# Superconducting qubits as a quantum detector

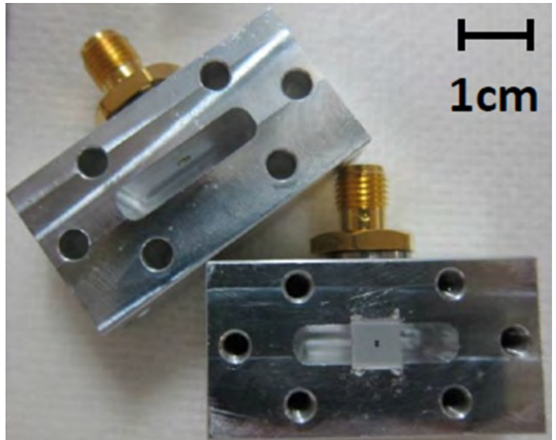
Yasunobu Nakamura　中村 泰信

RIKEN Center for Quantum Computing (RQC)

Research Center for Advanced Science and Technology (RCAST), The University of Tokyo

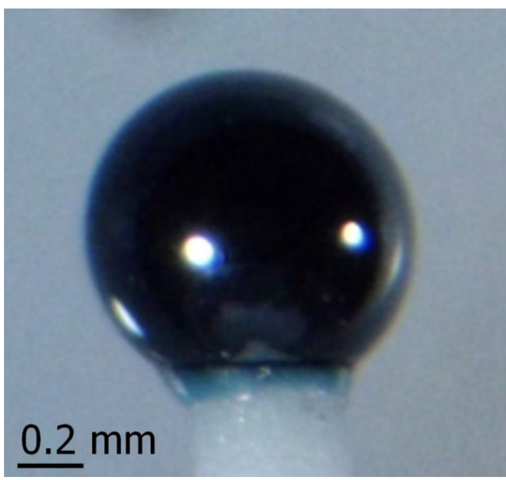
# Hybrid quantum systems using collective modes

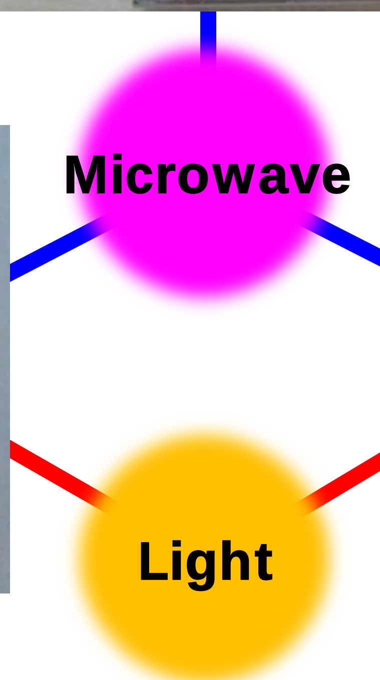
## Superconducting quantum electronics



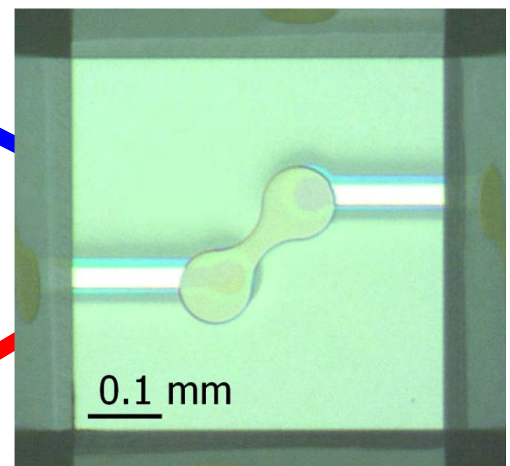

**Nonlinearity**

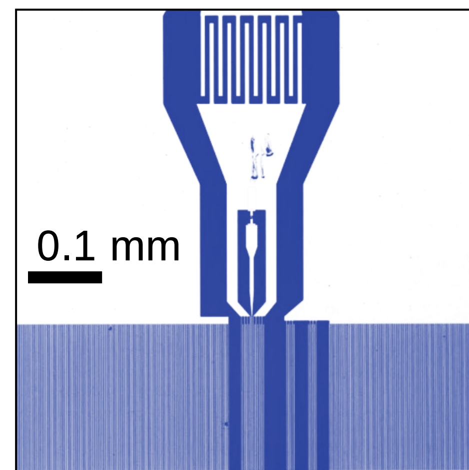
## Quantum magnonics




## Quantum nanomechanics



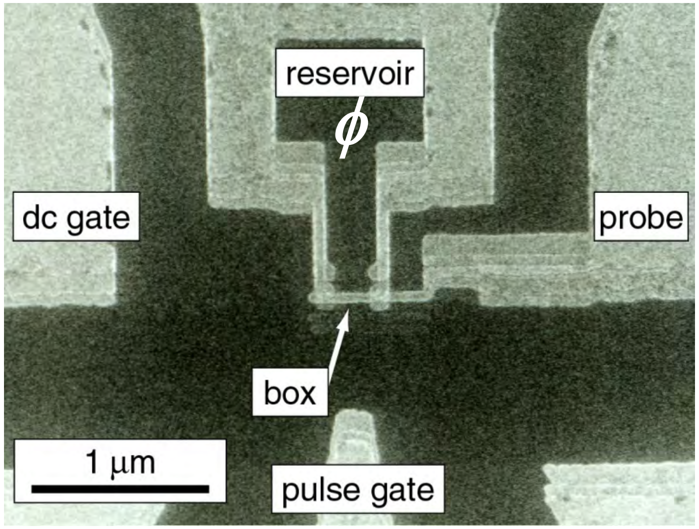



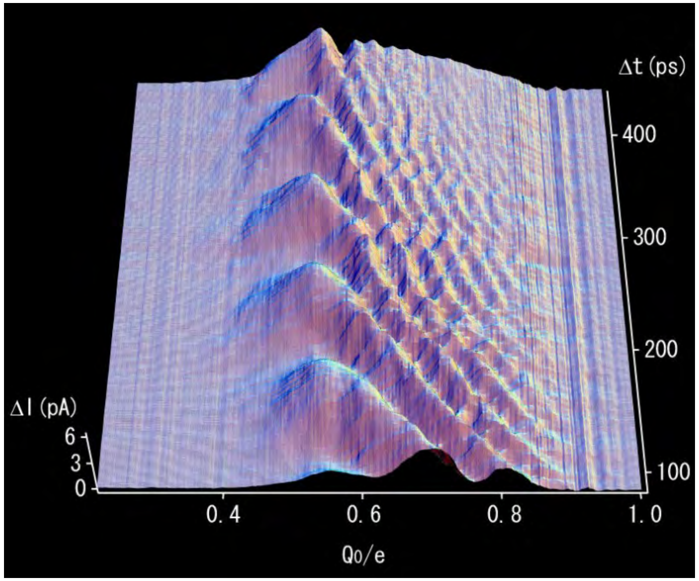

e.g., A. A. Clerk et al., Nature Physics 16, 257 (2020)

# Superconducting qubits

# Superconducting qubit

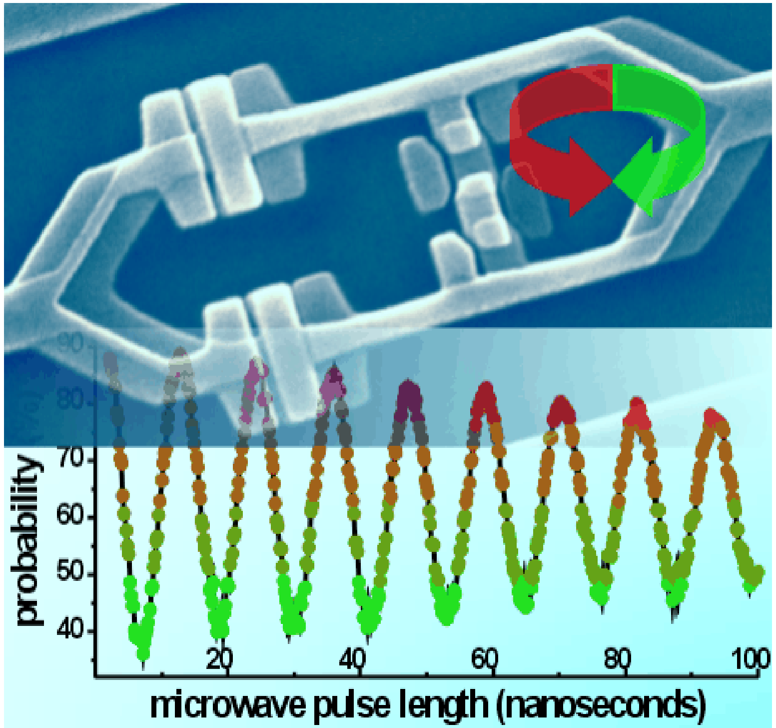
## Charge qubit




Nakamura, Pashkin, Tsai, Nature (1999)

## Flux qubit



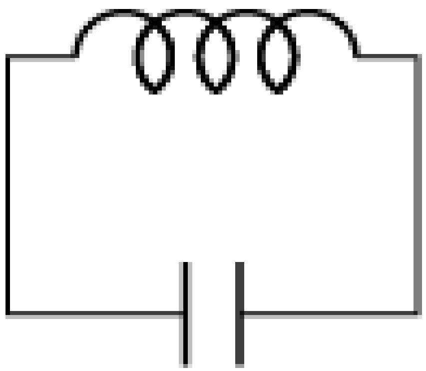

Chiorescu, Nakamura, Harmans, Mooij, Science (2003)

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Coherent manipulation of quantum states in circuits

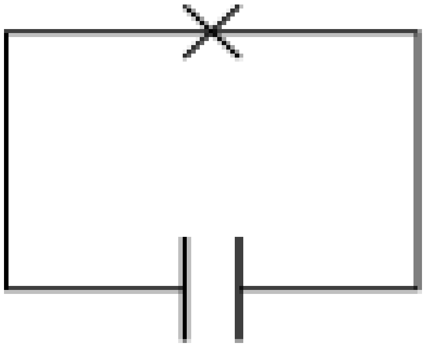
# Superconducting qubit – nonlinear resonator

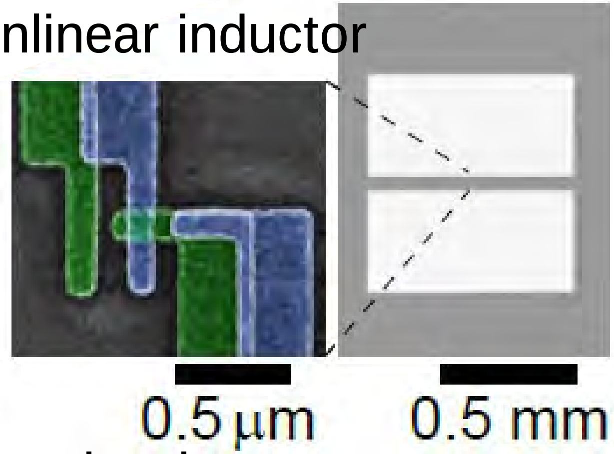
LC resonator



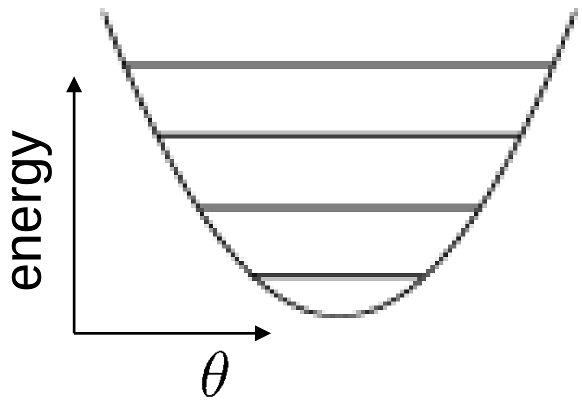
Josephson junction resonator

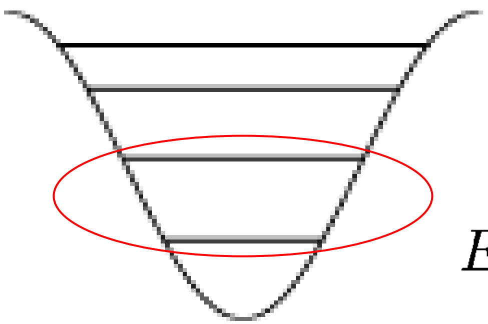
Josephson junction = nonlinear inductor






anharmonicity ⇒ effective two-level system



$$E_{01} \sim 10\,\mathrm{GHz} \sim 0.5\,\mathrm{K}$$

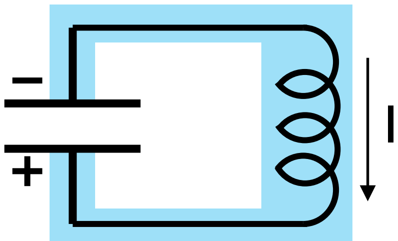
$$T \sim 0.01\,\mathrm{K}$$

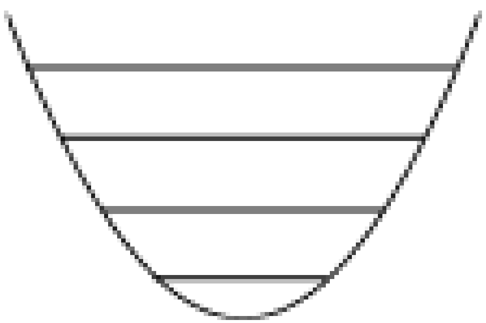
inductive energy = confinement potential

