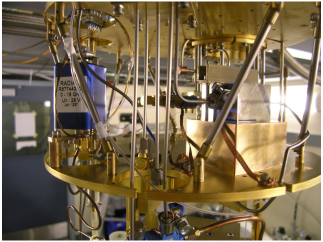
Particle Physics at the Yoctowatt Scale:

The ADMX-HF Experiment

Ben Brubaker



WIDG Seminar
November 18, 2014

Questions I hope to address

- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

Questions I hope to address

- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

The Strong CP Problem

- The axion is a pseudoscalar field motivated by the Peccei-Quinn solution to the **strong CP problem.**
- CP Violation: asymmetry between processes involving matter and antimatter.
- Two independent sources of CP Violation in QCD from different sectors of the theory: net effect is captured in a parameter θ.
- Neutron EDM searches constrain $\theta < 10^{-10}$.
- The strong CP problem: why is θ so small?

Solving the Strong CP Problem: Axions

- CP-violating term in QCD Lagrangian is

$$\mathcal{L} \subset \theta F^{a}_{\mu\nu}\widetilde{F}^{a\mu\nu}$$

  If θ were a field instead of a parameter, the strong CP problem would solve itself!

- Goal: introduce an **axion** field *a* with QCD coupling of the form

$$\mathcal{L} \subset \frac{a}{f_a} F^{a}_{\mu\nu}\widetilde{F}^{a\mu\nu}$$

Solving the Strong CP Problem: Axions

- CP-violating term in QCD Lagrangian is

  $$\mathcal{L} \subset \theta F^{a}_{\mu\nu} \widetilde{F}^{a\mu\nu}$$

  If θ were a field instead of a parameter, the strong CP problem would solve itself!

- Goal: introduce an **axion** field a with QCD coupling of the form

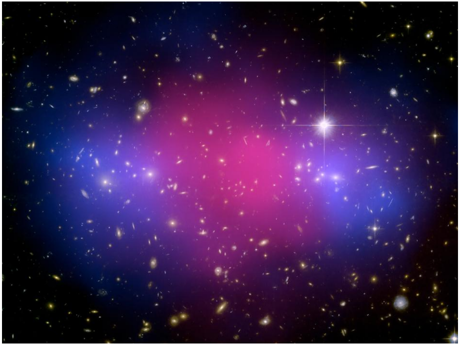
  $$\mathcal{L} \subset \frac{a}{f_a} F^{a}_{\mu\nu} \widetilde{F}^{a\mu\nu}$$

- The axion is the Goldstone boson of a new symmetry spontaneously broken at a scale f_a.
- Axion mass and all couplings suppressed by $f_a \Rightarrow m_a \propto g_{a\gamma\gamma}$.

Questions I hope to address

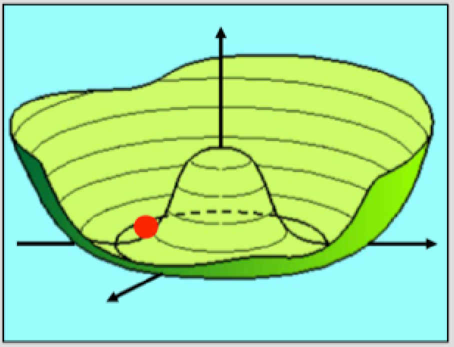
- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

Axions and Dark Matter



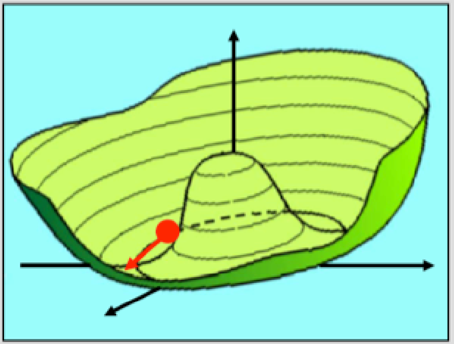
- $m_a \propto g_{a\gamma\gamma}$: sufficiently light axions interact very weakly with standard model fields.

Axions and Dark Matter



- $m_a \propto g_{a\gamma\gamma}$: sufficiently light axions interact very weakly with standard model fields.
- Misalignment produces cold axions in large numbers.

Axions and Dark Matter

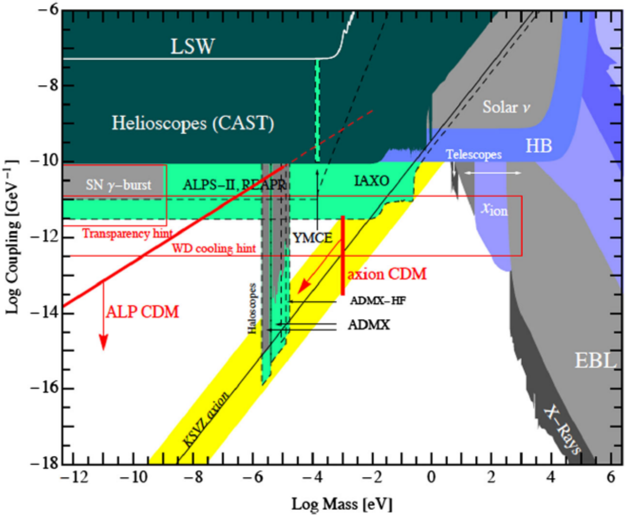


- $m_a \propto g_{a\gamma\gamma}$: sufficiently light axions interact very weakly with standard model fields.
- Misalignment produces cold axions in large numbers.
- Axions can account for cold dark matter!

Questions I hope to address

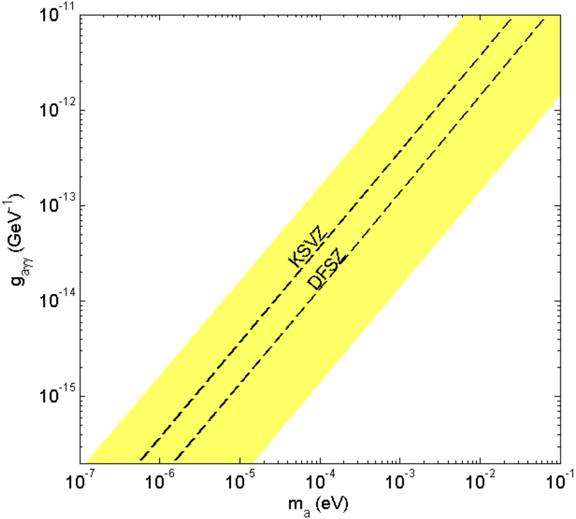
- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

