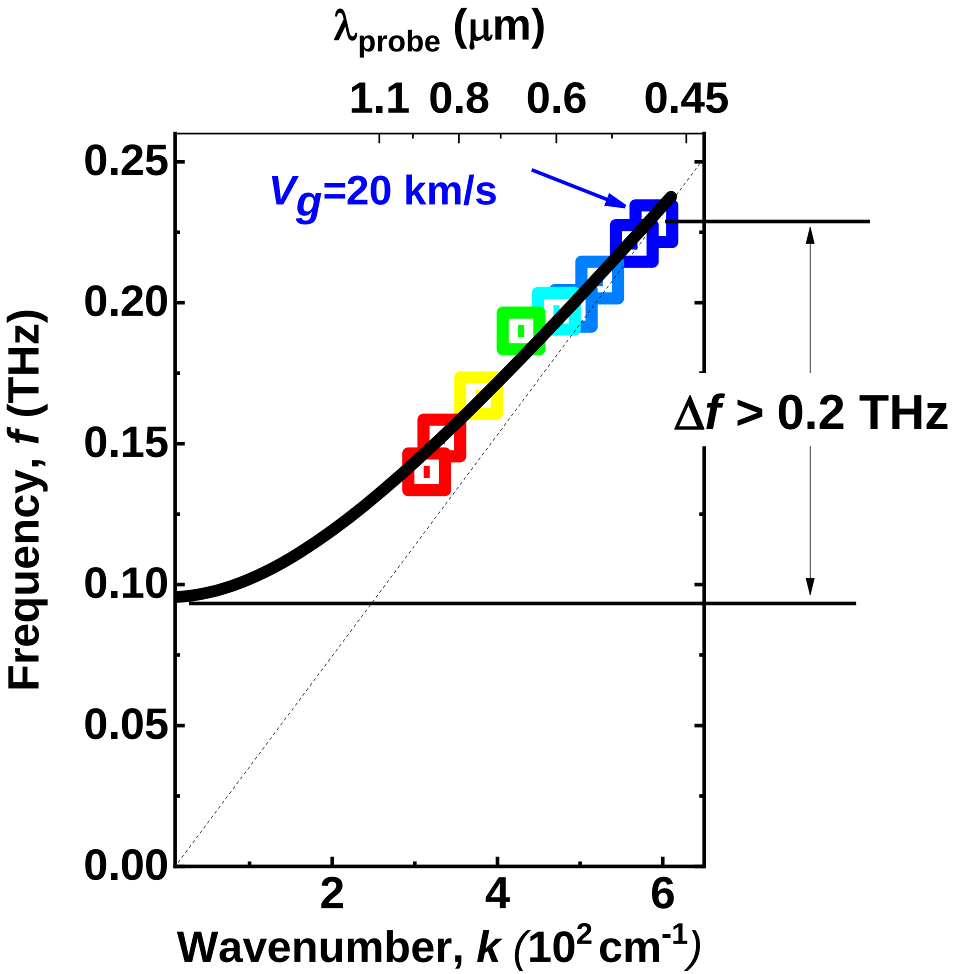
Frequency:

