CULTASK, Axion Experiment at CAPP in Korea

Woohyun Chung

Center for Axion and Precision Physics Research (CAPP)
Institute for Basic Science (IBS)
• Introduction
  – IBS/CAPP
  – Axion & Dark Matter

• CAPP’s Plan
  – Axion Detection Scheme (Haloscope)
  – R&D projects

• CULTASK 2017 (CAPP’s Ultra Low Temperature Axion Search in Korea)
  – Cavity + FTS Development & RF Receiver
  – Engineering Run with DAQ (complete RF chain) in 2017

• Plans beyond 2017
  – Low Vibration Pads (LVP) with Six Refrigerators in 2017
  – Physics Data by 2018

• Summary
Center for Axion and Precision Physics Research (CAPP)

Funded by the Institute for Basic Science (IBS)

• Led by Director, Yannis Semertzidis
• Annual Budget of ~ $10M
• Physics at CAPP:
  • Dark Matter Axion Search (Cosmic Frontier)
  • Storage Ring Proton EDM (Strong CP Problem, BAU)
  • Muon g-2, J-PARC, COMET, CAST, ARIADNE
• Located at and working with KAIST (Korea Advanced Institute of Science and Technology)
• 50+ members and growing
Axion Research at CAPP

CULTASK

Lead: Woohyun Chung
4 DRs installed and operational
Complete RF chain (w/ DAQ)
2 more frig. in 2017 at LVP

CAPP/CAST

Lead: Lino Miceli
First installation at CAST

ARIADNE

Lead: Yunchang Shin
NMR based
R&D in progress

Large Toroid

Lead: Byeongrok Ko
Requires big collaboration
R&D in progress
• Peccei and Quinn (1977) postulated an elegant solution by adding a new global symmetry to resolve the Strong CP Problem in Standard Model

• Axion is an excellent (and attractive) dark matter candidate
  – Pseudo Goldstone Boson
  – Small Mass \((1\mu\text{eV}<m_a<10\text{meV})\)
  – Extremely Weakly Interacting
  – Local Halo Density of \(0.45\ \text{GeV/cm}^3\)
  – \(\beta \sim 10^{-3} \rightarrow Q_a \sim 10^6\)

• Detection scheme by P. Sikivie (PRL 51:1415 1983) : Haloscopy
  – Axions will convert to photons in a strong magnetic field

\[
L_{\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \frac{E}{B}
\]
Axion Detection Scheme

P. Sikivie’s Haloscope:

Axion Conversion Power (~$10^{-24}$W):
$$P_{a \rightarrow \gamma \gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a B^2 V C_{mn}}{m_a} \min(Q_L, Q_a)$$

Signal to Noise Ratio:
$$SNR = \frac{P_{signal}}{P_{noise}} = \frac{P_{a \rightarrow \gamma \gamma}}{k_B T_{syst}} \frac{t_{int}}{\Delta f_a}$$

Scan rate:
$$\frac{df}{dt} \sim B^4 V^2 C^2 Q_L T_{syst}^{-2}$$

Cryogenics
$<$50mK

High Field SC Magnet
25T and then 35T
BNL (HTS Technology) Design

To RF Receiver

Quantum Limited Amplifier
SQUID or JPA (commercial?)

High Q Tunable Cavity
Superconducting Coating
Prof. Jhinhwan Lee of KAIST

(Reverse) Primakoff Effect

Energy levels of axion and photon
CAPP’s R & D

High Field SC Magnets

HTS 25T-10cm (->35T) by BNL 2019
HTS 18T-7cm (SuNAM) in Aug 2017
HTS 26T-3.5cm (SuNAM:WR)

Small Toroid 12T, V=80 L
Giant Toroid 5T, V=9900 L

SC High Q Cavity

Jhinhwan Lee
Equipment setup complete
First Sputtering Sc coating

R&D for Axion Research

Andrei Matlashov
JPA from K. Lehnert (JILA)
MSA from M. Mueck (ez-SQUID)
JBA/JPC from Yale (QCI)
SQUID from IPHT

