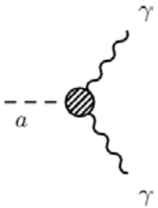
Axion Like Particle Dark Matter Search using Microwave Cavities

Yale Microwave Cavity Experiment (YMCE)

Ana Malagon

Mar 25, 2014 / WIDG Seminar

Weakly Interacting Sub-eV Particles



Axion-Like Particles (**ALPs**)

- come up in many Beyond the Standard Model theories
- low mass particles arise from symmetry breaking at high energy scales
- search for weakly interacting sub-eV particles is a probe of high energy scales
- could also be dark matter

strong CP problem

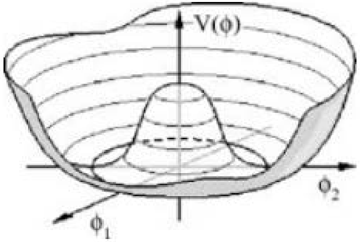
$$\boxed{\bar{\theta}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a}$$

- This term in the QCD lagrangian violates P, CP, and T.
- Non-observance of neutron EDM constrains $\bar{\theta} < 10^{-10}$
- $\bar{\theta}$ the sum of two independent terms from different sectors:
  - $\bar{\theta} = \theta + \arg\det\mathcal{M}$
- The strong CP problem asks why CP is conserved in QCD, or equivalently, why $\bar{\theta}$ is so close to 0

Peccei Quinn Solution

Postulate new global chiral $U(1)_{PQ}$ symmetry:

- symmetry spontaneously broken at energy scale f_a
  - massless Goldstone boson is the axion

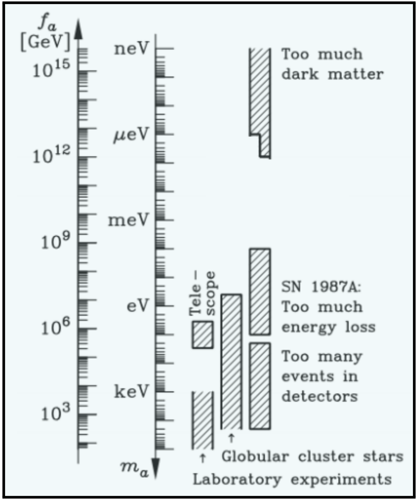


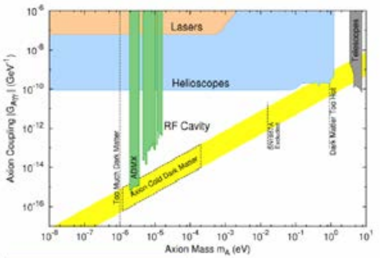
- Explicit symmetry breaking leads to:
  - mass for the axion: $m_a \sim \Lambda^2_{QCD}/f_a$
  - $\bar{\theta} \to 0$

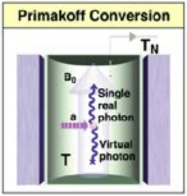
Axion coupling to matter

- Coupling to matter: $g_{ai} \propto m_a \propto f_a^{-1}$

higher energy scales $\Rightarrow$ lighter axions, weaker couplings.







Cosmic ALPs

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

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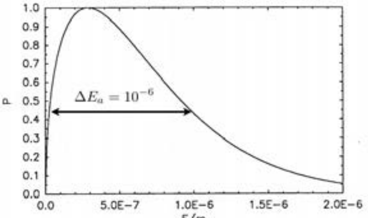
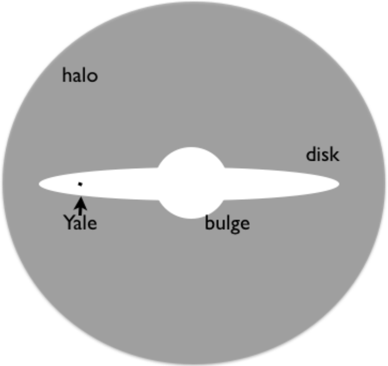
(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

