HAYSTAC

Haloscope at Yale Sensitive to Axion CDM (HAYSTAC) Overview and Phase II Upgrades

3rd Workshop on Microwave Cavities and Detectors for Axion Research @LLNL
08/22/18

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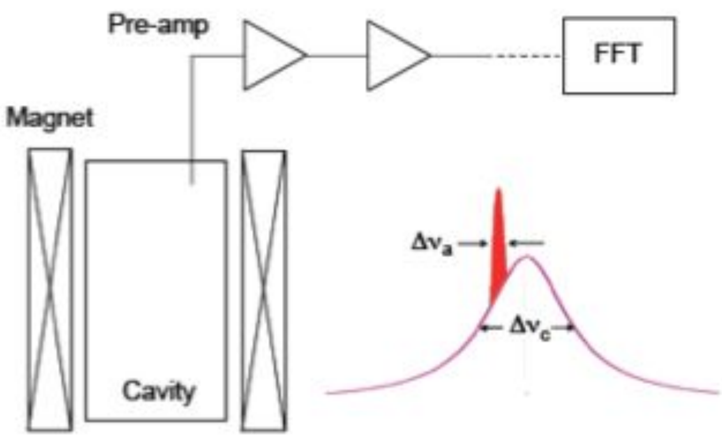
Outline

I. Reprise of microwave cavity experiment
II. HAYSTAC Description
III. Phase I Results
   - Exclusion plot
   - Hot rod problem
IV. Phase II Upgrades and Outlook
   - Improved cryogenics
   - Squeezed State Receiver (SSR)
V. Future Plans
   - PBGs and Metamaterials

Microwave Cavity Reprise

Cavity Experiment Overview

Axion detection – quantitative details



Cavity Bandwidth: $\Delta\nu_c / \nu_c = Q^{-1} \sim 10^{-4}$

Axion Bandwidth: $\Delta\nu_a / \nu_a \sim \beta^2 \sim 10^{-6}$

Conversion Power: $P \sim g_{a\gamma\gamma}^2 (\rho_a / m_a) B^2 Q_c V C_{nm\ell} \sim 10^{-23}$ watt

Signal to Noise Ratio: $$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

System Noise Temperature: $$kT_S = h\nu\left(\frac{1}{e^{h\nu/kT}-1}+\frac{1}{2}\right)+kT_A$$

Note $T_S \approx T + T_A$, for $T >> h\nu$

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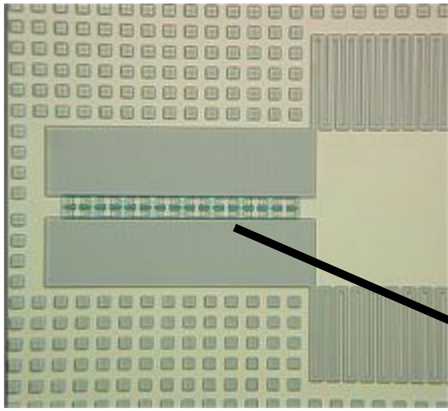
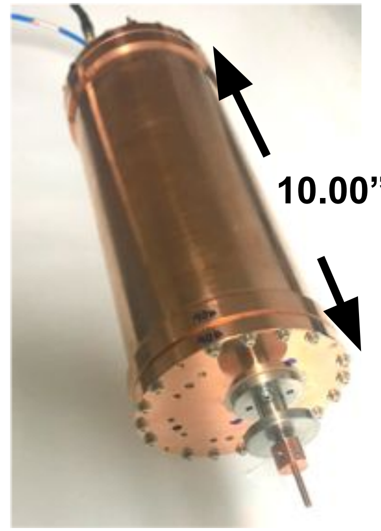
HAYSTAC Description

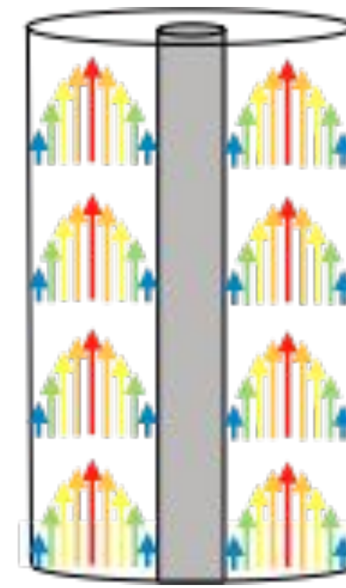
HAYSTAC Phase I Hardware

Josephson Parametric Amplifier

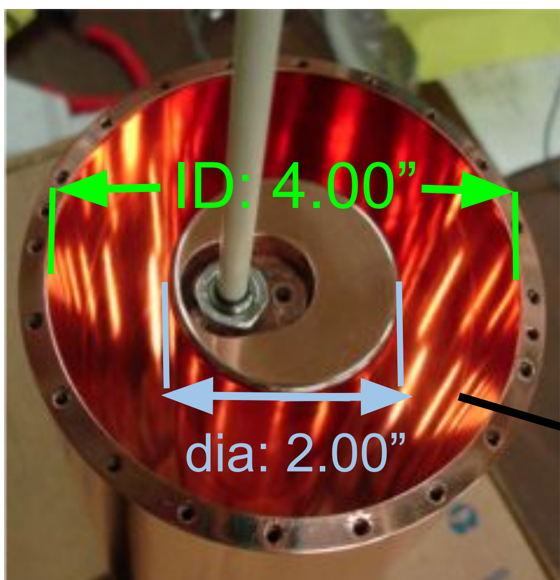




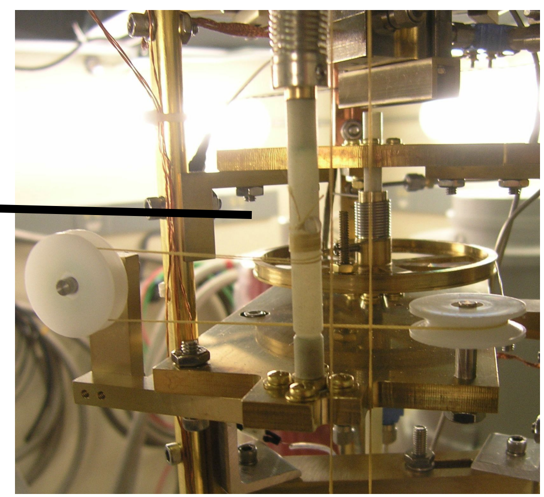
TM$_{010}$-like mode:
3.6-5.8GHz



Copper microwave cavity



Piezoelectric tuning mechanism



S. Al Kenany, *et al*, NIM A**854** (2017), 11-24.

Cryostat and Magnet

Cryostat

- Oxford dilution refrigerator
- Cooling power: 150 μW @127 mK
- Time to reach base temp (with load): ~3 days

