First results from a microwave cavity axion search at 24 μeV

Ben Brubaker
Yale University

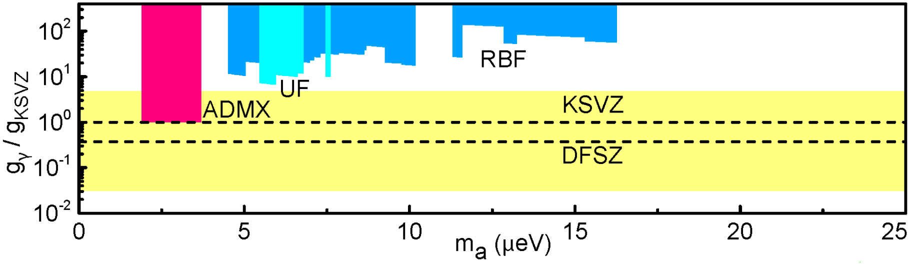
January 12, 2017

Axion Workshop – LLNL

Outline

- Introduction: challenges/motivation for high-mass searches
- JPA operation and noise performance
- First results
- Recent progress and near-term plans

Parameter Space



- 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,

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \sim \nu^{-14/3}$$

  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 Rapidis, Tim Shokair, Karl van Bibber

- CU Boulder/JILA

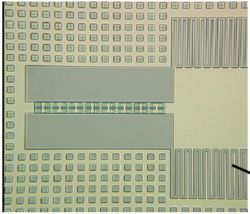
  Maxime Malnou, Dan Palken, William Kindel, Mehmet Anil, Konrad Lehnert

- Lawrence Livermore National Lab

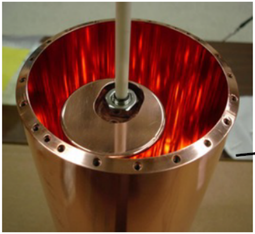
  Gianpaolo Carosi

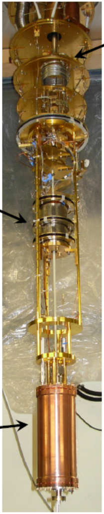
Detector Design

Josephson Parametric Amplifier



Microwave Cavity (copper)



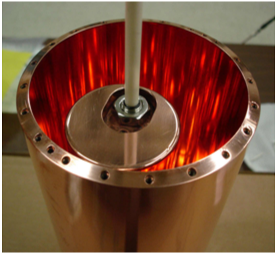


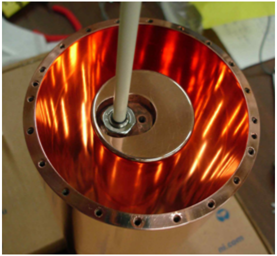
$^{3}He/^{4}He$ Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet

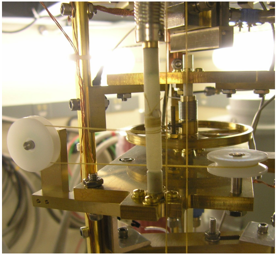
A *data pathfinder* and *innovation testbed* for the high-mass region

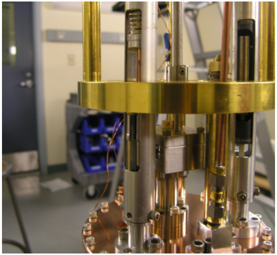
Cavity and Motion Control



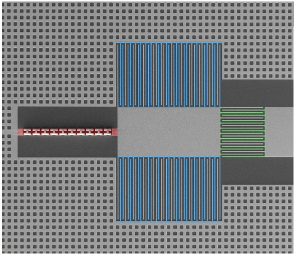


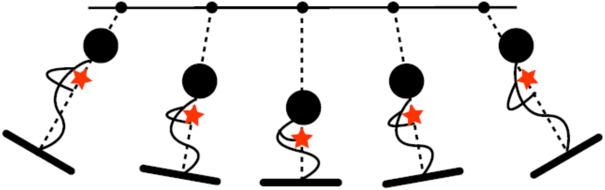
- Tuning via rotation of off-axis Cu rod
- Linear drives for dielectric fine tuning and antenna insertion
- $\sim$ annular geometry: maximizes V for TM_{010}-like mode at given ν
- $Q_0 \sim 3 \times 10^4$, $C_{010} \sim 0.5$ in initial operating range





