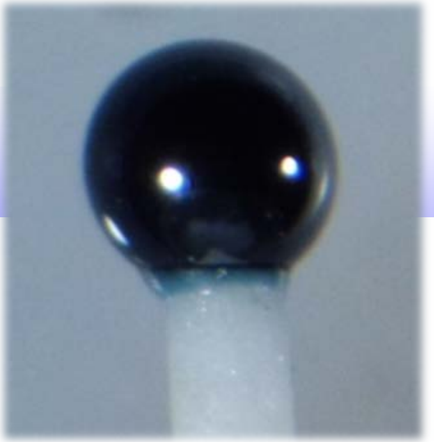
Quantum magnonics



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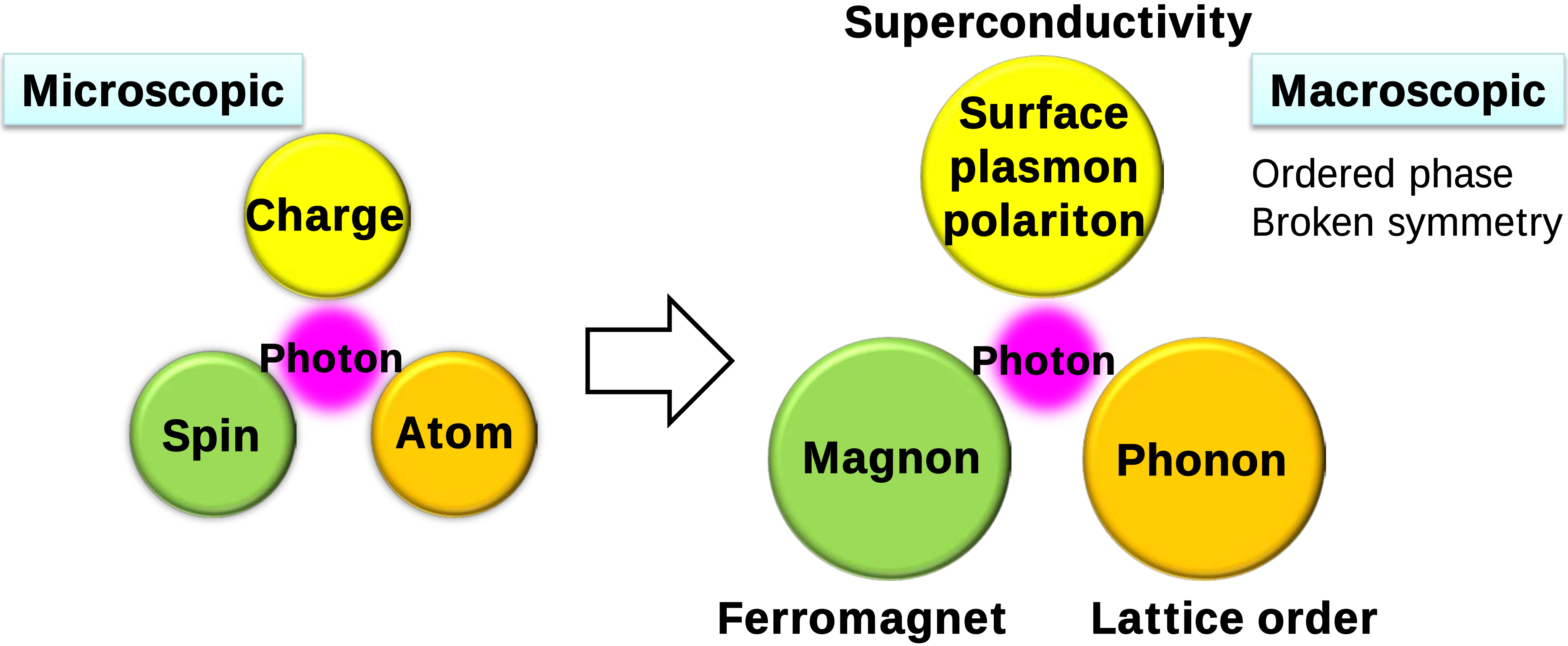
The University of Tokyo
Center for Emergent Matter Science (CEMS), RIKEN

Motivations for hybrid quantum systems

Quantum state control of collective excitation modes in solid and their hybrid systems



