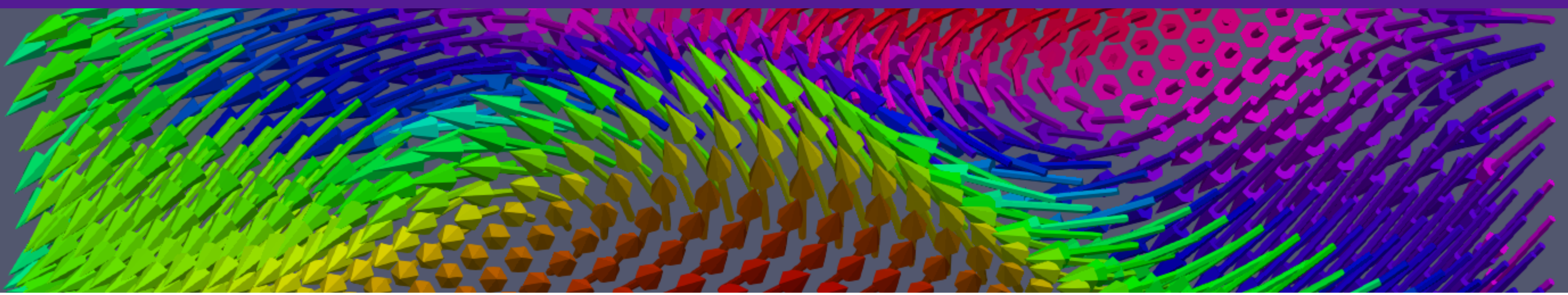
Cavity Optomagnonics with magnetic textures



Silvia Viola Kusminskiy

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

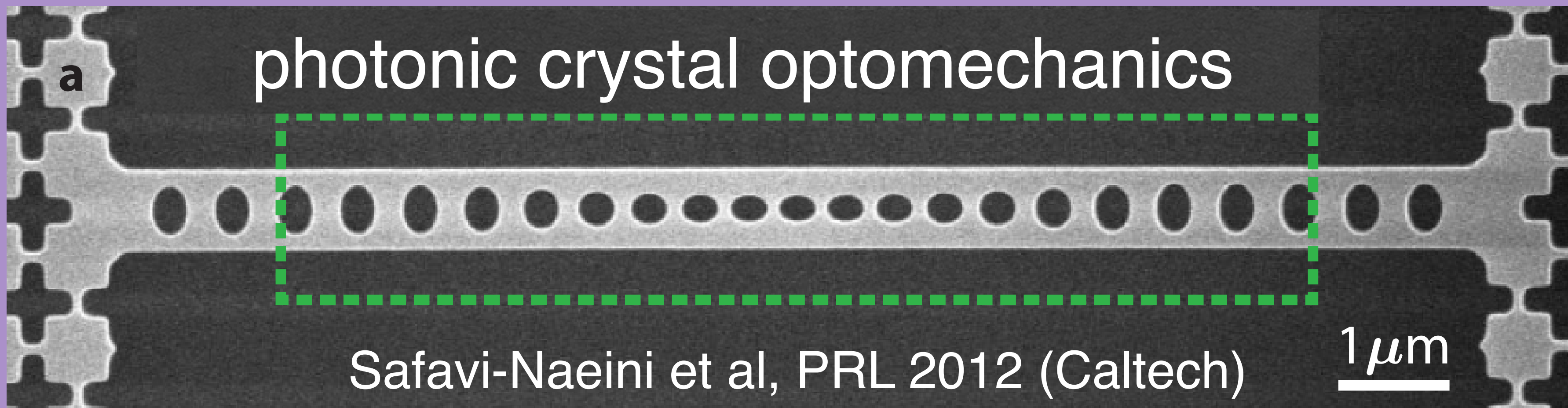
MAX PLANCK INSTITUTE for the science of light

Max Planck Research Group

Theory of hybrid quantum systems

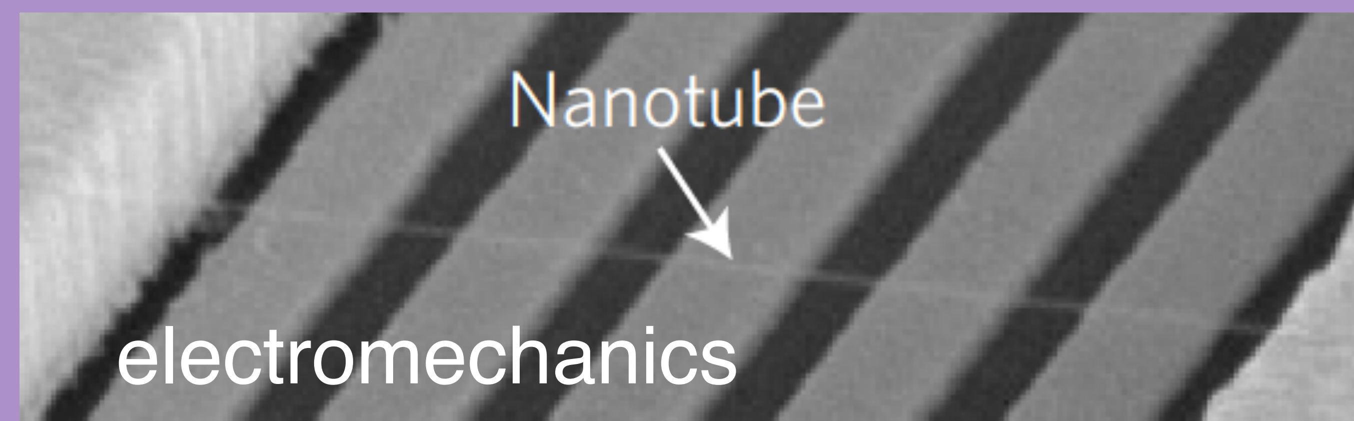
Theory of hybrid quantum systems

Hybrid Quantum Systems

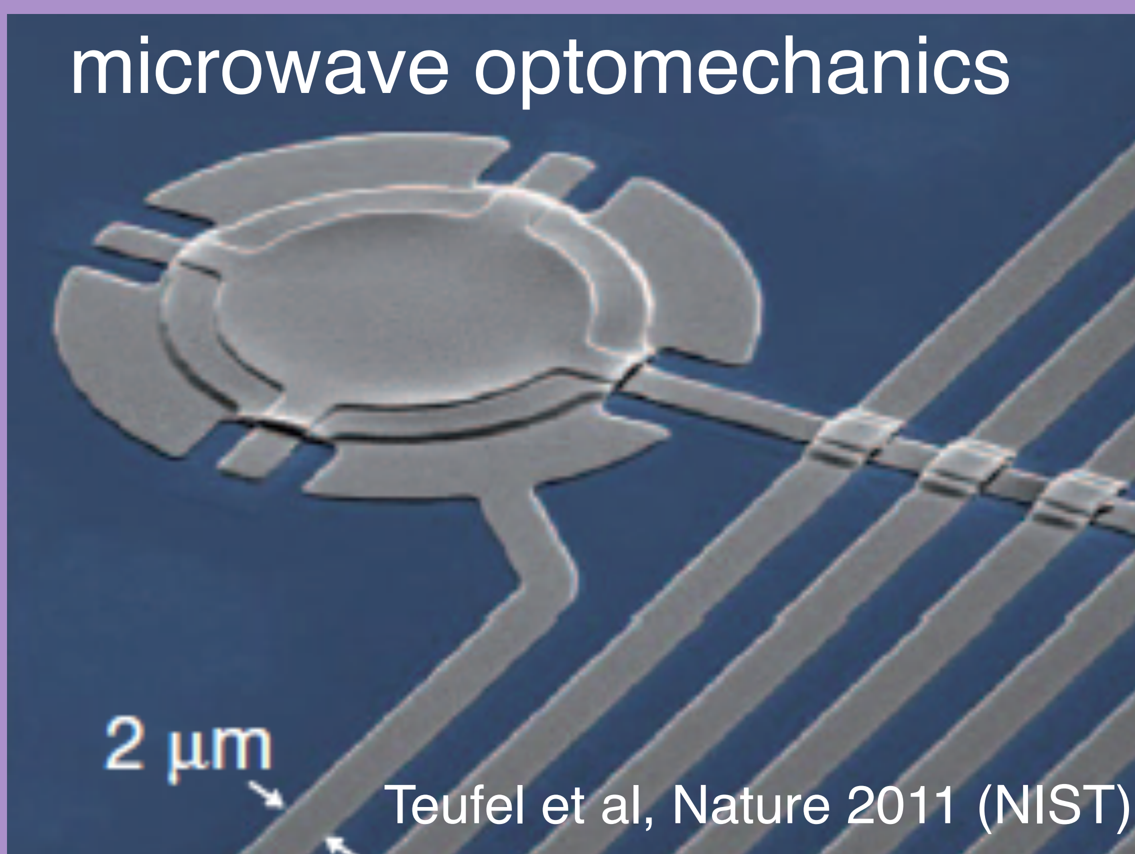


Safavi-Naeini et al, PRL 2012 (Caltech)

mesoscopic: nano/micro scale systems



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

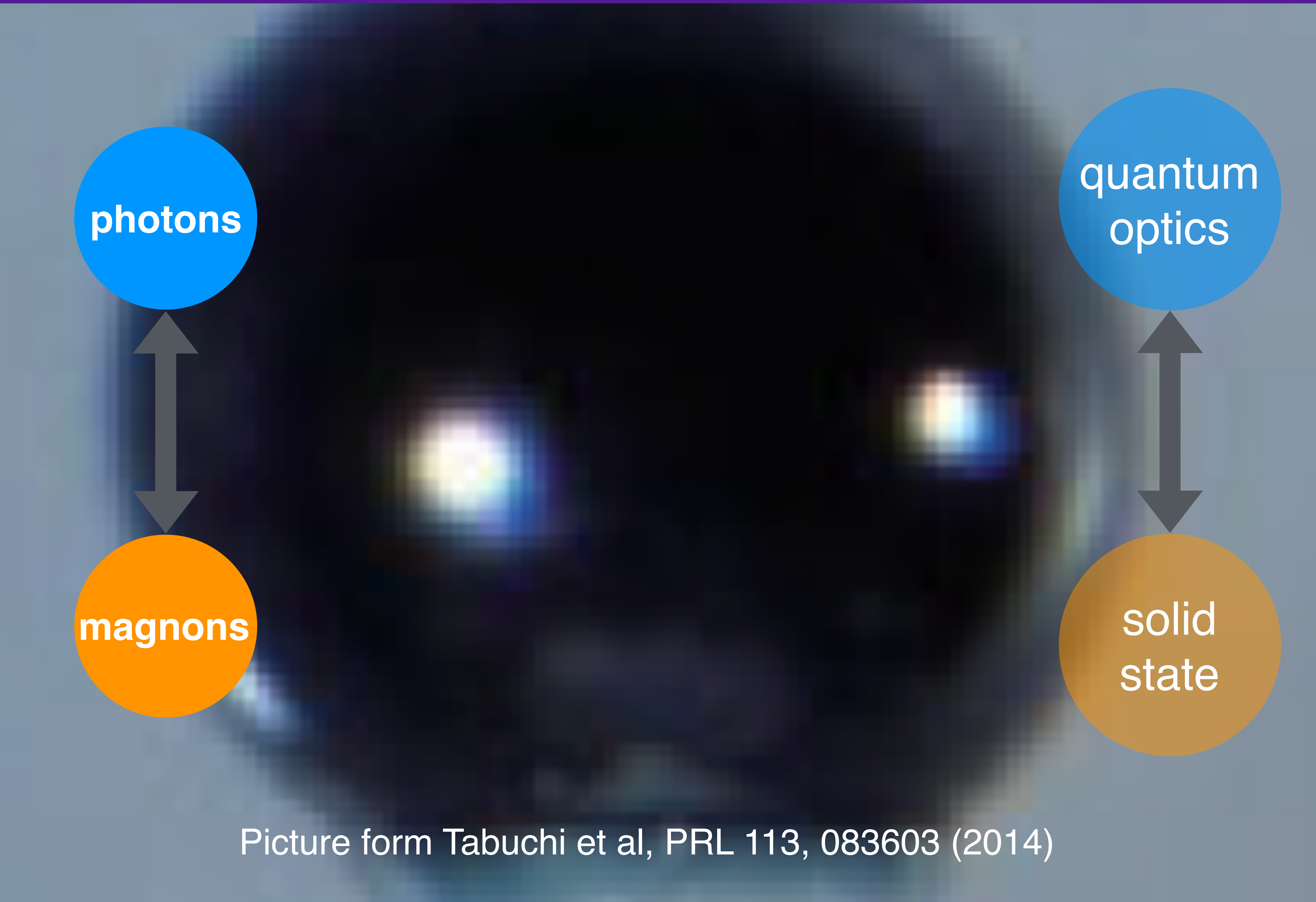


Teufel et al, Nature 2011 (NIST)

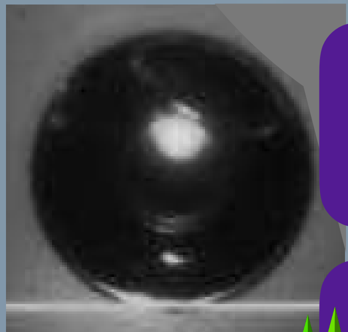
Osada et. al PRL 116, 223601 (2016)

use collective excitations

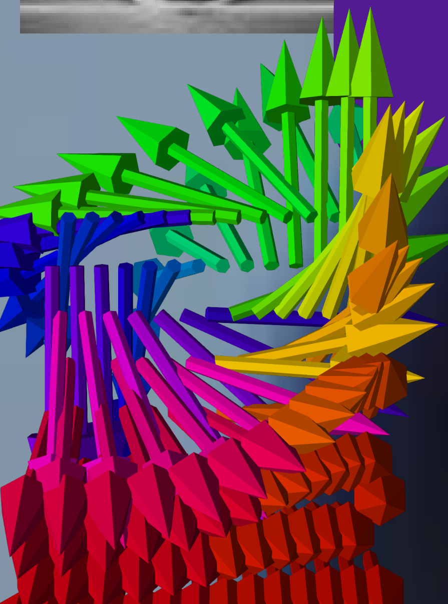
Optomagnonics



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

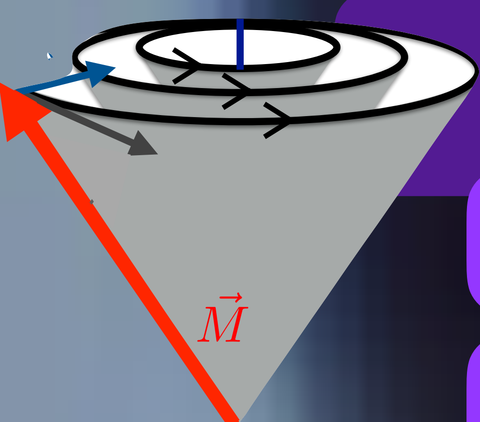


Introduction: cavity optomagnonics



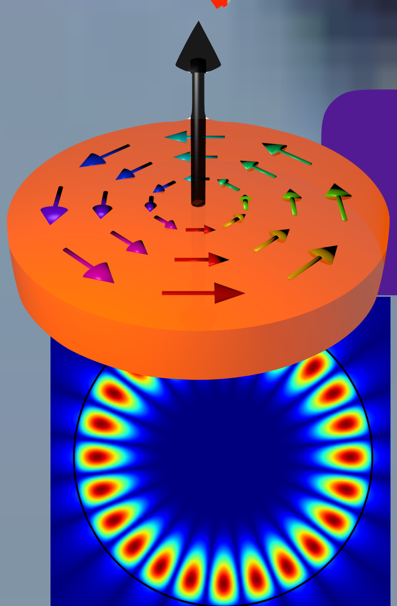
Magnetic textures

- Why do they form?
- Equilibrium condition
- Topology of smooth textures



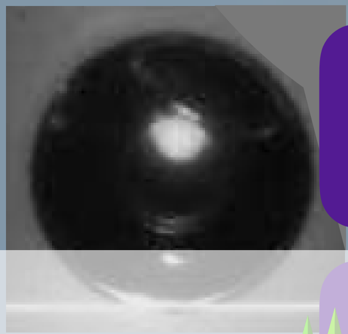
Dynamics of the magnetization

- Landau Lifschitz Gilbert equation
- Thiele equation for topological defects



Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
- Optomagnonic coupling: gyrotropic mode



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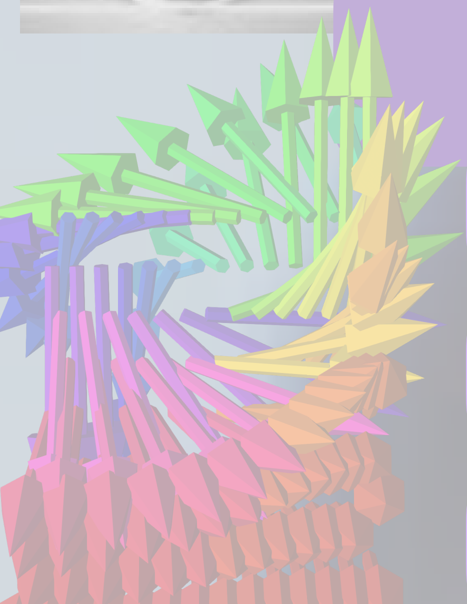

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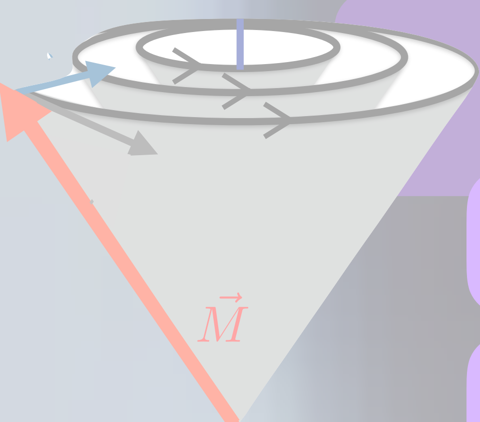

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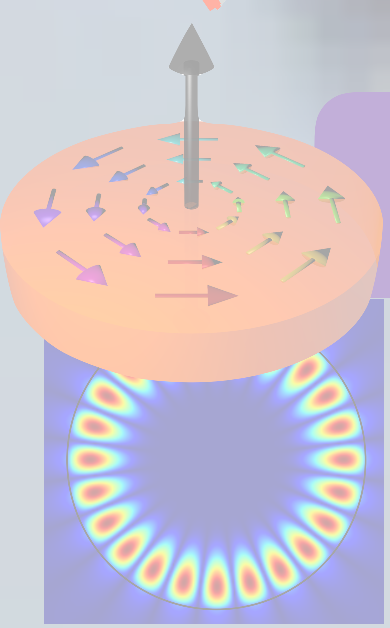


Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
- Optomagnonic coupling: gyrotropic mode

Magnonics

magnon

elementary magnetic
excitation
(quantum of spin wave)

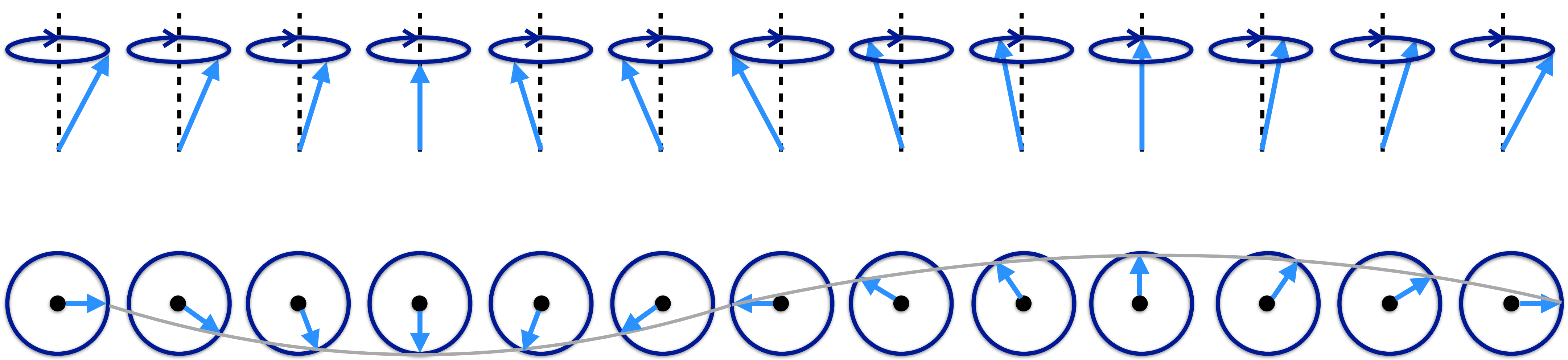
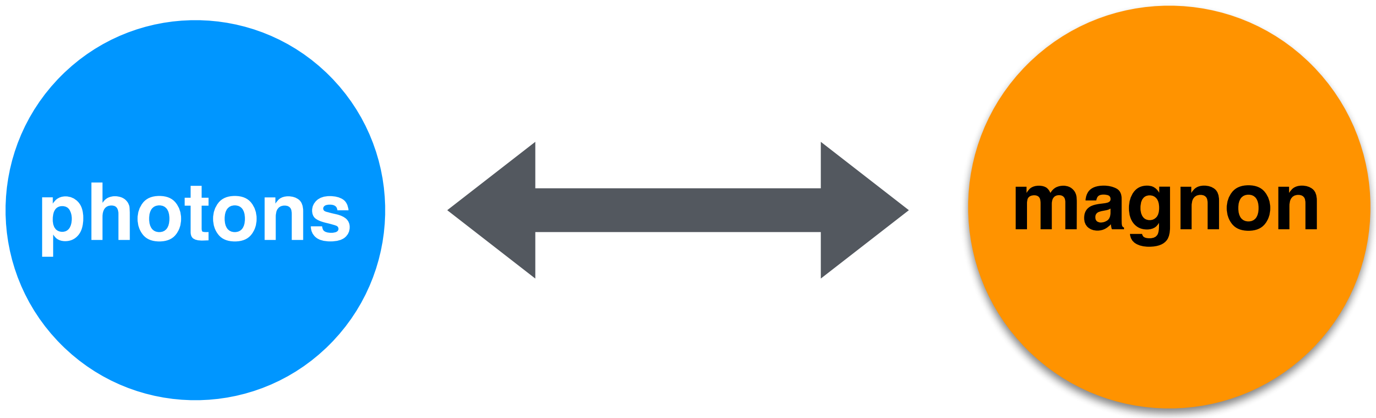


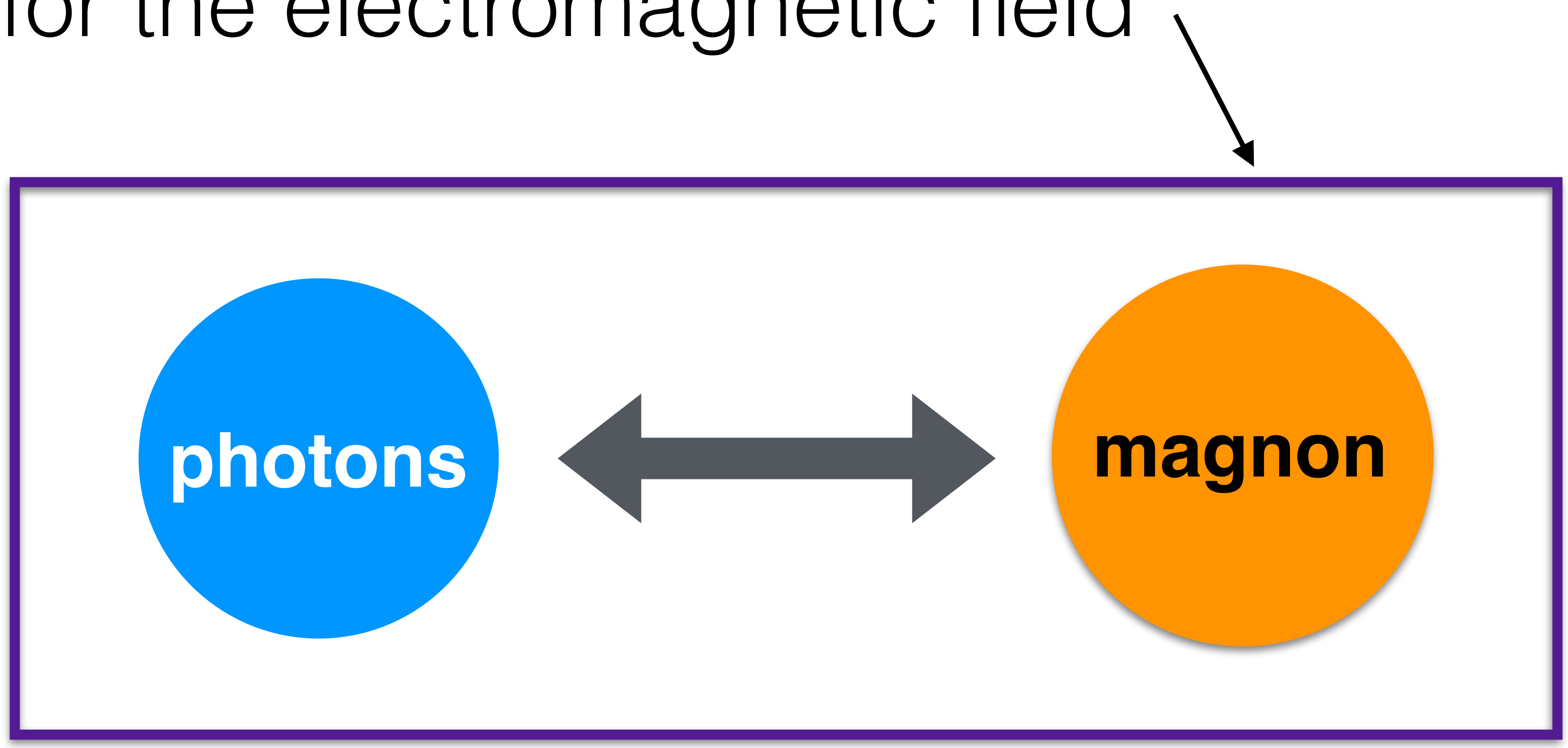
image: Jasmin Graf

Optomagnonics



Cavity Optomagnonics

“Box” for the electromagnetic field



Cavity Optomagnonics

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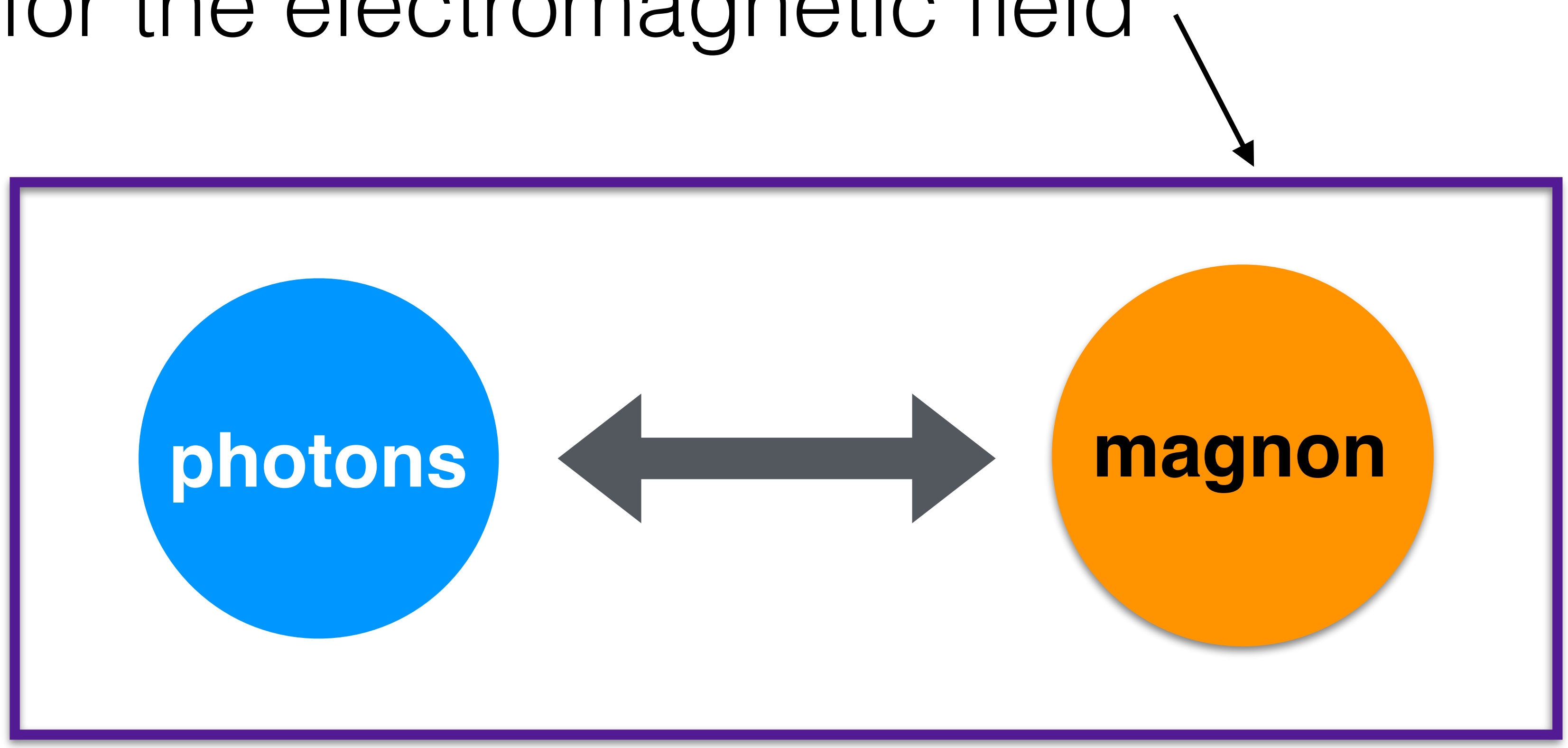
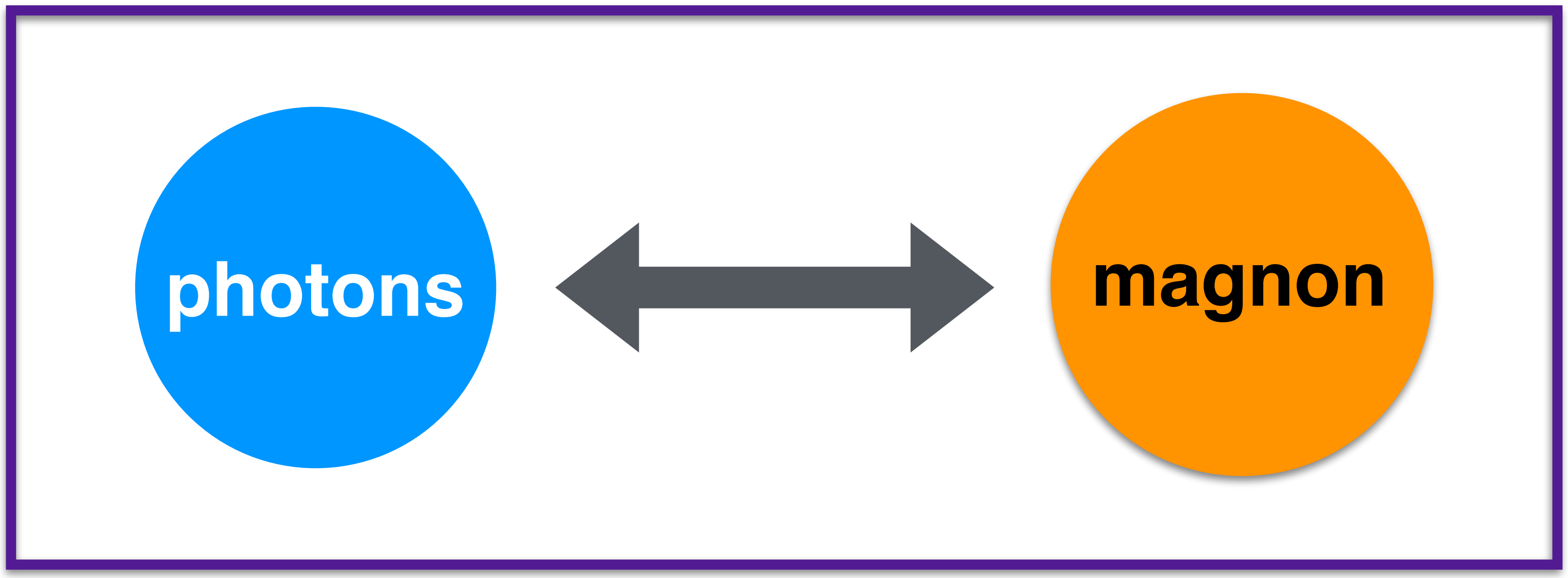