$$f = 0.23\ THz$$

Spin-wave propagation in other orthoferrites

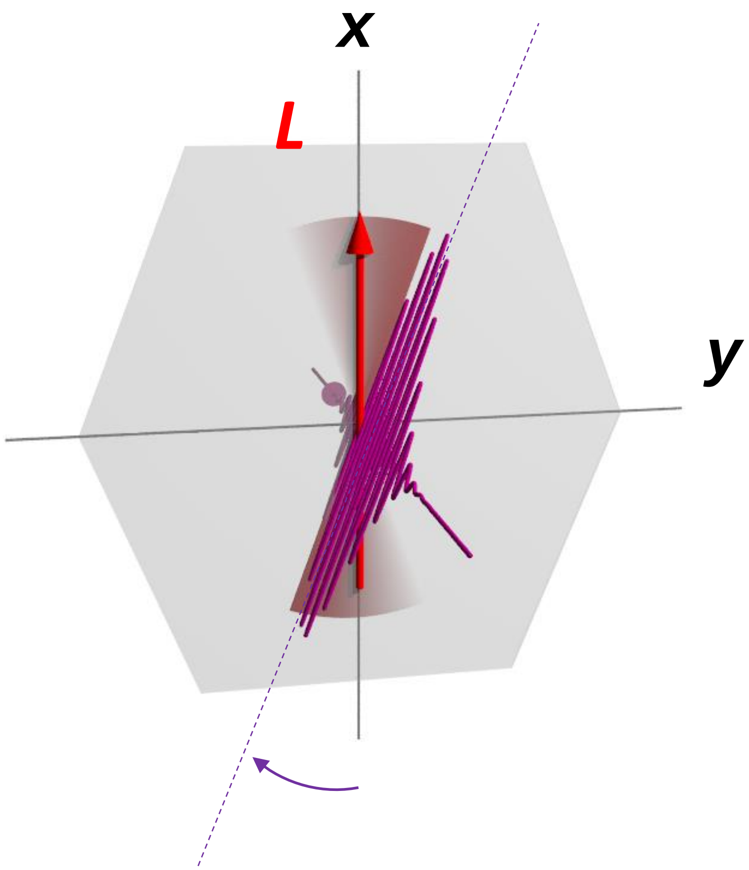
$HoFeO_3$, $(Sm,Tb)FeO_3$





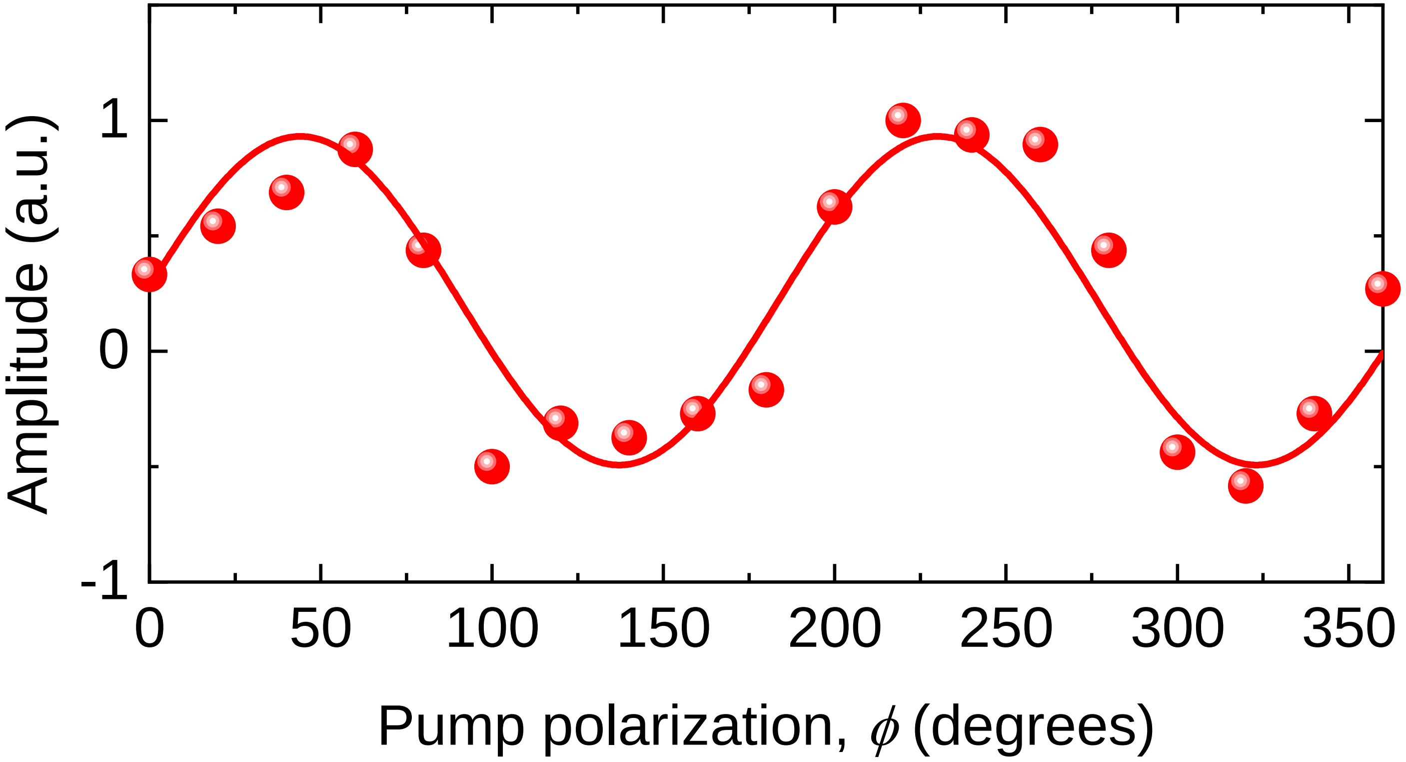
Mapping wavepacket of coherent spin-waves
in $HoFeO_3$ with a bandwidth of > 0.2 THz

Excitation mechanism

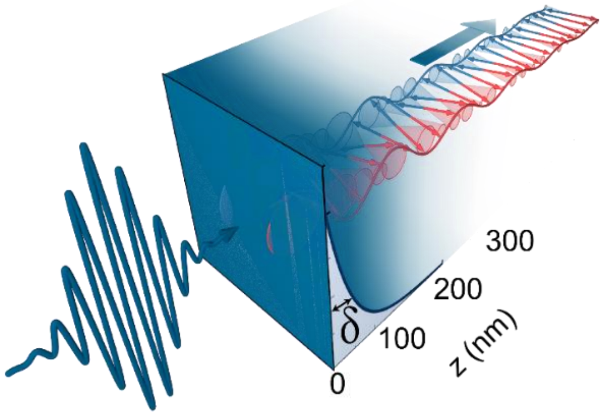


Inverse Cotton-Mouton effect
(ICME)

Although excitation is in the region of strong absorption
It is non-thermal as the phase can be controlled

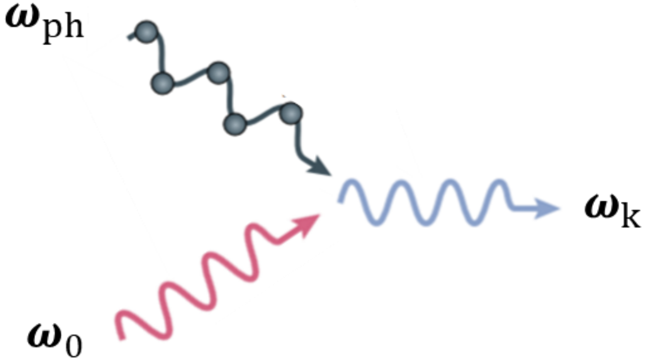


Light-induced broadband spin-wave packets

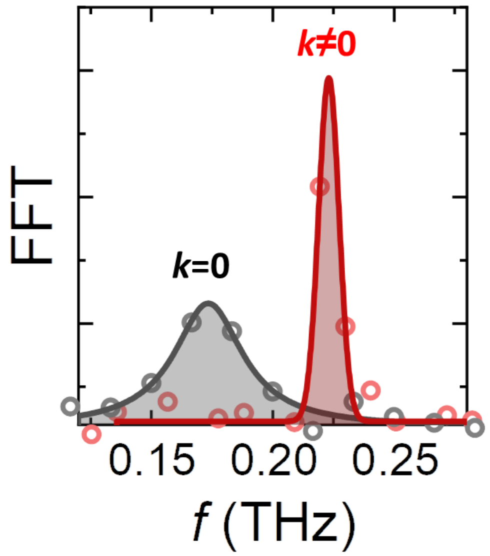


Spin-Wave Packet
($\Delta\nu > 0.2$ THz)

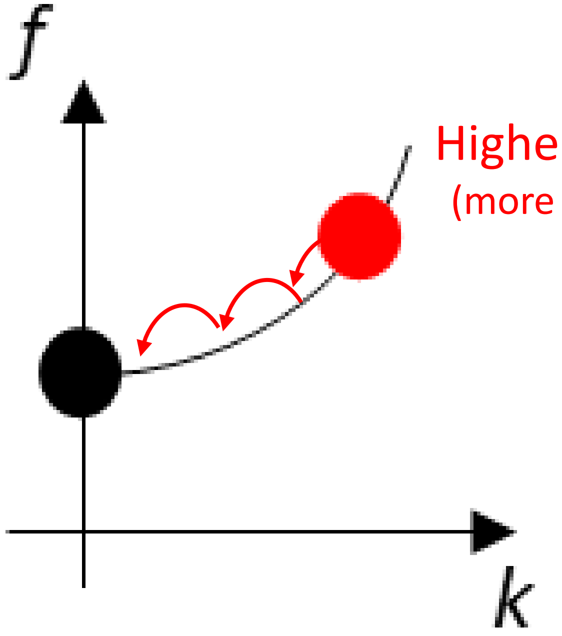
Can the spin-waves interact within the wavepacket?