SQUID Amp

Higher Frequencies

SungWoo Youn
Multiple cavities
Phase locking
Photonic crystal
R&D in progress
## CULTASK 2017 w/ Four DRs

<table>
<thead>
<tr>
<th></th>
<th>BF3</th>
<th>BF4</th>
<th>BF5</th>
<th>BF6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>BlueFors LD400</td>
<td>BlueFors LD400</td>
<td>BlueFors LD400</td>
<td>BlueFors LD400</td>
</tr>
<tr>
<td><strong>Magnet</strong></td>
<td>None</td>
<td>8T (AMI), 12cm</td>
<td>None</td>
<td>8T (AMI), 16cm</td>
</tr>
<tr>
<td><strong>RF lines</strong></td>
<td>24</td>
<td>8</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td><strong>DC lines</strong></td>
<td>72</td>
<td>72</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td><strong>Cool down to &lt;10 mK</strong></td>
<td><strong>24 hours</strong></td>
<td>48 hours</td>
<td>24 hrs</td>
<td>48 hrs</td>
</tr>
<tr>
<td><strong>Base temp at MXC</strong></td>
<td>9 mK</td>
<td>7 mK w/ SC magnet</td>
<td>7 mK</td>
<td>10 mK w/ SC magnet</td>
</tr>
<tr>
<td><strong>MXC temp w/ Load</strong></td>
<td>11 mk w/ Al cavity (4cm id) and HEMT amp</td>
<td>28 mk w/ 10 kg OFHC copper support structure and cavity + HEMT amp + Network Analyzer + Piezo Controller</td>
<td>Superconducting RF lines</td>
<td>Superconducting RF lines</td>
</tr>
</tbody>
</table>
• New Lab space in
  – KAIST Munji Campus Creation Hall (RF room + LVP) completed
• Installed two more Dilution Refrigerators (total of 4 running now) in Feb.
• “minAxion” is about to take data:
  – 8T 12.5 cm bore NbTi magnet (dry)
  – 9cm ID Cu cavity (~2.5 GHz)
  – FTS (freq. tuning system) with Sapphire rod
  – 1K HEMT LNA as a preamp
  – Cryo RF noise figure measurements: $T_{\text{system}} \sim 1.4$ K
  – Complete RF chain set-up with DAQ
  – Fake axion signal injection (blind test)
  – Take reasonable sensitivity DATA in 2017
  – Will boost DAQ efficiency
  – SQUID or JPA test
  – SC Cavity?
• “CAPP8Tb” is being ready
  – 8T 16.5 cm bore NbTi magnet (V~3.5 liter)
  – 15 cm cavity (~1.5 GHz) w/ FTS (being fabricated)

• 2 More refrigerators and 2 magnets in 2017 (LVP)
CULTASK 2017 w/ Four DRs

BF3 (RFR)  BF4 (RFR)  
BF5 (LVP)  BF6 (LVP)
CULTASK 2017 w/ Four DRs

Exploring the Dark Universe, Qui Nhon, Vietnam
OFHC Support Structure and Frequency Tuning System

- Cu Cavity of 10cm OD
- Modular design
- Sapphire tuning rod, 1cm OD
- Rotational piezo for tuning
- Linear piezo for antenna
- Piezo holder thermally linked to 1K plate
Cavity: OFHC Cu split type
Unloaded Q-factor of $\sim120,000$ w/ Sapphire rod
Pure (6N) Cu and Al (annealed) will be fabricated

FTS: Attocube piezoelectric actuators
Thermal link to 1K plate
$\rightarrow$ Sapphire rod to cavity by cryo bearing
Rotator resolution of 1/1000 deg $\rightarrow$ 2.5 ~ 5 kHz step
Cavity Delivered!

