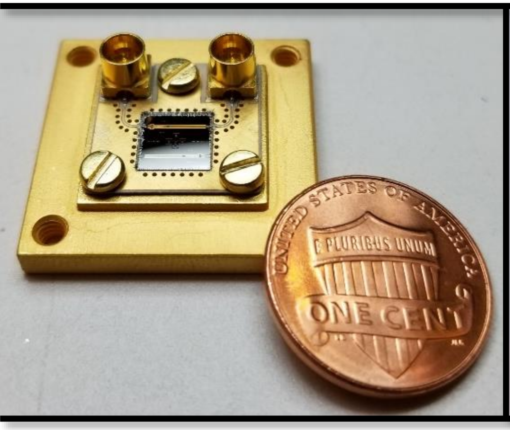
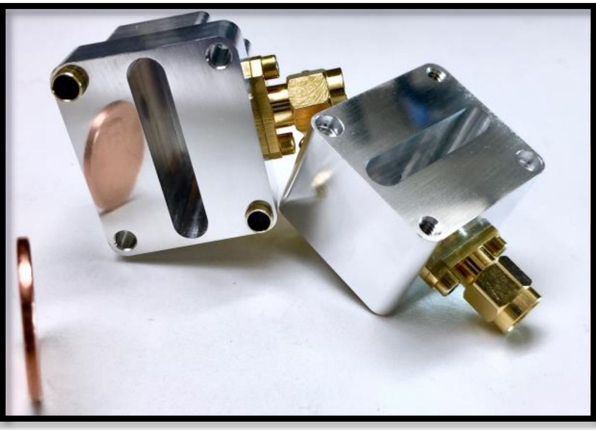
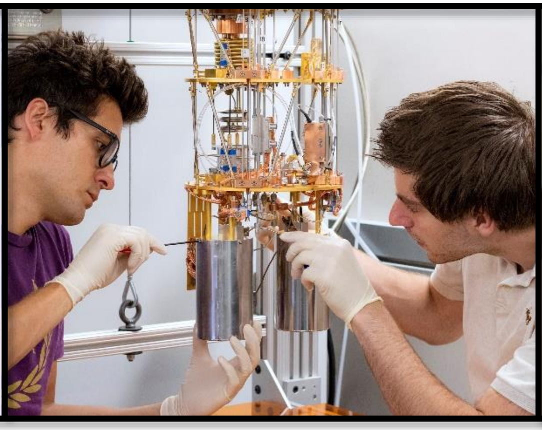
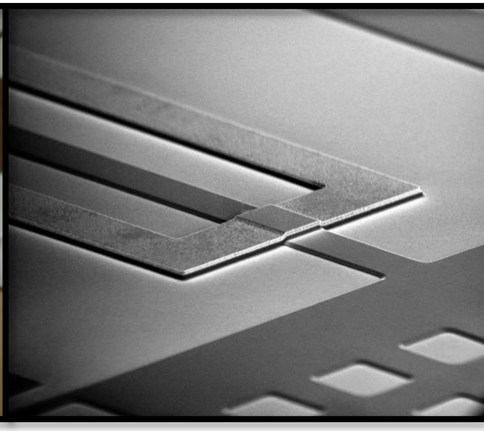
A quantum-enhanced search for a weak microwave signal with application to axion detection





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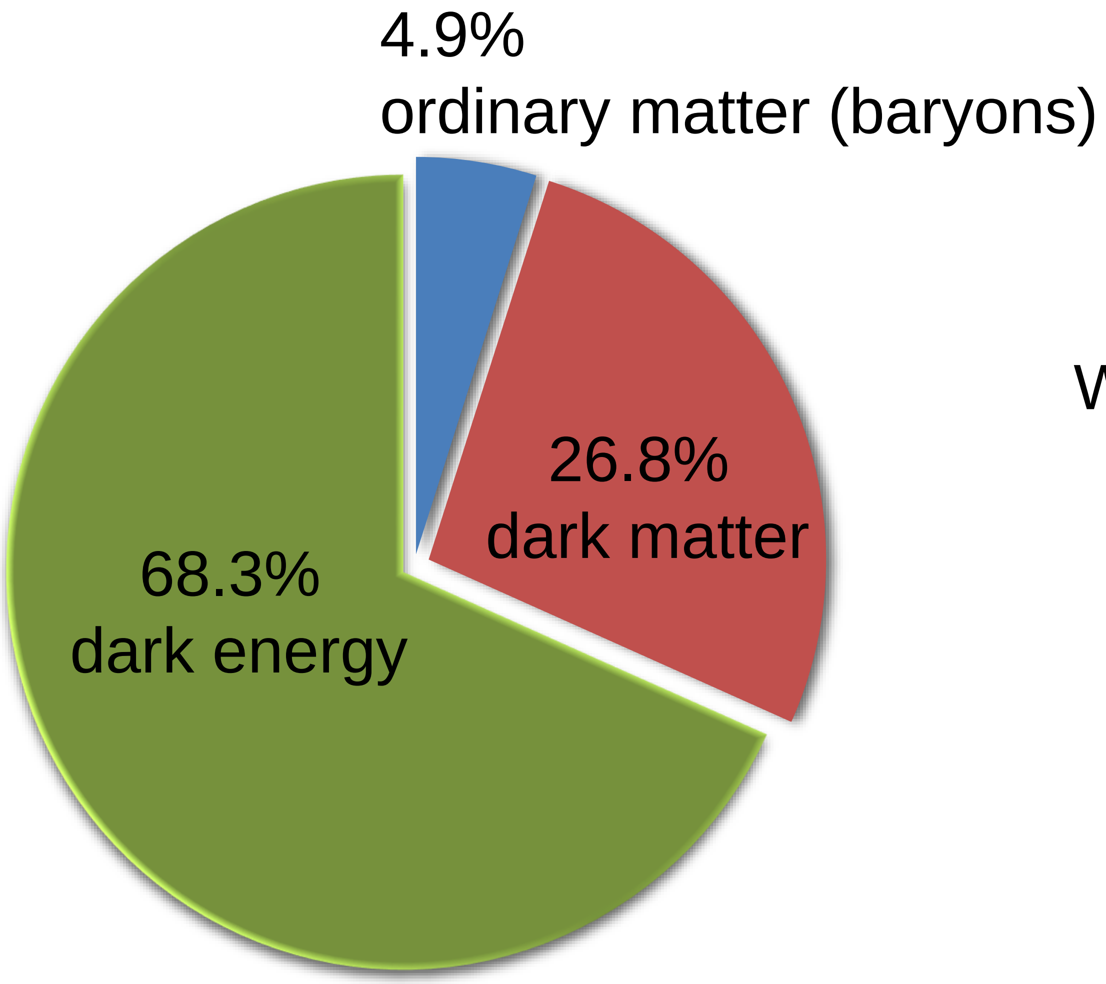
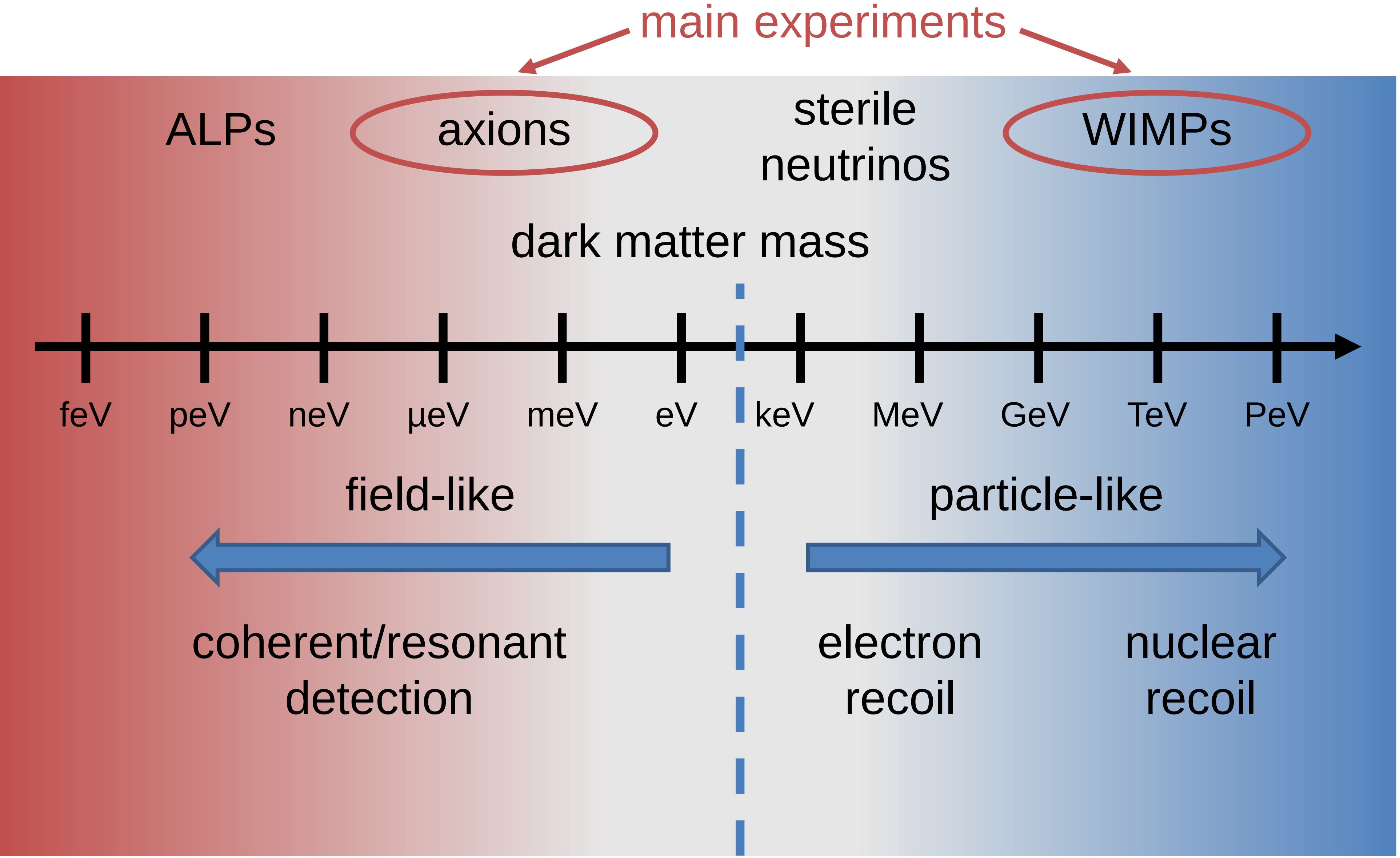
The standard model of cosmology - ΛCDM



What is dark matter?
several ideas to test

Modern cosmology: our profound ignorance with three digits of precision

Hypothetical fundamental particles may for dark matter



Most popular hypothesis, weakly interacting massive particles

consequence of supersymmetry

- no evidence yet at Large Hadron Collider
- no evidence from electron dipole moment searches

no widely accepted direct observation

growing experimental effort in other hypotheses

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

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

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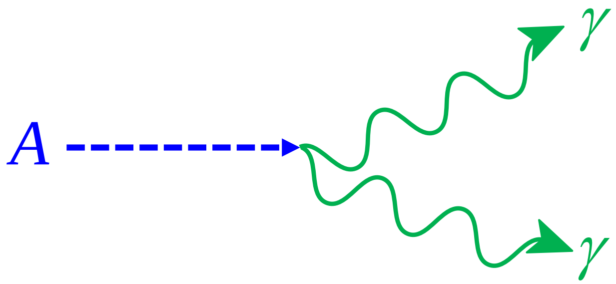
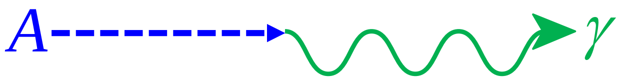
Axion field couples to electromagnetism