Magnet

- Cryomagnetics, Inc
- Strength: 9 T
- Field strength near JPA (with shielding): B ~ 1×10^{-3} G
- ~8 hours to ramp from 0 to 9 T

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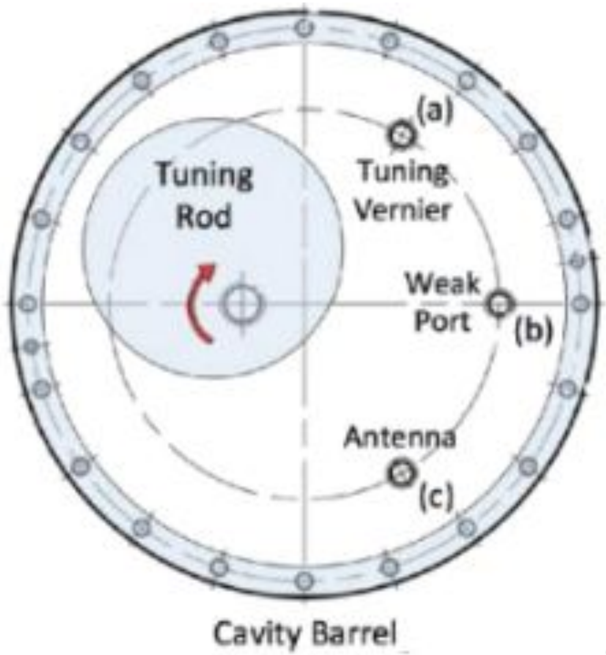
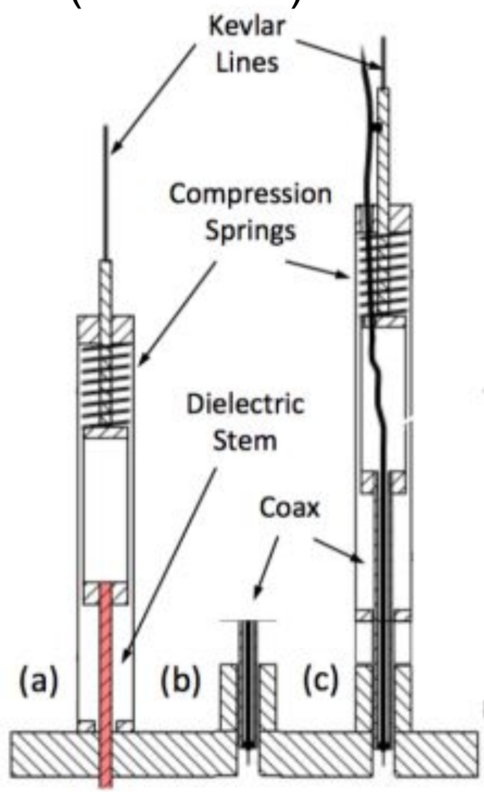
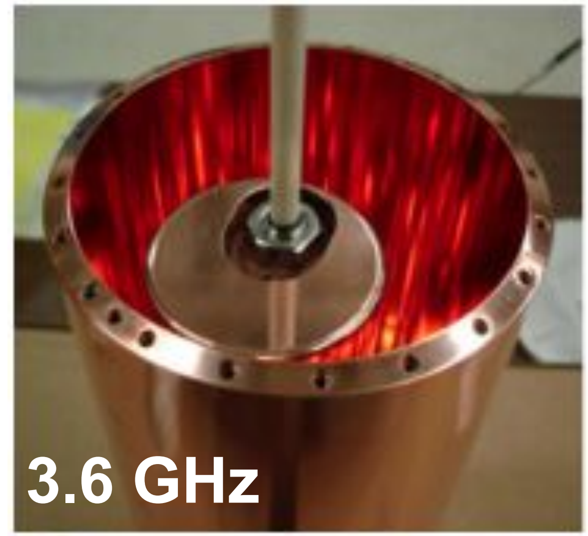
HAYSTAC Cavity and Tuning Mechanism

- **Copper plated** stainless steel cylinder
- **Off-axis copper rod** tunes in 100 kHz steps
- **Attocube** piezoelectric for rotary motion
- **Linear drives** for antenna insertion and dielectric insertion (fine tuning)
- Quality factor (cold, unloaded): **Q ~ 30,000**
- Form factor of TM_{010}-like mode (simulated): **C ≈ 0.5**





