Microwave Cavity Axion Searches

Ben Brubaker

ADMX-HF, Yale University

Dark Interactions
BNL
June 13, 2014

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- Resonant detection in a microwave cavity is the only method with proven sensitivity to the CDM axion model band.
- ADMX is the current leader in this field.
- ADMX-HF will extend the microwave cavity technique to higher masses, with sufficient sensitivity to probe the axion model band.

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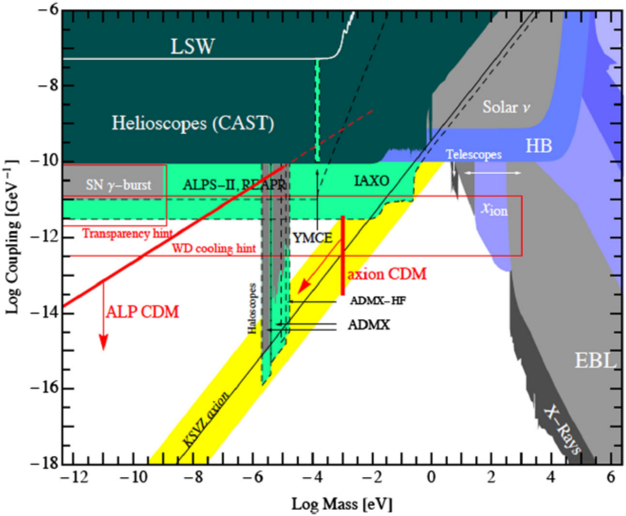
- Light axions associated with new physics at high energies can be dark matter!

Axion Parameter Space



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

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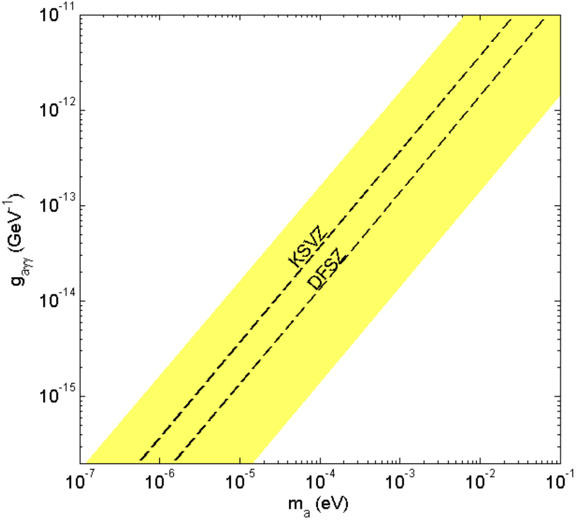

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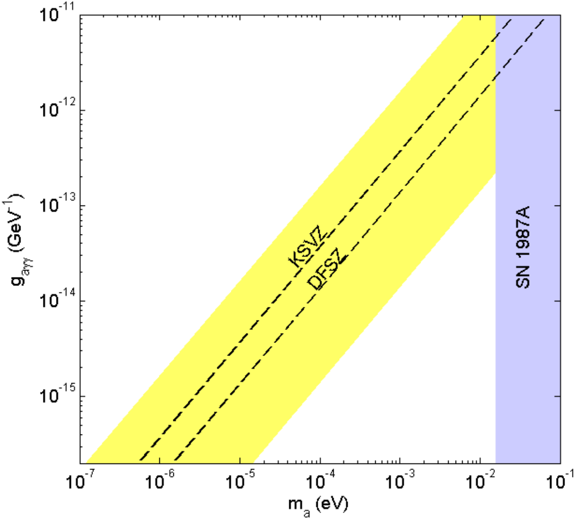

