Title: Accelerating an axionic dark matter search with quantum technology

Date: Aug 23, 2017 09:30 AM

URL: http://pirsa.org/17080028

Abstract:

Outline (and summary)

axion dark matter search: a microwave measurement problem

HAYSTAC search operates at the quantum limit

accelerating axion search with squeezing

- 2.5 times faster than quantum limit possible today
- 10-fold speed up with technical progress

accelerating axion search with photon counting

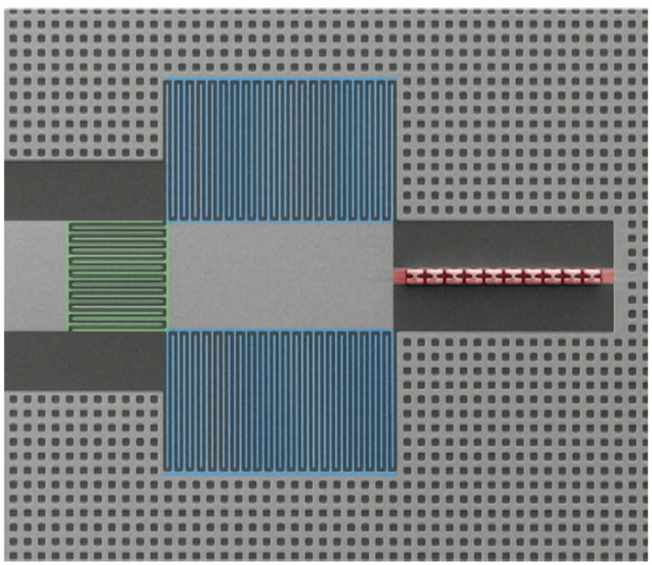
- 10,000-fold speed up might be possible

Accelerating axion dark matter searches with quantum information technology

Haystac

JILA, U. of Colorado

Konrad Lehnert
Maxime Malnou
Daniel Palken



Yale (Haystac)

Benjamin Brubaker
Ling Zhong
Kelly Backes
Steve Lamoreaux

UC Berkeley

Maria Simanovskaia
Saad Al Kenany
Samantha Lewis
Jaben Root
Nicholas Rapidis
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Yale (Theory)

Steve M. Girvin
Huaixiu Zheng
Matti Silveri,
R. T. Brierley,
Konrad Lehnert (YQI visitor)

arXiv:1607.02529

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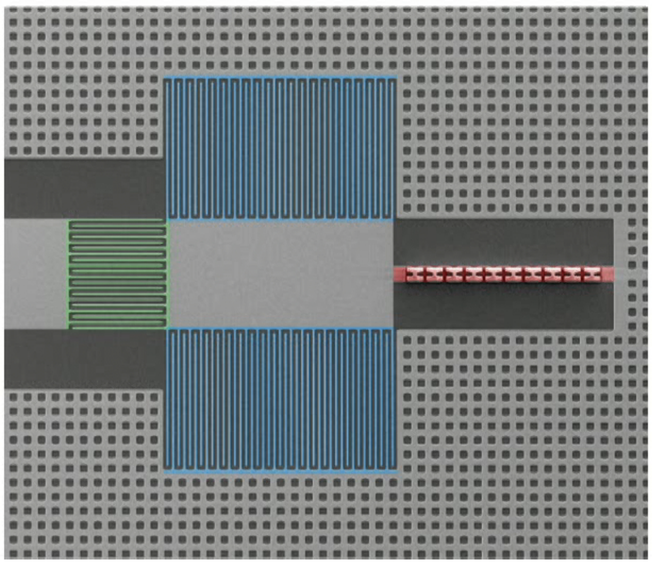

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NIST
JILA pfc an NSF physics frontier center
Y

Axion dark matter search

Hypothetical 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 approximately $2\ \mu\text{eV} < m_a c^2 < 2000\ \mu\text{eV}$

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

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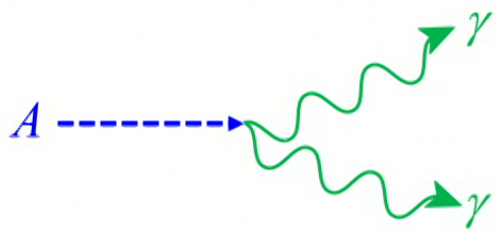
Axion field couples to electromagnetism

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

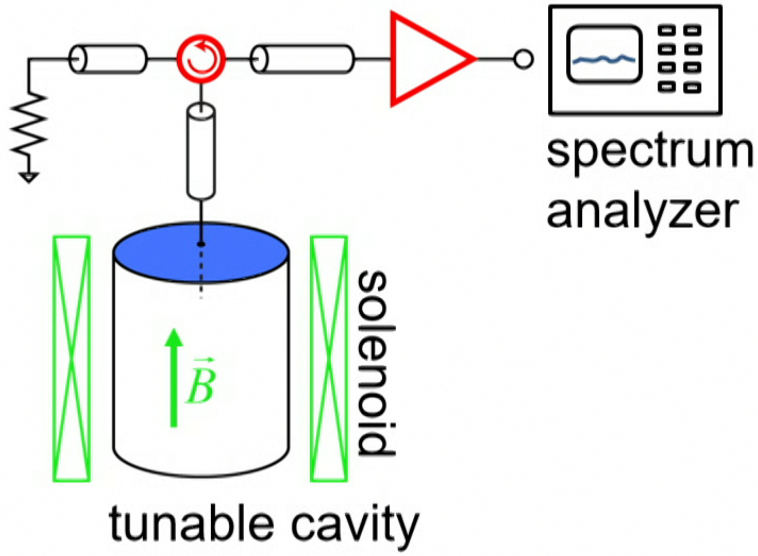


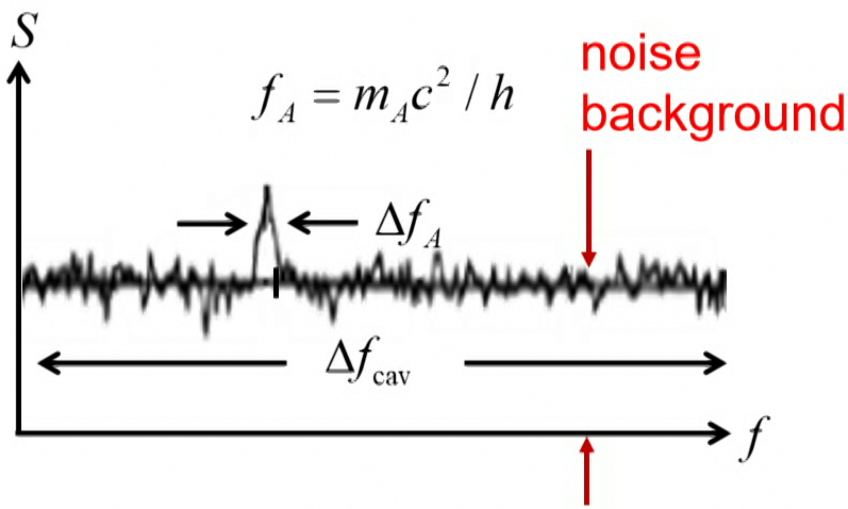
linearize coupling around static $\vec{B}$-field

$E_A = E_\gamma$

dark matter axions create microwave photons

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





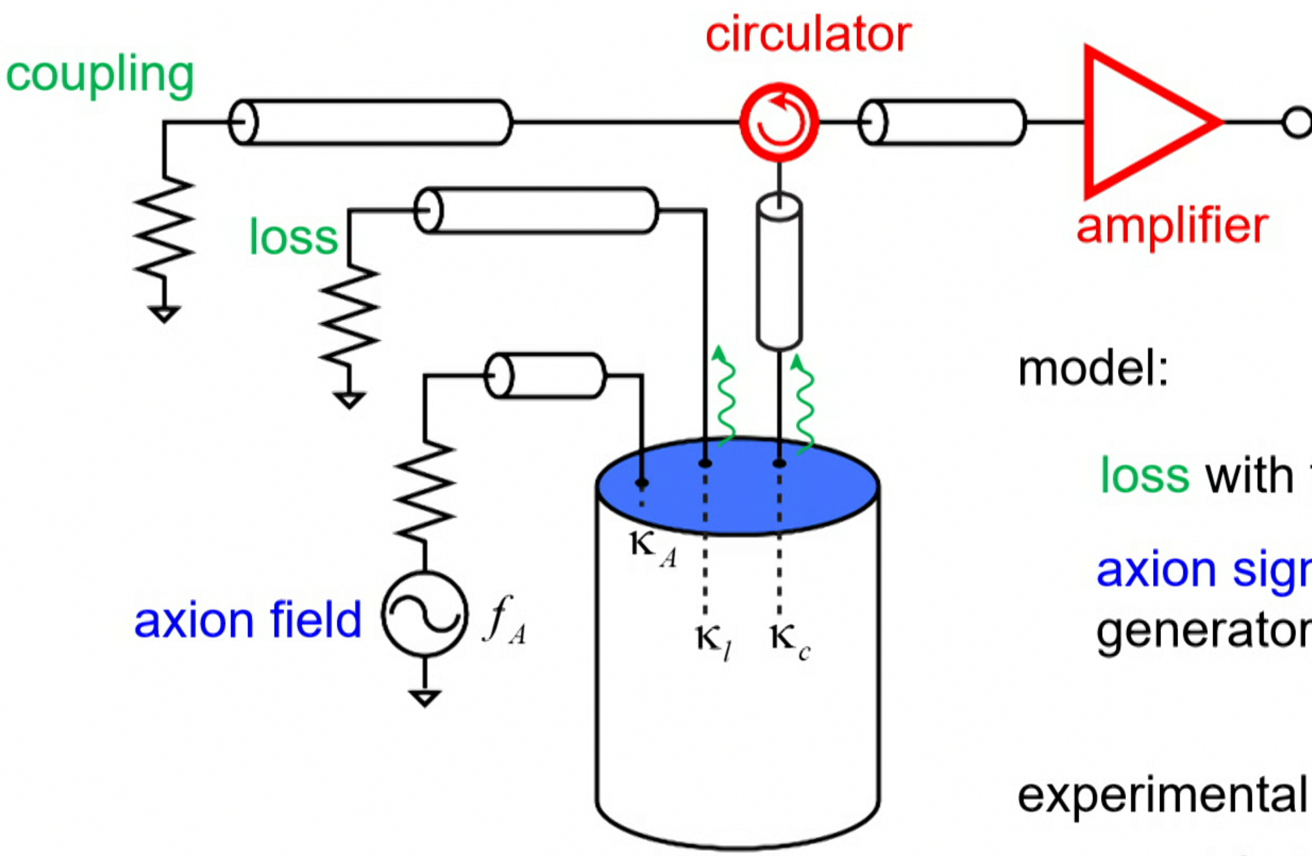
tune -> wait and integrate -> tune

axion line narrower than cavity

$$\frac{f_A}{\Delta f_A} \approx 10^6 \qquad \frac{f_{cav}}{\Delta f_{cav}} \approx 10^4$$

Noise in an axion haloscope

Signal and noise can be modeled as a microwave network



model:

- loss with fictitious port
- axion signal with weakly coupled generator $\kappa_A \ll \kappa_l$

experimental constraints today

$$\kappa_A \ll 2\pi\Delta f_A \ll \kappa_l$$

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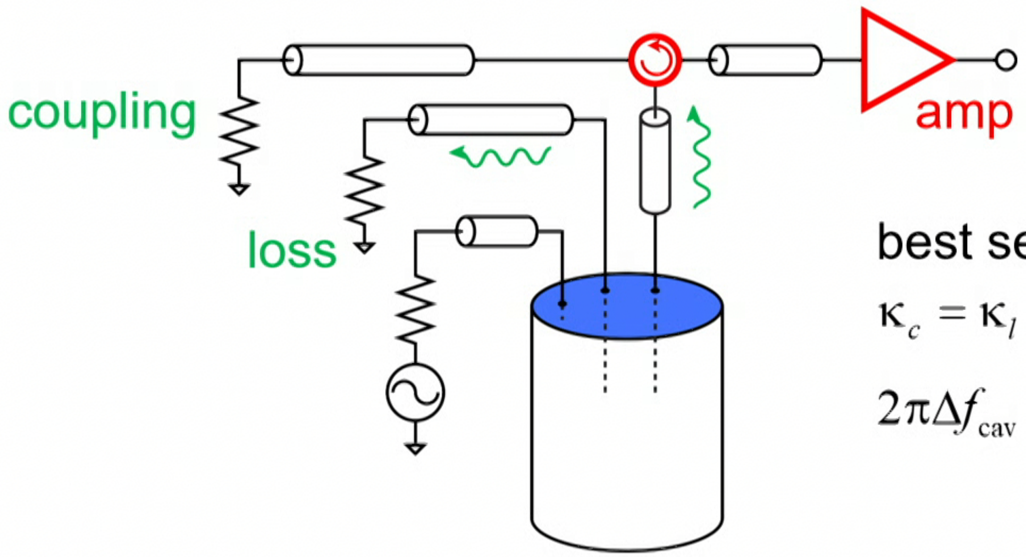
Microwave frequency fluctuations form the background for axion detection

noise sources:
- amplifier noise
- cavity dissipation

$$S_{\mathrm{amp}} = hf\left(N_{\mathrm{add}}\right)$$

$$S_d = hf\left(\frac{1}{\exp(hf/k_B T)-1}+\frac{1}{2}\right) = hf\left(N_T + \frac{1}{2}\right)$$



best sensitivity:

$$\kappa_c = \kappa_l$$

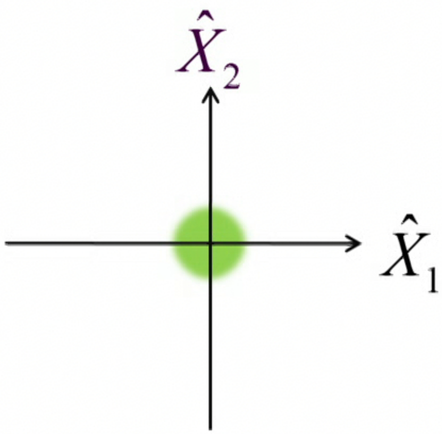
$$2\pi\Delta f_{\mathrm{cav}} = \kappa_c + \kappa_l$$

