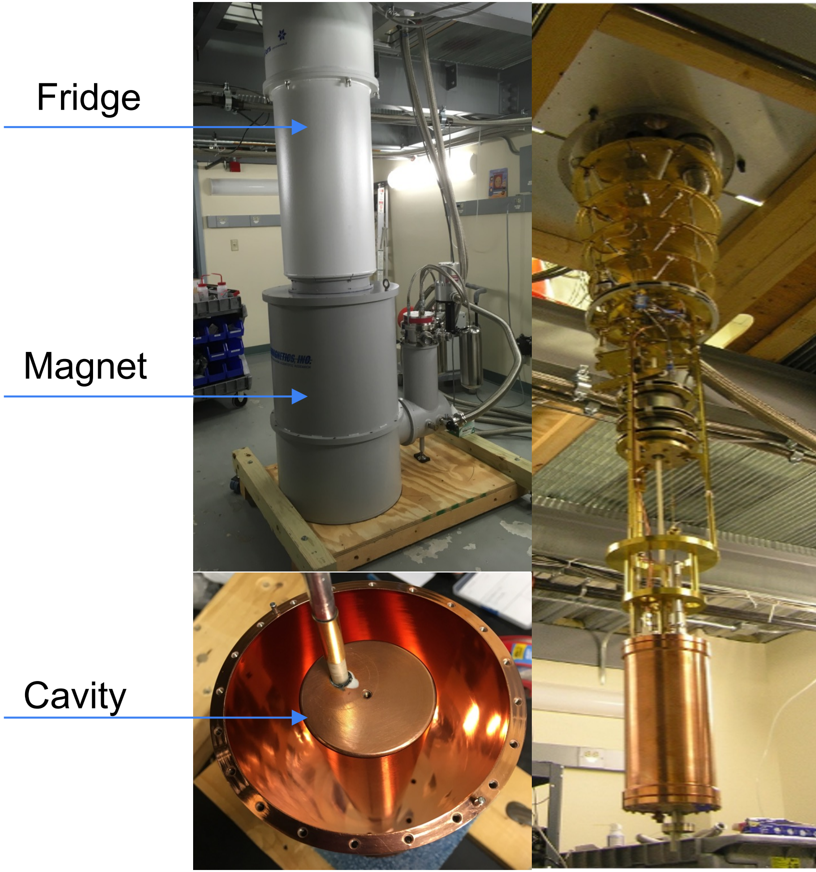
# New Axion Search Results from HAYSTAC Phase II

Xiran Bai
on behalf of HAYSTAC collaboration
Yale University

Patras, Sept. 2024

# Haloscope At Yale Sensitive To Axion CDM (HAYSTAC)

- A haloscope experiment searching for QCD axions at higher masses ($m_a > 15\ \mu eV$).
- Located in the Wright lab at Yale University
- Copper-plated microwave cavity
  - Single asymmetric rod
  - $\nu_c$: 3.6 - 5.8 GHz (15 – 24 $\mu eV$)
  - V: 1.5 L
  - Q:  avg. 45000
- Superconducting solenoid: 8 T
- Dilution fridge: 60 mK
- Low Noise Amplifiers: 2 JPAs+HEMT

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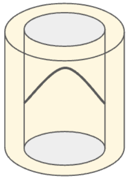
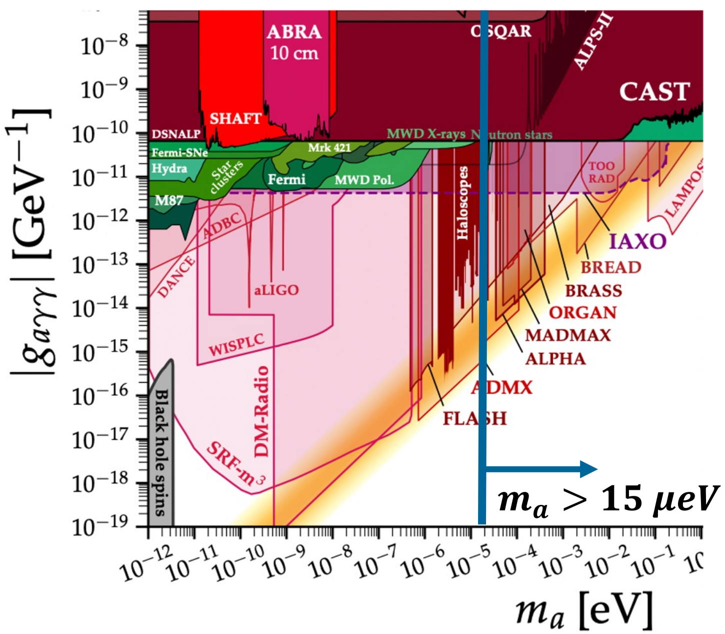
# Higher Mass Axion Challenge

- Cavity dimension shrinks as the frequency goes up.
- Quality factor also goes down.
- Our strategy: reduce system noise.

$$\frac{d\nu}{dt} \propto \frac{B^4 V^2 C_{mnl}^2 Q_0}{T_N^2} \propto \nu^{-14/3}$$



$\rho \propto \lambda^{-1}$



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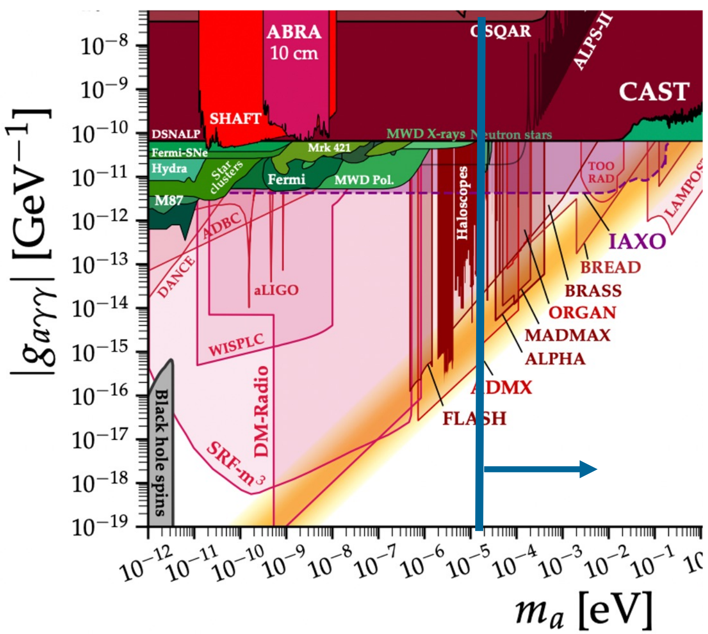
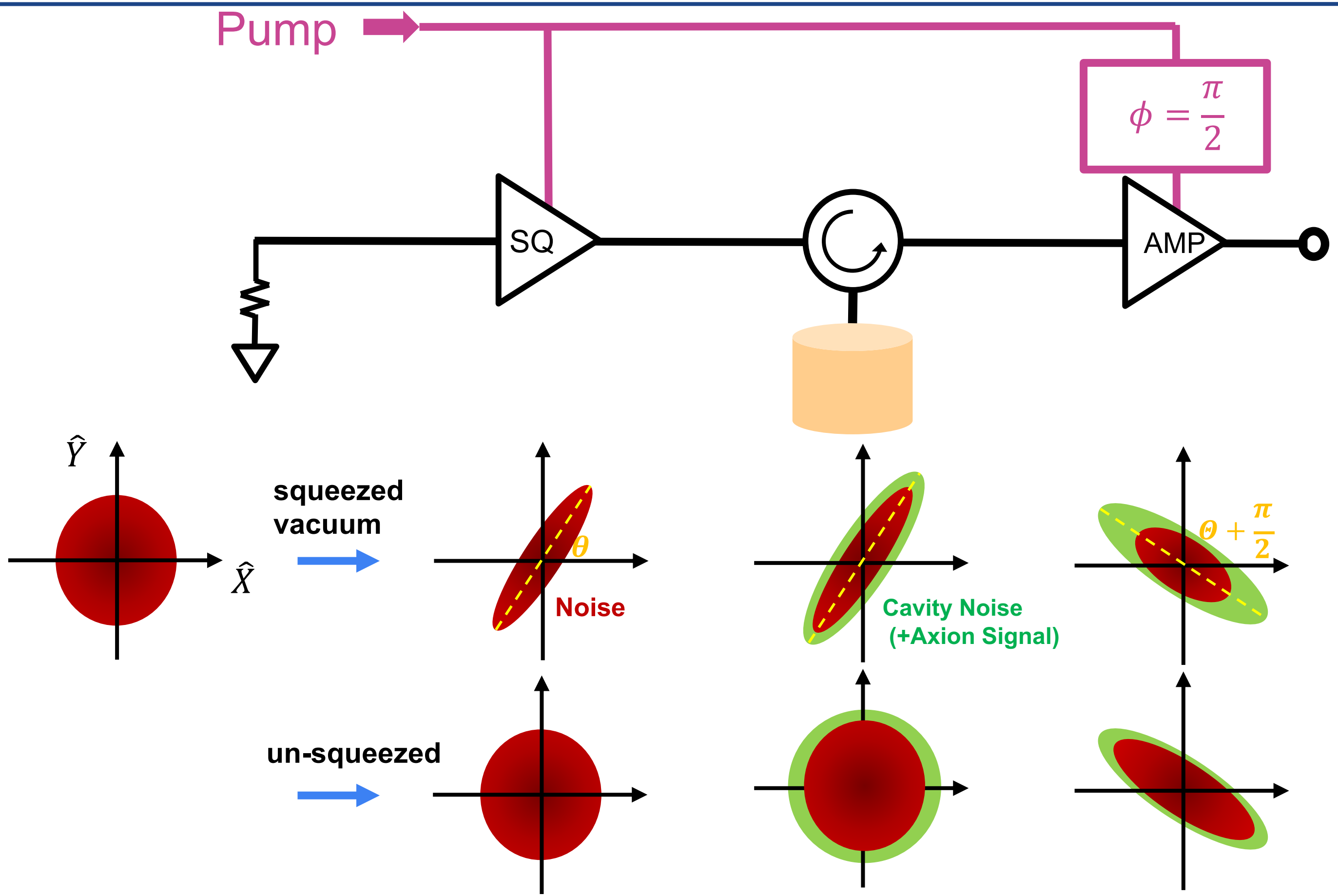


# Squeezed State Receiver (SSR)

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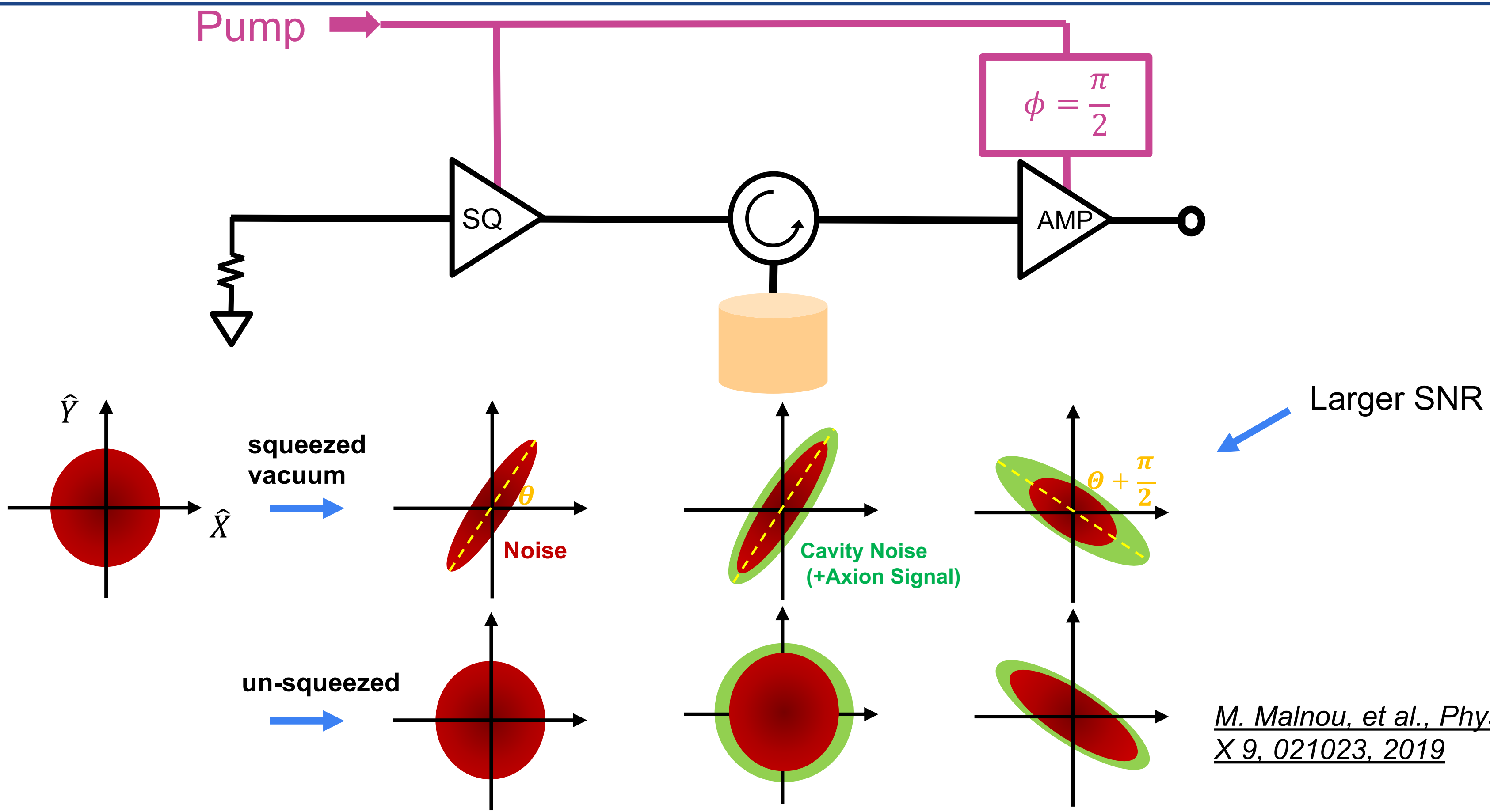


