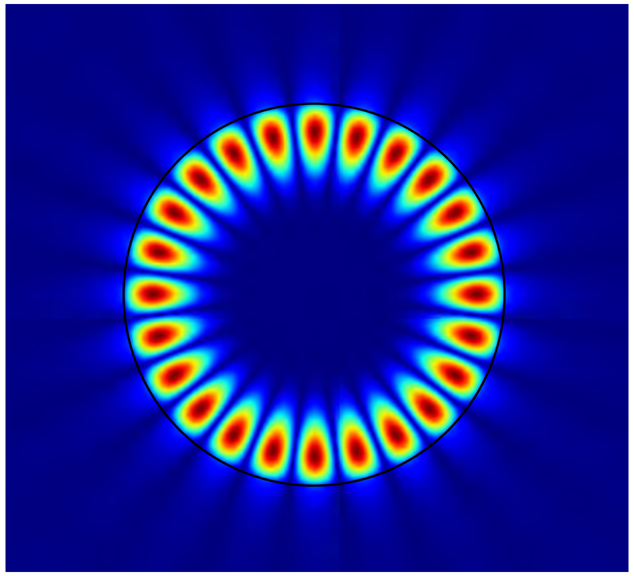
Cavity Optomagnonics

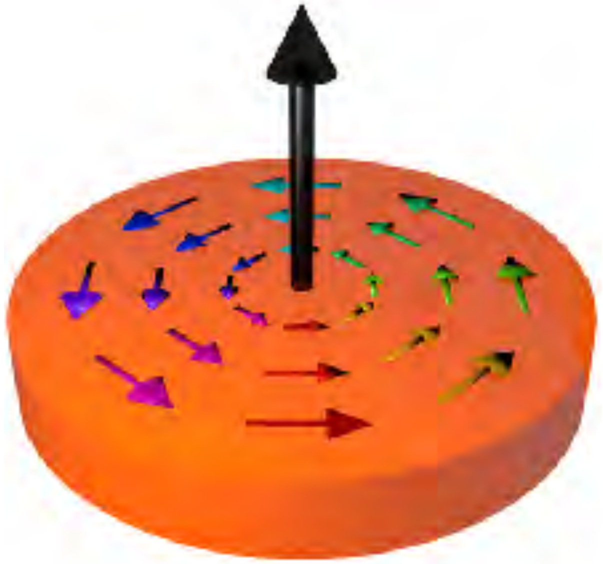
nonlinear dynamics and textures

Jasmin Graf, Hannes Pfeifer, Florian Marquardt
Hong Tang (Yale)

Silvia Viola Kusminskiy



MAX PLANCK INSTITUTE
for the science of light

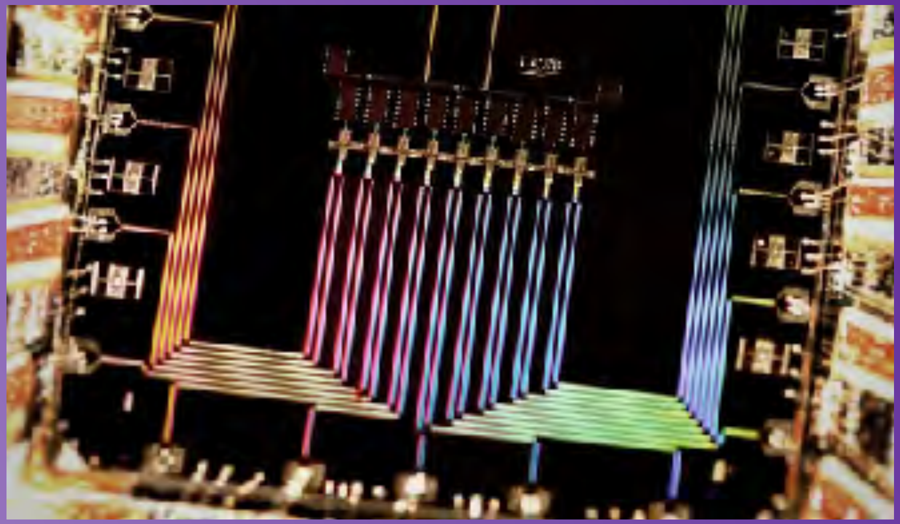


New Max Planck Research Group

classical technologies

quantum technologies

superconducting quantum circuit



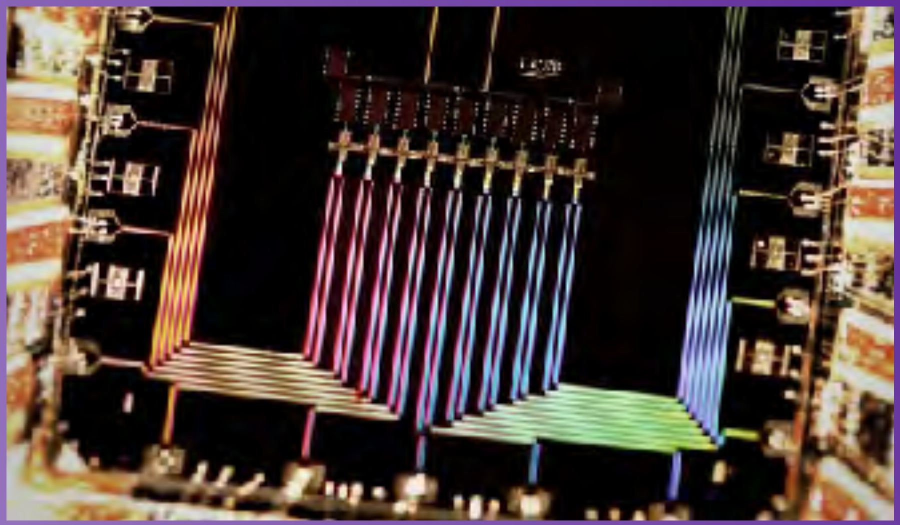
Martinis group
UCSB and Google (2015)

optical fiber

classical technologies

quantum technologies

superconducting quantum circuit



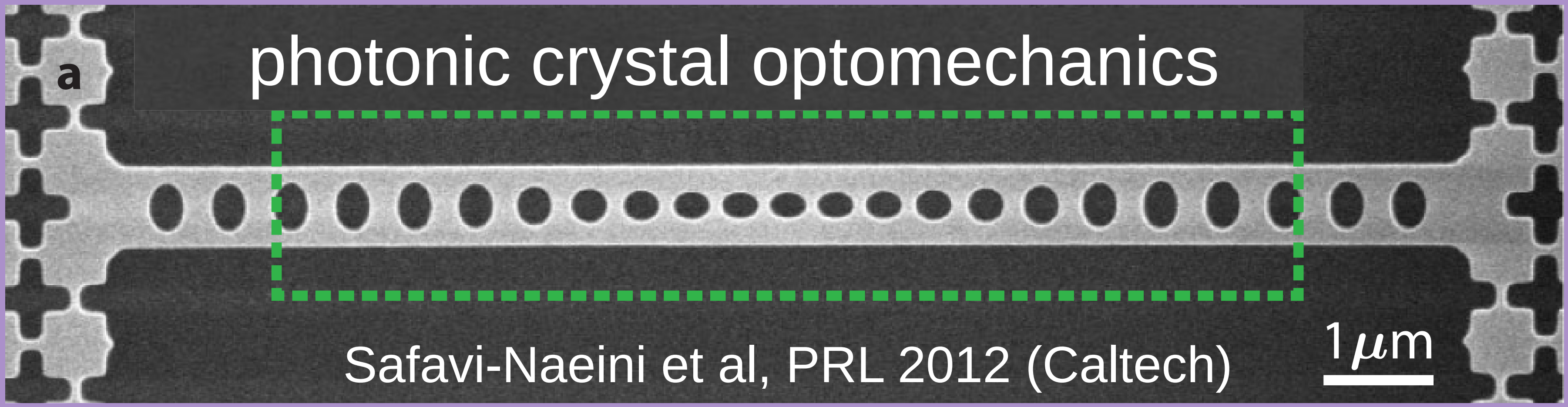
Martinis group
UCSB and Google (2015)

need hybrid systems

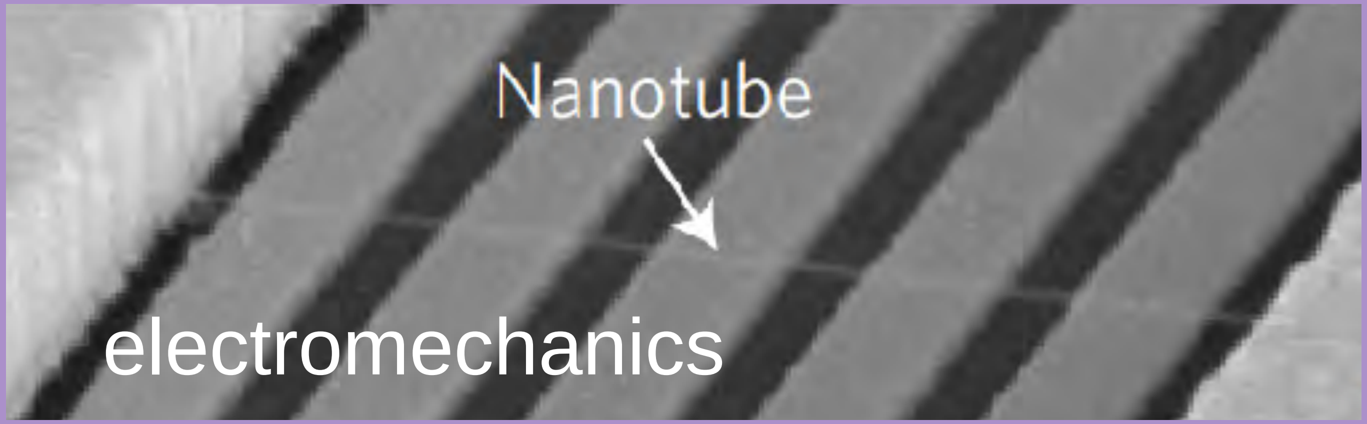
optical fiber

classical technologies

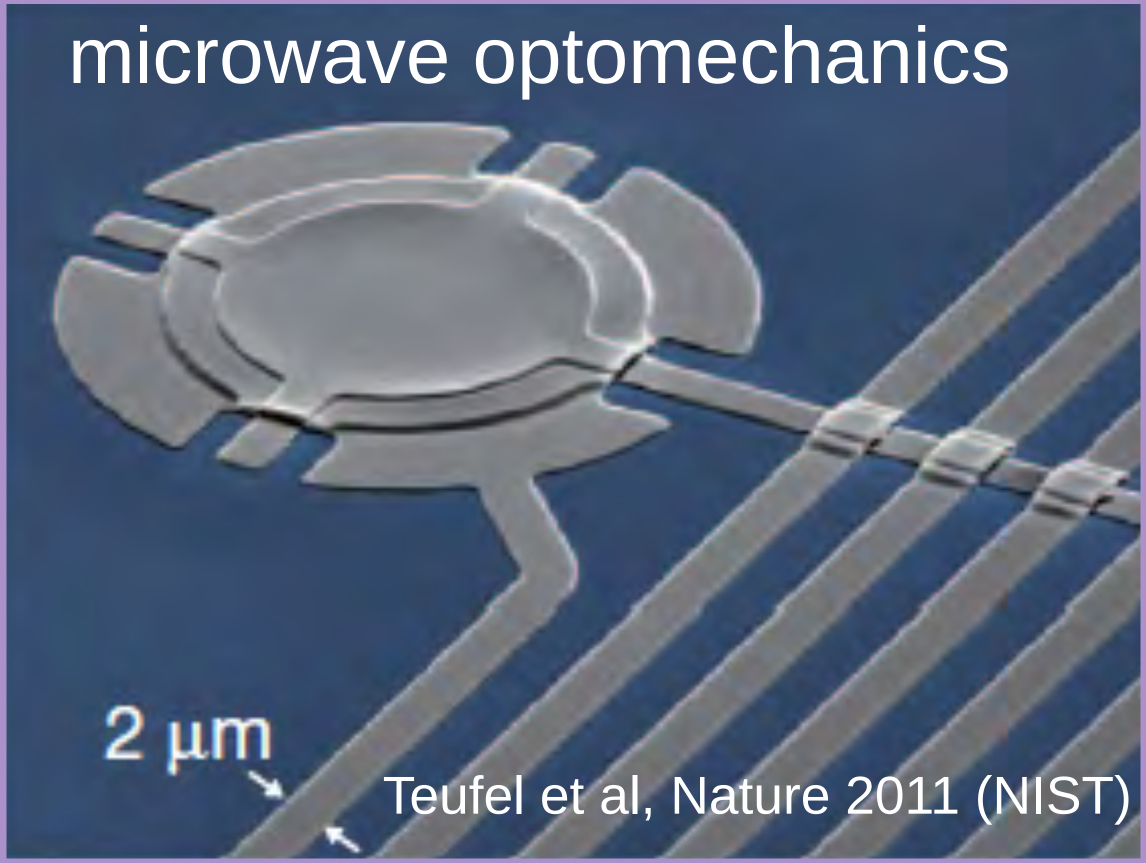
Hybrid Systems for Quantum Technologies



mesoscopic: nano/micro scale systems



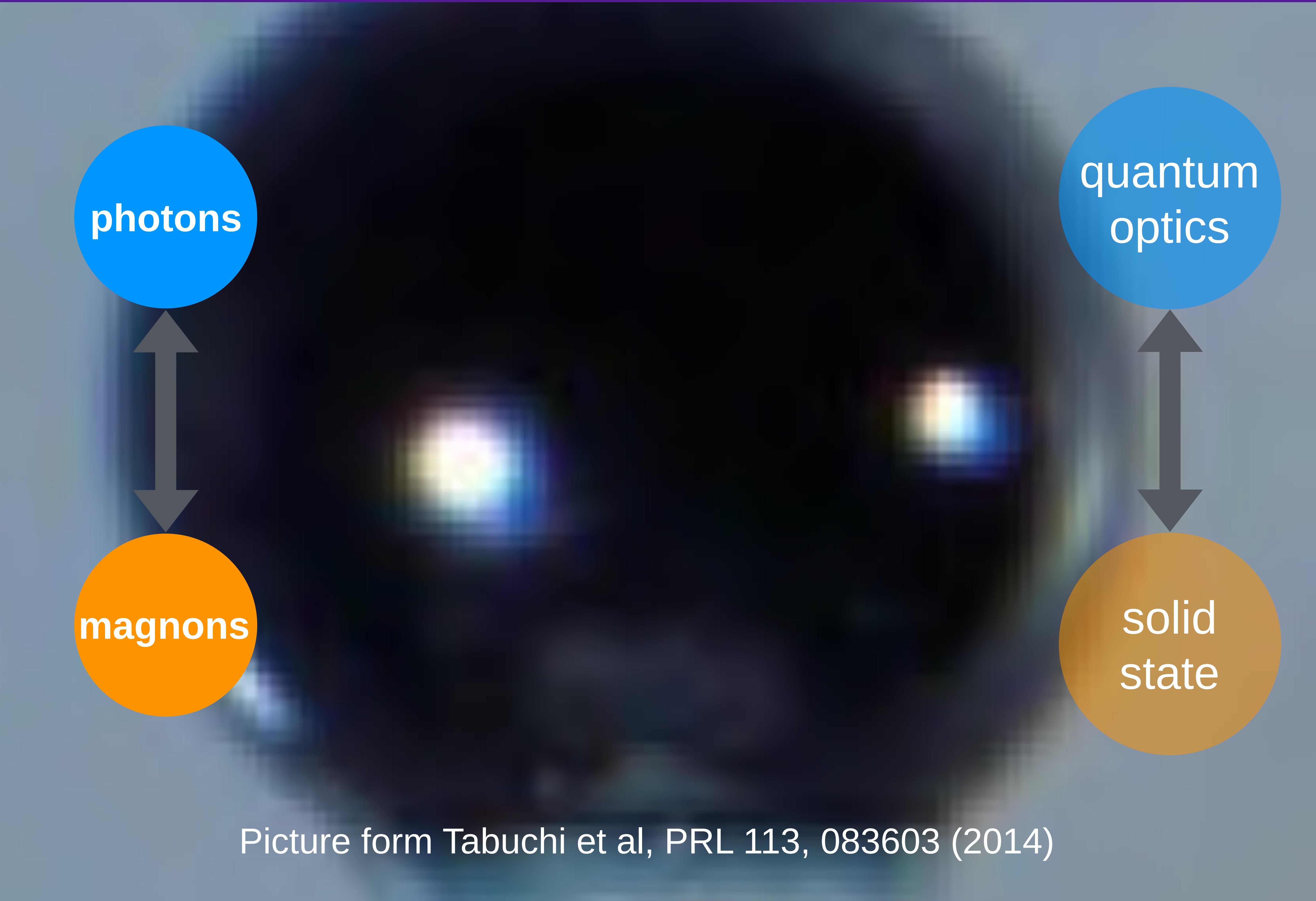
Benyamini et al, Nature Physics 10, 151 (2014)



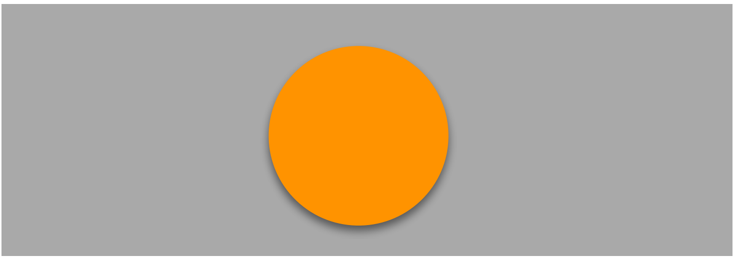
Osada et. al PRL 116, 223601 (2016)

use collective excitations

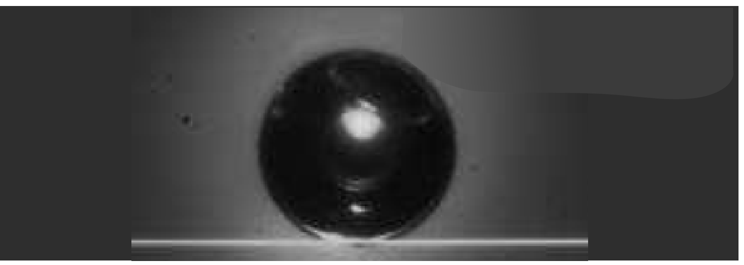
Optomagnonics



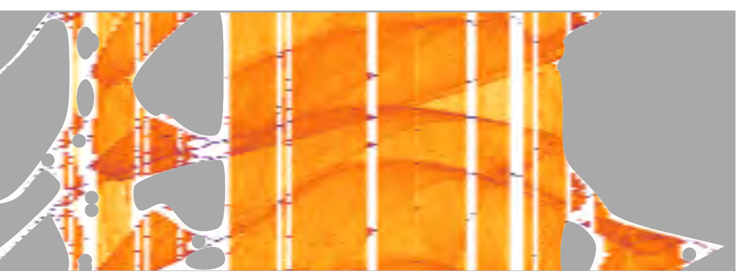
Picture form Tabuchi et al, PRL 113, 083603 (2014)



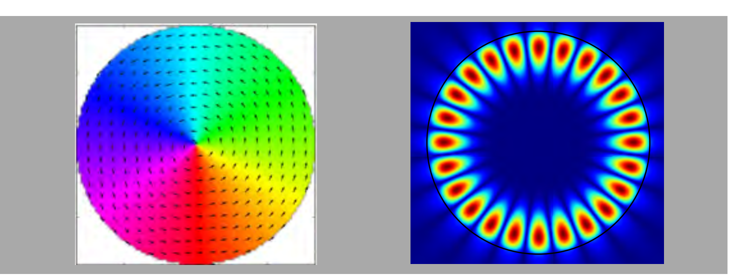
Introduction and motivation



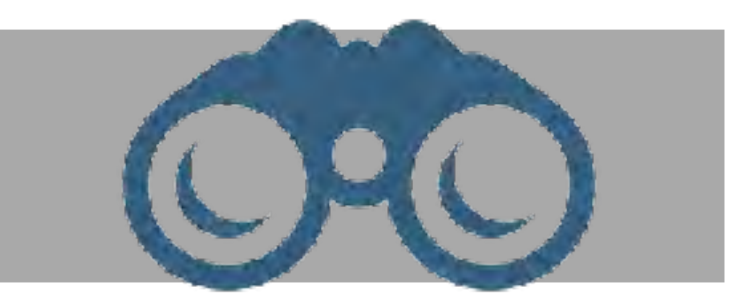
Optomagnonic Hamiltonian



Optically induced spin dynamics



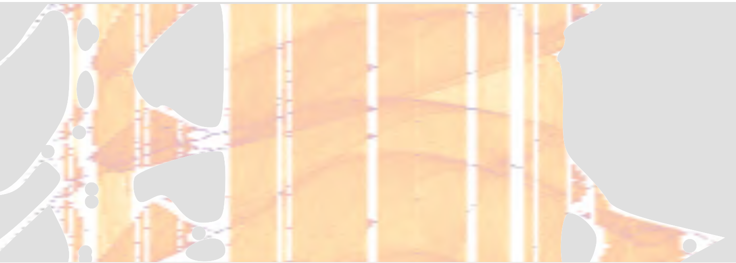
Magnetic textures: vortex in a disk



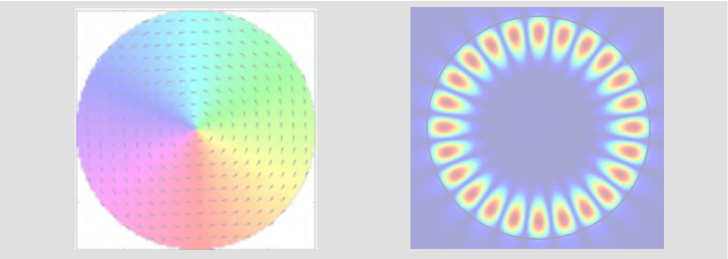
Summary

Introduction and motivation

Optomagnonic Hamiltonian



Optically induced spin dynamics



Magnetic textures: vortex in a disk

Summary

Magnonics

magnon

elementary magnetic excitation
(quantum of spin wave)

Magnonics

magnon

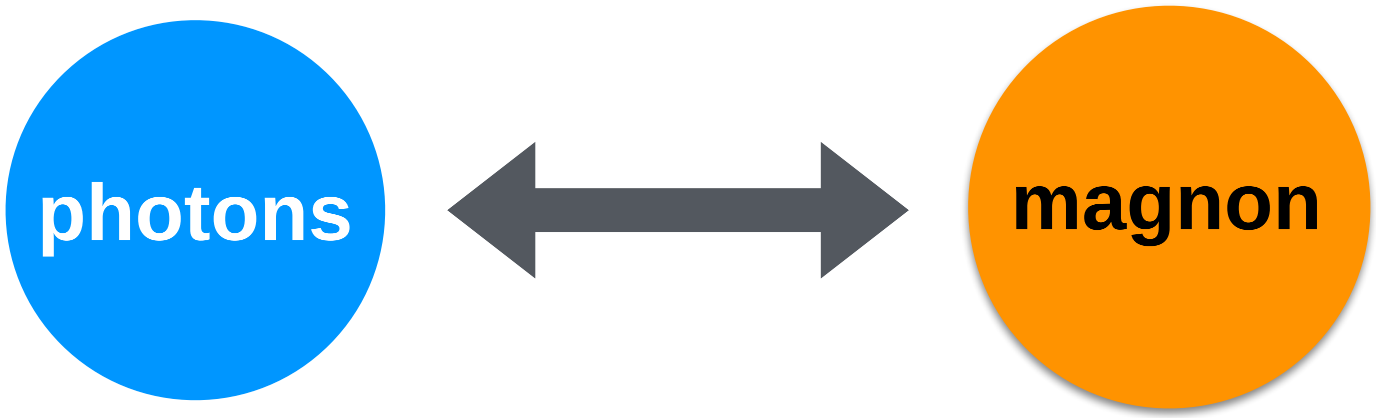
elementary magnetic excitation
(quantum of spin wave)

