Phase II of the **HAYSTAC** Axion Dark Matter Experiment: A New Application of Quantum Measurement Techniques

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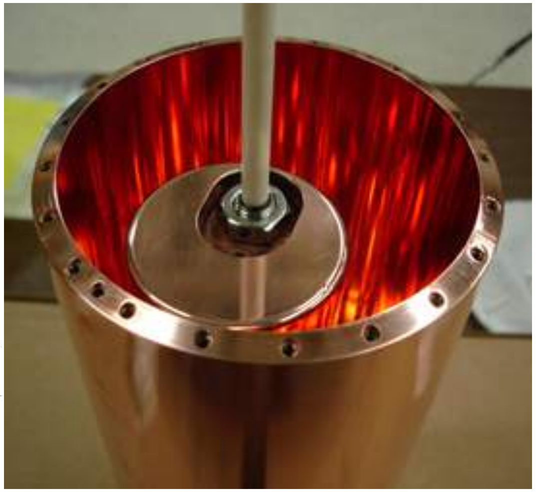
Yale University

Quantum Connections: Nov 28, 2018

Stockholm, Sweden

Haystac



THE UNIVERSITY OF CALIFORNIA BERKELEY 1868

JILA CU Boulder and NIST

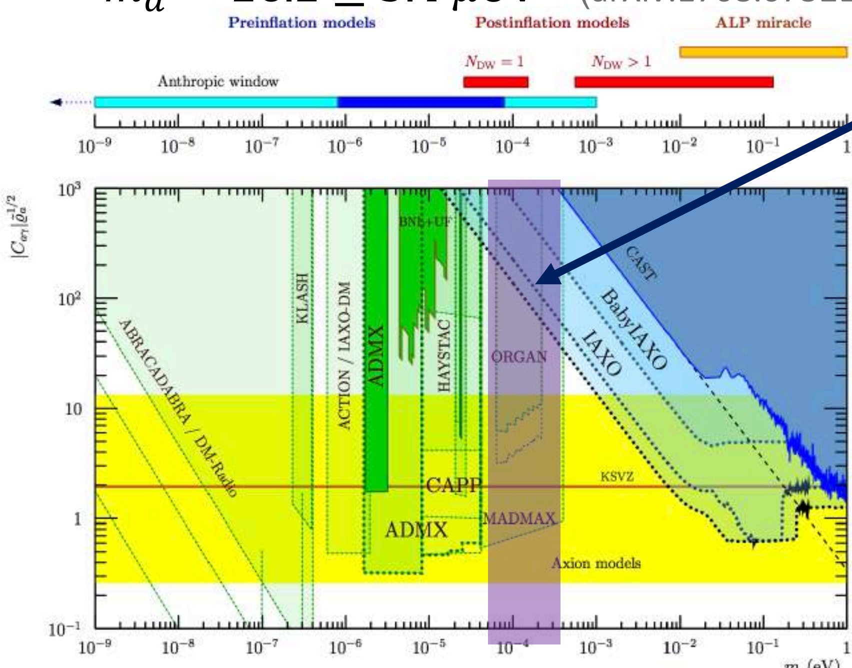
LUX ET VERITAS

Wright Laboratory

Motivation for a haloscope at high frequency

Astrophysical:

- Peccei Quinn symmetry broken after inflation: $m_a > 28\ \mu\text{eV}$ (Nature 539, 69)
- SMASH model: $50\ \mu\text{eV} \leq m_a \leq 200\ \mu\text{eV}$ (arXiv:1610.01639)
- V.B. Klaer, G. Moore: $m_a = 26.2 \pm 3.4\ \mu\text{eV}$ (arXiv:1708.07521)

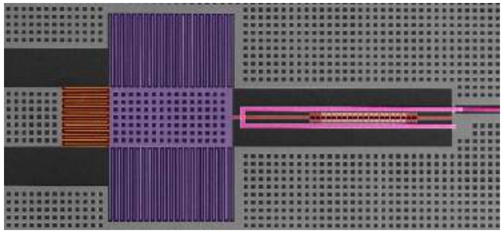


Well motivated region: 6.33 GHz to 48 GHz

(ArXiv:1801.08127)

Experimental:

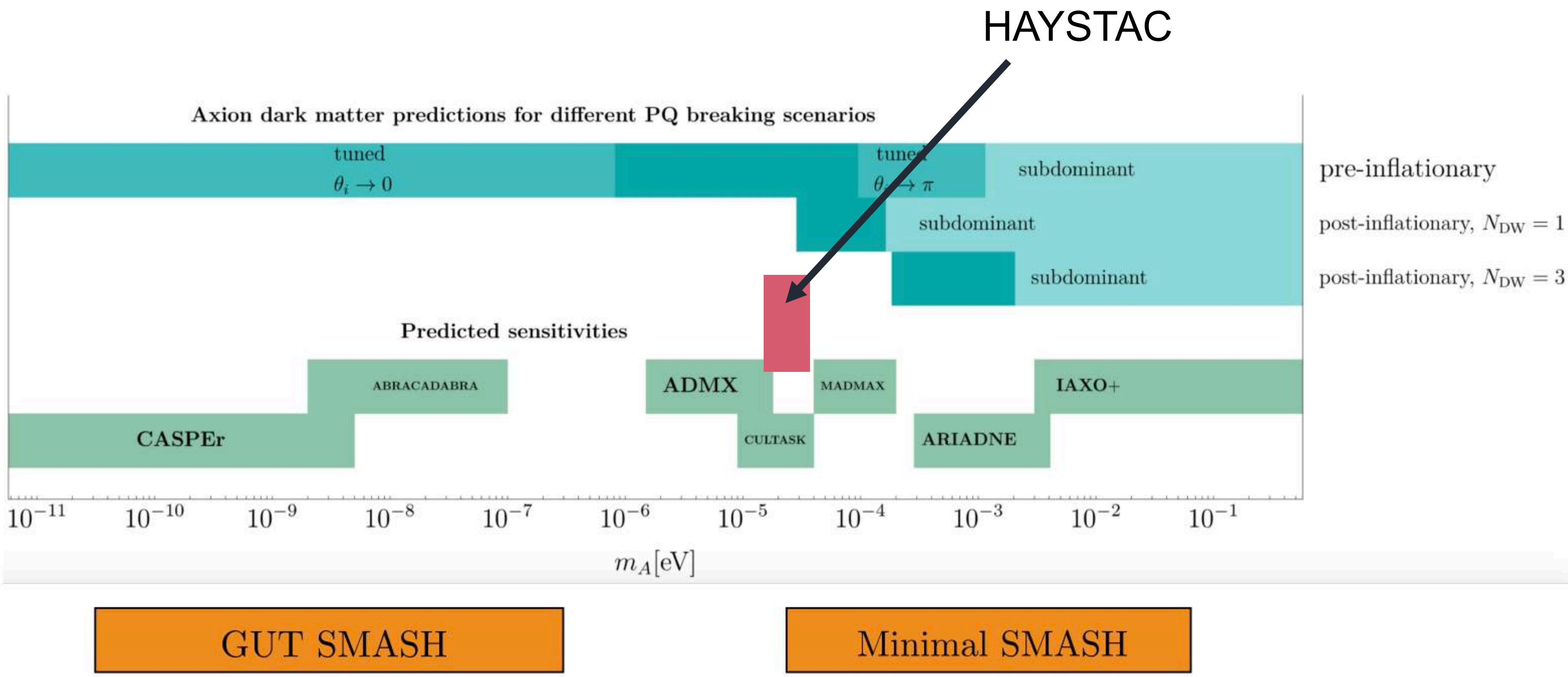
- Simplified cryogenics and smaller magnet



- Josephson parametric amplifiers (JPAs) work well in the 2-12 GHz range (Phys. Rev. Applied 9, 044023)

