First results from a microwave cavity axion search at 24 $\mu$eV

Ben Brubaker
Yale University

January 12, 2017
Axion Workshop – LLNL
Outline

- Introduction: challenges/motivation for high-mass searches
- JPA operation and noise performance
- First results
- Recent progress and near-term plans
Only ADMX has reached the model band to date.

The parameter space is mostly unexplored, especially at high frequencies.
The cavity search at high frequencies

Challenges

- At constant coupling,
  \[ \frac{d\nu}{dt} \sim \nu^{-14/3} \]
  for resonator geometries used in axion searches to date
- Largely due to small volume of high-frequency resonators
- Standard Quantum Limit (SQL): \( kT_S \geq h\nu \) for linear amplifiers

The Silver Lining

- Cryogenics much simpler at 5 cm scale than 50 cm scale
- Josephson parametric amplifiers (JPAs): tunable amplifiers in the 2-12 GHz range which can approach quantum noise limits
Our collaboration

- **Yale University (host)**
  - Ben Brubaker, Ling Zhong, Yulia Gurevich, Sid Cahn, Steve Lamoreaux

- **UC Berkeley**
  - Maria Simanovskaia, Jaben Root, Samantha Lewis, Saad Al Kenany, Kelly Backes, Isabella Urdinaran, Nicholas Raptopidis, Tim Shokair, Karl van Bibber

- **CU Boulder/JILA**
  - Maxime Malnou, Dan Palken, William Kindel, Mehmet Anil, Konrad Lehnert

- **Lawrence Livermore National Lab**
  - Gianpaolo Carosi
Detector Design

A data pathfinder and innovation testbed for the high-mass region

Josephson Parametric Amplifier

Microwave Cavity (copper)

\(^3\text{He}/\text{He} \) Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet
Cavity and Motion Control

- Tuning via rotation of off-axis Cu rod
- Linear drives for dielectric fine tuning and antenna insertion
- \( \sim \) annular geometry: maximizes V for \( \text{TM}_{010} \)-like mode at given \( \nu \)
- \( Q_0 \sim 3 \times 10^4, \; C_{010} \sim 0.5 \) in initial operating range
Josephson Parametric Amplifier

- An LC circuit with nonlinear SQUID inductance $\Rightarrow$ parametric gain from a strong pump tone applied near resonance.

- Analogous to modulating your center of mass at $2\omega_0$ on a swing (figure from arXiv 1103.0835): defines a preferred phase

- Signals detuned from the pump are superpositions of amplified and squeezed quadratures $\Rightarrow$ both direct and intermodulation gain

- Added noise is just thermal noise of the “idler mode” from opposite side of pump
Apply DC magnetic flux to tune $LC$ resonance from 4.4 to 6.5 GHz

Bias up to $\sim 21$ dB gain by varying pump power $P_p$ and detuning $\Delta$ between pump frequency and $LC$ resonance

In practice: want to keep $\omega_P$ at fixed detuning from cavity – use flux to adjust bias point

Bucking coil, Pb/Nb/Cryoperm shields, and passive NbTi coils for $\sim 10^8$ net reduction of field on JPA
JPA Biasing and Tuning

![Graph showing JPA frequency versus bias current with two magnetic field conditions: B = 0 T and B = 9 T.]
Noise calibration principle

\[ kT_S = h\nu \left( \frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2} + N_A \right) \]

- Linear detection: \( \geq 1/2 \) photon at the input of any linear amplifier, because quadrature amplitudes don’t commute with Hamiltonian.

- The Standard Quantum Limit: A phase-insensitive linear amplifier must add noise \( N_A \geq 1/2 \), because quadrature amplitudes don’t commute with each other.

- Measure \( N_A \) using blackbody source at known temperature (the Y-factor method) – includes JPA added noise, HEMT added noise and loss before JPA.

\[ Y = \frac{P_{\text{Hot}}}{P_{\text{Cold}}} = \frac{G_H [N_H + N_A (N_H)]}{G_C [N_C + N_A (N_C)]} \]
Noise calibration principle

\[ kT_S = h\nu \left( \frac{1}{e^{\frac{h\nu}{kT}} - 1} + \frac{1}{2} + N_A \right) \]

- **Linear detection:** \( \geq 1/2 \) photon at the input of any linear amplifier, because quadrature amplitudes don’t commute with Hamiltonian.

- The Standard Quantum Limit: A phase-insensitive linear amplifier must add noise \( N_A \geq 1/2 \), because quadrature amplitudes don’t commute with each other.