Axion Parameter Space

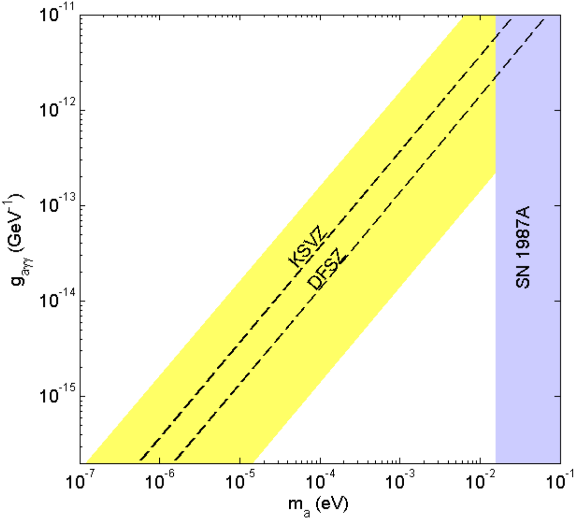


*: A. Ringwald, Phys. Dark. Univ. **1**, 116 (2012).

Axion Parameter Space

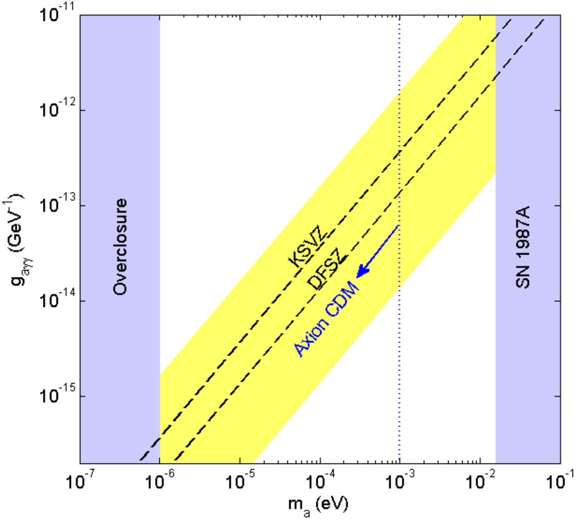


Axion Parameter Space



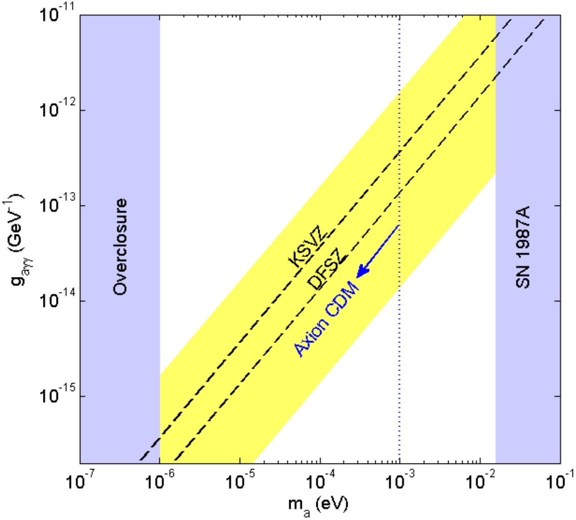
- SN 1987A axion emission too efficient for $m_a \gtrsim 10$ meV.

Axion Parameter Space



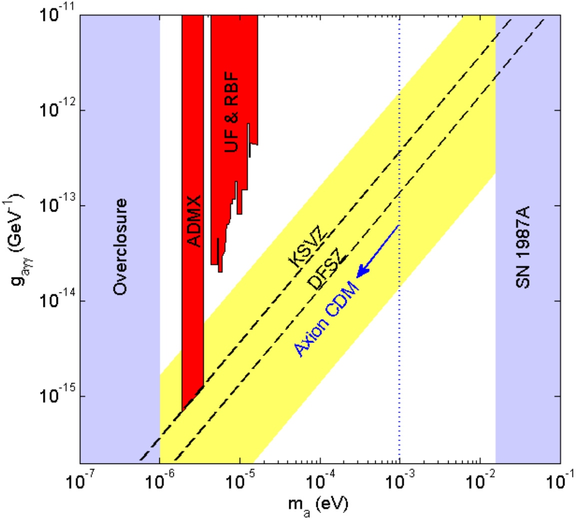
- SN 1987A axion emission too efficient for $m_a \gtrsim 10$ meV.
- $\Omega_a \propto m_a^{-7/6}$: axion dark matter fraction negligible for $m_a \gtrsim 1$ meV.
- too much dark matter for $m_a \lesssim 1\ \mu$eV.

Axion Parameter Space



- (At least) 3 orders of magnitude to scan.

Axion Parameter Space

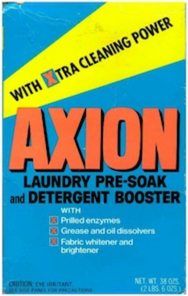


- (At least) 3 orders of magnitude to scan.
- Coupling is so small that we must use intrinsically narrow-band resonant detection.

Questions I hope to address

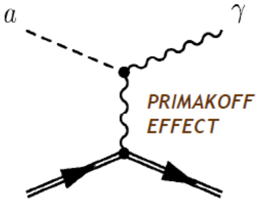
- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

Properties of Axion CDM



- Very light particles ⇒ huge number density.
- Virialization: $v \sim 270$ km/s $\rightarrow \beta \sim 10^{-3}$.
- Axion signal "quality factor:"
$$Q_a = E_{\text{mass}}/E_{\text{kin}} = \beta^{-2} \sim 10^6.$$
- De Broglie wavelength: $\lambda_a \sim \pi/m_a\beta \sim 100$ m for $m_a \sim 10^{-5}$ eV.
- Coherent effects on laboratory scales ⇒ more like a classical field than particles.

Microwave Cavity Axion Searches – Concept



- Sikivie*: search for axions with photon coupling $\mathcal{L} \subset g_{a\gamma\gamma} a \, \mathbf{E} \cdot \mathbf{B}$.
- The Primakoff Effect: classical field at one leg to compensate for weakness of vertex.
- Kinematics: $m_a = \nu \sim$ 250 MHz – 250 GHz.
- Resonant enhancement by Q of cavity.
- Cryogenics and low-noise amplifier to reduce noise.

*: P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).