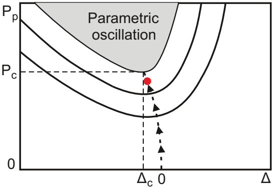
Josephson Parametric Amplifier

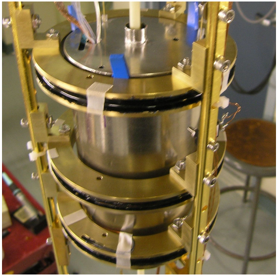




- An LC circuit with nonlinear SQUID inductance ⇒ parametric gain from a strong pump tone applied near resonance.
- Analogous to modulating your center of mass at $2\omega_0$ on a swing (figure from arXiv 1103.0835): defines a preferred phase
- Signals detuned from the pump are superpositions of amplified and squeezed quadratures ⇒ both direct and intermodulation gain
- Added noise is just thermal noise of the “idler mode” from opposite side of pump

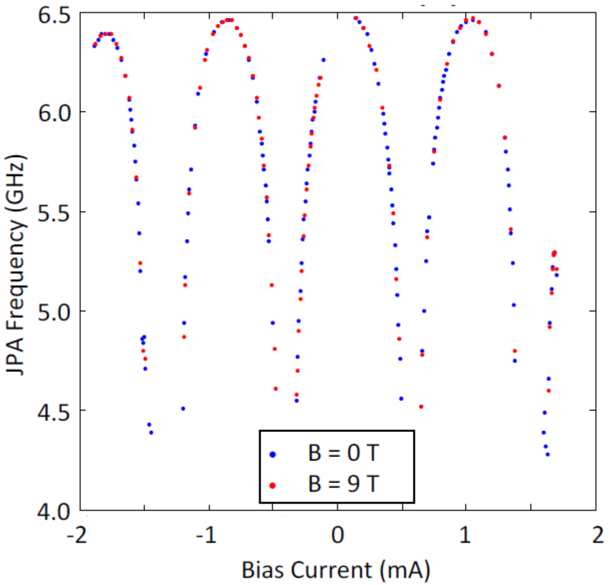
JPA Biasing and Tuning





- Apply DC magnetic flux to tune *LC* resonance from 4.4 to 6.5 GHz
- Bias up to ~ 21 dB gain by varying pump power P_p and detuning Δ between pump frequency and *LC* resonance
- In practice: want to keep ω_P at fixed detuning from cavity – use flux to adjust bias point
- Bucking coil, Pb/Nb/Cryoperm shields, and passive NbTi coils for ~ 10^8 net reduction of field on JPA

JPA Biasing and Tuning



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.

$$Y = \frac{P_{Hot}}{P_{Cold}} = \frac{G_H\left[N_H + N_A\left(N_H\right)\right]}{G_C\left[N_C + N_A\left(N_C\right)\right]}$$

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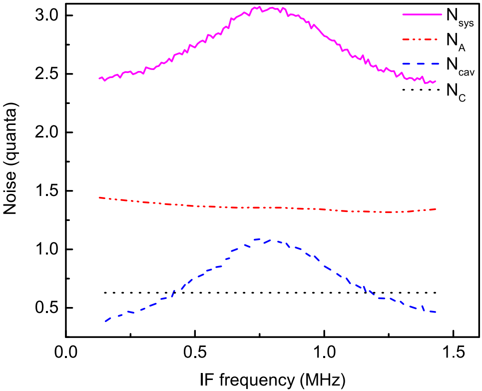
Noise calibration results

- 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, ~ 0.2 quanta from HEMT, ~ 0.5 quanta from ~ 2 dB loss before JPA
- Temperature- and gain-dependence of resonant noise bump implicates thermal link to tuning rod

