CENTER FOR QUANTUM SENSORS

Washington University in St.Louis

Developing New Directions in Fundamental Physics (DND) 2020

Session: New Technologies and Techniques

Superconducting Quantum Sensors and Tests of Quantum Mechanics

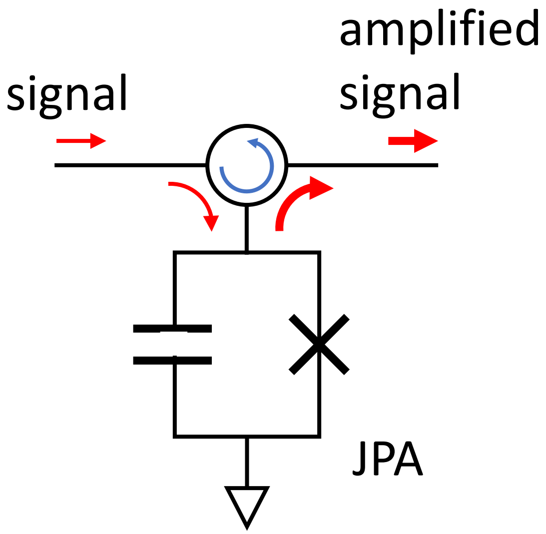
Weijian Chen

Murch group, Department of Physics

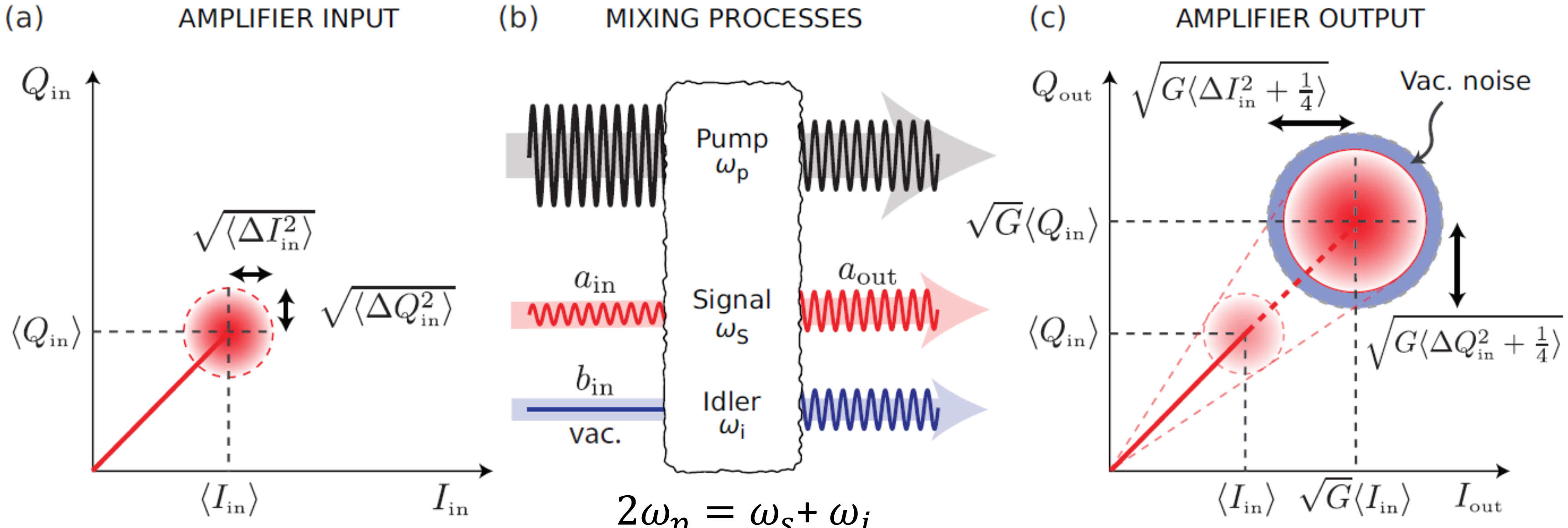
Washington University in St. Louis

Outline

- Quantum limited amplification
  - *Josephson parametric amplifier*
  - *Squeezing generation*
  - *Dark matter axion search*
- Superconducting qubit sensor
  - *Dispersive measurement*
  - *Photon/magnon detector*
  - *Noise mitigation and spectroscopy*
- Non-Hermitian quantum mechanics
  - *Exceptional points*
  - *Exceptional-point sensor*
  - *Non-Hermitian superconducting qubit*

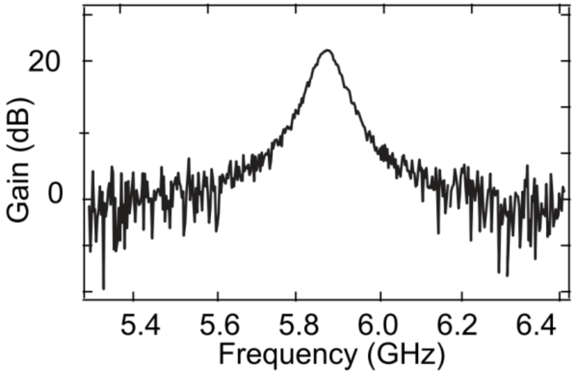


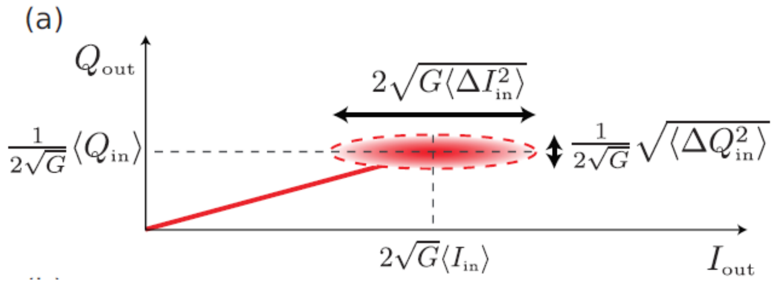
Parametric amplification

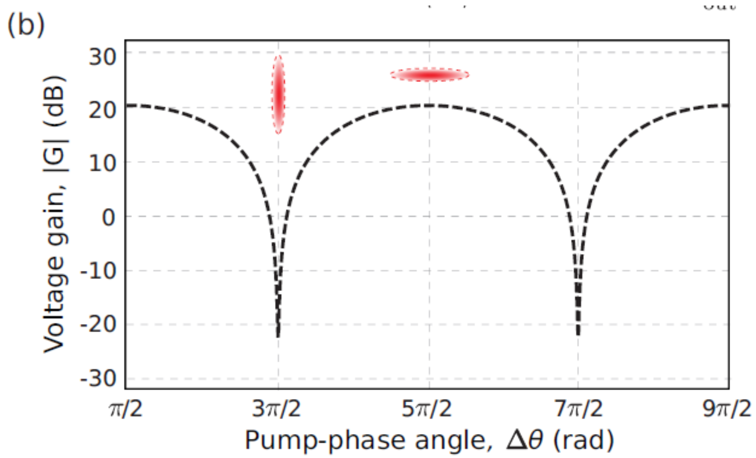


$$2\omega_p = \omega_s + \omega_i$$

Phase-preserving amplification



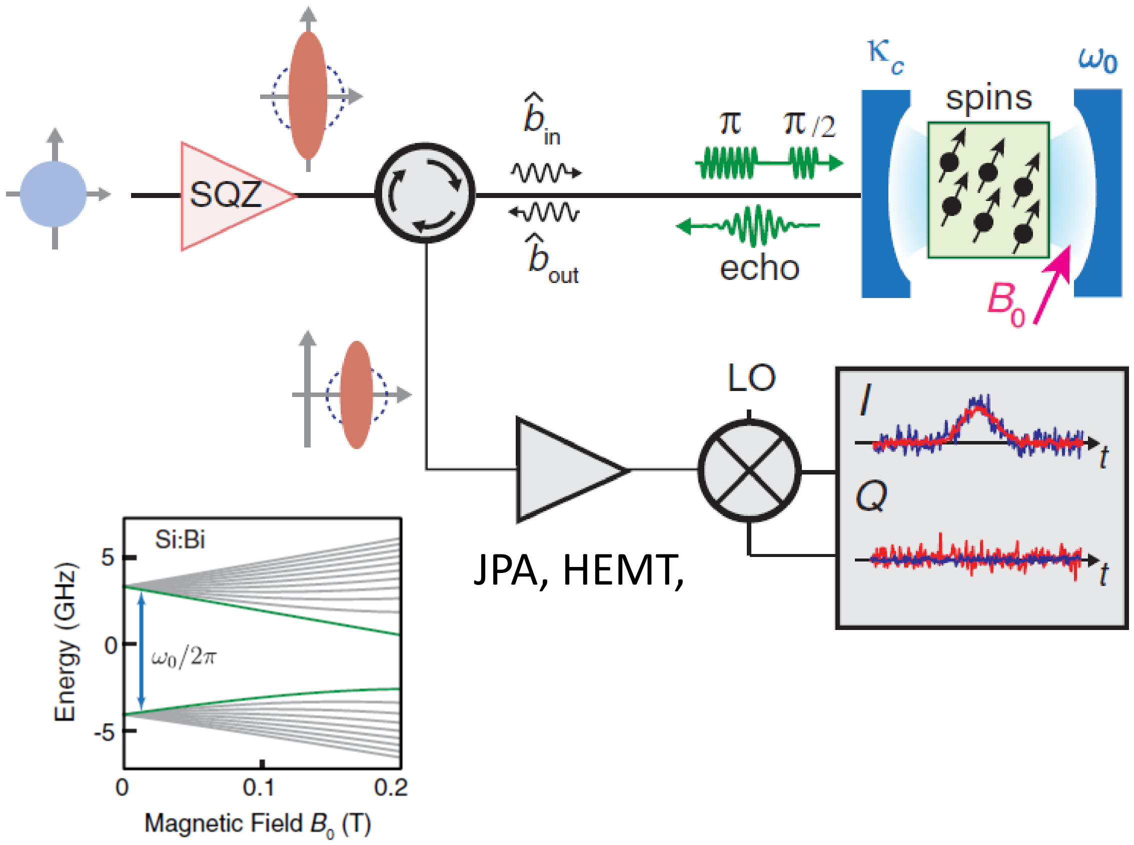


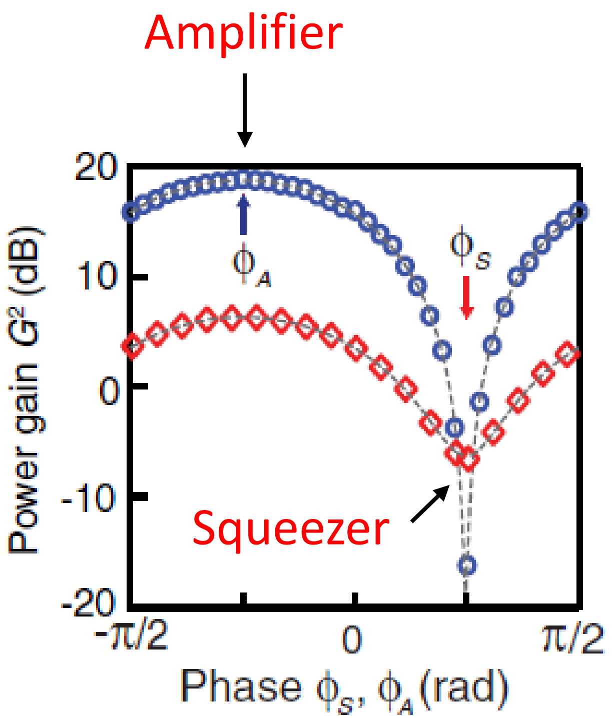


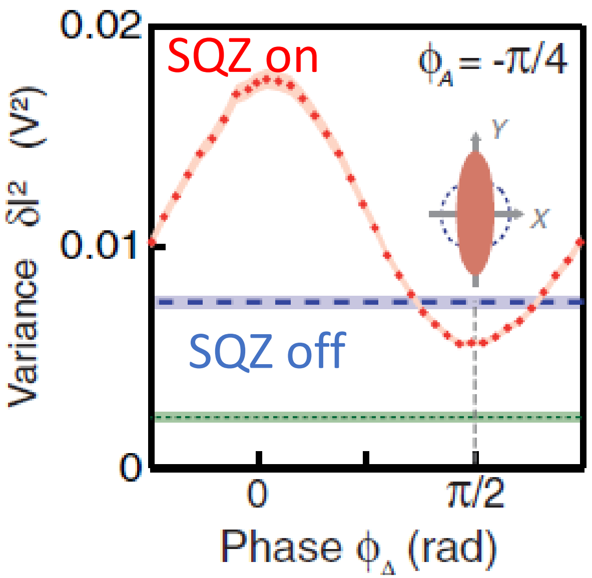
Phase-sensitive amplification

Krantz, *et al. Appl. Phys. Rev.* **6**, 021318 (2019).