charging energy = kinetic energy ⇒ quantized states

# Superconducting qubit – nonlinear resonator

## LC resonator

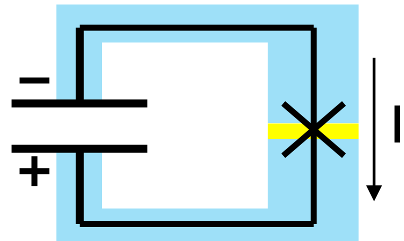


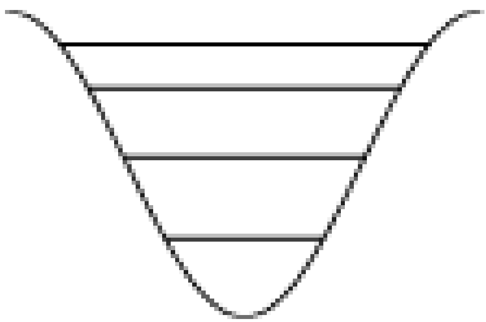



## Superconducting qubit

= Artificial atom

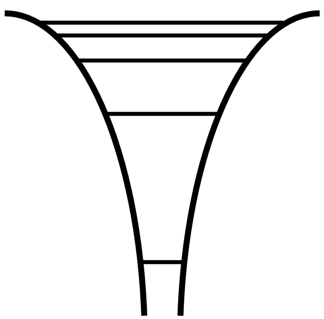
~mm



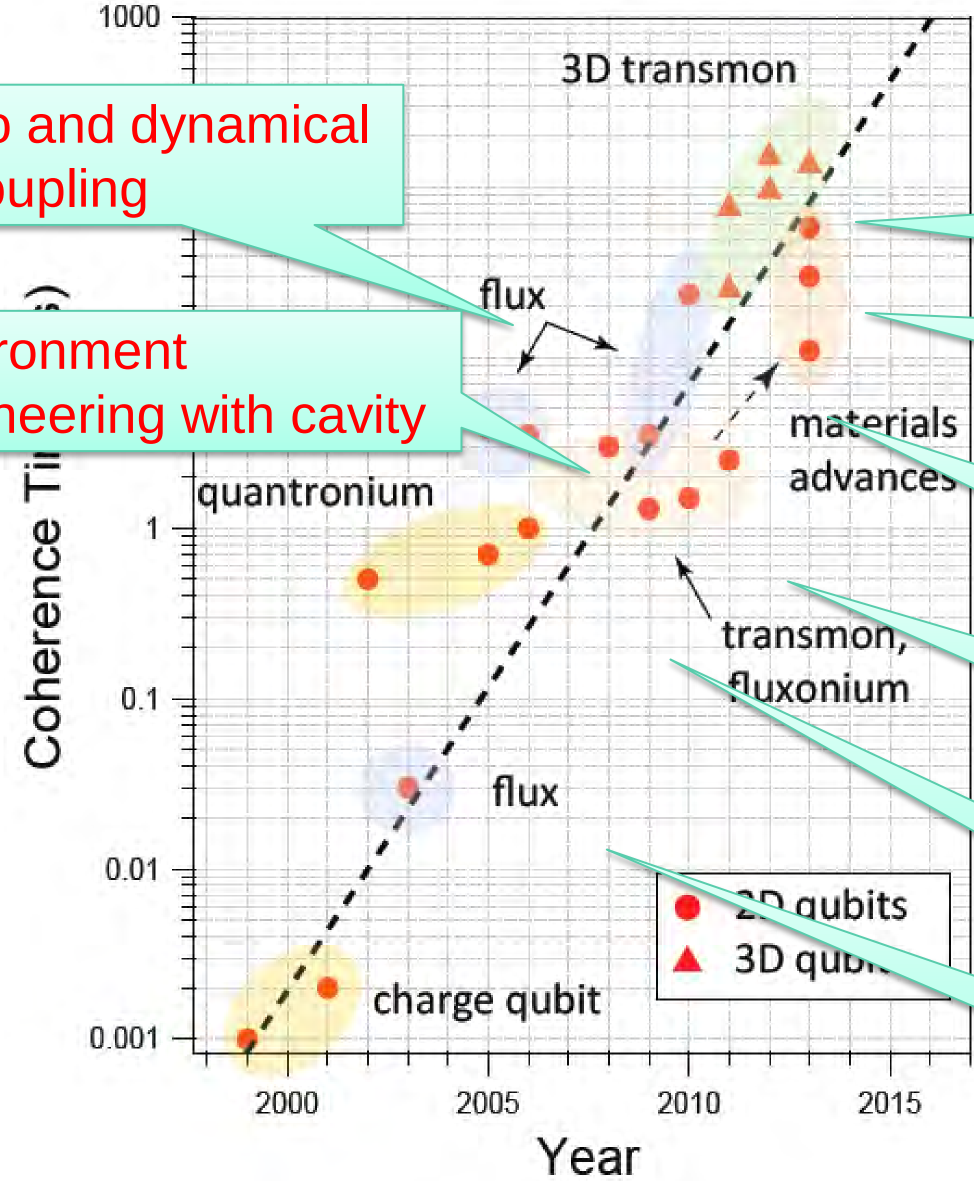
## Atom

~Å



- Superconductivity ⇒ low-loss
- Josephson effect ⇒ Strong nonlinearity
- Macroscopic size ⇒ Strong coupling

# Coherence time of superconducting qubits




Low-energy qubit

Echo and dynamical decoupling

Non-equilibrium quasiparticle engineering

High-frequency noise shielding

Environment engineering with cavity

Diluted surface/interface effect

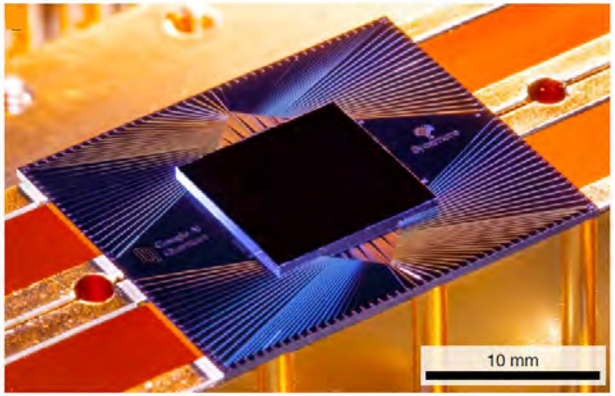
Improved surface/interface/dielectric

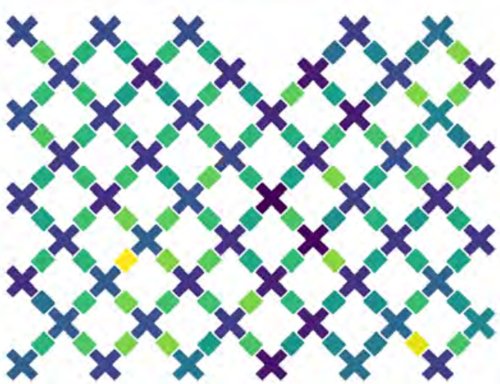
Energy-level engineering

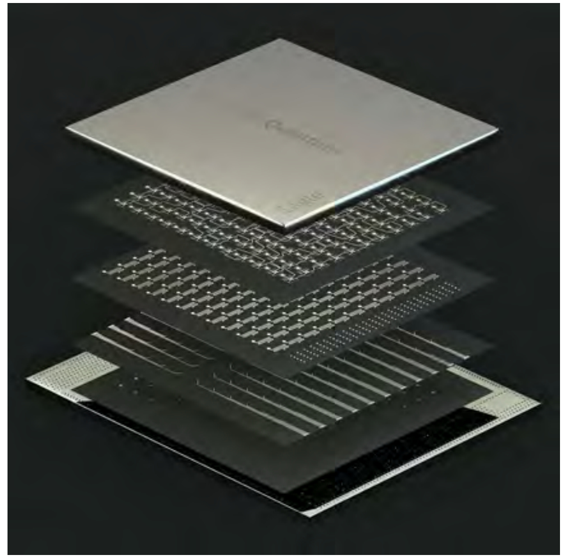
Decoupling from charge noise

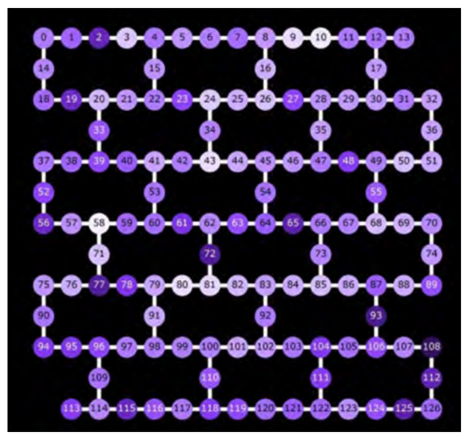
W. D. Oliver and P. Welander, MRS BULLETIN 38, 816 (2013) MIT-LL

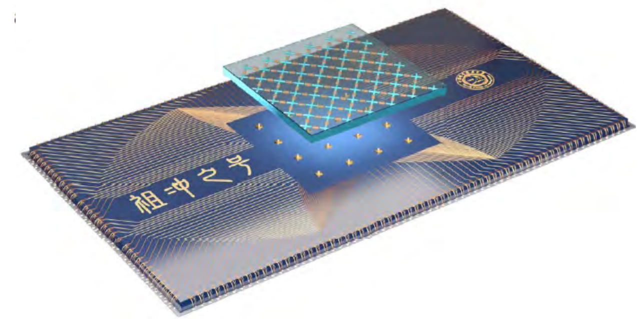
# Scaling-up superconducting quantum computers

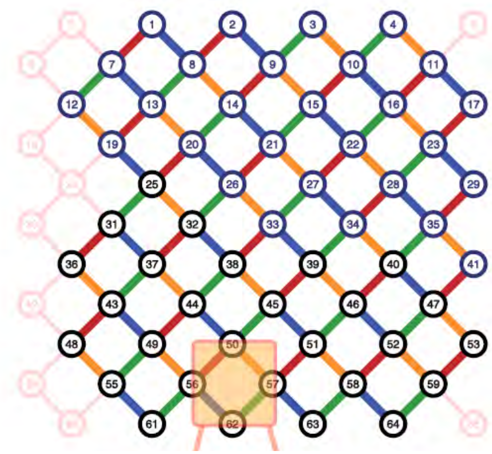








**54 qubits**

Google AI Quantum
Nature 574, 505 (2019)

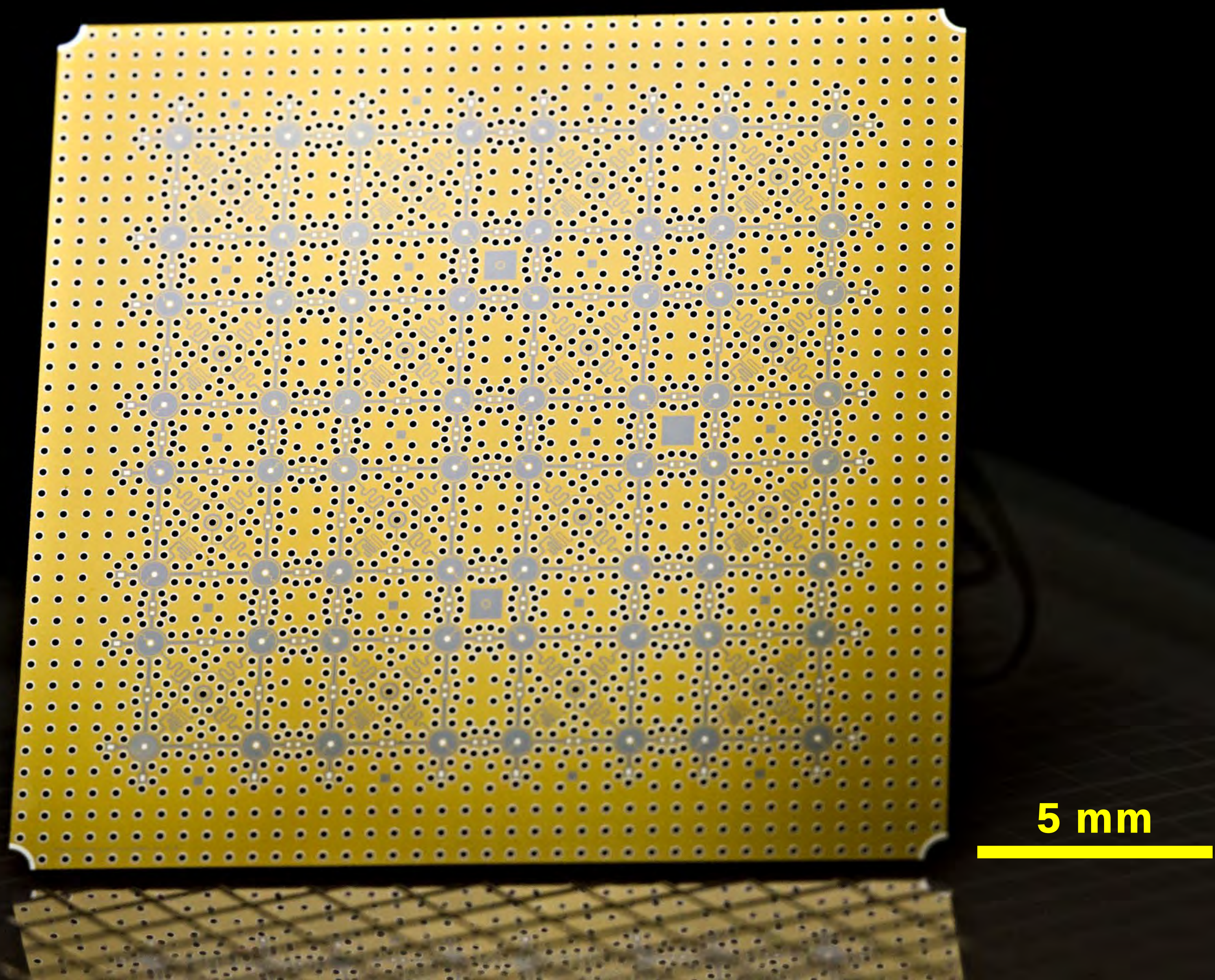
**127 qubits**

IBM
https://www.ibm.com/blogs/think/jp-ja/wp-content/uploads/sites/21/2021/11/IBM_ChipOpen_BLK_1000x1000.jpg

**66 qubits**

USTC
Phys. Rev. Lett. 127, 180501 (2021)

# 64-qubit chip @RIKEN

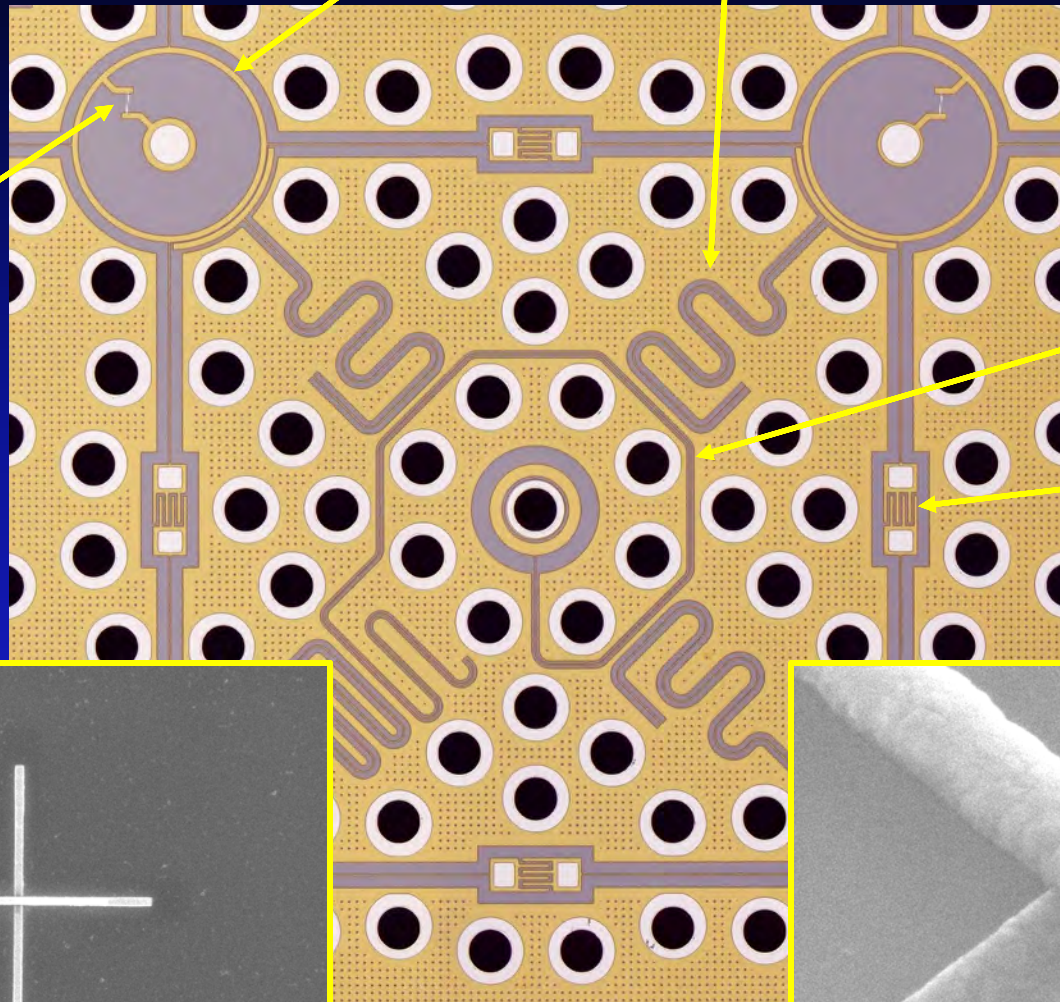


# Unit cell structure

Qubit

Readout resonator (λ/4)

