Outline

• Axion lecture #1: Current/ Past generation axion experiments
  • Theory motivation
  • “Light Shining Through Walls”
  • Solar axions
  • Sikivie haloscope (resonant cavity) technique and current results
    • ADMX, HAYSTAC

• Axion lecture #2: Future experiments, R&D
  • Higher frequency and mass
    • High frequency R&D- Magnets, Cavities & Electronics
    • Broadband detectors- dish antenna
    • Open resonators- Madmax, Orpheus
  • Lower frequency
    • LC circuits
    • ABRACADABRA, DM Radio
    • CASPER
“WIMP Miracle”: Current Status

• “WIMP Miracle” argument: Weakly interacting particles $M_{\text{wimp/boson}} \sim 100$ GeV produce the right abundance of dark matter.

• Many discussions motivated by supersymmetry: Lightest Supersymmetric Particle may be neutral and stable.

• But by 2018 has the most promising part of parameter space already been explored?
WIMPS vs. Axions

- Both are assumed to be cold dark matter with density \( \sim 0.3 \text{ GeV/cm}^3 \) and velocity determined by depth of Milky Way gravitational potential (escape velocity \( \sim 300 \text{ km/s} \) or \( v/c \sim 0.001 \)).
- Axions are much lighter and colder. They are not in thermal equilibrium.
- Small energy and long wavelength imply different detection techniques.

<table>
<thead>
<tr>
<th></th>
<th>WIMPs (typical)</th>
<th>Axions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass M ( M )</td>
<td>( \sim 100 \text{ GeV} )</td>
<td>( \sim 2-200 \mu \text{eV} ) post inflation PQ breaking</td>
</tr>
<tr>
<td>Velocity in galaxy</td>
<td>( &lt;0.001 \text{ c} )</td>
<td>( &lt;0.001 \text{ c} ) (escape velocity)</td>
</tr>
<tr>
<td>Kinetic energy ( \frac{1}{2} M V^2 )</td>
<td>( &lt;100 \text{ keV} )</td>
<td>( &lt;10^{-10} \text{ eV} )</td>
</tr>
<tr>
<td>De Broglie Wavelength (h/ MV)</td>
<td>( \sim 10^{-15} \text{ m} )</td>
<td>( \sim 10^{-15} \text{ m} )</td>
</tr>
</tbody>
</table>
Axions-- Motivation

• Protons and neutrons have a charged substructure (quarks)
• Naïve expectation: they should have electric dipole moment of order $10^{-16}$ e-m
Electric Dipole Moments Violate CP (or T) Symmetry

• Small electric dipole moment of neutron could be explained by approximate CP symmetry of strong interaction.

• But the strong interaction Lagrangian appears to have CP- violating terms that don’t need to be small.
CP Violation in QCD

- The QCD Lagrangian contains a term that changes sign under Parity or Time reversal

\[ L_\theta = \theta \frac{g^2}{32\pi^2} F_{\mu\nu}^a \tilde{F}_{a\mu\nu} \]

- Limits on the neutron electric dipole moment (< 3 x 10^{-26} e cm) constrain the CP violation parameter \( \Theta < 10^{-9} \)
Peccei Quinn Solution

- Introduce a new field $\phi$ coupled to GG with a spontaneously broken symmetry.
- To minimize vacuum energy, radial part of $\phi$ takes on a vacuum expectation value (VEV).
- CP violating term in QCD Lagrangian is cancelled out by the VEV of $\phi$.
- $\phi$ can still move in the axial direction— the axion!

$$\mathcal{L} = \left( \frac{\phi A}{f_A} - \bar{\Theta} \right) \frac{\alpha_s}{8\pi} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

$0$ in vacuum state

$$\phi_A = \bar{\Theta} f_A$$
Axion Mass

- QCD effects at the time of the QCD phase transition (quark- gluon plasma -> free particles) cause a small tilt in the Peccei Quinn potential producing an axion mass.
- Axion mass is determined by curvature of potential around minimum.

\[ m_A = 5.70(7) \left( \frac{10^9 \text{GeV}}{f_A} \right) \text{ meV} \]
Axion Inventors

- **Peccei & Quinn**: Postulate new field that dynamically zeros out CP violation.
- **Weinberg & Wilczek**: Implies a new Goldstone boson (the axion)

