Accelerating Axion Dark Matter Search using Quantum Measurement with HAYSTAC

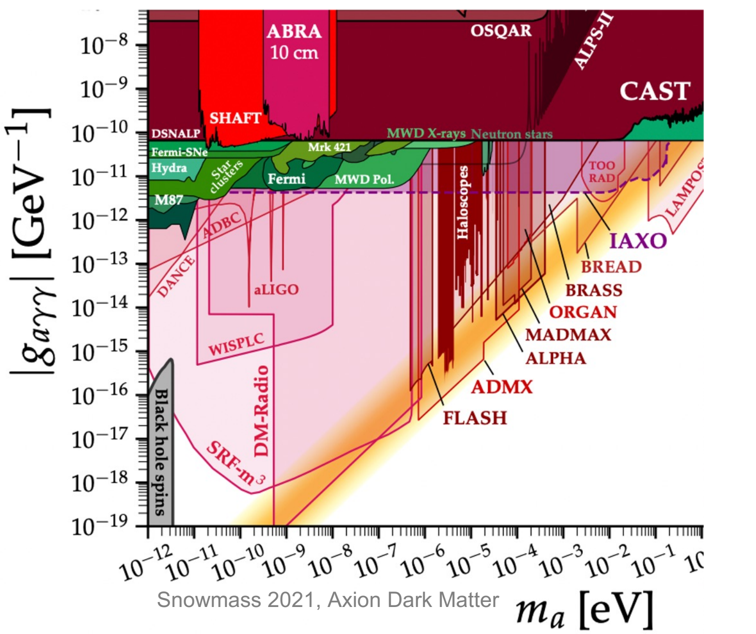
Xiran Bai
Yale University

CPAD, 2023

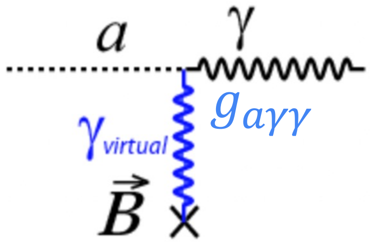
The HAYSTAC Collaboration

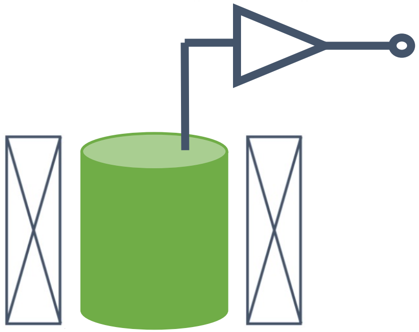
QCD Axions

- Simultaneously provide a solution to the Strong CP problem and account for the dark matter density in the universe.
- Mass and interactions are suppressed by PQ symmetry breaking scale - unknown.
- Search technique: Haloscope by Sikivie
  - Inverse Primakoff effect
  - Magnetic field + Resonant cavity + AMP



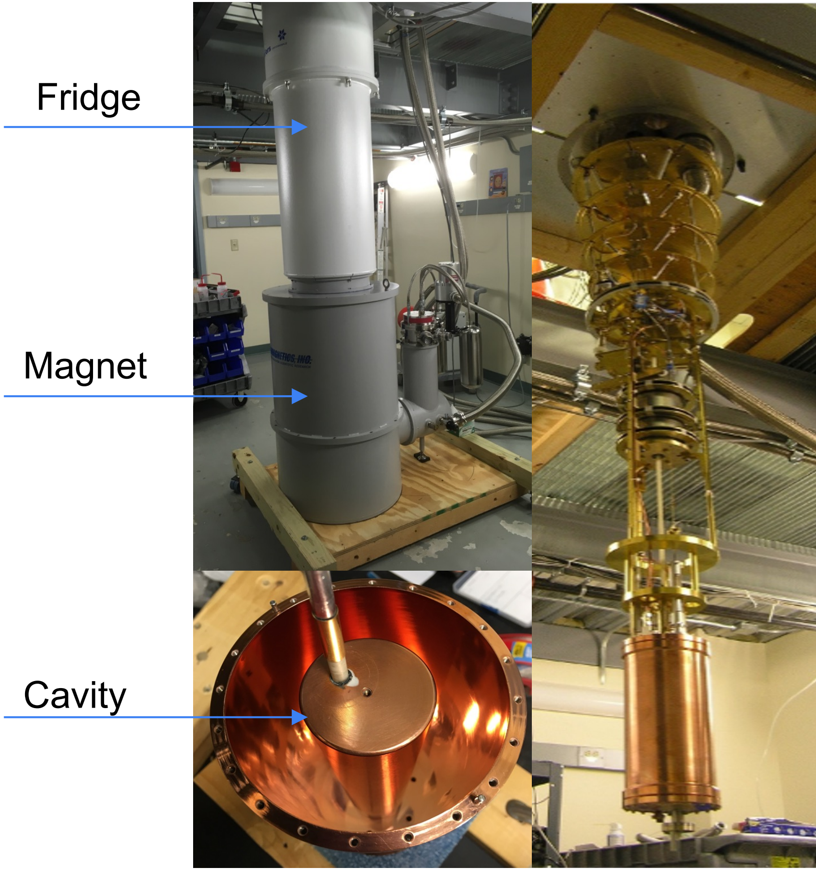
Snowmass 2021, Axion Dark Matter





Haloscope At Yale Sensitive To Axion CDM (HAYSTAC)

- Copper-plated microwave cavity
  - Single asymmetric rod
  - ν_c: 3.6-5.8 GHz
  - V: 1.5 L
  - Q: avg. 45k
- Superconducting solenoid: 8T
- Dilution fridge: 60mK
- Low Noise Amplifiers: JPA+HEMT
- Target post-inflation axions: PQ symmetry breaking occurs after inflation ($m_a > 10\ \mu eV$).

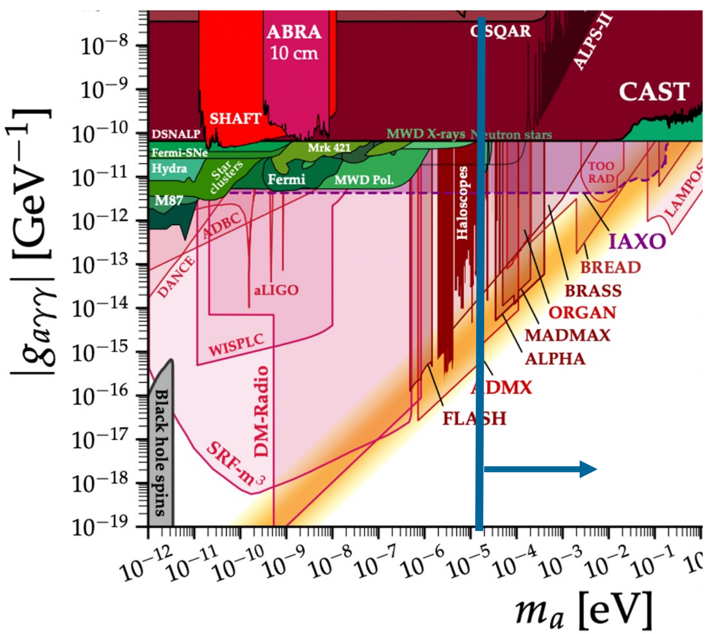


Higher Mass Axion Challenge: Cavity

- Post-inflation axions: $m_a > 10\ \mu eV$
- Cavity dimension shrinks as the frequency goes up.
- Quality factor of also goes down.

