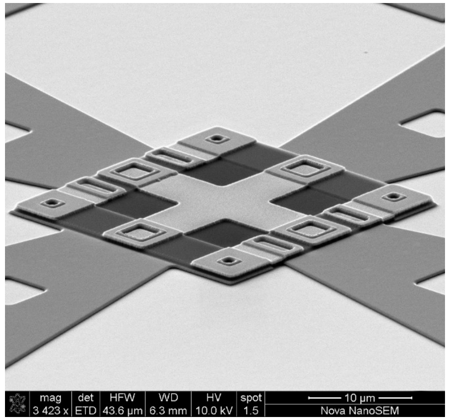
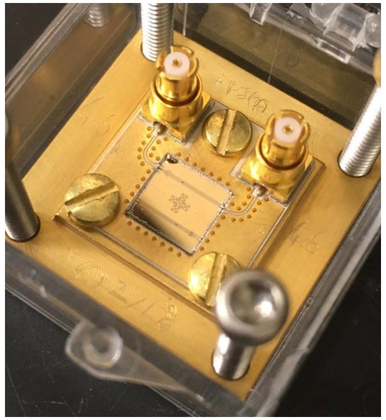
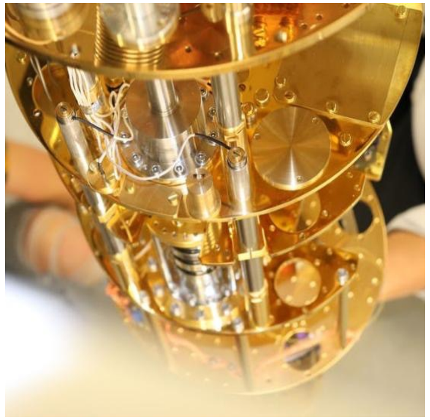
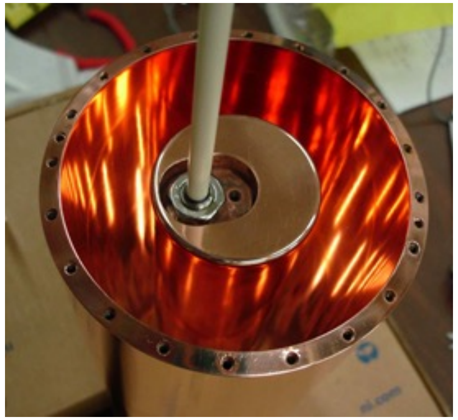
# Quantum information for high-energy and nuclear particle physics



Konrad W. Lehnert
SLAC Summer institute 2026
Palo Alto, California

HAYSTAC
The **H**aloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM

# What can Quantum info do for high-energy and nuclear particle physics?

many things, but I will discuss the example I know best

quantum enhanced sensing of classical fields

hypothetical ultralight dark matter, especially the QCD axion (this lecture)

gravitational wave detection

# Summary

quantum enhanced sensing: engineering design choice, not magic

reduces time or money needed to detect a signal

primary benefit is an increase in sensor bandwidth

useful if easier to lower noise than to increase signal

https://doi.org/10.48550/arXiv.2110.04912

# Outline

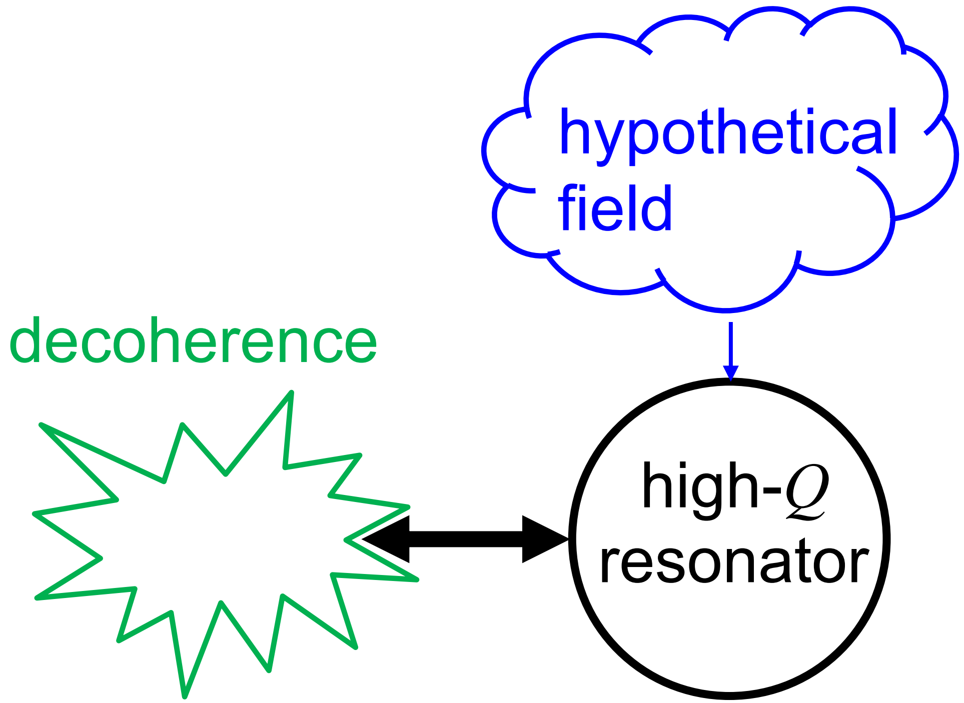


theory of quantum squeezing to enhance classical field sensing

squeezing deployed in a search for axionic dark matter

strategies for more quantum enhancement

# Classical fields: large amplitude but weak coupling to a sensor




possible sensor
- resonant circuit (DM Radio)
- microwave cavity (ADMX/HAYSTAC)
- spin ensemble (CASPER)
- mechanical resonator (Windchime)

distinguish evolution under

null hypothesis
$$\hat{H}_{\mathrm{r}} = \frac{\hbar\omega_{\mathrm{r}}}{2}\left(\hat{Q}^2 + \hat{P}^2\right)$$

field hypothesis
$$\hat{H}_{\mathrm{r}} = \frac{\hbar\omega_{\mathrm{r}}}{2}\left(\hat{Q}^2 + \hat{P}^2\right) + F(t)\hat{Q}$$

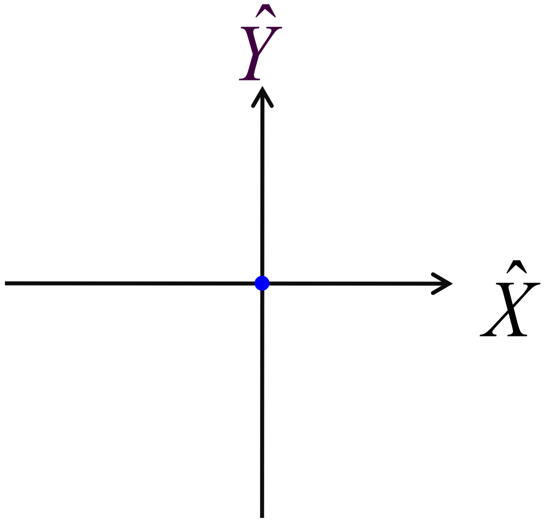
# If signal is an oscillatory "force" of unknown frequency

$$F(t) = \alpha \cos(\omega_a t + \phi) \qquad \omega_a = m_a c^2 / \hbar$$

$$\hat{X} = \hat{Q} e^{-i\omega_r t} \qquad \hat{Y} = \hat{P} e^{-i\omega_r t}$$ quadrature variables $$\Delta_{ar} = \omega_a - \omega_r$$

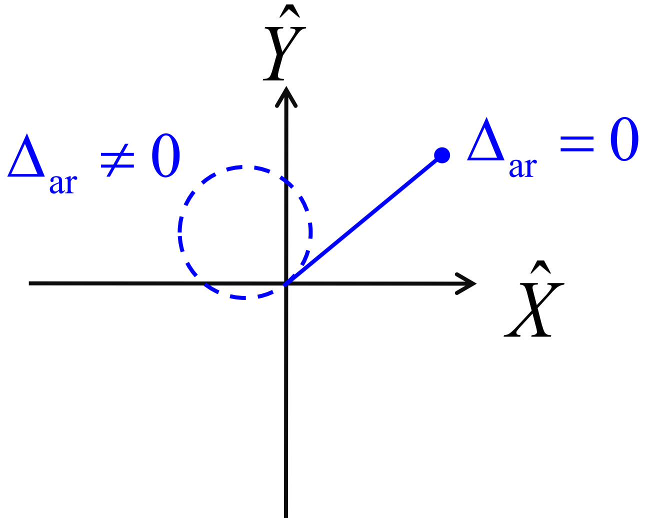
null hypothesis

$$\tilde{H}_r = 0$$




dark matter hypothesis

$$\tilde{H}_r \approx F_Y \sin(\Delta_{ar} t)\hat{X} + F_X \cos(\Delta_{ar} t)\hat{Y}$$



# Quantum noise pollutes inference of classical force

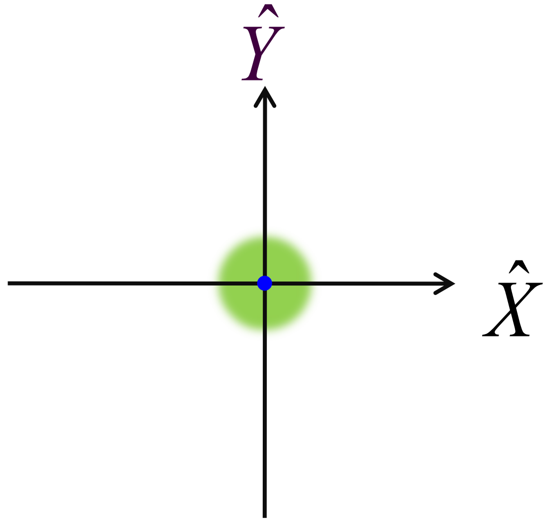
$$\left[\hat{X},\hat{Y}\right]=i$$

coherent state limit (CSL) also “SQL”

$$\delta\hat{X}\delta\hat{Y}\geq\frac{1}{2}$$

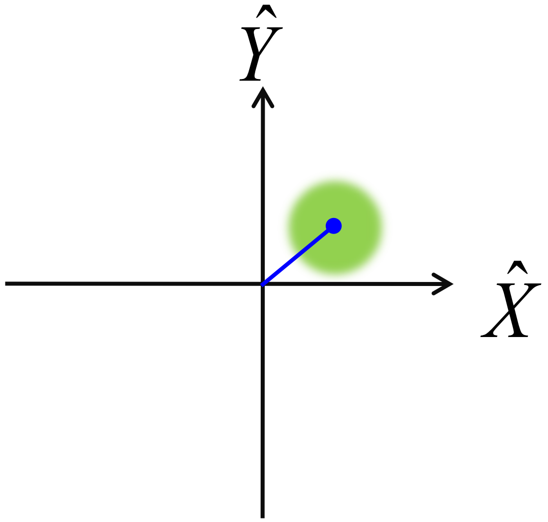
prepare in ground state, measure $X$ or $Y$

null hypothesis




ground state

field hypothesis



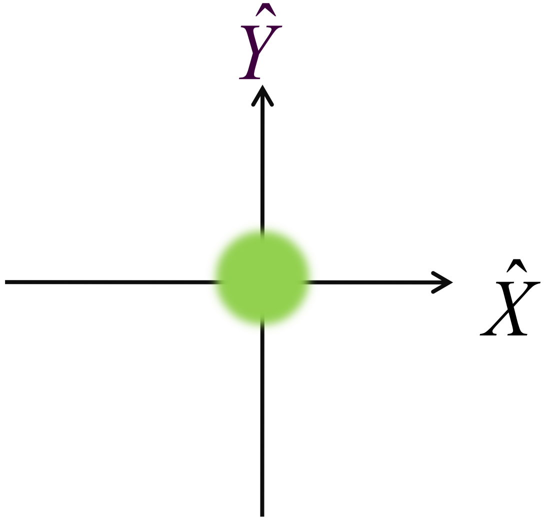

displaced ground state

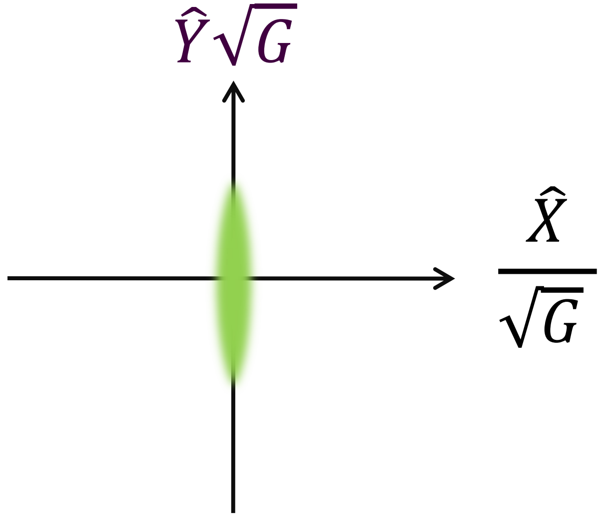
# Squeezed states approximate quadrature eigenstates



$$\left[\hat{X},\hat{Y}\right]=i$$

$$[\hat{X}/\sqrt{G},\hat{Y}\sqrt{G}] = i$$




phase space volume conserved
commutator preserved
no added noise

# Squeezing and noiseless measurement circumvent quantum limit



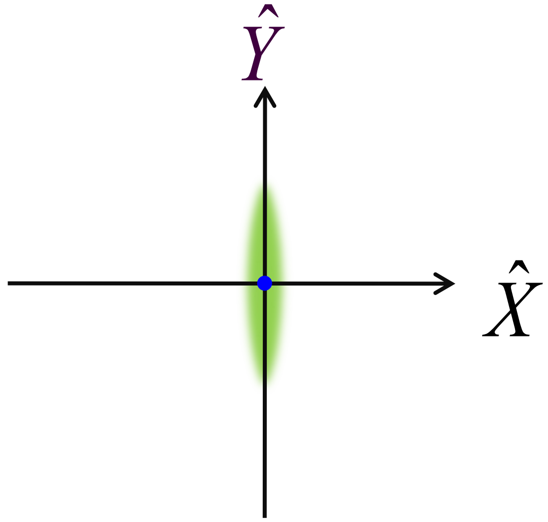
$$\left[\hat{X},\hat{Y}\right]=i$$

$$\delta\hat{X}\delta\hat{Y}\geq\frac{1}{2}$$

'beat' the CSL:

