Cavity Optomagnonics

Silvia Viola Kusminskiy

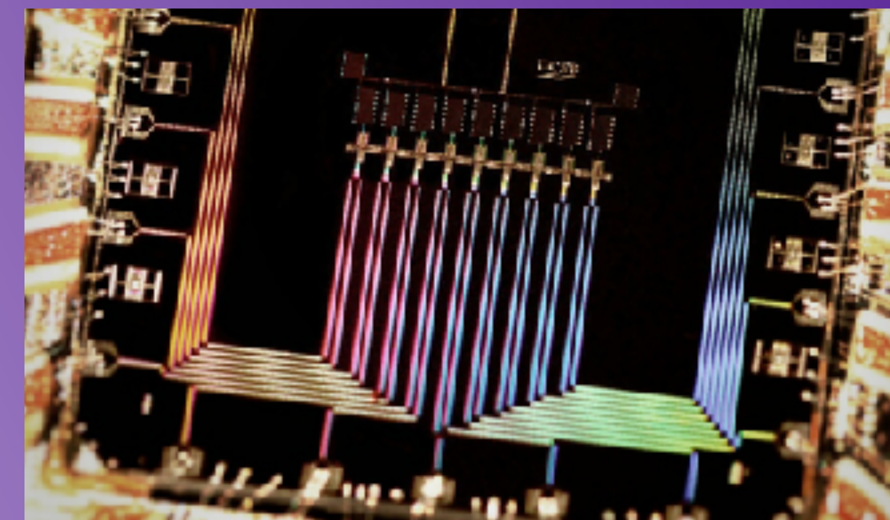
MAX PLANCK INSTITUTE
for the science of light

classical technologies

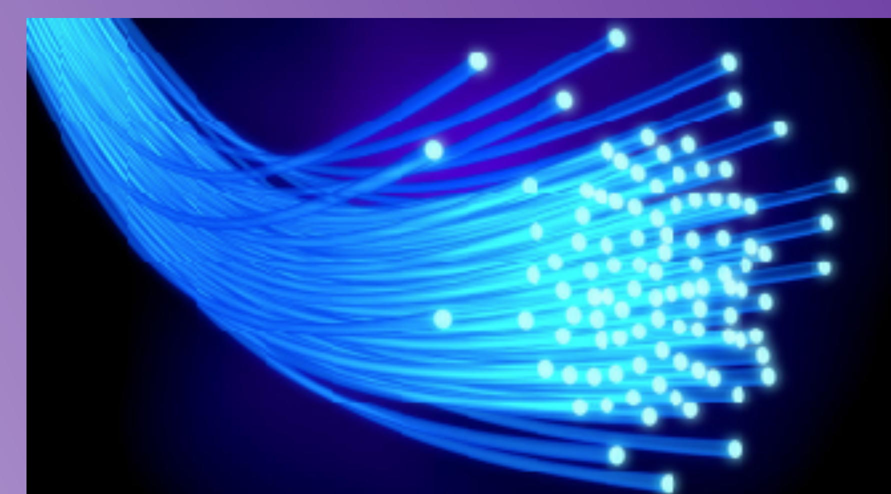
quantum technologies

- state preparation
- info processing
- communication

superconducting quantum circuit



Martinis group
UCSB and Google (2015)



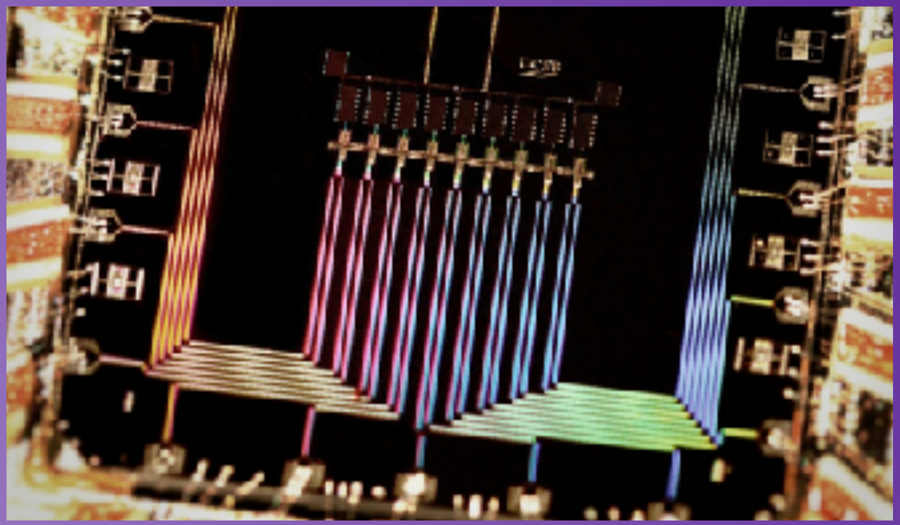
optical fiber

classical technologies

quantum technologies

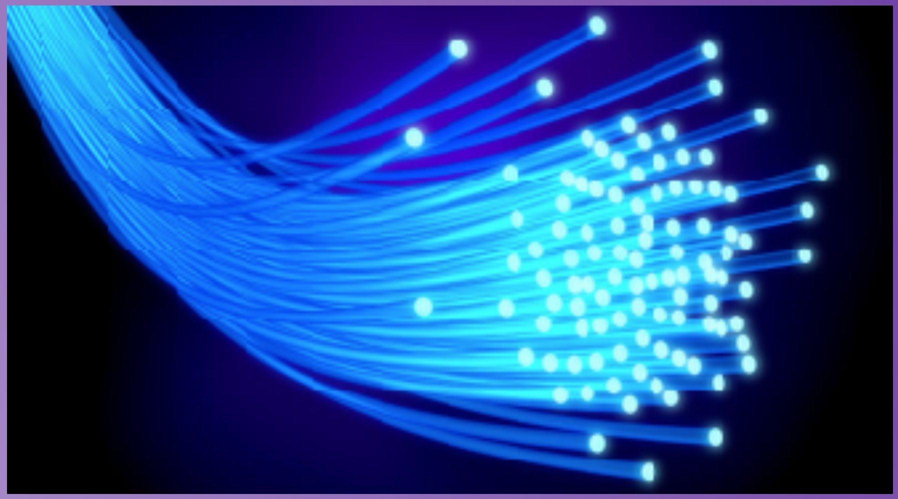
- state preparation
- info processing
- communication

superconducting quantum circuit



Martinis group
UCSB and Google (2015)

