Quantum enhanced methods for ultralight dark matter searches

TIPP talk May 28th 2021
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Haystac

U.S. DEPARTMENT OF ENERGY
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JILA pfc an NSF physics frontier center

Q-SEnSE

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DOE-HEP QuantISED program

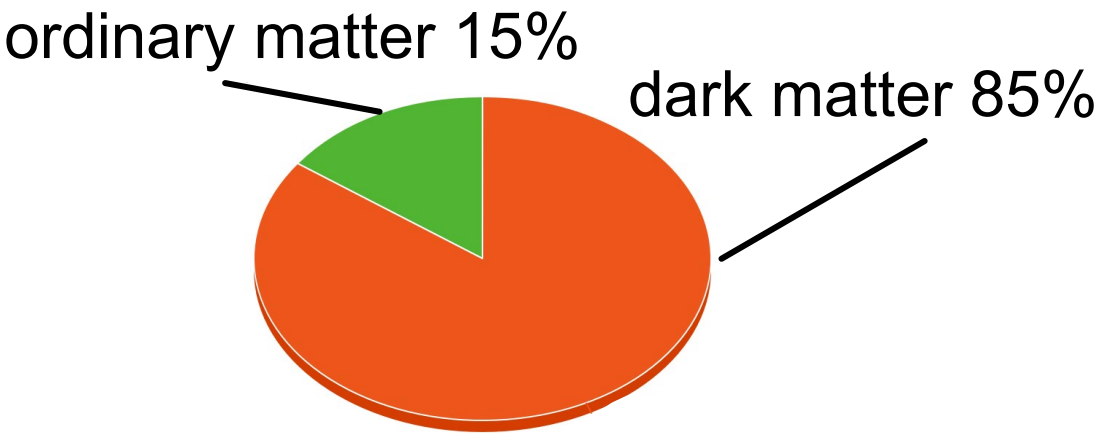
Outline

search for ultralight dark matter: a quantum metrology problem

quantum squeezing is already speeding up the search for axionic dark matter

quantum technology development may dramatically accelerate an axion search

Particle nature of dark matter remains unknown



dark matter:

85% of the matter in the universe

detected only gravitationally

cold (gravitationally bound)

mean density: ~ 0.4 GeV/cm^3

Ultralight dark matter must be bosonic

ultralight dark matter (e.g. axions):

quantum degenerate Bose gas

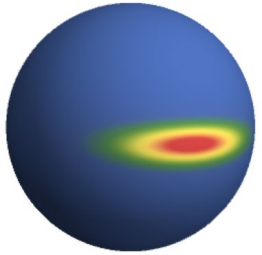
more wave-like than particle-like

tone: feeble, persistent, unknown frequency

Laboratory based searches for ultralight dark matter

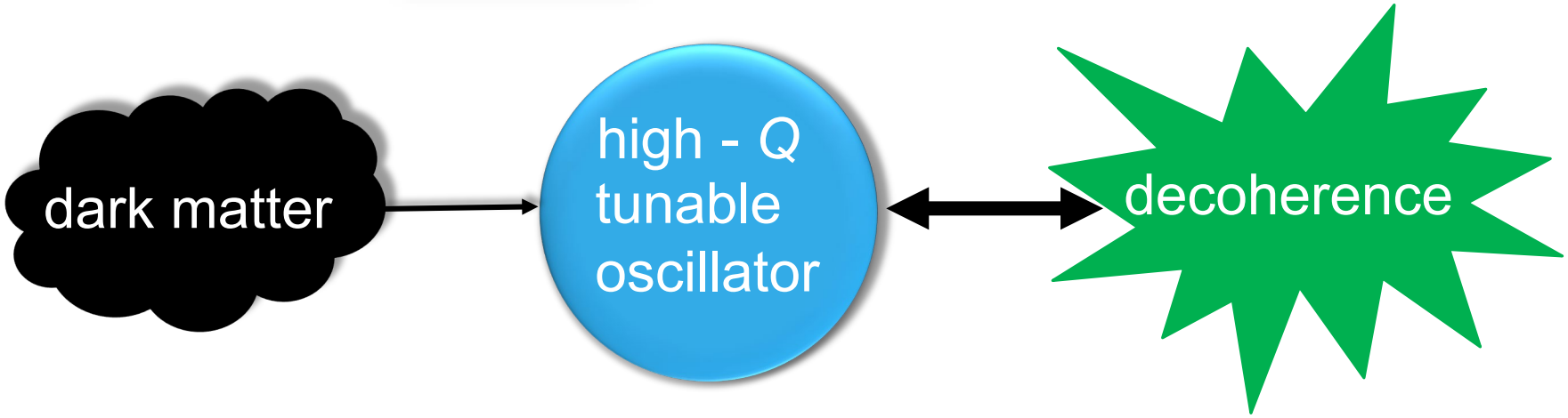
classical signal acting on a quantum harmonic oscillator

microwave cavities



spin ensembles

ADMX, HAYSTAC, CASPEr, DMradio



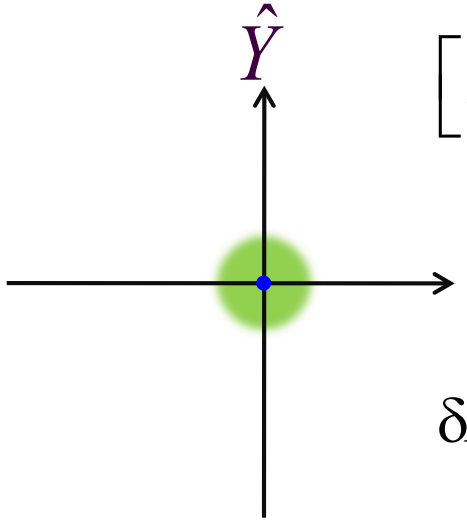
evolution in rotating frame

null hypothesis $\hat{H}_{\mathrm{r}} = 0$

dark matter hypothesis $\hat{H}_{\mathrm{r}} = F_Y(t)\hat{X} + F_X(t)\hat{Y}$

Quantum noise pollutes inference of classical force

null hypothesis

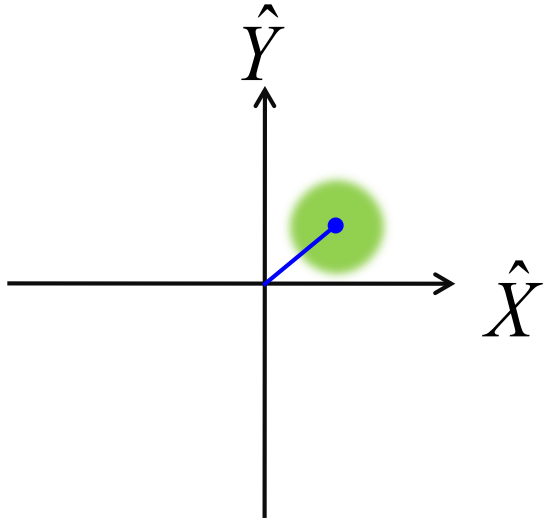


$$\left[\hat{X},\hat{Y}\right]=i$$

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

ground state

dark matter hypothesis



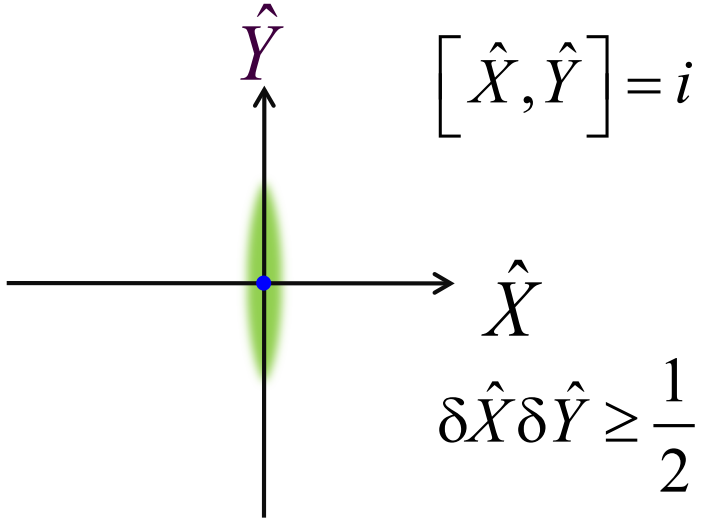
displaced ground state

"quantum limit"--- coherent state limit (CSL)

