Search for Axion Dark Matter with the TASEH experiment

Taiwan Axion Search Experiment with Haloscope

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Axion as a Dark Matter candidate

Axion is the consequence of the Peccei-Quinn symmetry (breaking), proposed to solve the strong CP problem:

- Axion is a pseudo-scalar particle (spin 0, parity -1).
- Axion couples to Standard Model particles very weakly.
- Expected to be produced with large quantity in the early universe.

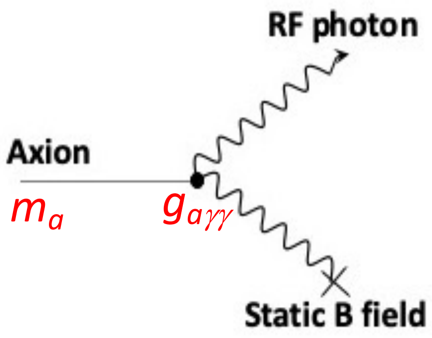
Axion is also a good candidate of Dark matter:

- Very stable
- Very weakly interact with SM particles
- Low mass (μeV to meV) but cold by production.

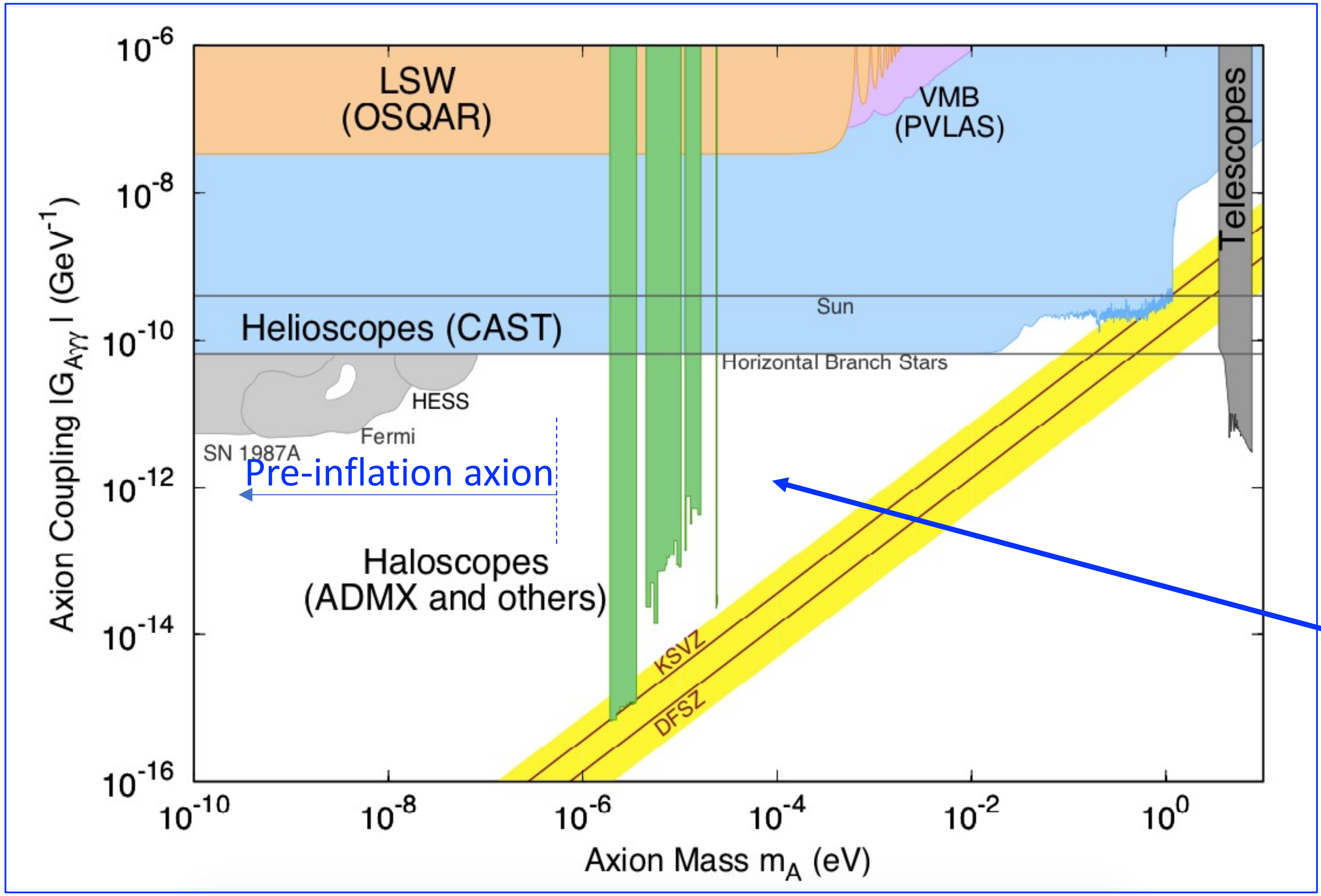
The Axion can interact with photons through the effective Lagrangian:

$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}\phi_a \vec{E} \cdot \vec{B}$$

➔ Only two parameters:
mass of axion (m_a) and the coupling constant ($g_{a\gamma\gamma}$)



Current status of Axion search:



Search Strategies:

- Haloscope (with Dark matter assumption)
- Helioscope
- Light-through-the-Wall
- …

Lots of room for new experiments

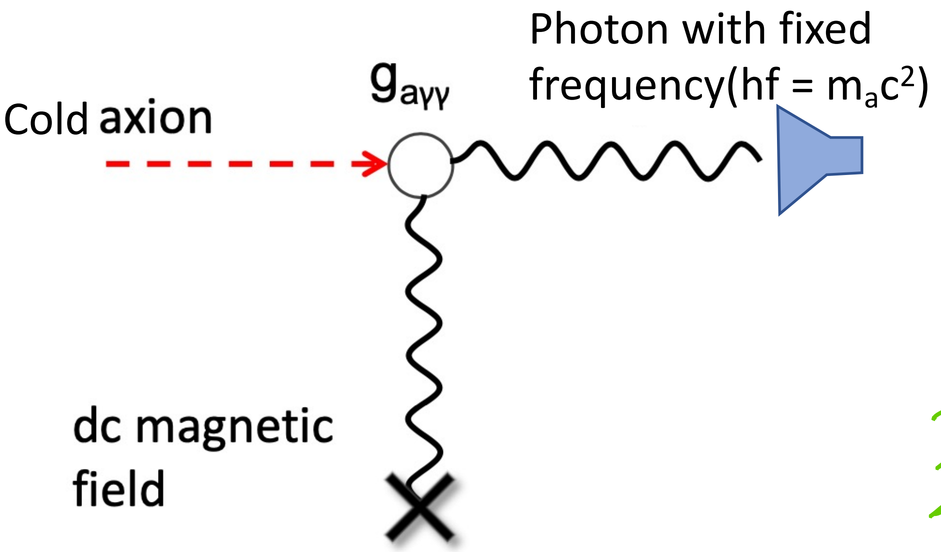
We considered to conduct a search with limited resources:

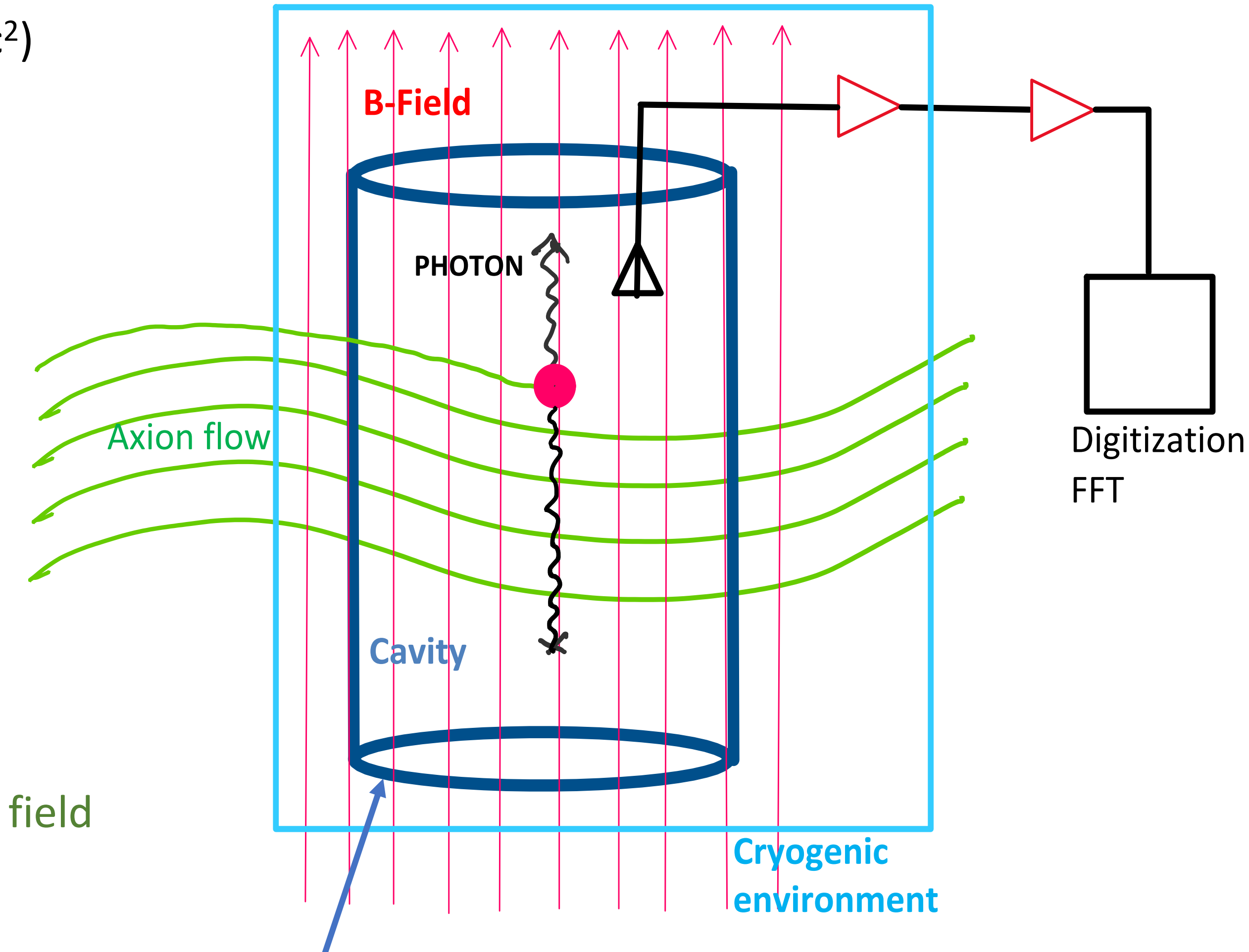
- Small scale (~ 100 m^2 lab. room)
- Low cost (~1 million US$)
- With existing instruments
- **Compatible sensitivity**

