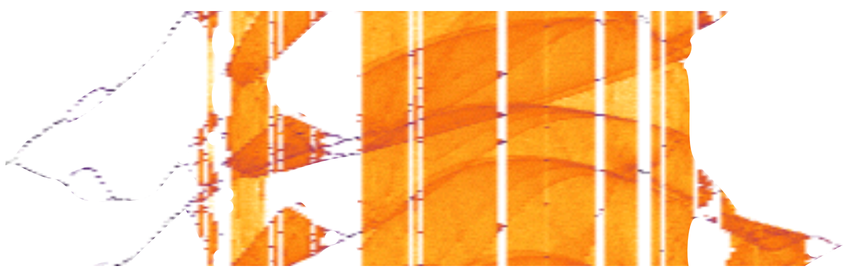
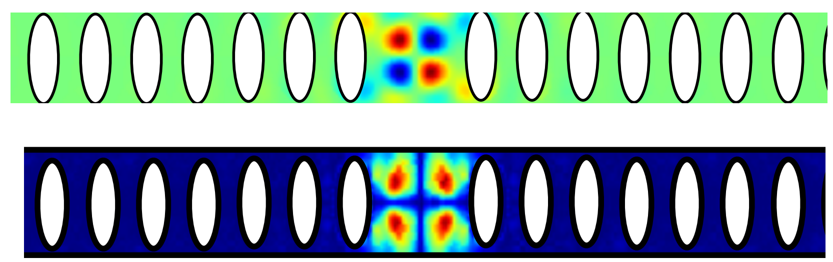
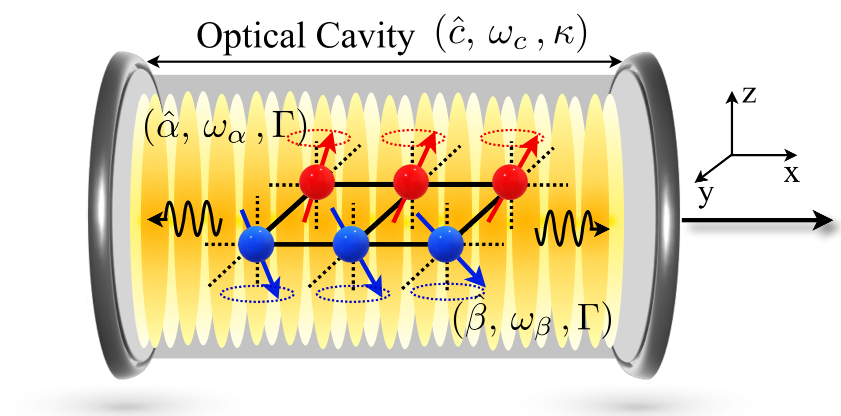
Cavity Optomagnonics







Silvia Viola Kusminskiy

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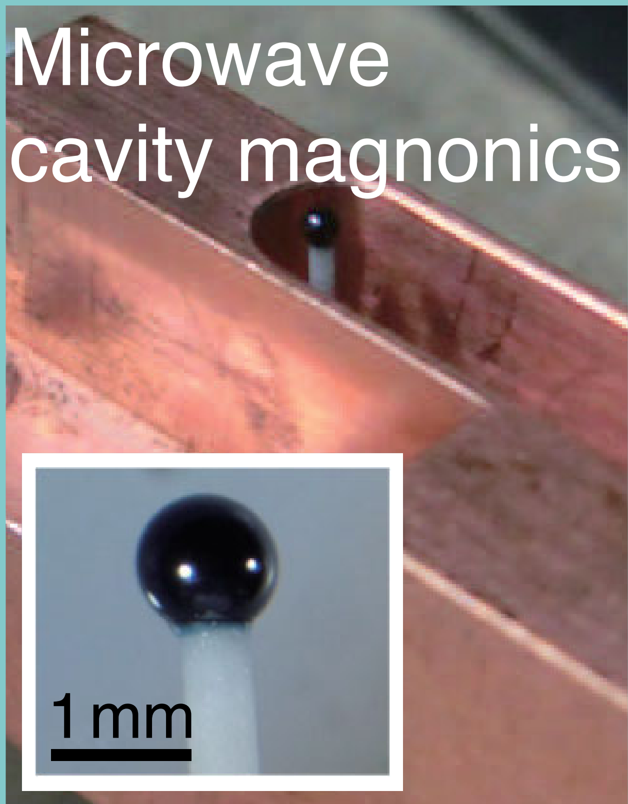
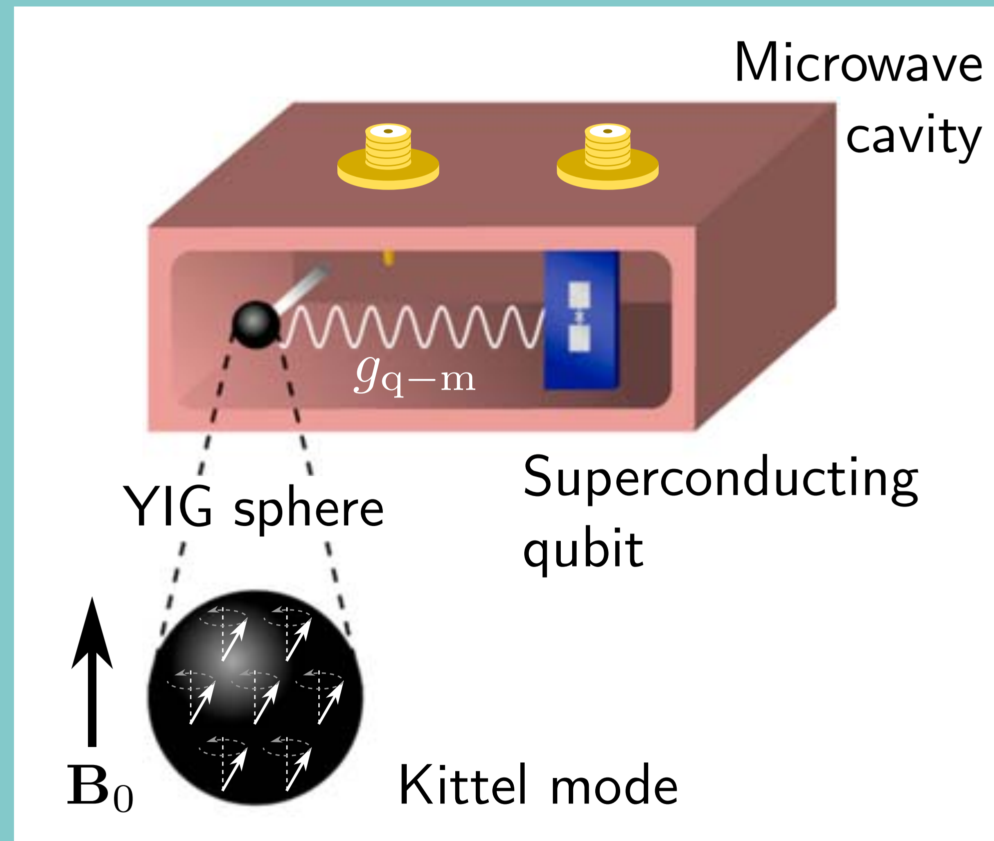
Theory of hybrid quantum systems

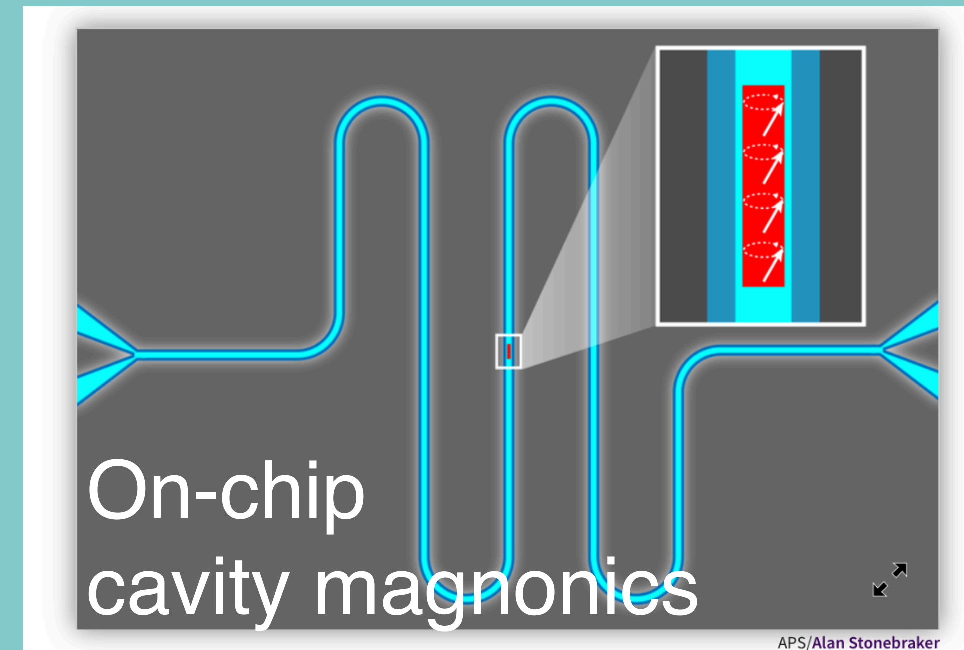
Hybrid quantum systems based on magnetic elements