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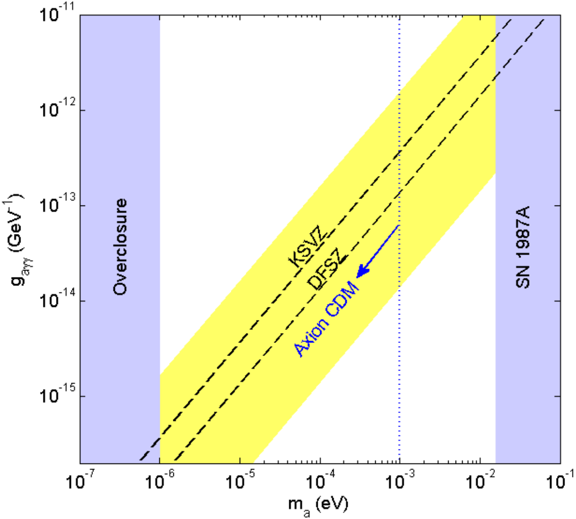

- SN 1987A axion emission too efficient for $m_a \gtrsim 10$ meV.
- $\Omega_a \propto m_a^{-7/6}$: axion dark matter fraction negligible for $m_a \gtrsim 1$ meV.
- too much dark matter (?) for $m_a \lesssim 1\ \mu$eV.

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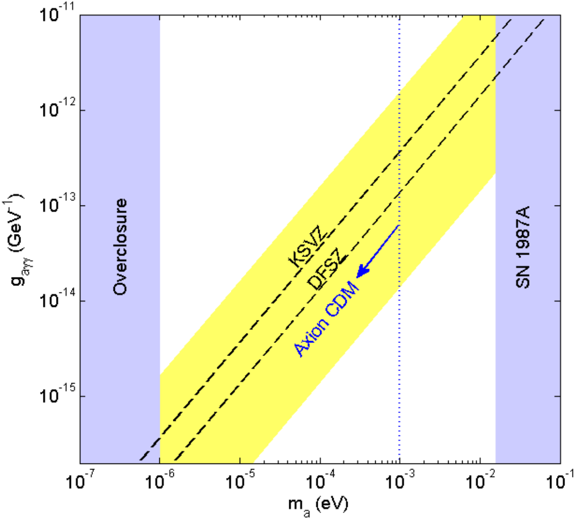

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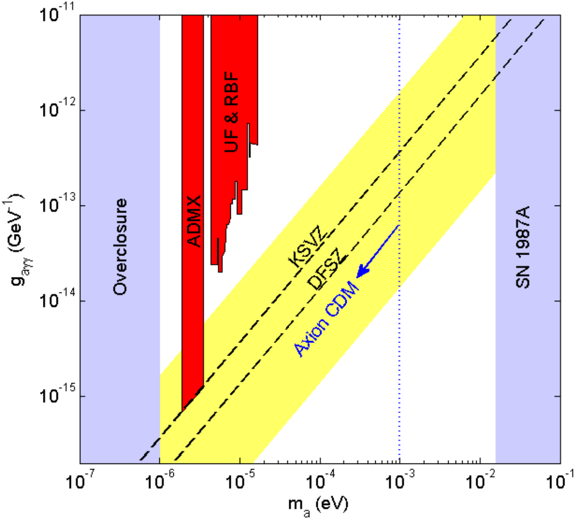

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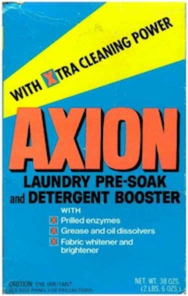
- Coupling is so small that we must use intrinsically narrow-band resonant detection.

Properties of Axion CDM



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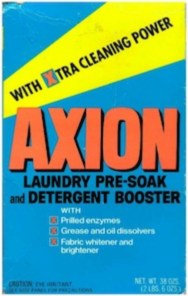

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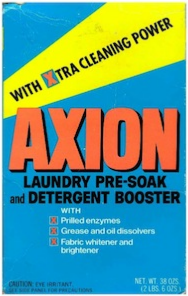

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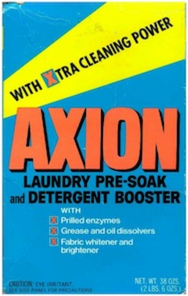

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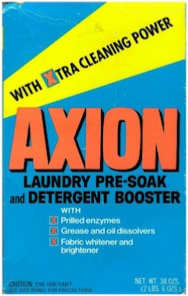

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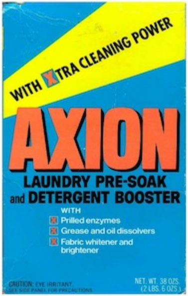

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- More like a classical field than particles.