“Clean up” the Strong-CP problem
Production of Dark Matter by Vacuum Realignment

- After PQ symmetry breaking the $\Theta$ angle is a random number.
- Tilting of PQ potential below QCD phase transition causes the field to roll to its minimum, converting vacuum energy to axion particles.
- Axion dark matter density today determined by random initial value of $\Theta$.
- Can assume different values in causally disconnected regions of space-> domain walls.
The QCD Axion- A Very Predictive Model

• Everything depends on just one unknown parameter— the axion decay constant $f_a$
  
  • The axion mass.

$$m_A = 5.70(7) \left( \frac{10^9 \text{ GeV}}{f_A} \right) \text{ meV}$$

• Coupling to gluons and photons.

$$\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu} : G_A \gamma\gamma E \cdot B \phi_A$$

$$G_A \gamma\gamma = \frac{\alpha}{2\pi f_A} \left( \frac{E}{N} - 1.92(4) \right)$$

• The cosmological abundance*

$$\Omega^\nu r h^2 \approx 0.12 \left( \frac{30 \text{ } \mu \text{eV}}{m_A} \right)^{1.165}$$

*Vacuum realignment contribution for post inflation scenario, not including cosmic strings & domain walls...
Predictions Vs. Previous Experiment Constraints

Classical “post inflation” axion window: fine tuning of $\Theta$ not required for axions to make up 100% of observed dark matter
Axion 2d Sensitivity Plot: Photon Coupling vs Mass

- Constructed to resemble standard WIMP sensitivity plot.
- Allows for a more general parameter space of “axion like particles” or ALPS with independent mass & cross section.
- QCD axion appears along diagonal band.

“Light Shining Through Walls” Experiments

- Photons convert into axions in magnetic field, then pass through a wall.
- Convert back into photons so they can be detected.
- Probability of gamma->axion-> gamma round trip goes as $g_{a\gamma\gamma}$

$$P(\gamma \rightarrow \text{axion}) = 4 \frac{g_{a\gamma\gamma}^2 B^2_{\text{ext}} E^2_\gamma}{m_a^4} \sin^2 \left( \frac{m_a^2 L}{4E_\gamma} \right)$$

$$P(\gamma \rightarrow \text{axion} \rightarrow \gamma) \propto \frac{g_{a\gamma\gamma}^4 B^4_{\text{ext}} E^4_\gamma}{m_a^8}$$

Primakoff Process
GammeV at Fermilab

- 5 ns wide pulses from Nd: YAG laser

A. S. Chou, W. Wester et al., 2008
Constraints on $g_{\gamma\gamma}$ from Completed LSW Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\omega$</th>
<th>$P_{\gamma}$</th>
<th>$\beta_{\gamma}$</th>
<th>Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPS (DESY) [61,62]</td>
<td>2.33 eV</td>
<td>4 W</td>
<td>300</td>
<td>$B_g = B_r = 5$ T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$L_g = L_r = 4.21$ m</td>
</tr>
<tr>
<td>BFRT (Brookhaven)</td>
<td>2.47 eV</td>
<td>3 W</td>
<td>100</td>
<td>$B_g = B_r = 3.7$ T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$L_g = L_r = 4.4$ m</td>
</tr>
<tr>
<td>BMV (LULI) [66,67]</td>
<td>1.17 eV</td>
<td>$8 \times 10^{21} \frac{\gamma}{\text{pulse}}$ (14 pulses)</td>
<td>1</td>
<td>$B_g = B_r = 12.3$ T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$L_g = L_r = 0.4$ m</td>
</tr>
<tr>
<td>GammeV (Fermilab)</td>
<td>2.33 eV</td>
<td>$4 \times 10^{17} \frac{\gamma}{\text{pulse}}$ (3600 pulses)</td>
<td>1</td>
<td>$B_g = B_r = 5$ T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$L_g = L_r = 3$ m</td>
</tr>
<tr>
<td>LIPSS (JLab) [69,70]</td>
<td>1.03 eV</td>
<td>180 W</td>
<td>1</td>
<td>$B_g = B_r = 1.7$ T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$L_g = L_r = 1$ m</td>
</tr>
<tr>
<td>OSQAR (CERN) [71,72]</td>
<td>2.5 eV</td>
<td>15 W</td>
<td>1</td>
<td>$B_g = B_r = 9$ T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$L_g = L_r = 7$ m</td>
</tr>
<tr>
<td>BMV (ESRF) [73]</td>
<td>50/90 keV</td>
<td>10/0.5 mW</td>
<td>1</td>
<td>$B_g = B_r = 3$ T</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$L_g = 1.5, L_r \sim 1$ m</td>
</tr>
</tbody>
</table>