Superconductivity

Microscopic

Charge

Photon

Spin

Atom

Surface plasmon polariton

Macroscopic

Ordered phase
Broken symmetry

Photon

Magnon

Phonon

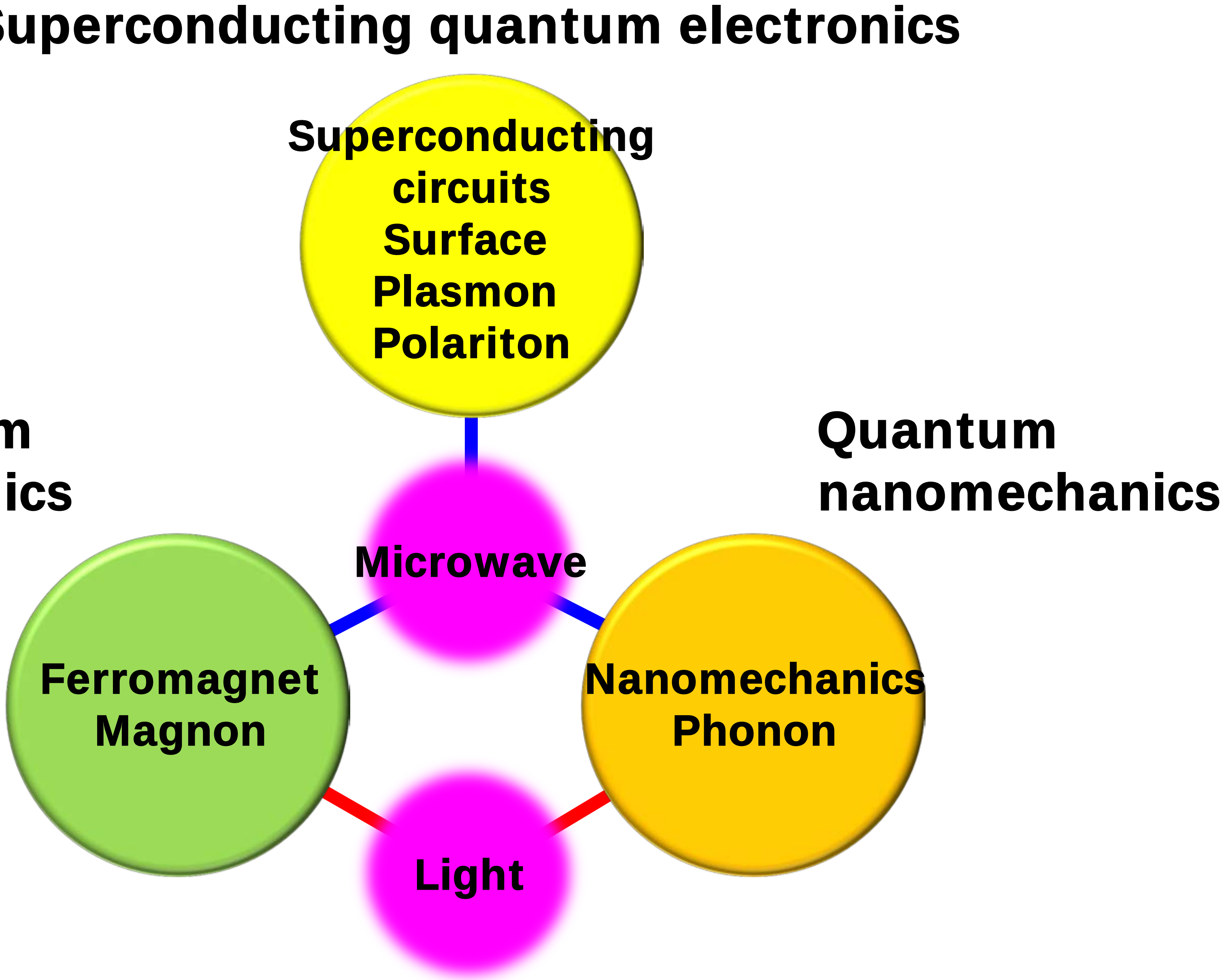
Ferromagnet

Lattice order

- Large transition moment
- Spatially extended rigid mode

⇒ Strong coupling and mode matching with electromagnetic waves

Hybrid quantum systems



Superconducting quantum electronics

Quantum magnonics

Quantum nanomechanics

Superconducting circuits
Surface Plasmon Polariton

Microwave

Ferromagnet
Magnon

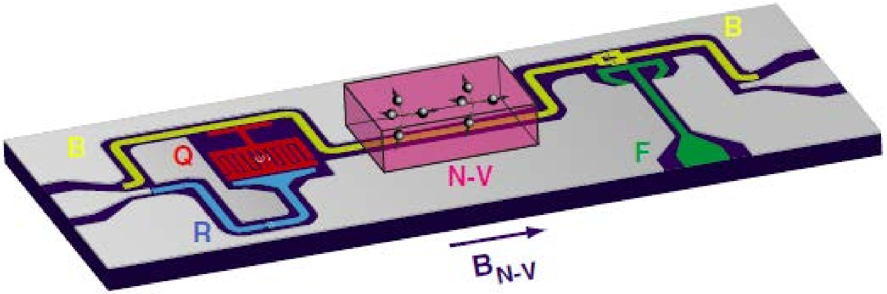
Nanomechanics
Phonon

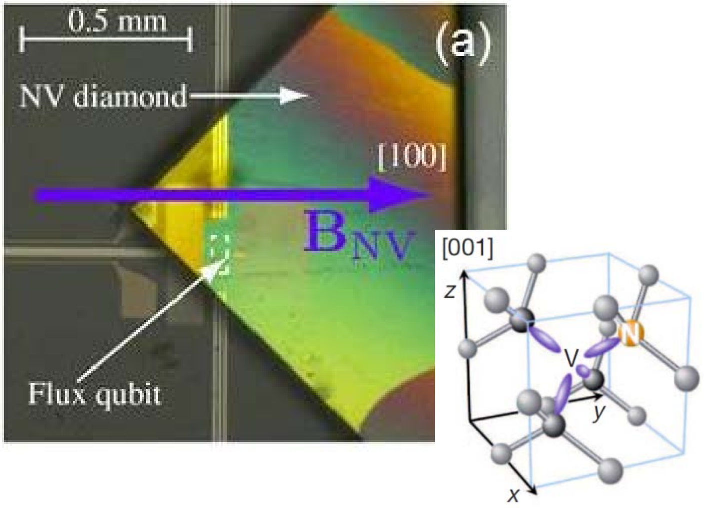
Light

Quantum magnonics

Hybrid with paramagnetic spin ensembles

Spin ensemble of NV-centers in diamond

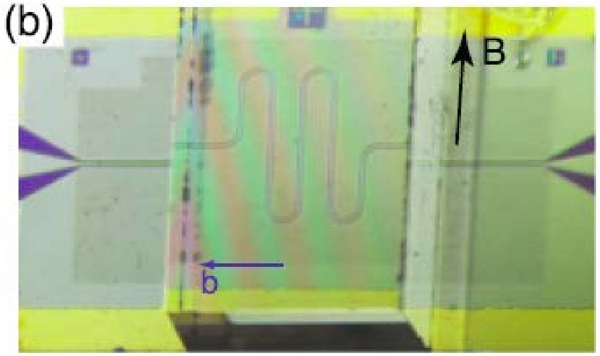




Kubo et al. PRL 107, 220501 (2011). CEA Saclay
R. Amsüss et al. PRL 107 060502 (2011). TUWien

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

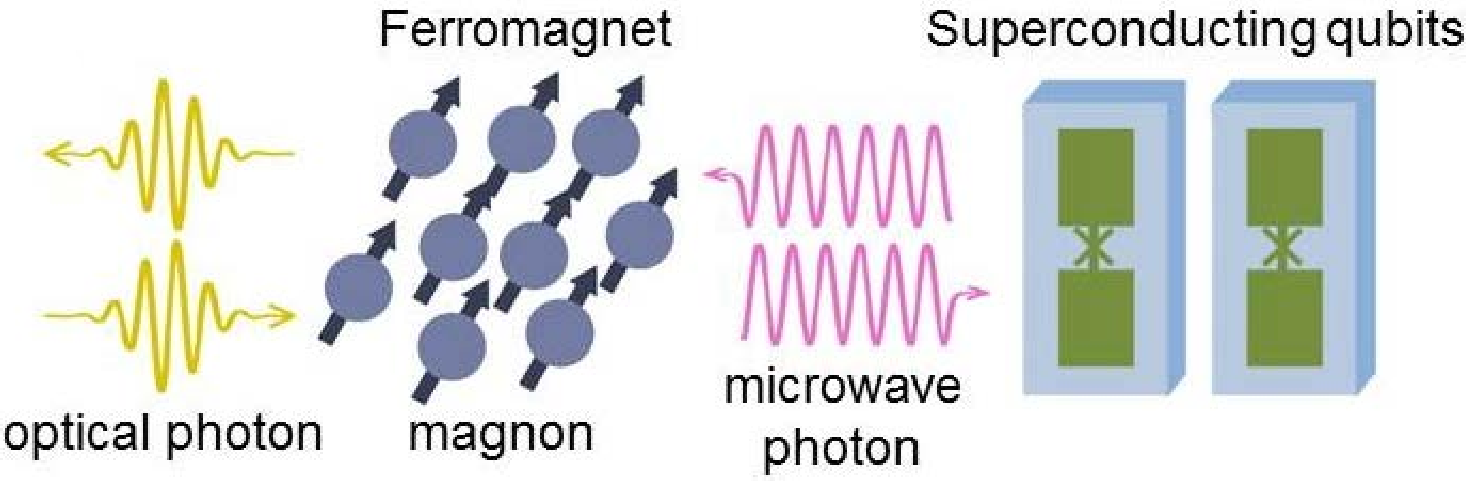
Optical quantum memory

Pr:Y_2SiO_5

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

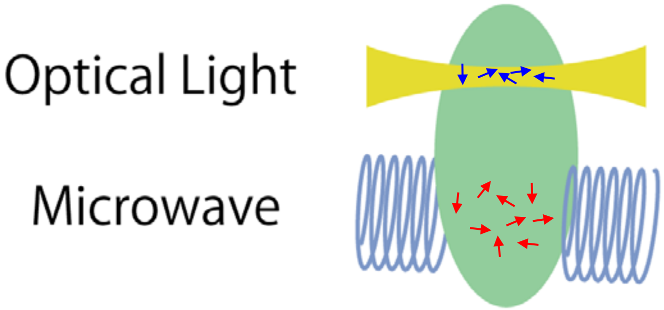
Hedges et al. Nature 465, 1052 (2010) Otago

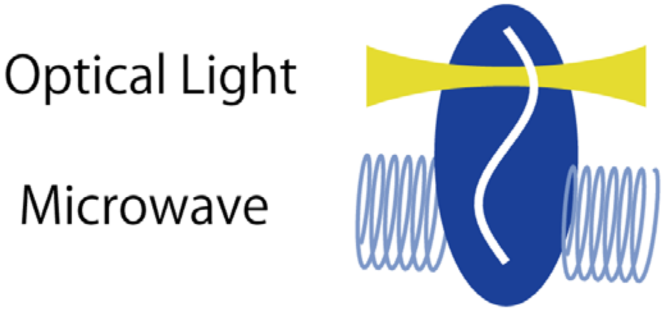
Hybrid with ferromagnetic magnons



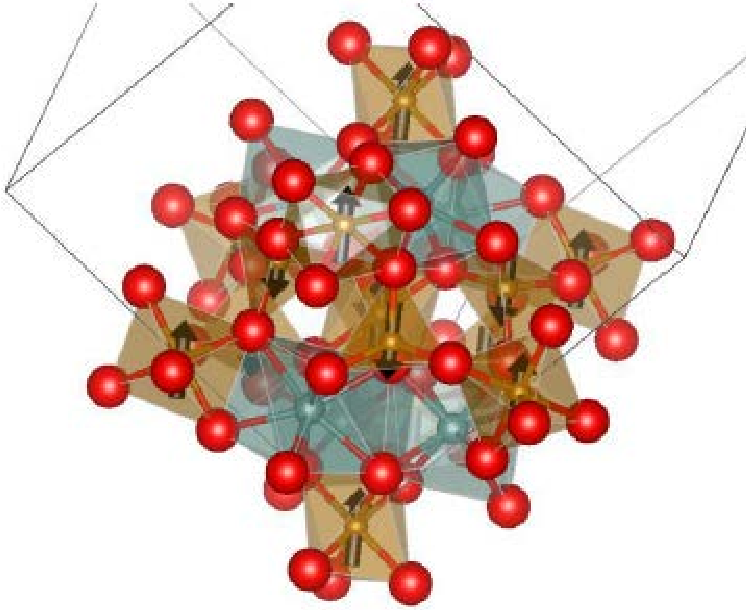
Paramagnet
Low spin density 10^{12}-10^{18} cm^{-3}
Spatial mode defined by EM fields