cavity-enhanced spin-photon interaction

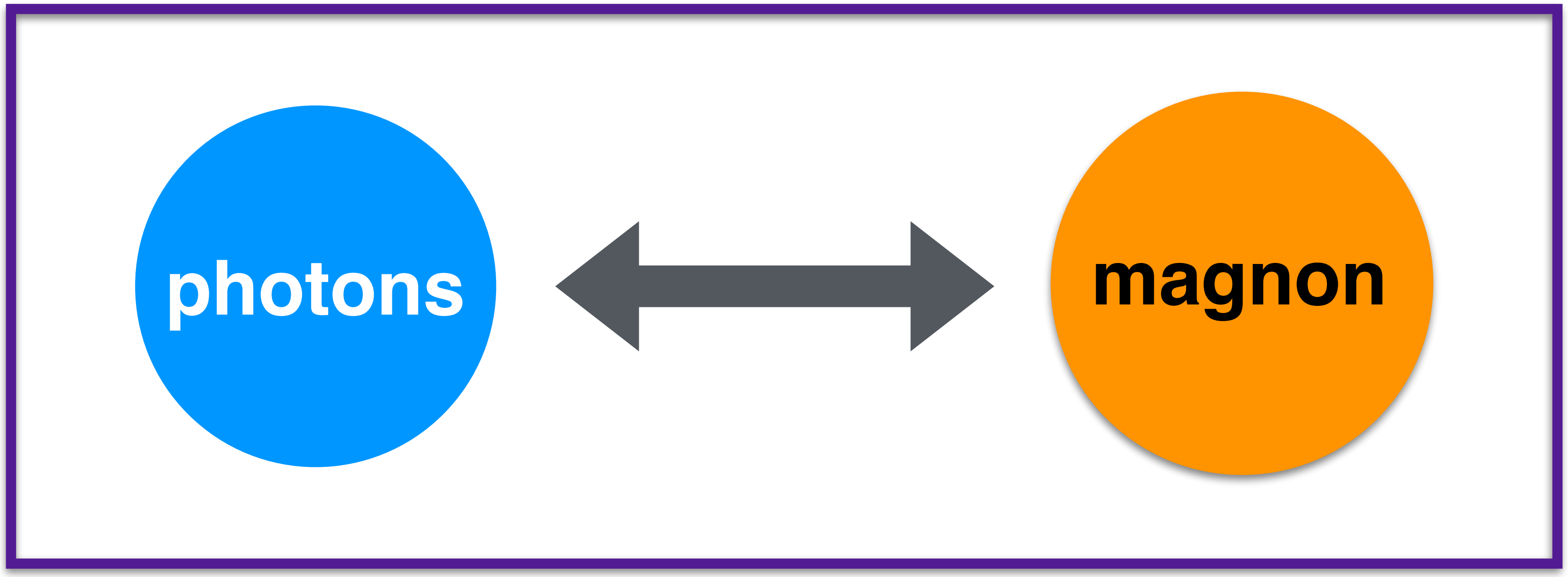
Cavity Optomagnonics

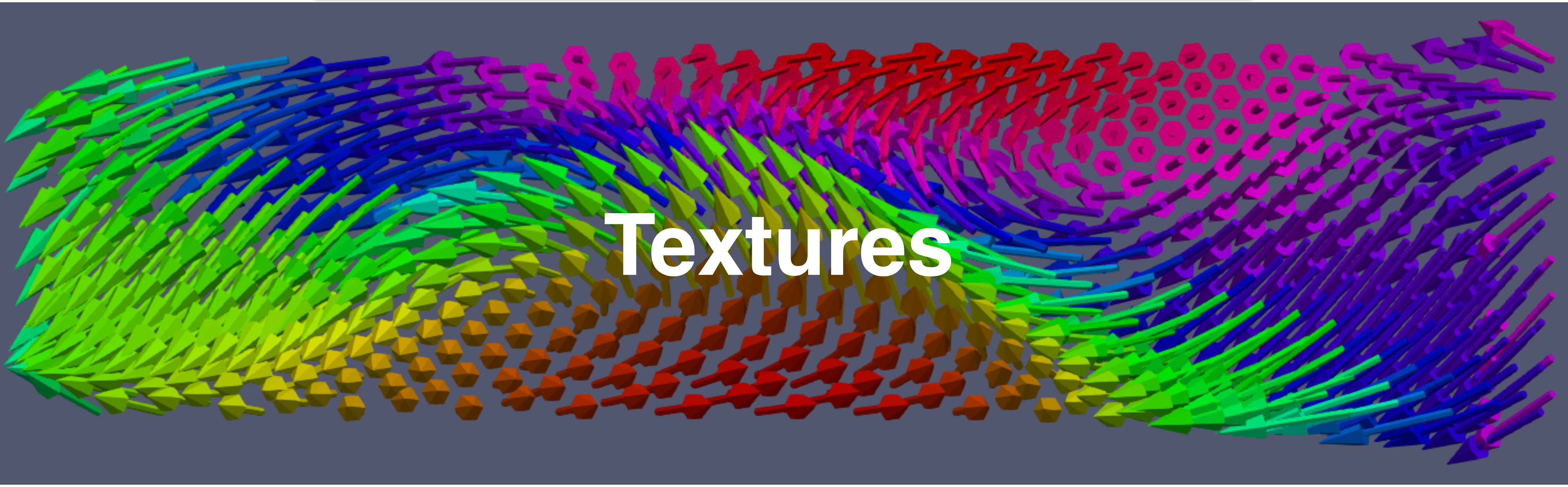


cavity-enhanced spin-photon interaction

cavity QED + magnetism

Cavity Optomagnonics

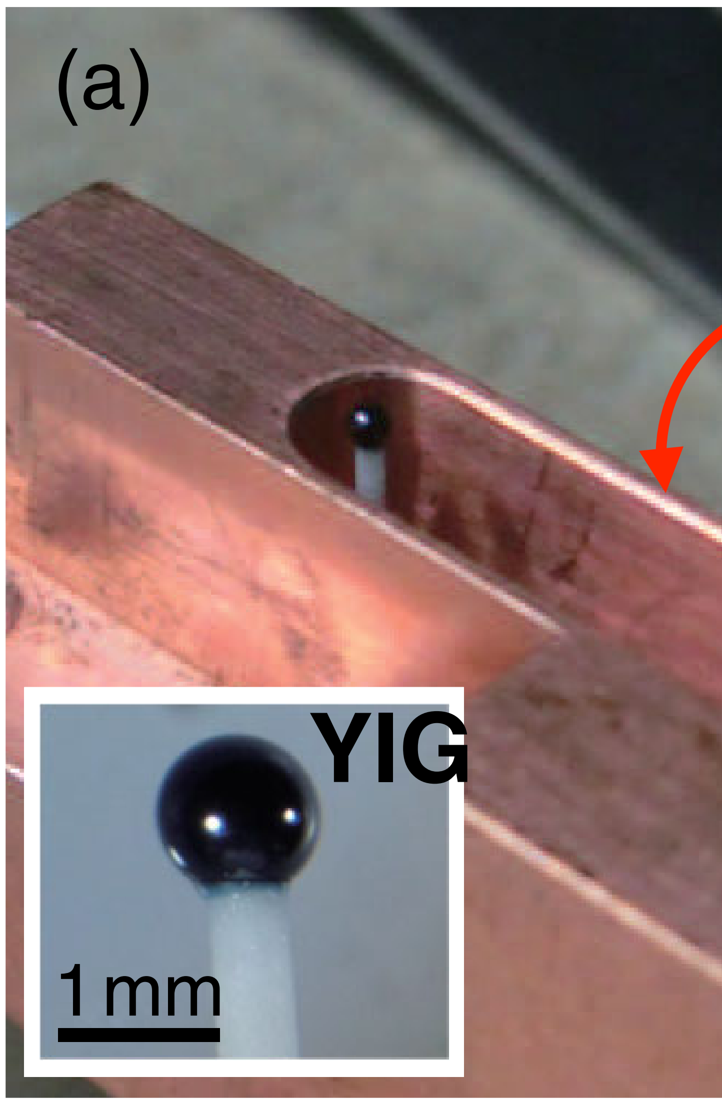




Microwave Regime

Magnons ⟷ **Microwaves**

Strong coupling demonstrated in 2014



Microwave cavity

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

Zhang et. al PRL 113, 156401 (2014)

Tabuchi et. al PRL 113, 083603 (2014)

YIG

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

YIG

Yttrium Iron Garnet

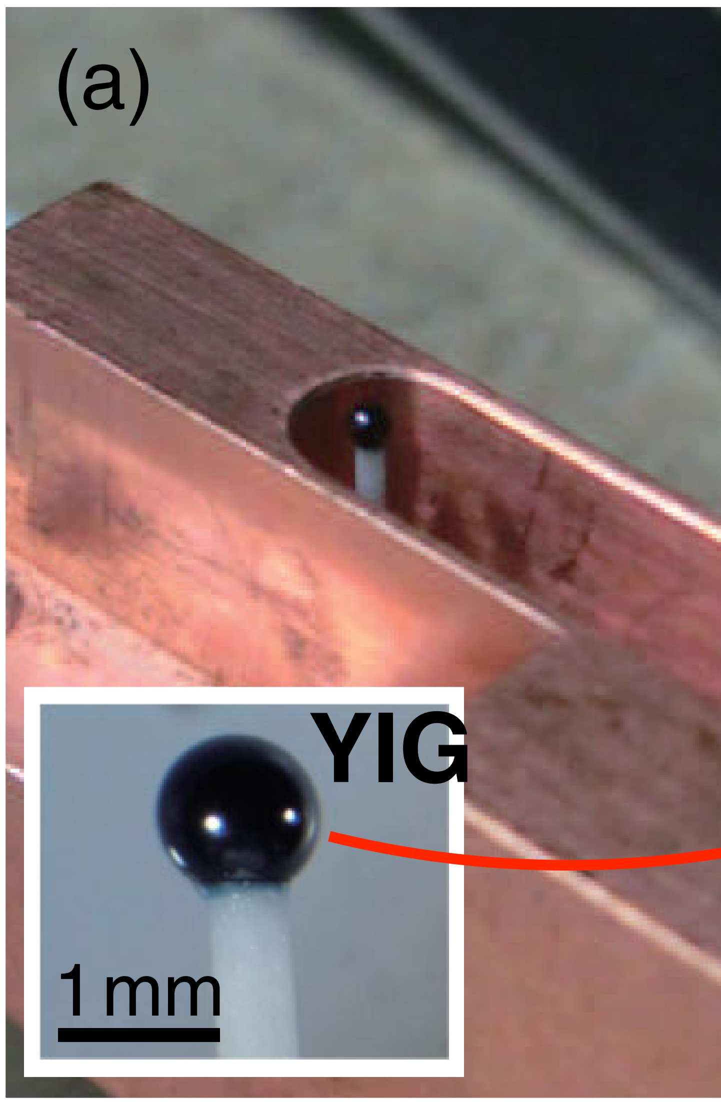
$$Y_3\,Fe_5\,O_{12}$$

- ferrimagnetic
- insulator
- transparent in the infrared

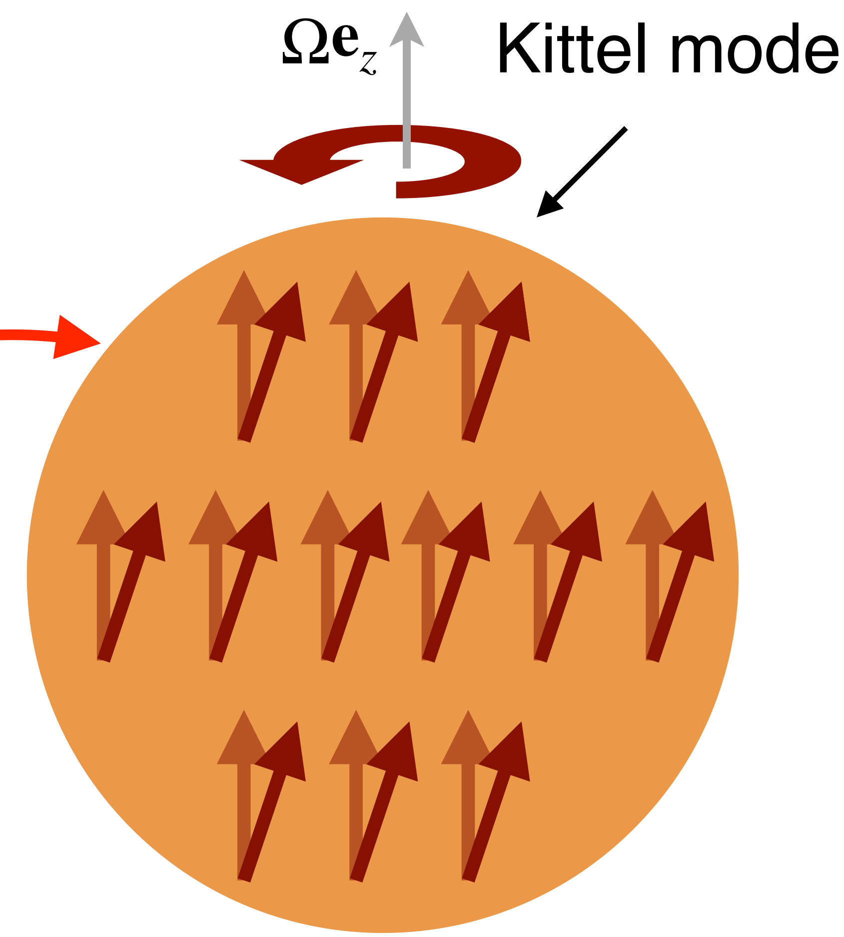
Microwave Regime

Magnons ⟷ **Microwaves**

Strong coupling demonstrated in 2014



Homogeneous magnon mode



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

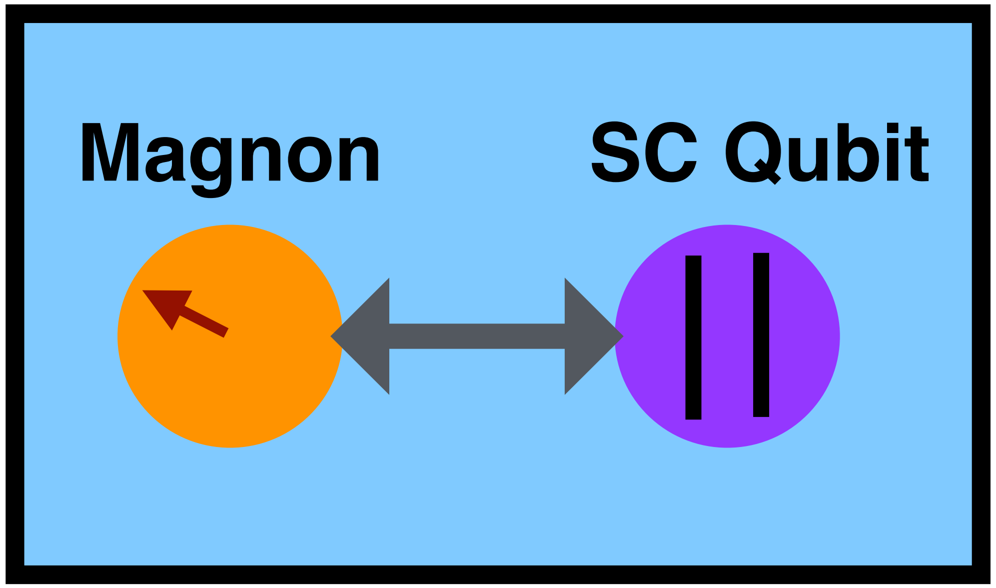
Zhang et. al PRL 113, 156401 (2014)

Tabuchi et. al PRL 113, 083603 (2014)

QUANTUM INFORMATION (Science 2015)

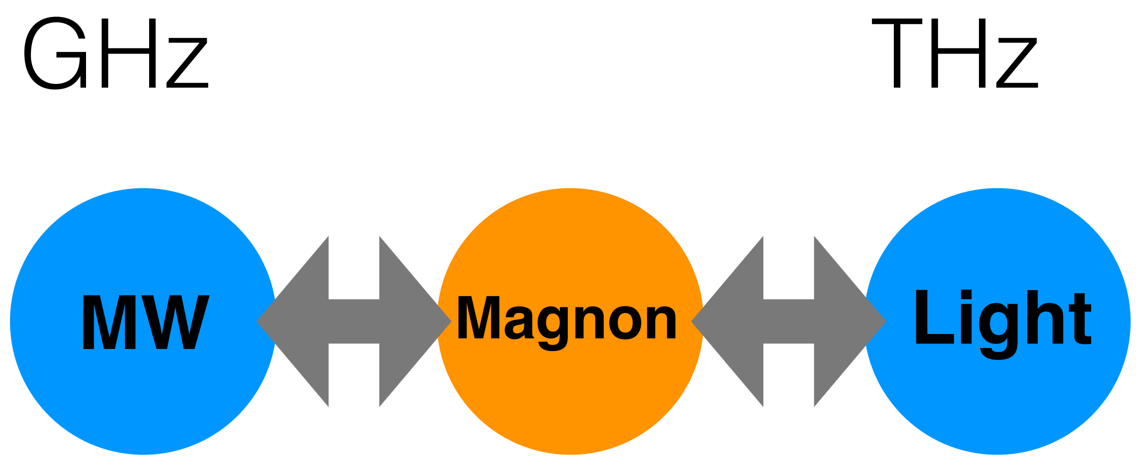
Coherent coupling between a ferromagnetic magnon and a superconducting qubit

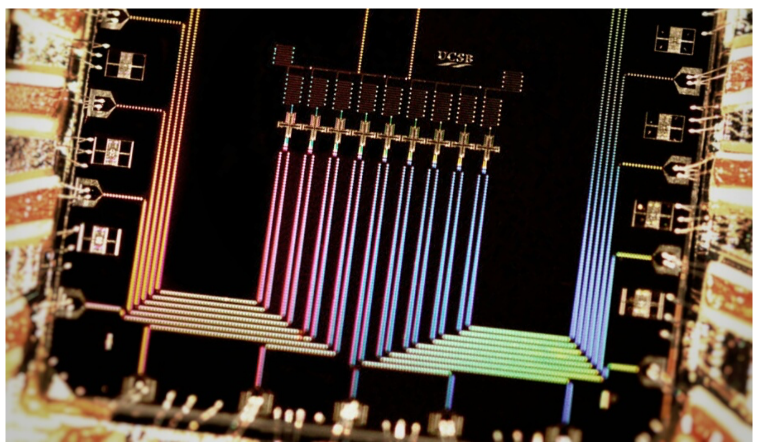
Yutaka Tabuchi,[1*] Seiichiro Ishino,[1] Atsushi Noguchi,[1] Toyofumi Ishikawa,[1] Rekishu Yamazaki,[1] Koji Usami,[1] Yasunobu Nakamura[1,2]

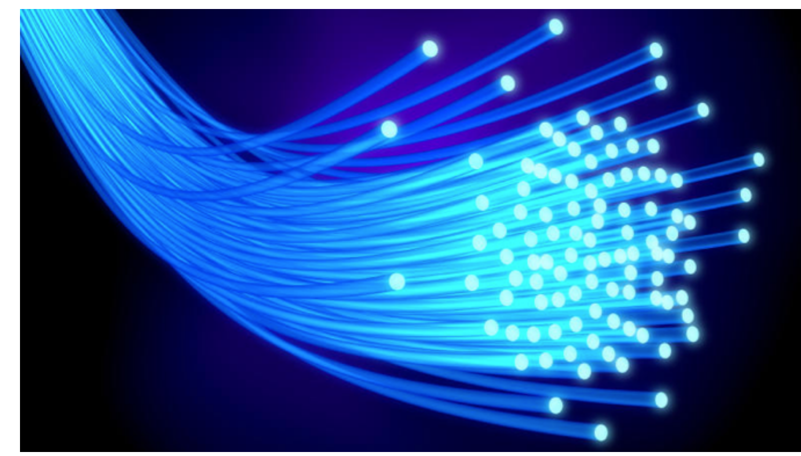


MW Cavity

Coupling to Optics?

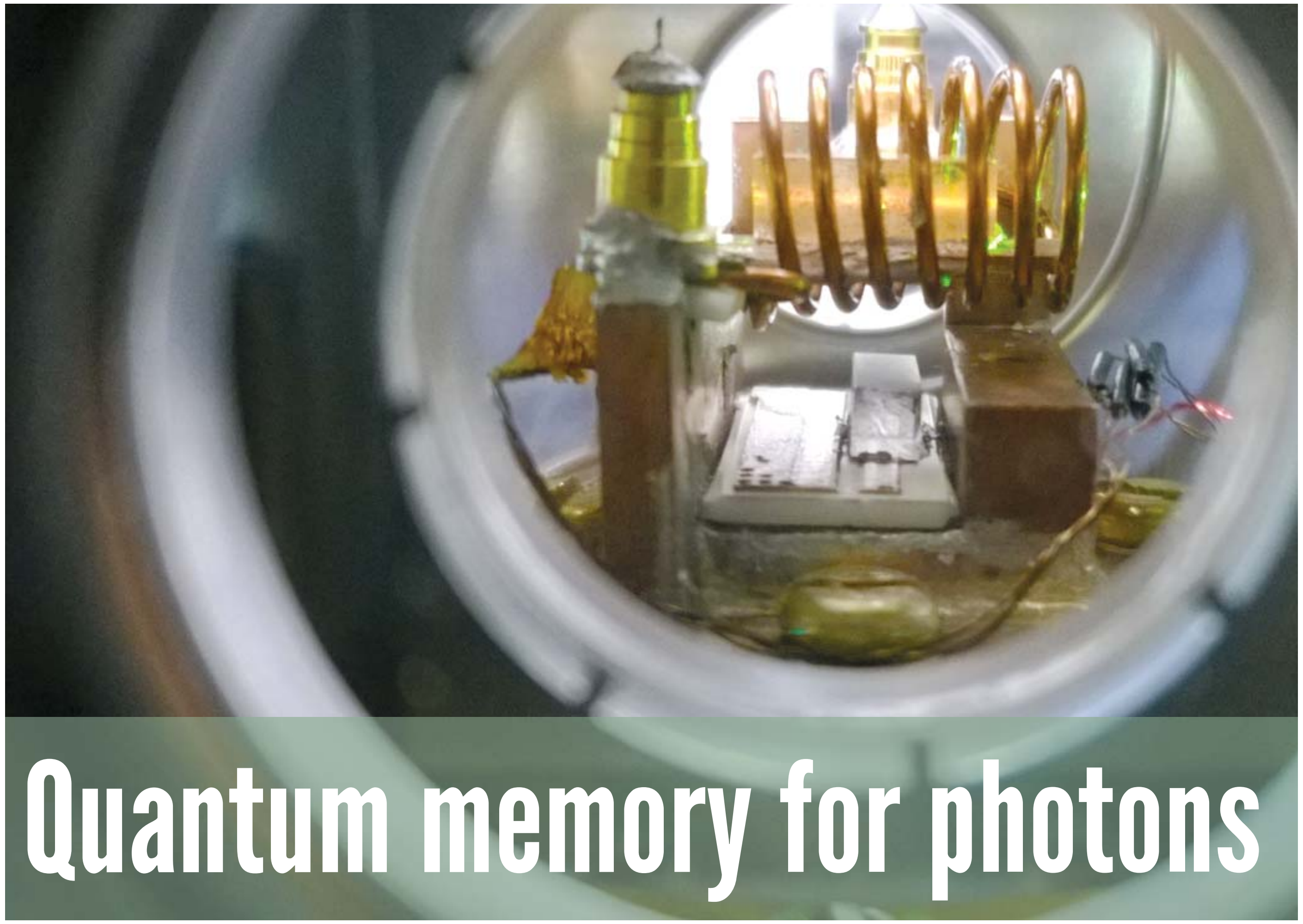




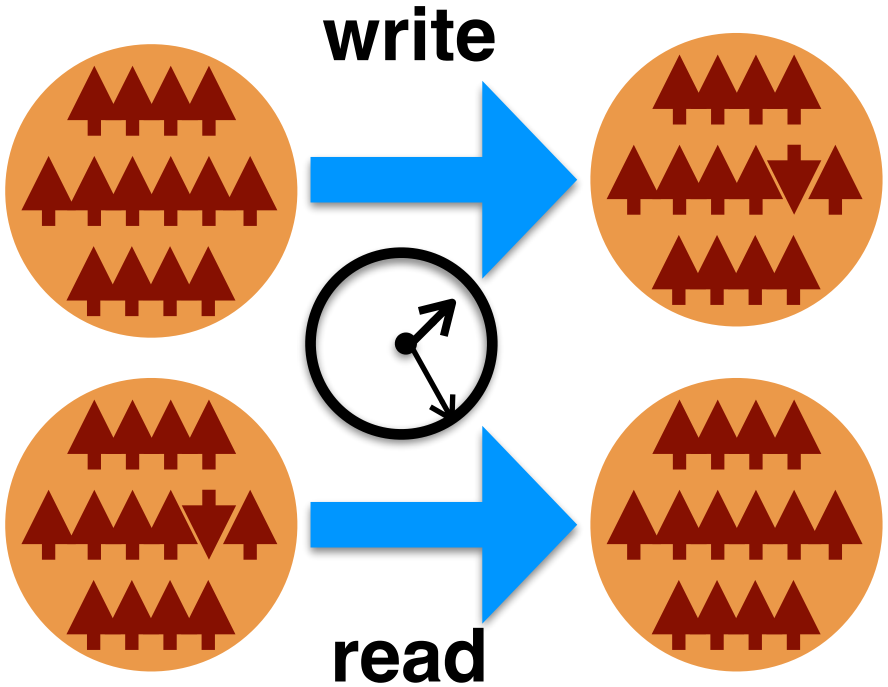


Motivation:
magnon as a transducer

Coupling to Optics?

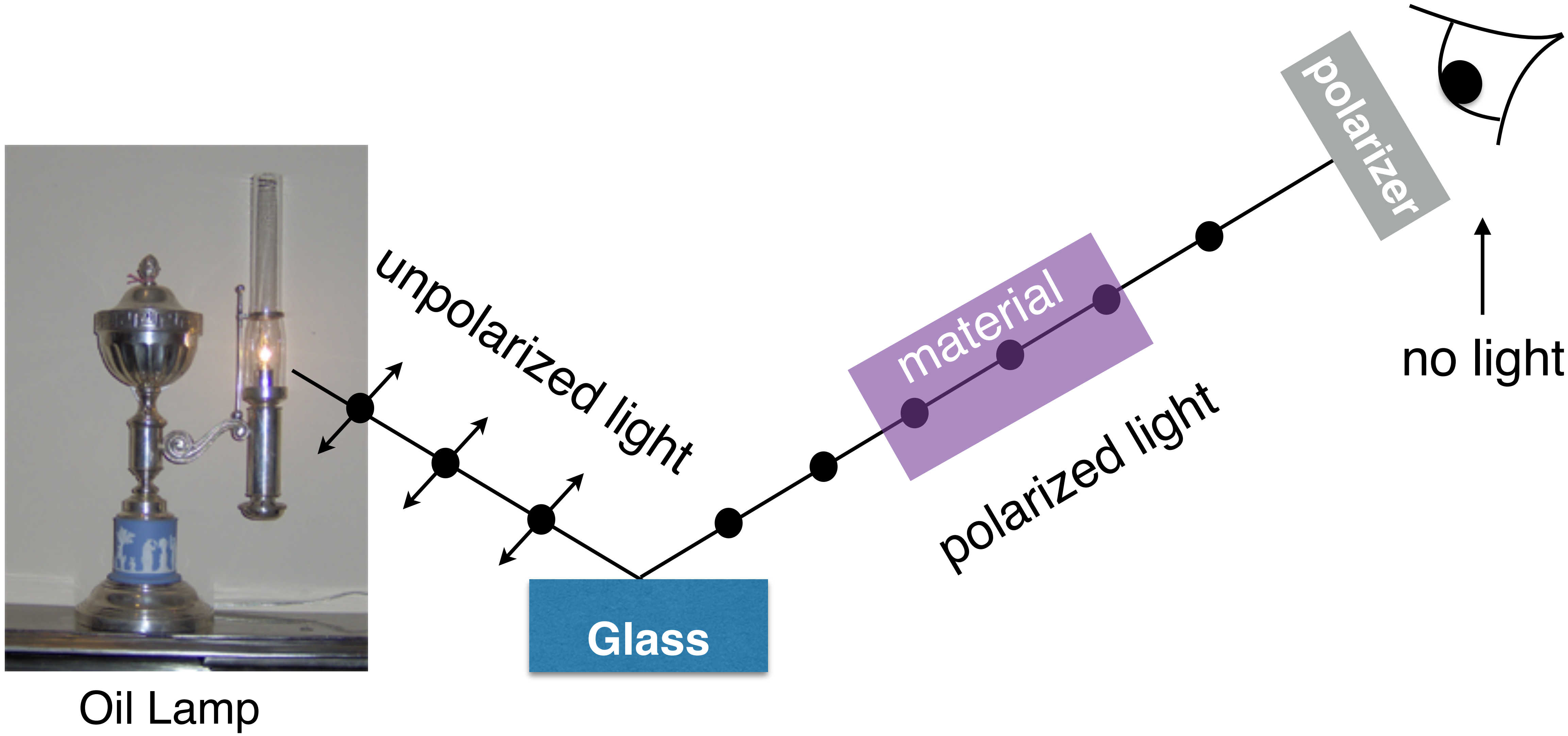


Afzelius, Gisin, de Riedmatten; Physics Today (2015)



Motivation:
magnon state as a quantum memory

Faraday Effect (1846)



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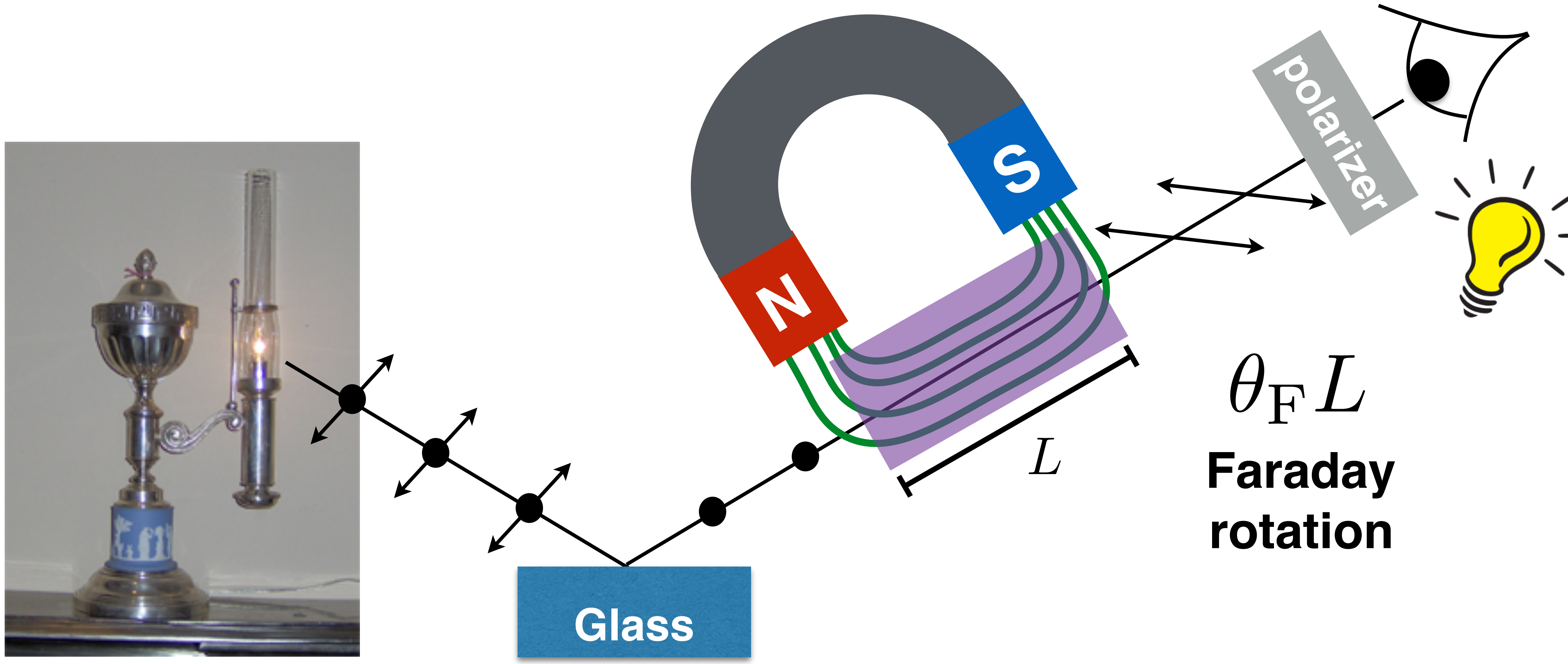
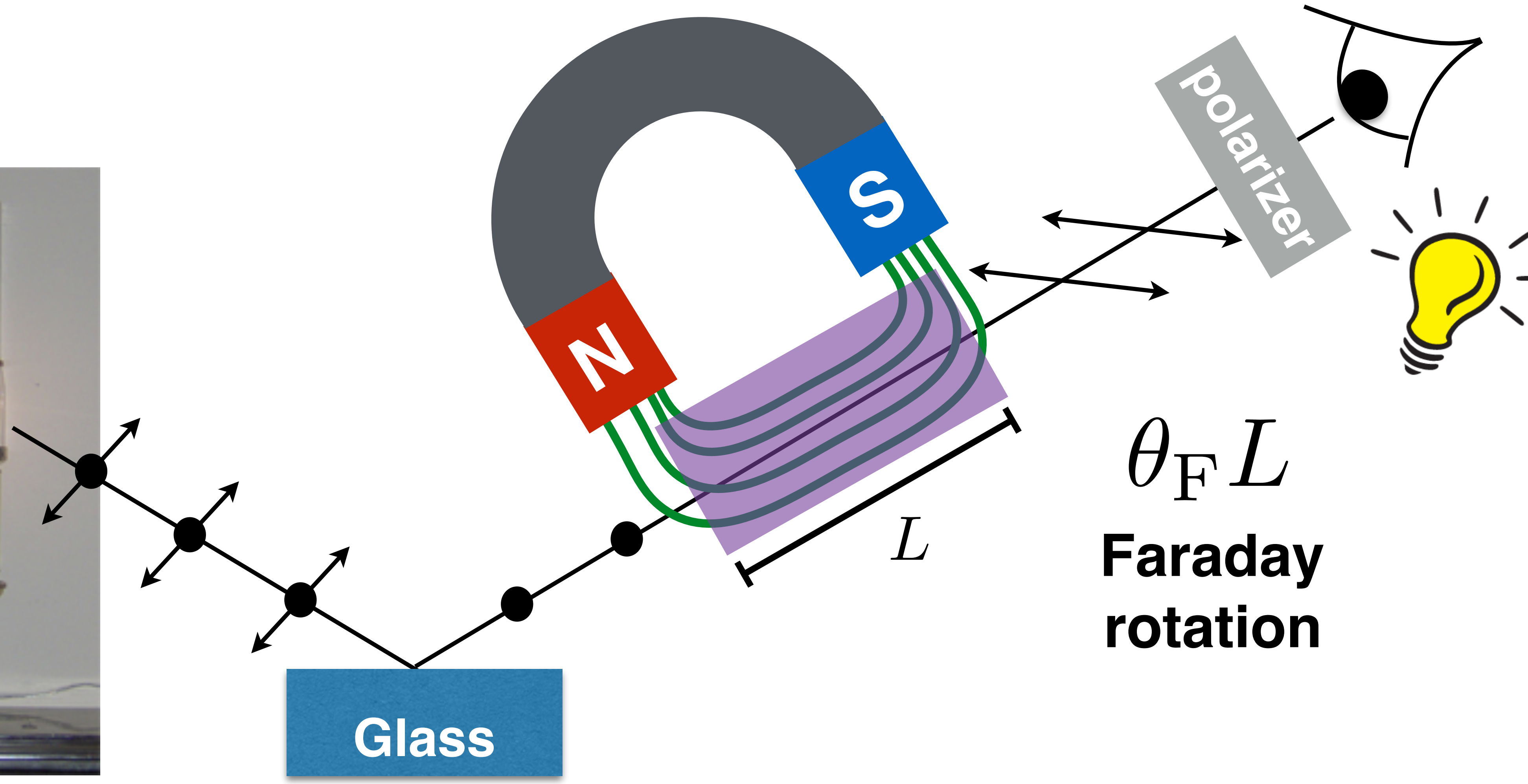


