

The TASEH Axion Haloscope Experiment

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On behalf of the TASEH Collaboration



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CHiP

高能與強場物理研究中心
CENTER FOR HIGH ENERGY AND
HIGH FIELD PHYSICS

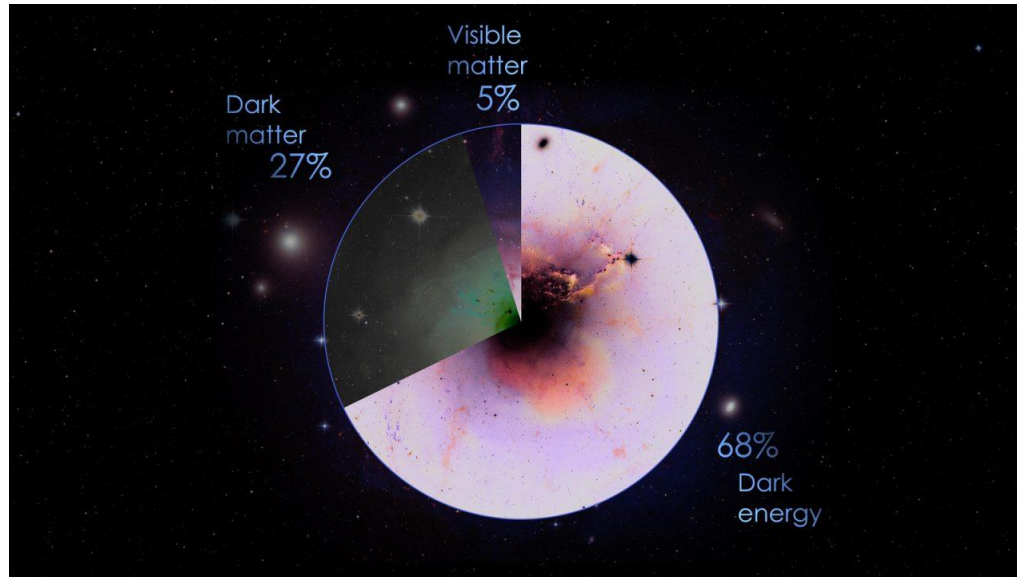
Frontiers in Axion Haloscope Experiment, September 2nd, 2026

Outline

- Axion introduction
- TASEH experiment overview
- First results at 5 GHz
- Preliminary results at 2 GHz with a 6 T magnetic field
- Current challenges and issues
- Plans

Dark Matter (Invisible Mass)

Composition of the universe



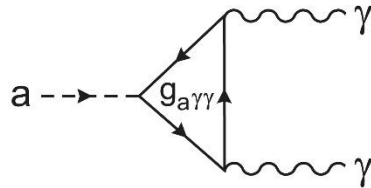
Source: NASA <https://science.nasa.gov/universe/>

- Dark matter is hypothesized to exist based on its gravitational effects observed on large astronomical scales. The mass of ordinary (baryonic) matter alone cannot account for various phenomena.
- Based on observations of the cosmic microwave background, approximately 80 – 85% of the matter in the universe is dark matter, which neither emits, absorbs, nor scatters light, making it invisible to electromagnetic observations.
- The composition of dark matter remains unknown.

Dark Matter Axion

Axion:

- A hypothetical particle proposed to solve the strong Charge-Parity problem in quantum chromodynamic (QCD).
Peccei and Quinn, *PRL* **38**, 1440; *PRD* **16**, 1791 (1977)
- Interacts extremely weakly with light and Standard Model particles, making them a well-motivated and compelling candidate for cold dark matter.
- The Primakoff effect arises from the QCD axial anomaly, which induces the axion–photon coupling term in the Lagrangian. This interaction allows axions to convert into photons in the presence of an external electromagnetic field.



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

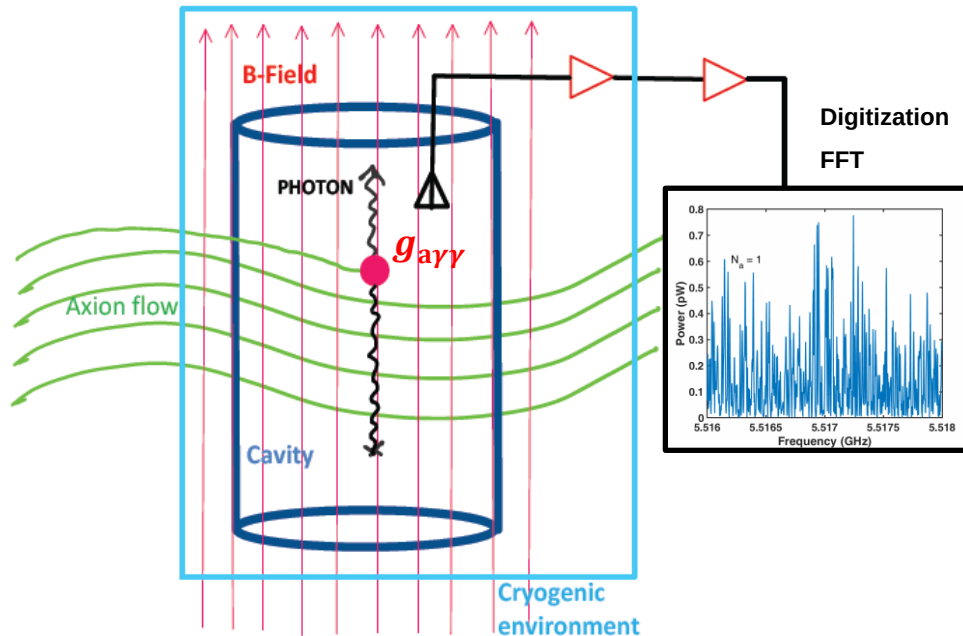
$$g_{a\gamma\gamma} = (g_\gamma \alpha / \pi \Lambda^2) m_a, \quad \Lambda = 78 \text{ MeV}$$

- g_γ is model dependent (KSVZ: -0.97, DFSZ: 0.36).
- Its mass m_a remains theoretically unconstrained; not found yet.
- A mass range of 1 – 100 μeV is motivated by a post-inflation symmetry-breaking scenario.

Axion Haloscope Search

Haloscope: axion search via tunable cavity

- Idea from Pierre Sikivie
- Based on inverse Primakoff coupling
- Listen to extremely weak radio signals (tuning and averaging)
- Require a strong magnetic field, cryogenic

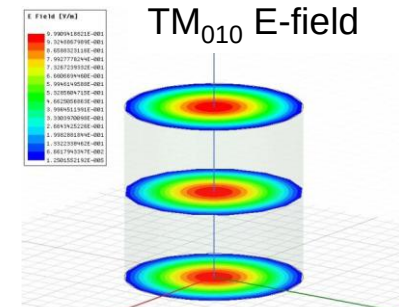


P. Sikivie, *PRL* **51**, 1415 (1983); *PRD* **32**, 2988 (1985)

- Signal power

$$P_s = \left(\frac{\hbar^2 c^5}{\mu_0} \right) g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a} \right) \eta B_0^2 V C_n Q$$

$$\text{Form factor } C_n = \frac{\left(\int d^3x \vec{E}_n \cdot \vec{B} \right)^2}{B_0^2 V \int d^3x \epsilon |\vec{E}_n|^2}$$



High form factor mode for uniform B-field

- Noise power

$$P_N = k_B T_{\text{sys}} \Delta f$$

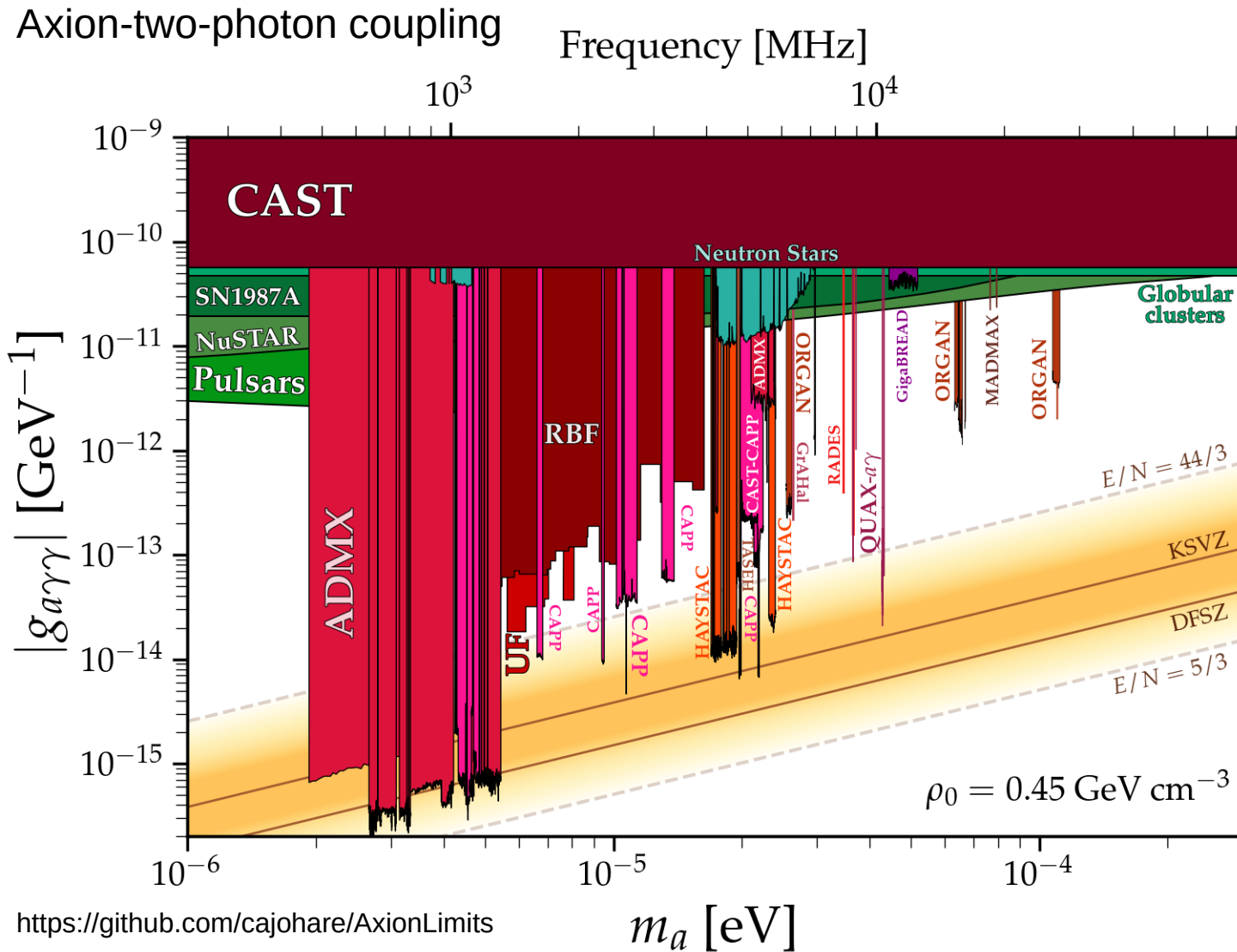
$$\sigma_{P_N} = P_N / \sqrt{N_{\text{ave}}} \\ = k_B T_{\text{sys}} \sqrt{\Delta f / t_{\text{ave}}}$$

- Detection signal-to-noise ratio

$$\Sigma = P_s / \sigma_{P_N} \propto \sqrt{t_{\text{ave}}} / T_{\text{sys}}$$

- Detection bandwidth ω_c / Q

Axion Haloscope Search Results



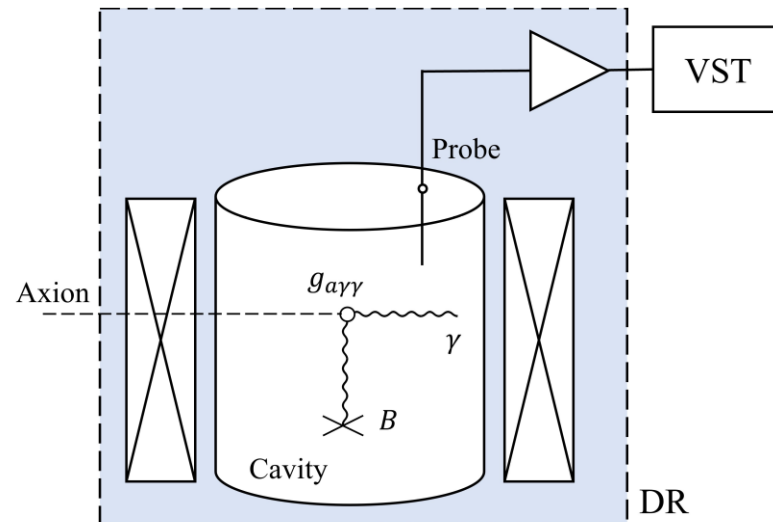
- ADMX and IBS-DMAG/CAPP mainly cover 1.9 – 5.4 μeV to the QCD limit and find null results.
- HAYSTAC looks for 17.0 – 19.5 and 23.1 – 24.0 μeV and also finds null results.

TASEH Collaboration



The collaboration, Taiwan Axion Search Experiment with Haloscope (TASEH), launched in 2020, with current members from AS, NCU, NSRRC, and VNUHCM.

