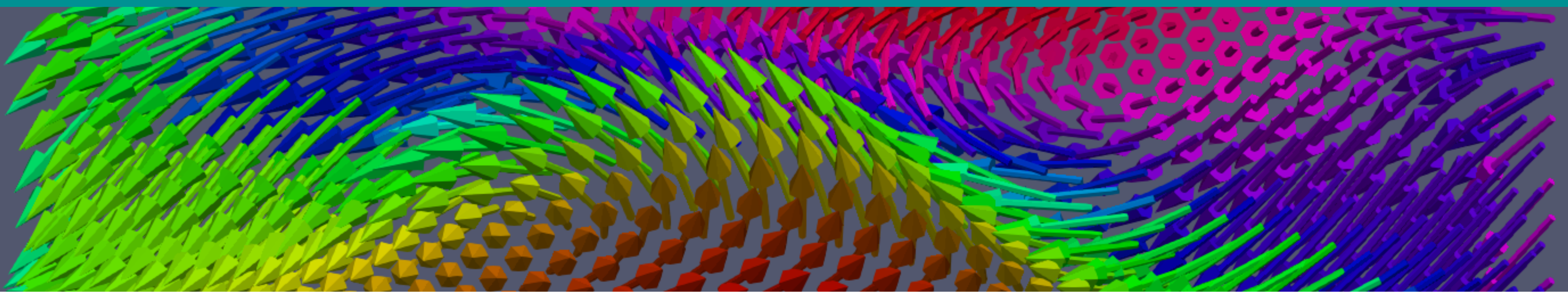
Quantum Magnonics: quantum optics with magnons



Silvia Viola Kusminskiy

MAX PLANCK INSTITUTE FOR THE SCIENCE OF LIGHT

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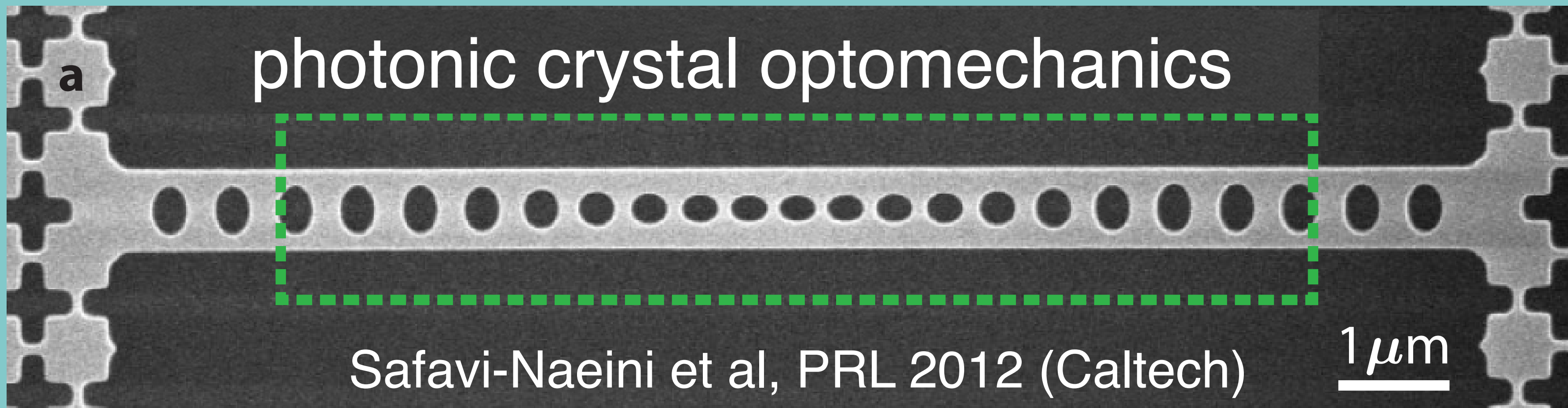
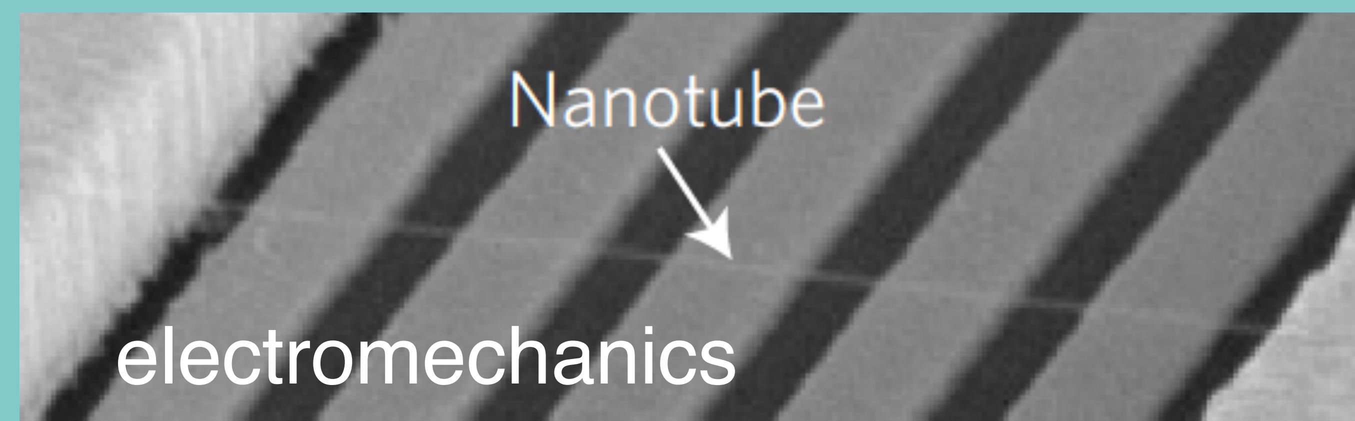
Max Planck Research Group

Theory of hybrid quantum systems

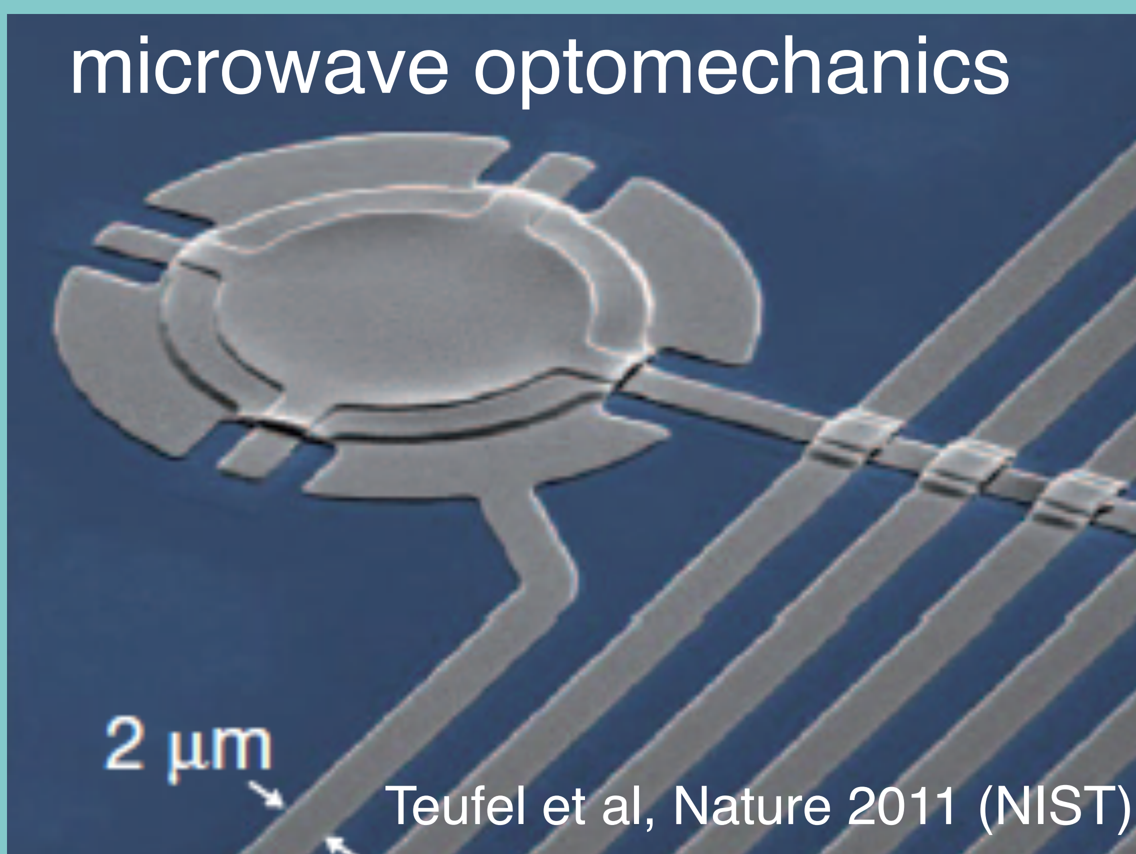
Examples of Hybrid Quantum Systems



nano/micrometer scale systems



Benyamini et al, Nature Physics 10, 151 (2014)



Osada et. al PRL 116, 223601 (2016)

use collective excitations

Applications: Quantum Technologies

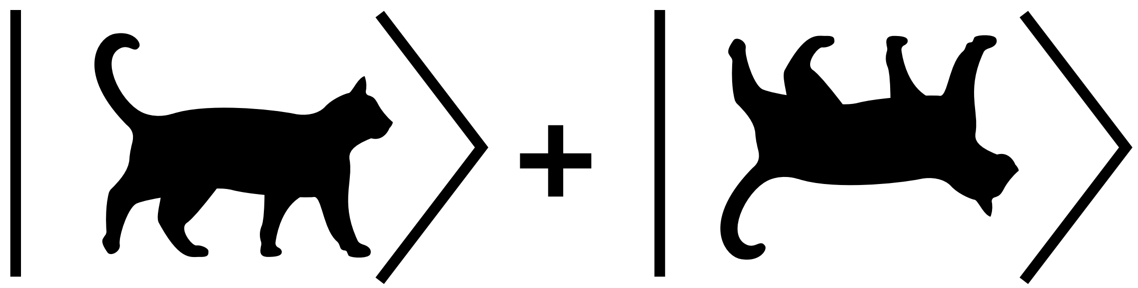
Communicate

Process

Quantum Information

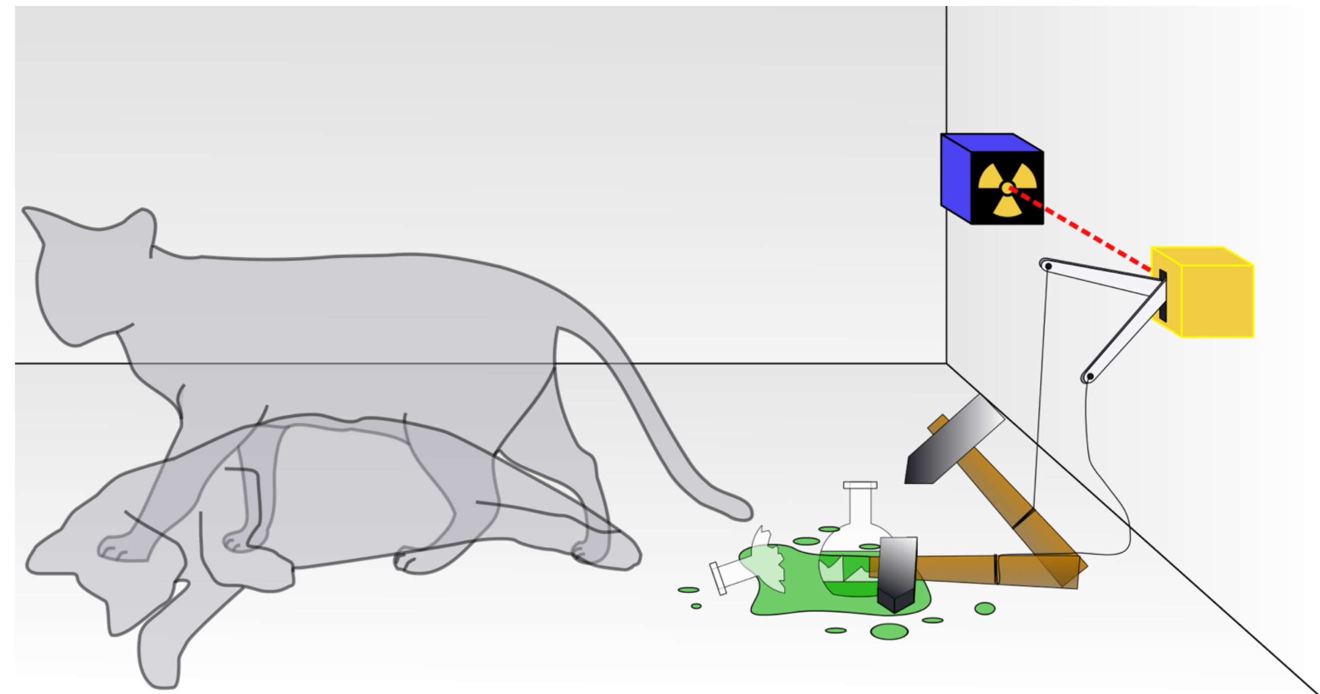
Store

Fundamentals: How macroscopic can a quantum state be?



Schrödinger's cat

Ultimate hybrid system!



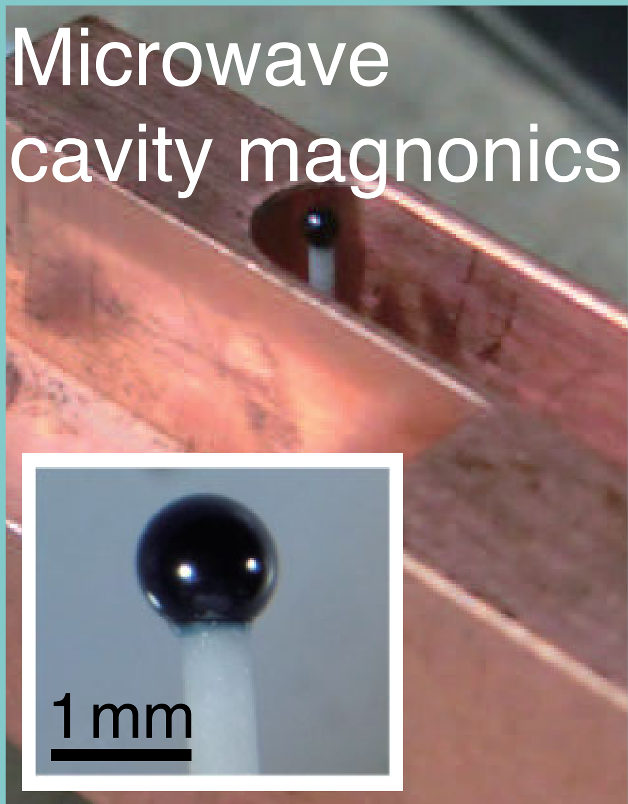
Schrödinger, Gedanken experiment (1935)

" Man kann burleske Fälle konstruieren."

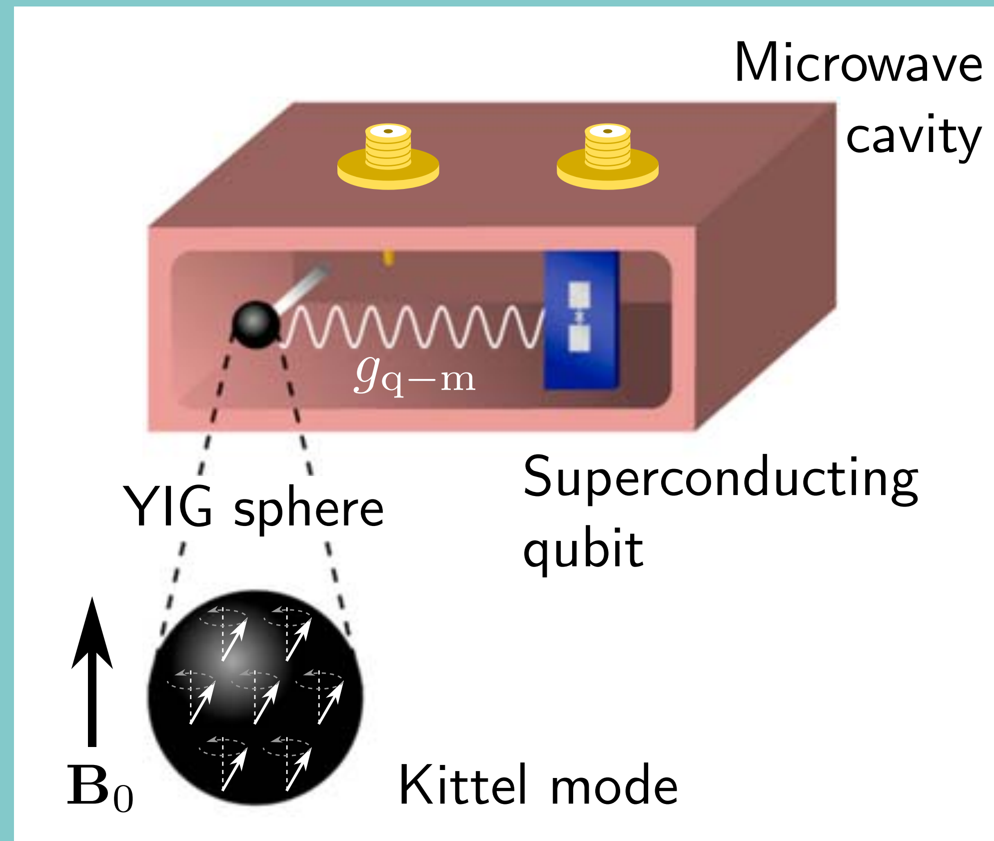
" One can construct absurd cases."

"Die Naturwissenschaften", 1935

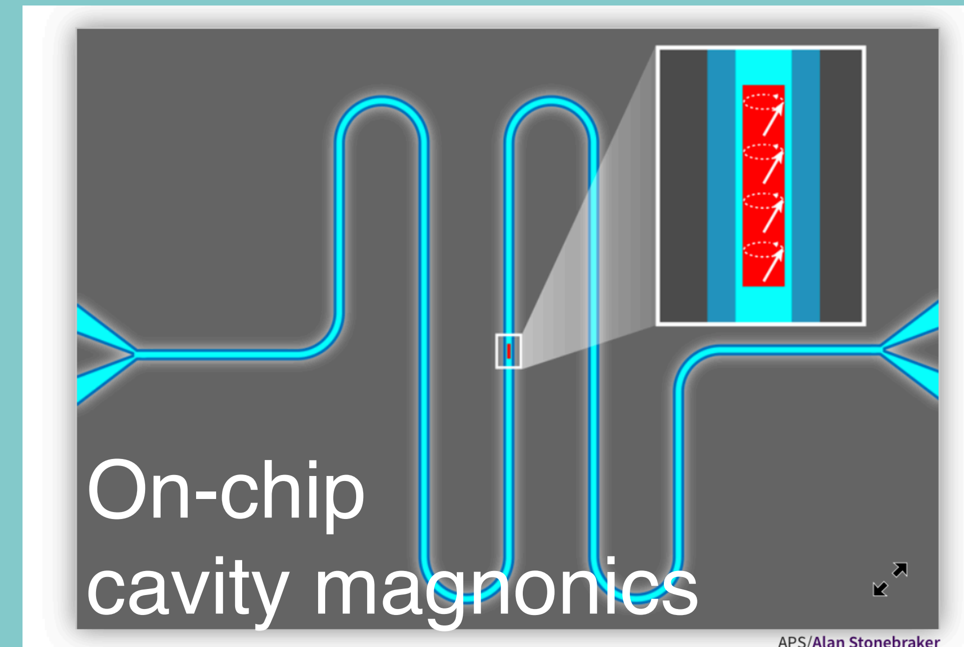
Hybrid quantum systems based on magnetic elements

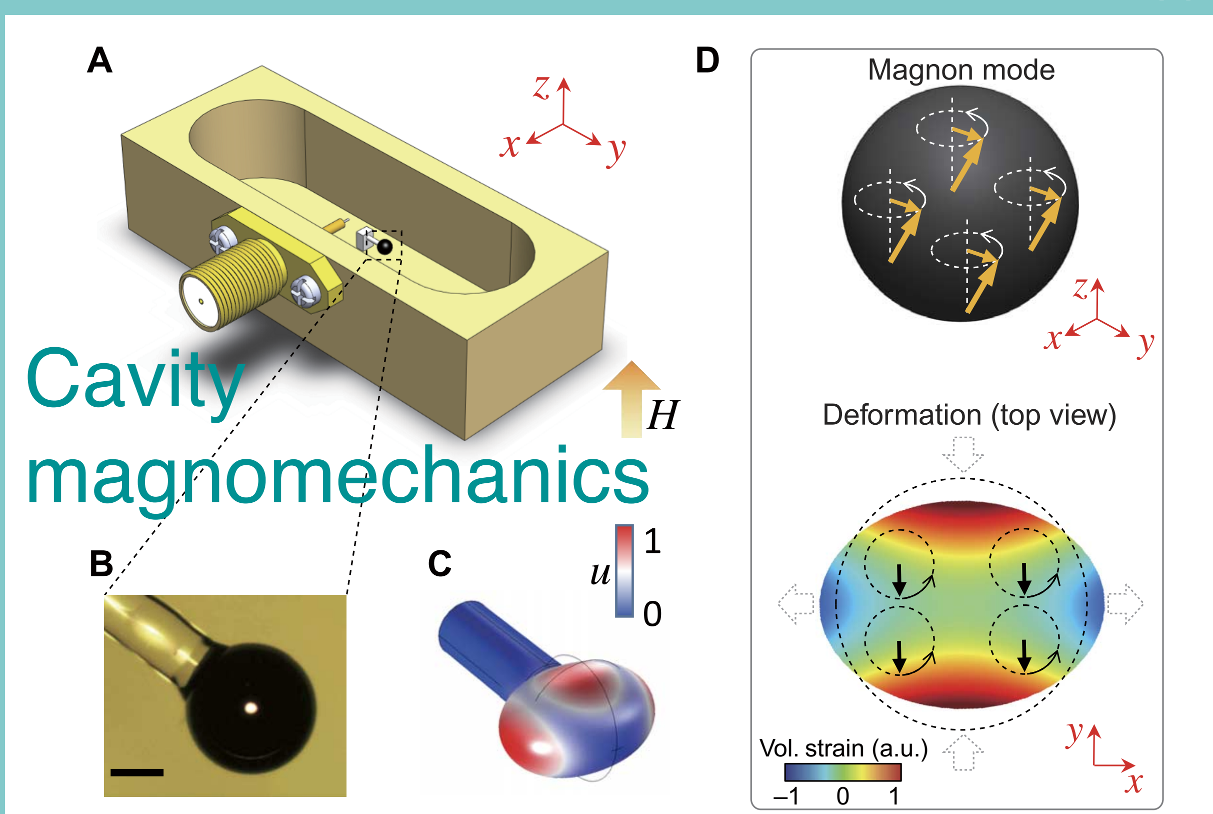


Tabuchi et. al PRL 2014

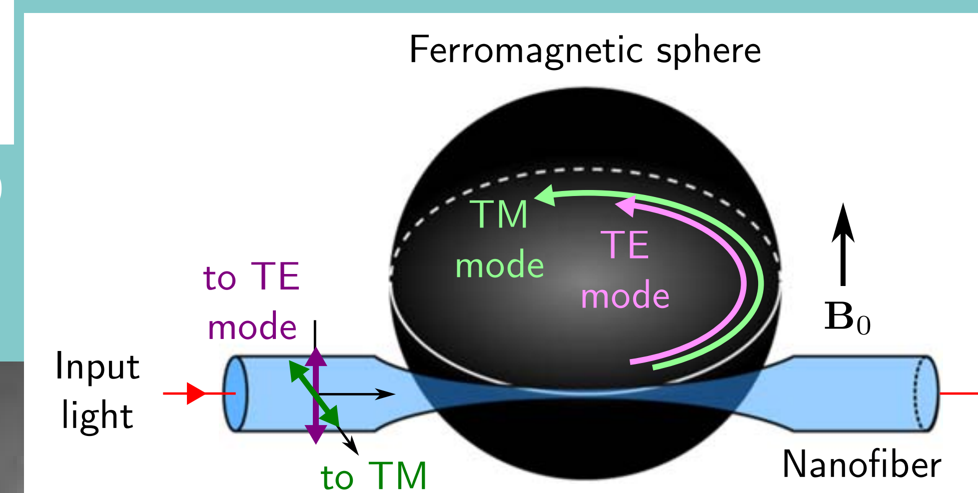


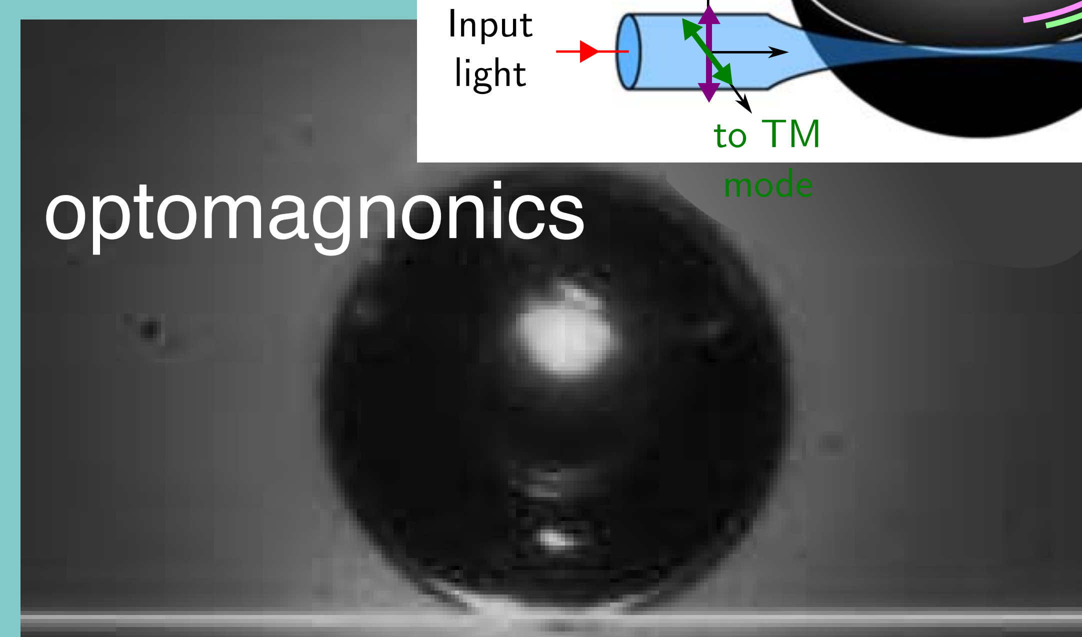
Lachance Quirion et. al Appl. Phys. Express 2019