Oil Lamp

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

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magnetization density

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broken time-reversal symmetry

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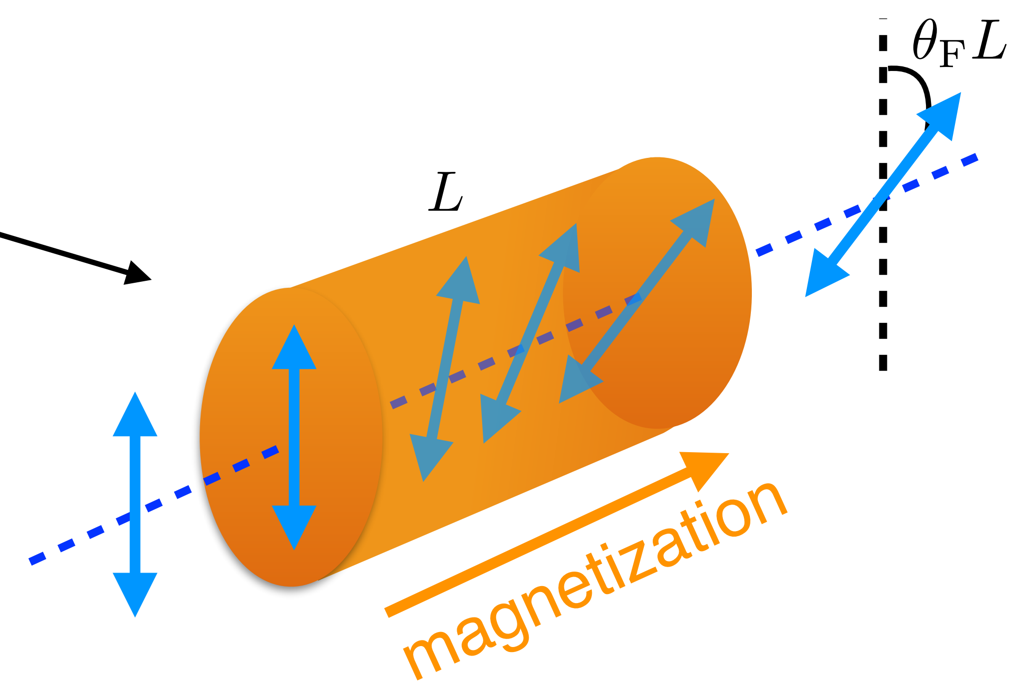


Optomagnonic Hamiltonian

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

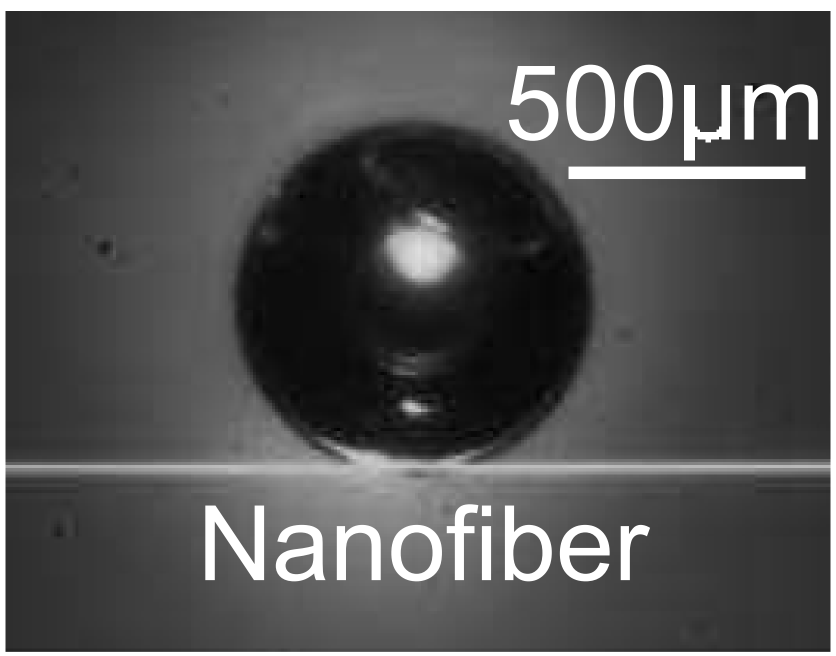
Quantize: $\hat{\mathbf{S}}$ $\hat{a}^\dagger$ $\hat{a}$

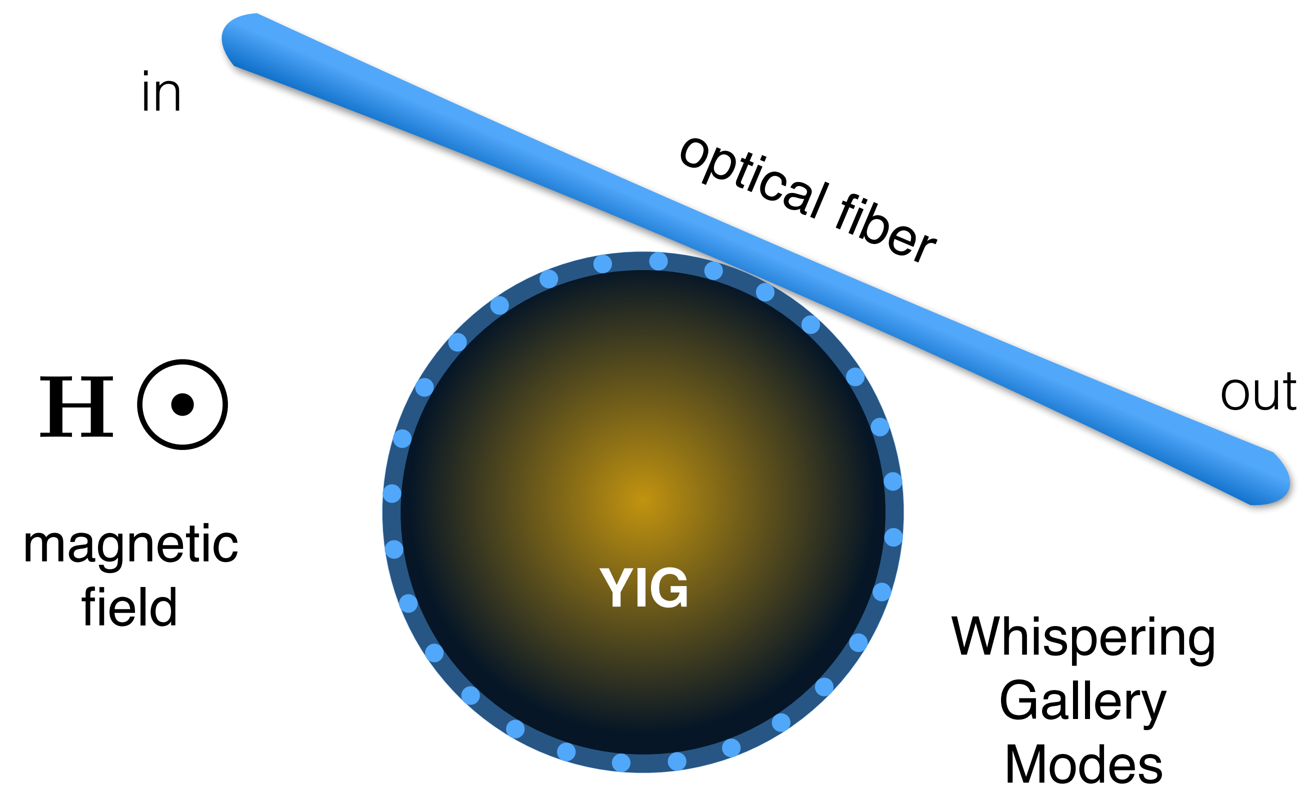
two-photon process

Cavity Optomagnonics

Magnons ⟷ **Optical photons**

Coherent coupling demonstrated in 2016

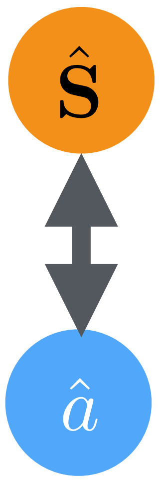




A cavity enhances the effect

- 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)

But…

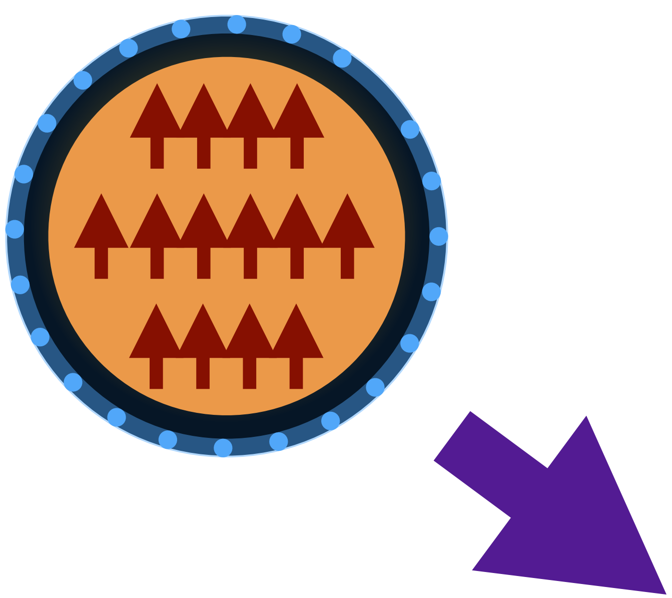


Problem

the state of the art optomagnonic coupling is very small

Some solutions

better overlap of modes



?

Optomagnonics beyond the Kittel mode

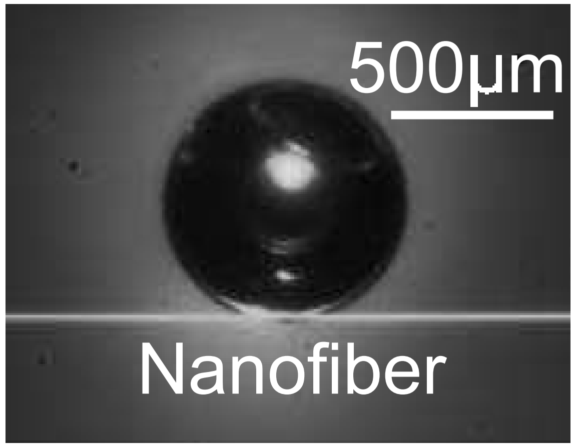
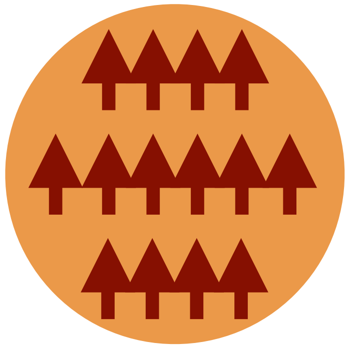
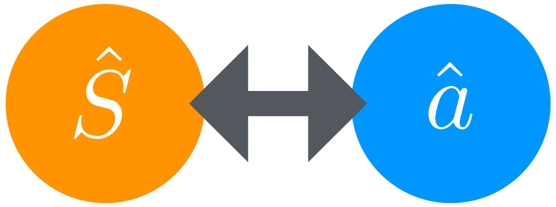


Fig: Osada et. al.
PRL 116, 223601

Optomagnonic coupling demonstrated

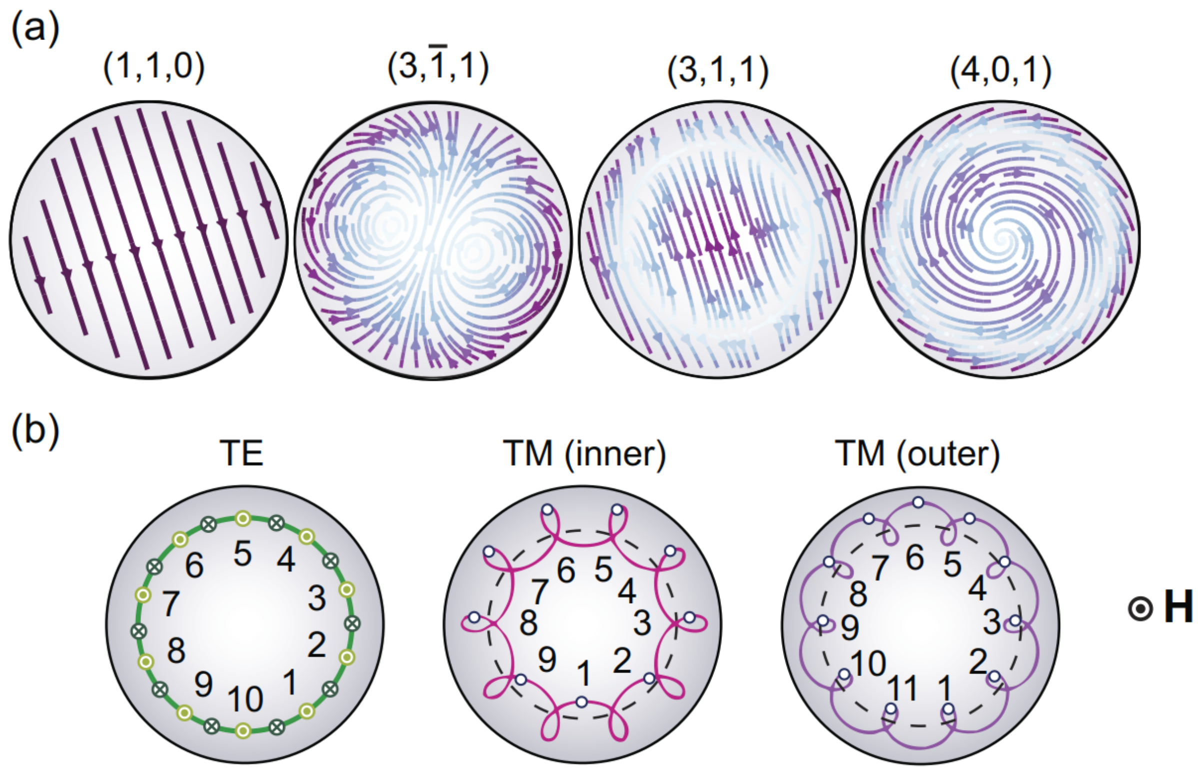
- Non-homogeneous magnon mode
- Homogeneous ground state





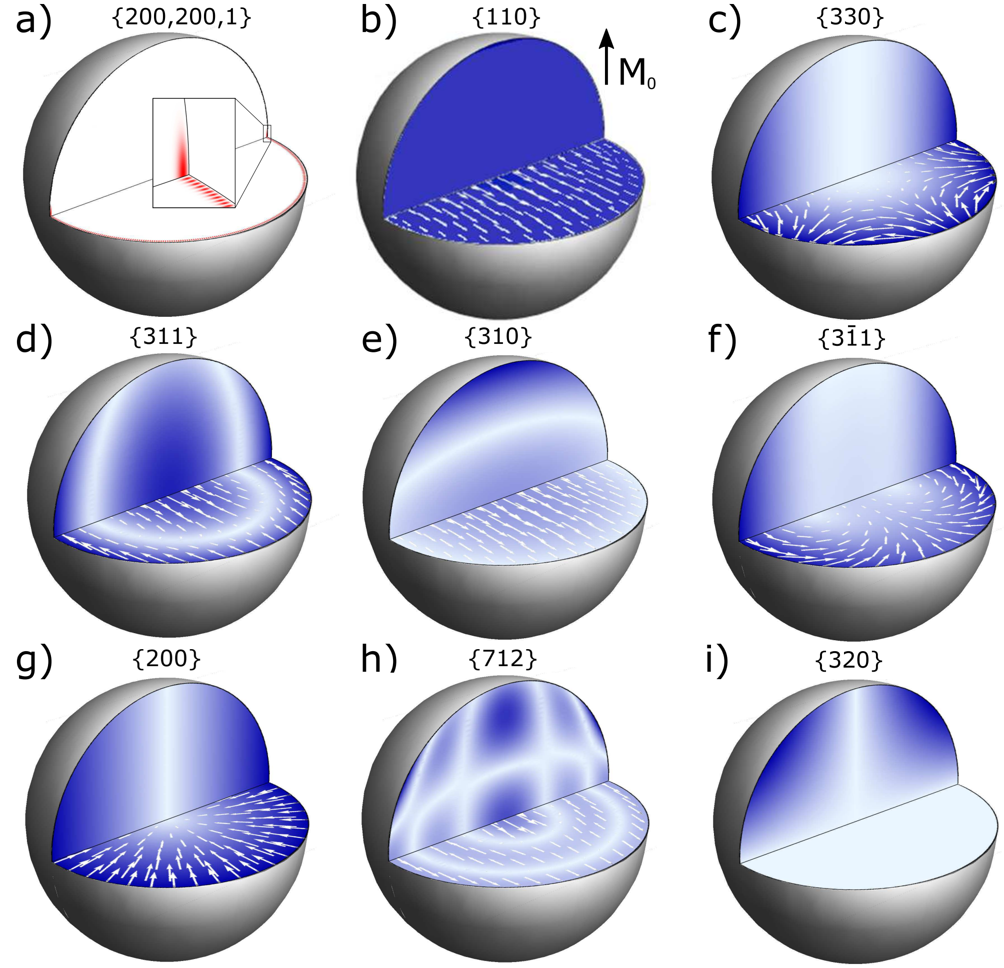
Magnon

Photon



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

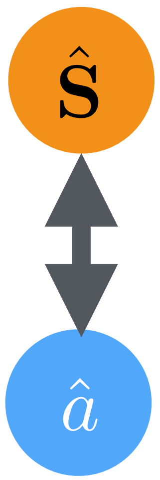
Photon



Magnon

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

But…



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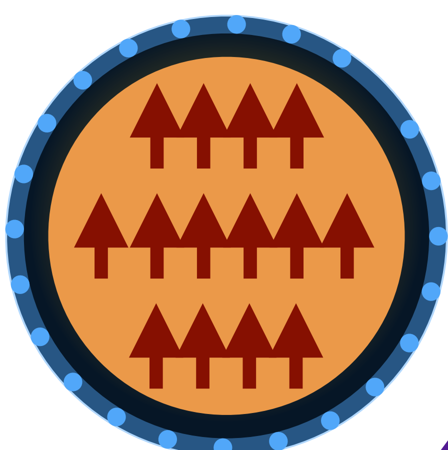


?

smaller systems

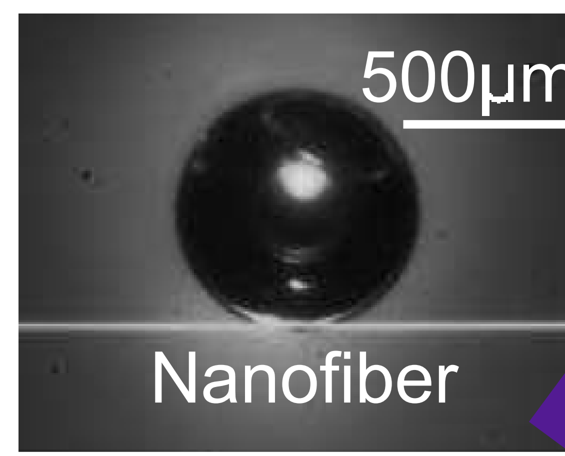
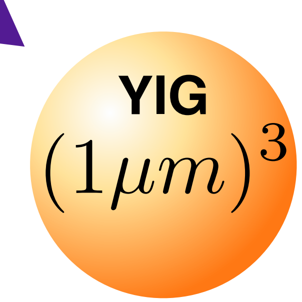
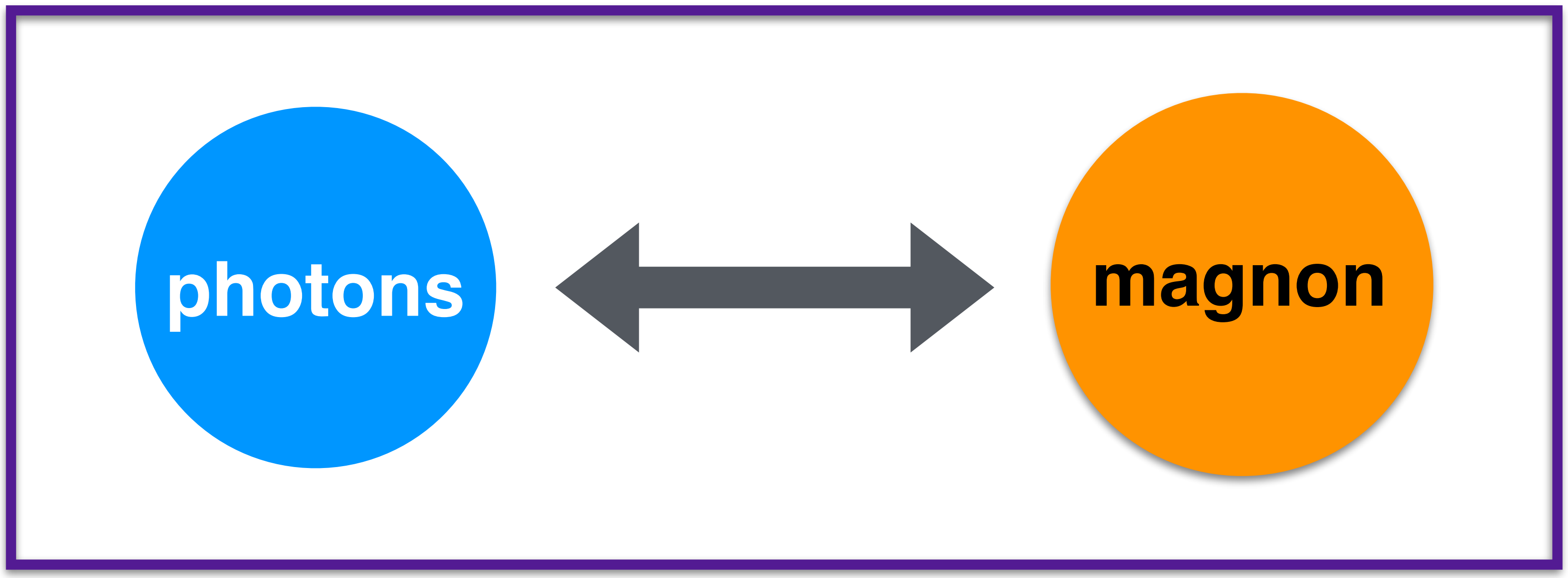
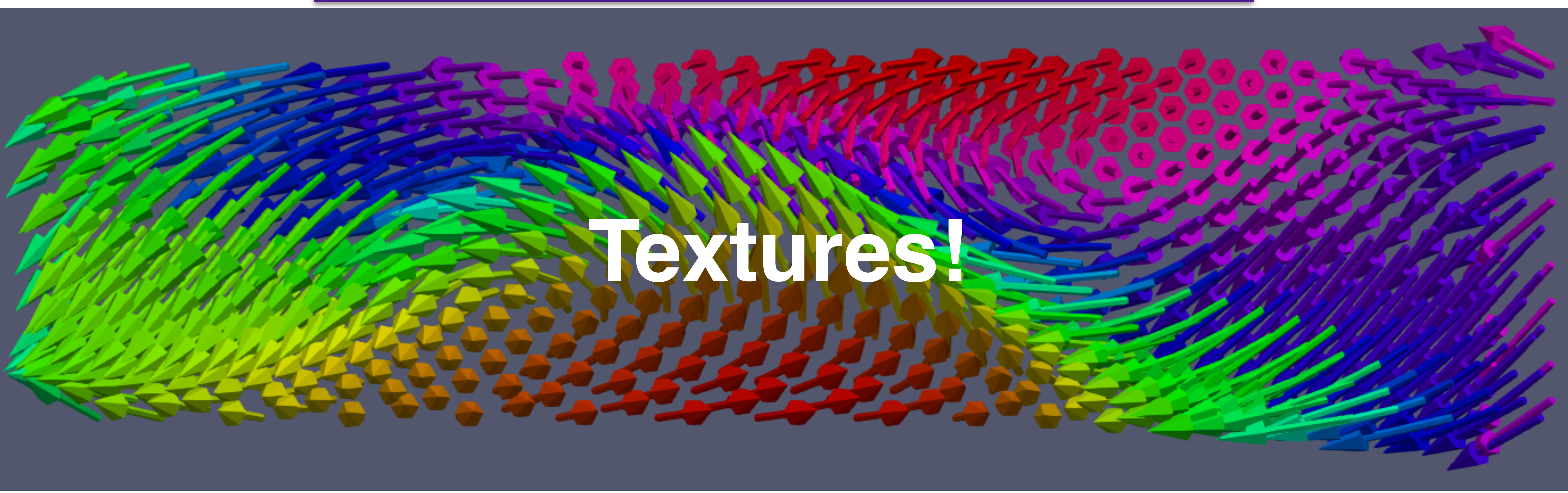


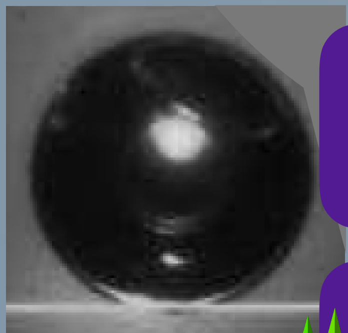
Fig: Osada et. al.
PRL 116, 223601



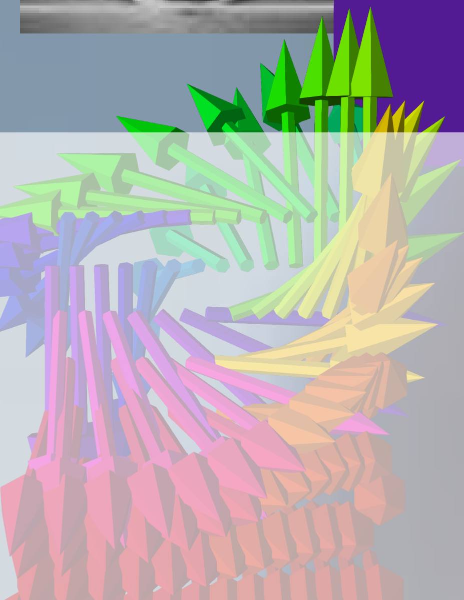
Cavity Optomagnonics







Introduction: cavity optomagnonics



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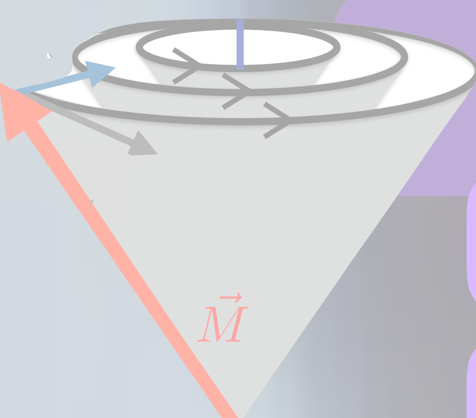

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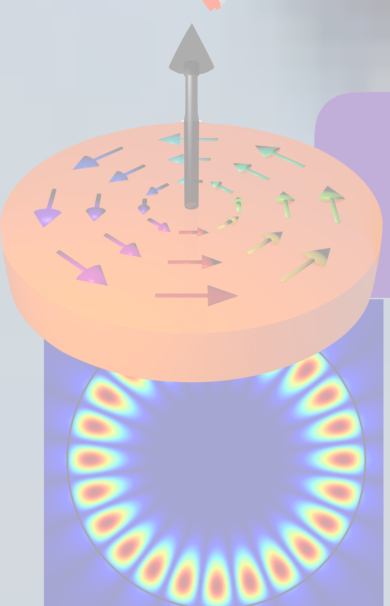

Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
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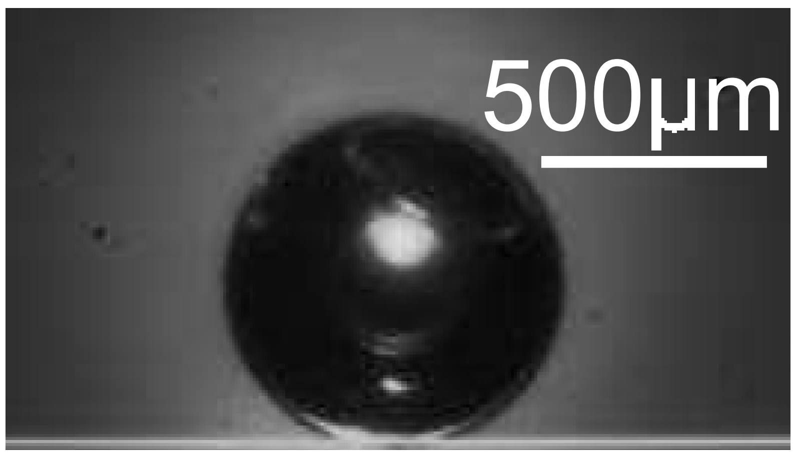
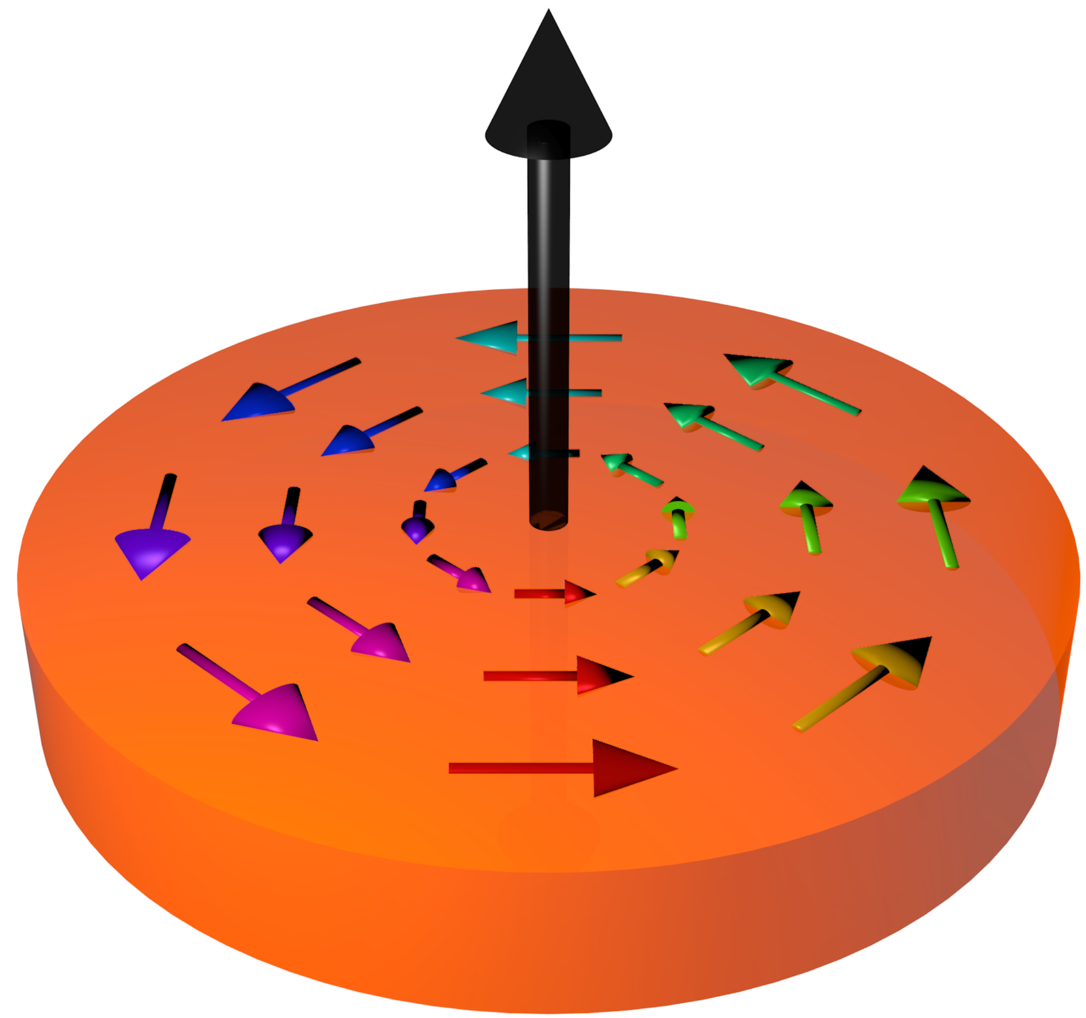
Magnetic Textures