prepare in ground state, evolve, measure X noiselessly

Squeezing and noiseless measurement circumvent quantum limit

null hypothesis

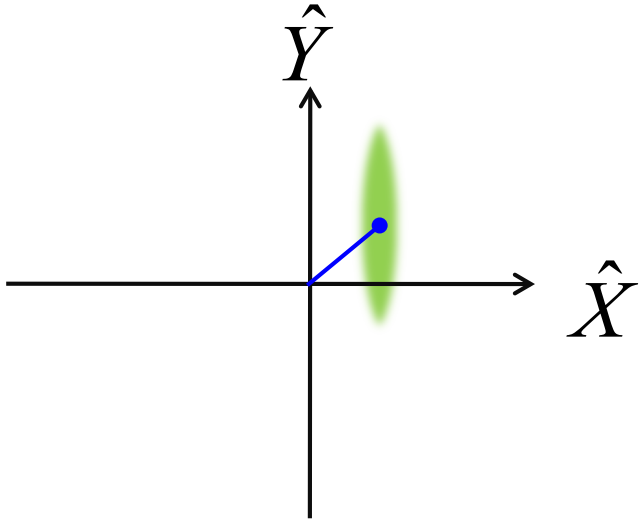


$$\left[\hat{X},\hat{Y}\right]=i$$

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

squeezed state

dark matter hypothesis



displaced squeezed state

beat the quantum limit

prepare in squeezed state, evolve, measure X noiselessly

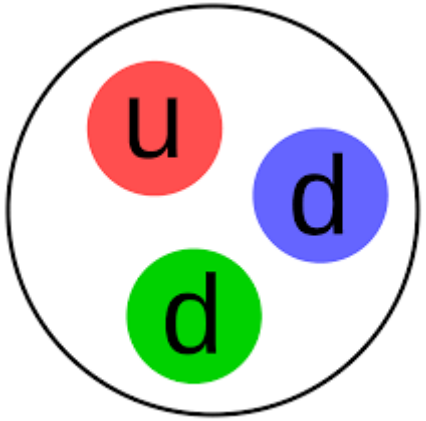
quantum enhanced axion search

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)

Why is CP symmetry well-preserved in QCD?

Why is the neutron so round?



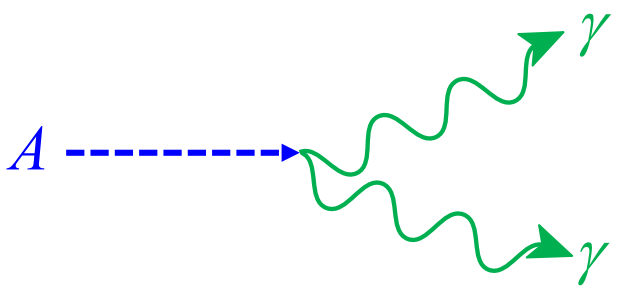
axion mass range $2\ \mu\text{eV} < m_a c^2 < 2000\ \mu\text{eV}$

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

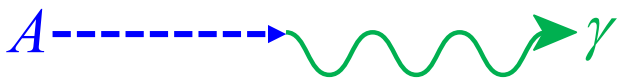
*post-inflation scenario

Axion field couples to electromagnetism

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



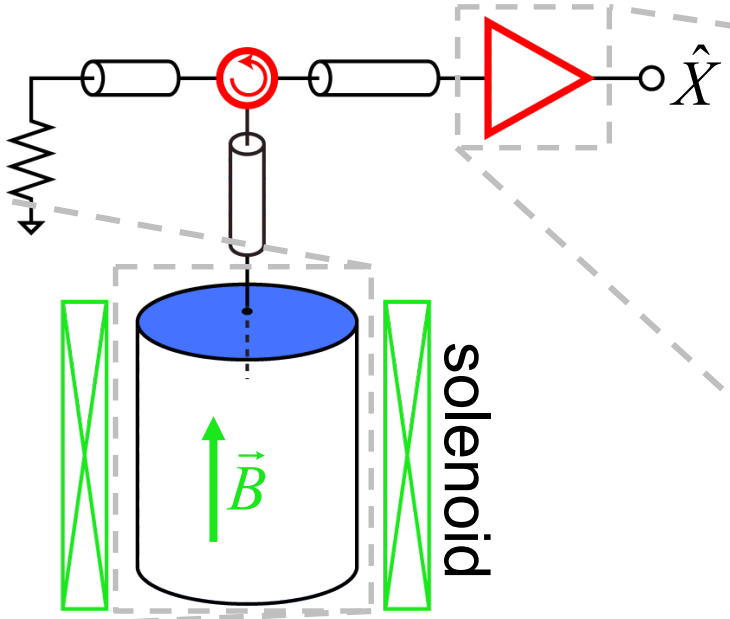
linearize coupling around static $\vec{B}$-field

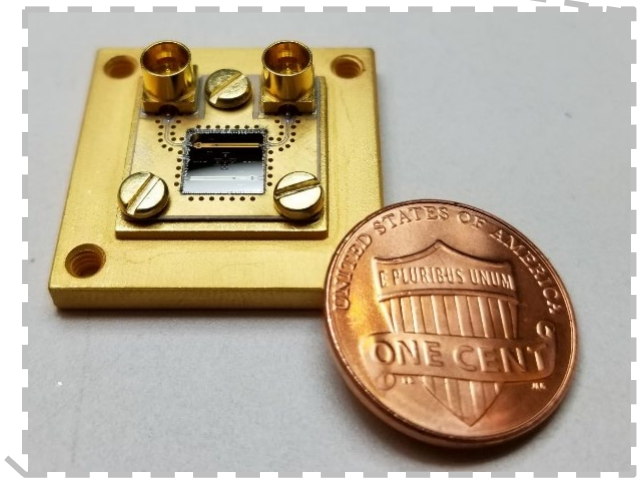


$E_A = E_\gamma$

dark matter axions create microwave photons

Scan cavity to search for resonant axion to photon conversion





1 L volume

$Q = 10^4$

$\omega_{\text{cav}} \sim 2\pi \times 5$ GHz

tunable cavity

$T \ll \frac{\hbar\omega_{\text{cav}}}{k_B}$

Josephson parametric amplifier (JPA)

measure $\hat{X}$ noiselessly

haloscope (Sikivie 1983) at the quantum limit (HAYSTAC 2017)