*M. Malnou, et al., Phys. Rev. X 9, 021023, 2019*

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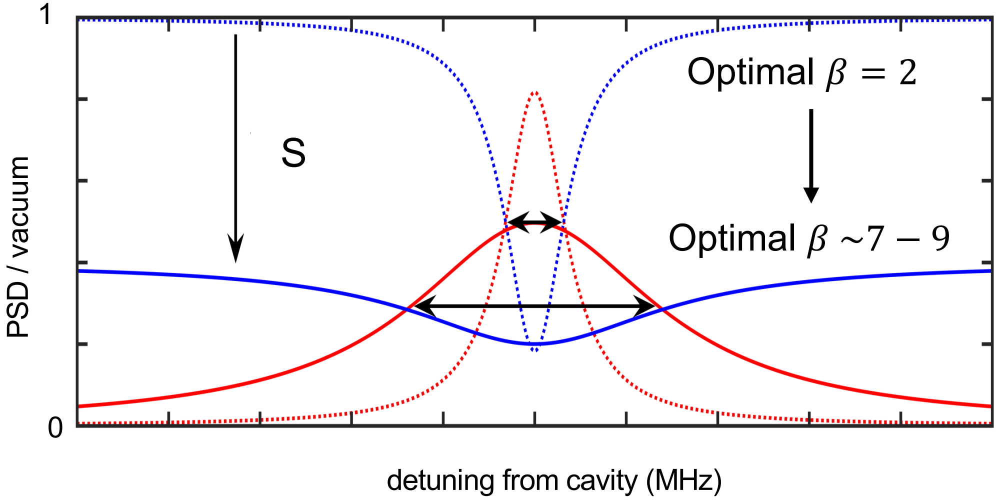
# Scan Rate Enhancement Benefit




cavity noise
reflected noise

SQ off
$2.0\times$ overcoupled

cavity noise
reflected noise

SQ on
$7.1\times$ overcoupled

**Reflected noise reduction:**
S ~ - 4.0 dB

**<u>up to 2x Speed Enhancement</u>**

*K. Backes, et al., Nature 590, 2021*

*M. Jewell, et al, PhysRevD.107.072007, 2023*

# HAYSTAC Timeline

- HAYSTAC Sub-QL search using SSR (Phase II - abcd).
- Just finished phase II, phase III in preparation.

| Name | | Amplifier | Dates | Freq. Range [GHz] | Publication |
|---|---|---|---|---|---|
| Phase I | | Phase Preserving | Jan. 2016 – Jan. 2017 | 5.6 – 5.8 | PhysRevD.97 (2018) |
| Phase II | a | Phase Sensitive | Sept. 2019 – April 2020 | 4.100 - 4.140<br>4.145 - 4.178 | Nature 590 (2021) |
| | b | | July 2021 – Nov. 2021 | 4.459 - 4.523 | PhysRevD.107.072007 (2023) |
| | c | | July 2022 – Mar. 2023 | 4.523 – 4.707 | arXiv:2409.08998 |
| | d | | June 2023 – **Aug. 2024** | 4.178 - 4.328<br>4.372 - 4.385<br>4.395 - 4.462 | |
| Phase III | | Phase Sensitive | Commission ~Jan. 2025 | Expected 6.3-8.5 | - |

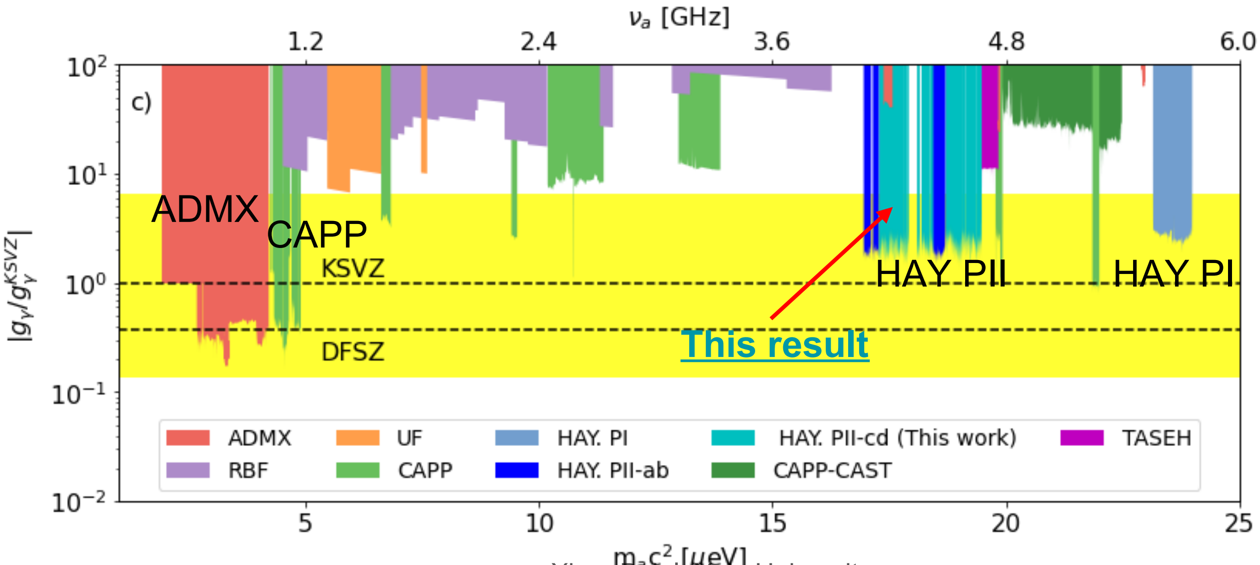
# Stable Operation of SSR over Wide Axion Mass Range

**New results** placed exclusion limit in the following regions:

Phase IId: 17.28 - 18.44 $\mu eV, |g_\gamma| > 2.75\ |g_{\mathrm{ksvz}}|$

Phase IIc: 18.71 - 19.46 $\mu eV,\ |g_\gamma| > 2.96\ |g_{\mathrm{ksvz}}|$

This result is the largest result HAYSTAC has ever released. It covered a total of **413 MHz** and it brings the total **sub-quantum limited axion search to 550 MHz.**

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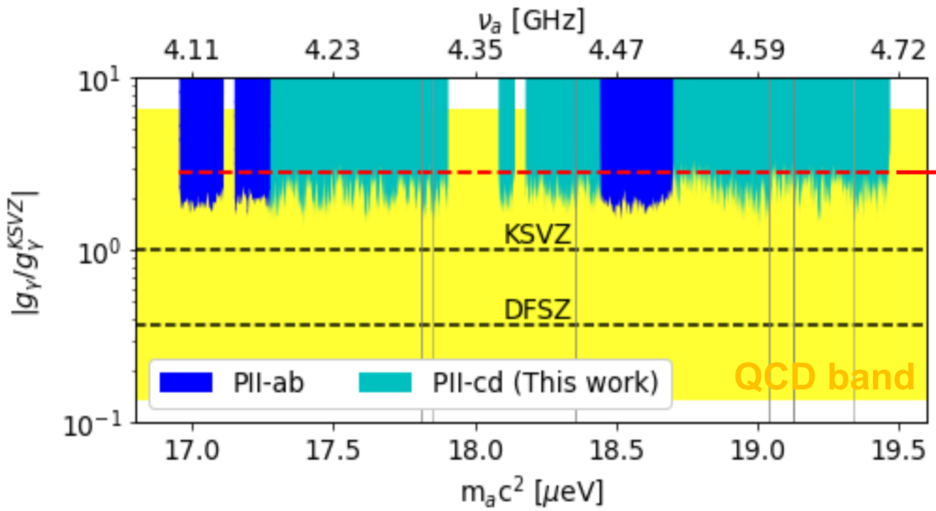


Aggregate exclusion at 90% c.l. of $|g_\gamma| > 2.86\ |g_{\mathrm{ksvz}}|$ over the entire Phase II range.

arXiv:2409.08998

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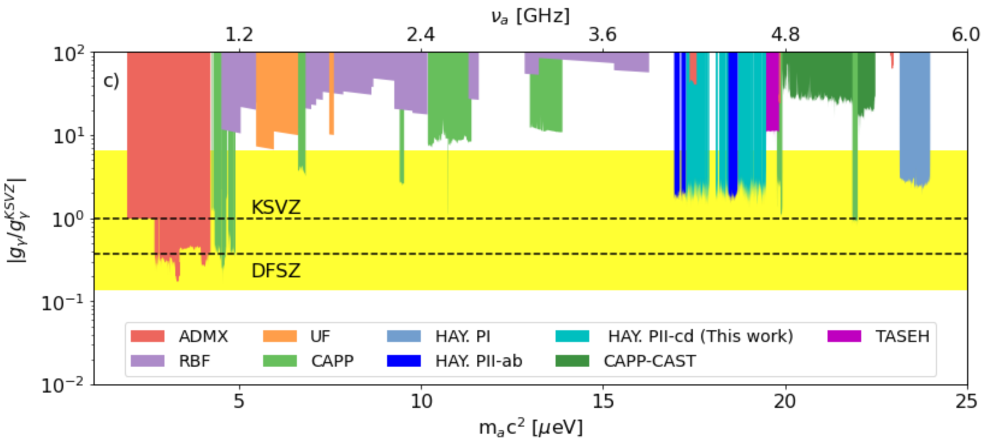
# Phase IIc+d New Results Summary

| PII | Op. days | $\Delta$ f. [MHz] | Sensitivity $\lvert g_\gamma / g_{ksvz} \rvert$ | Scan rate $[\frac{MHz}{day * g_{ksvz}}]$ | Rescans Cand. | SI | RFI | RF Def. |
|---|---|---|---|---|---|---|---|---|
| c | 72 | 188 | 3.04 | 0.030 | 98 | 3 | 7 | 8 |
| d | 111 | 237 | 3.06 | 0.024 | 120 | 3 | 5 | 16 |