- Measure \( N_A \) using blackbody source at known temperature (the Y-factor method) – includes JPA added noise, HEMT added noise and loss before JPA.

\[ Y = \frac{P_{\text{Hot}}}{P_{\text{Cold}}} = \frac{G_H [N_H + N_A (N_H)]}{G_C [N_C + N_A (N_C)]} \]
Noise calibration principle

\[ kT_S = h\nu \left( \frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2} + N_A \right) \]

- Linear detection: \( \geq 1/2 \) photon at the input of any linear amplifier, because quadrature amplitudes don’t commute with Hamiltonian.

- The Standard Quantum Limit: A phase-insensitive linear amplifier must add noise \( N_A \geq 1/2 \), because quadrature amplitudes don’t commute with each other.

- Measure \( N_A \) using blackbody source at known temperature (the Y-factor method) – includes JPA added noise, HEMT added noise and loss before JPA.

\[ Y = \frac{P_{Hot}}{P_{Cold}} = \frac{G_H [N_H + N_A (N_H)]}{G_C [N_C + N_A (N_C)]} \]
Noise calibration results

- We measure \( N_A \approx 1.35 \Rightarrow T_S \approx 550 \text{ mK off resonance} \)

- Total noise increases to \( T_S \approx 3h\nu \approx 830 \text{ mK on resonance} \)

- Off-resonance noise consistent with 20% thermal contribution, \( \sim 0.2 \text{ quanta from HEMT}, \sim 0.5 \text{ quanta from } \sim 2 \text{ dB loss before JPA} \)

- Temperature- and gain-dependence of resonant noise bump implicates thermal link to tuning rod
Noise calibration results

- We measure $N_A \approx 1.35 \Rightarrow T_S \approx 550$ mK off resonance
- Total noise increases to $T_S \approx 3h\nu \approx 830$ mK on resonance
- Off-resonance noise consistent with 20% thermal contribution, $\sim 0.2$ quanta from HEMT, $\sim 0.5$ quanta from $\sim 2$ dB loss before JPA
- Temperature- and gain-dependence of resonant noise bump implicates thermal link to tuning rod
Noise calibration results

- We measure $N_A \approx 1.35$ ⇒ $T_S \approx 550$ mK off resonance

- Total noise increases to $T_S \approx 3h\nu \approx 830$ mK on resonance

- Off-resonance noise consistent with 20% thermal contribution, $\sim 0.2$ quanta from HEMT, $\sim 0.5$ quanta from $\sim 2$ dB loss before JPA

- Temperature- and gain-dependence of resonant noise bump implicates thermal link to tuning rod
Noise calibration results

- We measure $N_A \approx 1.35 \Rightarrow T_S \approx 550 \text{ mK off resonance}$
- Total noise increases to $T_S \approx 3h\nu \approx 830 \text{ mK on resonance}$
- Off-resonance noise consistent with 20% thermal contribution, $\sim 0.2$ quanta from HEMT, $\sim 0.5$ quanta from $\sim 2 \text{ dB loss before JPA}$
- Temperature- and gain-dependence of resonant noise bump implicates thermal link to tuning rod
Timeline

- 4/2012 – 6/2014: Design/construction
- 7/2014 – 1/2016: Integration/commissioning
  - Eliminated vibrationally coupled JPA gain fluctuations by operating at 125 mK
  - Added analog flux feedback system to stabilize JPA gain
  - Implemented blind injection of synthetic axion signals
- 1/26/2016 – 9/1/2016: Operations
  - 3.5 months of automated data acquisition: ~ 7000 15-minute integrations covering 5.7 – 5.8 GHz
  - Campus-wide power outage on 3/7/2016 led to magnet quench: 2 months downtime for repairs
  - 28 candidate frequencies from final analysis: rescanned 8/2016
  - We did not find the axion!
Magnet Quench

- 500 kJ dissipated over a few seconds; warping due to eddy current forces
- Helium circulation lines unharmed!
- Shields rebuilt w/ less copper.
Analysis Procedure

Based on Asztalos et al. PRD (2001) w/ various refinements: fit out spectral baselines, construct maximum-likelihood-weighted sum of overlapping subspectra.
Set $3.46\sigma$ threshold on power excess within $\sim 5$ kHz, rescan candidate frequencies to check for coincidences

Innovations:

- Optimal Savitzky-Golay fitting of subspectra
- Maximum-likelihood weighting for both subspectra and adjacent bins
- Confidence levels from statistics rather than Monte Carlo
- Taking into account all possible loss factors not directly measured
2.3 × KSVZ over 100 MHz a decade higher in mass than ADMX.
Coverage will be extended to a few GHz over the next few years.
Now an operational platform for tests of new cavity and amplifier concepts!
Repeatable stepping with 45 V on Attocube ANR240
Recent Progress – Rod thermal link