Josephson junction

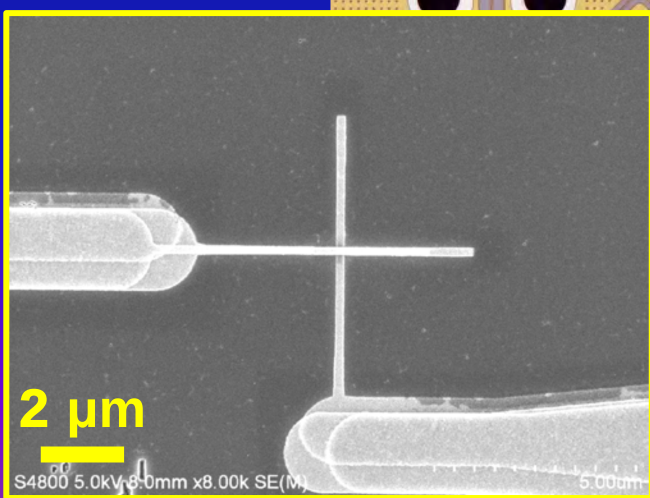


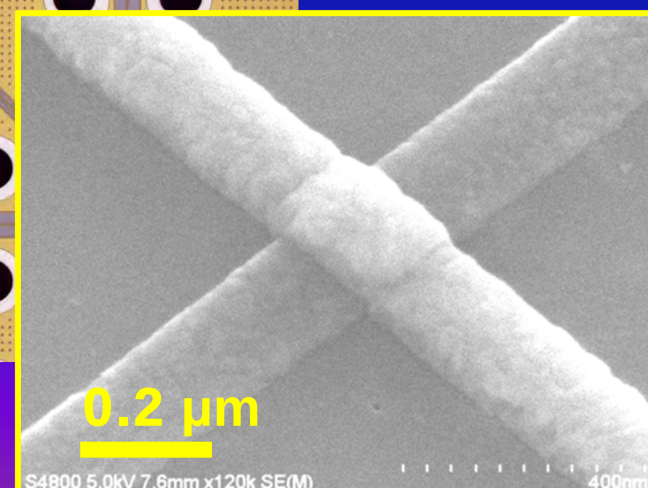
0.5 mm

Purcell filter (λ/2 resonator)

Capacitive coupler

Yellow: TiN
White: Al
Gray: Si
Black: TSV



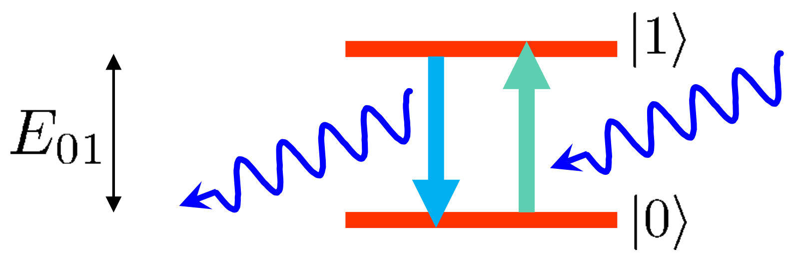
# Qubit as a quantum detector — relaxation

Fermi's golden rule

Double-sided power spectral density of the noise in the environment

Energy relaxation
$$\Gamma_\downarrow = \frac{2\pi}{\hbar^2} \underline{S_\lambda(\omega_{01})} \left| \left\langle 1 \left| \frac{\partial H}{\partial \lambda} \right| 0 \right\rangle \right|^2$$

Energy excitation
$$\Gamma_\uparrow = \frac{2\pi}{\hbar^2} \underline{S_\lambda(-\omega_{01})} \left| \left\langle 1 \left| \frac{\partial H}{\partial \lambda} \right| 0 \right\rangle \right|^2$$



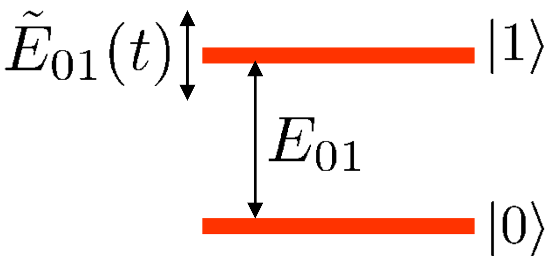
# Qubit as a quantum detector — dephasing

free evolution of the qubit phase

$$\alpha|0\rangle + \beta|1\rangle \Rightarrow \alpha|0\rangle + \beta e^{i\varphi(t)}|1\rangle$$

$$\varphi(t) = \bar{\varphi}(t) + \underline{\tilde{\varphi}(t)} \qquad \bar{\varphi}(t) = \frac{\overline{E_{01}}}{\hbar}t$$

dephasing




$$\langle \exp i\tilde{\varphi}(t)\rangle = \left\langle \exp\left(\frac{i}{\hbar}\int_0^\tau dt\,\tilde{E}_{01}(t)\right)\right\rangle$$

$$= \exp\left[-\frac{1}{2\hbar^2}\left(\frac{\partial E_{01}}{\partial\lambda}\right)^2 \underbrace{\int_{-\infty}^{\infty} d\omega\, \underline{S_\lambda(\omega)}\left(\frac{\sin(\omega t/2)}{\omega/2}\right)^2}\right]$$

for Gaussian fluctuations

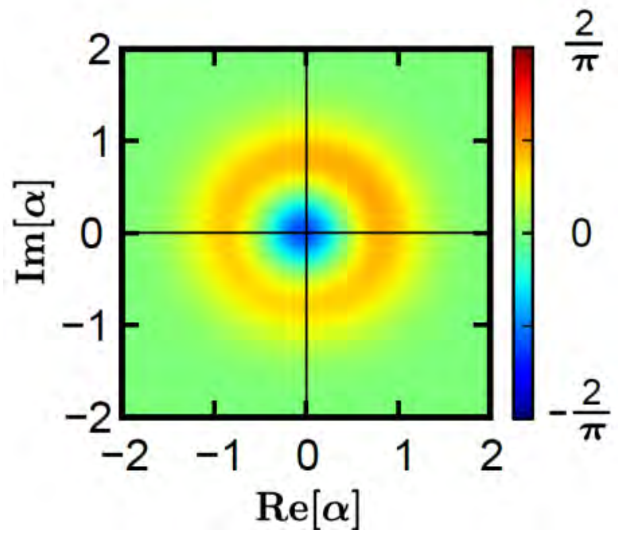
tunable

tunable

sensitivity of qubit energy to the fluctuations
of external parameter

information of S(ω) at low frequencies

# Quantum nondemolition (QND) detection of an itinerant microwave photon




S. Kono et al. Nature Physics 14, 546 (2018).
See also, J.-C. Besse et al., PRX 8, 021003 (2018). ETH Zurich
A. Reiserer et al. Science 342, 1350 (2011) MPQ

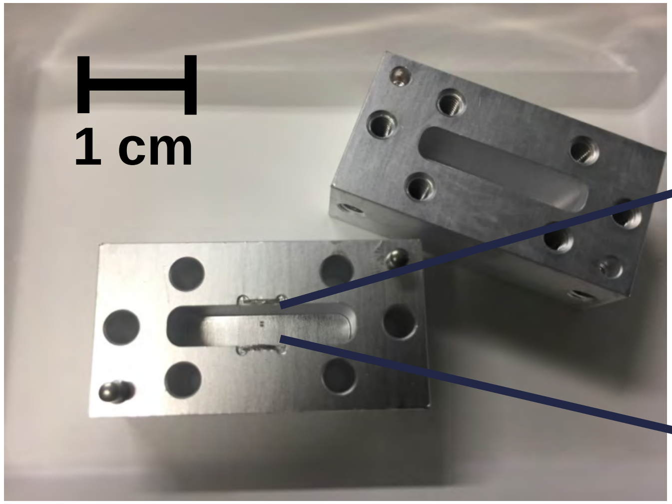
# Circuit quantum electrodynamics

$$H_{\mathrm{JC}} = \underbrace{\frac{\hbar\omega_{\mathrm{q}}}{2}\hat{\sigma}_z}_{\text{Qubit}} + \underbrace{\hbar\omega_{\mathrm{c}}\hat{a}^\dagger\hat{a}}_{\text{Cavity mode}} + \underbrace{\hbar g(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^\dagger)}_{\text{Interaction}}$$

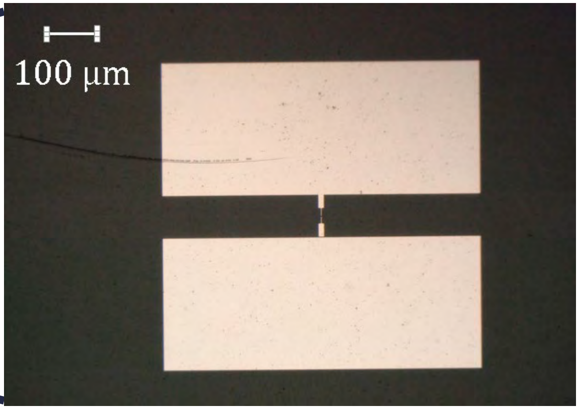
$g/2\pi$ = 0.2 GHz

$|\omega_{\mathrm{c}} - \omega_{\mathrm{q}}|/2\pi$ = 2.7 GHz

Al 3D cavity




transmon qubit




$\omega_{\mathrm{c}}/2\pi$ = 10.6 GHz

$\omega_{\mathrm{q}}/2\pi$ = 7.9 GHz

# Circuit QED in dispersive regime

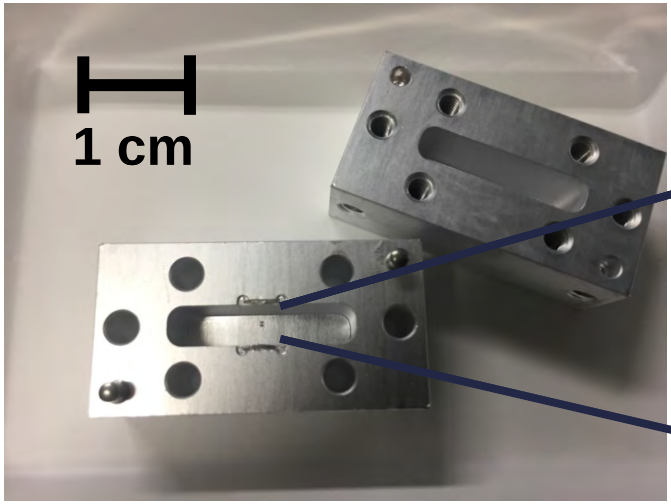
$$H_{\mathrm{dispersive}} = \underbrace{\frac{\hbar(\omega_{\mathrm{q}}-\chi)}{2}\hat{\sigma}_z}_{\text{Qubit}} + \underbrace{\hbar\omega_{\mathrm{c}}\hat{a}^\dagger\hat{a}}_{\text{Cavity mode}} - \underbrace{\hbar\chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z}_{\text{Interaction}}$$

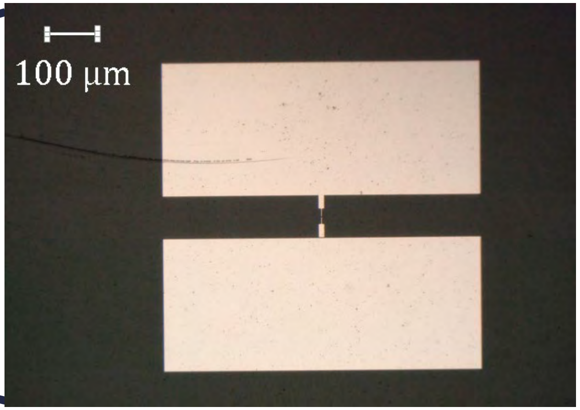
$$\chi = g^2/\Delta$$

$\chi/2\pi$ = 1.5 MHz

Al 3D cavity

transmon qubit



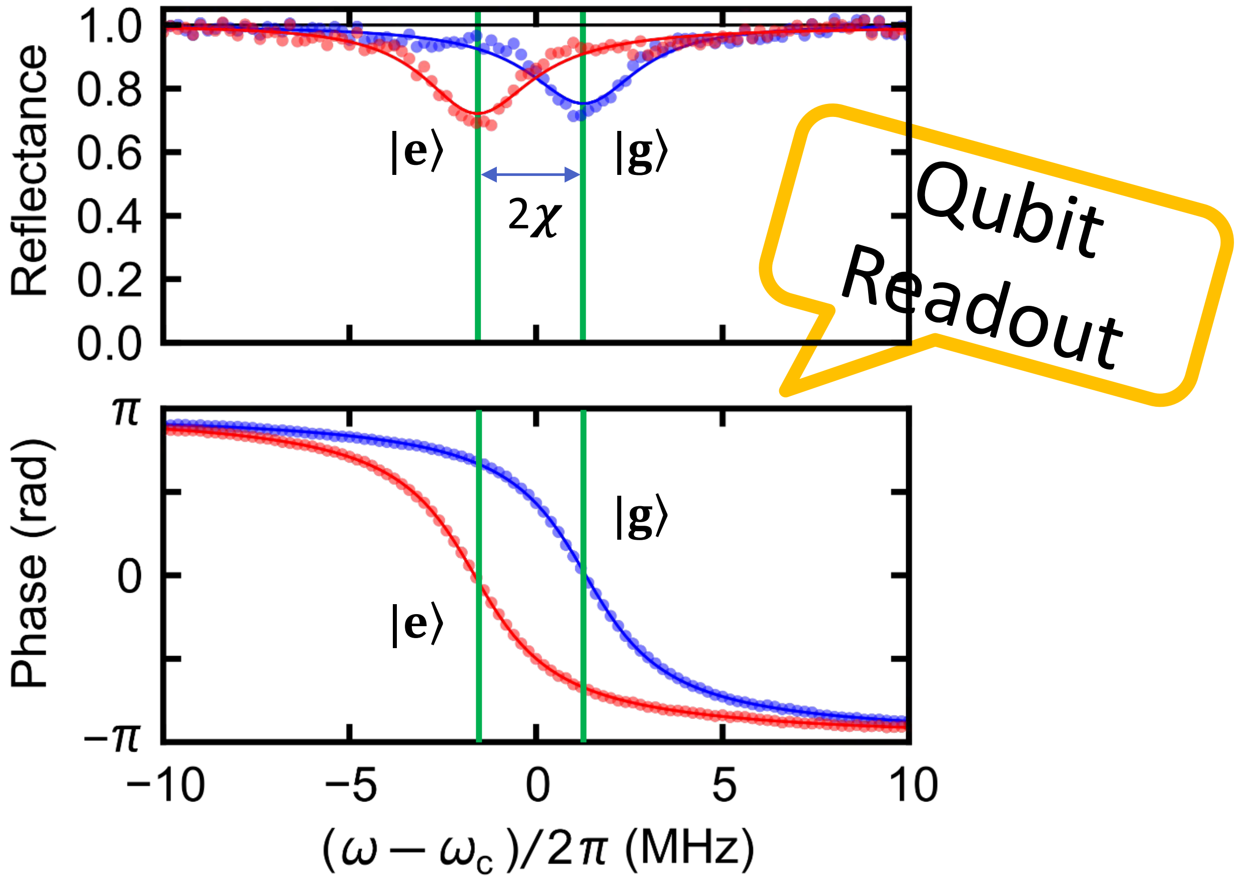




$\omega_{\mathrm{c}}/2\pi$ = 10.6 GHz

$\omega_{\mathrm{q}}/2\pi$ = 7.9 GHz

# Circuit QED in dispersive regime

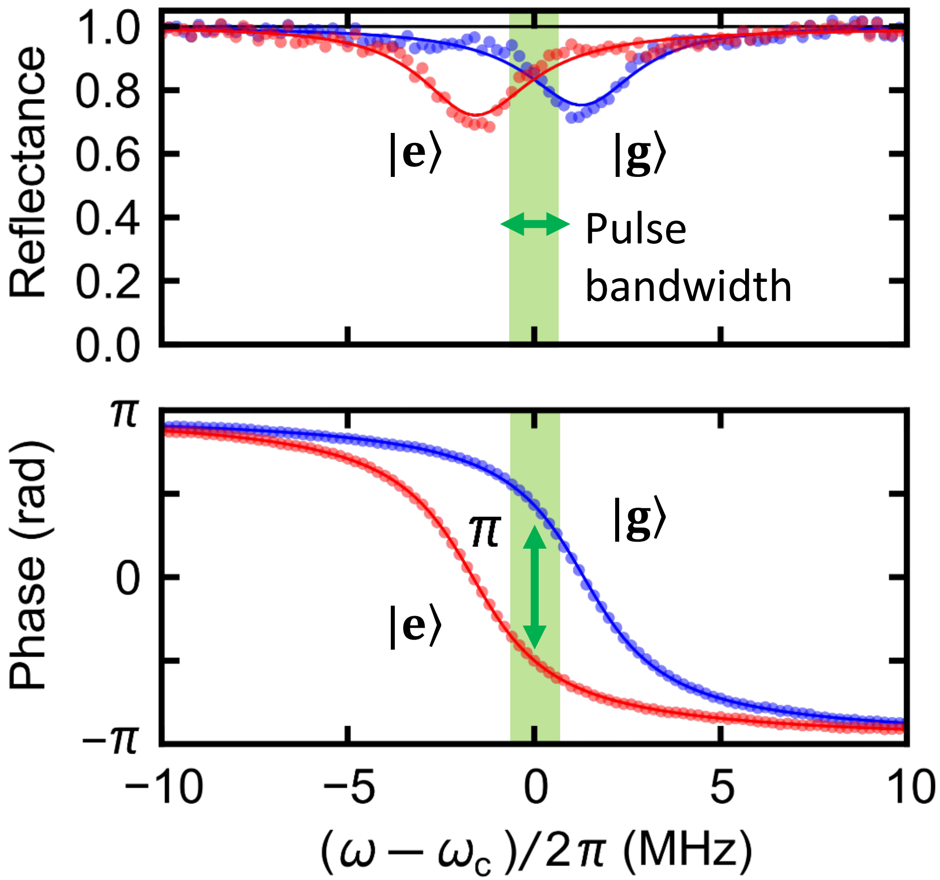
$$H_{\text{dispersive}} = \frac{\hbar(\omega_q - \chi)}{2}\hat{\sigma}_z \boxed{+\hbar(\omega_c - \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a}}$$