Magnetic resonance with squeezed microwaves







Bienfait, *et al. Phys. Rev. X* **7**, 041011 (2017).

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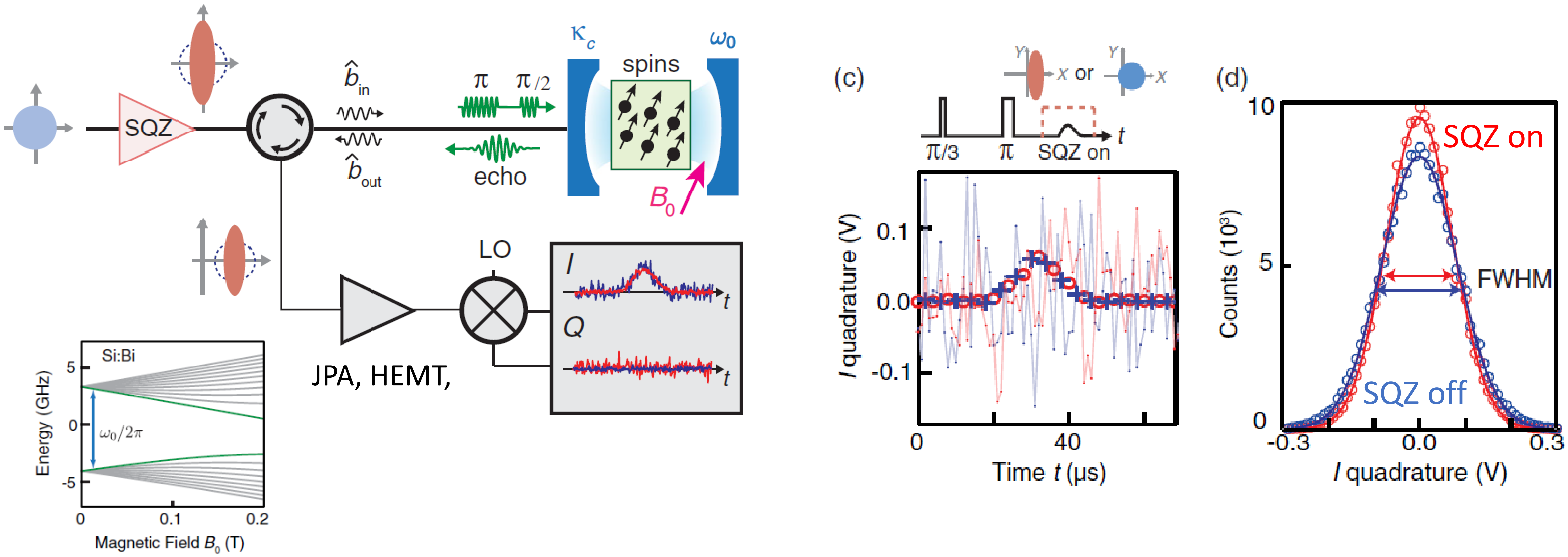
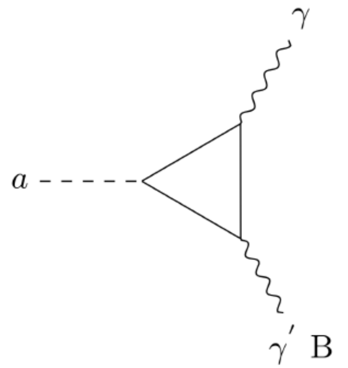
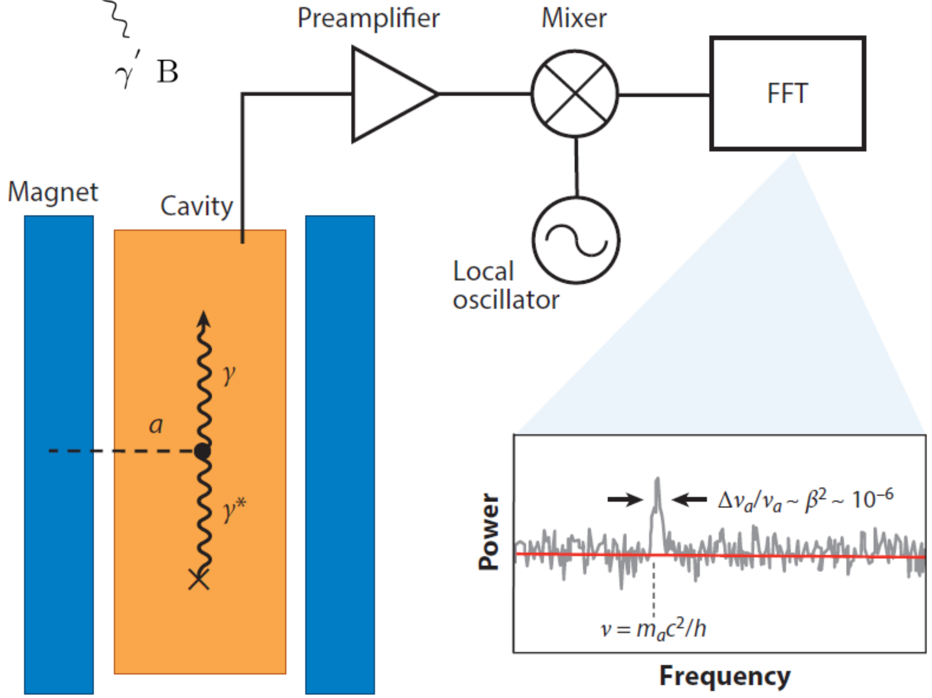
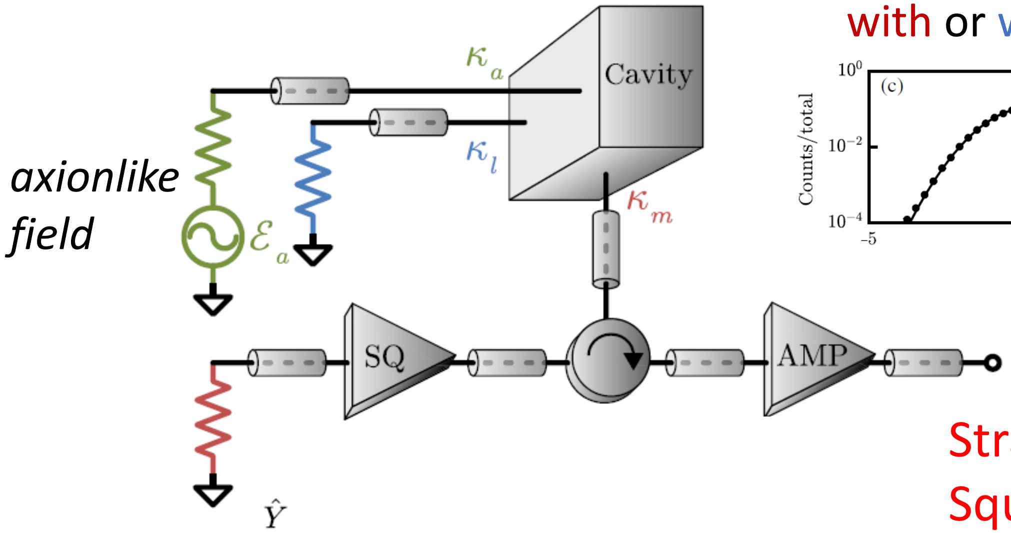


Bienfait, *et al. Phys. Rev. X* **7**, 041011 (2017).

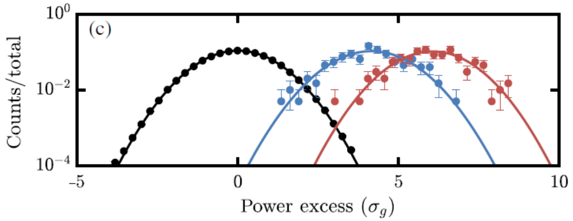
Accelerate dark matter axion search



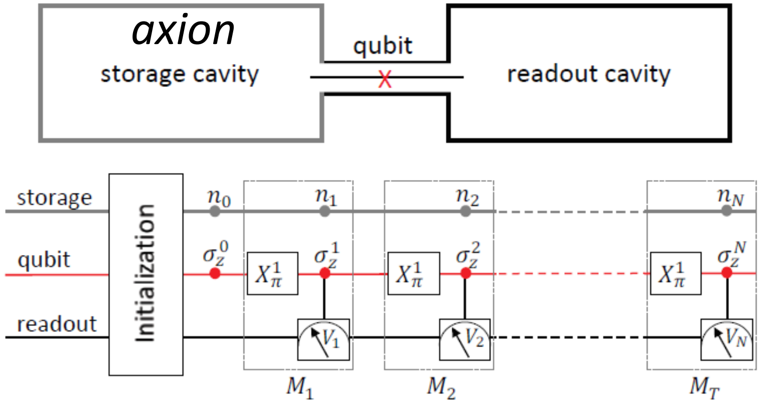




with or without squeezing



Strategy I: Squeezed vacuum



Strategy II: QND single photon detection

Graham *et al., Annu. Rev. Nucl. Part. Sci.* **65**, 485-514 (2015).

Zheng *et al.*, arXiv:1607.02529

Malnou *et al., Phys. Rev. X* **9**, 021023 (2019).