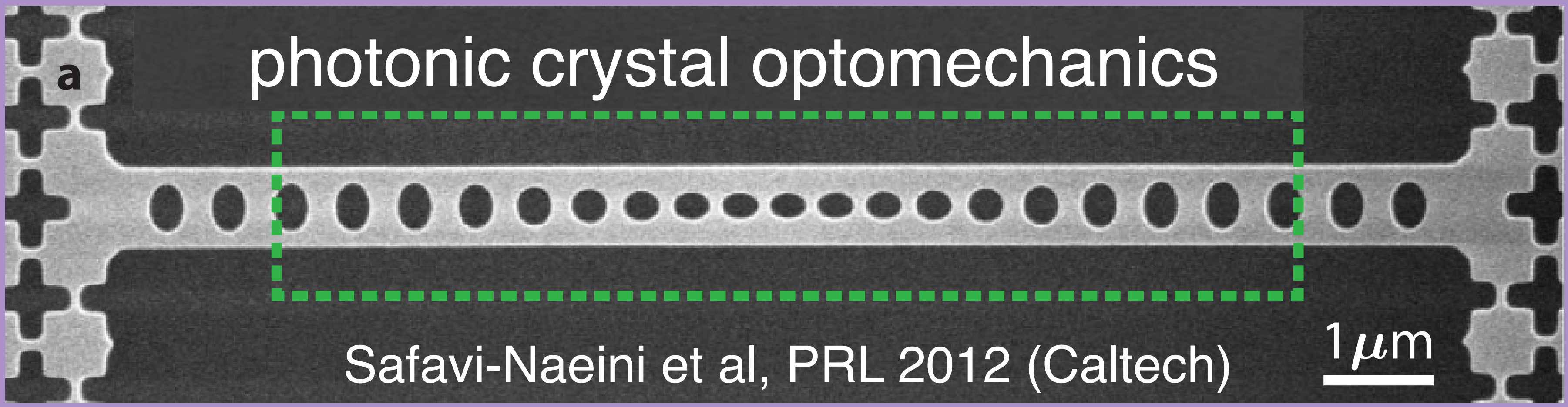
need hybrid systems



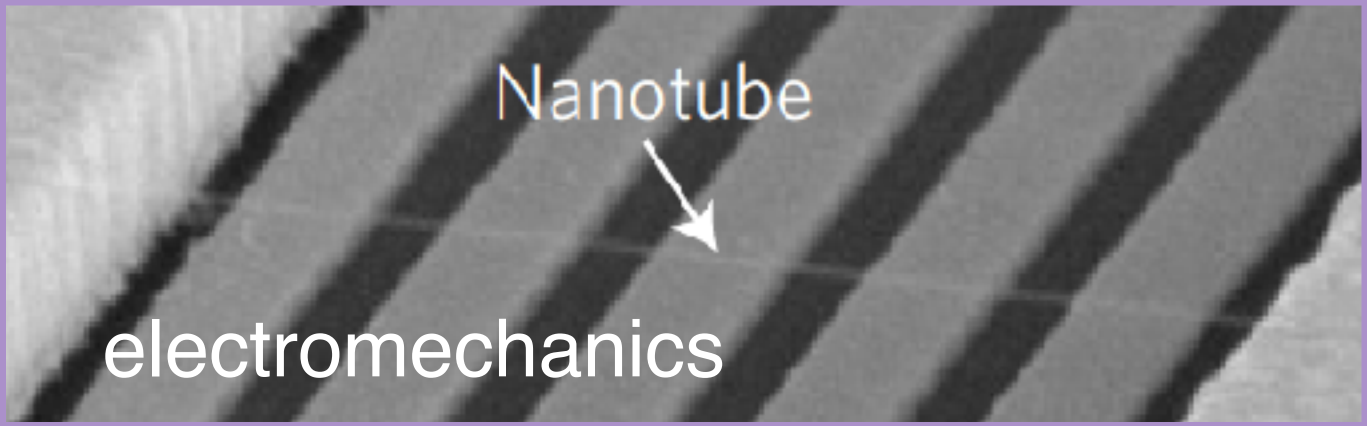
optical fiber

classical technologies

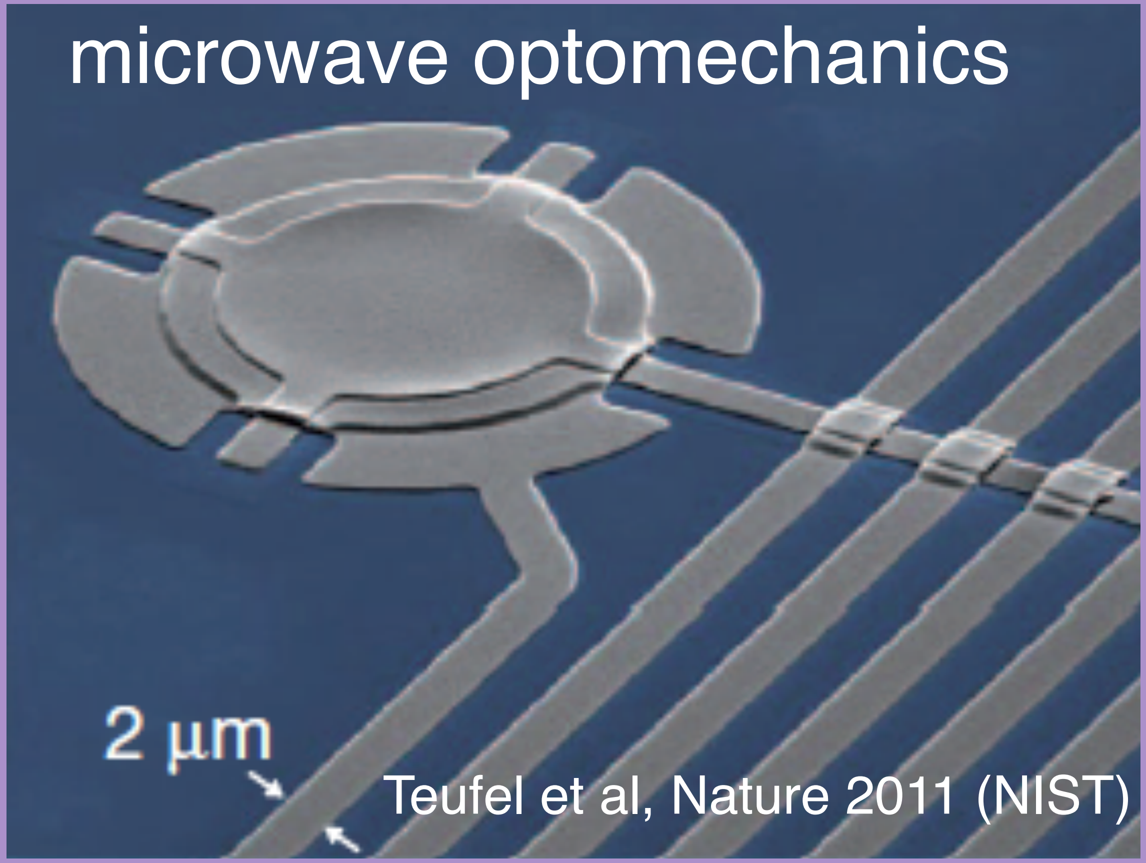
Hybrid Systems for Quantum Technologies

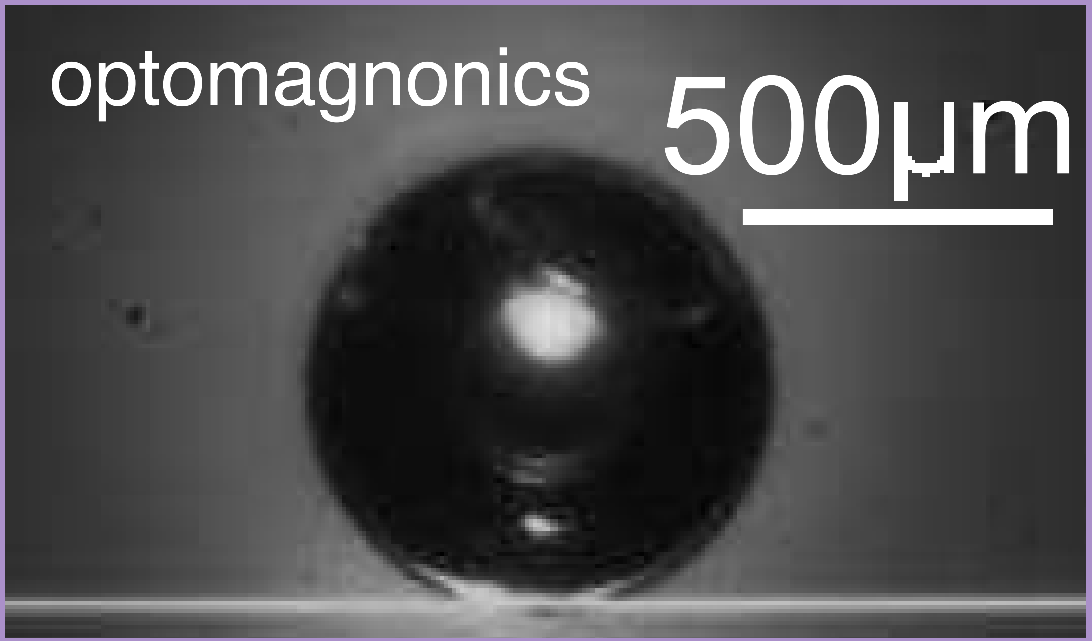


nano/micro scale systems



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

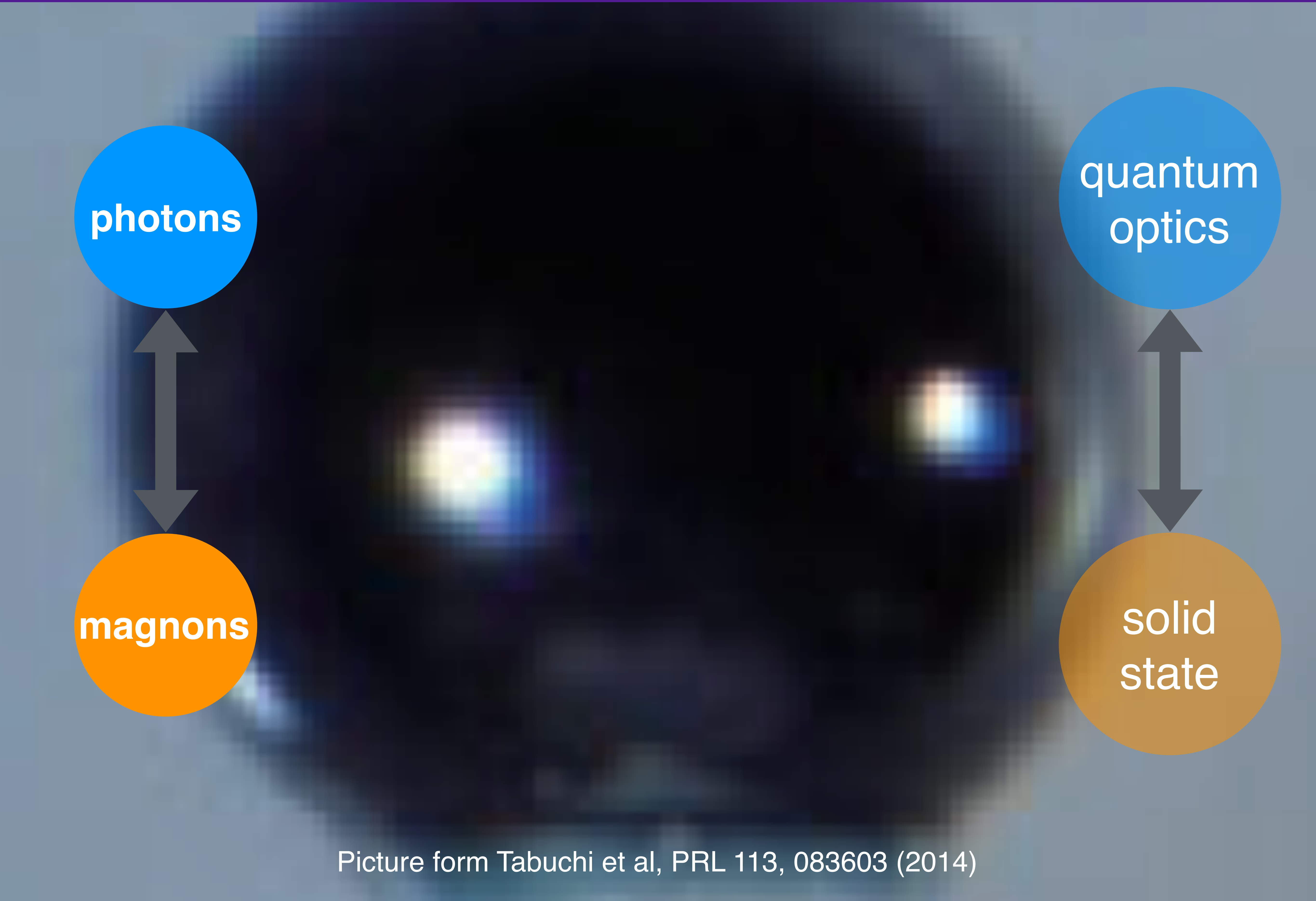




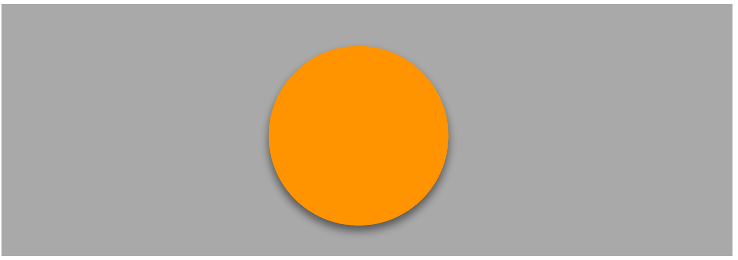
Osada et. al PRL 116, 223601 (2016)

use collective excitations

Optomagnonics

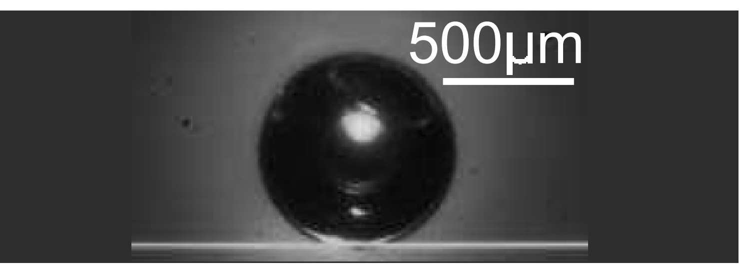


Picture form Tabuchi et al, PRL 113, 083603 (2014)

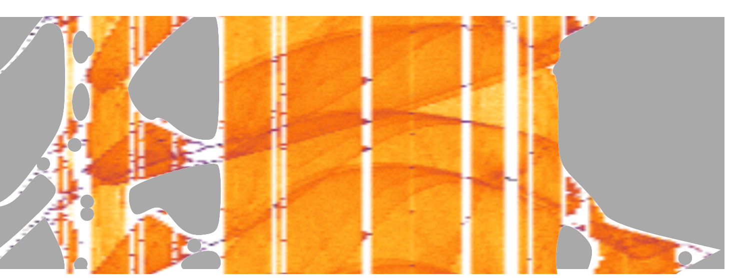


Magnons and the Kittel mode

Microwave regime

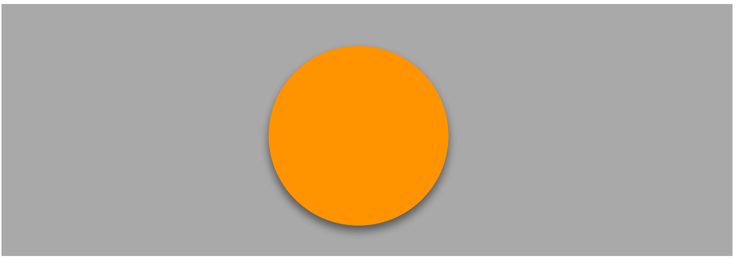


Optomagnonics

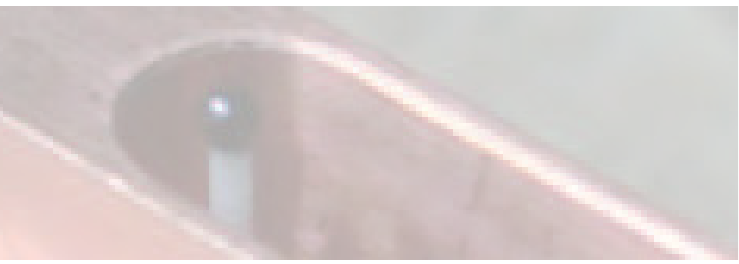


Optically induced spin dynamics

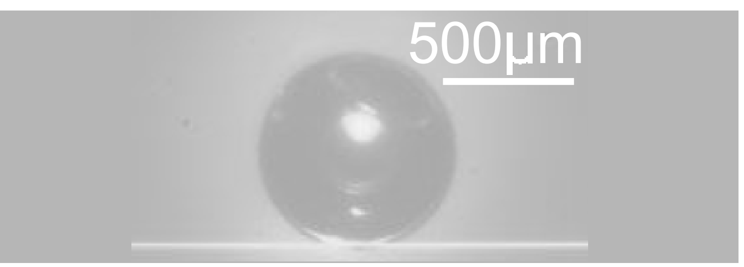
Outlook and Summary



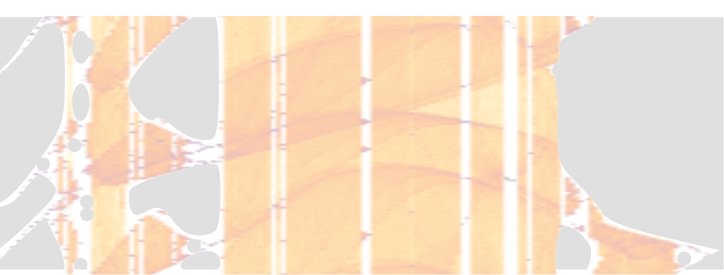
Magnons and the Kittel mode



Microwave regime



Optomagnonics



Optically induced spin dynamics

Outlook and Summary

Magnonics

magnon

elementary magnetic
excitation
(quantum of spin wave)

Magnonics

magnon

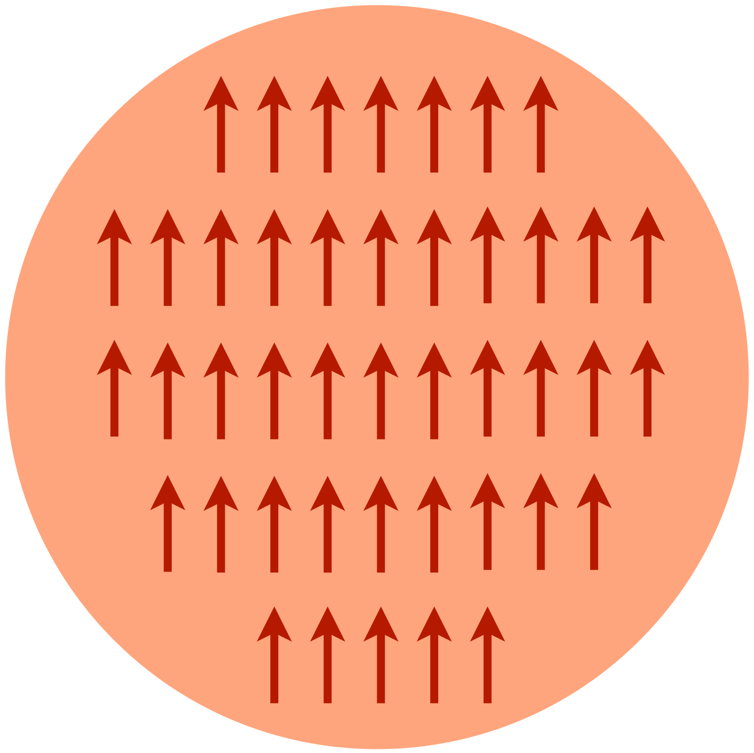
elementary magnetic
excitation
(quantum of spin wave)

