Outline

• Axion preliminaries

• Dark-Matter searches  \textit{ADMX, ADMX-HF}

• Solar searches  \textit{CAST, IAXO}

• Laboratory searches  \textit{ALPS, REAPR}

• Final comments

\textit{See Friday’s talk by Peter Graham on string-based axions and new detection concepts}
The axion.

A very small particle accompanying a very Big Bang...
The Strong-CP Problem

- $\mathcal{L}_{\text{QCD}} = \ldots + \frac{\theta}{32\pi^2} \, G \tilde{G}$
  - Explicitly CP-violating

- But neutron e.d.m.
  $|\text{ld}_n| < 10^{-25} \, \text{e cm}$
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving

- Why?

Peccei-Quinn / Weinberg-Wilczek

- $\theta$ a dynamical variable

- $T = f_a$ spontaneous symmetry breaking

- $T \lesssim 1 \, \text{GeV}$

- $\bar{\theta}$ dynamically $\to 0$
- Remnant oscillation = Axion
Axion basics  (What you learn for free)

Light cousin of $\pi^0$: $j^{\pi} = 0^-$

$m_a, g_{a\gamma\gamma} \propto f_a^{-1} \therefore g_{a\gamma\gamma} \propto m_a$

$\Omega_a \propto f_a^{7/6} \rightarrow m_a > 1 \mu eV$

Sn1987a ν pulse precludes $NN \rightarrow NNa$ for $m_a \sim 10^{-(3-0)}$ eV

Horizontal Branch Stars preclude $g_{a\gamma\gamma} > 10^{-10}$ GeV$^{-1}$

Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak

Axion-photon mixing provides the key

[ P. Sikivie, PRL 51, 1415 (1983)]

\[
L_{\text{int}} = a g_{\alpha \gamma \gamma} E \cdot B
\]

Coherent mixing of axions and photons over large spatial regions of strong magnetic fields (a sea of virtual photons) compensates for the extraordinarily small value of \(g_{\alpha \gamma \gamma}\)

Some new developments in the past two years...

40+ experimental Ph.D.s trace back to Pierre’s ‘83 PRL
(I) The Microwave Cavity Experiment  \textit{(Sikivie, 1983)}

\[ P_{\text{sig}} \propto (B^2 V Q_L)(g^2 m_a \rho_a) \sim 10^{-23} \text{ W} \]

\[ \frac{s}{n} = \frac{P_{\text{sig}}}{kT_{\text{sys}}} \sqrt{\frac{t}{\Delta v}} \]
Brief history and status of ADMX

- Covered octave 1.9 - 3.6 µeV
  - KSVZ sensitivity, mid-model band

- \( T_{\text{SYS}} = T_P + T_N = 1.3 + 1.5 \approx 3K \)
  - Pumped SHE
  - HEMT, and now DC SQUID amps

- Search for virial & late-infall axions
  - Medium-res & High-res analyses

- No axion yet ...

ADMX will soon achieve DFSZ sensitivity in 1-10 µeV range.
ADMX-HF launched 2011 for first look in 10-100 µeV range.
<table>
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<th>Environmental</th>
<th>Statistical</th>
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- **Environmental:**
  - Total
  - Frequency (MHz): 775.72 to 775.77
  - Power
  - Signal maximizes in the wings, and furthermore is episodic → Radio peak

- **Statistical:**
  - Total
  - Frequency (MHz): 772.11 to 772.17
  - Power
  - Distributed over many subspectra (good), but didn’t repeat → Statistical peak
ADMX is the world’s quietest spectral receiver – sensitive to 0.001 Yoctowatt.
ADMX results since 1995

HEMT <2004

SQUID 2007-09
Current Status of Searches for DM Axions (ADMX/ADMX-HF)

- ADMX – DOE funded @ Univ. Washington
  - Begin ~ 1 GHz @ better than DFSZ sensitivity
  - $^3$He fridge (400mK) & SQUID amplifiers
  - Dilution fridge (100mK) to be installed 2014