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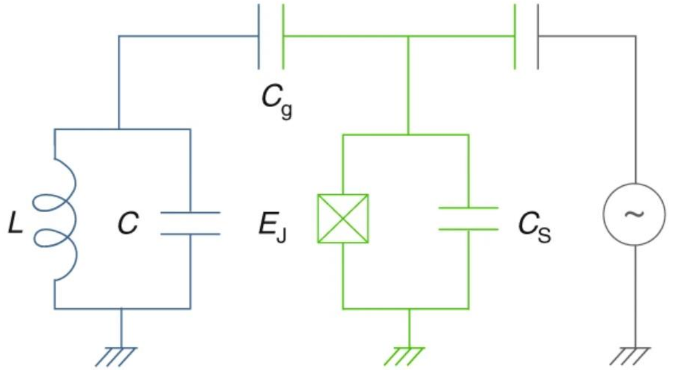
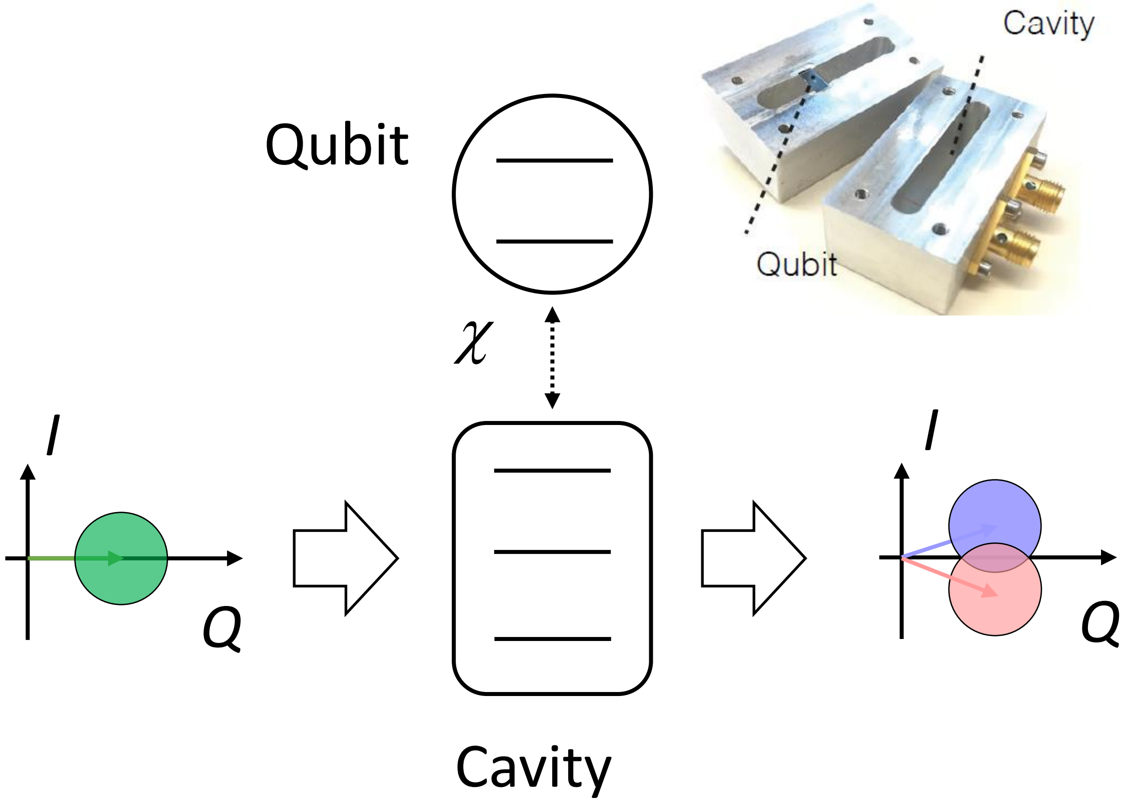
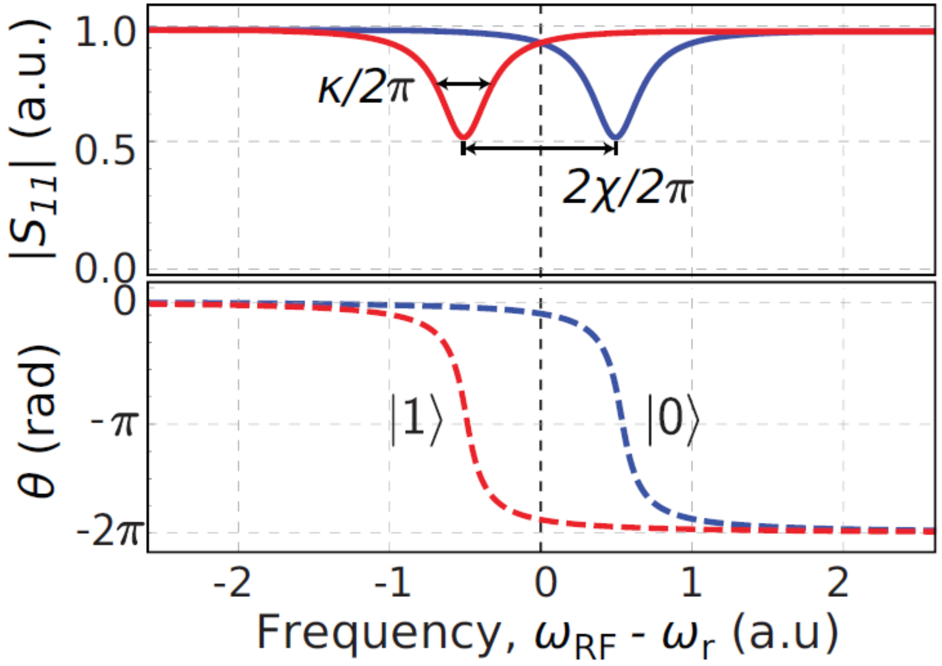


Blais *et al.*, *Nat. Phys.* **16**, 247 (2020)

Dispersive measurement





Dispersive approximation

$$H = \hbar\omega_c\left(a^\dagger a + \tfrac{1}{2}\right) + \frac{\hbar\omega_q}{2}\sigma_z + \hbar\chi\left(a^\dagger a + \tfrac{1}{2}\right)\sigma_z \quad = \hbar(\omega_c + \chi\sigma_z)\left(a^\dagger a + \tfrac{1}{2}\right) + \frac{\hbar\omega_q}{2}\sigma_z$$

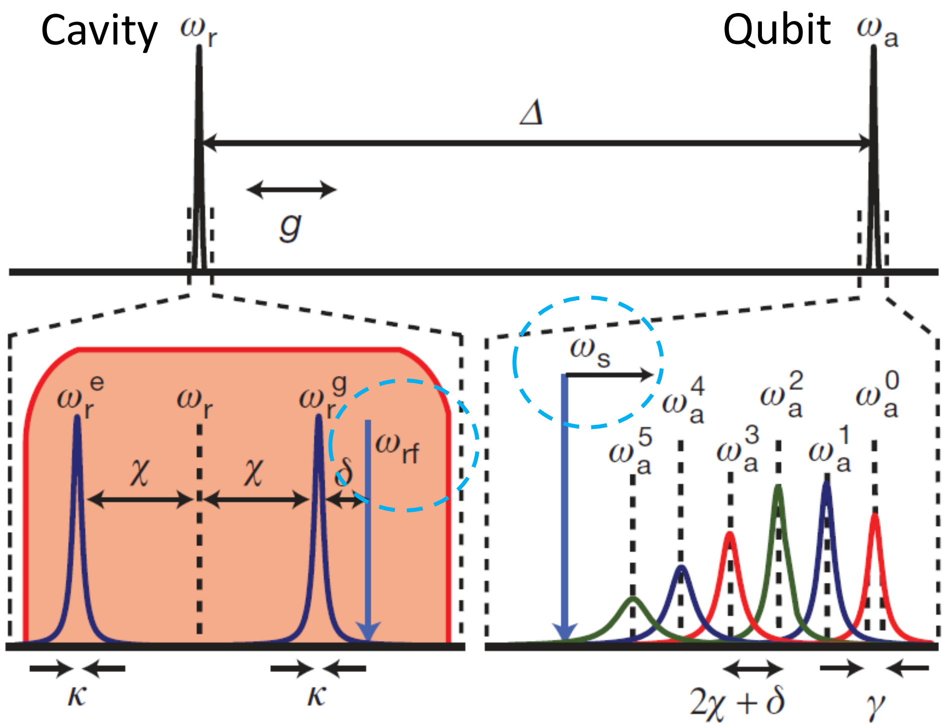
Krantz, *et al., Appl. Phys. Rev.* **6**, 021318 (2019).

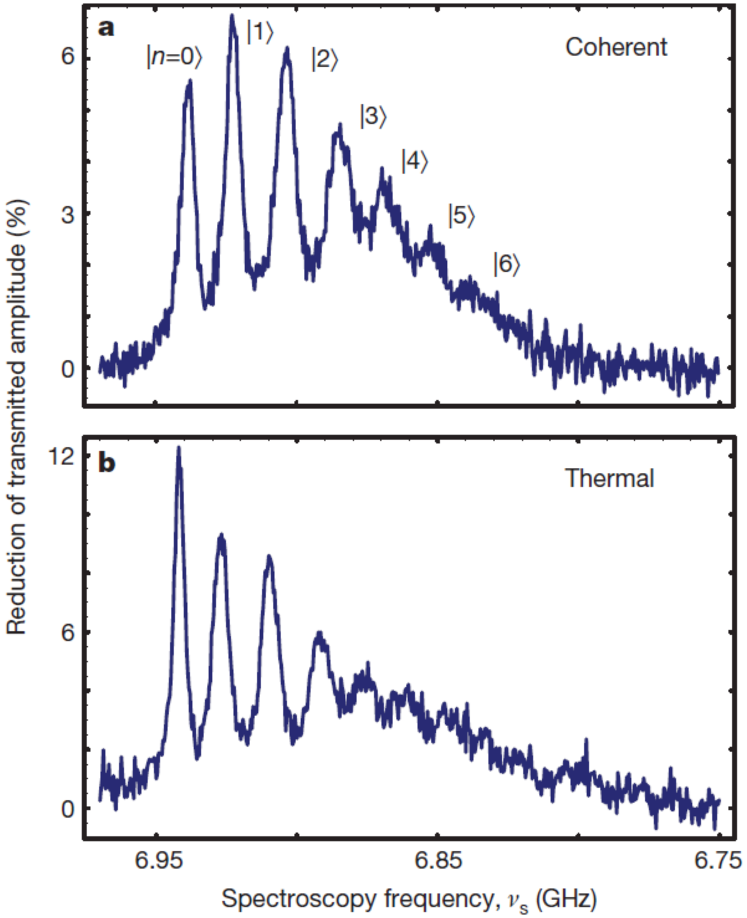
Resolving photon number states

$$H = \hbar\omega_c\left(a^\dagger a + \tfrac{1}{2}\right) + \frac{\hbar\omega_q}{2}\sigma_z + \hbar\chi\left(a^\dagger a + \tfrac{1}{2}\right)\sigma_z$$

$$= \hbar\omega_c\left(a^\dagger a + \tfrac{1}{2}\right) + \hbar\left(\frac{\omega_q}{2} + \chi a^\dagger a + \tfrac{1}{2}\chi\right)\sigma_z$$

