Experimental test of axion cosmology around 22 μeV [5.3 GHz] with a multi-cell cavity and a Josephson parametric amplifier

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International workshop on multi-probe approach to wavy dark matters

2023. 12. 01.

CAPP

Center for Axion and Precision Physics Research

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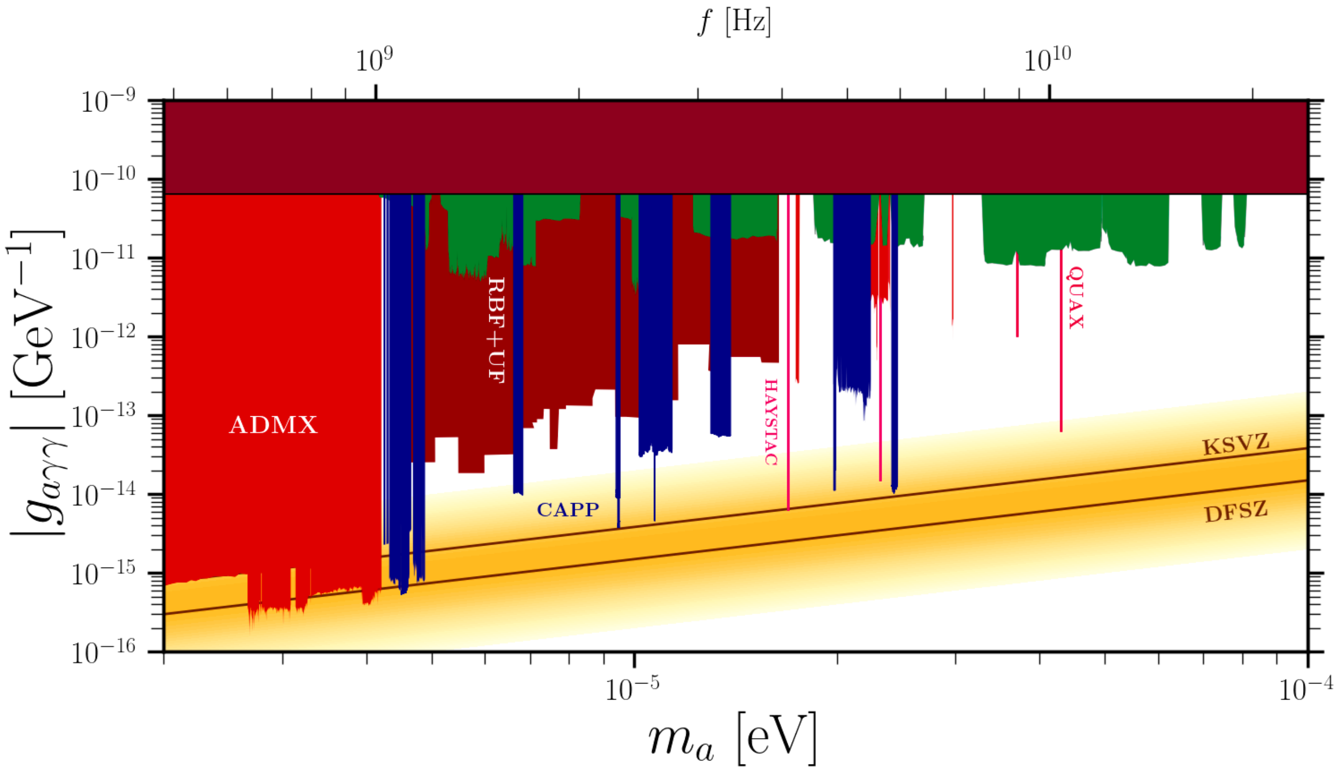
- Conclusion