The choice we made:

Haloscope experiment similar to ADMX but smaller (Very close to the pioneer Haystac experiment)

Search for light Axion dark matter with a Haloscope





Cold, light Axion:

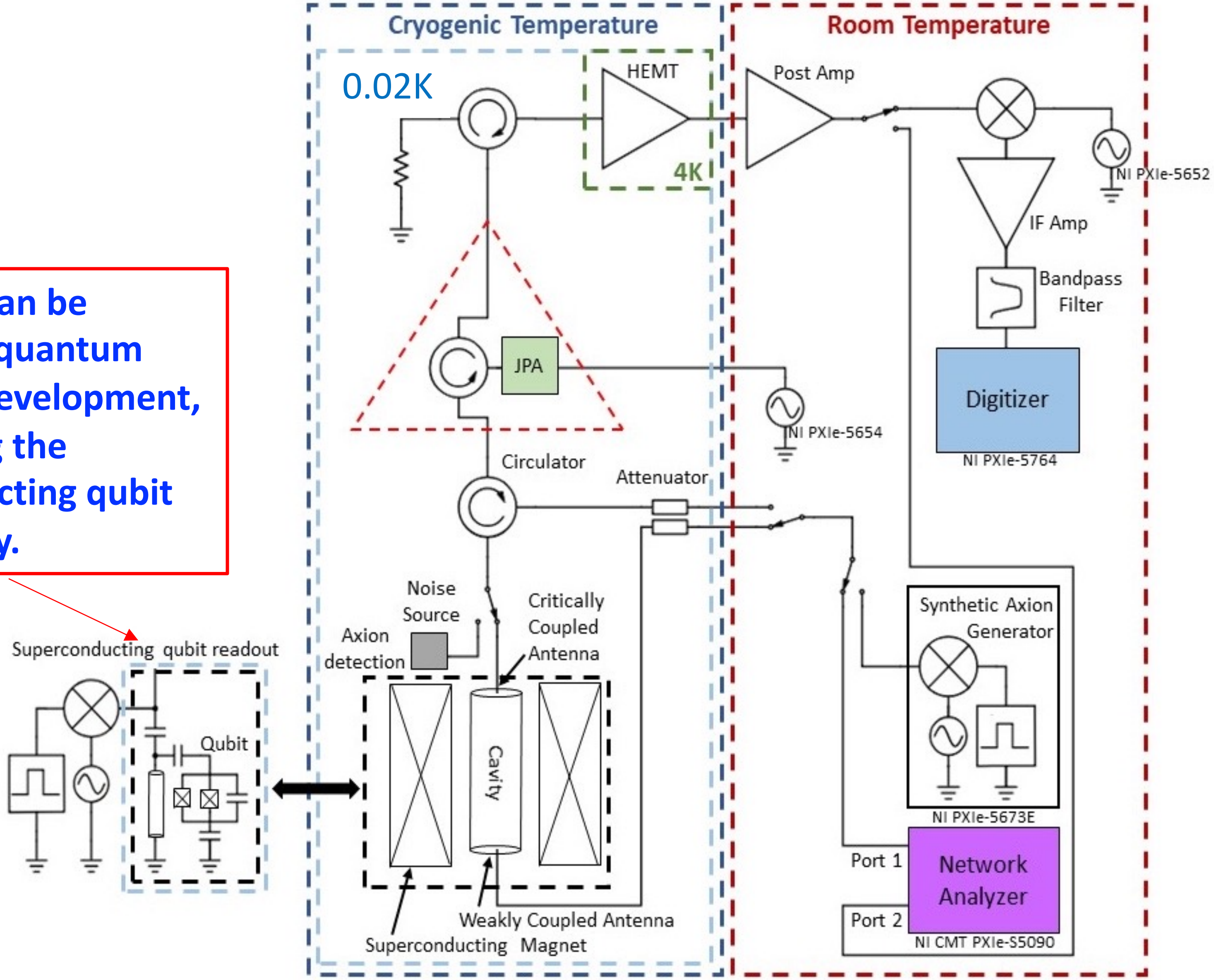
- Number density is large
- Long wavelength
- Coherent within the detector
- Look like a classical oscillating background field (thus called "halo")

In this scheme, kinematic energy of axion is small, and the produced photon has a wavelength corresponding to the mass of the axion.

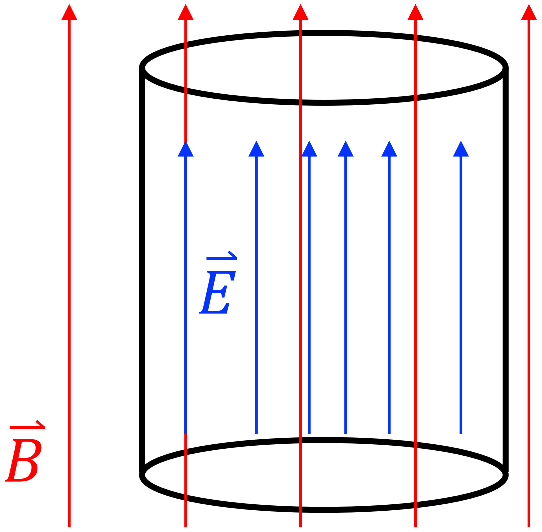
A cavity with resonance frequency hf = $m_a c^2$ is needed to trap the photon long enough to be picked up by the detector

System design configuration:

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



Except for JPA, the readout chain, cryosystem, and instruments exists in a Qubit research lab. We are able to use ~50% of their time to do the experiment.

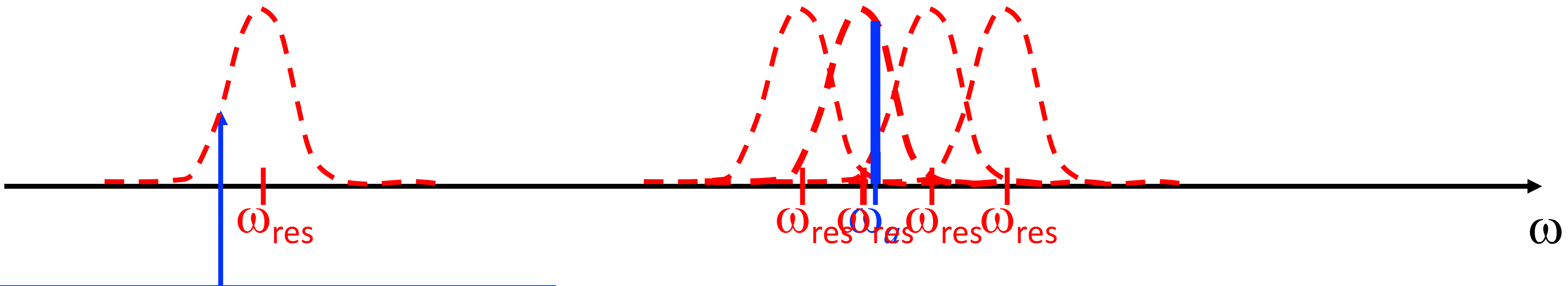


Detector:

- A cavity with tunable resonance frequency.
- Use a resonance mode such that $\vec{E} \cdot \vec{B}$ is maximized. $(\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma}\phi_a \vec{E} \cdot \vec{B})$ – **TM010 mode**
- Tune the resonance frequency to search for the axion.