Zhang et. al Science Advances 2016





Osada et. al PRL 116 2016

YIG

Picture form Tabuchi et al, PRL 113, 083603 (2014)

YIG

Yttrium Iron Garnet

$$\mathrm{Y}_3\,\mathrm{Fe}_5\,\mathrm{O}_{12}$$

- ferrimagnetic
- insulator
- transparent in the infrared

What is a magnon?

magnon

elementary magnetic
excitation
(quantum of spin wave)

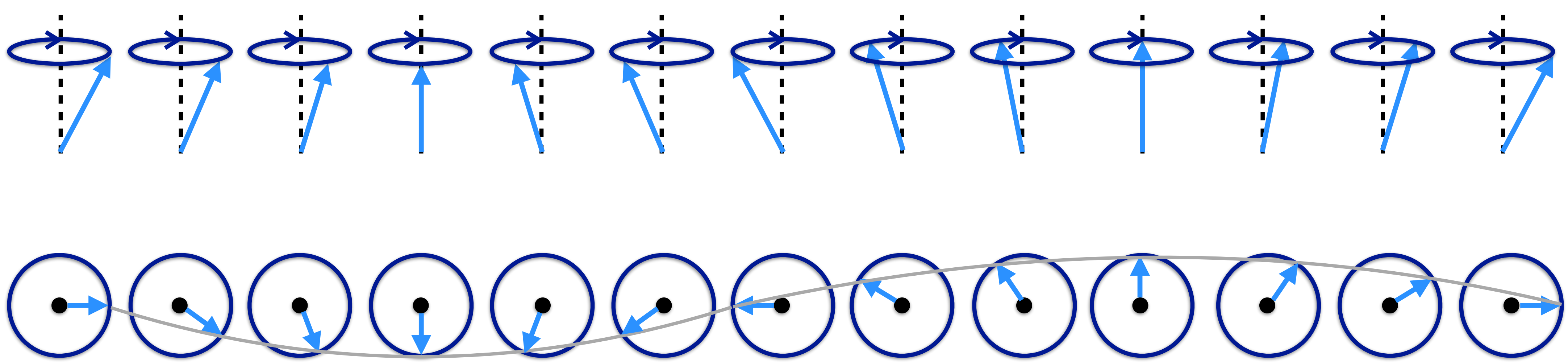


image: Jasmin Graf

Why do we like magnons?

magnon

elementary magnetic
excitation
(quantum of spin wave)

Rich physics

Amenable
to miniaturization

Robust

Low Power

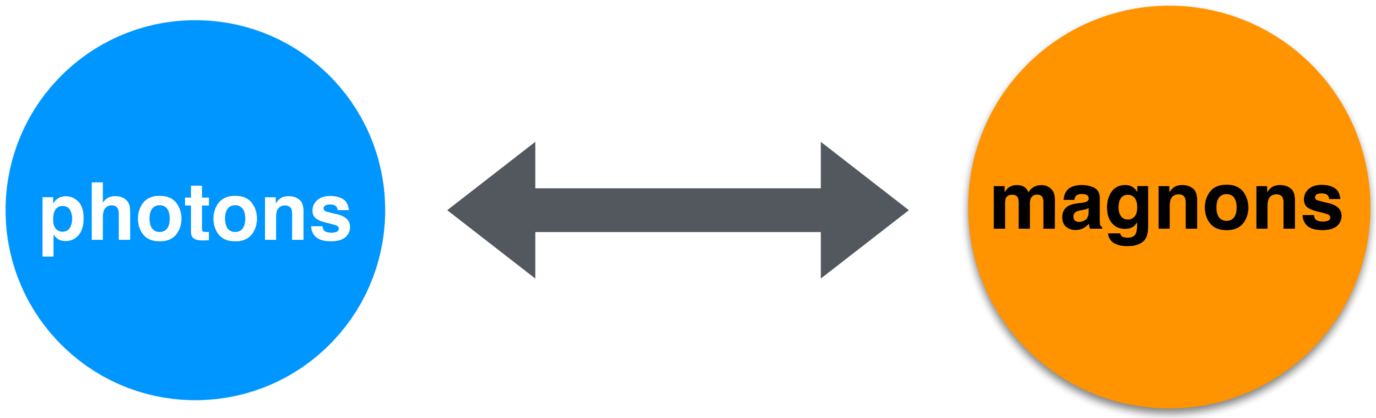
Tunable

Why do we like magnons?

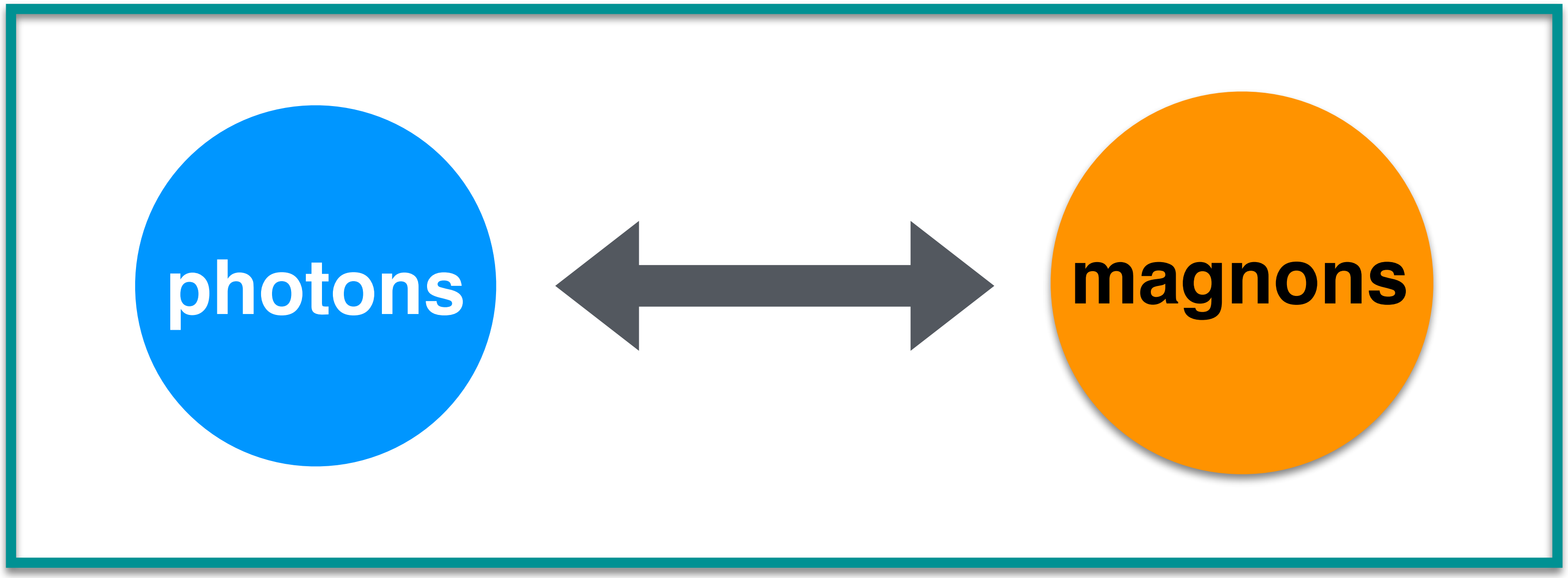
Figure: m&m's

Magnons are friendly: coupling to electrons, phonons, photons…

Optomagnonics

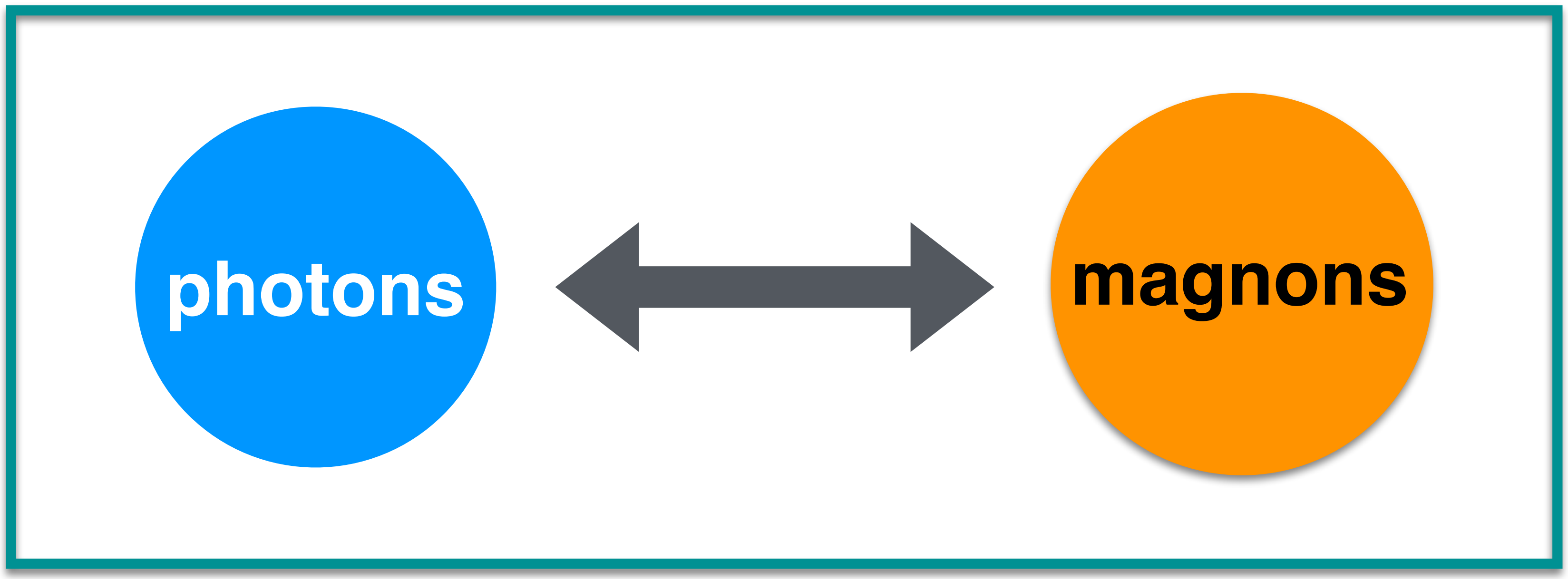


Cavity Optomagnonics



cavity-enhanced spin-photon interaction

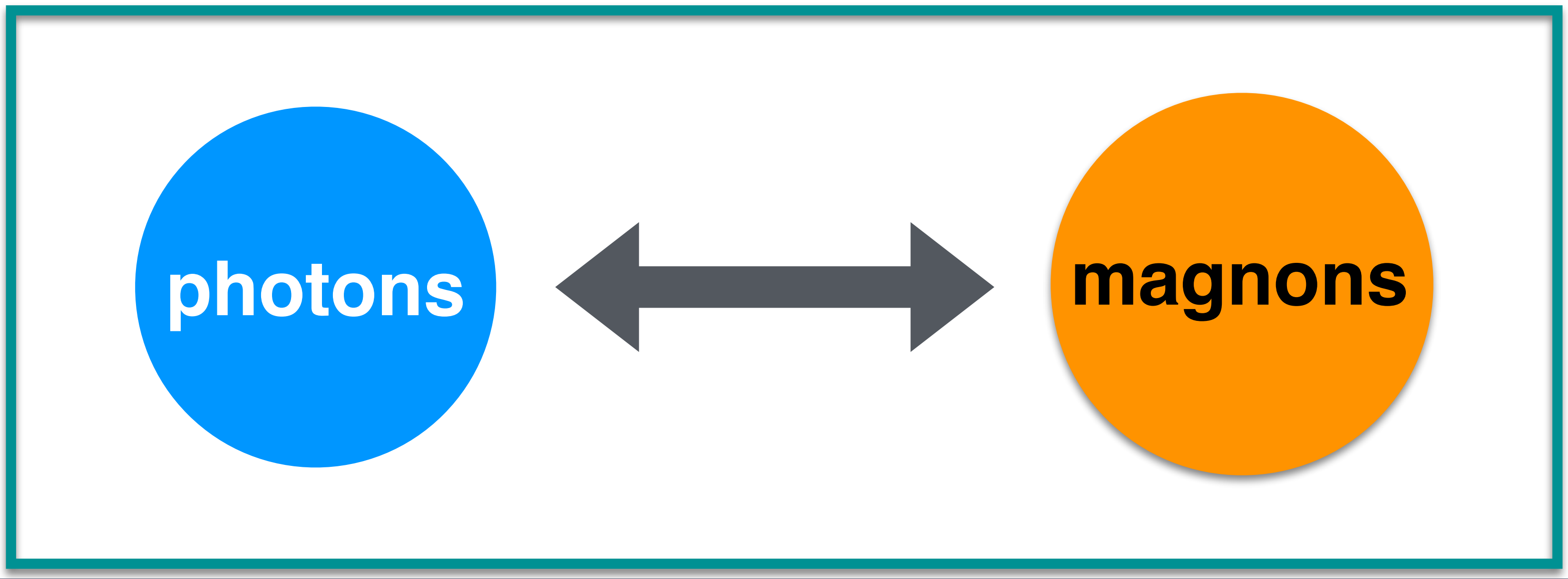
Cavity Optomagnonics

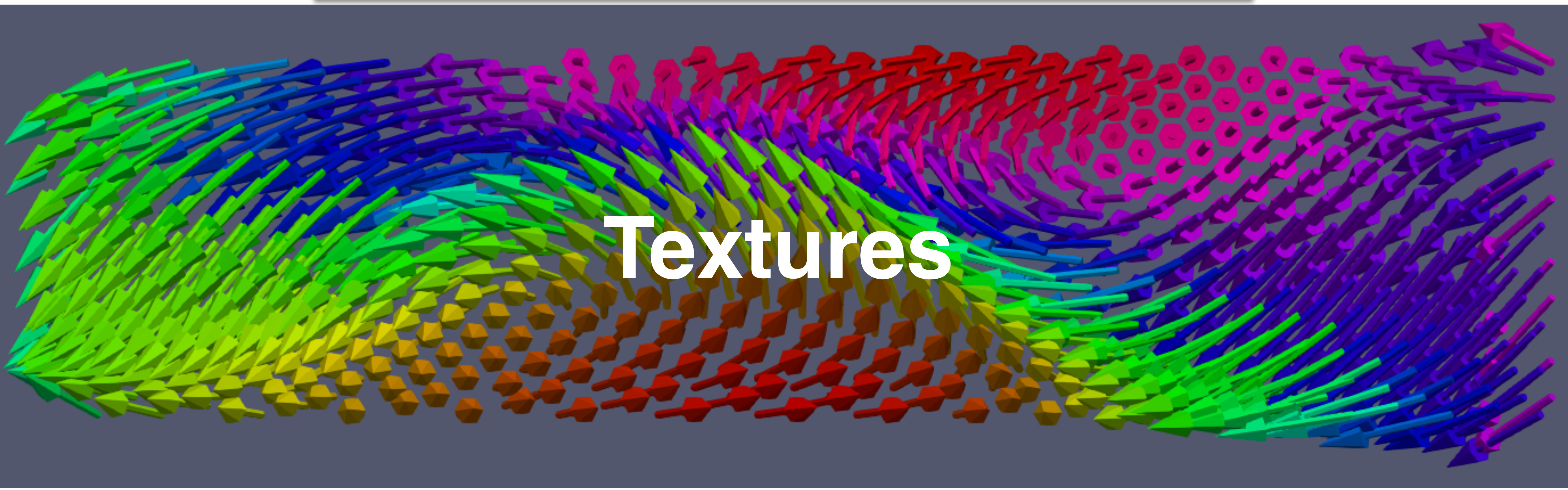


cavity-enhanced spin-photon interaction

cavity QED + magnetism

Cavity Optomagnonics

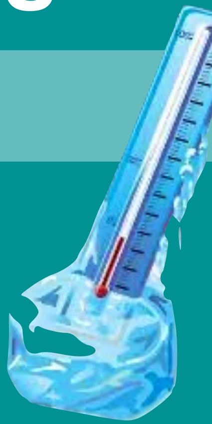


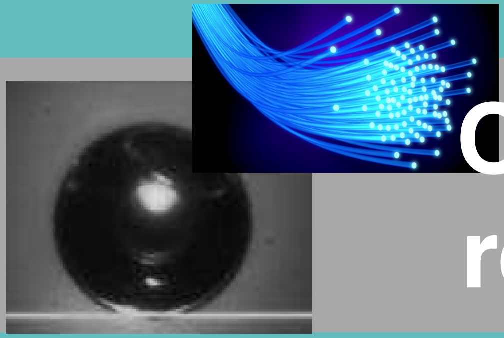


Microwave regime

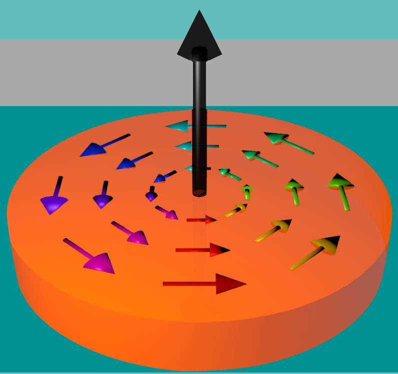
Spin cat states in ferromagnetic insulators