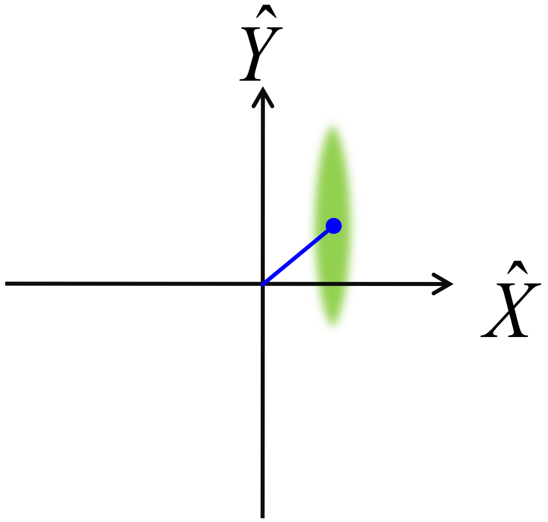
prepare in $X$ squeezed state, measure $X$ noiselessly

null hypothesis




squeezed state

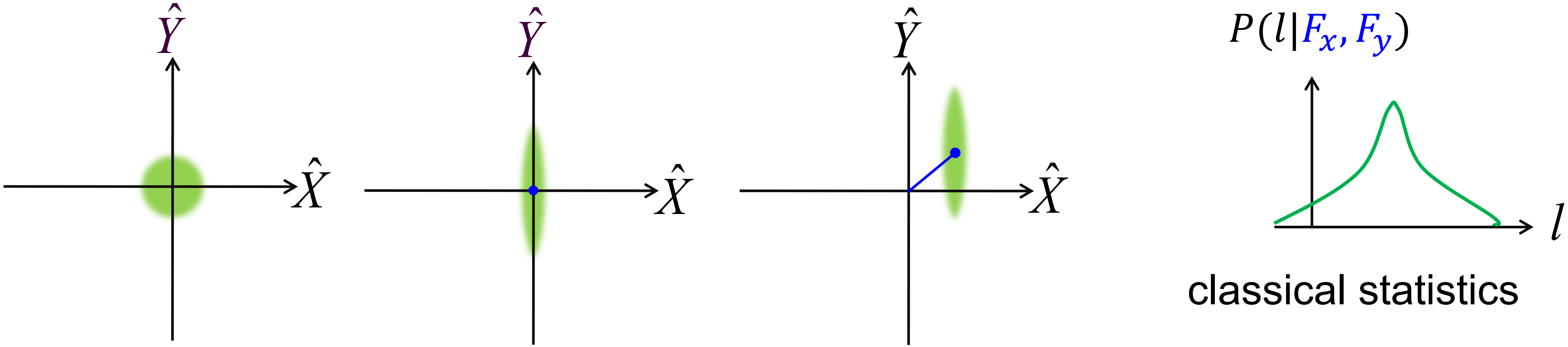
field hypothesis




displaced squeezed state

# Quantum state preparation and measurement access quantum metrology

$|\psi_0\rangle$ prepare $|\psi_{\text{in}}\rangle$ evolve $|\psi_{\text{out}}(F_x, F_y)\rangle$ measure $P_l = \langle \psi_{\text{out}} | \mathbf{M}_l | \psi_{\text{out}} \rangle$




optimize estimation of parameters over:

initial state preparation $|\psi_{\text{in}}\rangle$

measured quantity $\mathbf{M}_l$

# Frequently asked questions

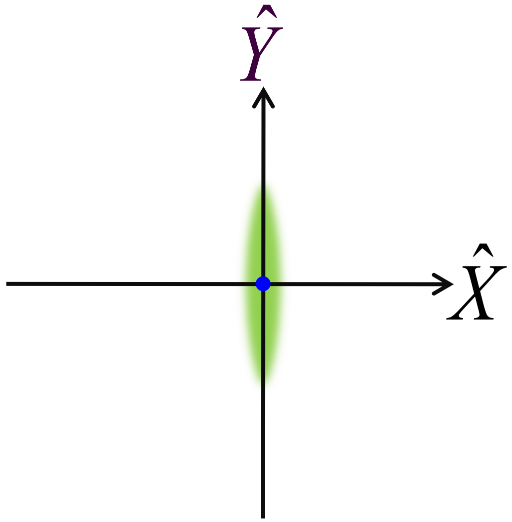


Does the quantum advantage disappear when considering decoherence?

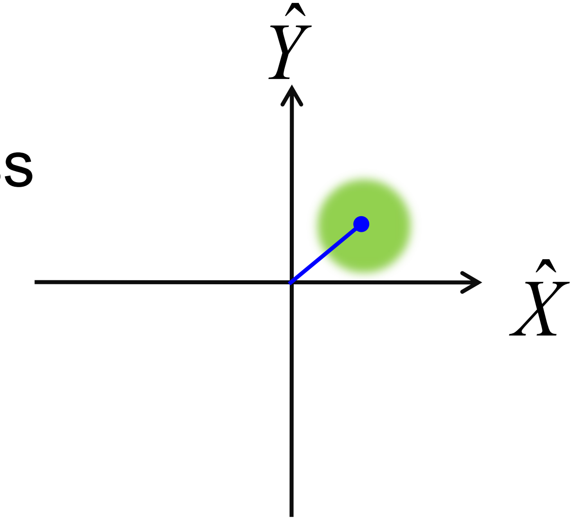
Do you need to know the phase of the signal to benefit from squeezing?

Can you measure both quadratures of the *signal* better than the CSL?