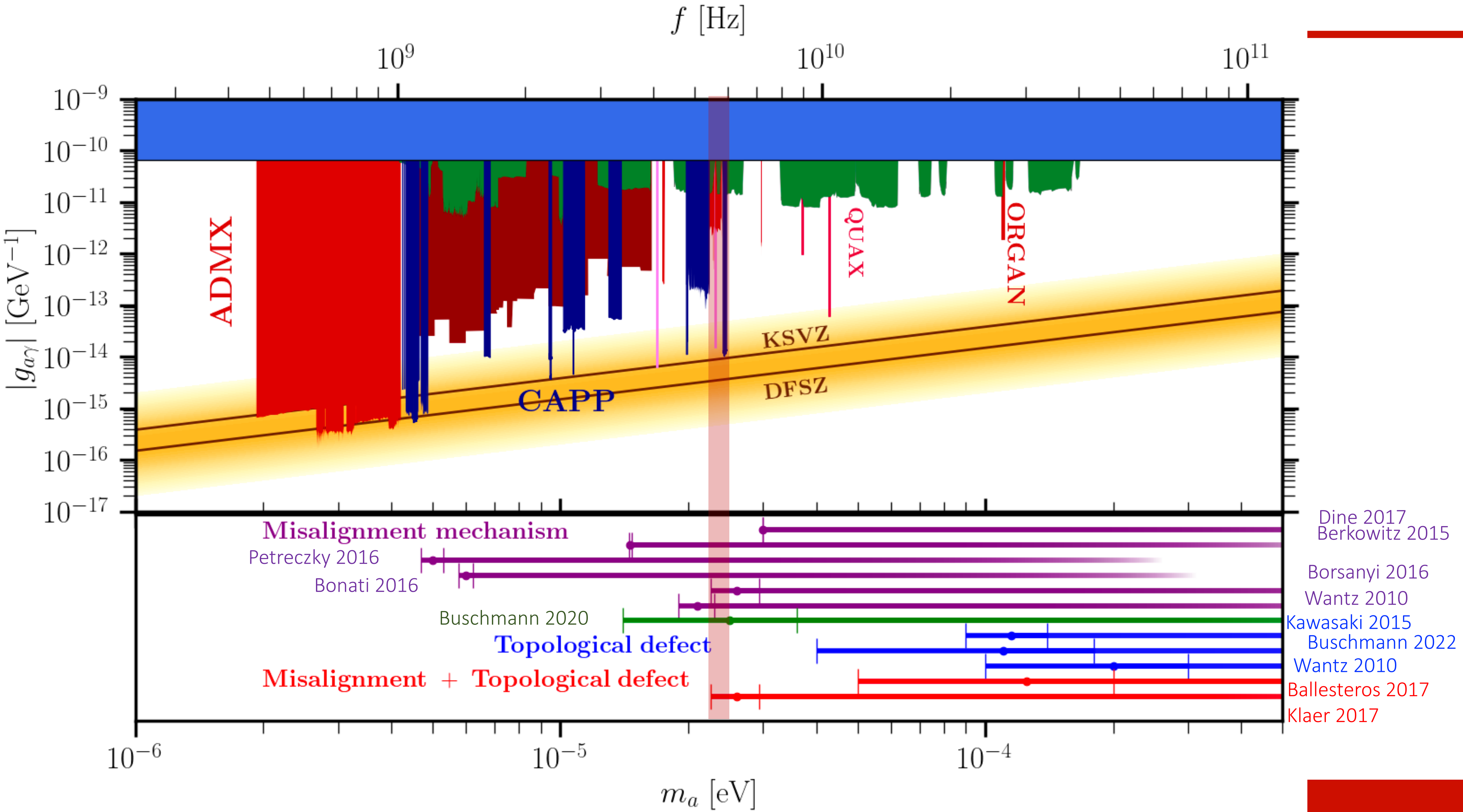
Axion haloscope

- QCD axion: Solution for the strong CP problem [1]
- QCD axion as Cold dark matter candidate: $1\ \mu\text{eV} < m_a < 10\ \text{meV}$ [2]
- Axion haloscope:
  - Detecting cold dark matter axion from $a - \gamma$ interaction using resonator cavity and high field magnet [3]
  - Scanning rate(SR):
    - $\frac{df}{dt} \propto \frac{g_{a\gamma\gamma}^4 B_0^4 V^2 C^2}{(T_{\text{eff}} + T_a)^2} \frac{Q_L Q_a}{Q_L + Q_a}$ [4]
  - High Q cavity:
    - Superconducting cavity [5]
  - Large volume
  - High magnetic field
  - **High form factor**
  - ***Low noise amplifier:***
    - **Quantum noise amplifier**



