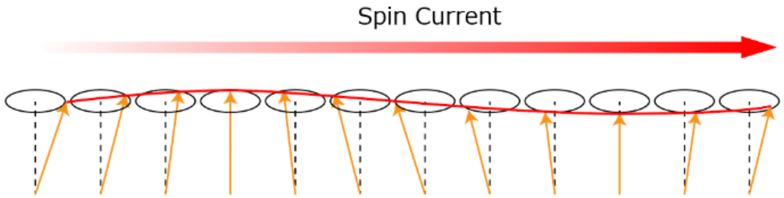
Laser-driven magnetostatic and exchange waves in confined structures

Alexandra Kalashnikova

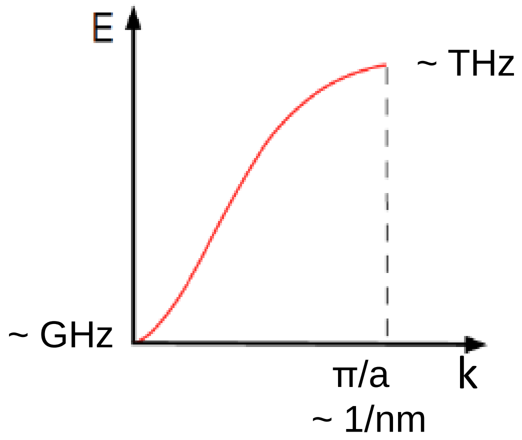
Ferroic Physics Laboratory – Ioffe Institute

SPICE workshop
Spin textures: magnetism meets plasmonics
July 25, 2024

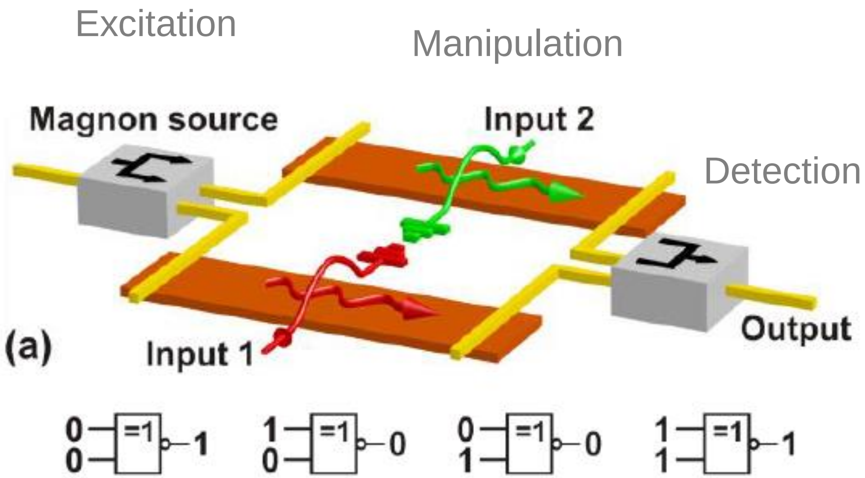
Spin waves (magnons)



Spin wave dispersion in a ferromagnet



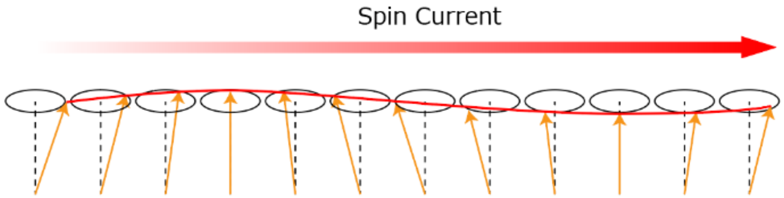
Example: XNOR gate



*[Schneider, et al., APL . **92**, 022505 (2008)]*

Excitation of spin waves

Spin waves (magnons)



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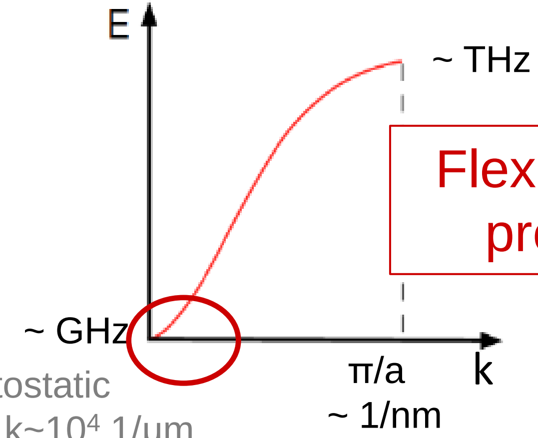
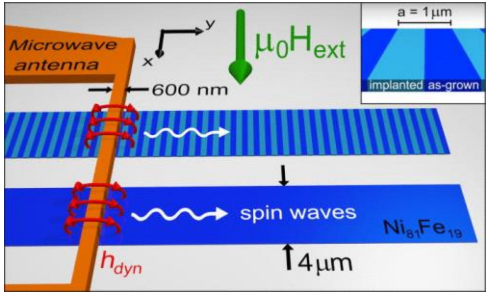


Magnetostatic waves: k~10^4 1/μm

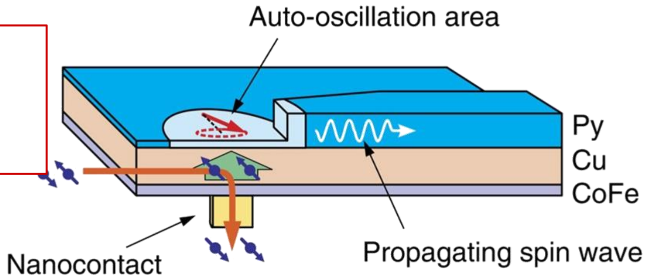
Flexibility & resolution provided by light?

Driving spin waves by ac magnetic field (microscale)



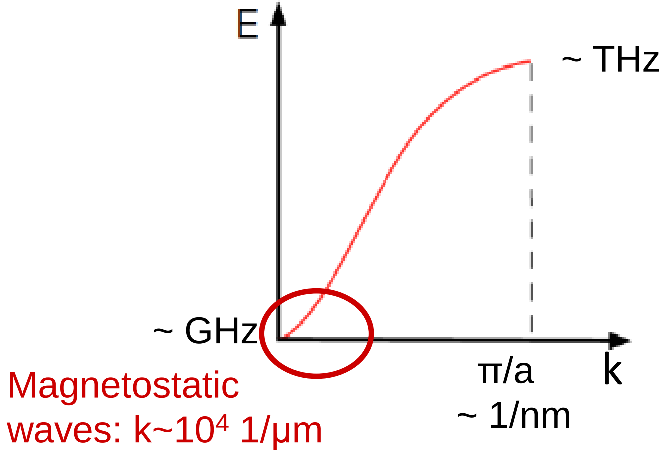
[Obry et al., APL 102, 202403 (2013)]

Driving spin waves by STT (nanoscale)

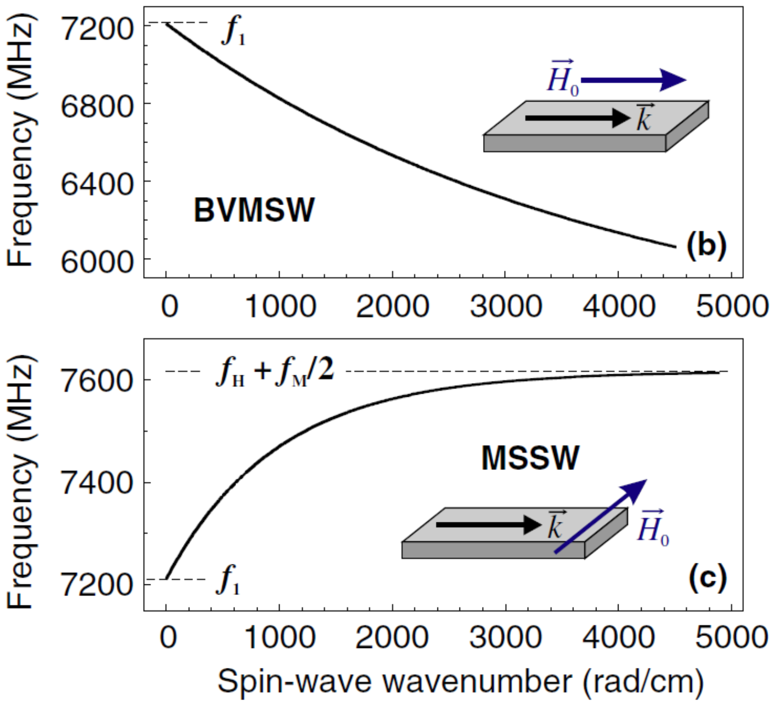


*[Demidov et al., Nature Comm. **7**, 10446 (2016)]*

Magnon dispersion in a ferromagnet



Magnetostatic waves



*[Serha et al., J. Phys. D **43**, 264002 (2010)]*

Backward Volume MagnetoStatic Wave

$$f_{BVMSW} = \sqrt{f_H\left(f_H + f_M\frac{1-e^{-kd}}{kd}\right)}$$

MagnetoStatic Surface Wave

$$f_{MSSW} = \sqrt{(f_H + 0.5f_M)^2 - (0.5f_M)^2 e^{-2kd}}$$

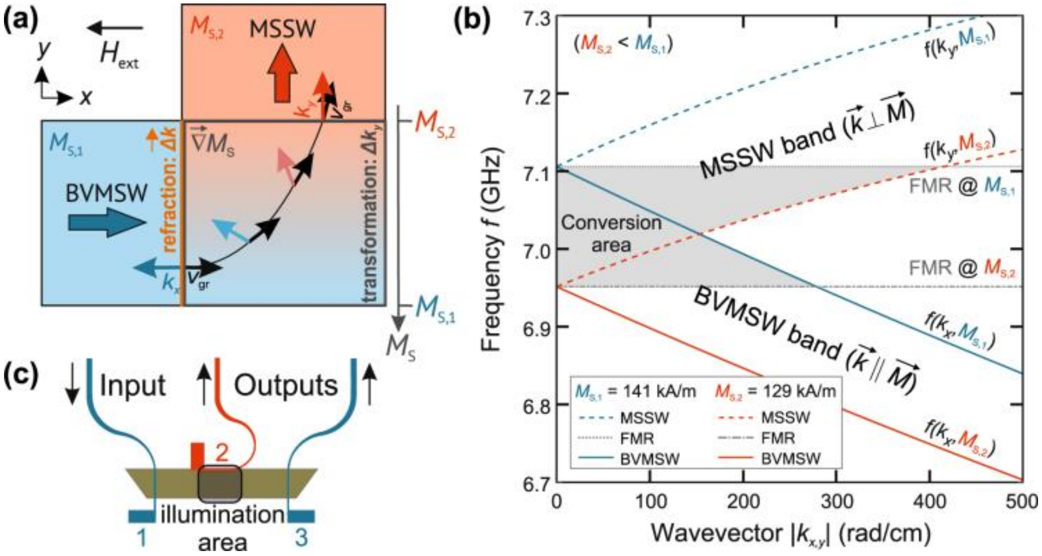
$$f_H = \gamma H_0 \qquad f_M = \gamma\mu_0 M_S$$