Magnon-phonon quantum thermometry

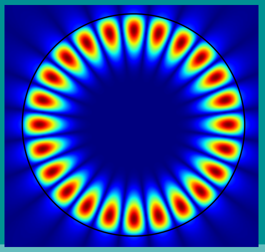




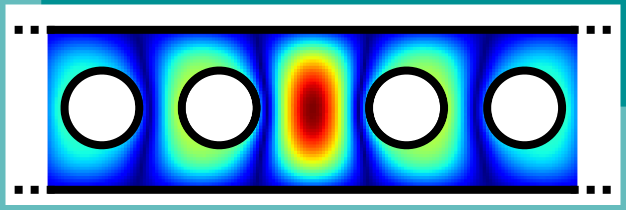
Optical regime

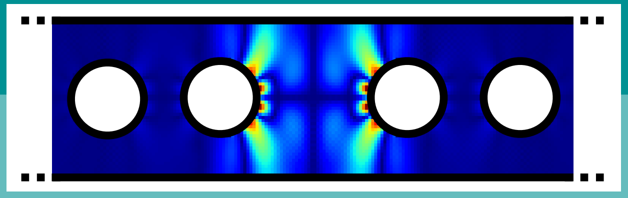


Optomagnonics with Magnetic textures



Optomagnonic crystals





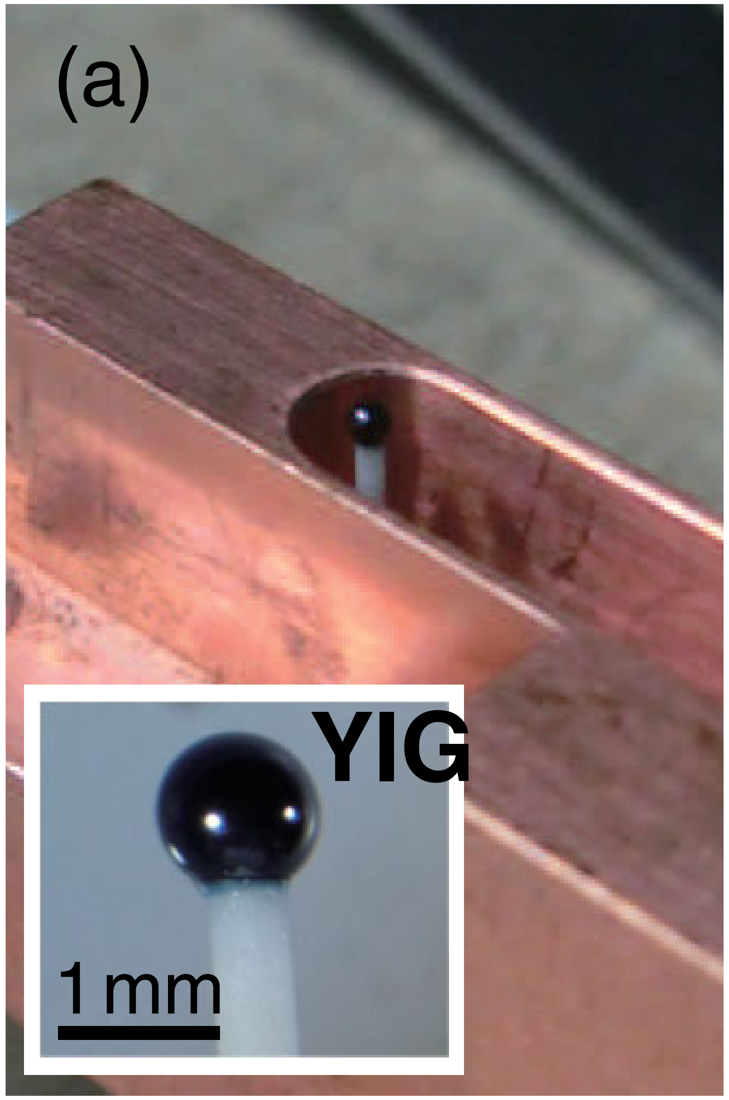
Outlook

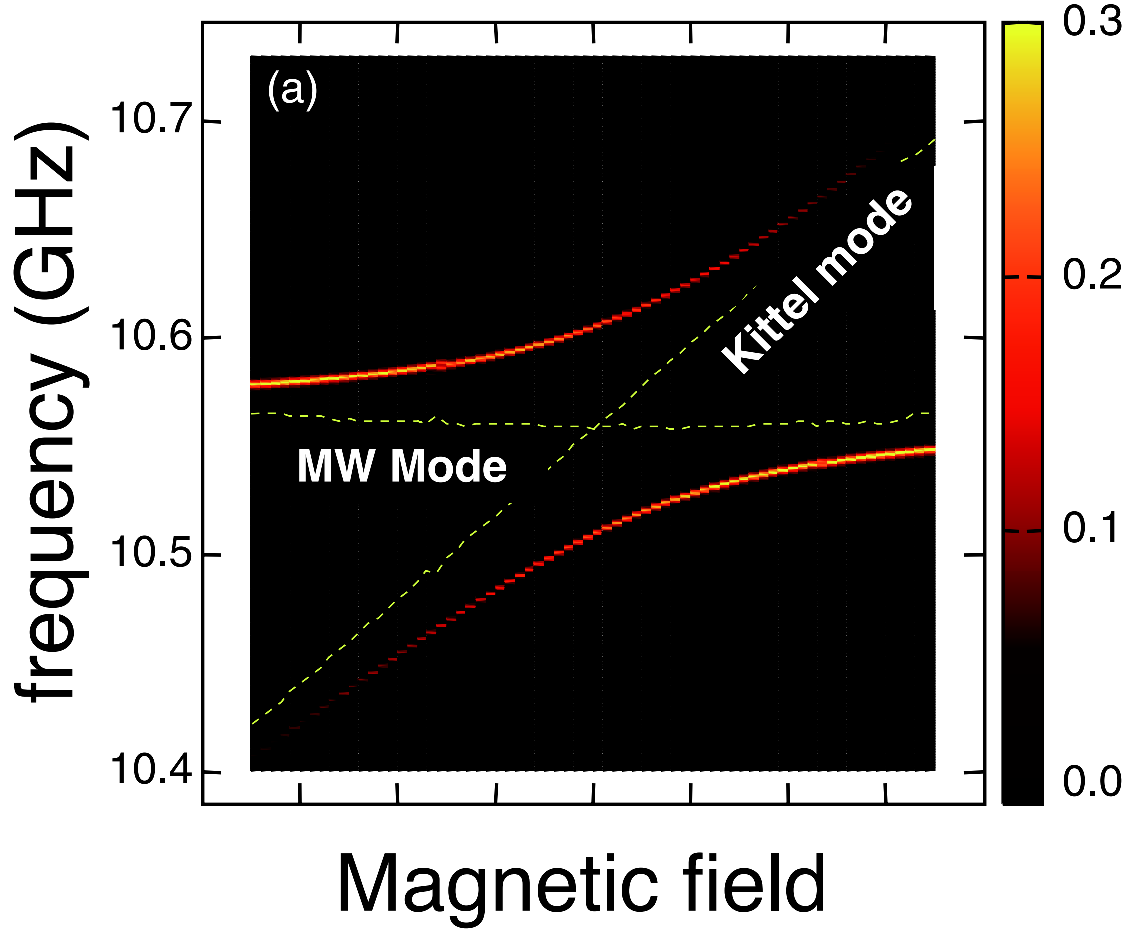
Microwave regime

Microwave Regime

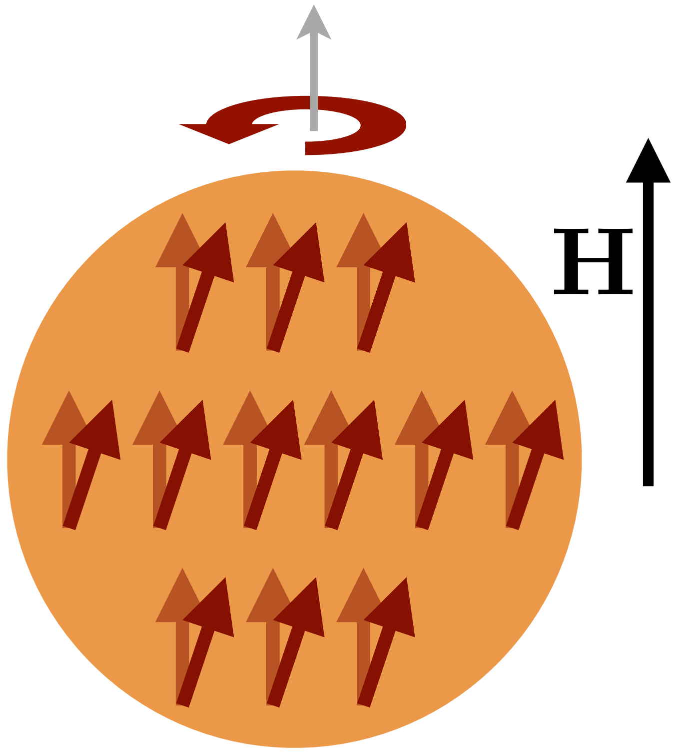
Magnons ⟷ **Microwaves**

Strong coupling regime





$\Omega \propto H$



$\Omega \sim \mathrm{GHz}$

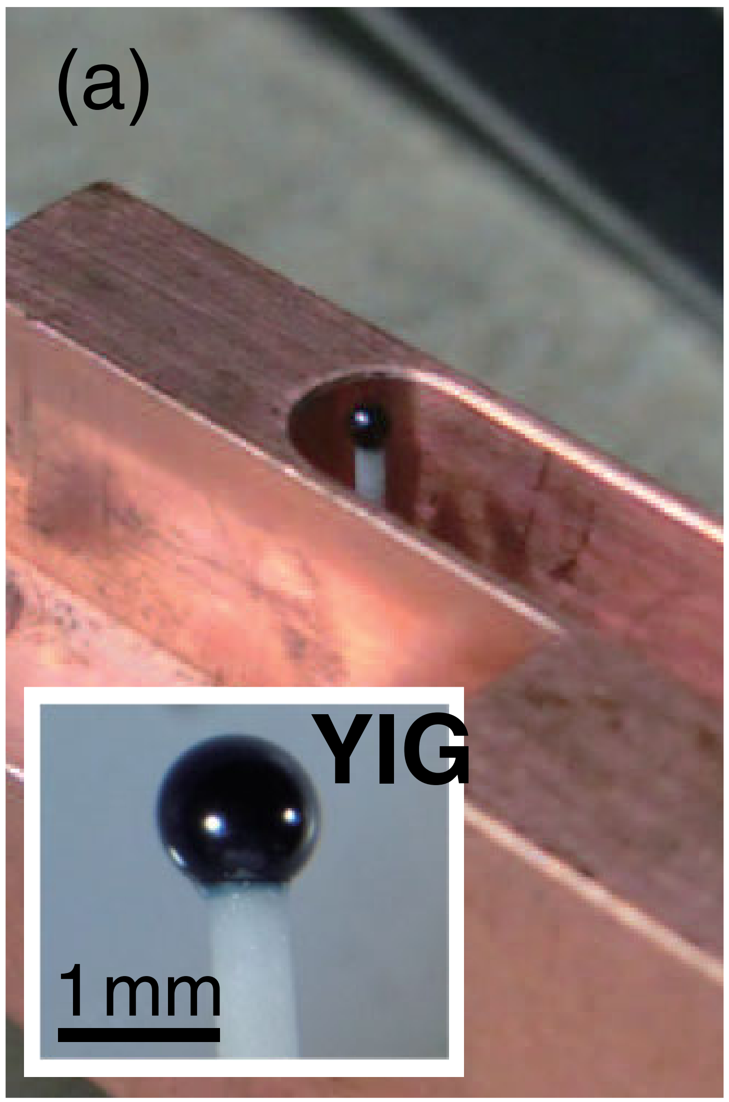
for 30mT

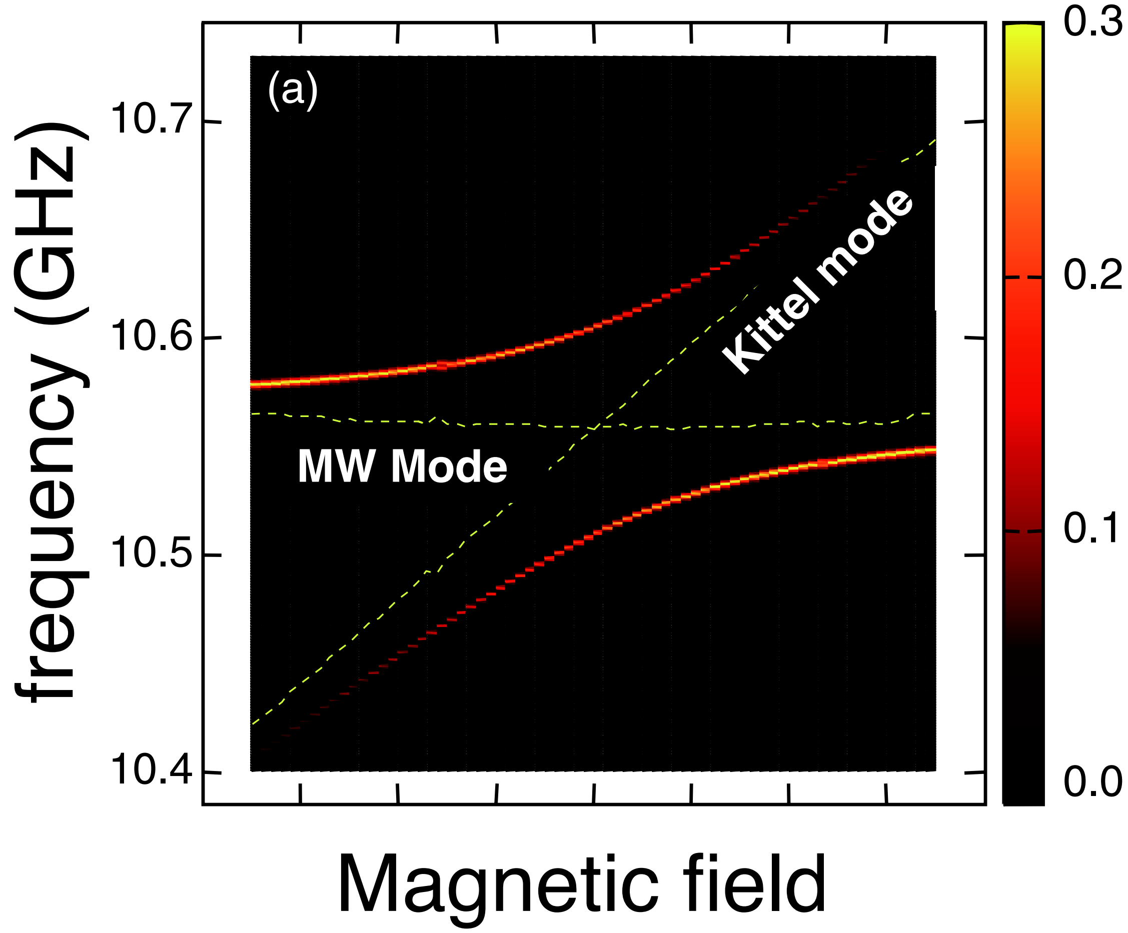
Huebl et. al, PRL 111, 127003 (2013)
Zhang et. al PRL 113, 156401 (2014)
Tabuchi et. al PRL 113, 083603 (2014)

Microwave Regime

Magnons ⟷ **Microwaves**

Strong coupling regime





Resonant coupling

$$-\frac{\mu_0}{2}\int d^3r\,\mathbf{M}\cdot\mathbf{H}_{\mathrm{MW}}$$

$$\hat{S}^{-}\hat{a}+\hat{S}^{+}\hat{a}^{\dagger}$$

$\hat{S}$ ⟷ $\hat{a}$

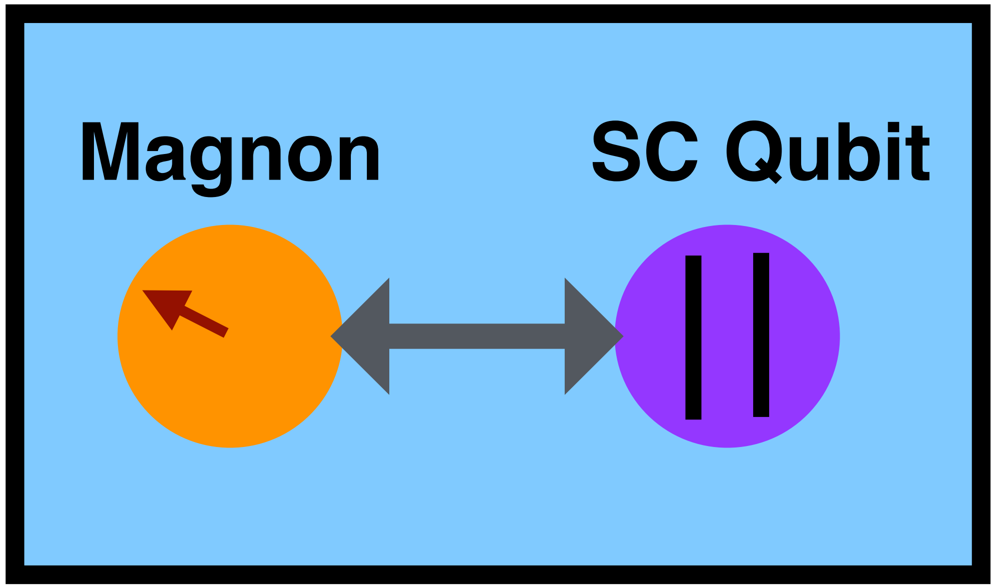
Huebl et. al, PRL 111, 127003 (2013)
Zhang et. al PRL 113, 156401 (2014)
Tabuchi et. al PRL 113, 083603 (2014)

Soykal and M. E. Flatte
PRL 104, 077202 (2010)

QUANTUM INFORMATION (Science 2015)

Coherent coupling between a ferromagnetic magnon and a superconducting qubit

Yutaka Tabuchi,[1*] Seiichiro Ishino,[1] Atsushi Noguchi,[1] Toyofumi Ishikawa,[1] Rekishu Yamazaki,[1] Koji Usami,[1] Yasunobu Nakamura[1,2]



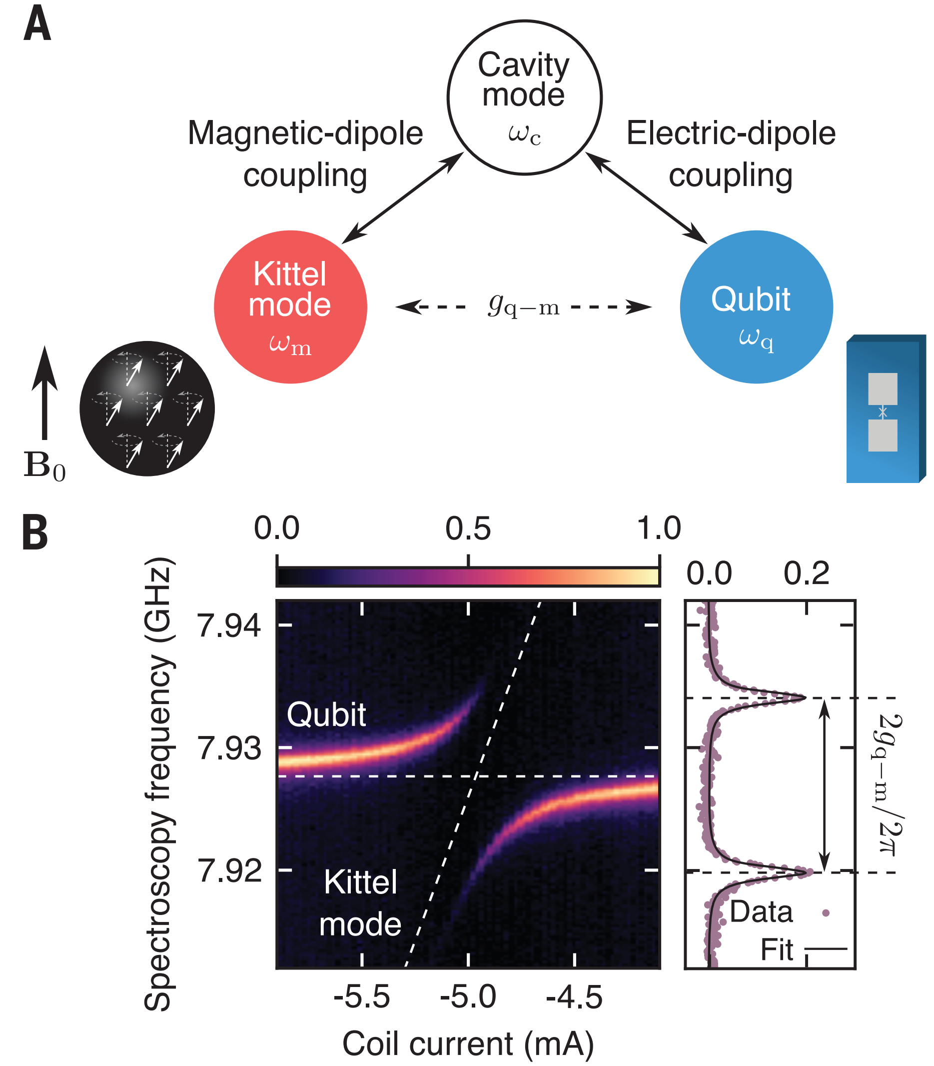
MW Cavity

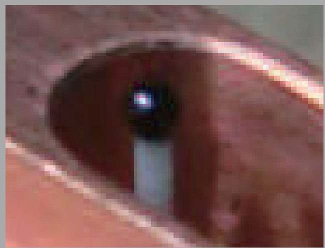
Microwave Regime: Single Magnon Detector

QUANTUM SENSING (Science 2020)

Entanglement-based single-shot detection of a single magnon with a superconducting qubit

Dany Lachance-Quirion[1], Samuel Piotr Wolski[1], Yutaka Tabuchi[1], Shingo Kono[1], Koji Usami[1], Yasunobu Nakamura[1,2]*





Microwave regime

Spin cat states in ferromagnetic insulators

S. Sharma, V. Bittencourt, A. Karenowska, SVK;
PRB 103, L100403 (2021)

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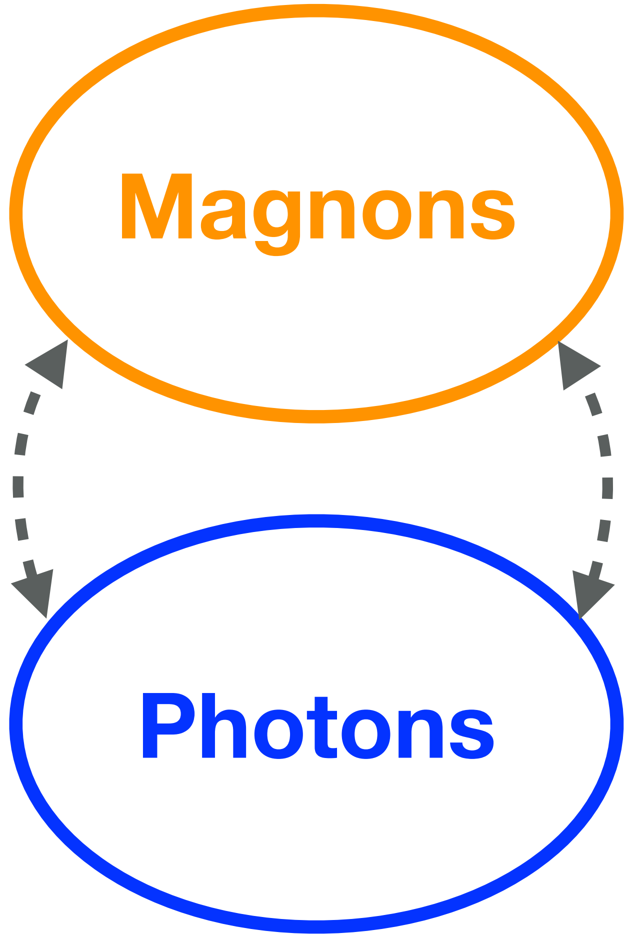
UNIVERSITY OF OXFORD

Proposal: Heralding Magnetic Cat States

Heralding



Generation of entangled state

+

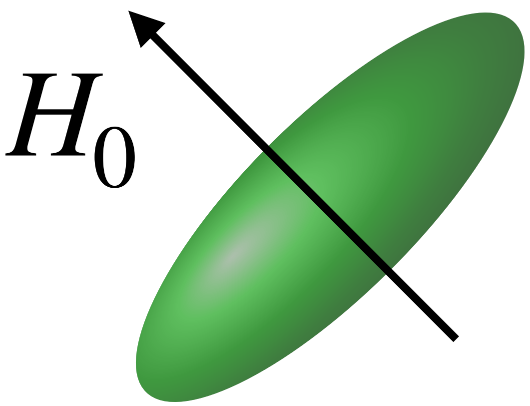
Measurement

C. K. Hong and L.Mandel, PRL 56 1 (1986)

Duan et al, Nature 414, 413 (2001)

Heralding Magnetic Cat States

Anisotropic Nanomagnet

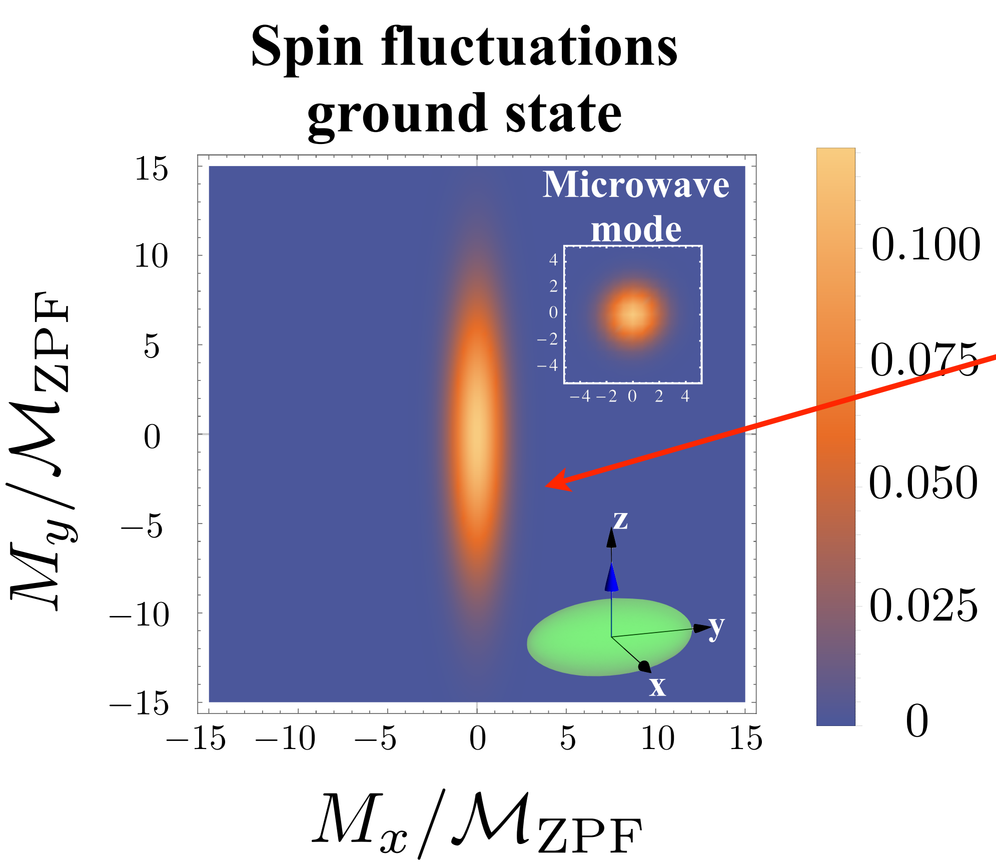


$$\mathcal{H}_{\text{mag}} = \frac{\mu_0}{2}\boldsymbol{M}\tilde{N}\boldsymbol{M} - \mu_0 M_z H_0$$

isotropic magnet

anisotropy

$$\frac{\hat{H}}{\hbar} = \omega_0 \hat{s}^\dagger \hat{s} + \frac{\omega_s}{2}\left(\hat{s}^2 + \hat{s}^{\dagger\,2}\right)$$



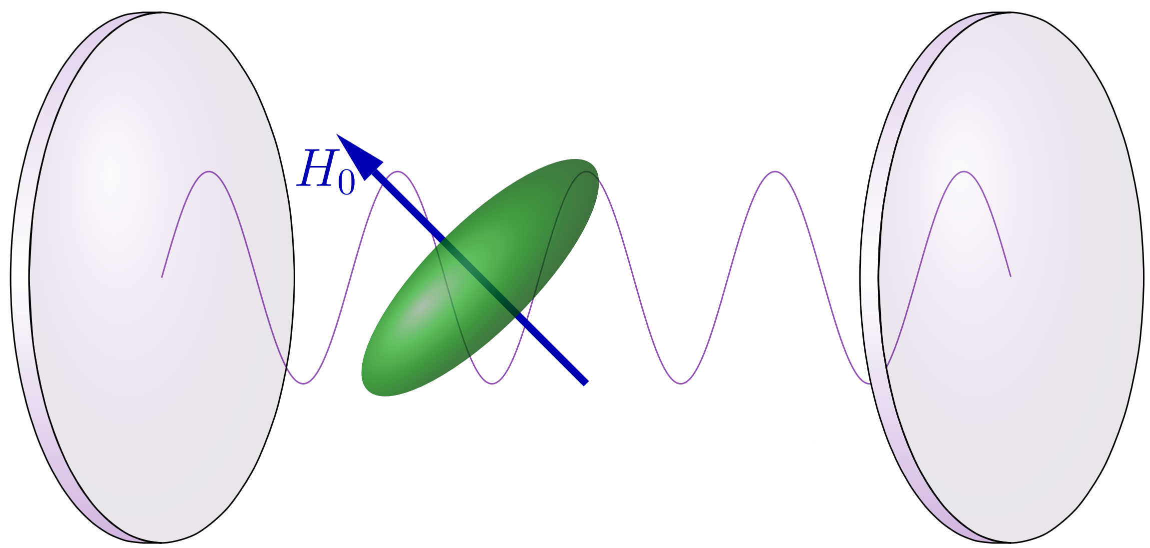
Squeezed magnetic ground state due to anisotropy

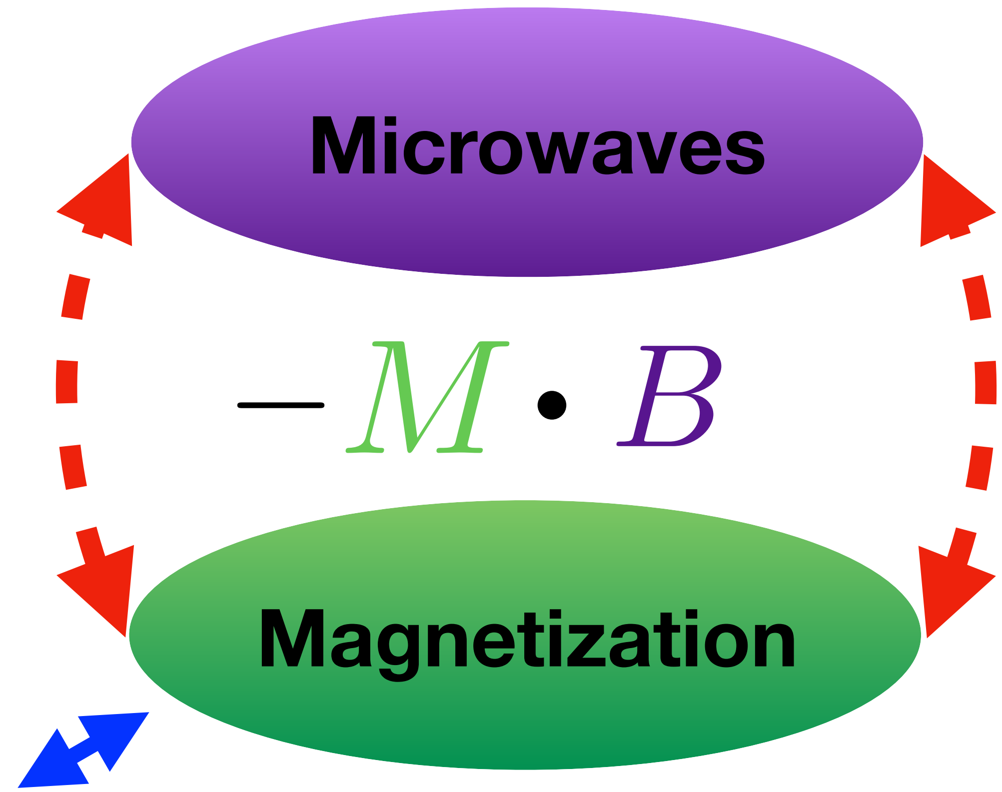
Kamra et al, PRL 2016

Anisotropic quantum fluctuations

Heralding Magnetic Cat States

MW Cavity + Anisotropic Nanomagnet





$$\frac{\hat{H}}{\hbar} = \omega_0 \hat{s}^\dagger \hat{s} + \frac{\omega_s}{2}(\hat{s}^2 + \hat{s}^{\dagger\,2}) + \omega_a \hat{a}^\dagger \hat{a} + g(\hat{s}\hat{a}^\dagger + \hat{s}^\dagger \hat{a})$$

cavity photons

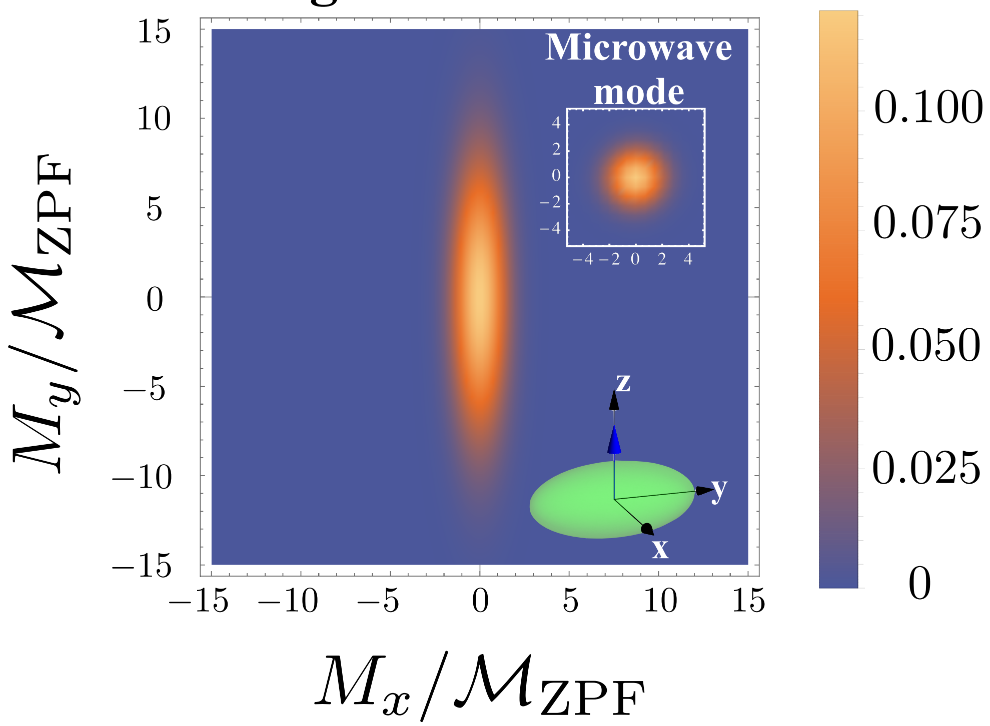
cavity-magnet interaction

The ground state of the coupled system is an entangled state of photons and flipped spins