Continued motivation

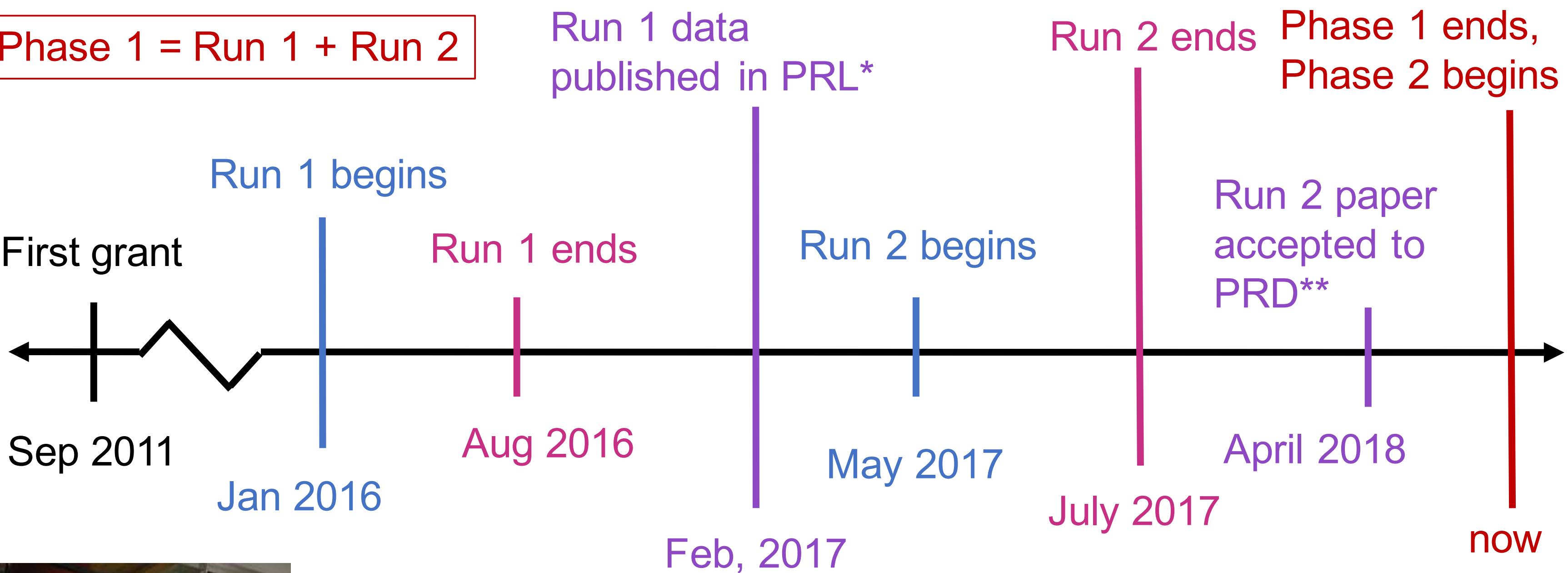
- In the format of Monday's talk

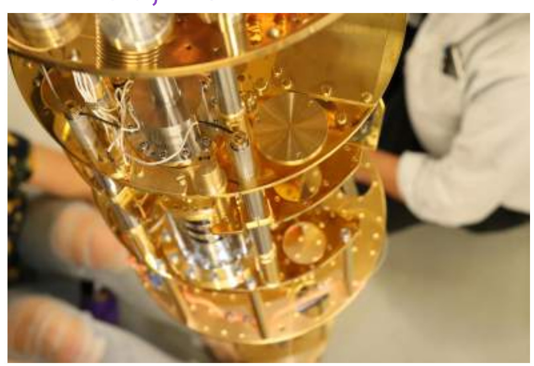


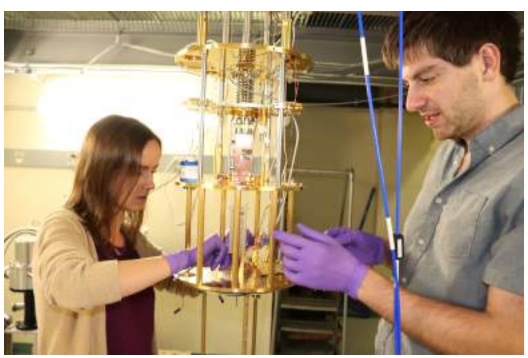
From Monday talk by A. Ringwald

A quick history of HAYSTAC

Phase 1 = Run 1 + Run 2



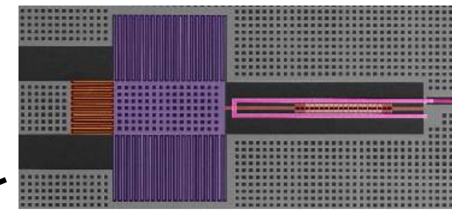




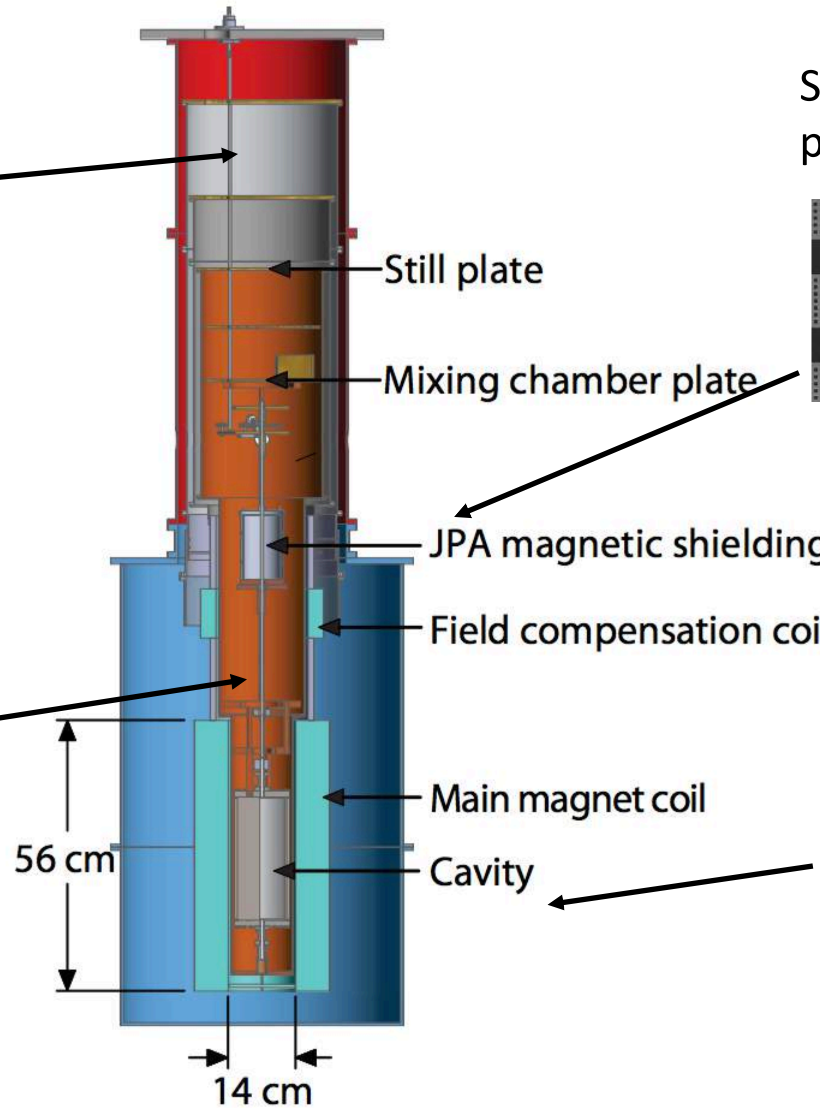
* Phys. Rev. Lett. 118, 061302 (2017).
** Phys. Rev. D 97, 092001 (2018).

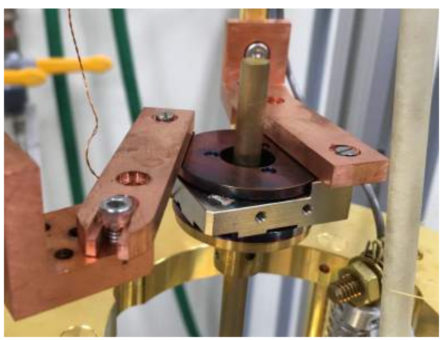
The phase 1 detector

Single Josephson parametric amplifier

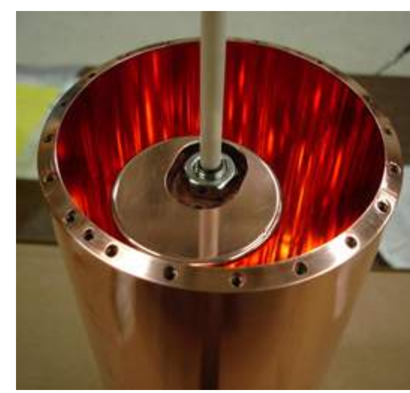


Oxford dilution refrigerator



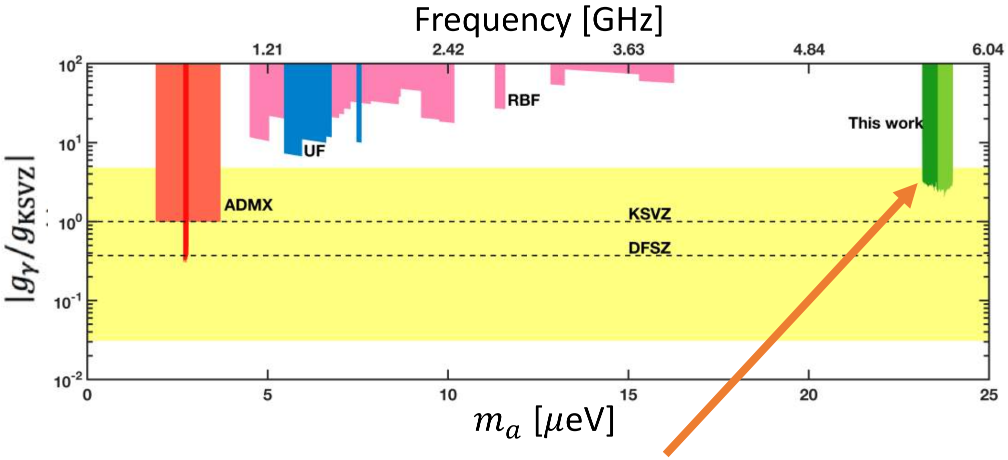


Piezoelectric tuning: Attocube ANC 240



Nucl. Instrum. Methods A 854, 11

Phase 1 standard parameter values



Frequency range: f_a = 5.6 – 5.8 GHz

Corresponding mass range: m_a = 23.15 – 24 μeV

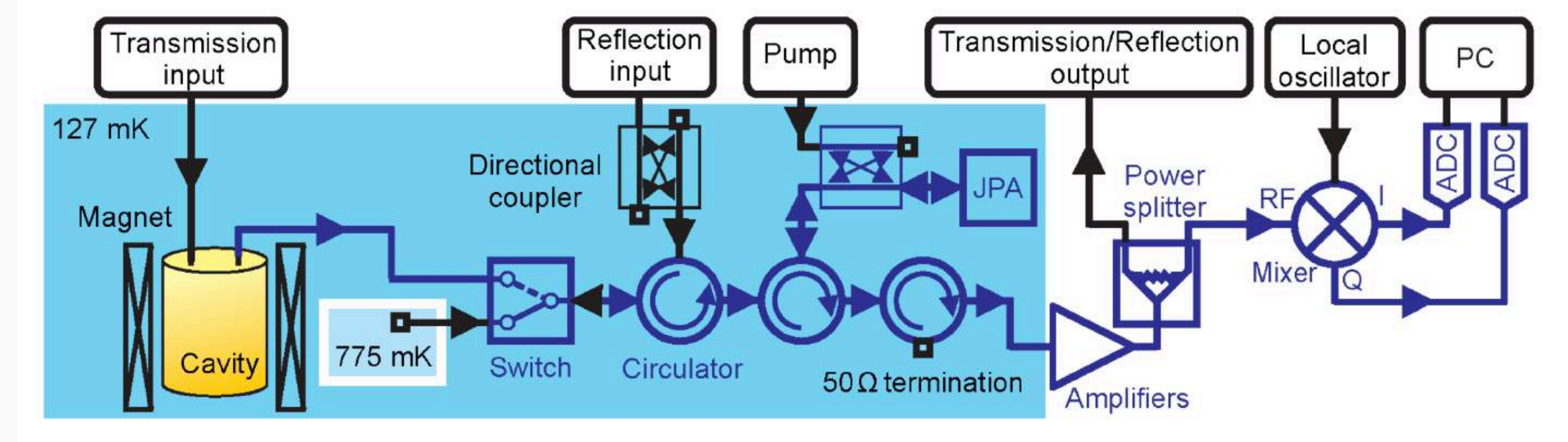
Operating temperature: T = 127 mK

System noise per unit bandwidth: N_a = 2.3 quanta

Magnetic field: B = 9 T

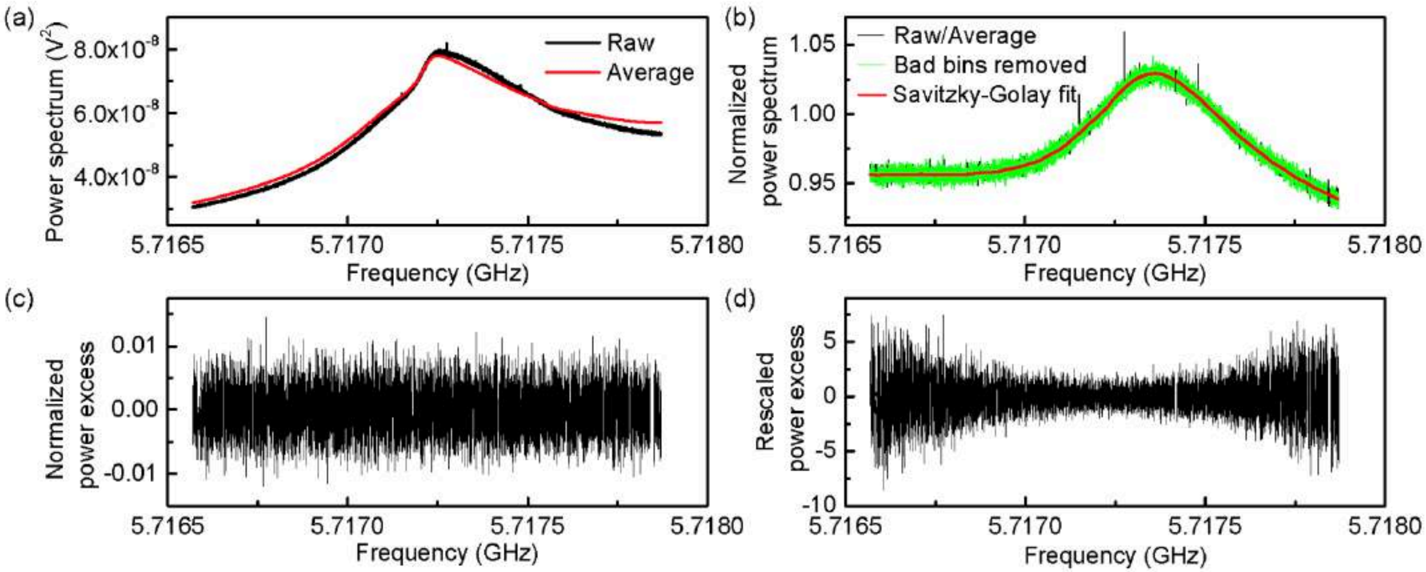
$\mathbf{TM_{010}}$ form factor: C = ~0.5

Phase 1 receiver system

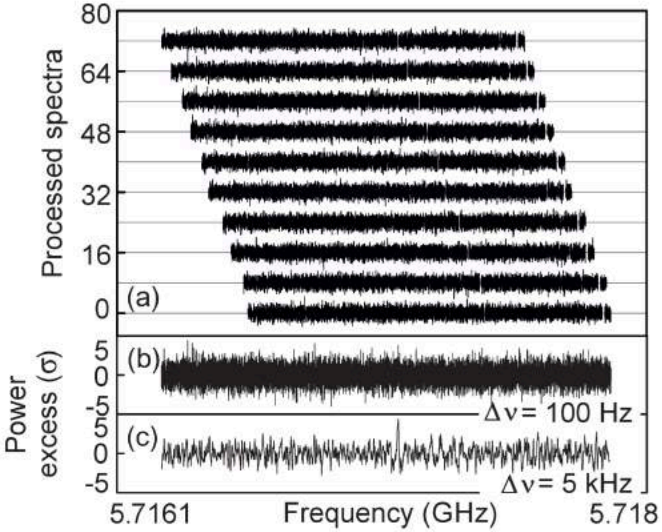


- Input-output microwave lines for transmission/reflection measurements, JPA pumping, and signal readout
- Switch for hot and cold load for calibration
- Signals are amplified at 127 mK and room temperature
- IQ mixer down-converts signal to IF band
- Both I and Q are read-out and used for analysis