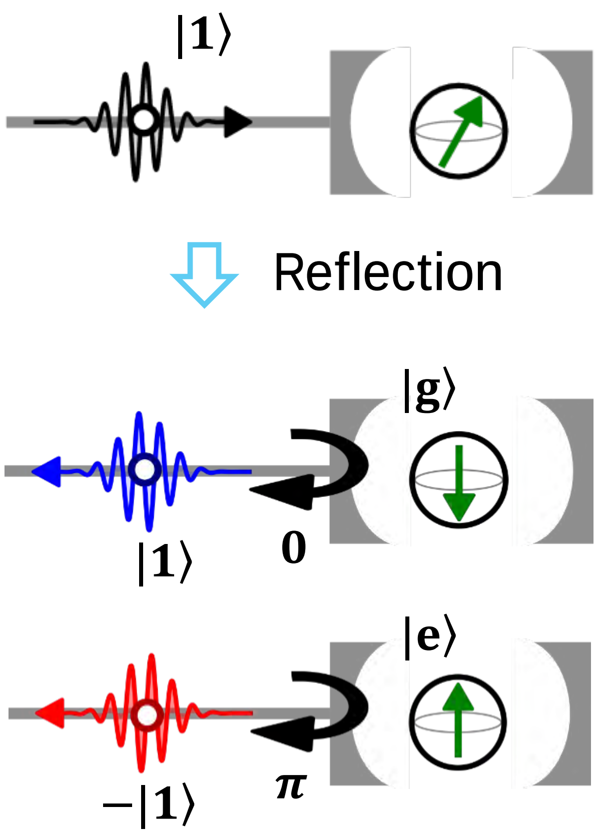


# Interaction between itinerant photon and qubit

Optimal condition for large bandwidth $\kappa_{\mathrm{ex}} = 2\chi$

Controlled $\pi$-phase gate depending on qubit state

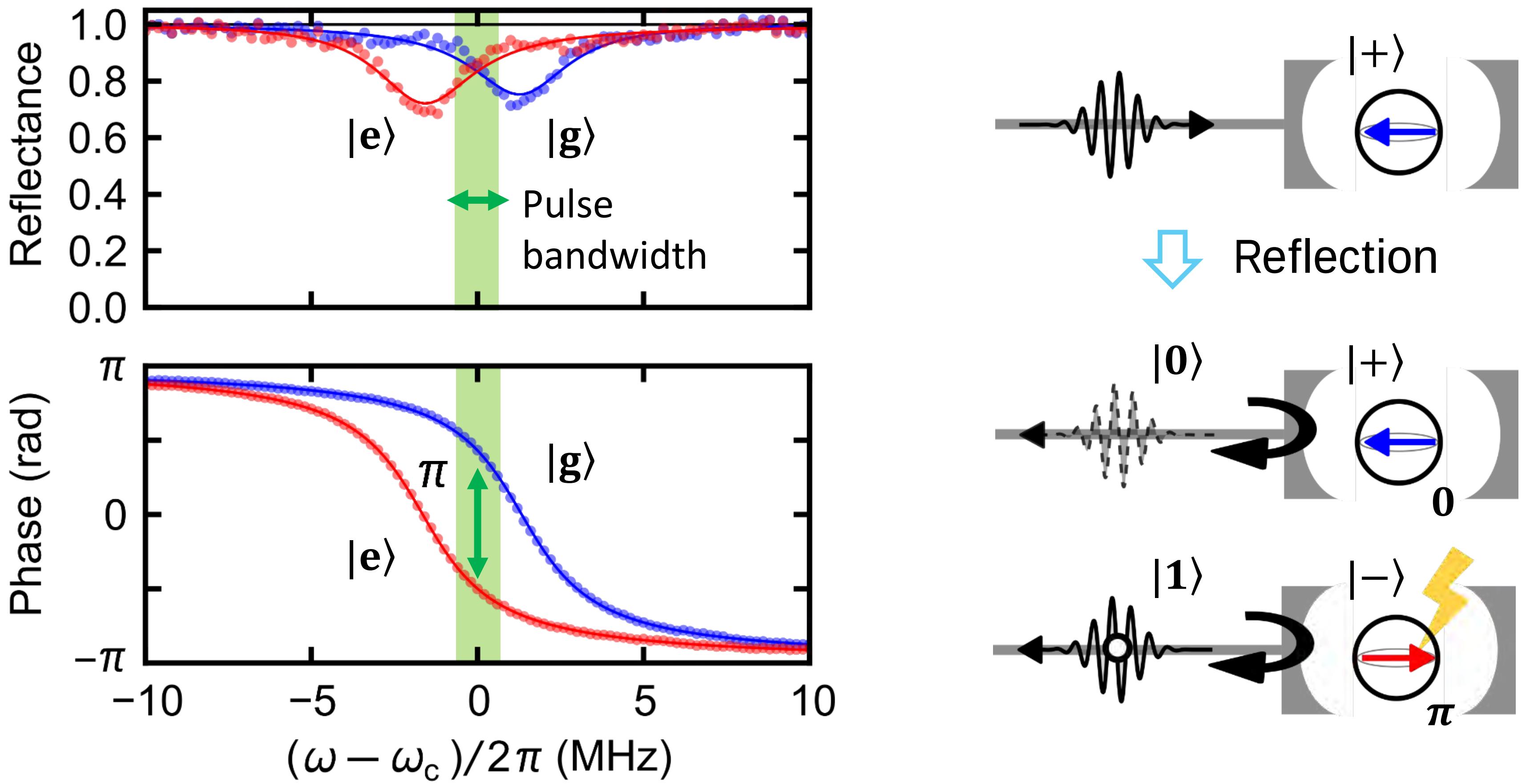


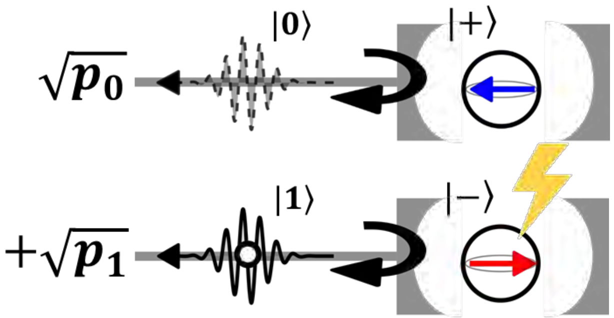
# QND detection of itinerant photon

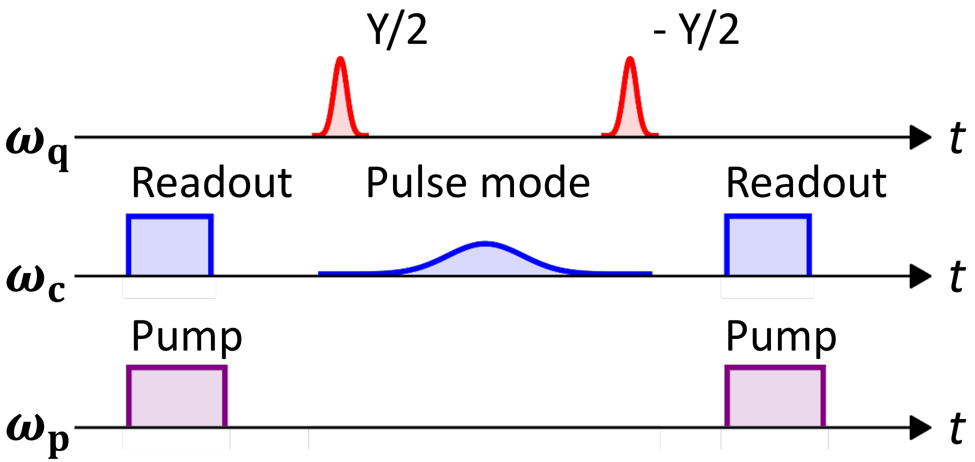
Optimal condition for large bandwidth $\kappa_{\mathrm{ex}} = 2\chi$

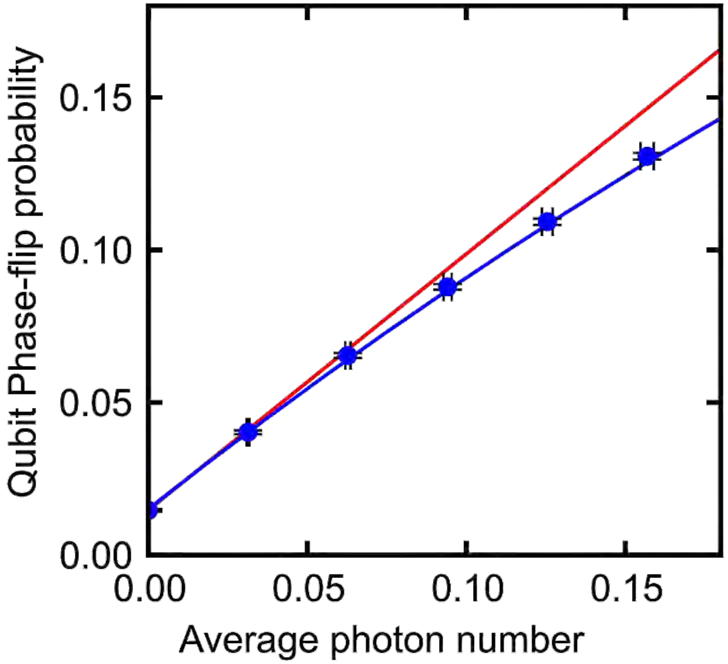
Controlled $\pi$-phase gate depending on photon state



# Quantum efficiency




- Dark counts due to qubit dephasing

  $P_{dc} = 0.0147$

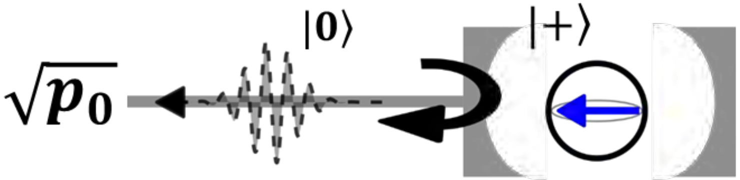
- Quantum efficiency

  $\eta = 0.84$

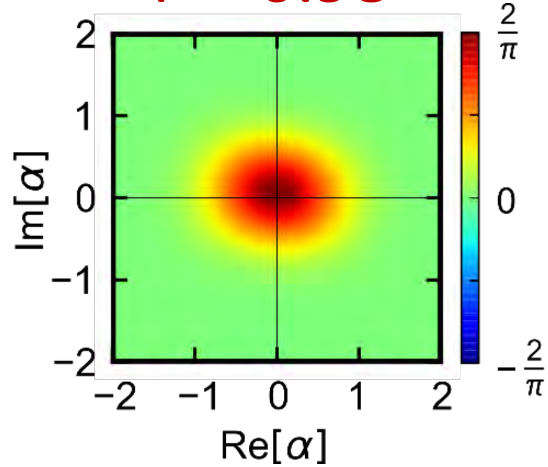
  - Internal loss of the cavity
  - Dephasing
  - Mismatch of $\kappa$ and $2\chi$

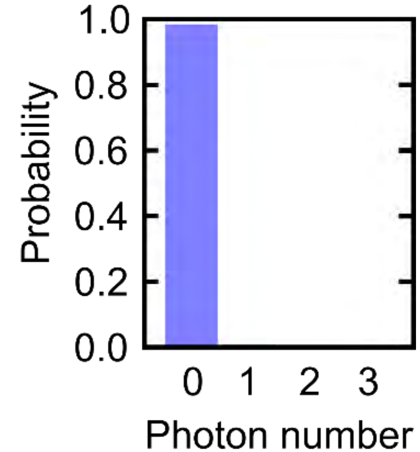
# Conditional Wigner function of pulse mode

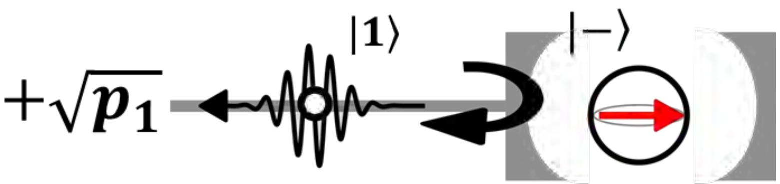
**Corrected**
**for $\eta_{\mathrm{det}} = 0.43$**