Microwave Cavity Axion Searches – Signal

Conversion Power:

$$P \sim g_{a\gamma\gamma}^2 \left(\rho_a / m_a\right) B^2 Q_c V C_{nml}$$

Microwave Cavity Axion Searches – Signal

Conversion Power:

$$P \sim g_{a\gamma\gamma}^2 \left(\rho_a/m_a\right) B^2 Q_c V C_{nml}$$

- (Matrix element)^2

Microwave Cavity Axion Searches – Signal

Conversion Power:

$$P \sim g_{a\gamma\gamma}^2 \left(\rho_a/m_a\right) B^2 Q_c V C_{nml}$$

- (Matrix element)^2
- Axion number density

Microwave Cavity Axion Searches – Signal

Conversion Power:

$$P \sim g_{a\gamma\gamma}^2 \left(\rho_a/m_a\right) B^2 Q_c V C_{nml}$$

- (Matrix element)^2
- Axion number density
- Virtual photon number density

Microwave Cavity Axion Searches – Signal

Conversion Power:

$$P \sim g_{a\gamma\gamma}^2 \, (\rho_a/m_a) \, B^2 \, Q_c \, V C_{nml}$$

- (Matrix element)^2
- Axion number density
- Virtual photon number density
- Resonant enhancement of axion-photon conversion

Microwave Cavity Axion Searches – Signal

Conversion Power:

$$P \sim g_{a\gamma\gamma}^2 \, (\rho_a / m_a) \, B^2 Q_c \, V C_{nml}$$

- (Matrix element)^2
- Axion number density
- Virtual photon number density
- Resonant enhancement of axion-photon conversion
- Effective volume occupied by cavity mode
  $\Rightarrow$ best for low-order TM modes: $L \sim \nu^{-1}$

Microwave Cavity Axion Searches – Signal

Conversion Power:

$$P \sim g_{a\gamma\gamma}^2 \left(\rho_a/m_a\right) B^2 Q_c V C_{nml}$$

- (Matrix element)^2
- Axion number density
- Virtual photon number density
- Resonant enhancement of axion-photon conversion
- Effective volume occupied by cavity mode
  $\Rightarrow$ best for low-order TM modes: $L \sim \nu^{-1}$
- $P \sim 5 \times 10^{-23}$ W ($\approx$ 1 10 keV WIMP event/year)

Microwave Cavity Axion Searches – Noise

The Radiometer Equation:

$$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

Microwave Cavity Axion Searches – Noise

The Radiometer Equation:

$$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

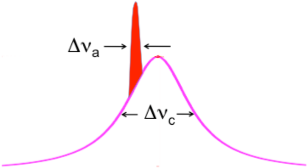
- Noise temperature $T_S \propto$ variance of Gaussian noise due to blackbody radiation of cavity.

Microwave Cavity Axion Searches – Noise

The Radiometer Equation:

$$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

- Noise temperature $T_S \propto$ variance of Gaussian noise due to blackbody radiation of cavity.
- Linear detection: $Q_a \gg Q_c \Rightarrow \Delta\nu_a \ll \Delta\nu_c$.

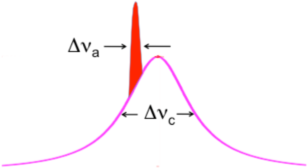


Microwave Cavity Axion Searches – Noise

The Radiometer Equation:

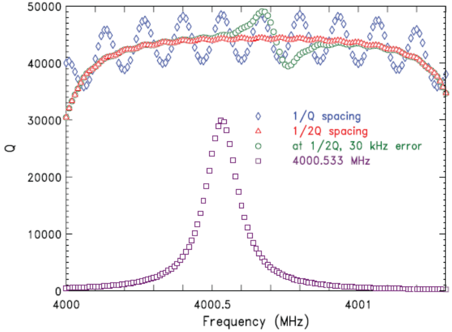
$$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

- Noise temperature $T_S \propto$ variance of Gaussian noise due to blackbody radiation of cavity.
- Linear detection:
  $Q_a \gg Q_c \Rightarrow \Delta\nu_a \ll \Delta\nu_c$.



- Measurement time: axion signal remains constant, noise decreases as $1/\sqrt{t}$.

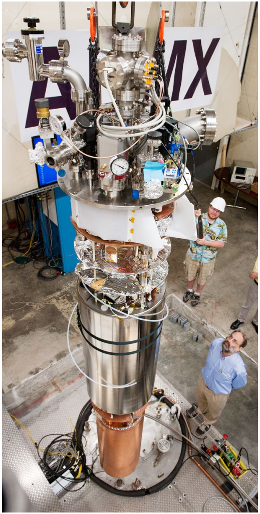
Microwave Cavity Axion Searches – Scan Rate



- After each measurement, tune cavity resonance by half-linewidth:
- Scan rate:

$$\boxed{\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2}$$

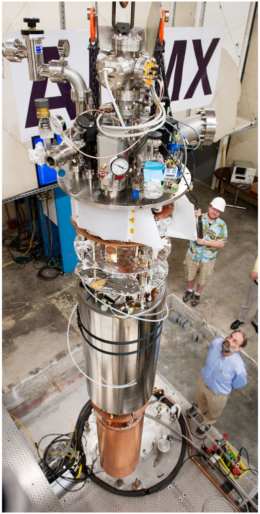
ADMX (The Axion Dark Matter eXperiment)



- Collaboration of **U. Washington (host)**, U. Florida, LLNL, UC Berkeley, NRAO, Sheffield U.
- 1996-2009: excluded KSVZ axions with $1.9\ \mu\text{eV} < m_a < 3.6\ \mu\text{eV}$ (460 – 860 MHz).*

*: S. J. Asztalos et al., Phys. Rev. Lett. **104**, 041301 (2010).

ADMX (The Axion Dark Matter eXperiment)



- Collaboration of **U. Washington (host)**, U. Florida, LLNL, UC Berkeley, NRAO, Sheffield U.
- 1996-2009: excluded KSVZ axions with $1.9\ \mu\text{eV} < m_a < 3.6\ \mu\text{eV}$ (460 – 860 MHz).*
- Current focus is reducing T_S to improve scan rate:
  - Liquid Helium → Dilution refrigerator expected in 2015.
  - Will improve $\frac{d\nu}{dt}$ by factor of 400!
  - Enabled by SQUID technology.

*: S. J. Asztalos et al., Phys. Rev. Lett. **104**, 041301 (2010).

Questions I hope to address

- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

ADMX-HF (High-Frequency)

- Will scan in parallel with ADMX starting around 5 GHz ($\sim$ 20 μeV).
- Will serve as an R&D testbed for extending the microwave cavity search principle to higher frequencies.
- Microwave cavity experiments get hard at high frequencies, but we can reach the axion model band with current technology.
    - Dilution refrigerator in initial design.
    - Tunable Josephson Parametric Amplifiers (JPAs): ultra-low-noise amplifiers developed $\sim$ 2009.