Robust

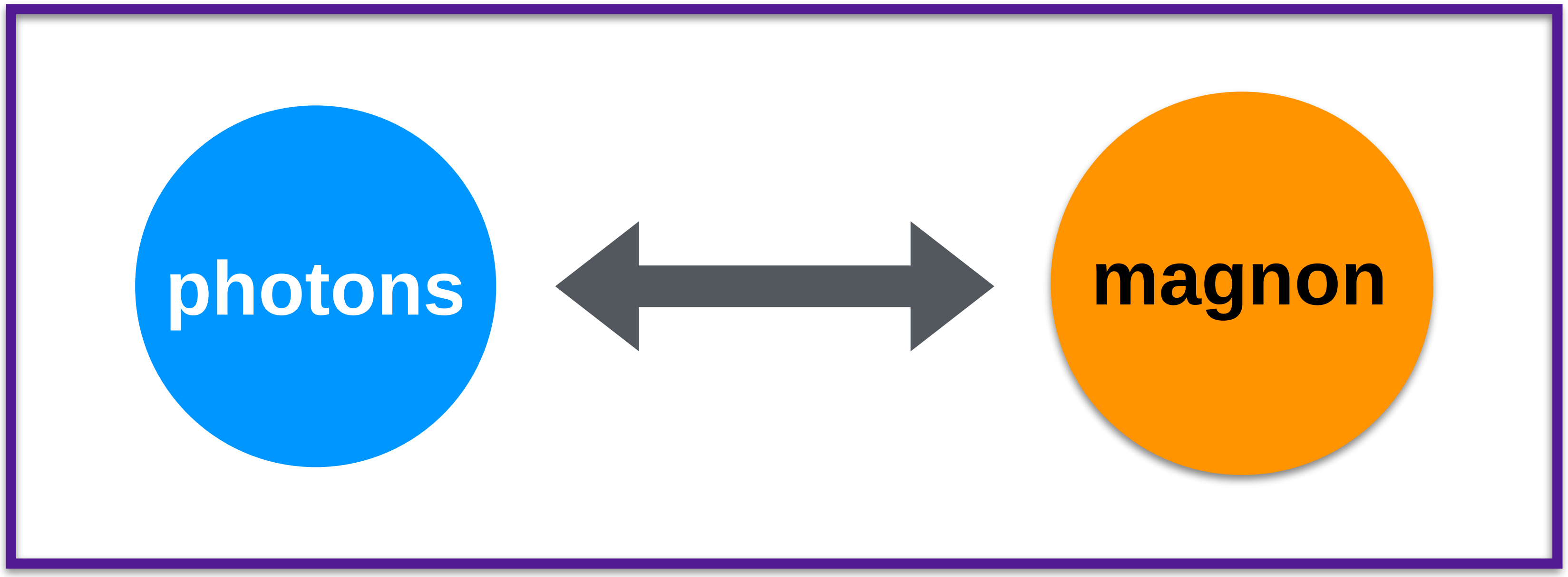
Low Power

Tunable

Optomagnonics

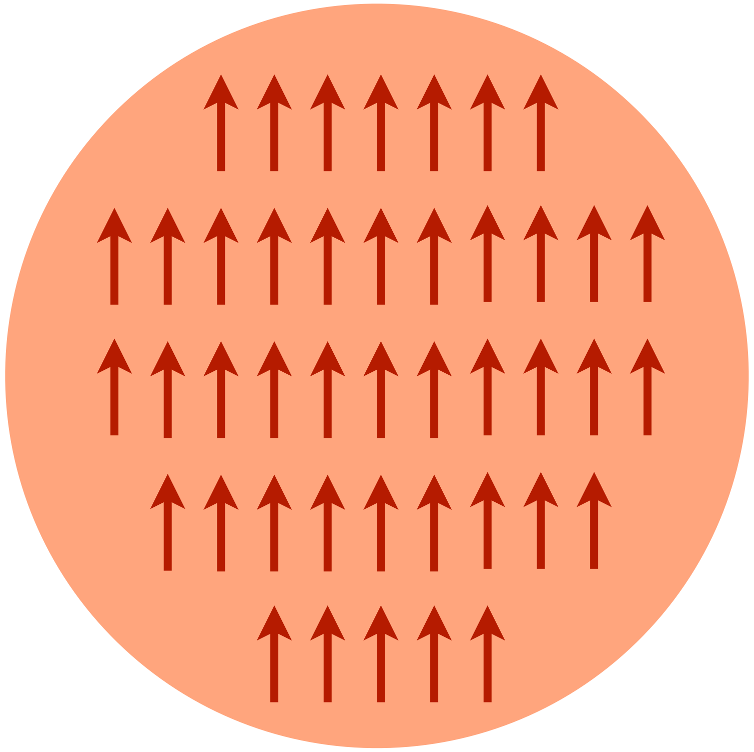


Cavity Optomagnonics



Magnonics

Kittel mode



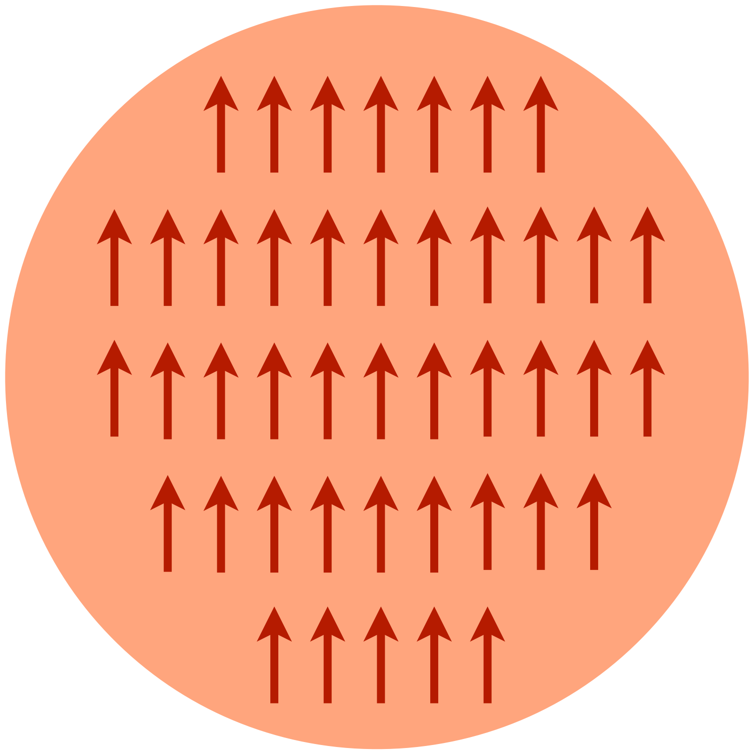
homogeneous
magnetic mode

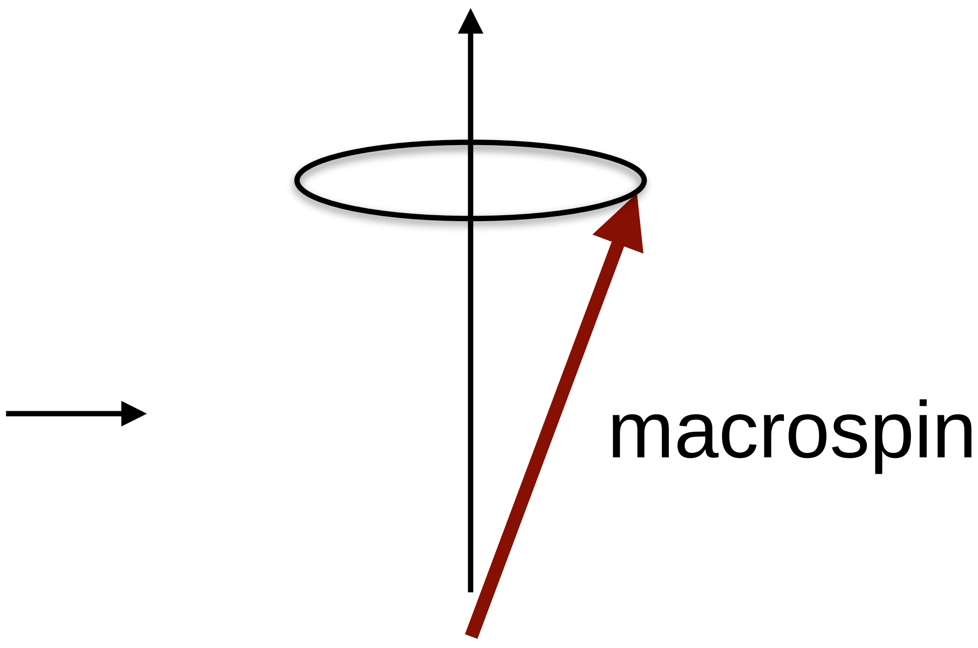
$$\mathbf{M}(\mathbf{r}) = \mathbf{M}$$

spin wave with k=0

Magnonics

Kittel mode





$$\Omega \propto H$$

homogeneous magnetic mode

$$\mathbf{M}(\mathbf{r}) = \mathbf{M}$$

tunable precession frequency

$$\Omega \sim \mathrm{GHz}$$

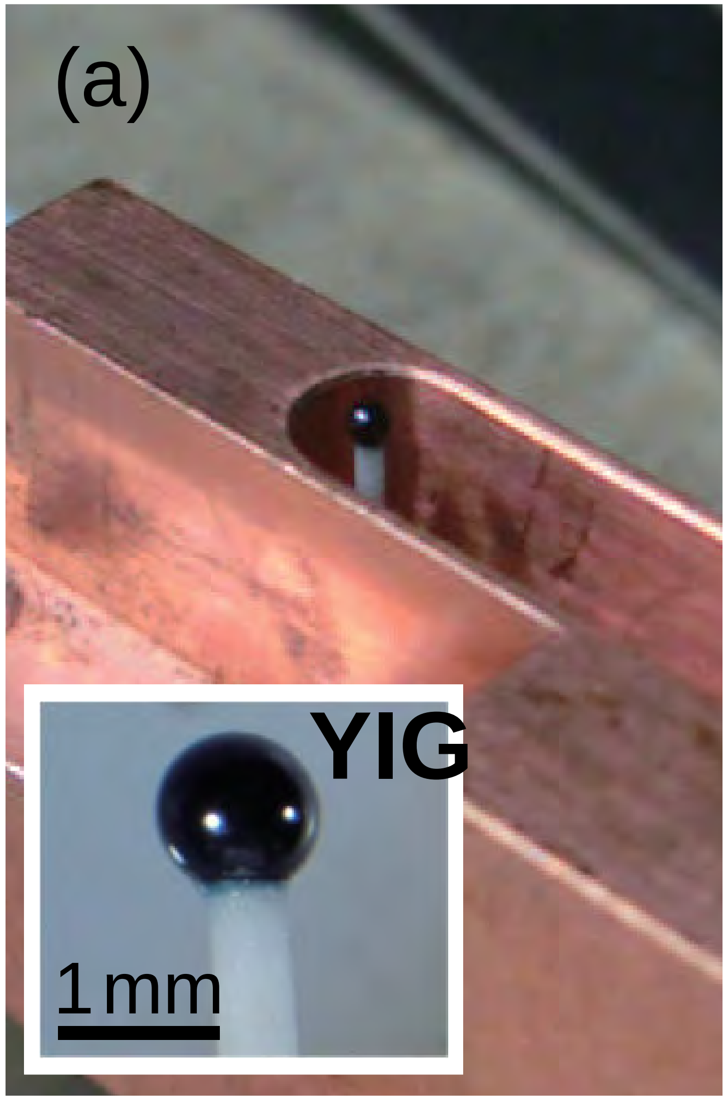
for 30mT

spin wave with $\mathbf{k} = 0$

Microwave Regime

Magnons ⟷ **Microwaves**

Strong coupling demonstrated in 2014



- Tabuchi et. al PRL 113, 083603 (Nakamura's group, Tokyo)
- Zhang et. al PRL 113, 156401 (Hong Tang's group, Yale)

YIG

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

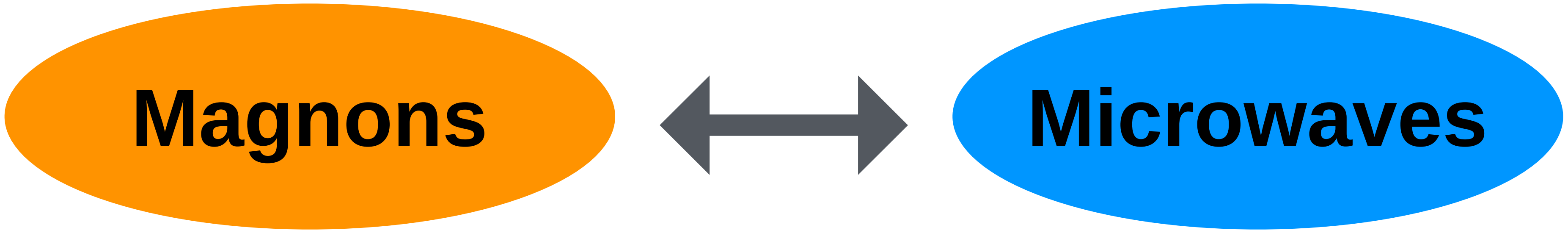
YIG

Yttrium Iron Garnet

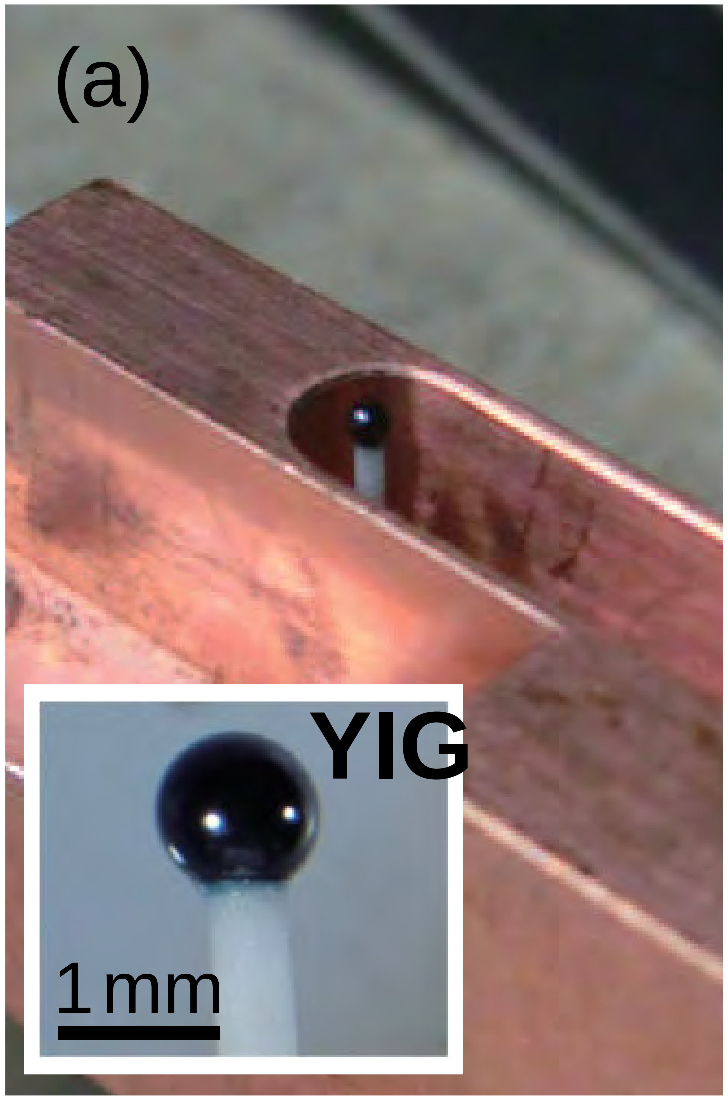
$$Y_3\,Fe_5\,O_{12}$$

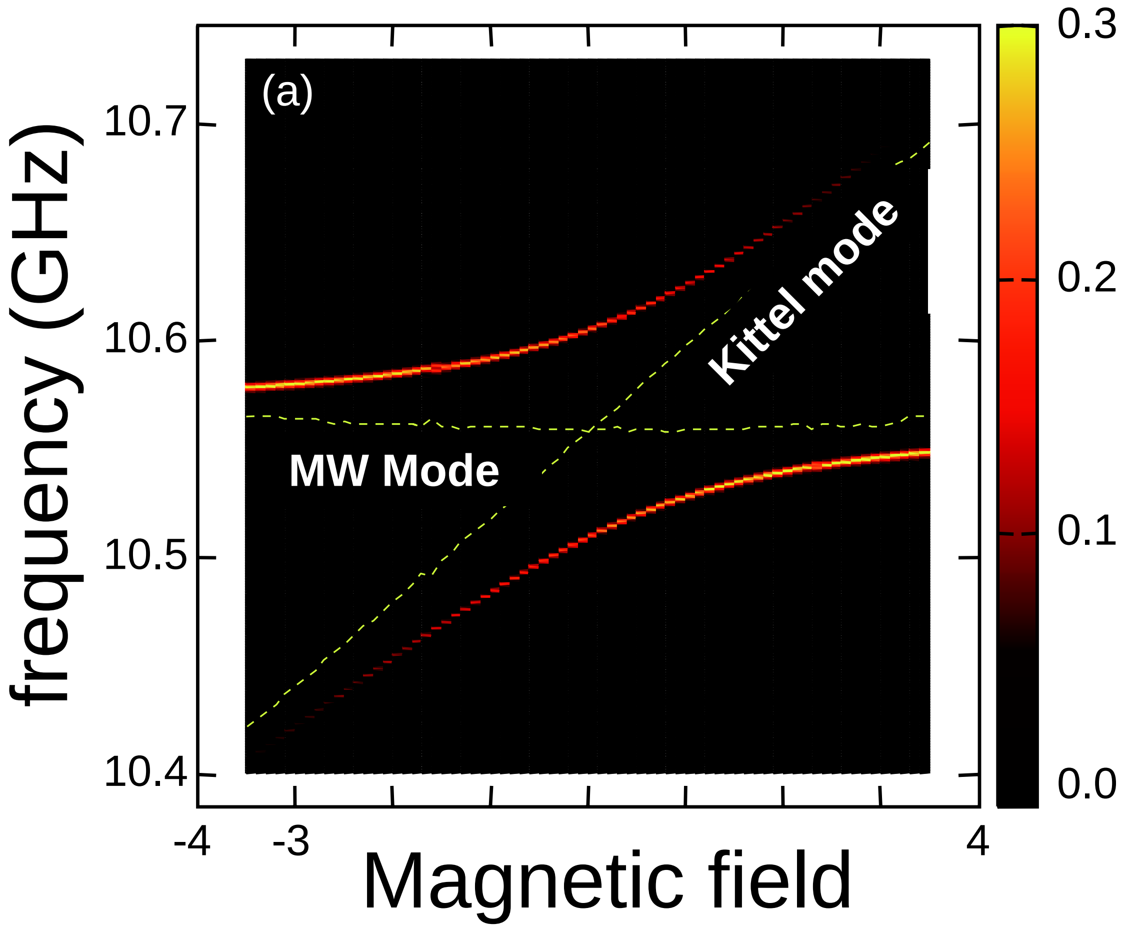
- ferrimagnetic
- insulator
- transparent in the infrared

Microwave Regime



Strong coupling demonstrated in 2014





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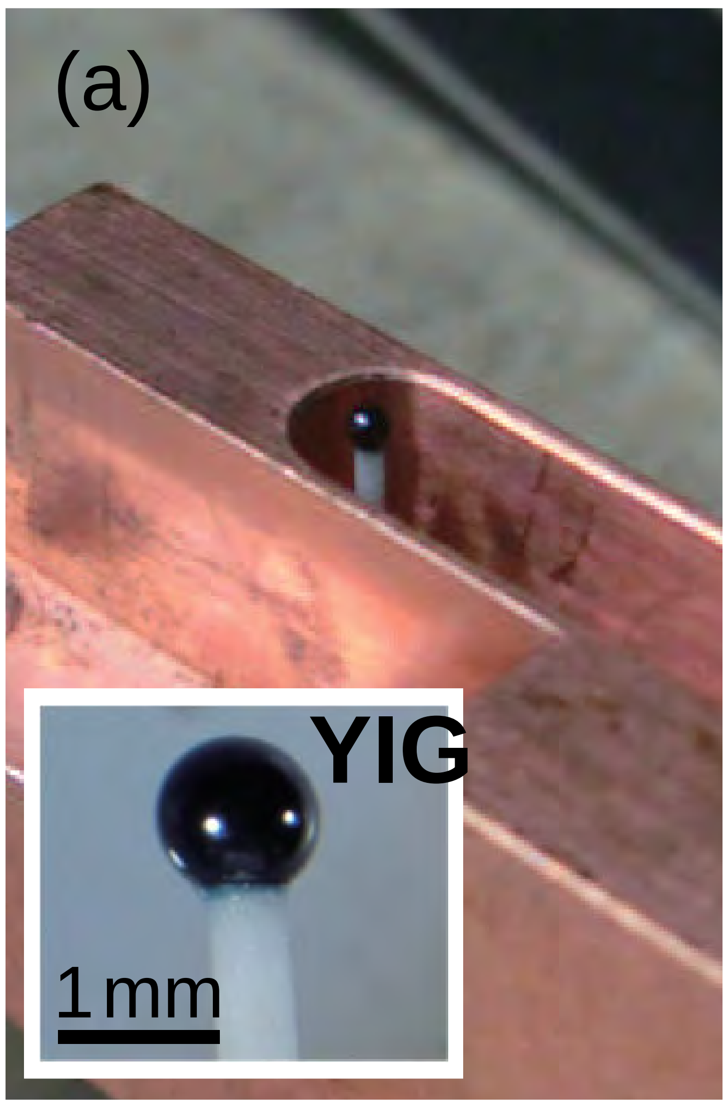
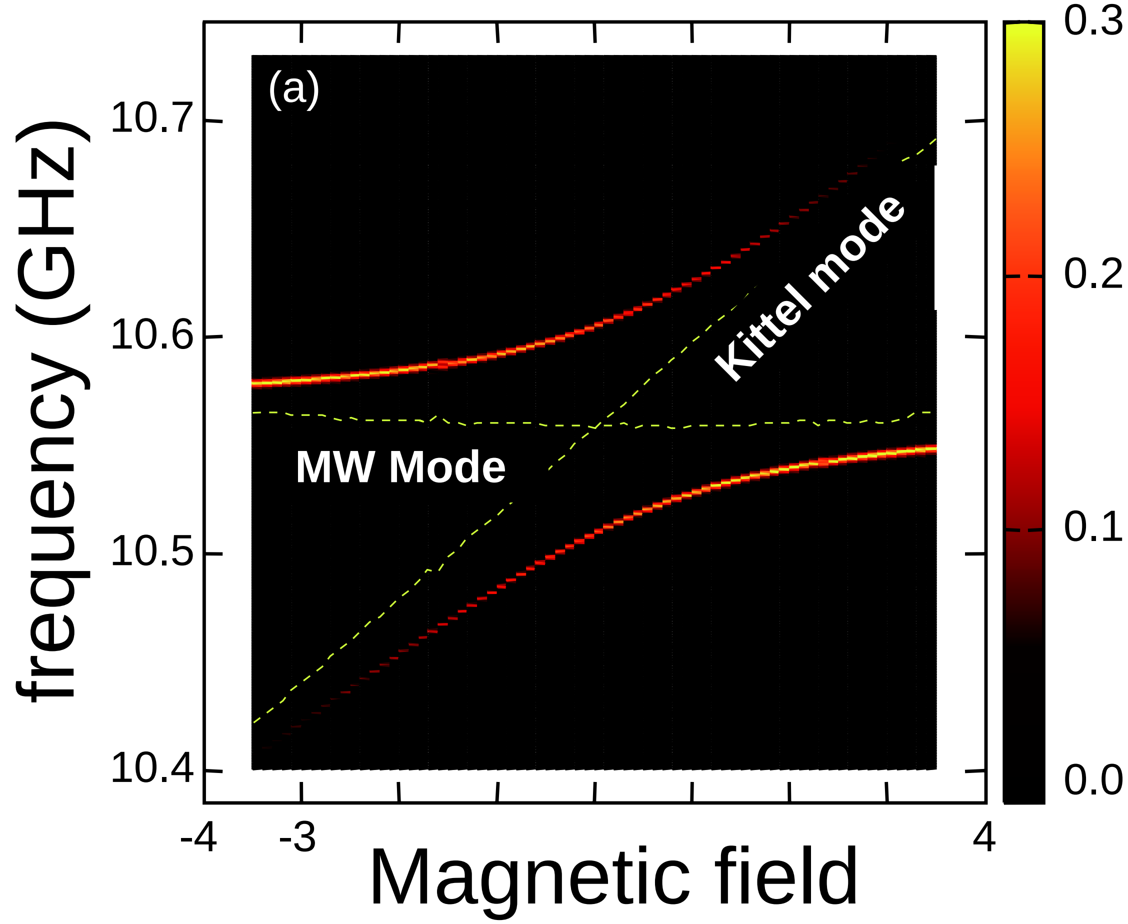
Microwave Regime

Magnons ⟷ **Microwaves**

Strong coupling regime





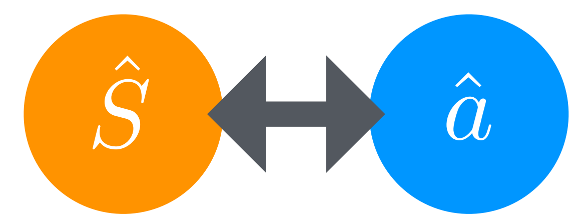
Huebl et. al, PRL 111, 127003 (2013)

Zhang et. al PRL 113, 156401 (2014)

Tabuchi et. al PRL 113, 083603 (2014)

Resonant coupling

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



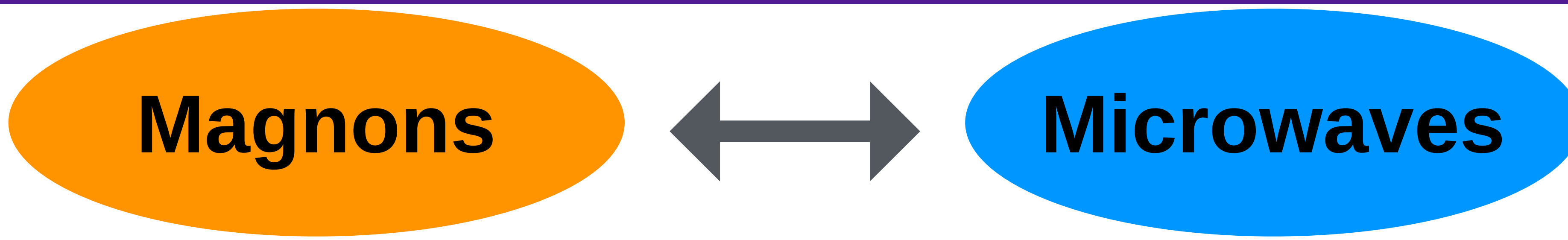
$\sim 50\mathrm{MHz}$

Cooperativity

$$\mathcal{C} = 3 \times 10^{3}$$

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

Microwave Regime

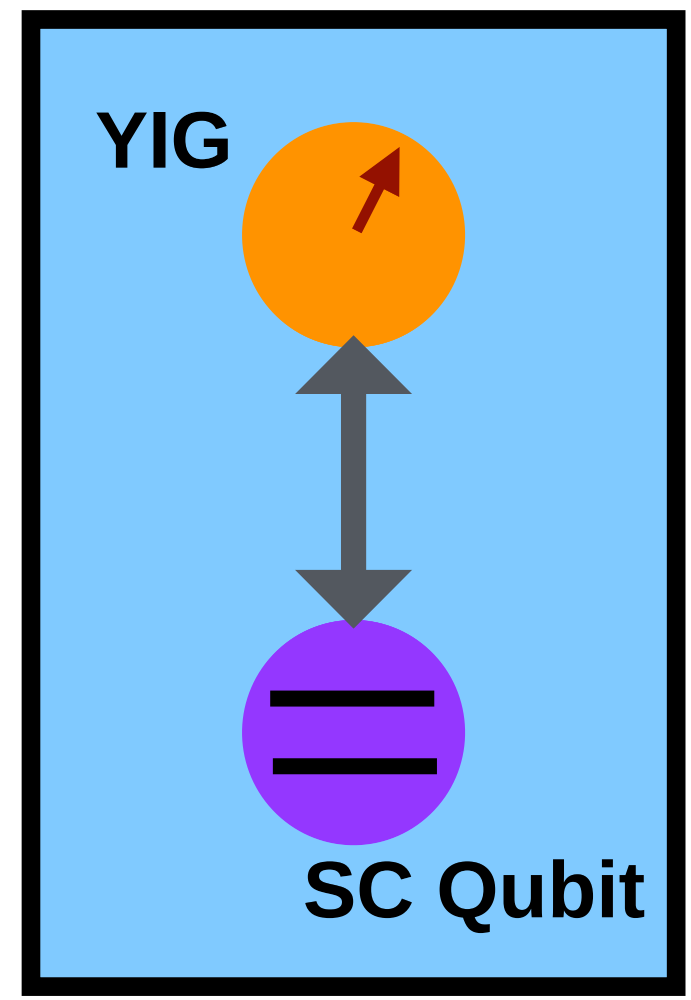


QUANTUM INFORMATION

(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

Coupling to Optics?

process information

GHz

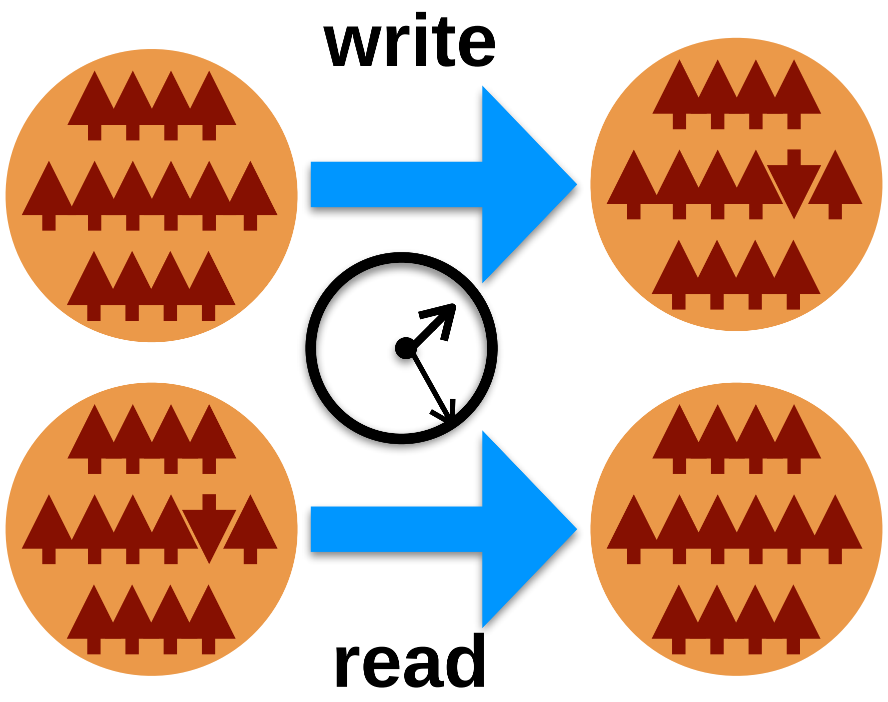
wavelength converter

THz

communicate information

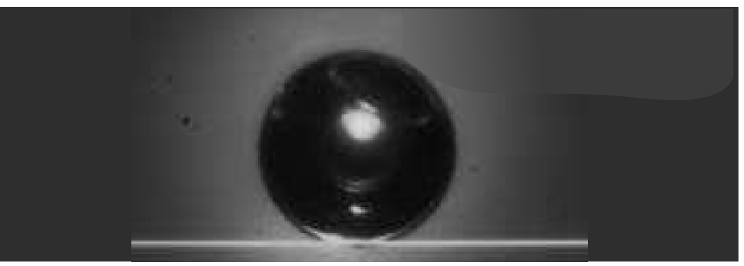
Motivation:
magnon as a transducer

Coupling to Optics?