Cool axion cavity to reach quantum limit

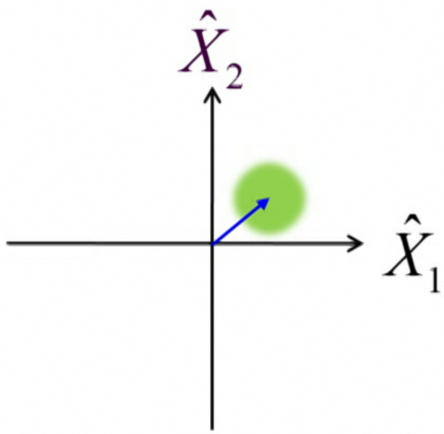
$$k_B T \ll \hbar\omega_{\text{cav}} \Rightarrow S_d = \hbar\omega_{\text{cav}}\left(\frac{1}{2}\right)$$

amplifiers measure cavity quadratures X_1 and X_2

$$\hat{H}_{\text{cav}} = \frac{hf}{2}\left(\hat{X}_1^{\,2} + \hat{X}_2^{\,2}\right) \qquad \left[\hat{X}_1, \hat{X}_2\right] = i \Rightarrow \Delta X_1 \Delta X_2 \geq \frac{1}{2}$$



vacuum state



axion displaced state

Microwave frequency fluctuations form the background for axion detection

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- amplifier noise
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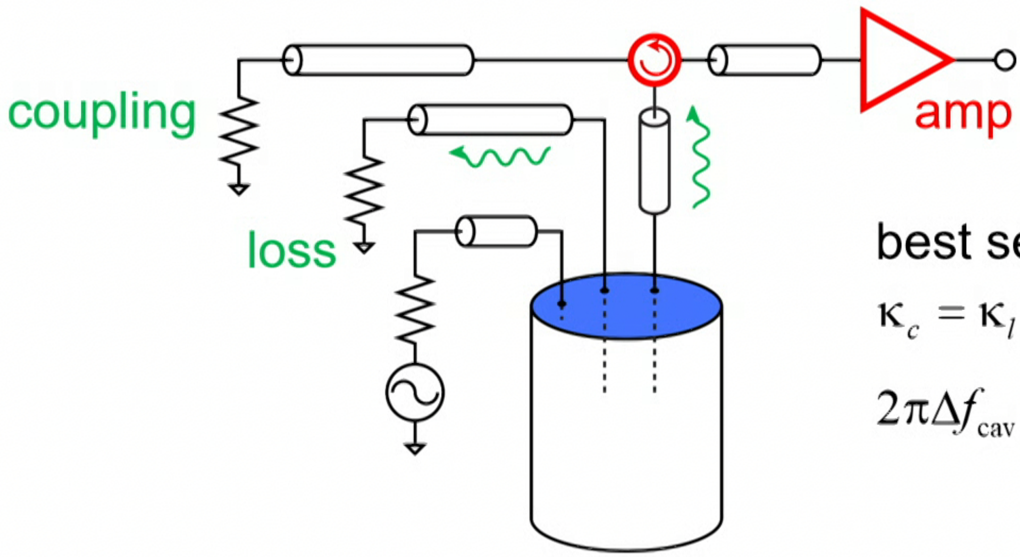

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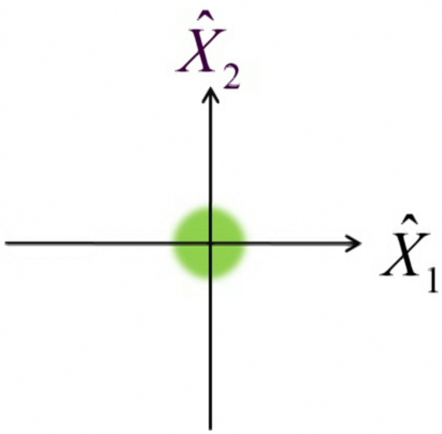

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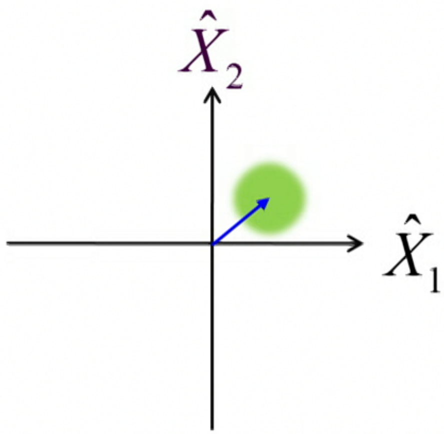
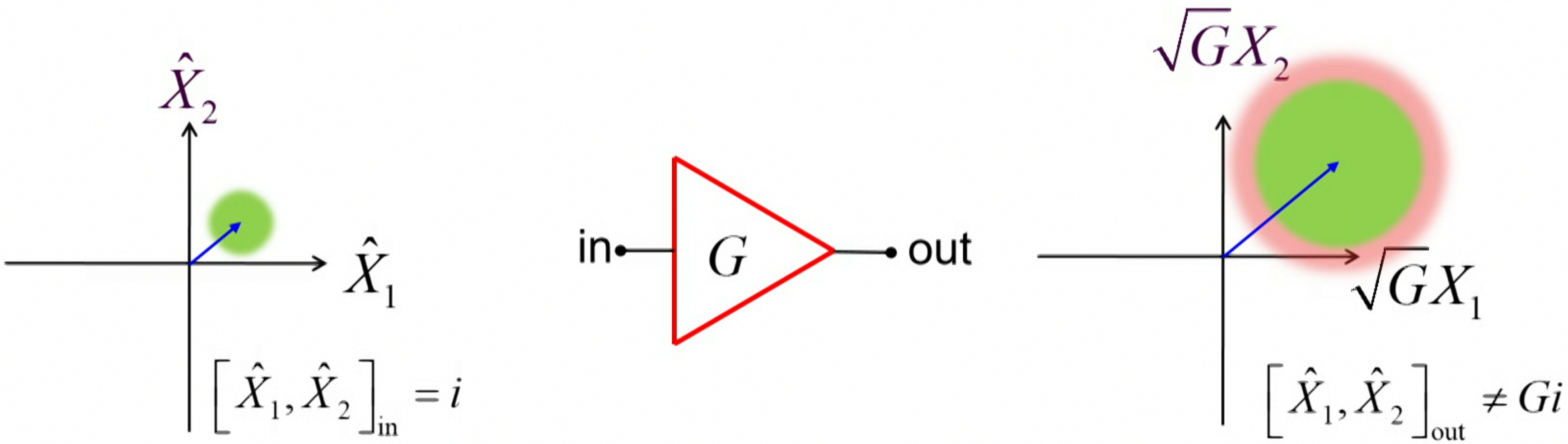


axion displaced state

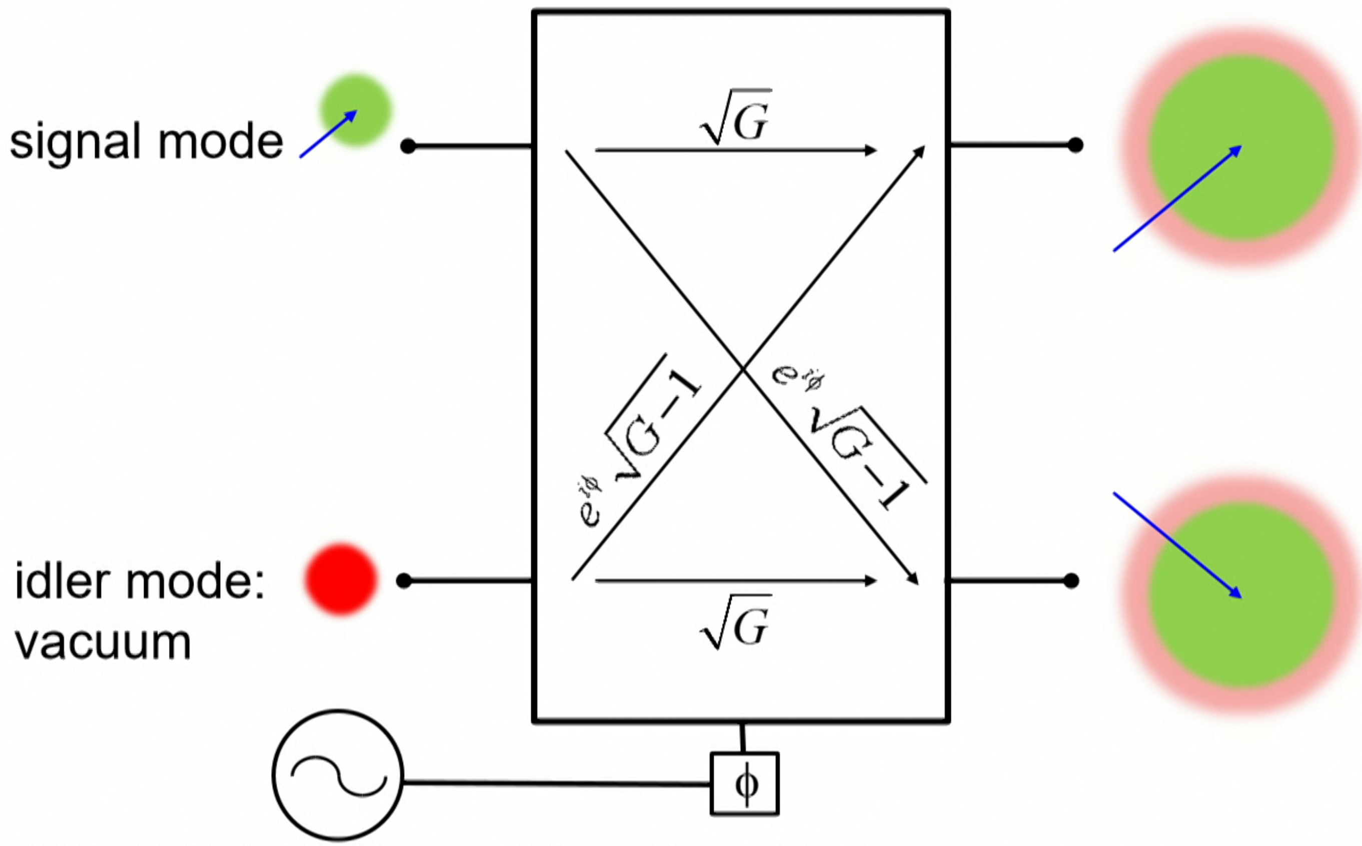
Quantum limited amplifiers add half a photon of noise



phase space volume not conserved => added noise

$$N_{add} \geq \frac{1}{2}$$

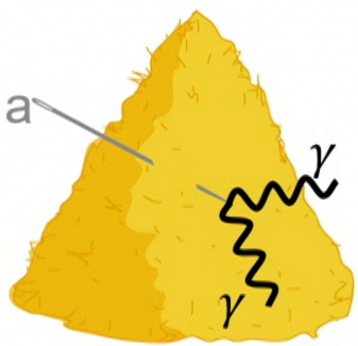
Josephson parametric amplifiers reach the quantum limit



measurement => irreversibility

R. Movshovich, B. Yurke *et al*. *Phys. Rev. Lett*. **65**, 1419–1422 (1990).
M.A. Castellanos-Beltran, KWL, *et al*., *Nature Physics* **4**, 929 - 931 (2008).
N. Bergeal, M. Devoret *et al*., *Nature* **465**,64–68 (2010).

Axion dark matter search at the quantum limit



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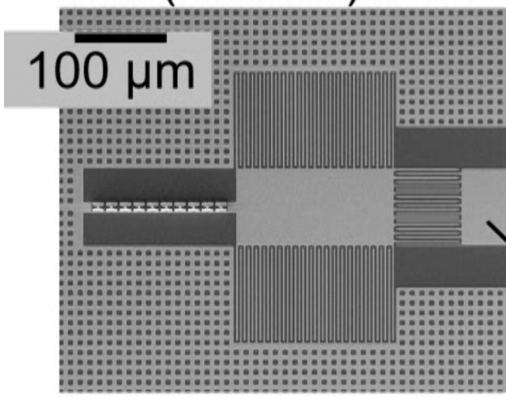
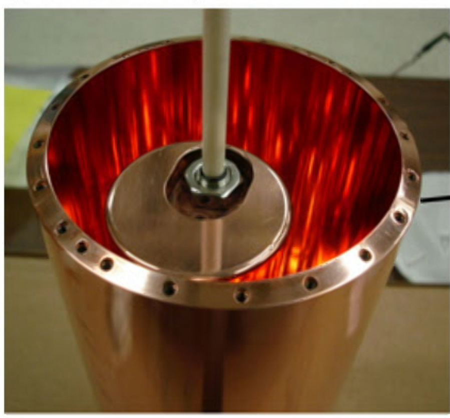
Haloscope At Yale Sensitive To Axion Coupling

Overview of the experiment and its integration

JPA (tunable)

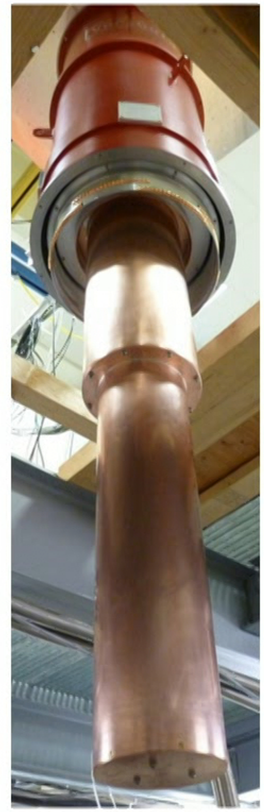


microwave cavity
(tunable)



$^3He/^4He$
dilution
refrigerator

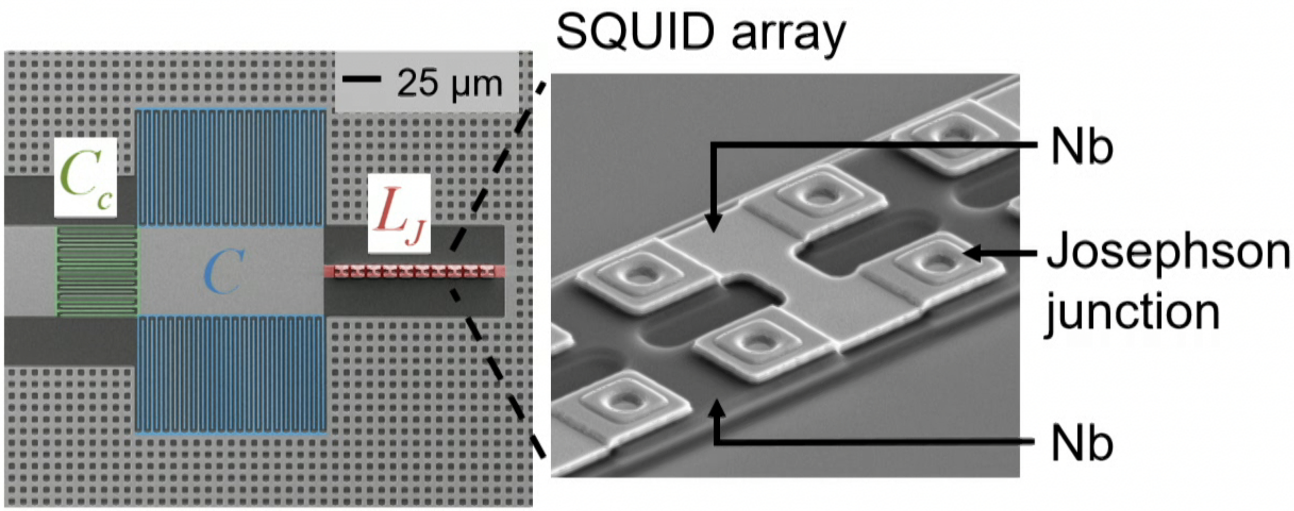
$T = 126$ mK



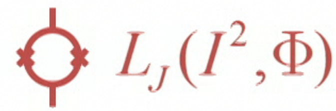
magnet : 9.4 T, 10 L

located at Yale's Wright laboratory
Steve Lamoreaux's group

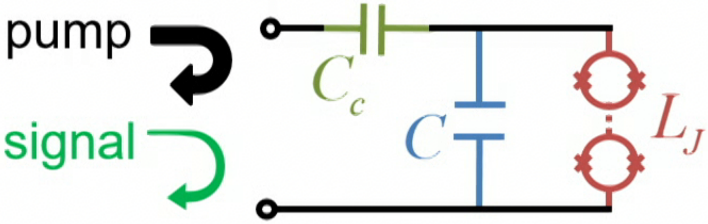
The JPA contains a flux tunable, dissipationless, and nonlinear resonant circuit