On average x1.7
scan rate enhancement over
QL-search

Average added noise from amplification chain (single quadrature) : 0.08 photon

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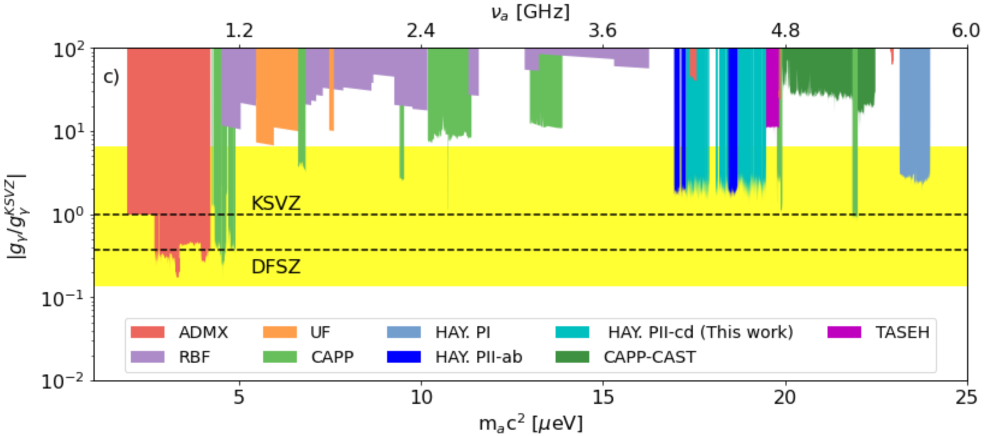


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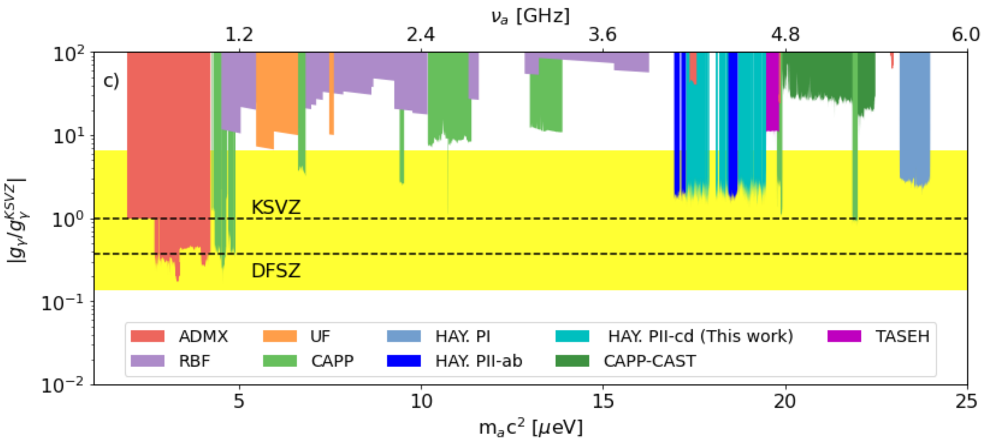


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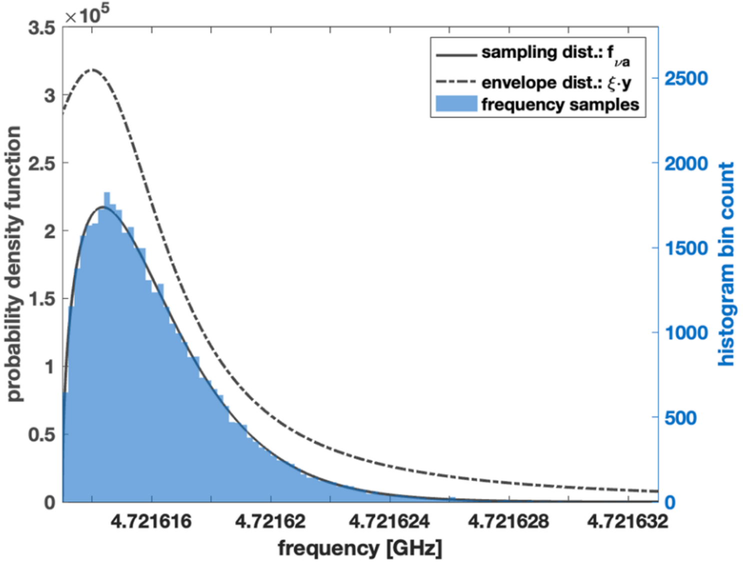
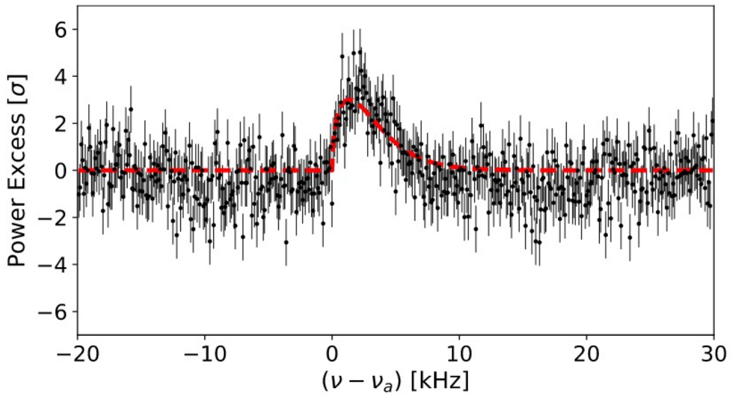
# Hardware Axion Signal Injection (SI)

- Synthetic axion signals are generated through a signal generator using frequency hopping technique with expected axion lineshape (Maxwell-Bolzmann Distribution).



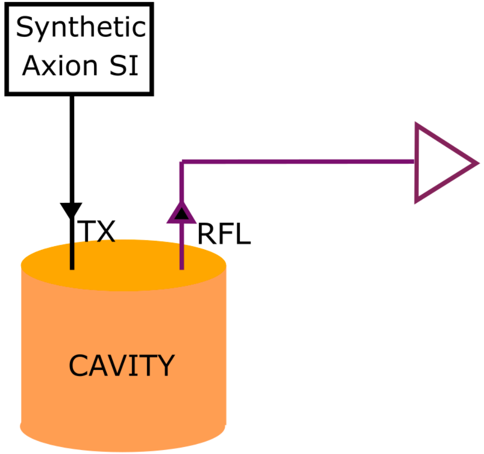

Synthetic Axion after pass through the cavity/receiver chain (post-processing)




*Y. Zhu, et. al, RSI, 10.1063/5.0137870, 2023*

# Hardware Signal Injection

- Synthetic axion signals are generated through a signal generator using frequency hopping technique with expected axion lineshape (Maxwell-Bolzmann Distribution).
- The signal passes through the cavity via the tx port and then goes through the receiver-chain to validate the detector response.

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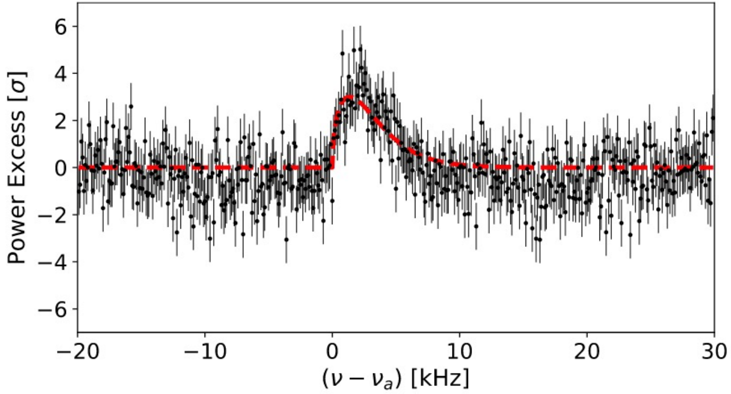
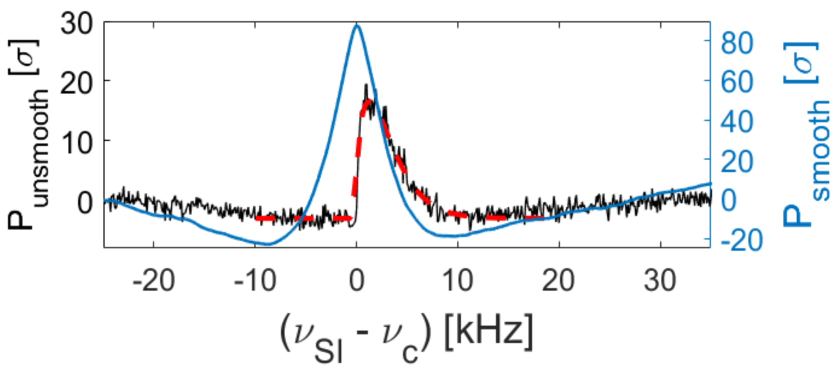


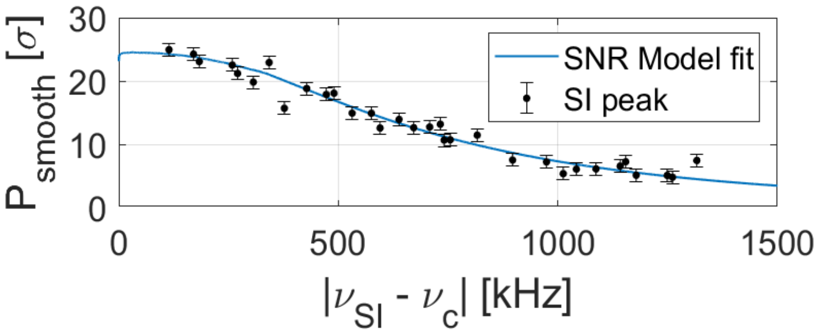

Y. Zhu, et. al, RSI, 10.1063/5.0137870, 2023

# Hardware Signal Injection

- Injected 6 in total in this new dataset.
- We are able to recover the all 6 injected signals at the correct frequency with the correct shape.
- Verify that the signal power vs. cavity detuning matches with our S/N model.

An injection during Phase IId at 4.459220 GHz



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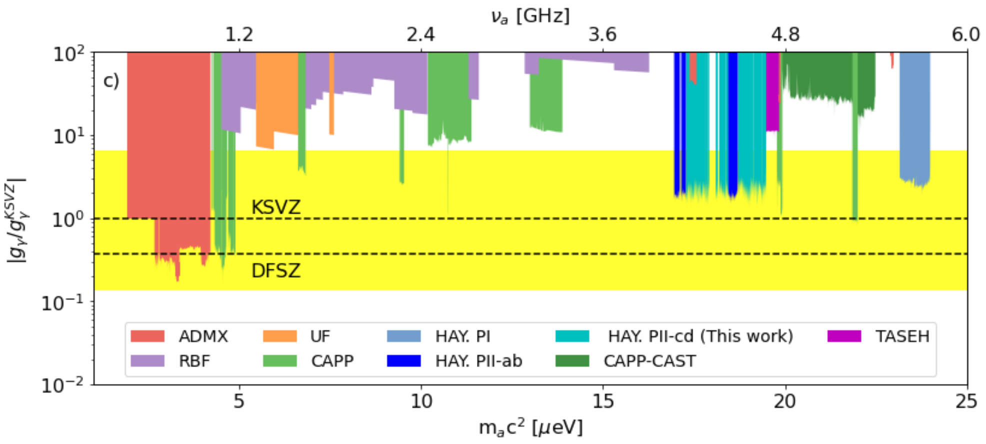


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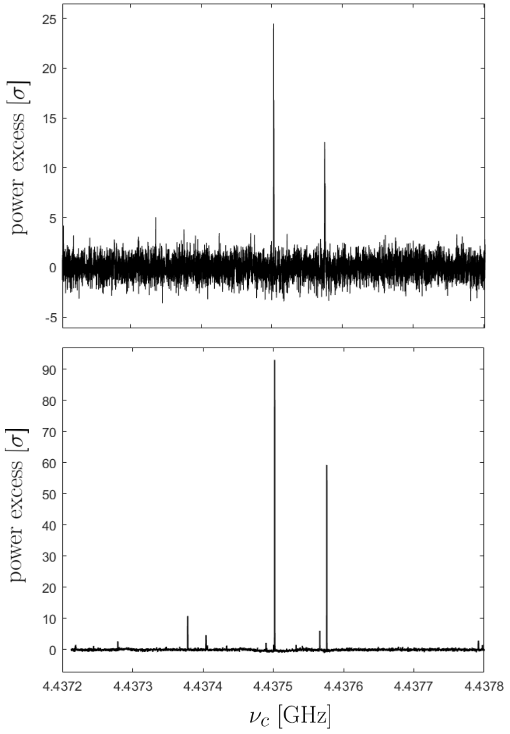
# Ambient RF Detector

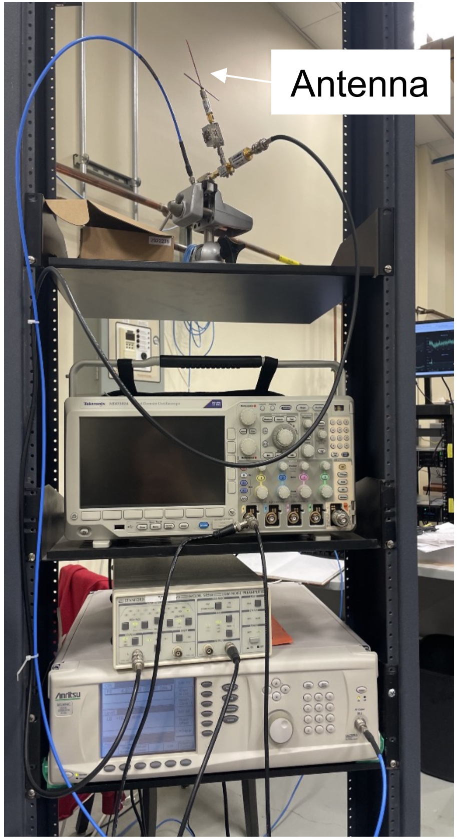
HAYSTAC is operating in a popular communication band (4-5 GHz).