$$\frac{dv}{dt} \propto QV^2 \propto v^{-14/3}$$

$$\boxed{\frac{dv}{dt} \propto \frac{B^4 Q V^2}{T_N^2}}$$

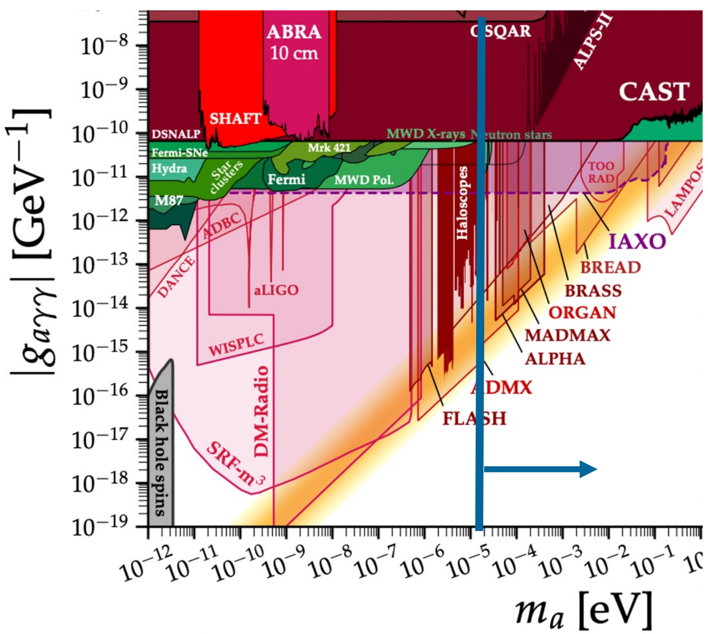


Higher Mass Axion Challenge: Cavity

- Post-inflation axions: $m_a > 10\ \mu eV$
- Cavity dimension shrinks as the frequency goes up.
- Quality factor of also goes down.

$$\frac{d\nu}{dt} \propto QV^2 \propto \nu^{-14/3}$$

$$\frac{d\nu}{dt} \propto \frac{B^4 QV^2}{T_N^2}$$

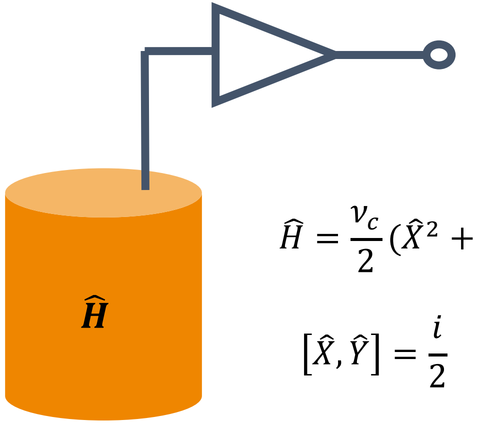


Higher Mass Axion Challenge: Standard Quantum Limit

SQL: lower limit of half a photon to the measurement noise for phase-preserving amplification of narrowband signals.

$$\boldsymbol{N_{sys}} \geq \frac{\mathbf{1}}{\mathbf{2}} + \frac{\mathbf{1}}{\mathbf{2}}$$

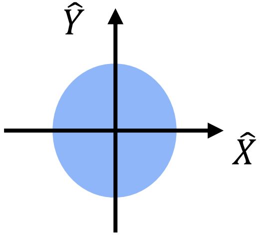
vacuum noise — measurement noise



$$\hat{H} = \frac{\nu_c}{2}(\hat{X}^2 + \hat{Y}^2)$$

$$[\hat{X}, \hat{Y}] = \frac{i}{2}$$

$$\Delta\hat{X}\Delta\hat{Y} > \frac{1}{2}$$

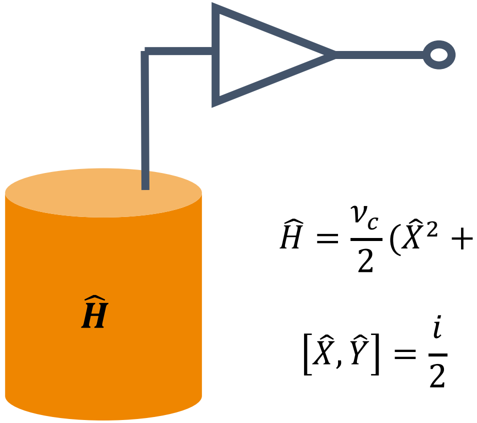


Higher Mass Axion Challenge: Standard Quantum Limit

SQL: lower limit of half a photon to the measurement noise for phase-preserving amplification of narrowband signals.

$$N_{sys} \geq \frac{1}{2} + \frac{1}{2}$$

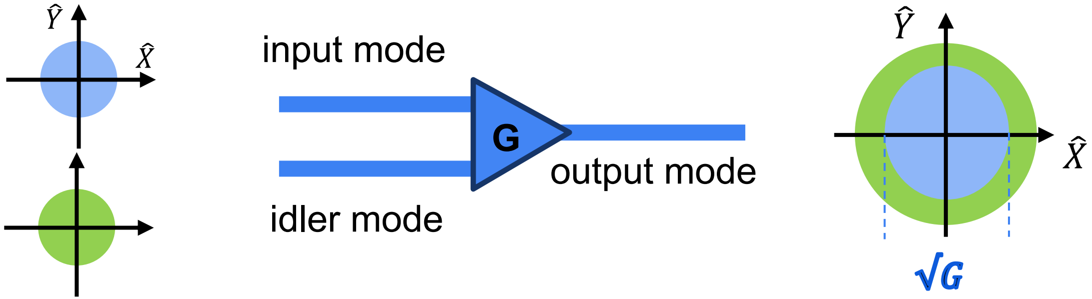
vacuum noise   measurement noise



$$\hat{H} = \frac{\nu_c}{2}(\hat{X}^2 + \hat{Y}^2)$$

$$[\hat{X}, \hat{Y}] = \frac{i}{2}$$

$$\Delta\hat{X}\Delta\hat{Y} > \frac{1}{2}$$



Higher Mass Axion Challenge: Standard Quantum Limit

SQL: lower limit of half a photon to the measurement noise for phase-preserving amplification of narrowband signals.

$$N_{sys} \geq \frac{1}{2} + \frac{1}{2}$$

vacuum noise (first $\frac{1}{2}$) measurement noise (second $\frac{1}{2}$)

$$T_{SQL} = \frac{h\nu}{k_B} \sim 240\, mK \;\; @ \;\; 5\, GHz$$

The system noise will not go down anymore even if the experiment is cooled to 0K.

Higher Mass Axion Challenge: Standard Quantum Limit

SQL: lower limit of half a photon to the measurement noise for phase-preserving amplification of narrowband signals.

$$N_{sys} \geq \frac{1}{2} + \frac{1}{2}$$

vacuum noise

measurement noise

not a fundamental limit

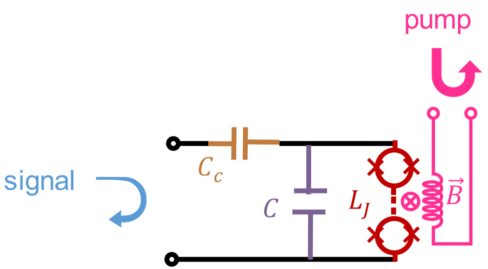
$$T_{SQL} = \frac{h\nu}{k_B} \sim 240\,mK \quad @ \quad 5\,GHz$$

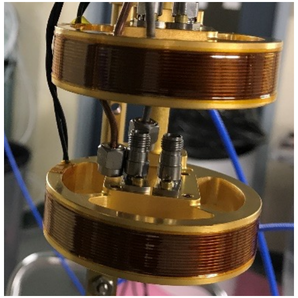
The system noise will not go down anymore even if the experiment is cooled to 0K.

Circumvent SQL: Squeezing

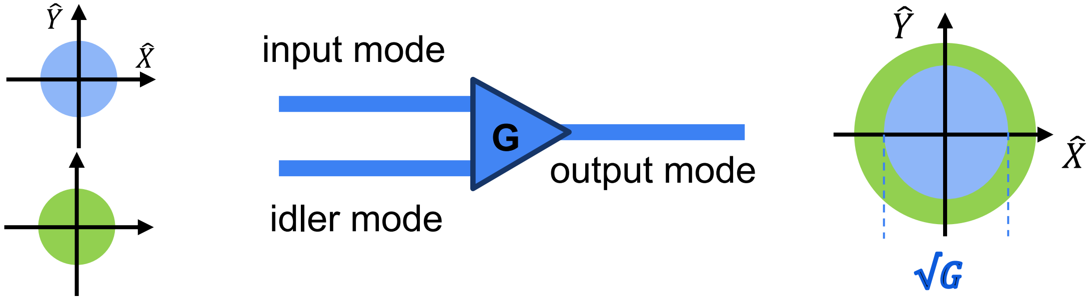
Josephson Parametric Amplifier in HAYSTAC

- Josephson junction: non-linear inductor
- Tunable LC resonator: SQUID (2 JJ) array + Capacitor
- Flux-pumped, frequency modulated at 2 ν_c