In the current experiment, every step moves ~100kHz, taking 30min. 10000 steps to reach 1GHz goal.

Scan the frequency range with a step size of ½ resonance width Δω



Response of the cavity when a signal of frequency ω is injected

Mass of the Axion

$m_a c^2 = \hbar\omega_a$

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

$$P_{sig} \propto g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \omega B_0^2 V C_n Q_i$$

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

ρ_a = density of axion darkmatter

m_a = mass of the axion

B_0 = Magnetic field

V = volume of the cavity

$C_n = \frac{\left(\int B\cdot E_n dV\right)^2}{B_0^2 V \int |E_n|^2 dV}$: The portion of the *E* field that is in the direction of *B* field in a particular resonance mode.

$Q_i = \frac{\omega}{\Delta\omega} = \omega \frac{U}{P}$. The quality factor of the cavity.

The noise power (integrated):

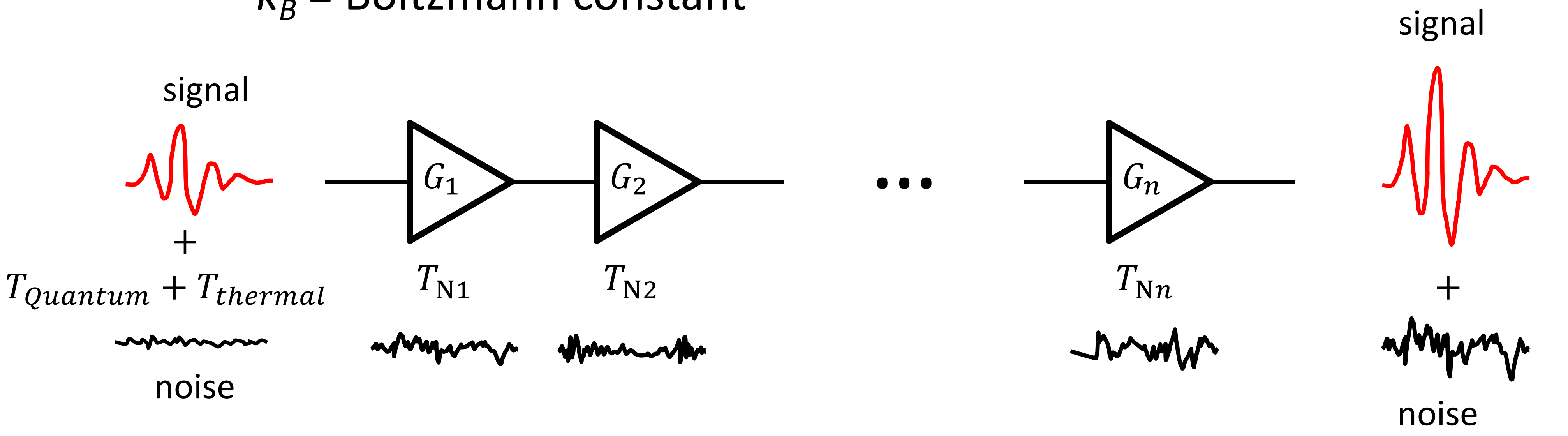
$$\boldsymbol{\sigma_N = k_B T_{sys}\sqrt{\frac{b}{t}}}$$

b = bandwidth of data taking instrument = 1kHz

t = Integration time

T_{sys} = System temperature (Noise equivalent)

k_B = Boltzmann constant



$$T_{sys} = T_{Quantum} + T_{thermal} + T_{N_1} + \frac{1}{G_1}T_{N_2} + \frac{1}{G_1 G_2}T_{N_3} + \cdots + \frac{1}{G_1 G_2 \cdots G_n}T_{N_n}$$

$T_{Quantum}$ **= ½ photon** = $\frac{1}{2}\frac{\hbar\omega}{k_B}$ = **120 mK** for 5 GHz photon

$T_{thermal}$= Environment temperature (Actual temperature of the cavity)

The best result can be achieved by:

- **Environmental temperature << 120mK**
  - Use a Dilution refrigerator to reach ~20mK
- **Amplifier should add only quantum-limited noise**
  - First amplifier should be quantum-limited ➔ Josephson Parametric Amplifier
  - Gain of 1st amplifier > ~30 (15dB). Because second amplifier (HEMT) has a noise of ~2K.

For a fixed SNR, and a fixed total data taking time, sensitivity to $g_{a\gamma\gamma}$ is inversely proportional to

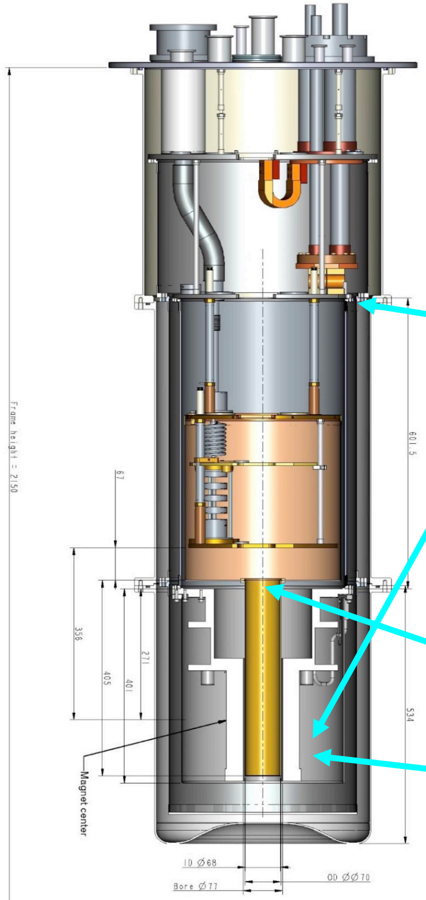
$$B_0\left(VCT_{sys}^{-1}\right)^{1/2}(Q_i t)^{1/4}$$

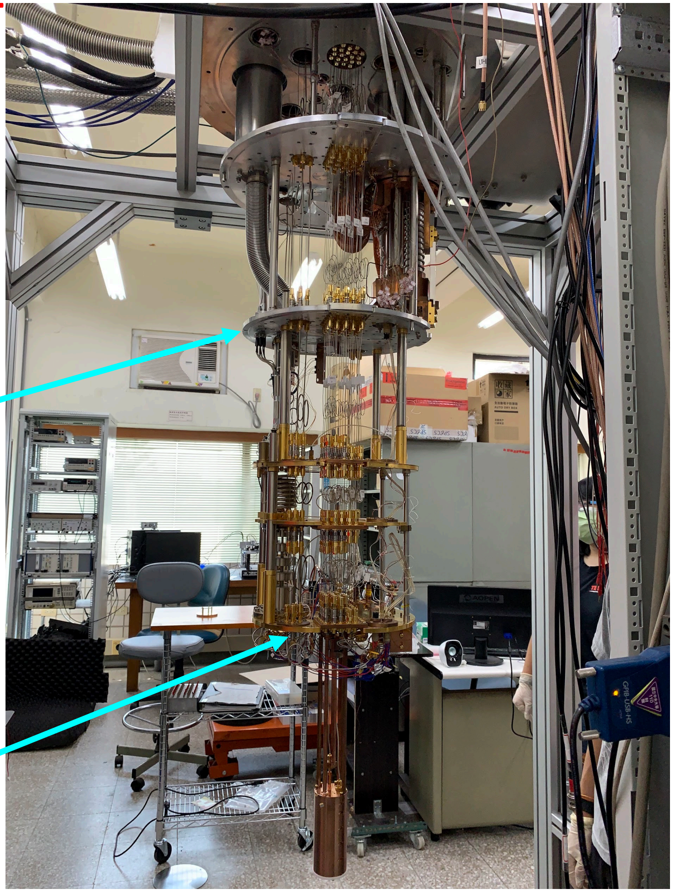
Optimization each of these parameters is the key to this experiment

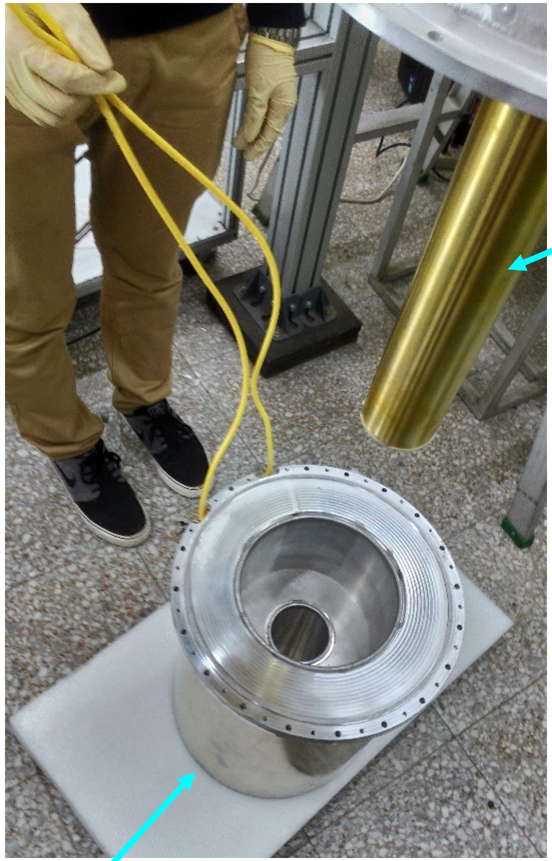
Order 1:	**Magnet:**	**B (magnetic field)**
Order ½:	**Cavity properties:**	**V (volume), C (form factor)**
Order ½:	**Readout chain:**	**T_{sys} (Noise temperature)**
Order ¼:	**Cavity property:**	**Q_i (Intrinsic quality factor)**
Order ¼:	**Operation:**	**Data taking time, Search Range**