# Impact of loss and decoherence on squeezing and signal




time evolution with decoherence from loss

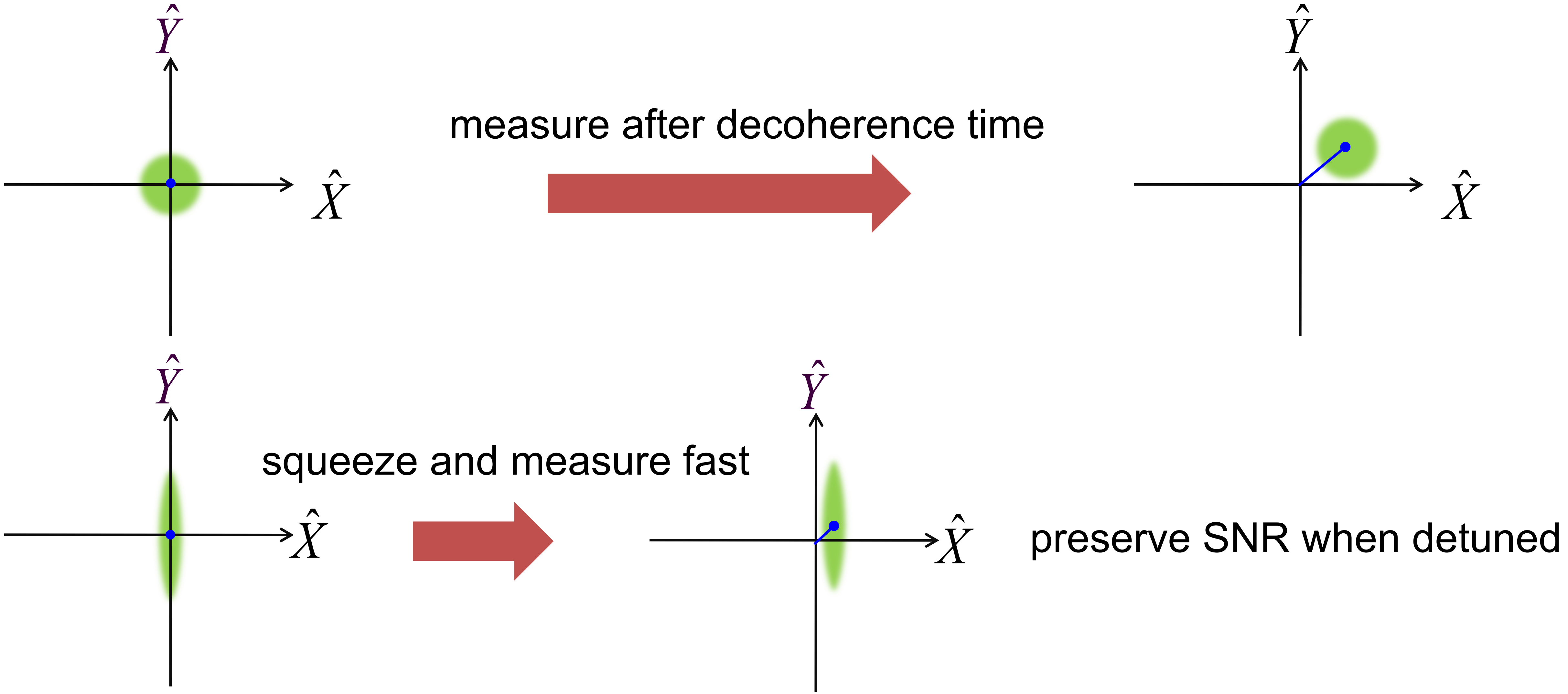



in a characteristic decoherence time

squeezing is lost

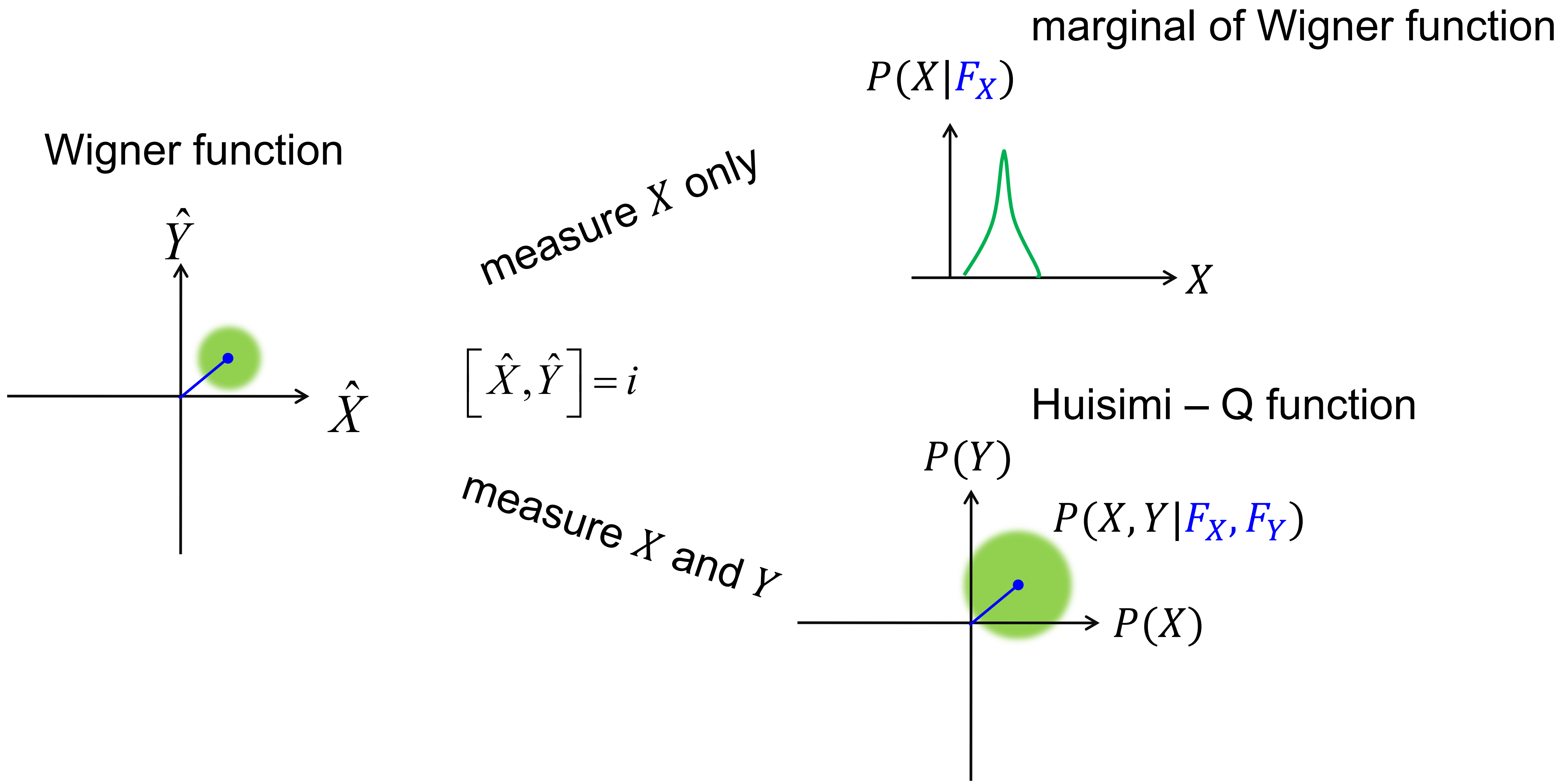
displacement reaches steady-state value

# Squeezing improves sensor bandwidth

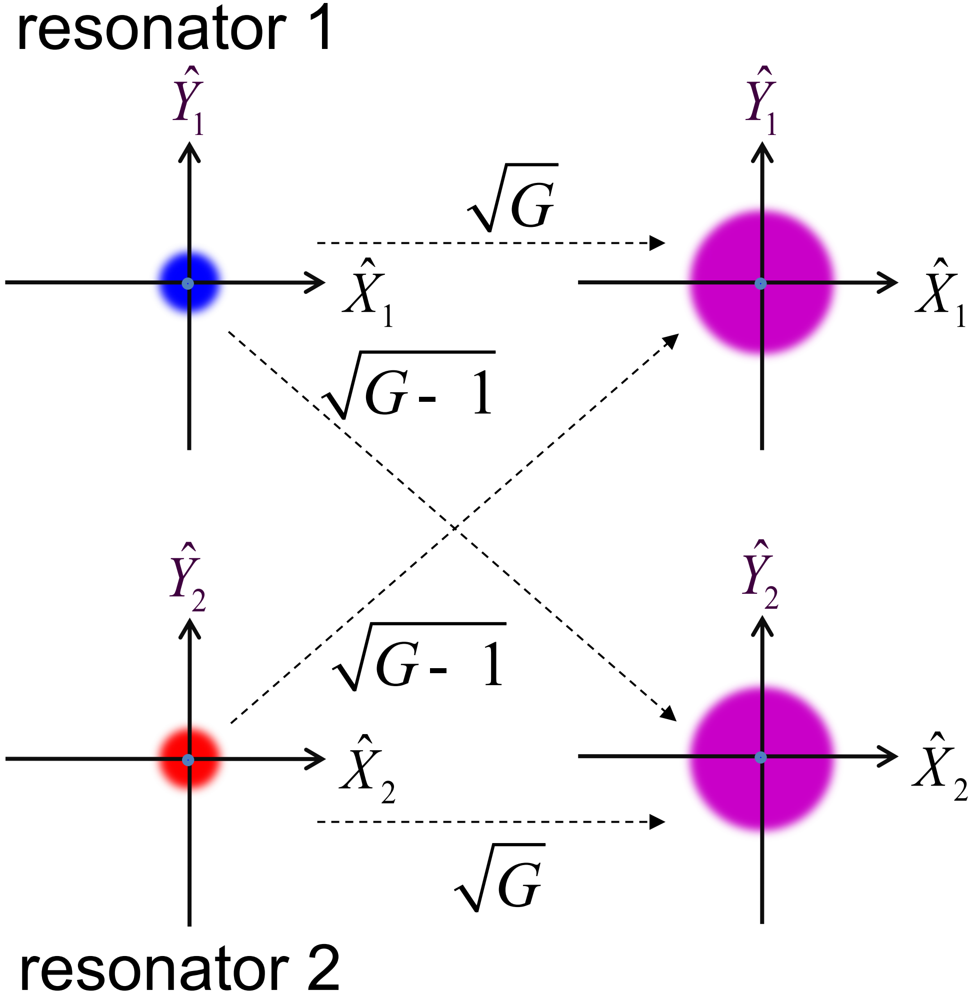


# Measuring both quadratures doubles the signal and noise power

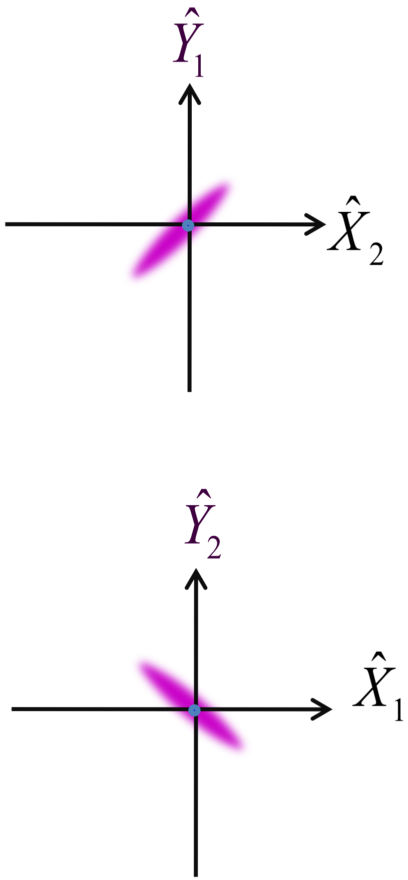




# Two-mode squeezing operation is unitary

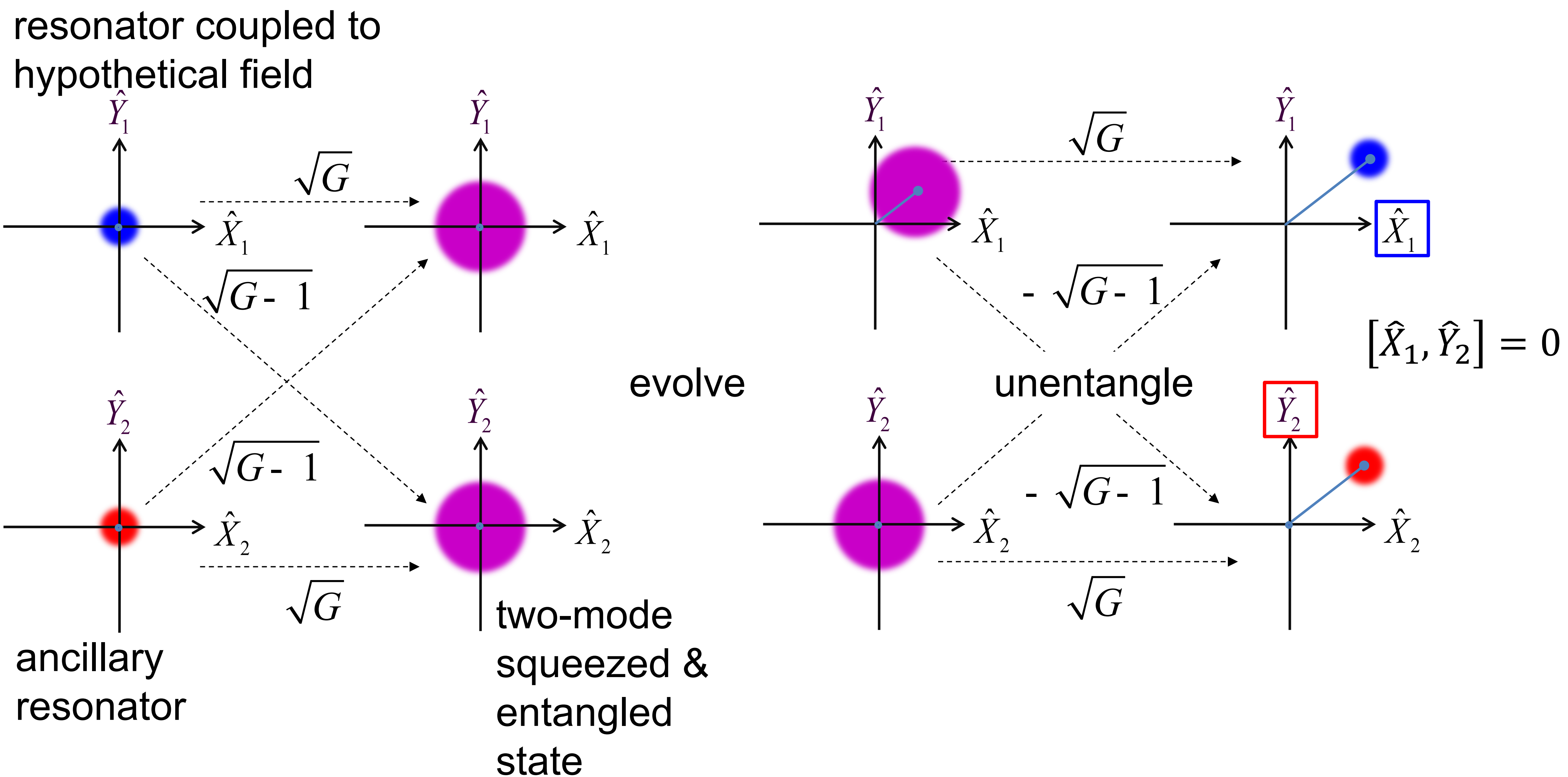



correlations reveal entanglement



# Quantum enhanced measurement of both quadratures



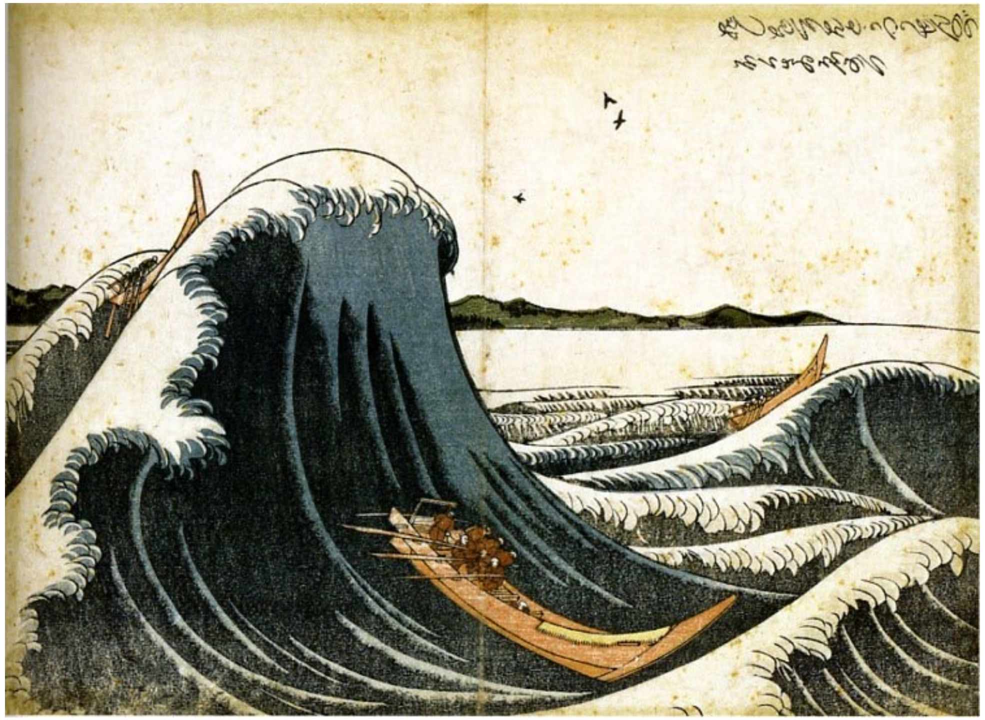


# Squeezing in an axion dark matter search

# Ultralight dark matter must be bosonic

dark matter ($\Lambda$CDM)

- "cold:" gravitationally bound to us
- mean density: ~ 0.4 GeV/cm$^3$
- weakly interacting



implications for particles with rest mass $m_a < 1\ \mathrm{eV}$

- quantum degenerate Bose gas
- more "field-like" than "particle-like"
- persistent, large amplitude, weakly coupled field

# Hypothetical QCD axion: a light particle that is cold and dense enough to contribute to dark matter

mechanism to resolve strong-CP problem (Peccei and Quinn)

associated particle (axion) is dark matter candidate

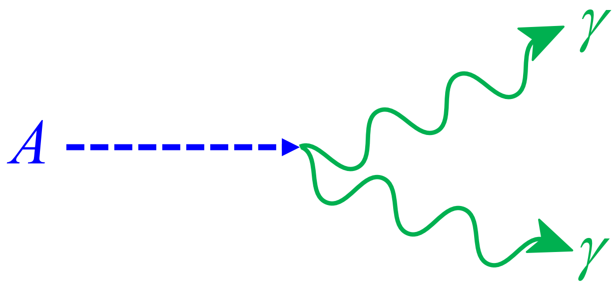
mass range $2\ \mu\text{eV} < m_a c^2 < 2000\ \mu\text{eV}$

as a frequency $500\ \text{MHz}^* < m_a c^2 / h < 500\ \text{GHz}$

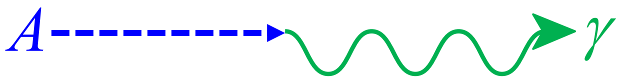
*post-inflation scenario

# Axion field couples (weakly) to electromagnetism

modified QCD Lagrangian $\Rightarrow g_{A\gamma\gamma} A\left(\vec{E}\cdot\vec{B}\right)$