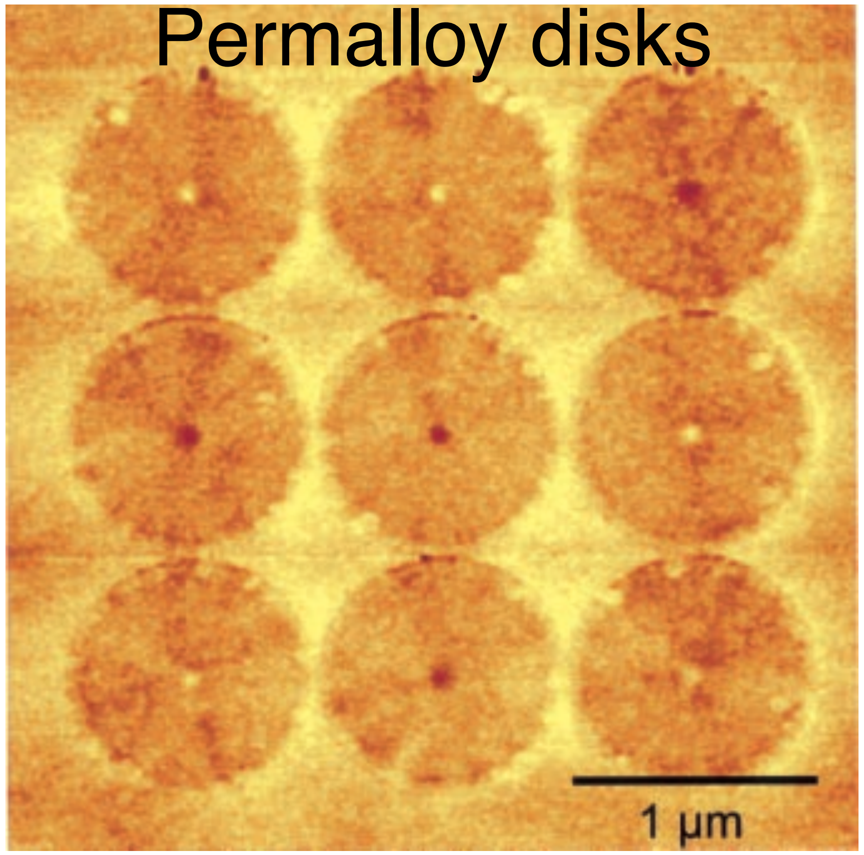
smaller systems → **Magnetic textures**





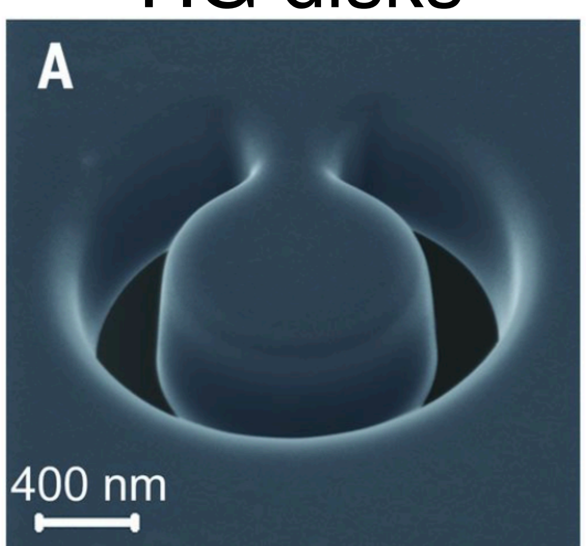
Example: Vortex in a micro disk

Magnetic Textures: Vortex in Microdisks

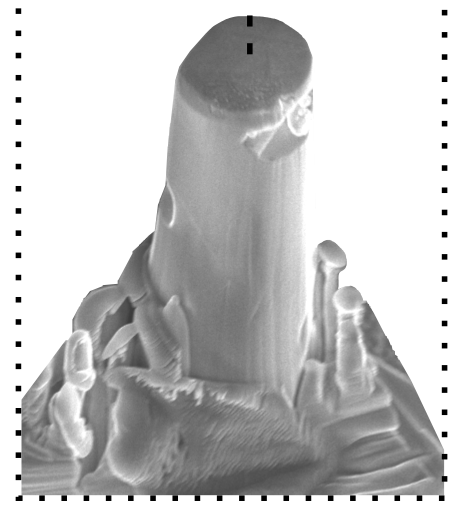


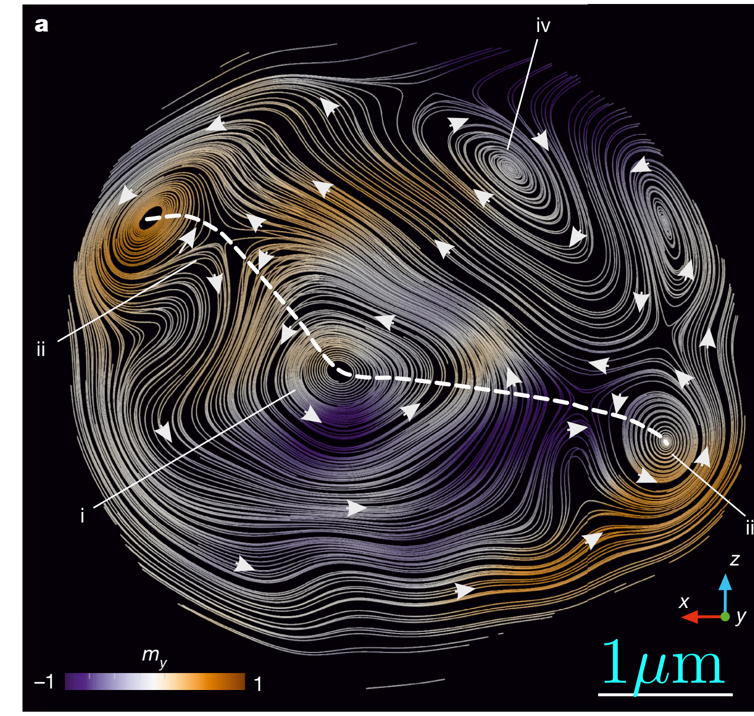
T.Shinjo et al, Science 289, 930 (2000)

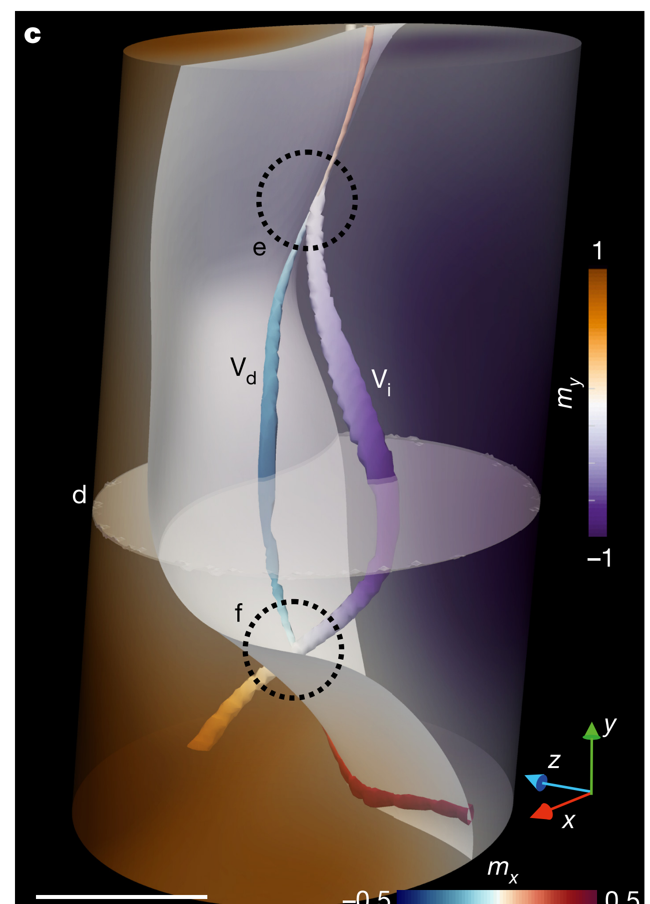
YIG disks



Losby et al, Science 350, 798 (2015)



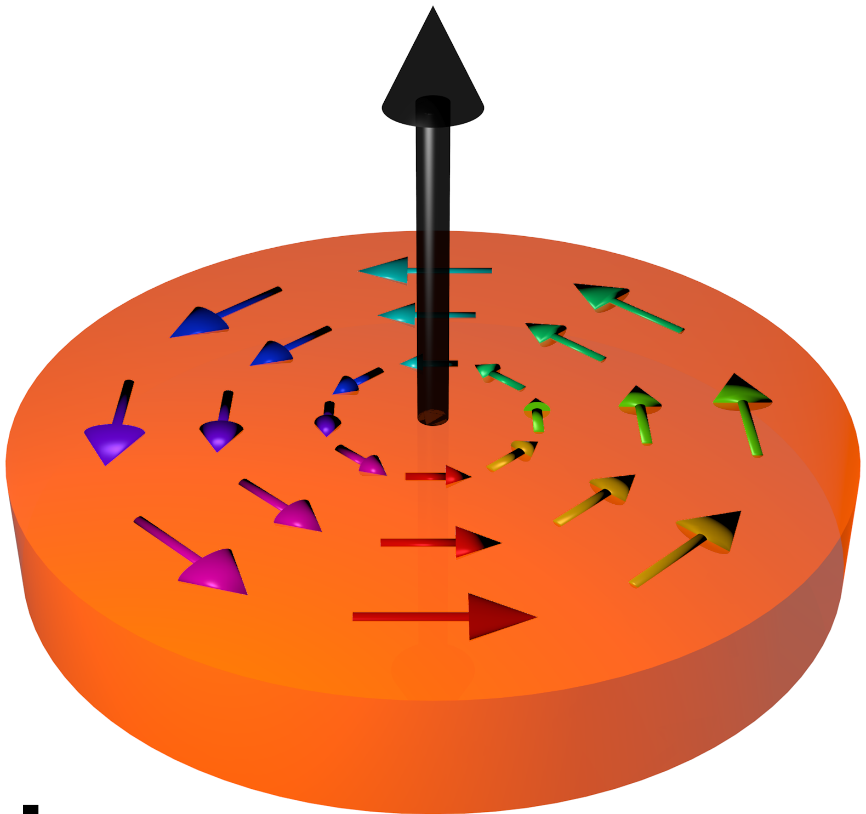




Cobalt Gadolinium pillars

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

Magnetic Vortex and Optical Cavity



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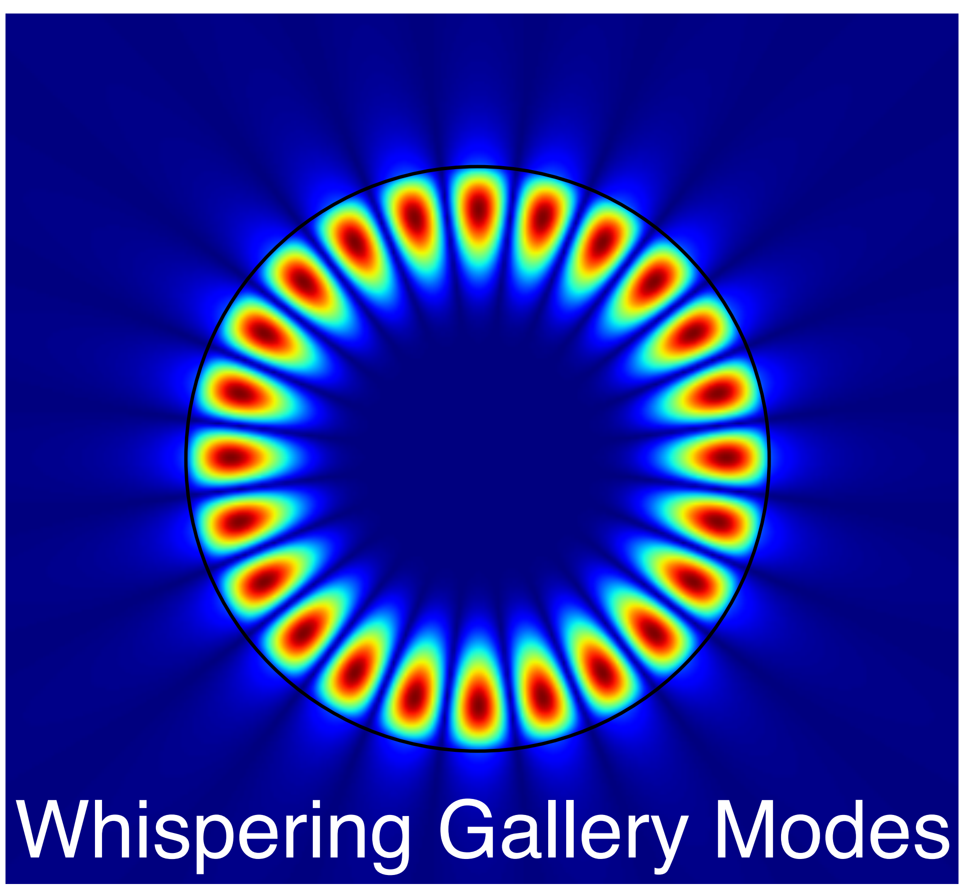
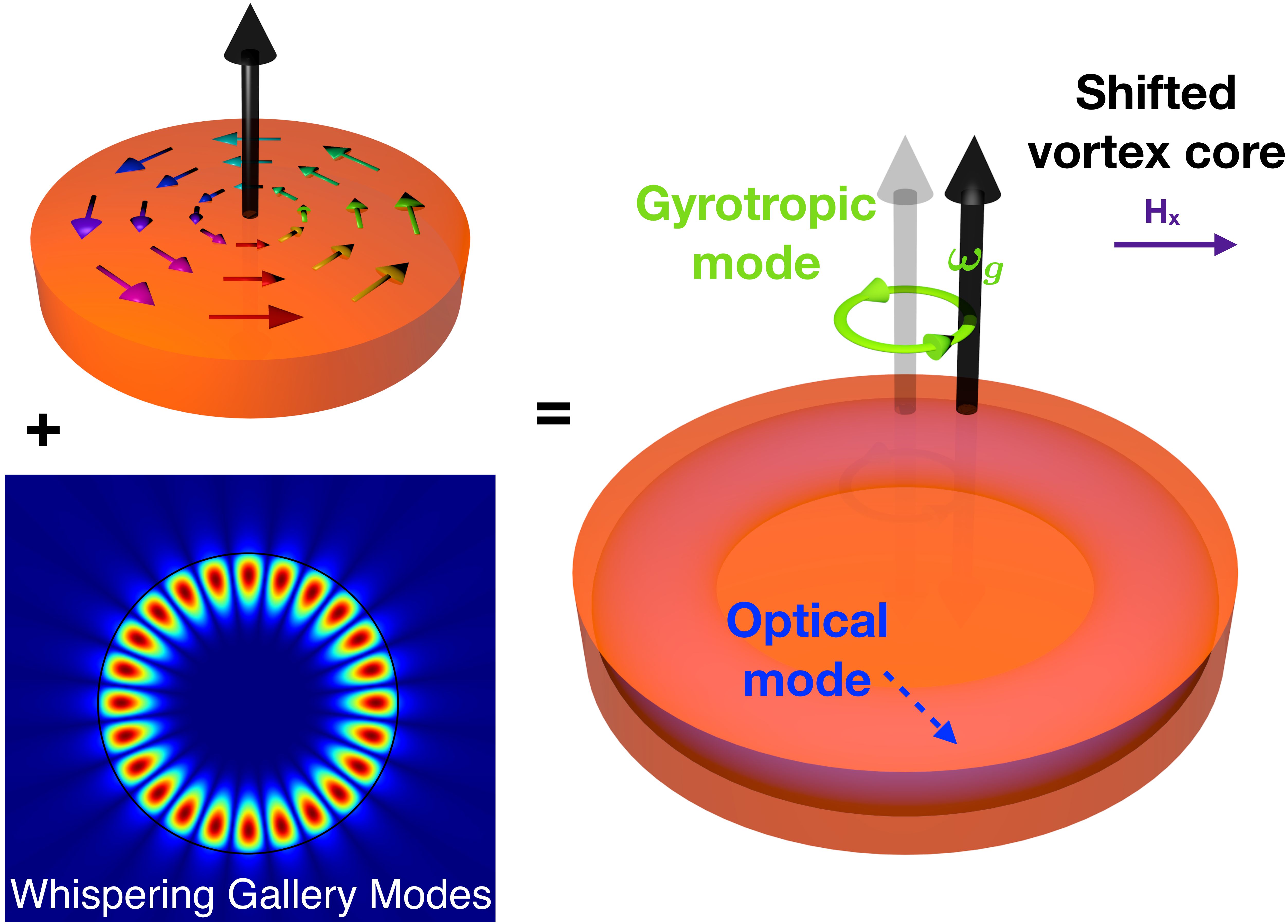
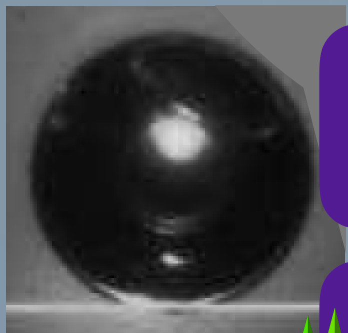
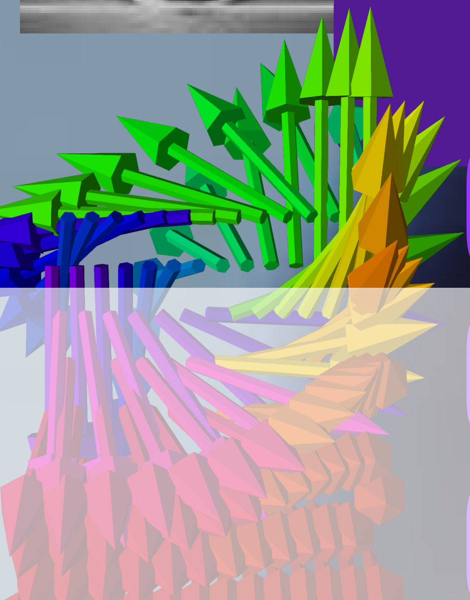


Magnetic Vortex and Optical Cavity



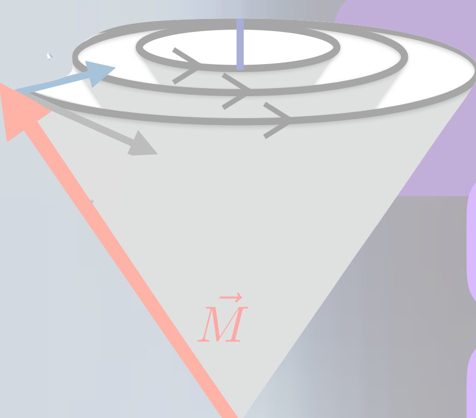


Introduction: cavity optomagnonics



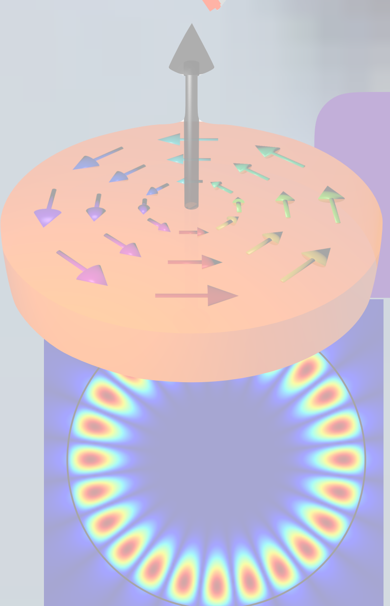
Magnetic textures

- **Why do they form?**
- Equilibrium condition
- Topology of smooth textures



Dynamics of the magnetization

- Landau Lifschitz Gilbert equation
- Thiele equation for topological defects



Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
- Optomagnonic coupling: gyrotropic mode

Magnetic Textures: why do they form?

Competition of interactions:

- Exchange energy:

  short range, strong

- Dipolar interactions:

  long range, weak

- Crystalline anisotropies

  short range, defines easy and hard axis

- …

  (e.g. Dzyaloshinskii-Moriya)

Magnetic Textures: why do they form?

exchange — external field — anisotropy — dipolar

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

Magnetic Textures: why do they form?

exchange — external field

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anisotropy — dipolar

saturation magnetization

$$|\mathbf{M}(\mathbf{r})| = M_\mathrm{s}$$

Magnetic Textures: why do they form?

exchange   external field

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

anisotropy   dipolar

obtained from
Heisenberg

$$-\frac{J}{2} \sum_{<i,j>} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j$$

Magnetic Textures: why do they form?

exchange — external field

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

anisotropy — dipolar

$$U_\mathrm{an}(\mathbf{M}) = -K_\mathrm{e} M_z^2 + K_\mathrm{h} M_x^2$$

Magnetic Textures: why do they form?

exchange

external field

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

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Magnetic Textures: why do they form?

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exchange — anisotropy — external field — dipolar

$\mathbf{H}_\mathrm{d}$ magnetostatic: demagnetizing (stray) fields

$$\nabla \times \mathbf{H}_\mathrm{d} = 0$$

$$-\nabla \cdot \mathbf{H}_\mathrm{d} = \nabla \cdot \mathbf{M}$$

⇒

$$\mathbf{H}_\mathrm{d} = -\nabla \phi \qquad \nabla^2 \phi = \nabla \cdot \mathbf{M}$$

Magnetic Textures: why do they form?

exchange — external field

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

anisotropy — dipolar

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Poisson equation, nonlocal

$$\phi = -\frac{1}{4\pi} \int_V \mathrm{d}^3 r' \frac{\nabla \cdot \mathbf{M}}{|\mathbf{r} - \mathbf{r}'|} + \frac{1}{4\pi} \int_{\partial V} \mathrm{d}^2 r' \frac{\hat{\mathbf{n}}' \cdot \mathbf{M}}{|\mathbf{r} - \mathbf{r}'|}$$

Magnetic Textures: why do they form?

exchange — external field

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M}\cdot\mathbf{H}_\mathrm{a} - \frac{\mu_0}{2}\mathbf{M}\cdot\mathbf{H}_\mathrm{d} \right]$$

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The magnetic energy is a non trivial functional of the magnetization

Magnetic Textures: why do they form?

exchange

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

dipolar

penalizes non uniformity

penalizes stray fields

Magnetic Textures: why do they form?

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$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

dipolar

penalizes non uniformity

penalizes stray fields

Equilibrium: Flux-closure configurations

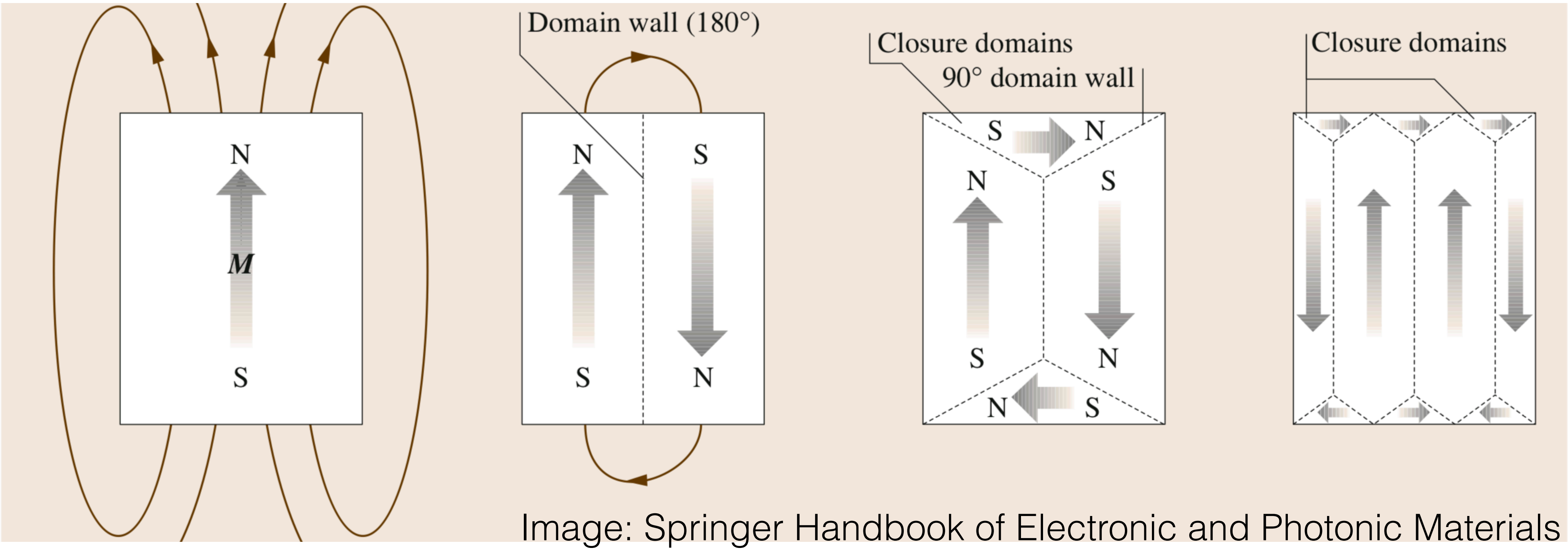
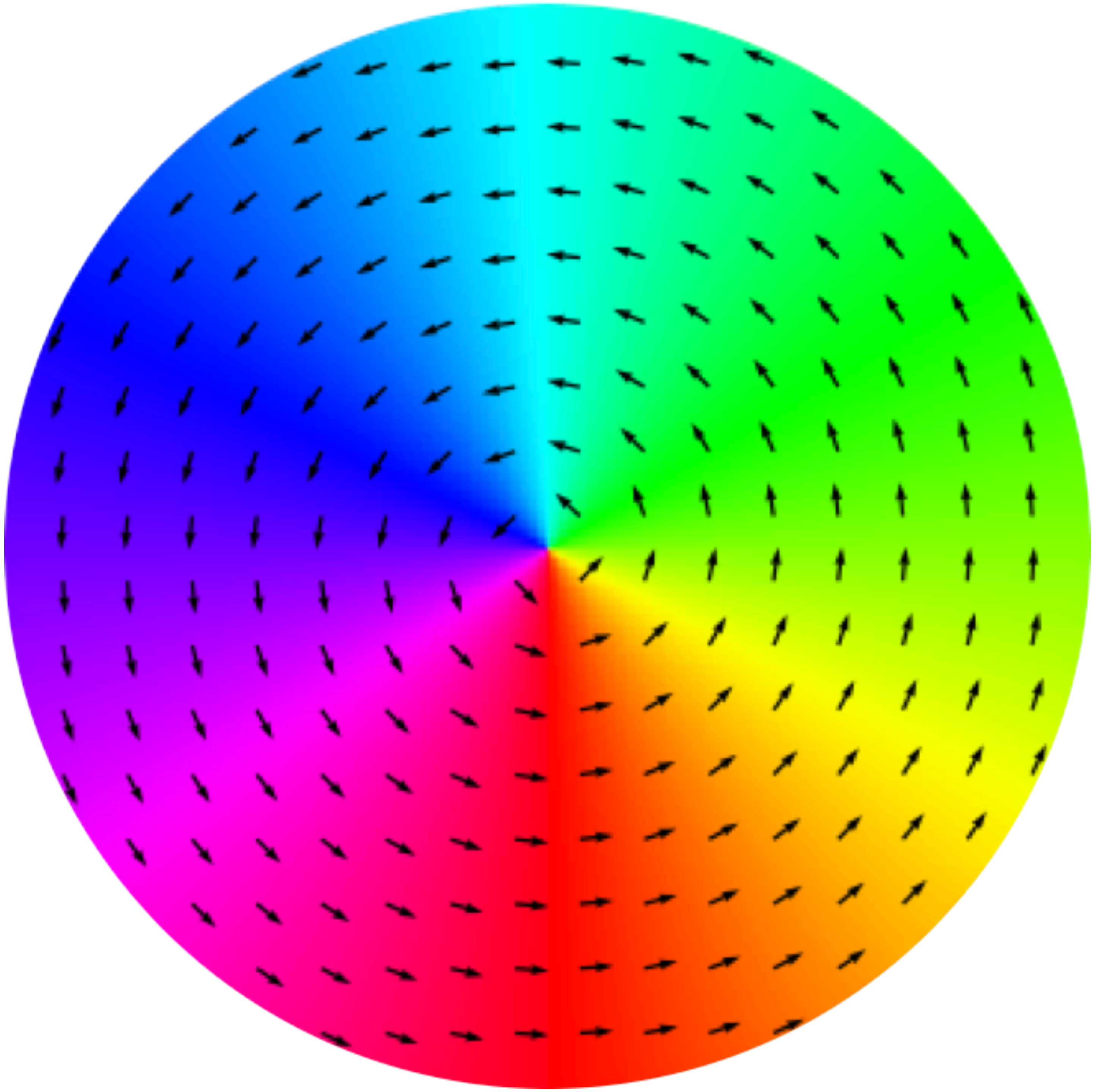


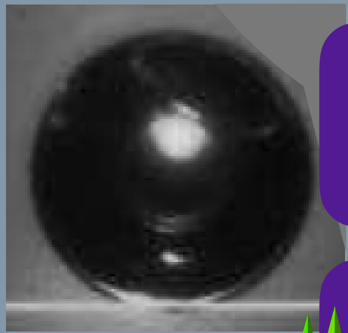
Image: Springer Handbook of Electronic and Photonic Materials

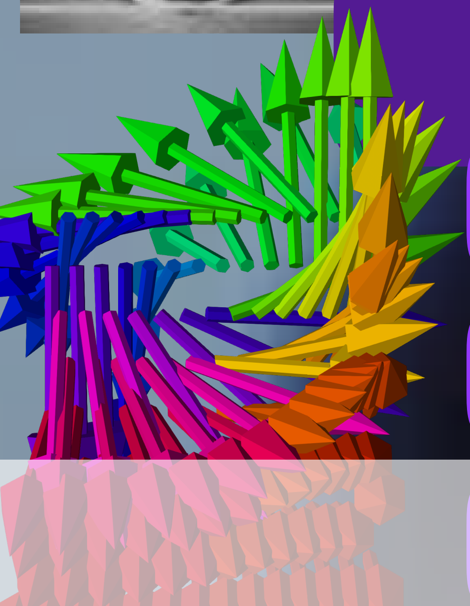
Magnetic Textures: why do they form?

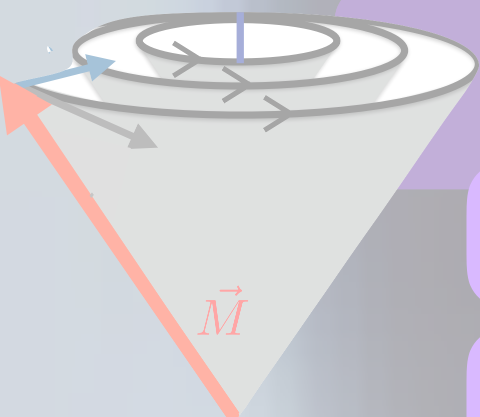
Vortex!