- Collaboration led by Prof. Yuan-Hann Chang
- Focus on axion haloscope experiment
- Experiment located at NCU



TASEH First Physics Experiment

Existing cryostat and magnet in NCU



Bluefors DR:

- Base: 27 mK

AMI magnet:

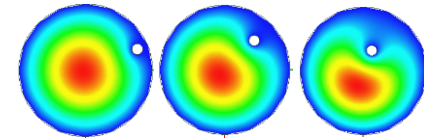
- Field: 8 T
- Bore: 6.8 mm

Detection cavity

Cavity detector

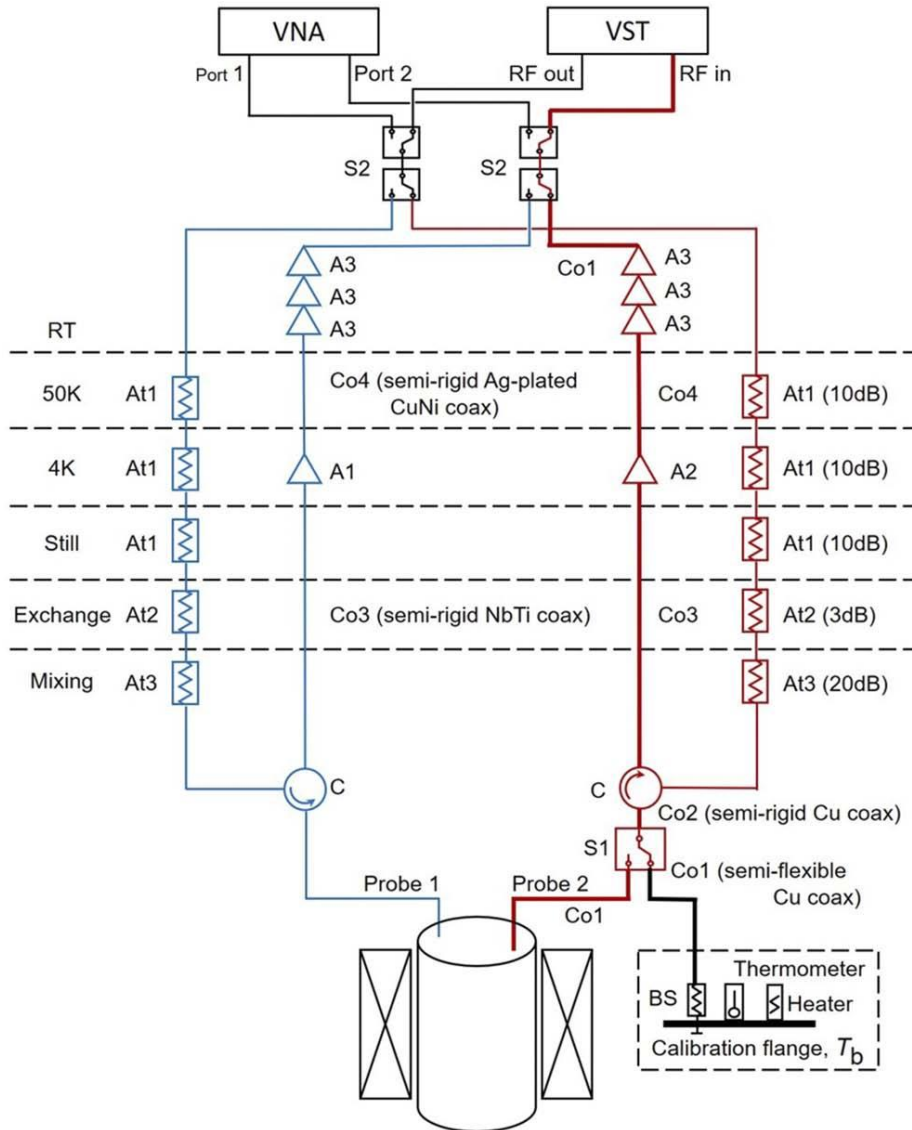


TM₀₁₀ mode pattern



- Split cylindrical cavity, OFHC copper
- Volume V : ~ 0.234 L
- High quality Q_0 : ~ 62000
- Large form factor C_{010} : ~ 0.62
- Tunable frequency f_c : 4.65 – 4.95 GHz
- Tunable coupling β_2 : 0.5 – 3
- Signal power P_s : $\sim 1.4 \times 10^{-24}$ W (KSVZ)

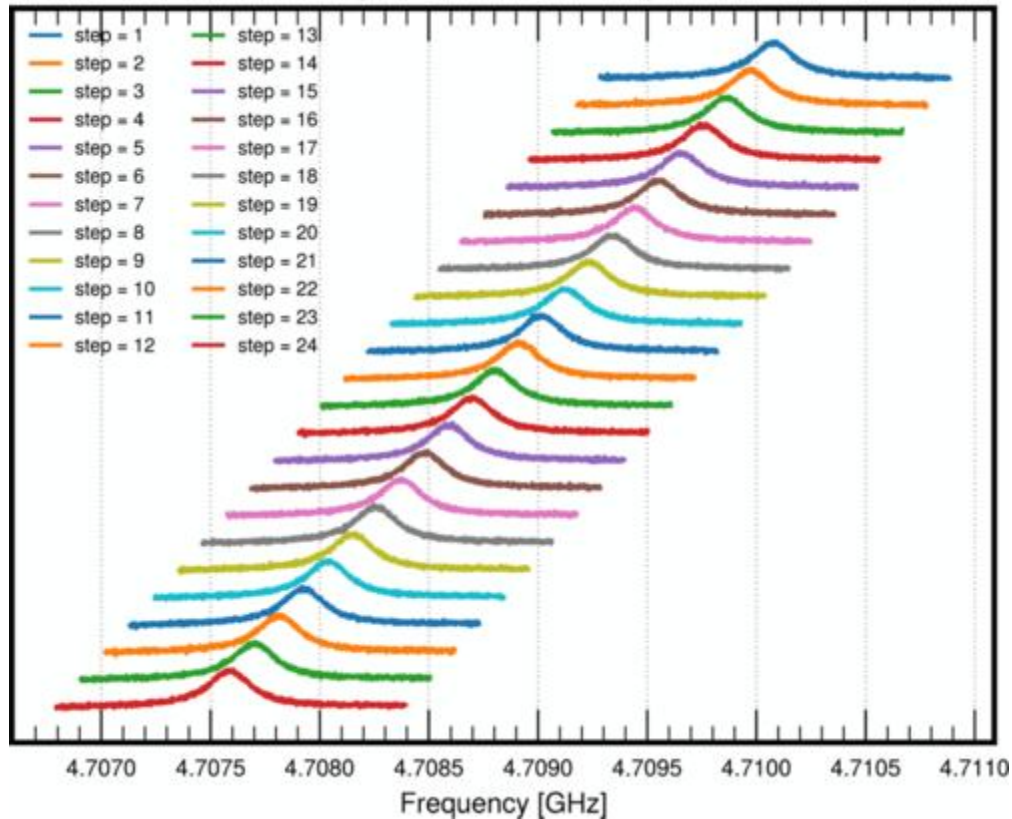
Signal Receiver Wiring



- Probe 2 for readout (strong coupling)
- Probe 1 for test signal (weak coupling)
- Two readouts to characterize cavity
- First-stage amplifier: HEMT
- Separate noise source for readout 2 calibration
- System noise T_{sys} : 2.1 – 2.4 K (9 – 10 photons)

Data Taking

spectrum in each step

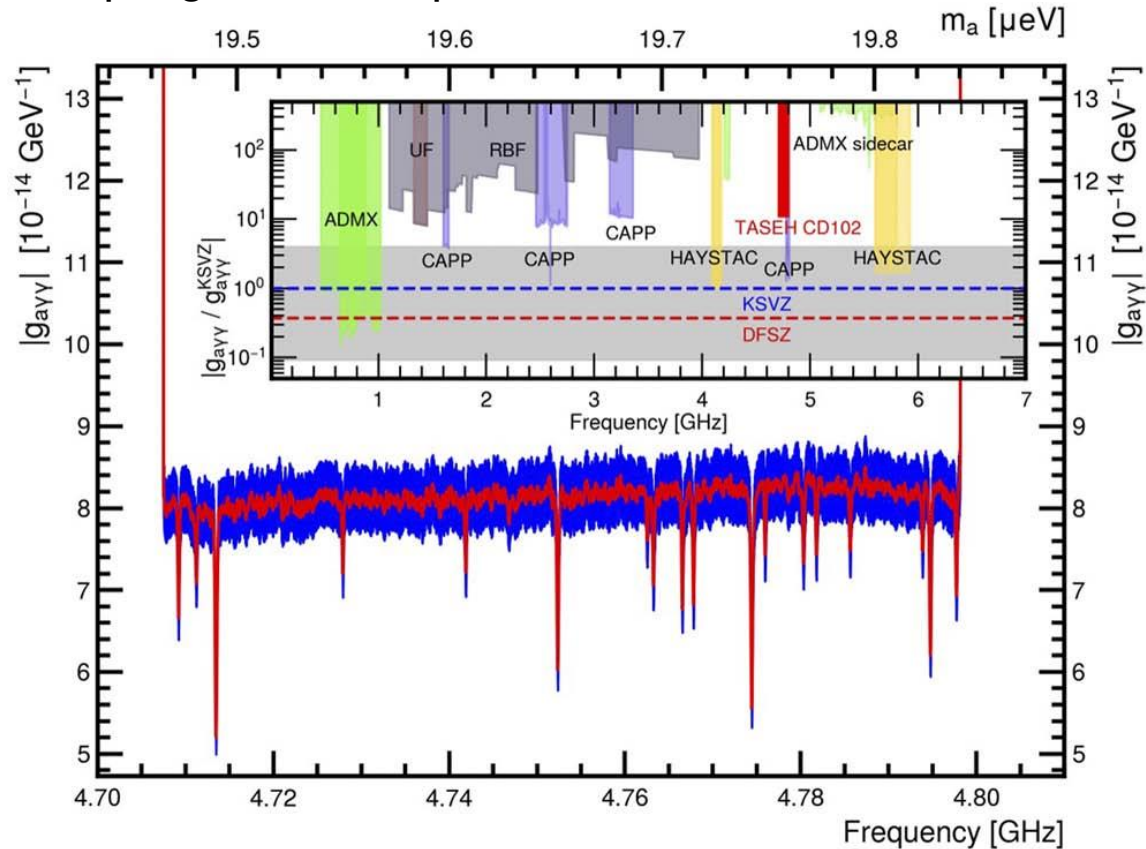


- ~110 kHz cavity frequency shift in step
- 837 steps
- Taking data for ~35 min in each step

TASEH First Results

Axion-two-photon coupling exclusion plot

TASEH collaboration, *PRL* **129**, 111802 (2022)



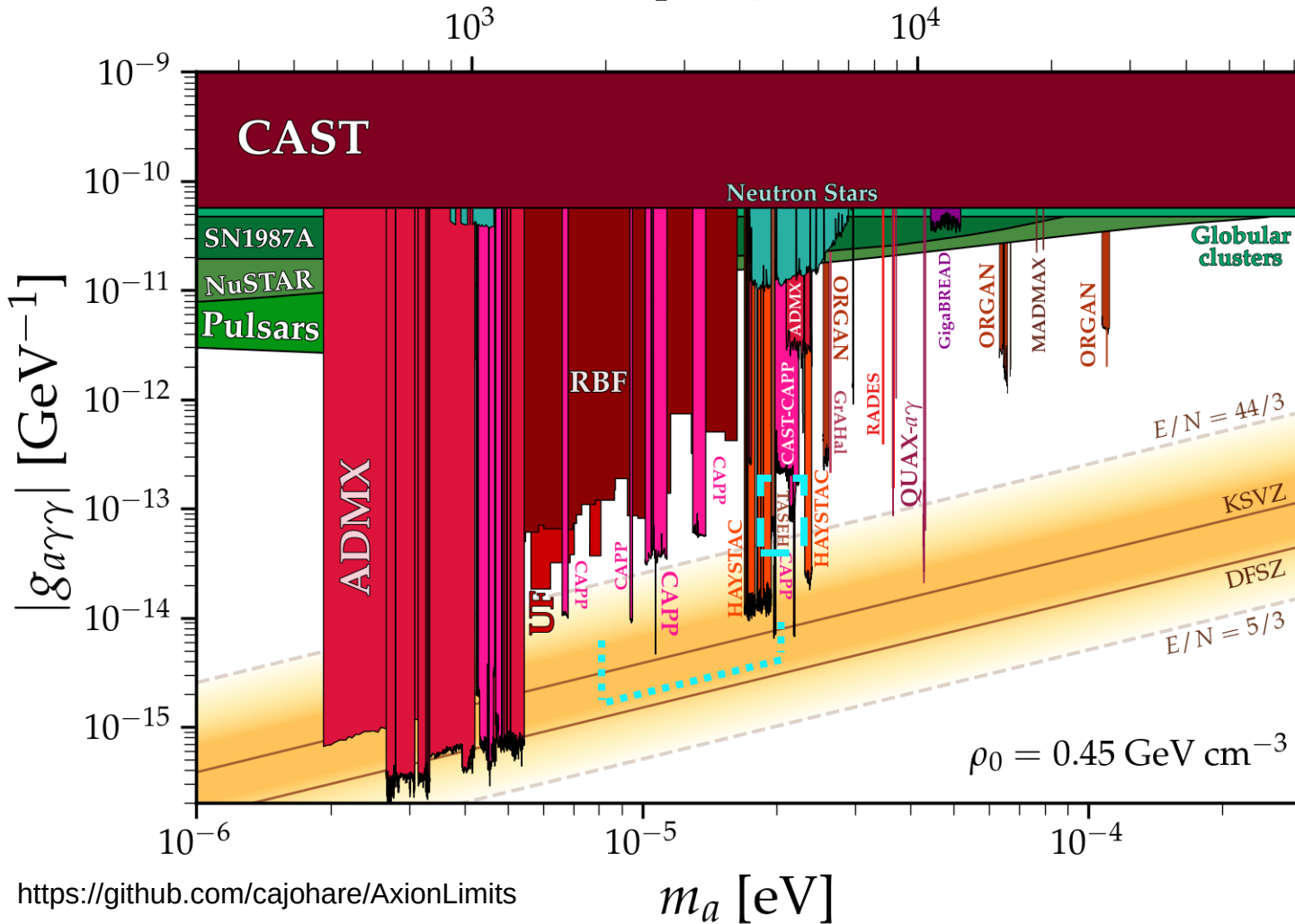
- ~ 1 month data taking in the end of Year 2021
- 19.4687 – 19.8436 μeV (4.707 50 – 4.798 15 GHz, ~ 90 MHz search range)
- Excludes models with the axion-two-photon coupling $g_{a\gamma\gamma} \geq 8.1 \times 10^{-14} \text{ GeV}^{-1}$ (~ 11 times above QCD KSVZ model limit)
- First-hand experience of operating axion haloscope

Axion Haloscope Search Results

Axion-two-photon coupling

Frequency [MHz]

Before 1995



- RBF
- UF

After 1995

- ADMX
- HAYSTAC
- MADMAX
- IBS-DMAG
- ORGAN
- QUAX
- TASEH
- ...

