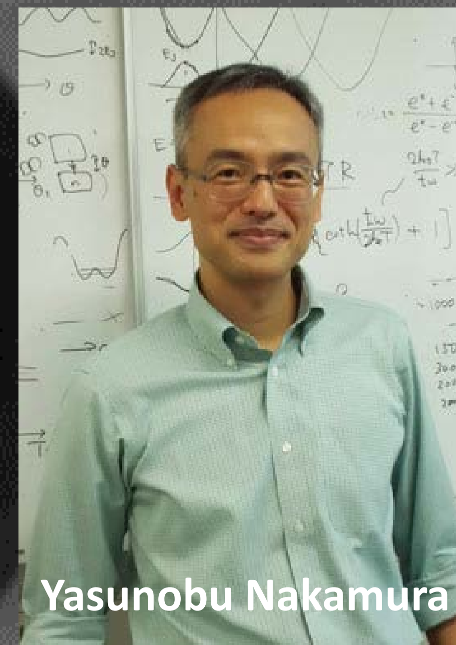
Magnonics in the quantum regime



Koji Usami

Research Center for Advanced Science and Technology (RCAST)

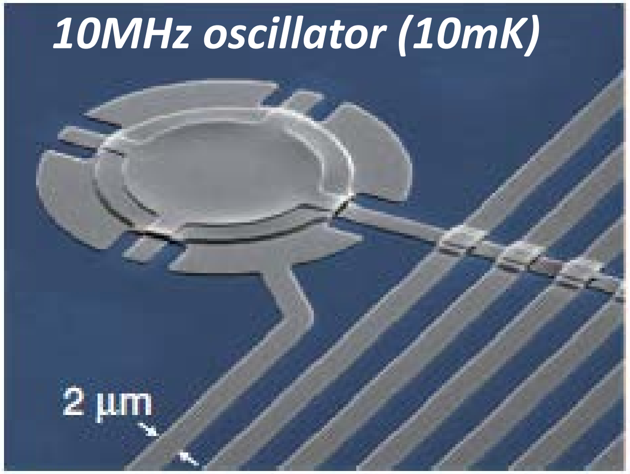
University of Tokyo

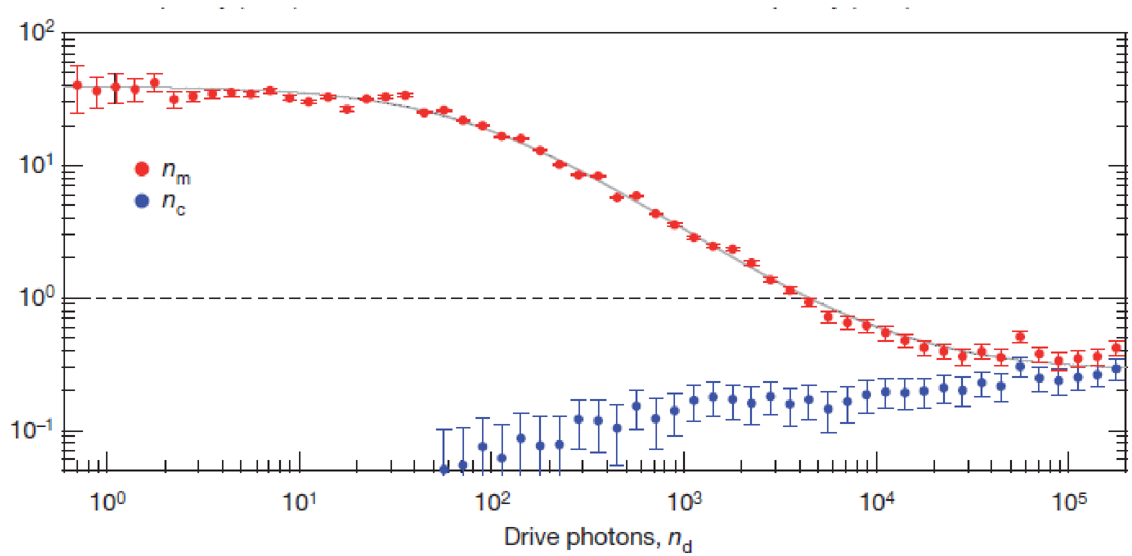
Putting Mechanics into Quantum Mechanics

Nanoelectromechanical structures are starting to approach the ultimate quantum mechanical limits for detecting and exciting motion at the nanoscale. Nonclassical states of a mechanical resonator are also on the horizon.

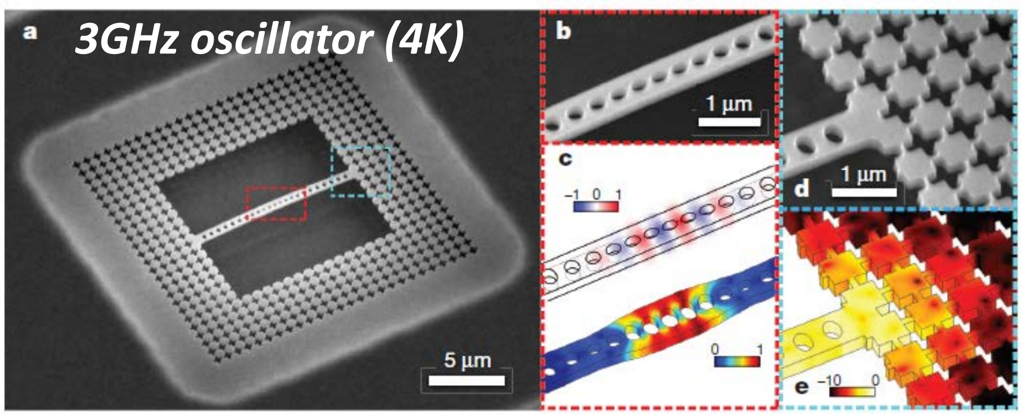
Keith C. Schwab and Michael L. Roukes

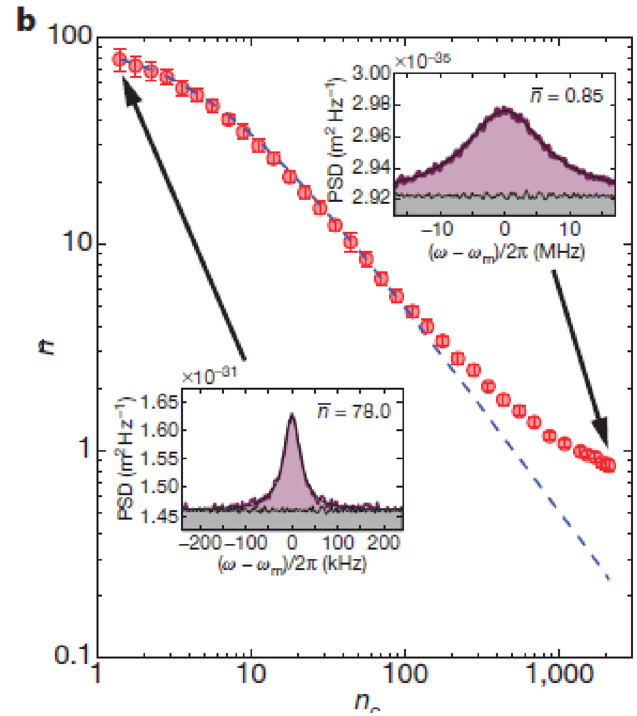
K.C. Schwab and M.L. Roukes, Physics Today **58**, 7, 36 (2005)





J.D.Teufel et al., Nature **475**, 359 (2011)





J.Chan et al., Nature **478**, 89 (2011)

Putting Magnonics into Quamtum Magnonics

Cavity (circuit) quantum magnonics

New possibility of optomagnonics

Posters

Magnetic quasi-vortex

Magnonic crystal

Cavity (circuit) quantum magnonics

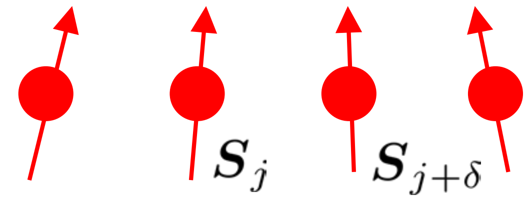
New possibility of optomagnonics

Magnons

$$H = \underbrace{-J\sum_{j,\delta}\boldsymbol{S}_j\cdot\boldsymbol{S}_{j+\delta}}_{\text{Exchange}} - \underbrace{g_s\mu_{\rm B}B_z\sum_j S_{jz}}_{\text{Zeeman}}$$

Exchange

Zeeman



Exchange interaction

Holstein-Primakoff transformation:

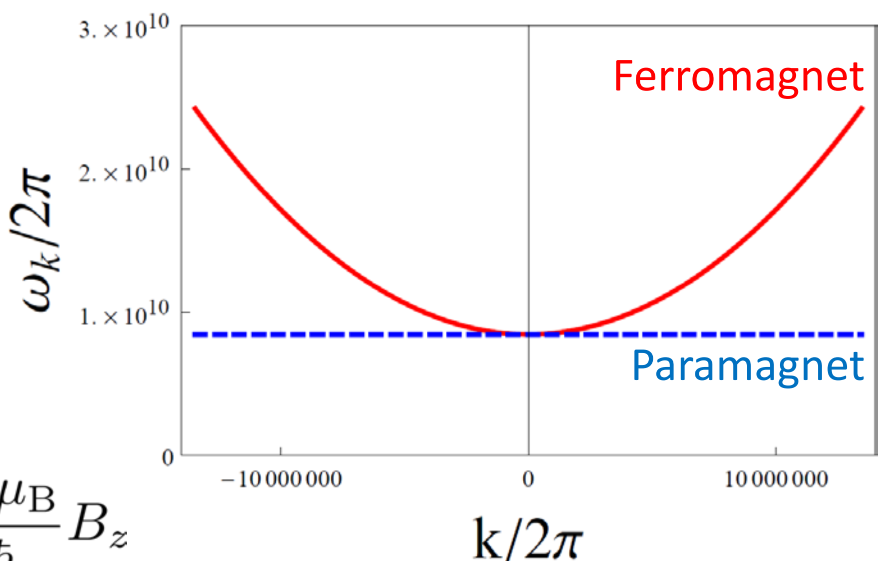
$$\begin{aligned} S_j^+ &= \frac{1}{\sqrt{N}}\sum_{\boldsymbol{k}} e^{-i\boldsymbol{k}\cdot\boldsymbol{x}_j}\hat{c}_k + \cdots \\ S_j^- &= \frac{1}{\sqrt{N}}\sum_{\boldsymbol{k}} e^{i\boldsymbol{k}\cdot\boldsymbol{x}_j}\hat{c}_k^\dagger + \cdots \\ S_{jz} &= \frac{1}{2} - \sum_{\boldsymbol{k}} \hat{c}_k^\dagger\hat{c}_k + \cdots \end{aligned}$$

$$H_1 = \sum_k \hbar\omega_k \hat{c}_k^\dagger \hat{c}_k$$

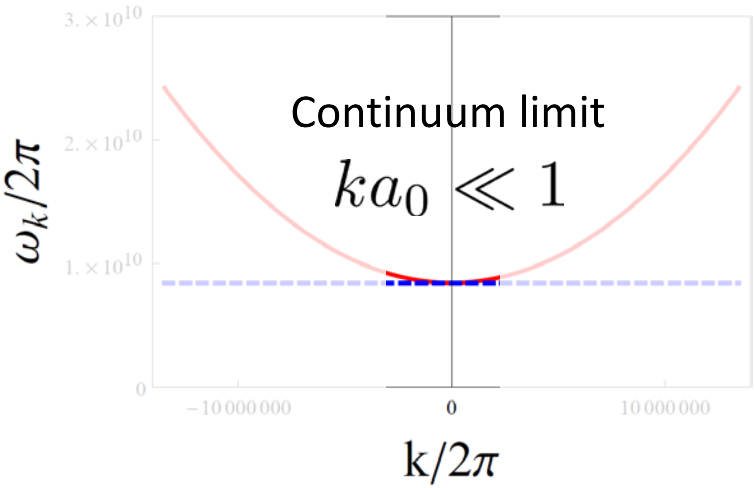
$$\omega_k = \underbrace{\frac{2J}{\hbar}\sin^2\left(\frac{ka_0}{2}\right)}_{\text{Exchange}} + \underbrace{\frac{g_s\mu_{\rm B}}{\hbar}B_z}_{\text{Zeeman}}$$

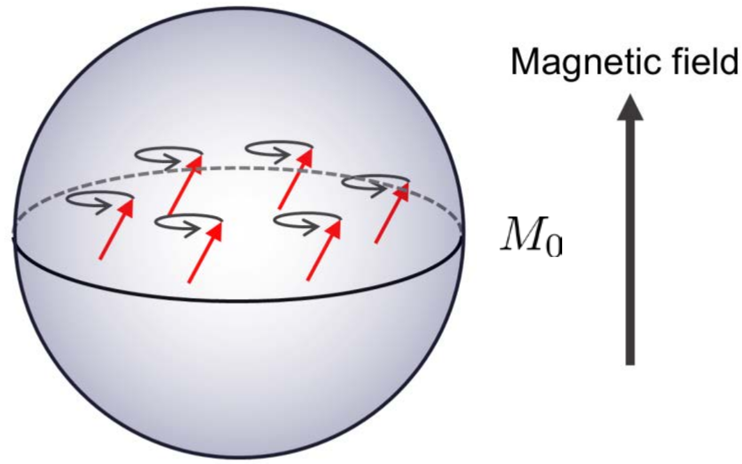
Exchange

Zeeman



Magnetostatic (Walker) modes





Walker equations $\boldsymbol{H} = \nabla\psi$

Maxwell equations

$$\nabla \times \boldsymbol{H} = 0$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\boldsymbol{B} = \mu_0 (\boldsymbol{H} + \boldsymbol{M})$$

Landau-Lifshitz equation

$$\frac{\partial \boldsymbol{M}}{\partial t} = \gamma (\boldsymbol{M} \times \boldsymbol{B})$$

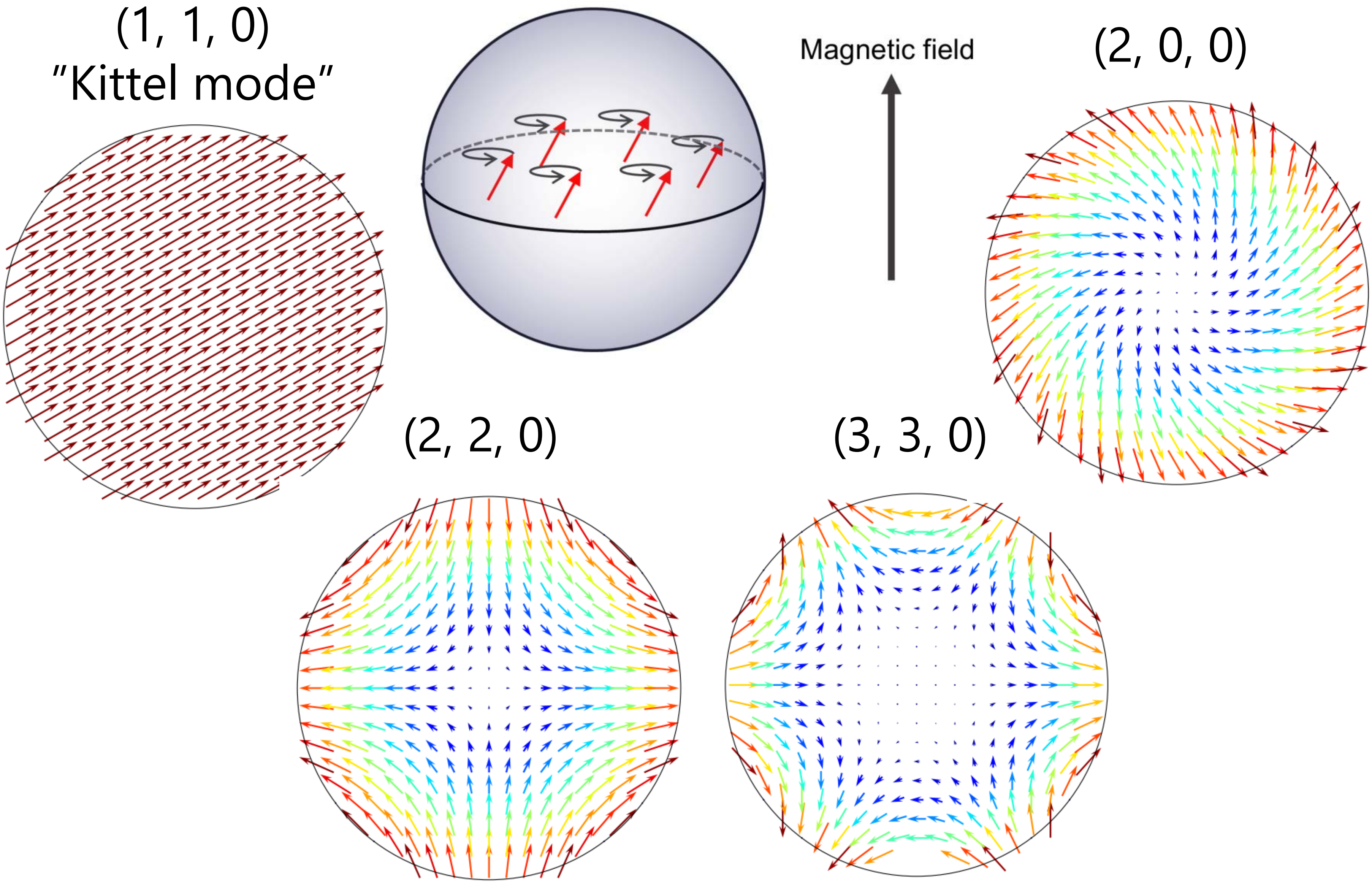
Inside: $$(1+\kappa)\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\psi + \frac{\partial^2}{\partial z^2}\psi = 0$$

Outside: $$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\psi = 0$$

$$\kappa = \frac{\Omega_H \Omega}{\Omega_H^2 - \omega^2}; \;\; \Omega_H = \gamma\mu_0 H, \;\; \Omega = \gamma\mu_0 M_0$$

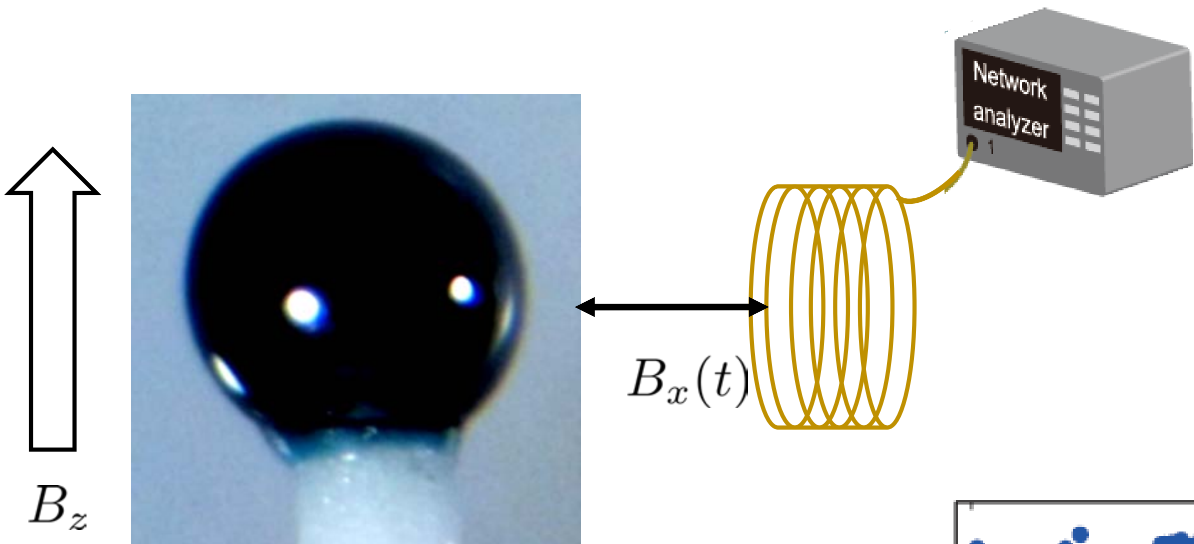
L. R. Walker, Phys. Rev. **105,** 390 (1957)

Magnetostatic (Walker) modes

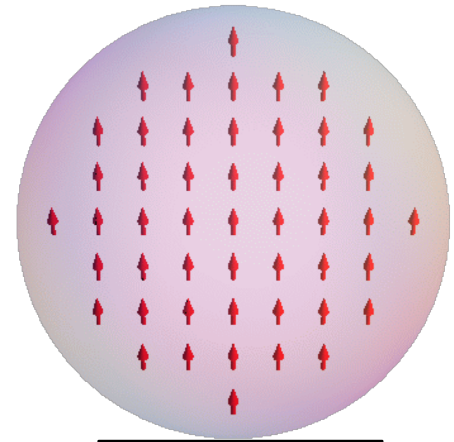


P. C. Fletcher and R. O. Bell, J. Appl. Phys. **30,** 687 (1959)

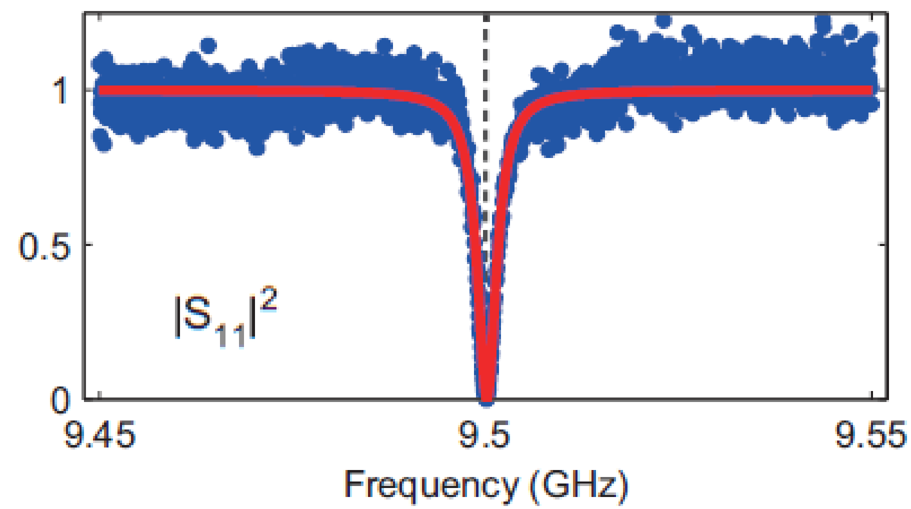
Ferromagnetic resonance



Yttrium Iron Garnet (YIG)

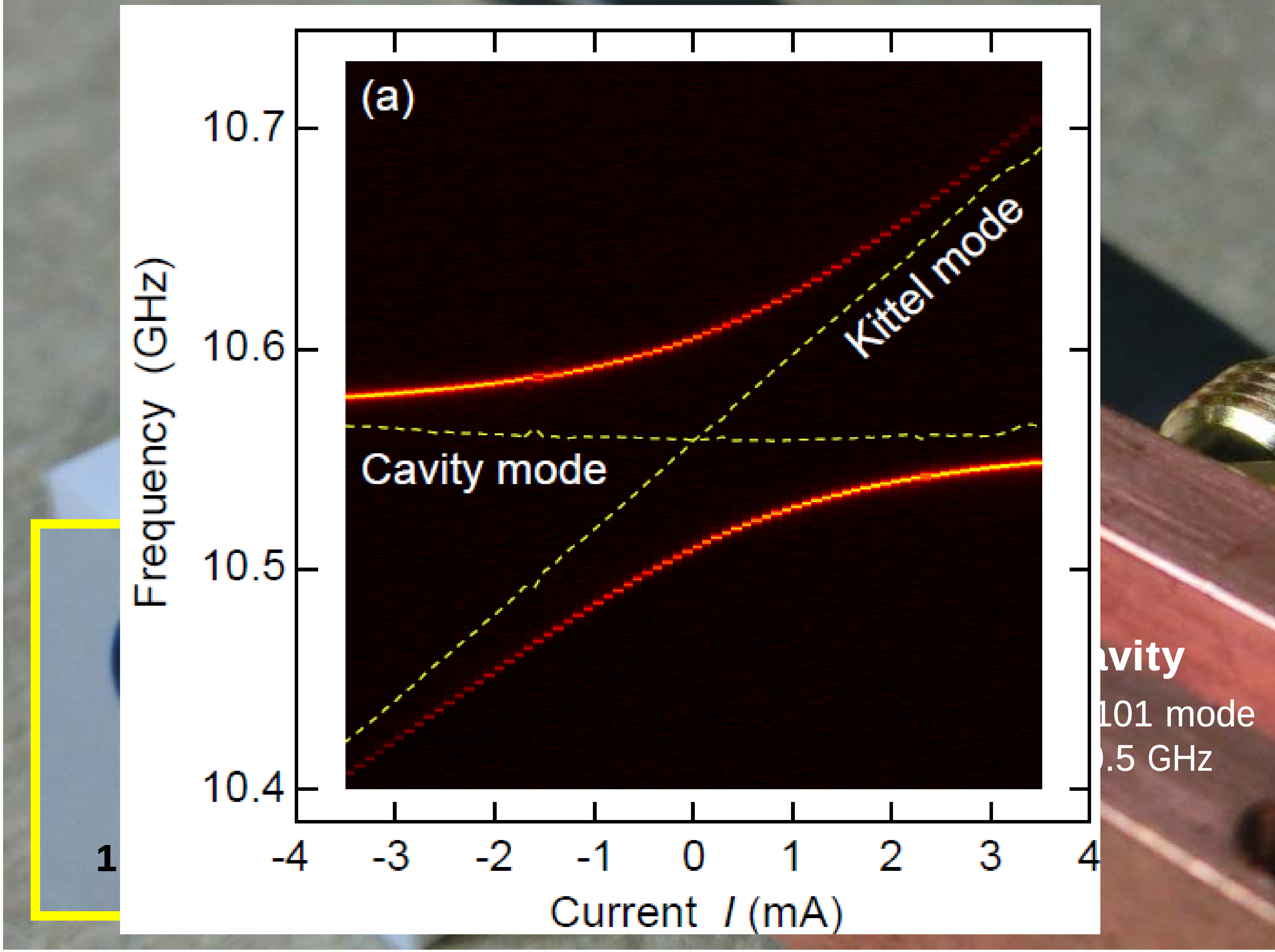


Kittel mode



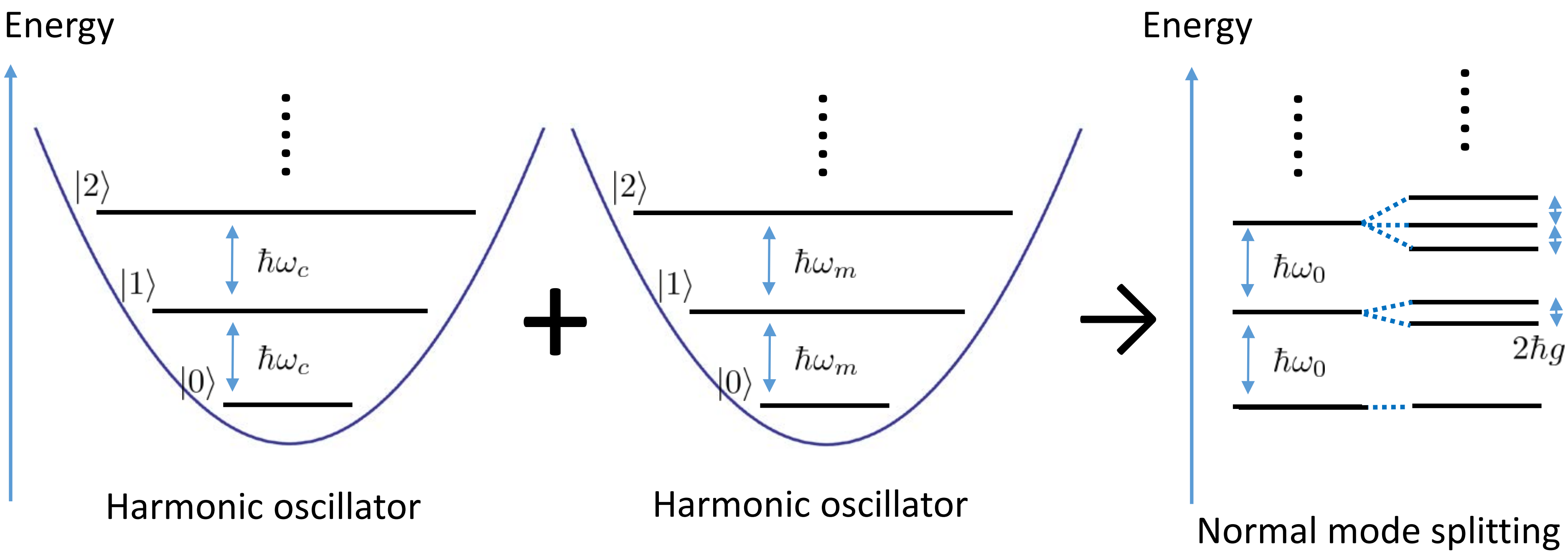
Ferromagnetic resonance (FMR)

Hybridizing magnons and microwave photons



Y. Tabuchi *et al.,* Phys. Rev. Lett. **113,** 083603 (2014)

Harmonic oscillator + harmonic oscillator

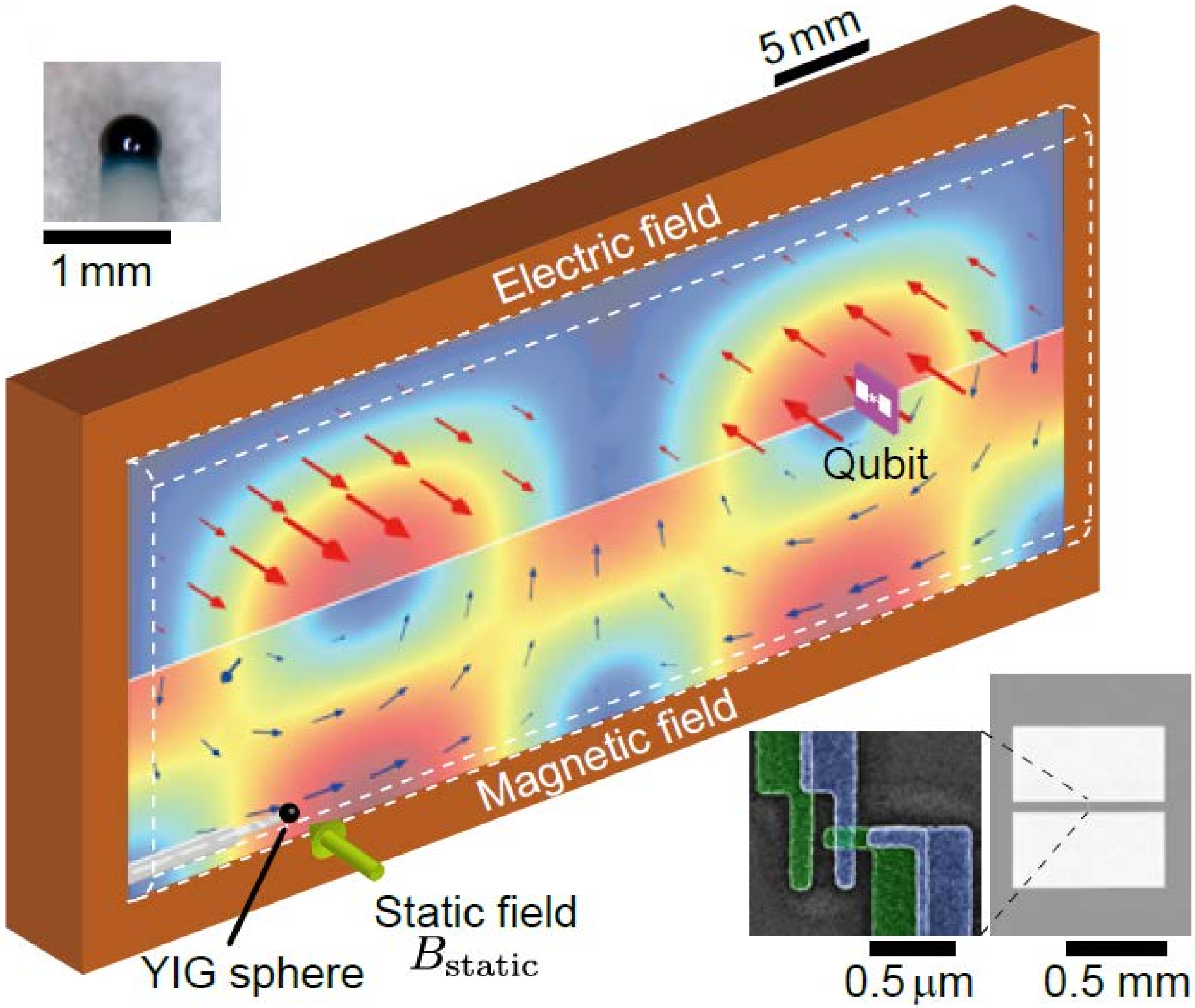


Resonance

$\omega_c = \omega_m \equiv \omega_0$

Linear energy level structure

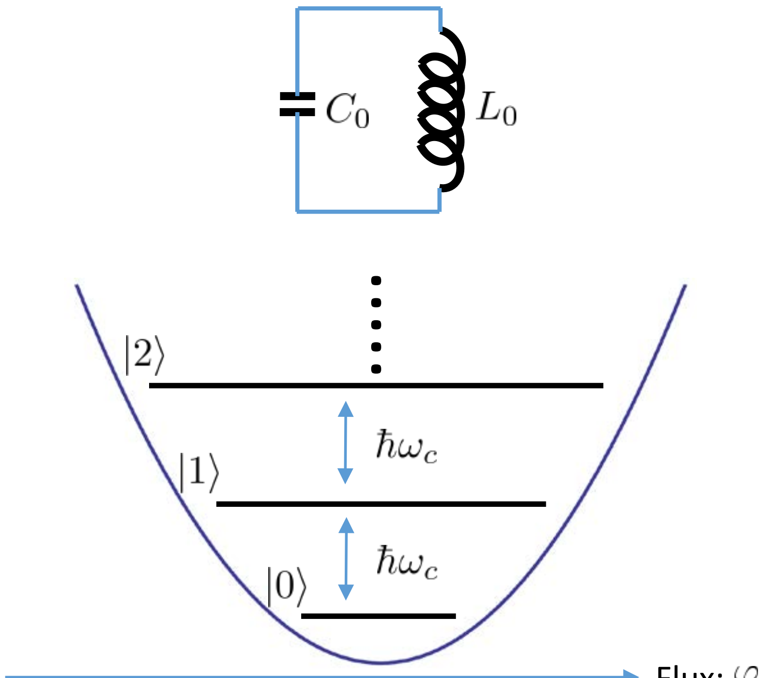
Meta cavity QED



Experimant: Y. Tabuchi *et al.,* Science **349,** 405 (2015)
Proposal: A. Imamoglu, Phys. Rev. Lett. **102,** 083602 (2009).

