Search for Axion Dark Matter with the TASEH experiment

Taiwan Axion Search Experiment with Haloscope

Axion 2025
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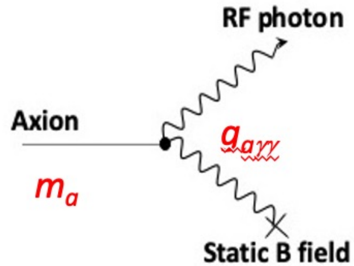
Academia Sinica

Axions as a Dark Matter candidate:

- Axion is stable.
- Axion is electric neutral
- Axion does not participate strong interaction
- Axion can be produced athermally in large quantity at early universe.

Axion can interact weakly with normal matter. One possibility is Axion-photon interaction:

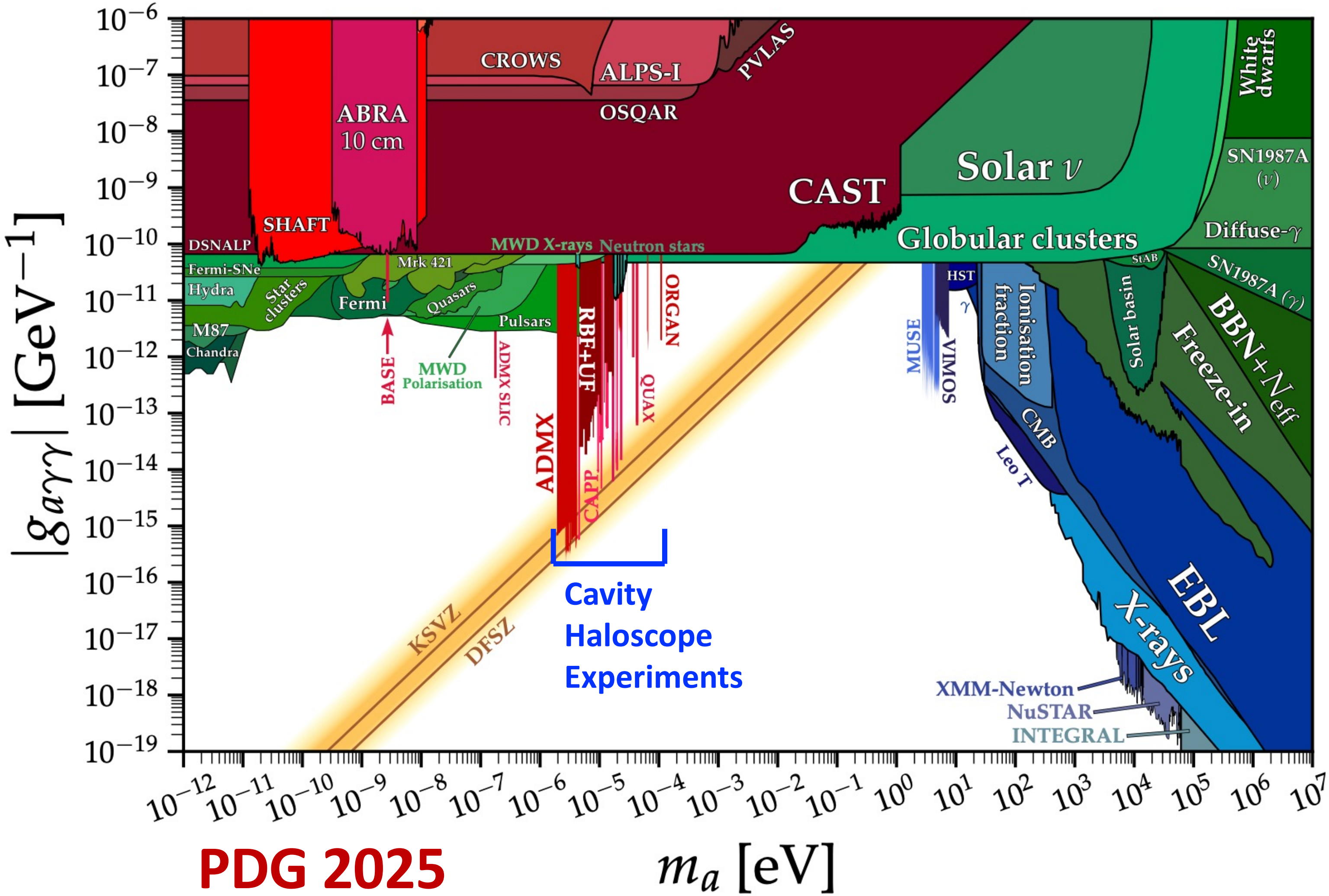


$$\text{Strength} \propto g_{a\gamma\gamma}\phi_a \vec{E}\cdot\vec{B}$$

Based on the assumption that DM is made of Axions, P. Sikivie proposed several search methods. The most sensitive of them is the "Haloscope" experiment.

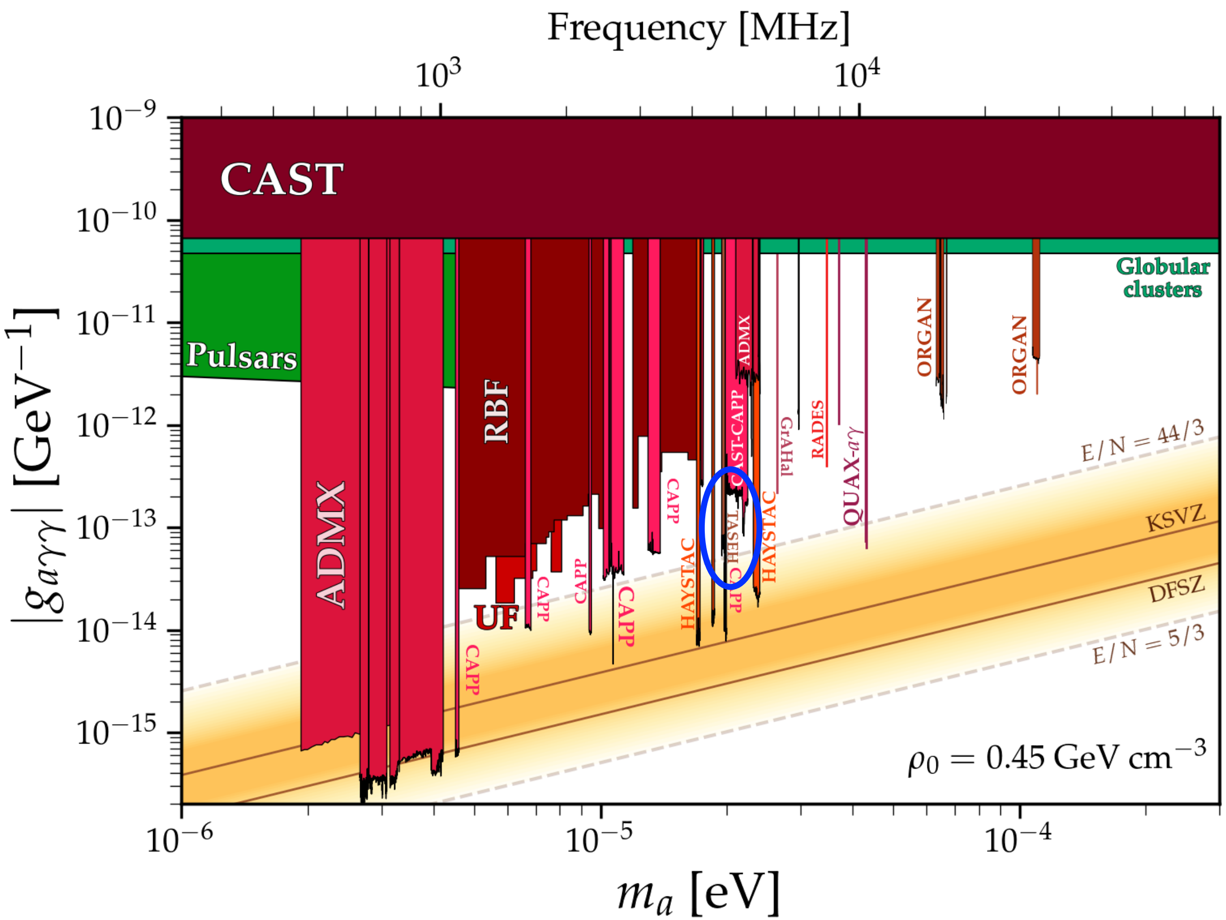
P. Sikivie, PRL 51, (1983) 1415
P. Sikivie, PRD 32 (1985) 2988