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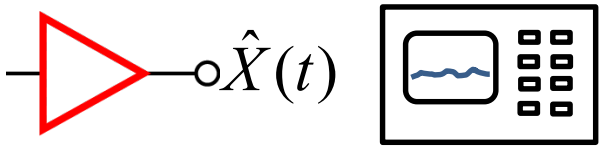
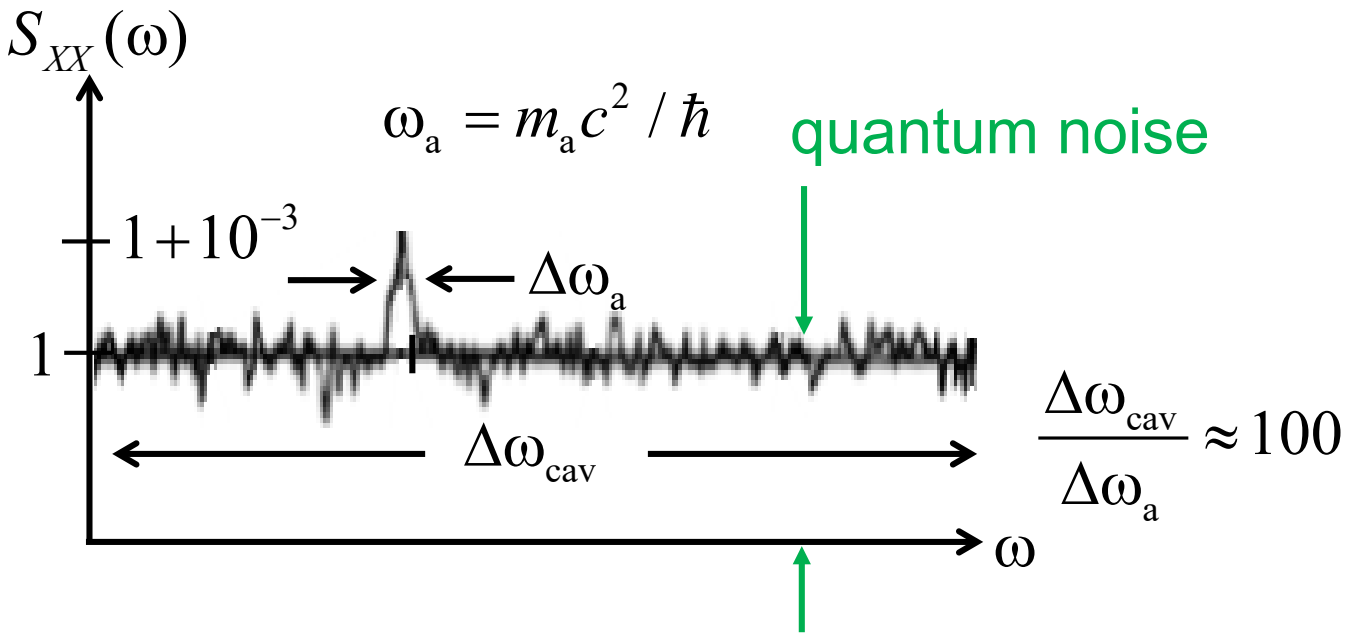
Average noise to resolve tiny excess axion power



spectrum analyzer



$$\frac{\Delta\omega_{cav}}{\Delta\omega_a} \approx 100$$

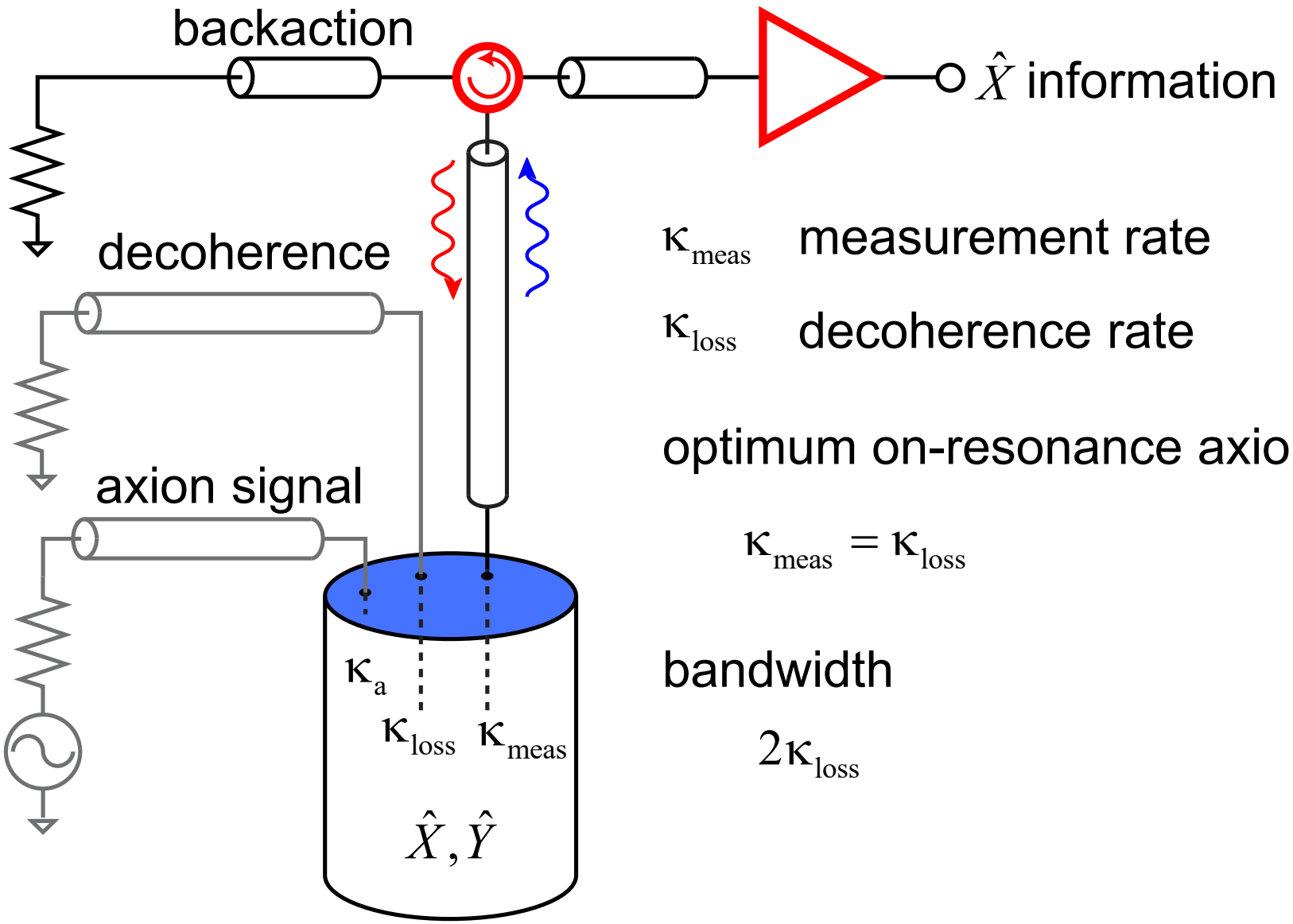
10^{-3} noise precision ⇨ 10^6 measurements