Anomalous damping of the zone-center magnon in $DyFeO_3$

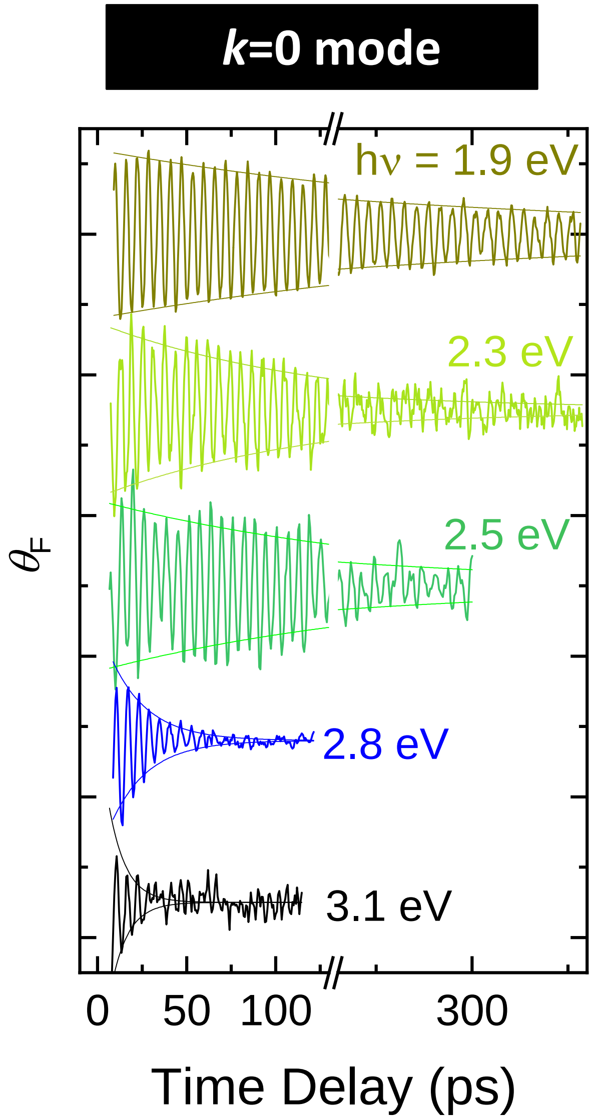


Damping of finite *k*-mode
is significantly smaller than *k*=0

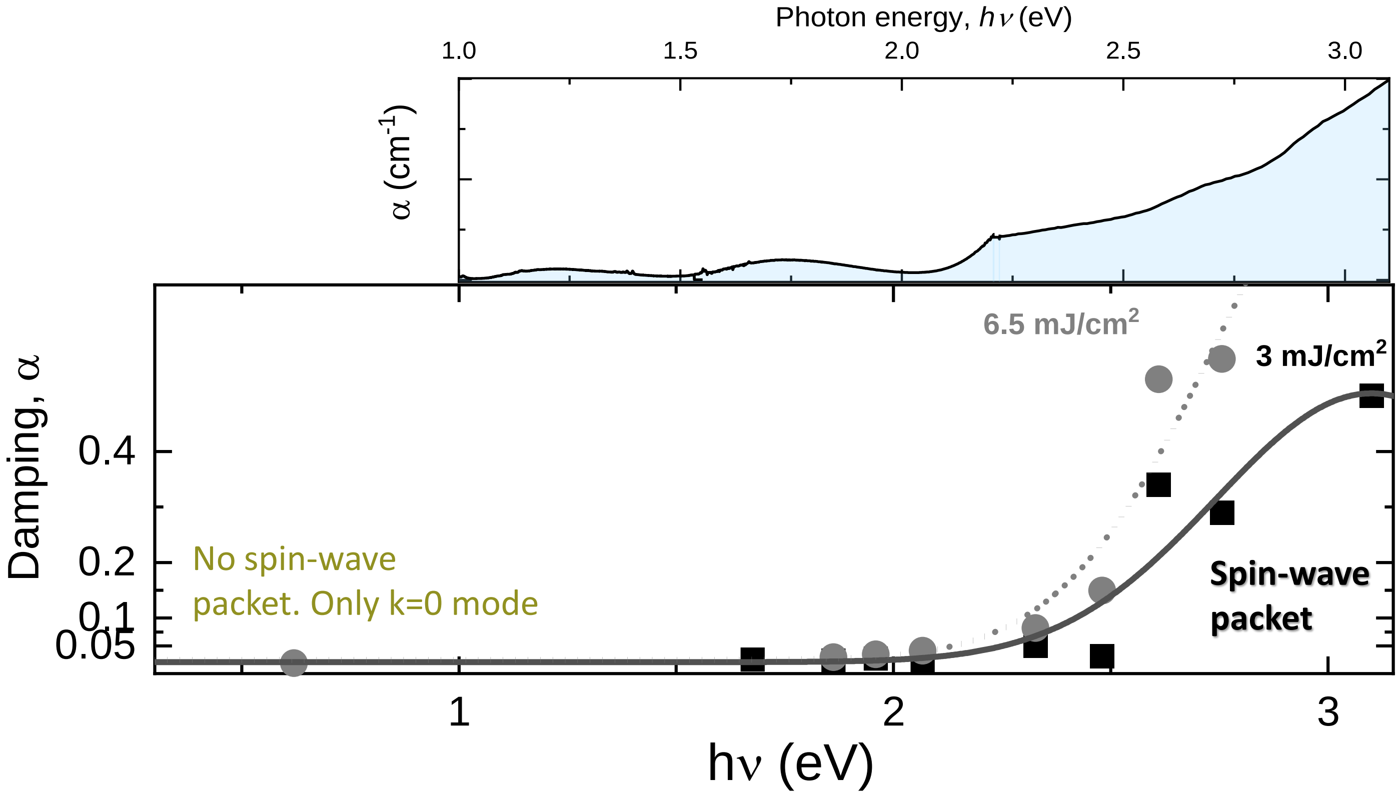


Higher energy magnon
(more scattering channels)