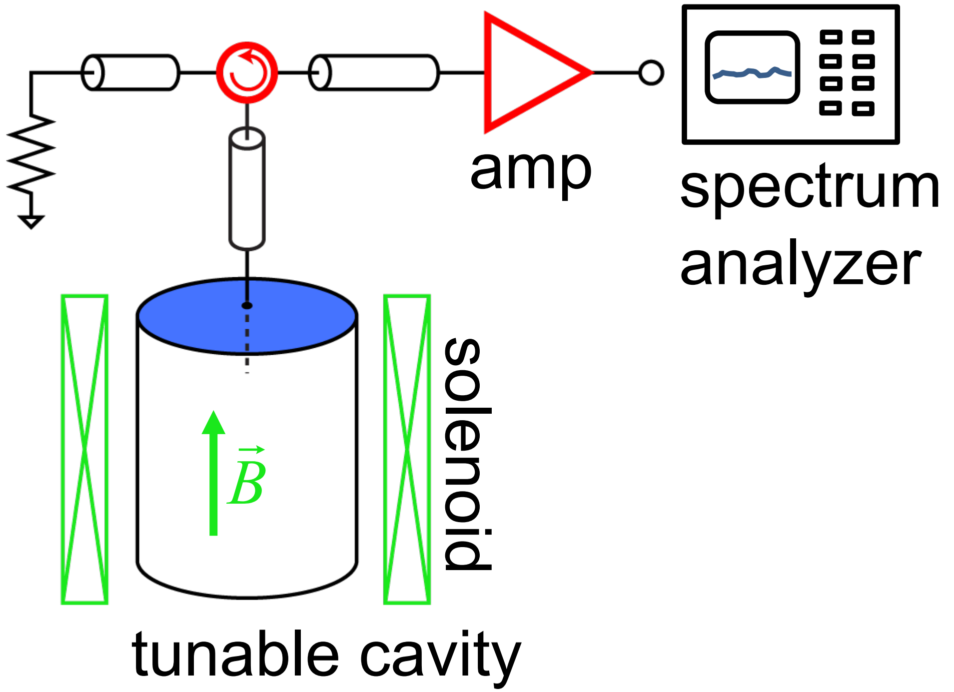

linearize coupling around static $\vec{B}$-field

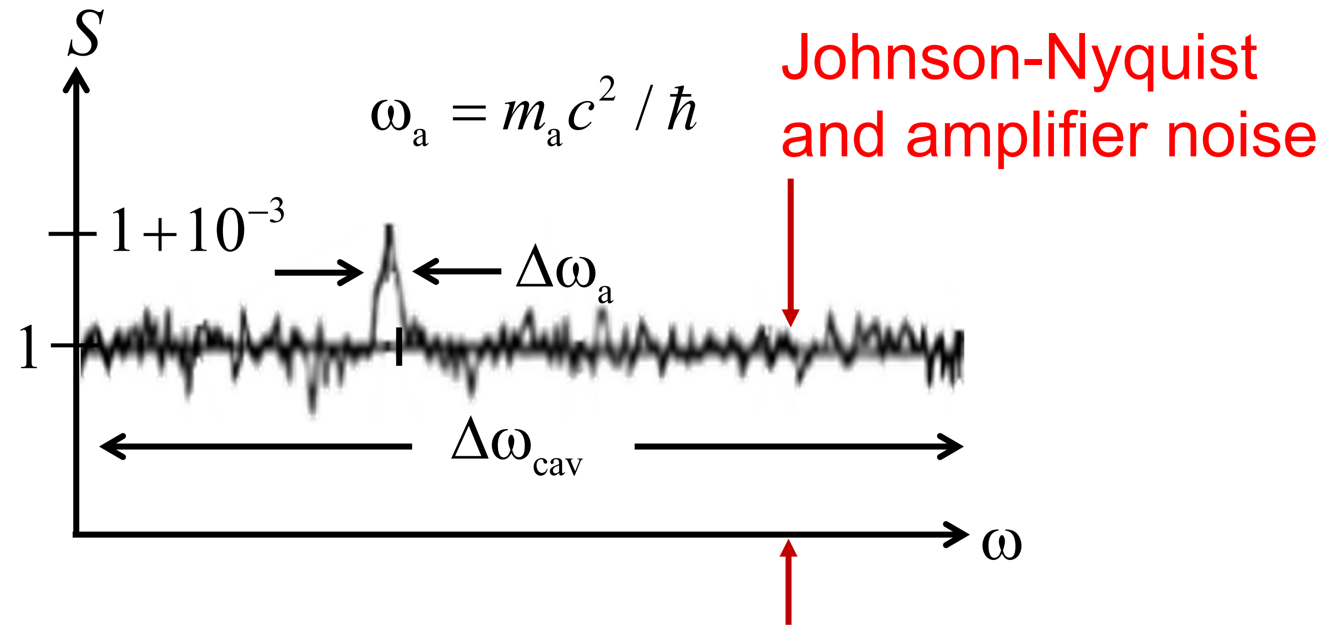



$E_A = E_\gamma$

dark matter axions create microwave photons

# Scan narrowband cavity to search for resonant axion to photon conversion: haloscope (Sikivie 1983)



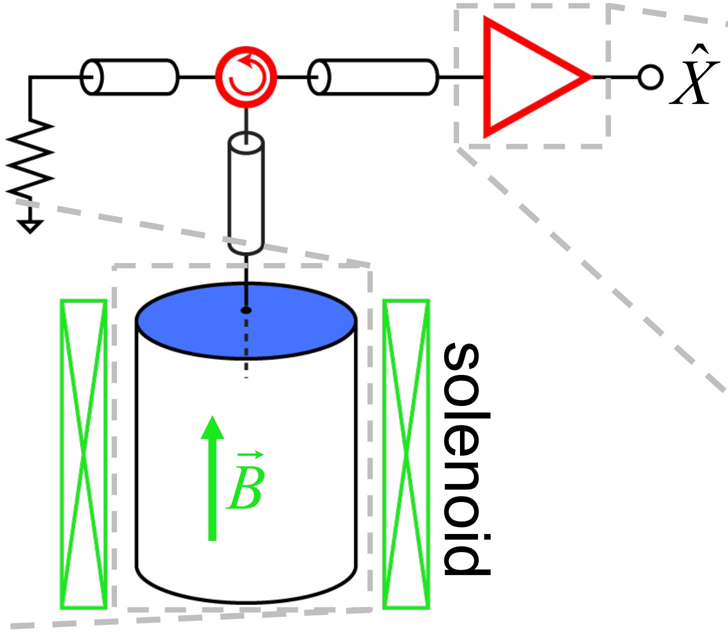

tune → wait and integrate → tune

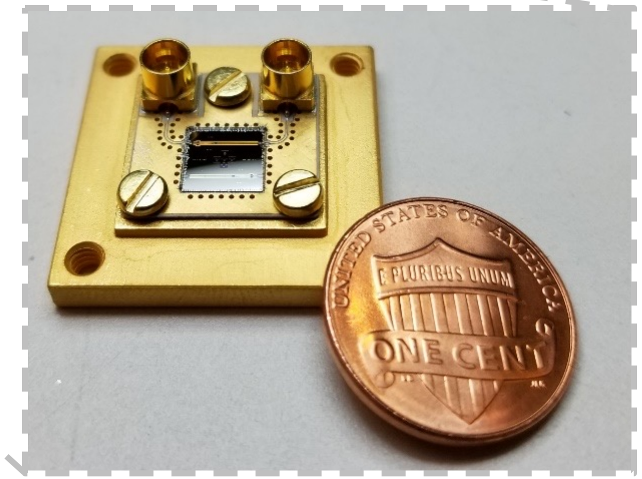
axion field more coherent than cavity

resolve variance with $10^{-3}$ precision
⇨ $10^6$ realizations of random process

$$\frac{\omega_a}{\Delta\omega_a} \approx 10^6 \qquad \frac{\omega_{cav}}{\Delta\omega_{cav}} \approx 10^4$$

# Cool cavity and measure with noiseless amplifier to reach CSL



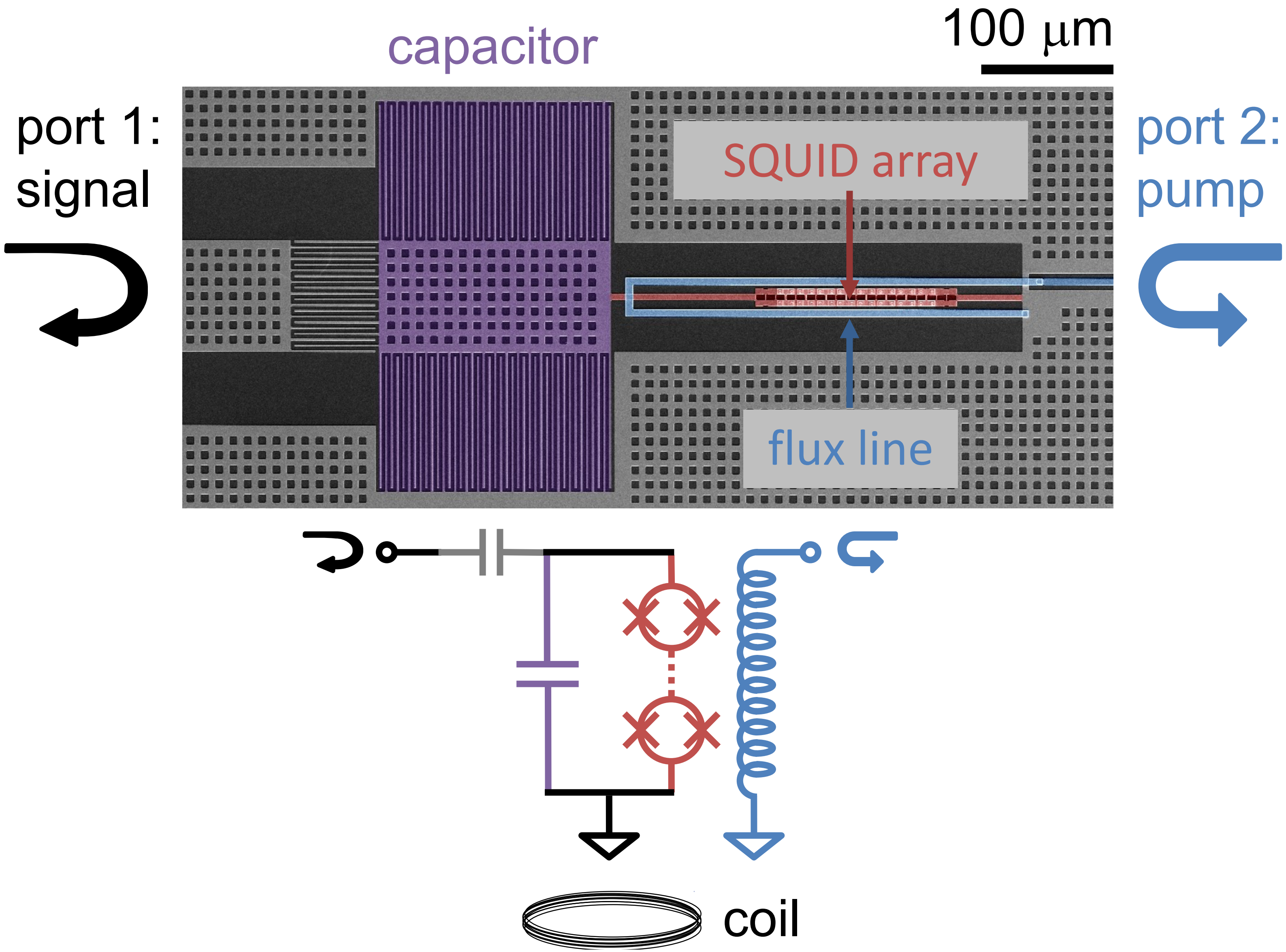

1 L volume
$Q = 10^4$
$\omega_{\text{cav}} \sim 2\pi \times 5$ GHz

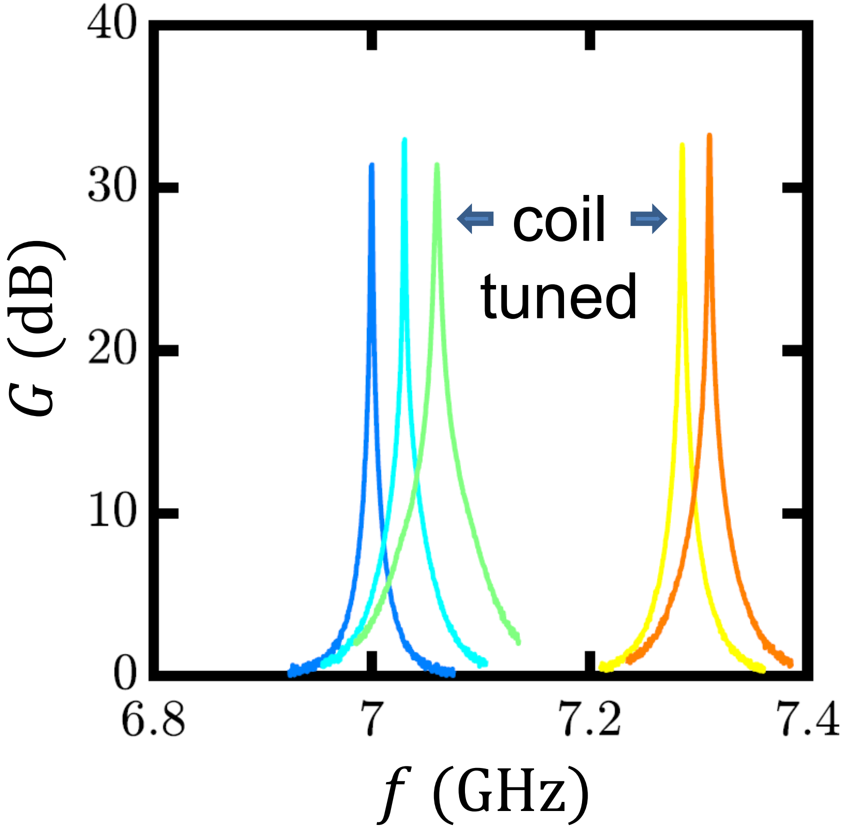
tunable cavity
$T \ll \dfrac{\hbar\omega_{\text{cav}}}{k_B}$

Josephson parametric amplifier (JPA)
measure $\hat{X}$ noiselessly

haloscope near the CSL (HAYSTAC 2017)