1. The Dilution Refrigerator and the Magnet

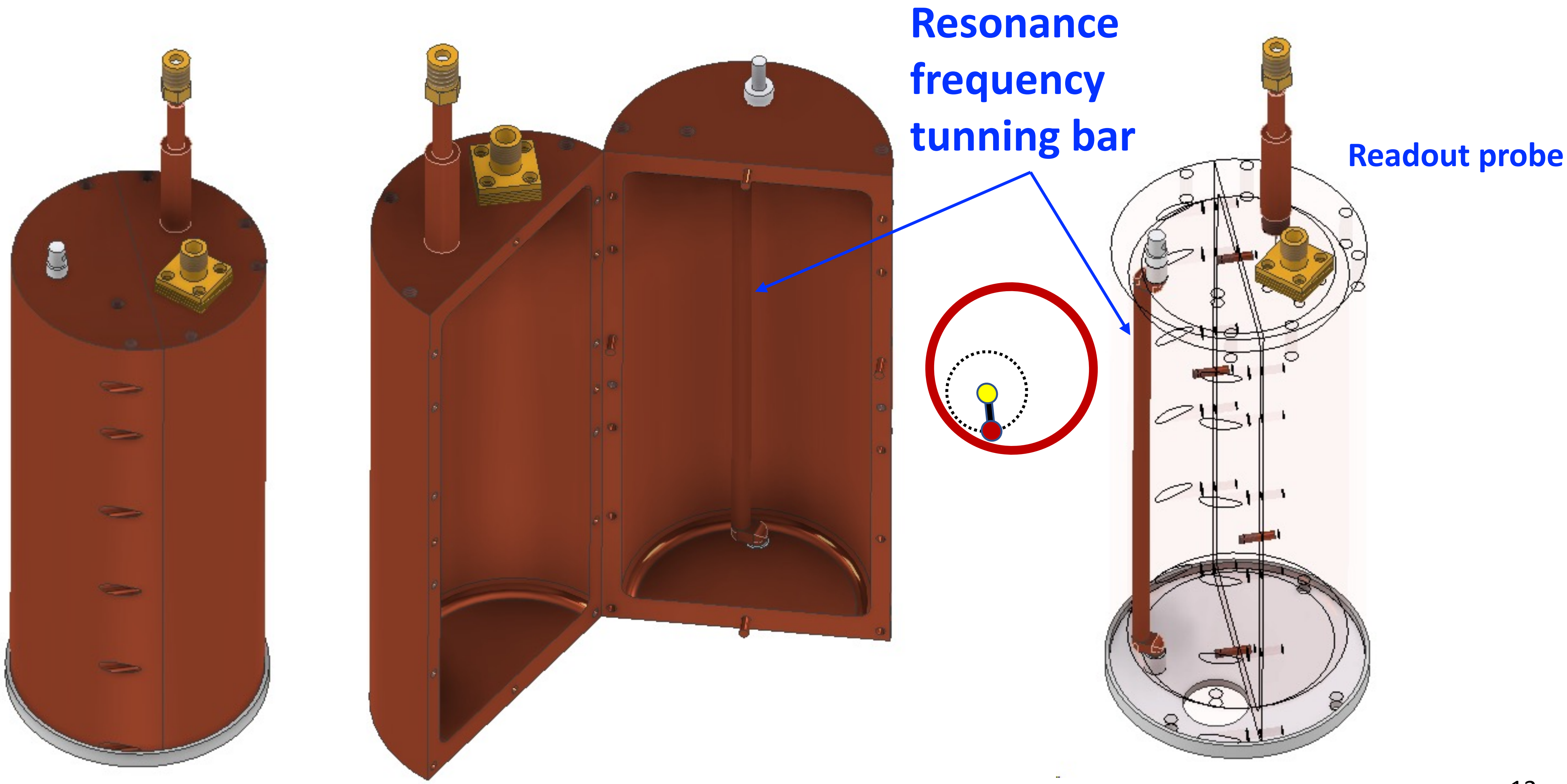
- Currently we use the existing DR and Magnet system in a Quantum computer lab. It is being used for Qubit studies. We get about 50% of the operation time.
- **Maximal magnetic field is 8T**.
- Cavity diameter: 3 inch – f_{res} **~ 5 GHz**
- **Cavity temperature: 20mK**



