Searching for Dark Matter Axions with HAYSTAC

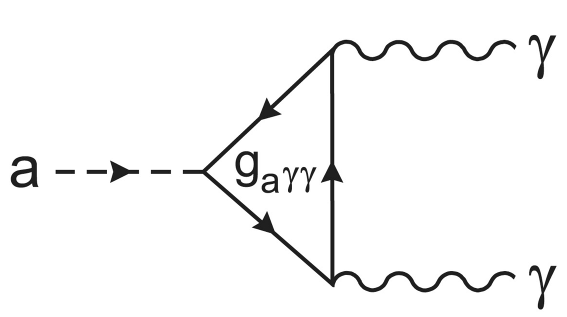
Kelly Backes for the Haloscope At Yale Sensitive To Axion CDM (HAYSTAC) Collaboration

Abstract

The axion is a well-motivated dark matter candidate whose existence would also explain the absence of CP violation in strong interactions. The use of Josephson parametric amplifiers and a dilution refrigerator has allowed HAYSTAC to reach cosmologically relevant sensitivity at an order of magnitude higher in mass than any experiment to date. HAYSTAC is an operational axion haloscope sited at Yale's Wright Lab operating in the 5 GHz range.

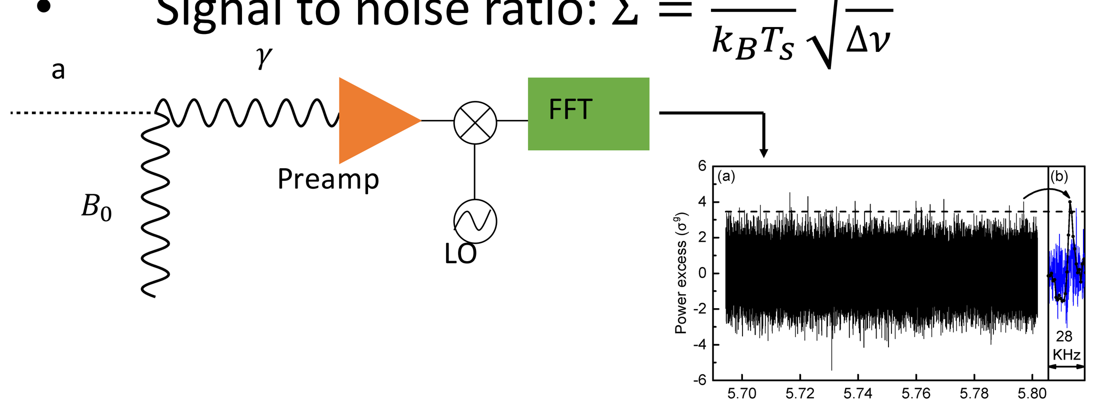
The Axion

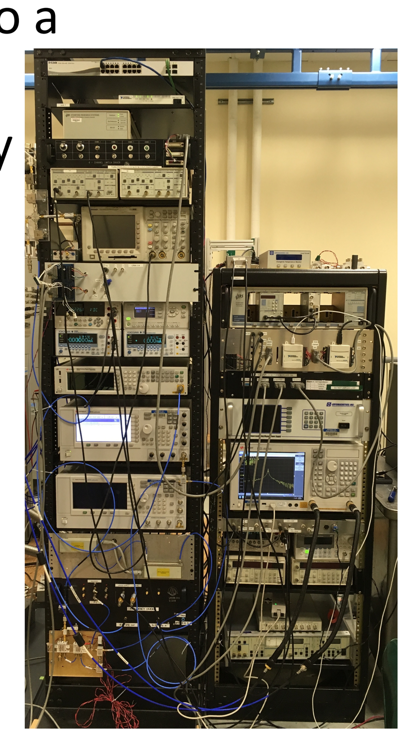
- Solves the "strong CP problem": Why is CP violation in QCD 10 orders of magnitude smaller than expected?
- A very light, very weakly coupled boson (lighter than a neutrino)
- Has a deBroglie wavelength of 100 m: more like a wave than a particle
- Interacts with electromagnetism: $\mathcal{L} = g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$
- Natural dark matter candidate!