S. Al Kenany et al, NIM 854 (2017), 11-24



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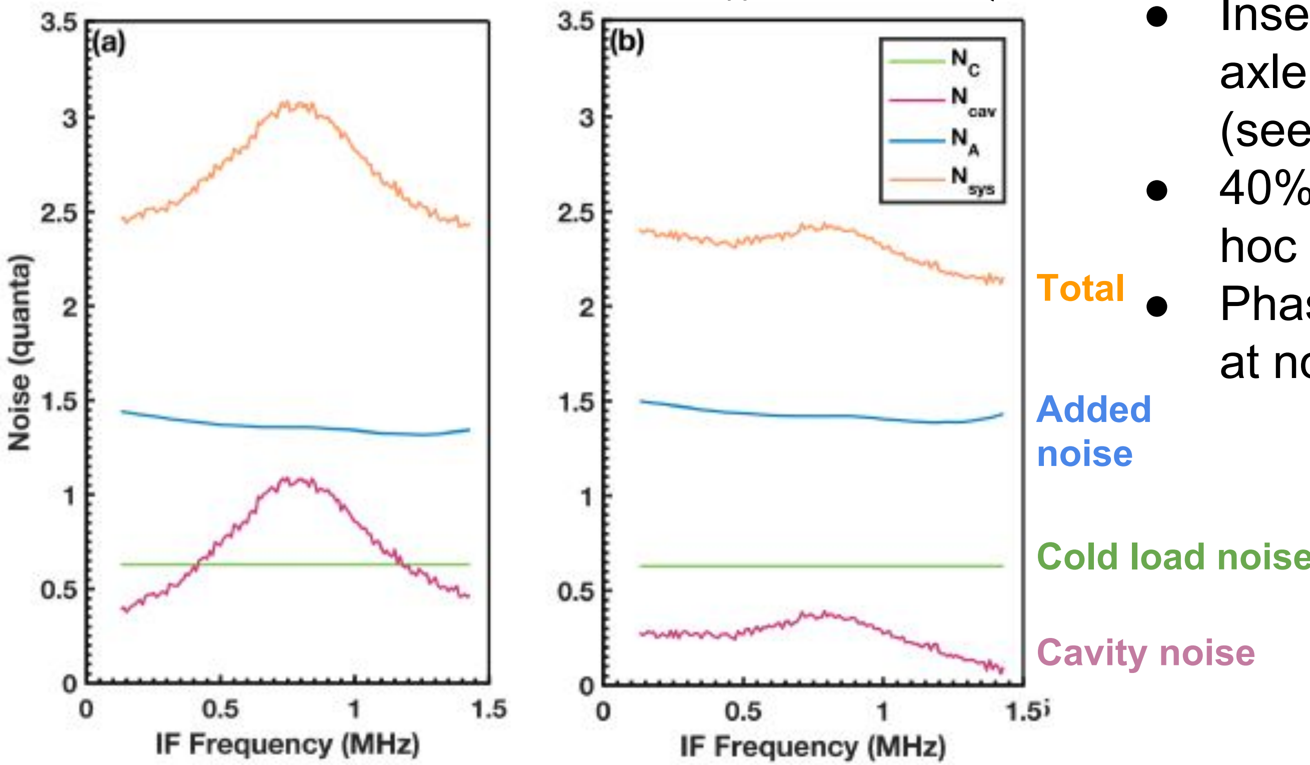
Hot Rod Problem and ad hoc Solution

Run 1 (without fix)
- T_{Rod} = 600mK

Run 2 (with ad hoc fix)
- T_{Rod} = 250mK
- 40% reduction in Q

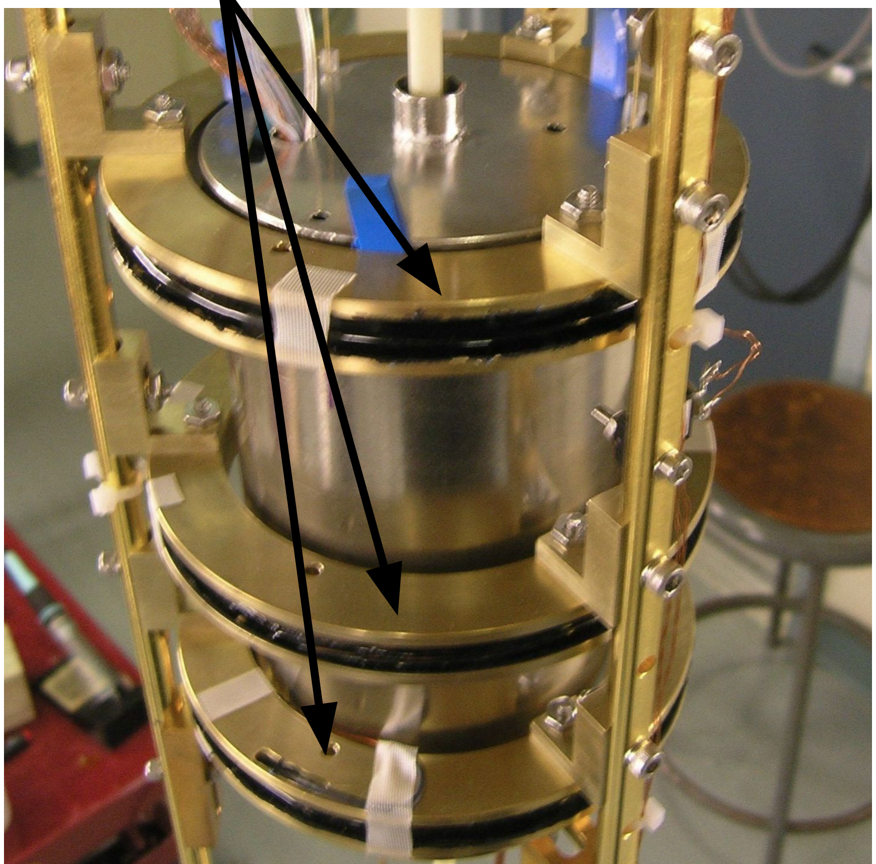


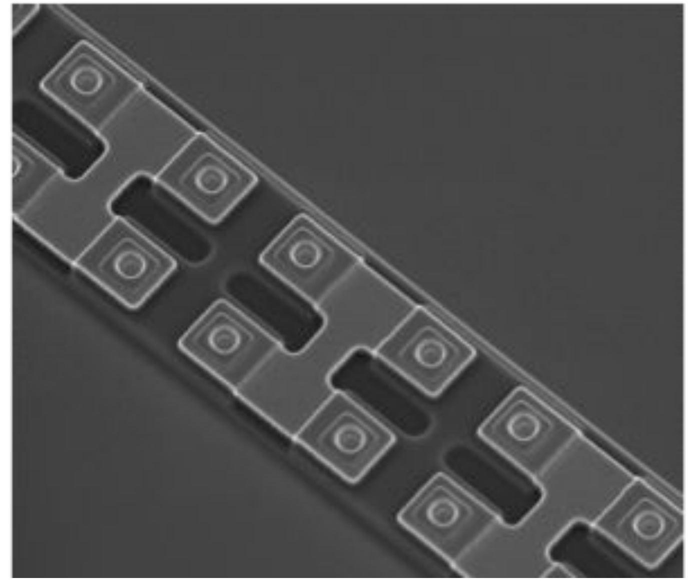
- Excess noise due to tuning rod failing to reach base temperature
- Inserting copper rods into the axle mitigated this problem (see figure)
- 40% reduction in Q due to ad hoc solution
- Phase II will solve this problem at no expense to Q