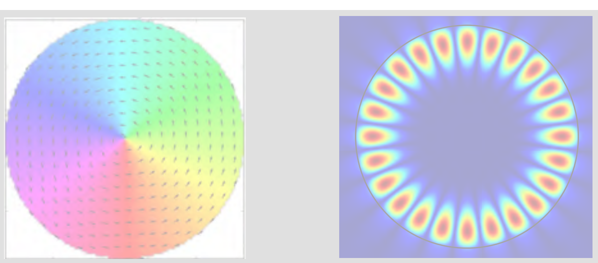
Motivation:
magnon state as a quantum memory

Introduction and motivation



Optomagnonic Hamiltonian

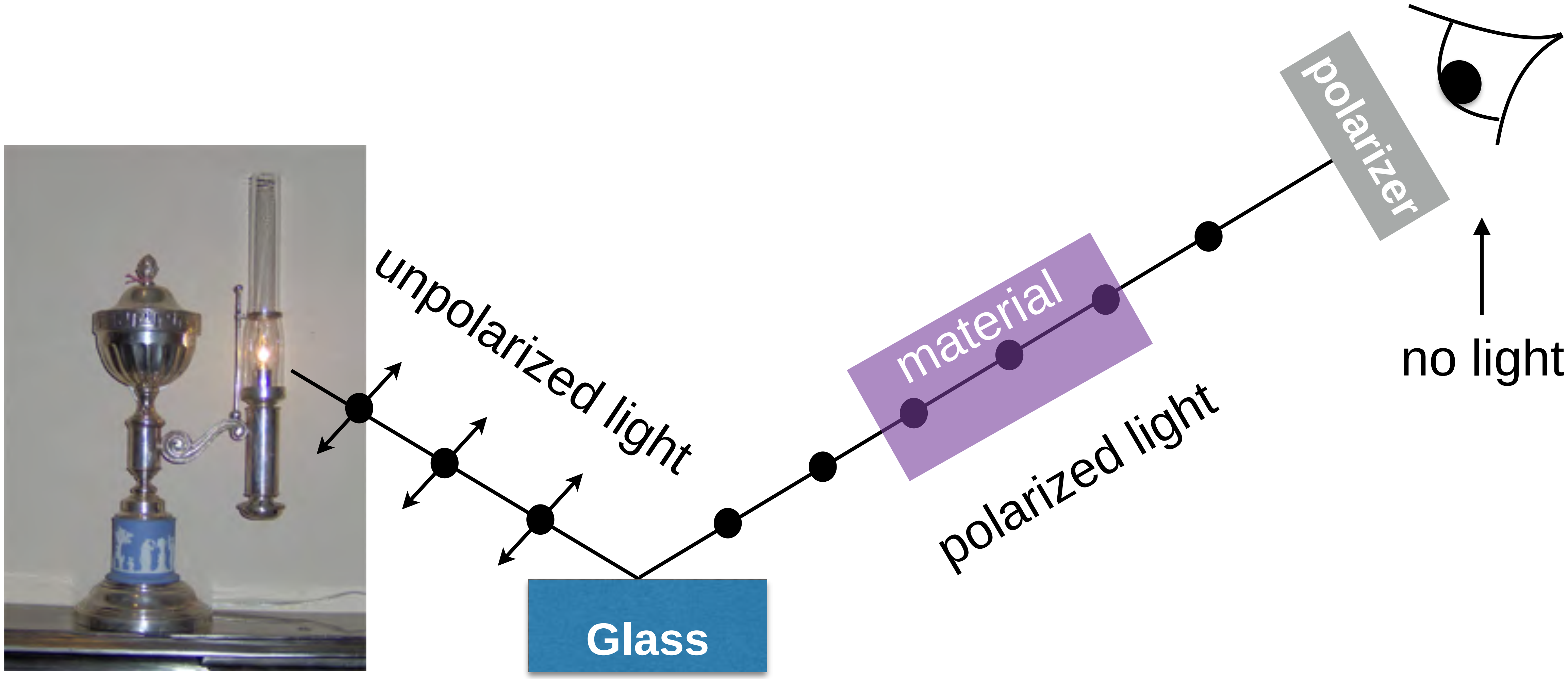
Optically induced spin dynamics



Magnetic textures: vortex in a disk

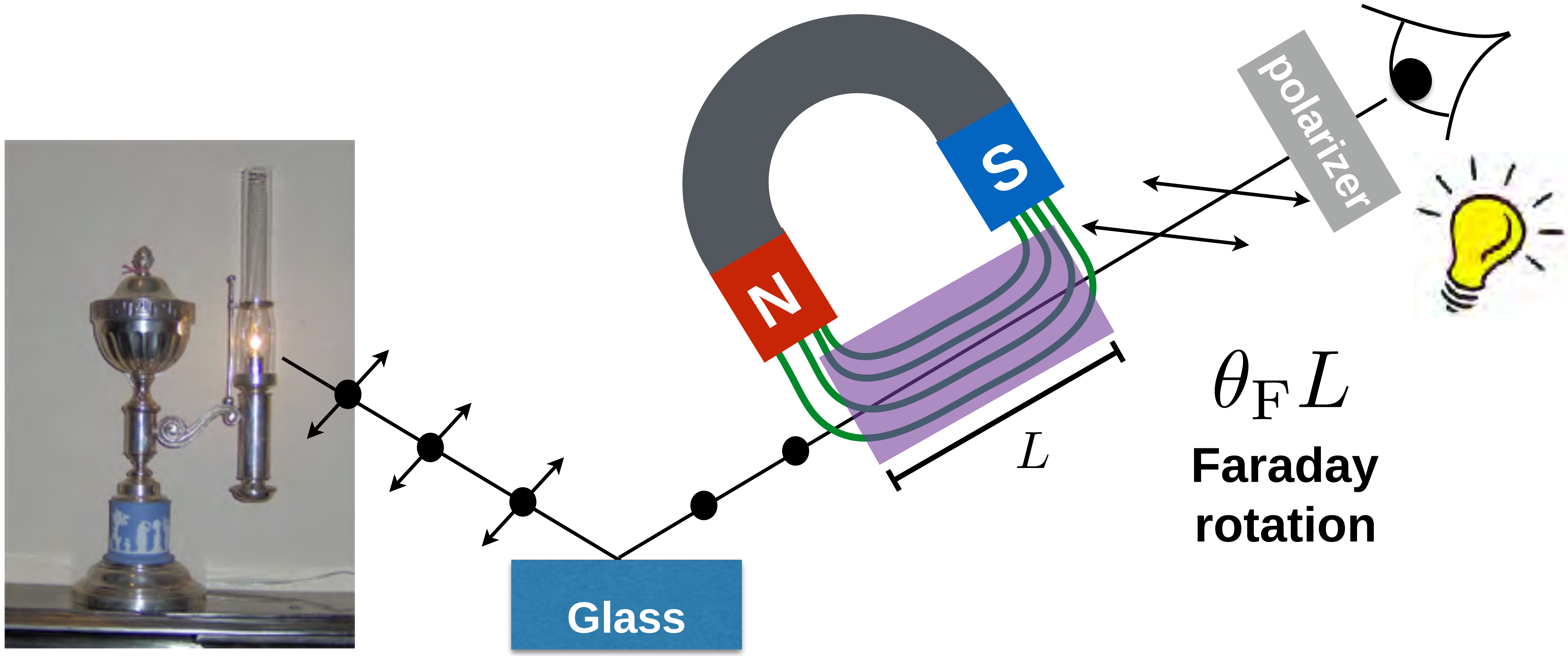
Summary

Faraday Effect (1846)



Oil Lamp

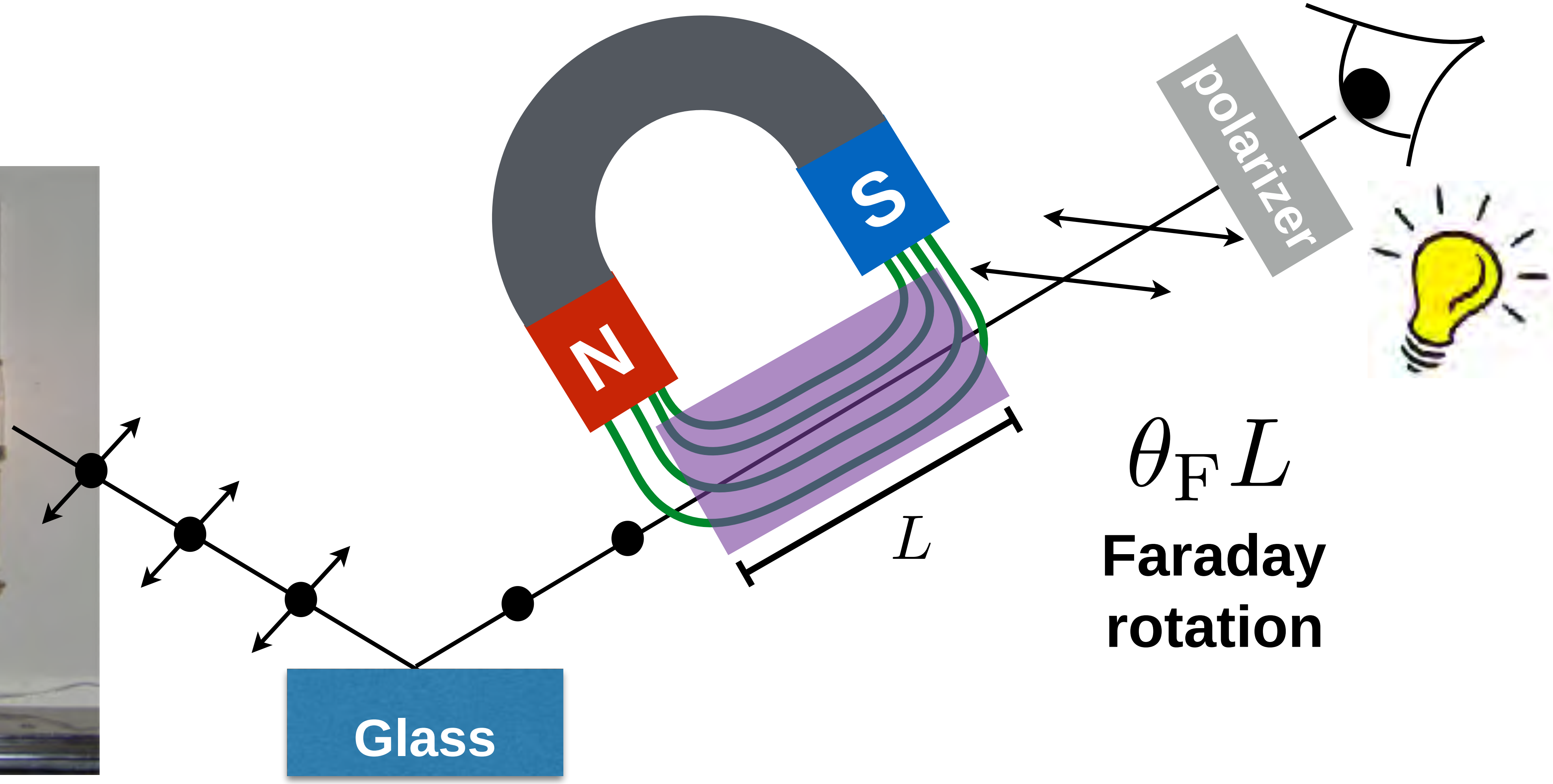
Faraday Effect (1846)



Oil Lamp

Faraday Effect (1846)

Oil Lamp



RELATION OF LIGHT TO THE MAGNETIC FORCE. 15

¶ iii. *General considerations.*

2221. Thus is established, I think for the first time*, a true, direct relation and dependence between light and the magnetic and electric forces; and thus a great

Phil. Trans. R. Soc. Lond. 1846 **136**, 1-20

Before Maxwell equations (1860)!

Coupling to Optics?: Faraday Effect

Faraday rotation

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

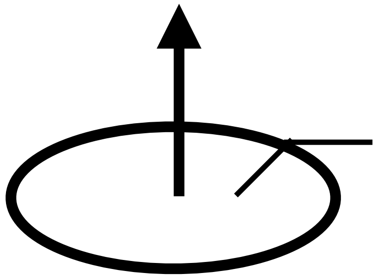
Faraday rotation

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

$$\mathbf{E}^*\times\mathbf{E}$$



Coupling to Optics?: Faraday Effect

Faraday rotation

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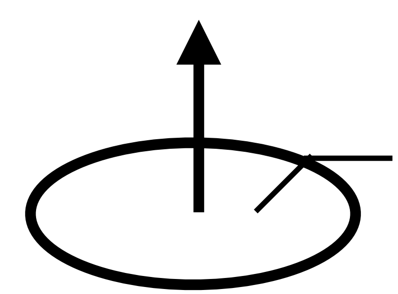
$$\bar{U}_{\mathrm{MO}} = \theta_{\mathrm{F}} \sqrt{\frac{\varepsilon}{\varepsilon_0}} \int \mathrm{d}\mathbf{r}\, \frac{\mathbf{M}(\mathbf{r})}{M_{\mathrm{s}}} \cdot \frac{\varepsilon_0}{2i\omega} \left[\mathbf{E}^*(\mathbf{r}) \times \mathbf{E}(\mathbf{r})\right]$$

magnetization density

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

broken time-reversal symmetry

$\mathbf{E}^* \times \mathbf{E}$



Optomagnonic Hamiltonian

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

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

two-photon process

Optomagnonic Hamiltonian

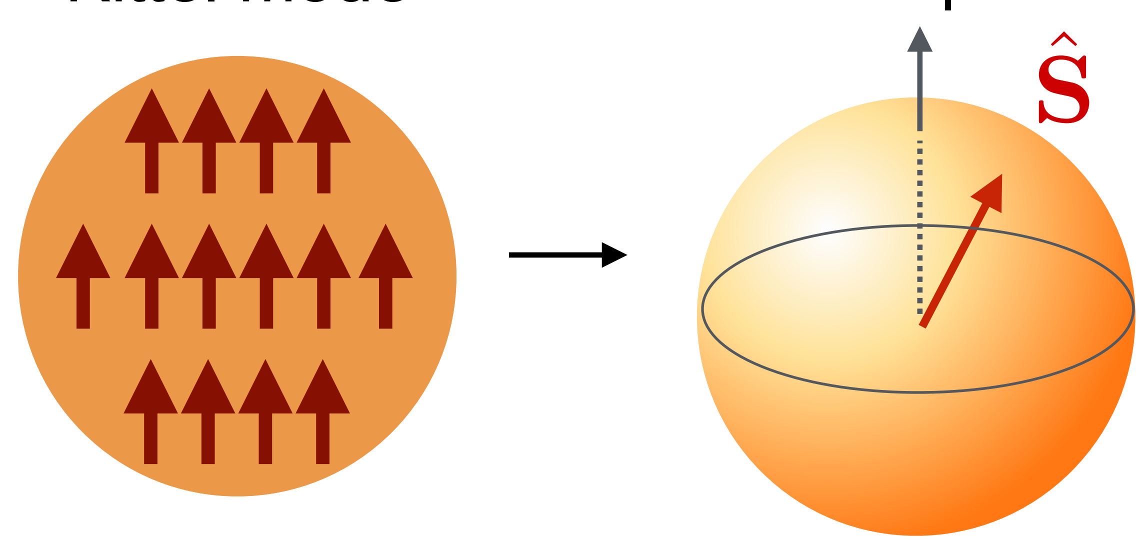
$$\bar{U}_{\mathrm{MO}} = \theta_{\mathrm{F}} \sqrt{\frac{\varepsilon}{\varepsilon_0}} \int \mathrm{d}\mathbf{r} \, \frac{\mathbf{M}(\mathbf{r})}{M_{\mathrm{s}}} \cdot \frac{\varepsilon_0}{2i\omega} \left[\mathbf{E}^*(\mathbf{r}) \times \mathbf{E}(\mathbf{r}) \right]$$

Quantize: $\hat{\mathbf{S}}$

$$\mathbf{M}(\mathbf{r}) = \mathbf{M}$$

Kittel mode

Bloch sphere



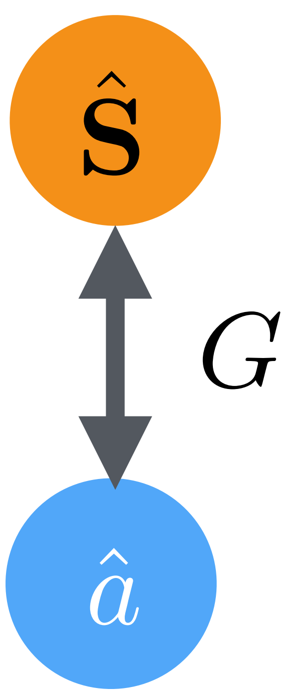
$\Omega \propto H$

Optomagnonic Hamiltonian

Microscopic Hamiltonian

Parametric coupling

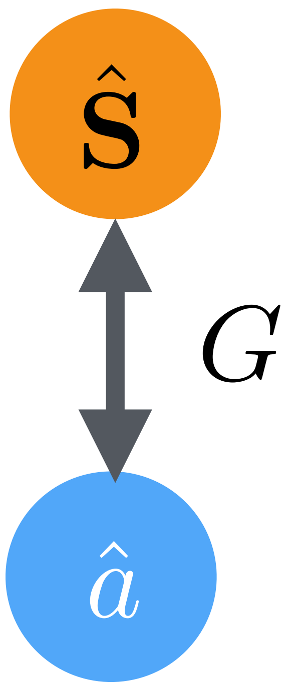
$$\hat{H}_{MO} = \hbar \sum_{j\beta\gamma} \hat{S}_j G^j_{\beta\gamma} \hat{a}^\dagger_\beta \hat{a}_\gamma$$



S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Optomagnonic Hamiltonian

Parametric coupling



Microscopic Hamiltonian

$$\hat{H}_{MO} = \hbar \sum_{j\beta\gamma} \hat{S}_j G^j_{\beta\gamma} \hat{a}^\dagger_\beta \hat{a}_\gamma$$

Optomagnonic coupling

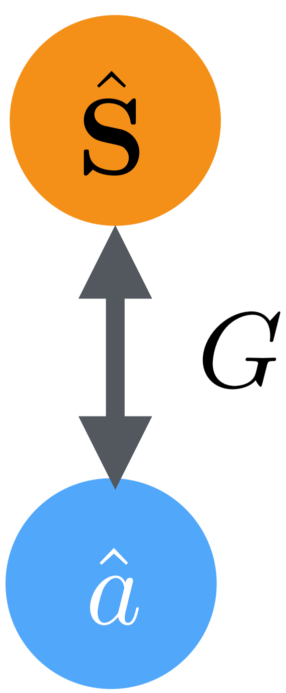
$$G^j_{\beta\gamma} = -i \frac{\theta_{\mathrm{F}}\lambda}{2\pi\hbar S} \frac{\varepsilon_0\varepsilon}{2} \epsilon_{jmn} \int \mathrm{d}\mathbf{r} E^*_{\beta m}(\mathbf{r}) E_{\gamma n}(\mathbf{r})$$

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Optomagnonic Hamiltonian

Microscopic Hamiltonian

Parametric coupling



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Optomagnonic coupling

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overlap electric field mode functions

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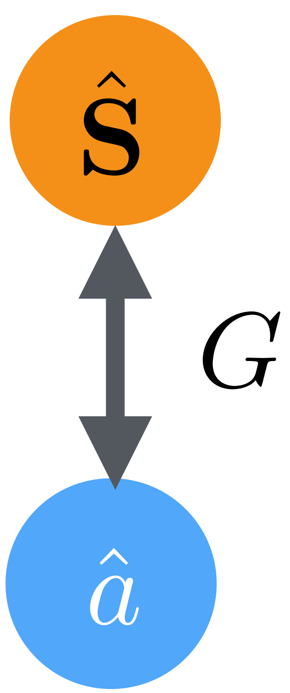
Optomagnonic Hamiltonian

Parametric coupling



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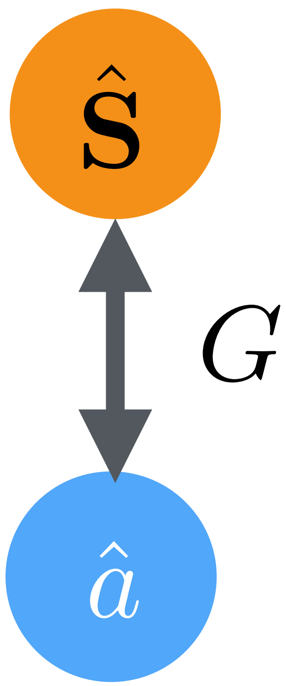
Faraday rotation

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Optomagnonic Hamiltonian

Microscopic Hamiltonian

Parametric coupling



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Optomagnonic coupling

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number of spins

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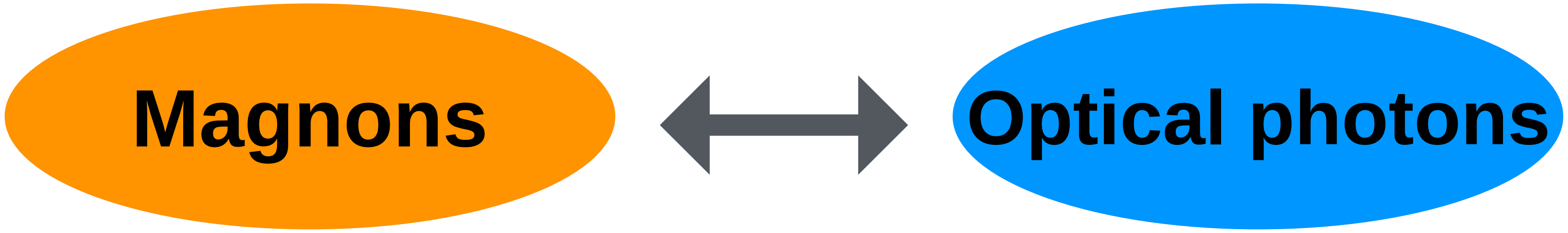
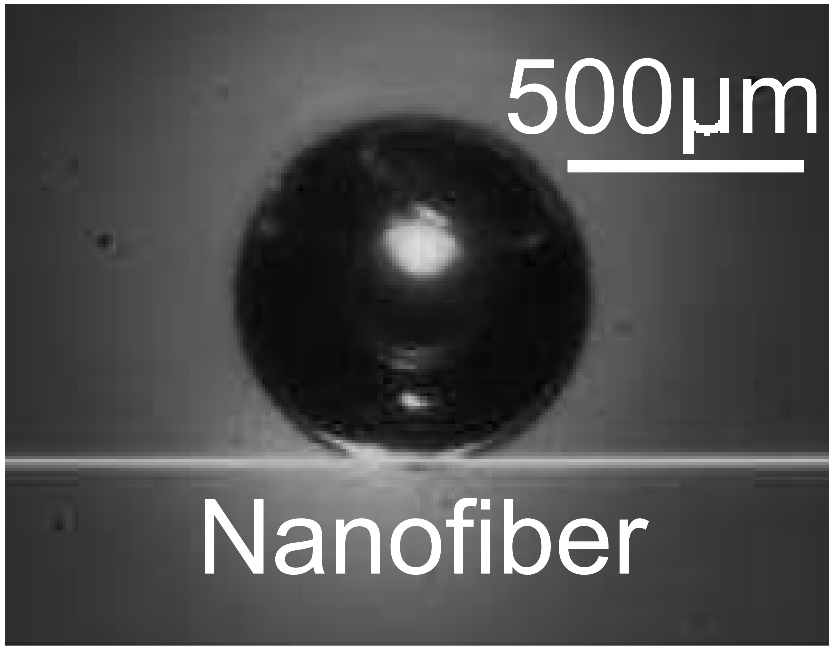
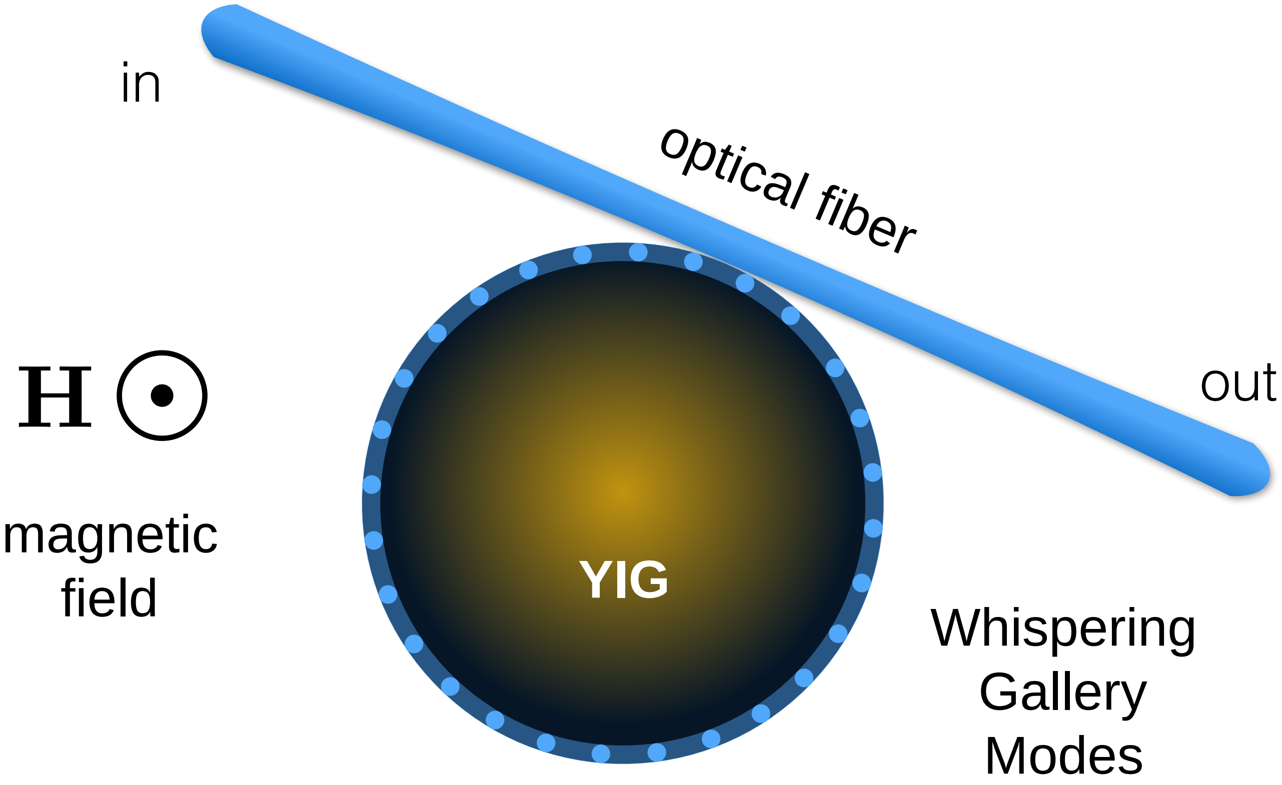
Cavity Optomagnonics



Coupling demonstrated in 2016



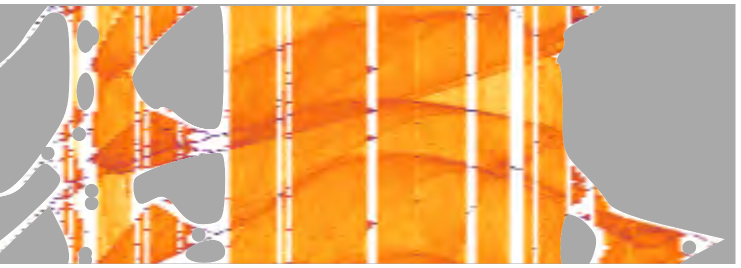


A cavity enhances the effect

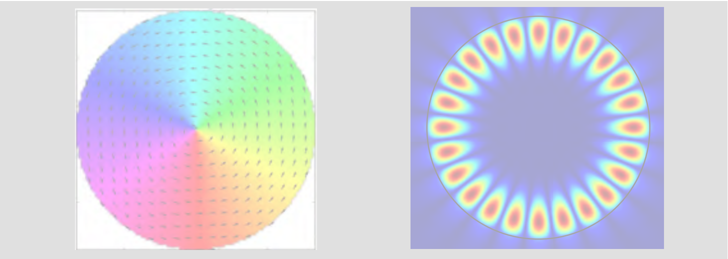
- Osada et. al PRL 116, 223601 (Nakamura's group, Tokyo)
- Haigh et. al PRL 117, 133602 (Cambridge Univ / Hitachi)
- Zhang et. al PRL 117, 123605 (Hong Tang's group, Yale)

Introduction and motivation

Optomagnonic Hamiltonian



Optically induced spin dynamics



Magnetic textures: vortex in a disk

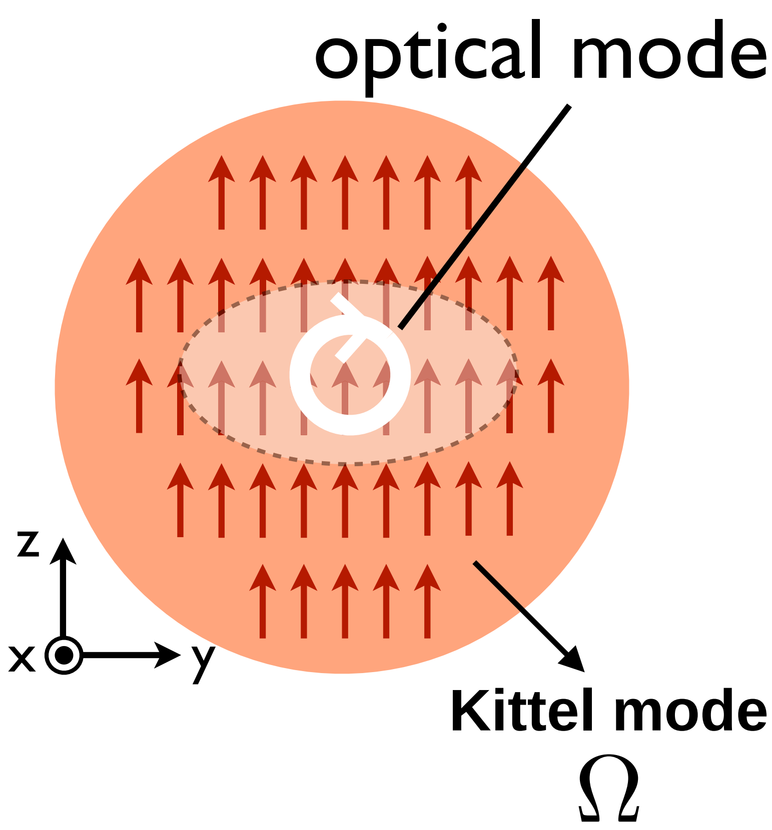
Summary

Cavity Optomagnonics: one optical mode

$$H = -\hbar\Delta\hat{a}^\dagger\hat{a} - \hbar\Omega\hat{S}_z + \hbar G\hat{S}_x\hat{a}^\dagger\hat{a}$$

driving laser detuning

$$\Delta = \omega_{las} - \omega_{cav}$$



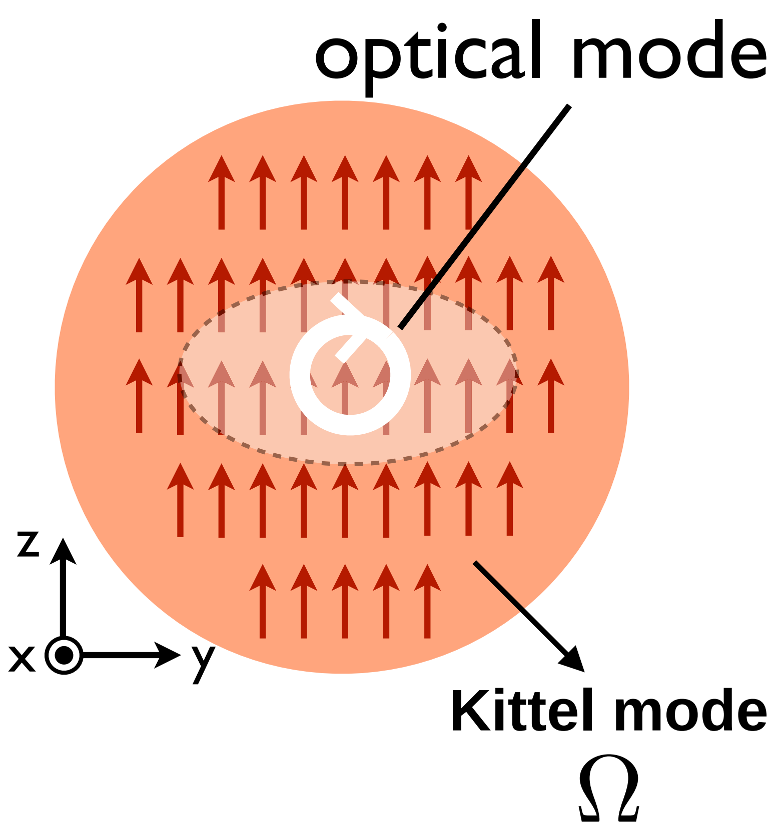
S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Cavity Optomagnonics: one optical mode

$$H = -\hbar\Delta\hat{a}^\dagger\hat{a} - \hbar\Omega\hat{S}_z + \hbar G\hat{S}_x\hat{a}^\dagger\hat{a}$$

driving laser detuning

$$\Delta = \omega_{las} - \omega_{cav}$$



$$G = \frac{1}{S}\frac{c\,\theta_F}{4\sqrt{\varepsilon}} \approx 1\mathrm{Hz}$$

YIG $(1\mu m)^3$

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

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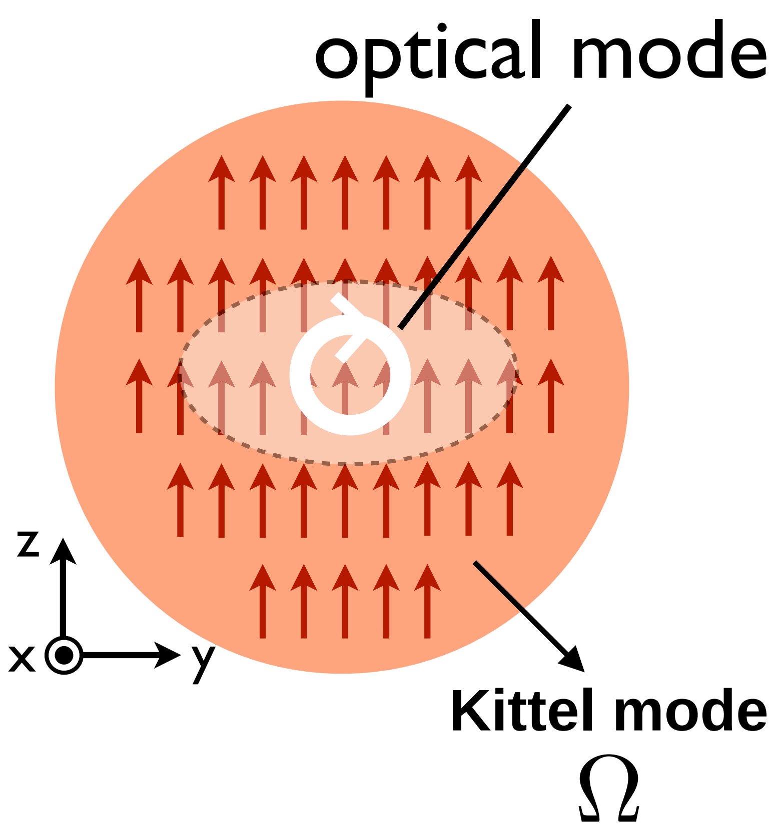