- TASEH target search range: 8 – 20 μeV (2 – 5 GHz)

Well-motivated by a particle cosmology argument; familiar and readily available technology

TASEH Haloscope Upgrade

- Magnet upgrade
- Large cavity
- Quantum-limited amplifier: Josephson parametric amplifier

New Dilution Refrigerator

New DR arrived in the 2022 Fall

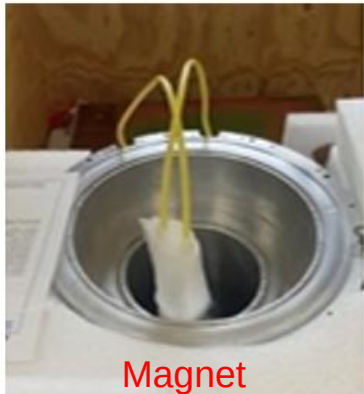
System parameters

Base temperature	10 mK
Central field B_0	9 T
Bore diameter	142 mm
Length	400 mm
30% reduction	250 mm
Inductance	93 H

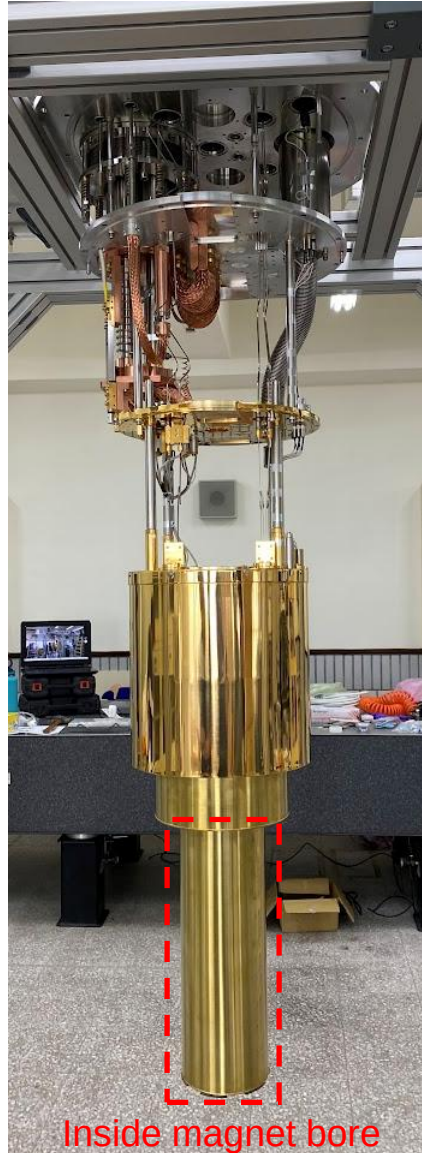
Target search range

$$2 \text{ GHz} < \omega_a/2\pi < 5 \text{ GHz}$$

$$8 \text{ } \mu\text{eV} < m_a < 20 \text{ } \mu\text{eV}$$



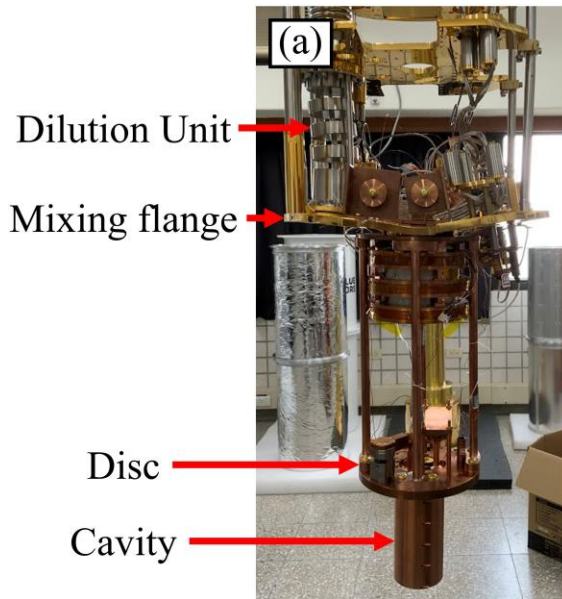
Magnet



Inside magnet bore

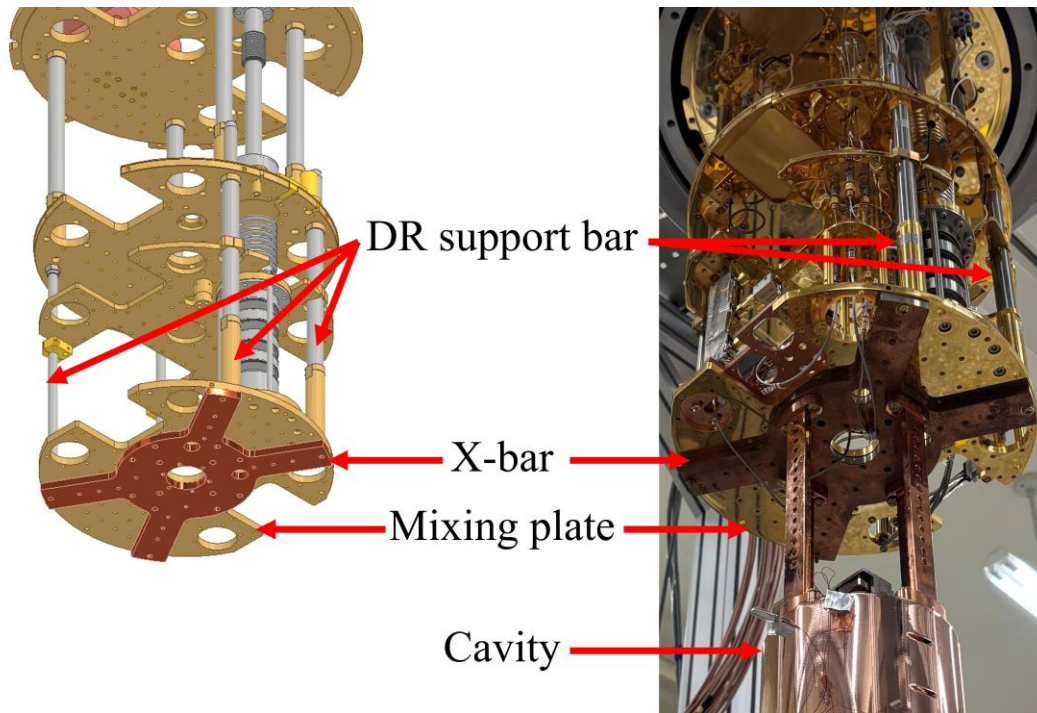
DR Damage

Deformed DR photos



- In December 2022, the DR suffered severe damage during a magnet quench caused by a large amount of high-conductivity copper inside the magnet.
- The incident resulted in significant deformation below the still flanges and a superfluid leak in the dilution unit.
- Fully recovered by the vendor in October 2023.

X-Shaped Support Bar



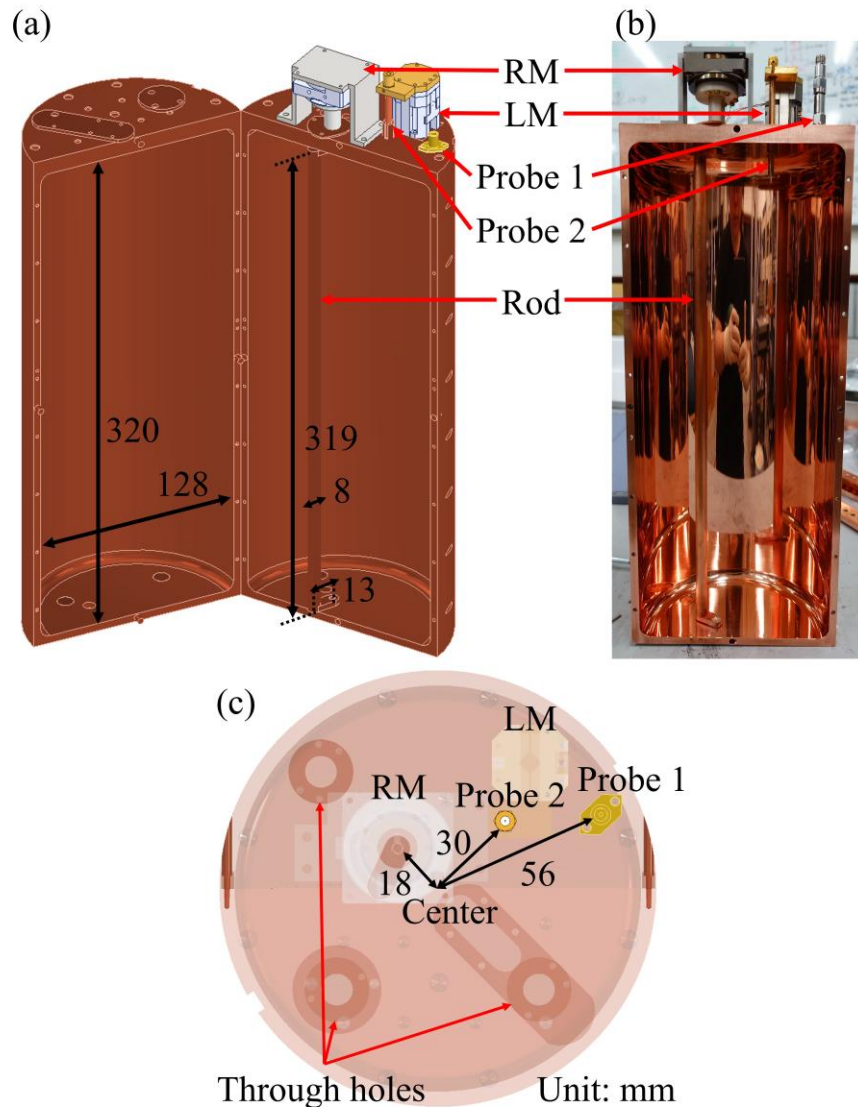
- Made of stainless steel, Cu coated
- Anchored at mixing flange
- The major experimental setup is anchored under the Xbar, preventing excessive force from acting on the copper mixing flange

Plan for 2-GHz Physics Run

- Large cylindrical cavity at lower frequency
- Josephson parametric amplifier

Large Cavity Development

Design and fabrication

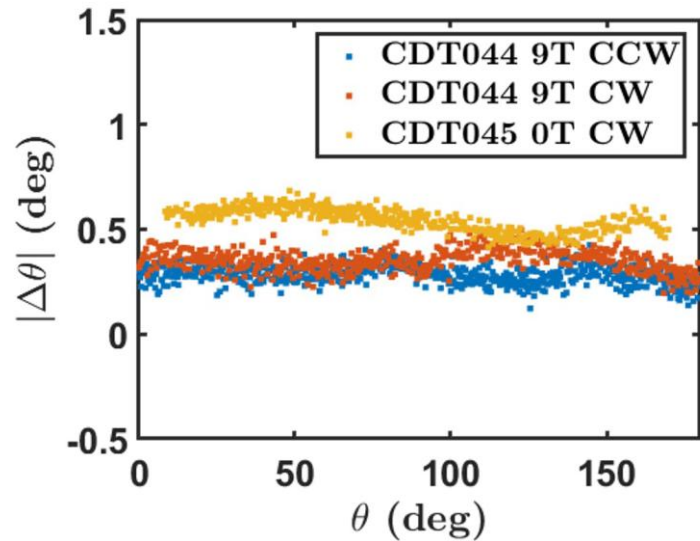


Features

- Split cylindrical cavity (similar design to the first-result cavity)
- Volume V : ~ 4.1 L
- Stainless steel, Cu coated
- Tunable frequency with a rod driven by an Attocube rotational motor
- Tunable coupling β_2 driven by an Attocube linear motor
- 4 – 5 similar cavities to cover 2 – 3 GHz

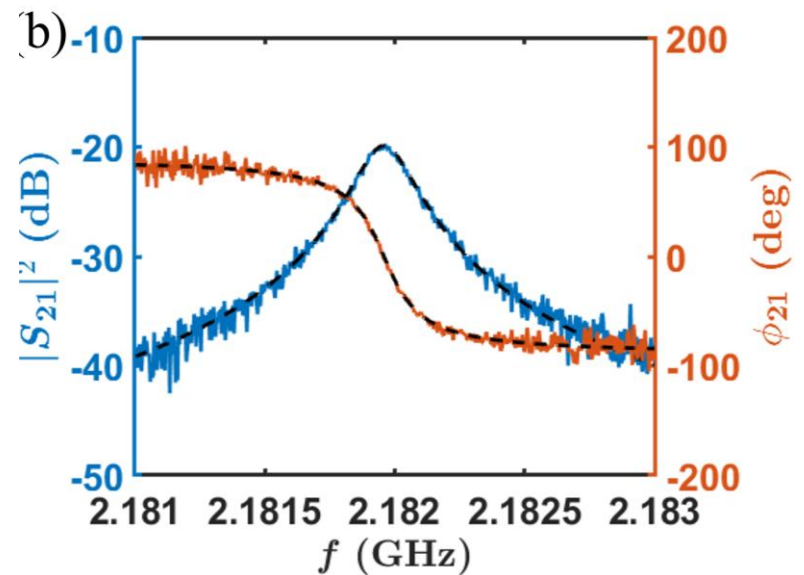
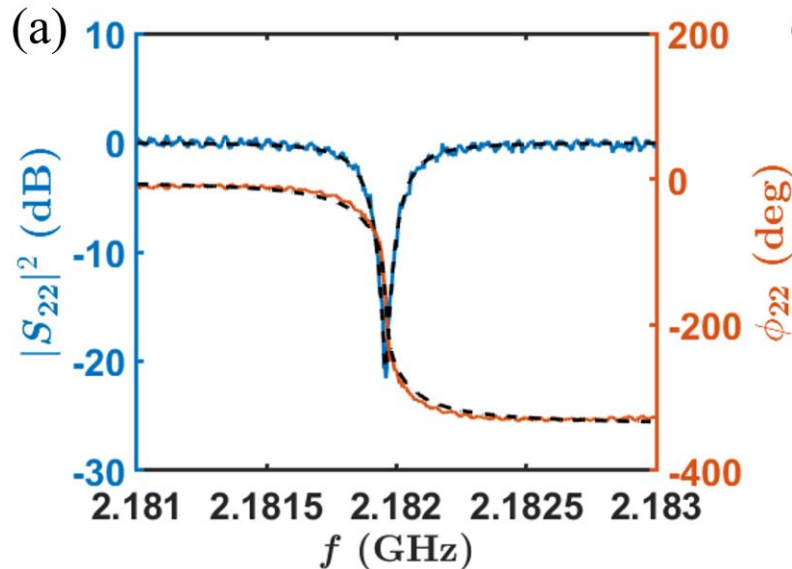
Characterization