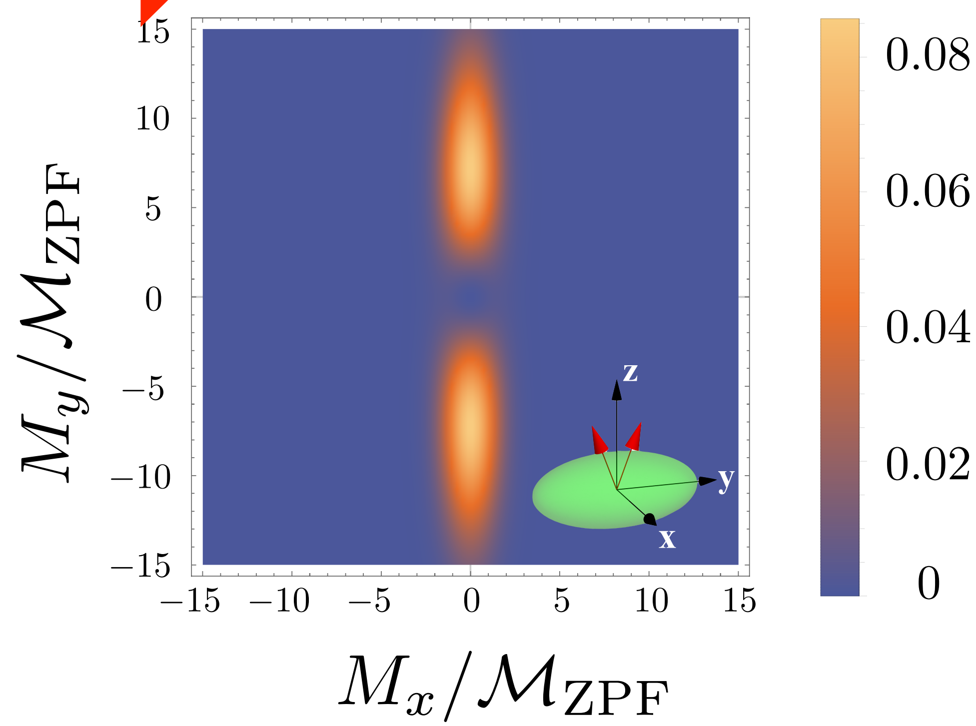
Heralding Magnetic Cat States

measurement of the state of the cavity

Spin fluctuations ground state



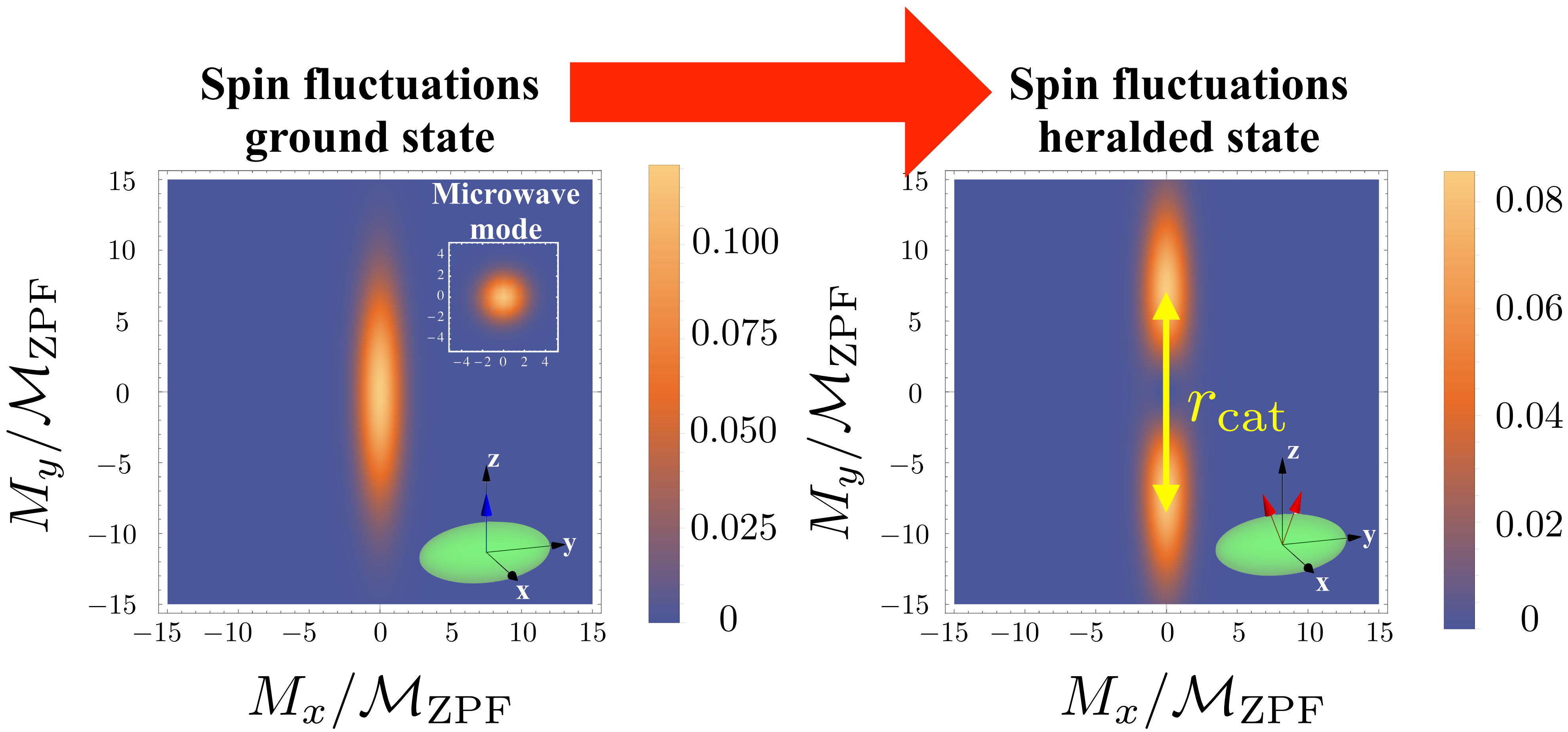
Spin fluctuations heralded state



The magnetization points simultaneously in two directions

Creating Magnetic Cat States

measurement of the state of the cavity



The magnetization points simultaneously in two directions

Experimental limitation

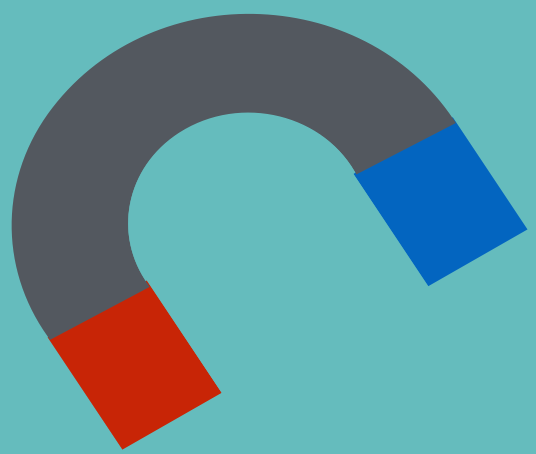
Low temperatures needed for a "large cat"

$$T < 5\,\mathrm{mK}$$

S. Sharma, V. Bittencourt, A. Karenowska, SVK; Physical Review B 103, L100403 (2021)

Microwave regime

Magnon-phonon quantum thermometry



C. Potts, V. Bittencourt, SVK, John P. Davis;
Phys. Rev. Applied 13, 064001 (2020)

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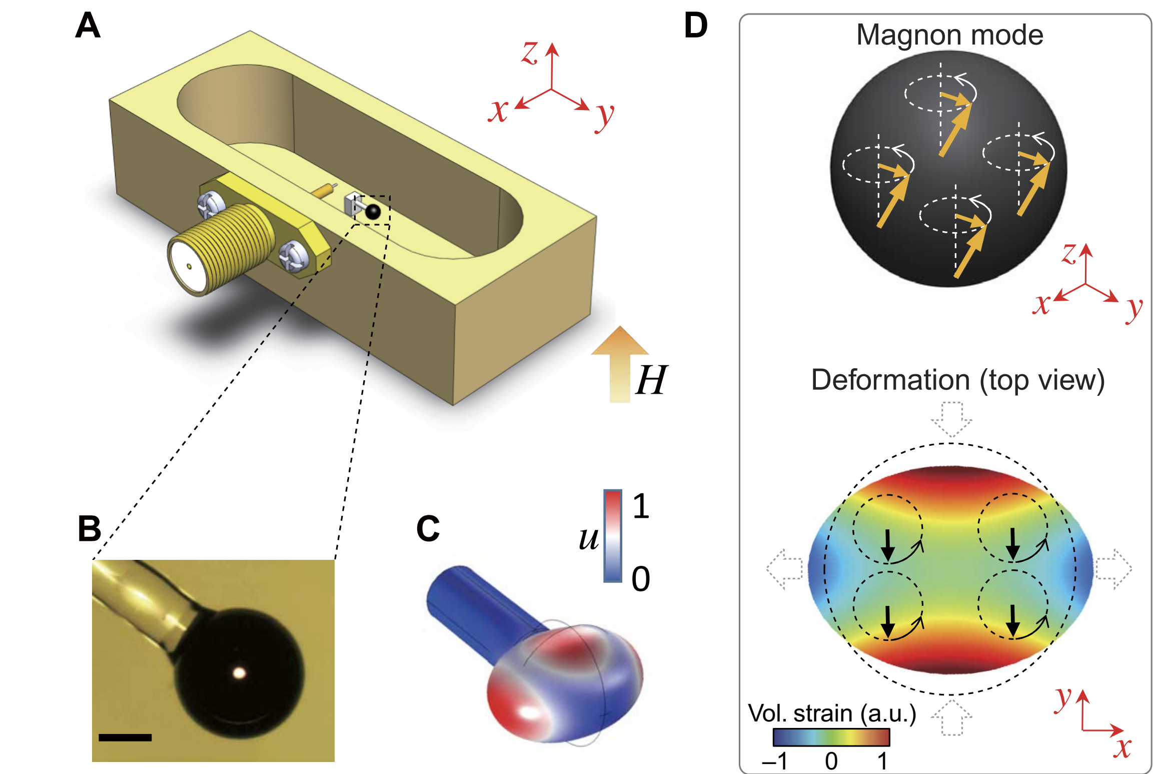
UNIVERSITY OF ALBERTA

Magnons can couple coherently to phonons

Cavity magnomechanics



Zhang et. al Science Advances 2016

Magnetoelastic energy

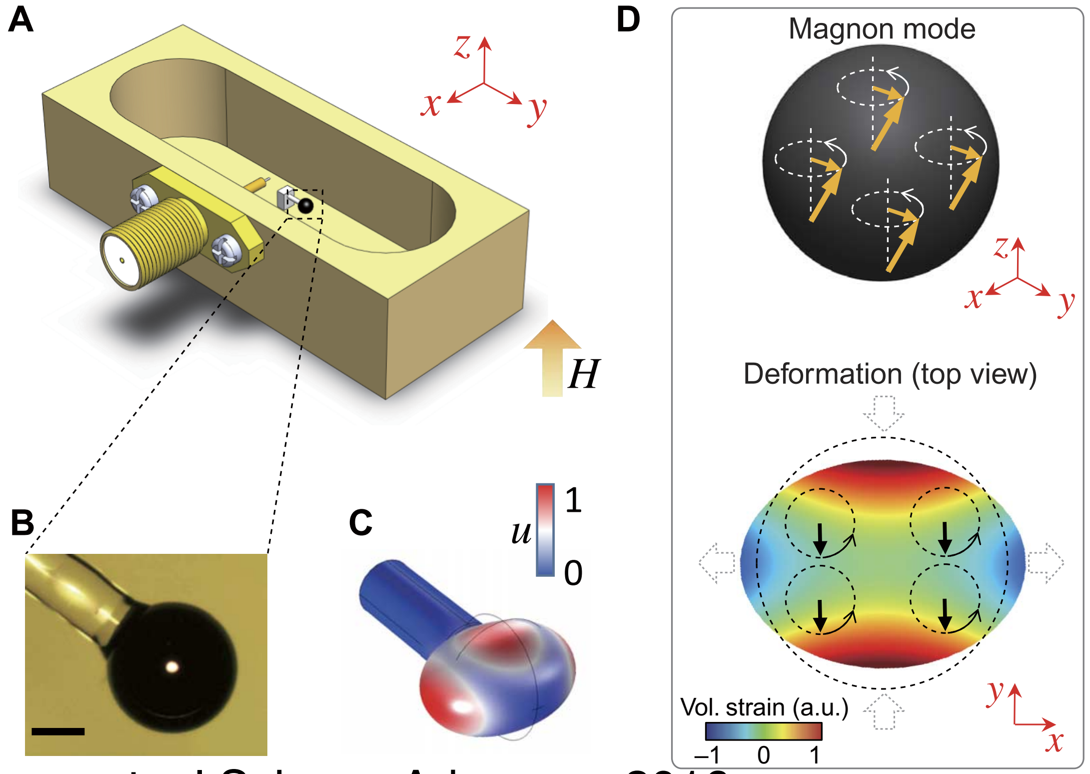
magnetoelastic constants

strain tensor

$$E_{mel} = \frac{B_1}{M_S^2} \int d^3r \, [M_x^2 u_{xx} + M_y^2 u_{yy} + M_z^2 u_{zz}] + \frac{2B_2}{M_S^2} \int d^3r \, [M_x M_y u_{xy} + M_y M_z u_{yz} + M_z M_x u_{zx}]$$

Magnons can couple coherently to phonons

Cavity magnomechanics



Zhang et. al Science Advances 2016

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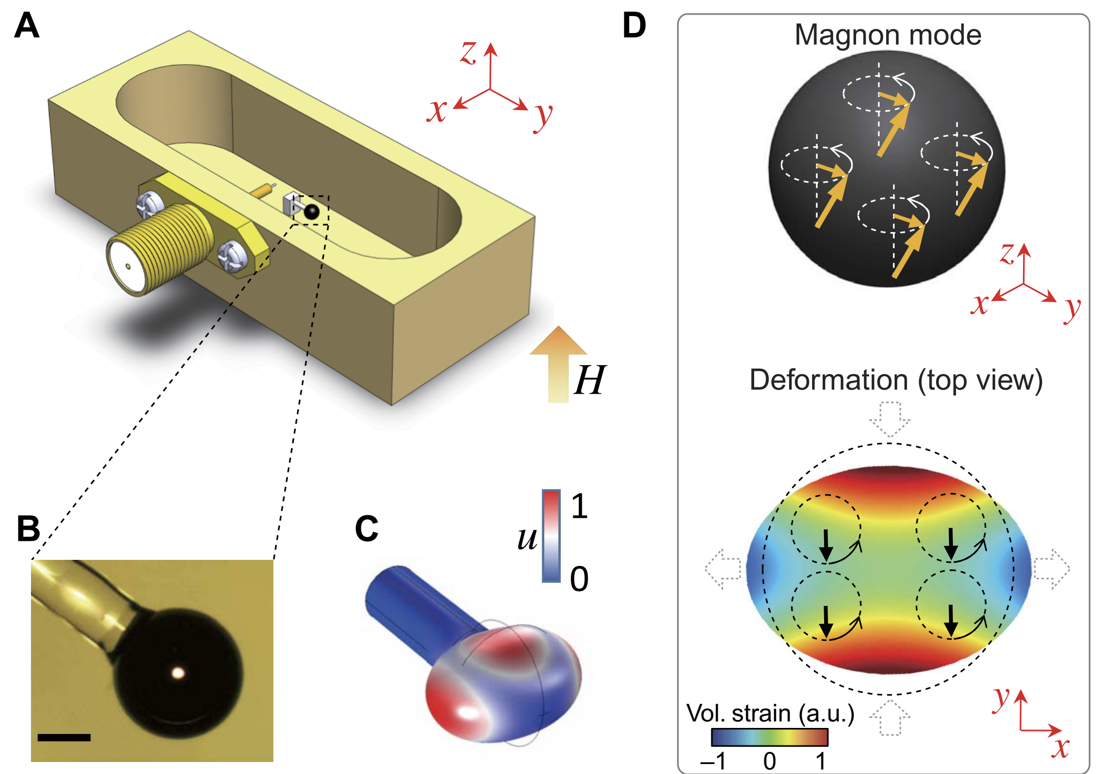
Quantizing in terms of magnon **m** and phonon **b** operators for an arbitrary magnetic texture

$$\hat{H}_{ME} = \sum_{\alpha\beta\gamma ij} \left[G^{ij}_{\alpha\gamma} \hat{m}_\alpha \left(\hat{b}_\gamma + \hat{b}^\dagger_\gamma\right) + T^{ij}_{\alpha\beta\gamma} \hat{m}_\alpha \hat{m}_\beta \left(\hat{b}_\gamma + \hat{b}^\dagger_\gamma\right) + P^{ij}_{\alpha\beta\gamma} \hat{m}^\dagger_\beta \hat{m}_\alpha \left(\hat{b}_\gamma + \hat{b}^\dagger_\gamma\right) + h.c.\right]$$

F. Engelhardt et al, in preparation

Magnons can couple to phonons

Cavity magnomechanics



Zhang et. al Science Advances 2016

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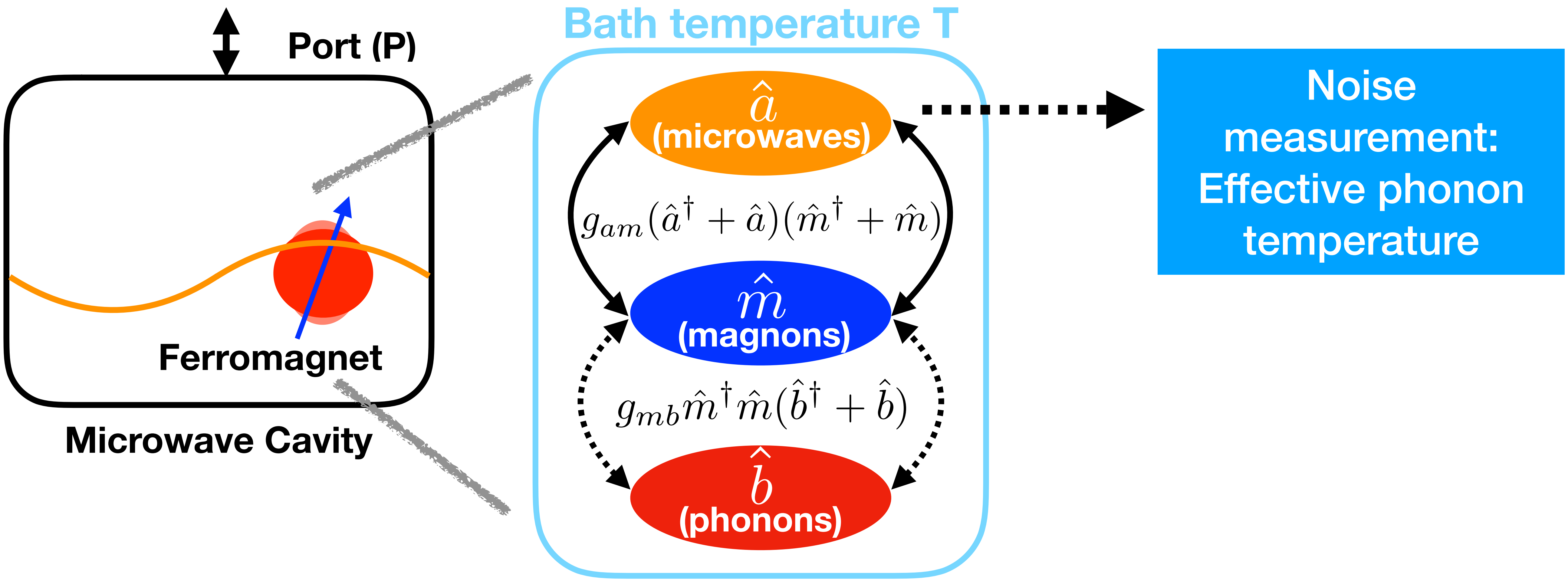
Parametric coupling

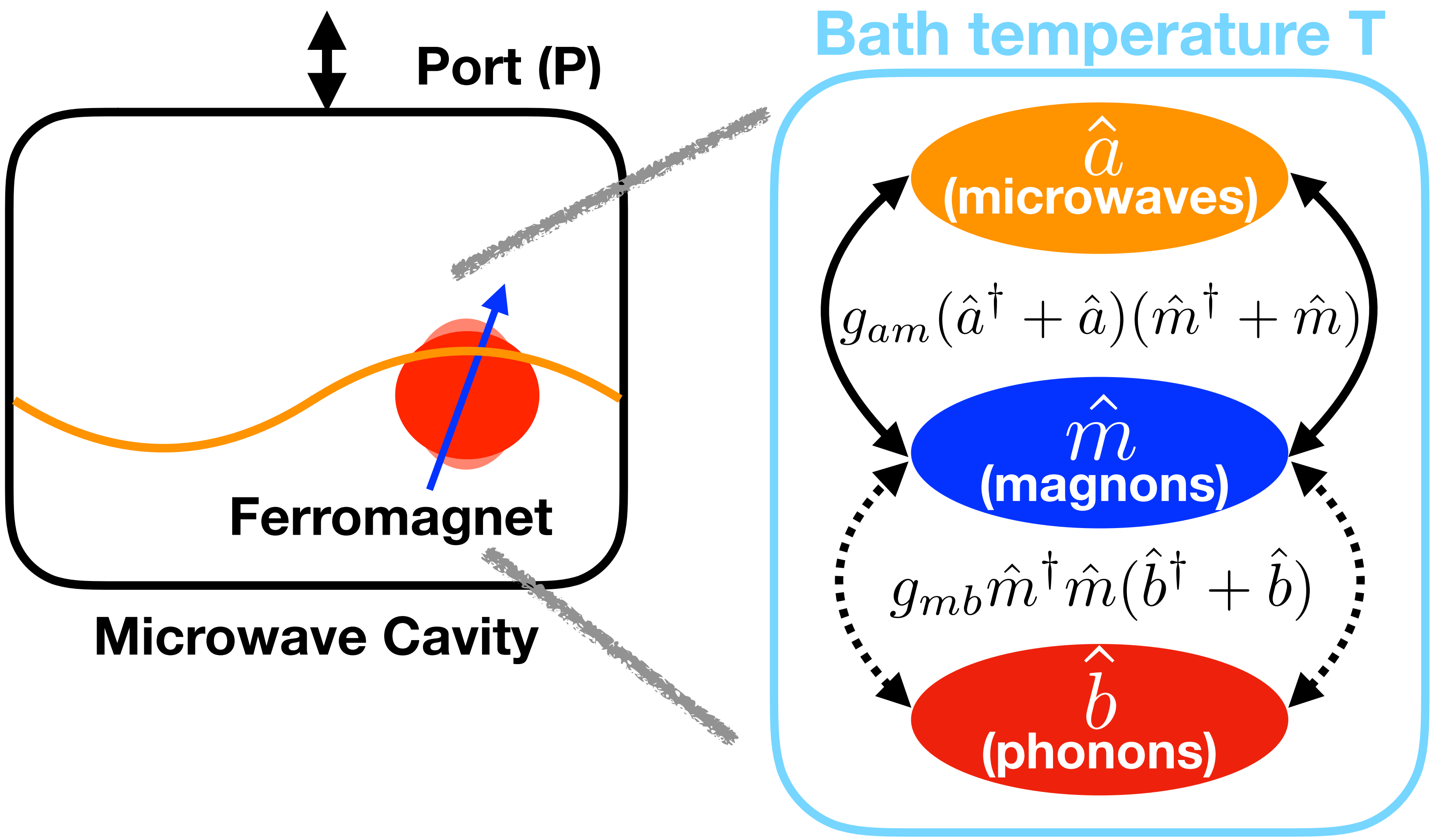
Magnons ~ GHz
Phonons ~kHz

Magnon - Phonon Quantum Correlation Thermometry



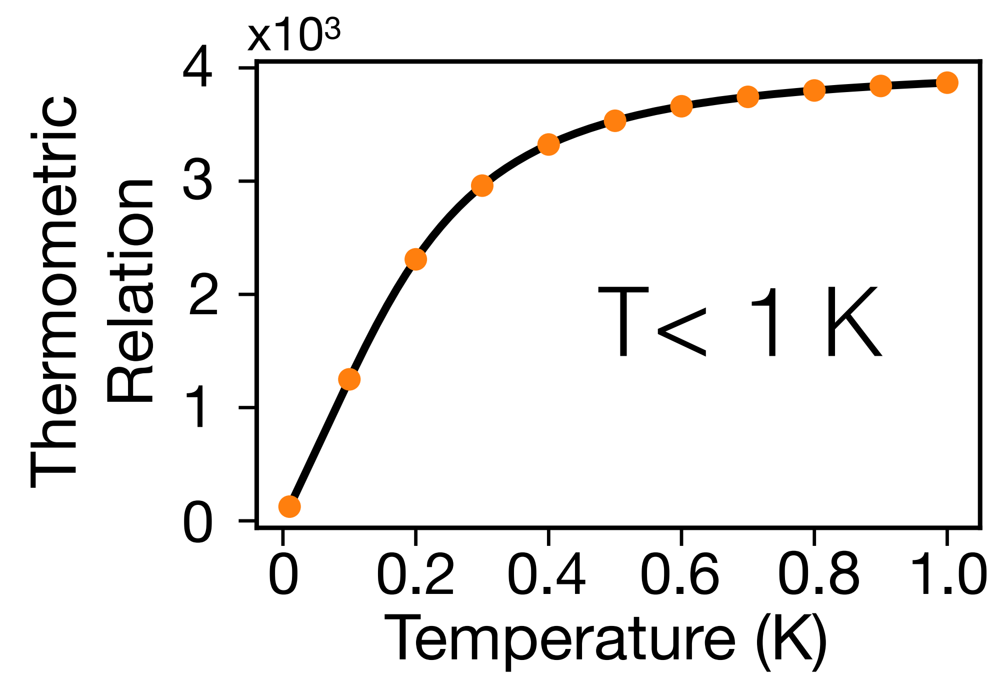
- Thermal vibrations imprinted on the magnetization
- Drive the MW at resonance and measure noise correlations