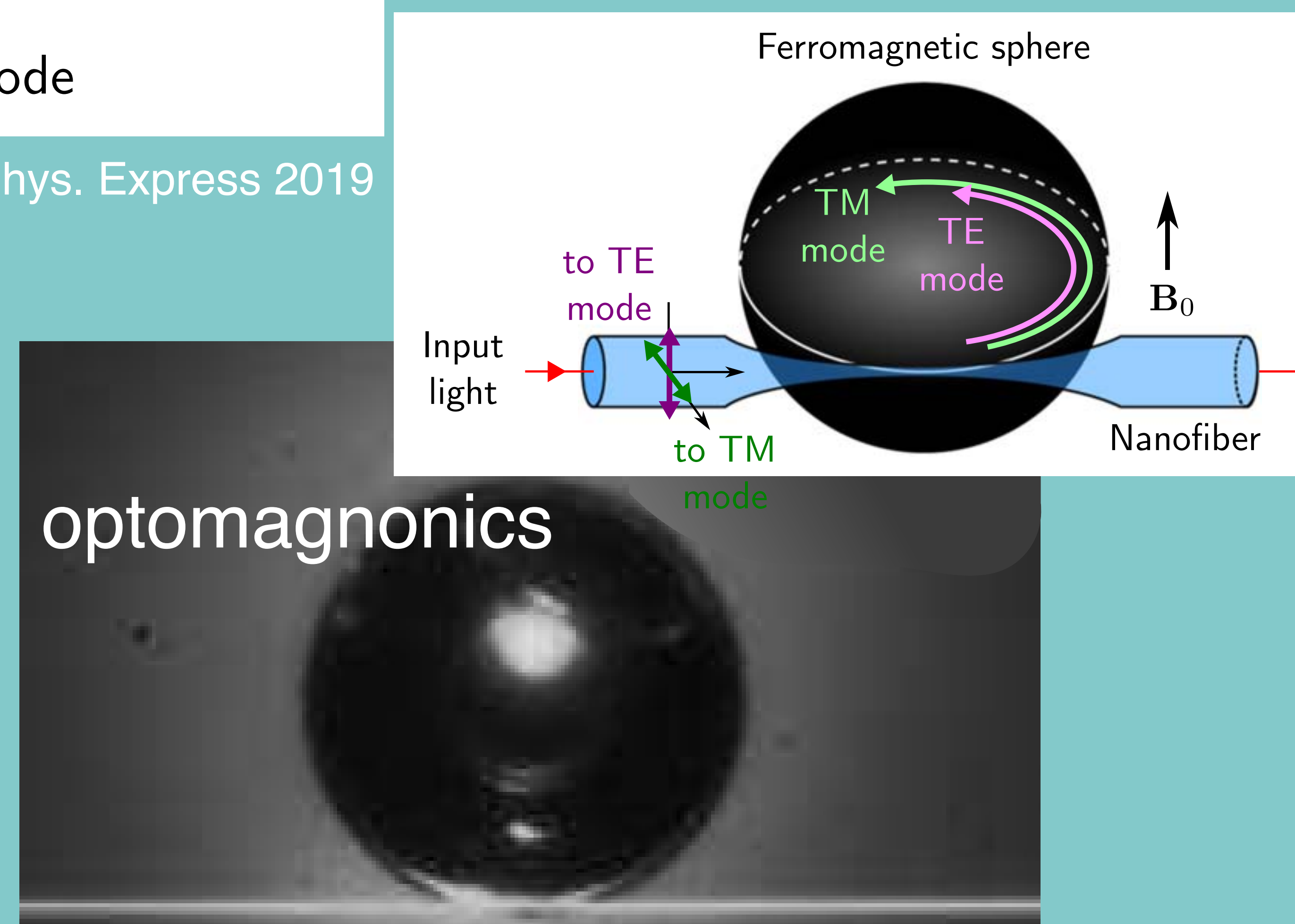


Tabuchi et. al PRL 2014

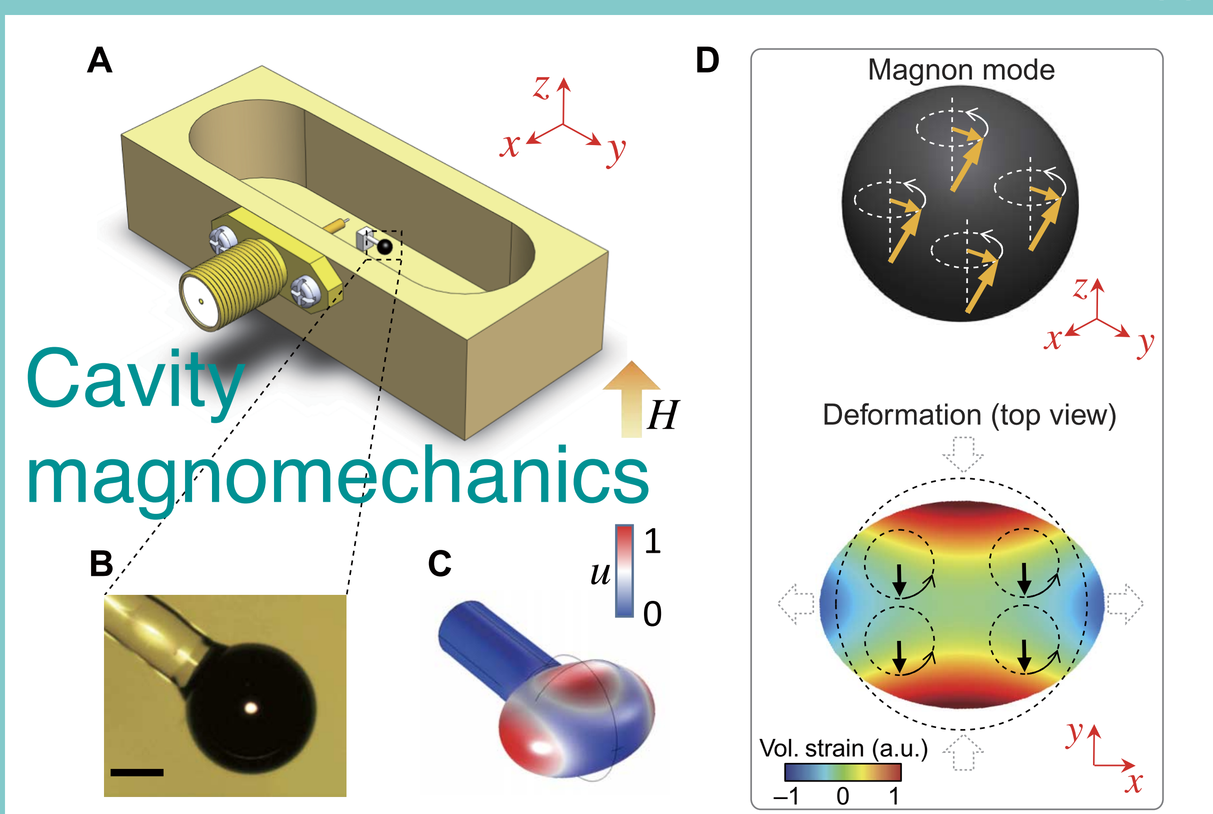


Lachance Quirion et. al Appl. Phys. Express 2019





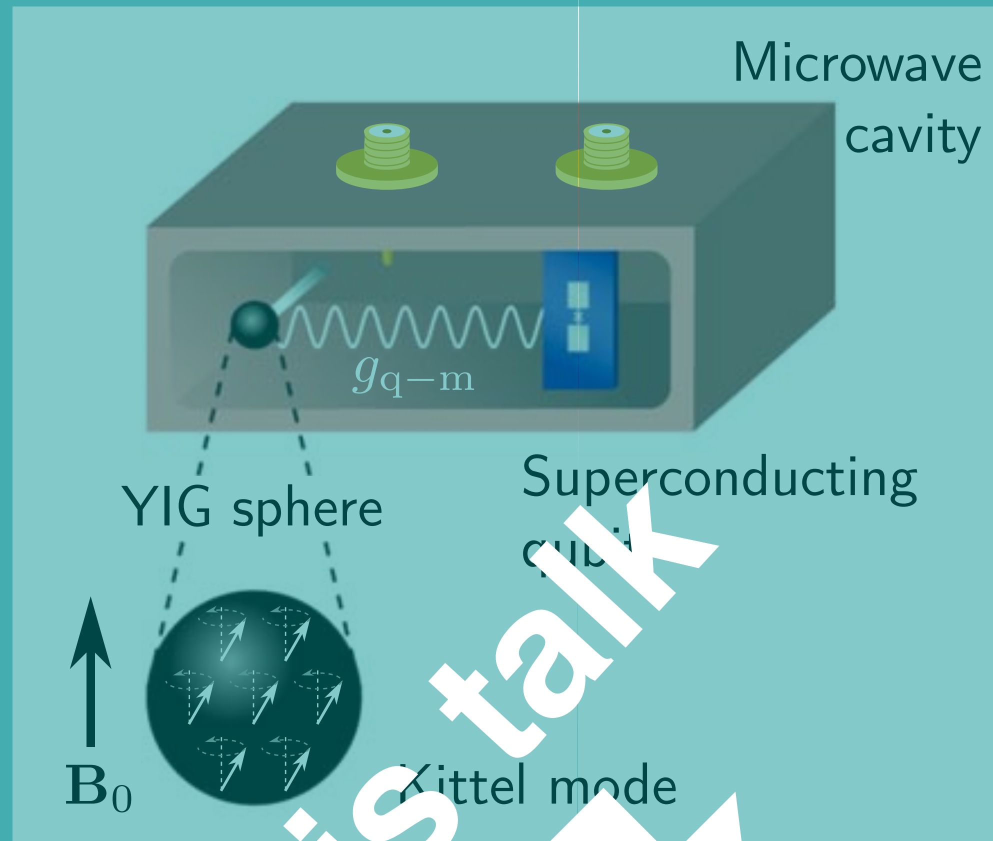
Osada et. al PRL 116 2016



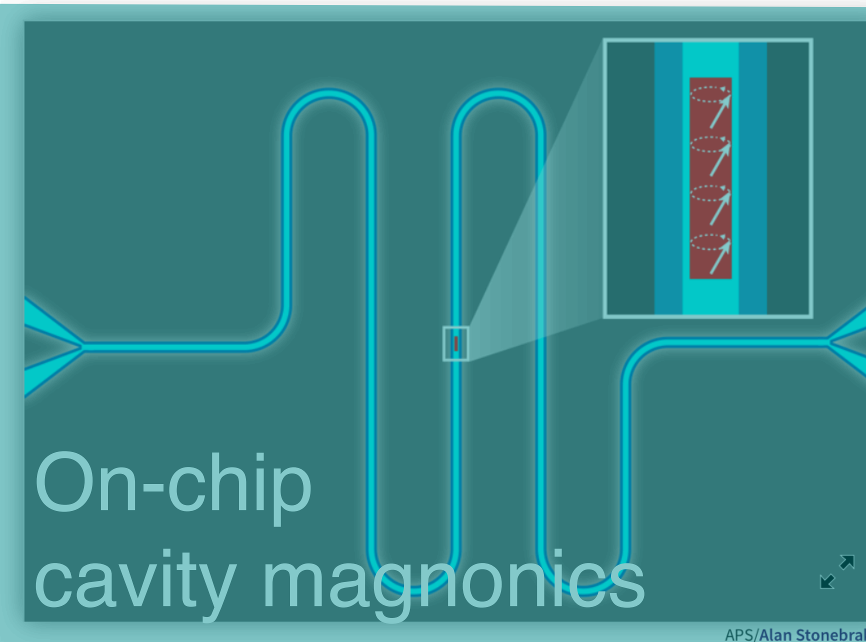
Zhang et. al Science Advances 2016

Hybrid quantum systems based on magnetic elements

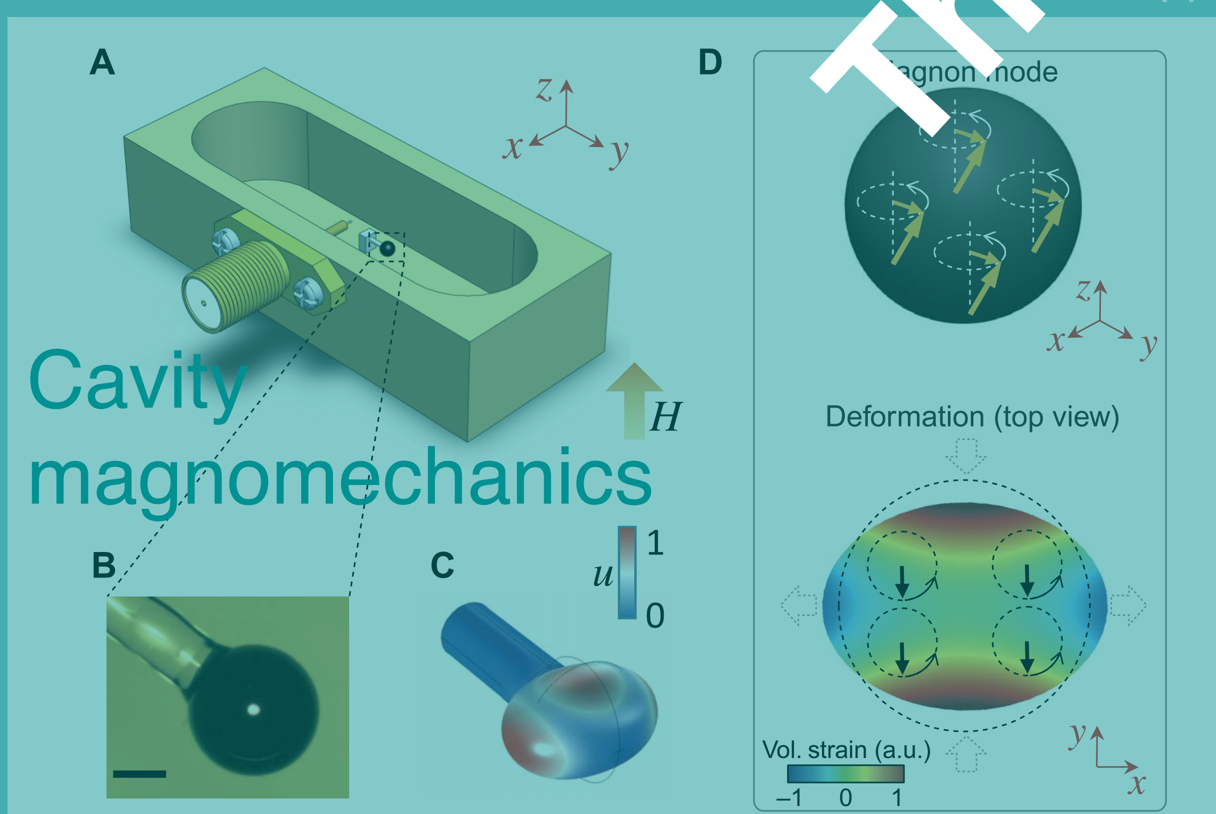
Tabuchi et. al PRL 2014



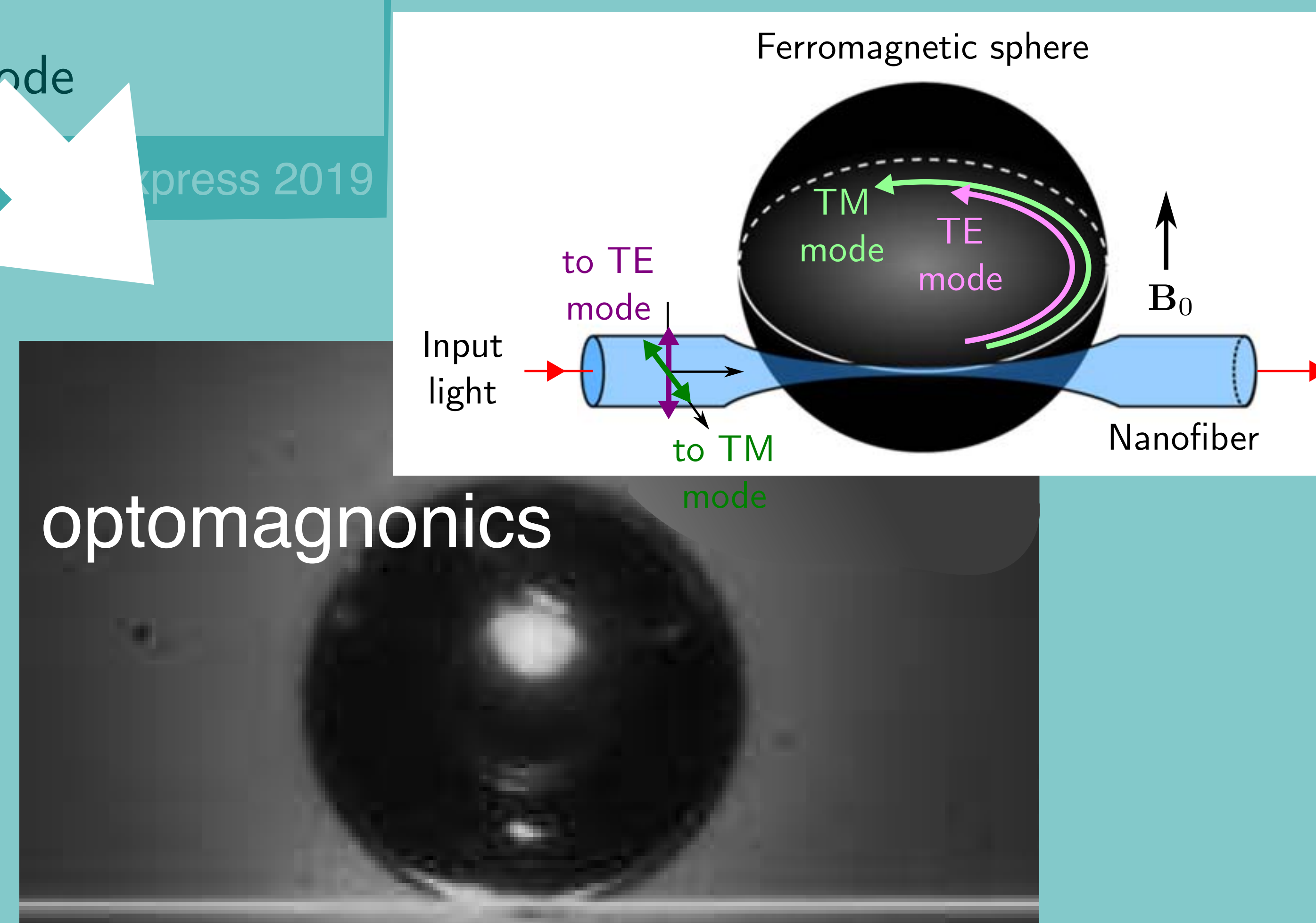
Lachance Quirion et. al Appl. Phys. Express 2019