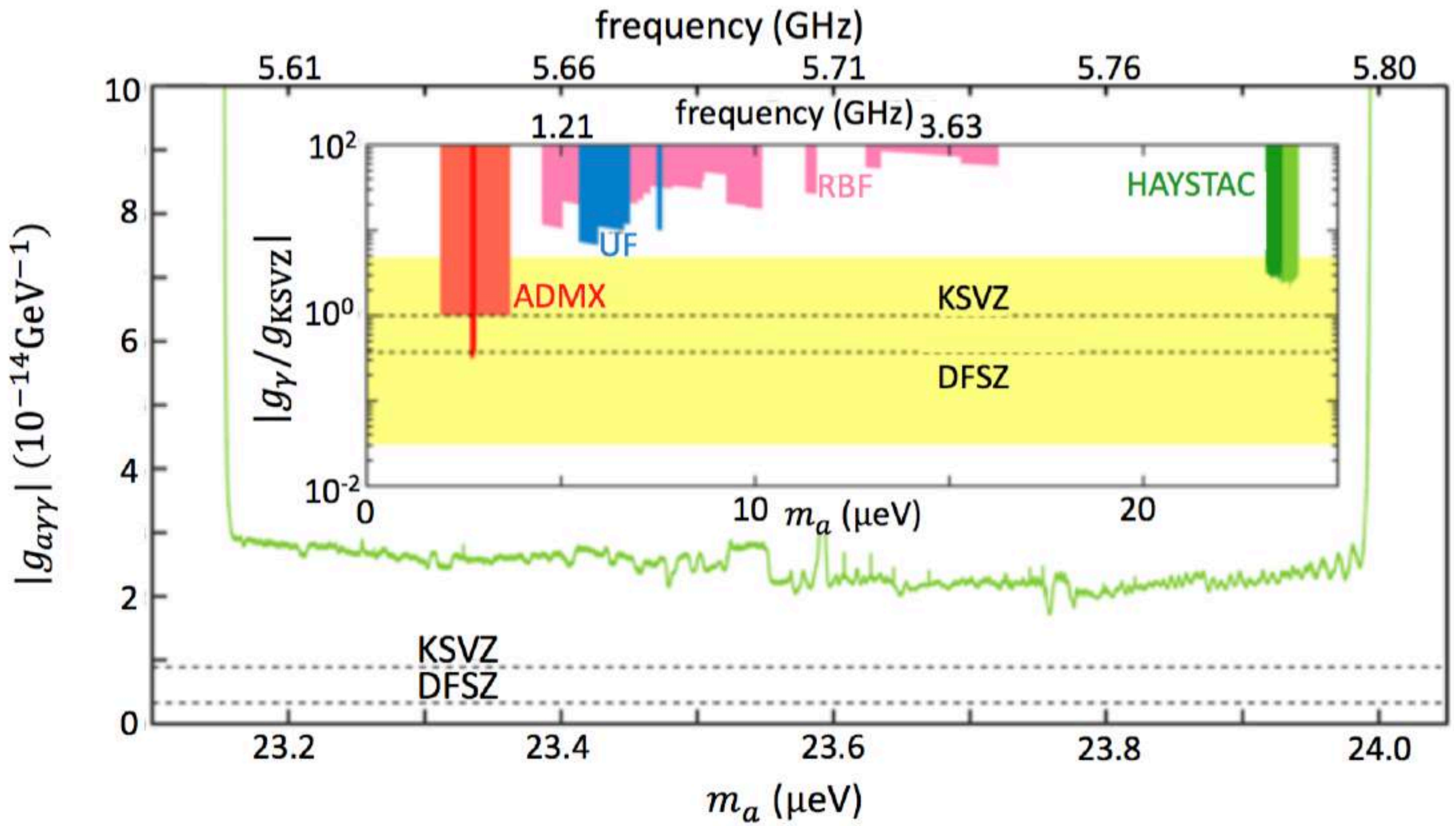
Analysis



- Remove baselines with Savitsky-Golay filter
- Combine spectra with maximum likelihood weighting
- Statistics of grand spectrum determine exclusion



Results from Phase 1

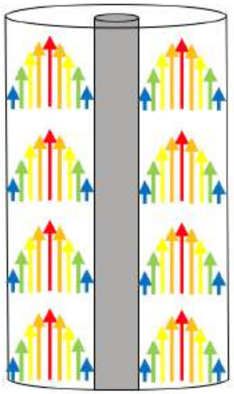


Exclusion of $|g_\gamma| \geq 2.7 \times |g_\gamma^{\text{KSVZ}}|$ over $23.15 \leq m_a \leq 24\ \mu$eV

First QCD axion exclusion above 20 μeV!

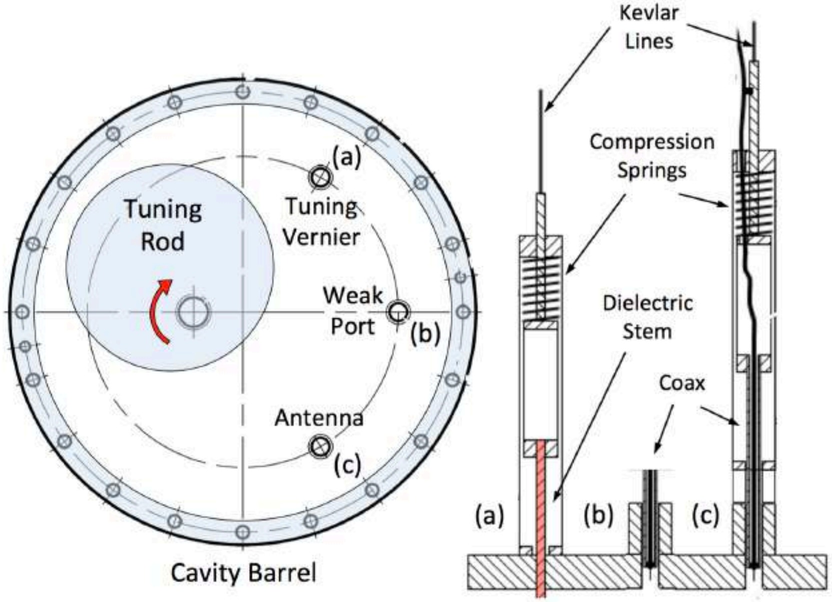
Model band: Cheng et al Phys. Rev. D 52, 3132 (1995)

Cavity



3 ports into the cavity

- Vernier: fine frequency tuning
- Weak port: fake axion injection and cavity transmission measurements
- Antenna: signal readout

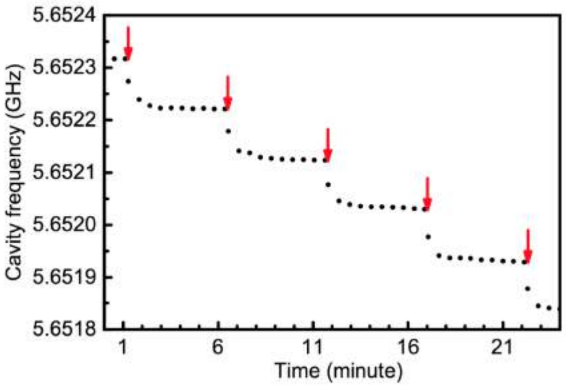


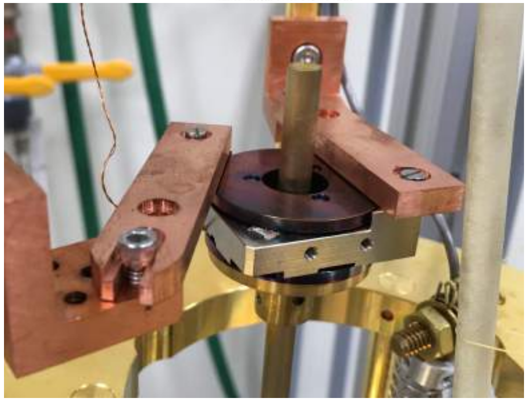
- Tunable from 3.5 – 5.8 GHz
- Off-axis Cu tuning rod for frequency tuning
- Cold, unloaded Q of 30,000

Two types of motion control

Piezoelectric movement of tuning rod

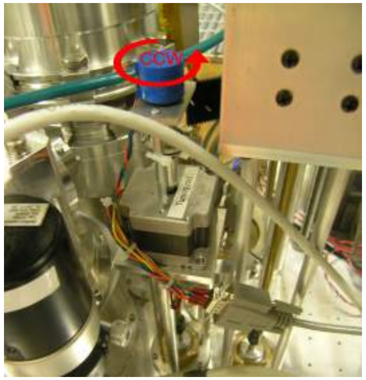
- Driven by a sawtooth waveform: 50 Vpp,1.5 A
- Easily automated
- 100 kHz steps



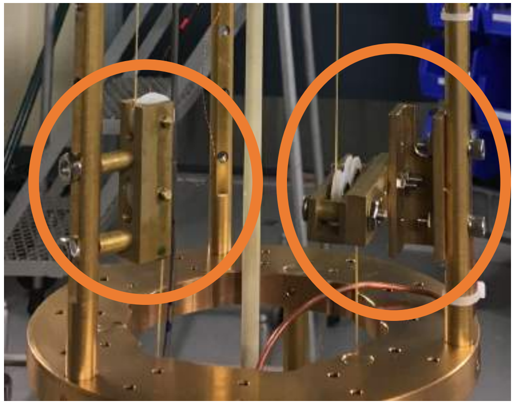


Stepper motor and kevlar line control of antenna and vernier

- Functions as linear drive for antenna and vernier



- Pulley system for redirection



The magnet and JPA shielding

- From Cryomagnetics, Inc.
- 9 T magnetic field
- 3.6 K operating temperature, cooled by the magnet's cryocooler

- Shielding is made of three superconducting bucking coils around cryoperm can
- Field inside can minimized: B = 10^{-3} G

Haloscope figures of merit

Figures of merit:

$$\mathrm{SNR} = \frac{P_S}{k_B T_S}\sqrt{\frac{\tau}{\Delta\nu_a}}$$

scan rate: $R \propto \mathrm{SNR}^2$

Scaling:

decreased signal power: $P \propto V^2 C^2 Q$

$$\mathrm{Q} \propto \nu^{-2/3} \quad C_{010}V \propto L\nu^{-2}$$

effective scan rate scaling: $R \propto \nu^{-14/3}$

increased density of TE modes: $\rho_{\mathrm{TE}} \propto \nu^2$

Standard quantum limit: $kT_N \geq h\nu$

10 in

Improving sensitivity

Figures of merit:

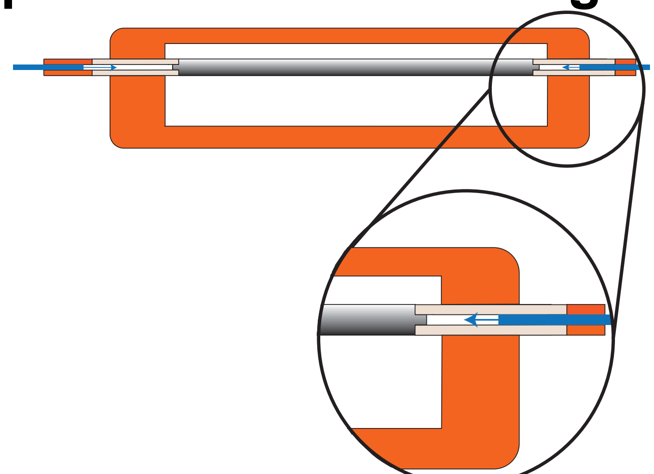
$$\mathrm{SNR} = \frac{P_S}{k_B T_S}\sqrt{\frac{\tau}{\Delta\nu_a}}$$

$$P_S \propto Q$$

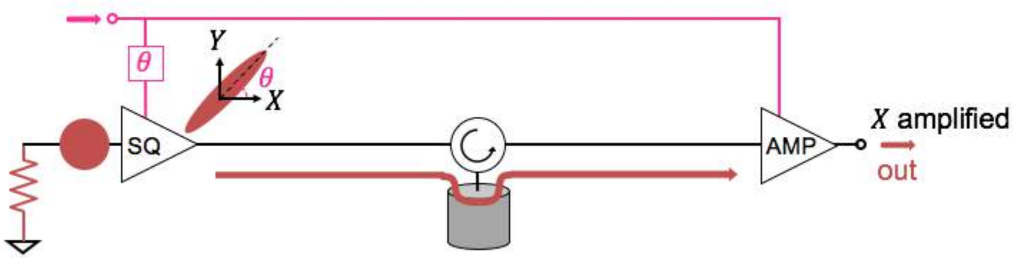
scan rate: $R \propto \mathrm{SNR}^2$

New dilution refrigerator

Improved thermal linking



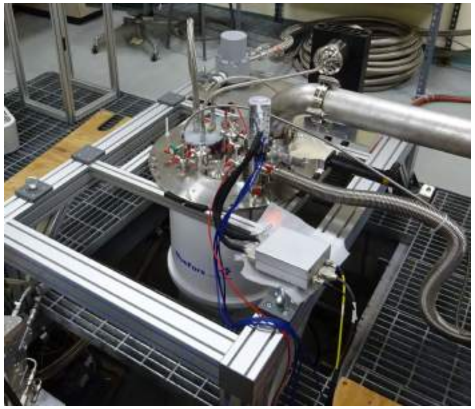
squeezed state receiver



Cryogenic upgrades

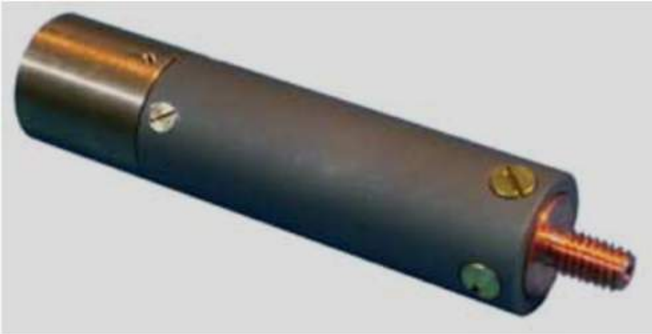
BlueFors BF-LD250 Dilution refrigerator:

- Liquid cryogen free
- Better vibrational isolation
- 460μW cooling power at 100 mK



Magnicon temperature sensor:

- Better monitoring of hot load temperature



Variable temperature stage:

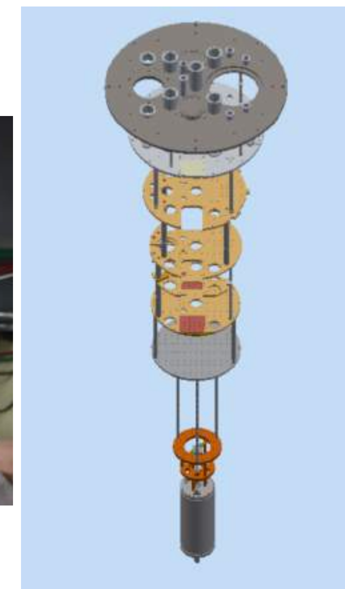
- Can now vary the temp of the hot load for hot-cold load calibration

Mechanical improvements

Cavity realignment:
- Cavity axes realigned for smoother tuning
- Increased usable frequency range
- Increased Q

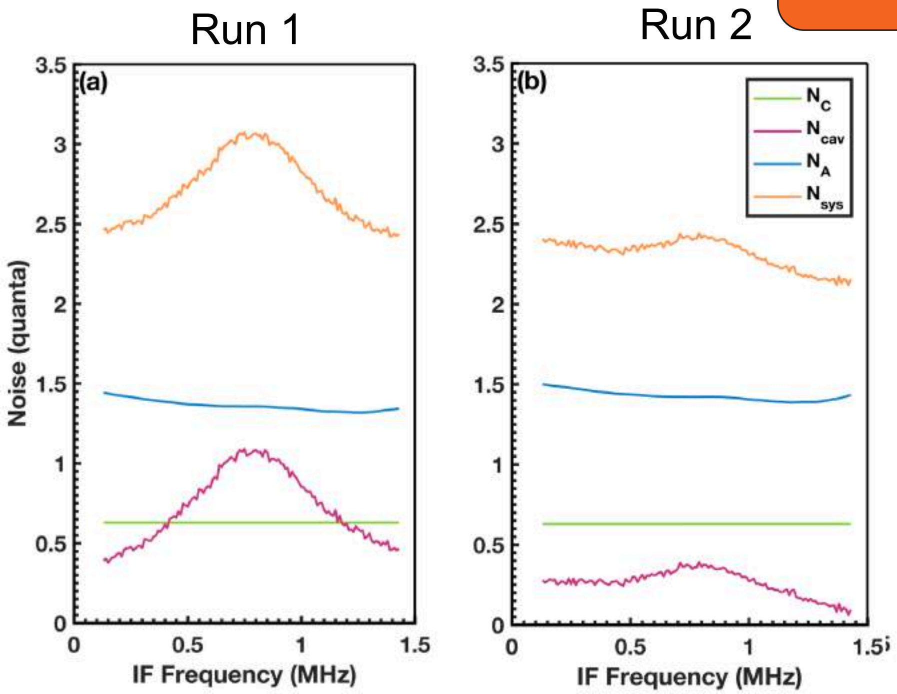
Redesigned cavity support:
- Fewer large copper pieces to reduce eddy currents in the case of a quench

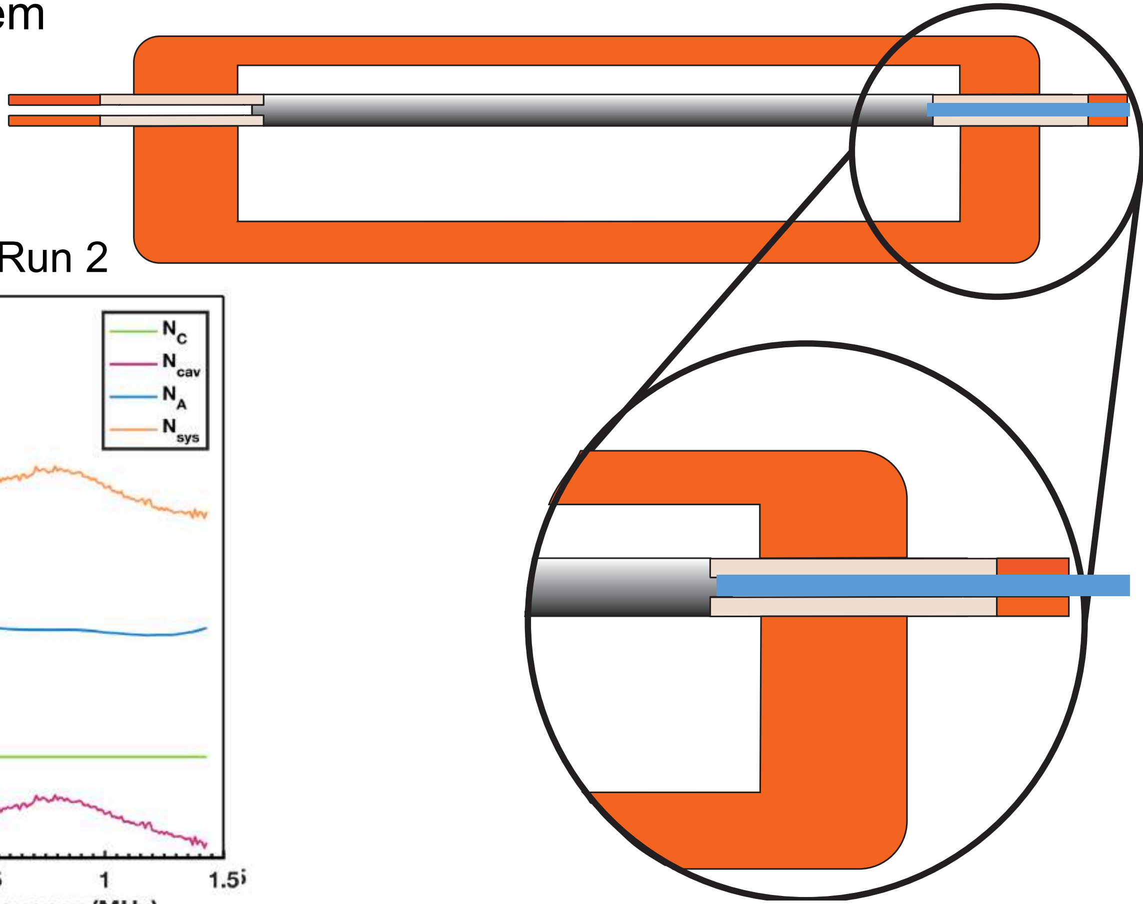


Improved tuning rod thermal link

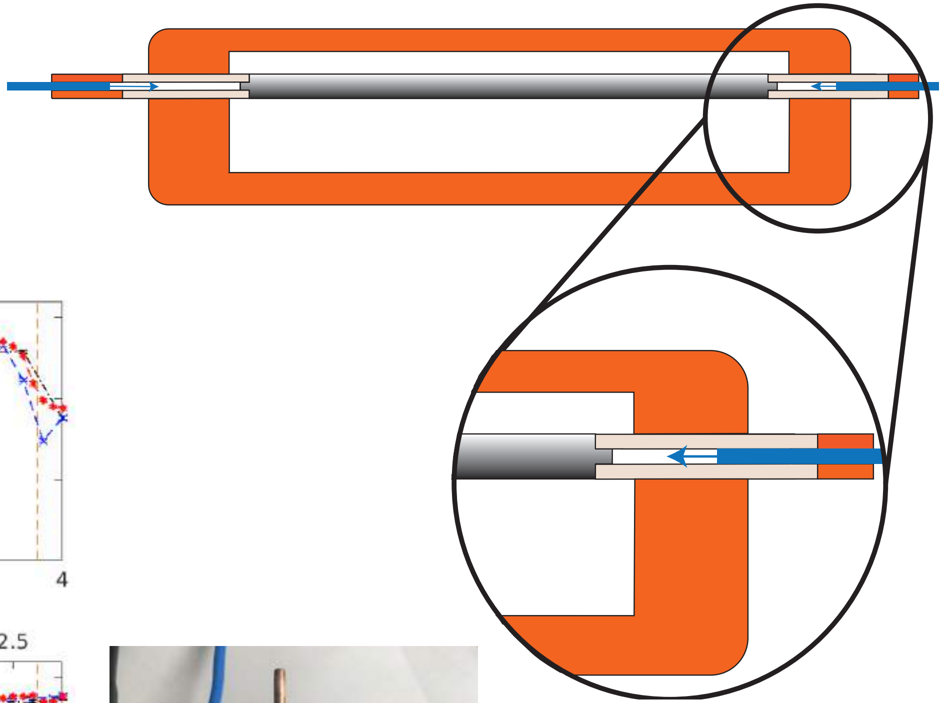
Before:
- Tuning rod thermalization problem fixed in between runs 1 and 2
- Led to reduced 40% Q

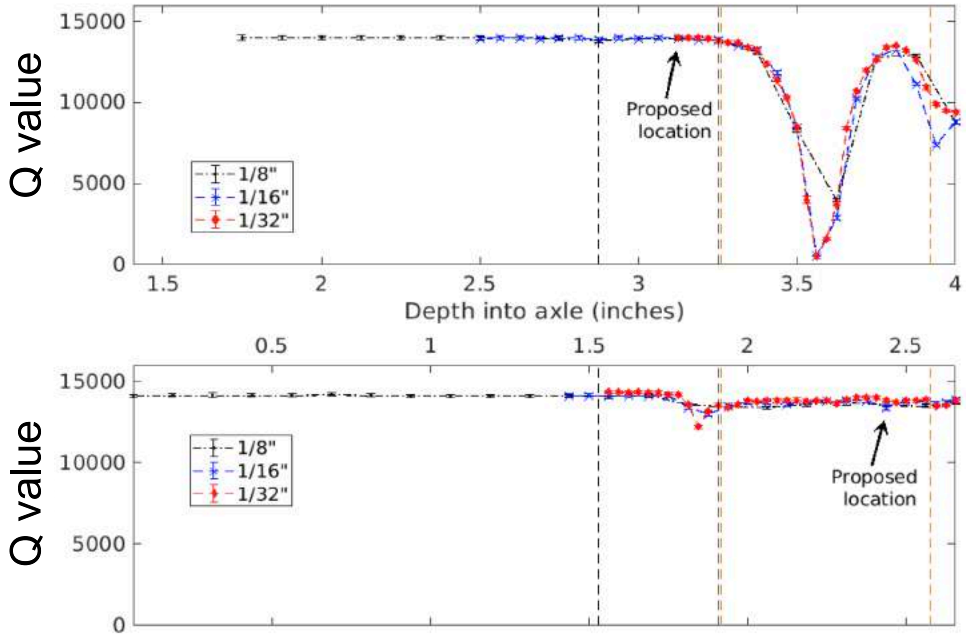




Improved tuning rod thermal link

After:
- No reduction of quality factor





Squeezed state receiver background

$$\mathrm{SNR} = \frac{P_S}{k_B T_S}\sqrt{\frac{\tau}{\Delta\nu_a}}$$

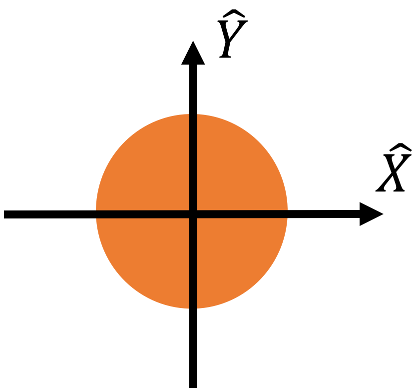
scan rate: $R \propto \mathrm{SNR}^2$

Signal: $\hat{V} = V_0(\hat{X}\cos(\omega t) + \hat{Y}\sin(\omega t))$

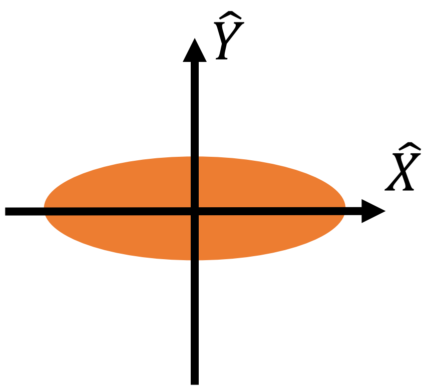
$\hat{X}, \hat{Y}$ are non-commuting observables: $[\hat{X}, \hat{Y}] = i$

