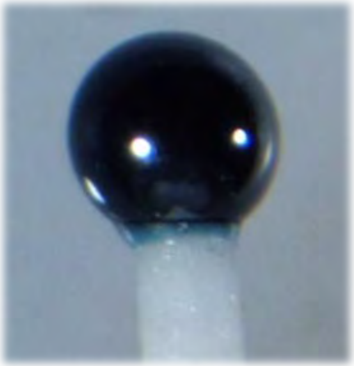
Quantum magnonics with a macroscopic ferromagnetic sphere



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Koji Usami

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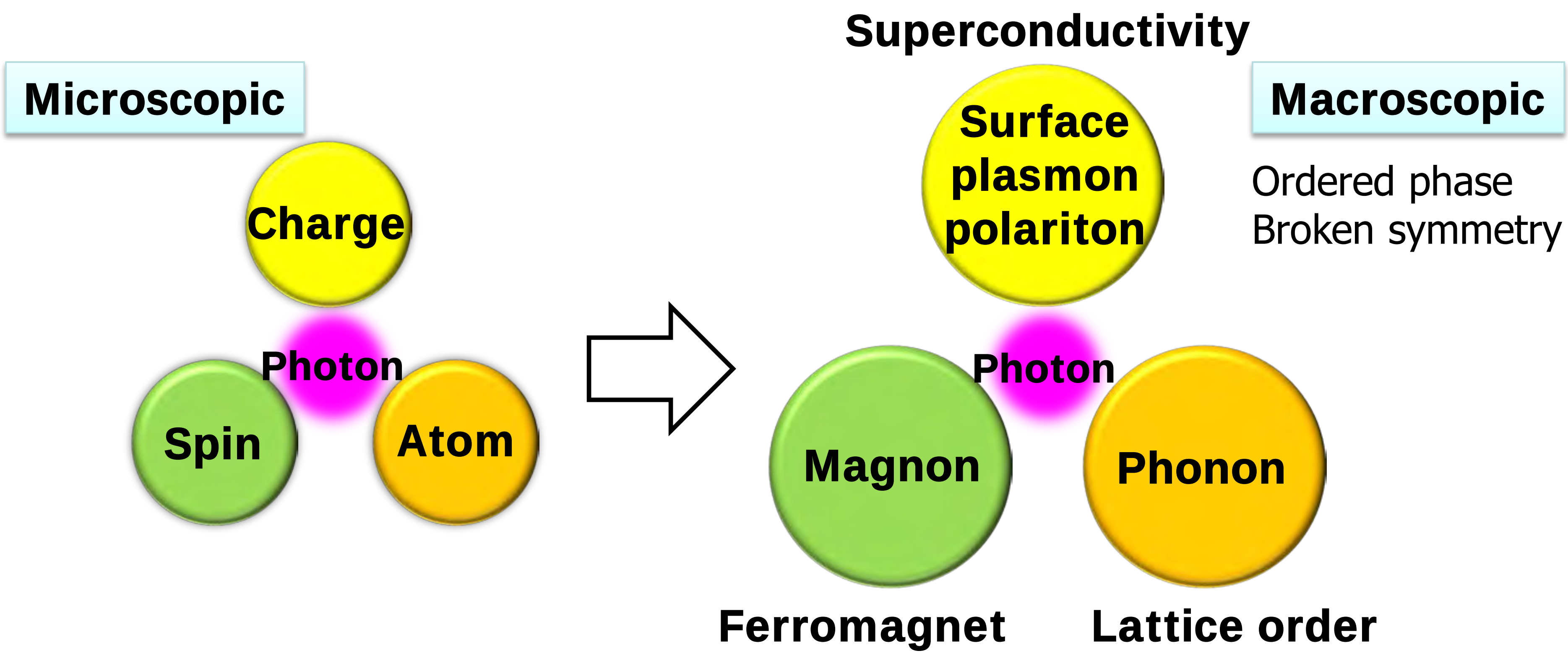
Quantum mechanics in macroscopic scale

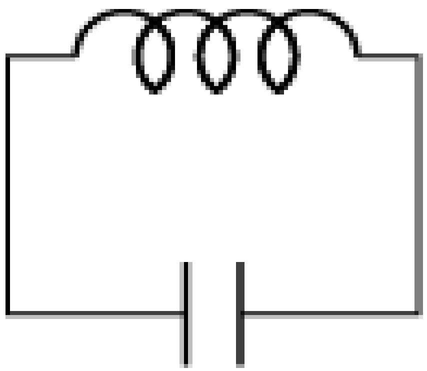
Quantum state control of collective excitation modes in solids



- Spatially-extended rigid mode
- Large transition moment

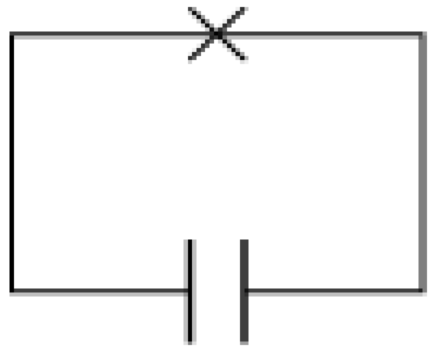
Superconducting qubit – nonlinear resonator

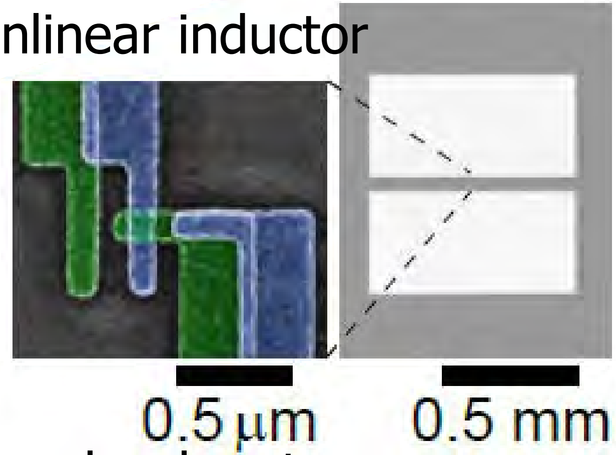
LC resonator



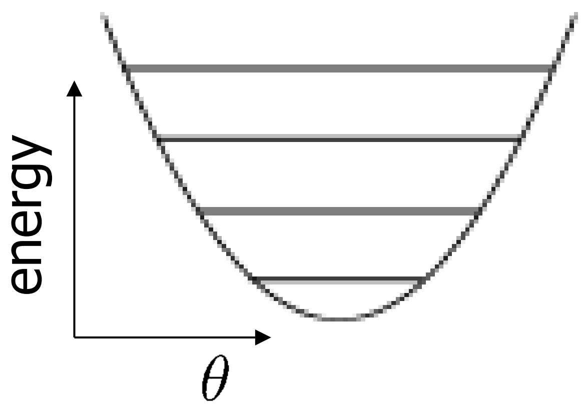
Josephson junction resonator

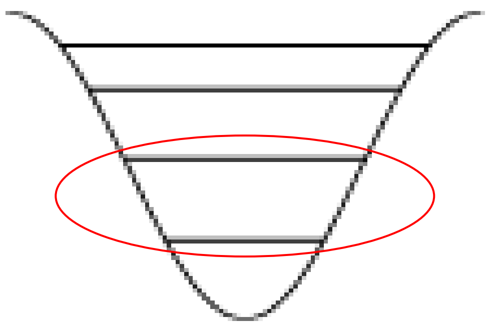
Josephson junction = nonlinear inductor





anharmonicity ⇒ effective two-level system



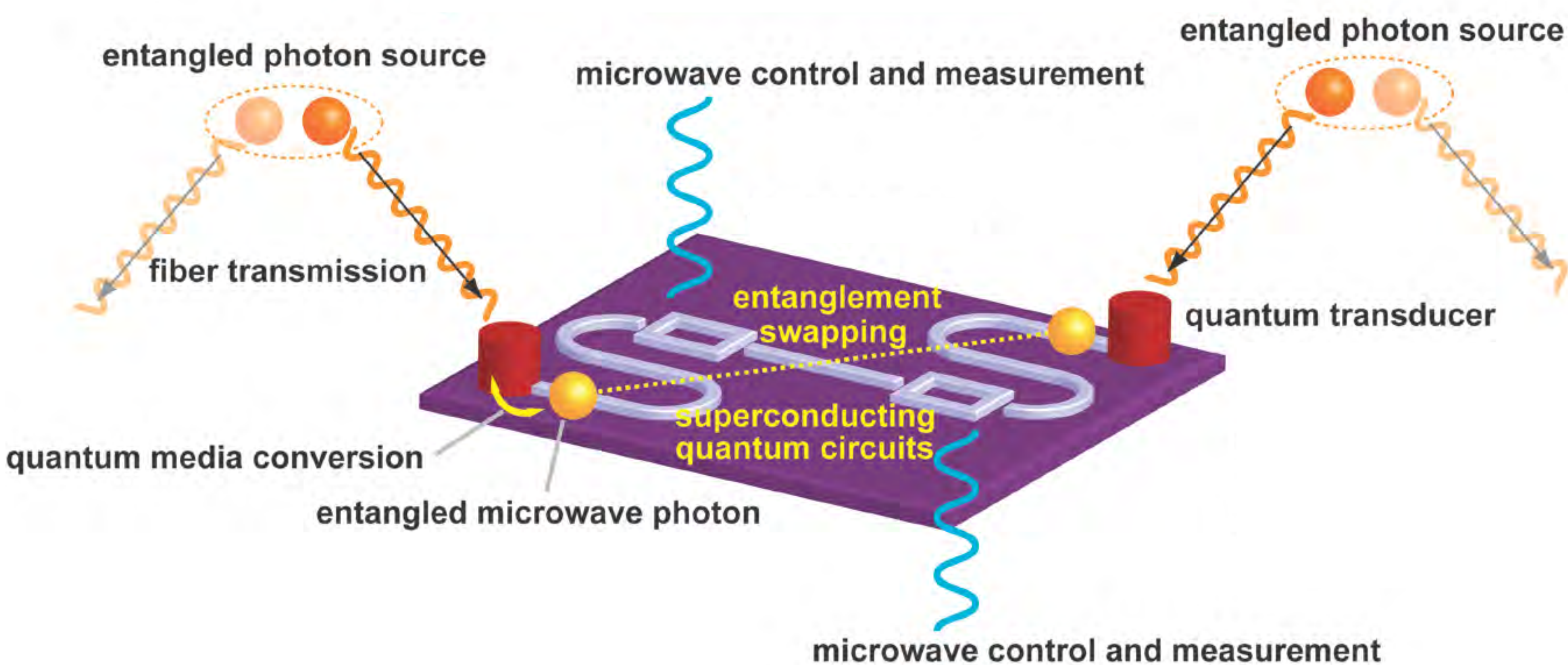


inductive energy = confinement potential

charging energy = kinetic energy ⇒ quantized states

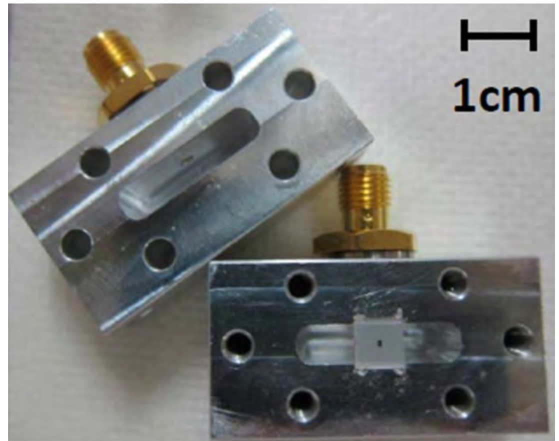
Quantum interface between microwave and light

- Quantum repeater
- Quantum computing network



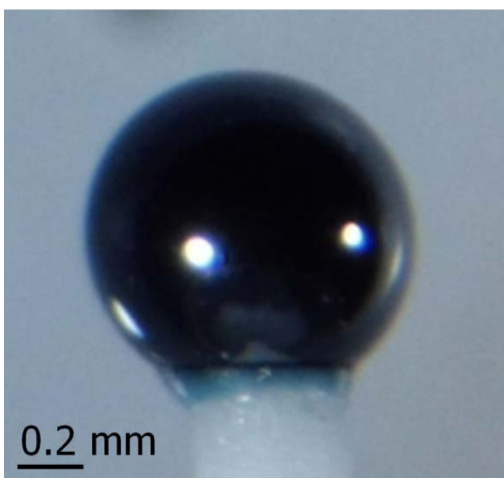
Hybrid quantum systems

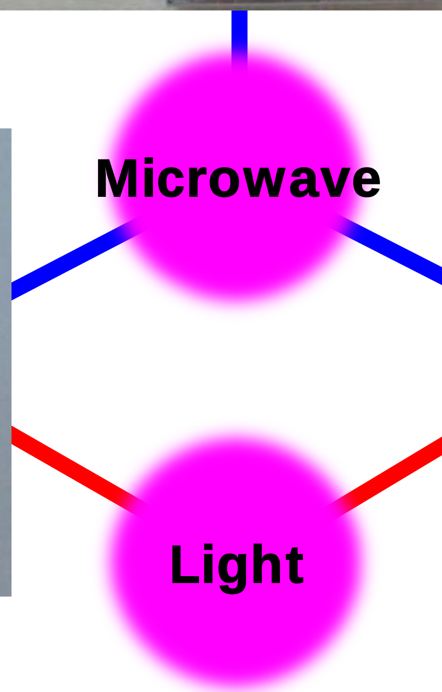
Superconducting quantum electronics



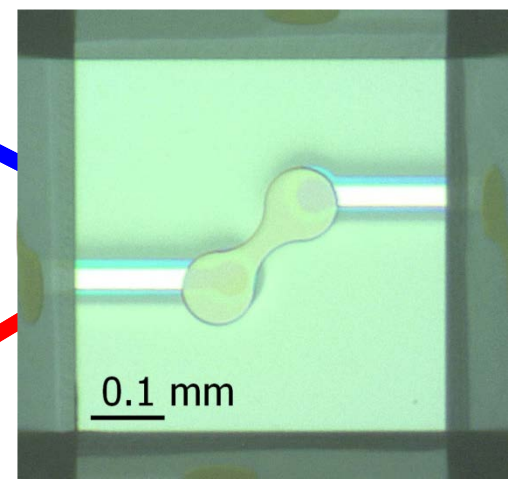
Nonlinearity

Quantum magnonics





Quantum nanomechanics

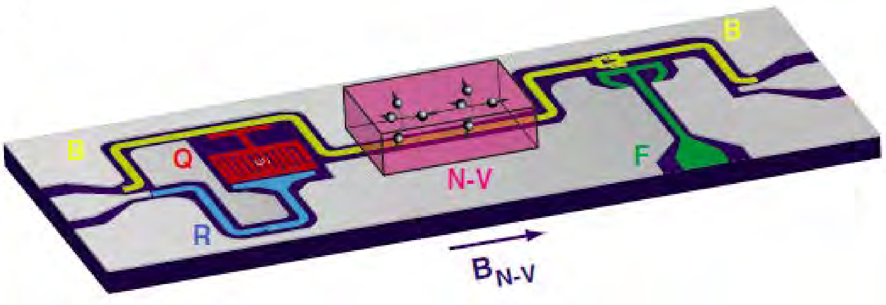


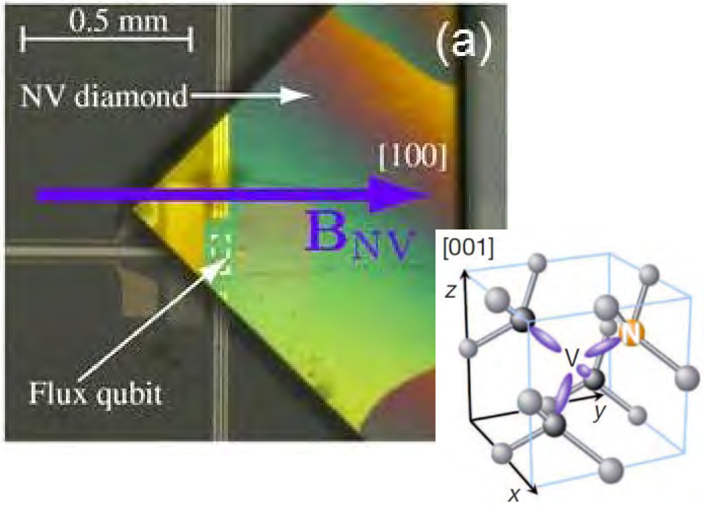
Quantum surface acoustics

Quantum magnonics

Hybrid with paramagnetic spin ensembles

Spin ensemble of NV-centers in diamond

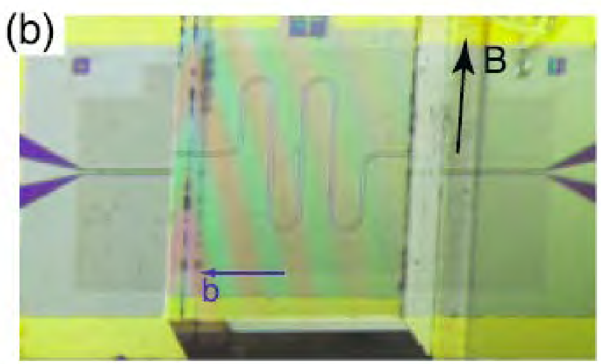




Kubo et al. PRL 107, 220501 (2011). CEA Saclay
R. Amsüss et al. PRL 107 060502 (2011). TUWien

Zhu et al. Nature 478, 221 (2011). (NTT)
Saito et al. Phys. Rev. Lett. 111, 107008 (2013). (NTT)

Rare-earth doped crystal



$Er:Y_2SiO_5$

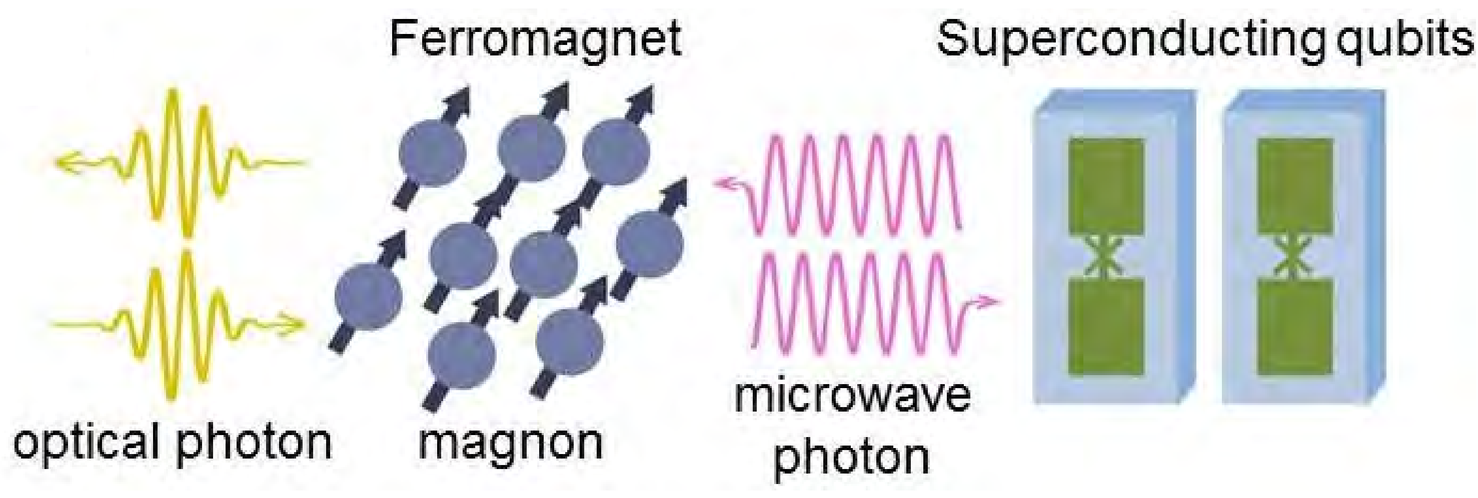
Bushev et al. PRB 84, 060501(R) (2011) Karlsruhe

Optical quantum memory

$Pr:Y_2SiO_5$

Hedges et al. Nature 465, 1052 (2010) Otago

Hybrid with ferromagnetic magnons



Paramagnet

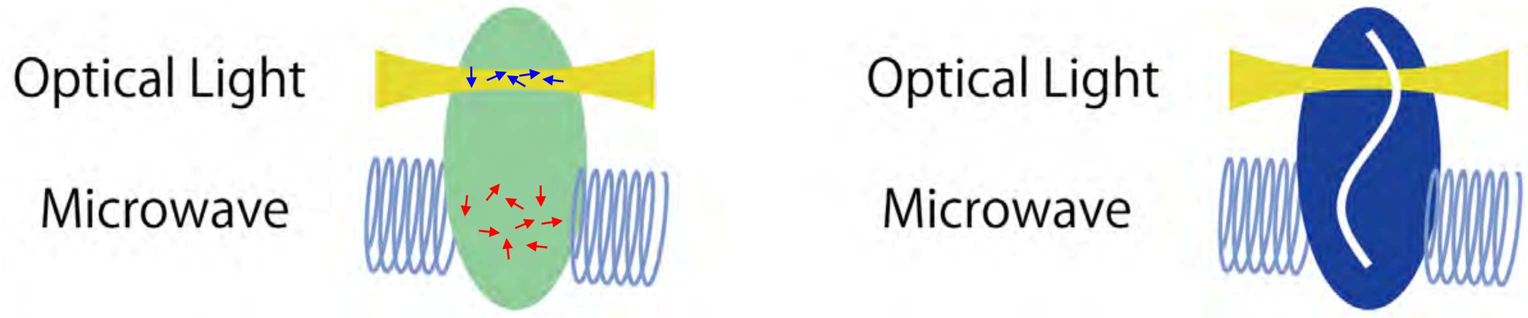
Low spin density 10^{12}-10^{18} cm^{-3}