Enhancement of the damping in the region of strong absorption

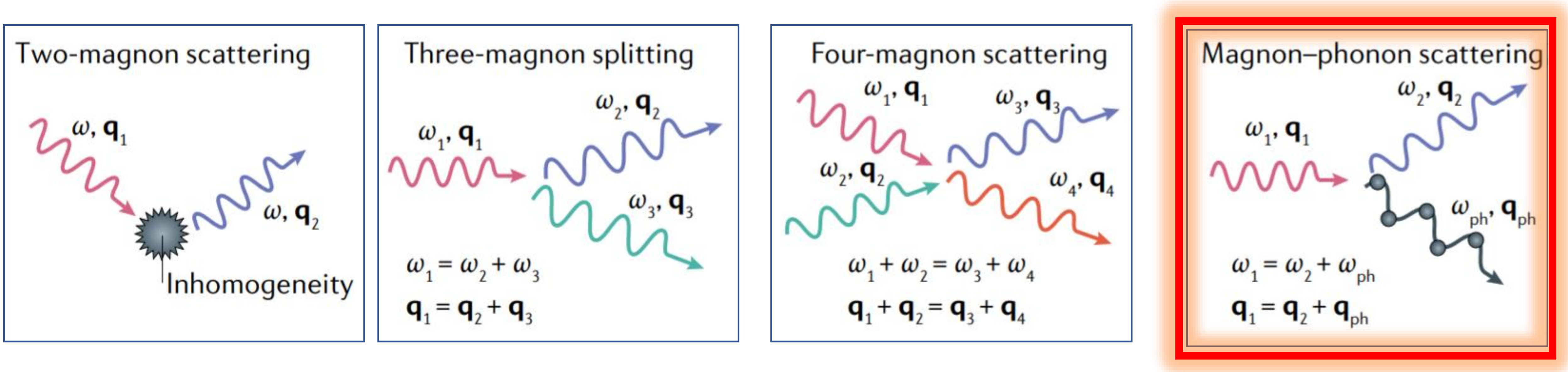


***k*=0 mode**



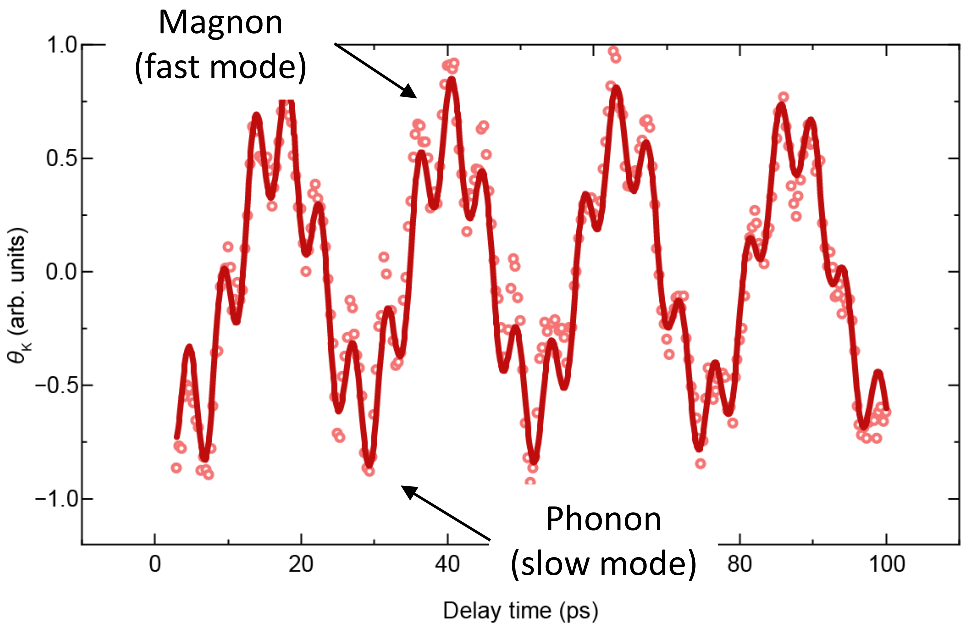
Upon entering in the absorption region damping of *k*=0 mode goes up by nearly 2 orders of magnitude