Ferromagnet
High spin density 10^{21}-10^{22} cm^{-3}
Robust extended spatial mode





Yttrium Iron Garnet (YIG)



● : O^{2-}

● : Fe^{3+}

● : Y^{3+}

↗ : spin $5\mu_B$

- Ferrimagnetic insulator
- Narrow FMR line
- Transparent at infrared

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

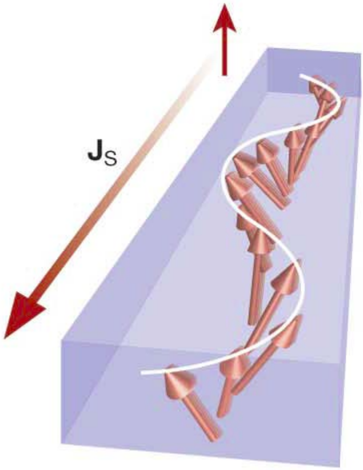
Microwave oscillators

CANDOX Corporation

Optical isolators

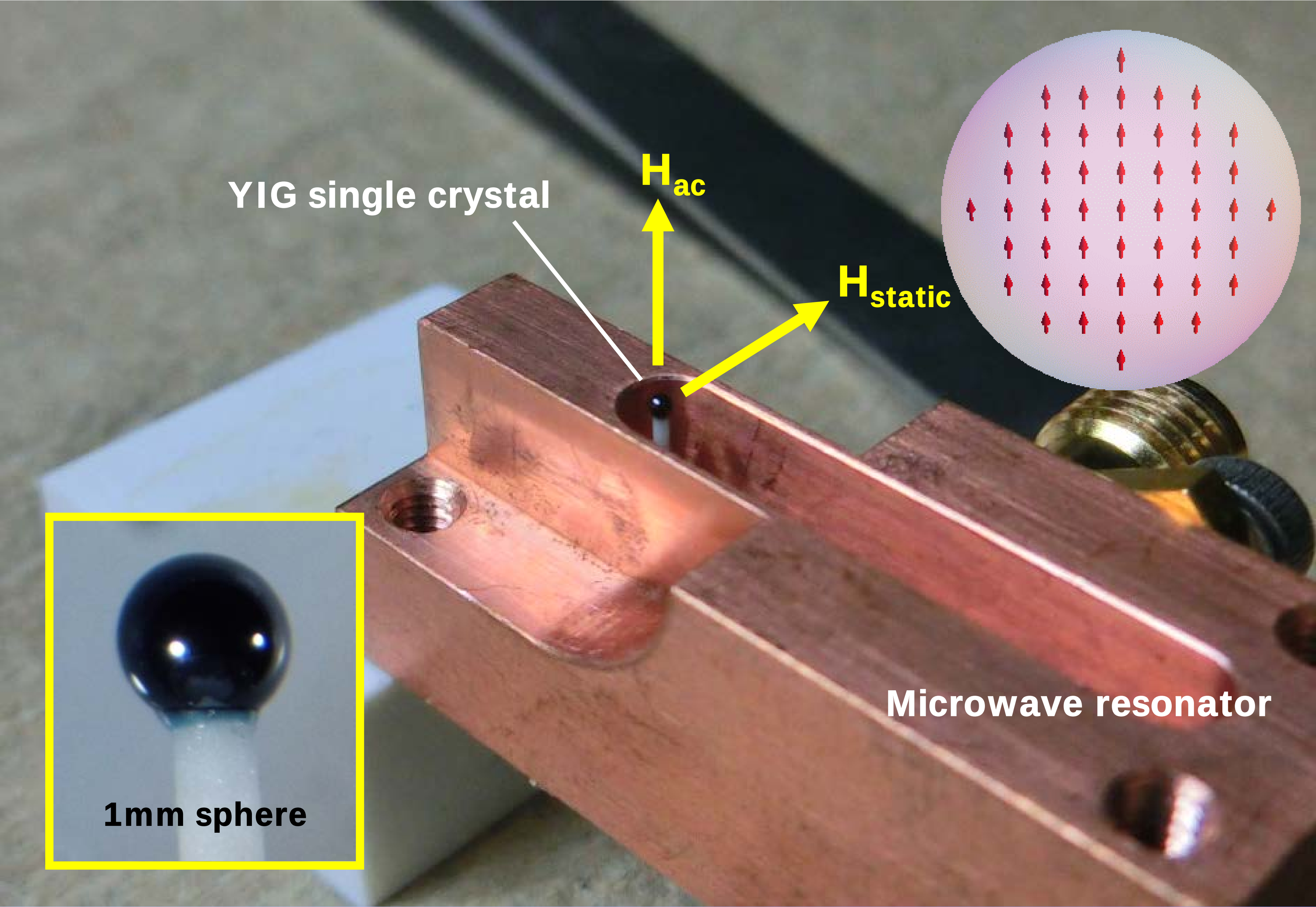
FDK Corporation

Spintronics

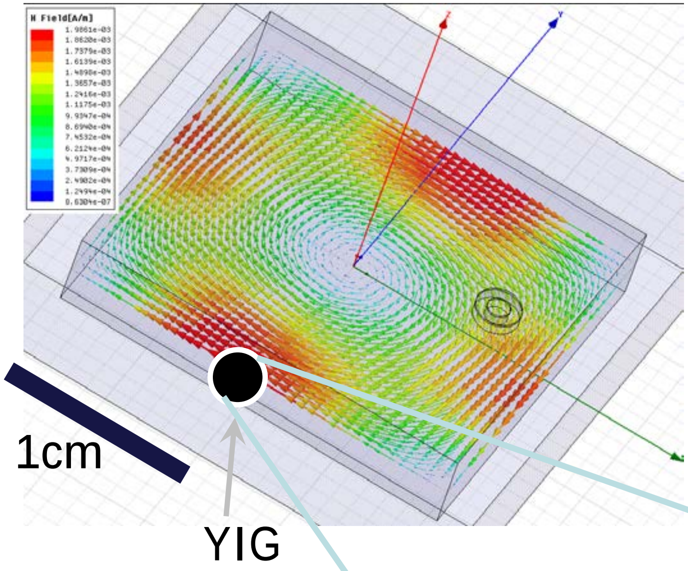