Tuning rod mobility (every 300 pulses)



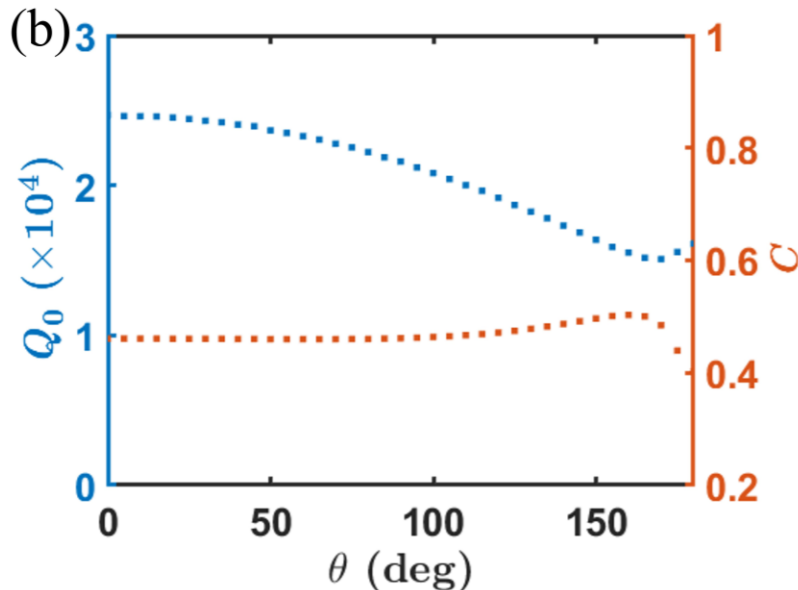
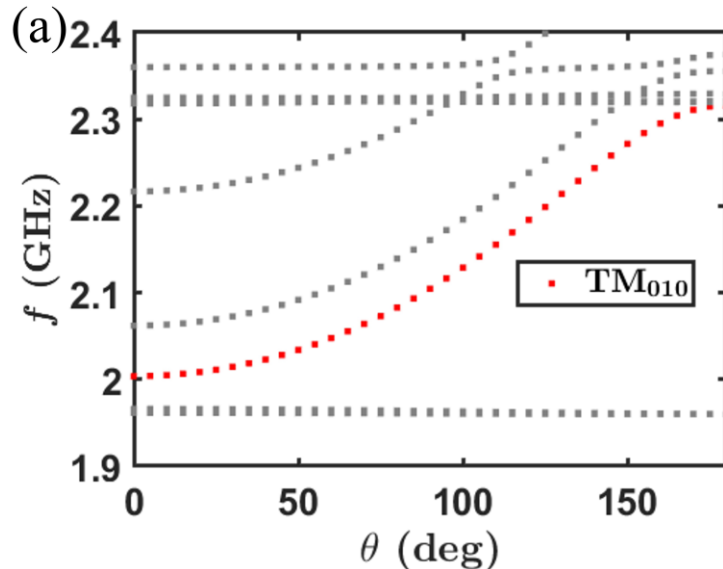
- Tuning rod typically works alright at cryogenic and high magnetic fields
- Cavity scattering matrices to retrieve resonance frequency, intrinsic quality factor, and external coupling

Cavity scattering matrices

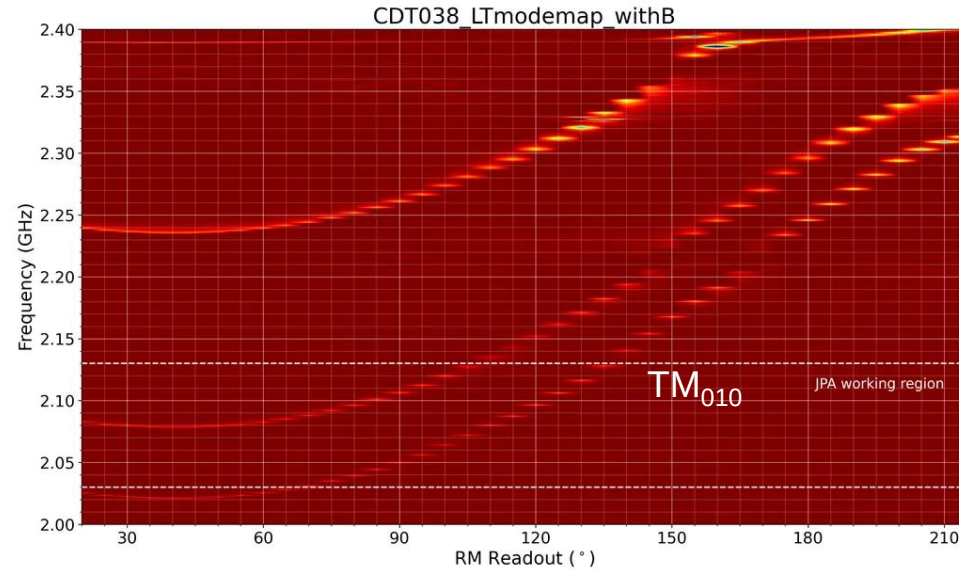


Simulation and Measured Mode Map

Simulation



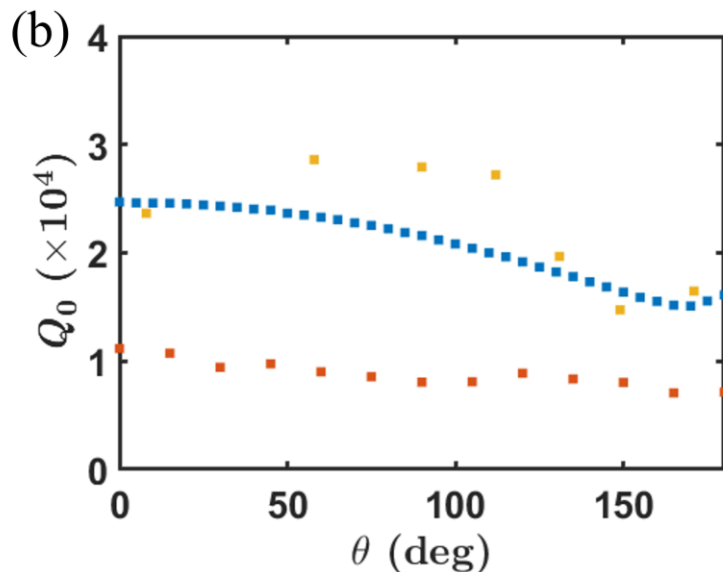
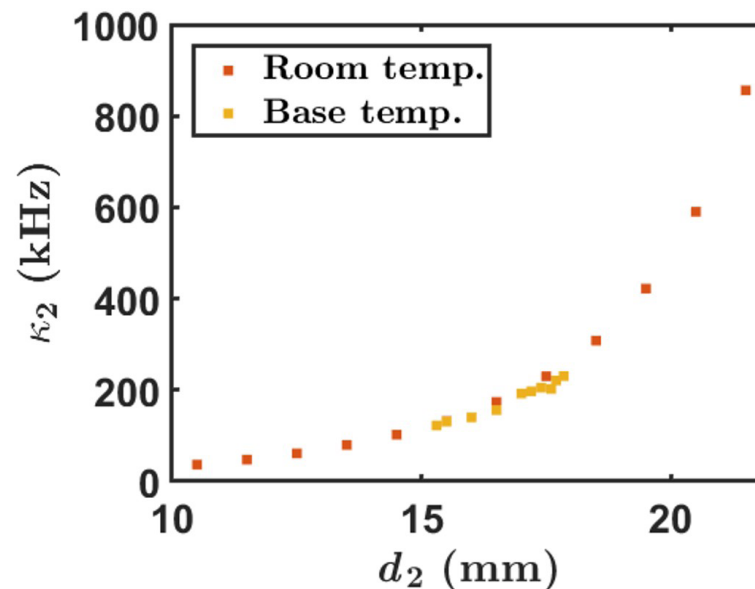
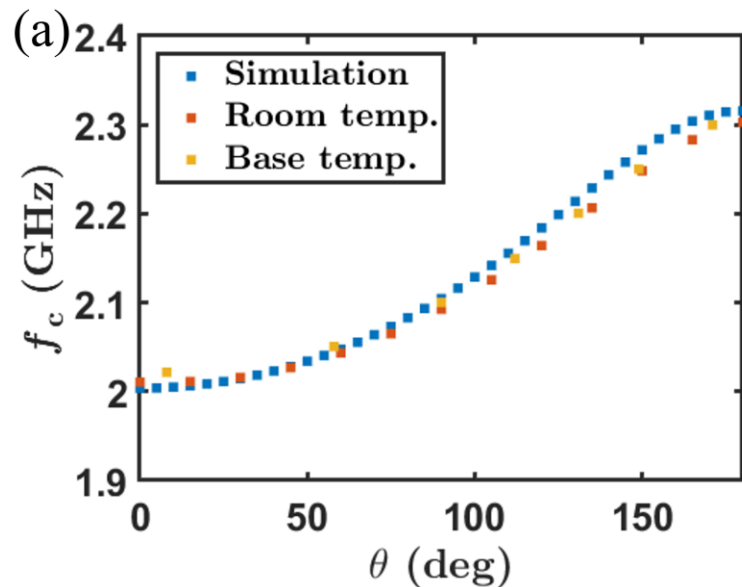
Measured mode map at 9 T



- Measured mode map matches simulation well
- Tunable frequency f_c : 2.0 – 2.3 GHz
- Form factor C_{010} : ~ 0.46
- Expect room-T quality Q_0 : ~ 20000

Cavity Tuning and Quality

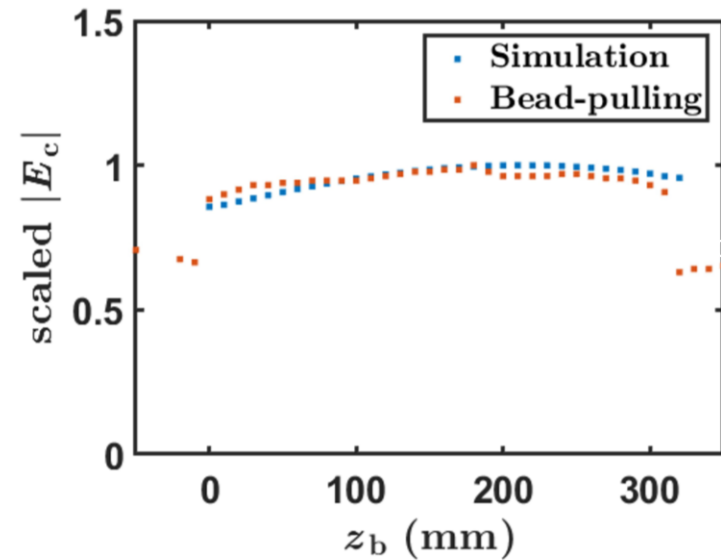
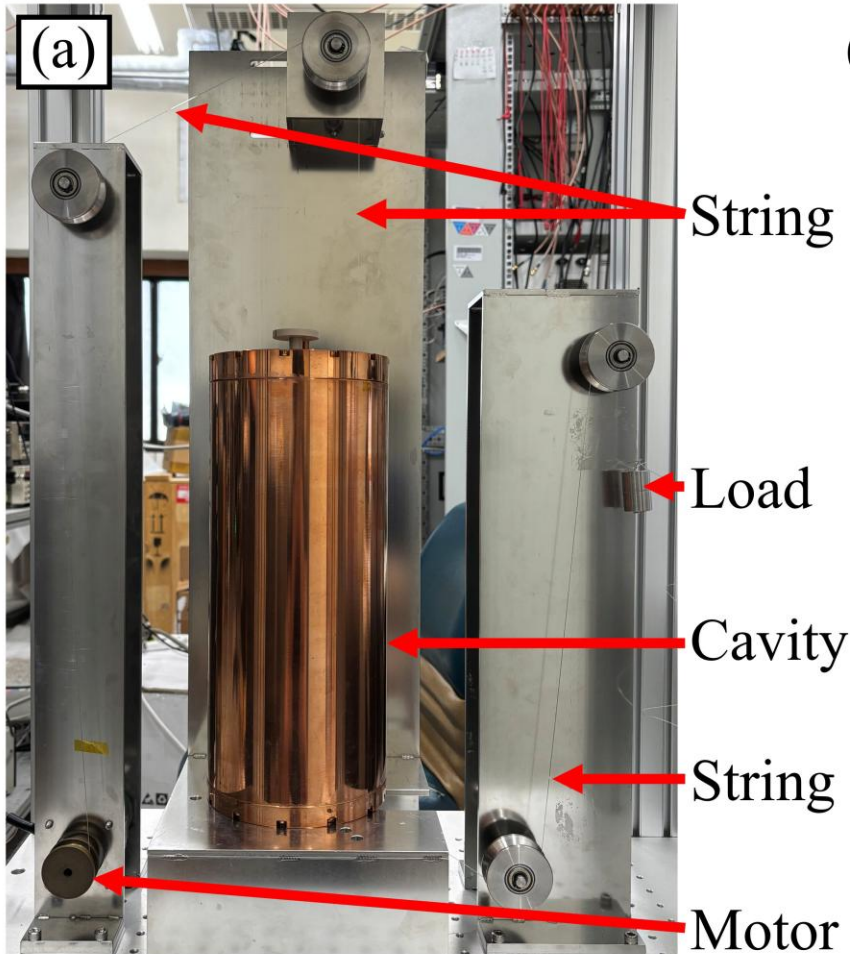
2 – 3 GHz big cylindrical cavity