Origin of the spin-wave damping



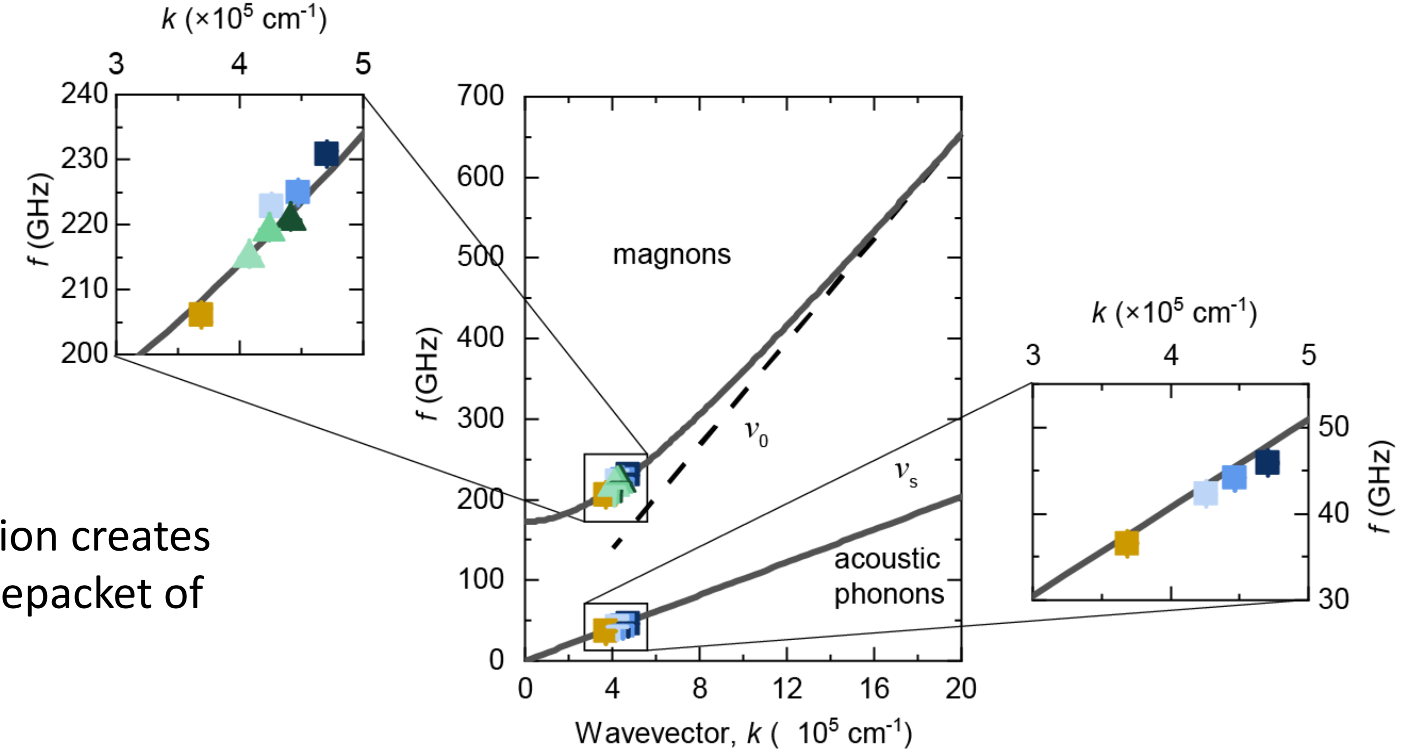
P. Pirro *et. al. Nat. Rev. Mater.* **6,** 1114–1135 (2021)

Simultaneous excitation of a phonon wavepacket


Magnon (fast mode)

Phonon (slow mode)

Ultrashort optical excitation in the absorption region creates not only wavepacket of spin waves but also a wavepacket of acoustic phonons

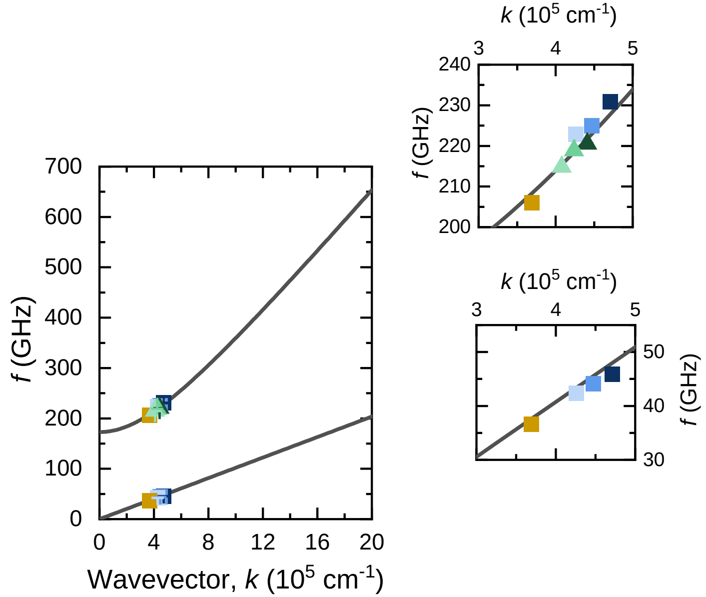


No direct coupling is allowed
(no hybridization)

Simultaneous excitation of a phonon wavepacket

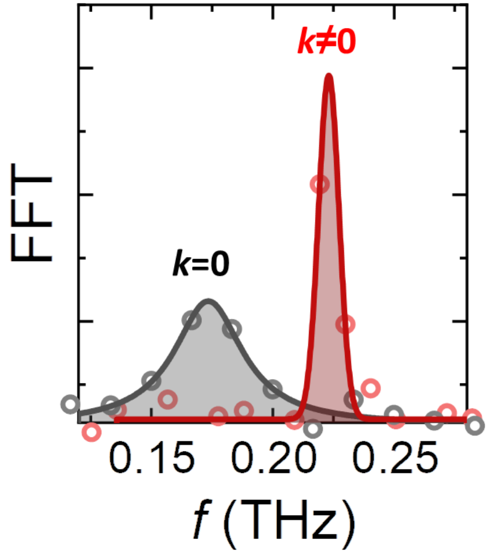
Magnon
(fast mode)

Phonon
(slow mode)



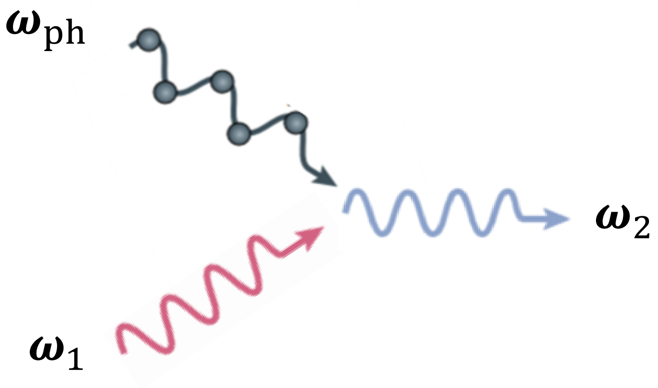
Ultrashort optical excitation in the absorption region creates not only wavepacket of spin waves but also a wavepacket of acoustic phonons

Possible mechanism



Damping of finite *k*-mode
is significantly smaller than *k*=0

Magnon-phonon coupling:

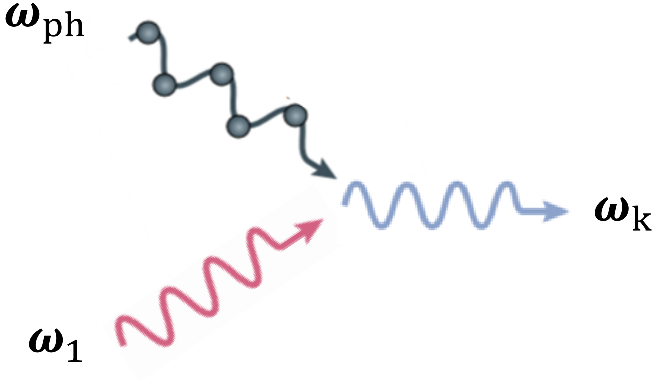


Merging of a phonon ω_{ph} and magnon ω_1
into another magnon ω_2

Why k=0 mode?