tune → wait and average → tune

100 axion bands per cavity tuning

scan rate proportional to bandwidth

Measurement backaction limits haloscope bandwidth



κ_{meas} measurement rate

κ_{loss} decoherence rate

optimum on-resonance axion sensitivity

$$\kappa_{meas} = \kappa_{loss}$$

bandwidth

$$2\kappa_{loss}$$

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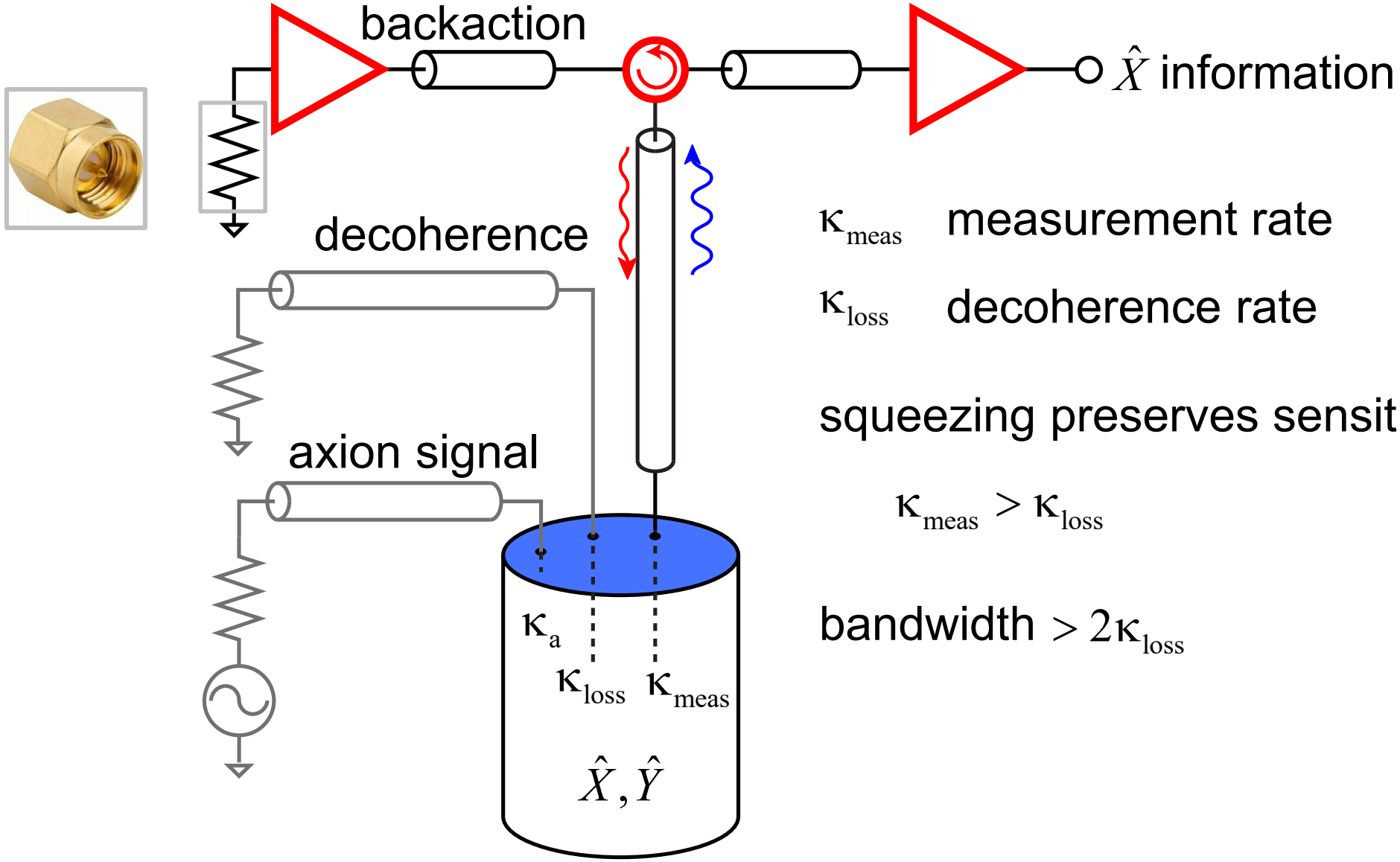
Squeezing yields larger bandwidth through backaction evasion



κ_{meas} measurement rate

κ_{loss} decoherence rate

squeezing preserves sensitivity with

$$\kappa_{meas} > \kappa_{loss}$$

bandwidth $> 2\kappa_{loss}$

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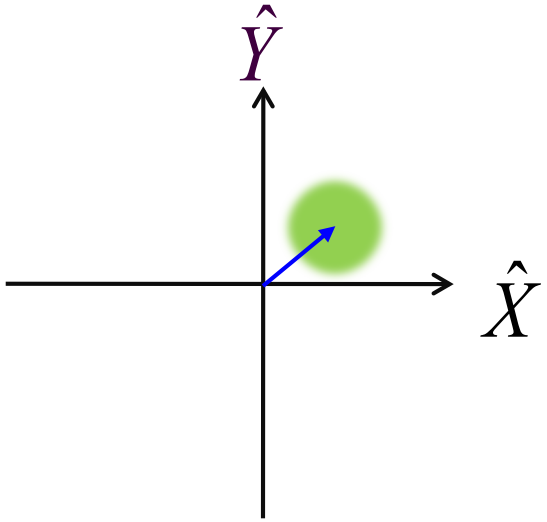
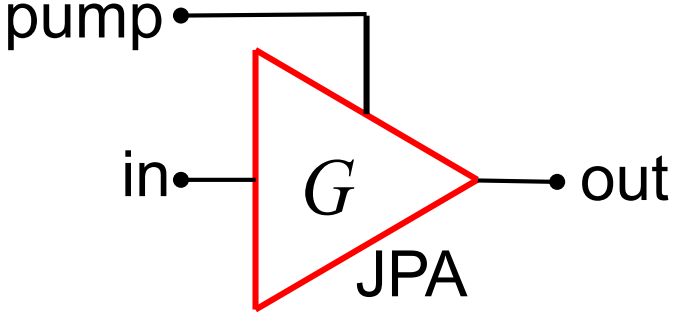
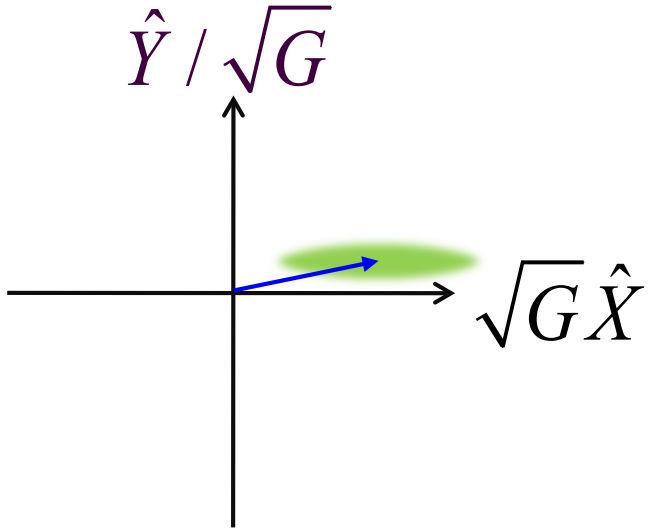
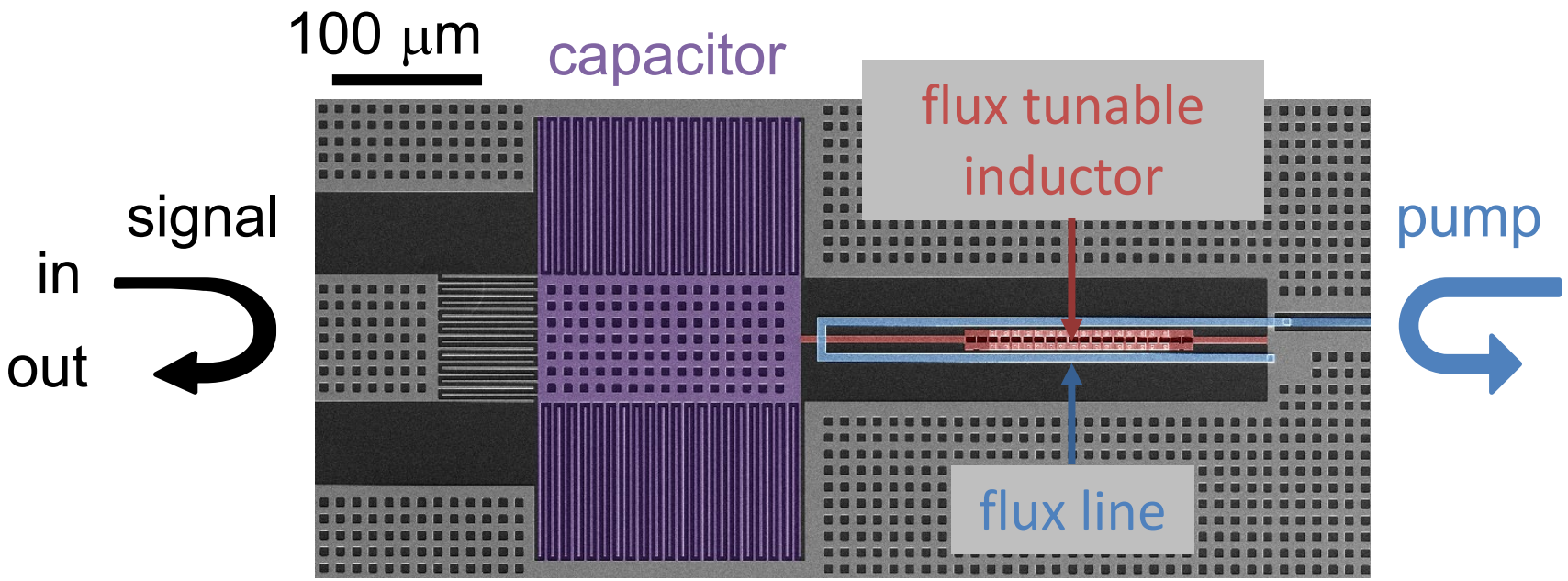
JPAs measure one quadrature noiselessly