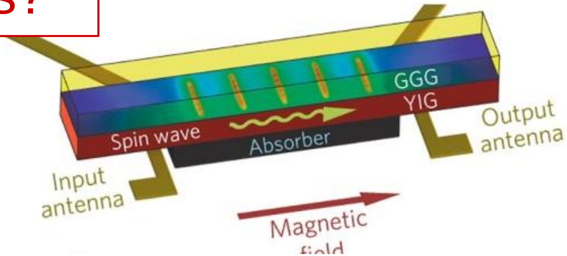
Steering spin waves by gradient illumination

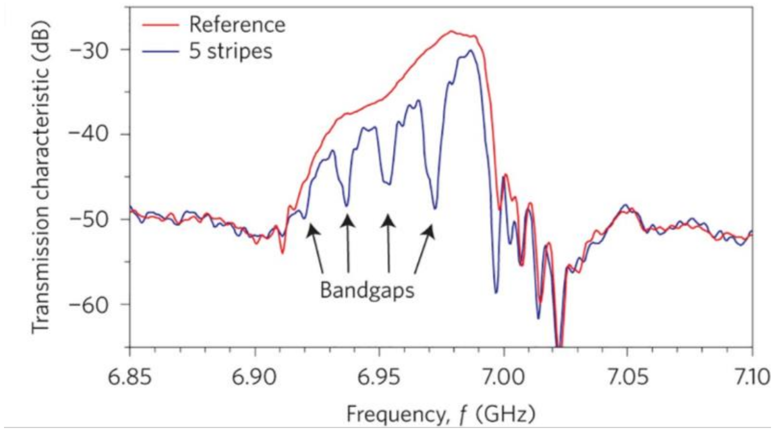
Laser-induced magnonic crystals

Ultrafast opto-magnonics?

BVMSW → MSSW

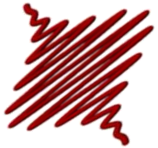




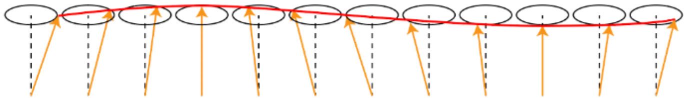


[Vogel et al., Sci. Rep. **8**, 11099 (2018); Fetisov et al., JAP 79, 5721 (1996)]

[Vogel et al., Nature Phys. **11**, 487 (2015)]



Light frequency: 10^6 GHz

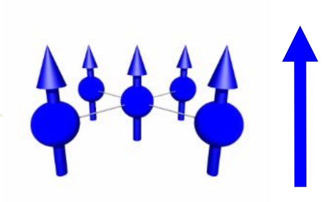


μ=1 at light frequency

Magnetic resonances: 1 GHz- 10^4 GHz

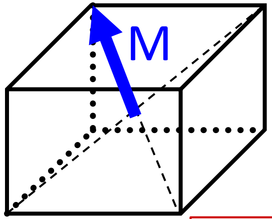
Interactions in a magnetic medium

Exchange coupling

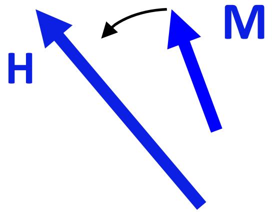


$$\mathbf{M} = \frac{1}{V}\sum \mathbf{m}_i$$

Spin-orbital coupling

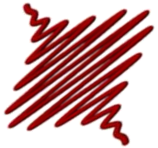


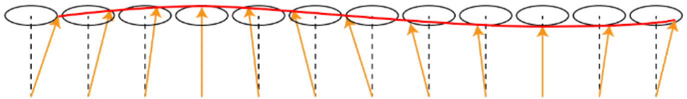
Zeeman coupling



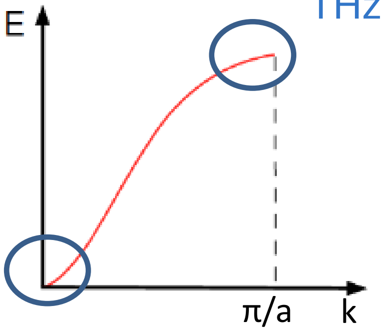
Light as an effective field pulse

Light as an ultrafast heater





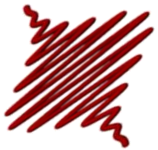
THz exchange waves

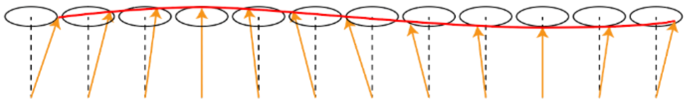


GHz magnetostatic waves

Generation of GHz spin waves
with tunable parameters

Generation of THz magnons
at the edge of BZ





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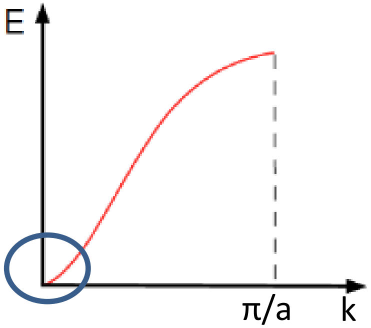

Generation of THz magnons
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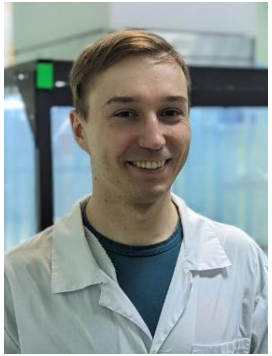
GHz magnetostatic waves

Nikolay Khokhlov

Petr Gerevenkov



Iaroslav Filatov

In collaboration with
Nikolai Pertsev, Andrey Azovtsev (Ioffe)
Andrew Rushforth (U Nottinham)
Alexey Scherbakov (TU Dortmund)

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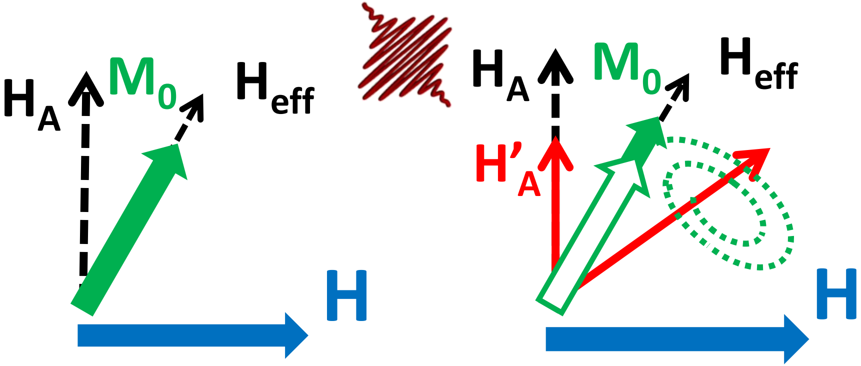


Effective magnetic anisotropy field

$$\mathbf{H}_A = \frac{2K}{M_S}\mathbf{m}$$

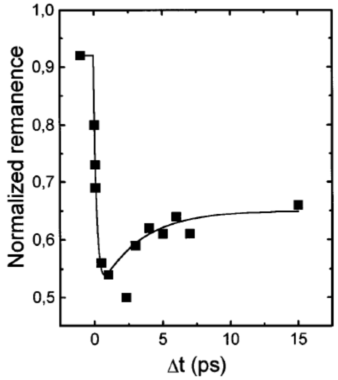
Magnetization and anisotropy vs. temperature

at equilibrium

$$\frac{K(T)}{K(0)} = \left(\frac{M_S(T)}{M_S(0)}\right)^{\frac{n(n+1)}{2}}$$

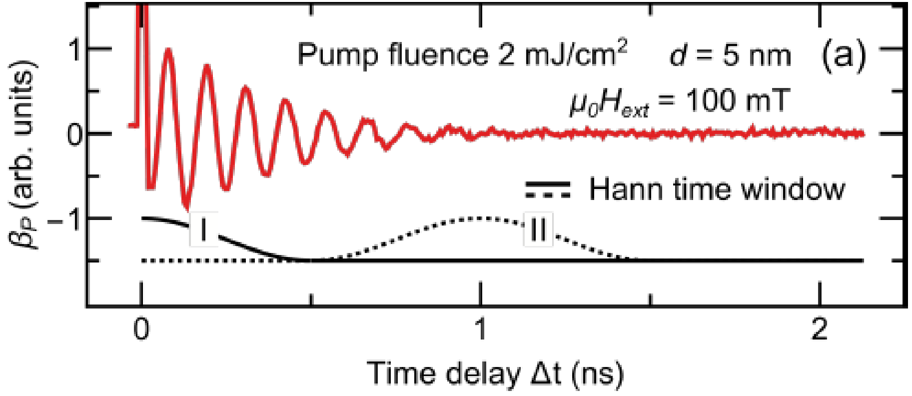
*[Callen and Callen, J. Phys. Chem. Solids **16**, 310 (1960)]*