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



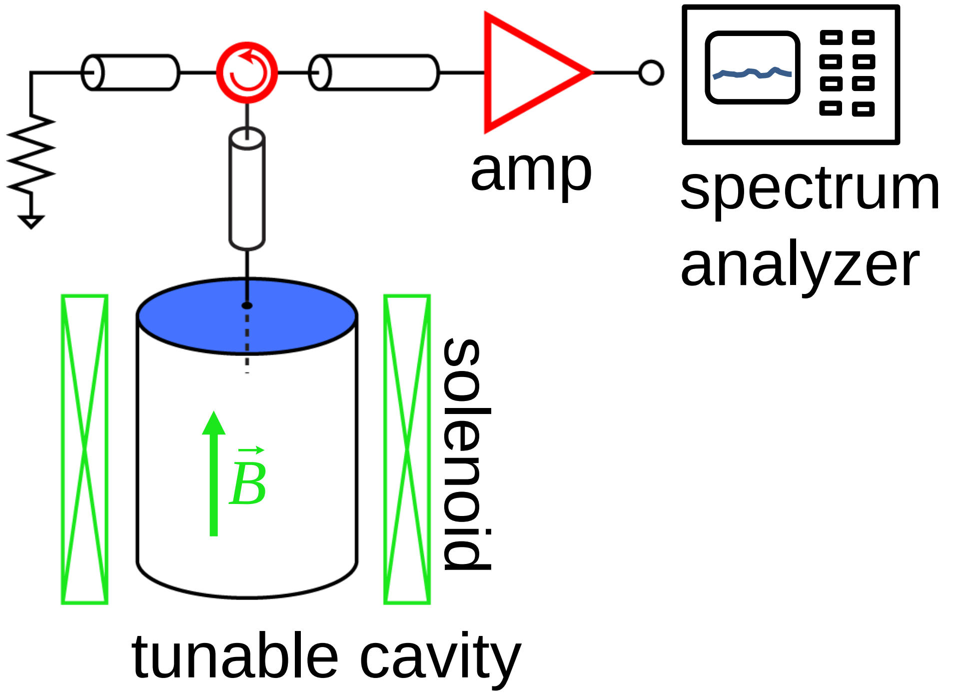
linearize coupling around static $\vec{B}$-field



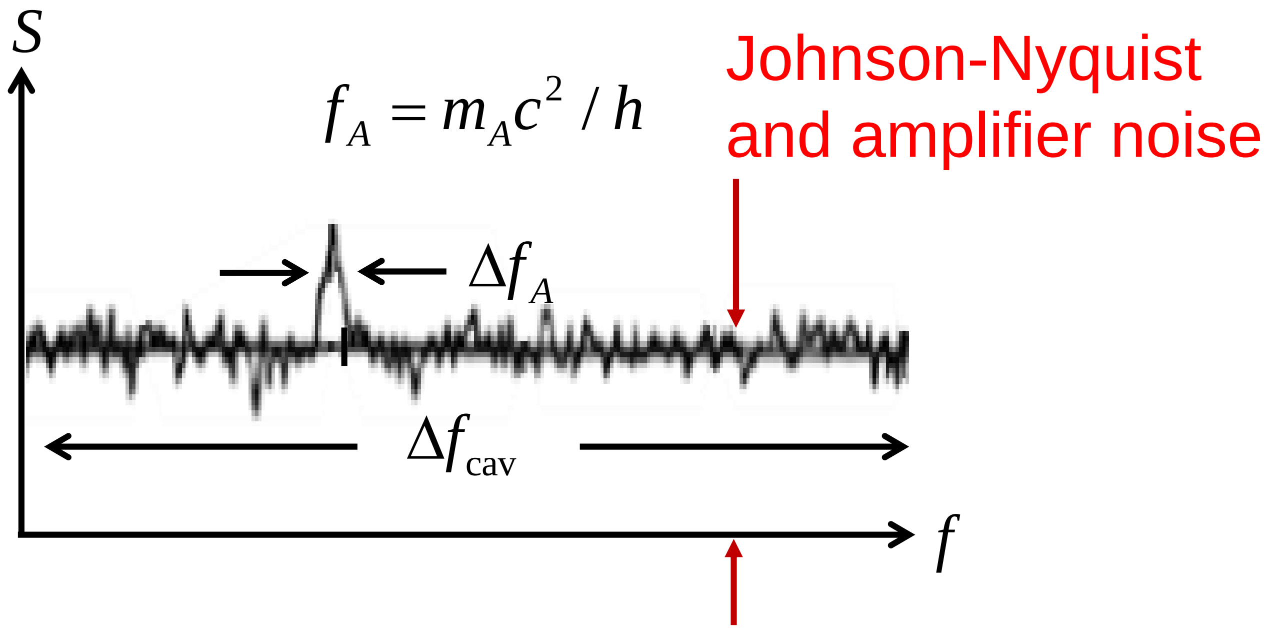
$E_A = E_\gamma$

dark matter axions create microwave photons

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



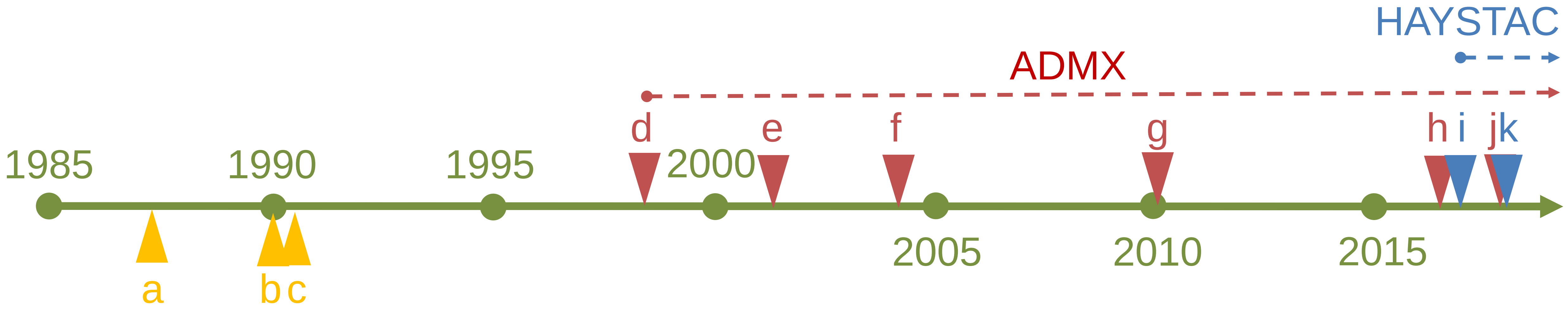
tune -> wait and integrate -> tune



axion line narrower than cavity

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

History of haloscopes searching for axioninc dark matter



pathfinder experiments
(insensitive to QCD axion)

exclusion data:

a) S. DePanfilis *et al.*, *Phys. Rev. Lett.*, **59**, 839 (1987)
b) C. Hagmann *et al., Phys. Rev. D,* **42**, 1297 (1990)
c) C. Hagmann, Ph.D. thesis (1990)
d) C. Hagmann *et al., Phys. Rev. Lett.,* **80**, 2043 (1998)
e) S.J. Asztalos *et al., Astrophys. J.,* **571**, L27 (2002)
f) S.J. Asztalos *et al., Phys. Rev. D,* **69**, 011101 (2004)
g) S.J. Asztalos *et al., Phys. Rev. Lett,* **104**, 041301 (2010)
h) J.V. Sloan *et al., Physics of the Dark Universe,* **14**, 95 (2016)
i) B.M. Brubaker, *et al., Phys. Rev. Lett.,* **118**, 061302 (2017)
j) N. Du *et al., Phys. Rev. Lett.,* **120**, 151301 (2018)
k) L. Zhong, D.A. Palken *et al., Phys. Rev. D*, **97**, 092001 (2018)

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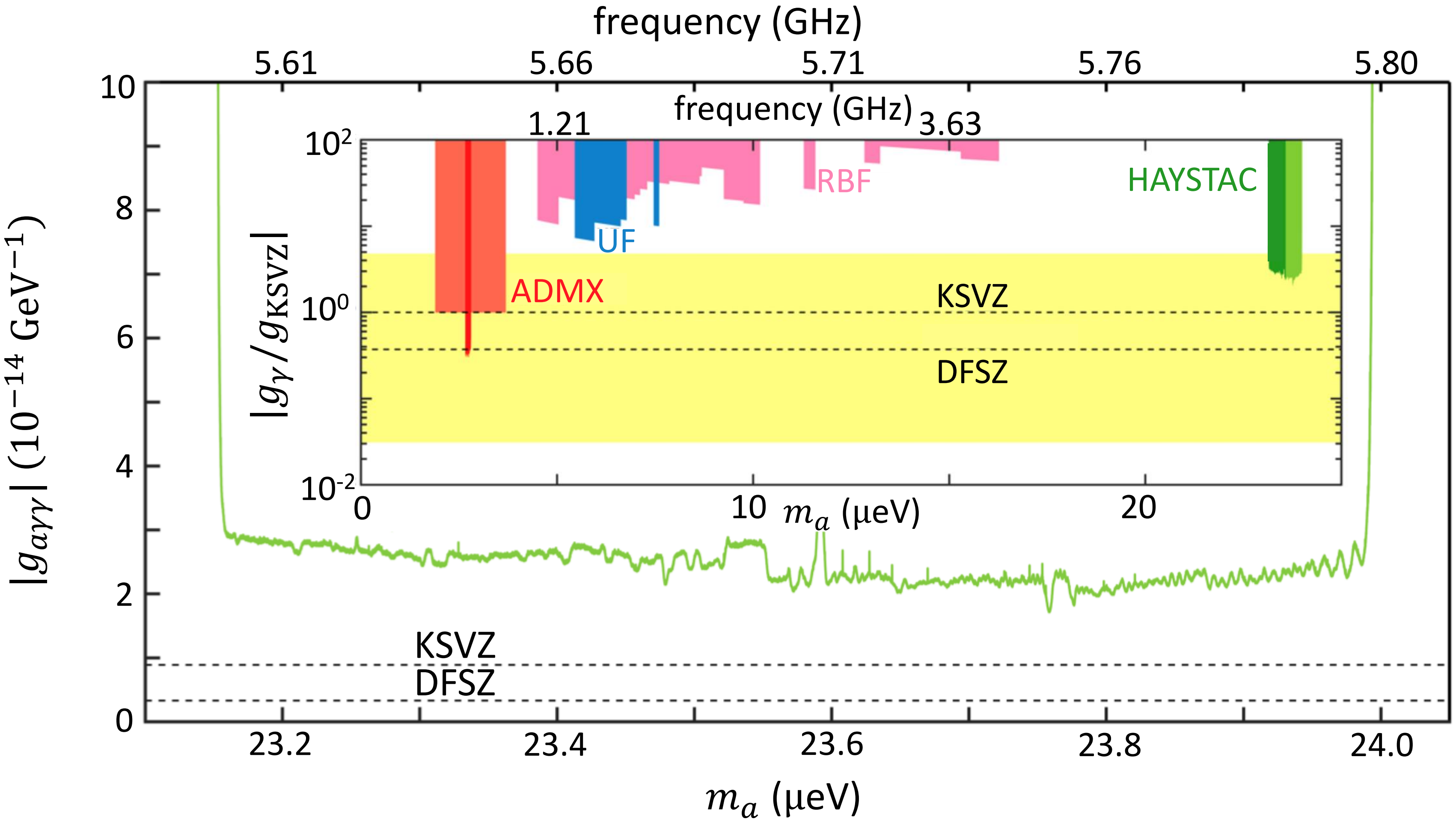
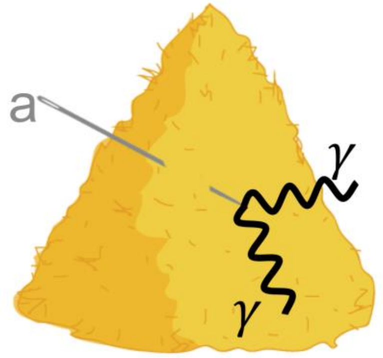
HAYSTAC: **H**aloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM

standard haloscope scan rate: $R \propto f^{-\frac{14}{3}} g_{a\gamma\gamma}^4$



1 – 10 GHz at DFSZ
~20,000 yrs at quantum limit, with one 9 Tesla magnet



$f^{-14/3}$ scaling: B.M. Brubaker, Ph.D. thesis (2017)
operation: S. Al Kenany, …, D.A. Palken *et al.*, *Nucl. Instr. Meth. Phys. Res. A.* **854**, 11 (2017)
exclusion: L. Zhong, …, D.A. Palken *et al.*, *Phys. Rev. D*, **97**, 092001 (2018)