Microwave Cavity Axion Searches – Concept

- Sikivie*: search for axions with photon coupling $\mathcal{L} \subset g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$.

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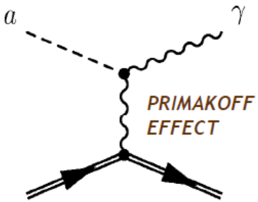

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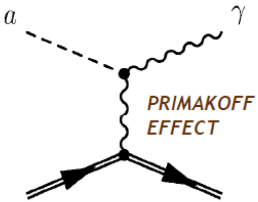

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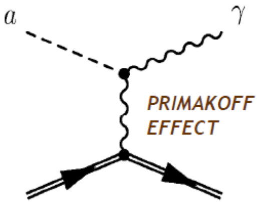

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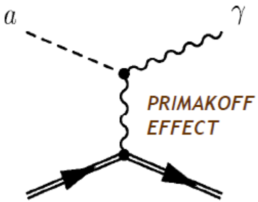

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- Cryogenics and low-noise amplifier to boost SNR.

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- Effective volume occupied by cavity mode

  $\Rightarrow$ best for low-order TM modes: $L \sim \nu^{-1}$

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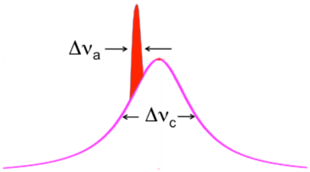

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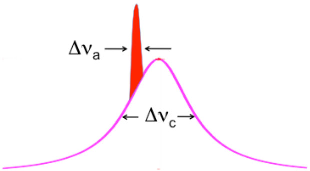

- In practice, use a tunable microwave cavity:

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

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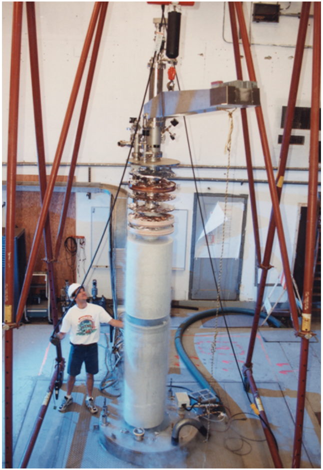

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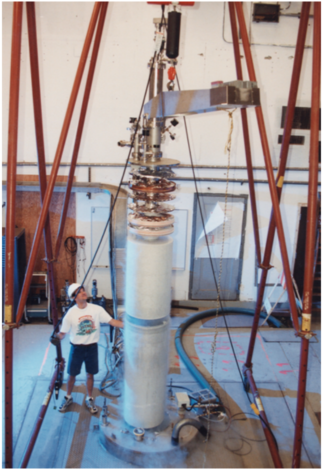

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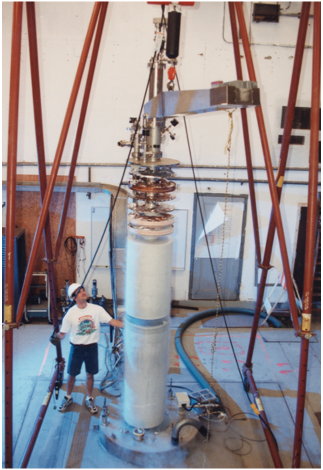

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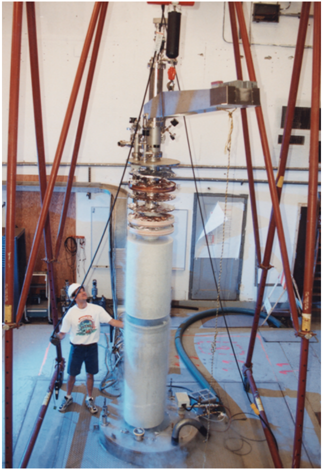