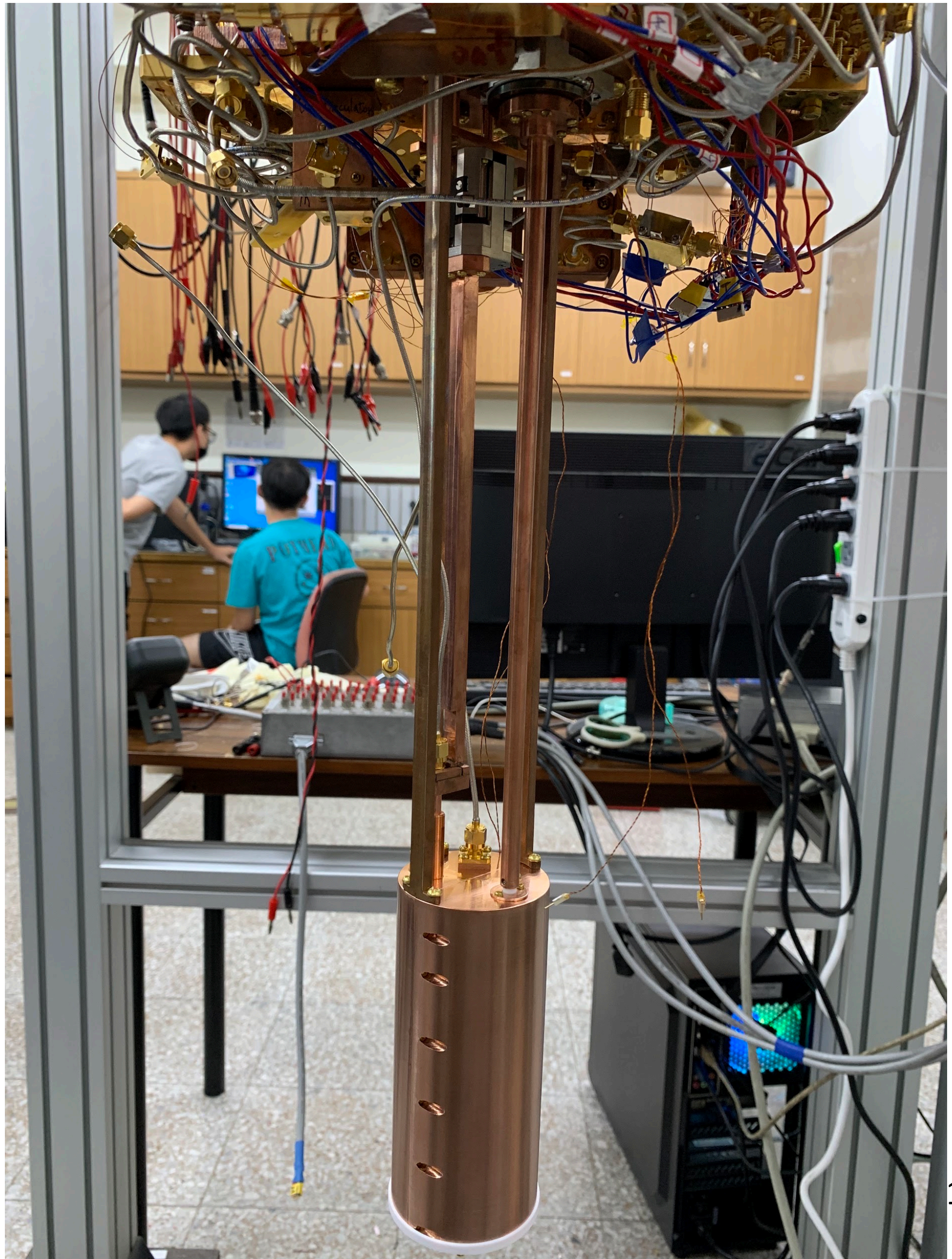




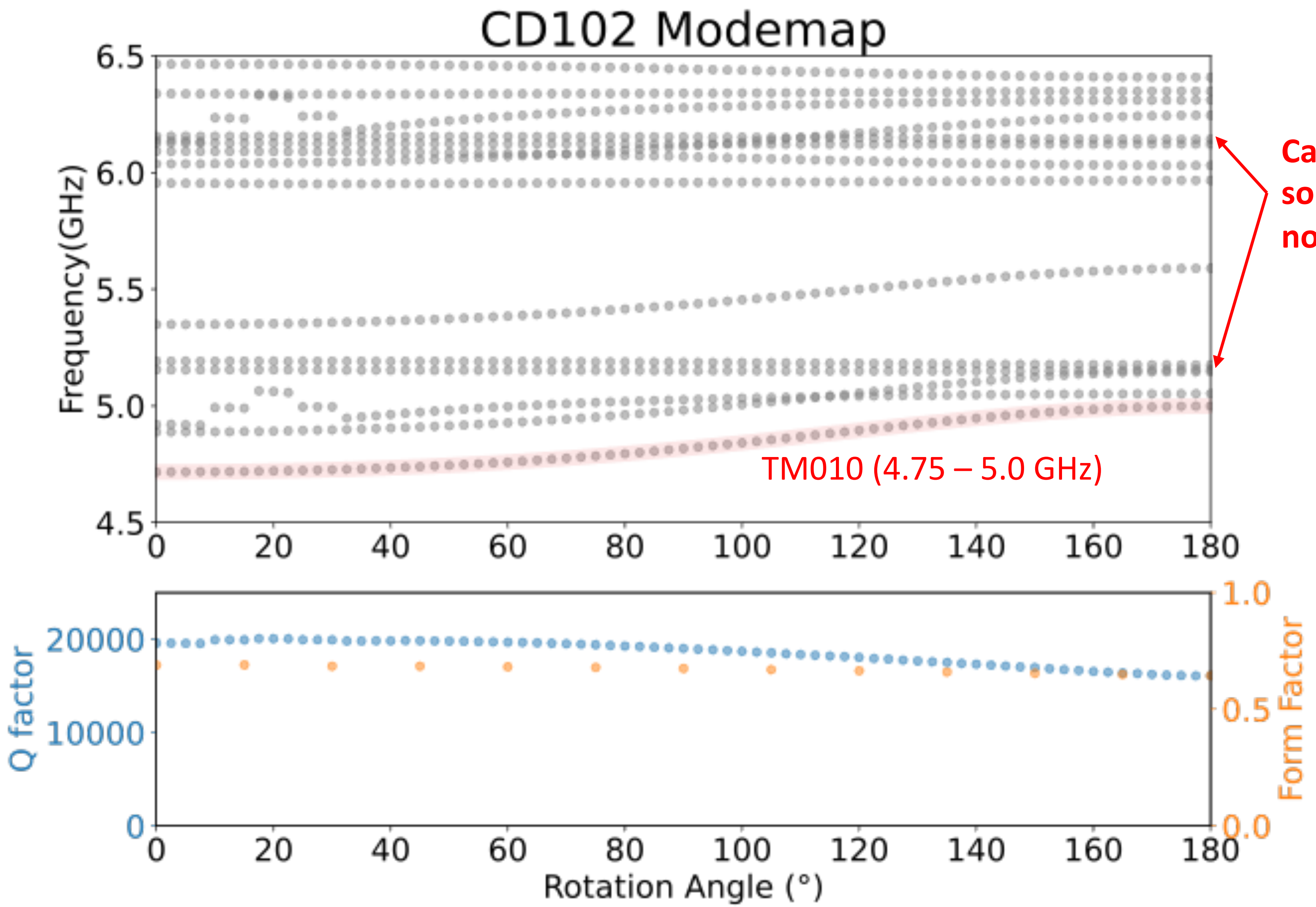
2. The Cavity design



The experimental setup



Resonance frequency, Q-factor, and Form factor calculated by HFSS



Cavity length set to 12cm so that other modes does not crossTM010 mode

Ideal cavity (no tunning bar):