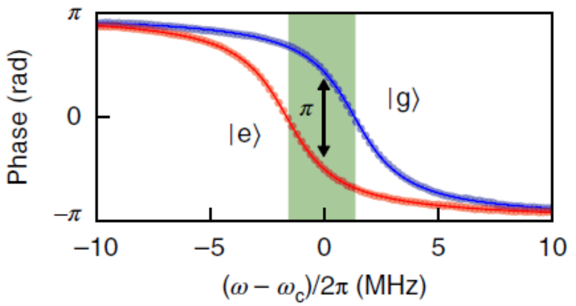
ac-Stark shift

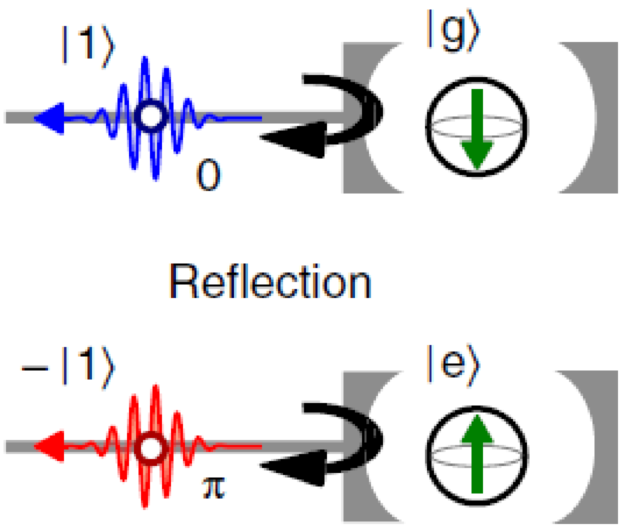




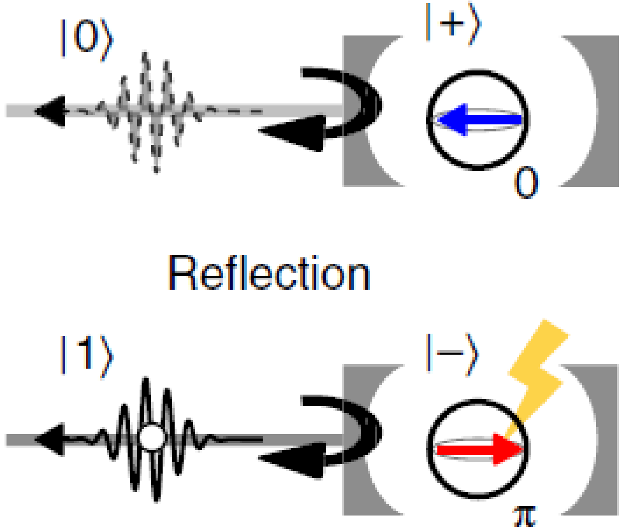
Schuster *et al.*, *Nature* **445**, 515-518 (2007).

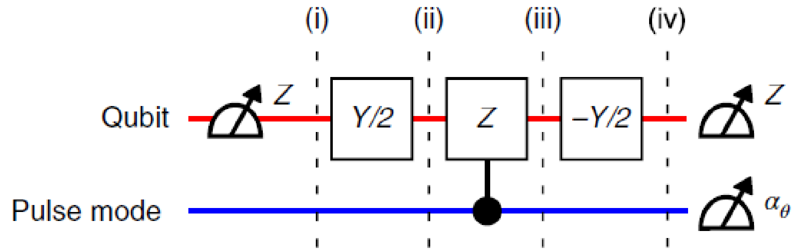
Detection of an itinerant photon



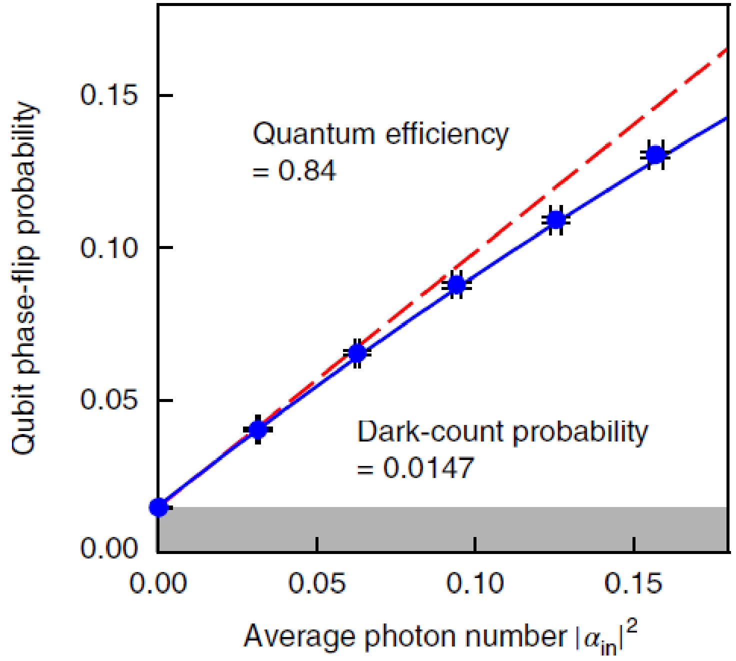


Control-Z gate



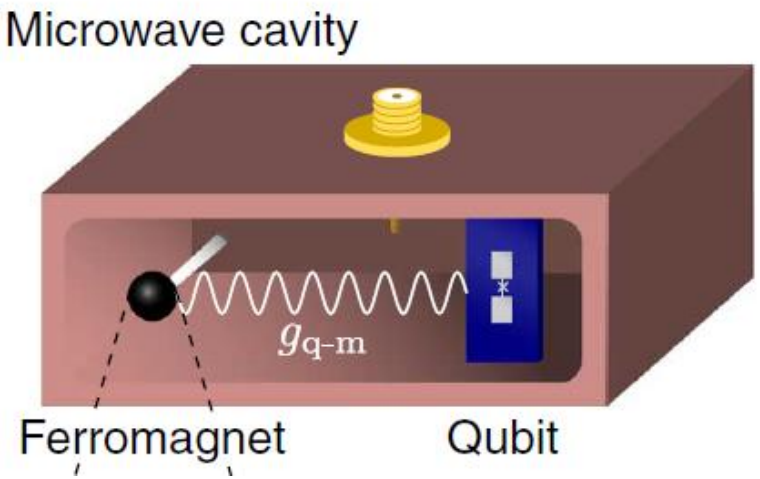


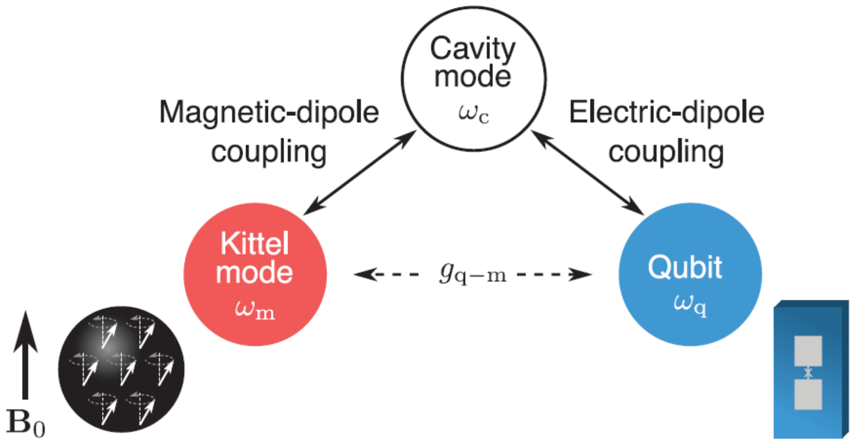
$p_0|0\rangle + p_1|1\rangle$

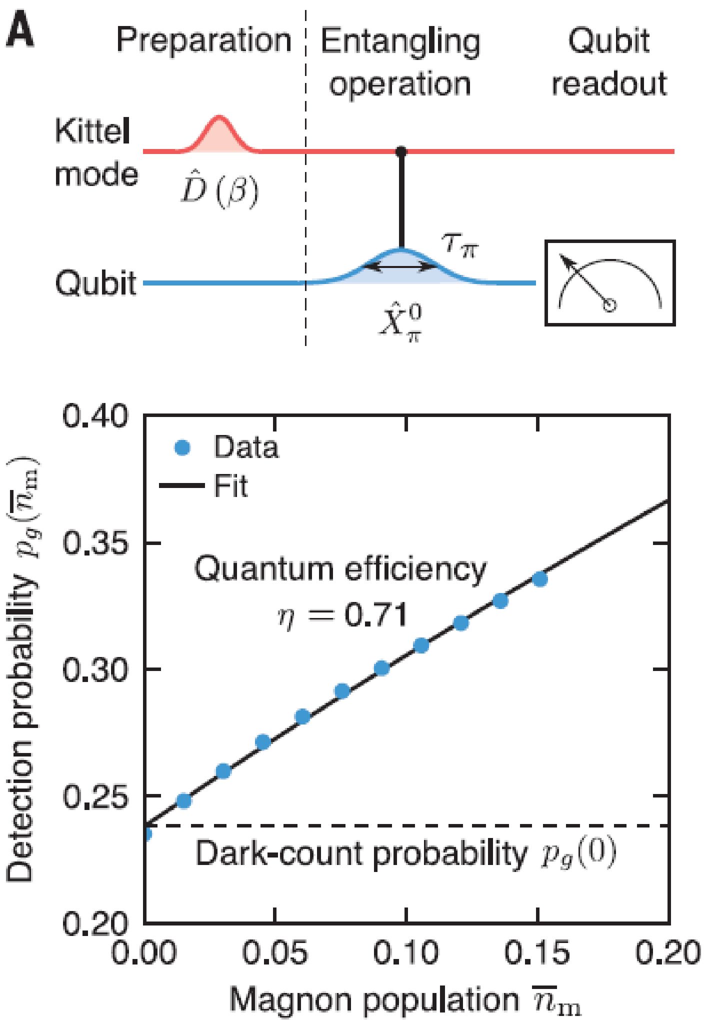


Kono *et al.*, *Nat. Phys.* **14**, 546-549 (2018).

Detection of single magnon







Lachance-Quirion *et al.*, *Sci. Adv.* **3**:e1603150 (2017);
Lachance-Quirion *et al.*, *Science* **367**, 425-428 (2020).