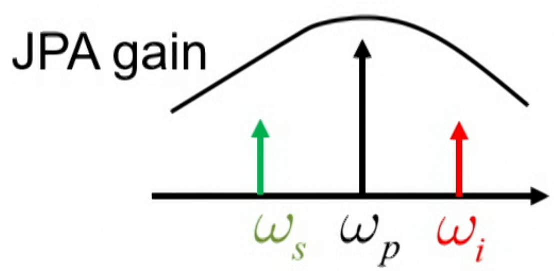


SQUID
two junction loop:



nonlinear tunable inductor

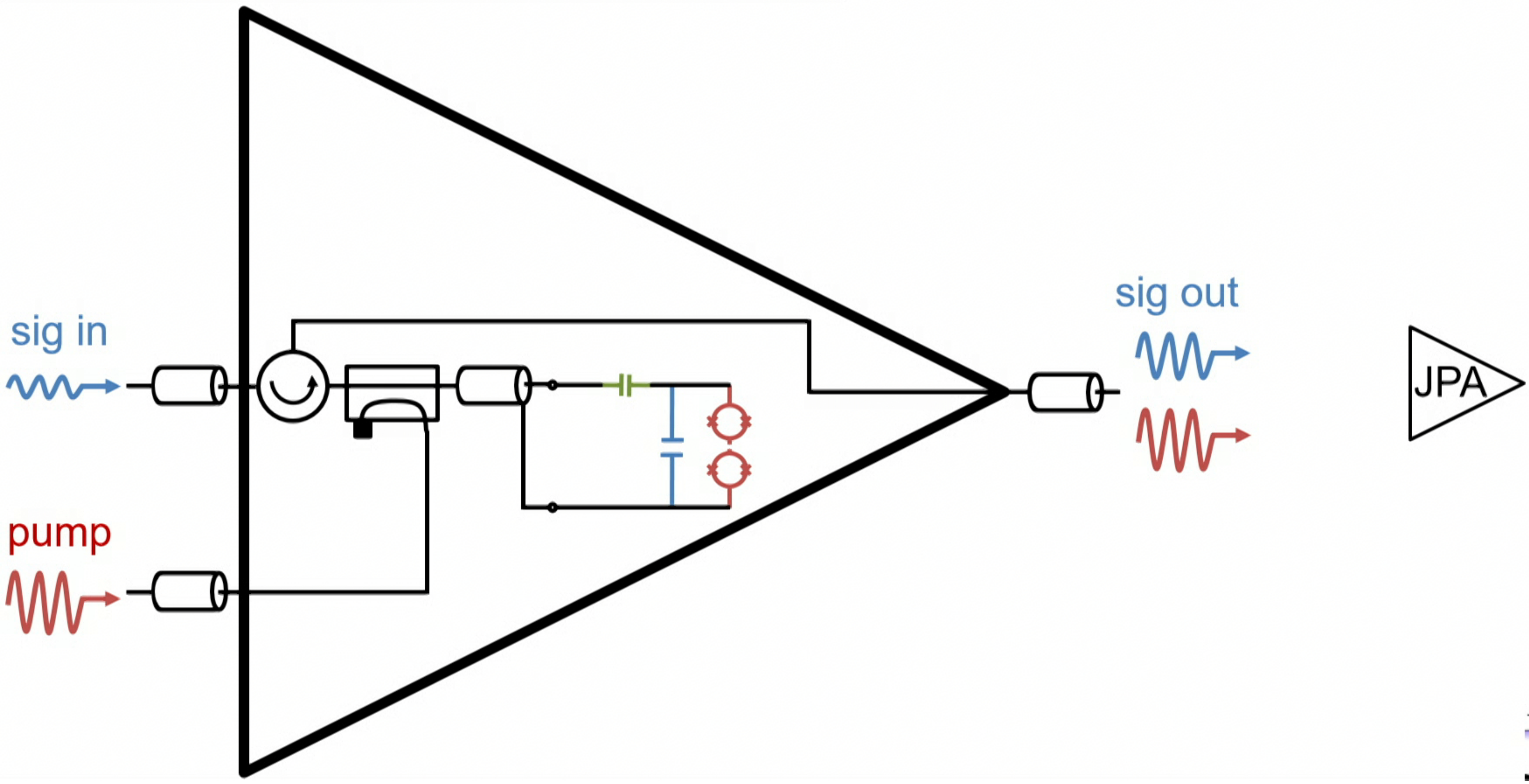




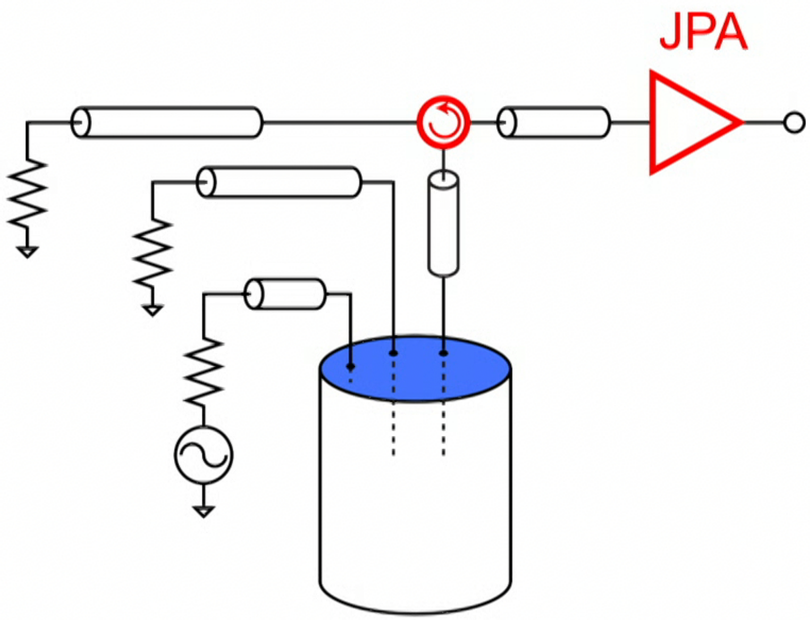
4 photon process

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

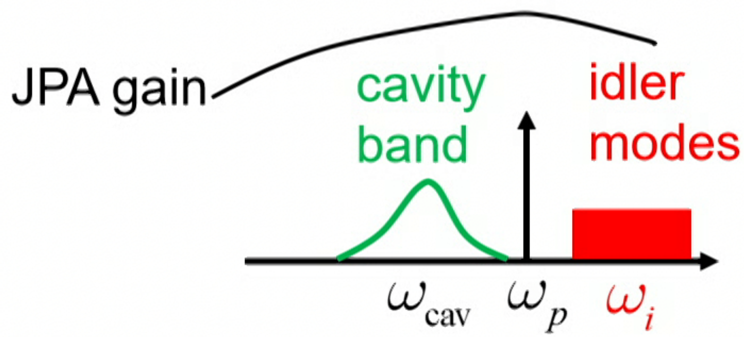
Directional coupler and circulator separate pump and signal, input and output



Reaching the quantum limit with a JPA: phase insensitive operation



phase insensitive:
cavity detuned from pump

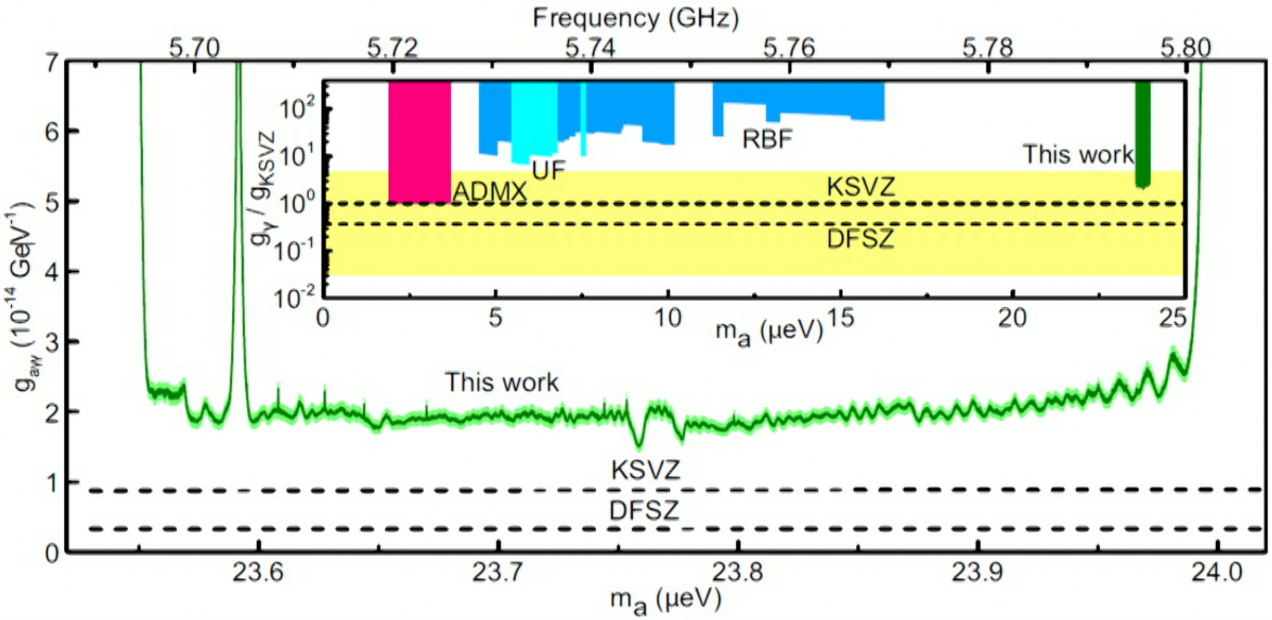


Al Kenany et al. *Nucl. Instr.* **854**, 11-24 (2017)

First near-quantum limited haloscope data

added noise: 0.63 photons

1.5 months data: 100 MHz scanned (no axion)



Brubaker et al. *Phys. Rev. Lett.* ***118***, 061302 (2017)

since publication:

- 200 MHz scanned
- operation at quantum limit
- upgrade in progress

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Josephson parametric amplifiers overcome quantum noise

Idealization: prepare cavity in eigenstate of X_1, wait, noiselessly measure X_1

JPAs prepare approximate eigenstates of X_1 (squeezed states), and measure X_1 noiselessly

Squeezed state receiver increases scan rate, not ultimate sensitivity

Quantum noise limits axion search rate

X_1 and X_2 don't commute with Hamiltonian or each other

$$S_d \to \frac{hf}{2} \qquad S_{\mathrm{amp}} \to \frac{hf}{2}$$

noise variance: 1 quantum (photon)

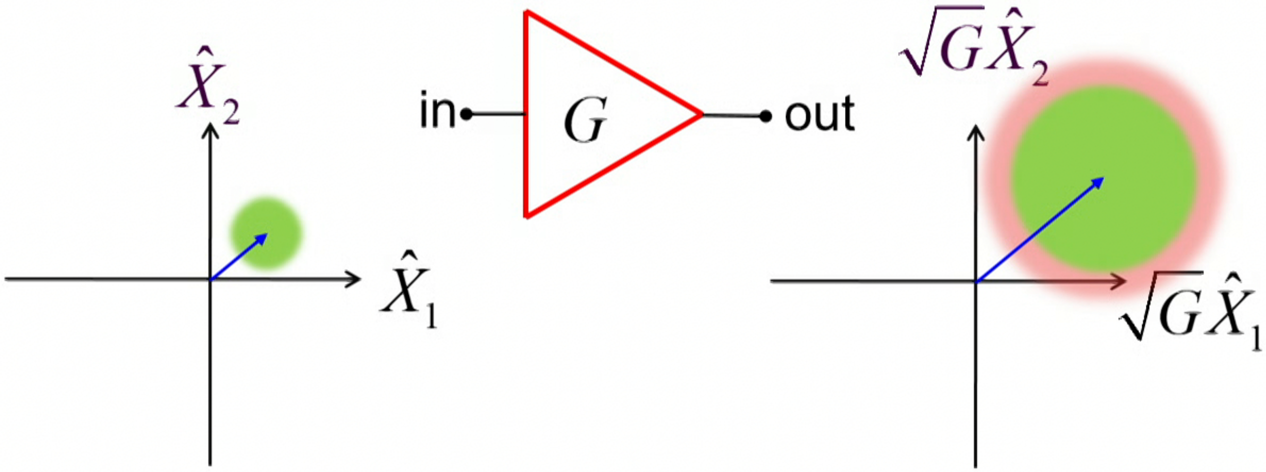
axion energy: $10^{-3} - 10^{-4}$ photon

resolve signal in $10^{6} - 10^{8}$ averages

$$\frac{\delta S}{S} = \frac{1}{\sqrt{\Delta f_a \tau}}$$

τ ~ 3 minutes: each cavity resonance
~ years: one octave

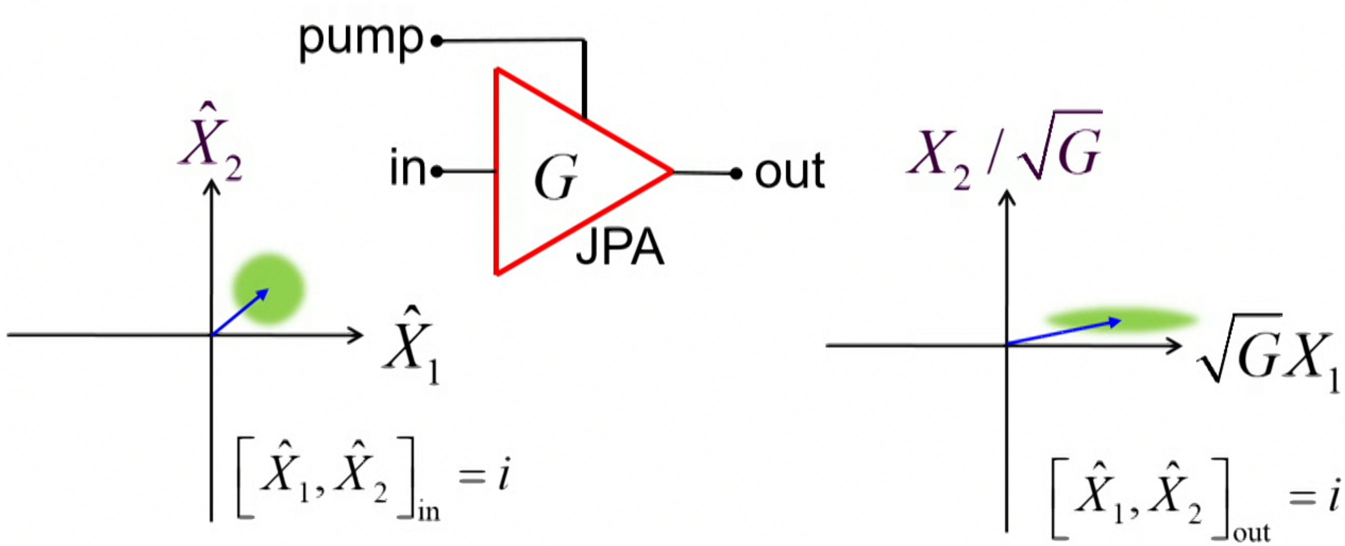
Linear, phase-insensitive amplifiers must add noise



