When the Darkness is Finally Dispelled …

…it’s the Axion

Embrace it.

Karl van Bibber
UC Berkeley
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Outline

- Some basics on the axion & dark matter
- The microwave cavity search for axionic dark matter
- Where we are today – ADMX & HAYSTAC
- Towards improved sensitivity, higher & lower masses
- Other axion searches
- When will the axion be found, and what then?

The Axion, Particle Physics & Cosmology
TSP’s* Conundrum

* Thinking Snookers Player


“The Pool-Table Analogy to Axion Physics”
TSP’s Hypothesis & First Experiment (unsuccessful)
The Key Insight
A High-Q Search for Relic Oscillations
The Axion

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.
  \( |d_n| < 10^{-25} \text{ e} \cdot \text{cm} \)
  – \( \tilde{\theta} < 10^{-10} \)
  – Strong-CP preserving

\[
T \begin{pmatrix}
\mu_n \\
\downarrow \\
d_n \\
\uparrow
\end{pmatrix} =
\begin{pmatrix}
\mu_n \\
\downarrow \\
d_n \\
\uparrow
\end{pmatrix} \neq \text{In}>
\]

\( T \rightarrow CP \)

• Why?
The Axion

The Strong-CP Problem

- $\mathcal{L}_{QCD} = \ldots + \frac{\theta}{32\pi^2} G \tilde{G}$
  - Explicitly CP-violating
- But neutron e.d.m.
  $|d_n| < 10^{-25} \text{ e} \cdot \text{cm}$
  - $\bar{\theta} < 10^{-10}$
  - Strong-CP preserving

$$T \left( \begin{array}{c} \mu_n \\ d_n \\ n \end{array} \right) = \begin{array}{c} d_n \\ \mu_n \\ n \end{array} \neq \begin{array}{c} \mu_n \\ d_n \\ n \end{array}$$

$T \rightarrow CP$

- Why?

Peccei-Quinn / Weinberg-Wilczek

- $\theta$ a dynamical variable
- $T = f_a$ spontaneous symmetry breaking

$\theta_1(x)$

- $T \lesssim 1 \text{ GeV}$
  - $\bar{\theta}$ dynamically $\rightarrow 0$
  - Remnant oscillation = Axion
Axion phenomenology & completing the pool-table analogy

Light cousin of $\pi^0$: $J^\pi = 0^-$

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

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

Sn1987a $\nu$ pulse precludes $NN \rightarrow NNa$ for $m_a \sim 10^{-3-0} \, eV$

Good news – Parameter space is bounded

Bad news – All couplings are *extraordinarily* weak

Why not just look for an unidentified radio line at which $E_\gamma = m_a / 2$?

(from anybody’s halo, including our own)

Problematically, the lifetime $\tau \sim 10^{60}$ sec for $m_a \sim \mu\text{eV}$
Microwave cavity searches for DM axions
The Primakoff Effect


Classical EM field

Sea of virtual photons

Primakoff Effect
Problem: How to accurately measure the lifetime of the neutral pion, $\tau_{\pi^0}$ which was known to be very short?
Primakoff – experiment (1965): $\tau \sim 8.7 \times 10^{-17}$ sec

$\sigma \leftarrow g_{\pi\gamma\gamma} \rightarrow \tau$
The microwave cavity axion search - Your car radio on steroids

For e.g., \( m_a = 10 \ \mu \text{eV} \):
\[
\rho_a \sim 10^{14} \ \text{cm}^{-3},
\]
\[
\lambda_{\text{DeB}} \sim 100 \ \text{m}.
\]
Signal to Noise & detectability

Cavity Bandwidth: \( \frac{\Delta \nu_c}{\nu_c} = Q^{-1} \sim 10^{-4} \)

Axion Bandwidth: \( \frac{\Delta \nu_a}{\nu_a} \sim \beta^2 \sim 10^{-6} \)