ADMX-HF Collaboration

- **Yale University (host)**

  Steve Lamoreaux, Yulia Gurevich, Ben Brubaker, Sid Cahn

- UC Berkeley

  Karl Van Bibber, Tim Shokair, Austin Lo, Maria Simanovskaia, Jaben Root

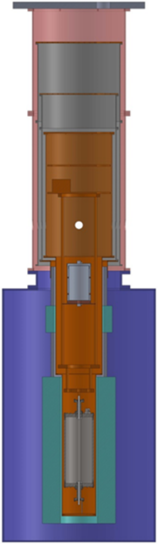
- Lawrence Livermore National Lab

  Gianpaolo Carosi

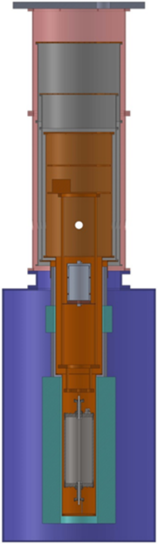
- CU Boulder/JILA

  Konrad Lehnert, Dan Palken

ADMX-HF Layout

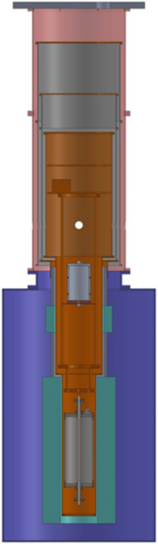


ADMX-HF Layout



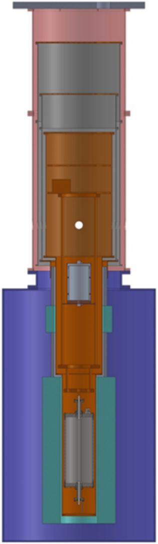
- 9 T superconducting solenoid

ADMX-HF Layout



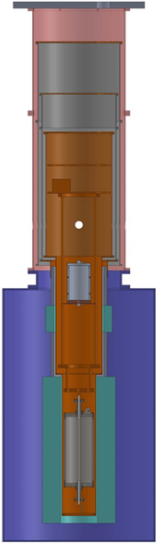
- 9 T superconducting solenoid
- Dilution Refrigerator: $T \sim 100$ mK

ADMX-HF Layout



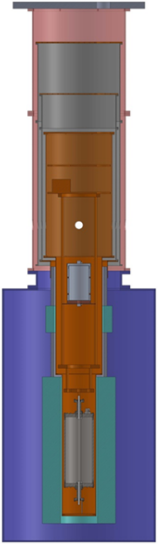
- 9 T superconducting solenoid
- Dilution Refrigerator: $T \sim 100$ mK
- Copper cavity with $Q_c \sim 20,000$, tunable from 3.5 to 5.85 GHz

ADMX-HF Layout



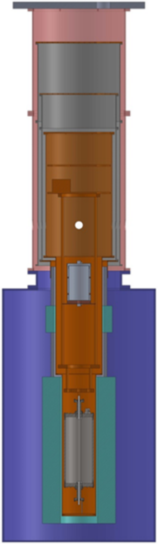
- 9 T superconducting solenoid
- Dilution Refrigerator: $T \sim 100$ mK
- Copper cavity with $Q_c \sim 20,000$, tunable from 3.5 to 5.85 GHz
- JPA: sub-quantum-limited, tunable from 4.4 to 6.4 GHz

ADMX-HF Layout



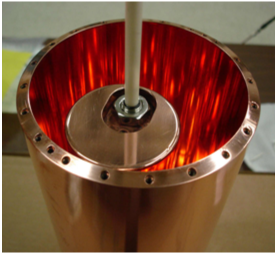
- 9 T superconducting solenoid
- Dilution Refrigerator: $T \sim 100$ mK
- Copper cavity with $Q_c \sim 20,000$, tunable from 3.5 to 5.85 GHz
- JPA: sub-quantum-limited, tunable from 4.4 to 6.4 GHz
- Whole experiment takes place in a room in WLab West!

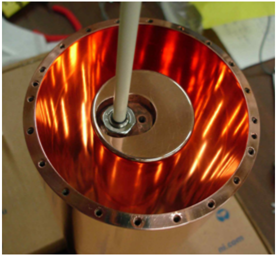
ADMX-HF Layout



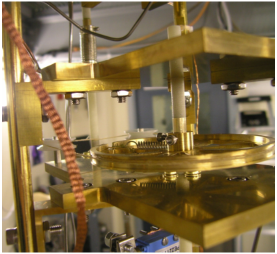
- 9 T superconducting solenoid
- Dilution Refrigerator: $T \sim 100$ mK
- Copper cavity with $Q_c \sim 20,000$, tunable from 3.5 to 5.85 GHz
- JPA: sub-quantum-limited, tunable from 4.4 to 6.4 GHz
- Whole experiment takes place in a room in WLab West!

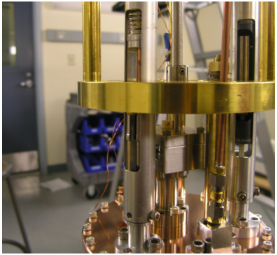
Cavity and Motion Control



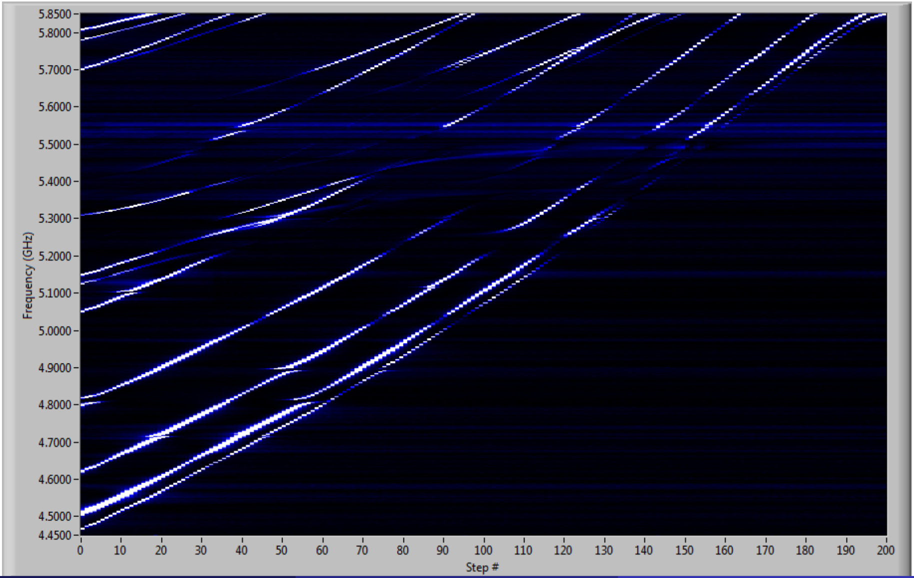


- $Q_c \sim 20,000$, tunable from 3.5 to 5.85 GHz.
- Tuning via rotation of off-axis Cu rod.
- Cryogenic motion control via stepper motors and kevlar lines – 0.003° precision.
- No heat load from motion control at 100 mK.