This talk

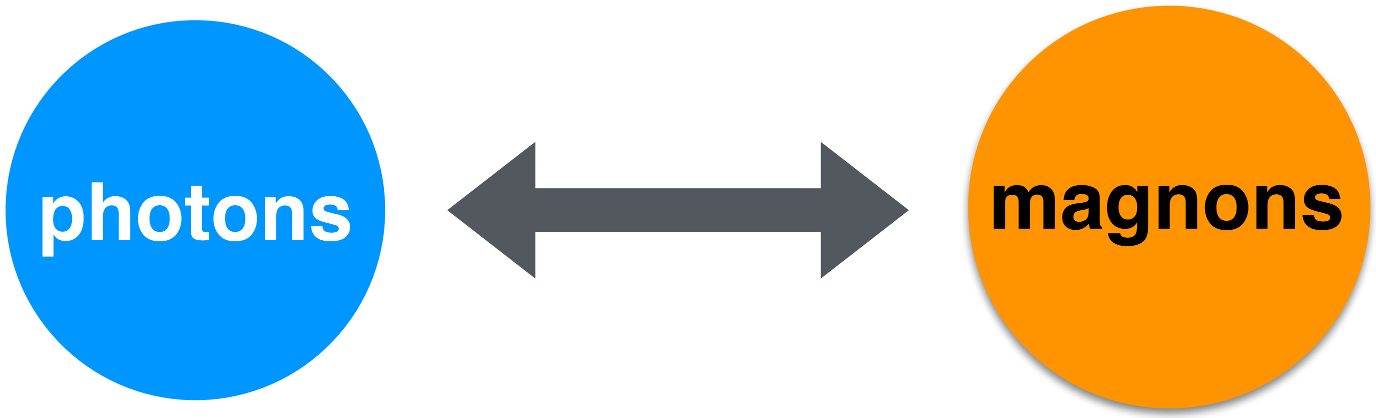


Zhang et. al Science Advances 2016

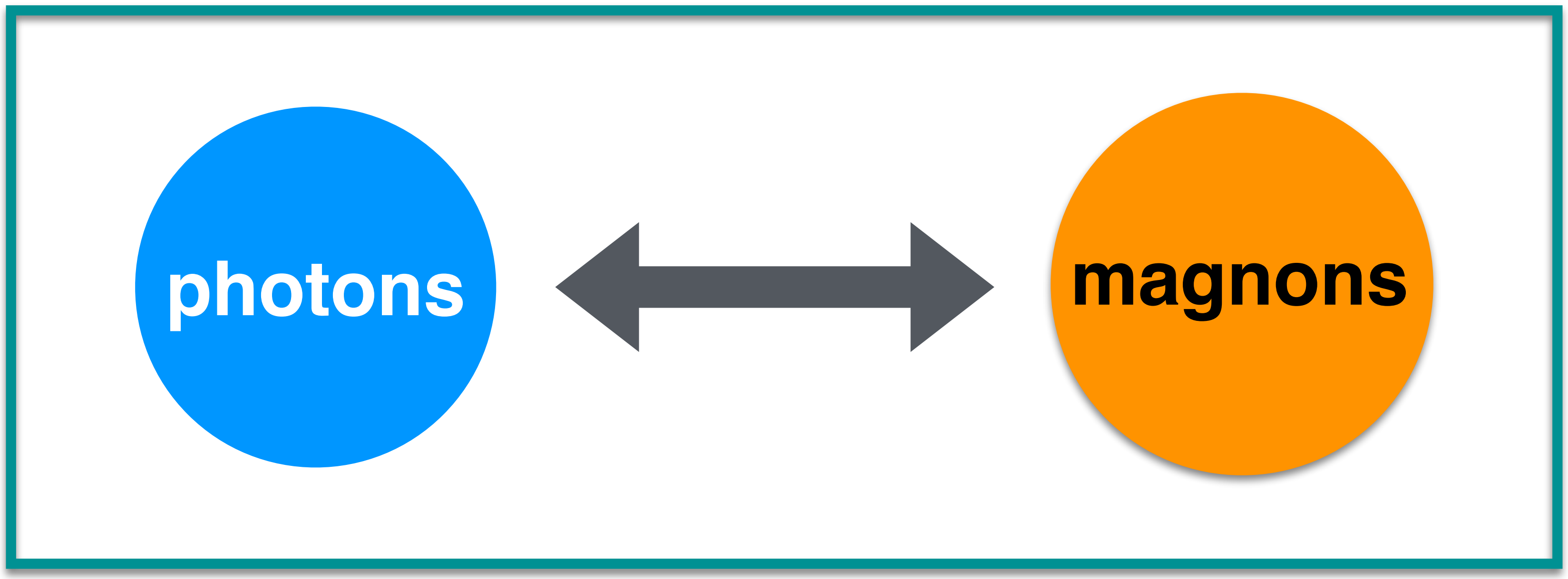


Osada et. al PRL 116 2016

Optomagnonics

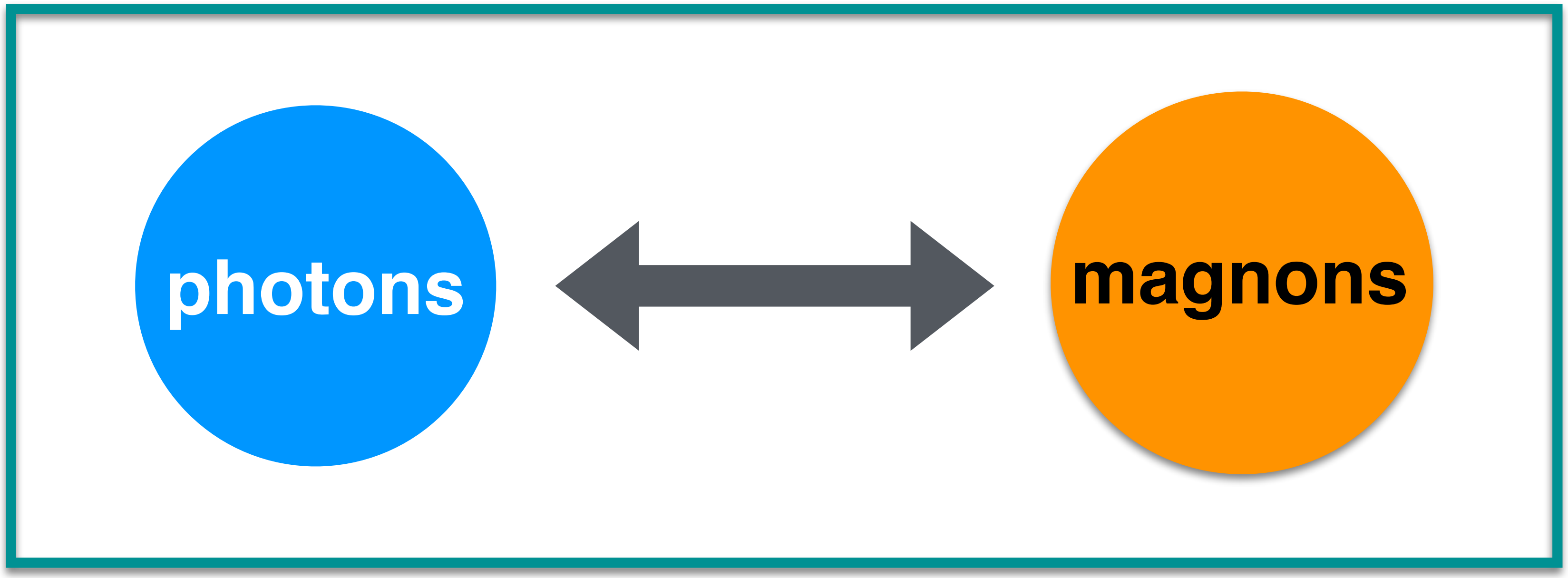


Cavity Optomagnonics



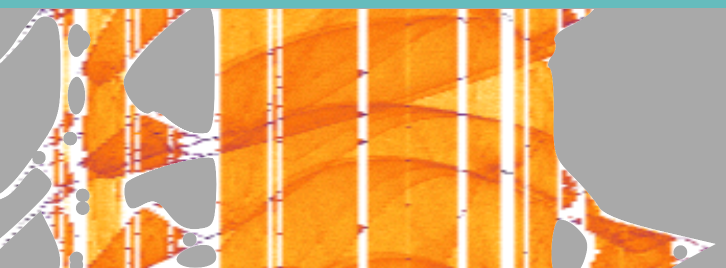
cavity-enhanced spin-photon interaction

Cavity Optomagnonics

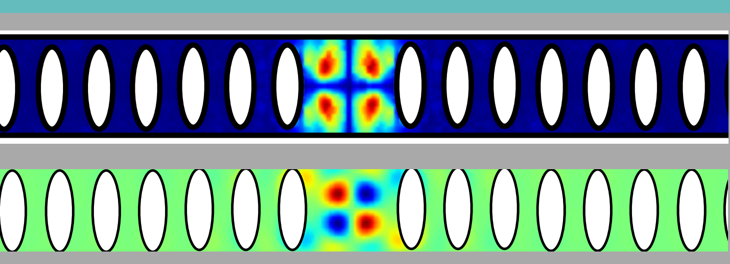


cavity-enhanced spin-photon interaction

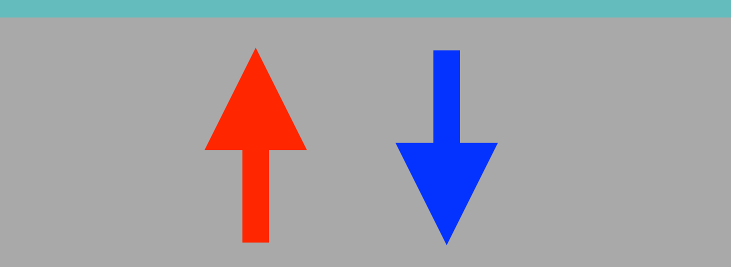
dynamical effects: frequency shifts, induced dissipation…



Optically induced spin dynamics



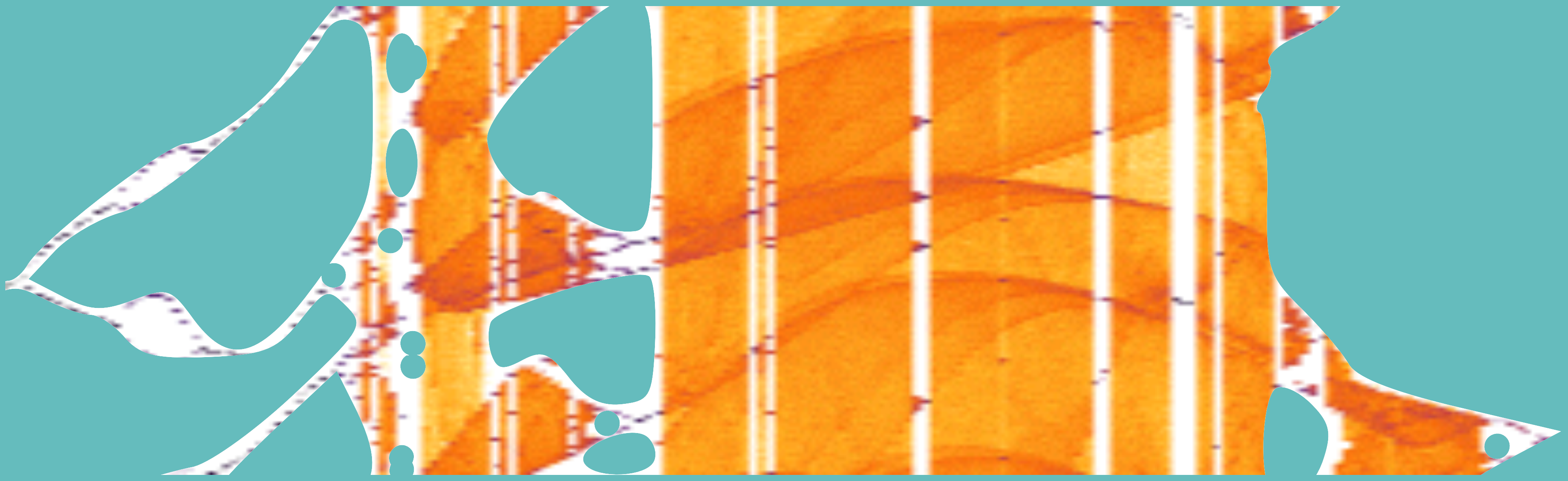
Optomagnonic crystals



AFM (cavity) optomagnonics

Outlook

Optically induced spin dynamics



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

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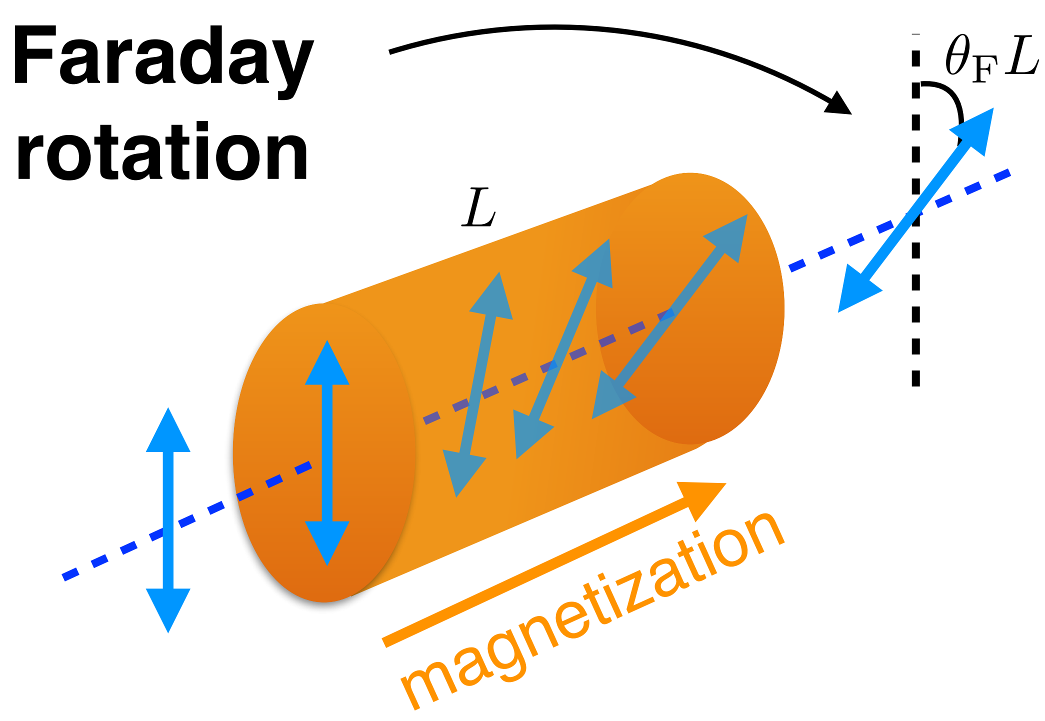
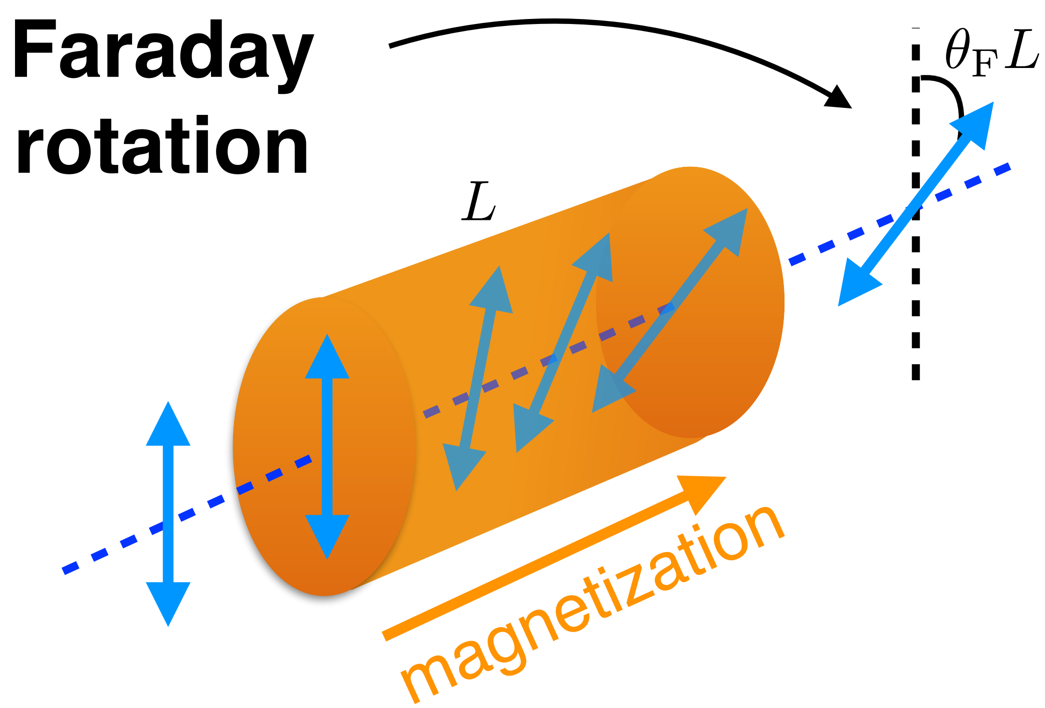
LUX ET VERITAS

Coupling to Optics?: Faraday Effect



Coupling to Optics?: Faraday Effect



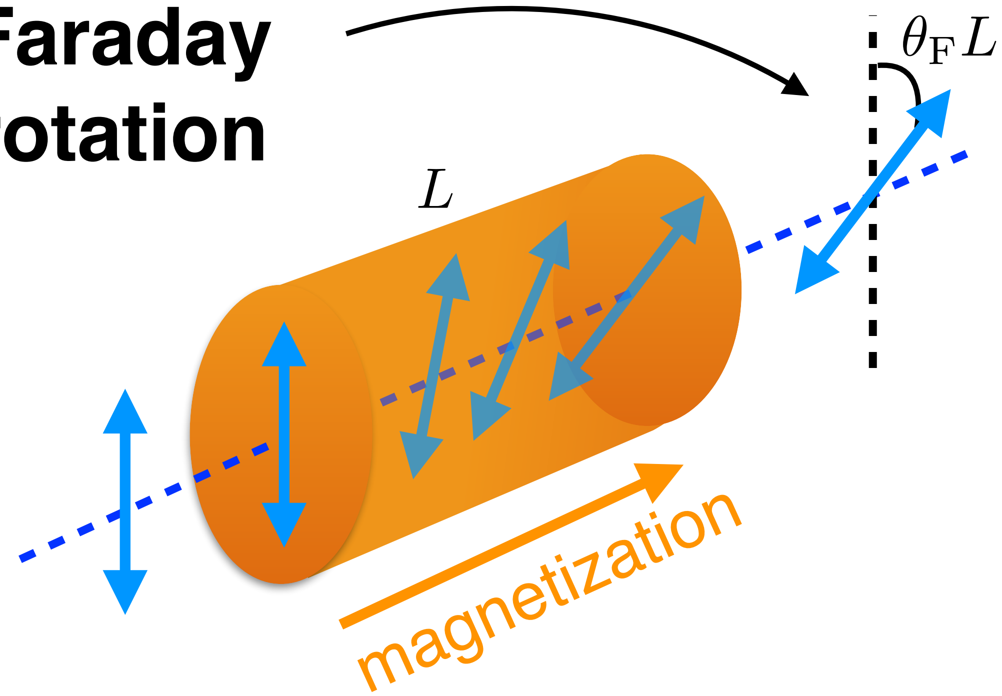
permittivity

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

broken time-reversal symmetry

Coupling to Optics?: Faraday Effect

Faraday rotation



permittivity

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

broken time-reversal symmetry

optical spin density

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

magnetization density

Optomagnonic Hamiltonian

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

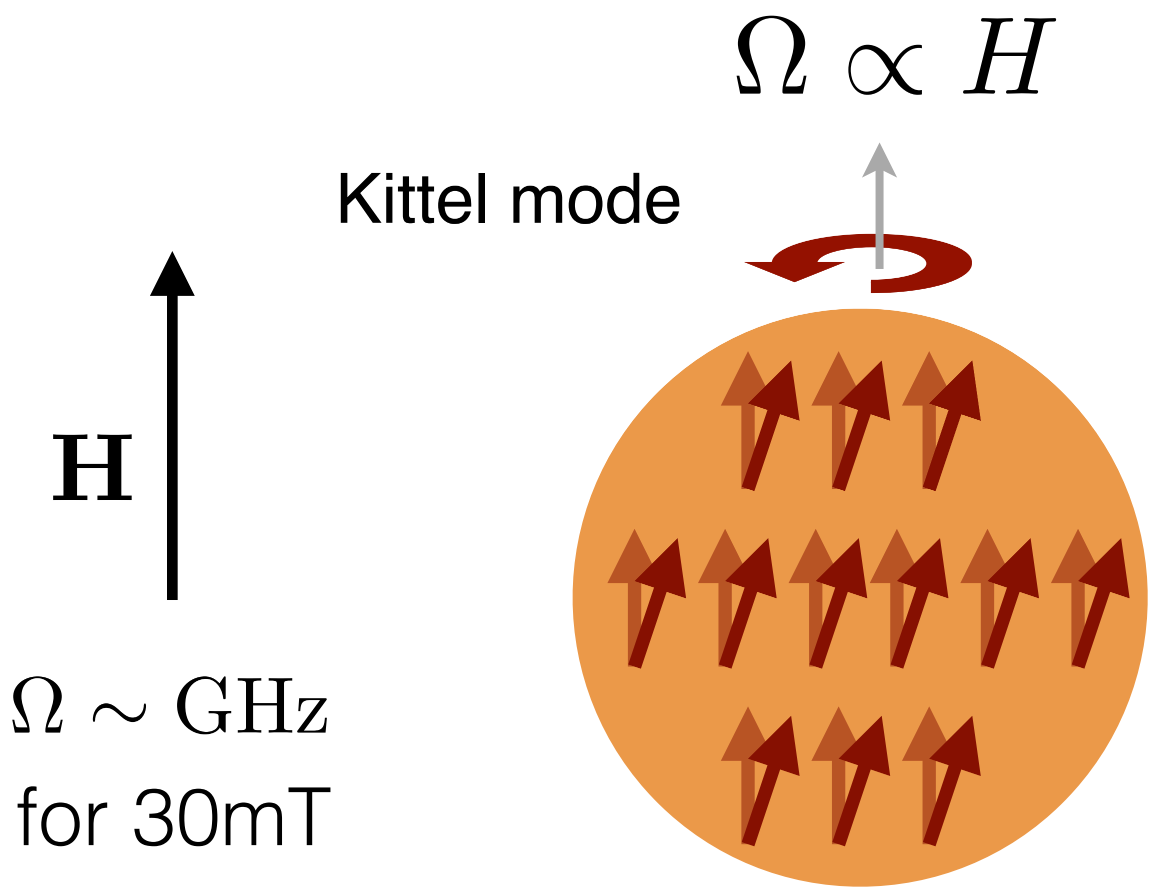
Quantize: $\hat{\mathbf{S}}$ $\hat{a}^\dagger$ $\hat{a}$