Conversion Power:
\[
P \sim g_{\alpha\gamma\gamma}^2 \left( \frac{\rho_a}{m_a} \right) B^2 Q_c V C_{nml} \sim 10^{-23} \text{ watt}
\]

Signal to Noise Ratio:
\[
\text{SNR} = \frac{P}{kT_S} \sqrt{\frac{t}{\Delta \nu_a}}
\]

System Noise Temperature:
\[
kT_S = h\nu \left( \frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2} \right) + kT_A
\]

Note: \( T_S \approx T + T_A \), for \( T \gg h\nu \)
Linear amplifiers are subject to the Standard Quantum Limit

\[ T_N > T_{SQL} \quad \text{where} \quad k_B T_{SQL} = h \nu \]

<table>
<thead>
<tr>
<th>ν [GHz]</th>
<th>( m_a ) [μeV]</th>
<th>( T_{SQL} ) [mK]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2.1</td>
<td>24</td>
</tr>
<tr>
<td>5</td>
<td>20.7</td>
<td>240</td>
</tr>
<tr>
<td>20</td>
<td>82.8</td>
<td>960</td>
</tr>
</tbody>
</table>

The SQL can be evaded by

- Squeezed-vacuum state receiver (e.g. GEO, LIGO)
- Single-photon detectors (e.g. qubits, bolometers)
The Prehistory c. 1989
The Florida Experiment – Williamson Hall c. 1989
Rochester-Brookhaven-Fermilab Experiment

BNL Magnet Lab, Bldg. 903
Axion Dark Matter eXperiment (ADMX)

Field Cancellation Coil
SQUID Amplifier package
Refrigeration
Antennas
8 Tesla Magnet
Microwave cavity

UW, UF, LLNL, UCB, NRAO, Sheffield, FNAL, LANL, PNNL, ...
Even at $T_{\text{SYS}} \sim 3$K ADMX was the world’s quietest radio receiver. Even at $T_{\text{SYS}} \sim 3$K ADMX was the world’s quietest radio receiver.

Systematics-limited for signals of $10^{-26}$ W – $10^{-3}$ of DFSZ axion power.

Last signal received from Pioneer 10 (6 billion miles away) $\sim 10^{-21}$ W.

Dicke Radiometer equation:

$$\frac{s}{n} = \frac{P_s}{kT_n} \sqrt{t/\Delta \nu}$$

![Graph](image-url)
In 1998 John Clarke saved the field – Microstrip SQUID amplifiers

High frequency SQUID amplifiers have become a cornerstone of QI/QC
ADMX Gen.2 preliminary result – DFSZ reached!

Existing data goes to 645 MHz

T_{SYS} \sim 300 \text{ mK} 
\sim 10 \times T_{\text{SQL}}
Will improve by next run
The situation 25 years later – We need to pick up the pace!
Motivation & philosophy

- Concept born at Sikivie *festschrift* in 2010
- Serves both as *Data Pathfinder & Innovation Test-bed* in the 10-50 μeV mass range
- Develop new cavity & amplifier technologies in the 3-12 GHz range
- Small, agile platform that can be quickly reconfigured to try new things
- Work with the greatest degree of informality; no formal project management, etc.

BTW, the drawing on Steve Lamoreaux’s blackboard was our TDR!
The team

Yale University
Steve Lamoreaux, Yulia Gurevich, Ling Zhong, Ben Brubaker, Sid Cahn

UC Berkeley
Karl van Bibber, Maria Simanovskaia, Samantha Lewis, Jaben Root, Saad Al Kenany, Kelly Backes, Nicholas Rapidis, Isabella Urdinaran, Tim Shokair

CU Boulder/JILA
Konrad W. Lehnert, Daniel Palken, William F. Kindel, Maxime Malnou, M.A. Anil

Lawrence Livermore National Lab
Gianpaolo Carosi
Integration at Yale

Josephson Parametric Amplifier

Microwave Cavity (copper)

$^3$He/$^4$He Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet
Cu body with off-axis tuning rod

