First results from a cavity haloscope experiment with a novel frequency tuning system using a qubit

19th Patras Workshop on Axions, WIMPs and WISPs,

University of Tokyo

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Introduction

Today's talk

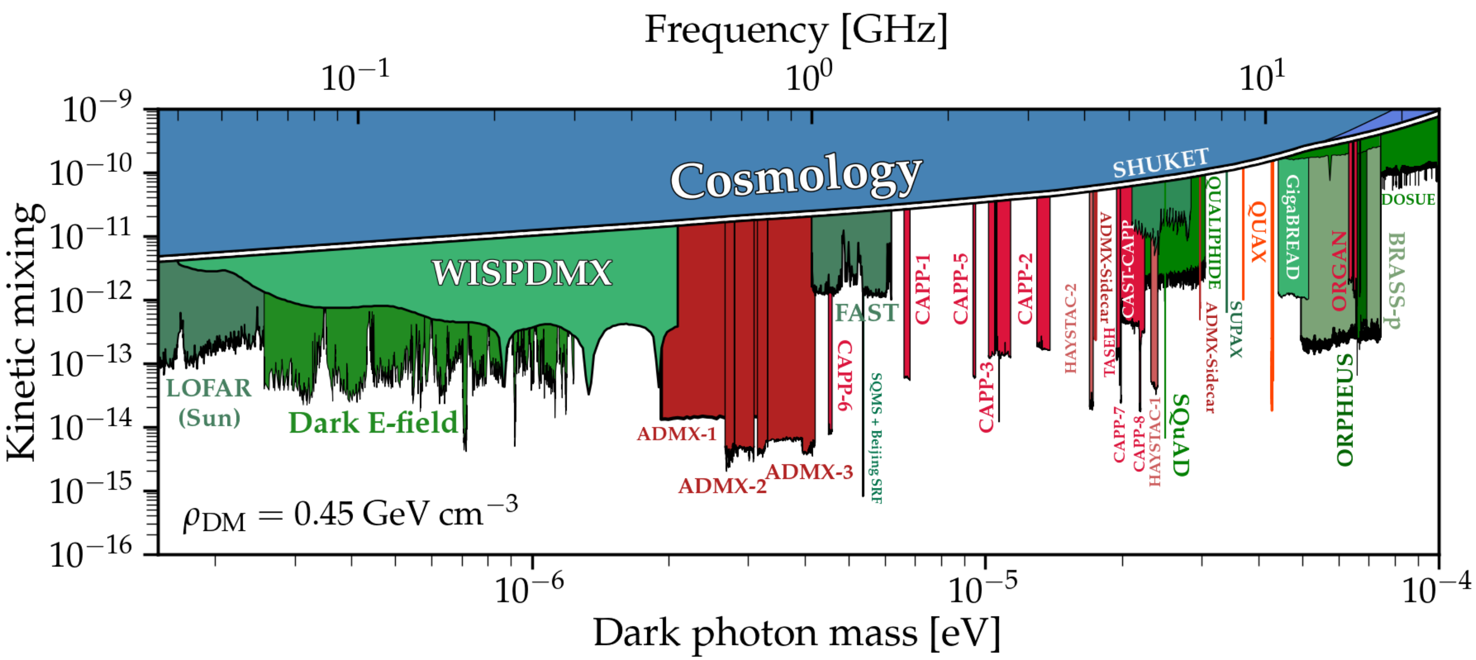
- In the context of cavity haloscope experiments, Introducing a novel frequency tuning system, using interaction between cavity and qubit.

- Report preliminary Dark photon (DP) exclusion limit using this new system around 36.1 μeV.

  (~8.73GHz)

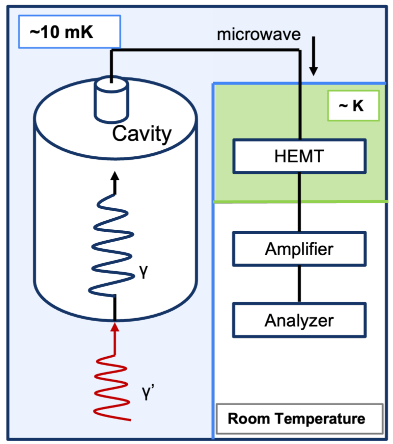
Dark photon

- One of the candidates of DM
- Mixed with photon in kinetic mixing parameter χ
- Conversion photon can be measured.



Caputo et al. 2021

cavity haloscope

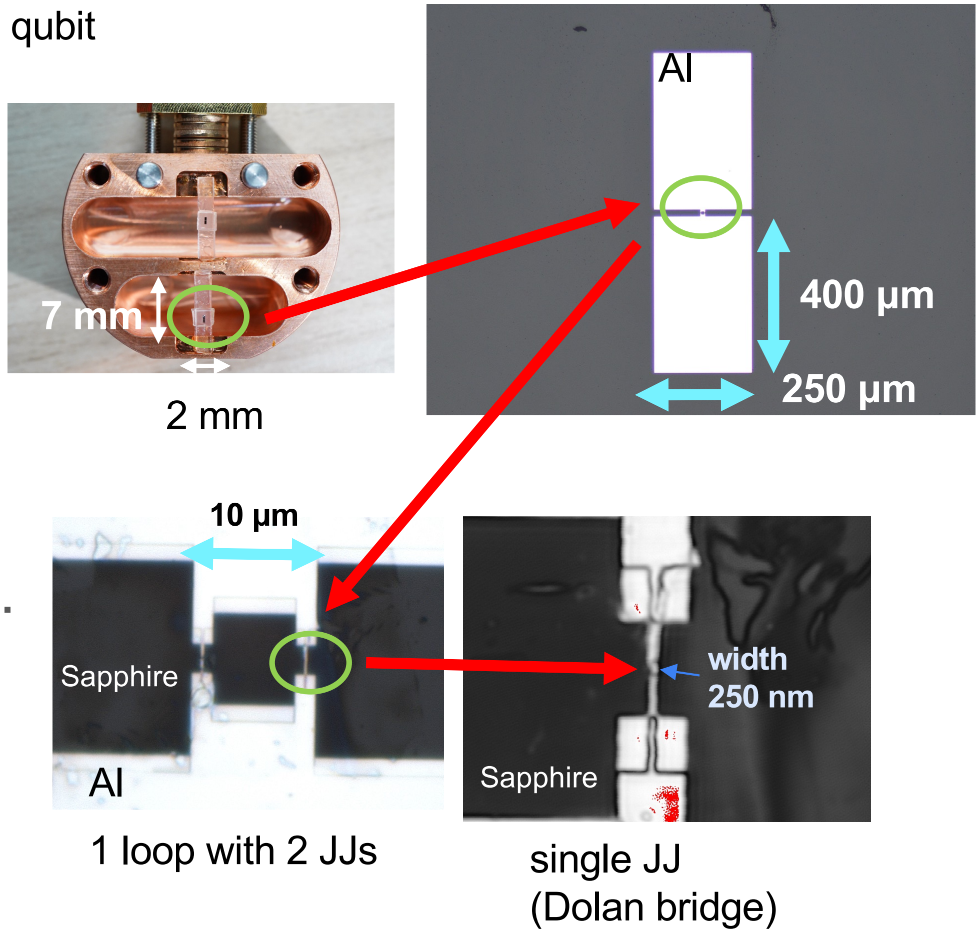


What is “qubit”?

Superconducting charge qubit ← Transmon qubit

- Josephson Junctions (~100nm) between two large islands (~100μm).

- Equal to non-linear LC circuit



Tunable qubit(SQUID-based qubit)

- Tunable qubit has one loop with two JJs.

→Enable to change energy gaps (= qubit’s resonant frequency) by varying magnetic flux penetrating the qubit.

$$E_j(\phi) = E_{j\Sigma}\cos(\frac{\pi\phi}{\phi_0})\sqrt{1 + d^2\tan^2(\frac{\pi\phi}{\phi_0})}$$

(Koch et al., 2007)

Interaction between cavity and qubit

Jaynes-Cummings model

$$H = \frac{\hbar\omega_q}{2}\sigma_z + \hbar\omega_c a^\dagger a + \hbar g(\sigma_+ a + a^\dagger \sigma_-)$$

$$\longrightarrow \quad H = \frac{\hbar}{2}(\omega_q + \frac{g^2}{\Delta})\sigma_z + \hbar[\omega_c + \frac{g^2}{\Delta}\sigma_z]a^\dagger a$$

qubit (ω_q), cavity (ω_c)

σ_z	…Pauli spin Z
$\Delta = \omega_q - \omega_c$	…Detuning
$g \sim \mu E$	…Coupling constant

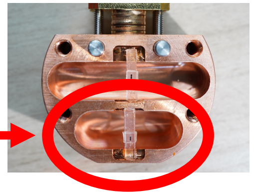
Important point

frequency's shift $\propto \frac{g^2}{\Delta}$

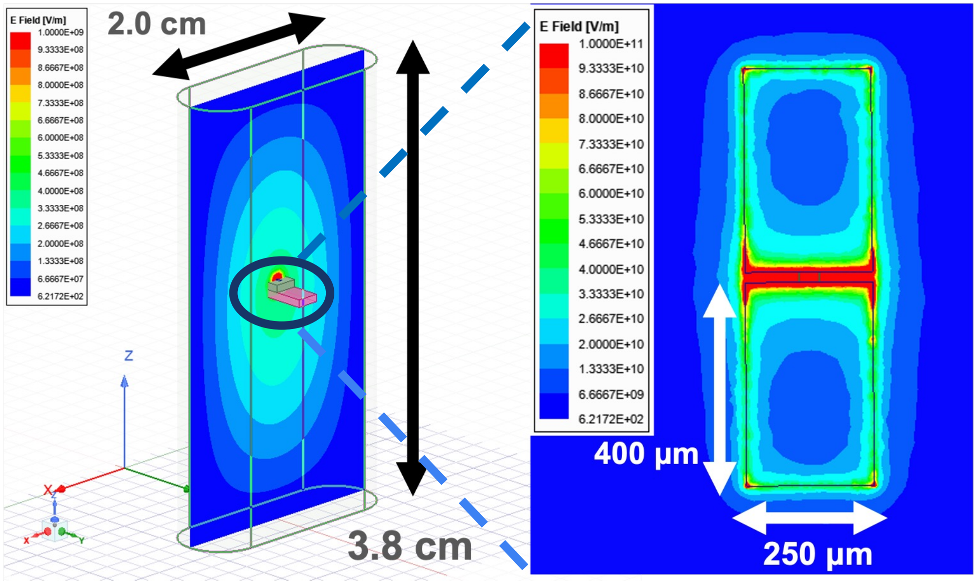
TE101 mode simulation

<u>The same design and material of the actual cavity and qubit</u>

here!