Energy and momentum constrains

Magnon-phonon coupling:

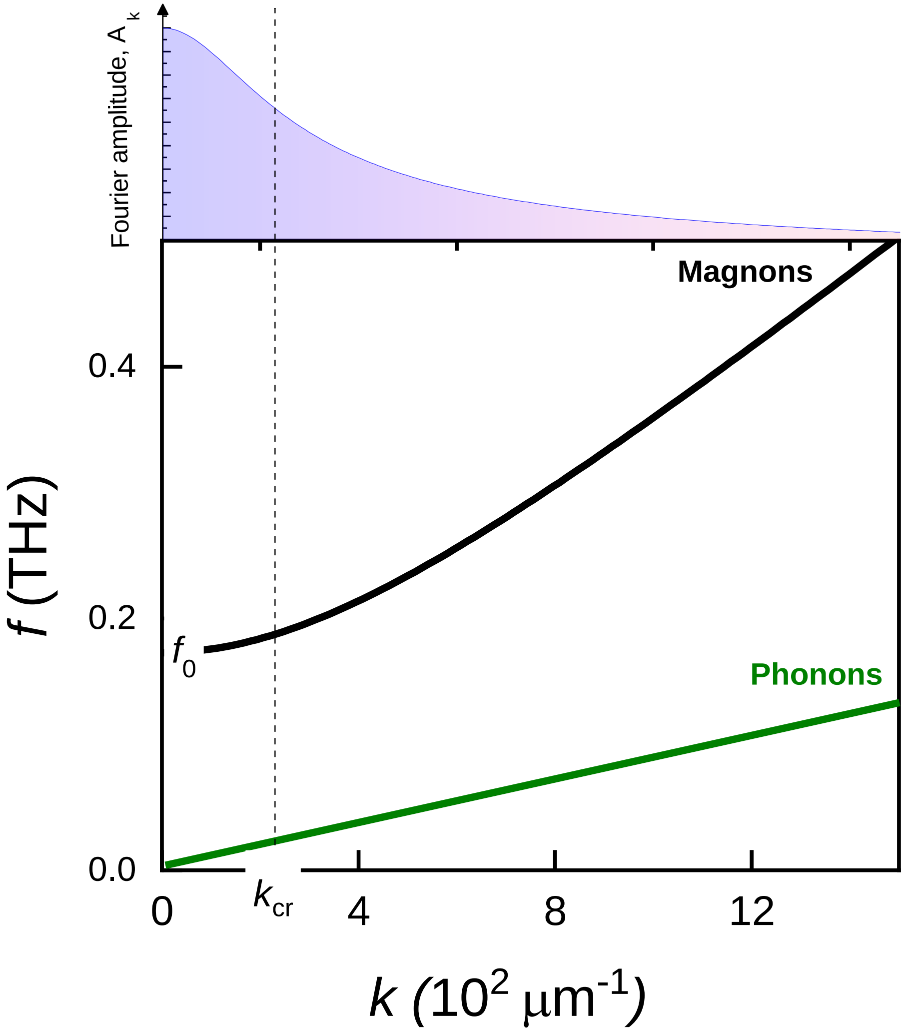


Conservation of
momentum and energy:

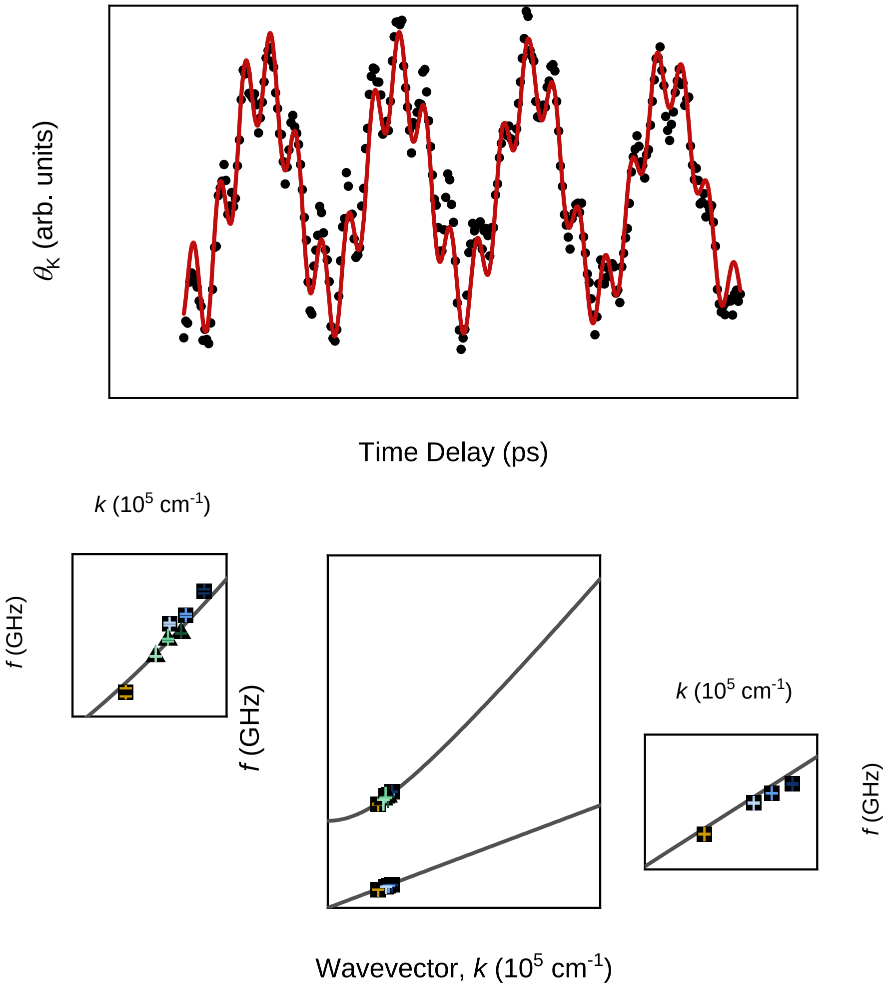
$$\omega_1 + \omega_{ph} = \omega_2$$
$$k_1 + k_{ph} = k_2$$