Noise mitigation and spectroscopy

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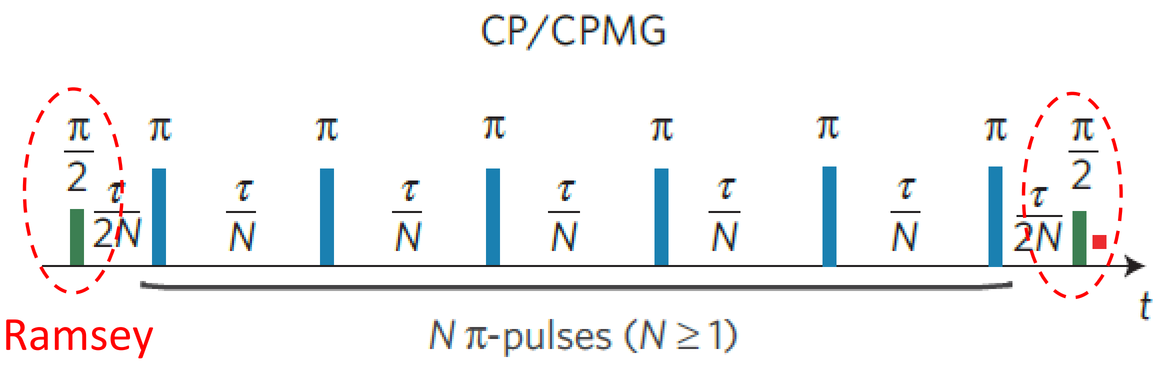
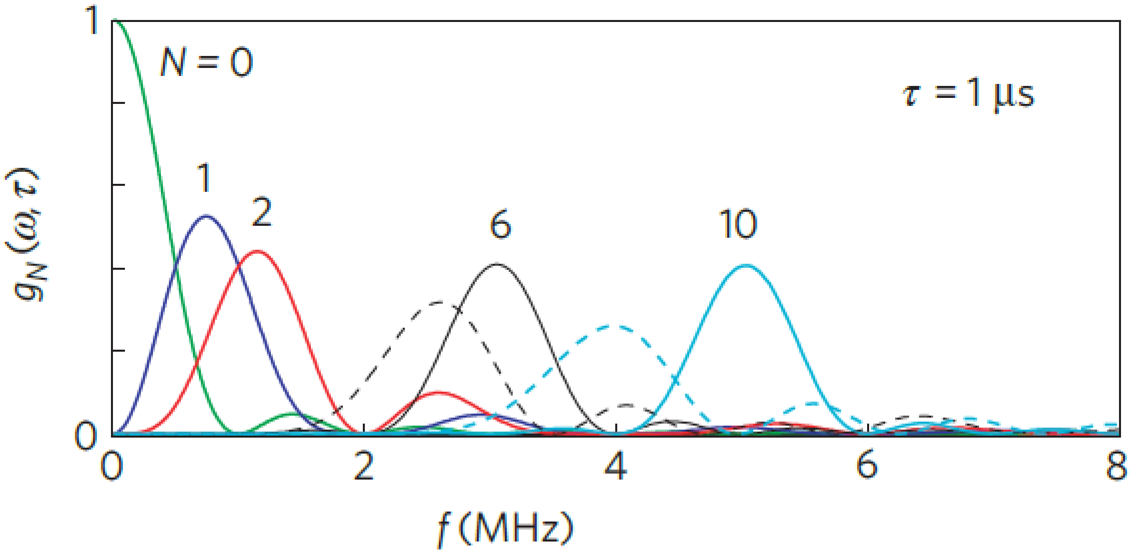
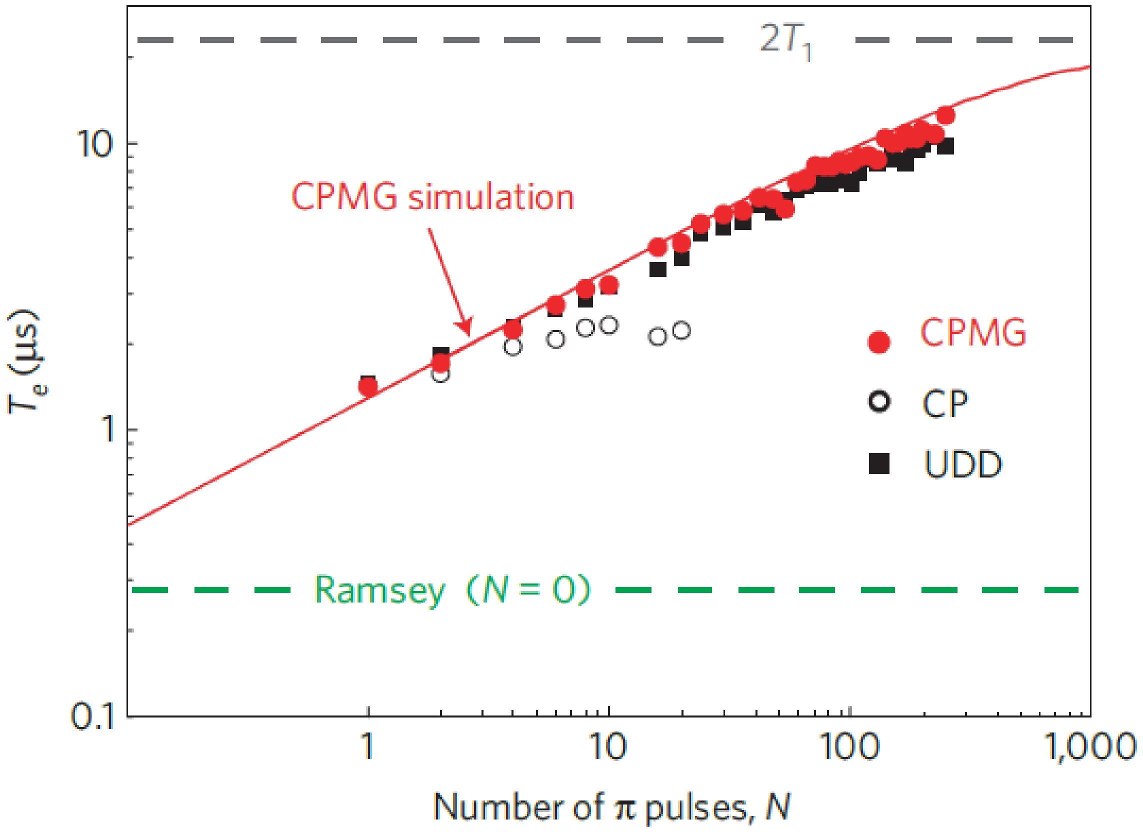


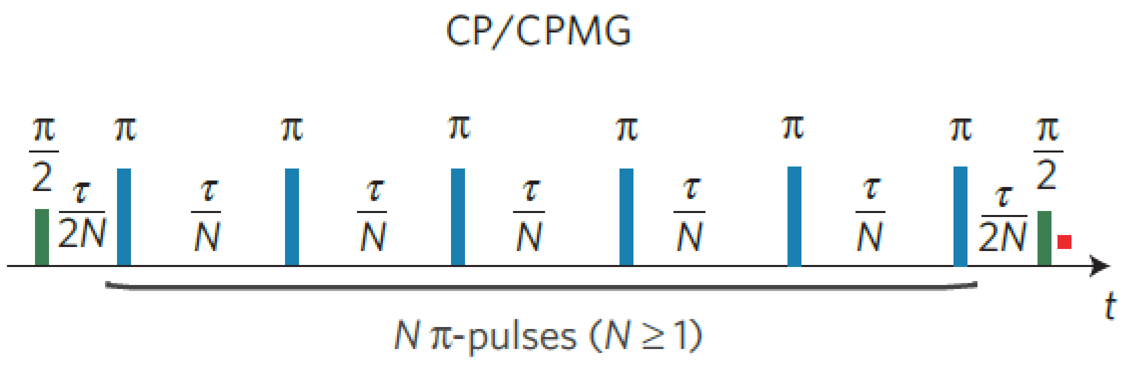
Noise-shaping filter function





Degen *et al.*, *Rev. Mod. Phys.* **89**, 035002 (2017);
Bylander *et al.*, *Nat. Phys.* **7**, 565 (2011).

Noise mitigation and spectroscopy



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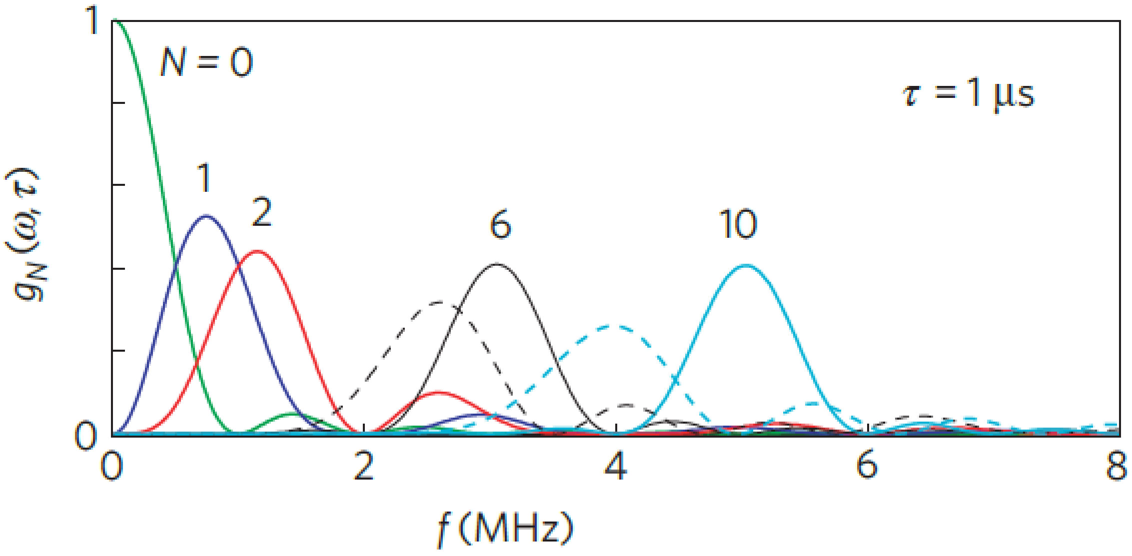

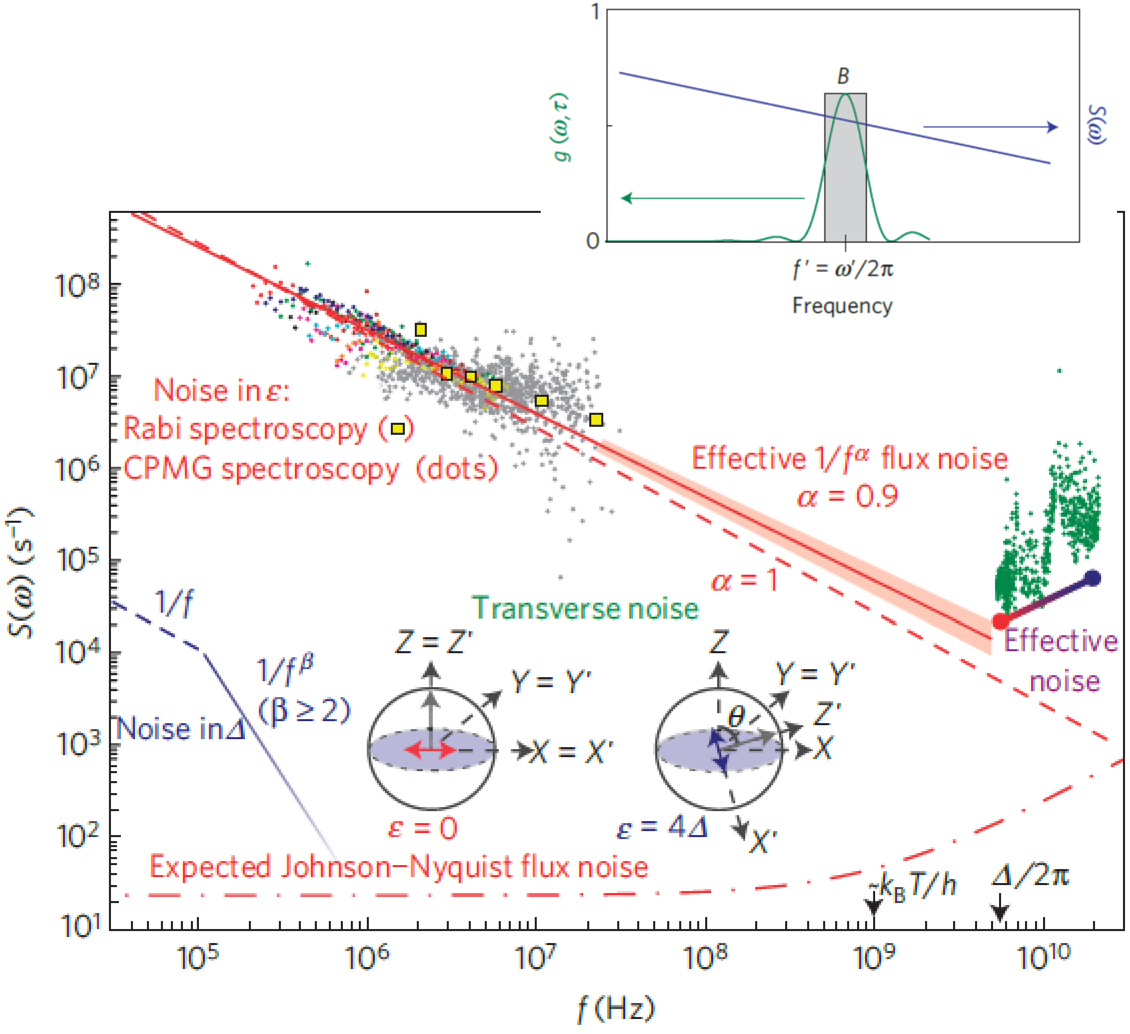

Bylander *et al.*, *Nat. Phys.* **7**, 565 (2011).