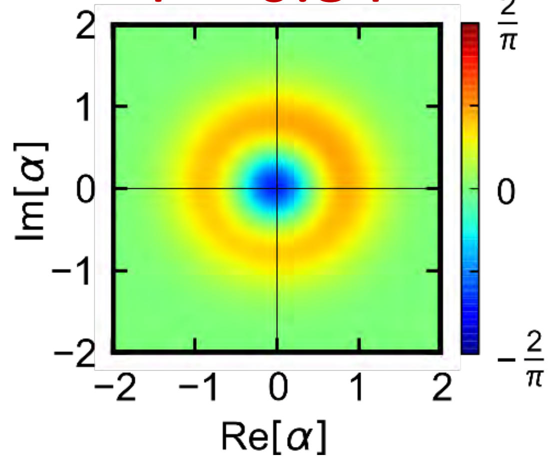

F= 0.98

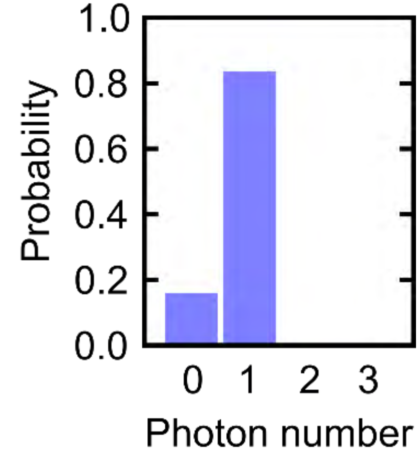



F= 0.84

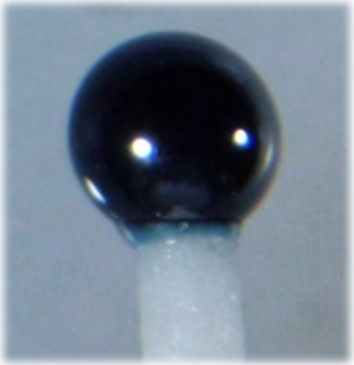



Heralded
single photon generation

# Quantum magnonics

# Quantum magnonics

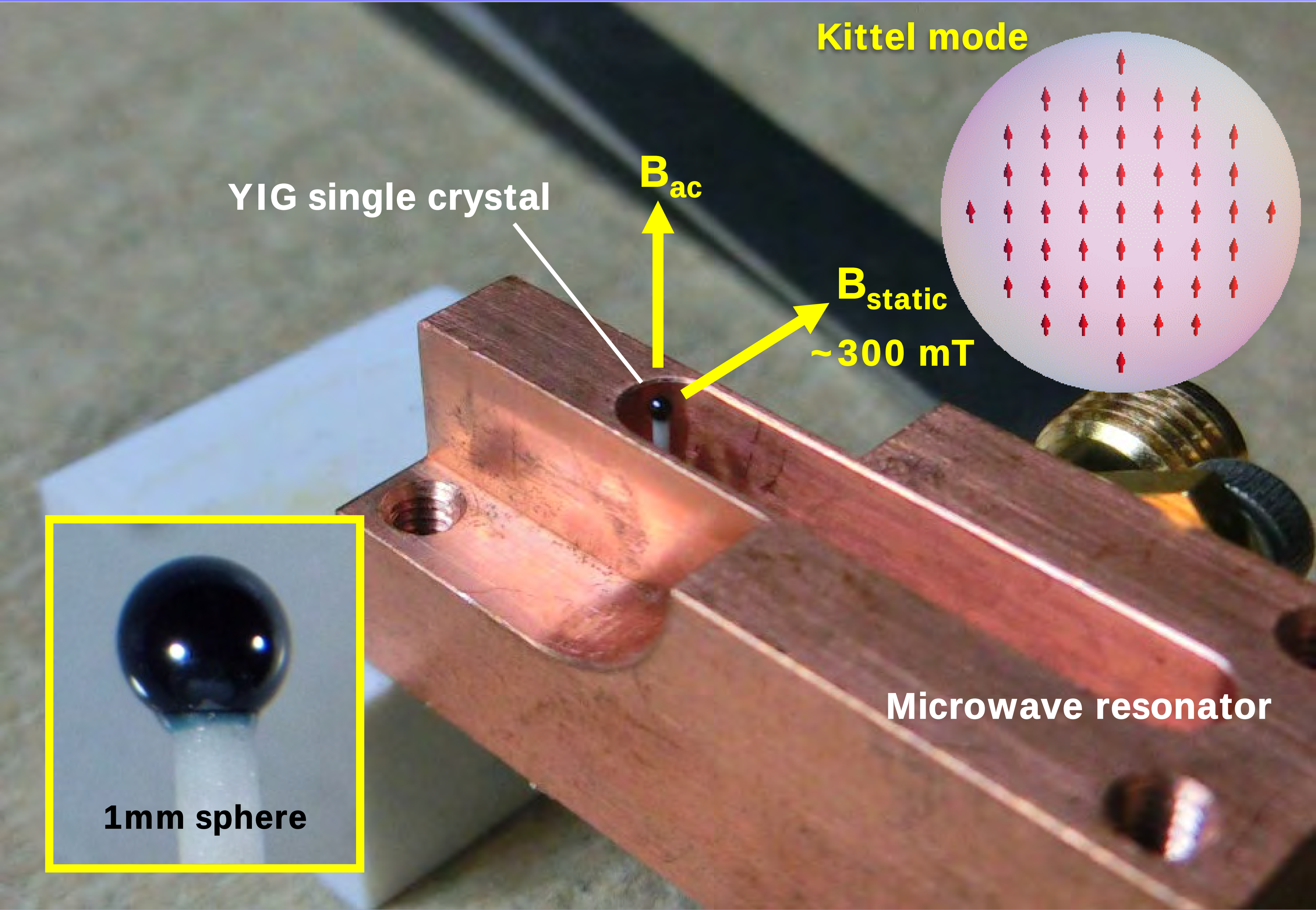


Magnon is a quantum of collective spin excitation in a magnetically ordered system

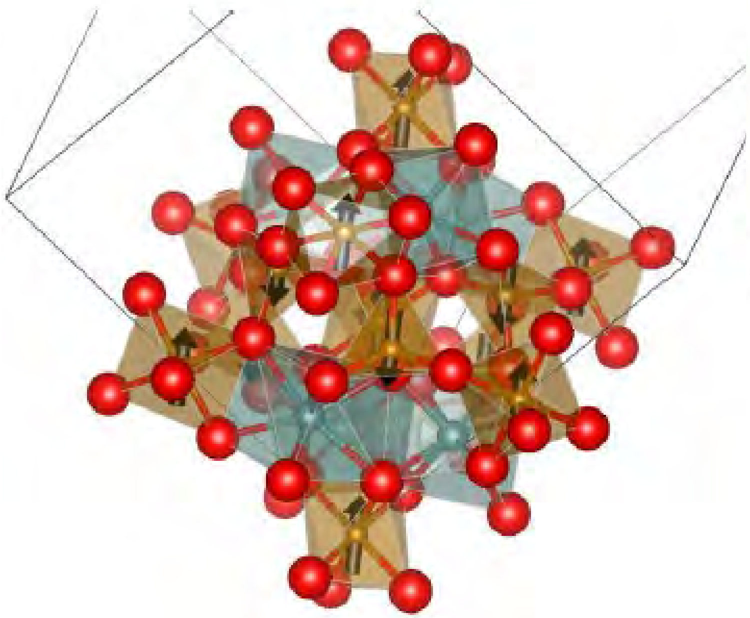
Can we control and detect a single magnon (with an angular momentum of $1\hbar$) in a macroscopic object?

Yes, we can, with an aid of a superconducting qubit.

# Hybrid with ferromagnet magnons



# 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: $2.1\times10^{22}$ cm$^{-3}$

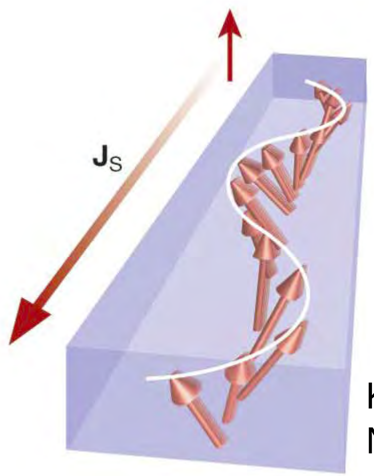
Microwave oscillators


CANDOX Corporation

Optical isolators


FDK Corporation

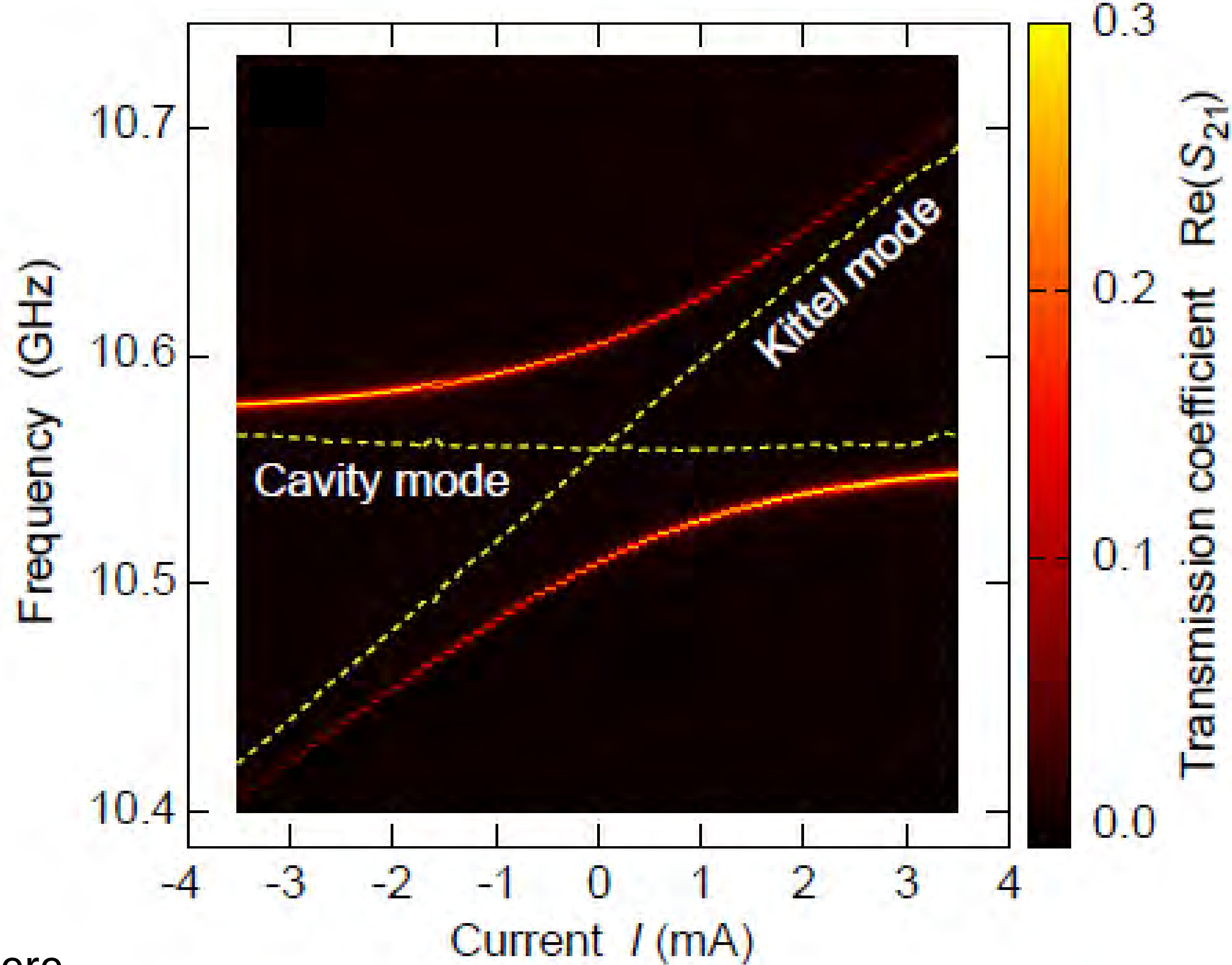
Spintronics




Kajiwara et al.
Nature 2010

# Magnetic-field dependence

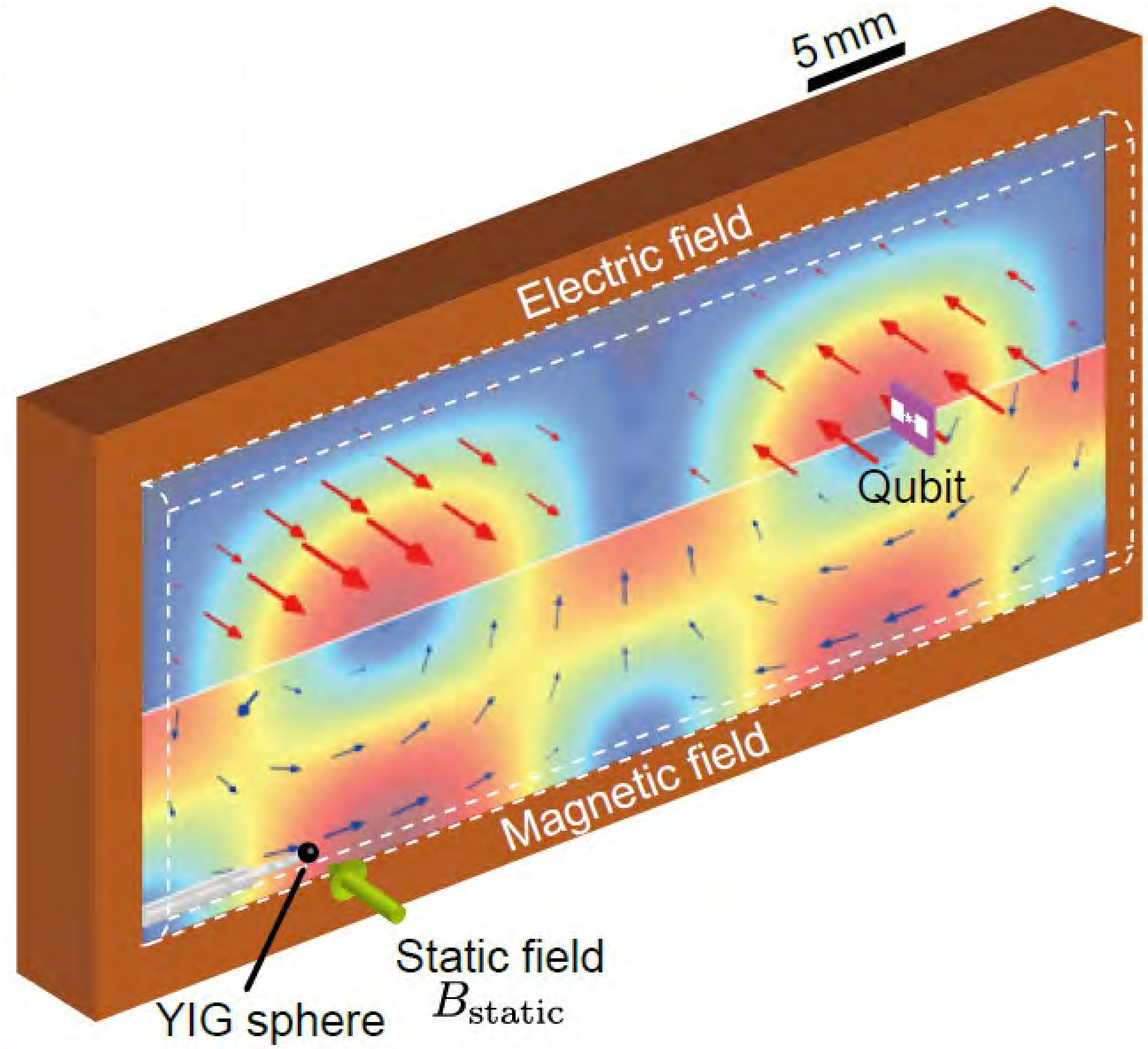
Low temperature ~ 10 mK; ~0 thermal magnon & photon
Microwave power: ~0.9 photons in cavity