Spatial mode defined by EM fields

Ferromagnet

High spin density 10^{21}-10^{22} cm^{-3}

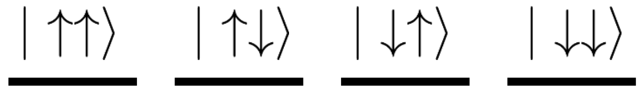
Robust extended spatial mode



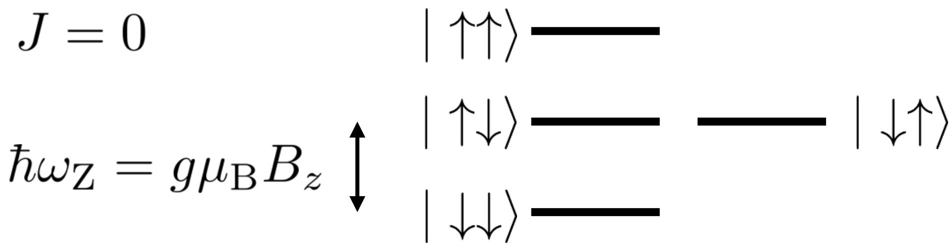
Two coupled spins

$$H = -g\mu_{\mathrm{B}} B_z S_z - 2J\mathbf{S}_1 \cdot \mathbf{S}_2$$

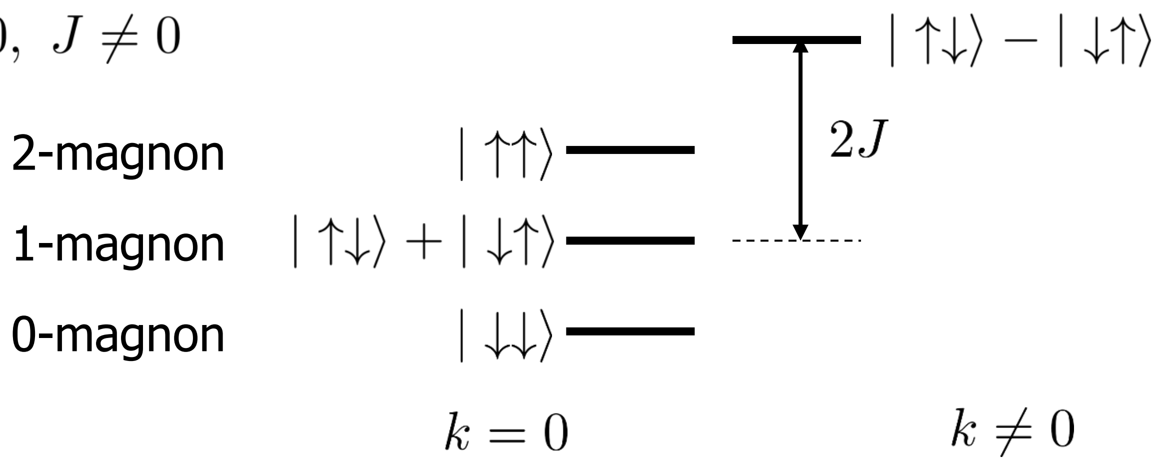
$B_z = 0,\ J = 0$



$B_z \neq 0,\ J = 0$

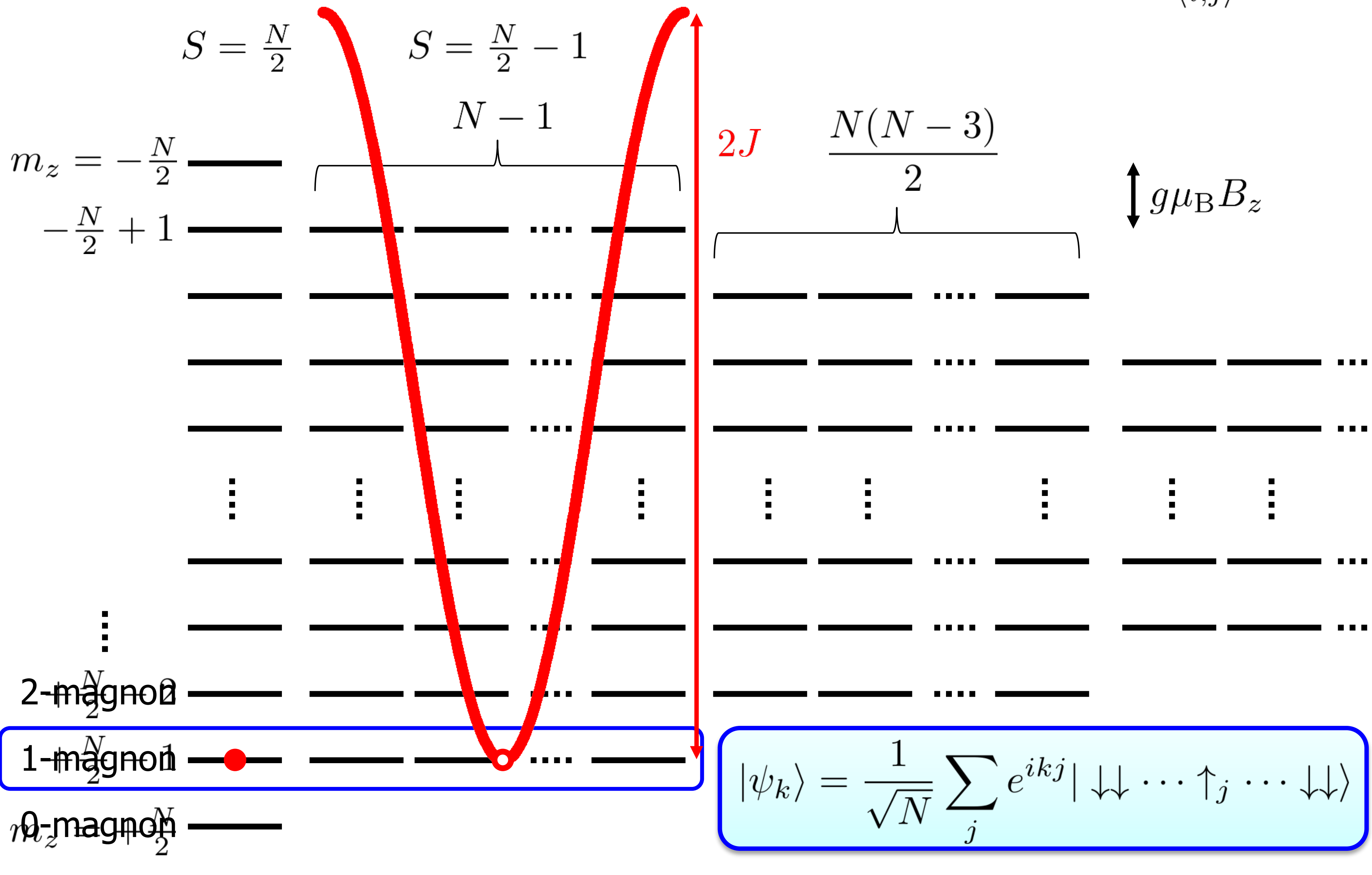


$B_z \neq 0,\ J \neq 0$



N coupled spins

$$H = -g\mu_{\mathrm{B}} \sum_i B_z S_z^i - 2J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

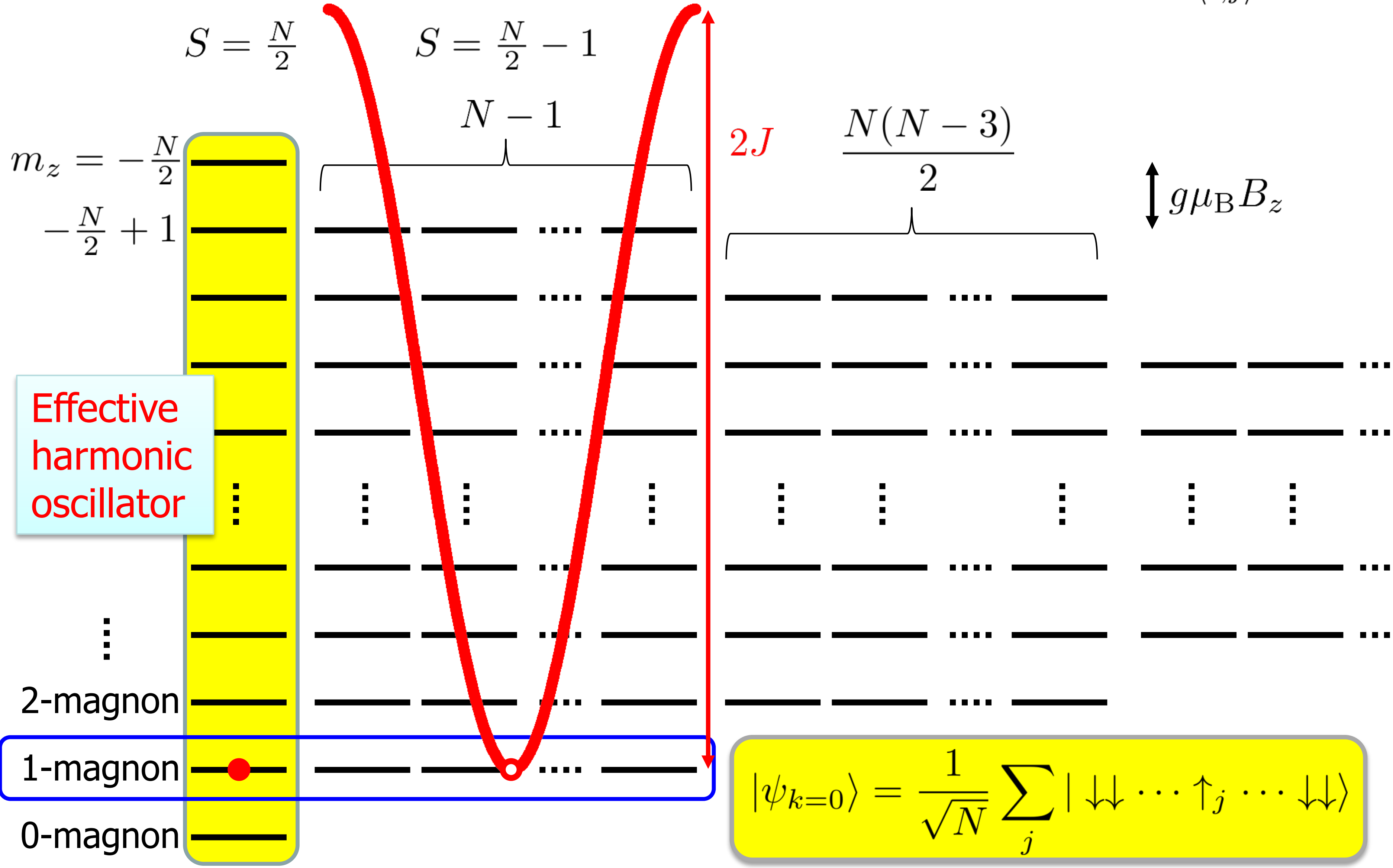


$$|\psi_k\rangle = \frac{1}{\sqrt{N}} \sum_j e^{ikj} | \downarrow\downarrow \cdots \uparrow_j \cdots \downarrow\downarrow \rangle$$

cf. Dicke, Phys. Rev. 93, 99 (1954)

N coupled spins

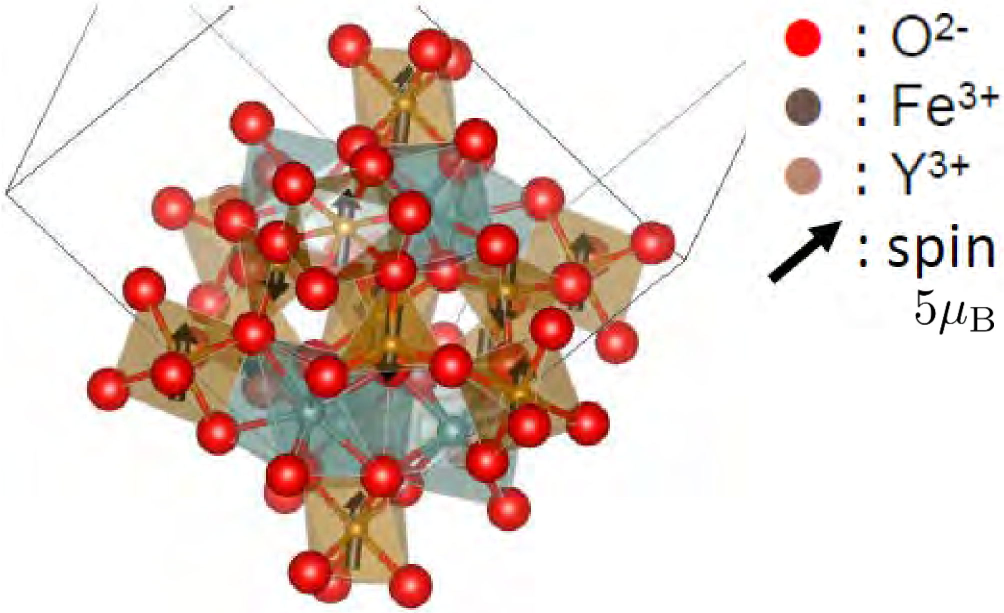
$$H = -g\mu_{\mathrm{B}} \sum_i B_z S_z^i - 2J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$



$k = 0$ $k \neq 0$

cf. Dicke, Phys. Rev. 93, 99 (1954)

Yttrium Iron Garnet (YIG)