- ADMX-HF (High Frequency) – NSF funded @ Yale Univ.
  - Pathfinder for higher masses, and innovation test-bed
  - Begin ~ 5 GHz @ KSVZ sensitivity
  - Dilution fridge (25mK) & Josephson Parametric Amps

- Robust concurrent R&D program
  - Hybrid superconducting cavities (Type-II thin film s’con)
  - Photonic band-gap resonators for higher frequencies
  - Higher TM mode read-out in parallel
  - Single-photon & squeezed state amplifier technologies

ADMX & HF well-poised to cover 1-100 $\mu$eV over next few years
Quantum-limited amplifiers: MSAs for ADMX

- John Clarke et al. developed Microstrip SQUID Amps (MSA) for ADMX in ’90s
- At $T_p \sim 1.5K$, not better than HEMTs
- With $^3$He or dil-fridge, it will now matter
ADMX-HF: Josephson Parametric Amplifiers
(Konrad Lehnert, JILA/CU)

- Natural for higher frequencies
- Broadly & easily tunable
- Operates at the SQL or below (squeezing)
- ADMX-HF will initially utilize an existing and proven system design
  - 4-8 GHz
  - Quantum-limited T
Microwave cavities for ADMX-HF

Cavities become more complex going up in frequency
Strategies for 10 GHz and beyond

Power-combine cavities (1-10 GHz)  Photonic band-gap resonators (10-100 GHz)


Prototype multi-post cavity
Conversion power is proportional to $Q$, which can be increased by $\times 10$

Type-II superconductors have been demonstrated to support $B_{||} = 10$ T

We have now made very high quality NbTiN thin films with $T_C > 12$K

TFS cavities can be developed on ADMX-HF and migrated to ADMX
“Lasciate ogni speranza, voi ch’intrate” *

* Italian for “Dilution Refrigerator”  (Dante, Inferno, Canto III, 9)

(Pesky superleaks in VeriCold fridge have been a drag on commissioning)
(II) Principle of the Solar Axion experiment

\[ L_{a\gamma\gamma} = a g_{a\gamma\gamma} E \cdot B \]

\[ \Pi(a \leftrightarrow \gamma) = \frac{1}{4} (g_{a\gamma\gamma} B_0 L)^2 |F(q)|^2 \]

where \[ F(q) = \frac{\sin(qL/2)}{(qL/2)} \], \[ F(0) = 1 \] and \[ q = k_\gamma - k_a \approx \frac{m_a^2}{2\omega} \]
Produced by a Primakoff interaction, with a mean energy of 4.2 keV

$T_{central} = 1.3$ keV, but plasma screening suppresses low energy part of spectrum

The total flux (for KSVZ) at the Earth:

$$\Phi_a = 7.44 \times 10^{11} \text{cm}^{-2} \text{sec}^{-1} (m_a / 1\text{eV})^2$$

The dominant contribution is confined to the central 20% of the Sun’s radius
The CERN Axion Solar Telescope (CAST)

Prototype LHC dipole magnet, double bore, 50 tons, $L = 10m$, $B = 10T$

Tracks the Sun for 1.5 hours at dawn & 1.5 hours at dusk

Instrumented w. 3 technologies: CCD w. x-ray lens; Micromegas; TPC
CAST results and future prospects

CAST has published limits equaling those from Horizontal Branch Stars

The Phase II run with $^3$He pushed the mass limit up into the region of axion models, 0.1-1 eV

Fill the magnet bore with gas (e.g. helium), and tune the pressure

When the plasma frequency equals the axion mass, full coherence and conversion probability are restored:

$$\omega_p = \left(4\pi\alpha N_e / m_e\right)^{1/2} \equiv m_\gamma$$

A Next Generation Axion Helioscope is being proposed at CERN
The International Axion Observatory (IAXO)

E. Armengaud et al., Letter of Intent to the CERN SPC, August 7, 2013
(III) Photon regeneration – simple ("shining light through walls")

KvB et al., PRL 59 (1987) 759

\[ P(\gamma \rightarrow a \rightarrow \gamma) = \Pi^2 = \frac{1}{16} (gB_0L)^4 |F(q)|^4 \]

Note that this is also a \( g^4 \) experiment, and therefore will be very difficult to improve!
Several new photon regeneration experiments launched – ALPS best to date