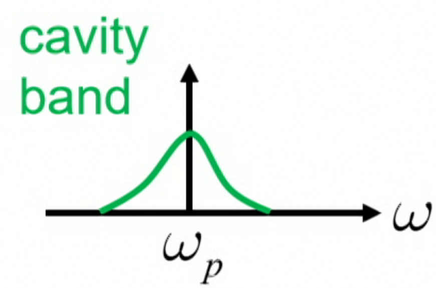
phase space volume not conserved => added noise

$$N_{\mathrm{add}} \geq \frac{1}{2}$$

Phase sensitive amplifier measures one quadrature noiselessly



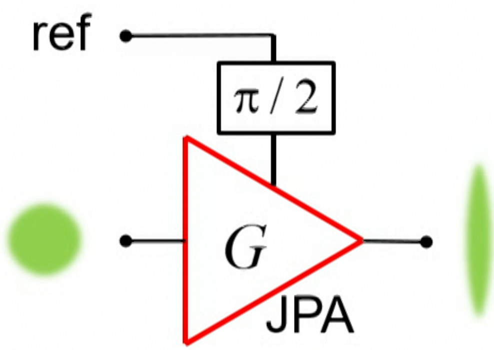
phase sensitive mode:
pump resonant with cavity



phase space volume conserved <= no added noise

$$N_{\text{add}} \geq 0$$

Ideal JPA noiselessly transforms vacuum state into squeezed state



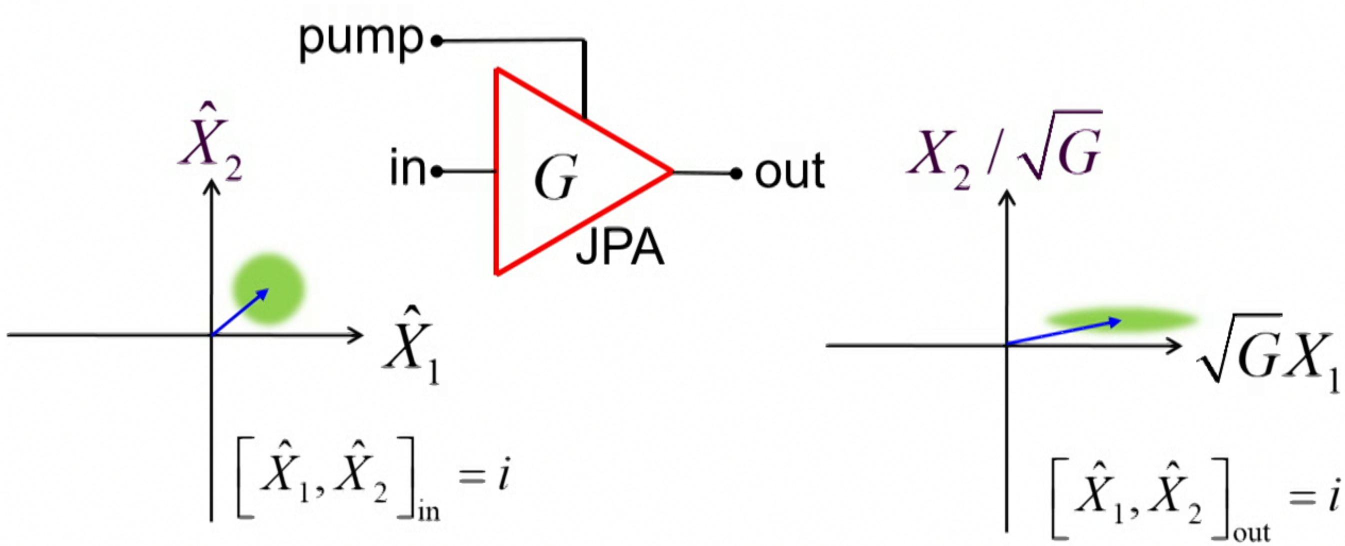
$$\mathrm{var}\left(\hat{X}_2\right) = \frac{G}{2}$$

$$\mathrm{var}\left(\hat{X}_1\right) = \frac{1}{2G}$$

squeezed quadrature: quantum noise suppressed

use JPA to prepare cavity in squeezed state

Phase sensitive amplifier measures one quadrature noiselessly



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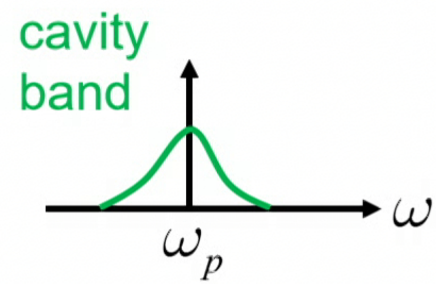
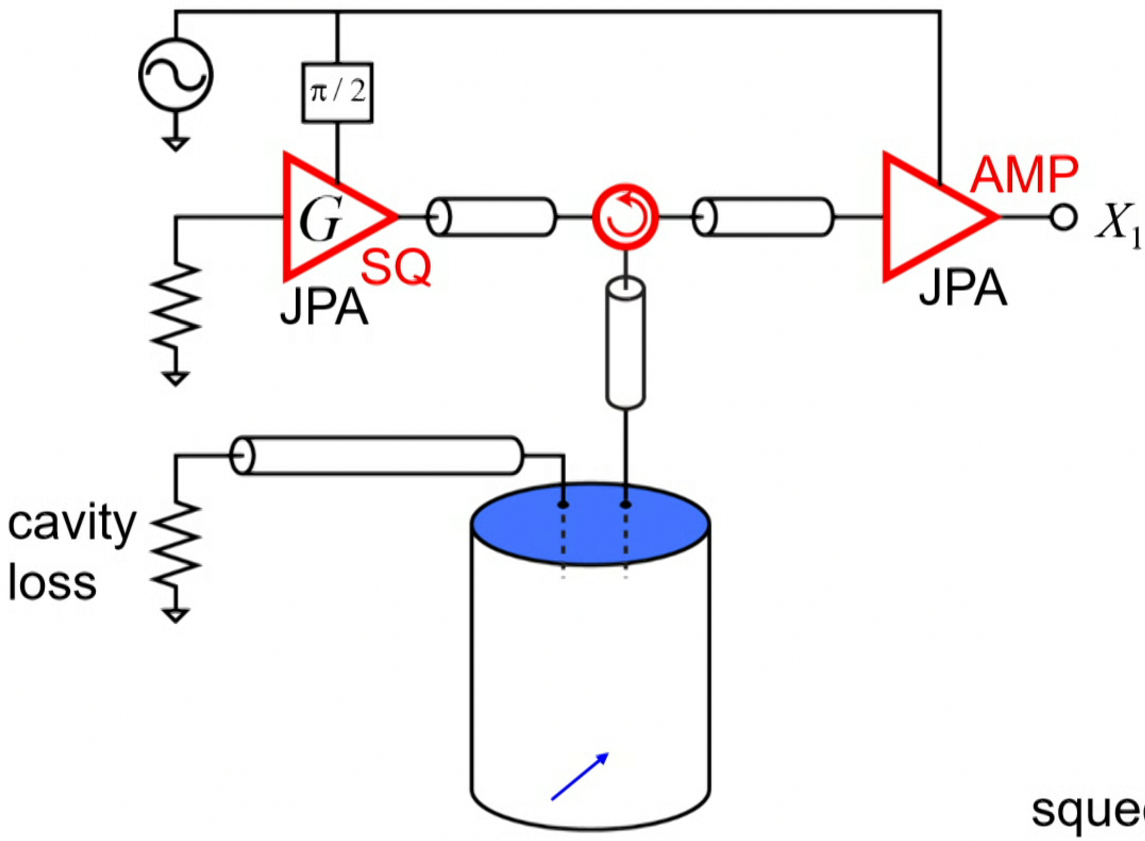


phase space volume conserved <= no added noise

$$N_{\text{add}} \geq 0$$

Squeezing does not improve on-resonance and critically coupled sensitivity



axion signal at amplifier

$$\text{sig} \propto \frac{2\sqrt{\kappa_c \kappa_A}}{\kappa_c + \kappa_l - i\Delta}$$

$$\Delta = \omega_{\text{cav}} - \omega_A$$

maximum: critical coupling on resonance

$$\kappa_c = \kappa_l \qquad \Delta = 0 \qquad \text{sig} \propto \sqrt{\frac{\kappa_A}{\kappa_l}}$$

squeezed state absorbed in cavity

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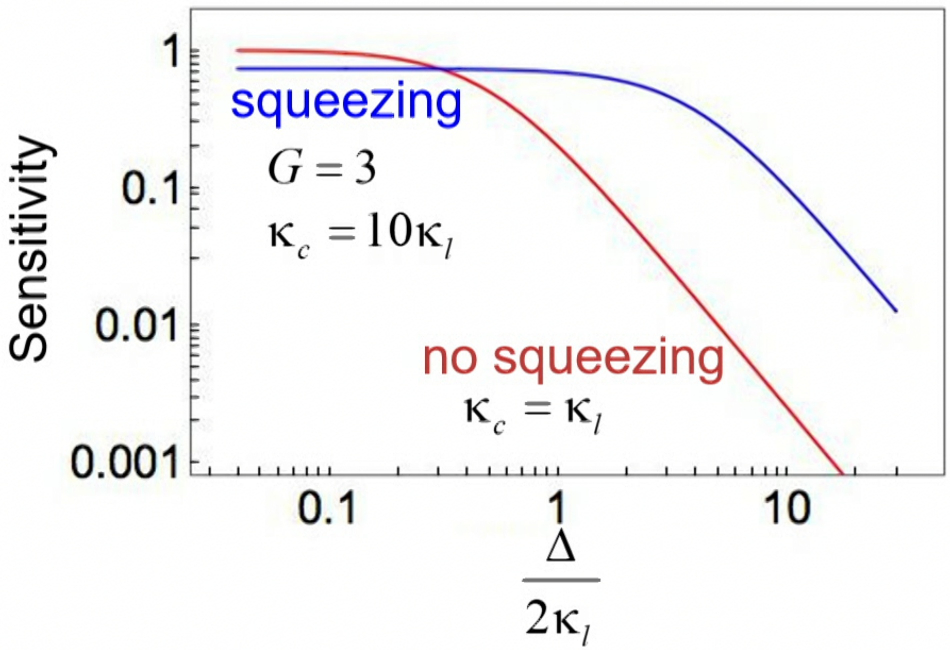
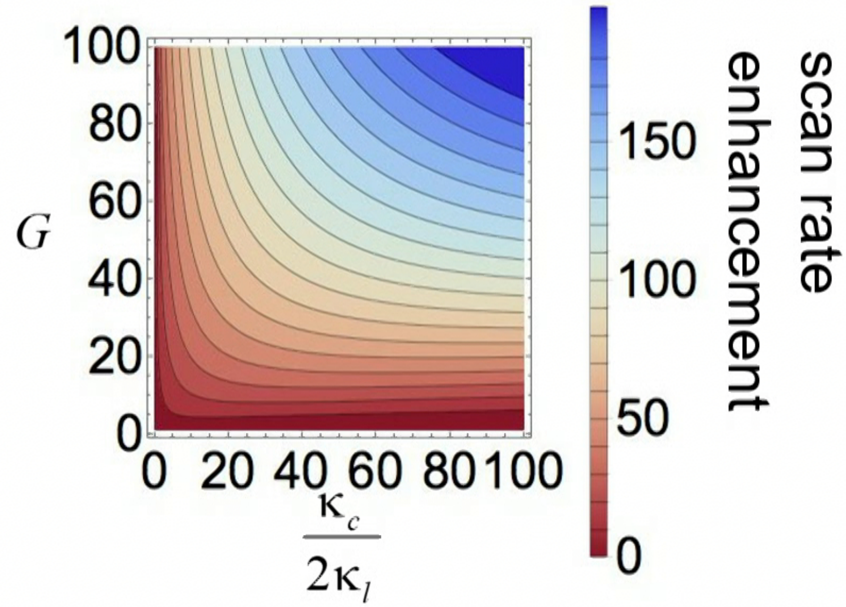
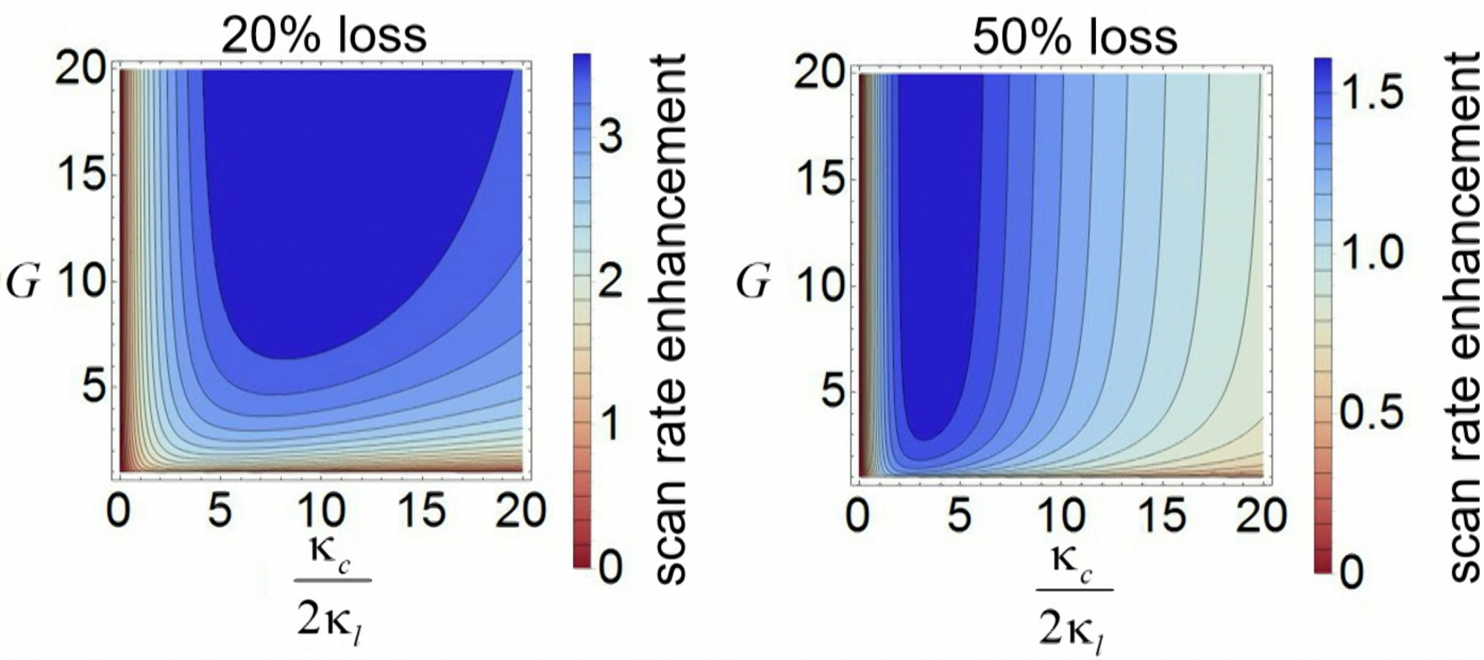
Scan rate enhancement, perfect efficiency