Table 1. Some experimental parameters of the past and current generation of LSW experiments.
Resonant Regeneration of Axion Signal

- Optical resonators are placed on both the source and receiver side of the wall.
- Resonators are phase locked to each other;
- Receiver power is enhanced by the product of the finesse of the two optical resonators.
  - Enhancement factor in signal power can be $\sim 10^5 \times 10^4 = \sim 10^9$ at optical frequencies
  - But coupling sensitivity scales only as $power^{1/4}$ ...

Sikivie, Tanner & Van Bibber 2007
### ALPS I and ALPS II at DESY: Any Light Particle Search

![Image of ALPS experiment setup]

<table>
<thead>
<tr>
<th>parameter</th>
<th>scaling</th>
<th>ALPS I</th>
<th>ALPS IIc</th>
<th>sens. gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B L$ (total)</td>
<td>$g_{ay} \propto (B L)^{-1}$</td>
<td>22 Tm</td>
<td>468 Tm</td>
<td>21</td>
</tr>
<tr>
<td>PC built up ($P_{laser,eff}$)</td>
<td>$g_{ay} \propto P_{PC}^{-1/4}$</td>
<td>1 (kW)</td>
<td><strong>150 (kW)</strong></td>
<td>3.5</td>
</tr>
<tr>
<td>rel. photon flux $\hat{n}_{prod}$</td>
<td>$g_{ay} \propto \hat{n}_{prod}^{-1/4}$</td>
<td>1 (532 nm)</td>
<td>2 (1064 nm)</td>
<td>1.2</td>
</tr>
<tr>
<td>RC built up $\beta_{RC}$</td>
<td>$g_{ay} \propto \beta_{RC}^{-1/4}$</td>
<td>1</td>
<td><strong>40,000</strong></td>
<td>14</td>
</tr>
<tr>
<td>detector eff. $DE$</td>
<td>$g_{ay} \propto DE^{-1/4}$</td>
<td>0.9</td>
<td>0.75</td>
<td>0.96</td>
</tr>
<tr>
<td>detector noise $DC$</td>
<td>$g_{ay} \propto DC^{1/8}$</td>
<td>$1.8 \times 10^{-3}$ s$^{-1}$</td>
<td>$10^{-6}$ s$^{-1}$</td>
<td>2.6</td>
</tr>
<tr>
<td>combined</td>
<td></td>
<td></td>
<td></td>
<td><strong>3082</strong></td>
</tr>
</tbody>
</table>

Aaron Spector, Patras 2018
Solar Axions

• Similar to “light shining through walls”, but replace laser with the Sun.
• Electromagnetic fields in solar plasma convert X-ray photons to axions.
• Solar axion flux: 0.2% $L_{solar}$ or $3.75 \times 10^{11}$ cm$^{-2}$ s$^{-1}$ for $g_{a\gamma\gamma} = 10^{-10}$ GeV$^{-1}$ (Raffelt, 2006)
IAXO – Conceptual Design

- Large toroidal 8-coil magnet $L = \sim 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services
IAXO technologies

IAXO magnet
- Superconducting “detector” magnet.
- Toroidal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore

IAXO telescopes
- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Similar to NuSTAR optics
- Focal length ~5 m
- 60-70% efficiency
- LLNL+UC+DTU + MIT + INAF

Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022
Solar Axion Telescopes- Summary

Irastorza and Redondo, 2018
Haloscope Technique

- Axions from galaxy halo convert to microwave photons in a magnetic field.