- Ferrimagnetic insulator
- Narrow FMR line
- Transparent at infrared

- High Curie temperature: ~550 K
- Large spin density: 2.1×10^{22} cm^{-3}

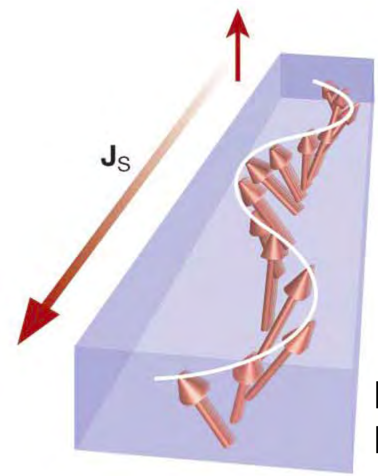
Microwave oscillators

CANDOX Corporation

Optical isolators

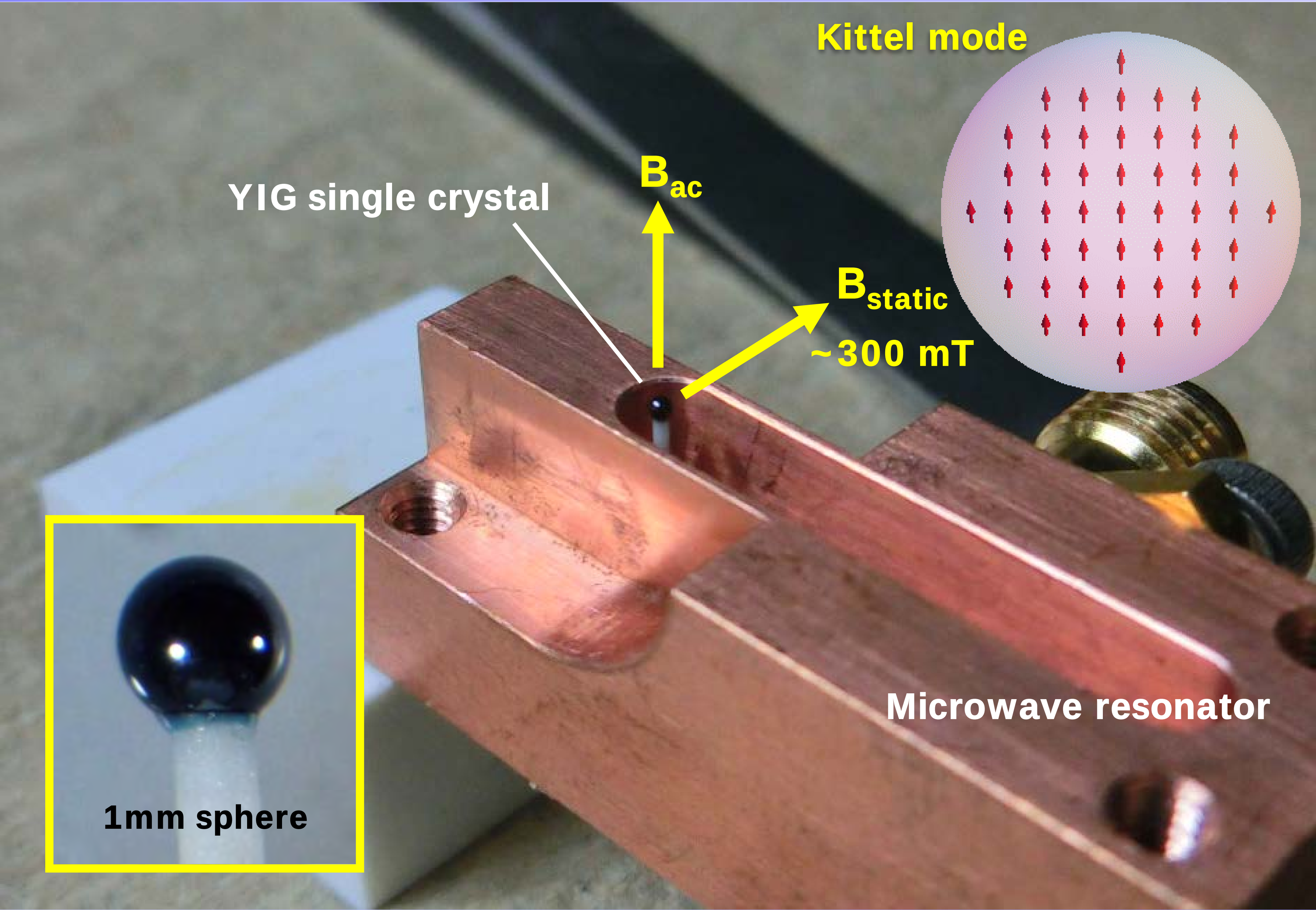
FDK Corporation

Spintronics

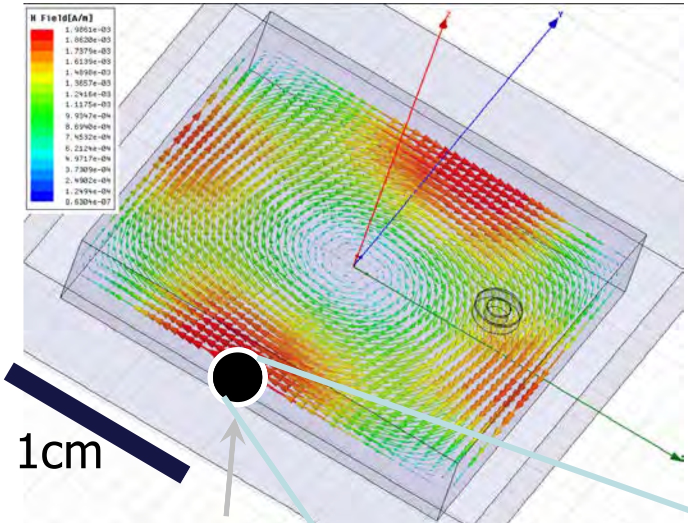


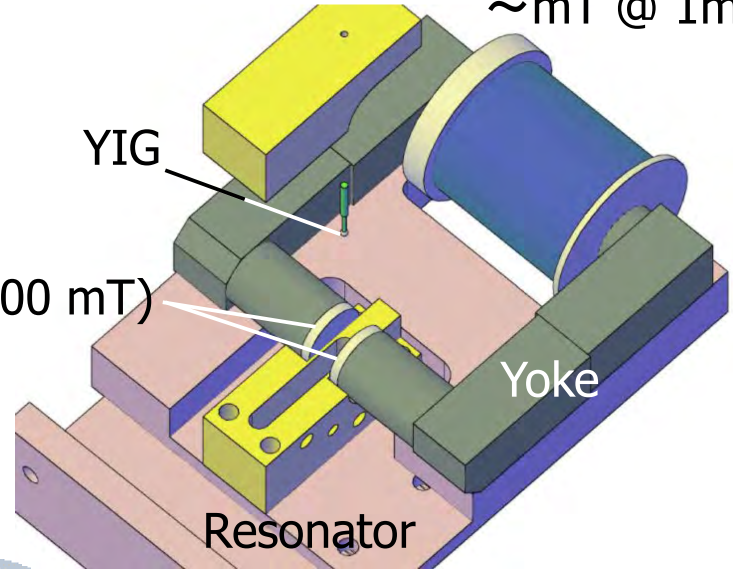
Kajiwara et al.
Nature 2010

Hybrid with ferromagnet magnons

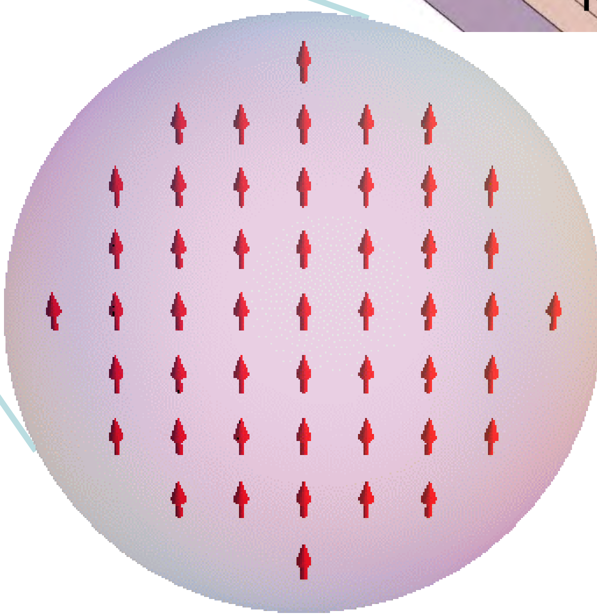


Experimental setup



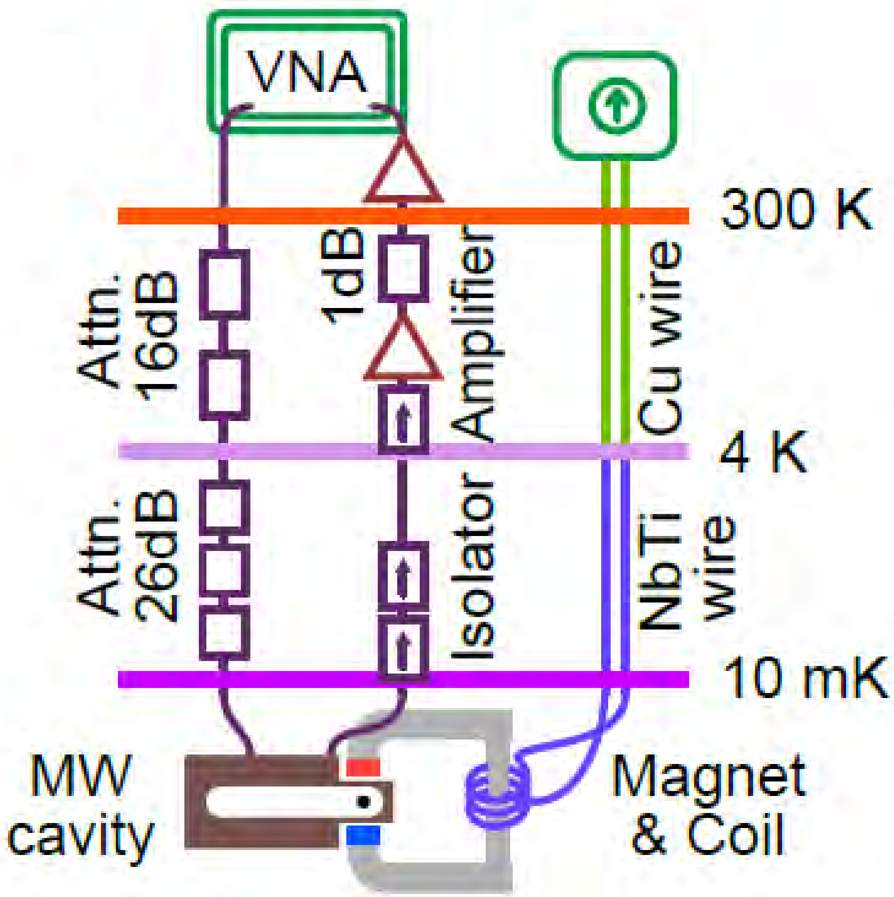


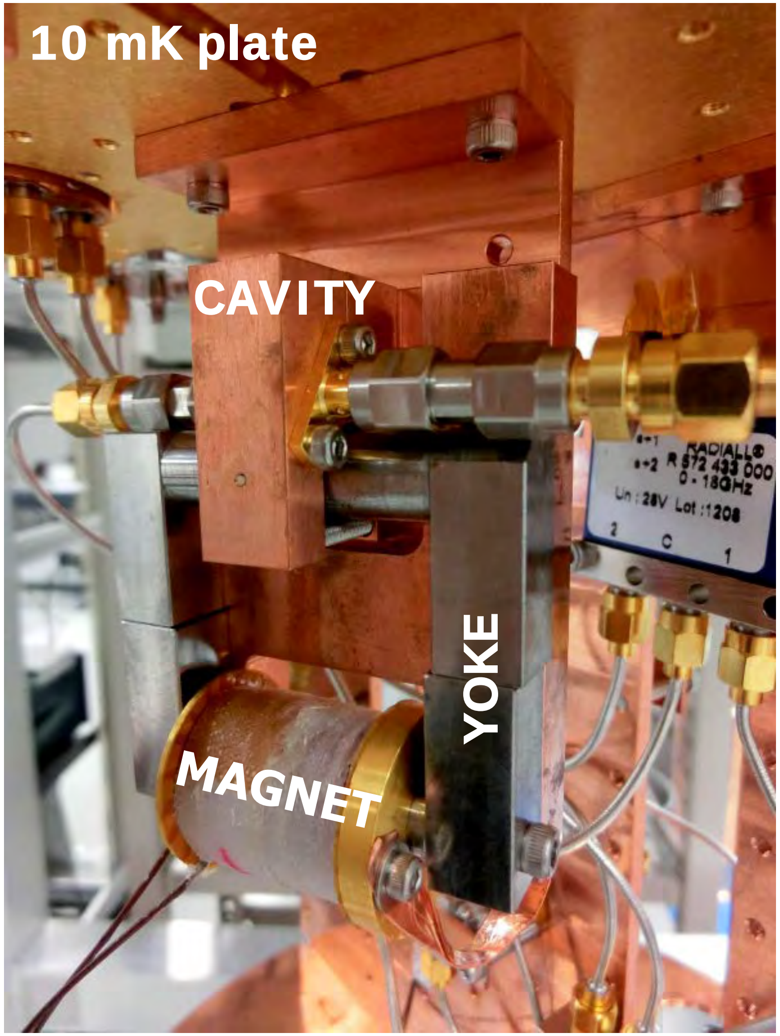
- Copper resonator
  - Rectangular TE_{101} mode
- YIG sphere
  - Magnetostatic mode with uniform precession (Kittel mode)



Y. Tabuchi
S. Ishino

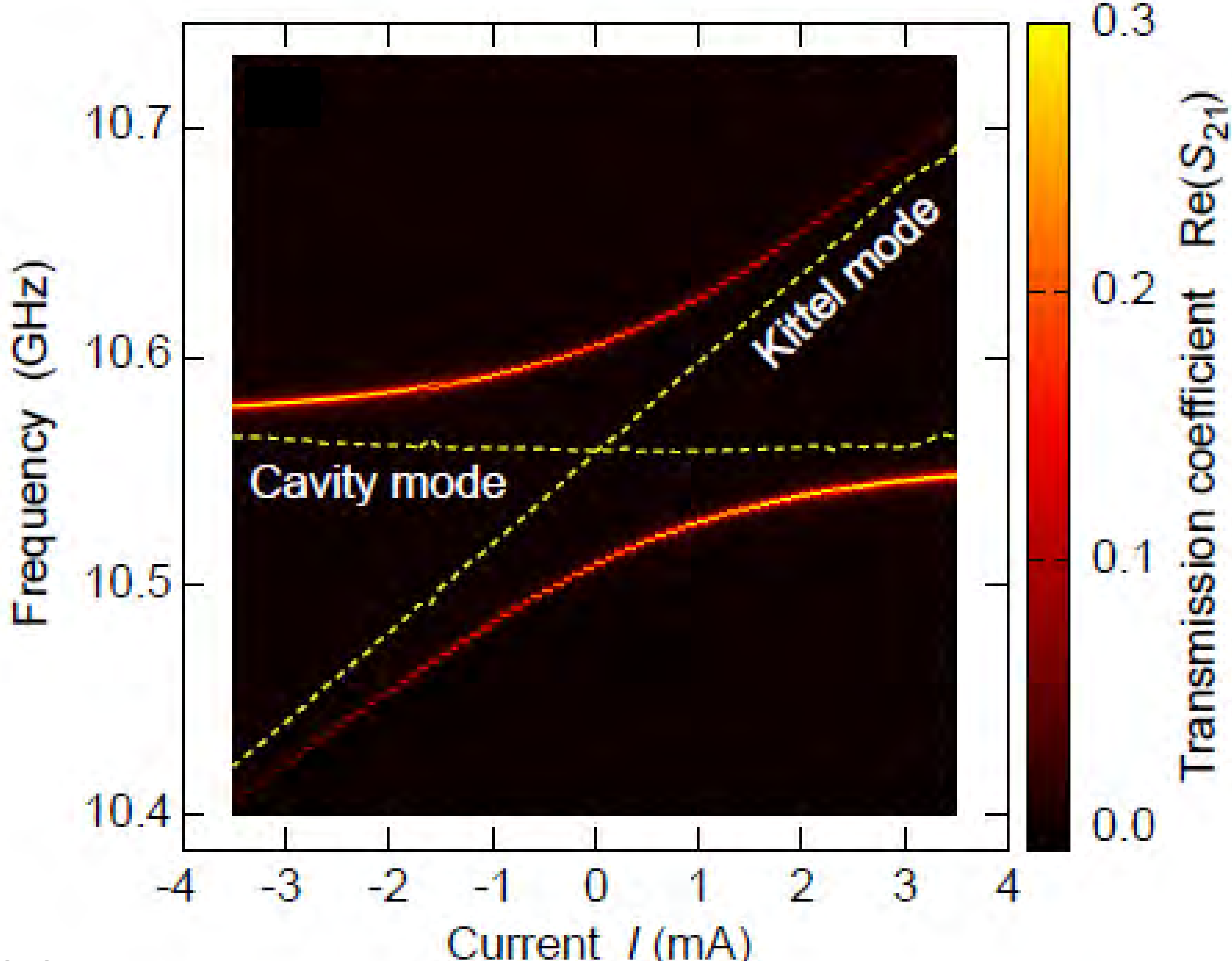
Experimental setup





Magnetic-field dependence

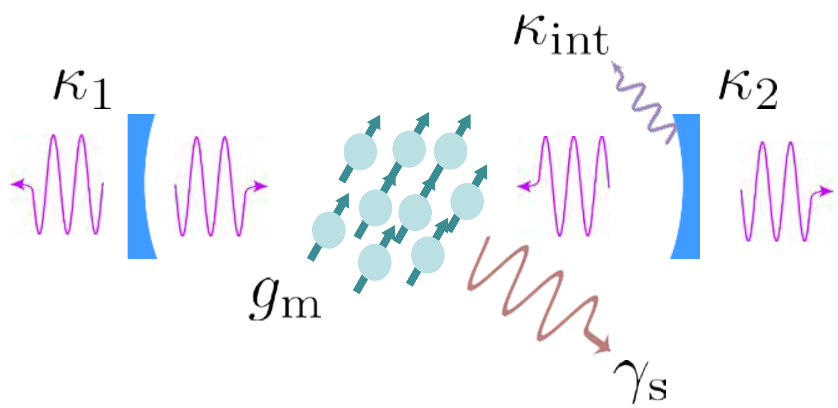
Low temperature ~ 10 mK; ≪ 1 thermal magnon & photon
Microwave power: ~0.9 photons in cavity

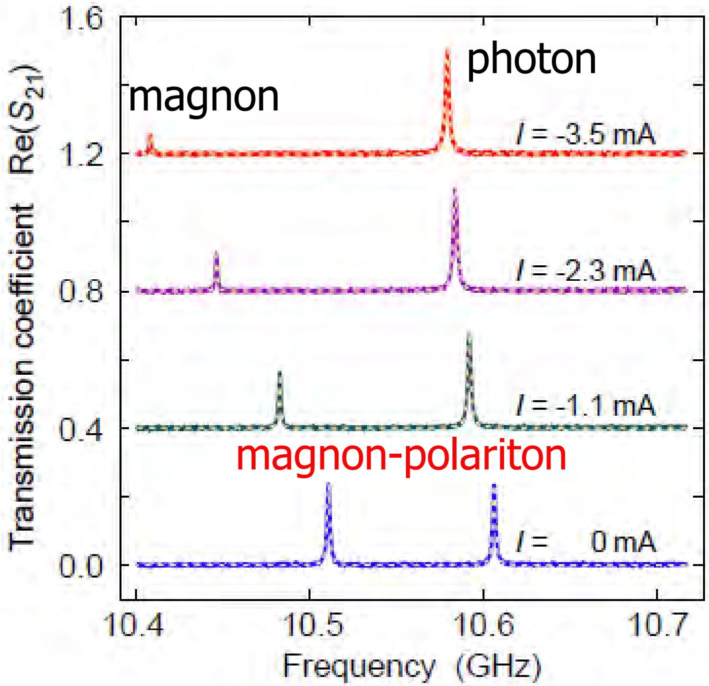


0.5-mm sphere

Y. Tabuchi et al. PRL 113, 083603 (2014)

Coupling strength and cooperativity





Strong coupling condition

$$g_{\mathrm{m}} \gg \kappa_{\mathrm{tot}},\ \gamma_{\mathrm{S}}$$

	Parameter	Value
Cavity external coupling	$(\kappa_1+\kappa_2)/2\pi$	1.6 MHz
Cavity intrinsic loss	$\kappa_{\mathrm{int}}/2\pi$	1.1 MHz
Magnon linewidth	$\gamma_{\mathrm{S}}/2\pi$	1.1 MHz
Magnon-photon coupling	$g_{\mathrm{m}}/2\pi$	47 MHz
Cooperativity	$4{g_{\mathrm{m}}}^2/\gamma_{\mathrm{S}}(\kappa_{\mathrm{c}}+\kappa_{\mathrm{int}})$	3.0×10^3

Sphere-size dependence of coupling strength

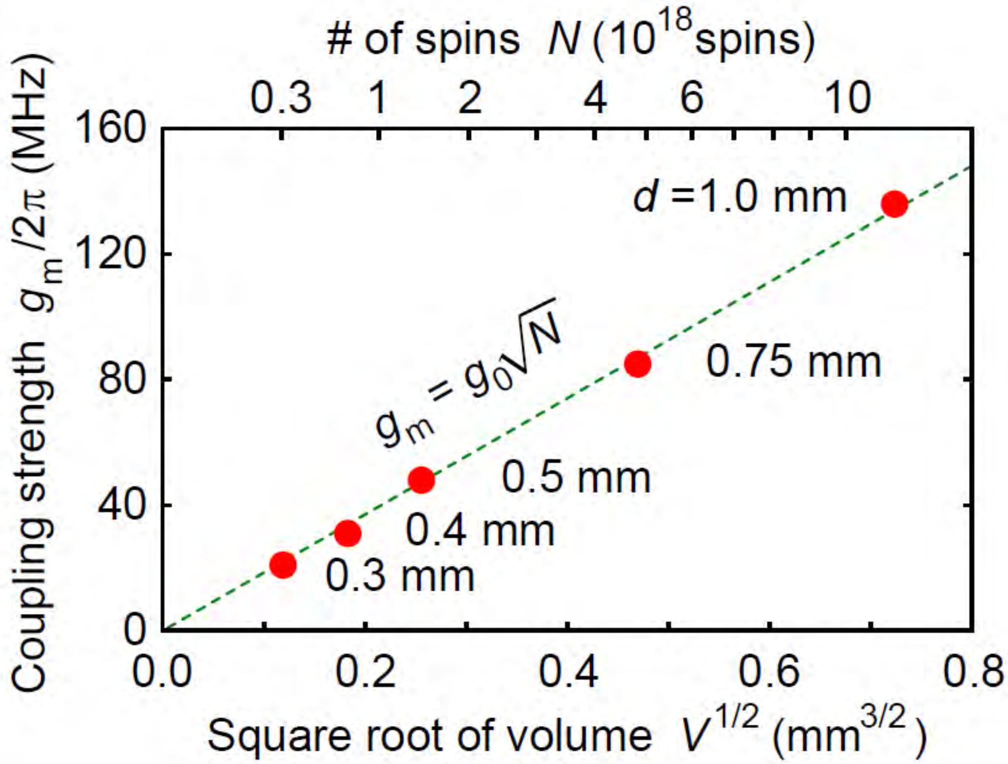
$$g_{\rm m} = g_0\sqrt{N}$$

$$d = 1\,{\rm mm}$$

$$N = 1.1\times 10^{19}\,{\rm spins}$$

$$\Rightarrow \quad g_0/2\pi = 39\,{\rm mHz}$$

Coupling strength per spin

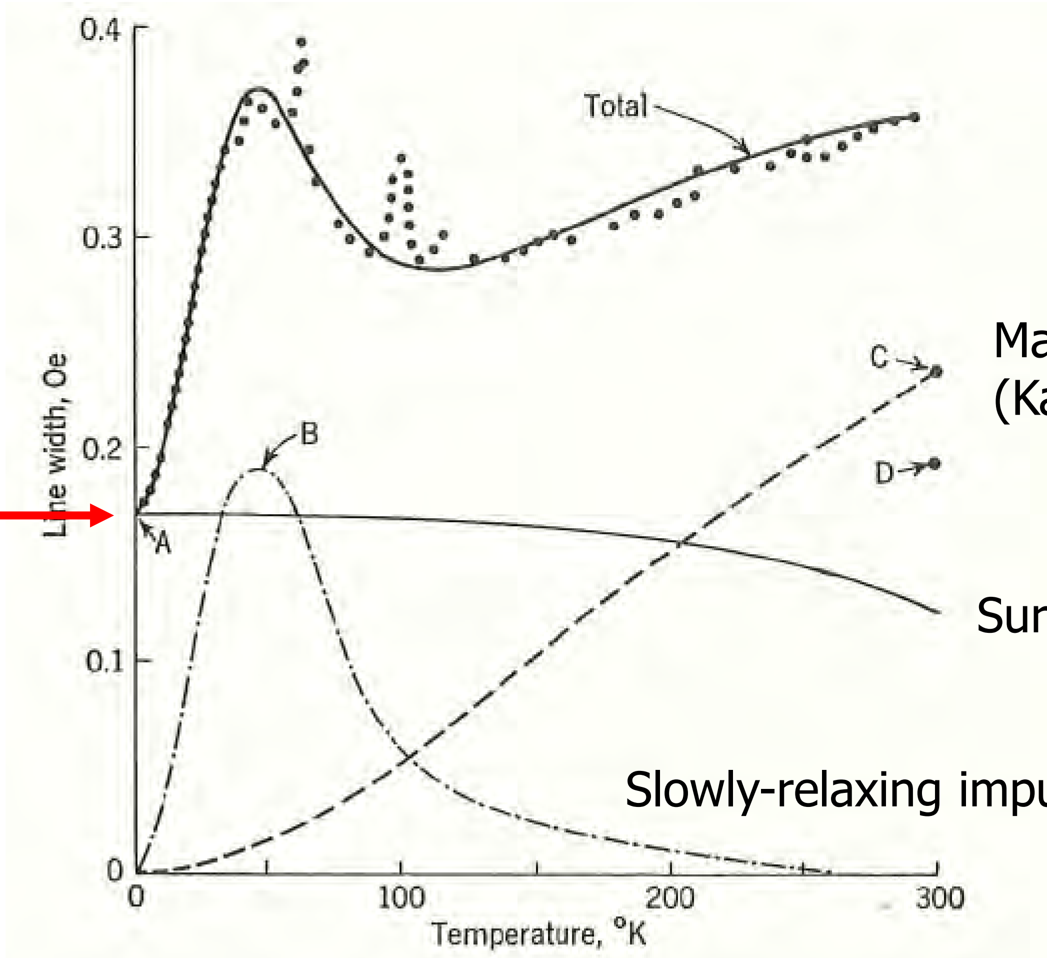


Estimation from vacuum fluctuation amplitude

$$g_0/2\pi = g\mu_{\rm B}B_{\rm vac}/2\pi\hbar \sim 38\,{\rm mHz} \qquad B_{\rm vac} = \sqrt{\frac{\mu_0\hbar\omega_{\rm r}}{2V_{\rm r}}} \sim 10\,{\rm nG}$$

Y. Tabuchi et al. PRL 113, 083603 (2014)

Magnon linewidth vs. temperature



~ 500 kHz
@ 4.2 K

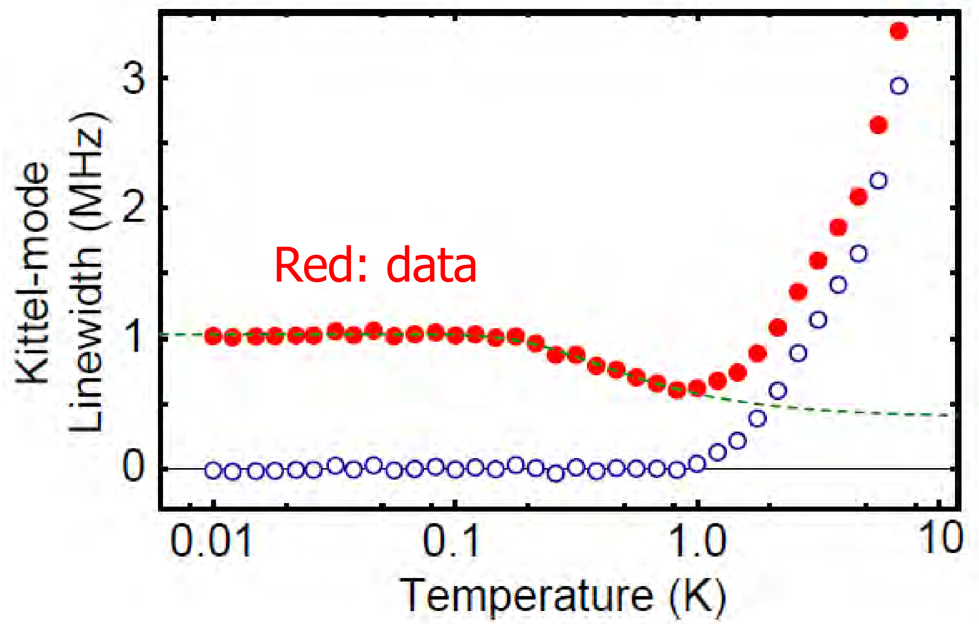
Magnon-phonon
(Kasuya-LeCraw)

Surface roughness

Slowly-relaxing impurity

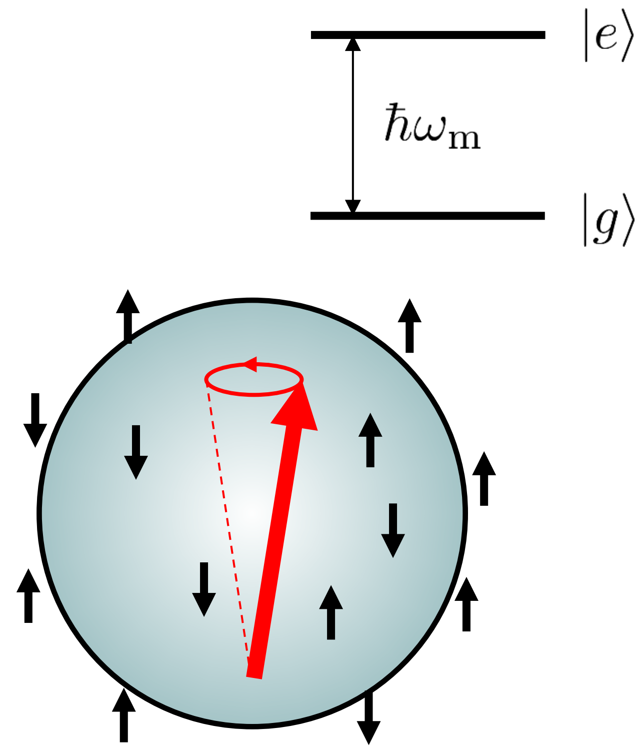
M. Sparks, Ferromagnetic-Relaxation Theory (1964);
Data: E. G. Spencer et. al. Phys. Rev. Lett. 3, 32 (1959).