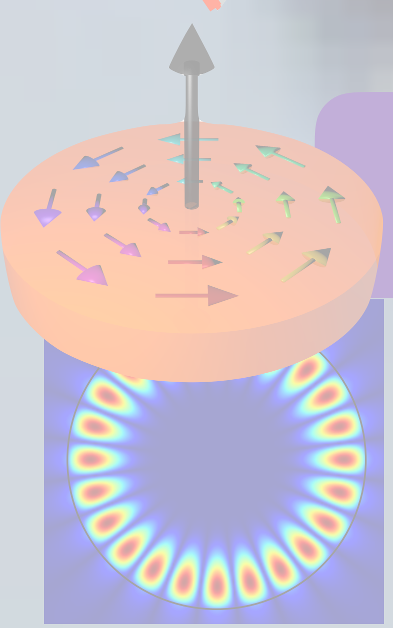


Microscale: Exchange energy ~ dipolar energy









- Introduction: cavity optomagnonics
- Magnetic textures
  - Why do they form?
  - Equilibrium condition
  - Topology of smooth textures
- Dynamics of the magnetization
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Magnetic Textures: Equilibrium

The magnetic energy is a non trivial functional of the magnetization

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M}\cdot\mathbf{H}_\mathrm{a} - \frac{\mu_0}{2}\mathbf{M}\cdot\mathbf{H}_\mathrm{d} \right]$$

Equilibrium condition: minimize the energy functional

$$\delta E = -\mu_0 \int_V \mathrm{d}^3 r \mathbf{H}_\mathrm{eff} \cdot \delta\mathbf{M} - \frac{2A}{\mu_0 M_\mathrm{s}^2} \oint_{\partial V} \mathrm{d}^2 r \frac{\partial \mathbf{M}}{\partial \mathbf{n}} \cdot \delta\mathbf{M} = 0$$

Magnetic Textures: Equilibrium

The magnetic energy is a non trivial functional of the magnetization

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

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Effective magnetic field

$$\mathbf{H}_\mathrm{eff} = \mathbf{H}_\mathrm{a} + \mathbf{H}_\mathrm{d} + \mathbf{H}_\mathrm{an} + \mathbf{H}_\mathrm{ex}$$

$$\mathbf{H}_\mathrm{an} = -\frac{1}{\mu_0} \frac{\partial U_\mathrm{an}}{\partial \mathbf{M}} \qquad \mathbf{H}_\mathrm{ex} = \frac{2A}{\mu_0 M_\mathrm{s}^2} \nabla^2 \mathbf{M}$$

Magnetic Textures: Equilibrium

The magnetic energy is a non trivial functional of the magnetization

$$E = \int_V \mathrm{d}^3 r \left[\frac{A}{M_\mathrm{s}} \sum_{i=x,y,z} |\nabla M_i|^2 + U_\mathrm{an}(\mathbf{M}) - \mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{a} - \frac{\mu_0}{2} \mathbf{M} \cdot \mathbf{H}_\mathrm{d} \right]$$

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Effective magnetic field

$$\mathbf{H}_\mathrm{eff} = \mathbf{H}_\mathrm{a} + \mathbf{H}_\mathrm{d} + \mathbf{H}_\mathrm{an} + \mathbf{H}_\mathrm{ex}$$

imposing the constraint:

$$|\mathbf{M}(\mathbf{r})| = M_\mathrm{s}$$

$$\delta \mathbf{M} = \mathbf{M} \times \delta \mathbf{v}$$

arbitrary vector

Magnetic Textures: Equilibrium

$$\delta E = -\mu_0 \int_V \mathrm{d}^3 r \mathbf{H}_{\mathrm{eff}} \cdot \delta \mathbf{M} - \frac{2A}{\mu_0 M_\mathrm{s}^2} \oint_{\partial V} \mathrm{d}^2 r \frac{\partial \mathbf{M}}{\partial \mathbf{n}} \cdot \delta \mathbf{M} = 0$$

imposing the constraint: $|\mathbf{M}(\mathbf{r})| = M_\mathrm{s}$

$$\Rightarrow \quad \delta E = \mu_0 \int_V \mathrm{d}^3 r \mathbf{M} \times \mathbf{H}_{\mathrm{eff}} \cdot \delta \mathbf{v} + \frac{2A}{\mu_0 M_\mathrm{s}^2} \oint_{\partial V} \mathrm{d}^2 r \left(\frac{\partial \mathbf{M}}{\partial \mathbf{n}} \times \mathbf{M} \right) \cdot \delta \mathbf{v}$$

Magnetic Textures: Equilibrium

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equilibrium condition

$$\mathbf{M} \times \mathbf{H}_{\mathrm{eff}}(\mathbf{M}) = 0$$

$$\left. \frac{\partial \mathbf{M}}{\partial \mathbf{n}} \right|_{\delta V} = 0$$

$$\mathbf{H}_{\mathrm{eff}} = \mathbf{H}_{\mathrm{a}} + \mathbf{H}_{\mathrm{d}} + \mathbf{H}_{\mathrm{an}} + \mathbf{H}_{\mathrm{ex}}$$

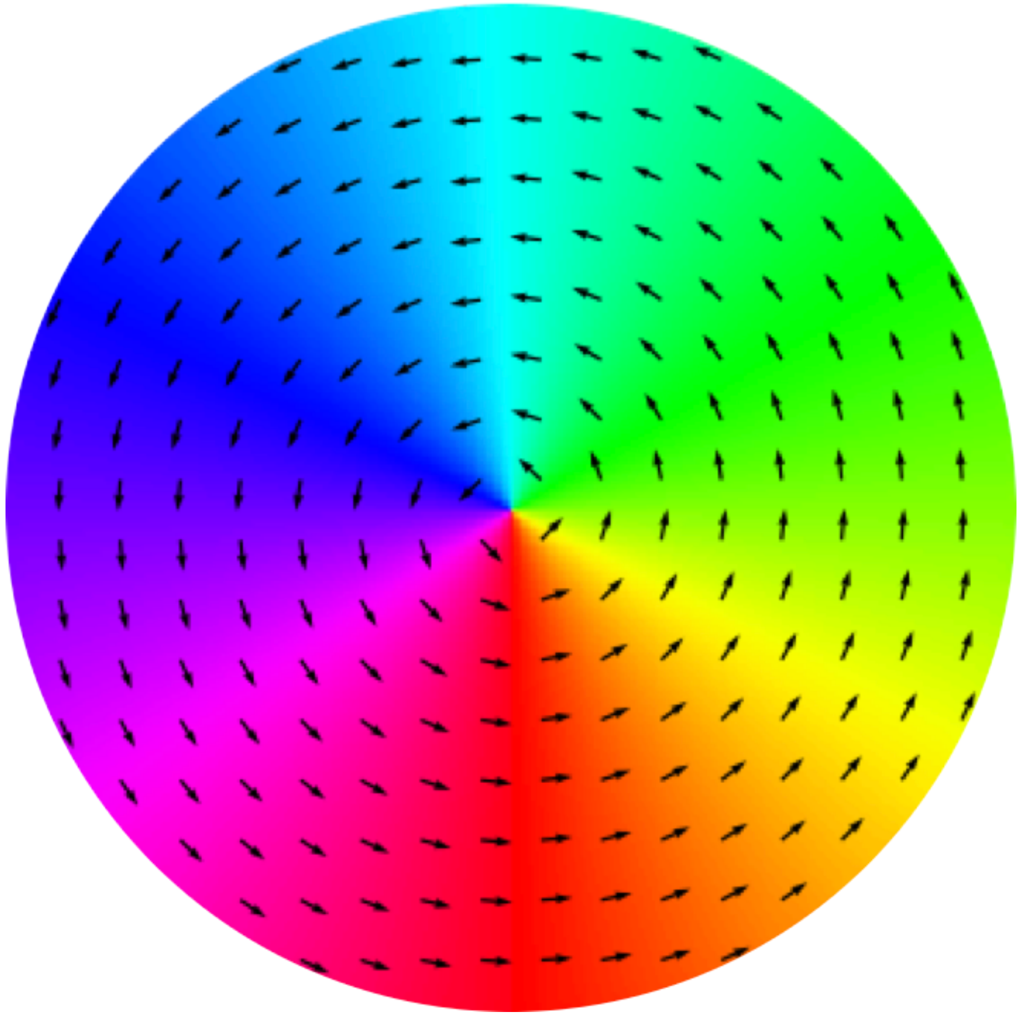
Very difficult to solve in general

→ micromagnetic simulations

computationally costly

Example: Vortex in thin microdisk

Height of disk $h < L_{\mathrm{ex}} = \dfrac{1}{M_{\mathrm{s}}}\sqrt{\dfrac{2A}{\mu_0}}$ **2D description**

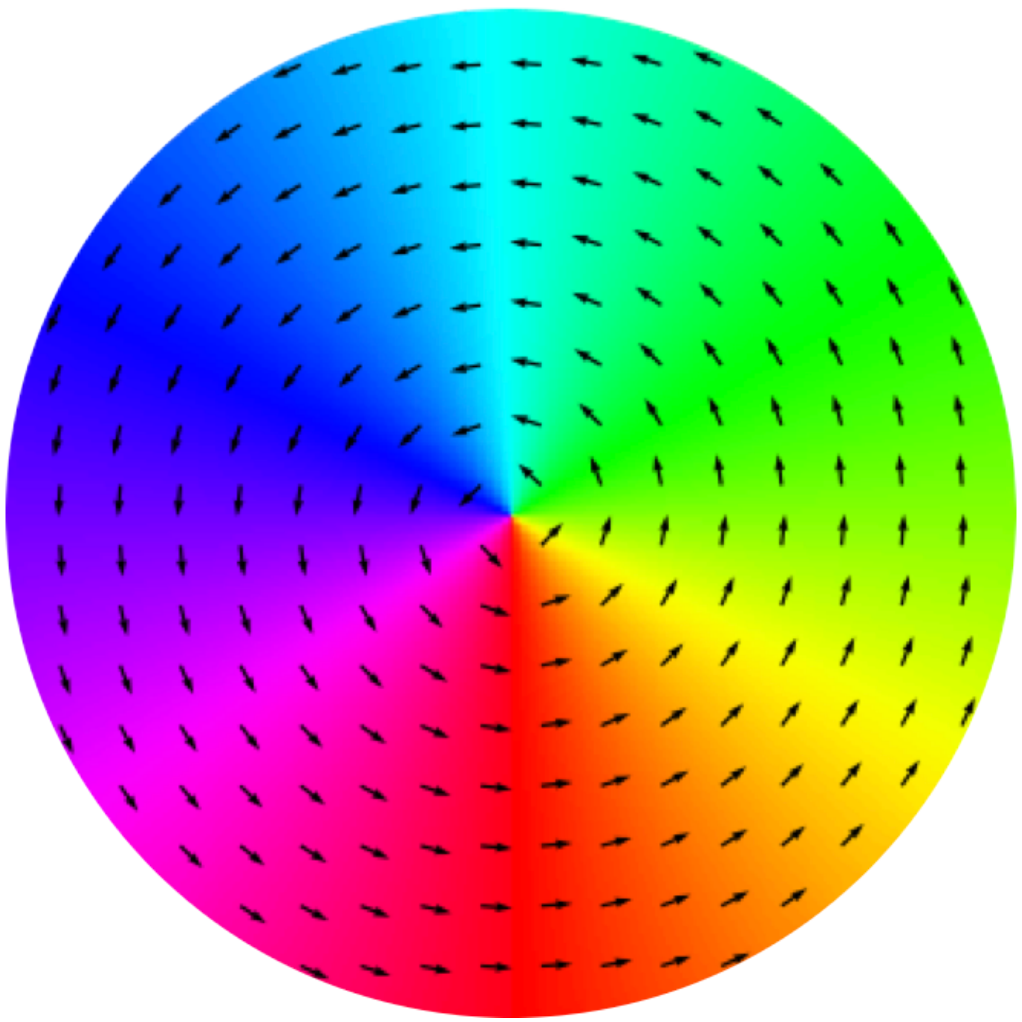


$\mathbf{H}_{\mathrm{a}} = 0$

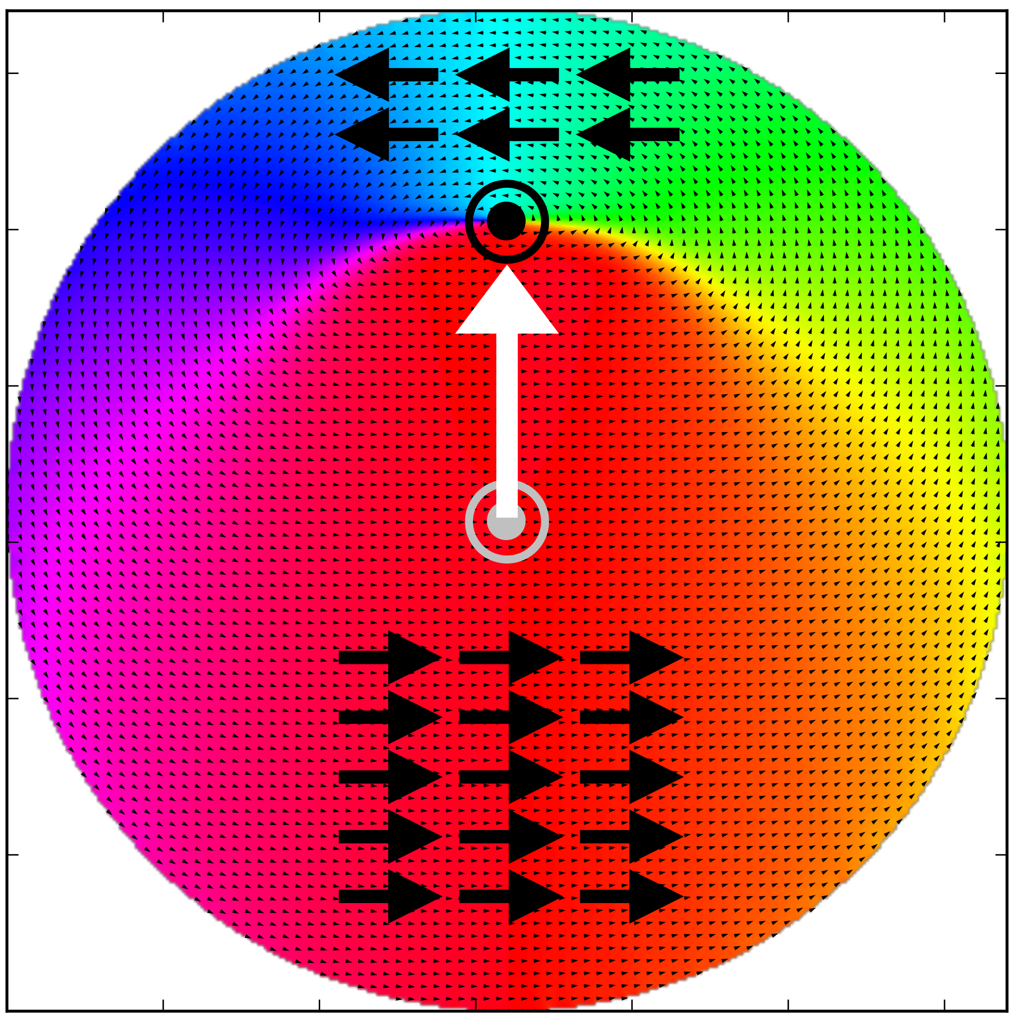
Example: Vortex in thin microdisk

Height of disk $h < L_{\mathrm{ex}} = \frac{1}{M_{\mathrm{s}}}\sqrt{\frac{2A}{\mu_0}}$ **2D description**

Position tunable by a magnetic field



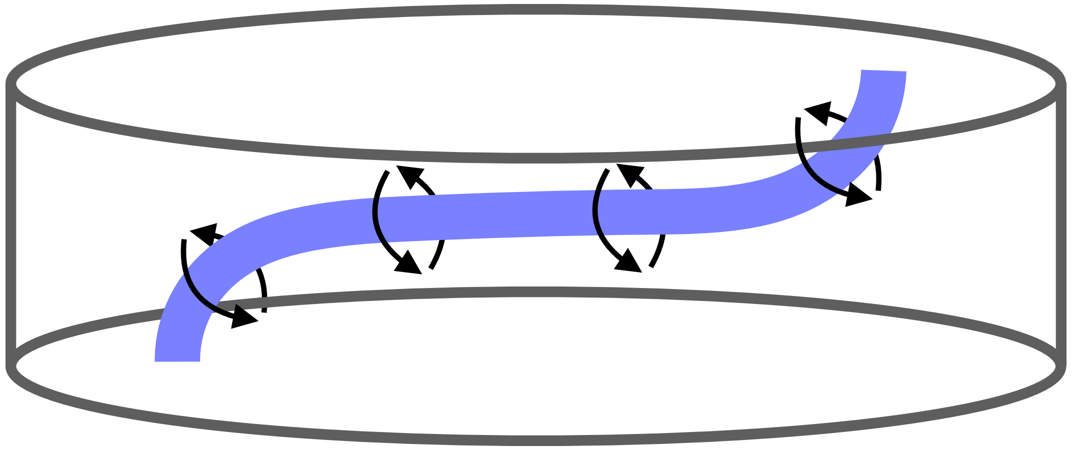
$\mathbf{H}_{\mathrm{a}} = 0$

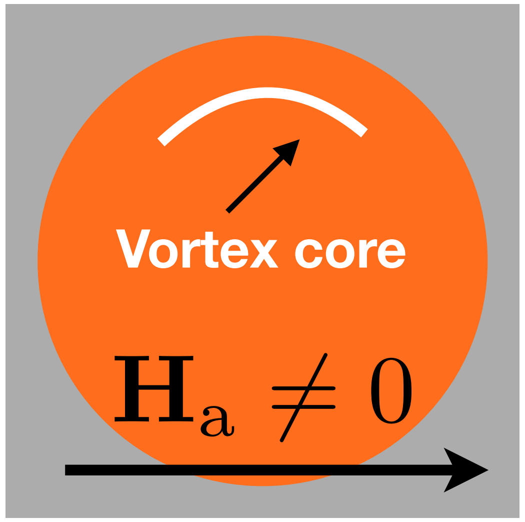


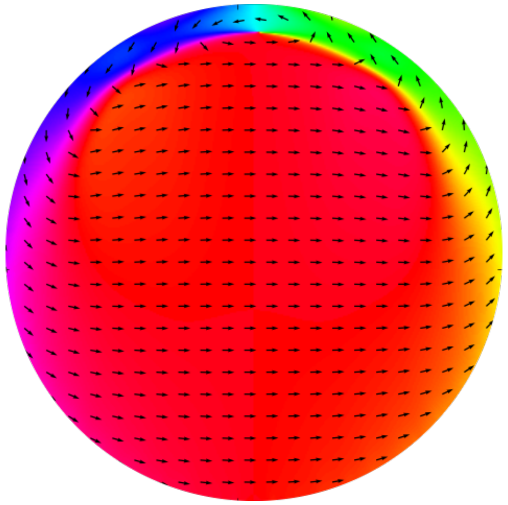
$\mathbf{H}_{\mathrm{a}} \neq 0$

Vortex in a thick microdisk

Vortex

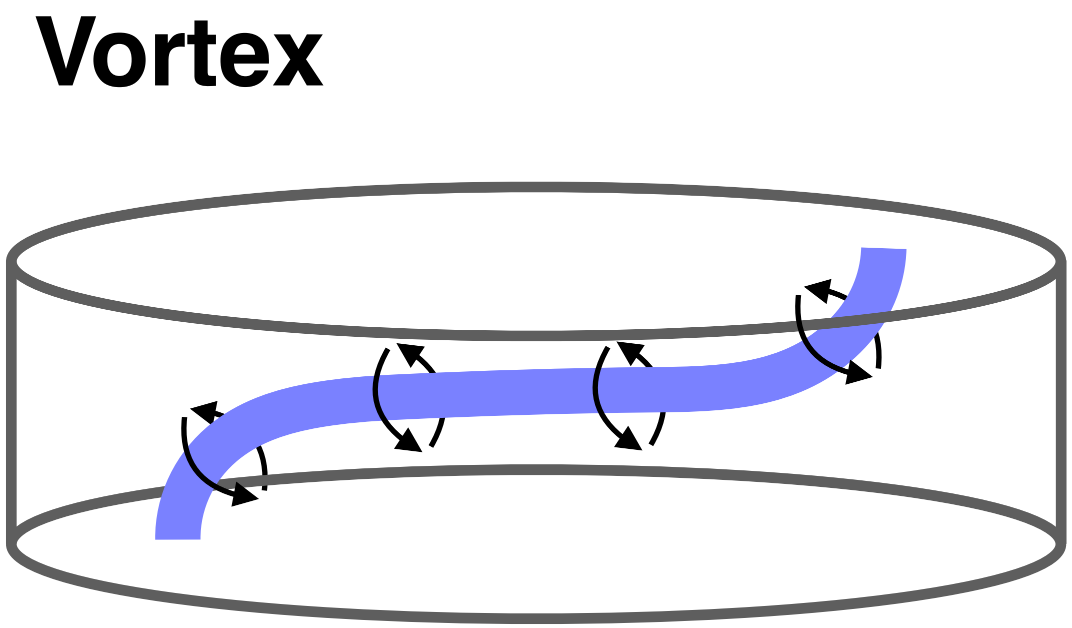


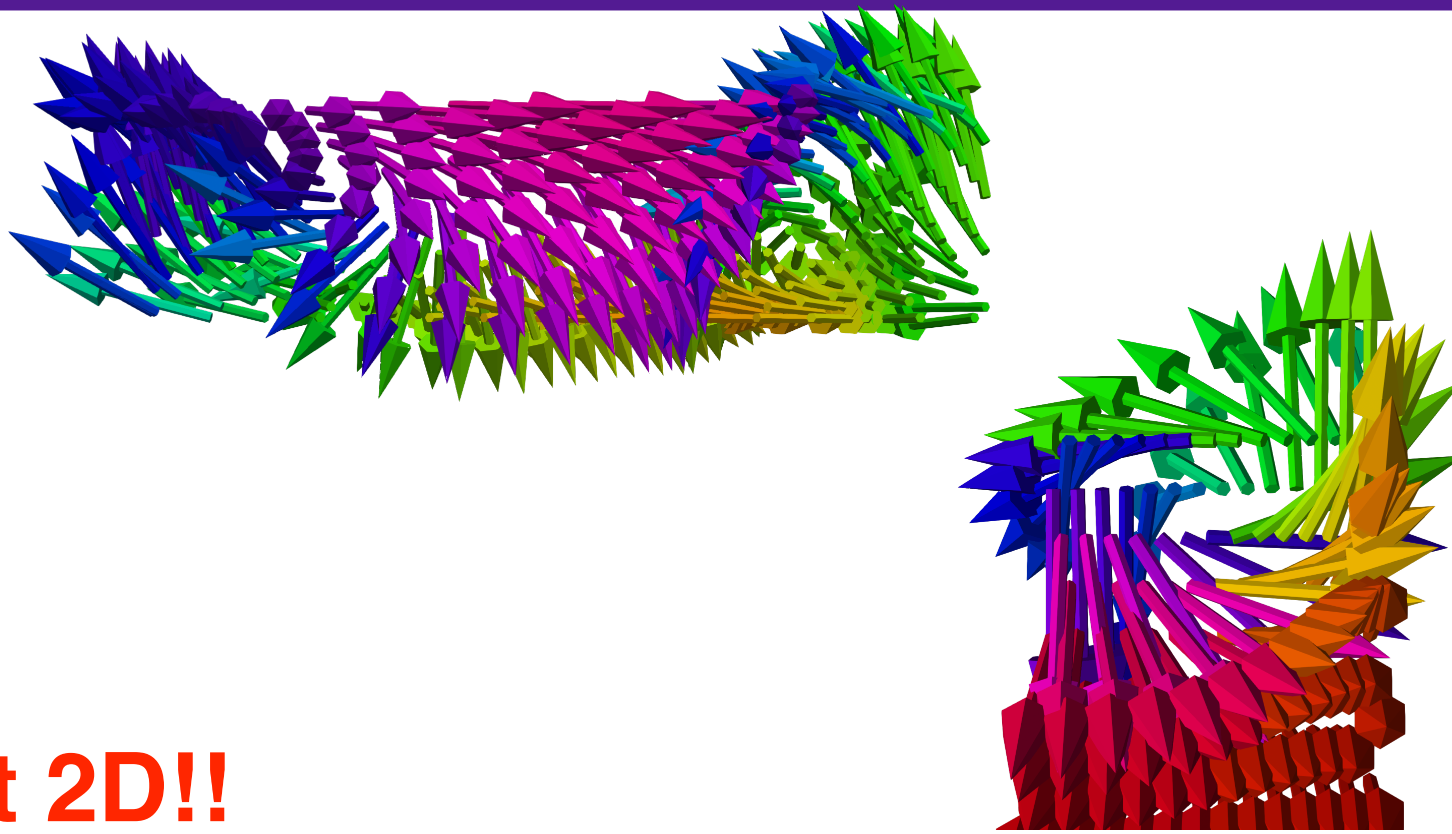




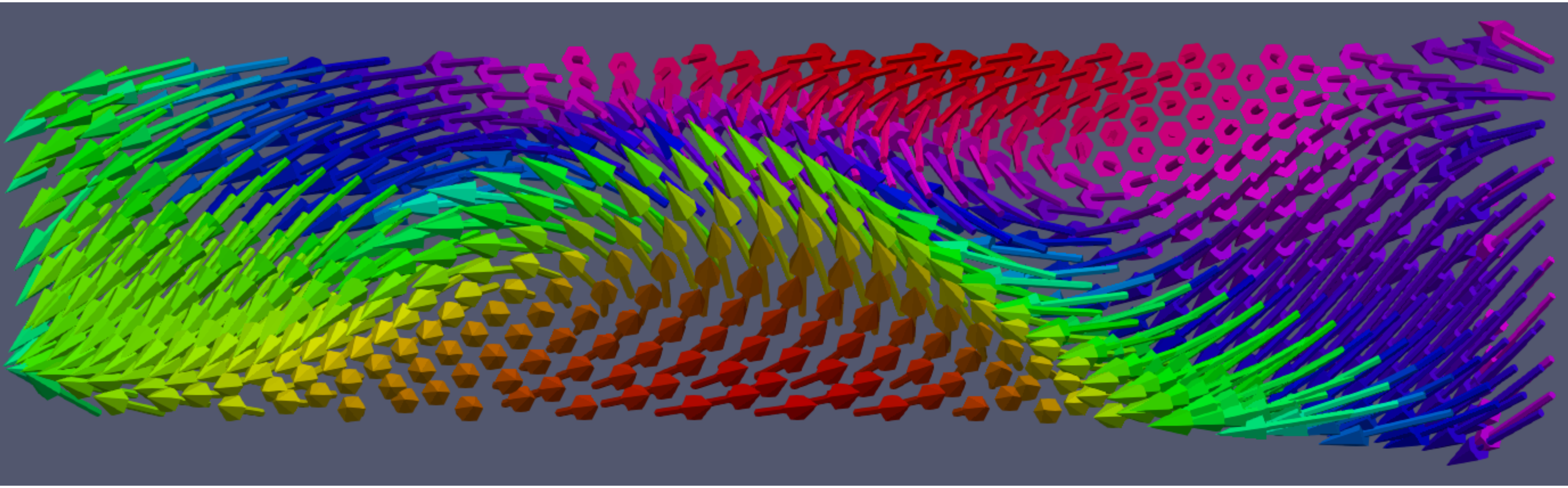
J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, Phys. Rev. B 98, 241406(R), (2018)

Vortex in a thick microdisk





Definitely not 2D!!



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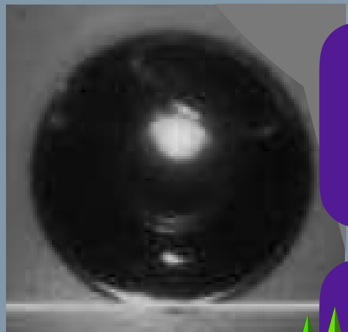
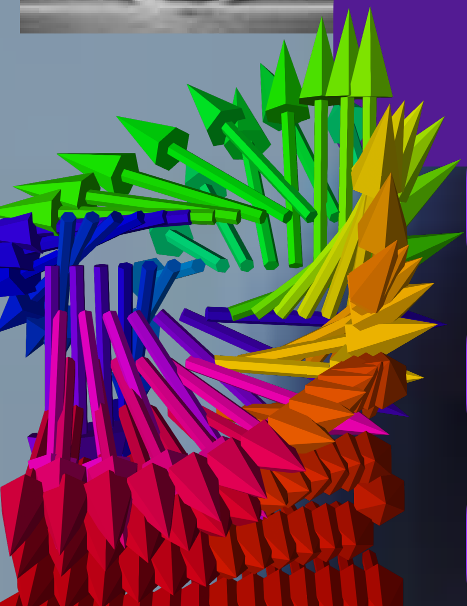
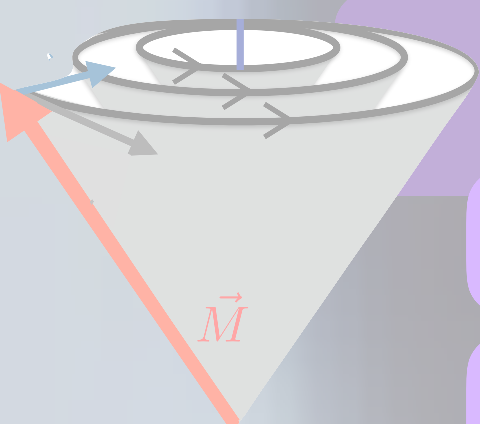


Introduction: cavity optomagnonics



Magnetic textures

- Why do they form?
- Equilibrium condition
- Topology of smooth textures



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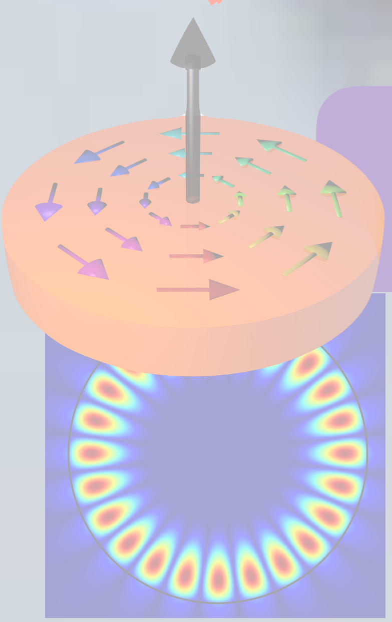
- Thiele equation for topological defects



Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
- Optomagnonic coupling: gyrotropic mode

Topology of smooth magnetic textures

Two relevant topological numbers

Easy-plane spins:

$$f : S^1 \to S^1 \qquad \text{e.g.:} \quad f \equiv \mathbf{m} = (\cos\phi(x), \sin\phi(x), 0)$$

$$w_{S^1} = \frac{1}{2\pi} \oint \mathrm{d}x \, \partial_x \phi$$

"winding number" q

Topology of smooth magnetic textures

Two relevant topological numbers

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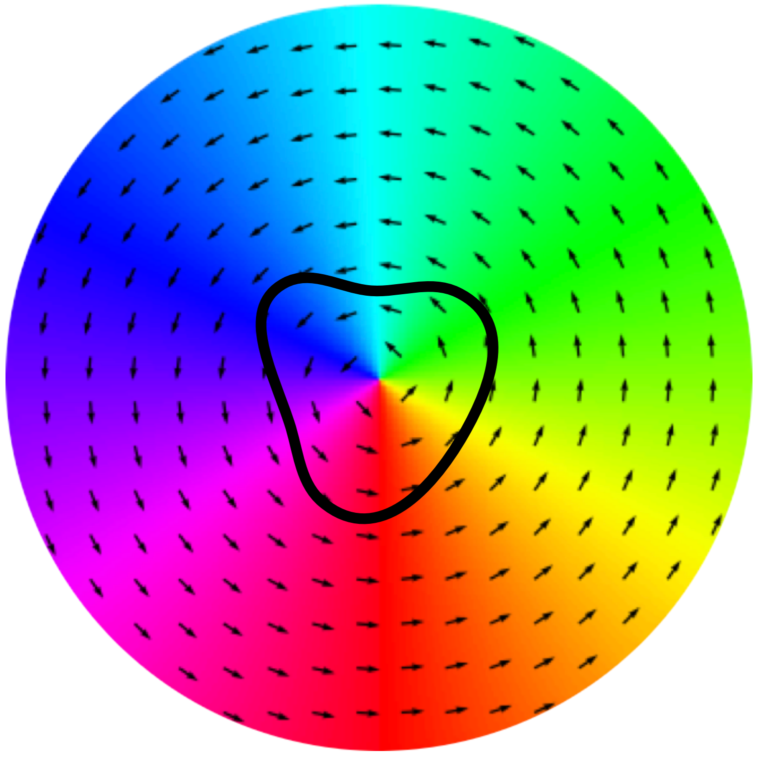


E.g. 2D vortex

$q = 1$

Topology of smooth magnetic textures

Two relevant topological numbers

see e.g. H.B Braun, Adv. in Phys. 61, 1 (2011)

Easy-plane spins:

$f : S^1 \to S^1$ e.g.: $f \equiv \mathbf{m} = (\cos\phi(x), \sin\phi(x), 0)$

$$w_{S^1} = \frac{1}{2\pi} \oint \mathrm{d}x \, \partial_x \phi$$ "winding number" q

Bloch-sphere spins:

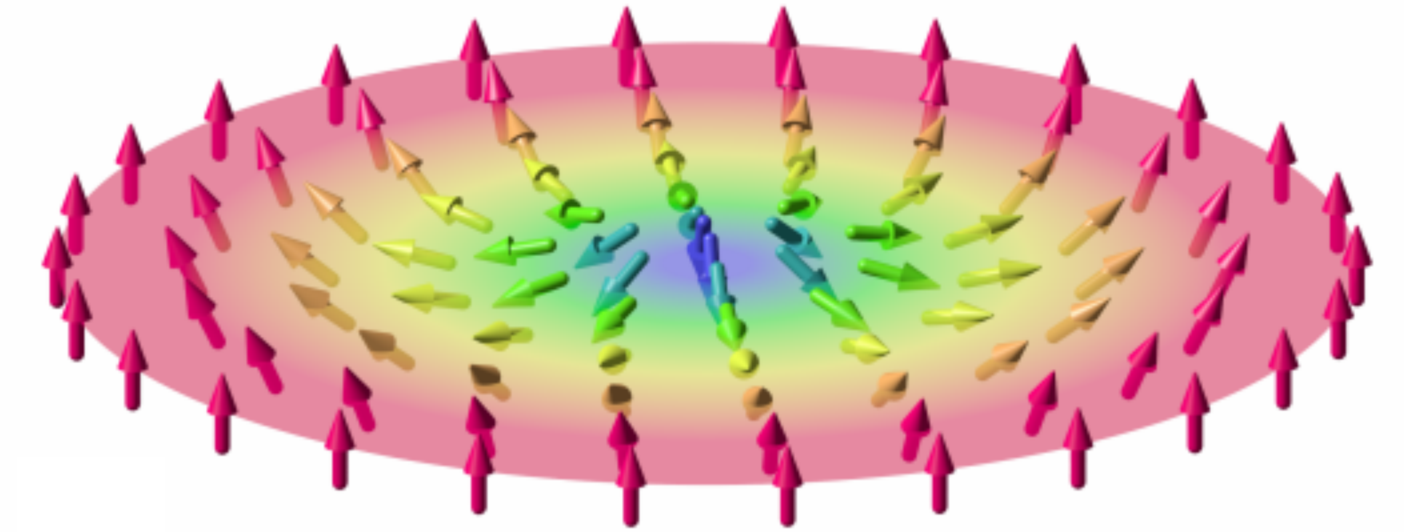
$f : S^2 \to S^2$ e.g.: $f \equiv \mathbf{m} = (m_1(x_1, x_2), m_2(x_1, x_2), m_3(x_1, x_2))$

$$w_{S^2} = \frac{1}{4\pi} \int_M \mathbf{m} \cdot (\partial_1 \mathbf{m} \times \partial_2 \mathbf{m}) \, \mathrm{d}x_1 \mathrm{d}x_2$$