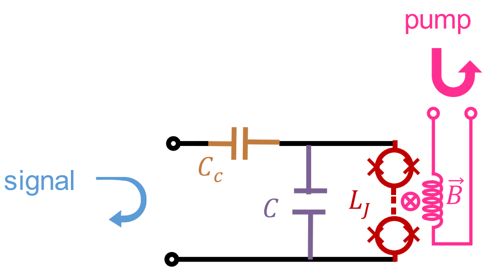
Phase-preserving Mode

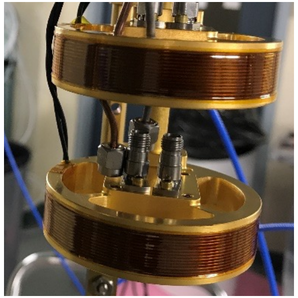


Circumvent SQL: Squeezing

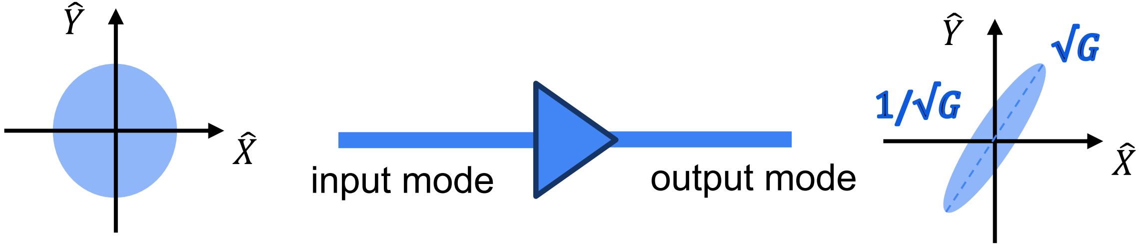
Josephson Parametric Amplifier in HAYSTAC

- Josephson junction: non-linear inductor
- Tunable LC resonator: SQUID (2 JJ) array + Capacitor
- Flux-pumped, frequency modulated at 2 ν_c





<u>Phase-sensitive Mode</u>

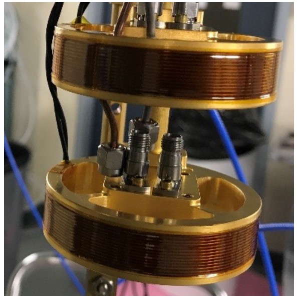


Squeezing

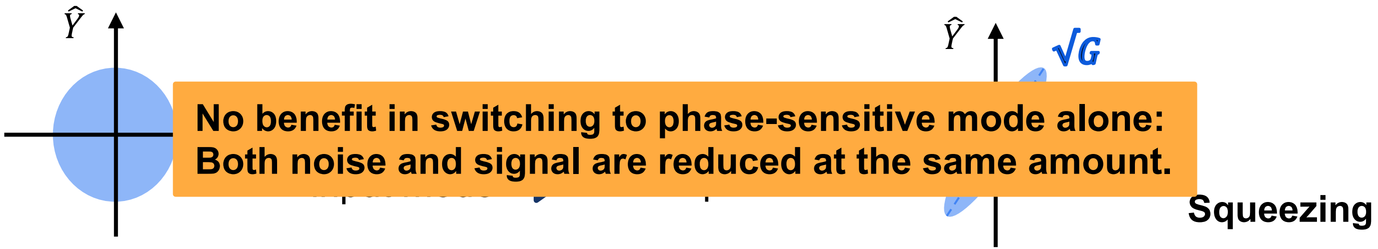
Circumvent SQL: Squeezing

Josephson Parametric Amplifier in HAYSTAC

- Josephson junction: non-linear inductor
- Tunable LC resonator: SQUID (2 JJ) array + Capacitor
- Flux-pumped, frequency modulated at 2 ν_c