Magnon linewidth vs. temperature



$$\Delta\omega \propto \tanh\left(\frac{\hbar\omega_{\mathrm{m}}}{2k_{\mathrm{B}}T}\right)$$

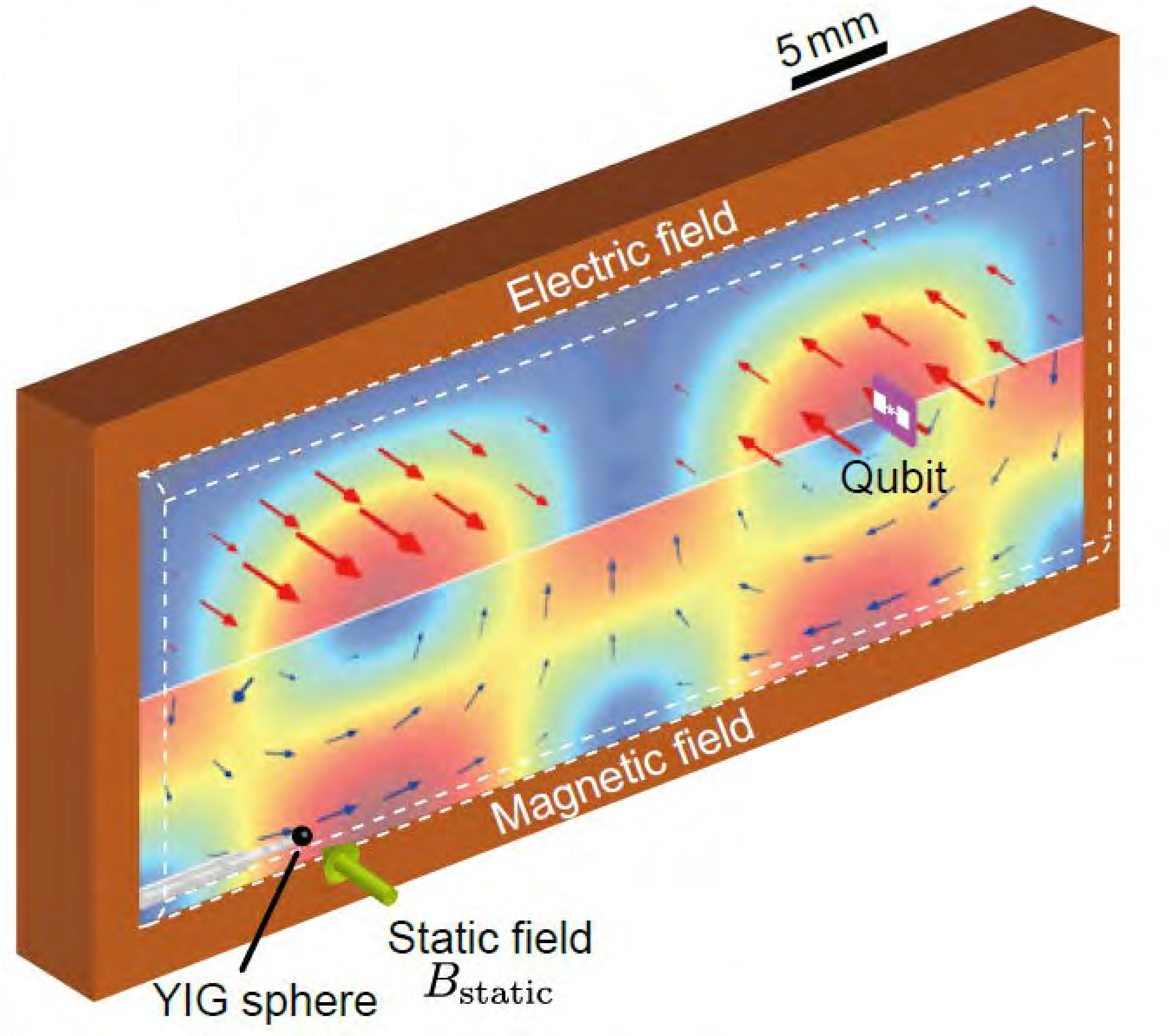
Coupling to ensemble of two-level systems



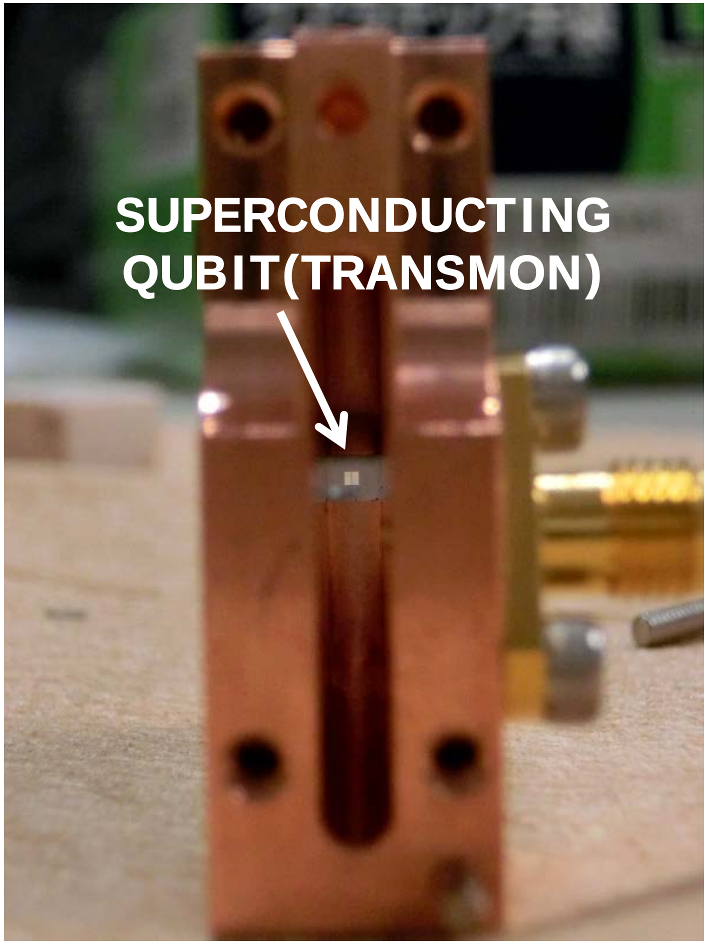
cf. superconducting resonator, Martinis 2005
glass physics, Hunklinger ~1980

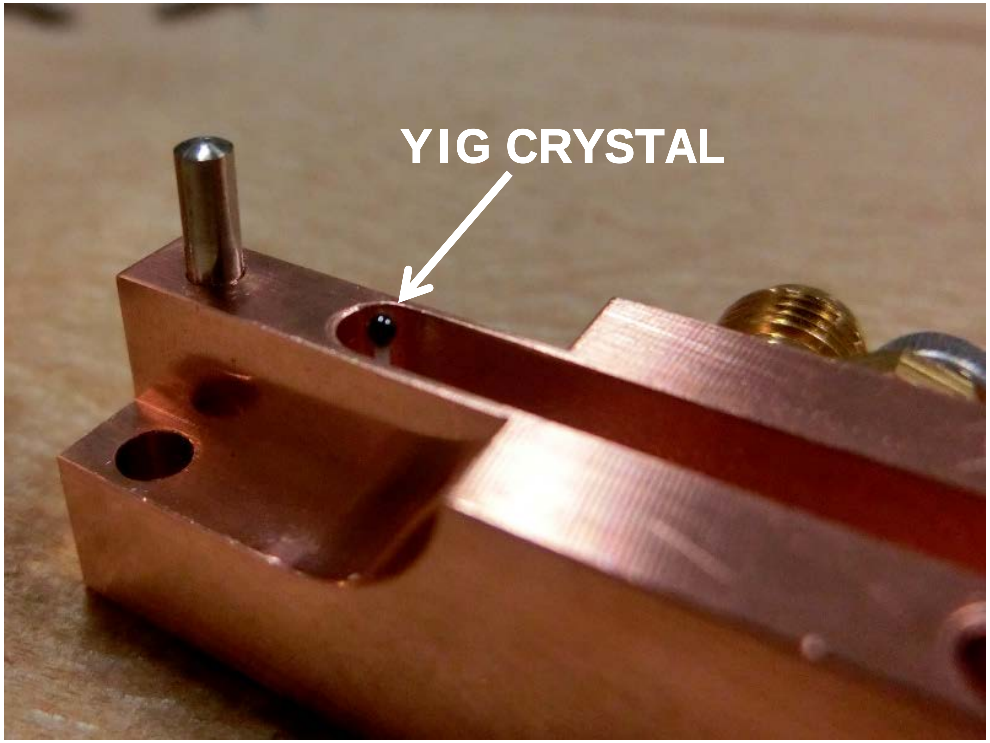
Theory: J. H. Van Vleck, J. Appl. Phys. 35, 882 (1964).

Coupling with a superconducting qubit

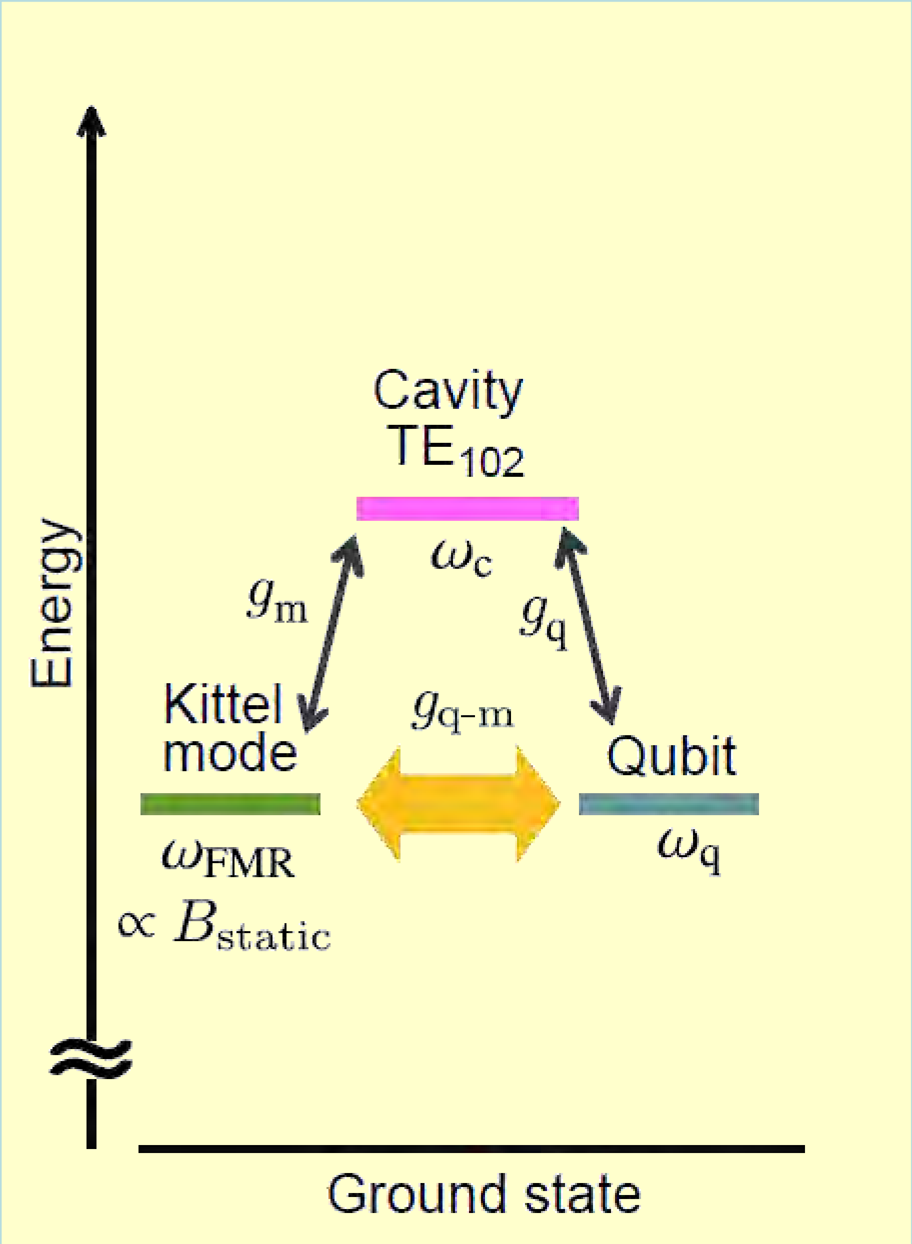


Inside the cavity





Qubit-magnon coupling



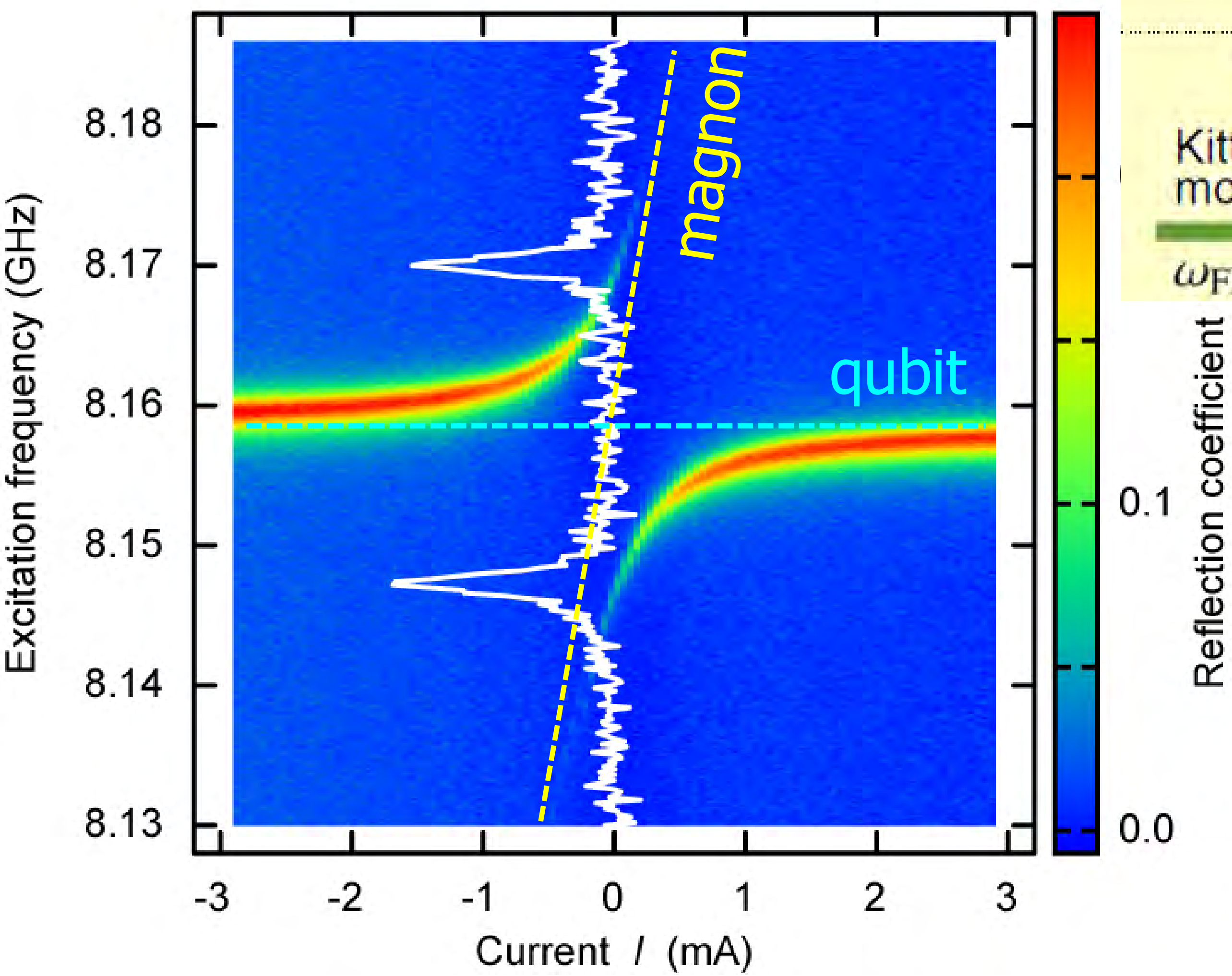
Qubit-magnon coupling
mediated by virtual photon excitation
in cavity

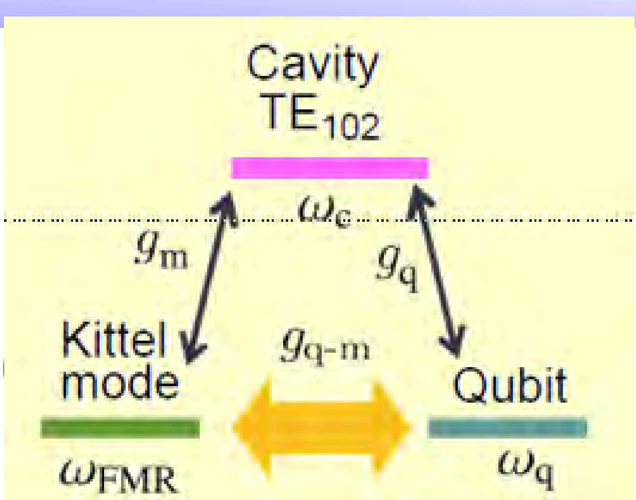
$$\hat{\mathcal{H}}_{q\text{-}m}/\hbar \sim g_{q\text{-}m}\left(\hat{a}_m^\dagger \hat{\sigma}_- + \hat{a}_m \hat{\sigma}_+\right)$$