- Two cavities [conventional and split] (ID=134 mm, H=246 mm) have been delivered on May 26
Inside Cyrostat

Piezo control

Fake axion input (weak)

Coupler

Axion detection (Strong)

1k

<20mK

4K

magnet

Cavity

magnet

REFRIGERATOR

Linear piezo (control antenna)
Exploring the Dark Universe, Qui Nhon, Vietnam
## Refrigerators & SC Magnets

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Installation</th>
<th>Usage</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>BlueFors</td>
<td>LD400</td>
<td>Installed 2016.02</td>
<td>RF and SC cavity test</td>
<td>RF room</td>
</tr>
<tr>
<td>BlueFors</td>
<td>LD400</td>
<td>Installed 2016.02</td>
<td>Mini Axion: DAQ and RF chain</td>
<td>RF room</td>
</tr>
<tr>
<td>Janis</td>
<td>HE3</td>
<td>Installed 2017.03</td>
<td>Magnet tests</td>
<td>LVP 4</td>
</tr>
<tr>
<td>BlueFors</td>
<td>LD400</td>
<td>2017.02</td>
<td>Axion Exp JPA test DAQ</td>
<td>LVP 6</td>
</tr>
<tr>
<td>BlueFors</td>
<td>LD400</td>
<td>2017.02</td>
<td>Axion Exp Multi-cavity</td>
<td>LVP 7</td>
</tr>
<tr>
<td>Leiden</td>
<td>DRS1000</td>
<td>2017.08</td>
<td>Axion Exp HFmagnet</td>
<td>LVP 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>Field Strength</th>
<th>Bore Size</th>
<th>Installations/Delivery</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>AMI</td>
<td>8T</td>
<td>12cm</td>
<td>2016.02</td>
</tr>
<tr>
<td>NbTi</td>
<td>AMI</td>
<td>9T</td>
<td>12cm</td>
<td>2017.01</td>
</tr>
<tr>
<td>NbTi</td>
<td>AMI</td>
<td>8T</td>
<td>16cm</td>
<td>2017.01</td>
</tr>
<tr>
<td>HTS</td>
<td>SuNAM</td>
<td>18T</td>
<td>7cm</td>
<td>2017.08</td>
</tr>
<tr>
<td>HTS</td>
<td>BNL</td>
<td>25T</td>
<td>10cm</td>
<td>2018.12</td>
</tr>
<tr>
<td>HTS</td>
<td>SuNAM</td>
<td>26.4T</td>
<td>3.5cm</td>
<td>2017.01</td>
</tr>
</tbody>
</table>
Ingredients for reasonably sensitive axion experiment

**B**²: Ultra high magnetic field \(\Rightarrow\) 25 T 10 cm bore HTS magnet (delivery in early 2019)
18 T 7 cm bore HTS magnet (one week from today)
12 T 32 cm bore LTS magnet (sometime in 2019)

**V:** B²V matters, but higher freq. means small volume \(\Rightarrow\)
Multi-vane cavity, photonic crystals, Bragg reflectors and so on

**Q:** Superconducting coating (NbTi, NbSn, YBCO…) + Vortex pinning
Superconducting film (HTS tapes)
Pure metals (6N Cu, 7N Al) + proper annealing technique to increase RRR

**Ultra low temperature** \(T_s: T_s = T_{\text{physical}} + T_{\text{noise}}\)
\(T_{\text{physical}} < 50 \text{ mK (done)}, T_{\text{noise}} \text{ (mostly pre-amp): 1 K HEMT } \Rightarrow \text{ SQUID or JPA}\)
Pushing standard quantum limit (50~75 mK per GHz)
Quantum squeezing for higher frequencies
CULTASK 2017 Plan

Ultra High Field Superconducting HTS Magnet(s)

- R&D Program with BNL’s Superconducting Magnet R&D Group (Dr. R. Gupta)
- Compact design: 10 cm inner bore 25T (35T even 40T w/ out-cert) with HTS tape
- SuNAM is delivering 18 T 7cm bore HTS magnet in one week
- Commercial (Oxford) 32cm bore 12 T LTS magnet will be ordered