Uncertainty: $\mathrm{Var}(\hat{X})\mathrm{Var}(\hat{Y}) \geq 1/4$

Unsqueezed coherent state:



Squeezed state:

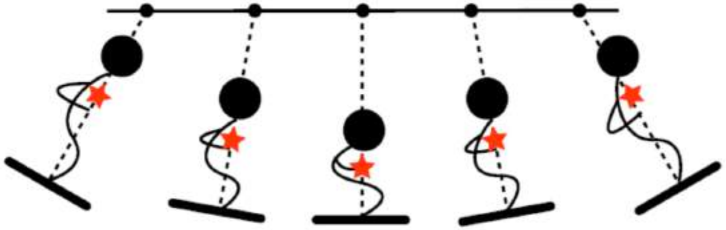


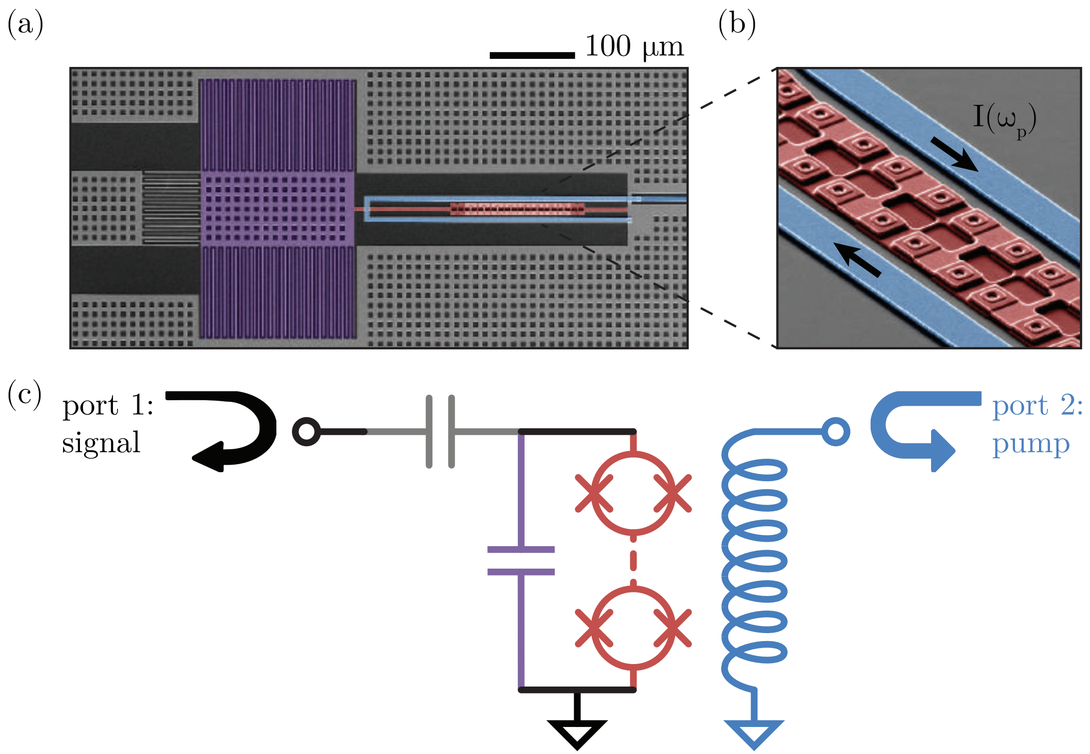
Area of the state is unchanged: No added noise

Squeezed state receiver background

Signal: $\hat{V} = V_0(\hat{X}\sin(\omega t + \phi) + \hat{Y}\sin(\omega t))$

Now a phase-sensitive parametric amplifier can tell the quadratures apart

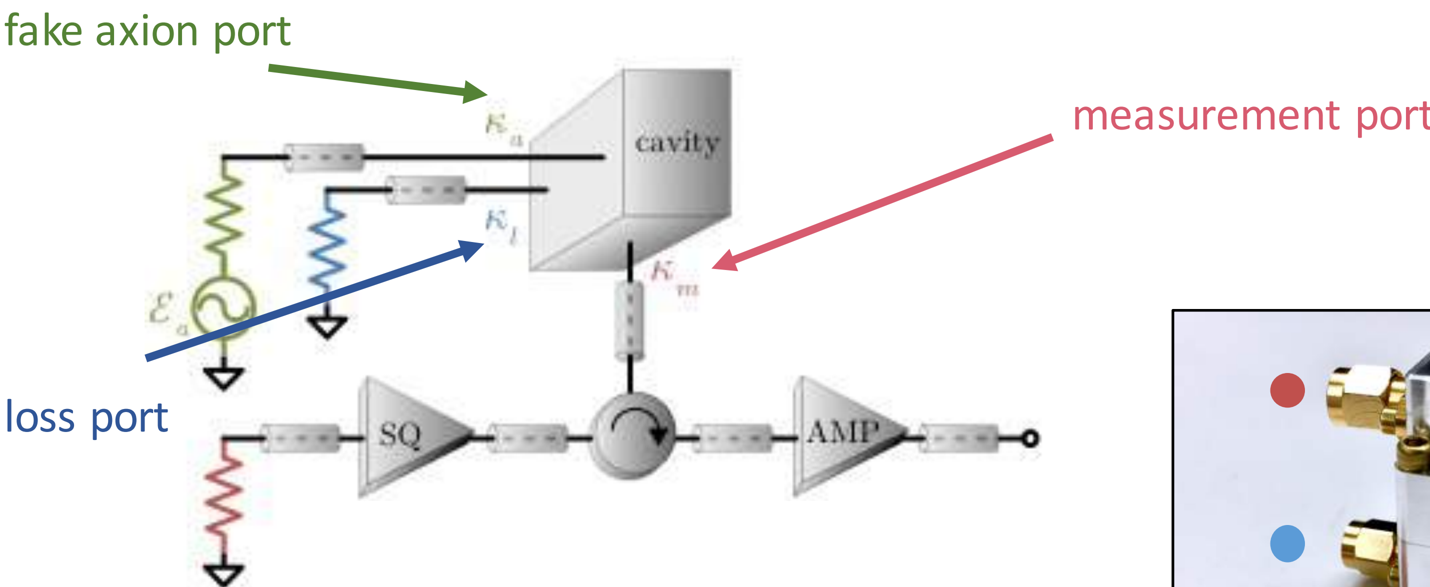


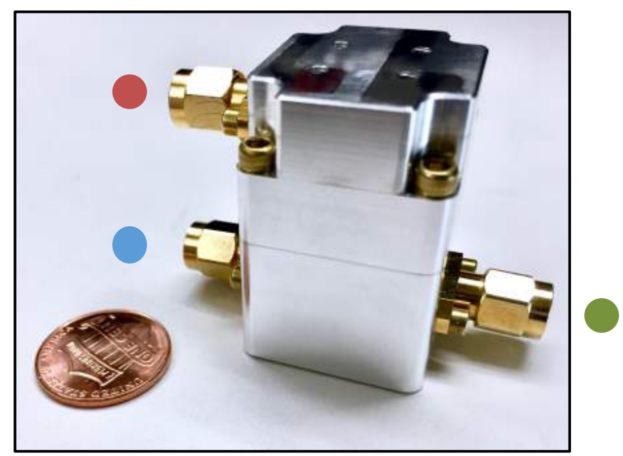


arXiv:1809.06470v1

Mock axion experiment

- Done at CU Boulder as a proof of principle before installing the system in HAYSTAC
- Non-tunable cavity and no magnetic field