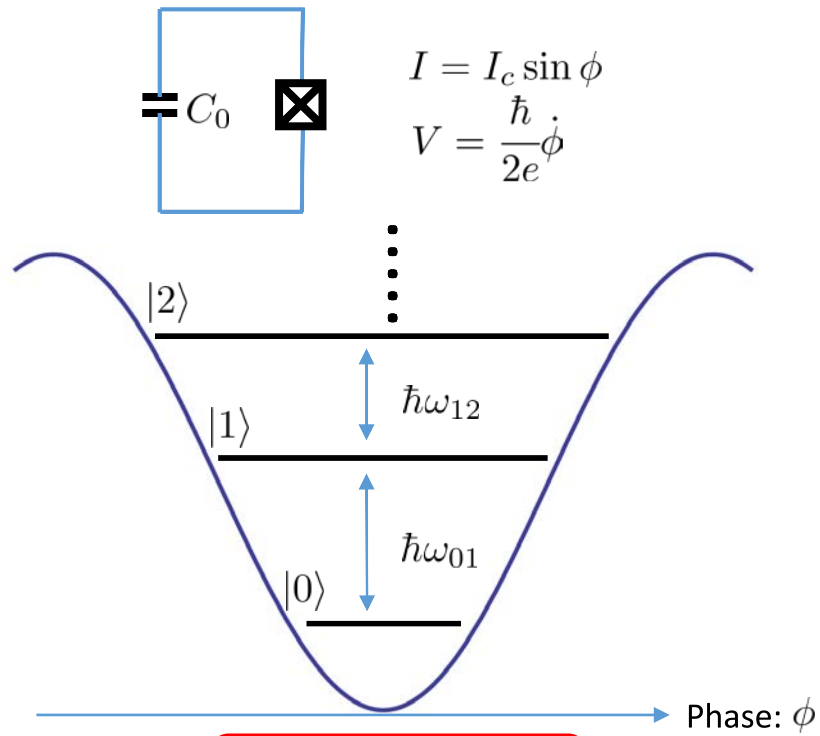
Superconducting qubit

LC circuit



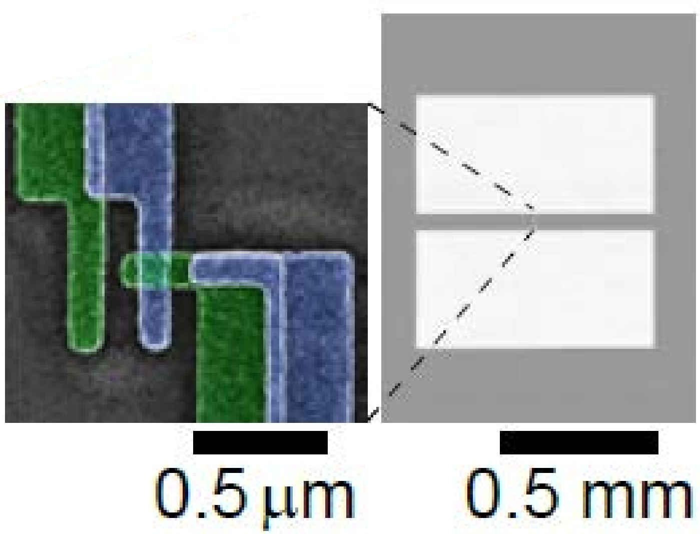
$$\ddot{\varphi} + \frac{1}{L_0 C_0}\varphi = 0$$

Capacitor with Josephson junction

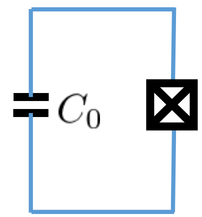


$$\ddot{\phi} + \frac{2eI_c}{\hbar C_0}\sin\phi = 0$$

Superconducting qubit

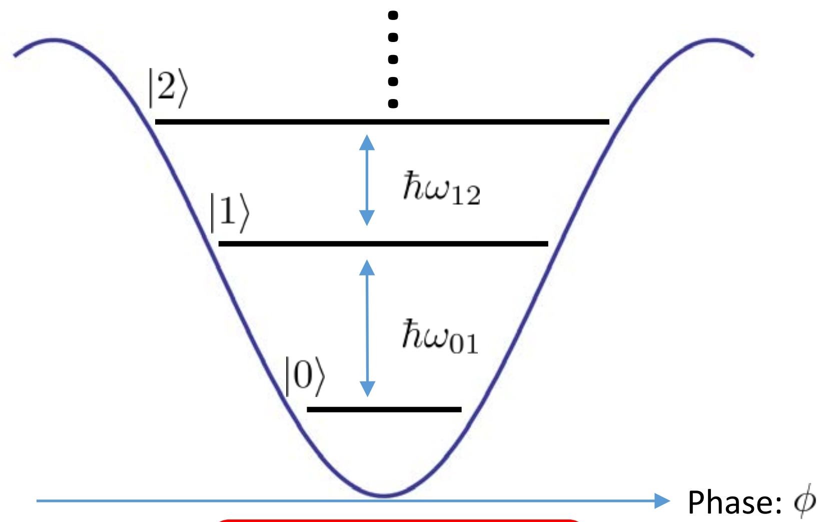


Capacitor with Josephson junction



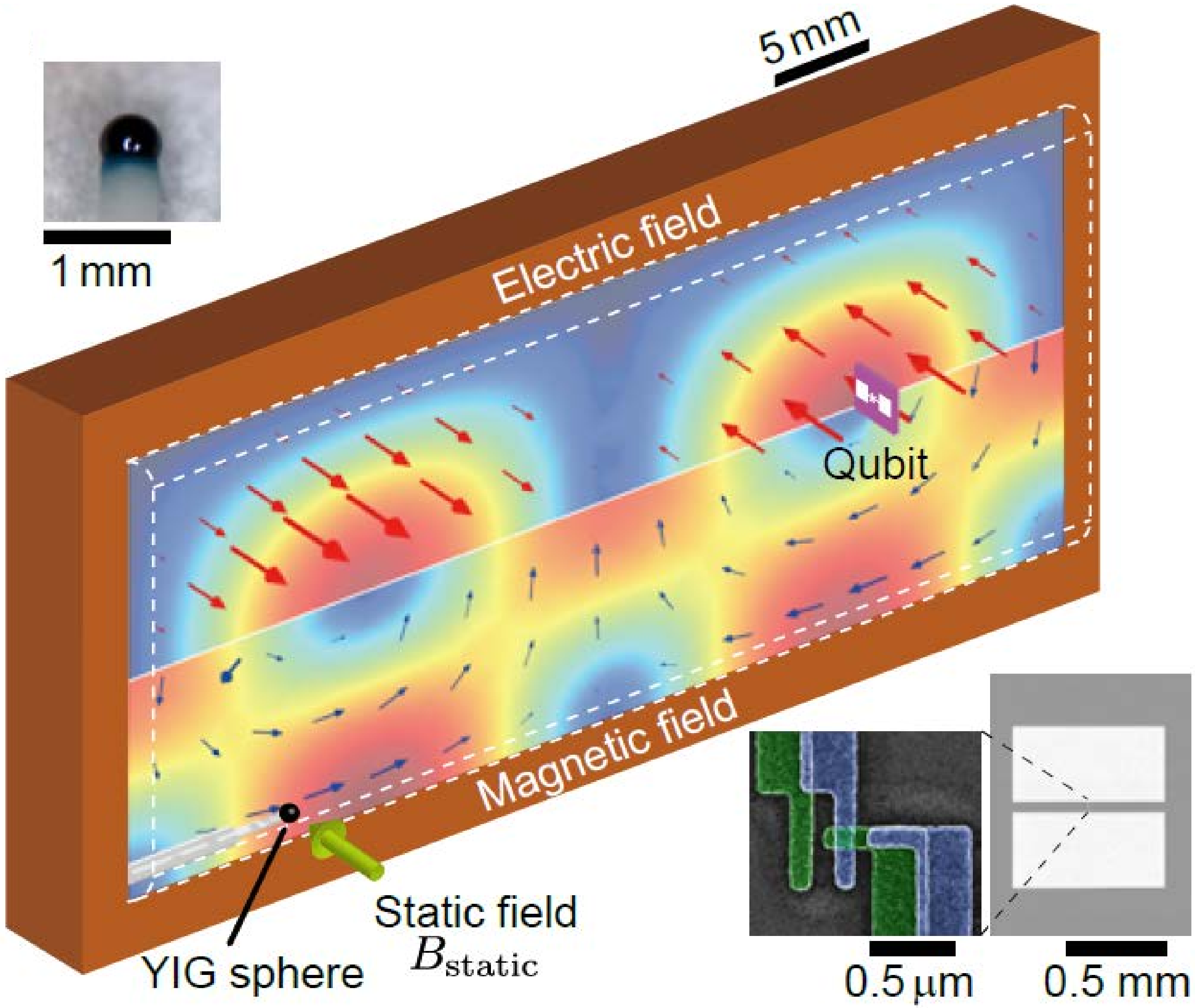
$$I = I_c \sin\phi$$

$$V = \frac{\hbar}{2e}\dot{\phi}$$



$$\ddot{\phi} + \frac{2eI_c}{\hbar C_0}\sin\phi = 0$$

Meta cavity QED



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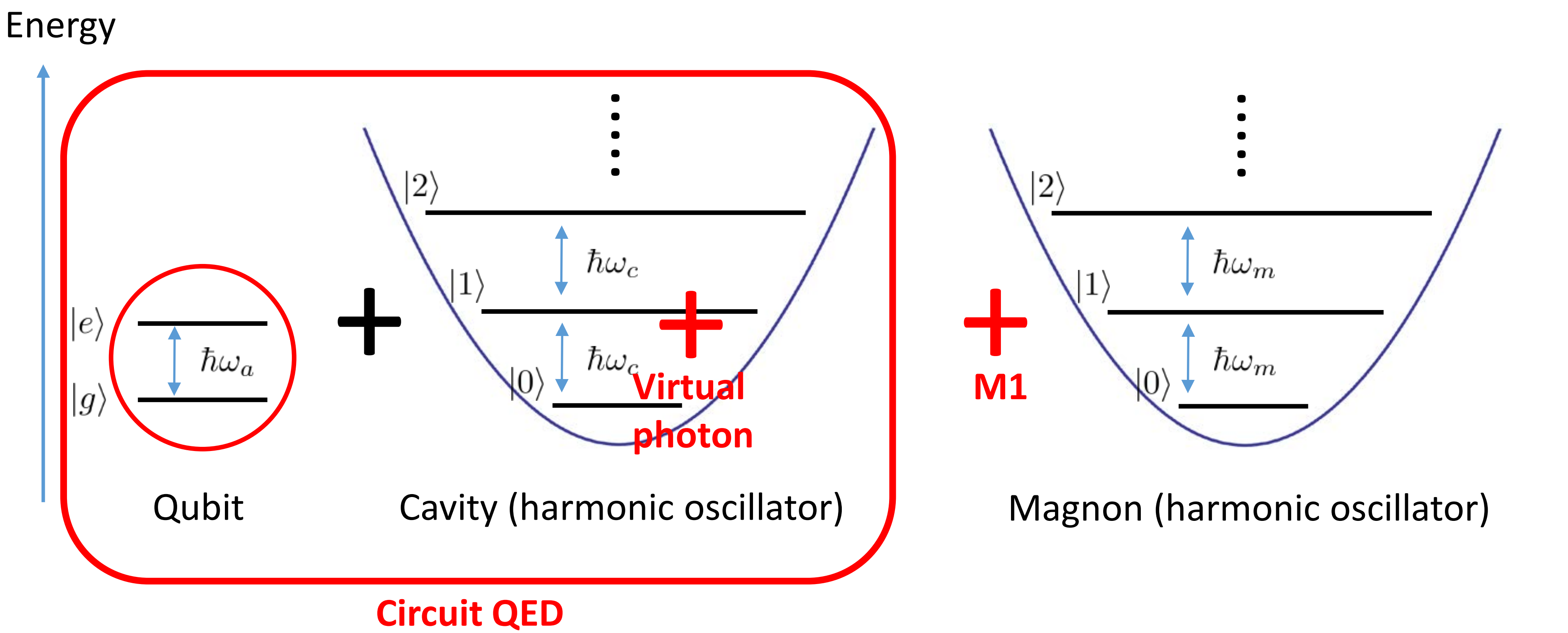
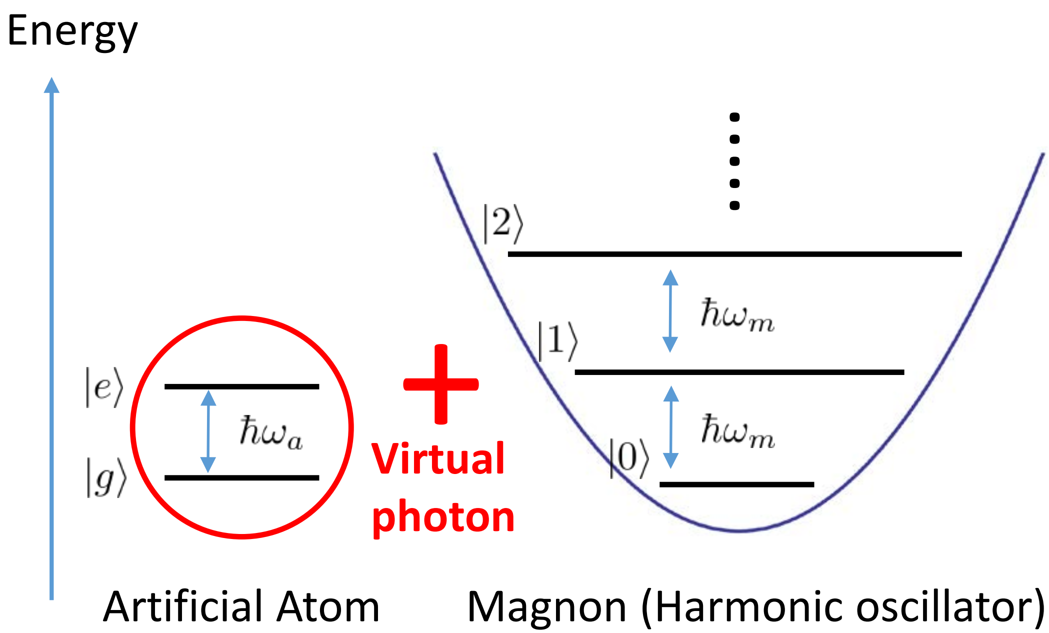
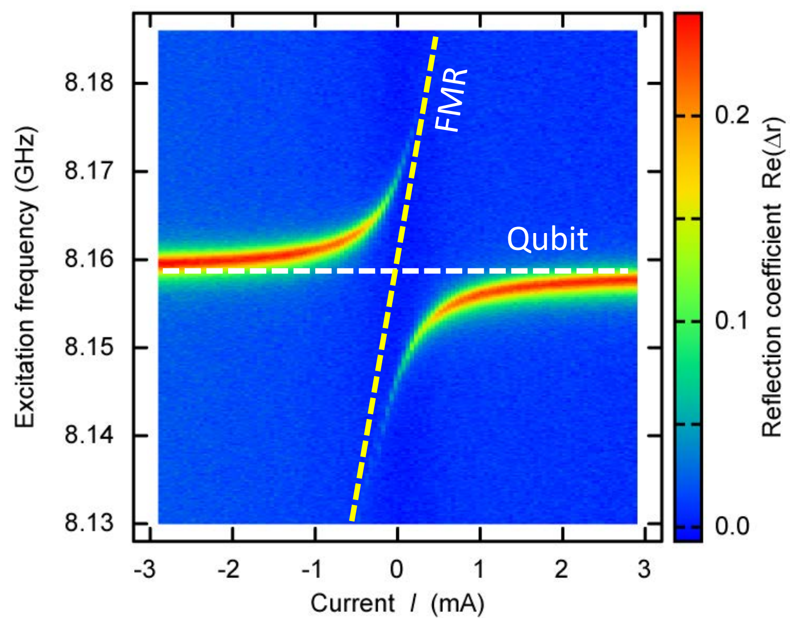
Meta cavity QED



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

Magnon-vacuum Rabi splitting





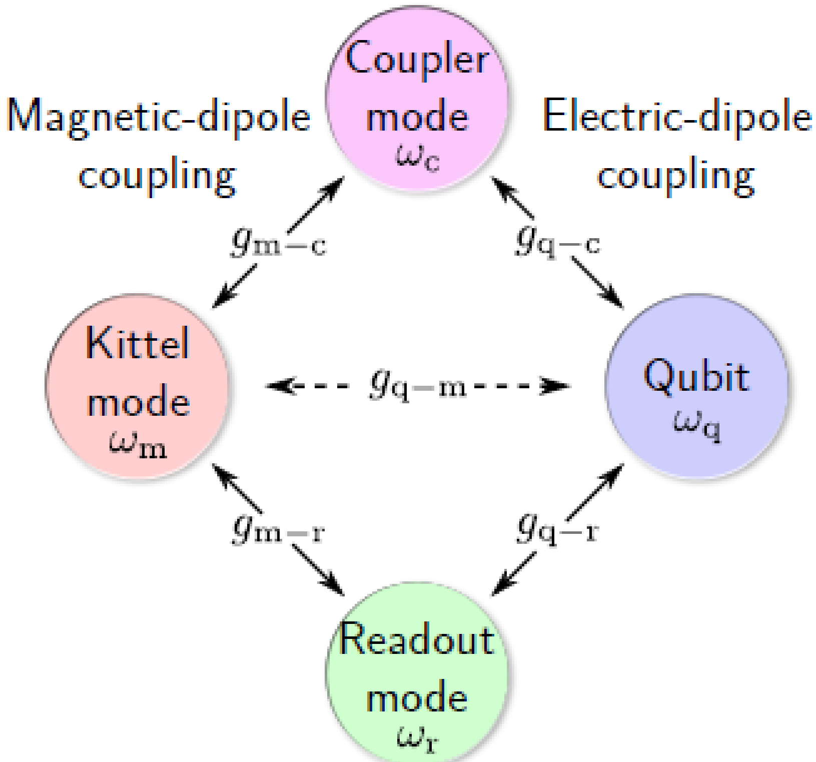
Resonance

$\omega_a = \omega_m \equiv \omega_0$

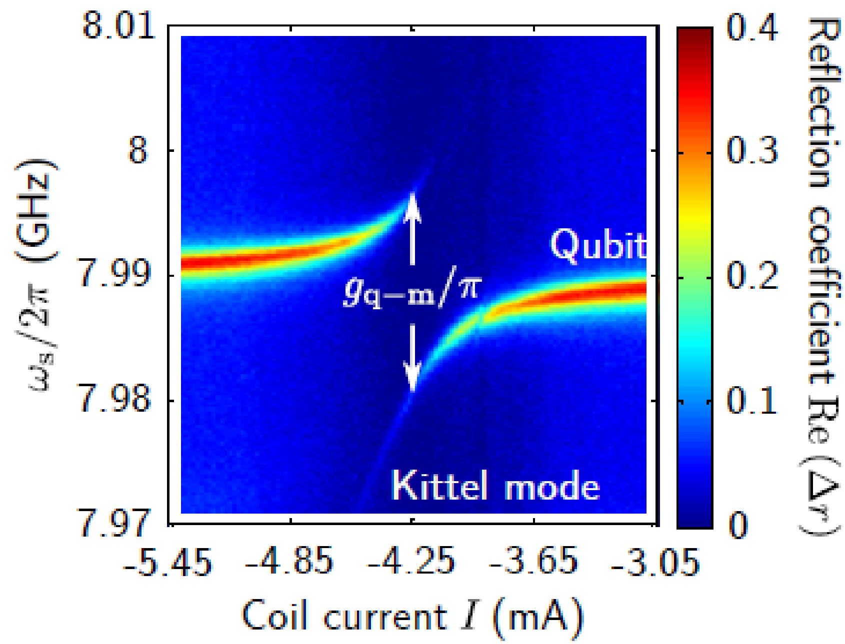
Magnon-vacuum Rabi splitting

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

Resonant coupling



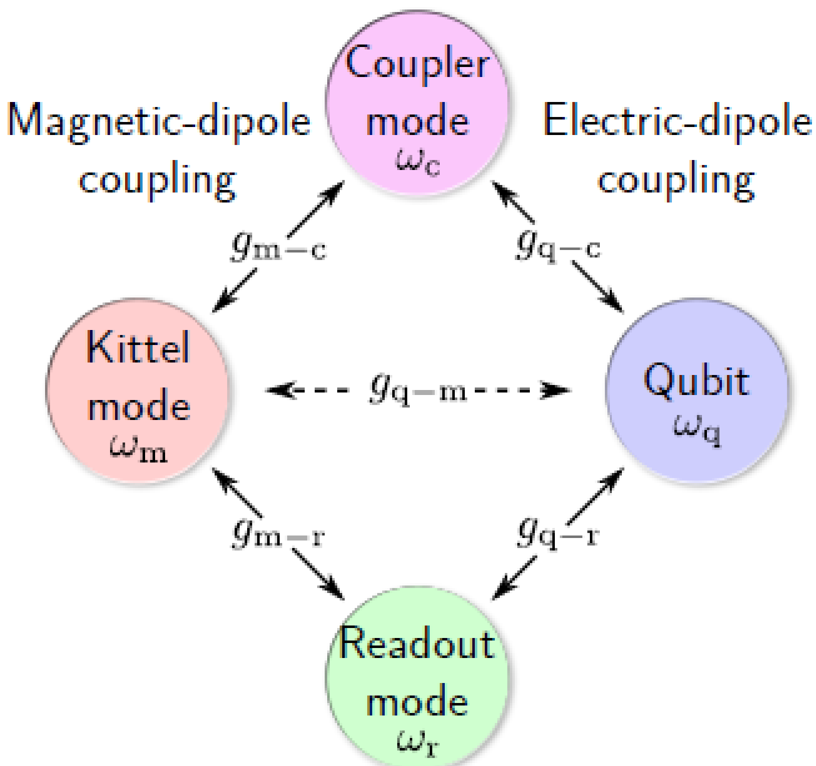
$$g_{q-m} = \sum_{i=c,r,\dots} \frac{g_{q-i}\, g_{m-i}}{\omega_i^{bare} - \omega_{q,m}^{bare}}$$