Tunable over 3.6 – 5.8 GHz

Q_c ~ 20,000

Stepping motors and Kevlar lines used for motion
Josephson Parametric Amplifier composed of SQUIDs

Tunable from 4.4-6.5 GHz with 20 dB of gain

Persistent coils for cancellation of fringe fields

JPA (Colorado/JILA)
What the data looks like

\[ T_{\text{SYS}} \approx 3 \times T_{\text{SQL}} \] for first run; ‘hot rod’ implicated, thermal link improved

\[ T_{\text{SYS}} \approx 2 \times T_{\text{SQL}} \] for second run recently concluded
One of the myriad of challenges: Magnetic shielding of the JPA
Experienced a magnet quench in early March 2016

Surprisingly little damage

Repairs completed, experiment back in operation by May

"It takes a licking & keeps on ticking!" (Timex watch commercial, 1950’s)

Experiment rebuilt with much less mass of copper
Results from 2016-17 run

PRL Editor’s Suggestion & APS Highlight
Innovations: Deeper, Higher, Lower
As one reduces losses in the system, the sensitivity optimizes for overcoupling the cavity, thus broadening the bandwidth & increasing the scan rate.

"Accelerating dark-matter axion searches with quantum information technology"
(S. Girvin, K. Lehnert & students), arXiv:1607.02529v1

Evading the Standard Quantum Limit

\[ kT_S = h\nu \left( \frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2} \right) + kT_A \]
Lehnert group has built squeezed-state receivers; achieved $T_{\text{SYS}} \sim \frac{1}{4} T_{\text{SQL}}$ [F. Mallet et al., PRL 106 (2011) 220502]. Integration in HAYSTAC this year.
Higher Frequencies – Open Resonators (Orpheus, MADMAX)


Potential reach of exp’t:

Resonant Mode in Periodic Dielectric Loaded Waveguide

Shorter wavelength in dielectric

Longer wavelength in vacuum

Axion Coupling ($g_{A\gamma}$) vs. Axion Mass ($m_A$) (eV)

Orpheus Excluded Region

QCD Axion Dark Matter

Potential reach of exp’t
Lower Frequencies – Lumped Parameter Oscillators
(See Peter Graham’s talk tomorrow)

In a nutshell – Break the relationship between cavity diameter & frequency.


(All figures from DM Radio)
NMR-based search for dark matter axions: CASPEr

(See Peter Graham’s talk tomorrow)

**CASPEr Wind:** Direct coupling of axions to the nucleus; look for spin precession around spatial gradient of the axion field.

\[
\mathcal{L} = \ldots + g_{aNN} (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N
\]

**CASPEr Electric:** Look for time-varying EDM due to coupling of axion to the nucleon; requires an external E-field.

\[
\mathcal{L} = \ldots - \frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}
\]
Laboratory searches
Axion-photon mixing in a transverse magnetic field


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

\[ F(q) = \frac{\sin(qL/2)}{(qL/2)}, \quad F(0) = 1 \]

where

\[ q = k_\gamma - k_a \approx m_a^2 / 2\omega \]

\[ l_{osc} = \frac{2\pi}{q} \]
Photon Regeneration – “Shining Light through Walls”

Where we projected the laser experiments would get to, and about where they actually did get to. The $g^4$ scaling makes this very hard to push.
Resonantly-enhanced Photon Regeneration


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

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

ALPS-II

With \( F \sim 10^{5-6} \), gains of \( 10^{10-12} \) in probability, and \( 10^{2.5-3} \) in coupling constant are possible
ALPS-II & III (DESY, Florida, Hannover, Mainz, Hamburg)

10+10 HERA dipoles
8.8 m, 5.4 T, 50 mm bore
LIGO optics
Pound-Drever-Hall locking

Removing the 15 mm Sagitta Occluded bore

ALPS III

HBS limits

“Wiggler”

Occluded bore 50 mm
Solar axion searches
Filling the magnet bore with a gas (H, He) endows the photon with an effective mass, restoring full coherence at one axion mass; tune the pressure: 

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

The International Axion Observatory (IAXO)