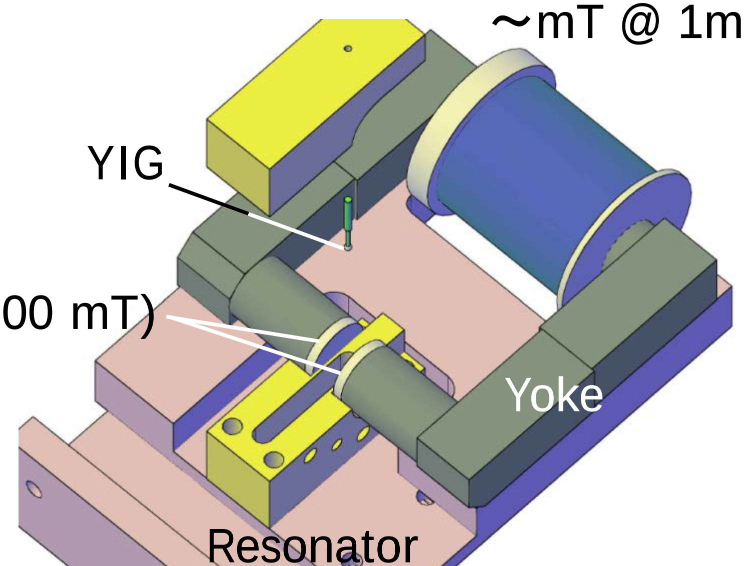
Kajiwara et al.
Nature 2010

Hybrid with ferromagnet magnons



Experimental setup





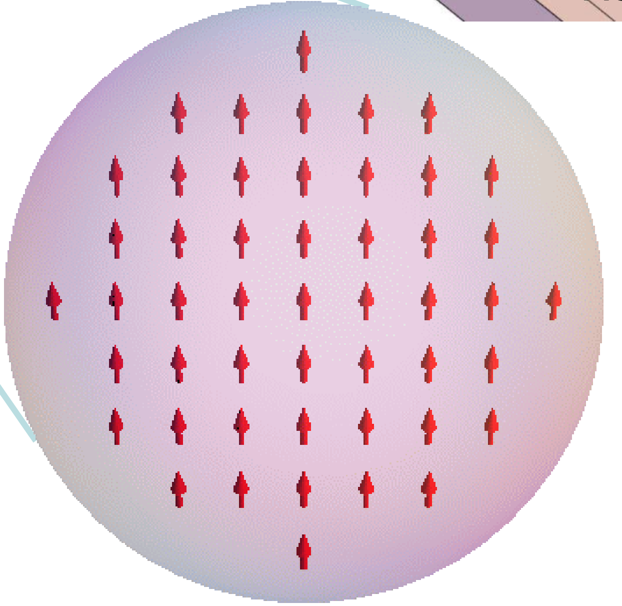
- Copper resonator

  Rectangular TE_{101} mode
- YIG sphere

  Magnetostatic mode

  with uniform precession

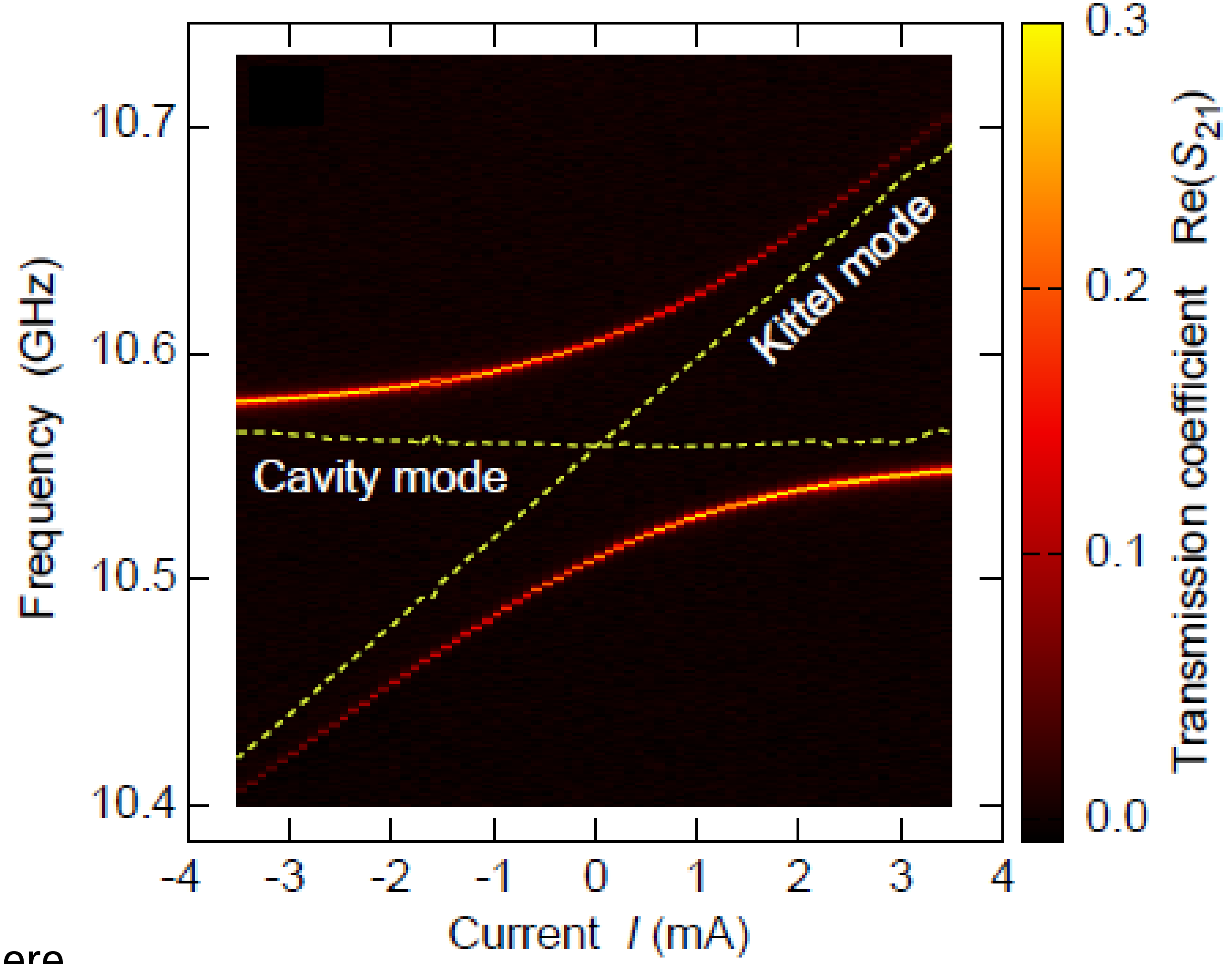
  (Kittel mode)



Y. Tabuchi
S. Ishino

Magnetic-field dependence

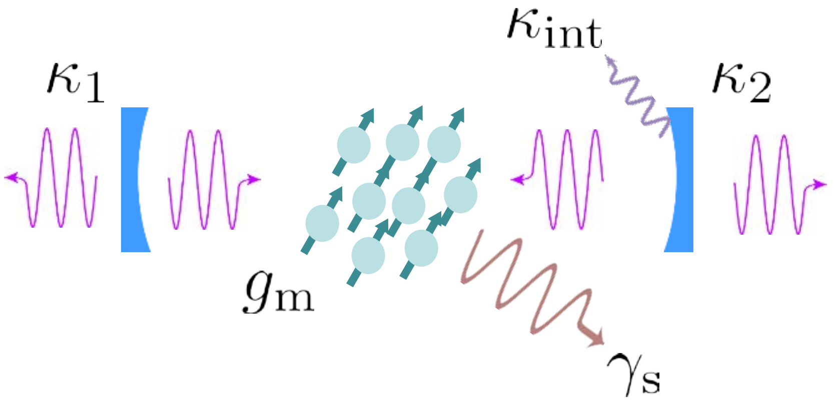
Low temperature ~ 10 mK; □ 1 thermal magnon & photon
Microwave power: ~0.9 photons in cavity