Axion searches is a fast growing field

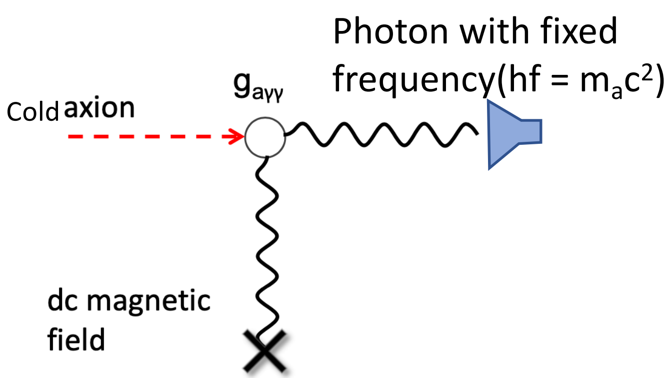


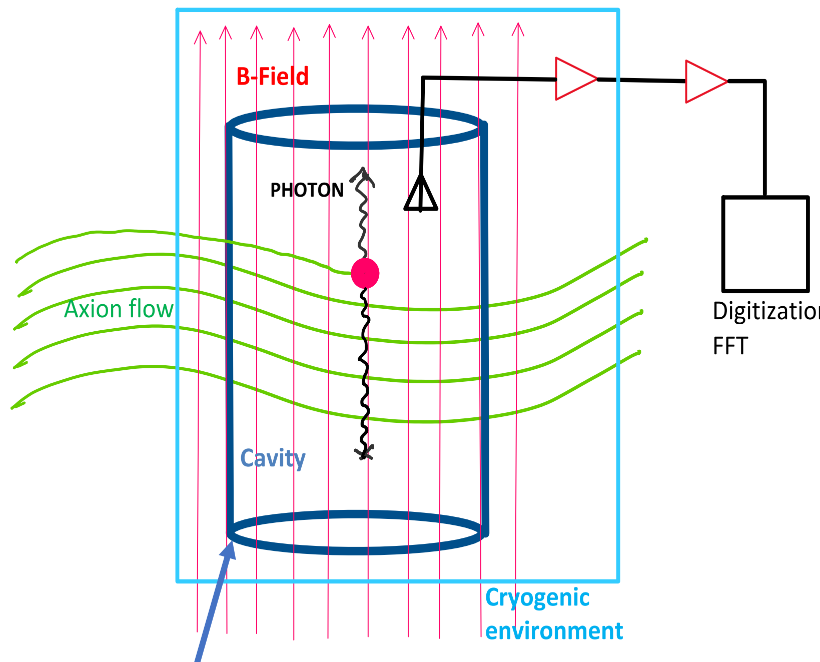
PDG 2025

- ADMX will soon scan from 500MHz – 2GHz down to DFSZ benchmark model
- Haystack and CAPP set limits close to KSVZ model in various frequencies



Search for light Axion dark matter with a Haloscope





A cavity with resonance frequency hf = $m_a c^2$ is needed to trap the photon long enough to be picked up by the detector

Experimental considerations:

- **TM010 mode of the resonance cavity provides the highest $\vec{E} \cdot \vec{B}$**
- **Environment temperature << quantum limits: $T_{env} \ll h\nu \sim 250mK$**
- **Resonance frequency of the cavity should be tunable, such that we can scan through a range of frequencies for the Axions.**

P. Sikivie, PRL 51, (1983) 1415
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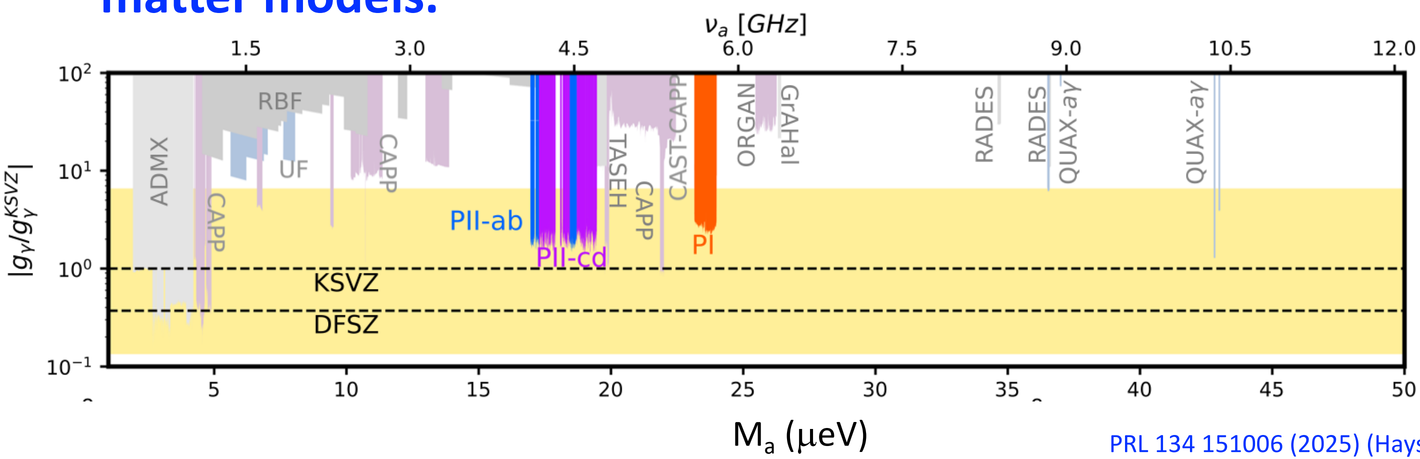
Cavity Haloscope search for Axions and ALP is the most sensitive method in the mass range from 1 – 100 μeV

- **Based on the assumption that dark matter is made of Axion/ALP.**
- **Mass range limited by the physical dimension of the cavity:**
  cavity diameter ~ λ ~ $h/m_a c$ ➔ m_a ~ 100 μeV/λ(cm).
    - λ < 1cm : difficult to build the cavity with tuning mechanism.
    - λ > 1 m : difficult to find large magnet with strong field.

  ➔ 1 μeV < m_a < 100 μeV is the mass range that cavity haloscope dominate.

This is also the mass range favored by post-inflation dark matter models.



PRL 134 151006 (2025) (Haystack)

Power output from the cavity due to Axion conversion at resonance:

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}\phi_a \vec{E}\cdot\vec{B} \rightarrow P_{sig} \propto g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2}\omega B_0^2 V C_n Q_i$$

$g_{a\gamma\gamma}$ = Axion photon coupling constant

ρ_a = local density of axion darkmatter

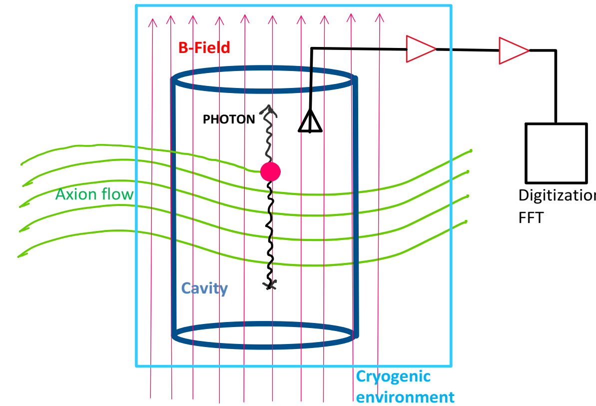
m_a = mass of the axion

B_0 = Magnetic field

V = volume of the cavity

$C_n = \frac{\left(\int B\cdot E_n dV\right)^2}{B_0^2 V \int |E_n|^2 dV}$: How much the resonant *E* field aligns with the extern *B* field.

$Q = \frac{\omega}{\Delta\omega}$. The quality factor of the cavity.