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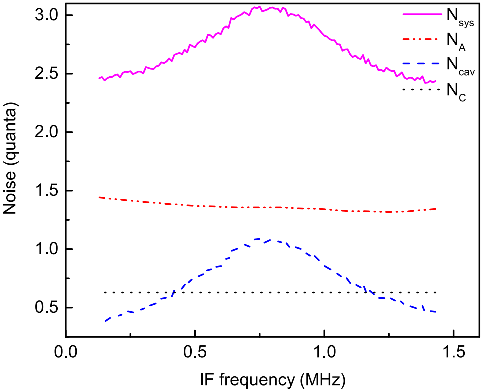

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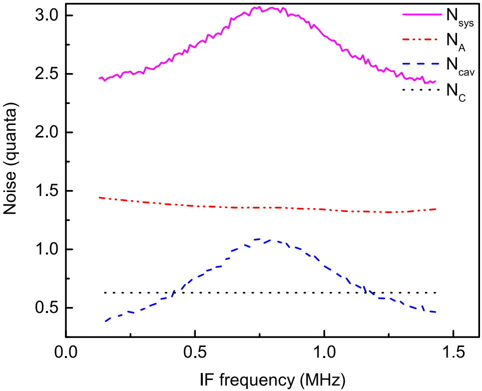

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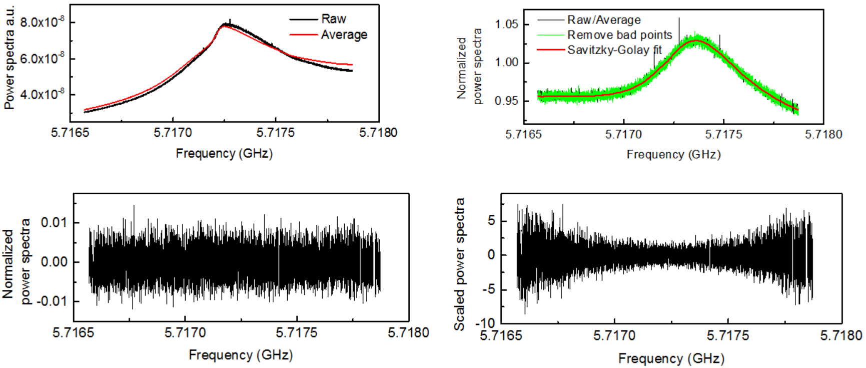
Timeline

- 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: $\sim$ 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

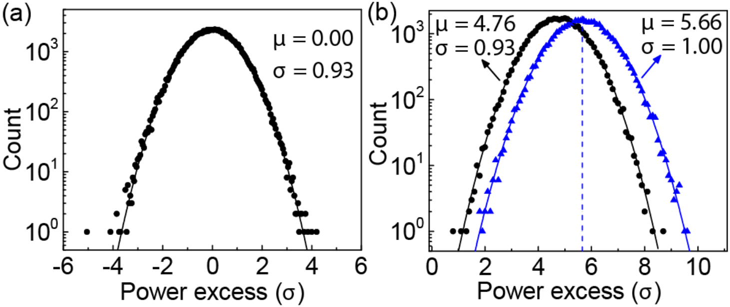
- 500 kJ dissipated over a few seconds; warping due to eddy current forces
- Helium circulation lines unharmed!
- Shields rebuilt w/ less copper.