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Optical magnetic field density

$$b_{\mathrm{opt}} \sim \frac{10^{-11}\mathrm{T}}{\mathrm{photon}/(\mu\mathrm{m})^3}$$

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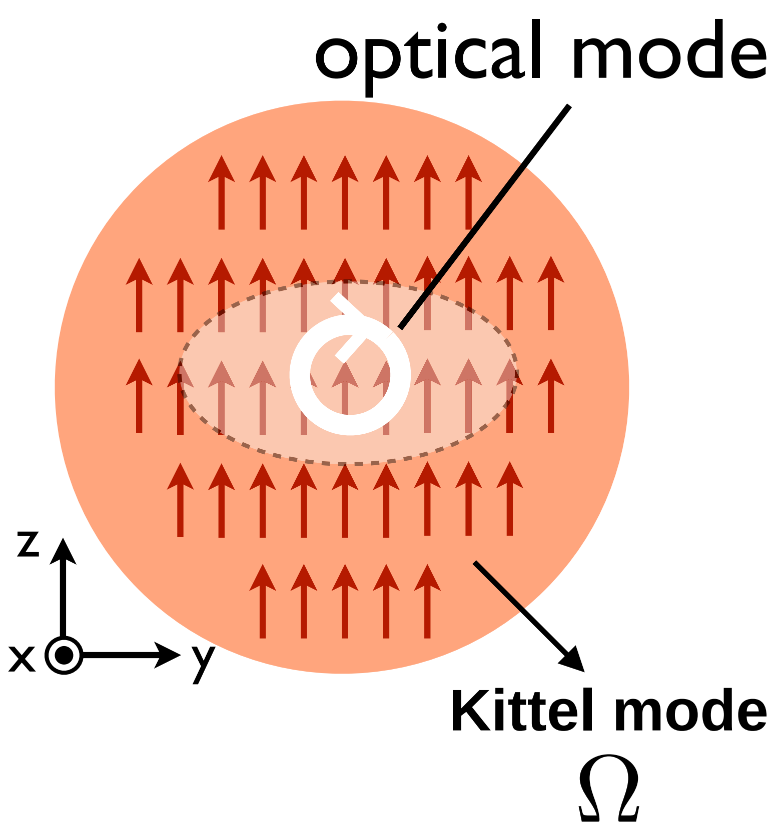

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Optical magnetic field density

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Enhanced by # photons in the cavity!

Cavity Optomagnonics: one optical mode

Classical Equation of Motion

Cavity decay rate

initial light amplitude

$$\dot{a} = -i\left(GS_x - \Delta\right)a - \frac{\kappa}{2}\left(a - \alpha_{\mathrm{max}}\right)$$

$$\dot{\mathbf{S}} = \left(Ga^*a\,\mathbf{e}_x - \Omega\,\mathbf{e}_z\right) \times \mathbf{S} + \frac{\eta_{\mathrm{G}}}{S}(\dot{\mathbf{S}} \times \mathbf{S})$$

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Effective Equation of Motion for the Spin

Fast cavity limit: integrate out the light field

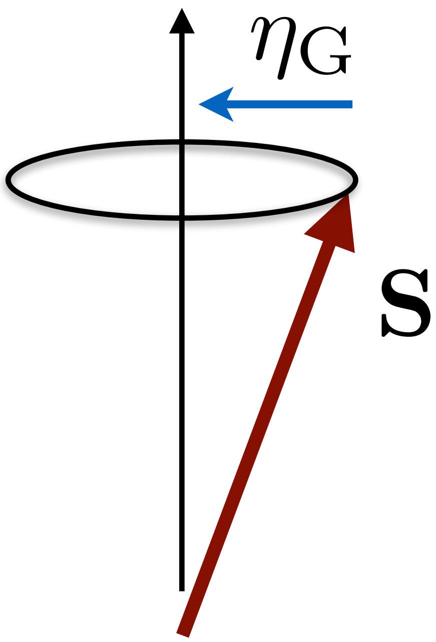
$$\dot{\mathbf{S}} = \mathbf{B}_{\mathrm{eff}} \times \mathbf{S} + \frac{\eta_{\mathrm{opt}}}{S} \left(\dot{S}_x \, \mathbf{e}_x \times \mathbf{S} \right)$$

Effective Landau-Lifshitz-Gilbert equation of motion

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Landau-Lifschitz-Gilbert Equation

Dynamics of the macrospin



$$\Omega \propto H$$

precession frequency

damping constant

$$\dot{\mathbf{S}} = -\Omega \mathbf{e}_z \times \mathbf{S} + \frac{\eta_{\mathrm{G}}}{S}\left(\dot{\mathbf{S}} \times \mathbf{S}\right)$$

phenomenological damping term
(Gilbert damping)

Effective Equation of Motion for the Spin

Fast cavity limit: integrate out the light field

$$\dot{\mathbf{S}} = \mathbf{B}_{\mathrm{eff}} \times \mathbf{S} + \frac{\eta_{\mathrm{opt}}}{S} \left(\dot{S}_x \, \mathbf{e}_x \times \mathbf{S} \right)$$

Effective Landau-Lifshitz-Gilbert equation of motion

Optically induced

- magnetic field $\mathbf{B}_{\mathrm{eff}}$
- dissipation η_{opt}

non-linear functions of $\mathbf{S}$

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Fast Cavity Limit

$$\dot{\mathbf{S}} = \mathbf{B}_{\text{eff}} \times \mathbf{S} + \frac{\eta_{\text{opt}}}{S}\left(\dot{S}_x\,\mathbf{e}_x \times \mathbf{S}\right)$$

effective field

$$\mathbf{B}_{\text{eff}} = -\Omega\mathbf{e}_z + \mathbf{B}_{\text{opt}}$$

$$\mathbf{B}_{\text{opt}} = \frac{G}{[(\frac{\kappa}{2})^2 + (\Delta - GS_x)^2]}\left(\frac{\kappa}{2}\alpha_{\text{max}}\right)^2 \mathbf{e}_x$$

damping
can change sign

$$\eta_{\text{opt}} = -2G\kappa S\left|\mathbf{B}_{\text{opt}}\right|\frac{(\Delta - GS_x)}{[(\frac{\kappa}{2})^2 + (\Delta - GS_x)^2]^2}$$

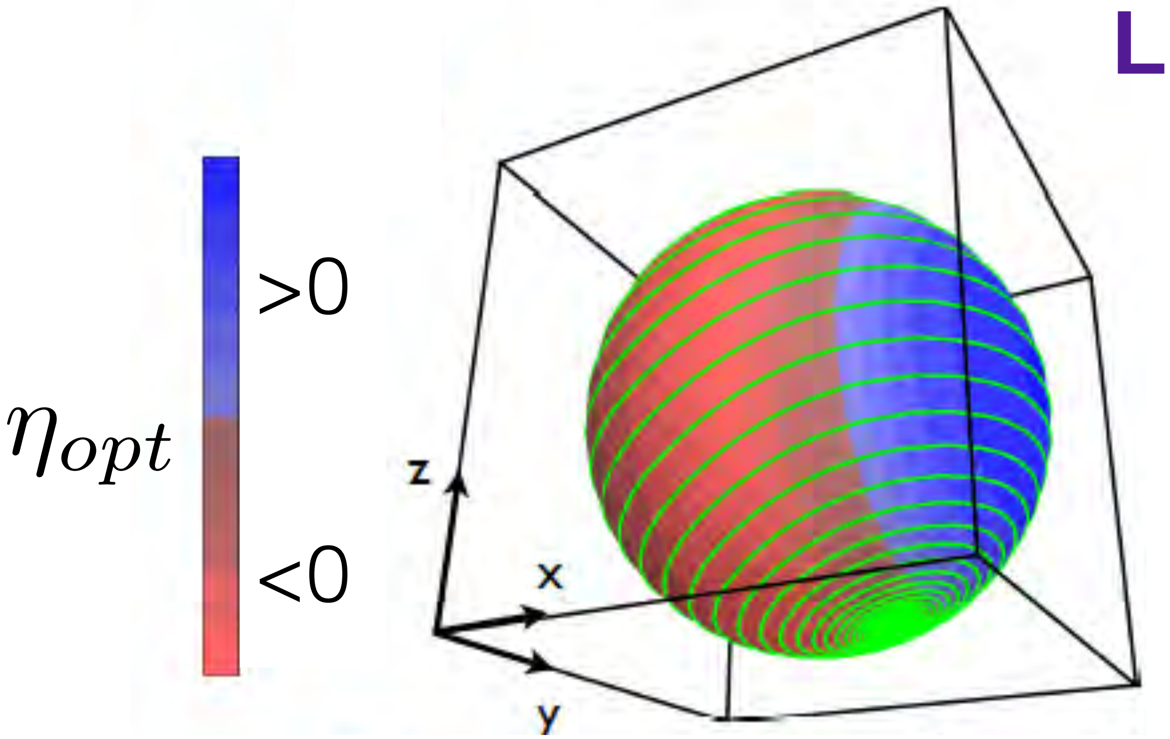
tunable by the external laser drive

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Spin Dynamics: Fast Cavity Limit

Blue detuned case:

dissipation changes sign



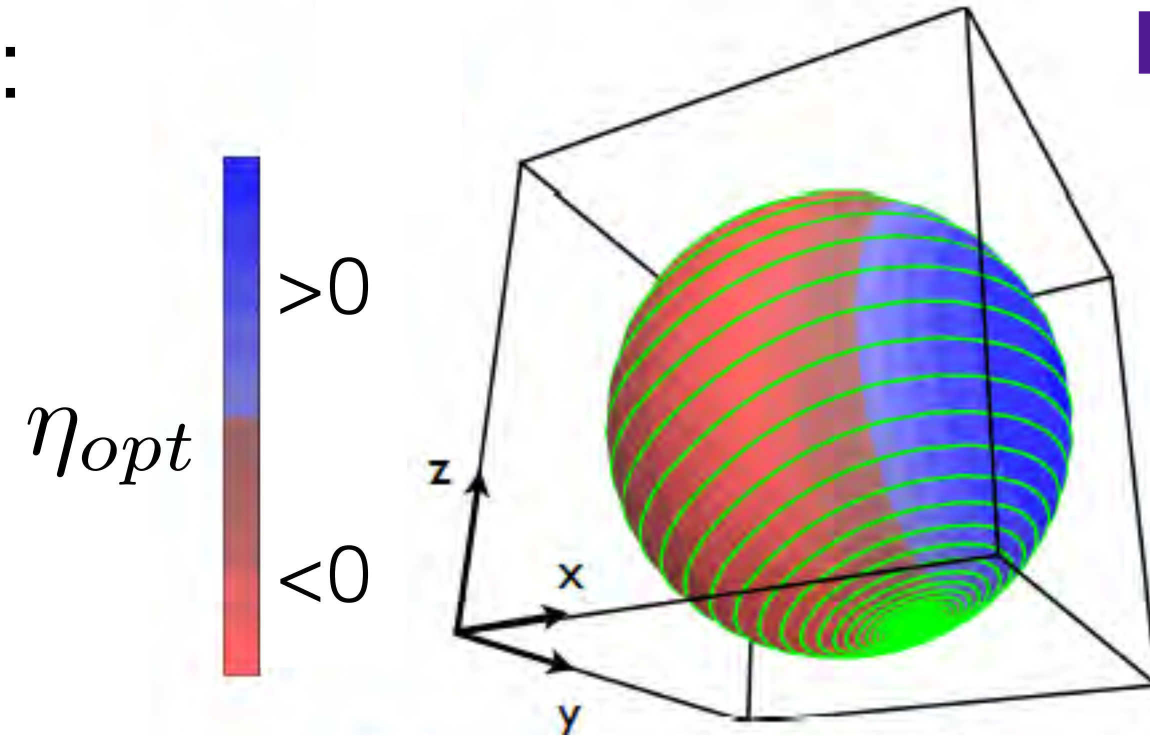
Light induced magnetic switching

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Spin Dynamics: Fast Cavity Limit

Blue detuned case:

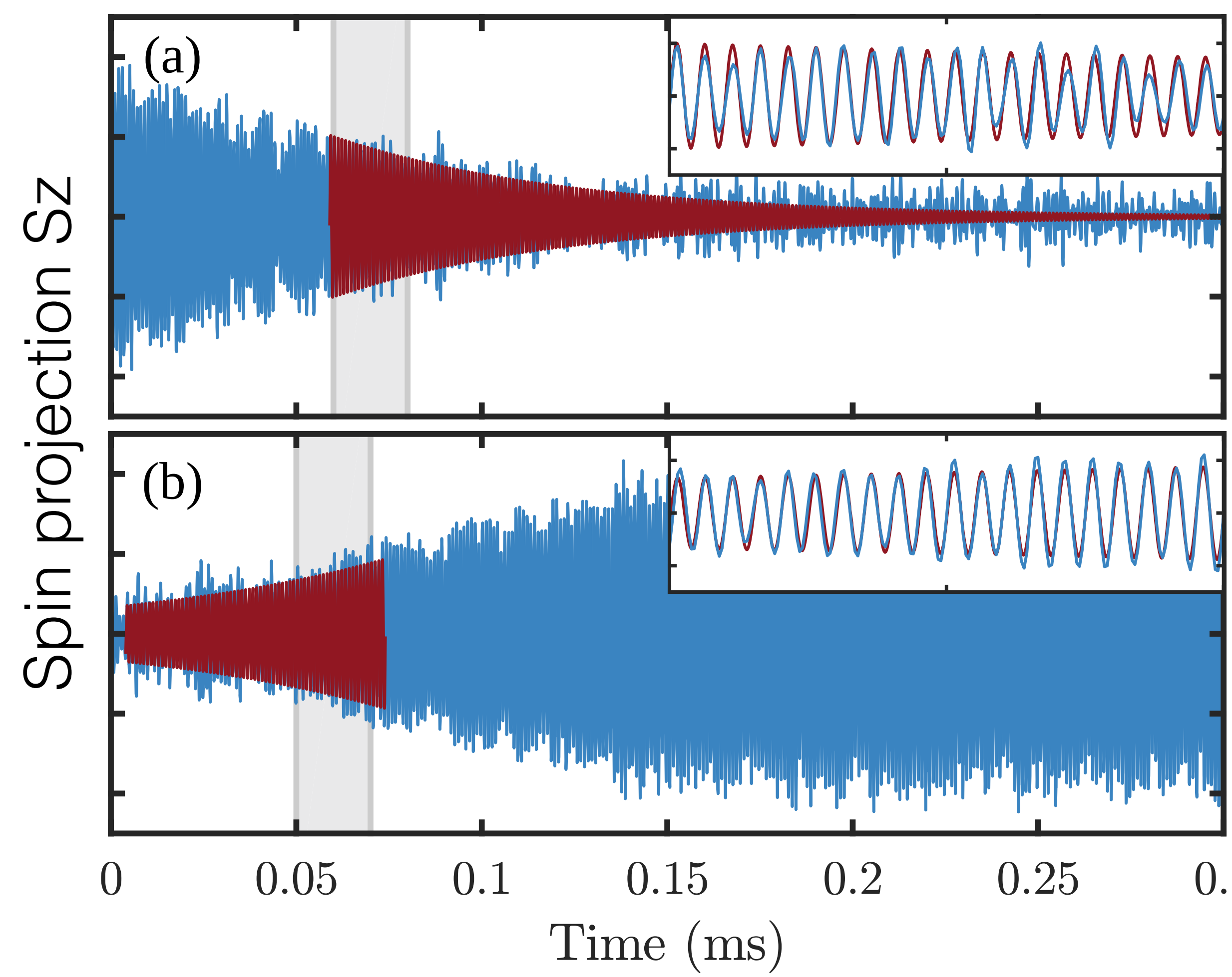
dissipation changes sign



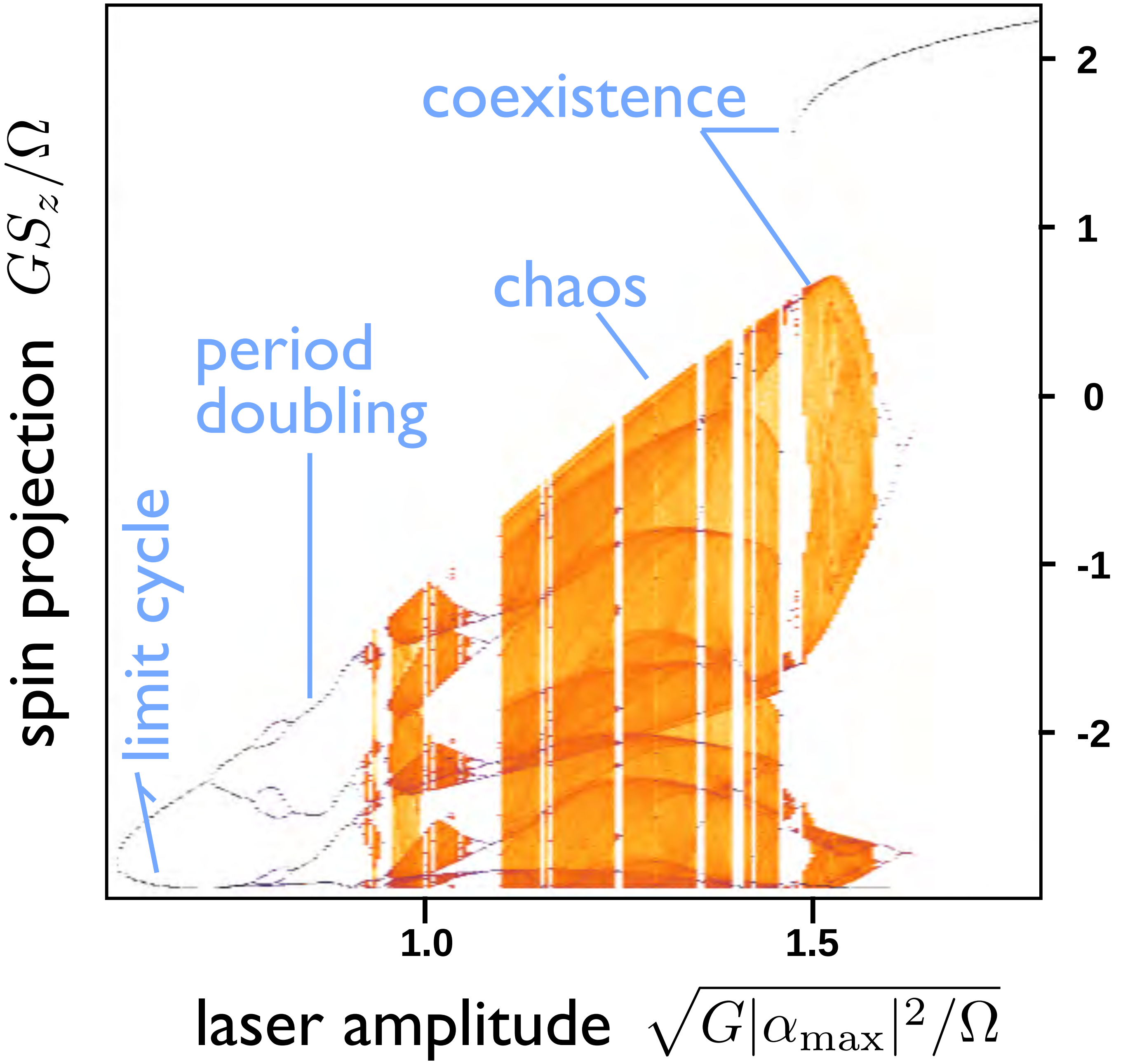
Light induced magnetic switching

See experimental realization with cold atoms, Dan M. Stamper-Kurn Group Phys. Rev. Lett. **118**, 063604 (2017)

→



Full Nonlinear Dynamics



» **Coherent optical control**

» **Magnetic switching**

» **Self-sustained oscillations**

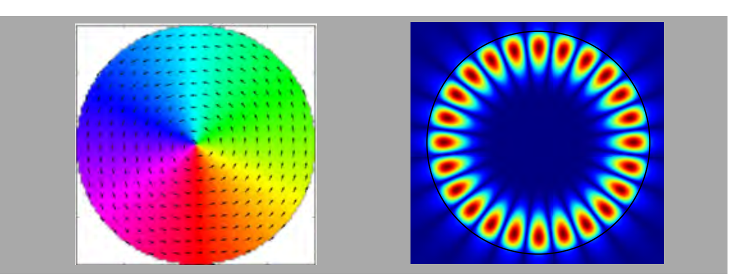
» **Optically induced route to chaos**

S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Introduction and motivation

Optomagnonic Hamiltonian

Optically induced spin dynamics

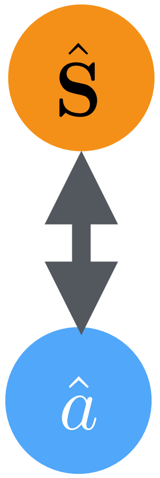


Magnetic textures: vortex in a disk

Summary

But…

Problem



the state of the art optomagnonic coupling is very small

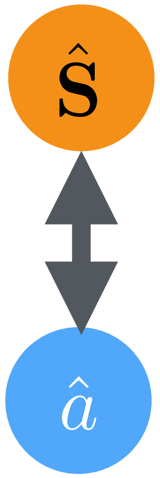
Coupling per photon $g_0 \approx 60\mathrm{Hz}$ Cooperativity $\mathcal{C} \approx 10^{-7}$

(for small oscillations: spin $\longrightarrow$ harmonic oscillator)

$$\hbar G \hat{S}_x \hat{a}^\dagger \hat{a} \approx \hbar \underbrace{G\sqrt{S/2}}_{g_0}\, \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$$

But…

Problem



the state of the art optomagnonic coupling is too small

Coupling per photon $g_0 \approx 60\mathrm{Hz}$

Cooperativity $\mathcal{C} \approx 10^{-7}$

Some solutions

smaller systems

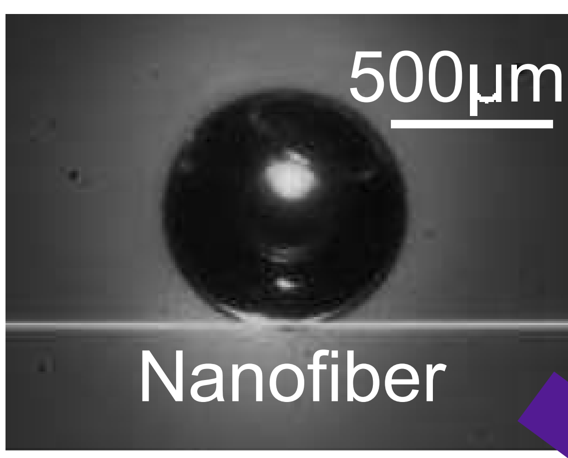
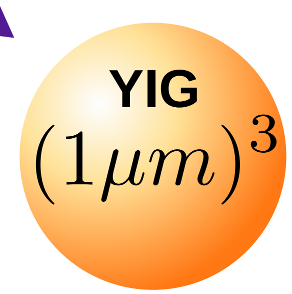
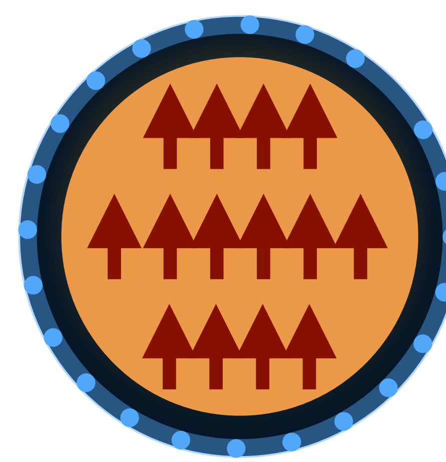


Fig: Osada et. al.
PRL 116, 223601



better overlap of modes



?