P. Sikivie, PRL 51, (1983) 1415

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Noise Poser (Johnson-Nyquist noise):

$$\sigma_N = k_B T_{sys}\sqrt{b/t}$$

T_{sys} = System temperature

b = bandwidth

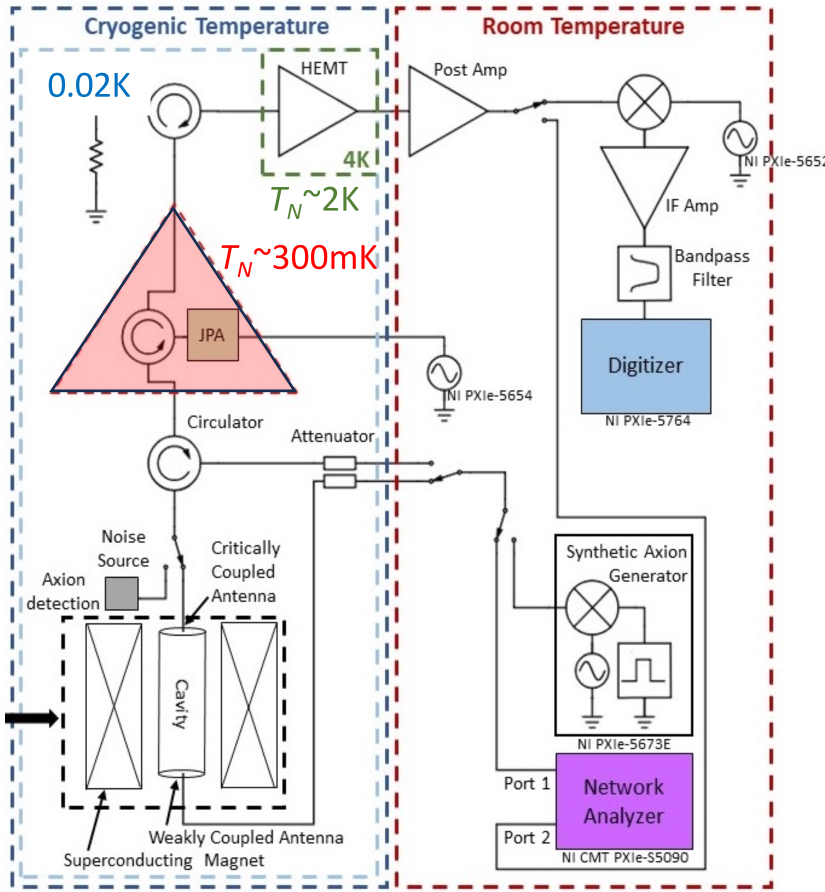
t = data taking time

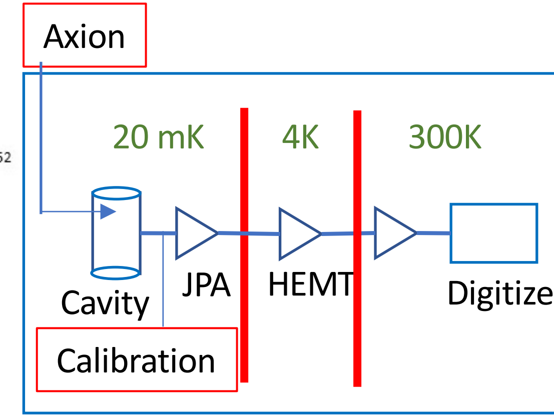
Search for Axion : P_{sig}/σ_N exceed certain threshold.

Figure of Merit (sensitivity of $g_{a\gamma\gamma}$ limit) : $\frac{B\sqrt{V\,C}\;\sqrt[4]{Q\,t}}{\sqrt{T_{sys}}}$

TASEH Design configuration:

This setup can be adapted to quantum computer development, by replacing the cavity with a superconducting qubit.

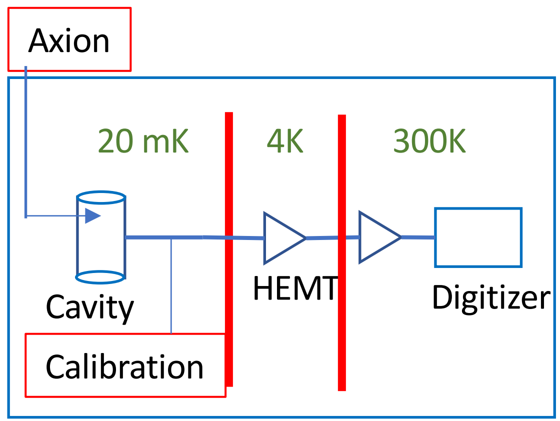




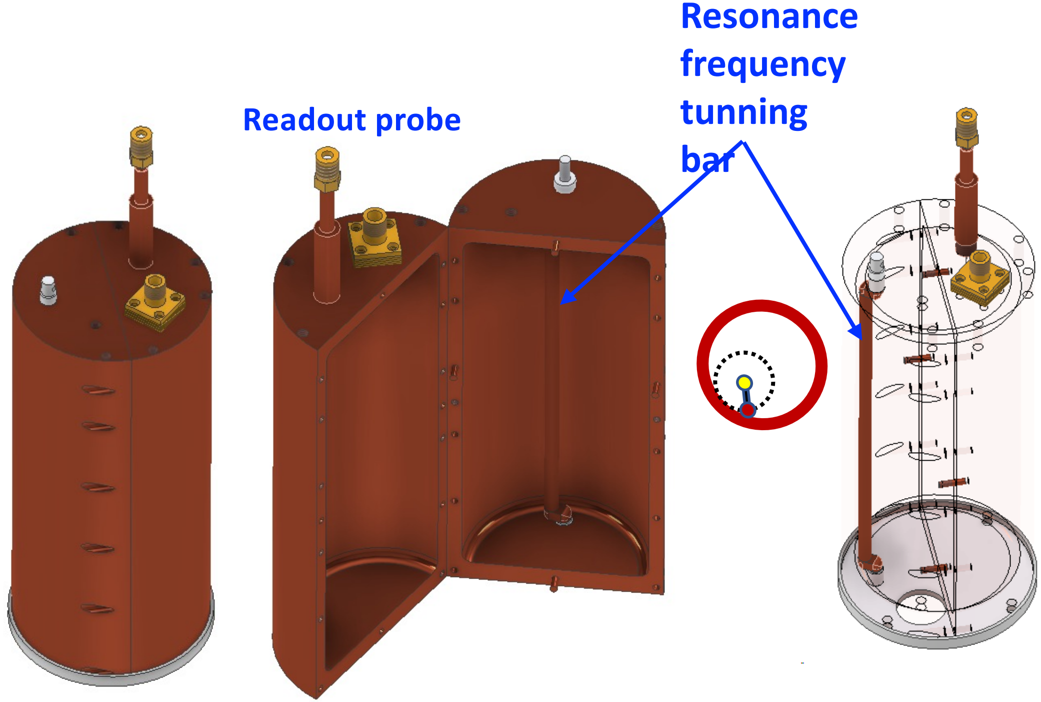
Simplified readout schematics

Except for JPA, a limited version of the readout chain, cryosystem, and instruments exists in a quantum qubit lab.

TASEH DATA Taking in 2021:
CD102 run (without JPA)