Analysis Procedure



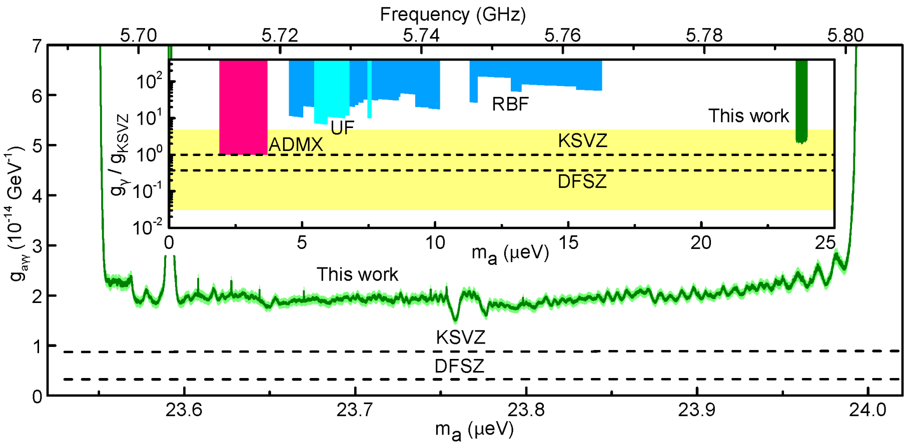
Based on Asztalos et al. PRD (2001) w/ various refinements: fit out spectral baselines, construct maximum-likelihood-weighted sum of overlapping subspectra.

Analysis Procedure



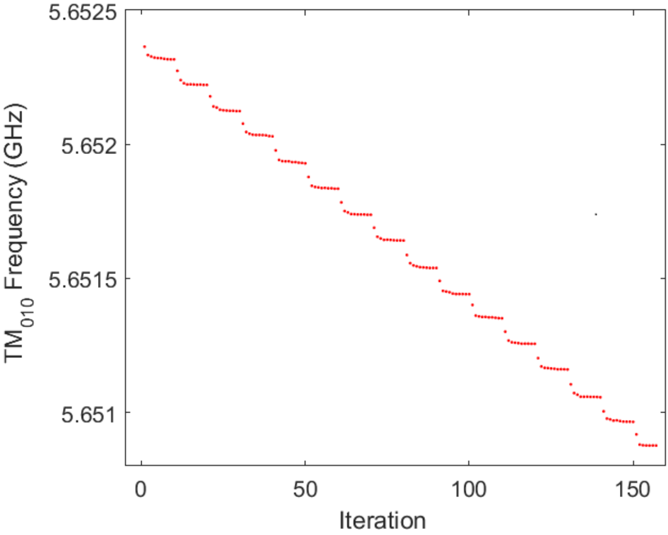
- Set 3.46σ threshold on power excess within $\sim$ 5 kHz, rescan candidate frequencies to check for coincidences
- Innovations:
  - Optimal Savitzky-Golay fitting of subspectra
  - Maximum-likelihood weighting for both subspectra and adjacent bins
  - Confidence levels from statistics rather than Monte Carlo
  - Taking into account all possible loss factors not directly measured

Results



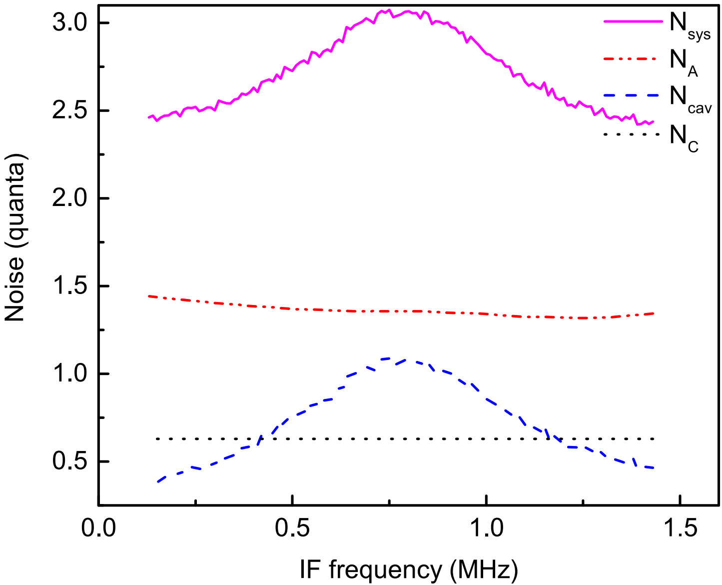
- 2.3 × KSVZ over 100 MHz a decade higher in mass than ADMX.
- Coverage will be extended to a few GHz over the next few years.
- Now an operational platform for tests of new cavity and amplifier concepts!