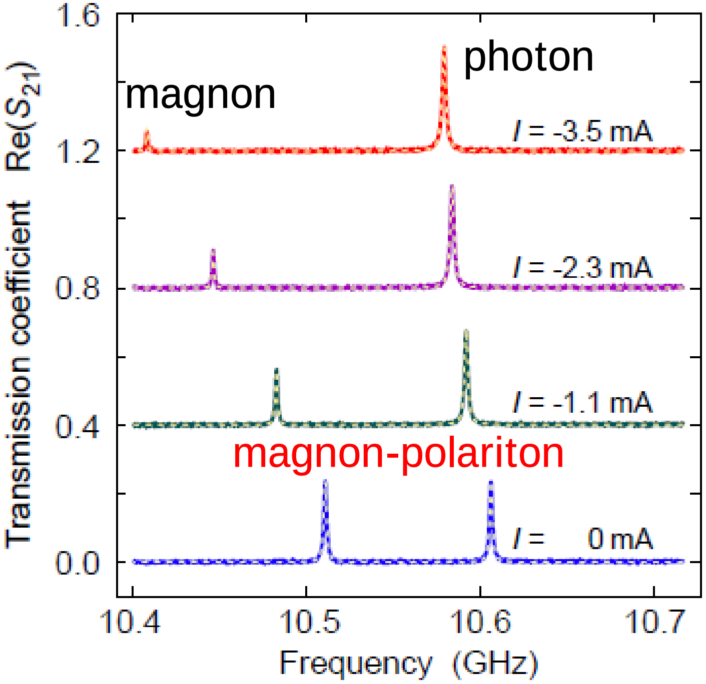


0.5-mm sphere

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

Coupling strength and cooperativity





Strong coupling condition

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

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

Sphere-size dependence of coupling strength

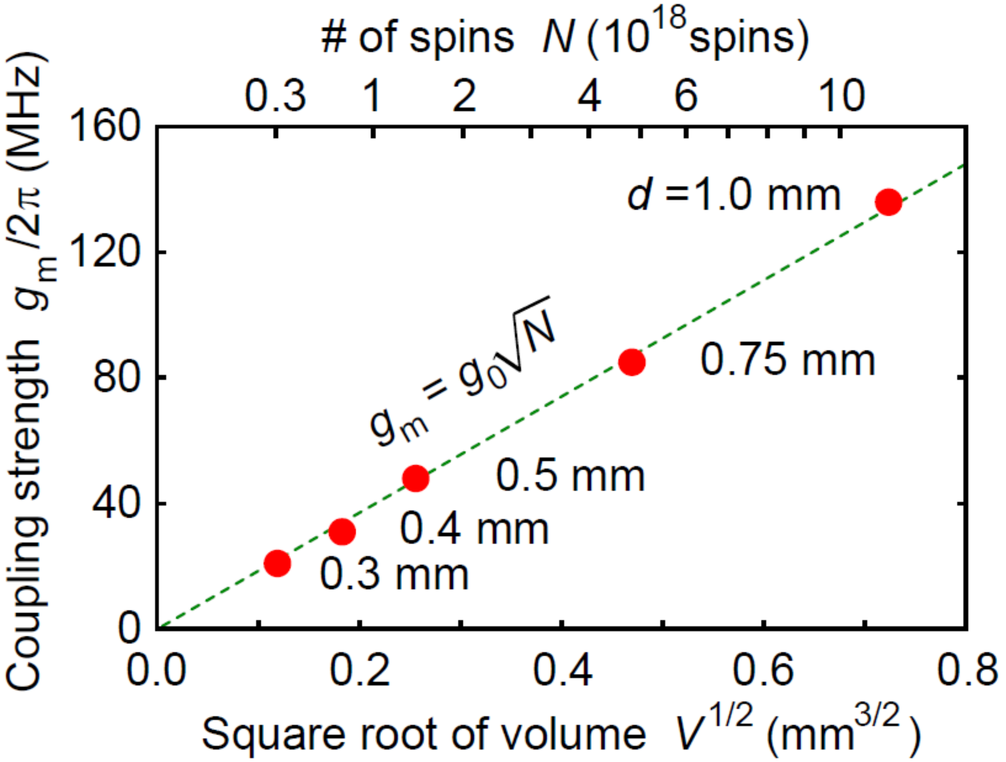
$$g_{\mathrm{m}} = g_0\sqrt{N}$$

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

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

⇒ $$g_0/2\pi = 39\,\mathrm{mHz}$$

Coupling strength per spin

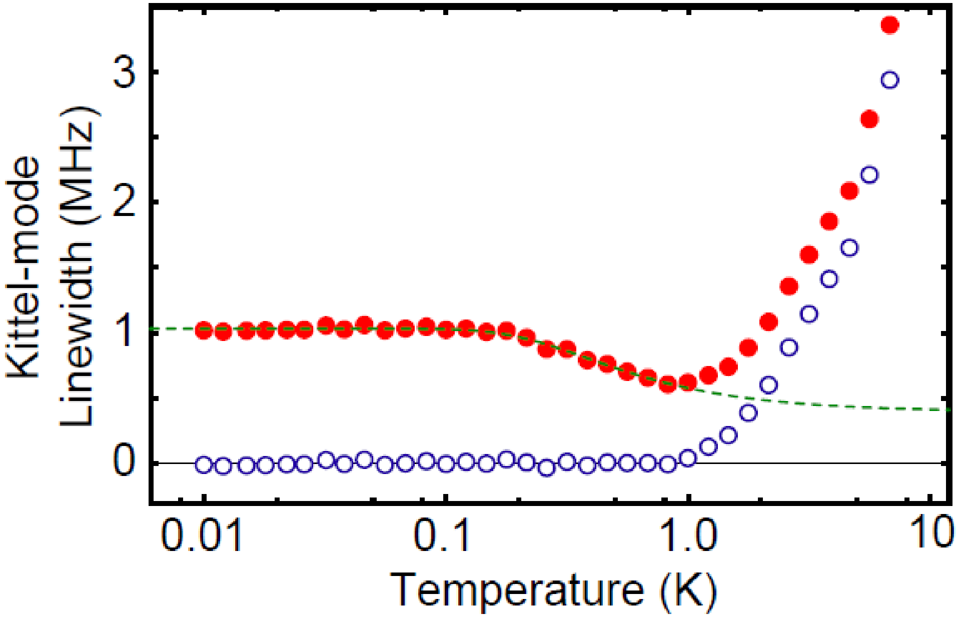


Estimation from vacuum fluctuation amplitude

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

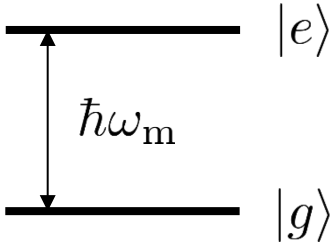
Y. Tabuchi et al. PRL 113, 083603 (2014)