Ni

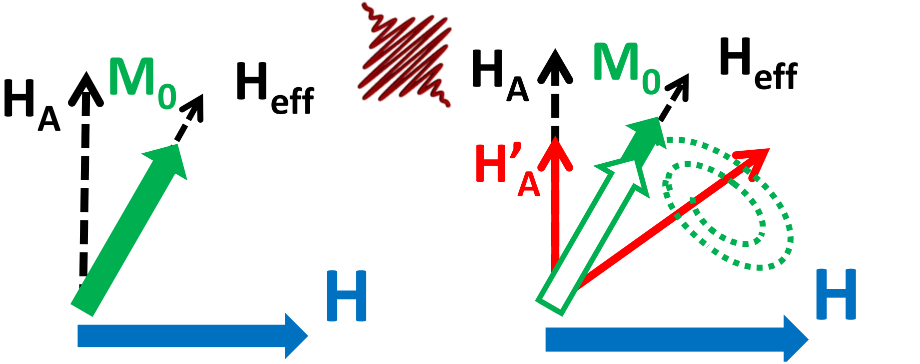


*[Beaurepaire et al., PRL **76**, 4250 (1996)]*

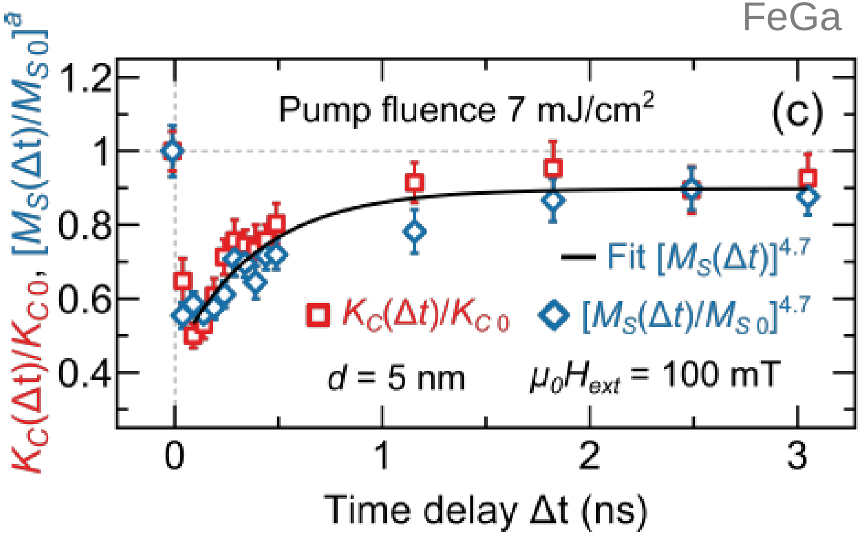
FeGa



*[Gerevenkov et al., PR Mater. **5**, 094407 (2021)]*



FeGa



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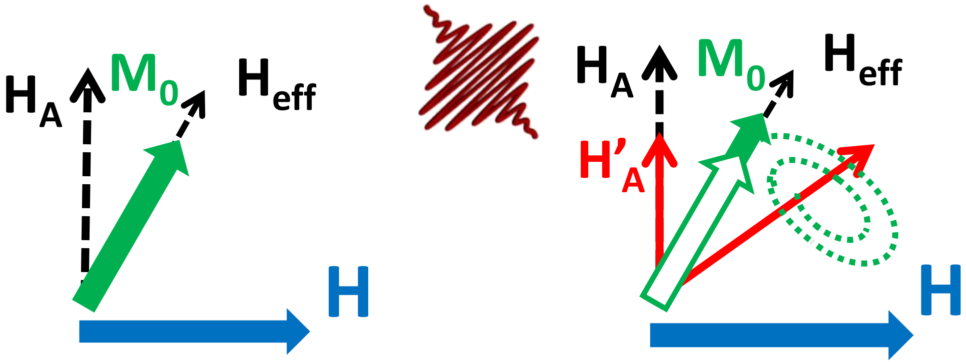
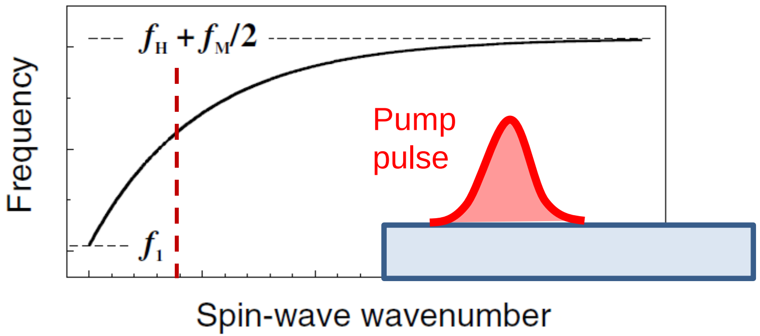
[Callen and Callen, J. Phys. Chem. Solids ***16****, 310 (1960)]*

- ✓ Magnetocrystalline
- ✓ Growth-, Strain-, Shape-induced
- ✓ Interfacial

[Review: Kalashnikova et al., Tech. Phys. ***68****, 574 (2023)]*

Ultrafast excitation of magnetostatic waves

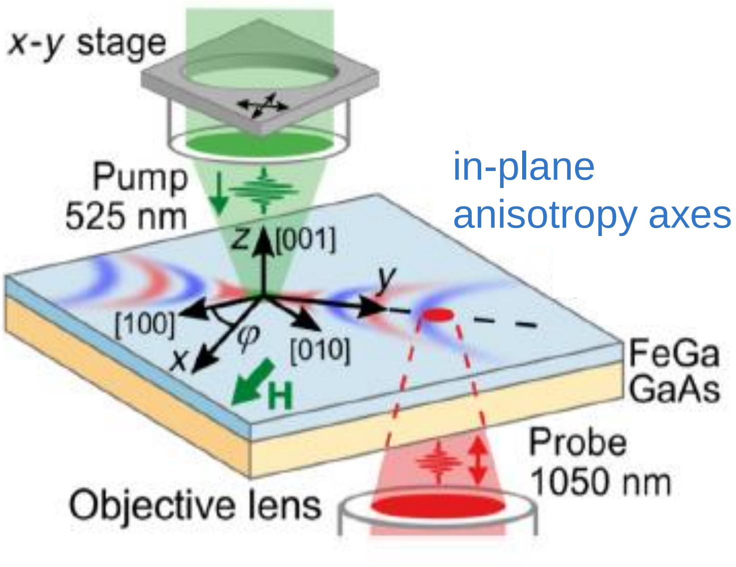




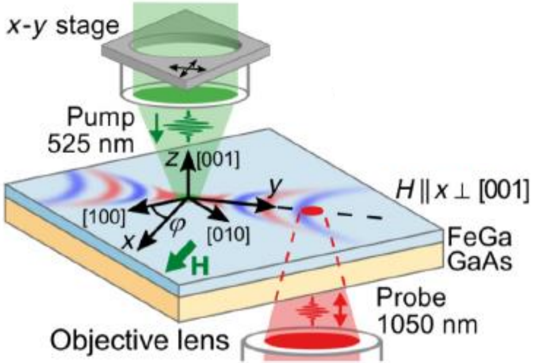
Pulse duration limits frequency → ~THz

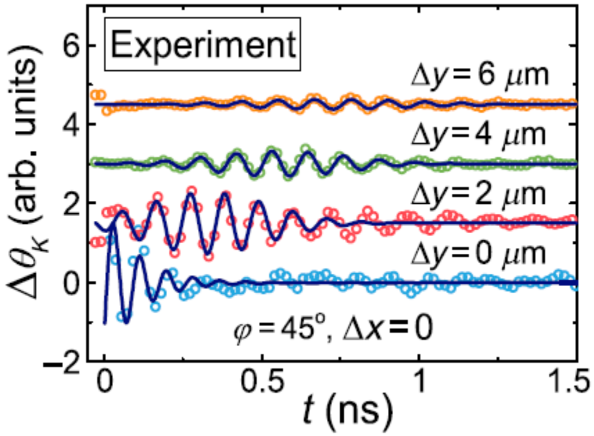
Pulse focusing limits wavevectors → ~1/μm

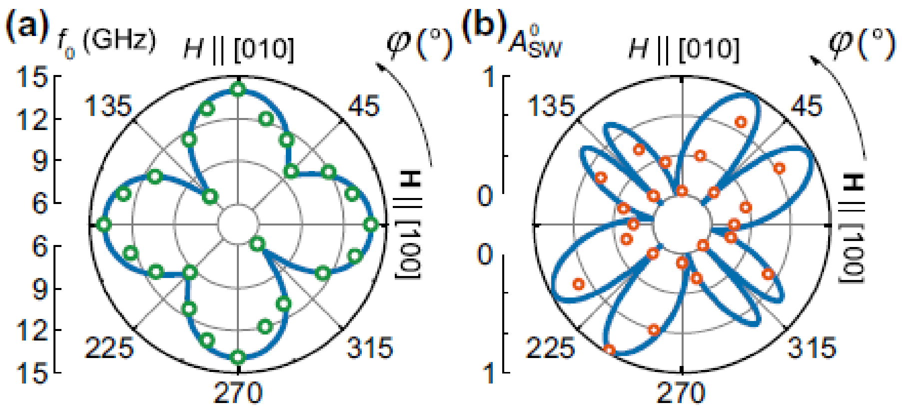
Experiment



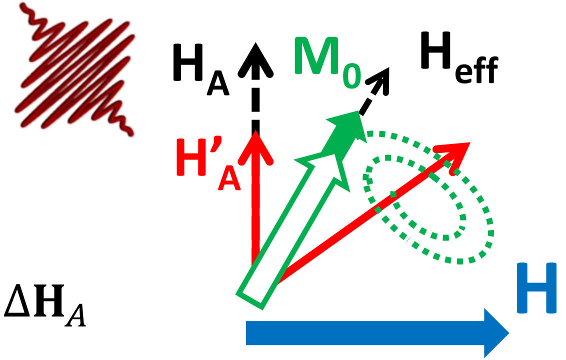
[Khokhlov et al, PR Appl. **12**, 044044 (2019)]