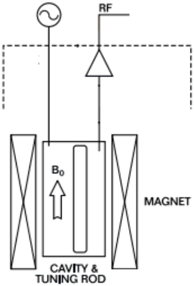
$\rho_a = 0.3\ \mathrm{GeV/cm^3}$
$n_a = 3 \times 10^{12}\ 1/\mathrm{cm^3}$
$\lambda_a = h/(m_a v) > 1\ \mathrm{m}$
$E_a = m_a + \frac{1}{2} m_a v^2,\ \beta \sim \mathcal{O}(10^{-3})$

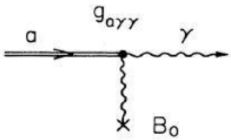




Resonant Detection

$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$





Axion Power on Resonance:

$$P_a = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C_{lmn} \min(Q_{\rm cav}, Q_a)$$

- $B_0 \sim 7$ Tesla
- $Q_{\rm cav} \sim 10^4$
- $C_{lmn} = \frac{|\int_V \vec{E}_{lmn} \cdot \hat{z}\, d^3x|^2}{V \int_V \epsilon |\vec{E}_{lmn}|^2\, d^3x}$
- $V = 1.6\ {\rm cm}^3,\ V \propto \lambda_\gamma^3 \propto m_a^{-3}$
- $C_{020} = 0.13$

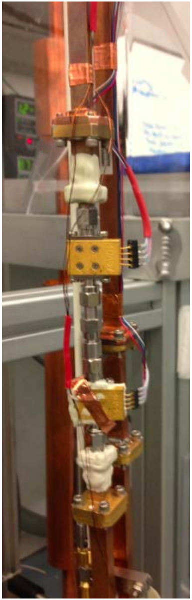
Noise

fluctuations in average noise power:

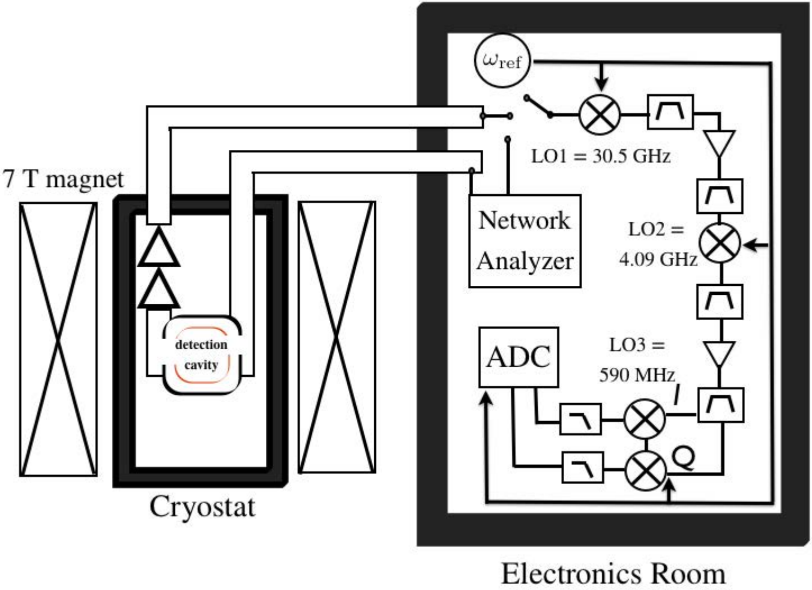
$$P_N = k_B T_N \sqrt{\frac{\Delta\nu_a}{\tau}}$$

- system noise temperature
  $T_N = T_{\text{phys}} + T_{\text{elec}} \approx 22$ K
- width of axion signal $\Delta\nu_a = 34$ kHz
  for $\nu_a = 34$ GHz (140 μeV)
- integration time $\tau = 1$ hour
- $P_N \simeq 10^{-21}$ W

Note: linear amplifiers have standard quantum limit noise: $T_{SQL} = h\nu$ Lamoreaux et al, arXiv[1306:3591]



Experiment



7 T magnet
detection
cavity
Cryostat
ω_{ref}
LO1 = 30.5 GHz
Network
Analyzer
LO2 =
4.09 GHz
ADC
LO3 =
590 MHz
I
Q
Electronics Room

The Lab: Electronics

Triple Heterodyne Receiver

- mixes RF signal to baseband. Tunable first LO.