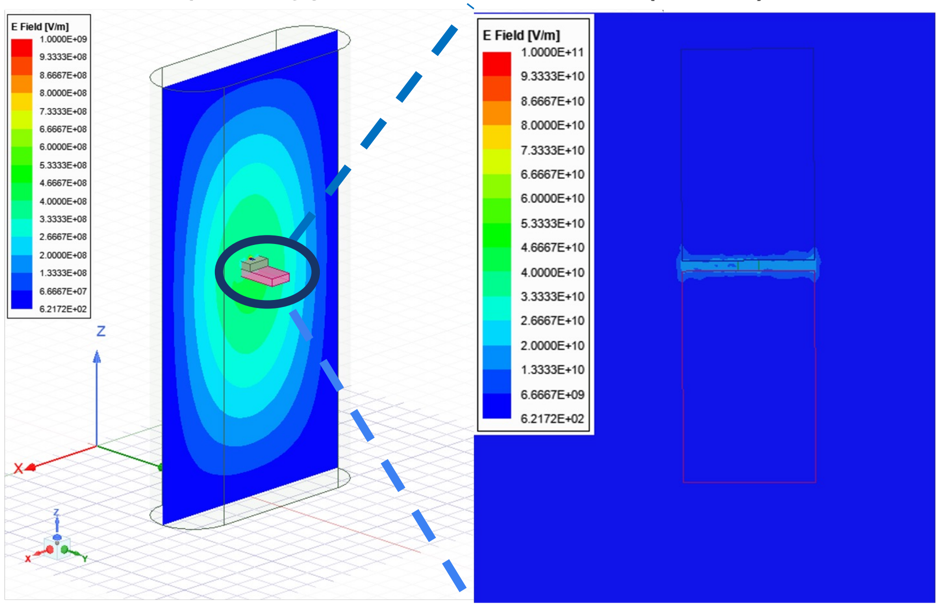


(Cavity) (Qubit)



Interaction Maximum

(Cavity) (Qubit)

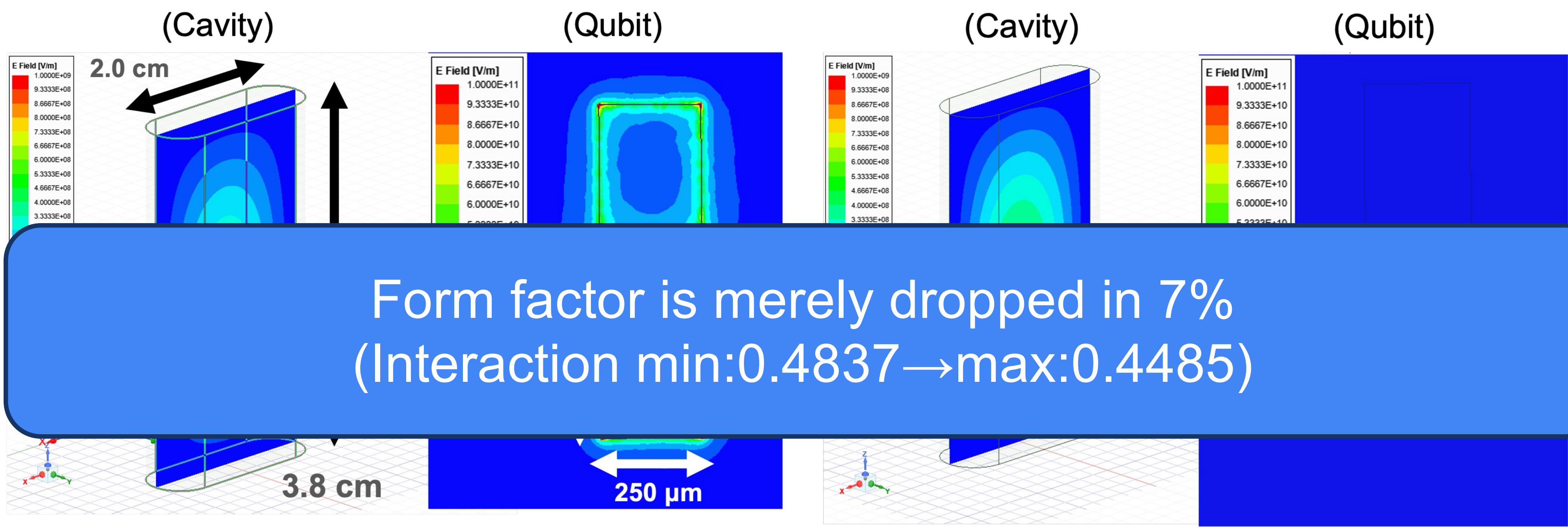


Interaction Minimum

Cavity frequency ≒ Qubit frequency → Mode crossing is maximum.

TE101 mode simulation

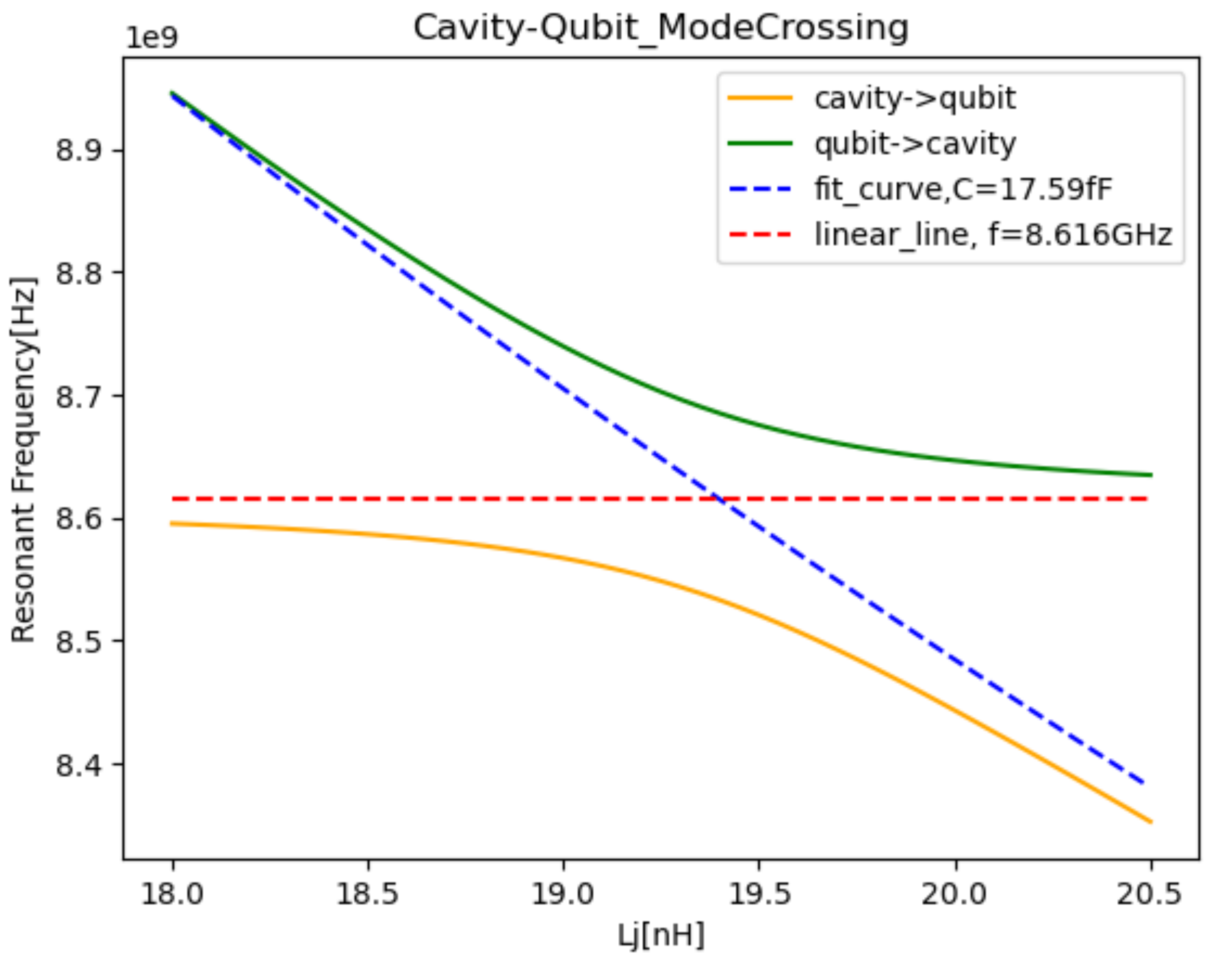
The same design and material of the actual cavity and qubit



Form factor is merely dropped in 7%
(Interaction min:0.4837→max:0.4485)

Cavity frequency ≒ Qubit frequency → Mode crossing is maximum.

Mode crossing simulation



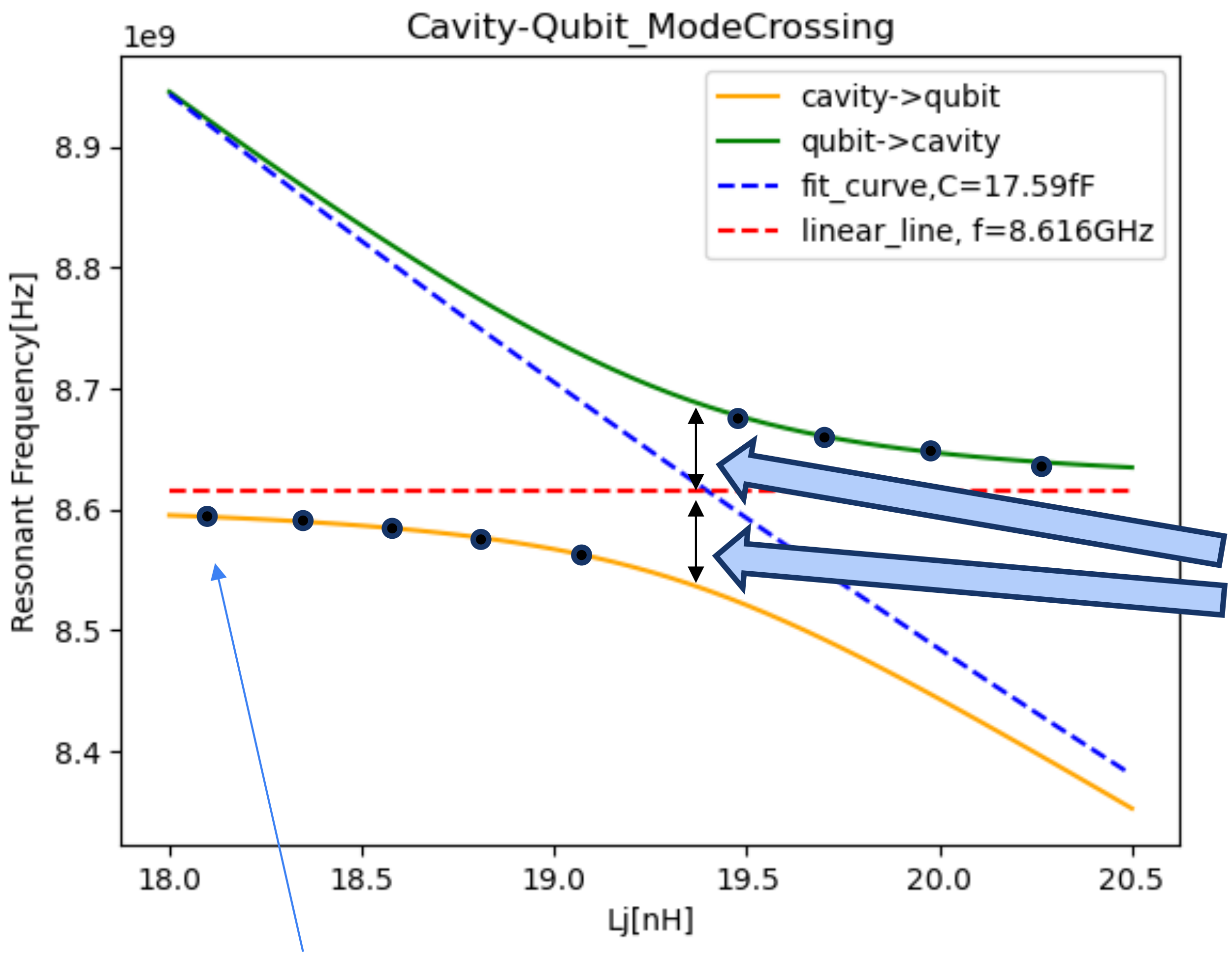
Blue dashed line
estimated qubit frequency
without interaction

