Taiwan Axion Search
Experiment with Haloscope

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On behalf of the TASEH Collaboration
We Know Very Little about Dark Matter

- Evidence of dark matter well established from astrophysical observations
  - CMB power spectrum, rotation curves, gravitational lensing
- No evidence so far from laboratory experiments
- Local DM density $\sim 0.45$ GeV/cm$^3$

Matter/Energy Today

- Dark Energy 68.3%
- Ordinary Matter 4.9%
- Dark Matter 26.8%

Collider Reach

$\sim 10^{-22}$ eV $\sim 100$ eV $\sim 10^{19}$ GeV $\sim 100 M_\odot$

$1 \text{ GeV} \sim 1 \text{ TeV}$

must be bosonic

must be composite

$m_{DM}$

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Dark Matter and Axion

- Axion was proposed to solve the strong CP problem
  - A pseudo-scalar particle (spin 0 with parity -1), low mass ($10^{-12}$~$10^{-2}$ eV)
  - Could be produced with large quantity in the early universe
- Axion is a good dark matter candidate
  - Stable, weakly interacting, and cold
- Axion could be detected via its two-photon coupling

$$L_{a\gamma\gamma} = -g_{a\gamma\gamma} \phi_a \vec{E} \cdot \vec{B}$$

Two free parameters: $m_a$, $g_{a\gamma\gamma}$

For QCD axion models, these two parameters are related

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Current Status of Axion Searches

TASEH aims for $m_a \sim 20 \mu$eV with $\Delta m = 4 \mu$eV
($f_a = 5 \text{ GHz with 1 GHz span}$)
CAPP and HAYSTAC Results

- **CAPP**
  - $m_a=6.62-6.82, \ 10.16-11.37, \ 13.0-13.9 \ \mu eV$
  - Best limit at $10.7126-10.7186 \ \mu eV$

- **HAYSTAC**
  - $m_a=16.96-17.28 \ \text{and} \ 23.15-24 \ \mu eV$
  - Best limit at $1.38 \times \ \text{KSVZ model for} \ 16.96-17.28 \ \mu eV$
Team Members

- **Academia Sinica**: Prof. Yuan-Hann Chang, Hien Doan
- **Ming Chi University of Technology/National Synchrotron Radiation Research Center**: Prof. Wei-Yuan James Chiang, Yi-Chieh Chang
- **National Central University**: Prof. Yung-Fu Chen, Prof. Shin-Shan Eiko Yu, Hsin Chang, Ching-Fang Chen, Guan-Yu Chen, Wei-Cheng Hong, Chun-Chung Lu, Min-Wei OuYang, Ping-I Wu, Jing-Yang Zhang
- **National Chung Hsing University**: Prof. Watson Kuo, Wei-Chen Chien, Yu-Han Chang

17 Members
Basic Experimental Setup

- A strong magnetic field \( (B) \) and a high-Q cavity \( (E) \) to convert axions to photons
- Large volume of cavity to enhance the conversion probability
- Low-temperature environment to reduce the background thermal photon
- Small signal power → low-noise quantum-limited amplifier

\[ g_{\alpha\gamma} \propto B \sqrt{\frac{VQ}{T_{\text{sys}}}} \]

- 5 GHz single photon = 0.2 K
Our Cryogenic System

- Initial runs with existing magnet (8 Tesla, 3-inch bore) from Prof. Yung-Fu Chen’s lab

- Plan to procure a commercial system (likely 9 Tesla with 15-cm bore), providing ~ 5x better sensitivity
Current Status: Cavity

- Pre-studies with HFSS
- Fabricated a single-frequency and a tunable cavity. Tested in the room temperature
  - Initial measurement of Q was a factor of 3 lower, due to discontinuous/non-clean surface and mode crossing
  - Reducing the height, polishing, silver plating, brazing, chemical cleaning + H firing, additional 9 cavities are produced for testing
- Investigating multi-cell cavities so to enhance effective volume

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Current Status: Near-Term Readout

- For initial runs, the first-stage amplifier will be two high-electron-mobility transistors (HEMT) ($T_{\text{sys}} \sim 2$ K, frequency span 4-8 GHz)