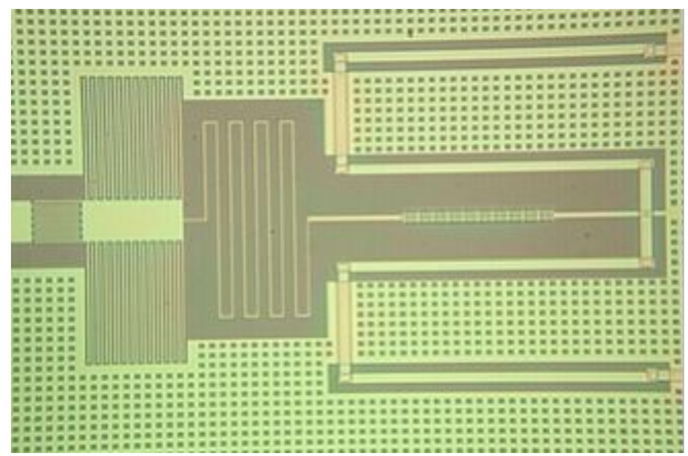
L. Zhong *et al.*, Phys. Rev. D 97 (2018) 092001

Phase I Amplifiers

- Single JPA
- 20 dB gain, quantum limited
- Tunable over 4.4-6.5 GHz
- Persistent coils for magnetic shielding







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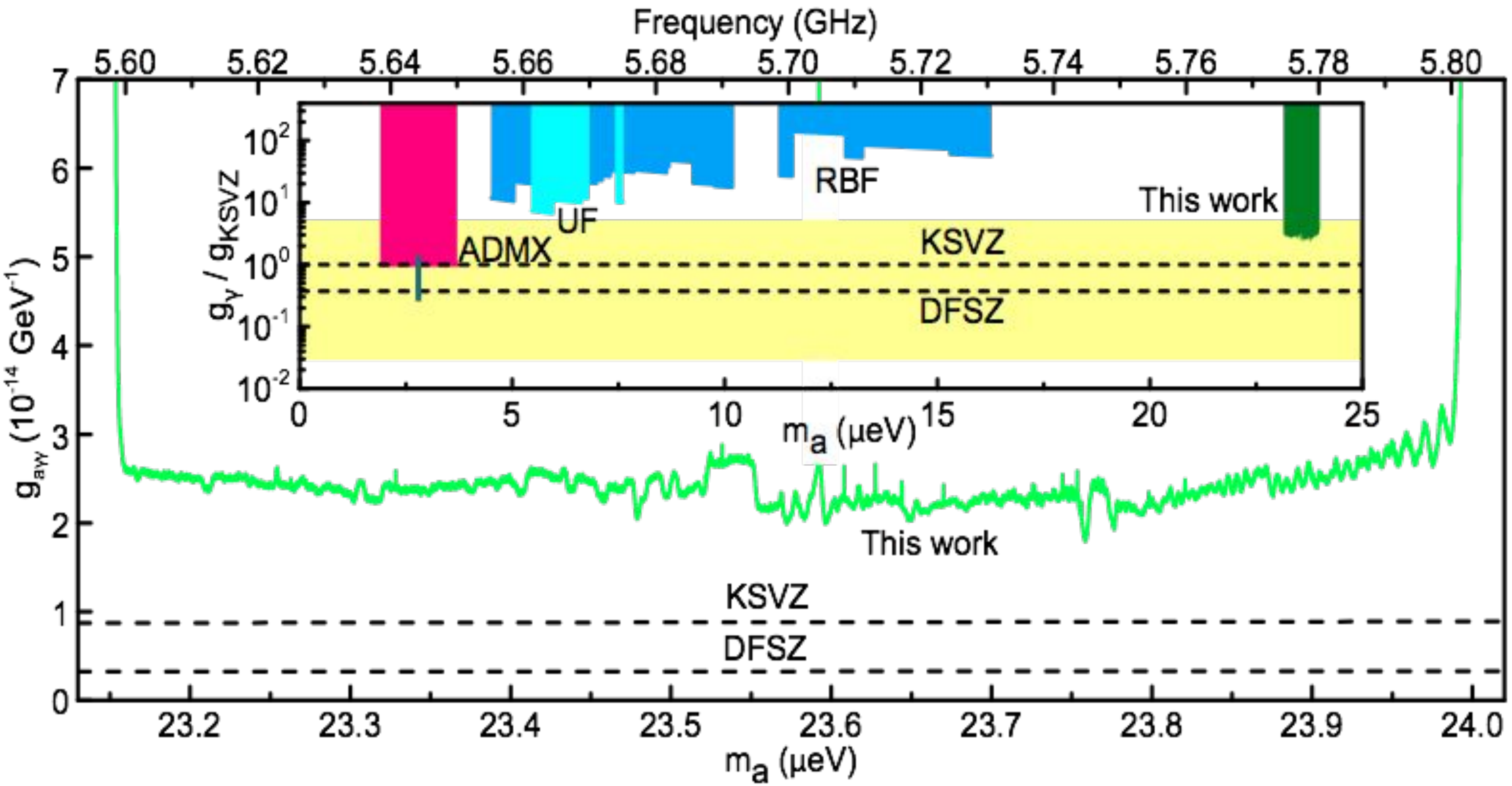
Phase I Results

Results from Phase I (2016-17)



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

L. Zhong *et al.*, Phys. Rev. D 97 (2018) 092001

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Results from Phase I (2016-17)

- Exclusion of $|g_{\gamma}| \geq 2.7 \times |g_{\gamma}^{KSVZ}|$ for mass range $23.15 \leq m_a \leq 24.00$ μeV
  - First exclusion of QCD axion over 20 μeV

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Phase II Upgrades and Outlook

Phase II Improvements

ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	21	240
20	83	960

Phase I

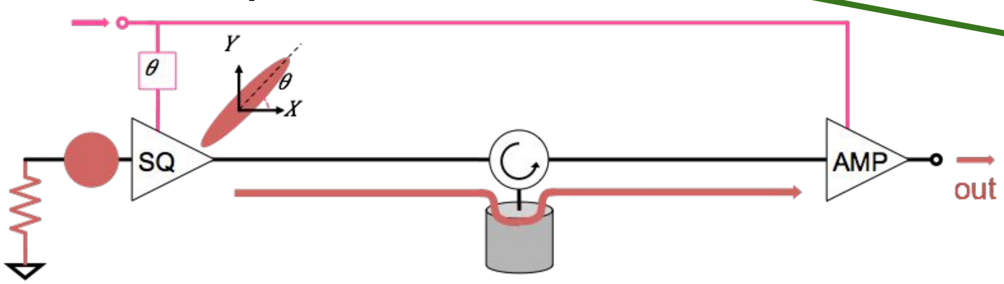
- Data run 1: $T_{SYS} \sim 3 \times T_{SQL}$
- Data run 2: $T_{SYS} \sim 2 \times T_{SQL}$ (40% reduction in Q due to ad hoc thermal link)