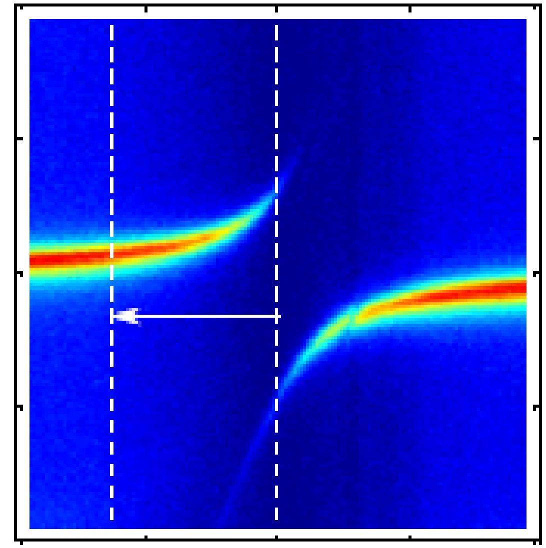


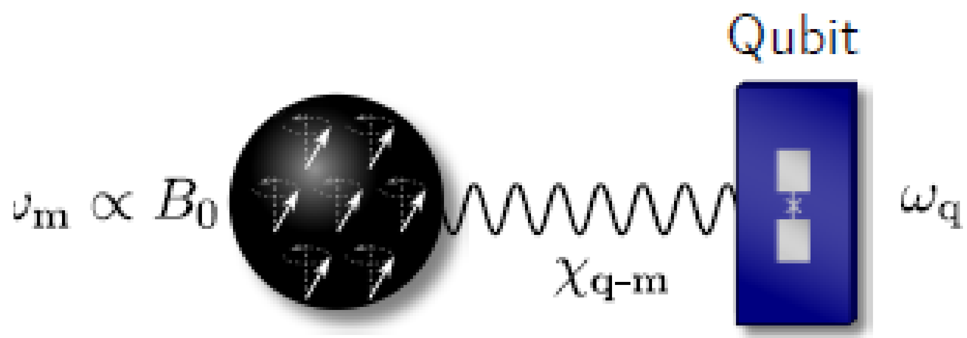
Experiment: $g_{q-m}/2\pi = 7.79$ MHz

D. Lachance-Quirion *et al.,* Sci. Adv. **3,** e1603150 (2017)

Dispersive coupling



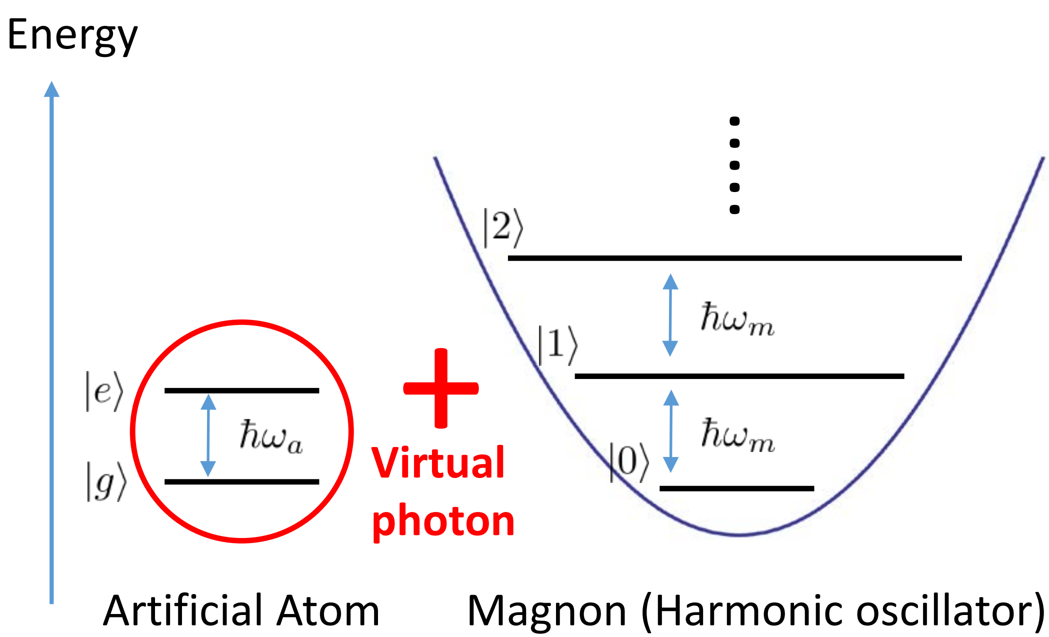


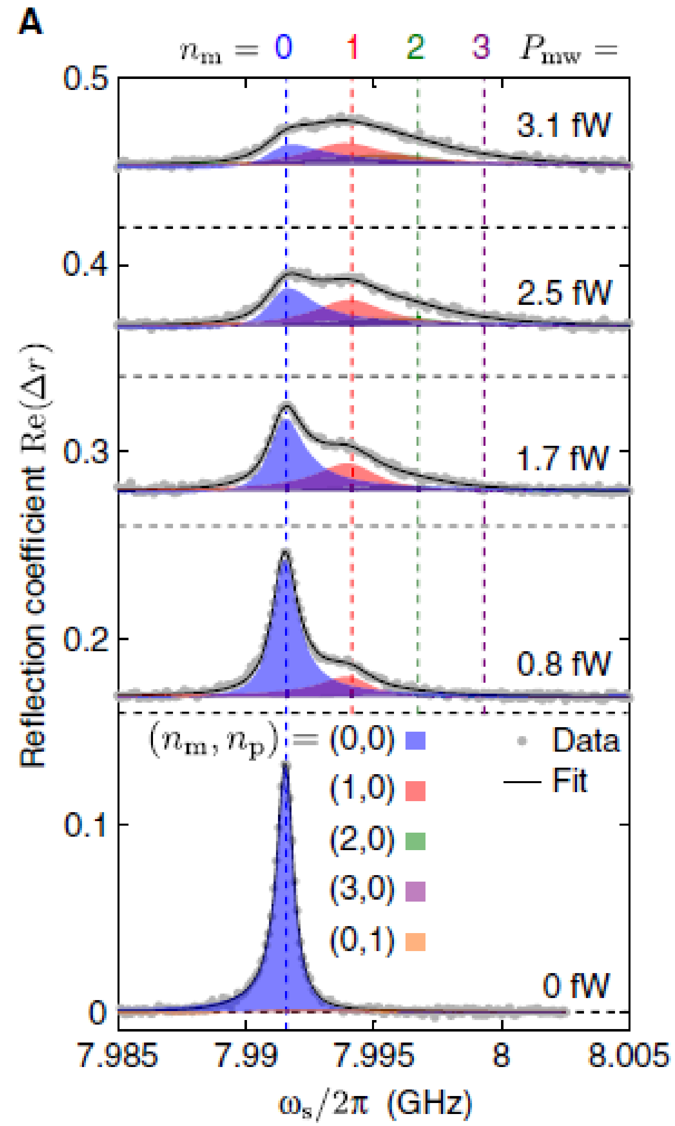


$\chi_{q-m}/2\pi = 1.5$ MHz

D. Lachance-Quirion *et al.,* Sci. Adv. **3,** e1603150 (2017)

“Magnon-polariton” shift





Off - resonance

$\omega_a \neq \omega_m$

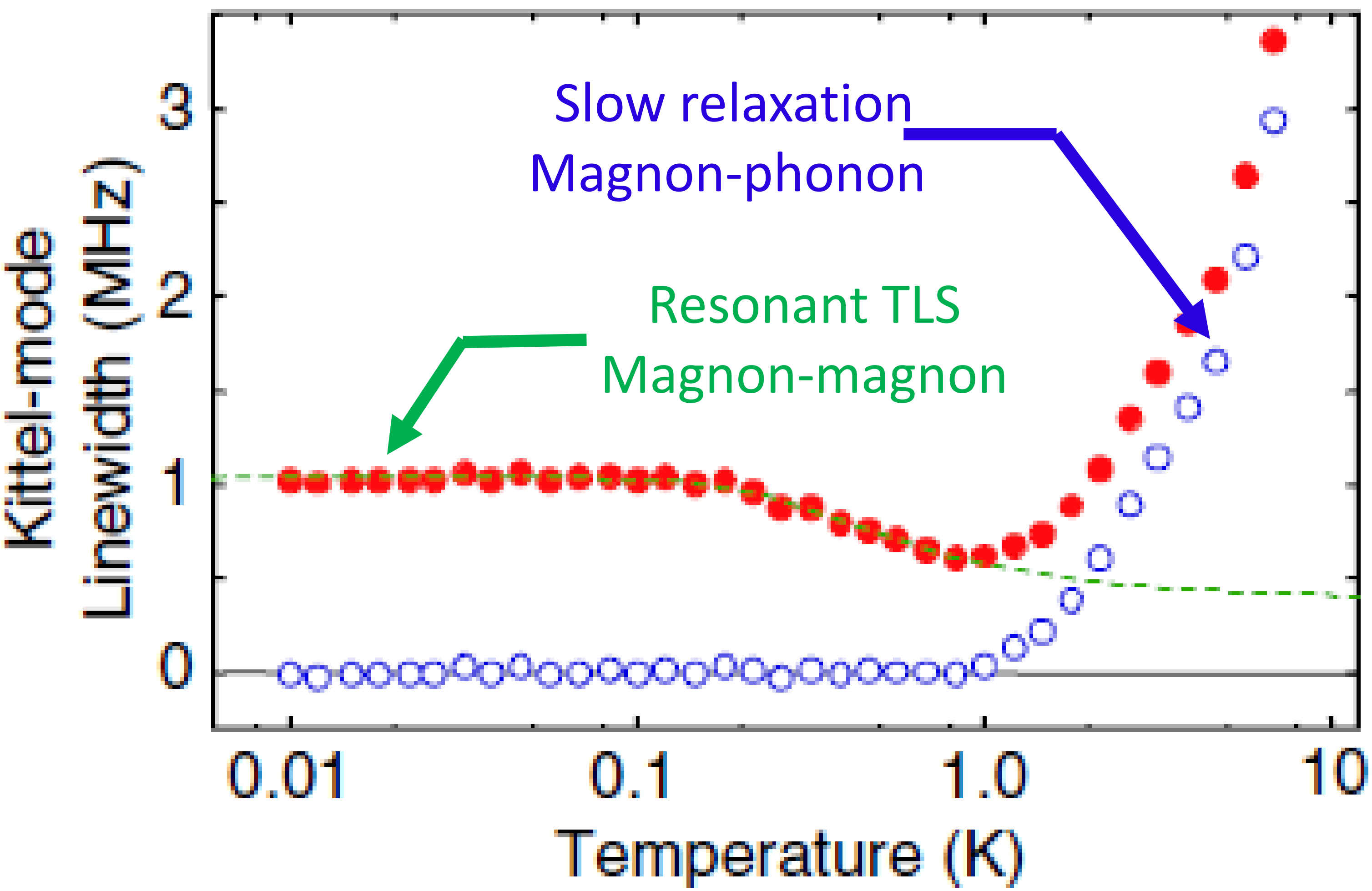
$\chi_{q-m}/2\pi = 1.5$ MHz

“Magnon-polariton” shift

D. Lachance-Quirion *et al.*, Sci. Adv. **3,** e1603150 (2017)

New developments of quantum magnonics

Magnon linewidth vs. temperature

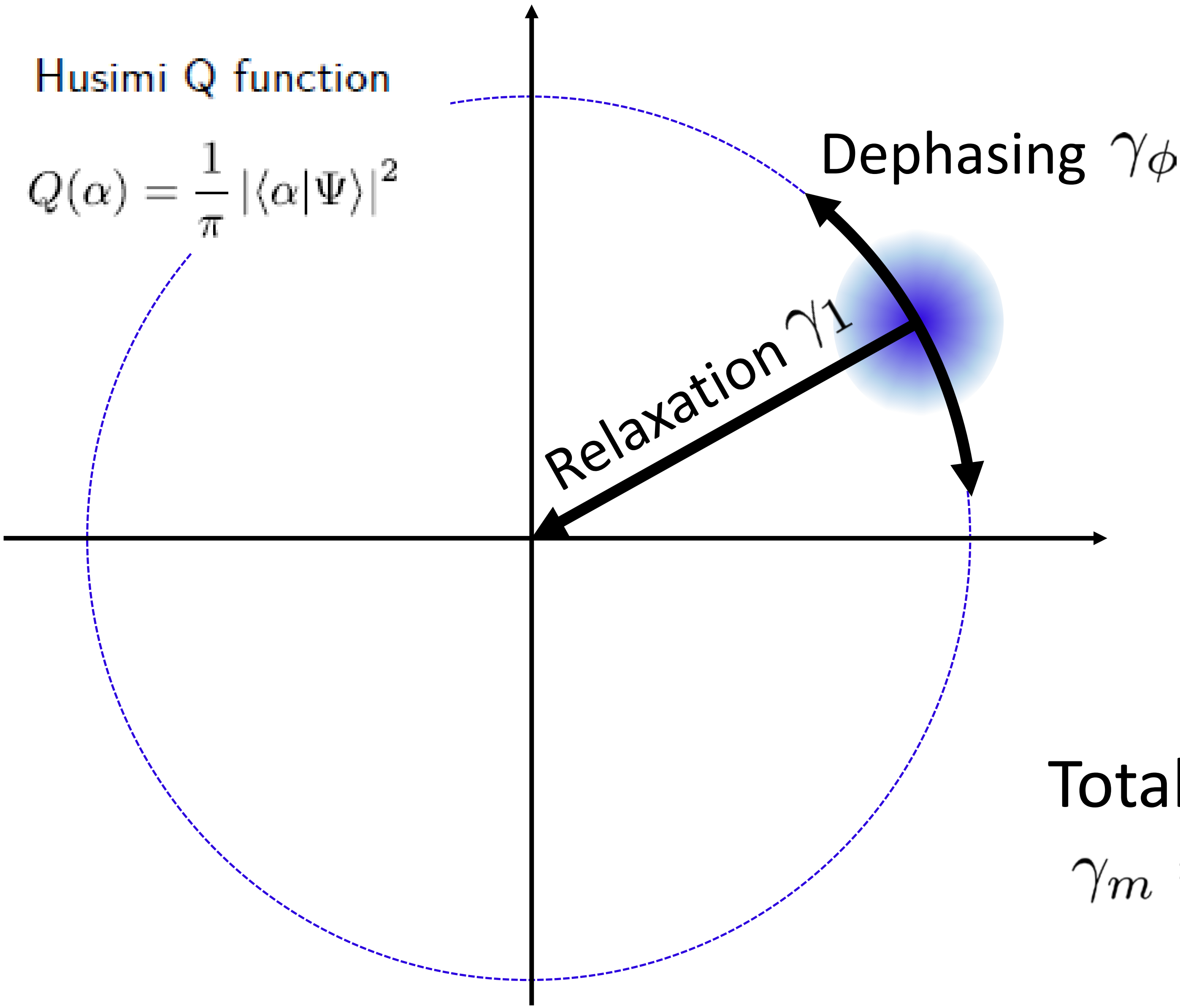


Y. Tabuchi *et al.*, Phys. Rev. Lett. **113,** 083603 (2014)

Relaxation and dephasing

Husimi Q function

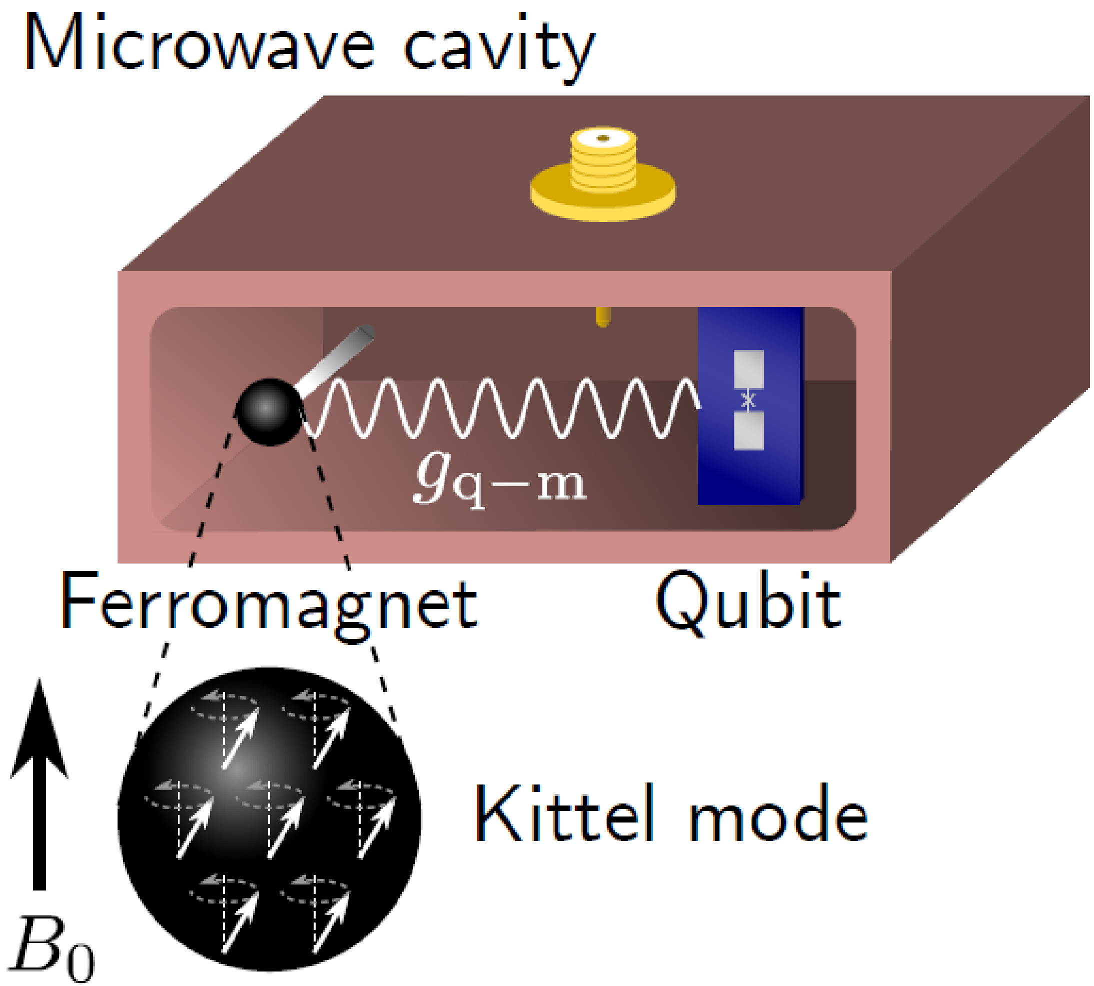
$$Q(\alpha) = \frac{1}{\pi} \left| \langle \alpha | \Psi \rangle \right|^2$$



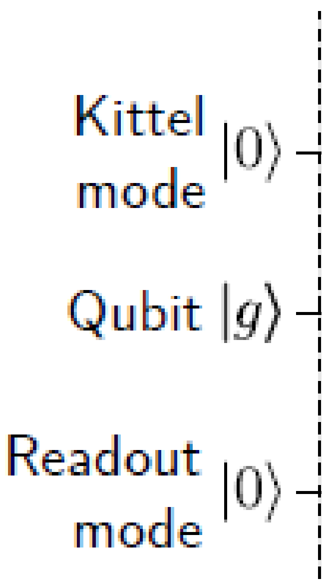
Total linewidth

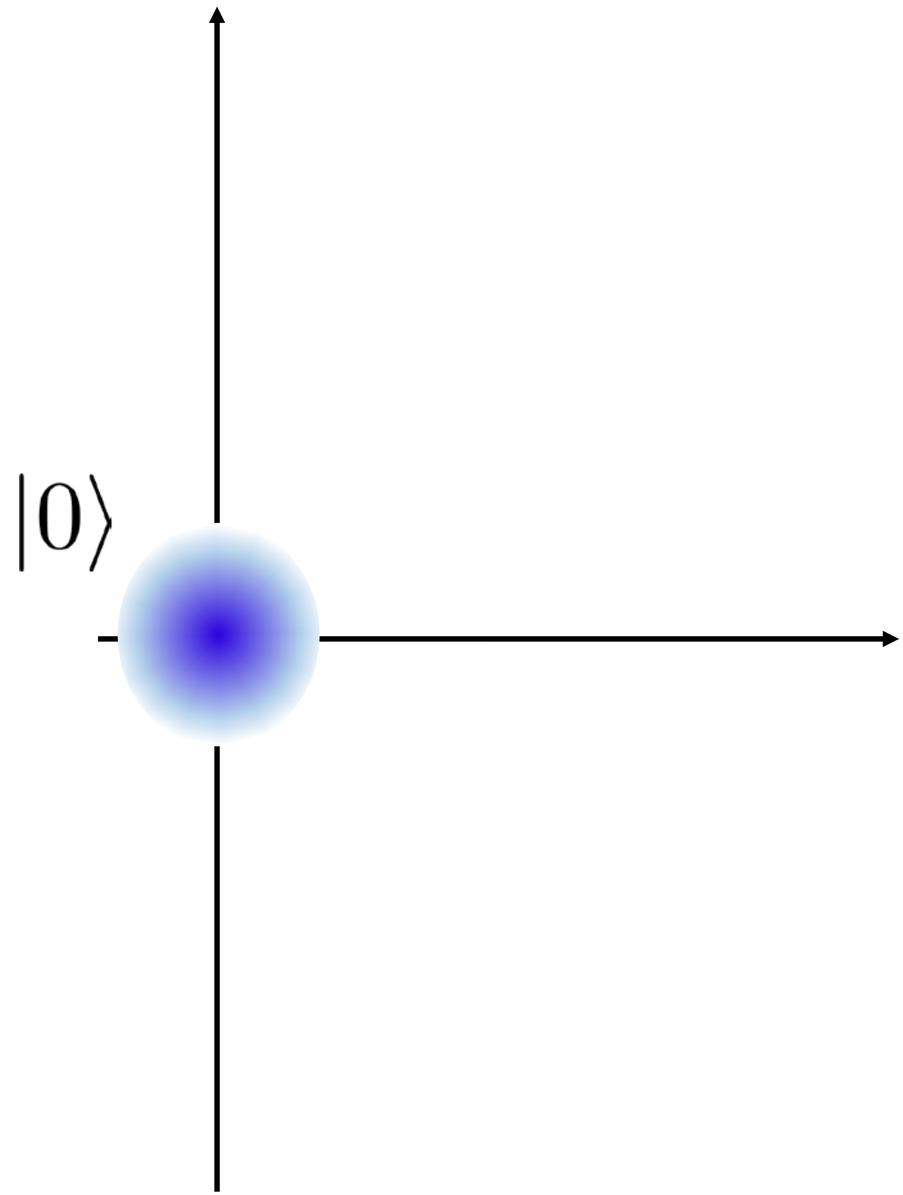
$$\gamma_m = \gamma_\phi + \frac{\gamma_1}{2}$$