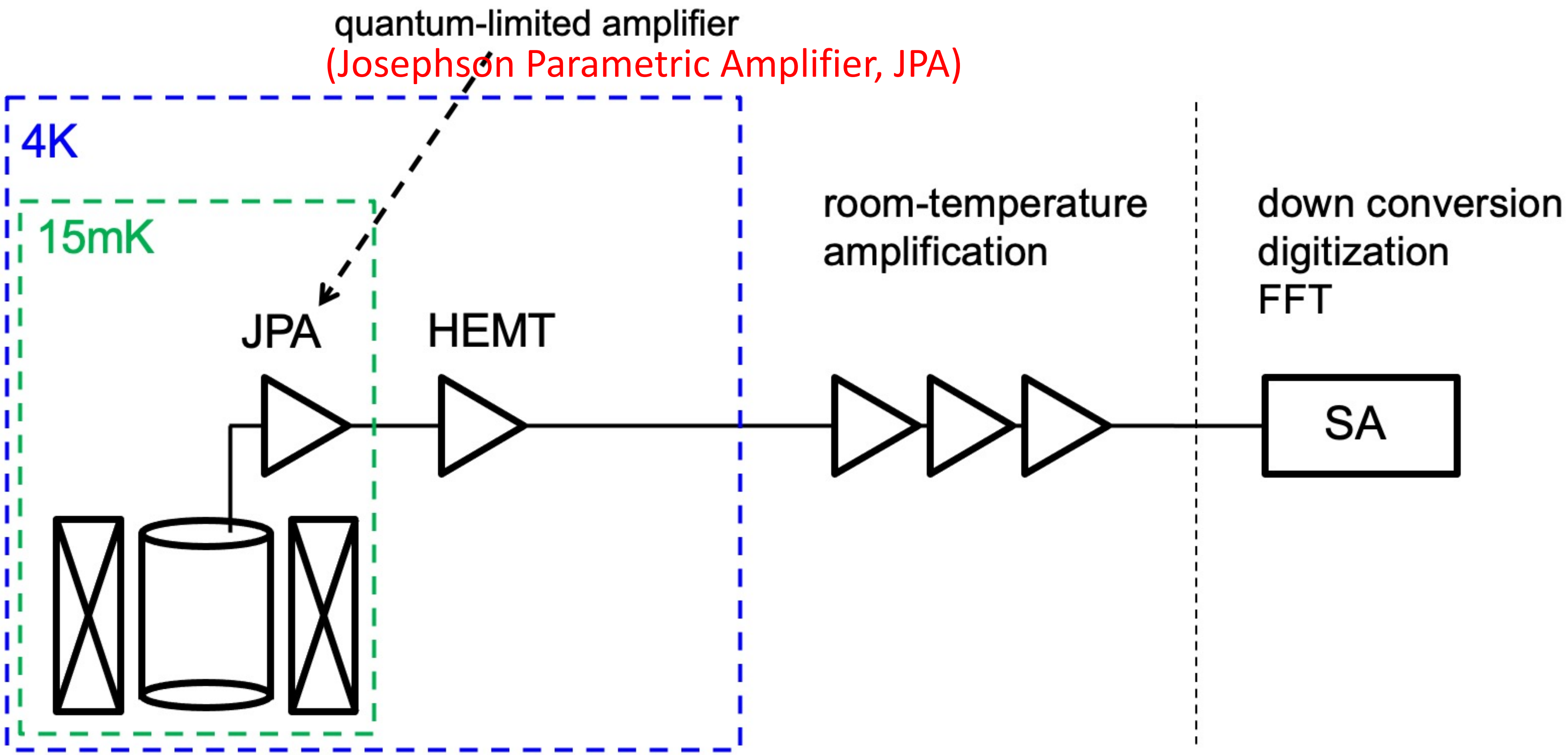
f_{res} = 4.6 GHz

C = 0.692

Q = 22000

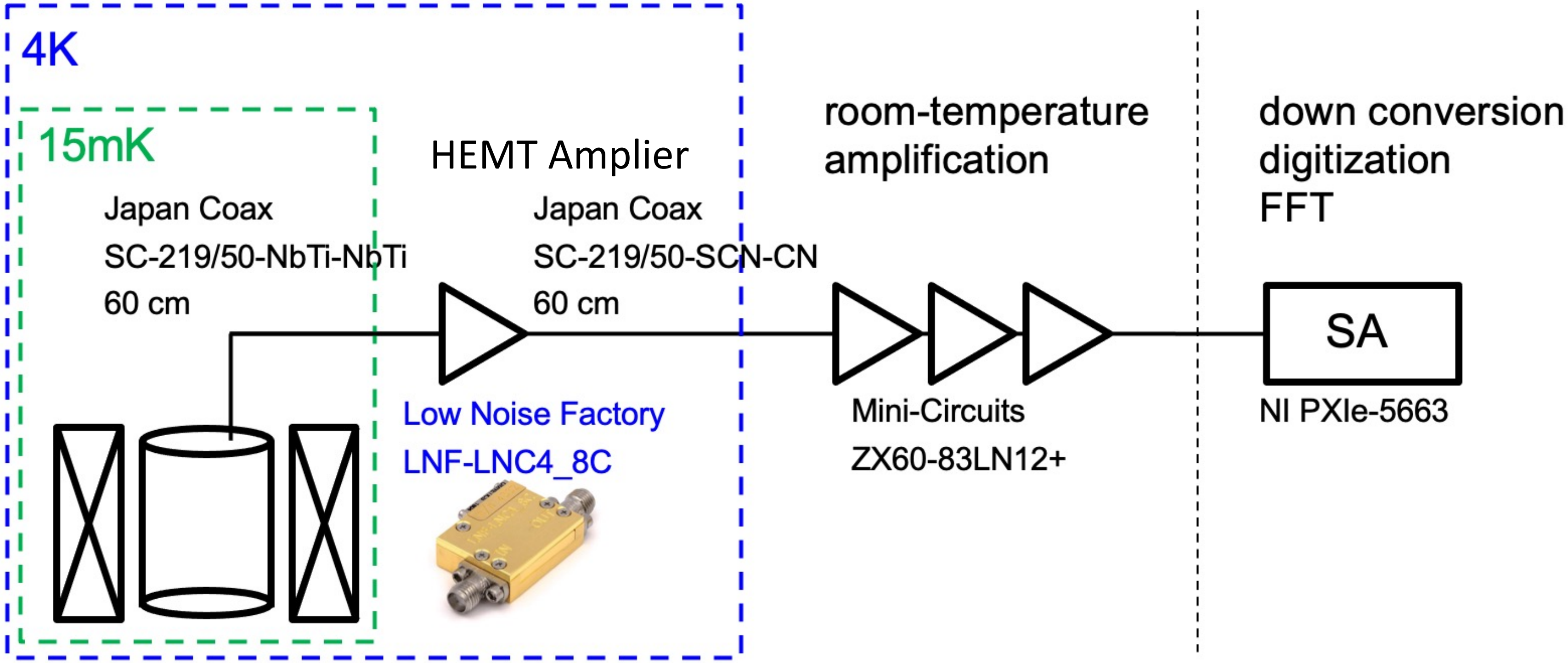
3. Data acquisition and Operation

Aimed Readout Scheme (expected noise temperature ~240mK):



Current Data acquisition scheme:

- Currently we do not have a working JPA, the first stage amplifier is a HEMT amplifier with noise temperature about 2K.

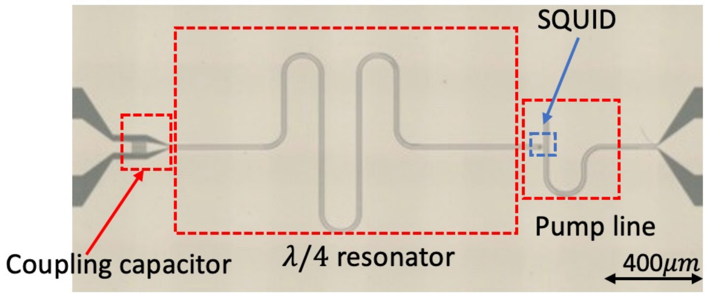


4. JPA Development

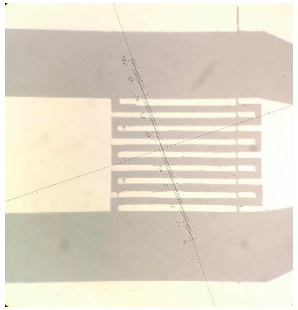
Device fabricated by Quantum device Lab in Academia Sinica

Single e-beam – all aluminum process

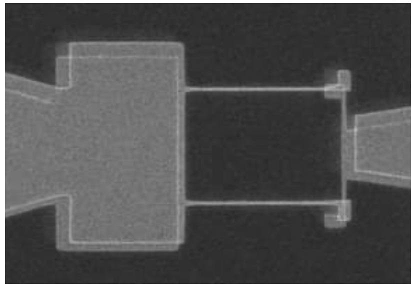
Turn-around time ~ 1 week. 🡸 Major advantage for our development plan



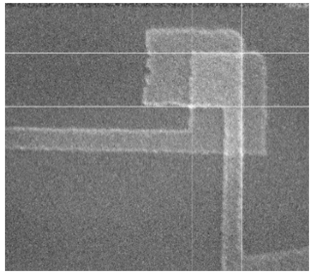
JPA V1 overview



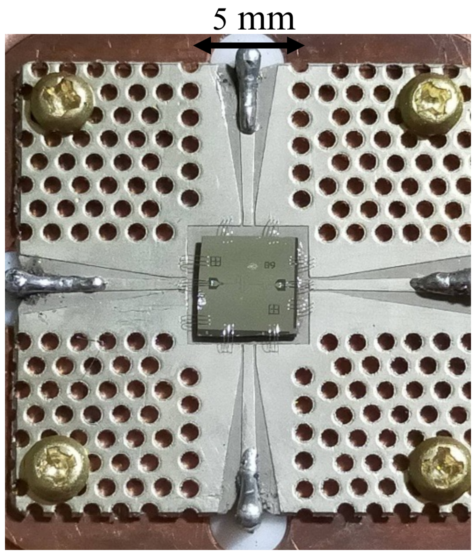
coupling capacitor



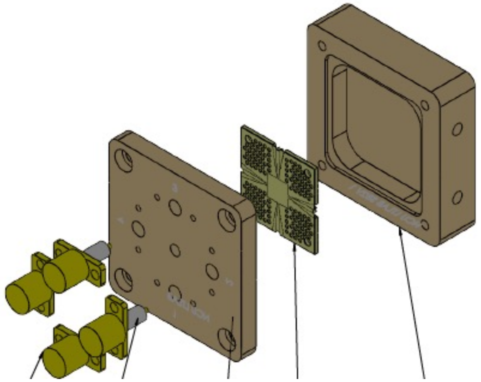
SQUID



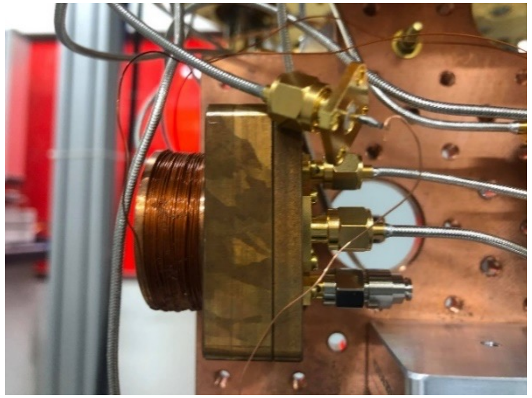
Josephson Junction



chip packaging



sample box assembly

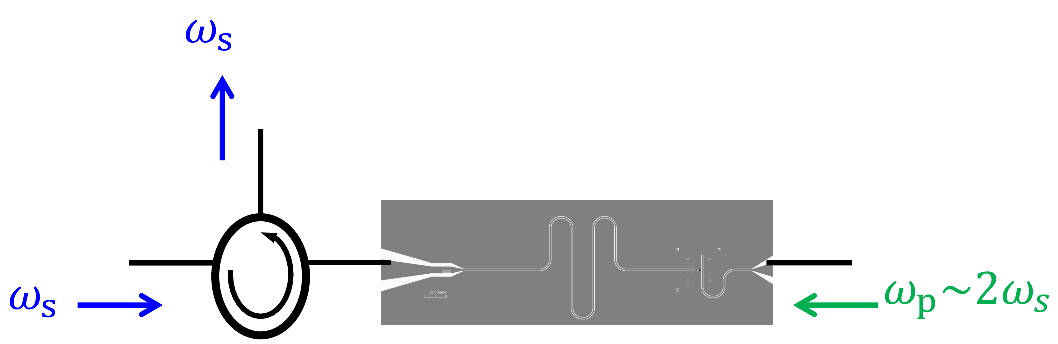


sample mounting

JPA V1 Performance

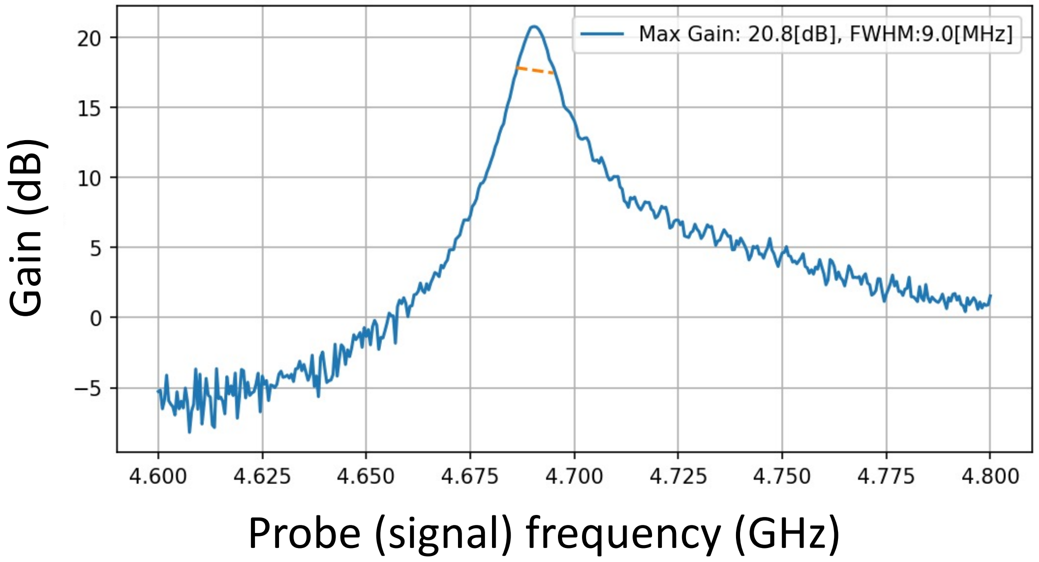
The third production batch produced working amplifiers!