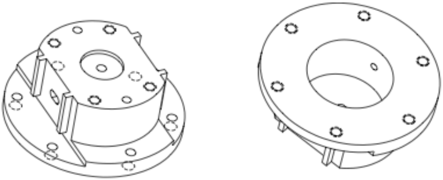
Digitizer

- PCI-5114 card; $F_s = 10$ MHz

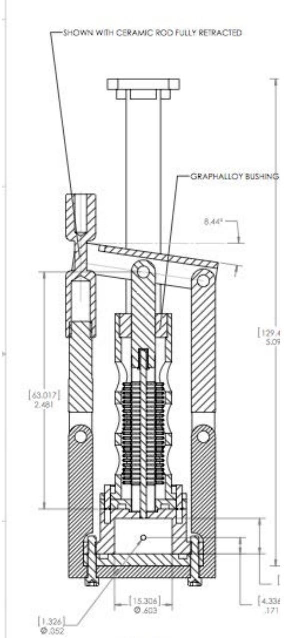
Microwave Cavity

Engineering concerns:

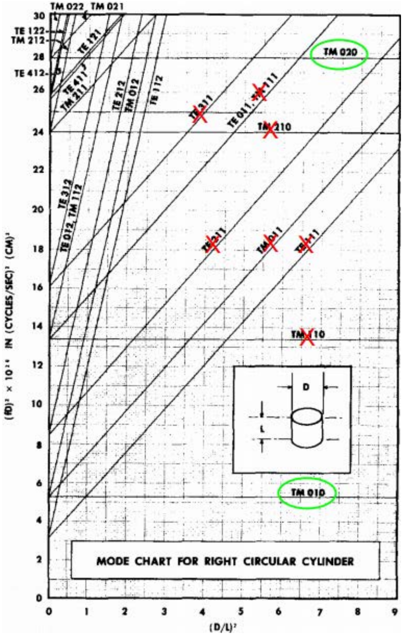
- tunable
- high-Q
- vacuum tight
- two ports - one critically coupled, one weakly coupled

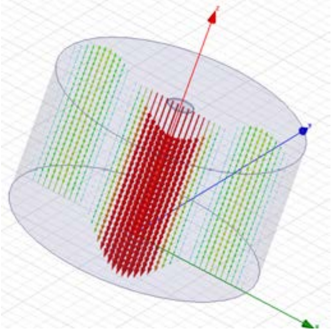


engineering drawings by Will Emmett



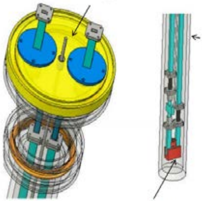
TM_{020} mode





Cavity frequency $f \sim \frac{1}{r}$

Assembly



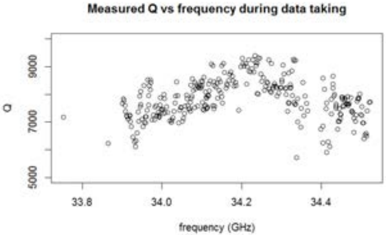
Runs Summary

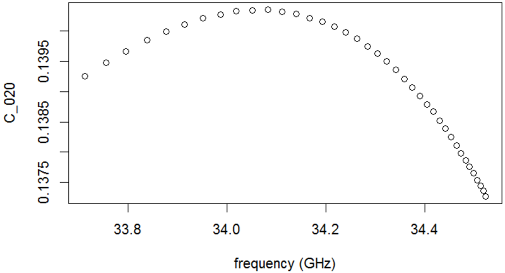
Run	No. of Freq.'s	State
11/19-11/22	9	slow DAQ
12/03-12/07	39	faster DAQ
12/10-12/13	22	tuning rod froze
12/16-12/20	27	–
01/08-01/11	46	heater feedback loop online
01/14-01/18	69	RF switch added
01/23	5	–
01/28-02/01	41	test tone added
02/04-02/07	33	tuning rod froze
02/11-02/13	19	–
03/10-03/13	16	–