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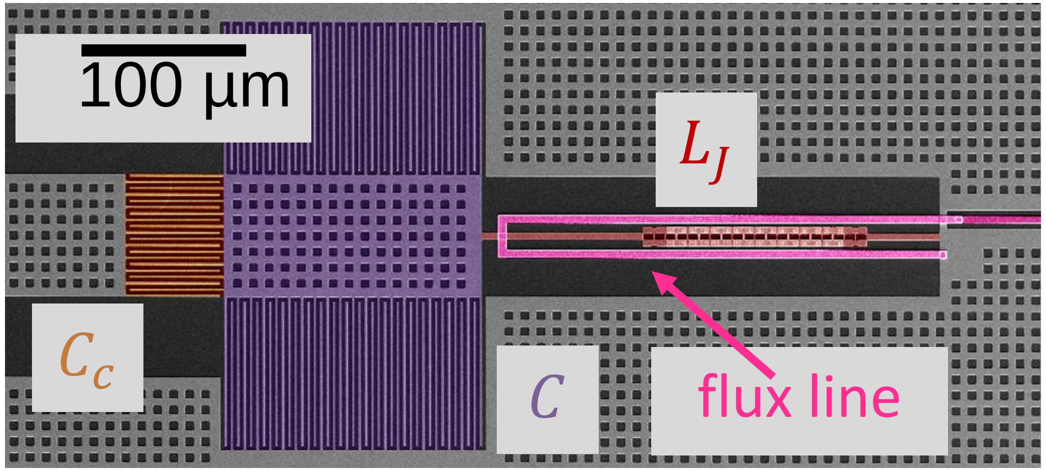
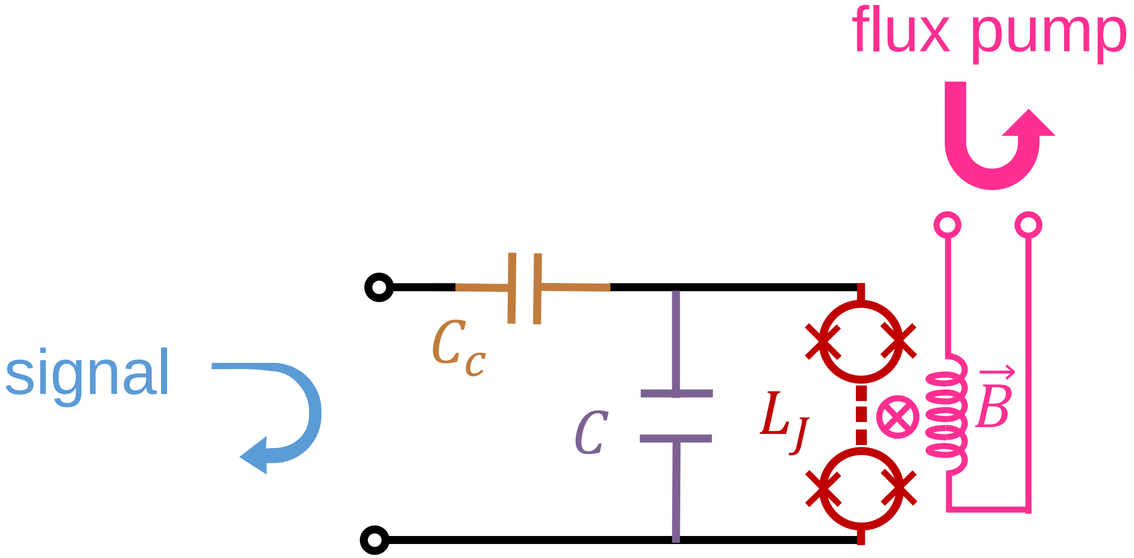
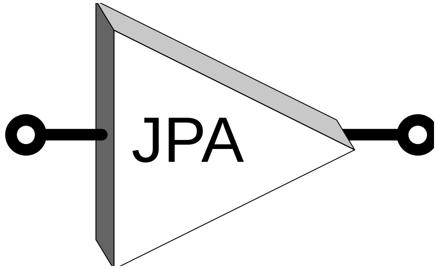
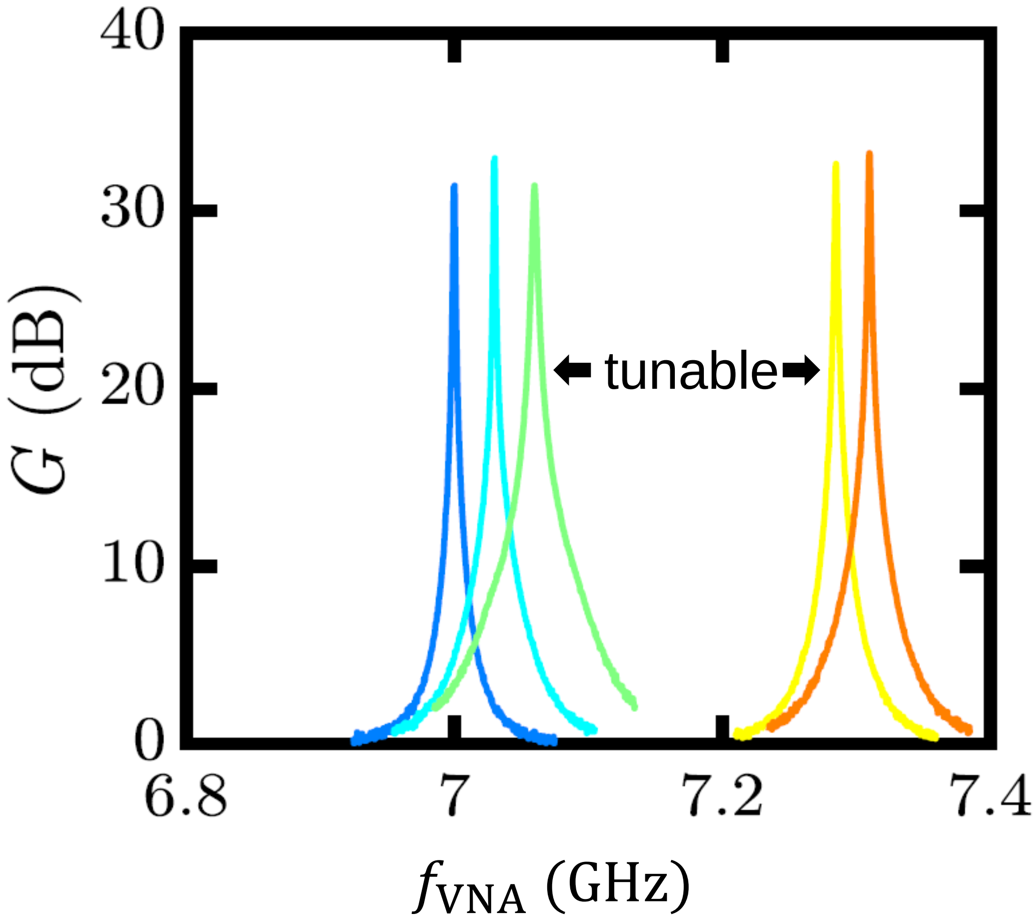
quantum amplification and squeezing

JPAs: quantum-limited, tunable amplifiers









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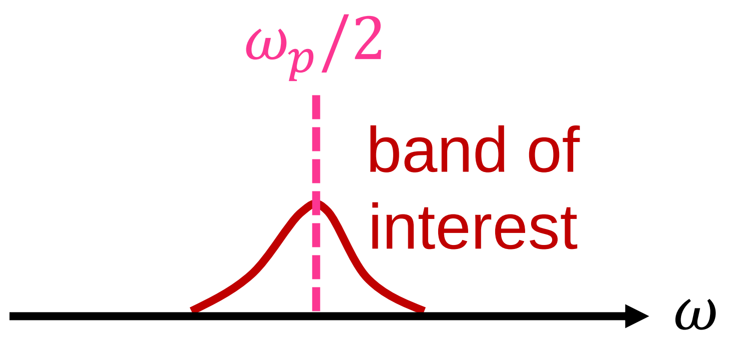
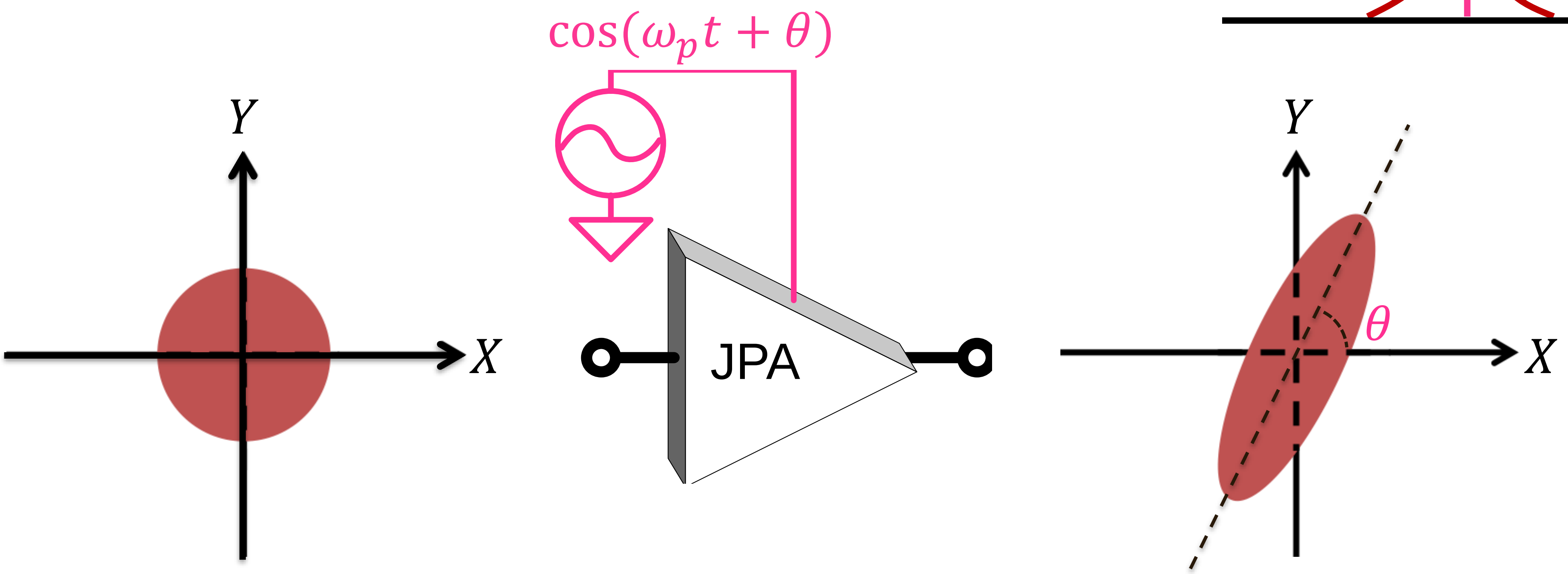
JPA can squeeze, amplify noiselessly