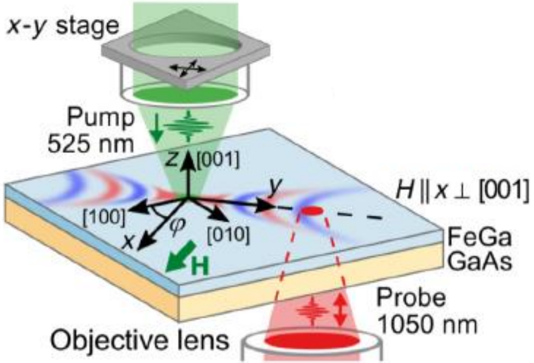


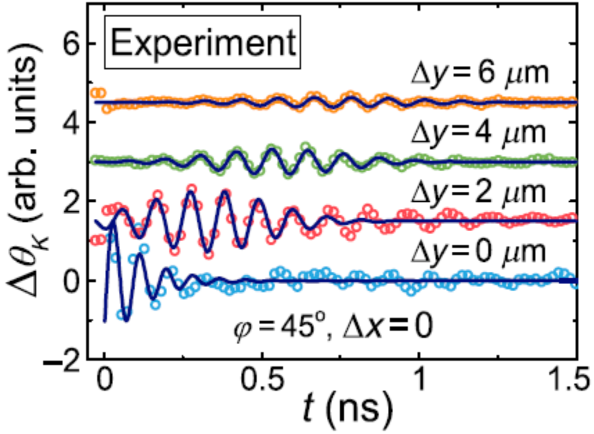


$$\mathbf{T}(t = 0) = -\gamma \mathbf{M} \times \Delta \mathbf{H}_A$$



[Khokhlov et al, PR Appl. **12**, 044044 (2019)]

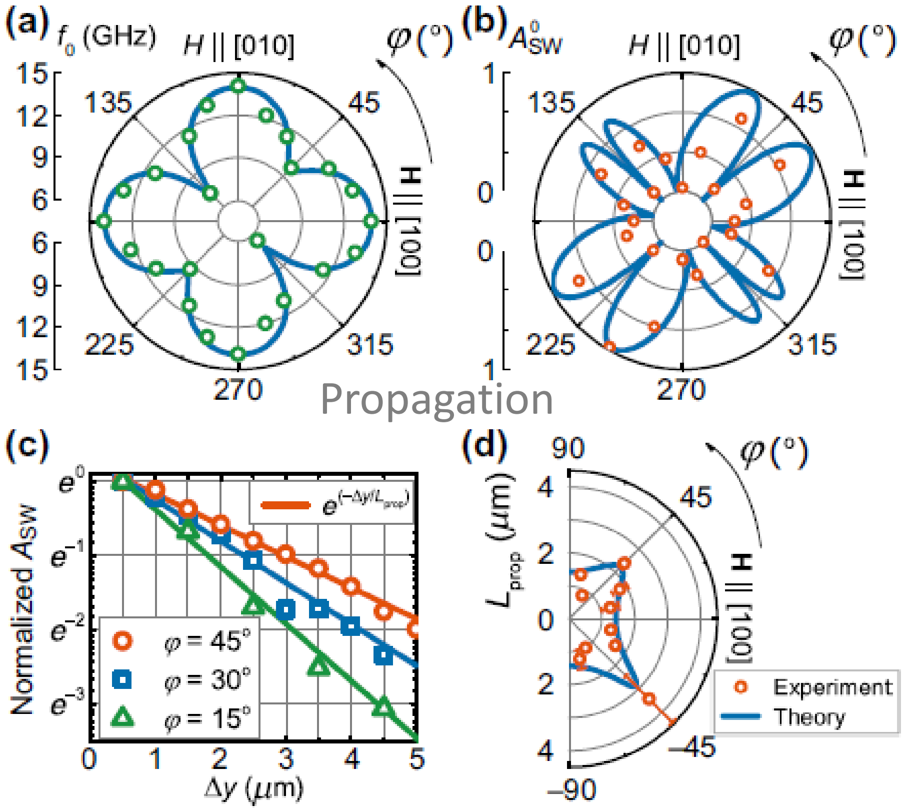




Frequency

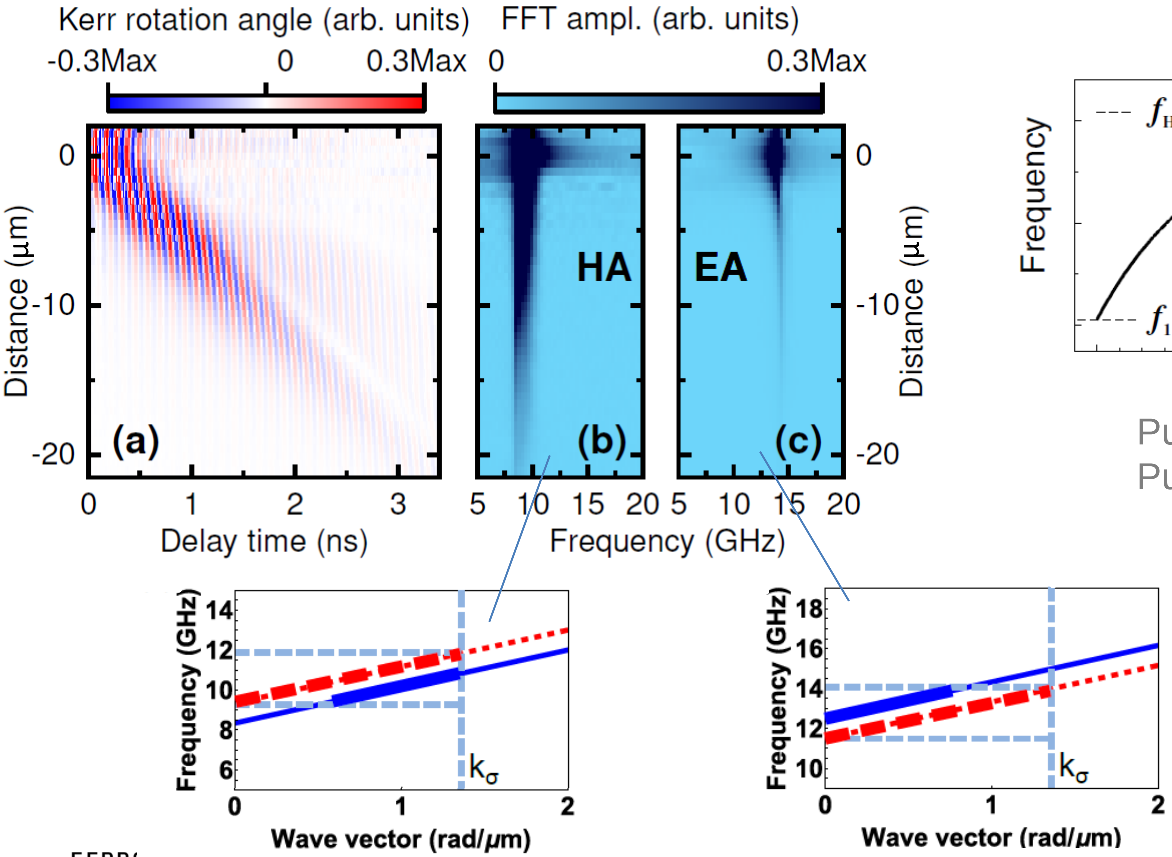
Amplitude

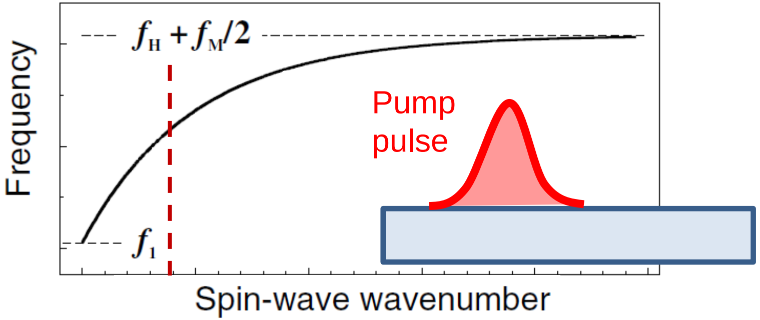
Propagation



[Khokhlov et al, PR Appl. **12**, 044044 (2019)]

Spectrum narrowing





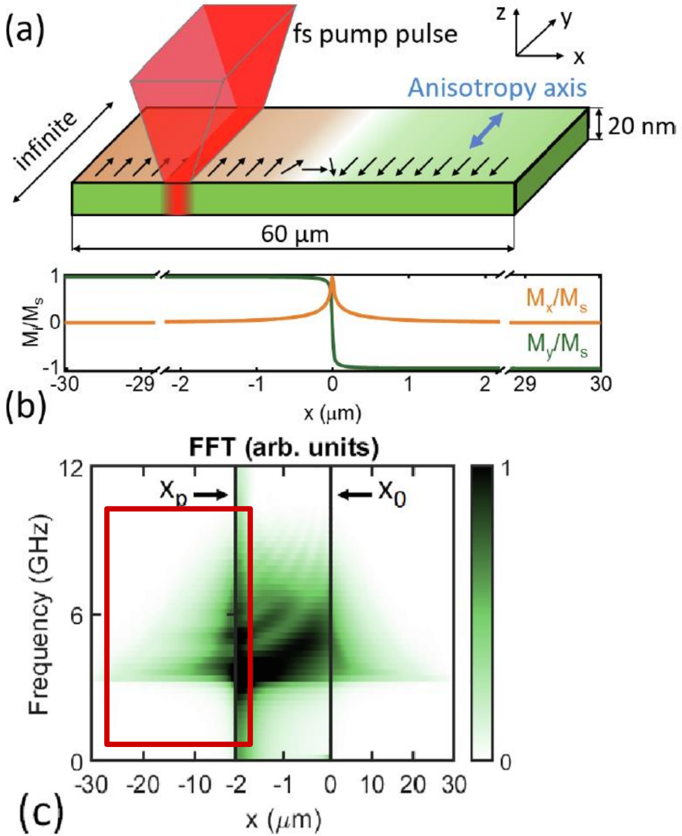
Pulse duration limits frequency → ~THz
Pulse focusing limits wavevectors → ~1/μm