Optomagnonics beyond the Kittel mode

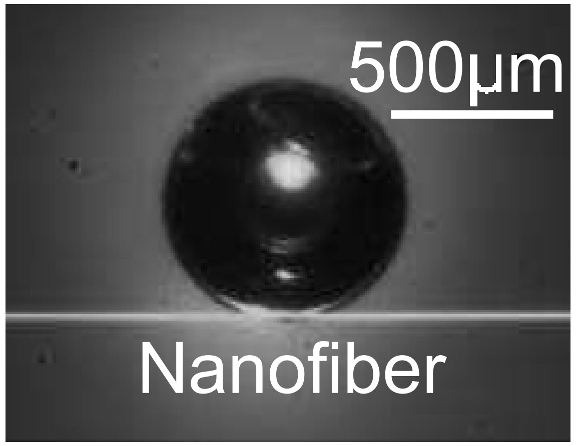
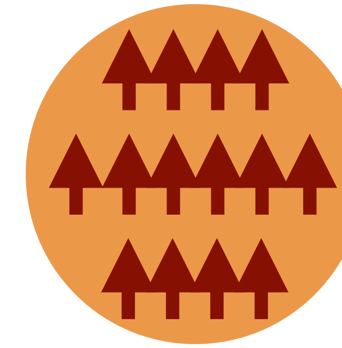
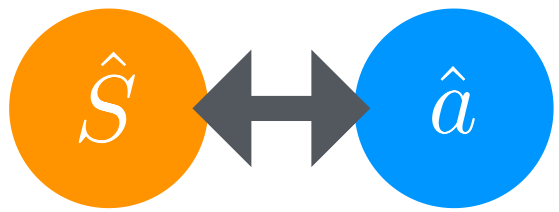


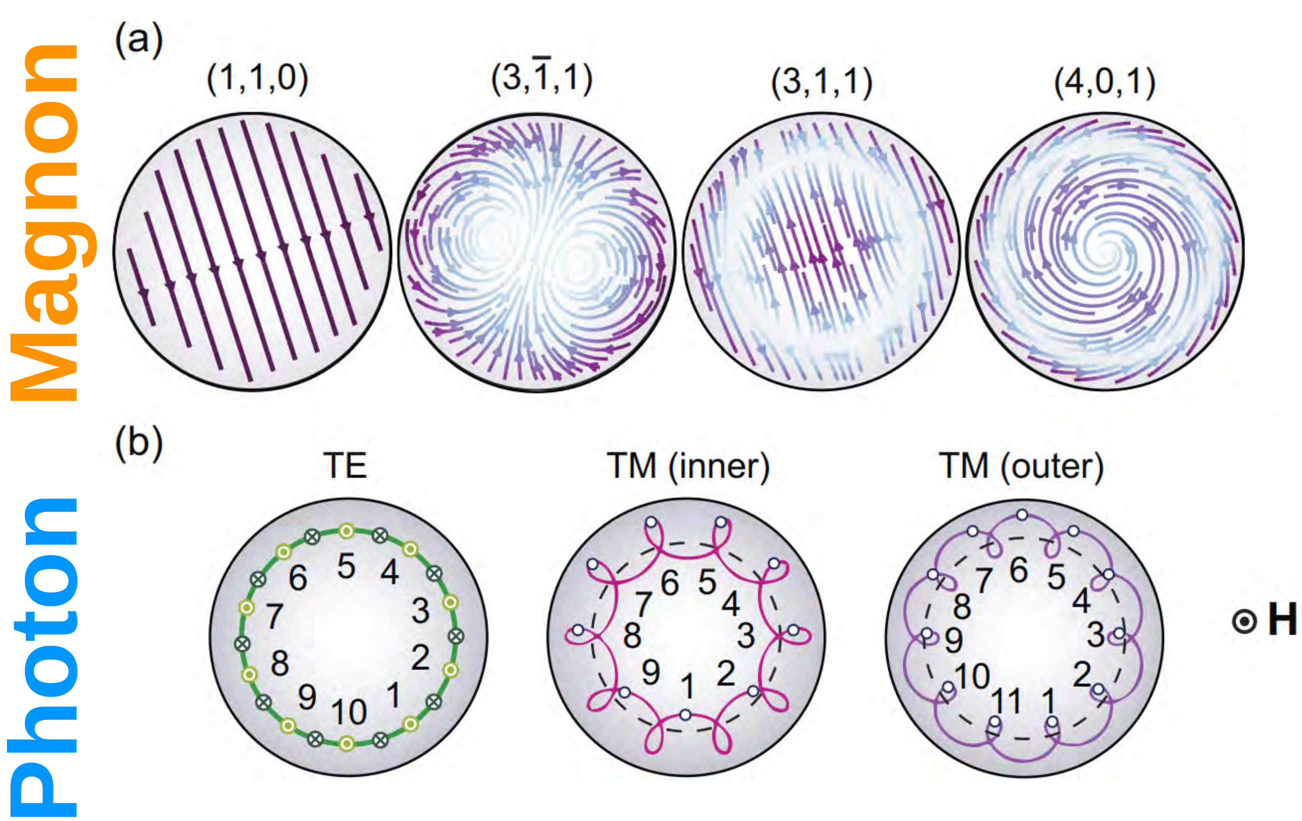
Fig: Osada et. al.
PRL 116, 223601

Optomagnonic coupling demonstrated

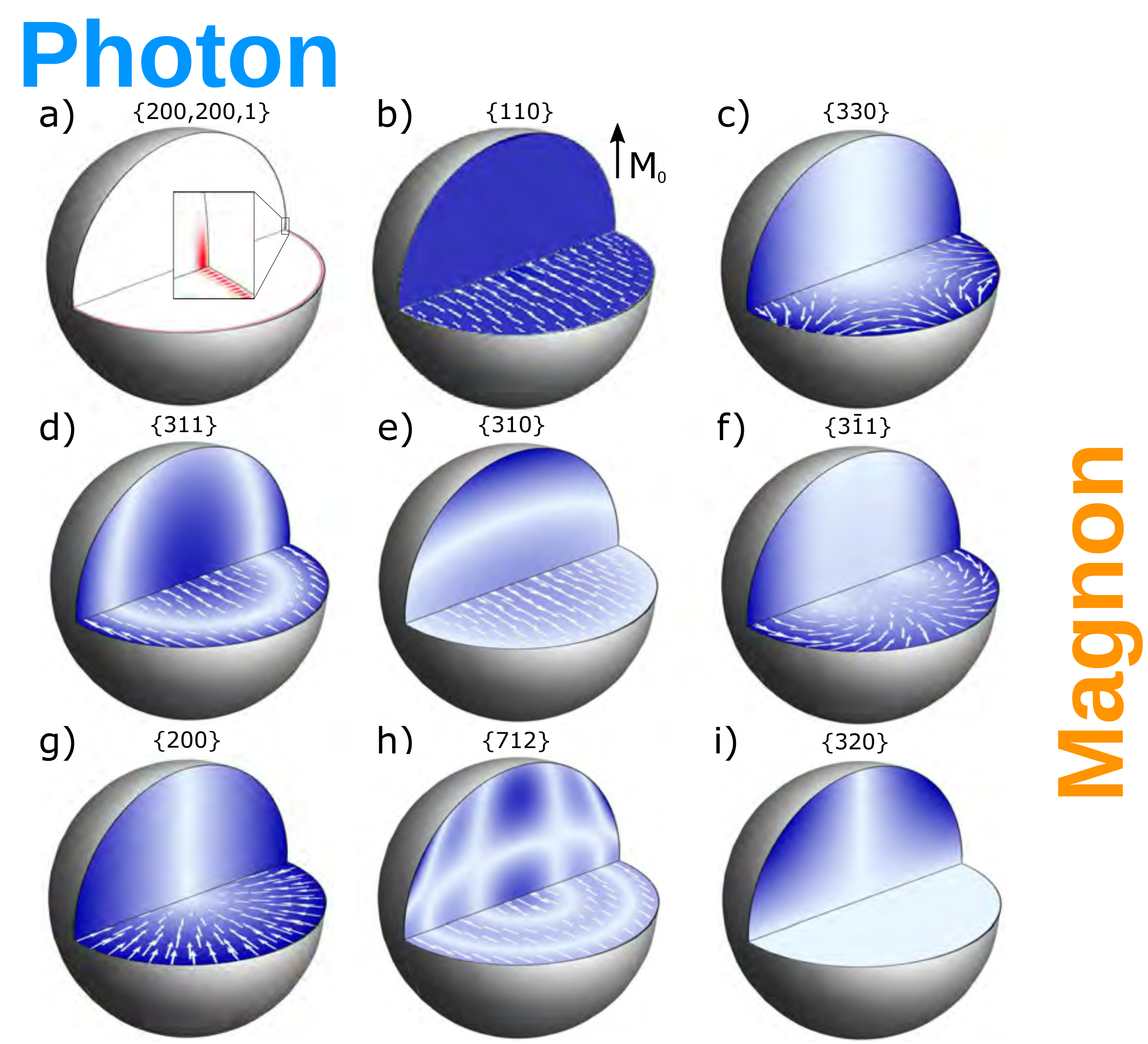
- Non-homogeneous magnon mode
- Homogeneous ground state







A. Osada et al, PRL 120, 123602 (2018)

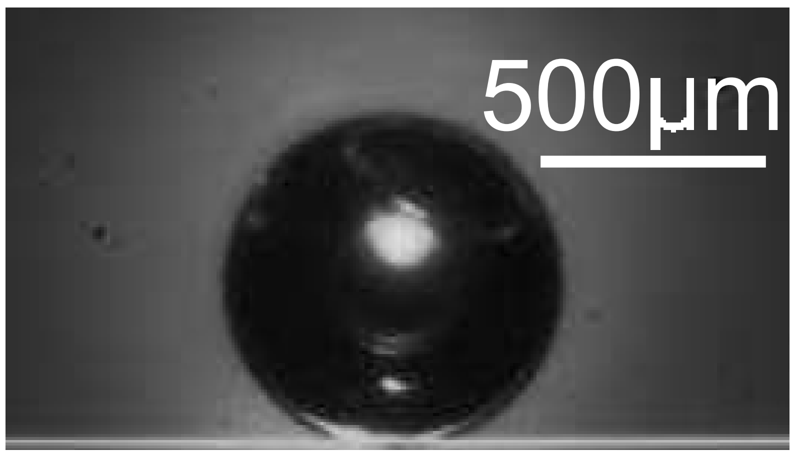


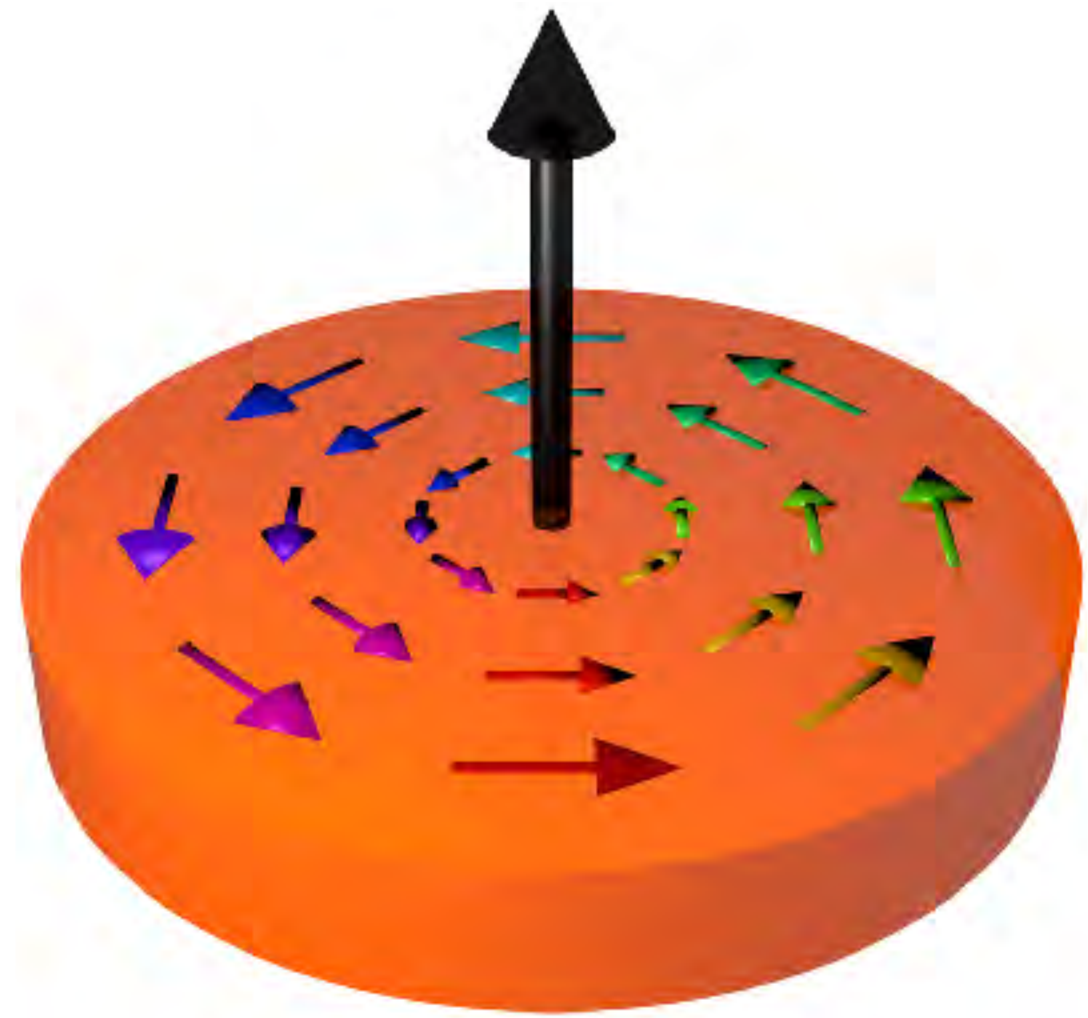
J.A. Haigh et al, Arxiv:1804.00965v1 (2018)

Magnetic Textures

smaller systems

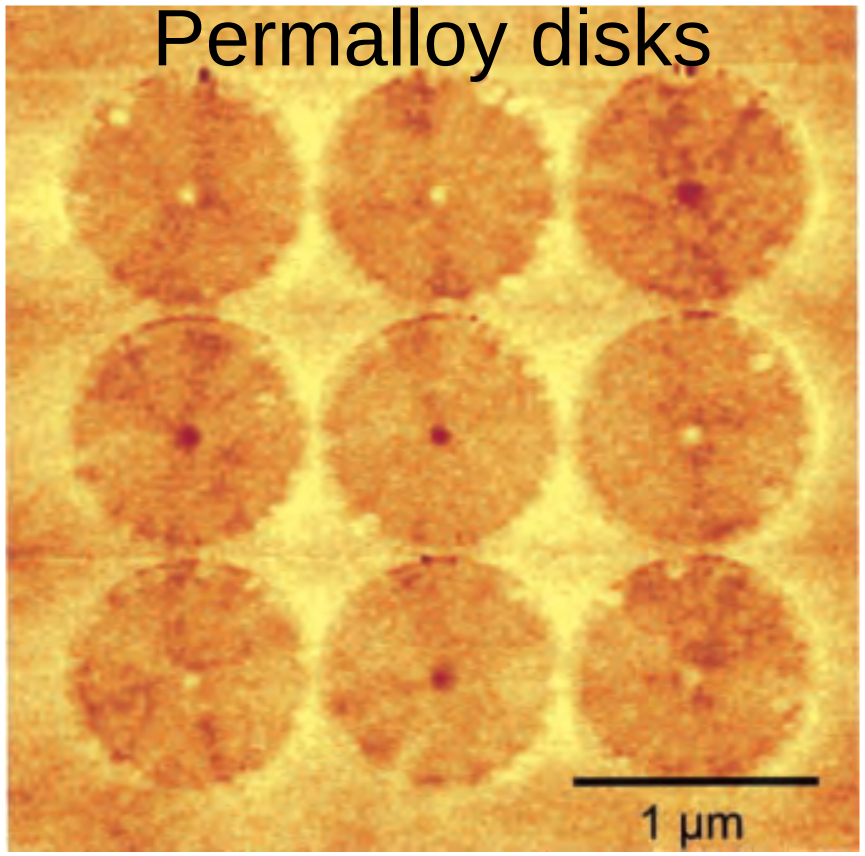
Magnetic textures





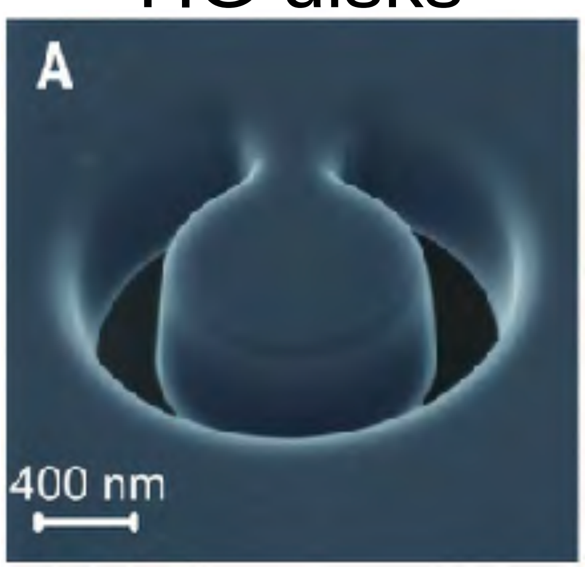
Vortex in a micro disk

Magnetic Textures: Vortex in Microdisks

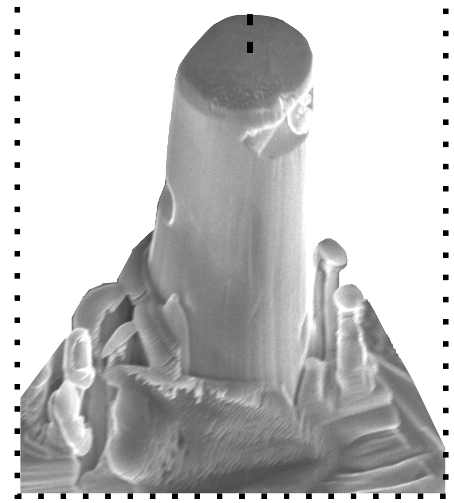


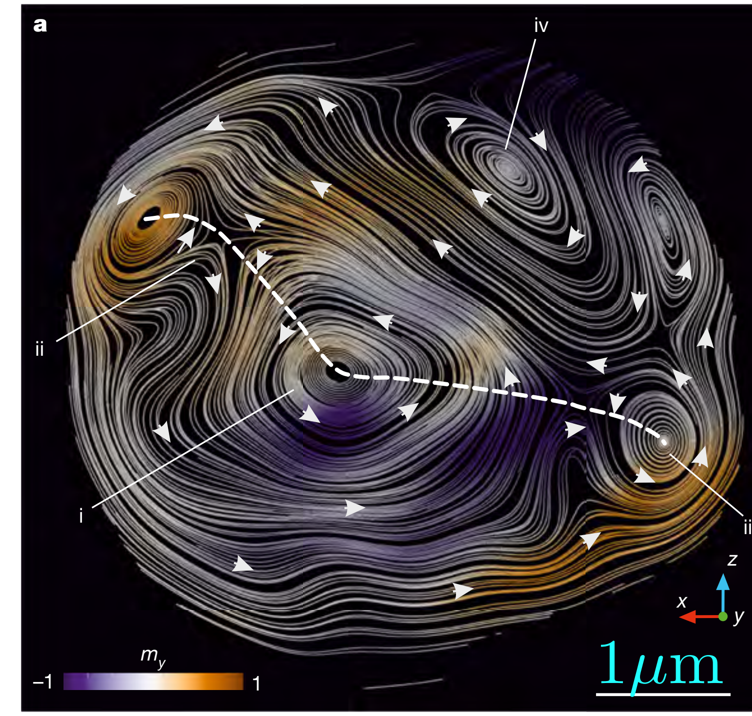
T.Shinjo et al, Science 289, 930 (2000)

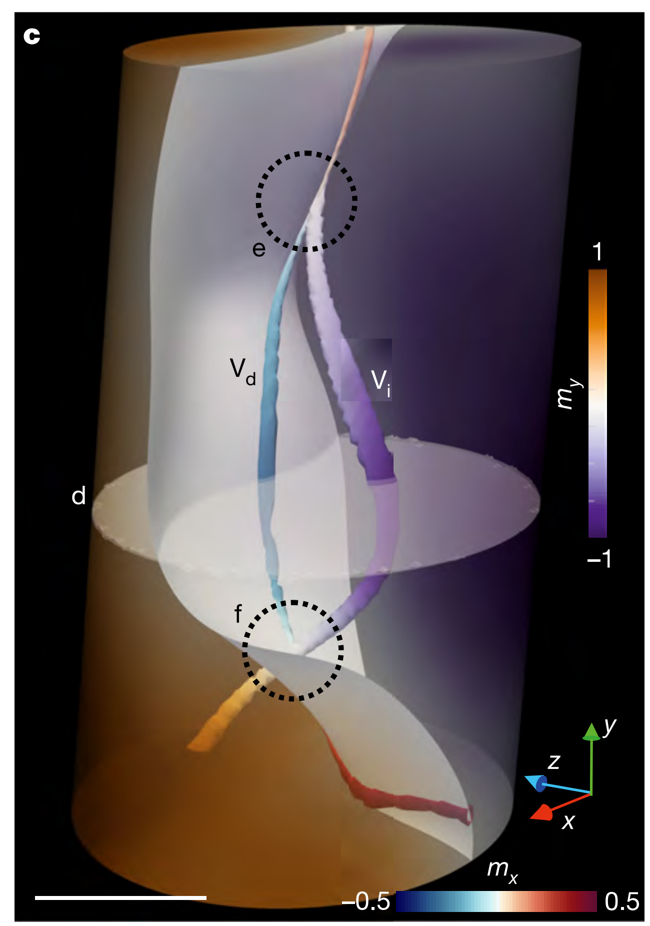
YIG disks



Losby et al, Science 350, 798 (2015)