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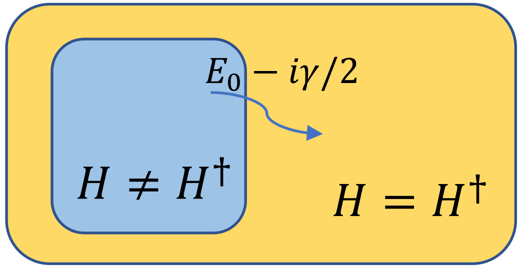
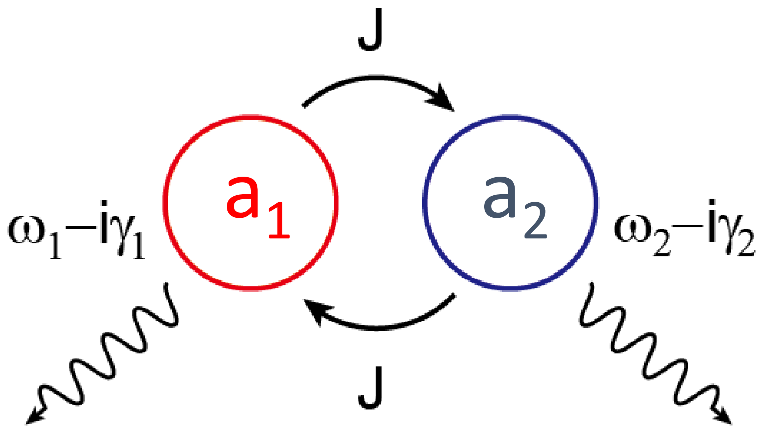
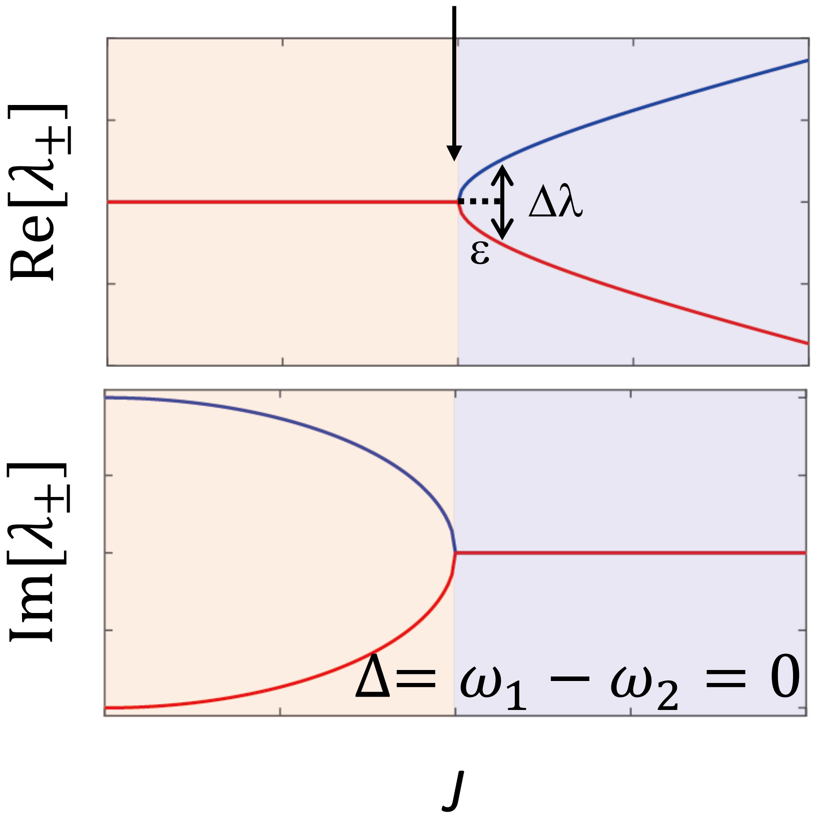


Non-Hermitian physics and exceptional points

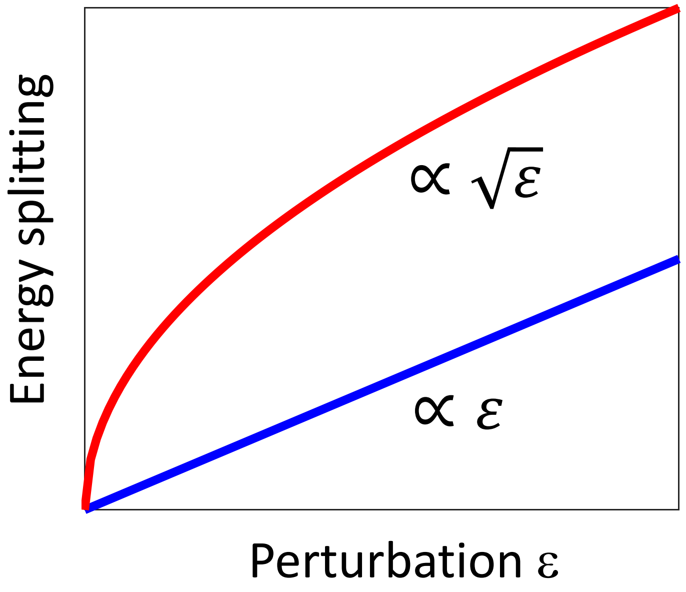


$$H_{\text{eff}} = \begin{pmatrix} \omega_1 - i\gamma_1 & J \\ J & \omega_2 - i\gamma_2 \end{pmatrix}$$