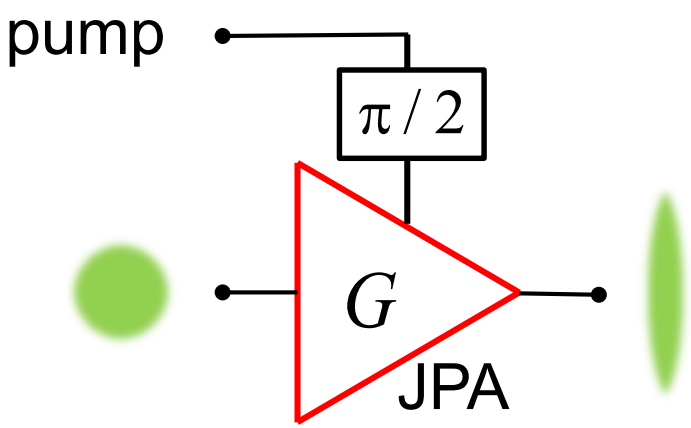








JPAs prepare microwave squeezed states

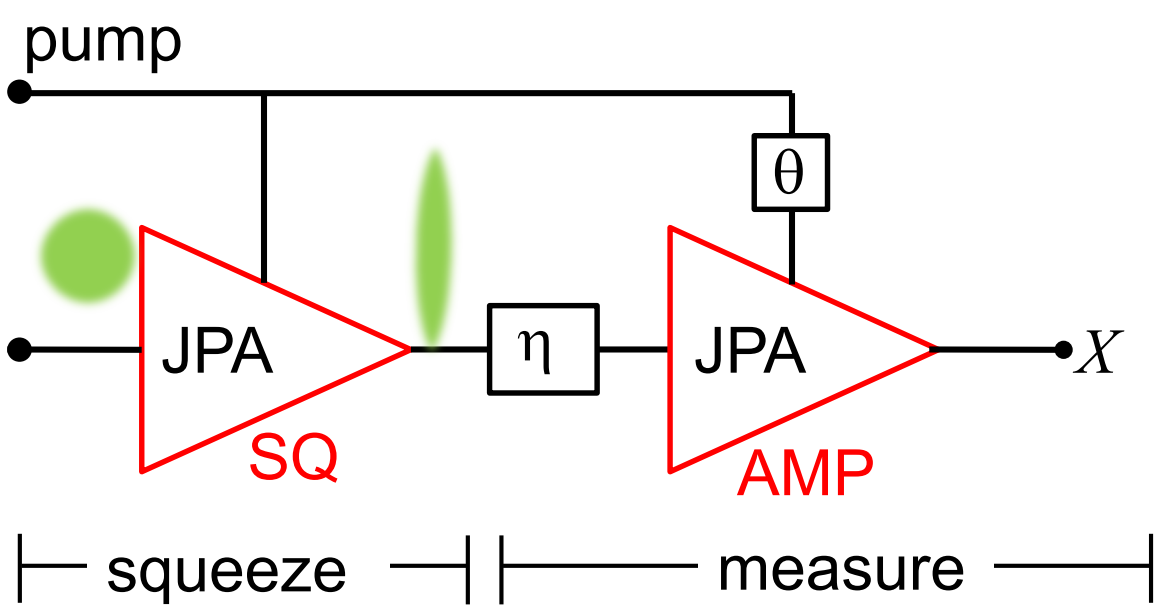


$$\delta^2 \hat{Y} = \frac{G}{2}$$

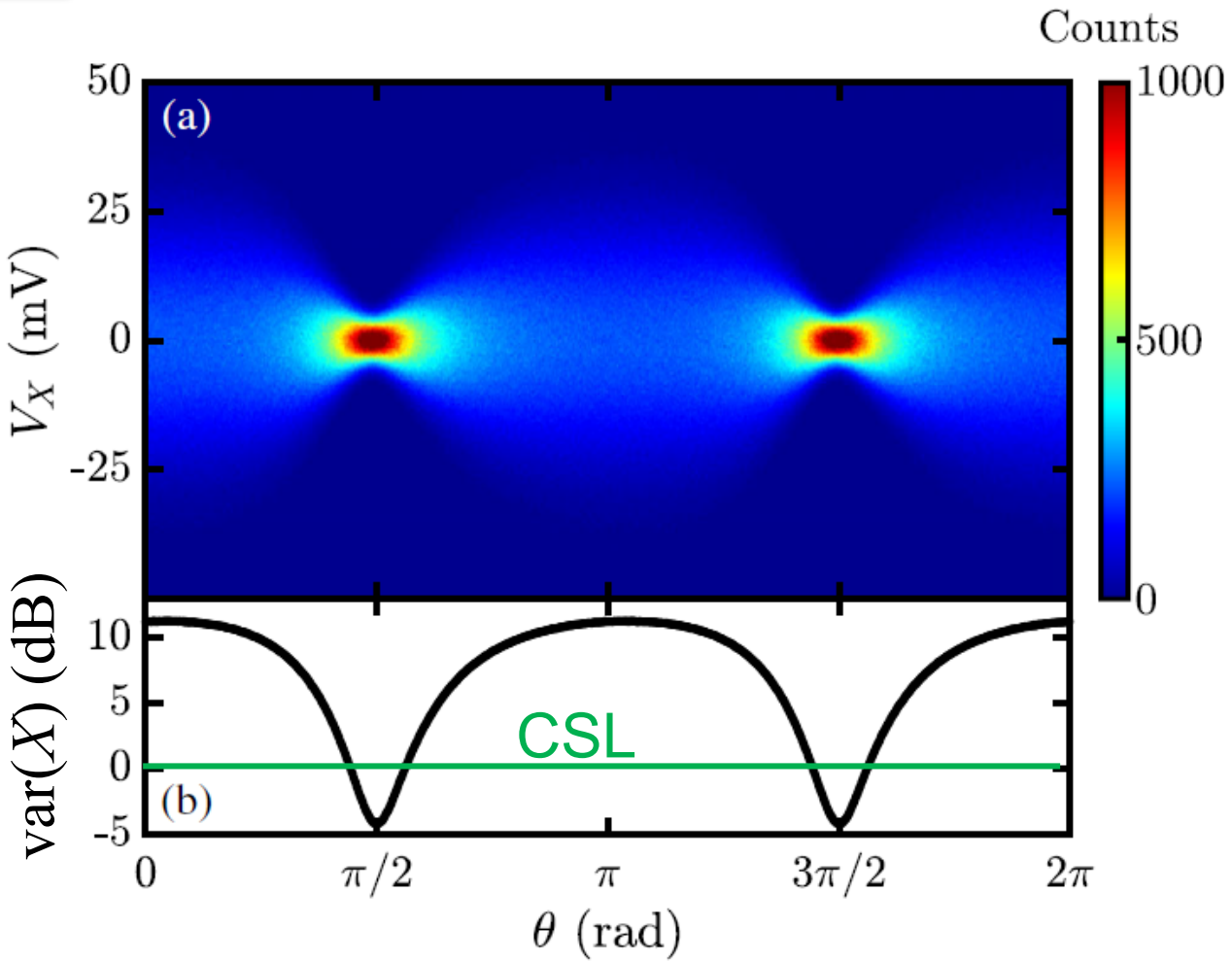
$$\delta^2 \hat{X} = \frac{1}{2G}$$

squeezed quadrature: quantum noise suppressed

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