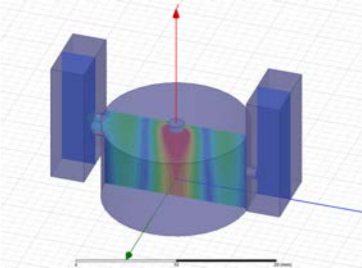
State Parameters

Operational Procedure:

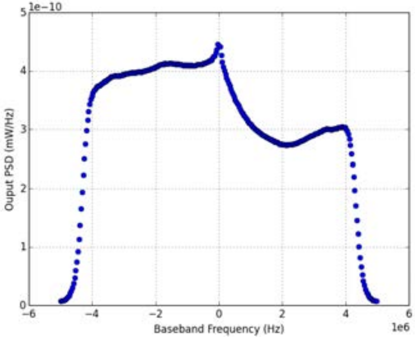
- Tune cavity
- Set first LO so that cavity mixes down to 2 MHz
- Save S21 trace
- Take data for 1 hour
- Tune cavity by 3 MHz
- repeat cycle







Spectra

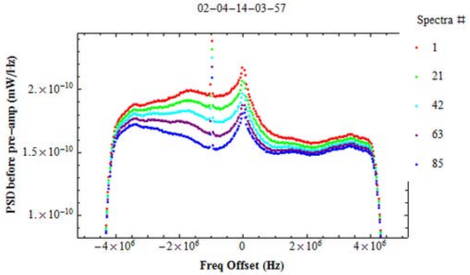


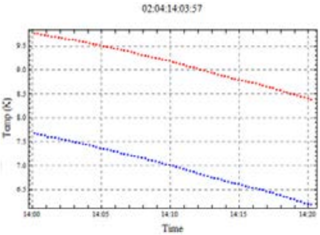
Features

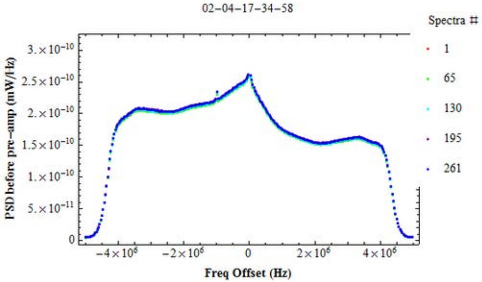
- Low Pass Filter Roll-off
- DC and $1/f$ noise
- Cavity + Amplifier Interaction
- For later runs: test tone at -1 MHz

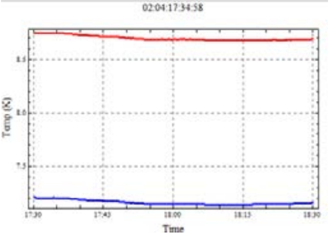
We average 5×10^5 spectra at a time. Each hour long run contains 261 such blocks.
We expect the axion signal to look like a single bin excess.