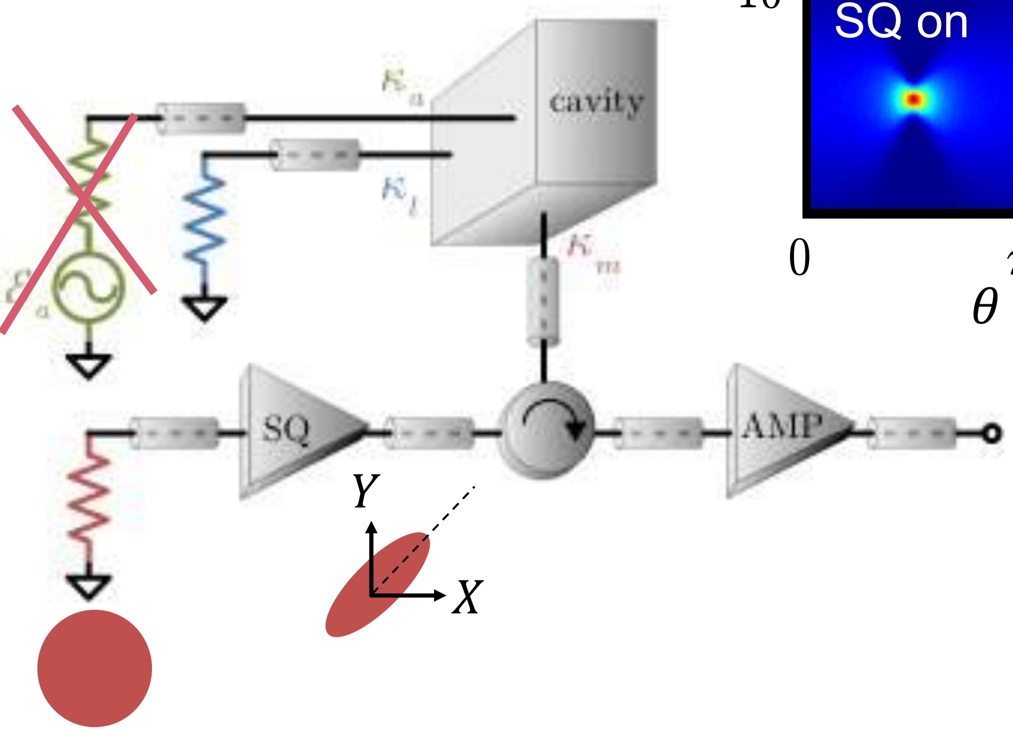


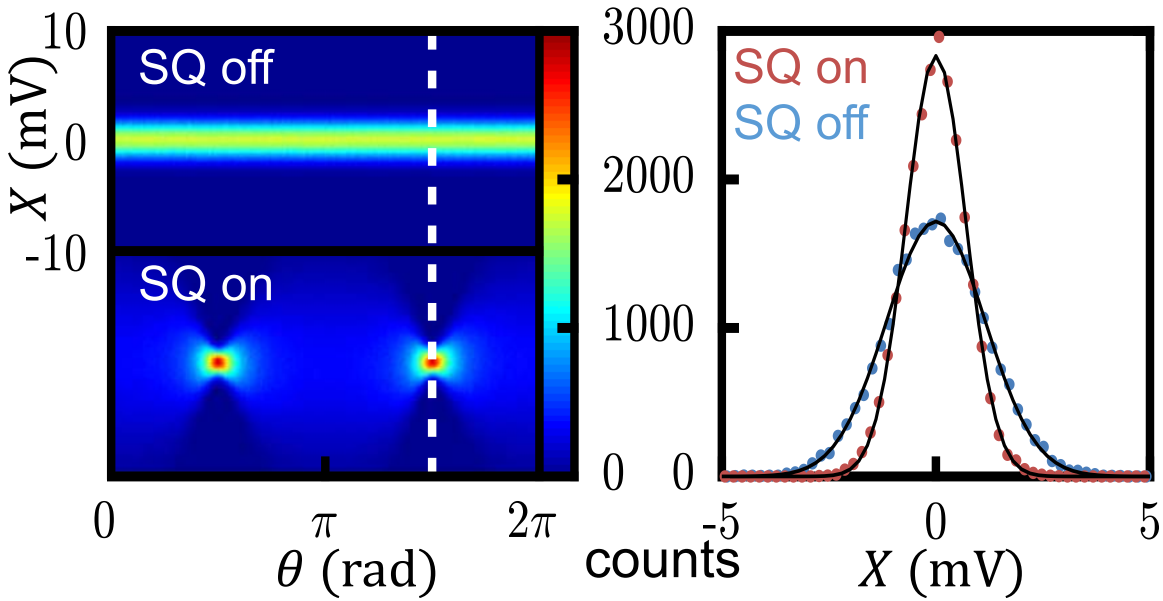


arXiv:1809.06470v1

Squeezing to below vacuum

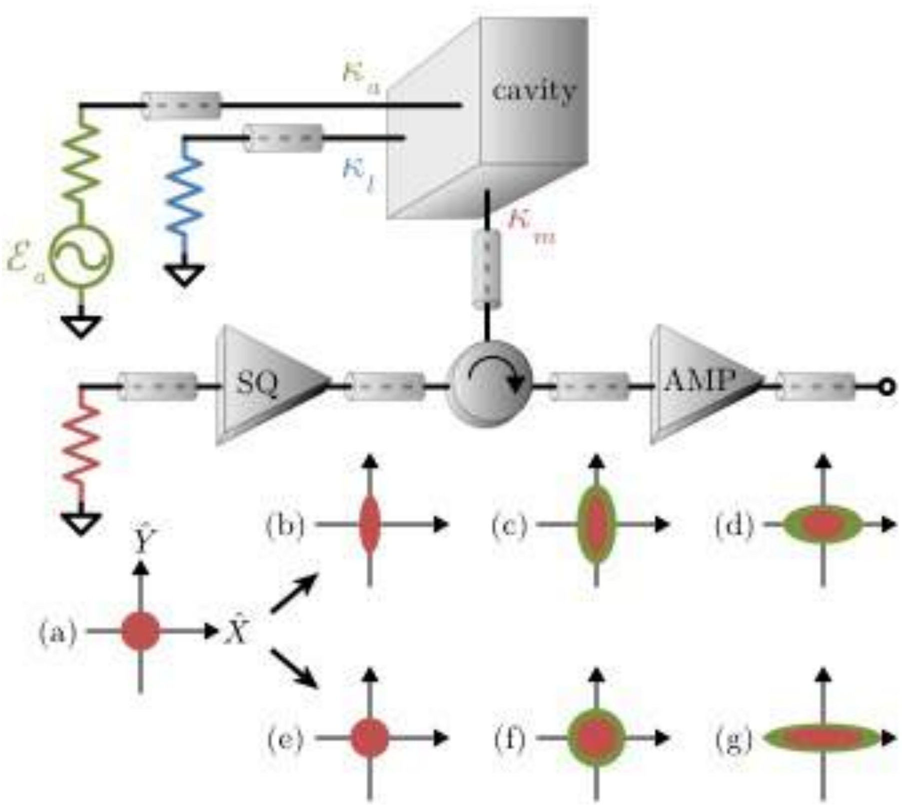
Noise reduced to below vacuum



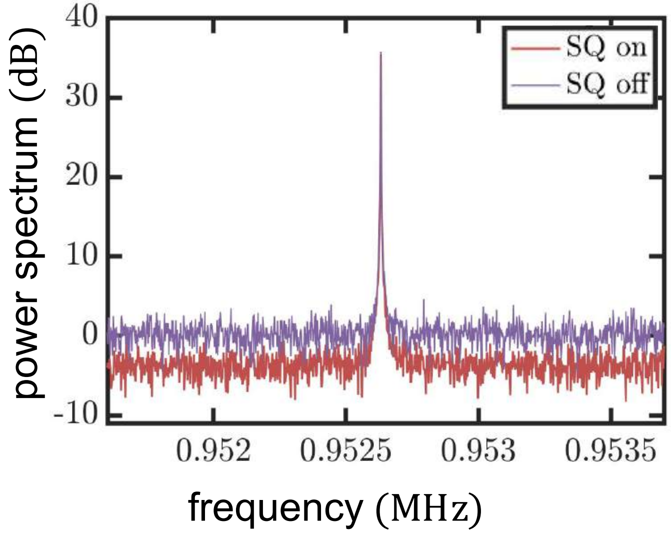


$$\frac{\sigma_{\text{off}}^2}{\sigma_{\text{on}}^2} = 4\ \text{dB}$$

Enhanced signal visibility

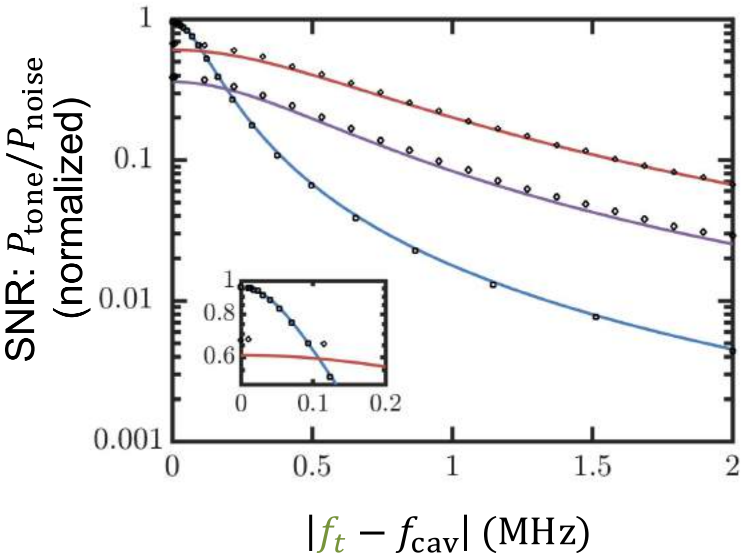


- Large tone is injected into cavity
- Signal read through measurement port and amplified by amplifier JPA



Lower noise floor
Signal remains same height

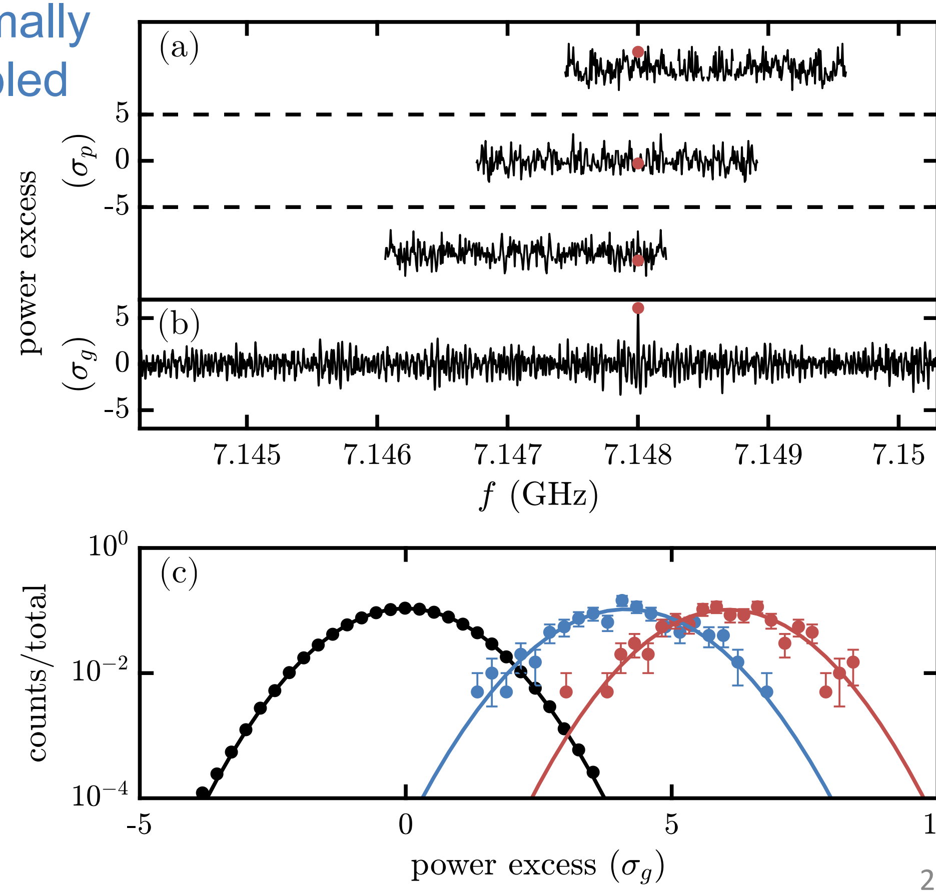
SNR and scan time improvement



squeezed

not squeezed

not squeezed optimally coupled



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

$$\frac{R_{\mathrm{SQ}}}{R_{\mathrm{no\ SQ}}} = 2.3 \pm 0.1$$

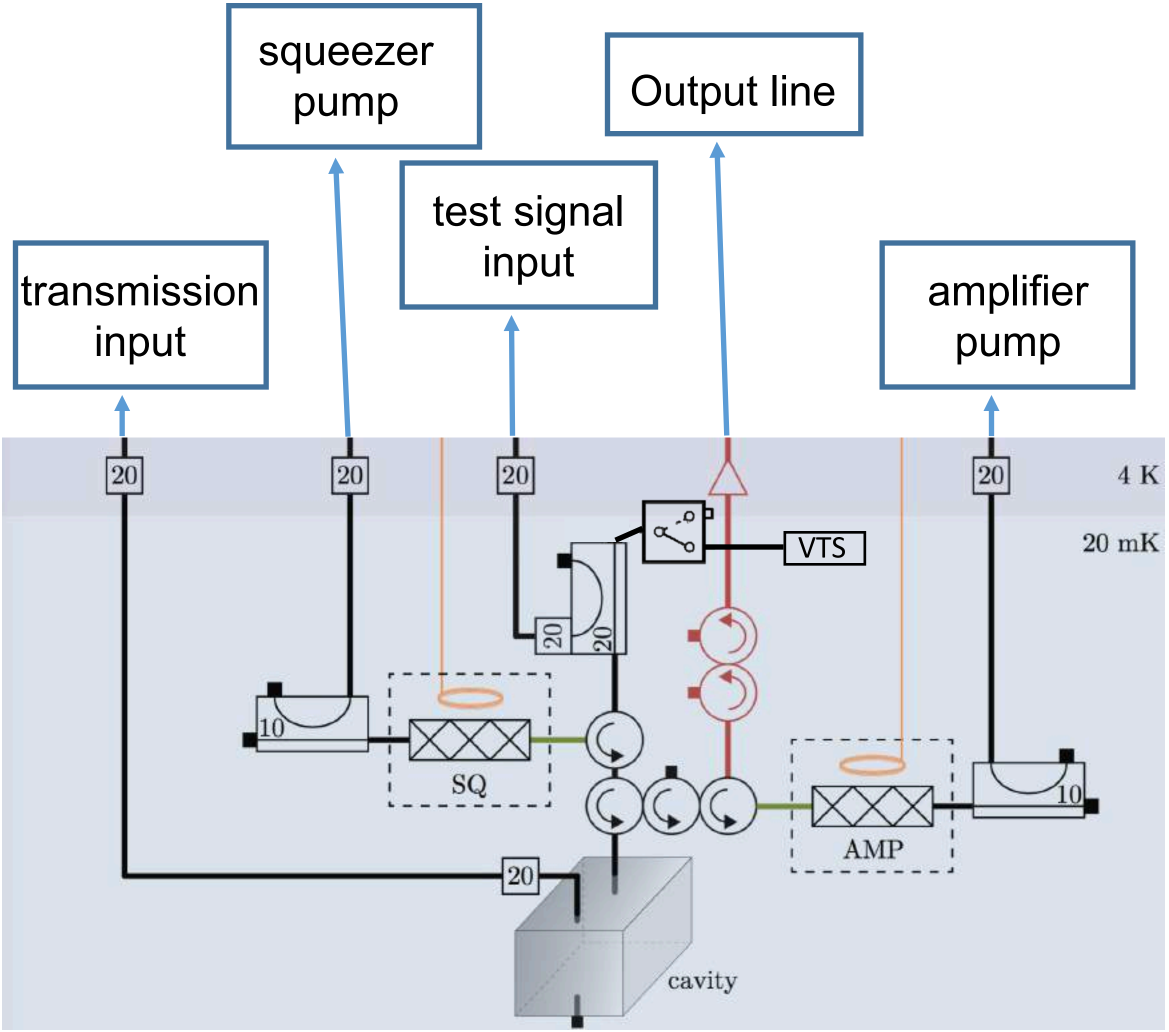
arXiv:1809.06470v1

Single quadrature measurement

- Causes no decrease in SNR

	Signal power per quadrature	Noise power per quadrature	Single quadrature SNR	Final SNR
Single quadrature measurement	$\frac{P_a}{2}$	$\frac{\hbar\omega}{4}$	$\frac{2P_a}{\hbar\omega}$	$\frac{\sqrt{2}P_a}{\hbar\omega}$
Double quadrature measurement	$\frac{P_a}{2}$	$\frac{\hbar\omega}{2}$	$\frac{P_a}{\hbar\omega}$	$\frac{\sqrt{2}P_a}{\hbar\omega}$

Microwave layout

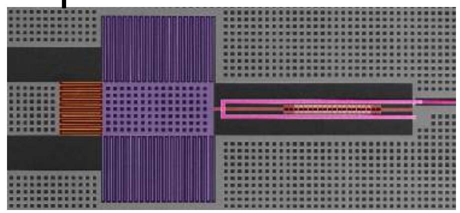


Key differences:

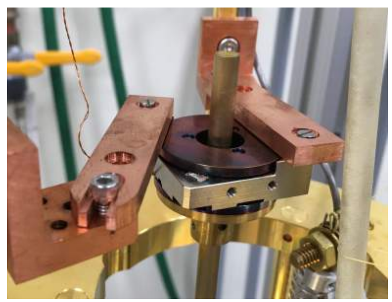
- Five input-output lines
- Squeezer injects squeezed vacuum into cavity
- Switch for variable hot load and cold load for calibration
- Only one quadrature used for analysis

The phase 2 HAYSTAC detector

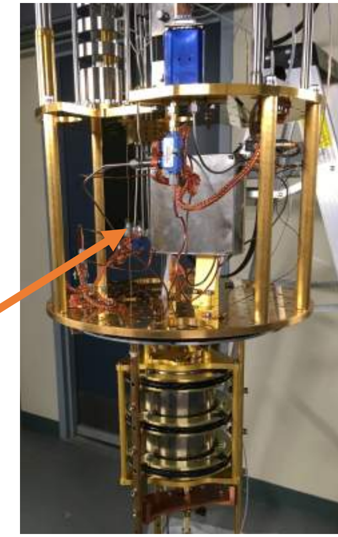
Josephson parametric amplifiers



Piezoelectric tuning



microwave cavity



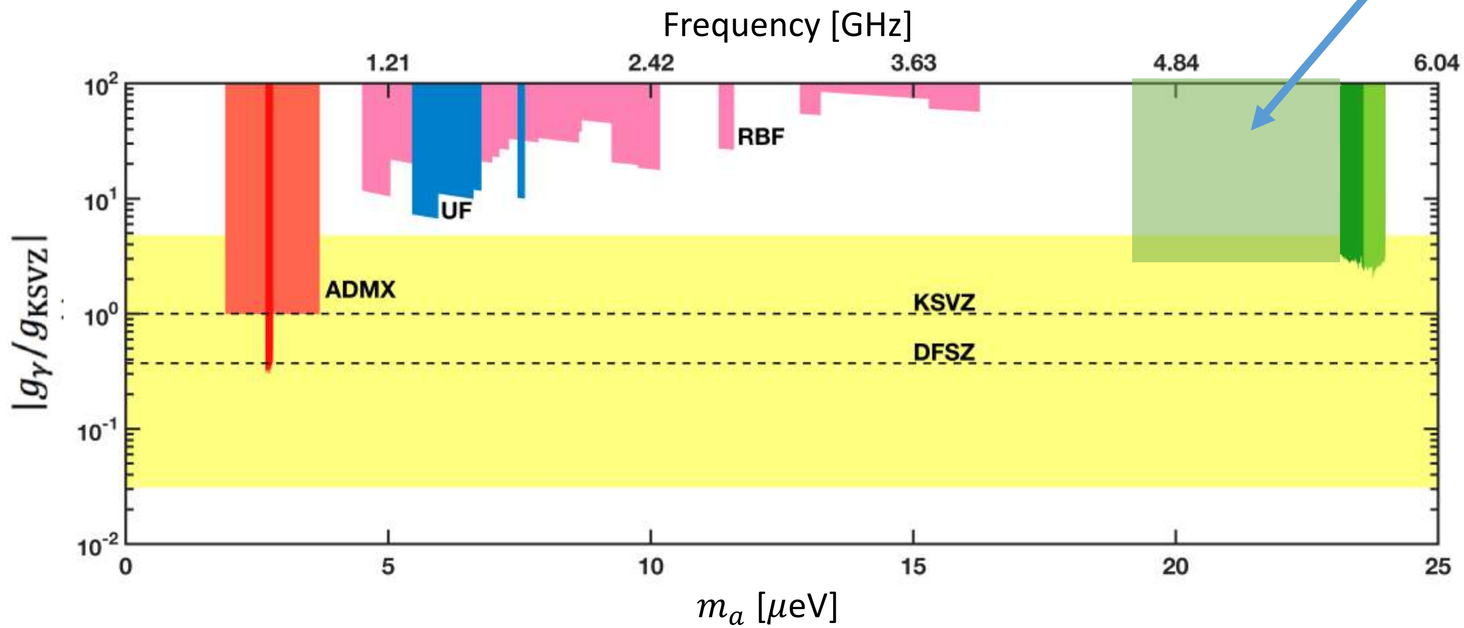
5 port circulator

9 T dry magnet

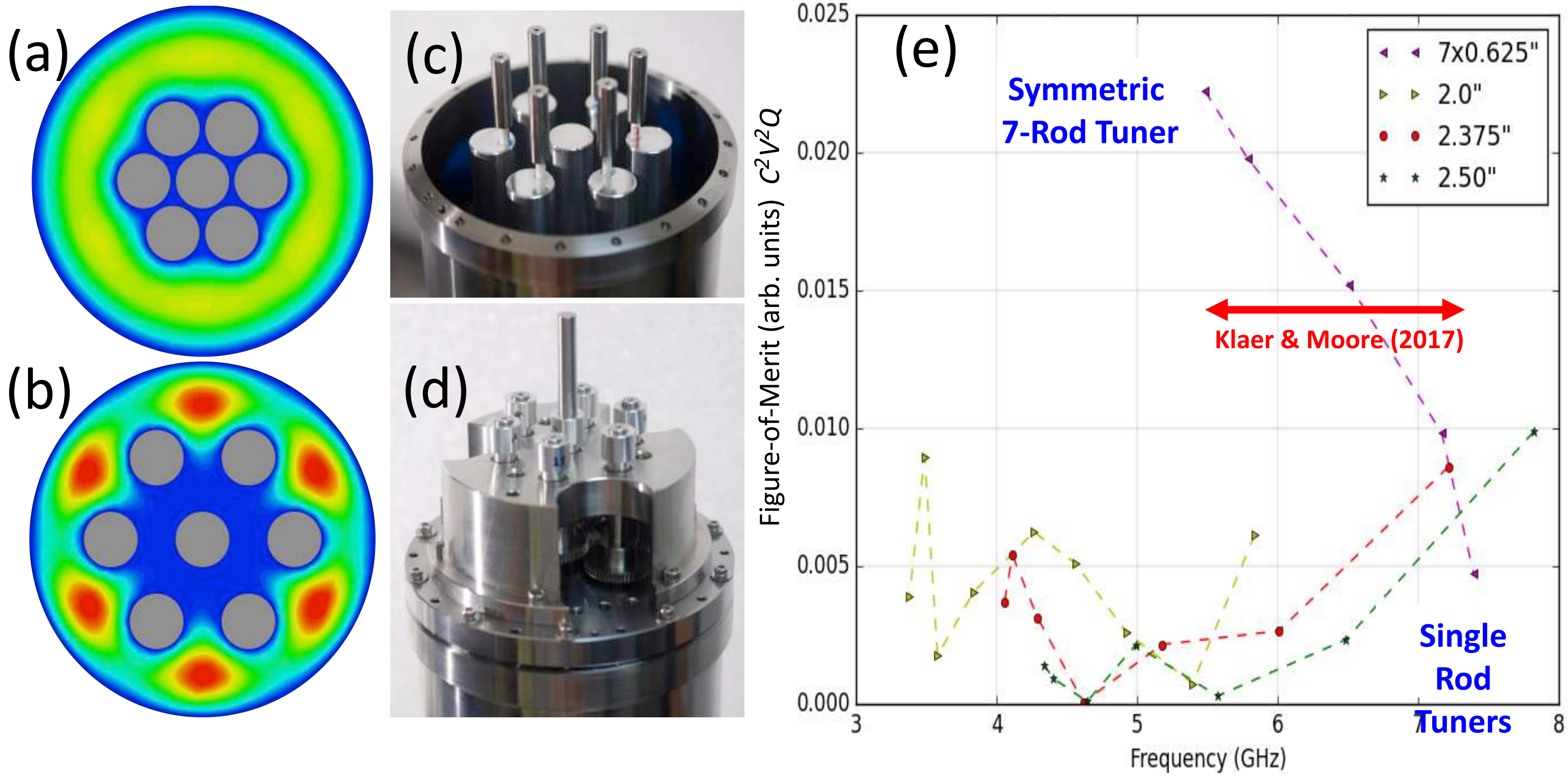
Expectations for Phase 2

- Integrate the Boulder SSR into HAYSTAC
- Continuing to explore in our 4-8 GHz range of interest
- Scan at comparable depth to our Phase 1 results – wide and fast
- Show that haloscope scan-rates can continue to be improved through synergy with quantum information

HAYSTAC projected



Seven rod cavity



- Will cover 5.48-7.41 GHz (22.7-30.7 µeV)
- Same cavity volume
- Currently being tested to find the “usable range” and study mode crossings

Future plans

single photon detection:

- Considering two methods: qubits and Rydberg atoms
- Above 10 GHz, single photon detection wins out over phase sensitive detectors

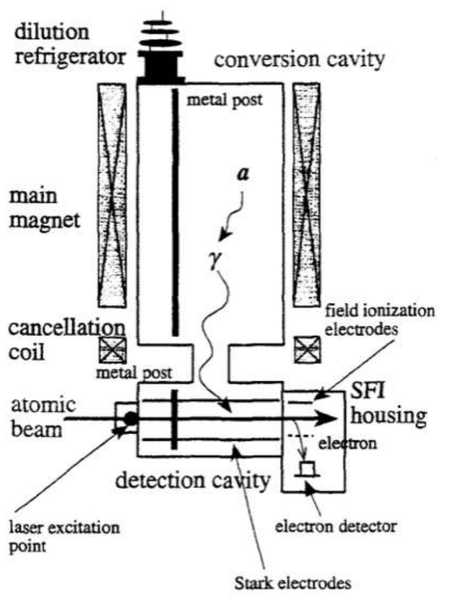
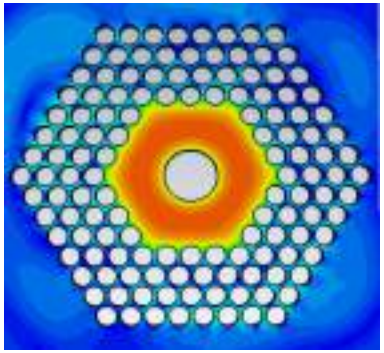


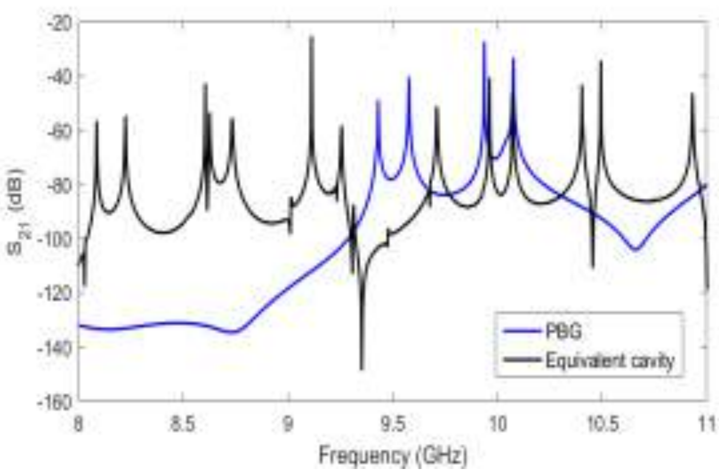
Figure 1. Schematic diagram of CARRACK II experimental system.