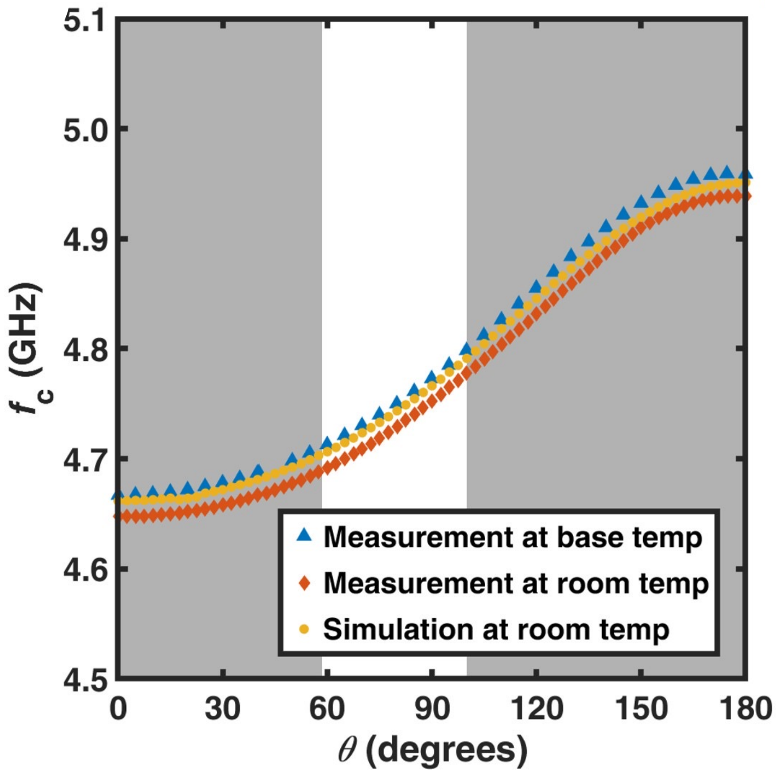


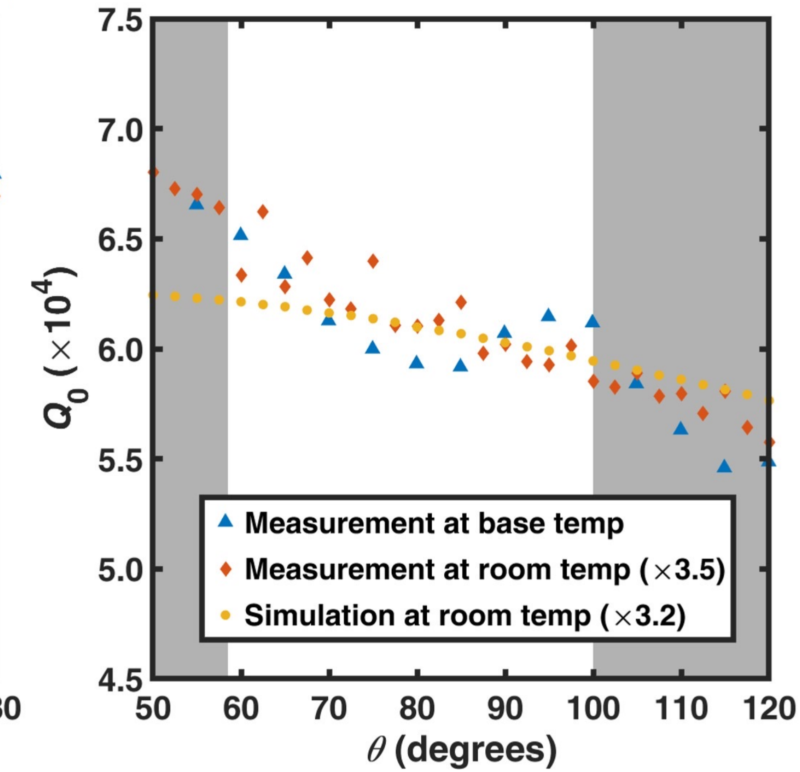
The Cavity



Volume = 0.23 ℓ

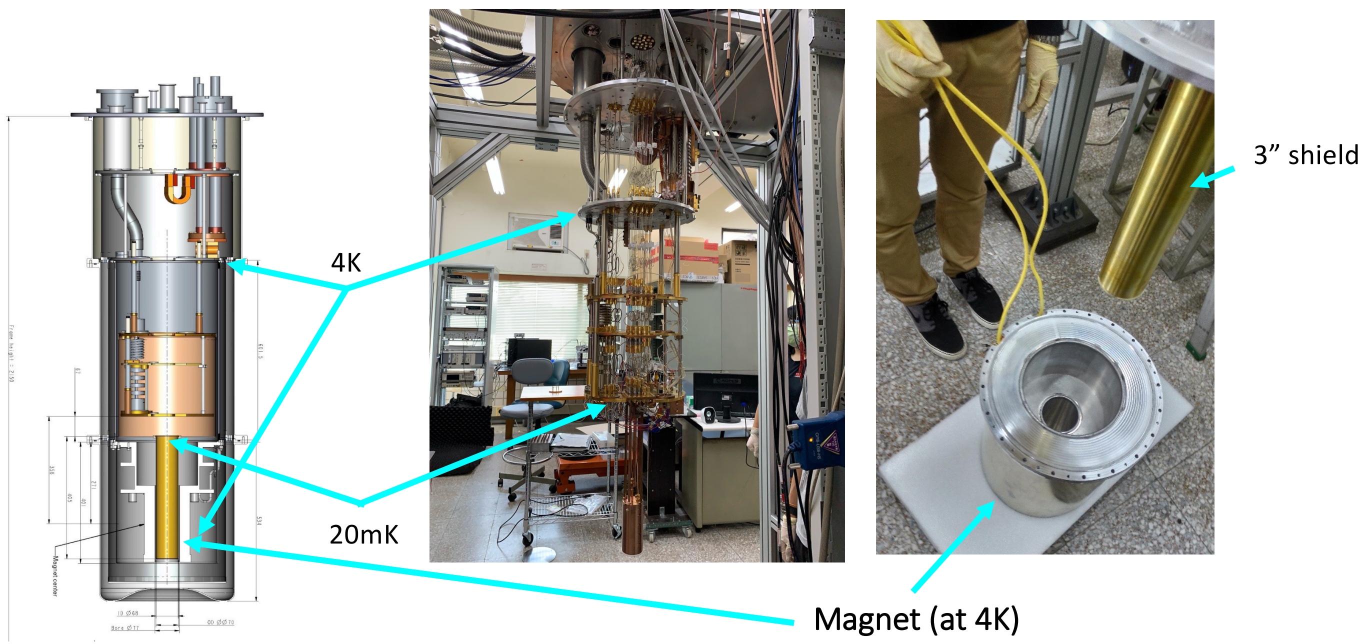
Mode map and quality factor





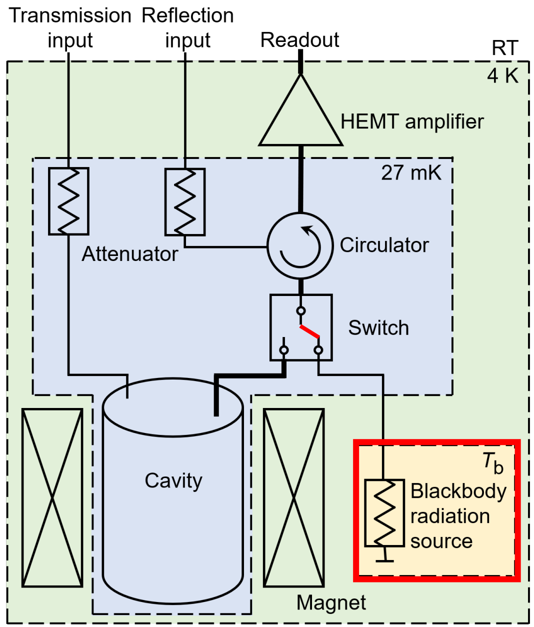
The Dilution Refrigerator and the Magnet

- The existing DR and Magnet system in a Quantum computer lab: It is being used for Qubit studies. We get about 50% of the operation time.
- **Maximal magnetic field = 8T**.
- Bore diameter: 3 inch – ***f*$_{res}$ ~ 5 GHz**
- **Cavity temperature: 20mK**

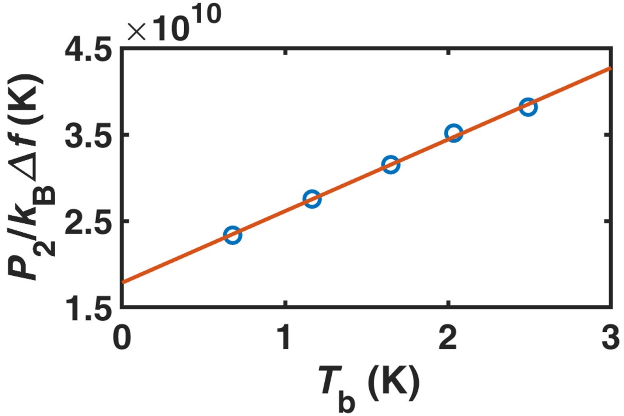


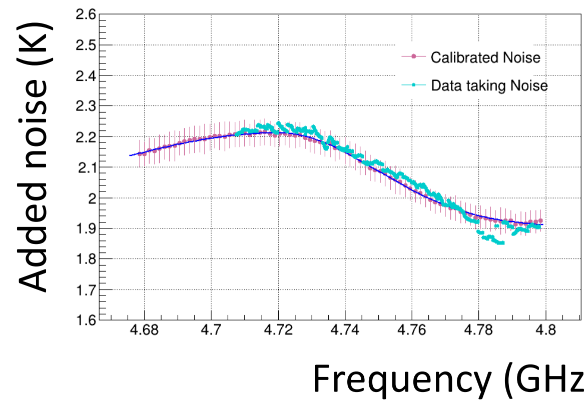
Readout and Calibration

- The calibration was done to obtain the added noise T_A and gain G of the application chain
- Added noise: primary contribution from 1st stage amplifier, i.e., HEMT in our system
- T_A and G were extracted by fitting the output power as a linear function of temperature of the heat source: $P_{out} = G \cdot (T_b + T_A)$

