Axion Research at CAPP/IBS

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CAPP/IBS

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M33 rotation curve
(fig. 1)
CAPP/IBS

- **Center for Axion and Precision Physics Research**
  - Funded by the Institute for Basic Science
  - Located at KAIST campus in Daejeon, Korea
  - Led by Prof. Semertzidis Yannis

- **Experimental efforts to address the Strong-CP problem**
  - State of the art dark matter axion experiment
  - Storage ring proton EDM

- **Leading roles in international collaborations in intensity frontier**
  - Muon g−2
  - COMET (μ→e conversion)

- **Plenary talk by Prof. Semertzidis tomorrow for more details**
Strong-CP Problem

- **CP symmetry breaking (CPV)**
  - Matter-antimatter imbalance in our universe

- **CPV in electroweak interaction**
  - Observations are consistent with predictions
  - CPV phase in CKM matrix

- **CPV in strong interaction**
  - Theory: natural CPV term due to non-zero QCD vacuum
    - Sizable neutron dipole moment \( (d_n) \)
    - At least one of the quarks are massless
  - Experiment: QCD respects CP symmetry
    - \( d_{n,\text{exp}} \leq 10^{-26} \text{ e*cm} \) => \( \Theta_{\text{QCD}} \leq 10^{-10} \)
    - None of the quarks are massless
  - This is known as **strong-CP problem**
  - One of the most important but unsolved problems in physics
Axion

- **Peccei-Quinn theory (1977)**
  - An elegant idea to solve the strong CP problem
  - A new global symmetry, \( U(1)_{PQ} \), with a scalar field permeating all space
  - Spontaneous (explicit) PQ symmetry breaking involving a **new Goldstone boson: axion**
  - Similar to Higgs mechanism
    - Spontaneous EWSB involving the Higgs boson
    - Discovery in 2012 has enhanced the interest in the axion and the possibility of its existence

<table>
<thead>
<tr>
<th><strong>Axion properties</strong></th>
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<tr>
<td><strong>Interaction</strong></td>
</tr>
<tr>
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<td>( C )</td>
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Axion and Dark Matter

- **Attractive dark matter candidate**
  - If its mass lies between 1 $\mu$eV and 100 $\mu$eV, the axion can fit the halo model
  - Referred to as *axion dark matter*

**Axions**

$f_a$ (GeV)

$m_a$ (eV)
Detection Strategy

- **Primakoff Effect**
  - Pseudoscalar production by a photon scattering with an EM field
  - $\gamma\gamma \rightarrow \pi^0, \eta, \ldots$

- **P. Sikivie’s method (1983)**
  - Reverse Primakoff effect
  - Conversion of axions into microwave photons
    - $a \rightarrow \gamma\gamma$ (cf. $\pi^0 \rightarrow \gamma\gamma$)
    - Detectable in a EM resonator in the presence of a strong magnetic field
      - Principle of haloscope
      - Most promising technique for the faintest axion-photon coupling
Axion Coupling to Photons

- **Lagrangian**

\[
L_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} \phi_a F_{\mu\nu} \mathcal{F}^{\mu\nu} = -g_{a\gamma\gamma} \phi_a E \cdot B, \quad g_{a\gamma\gamma} \equiv \frac{\alpha g_\gamma}{\pi f_{PQ}}
\]

- \(g_{a\gamma\gamma}\): coupling constant
- \(\phi_a\): axion field
- \(F\): EM field-strength tensor
- \(\alpha\): fine structure constant
- \(g_\gamma\): model-dependent coefficient
  - 0.97 for KSVZ (hadronic)
  - \(-0.36\) for DFSZ (minimum)
- \(f_{PQ}\): PQ symmetry breaking scale \((10^{10} \sim 10^{12} \text{ GeV})\)

\[
m_a = \frac{f_{PQ}}{f_\pi \pi} \frac{\sqrt{z}}{1+z} \approx 6 \mu \text{eV} \frac{10^{12} \text{GeV}}{f_{PQ}}, \quad z = \frac{m_u}{m_d}
\]
Axion Detection

Power from photon signal

Amp.