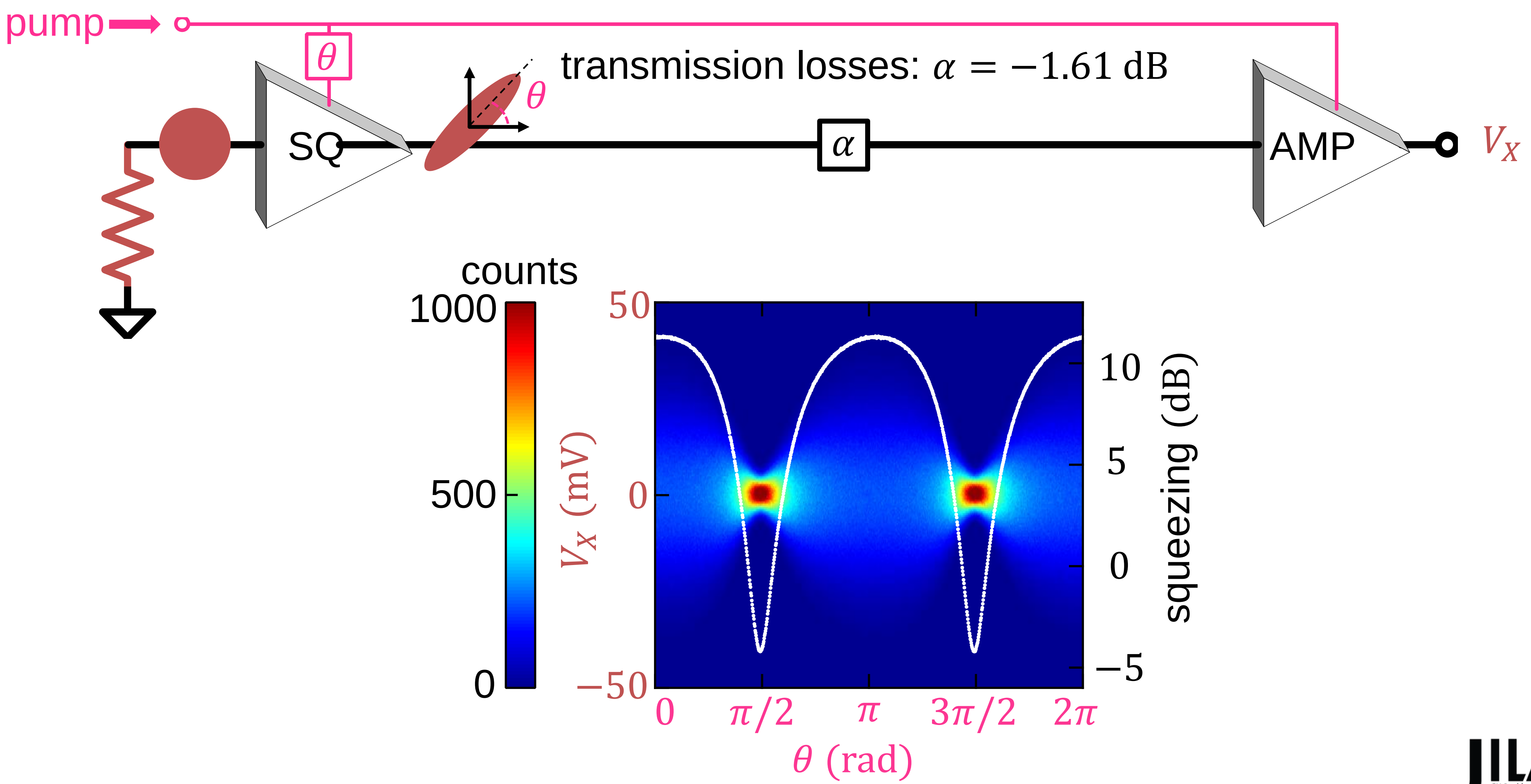
$$\hat{V}_{\omega_{\text{cav}}} = \hat{X}\cos(\omega_{\text{cav}} t) + \hat{Y}\sin(\omega_{\text{cav}} t)$$

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

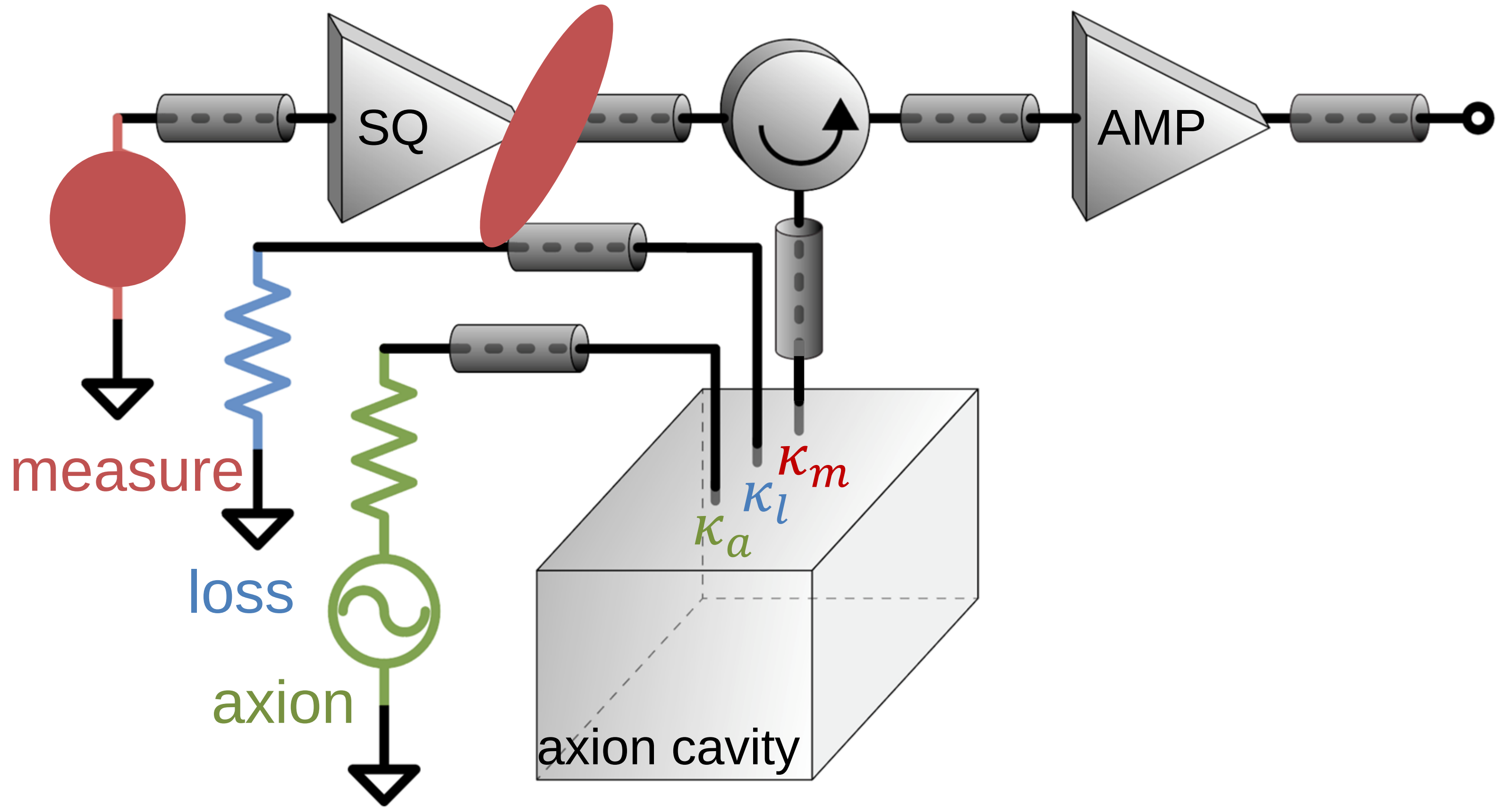




Transmission losses limit squeezing



Squeezing to circumvent the quantum limit: modeling the squeezed state receiver



axion: weak classical force

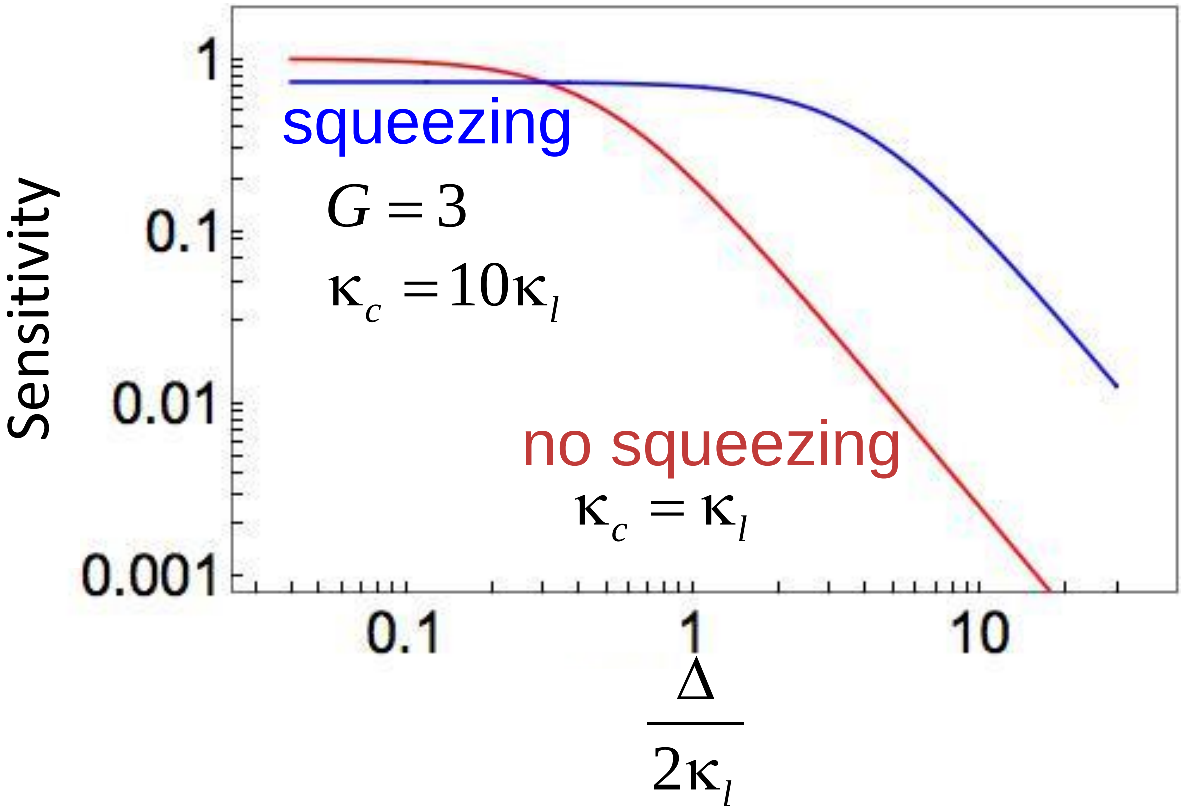
$\kappa_a \ll \kappa_l$

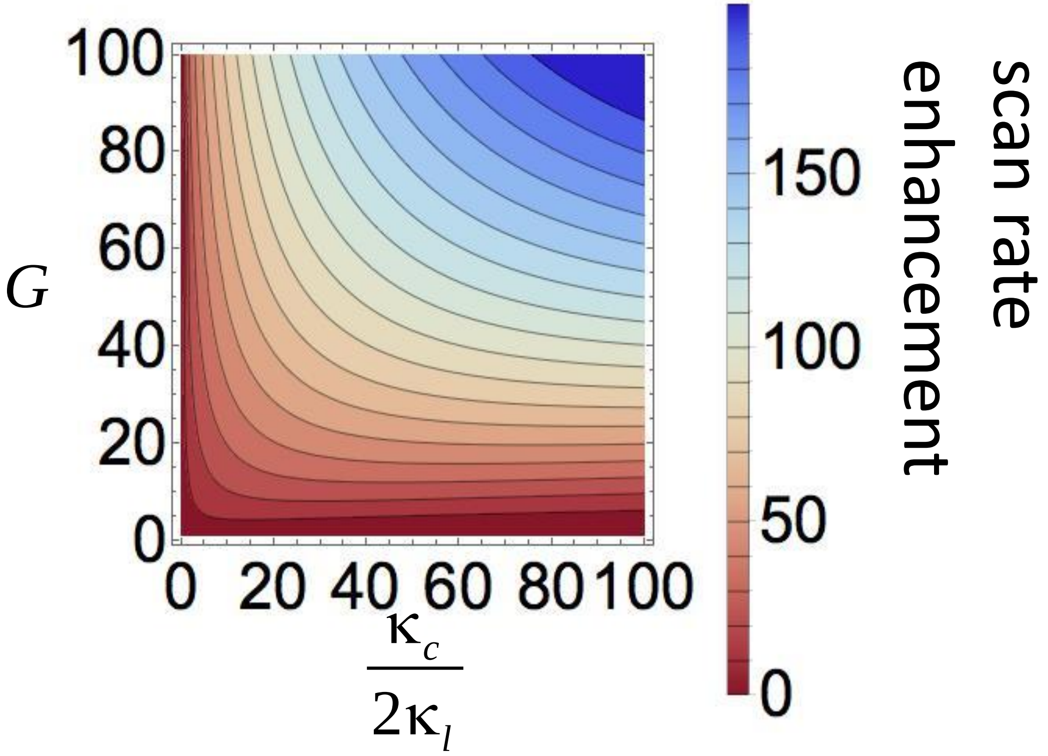
overcouple: increase measurement port noise