Haloscope Detection Principle

- Primakoff effect: an axion with mass $m_a = \hbar\nu$ scatters off magnetic field and converts into a photon with frequency ν
- Resonantly enhanced in a microwave cavity
- Signal power: $P = g_{a\gamma\gamma}^2 (\rho_a/m_a) B_0^2 VCQ$
- Signal to noise ratio: $\Sigma = \frac{P}{k_B T_S}\sqrt{\frac{\tau}{\Delta\nu}}$





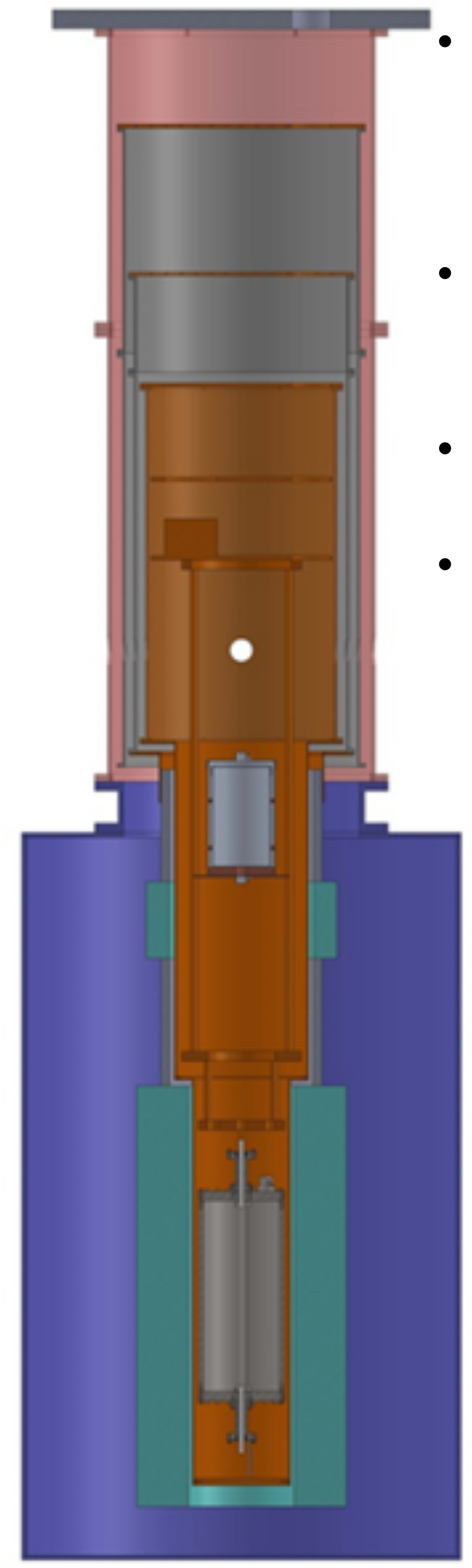
Collaboration

Haystac

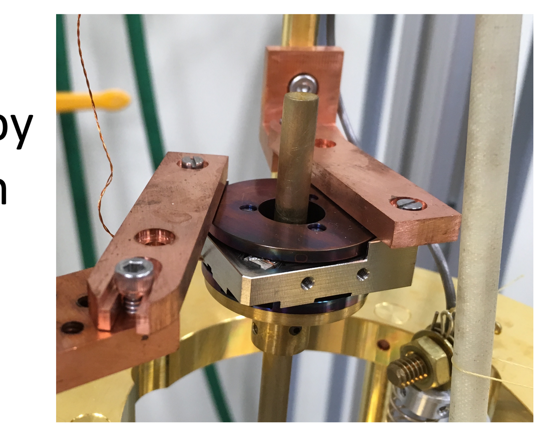
Wright Laboratory

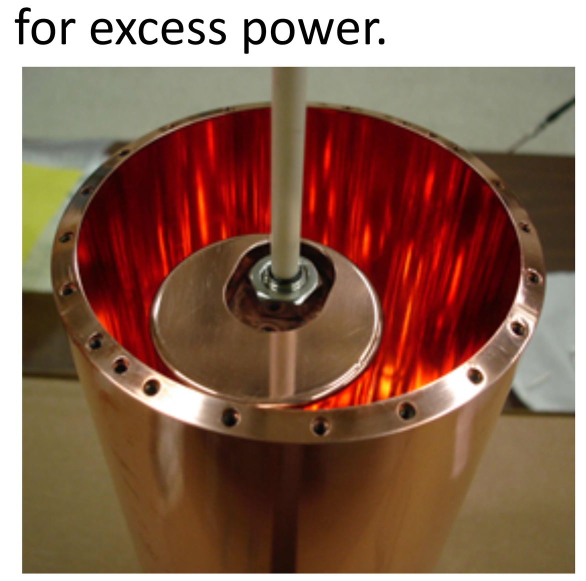
JILA