- Measurement of noise temperature done with initial setup

\[
GT_s = GT_p + GT_n
\]
Current Status: Long-Term Readout

- Development, fabrication, and test of Josephson Parametric Amplifier (JPA) \( (T_{sys} \sim 0.2 \, K, \, \text{frequency span} \, 1.8 \, \text{MHz}) \) ongoing
- Collaborating with Prof. Chii-Dong Chen from Academia Sinica
- V1 (coplanar wave guide resonator) and V2 (LC tank resonator)
- Two V1 chips are in DRs and will be tested
Near-Term Reach of Sensitivity

- Benchmark QCD axion model: KSVZ
- For $m_a=20 \ \mu\text{eV}$, $g_{a\gamma\gamma}=7.4 \times 10^{-15} \text{ GeV}^{-1}$
- Assuming 1 month of data taking and scan 1.1 GHz frequency range, $T_{\text{sys}}=2 \ \text{K}$, $Q=10000$, we may reach $g_{a\gamma\gamma}=2.6 \times 10^{-13} \text{ GeV}^{-1}$ at 95% CL
Near-Term Reach of Sensitivity

- Benchmark QCD axion model: KSVZ

- For \( m_a = 20 \mu eV \), \( g_{a\gamma\gamma} = 7.4 \times 10^{-15} \text{ GeV}^{-1} \)

- Assuming 1 month of data taking and scan 1.1 GHz frequency range, \( T_{sys} = 2 \text{ K} \), \( Q = 10000 \), we may reach \( g_{a\gamma\gamma} = 2.6 \times 10^{-13} \text{ GeV}^{-1} \) at 95% CL
Conclusion and Outlook

- We are looking for axion with a mass of ~20 µeV using a haloscope.
- We have formed a team with diversified expertise in particle physics, RF cavity, and low-temperature solid state physics.
- With future improvements, we may constrain the QCD $g_{a\gamma\gamma}$
  - Use of JPAs as the first-stage amplifiers $\rightarrow T_{\text{sys}} = 0.2 \text{ K}$ (x3)
  - Upgrade of the cryogenic system and the magnet $\rightarrow 9 \text{ Tesla}$ (x1.125)
  - Explore cavity ideas to increase effective volume and Q $\rightarrow$ (x10)

W-Meander by Prof. Chao-Lin Kuo
arXiv: 2010.04337
Backup Slides
Basic Formulas

\[ P_{\text{sig}} = \left( g_\gamma^2 \frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4} \right) \times \left( \frac{\beta}{1 + \beta} \omega_c \frac{1}{\mu_0} B_0^2 V C_{mn} Q_L \right) \]

\[ \Lambda = 78 \text{ MeV} \]

\[ \rho_a = 0.45 \text{ GeV/cm}^3 \]

\[ g_{\gamma\gamma} = \left( \frac{g_\gamma \alpha}{\pi \Lambda^2} \right) m_a \]

\[ Q_L = \frac{Q_0}{1 + \beta} \]

\[ \sigma_N = k_B T_s \sqrt{\frac{b}{t}} \]
\[ G_{\alpha\gamma\gamma} \]

\[ = \sqrt{\frac{h^3 c^3 \rho_a}{m_a^2}} \cdot \frac{\beta}{1 + \beta} \frac{\omega_c}{\mu_0} B_0^2 V C_{mn} Q_L \cdot \frac{k_B T_s \Delta w}{\Delta v \cdot \text{total time} \times \frac{\text{Scan windows}}{\text{Scan range}}} \]

\[ G_{\alpha\gamma\gamma} \]

\[ = 3.27 \times 10^{-14} \left(\text{GeV}^{-1}\right) \left(\frac{B}{9(T')}\right)^{-1} \left(\frac{V}{4.8338 \times 10^{-5}(m^3)}\right)^{-\frac{1}{2}} \left(\frac{Q}{10000}\right)^{-\frac{1}{2}} (\text{SNR})^{\frac{1}{2}} \left(\frac{f}{5(\text{GHz})}\right)^{\frac{1}{2}} \]