GHz

10.7 MHz

35 kHz

Integration:
Resolution:

8 msec 125 Hz

FFT

50 sec 0.02 Hz

Maxwellian

Fine-Structure

$\Delta E/E \sim 10^{-17}$

$\Delta E/E \sim 10^{-6}$

Frequency (energy)

Power

Frequency

$\gamma \gamma$ occurs in a cavity within $B$

cavity magnet

Energy spread = kinetic energy

Peak search in power spectrum

Fourier Transform
Conversion Power

- Conversion power

\[ P_{a \rightarrow \gamma \gamma} = g_{a\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a) \]

- Theoretical parameters
- Experimental parameters

\[ P_a = 5.2 \times 10^{-22} W \left( \frac{g_\gamma}{0.97} \right)^2 \left( \frac{\rho_a}{0.45 \text{ GeV/cc}} \right) \left( \frac{f_a}{6 \text{ GHz}} \right) \left( \frac{B}{8 \text{ T}} \right)^2 \left( \frac{V}{1 \text{ L}} \right) \left( \frac{C_{010}}{0.6} \right) \left( \frac{Q_L}{10^6} \right) \]
Conversion Power and Sensitivity

- **Conversion power**

\[
P_{a \rightarrow \gamma \gamma} = g_{a \gamma \gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)
\]

- **Signal-to-noise ratio (SNR)**

\[
SNR \equiv \frac{P_{\text{signal}}}{P_{\text{noise}}} = \frac{P_{a \rightarrow \gamma \gamma}}{k_B T_{\text{syst}}} \sqrt{\frac{t_{\text{int}}}{\Delta f_a}}
\]

- **Scan rate**

\[
\frac{df}{dt} = \left( \frac{1}{SNR} \right)^2 \left( \frac{P(f)}{k_B T_{\text{syst}}} \right)^2 \frac{Q_a}{Q_L} \sim B^4 V^2 C^2 Q_L T_{\text{syst}}^{-2}
\]

\[
\frac{df_d}{dt} = \frac{140 \text{MHz}}{\text{year}} \left( \frac{g_y}{0.97} \right)^4 \left( \frac{\rho_a}{0.45 \text{GeV/cc}} \right)^2 \left( \frac{B}{8T} \right)^4 \left( \frac{V}{1L} \right)^2 \left( \frac{C_{010}}{0.6} \right)^2 \frac{Q_L}{Q_a} \left( \frac{4}{\text{SNR}} \right)^2 \left( \frac{4.5 K}{T_{\text{syst}}} \right)^2 \left( \frac{f}{6 \text{GHz}} \right)^2
\]
Experimental Setup

- **Axion conversion power:**
  \[
  P_{a \rightarrow \gamma \gamma} = \frac{g_{a \gamma \gamma}^2}{m_a} \frac{\rho_a}{B^2 V C_{mnp}} \min(Q_L, Q_a)
  \]

- **High field SC magnet**
  25T and then 35T or 40T
  From BNL (HTS Technology)

- **High Q tunable cavity**
  Superconducting Coating
  From Prof. Jhinwhan Lee of KAIST

- **Primakoff Effect**
Experimental Setup

- **Axion conversion power:**
  \[ P_{a\rightarrow\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a) \]

- **Signal-to-Noise Ratio:**
  \[ SNR \equiv \frac{P_{\text{signal}}}{P_{\text{noise}}} = \frac{P_{a\rightarrow\gamma\gamma}}{k_B T_{\text{syst}}} \sqrt{\frac{t_{\text{int}}}{\Delta f_a}} \]

**Cryogenics**
- <100mK
- Prof. Hyoungsoon Choi from KAIST

**High field SC magnet**
- 25T and then 35T or 40T
- From BNL (HTS Technology)

**SQUID amplifier**
- Outsourced Research from KRISS

**High Q tunable cavity**
- Superconducting Coating
- From Prof. Jhinhwan Lee of KAIST

**Primakoff Effect**
CAPP/IBS Axion Research

- **Focuses on improvements in experimental parameters**
  \[
  \frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}
  \]