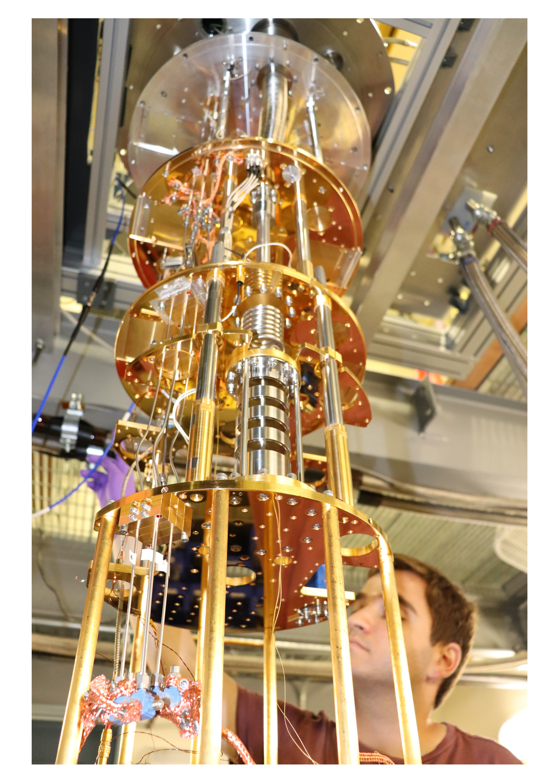
Our Detector



- Copper cavity and quantum limited preamplifier housed in a dilution refrigerator at 125 mK
- Cavity designed to reach a theoretical maximum Q of 20,000 at 5 GHz
- 9 T Superconducting Magnet: 500 kJ stored energy!
- Cavity is inserted into magnet bore and resonance is tuned by moving the tuning rod with an Attocube piezoelectric motor
- Cavity noise is measured at each step. Time streamed power data is also taken at each step. It is then FFT'ed and analyzed offline to look for excess power.