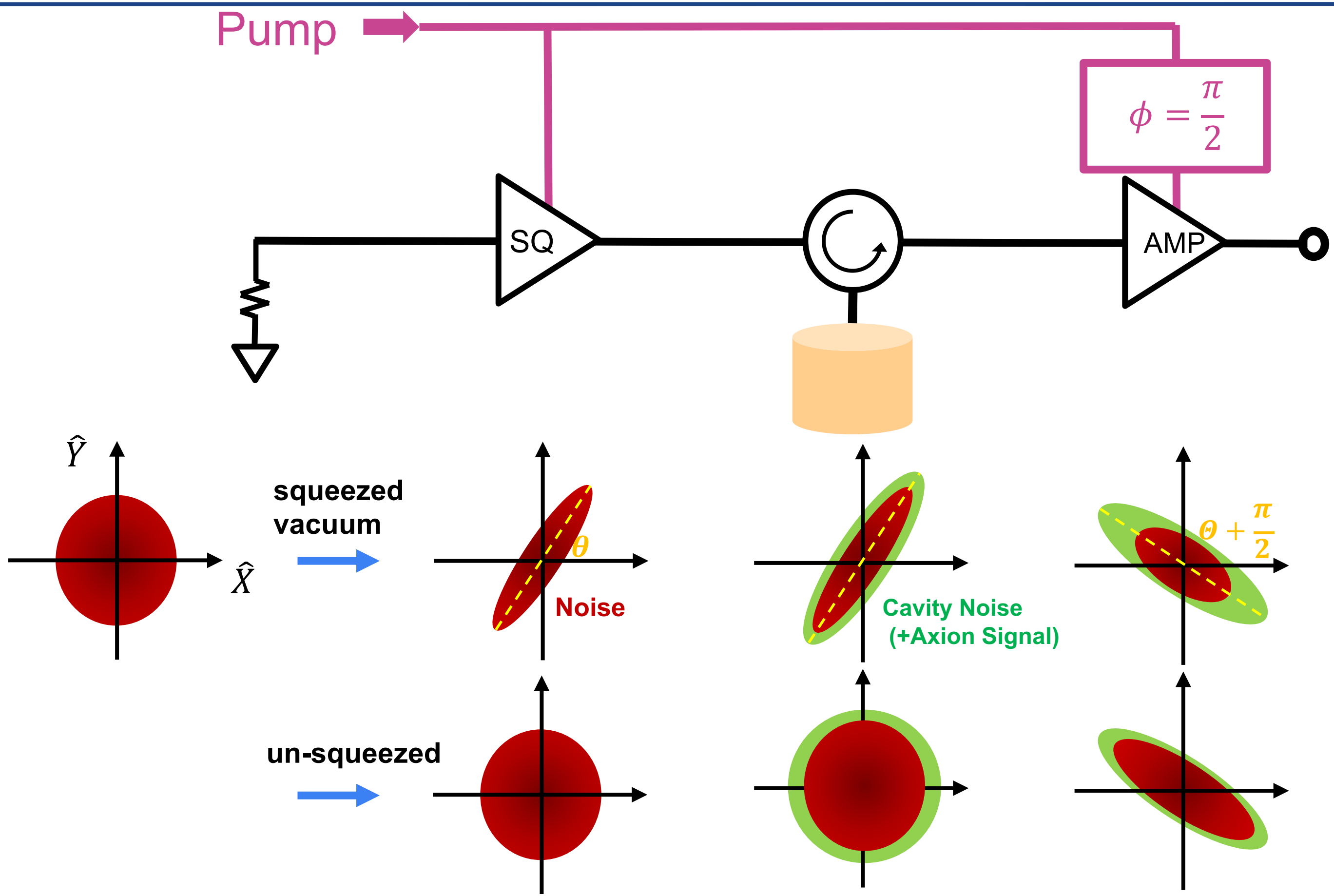


Phase-sensitive Mode

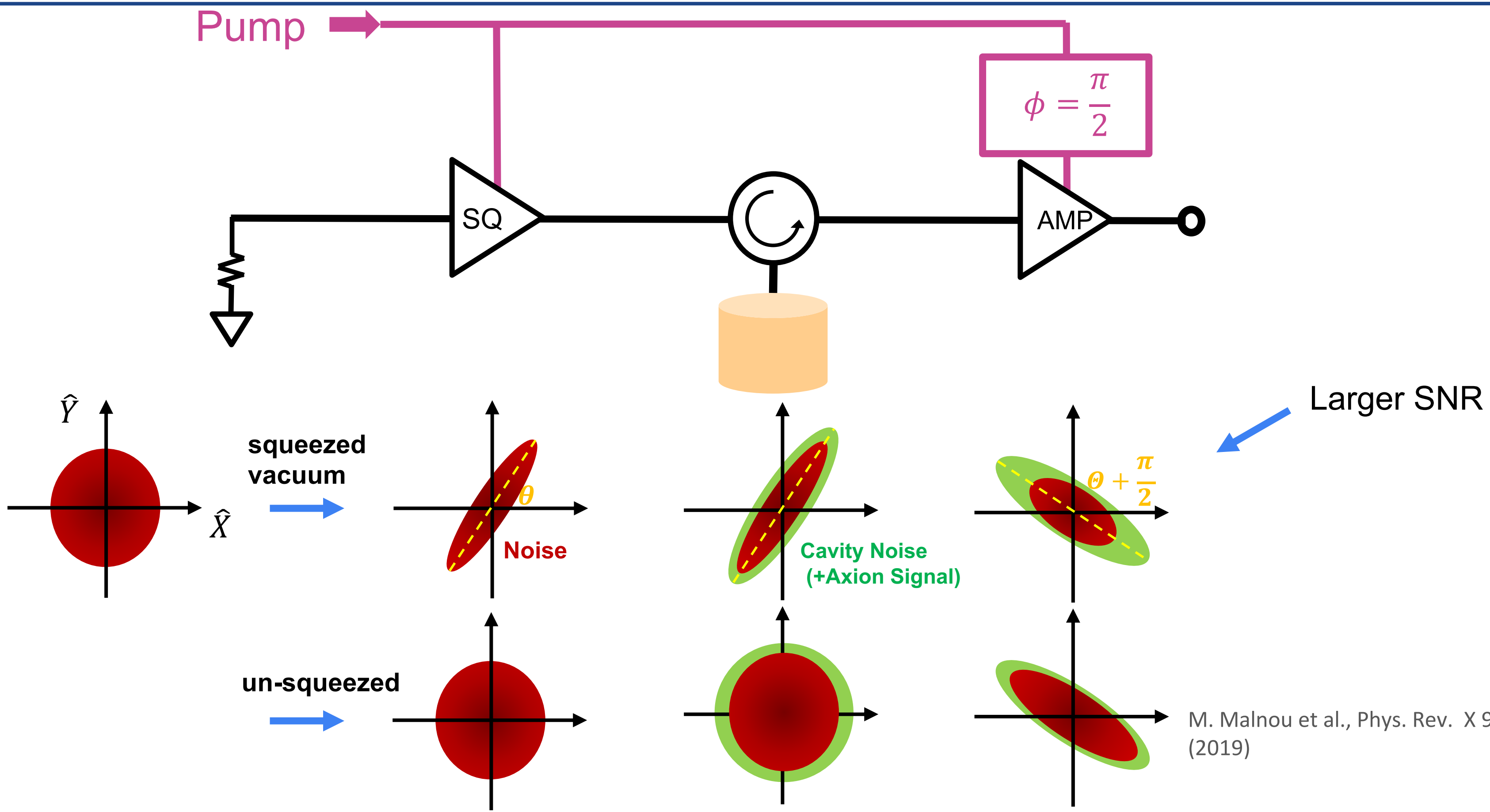


No benefit in switching to phase-sensitive mode alone: Both noise and signal are reduced at the same amount.

Squeezed State Receiver

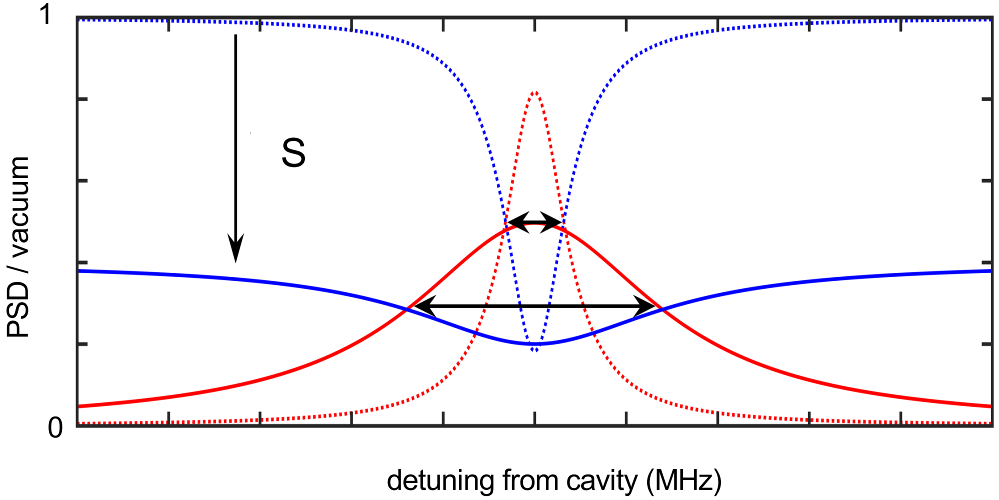


Squeezed State Receiver



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

Scan Rate Enhancement Benefit

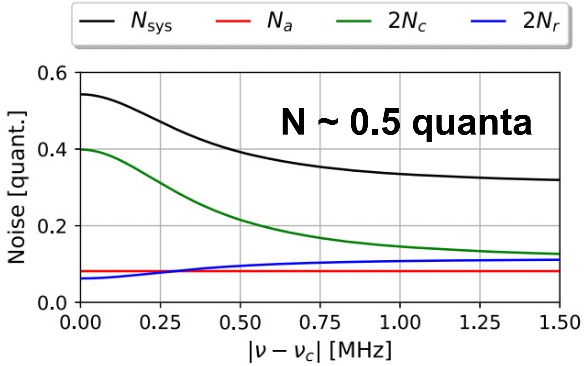


cavity noise
reflected noise
cavity noise
reflected noise

SQ off
2.0× overcoupled

SQ on
7.1× overcoupled

Reflected noise reduction:
S ~ - 4.0 dB



K.M. Backes et al., Nature 590, 2021
Jewell, PhysRevD.107.072007, 2023

2x Speed Enhancement

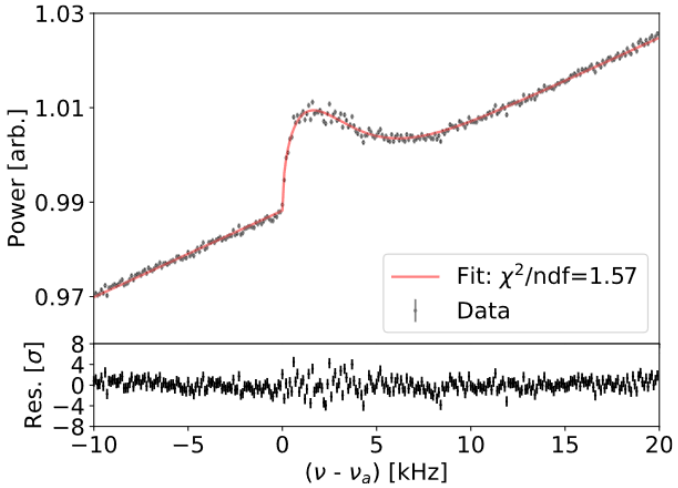
Further Improve the System

- Reduction of data acquisition deadtime by X1.6.

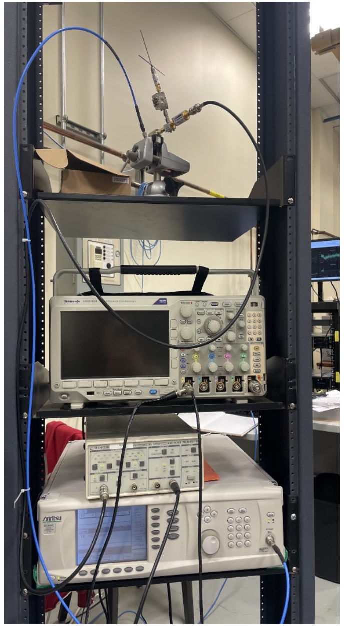
  Jewell, PhysRevD.107.072007, 2023

- Blind signal injection of realistic axion lineshape.