Robust

Low Power

Tunable

Kittel mode



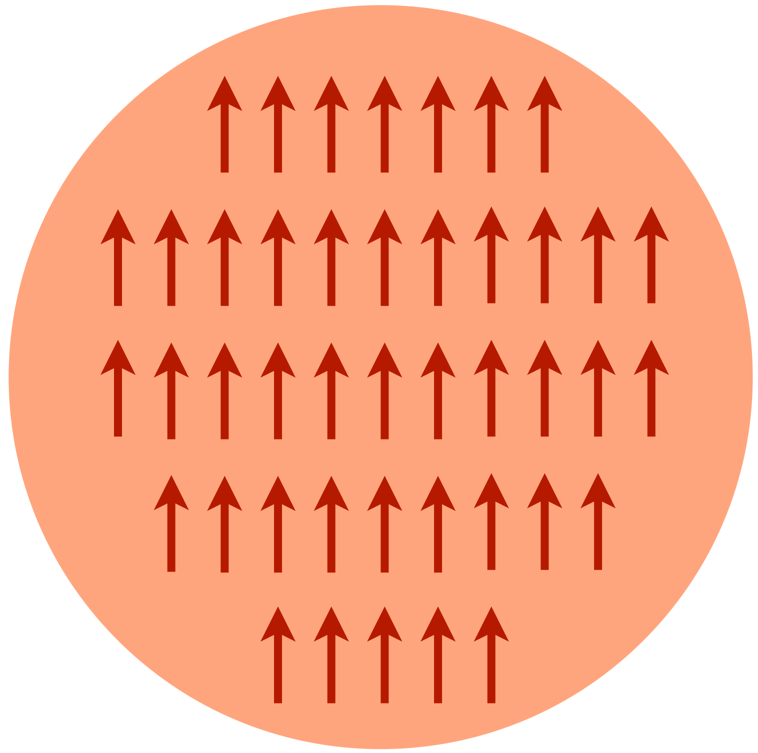
homogeneous
magnetic mode

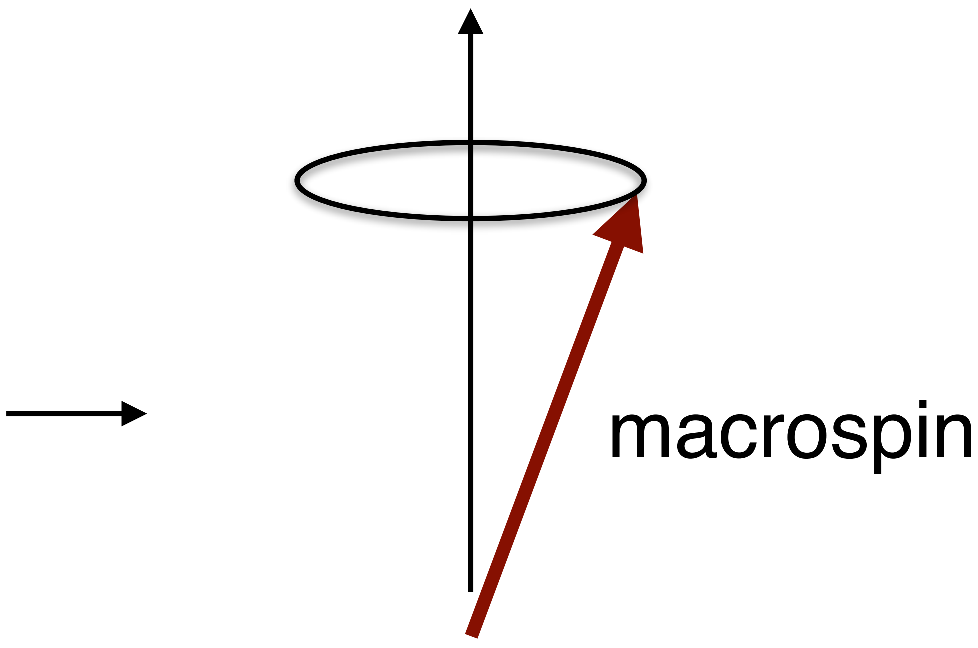
$$\mathbf{M}(\mathbf{r}) = \mathbf{M}$$

spin wave with k=0

Magnonics

Kittel mode





$$\Omega \propto H$$

homogeneous
magnetic mode

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

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

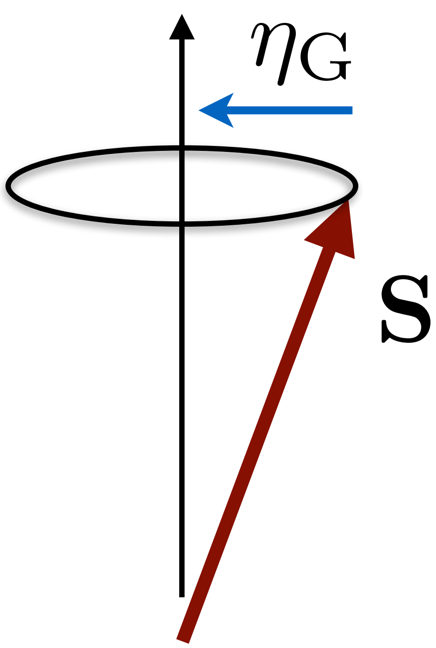
tunable precession frequency

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

for 30mT

Landau-Lifschitz-Gilbert Equation

Dynamics of the macrospin



$\Omega \propto H$

precession frequency

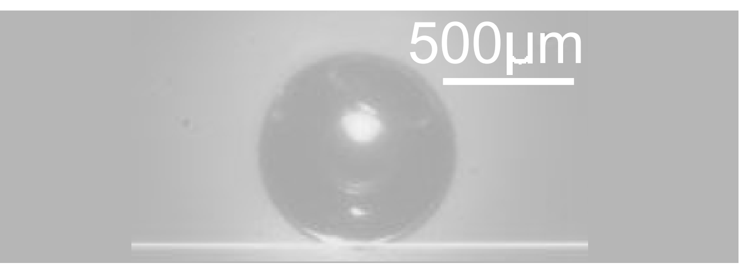
damping constant

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

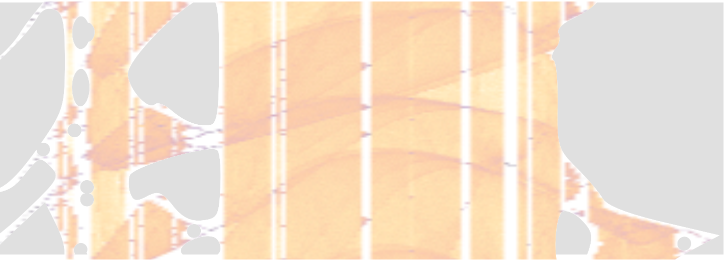
phenomenological damping term
(Gilbert damping)

Magnons and the Kittel mode

Microwave regime



Optomagnonics



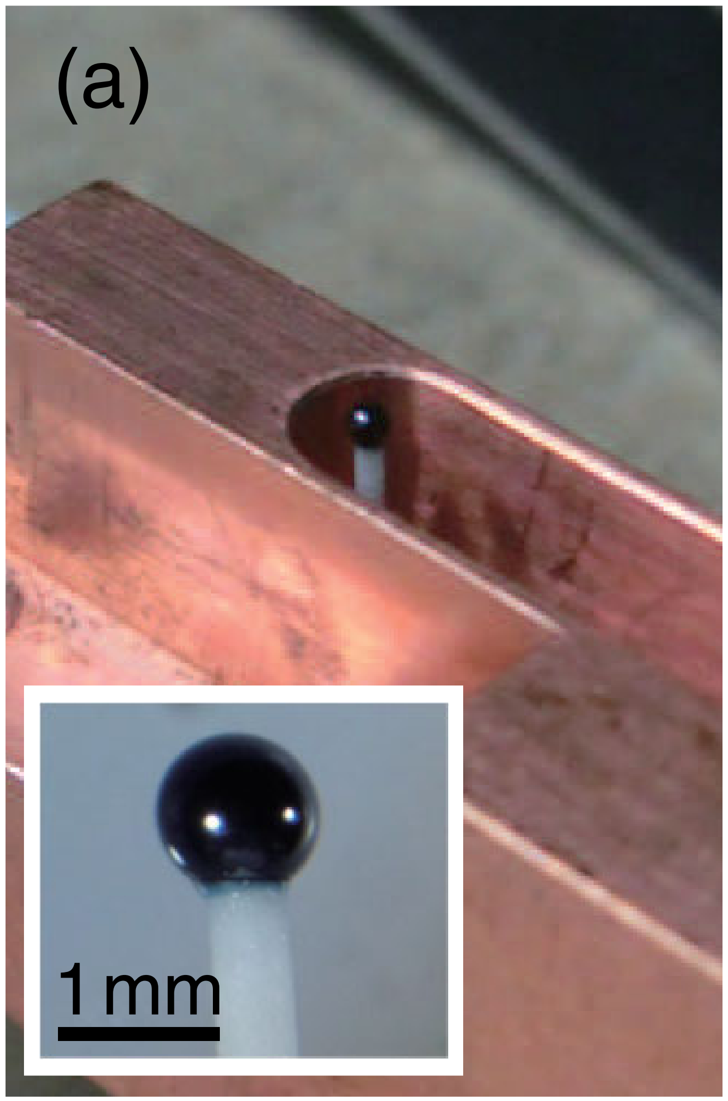
Optically induced spin dynamics

Outlook and Summary

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

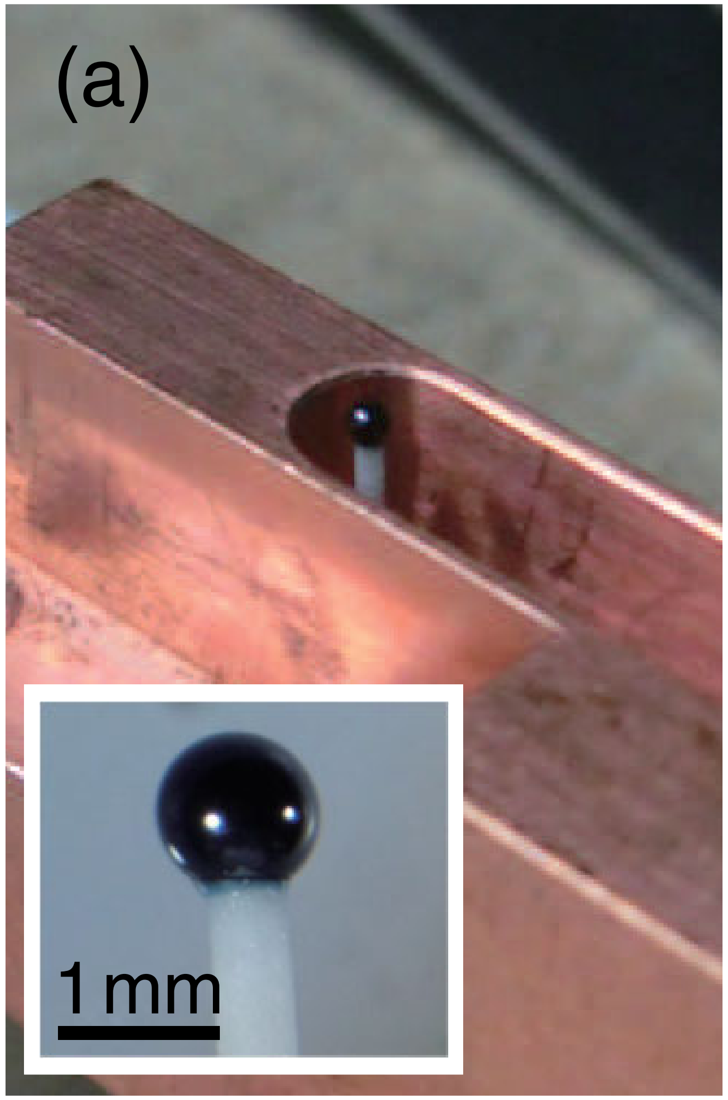
$$Y_3\,Fe_5\,O_{12}$$

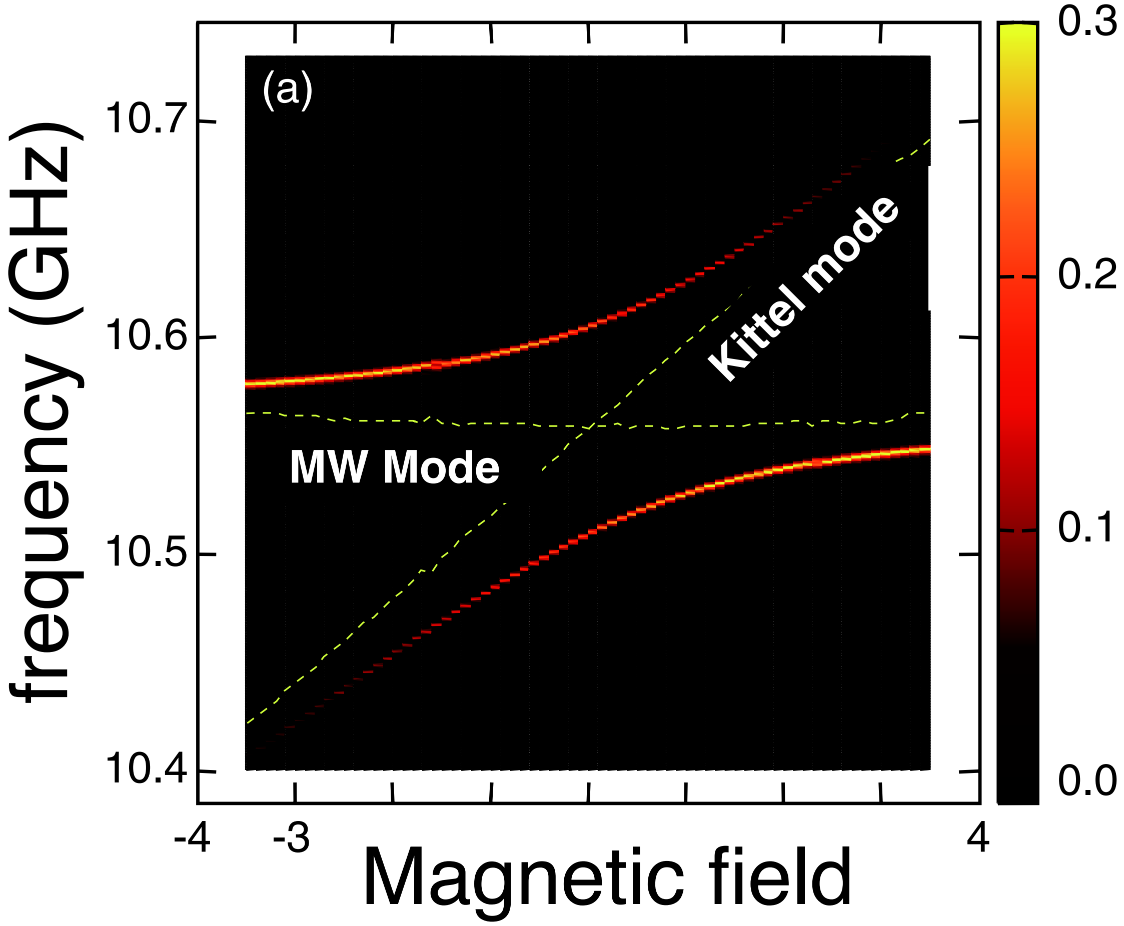
- ferrimagnetic
- insulator
- transparent in the infrared

Microwave Regime

Magnons ⟷ **Microwaves**

Strong coupling demonstrated in 2014





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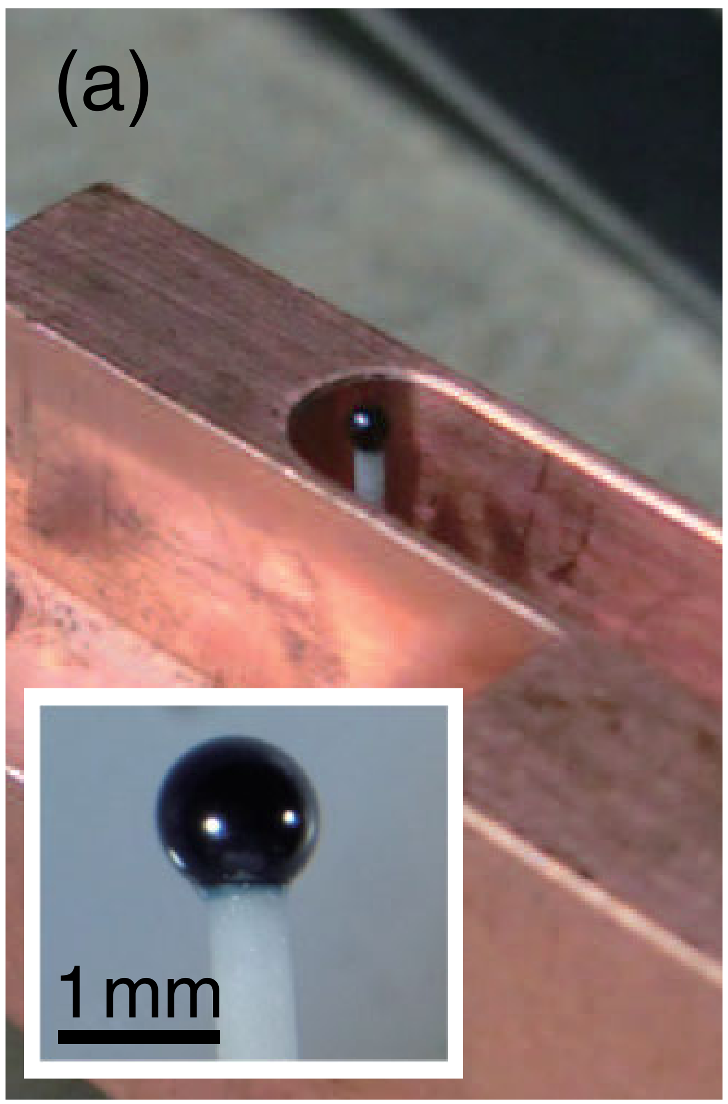
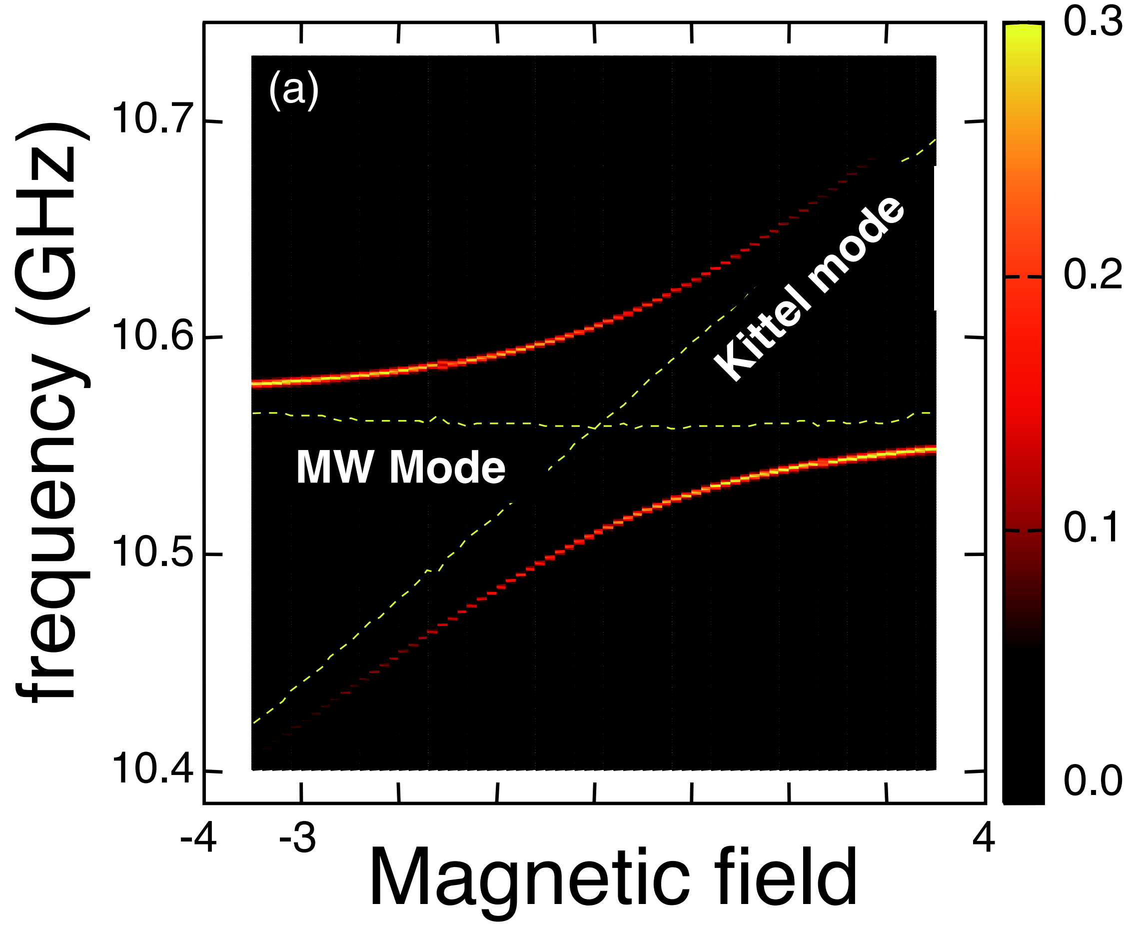
Microwave Regime