Temperature Drifts

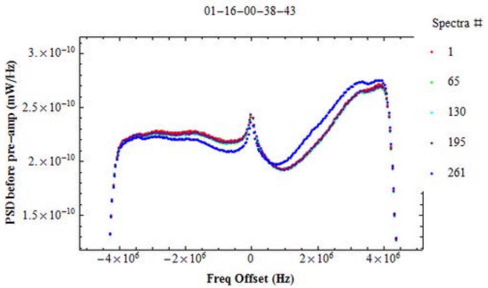


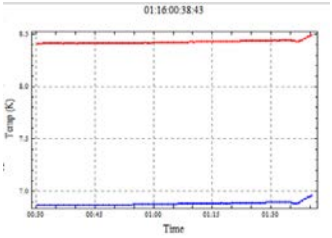


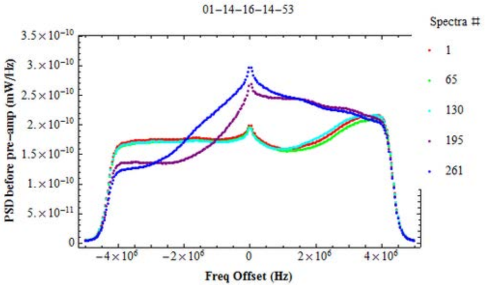


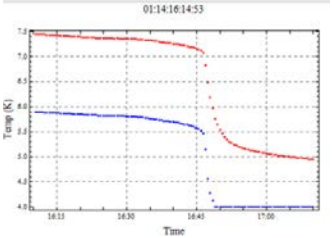


Frequency Drifts

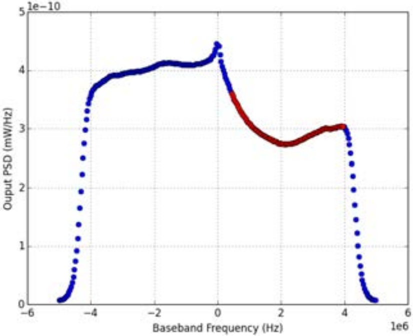






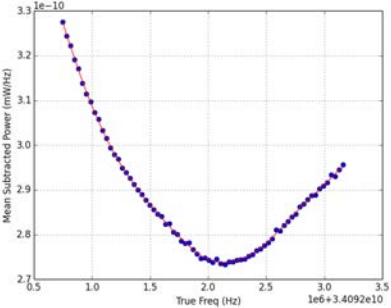


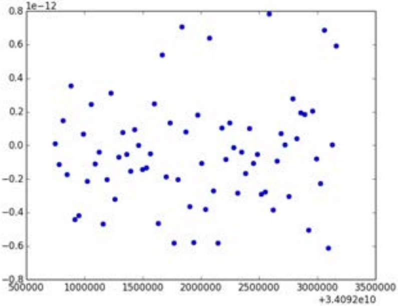
Data Analysis: Ongoing



- Cut on cavity
- Subtract out structure
- Divide by expected axion power
- Co-add spectra with overlapping frequency bins
- Set threshold; retake runs where candidates detected

Data Analysis: Ongoing



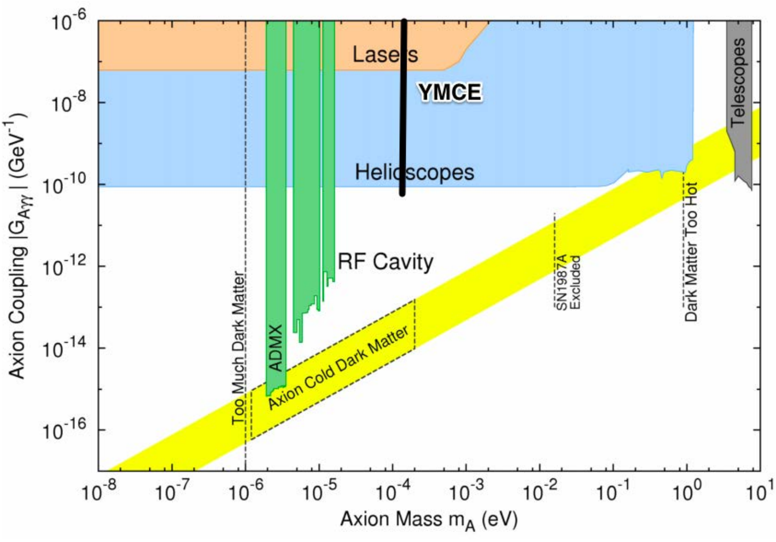


- Cut on cavity
- Subtract out structure
- Divide by expected axion power
- Co-add spectra with overlapping frequency bins
- Set threshold; retake runs where candidates detected

Ongoing...

Projected Exclusion Results

Expect $g_{a\gamma\gamma} < 6 \times 10^{-11}$ $1/\text{GeV}$ for $140.2 \leq m_a \leq 142.7$ μeV



Next Steps

- Outlook
  - take last spectra to fill in gaps
  - rescan candidates
  - run with liquid helium in cavity to access lower frequency range
  - Build cavity to operate at lower frequencies.