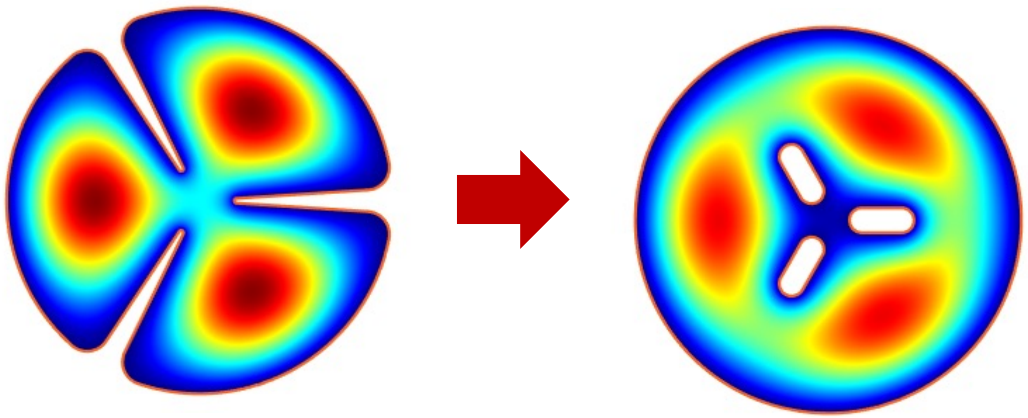
[1] R. D. Peccei and H. R. Quinn, 1977
[2] C. Hagmann and P. Sikivie, 1991, G. Raffelt and D. Seckel, 1988
[3] P. Sikivie. 1983
[4] D. Kim, J. Jeong, S. Youn, Y. Kim, and Y. K. Semertzidis, 2020
[5] D. Ahn, et al, 2022,