Status of High Field MAP Solenoids

Two HTS coils together made with SuperPower HTS is expected to create 20-25 T, if successful

~30 T with NbTi outer (40 T with Nb₃Sn or more HTS)
CULTASK 2017 Plan

SQUID + JPA Options (Andrei Matlashov)

SQUID from KRISS (Korea)
EZ SQUID (commercial, Germany)
CE1K2 SQUID (IPHT, Germany)

JPA from JILA (Konrad Lehnert)
   We have it (shielding and flux coil being fabricated)
JPC by QCI of Yale (Commercial)
JPA at WMI (TUM)
   from U. of Tokyo (Y. Nakamura)
Quantum squeezing now
JTWPA used by Jan Goetz (Aalto U. of Finland)
   from MIT (Lincoln Lab: W. Oliver)
broadband ( > 1 GHz) with gain more than 20 dB

Quantum Limited Amp.
50 ~ 75 mK of noise temp per GHz
CULTASK 2017 Plan

Process for manufacturing of superconducting cavity

<table>
<thead>
<tr>
<th>R&amp;D of recipe for Nb$_3$Sn or FeSe film on small substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Molecular beam epitaxy system (Growth of Nb$_3$Sn film)</td>
</tr>
<tr>
<td>2. LEED &amp; RHEED (Characterization of Nb$_3$Sn film)</td>
</tr>
<tr>
<td>3. Low temperature UHV-STM (Superconductivity)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Application of growth of Nb$_3$Sn film on cavity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Molecular beam epitaxy system (Growth of Nb$_3$Sn film)</td>
</tr>
<tr>
<td>2. Radiative thermal heater (Superconductivity)</td>
</tr>
<tr>
<td>3. 4 probe measurement (Superconductivity)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Anodized Al oxide for vortex pinning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chemical etching system (Growth of AAO surface)</td>
</tr>
<tr>
<td>2. Atomic force microscope (Characterization of AAO surface)</td>
</tr>
</tbody>
</table>

By Won-Jun Jang
Superconducting Cavity Development

Cavity with YBCO Tape – Plan for making

1. Wet fabrication equipment
2. Coat silver on the cross-section of the tape.
3. Protect certain area with photoresist
4. Remove silver layer with Ammonia water and Hydrogen peroxide. Also remove photoresist.

Superpower ReBCO Tape
- Silver (20um)
- YBCO (1um)
- Buffer layer (1um)
- Ni Alloy (50um)

5. High Field Vector Magnet for LT STM (Electrical characterization and vortex research)
3. High $T_c$ & $H_c$ superconductor materials growth system
2. Thermal treatment system for SC films and substrates
0. Machined cavity parts and single crystal substrates

CULTASK 2017 Plan

Exploring the Dark Universe, Qui Nhon, Vietnam
Scanning Speed:

\[
\frac{dv}{dt} = \left[ \eta \cdot \frac{4}{5} \cdot Q_L Q_a \cdot \frac{1}{SNR^2} \right] \cdot \left[ g_\gamma^2 \frac{\alpha^2}{\pi^2} \right]^2 \cdot \left[ \frac{h^3 c^3 \rho_a}{\Lambda^4} \right]^2 \cdot \left[ \omega_0 \right] \cdot \frac{1}{\mu_0} \cdot \frac{B_0^2 V}{k_B T_s} \cdot \left[ \frac{\beta}{1 + \beta C_{nlm}} \right]^2
\]