Magnon linewidth vs. temperature



Coupling to ensemble of two-level systems

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

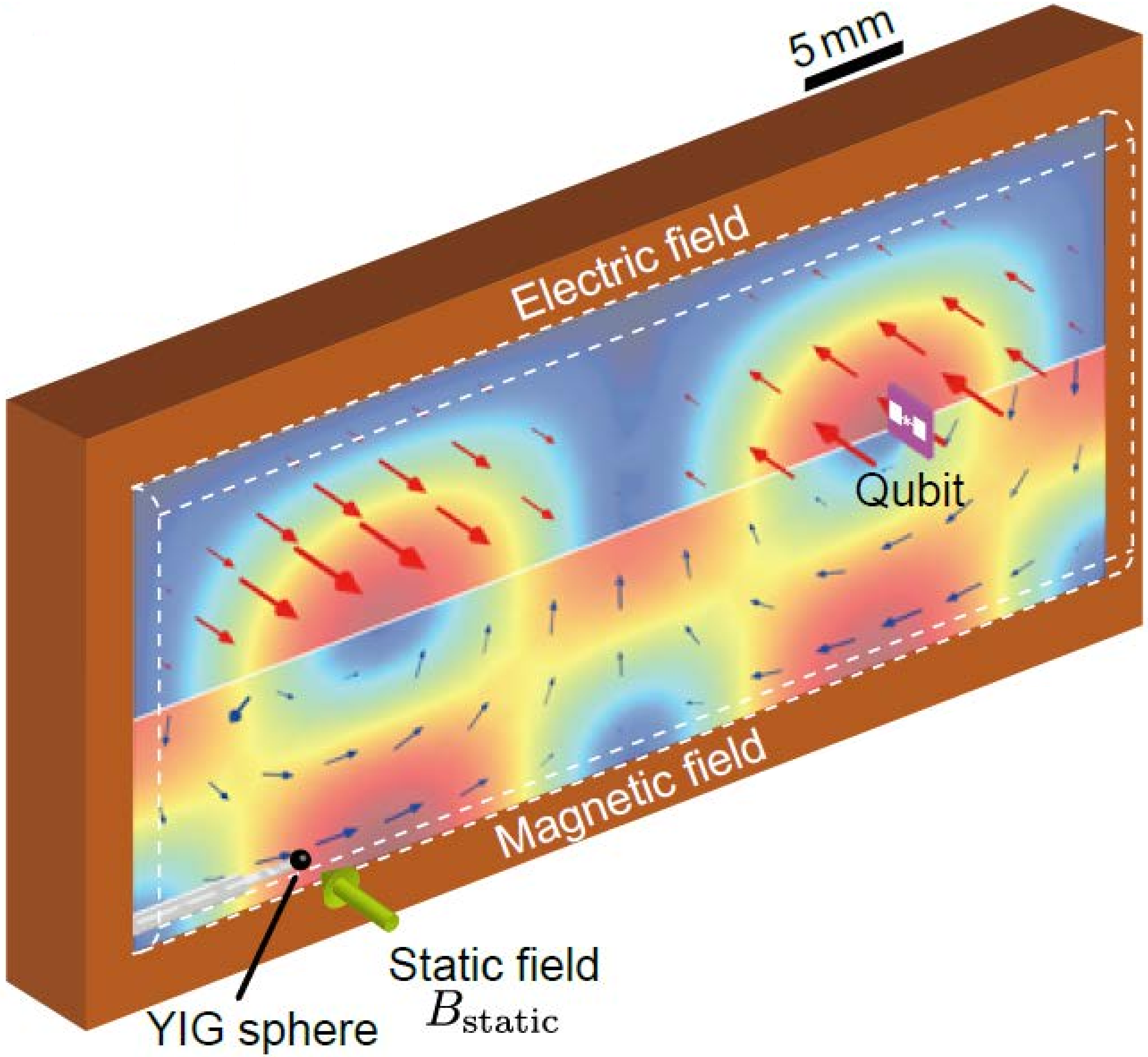


cf. superconducting resonator, Martinis 2005

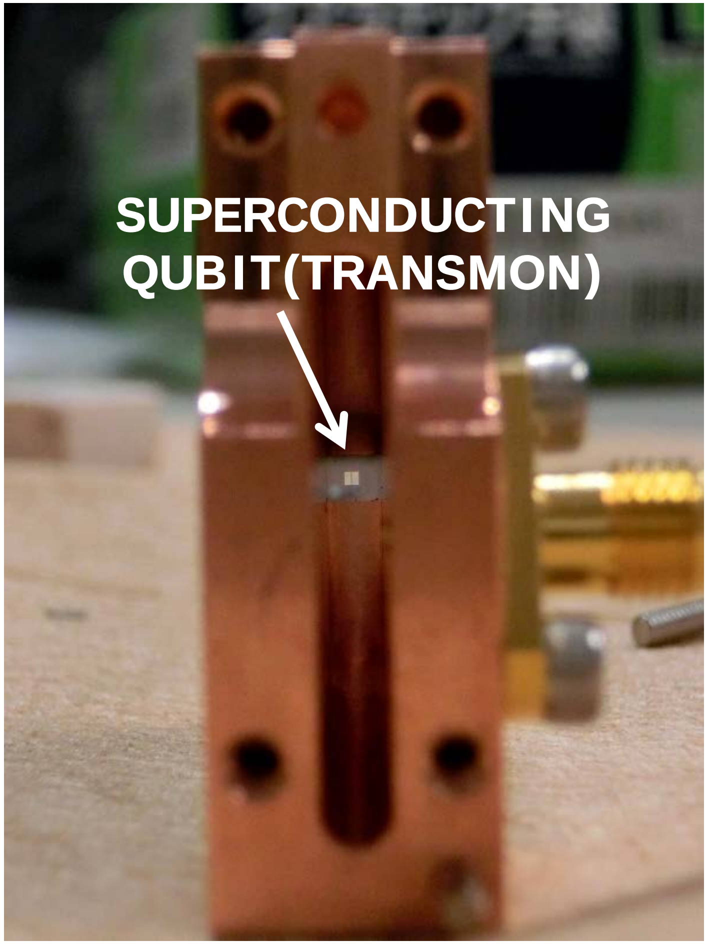
glass physics, Hunklinger ~1980

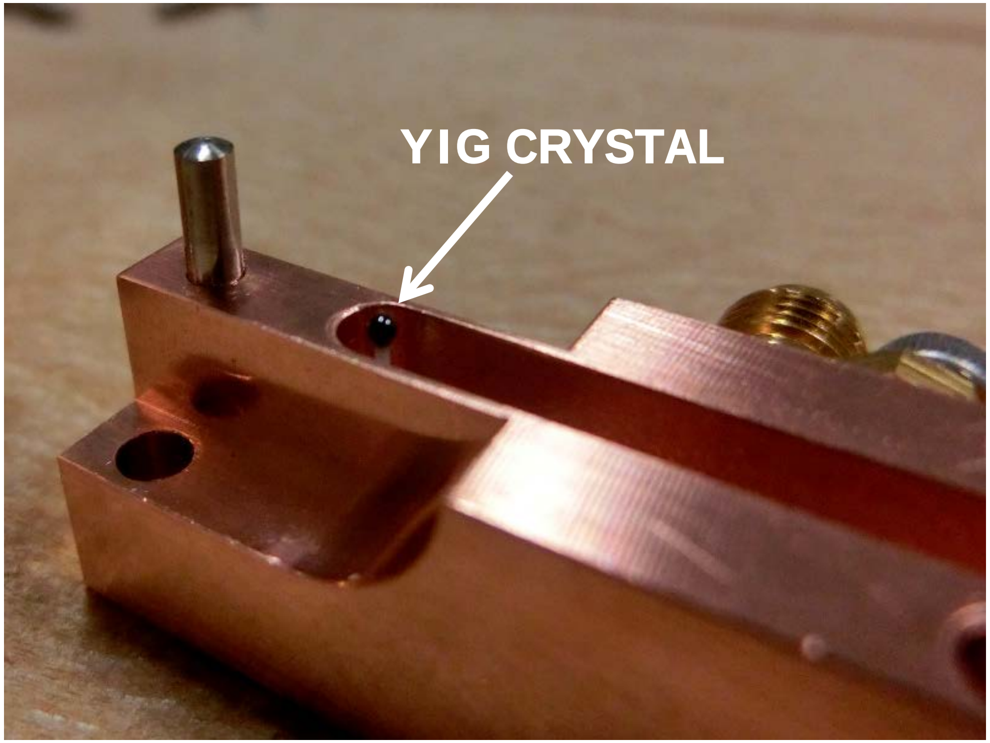
Theory: J. H. Van Vleck, J. Appl. Phys. 35, 882 (1964).