squeezing reduces that noise

wideband axion sensitivity

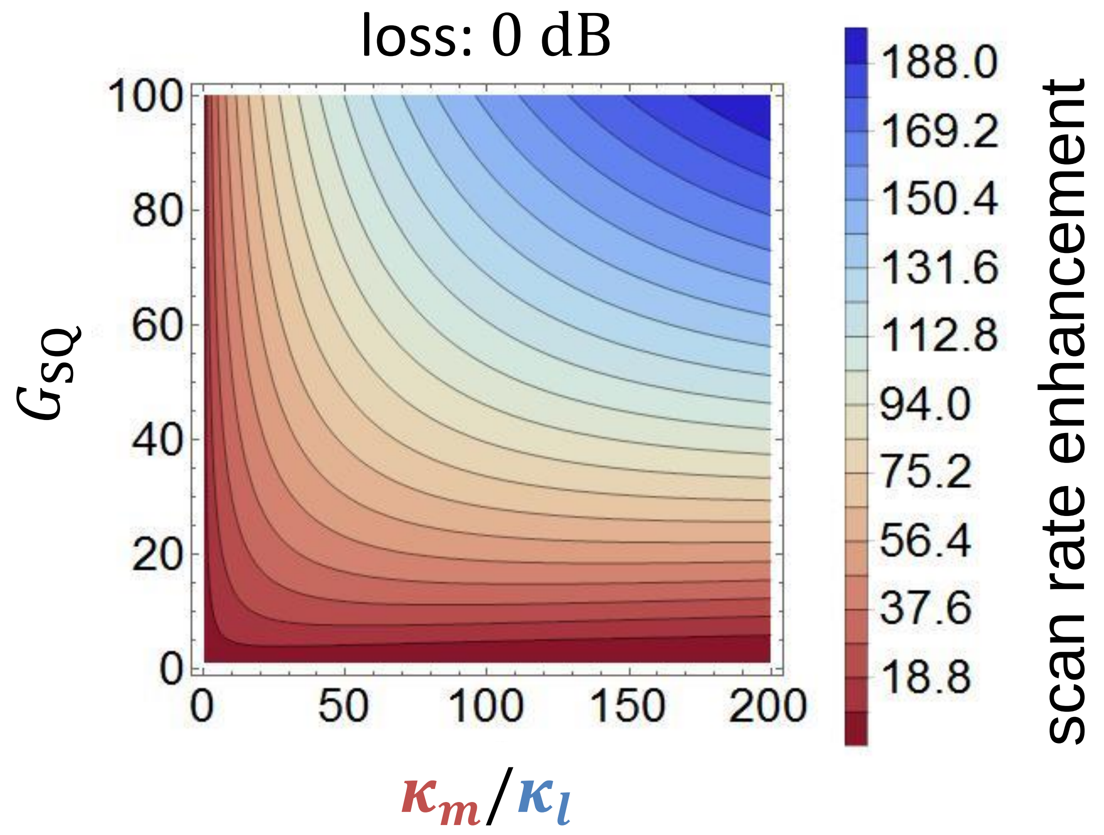
Scan rate enhancement, perfect efficiency

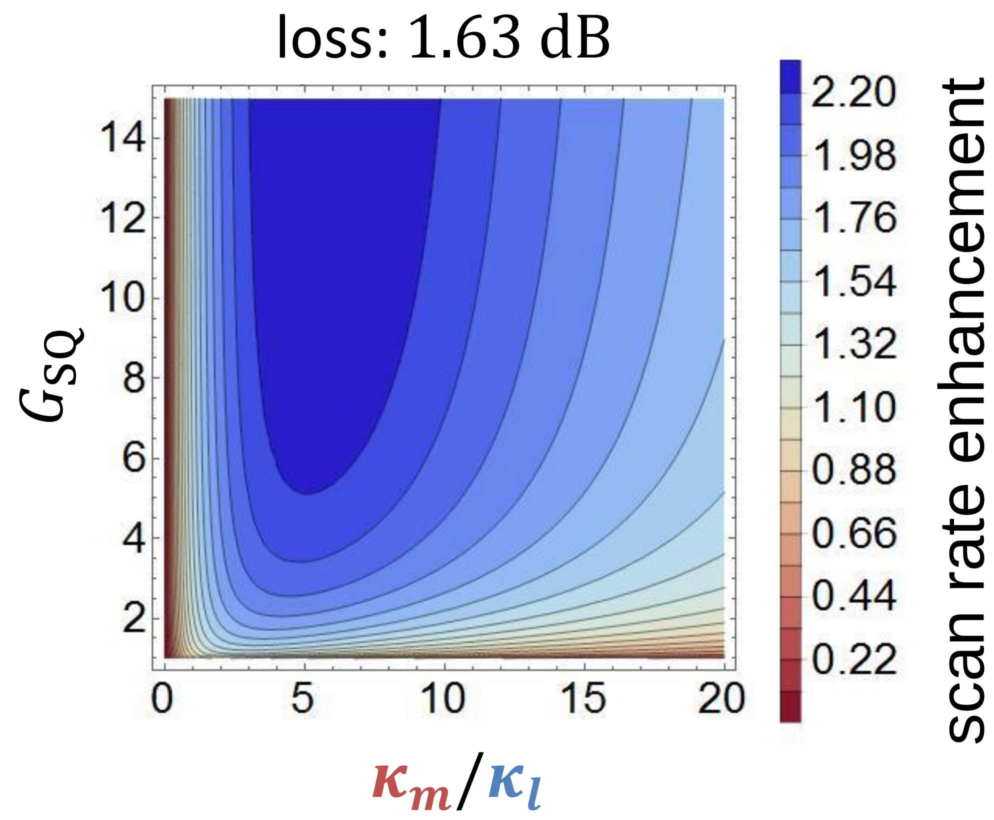




slight reduction in sensitivity
much larger bandwidth

Effect of losses on the scan rate



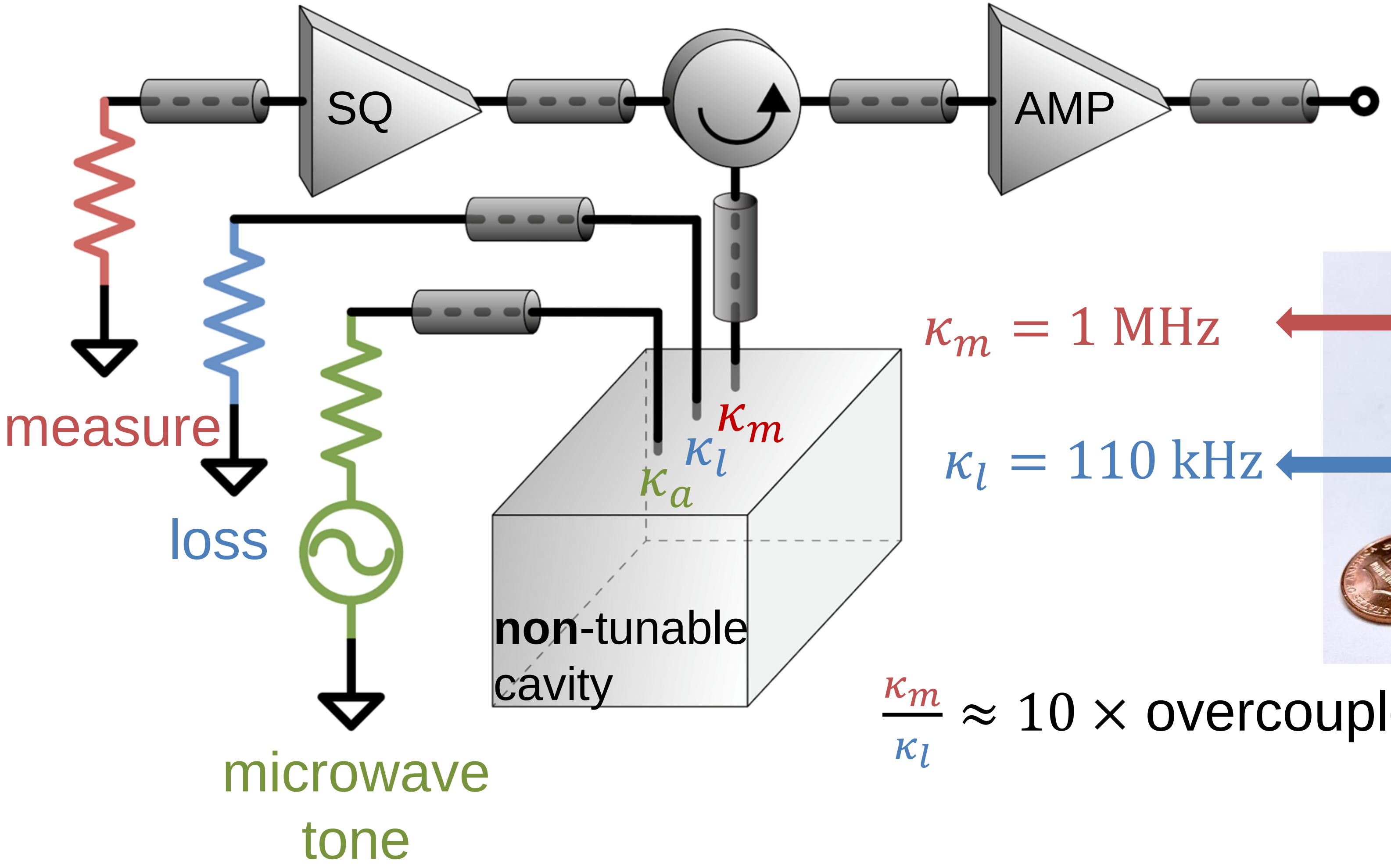


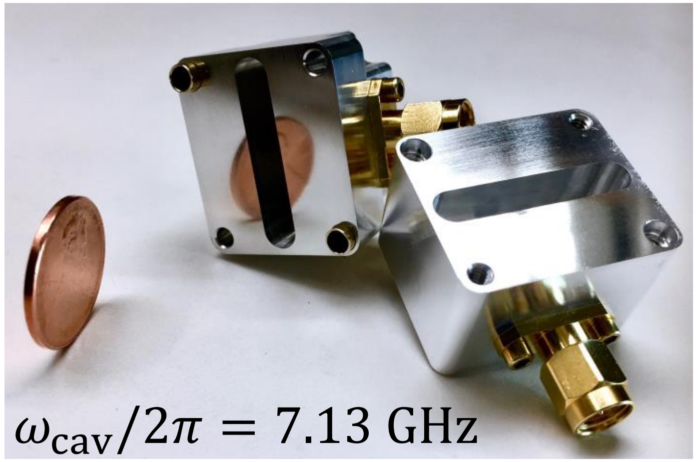
loss 1.63 dB: $G_s = 6, \kappa_m = 9\kappa_l$