High mass axion haloscope

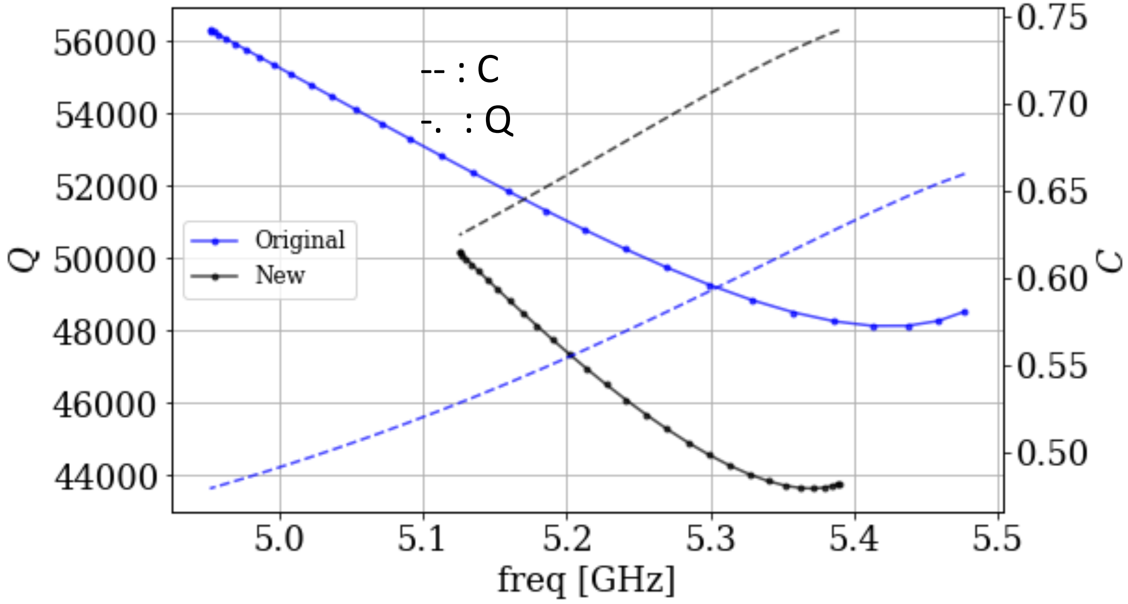


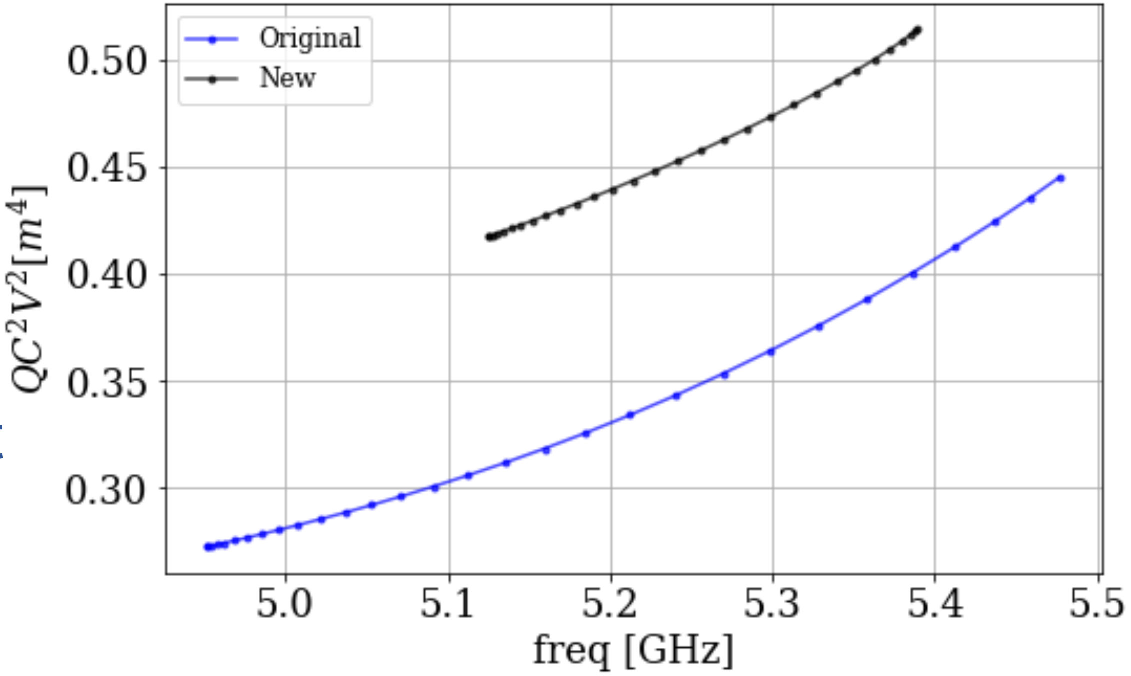
CAPP-12T experimental setup

CAPP -12T -cavity



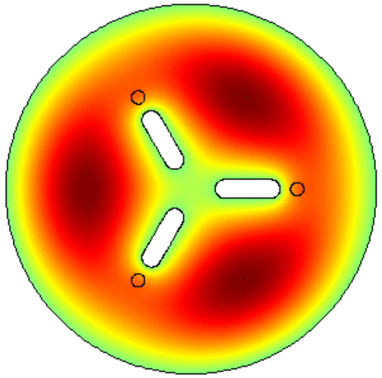
- Original: Pizza cavity [1]
  - Center gap affects tolerance
  - Form factor loss at the edge of chamber
- New: Kiwi cavity
  - Higher form factor → Higher figure of merit
  - Robust against tolerance
  - Narrow tuning range