slight reduction in sensitivity
much larger bandwidth

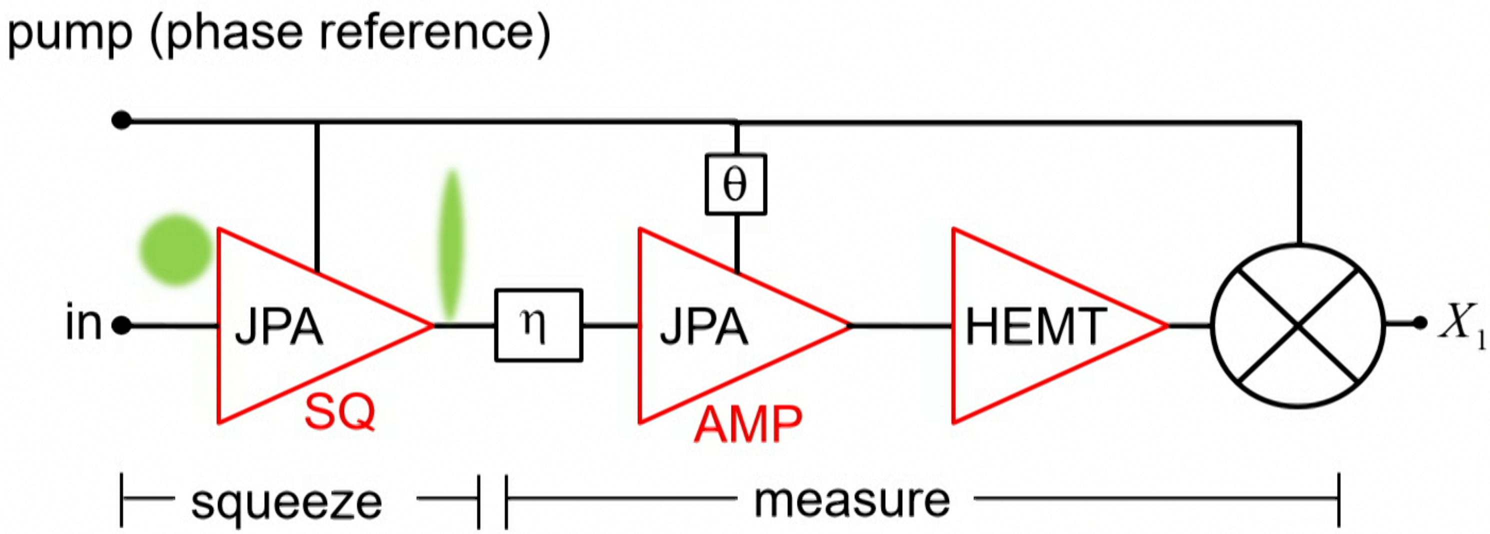
Propagation loss reduces benefit of squeezing



20% loss: scan rate x 3.5

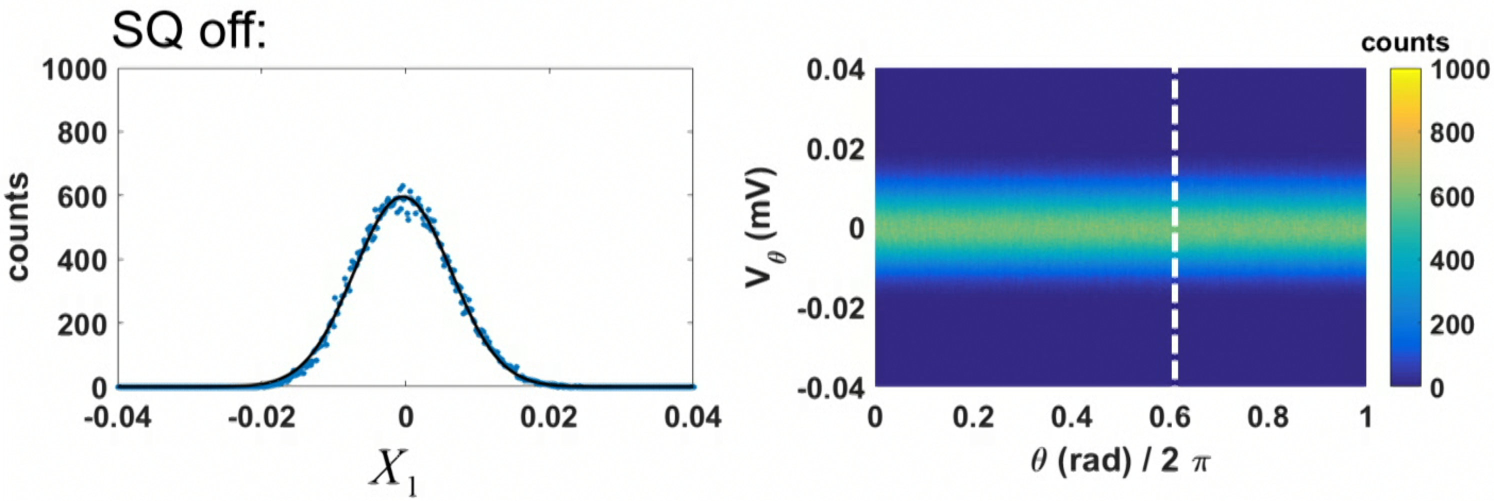
50% loss: scan rate x 1.5

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



phase θ chooses measured quadrature
relative to squeezed quadrature

Vacuum fluctuations are squeezed



best performance

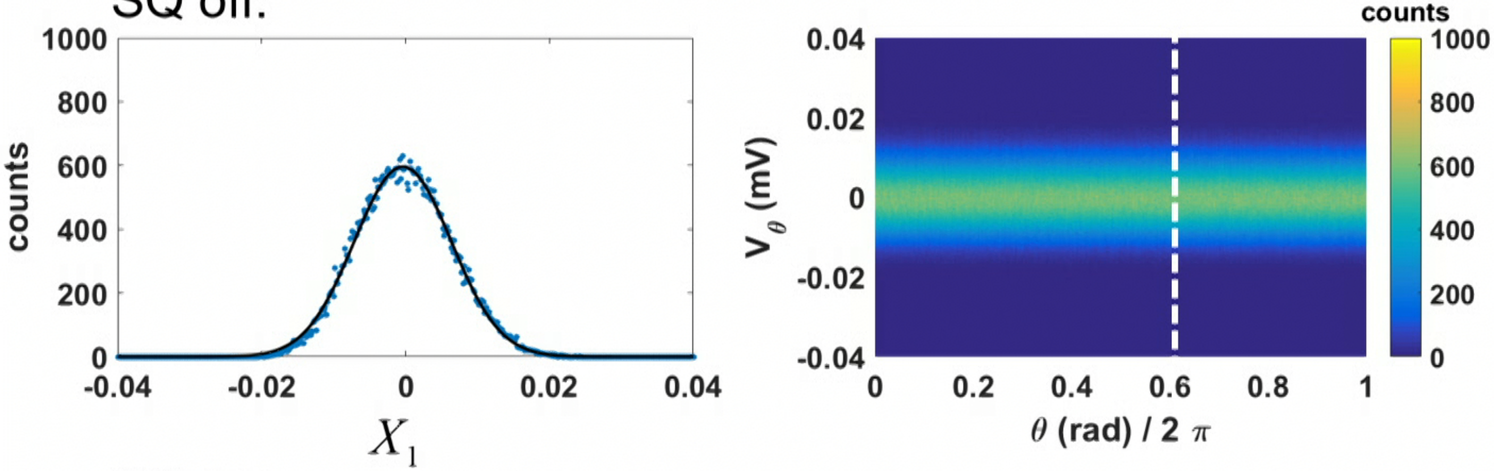
40% loss:
scan rate x 2.5

next: deploy in
HAYSTAC

F. Mallet, KWL et al.,
PRL **106**, 220502 (2011).

Vacuum fluctuations are squeezed

SQ off:



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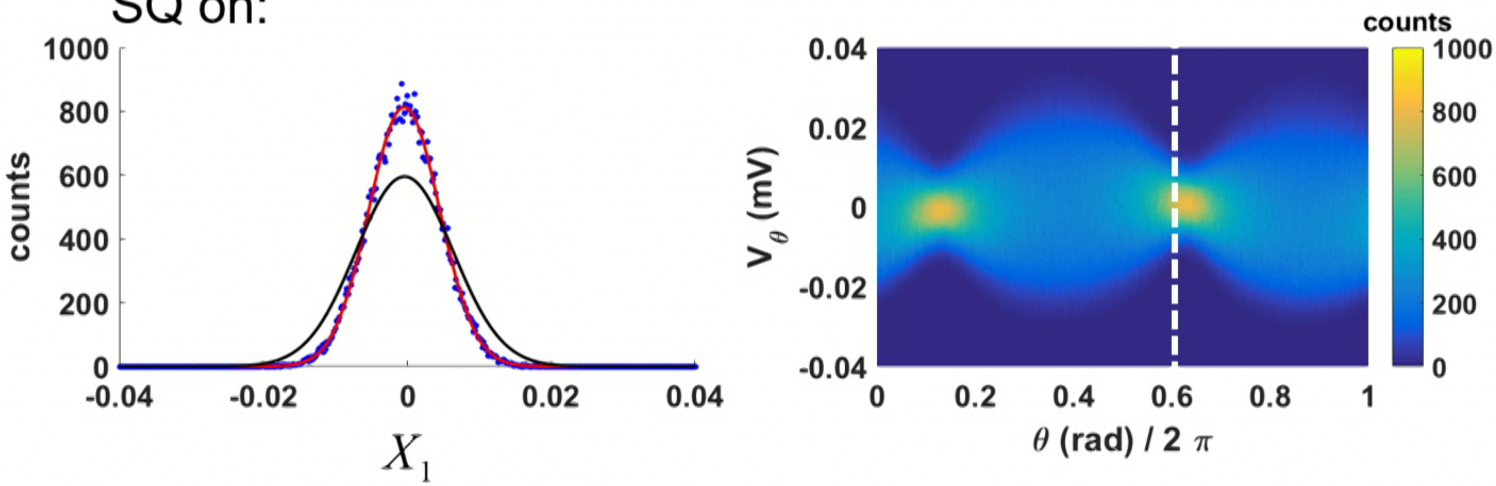

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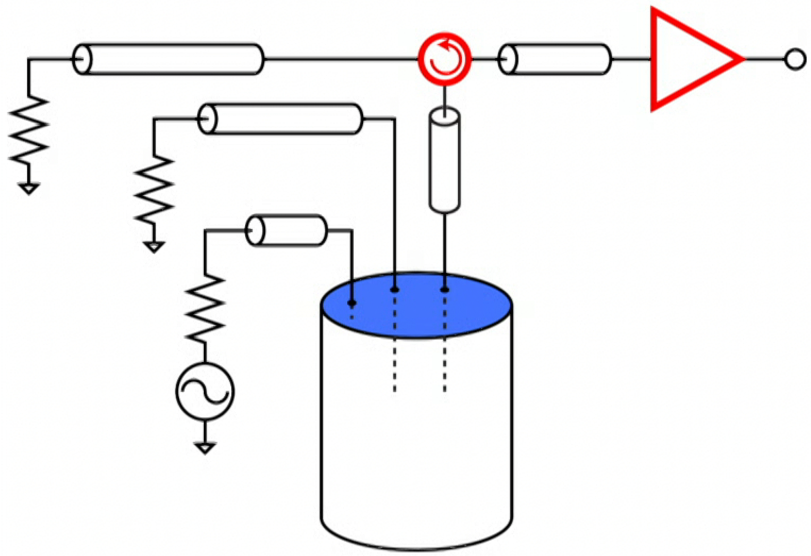
Both axion quadratures can be measured without quantum noise



axion field:

large amplitude coherent state

weakly coupled

$$\hat{A} = \alpha + \delta\hat{A} \qquad \kappa_A \ll \kappa_l$$

axion appears in Hamiltonian as a parameter

$$\hat{H}_{\text{cav}} \approx \hbar\omega_{\text{cav}}\left(\hat{X}_1^{\,2} + \hat{X}_2^{\,2}\right) + \sqrt{\kappa_A}\,\text{Re}(\alpha)\hat{X}_1 + \sqrt{\kappa_A}\,\text{Im}(\alpha)\hat{X}_2$$

commutation relations don't limit knowledge of α

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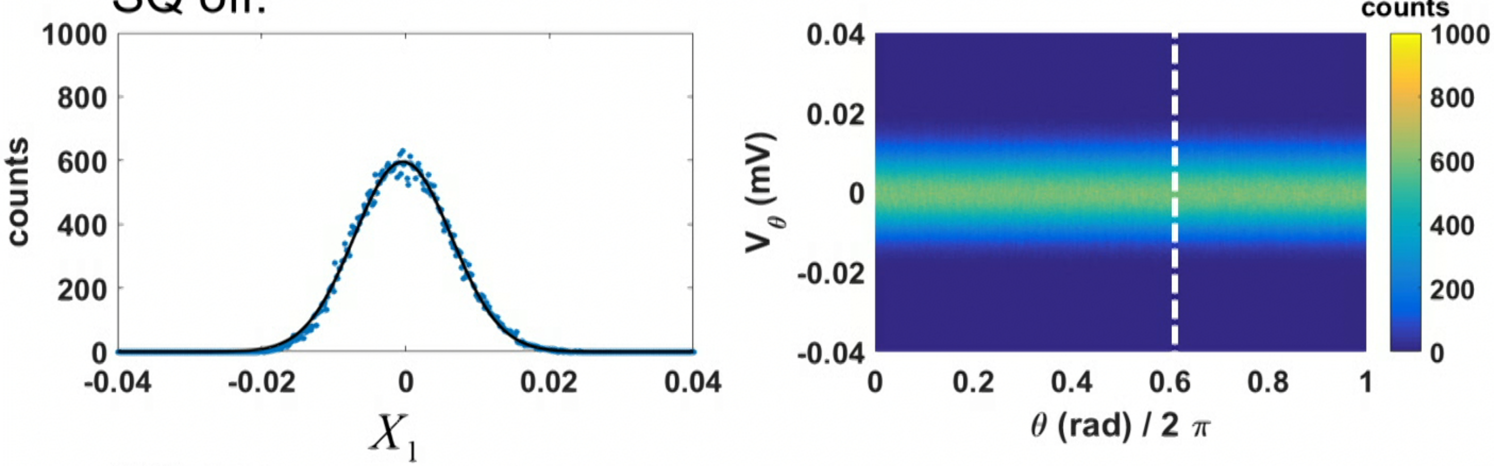
Vacuum fluctuations are squeezed