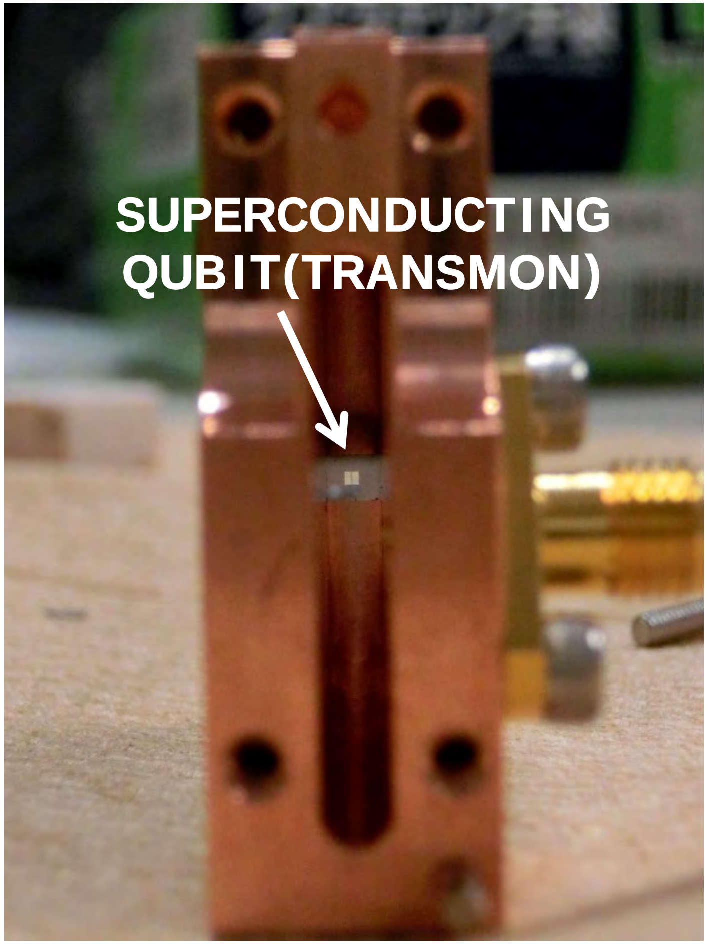

0.5-mm sphere

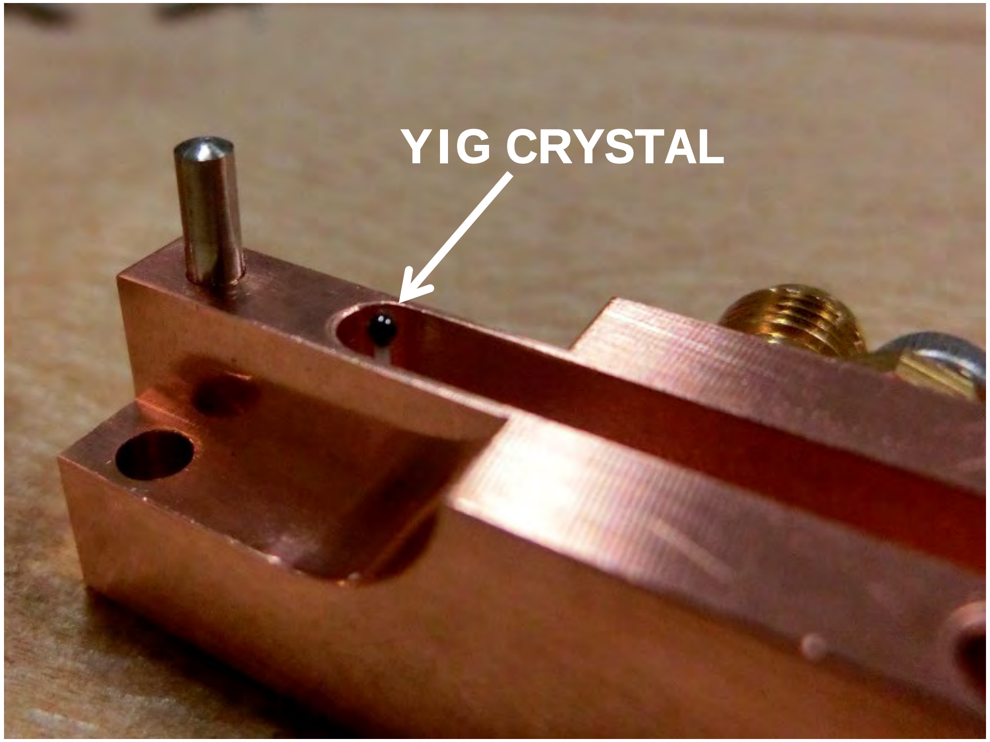
Y. Tabuchi et al. PRL 113, 083603 (2014)

# Coupling with a superconducting qubit

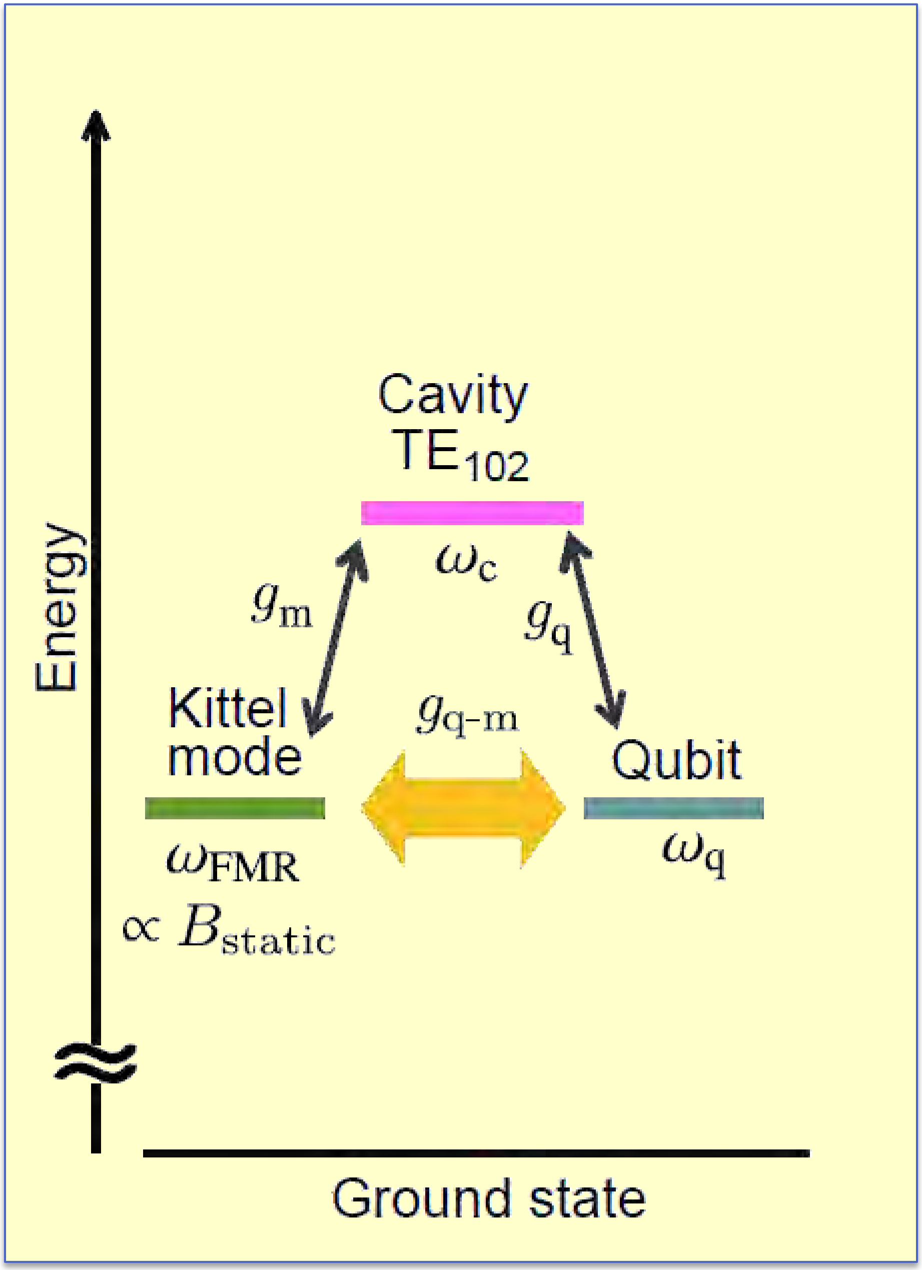


# Inside the cavity



# Qubit-magnon coupling




Qubit-magnon coupling
mediated by virtual photon excitation
in cavity

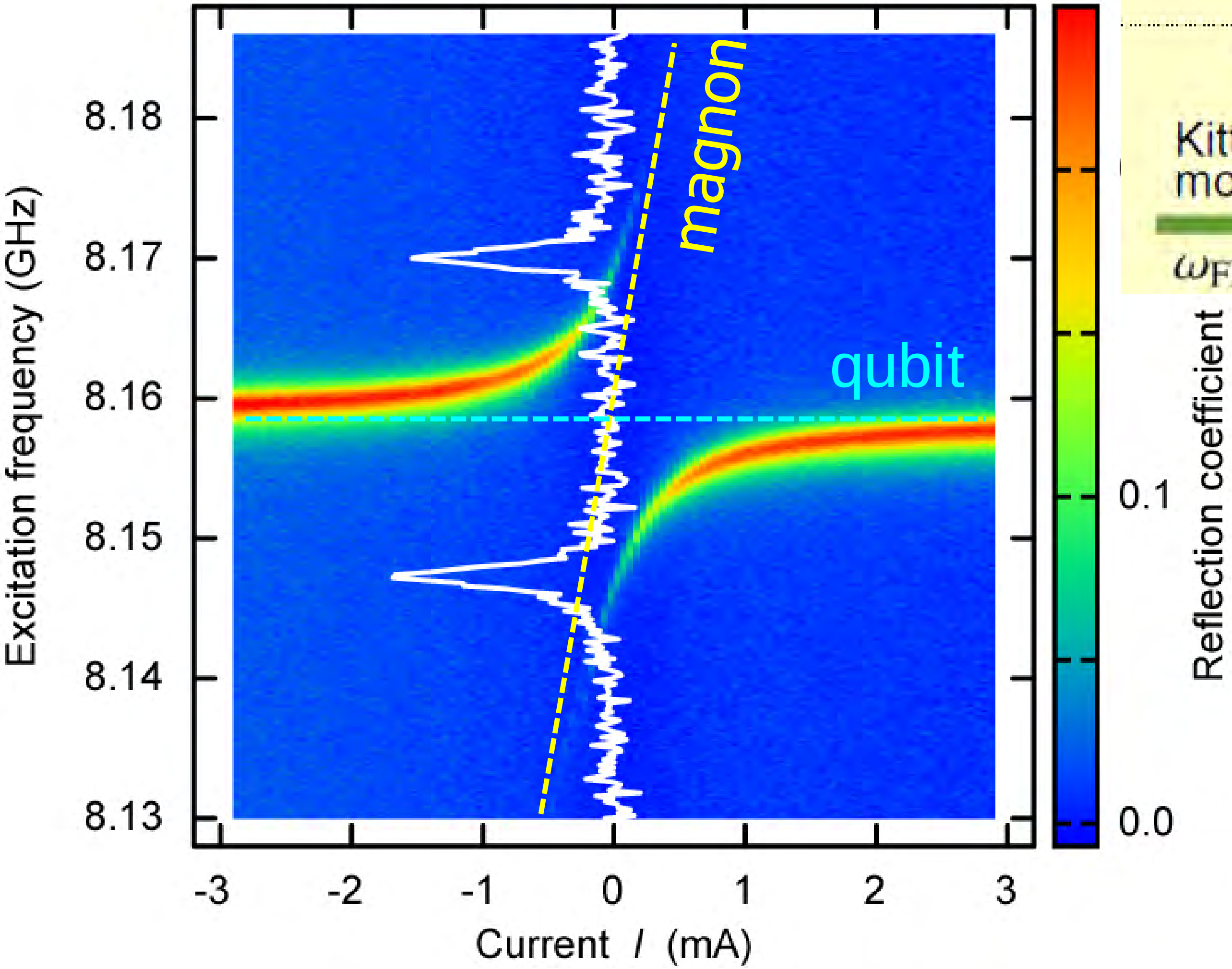
$$\hat{\mathcal{H}}_\text{q-m}/\hbar \sim g_\text{q-m}\left(\hat{a}_\mathrm{m}^\dagger \hat{\sigma}_- + \hat{a}_\mathrm{m}\hat{\sigma}_+\right)$$

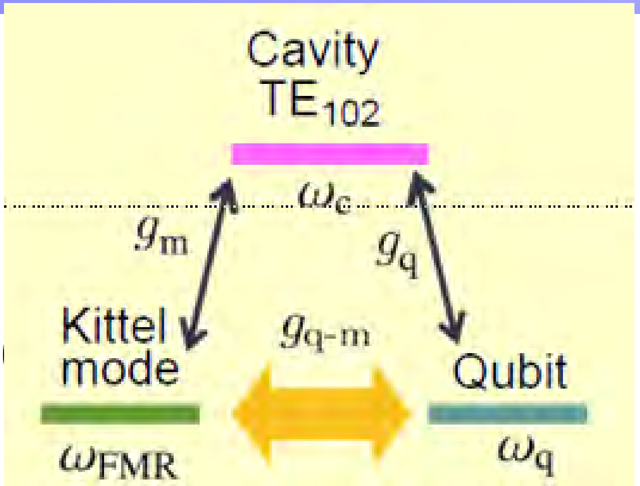
$$g_\text{q-m}/\hbar = \frac{g_\mathrm{q} g_\mathrm{m}}{\omega_\mathrm{c} - \omega_\mathrm{q}}$$

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

# Vacuum Rabi splitting

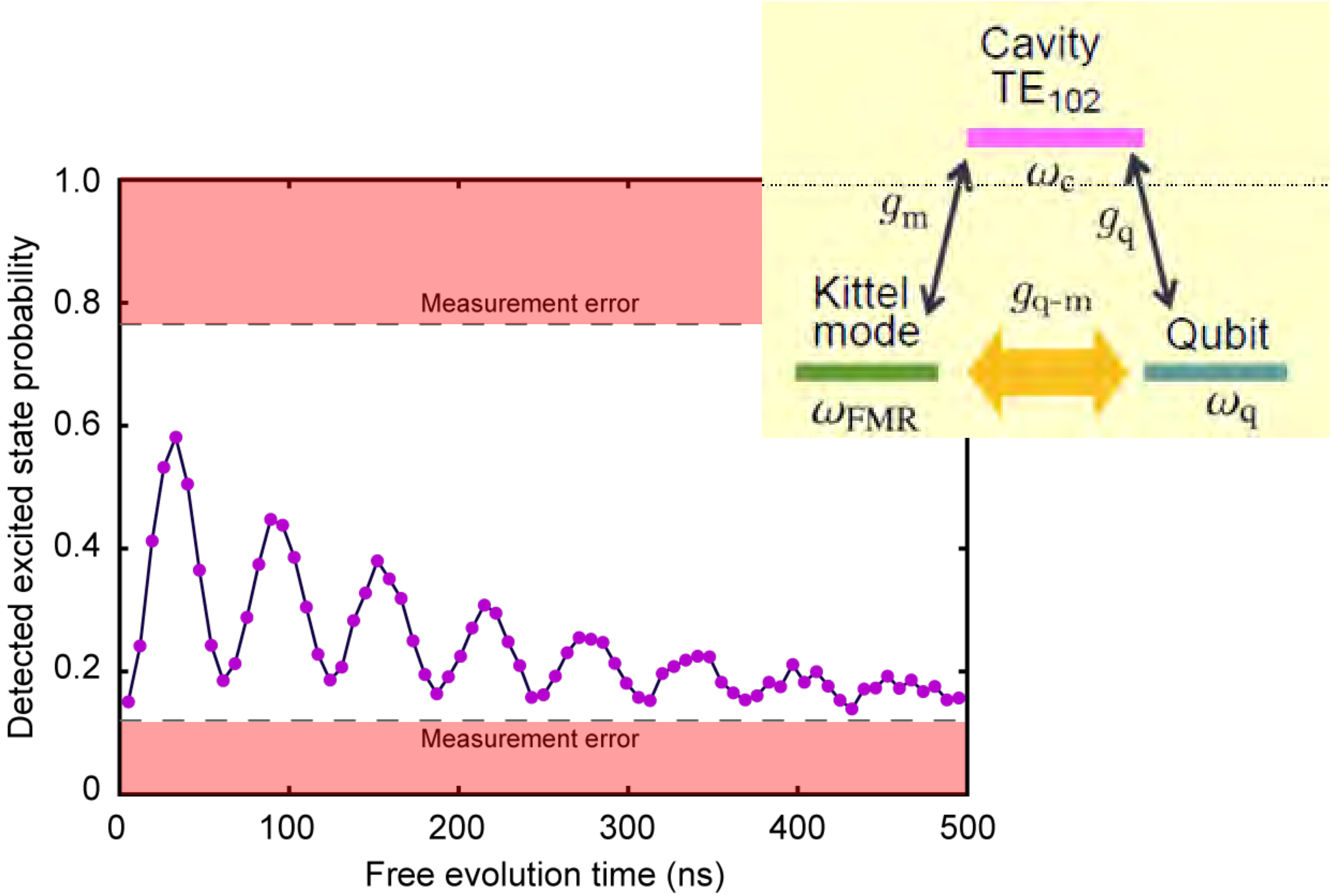
Strong coupling regime $g_{\text{q-m}} \gg \gamma_{\text{q}}, \gamma_{\text{m}}$