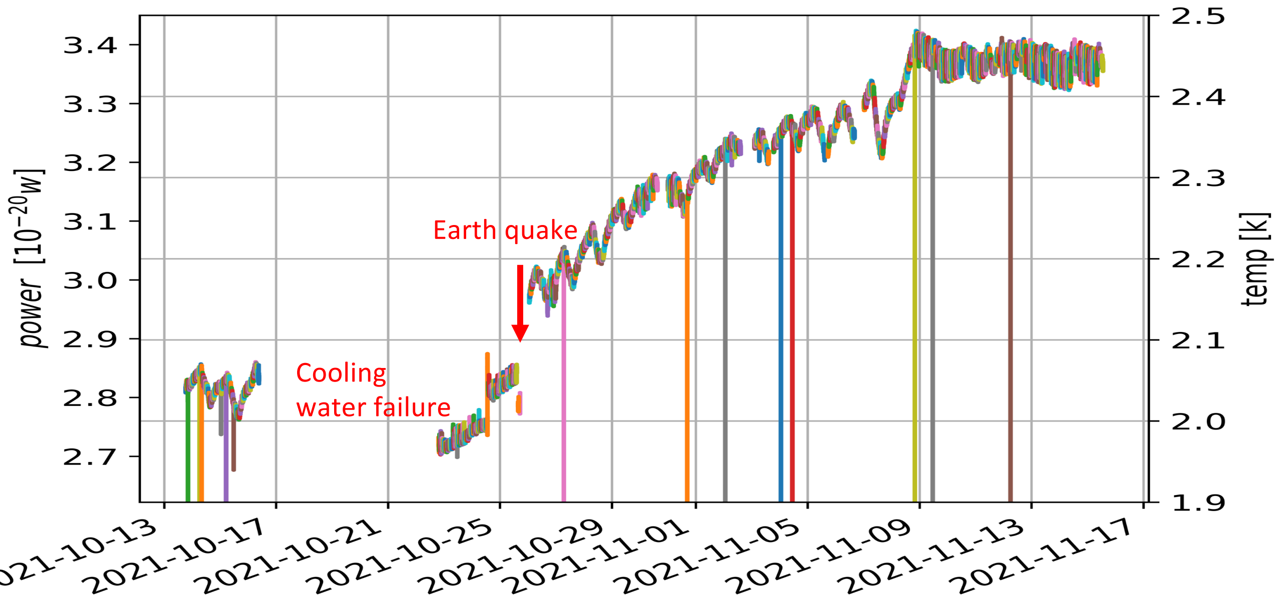


T_{sys} ~ 2K (without JPA)





Physics Run in Oct. - Nov. 2021

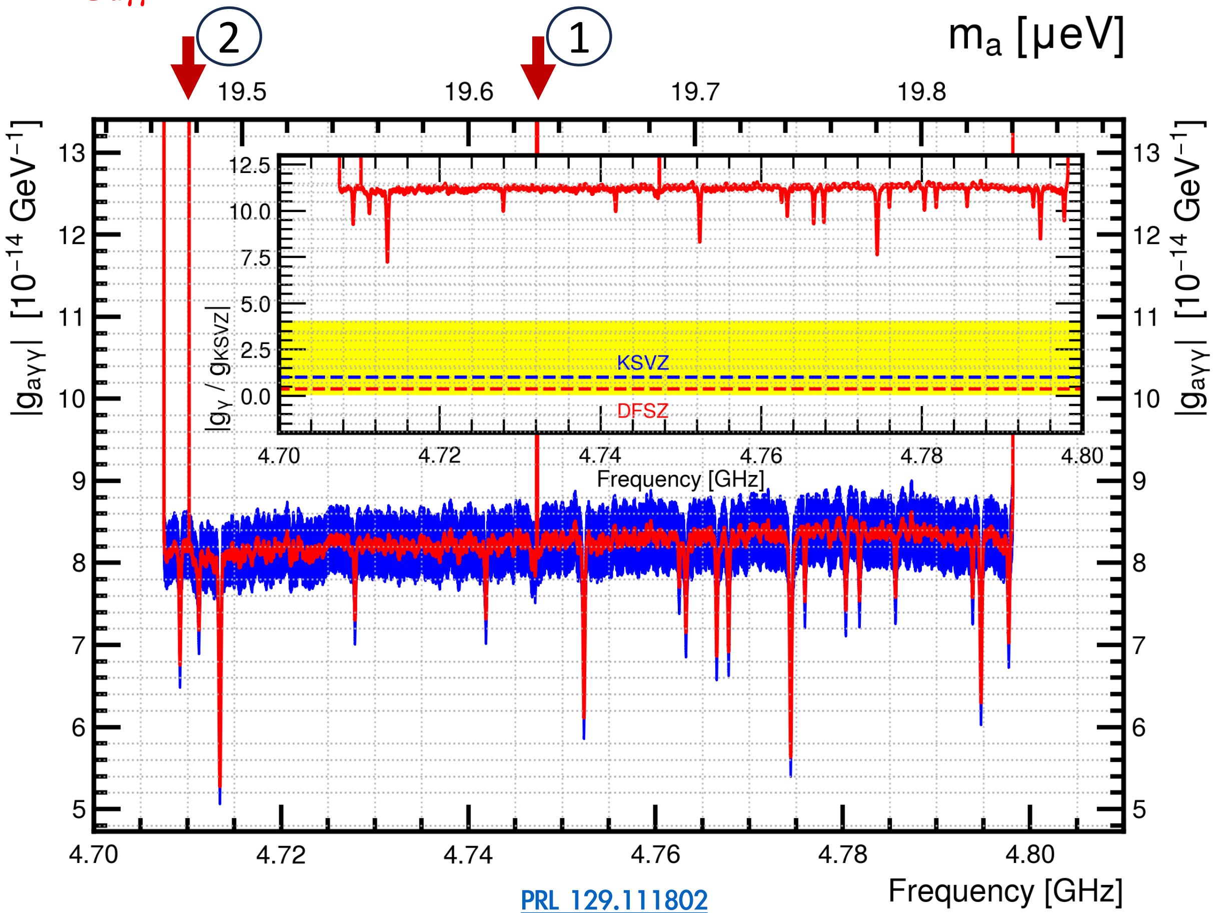


Every colored slice shows the power output of one step (~110 kHz)

- ~30 min of data taking per step. ~1000 steps
- **Daily variation due to diurnal temperature variation.**
- **Overall power increases due to noise level changes with frequency.**
- **90MHz range covered in 1 month of data taking.**

No signal found between 4.70750 and 4.79815 GHz, corresponding to 19.4678 < m_a < 19.8436 μeV.

We set $g_{a\gamma\gamma}$ limit at about 11 times the KSVZ benchmark model in this range.



PRL 129.111802

Rescan:

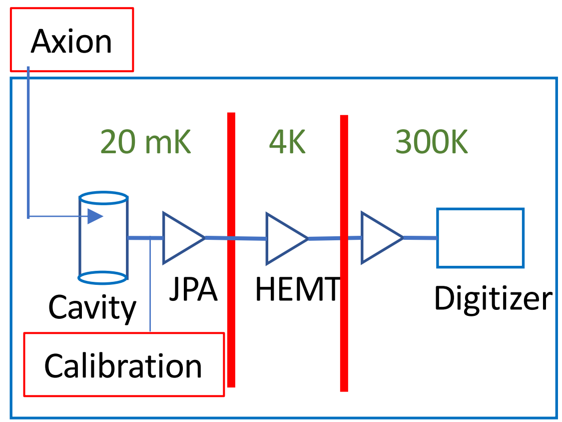
We observed 22 frequencies with high power "signals":

1. Due to statistical fluctuation.
2. Pick up external Noise
3. Photon conversion from Axion or other new particles.

Rescan the frequency step of these "signals" every 10MHz

1. 20 of them disappeared after rescan → statistical fluctuation.
2. One external source was identified by a portable microwave detector, it was from the data taking computer. → **no coupling limit set.** ①
3. **One signal remains high after 15 rescan (30min each).**
   - Signal remain high in 13 rescan **after power down the magnet**.
     → excluded as a Axion signal
   - **No coupling limit set.** ②
   - Remains a Dark Photon candidate → See Prof. Jinmian Li's presentation.