phase θ chooses measured quadrature relative to squeezed quadrature

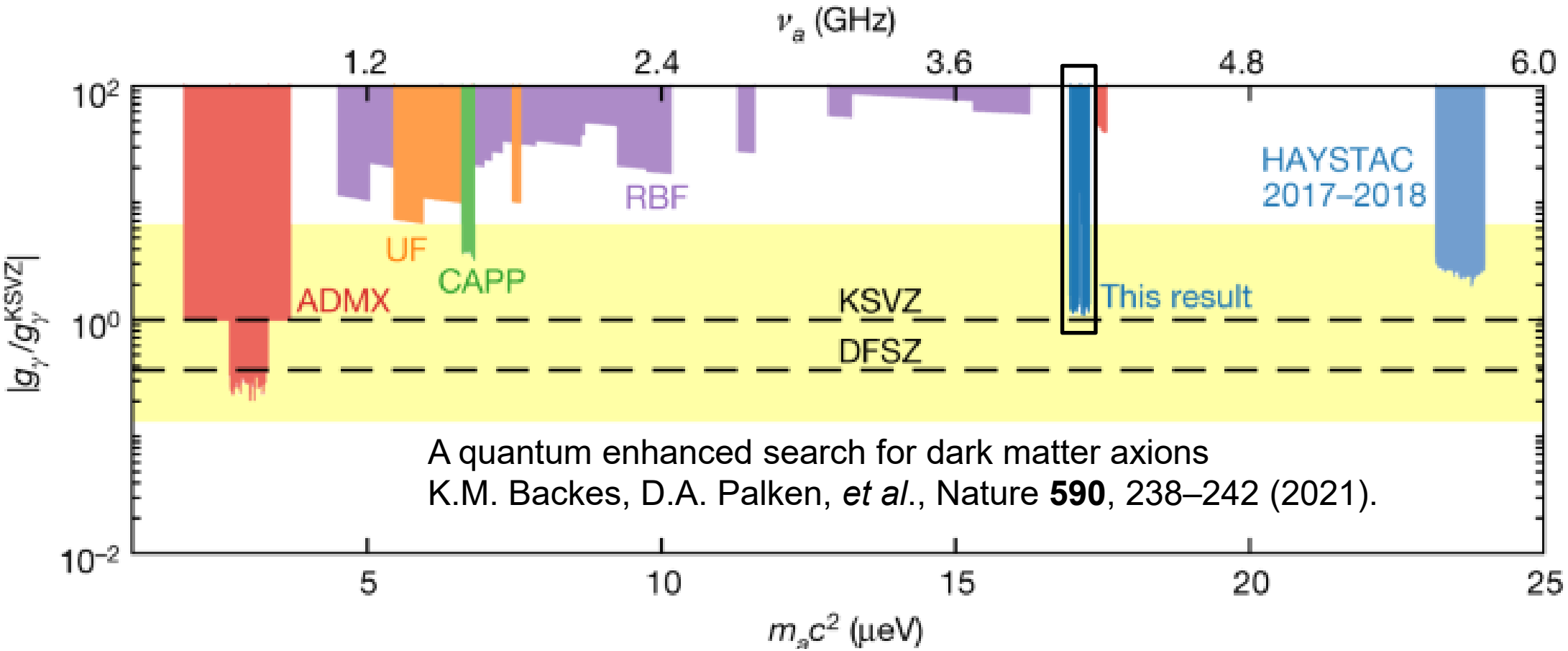


M. Malnou, KWL et al., Phys. Rev. X **9**, 021023 (2019)

loss η: 1.63 dB

First quantum enhanced dark matter search

double the CSL scan rate



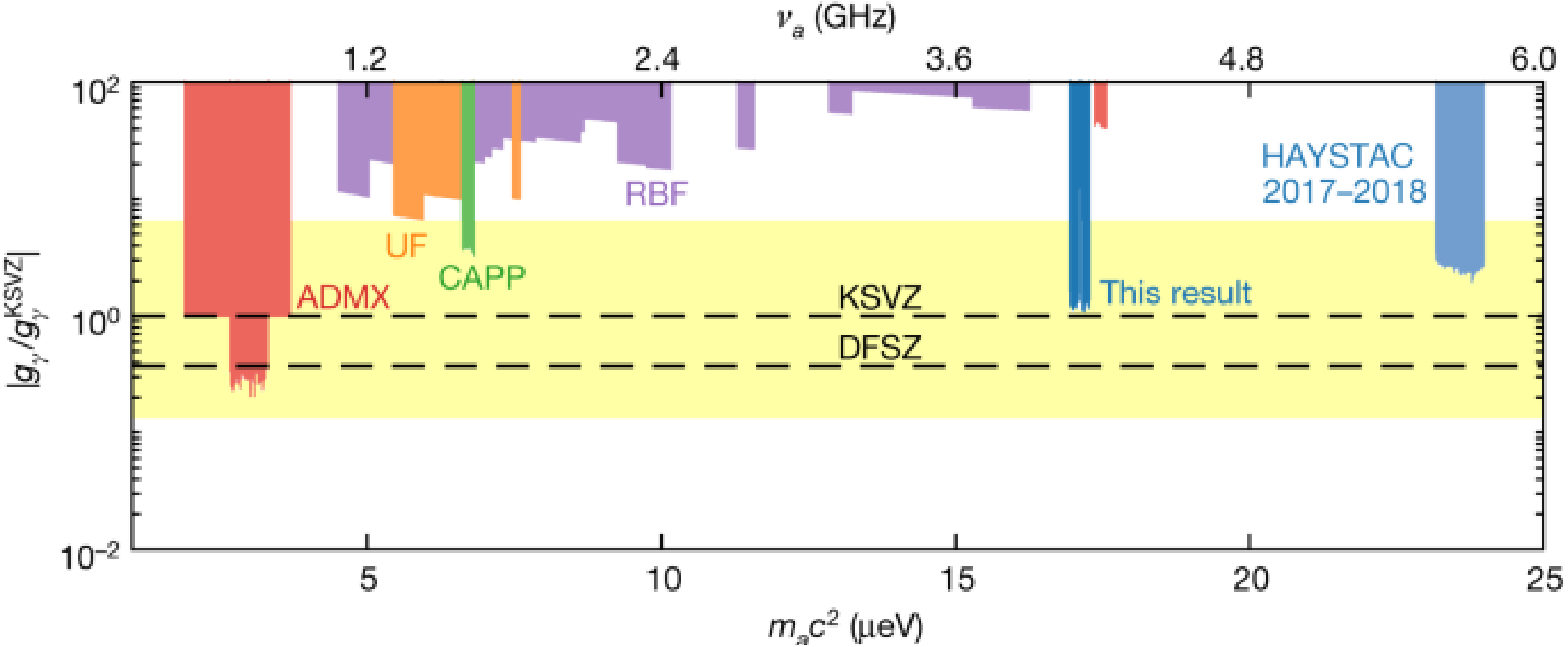
A quantum enhanced search for dark matter axions
K.M. Backes, D.A. Palken, *et al.*, Nature **590**, 238–242 (2021).