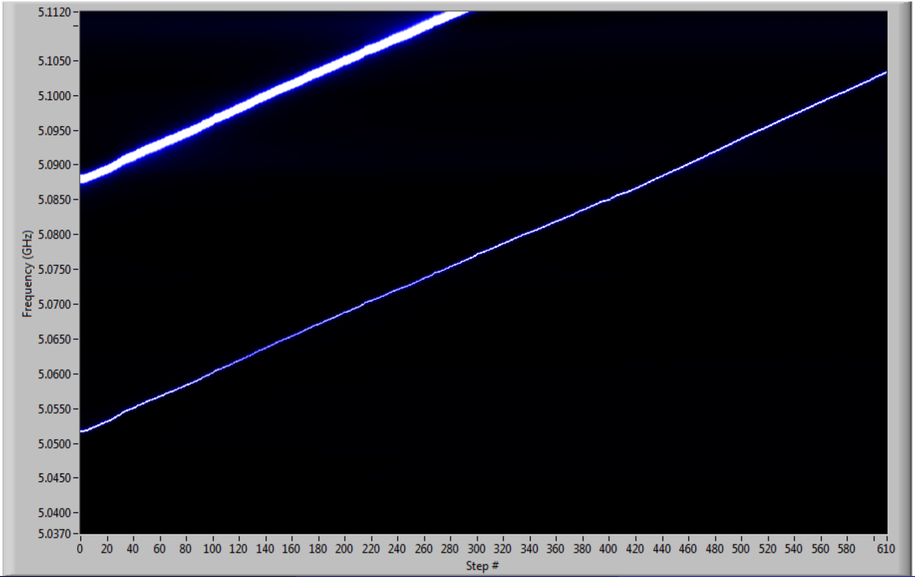




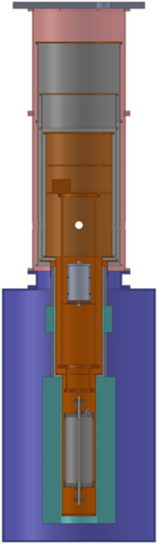
Cavity Mode Maps



Cavity Mode Maps



ADMX-HF Layout



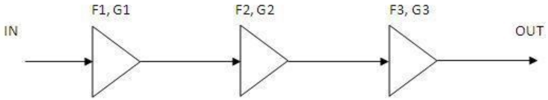
- 9 T superconducting solenoid
- Dilution Refrigerator: $T \sim 100$ mK
- Copper cavity with $Q_c \sim 20,000$, tunable from 3.5 to 5.85 GHz
- JPA: sub-quantum-limited, tunable from 4.4 to 6.4 GHz

Quantum Limits on Noise Performance

- Linear detection: measuring amplitude and phase simultaneously $\Rightarrow T_S = h\nu/2$ even at $T = 0$ K.

Quantum Limits on Noise Performance

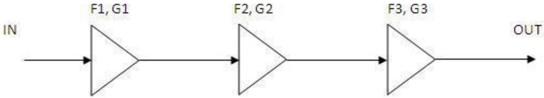
- Linear detection: measuring amplitude and phase simultaneously $\Rightarrow T_S = h\nu/2$ even at $T = 0$ K.
- Need to amplify signal: all loss to room temperature degrades SNR.
- Noise performance of first amplifier is critical:



$$F_n = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots + \frac{F_n - 1}{G_1 G_2 \dots G_{n-1}}$$

Quantum Limits on Noise Performance

- Linear detection: measuring amplitude and phase simultaneously $\Rightarrow T_S = h\nu/2$ even at $T = 0$ K.
- Need to amplify signal: all loss to room temperature degrades SNR.
- Noise performance of first amplifier is critical:

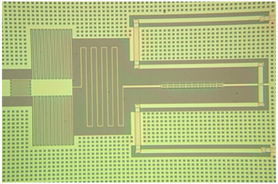


$$F_n = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots + \frac{F_n - 1}{G_1 G_2 \dots G_{n-1}}$$

- The Standard Quantum Limit: A phase-insensitive linear amplifier must add noise $\geq h\nu/2$.*

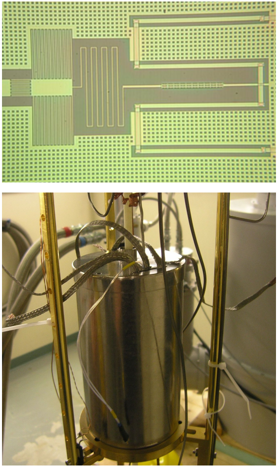
*: C. M. Caves, Phys. Rev. D **26**, 1817 (1982).

Josephson Parametric Amplifier



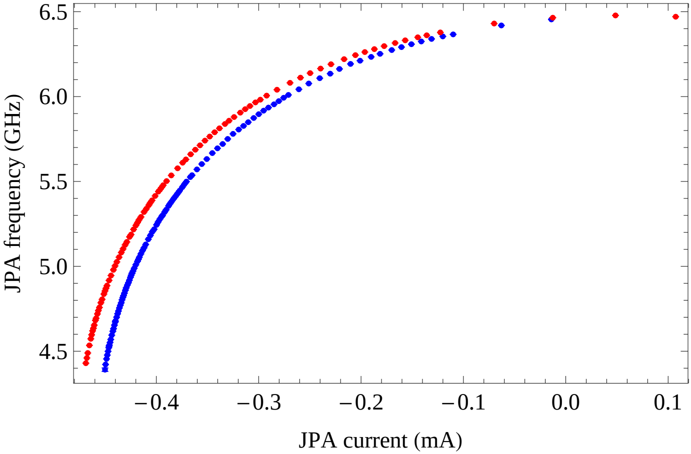
- An LC circuit with nonlinear SQUID inductance ⇒ parametric gain.
- Energy transfer from an intense pump tone near resonance to nearby frequencies.
- The JPA gain is phase-sensitive: no standard quantum limit!