- Signal power:

\[ P = 4 \times 10^{-22} \text{ W} \left( \frac{V}{200 \ell} \right) \left( \frac{B_0}{8 \text{ Tesla}} \right)^2 C_{nl} \left( \frac{g_\gamma}{0.97} \right)^2 \left( \frac{\rho_a}{0.5 \times 10^{-24} \text{ g/cm}^3} \right) \left( \frac{m_a}{1 \text{ GHz}} \right) \left( \frac{\min(Q_L, Q_a)}{1 \times 10^5} \right) \]

Form Factor $C_{nl}$, overlap of cavity mode $E \cdot B_0$
Dark Matter Density $\rho_a$
Axion Mass $m_a$
Resonator Quality Factor $Q_L \sim 10^5$
Axion Q from velocity dispersion $Q_a \sim 10^6$
Couplings to Photon $g_\gamma \sim 0.97$ for KSVZ model
$g_\gamma \sim 0.36$ for DFSZ

History

First and second generation haloscope experiments (1980s-90s):
Cooled to 4 K w/FET transistor amplifiers, noise temperature range 3 - 20 K.
• BNL
• University of Florida
• Rochester/ Brookhaven/ Fermilab (RBF)
• ADMX- achieved KFVZ sensitivity

3rd generation (current):
Superconducting amplifiers <100 mK approaching standard quantum limit of noise.
Microstrip Squid Amplifiers & Josephson Parametric Amplifiers.
• ADMX-G2.
• Haystac
• CAPP

4th Generation? Beyond standard quantum limit?
ADMX Experiment Design

Field Cancellation Coil
SQUID Amplifier Package
Dilution Refrigerator
Antennas
8 Tesla Magnet
Microwave Cavity
Tuning Rods

Warm Space Liquid Helium Reservoir
Cold Space

Dilution refrigerator
$^3$He/$^4$He mixing chamber

Microwave Cavity

2017 Run: 150 mK
2018 Run: 90 mK
ADMX site: University of Washington
Center for Experimental Nuclear Physics and Astrophysics (CENPA)

ADMX DAQ & Controls

Cleanroom (with insert hanging)  ADMX Magnet  Helium liquefier
ADMX Magnets

field cancellation coil

ADMX 8-Tesla x 50 cm solenoid
Key Microwave Cavity Design Constraints

- Maximize product of $B^2 \cdot V \cdot Q_L \cdot C_{lmn}$ to maximize axion-to-photon conversion power
  - $B^2 V$ set by the magnet bore: $(8T)^2 \cdot (~100$ liters)
- Loaded Quality factor $Q_L = \text{frequency}/\text{bandwidth}$
  - ($Q_L \sim 10^5$ for copper cavity $\sim 1$ GHz)
- Mode Form Factor $C_{lmn}$
- Tunability: must be able to shift resonant frequency over an appreciable range (typically 30-50%)
The Resonator

Tuning Rods

- Frequency steps typically 1/10 cavity line width ~ 2 KHz
Microstrip SQUID Amplifier (MSA)

- Very similar to conventional DC SQUID.
- Flux to voltage converter sensitive to a fraction of a flux quantum.
- Adapted for high frequency use.
- Supplied to ADMX by Clarke group at UC Berkeley.
Microstrip Squid Amplifier (MSA)

- To couple a microwave signal into the SQUID:
  - Cover the washer with an insulating layer (350nm of SiO$_2$)
  - Add a spiral path of conductor around central hole
  - This creates a microstrip transmission line resonator between the input coil and SQUID washer.
- GaAs varactor used to tune the microstrip resonator.
Noise Performance of Microstrip Squid Amplifiers

- \[ T_{\text{Noise}} = \frac{1}{k_B} \frac{\text{Noise Power}}{\text{Bandwidth}} \]

- Achieved \( T_N = 48 \text{ mK} \) at 600 MHz during testing at UC Berkeley

- 1.7 x quantum limit.

- In ADMX operation, system noise temperatures has additional contributions from:
  - Black body radiation in cavity
  - Attenuation
  - Post amplification stages
Cryogenic Electronics System Package - 2017/2018

-20 dB -20 dB
300 K

-20 dB -20 dB
4 K

Cavity (150 mK)

50 Ω

C2

to receiver

HEMTs

hot load

300 mK

MSA

Switch

Directional coupler

JPA

Circulator

Mu-metal shield cap

~22 cm

~13 cm

RC filtering for DC lines
MSA Operation in ADMX 2017/2018 Runs

- Amplifier package at higher temperature than resonator due to thermal short.
- Causes distinctive “dip” in noise power at cavity resonance.
- Typical system noise temperature was ~500 mK.
Experiment Operation Procedure

- The cavity frequency is scanned over a region until the desired SNR is achieved.
- Convolution with filter matched to expected axion linewidth.
- Typically we have $\sim 10^6$ independent measurements on each axion linewidth, averaged to reduce noise by $\sqrt{10^6}$.
- We then examine the combined power spectrum for signs of excess.
- Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions.
- Excess power regions are rescanned to see if they persist.
- Persistent candidates are subjected to a variety of confirmation tests: for example: magnet field changes or probing with other cavity modes.
- We do blind signal injection, so we always have candidates.
Recent N-Body models actually suggest the axion lineshape is narrower than the standard virialized model.