Magnon - Phonon Quantum Correlation Thermometry



Noise measurement: Effective phonon temperature

Primary thermometer



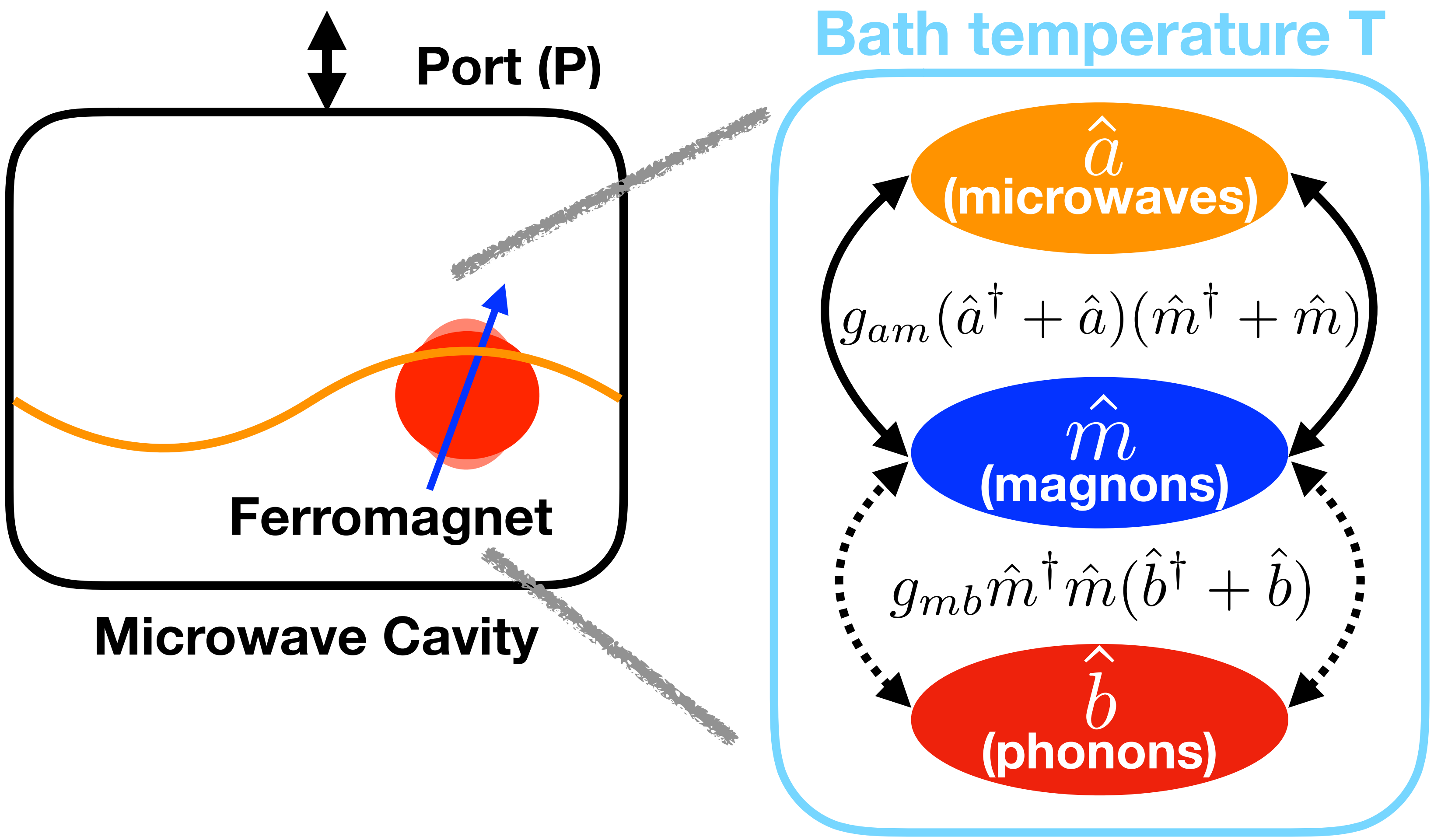
MW output noise correlation

$$\frac{\mathrm{Re}\{S_{\frac{\pi}{2},\frac{\pi}{2}}[\omega]\}}{\mathrm{Im}\{S_{0,\frac{\pi}{2}}[\omega]\}} = \frac{4\coth\left(\frac{\hbar\omega}{2k_{\mathrm{B}}T}\right)}{2n_{\mathrm{th}}+1}$$

Obtained by solving the quantum Langevin equations (input-output theory)

Measurement: two quadratures

Magnon - Phonon Quantum Correlation Thermometry



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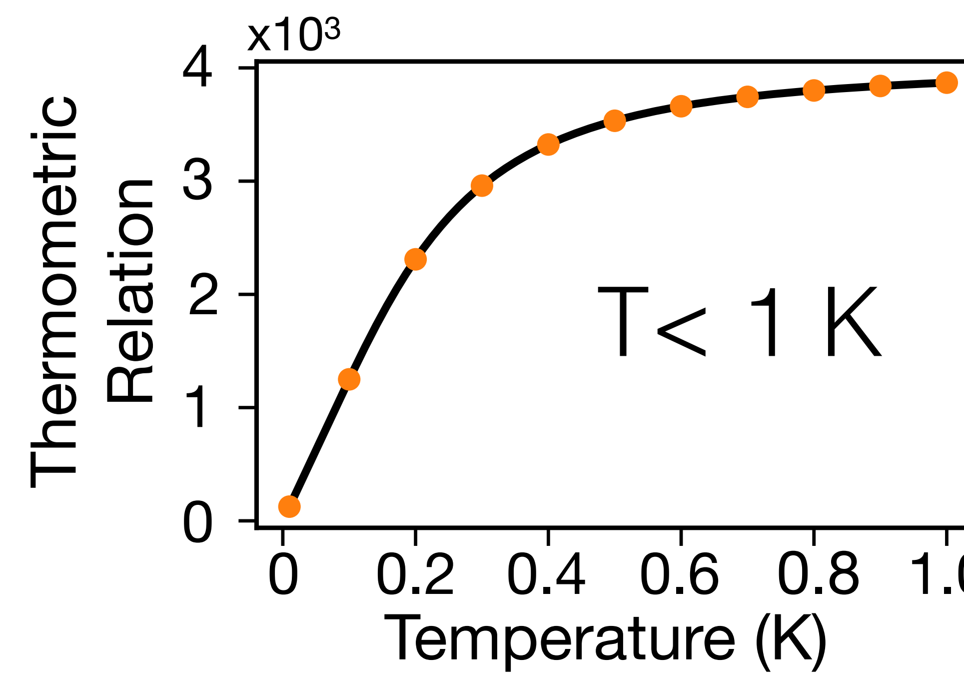
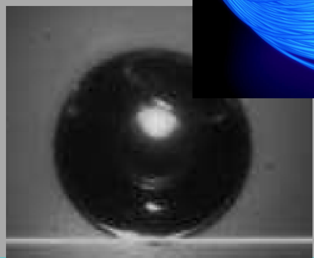
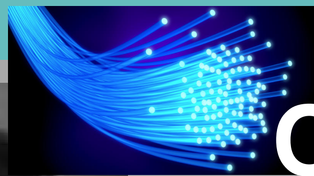


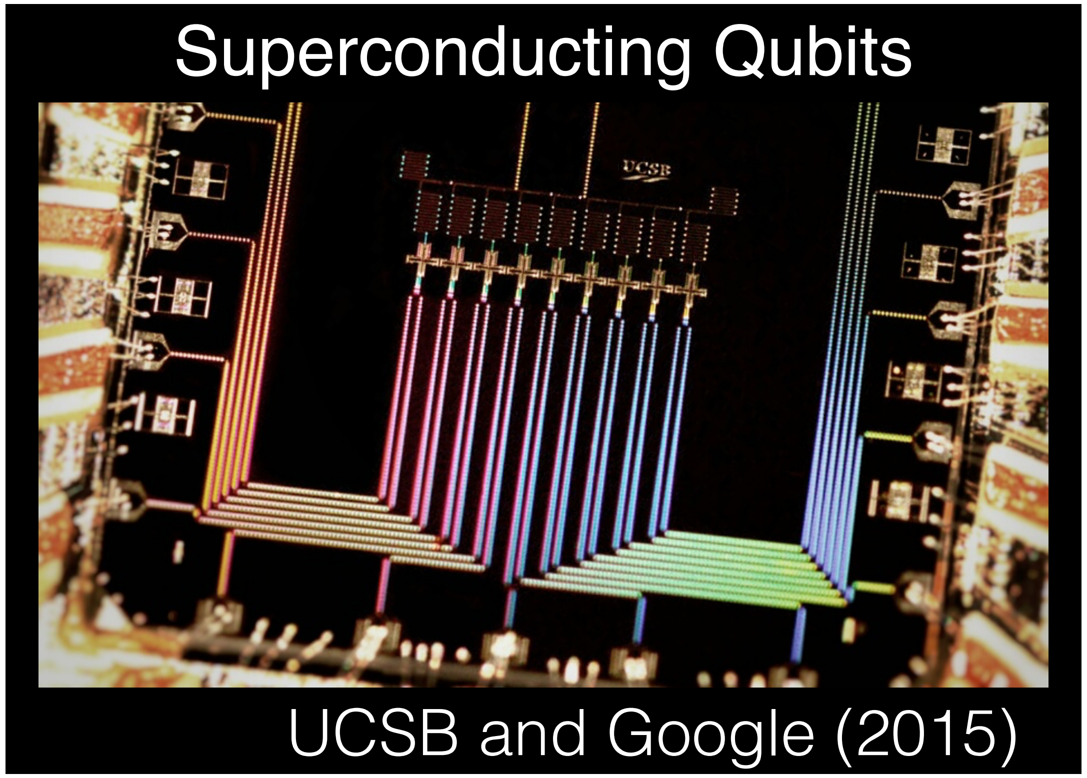
- No-calibration thermometer for cryogenic temperatures with low heating effects
- Compatible with current experimental setups
- Experimental imperfections sources: Finite detuning and deviations from the optimal driving condition

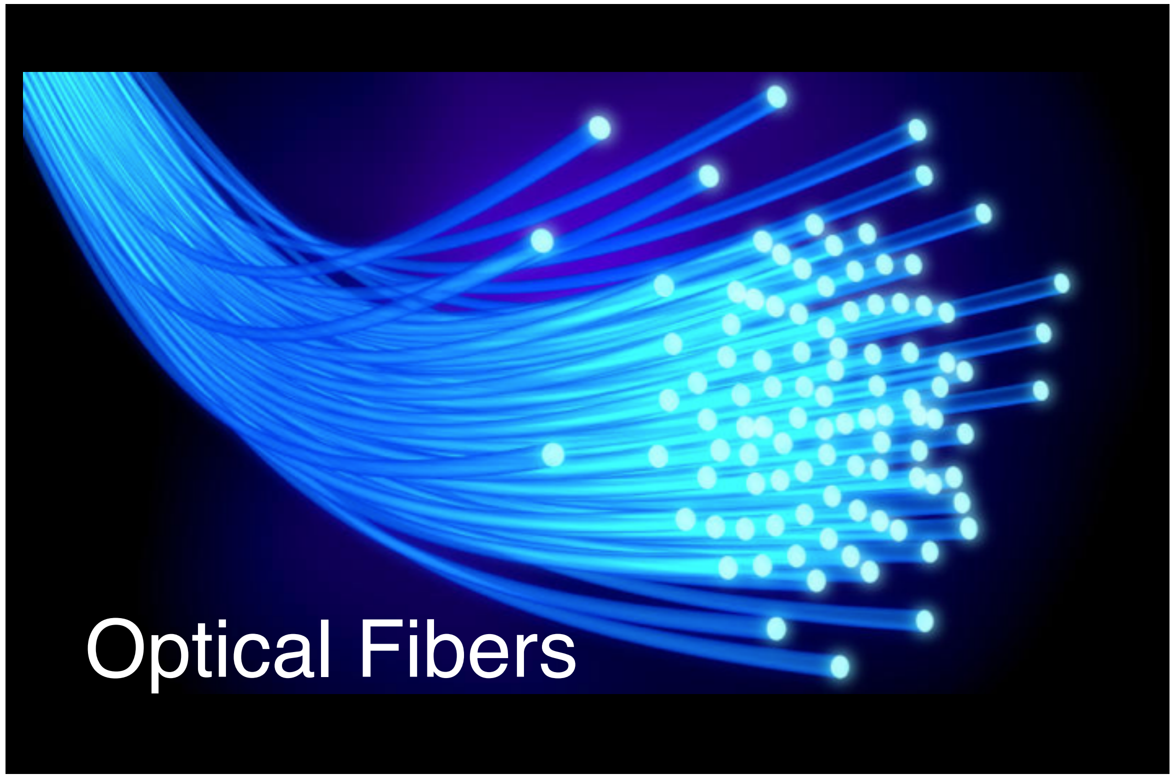
C. Potts, V. Bittencourt, SVK, John P. Davis; Phys. Rev. Applied 13, 064001 (2020)

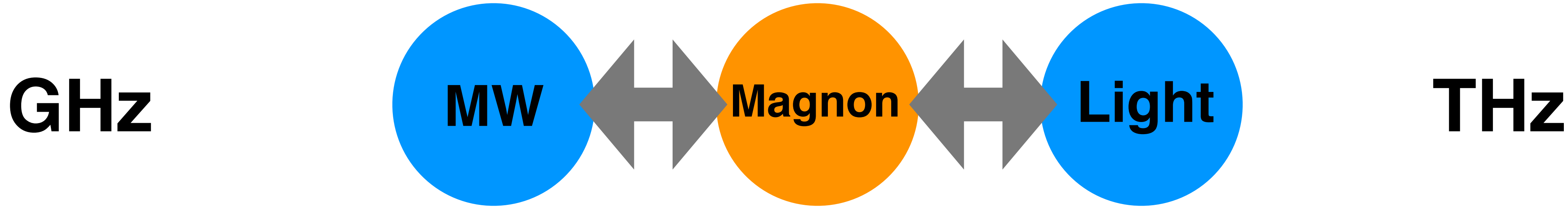



Optical regime

Coupling to Optics?



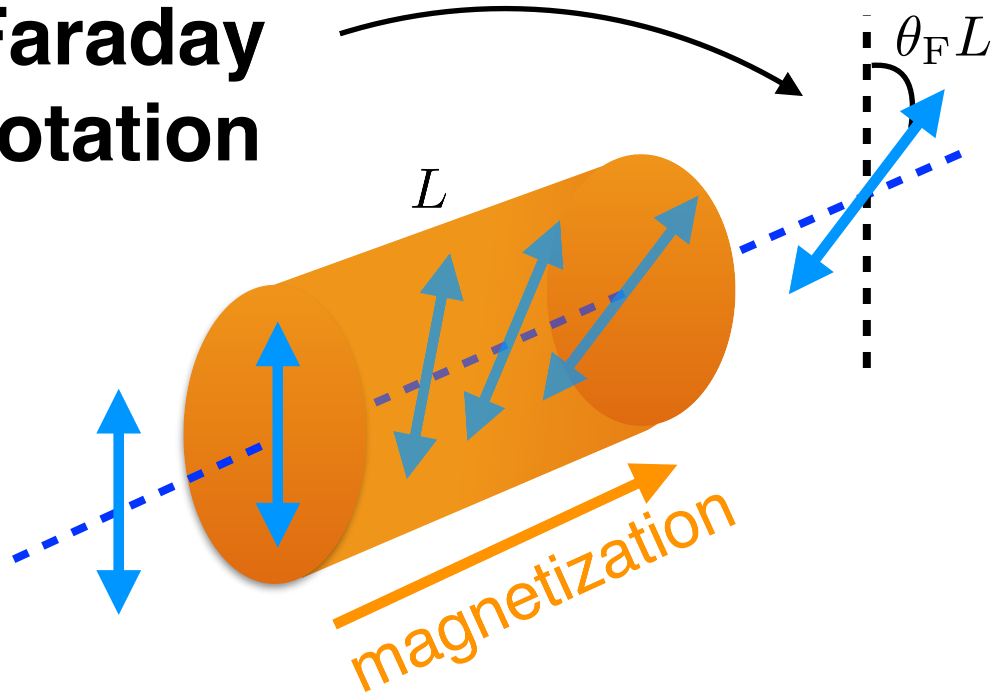




Motivation:
magnon as a transducer

Coupling to Optics?: Faraday Effect

Faraday rotation



permittivity

$$\varepsilon_{ij}\left(\mathbf{M}\right)=\varepsilon_0\ \left(\varepsilon\delta_{ij}-if\epsilon_{ijk}M_k\right)$$

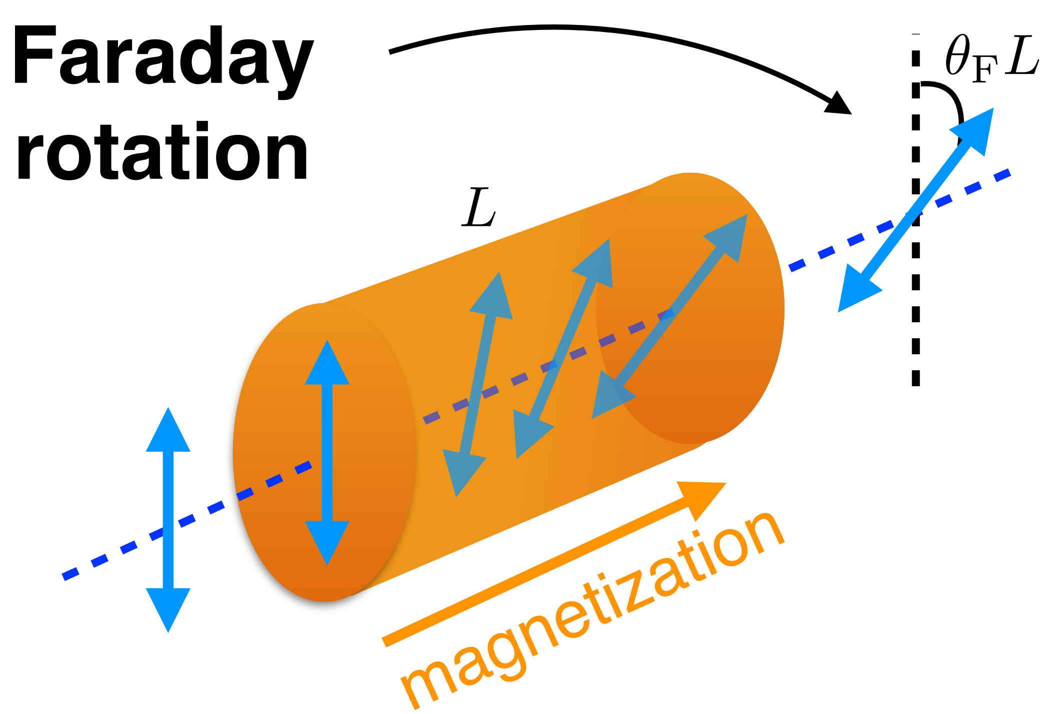
broken time-reversal symmetry

optical spin density

$$\bar{U}_{\mathrm{MO}}=\theta_{\mathrm{F}}\sqrt{\frac{\varepsilon}{\varepsilon_0}}\int \mathrm{d}\mathbf{r}\,\frac{\mathbf{M}(\mathbf{r})}{M_{\mathrm{s}}}\cdot\frac{\varepsilon_0}{2i\omega}\left[\mathbf{E}^*(\mathbf{r})\times\mathbf{E}(\mathbf{r})\right]$$

magnetization density

Coupling to Optics?: Faraday Effect



permittivity

$$\varepsilon_{ij}\left(\mathbf{M}\right)=\varepsilon_0\ \left(\varepsilon\delta_{ij}-if\epsilon_{ijk}M_k\right)$$

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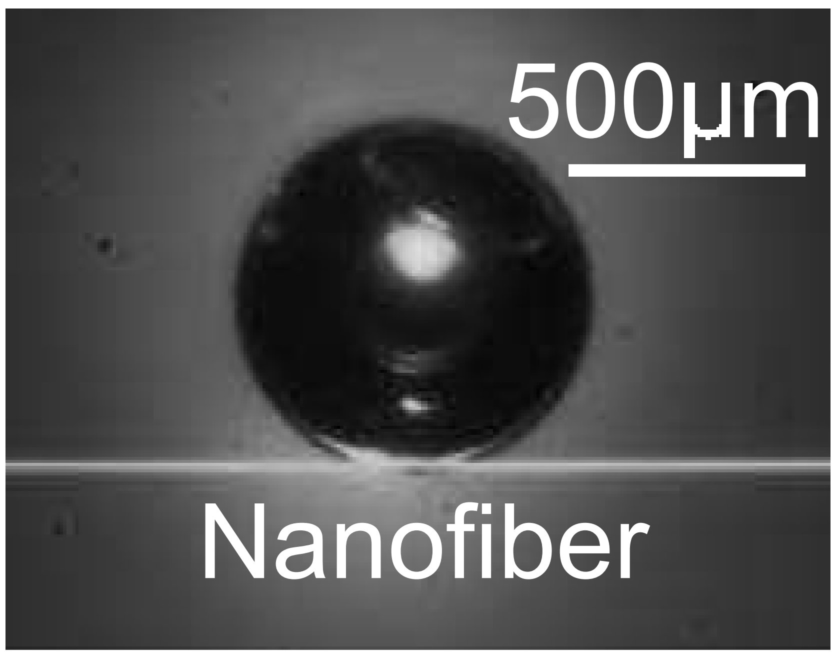
$$\bar{U}_{\mathrm{MO}}=\theta_{\mathrm{F}}\sqrt{\frac{\varepsilon}{\varepsilon_0}}\int \mathrm{d}\mathbf{r}\,\boxed{\frac{\mathbf{M}(\mathbf{r})}{M_{\mathrm{s}}}}\cdot\boxed{\frac{\varepsilon_0}{2i\omega}\left[\mathbf{E}^*(\mathbf{r})\times\mathbf{E}(\mathbf{r})\right]}$$

$\hat{\mathbf{S}}$ $\hat{a}^\dagger$ $\hat{a}$

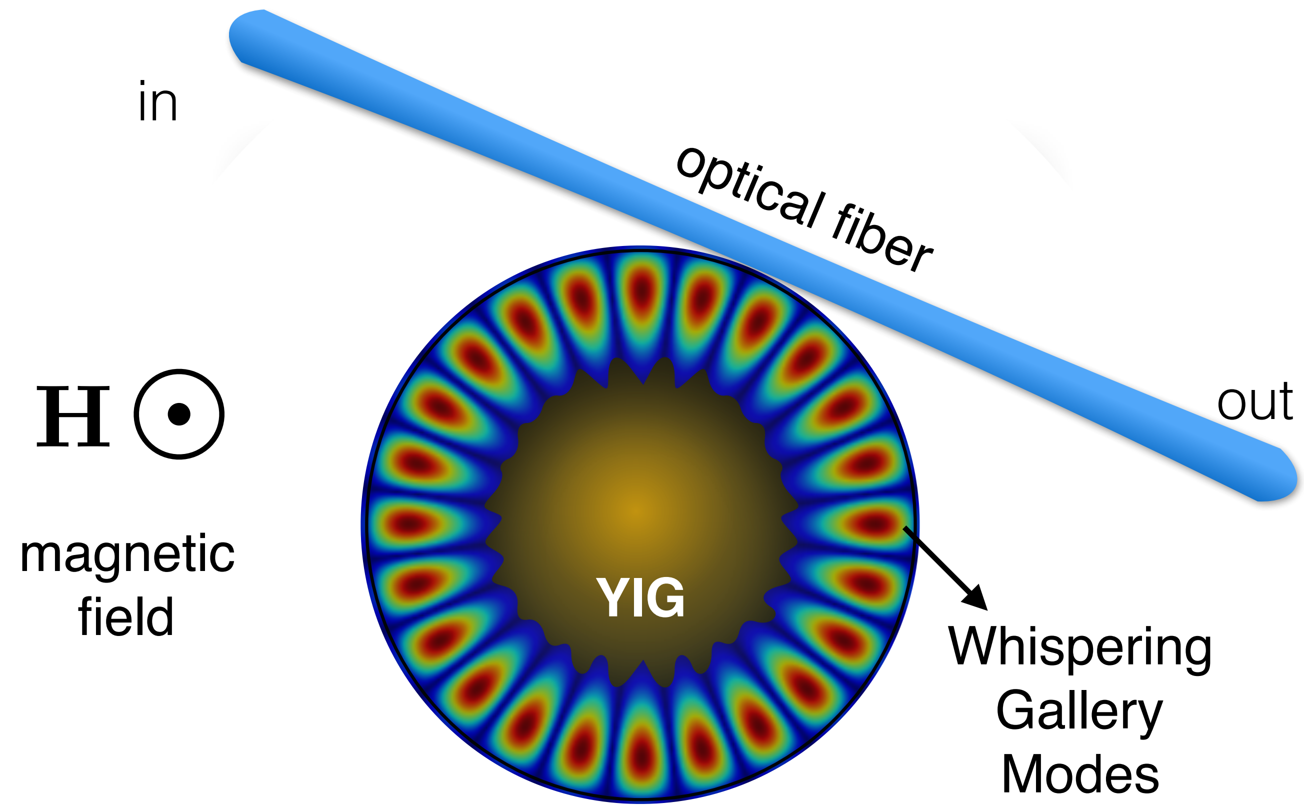
Cavity Optomagnonics

Magnons ⟷ **Optical photons**

Coupling demonstrated in 2016

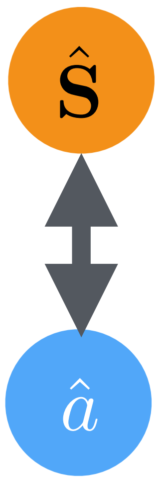


- Osada et. al PRL 116, 223601 (Nakamura's group, Tokyo)
- Haigh et. al PRL 117, 133602 (Cambridge Univ / Hitachi)
- Zhang et. al PRL 117, 123605 (Hong Tang's group, Yale)



Cavity Enhanced Coupling

But…



Problem

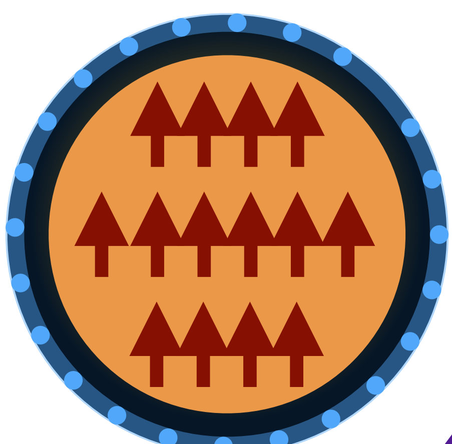
the state of the art optomagnonic coupling is small

We have shown that the theoretical limit is much larger

SVK, H. X. Tang, and F. Marquardt
PRA 94, 033821 (2016)