$$g_{q\text{-}m}/\hbar = \frac{g_q g_m}{\omega_c - \omega_q}$$

$$\sim 10\text{-}50\ \mathrm{MHz}$$

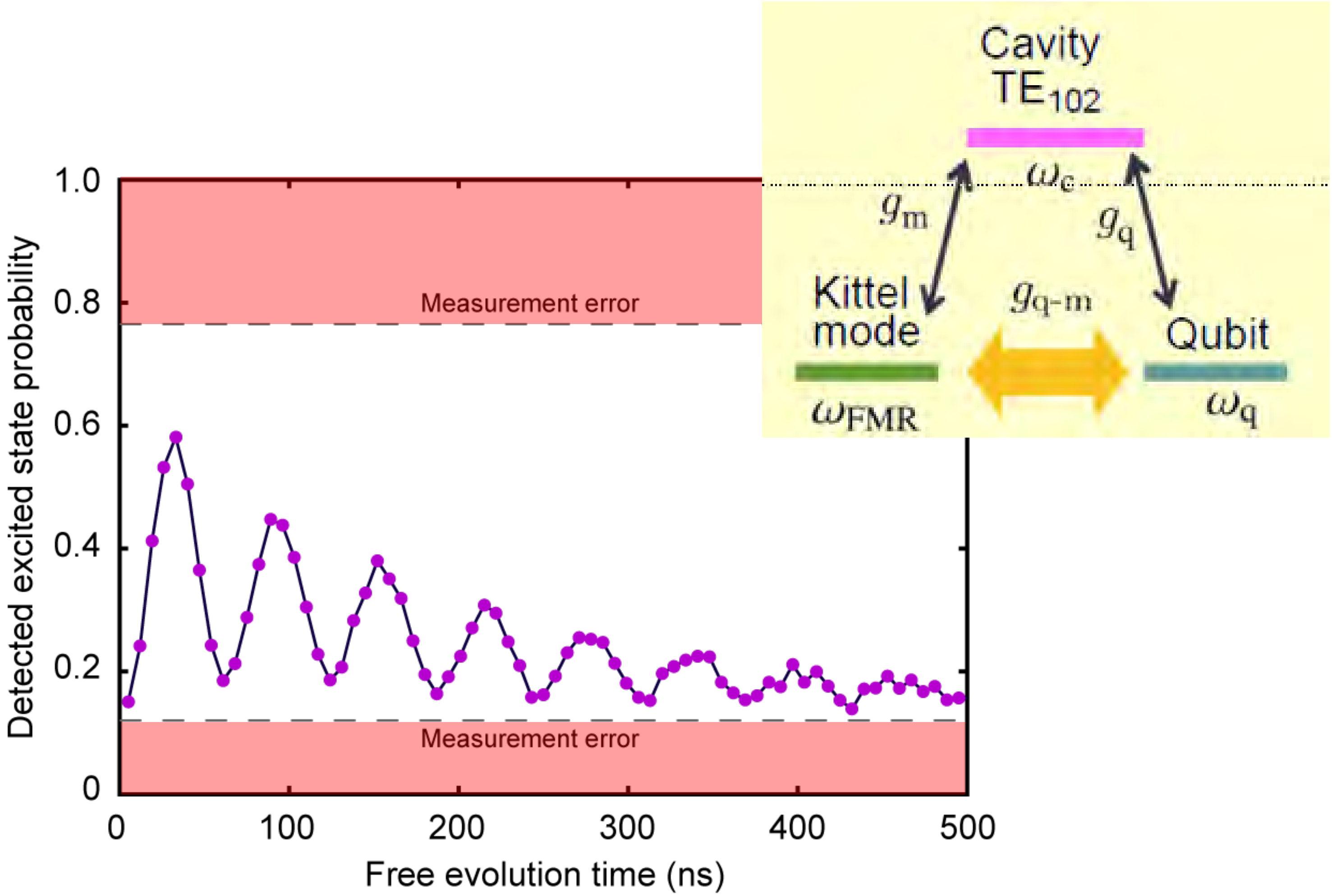
Vacuum Rabi splitting





Y. Tabuchi et al. Science 349, 405 (2015)

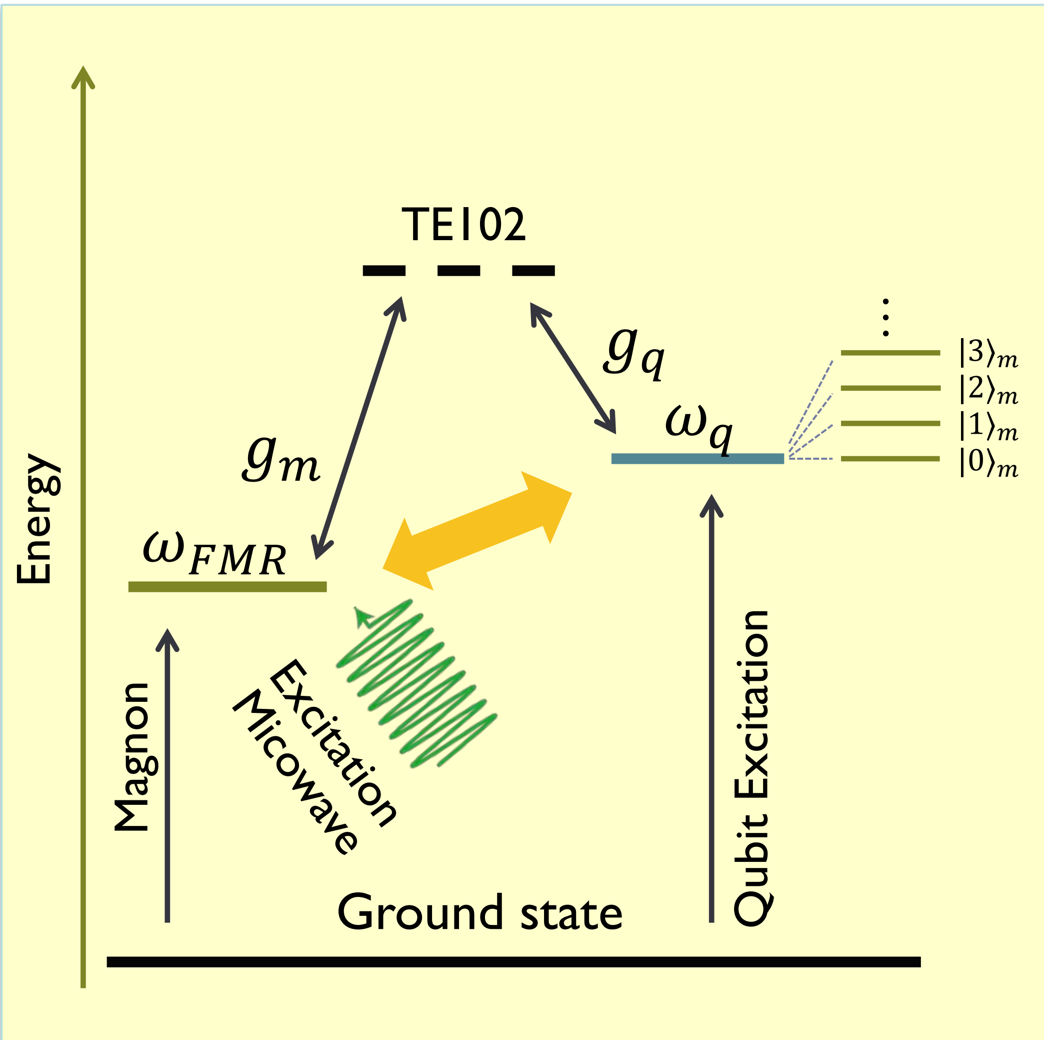
Vacuum Rabi oscillations

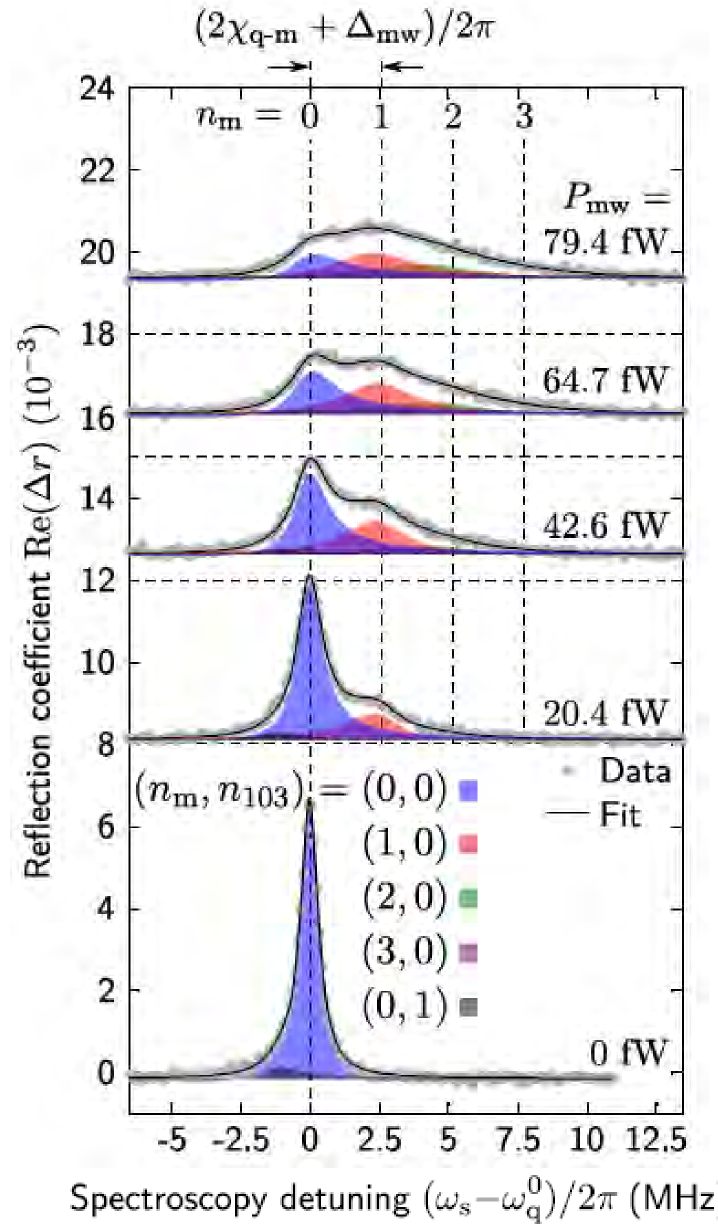


Y. Tabuchi et al. unpublished

Magnon-number-resolving spectroscopy

D. Lachance-Quirion et al.
unpublished

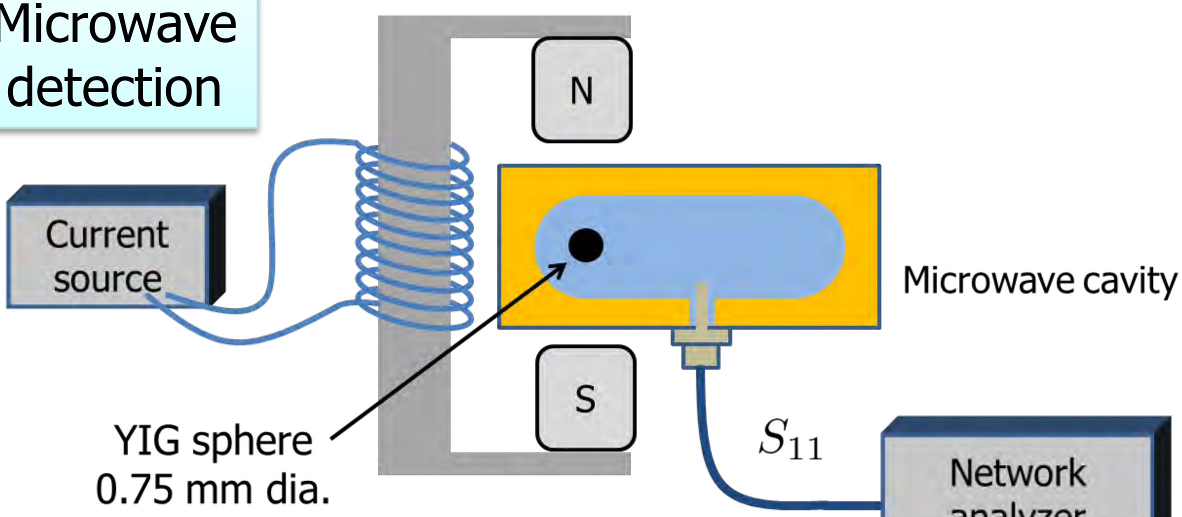


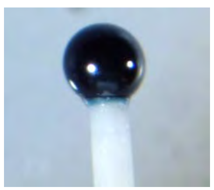


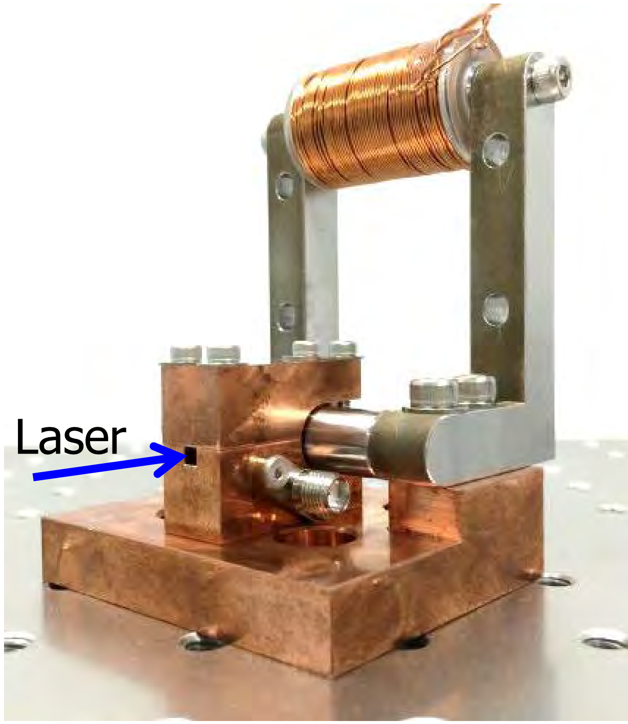
(Quantum) optomagnonics

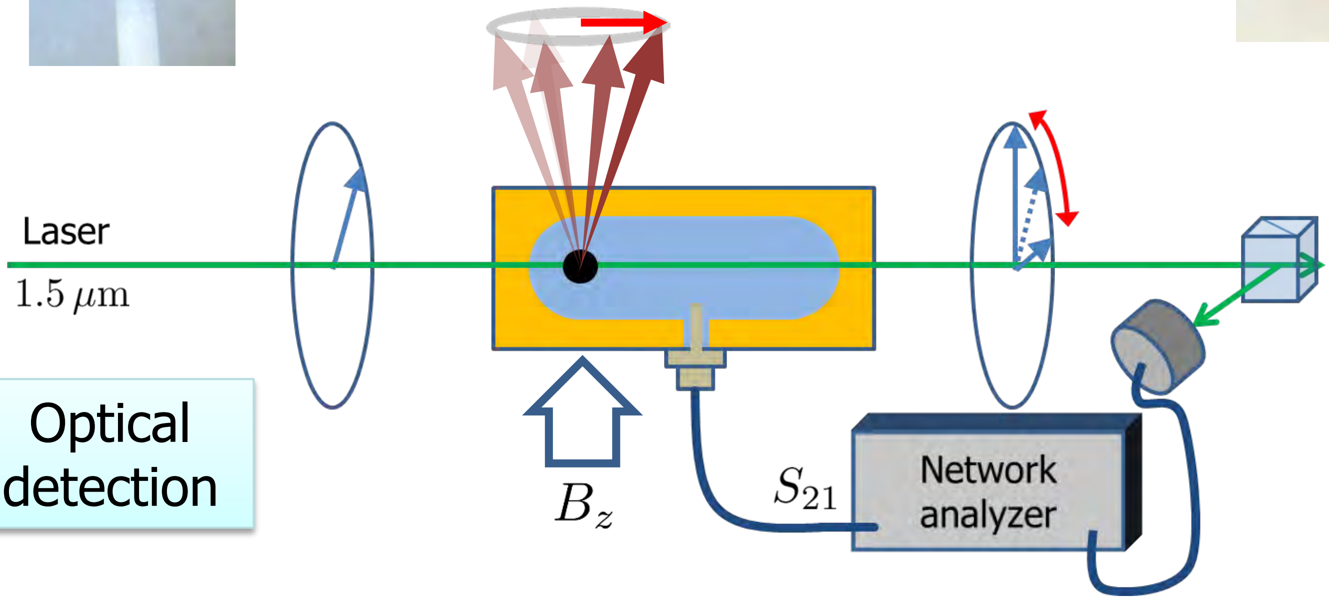
Optical detection of magnon excitations

Microwave detection







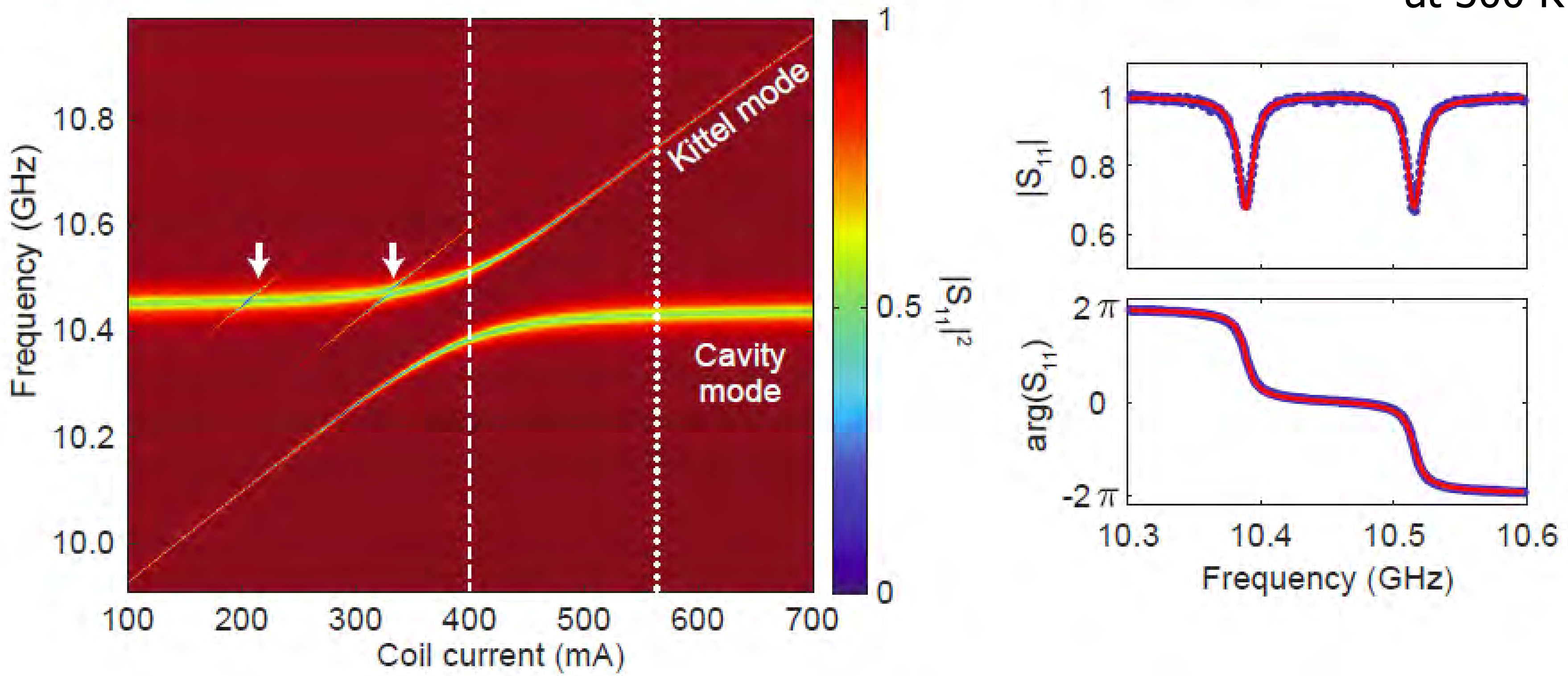


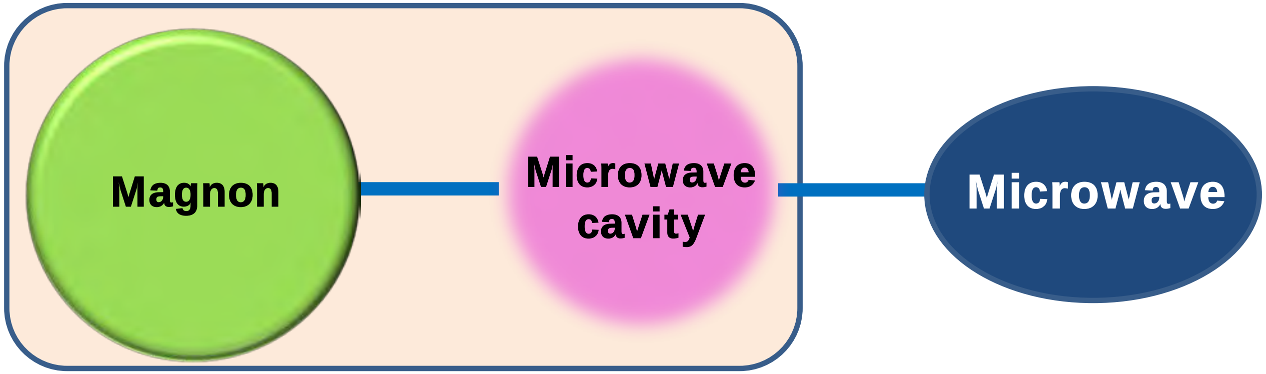
Optical detection

R. Hisatomi et al.
arXiv:1601.03908;
to appear in PRA

Optical detection of magnon excitations

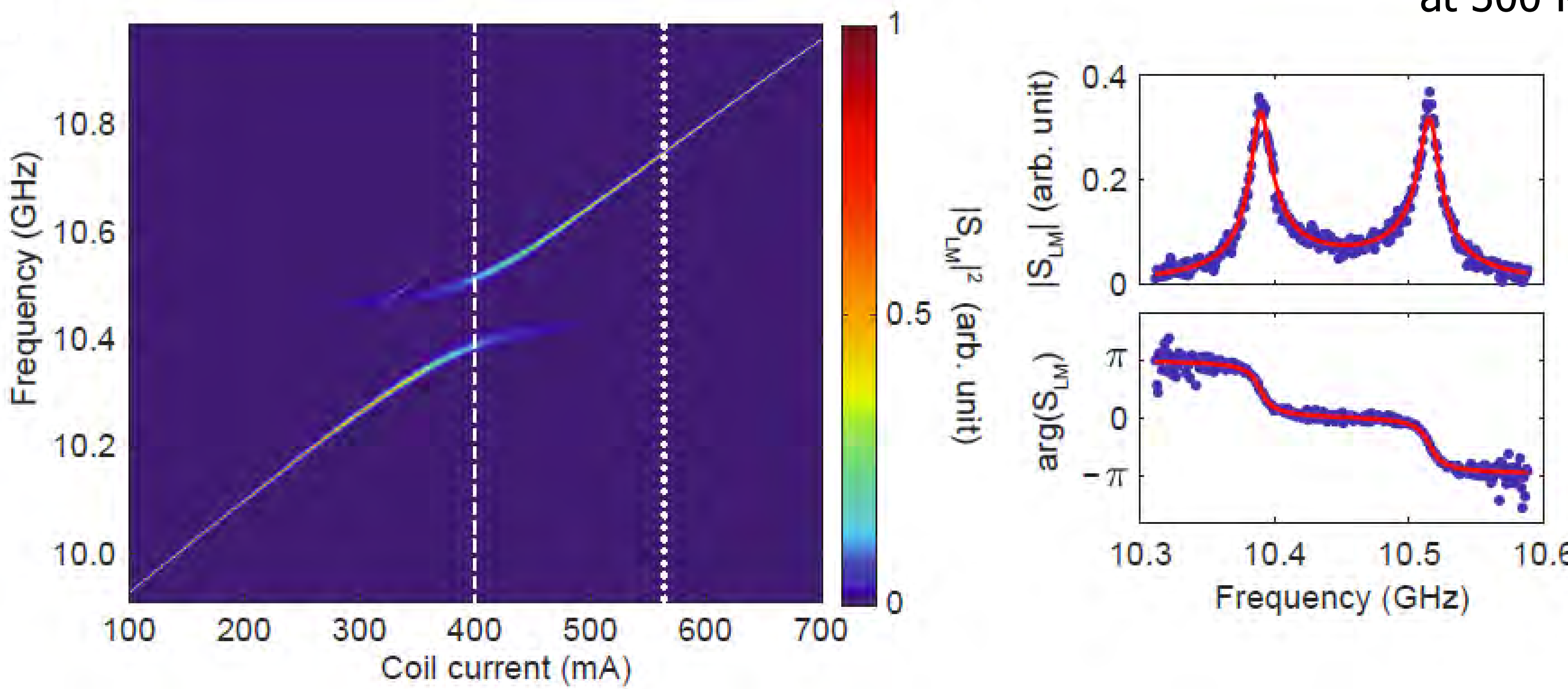
at 300 K

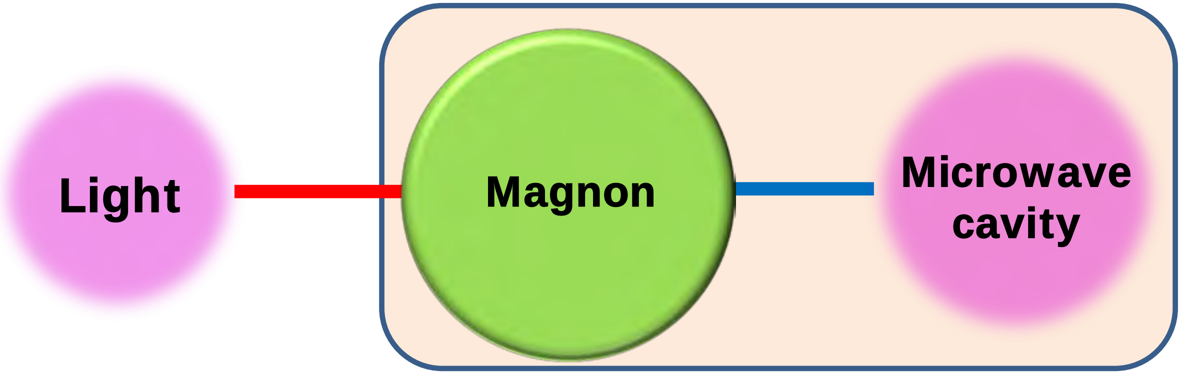




Optical detection of magnon excitations