- **Magnetic Field**
  - Critical (4\textsuperscript{th} power), but technically challenging and expensive

- **Cavity volume**
  - Limited by the magnet bore size
  - Higher frequencies require smaller cavities

- **Quality factor**
  - Several ideas in community – pure metal, superconductor, …

- **System temperature**
  - Dilution refrigerator technique
  - SQUID amplifier
High Magnetic Field: \( B \)

- **Launched a R&D program**
  - BNL’s Superconducting Magnet R&D Group (Dr. R. Gupta)
  - Determining the cable for the final design within a year

- **Two stage program**
  - 25 T with 10 cm bore (HTS)
  - 35(40) T with 10 cm bore – hybrid design HTS(inner)/LTS(outer)

- cf. current axion experiments use < 10 T
Large Cavity Volume: V

- **Multiple cavities in-phase**
  - First experimental trial by ADMX (2000) using a 4 cavity system

- **Improves sensitivity by up to N w.r.t. a single cavity system**

  \[ \text{SNR: } \frac{N \cdot P_S}{\sqrt{N \cdot P_C + P_A}} \text{ v.s. } \frac{P_S}{P_C + P_A} \]

  - \( N \): cavity multiplicity

- **Key issue is phase-locking**
  - Challenging
  - Phase matching in both frequency and time domains

- **I have received the 5-year IBS Young-Scientist award with CAPP to develop this system**
High Quality Factor: $Q$

- **Typical Cu cavity**
  - $Q_{\text{max}} \sim 10^5$ with annealing
  - cf. $Q_a \sim 10^6$

- **Superconducting cavity**
  - Hybrid design improves $Q$ by $(1+L/R)$

\[ Q = \frac{\omega \text{ Stored energy}}{\text{Power loss}} = \left( \frac{2V}{SD} \right) = \frac{2\pi R^2L}{2\pi R^2 + 2\pi RL} \cdot \frac{1}{\delta} = \frac{L}{R + L} \cdot \frac{R}{\delta} \]

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

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

- **R&D program with Prof. J. Lee (KAIST/IBS) for SC cavity**
  - SC walls including top/bottom plates
  - CAPP goal: up to $Q \sim 10^7$ in high B-field
## Low System Temperature: T – Cryostats

<table>
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<tr>
<th>Year</th>
<th>Essential Equipments</th>
<th>Quantum Amplifier Research</th>
<th>Small-scale Integration</th>
<th>Low-noise Experiments</th>
<th>Axion Detector main</th>
<th>Helium Liquefier</th>
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<tr>
<td>2014</td>
<td>CF-DR(RF1)</td>
<td></td>
<td>CF-DR(RF2)</td>
<td>Wet-DR1 (precision)</td>
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<td></td>
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<tr>
<td></td>
<td>CF-DR(magnet)</td>
<td></td>
<td></td>
<td>Wet-DR2 (precision)</td>
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<tr>
<td></td>
<td>Wet-He3 (large bore)</td>
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</table>

*Example of a 7T-100mm cryogen free AMI magnet integrated with a BF-LD system (Protective aluminum magnet cover shield not shown in picture).*

Yonuk Chong, KRISS
Low System Temperature: T – SQUID

- **Started a development program with KRISS (5 year)**
  - Korea Research Institute of Standards and Science
  - Providing us with (near) quantum noise limited SQUID amplifiers in the 1-20 GHz range
    - $T_{\text{quantum}} \approx 50 \text{ mK} \times f \text{ (GHz)}$
  - Evaluating methods for higher frequencies
CULTASK

- **CAPP Ultra Low Temp Axion Search in Korea**
  - Corporate body of axion research efforts at CAPP
  - Coldest axion experiment (<100 mK)