Tomography of magnon states

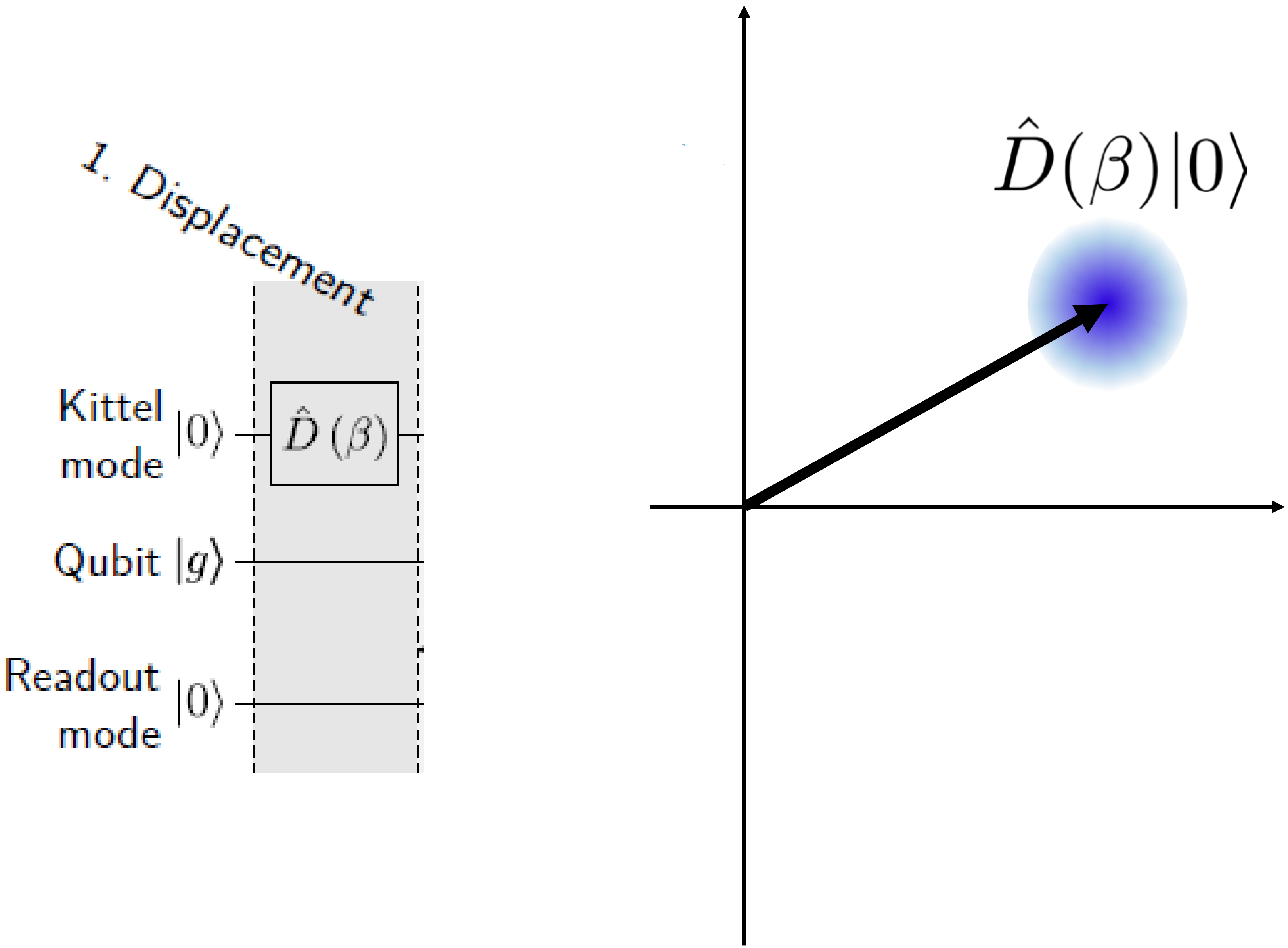


Tomography of magnon states

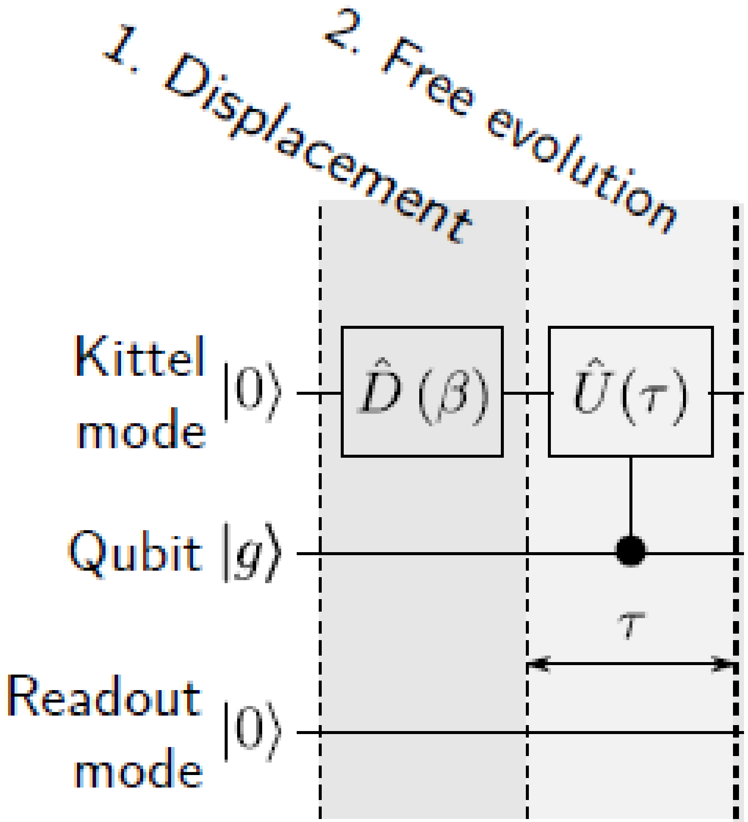


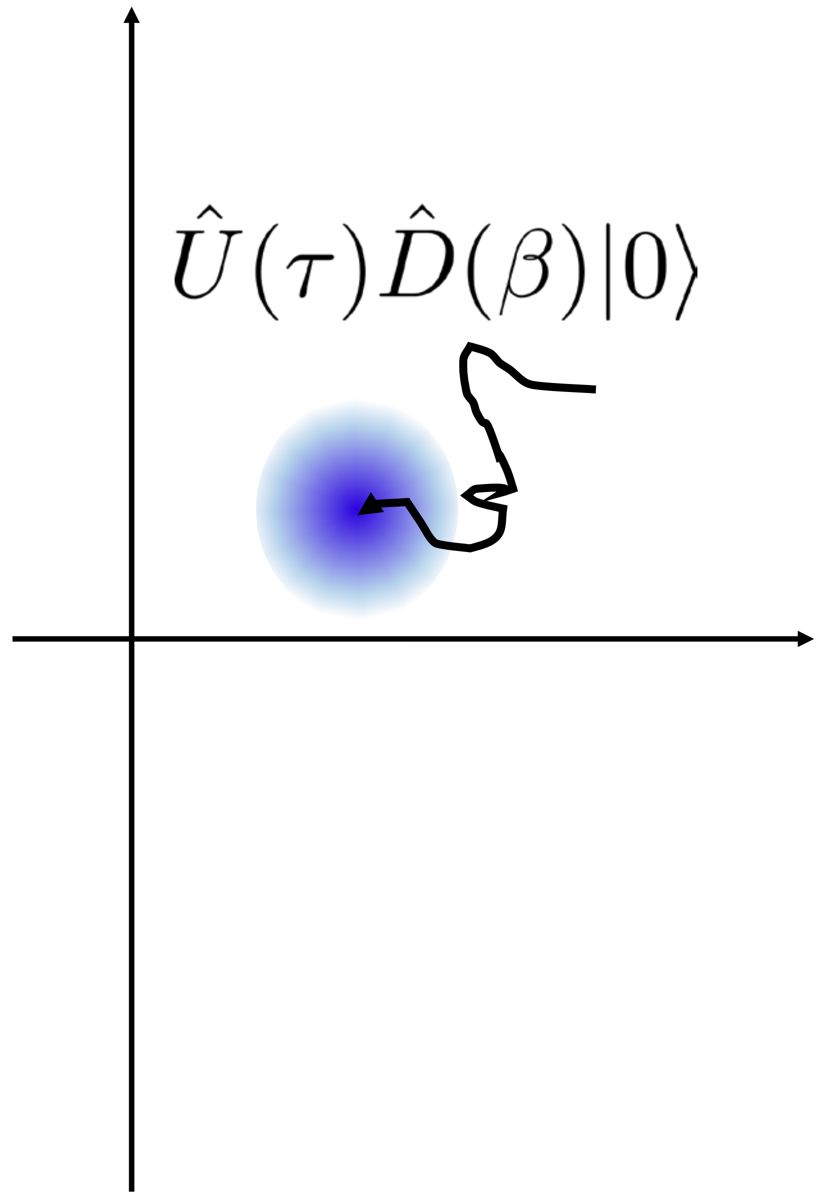


Tomography of magnon states

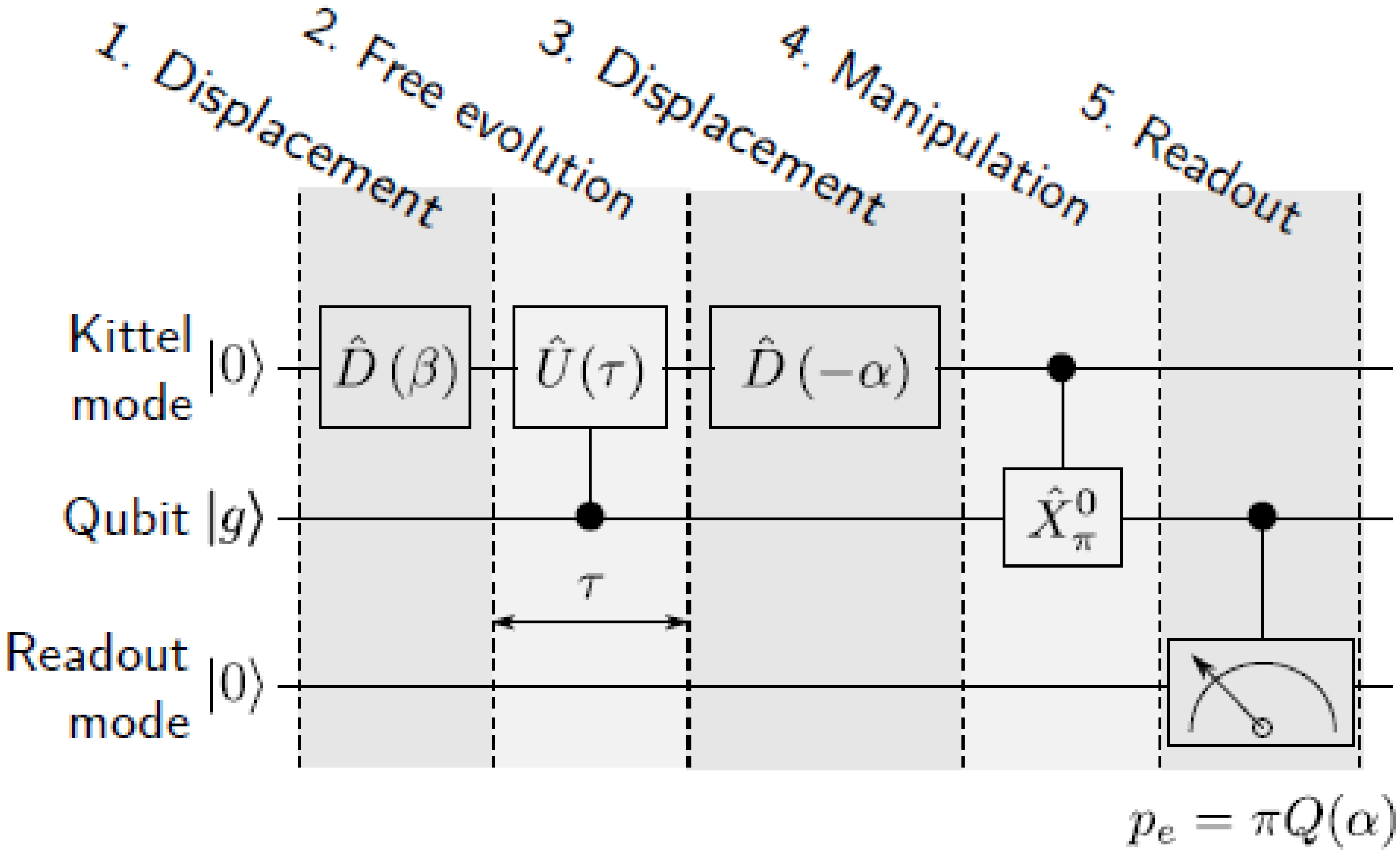


Tomography of magnon states

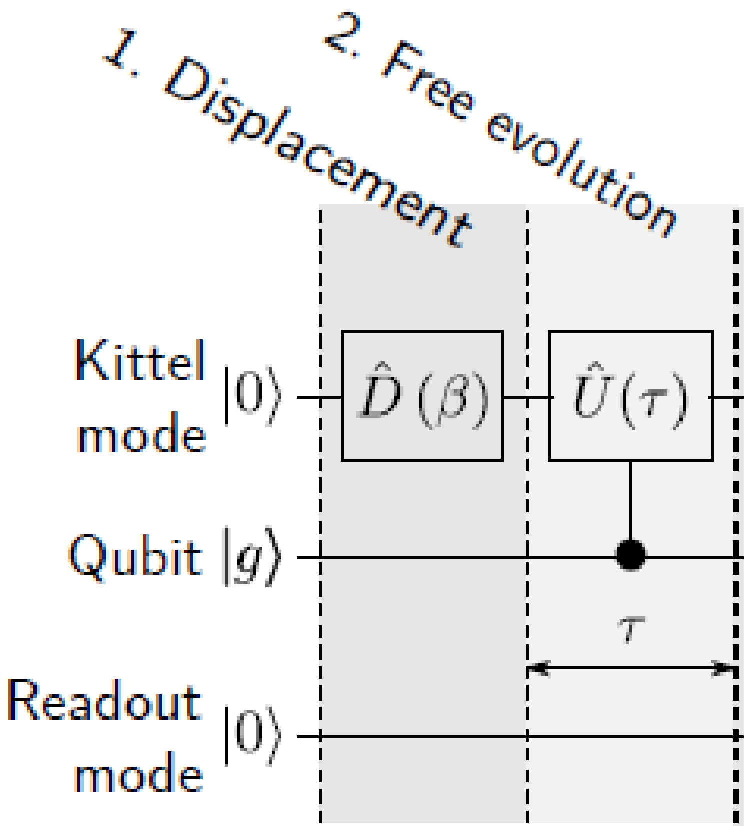


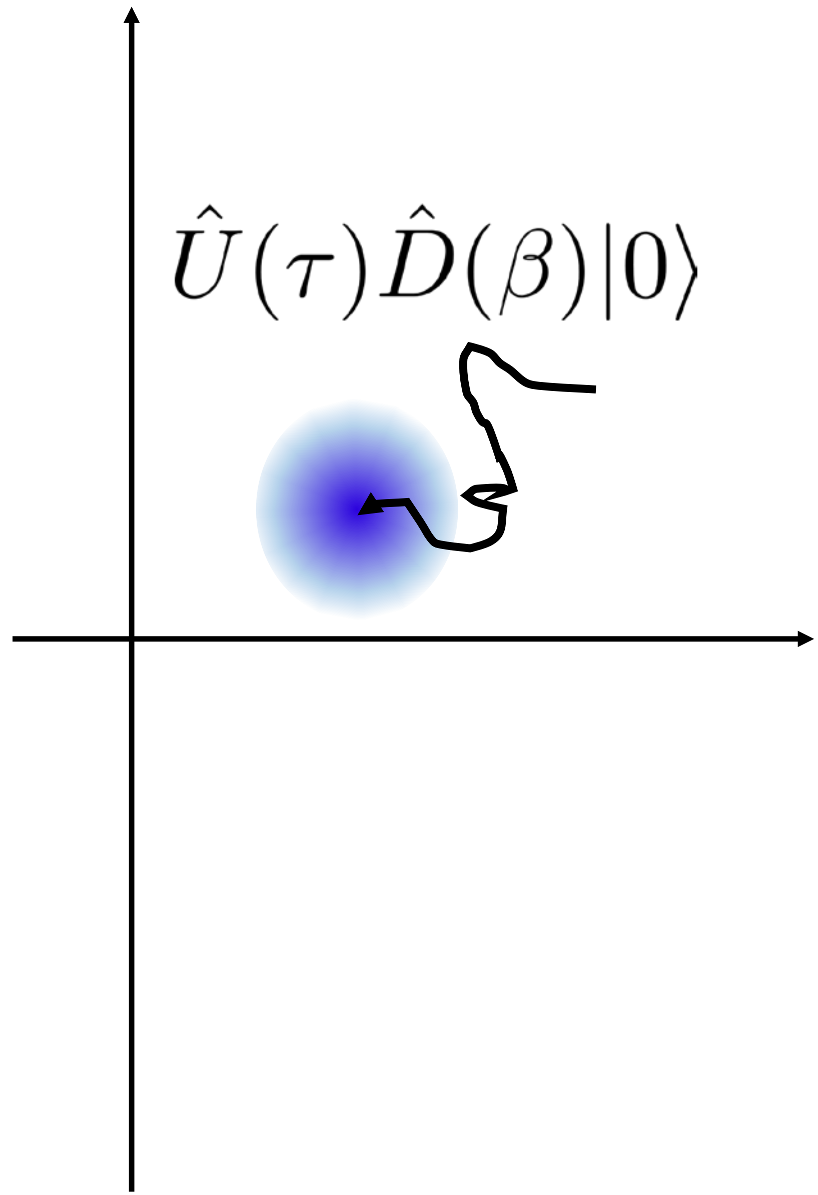


Tomography of magnon states

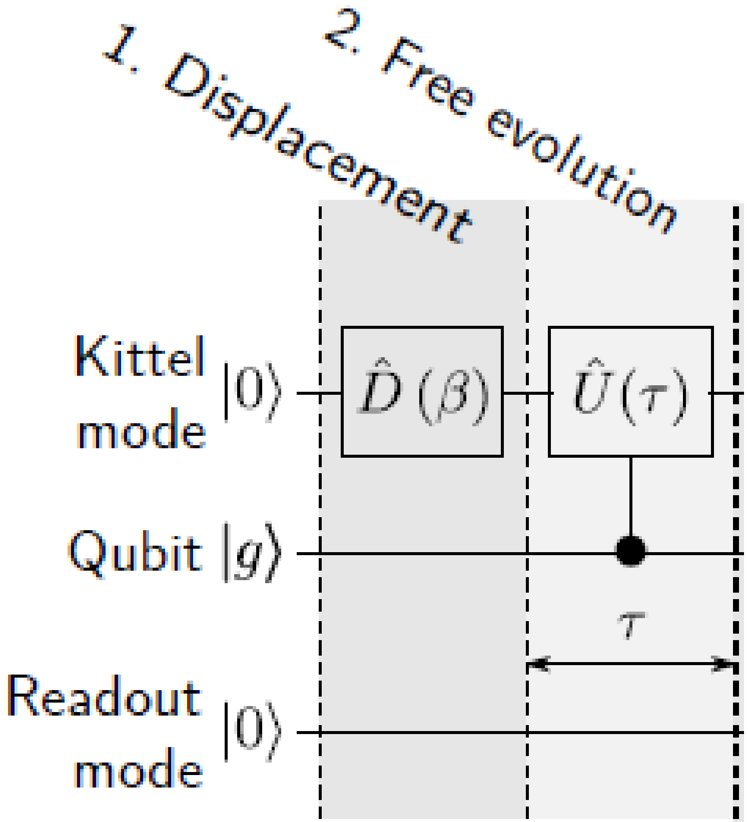


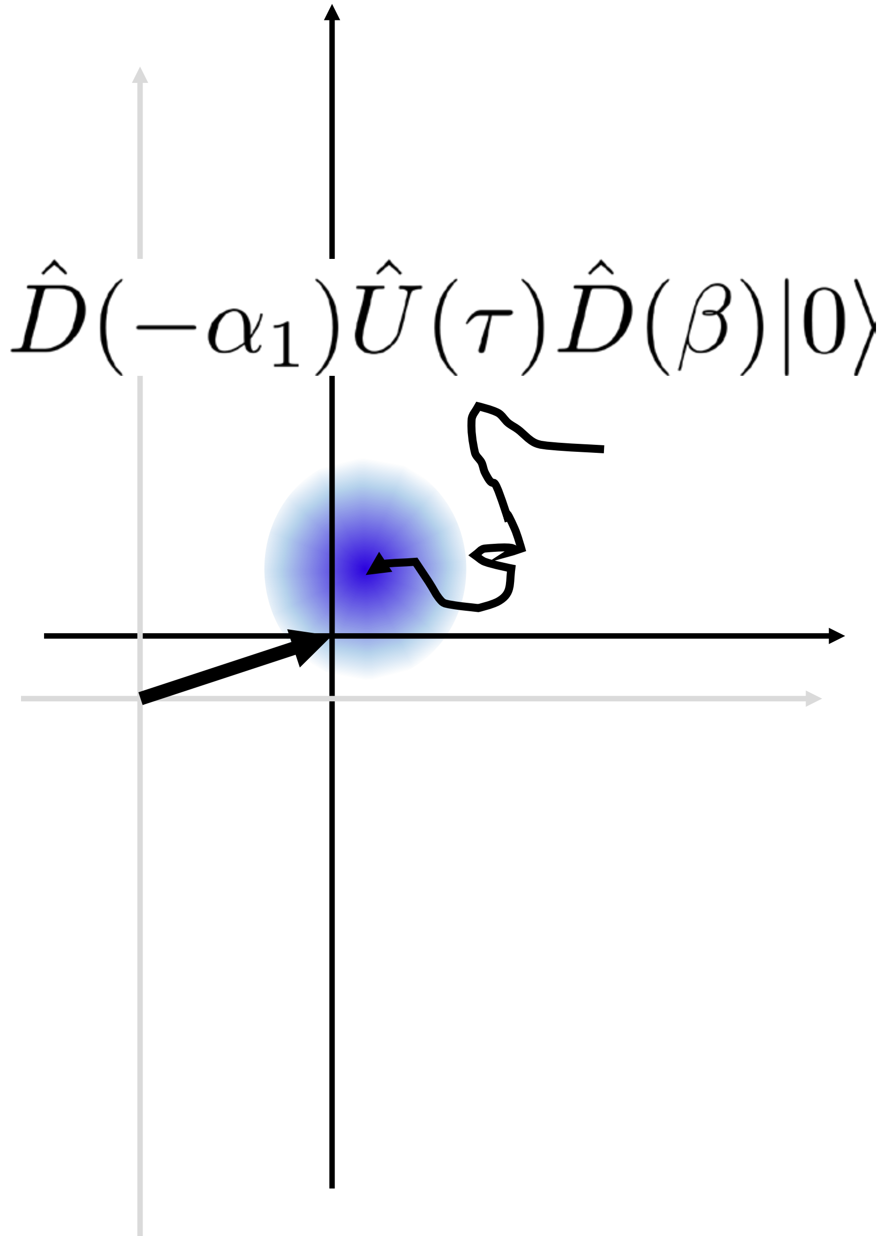
Tomography of magnon states





Tomography of magnon states





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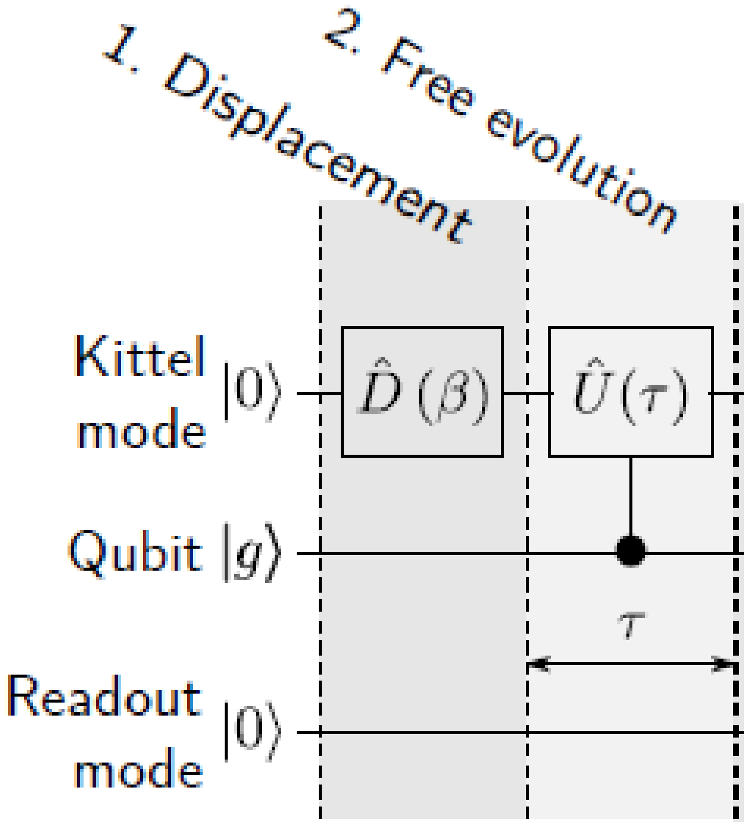
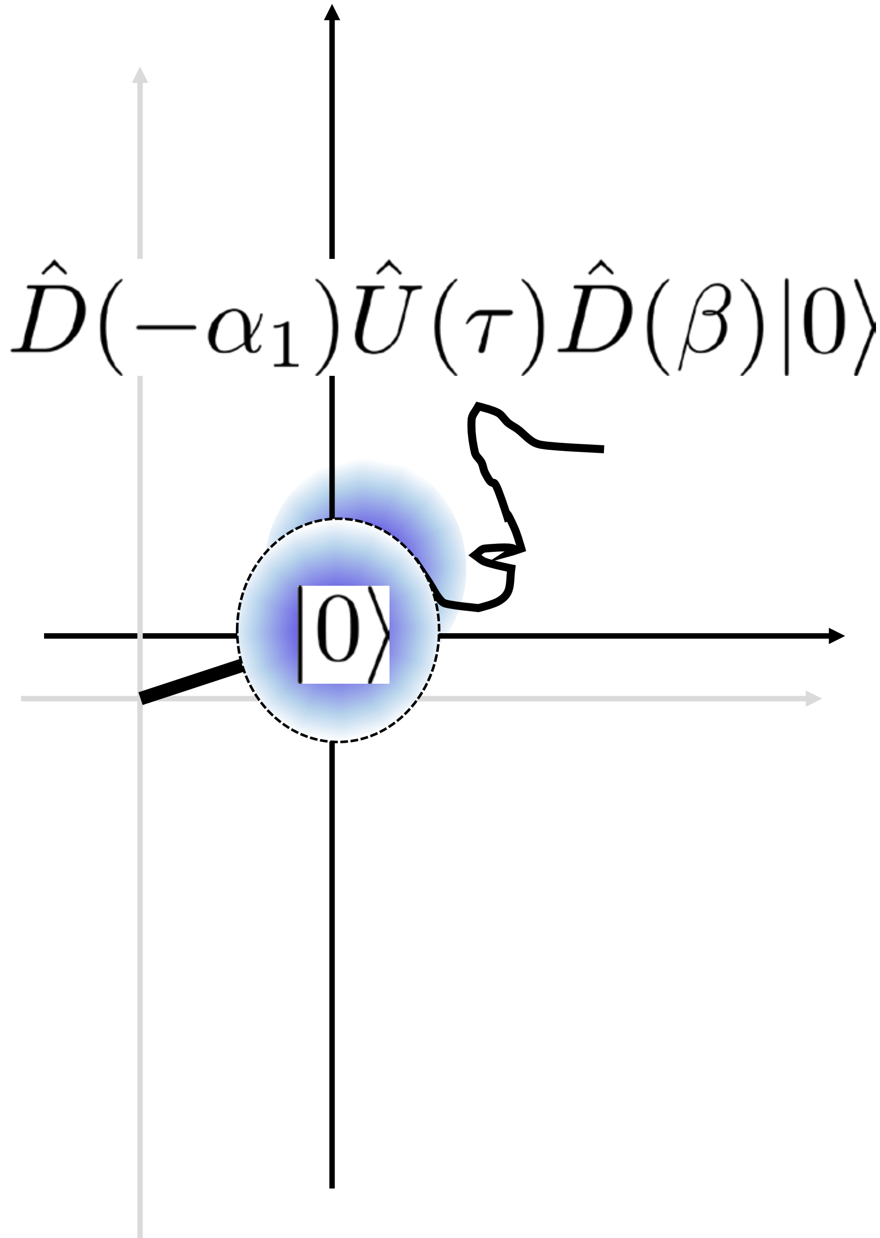
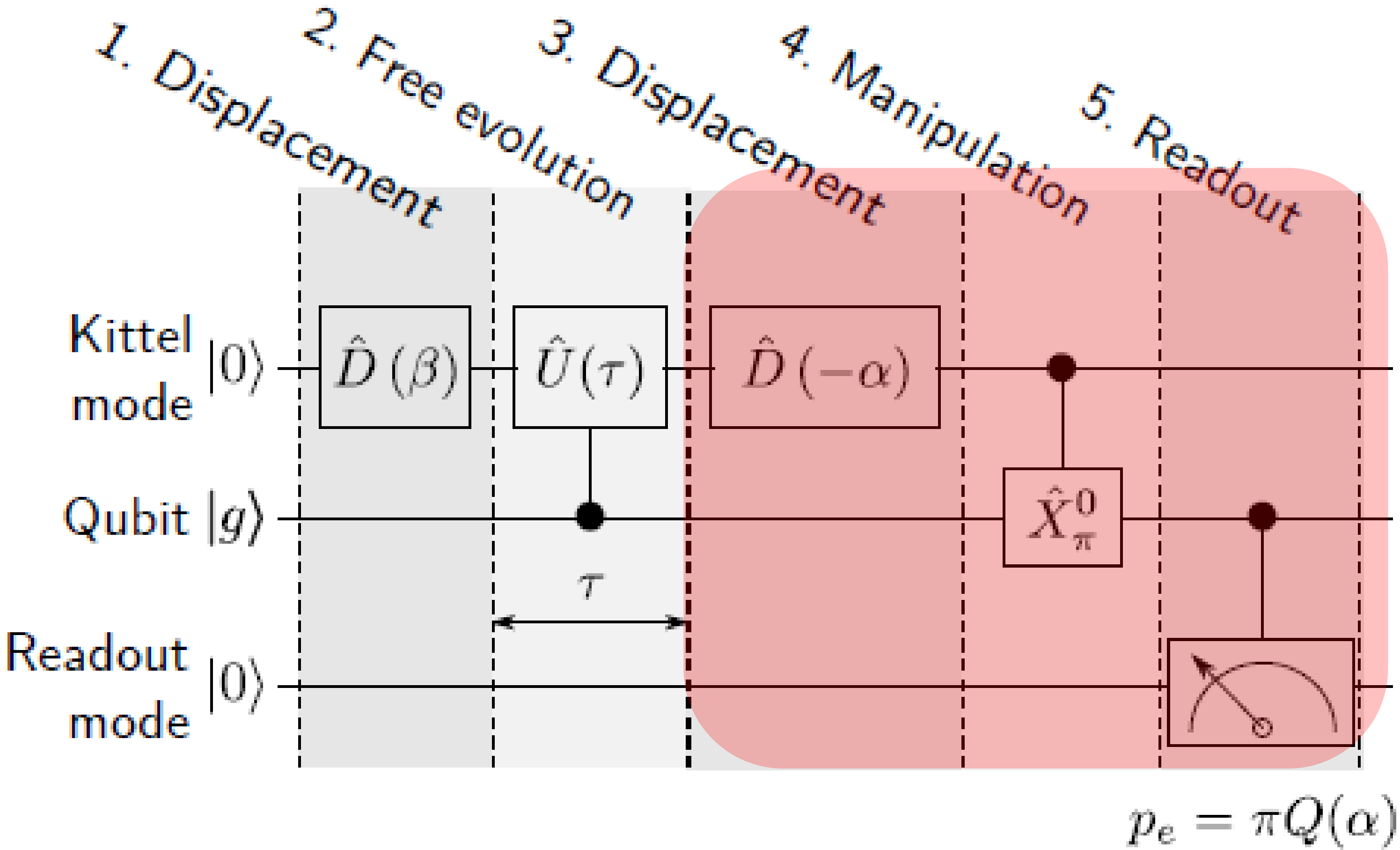
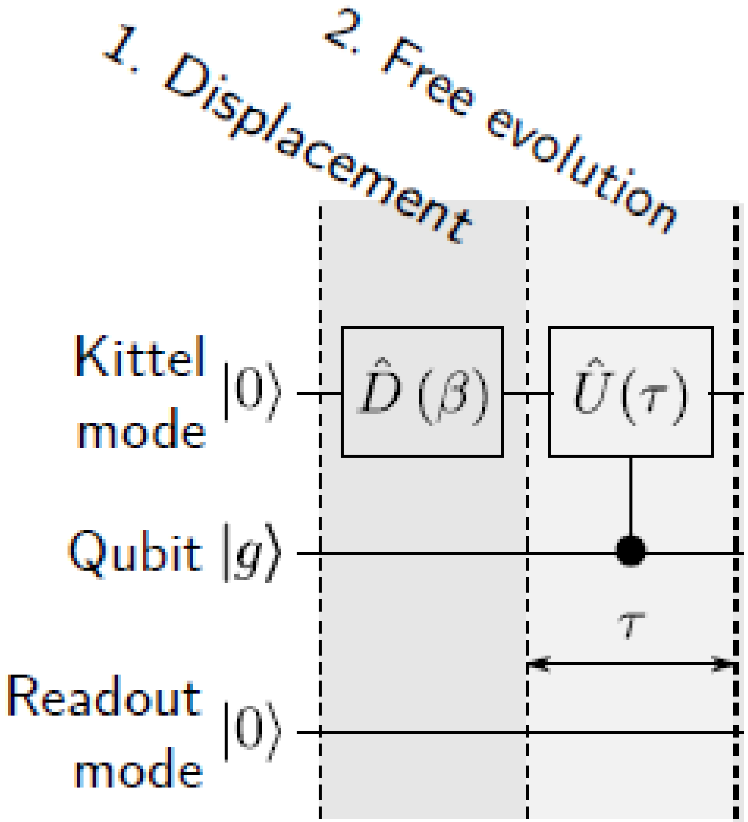




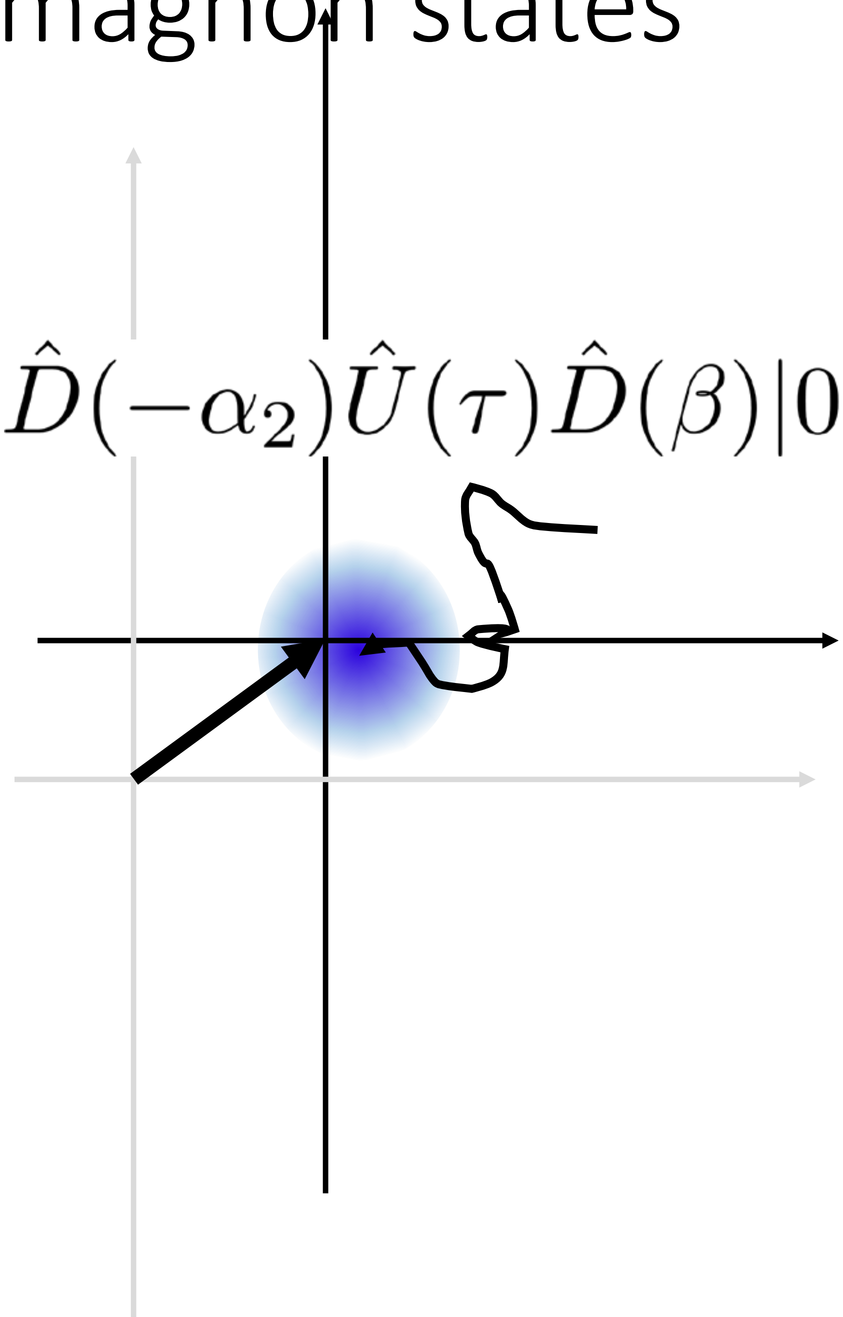
Tomography of magnon states



Tomography of magnon states



$$\hat{D}(-\alpha_2)\hat{U}(\tau)\hat{D}(\beta)|0\rangle$$



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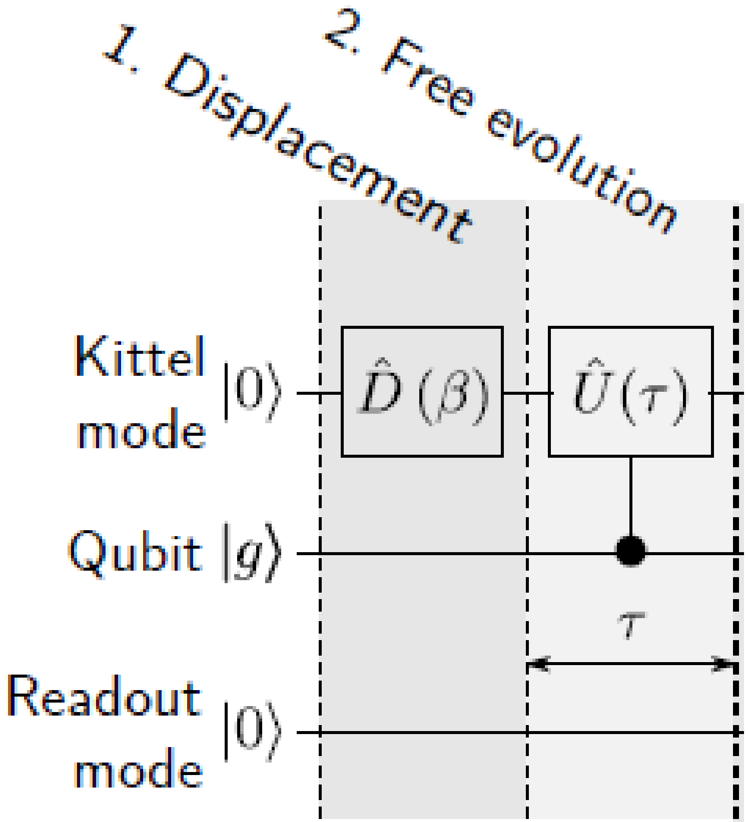
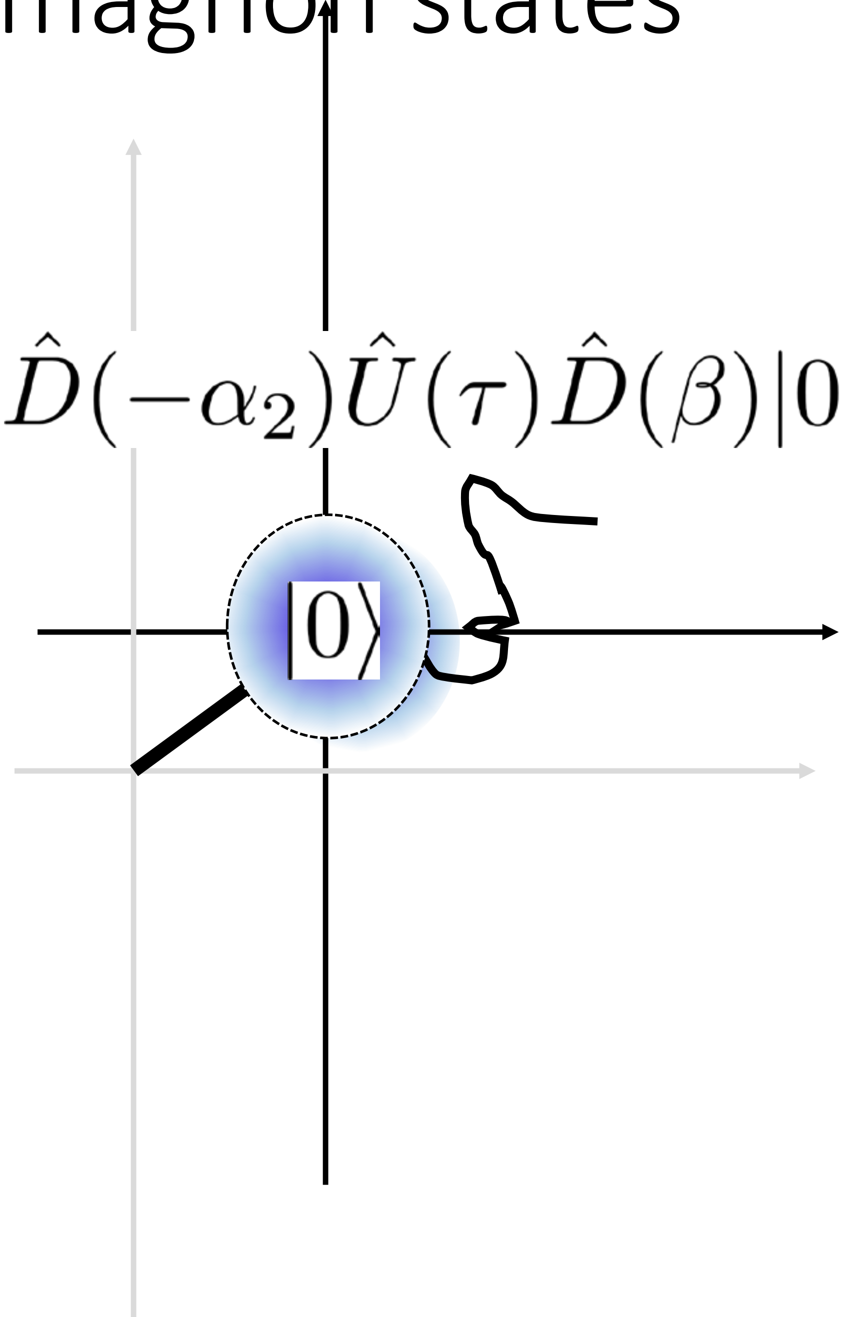
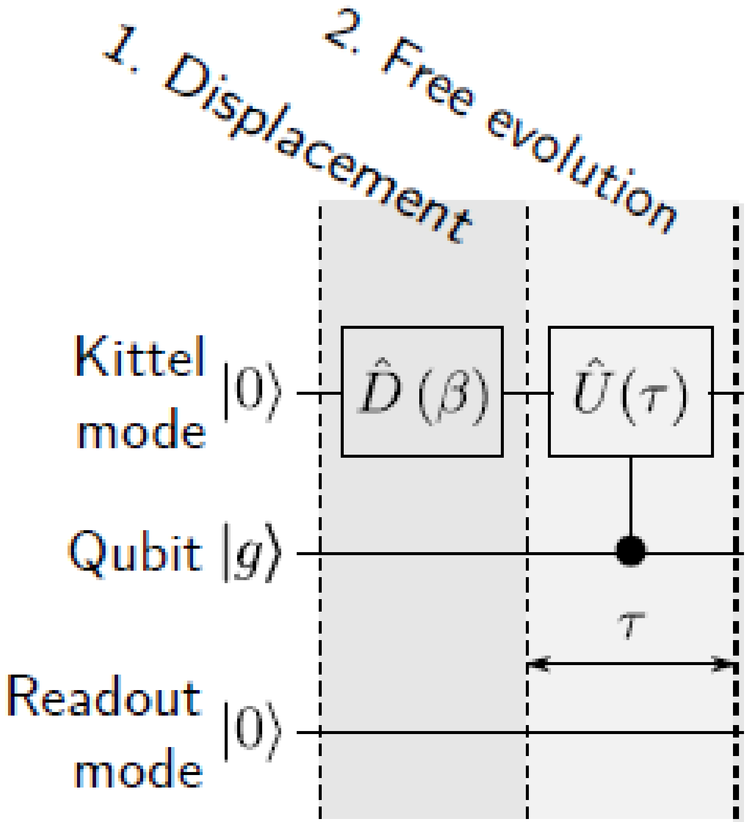
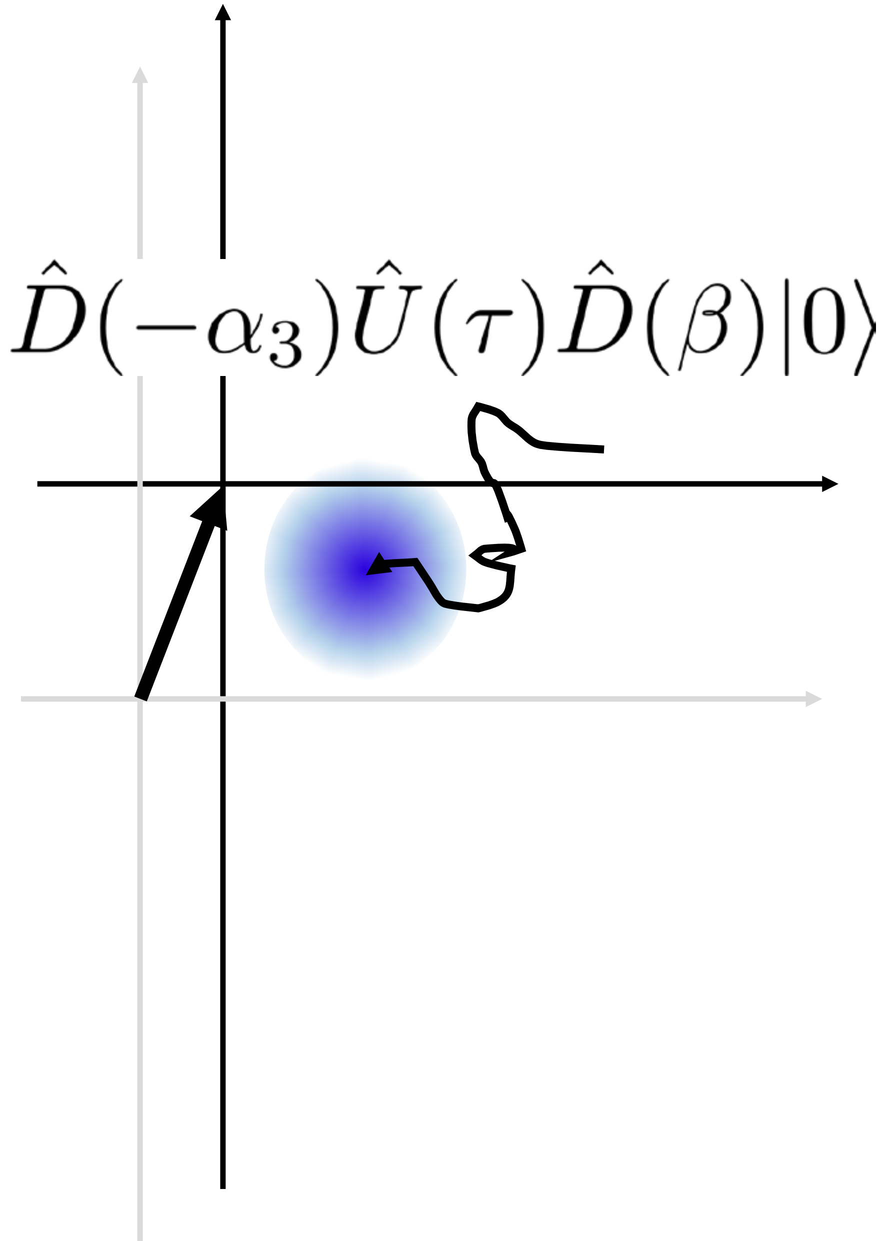