two-photon process

Optomagnonic Hamiltonian: Kittel Mode

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

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



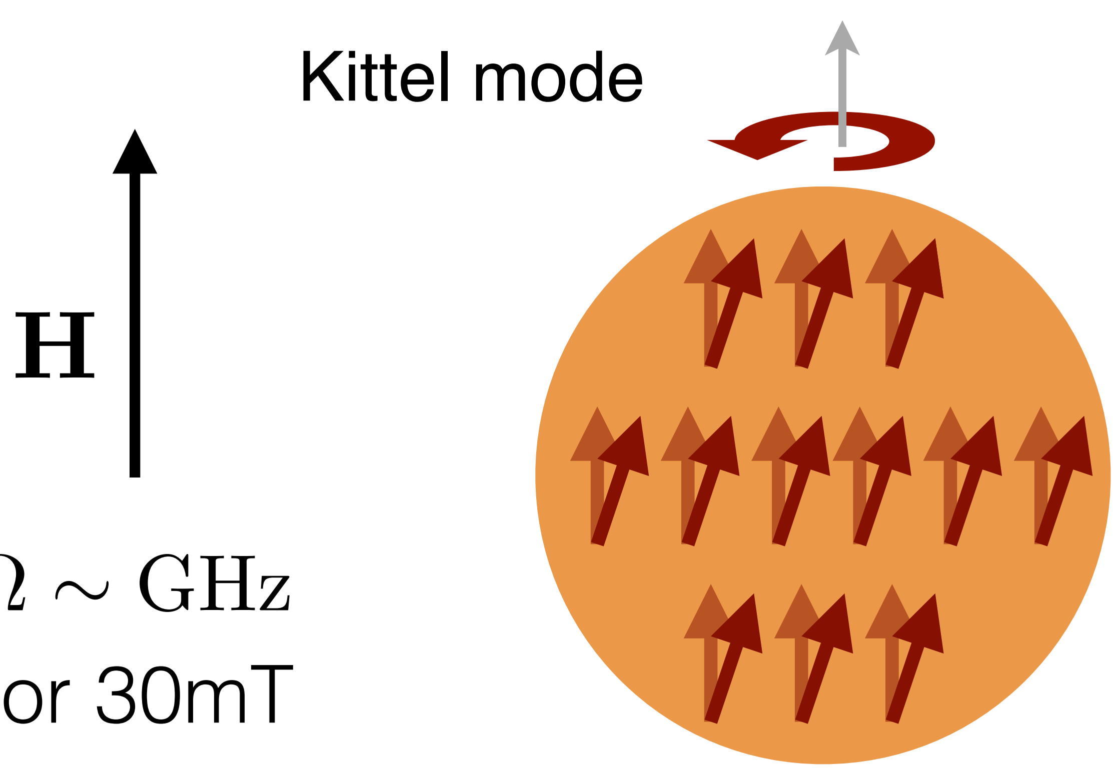
Optomagnonic Hamiltonian: Kittel Mode

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

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

$$\Omega \propto H$$

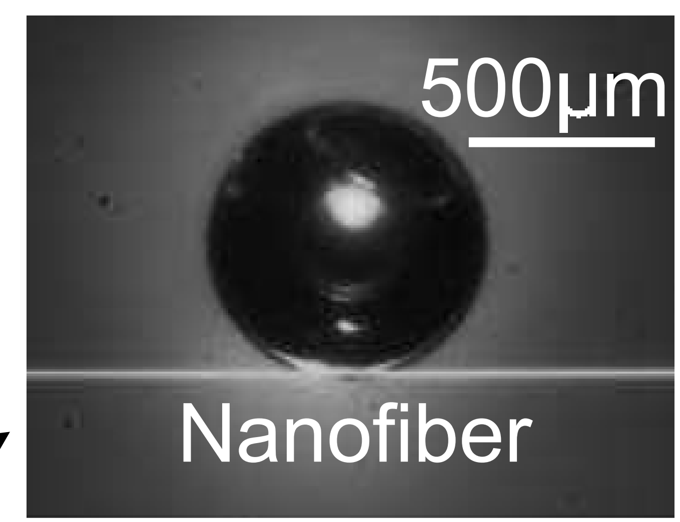
Kittel mode



$\Omega \sim \mathrm{GHz}$

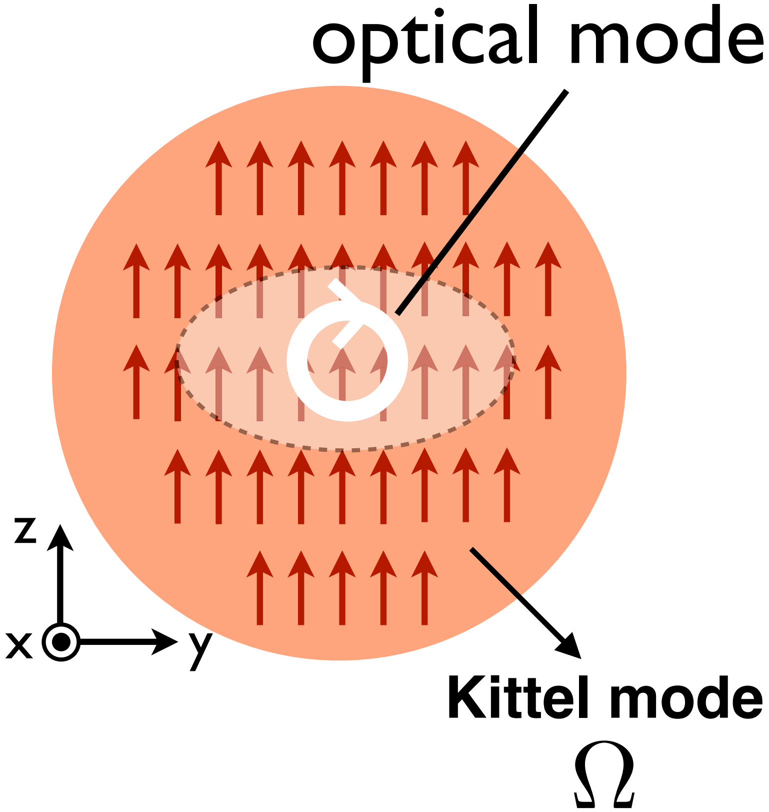
for 30mT

Yttrium Iron Garnet (YIG)



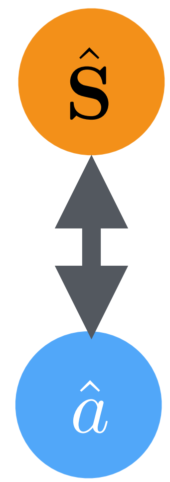
- Osada et. al PRL 116, 223601 (2016)
- Haigh et. al PRL 117, 133602 (2016)
- Zhang et. al PRL 117, 123605 (2016)

Cavity Optomagnonics: simple model



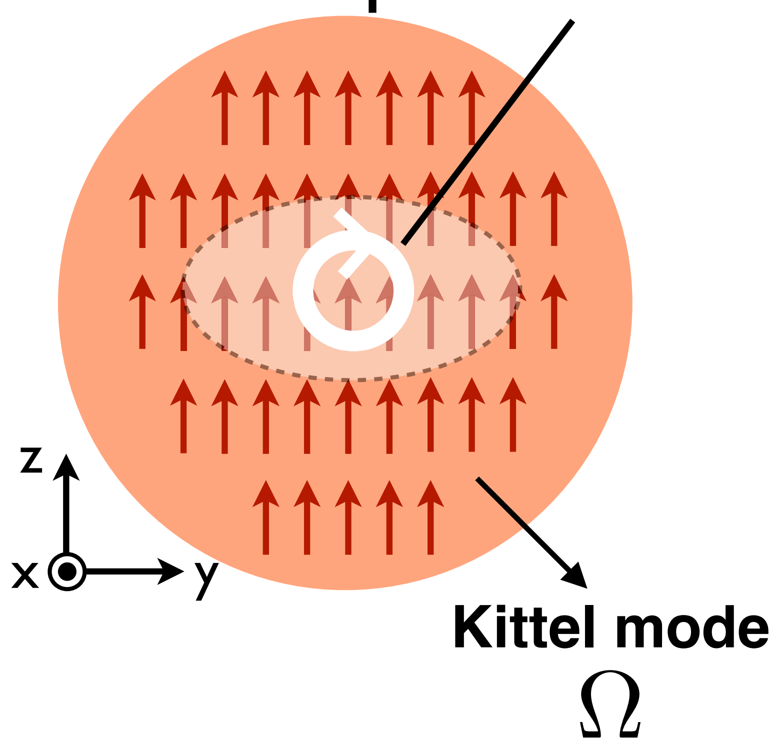
Simplest Coupling

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

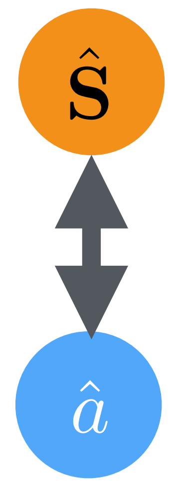


$$G = \frac{1}{S}\frac{c\,\theta_F}{4\sqrt{\varepsilon}}$$

Cavity Optomagnonics: simple model



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



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

driving laser detuning

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

Hamiltonian

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

in rotating frame

+ magnon and cavity decay rates

Γ κ

Fast Cavity Limit

Fast cavity limit: integrate out the light field

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

Effective Landau-Lifshitz-Gilbert equation of motion

effective field

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

frequency shift

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

damping

can change sign

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

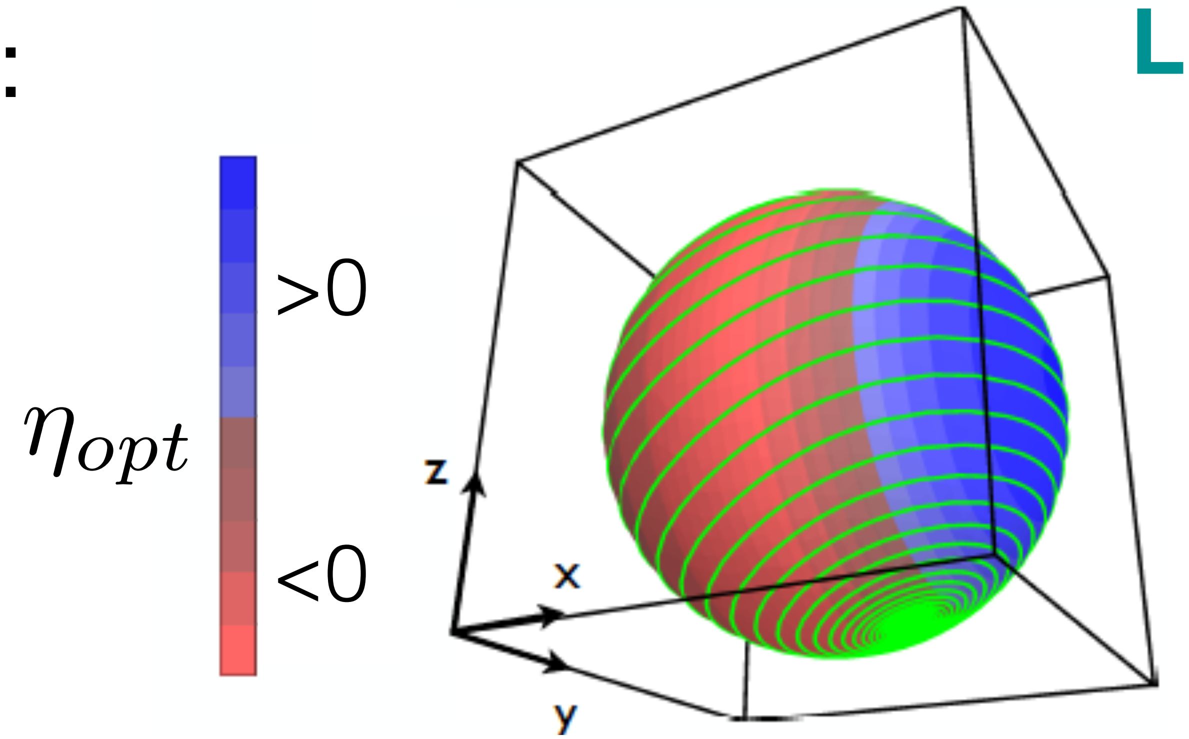
tunable by the external laser drive

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

Spin Dynamics: Fast Cavity Limit

Blue detuned case:

dissipation changes sign



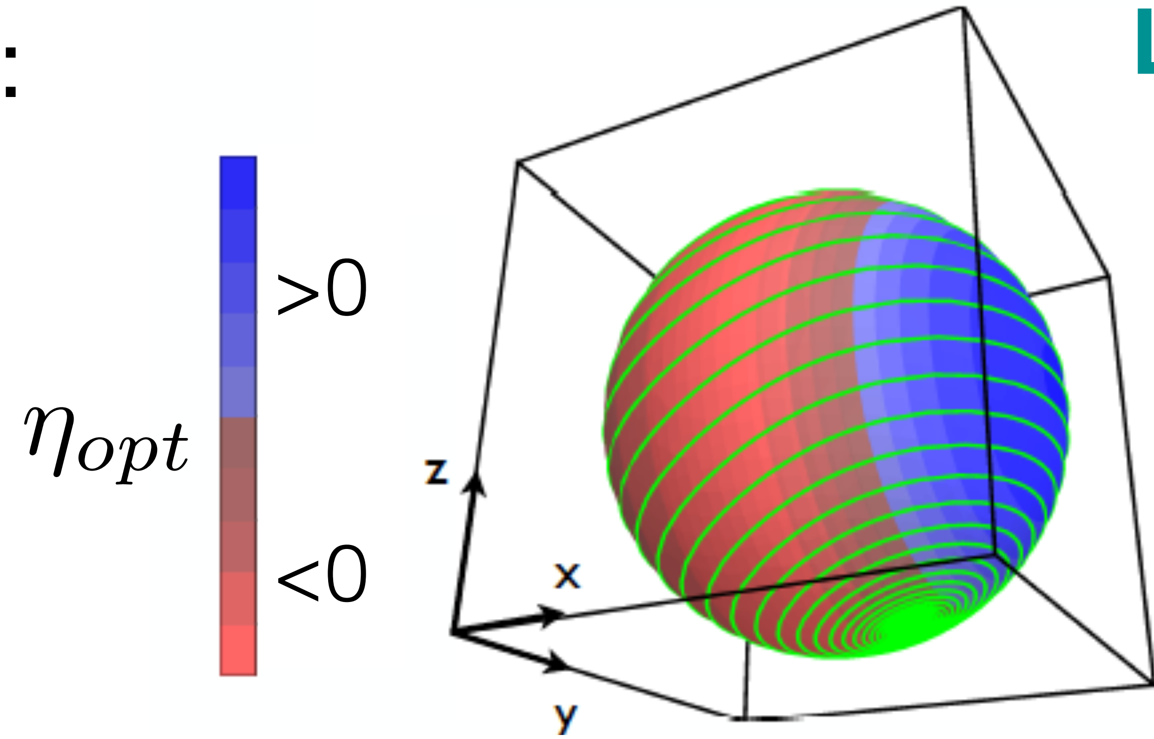
Light induced magnetic switching

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

Spin Dynamics: Fast Cavity Limit

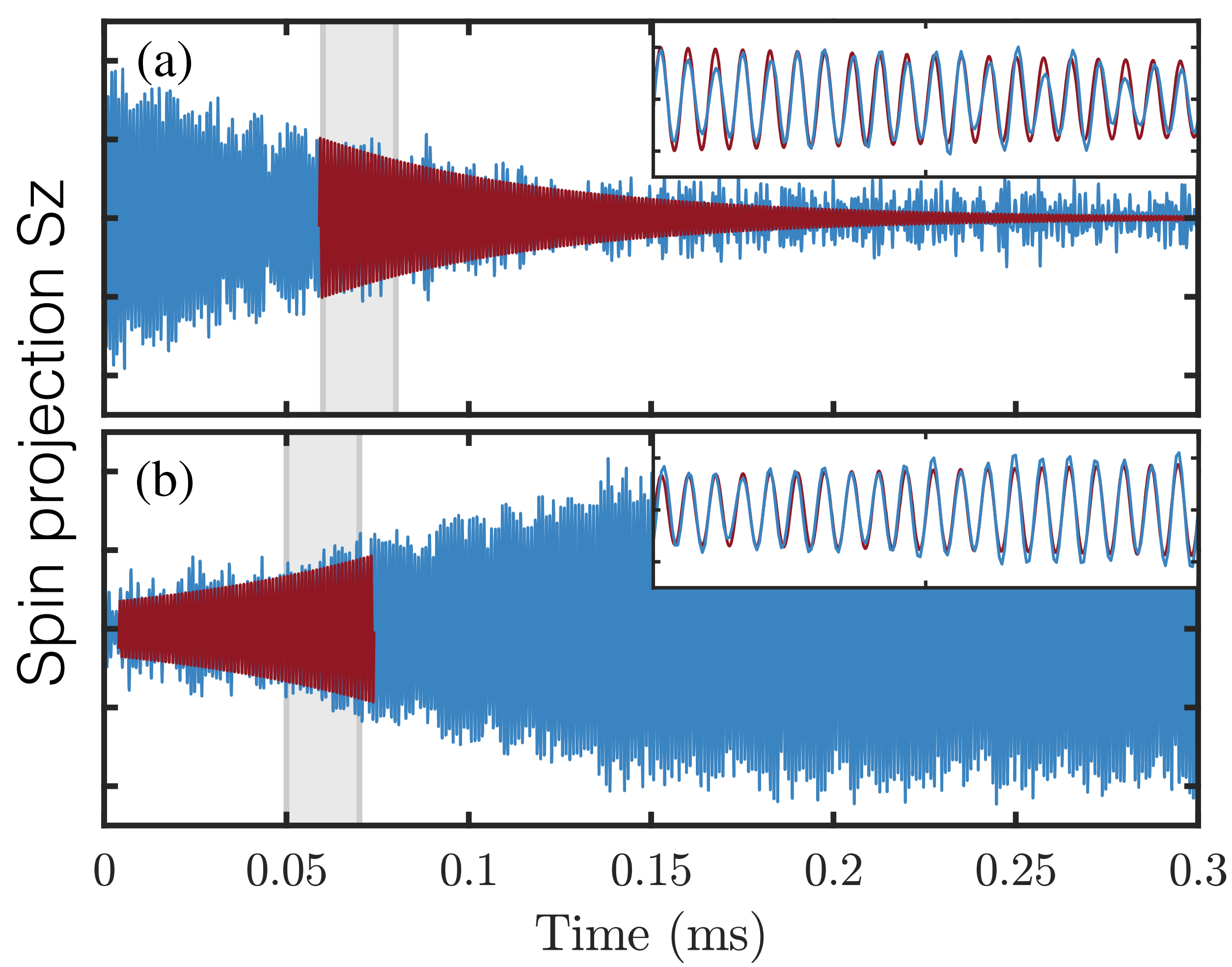
Blue detuned case:

dissipation changes sign



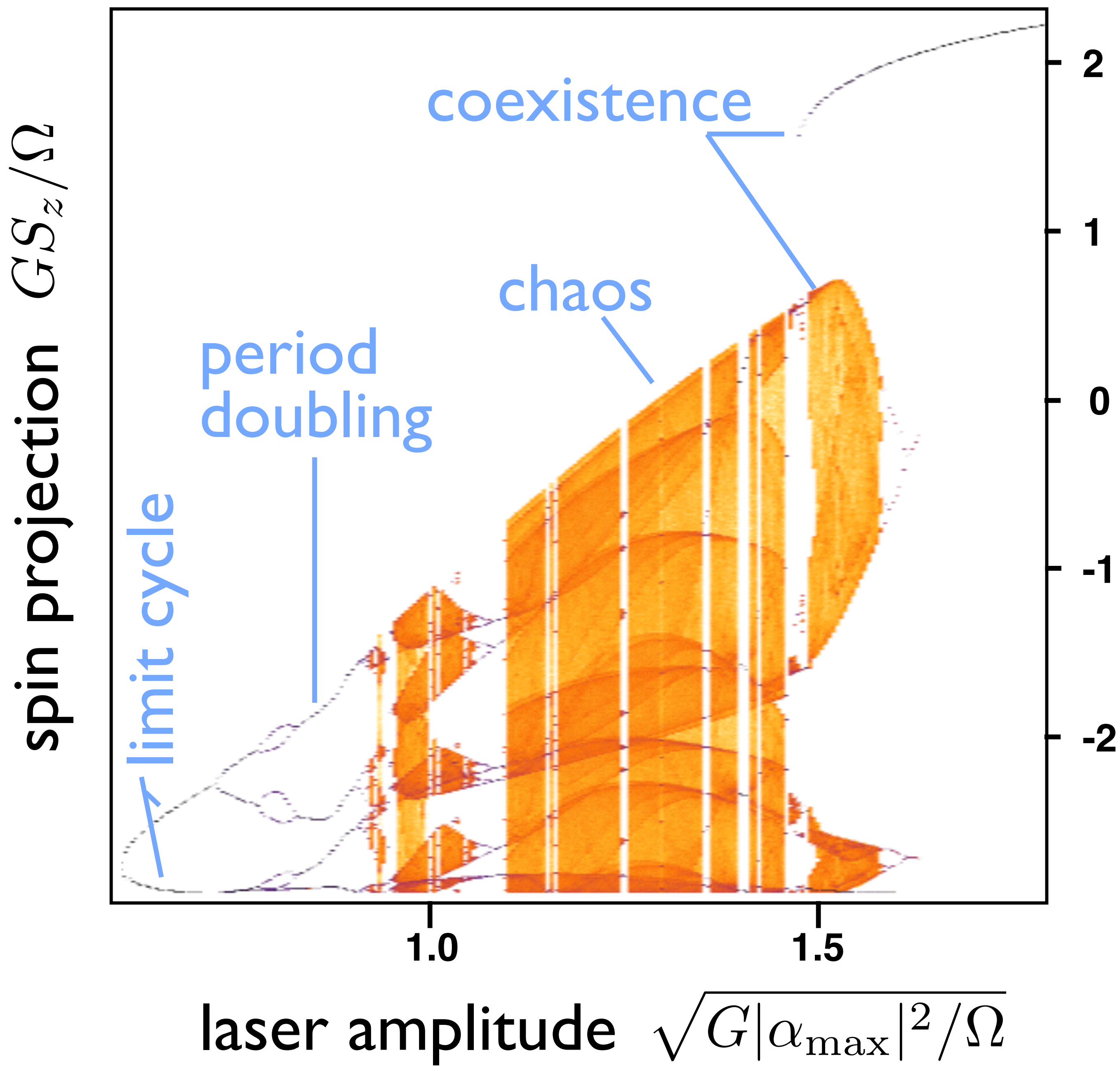
Light induced magnetic switching

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



Optically Induced Spin Dynamics

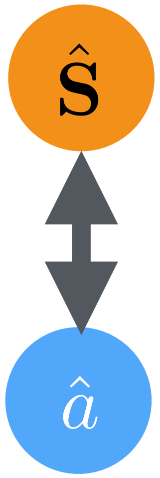
Classical Dynamics



- » **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)

But…



Problem

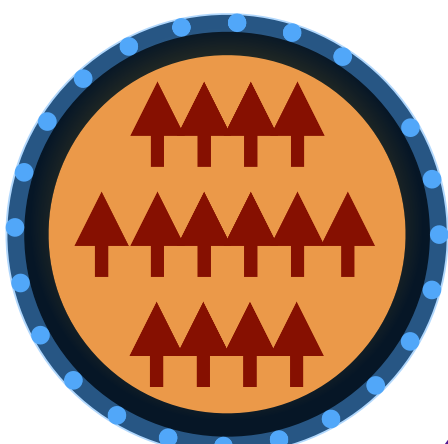
the state of the art optomagnonic coupling is small

We have shown that the theoretical limit is much larger

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

What we need:

better overlap of modes



?

smaller systems

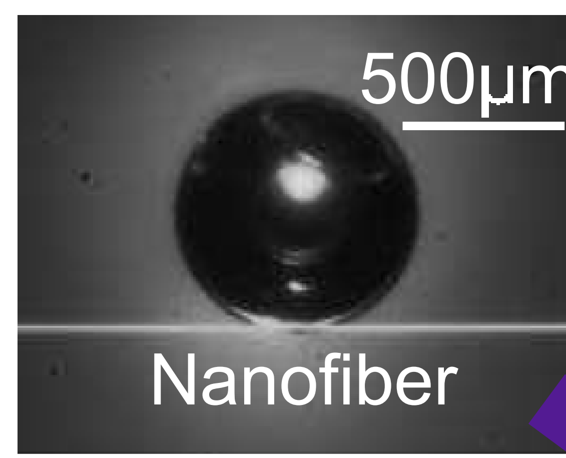
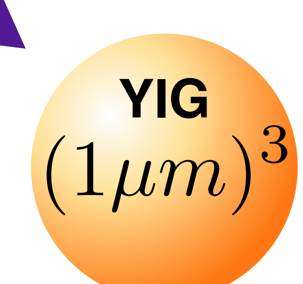
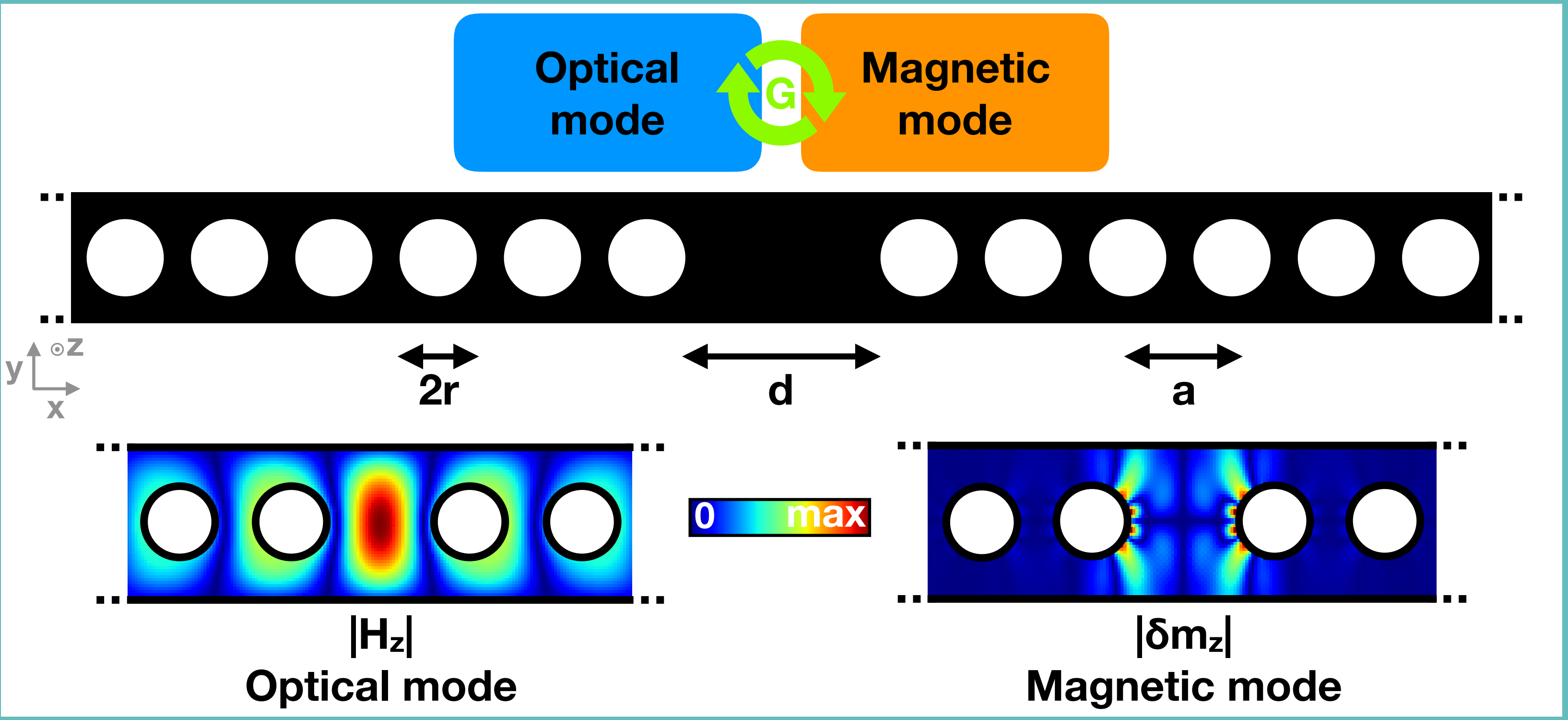


Fig: Osada et. al.
PRL 116, 223601



Optomagnonic Crystals



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

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WMI

TUM

MCQST

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

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

magnon mode index

bosonic operator

mode functions

Optomagnonics beyond the Kittel mode

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

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

Quantize: Holstein Primakoff to first order

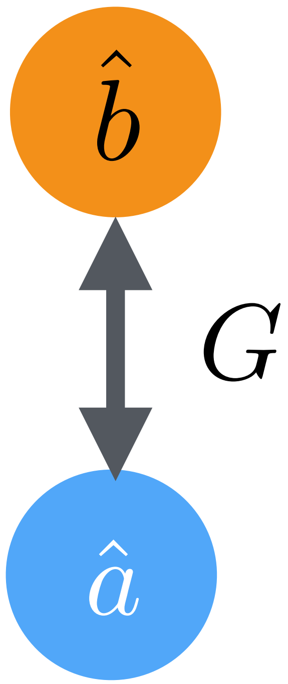
$$\delta\mathbf{m}(\mathbf{r},t) \to \frac{1}{2}\sum_{\gamma}\left(\delta\mathbf{m}_\gamma(\mathbf{r})\hat{b}_\gamma e^{-i\omega_\gamma t} + \delta\mathbf{m}^*_\gamma(\mathbf{r})\hat{b}^\dagger_\gamma e^{i\omega_\gamma t}\right)$$