Recent Progress – Piezo tuning



Repeatable stepping with 45 V on Attocube ANR240

Recent Progress – Rod thermal link

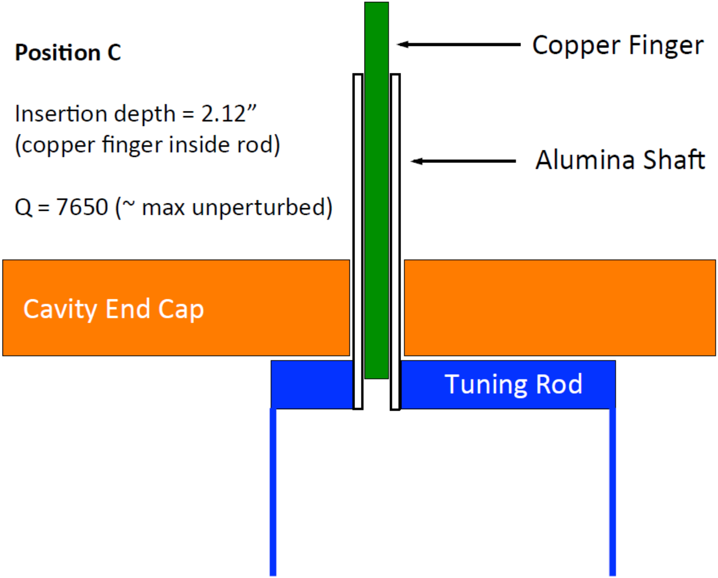


Recent Progress – Rod thermal link

Position C

Insertion depth = 2.12”
(copper finger inside rod)

Q = 7650 (~ max unperturbed)



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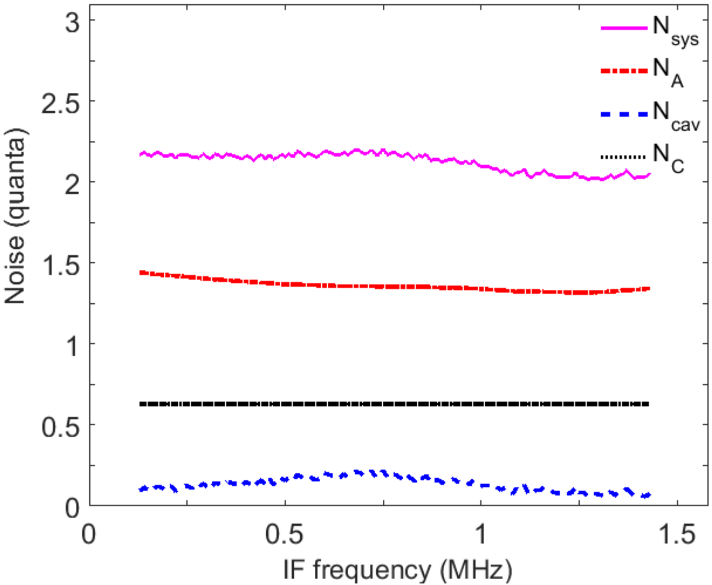
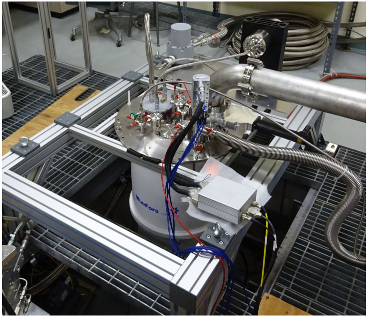
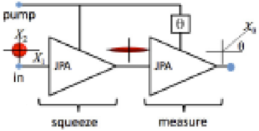


What's Next?