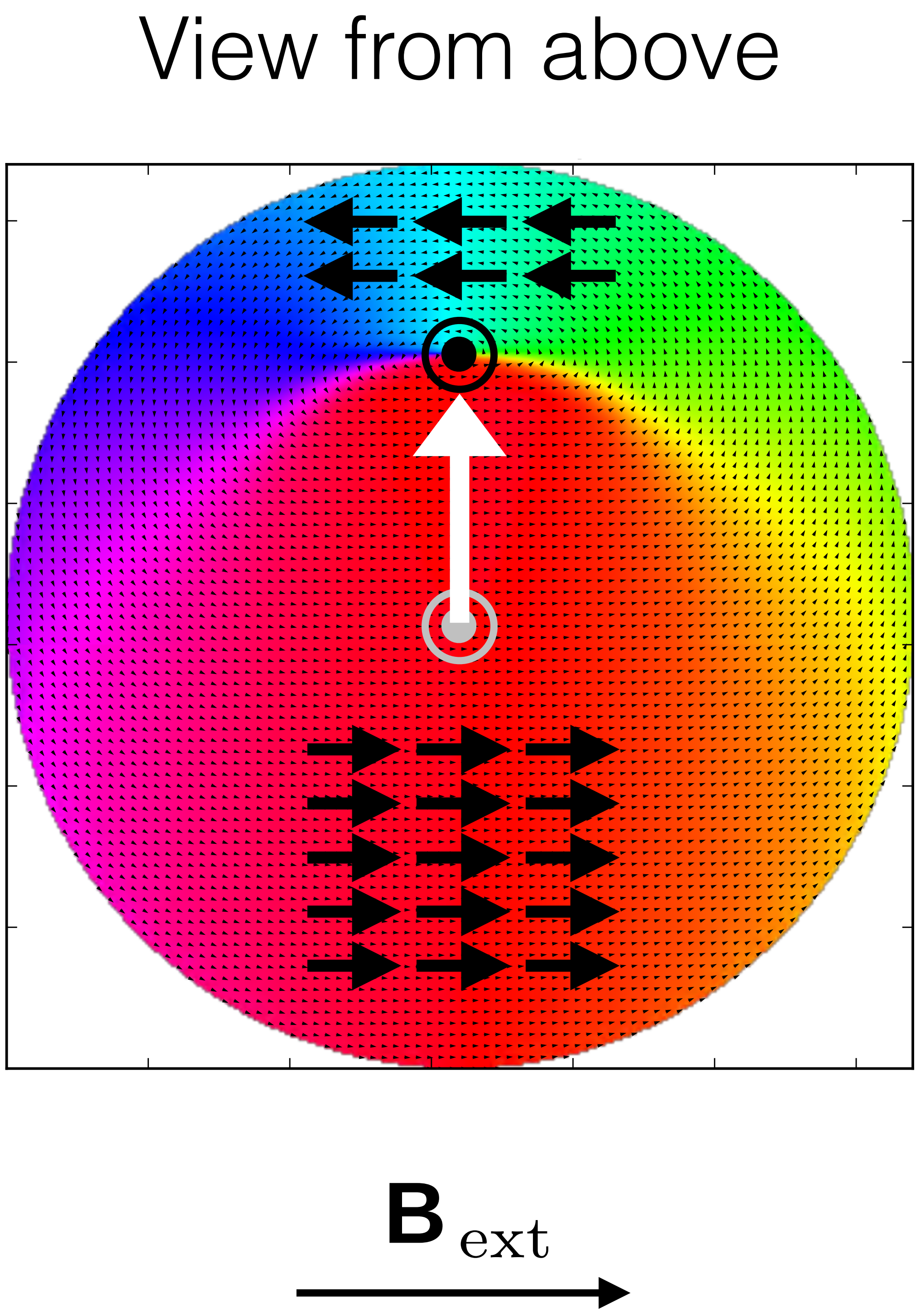


Cobalt Gadolinium pillars

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

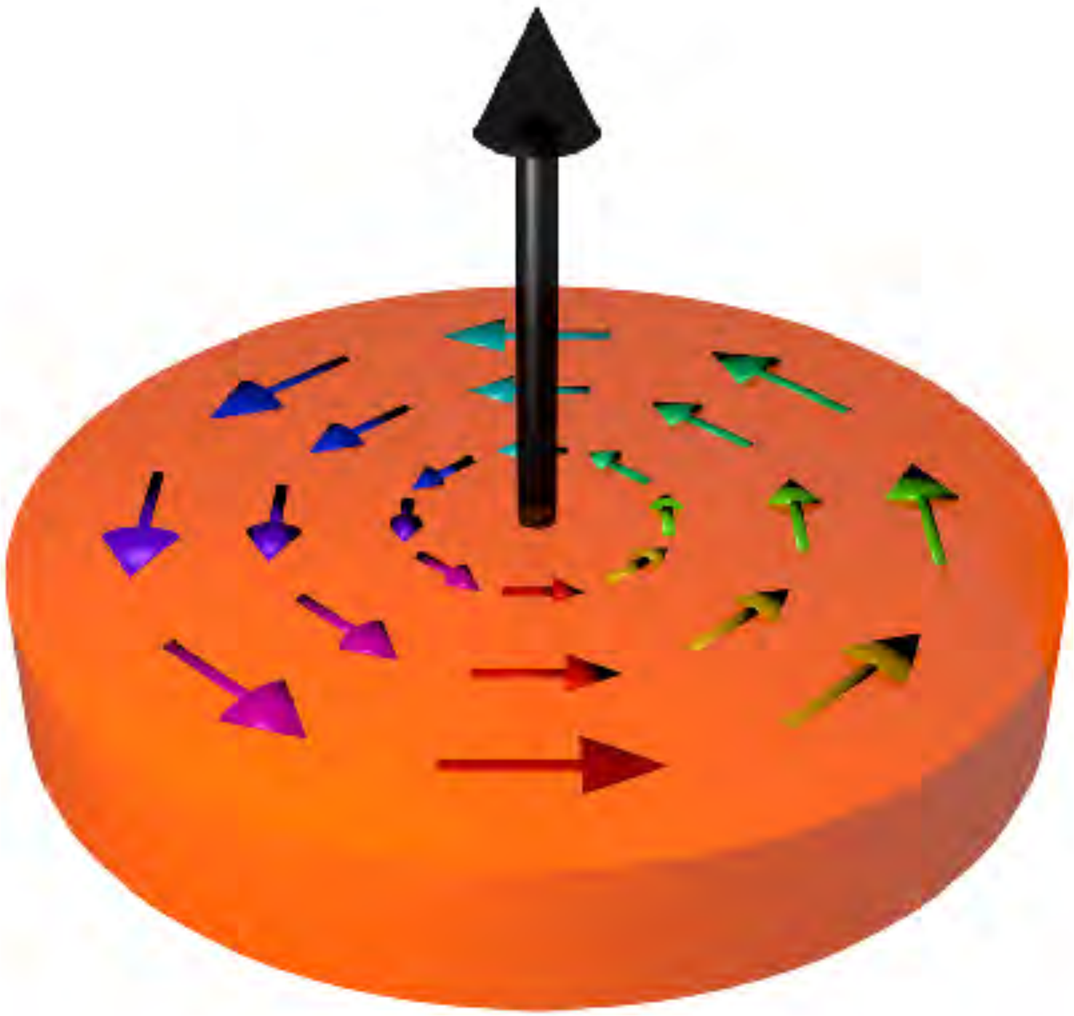
Vortex

- **Position tunable by a magnetic field**



Vortex

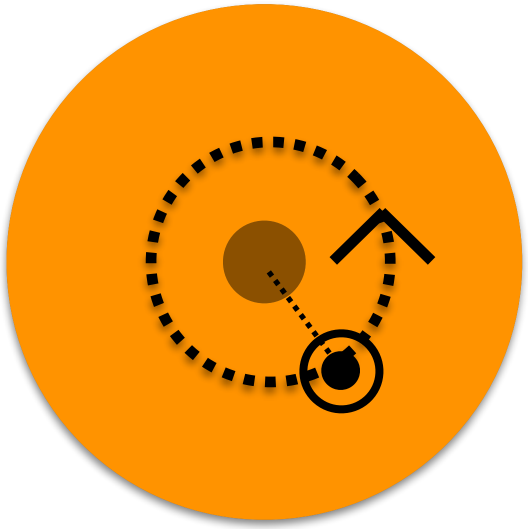
- Supports localized magnon modes



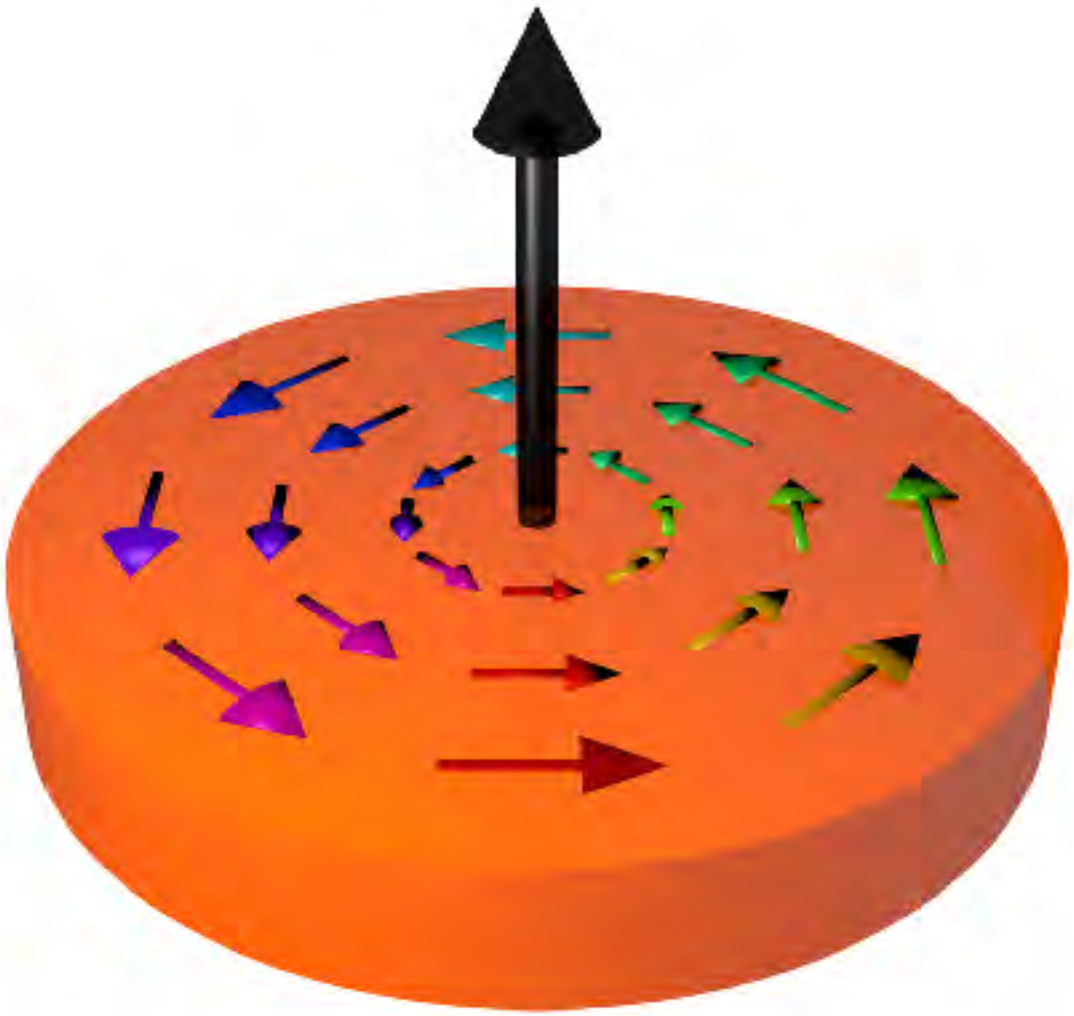
Vortex

- **Supports localized magnon modes**

Gyrotropic mode

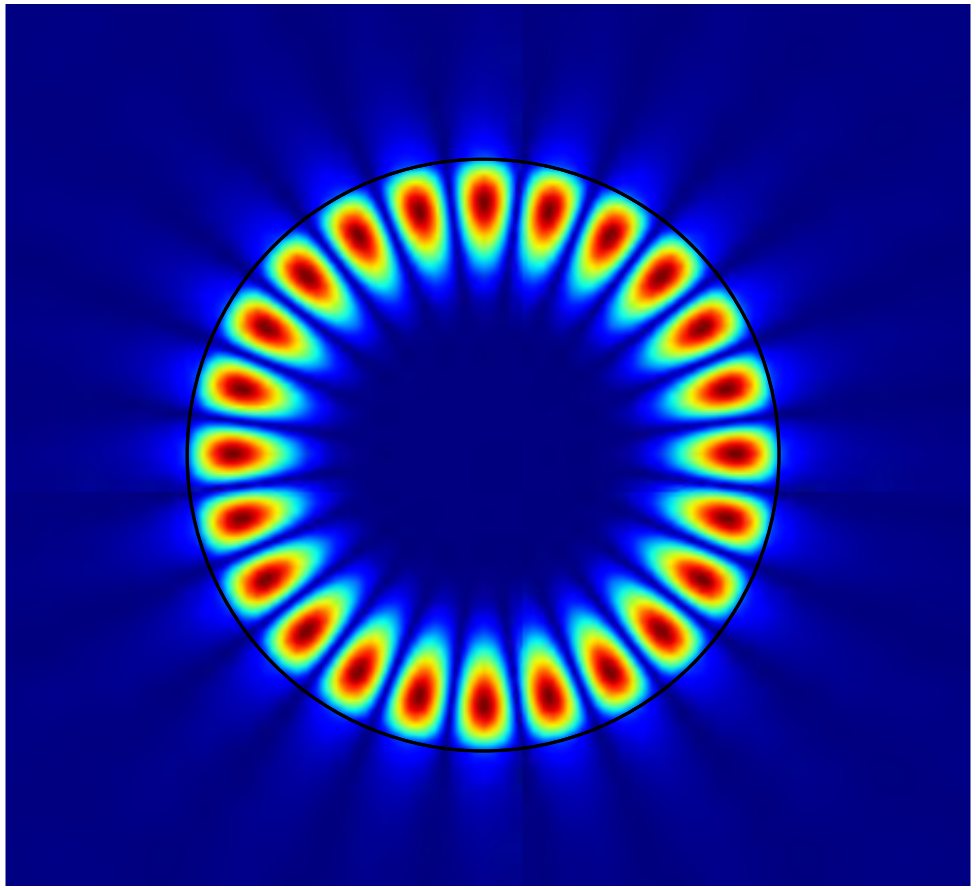


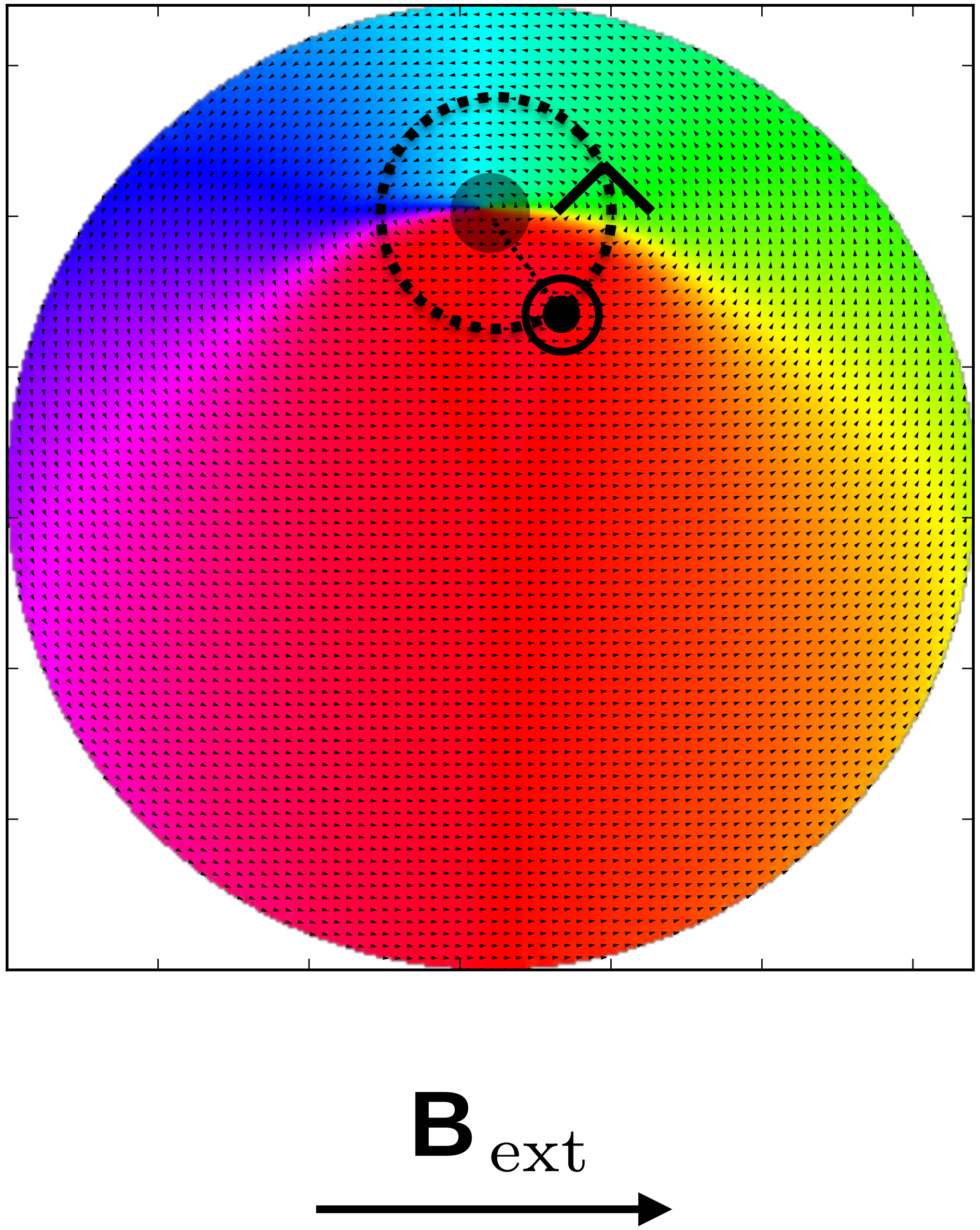
- Sub -GHz
- Gapped



Vortex

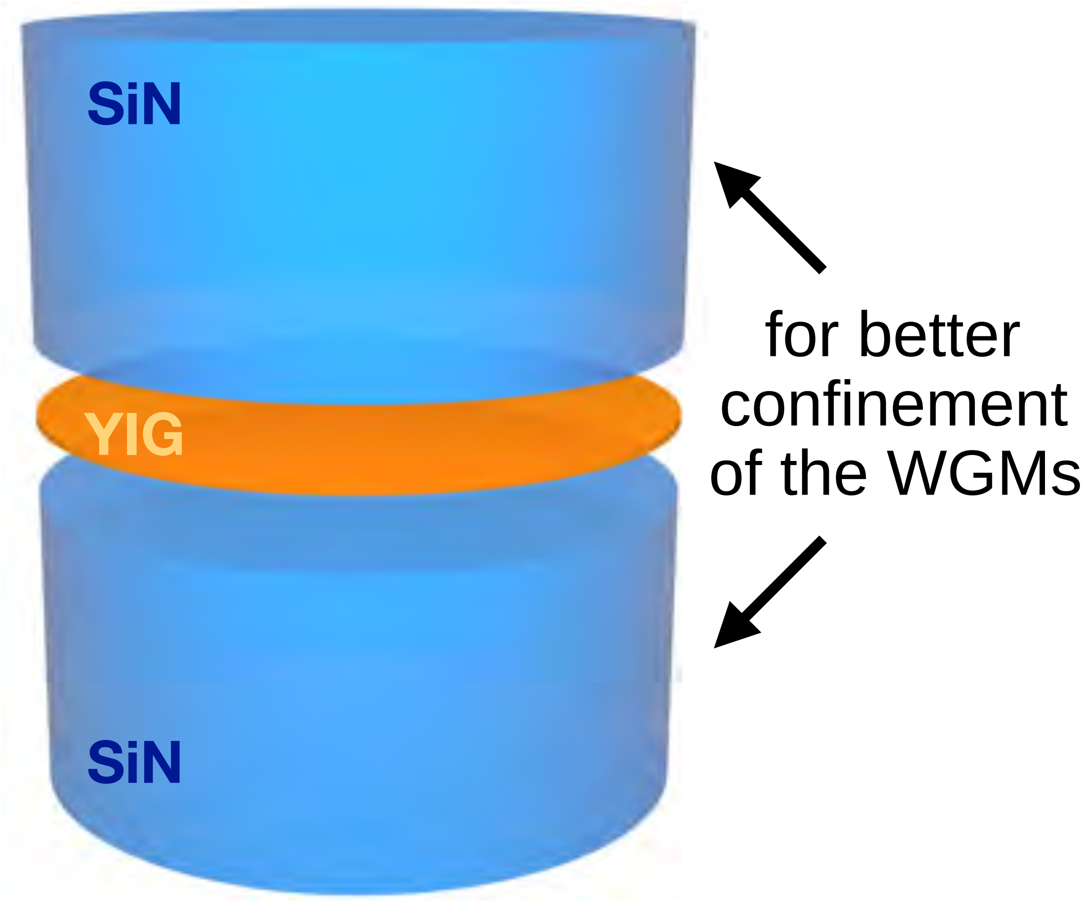
Coupling to optical
Whispering Gallery Modes?





Setup: two cases

Thin Disk Heterostructure

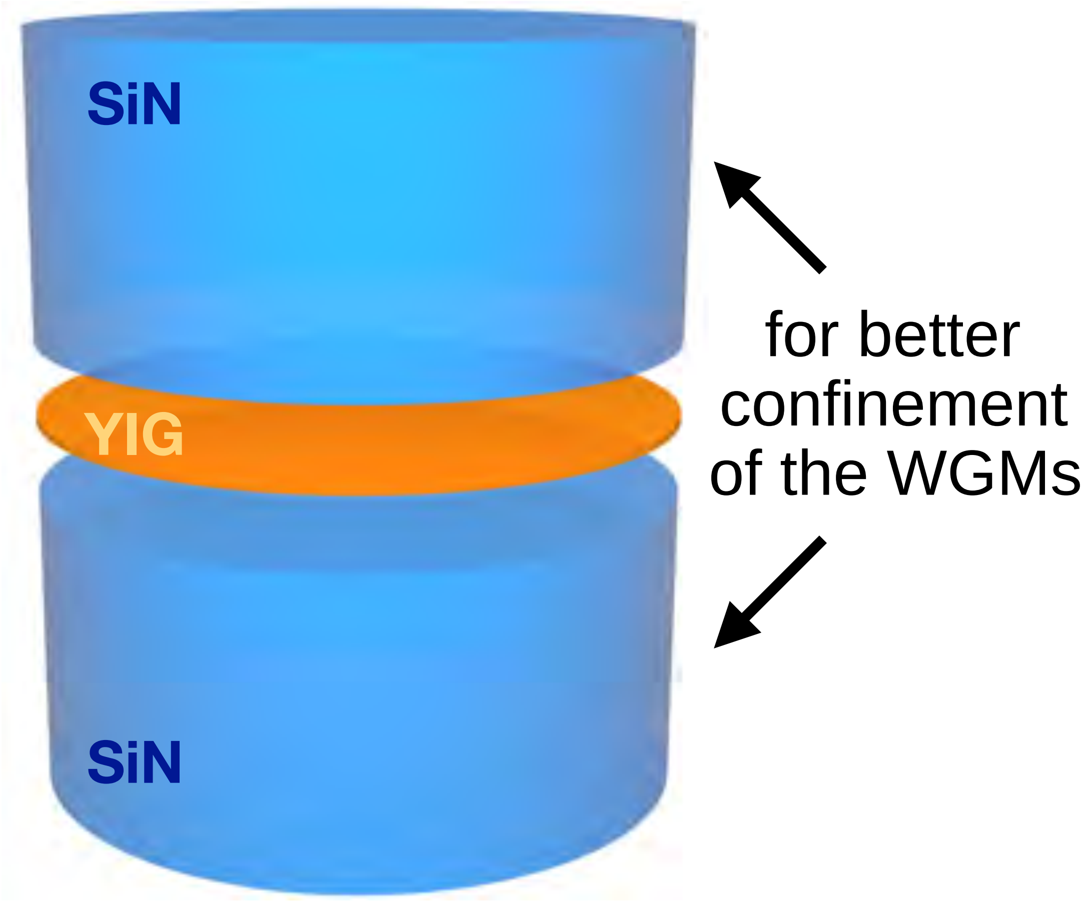


$$h_{\text{YIG}} \sim l_{ex} \sim 10\text{nm}$$

- The magnon modes live in the thin YIG disk
- The optical WGMs live in the whole structure

Setup: two cases

Thin Disk Heterostructure



$$h_{\text{YIG}} \sim l_{ex} \sim 10\text{nm}$$

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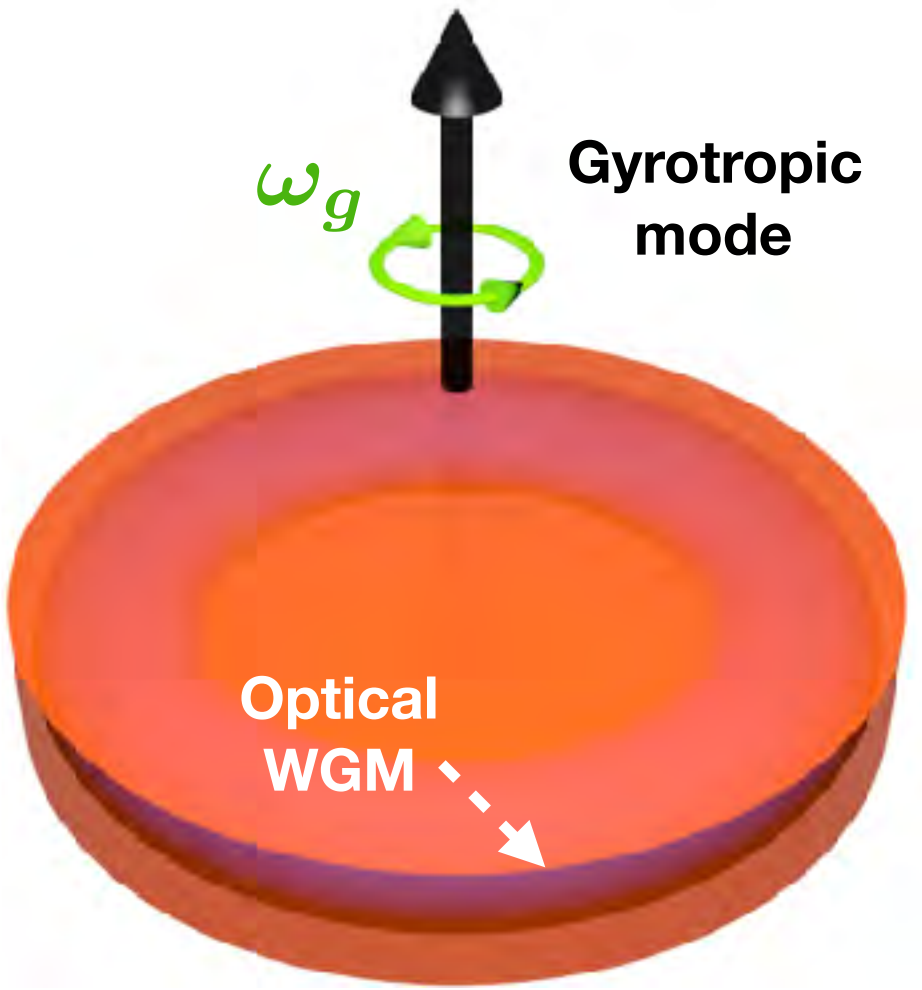
"Thick" YIG Disk

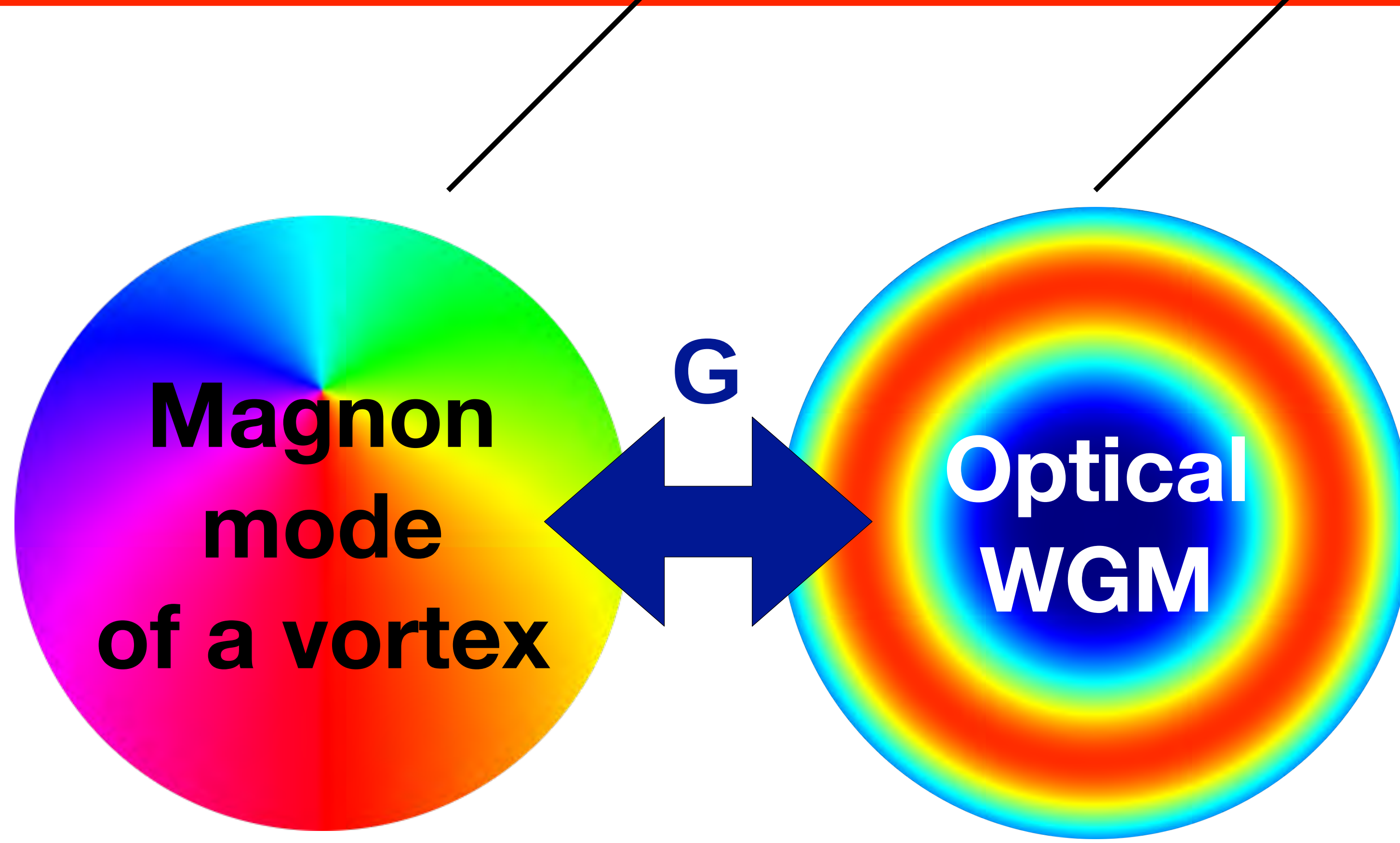


$$h_{\text{YIG}} \sim R_{\text{YIG}} \sim 1\mu\text{m}$$

- YIG disk: magnons + optical cavity
- Magnetic texture: Non-trivial z-dependence

Optomagnonic Coupling

$$H_c = -i \frac{\theta_F \lambda_n}{4\pi} \frac{\varepsilon_0 \varepsilon}{2} \int d\boldsymbol{r}\ \boldsymbol{m}(\boldsymbol{r},t) \cdot [\boldsymbol{E}^*(\boldsymbol{r},t) \times \boldsymbol{E}(\boldsymbol{r},t)]$$



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

MuMax3

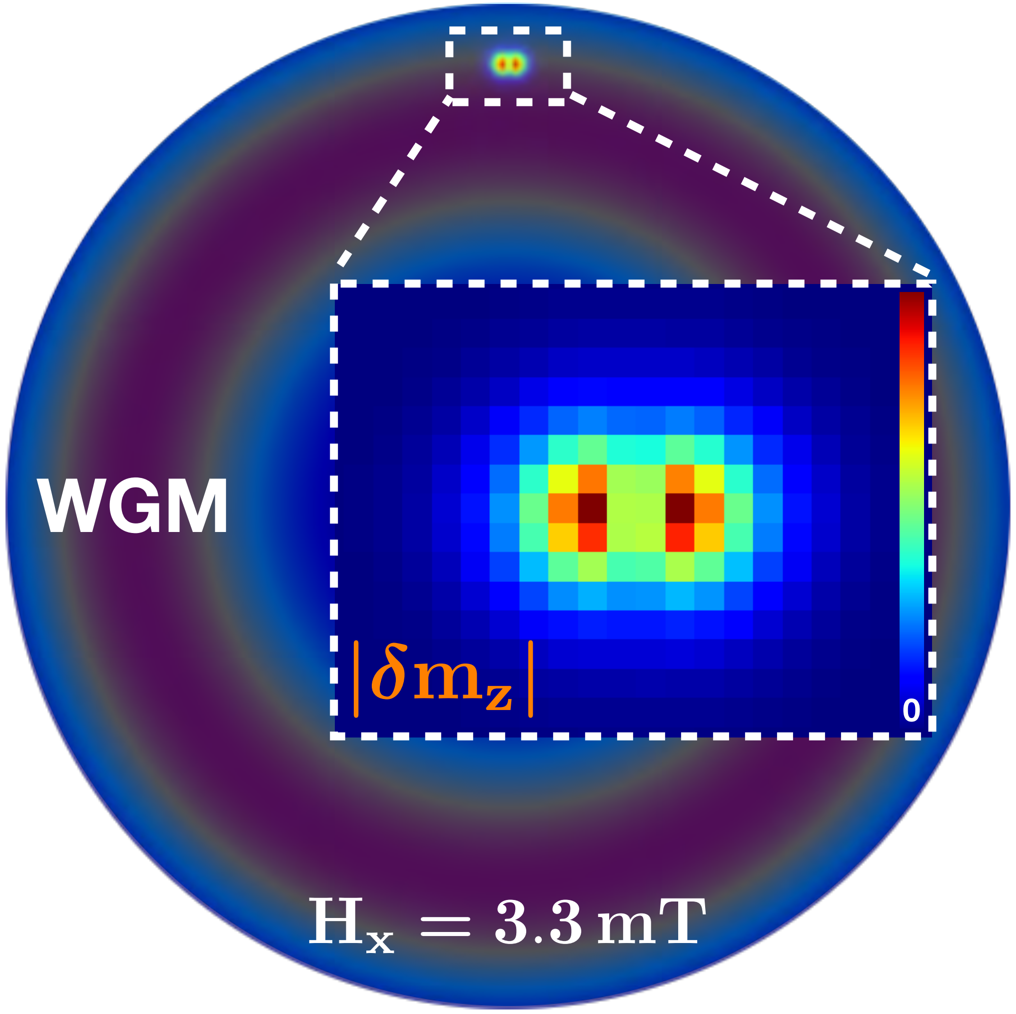
COMSOL

Simulation software

Vortex in a thin disk: optomagnonic coupling

spatial dependence

Magnon and optical modes



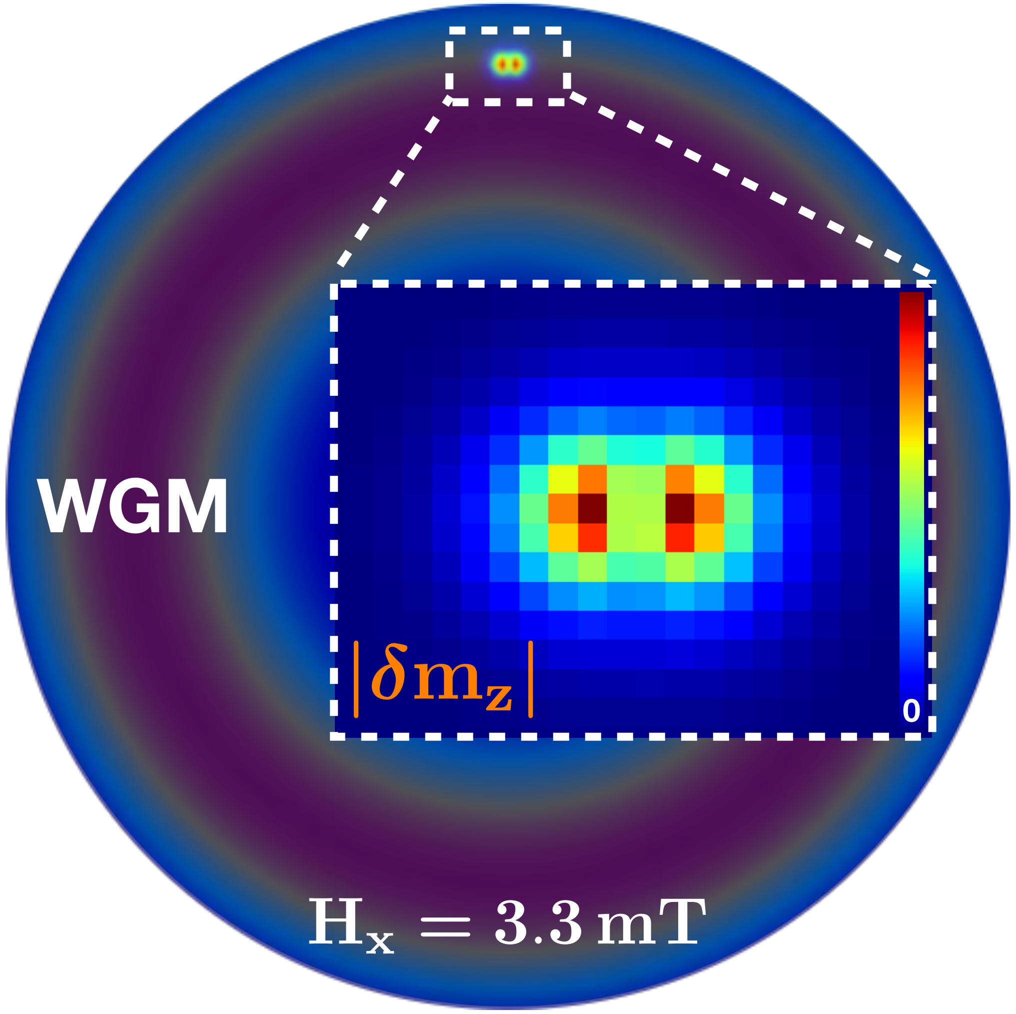
Gyrotropic mode $\omega_g \approx 30\,\mathrm{MHz}$