Our analysis searches for both.

You might have an axion if the signal...

- Can’t be seen in the room outside of the magnetic field
- Persists all the time
- Follows the Lorentzian lineshape of the cavity
- Is suppressed in non TM010 modes
- Scales with the $B^2$ of the magnet
- Has a tiny daily and annual frequency modulation

No candidates passed tests in 2017 run.
First ADMX-G2 Result (Data from 2017 Run)

- Exclude DFSZ models at 90% CL from 2.66-2.82 μeV.
2018 Operations

- Improved performance in 2018 running—lower temperatures and more efficient data collection.
Setup: Cavity

Resonant Microwave Cavity

TM_{010}-like mode:
3.6-5.8 GHz

Piezo electric motor controls position of rod

Rapidis, Patras 2018, June 17-22, 2018

Setup: Magnet & Cryogenics

He$^3$/He$^4$ dilution refrigerator

Josephson Parametric Amplifiers

Final phase at 127 mK

9.4 Tesla Magnet

10L Magnet

Rapidis, Patras 2018, June 17-22, 2018
Results of Phase I

Rapidis, Patras 2018, June 17-22, 2018

Moving forward to higher frequencies

As search frequency increases:

- Expected axion coupling increases
- Cavity volume decreases, decreasing signal
- Cavity Q decreases, decreasing signal
- Quantum limit increases, increasing noise
Extra Slides
Laser → Magnet → "Wall" → Magnet → Photon detector

$g_{a\gamma\gamma}$
The $TM_{010}$ and $TM_{020}$ modes tune together: data from both modes are taken in parallel.

The $TM_{020}$ mode has acceptable “form factor.”

Complementary frequency coverage.

For open cylinder

<table>
<thead>
<tr>
<th>Mode</th>
<th>Relative frequency</th>
<th>Tuning range (MHz)</th>
<th>Relative power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$TM_{010}$</td>
<td>1</td>
<td>400-900</td>
<td>1</td>
</tr>
<tr>
<td>$TM_{020}$</td>
<td>2.3</td>
<td>920-2,100</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Concurrent “Sidecar” High-Frequency Prototype

Smaller cavity = higher-mass axion search

Characteristic Frequency:
TM010: 4-6 GHz
TM020: 7 GHz

Prototype: not yet sensitive to QCD axions
The signals are very weak

- Power from the cavity is
  \[
  P = 2.3 \cdot 10^{-26} \text{Watt} \left( \frac{V}{200 \ell} \right) \left( \frac{B_0}{8 \text{Tesla}} \right)^2 C_{nl} \left( \frac{g_\gamma}{0.97} \right)^2 \left( \frac{\rho_a}{0.5 \cdot 10^{24} \text{g/cm}^3} \right) \left( \frac{m_a}{2\pi \text{GHz}} \right) \min(Q_L, Q_a)
  \]

- \( Q_L \sim 70000 \ (\text{GHz}/f)^{2/3} \) (ASE) and \( Q_a \sim 10^6 \)

- \( g_\gamma \sim 0.97 \) (KSVZ)

- \( g_\gamma \sim 0.36 \) (DFSZ)
$f_A$ : One Parameter Controls Everything

- $f_A$ is the “axion decay constant”, an unknown energy scale in the theory.
- Determines axion mass and all couplings

\[ m_A = 5.70(7) \left( \frac{10^9 \text{ GeV}}{f_A} \right) \text{ meV} \]

Coupling to gluon field

\[ \frac{a}{f_A} G_{\mu\nu} \tilde{G}^{\mu\nu} \]

Coupling to electromagnetic field

\[ \frac{a}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu} \]

Coupling to fermions

\[ \frac{\partial \mu a}{f_A} \bar{\Psi}_f \gamma^\mu \gamma^5 \Psi_f \]

- $f_A$ Originally identified with the electroweak symmetry breaking scale by Peccei and Quinn (~100 GeV), predicting axion mass to be ~ 100 keV.