- 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")*.
- "Design and operational experience of a microwave cavity axion detector for the 20 – 100 μeV Range," S. Al Kenany *et al.*, arXiv:1611.07123 *(submitted to NIM A)*.
- Detailed analysis paper coming soon!

Extra Slides

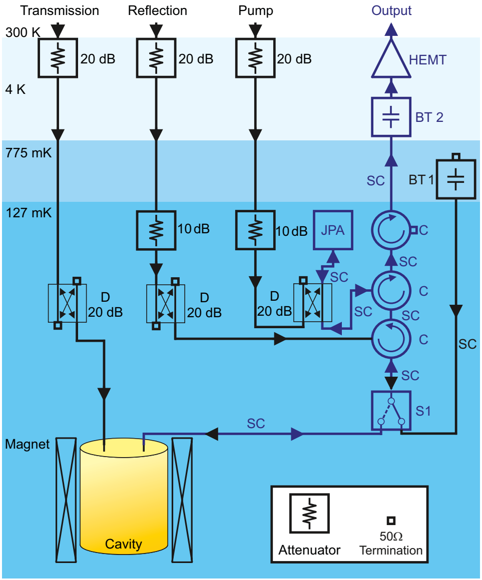
Signal Power and Scan Rate

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

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

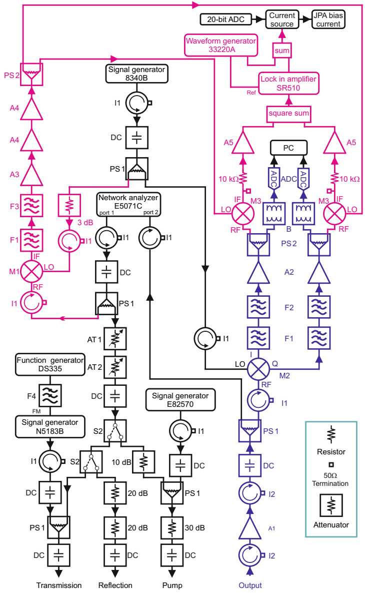
$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \approx \frac{4}{5}\eta\frac{Q_L Q_a}{\mathrm{SNR}^2}\left(g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4}\right)^2\left(\frac{1}{\hbar\mu_0}\frac{\beta}{1+\beta} B_0^2 V C_{mn\ell}\frac{1}{N_S}\right)^2$$

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.

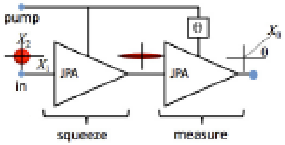
Microwave Layout

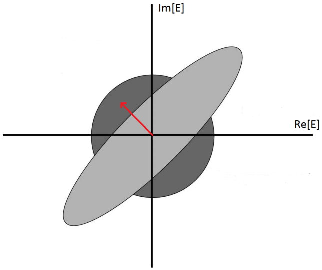


- GaGe Oscar CSE4344 ADC: 14 bits, 25 MS/s sampling.
- Agilent E5071C VNA for cavity and JPA measurements.
- Keysight N5183B (w/ white noise at FM input) for fake axion injection.
- JPA flux bias: 20-bit ADC w/ 1 μV resolution and 1 mA/V current source.
- Flux feedback system (in pink).