Red dashed line
estimated cavity's frequency
without the interaction

Yellow line
Cavity→(mode crossing)→Qubit

Green line
Qubit→(mode crossing)→cavity

Mode crossing simulation



※Black dots... points of cavity frequency

Blue dashed line
estimated qubit frequency
without interaction

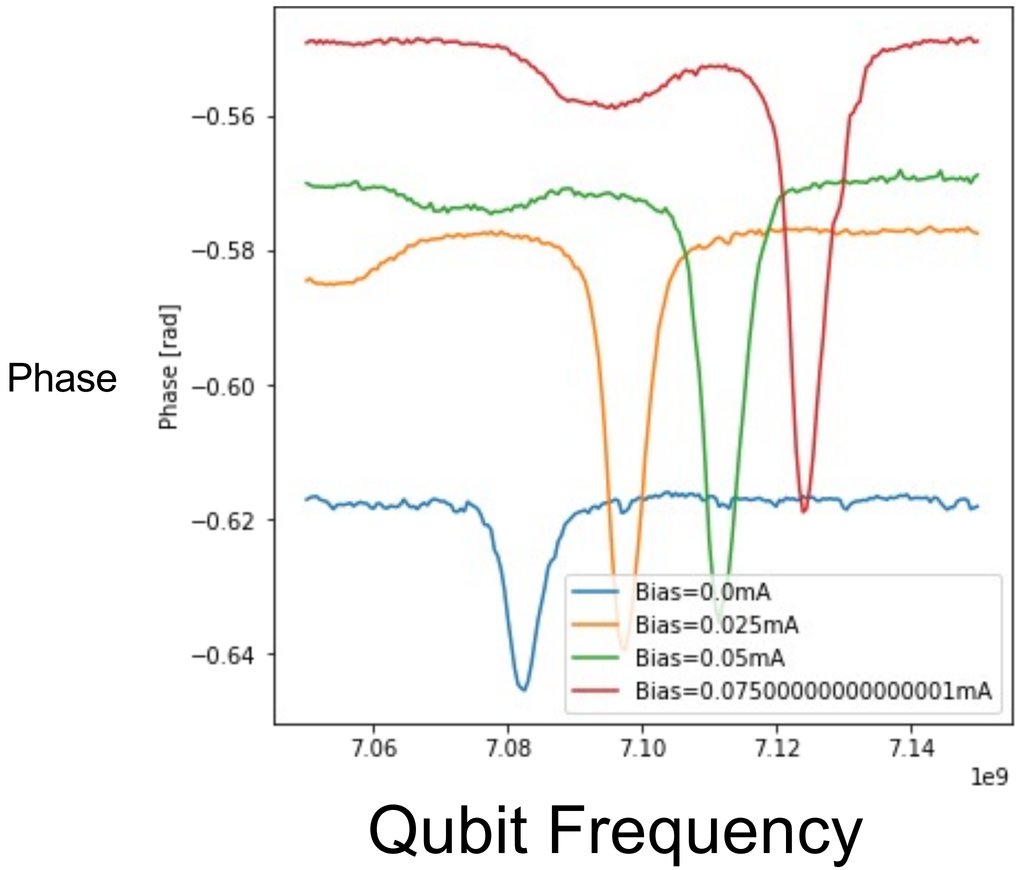
Red dashed line
estimated cavity's frequency
without the interaction

Maximum
frequency shift

when $\omega_c \sim \omega_q$

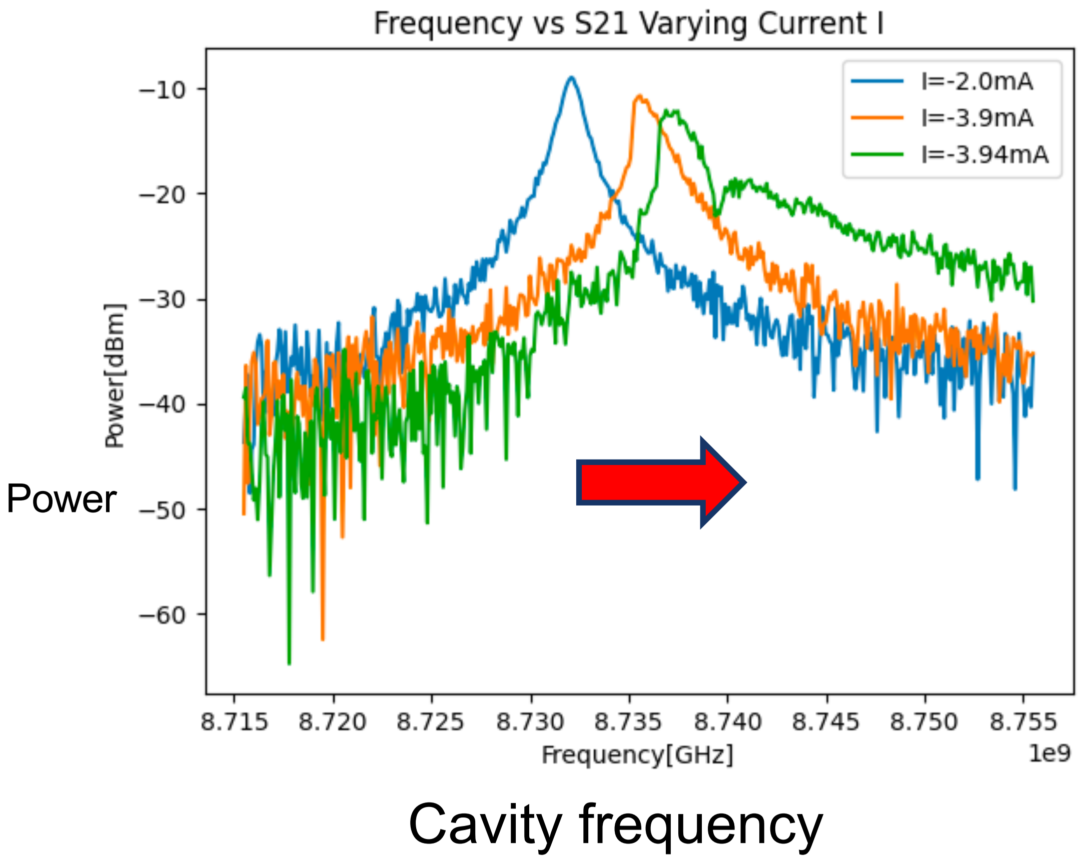
Test for Tuning qubit's frequency by DC current

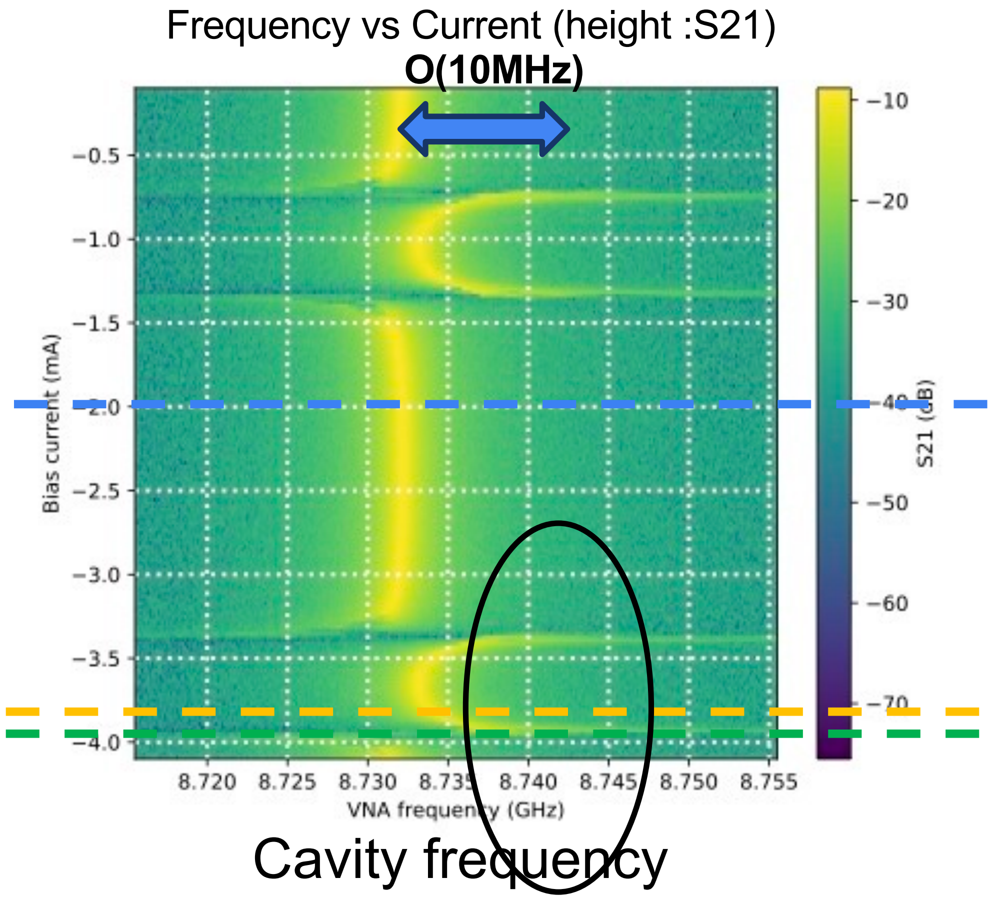
Tunable qubit frequency



Performance Check and Calibrations for cavity tuning

Measuring S21(transmission wave) while varying DC current through the coil.





We want to use this regime

Why is “qubit”?

In this experiment, we assume some features that...

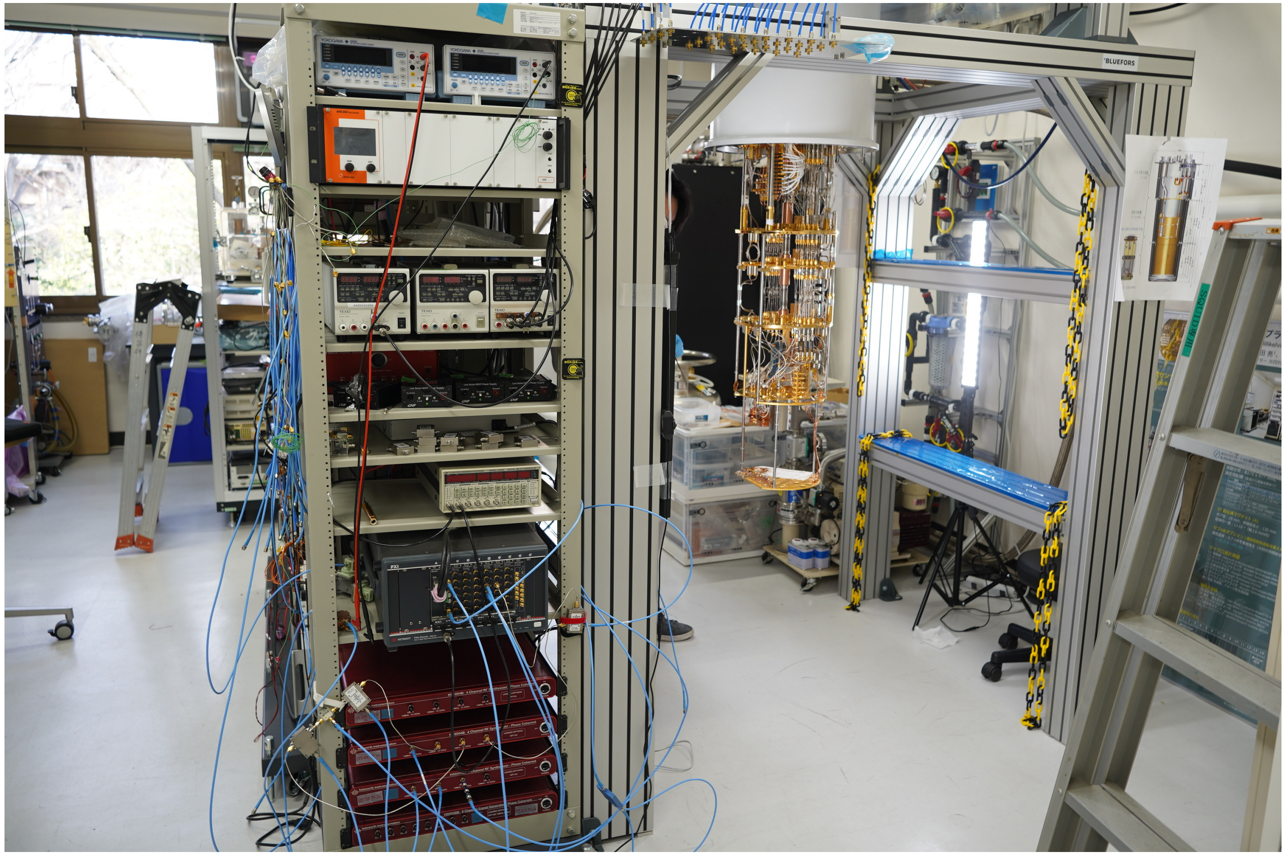
1. Easy implementation
    - only with coils and qubits
    - without physical restriction