# Low noise amplification with Josephson parametric amplifiers

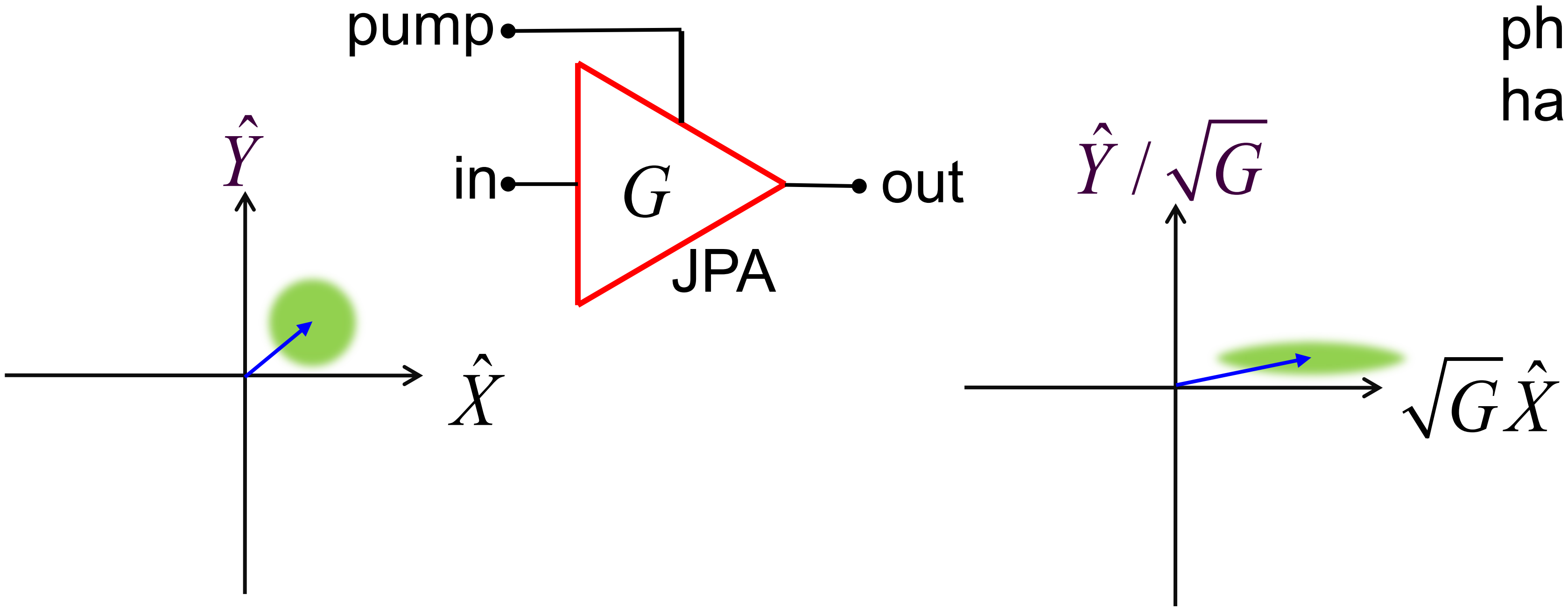


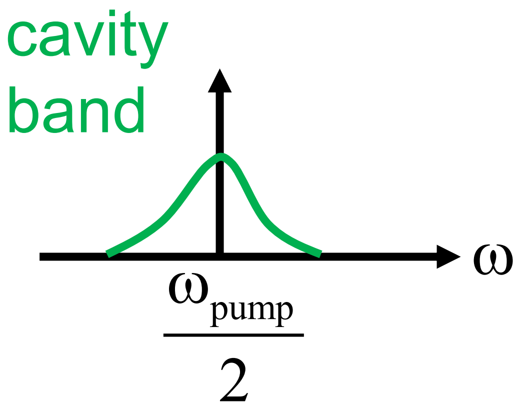

tunable over 1.5 GHz
gain > 30 dB

# Phase sensitive amplifier measures one quadrature noiselessly

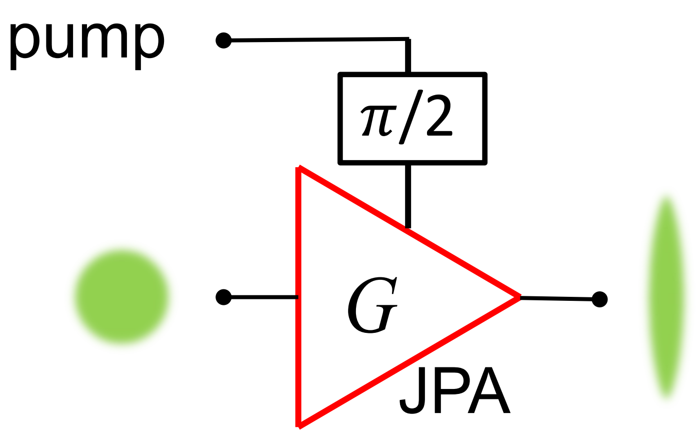





phase sensitive mode:
half-pump resonant with cavity



# JPA noiselessly transforms ground state into squeezed state



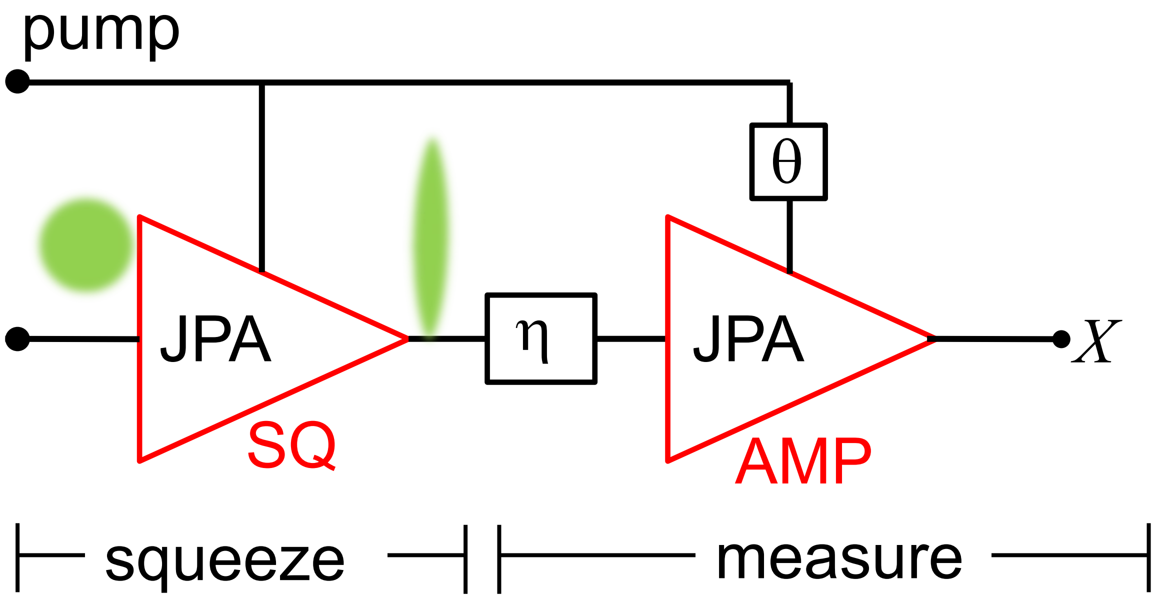

$$\delta^2 \hat{Y} = \frac{G}{2}$$

$$\delta^2 \hat{X} = \frac{1}{2G}$$

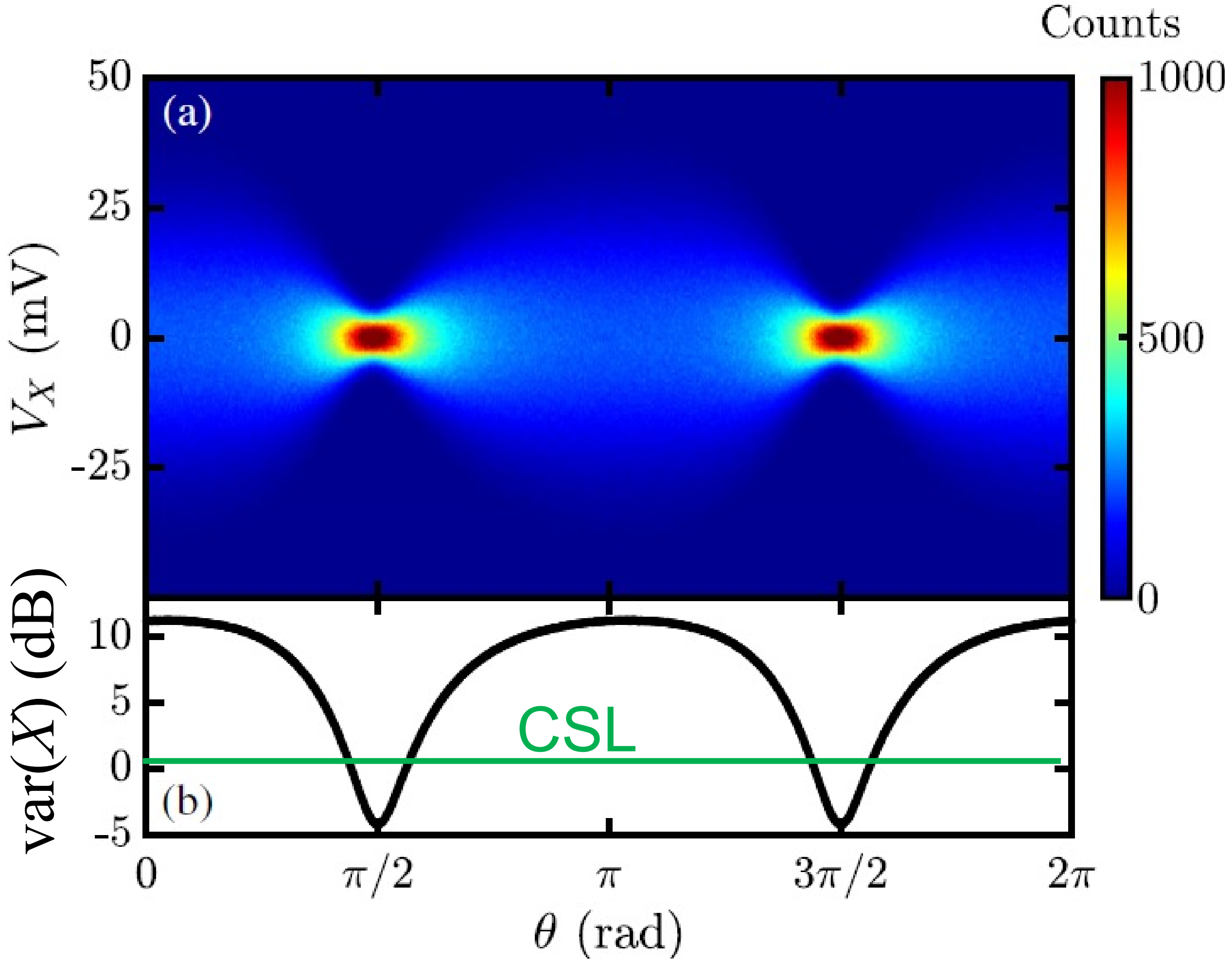
squeezed quadrature: quantum noise suppressed

use JPA to prepare cavity in squeezed state

# Demonstration of squeezing and determination of loss: second JPA analyzes squeezed state created by first

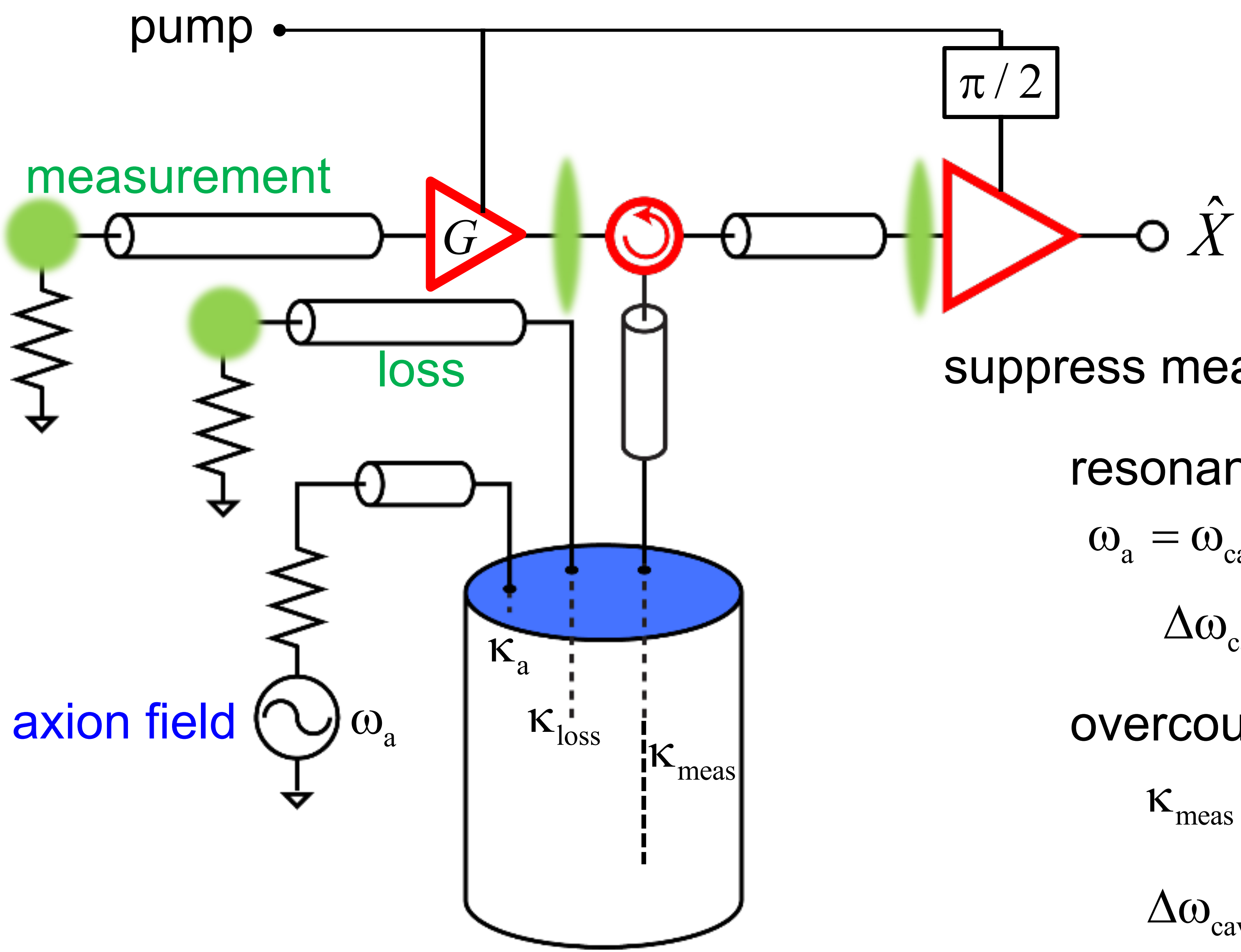



phase θ chooses measured quadrature relative to squeezed quadrature




loss η: 1.63 dB

# Squeezing achieves best sensitivity over a wider bandwidth




suppress measurement port noise

resonant signal and critically coupled

$$\omega_a = \omega_{cav} \qquad \kappa_{meas} = \kappa_{loss}$$

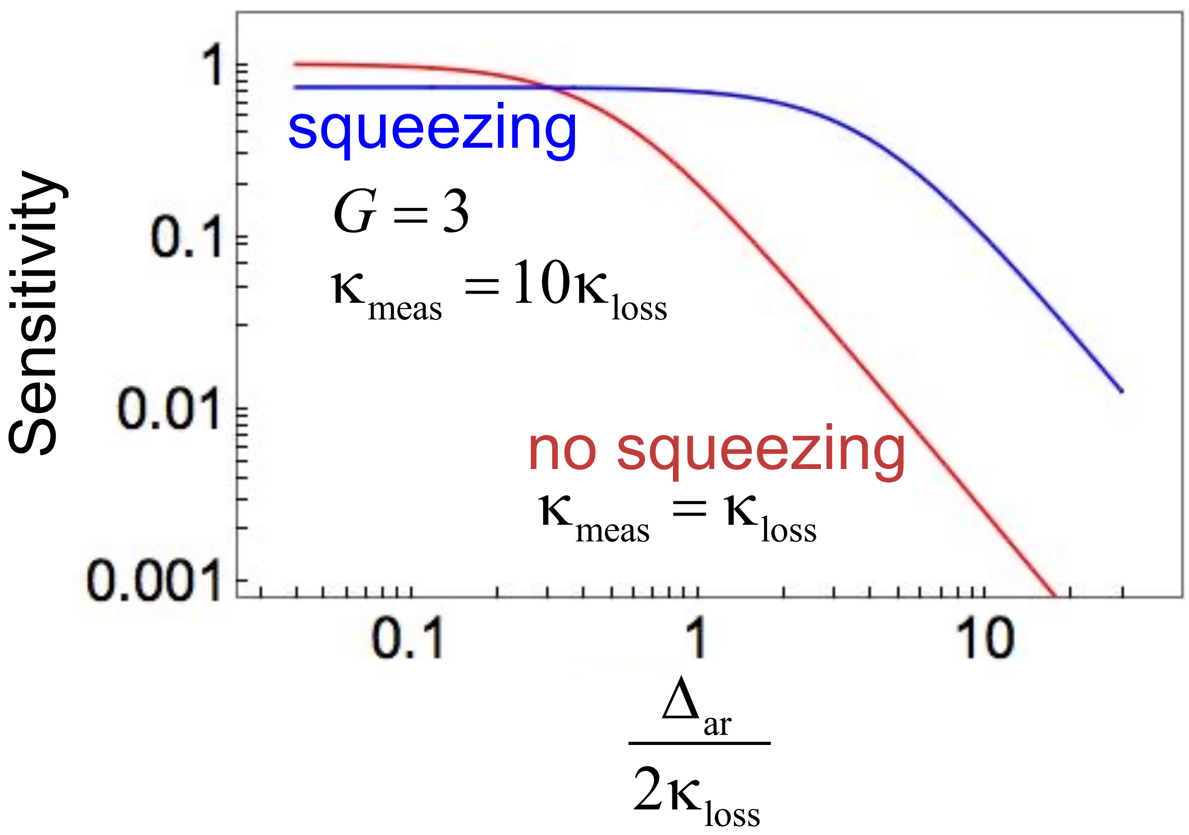
$$\Delta\omega_{cav} = 2\kappa_{loss} \qquad G = 1$$

