ADMX Phase II+

Gianpaolo Carosi

Lawrence Livermore National Laboratory
USA

ADMX Collaboration

Vistas in Axion Physics

04/24/2012

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
The dark matter axion.
ADMX collaboration

- **University of Washington**
  Leslie Rosenberg*spokesman*, Gray Rybka, Michael Hotz, Andrew Wagner, Doug Will, Dmitry Lyapustin, Christian Boutan

- **University of Florida**
  David Tanner, Pierre Sikivie, Neil Sullivan, Jeff Hoskins, Jungseek Hwang, Catlin Martin, Ian Stern

- **Lawrence Livermore National Laboratory**
  Gianpaolo Carosi (PI @ LLNL), Darrell Carter, Chris Hagmann, Darin Kinion, Wolfgang Stoeffl, Karl van Bibber
  *currently @ UC Berkeley, Nuclear Engineering Dept, CA*

- **National Radio Astronomy Observatory**
  Richard Bradley

- **University of California, Berkeley**
  John Clarke

- **Yale University**
  Steve Lamoreaux

- **Sheffield University**
  Edward Daw
ADMX collaboration (at least a good portion of us)
The radiometer eqn.* dictates the strategy

\[
\frac{s}{n} = \frac{P_{\text{sig}}}{kT_S} \cdot \sqrt{t} \\Delta v
\]

* Dicke, 1946

But integration time limited to ~ 100 sec

System noise temp. now

\[T_S = T + T_N \sim 1.5 + 1.5 \text{ K}\]

But \[T_{\text{Quant}} \sim 30 \text{ mK}\]

Invest Here!

\[P_{\text{sig}} \sim (B^2V)Q_{\text{cav}}(g^2m_a\rho_a) \sim 10^{-23} \text{ watts}\]

But magnet size, strength \[B^2V \sim \$\]
The Axion Dark Matter eXperiment

<table>
<thead>
<tr>
<th>Stage</th>
<th>Phase 0</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>HEMT; Pumped LHe</td>
<td>Replace w. SQUID</td>
<td>Add Dilution Fridge</td>
</tr>
<tr>
<td>$T_{\text{phys}}$</td>
<td>2 K</td>
<td>2 K</td>
<td>100 mK</td>
</tr>
<tr>
<td>$T_{\text{amp}}$</td>
<td>2 K</td>
<td>1 K</td>
<td>100 mK</td>
</tr>
<tr>
<td>$T_{\text{sys}} = T_{\text{phys}} + T_{\text{amp}}$</td>
<td>4 K</td>
<td>3 K</td>
<td>200 mK</td>
</tr>
<tr>
<td>Scan Rate</td>
<td>$\propto (T_{\text{sys}})^{-2}$</td>
<td>$1 @ \text{KSVZ}$</td>
<td>$5 @ \text{DFSZ}$</td>
</tr>
<tr>
<td>Sensitivity Reach</td>
<td>$g^2 \propto T_{\text{sys}}$</td>
<td>$1.75 @ \text{KSVZ}$</td>
<td>$0.75 \times \text{KSVZ}$</td>
</tr>
</tbody>
</table>
Phase I & II Upgrade path: Quantum-limited SQUID-based amplification

- SQUIDs have been measured with $T_N \approx 50 \text{ mK}$
- Near quantum-limited noise
- This provides an enormous increase in ADMX sensitivity
- See Prof Clarke’s talk earlier
Cooling with SQUID amplifiers greatly increases scan rate.

Scan Rate comparison for KSVZ sensitivity

Physical Temperature (K)
ADMX Phase II: Moved ADMX main magnet and insert to the U. of Washington

Moved Main Magnet at LN2 temperatures Summer 2010
ADMX Main Magnet installed at CENPA, U.W.
Site Layout at CENPA: Lots of legacy infrastructure

Andrew Wagner*
**ADMX Phase II: Large amount of Technical Upgrades!**

<table>
<thead>
<tr>
<th>Helium Liquifier</th>
<th>Dynamic SQUID Gain Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved Cryogenics</td>
<td>In-Situ Noise Calibration Suite Tunable SQUIDs</td>
</tr>
<tr>
<td>Piezoelectric Rod Motion</td>
<td>Improved Receiver Chain</td>
</tr>
<tr>
<td>Rod location Tracking</td>
<td>Digital Filtering</td>
</tr>
<tr>
<td>Improved Thermometry</td>
<td>Better Timing Standard</td>
</tr>
<tr>
<td>Real-Time Analysis</td>
<td>Cavity Plating Upgrade</td>
</tr>
<tr>
<td>Clean assembly Area</td>
<td>All High Resolution Time Series Data</td>
</tr>
<tr>
<td>Better Cavity Modeling</td>
<td>New Magnet Leads</td>
</tr>
<tr>
<td>New Paint Job</td>
<td>HFET Bias Monitor</td>
</tr>
</tbody>
</table>
ADMX Phase II: Experimental Insert completely redesigned.