"skyrmion number"

Topology of smooth magnetic textures

Skyrmion in a magnetic thin film



$q = 1$
$p = -1$

Image: Karin Everschor-Sitte (Wikipedia)

$$w_{S^2} = \frac{1}{4\pi}\int_M \mathbf{m}\cdot(\partial_1 \mathbf{m} \times \partial_2 \mathbf{m})\,\mathrm{d}x_1 \mathrm{d}x_2$$

Skyrmion number

$$w_{\mathrm{S}^2} = p\, w_{\mathrm{S}^1} = p\, q$$

polarity: ↑ or ↓

+1 -1

Topology of smooth magnetic textures

Skyrmion in a magnetic thin film

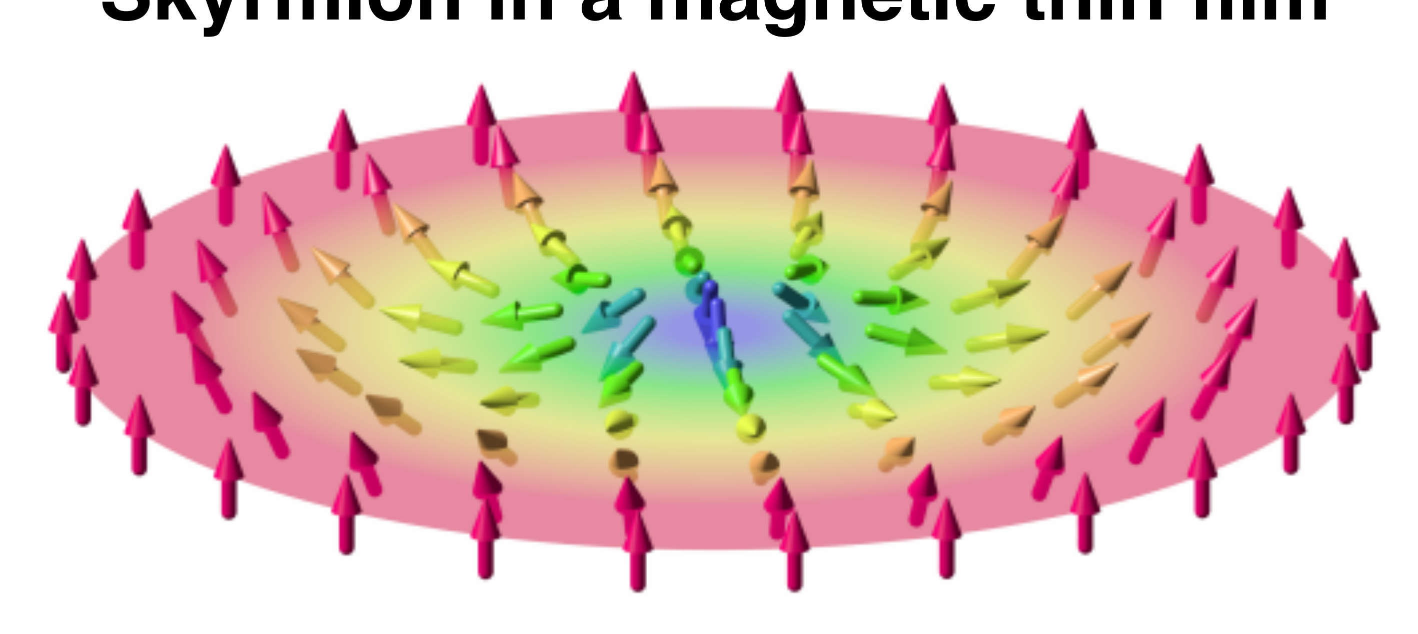


Image: Karin Everschor-Sitte (Wikipedia)

$$w_{S^2} = \frac{1}{4\pi}\int_M \mathbf{m}\cdot(\partial_1\mathbf{m}\times\partial_2\mathbf{m})\,\mathrm{d}x_1\mathrm{d}x_2$$

Skyrmion number

$$w_{S^2} = p\,w_{S^1} = p\,q$$

polarity: ↑ or ↓

+1 -1

Vortex in a magnetic thin microdisk

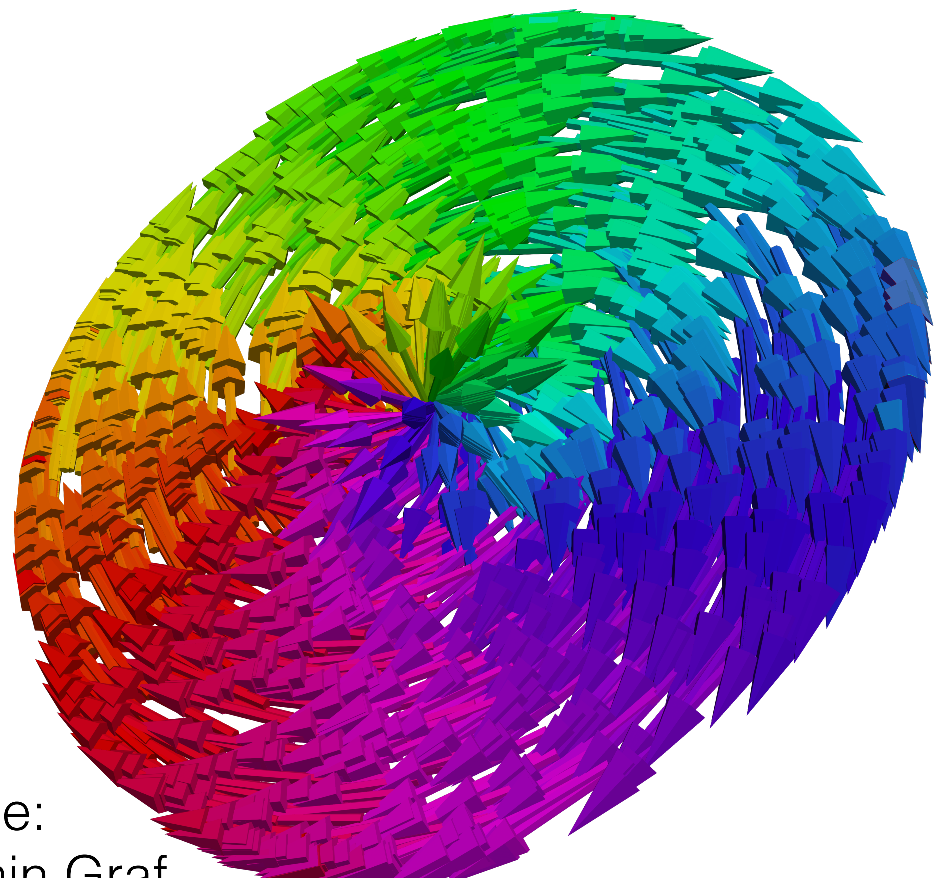


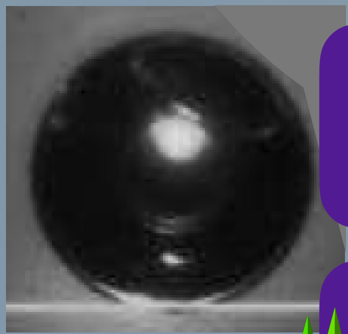
Image: Jasmin Graf

(Meron)

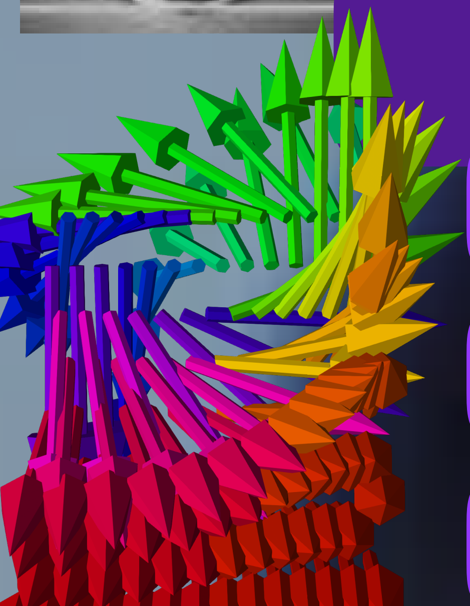
Skyrmion number

$$w_{S^2} = \frac{p\,q}{2}$$

“half a skyrmion”

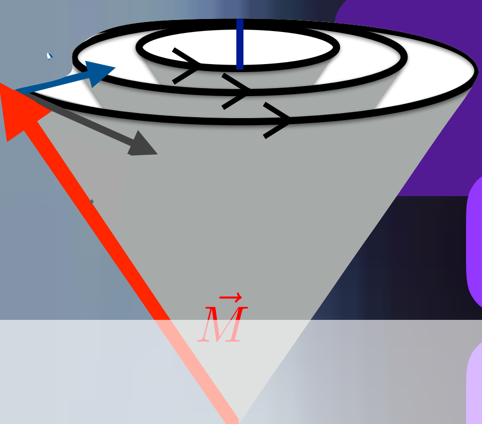


Introduction: cavity optomagnonics



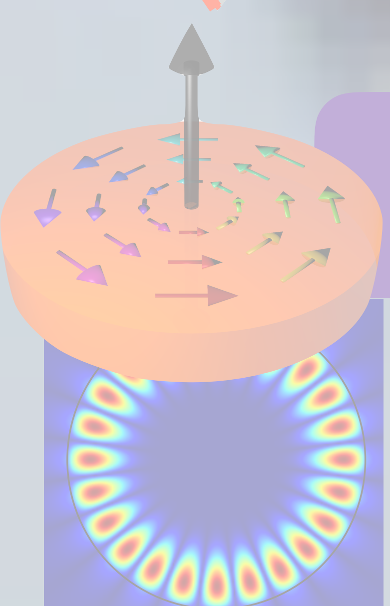
Magnetic textures

- Why do they form?
- Equilibrium condition
- Topology of smooth textures



Dynamics of the magnetization

- Landau Lifschitz Gilbert equation
- Thiele equation for topological defects



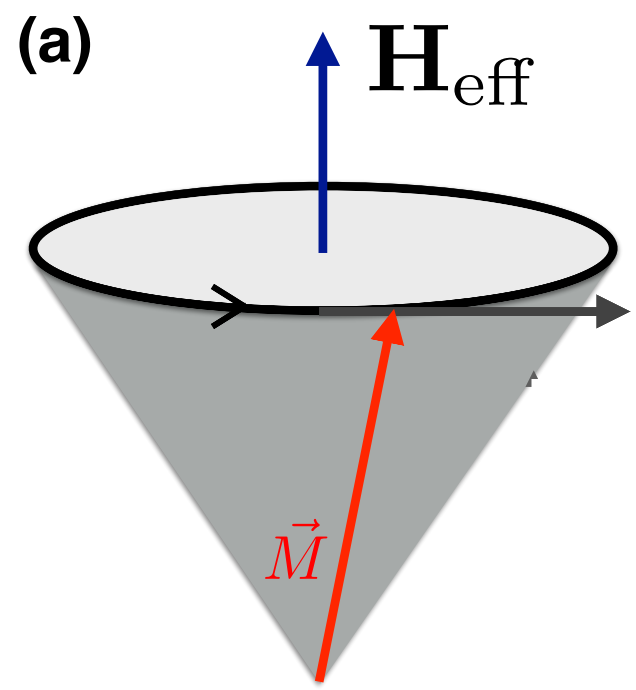
Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
- Optomagnonic coupling: gyrotropic mode

Dynamics of M: Landau Lifschitz equation

Precession of the magnetization

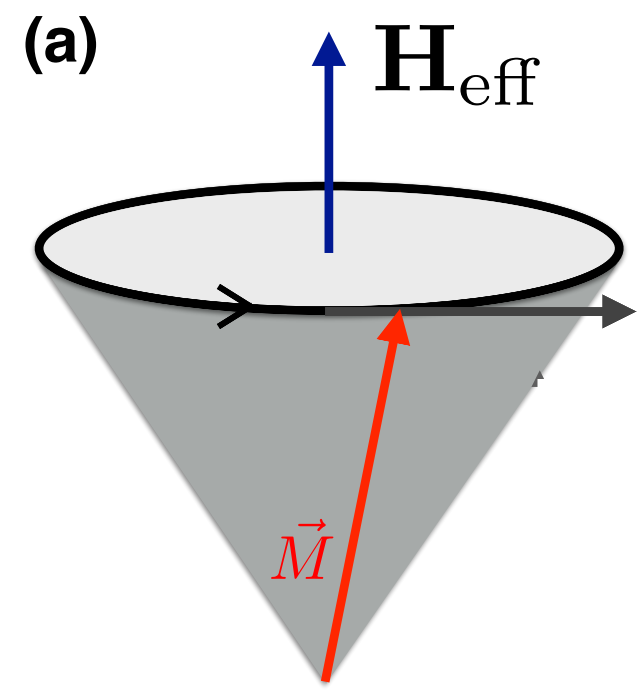
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}}$$



Dynamics of M: Landau Lifschitz equation

Precession of the magnetization

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\mathrm{eff}}$$



Can be derived from the Lagrangian

$$L = \frac{M_{\mathrm{s}}}{\gamma} \int_V \mathrm{d}^3 r (1 - \cos\theta)\dot{\phi} - E$$

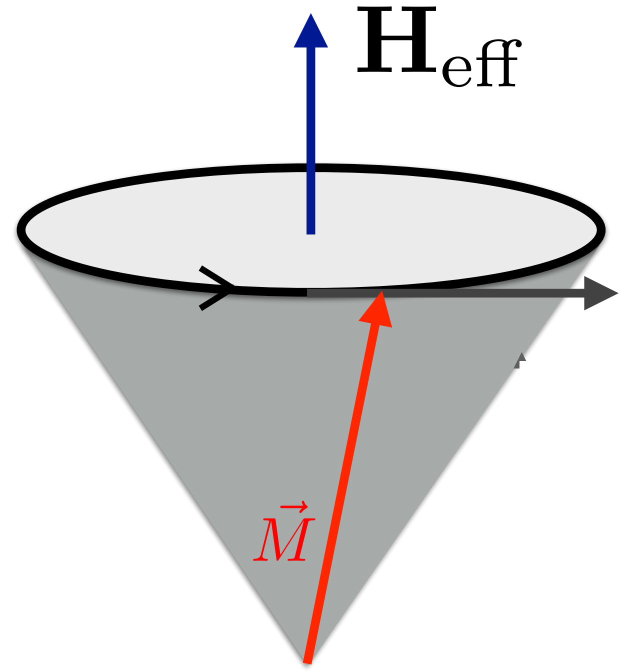
geometrical phase

$$\frac{\mathbf{M}}{M_{\mathrm{s}}} = \mathbf{m} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

Dynamics of M: Landau Lifschitz equation

Precession of the magnetization

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\rm eff}$$



Can be derived from the Lagrangian

$$L = \frac{M_{\rm s}}{\gamma} \int_V {\rm d}^3 r (1 - \cos\theta)\dot{\phi} - E$$

geometrical phase

$$\frac{\mathbf{M}}{M_{\rm s}} = \mathbf{m} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

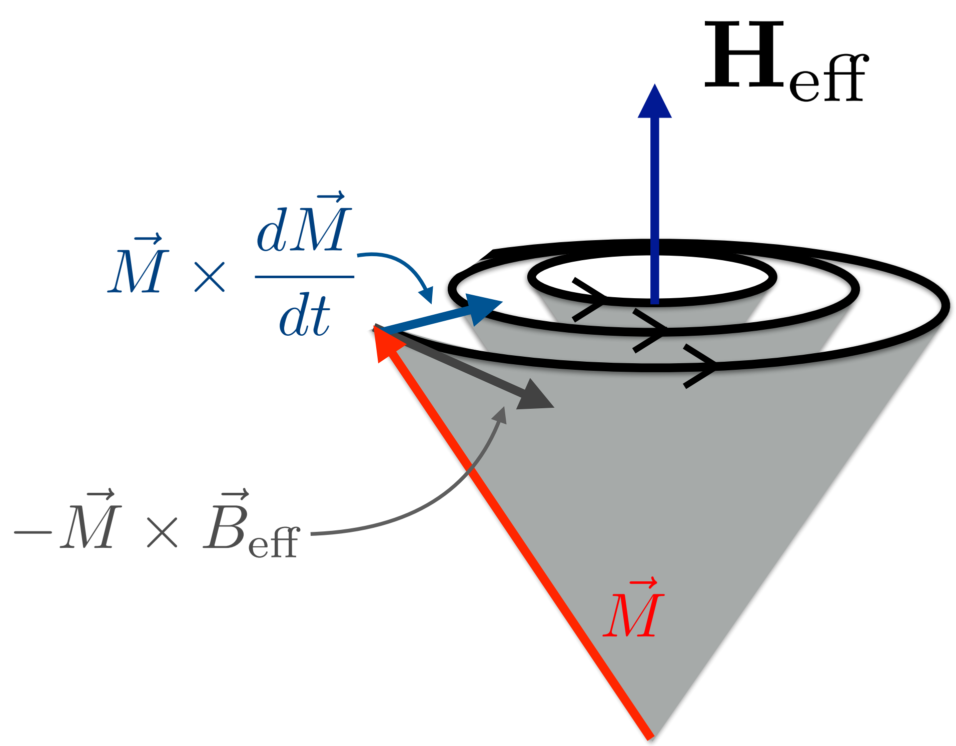
or from the quantum Hamiltonian via Heisenberg EOM

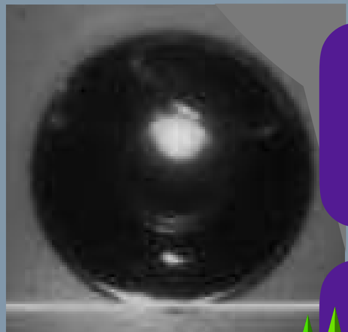
Dynamics of M: Landau Lifschitz Gilbert equation

Damped precession

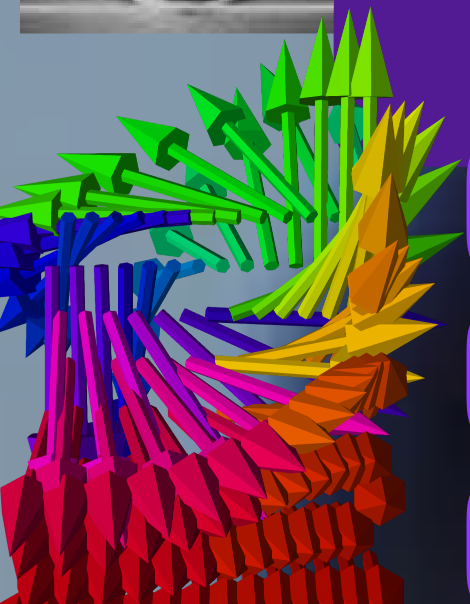
$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_{\text{s}}} \left(\mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} \right)$$

Gilbert damping





Introduction: cavity optomagnonics

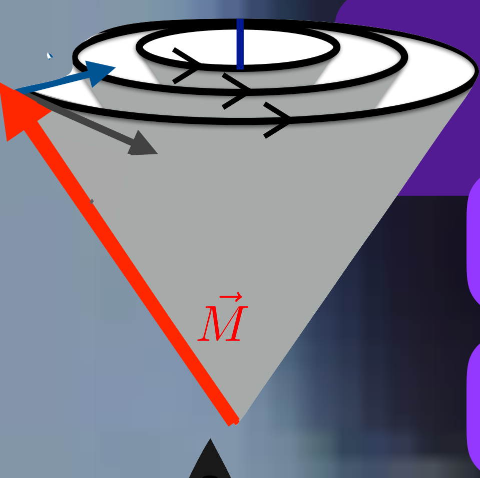


Magnetic textures

Why do they form?

Equilibrium condition

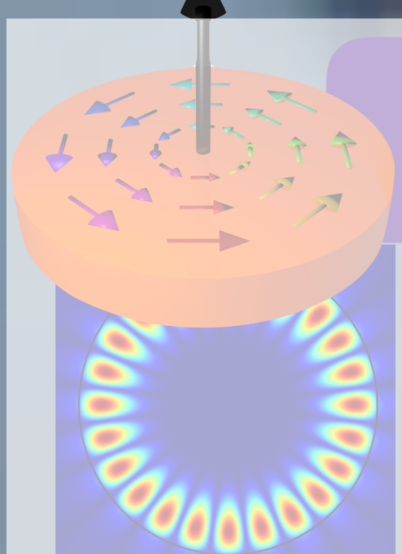
Topology of smooth textures



Dynamics of the magnetization

Landau Lifschitz Gilbert equation

Thiele equation for topological defects



Cavity optomagnonics with magnetic textures

Hamiltonian: Holstein-Primakoff

Optomagnonic coupling: gyrotropic mode

Dynamics of the vortex: Thiele equation

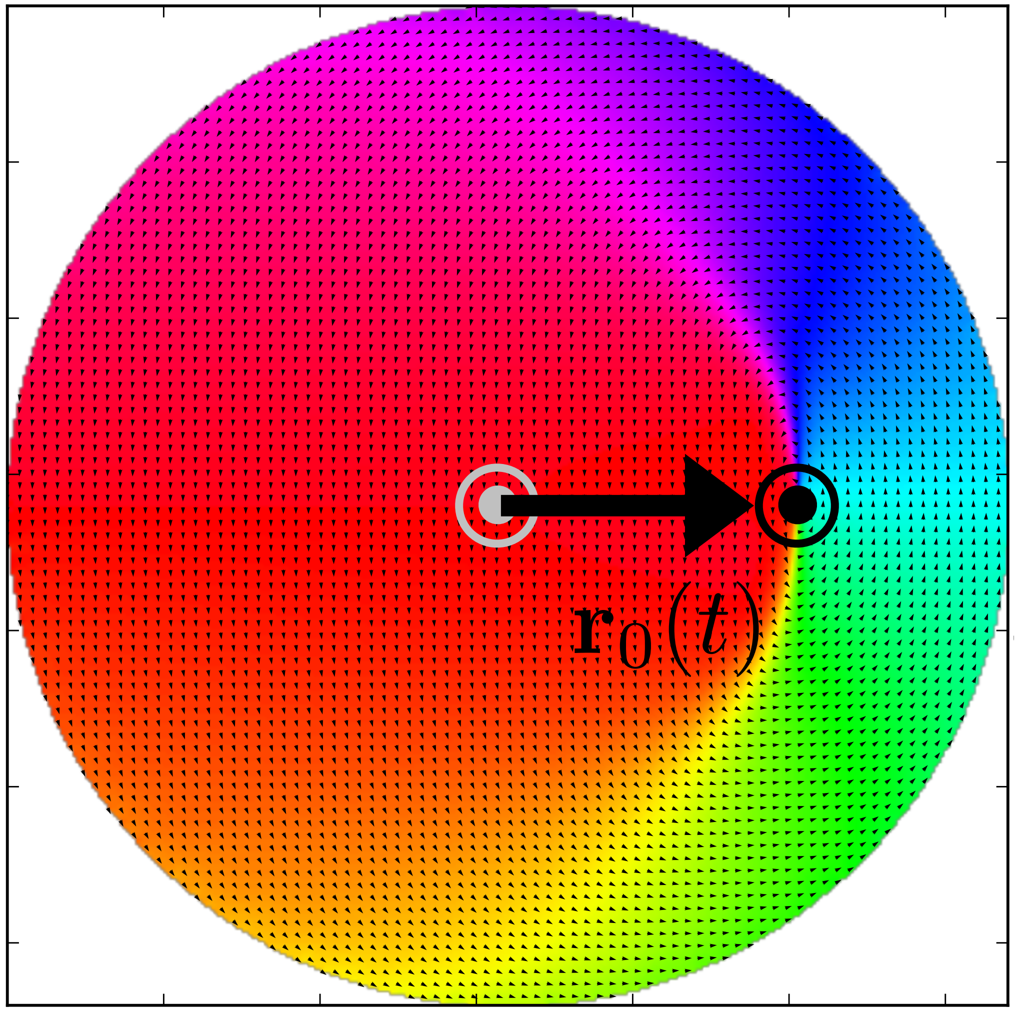
Rigid translation: vortex parametrized just by the core's position

$$\mathbf{m}(\mathbf{r},t)=\mathbf{m}(\mathbf{r}-\mathbf{r_0}(\mathbf{t}))$$

$$\mathbf{m}=(\sin\theta\cos\phi,\sin\theta\sin\phi,\cos\theta)$$

$$\theta(\mathbf{r},t)=\theta(\mathbf{r}-\mathbf{r_0}(\mathbf{t}))$$

$$\phi(\mathbf{r},t)=\phi(\mathbf{r}-\mathbf{r_0}(\mathbf{t}))$$



Dynamics of the vortex: Thiele equation

Rigid translation: vortex parametrized just by the core's position

$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}(\mathbf{r} - \mathbf{r_0}(\mathbf{t}))$$

$$\mathbf{m} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$\theta(\mathbf{r},t) = \theta(\mathbf{r} - \mathbf{r_0}(\mathbf{t}))$$

$$\phi(\mathbf{r},t) = \phi(\mathbf{r} - \mathbf{r_0}(\mathbf{t}))$$

need only the EOM for $\mathbf{r}_0(t)$

Thiele derived it from the LLG equation:

$$\mathbf{H}_{\text{eff}} = \frac{1}{\gamma}(\mathbf{m} \times \dot{\mathbf{m}} + \alpha\dot{\mathbf{m}})\ .$$

$$\dot{\mathbf{m}} = -\sum_i v_i \frac{\partial \mathbf{m}}{\partial r_i}$$

with $\mathbf{v} = \dot{\mathbf{r}}_0$

A.A. Thiele, PRL 230 (1972)

Dynamics of the vortex: Thiele equation

$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}(\mathbf{r} - \mathbf{r_0}(\mathbf{t}))$$

$$\mathbf{H}_{\text{eff}} = \frac{1}{\gamma}\left(\mathbf{m} \times \dot{\mathbf{m}} + \alpha \dot{\mathbf{m}}\right)$$

$$\dot{\mathbf{m}} = -\sum_i v_i \frac{\partial \mathbf{m}}{\partial r_i}$$

$$\mathbf{v} = \dot{\mathbf{r}}_0$$

The force on the "particle" is

$$F_i = -\frac{dE}{dr_{0_i}} = \mu_0 M_{\text{s}} \int_V \mathrm{d}^3 r \mathbf{H}_{\text{eff}} \cdot \frac{\partial \mathbf{m}}{\partial r_{0_i}} = -\mu_0 M_{\text{s}} \int_V \mathrm{d}^3 r \mathbf{H}_{\text{eff}} \cdot \frac{\partial \mathbf{m}}{\partial r_i}$$

Dynamics of the vortex: Thiele equation

$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}(\mathbf{r} - \mathbf{r_0}(\mathbf{t}))$$

$$\mathbf{H}_{\text{eff}} = \frac{1}{\gamma}\left(\mathbf{m} \times \dot{\mathbf{m}} + \alpha\dot{\mathbf{m}}\right)$$

$$\dot{\mathbf{m}} = -\sum_i v_i \frac{\partial \mathbf{m}}{\partial r_i} \qquad \mathbf{v} = \dot{\mathbf{r}}_0$$

The force on the "particle" is

$$F_i = -\frac{dE}{dr_{0_i}} = \mu_0 M_\text{s} \int_V \mathrm{d}^3 r \mathbf{H}_{\text{eff}} \cdot \frac{\partial \mathbf{m}}{\partial r_{0_i}} = -\mu_0 M_\text{s} \int_V \mathrm{d}^3 r \mathbf{H}_{\text{eff}} \cdot \frac{\partial \mathbf{m}}{\partial r_i}$$

$$F_i = -\frac{\mu_0 M_\text{s}}{\gamma} \int_V \mathrm{d}^3 r \sum_j v_j \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial r_i} \times \frac{\partial \mathbf{m}}{\partial r_j}\right) + \alpha \frac{\mu_0 M_\text{s}}{\gamma} \int_V \mathrm{d}^3 r \sum_j v_j \left(\frac{\partial \mathbf{m}}{\partial r_i} \cdot \frac{\partial \mathbf{m}}{\partial r_j}\right)$$

Gyrotropic force — Dissipative force

Dynamics of the vortex: Thiele equation

$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}(\mathbf{r}-\mathbf{r_0}(\mathbf{t}))$$

$$\mathbf{H}_{\text{eff}} = \frac{1}{\gamma}\left(\mathbf{m}\times\dot{\mathbf{m}} + \alpha\dot{\mathbf{m}}\right)$$

$$\dot{\mathbf{m}} = -\sum_i v_i \frac{\partial \mathbf{m}}{\partial r_i} \qquad \mathbf{v} = \dot{\mathbf{r}}_0$$

The force on the "particle" is

$$F_i = -\frac{dE}{dr_{0_i}} = \mu_0 M_\text{s} \int_V \mathrm{d}^3 r\, \mathbf{H}_{\text{eff}} \cdot \frac{\partial \mathbf{m}}{\partial r_{0_i}} = -\mu_0 M_\text{s} \int_V \mathrm{d}^3 r\, \mathbf{H}_{\text{eff}} \cdot \frac{\partial \mathbf{m}}{\partial r_i}$$

$$F_i = -\frac{\mu_0 M_\text{s}}{\gamma} \int_V \mathrm{d}^3 r \sum_j v_j \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial r_i} \times \frac{\partial \mathbf{m}}{\partial r_j}\right) + \alpha \frac{\mu_0 M_\text{s}}{\gamma} \int_V \mathrm{d}^3 r \sum_j v_j \left(\frac{\partial \mathbf{m}}{\partial r_i} \cdot \frac{\partial \mathbf{m}}{\partial r_j}\right)$$

Gyrotropic force $\mathbf{F}_\text{g}$

A.A. Thiele, PRL 230 (1972)

Dynamics of the vortex: Thiele equation

$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}(\mathbf{r}-\mathbf{r_0}(\mathbf{t})) \qquad \mathbf{v} = \dot{\mathbf{r}_0}$$

Gyrotropic force on the topological defect

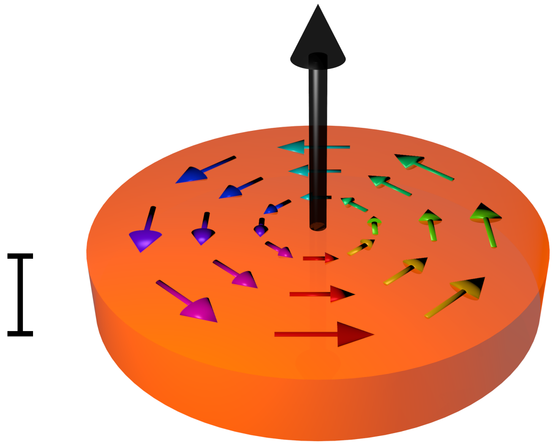
$$\mathbf{F}_\mathrm{g} = \mathbf{G} \times \mathbf{v}$$

with $$G_i = \frac{\mu_0 M_\mathrm{s}}{|\gamma|} \frac{\epsilon_{ijk}}{2} \int_V \mathrm{d}^3 r \mathbf{m} \cdot \underbrace{\left(\frac{\partial \mathbf{m}}{\partial r_j} \times \frac{\partial \mathbf{m}}{\partial r_k} \right)}$$

skyrmion number!

for the vortex:

h



$$G_z = h \frac{\mu_0 M_\mathrm{s}}{2|\gamma|} pq$$

like a Lorentz force!