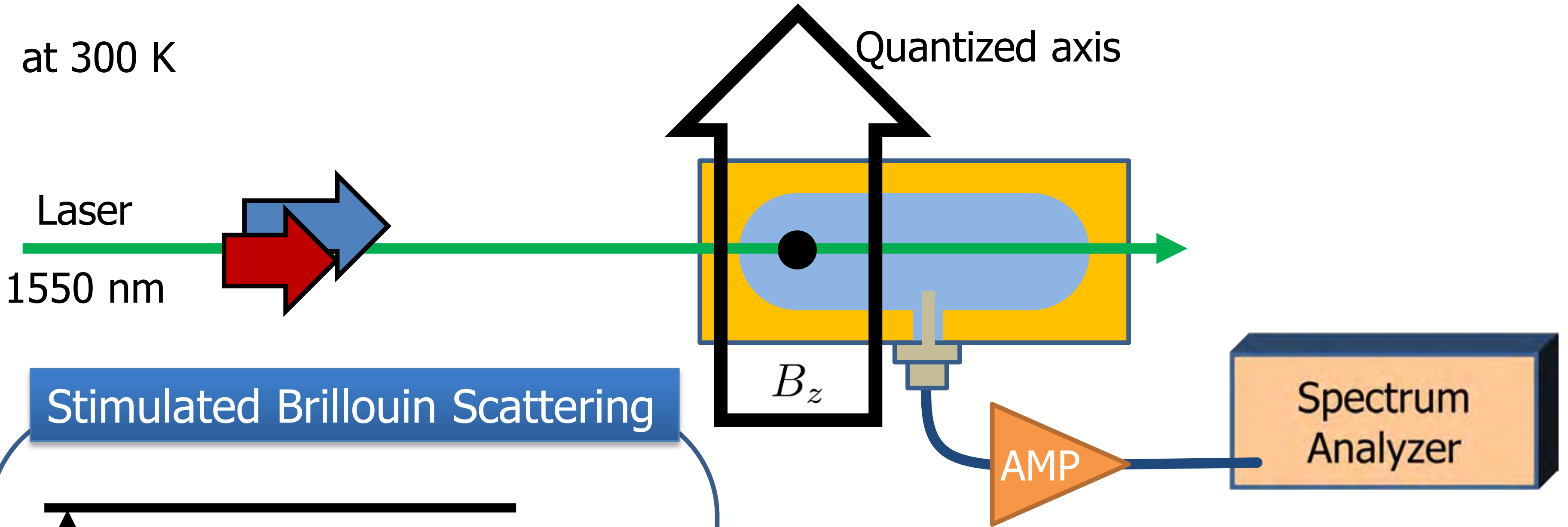
at 300 K

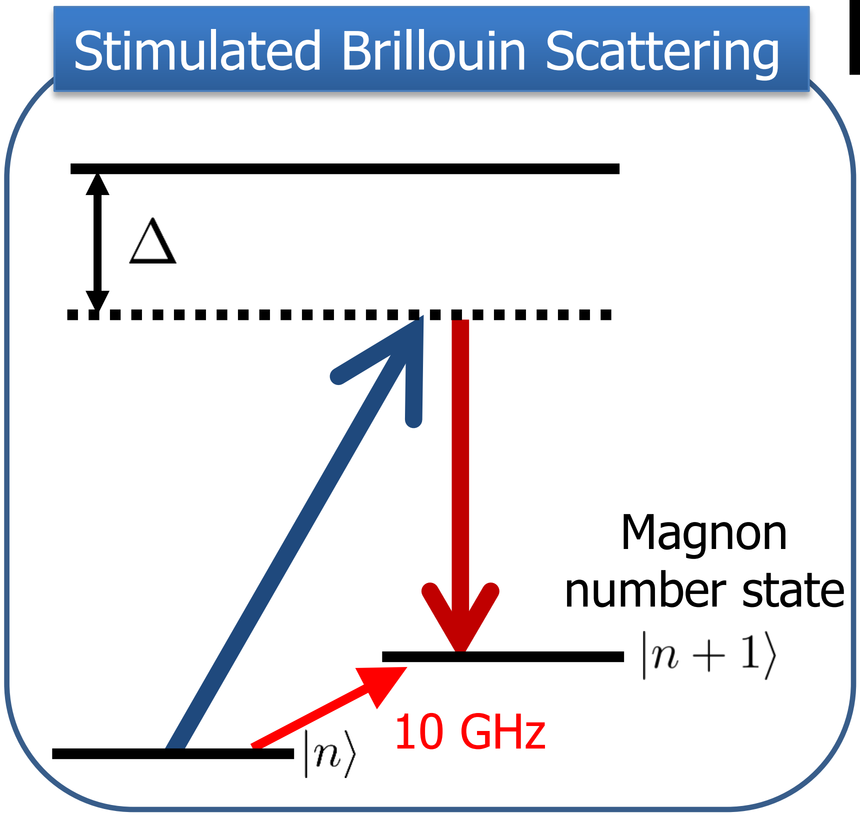


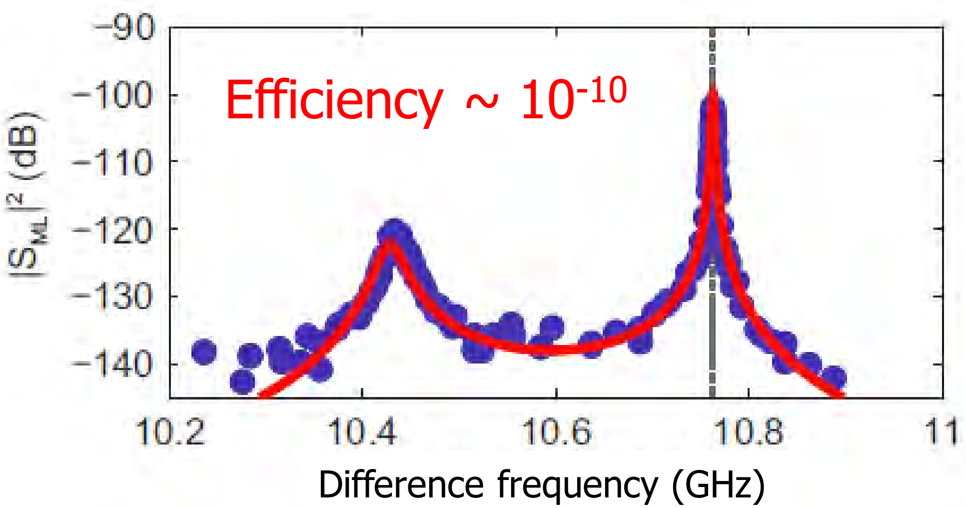


Coherent microwave generation via magnon Brillouin scattering

at 300 K





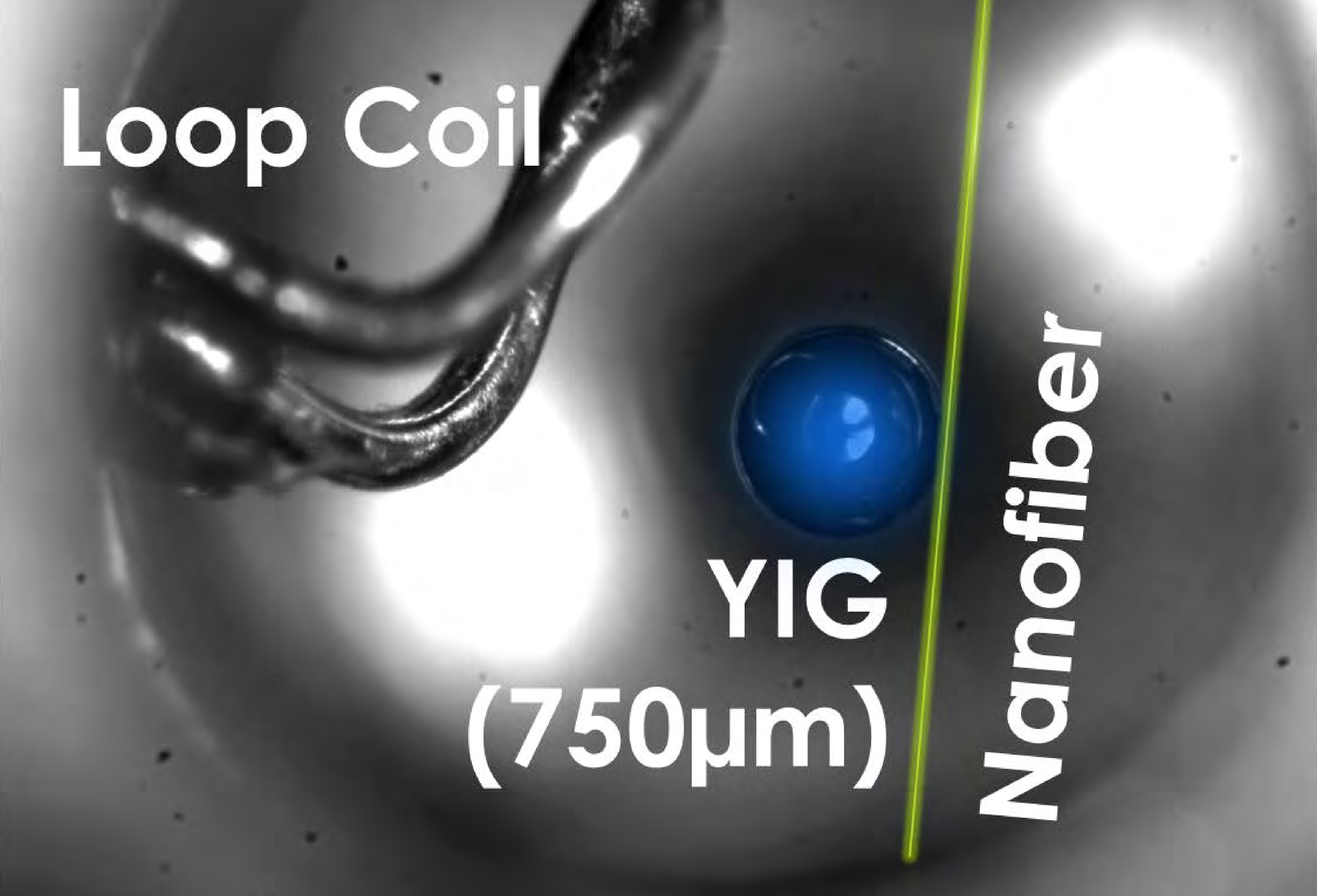


R. Hisatomi et al. arXiv:1601.03908; to appear in PRA

Cavity optomagnonics

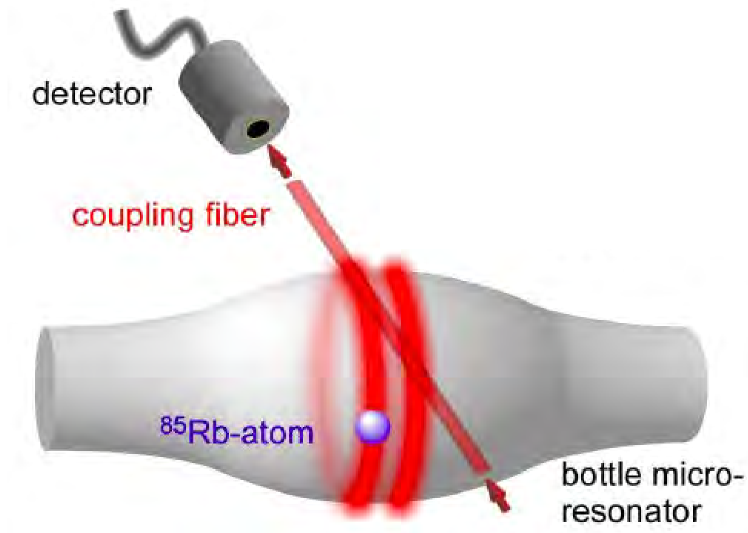
See also
J. A. Haigh et al. PRA 92, 063845 (Cambridge)
X. Zhang et al. arXiv:1510.03545 (Yale)

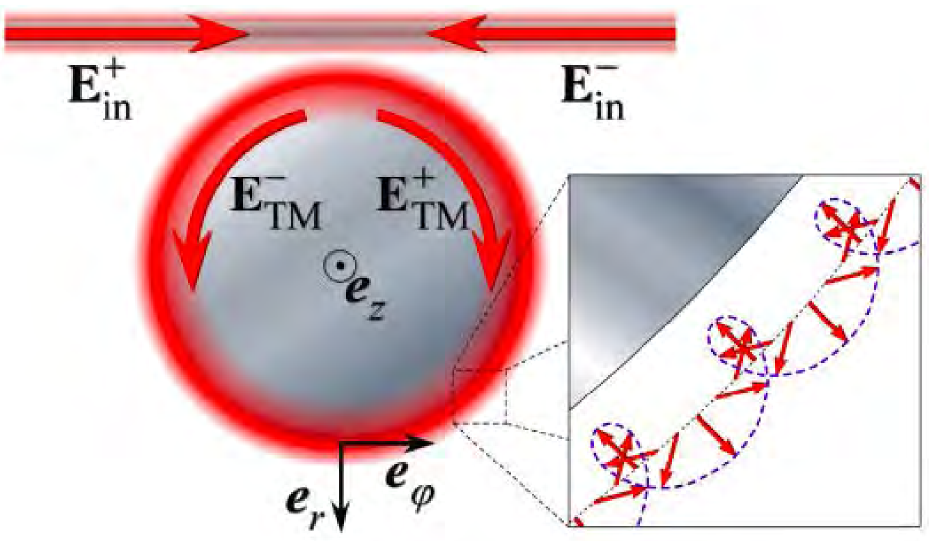
Coupling to whispering gallery mode



Photonic chiral modes

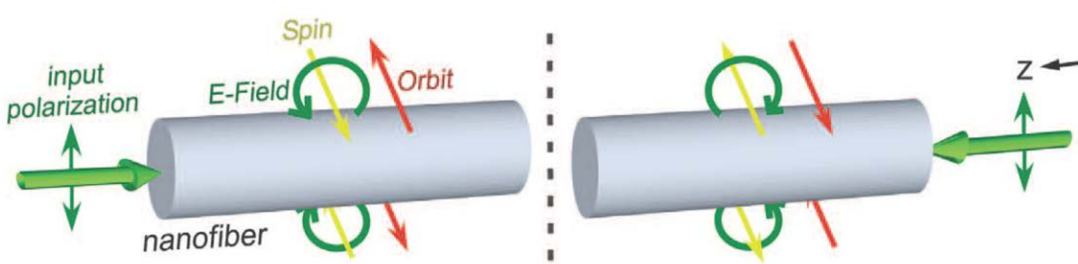
Chirality in WGM

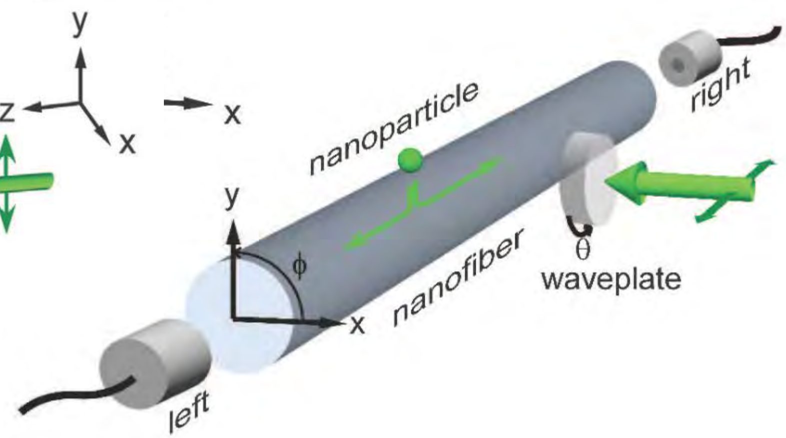




Junge et al. PRL 110, 213604 (2013) TUWien

Chiral nanophotonic waveguide



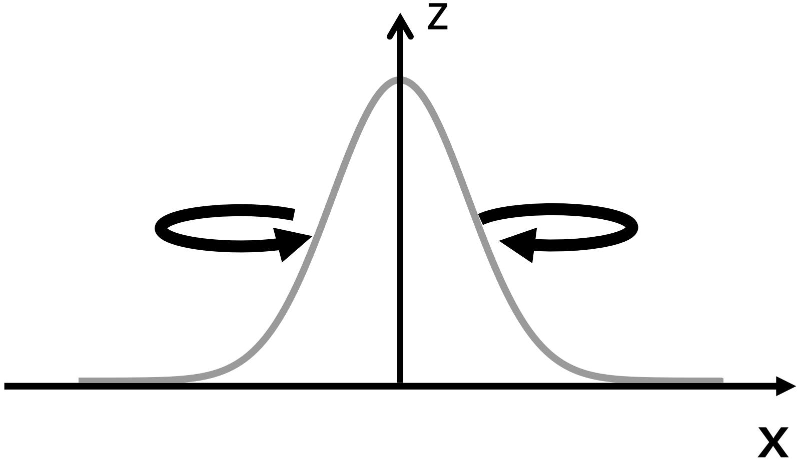


Petersen et al. Science 346, 67 (2014) TUWien

Beyond paraxial approximation

$$\mathrm{div}E = \partial_\perp E_\perp + \partial_z E_z = 0$$

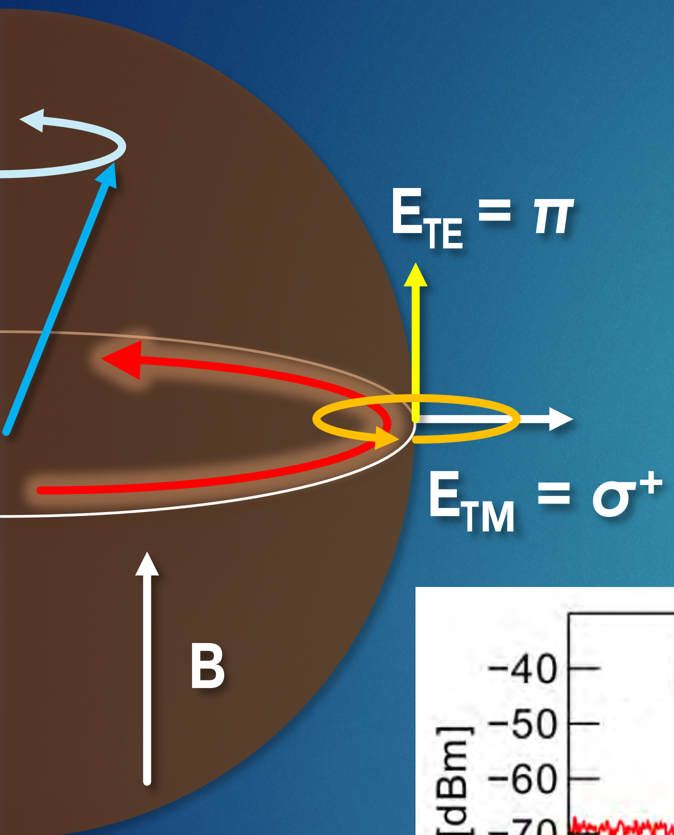
$$\partial_\perp E_\perp = -ikE_z$$ =0 for plane wave