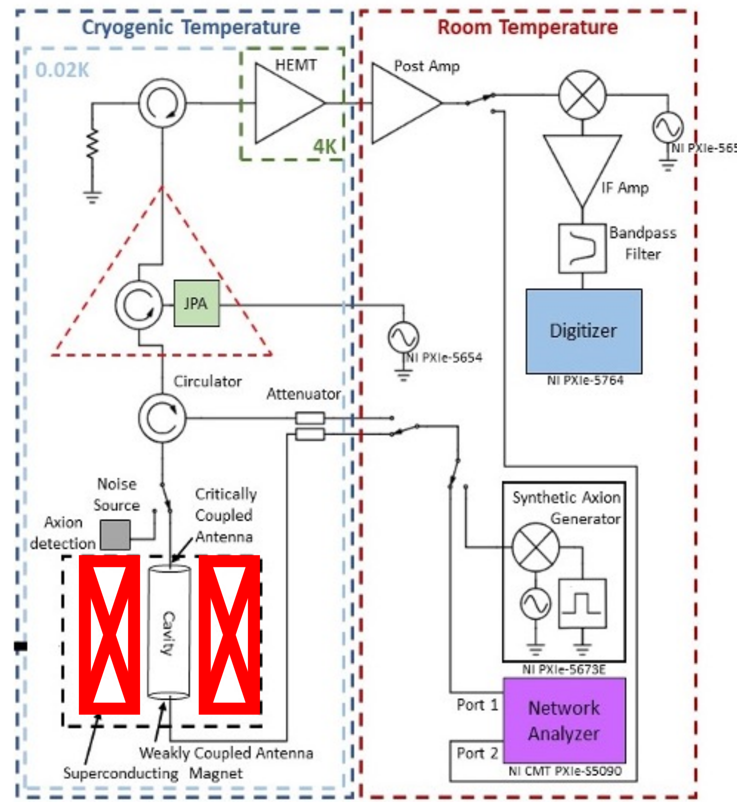
Upgrade since CD102



Key upgrade item: Magnet

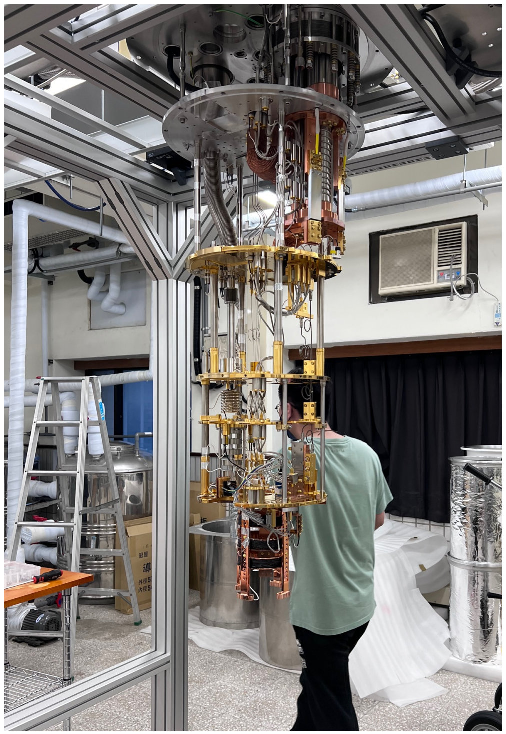
Figure of Merit: $\dfrac{B\sqrt{V\,C}\;\sqrt[4]{Q\,t}}{\sqrt{T_{sys}}}$

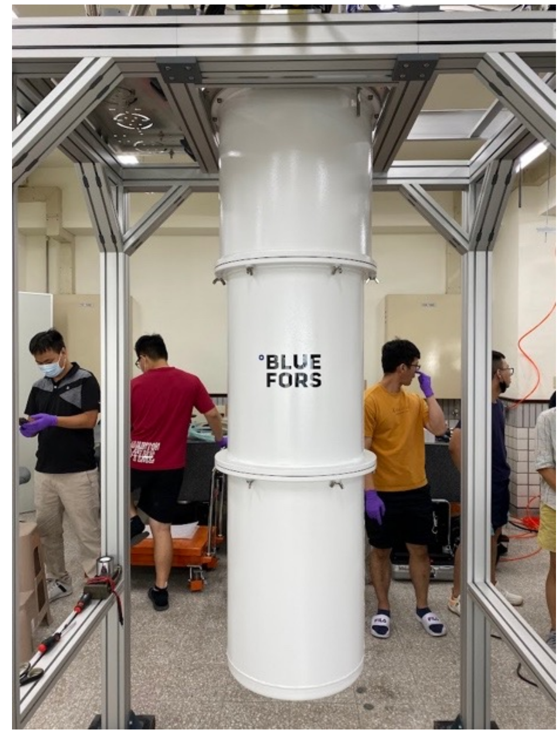
B: magnetic field, *V*: volume of the cavity, *C*: form factor, T_{sys} : System noise, *Q*: quality factor, *t*: data taking time



A new Dilution Refrigerator with a new magnet is procured:

- 9T field (9/8 times in sensitivity)
- 6 inch bore diameter (2x previous magnet)

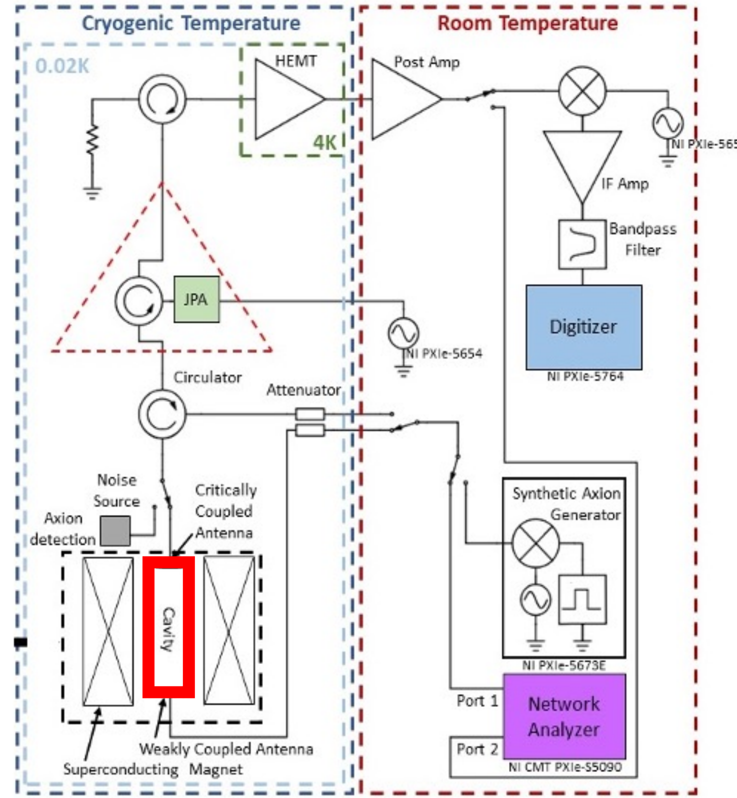




Key upgrade item: Cavity

Figure of Merit: $\frac{B\sqrt{V\,C}\ \sqrt[4]{Q\,t}}{\sqrt{T_{sys}}}$

B: magnetic field, ***V*: volume of the cavity**, *C*: form factor, T_{sys} : System noise, *Q*: quality factor, *t*: data taking time

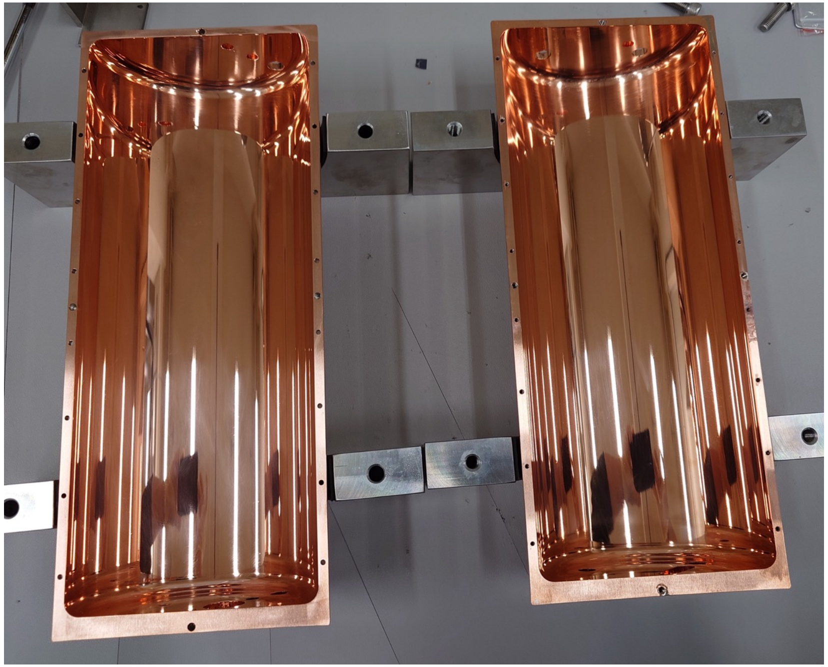


New cavity targeting 2 – 3 GHz:

- 2x in every dimension.
- 1/2 Resonance frequency
- Targeting 8-10 μeV Axions

Challenge:

- Copper coated Stainless Steel instead of pure copper.
- High quality copper coating is surprisingly not readily available in Taiwan.
- Weight and thermal conductivity considerations.