What we need:

better overlap of modes



?

smaller systems

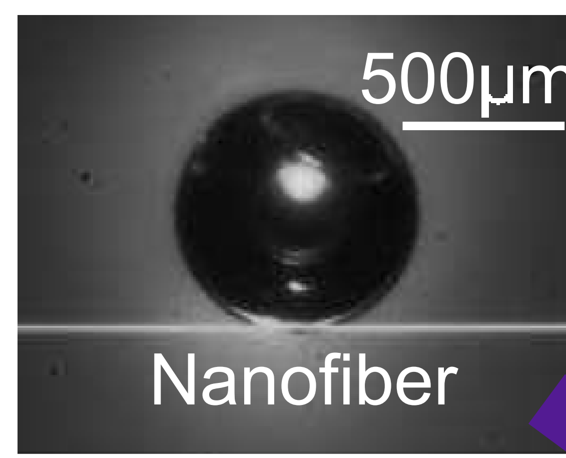
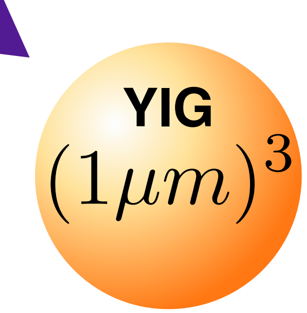
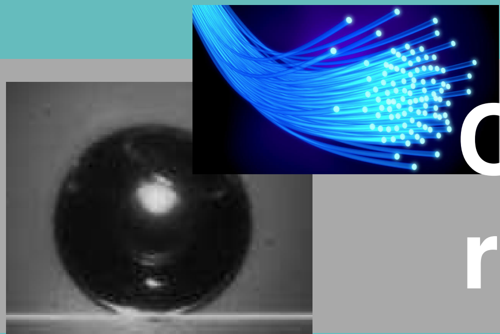


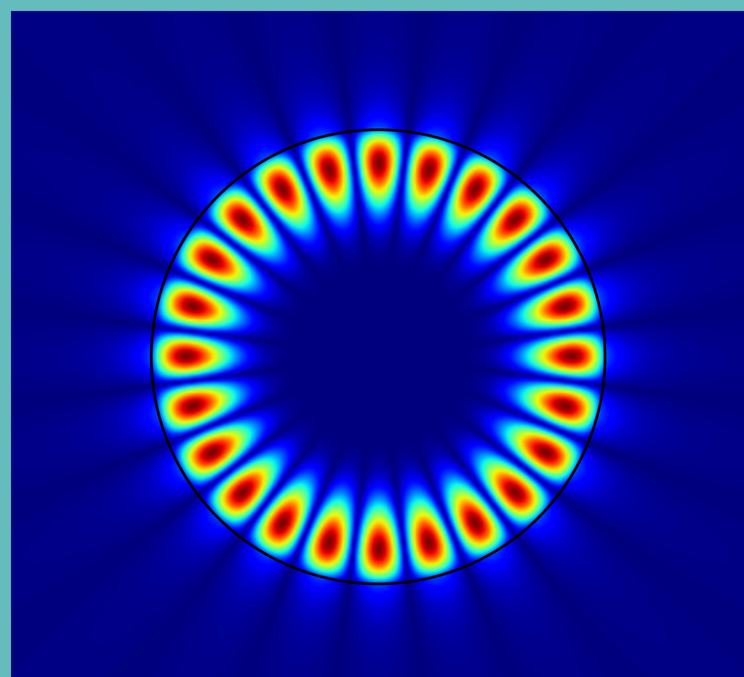
Fig: Osada et. al.
PRL 116, 223601

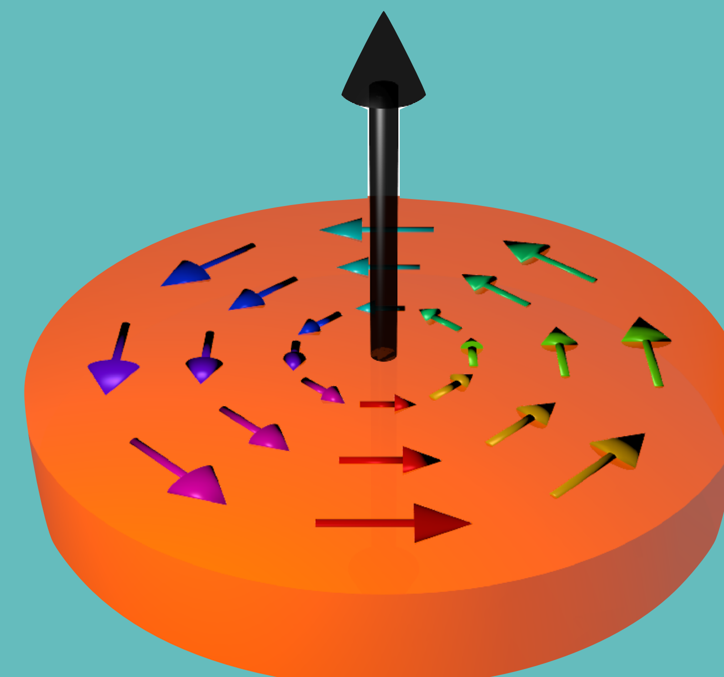




Optical regime

Optomagnonics with Magnetic textures

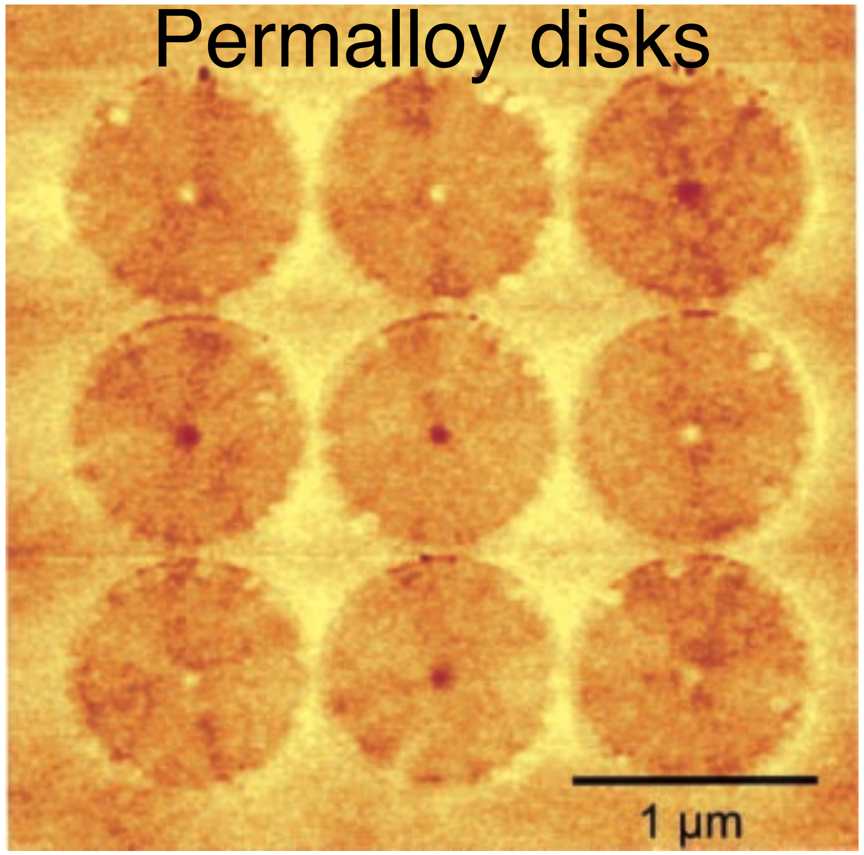




J. Graf, H. Pfeifer, F. Marquardt, SVK;

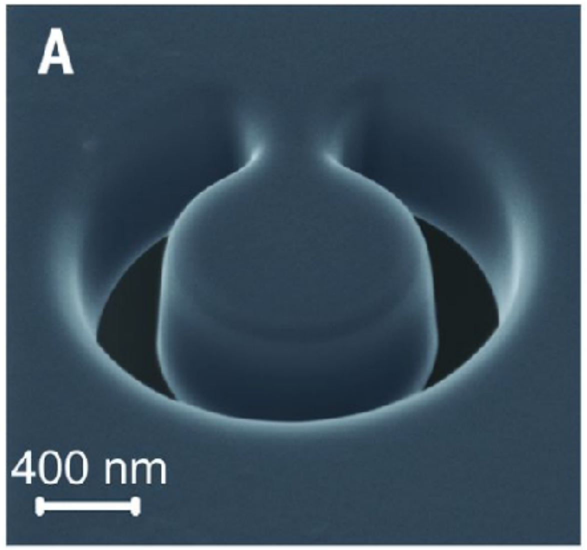
PRB 98, 241406(R) (2018)

Magnetic Textures: Vortex in Microdisks

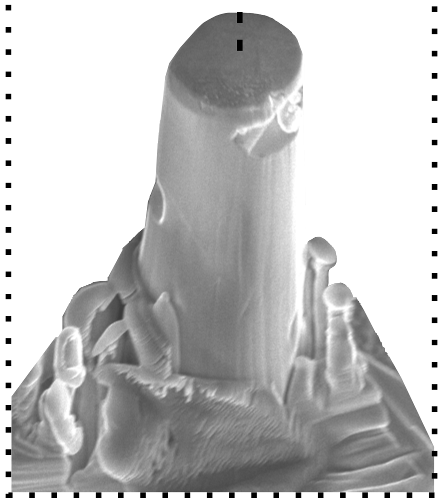


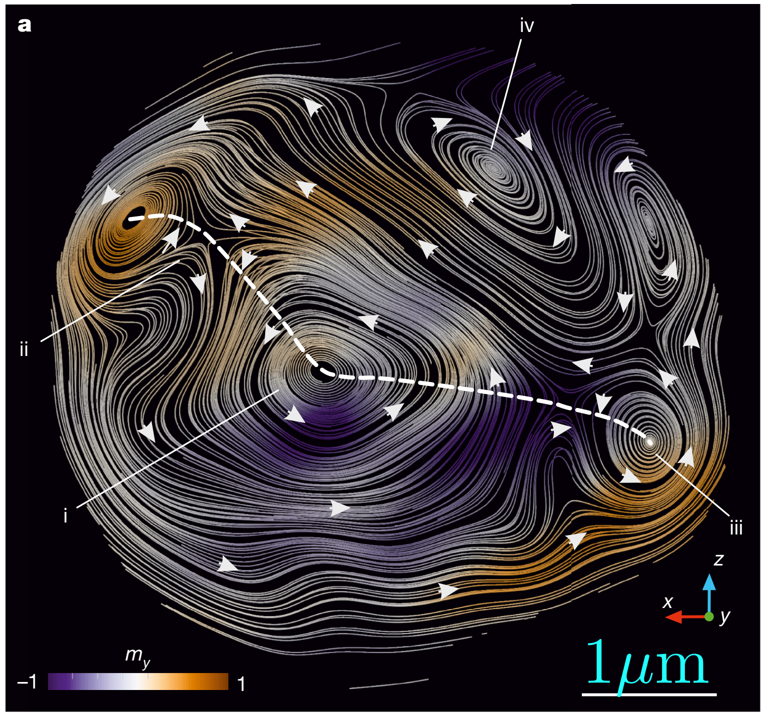
T.Shinjo et al, Science 289, 930 (2000)

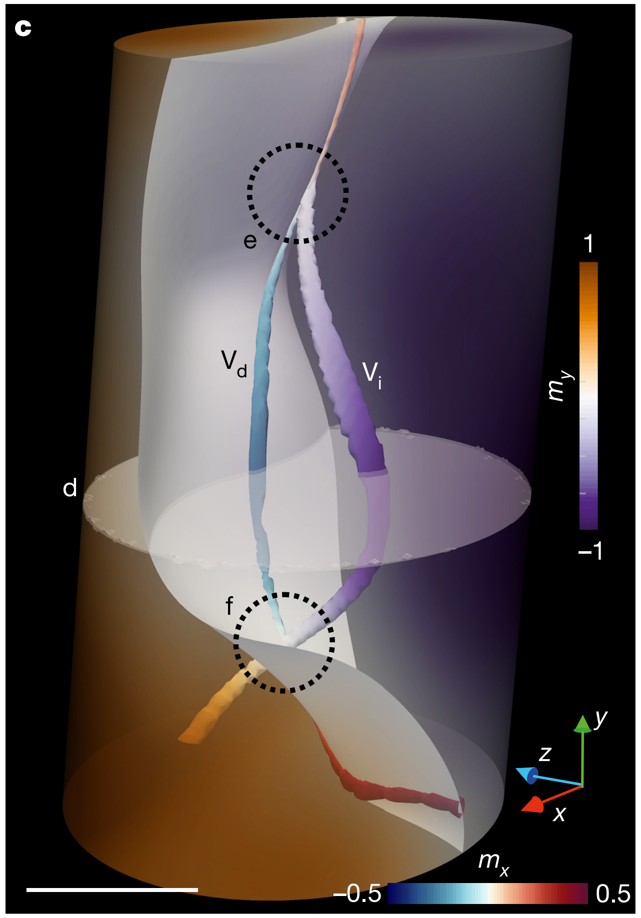
YIG disks



Losby et al, Science 350, 798 (2015)







Cobalt Gadolinium pillars

C. Donally et al, Nature 547 328 (2017)

Optomagnonics beyond the Kittel mode

$$H_{\mathrm{MO}} = -i\frac{\theta_{\mathrm{F}}\lambda_n}{2\pi}\frac{\varepsilon_0\varepsilon}{2}\int \mathrm{d}\mathbf{r}\ \mathbf{m}(\mathbf{r},t)\cdot\left[\mathbf{E}^*\left(\mathbf{r},t\right)\times\mathbf{E}\left(\mathbf{r},t\right)\right]$$

Optomagnonics beyond the Kittel mode

$$H_{\mathrm{MO}} = -i\frac{\theta_{\mathrm{F}}\lambda_n}{2\pi}\frac{\varepsilon_0\varepsilon}{2}\int \mathrm{d}\mathbf{r}\ \mathbf{m}(\mathbf{r},t)\cdot\left[\mathbf{E}^*\left(\mathbf{r},t\right)\times\mathbf{E}\left(\mathbf{r},t\right)\right]$$

$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}_0(\mathbf{r}) + \delta\mathbf{m}(\mathbf{r},t)$$

small

Optomagnonics beyond the Kittel mode

$$H_{\mathrm{MO}} = -i\frac{\theta_{\mathrm{F}}\lambda_n}{2\pi}\frac{\varepsilon_0\varepsilon}{2}\int \mathrm{d}\mathbf{r}\ \mathbf{m}(\mathbf{r},t)\cdot\left[\mathbf{E}^*\left(\mathbf{r},t\right)\times\mathbf{E}\left(\mathbf{r},t\right)\right]$$

$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}_0(\mathbf{r}) + \delta\mathbf{m}(\mathbf{r},t)$$

Quantize: Holstein Primakoff to first order

$$\delta\mathbf{m}(\mathbf{r},t) \rightarrow \frac{1}{2}\sum_{\gamma}\left(\delta\mathbf{m}_\gamma(\mathbf{r})\hat{b}_\gamma e^{-i\omega_\gamma t} + \delta\mathbf{m}_\gamma^*(\mathbf{r})\hat{b}_\gamma^\dagger e^{i\omega_\gamma t}\right)$$

magnon mode index

bosonic operator

mode functions

Optomagnonics beyond the Kittel mode

$$H_{\mathrm{MO}} = -i\frac{\theta_{\mathrm{F}}\lambda_n}{2\pi}\frac{\varepsilon_0\varepsilon}{2}\int \mathrm{d}\mathbf{r}\ \mathbf{m}(\mathbf{r},t)\cdot\left[\mathbf{E}^*\left(\mathbf{r},t\right)\times\mathbf{E}\left(\mathbf{r},t\right)\right]$$

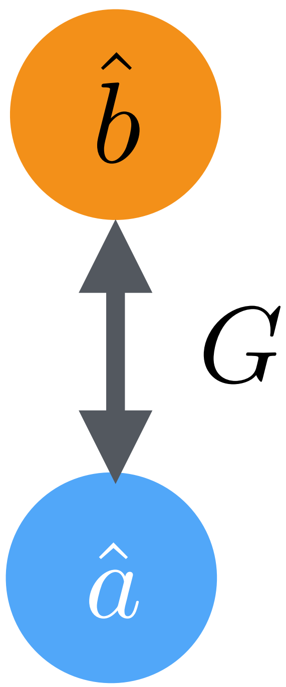
$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}_0(\mathbf{r}) + \delta\mathbf{m}(\mathbf{r},t)$$

$$\delta\mathbf{m}(\mathbf{r},t) \to \frac{1}{2}\sum_\gamma\left(\delta\mathbf{m}_\gamma(\mathbf{r})\hat{b}_\gamma e^{-i\omega_\gamma t} + \delta\mathbf{m}^*_\gamma(\mathbf{r})\hat{b}^\dagger_\gamma e^{i\omega_\gamma t}\right)$$

$$\mathbf{E}^{(*)}(\mathbf{r},t) \to \sum_\beta \mathbf{E}^{(*)}_\beta(\mathbf{r})\hat{a}^{(\dagger)}_\beta e^{-(+)i\omega_\beta t}$$

Optomagnonics beyond the Kittel mode

Optomagnonic Hamiltonian in the spin-wave limit



$$\hat{H}_{MO} = \sum_{\alpha\beta\gamma} G_{\alpha\beta\gamma} \hat{a}^{\dagger}_{\alpha} \hat{a}_{\beta} \hat{b}_{\gamma} + \mathrm{h.c.}$$

Optomagnonic coupling

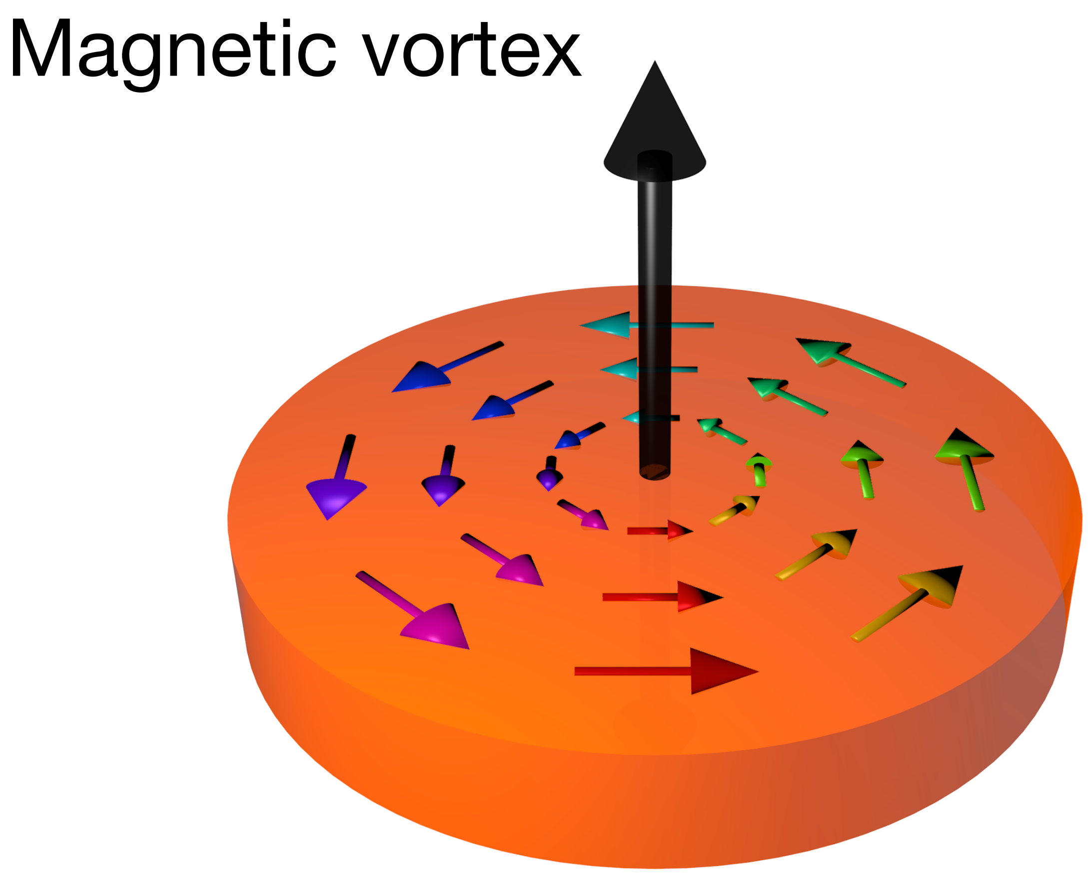
$$\boxed{G_{\alpha\beta\gamma} = -i \frac{\theta_{\mathrm{F}} \lambda_n}{4\pi} \frac{\varepsilon_0 \varepsilon}{2} \int \mathrm{d}\mathbf{r}\, \delta\mathbf{m}_{\gamma}(\mathbf{r}) \cdot [\mathbf{E}^{*}_{\alpha}(\mathbf{r}) \times \mathbf{E}_{\beta}(\mathbf{r})]}$$

magnon mode function

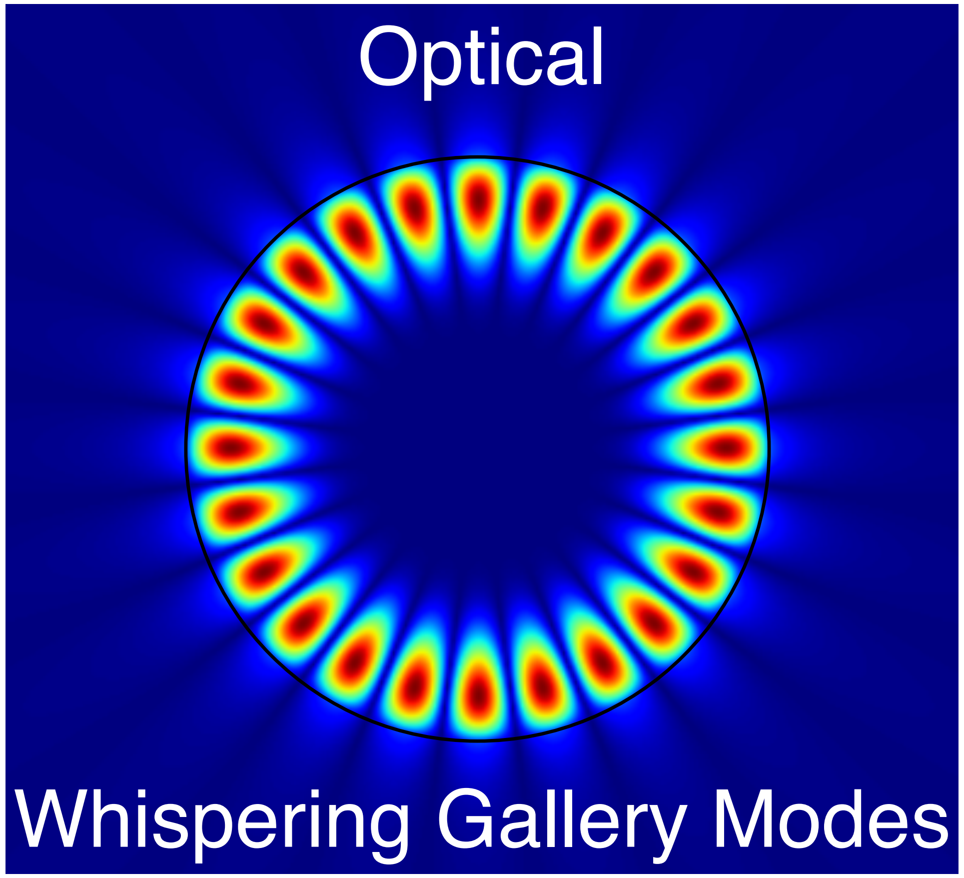
photon mode functions

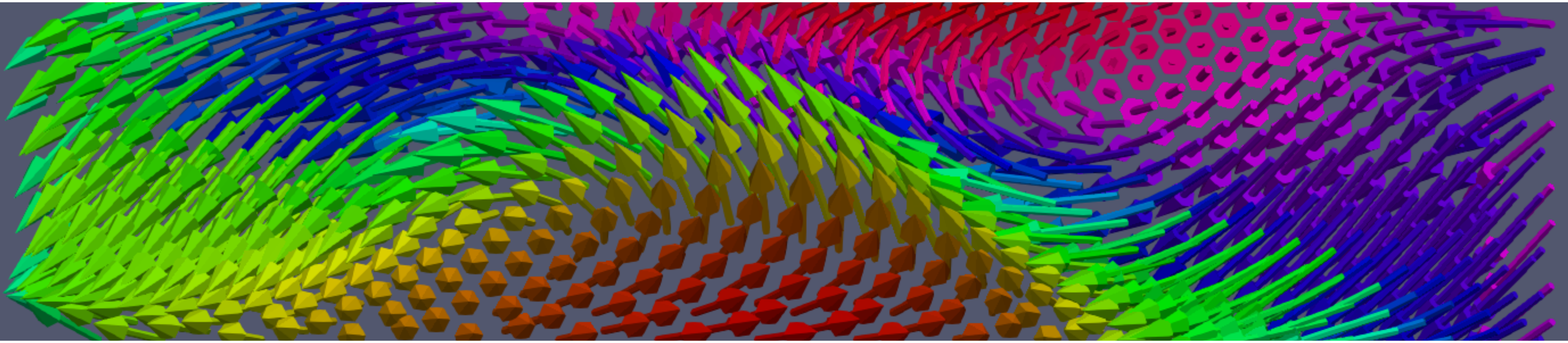
J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, Phys. Rev. B 98, 241406(R), (2018)