SQ off:



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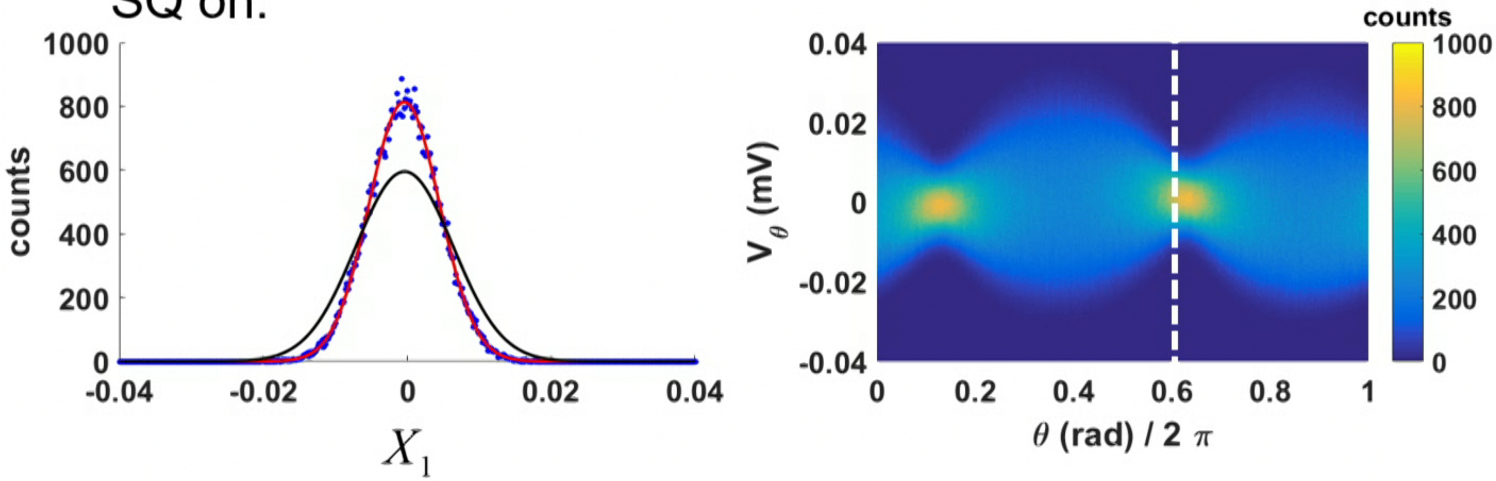

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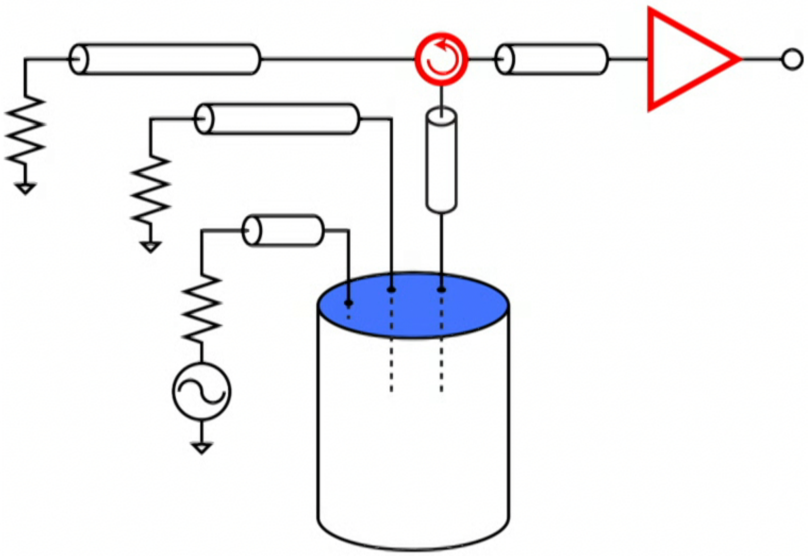
Both axion quadratures can be measured without quantum noise



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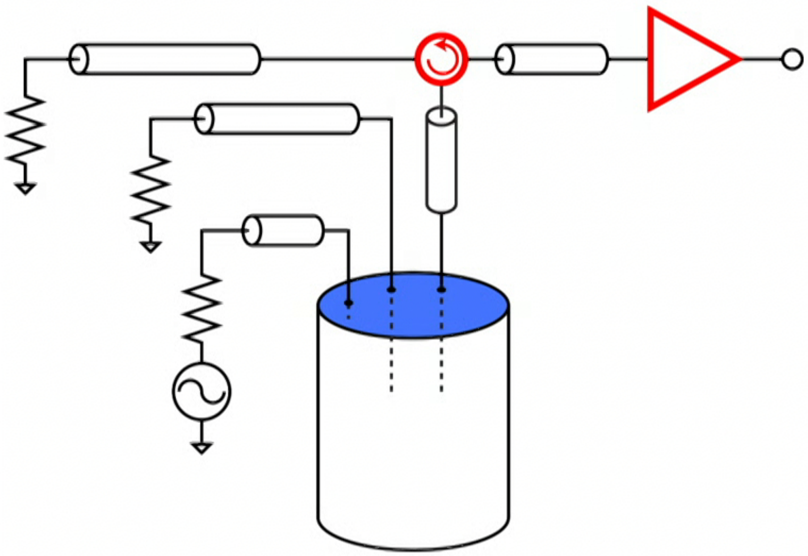

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commutation relations don't limit knowledge of α

parameter estimation problem: no quantum policeman…

arXiv:1607.02529

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Circumventing the quantum limit with CQED photon counting

Circuit quantum electrodynamical devices enable microwave photon counting in an axion experiment

Key idea: to a photon counter, vacuum is noiseless*

much less sensitive to transmission loss than squeezed state receiver

CQED devices efficiently detect microwave photons without destroying them (QND)

CQED: superconducting quantum bit + microwave cavities
invented by Robert Schoelkopf and Michel Devoret

QND measurements => measure same photon many times => vanishing dark counts

*Matsuki, S., and K. Yamamoto, 1991, *Phys. Lett. B* **263**, 523 (1991). [Carrack concept]
S. K. Lamoreaux, K. A. van Bibber, KWL, G. Carosi Phys. Rev. D **88**, 035020 (2013).

Photon number commutes with no-axion Hamiltonian

axion hypothesis

$$\hat{H}_{\text{cav}} = \hbar\omega_{\text{cav}}\left(\hat{X}_1^{\,2} + \hat{X}_2^{\,2}\right) + \sqrt{\kappa_A}\,\text{Re}(\alpha)\hat{X}_1 + \sqrt{\kappa_A}\,\text{Im}(\alpha)\hat{X}_2$$

$$\hat{H}_{\text{cav}} = \hbar\omega_{\text{cav}}\left(a^\dagger a + \frac{1}{2}\right) + \sqrt{\kappa_A}\,\text{Re}(\alpha)\hat{X}_1 + \sqrt{\kappa_A}\,\text{Im}(\alpha)\hat{X}_2$$

null hypothesis

$$\hat{H}_{\text{cav}} = \hbar\omega_{\text{cav}}\left(a^\dagger a + \frac{1}{2}\right)$$

idealized notion

prepare cavity in ground state, wait, measure photon number

$N \neq 0$ => axion

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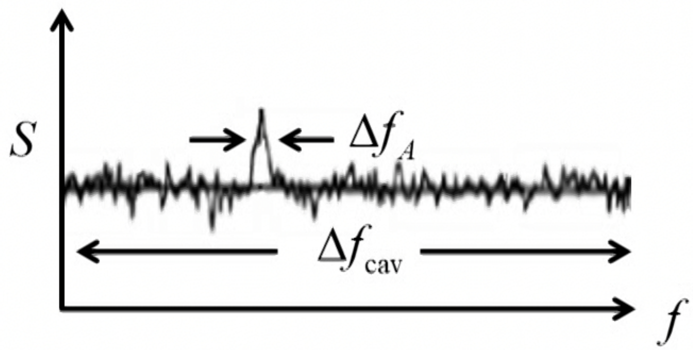
Comparison between quantum limited amplifiers and photon counters



$$\frac{\text{counter scan rate}}{\text{amplifier scan rate}} \approx \frac{\Delta f_A}{\Delta f_{\text{cav}}} \frac{1}{N_T + n_{\text{dark}}}$$

linear amplifier resolves many possible axion lines simultaneously $\frac{\Delta f_{\text{cav}}}{\Delta f_A} \sim 10 \to 100$

noise of photon counters: thermal back ground and dark count probability

prefer photon counter when $N_T + n_{\text{dark}} < 1\%$

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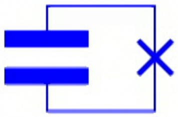
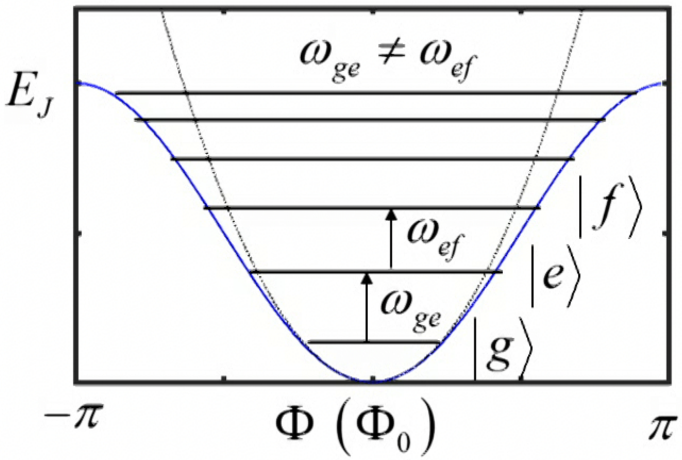
Transmon qubit: a strongly nonlinear LC circuit

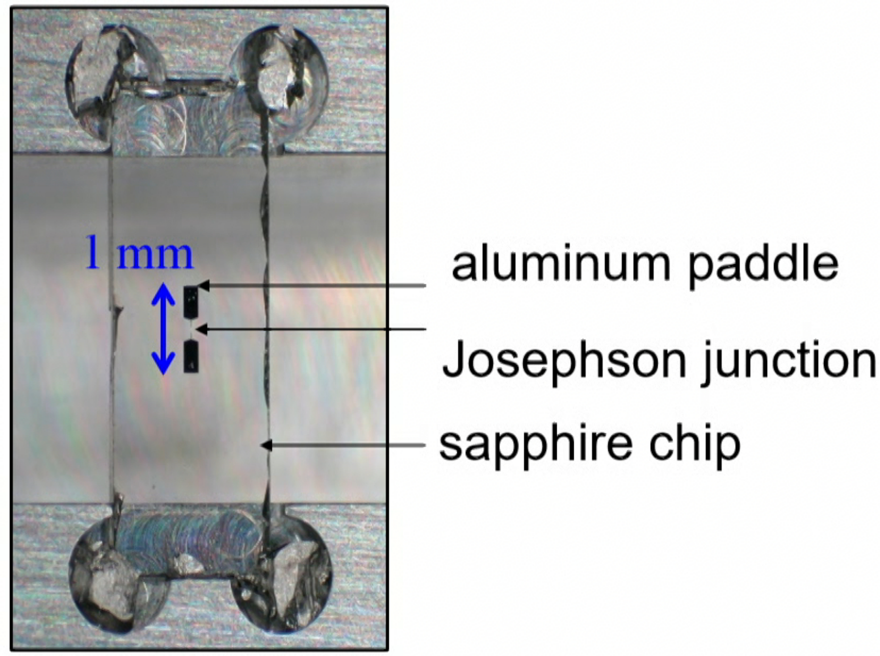


$$\hat{H} = \frac{E_J}{2}\left(1-\cos\left(2\pi\frac{\hat{\Phi}}{\Phi_0}\right)\right) + \frac{\hat{Q}^2}{2C}$$

$$\hat{H} = \frac{\hat{\Phi}^2}{2L} + \frac{\hat{Q}^2}{2C}$$

$\omega_{ge} \sim 5-10\ \mathrm{GHz}$





pseudo-spin-1/2

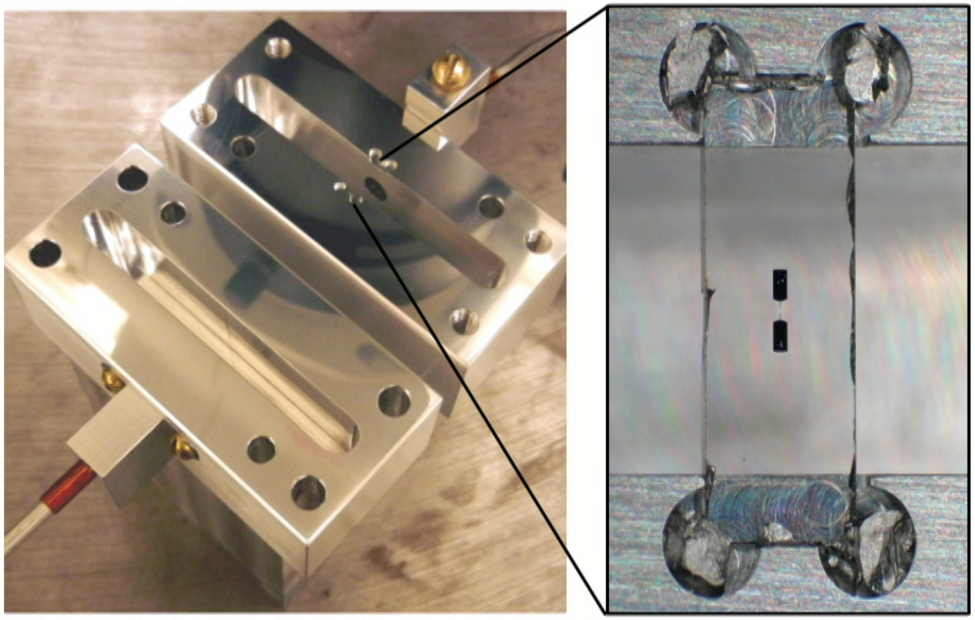
$$\hat{H} = \frac{\omega_{ge}}{2}\hat{\sigma}^z$$