- Tunable frequency f_c : 2.0 – 2.3 GHz
- Quality Q_0 at cold: ~ 30000
- Tunable coupling β_2 : similar at both room temperature and low temperature
- Cavity temperature T_{cav} : ~ 50 mK at 0 T, ~ 170 mK at 9 T

Bead-Pull Measurement

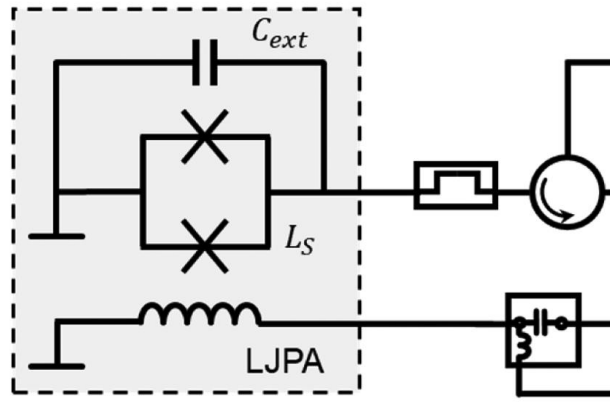
Setup



- Cylindrical Teflon bead with a diameter of 4.6 mm and a length of 6 mm
- The frequency shift profile matches the simulation field profile well

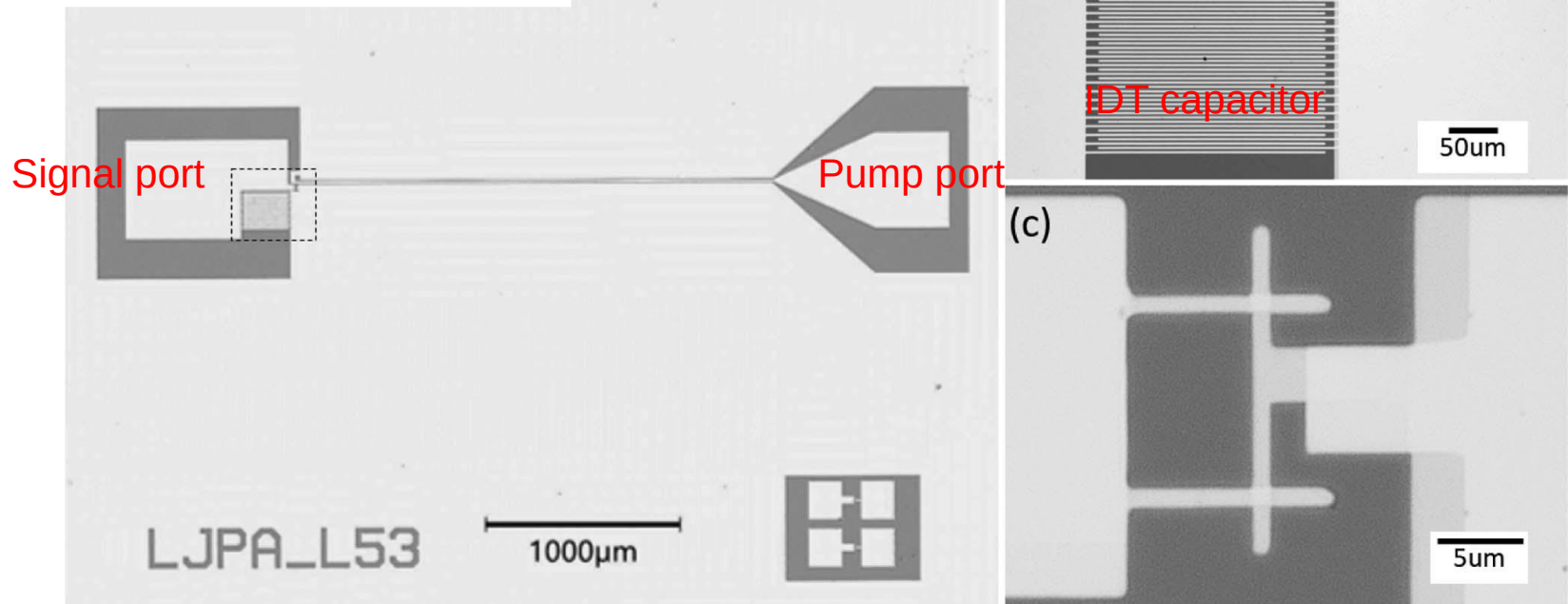
Low-Noise Josephson Parametric Amplifier (JPA)

Lumped-element JPA (LJPA)
device schematic and photos



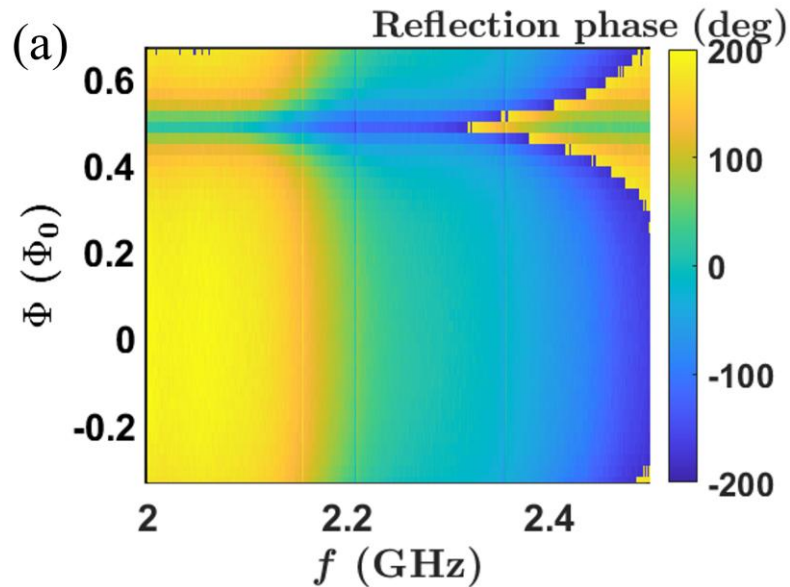
Features

- Superconducting circuit
- Lithography and thin-film process
- Quantum-limited noise performance
- See Wei-Cheng Hung's talk

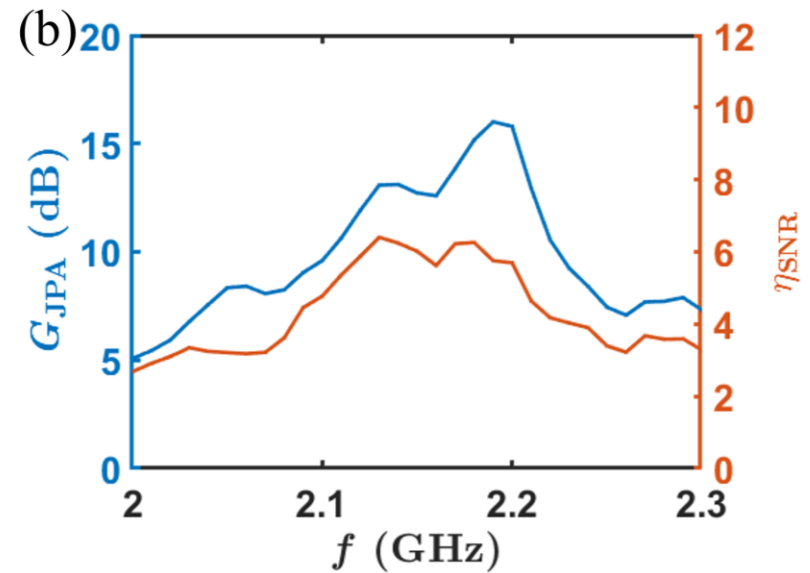


LJPA Performance at 2 GHz

Resonator frequency tuning

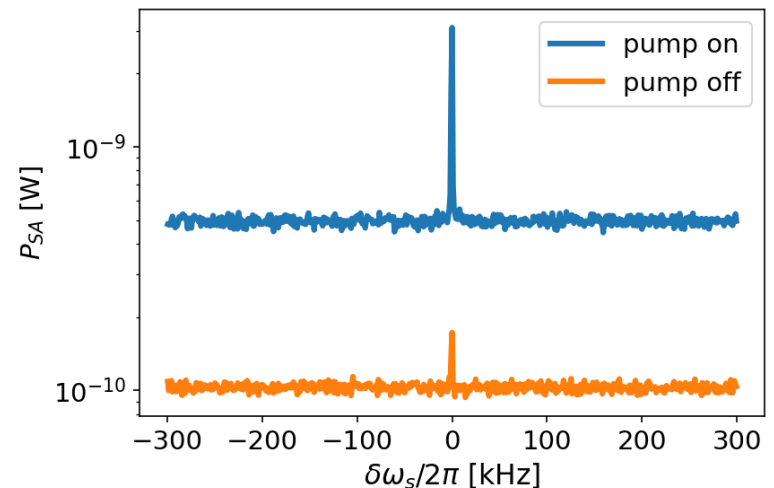


Gain and noise



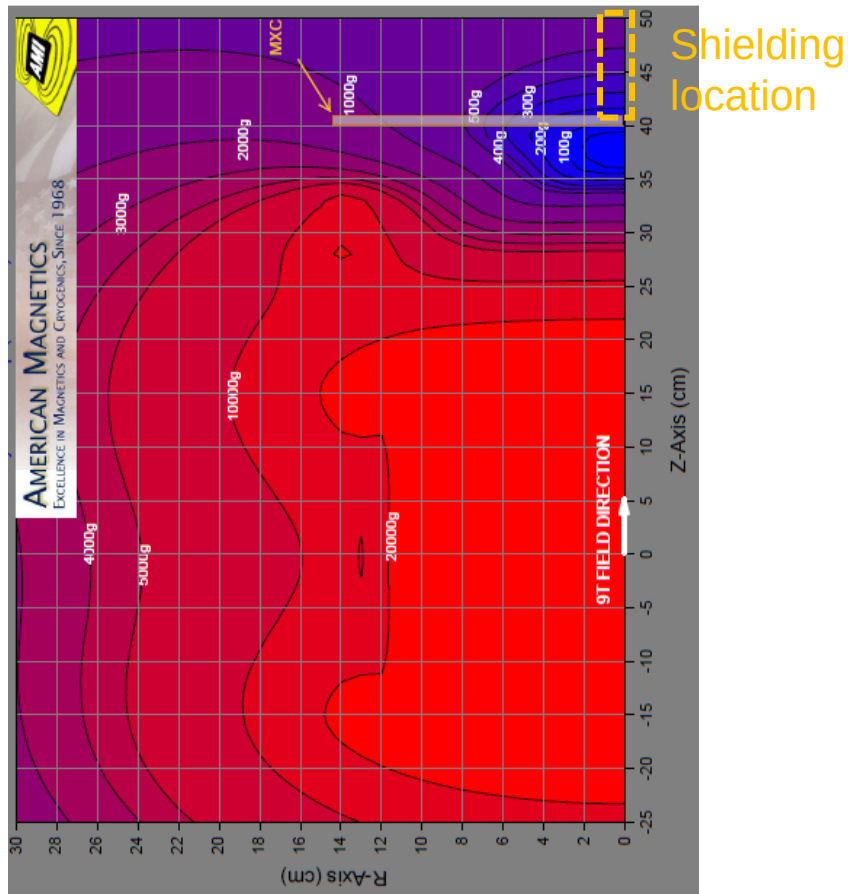
Performance at 2 GHz

Gain	15 dB
Bandwidth	100 MHz
Frequency tuning range	2 – 2.3 GHz
Saturation power	-125 dBm
System noise	< 0.25 K (2 photons)