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

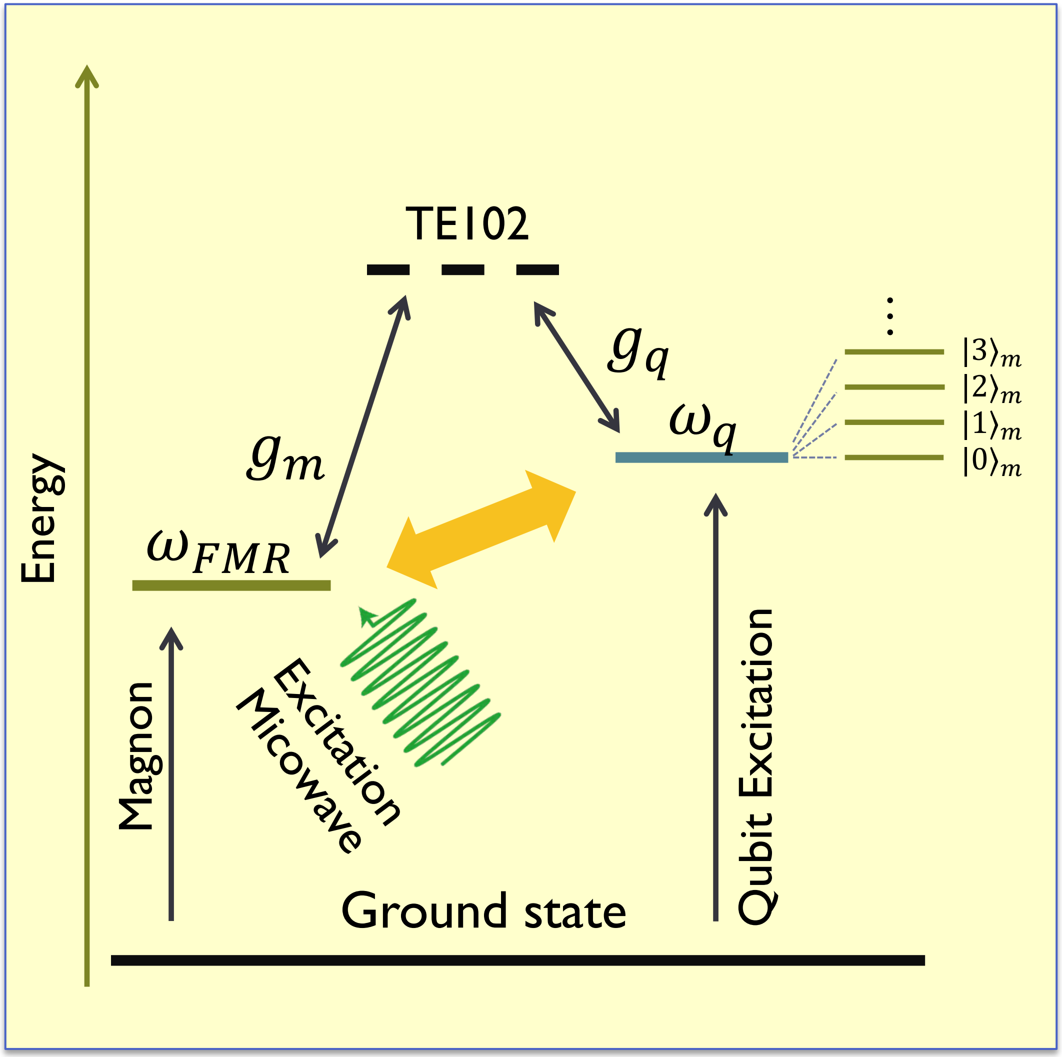
# Vacuum Rabi oscillations

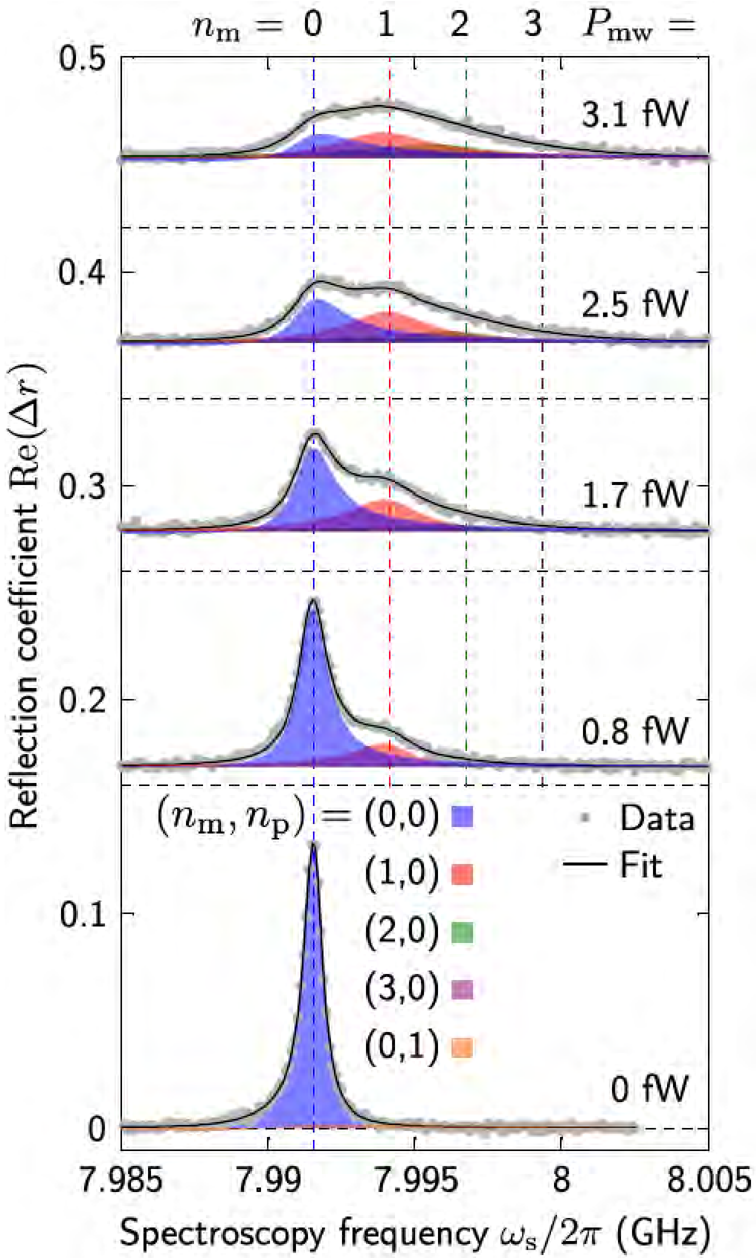



Y. Tabuchi et al. unpublished

# Magnon-number-resolving spectroscopy

Strong dispersive regime $2|\chi_{\text{q-m}}| \gg \gamma_{\text{q}}, \gamma_{\text{m}}$

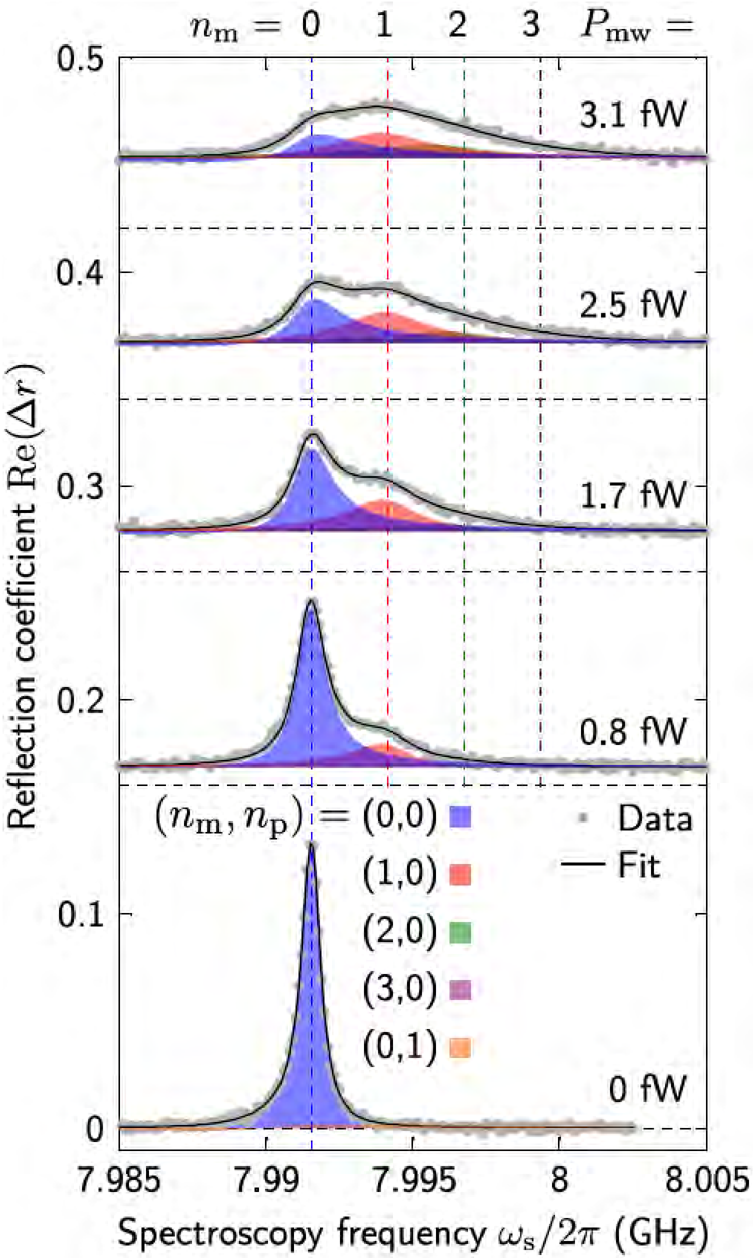


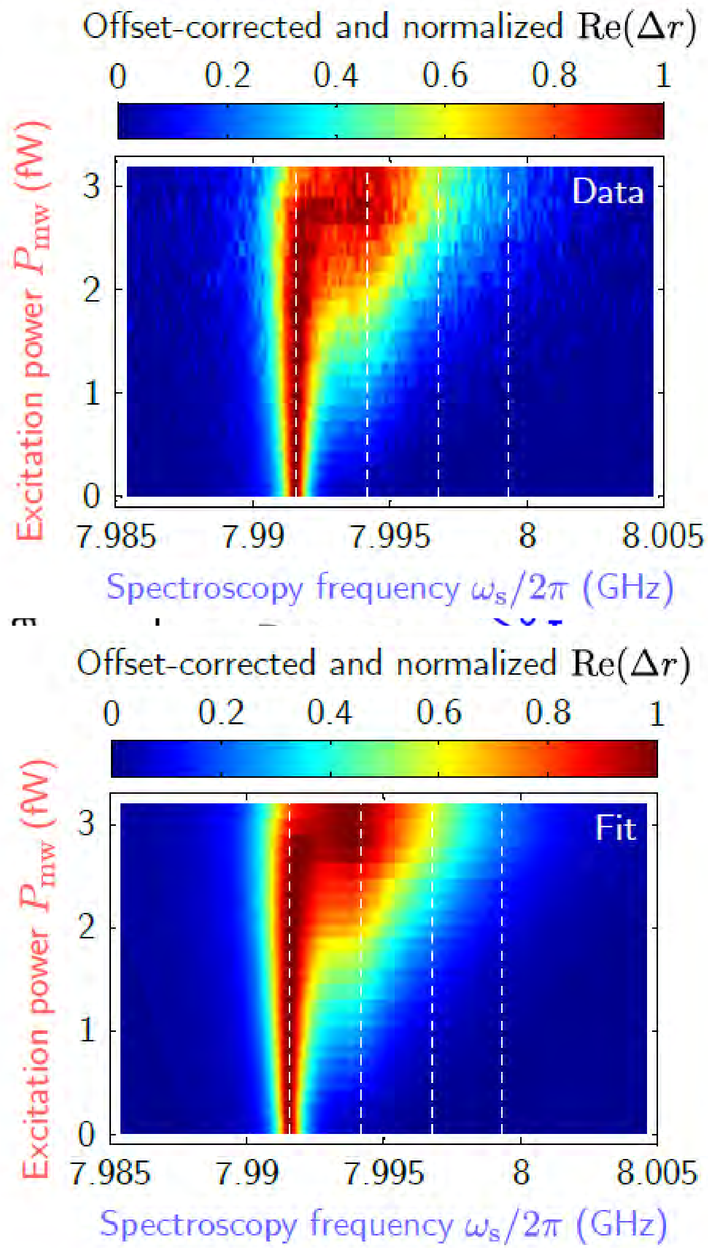





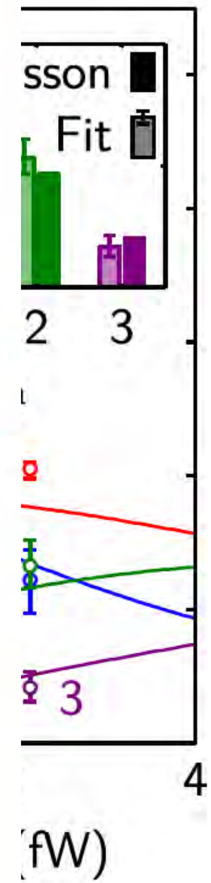
D. Lachance-Quirion et al. Sci. Adv. 3, e1603150 (2017).

# Magnon-number-resolving spectroscopy



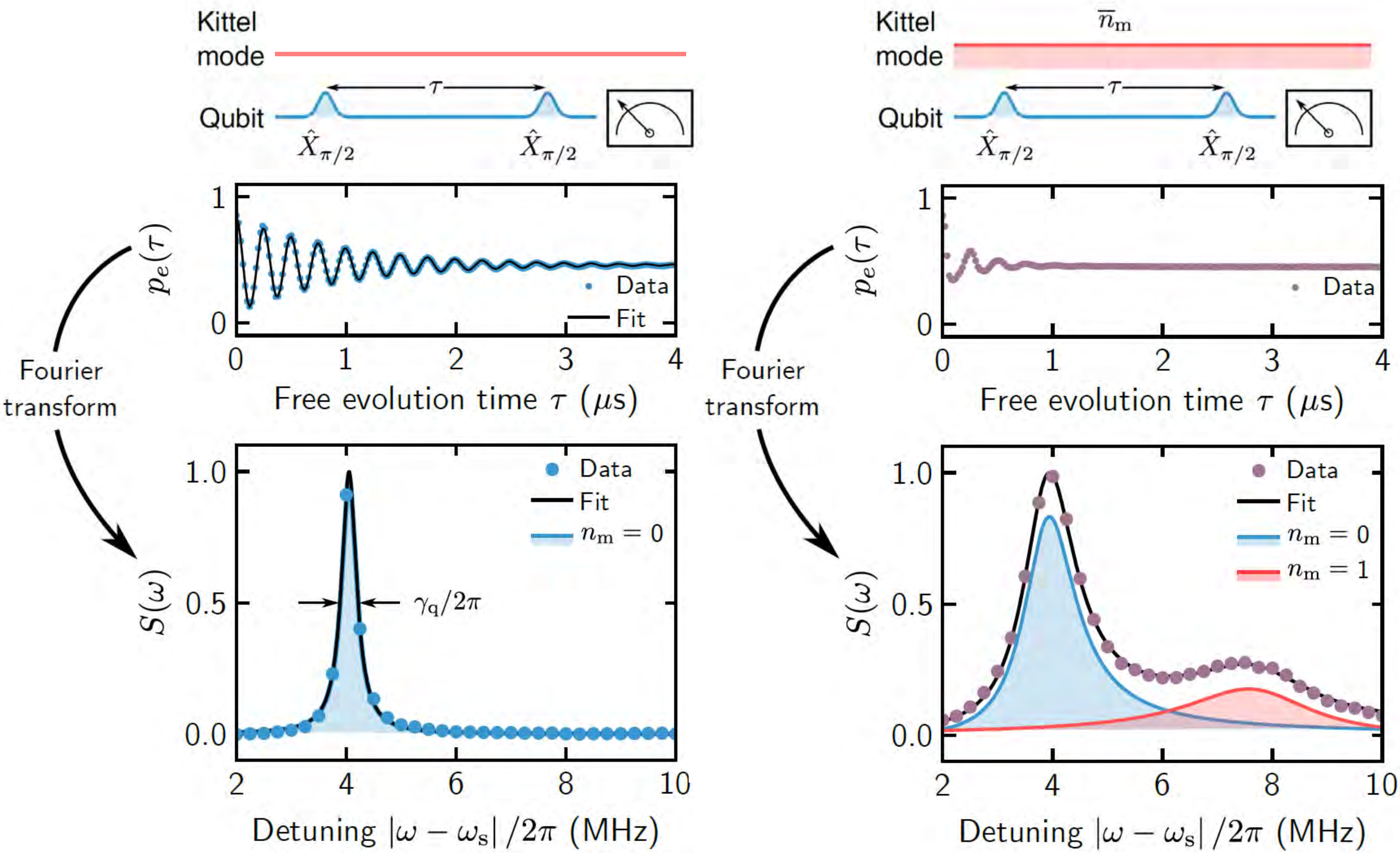

uirion et al.
.50 (2017).