Prohibitive resources required to scan one decade at CSL

1 – 10 GHz at CSL for DFSZ

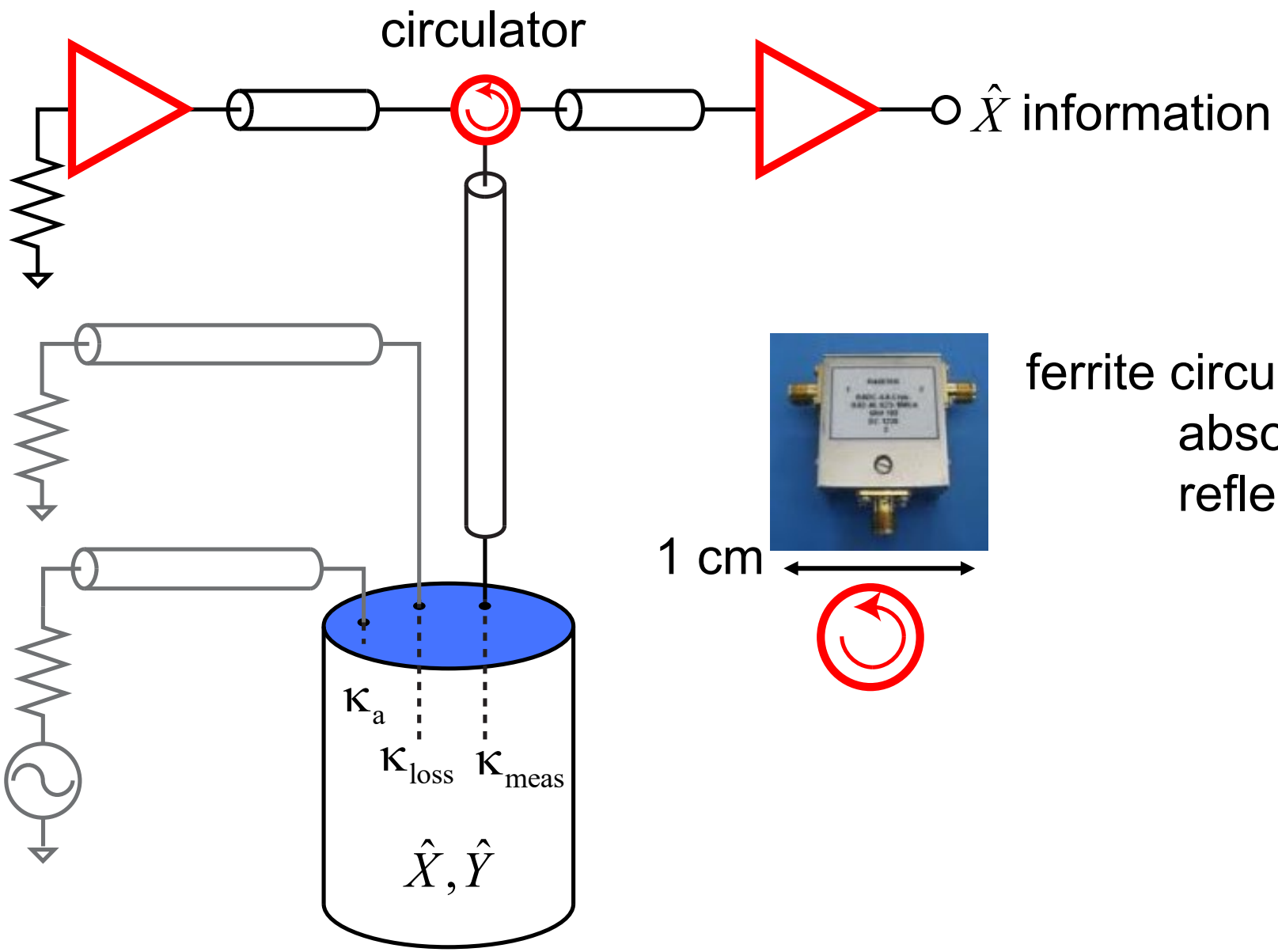
1 x 9T magnet or 16 x 30T magnets

~20,000 yrs ~10 yrs + 1.2 B$



engineering more quantum enhancement

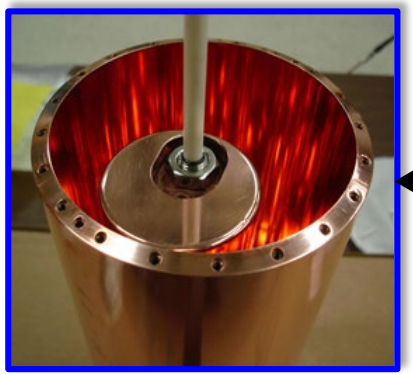
Squeezing diminished by circulator and cascaded signal path



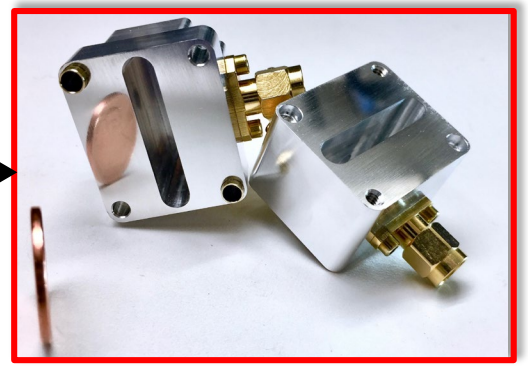
ferrite circulator loss
absorption
reflection

A better approach to backaction evading measurements

axion cavity



readout cavity



ω_A ω_R

no ferrite circulators
no loss from reflection

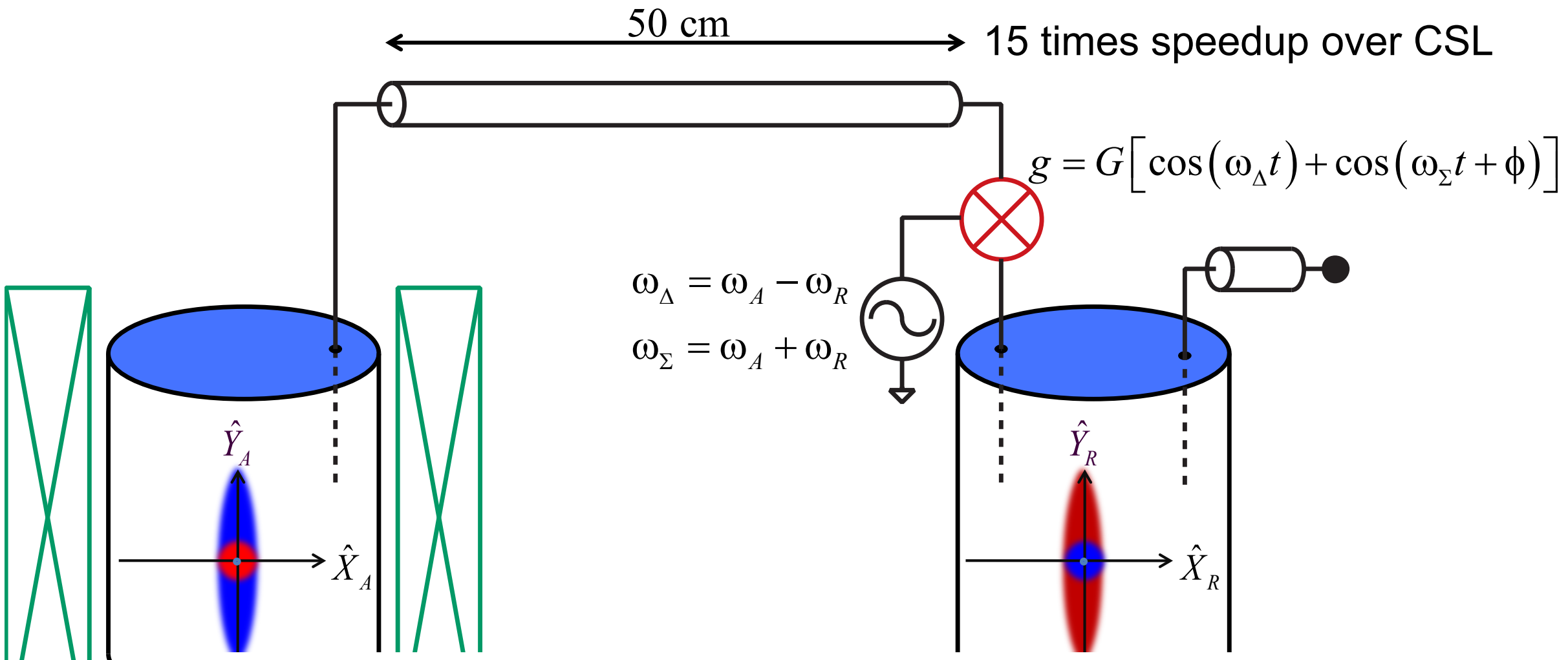
engineering QND interaction between two cavities

$$\hat{H}_I = \hbar G \hat{X}_R \hat{X}_A \qquad \frac{d}{dt}\hat{Y}_R = -G\hat{X}_A$$

monitor $\hat{Y}_R$ infer $\hat{X}_A$

backaction deposited in unmonitored quadrature

Two mode squeezing, state swapping yield QND Hamiltonian



15 times speedup over CSL

CEASEFIRE: Cavity Entanglement And Swapping Experiment For Improving Readout Efficiency