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

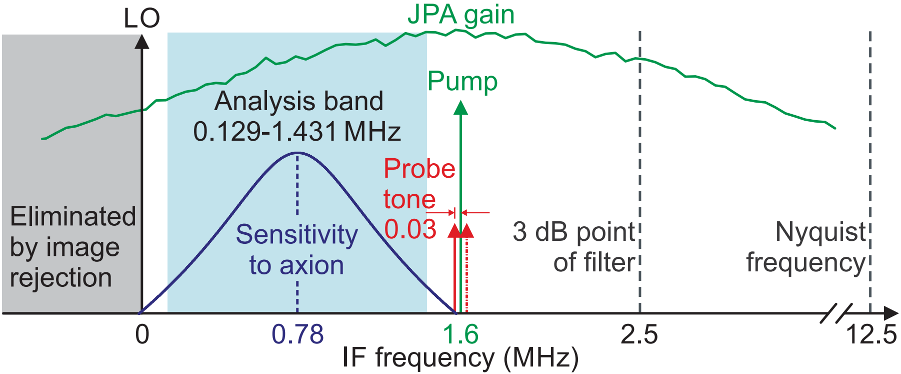




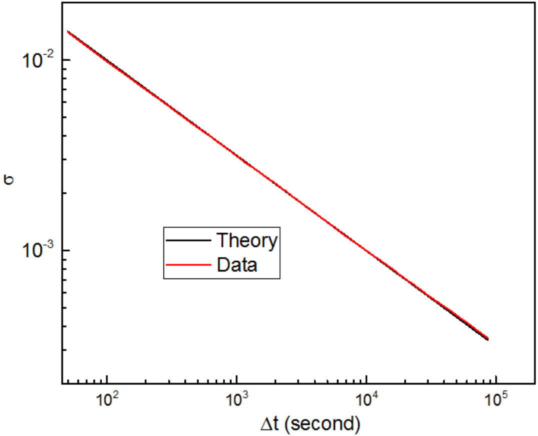
DAQ procedure

- 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 $\mathcal{O}\left(10^4\right)$ times.
- At each step, we measure Q_L and β 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



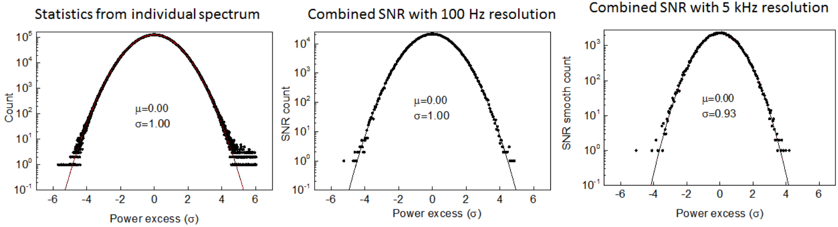
Allan Variance Measurement



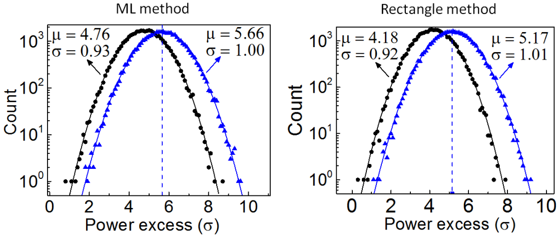
Noise decreases as $\tau^{-1/2}$ out to at least 24 hours.

Histograms

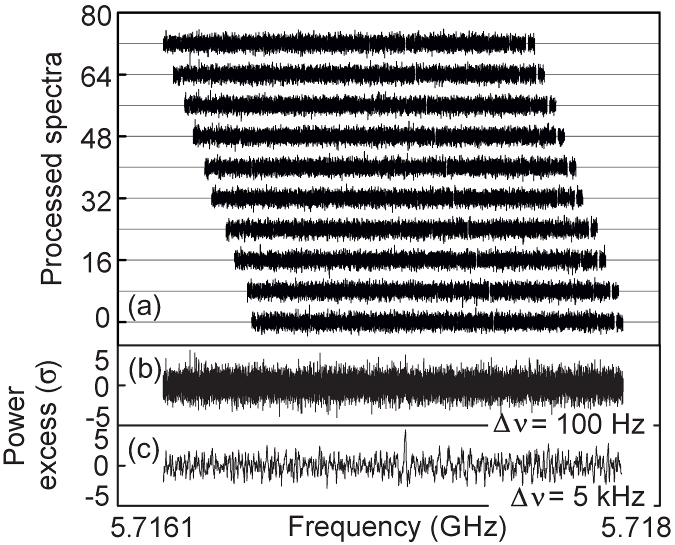
Real data:



Simulation:



Synthetic axion injection



Cavity Tuning