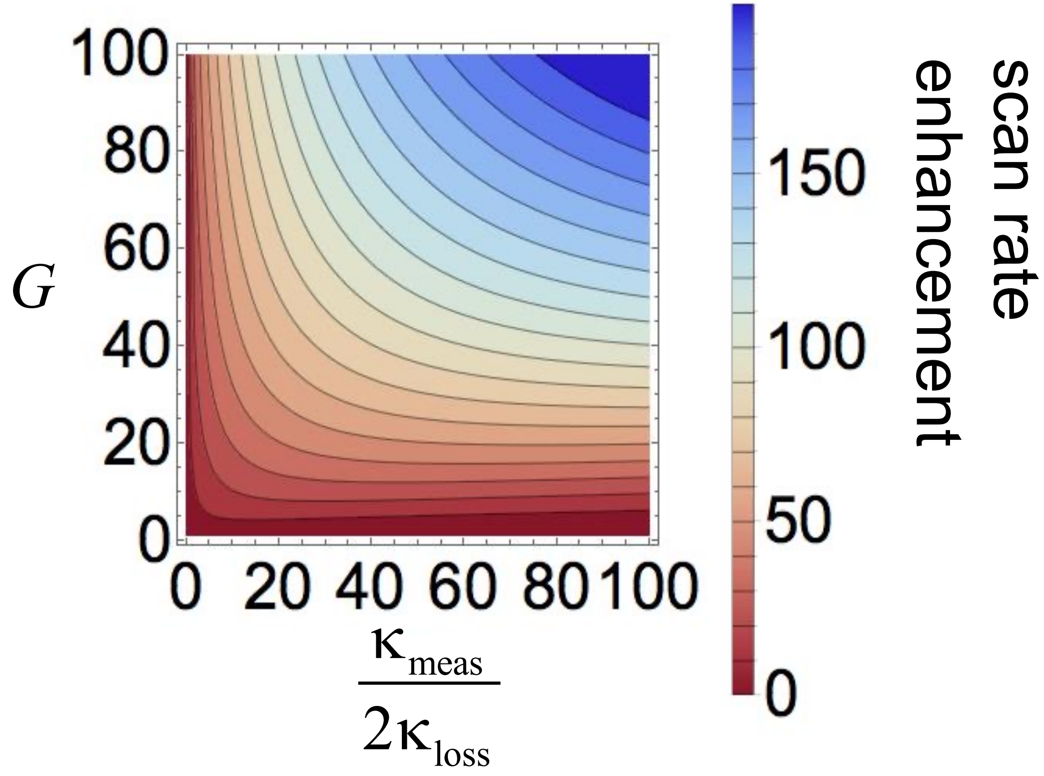
overcoupled cavity with squeezing

$$\kappa_{meas} = 9\kappa_{loss} \qquad G \gg 5$$

$$\Delta\omega_{cav} = 10\kappa_{loss}$$

# Scan rate enhancement, perfect efficiency

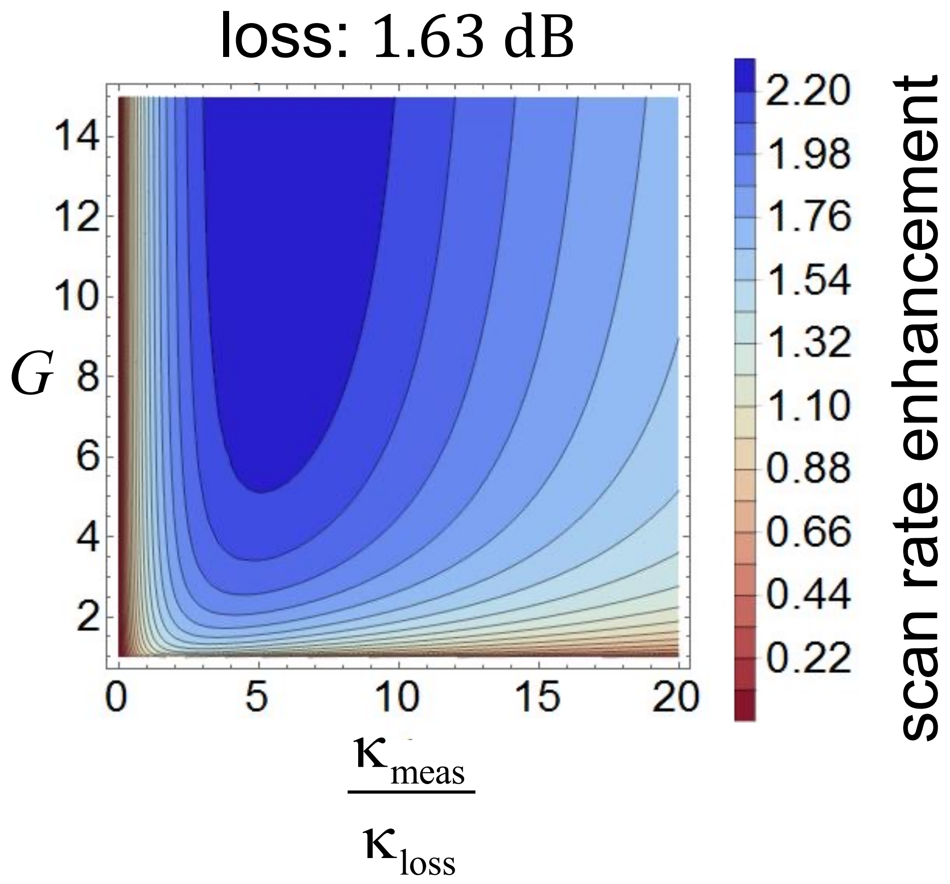



slight reduction in sensitivity
much larger bandwidth

# Effect of propagation losses on the scan rate

transmission loss diminishes benefit



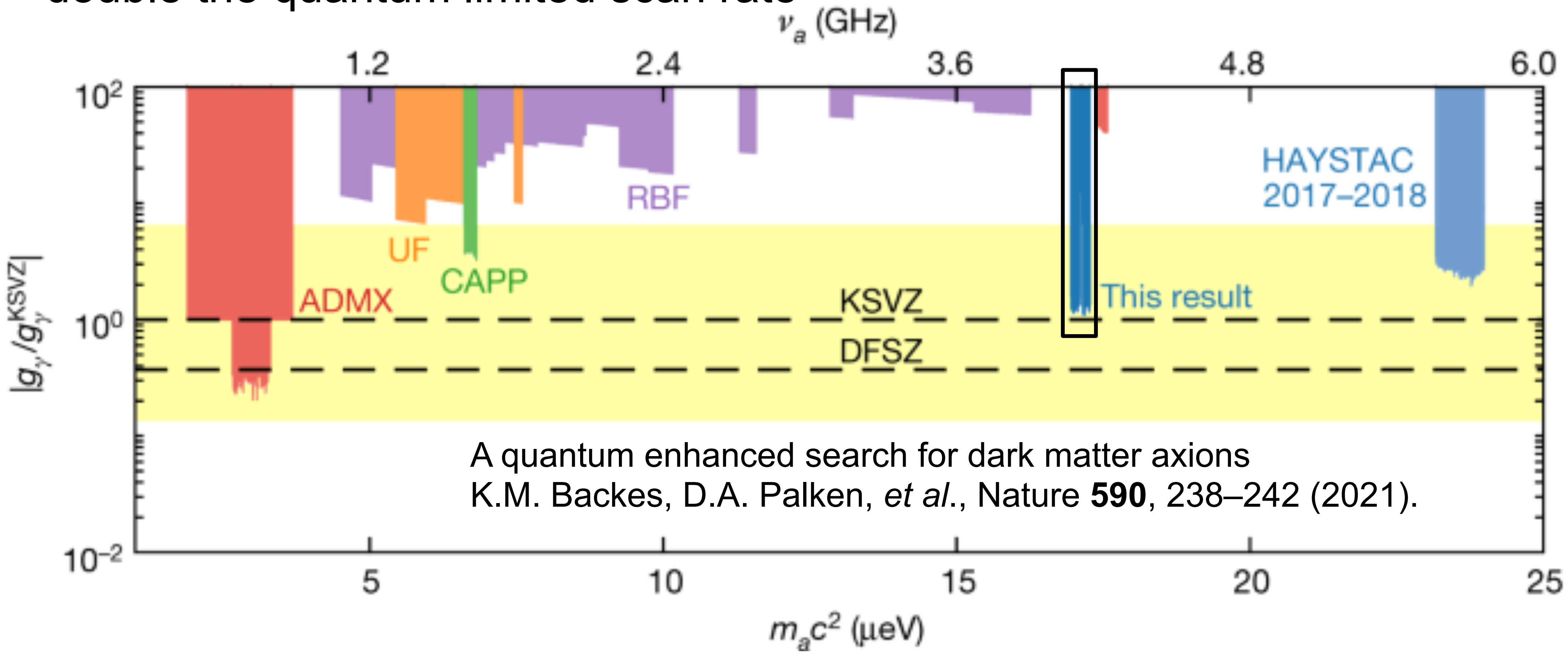

Is doubling the search rate meaningful?

saves 10,000 years or 600 M$

dramatic improvement with reduced loss

# Quantum enhanced sensing is now routine in HAYSTAC

double the quantum limited scan rate




A quantum enhanced search for dark matter axions
K.M. Backes, D.A. Palken, *et al*., Nature **590**, 238–242 (2021).

M. J. Jewell *et al.* (HAYSTAC Collaboration)
Phys. Rev. D **107**, 072007 (2023).

X. Bai *et al.* (HAYSTAC Collaboration)
Phys. Rev. Lett. **134**, 151006 (2025).

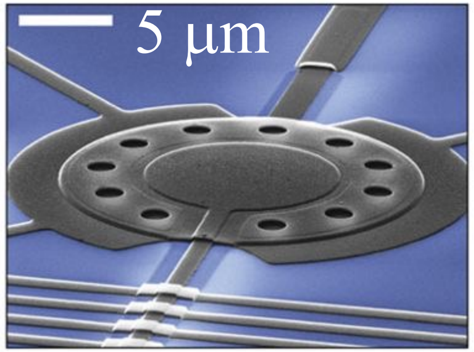
# The coherent state limit is hard to beat in a search for fundamental fields

On the measurement of a weak classical force coupled to a quantum-mechanical oscillator. I. Issues of principle

Carlton M. Caves, Kip S. Thorne, Ronald W. P. Drever, Vernon D. Sandberg, and Mark Zimmermann
Rev. Mod. Phys. **52**, 341 – Published 1 April 1980

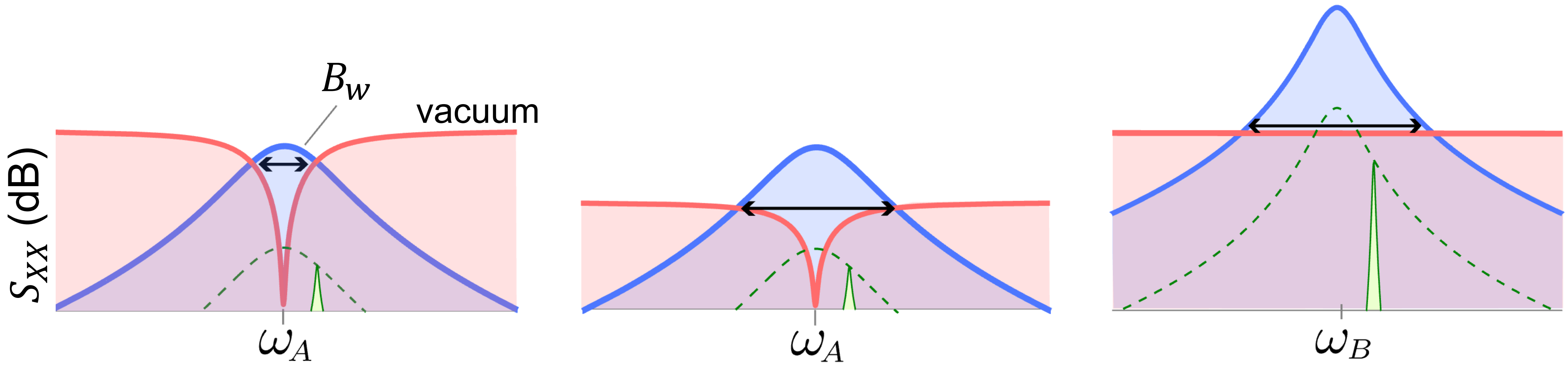
hard to beat CSL

- coupling to fundamental fields: big objects
- quantum control and measurement: small systems
- near technical perfection required