Veto power excesses from the environment.

Candidates from real data

From the ambient detector



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HAYSTAC is operating in a popular communication band (4-5 GHz).

We identified **12 RFI** in total in this new result.

Candidates from real data

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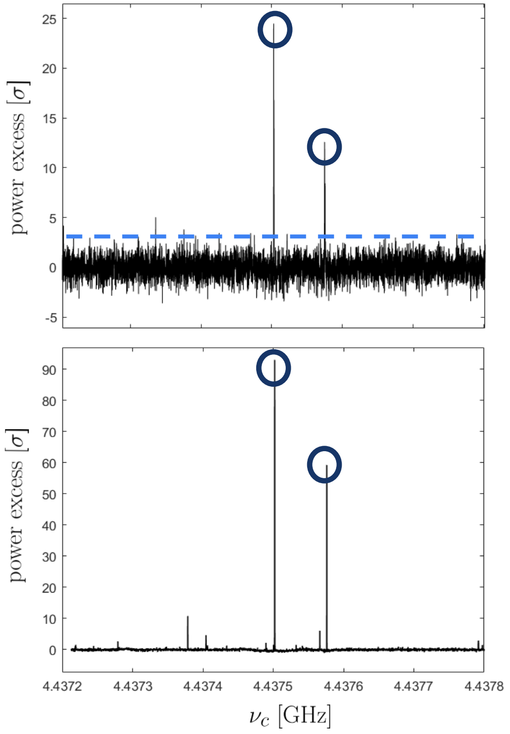


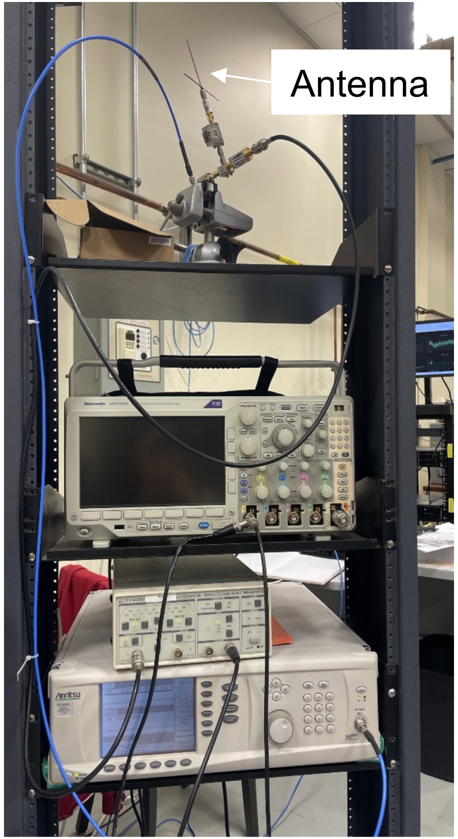

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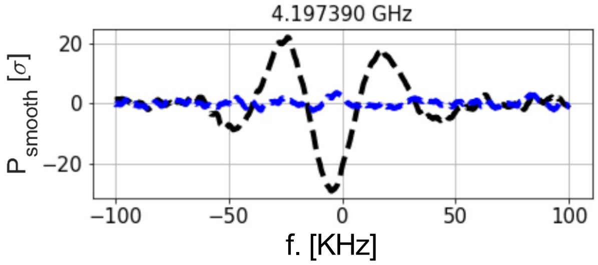


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**RF deficits:**

- **Large power "deficit" > -5 sigma**
- **Been seen it since PIIa**
- **Sources unknown, but never persisted upon rescan.**
- **Does not seem to scale with cavity detuning.**
- **Refill the data afterwards.**

# Scan Rate Enhancement over the New Range

The SSR showed scan rate enhancement across the ranges covered in this new result.

| PII | Scan rate $[\frac{MHz}{day * g_{ksvz}}]$ | Rescans Cand. | SI | RFI | RF Def. |
|---|---|---|---|---|---|
| c | 0.030 | 98 | 3 | 7 | 3 |
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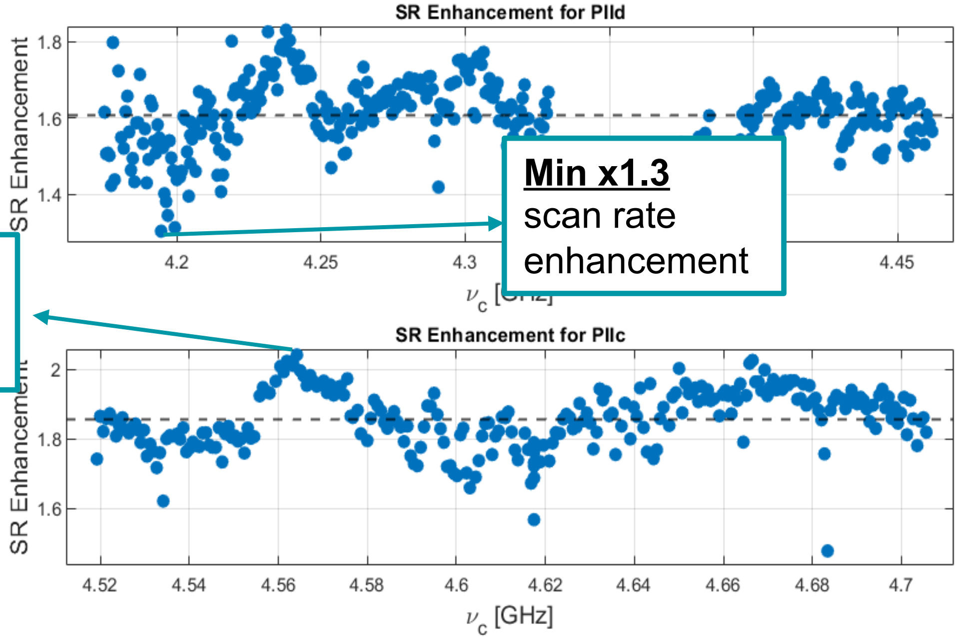
**On average x1.7**
scan rate enhancement over QL-search

**Max x2**
scan rate enhancement

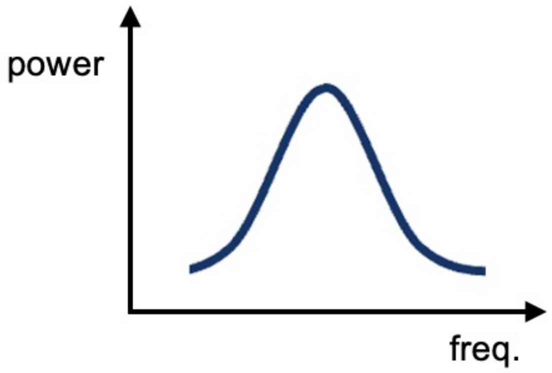



**Min x1.3**
scan rate enhancement

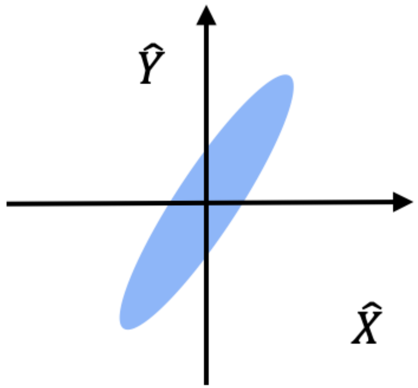
What cause the variations?
Frequency dependency of the losses, cavity performances (Q/beta), cavity noise, vibration noise, etc

# Vibration Degrades Squeezing

Sources: Vibration of the compressors and the rotating valves from the cooling system coupling down to the cavity.




cavity profile




squeezed state after cavity

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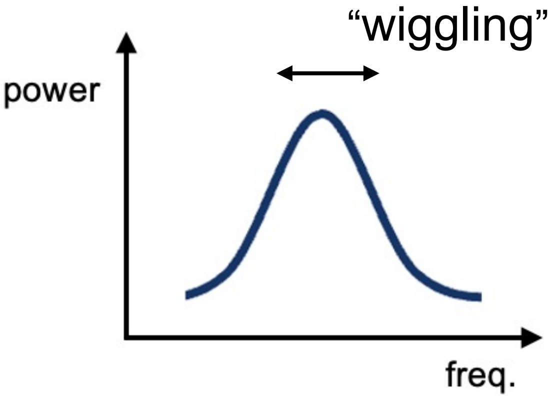


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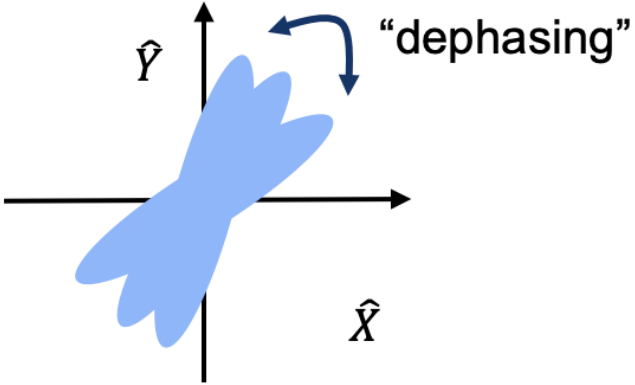