$$\hat{D}(-\alpha_2)\hat{U}(\tau)\hat{D}(\beta)|0\rangle$$

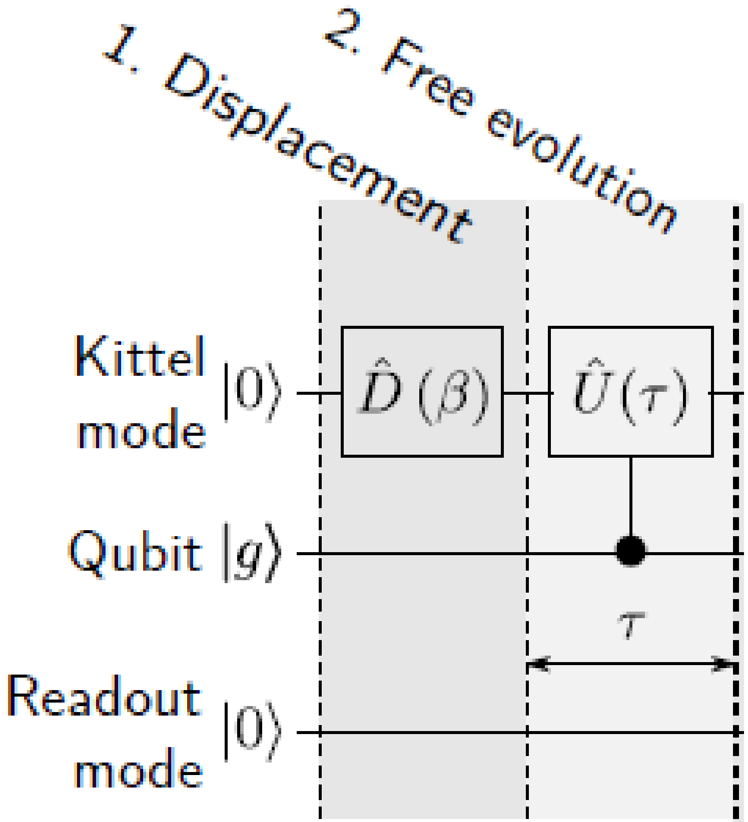


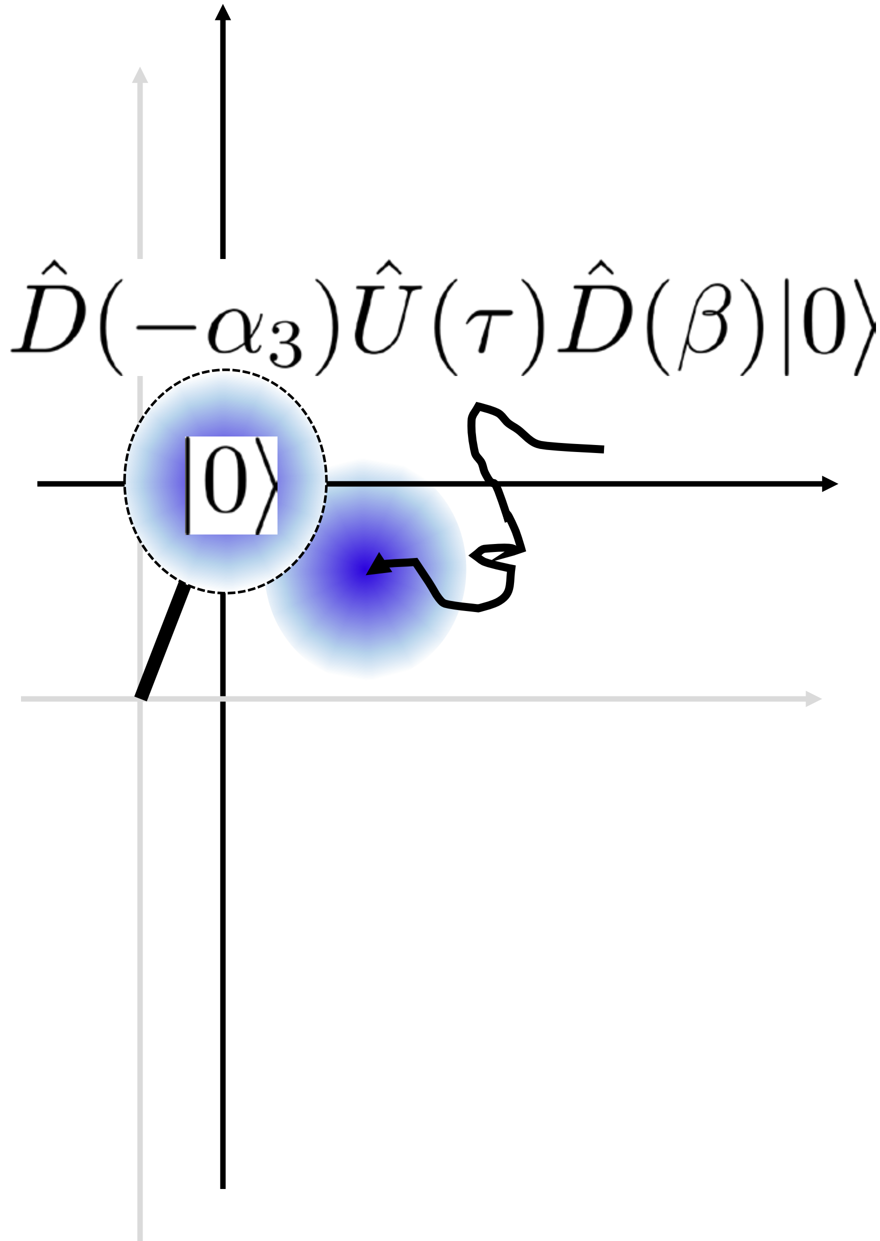
Tomography of magnon states



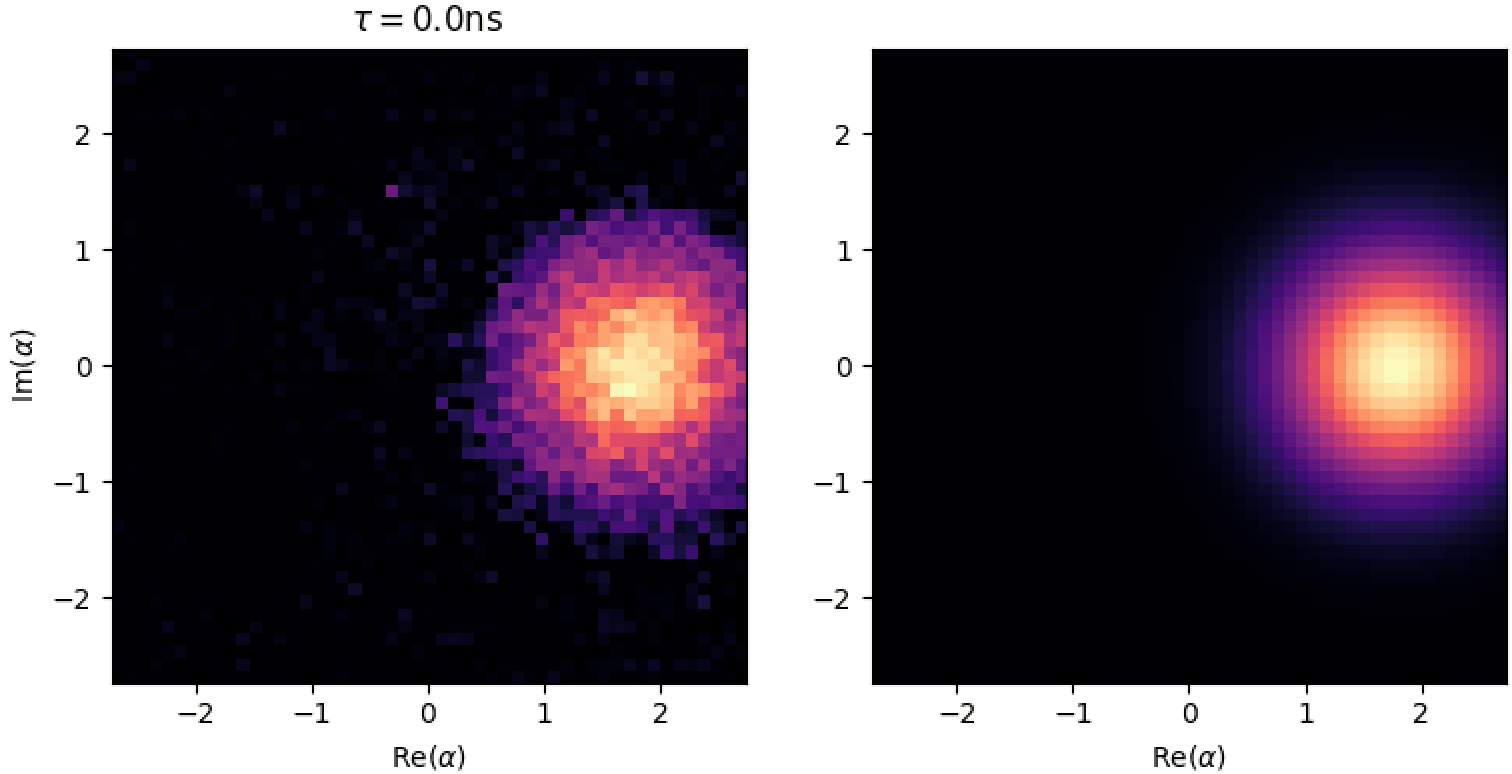


Tomography of magnon states

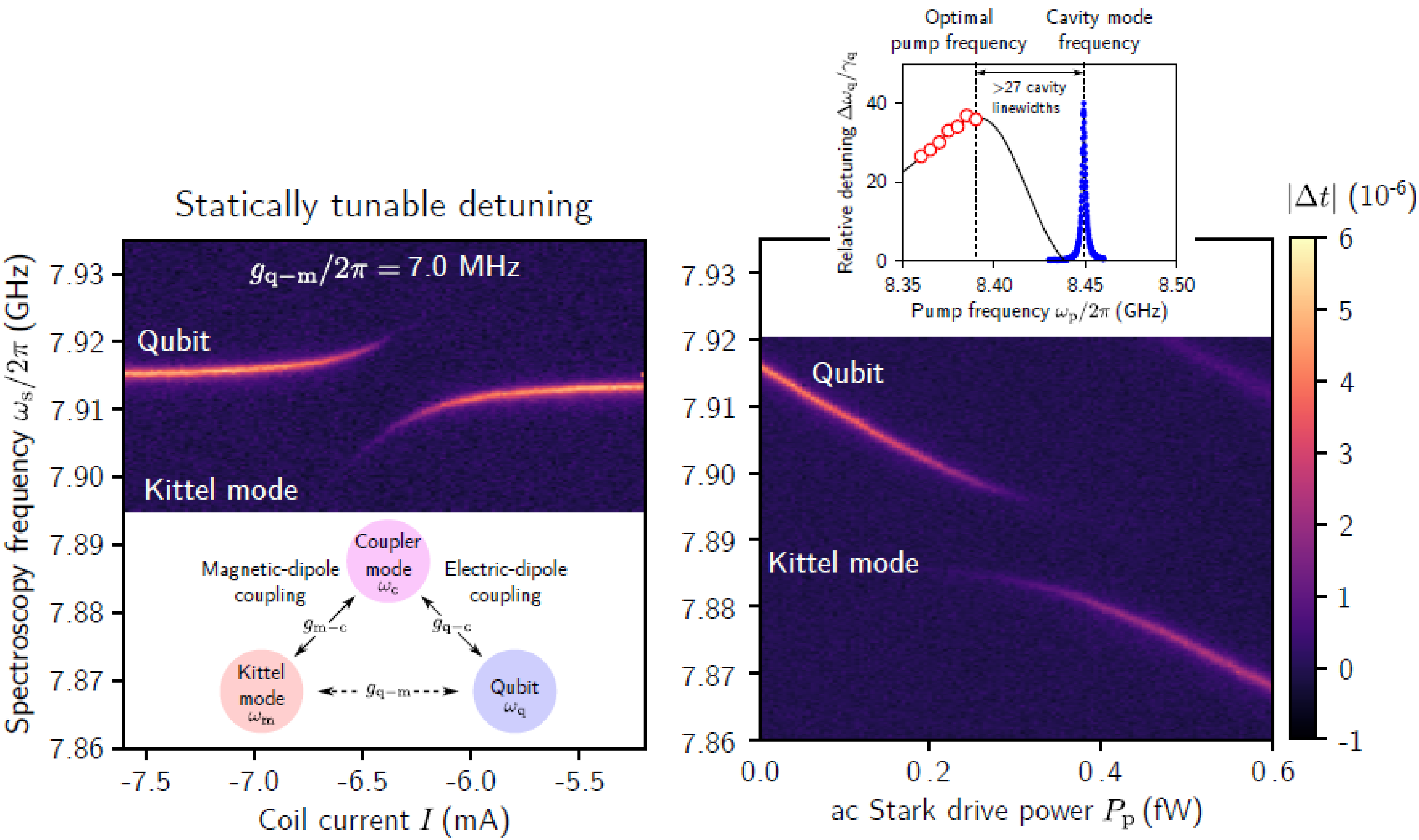




Tomography of magnon states

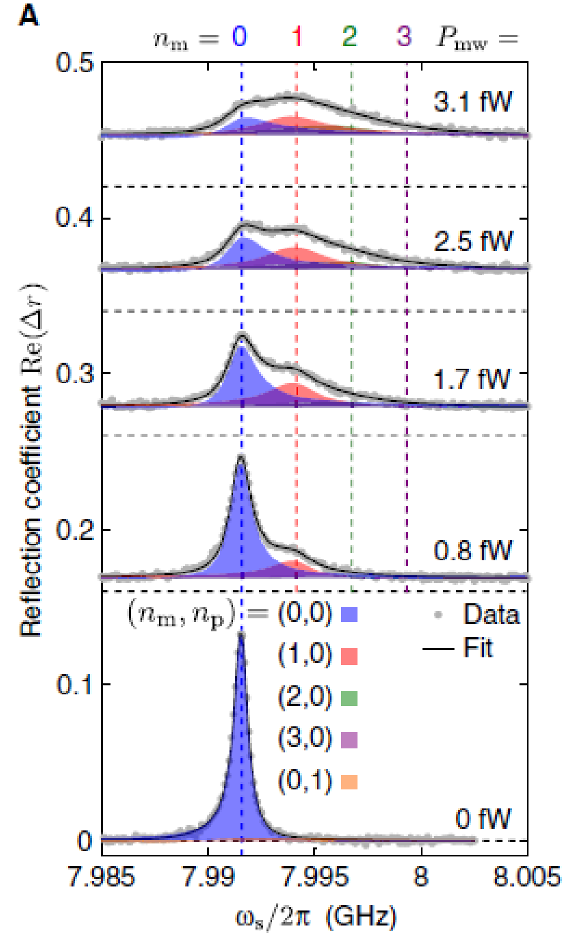


From coil current to ac-Stark drive



Idea from Patrice Bertet, thanks!

Summary

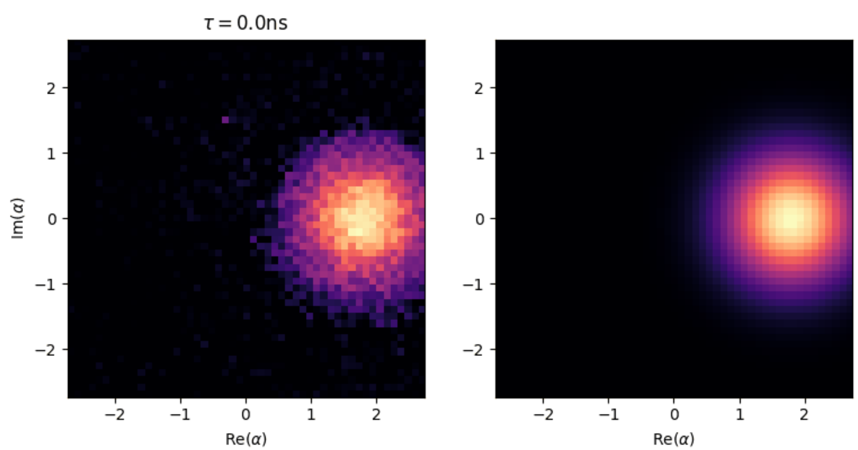


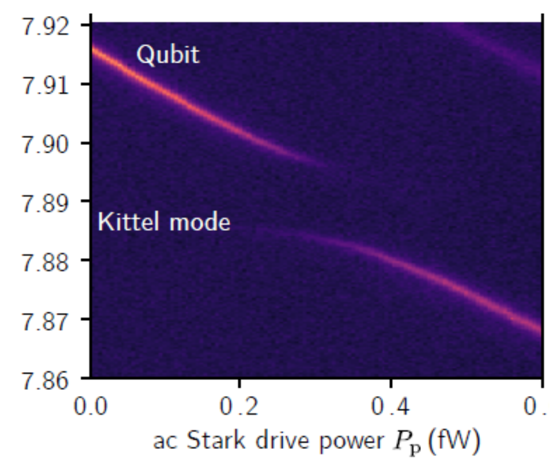
Quantum magnonics with ferromagnet

- Strong coupling with microwave cavity
- Vacuum Rabi splitting
- Magnon-number-resolving spectroscopy

In progress

- Magnon-state tomography
- Quantum magnon state generation

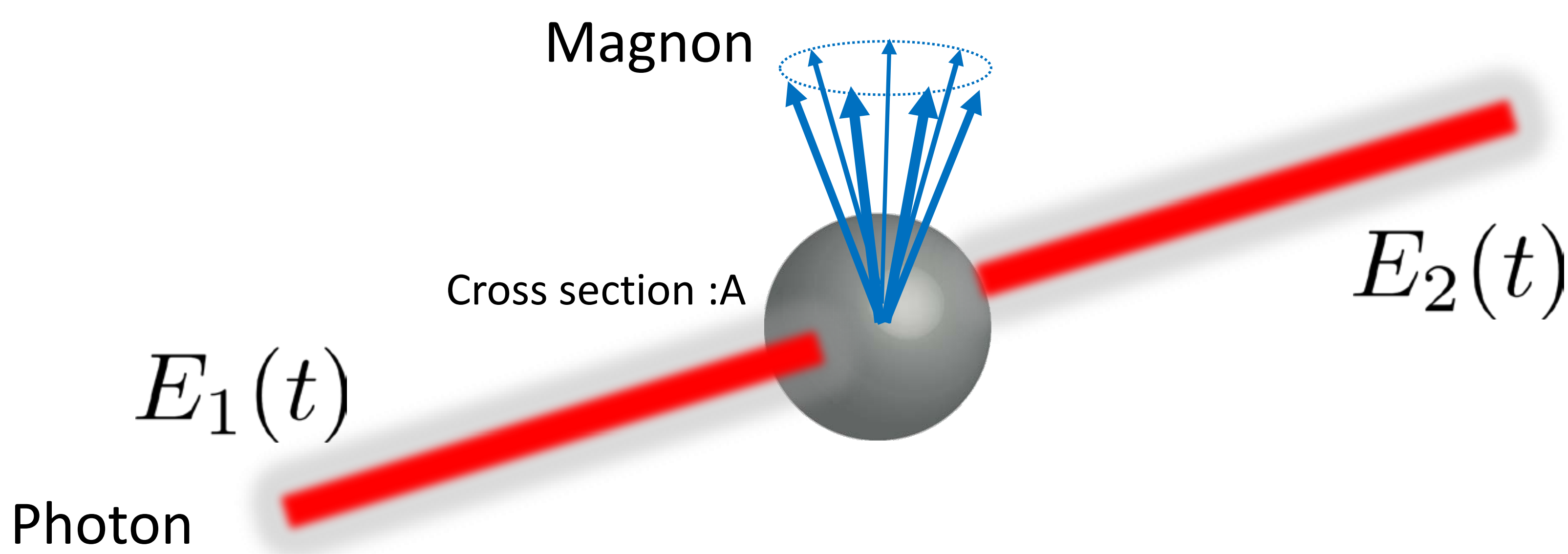




Cavity (circuit) quantum magnonics

New possibility of optomagnonics

Effective Hamiltonian



Dielectric tensor

$$H_I = \frac{1}{2}\int_0^\tau E_2^*(t)\,\epsilon(\tilde{t})\,E_1(t)\,A c\,dt$$

W. Happer and B.S. Mathur, Phys. Rev. **163,** 12 (1967);
J.M. Geremia, J.K. Stockton, and H. Mabuchi, PRA **73,** 042112 (2006).
K. Hammerer, A.S.Sorensen, and E.S.Polzik, Rev. Mod. Phys. **82,** 1041 (2010).

Symmetry requirements of $\tilde{\epsilon}$

Hermiticity (losslessness):

$$\begin{aligned} \tilde{\epsilon} &= \tilde{\epsilon}_R + i\tilde{\epsilon}_I \\ \tilde{\epsilon}^\dagger &= \tilde{\epsilon}_R^\dagger - i\tilde{\epsilon}_I^\dagger \end{aligned}$$

$$\tilde{\epsilon}_R = \tilde{\epsilon}_R^\dagger$$ (symmetric)

$$\tilde{\epsilon}_I = -\tilde{\epsilon}_I^\dagger$$ (anti-symmetric)

Symmetry requirements of $\tilde{\epsilon}$

Reciprocity:

$$\tilde{\epsilon}_{ij}(\boldsymbol{M}) = \tilde{\epsilon}_{ji}(-\boldsymbol{M})$$

Symmetric part: $\tilde{\epsilon}_R$ $\Rightarrow$ even powers of M

Anti-symmetric part: $\tilde{\epsilon}_I$ $\Rightarrow$ odd powers of M

Dielectric tensor

$$\tilde{\epsilon} = \tilde{\epsilon}_0 + \tilde{\epsilon}_1 + \tilde{\epsilon}_2,$$

Scalar light shift (symmetric)

$$\tilde{\epsilon}_0 = \epsilon_0 \epsilon_r \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{aligned} \Sigma_{xx} &= M_x M_x \\ \Sigma_{yy} &= M_y M_y \\ \Sigma_{zz} &= M_z M_z \\ \Sigma_{xy} &= \frac{1}{2}(M_x M_y + M_y M_x) \\ \Sigma_{yz} &= \frac{1}{2}(M_y M_z + M_z M_y) \\ \Sigma_{zx} &= \frac{1}{2}(M_z M_x + M_x M_z) \end{aligned}$$

Vector light shift (anti-symmetric)

$$\tilde{\epsilon}_1 = \begin{bmatrix} 0 & -ifM_z & ifM_y \\ ifM_z & 0 & -ifM_x \\ -ifM_y & ifM_x & 0 \end{bmatrix}$$

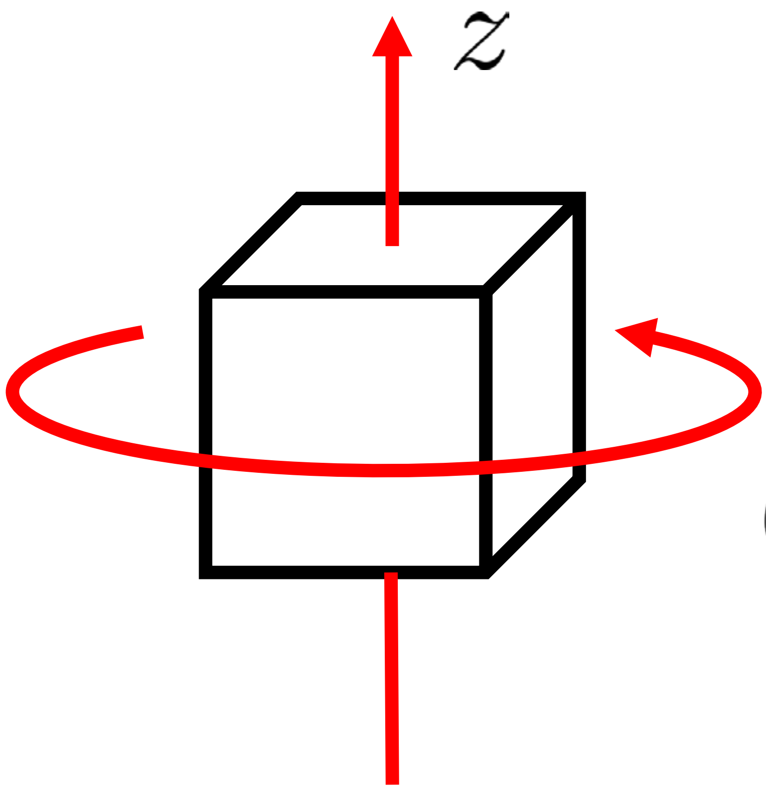
Tensor light shift (symmetric)

$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

Vector light shift (Faraday effect)

$$\tilde{\epsilon}_1 = \begin{bmatrix} 0 & -ifM_z & ifM_y \\ ifM_z & 0 & -ifM_x \\ -ifM_y & ifM_x & 0 \end{bmatrix}$$

Rotation matrix



$$\theta_z = fM_z$$

Tensor light shift (Cotton-Mouton effect)

$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

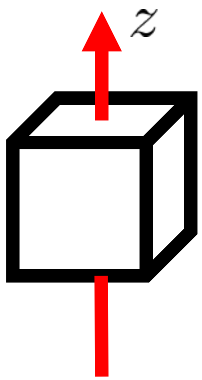
Stress tensor *Stiffness matrix* *Strain tensor*

$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ \epsilon_{yz} \\ \epsilon_{zx} \\ \epsilon_{xy} \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{12} & 0 & 0 & 0 \\ G_{12} & G_{11} & G_{12} & 0 & 0 & 0 \\ G_{12} & G_{12} & G_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{44} \end{bmatrix} \begin{bmatrix} \Sigma_{xx} \\ \Sigma_{yy} \\ \Sigma_{zz} \\ 2\Sigma_{yz} \\ 2\Sigma_{zx} \\ 2\Sigma_{xy} \end{bmatrix}$$

For **cubic** crystal like YIG (H // 100)

DC response

DC response



Scalar light shift

$$\tilde{\epsilon}_0 = \epsilon_0 \epsilon_r \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Vector light shift (anti-symmetric tensor)

$$\tilde{\epsilon}_1 = \begin{bmatrix} 0 & -ifM_z & ifM_y \\ ifM_z & 0 & -ifM_x \\ -ifM_y & ifM_x & 0 \end{bmatrix}$$

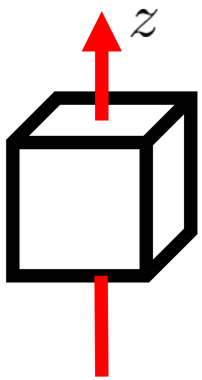
Tensor light shift (symmetric tensor)

$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

$$\begin{aligned} \Sigma_{xx} &= M_x M_x \\ \Sigma_{yy} &= M_y M_y \\ \Sigma_{zz} &= M_z M_z \\ \Sigma_{xy} &= \frac{1}{2}(M_x M_y + M_y M_x) \\ \Sigma_{yz} &= \frac{1}{2}(M_y M_z + M_z M_y) \\ \Sigma_{zx} &= \frac{1}{2}(M_z M_x + M_x M_z) \end{aligned}$$

One-magnon processes

One-magnon process



Scalar light shift

$$\tilde{\epsilon}_0 = \epsilon_0 \epsilon_r \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{aligned} \Sigma_{xx} &= M_x M_x \\ \Sigma_{yy} &= M_y M_y \\ \Sigma_{zz} &= M_z M_z \\ \Sigma_{xy} &= \frac{1}{2}(M_x M_y + M_y M_x) \\ \Sigma_{yz} &= \frac{1}{2}(M_y M_z + M_z M_y) \\ \Sigma_{zx} &= \frac{1}{2}(M_z M_x + M_x M_z) \end{aligned}$$

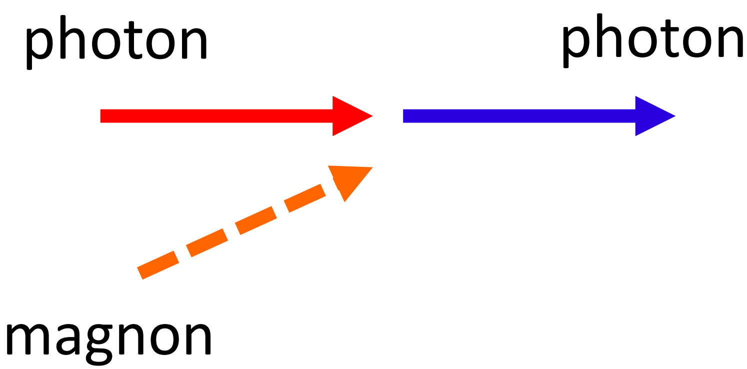
Vector light shift (anti-symmetric tensor)

$$\tilde{\epsilon}_1 = \begin{bmatrix} 0 & -ifM_z & ifM_y \\ ifM_z & 0 & -ifM_x \\ -ifM_y & ifM_x & 0 \end{bmatrix}$$