M. Tada, *et al.* Nuc. Phys. B 72, 164 (1999)

Photonic bandgap cavities:

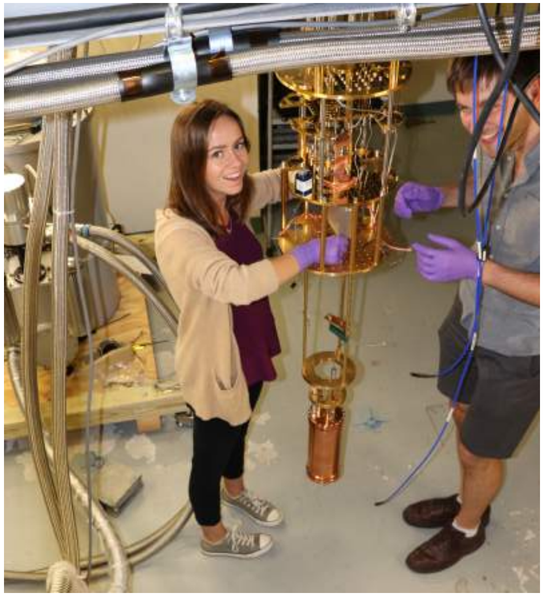
- Can reach higher frequencies without mode crossings

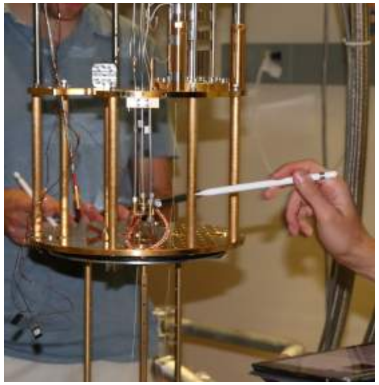


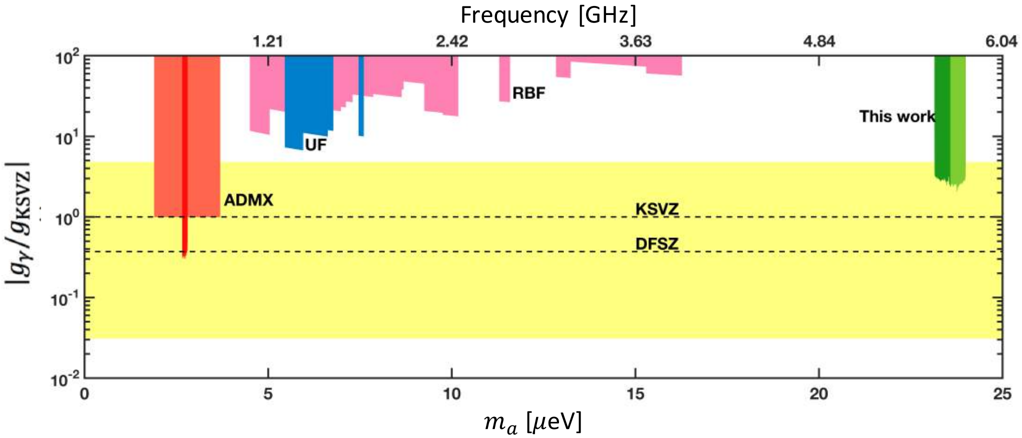


Conclusion

- Phase 1 was run with a single-rod copper cavity and a single JPA
- Phase 1 excluded axions with coupling of $|g_\gamma| \geq 2.7 \times |g_\gamma^{\mathrm{KSVZ}}|$ over $23.15 \leq m_a \leq 24\ \mu\mathrm{eV}$
- Squeezed state receiver allows for noise below standard quantum limit and faster scan times
- HAYSTAC will continue to serve as a development testbed for new technology







Further reading:

Squeezed state receiver: arXiv:1809.06470v1 (2018)

Phase 1 results: Rev. D 97, 092001 (2018).

Analysis: Phys. Rev. D 96, 123008 (2017).

First results: Phys. Rev. Lett. 118, 061302 (2017).

Instrumentation: Nucl. Instrum. Methods A 854, 11 (2017).

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Collaboration:

Yale: Kelly Backes, Danielle Speller, Yong Jiang, Sidney Cahn, Reina Maruyama, Steve Lamoreaux

Colorado: Daniel Palken, Maxime Malnou, Konrad Lehnert

Berkeley: Maria Simanovskaia, Samantha Lewis, Saad Al Kenany, Nicholas Rapidis, Isabella Urdinaran, Alex Droster, Karl van Bibber

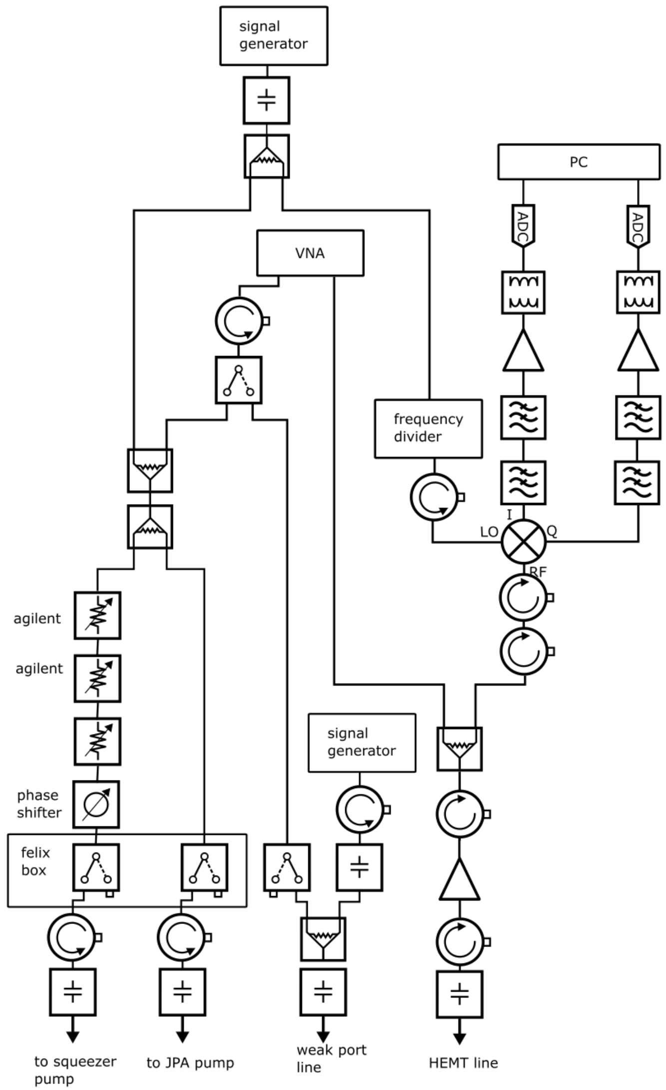
Haystac

NSF

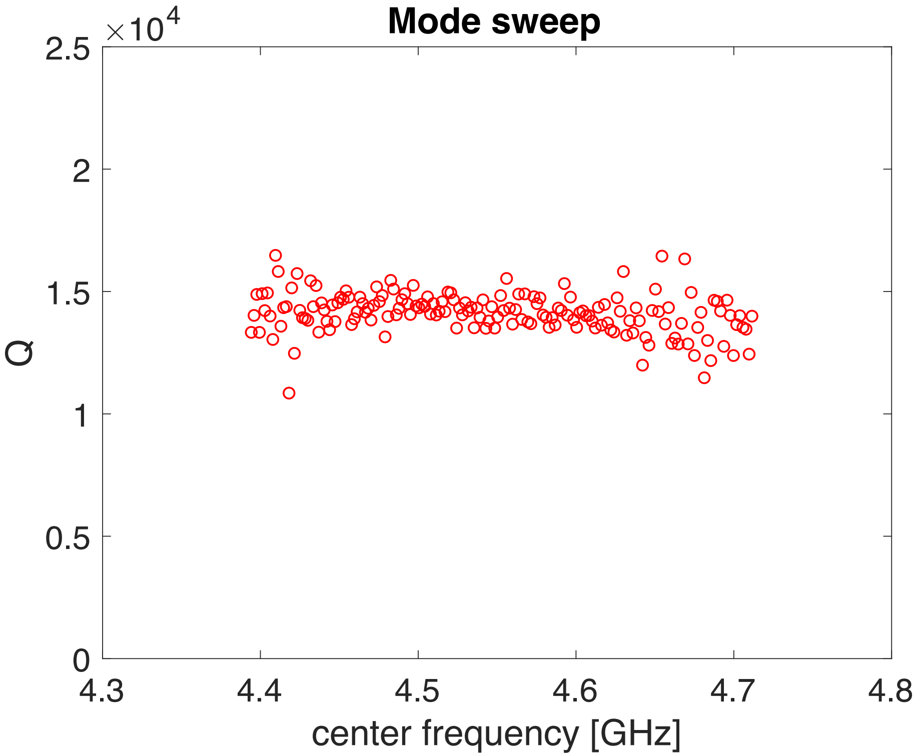
HEISING - SIMONS FOUNDATION

*Sid Cahn and Konrad Lehnert not pictured

Room-temp microwave layout



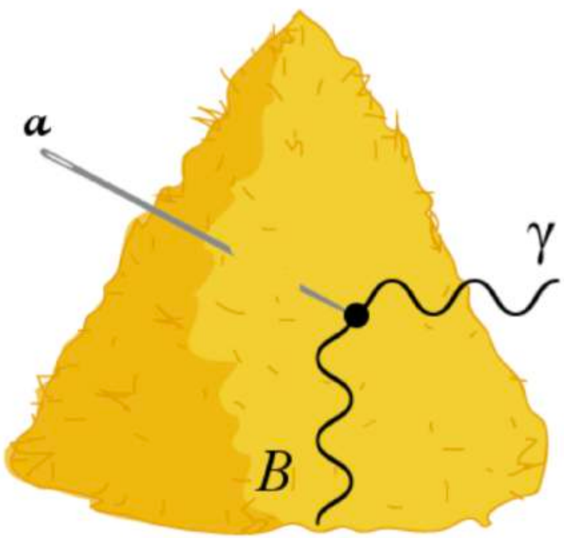
Cavity Q

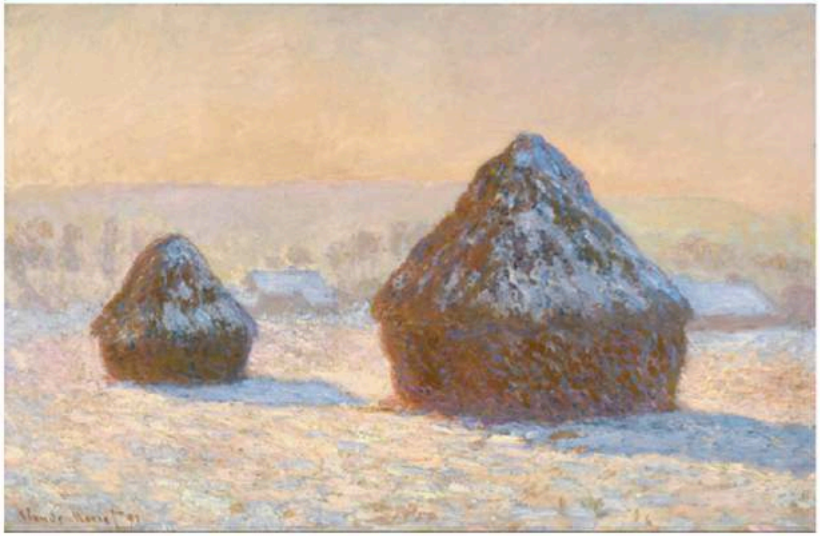


Mode sweep
×10^4
2.5
2
1.5
1
0.5
0
Q
4.3
4.4
4.5
4.6
4.7
4.8
center frequency [GHz]

A needle in a HAYSTAC

Haystac



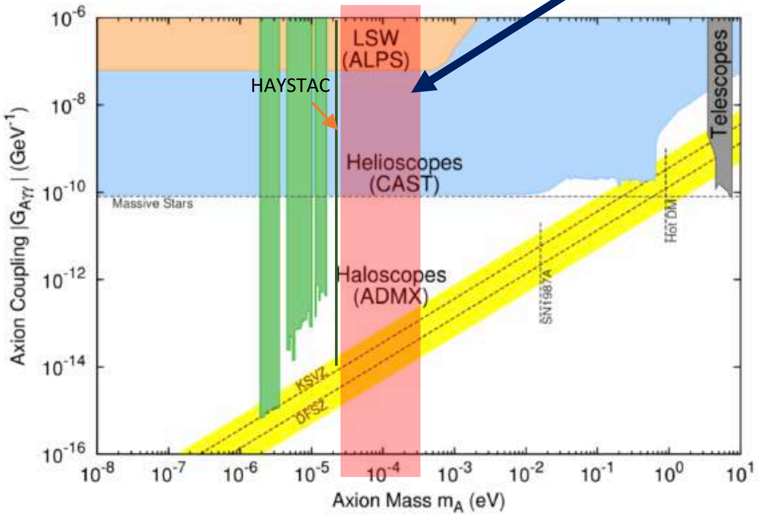


Motivation for a haloscope at high frequency

Astrophysical:

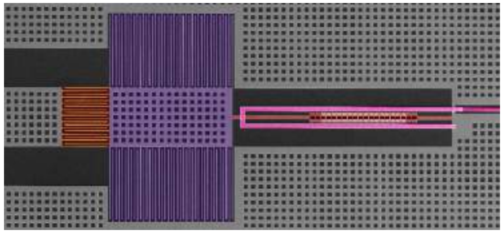
- Peccei Quinn symmetry broken after inflation: $m_a > 28\ \mu\text{eV}$
(Nature 539, 69)
- SMASH model:
$50\ \mu\text{eV} \leq m_a \leq 200\ \mu\text{eV}$
(arXiv:1610.01639)
- V.B. Klaer, G. Moore:
$m_a = 26.2 \pm 3.4\ \mu\text{eV}$
(arXiv:1708.07521)

6.33 GHz to 48 GHz



Experimental:

- Simplified cryogenics and smaller magnet



- Josephson parametric amplifiers (JPAs) work well in the 2-12 GHz range (Phys. Rev. Applied 9, 044023)