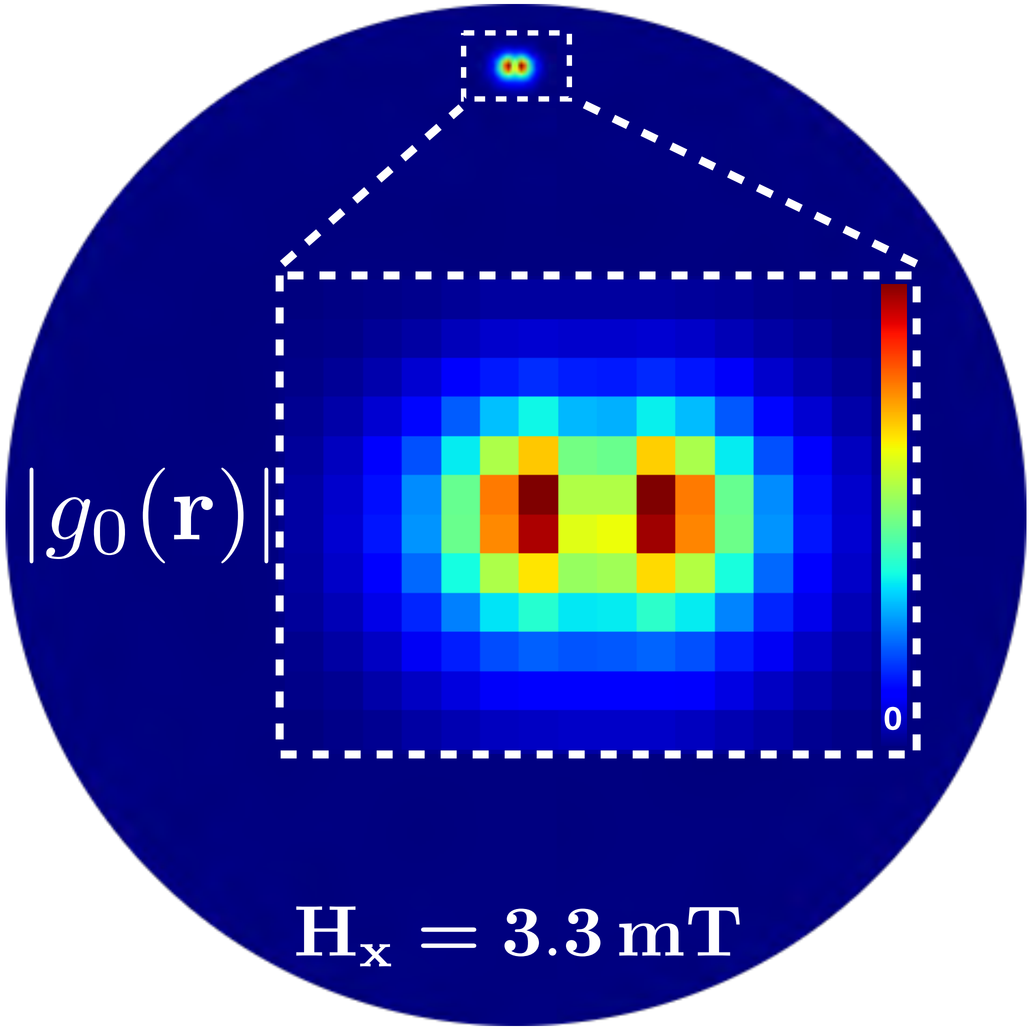
Vortex in a thin disk: optomagnonic coupling

spatial dependence

Magnon and optical modes

Optomagnonic coupling

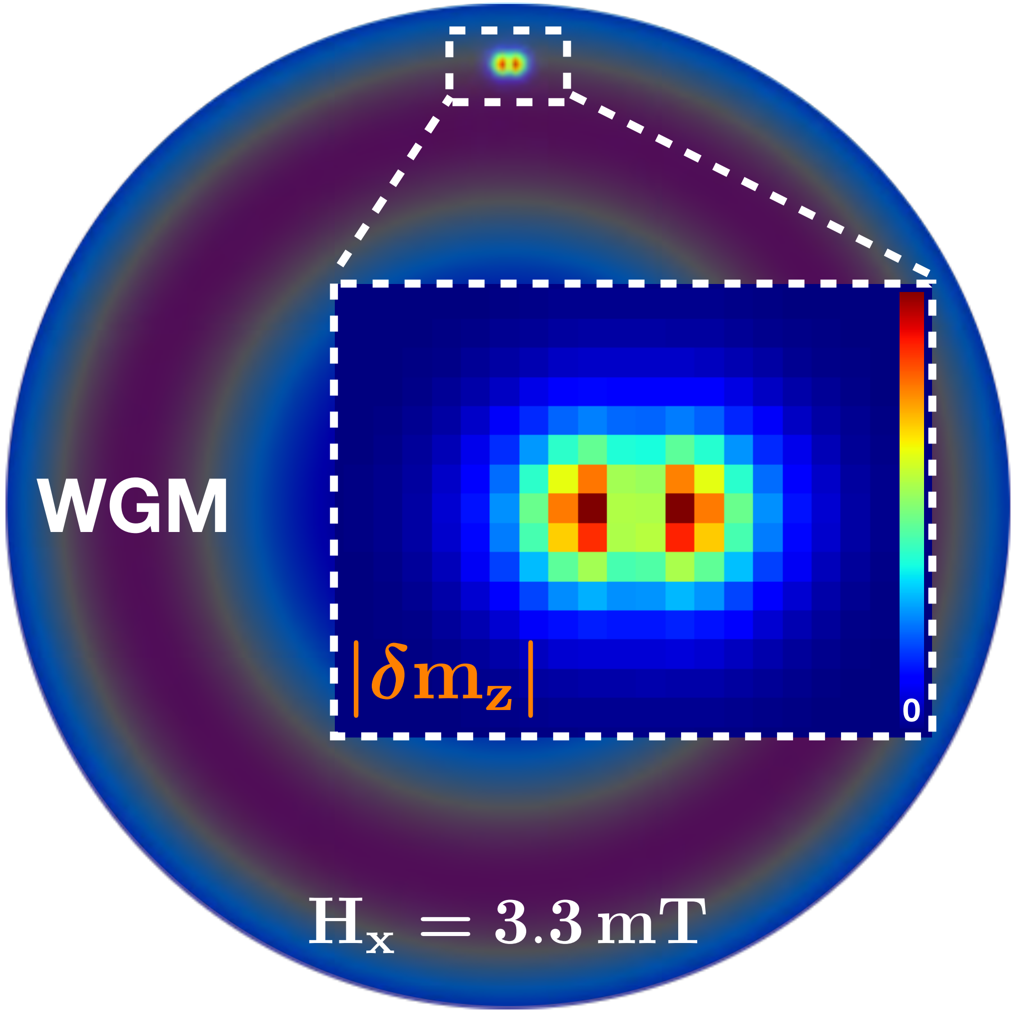




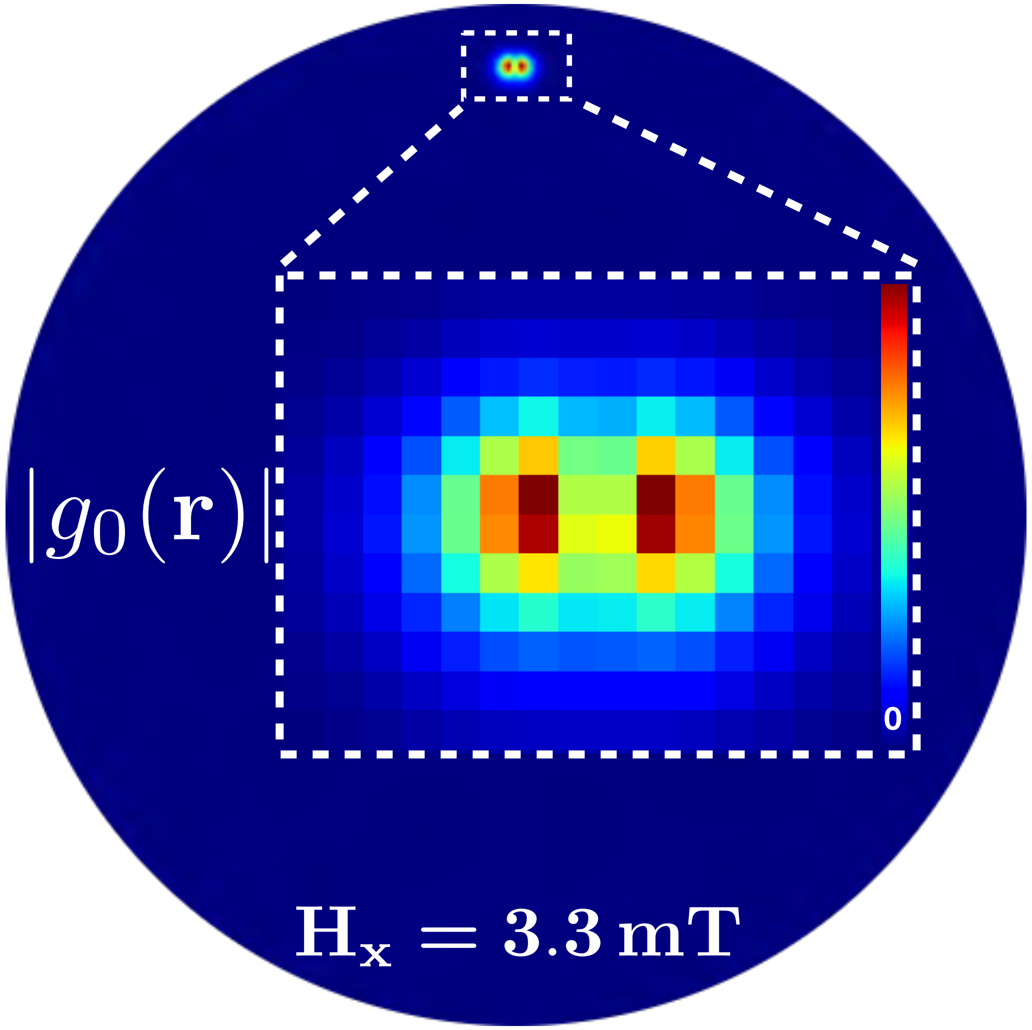
Vortex in a thin disk: optomagnonic coupling

spatial dependence

Magnon and optical modes



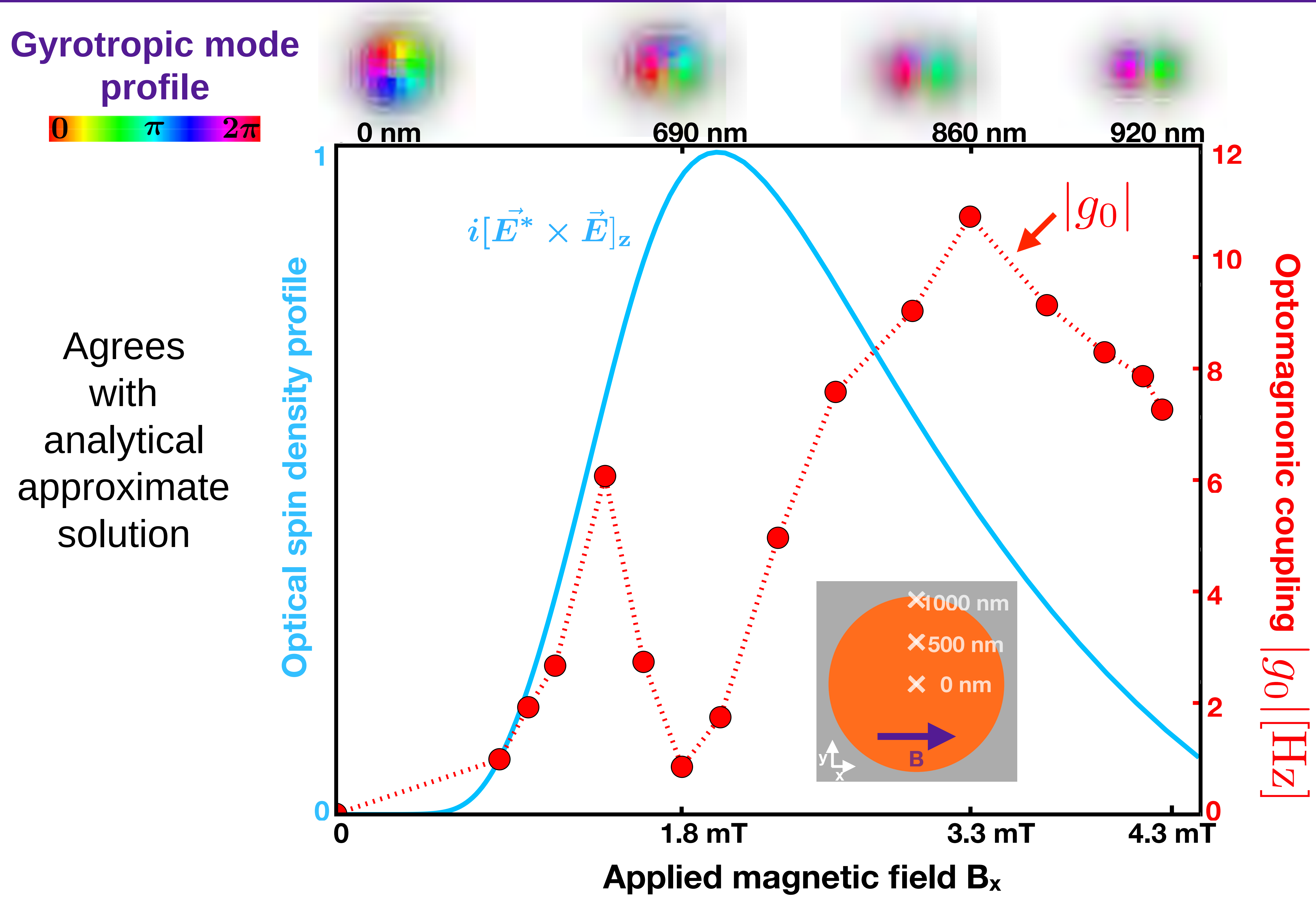
Optomagnonic coupling



integrate over the whole volume

Thin disk: tuneable coupling via B-field

Agrees with analytical approximate solution

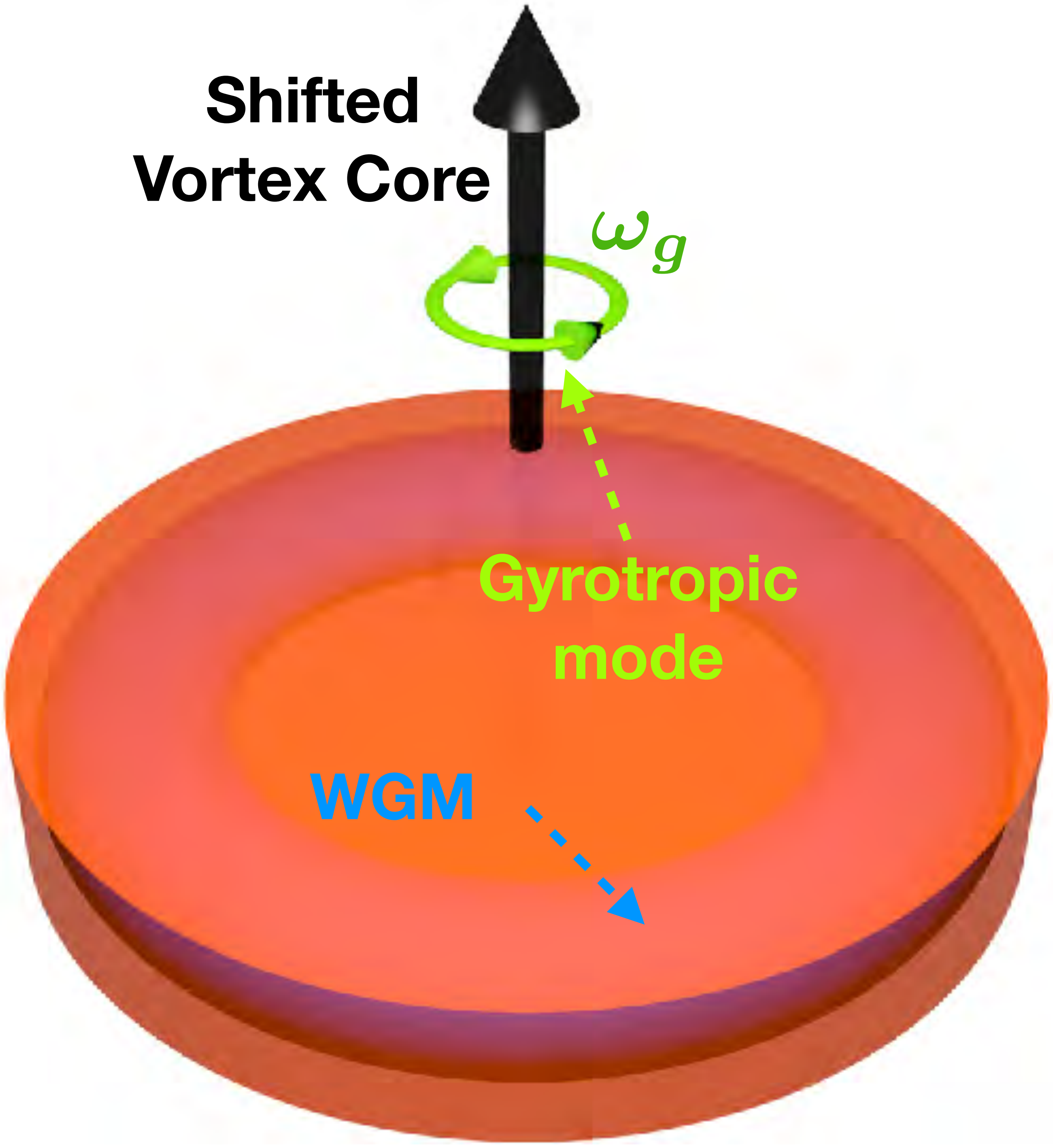


J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, arXiv:1806.06727 (2018)

Full YIG microdisk

$R = 2\mu\text{m}$

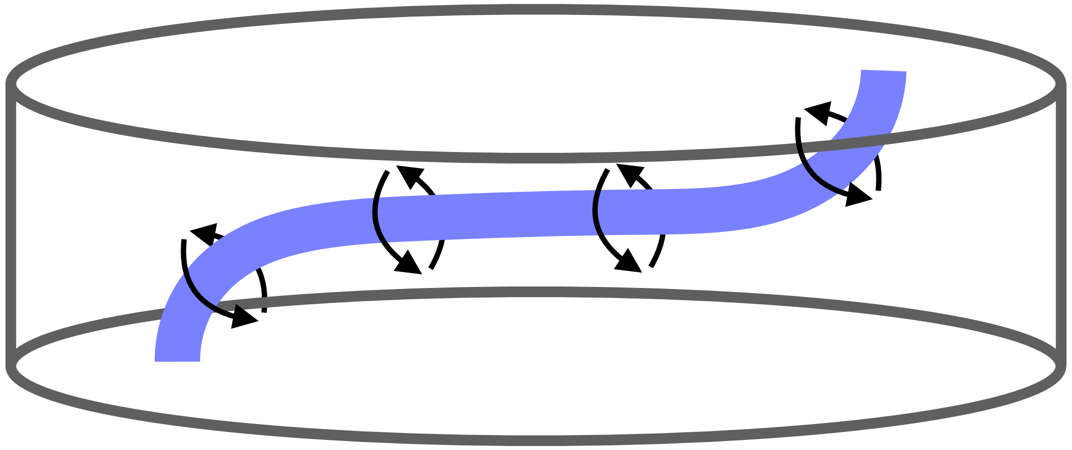
$h = 500\text{nm}$

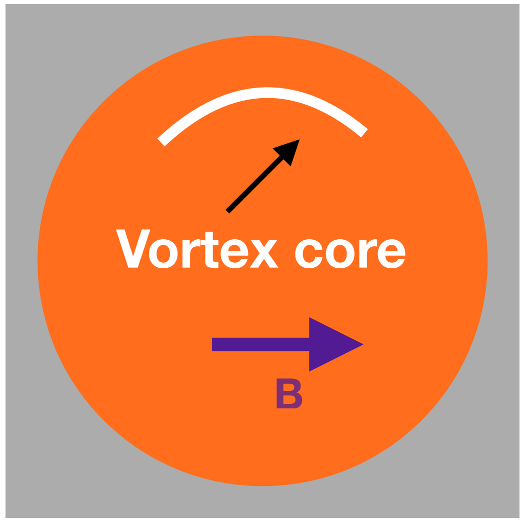


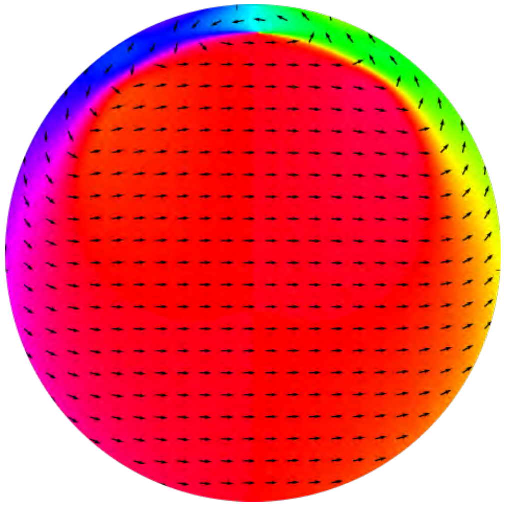
Simple picture of the vortex breaks down:
Non-trivial z dependence

Full YIG microdisk

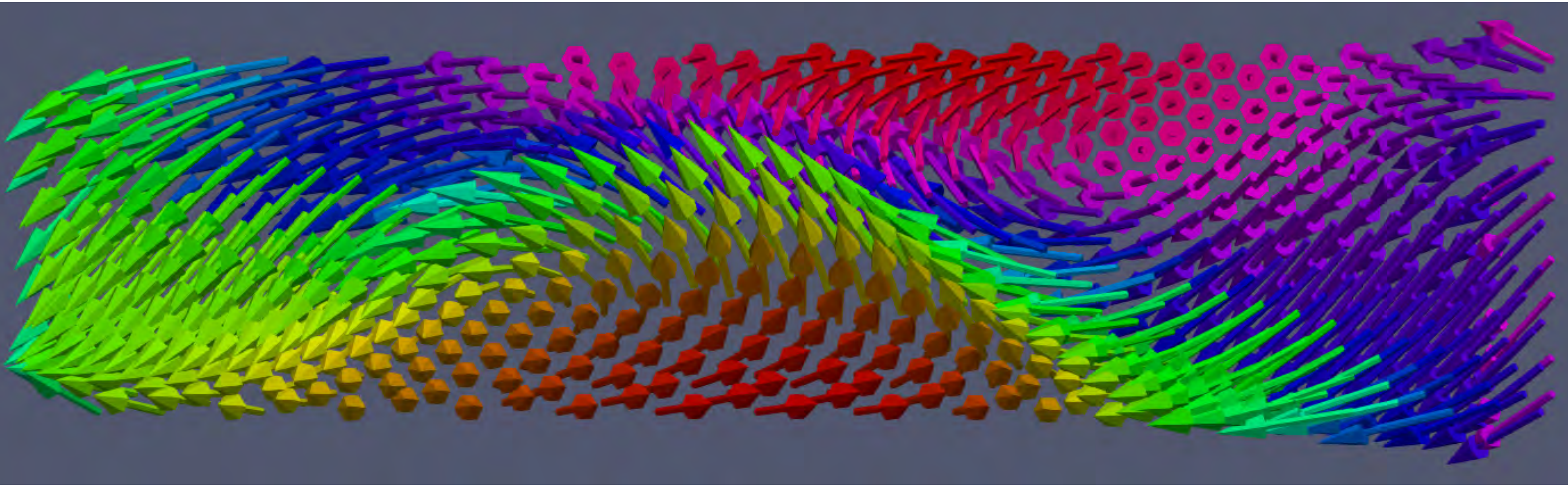
Vortex



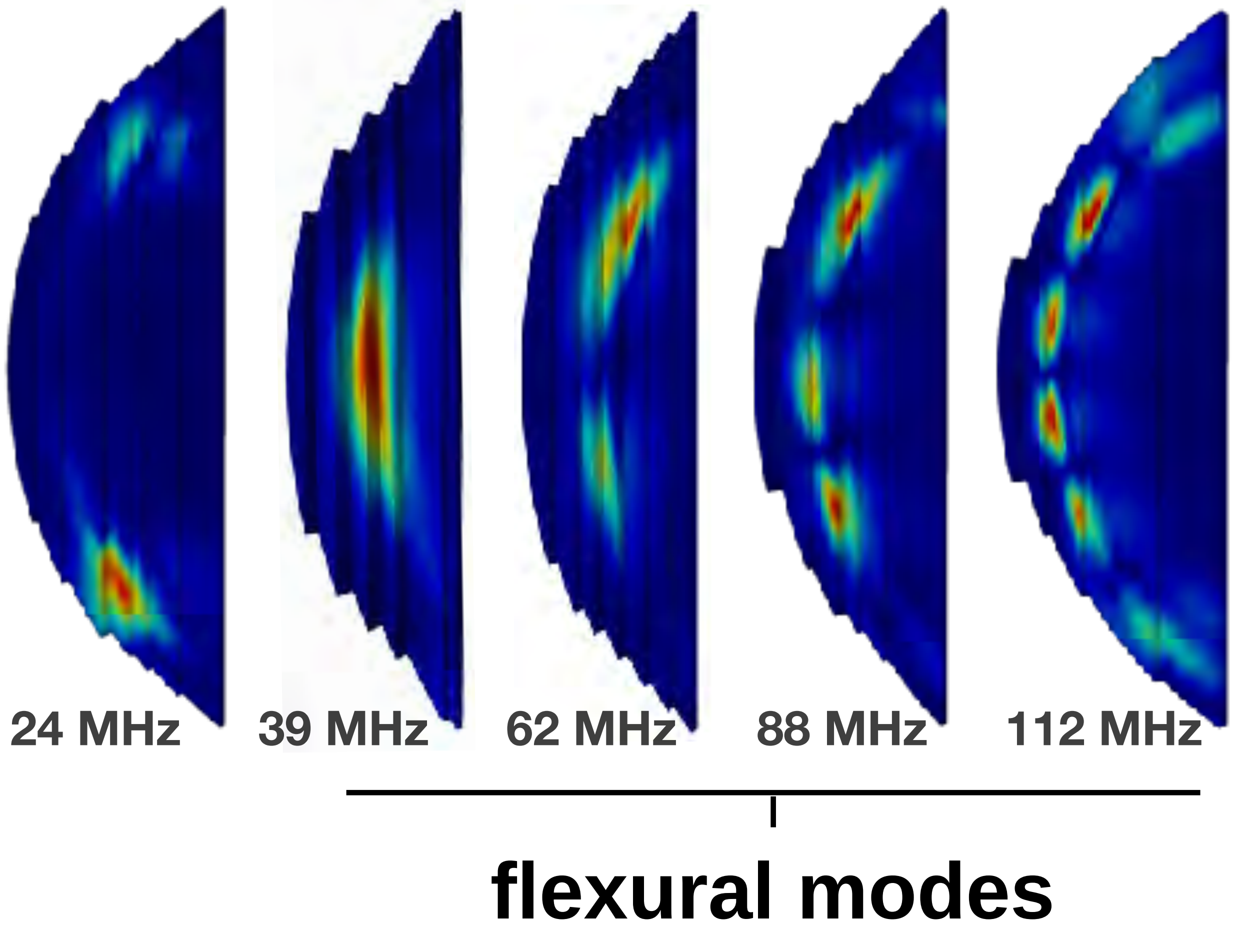


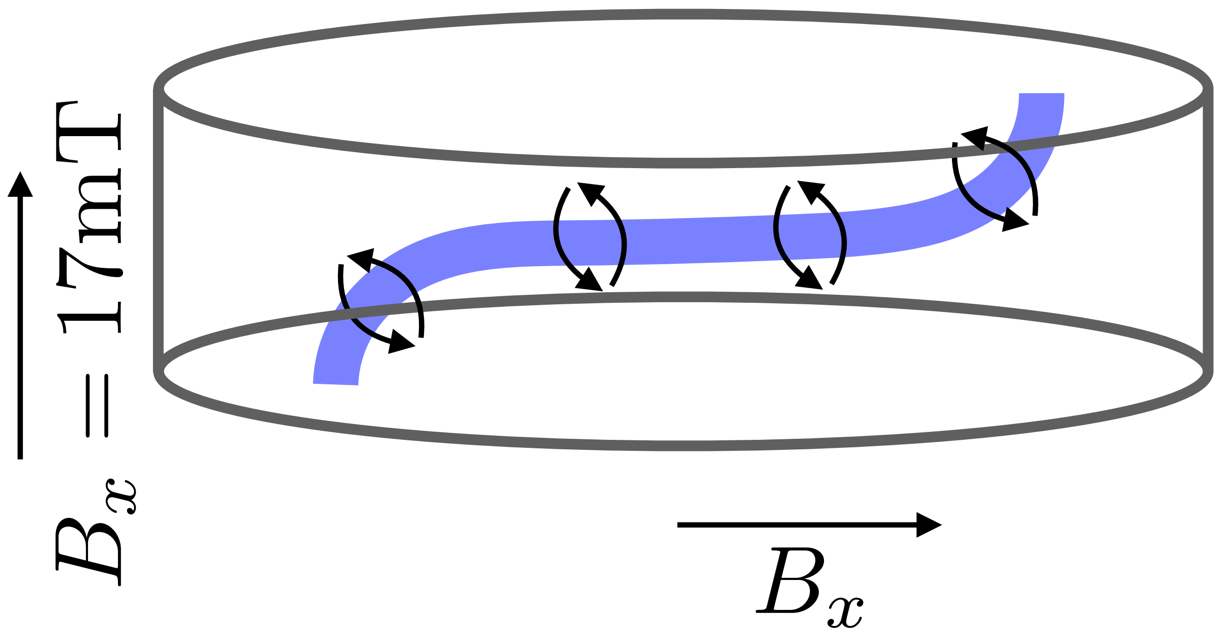


Definitely not 2D!!