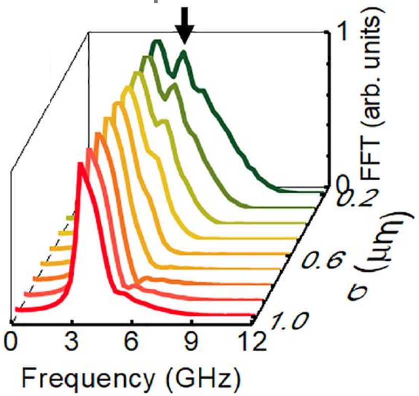
*[Filatov et al., APL **120**, 112404 (2022)*
*Filatov et al., JPCS **1697**, 012193 (2020)]*

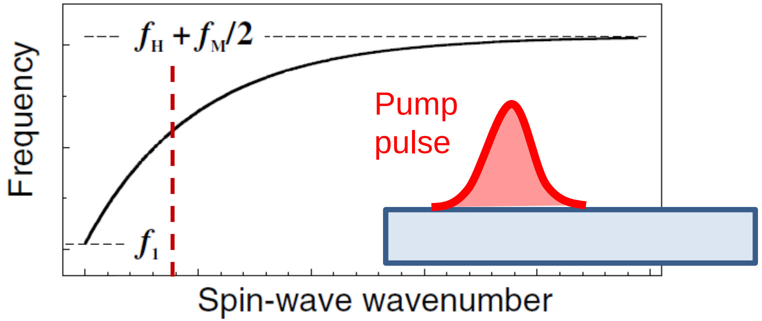
Tunable source and filter of MSW

Spectrum controlled by

laser spot size



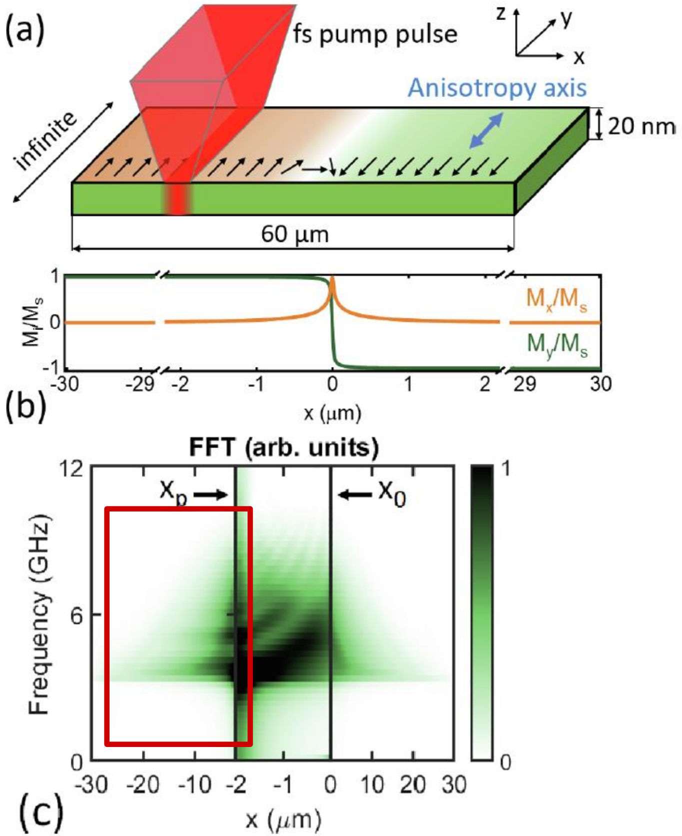




[Khokhlov et al., JMMM **534**, 168018 (2021)]

Ultrafast excitation and control of magnetostatic waves

Tunable source and filter of MSW



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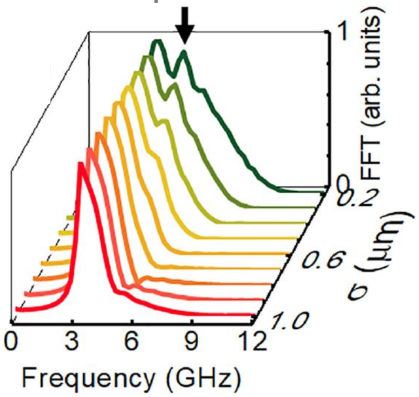
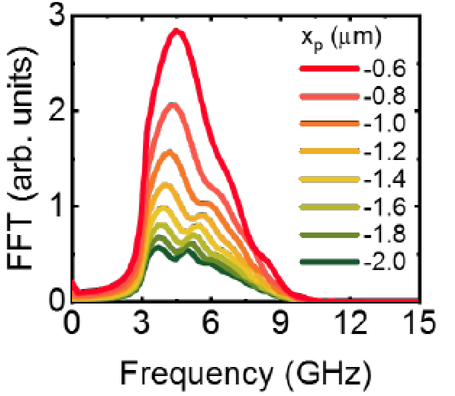


DW-laser spot distance



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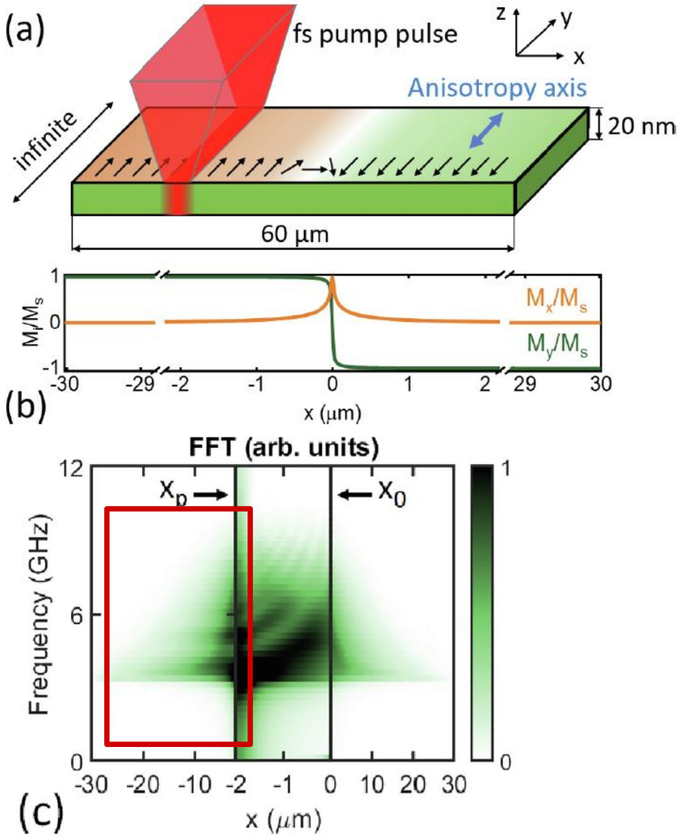

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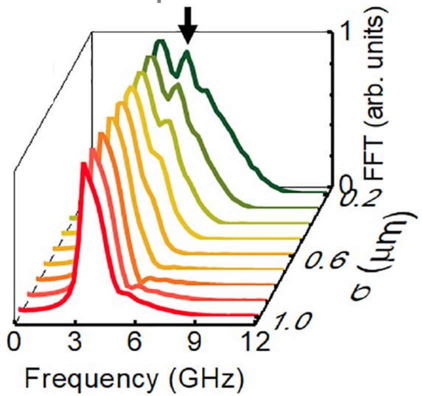

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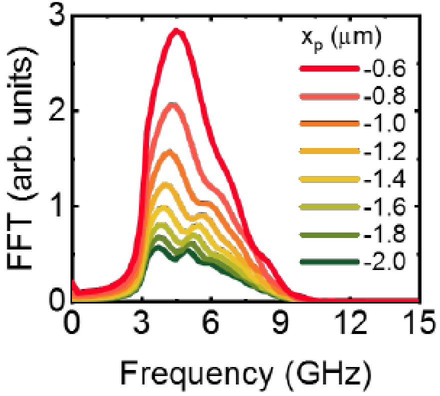
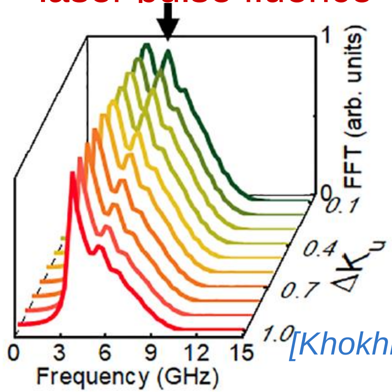
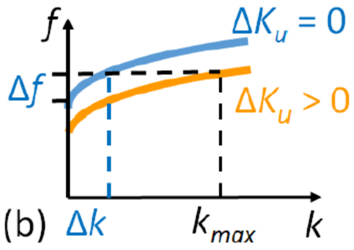