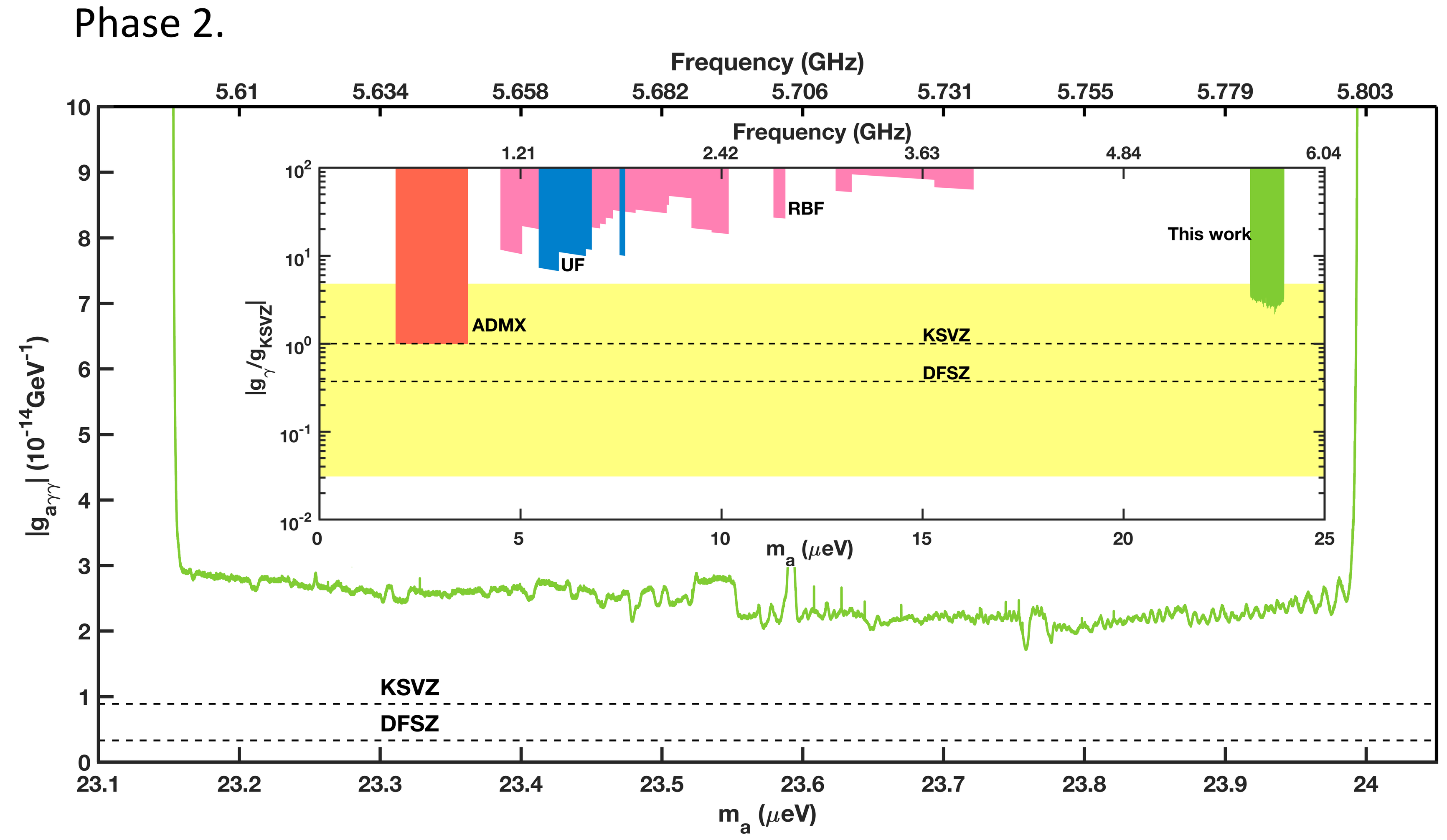






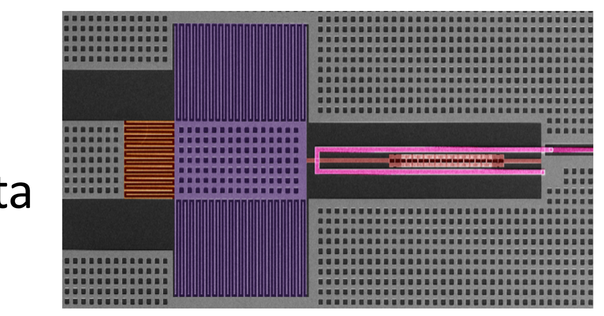
Results

- We excluded axions with $g_{a\gamma\gamma} > 2.7\times$KSVZ over the range $23.15 < m_a < 24.0 \mu eV$. This data run covered the frequency range $5.6 < f < 5.8$ GHz.
- These were the first results to reach the model band in the μeV mass decade. This concludes the first phase of the experiment. It is now being upgraded for Phase 2.