M

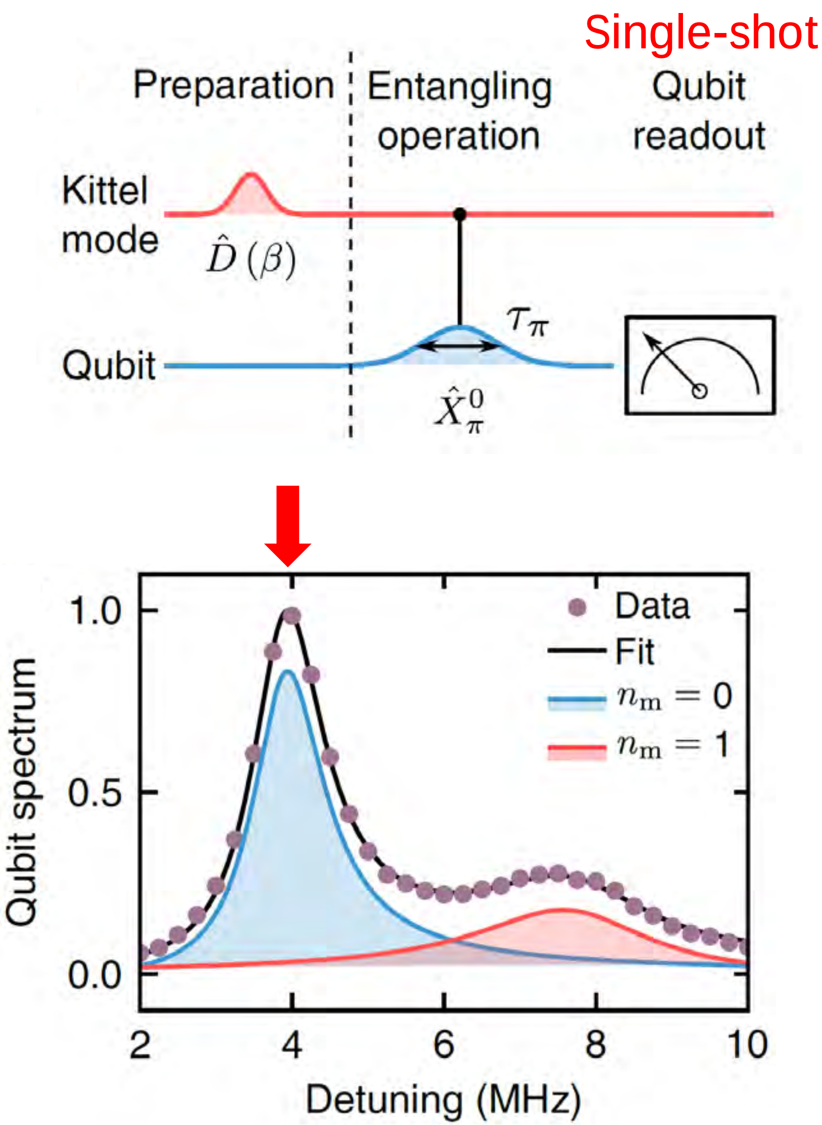
318 (2006) Yale

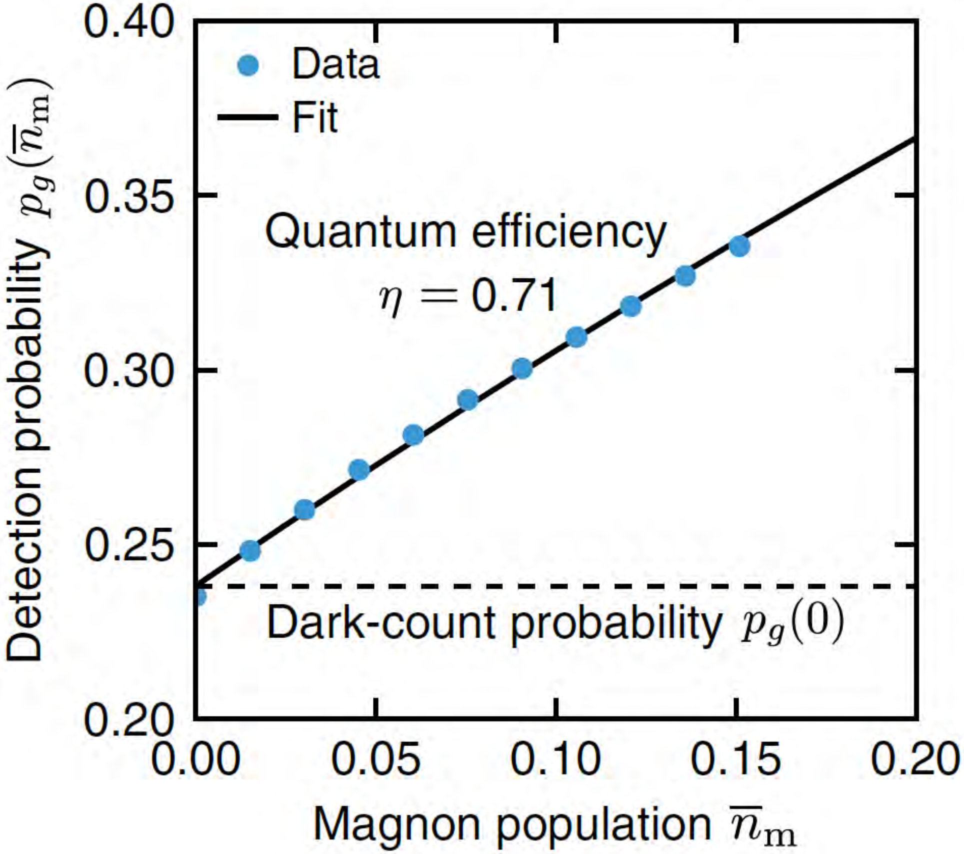
# Magnon number resolving via Ramsey interferometry




D. Lachance-Quirion et al. Applied Physics Express 12, 070101 (2019);
See also D. Lachance-Quirion et al. Sci. Adv. 3, e1603150 (2017)

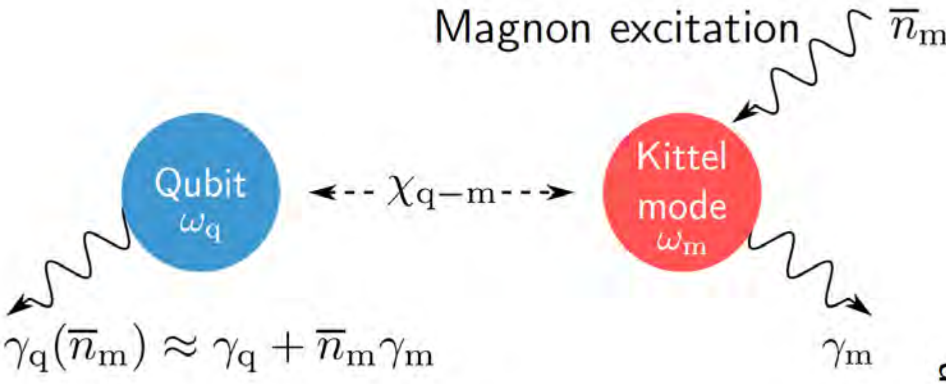
# Single-shot detection of a magnon

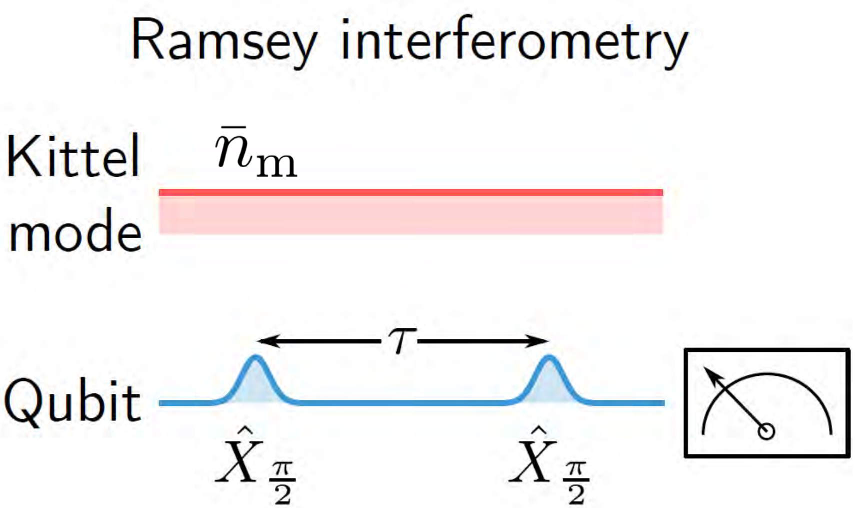


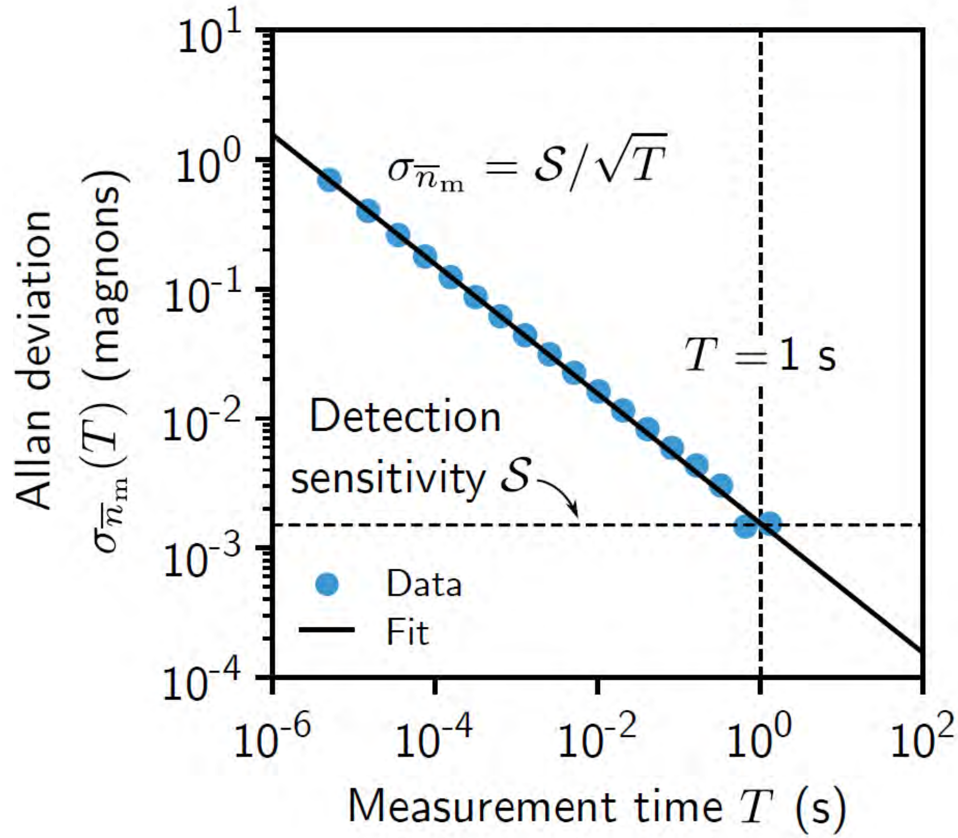

D. Lachance-Quirion et al. Science 367, 425 (2020)

# Dissipation-based quantum sensing




$$S \sim 10^{-3}\ \mathrm{magnon}/\sqrt{\mathrm{Hz}}\ @\,1\,\mathrm{Hz}$$




S. Wolski et al. PRL 125, 117701 (2020)

# Summary

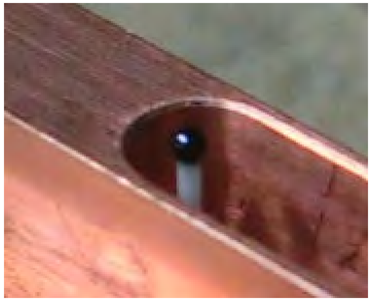
Quantum magnonics with ferromagnet

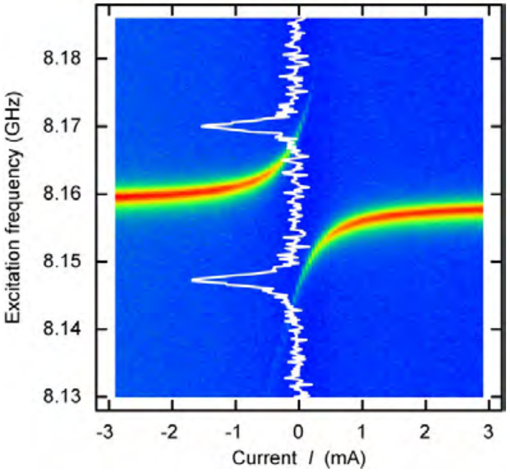
- Strong coupling with superconducting qubit
- Vacuum Rabi splitting/oscillations
- Magnon-number-resolving spectroscopy
- Single-shot detection of a magnon
- Dissipation-based quantum sensing

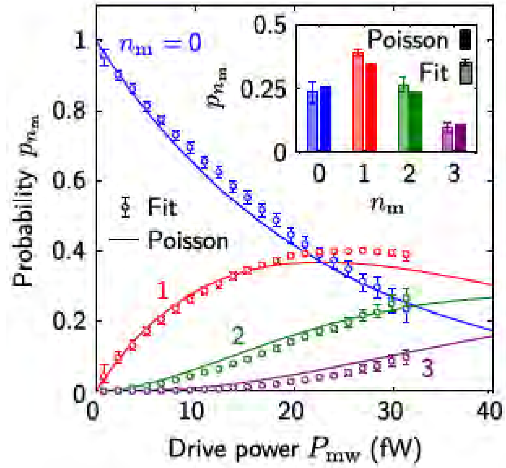
Prospects

- Investigation of magnon decoherence
- Generation of non-classical magnon states
- Applications of magnon quantum sensing
- Axion detection?

Review:
D. Lachance-Quirion et al.
Applied Physics Express 12, 070101 (2019)





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Quantum Information Physics
and Engineering Group @UTokyo

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