Josephson Parametric Amplifier



- An LC circuit with nonlinear SQUID inductance ⇒ parametric gain.
- Energy transfer from an intense pump tone near resonance to nearby frequencies.
- The JPA gain is phase-sensitive: no standard quantum limit!
- Narrow-band, but SQUID inductance also a function of flux ⇒ resonance is tunable, but very good magnetic shielding required.

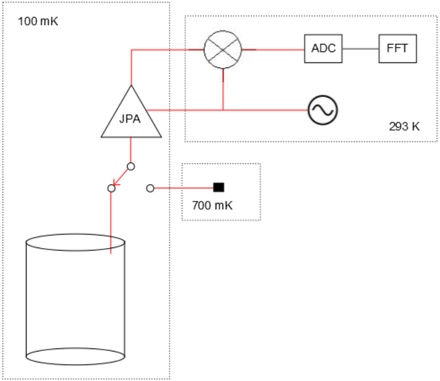
JPA Tuning



In 5 T field (blue) and no field (red)

Signal Chain

Analysis is conceptually simple, requires minimal data processing:



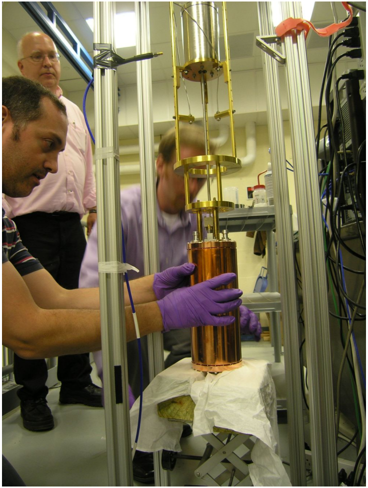
- Cavity signal is mixed down to MHz and digitized for $t \sim 25$ min.
- Compute power spectrum and look for excess power in each axion-width bin.
- Step resonance by $\Delta\nu_c/2$ and repeat $\mathcal{O}\left(10^4\right)$ times.
- T_S calibrated in situ using blackbody source at known temperature.

Questions I hope to address

- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

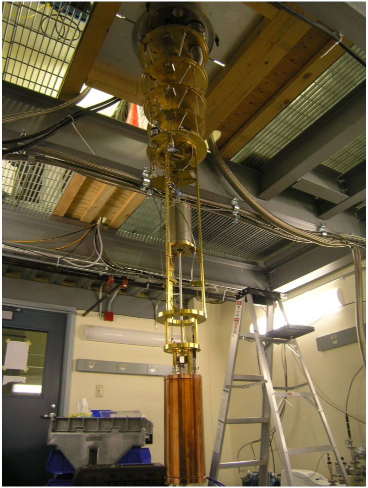
Recent Progress – Summer 2014

- 6/23-7/1: cavity delivered to Yale, characterized on teststand and in fridge.



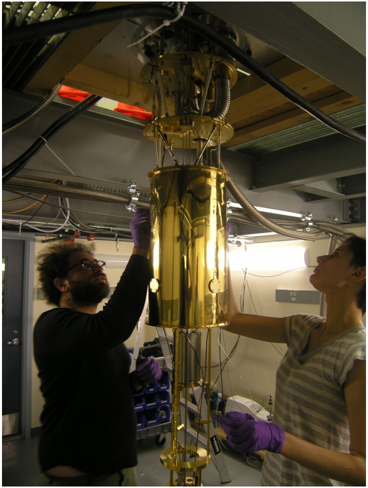
Recent Progress – Summer 2014

- 6/23-7/1: cavity delivered to Yale, characterized on teststand and in fridge.



Recent Progress – Summer 2014

- 6/23-7/1: cavity delivered to Yale, characterized on teststand and in fridge.
- 7/2-7/15: first full system assembly; first cold comissioning run: tests of JPA operation, field ramping.



Recent Progress – Summer 2014

- 6/23-7/1: cavity delivered to Yale, characterized on teststand and in fridge.
- 7/2-7/15: first full system assembly; first cold comissioning run: tests of JPA operation, field ramping.

Recent Progress – Summer 2014

- 6/23-7/1: cavity delivered to Yale, characterized on teststand and in fridge.
- 7/2-7/15: first full system assembly; first cold comissioning run: tests of JPA operation, field ramping.

Recent Progress – Summer 2014

- 6/23-7/1: cavity delivered to Yale, characterized on teststand and in fridge.
- 7/2-7/15: first full system assembly; first cold comissioning run: tests of JPA operation, field ramping.

Recent Progress – Summer 2014

- 6/23-7/1: cavity delivered to Yale, characterized on teststand and in fridge.
- 7/2-7/15: first full system assembly; first cold comissioning run: tests of JPA operation, field ramping.
- 7/20-9/8: system warm; upgrades to motion control, signal chain.

Recent Progress – Fall 2014

- 9/15-10/24: second cold comissioning run:
    - Cold motion control tests: repeatable 100 kHz stepping
    - Succesful simultaneous tuning of cavity and JPA.
    - Measurement of total added noise above zero-point motion: $(0.3 \pm 0.15)\,h\nu$: JPA is sub-quantum-limited!
    - Proof-of-principle axion data: two points, $t = 200$ s at $B = 3.7$ T $\Rightarrow$ 300 kHz at $g_{a\gamma\gamma} \approx 16\times$ KSVZ (more careful analysis in progress).

Recent Progress – Fall 2014

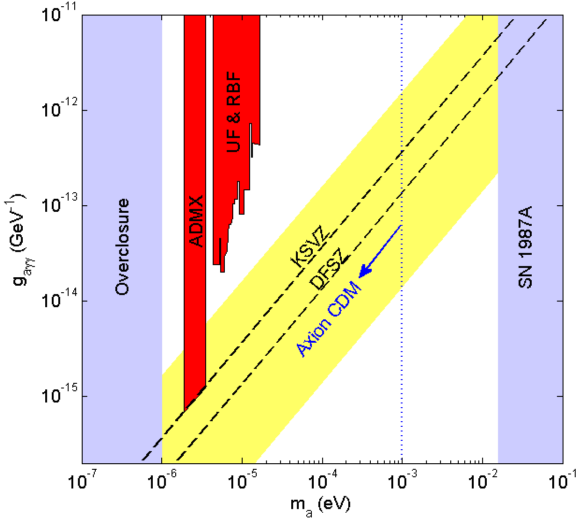
- 9/15-10/24: second cold comissioning run:
  - Cold motion control tests: repeatable 100 kHz stepping
  - Succesful simultaneous tuning of cavity and JPA.
  - Measurement of total added noise above zero-point motion: $(0.3 \pm 0.15)\, h\nu$: JPA is sub-quantum-limited!
  - Proof-of-principle axion data: two points, $t = 200$ s at $B = 3.7$ T $\Rightarrow$ 300 kHz at $g_{a\gamma\gamma} \approx 16\times$ KSVZ (more careful analysis in progress).
- 10/29-11/11: system warm for cryocooler upgrade.
- Late 2014: reconfigure magnetic shielding to mitigate JPA gain fluctuations due to vibration in inhomogeneous field.