These limits however are still orders of magnitude weaker than the Limits established by astrophysics (Horizontal Branch Stars), and CAST
Resonantly-Enhanced Photon Regeneration

Basic concept – encompass the production and regeneration magnet regions with Fabry-Perot optical cavities, actively locked in frequency


\[ P_{\text{Resonant}}(\gamma \rightarrow a \rightarrow \gamma) = \frac{2}{\eta \eta'} \cdot P_{\text{Simple}}(\gamma \rightarrow a \rightarrow \gamma) = \frac{2}{\pi^2} FF' \cdot P_{\text{Simple}}(\gamma \rightarrow a \rightarrow \gamma) \]

where \( \eta, \eta' \) are the mirror transmissivities & \( F, F' \) are the finesses of the cavities

For \( \eta \sim 10^{(5-6)} \), the gain in rate is of order \( 10^{(10-12)} \) and the limit in \( g_{a\gamma\gamma} \) improves by \( 10^{(2.5–3)} \)
ALPS II at DESY and GRIM REPR at FNAL both propose to improve on CAST & HBS

Point-design 6+6 Tev magnets - 36m x 5T each leg

GRIM REPR is a collaboration of FNAL, UCB, Florida & Michigan, including LIGO experts
Excluded $g_{A\gamma\gamma}$ vs. $m_A$ with all experimental & observational constraints
Summary & projections

- Axion sector is finally at critical mass – operations, R&D, etc. 😊
  - ADMX & -HF will have ample sensitivity, but mass coverage, esp. > 100 µeV hard
  - IAXO can reach ~ 5 x 10^{-12} GeV⁻¹, real discovery potential; can build the magnet?
  - ALPS-II is a technical *tour de force*; physics rationale good if reaches ~ 10^{-11} GeV⁻¹

- PQ axion in the 10^{-(2-4)} eV range will be hard without new ideas

- Axionic DM may reveal intermediate- or fine-structure
  - Diurnal & sidereal modulation could open up field of *DM astronomy*

- If things go reasonably well for ADMX/-HF, the two major thrusts will be:
  - Hybrid cavities with Type-II superconductor thin-film coatings
  - JPAs in squeezed-state mode to attain \( T_N \ll T_{SQ} \)
(a) No angular momentum
(b) Finite angular momentum

$E_k = \left( \frac{v_k}{300 \text{ km s}^{-1}} \right)^2$
Modulation of one infall line

Vector DM Flow is uniquely determined

Annual Modulation: Earth’s orbit around Sun

Daily Modulation: Earth’s spin on its axis
TMI*

(*Too much information)
ADMX innovation: Taking data simultaneously on $TM_{010}$ and at higher harmonic $TM_{0n0}$ modes

**$TM_{020}$ Mode**
- Relative Frequency: 2.3
- Tuning Range: 920-2,100 MHz
- Relative Power: 0.41

**$TM_{010}$ Mode**
- Relative Frequency: 1.0
- Tuning Range: 400-900 MHz
New Development in MSA: Varactor-diode tuning

- Clarke et al. demonstrated varactor-diode tuning on MSA long ago

- Terminating microstrip with back-biased diode allows capacitive tuning, by effectively changing the strip length

- Recently, use of unpackaged diodes with very low parasitic inductance allows this tuning with no added noise

- Tuning from 443 – 807 MHz shown, and MSA ought to be quantum-limited

- Will now make one for ~1.5 GHz

(Courtesy Sean O’Kelley, UC Berkeley)
• ADMX-HF will use JPA right from the start

• The first JPA to be used is a copy of Konrad Lehnert’s (JILA/CU) 4-8 GHz system (2007)

• Quantum-limited including HEMT post-amp

• Already tested at Yale @ 900mK (4/2013) and demonstrated tuning from 4.7–6.5 GHz

• Will be fully integrated and tested in the ADMX-HF magnetic field in mid-July
Demonstration of JPA tuning over large dynamic range
CAST constraints on the axion-electron coupling

K. Barth et al., JCAP 05 (2013) 010, arXiv:1302.62831v1