Coupling with a superconducting qubit

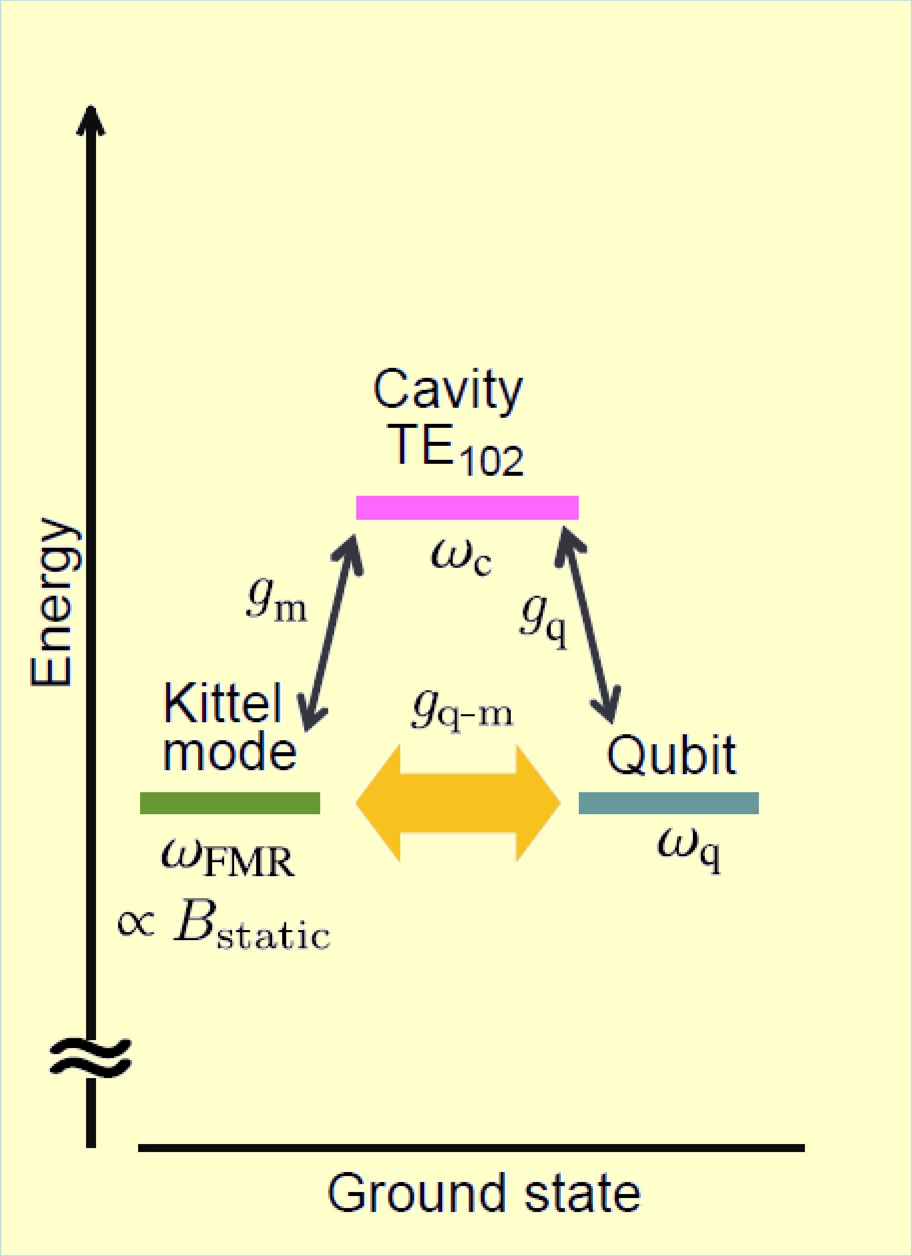


Inside the cavity





Qubit-magnon coupling



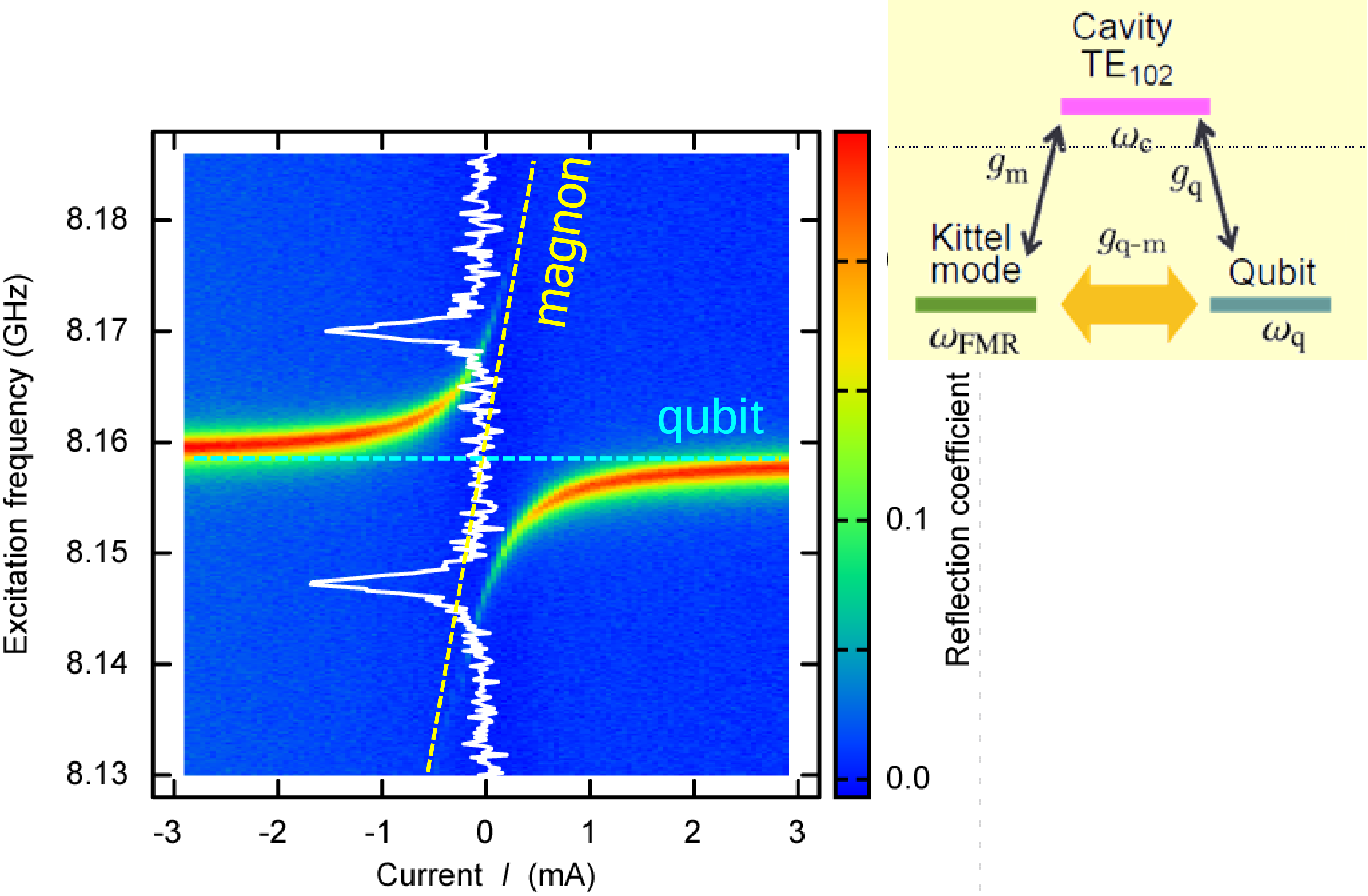
Qubit-magnon coupling
mediated by virtual photon excitation in cavity