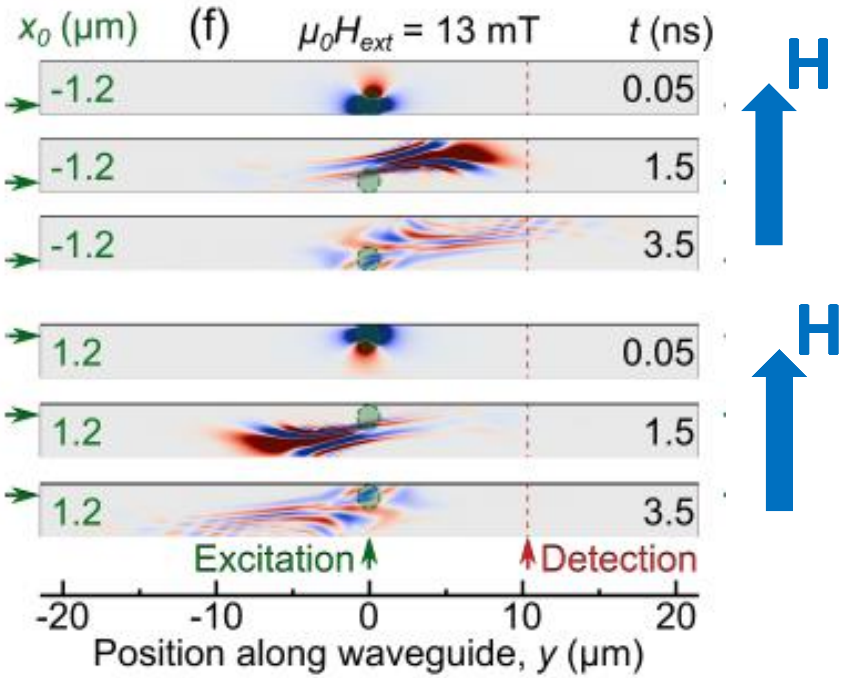
laser pulse fluence

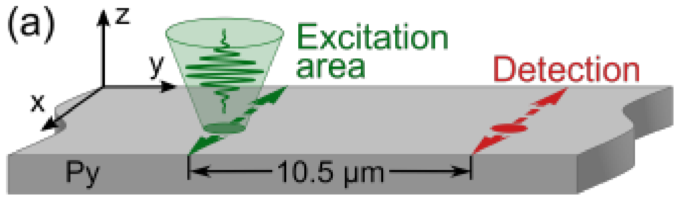


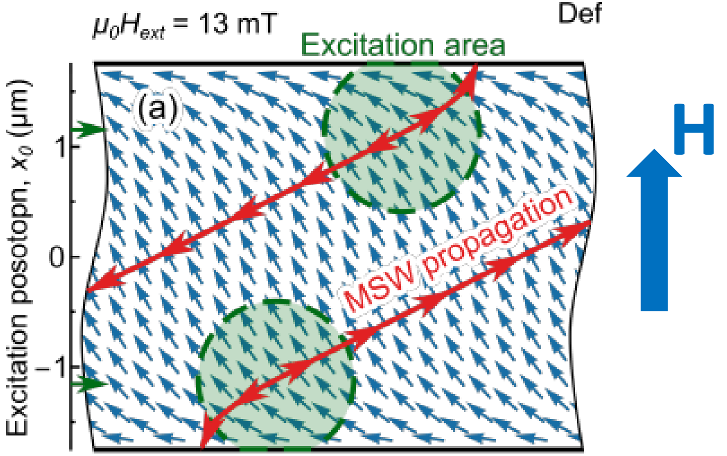


*[Khokhlov et al., JMMM **534**, 168018 (2021)]*

Source of unidirectional MSW



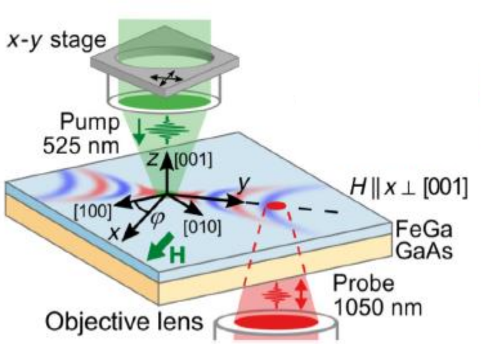


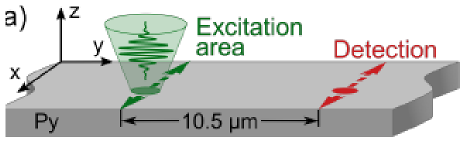


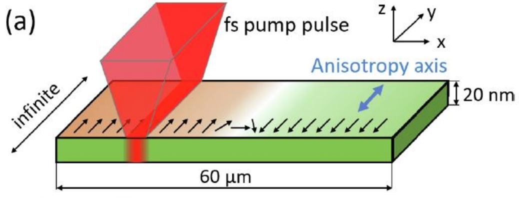
[Gerevenkov et al., PR Appl. **19** 024062 (2023)]

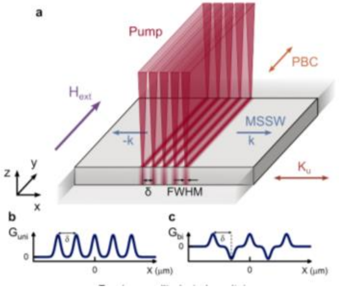
- ✓ MSW is excited by ultrafast local heating
- ✓ Frequency, amplitude and propagation are controlled by applied field direction *(total effective field)*
- ✓ Laser-induced MSW + spin texture enable control of their spectrum and propagation

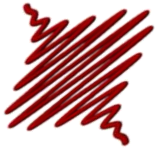
Khokhlov et al, PR Appl. ***12****, 044044 (2019)*
Filatov et al., APL ***120****, 112404 (2022)*
Khokhlov et al., JMMM ***534****, 168018 (2021)*
Khokhlov et al., JMMM ***589****, 171514 (2024)*
Gerevenkov et al., PR Appl. ***19*** *024062 (2023)*
Filatov et al., JAP (accepted), arXiv:2404.17889

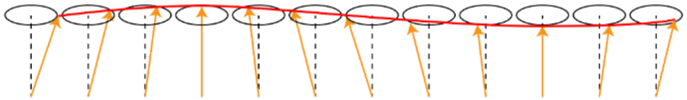












Generation of GHz spin waves
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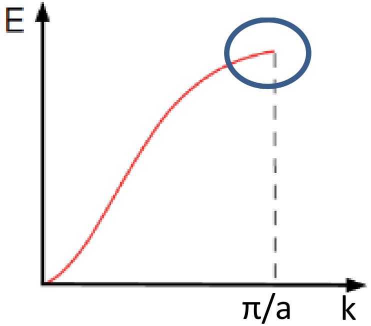
THz exchange waves



Generation of THz magnons
at the edge of BZ

Anatolii Fedianin

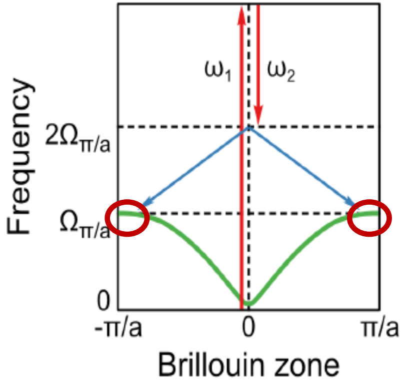
Generation of GHz spin waves with tunable parameters

Generation of THz magnons at the edge of BZ

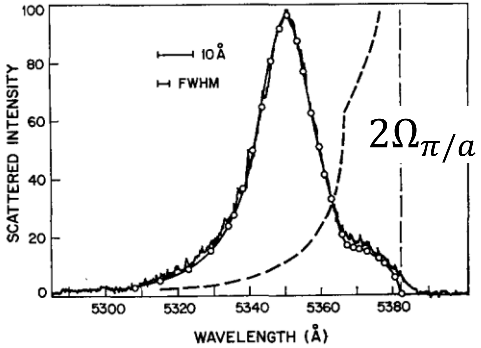
In collaboration with
Johan Mentink, Alexey Kimel (Radboud U)
Roman Dubrovin, Roman Pisarev (Ioffe)

Magnons at the edge of BZ

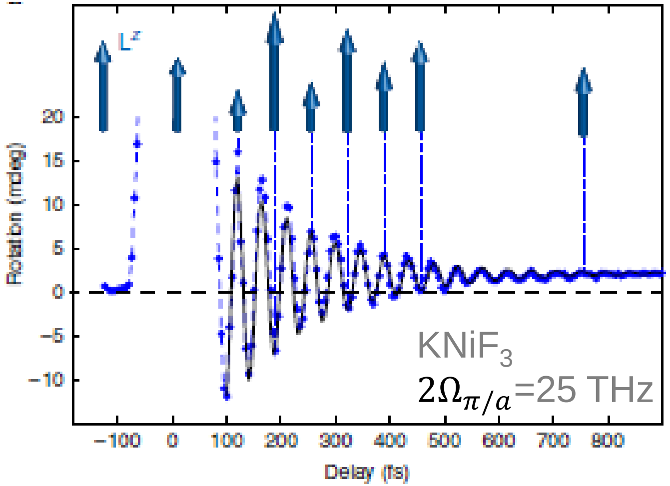
Two-magnon mode in antiferromagnets

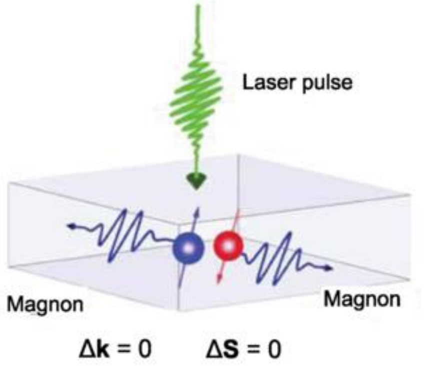


Raman scattering spectrum



Excitation of an antiferromagnet by fs laser pulse





[Bossini et al., Nature Commun. ***7****, 10645 (2016); PRB* ***100****, 024428 (2019)]*

What oscillates?
How is it excited and detected?
Selection rules for excitation?