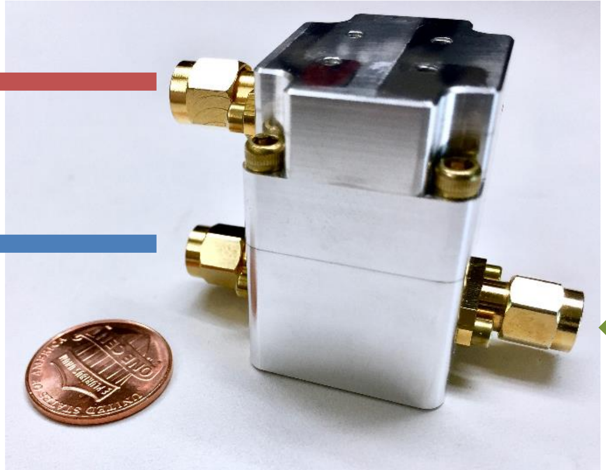
simulated axion search

A mock-haloscope to experimentally test the SSR concept

non-tunable cavity without magnetic field







$\kappa_m = 1$ MHz

$\kappa_l = 110$ kHz

$\kappa_a = 130$ Hz

$\frac{\kappa_m}{\kappa_l} \approx 10 \times$ overcoupled

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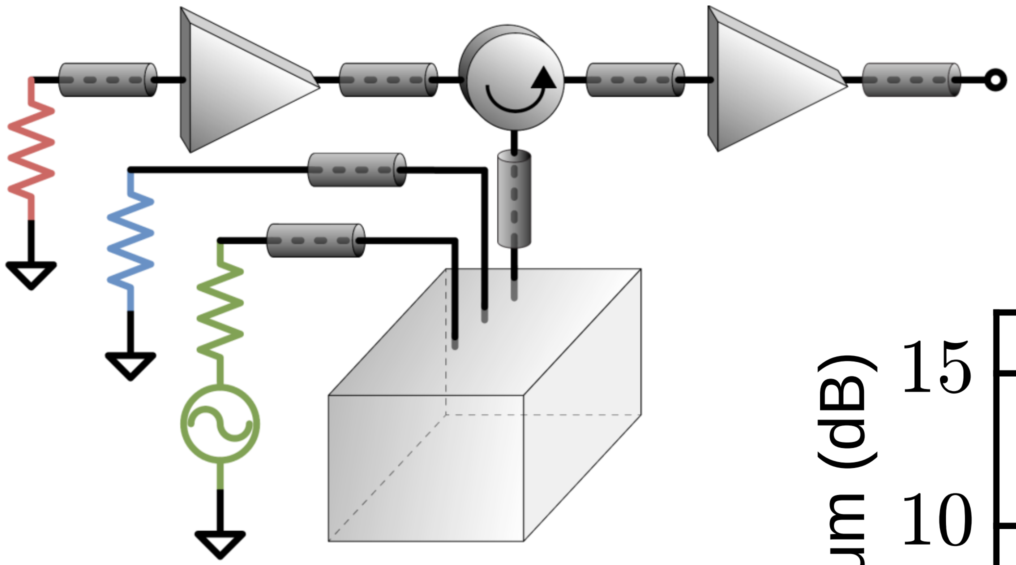
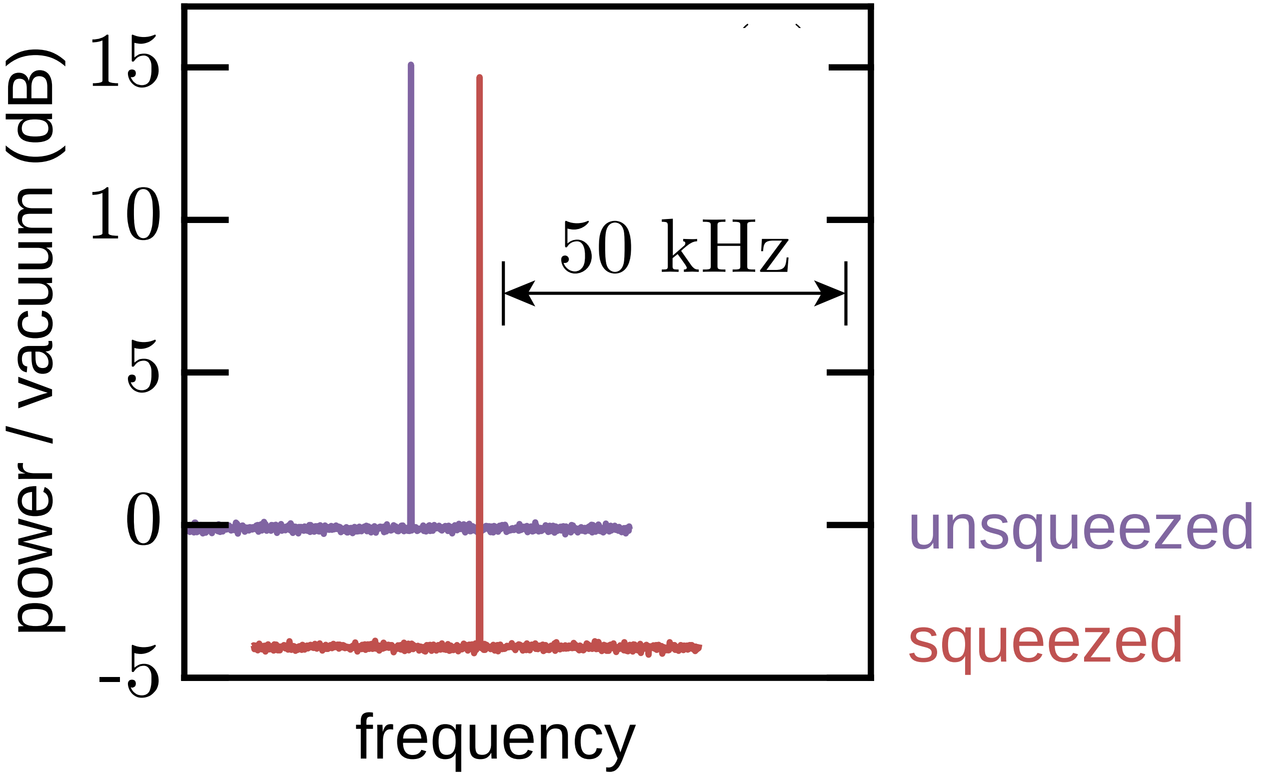
Squeezing reduces the noise without degrading the signal

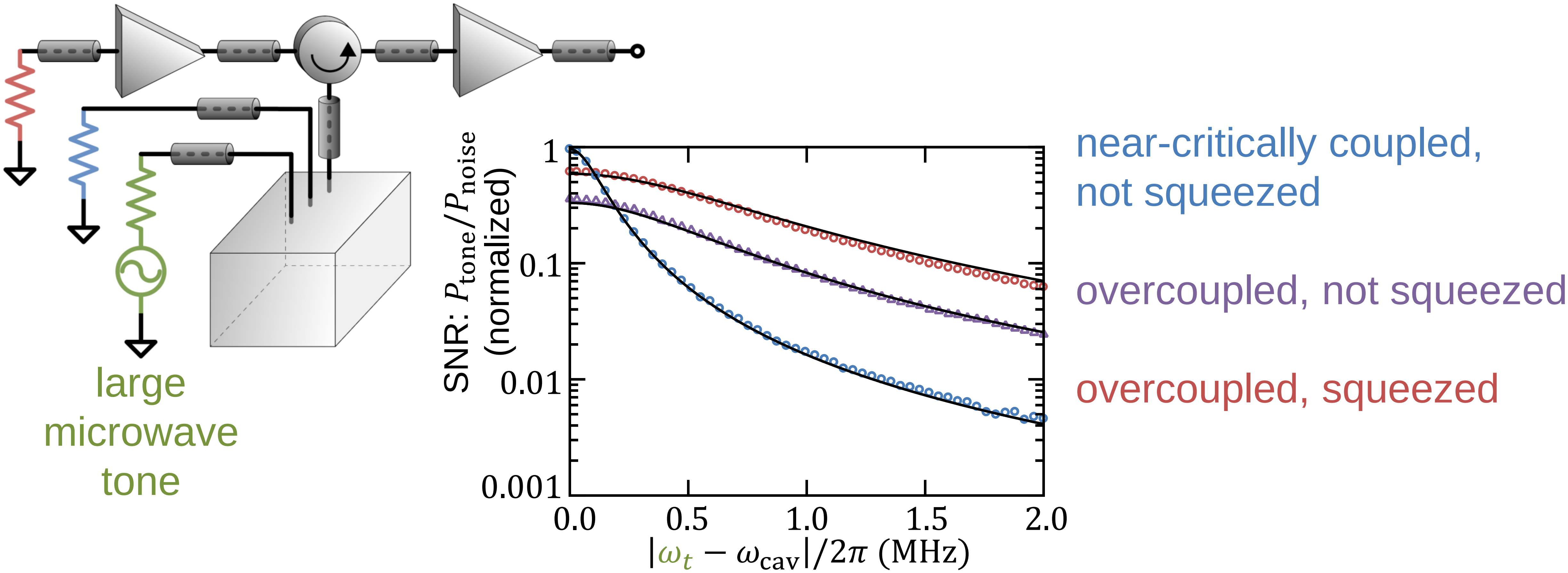


large microwave tone

tone injected off cavity resonance



Squeezing favorably trades off peak sensitivity for bandwidth



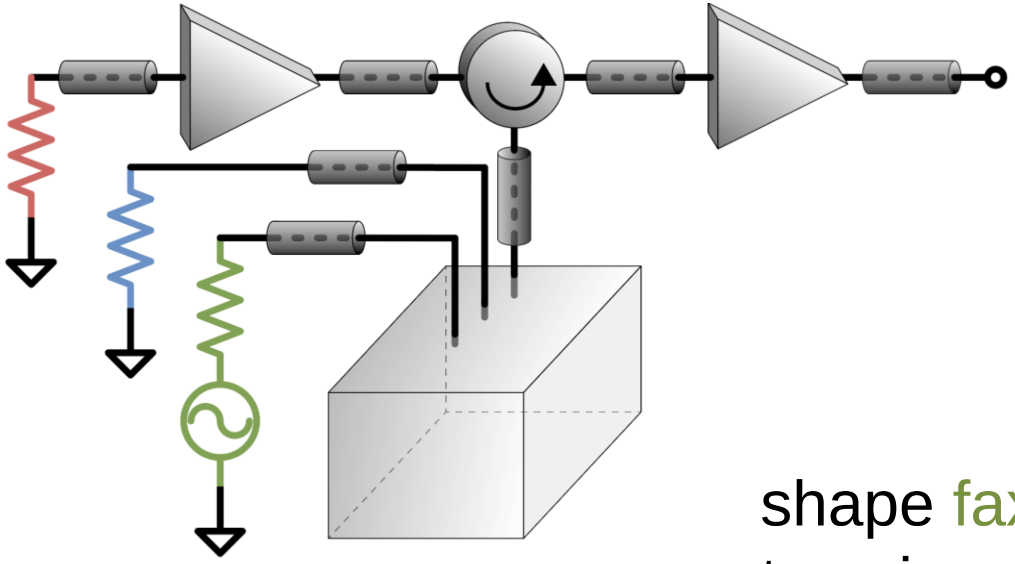
scan rate: $R \propto \int [\mathrm{SNR}(\omega)]^2 d\omega$