Quantization of E optical fields

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

Optomagnonics beyond the Kittel mode

Coupling Hamiltonian in the spin-wave limit



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

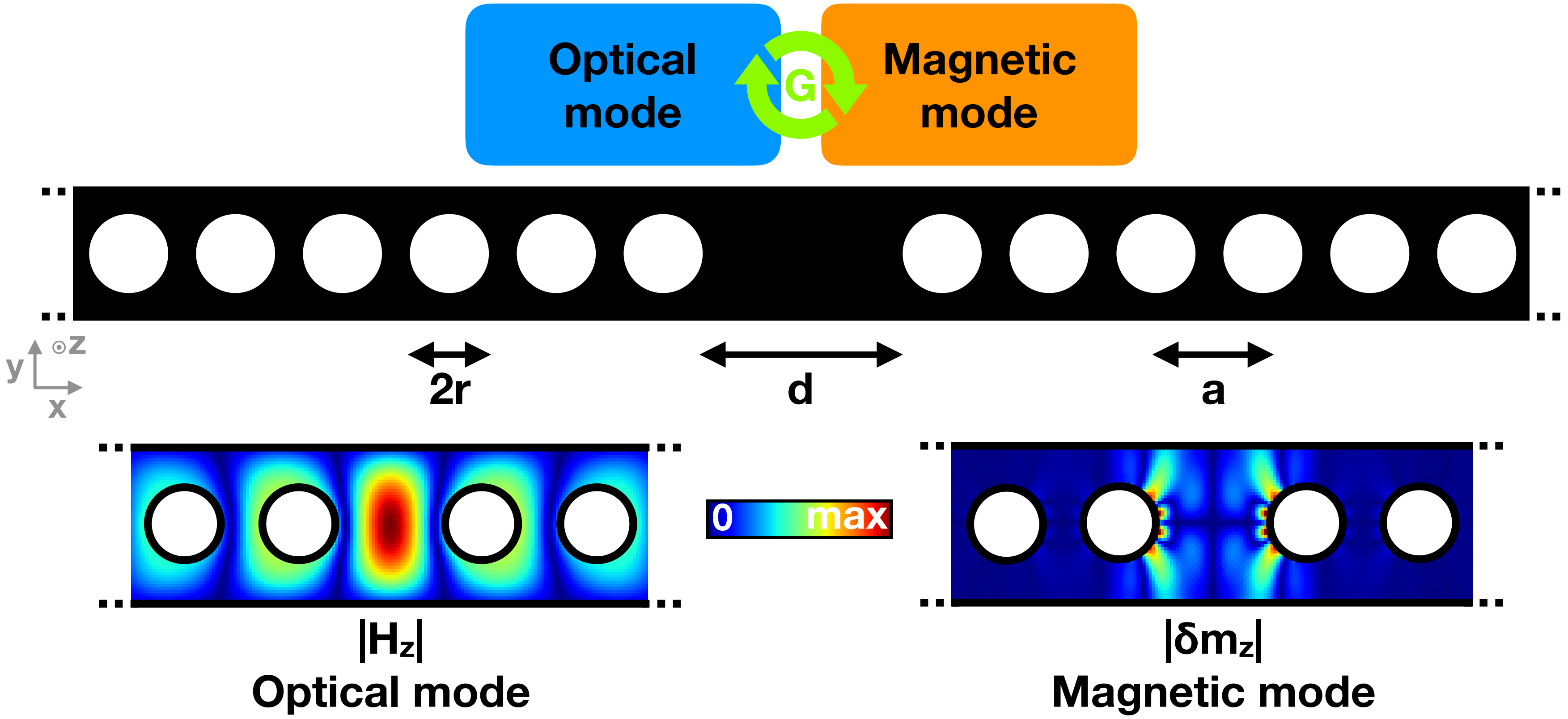
Optomagnonic coupling

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

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

Optomagnonic Coupling

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



finite element

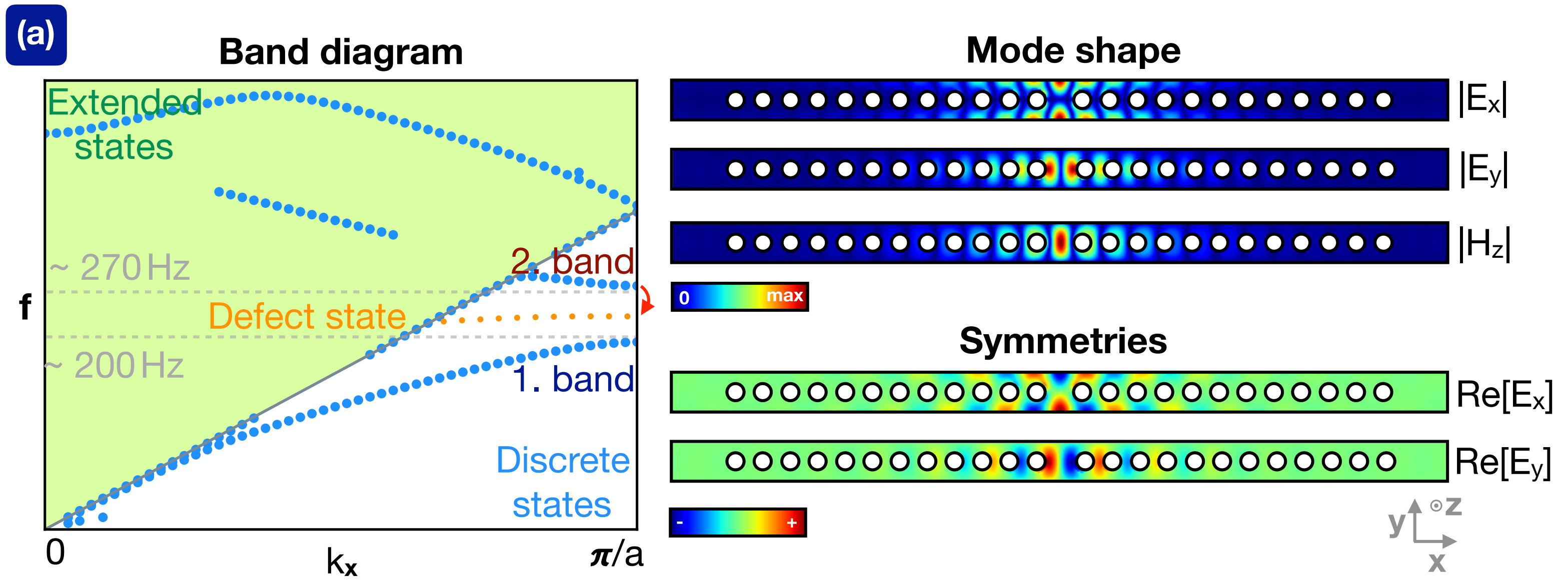
micromagnetics

MuMax3

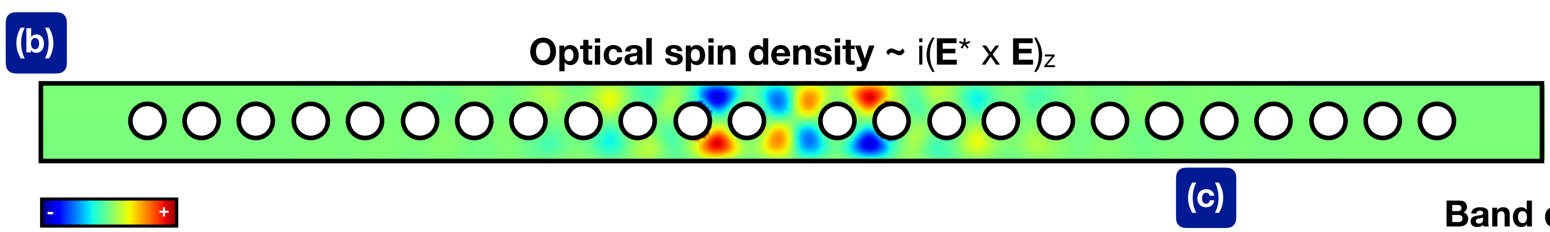
Vansteenkiste et. al AIP Advances 4, 107133 (2014)

Design: towards optimal mode matching

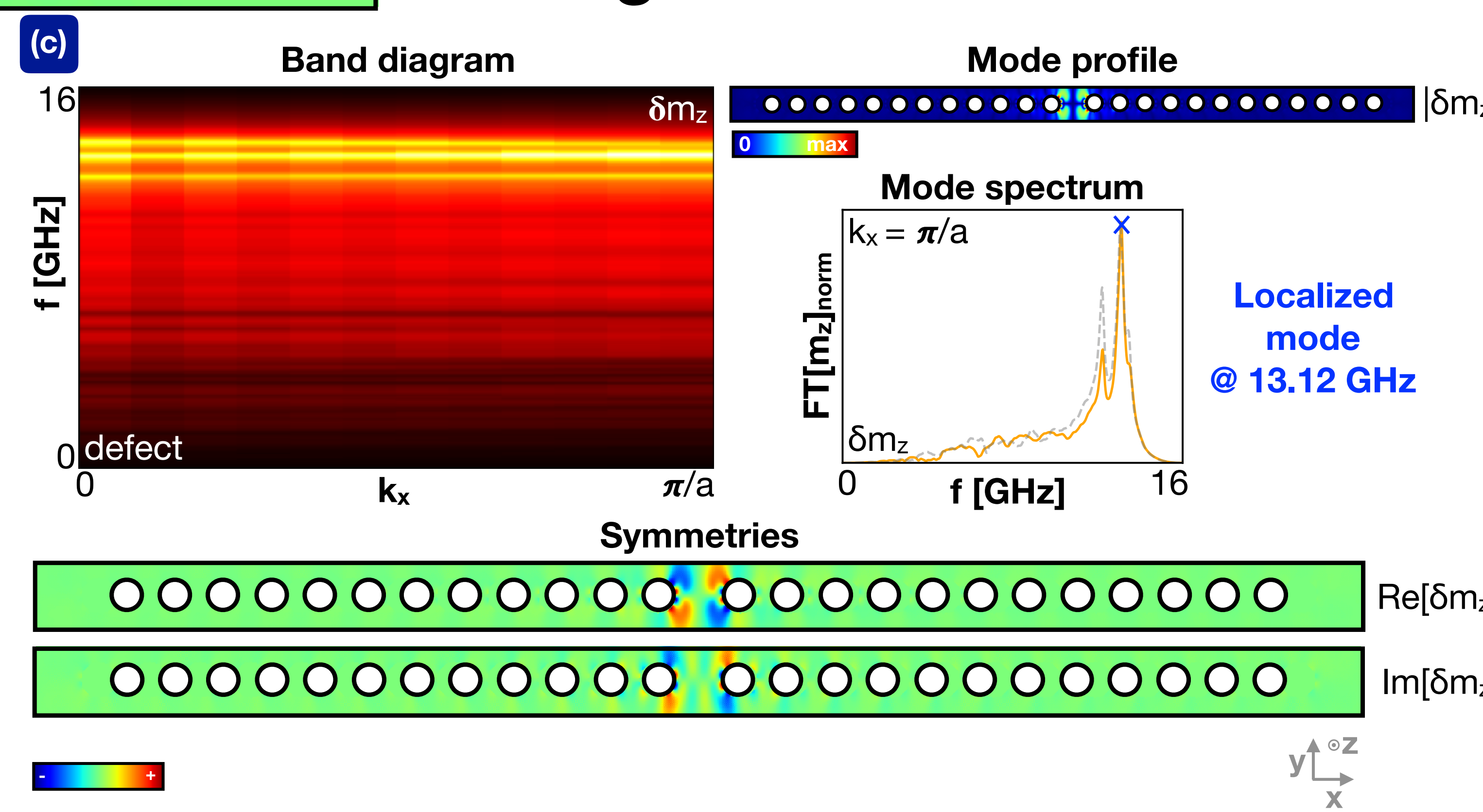
Optics



→ Localized optical mode



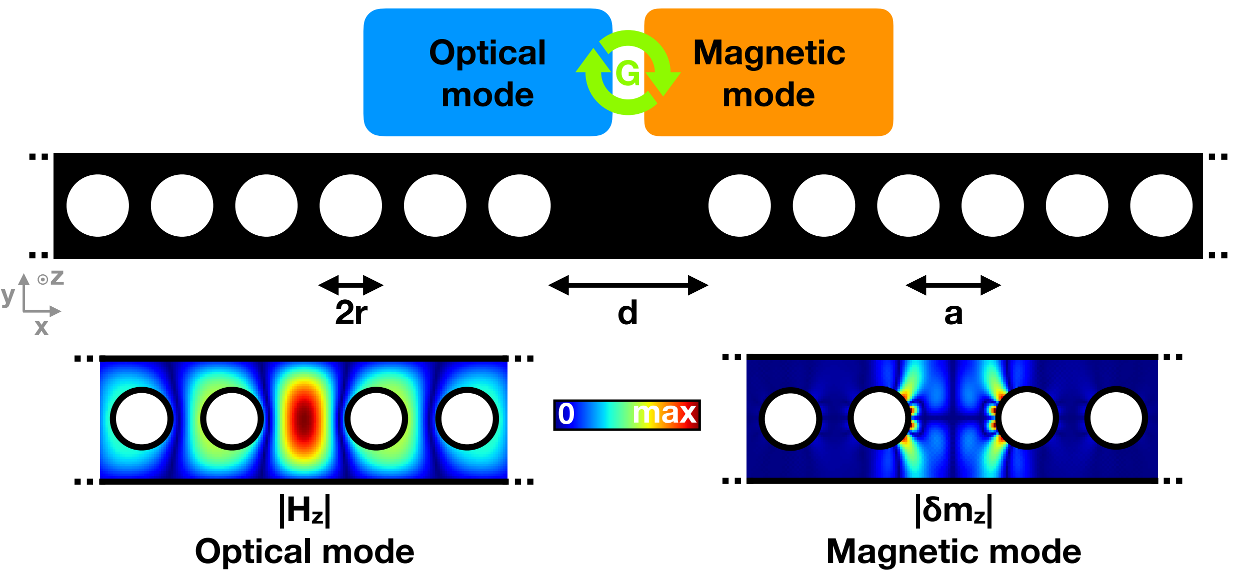
Magnetics

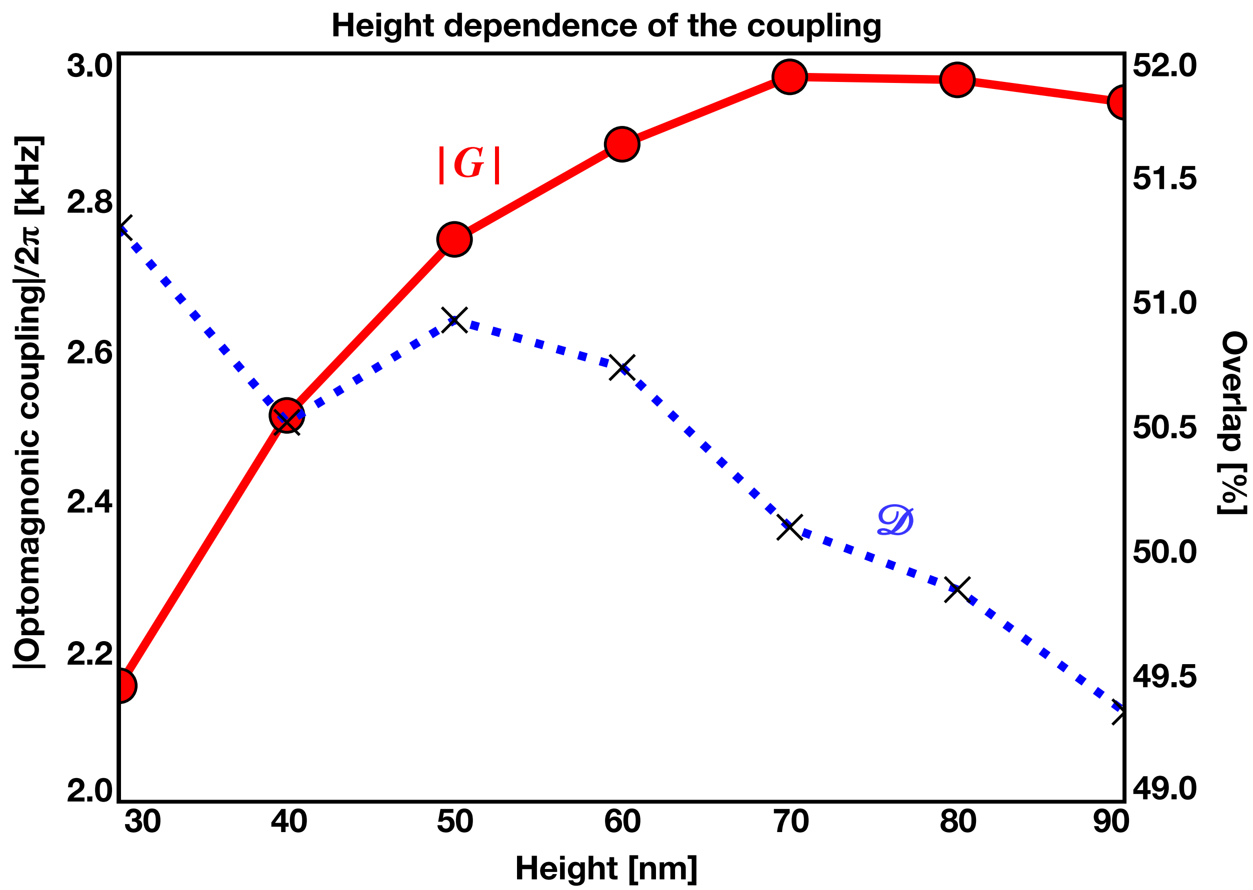


Localized magnon mode ←

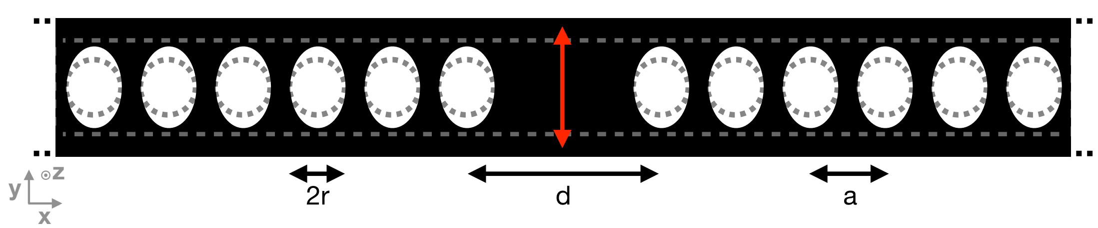
Match symmetries of magnon mode and optical spin density