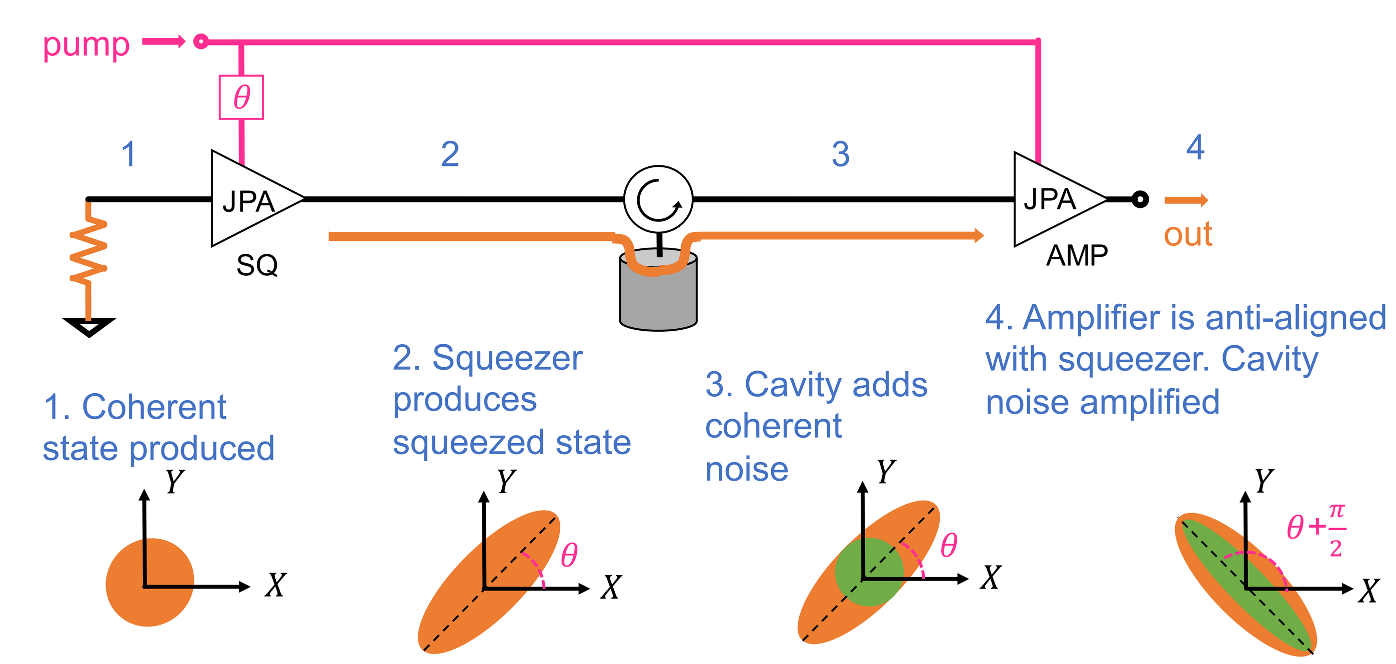
JPA Preamplifier

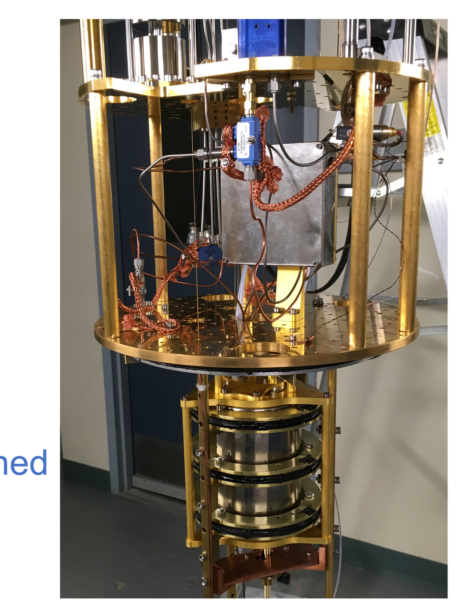
- Josephson Parametric Amplifier designed by collaborators at CU Boulder
- An LC circuit with nonlinear SQUID inductance.
- Quantum limited noise performance: ≈ 2 quanta
- Tunable over the range 4.4-6.4 GHz while maintaining 21dB of gain



Squeeze State Receiver

- We inject a squeeze state with Var(X)≪Var(Y). This saturates the Heisenberg uncertainty limit Var(X)Var(Y)=$\frac{1}{4}$. X now evolves with the cavity Hamiltonian and a measurement of only X that beats the standard quantum noise measurement can be made.
- Will speed up our scan rate by a factor of 2.3!





High-Frequency R&D

- Haloscopes scale poorly with increasing frequency
- $P \propto VC$: Effective volume decreases which decreases signal power
- $\frac{dv}{dt} \propto \nu^{-14/3}$: Scan time dramatically increases
- We are investigating novel cavity designs to increase volume at high frequency (e.g. photonic bandgap cavities)
- Single photon detection will further decrease scan rate
- Our cavity will function as a storage cavity for photons produced by axion-photon conversion. Then a π pulse applied to the qubit will flip the qubit state if and only if a single photon is present. The qubit state can then be read out in the readout cavity.