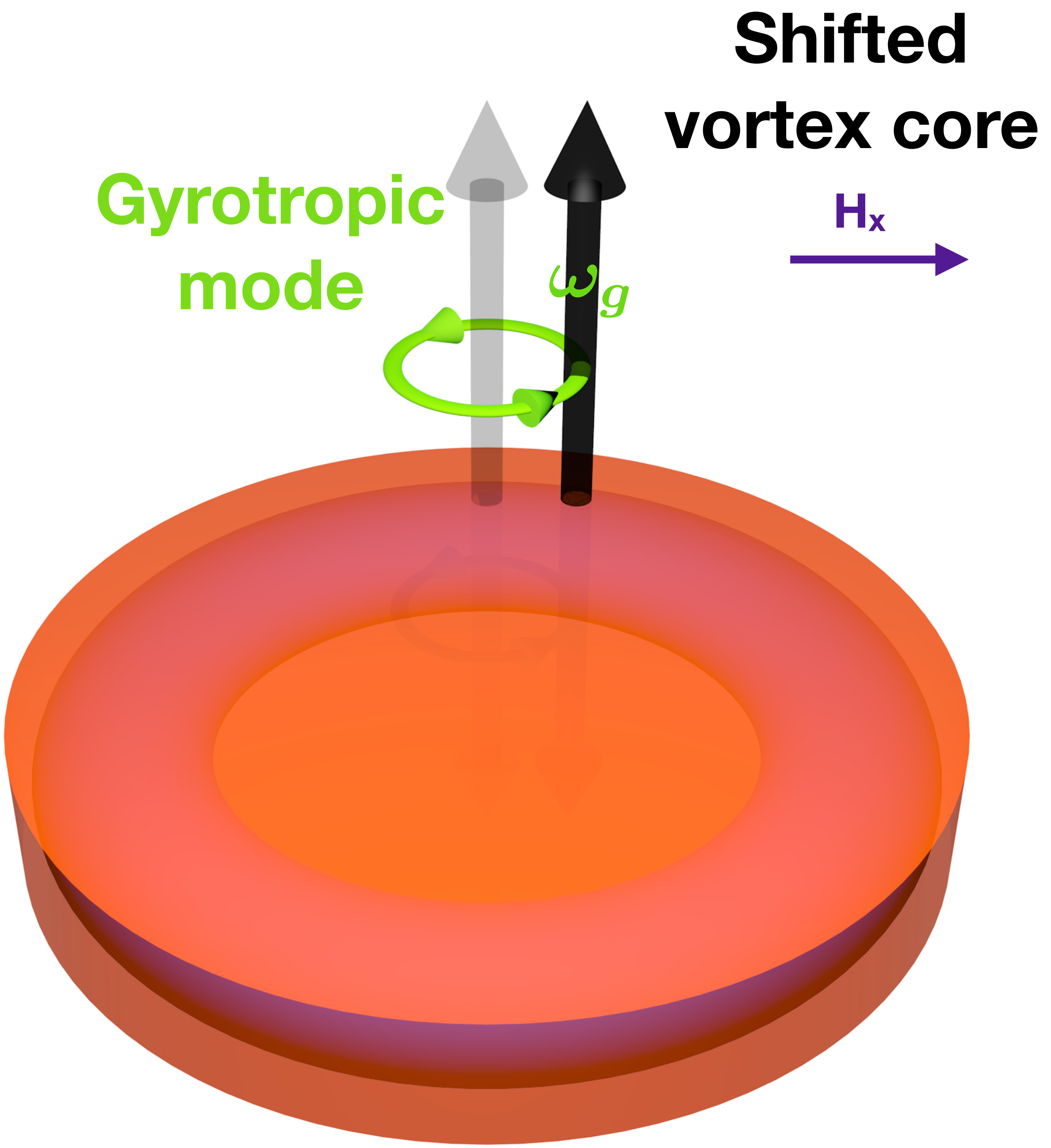
Dynamics of the vortex: Gyrotropic mode

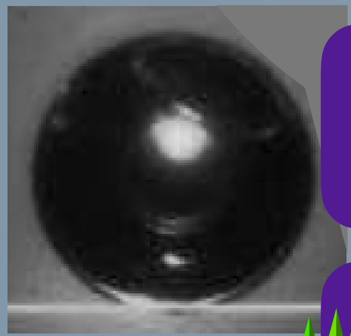
$$\mathbf{F}_\mathrm{g} = \mathbf{G} \times \mathbf{v}$$

$$G_z = h\frac{\mu_0 M_\mathrm{s}}{2|\gamma|}pq$$

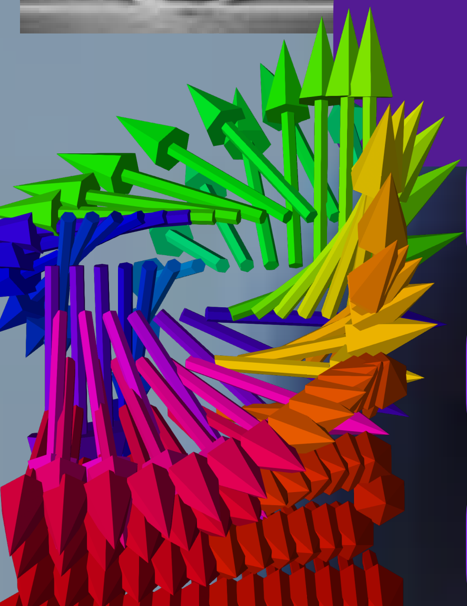
like a Lorentz force!

The vortex acts like
a charge in a magnetic
field:
circular motion of the core
around its equilibrium position



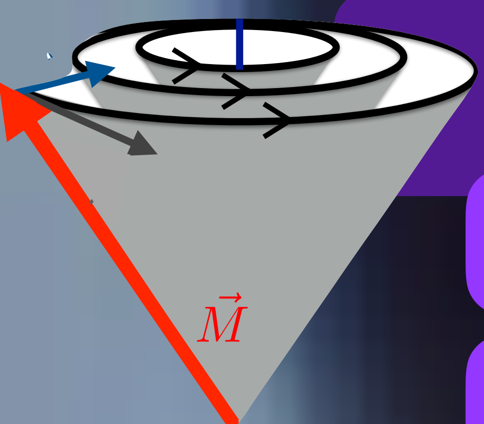


Introduction: cavity optomagnonics



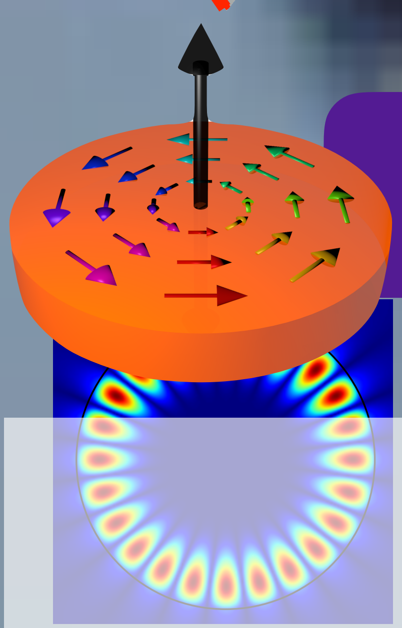
Magnetic textures

- Why do they form?
- Equilibrium condition
- Topology of smooth textures



Dynamics of the magnetization

- Landau Lifschitz Gilbert equation
- Thiele equation for topological defects



Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
- Optomagnonic coupling: gyrotropic mode

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

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

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

magnon mode index

bosonic operator

mode functions

Optomagnonics beyond the Kittel mode

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

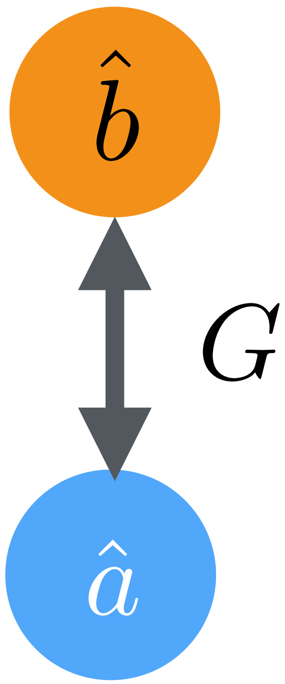
$$\mathbf{m}(\mathbf{r},t) = \mathbf{m}_0(\mathbf{r}) + \delta\mathbf{m}(\mathbf{r},t)$$

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

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

Optomagnonics beyond the Kittel mode

Optomagnonic Hamiltonian in the spin-wave limit

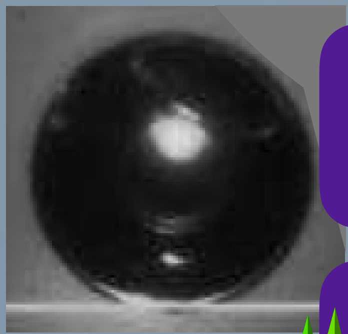


$$\hat{H}_{MO} = \sum_{\alpha\beta\gamma} G_{\alpha\beta\gamma} \hat{a}^{\dagger}_{\alpha} \hat{a}_{\beta} \hat{b}_{\gamma} + \text{h.c.}$$

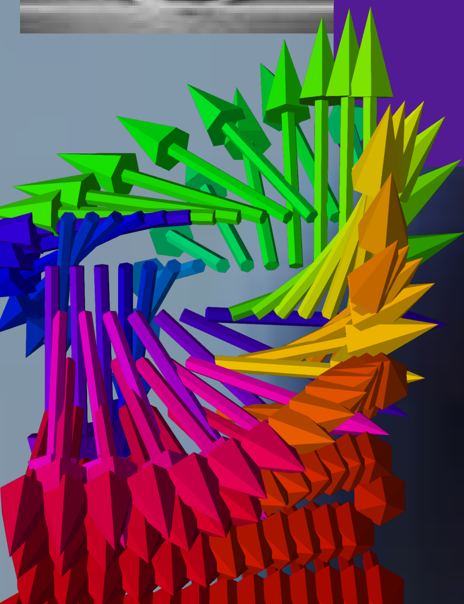
Optomagnonic coupling

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

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



Introduction: cavity optomagnonics



Magnetic textures

- Why do they form?
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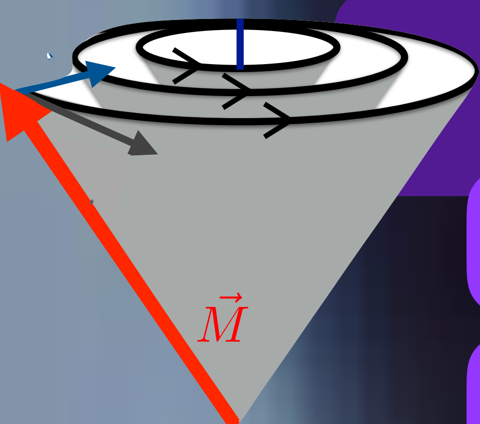
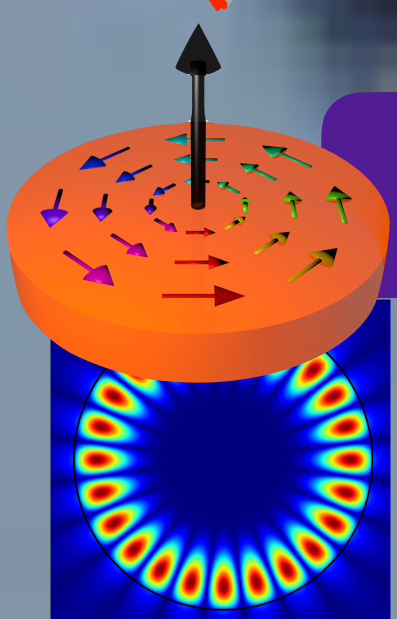


Dynamics of the magnetization

- Landau Lifschitz Gilbert equation
- Thiele equation for topological defects

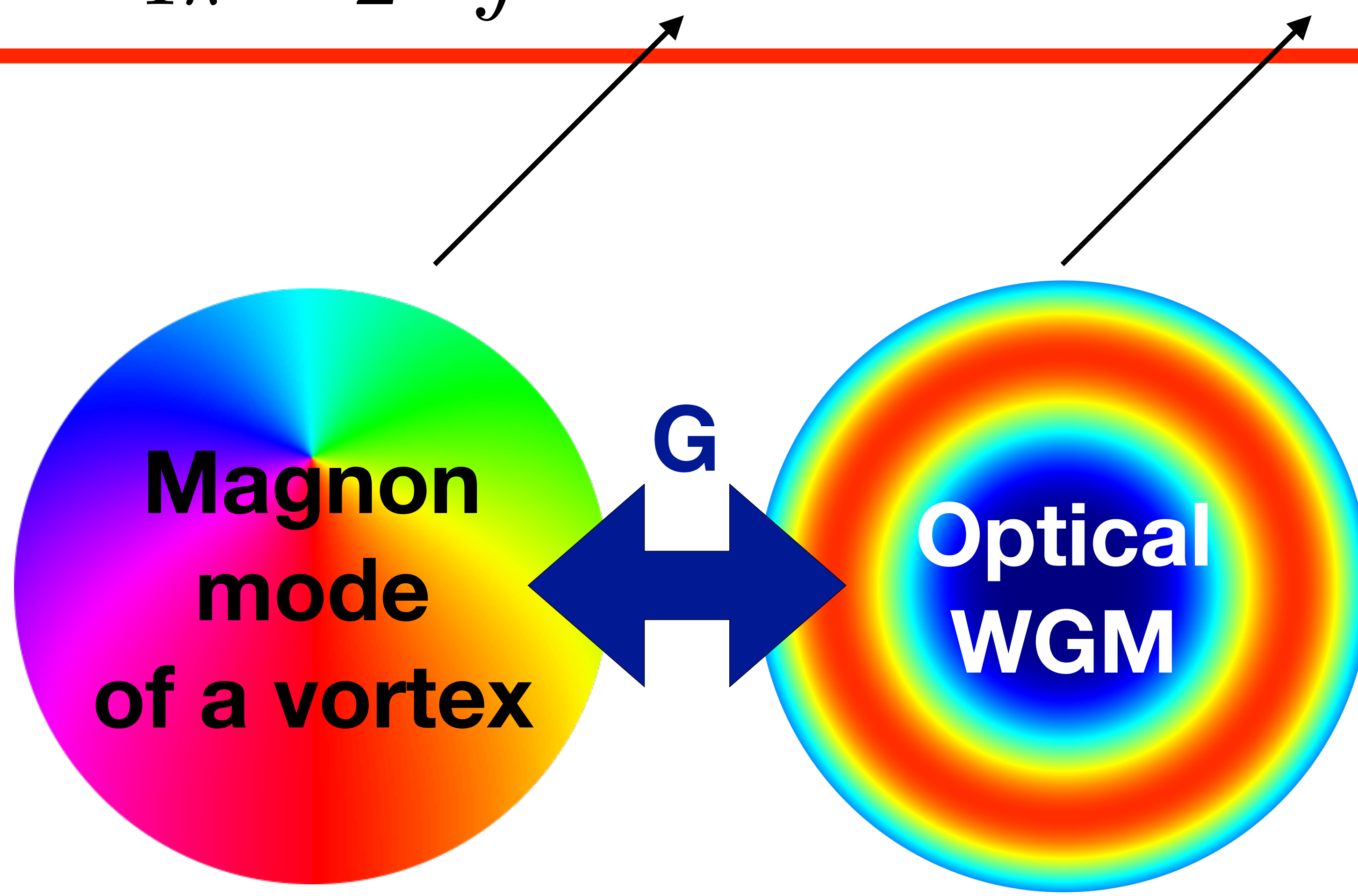


Cavity optomagnonics with magnetic textures

- Hamiltonian: Holstein-Primakoff
- Optomagnonic coupling: gyrotropic mode

Optomagnonic Coupling

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

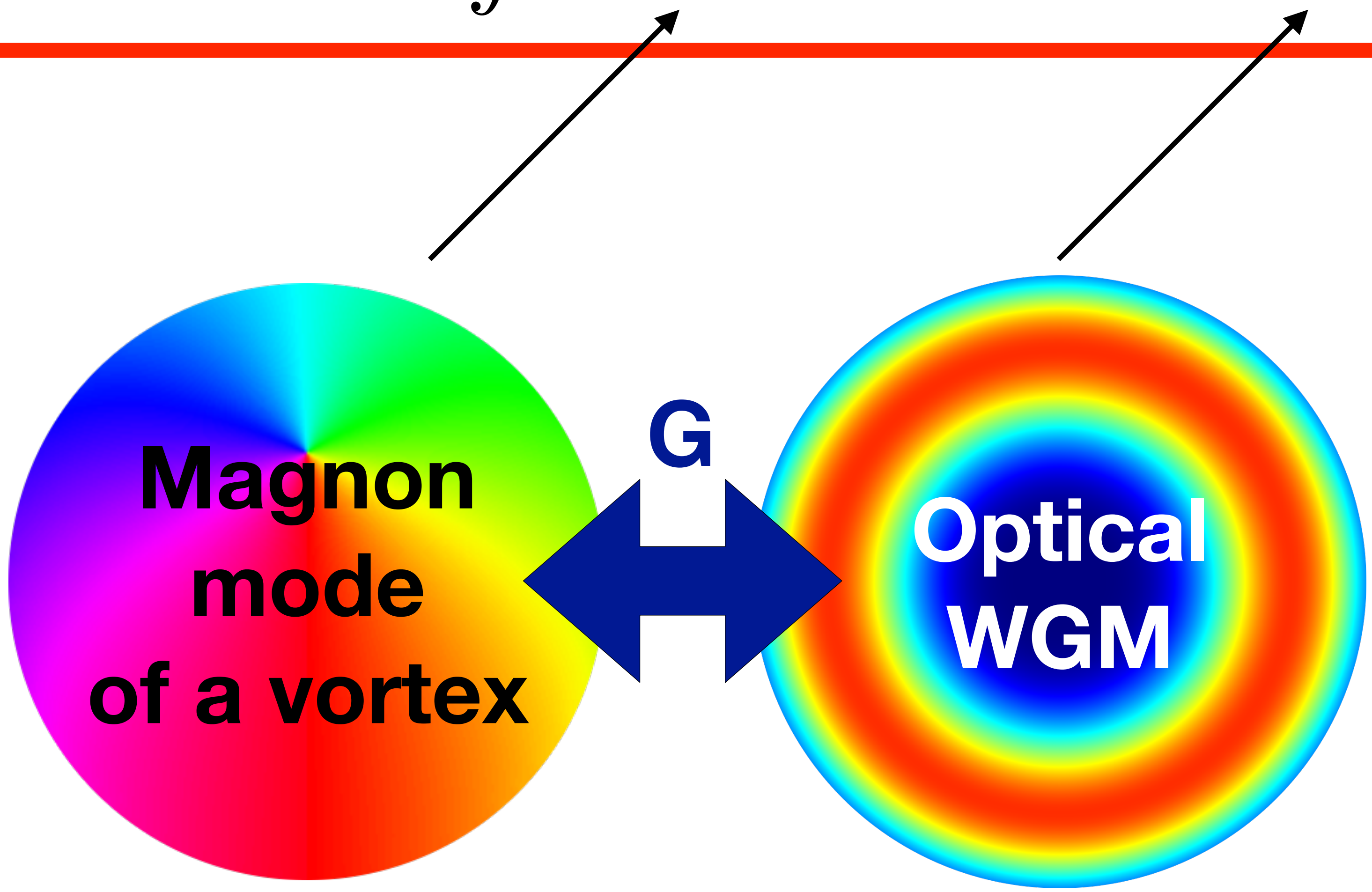


Analytical results for very thin micromagnetic disk (2D)

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

Optomagnonic Coupling

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



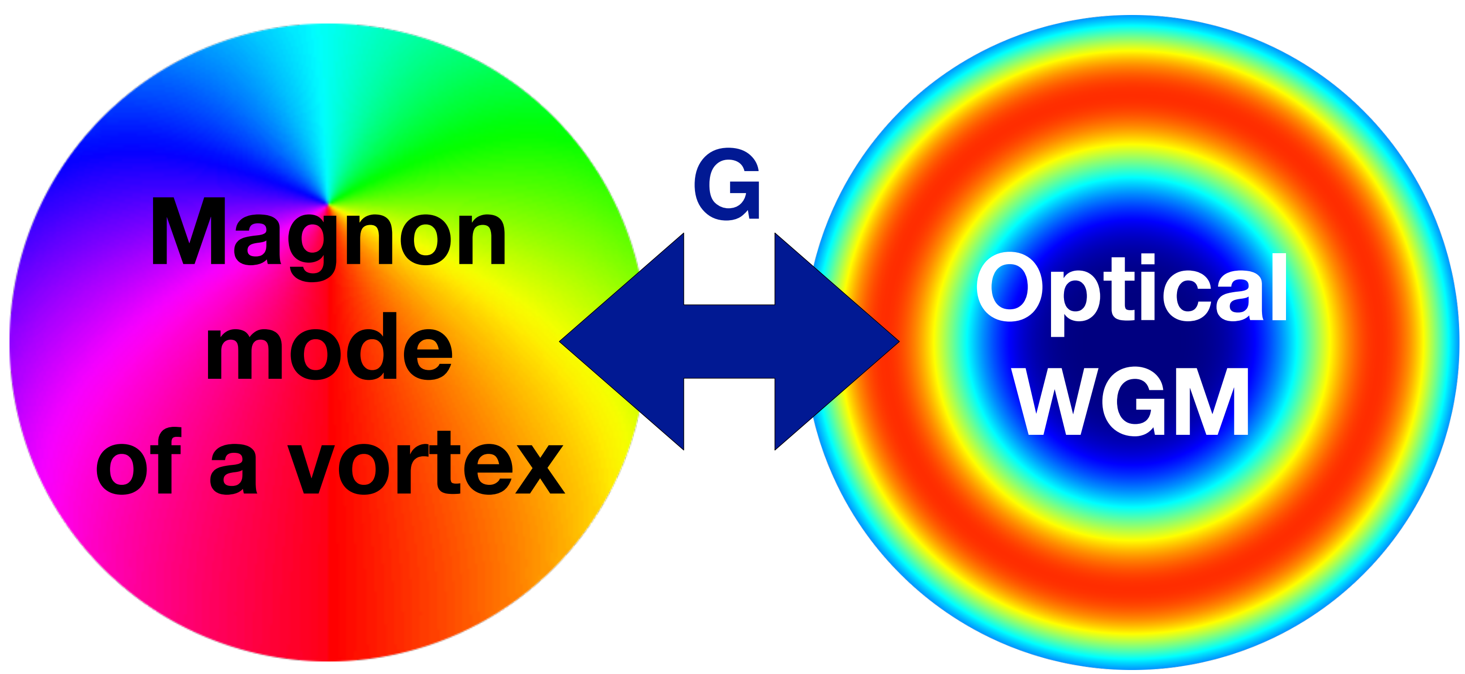
Analytical results for very thin micromagnetic disk (2D)

Coupling proportional to the gradient of the optical spin density

$$|G(s)| \propto \left|\partial_s\left[(\mathbf{E}^{\mathrm{TE}*}_m \times \mathbf{E}^{\mathrm{TE}}_m)_z\right]\right| \qquad (s \text{ vortex position})$$

Optomagnonic Coupling

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



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

micromagnetics

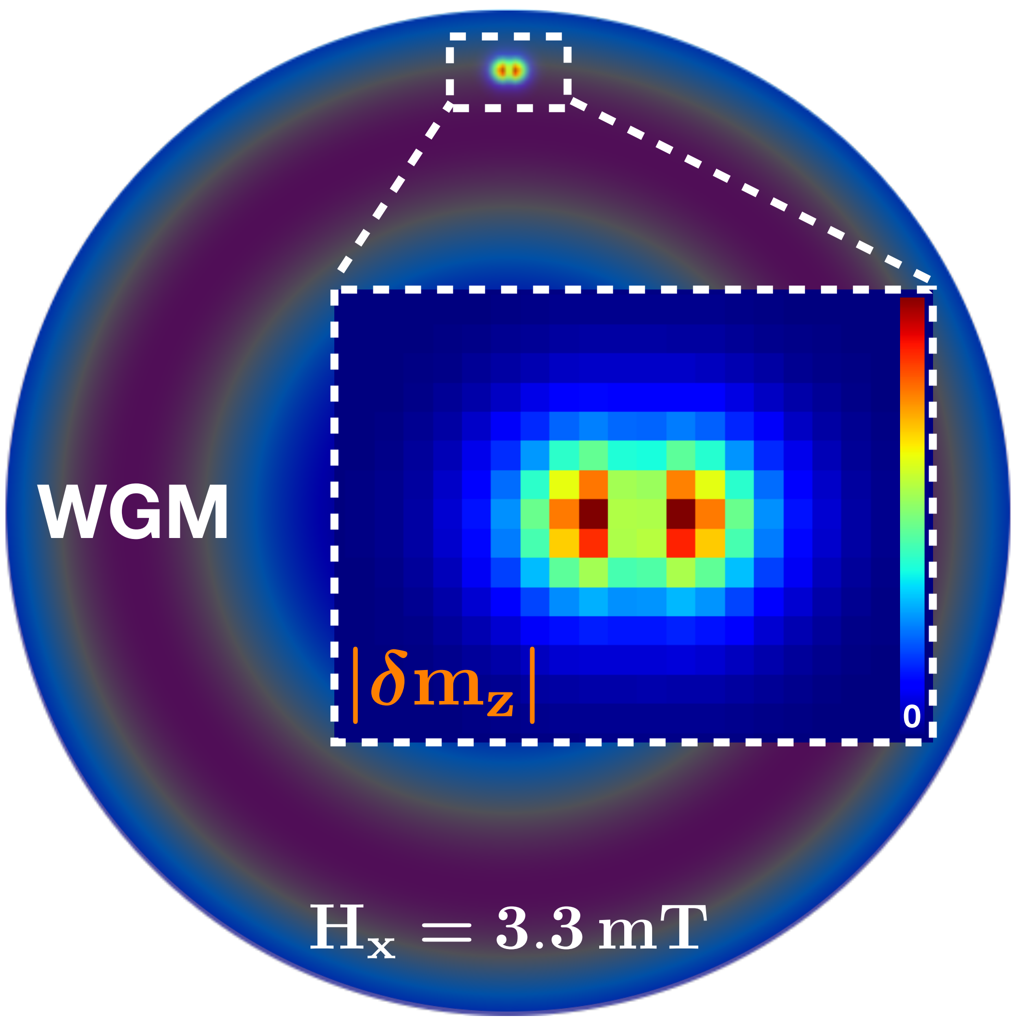
finite element

Simulation software

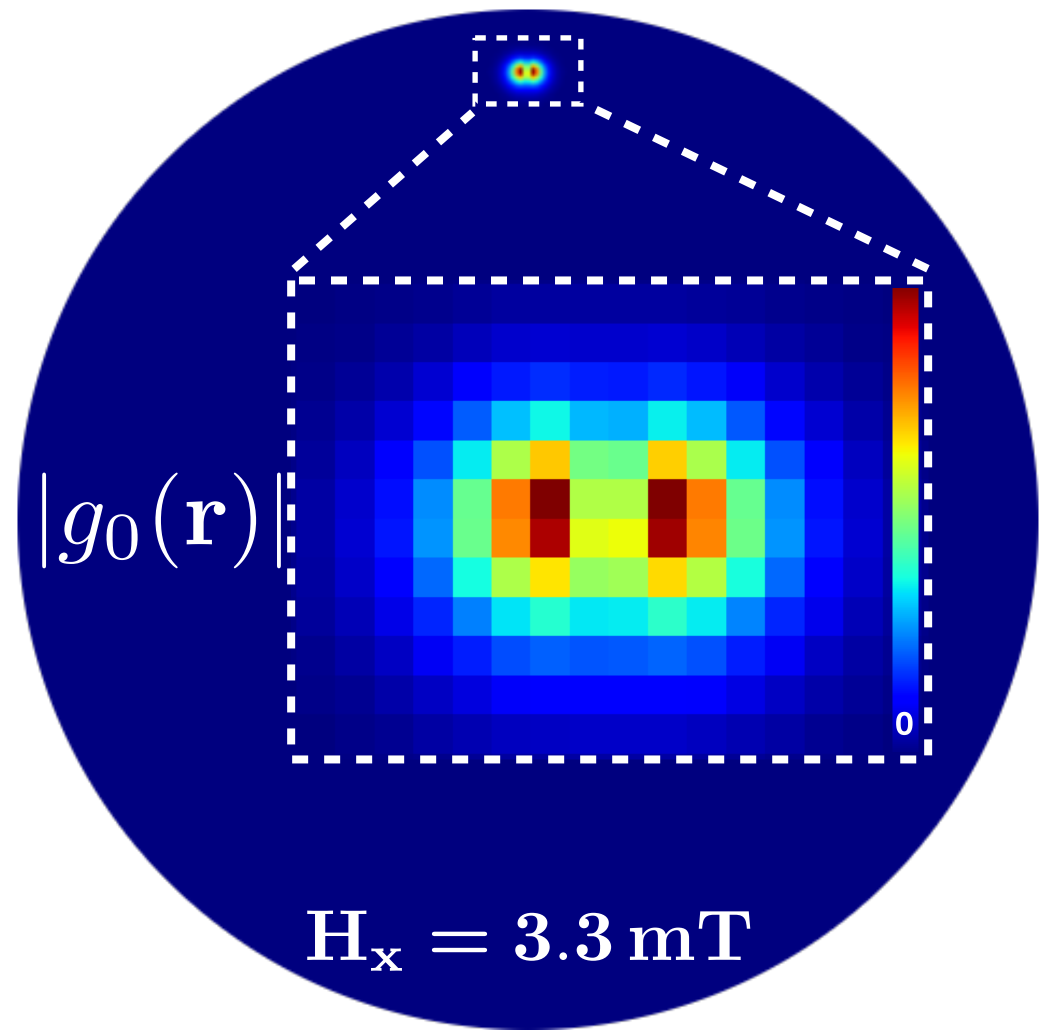
Optomagnonic coupling: gyrotropic mode

spatial dependence

Magnon and optical modes

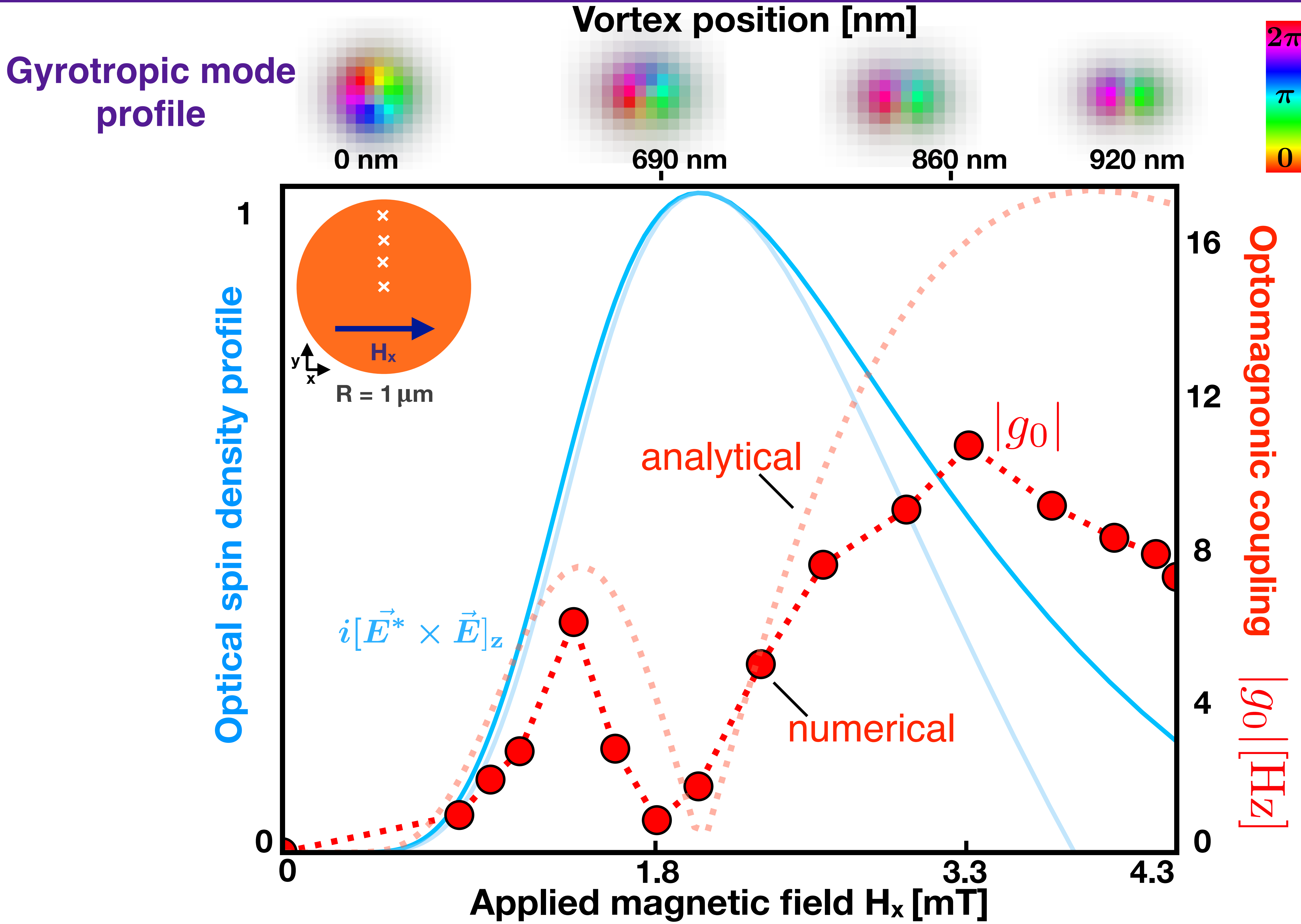


Optomagnonic coupling



integrate over the whole volume

Optomagnonic coupling: gyrotropic mode



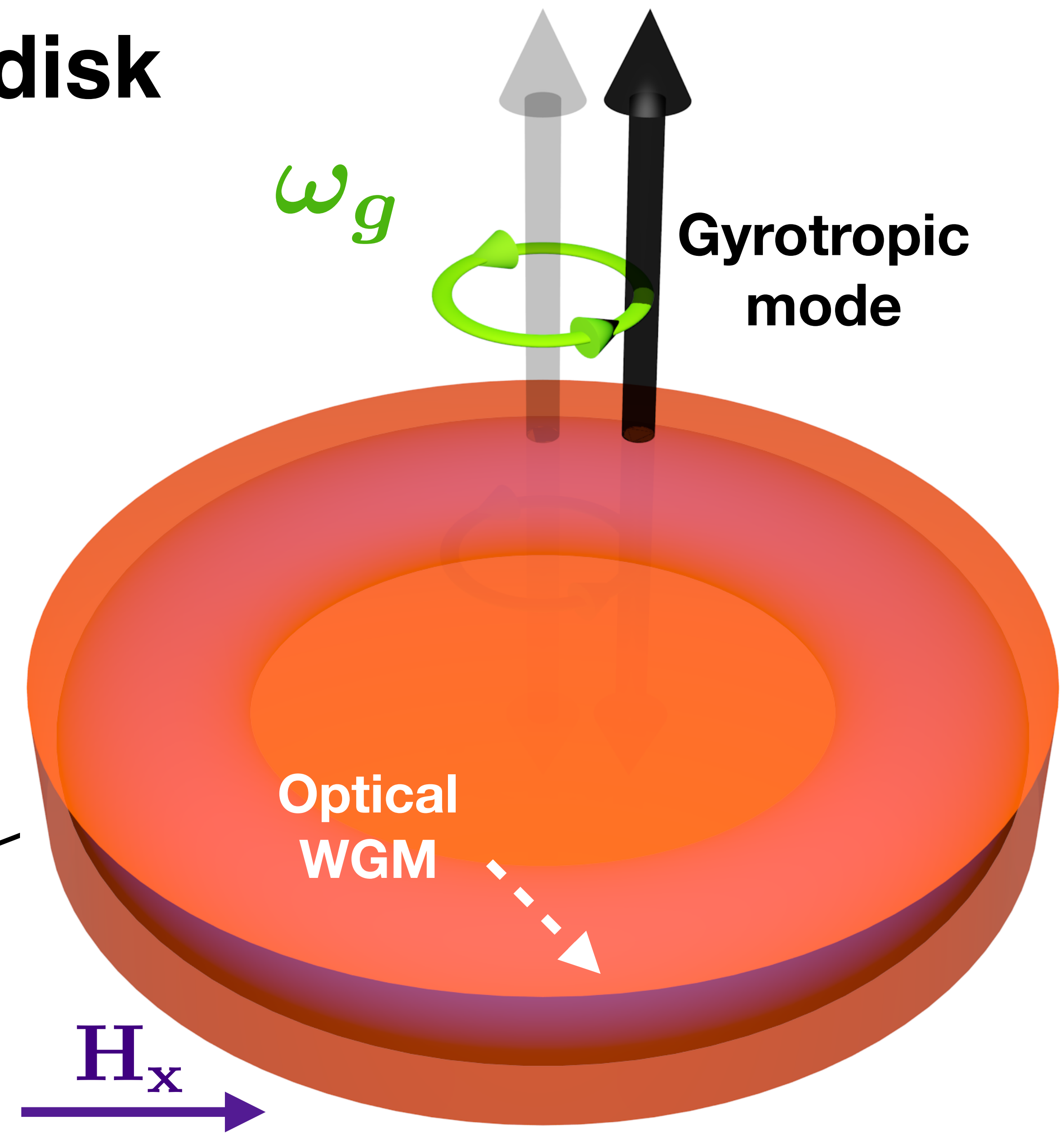
J. Graf, H. Pfeifer, F. Marquardt, S. Viola Kusminskiy, Phys. Rev. B 98, 241406(R), (2018)