} Hot rod problem

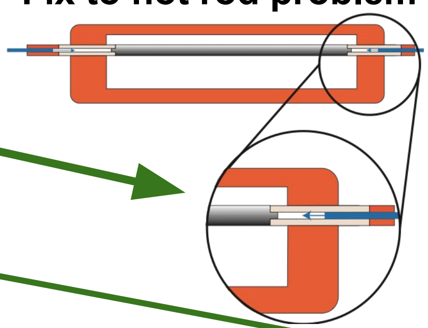
Phase II Improvements

$$\mathrm{SNR} = \frac{P}{k_B T_S}\sqrt{\frac{t}{\Delta\nu_A}}, \quad P \propto Q$$

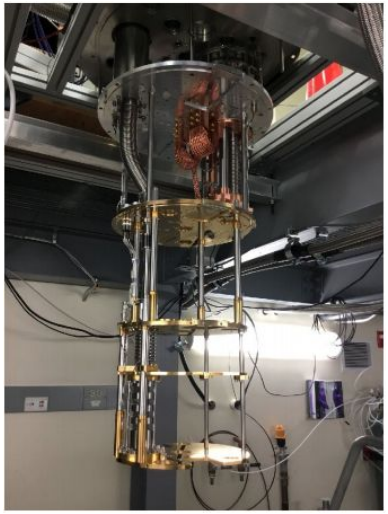
Squeezed State Receiver



Fix to hot rod problem



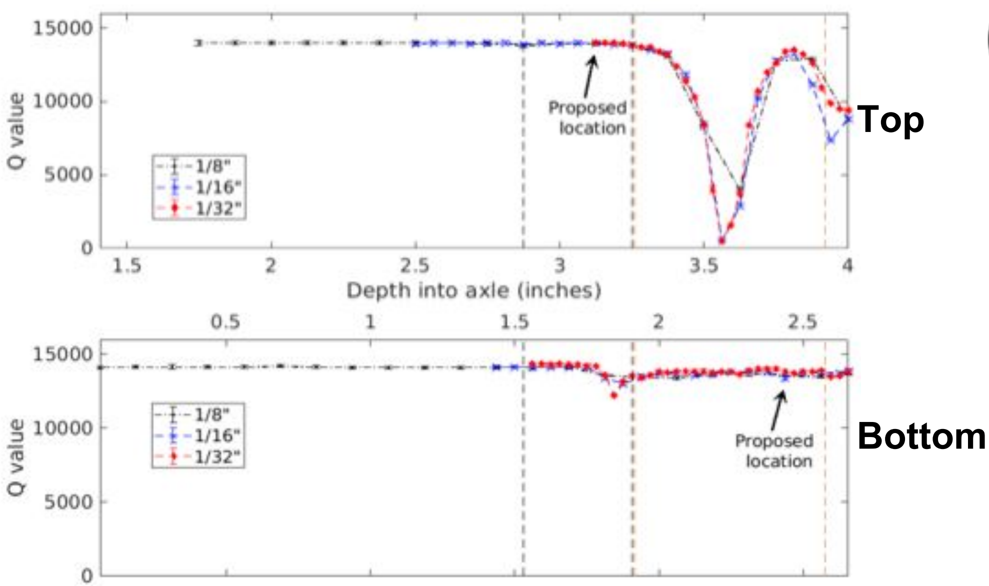
New dil fridge

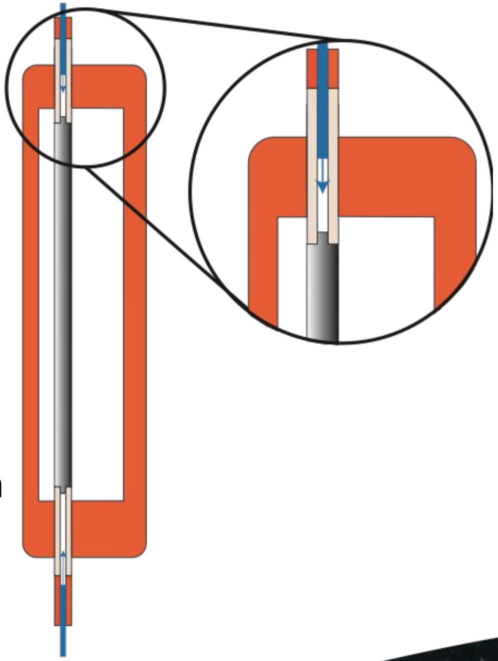


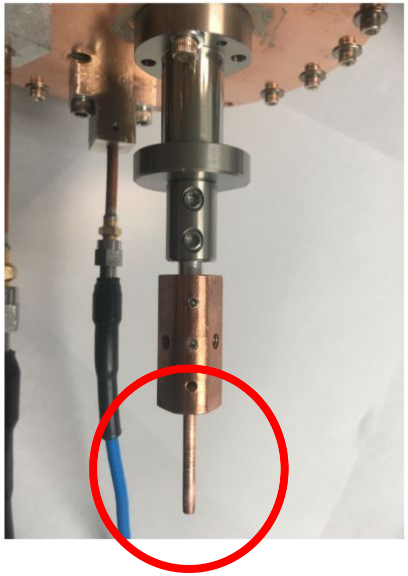
Improved Cryogenics

- **Cavity axle realigned** for smoother tuning ⇒ reduced thermal noise for each tuning step
- New **tuning rod thermal link** solves hot rod problem with no reduction in Q