2. No need to be worry about electromagnetic wave leakage
    - the risk caused by physical gaps of a cavity

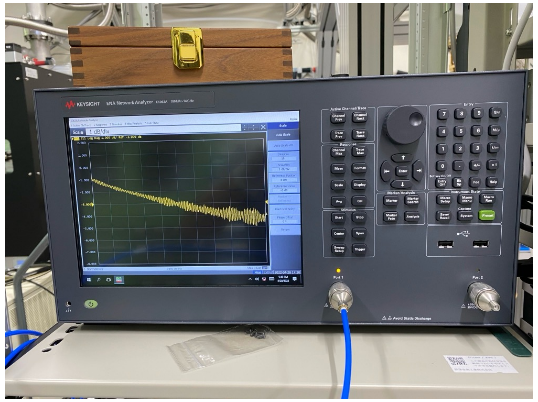
3. Fast scanning because of no thermal noise from the friction.

The setup and equipment

The dilution refrigerator cool down to 10mK



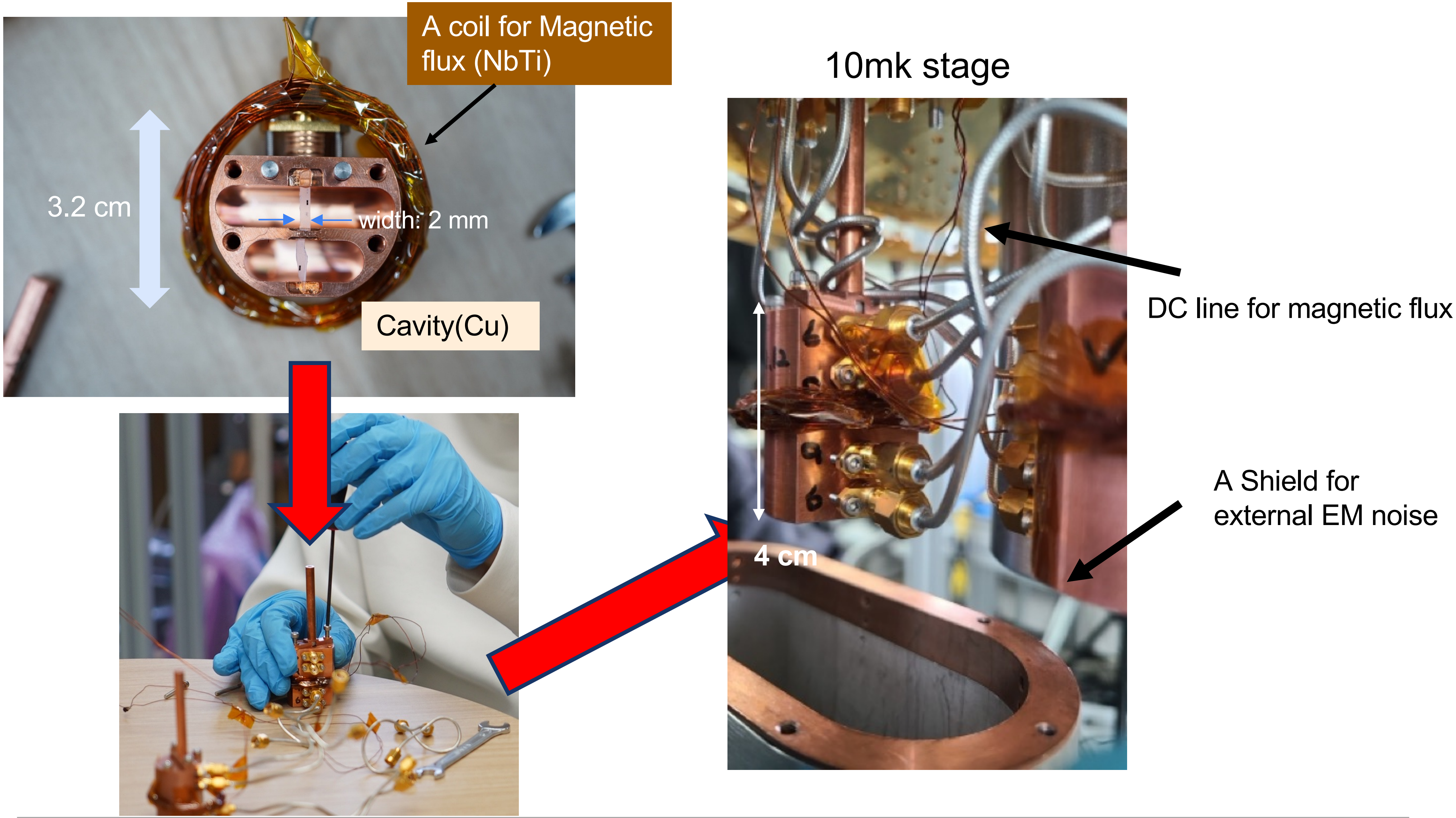
VNA



Spectrum analyzer

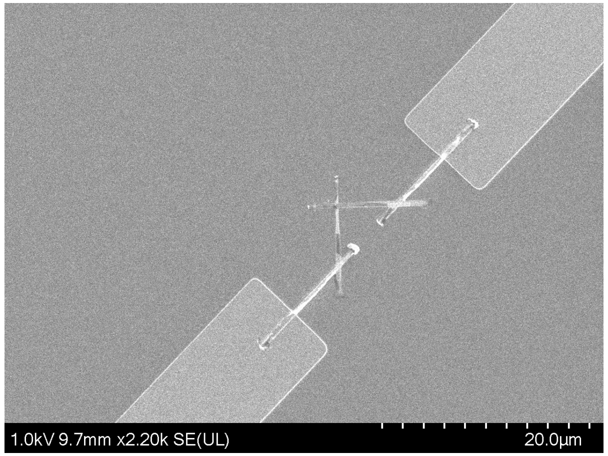
Cryogenic Research Center, The University of Tokyo

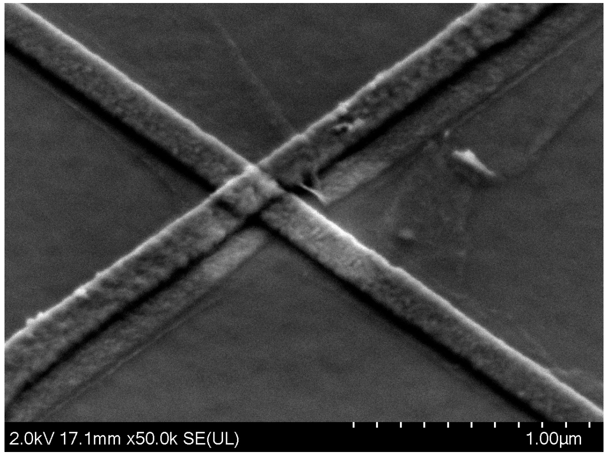
The setup of cavity and qubit

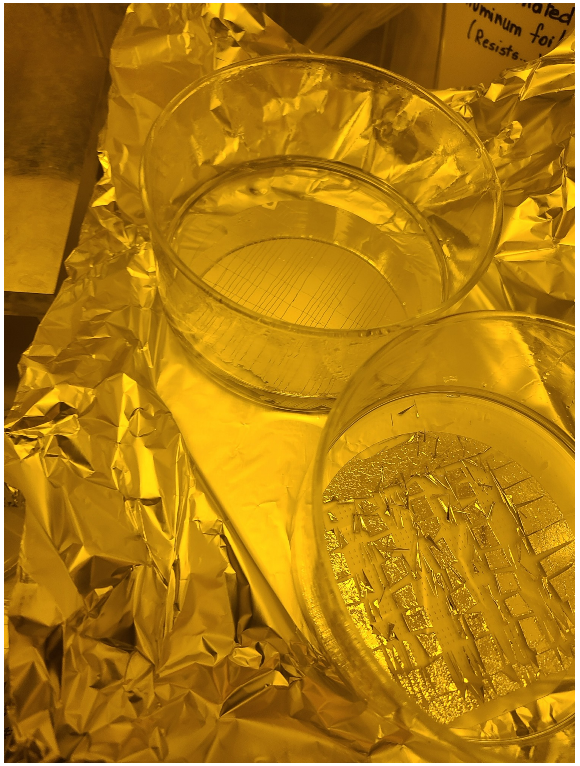


Qubit fabrication

We made our qubits by our selves







Manhattan style JJ

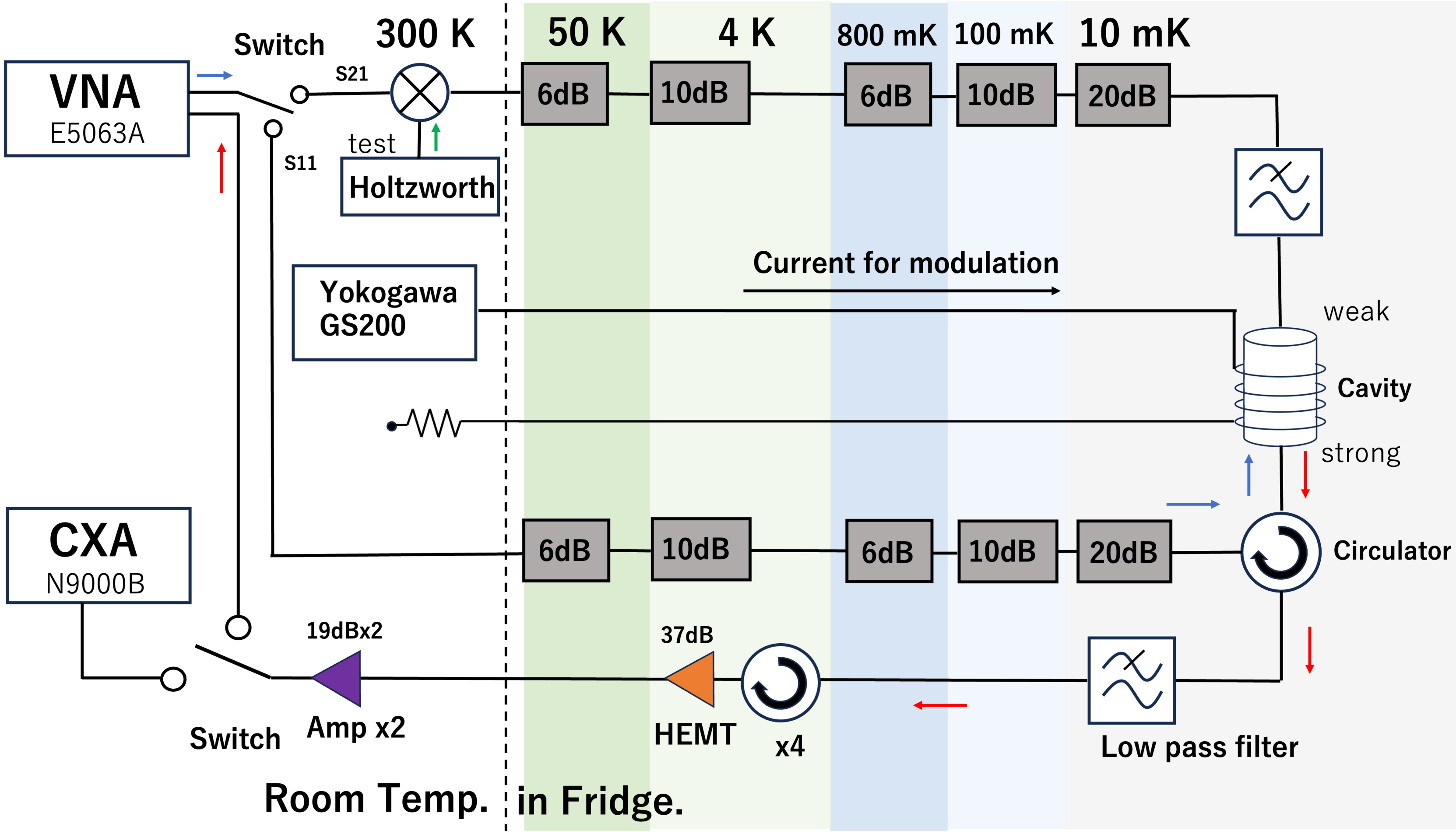
Thank you for much help!