Exceptional Point



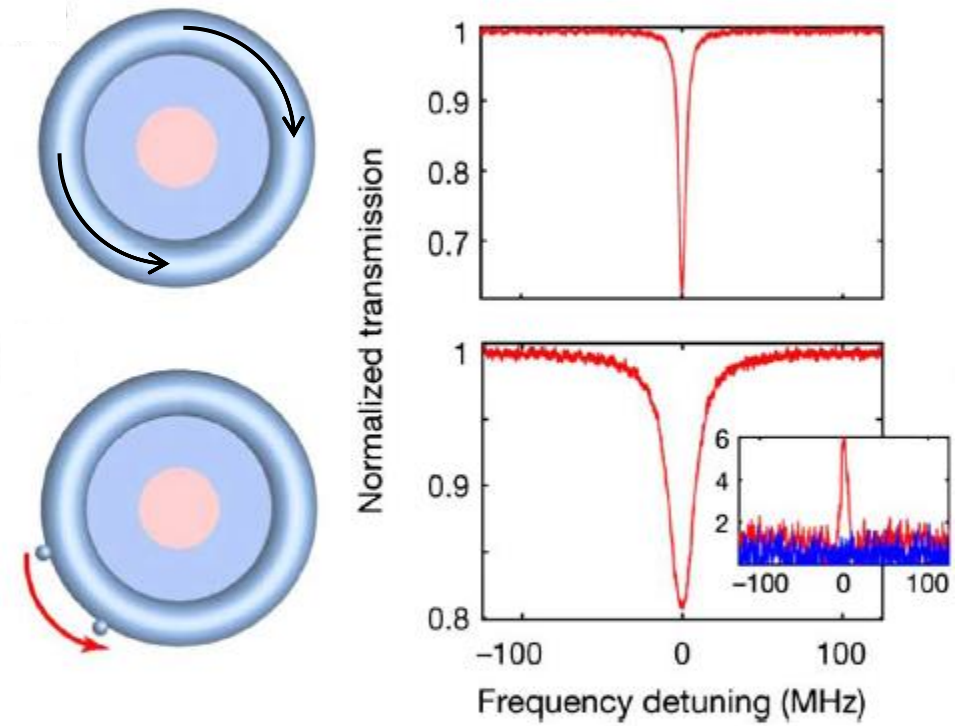
EP enhanced energy splitting



Exceptional point (EP): both the eigenvalues and the eigenstates are degenerate

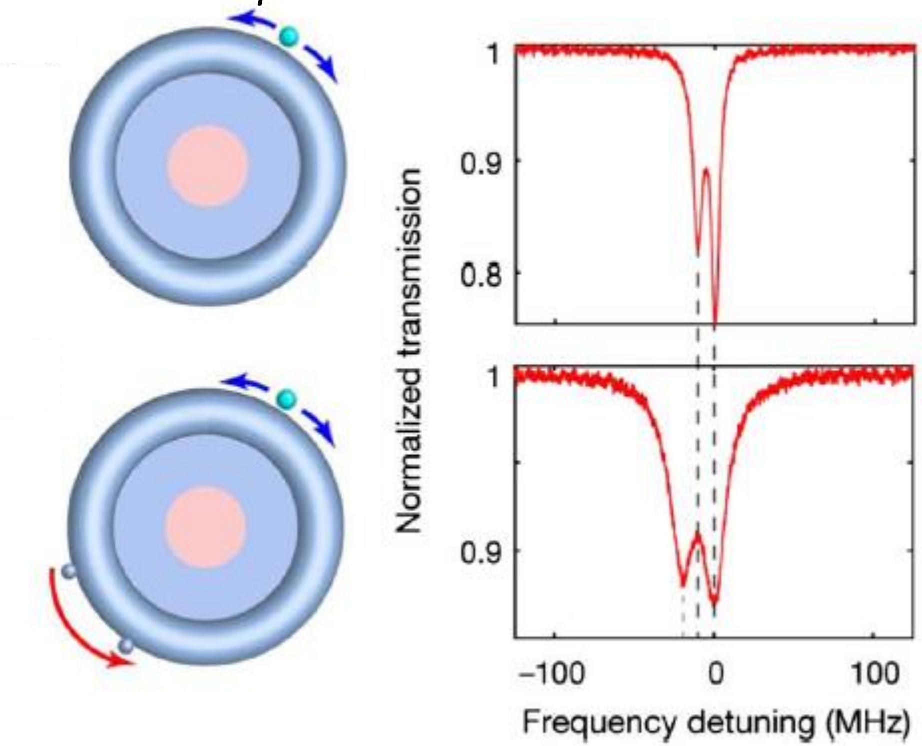
Exceptional-point sensor

Hermitian Degeneracy



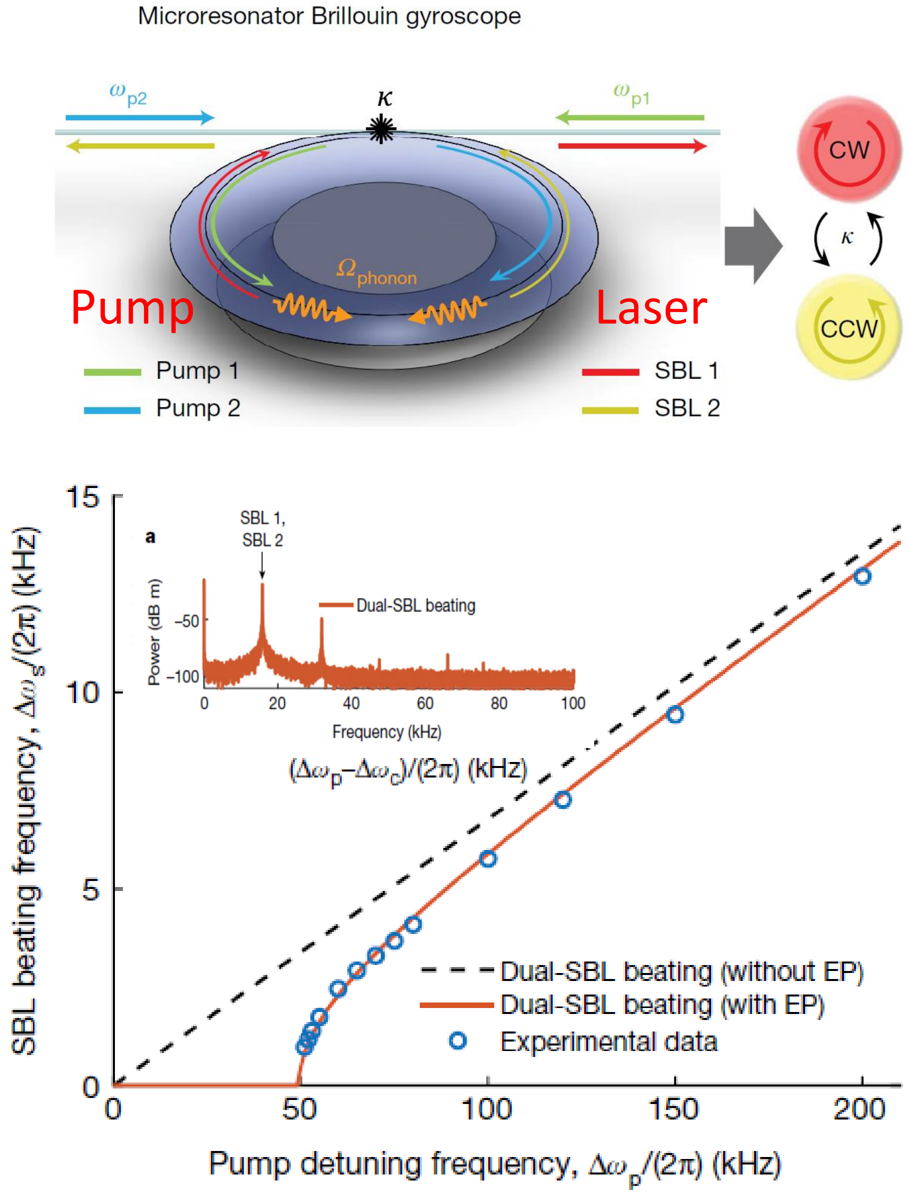
Non-Hermitian Degeneracy

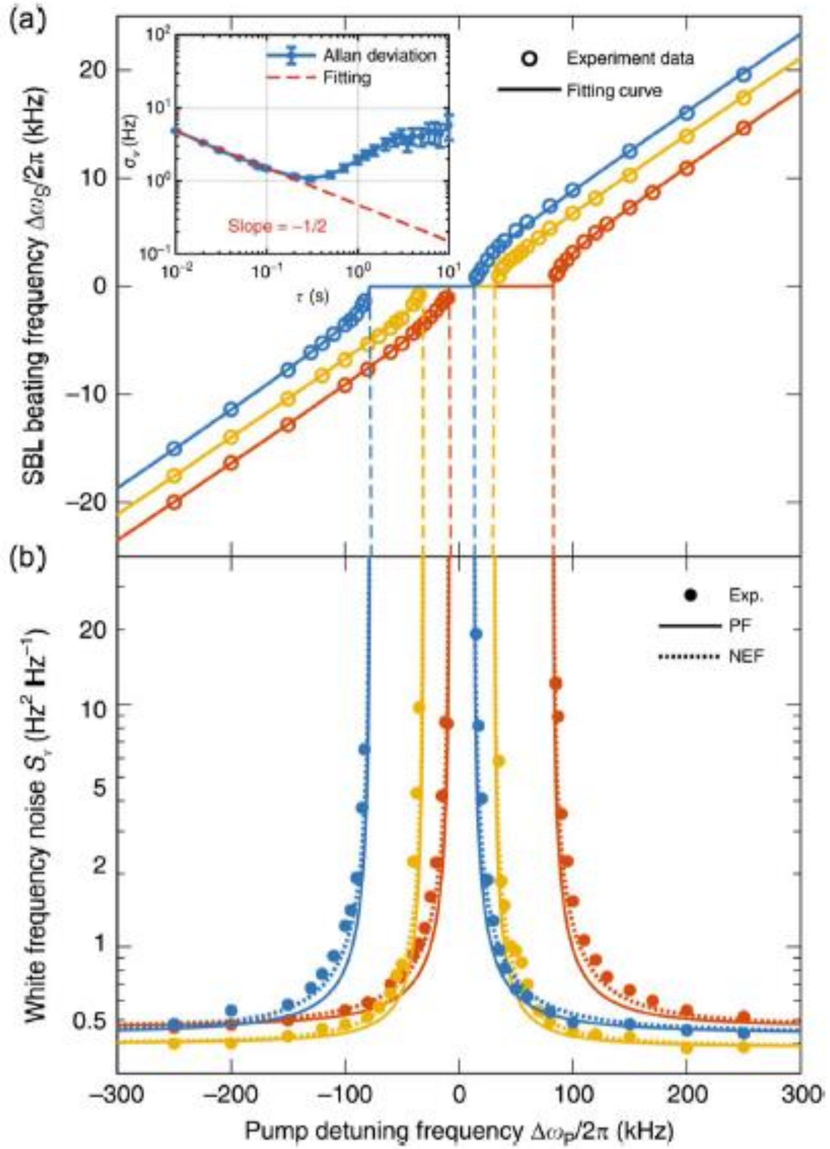
perturbation



Chen *et al., Nature* **548**, 192-196 (2017).

Exceptional-point sensor





Non-Hermitian sensing:

Lau *et al.*, *Nat. Commun.* **9**, 4320 (2018);
Roy *et al.*, arXiv:2009.07522;
McDonald *et al.*, *Nat Commun.* **11**, 5382 (2020).

Linewidth broadening

Lai *et al.*, *Nature* **576**, 65-69 (2019);
Wang *et al.*, *Nat. Commun.* **11**, 1610 (2020)

Exceptional points in superconducting qubits

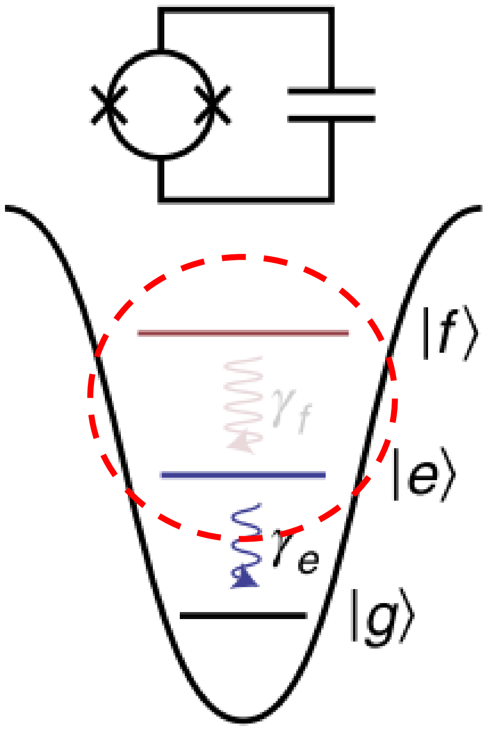
Qutrit in a Transmon Circuit

Bath engineering

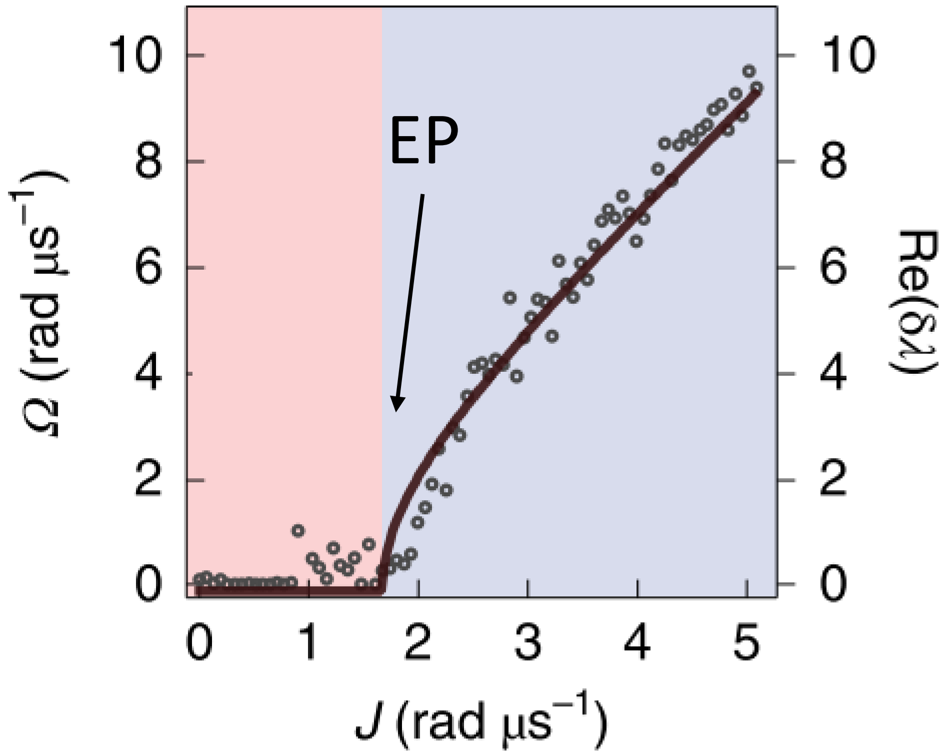
$\gamma_e \gg \gamma_f$

Post-selection

Non-Hermitian Qubit



$$H = \begin{pmatrix} -i\gamma_e/2 & J \\ J & 0 \end{pmatrix}$$



Naghiloo *et al.*, *Nat. Phys.* **15**, 1232-1236 (2019)

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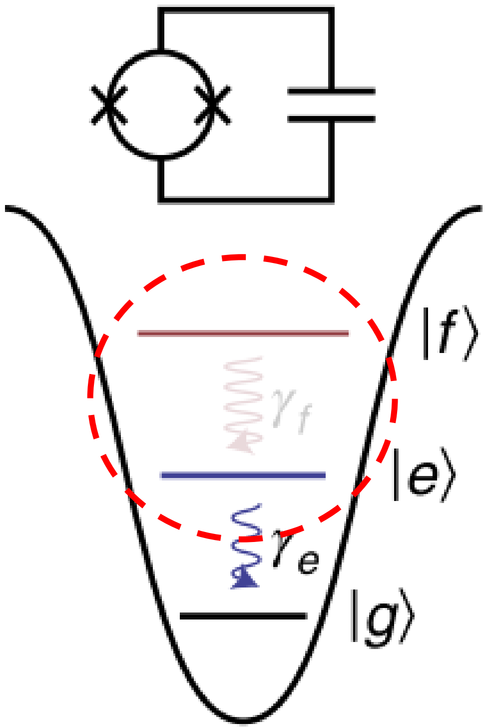