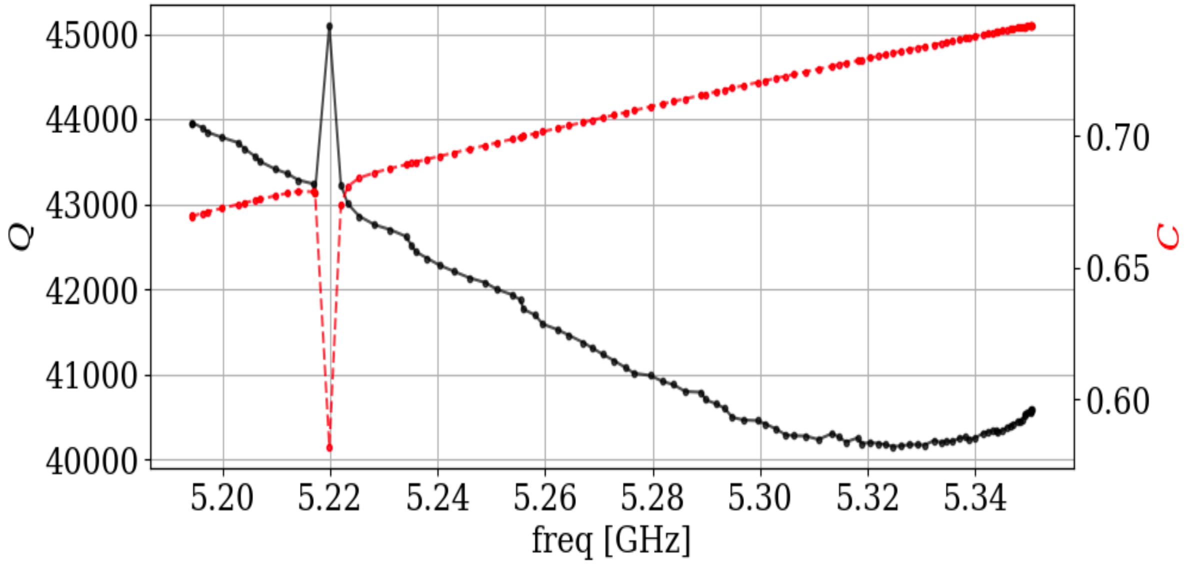
[1] J. Jeong, et al, 2018

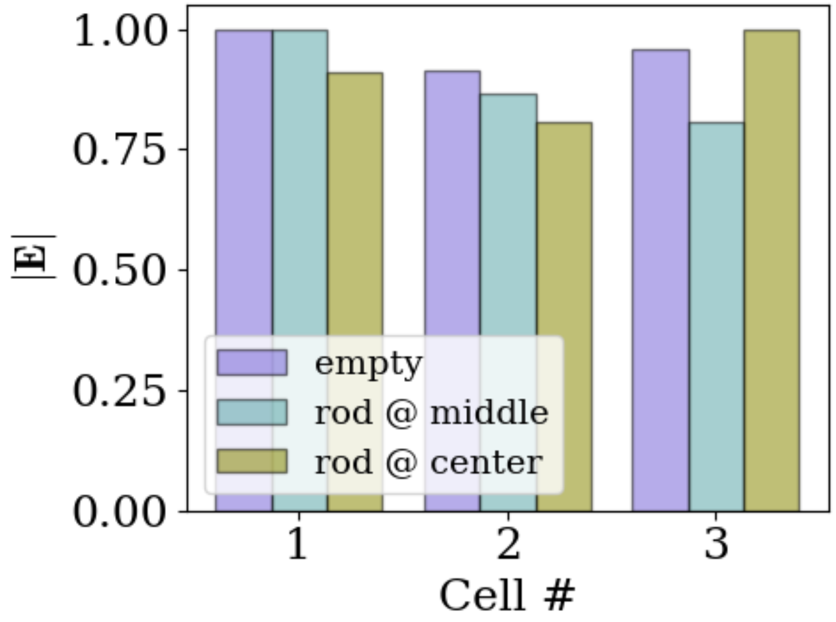
CAPP -12T -cavity



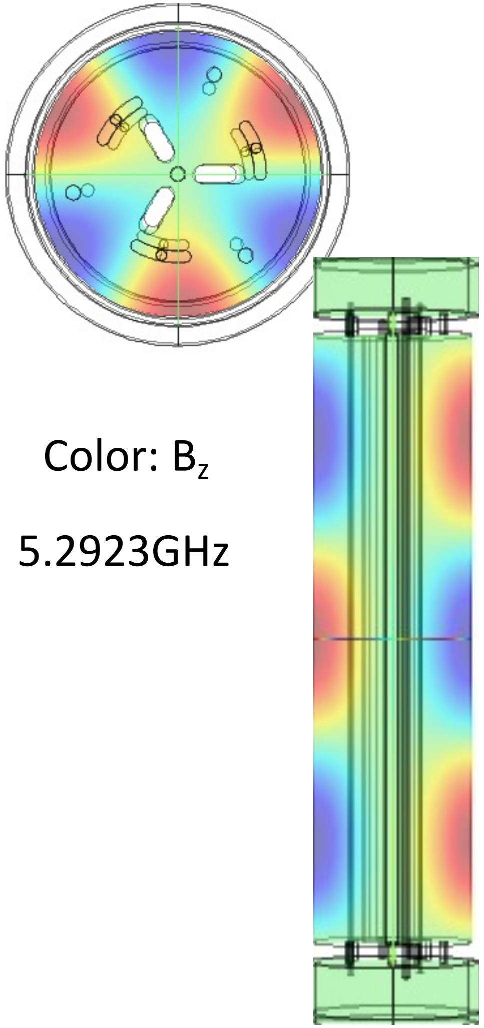
- Kiwi cavity
  - ID: 78 mm
  - IH: 300 mm
  - Rod (2.6mm): Alumina

	$\delta C/C$
Empty [No rods]	0.0013
Rod [Middle of tuning position]	0.0082
Rod [Center of chamber]	0.0075