We make at...

- U-Tokyo
- OIST
- EPFL
- U-Chicago

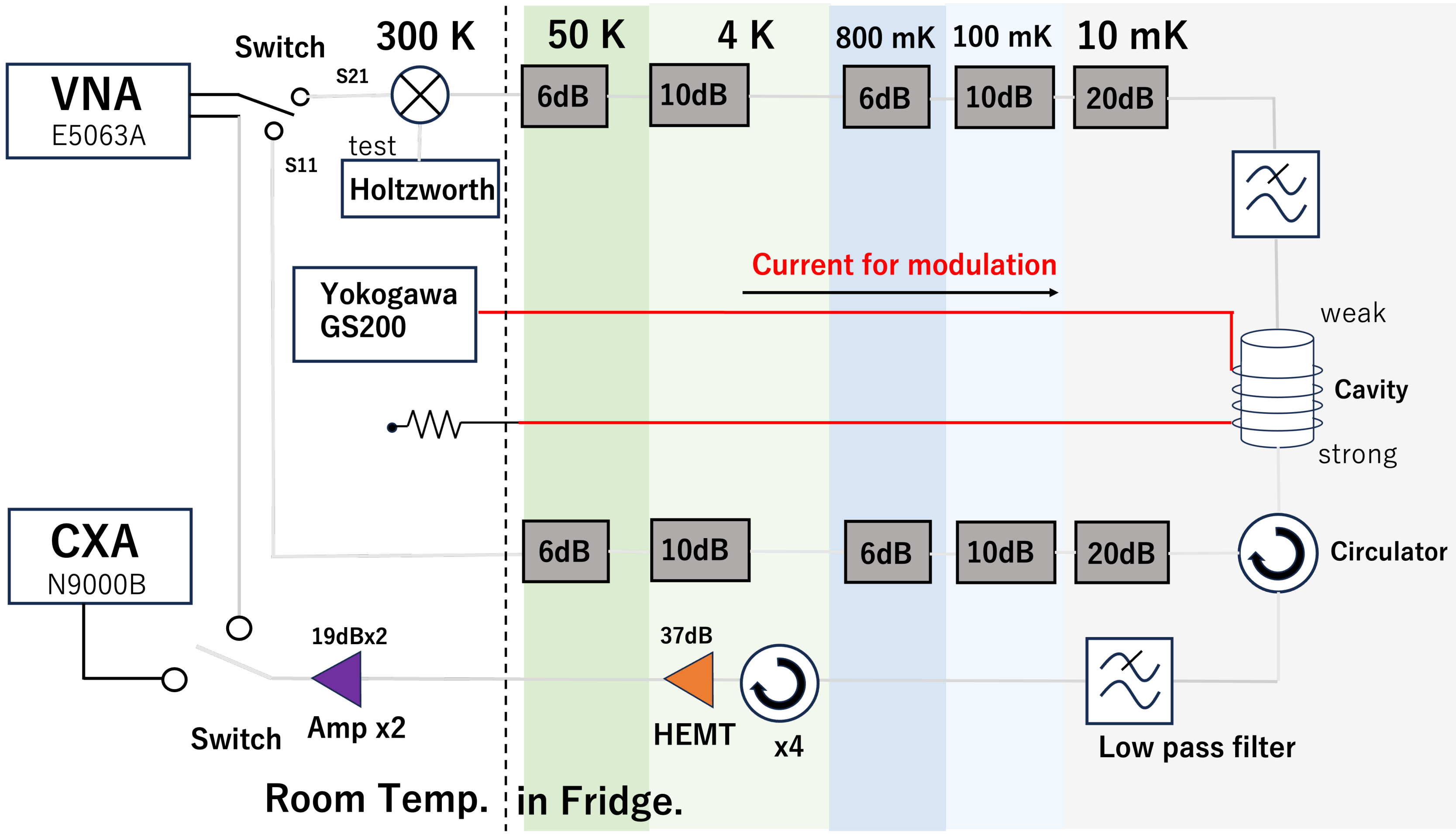
Measurement methods

Well-established measurement methods in haloscope experiments



Methods step by step part0

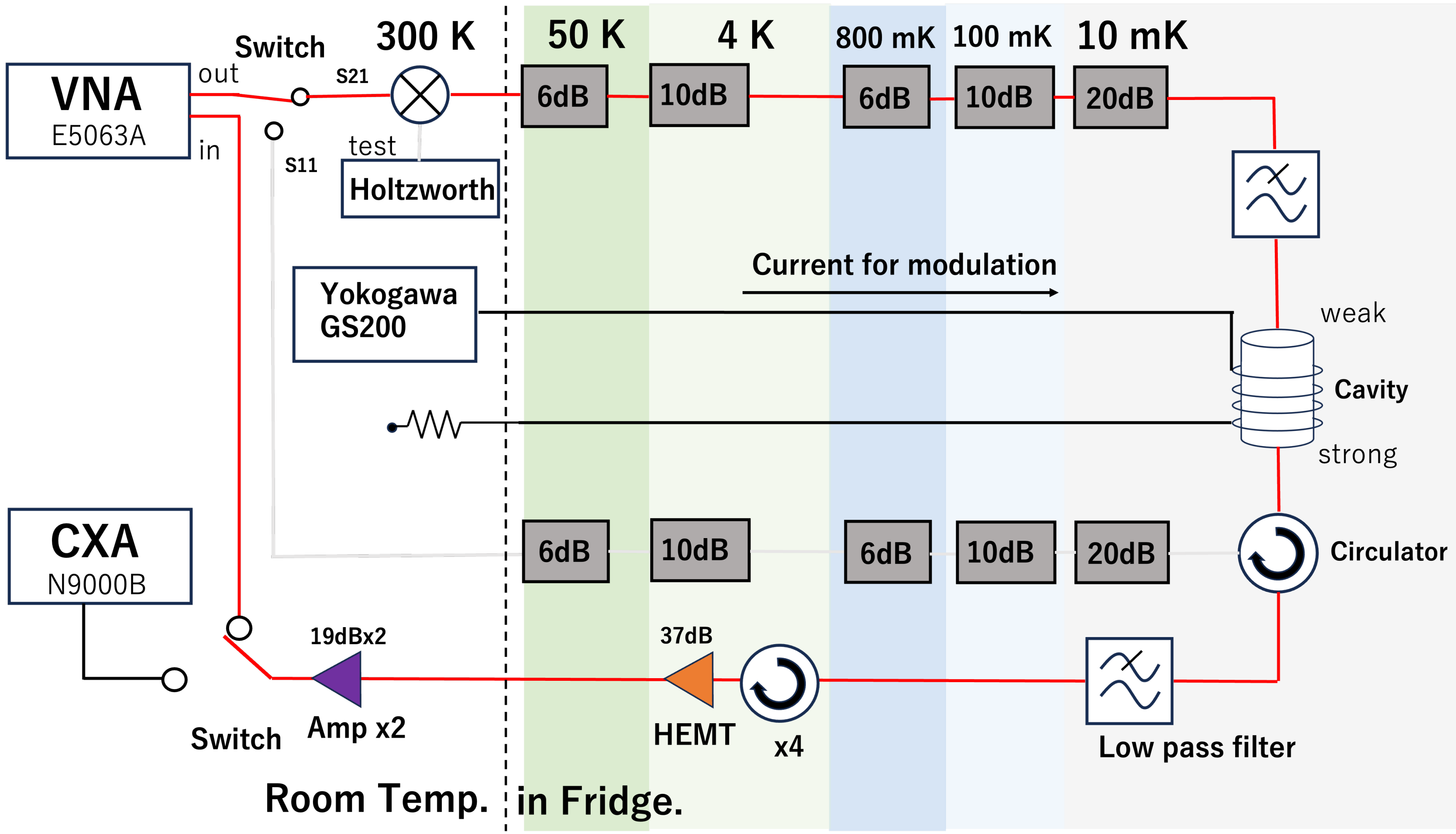
0.Varying DC current suitably (considering the performance check)