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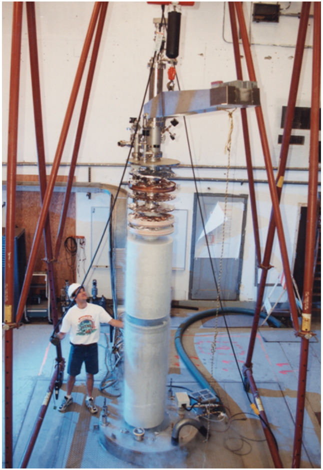

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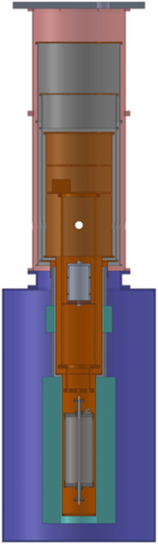
  - Dilution refrigerator in initial design
  - Tunable Josephson Parametric Amplifiers (JPAs): low-noise amplifiers developed $\sim$ 2009

ADMX-HF Collaboration

- **Yale University (host)**
  Steve Lamoreaux, Yulia Gurevich, Ben Brubaker, Sid Cahn
- UC Berkeley
  Karl Van Bibber, Tim Shokair, Austin Lo, Jaben Root
- Lawrence Livermore National Lab
  Gianpaolo Carosi
- CU Boulder/JILA
  Konrad Lehnert

ADMX-HF Layout



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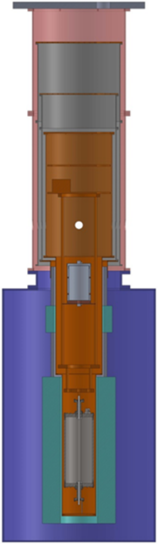

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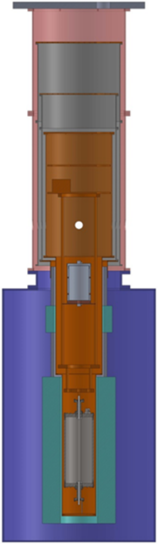

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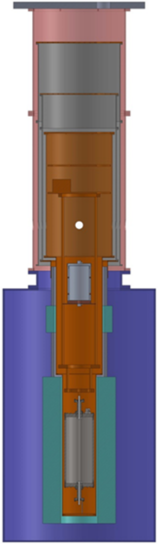

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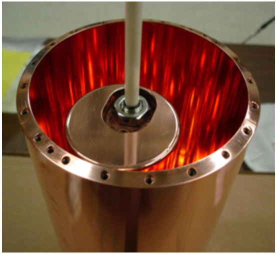
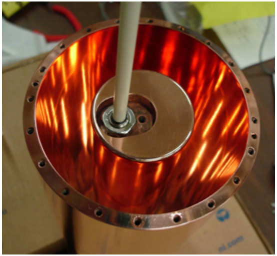
- Magnet and fridge vacuum and cryogenic systems integrated summer 2013.

Cavity and Motion Control





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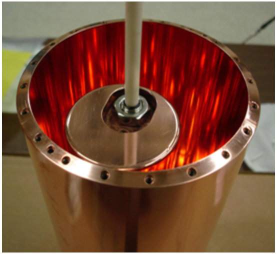

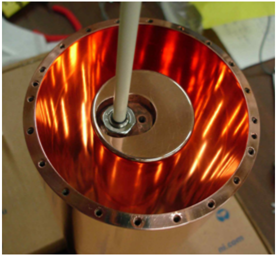

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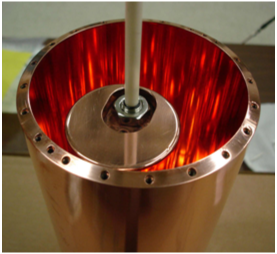