  Zhu, RSI, 10.1063/5.0137870, 2023

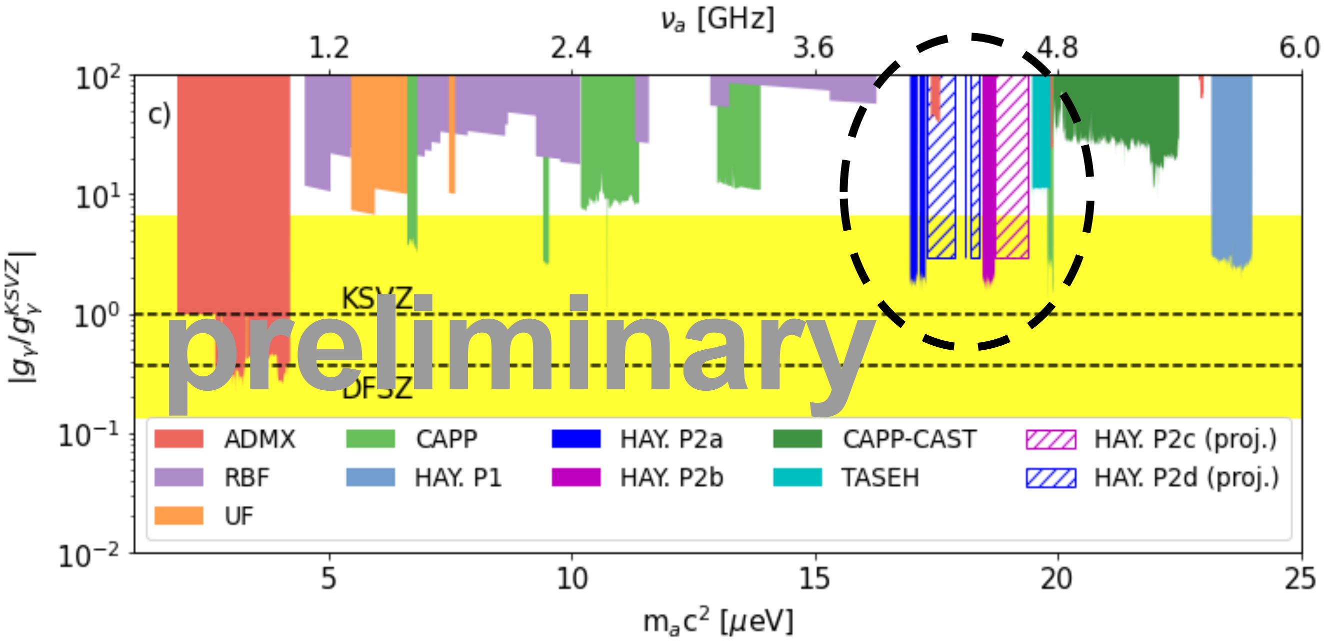


- Improve squeezing optimization stability.
- Ambient RF interferences scanning.



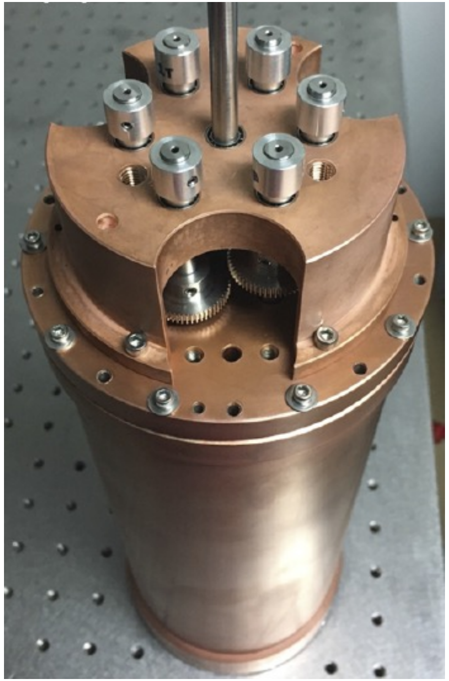
Stable Operation over Large Axion Mass Range

Quantum enhanced axion search is not just a demonstration anymore.
It is able to enter mass production as we are currently close to finish a large dataset → bring the total **sub-quantum limited axion search ~600 MHz in the QCD band.**

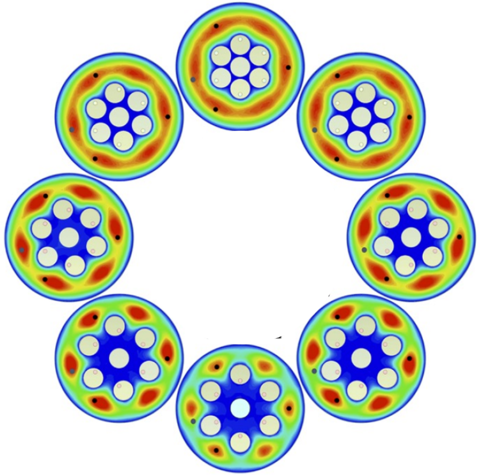


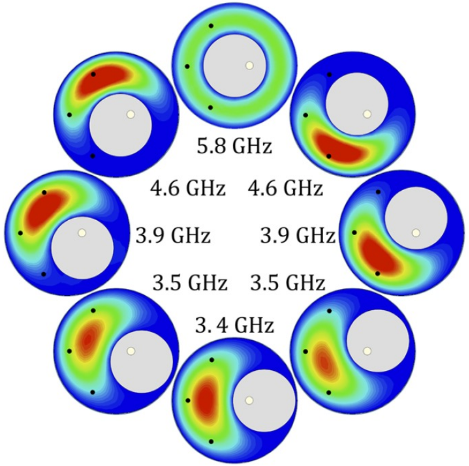
Next Phase: Go to Higher Mass Axions with Multi-rod Cavity

$$\mathrm{FOM} = C^2V^2Q \propto \nu^{-14/3}$$

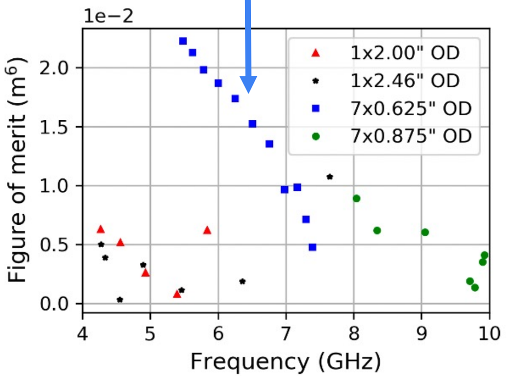


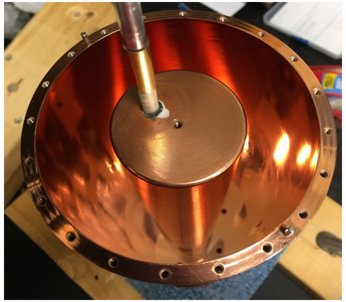
M. Simanovskaia, Rev. Sci. Instrum. 92 (2021) 033305





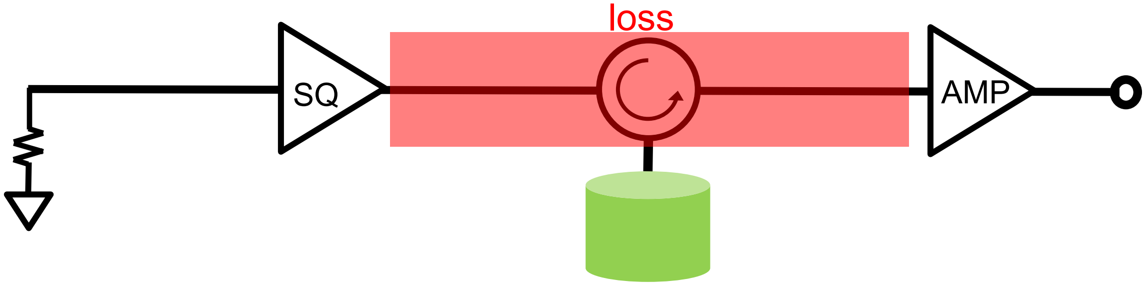
Symmetric features gives higher FOM.