Method step by step part1

1.Measure S21 by VNA

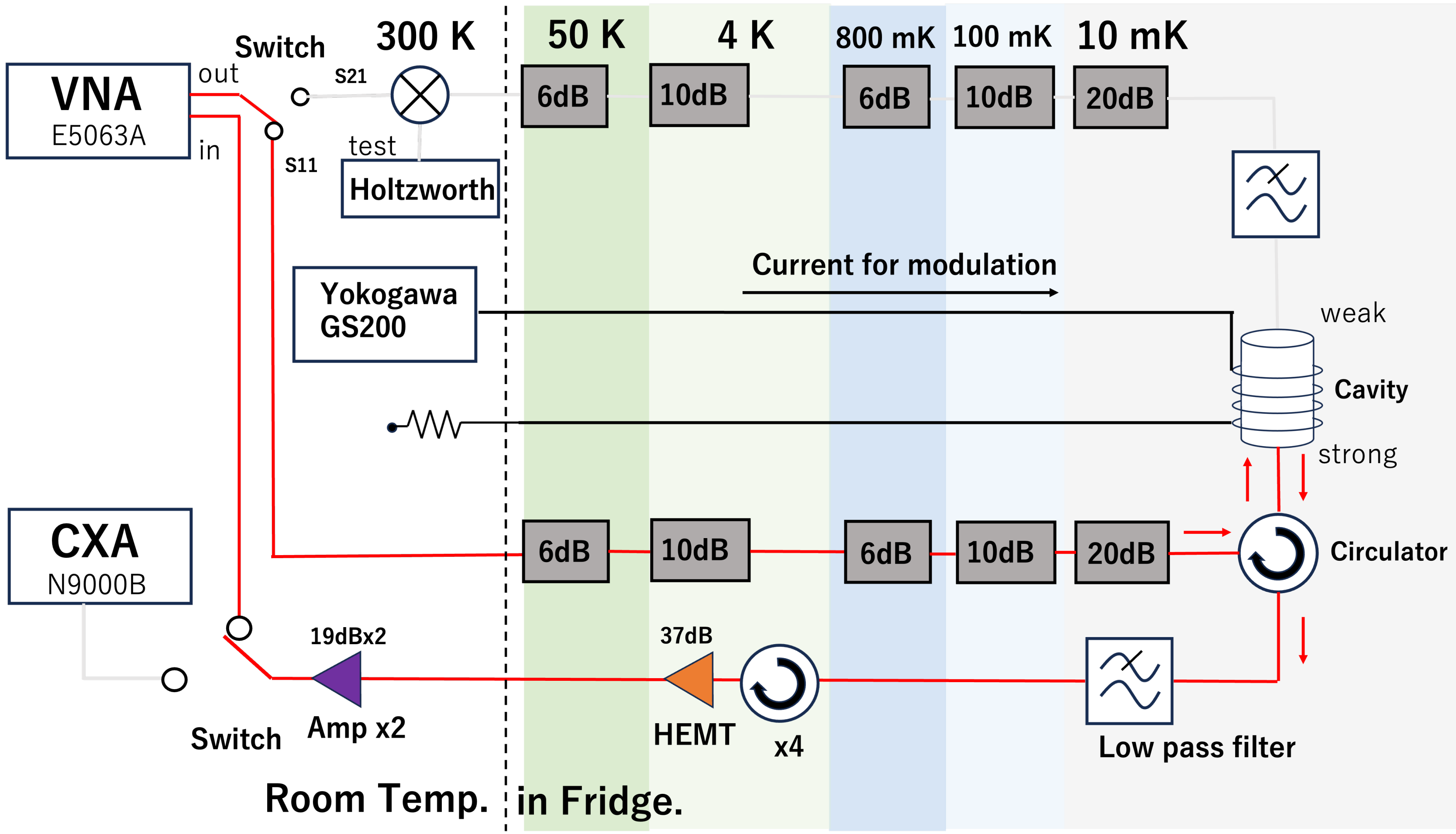
for Q and center frequency



Method step by step part2

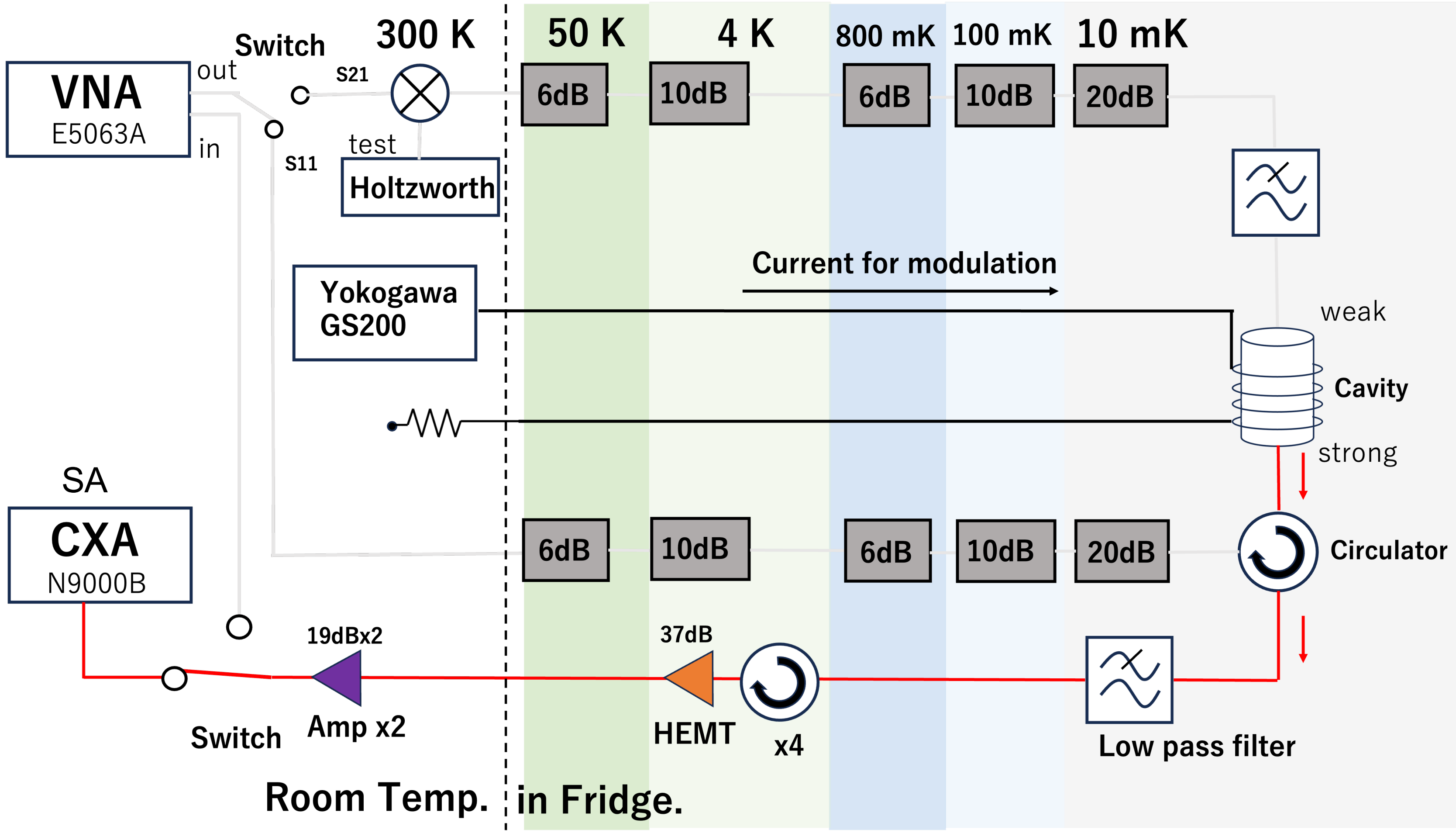
2.Measure S11 by VNA

for β



Method step by step part3

3.Data-taking by spectrum analyzer



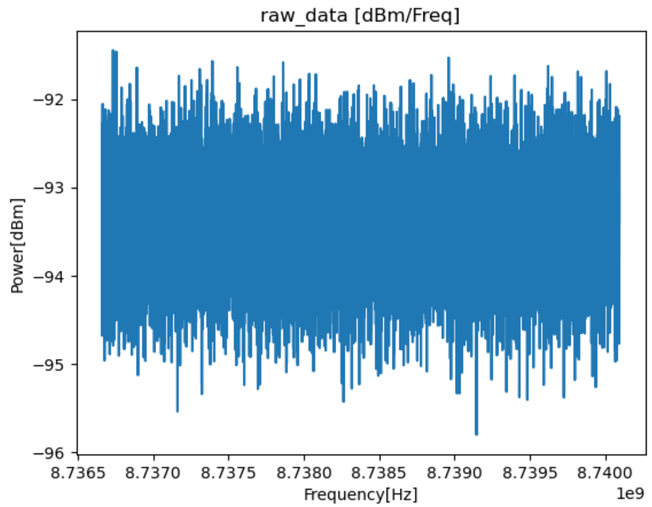
Data taking & Analysis

Data taking:

・Data was taken on July 24th, July 30th, and Aug 1st in 2024.

・About 1600 Spectra is totally taken.

・one Measurement of data-taking 1 spectrum took 1 min.



A sample of raw data

Data selection and filters:

・Exclude data in which cavity's line shape collapsed

judged by β, Q, χ^2

・2-order Savitzky-Golay filter

・Maxwell-Boltzmann filter

⟶ All filtered spectra are finally combined.

The Parameters in this experiment

The parameters of our setup

Each parameter is in the below table,

parameter	value	explanation	others
$m_{A'}$	Resonant frequency	dark photon mass	8.733 GHz$=36.1$ μeV
$\rho_{A'}$	0.45 GeV/cm^3	dark photon density	SJ Asztalos et al. (2001)
β	measured	antenna coupling	
b	200 Hz	bandwidth	setting of spectrum analyzer
T_{sys}	3.76 K	system noise	extrapolate hotload measurement
V_{eff}	3.15 cm^3	effective volume	$V \times \mathrm{formfactor}$
Q_L	measured	(loaded) quality factor	
η	0.98	attenuation factor	
N	100	sample number	

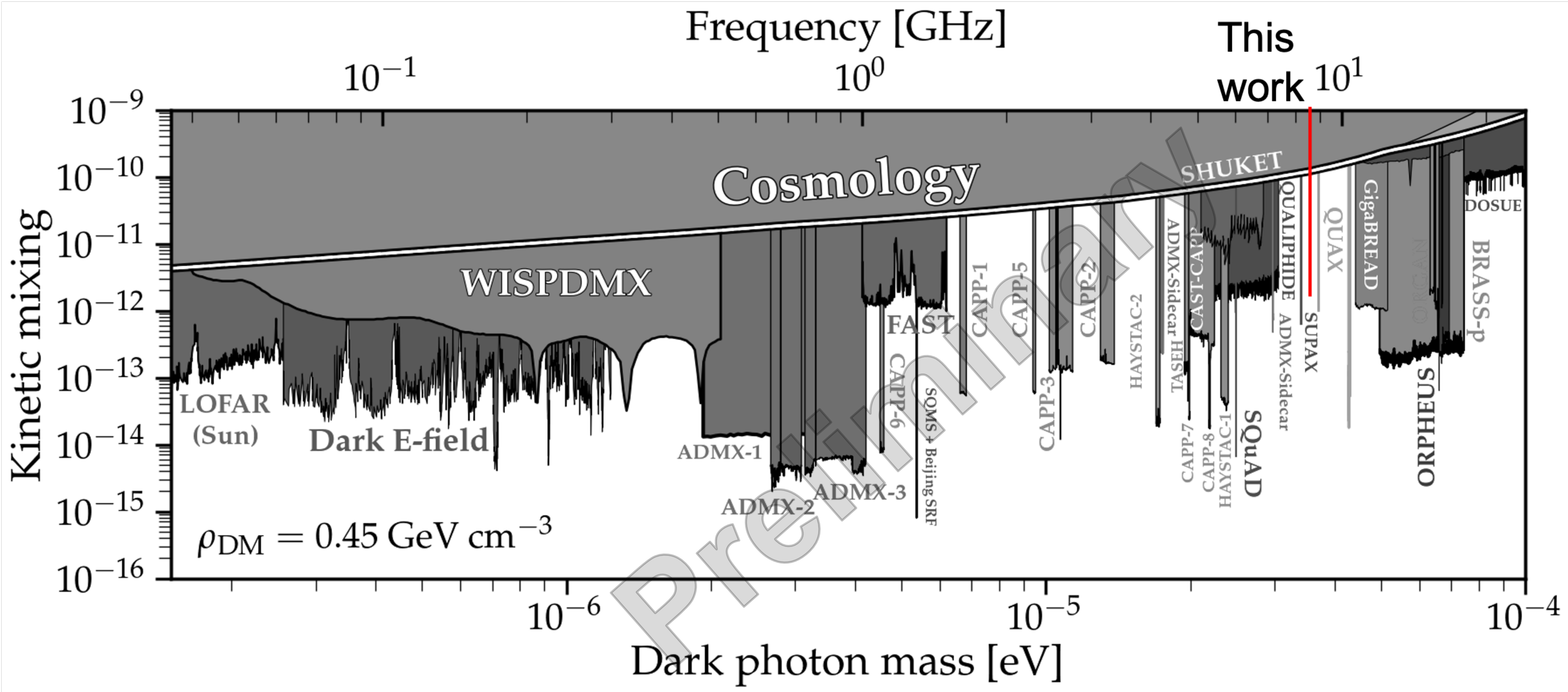
$$P_{A'} = \eta \chi^2 m_{A'} \rho_{A'} V_{eff} Q_L \frac{\beta}{\beta + 1}$$