Magnons ⟷ **Microwaves**

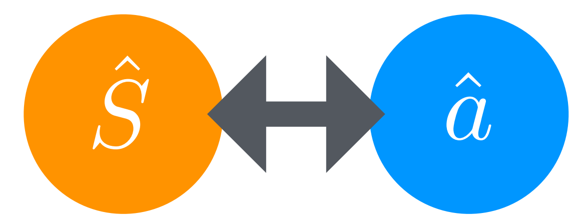
Strong coupling demonstrated in 2014





Resonant coupling

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



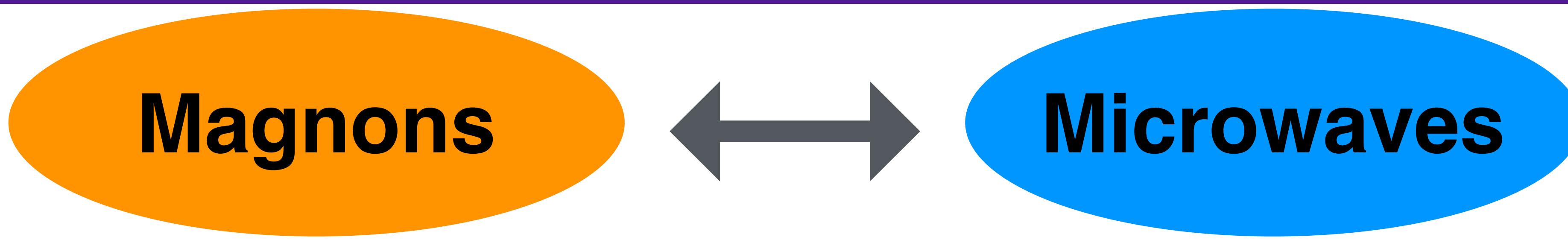
$\sim 50\text{MHz}$

Cooperativity

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

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

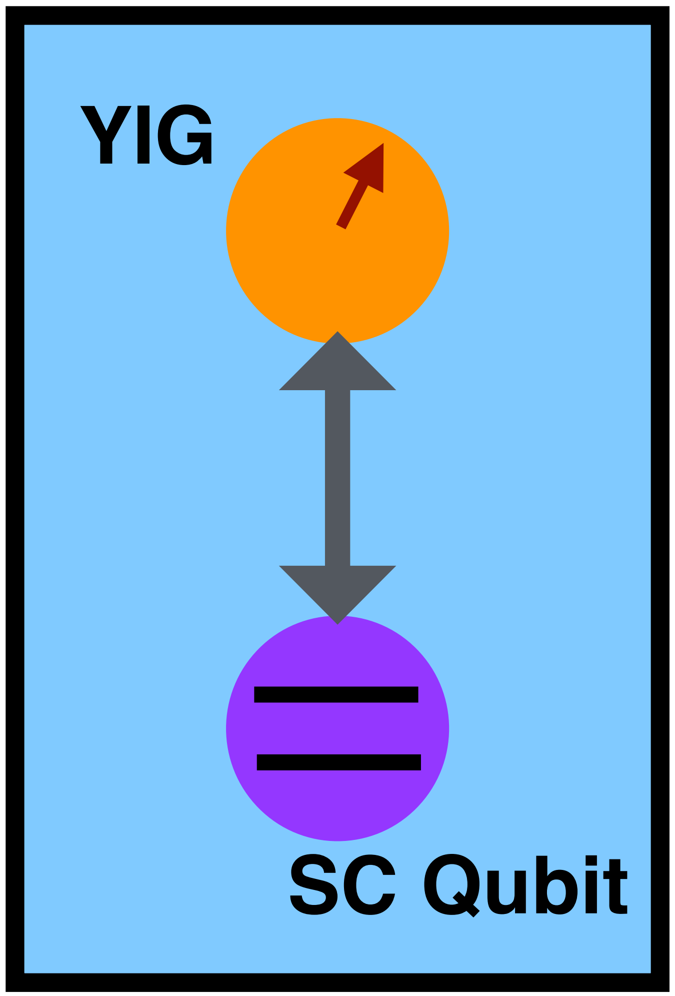
Microwave Regime



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

THz

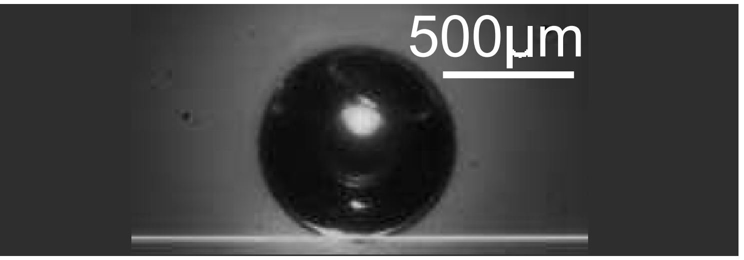
communicate information

wavelenght converter

Motivation:
magnon as a transducer

Magnons and the Kittel mode

Microwave regime

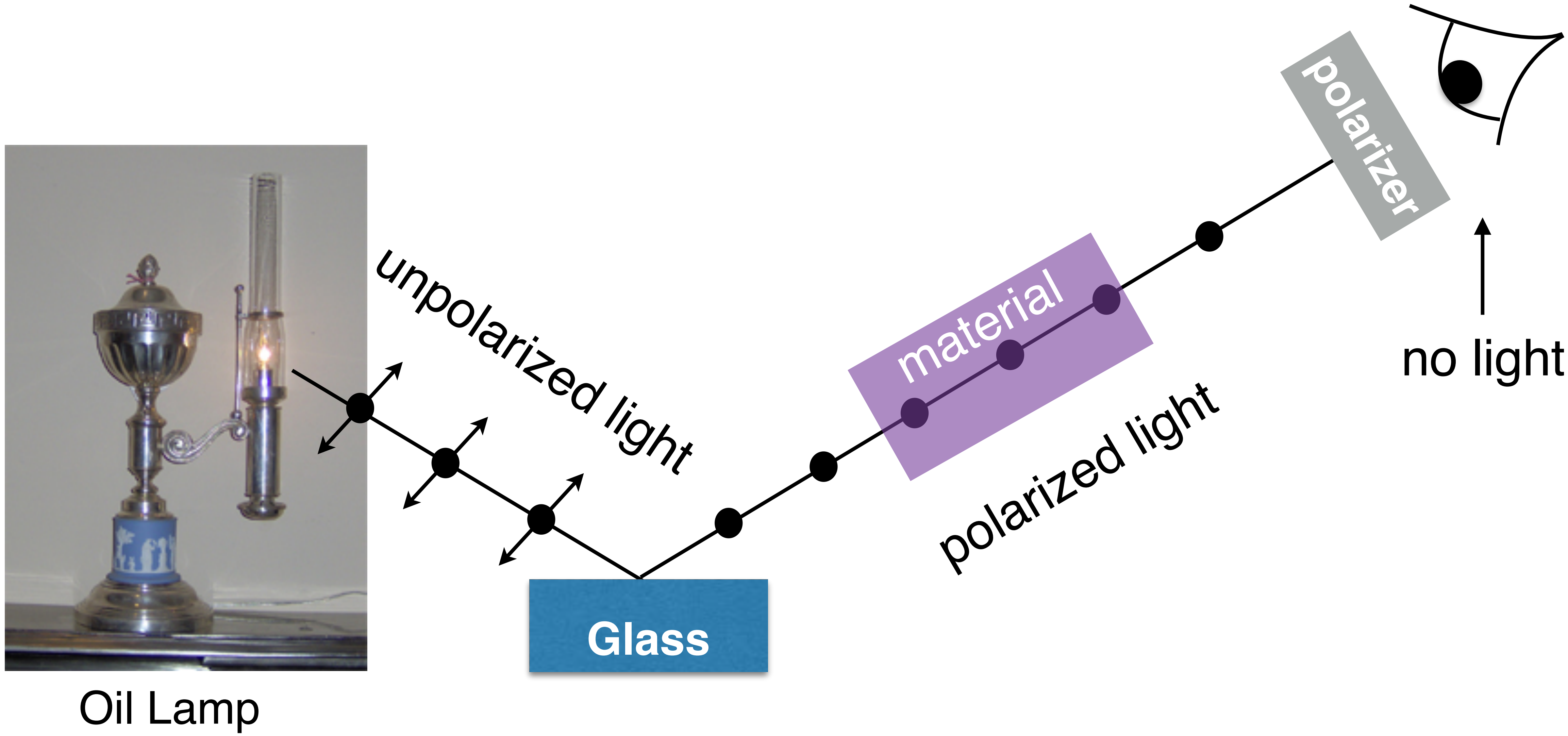


Optomagnonics

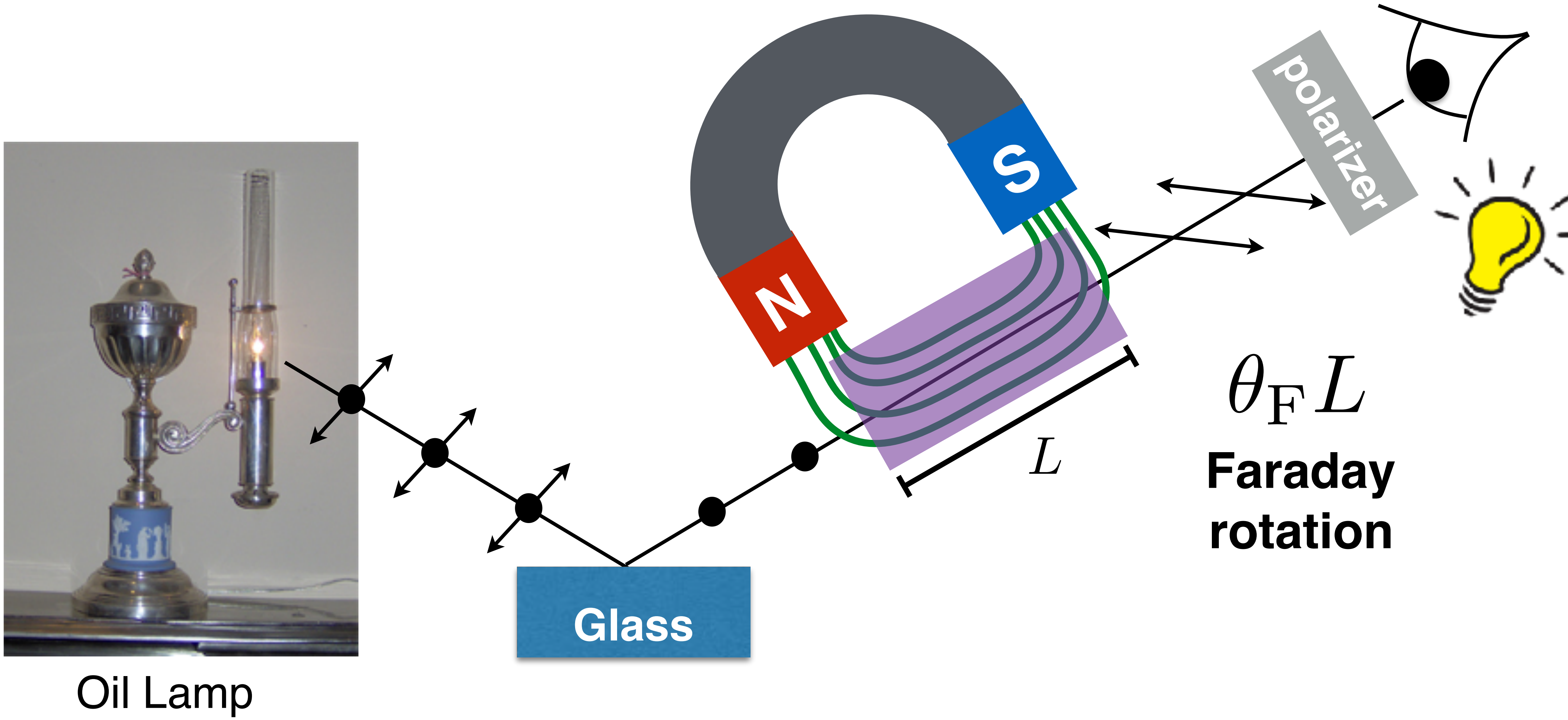
Optically induced spin dynamics

Outlook and Summary

Faraday Effect (1846)