- Cryocooler improves helium consumption
- Same field cancellation magnet as before
- SQUID in zero field region, linked to dil fridge by cold finger
- 1K shield protects 100 mK space
- Dilution refrigerator
- New cavity, improved plating
ADMX Phase II construction well underway!

Top Plate has been welded and is being leak tested.

Bucking magnet installed in new reservoir
ADMX Phase II: Cryogenics being design by U. of Florida (N. Sullivan)

Have been approved for 50 liters STP He$^3$.

Initially data run with pumped He$^3$ pot to ~ 300 mK while awaiting dilution refrigerator.

Much of the same infrastructure will be used for dilution fridge ~ 100 mK.

Dilution Refrigerator based on Janis 750 model
Motion Control for Tuning Rods (attached to 1k stage).

19600:1 gear reduction

Heat budget: ~ 1 mW continuous running
(factor of 100 lower for 10 mHz cadence)
Continued R&D effort to potentially use Piezoelectric rotary drive

**Stick-slip design with piezo stacks from Physik Instruments.**

Harvey Mudd College Clinic Team designed & constructed prototype
ADMX Phase II: New Microwave cavity and tuning rod plating

- Cavity and Tuning rods: Stainless steel plated with high quality copper.
  - Q near that given by cryogenic anomalous skin depth.
  - Expected unloaded Q of ~ 200,000.

- Main cavity to be delivered to U.W. late summer.
- Continued R&D to improve quality factor and form factor.
Revamped Receiver Chain: Take advantage of digital electronics

All “High Resolution” data
New DAQ based on EPICS

“Medium Resolution” channel

“High Resolution” channel

$\Delta E/E \sim 10^{-6}$
ADMX Phase II: Instrument the $TM_{010}$ & $TM_{020}$ 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
ADMX Phase II: Instrument the TM$_{010}$ & TM$_{020}$ modes

Receiver chain now requires 2 parallel sets of 1$^{st}$ stage amplifiers and antennas and modest amount of filtering.
Amplifiers: Steady stream of SQUID and HFET amps

John Clarke’s group at UC Berkeley providing baseline SQUID amplifiers

Andrew Wagner coming up to speed to be local (UW) SQUID manufacturer

Richard Bradley at NRAO onboard to provide 2\textsuperscript{nd} stage HFET amps
Current Schedule

Summer 2011 Funding for Phase II arrived!


2012 – 2013 Commission Phase II detector
   (pumped LHe$_3$ system ~ temp at 300 mK)
   Order Dilution Refrigerator (1 year lead time)
   Short Axion Search while awaiting Dil. Fridge

2013 – 2014 Install Dilution Refrigerator, Commissioning

2015+ Definitive Dark Matter Axion search commences!
ADMX Upgrade + ADMX-HF – year one

ADMX Achieved and Projected Sensitivity

Cavity Frequency (GHz)

Axion Coupling $g_{a\gamma}$ (GeV$^{-1}$)

Axion Cold Dark Matter

"Hadronic" Coupling

Minimum Coupling

ADMX Next Generation Target

Supernova and White Dwarf Bounds

Non RF-cavity Techniques
ADMX – HF: High Frequency (> 2 GHz)

Second ADMX site: Yale University
PI: Prof. Steve Lamoreaux

- New Superconducting Magnet
  5” diameter, 20” long, 9.4 T
- Dilution fridge already in place.

• Recently awarded NSF funding... magnet under construction
The radiometer eqn.* dictates the strategy

\[ \frac{s}{n} = \frac{P_{\text{sig}}}{kT_S} \cdot \sqrt{\frac{t}{\Delta v}} \]

* Dicke, 1946

But integration time limited to \( \sim 100 \) sec

System noise temp. now

\[ T_S = T + T_N \sim 1.5 + 1.5 \text{ K} \]

But \( T_{\text{Quant}} \sim 30 \text{ mK} \)

HAVE INVEST HERE!

\[ P_{\text{sig}} \sim \left( \frac{B^2V}{Q_{\text{cav}}} \right) \left( g^2 m_a \rho_a \right) \]

\( \sim 10^{-23} \text{ watts} \)

Magnet size, strength \( B^2V \sim $
To get > 10 μeV... Additional higher-frequency R&D required

More Powerful Magnets!