<table>
<thead>
<tr>
<th>Scanning Speed</th>
<th>KSVZ (MHz/yr)</th>
<th>100 MHz (months)</th>
<th>g(gamma)</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADMX-HF</td>
<td></td>
<td>11.223</td>
<td>2.737</td>
<td>2.5KSVZ</td>
<td>J</td>
</tr>
<tr>
<td>MinAxion-Now</td>
<td>n=0.25</td>
<td>0.091</td>
<td>21.201</td>
<td>5.0KSVZ</td>
<td>J</td>
</tr>
<tr>
<td>MinAxion-Heff</td>
<td>n=0.9, V=0.5</td>
<td>0.326</td>
<td>5.889</td>
<td>5.0KSVZ</td>
<td>J</td>
</tr>
<tr>
<td>MinAxion-Heff-LV</td>
<td>V=1.5, T=2.0</td>
<td>2.093</td>
<td>0.917</td>
<td>5.0KSVZ</td>
<td>J</td>
</tr>
<tr>
<td>MinAxion-Heff-LV-SQ</td>
<td>V=1.5, T=1.0</td>
<td>8.372</td>
<td>143.333</td>
<td>KSVZ</td>
<td>J</td>
</tr>
<tr>
<td>MinAxion-Heff-LV-SQ-300</td>
<td>V=1.5, T=0.3, B=8</td>
<td>93.024</td>
<td>12.900</td>
<td>KSVZ</td>
<td>J</td>
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<tr>
<td>CAPP8Tb</td>
<td>V=3.5, T=0.3, B=8</td>
<td>215.414</td>
<td>5.571</td>
<td>KSVZ</td>
<td>J</td>
</tr>
<tr>
<td>CAPP18T</td>
<td>V=1.0, T=0.3, B=18</td>
<td>7210.878</td>
<td>0.166</td>
<td>KSVZ</td>
<td>J</td>
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<tr>
<td>CAPP25T</td>
<td>V=1.0, T=0.3, B=25</td>
<td>11925.474</td>
<td>0.101</td>
<td>KSVZ</td>
<td>J</td>
</tr>
</tbody>
</table>
Plans beyond 2017

Axion Lab with 7 Low Vibration Pads in KAIST Munji campus

Exploring the Dark Universe, Qui Nhon, Vietnam
### Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Lab Space</th>
<th>High Field Magnet</th>
<th>SC Cavity Development</th>
<th>SQUID Amplifier</th>
<th>Axion Cavity Experiment</th>
<th>Cryogenics</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Munji Campus Design &amp; Renovation</td>
<td>Prototype, testing of SuperC cables</td>
<td>Procure Equip. Study res. and geom.</td>
<td>Design and production of prototype SQUID for 1-10 GHz Acquire JPA</td>
<td>Building infrastructure. Engineering Run at KAIST</td>
<td>Setup plan, acquisition</td>
</tr>
<tr>
<td>2016</td>
<td>LVP</td>
<td>25T-10 contract</td>
<td>Development of high Q SC resonator</td>
<td>JPA test and Run</td>
<td>Experimental Setup at Munji R&amp;D and Test Runs</td>
<td>2 BFs</td>
</tr>
<tr>
<td>2017</td>
<td>Occupation</td>
<td>18T-7 contract</td>
<td>Production of high Q resonator</td>
<td>Ez-SQUID Procure, Test and Run</td>
<td>High Field Magnet + SQUID + SC Cavity</td>
<td>2 BFs at RFR</td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td>12T-32 contract</td>
<td></td>
<td>QCI JPA Procure, Test and Run</td>
<td></td>
<td>2 BFs + Janis + Leiden at LVP</td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
• **State of the Art** Axion Research at CAPP/IBS in Korea

• **Major R&D Efforts**
  – Higher B Field: HTS (18T, 25T…)
  – Higher Q Factor with B Field: Factor of >10 Improvement
  – Adding SQUID or JPA
  – Larger Volume: Toroidal Cavity
  – R&D for Higher Frequencies (>10 GHz)

• **CULTASK 2017** ready for a complete experiment
  – Cavity R&D and Cryo-RF testing
  – DAQ running now
  – Testing Quantum Amplifiers

• **Stay Tuned:** We will take physics quality data Soon!
Thank You For Your Attention!