Q vs insertion depth

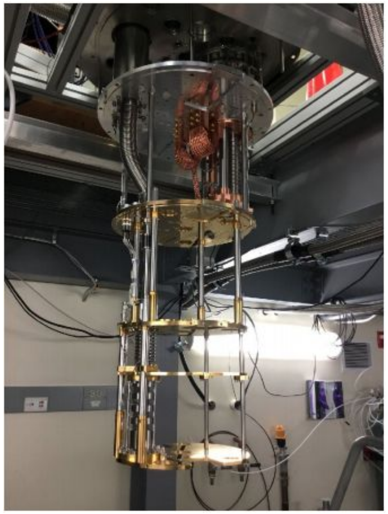


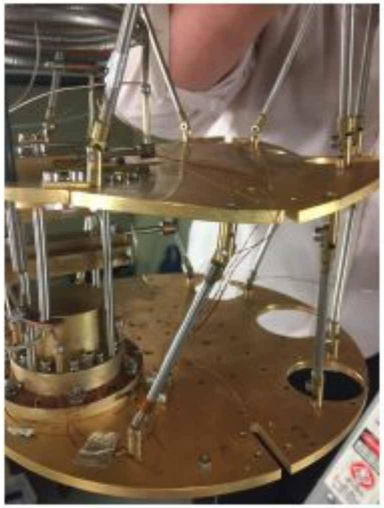




Improved Cryogenics, cont’

- New **BlueFors LD250** dil fridge
  - Improved vibration isolation ⇒ reduced thermal noise
  - 460 μW cooling power @100mK
- New **variable temperature stage** for calibration purposes
- **Redesigned cavity support structure** to mitigate damage in case of a magnet quench





Quench damage (2017 power outage)

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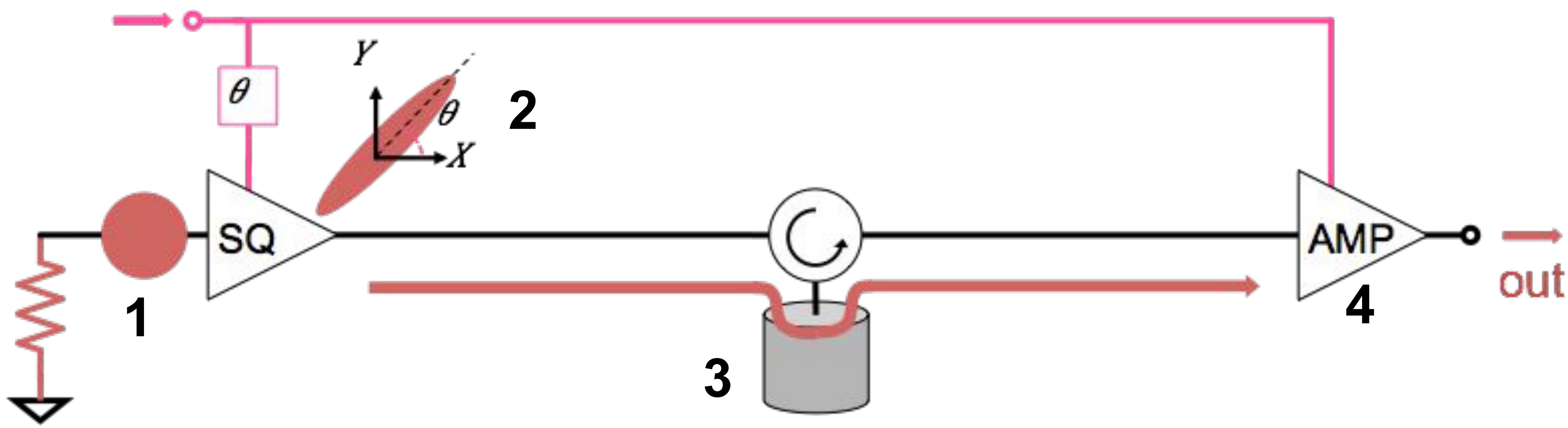
Squeezed-Vacuum State Receiver

Phase I: Single JPA, double quadrature amplification
Phase II: Two JPAs, one to create squeezed state, one for single quadrature amplification



1. Coherent state is produced

2. Squeezer produces squeezed state at some phase angle

3. Cavity injects coherent noise

4. Anti-aligned JPA amplifies cavity noise in orthoganal quadrature

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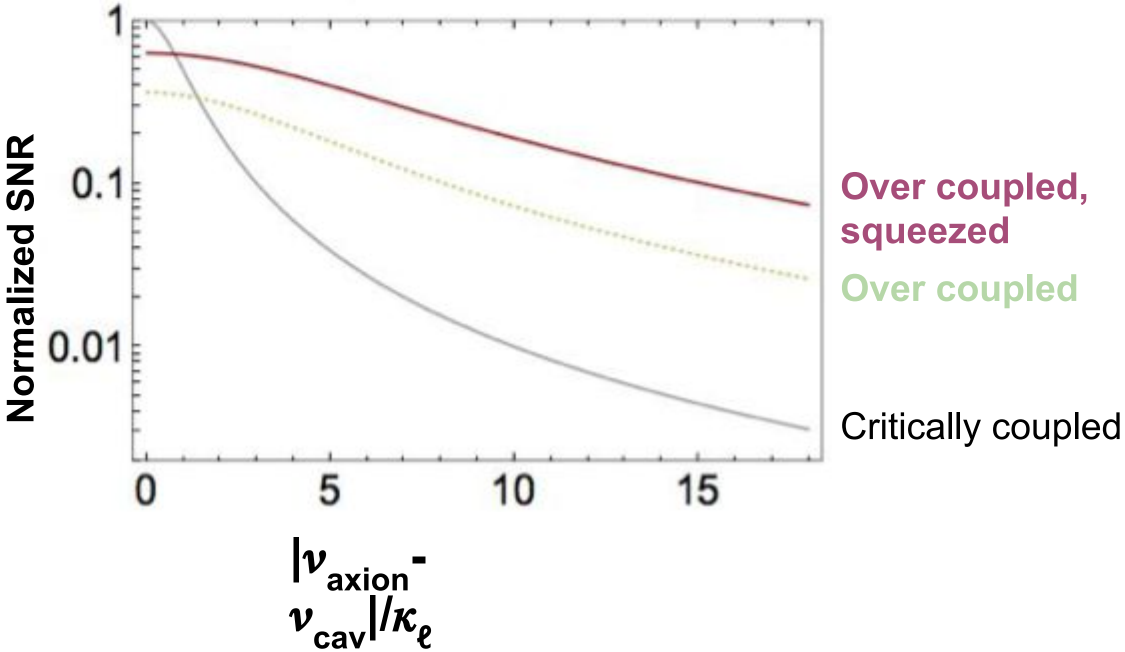
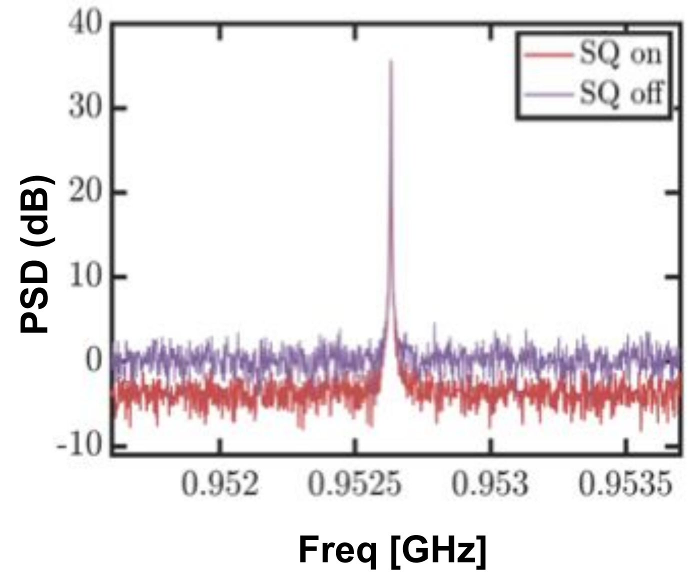
Improvements from Squeezing