Higher-frequency near quantum-limited SQUIDs

higher-frequency, large volume resonant structures

“Hybrid” superconducting cavities
Goal: Higher frequencies without sacrificing volume

4 cavity array operated

D. Kinion Thesis

Multipost systems possible

C. Hagmann simulation
Multi-cavity array – work at U. of Florida

- Partitions reduce scale, increase frequency
- Efficient use of magnetic volume compared to, e.g., 4 parallel cylinders.
- Tune by moving rods from corner to center in each partition
- Issues with Q, coupling
Segmented Resonator

- Method becomes highly complex above 8 segments
  - Maximum $\text{TM}_{010}$ Frequency for full scale cavity:
    $\sim 2.2 \text{ GHz} (9\mu\text{eV})$

- Project going through cavity redesign and improvements...
  - continued R&D effort
The “Hybrid” superconducting cavity concept

What’s the point?

\[ P \propto g^2 \cdot B^2 V \cdot \min(Q_L, Q_a) \]

\[ \frac{1}{f} \cdot \frac{df}{dt} \propto g^4 \cdot B^4 V^2 \cdot \min(Q_L, Q_a) \]

For copper cavities, \( Q_a \sim 10^6 \), whereas \( Q_L \sim 50,000 \)

If you could increase \( Q_L \) by a factor of e.g. x10:
- \( P \) would increase by x10
- \( \frac{df}{dt} \) would increase by x10 (for constant \( g \))
- \( g \) would improve by \( \div 1.8 \) (for constant scan speed)

*slides from Karl van Bibber*
The “Hybrid” superconducting cavity concept

Q of the TM$_{010}$ mode for a conventional Cu cavity:

\[ Q = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta} \]

Skin depth of Copper

*slides from Karl van Bibber*
The “Hybrid” superconducting cavity concept

The concept of a hybrid superconducting cavity:

\[ Q = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta} \]

This term goes away for a superconducting barrel

\[ Q_{hybrid} = (1 + L/R) \cdot Q_{cu} \]

For typical ADMX cavity, L/R = 5, enhancement factor = 6

*slides from Karl van Bibber*
The “Hybrid” superconducting cavity concept

The science of thin-film superconductors is mature

10 nm Nb$_{0.5}$Ti$_{0.5}$N is perfect. Supports $B_{||}$ up to 10 Tesla

*slides from Karl van Bibber*
R&D has already begun on NbTiN superconducting coatings

Currently in the process of setting up RF vapor deposition on foils for
Rutherford backscattering of 20 min NbTi deposition on copper foil

45 nm Ti$_{0.48}$Nb$_{0.63}$O$_{1.9}$ on 40 nm Ti$_{0.36}$Cu$_{0.15}$Nb$_{0.66}$O$_{1.8}$

*courtesy of Dr. Kin Man Yu of LBNL
Superconducting coatings will be placed on 1” cavity barrels

Initial cryogenic tests on small cavities at LLNL followed by magnetic field at Yale.

If successful scale to larger cavities.
Higher Frequency Amplifiers

Current Microstrip SQUID Amplifiers have gain fall off at around a few GHz… need new ideas.

Several possibilities:

- in-line SQUIDs
- “The Slug”
- Josephson Parametric Amps

Konrad Lenhert
NIST
$B_0^{2V}$ for Solenoids

Mark D. Bird
Director of Magnet Science & Technology at the National High Magnetic Field Lab, Tallahassee, FL
Utilizing ADMX for a Chameleon search

Step 1: Injected RF power excites E&M and chameleon modes

Step 2: Power is turned off, E&M modes decay

Step 3: Chameleon modes slowly decay into E&M modes which are detected through antenna

Timescale: 10 minutes
Power in ~ 25 dBm

Timescale: 100 milliseconds

Timescale: 10 minutes
Sensitivity ~ $10^{-22}$ W
Bandwidth ~ 20 kHz
ADMX for a Chameleon search results (published in PRL)

Laboratory Dark Energy Search
Other light bosons: **Hidden Sector Photons**

Additional U(1) symmetries that mix kinetically with the photon are ubiquitous in beyond-the-standard model physics. Other Names: U Boson, Paraphoton, Z', etc.
Utilizing ADMX as a Hidden Sector Photon Receiver

1 day of data taking as a proof of concept.

1
Photons in this driven cavity mix with HSPs and escape

2
HSPs mix with photons and are detected in the ADMX cavity

1 day of data taking as a proof of concept.
Results of ADMX search for hidden sector photons (published in PRL)

100x more sensitive than previous cavity search!
Competitive with indirect searches!

Run concurrently with Dark Matter Axion Search!

Paraphoton coupling, $\chi$

Paraphoton mass, $m_\gamma$ (eV)

ADMX 2010

Povey, Hartnett, Tobar

Coulomb Exclusion Region
Questions?
View from 40,000 feet: Axion and Axion-Like-Particle Searches