Fulfilled only if $k_1 < k_{cr} = 2 \cdot 10^2$ μm

$\omega_1 < \omega_{cr} \approx \omega_0$



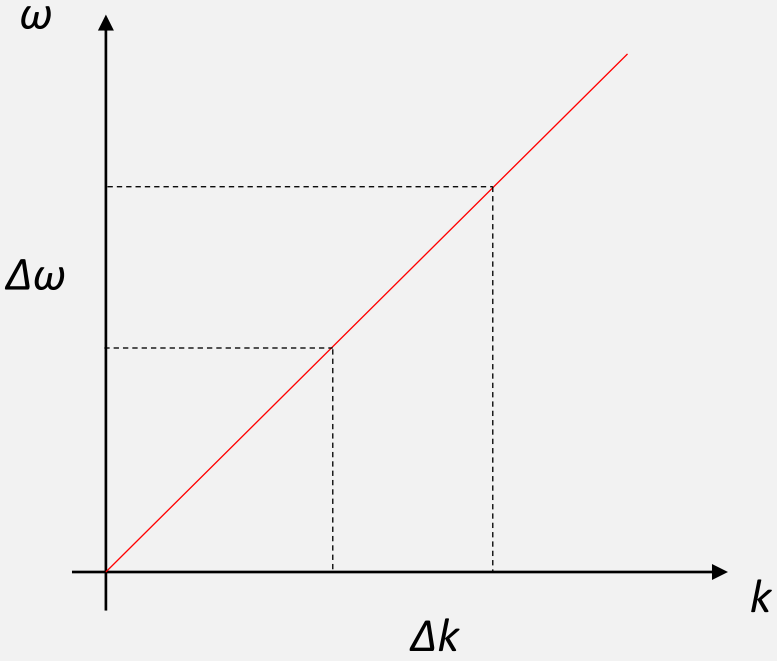
Energy and momentum exchange are allowed only for magnons close to the zone-center


θK (arb. units)
Time Delay (ps)
k (10^5 cm^-1)
f (GHz)
f (GHz)
k (10^5 cm^-1)
f (GHz)
Wavevector, k (10^5 cm^-1)

Outlook

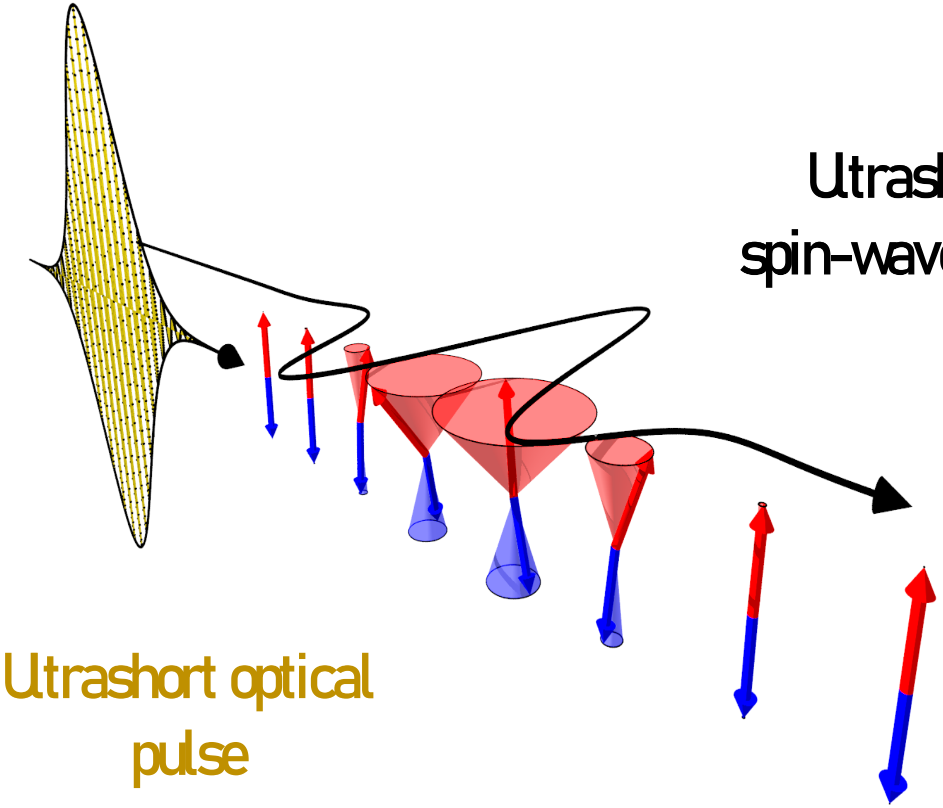
Linear Dispersion relation

(light waves, relativistic particles)