Optomagnonic coupling: beyond 2D

“Thick” micromagnetic disk

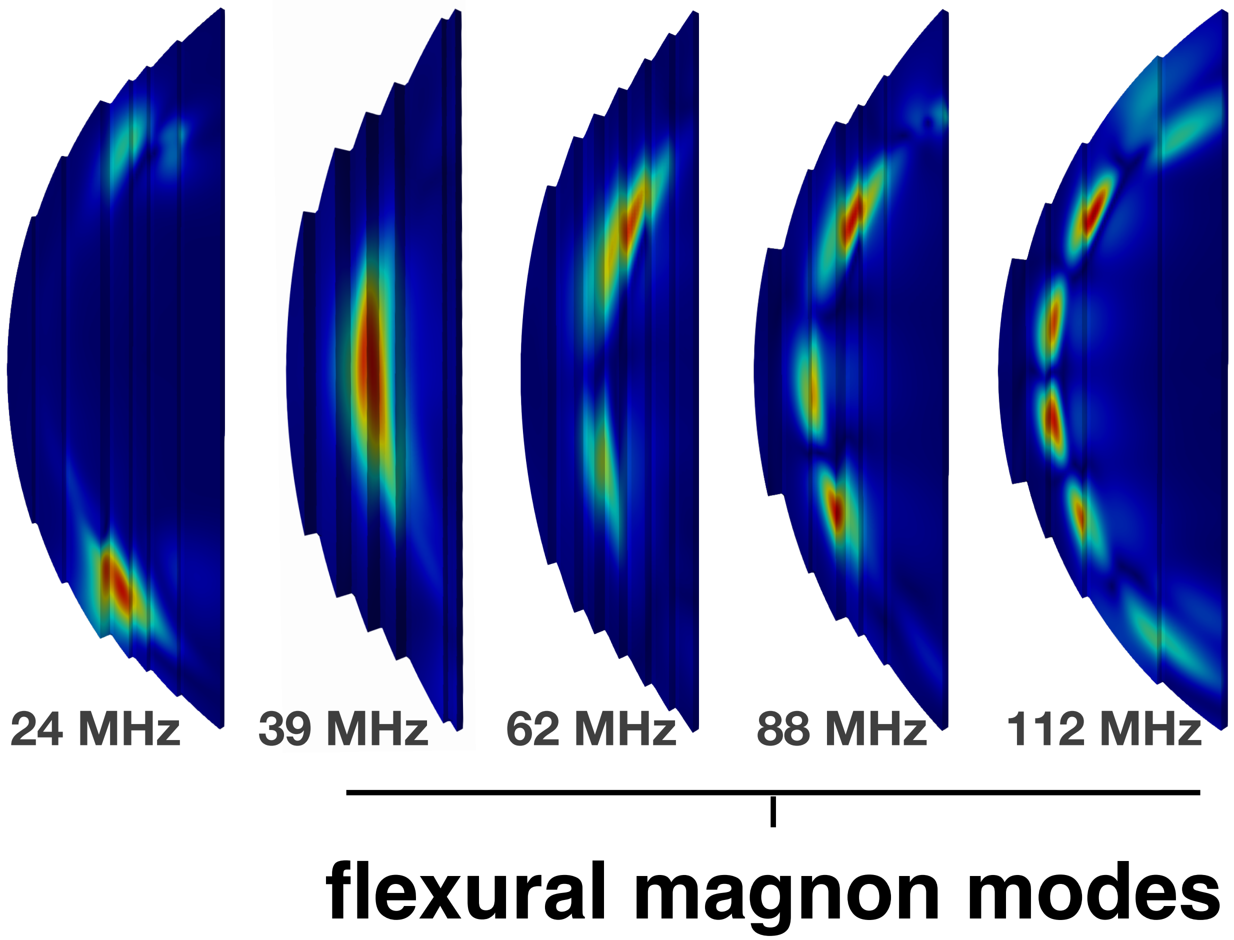
$$R = 2\mu\text{m}$$
$$h = 500\text{nm}$$

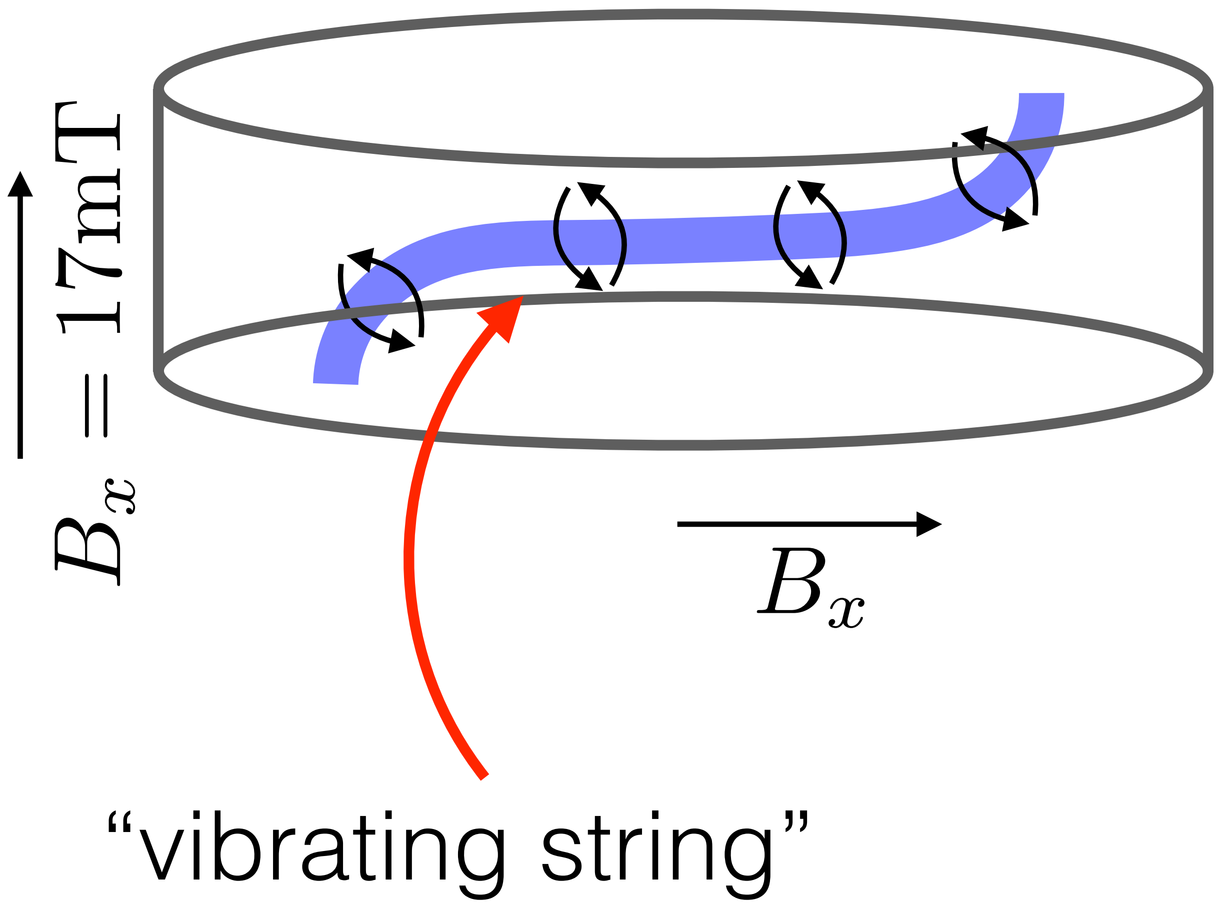
YIG disk: magnons
+ optical cavity



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

Optomagnonic coupling: beyond 2D





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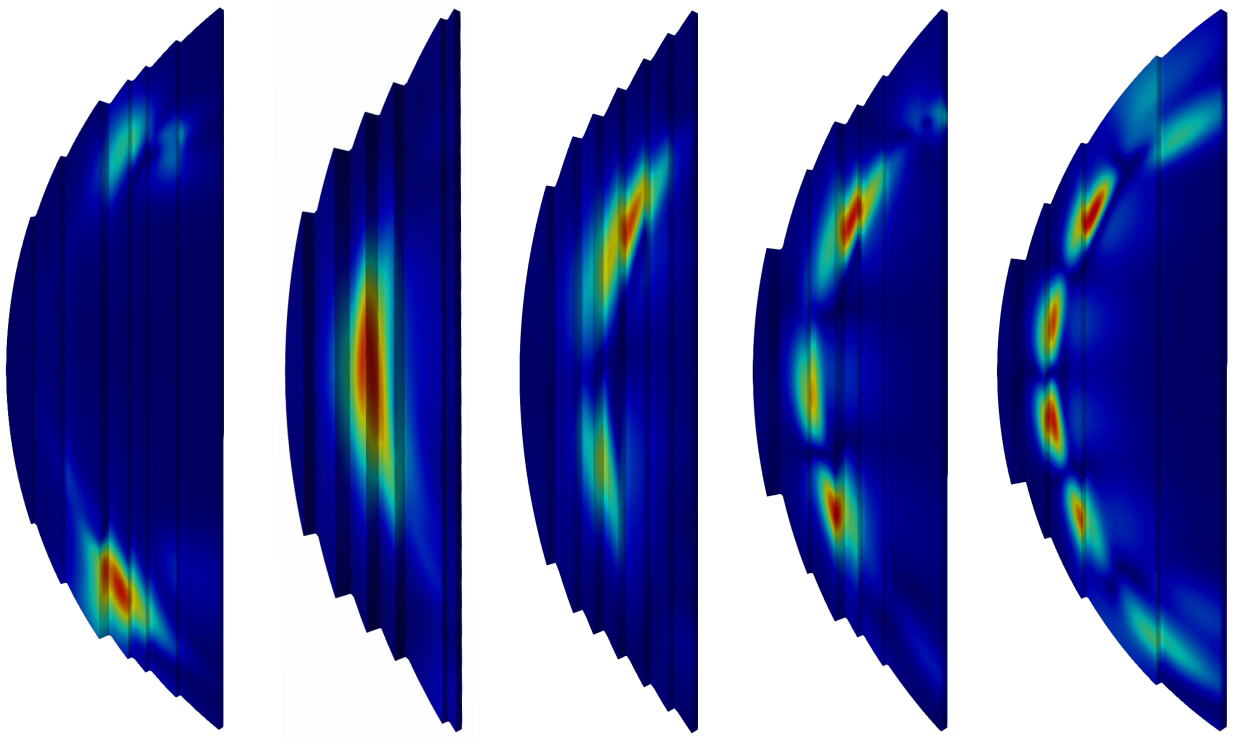
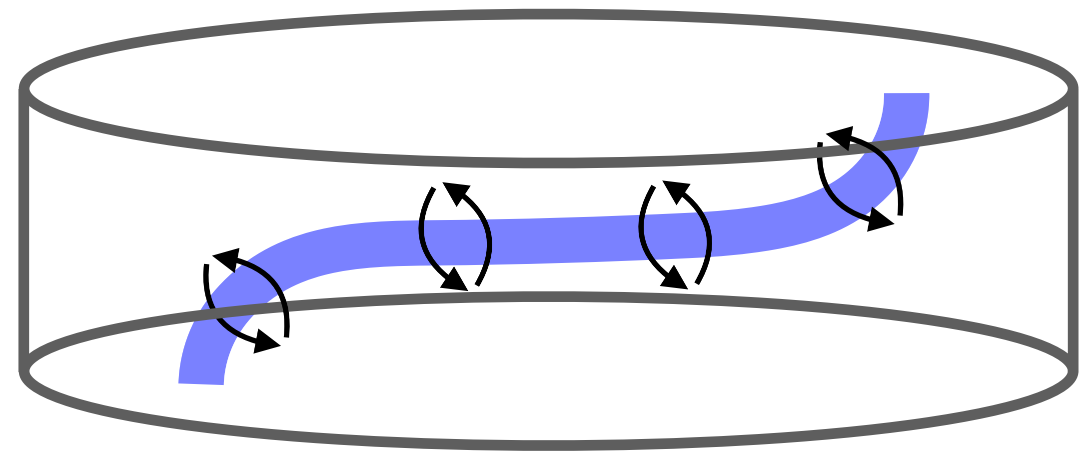
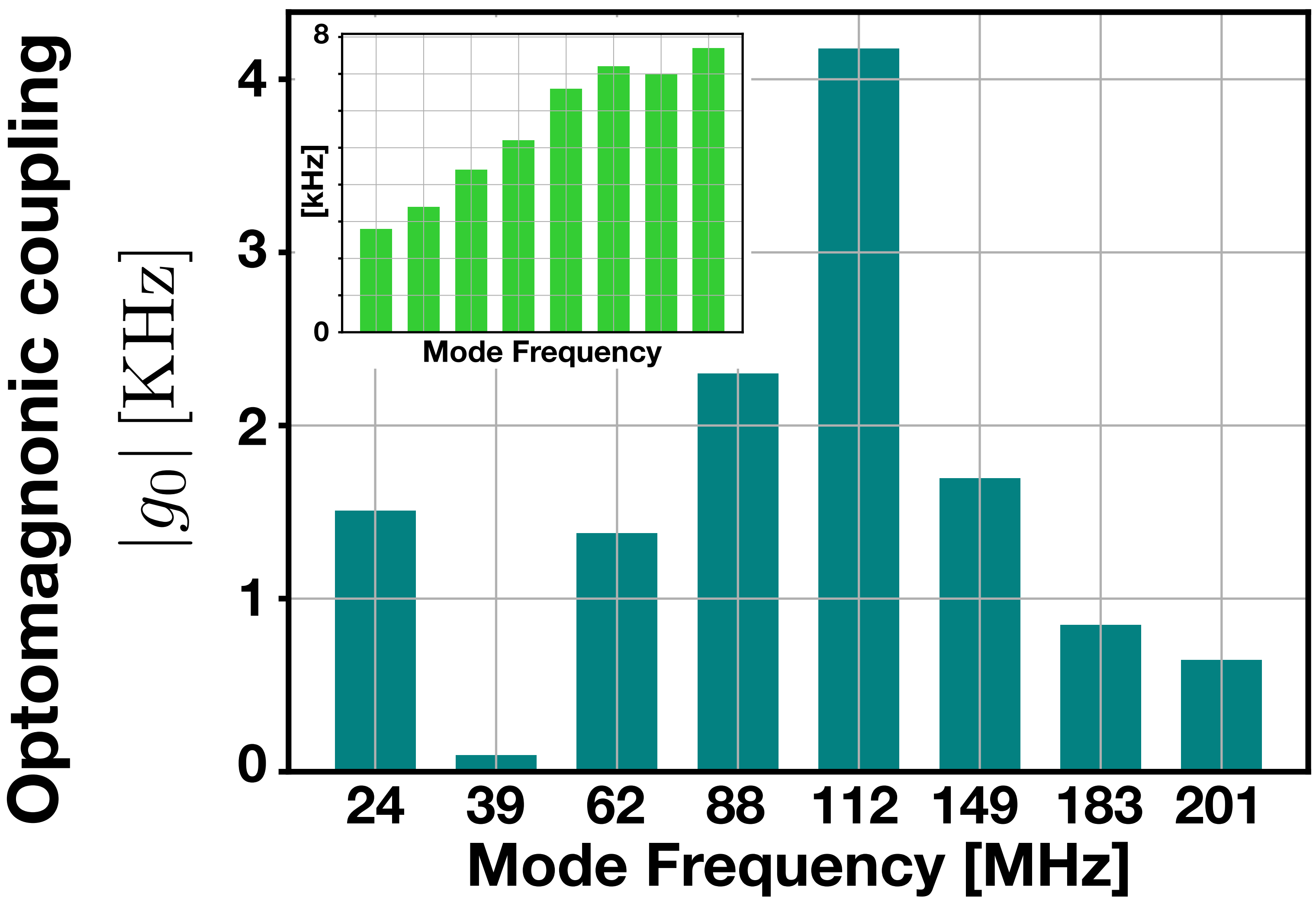
Optomagnonic coupling: beyond 2D

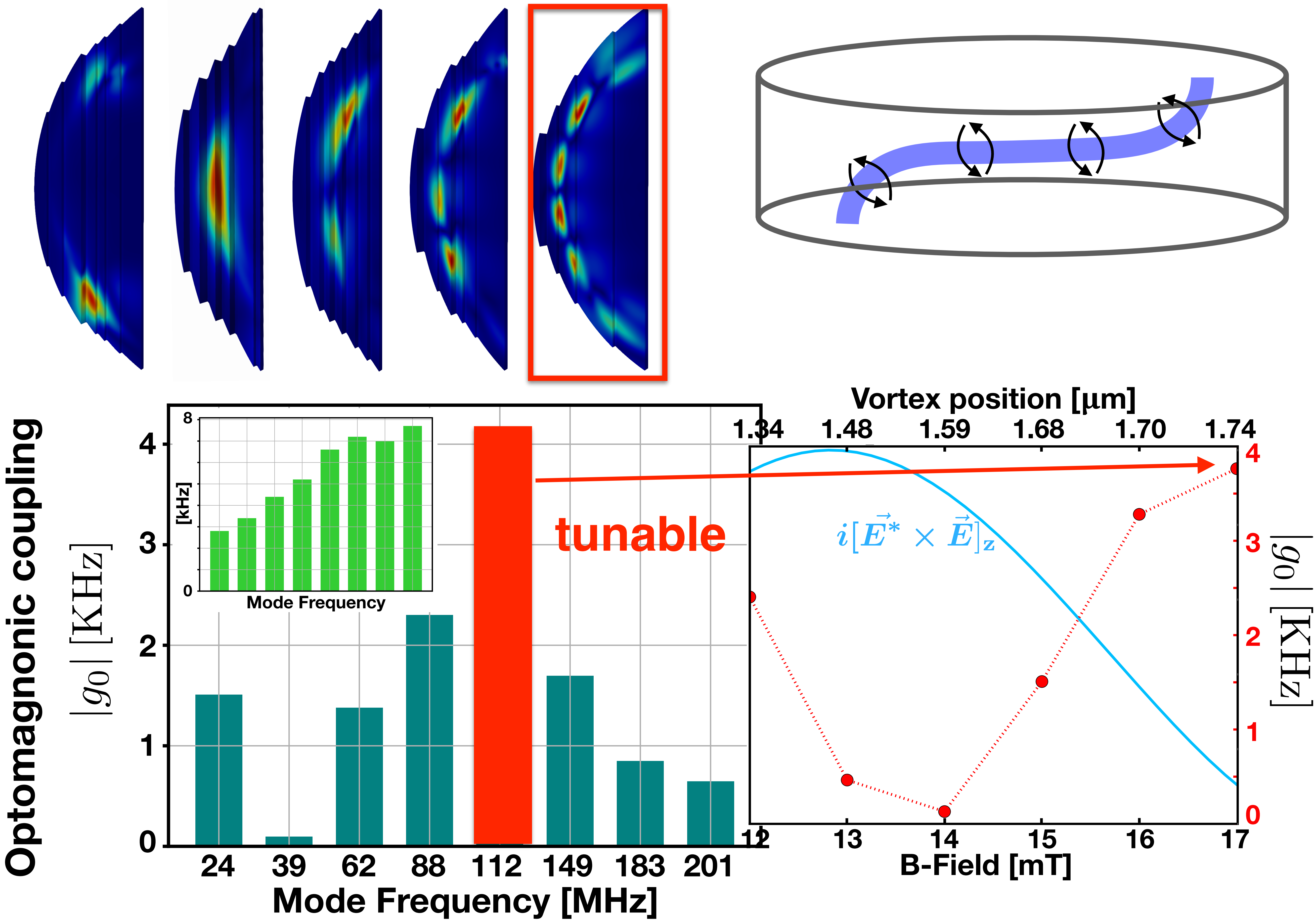




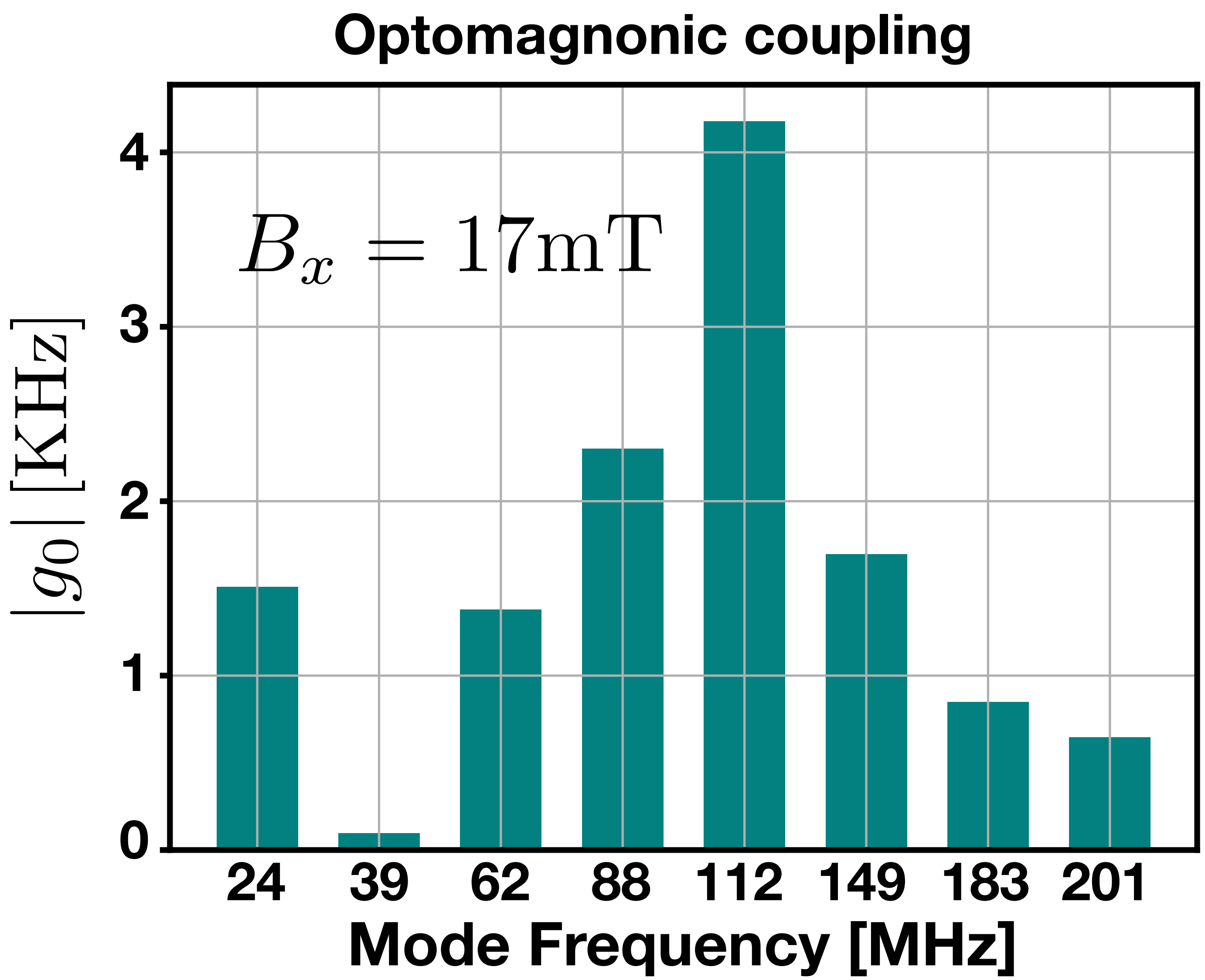
$B_x = 17\text{mT}$

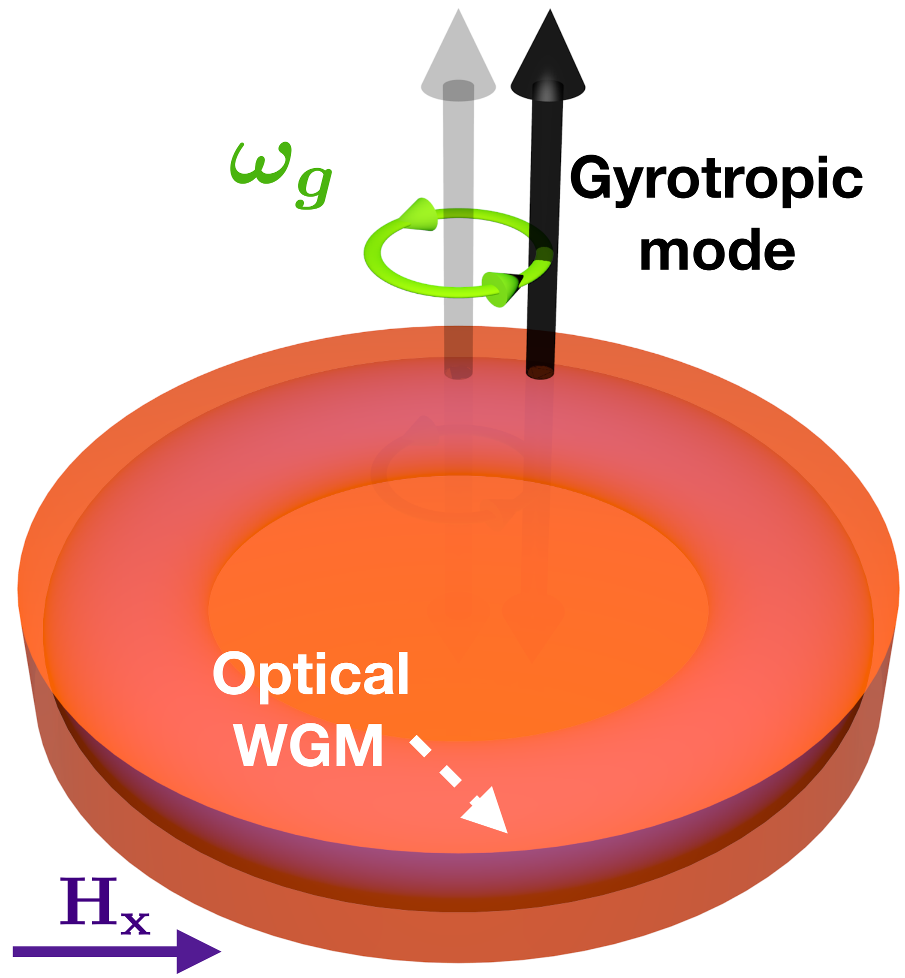


Optomagnonic coupling: beyond 2D



Optomagnonic coupling: beyond 2D



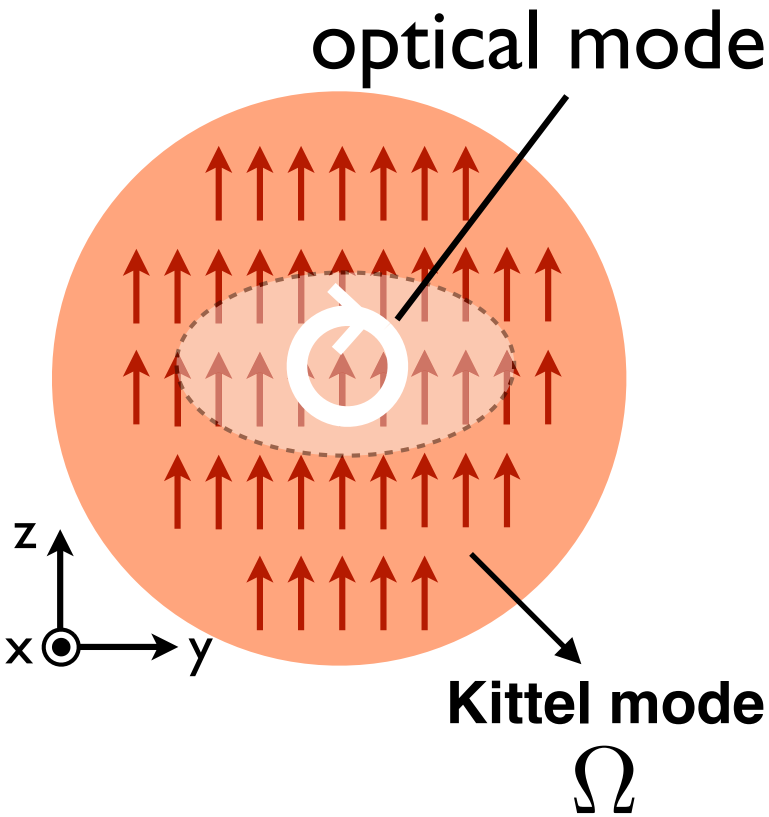


- First time optomagnonics with textures
- Promising values for coupling, tunable - design!
- Coupled Dynamics?

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

Coupled dynamics?

Cavity Optomagnonics: simple model



Simplest Coupling $\hbar G \hat{S}_x \hat{a}^\dagger \hat{a}$

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

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

driving laser detuning

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

Effective Equation of Motion for a Macrospin

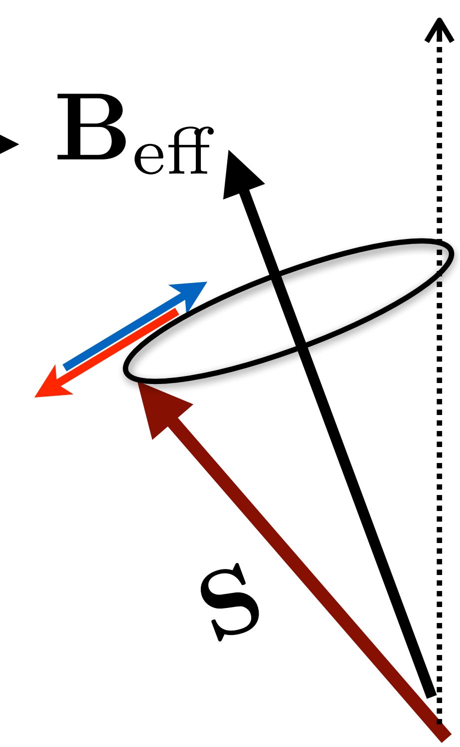
For the homogeneous (Kittel) mode

Fast cavity limit: integrate out the light field

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

Effective Landau-Lifshitz-Gilbert equation of motion

Optically induced
- magnetic field → $\mathbf{B}_{\text{eff}}$
- 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

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

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

damping

can change sign

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

tunable by the external laser drive

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

Fast Cavity Limit

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can change sign

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

with textures and defects?

tunable by the external laser drive

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