# strategy for more quantum enhancement

# Amplify signal before encountering measurement port noise




standard quantum limit

$\boxed{\times 2}$

squeezing
HAYSTAC apparatus

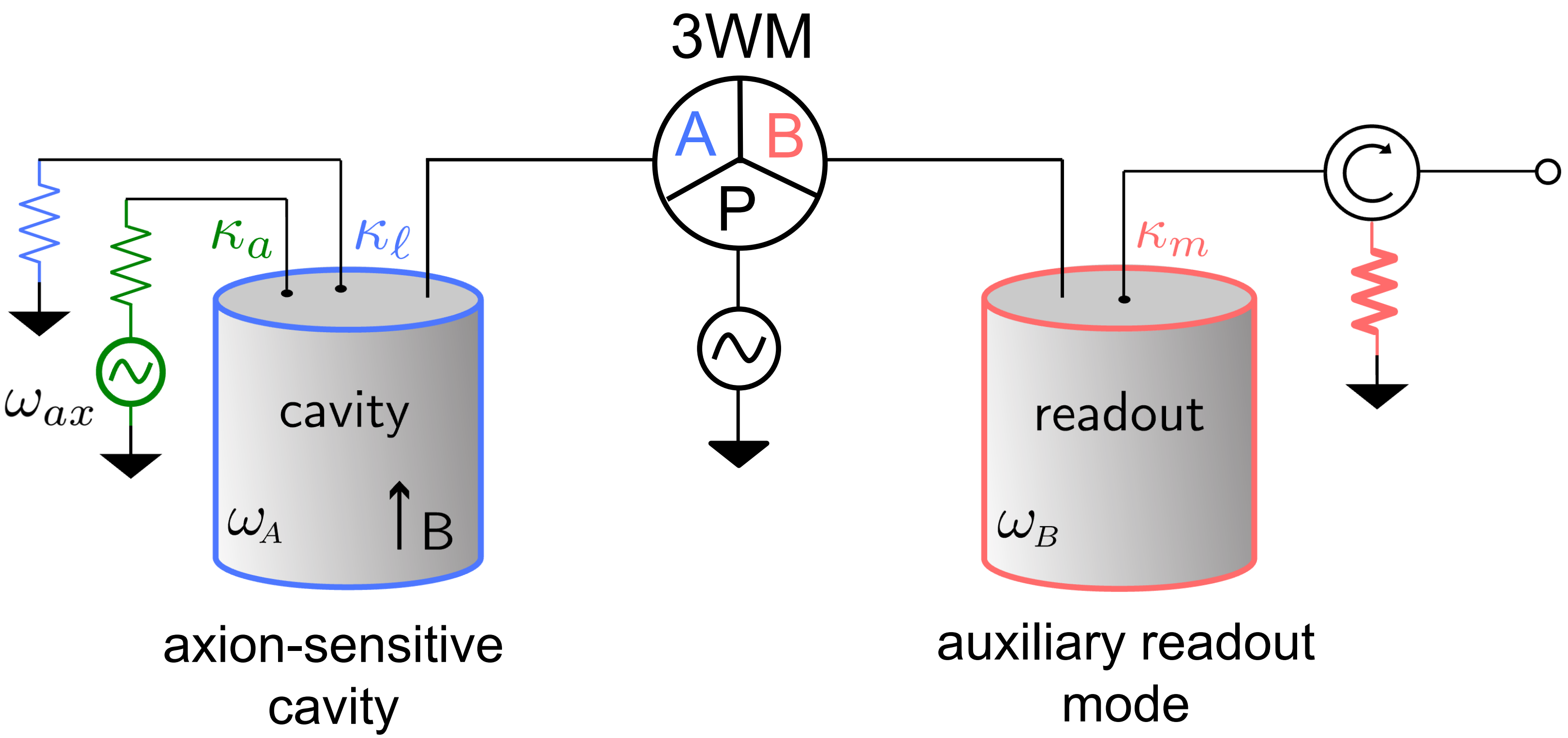
$\boxed{\times 8.2}$

cavity entanglement
“CEASEFIRE” Demo

Y. Jiang, E.P. Ruddy, K.O. Quinlan, M. Malnou, N.E. Frattini, KWL, *PRX Quantum* **4**, 020302 (2023)

K. Wurtz, Benjamin Brubaker, Y. Jiang, E. Ruddy, Daniel Palken, KWL, *PRX Quantum* **2**, 040350 (2021)

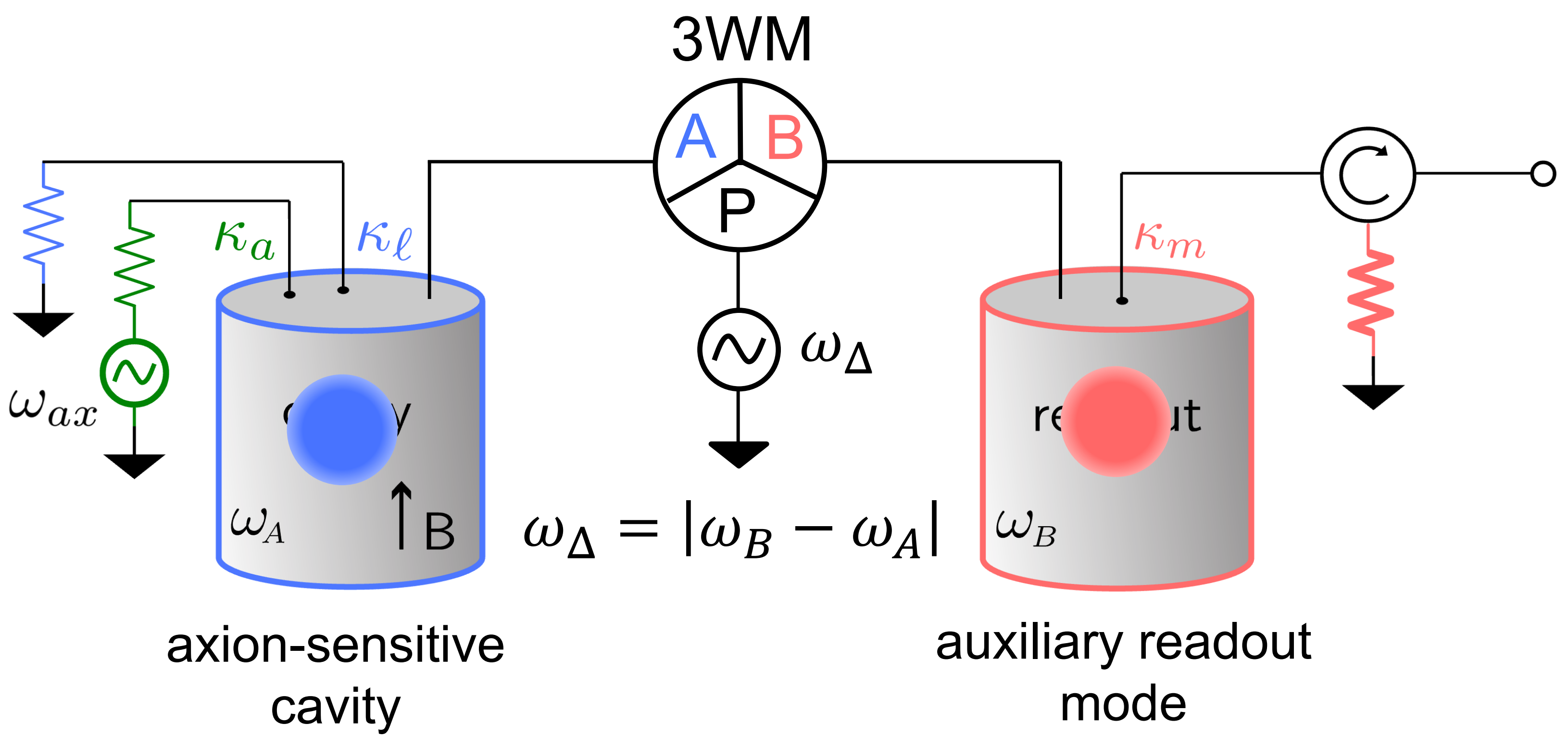
# Dynamically couple axion cavity and readout mode by 3-wave mixing




$$\hat{\mathrm{H}}_{3\mathrm{WM}} \propto (\hat{A} + \hat{A}^\dagger)(\hat{B} + \hat{B}^\dagger)(\hat{P} + \hat{P}^\dagger)$$

# State swapping (C) interaction swaps states between two modes

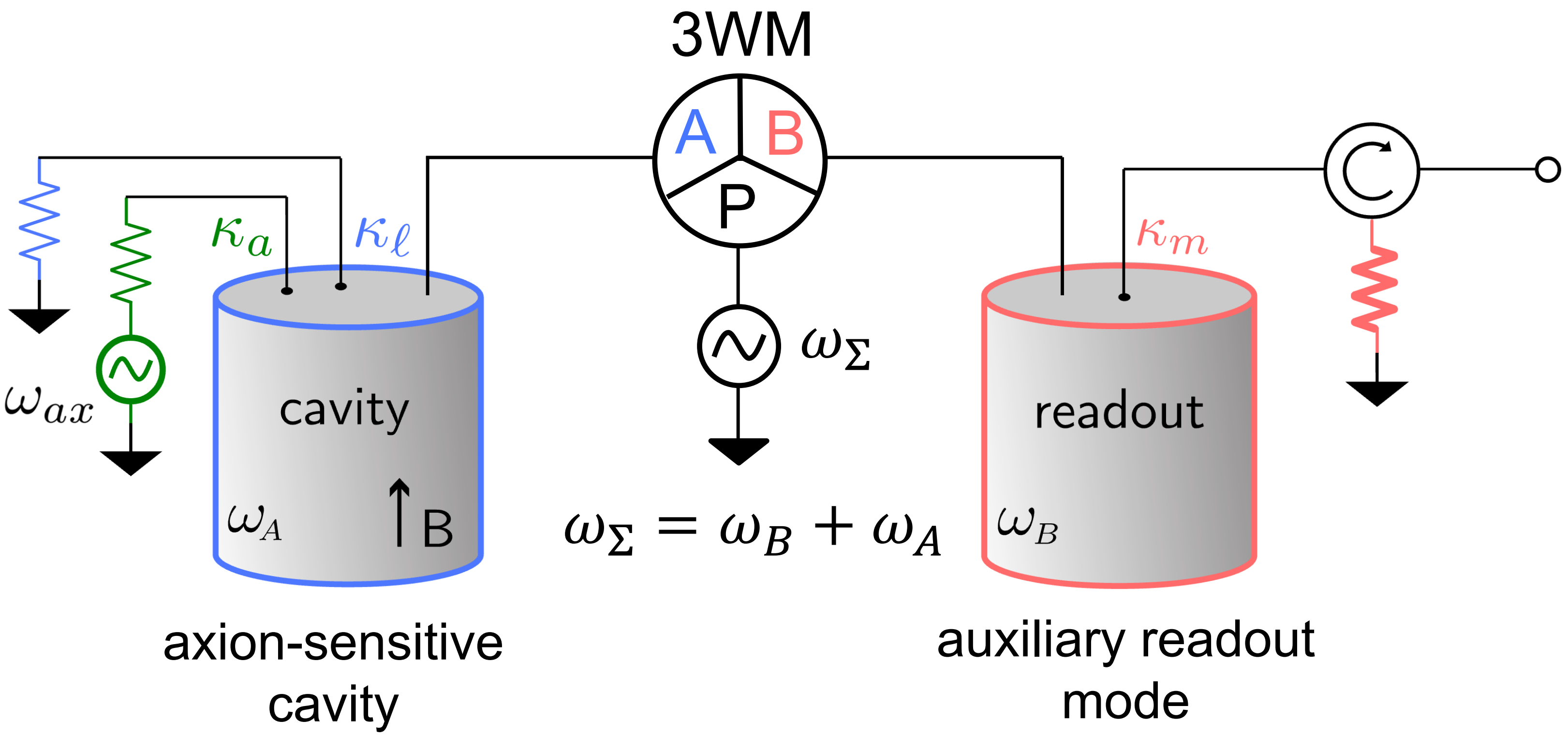





$$\hat{\mathrm{H}}_{3\mathrm{WM}} \propto (\hat{A} + \hat{A}^\dagger)(\hat{B} + \hat{B}^\dagger)(\hat{P} + \hat{P}^\dagger)$$

$$\hat{P} \rightarrow g_C e^{-i\omega_\Delta t} + \text{c.c.} \quad \boxed{\rightarrow g_C(\hat{A}\hat{B}^\dagger + \hat{A}^\dagger\hat{B})}$$ state-swapping

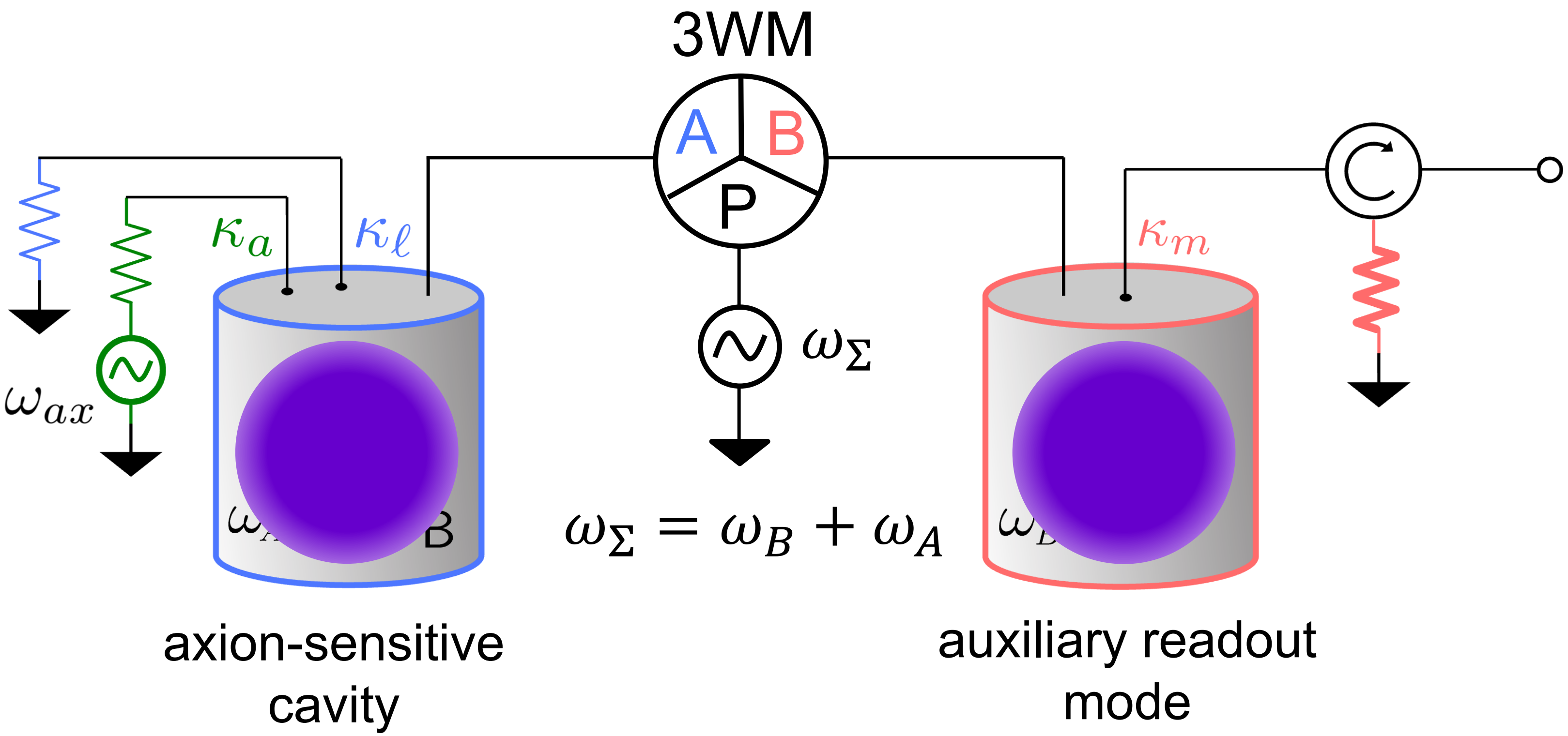
# Two-mode squeezing (G) induces amplification and entanglement




$$\hat{H}_{3WM} \propto (\hat{A} + \hat{A}^\dagger)(\hat{B} + \hat{B}^\dagger)(\hat{P} + \hat{P}^\dagger)$$

$$\hat{P} \rightarrow g_G e^{-i\omega_\Sigma t} + \text{c.c.} \quad \boxed{\rightarrow g_G(\hat{A}^\dagger \hat{B}^\dagger + \hat{A}\hat{B})}$$ two-mode squeezing

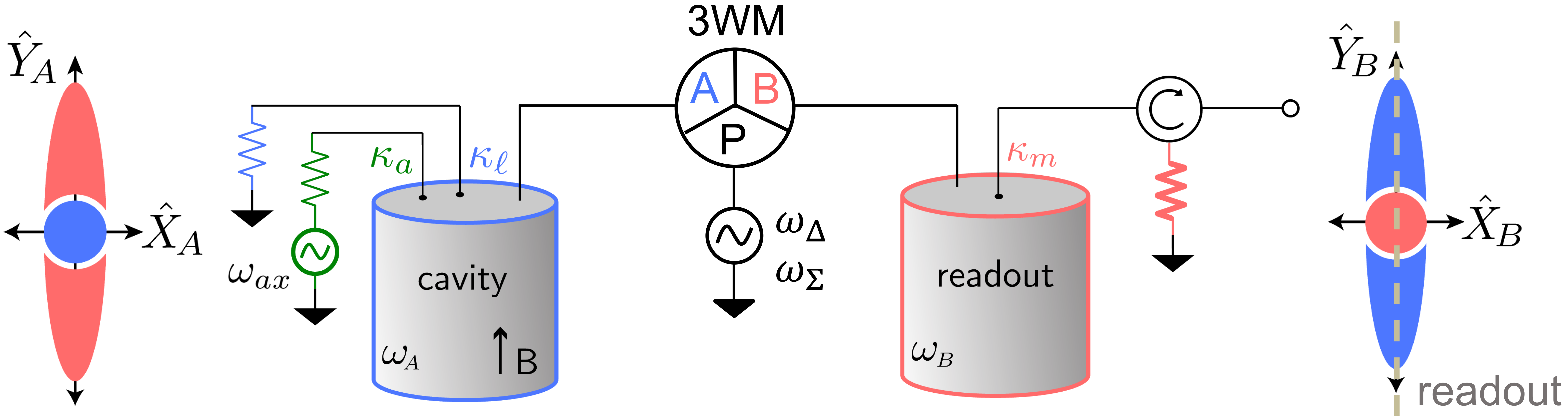
# Two-mode squeezing (G) induces amplification and entanglement




$$\hat{\mathrm{H}}_{3\mathrm{WM}} \propto (\hat{A} + \hat{A}^\dagger)(\hat{B} + \hat{B}^\dagger)(\hat{P} + \hat{P}^\dagger)$$