Nanostrutures: magnetic textures + light



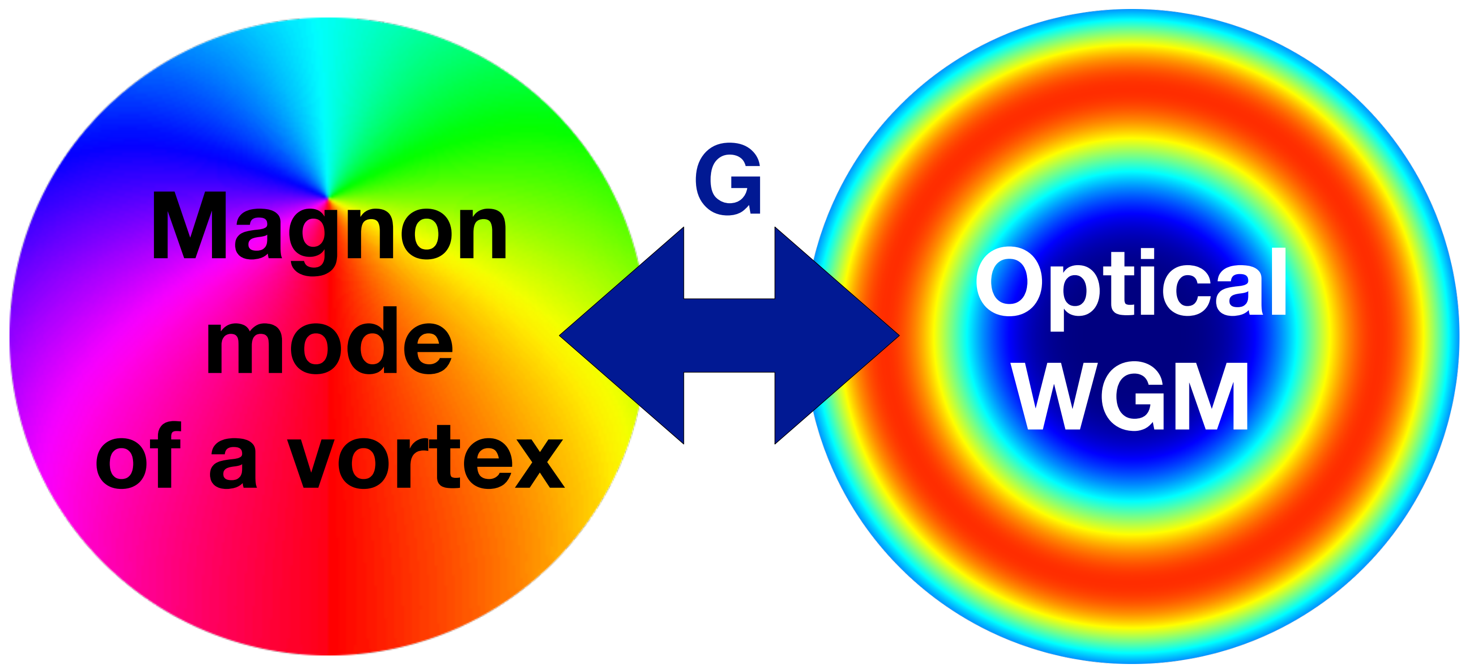
+





Optomagnonic Coupling

$$G_{\alpha\beta\gamma} = -i\frac{\theta_{\mathrm{F}}\lambda_n}{4\pi}\frac{\varepsilon_0\varepsilon}{2}\int \mathrm{d}\mathbf{r}\,\delta\mathbf{m}_\gamma(\mathbf{r})\cdot\left[\mathbf{E}^*_\alpha(\mathbf{r})\times\mathbf{E}_\beta(\mathbf{r})\right]$$

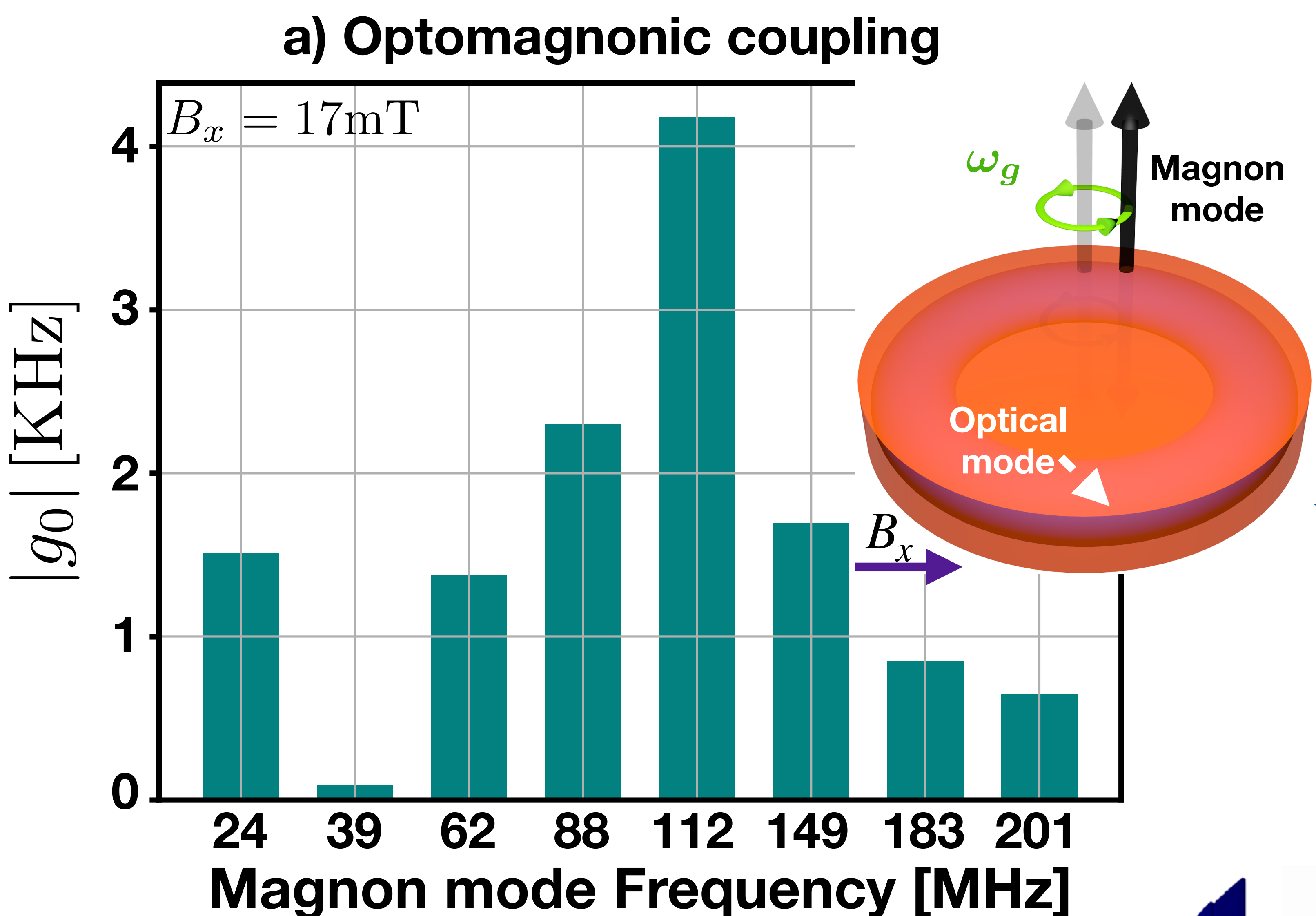


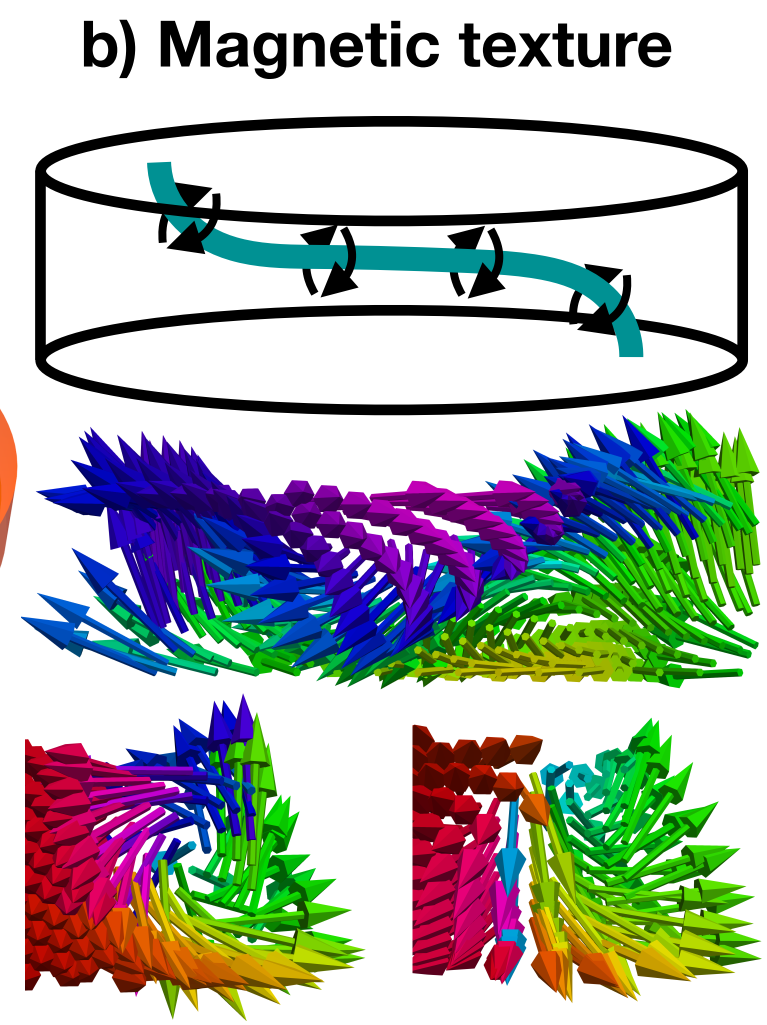
MuMax3
Vansteenkiste et. al AIP Advances 4, 107133 (2014)

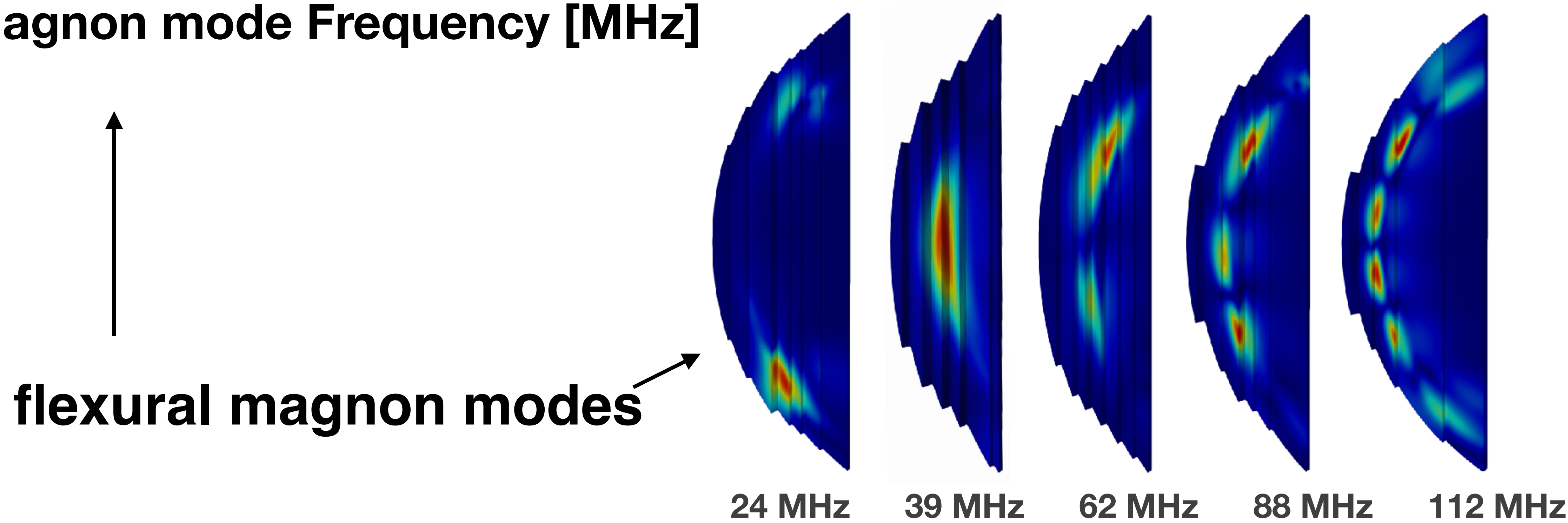
micromagnetics | **finite element**

Simulation software

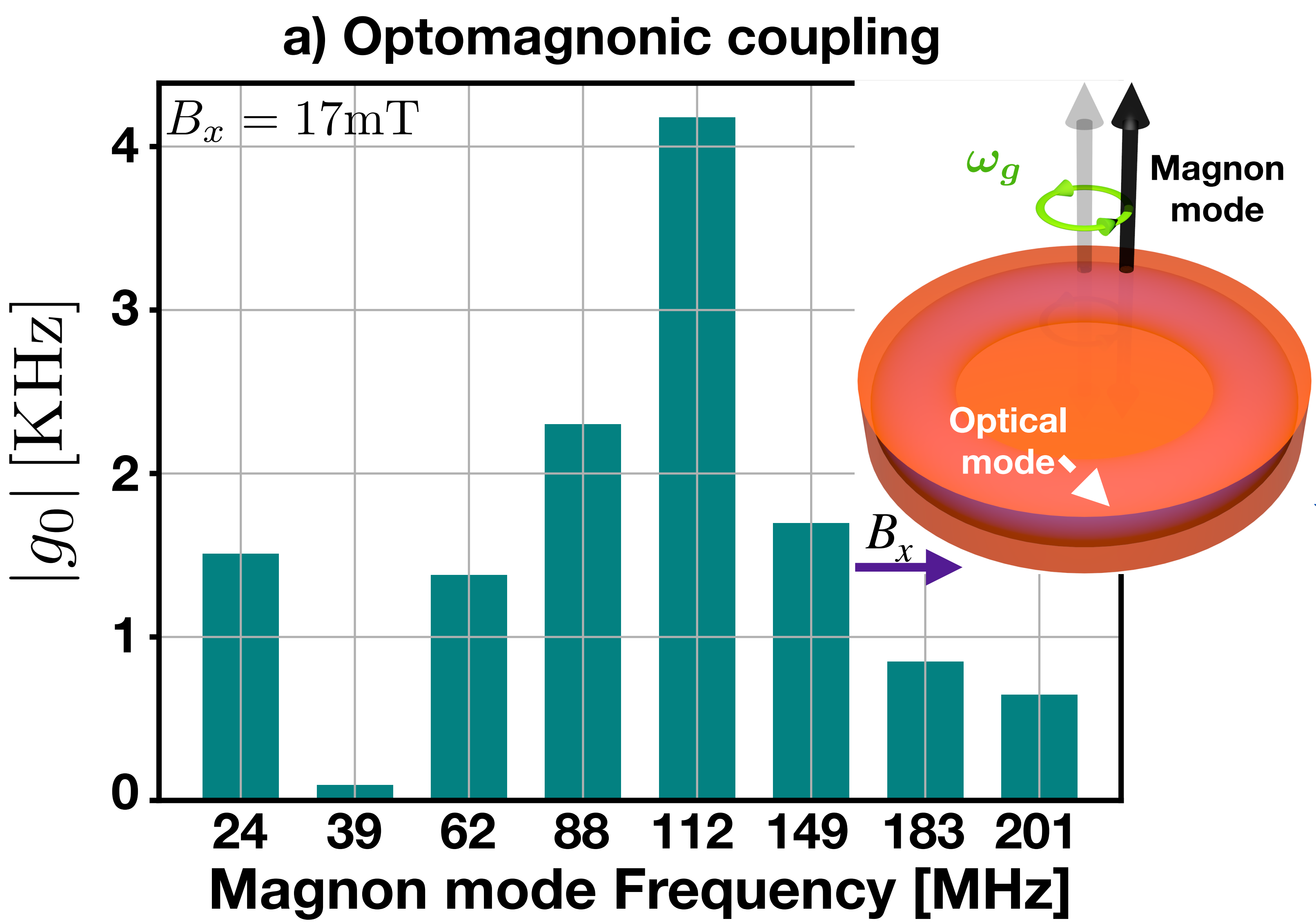
Nanostrutures: magnetic textures + light

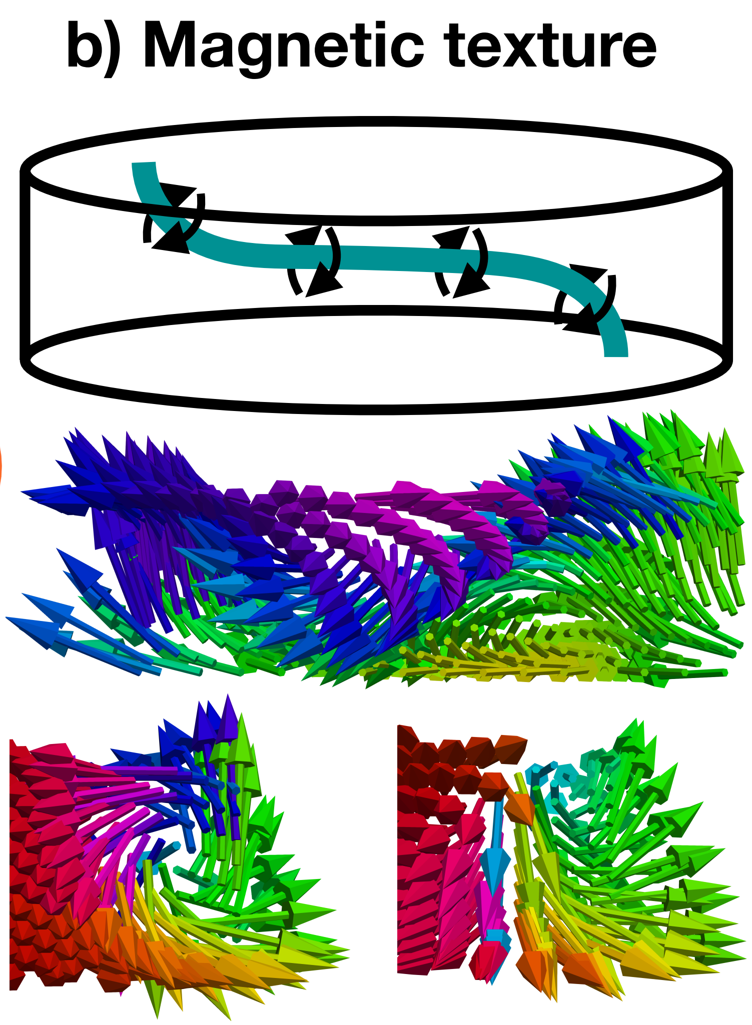






Nanostrutures: magnetic textures + light

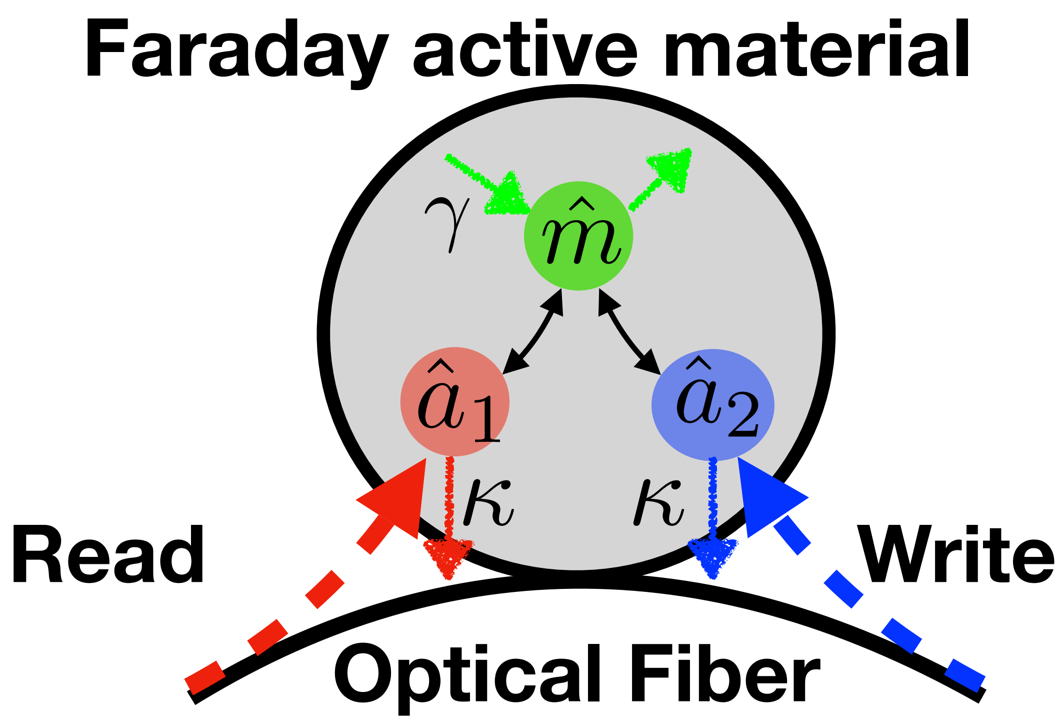




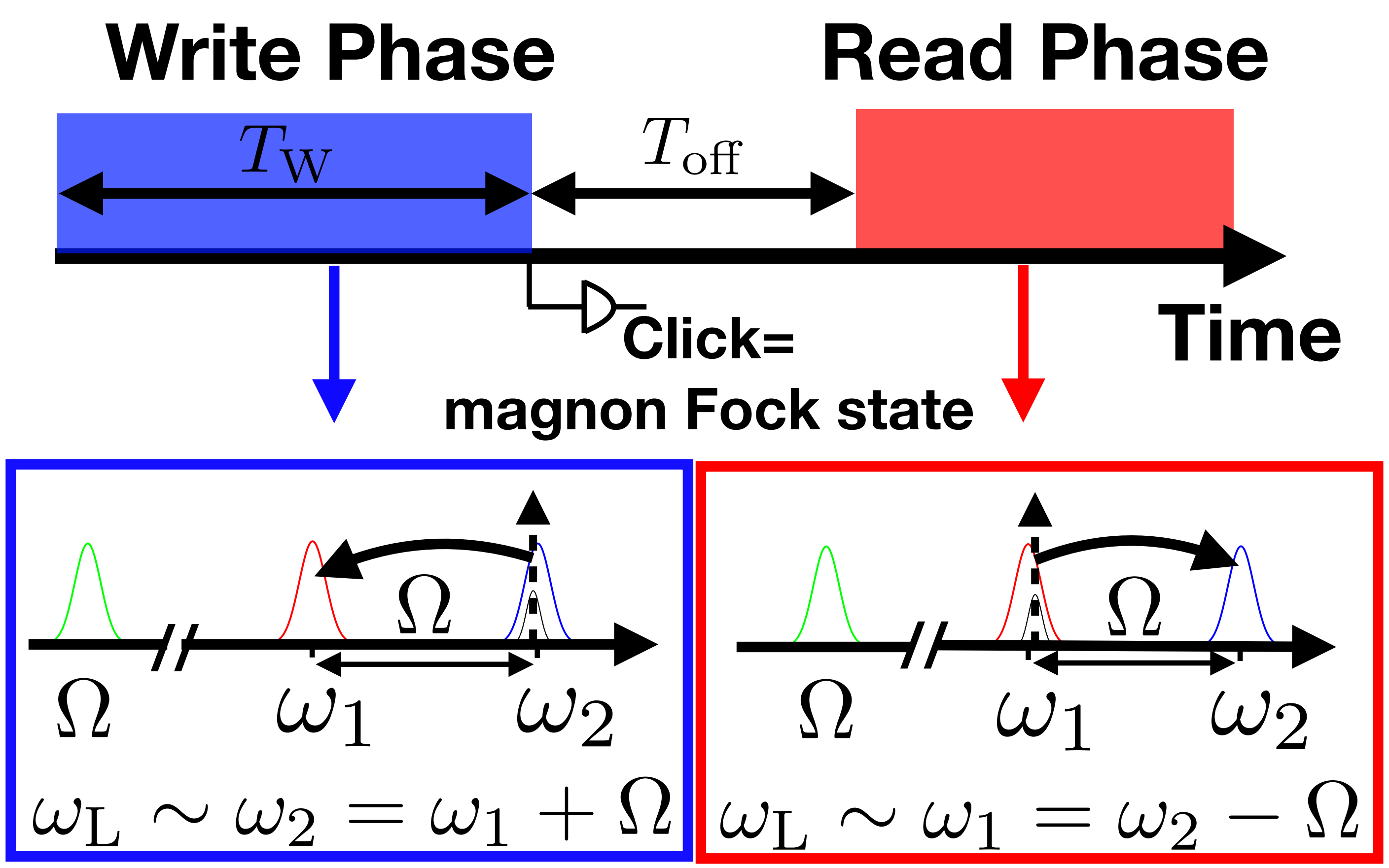
- Coupling for each mode tunable by a magnetic field
- Predicted cooperativity $$\mathcal{C} = 4n_{\mathrm{ph}}\frac{g_0^2}{\Gamma\kappa} \approx 10^{-2}$$