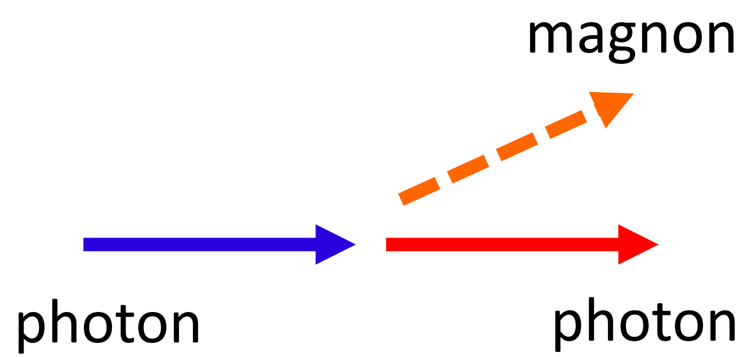
Tensor light shift (symmetric tensor)

$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

one-magnon processes

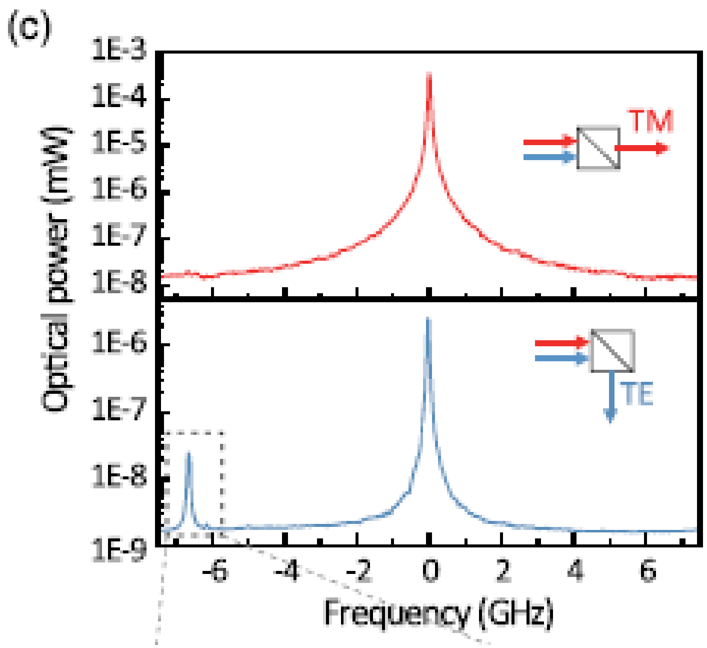


Anti-Stokes scattering

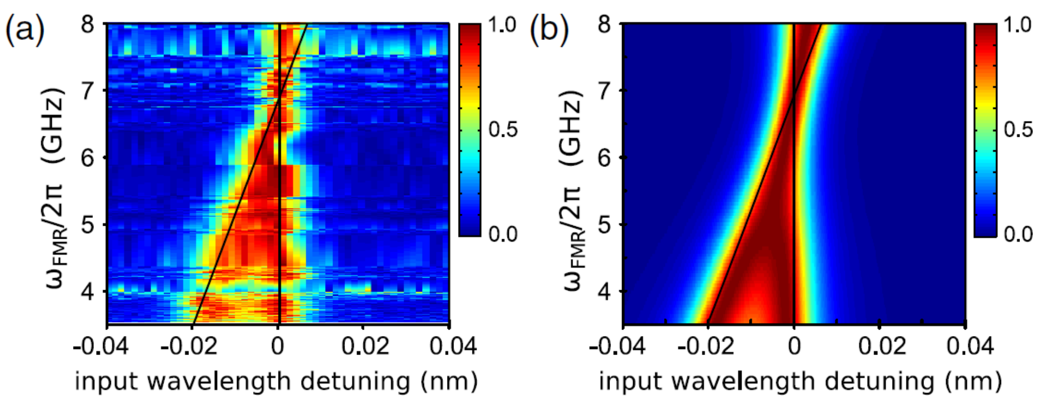


Stokes scattering

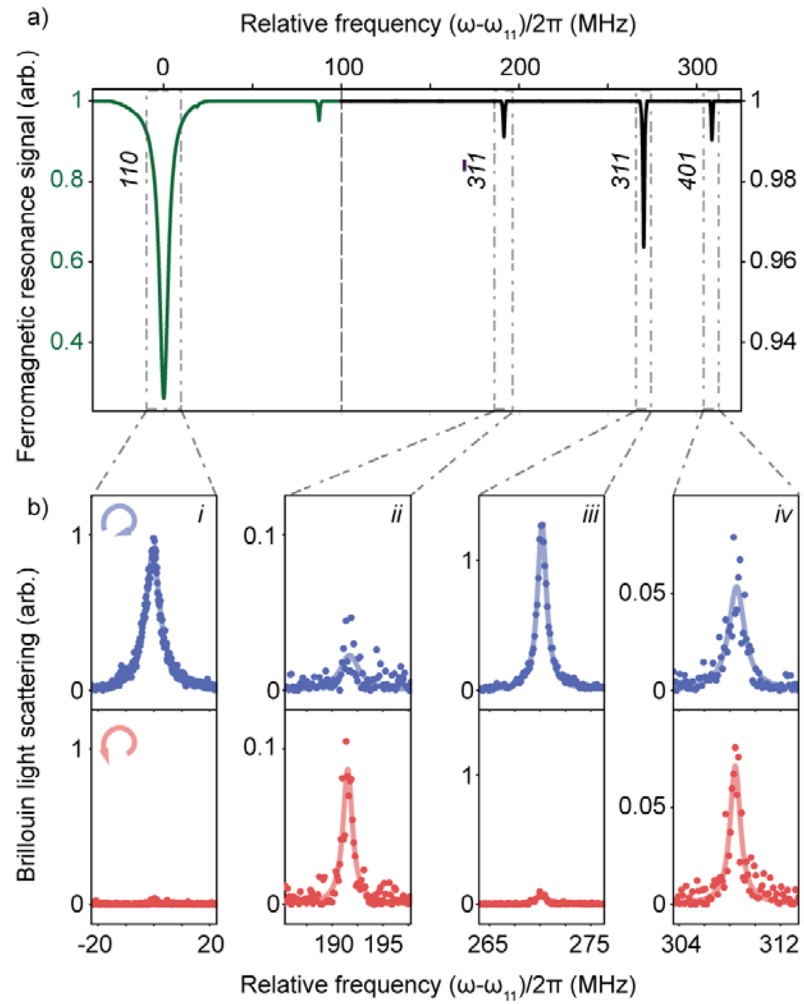
Cavity optomagnonics



X. Zhang *et al.*, PRL **117,** 123605 (2016)



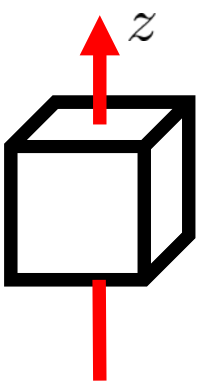
J.A. Haigh *et al.*, PRL **117,** 133602 (2016)



A. Osada *et al.*, PRL **120,** 133602 (2018)

Two-magnon processes

Two-magnon process



Scalar part

$$\tilde{\epsilon}_0 = \epsilon_0 \epsilon_r \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Vector part (anti-symmetric)

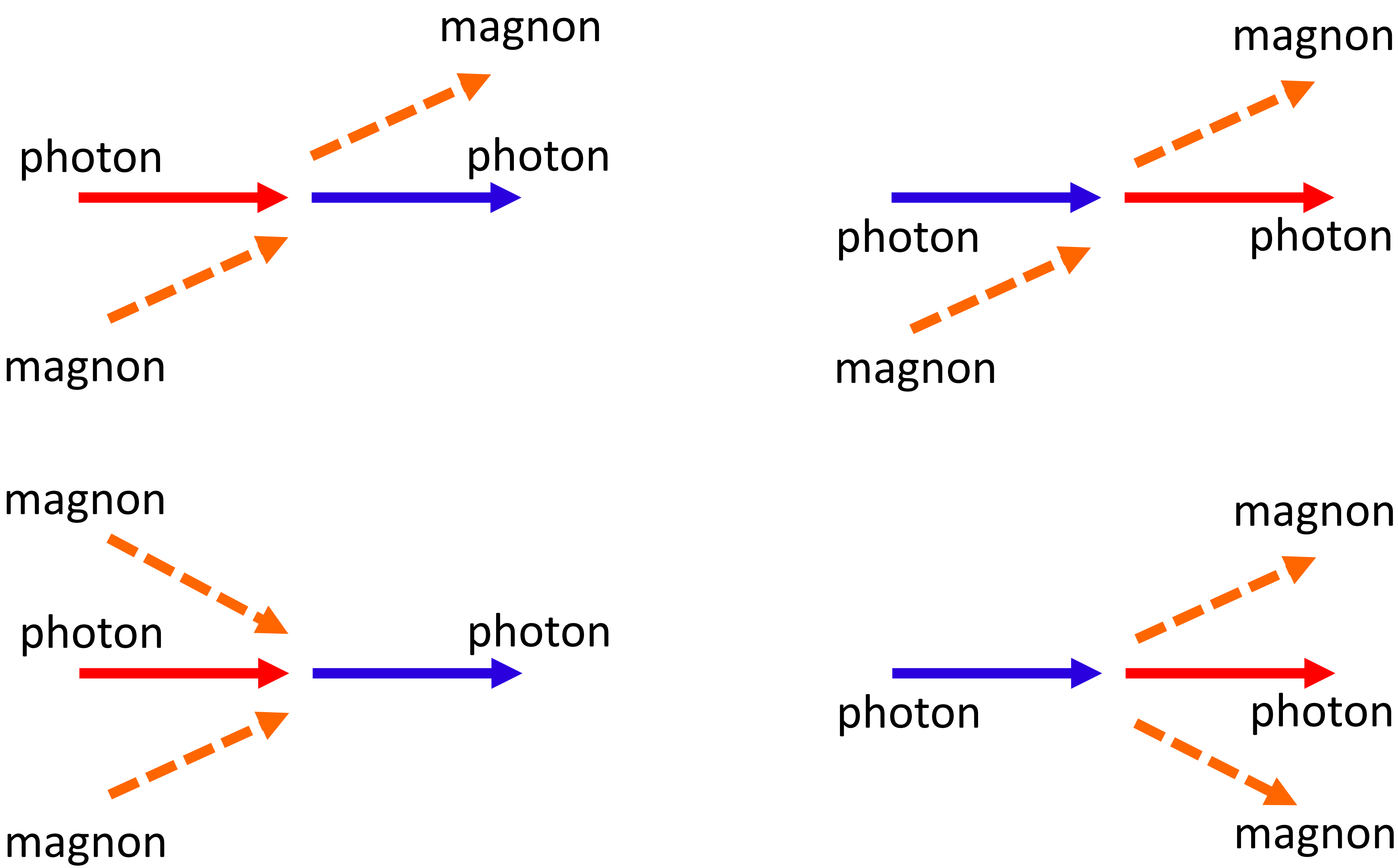
$$\tilde{\epsilon}_1 = \begin{bmatrix} 0 & -ifM_z & ifM_y \\ ifM_z & 0 & -ifM_x \\ -ifM_y & ifM_x & 0 \end{bmatrix}$$

$$\begin{aligned} \Sigma_{xx} &= M_x M_x \\ \Sigma_{yy} &= M_y M_y \\ \Sigma_{zz} &= M_z M_z \\ \Sigma_{xy} &= \frac{1}{2}(M_x M_y + M_y M_x) \\ \Sigma_{yz} &= \frac{1}{2}(M_y M_z + M_z M_y) \\ \Sigma_{zx} &= \frac{1}{2}(M_z M_x + M_x M_z) \end{aligned}$$

Tensor part (symmetric)

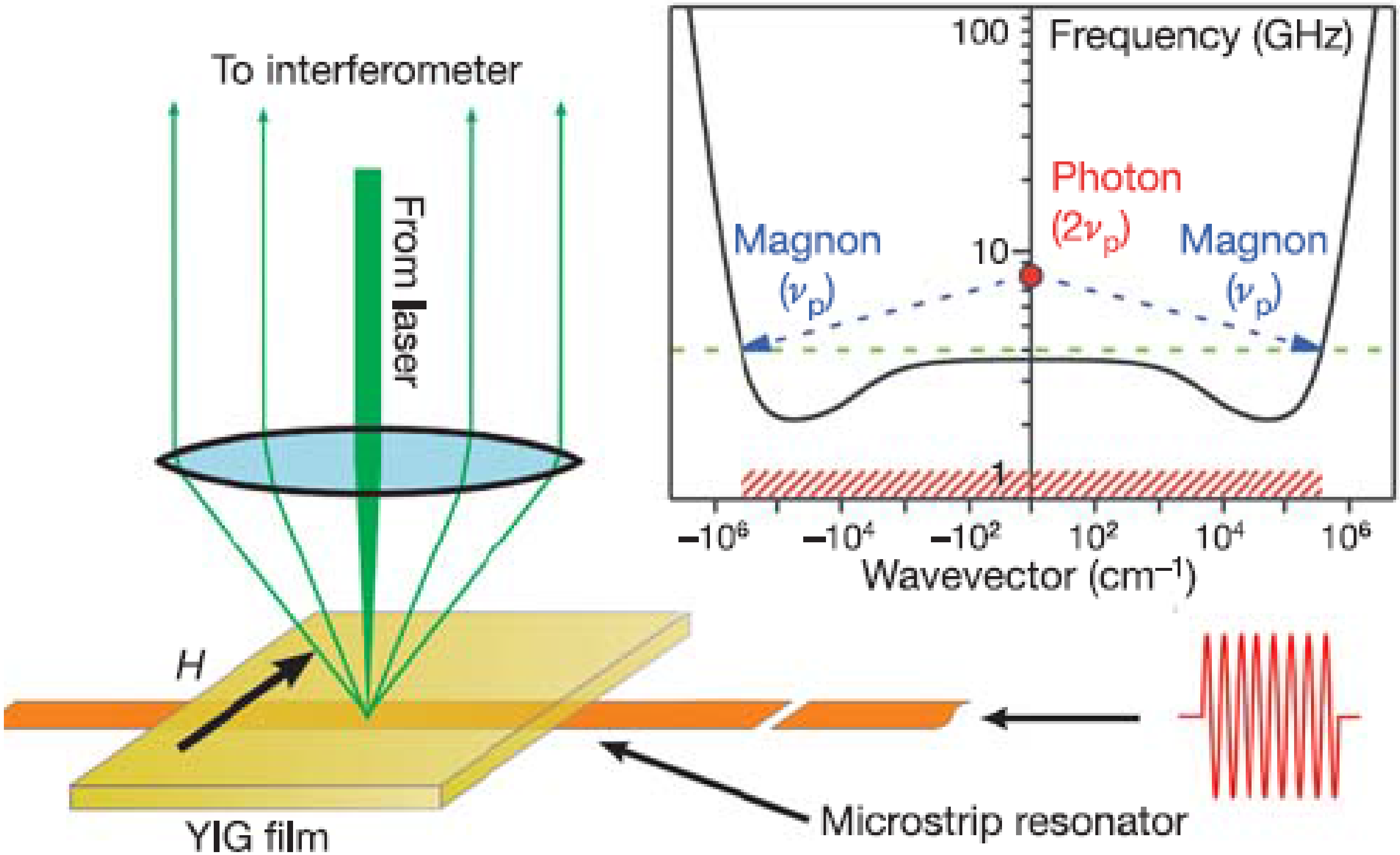
$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

Two-magnon processes



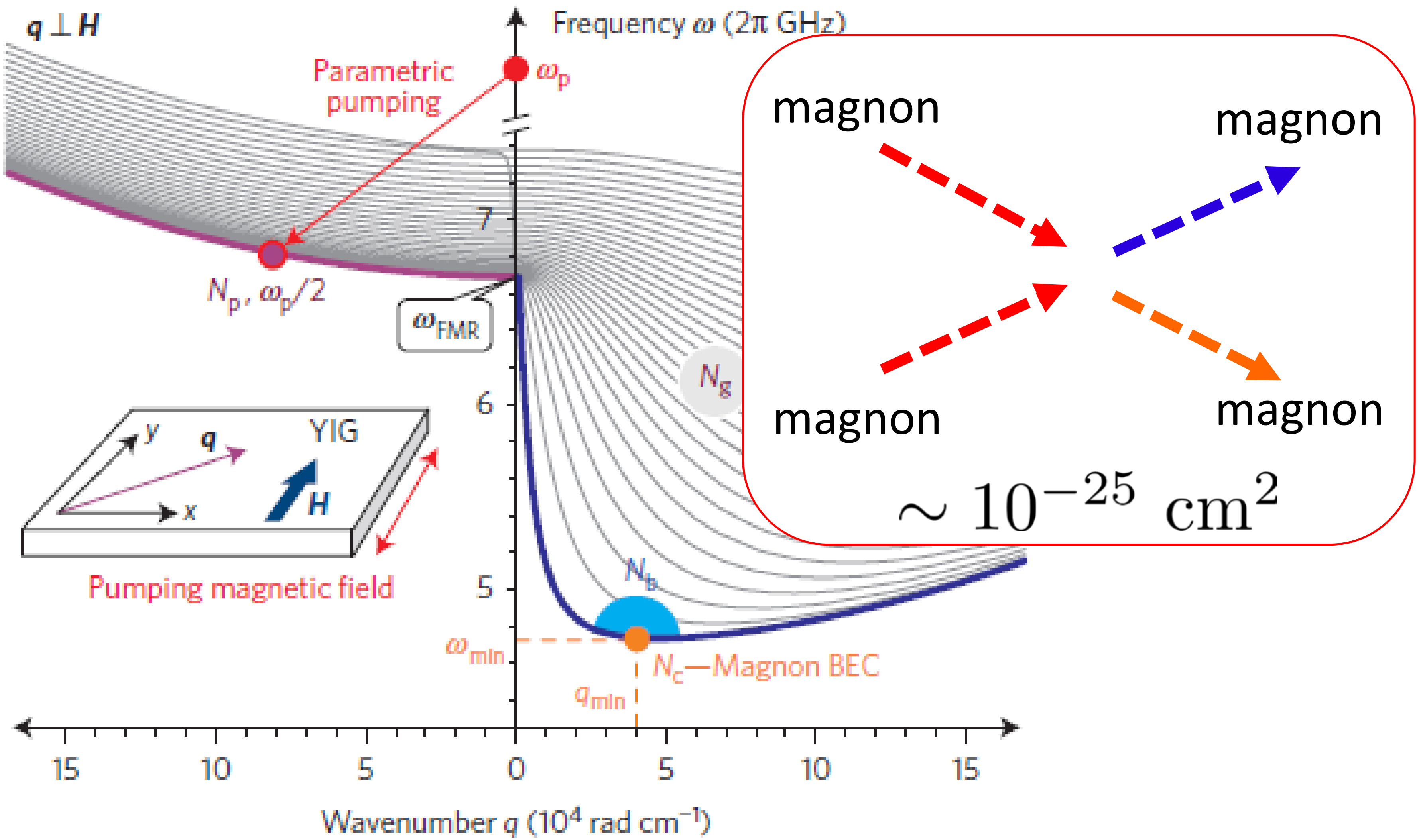
What is it good for?

Magnon BEC



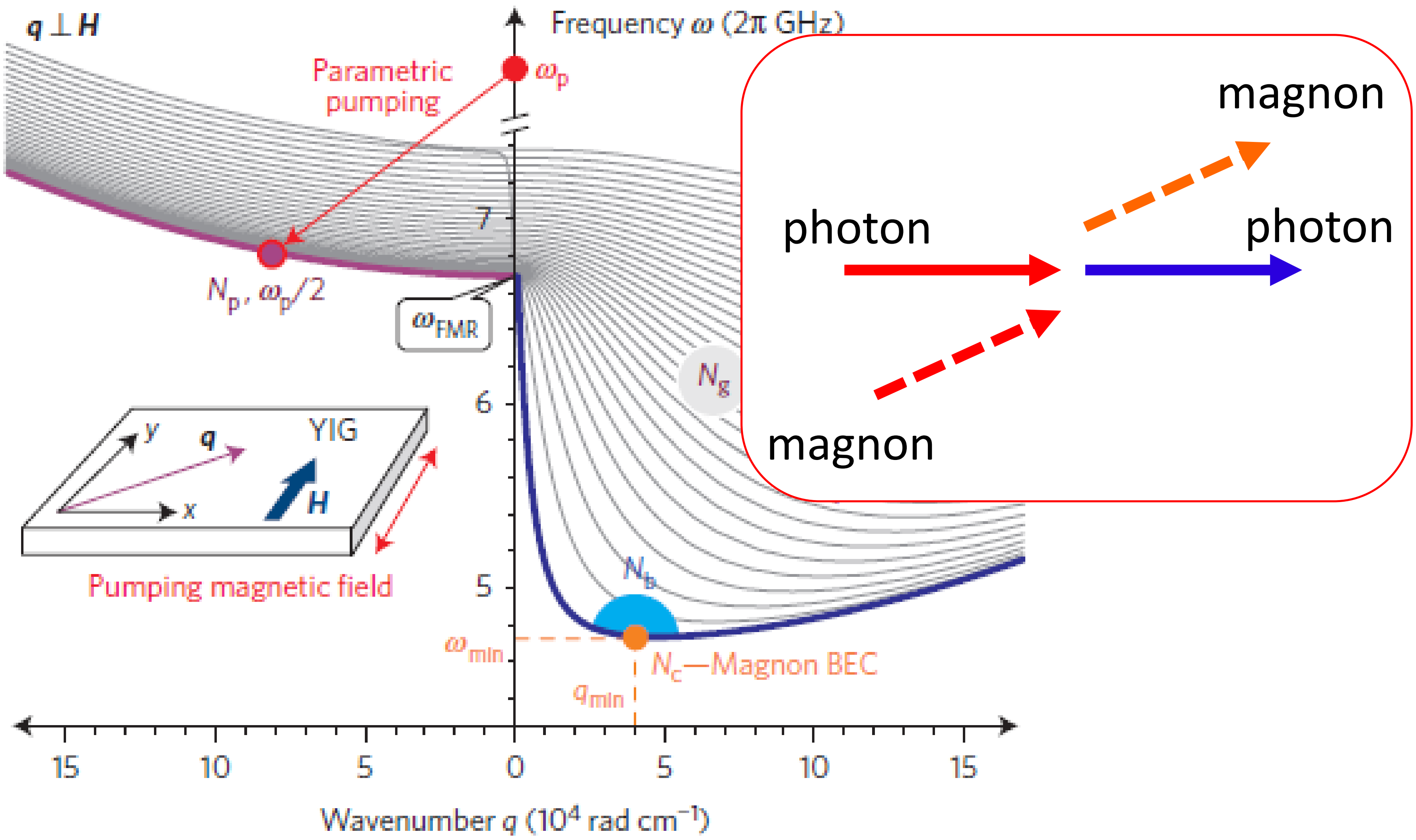
S.O. Demokritov *et al.,* Nature **443,** 430 (2006)

Magnon BEC



D.A. Bozhko *et al.,* Nature Physics **12,** 1057 (2016)

Magnon BEC



D.A. Bozhko *et al.,* Nature Physics **12,** 1057 (2016)

Who have ever observed it?

Antiferromagnet

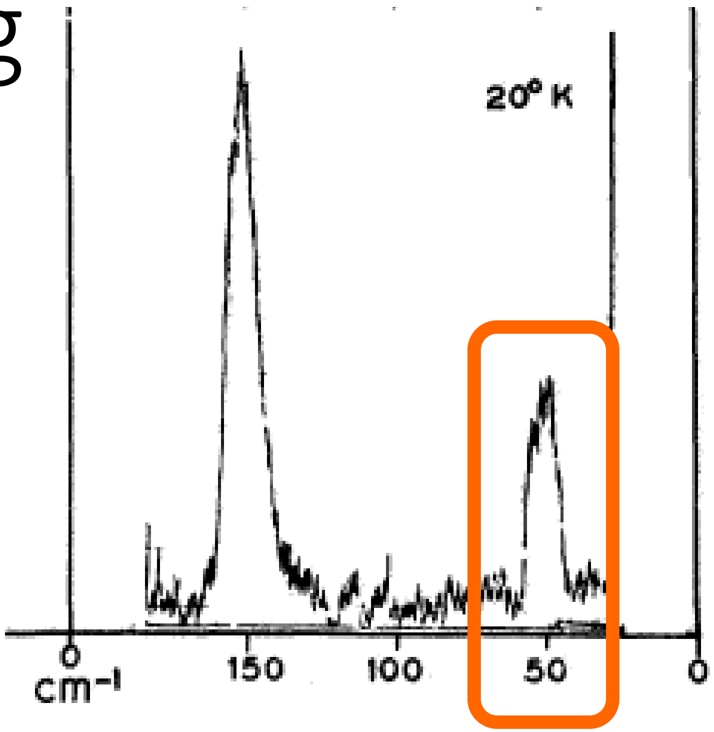
LIGHT SCATTERING BY SPIN WAVES IN FeF_2

P. A. Fleury, S. P. S. Porto, L. E. Cheesman, and H. J. Guggenheim
Bell Telephone Laboratories, Murray Hill, New Jersey

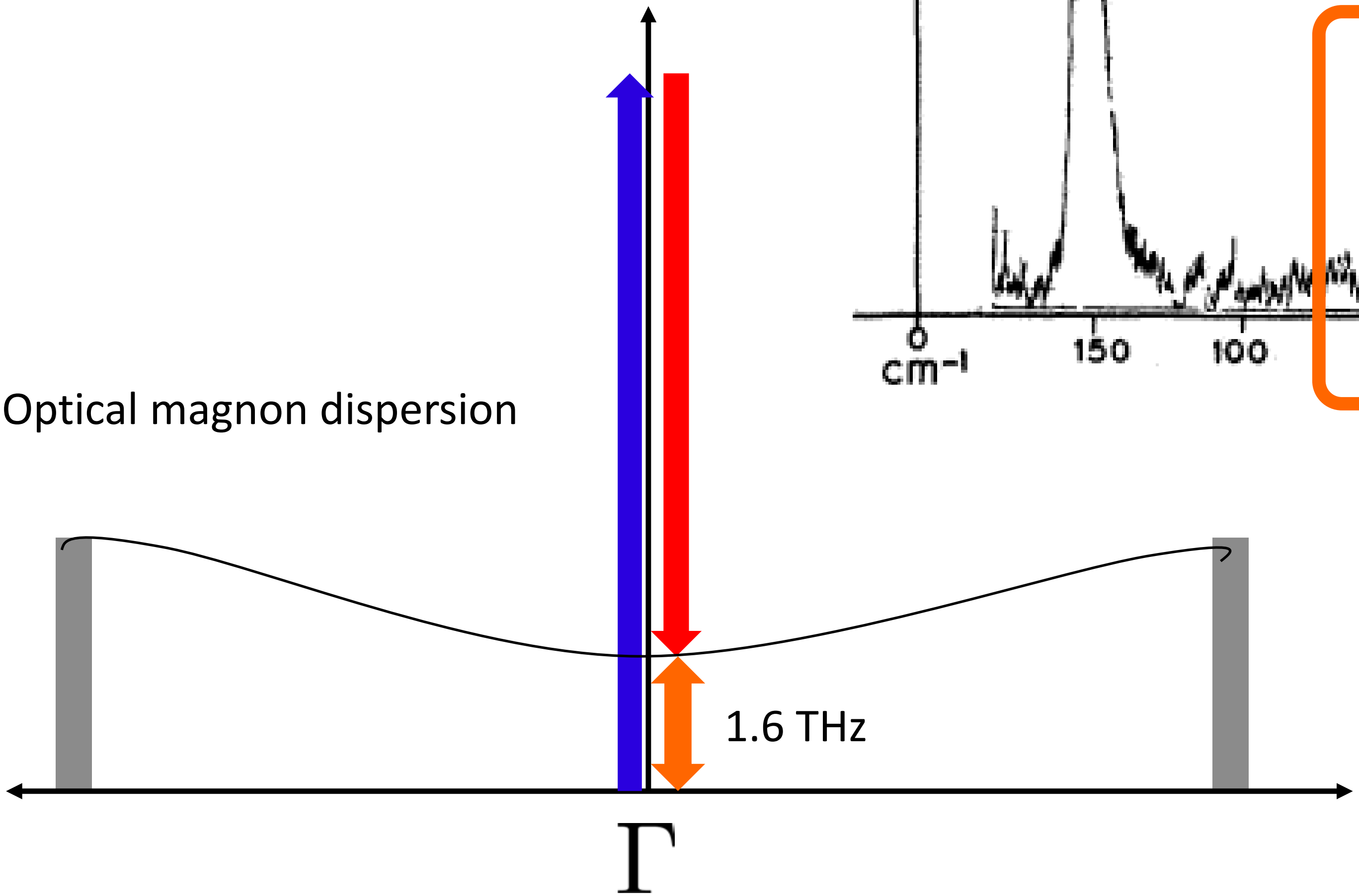
(Received 27 May 1966)

P.A. Fleury *et al.,* Phys. Rev. Lett. **17,** 84 (1966)