$|g\rangle = |\downarrow\rangle$

$|e\rangle = |\uparrow\rangle$

Jens Koch, et al., *Phys. Rev. A* **76**, 042319 (2007)

CQED: transmon qubit in a microwave cavity



$$g = \frac{\vec{d} \cdot \vec{E}_{\mathrm{rms}}}{\hbar}$$

$$\left|\vec{d}\right| = 2e \times 1 \text{ mm} \approx 10^7 \text{Debye!}$$

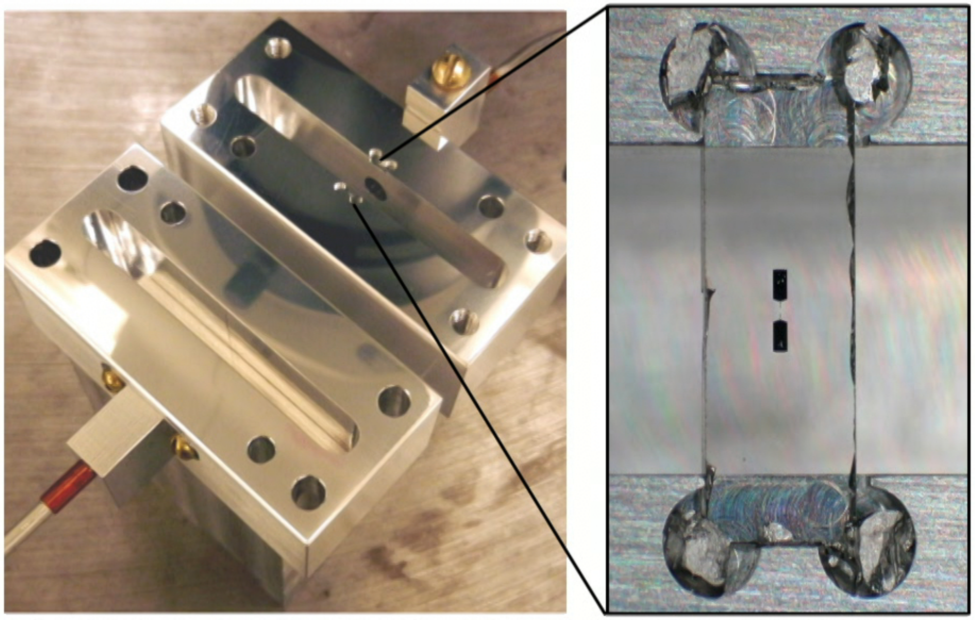
$$g \approx 2\pi \times 100 \text{ MHz}$$

$$\hat{V}_{\mathrm{dipole}} = g\hat{\sigma}_x\left(\hat{a}^\dagger + \hat{a}\right)$$ spin flip

huge dipole moment: strong coupling

Hanhee Paik et al., *Phys. Rev. Lett.* **107**, 240501 (2011).

CQED: transmon qubit in a microwave cavity



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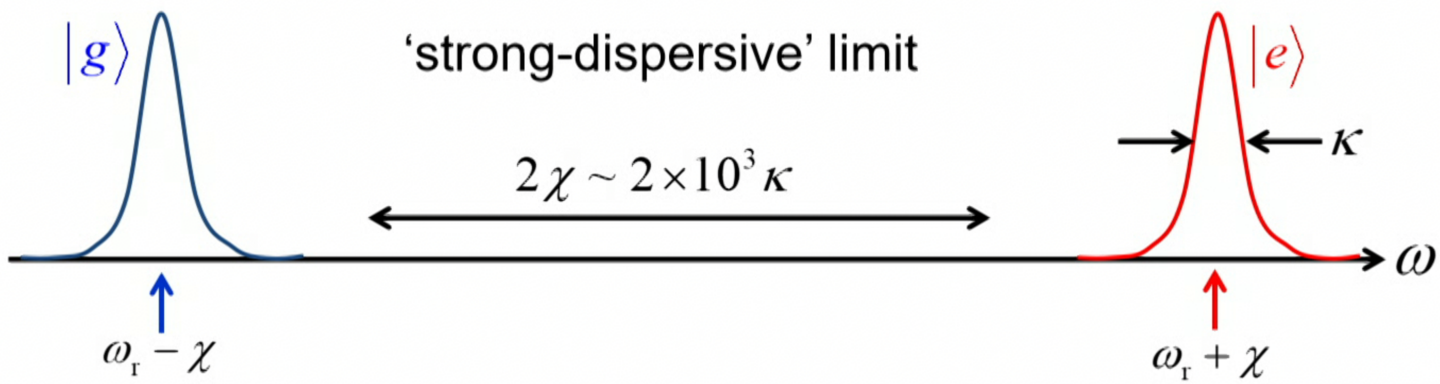
Strong dispersive regime: cavity measures qubit state

$$|\omega_r - \omega_q| \gg g \qquad \hat{H} = \omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q}{2}\hat{\sigma}^z + \chi \hat{\sigma}^z \hat{a}^\dagger \hat{a}$$

cavity qubit dispersive coupling

cavity frequency = $\omega_r + \chi\hat{\sigma}^z$



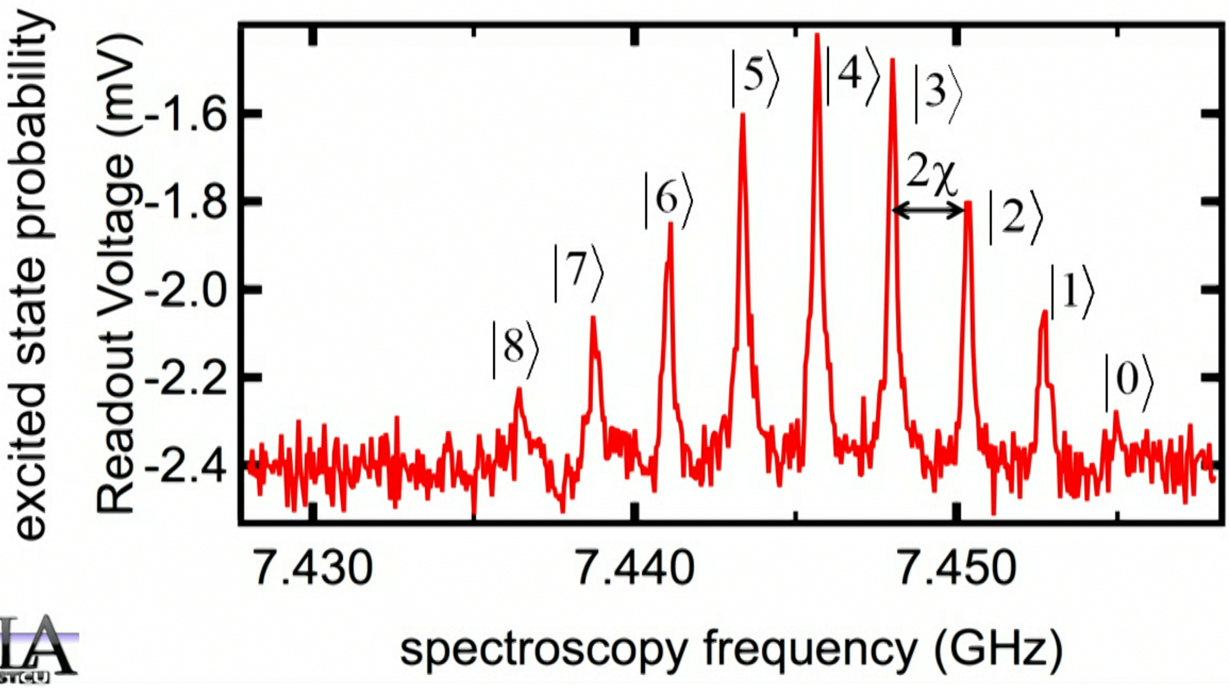
qubit readout: 300 ns, 99% fidelity, QND

R. Vijay et al., *Phys. Rev. Lett.* **106**, 110502 (2011).

Strong dispersive regime: qubit measures cavity state

$$\left|\omega_r - \omega_q\right| \gg g \qquad \hat{H} = \omega_r \hat{a}^\dagger \hat{a} + \frac{\omega_q + 2\chi \hat{a}^\dagger \hat{a}}{2} \hat{\sigma}^z$$

qubit frequency depends on cavity photon number

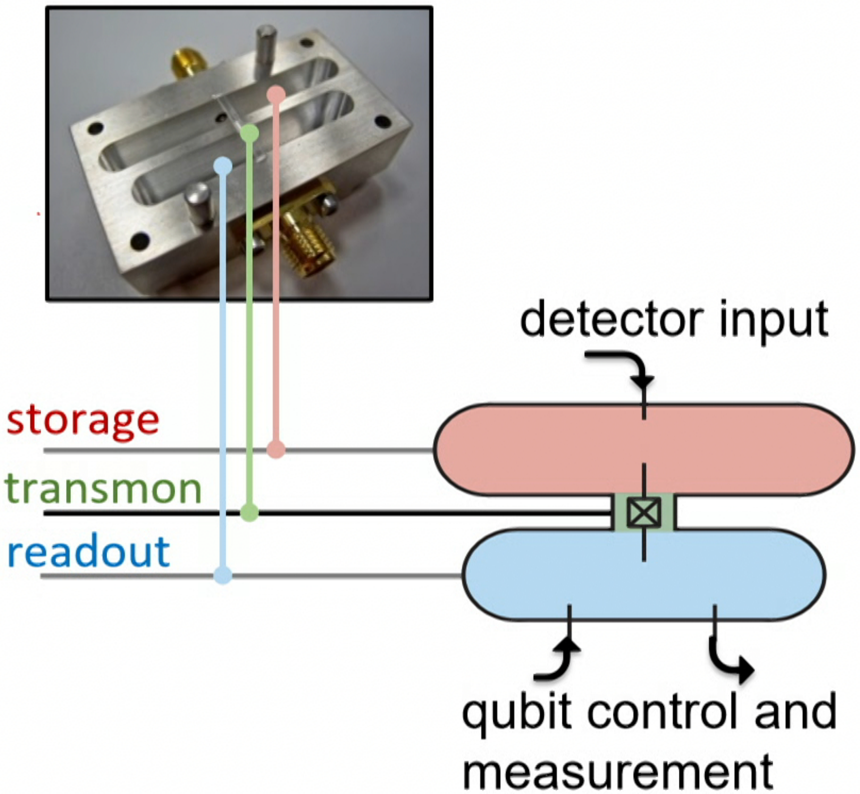


spectrally resolve cavity photon number

micro-"waves" are particles!

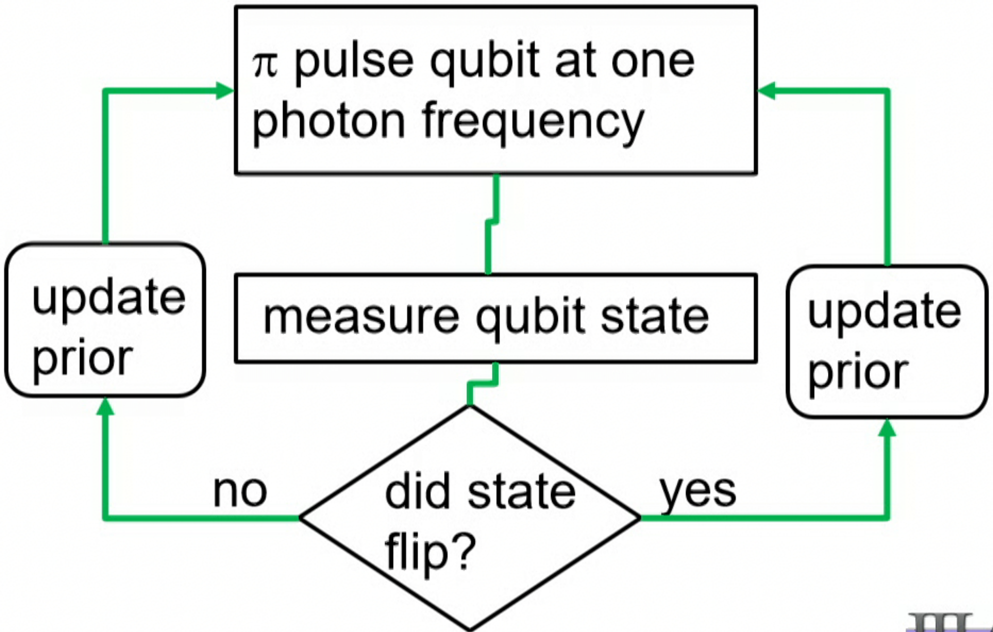
D. I. Schuster *et al.*, *Nature* **445**, 515-518 (2007).