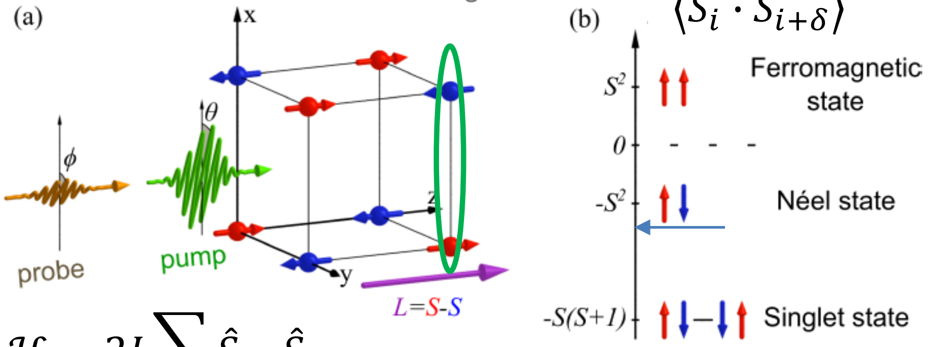
Laser-induced perturbation of exchange coupling

Model

Heisenberg antiferromagnet

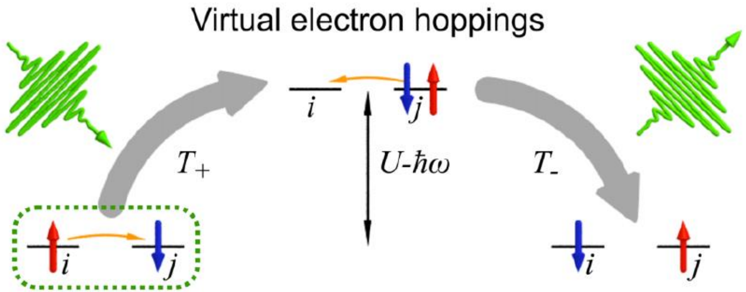
Spin correlation

$\langle \hat{S}_i \cdot \hat{S}_{i+\delta} \rangle$



$$\mathcal{H} = 2J \sum_{i,\delta} \hat{S}_i \cdot \hat{S}_{i+\delta}$$

Excitation



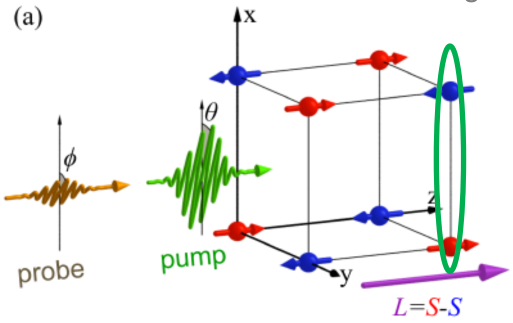
Perturbation of exchange along one bond: ΔJ

[Fediannin, et al., PRB **107**, 144430 (2023)]

Laser-induced spin correlations dynamics

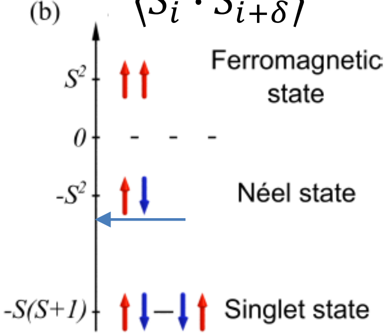
Model

Heisenberg antiferromagnet

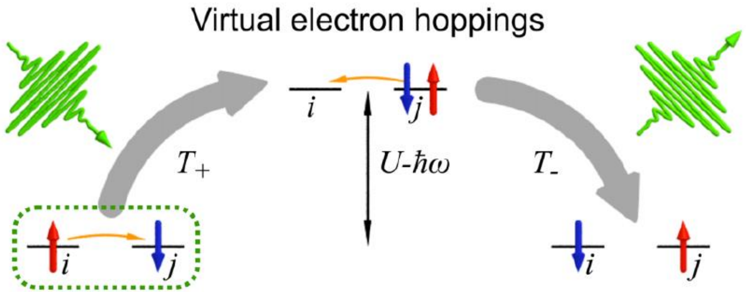


Spin correlation

$$\langle \hat{S}_i \cdot \hat{S}_{i+\delta} \rangle$$

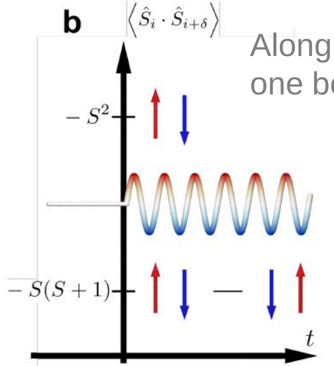


Excitation

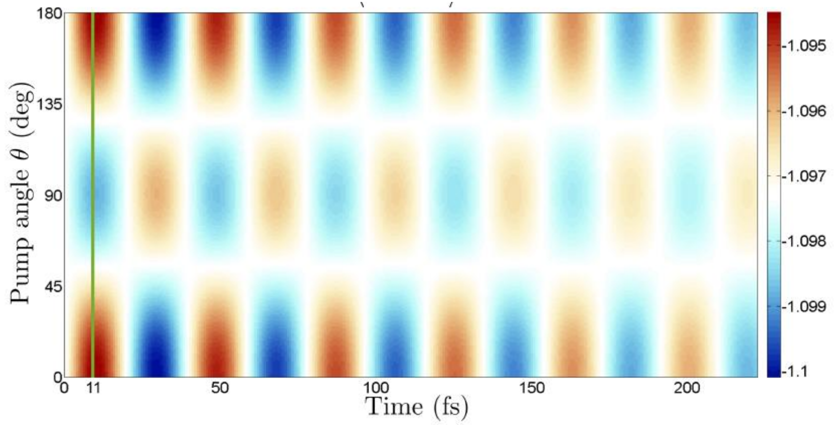


Perturbation of exchange along one bond: ΔJ

Laser-driven spin correlation



Along one bound

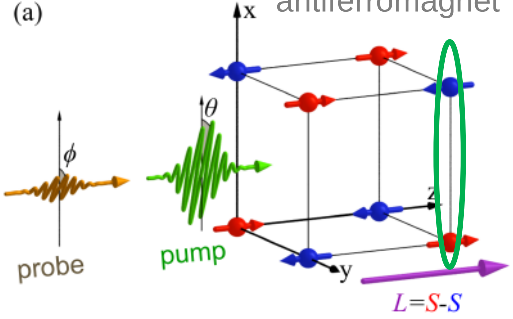


*[Fedianin, et al., PRB **107**, 144430 (2023)]*

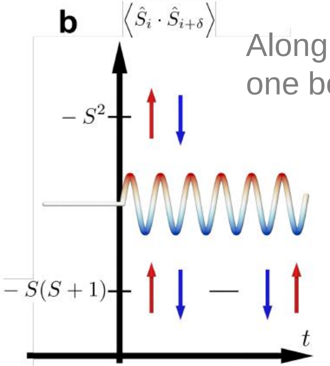
Laser-induced spin correlations dynamics and macroscopical values

Model

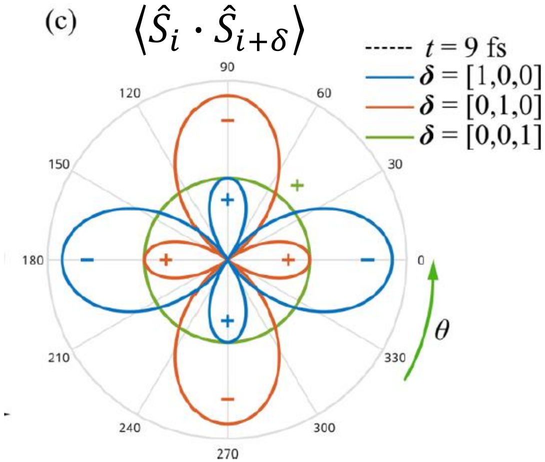
Heisenberg antiferromagnet



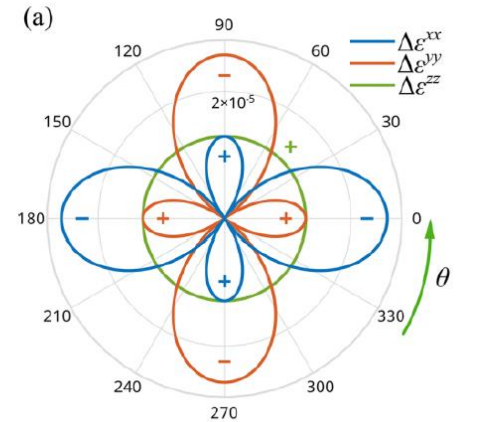
Laser-driven spin correlation



Along one bound



Modulation of dielectric permittivity

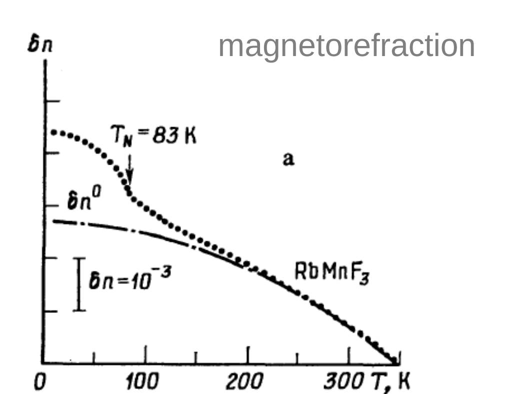


Not a dynamics of L!

$$\langle L^z \rangle \propto \sum_{i,\delta} \langle \hat{S}_i^z \cdot \hat{S}_{i+\delta}^z \rangle$$

$$\langle \varepsilon^{xx} \rangle \propto J \sum_{i,\delta} \langle \hat{S}_i \cdot \hat{S}_{i+\delta} \rangle \delta^x \delta^x$$

magnetorefraction

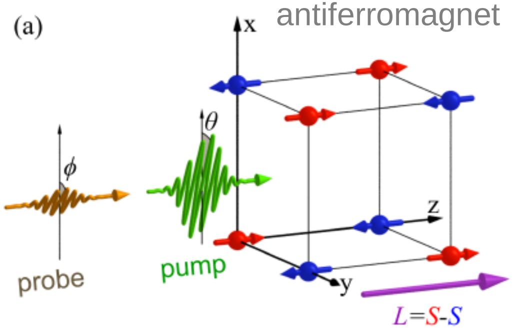


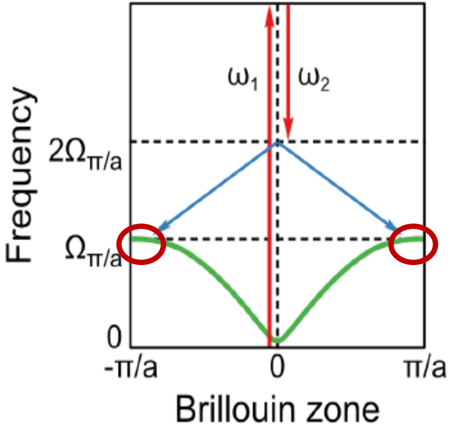
*[Krichevtsov et al., Sov. Phys. JETP **59**, 1316 (1984)]*