Design: towards optimal mode matching

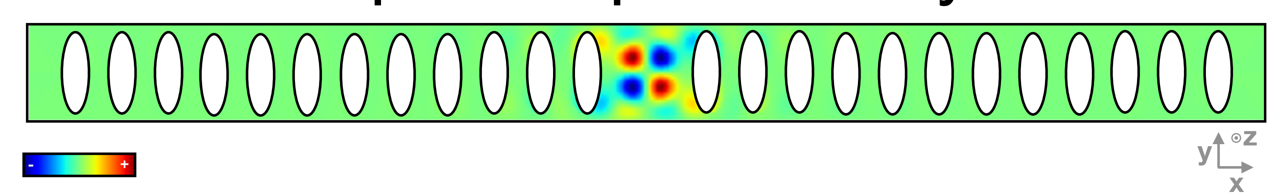




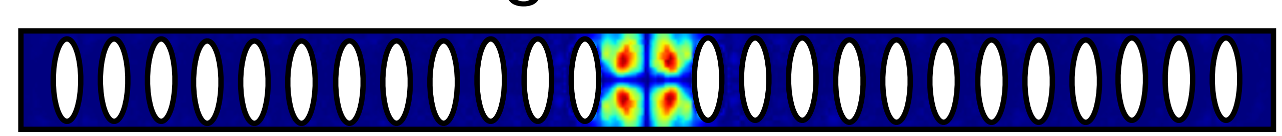
Optimization



Optical spin density



Magnon mode

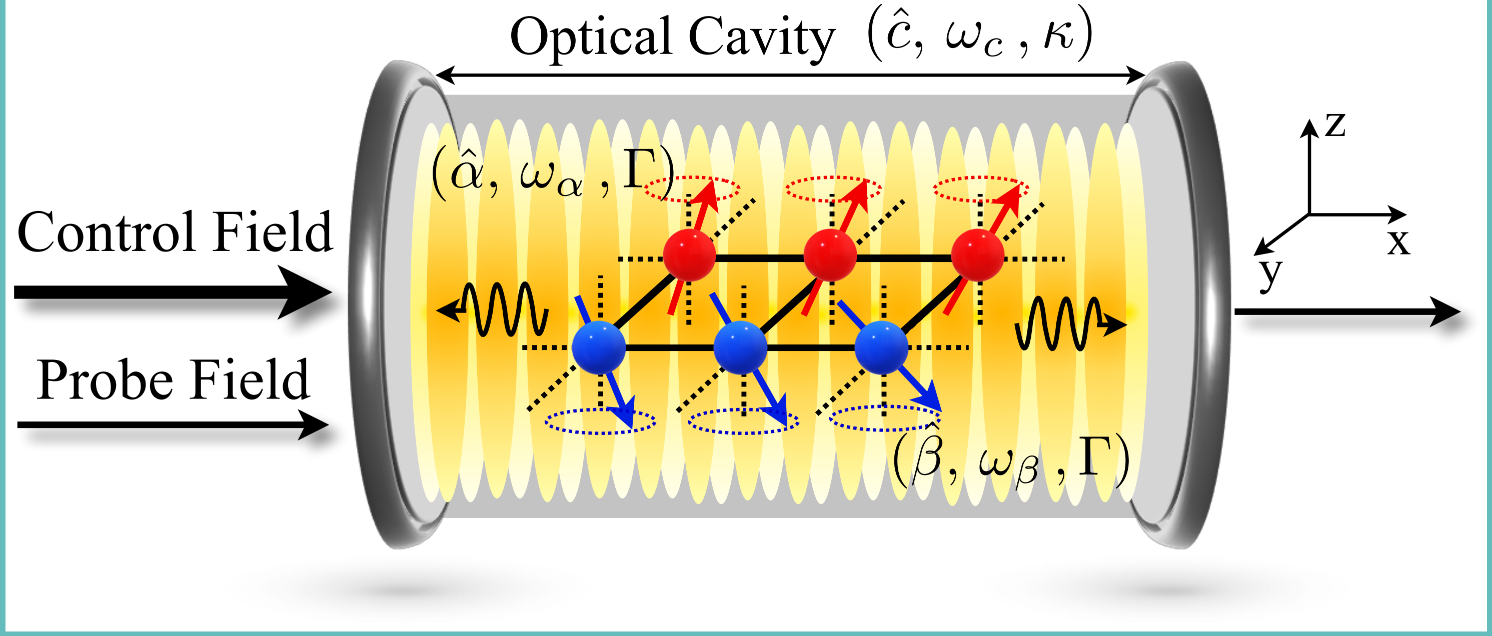


- One order of magnitude gain in coupling
- **However very lossy optical mode**

further work needed

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

Cavity Optomagnonics with Antiferromagnets



T.S. Parvini, V.A.S.V. Bittencourt, SVK
Phys. Rev. Res. 2, 022027(R) (2020)

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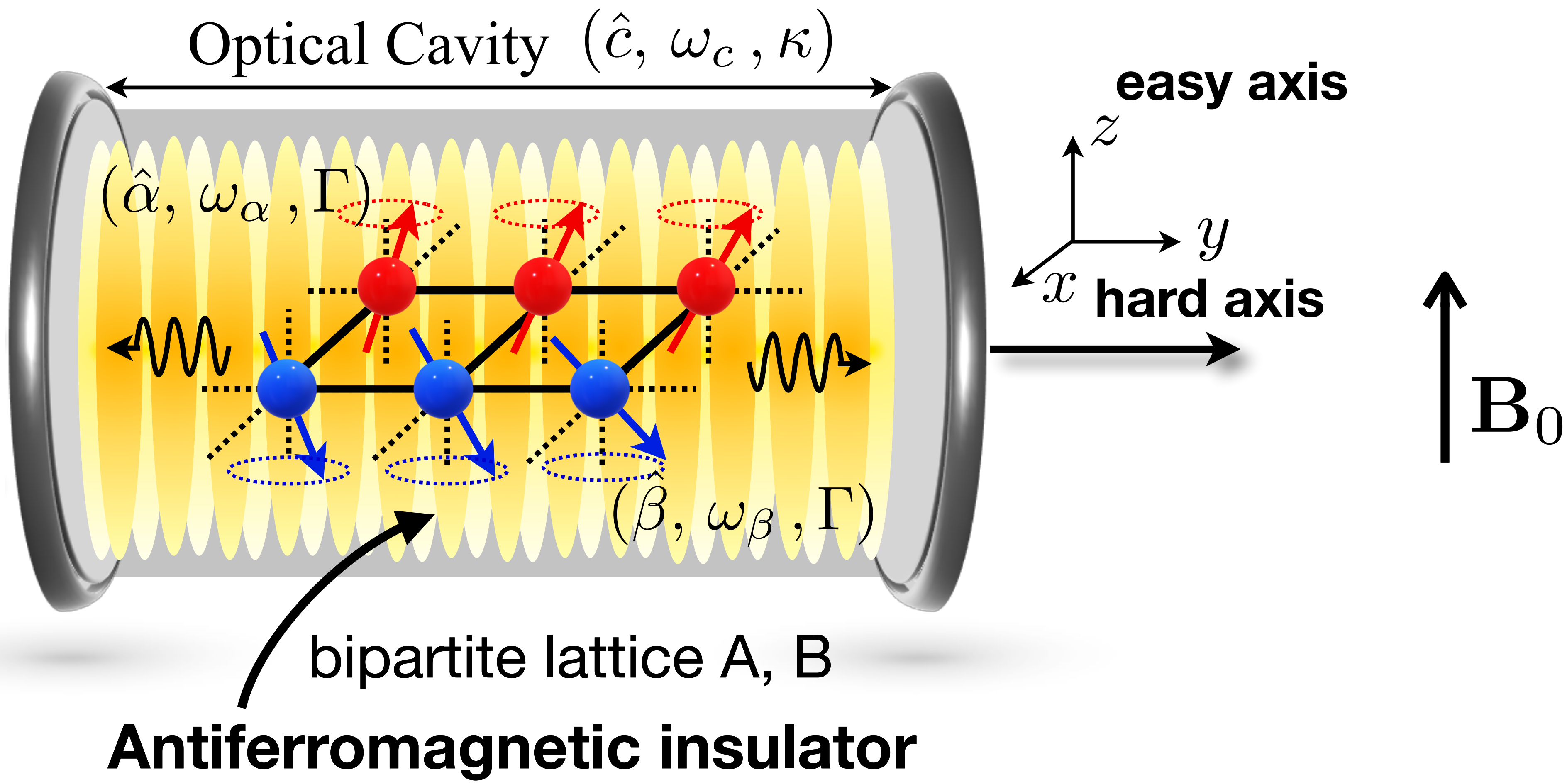
Cavity optomagnonics with AFMs

Cavity optical field

$$\hat{H}_{\rm ph} = \hbar\omega_c \hat{c}^\dagger \hat{c}$$



easy axis anisotropy

$$\hat{H}_{\rm AFM} = \hbar \sum_{\langle i\neq j\rangle} J\hat{\mathbf{S}}^i\cdot\hat{\mathbf{S}}^j + \hbar\,|\gamma|\,\mathbf{B}_0.\sum_i \hat{\mathbf{S}}^i - \frac{\hbar K_\parallel}{2}\sum_i \left(\hat{S}^i_z\right)^2 + \frac{\hbar K_\perp}{2}\sum_i\left(\hat{S}^i_x\right)^2$$

hard axis anisotropy

AFMs: Optomagnonic coupling

Fleury & Loudon 1968 $\longrightarrow$ $$\hat{H}_{\text{int}} = \sum_{\mu,\nu,\mathbf{R}} E_1^{\mu} E_2^{\nu} \chi^{\mu\nu}(\mathbf{R})$$

permittivity correction

$$\chi^{\mu\nu}(\mathbf{R}) = \sum_{\gamma} K_{\mu\nu\gamma}(\mathbf{R}) S_{\mathbf{R}}^{\gamma}$$

$$\hat{\mathcal{H}}_{\text{OM}} = -\hbar G \hat{c}^{\dagger}\hat{c}(g_{\alpha}\hat{\alpha}^{\dagger} + g_{\beta}\hat{\beta}^{\dagger} + \text{h.c.})$$

photon

two magnon branches

$$g_{\alpha(\beta)} = \left(u^{+}_{\alpha(\beta)} + v^{+}_{\alpha(\beta)}\right) + K\left(u^{-}_{\alpha(\beta)} + v^{-}_{\alpha(\beta)}\right)$$

Bogoliubov transformation coefficients:
from sublattice to collective modes

T.S. Parvini, V.A.S.V. Bittencourt, SVK, Phys. Rev. Res. **2**, 022027(R) (2020)

AFMs: Optomagnonic coupling

$$\hat{\mathcal{H}}_{\mathrm{OM}} = -\hbar G \hat{c}^{\dagger}\hat{c}(g_{\alpha}\hat{\alpha}^{\dagger} + g_{\beta}\hat{\beta}^{\dagger} + \mathrm{h.c.})$$

Bogoliubov Factor

$$g_{\alpha(\beta)} = \left(u^{+}_{\alpha(\beta)} + v^{+}_{\alpha(\beta)}\right) + K\left(u^{-}_{\alpha(\beta)} + v^{-}_{\alpha(\beta)}\right)$$

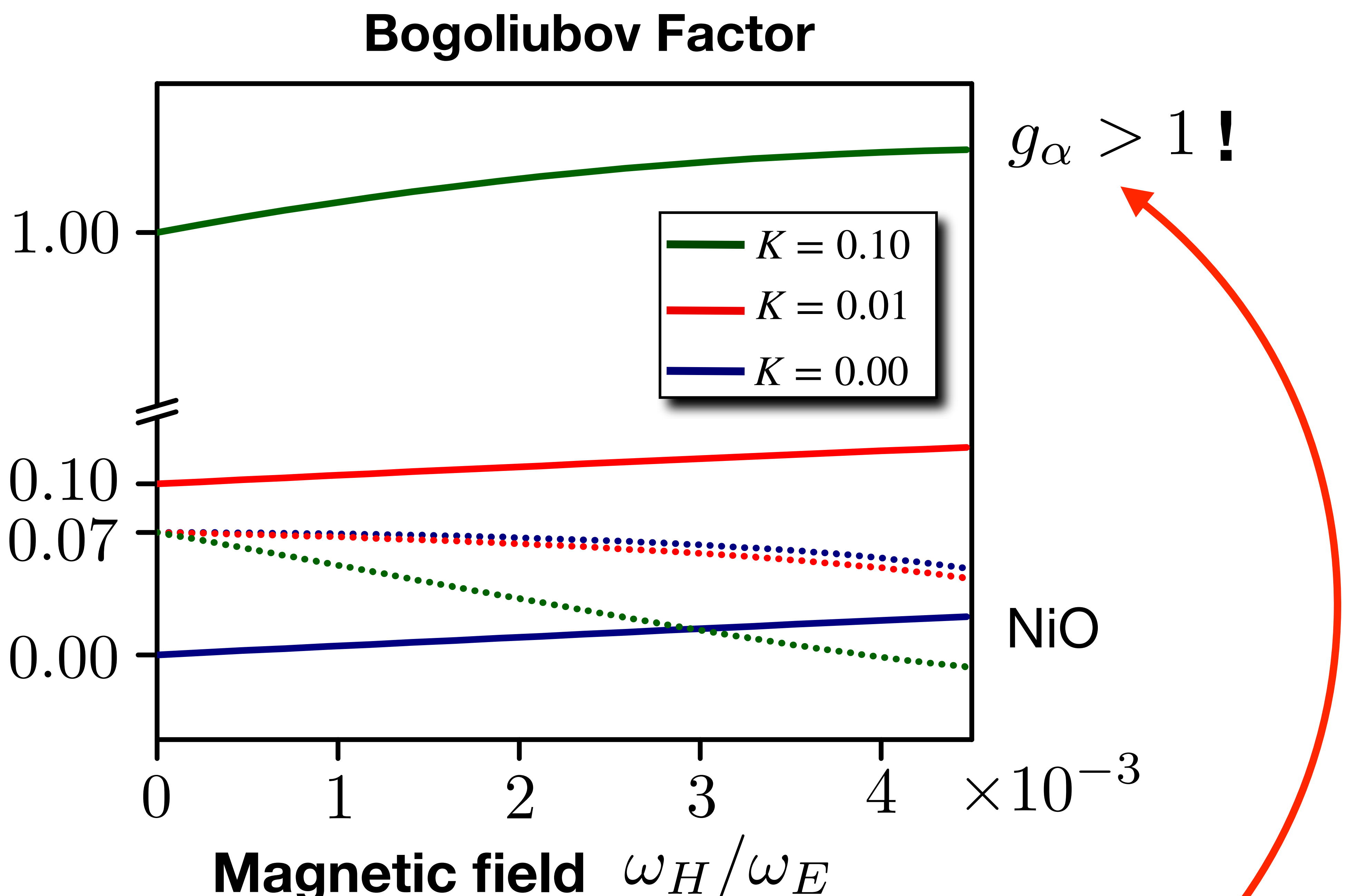
Bogoliubov transformation coefficients:
from sublattice to collective modes

$$K = \frac{K_{-}}{K_{+}} \approx 0.01 \quad \begin{array}{c} \mathrm{MnF_2} \\ \mathrm{FeF_2} \end{array}$$

characterizes magneto-optical asymmetry between sublattices

Example: hard-axis dominated AFM $\omega_\perp > \omega_\parallel$

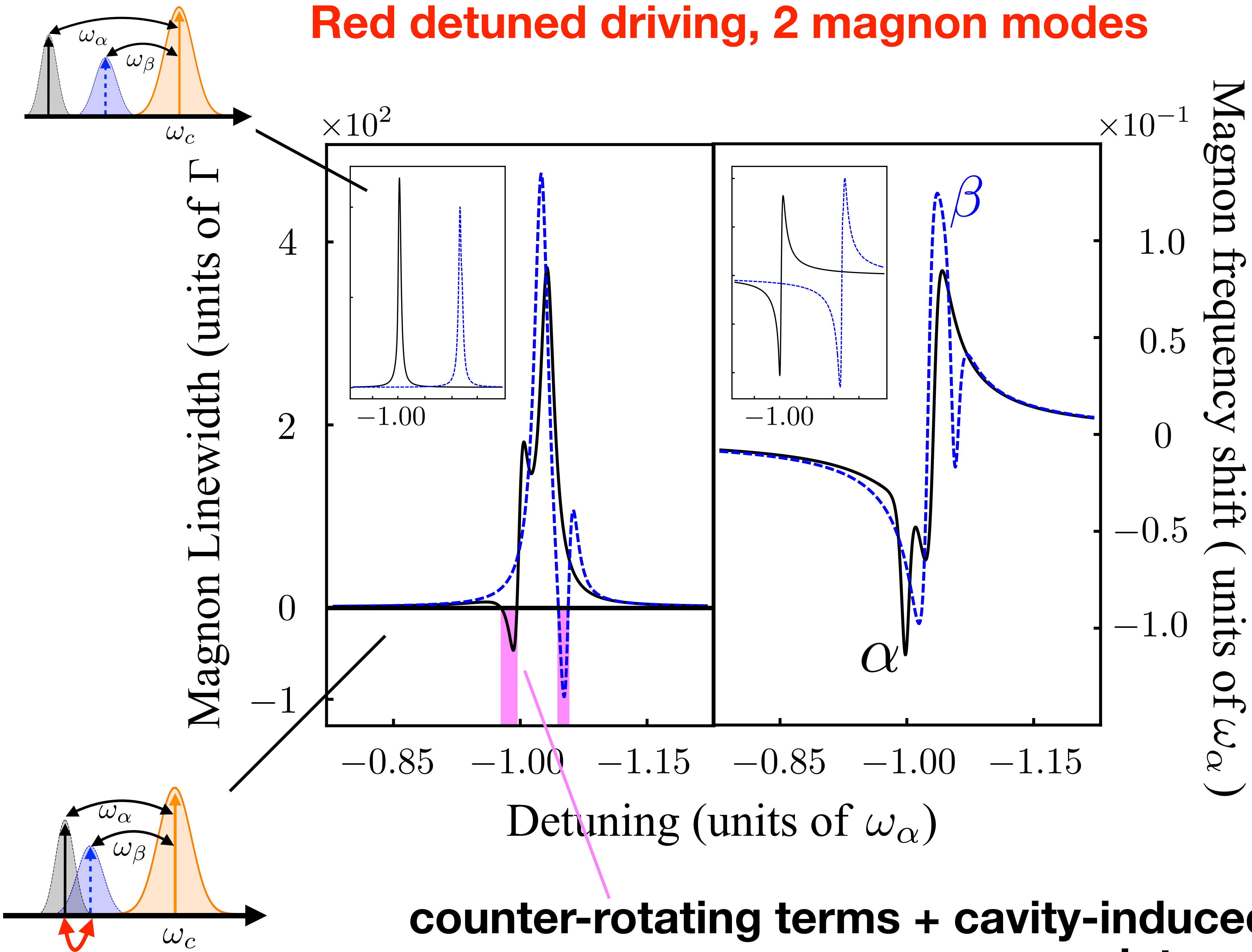
$$\omega_\parallel/\omega_E = 1.3\times 10^{-5} \qquad \omega_\perp/\omega_E = 7.6\times 10^{-4}$$



Enhancement factor possible for larger magneto-optical anisotropy

Dynamical response: strong coupling regime

Red detuned driving, 2 magnon modes



counter-rotating terms + cavity-induced magnon interaction

Two-magnon processes?