squeezed state after cavity

# Outlook

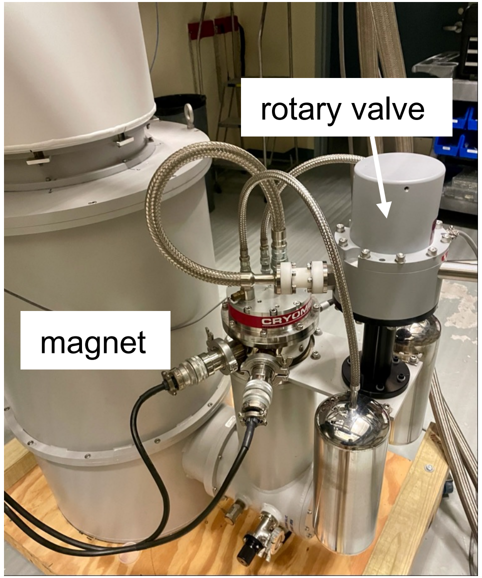
Plan for the Next Phase

# Phase III: Vibration Mitigation

1. Control the relative phases of the pulse tube oscillations:

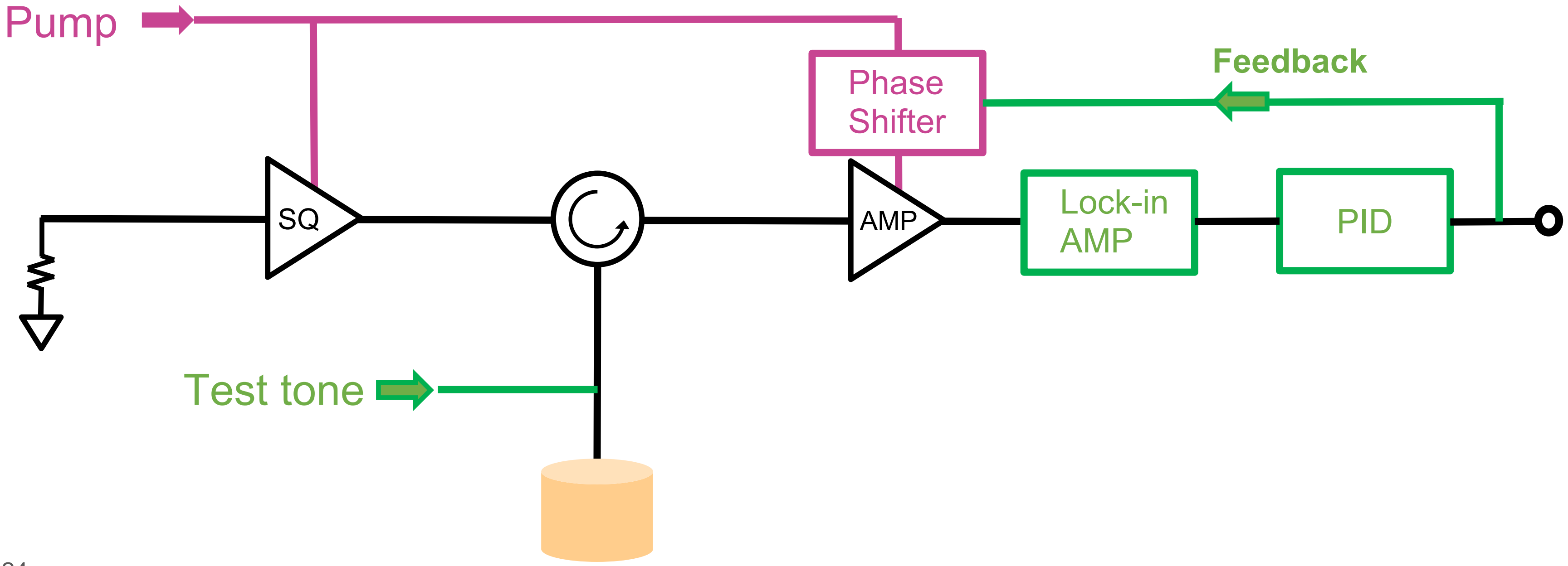
Vibrations from the PT rotary valve at room temperature can couple to cryogenic stages and to the cavity.
Two PTs: one for the fridge and one for the magnet.

Active noise cancellation (D’Addabbo et al, 2018):
1. replace the cryomech stepper motor drivers with new linear stepper motor dirver for precision control of the rotary valve.
2. tune the relative phases of the two PT rotary valve such that it minimize the vibration noise.



# Phase III: Vibration Mitigation

2. Via feedback:
Inject test tone into the rfl port -> track the phase changes using Lock-in amplifier -> PID control loop -> Feedback to the phase shifter

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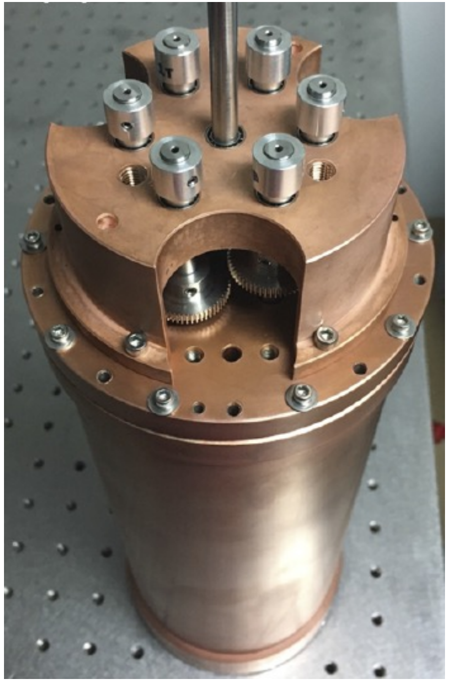
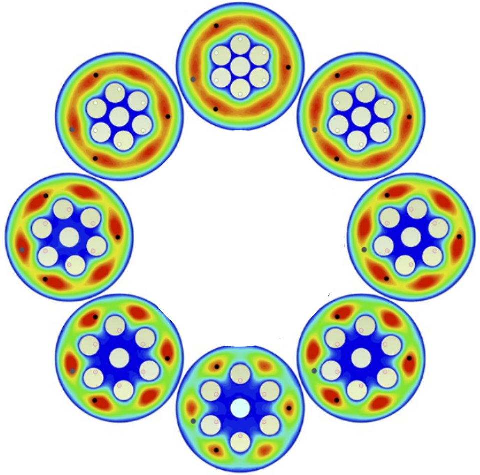
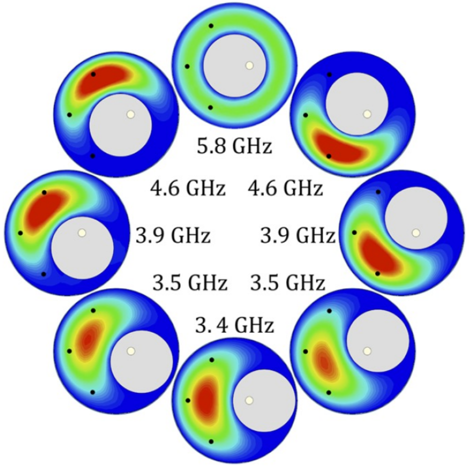
# Phase III: Higher Mass Axions with Multi-rod Cavity

26 – 35 $\mu eV$

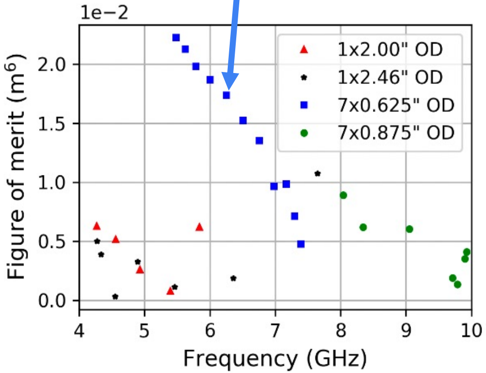
$$\mathrm{FOM} = C^2V^2Q \propto \nu^{-14/3}$$

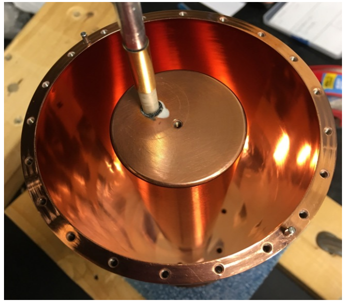







Symmetric features give higher FOM.



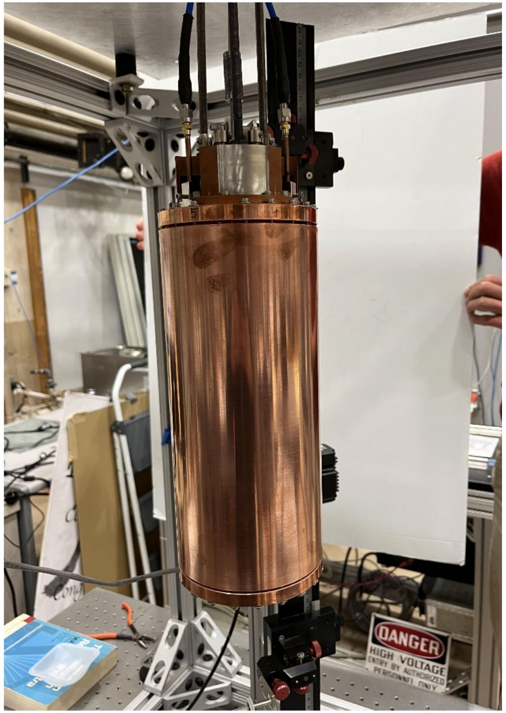



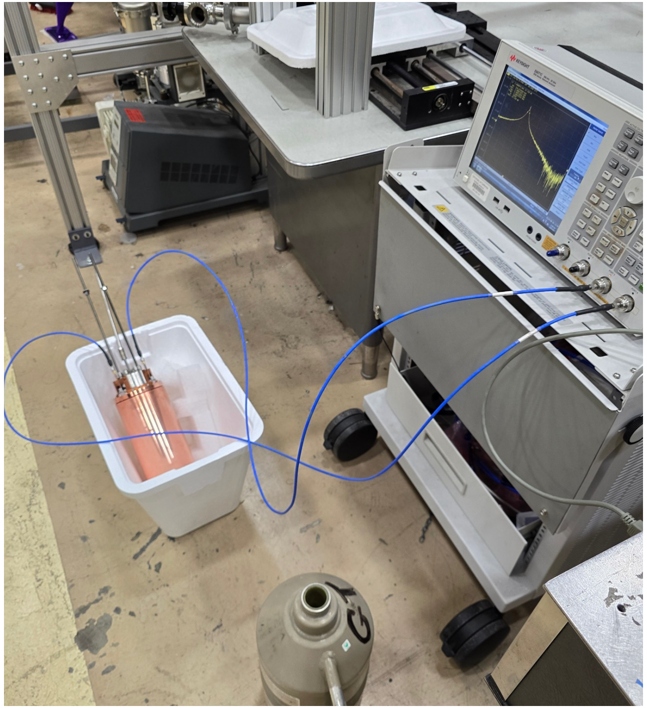
Current Cavity

*Van Bibber Group at Berkeley*
*M. Simanovskaia, et al., Rev. Sci. Instrum. 92 (2021)*

# Phase III: Higher Mass Axions with Multi-rod Cavity

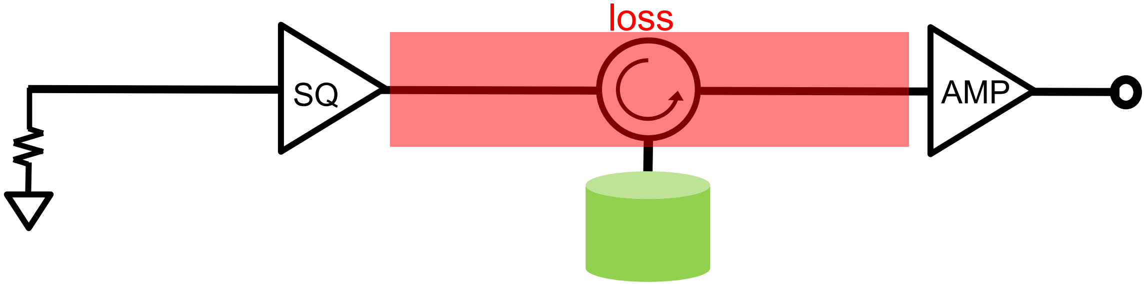
$26 - 35\ \mu eV$



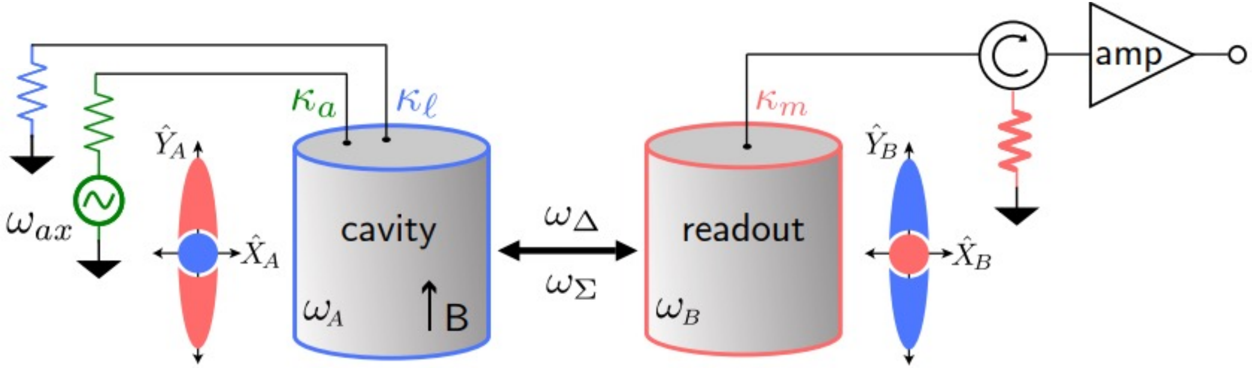
*Van Bibber Group at Berkeley*
*Image credit: Dillon Goulart*

# 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**




*Lehnert Group at Yale/JILA*
*Jiang et al.,10.1103/prxquantum.4.020302*

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# Summary

- New results released using SSR between 17.28 - 18.44 $\mu eV$, $|g_\gamma| > 2.75\,|g_{\mathrm{ksvz}}|$, 18.71 - 19.46 $\mu eV$, $|g_\gamma| > 2.96\,|g_{\mathrm{ksvz}}|$, covering a newly explored range of 413MHz **arXiv:2409.08998**.
- Next phase: moving to higher mass range of 26 – 35 $\mu eV$
- Testing of a new multi-rod cavity is on-going.
- Testing of the vibration feedback for squeezing stabilization is on-going.
- Expected commission of the next phase: Jan. 2025.