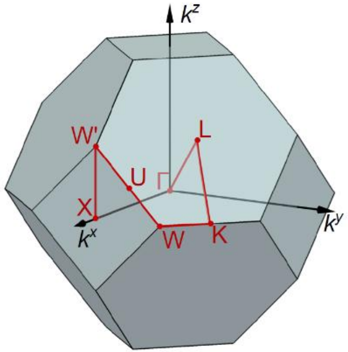
Laser-induced spin correlations and wavevector selectivity

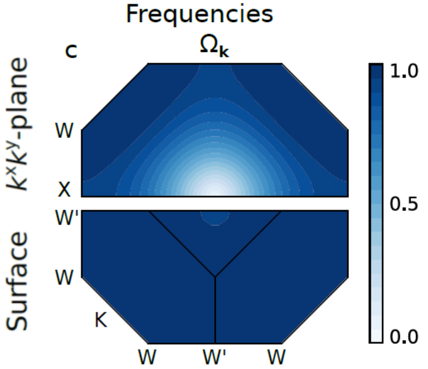
Model

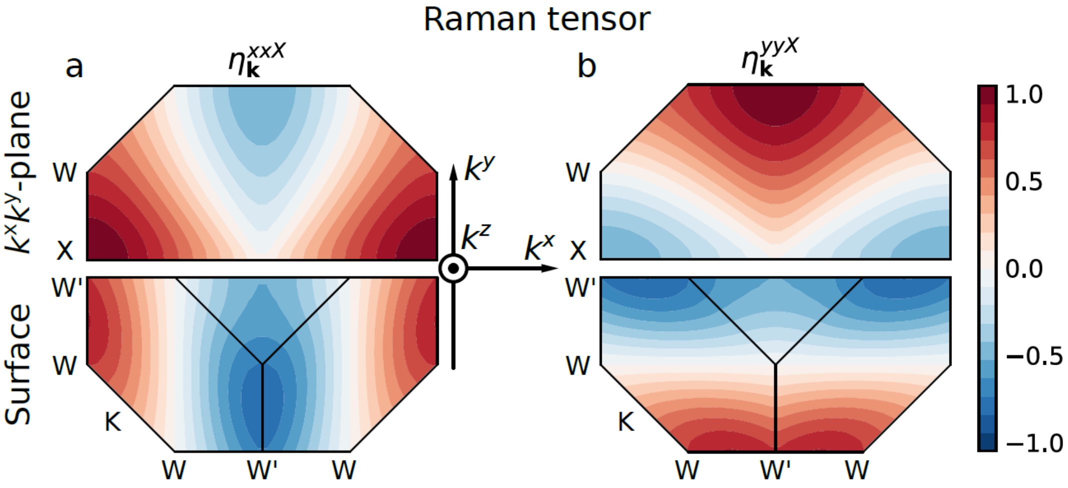
Heisenberg antiferromagnet









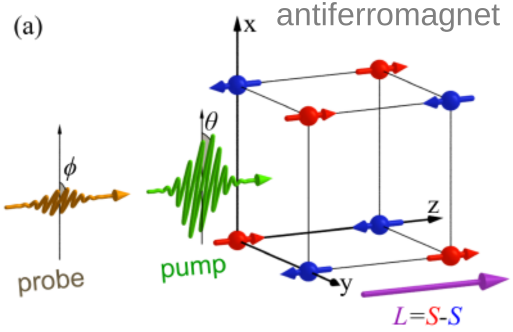


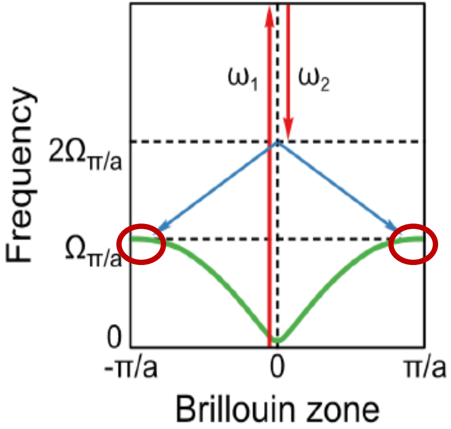
[Fedianin, et al., arXiv:2407.15962]

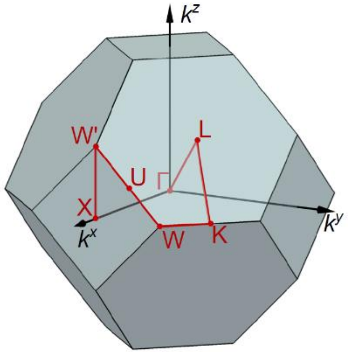
Laser-induced spin correlations and wavevector selectivity

Model

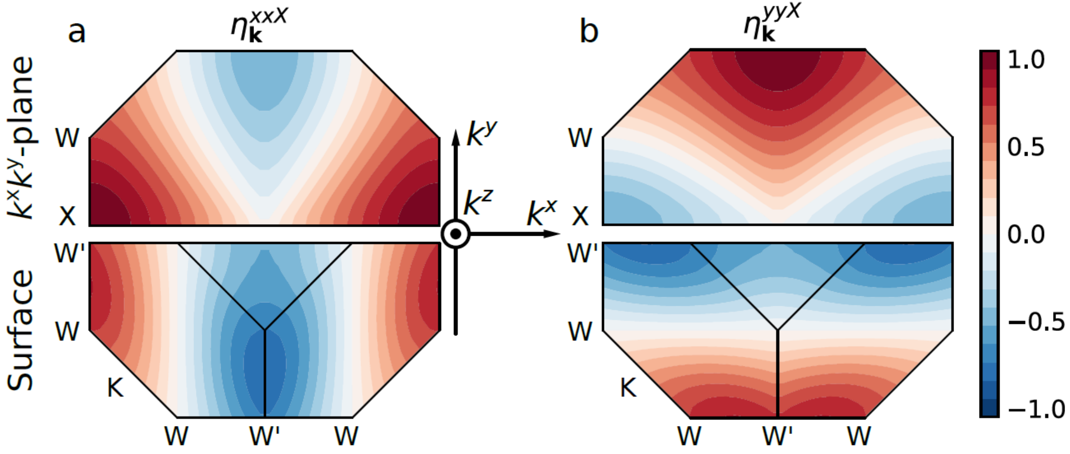
Heisenberg antiferromagnet







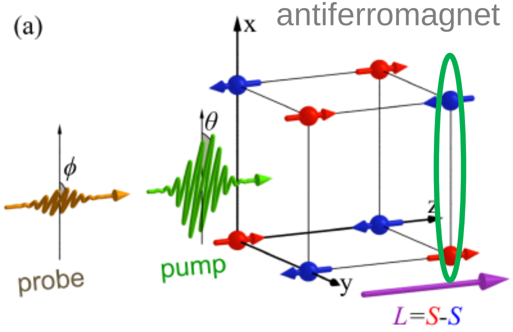
Light with different polarizations couples to two-magnon modes in different parts of BZ

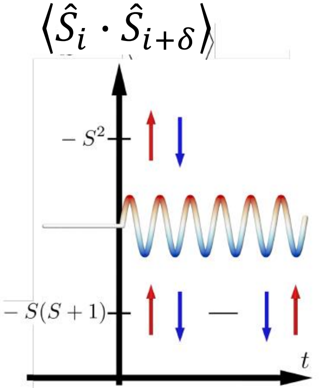


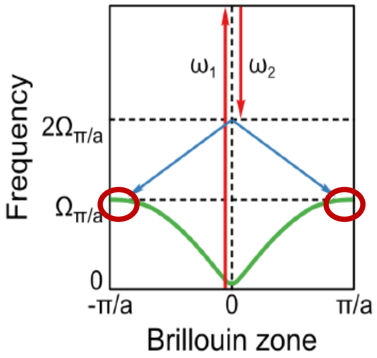
[Fedianin, et al., arXiv:2407.15962]

Laser-induced spin waves at the edge of BZ

Heisenberg antiferromagnet







- ✓ Laser-induced exchange coupling change leads to anisotropic dynamics of spin correlations at a frequency of magnons at the edge of BZ
- ✓ Spin correlations, but not L, is the parameter, for which one should consider equation of motion
- ✓ Spin dynamics in different points of BZ can be selectively excited and probed

*Fedianin, et al., PRB **107**, 144430 (2023)*
*Formisano, et al., APL Mater **12**, 011105 (2024)*
Fedianin, et al. (submitted), arXiv:2407.15962

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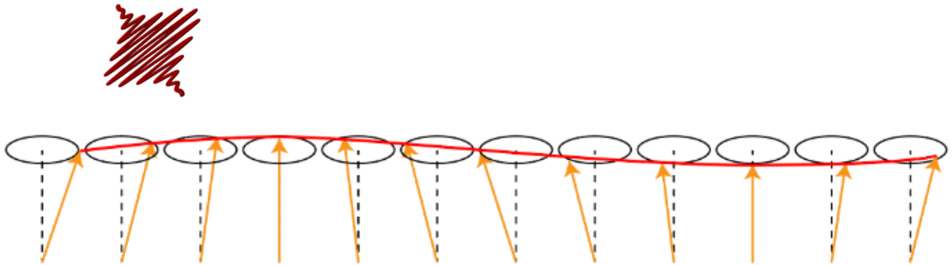
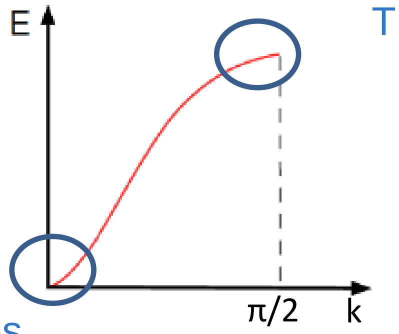


THz spin waves

Generation of GHz spin waves
with tunable parameters



Generation of magnons
at the edge of BZ

GHz spin waves