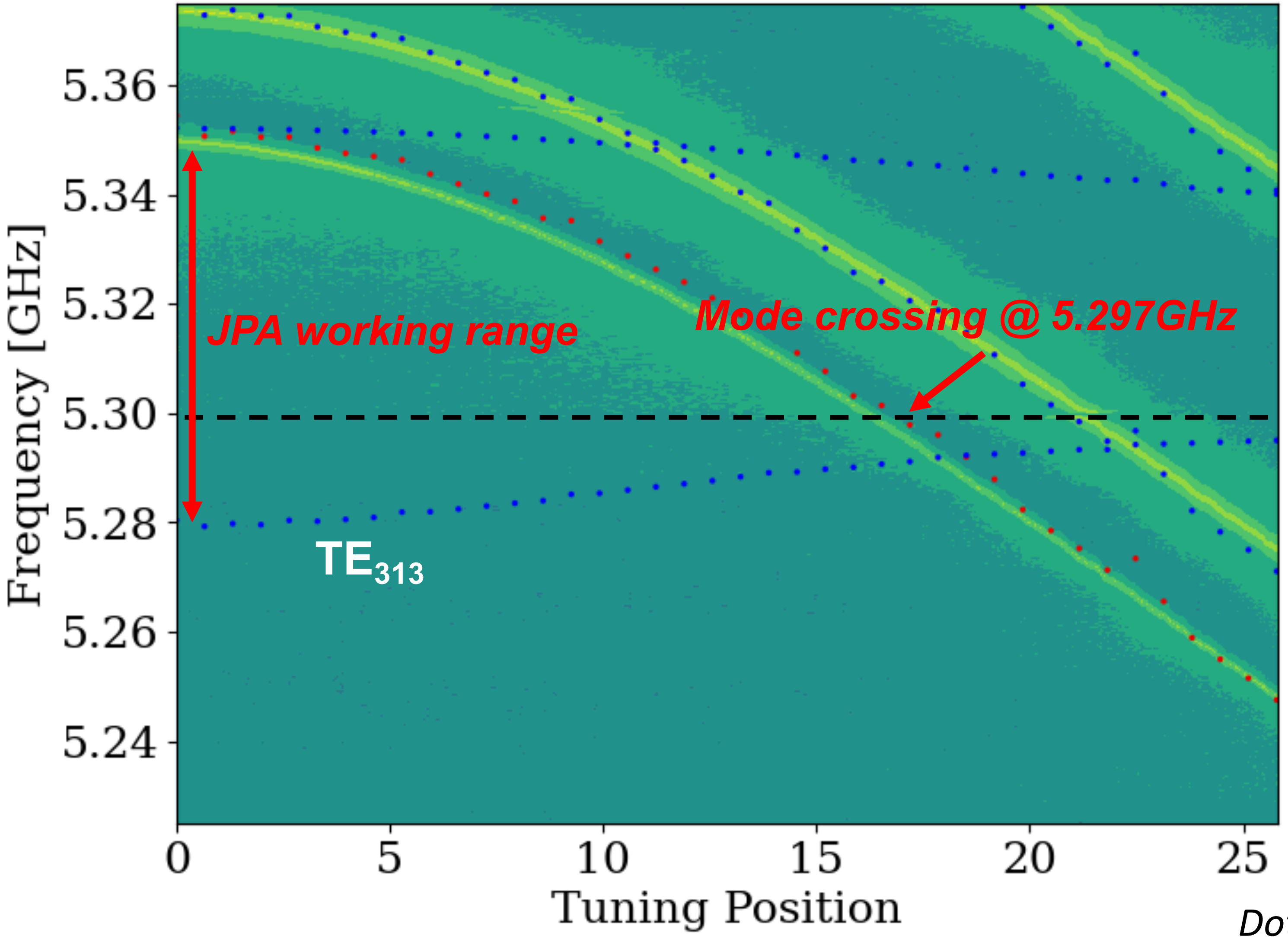


Cavity mode map



Color: B_z

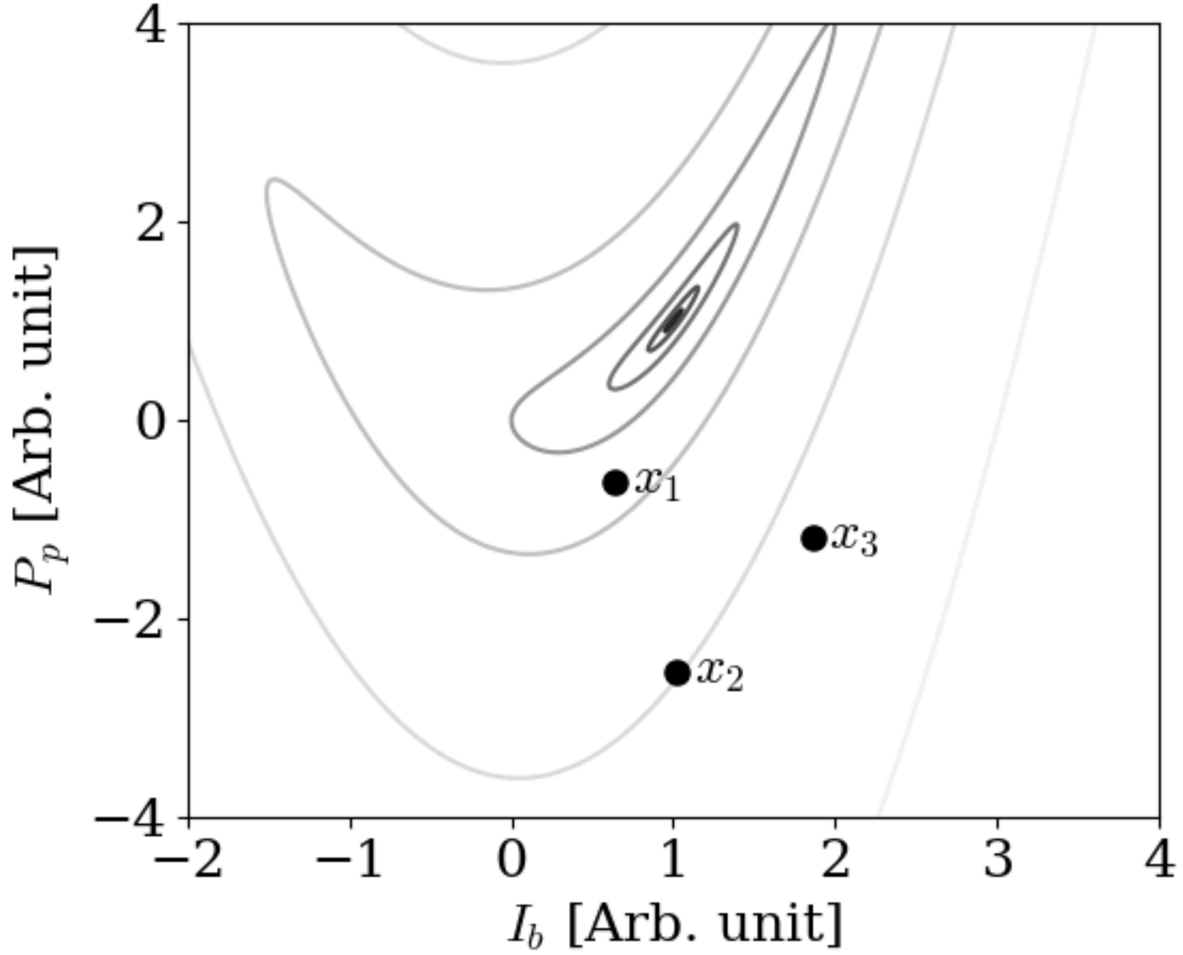
5.2923GHz



Dotted: COMSOL simulation

JPA working point search

- Look up table