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

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

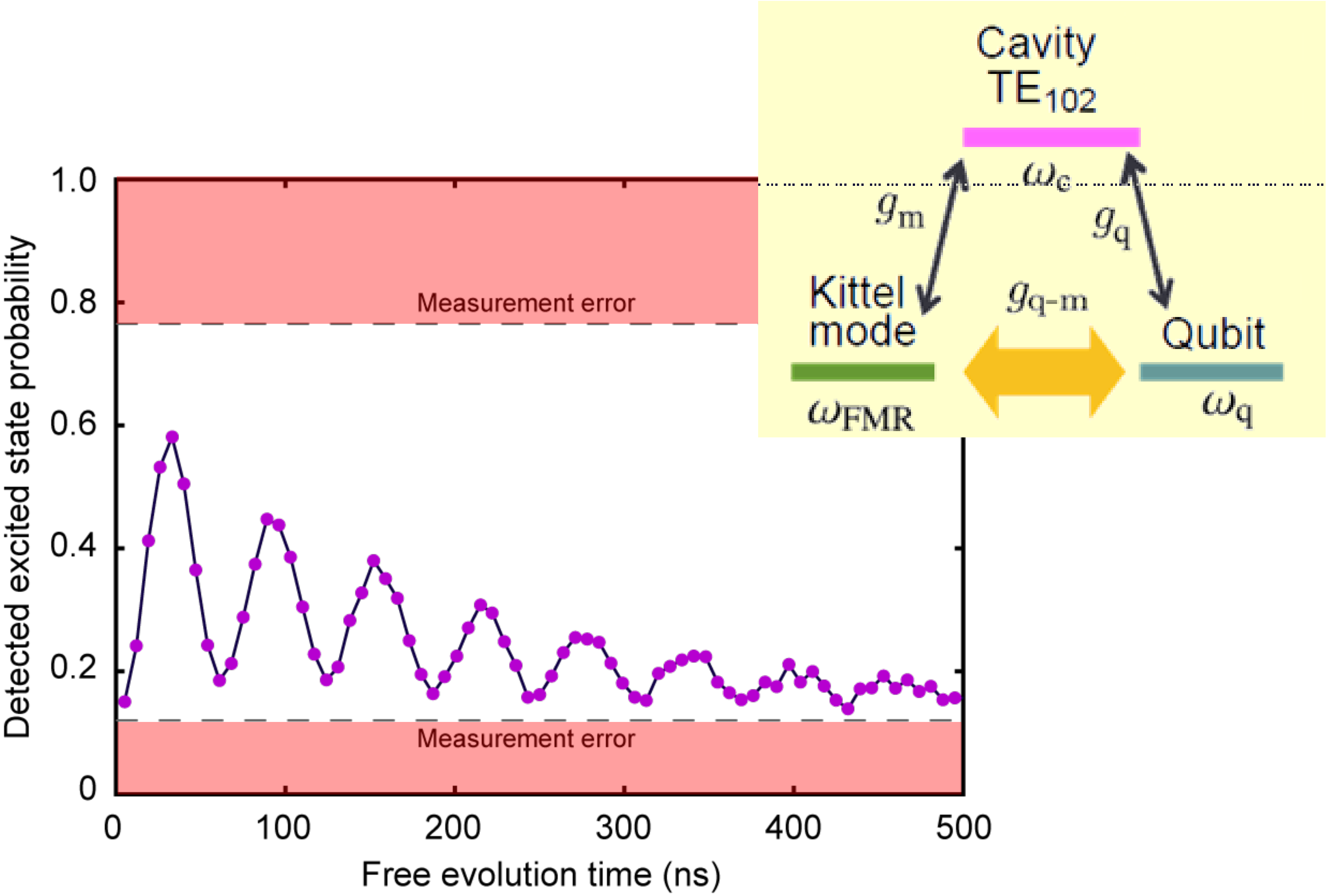
$$\sim 10\text{-}50\ \mathrm{MHz}$$

Vacuum Rabi splitting



Y. Tabuchi et al. arXiv:1410.3781

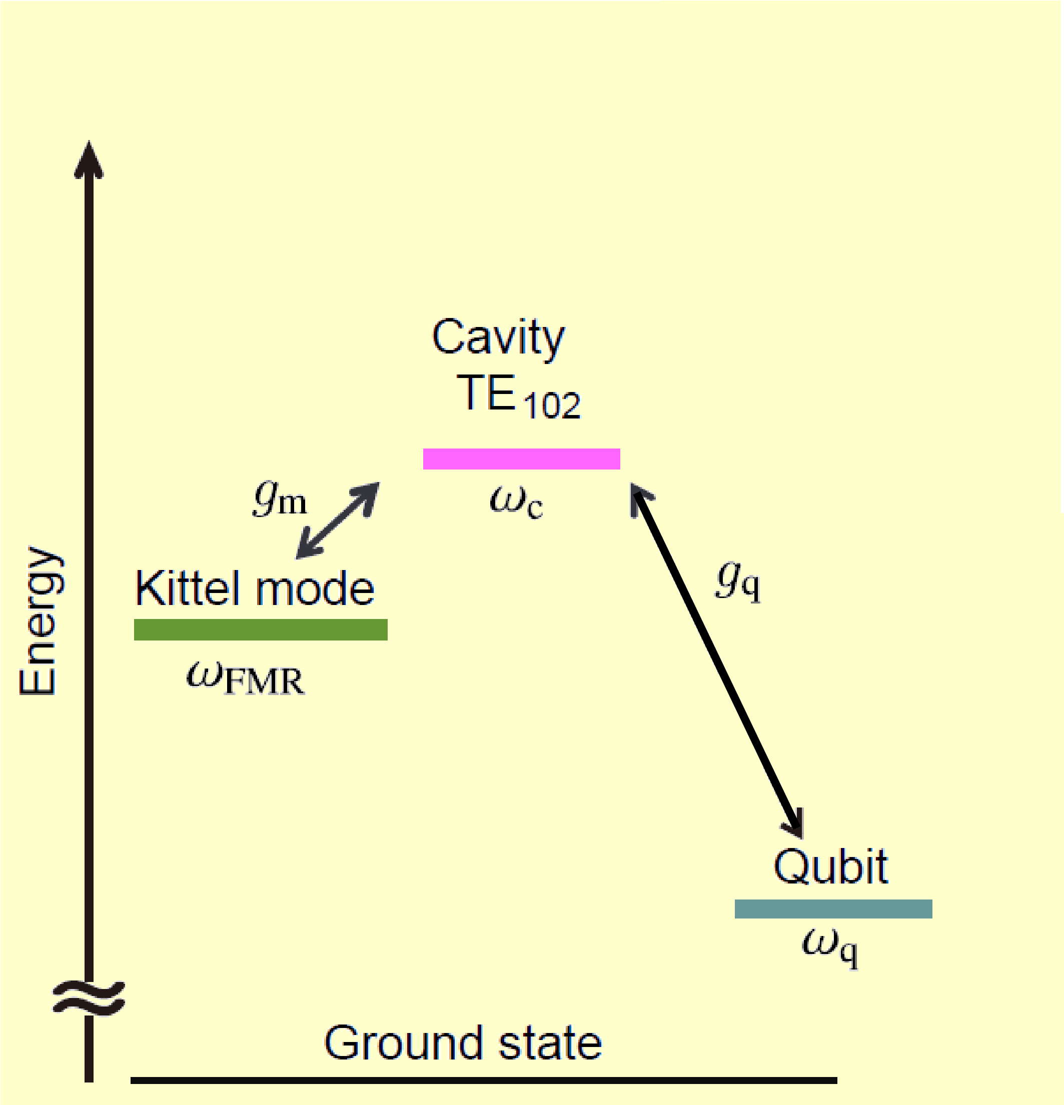
Vacuum Rabi oscillations



Tunable coupling with parametric drive

Qubit-magnon parametric coupling

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

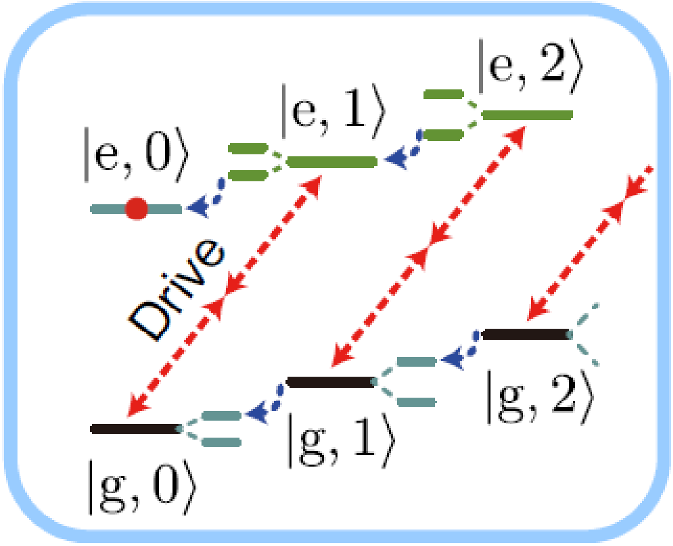


Parametric drive at

$$\frac{\omega_{\mathrm{FMR}} + \omega_{\mathrm{q}}}{2}$$

Two-photon transition between $|\mathrm{g}, 0\rangle \Leftrightarrow |\mathrm{e}, 1\rangle$

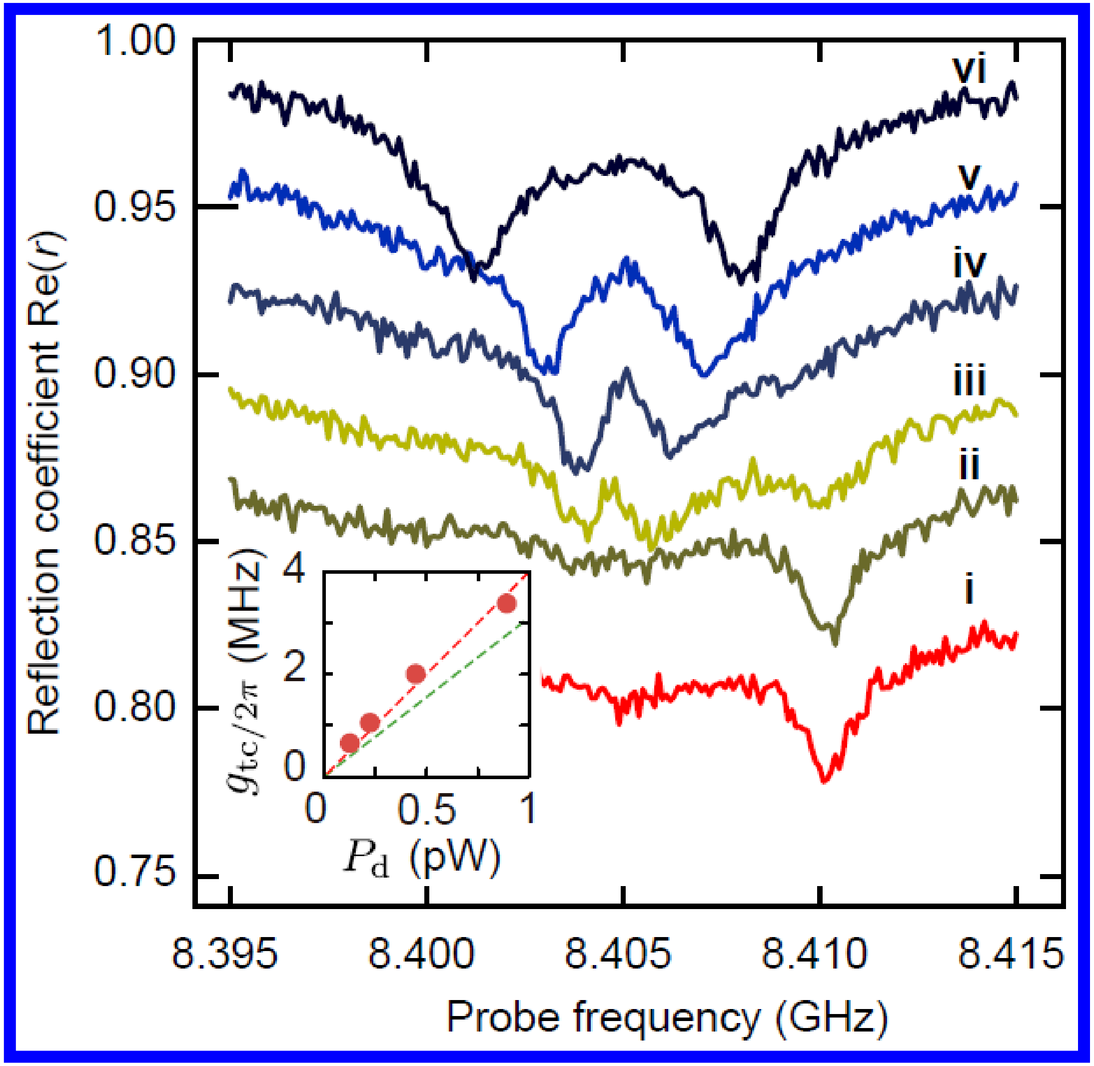
qubit magnon



Tunable coupling with parametric drive

Qubit-magnon parametric coupling

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



8200 MHz

Y. Tabuchi et al. arXiv:1410.3781

Conclusions

- Hybrid quantum systems
  with collective excitations in solids

- Quantum magnonics with ferromagnet
  - Strong coupling between magnon and cavity modes in quantum limit
  - Strong coupling with superconducting qubit
  - Vacuum Rabi oscillations
  - Tunable coupling with parametric drive

In progress

- Manipulation and measurement of non-classical states of magnon mode
- Coupling with optical modes
- ErIG instead of YIG