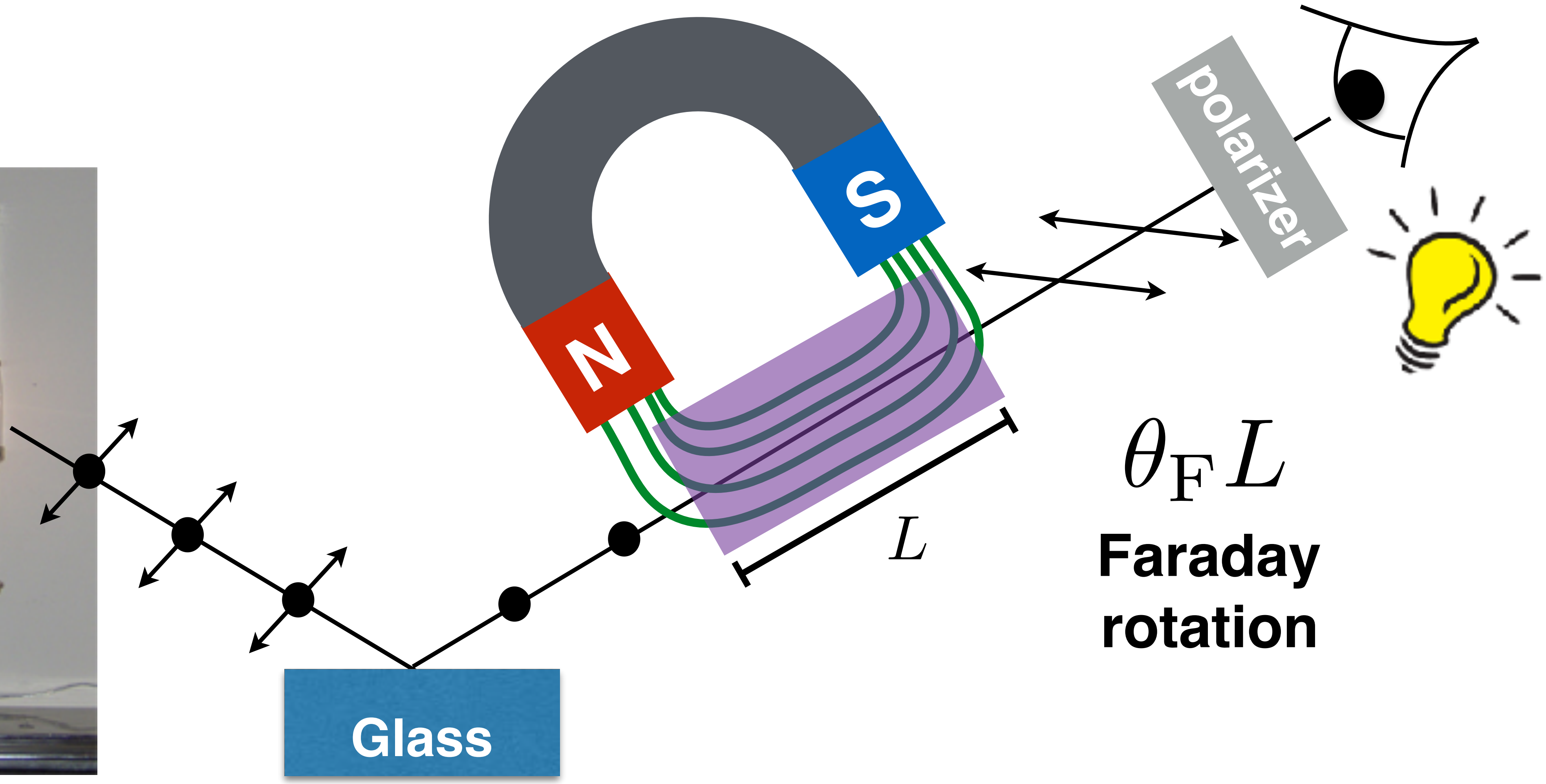


Faraday Effect (1846)



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)!

Optomagnonic Hamiltonian

optical
spin density

Faraday
rotation

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

magnetization
density

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

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

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

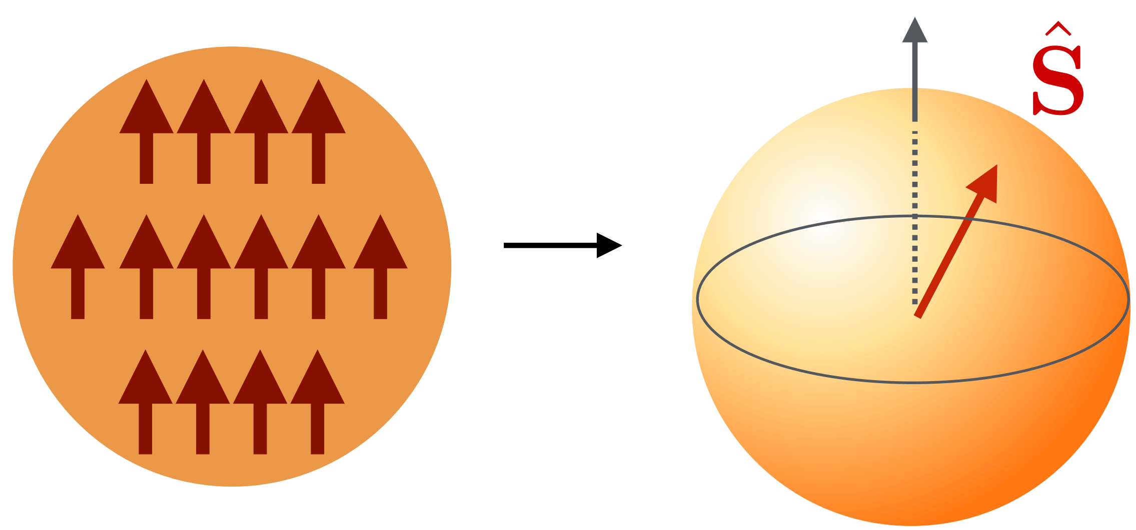
Quantize: $\hat{\mathbf{S}}$ $\hat{a}^\dagger$ $\hat{a}$

two-photon process

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

Kittel mode

Bloch sphere

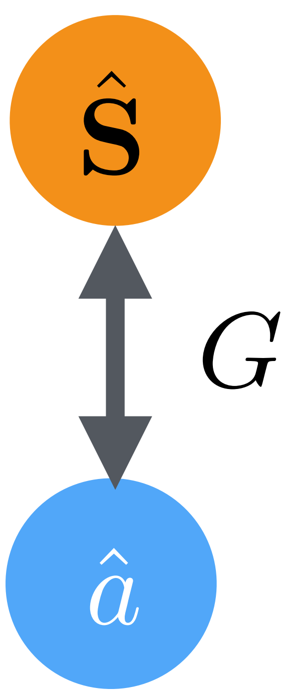


$\Omega \propto H$

Optomagnonic Hamiltonian

Microscopic Hamiltonian

Parametric coupling

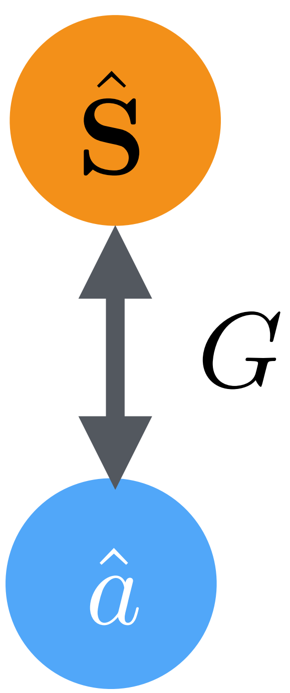


$$\hat{H}_{MO} = \hbar \sum_{j\beta\gamma} \hat{S}_j G^j_{\beta\gamma} \hat{a}^\dagger_\beta \hat{a}_\gamma$$

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

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

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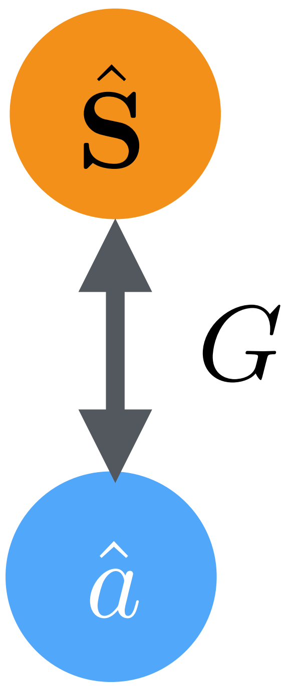
Optomagnonic Hamiltonian

Parametric coupling



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overlap electric field mode functions

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

Optomagnonic Hamiltonian

Microscopic Hamiltonian

Parametric coupling

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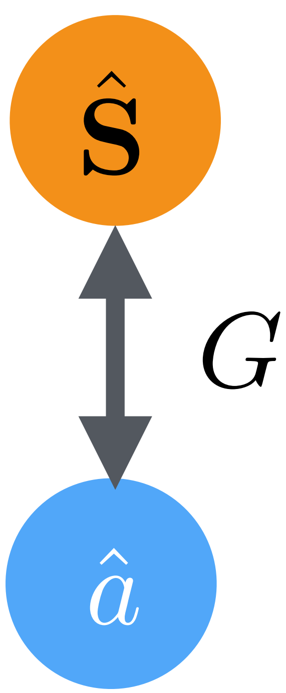

Optomagnonic coupling

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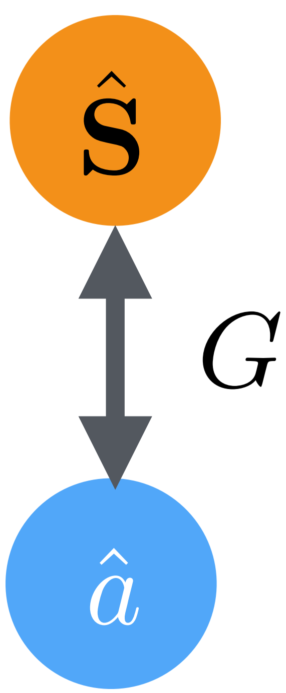
Faraday rotation

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

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

number of spins (S)

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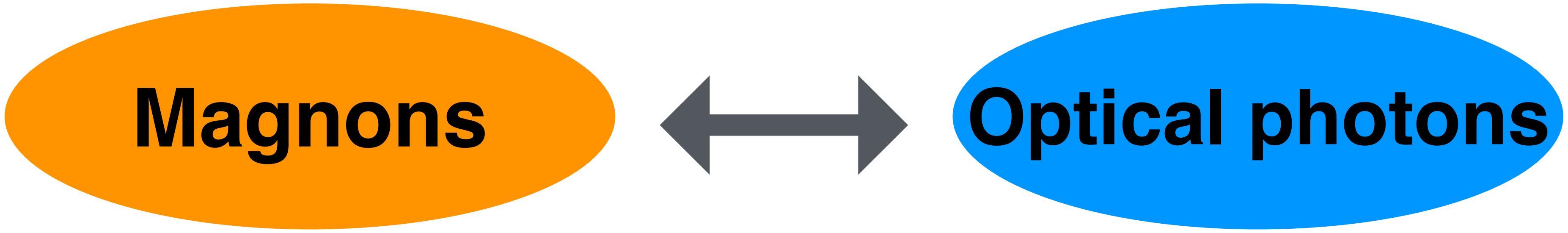
Cavity Optomagnonics