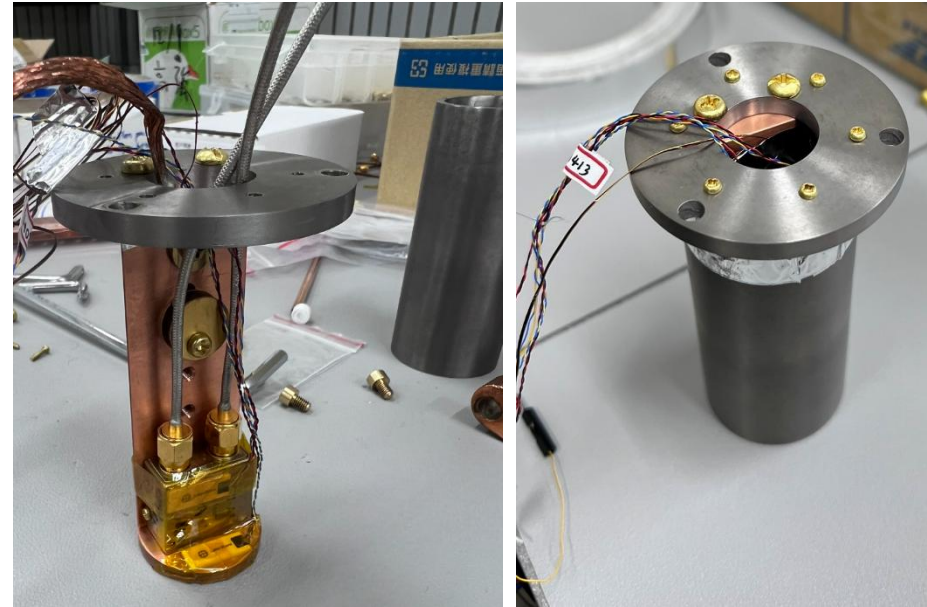


Magnetic Field Shielding

Field map of magnet

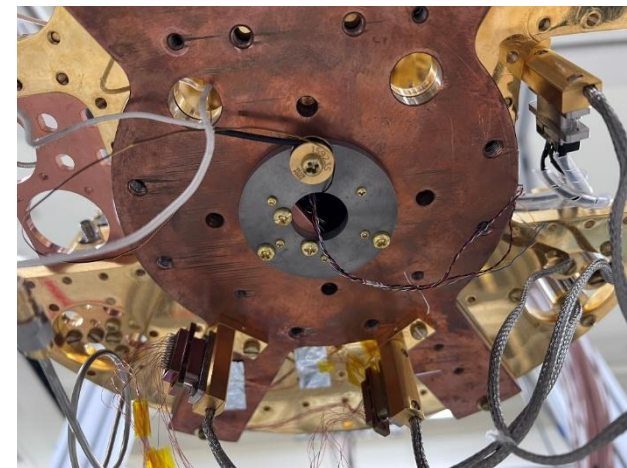


Magnetic field shielding assembly



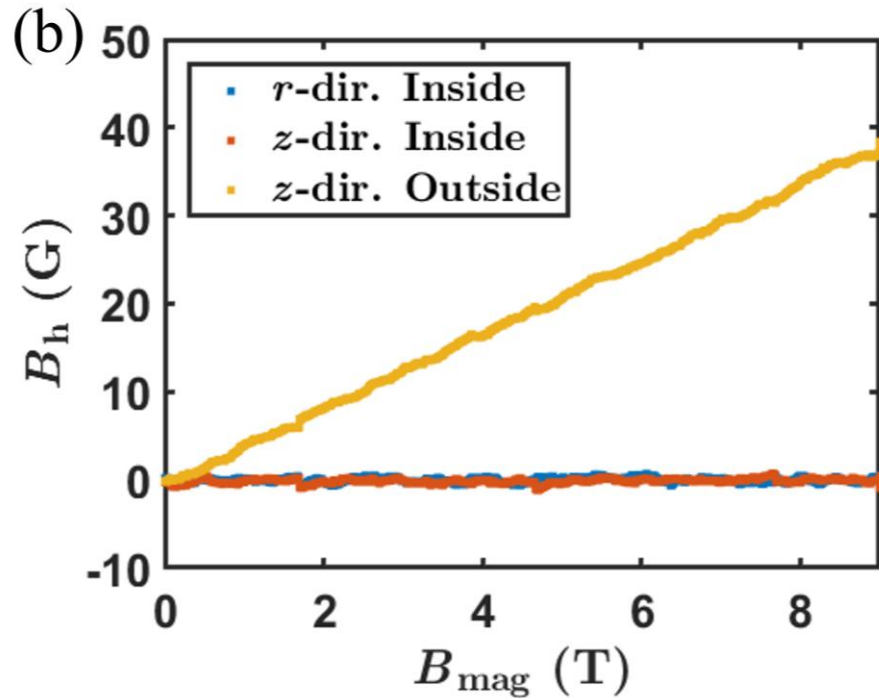
Features

- Niobium (superconducting) shield
- Simple one-layer design

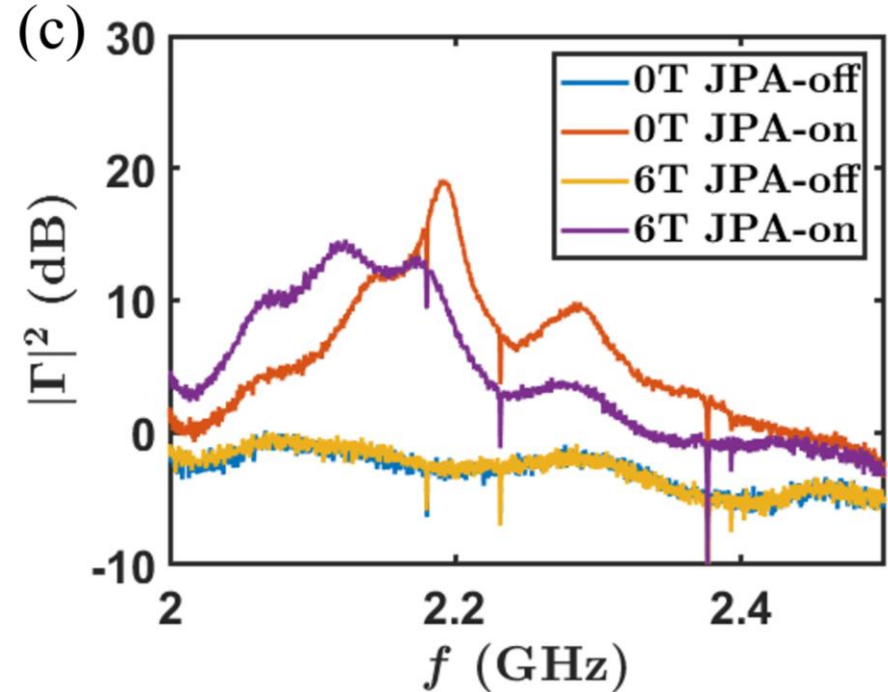


Shielding Effect

Hall sensor measurement



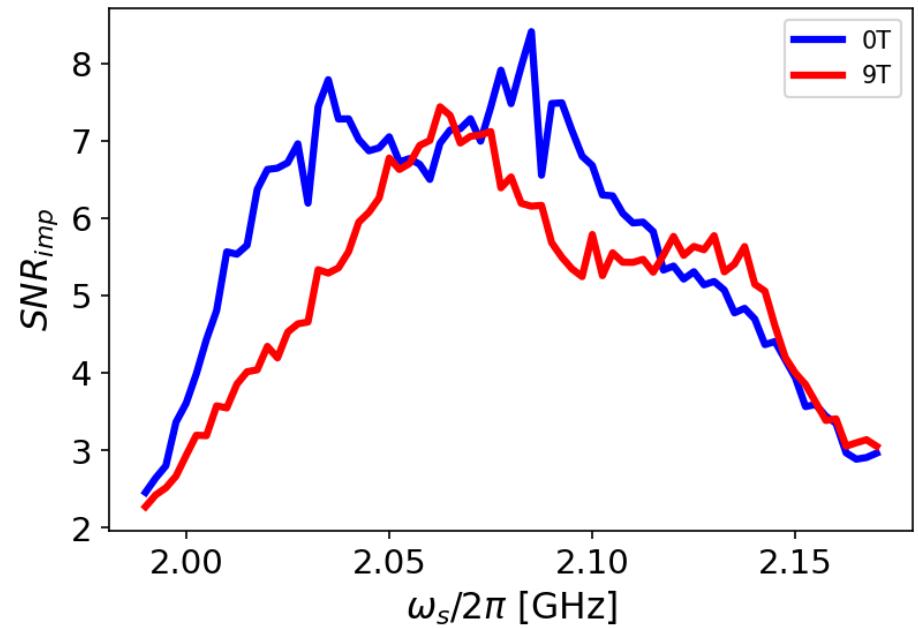
LJPA characteristics at 6 T



- No significant field change (> 0.1 gauss) inside the shielding is detected when a 9T magnetic field is applied to the cavity.
- Field attenuation factor greater than 10,000.
- JPA, however, is affected but still maintains good performance.

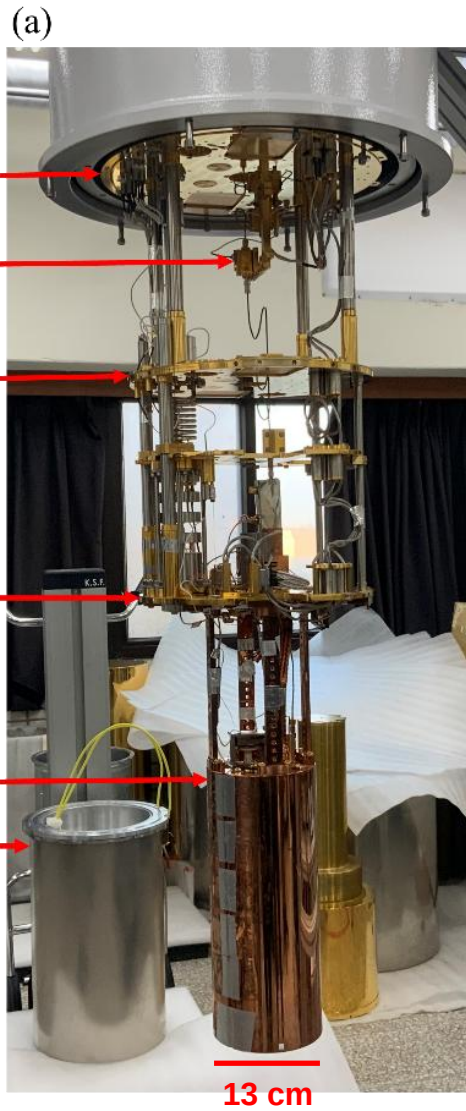
Shielding Effect

LJPA characteristics at 9 T

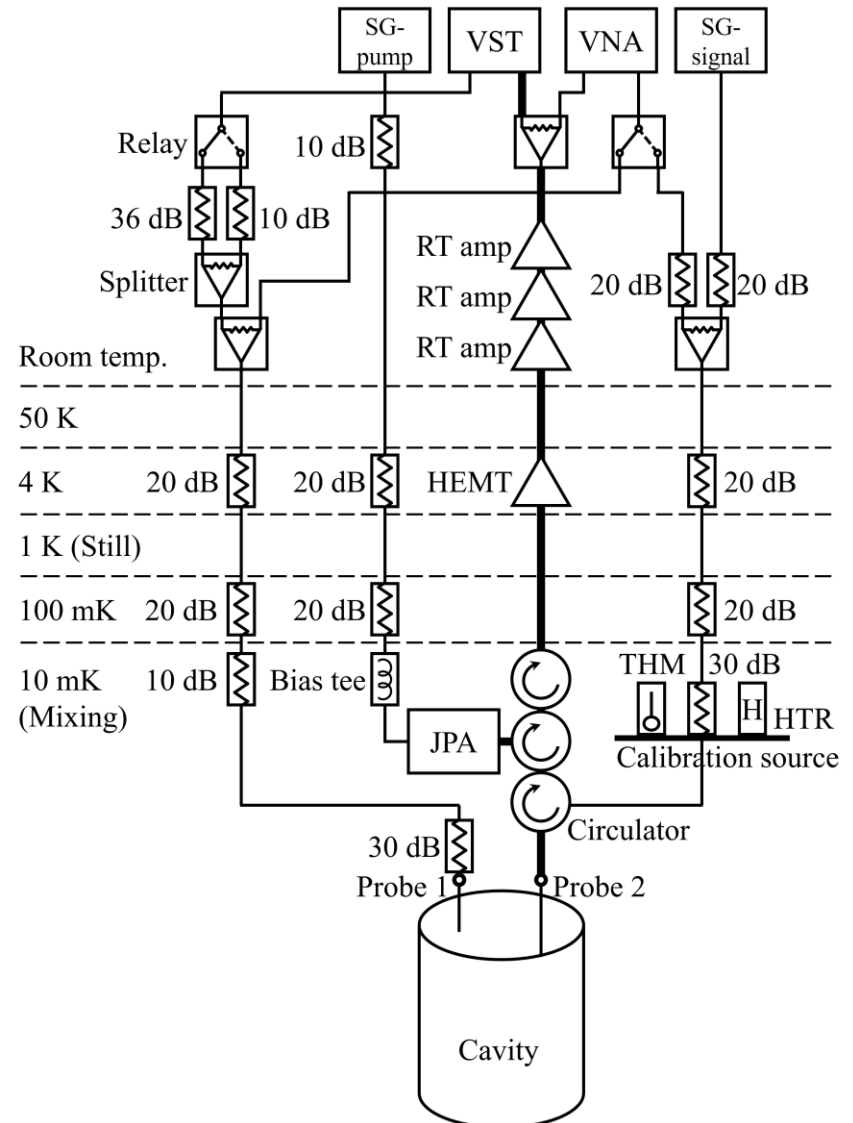


2-GHz Haloscope Setup

Setup overview

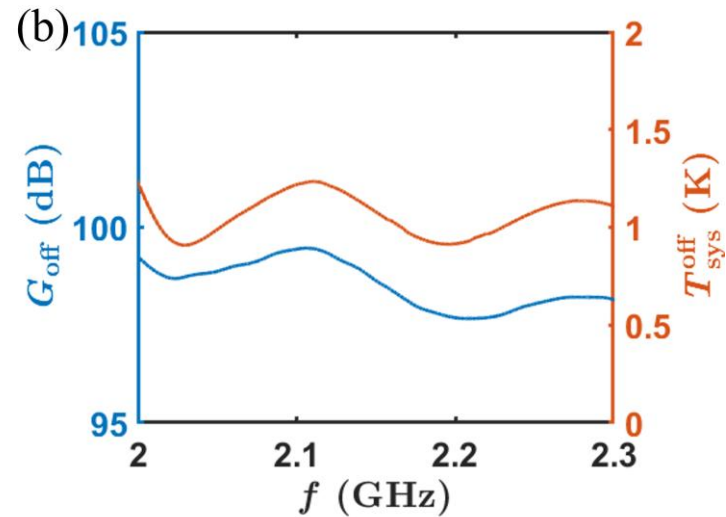
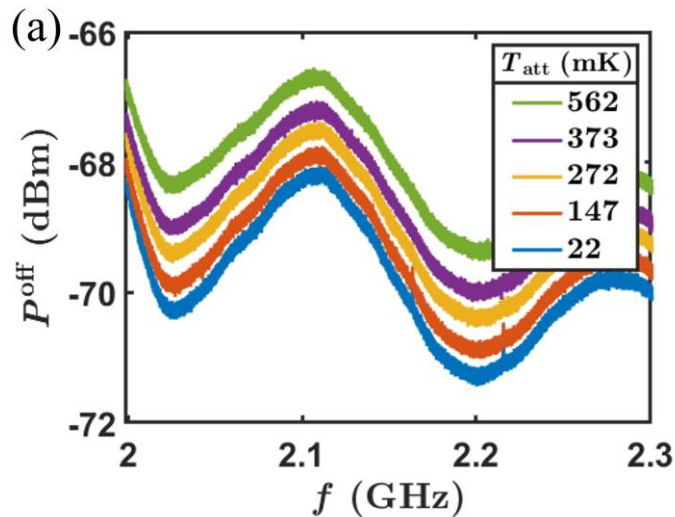