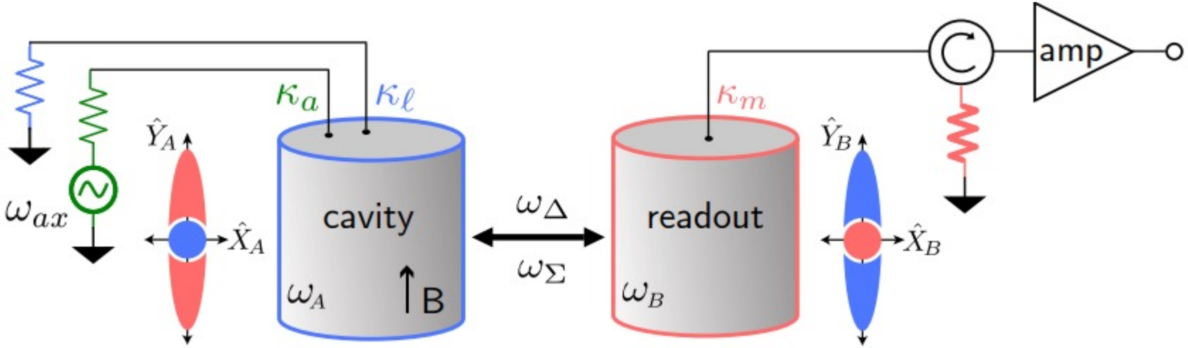
Current Cavity

R&D: Two Mode Squeezing + State Swapping



- Squeezing in the current setup is limited by the **loss between two JPAs**.
- Can be improved by entangle the cavity and readout + state swapping.

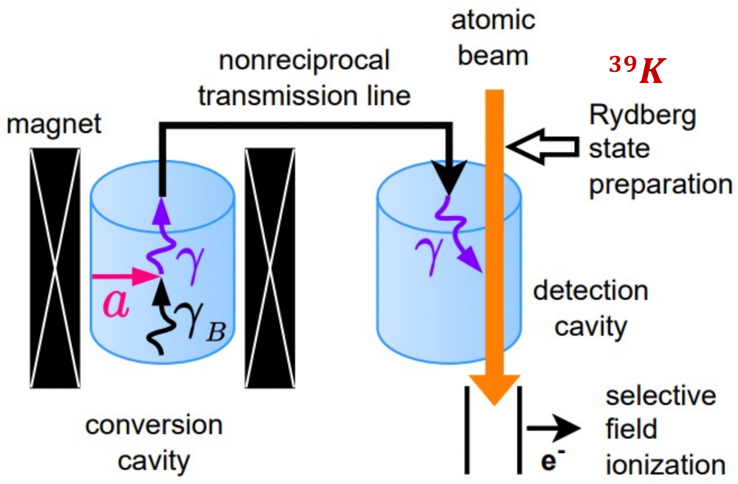
8x Speed Enhancement

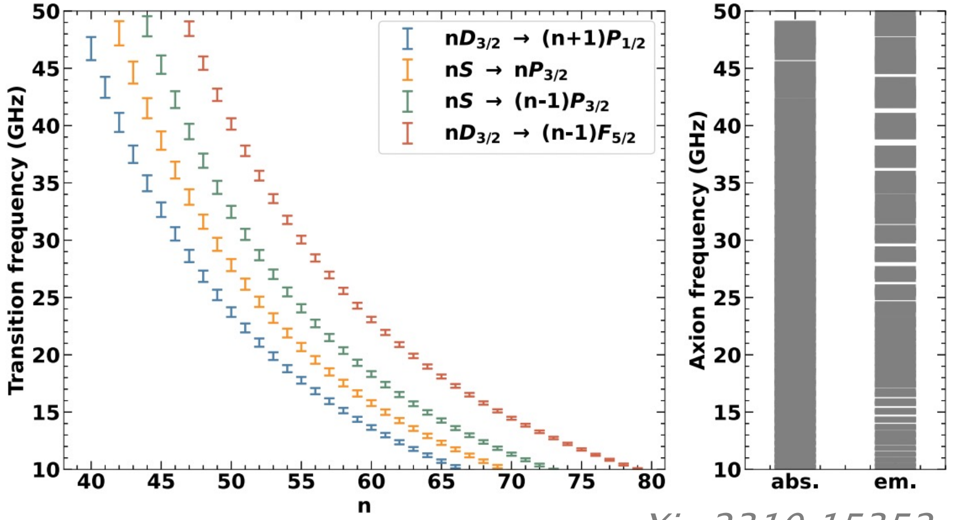


Jiang et al.,10.1103/prxquantum.4.020302

R&D: Rydberg-atom-based Single Photon Detection

- Target QCD axions at even higher mass ($m_a > 40\ \mu eV$; 10 – 50 GHz).
- Photon → Transition between two neighboring Rydberg levels → SFI (Detect the change in the Rydberg levels.)
- Not subject to SQL → Scan rate enhancement up to 10^4.



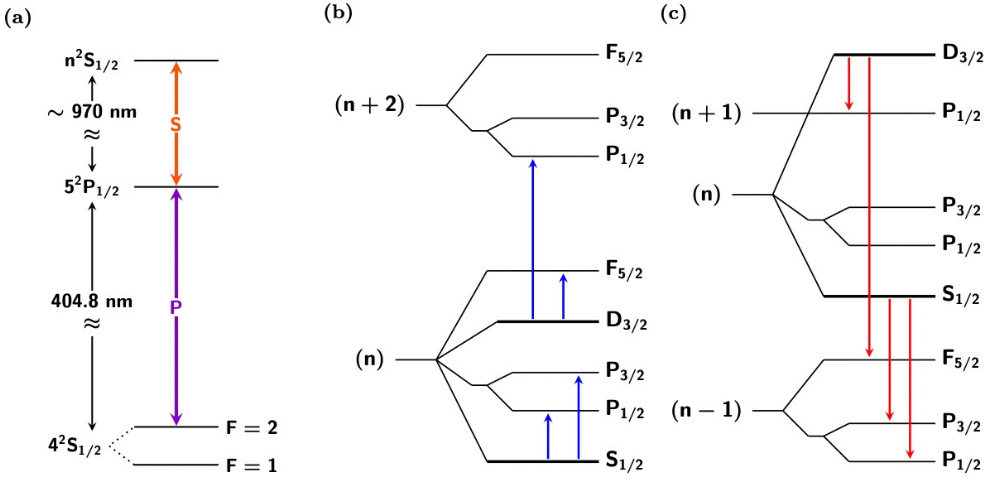


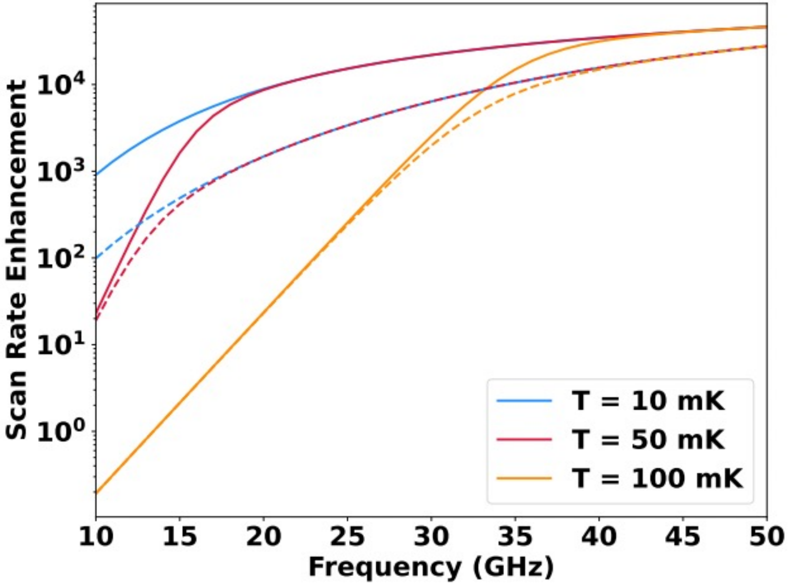
arXiv:2310.15352v1

Summary

- HAYSTAC has demonstrated the use of quantum squeezing in a particle experiment. We have achieved sub-quantum limit and has entered production mode, producing high quality data over a substantial range.
- Will go for higher mass axions and keep pushing for innovations in quantum measurements.