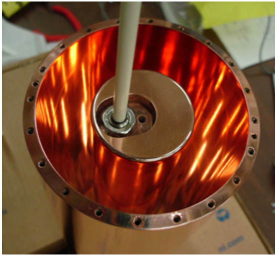

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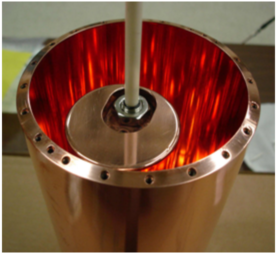

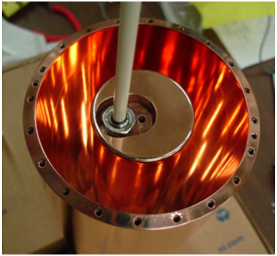

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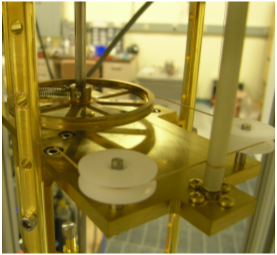

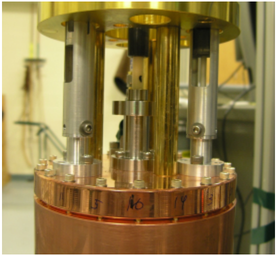

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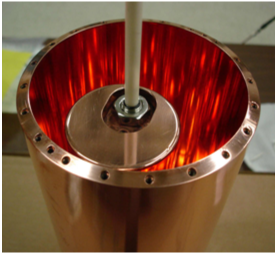

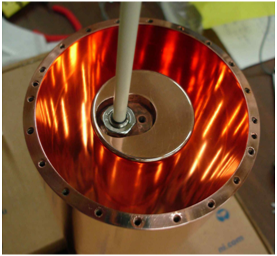

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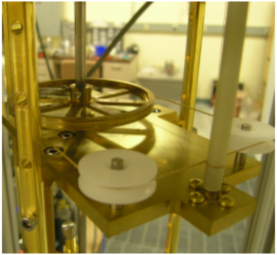
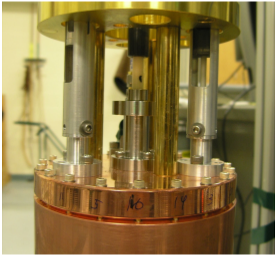
- Cryogenic motion control via stepper motor/kevlar line – 0.01° precision.
- Final cryogenic testing at LLNL: shipping to Yale by end of June.





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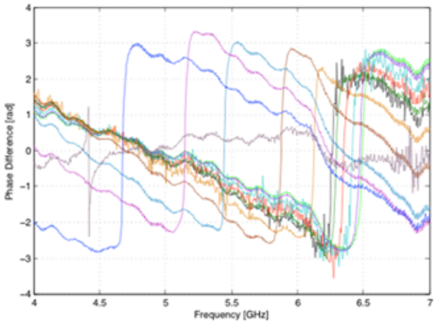
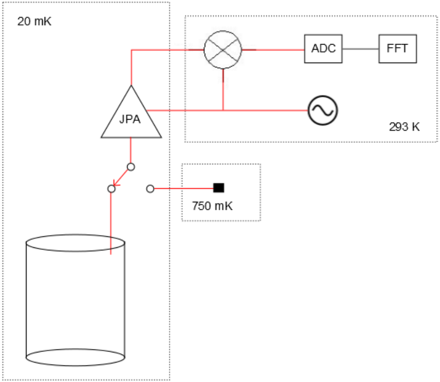
- Installed at Yale summer 2013: in situ tuning 4.6 – 6.4 GHz.