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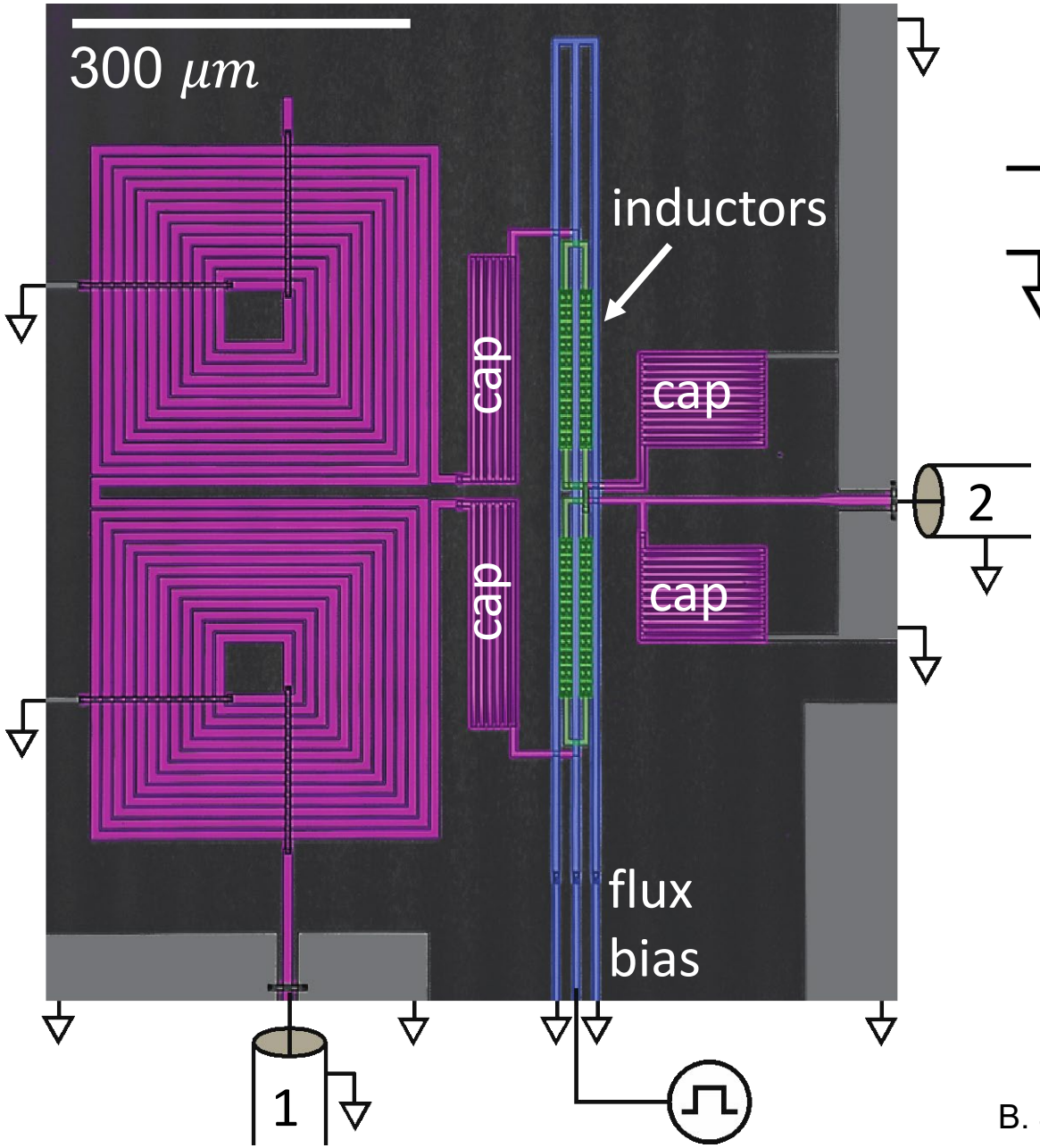
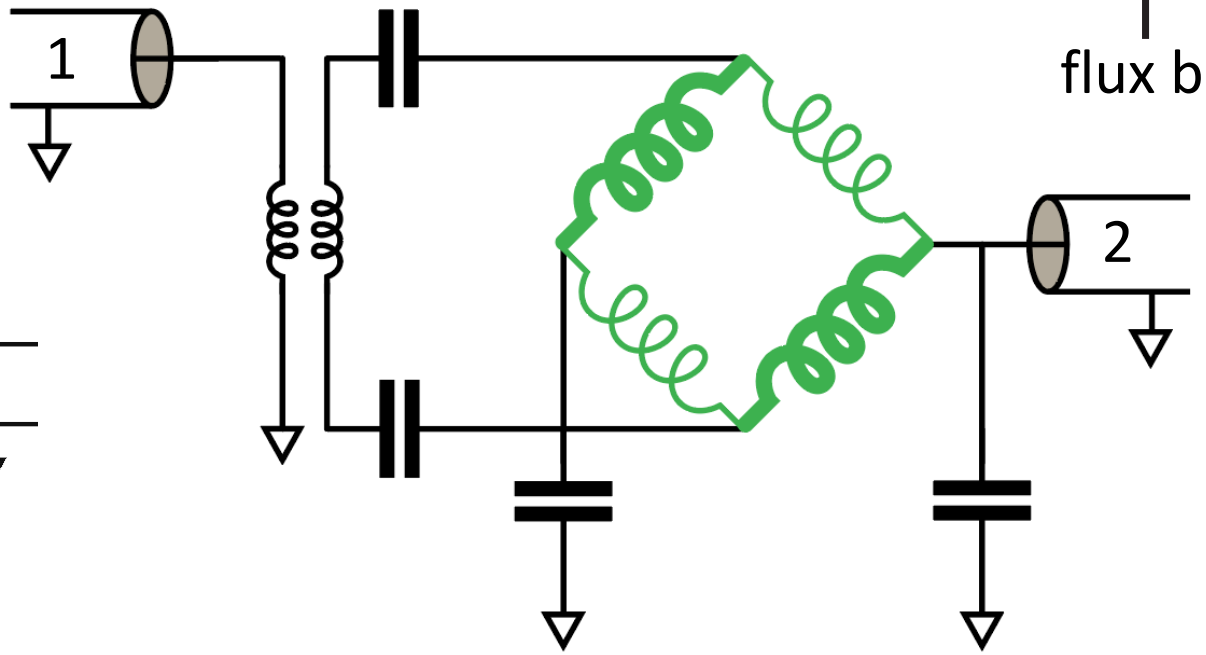
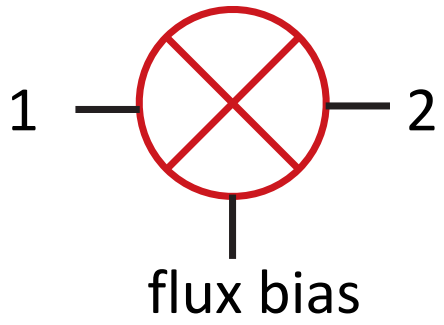
Tunable coupler from an inductor bridge







tune bridge balance/imbalance with

one on-chip bias line

B. J. Chapman, KWL *et al.*, *Appl. Phys. Lett.* 222602 **108** (2016)

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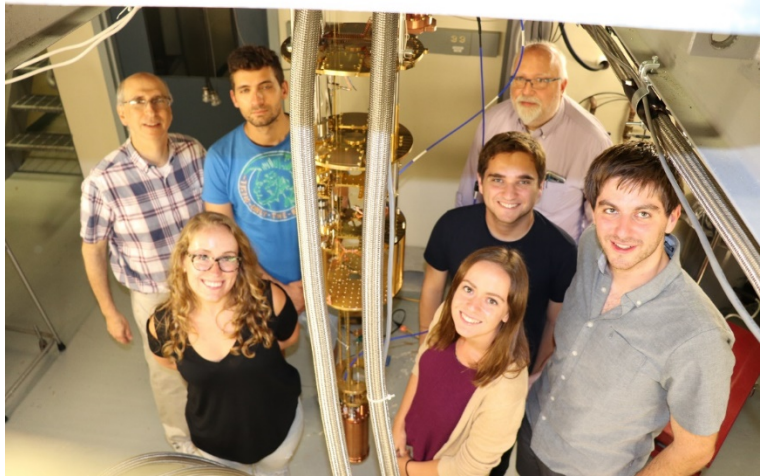
Conclusions

superconducting quantum technology accelerates the search for dark matter

quantum squeezing doubles search rate in HAYSTAC apparatus

greater speedup possible with circulator-less concepts

Yale, August 2018, SSR commissioning



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