Questions I hope to address

- Why do we think axions exist?
- Why do we think dark matter is made of axions?
- What parameter space is available to axions?
- What are the principles of microwave cavity axion detection?
- How are these principles realized in ADMX-HF at Yale?
- What is the current status of ADMX-HF?
- What does ADMX-HF hope to accomplish?

Projected Exclusion

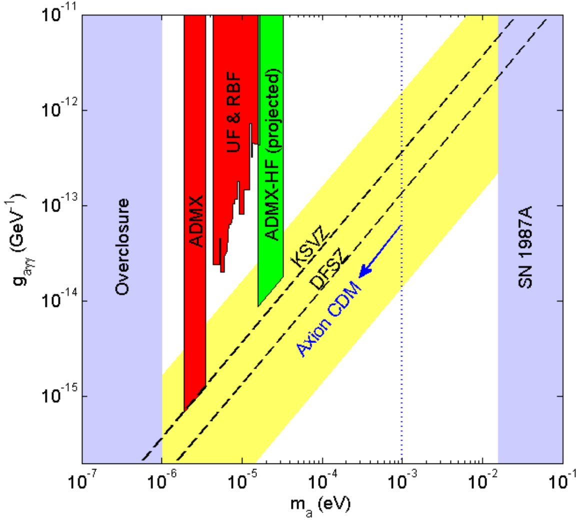
- Full data run beginning early 2015!



Projected Exclusion

- Full data run beginning early 2015!
- Three years of data with current technology:

  16 – 33 μeV at 1.5 × KSVZ



Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$

Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$
- $B \propto \$\$$

Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$
- $B \propto \$\$$
- $Q_c \propto \nu^{-2/3}$ for copper.

Outlook: High Frequency Challenges

$$\frac{d\nu}{dt} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$
- $B \propto \$\$$
- $Q_c \propto \nu^{-2/3}$ for copper.
- $V \propto \nu^{-3}$

Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$
- $B \propto \$\$$
- $Q_c \propto \nu^{-2/3}$ for copper.
- $V \propto \nu^{-3}$

High frequencies are hard. What can we improve?

Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$
- $B \propto \$\$$
- $Q_c \propto \nu^{-2/3}$ for copper.
- $V \propto \nu^{-3}$

High frequencies are hard. What can we improve?

- Boost Q_c: Hybrid superconducting-normal cavities.

Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$
- $B \propto \$\$$
- $Q_c \propto \nu^{-2/3}$ for copper.
- $V \propto \nu^{-3}$

High frequencies are hard. What can we improve?

- Boost Q_c: Hybrid superconducting-normal cavities.
- Evade SQL: Single-photon detection and/or squeezed states.

Outlook: High Frequency Challenges

$$\frac{\mathrm{d}\nu}{\mathrm{d}t} \propto g_{a\gamma\gamma}^4 \frac{m_a^2}{T_S^2} B^4 Q_c V^2$$

- SQL: $T_S \geq \frac{1}{2}\nu = \frac{1}{2}m_a$
- $B \propto \$\$$
- $Q_c \propto \nu^{-2/3}$ for copper.
- $V \propto \nu^{-3}$

High frequencies are hard. What can we improve?

- Boost Q_c: Hybrid superconducting-normal cavities.
- Evade SQL: Single-photon detection and/or squeezed states.
- Avoid V suppresion: Higher-order modes and/or power-combining cavities.

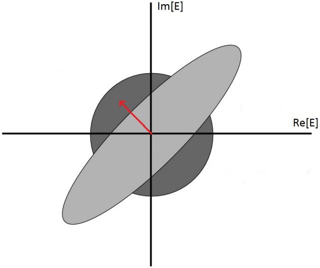
Extra Slides

Hybrid Superconducting Cavities

- Superconducting cavities: high Q, but not in high field.
- Type-II superconducting thin films: $(B_{c1})_{\|} \sim (\lambda/d)^2$ for $d < \lambda$.
- With appropriate coatings on barrel and copper endcaps, we can increase Q by $\sim$ the aspect ratio of the cavity ($\sim 6\times$).
- Promising materials: NbTiN, NbN, MgB_2.
- Field uniformity ($B_r < 50$ G) built in to ADMX-HF design.
- Challenges: good microwave reflectivity, proximity effect, details of stoichiometry, etc.

Single Photon Detection and Squeezed States

- Single-photon detection ⇒ no spectral resolution: thermal noise from whole cavity band but no standard quantum limit!
- $\frac{\delta P_\ell}{\delta P_{\mathrm{sp}}} \sim \sqrt{\frac{Q_c}{Q_a} e^{h\nu/kT}} > 1$ above ~ 10 GHz, or lower with better Q_c.*



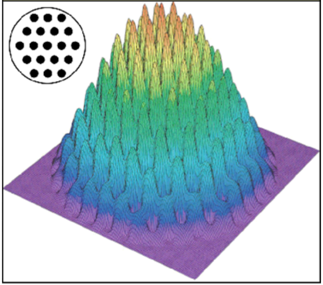
- Squeezed states: beat SQL without sacrificing phase information!
- Axion signal uncorrelated with lab phase reference on long timescales.
- Practical utility limited by loss in commercial components, but may soon be worthwhile.

*: S. K. Lamoreaux et al., Phys. Rev. D **88**, 035020 (2013).

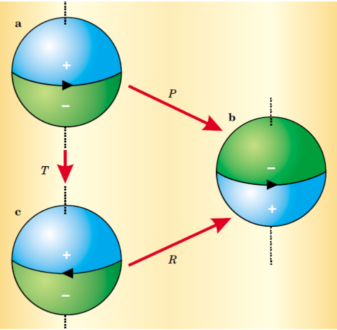
Large volumes at high frequencies

- Higher-order TM modes of a large cavity: $C_{0n0} \propto \nu^{-2}$ (better than $V \propto \nu^{-3}$), but mode crossings are increasingly a problem for $n \gtrsim 3$.
- Power-combining multiple small cavities in a large magnetic field volume: practical challenges keeping resonances in step.
- Photonic band gap cavities?