J. Graf, H. Pfeifer, F. Marquardt, SVK; Phys. Rev. B 98, 241406(R), (2018)

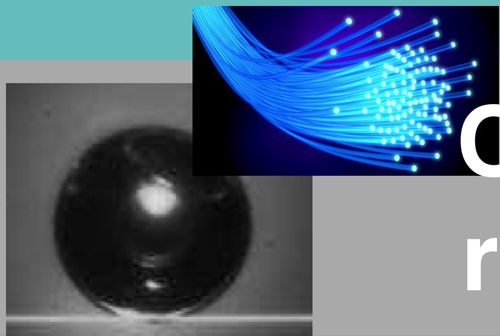
Application: Magnon heralding



All-optical protocol for generating magnon Fock states

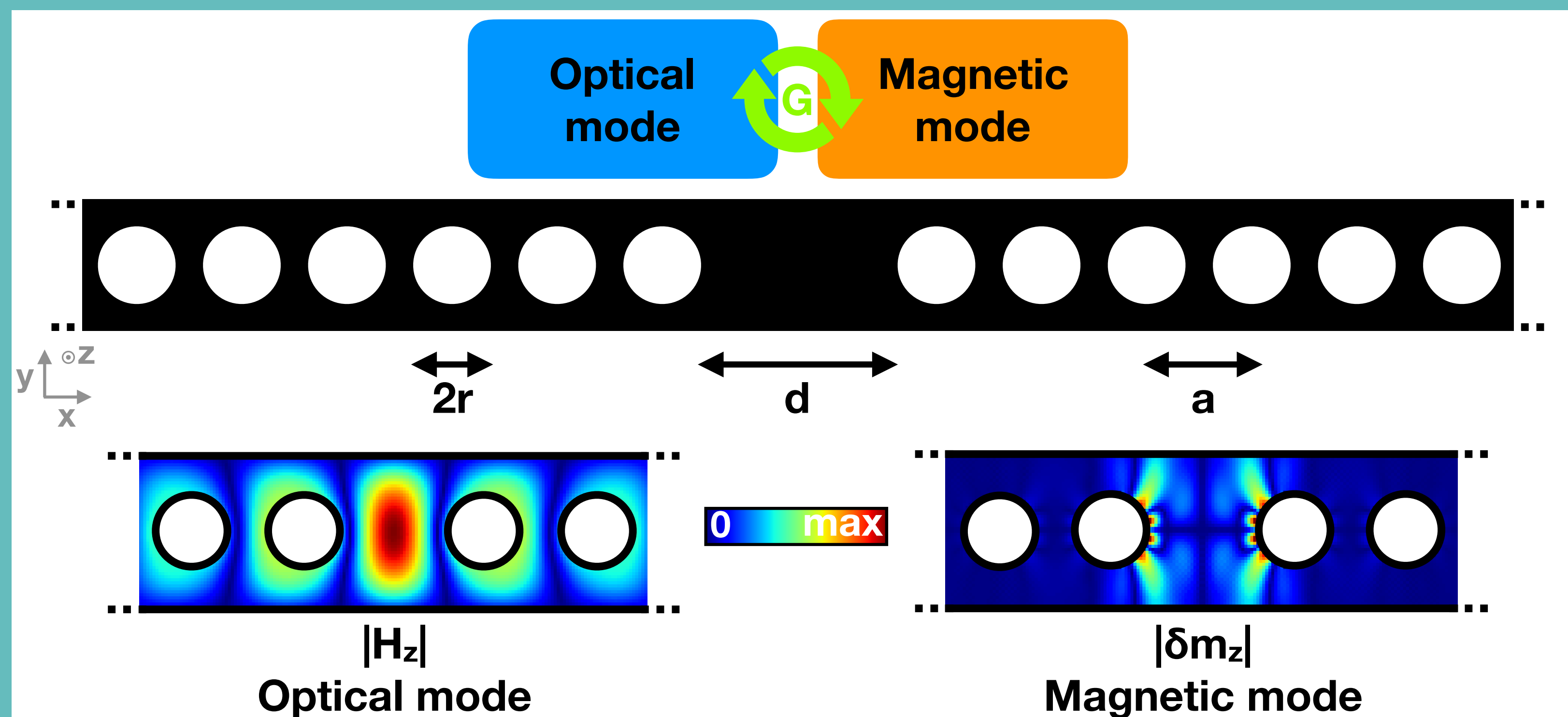


V. Bittencourt, V. Feulner, SVK;
PRA **100**, 013810 (2019)



Optical regime

Optomagnonic crystals



J. Graf, S. Sharma, H. Huebl, SVK;
Physical Review Research 3, 013277 (2021)

MAX PLANCK INSTITUTE FOR THE SCIENCE OF LIGHT

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

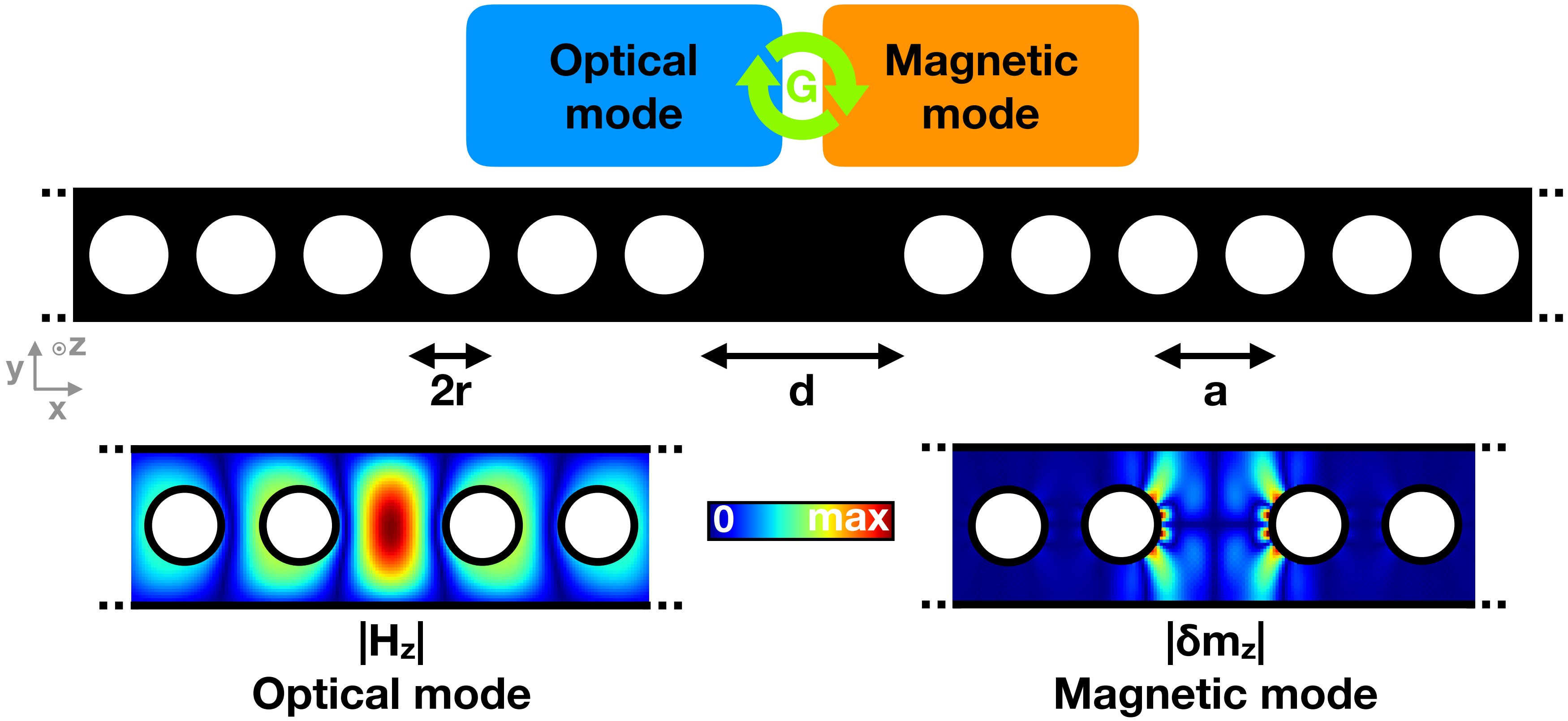
WMI

TUM

MCQST

Optomagnonic Coupling

$$G_{\alpha\beta\gamma} = -i\frac{\theta_\mathrm{F}\lambda_n}{4\pi}\frac{\varepsilon_0\varepsilon}{2}\int \mathrm{d}\mathbf{r}\,\delta\mathbf{m}_\gamma(\mathbf{r})\cdot\left[\mathbf{E}^*_\alpha(\mathbf{r})\times\mathbf{E}_\beta(\mathbf{r})\right]$$

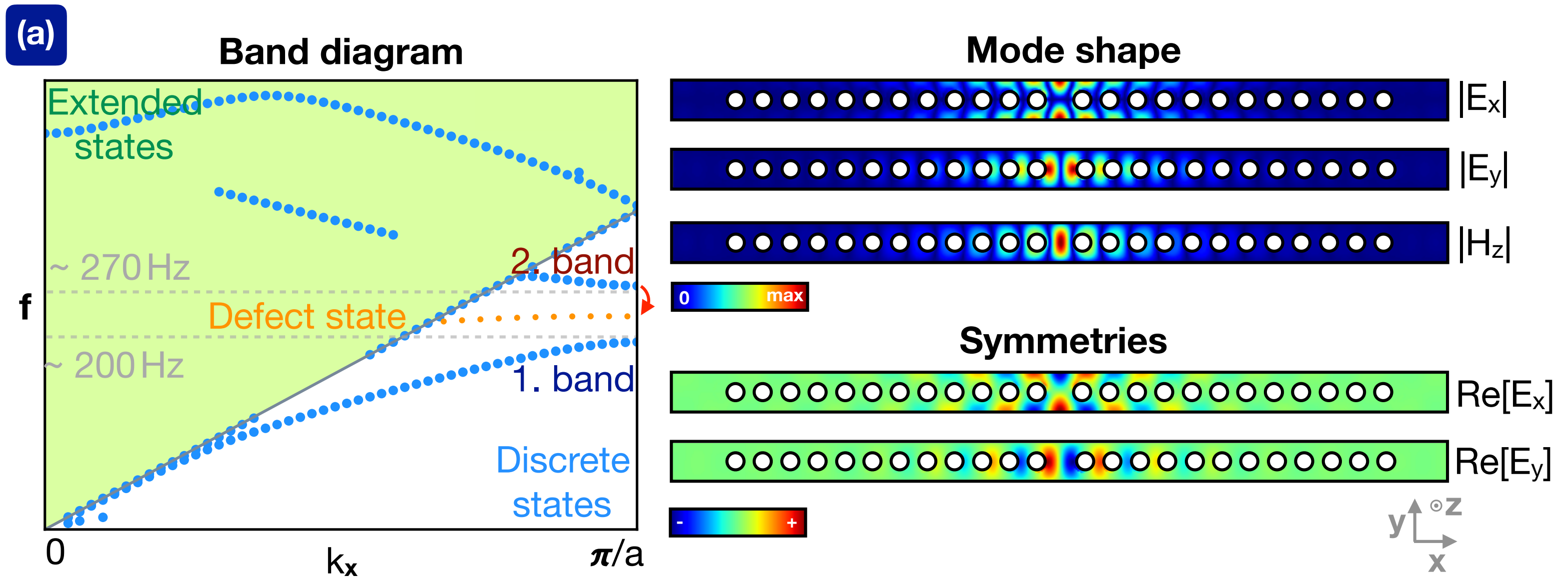


finite element

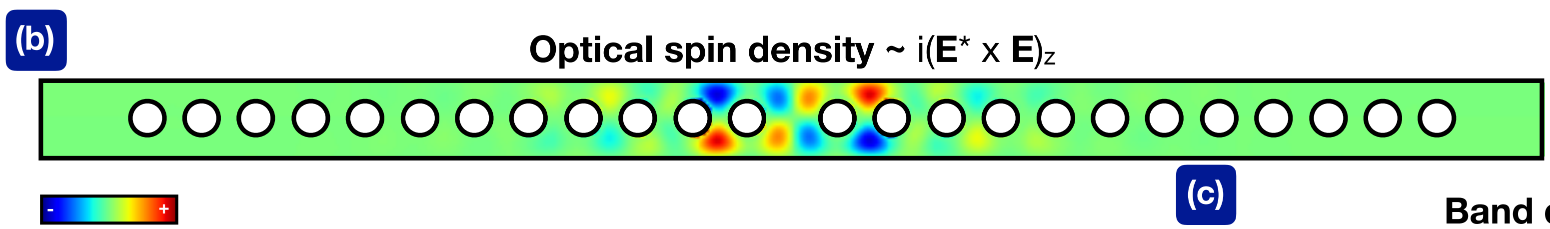
micromagnetics

Design: towards optimal mode matching

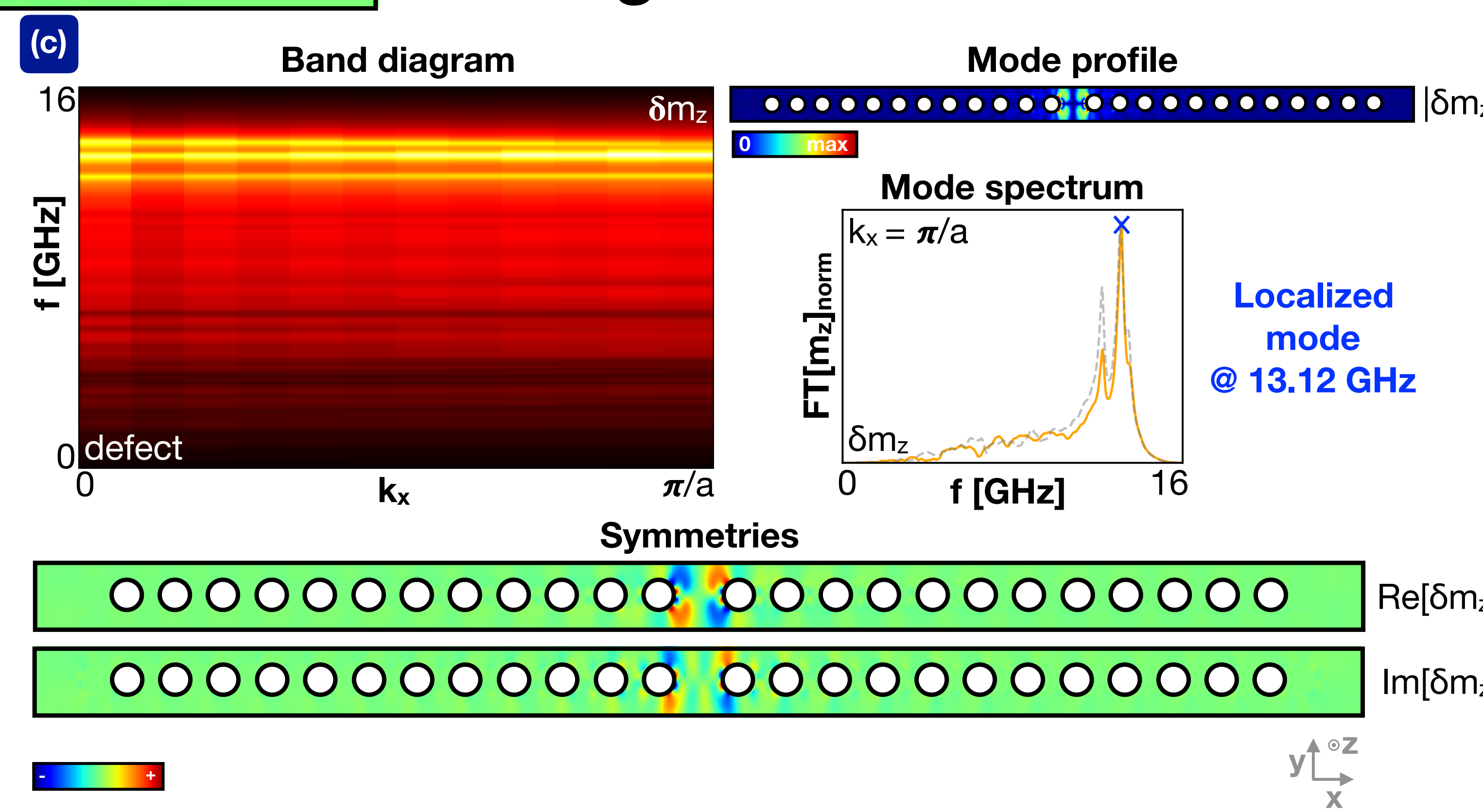
Optics



→ Localized optical mode



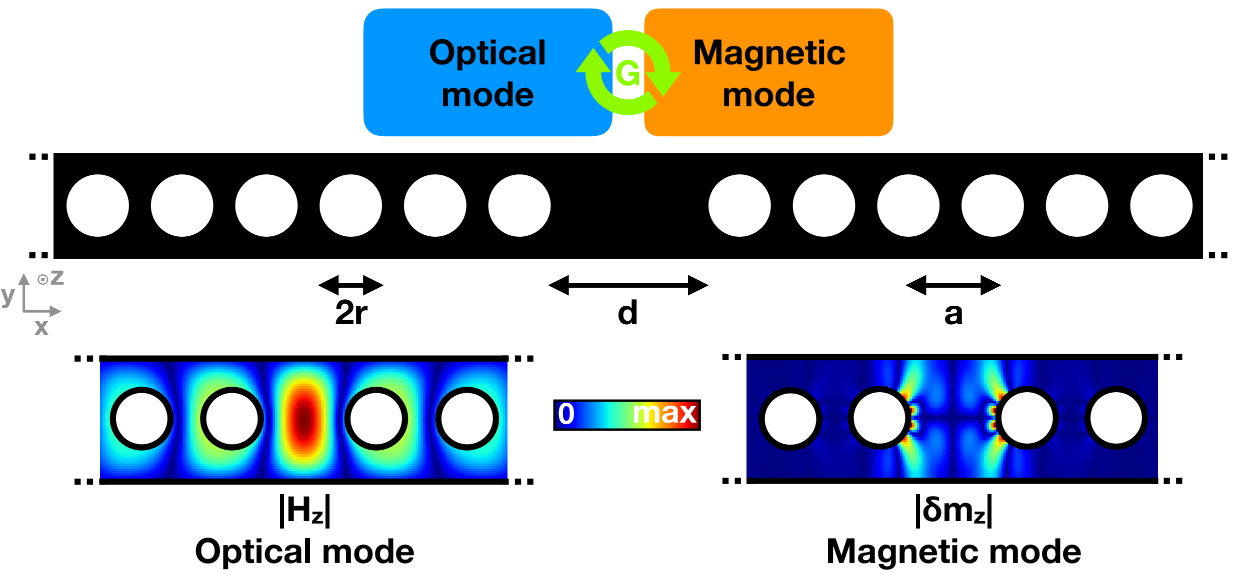
Magnetics

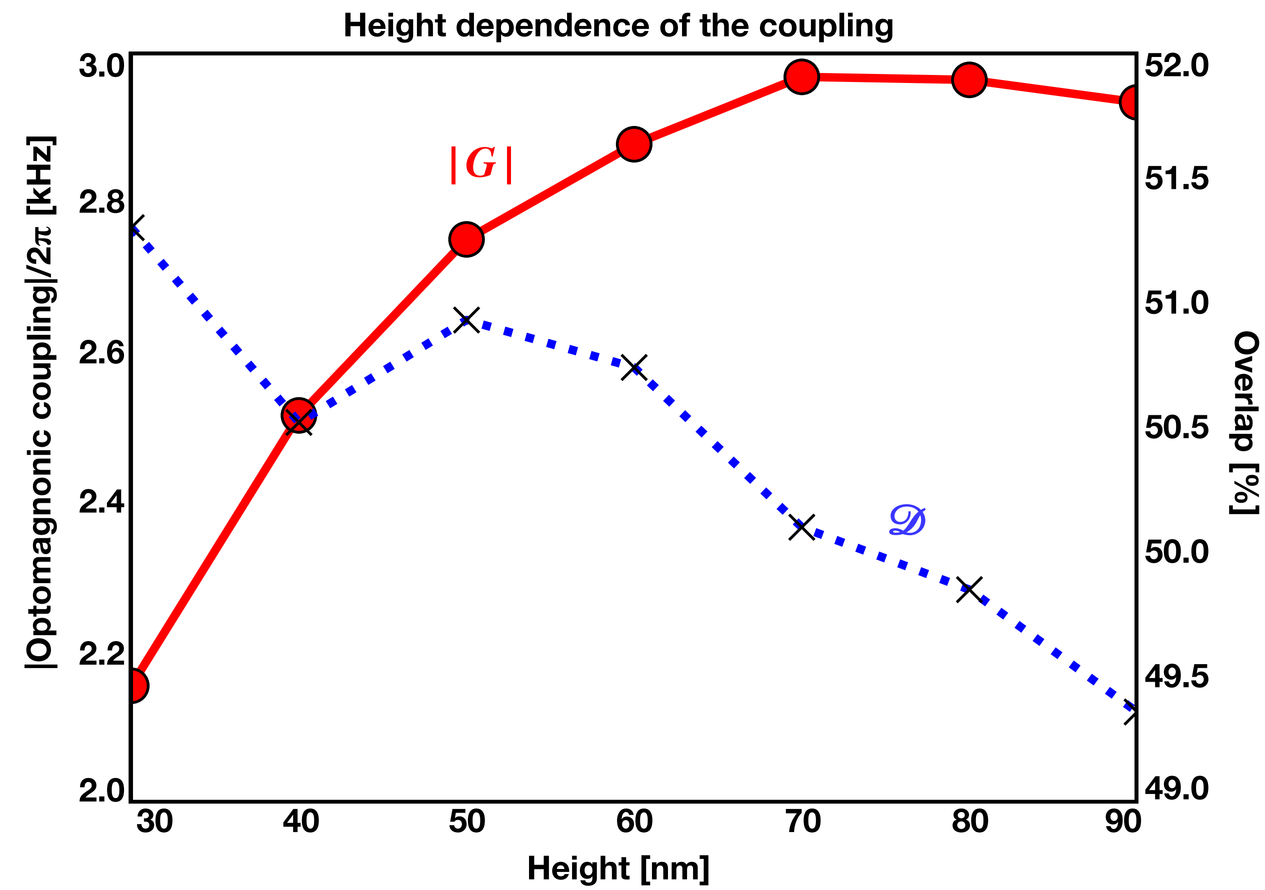


Localized magnon mode ←

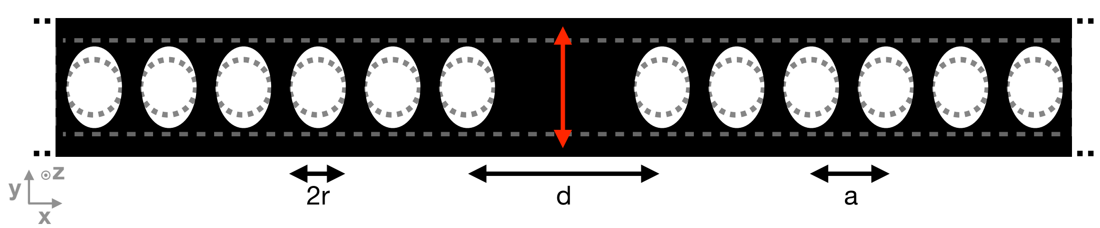
Match symmetries of magnon mode and optical spin density

Design: towards optimal mode matching

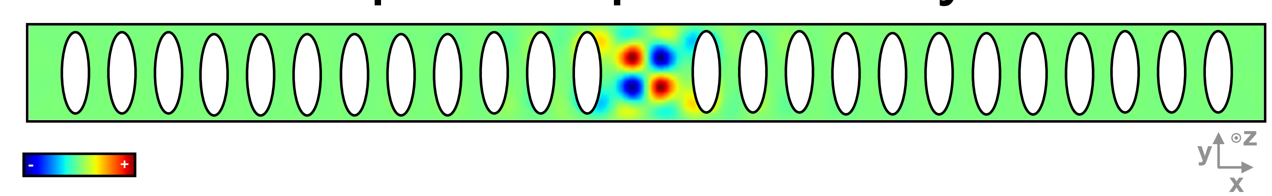




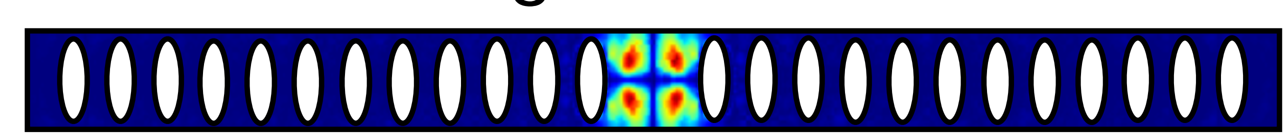
Optimization



Optical spin density



Magnon mode



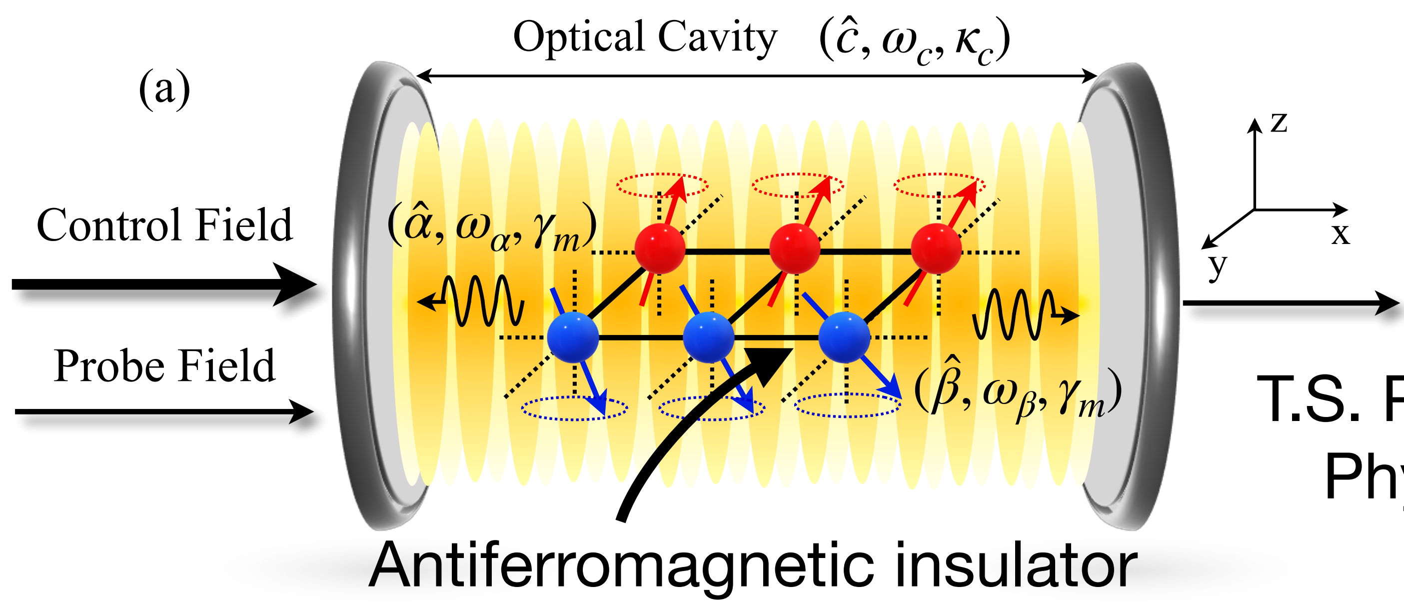
- One order of magnitude gain in coupling
- **However very lossy optical mode**

further work needed

J. Graf, S. Sharma, H. Huebl, SVK; Physical Review Research 3, 013277 (2021)

What about Antiferromagnets?

Antiferromagnetic cavity optomagnonics



T.S. Parvini, Victor A.S.V. Bittencourt, SVK; Phys. Rev. Research 2, 022027 (2020)

- Model for cavity optomagnonics with antiferromagnetic insulators
  (one-magnon scattering processes)
- Strong coupling requires large magneto-optical asymmetry
  (compared with known values for simple AFMs)
- Tunable coupling with a magnetic field
  (for finite hard-axis anisotropy)
- Dark-to-bright transition for magnon modes possible

Outlook

- State of the art in the MW regime ripe for generation of macroscopic non-classical states of the manetization: e.g. cat states
- Coupling to vibrations at the single quanta can be harnessed for applications: e.g. quantum thermometer
- Design of optomagnonic systems in the optical regime shows promise

for improved coupling values

- Developed a method for calculating the optomagnonic coupling in the presence of magnetic textures: more to follow

Thank you

MAX-PLANCK-GESELLSCHAFT

IMPRS physics of light

DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Mitacs