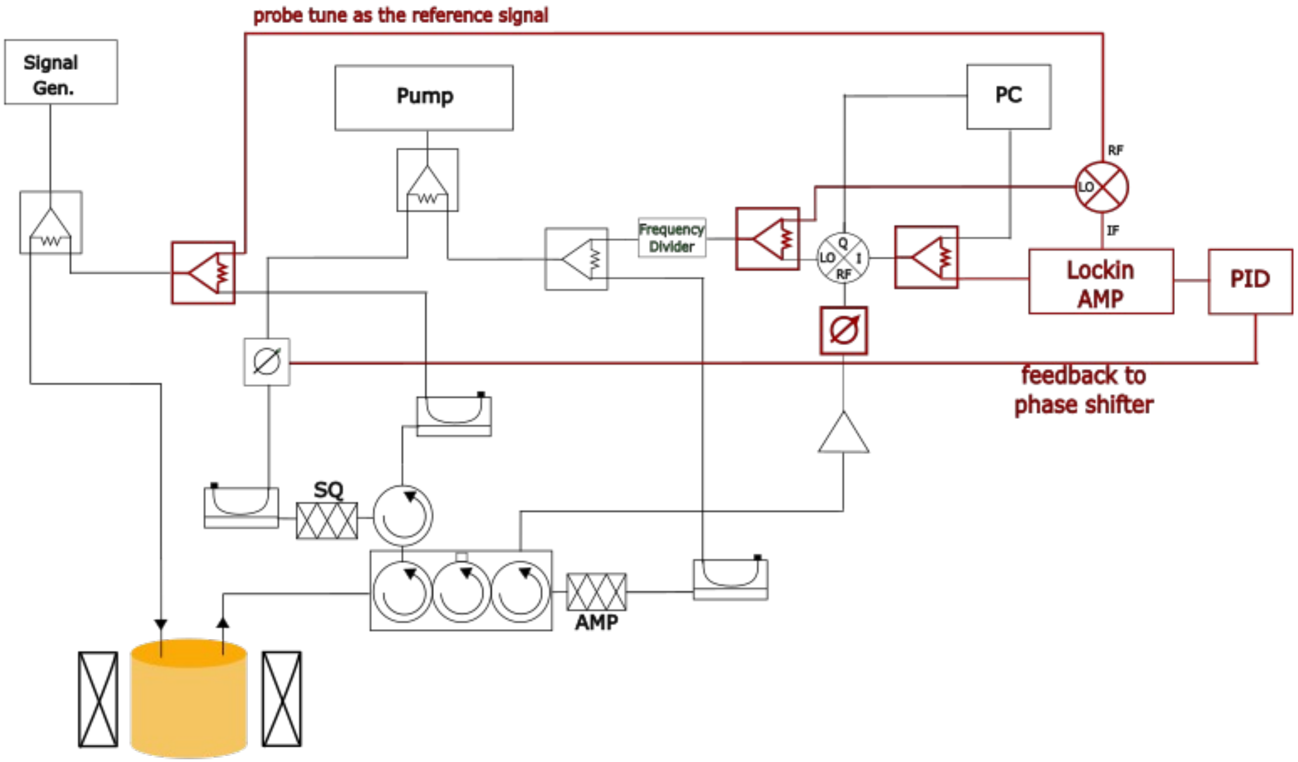
# Thank you!

# Backups

# Preparation for Phase III

- The cavity is currently being tested at UC Berkeley. Projected operating range of the new cavity: 6.3 – 8.5 GHz (26 – 35 $\mu eV$).
- New pair of JPAs provided by JILA.
- RF components (IQ mixer, switches, etc.) at the new frequency range are purchased.
- Testing of the vibration feedback for squeezing stabilization is on-going.
- Expected commission time: Spring 2025.

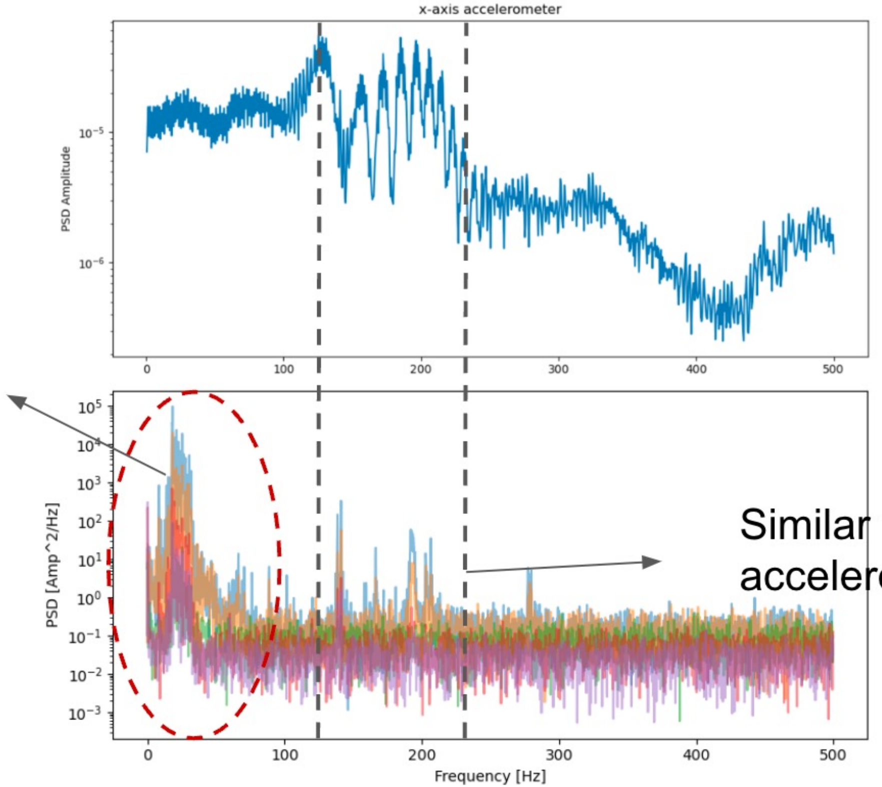
# Feedback Diagram



# Compared with Accelerometer Data

We installed an accelerometer on top of the fridge. Compared with accelerometer:

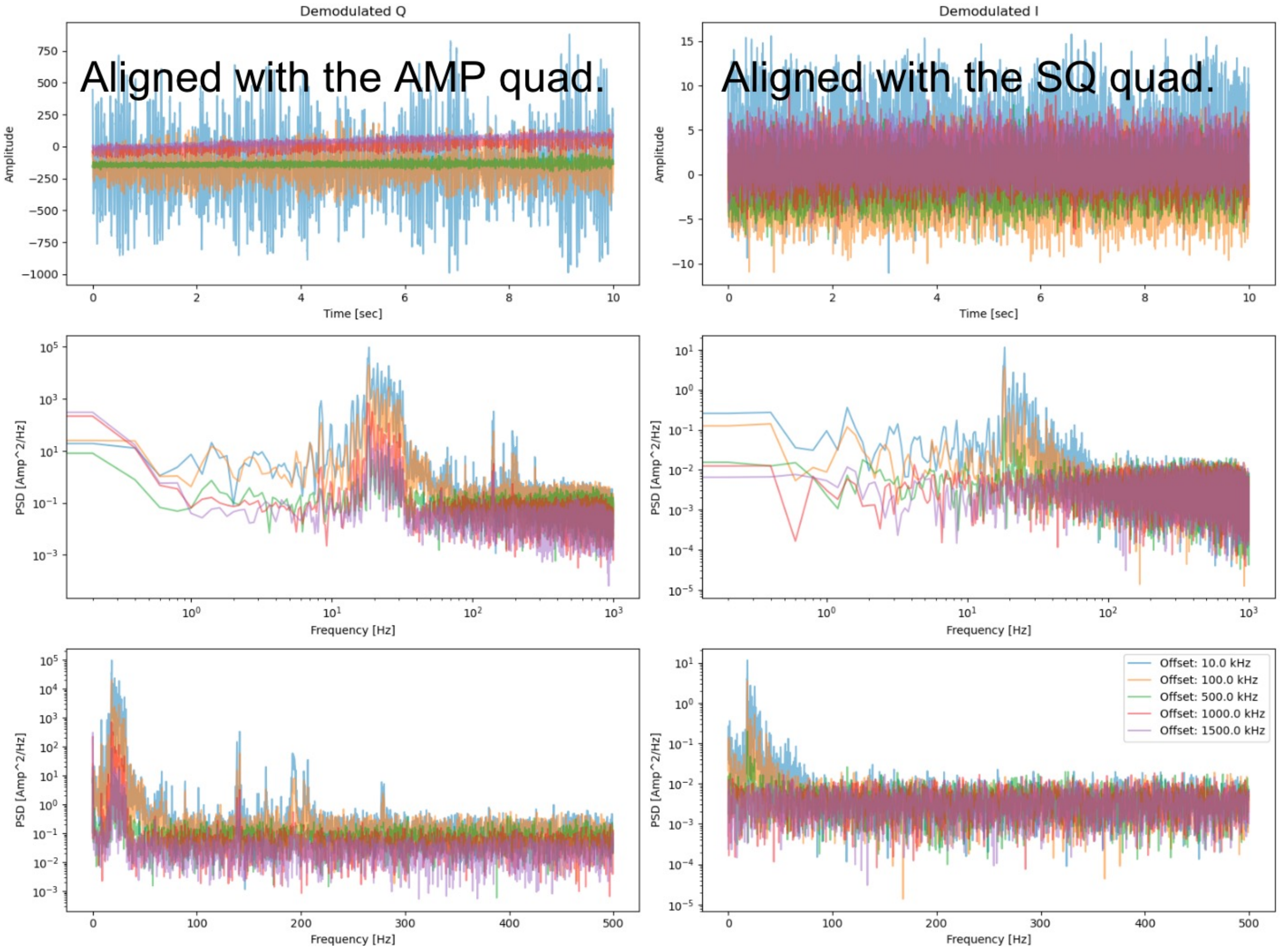
Different from the accelerometer: excited resonance by something in the cavity?




Similar to the accelerometer

# Demo Control Signal

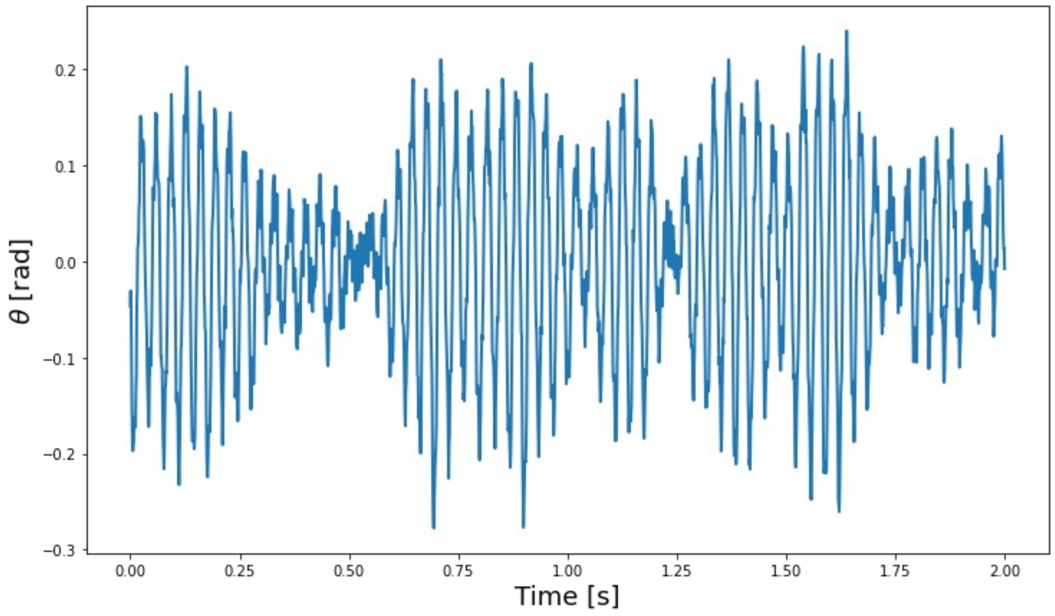
- As we move the probe tone offset out toward the cavity BW the amplitude drops off to zero.
- Vibration < 300 Hz < Lockin Amp filter cutoff (1000Hz)
- Will be the input of PID.