2ω-pumping



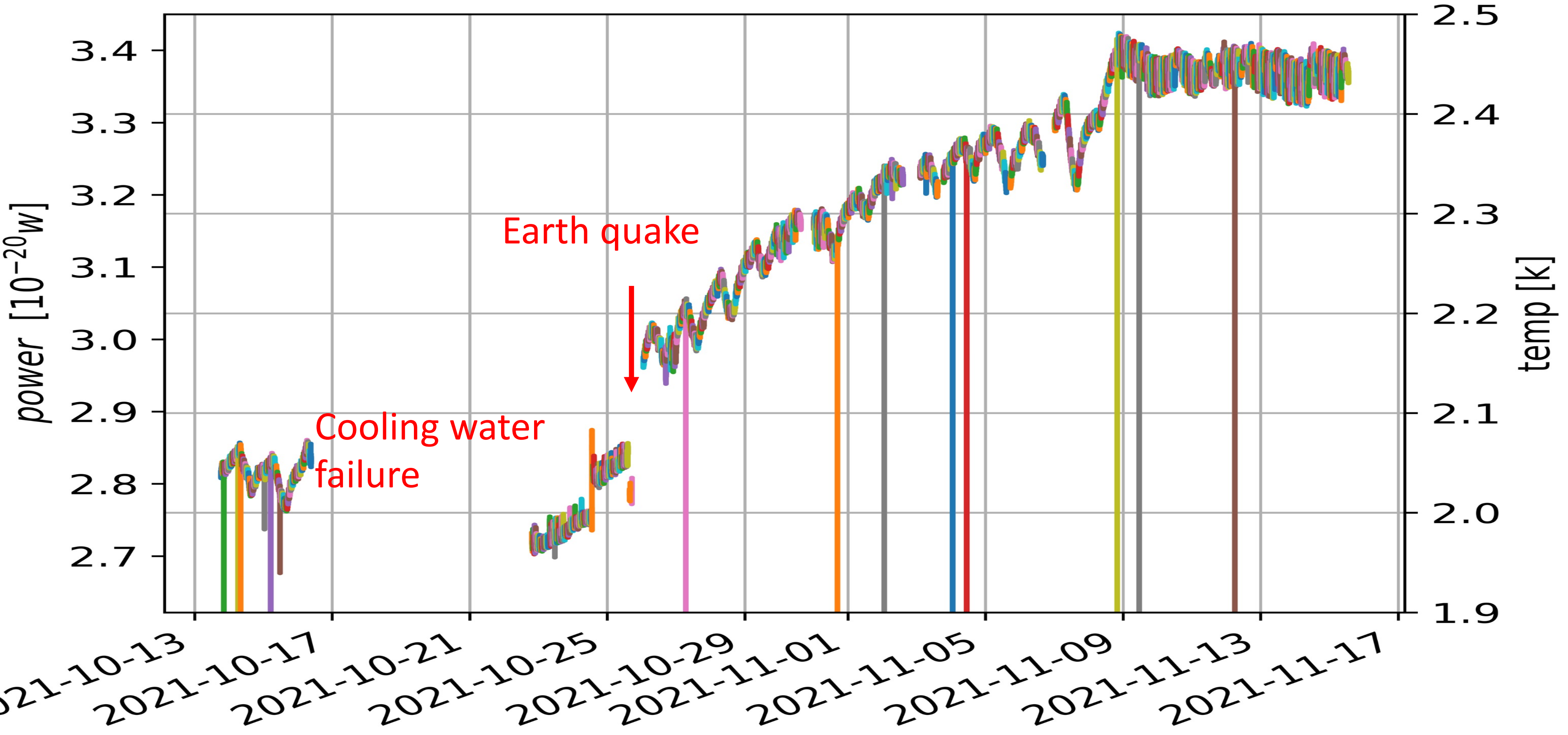
pump frequency $\omega_p / 2\pi$ = 9.2275 GHz
pump power P_p = 18 dBm
signal power P_s = -55 dBm

gain profile



- **resonance frequency G_{max} = 20 dB (~ 100x)**
- **Added Noise = 271 mK**
- **Bandwidth = 9 MHz**
- **Band central frequency does not shifts with P_p**