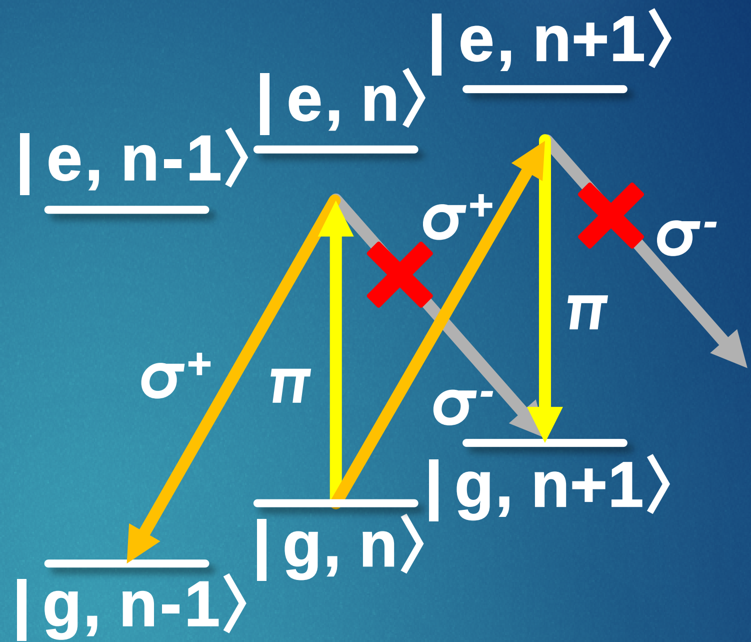


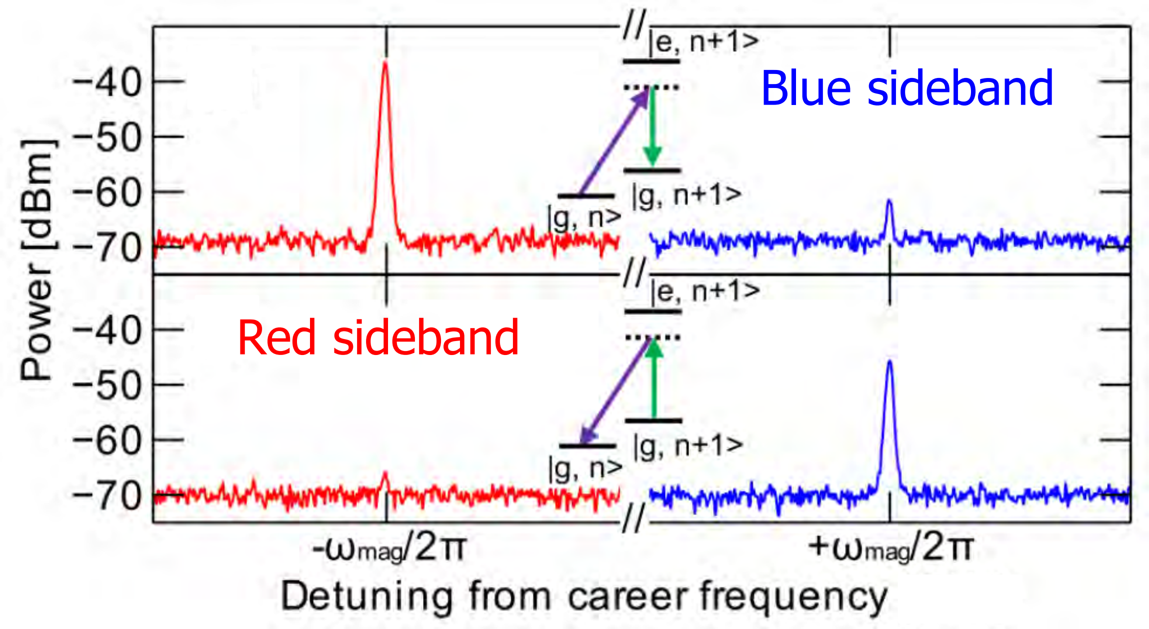
Spin–orbit interactions of light

Review: K. Y. Bliokh et al. Nat. Photo. 9, 796 (2015)

Angular momentum selection rule



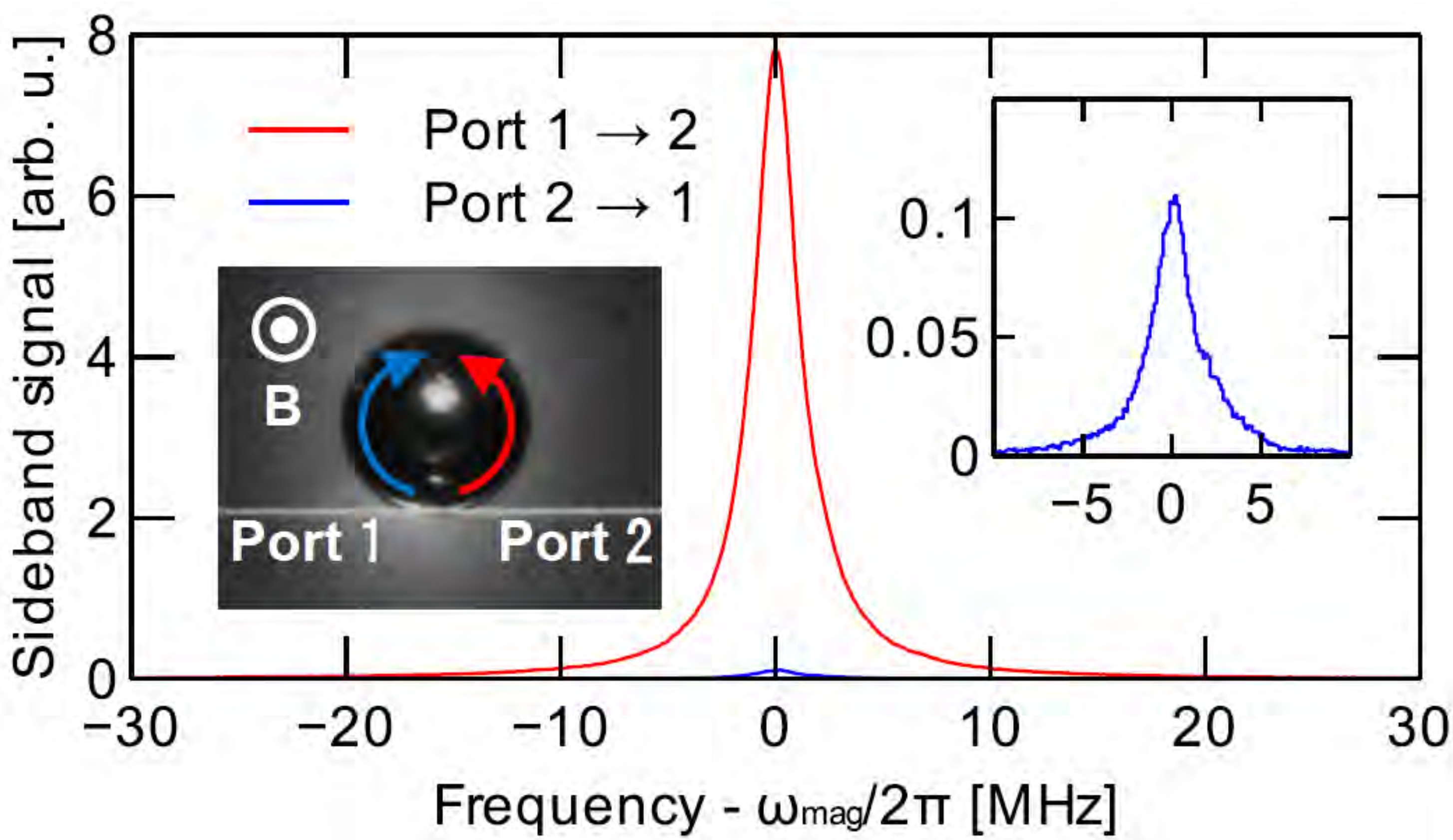




A. Osada et al. arXiv:1510.01837; to appear in PRL

Non-reciprocal sideband generation

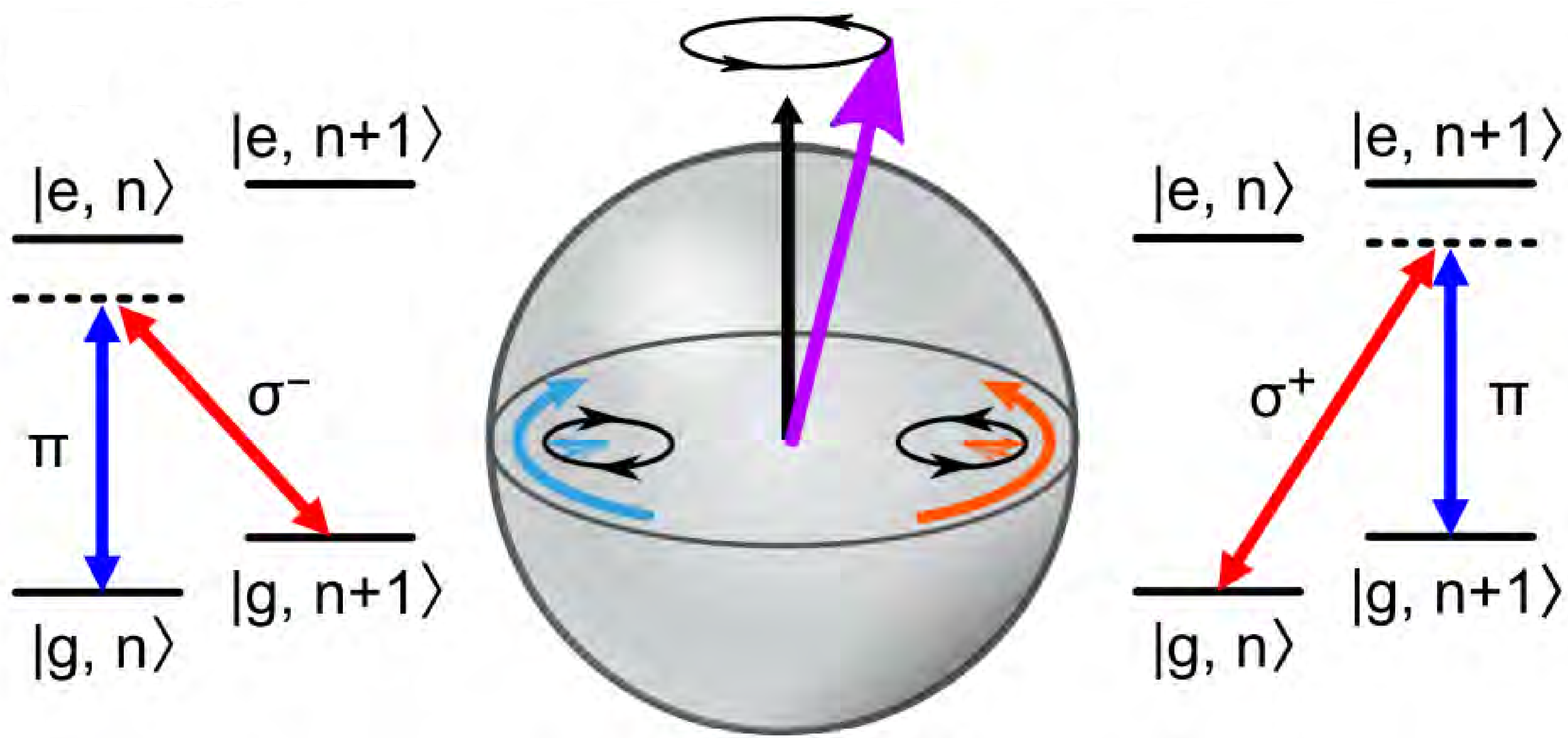
TM-input



A. Osada et al. arXiv:1510.01837; to appear in PRL

Non-reciprocal sideband generation

TM-input

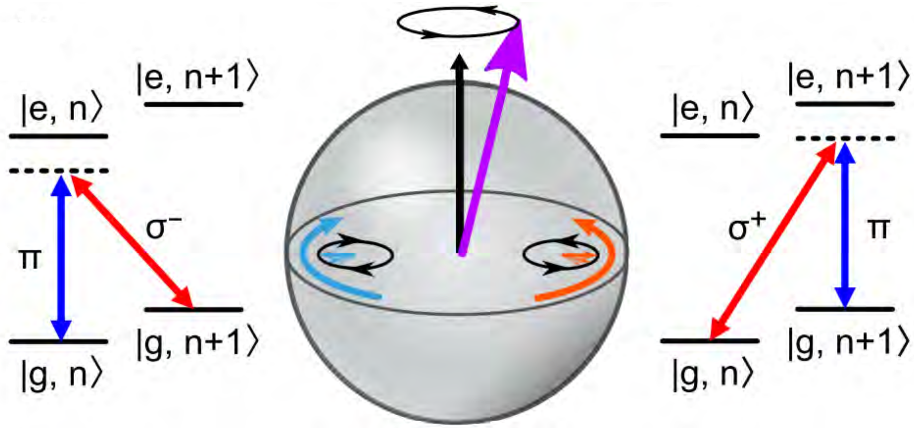


$\omega_{\mathrm{TM}} < \omega_{\mathrm{TE}}$

$\omega_{\mathrm{TM}} > \omega_{\mathrm{TE}}$

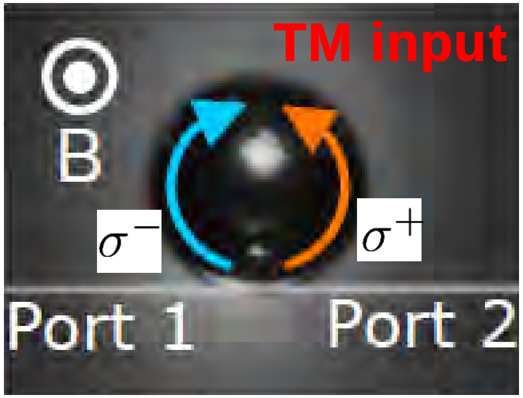
A. Osada et al. arXiv:1510.01837; to appear in PRL

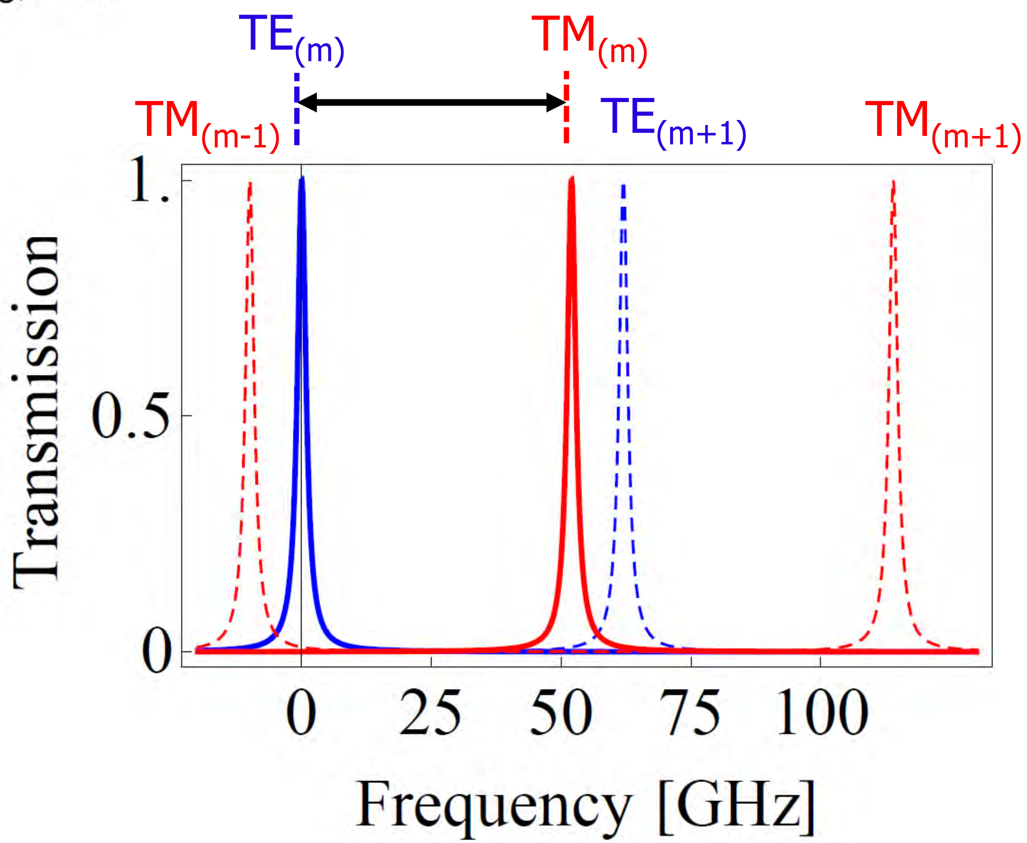
Role of geometric birefringence



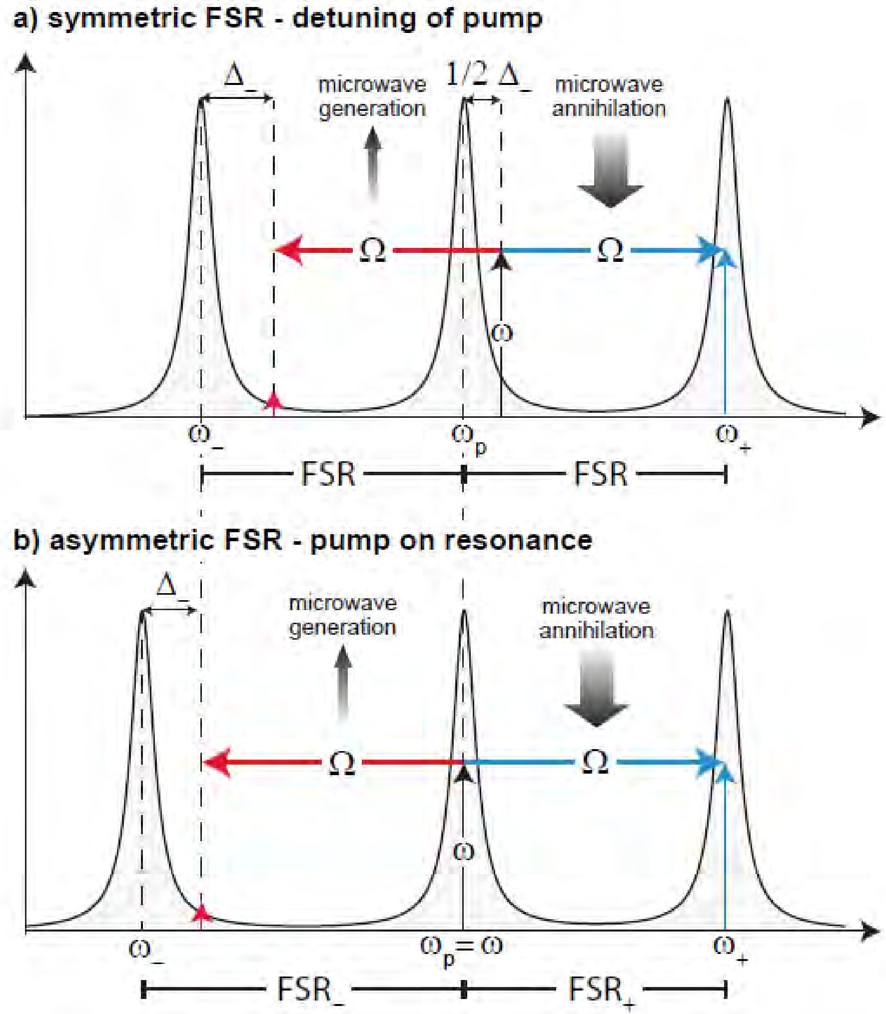
Geometrical birefringence

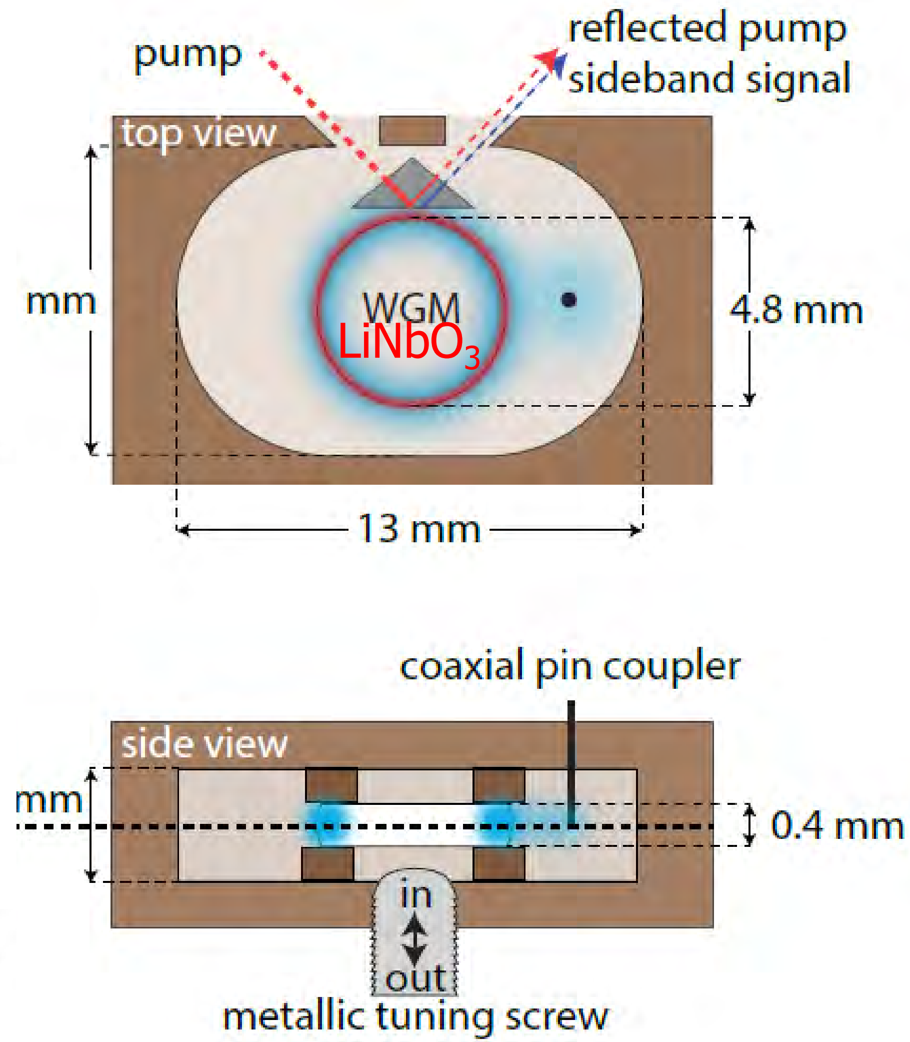
$$\mathrm{FSR} \times \sqrt{1 - \frac{1}{m^2}}$$