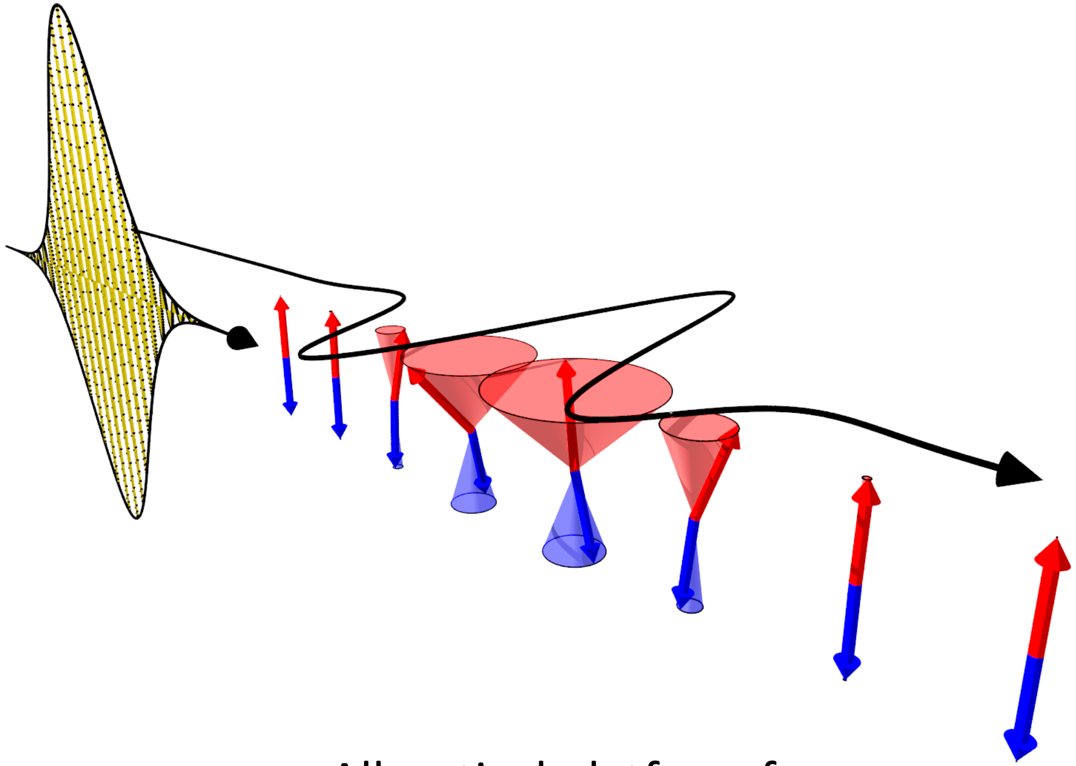
Nondispersive propagation

(Propagation velocity does not depend on w)



Summary

- All-optical excitation of a broadband (>0.2 THz) wavepacket of coherent propagating AFM magnons
- Mechanism is verified in a broad class of rare-earth orthoferrites
- Fingerprints of many-body interactions within the light-driven magnon wavepacket



All-optical platform for
coherent antiferromagnetic magnonics

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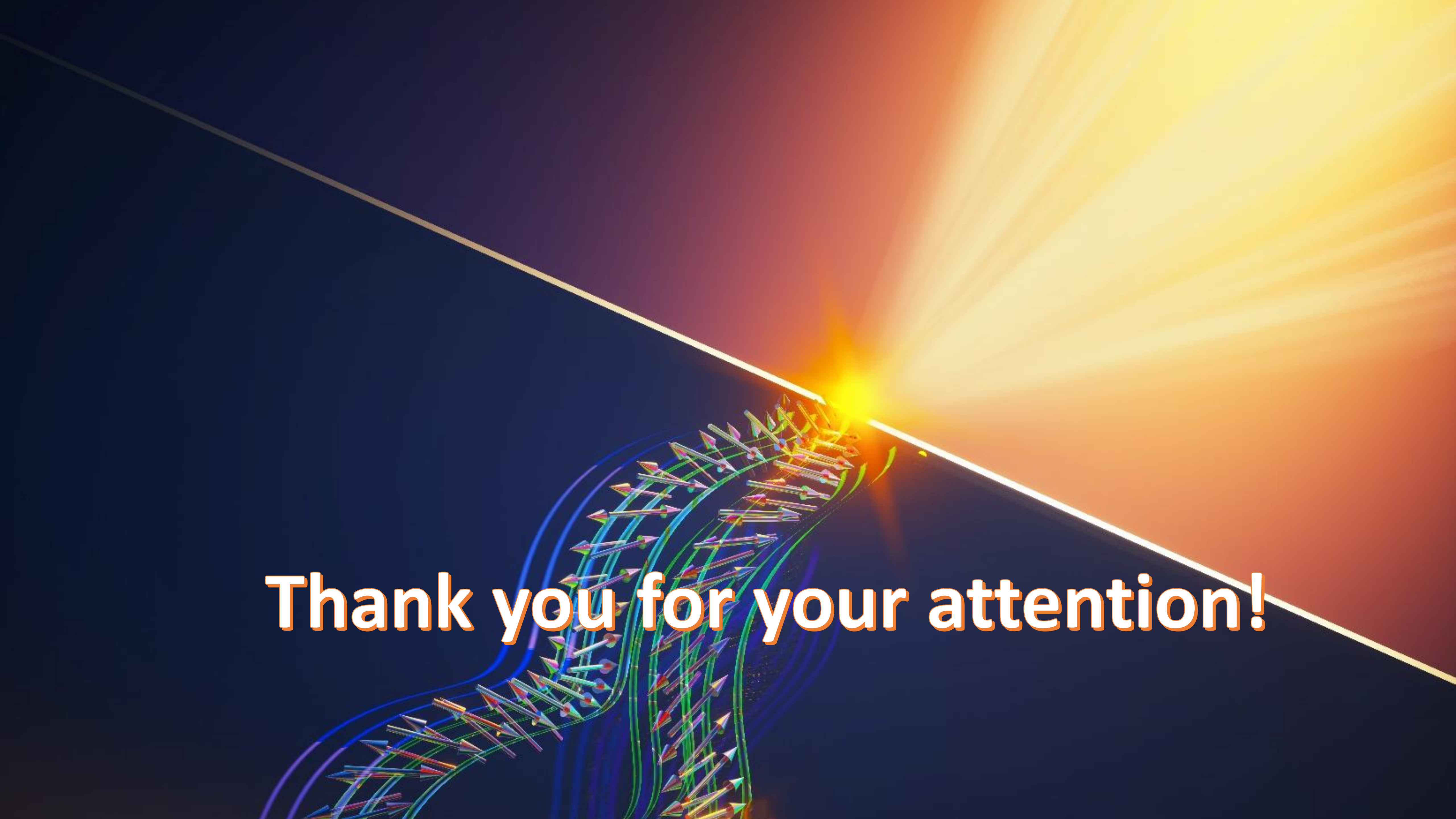
Ruben Leenders



Thank you for your attention!