Signal Chain

Analysis is conceptually simple, requires minimal data processing:



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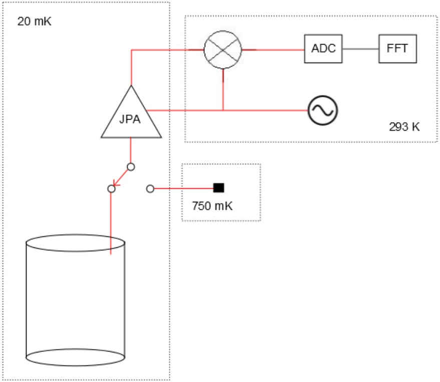

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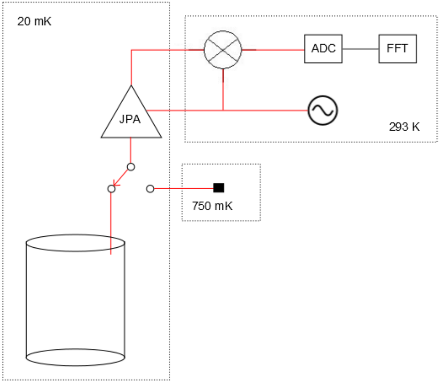

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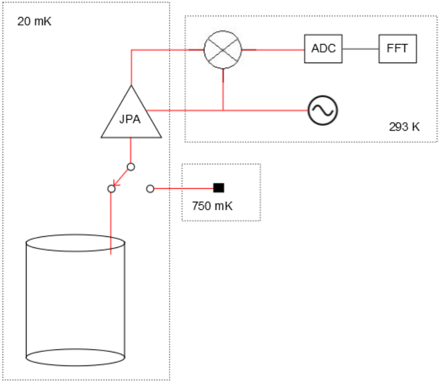

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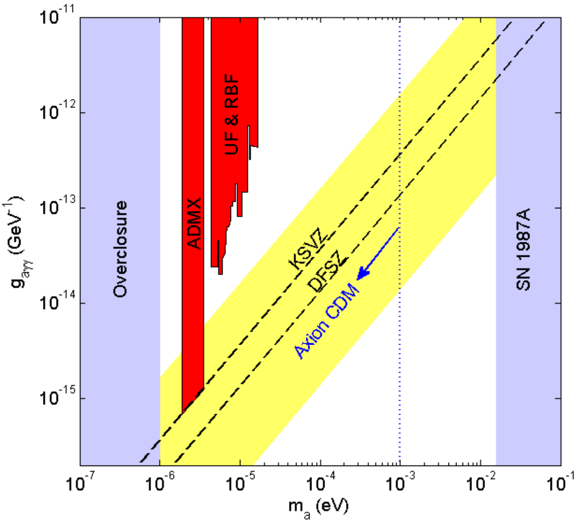
- T_S calibrated in situ using blackbody source at known temperature.

Status and Projected Exclusion

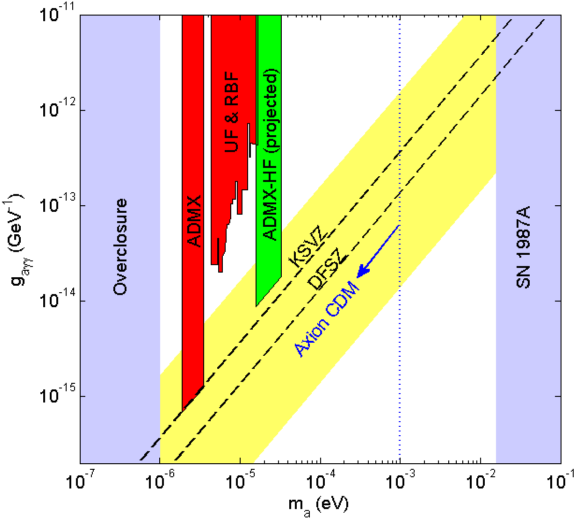
- ADMX-HF commissioning this summer, taking data within the year.



Status and Projected Exclusion

- ADMX-HF commissioning this summer, taking data within the year.
- Three years of data with current technology:

  16 – 33 μeV at 1.5 $\times$ KSVZ



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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.