Two-cavity one-qubit device is a QND photon counter

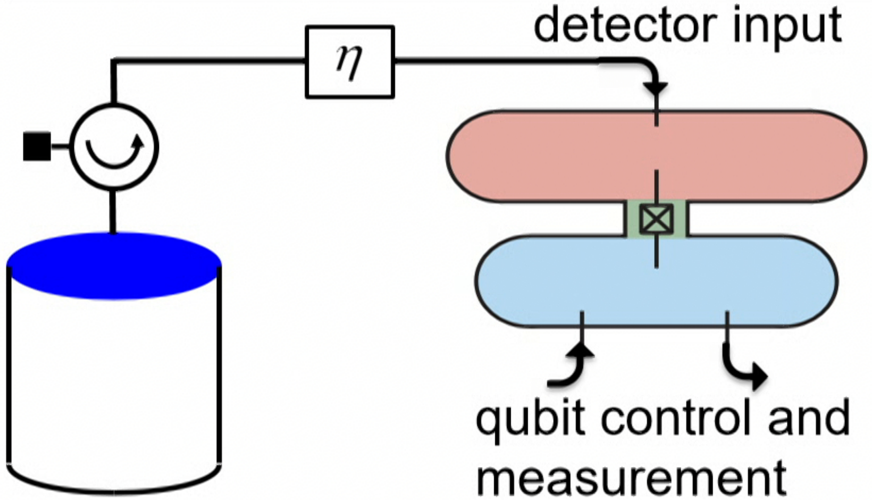


measurement time << storage cavity lifetime

QND photon counting with Bayesian filter



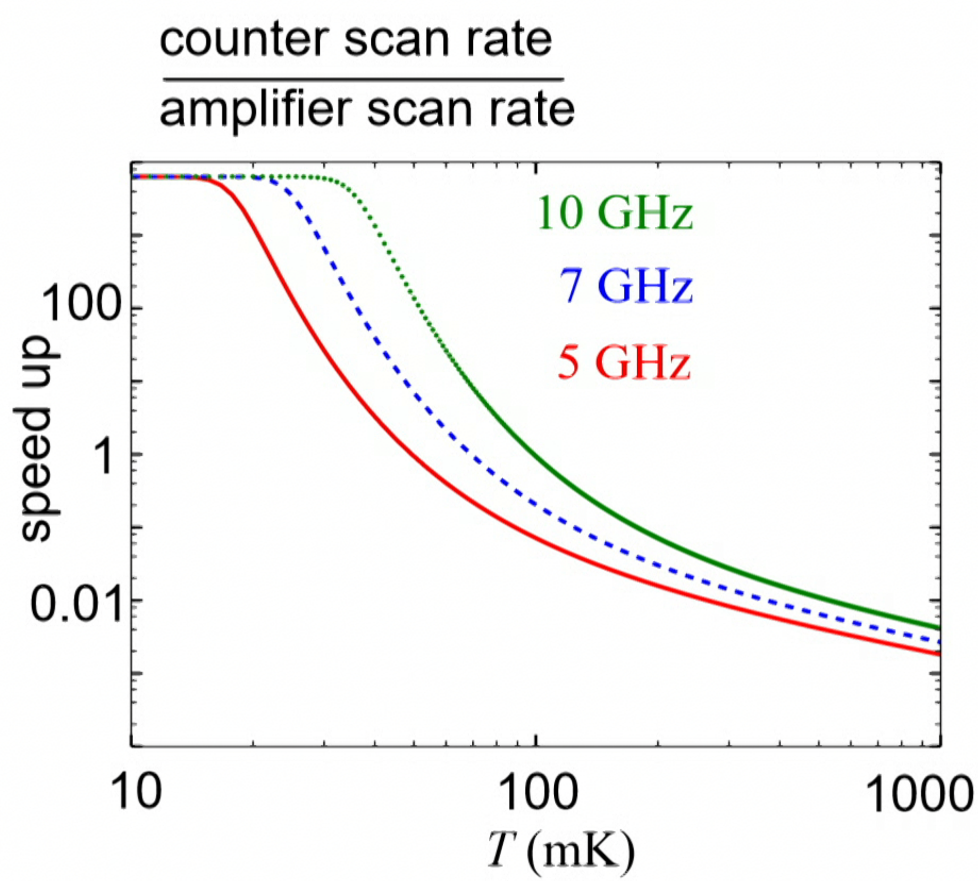
QND photon measurement suppresses dark counts



intrinsic error “dark counts” $n_{\mathrm{dark}} = 10^{-2}$

detect same photon 3 times $n_{\mathrm{dark}}^3 \approx 10^{-6}$

no extra noise from loss (c.f. squeezing)



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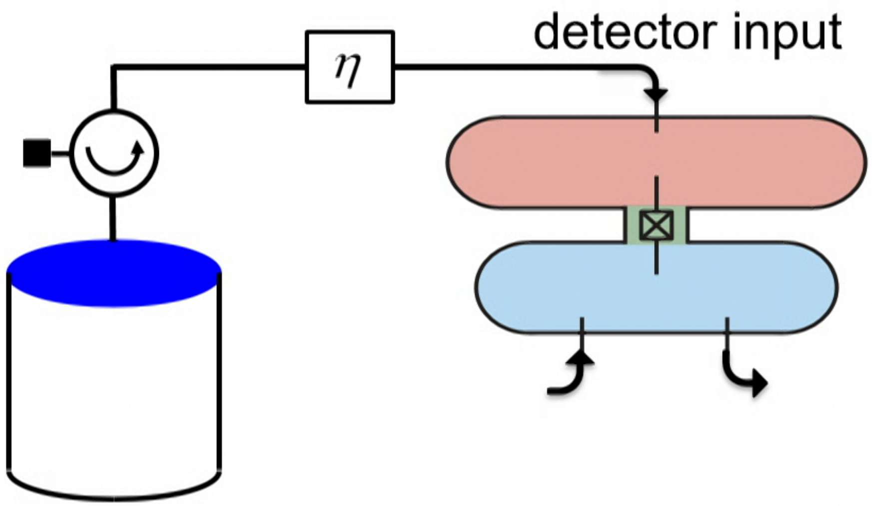
Progress required to implement photon counting receiver in an axion haloscope



tunable CQED photon counter

cooling E+M environment to $T = 20\ \mathrm{mK}$

$$N_T = 10^{-6}\ @\ 20\ \mathrm{mK}$$

discriminating background photons from signal

compatibility with large magnet

Conclusions and acknowledgements

cavity haloscope searches operate at the quantum limit

quantum noise in axion search can be overcome

possible today: 2.5-fold speed up with squeezing

future: potential to speed up 10,000 - fold

quantum noise evading concepts already demonstrated

JILA JPAs and axions

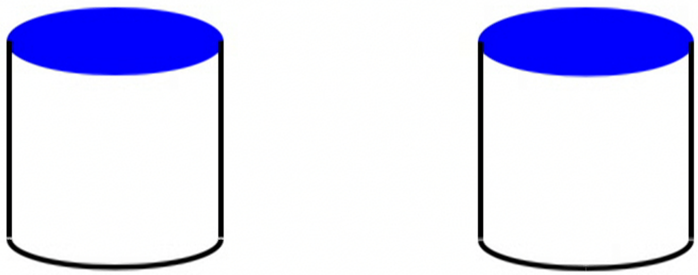
Maxime Malnou
Dan Palken
Manuel Castellanos-Beltran
Francois Mallet
Mehmet Anil
Will Kindel
Hsiang-Shen Ku

HEISING - SIMONS FOUNDATION

NSF

JILA NIST CU

EPR observables of two cavities commute



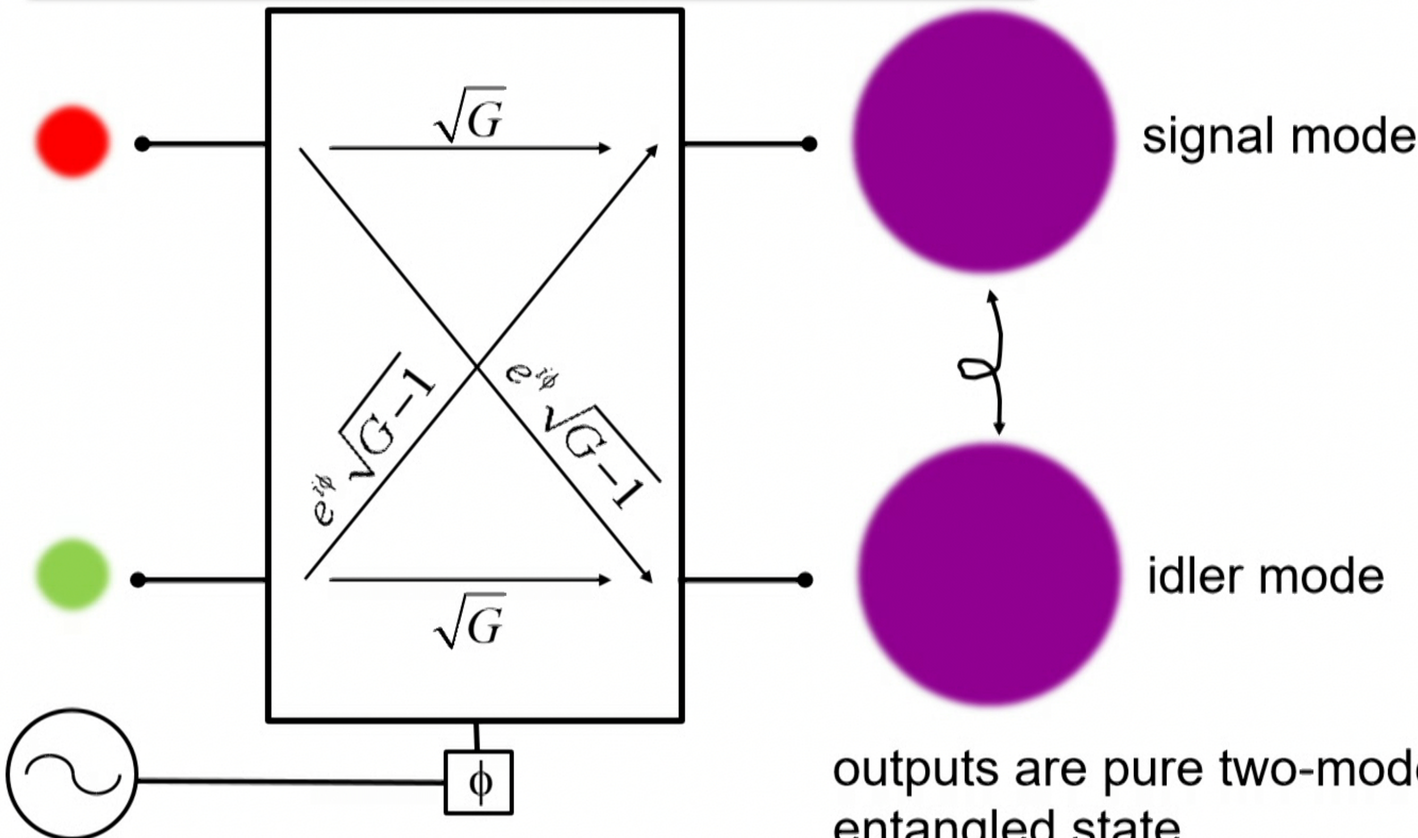
$\left[\hat{X}_1, \hat{X}_2\right] = i$ $\left[\hat{Y}_1, \hat{Y}_2\right] = i$

$\hat{Q} = \hat{X}_1 + \hat{Y}_1;\ \hat{P} = \hat{X}_2 - \hat{Y}_2$

$\left[\hat{Q}, \hat{P}\right] = 0$

measure both Q and P
without added noise

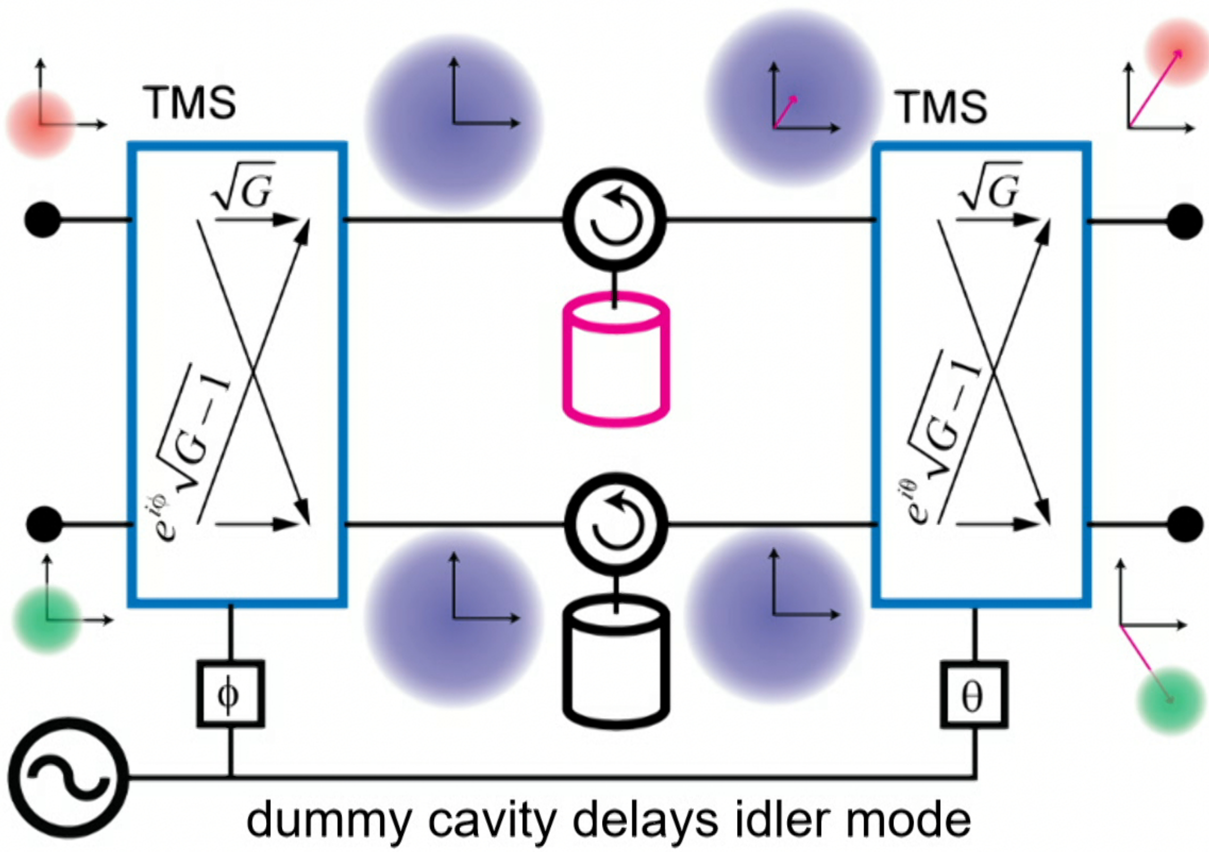
Two-mode squeezer prepares simultaneous eigenstates of EPR observables



outputs are pure two-mode entangled state

N. Bergeal, M. Devoret *et al.*, Nature **465**,64–68
E. Flurin, B. Huard *et al.*, Phys. Rev. Lett. **109**, 183901

Concept for noiseless measurement of both quadratures



dummy cavity delays idler mode

B. Yurke and J. S. Denker, *Phys. Rev. A* **29**, 1419

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