- So far we have used one-magnon Fleury-Loudon processes
- In AFMs, two-magnon processes are usually dominant

$$\hat{H}_{\text{int}} = \sum_{\mu,\nu,\mathbf{R}} E_1^{\mu} E_2^{\nu} \chi^{\mu\nu}(\mathbf{R})$$

$$\chi^{\mu\nu}(\mathbf{R}) = \sum_{\gamma} K_{\mu\nu\gamma}(\mathbf{R}) S_{\mathbf{R}}^{\gamma} + \sum_{\gamma,\delta} G_{\mu\nu\gamma\delta}(\mathbf{R}) S_{\mathbf{R}}^{\gamma} S_{\mathbf{R}}^{\delta} + \boxed{\sum_{\gamma,\delta,\mathbf{r}} L_{\mu\nu\gamma\delta}(\mathbf{R},\mathbf{r}) S_{\mathbf{R}}^{\gamma} S_{\mathbf{R}+\mathbf{r}}^{\delta}}$$

$$\mathbf{\Xi}_{\lambda_1\lambda_2}^{\alpha\beta} = \left(\hat{\mathbf{e}}_{\lambda_1}^*\right)^{\alpha} \hat{\mathbf{e}}_{\lambda_2}^{\beta} + \left(\hat{\mathbf{e}}_{\lambda_1}^*\right)^{\beta} \hat{\mathbf{e}}_{\lambda_2}^{\alpha}$$

photons

polarization dependence

$$\left[\hat{\mathcal{H}}_R\right]_{\lambda_1\lambda_2} = \frac{\hbar S}{2\epsilon_0 V} C \sum_{\mathbf{k}} \sum_{\omega_1,\omega_2} \sqrt{\omega_1\omega_2} \left\{\hat{c}_1^{\dagger}\hat{c}_2 \mathbf{\Xi}_{\lambda_1\lambda_2}^{xy} + \hat{c}_1\hat{c}_2^{\dagger}\left[\mathbf{\Xi}_{\lambda_1\lambda_2}^{xy}\right]^*\right\} \times$$

$$\times \left\{2u_{\mathbf{k}}v_{\mathbf{k}}\left(\hat{\alpha}_{\mathbf{k}}^{\dagger}\hat{\alpha}_{\mathbf{k}} + \hat{\beta}^{\dagger}_{-\mathbf{k}}\hat{\beta}_{-\mathbf{k}} + 1\right) + \left(u_{\mathbf{k}}^2 + v_{\mathbf{k}}^2\right)\underline{\left(\hat{\alpha}_{\mathbf{k}}\hat{\beta}_{-\mathbf{k}} + \hat{\alpha}_{\mathbf{k}}^{\dagger}\hat{\beta}^{\dagger}_{-\mathbf{k}}\right)}\right\}$$

magnon pairs

Two-magnon processes + cavity?

$$\Xi^{\alpha\beta}_{\lambda_1\lambda_2} = \left(\hat{\mathbf{e}}^*_{\lambda_1}\right)^{\alpha}\hat{\mathbf{e}}^{\beta}_{\lambda_2} + \left(\hat{\mathbf{e}}^*_{\lambda_1}\right)^{\beta}\hat{\mathbf{e}}^{\alpha}_{\lambda_2}$$

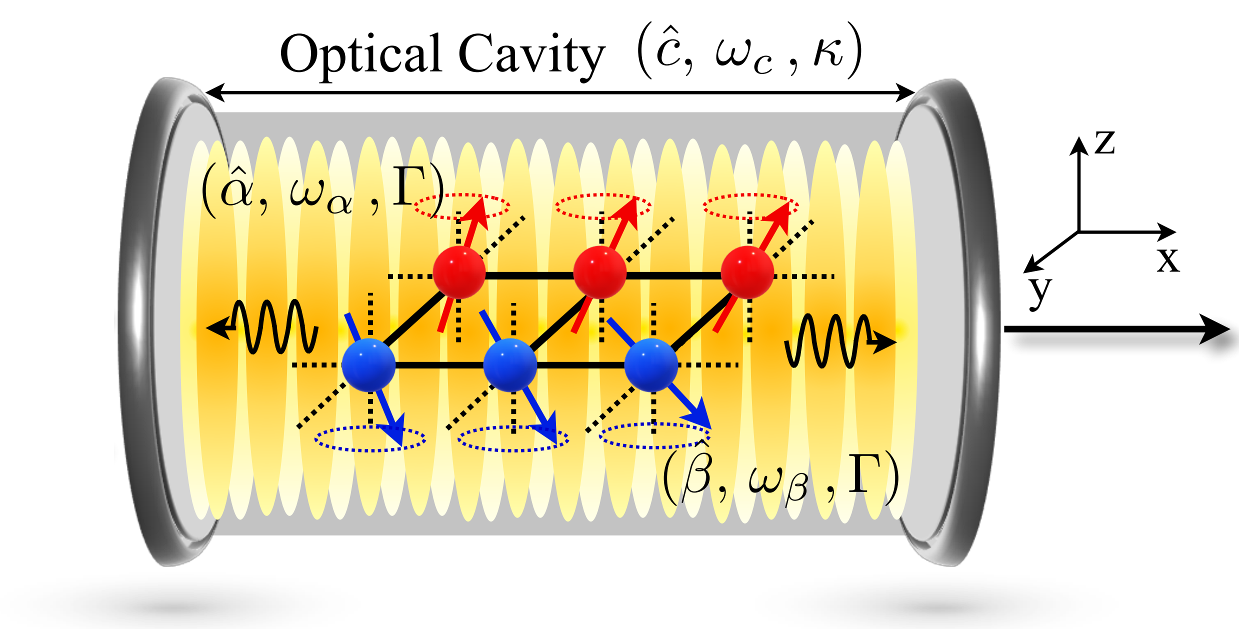
photons

polarization dependence

$$\left[\hat{\mathcal{H}}_R\right]_{\lambda_1\lambda_2} = \frac{\hbar S}{2\epsilon_0 V} C \sum_{\mathbf{k}} \sum_{\omega_1,\omega_2} \sqrt{\omega_1\omega_2}\left\{\hat{c}^\dagger_1\hat{c}_2\Xi^{xy}_{\lambda_1\lambda_2} + \hat{c}_1\hat{c}^\dagger_2\left[\Xi^{xy}_{\lambda_1\lambda_2}\right]^*\right\}\times$$

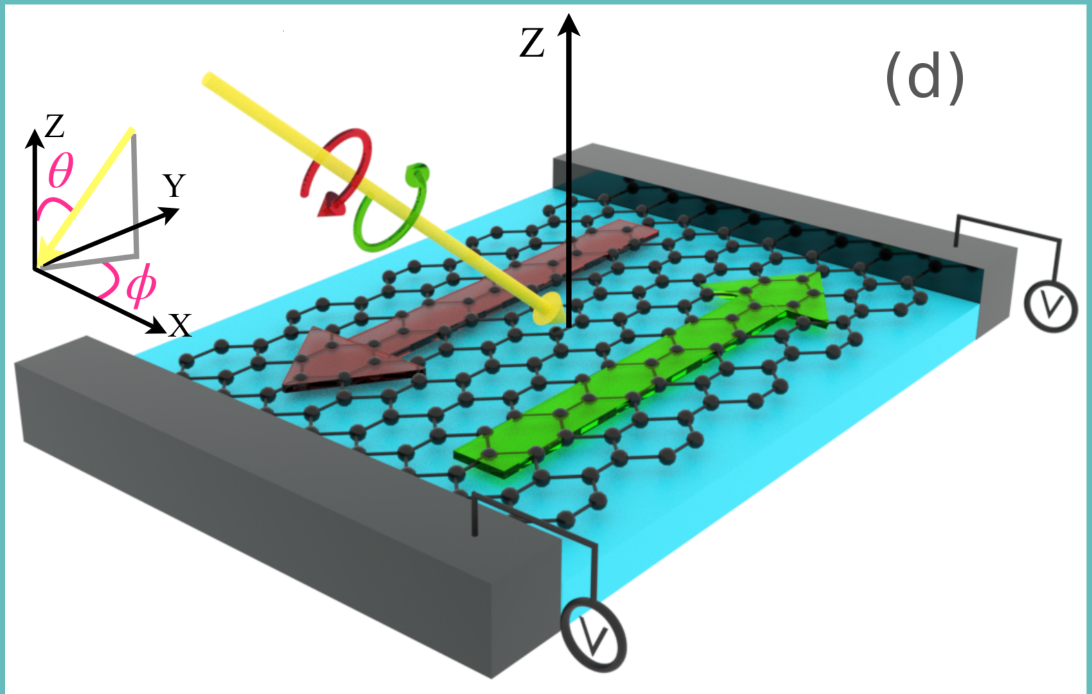
$$\times\left\{2u_{\mathbf{k}}v_{\mathbf{k}}\left(\hat{\alpha}^\dagger_{\mathbf{k}}\hat{\alpha}_{\mathbf{k}} + \hat{\beta}^\dagger_{-\mathbf{k}}\hat{\beta}_{-\mathbf{k}} + 1\right) + \left(u^2_{\mathbf{k}} + v^2_{\mathbf{k}}\right)\underline{\left(\hat{\alpha}_{\mathbf{k}}\hat{\beta}_{-\mathbf{k}} + \hat{\alpha}^\dagger_{\mathbf{k}}\hat{\beta}^\dagger_{-\mathbf{k}}\right)}\right\}$$

magnon pairs



Coming soon!

All-Optical Generation of Antiferromagnetic Magnon Currents via the Magnon Circular Photogalvanic Effect



E.V. Böstrom, T.S. Parvini, J.W. McIver, A. Rubio, SVK, M.A. Sentef,
arXiv:2104.10914 (2021)

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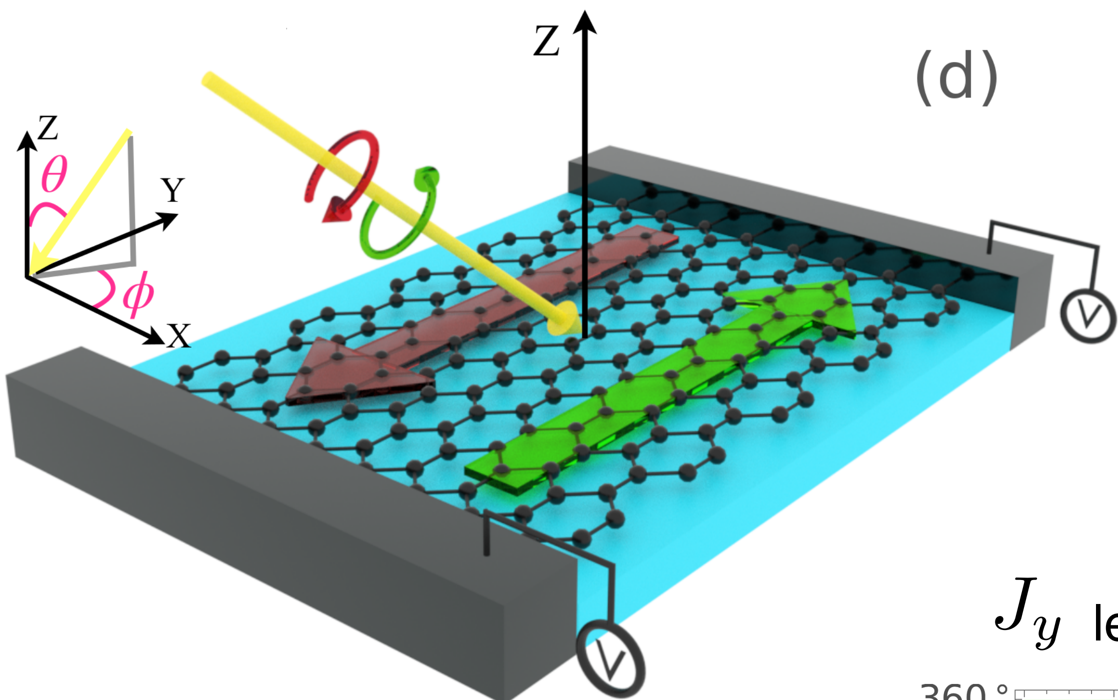
mpsd
Max Planck Institute for the Structure and Dynamics of Matter

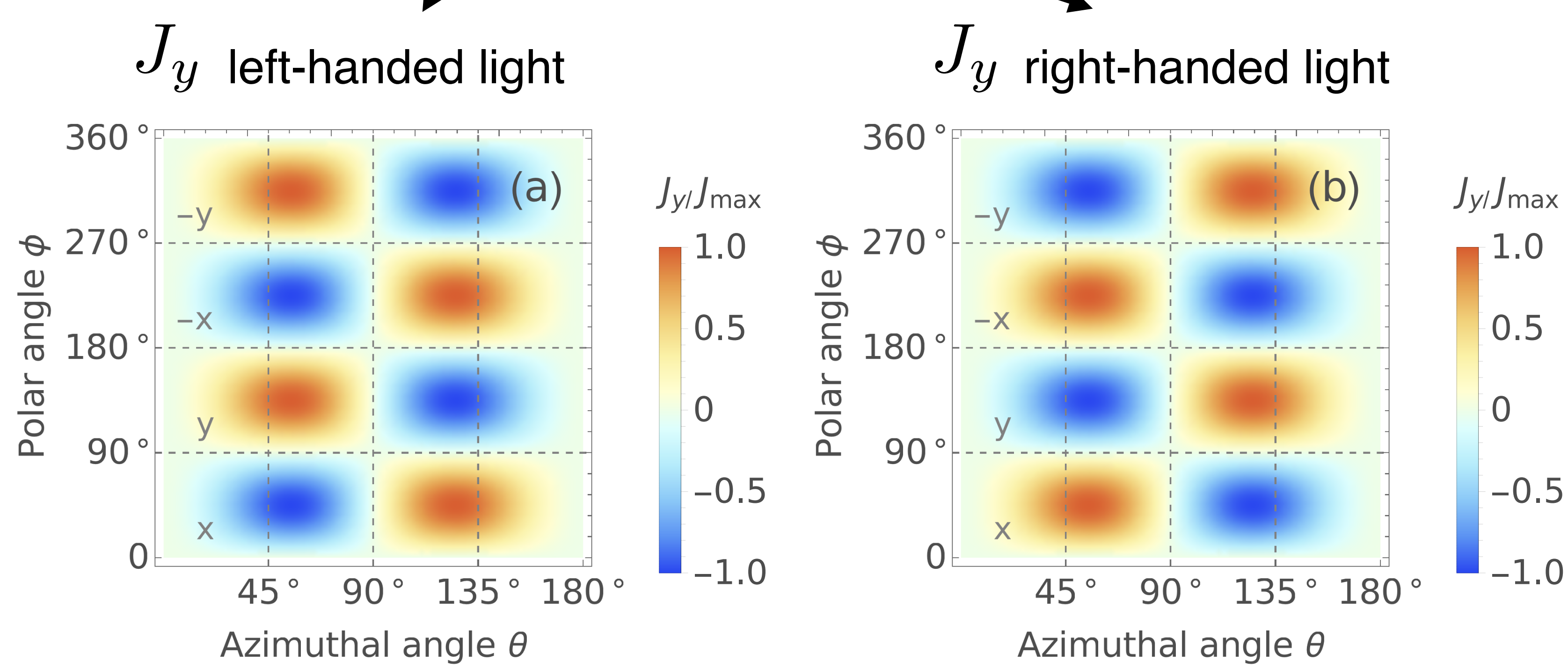
Magnon circular photogalvanic effect in 2D AFMs

- Directed magnon currents via stimulated two-magnon Raman scattering
- Current controlled by polarization and angle of incidence of light
- Measurable by Inverse Spin Hall Effect



optical susceptibility

$$\langle \mathbf{J} \rangle = \zeta \, \mathrm{Im}(\sigma) \cos\theta \sin^2\theta (\sin 2\phi \hat{\mathbf{e}}_y - \cos 2\phi \hat{\mathbf{e}}_x)$$



E.V. Böstrom, T.S. Parvini, J.W. McIver, A. Rubio, SVK, M.A. Sentef, arXiv:2104.10914 (2021)

Outlook

- Cavity-induced dynamical effects can be cast in the form of a LLG equation of motion for the spin with effective magnetic fields and optically induced “Gilbert” damping
- Design of optomagnonic systems in the optical regime shows promise

  for improved coupling values
- AFMs can present rich new physics: tunable optomagnonic coupling, dark-to-bright transition, cavity-induce magnon interaction
- All-optical generation of magnon currents in 2D by stimulated Raman scattering (2-magnon processes)