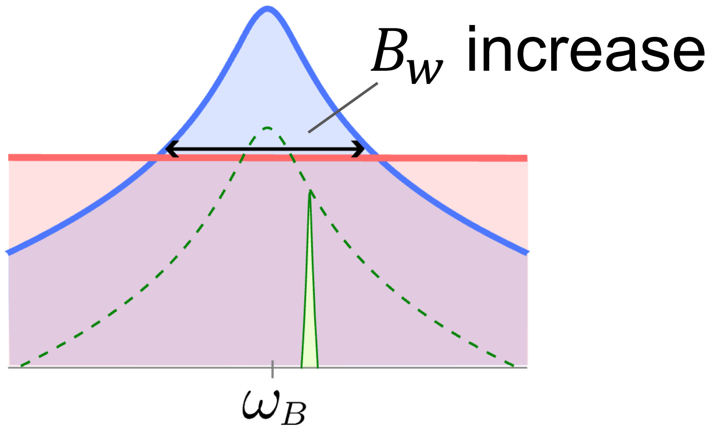
$$\hat{P} \rightarrow g_G e^{-i\omega_\Sigma t} + \text{c.c.} \quad \boxed{\rightarrow g_G(\hat{A}^\dagger \hat{B}^\dagger + \hat{A}\hat{B})}$$ two-mode squeezing

# Quantum non-demolition interaction yields bandwidth increase



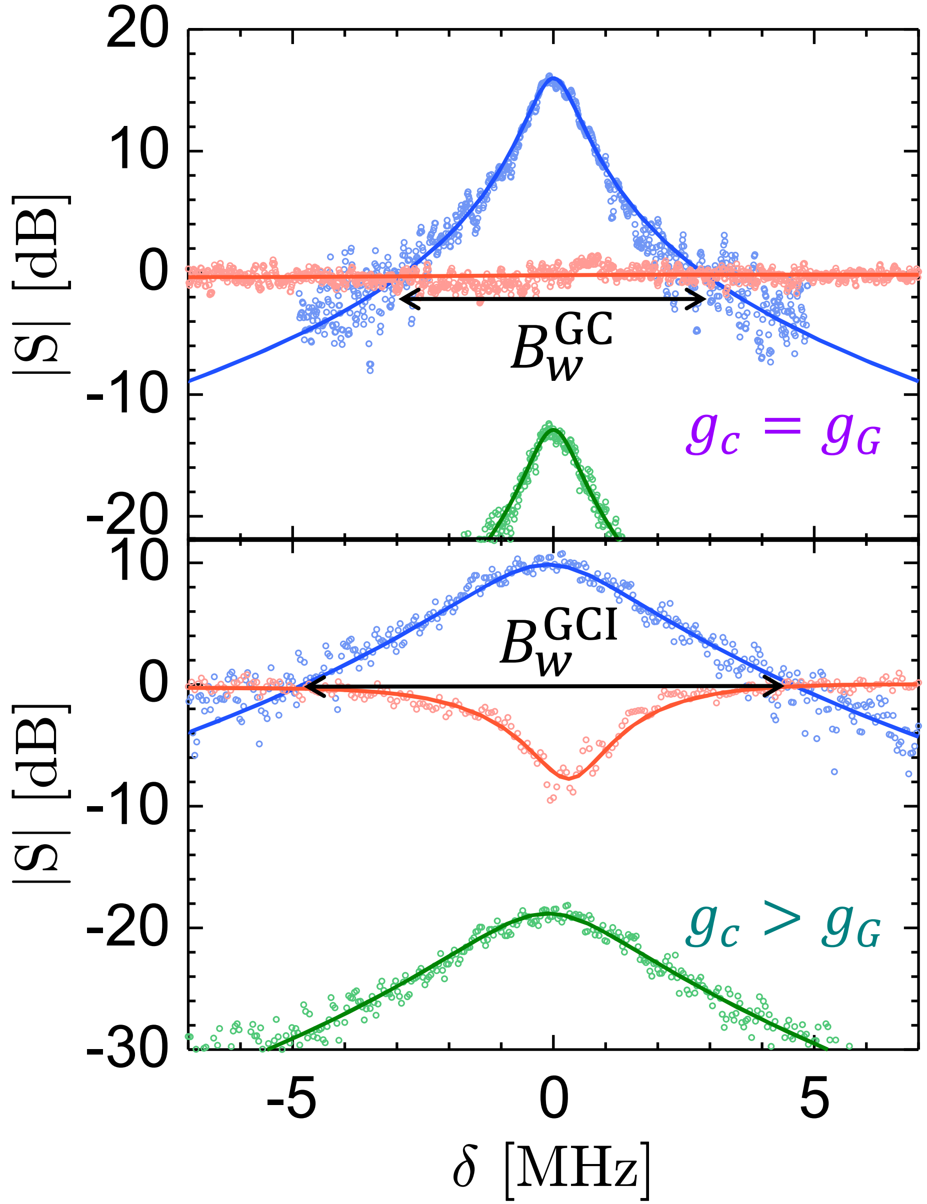

$$\hat{\mathrm{H}}_{3\mathrm{WM}} = g_C \hat{A}\hat{B}^\dagger + g_G \hat{A}^\dagger \hat{B}^\dagger + \text{c.c.} \quad \boxed{\xrightarrow{\text{QND}} \; 2g\hat{X}_A\hat{X}_B}$$

| $d\hat{Y}_B/dt = -2g\hat{X}_A$ | $d\hat{X}_A/dt = 0$ |
|---|---|
| amplification | QND |




Metelmann, A. and Clerk, A.A., *Physical Review X* 5.2 (2015): 021025. Chien, T-C., et al. *Physical Review A* 101.4 (2020): 042336.

# Imbalanced GC operation for further scan rate enhancement

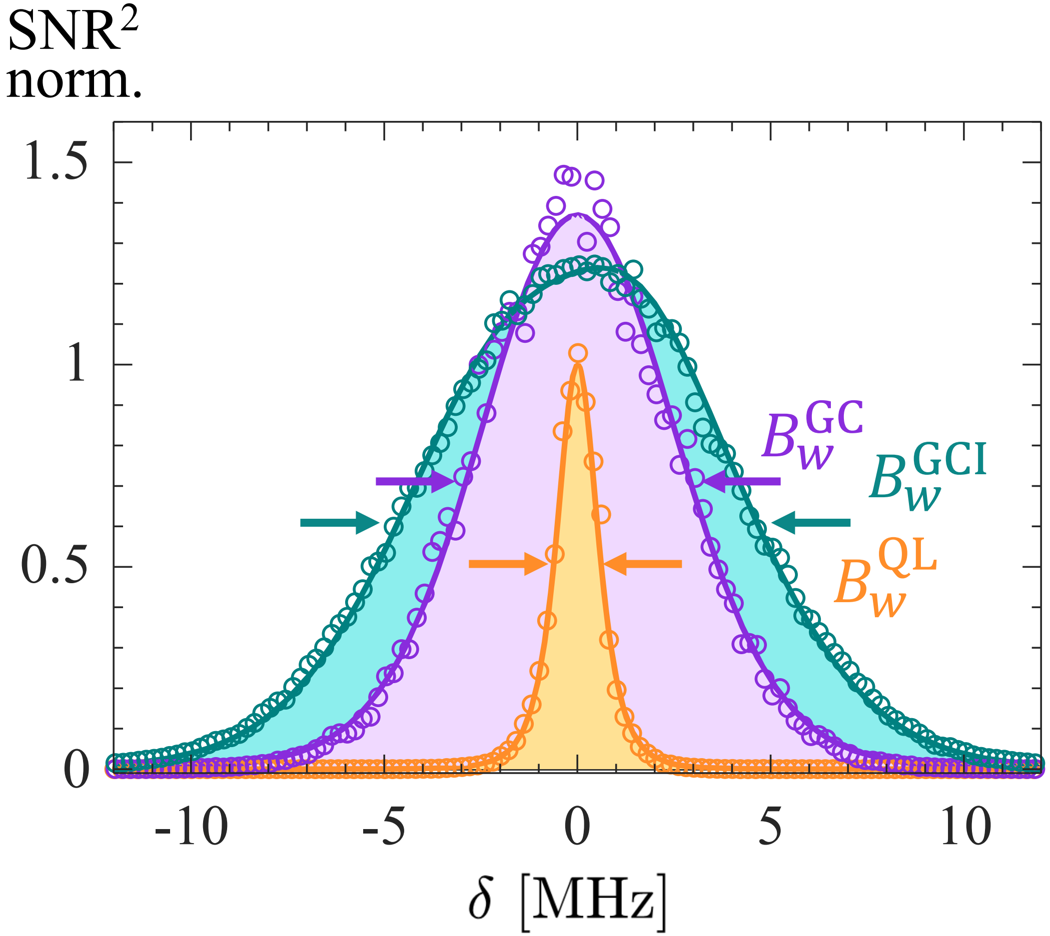



$B_w^{GC}$ = 6 MHz

**×5.6**

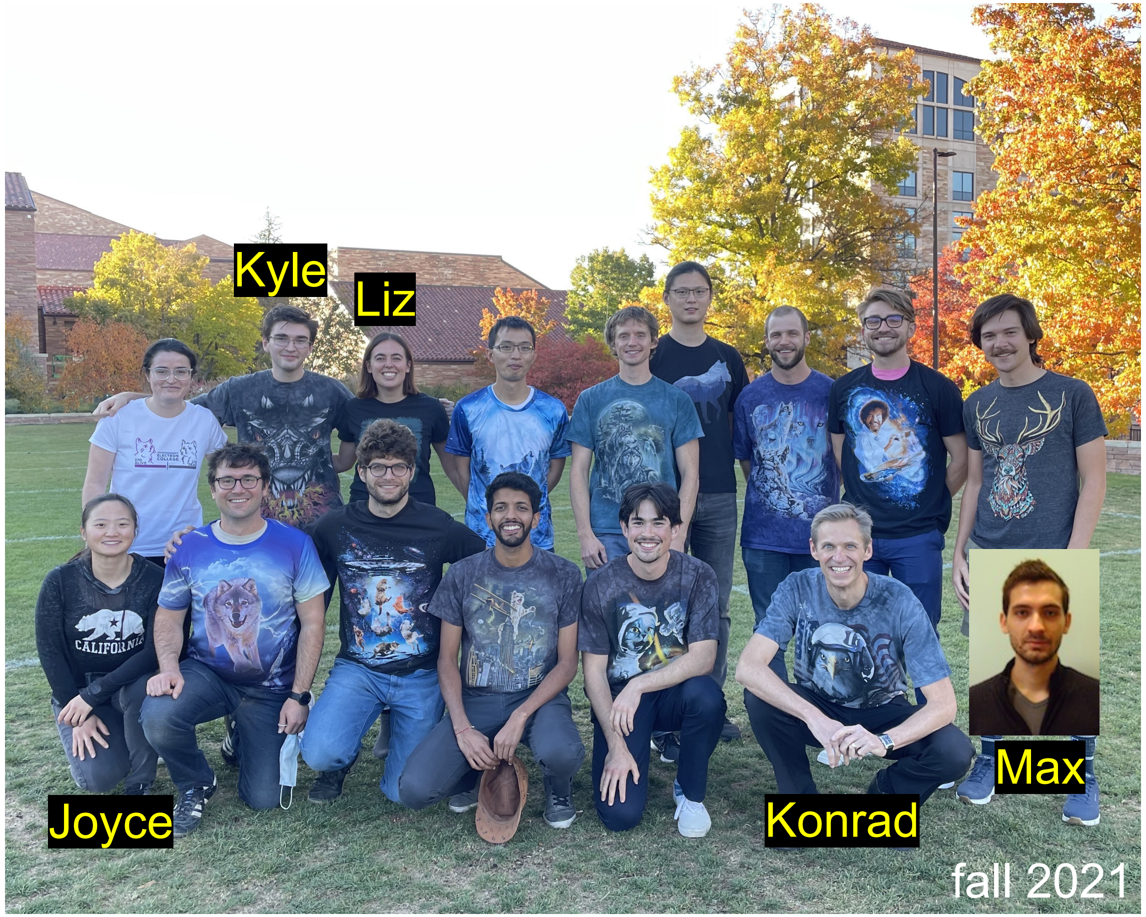
$B_w^{GCI}$ =10 MHz

**×8.2**




**Y Jiang**, et, al., PRX Quantum 4 (2), 020302. (2023)

# Acknowledgements for CEASEFIRE data

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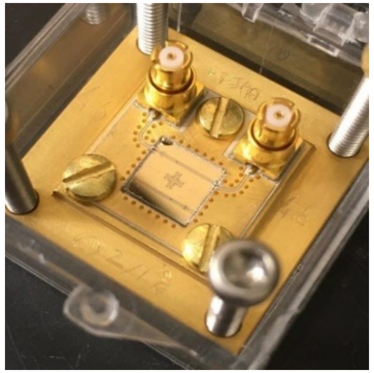

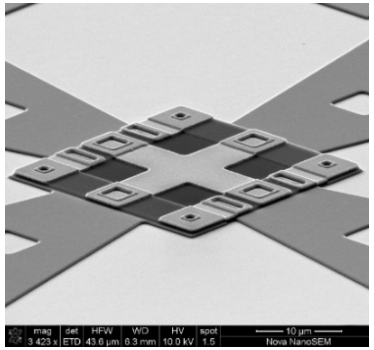

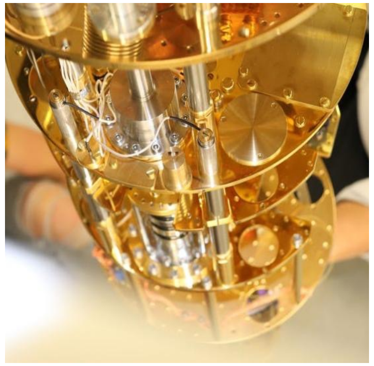

The **H**aloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM

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