TM$_{010}$ Electric Field for 96-post Array

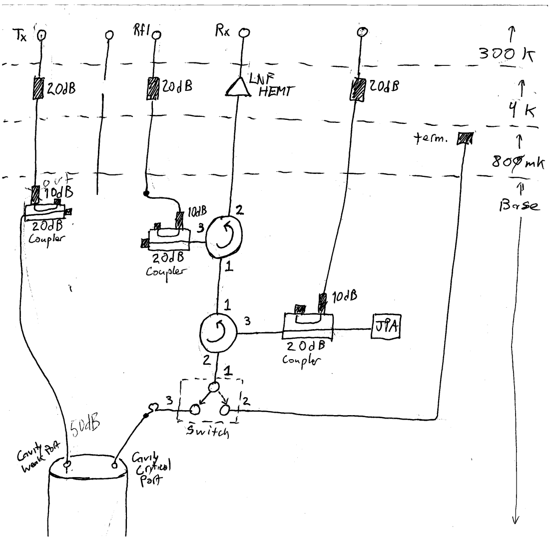


Symmetry Violation and EDMs



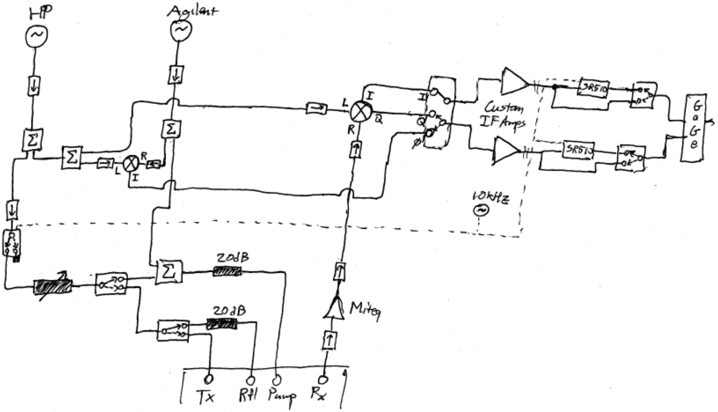
- By Wigner-Eckart Theorem, expectation values of vector operators must point along spin quantization direction.
- Magnetic and Electric Dipole Moments transform oppositely under *P* and *T* reversal.
- *CP* violation in QCD ⇒ neutron EDM. Non-observation constrains $\theta < 10^{-10}$ rad

Microwave Layout



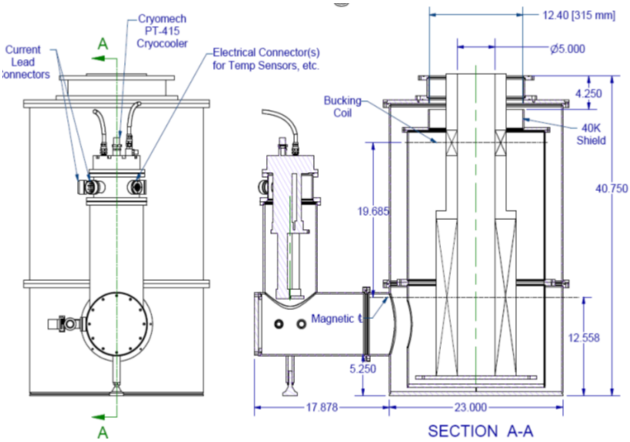
- 3 paths for injection into fridge: transmission, reflection, JPA pump.
- Cryo microwave switch (Radiall) and terminator at still plate for hot/cold load measurement.
- Second-stage amplifier: LNF LNC4_8A: $T_N \approx 3$ K.

Microwave Layout



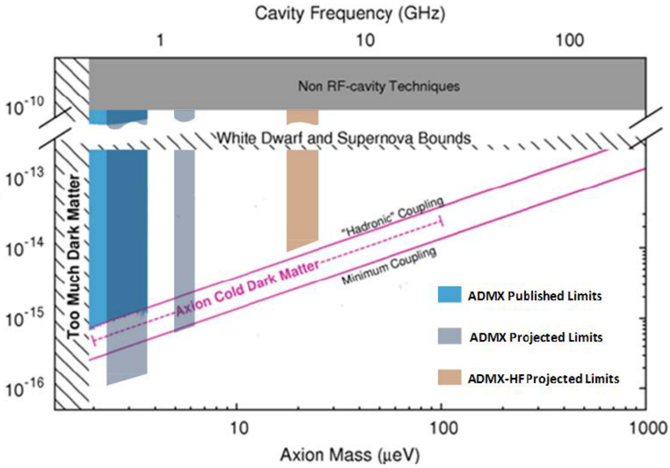
- GaGe ADC: 14 bits, 2 GS memory, 50 MS/s max sampling.
- Lock-in detection for network analysis.

Magnet



- 9 T field at 72 A
- Liquid cryogen free
- Persistent
- 16.5 cm bore

ADMX near-term projections



*: I. Stern, arXiv:1403.5332 (2014).

Cold Dark Matter Axions?

- If axions are so light, why do they form CDM rather than HDM?
- Thermal relic axions *do* form hot dark matter, like neutrinos, but there is a non-thermal axion production mechanism.
- The misalignment mechanism: anomalous PQ symmetry breaking at $\Lambda_{\mathrm{QCD}} \Rightarrow$ a condensate of zero-momentum axions.*
- Sikivie argues that axions can re-thermalize through gravitational interactions and form a BEC.[†]

*: J. Preskill, M. Wise, and F. Wilczek, Phys. Lett. B **120**, 127 (1983).

[†]: P. Sikivie and Q. Yang, Phys. Rev. Lett. **103**, 111301 (2009).

Photos and figures from

- A. S. Chou, U. of M. Cosmology Seminar, 2011.
- NASA: `http://www.nasa.gov/multimedia/imagegallery/image_feature_1163.html`
- I. G. Irastorza, U. W. Axion Physics Workshop, 2012.
- U. Washington: `http://spectrum.ieee.org/aerospace/astrophysics/the-hunt-for-the-invisible-axion/`
- `http://www.rfwireless-world.com/Terminology/noise-factor-versus-noise-figure.html`
- N. Fortson, P. Sandars, and S. Barr, Physics Today **56** (6), 33 (2003).