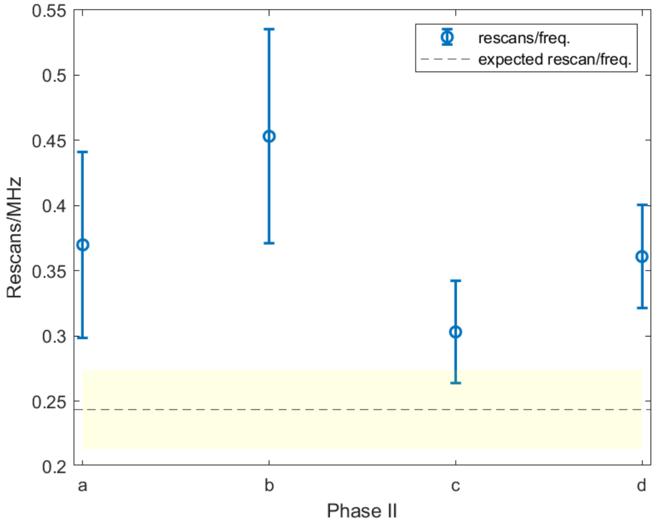
Backups


(a)
$n^2S_{1/2}$
~ 970 nm
S
$5^2P_{1/2}$
404.8 nm
P
$4^2S_{1/2}$
F = 2
F = 1
(b)
(n + 2)
$F_{5/2}$
$P_{3/2}$
$P_{1/2}$
(n)
$F_{5/2}$
$D_{3/2}$
$P_{3/2}$
$P_{1/2}$
$S_{1/2}$
(c)
$D_{3/2}$
(n + 1)
$P_{1/2}$
(n)
$P_{3/2}$
$P_{1/2}$
$S_{1/2}$
(n − 1)
$F_{5/2}$
$P_{3/2}$
$P_{1/2}$


Scan Rate Enhancement
Frequency (GHz)
T = 10 mK
T = 50 mK
T = 100 mK

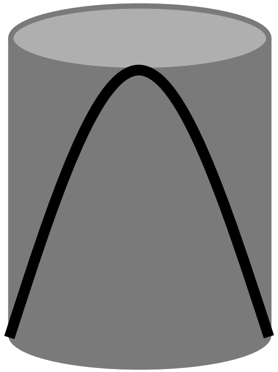
$$\hat{X}(\tilde{\Delta}) = \frac{1}{\sqrt{2}}\left(\hat{a}(\tilde{\Delta}) + \hat{a}^{\dagger}(-\tilde{\Delta})\right)$$

$$\hat{Y}(\tilde{\Delta}) = \frac{1}{\sqrt{2}i}\left(\hat{a}(\tilde{\Delta}) - \hat{a}^{\dagger}(-\tilde{\Delta})\right),$$



$$SNR = \frac{P_a}{k_B T_N}\sqrt{\frac{\tau}{\Delta v}}$$

Scan rate: $R \propto \int \mathrm{SNR}(f)^2$

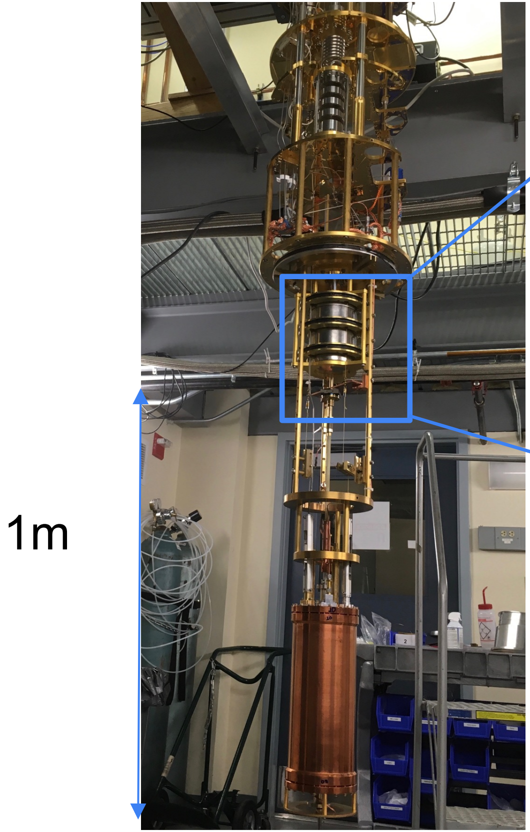


$$V \propto L v^{-2}$$

$$Q \propto v^{-2/3}$$

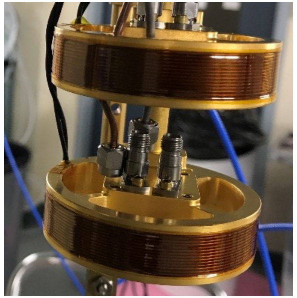
$$\frac{dv}{dt} \propto QV^2 \propto v^{-14/3}$$