$$P_{noise} \sim \frac{k_b b T_{sys}}{\sqrt{N}}$$

Results

90% exclusion limit of kinetic mixing χ

No significant excess



Results

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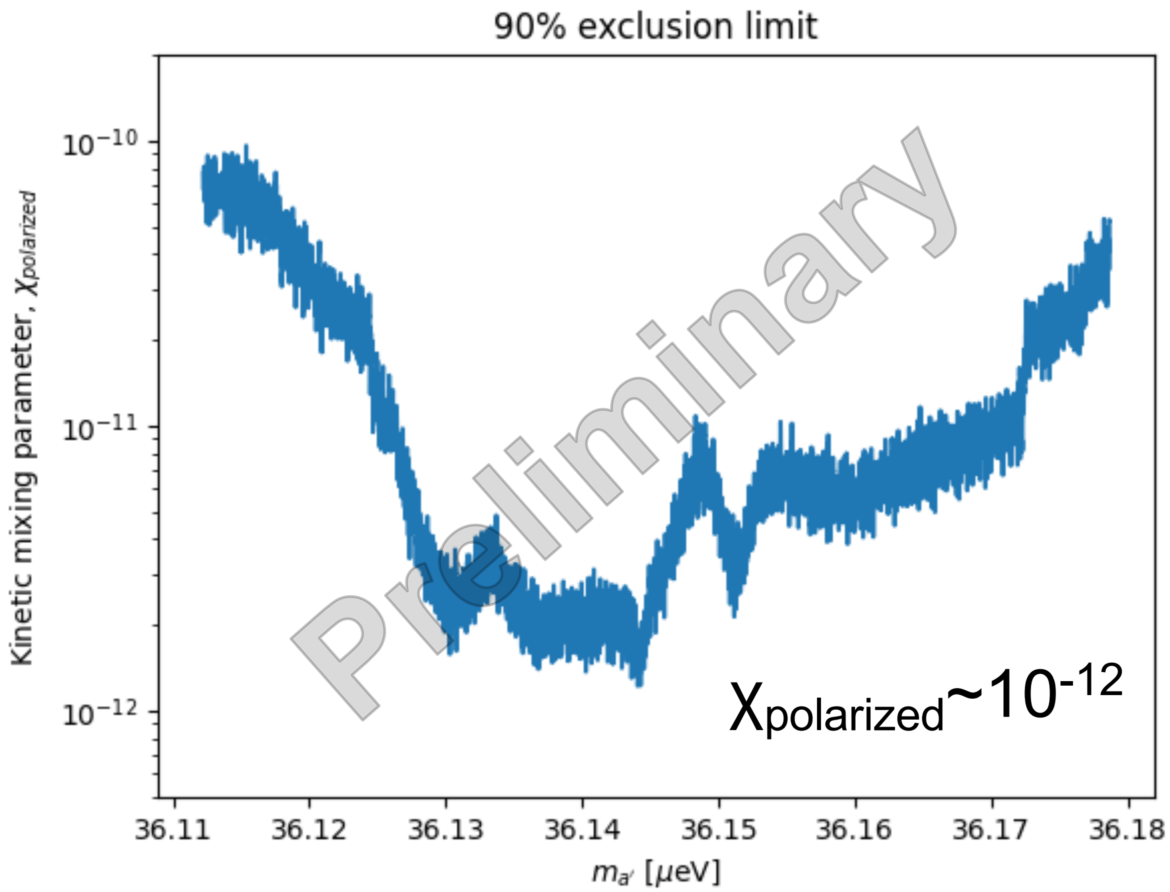
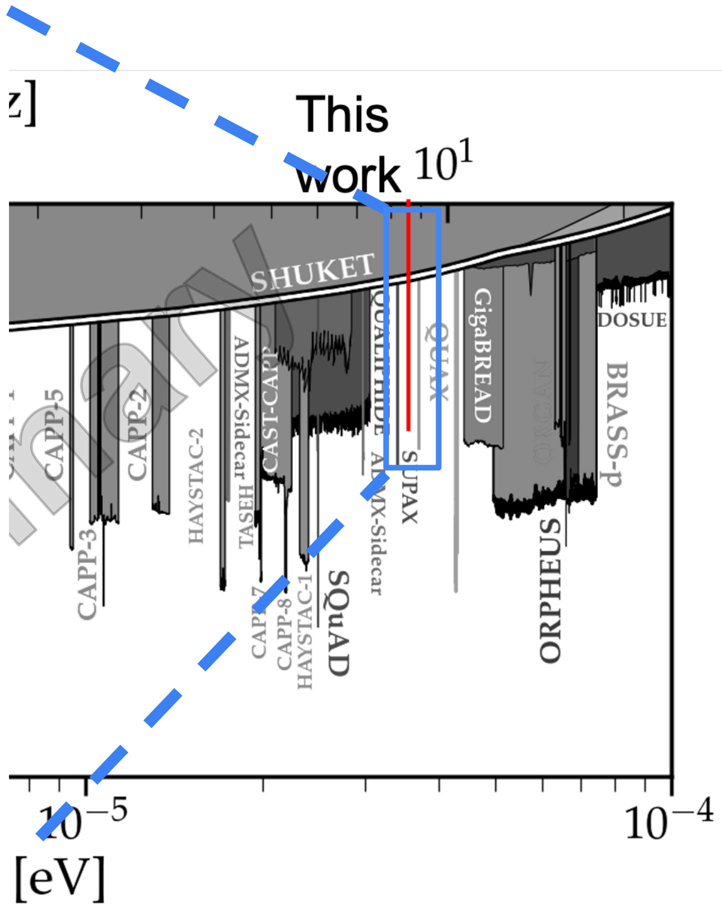




Future prospect

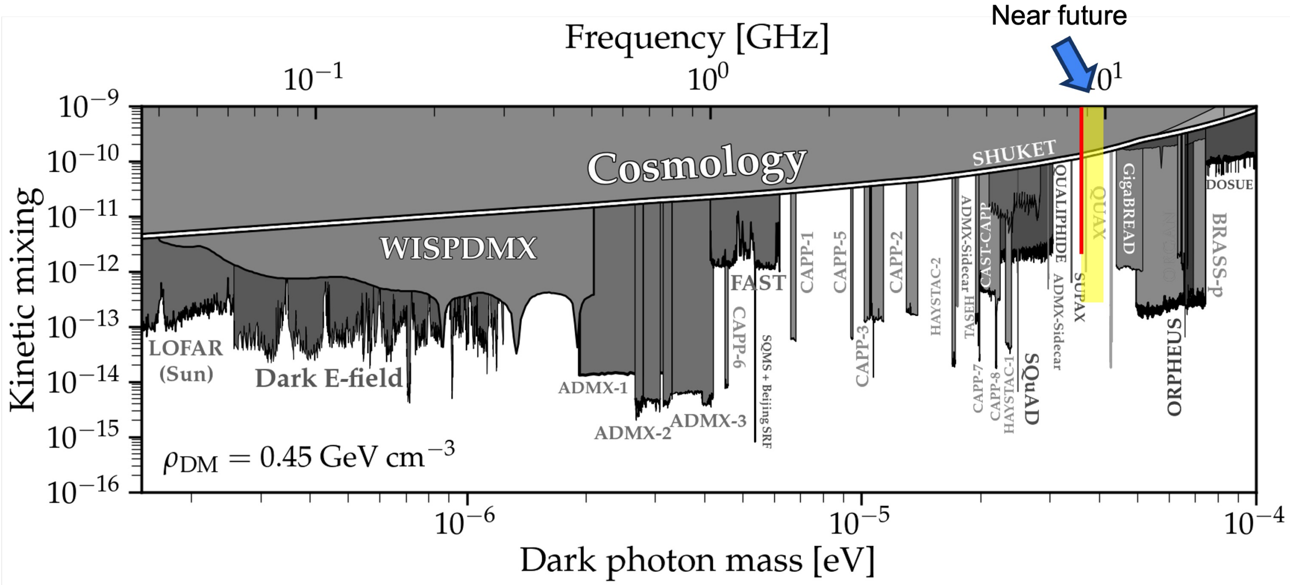
- Expand search regime (sensitivity, wide scan range)
  - Sensitivity→ high Q cavity (now: Cu cavity, Q=10^4), low system noise
  - scan range→ high Q, strongly coupled qubit

Now trying

Both cavity and qubit *(Long lifetime)*

e.g.)Change islands distance *d...(shift~1GHz)*

Near future



Future prospect

- Expand search regime (sensitivity, wide scan range)
  - Sensitivity→ high Q cavity (now: Cu cavity, Q=10^4), low system noise
  - scan range→ high Q, strongly coupled qubit **Now trying**

  Both cavity and qubit *(Long lifetime)*

  e.g.)Change islands distance *d...(shift~1GHz)*

- Combine with a qubit measurement
  - Single photon counting
  - Direct excitation enhancement (related poster by Karin Watanabe)

- For Axion detection (to introduce strong B field)

Thank you for your attention!

APPENDIX

How to calculate the 90% exclusion limit

90% exclusion limit

P and χ^2 have proportional relationship, so

$$\frac{\chi_{90\%}}{\chi} = \sqrt{\frac{P_{90\%}}{P}}$$

that is,...

$$\frac{\chi_{90\%}}{\chi(=1)} = \sqrt{\frac{P_{90\%}}{P(\chi=1)}}$$

$P(\chi = 1)$ is a constant and determined by the parameters of the set up.
You should find the $P_{90\%}$.

Truncated gaussian distribution

- ***P>0*** **is imposed on Dark photon signal power**

When you observed a particular power excess δ_s,

$$90\% = \frac{\int_0^{P_a} N(\mu = \delta_s, \sigma = \sigma_s) dP_a}{\int_0^{\infty} N(\mu = \delta_s, \sigma = \sigma_s) dP_a}$$

P_a...Dark matter signal power

Savitzky-Golay filter 1/4

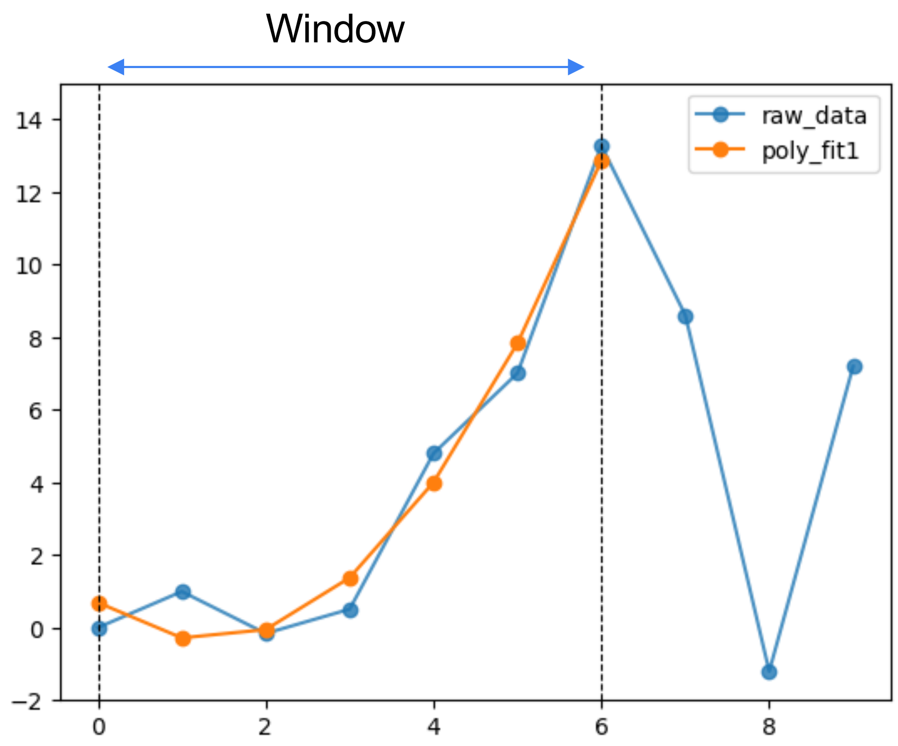
A kind of moving average to ignore sharp peaks and smooth the signal.