\[ \left(\frac{T_s}{0.3(k)}\right)^{\frac{1}{2}} \left(\frac{\text{total time}}{1(\text{month})}\right)^{-\frac{1}{4}} \left(\frac{\text{Scan Windows}}{1.8(\text{MHz})}\right)^{-\frac{1}{4}} \left(\frac{\text{Scan Range}}{1.1(\text{GHz})}\right)^{\frac{1}{4}} \left(\frac{\Delta w^2}{\Delta v \ 1125(\text{Hz})}\right)^{\frac{1}{4}} \]
Benchmark QCD axion model: KSVZ

For $m_a=20 \, \mu eV$, $g_{a\gamma\gamma}=7.4 \times 10^{-15} \, GeV^{-1}$

Assuming 1 month of data taking and scan 1.1 GHz frequency range, $T_{sys}=0.2 \, K$, $Q=50000$, we may reach $g_{a\gamma\gamma}=7.1 \times 10^{-15} \, GeV^{-1}$ at 95% CL
Benchmark QCD axion model: KSVZ

For $m_a = 20 \mu$eV, $g_{\text{ayy}} = 7.4 \times 10^{-15}$ GeV$^{-1}$

Assuming 1 month of data taking and scan 1.1 GHz frequency range, $T_{\text{sys}} = 0.2$ K, $Q = 50000$, we may reach $g_{\text{ayy}} = 7.1 \times 10^{-15}$ GeV$^{-1}$ at 95% CL
Comparison with HAYSTAC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HAYSTAC 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>4.1-4.178 GHz</td>
</tr>
<tr>
<td>Amplifier</td>
<td>2 JPAs</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>8T</td>
</tr>
<tr>
<td>Volume</td>
<td>1.5 L</td>
</tr>
<tr>
<td>Quality factor</td>
<td>47000 (Q₀)</td>
</tr>
</tbody>
</table>

- Benchmark QCD axion model: KSVZ

- For mₐ=20 µeV, gₐγγ=7.4×10⁻¹⁵ GeV⁻¹

- Assuming 1 month of data taking and scan 1.1 GHz frequency range, Tsys=0.2 K, Q=50000, we may reach gₐγγ=7.1×10⁻¹⁵ GeV⁻¹ at 95% CL
QCD Axion

- Proposed to solve the strong CP problem —- Why is CP conserved in the strong interaction?
  - the lack of neutron electric dipole moment: PRL 97, 131801 (2006) \( |d_n| < 2.9 \times 10^{-26} \text{ e cm} \) (90% C.L.)

- The Peccei-Quinn Solution
  - Add a dynamic field, spontaneous broken and cancels any strong CP violation, resulting in a new pseudo-scalar particle, the Axion

\[
\mathcal{L} = \left( \frac{\phi_A}{f_A} - \Theta \right) \frac{\alpha_s}{8\pi} \tilde{G}_{\mu\nu} \hat{a} G^a_{\mu\nu}
\]

\[
m_A = 5.70(7) \left( \frac{10^9 \text{ GeV}}{f_A} \right) \text{ meV}
\]

Original CP-violating term in the QCD Lagrangian

\[ \phi_A : \text{axion field,} \]
\[ f_A : \text{axion decay constant} \]
Readout Chain
JPA v1 (coplanar waveguide resonator)
JPA v2

JPA v2 (LC tank resonator)

Lump Element JPA layout
Additional Cavities for Testing

<table>
<thead>
<tr>
<th>Single/Tunable</th>
<th>Cavity Height (Unit: mm)</th>
<th>Connection</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC: Single Cavity</td>
<td>S6: 6 screws</td>
<td>S12: 12 screws</td>
<td>SP: Silver-plated</td>
</tr>
<tr>
<td>TC: Tunable Cavity</td>
<td>Br: Brazing</td>
<td>Cu: Copper</td>
<td>Al: Aluminum</td>
</tr>
</tbody>
</table>

SC-46-S6-Al  | TC-25-S6-Cu  | SC-46-S6-Cu  | SC-30-S12-Cu  | SC-30-S6-Cu