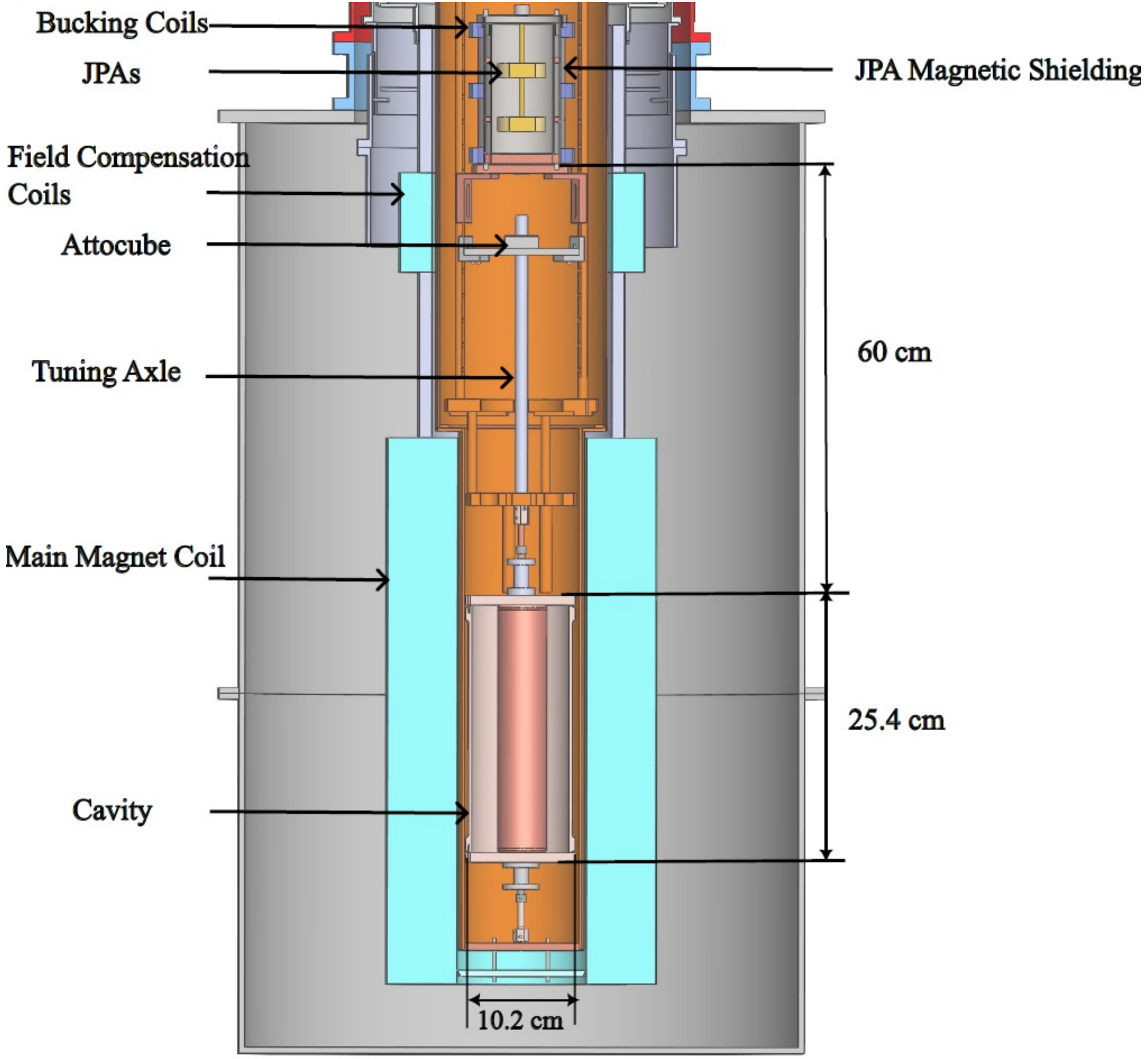
Magnetic Shielding



JPA housing

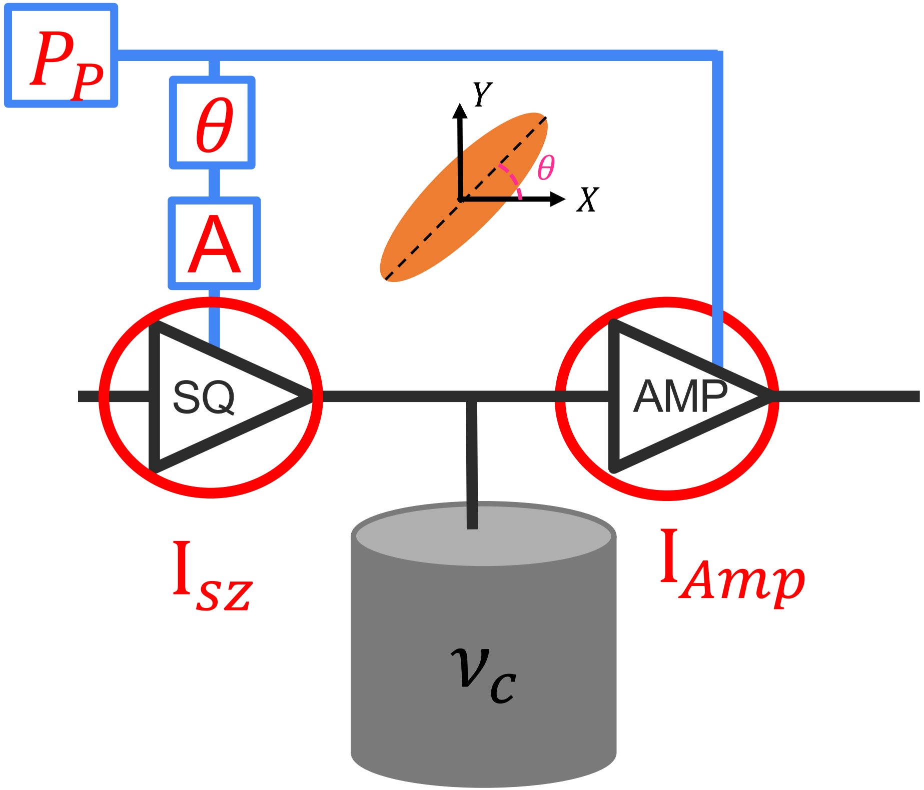
- 3-layer shield: A4K-Al-A4K
- Superconducting bucking coils



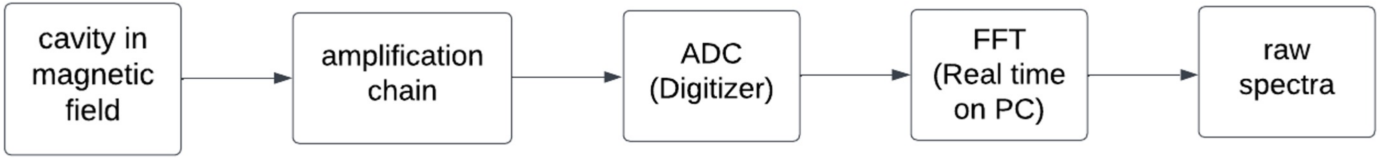

Bucking Coils
JPAs
JPA Magnetic Shielding
Field Compensation Coils
Attocube
Tuning Axle
60 cm
Main Magnet Coil
25.4 cm
Cavity
10.2 cm

SSR Tuning

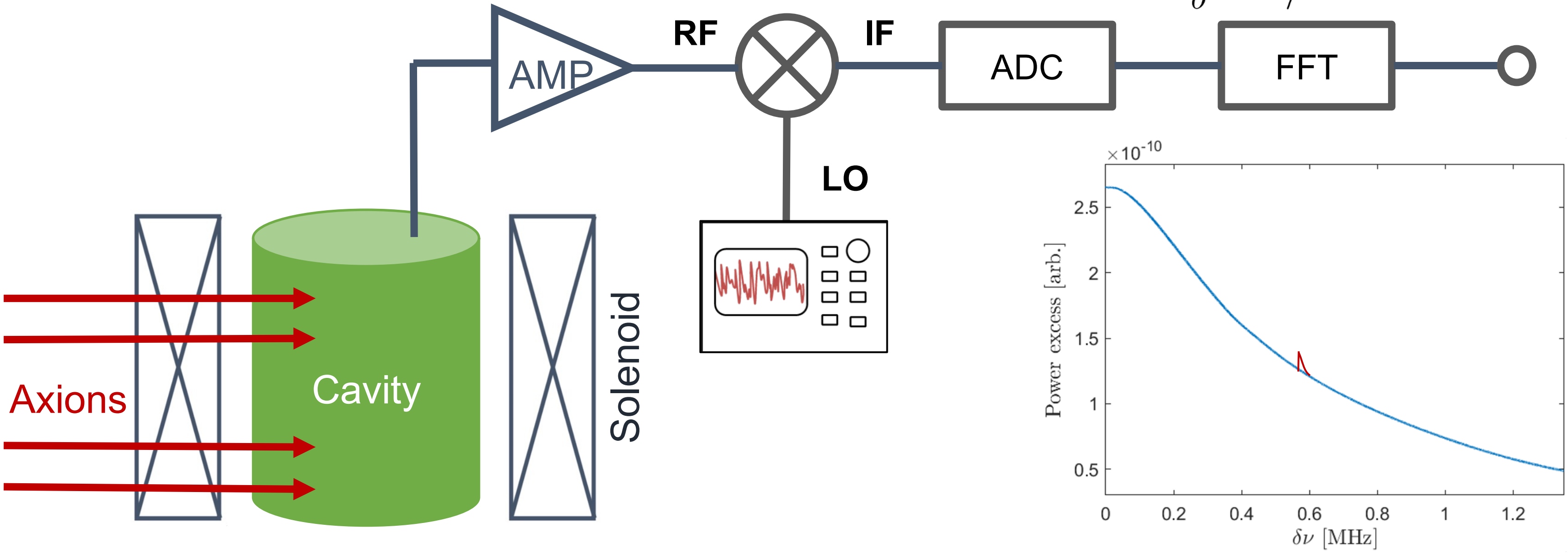
- Five parameter optimization
- JPAs tuned to match Cavity Resonance
  - I_{SZ}: Squeezer Flux Bias
  - I_{AMP}: Amplifier Flux Bias
- Amplifiers share same Pump Source
  - P_P: Amplifier Gain
  - A: Squeezer Gain
  - θ: Phase difference



Data Acquisition: Get the raw spectra



$$\Delta\nu_b = 1/10\text{ms} = 100\text{Hz}$$

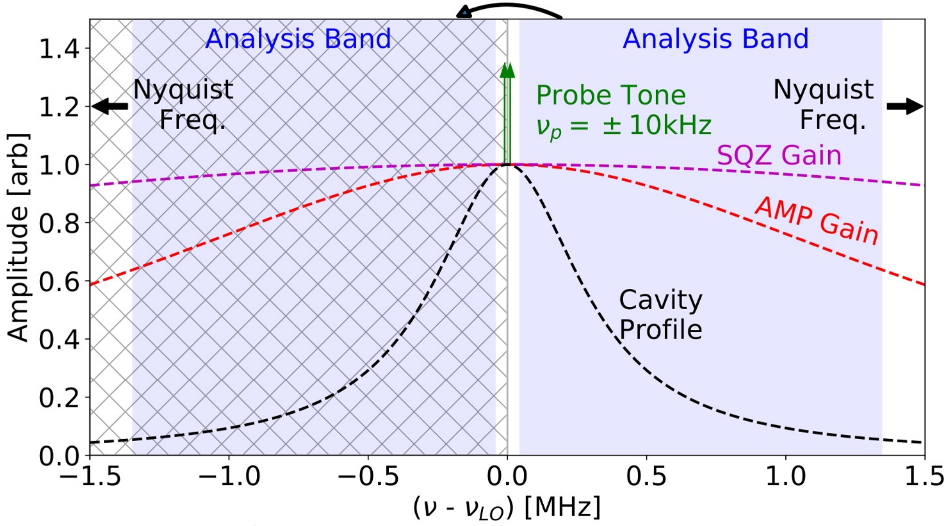


Data Acquisition: Get the raw spectra

Shape of the raw spectra:

cavity (Lorentzian) + amplifiers (JPAs + HEMT) + bandpass filters

probe tune: measure gain of the amplifiers



M. Jewell, et al. doi:10.1103/PhysRevD.107.072007