# Phase Noise Confirmation

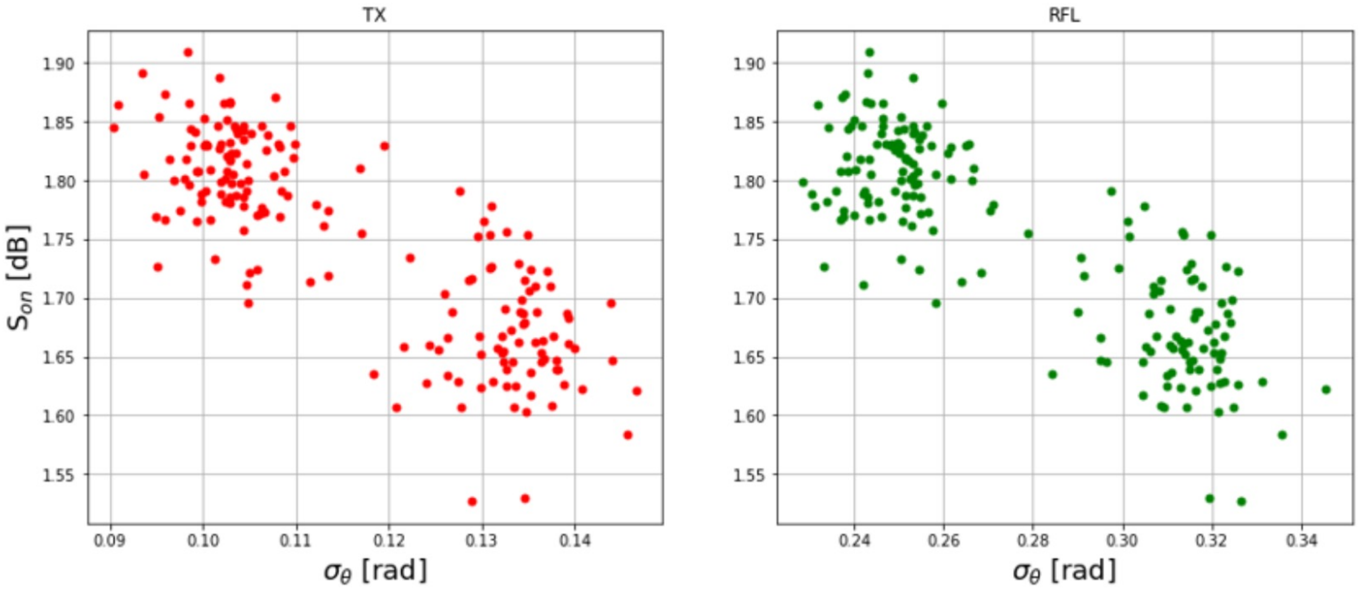
Use ENA to measure Phase Noise

- 0 span
- sit at cavity resonance
- measure I/Q

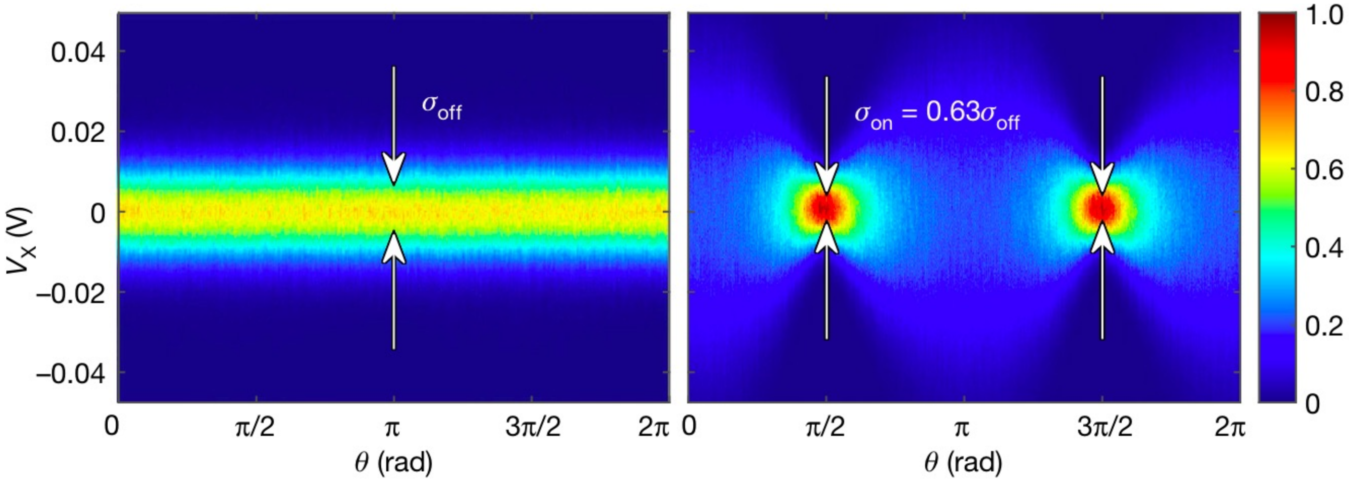


# Phase Noise Confirmation

- Use ENA to measure Phase Noise
  - 0 span
  - sit at cavity resonance
  - measure I/Q



# Measure Squeezing




$$S = \frac{\sigma_{on}^2}{\sigma_{off}^2}$$

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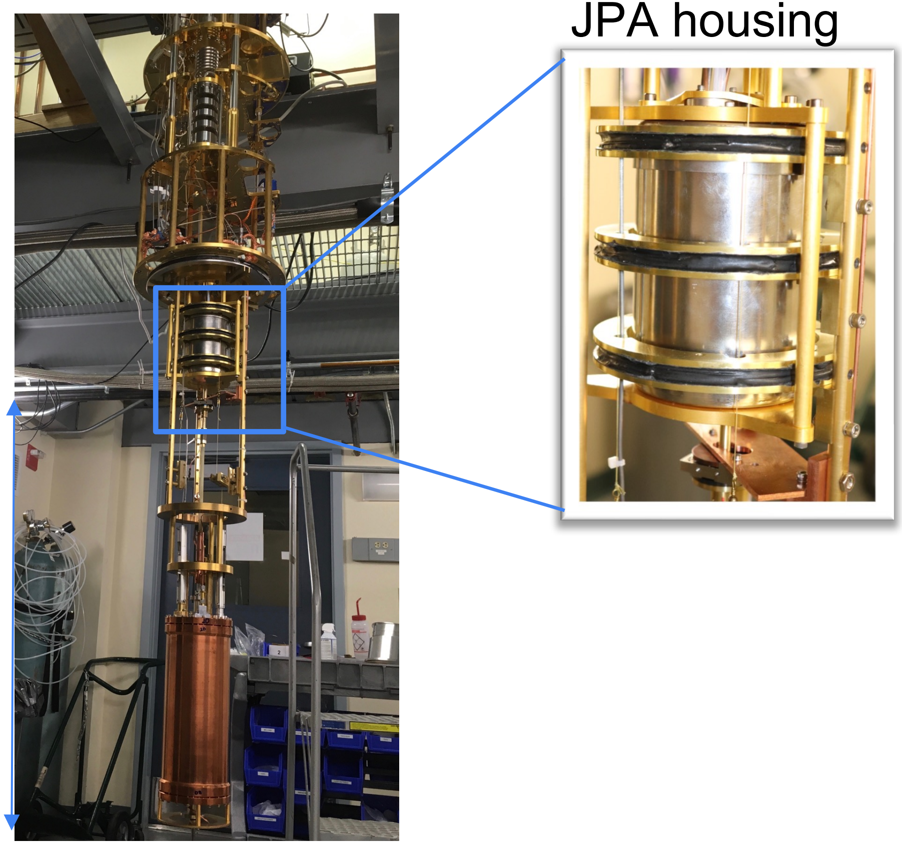
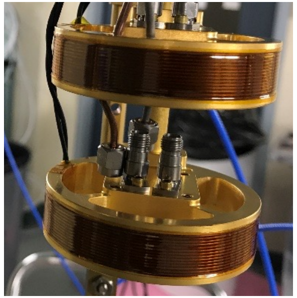
# Magnetic Shielding