Setup schematic



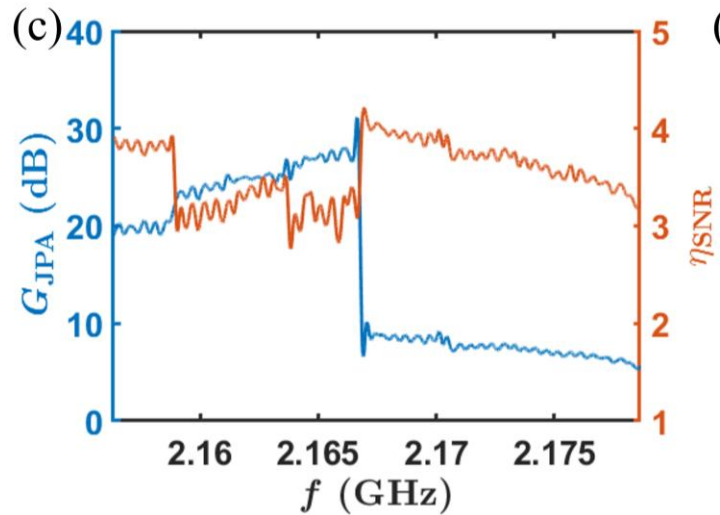
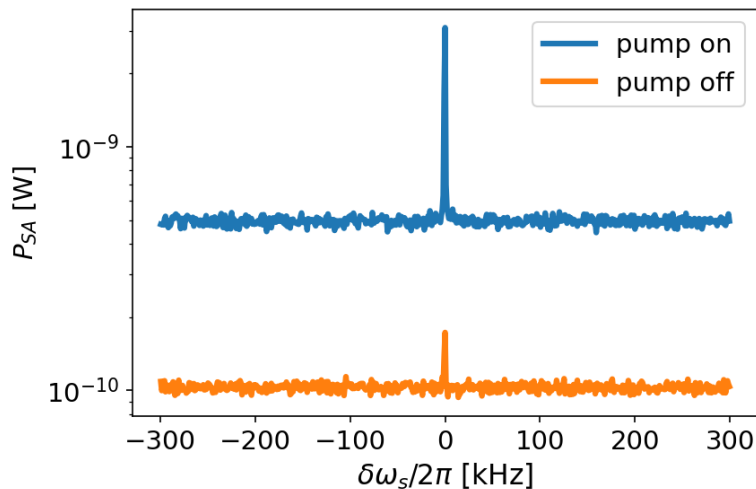
System Noise Calibration

- JPA pump-off calibration: gain without JPA G_{off} and added noise
- JPA pump on/off calibration: JPA gain G_{JPA} and SNR improvement
- Total Gain: $G = G_{\text{off}} G_{\text{JPA}}$
- Derived system noise: $T_{\text{sys}} = P_{\text{m}}/k_{\text{B}}\Delta f G$



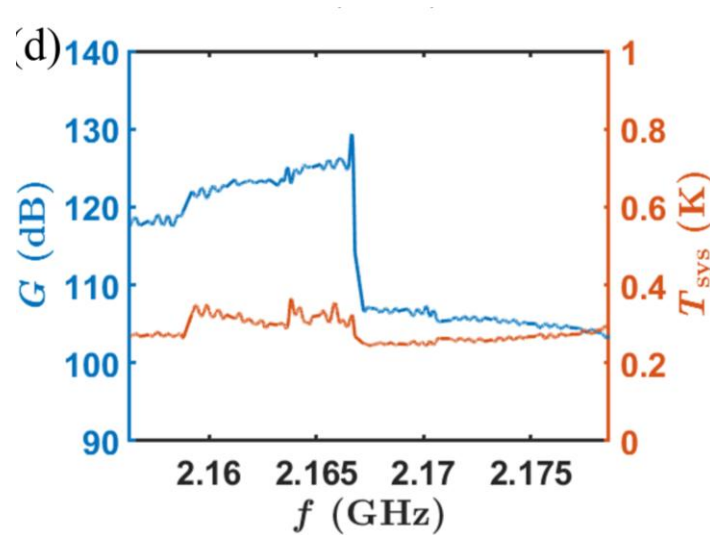
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- Derived system noise: $T_{\text{sys}} = P_{\text{m}}/k_{\text{B}}\Delta f G$



Expected Sensitivity at 9 T

Key experiment parameters

Parameter \ Run	First results	2-GHz expectation
Frequency $\omega/2\pi$	4.75 GHz	2 GHz
Magnetic field B_0	8 T	9 T
Volume V	0.234 L	4.1 L
Form factor C	0.62	0.46
Cavity Q_0	62000	30000
System noise T_s	2.3 K	0.3 K
Expected sensitivity $g_{a\gamma\gamma}$	$8.1 \times 10^{-14} \text{ GeV}^{-1}$ (11 times of KSVZ)	$6.5 \times 10^{-15} \text{ GeV}^{-1}$ (2 times of KSVZ)

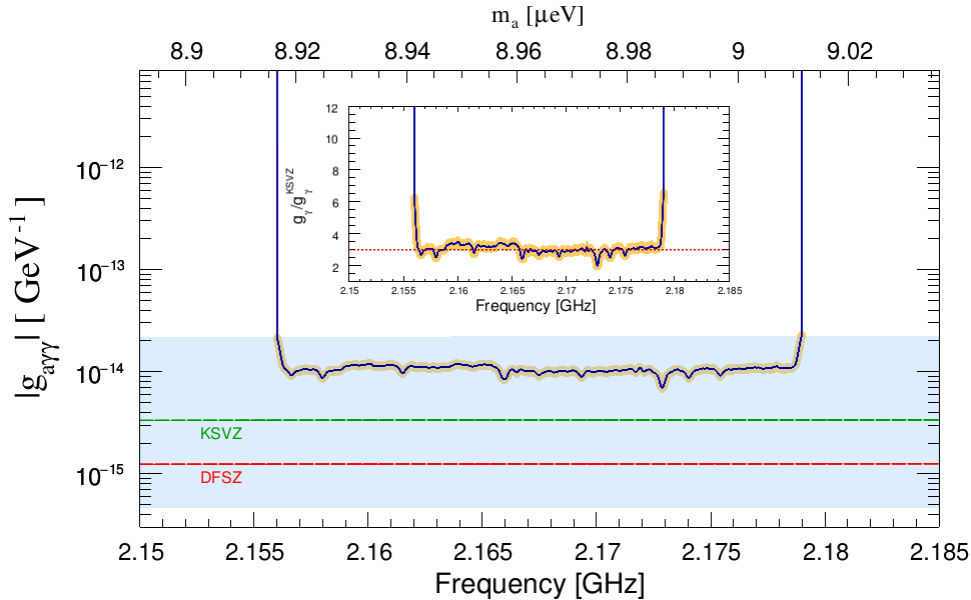
2-GHz Preliminary Physics Run

- Magnet issue: consecutive quenches at 7.2 T during charging
- Testing the operation procedure at a 6 T magnetic field
- 146 frequency tuning steps
- 40 minutes of data taking at each step to achieve sensitivity $g_{a\gamma\gamma} \approx 1.0 \times 10^{-14} \text{ GeV}^{-1}$

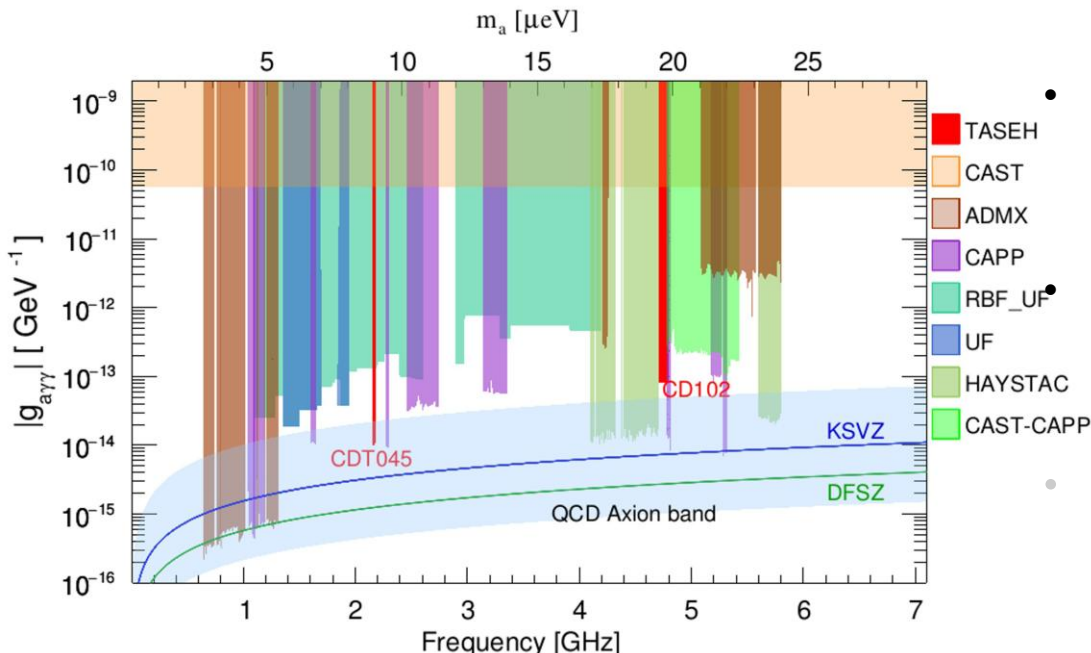
Results

Axion-two-photon coupling exclusion plot

TASEH collaboration, *in preparation*



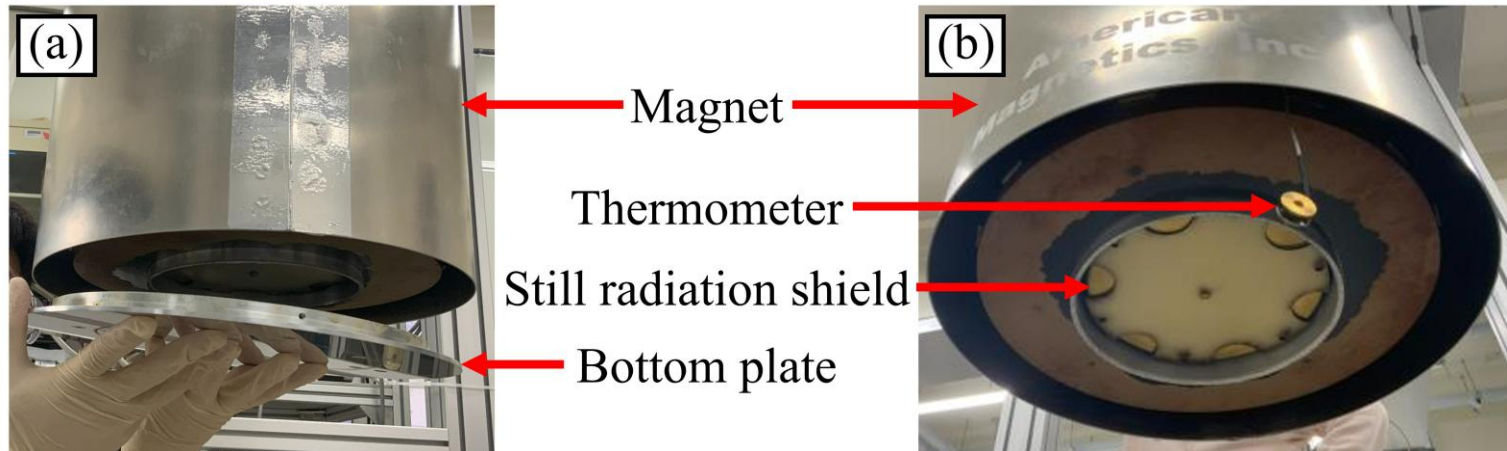
- 12 candidate frequencies were identified
- After rescan, no axion signal was found
- Achieved a sensitivity of $g_{\gamma\gamma} \geq 1 \times 10^{-14} \text{ GeV}^{-1}$ at 2.17 GHz over a 24 MHz bandwidth, corresponding to about three times the KSVZ benchmark



- The fifth experimental team has reached the parameter space relevant to QCD axions

Searches at 9 T are planned to improve further the sensitivity to twice the KSVZ model across the 2.0–2.3 GHz range