- **Currently in engineering run**
  - Building infrastructure

- **Status**
  - Designing cavities with tuning mechanism
  - Completed RT electronics test
  - Cryogenic RF circuits test ongoing
  - DAQ system ready
  - Start with ~ 5GHz (ID: 4.5 cm)
CULTASK

Suggestions to Mate to CAPP System

Approved for Fabrication

DAQ Overview (Target)

- Currently using home-brewed system

Based on Equipment classes and fundamentals written by Dr. Myungjae Lee and myself

Frontend

Web

Backstage
<table>
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<th>Timeline</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
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<td><strong>Lab Space</strong></td>
<td>Munji Campus Design &amp; Renovation</td>
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<td>Occupation</td>
<td></td>
</tr>
<tr>
<td><strong>High Field Magnet</strong></td>
<td>Prototype, testing of SuperC cables</td>
<td>25T, 10cm bore SuperC Magnet design</td>
<td>Work on 35T, 10 cm bore SuperC magnet</td>
<td></td>
<td>Magnet Delivery</td>
</tr>
<tr>
<td><strong>SC Cavity Development</strong></td>
<td>Procure Equip. Study res. and geom.</td>
<td>Development of high Q SC resonator</td>
<td></td>
<td>Production of high Q resonator</td>
<td></td>
</tr>
<tr>
<td><strong>SQUID Amplifier</strong></td>
<td>Design and production of prototype SQUID for 1-10 GHz Acquire JPA and test</td>
<td></td>
<td>SQUID delivery from KRISS Develop higher freq. amplifier</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Axion Cavity Experiment</strong></td>
<td>Building infrastructure. Engineering Run at KAIST</td>
<td>Experimental Setup at Munji Test Runs</td>
<td></td>
<td>High Field Magnet + SQUID + SC Cavity</td>
<td></td>
</tr>
<tr>
<td><strong>Cryogenics</strong></td>
<td>Setup plan, acquisition</td>
<td>DR’s(2) + Wet He3 &amp; DR</td>
<td>DR’s(2)</td>
<td></td>
<td>Main DR and He liquefier</td>
</tr>
</tbody>
</table>
Projected Sensitivity – ADMX Gen 2

Gen 2 ADMX Projected Sensitivity

Cavity Frequency (GHz)

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

Axion Mass ($\mu$eV)

- Too Much Dark Matter
- ADMX Published Limits
- ADMX Cold Dark Matter
- White Dwarf and Supernova Bounds
- Non RF-cavity Techniques
- "Hadronic" Coupling
- Minimum Coupling
- Warm Dark Matter

2015 2016 2017 2018 2019

--- ADMX HF
Projected Sensitivity – CAPP

CAPP Projected Sensitivity
Cavity Frequency (GHz)

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

Axion Cold Dark Matter

Axion Published Limits

White Dwarf and Supernova Bounds

Non RF-cavity Techniques

Too Much Dark Matter

--- ADMX HF
--- Current plan
--- B field 25 T
--- B field 35 T
Summary

• Axion is the key particle to solve the strong-CP problem and dark matter issue

• Cavity-based approach is promising to detect the challenging axion-photon coupling

• CAPP/IBS is an experimental particle physics group dedicated to dark matter axion searches in Korea

• Exciting results are expected in a few years
Our Universe

**Dark Energy**
Expanding universe

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**Dark Matter**
Rotation velocity of galaxies
Gravitational Lensing
Cosmic Microwave Background

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**Normal Matter**
Standard Model
(EM, weak, strong)
High Quality Factor: $Q$ (II)

- **RRR (Residual Resistance Ratio)**
  \[ Q \sim \frac{V}{S\delta}, \quad \delta = \sqrt{\frac{2}{\omega \mu \sigma}} \]
  - Comprehensive studies for Cu and Al
  - Magnetic field effect
- **DC vs. AC**
  - Anomalous behavior of skin depth at high frequencies at low temperatures
  - High purity Al is preferable (?)
  - Dedicated study is planned