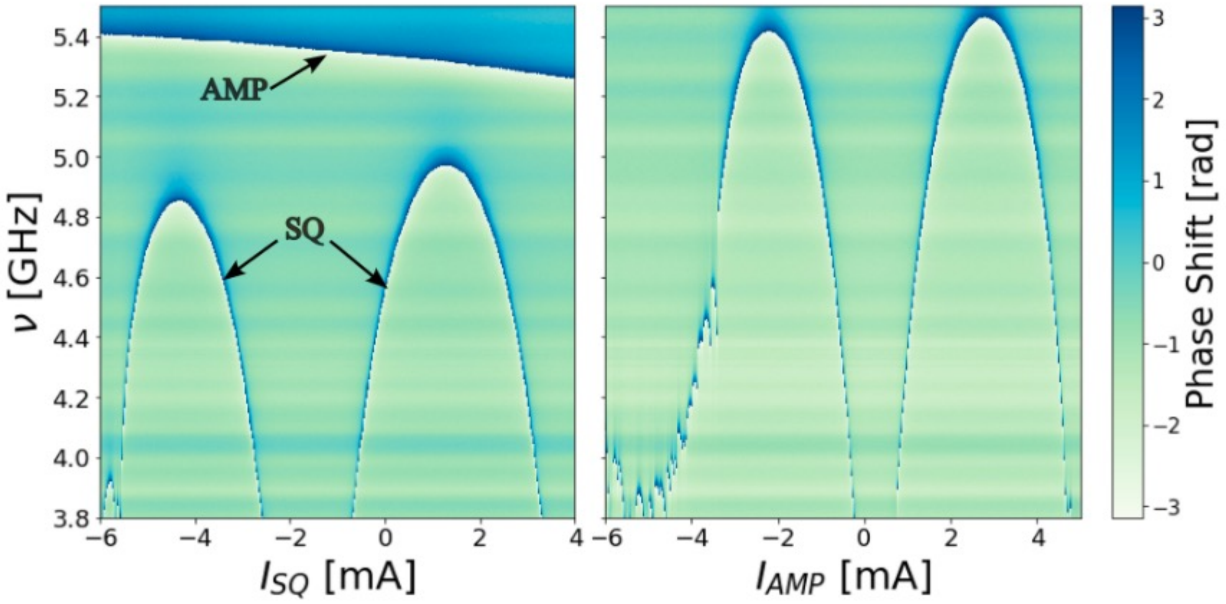
1m

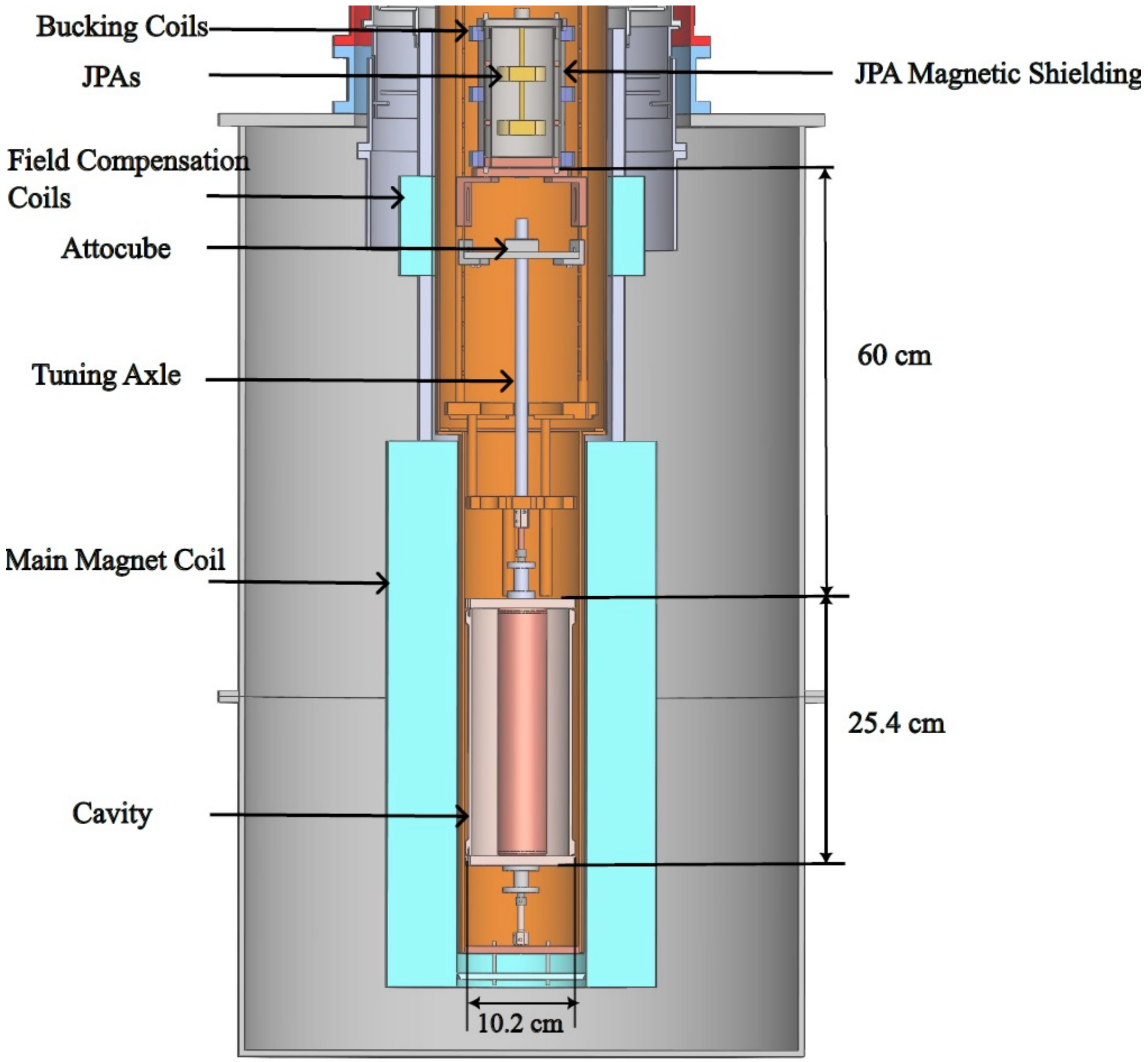
JPA housing



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

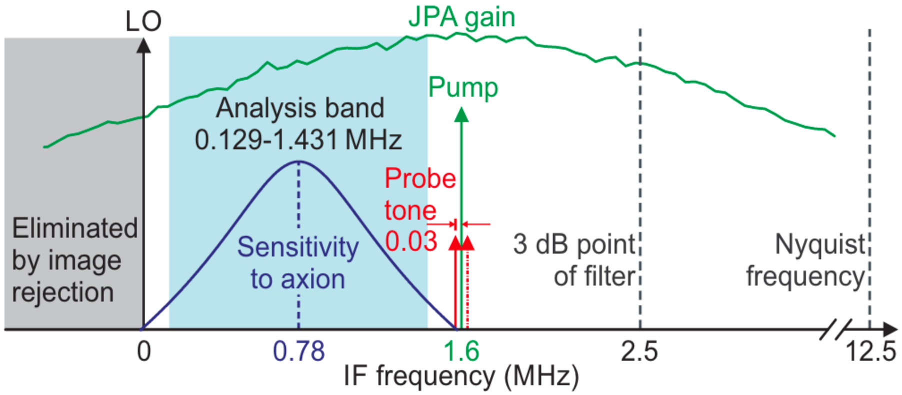


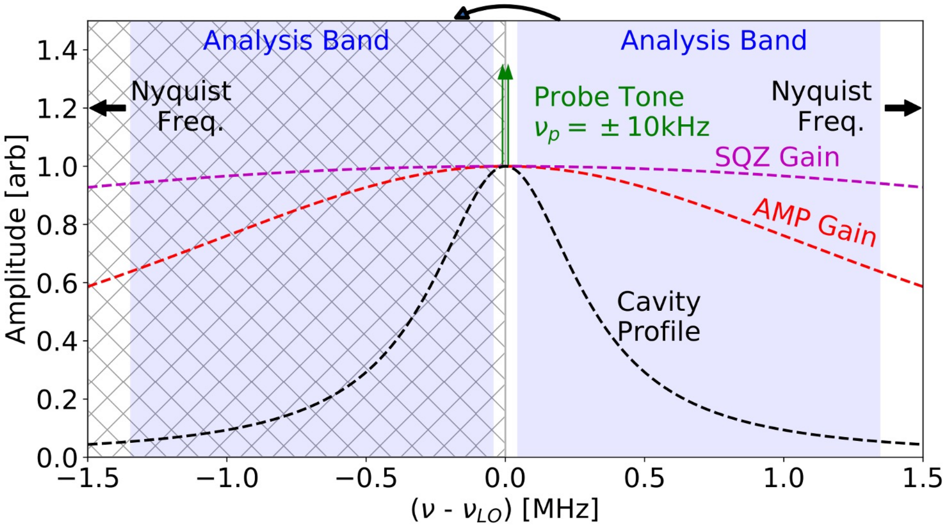

AMP
SQ
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
3.8
ν [GHz]
−6
−4
−2
0
2
4
$I_{SQ}$ [mA]
$I_{AMP}$ [mA]
3
2
1
0
−1
−2
−3
Phase Shift [rad]



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

# Phase I vs Phase II JPA pump configuration

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# System Noise Calibration

**Goal:** Get the system noise. Map voltage values to physical unit by using a calibration source at a known temperature.

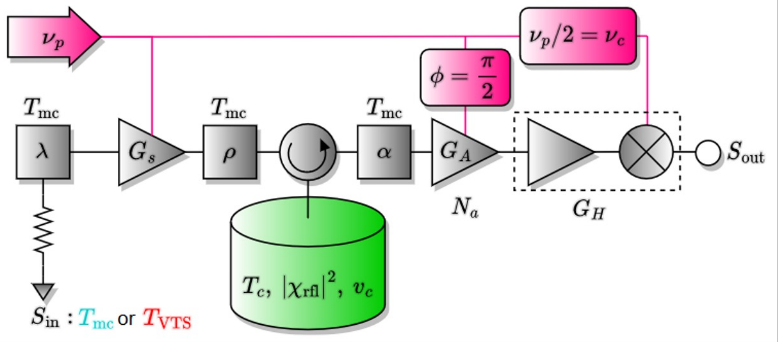
Variable Temperature Stages (VTS): a resistor whose temperature is kept stable by a PID loop.

**System Noise Model:**

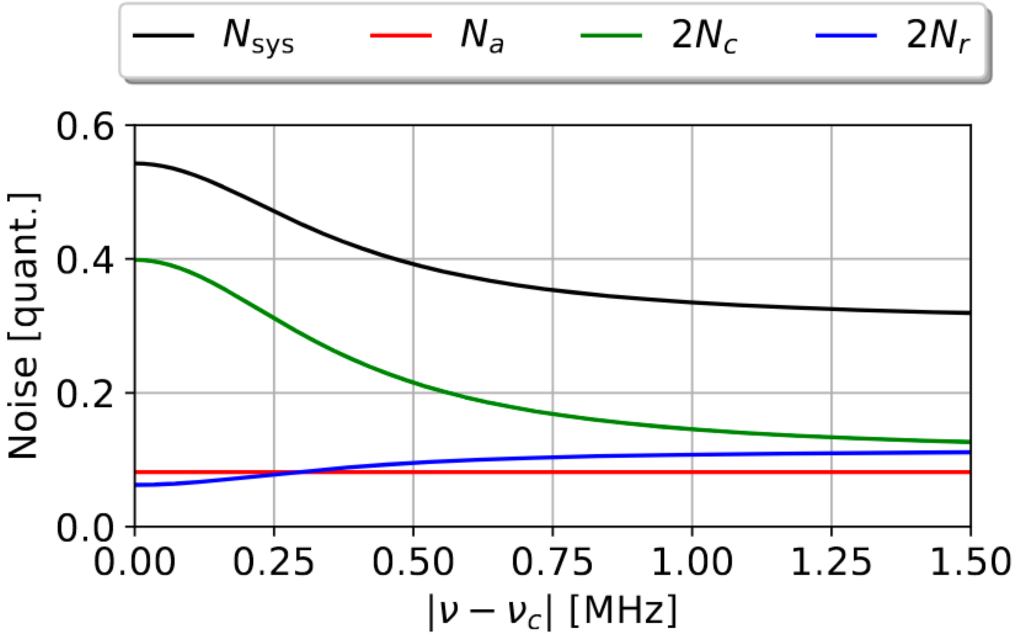
$N_c$ $N_a$ $N_r$

cavity noise (black body radiation), amplifier noise (added noise + reflected noise), transmission efficiency (loss)

$$S_{\text{out}} = G_A G_H \underbrace{(N_a + 2(N_r + N_c))}_{N_{\text{sys}}}$$




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



$N_{\rm sys}$
$N_a$
$2N_c$
$2N_r$
0.6
0.4
0.2
0.0
Noise [quant.]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
$|\nu - \nu_c|$ [MHz]

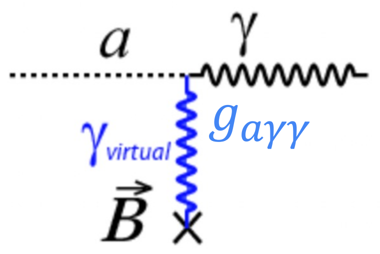
# Haloscope At Yale Sensitive To Axion CDM (HAYSTAC)

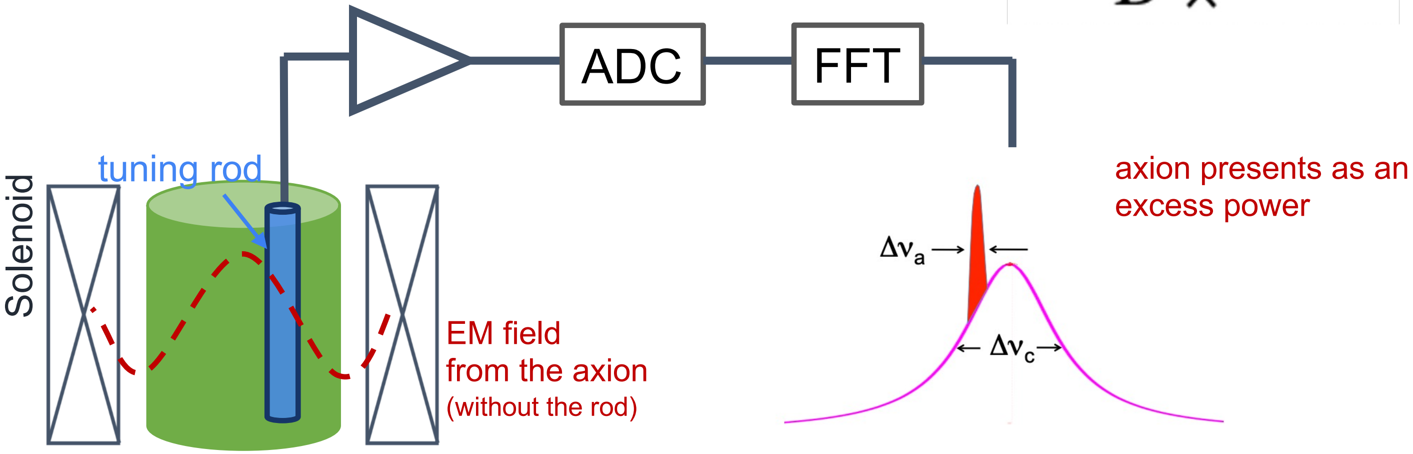
An haloscope experiment

Explore axion's coupling to photons

- $\mathcal{L} = -\frac{1}{4} g_{\alpha\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

$\nu_a \approx m_a c^2 / h$




Size of the signal is exaggerated.

$P_a \sim 10^{-24}$ Watts

$k_B T_N \sim 10^{-21}$ Watts

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

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