Acknowledgments

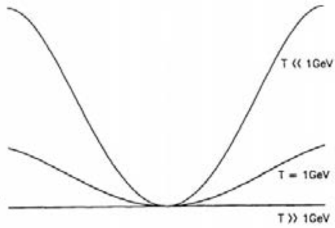
Group: O.K. Baker, A.T. Malagon, A. J. Martin, P.L. Slocum
A. Szymkowiak
Beam lab: J.L. Hirshfield, M. LaPointe, Y. Jiang, S. Shchelkunov
magnet on loan from K. Zilm in Chemistry Dept.

Thanks!

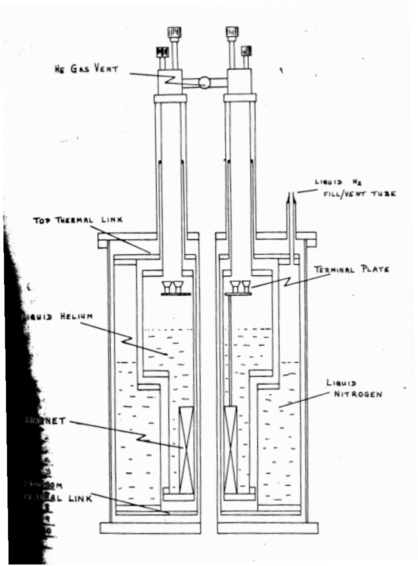
Backup Slides

Axions as cold dark matter

- Misalignment mechanism - non-thermal, coherent process
- leads to non-relativistic axions today with the properties of cold dark matter



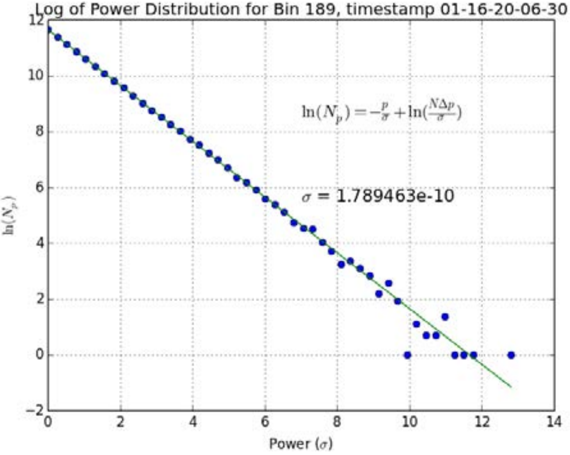
Magnet



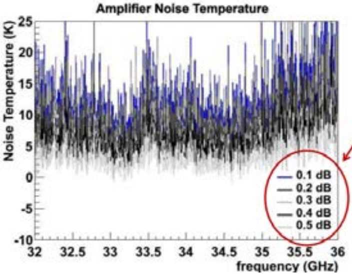
- superconducting NMR magnet
- $B_0 = 7$ Tesla
- warm bore I.D. =8.9 cm

Statistical Distribution of Noise in 1 Bin

σ in units of output power - translates to 12.9 K input temperature.

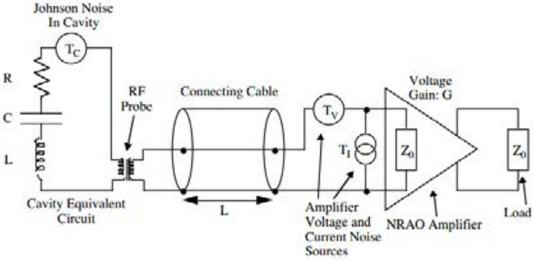


Noise Temperature: Y Factor Measurement



Uncertainties:
- Stainless steel cable loss. 0.9 dB at room temperature.
- Thermal equilibrium between Cu block and 50 Ω termination (overestimate T_a).
- Time lag between heating and DAQ (underestimate T_a by 1-2 K).

Equivalent Circuit Model of Cavity



[0] Ed Daw, thesis

Cryostat and Insert

- gas flow cryostat. ID =1.625"
- insert
  - waveguides
  - baffles
  - amplifiers
  - cavity