$$\frac{R_{\mathrm{SQ}}}{R_{\mathrm{noSQ}}} = 2.05 \pm 0.04$$

primary limitation: 1.61 dB transmission loss

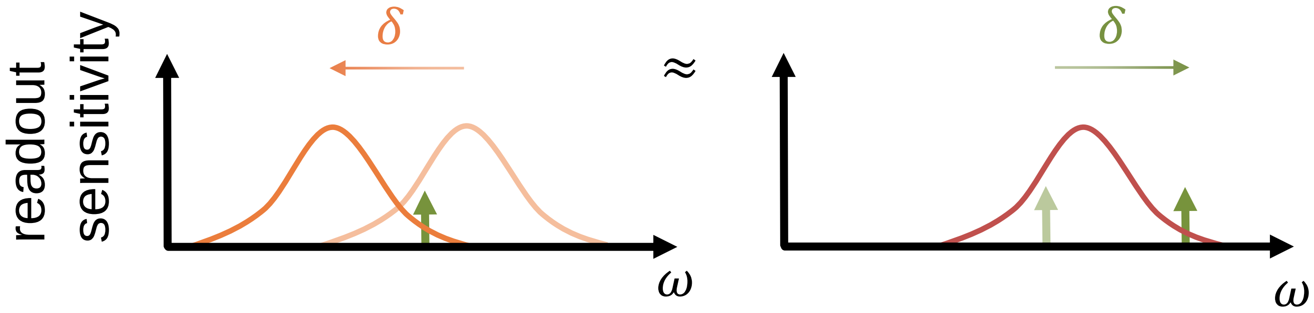
Search for a fake axion of unknown frequency

aim to detect small excess power $P_{\text{fax}} \ll P_{\text{vac}}$



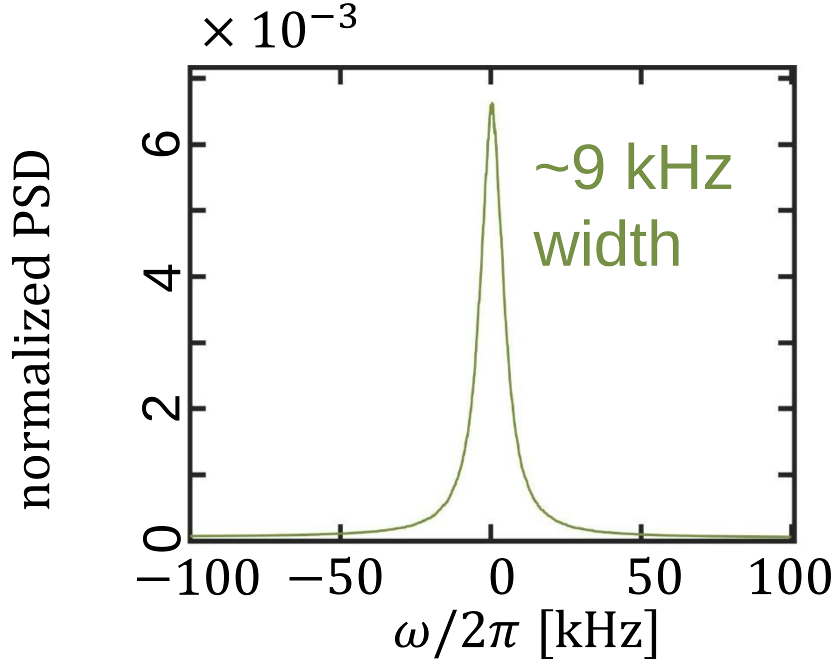
fake axion (faxion)

tune cavity ≈ tune faxion



shape faxion to axion width:

$P_{\text{fax}} \approx 5 \times 10^{-3} P_{\text{vac}}$



A fake axion tone of unknown frequency stands out against the squeezed noise

no faxion:

$$\mu_{\text{vac}} = 0, \ \sigma = 1$$

faxion, critically coupled unsqueezed:

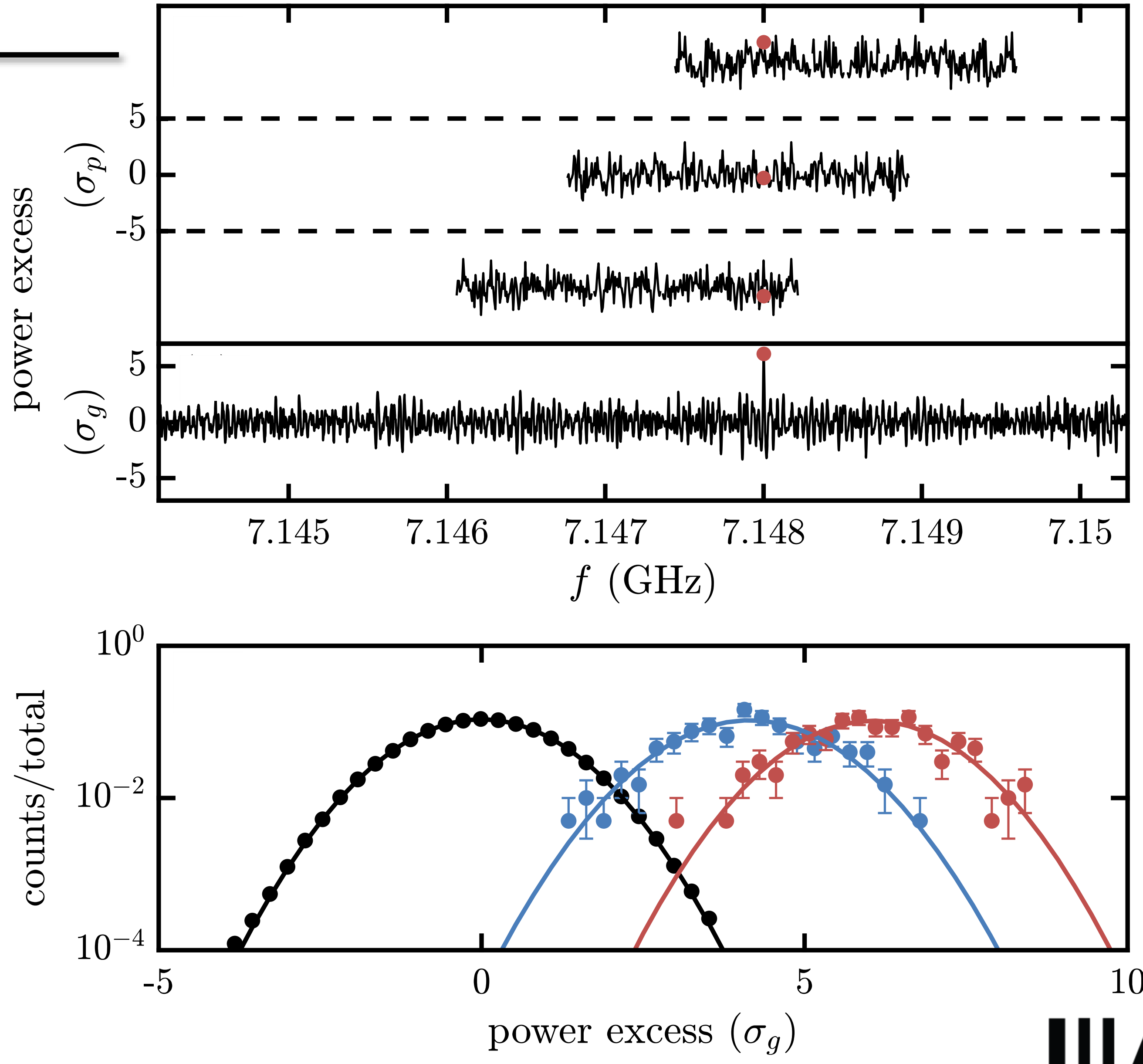
$$\mu_{\text{noSQ}} = 4.2 \pm 0.1, \ \sigma = 1$$

faxion, overcoupled, squeezed:

$$\mu_{\text{SQ}} = 6.0 \pm 0.1, \ \sigma = 1$$

scan rate enhancement:

$$\left(\frac{\mu_{\text{SQ}}}{\mu_{\text{noSQ}}}\right)^2 = 2.12 \pm 0.08$$



arxiv:1809.06470

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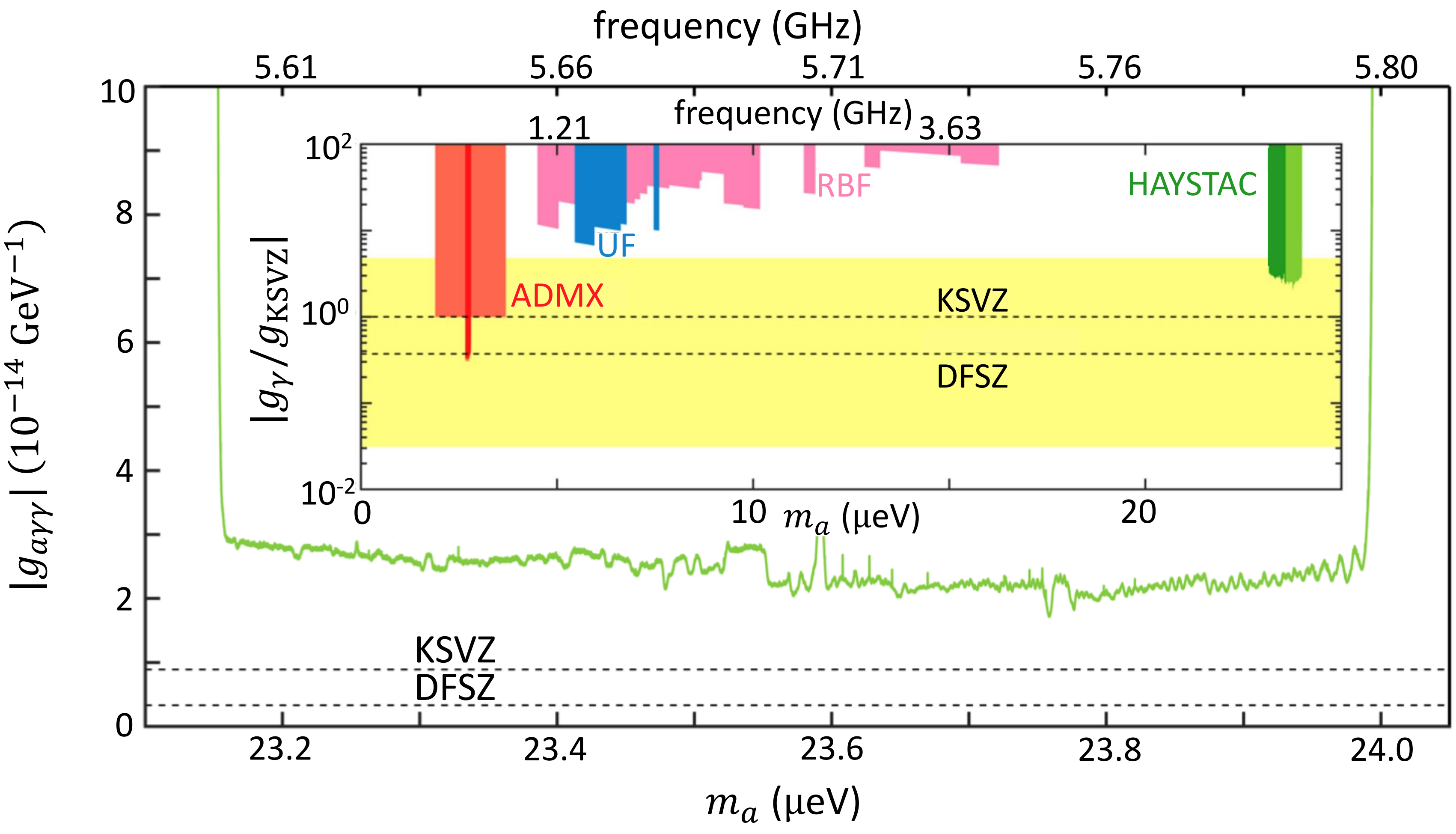
Impact of a doubled search rate

haloscope scan rate: $R \propto B^2$



1 – 10 GHz at DFSZ
~20,000 yrs at quantum limit, with one 9 Tesla magnet

10 yrs at quantum limit
with 200 x 30 Tesla magnet
~ $1.6 billion

quantum squeezing today
save $800 million!