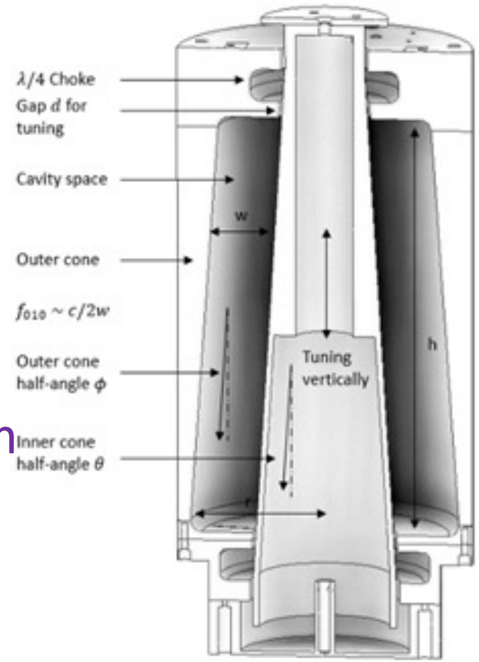


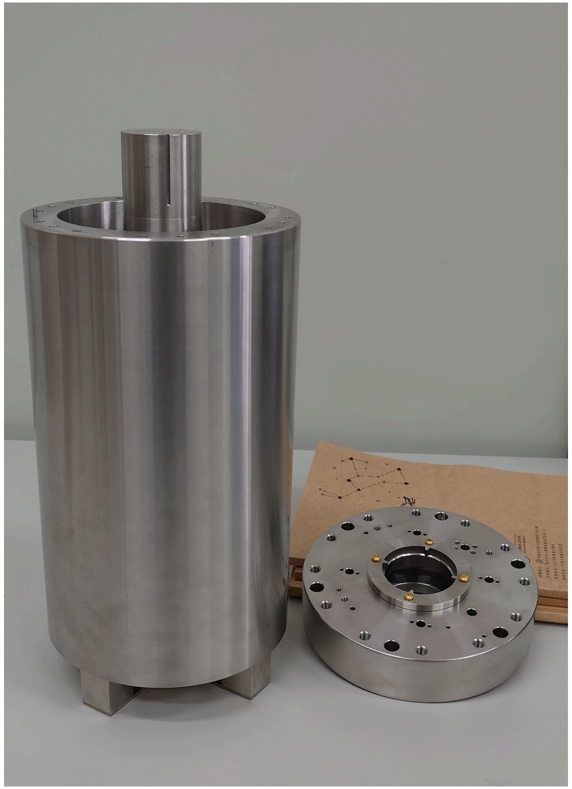
Prototyping a new cavity concept for 4.5-5 GHz

- Cavity of double-cone shape.
- 7x in volume
- Same resonance frequency as in CD102.
- Targeting 16-20 μeV Axions

Challenges:

- Alignment: better than 100μm concentric.
- Vertical motion inside the DR
- Field leakage
- Unexpected extra modes.
- Weight and thermal considerations

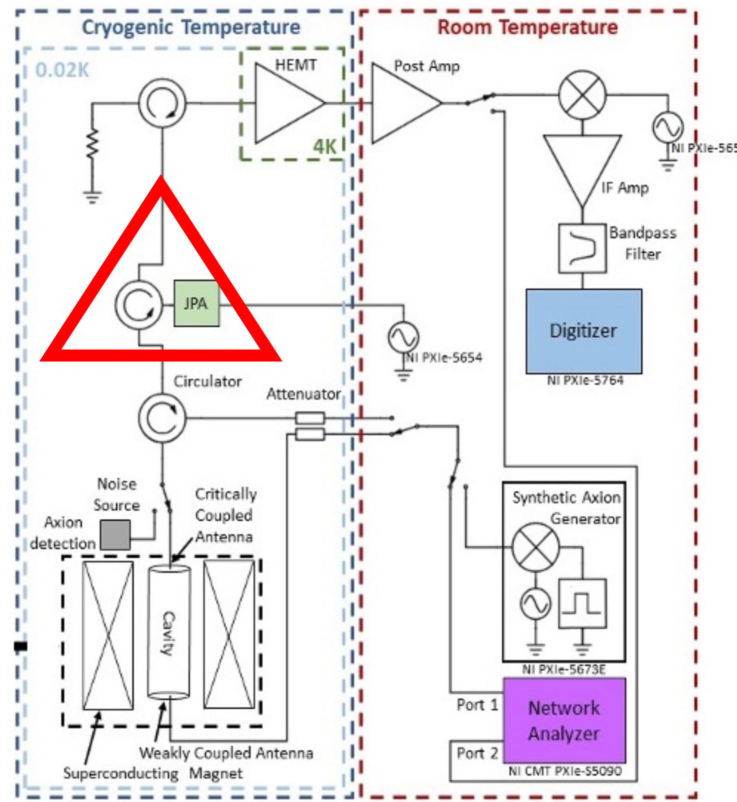




Key upgrade item: Quantum limited amplifier (JPA)

Figure of Merit: $\dfrac{B\sqrt{V\,C}\;\sqrt[4]{Q\,t}}{\sqrt{T_{sys}}}$

B: magnetic field, *V*: volume of the cavity, *C*: form factor, T_{sys} **: System noise**, *Q*: quality factor, *t*: data taking time

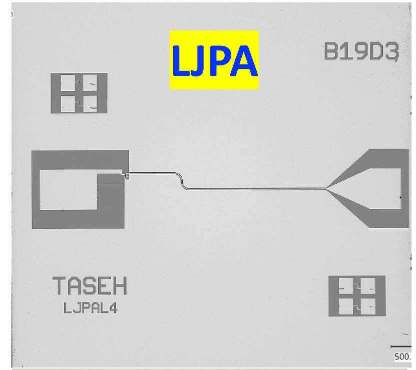


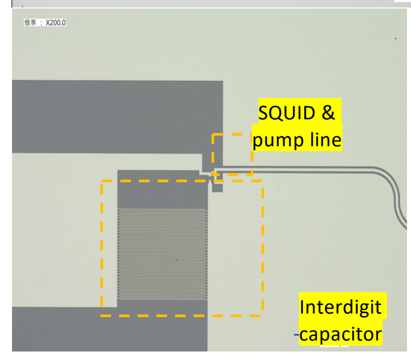
Development of the Josephson Parametric Amplifier (JPA)

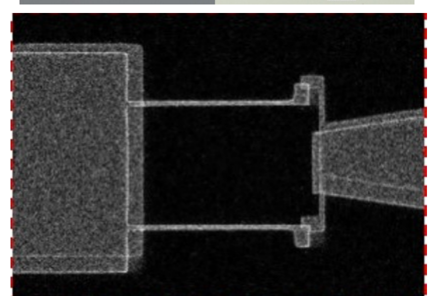
- **Currently achieved:**
  - FDJPA: 4-5 GHz, 300mK system noise (~1.2 photon), 3MHz bandwidth.
  - LJPA: 2-3 GHz, 240 mK system noise (~2 photons), 10MHz bandwidth.
  - **Few hundred MHz operational range.**

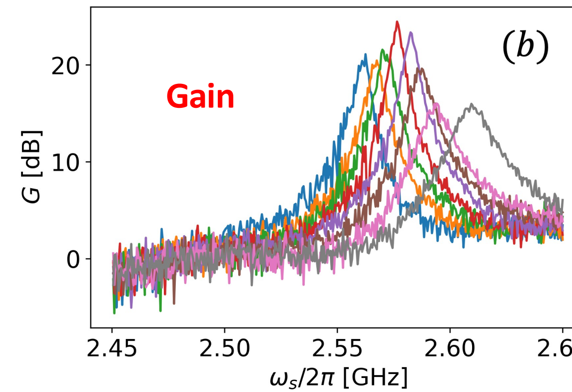
Development plan:

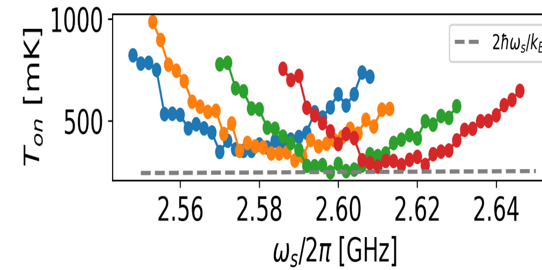
- Wider bandwidth (~100MHz) LJPA, with 500MHz operational range.
- Magnetic shielding: reduce magnetic field from ~2000 Gauss to 0.001 Gauss.
- Squeezed vacuum technology to reach noise level below the quantum limit.