1. Set window.
2. Approximate n-order polynomial equation

$$f_n = C_0 + C_1 x + C_2 x^2 + \ldots + C_n x^n$$

3. Pick up the center point of the fit curve

e.g.) When you set window=7, you should pickup 4th point of the curve.



↑ 2nd order approximation

Savitzky-Golay filter 2/4

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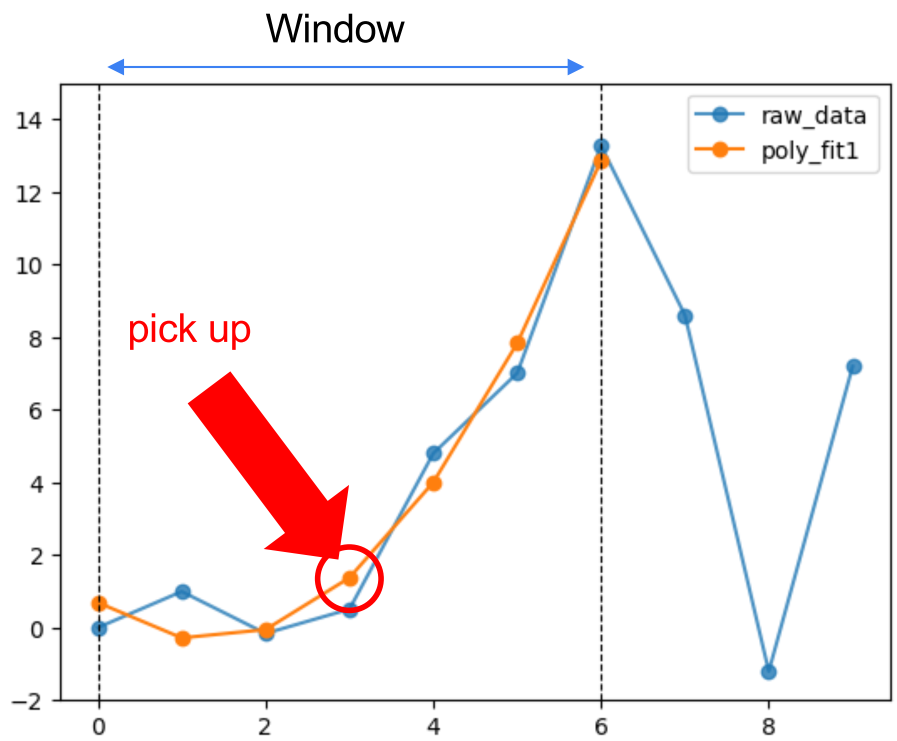
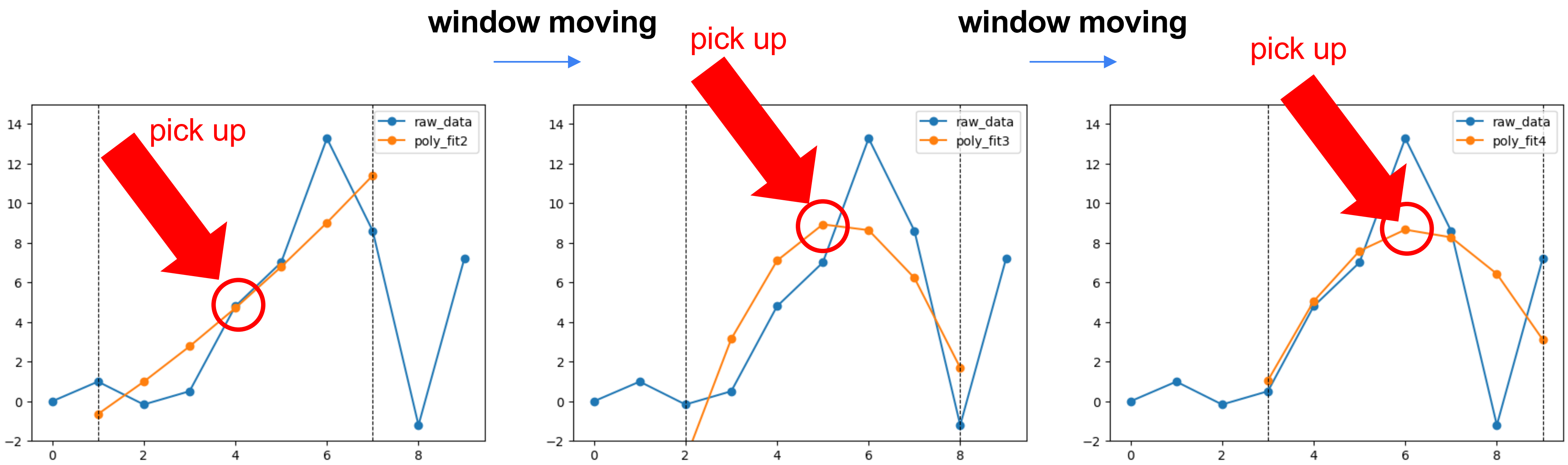


↑ 2nd order approximation

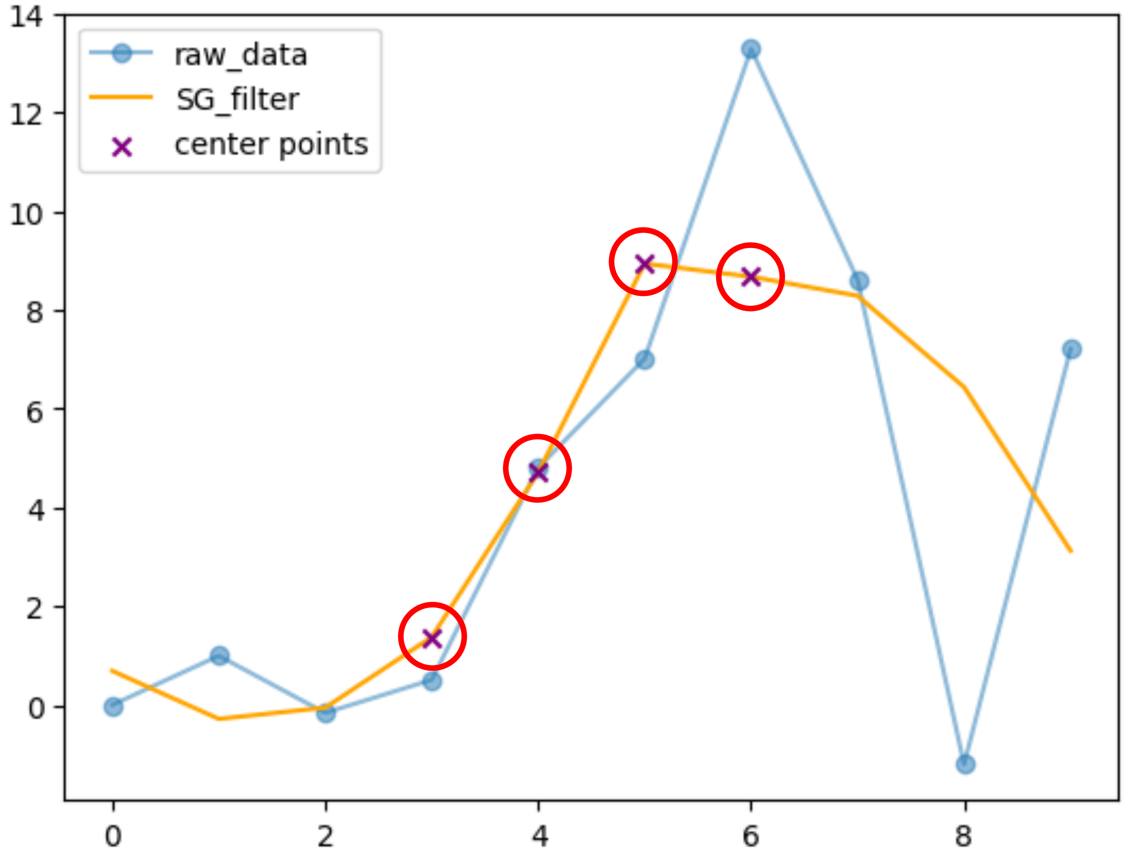
Savitzky-Golay filter 3/4

Then you move the window in parallel, fit, and pick up each center point...



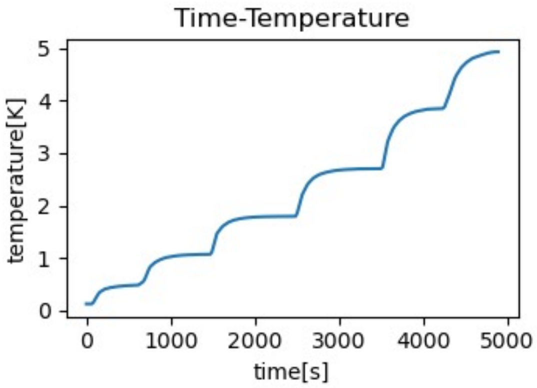
Savitzky-Golay filter 4/4

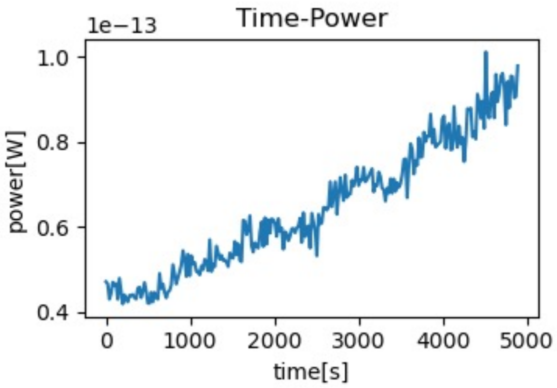
Finally, the picked-up center points are filtered spectrum.

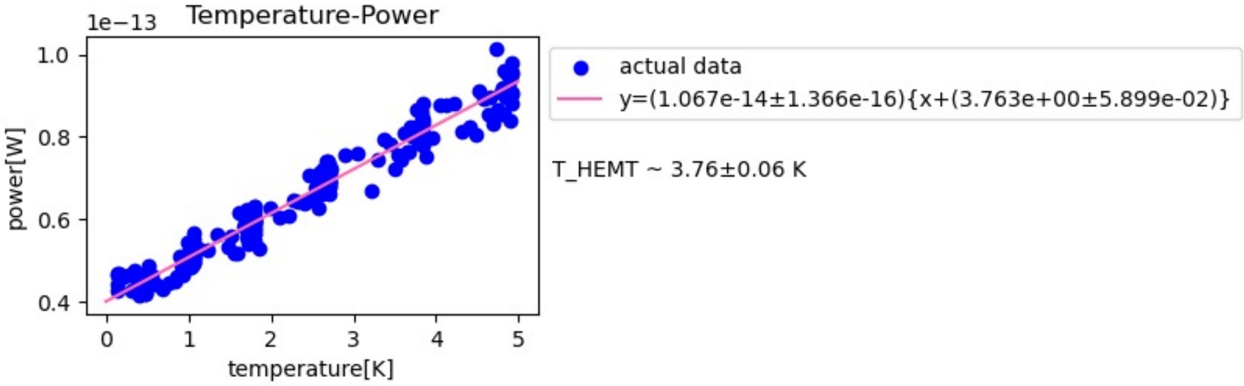


Tsys estimation

$$T_{sys} \sim 3.76\,\mathrm{K}$$







T_HEMT ~ 3.76±0.06 K