Microwave-light conversion via electro-optical WGM resonator





Conversion efficiency ~ 10^{-3}

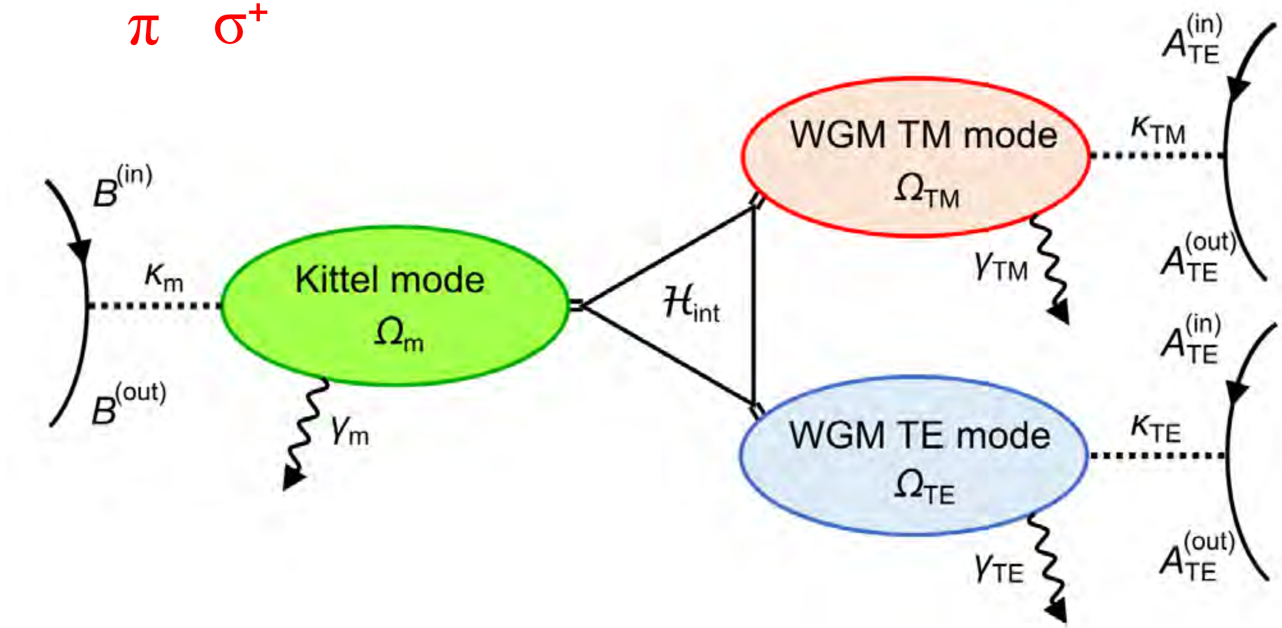
A. Rueda et al. arXiv:1601.07261 (Erlangen)

Model

$$\mathcal{H} = \hbar\Omega_{\mathrm{TE}} a^\dagger_{\mathrm{TE}} a_{\mathrm{TE}} + \hbar\Omega_{\mathrm{TM}} a^\dagger_{\mathrm{TM}} a_{\mathrm{TM}} + \hbar\Omega_{\mathrm{m}} b^\dagger b$$
$$+\hbar g(a_{\mathrm{TE}} a^\dagger_{\mathrm{TM}} b + a^\dagger_{\mathrm{TE}} a_{\mathrm{TM}} b^\dagger)$$

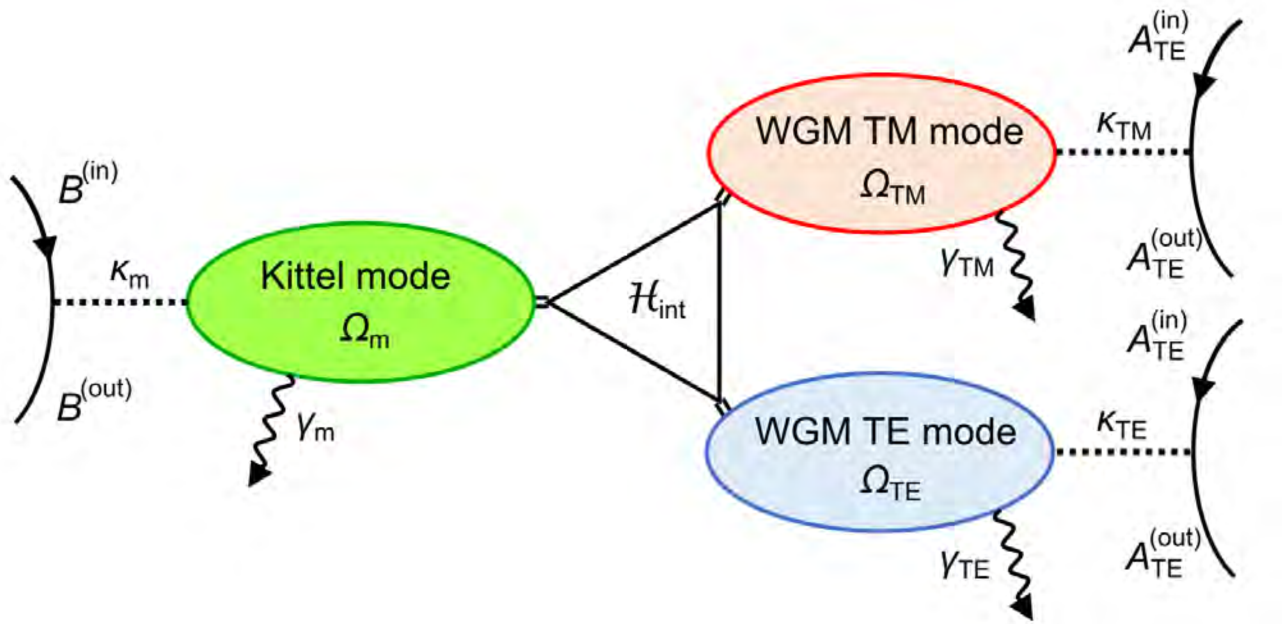
π σ^+

$$\delta = \omega_{\mathrm{TM}} - \omega_{\mathrm{TE}} - \omega_{\mathrm{m}} = 0$$



$$n^{(\mathrm{out})}_{\mathrm{TM}} = g^2 \frac{\kappa_{\mathrm{TE}}}{\Delta^2_{\mathrm{TE}} + (\Gamma_{\mathrm{TE}}/2)^2} \frac{\kappa_{\mathrm{TM}}}{\Delta^2_{\mathrm{TM}} + (\Gamma_{\mathrm{TM}}/2)^2} \frac{\kappa_{\mathrm{m}}}{\Delta^2_{\mathrm{m}} + (\Gamma_{\mathrm{m}}/2)^2} n^{(\mathrm{in})}_{\mathrm{TE}} \quad n^{(\mathrm{in})}_{\mathrm{MW}}$$

Possible optimization



$$n_{\mathrm{TM}}^{(\mathrm{out})} = g^2 \frac{\kappa_{\mathrm{TE}}}{\Delta_{\mathrm{TE}}^2 + (\Gamma_{\mathrm{TE}}/2)^2} \frac{\kappa_{\mathrm{TM}}}{\Delta_{\mathrm{TM}}^2 + (\Gamma_{\mathrm{TM}}/2)^2} \frac{\kappa_{\mathrm{m}}}{\Delta_{\mathrm{m}}^2 + (\Gamma_{\mathrm{m}}/2)^2} n_{\mathrm{TE}}^{(\mathrm{in})} \; n_{\mathrm{MW}}^{(\mathrm{in})}$$

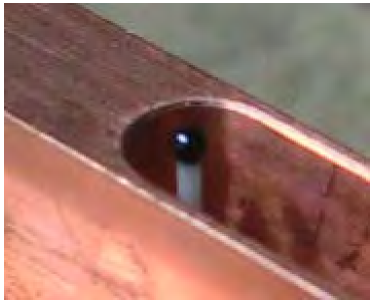
- Set all detuning to zero, Ω_{TM}-Ω_{TE}-Ω_{m}=0 x7000
- Make a better cavity x3500
- Reduce sample volume x100

➔ Conversion efficiency ~ 1×10^{-3} +Larger g ∝ Verdet const.

Conclusions

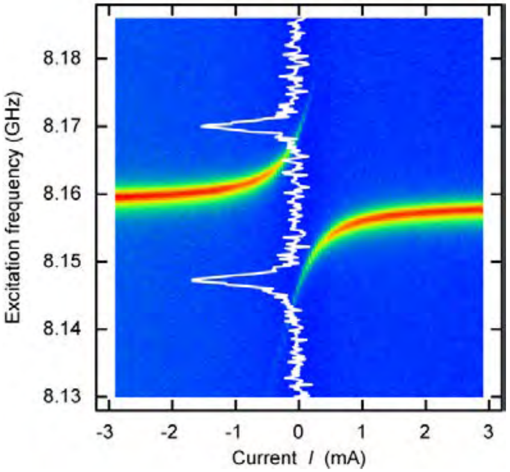
Quantum magnonics with ferromagnet

- Strong coupling with superconducting qubit
- Vacuum Rabi oscillations
- Magnon-number-resolving spectroscopy



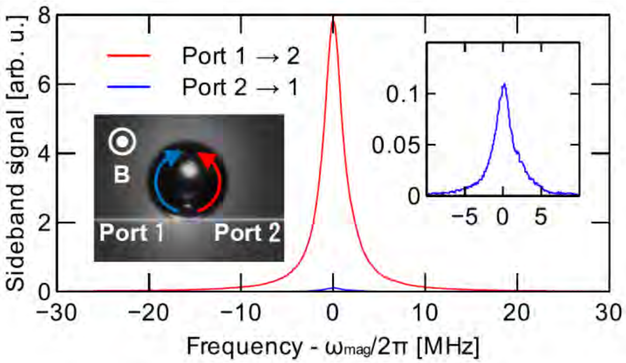
Optomagnonics

- Microwave-light conversion
- Cavity optomagnonics with WGM

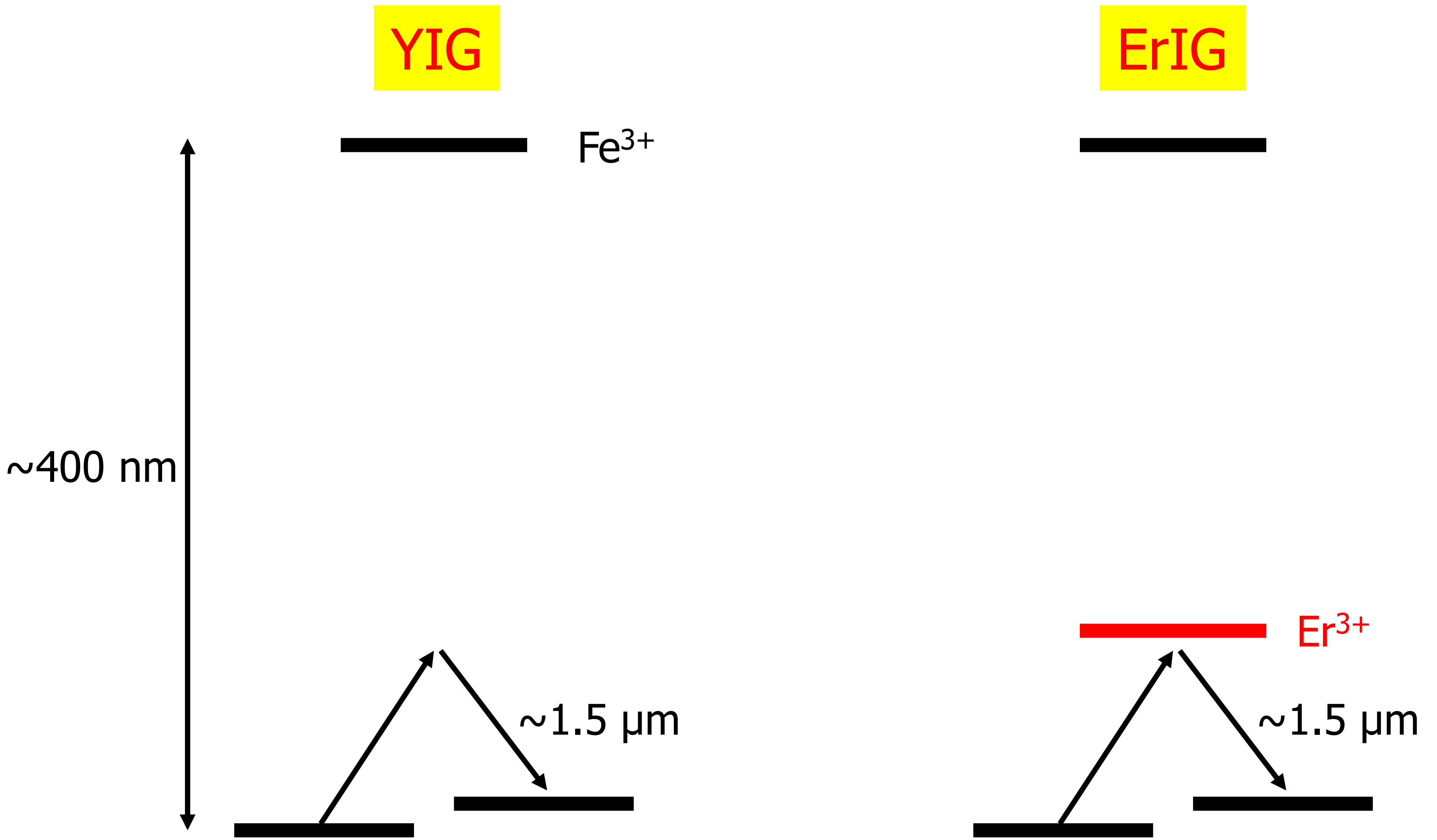


In progress

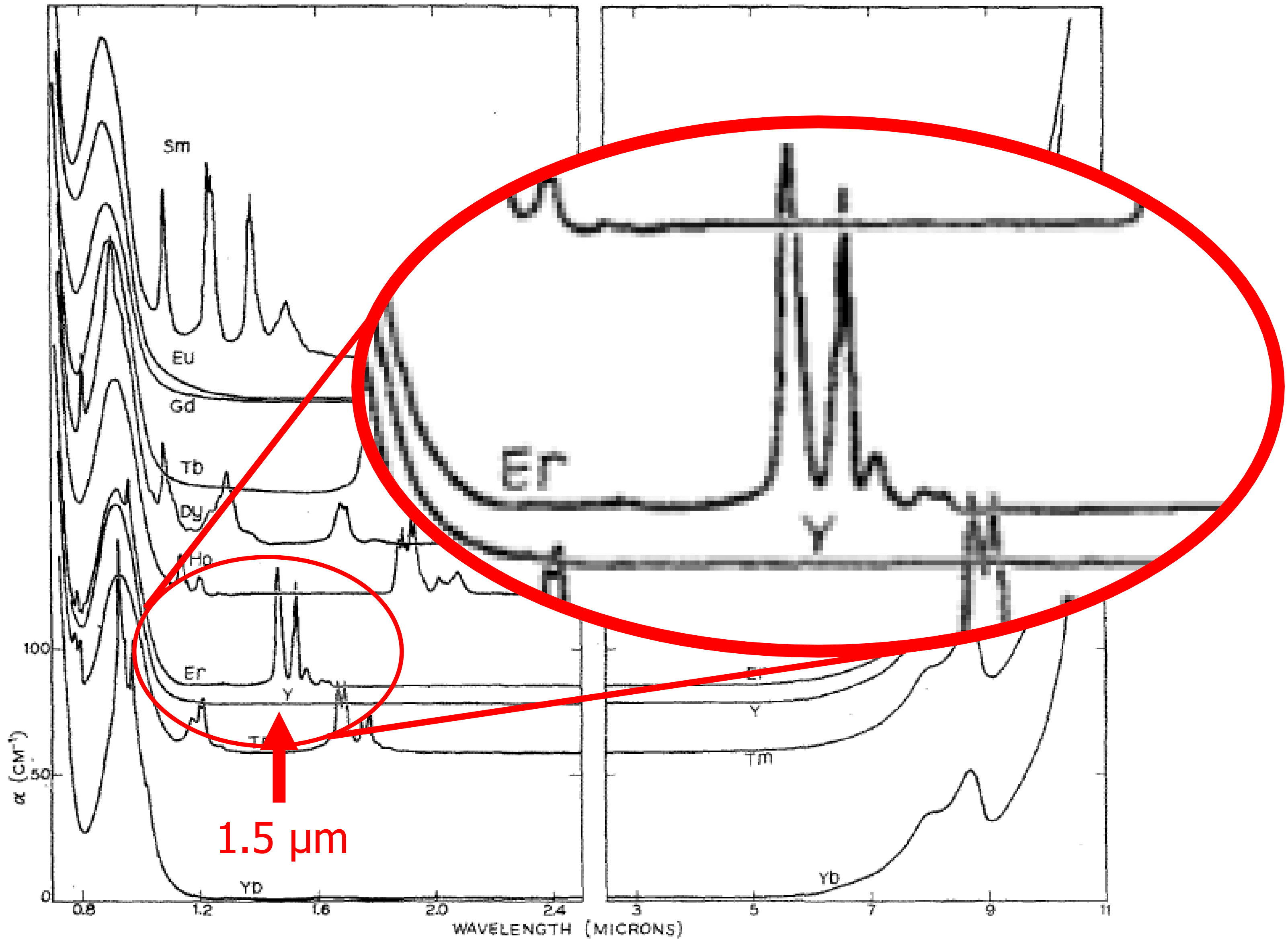
- Manipulation and measurement of non-classical states of magnon mode
- Optimization of optical coupling
- ErIG instead of YIG



Optical transitions in Yttrium and Erbium iron garnet

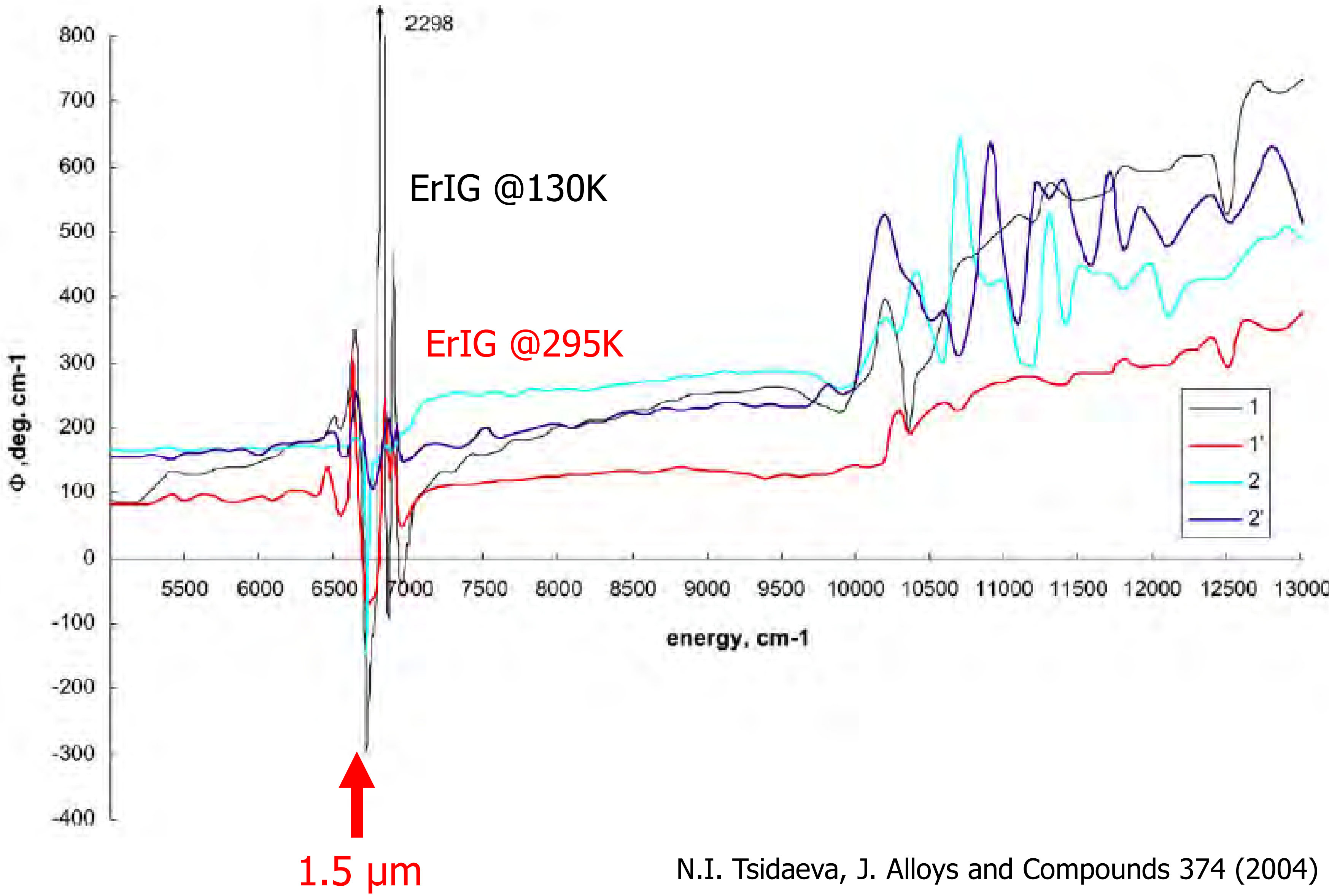


Optical absorption of REIG



Wood and Remeika, JAP 38, 1038 (1967) Bell Lab

Faraday rotation in ErIG



N.I. Tsidaeva, J. Alloys and Compounds 374 (2004) 160