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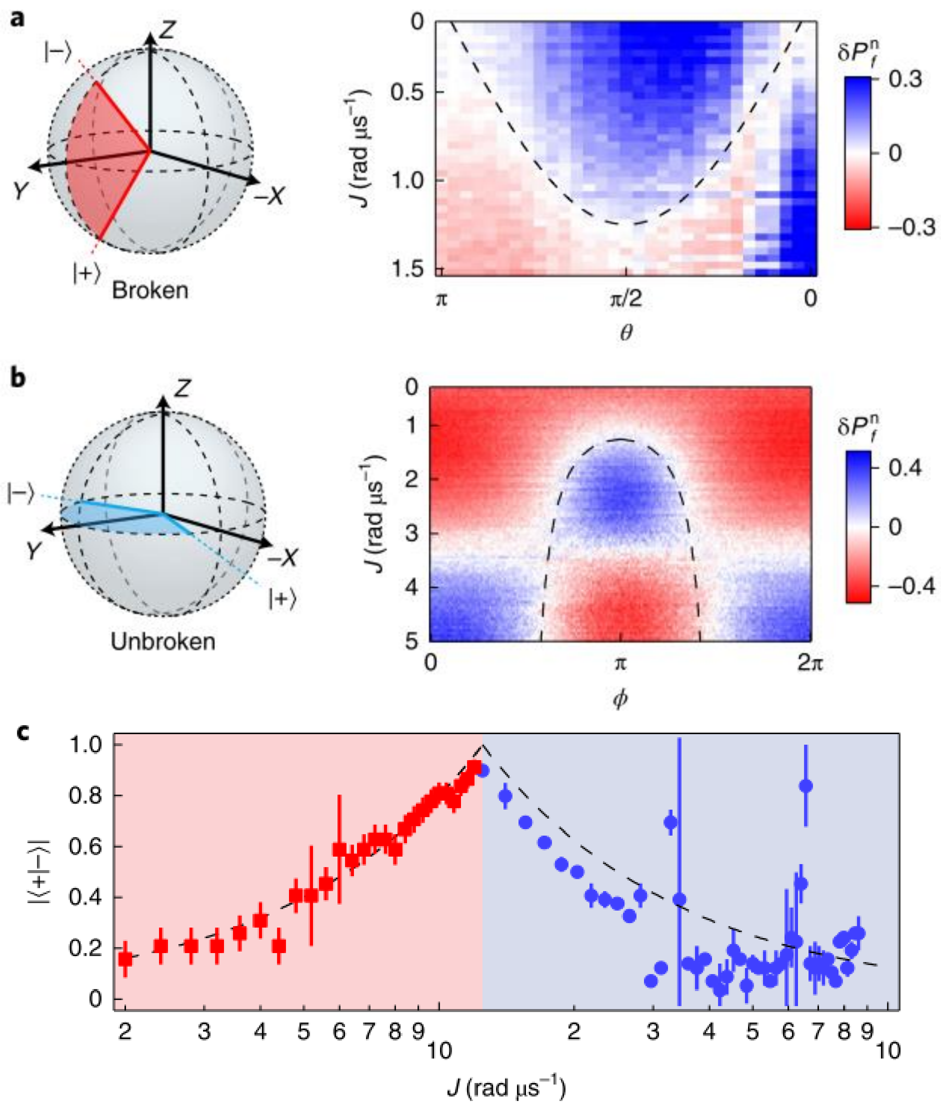

Naghiloo *et al.*, *Nat. Phys.* **15**, 1232-1236 (2019)

Summary

Washington University in St. Louis

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CENTER FOR QUANTUM SENSORS

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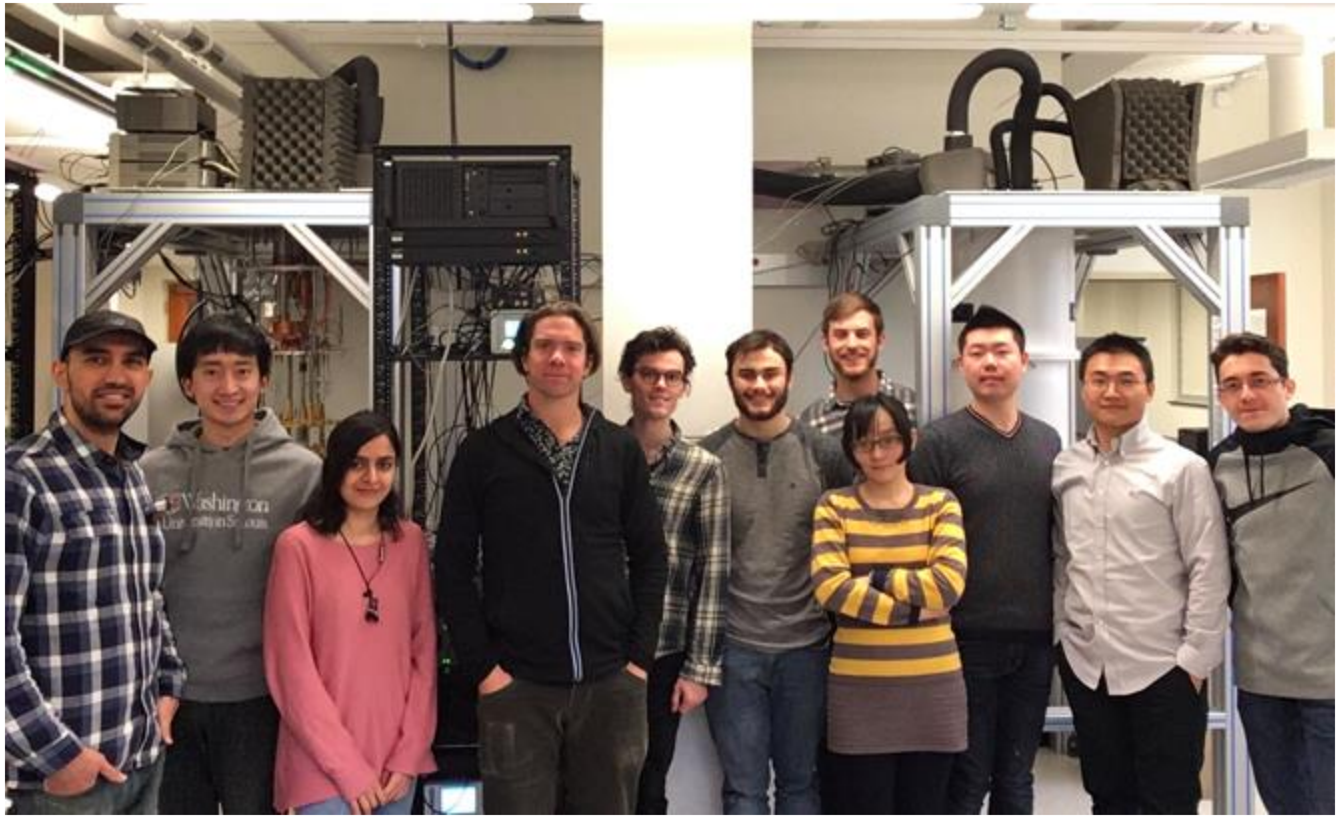
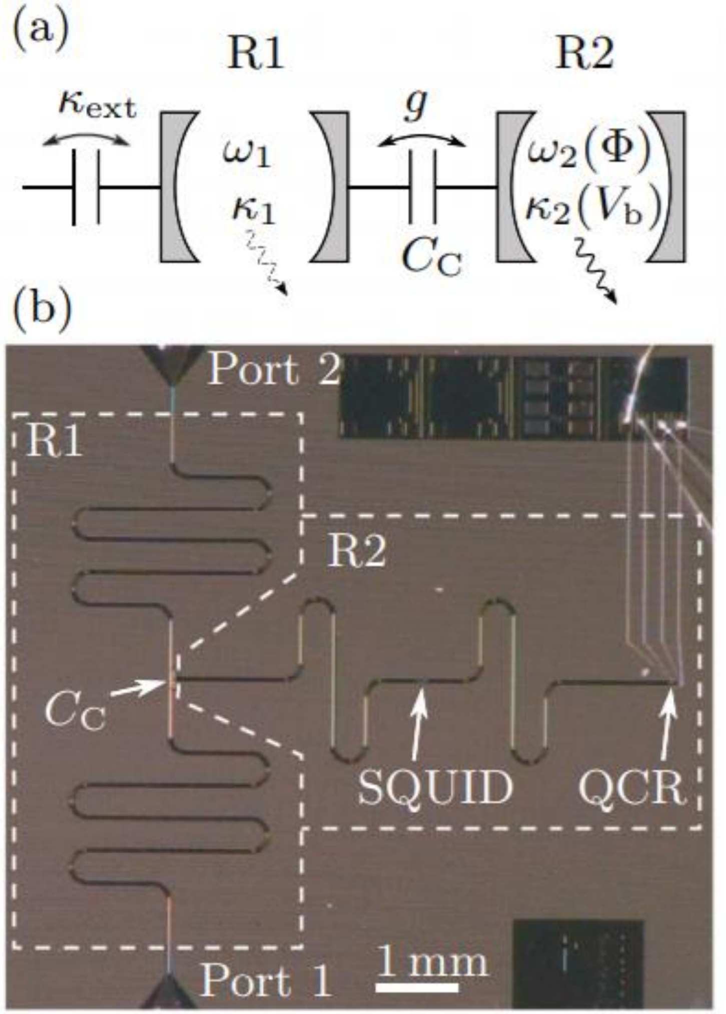
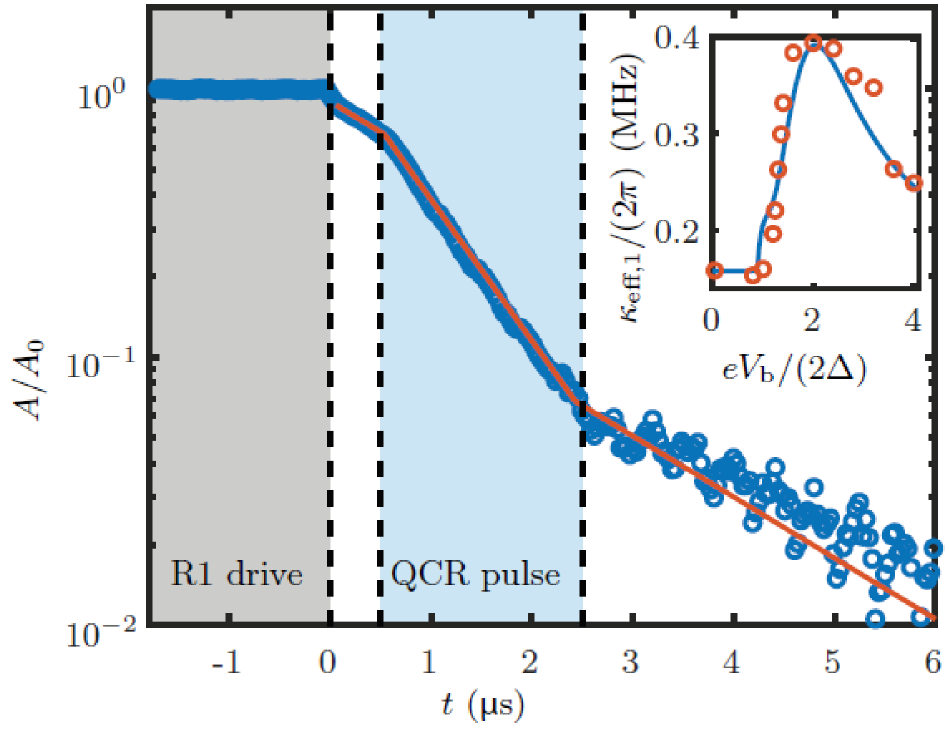


Murch Group

Exceptional points in superconducting circuits



Ring-down measurement of R1



Partanen *et al.* Phys. Rev. B **100**, 134505 (2019).