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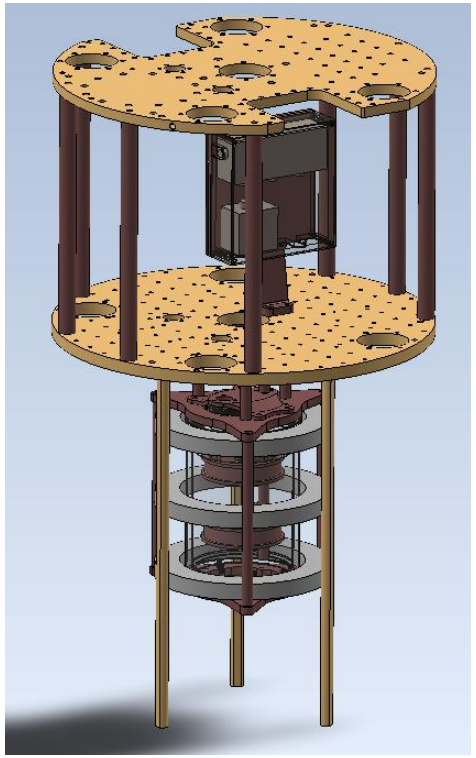
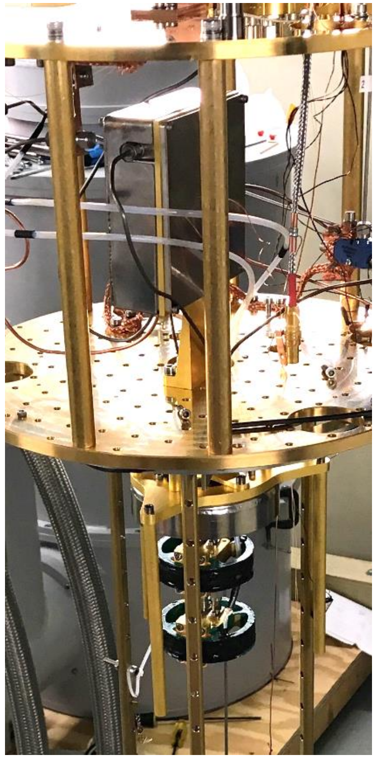
Acquisition: deploying our SSR with HAYSTAC's tunable cavity, 9 T magnetic field

operation of squeezed state receiver (setup, tune, bias, calibration)

challenges:

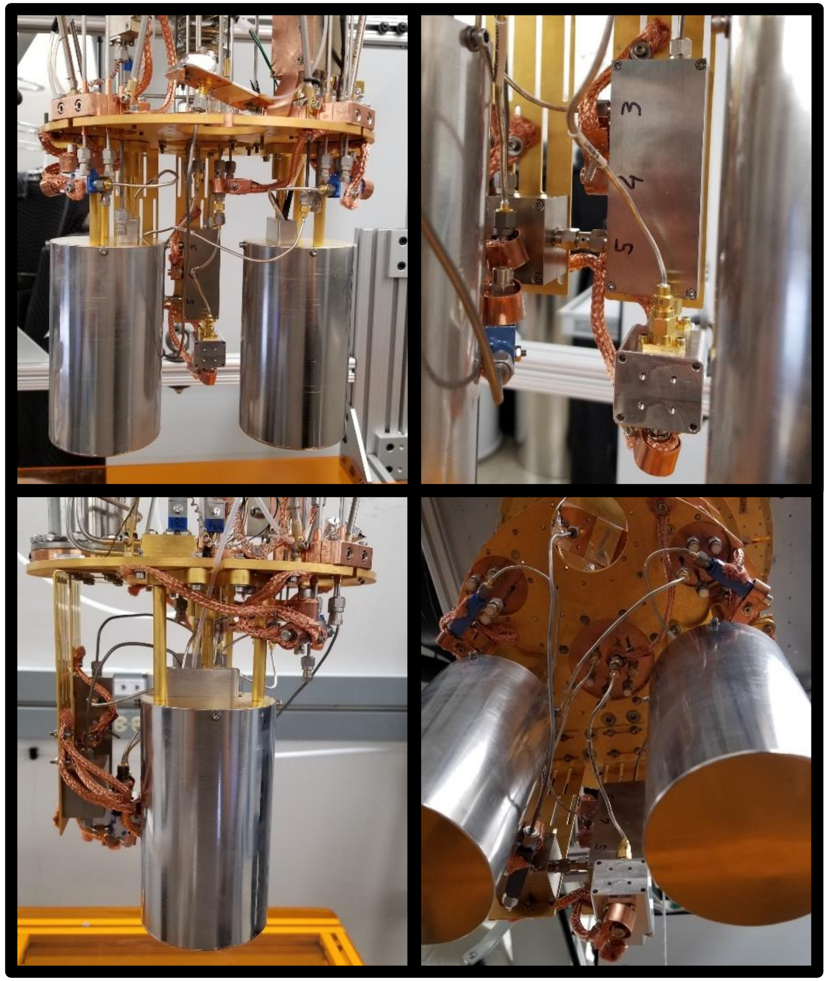
- two JPAs near 9 T magnetic field
- automated JPA tuning with cavity



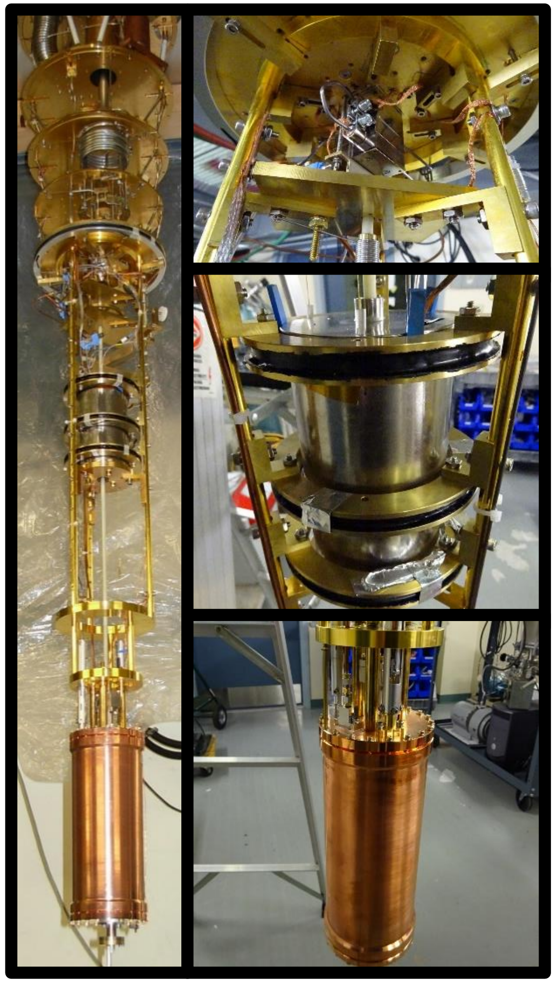


Transfer the squeezed state receiver to Yale

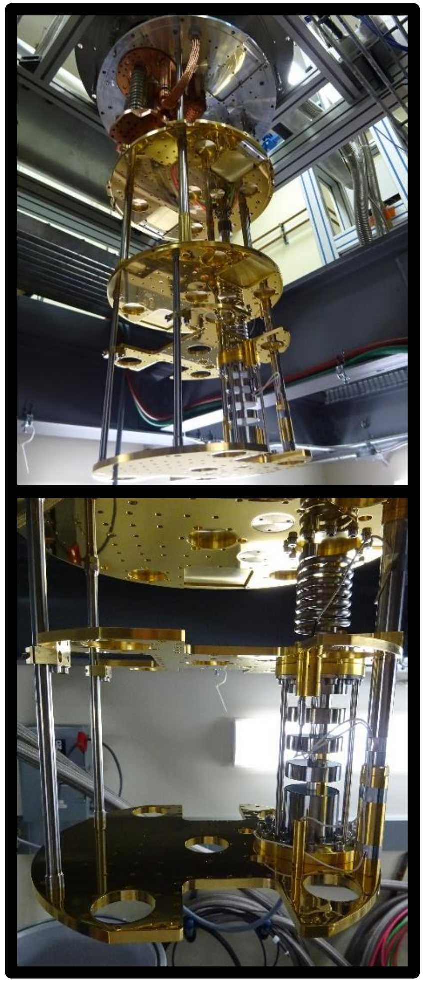
Colorado



Yale (old fridge)



Yale (new fridge)



Operating the SSR receiver in HAYSTAC phase II

acquisition

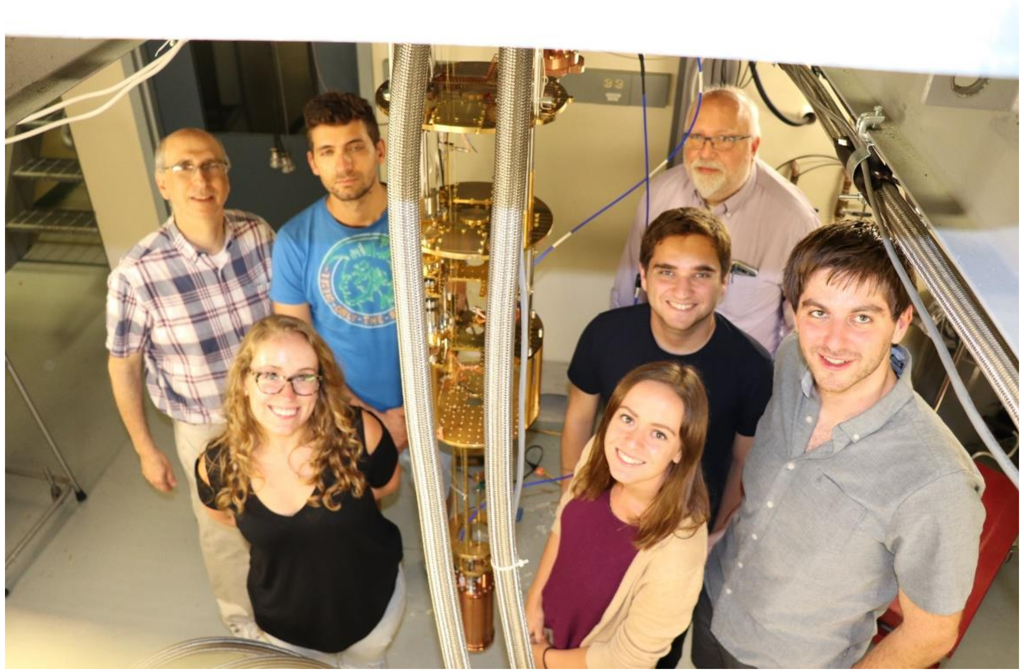
install, calibrate, and operate SSR

processing

near-real-time

analysis

use Bayesian power measured for phase II data



Yale, August 2018. SSR commissioning

Conclusions and acknowledgements

quantum noise in axion search can be overcome

demonstrated: 2.1-fold speed up with squeezing

squeezed state received installed in Haystac phase II

JILA JPAs and axions

Maxime Malnou
Dan Palken
Manuel Castellanos-Beltran
Francois Mallet

Mehmet Anil
Will Kindel
Hsiang-Shen Ku

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