One-magnon scattering

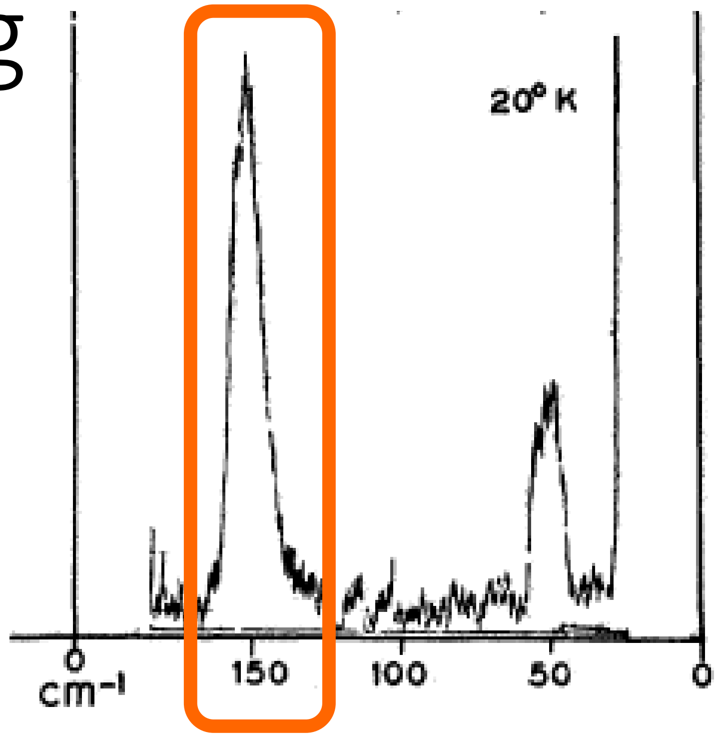


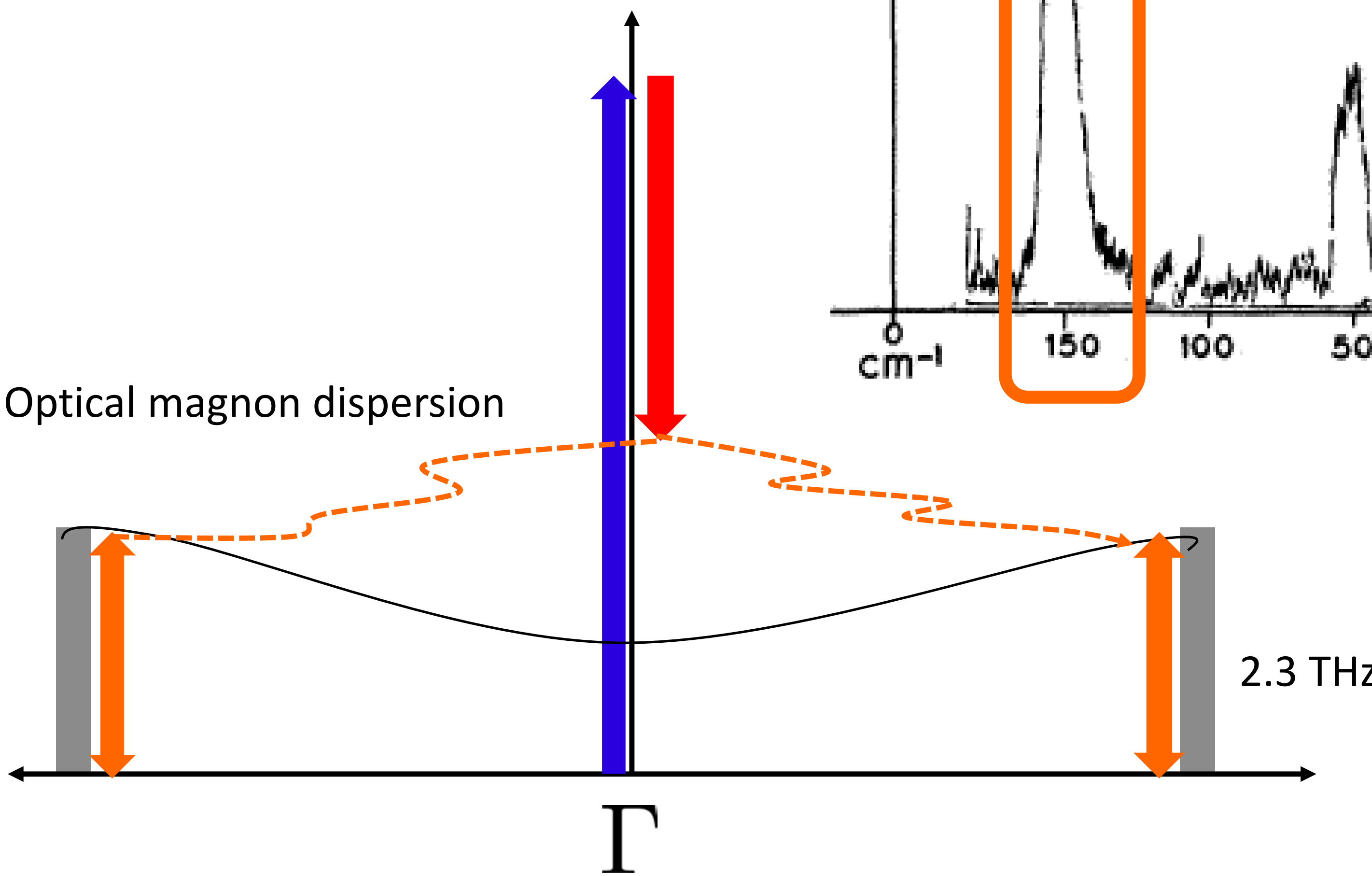
Optical magnon dispersion



P.A. Fleury *et al.,* Phys. Rev. Lett. **17,** 84 (1966)

Two-magnon scattering

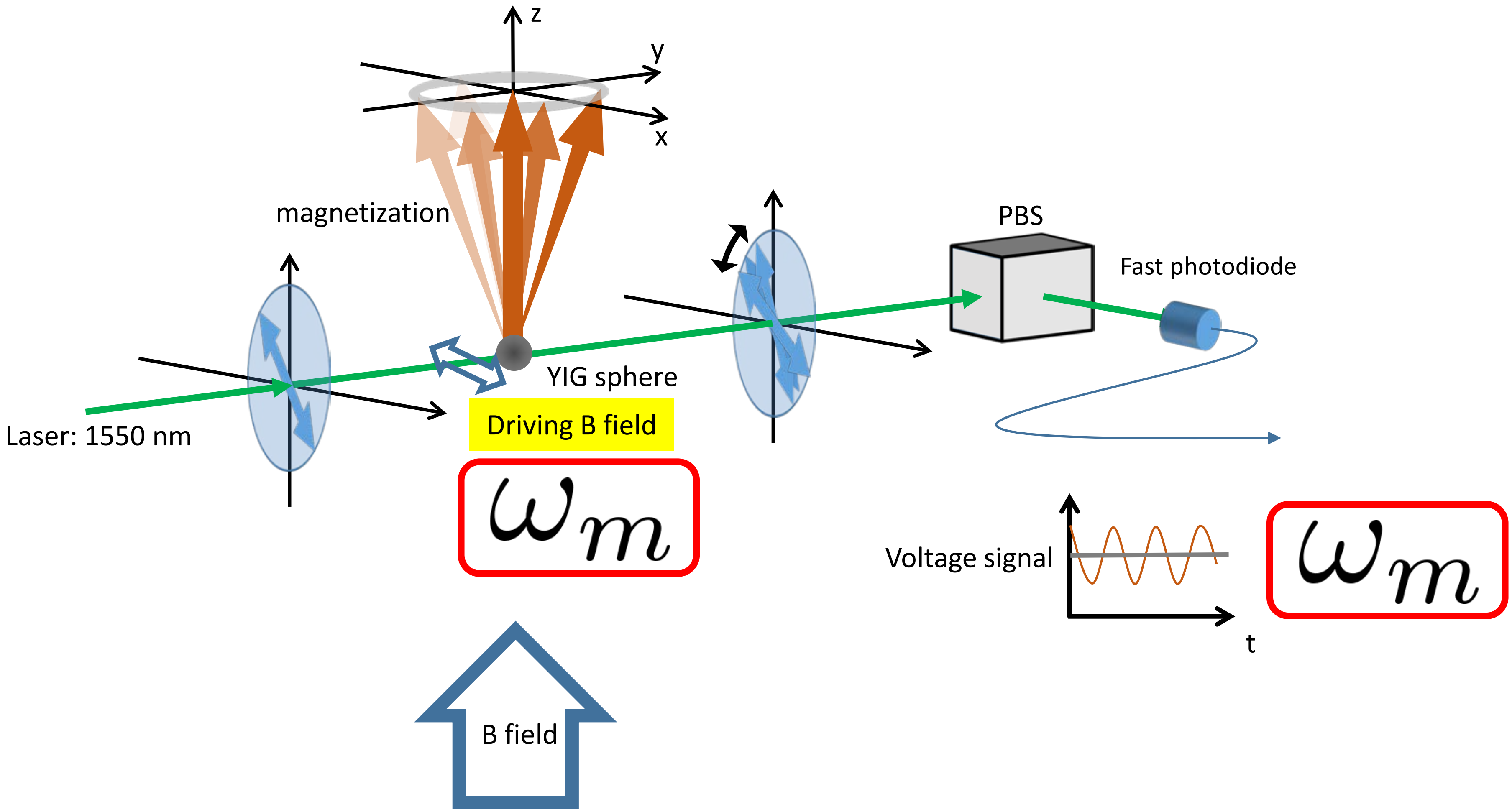




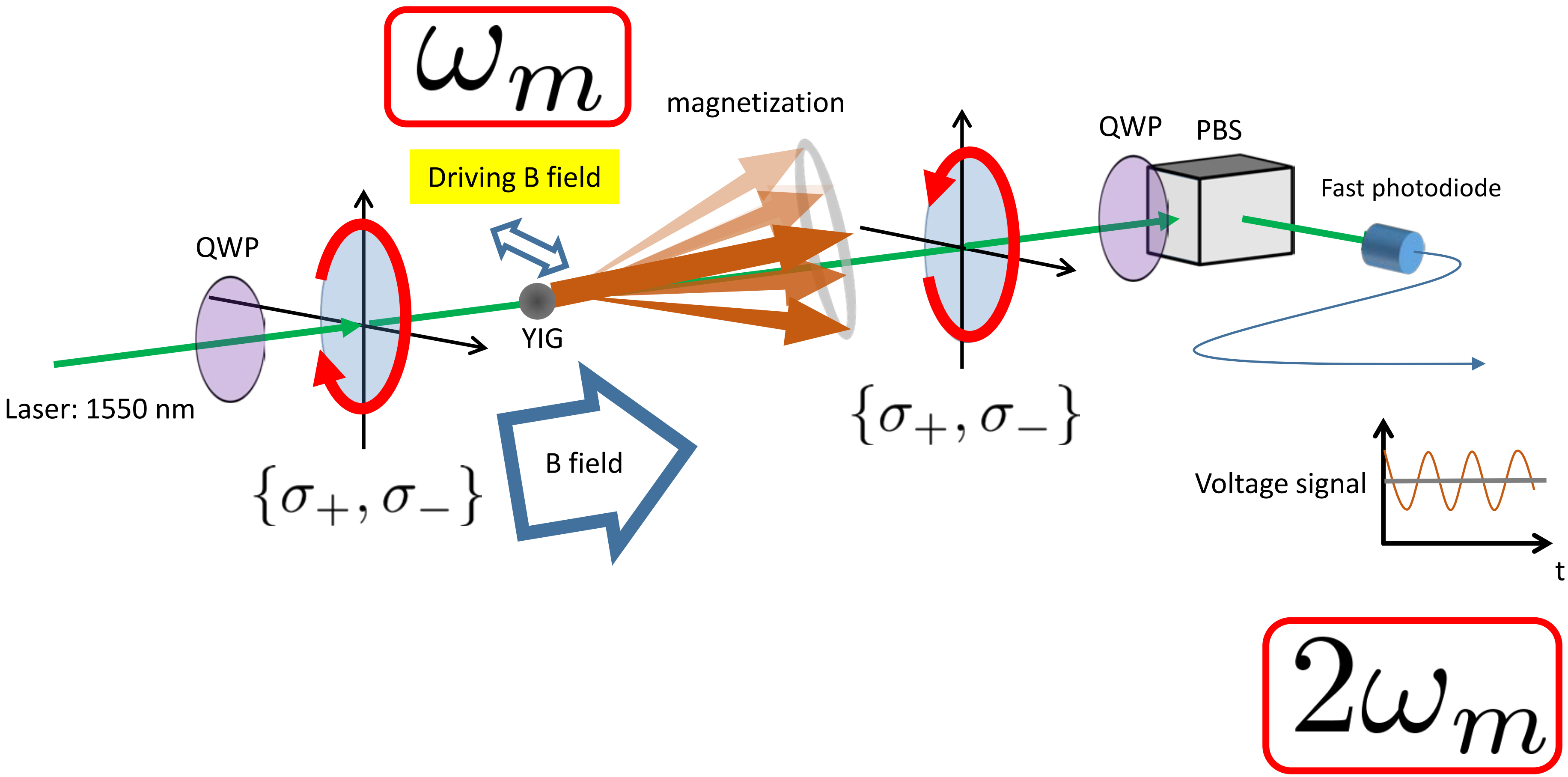
P.A. Fleury *et al.,* Phys. Rev. Lett. **17,** 84 (1966)

What about ferromagnets?

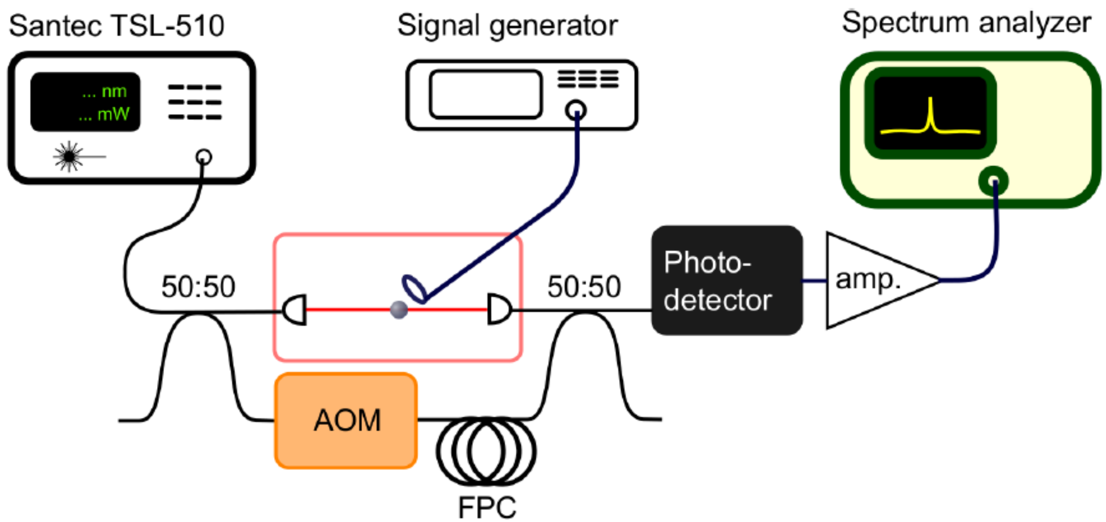
One-magnon scattering

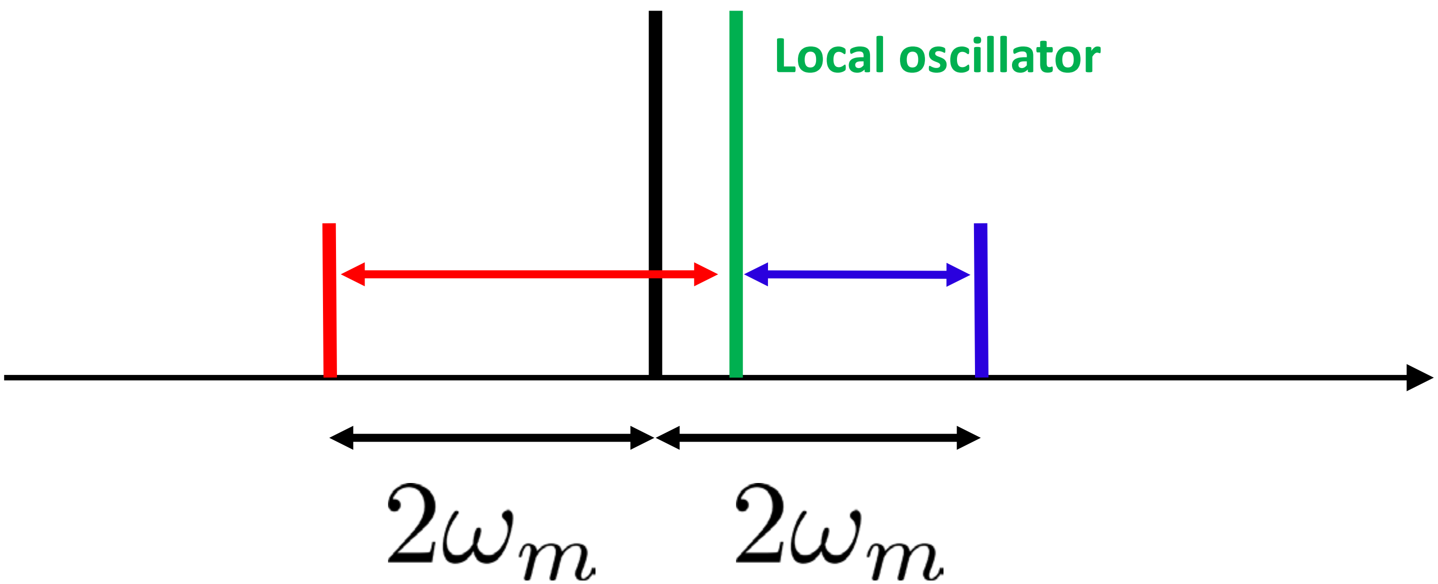


Two-magnon scattering

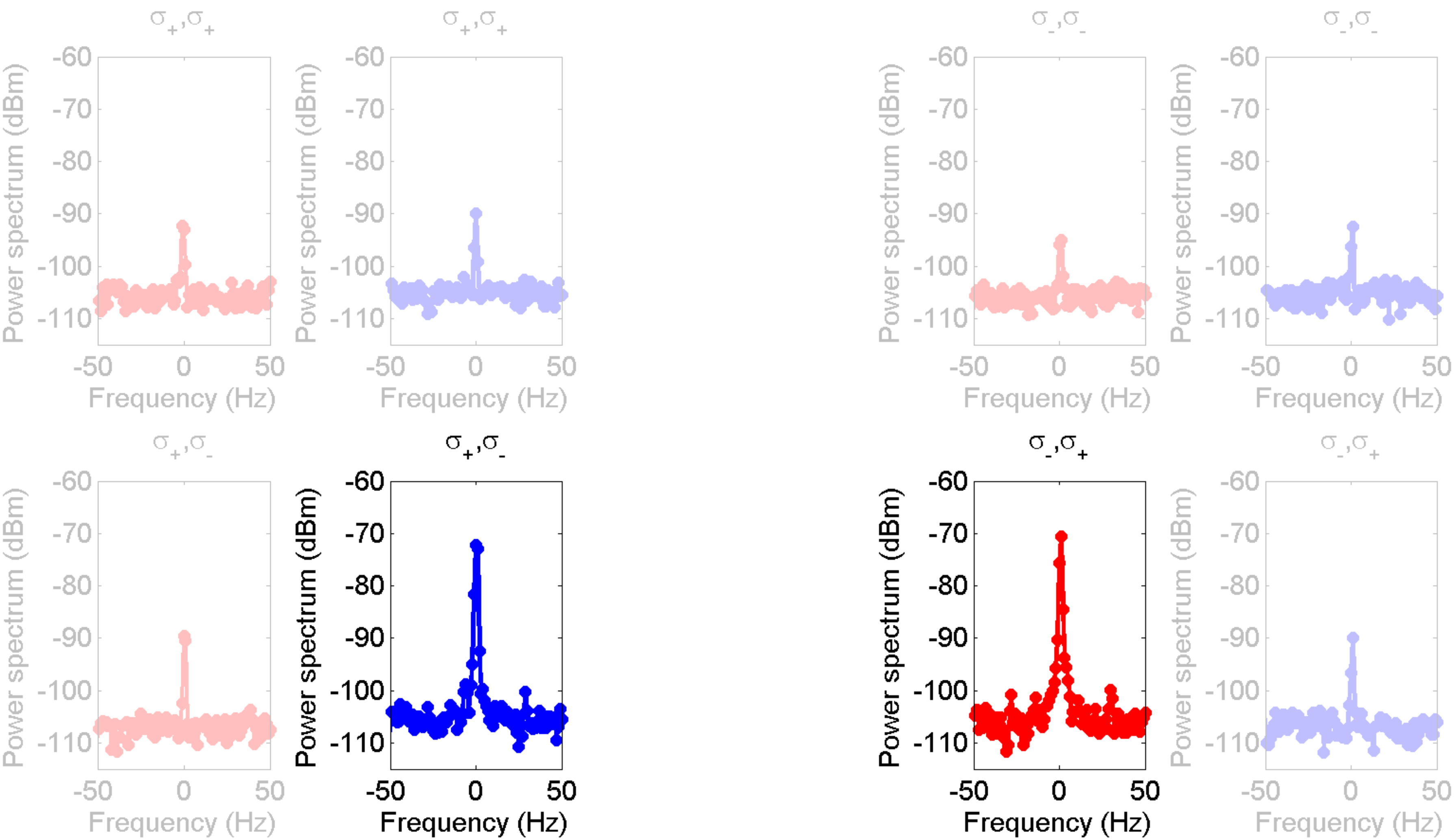


Sideband separation

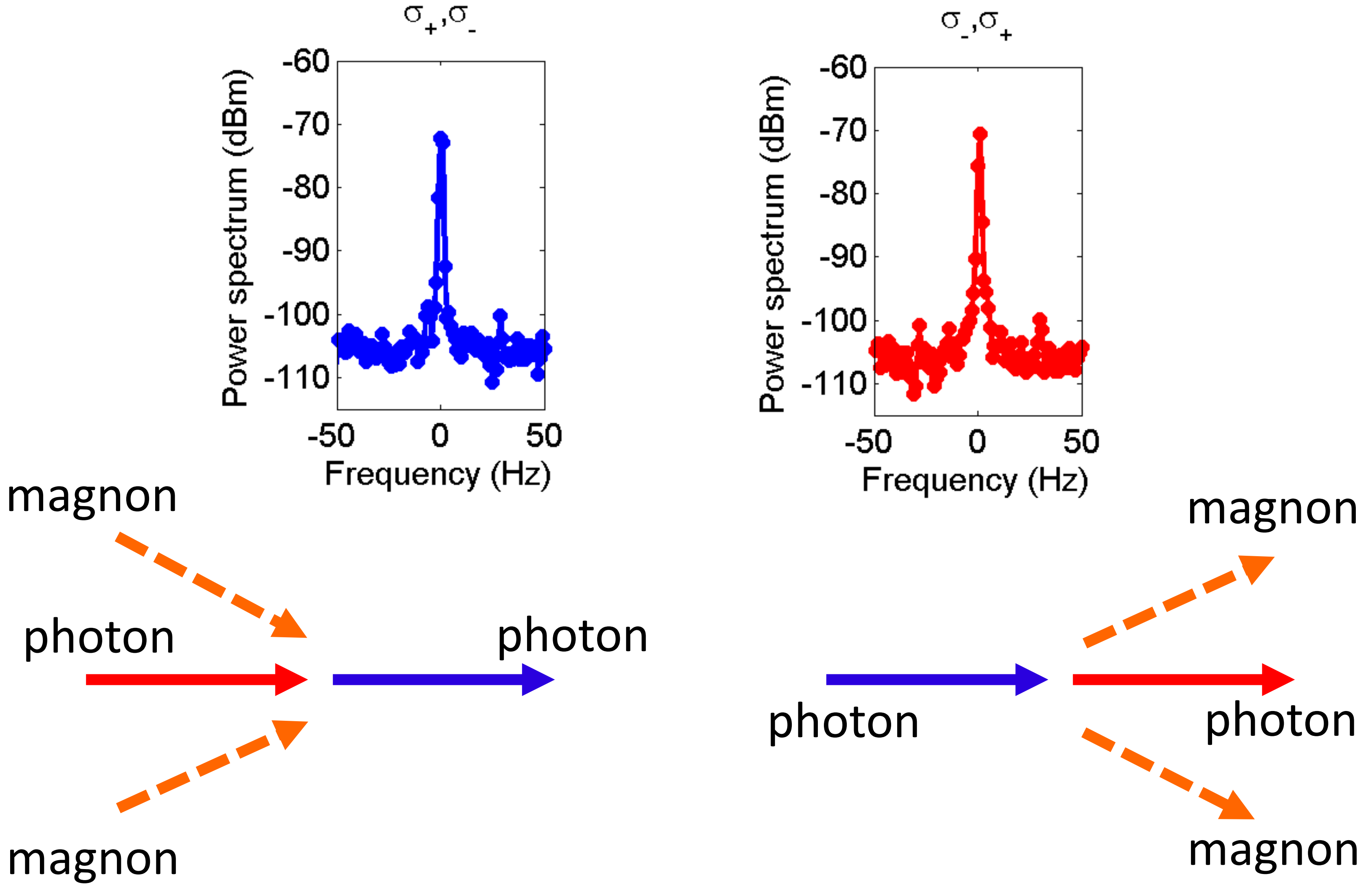




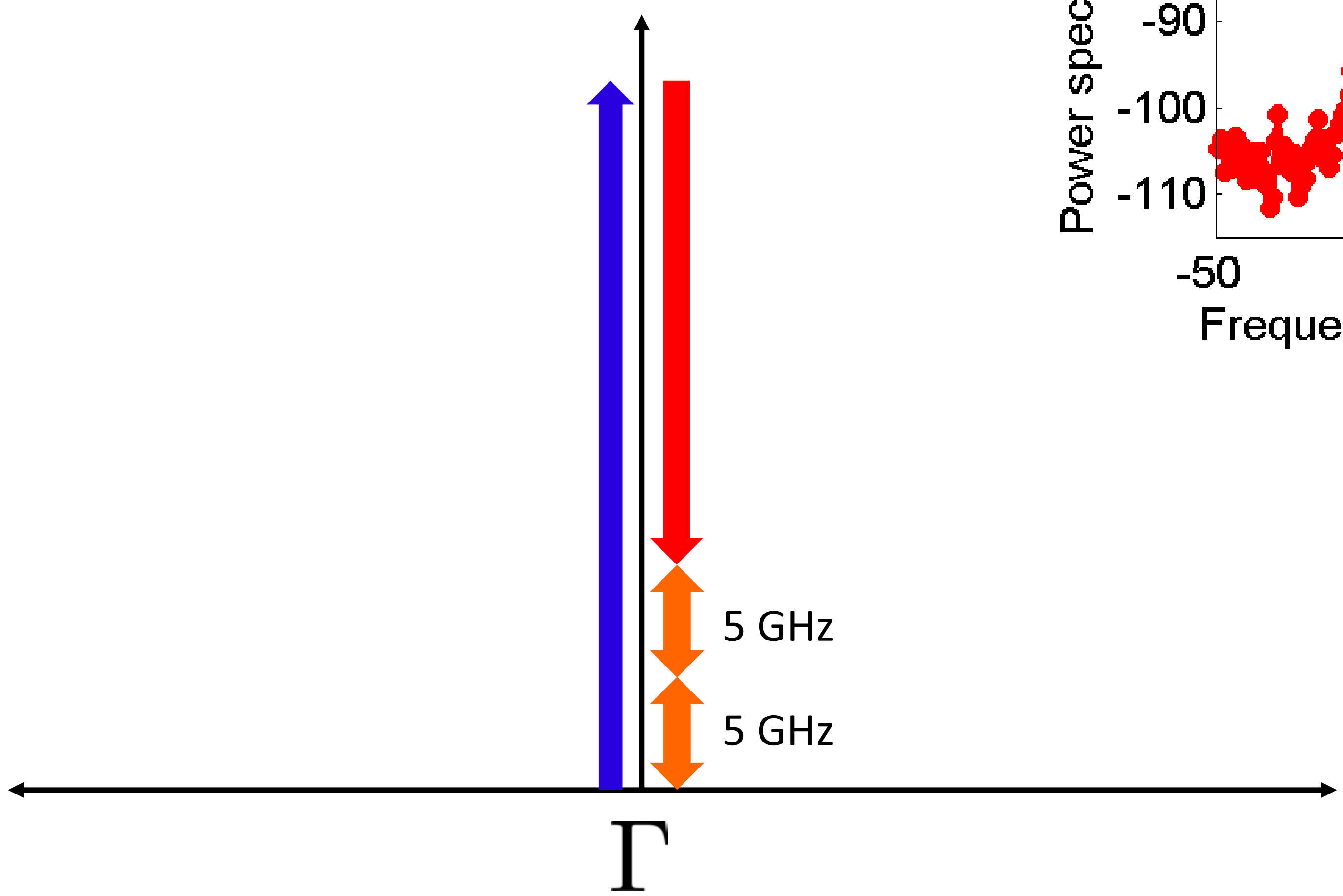
2 Kittel magnon scattering (100 // H)