Proposed US contribution
NuSTAR design focusing X-Ray optics (Wolter)
MIT, Columbia LLNL

E. Armengaud et al., Letter of Intent to the CERN SPC, August 7, 2013
Excluded $g_{A\gamma\gamma}$ vs. $m_A$ with all experimental & observational constraints
When shall the axion be found?
And then what?
“All real axion hunters are Red Sox fans. It prepares you for life” Richard Panek

The 4% Universe
Dark Matter, Dark Energy & the Race to Discover the Rest of Reality
Harcourt, Houghton & Mifflin, 2010

Richard Panek

(See the chapter “The Curse of the Bambino”, about ADMX)
Forget Solar Eclipses – Lunar is the real deal

Two cosmic events took place simultaneously on October 27, 2004
And if you thought it was just a coincidence...

The Boston Bruins won their first Stanley Cup in 39 years, on June 15, 2011, under a blood red lunar eclipse.
And should the axion possess fine-structure, it would constitute a “movie” of the formation of our Milky Way galaxy

Modulation of fine structure may enable precision geolocation without GPS
Late-infall axions pass through our position with specific velocities
Axionic phase space in a Sikivie infall model

- Model begins with
  - Zero Temperature CDM
  - Hubble expansion
  - Initial density perturbation $r = 0$

- Grows self-consistent potential
Sikivie infall model (II)

(a) No angular momentum
(b) Finite angular momentum
Modulation of one infall line

Annual Modulation: Earth’s orbit around Sun

Vector DM Flow is uniquely determined

Daily Modulation: Earth’s spin on its axis

\[ \vec{v}_{\text{rel}} = \vec{v}_{\text{infall}} - \vec{v}_{\text{Sun}} - \vec{v}_{\text{Orb}}(t) - \vec{v}_{\text{Rot}}(t) \]

- \( V_{\text{Rot}} \sim 0.4 \)
- \( V_{\text{Orb}} \sim 30 \)
- \( V_{\text{Sun}} \sim 230 \text{ km/sec} \)
Final thoughts

Progress over the past quarter-century has been solid.

The axion search is the one experiment where sensitivity is \textit{not} the problem, but mass coverage – both in extent and in speed – continues to be. We have not turned the corner yet.

The goal posts have moved; we have much more ground to cover than we thought a decade ago: at least neV to meV.

The state of R&D is excellent; there is now a critical mass community to tackle the problems, and the agencies are to be thanked for their increased support.

But new ideas are needed – join us!

\textit{See Peter Graham’s talk tomorrow at 10:30!}
And profound gratitude to our sponsors

The National Science Foundation

The US Department of Energy

The Heising-Simons Foundation
Backup Slides
Bane of the search – thicket of TE-TM$_{010}$ mode crossings
Two-level mixing of $\text{TM}_{010}$ & $\text{TE}$ modes
Cutting down the forest: Photonic Band Gap resonators

Eli Yablonovitch
No TE modes in evidence, but more studies being done; next step is to make the resonator tunable
Development of cavities with thin film coatings of Type-II superconductors, e.g. $\text{Nb}_x\text{Ti}_{1-x}\text{N}$ by RF plasma deposition

RF plasma deposition technology pioneered by Ka-Ngo Leung
Thin films of the desired stoichiometry, thickness and transition temperature have been successfully made – RF cavity prototype is next.

\[ \text{Nb}_{0.30} \text{Ti}_{0.67} \text{O}_{0.03} : 280 \text{ nm} \]
Final provocative thought  (“Throw deep, Mr. President”*)

Imagine you continuously convert all the dark matter within the de Broglie wavelength of your detector into RF power.

\[ V_{\text{virial}} \sim 10^{-3} \, c \]

 Persistent superconducting magnet

\[ \lambda_{\text{de Broglie}} \]

It’s about a Megawatt. Now there’s a challenge worthy of our brilliant Berkeley NE students!

* Ken Stabler, when asked by President Ronald Reagan whether the US should build the SSC