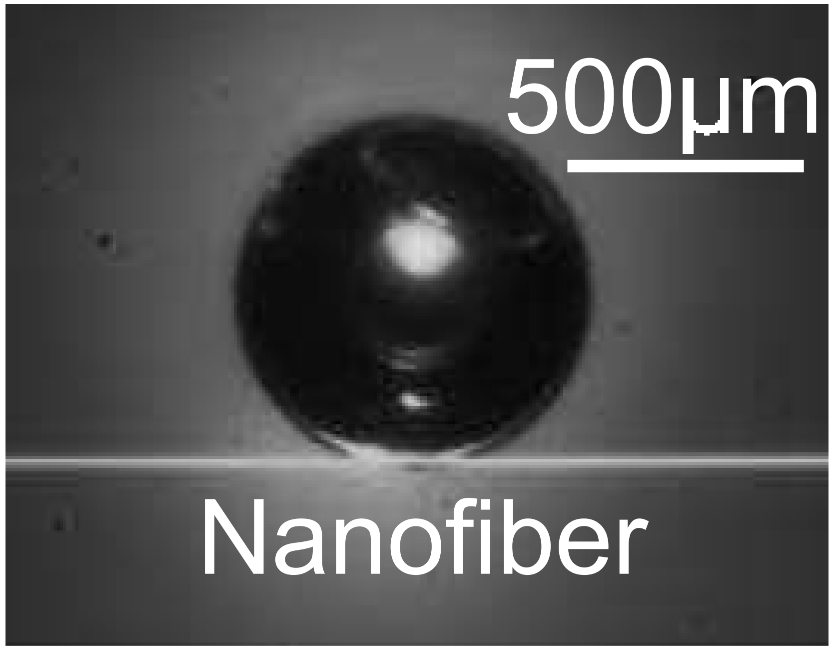


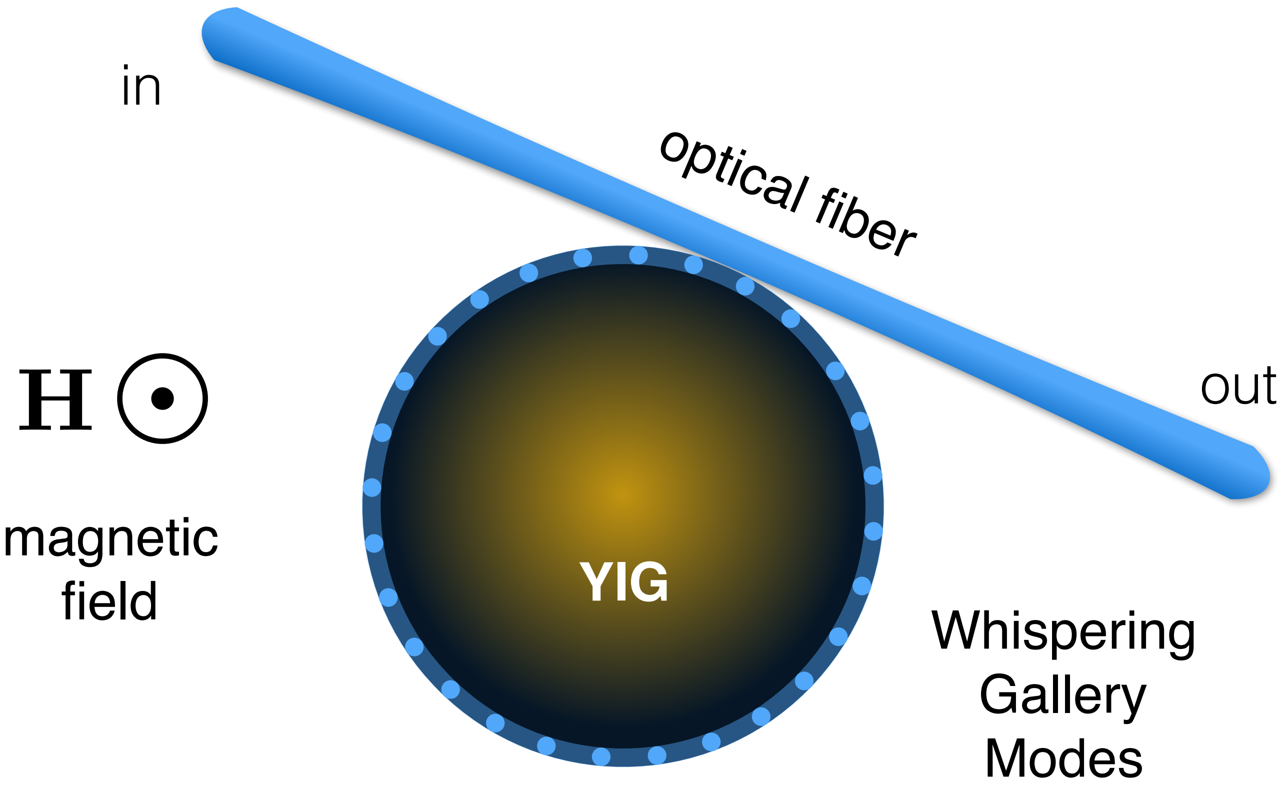
Coupling demonstrated in 2016

Cavity Optomagnonics

Magnons ⟷ **Optical photons**

Coupling demonstrated in 2016



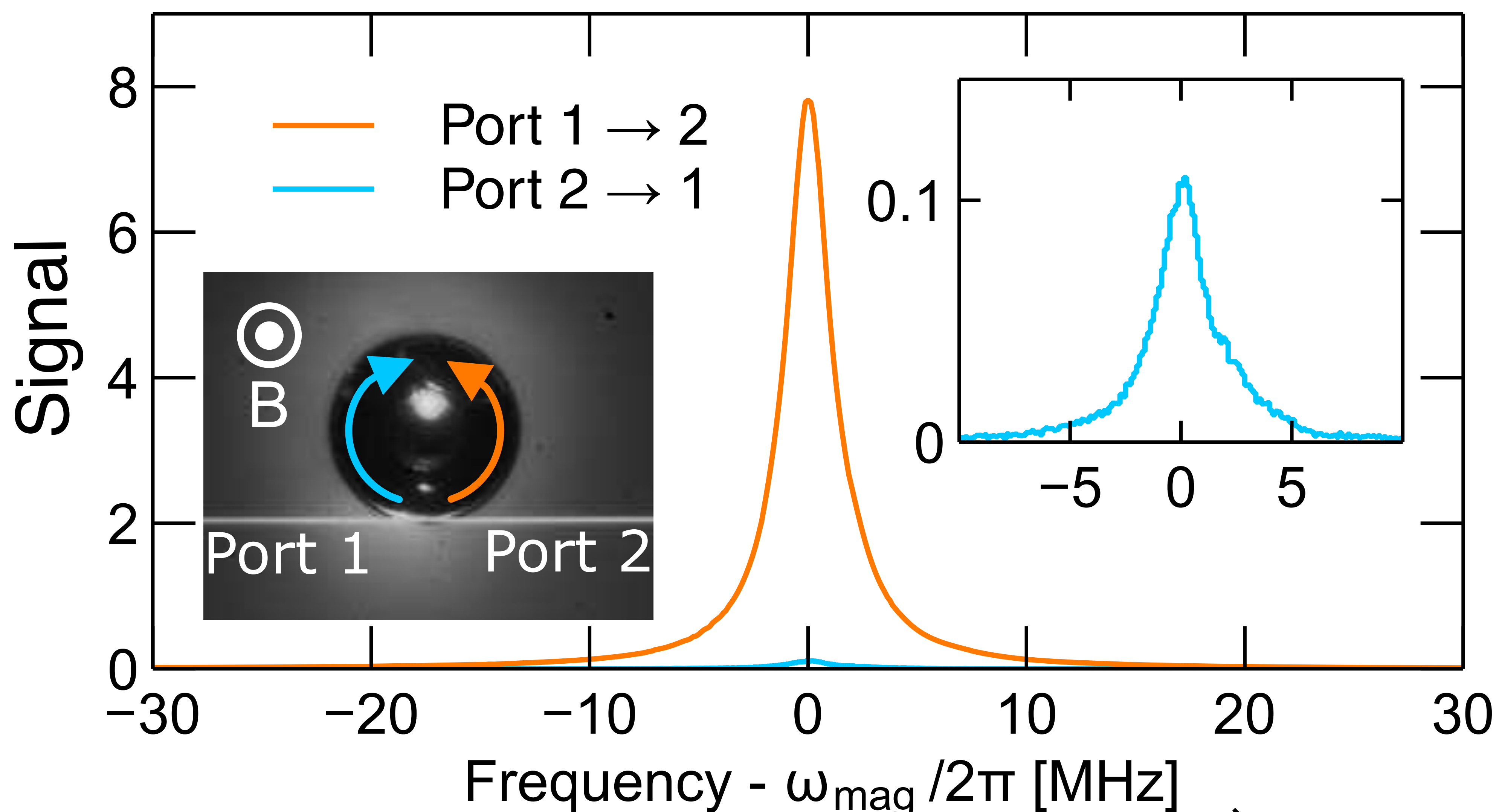


A cavity enhances the effect

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

Cavity Optomagnonics

Magnons ⟷ **Optical photons**

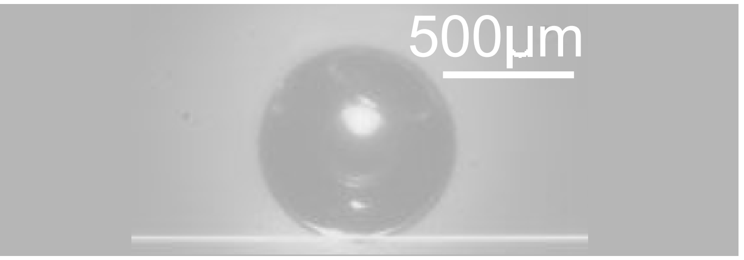


- Osada et. al PRL 116, 223601
(Nakamura's group, Tokyo)

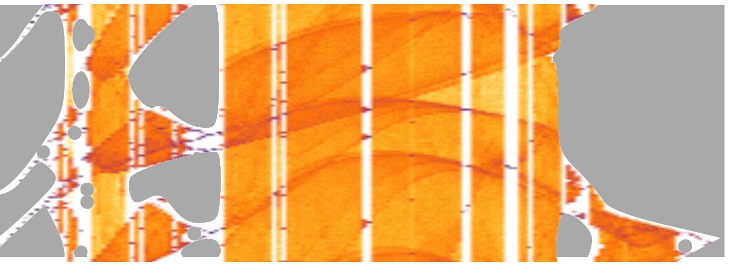
Sidebands at the magnon frequency

Magnons and the Kittel mode

Microwave regime



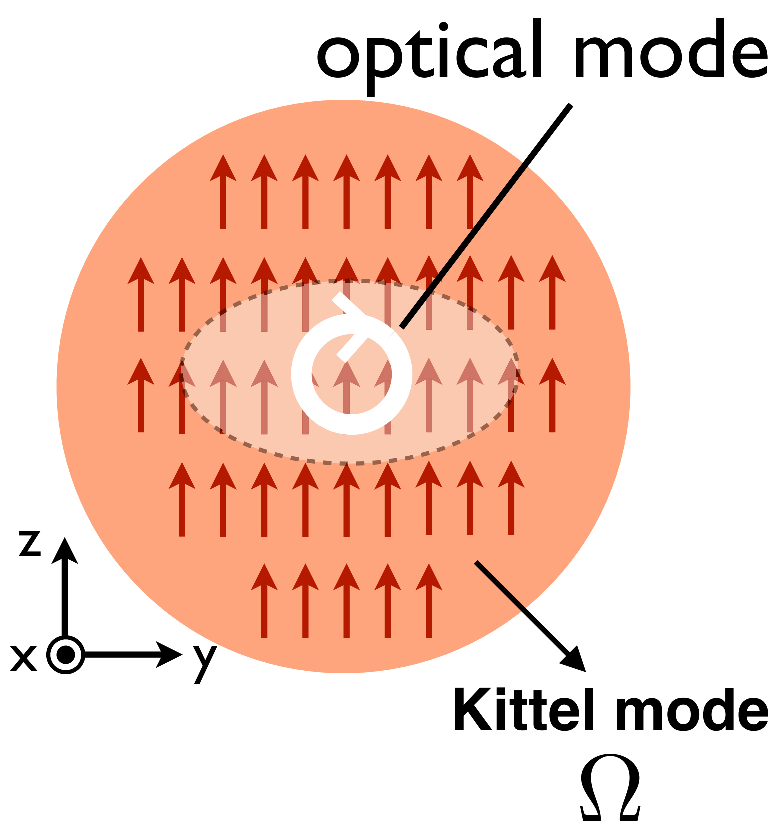
Optomagnonics



Optically induced spin dynamics

Outlook and Summary

Cavity Optomagnonics: 1 optical mode



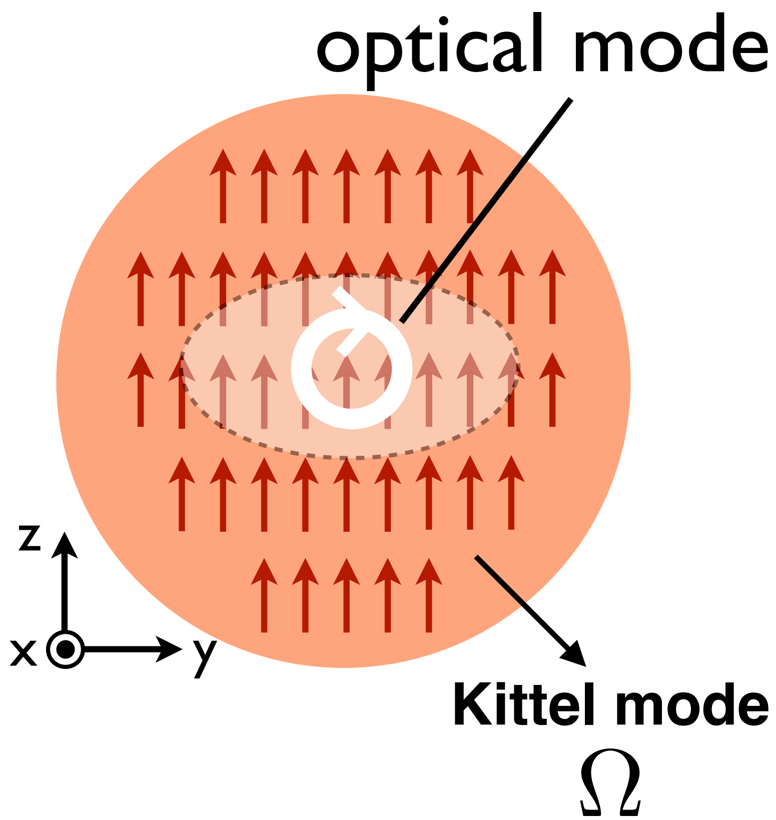
Coupling

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

acquires a simple form

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

Cavity Optomagnonics: 1 optical mode



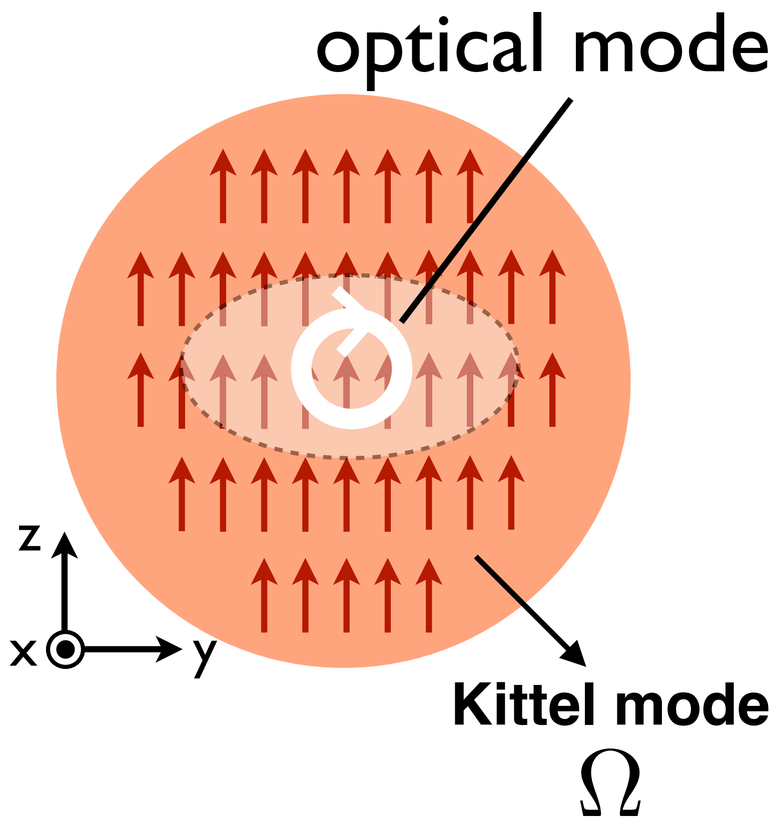
Total Hamiltonian for one optical mode

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

driving laser detuning $\Delta = \omega_{las} - \omega_{cav}$

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

Cavity Optomagnonics



Total Hamiltonian for 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 $\Delta = \omega_{las} - \omega_{cav}$

$$G = \frac{1}{S}\frac{c\,\theta_F}{4\sqrt{\varepsilon}}\xi$$

mode overlap factor

$G \approx 1\text{Hz}$

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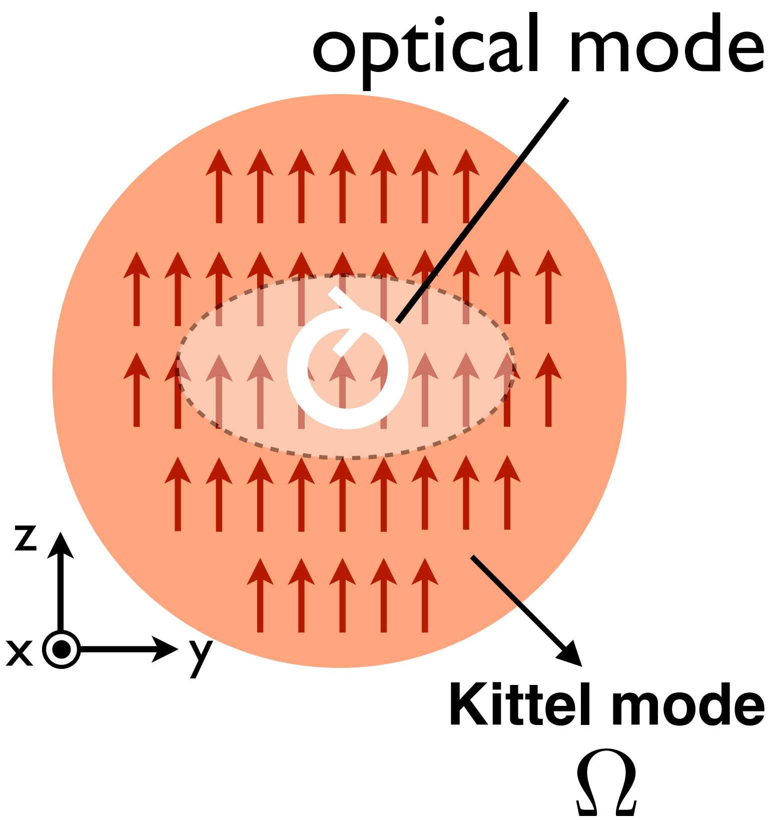

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Optical magnetic field density

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

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)

Fast Cavity Limit

$\kappa \gg \Omega$ integrate out the light field

Effective equation of motion for $\mathbf{S}$:

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

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optically induced

effective field

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

tunable by the external laser drive

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

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

damping

can change sign

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

tunable by the external laser drive

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

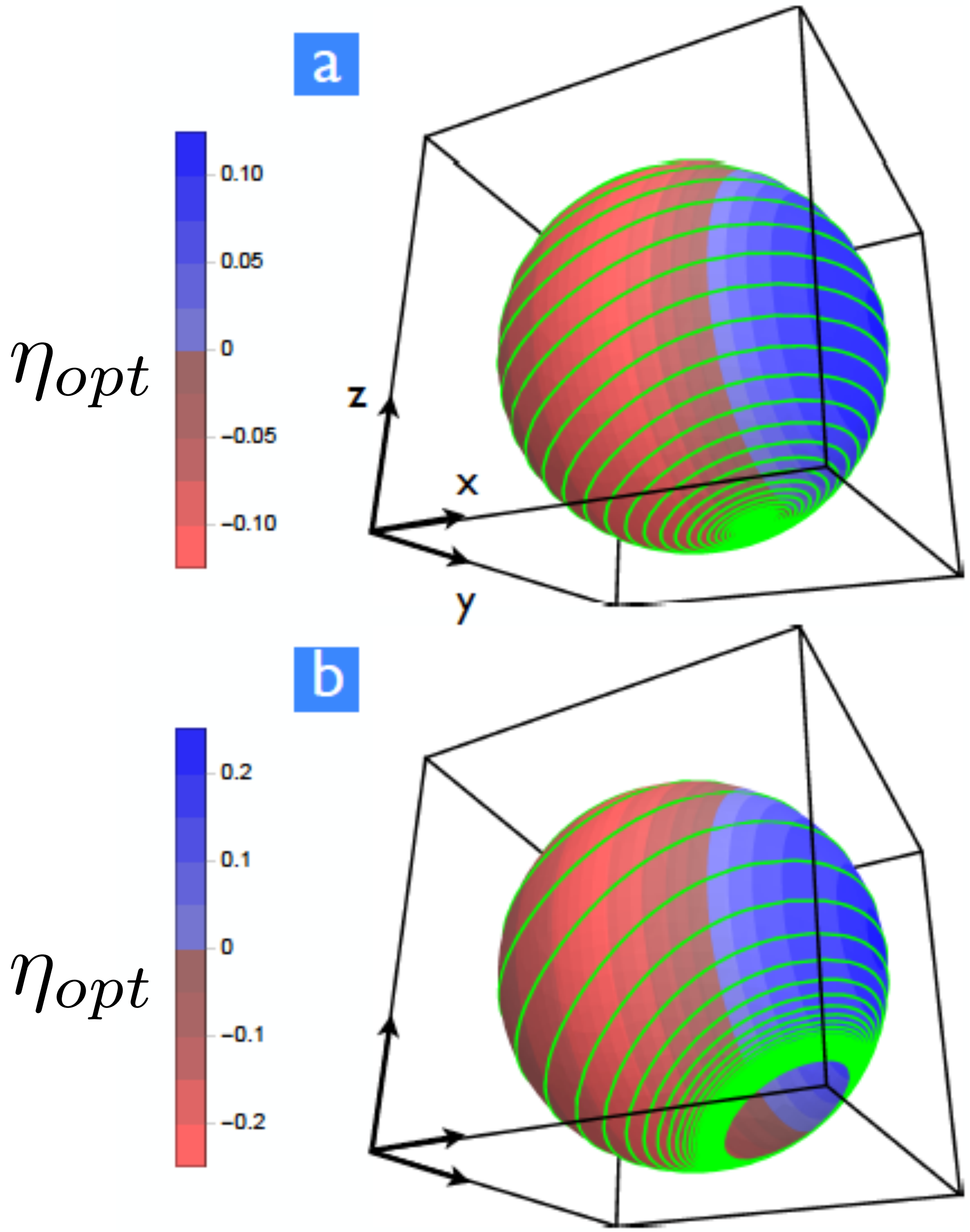
Fast Cavity Limit: Spin Dynamics

magnetic switching

$G\alpha^2_{\max}/\Omega = 0.6$

self-sustained oscillations

$G\alpha^2_{\max}/\Omega = 0.8$



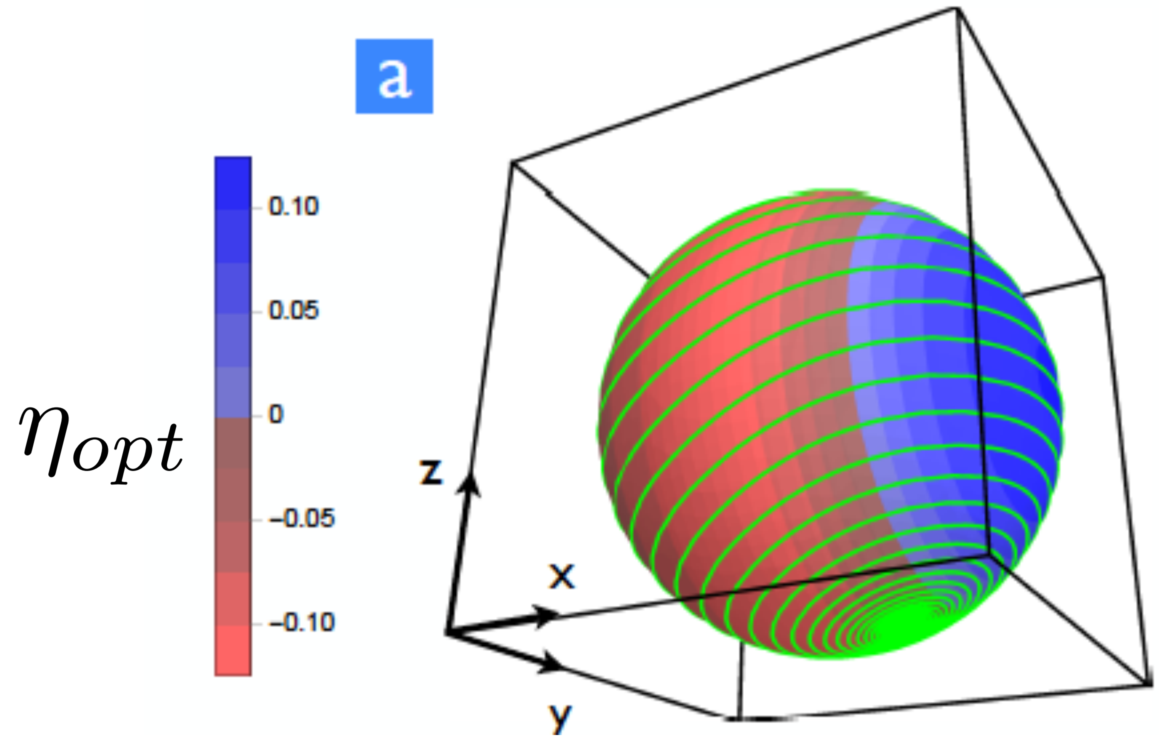
Increasing light intensity

$$\Delta = \Omega\,,\ GS/\Omega = 2\,,\ \kappa/\Omega = 5$$

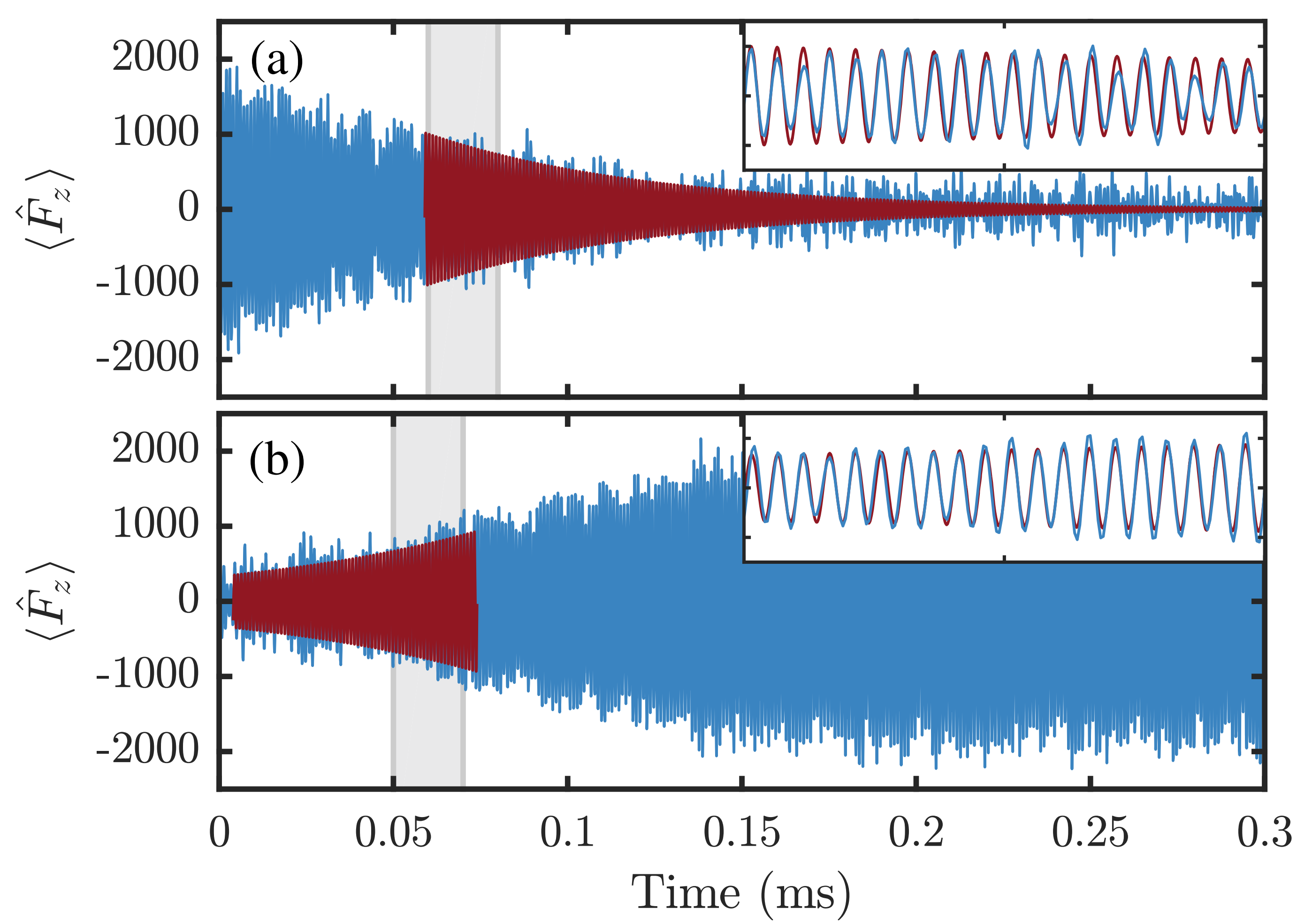
S. Viola Kusminskiy, H. X. Tang, and F. Marquardt, PRA 94, 033821 (2016)

Fast Cavity Limit: Spin Dynamics

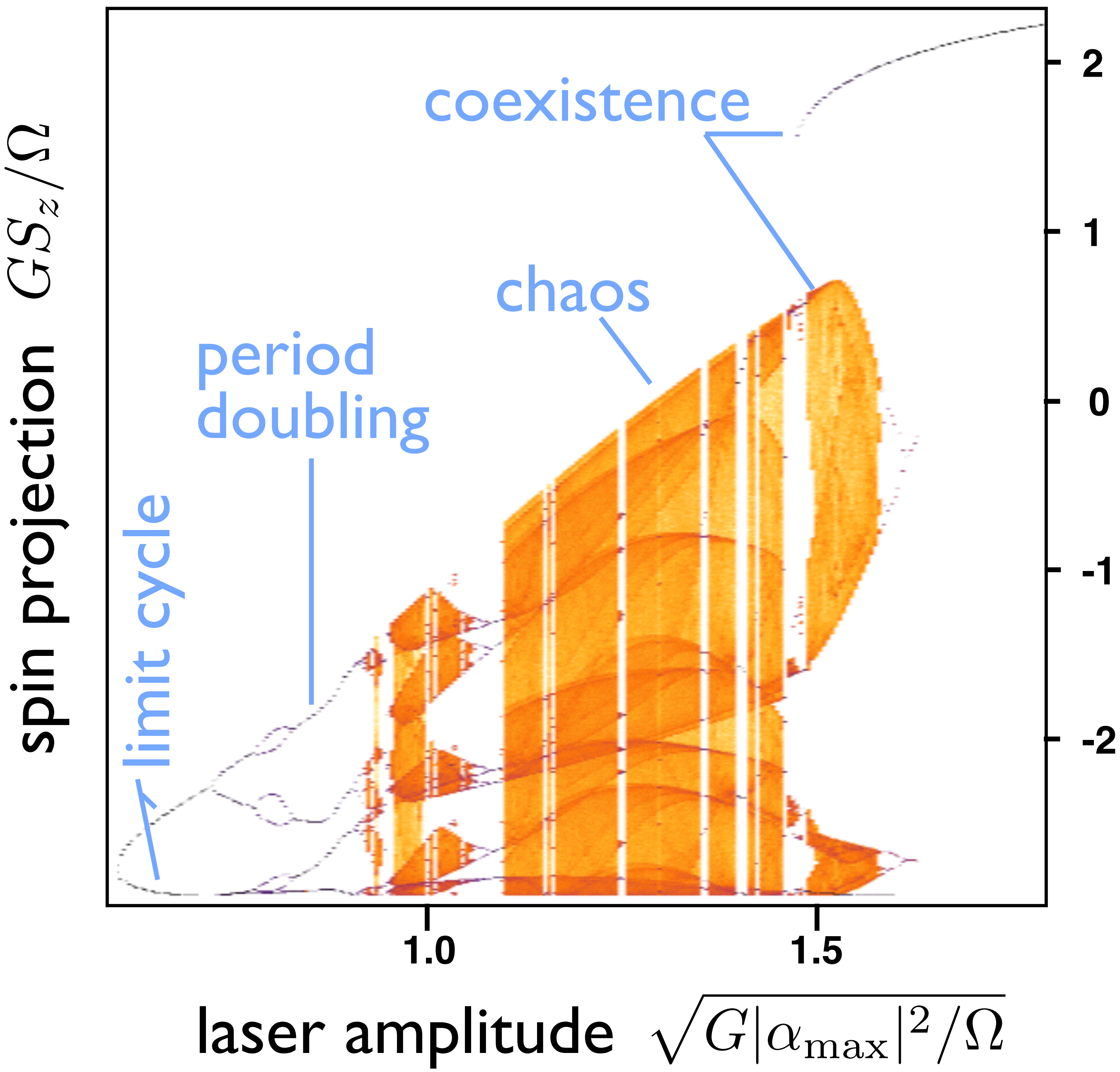
magnetic switching



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



Full Nonlinear Dynamics



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

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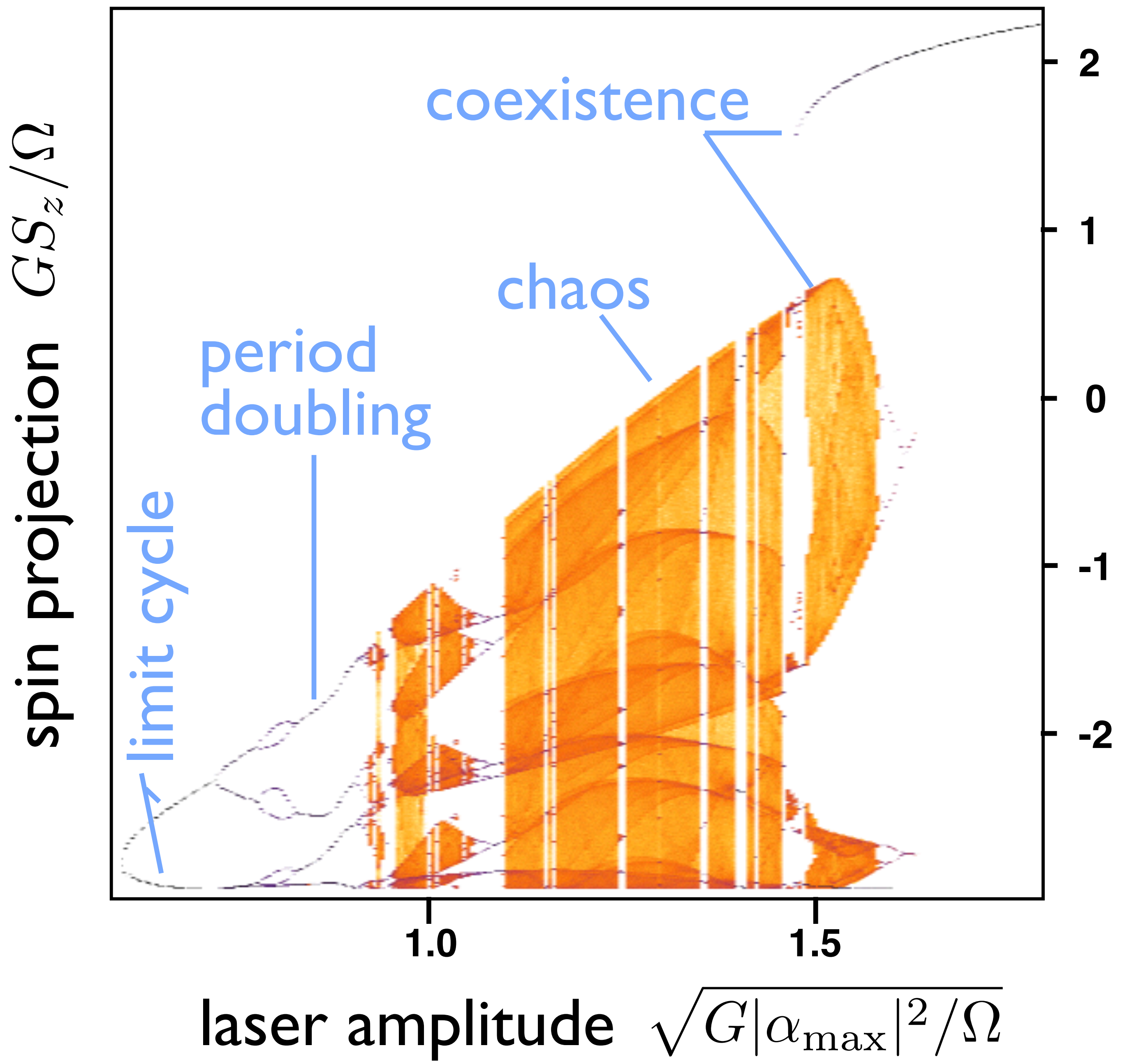