5. Physics Run in Oct. - Nov. 2021

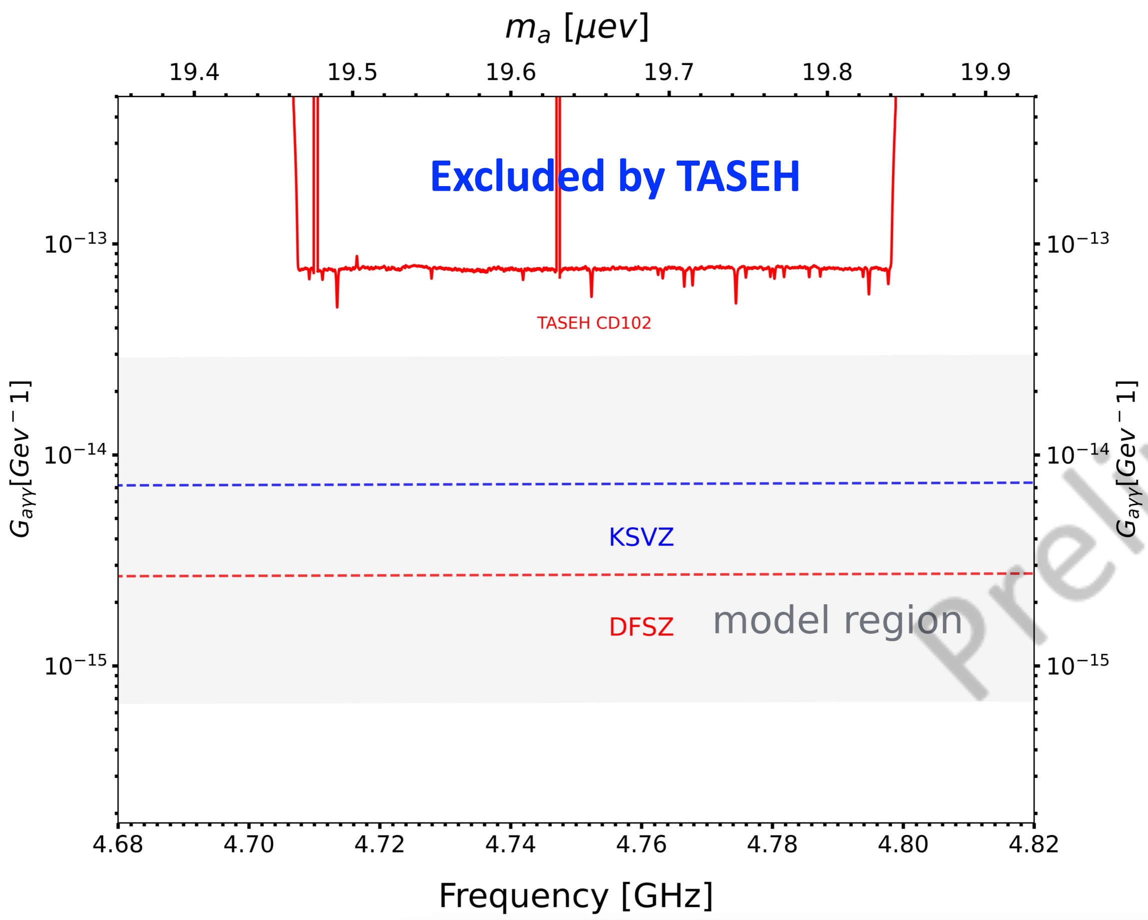


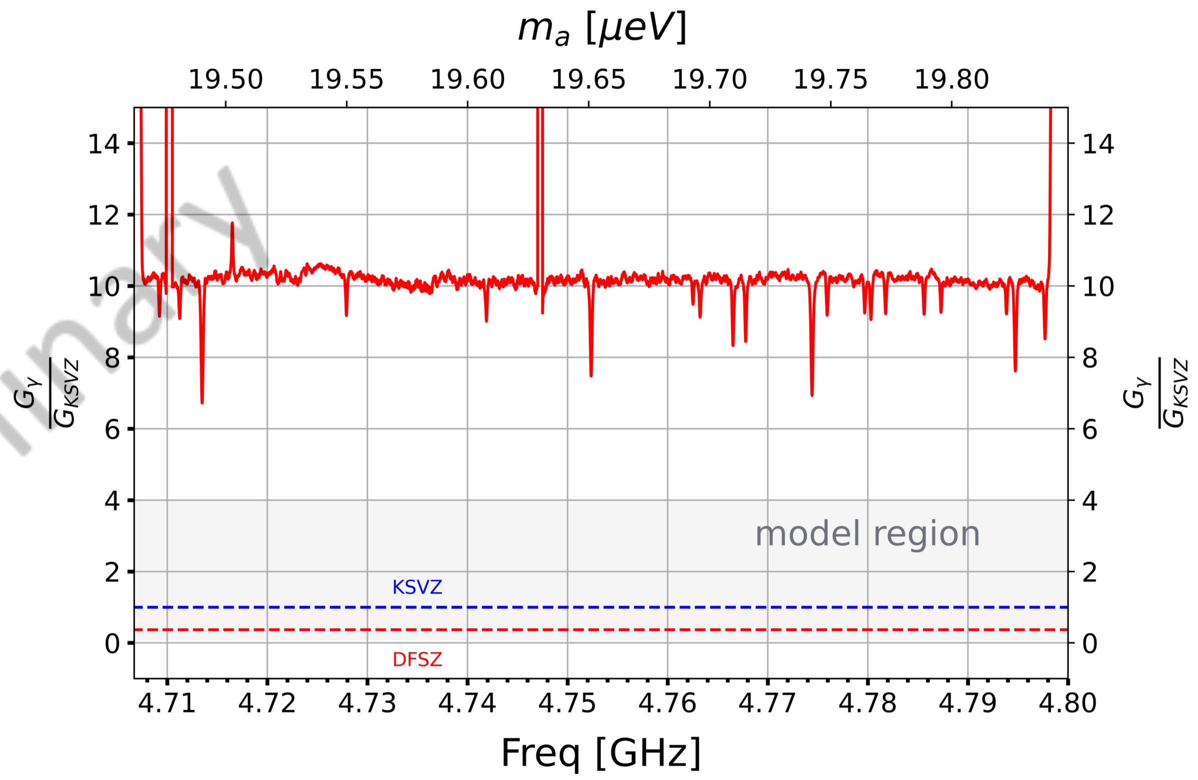
Every colored slice shows the power output of one step (~110 kHz)

- ~30 min of data taking per step.
- **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.**

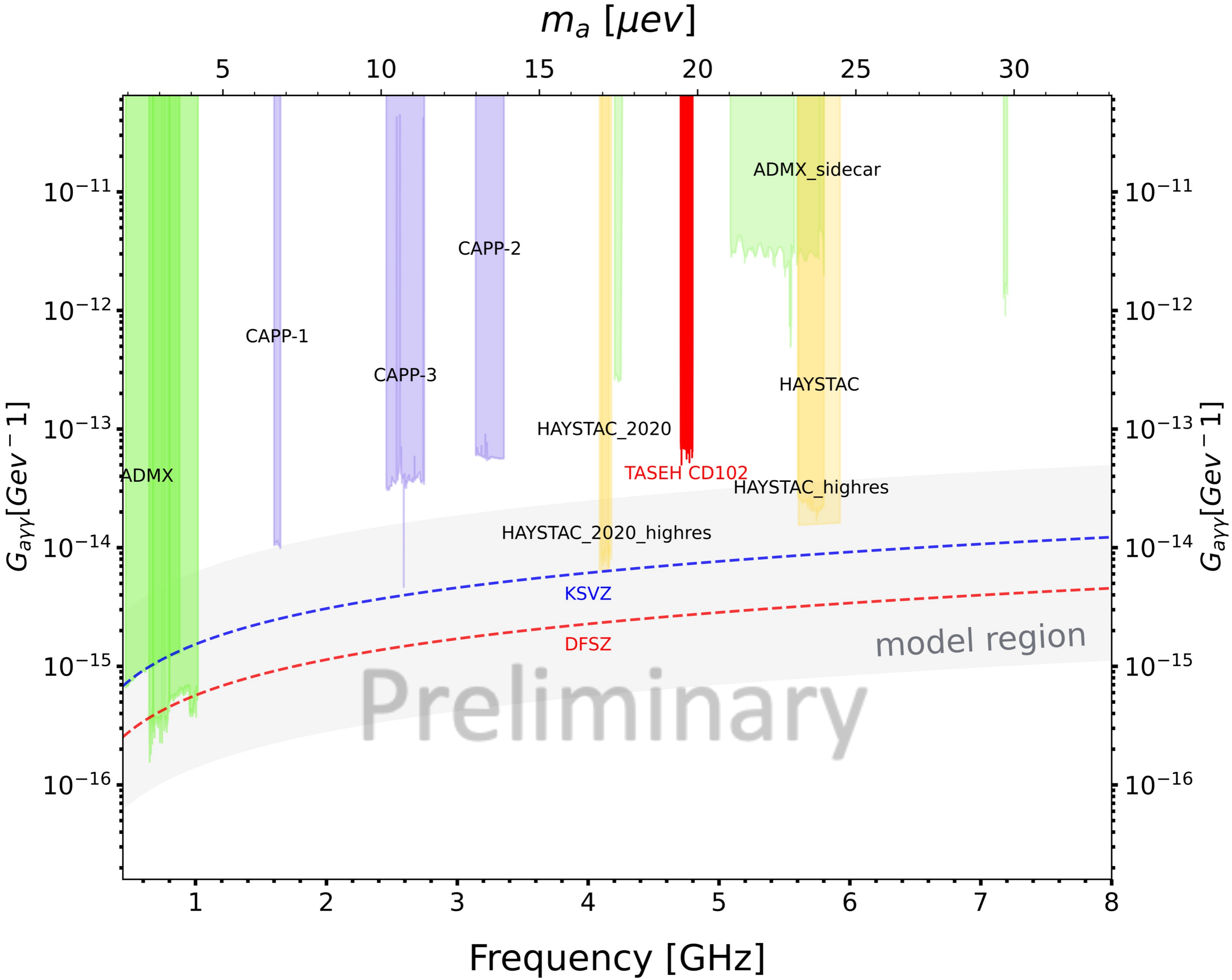
No signal exceeding 3.35 σ observed:

Exclusion limit of $g_{a\gamma\gamma}$ at 95% confidence level in a 90 MHz range



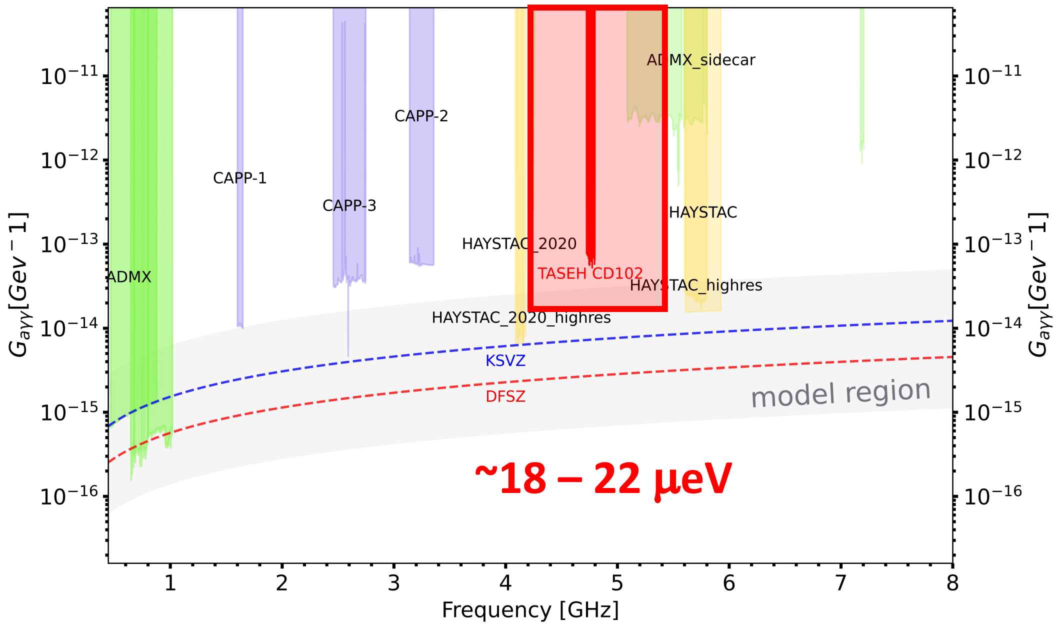


We reach a limit which is still 10x the theoretical value.


m_a [μev]
5
10
15
20
25
30
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
$G_{a\gamma\gamma}[Gev^-1]$
ADMX_sidecar
CAPP-2
CAPP-1
CAPP-3
HAYSTAC
HAYSTAC_2020
ADMX
TASEH CD102
HAYSTAC_highres
HAYSTAC_2020_highres
KSVZ
DFSZ
model region
Preliminary
1
2
3
4
5
6
7
8
Frequency [GHz]

Plan for the next stage

1. Integrate JPA in the readout chain, expect to improve the sensitivity by a factor of ~3.
2. Procure a new DR/Magnet – Increase B and V: improve sensitivity by ~1.5
3. Expected limit will be a factor ~2x theoretical value. We can cover ~ 1.0 GHz for one year operation time.



Conclusion:

- TASEH group conducted a Haloscope Axion Darkmatter search. The Axion-photon coupling is excluded at ~10x theoretical expected value in a 90MHz frequency range.
- Improvements by implementing a JPA and with new Dilution Refrigerator are expected to enable TASEH to search in a range of 1GHz and set Axion-photon coupling limit close to KSVZ model.
- **Taking advantage of the fast-growing Superconducting Qubit developments, Haloscope axion search can be carried out by small group with limited resources.**