![Graph showing noise (quanta) vs. IF frequency (MHz)]

- $N_{sys}$
- $N_A$
- $N_{cav}$
- $N_C$
Recent Progress – Rod thermal link

Position C

Insertion depth = 2.12” (copper finger inside rod)

Q = 7650 (~ max unperturbed)

Cavity End Cap

Tuning Rod

Copper Finger

Alumina Shaft
Recent Progress – Rod thermal link

![Graph showing noise vs. IF frequency (MHz) with different lines representing N_sys, N_A, N_cav, and N_C.](image)
What’s Next?

- Now: double coverage at 150% initial scan rate
- Transfer experiment to new BlueFors dil fridge: more stable, reduced vibrations ⇒ colder
- JPA/cavity fabrication to extend frequency range
- R&D for next-generation searches:
  - Squeezed state receiver (CU) – to be installed in 2017
  - New cavity concepts: PGBs, DBRs, superconducting thin films (UCB)
Further reading and acknowledgments

- “First results from a microwave cavity at 24 micro-eV,” B. M. Brubaker et al., arXiv:1610.02580 (to be published in PRL, designated an “Editors’ Suggestion”).


- Detailed analysis paper coming soon!

---

[Logos of NSF, HSF, and Department of Energy]
Extra Slides
Signal Power and Scan Rate

\[ P_S = \left( g_\gamma^2 \alpha^2 \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \left( \frac{\beta}{1 + \beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mn\ell} Q_L \frac{1}{1 + (2\delta\nu/\Delta\nu_c)^2} \right) \]

\[ \text{SNR} = \frac{P_S}{k_B T_S} \sqrt{\frac{\tau}{\Delta\nu_a}} \]

\[ \frac{d\nu}{dt} \approx \frac{4}{5} \frac{Q_L Q_a}{\text{SNR}^2} \left( g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right)^2 \left( \frac{1}{\hbar \mu_0} \frac{\beta}{1 + \beta} B_0^2 V C_{mn\ell} \frac{1}{N_S} \right)^2 \]
Microwave Layout

- 3 paths for injection into fridge: transmission, reflection, JPA pump.

- Cryo microwave switch (Radiall) and terminator at still plate for Y-factor measurement.

- Second-stage amplifier: LNF LNC4_8A: $T_N \approx 4$ K.
- GaGe Oscar CSE4344 ADC: 14 bits, 25 MS/s sampling.

- Agilent E5071C VNA for cavity and JPA measurements.

- Keysight N5183B (w/ white noise at FM input) for fake axion injection.

- JPA flux bias: 20-bit ADC w/ 1 $\mu$V resolution and 1 mA/V current source.

- Flux feedback system (in pink).
Squeezed states for axion detection

- JPAs can operate in a mode where they amplify one signal quadrature and squeeze the other: no SQL.
- If we align the squeezed quadrature of one JPA with the amplified quadrature of another, no 1/2 photon from linear detection either: $kT_S \ll h\nu$!
- Cavity must be overcoupled; squeezed state injected in reflection. Works due to finite axion coherence time $\sim 200 \mu s$.
- Eliminating loss before JPA is a challenge.
- See H. Zheng et al., arXiv:1607.02529
DAQ procedure

- Noise is mixed down to MHz and digitized at 25 MS/s for $t \sim 15$ min.

- In-situ FFT computation, image rejection, and averaging of power spectra with 100 Hz resolution.

- Step resonance by $\sim \Delta \nu_c / 4$ and repeat $O\left(10^4\right)$ times.

- At each step, we measure $Q_L$ and $\beta$ and rebias JPA.

- Noise calibrations interleaved into the axion search (every 10 iterations).

- Data rate $\sim 20$ GB/100 MHz (500 TB/100 MHz to save full time series data).
IF configuration

Eliminated by image rejection

Analysis band 0.129-1.431 MHz

Sensitivity to axion

0.78

1.6

3 dB point of filter

Nyquist frequency

IF frequency (MHz)

LO

JPA gain

Pump

Probe tone 0.03
Noise decreases as $\tau^{-1/2}$ out to at least 24 hours.
Histograms

Real data:

Simulation:
Synthetic axion injection

(a)

(b)

(c)

Δν = 100 Hz

Δν = 5 kHz

5.7161

5.718

Frequency (GHz)
Cavity Tuning