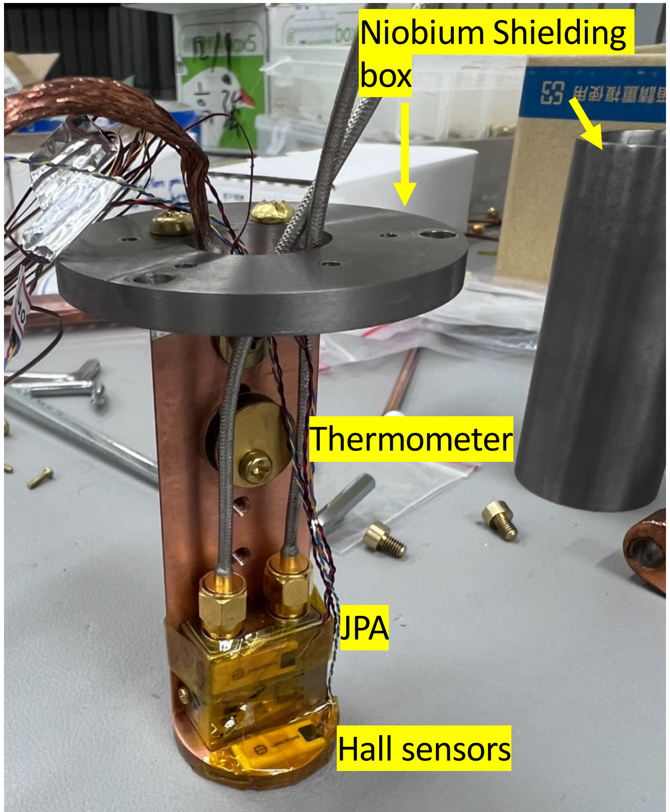




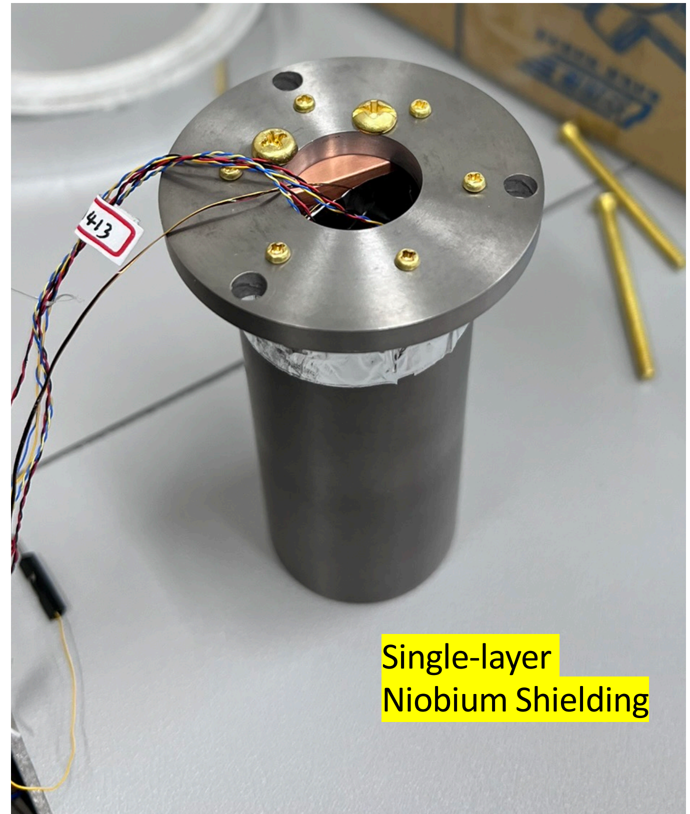




Magnetic shielding



How JPA sit inside the shielding box.



Assembled shielding box.

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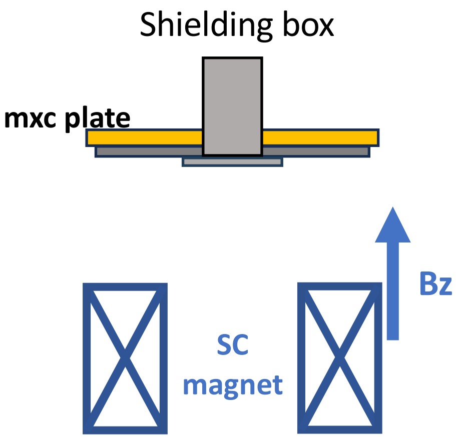
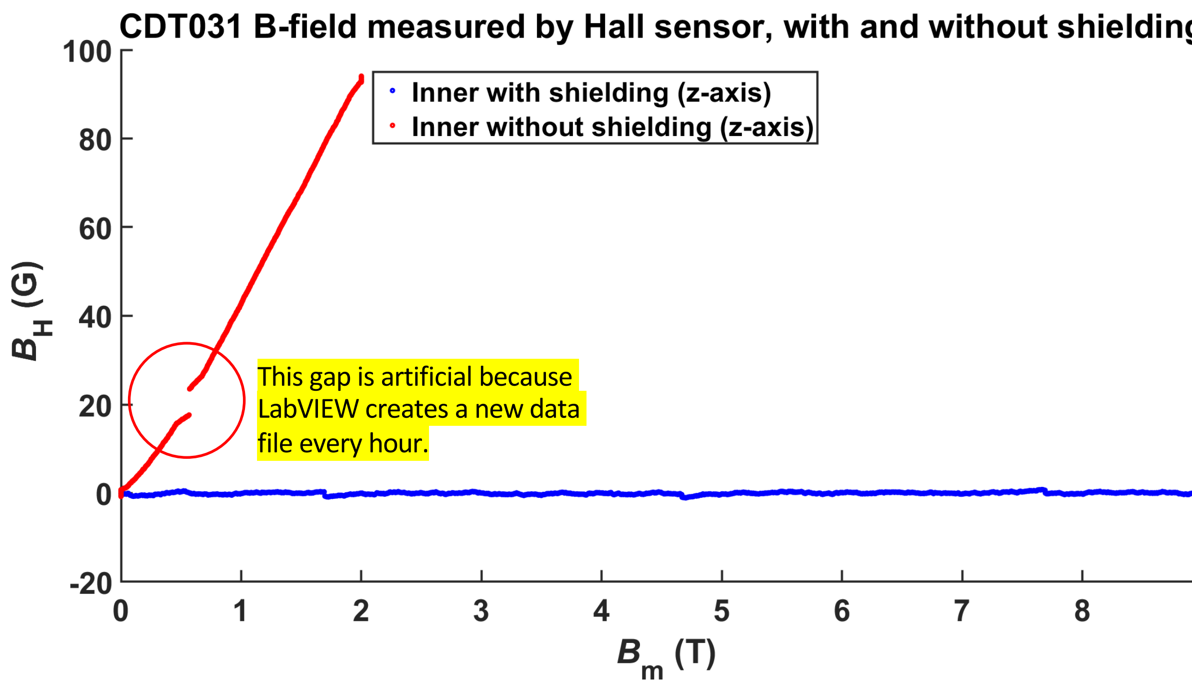
Magnetic shielding result



Shielding of setup



Conclusions:

1. TASEH collaboration conducted one Axion Dark Matter search in 2021, setting axion-photon coupling constant exclusion limit at ~11x KSVZ model, in the range of **$19.4678 < m_a < 19.8436$ μeV.**
2. Upgrade of TASEH include:
    1. Higher B field
    2. Larger volume
    3. Low noise amplifier

    Expect to improve the sensitivity to ~1.5 x KSVZ
3. We are conducting the experiment to scan the range 2 – 2.3 GHz.

Current members of the TASEH team:

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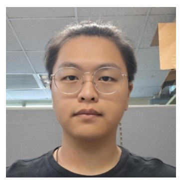

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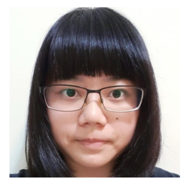

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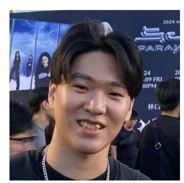

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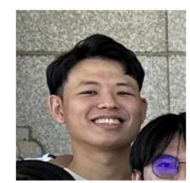

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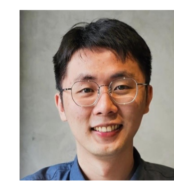

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