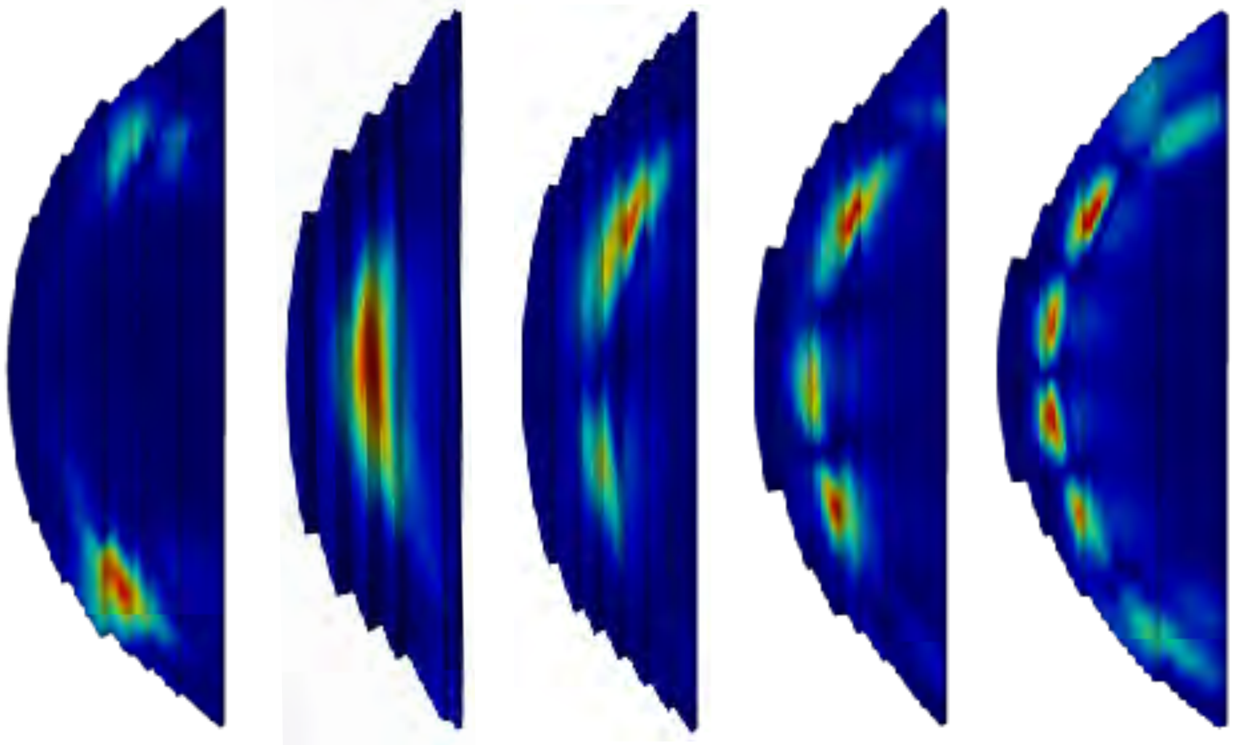
Full YIG microdisk

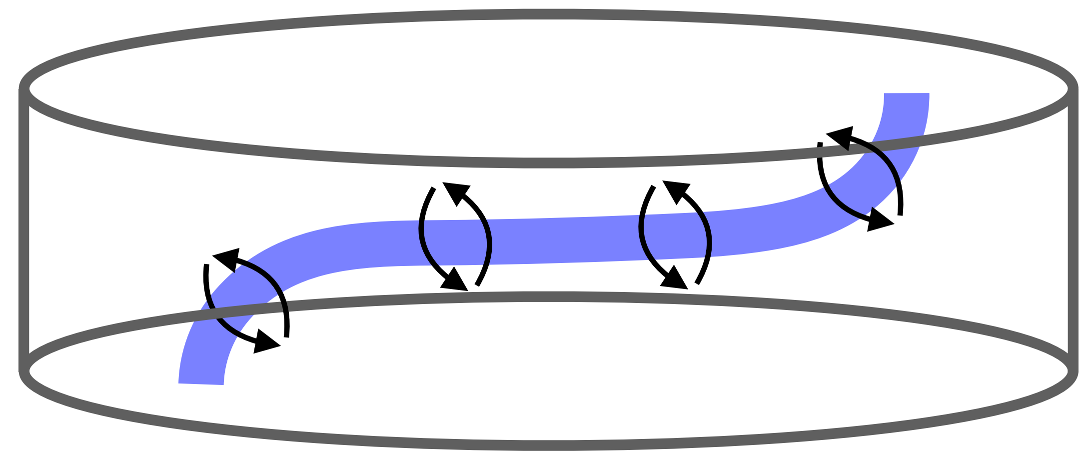


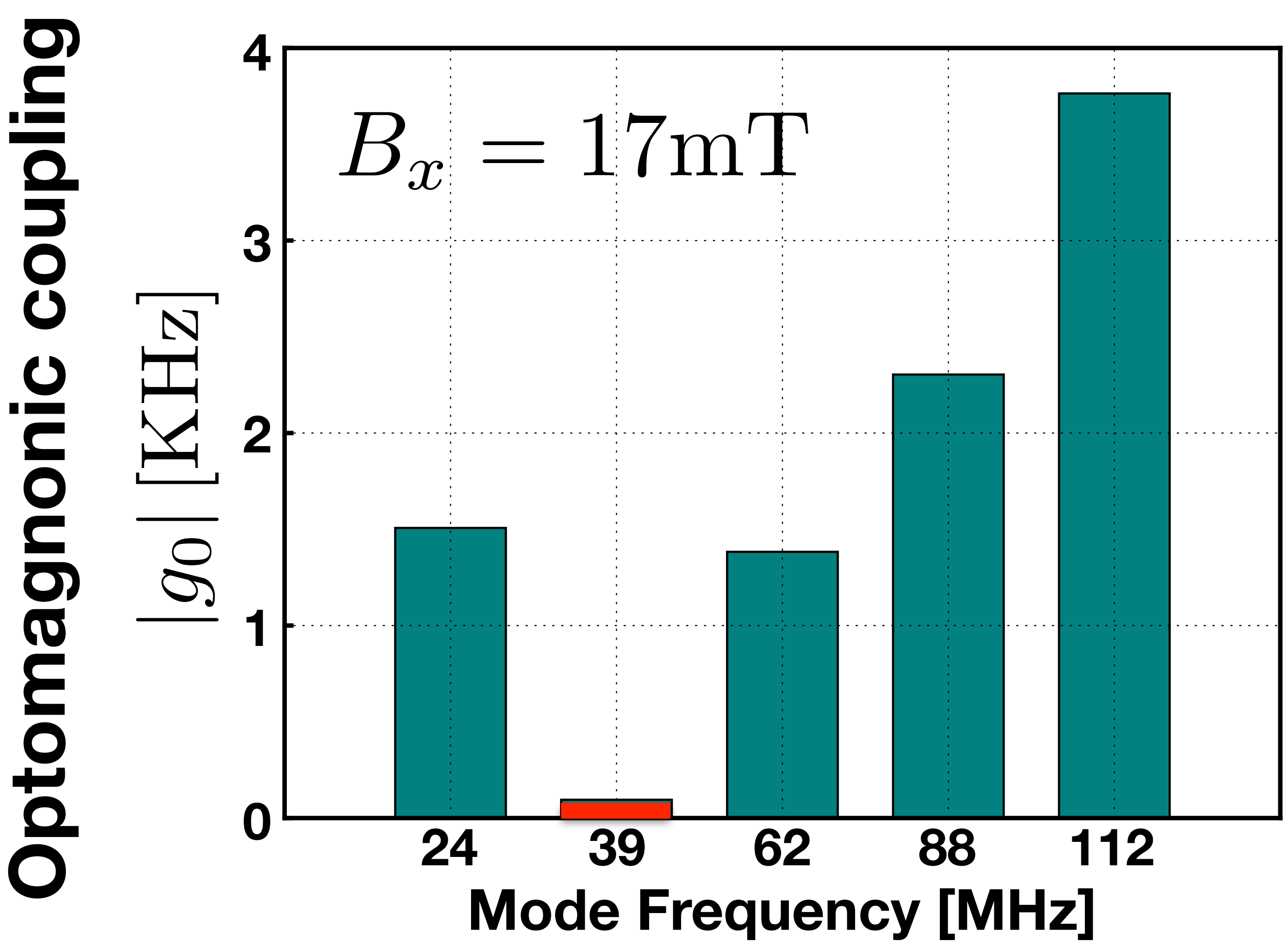


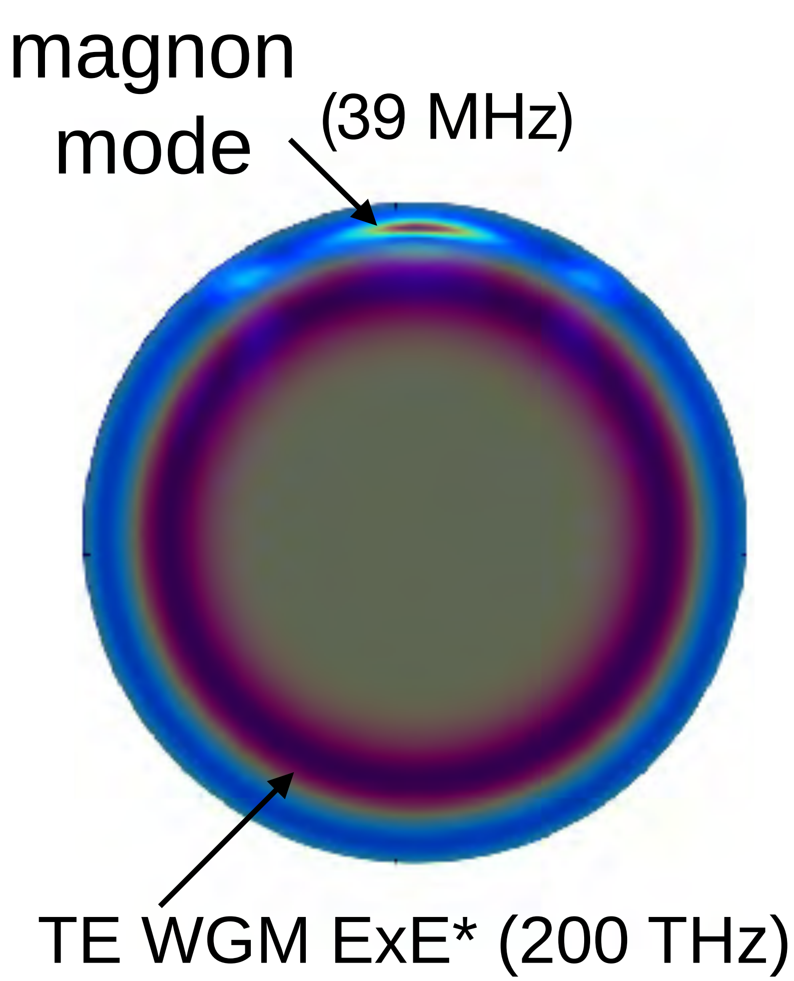
J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, arXiv:1806.06727 (2018)

Full YIG microdisk



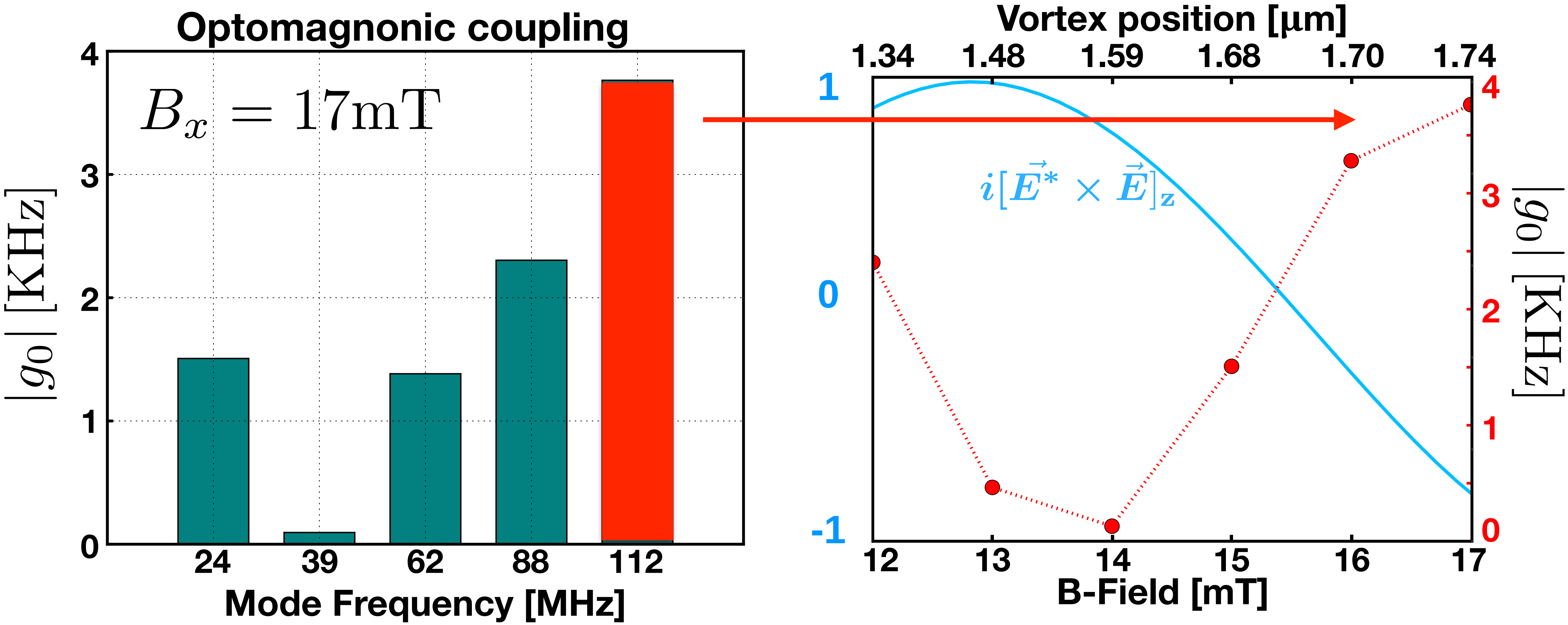


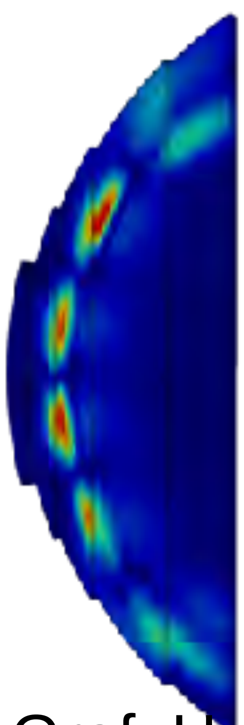




J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, arXiv:1806.06727 (2018)

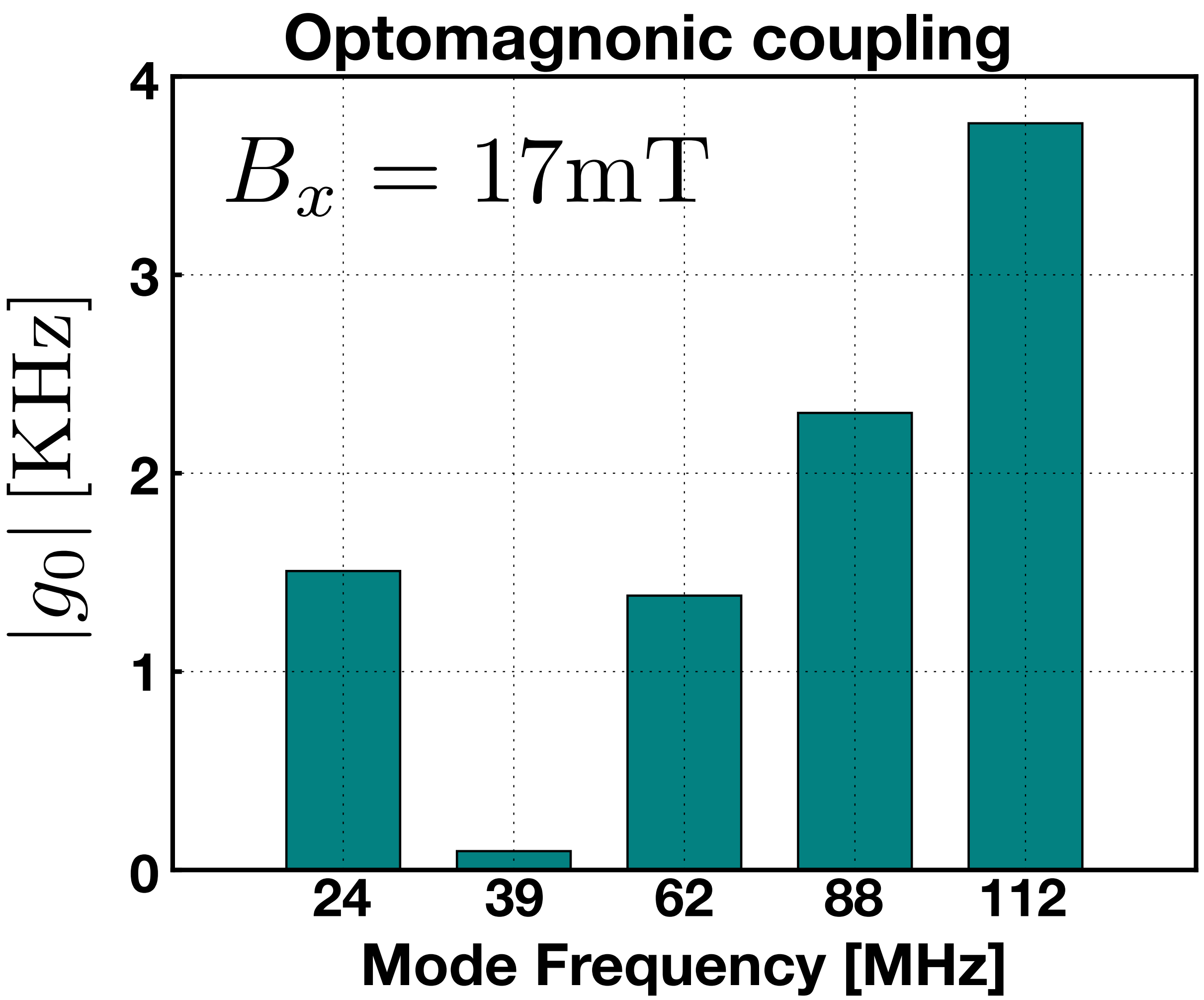
Full YIG microdisk





J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, arXiv:1806.06727 (2018)

Full YIG microdisk

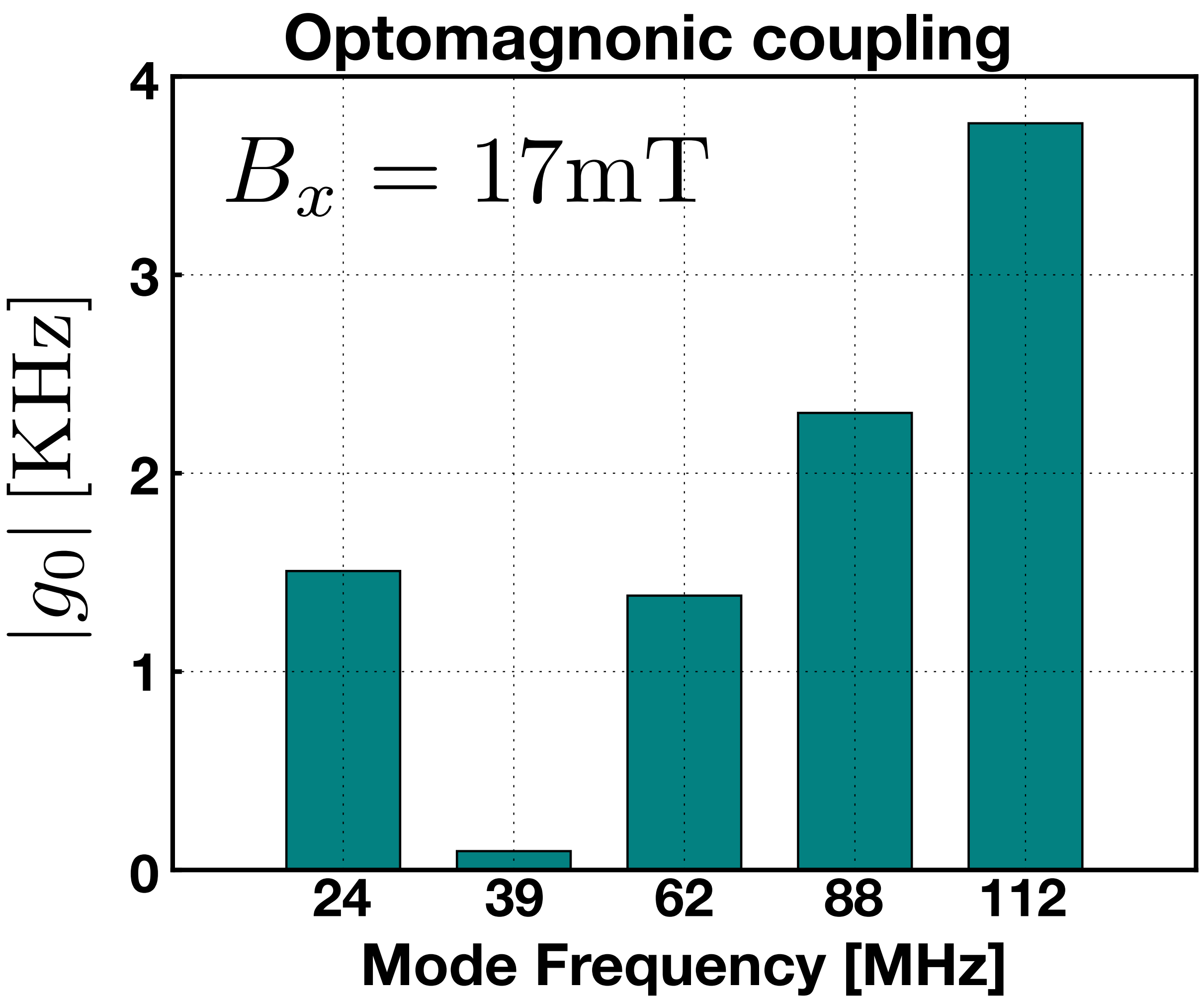


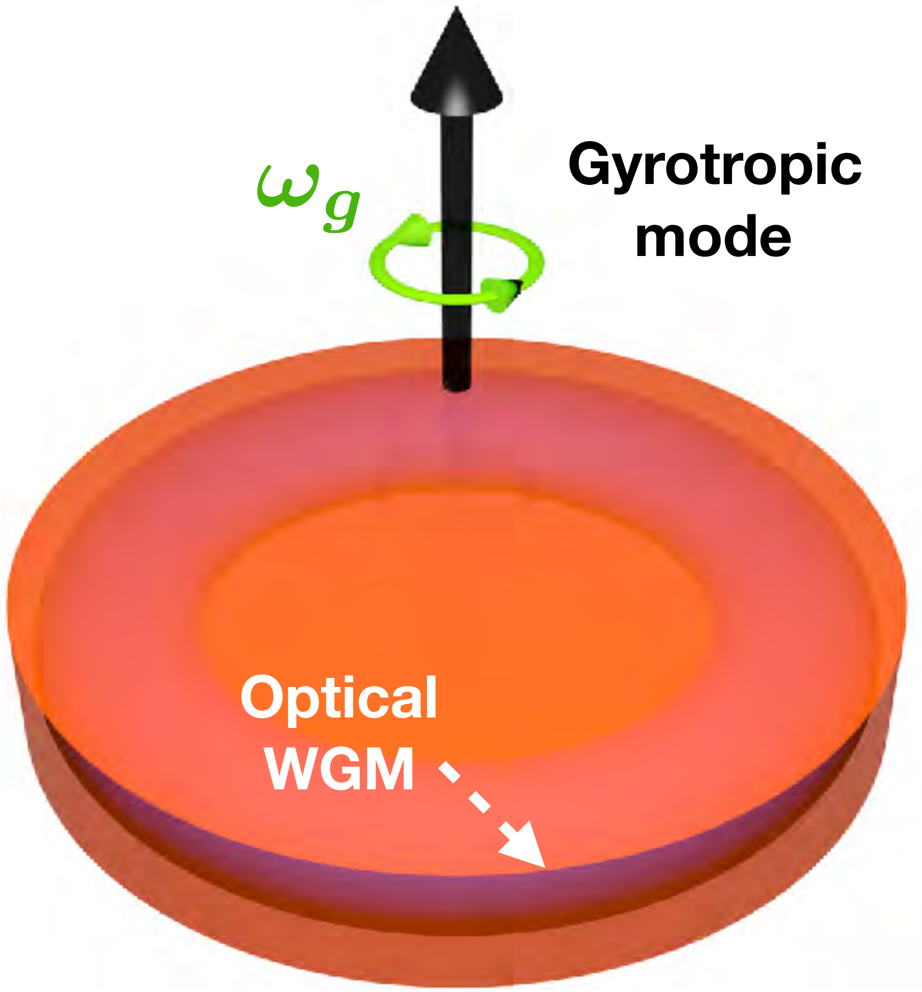
Single photon Cooperativity: $$\mathcal{C}_0 = 4\frac{g_0^2}{\Gamma\kappa} \approx 10^{-7}$$

Cooperativity at maximum photon density: $$\mathcal{C} = 4n_{\text{ph}}\frac{g_0^2}{\Gamma\kappa} \approx 10^{-2}$$

J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, arXiv:1806.06727 (2018)

Full YIG microdisk



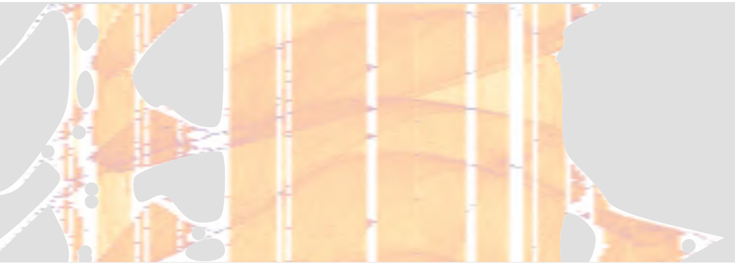


- Promising values for coupling - other modes?
- Tuneable coupling by an external magnetic field
- Coupled dynamics of the system?

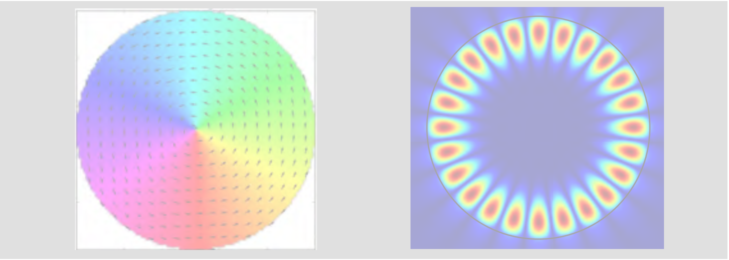
J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, arXiv:1806.06727 (2018)

Introduction and motivation

Optomagnonic Hamiltonian



Optically induced spin dynamics

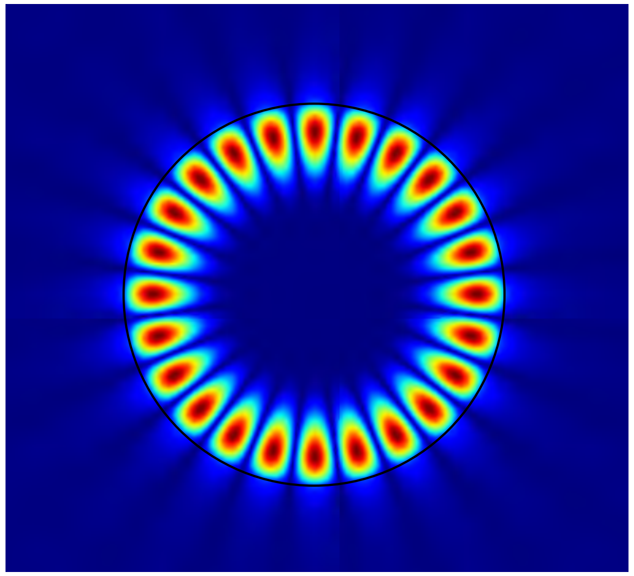


Magnetic textures: vortex in a disk

Summary

Summary

- Light-induced nonlinear spin dynamics (Kittel mode)
- First time optomagnonics with magnetic textures
- Coupling to magnetic vortex modes
- Promising values of coupling by engineering



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