- Over couple and squeeze: search over a large bandwith
  - Calculations include a realistic 32% power loss

SNR vs Detuning



Squeezing lowers noise floor



Projected 2.3X scan rate speed up in Phase II

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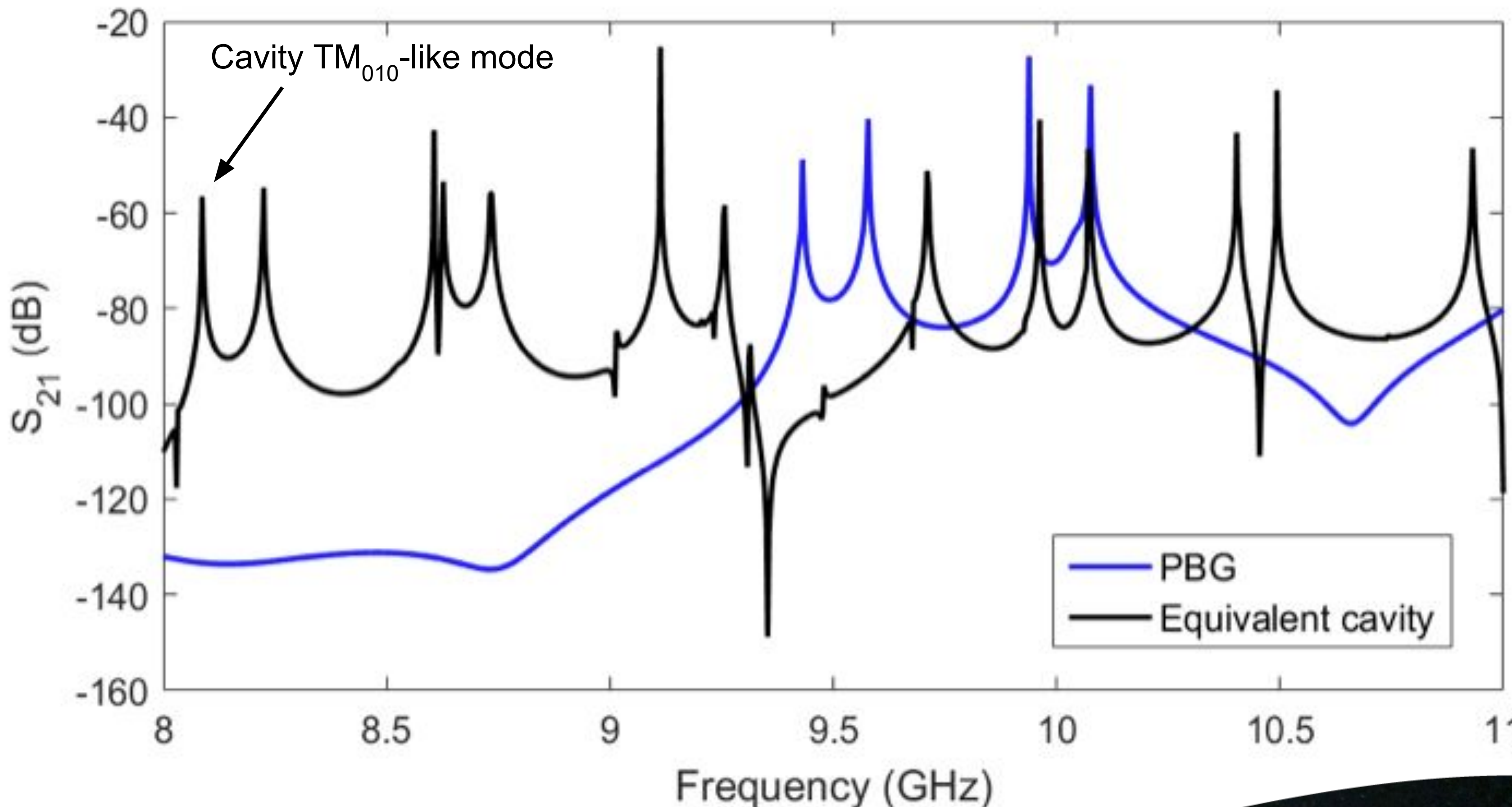
Future Plans

Photonic Band Gap (PBG) Resonator

Motivation

- TE modes don't tune, causing mode crossings
- PBG structure confines TM modes while TE modes "leak" out