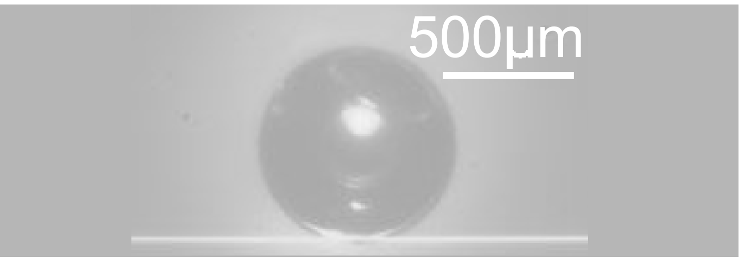
- » **Coherent optical control**
- » **Magnetic switching**
- » **Self-sustained oscillations**
- » **Optically induced route to chaos**

Collaborators

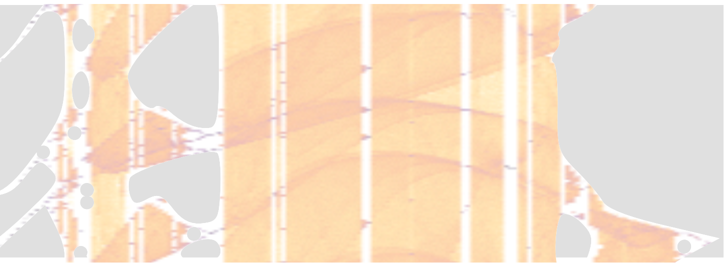
- Florian Marquardt (Erlangen)
- Hong Tang (Yale)

Magnons and the Kittel mode

Microwave regime



Optomagnonics

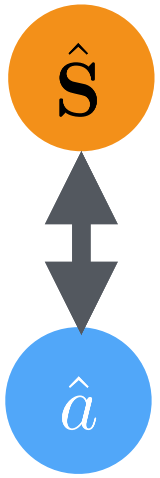


Optically induced spin dynamics

Outlook and Summary

Outlook

Problem



the state of the art optomagnonic coupling is too small

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

Cavity Optomagnonics

for small oscillations: spin $\longrightarrow$ harmonic oscillator

$$\Rightarrow \quad \hbar G \hat{S}_x \hat{a}^\dagger \hat{a} \approx \hbar G \sqrt{S/2} \hat{a}^\dagger \hat{a} (\hat{b} + \hat{b}^\dagger)$$

same form as the optomechanical Hamiltonian

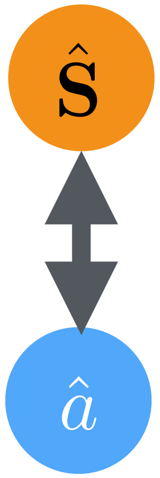
coupling per magnon

$$g_0 = G\sqrt{S/2} \approx 0.1\text{MHz}$$

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

Outlook

Problem



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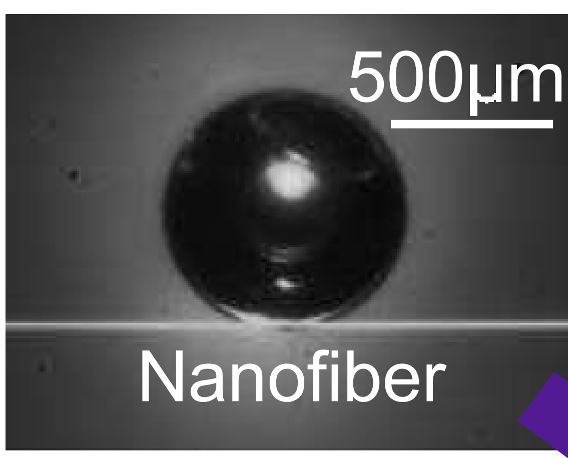
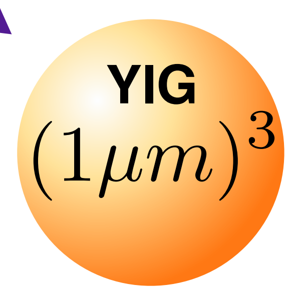
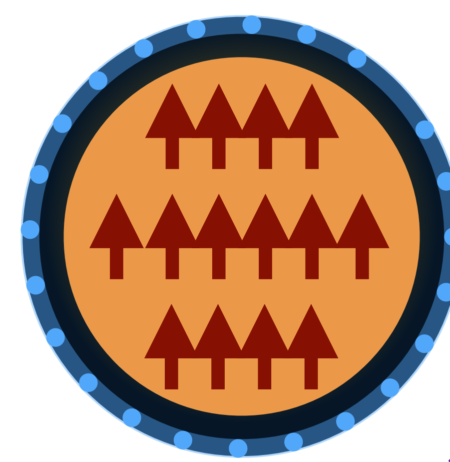
Some solutions

smaller systems





better overlap of modes

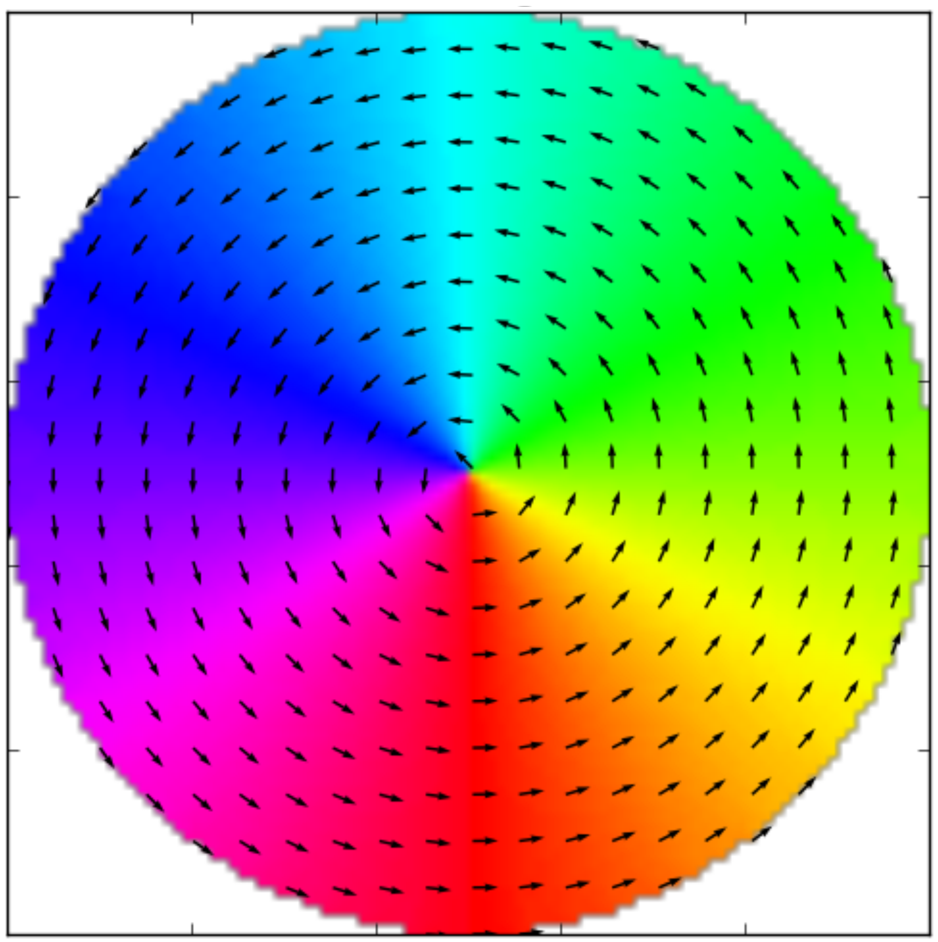


?

Outlook

smaller systems

Magnetic textures

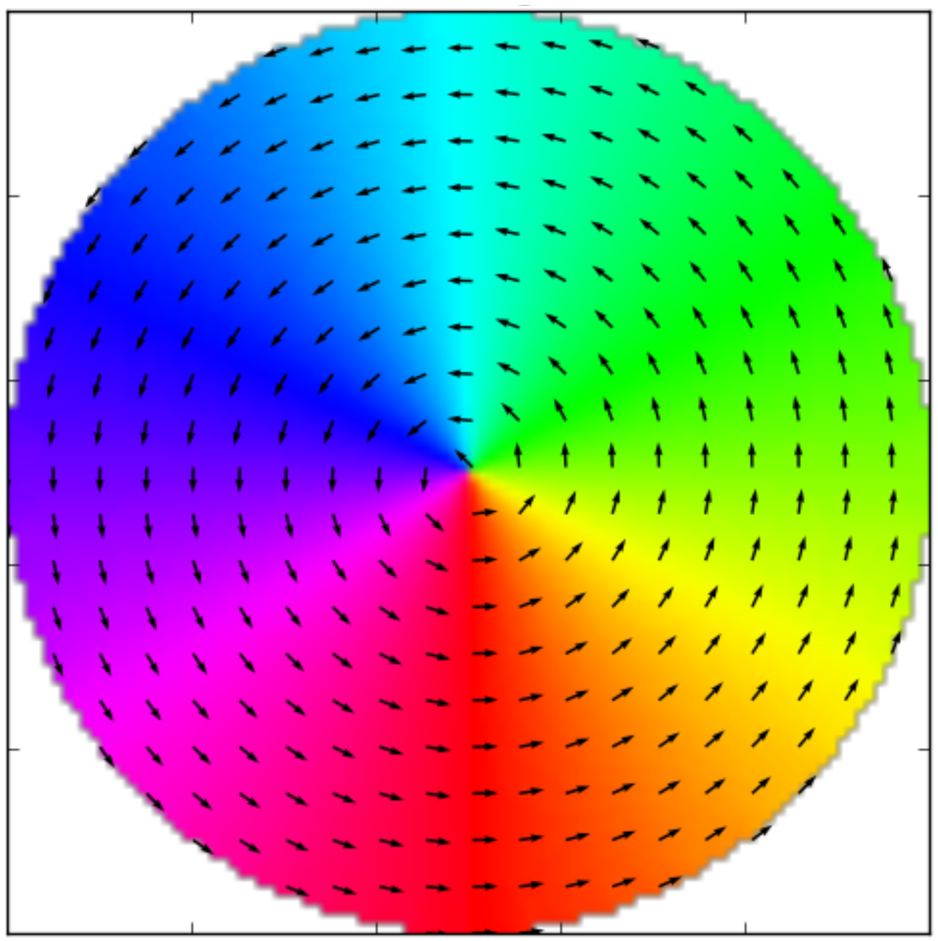


Vortex in a micro disk

Outlook

smaller systems

Magnetic textures

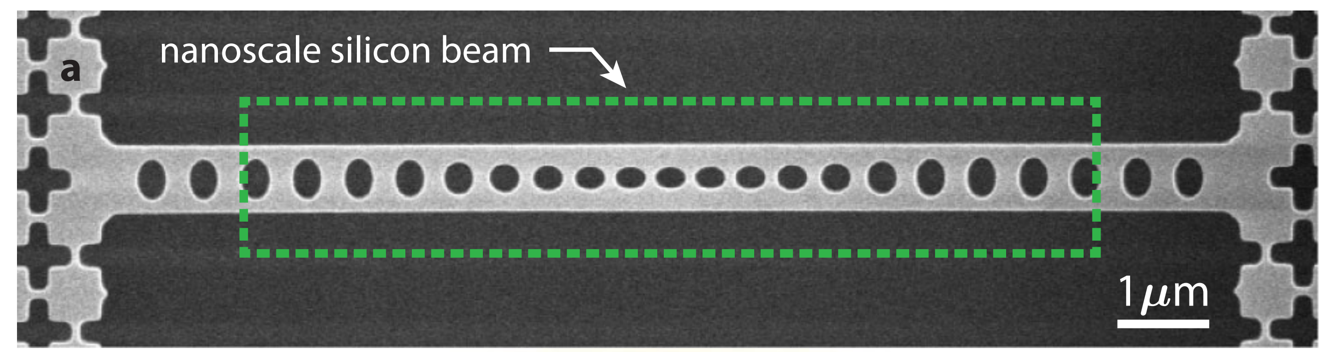


Vortex in a micro disk

better overlap of modes

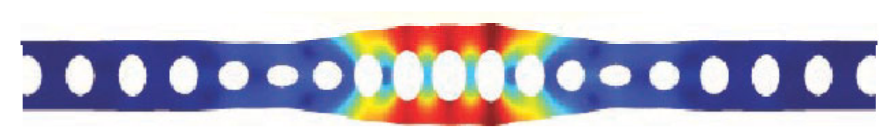
optomechanical crystals

Safavi-Naeini et al, PRL 2012 (Caltech)



optical mode

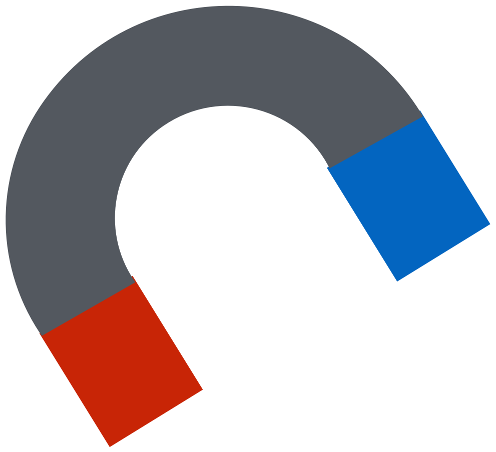
mechanical mode



Optomagnonic crystals?

Summary

- Hybrid systems for quantum technologies
- Magnetic excitations: robust, designable, quantum
- Cavity optomagnonics: promising new field



Open positions starting January 2018!