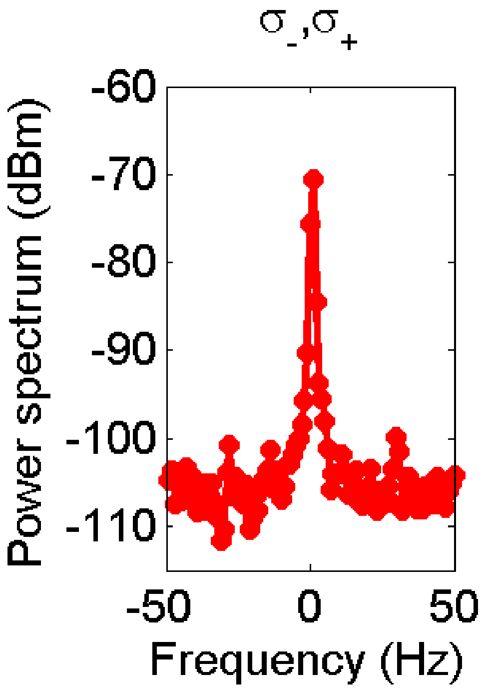


2 Kittel magnon scattering (100 // H)

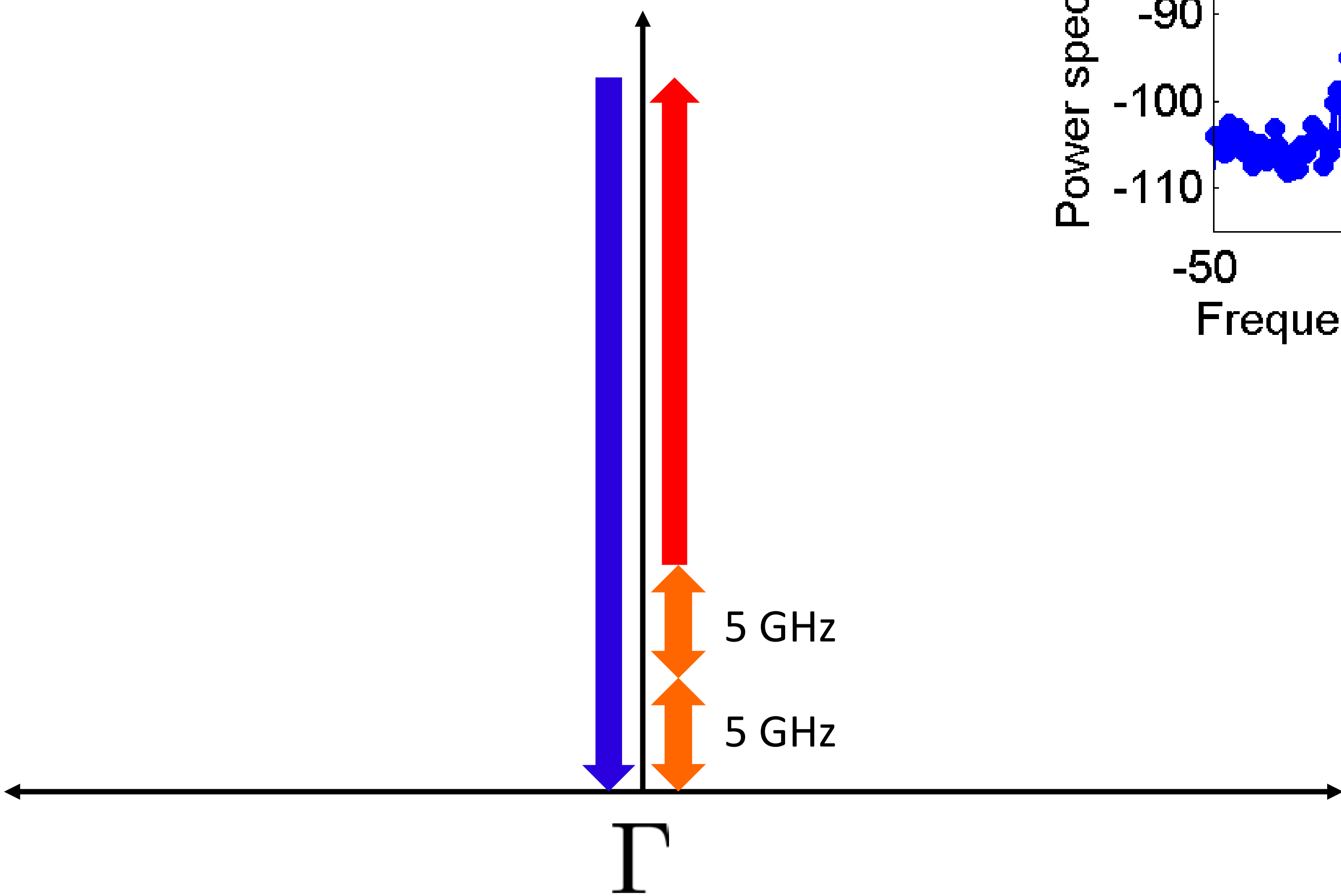


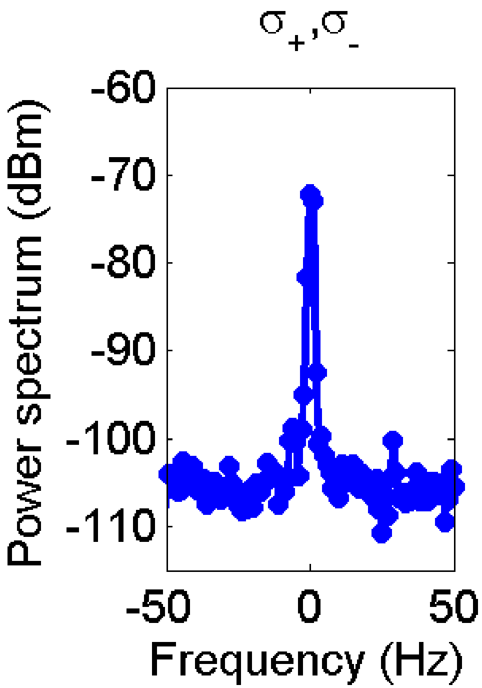
Two-magnon scattering



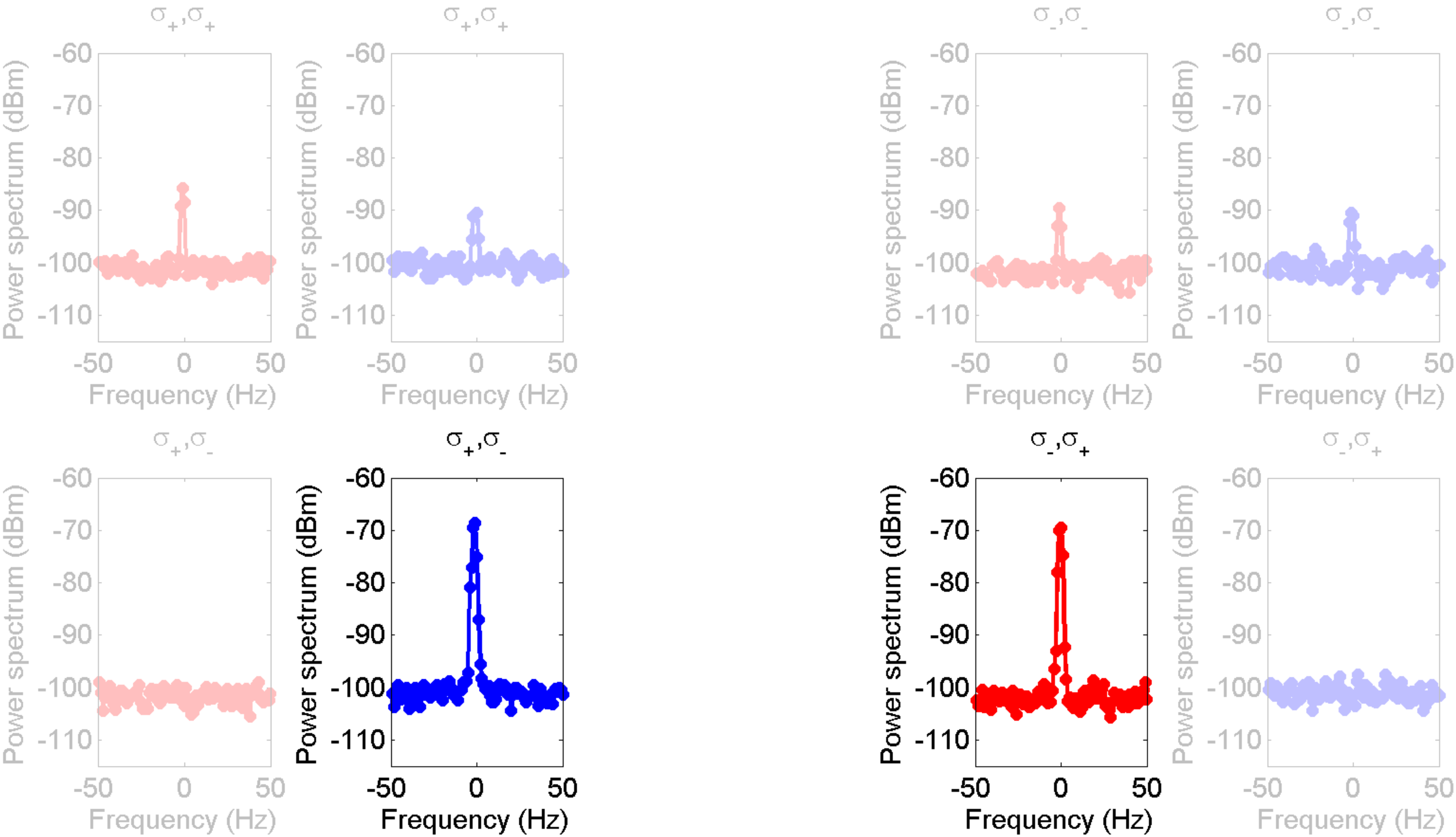


Two-magnon scattering





2-Kittel magnon scattering (111 // H)



Tensor light shift (Cotton-Mouton effect)

$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ \epsilon_{yz} \\ \epsilon_{zx} \\ \epsilon_{xy} \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & G_{12} & 0 & 0 & 0 \\ G_{12} & G_{11} & G_{12} & 0 & 0 & 0 \\ G_{12} & G_{12} & G_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{44} \end{bmatrix} \begin{bmatrix} \Sigma_{xx} \\ \Sigma_{yy} \\ \Sigma_{zz} \\ 2\Sigma_{yz} \\ 2\Sigma_{zx} \\ 2\Sigma_{xy} \end{bmatrix}$$

For **cubic** crystal like YIG (H // 100)

Tensor light shift (Cotton-Mouton effect)

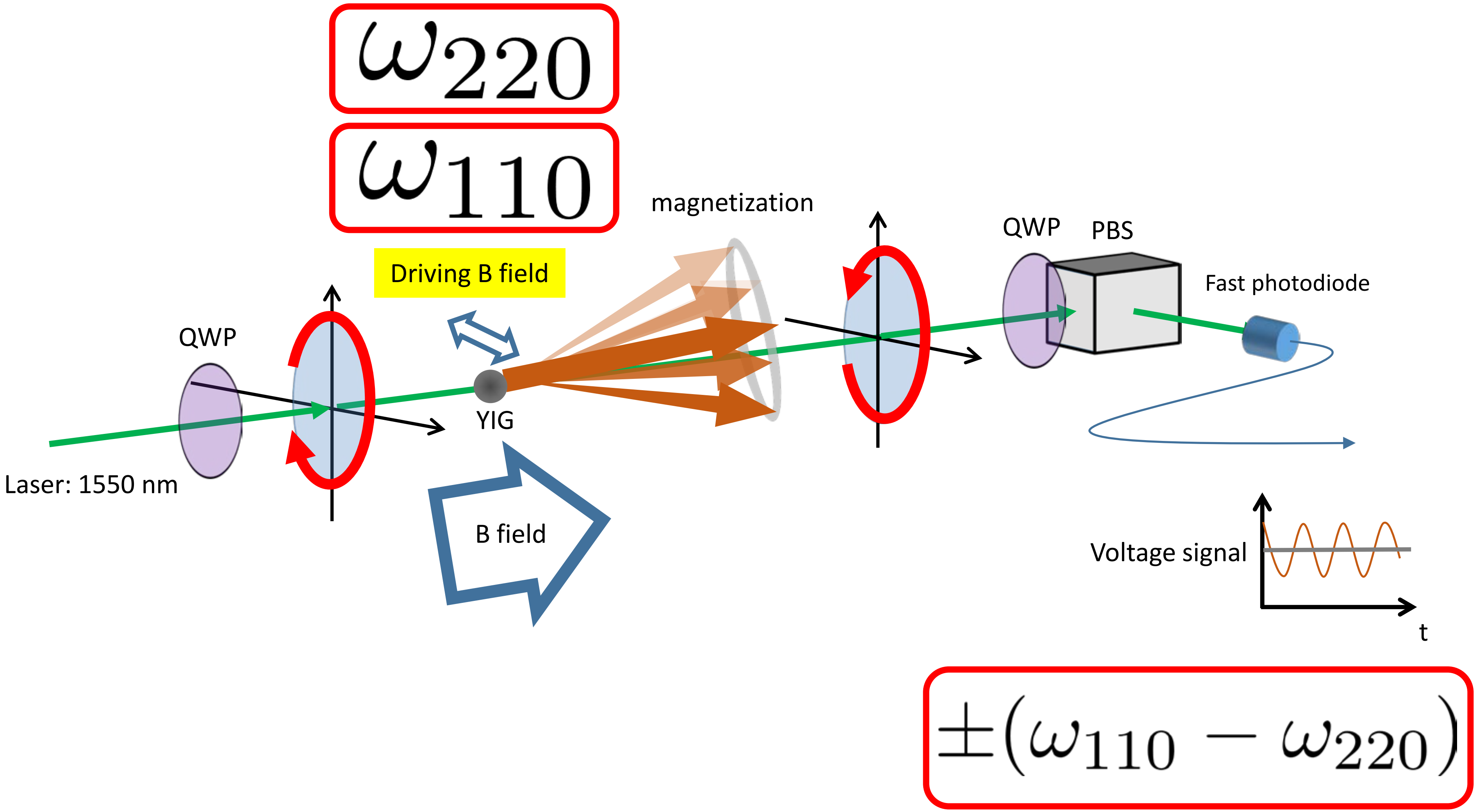
$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ \epsilon_{yz} \\ \epsilon_{zx} \\ \epsilon_{xy} \end{bmatrix} = \begin{bmatrix} 2\mu + \lambda & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & 2\mu + \lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & 2\mu + \lambda & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu \end{bmatrix} \begin{bmatrix} \Sigma_{xx} \\ \Sigma_{yy} \\ \Sigma_{zz} \\ 2\Sigma_{yz} \\ 2\Sigma_{zx} \\ 2\Sigma_{xy} \end{bmatrix}$$

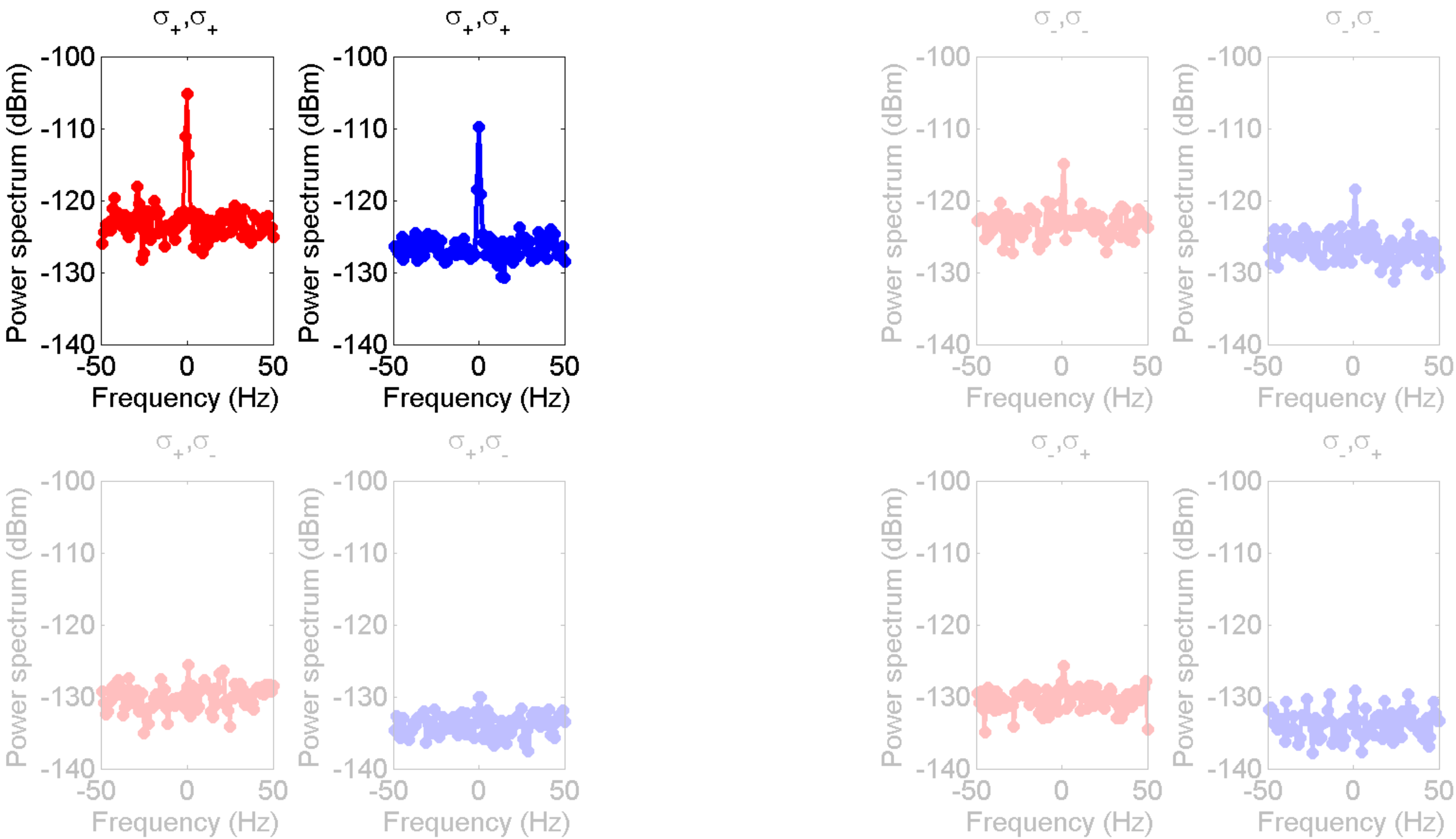
Isotropic

Magnon-mode transfer

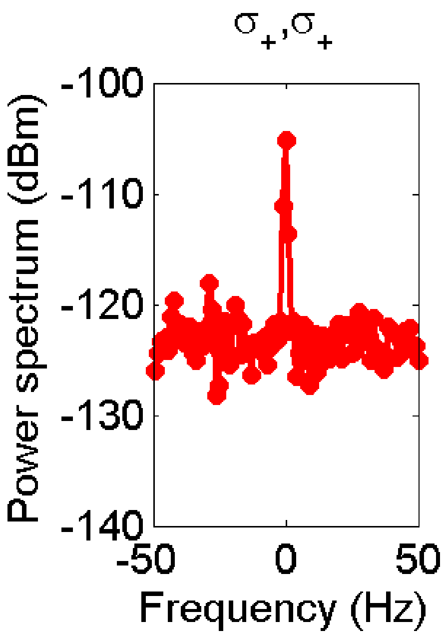
Dynamic Cotton-Mouton effect

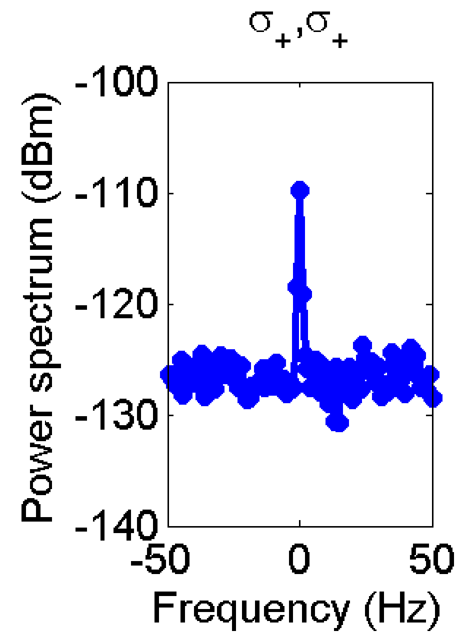


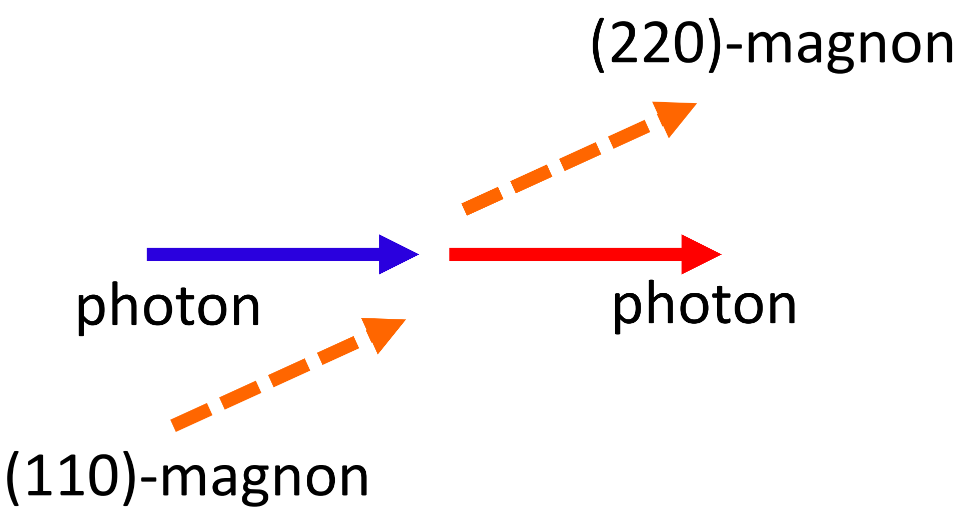
(220)-magnons ⇔ (110)-magnons

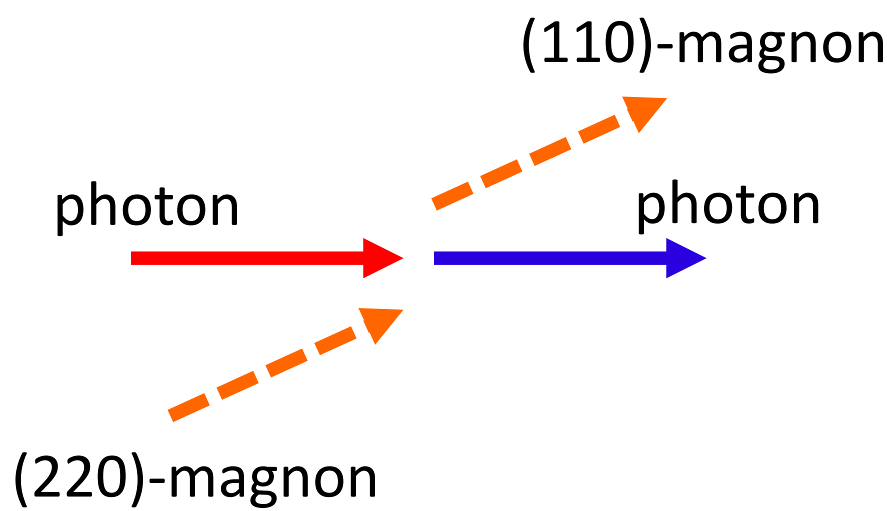


(220)-magnons $\Leftrightarrow$ (110)-magnons

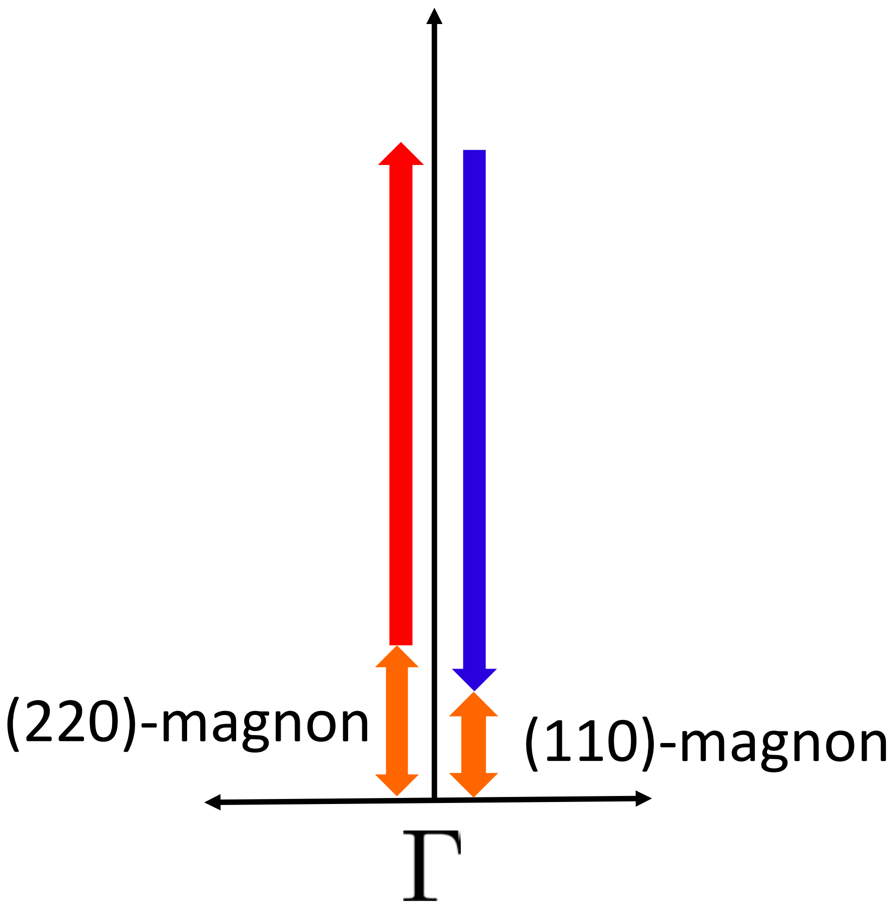


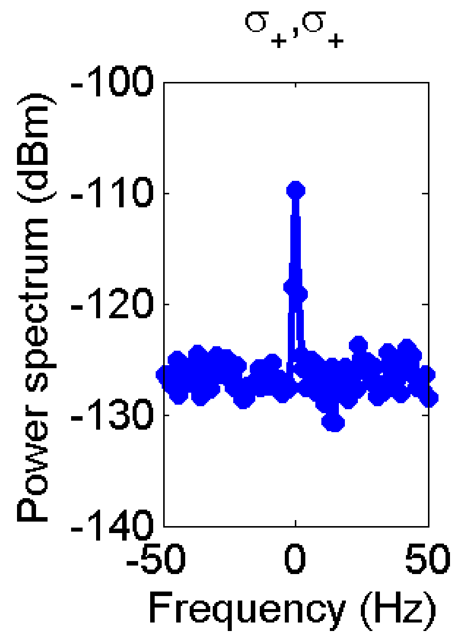


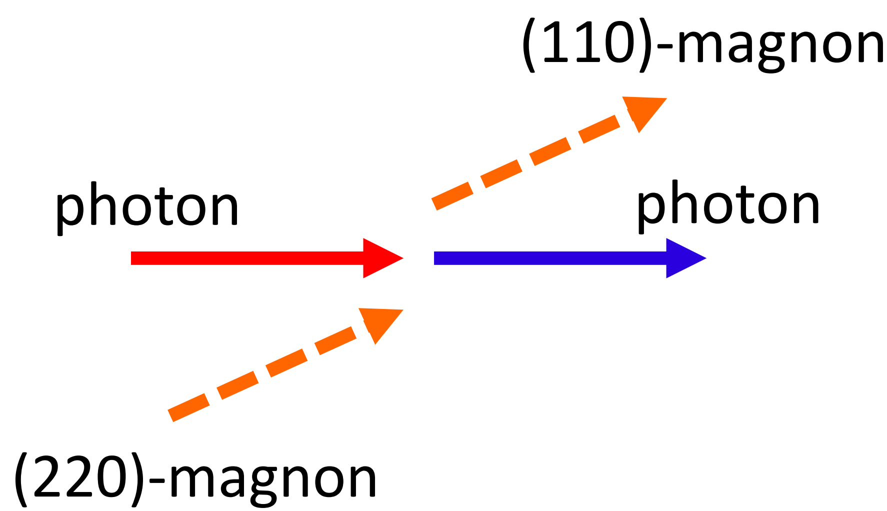




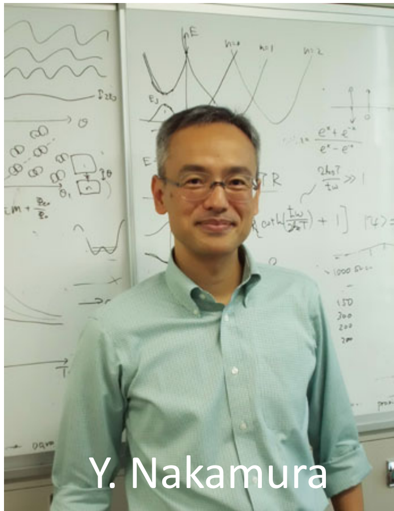
Two-magnon scattering







Team



Y. Nakamura

Y. Tabuchi

S. Ishino

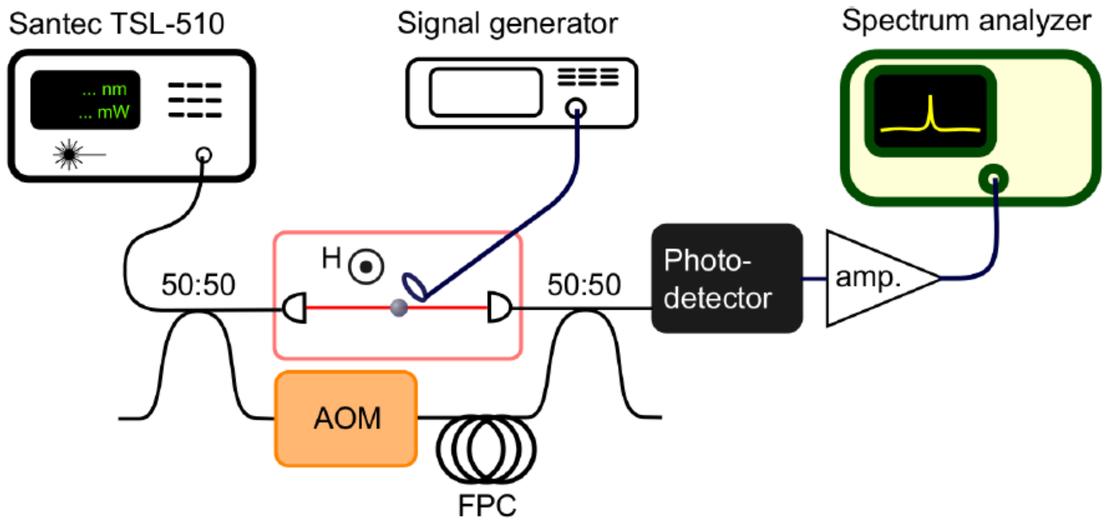
R. Hisatomi

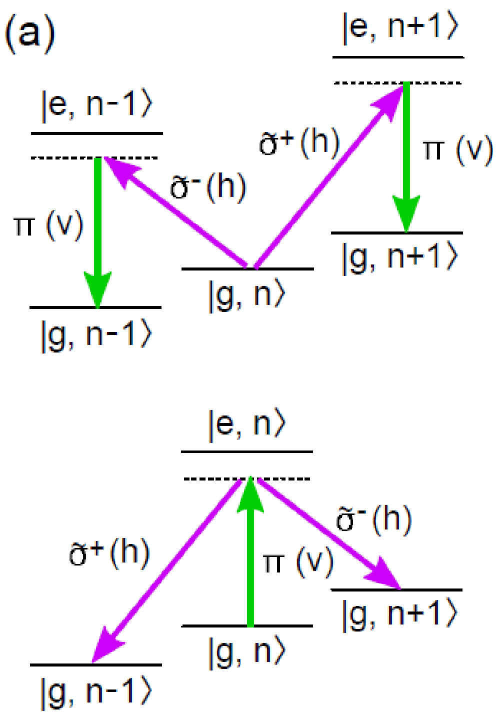
D. Lachance-Quirion

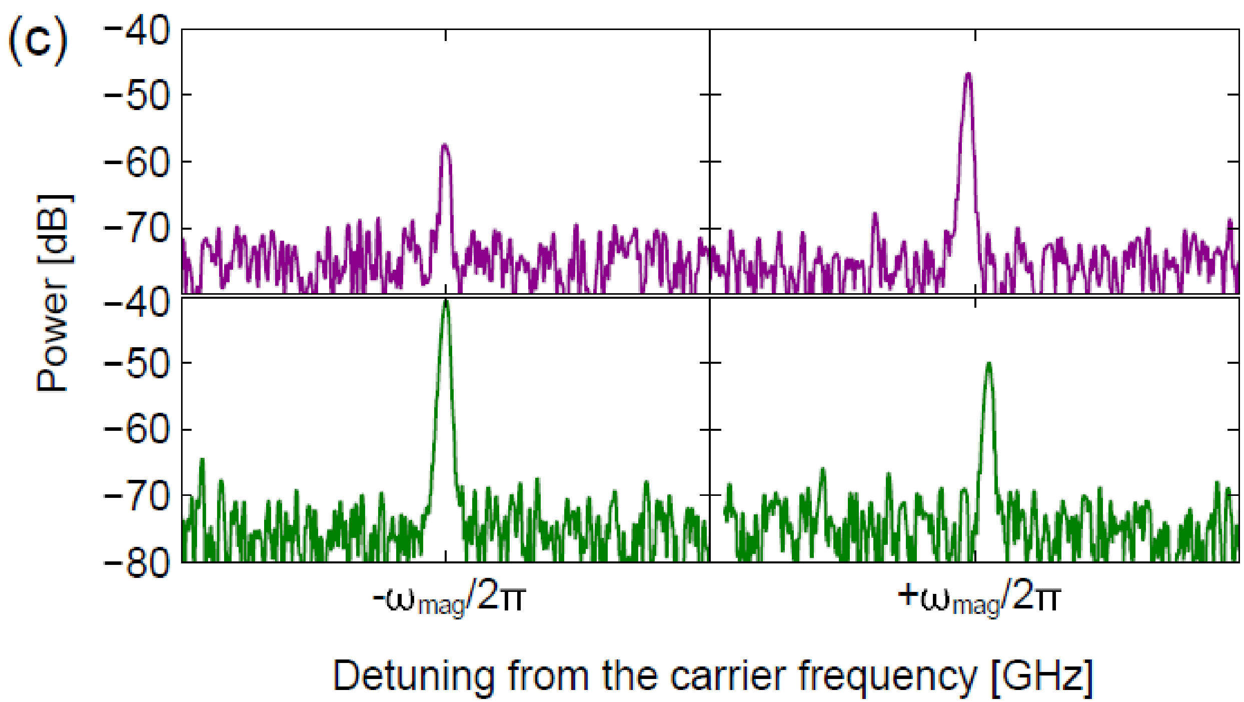
How large?

Look at one-magnon process again

“Intrinsic” sideband asymmetry







One-magnon process

$$\tilde{\epsilon} = \tilde{\epsilon}_0 + \tilde{\epsilon}_1 + \tilde{\epsilon}_2,$$

Scalar part

Saturation magnetization

$$f \sim 2G_{44} M_z$$

Vector

Tensor part (symmetric)

$$\tilde{\epsilon}_2 = \begin{bmatrix} G_{11}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{xy} & 2G_{44}\Sigma_{zx} \\ 2G_{44}\Sigma_{xy} & G_{12}\Sigma_{xx} + G_{11}\Sigma_{yy} + G_{12}\Sigma_{zz} & 2G_{44}\Sigma_{yz} \\ 2G_{44}\Sigma_{zx} & 2G_{44}\Sigma_{yz} & G_{12}\Sigma_{xx} + G_{12}\Sigma_{yy} + G_{11}\Sigma_{zz} \end{bmatrix}$$

Two-magnon process

magnetization due to magnon

$$2G_{44}M_x$$

$$M_x \sim 10^{-3} M_z$$