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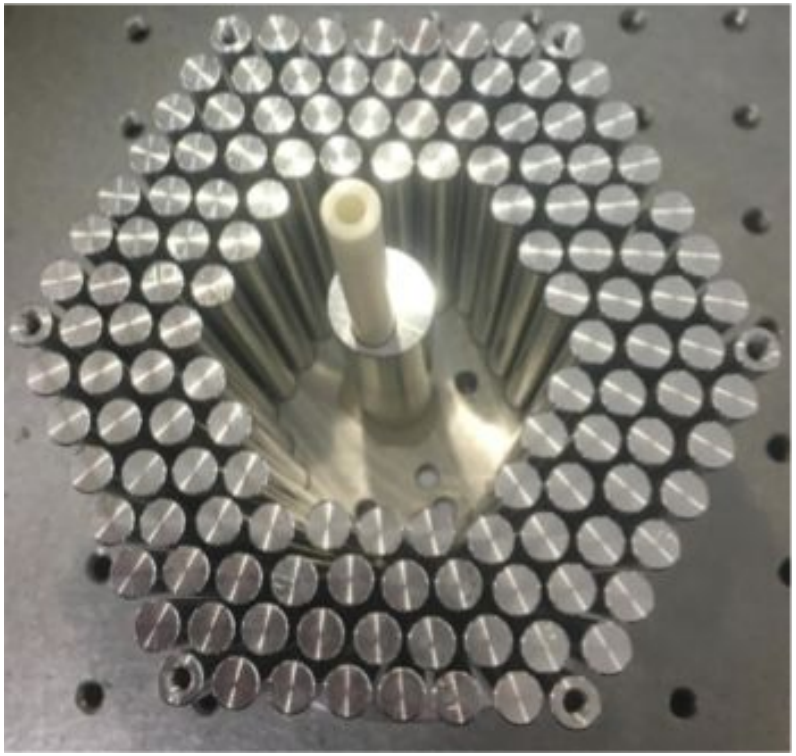
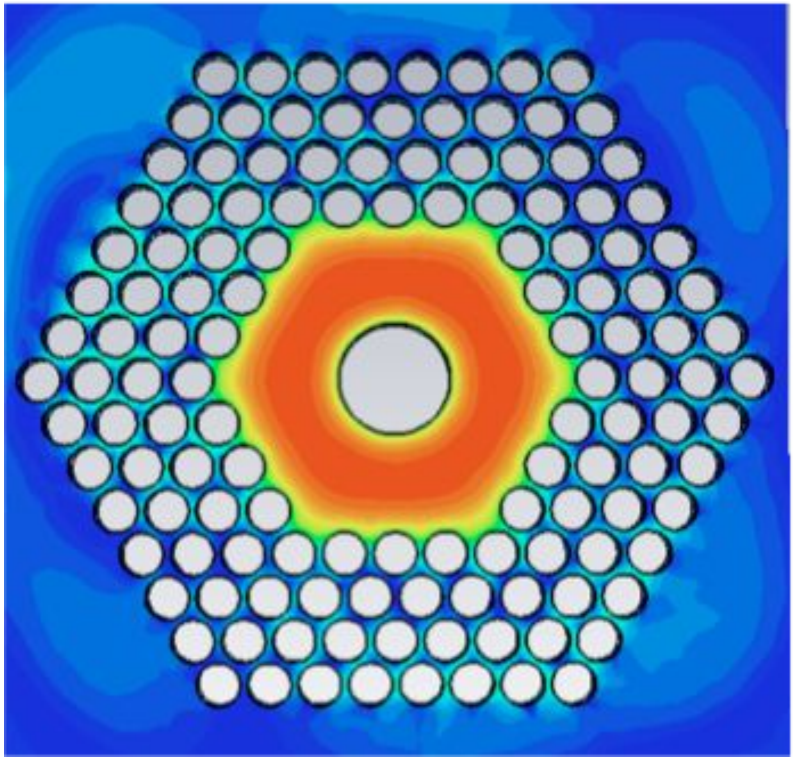
Photonic Band Gap (PBG) Resonator, cont’

- Periodic lattice of rods
- Resonator: defect in lattice confines disallowed modes
- All other modes propagate out





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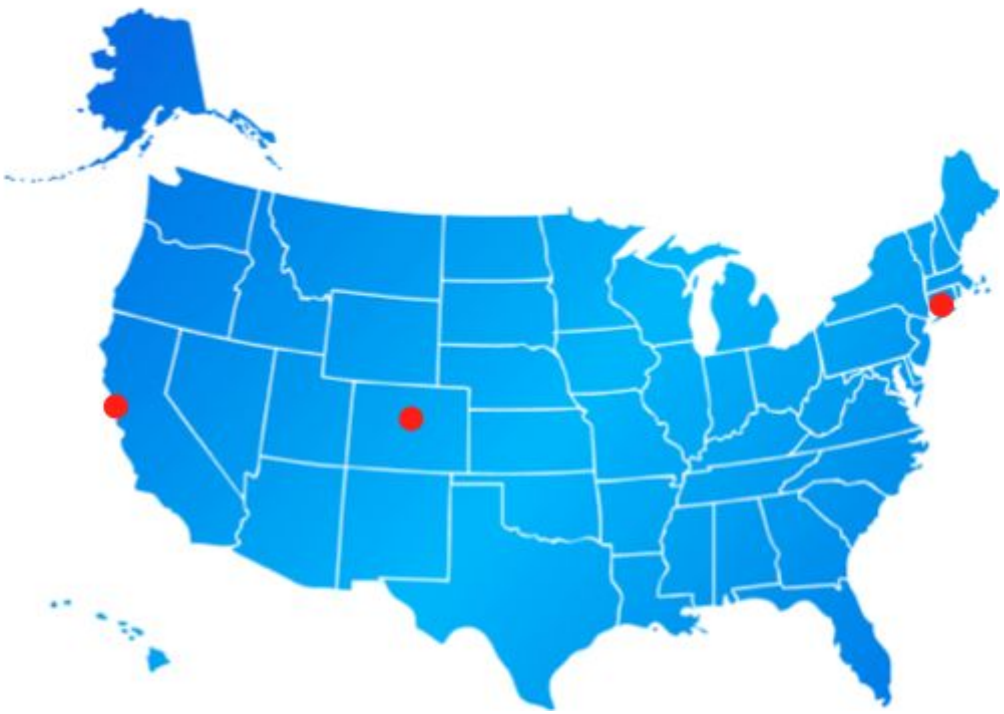
Conclusion

Conclusion

- **HAYSTAC has excluded parameter space** $23.15 \leq m_a \leq 24.00$ μeV to sensitivity $|g_\gamma| \geq 2.7 \times |g_\gamma^{KSVZ}|$ where g_γ is axion-photon coupling constant
- **Upgrades to cryogenics and cavity** will improve sensitivity and scan rate in Phase II
- **Squeezed-vacuum state receiver** will push noise below SQL and offers 2.3X scan rate enhancement
- Phase II data runs will begin fall 2018
- R&D continues on **novel cavity designs** (PBG)
- R&D begins on **single photon detection techniques**, both qubit and Rydberg atom based

Thank you!

The HAYSTAC Collaboration



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