Magnet Issue



- Soldered bottom plate drops
- Repaired by AMI
- Returned in April 2026

Sensitivity for 2-GHz Test Run at 9 T

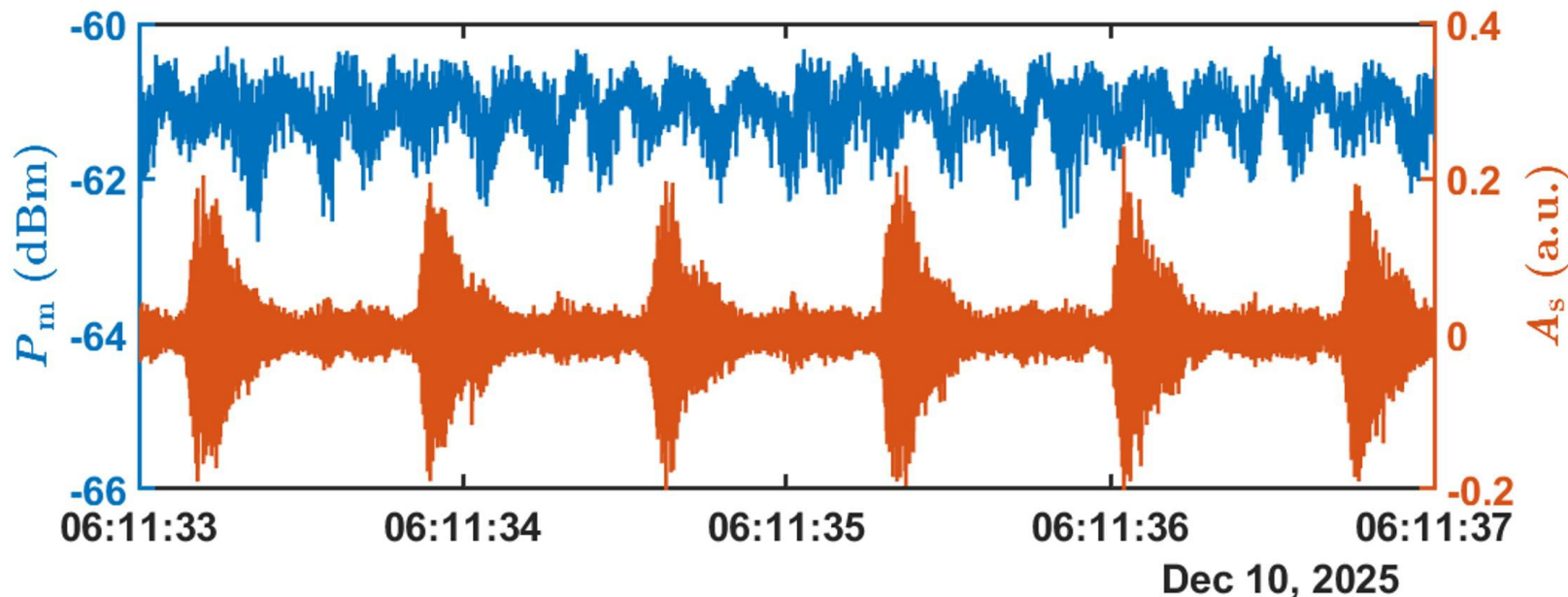
Key experiment parameters

Parameter \ Run	2-GHz expectation	2-GHz test run
Frequency $\omega/2\pi$	2 GHz	2 GHz
Magnetic field B_0	9 T	9 T
Volume V	4.1 L	4.1 L
Form factor C	0.46	0.46
Cavity Q_0	25000	25000
System noise T_s	0.3 K	0.55 K
Expected sensitivity $g_{a\gamma\gamma}$	$6.5 \times 10^{-15} \text{ GeV}^{-1}$ (2 times of KSVZ)	$1.2 \times 10^{-14} \text{ GeV}^{-1}$ (3.6 times of KSVZ)

$$\beta_2 \sim 4.5$$

Key Issues for 2-GHz Physics Run

- Temporal variation of JPA gain induced by pulse tube vibration (Yi-Hsiang Kuo's talk)



- Cavity tuning operations at cold (James Chiang's talk)
- Cavity quality factor, elevated temperature at high field (James Chiang's talk)
- Analysis: confidence level selection; use of rescan data for limit (Hien Doan's talk)

Plan for 5-GHz Physics Run

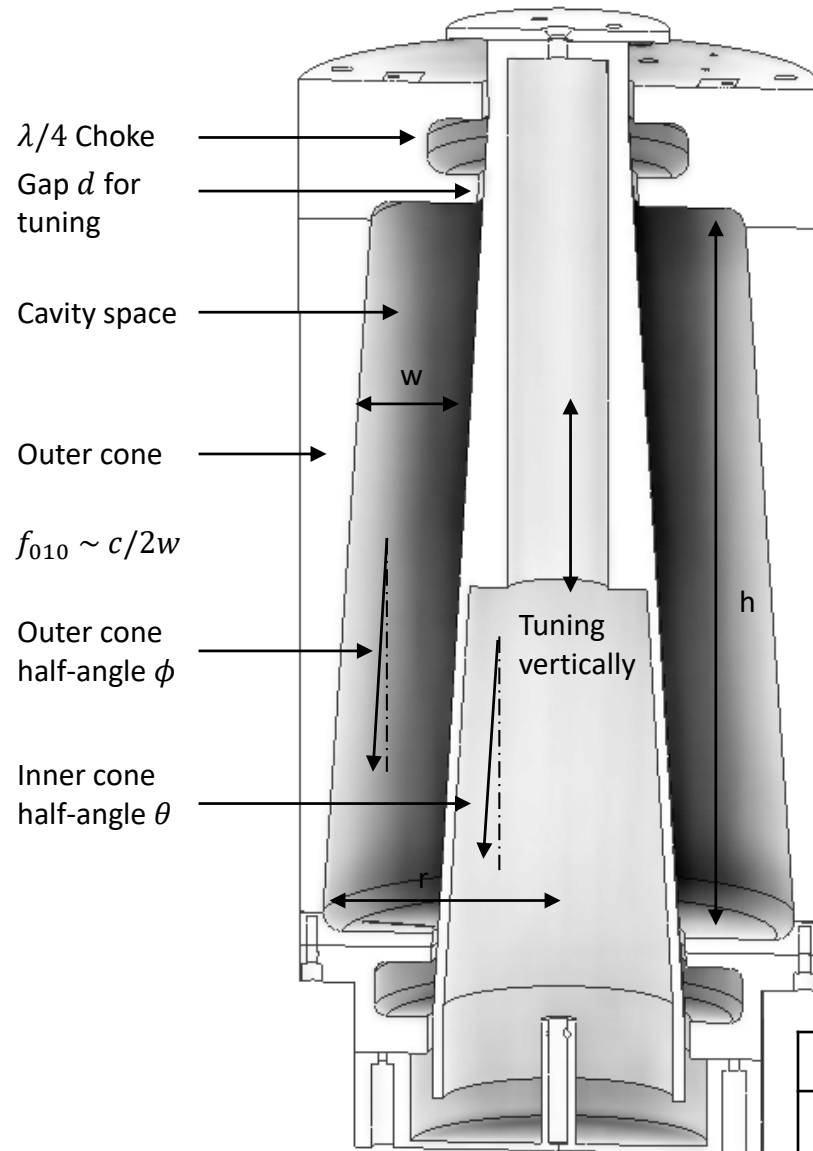
- Large conic shell cavity

Key experiment parameters

Parameter \ Run	First results	5-GHz expectation
Frequency $\omega/2\pi$	4.75 GHz	4.8 GHz
Magnetic field B_0	8 T	9 T
Volume V	0.234 L	1.66 L
Form factor C	0.62	0.73
Cavity Q_0	62000	50000
System noise T_s	2.3 K	0.4 K
Expected sensitivity $g_{\gamma\gamma}$	$8.1 \times 10^{-14} \text{ GeV}^{-1}$ (11 times of KSVZ)	$1.1 \times 10^{-14} \text{ GeV}^{-1}$ (1.5 times of KSVZ)

Conic Shell Cavity Development

4 – 5 GHz conic shell cavity design model



E-field pattern of TM_{010}



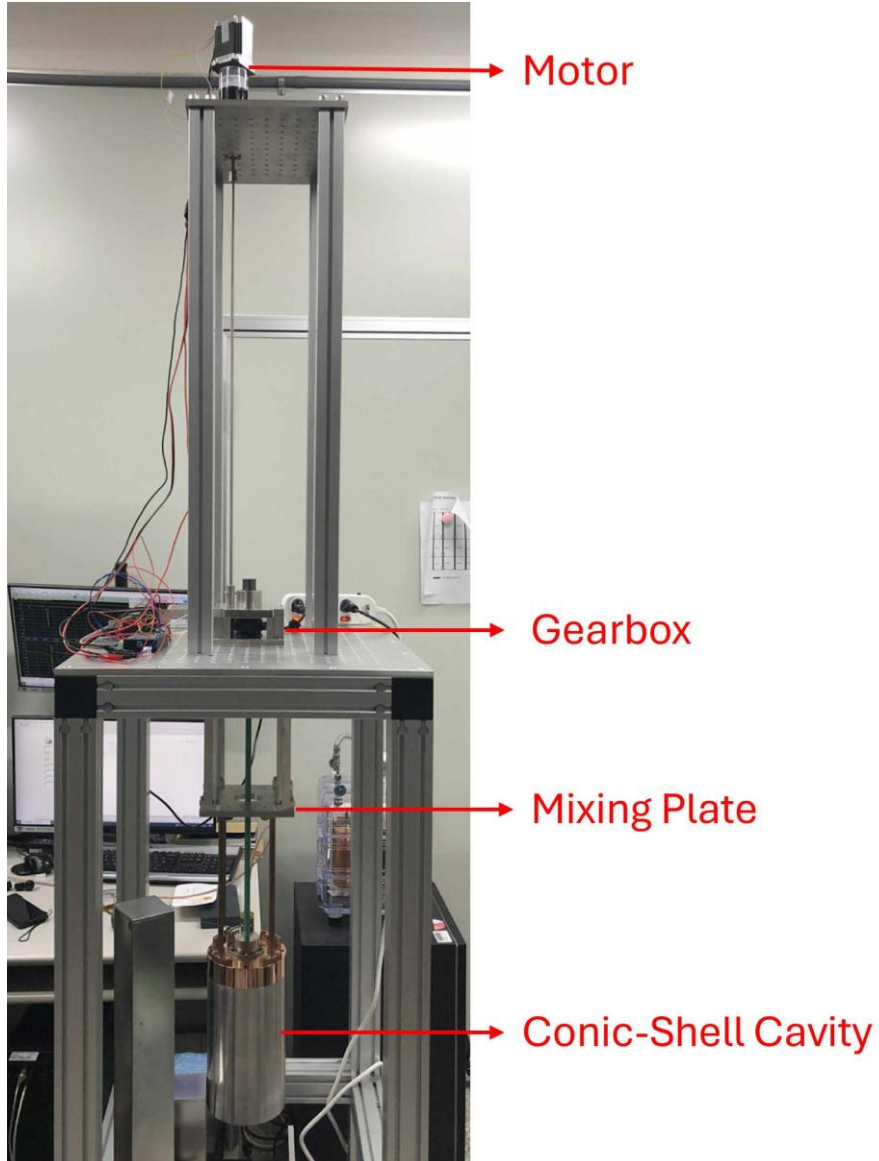
Features

- TM_{010} mode exists between two cones
- Frequency tuning of 200 MHz via inner position and different angles of cones
- Maximize available space in the magnet bore
- $f_{TM010} \sim 4.75 \text{ GHz}$, $V \sim 1.66 \text{ L}$
- Form factor C_{010} : ~ 0.73
- TE modes are away from TM_{010}
- $\lambda/4$ RF choke to reduce radiation loss from gaps

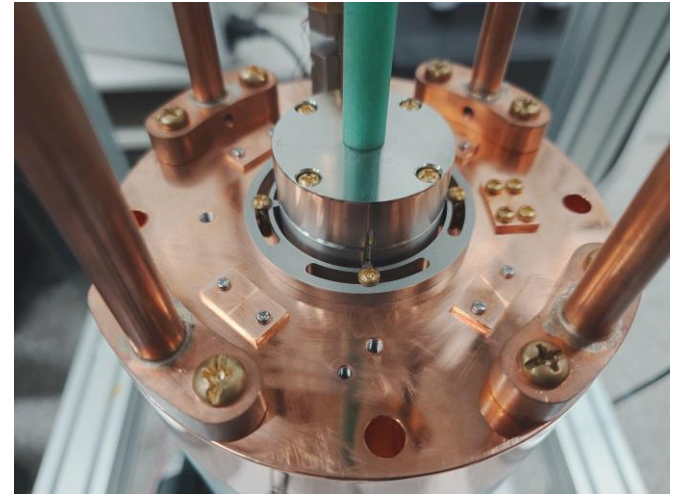
Material	R	w	h	f_{TM010}	θ	ϕ	d
Cu coated s.s.	64 (mm)	31.35 (mm)	200 (mm)	4.785 (GHz)	3.5 (deg)	3.55 (deg)	1.5 (mm)

Test Setup

Side view



Top view



See Ching-Fang Chen's talk

Future Directions Yet to Be Defined

Cavity:

- Superconducting cavity
- Plasma cavity
- Multi-cell cavity
- ...

Signal receiver:

- Squeezed state receiver
- Bolometer
- Qubit
- ...

Summary

- TASEH is a domestic collaboration, targeting a search range of 8 – 20 μeV (2 – 5 GHz).
- Achieve first results in 2022
 - 19.4687 – 19.8436 μeV (4.707 50 – 4.798 15 GHz, ~ 90 MHz search range)
 - Excludes models with the axion-two-photon coupling $g_{a\gamma\gamma} \geq 8.1 \times 10^{-14} \text{ GeV}^{-1}$
(~ 11 times above QCD KSVZ model limit, the world's best axion limit in this range)
- Preliminary result from 2-GHz setup with 9-T magnet, 4-L cylindrical cavity, and quantum-limited amplifier at 6 T
 - 8.916 – 9.011 μeV (2.155 – 2.179 GHz, ~ 24 MHz search range)
 - Excludes models with the axion-two-photon coupling $g_{a\gamma\gamma} \geq 1 \times 10^{-15} \text{ GeV}^{-1}$
(~ 3 times above QCD KSVZ model limit, the world's best axion limit in this range)
- Almost ready for 2-GHz physics run at 9 T
- Gradually prepare for 5-GHz physics run with conic shell cavity

Thanks to Funding Supports



Thanks to TASEH Members



Current members:



Yuan-Hann Chang
AS



Yung-Fu Chen
NCU



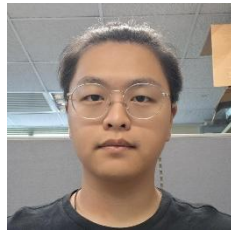
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Thank you for listening.

Comment/question?