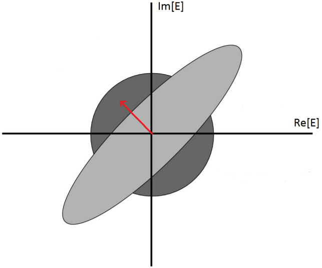
Extra Slides

Hybrid Superconducting Cavities

- Superconducting cavities: high Q, but not in high field.
- Type-II superconducting thin films: $(B_{c1})_{\parallel} \sim (\lambda/d)^2$ 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

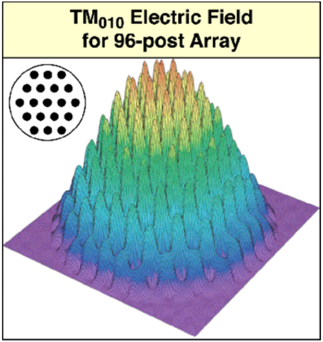
- Single-photon detection ⇒ no spectral resolution: thermal noise from whole cavity band but no standard quantum limit!
- $\frac{\delta P_\ell}{\delta P_{\text{sp}}} \sim \sqrt{\frac{Q_c}{Q_a} e^{h\nu/kT}} > 1$ above ~ 10 GHz, or lower with better Q_c.*
- Squeezed states: beat SQL without sacrificing 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?

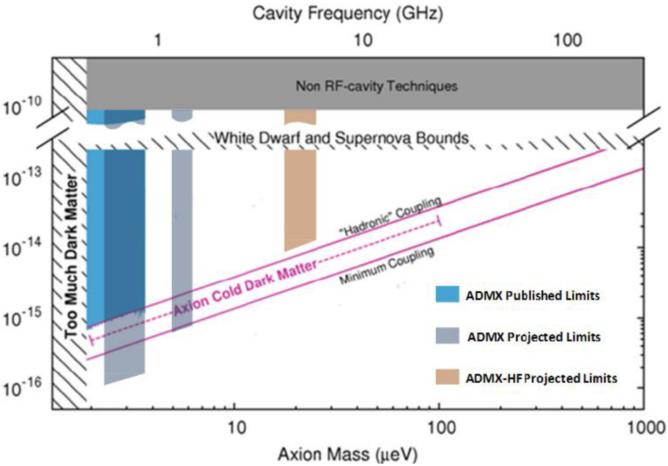


ADMX and ADMX-HF Parameters

	AMDX	ADMX-HF
B	7 T	9 T
V	220 L	1.5 L
Q_c	80,000	20,000
T	2 K (100 mK)	20 mK
T_N	1 K (50 mK)	250 mK

- $\rho_a \approx 0.45$ GeV/cm$^3 \approx 7.5 \times 10^{-25}$ g/cm$^3(\pm 50\%)$.
- ADMX-HF Tuning: 80 mK for 180° over 2 minutes.
- For Copper at 5 GHz, theoretical $Q \sim 200,000$. Reduction factors:
  - Real materials: $\sim 2\times$
  - Extra tuning rod surface area: $\sim 1.5\times$
  - Real tuning rods: $\sim 1.5\times$
  - Critical coupling: $2\times \Rightarrow Q_c \sim 20,000$

ADMX Prospects



*: 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 $\Lambda_{\text{QCD}} \Rightarrow$ 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).

BICEP2 and Axions

- BICEP2: $H_I \sim 10^{14}$ GeV
- $m_a \sim 10^{-8}$ eV $\Leftrightarrow f_a \sim 10^{14}$ GeV
  $m_a \sim 10^{-5}$ eV $\Leftrightarrow f_a \sim 10^{11}$ GeV
- Inflation only creates problems for axions with $f_a \lesssim H_I$.
  (inflationary fluctuations of axion field should be observable in CMB as unobserved isocurvature perurbations).
- A few papers* claim cosmology now favors axions with $m_a \sim 70 - 80\ \mu$eV.

*: e.g., E. Di Valentino et al., arXiv:1405.1860 (2014).