  - Scan all parameters of full combination of pump power and bias current
  - Can find least noise working point,
  - Too much time cost
    - JPA power saturation
- Nelder-Mead Method [1]
  - Numerical method to find local minimum of given function
  - Direct search method (derivative-free)
  - Iteration determines time cost
  - Less time cost

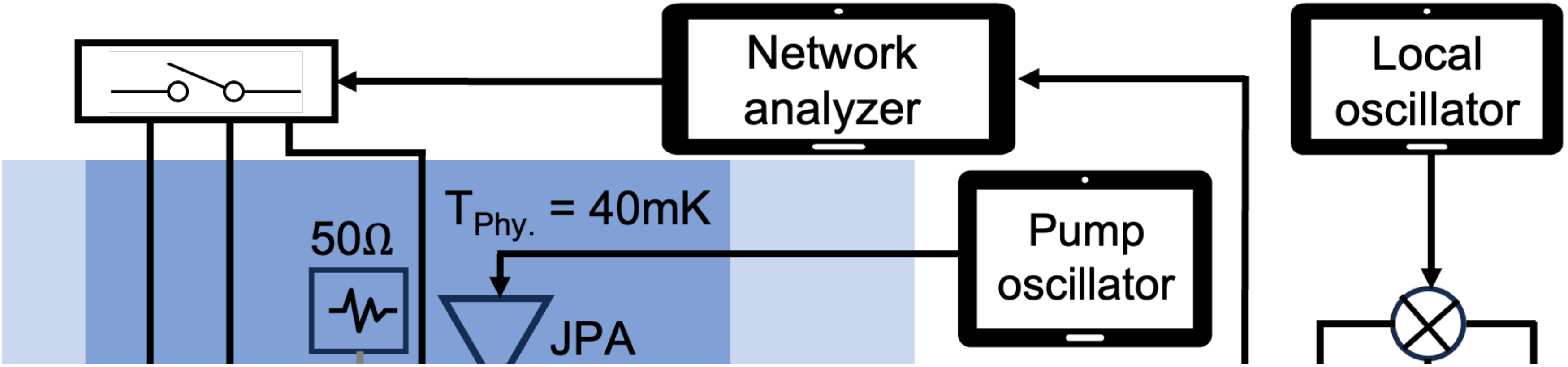


[1] J. A. Nelder and R. Mead, Comput. J. 7, 308 (1965)

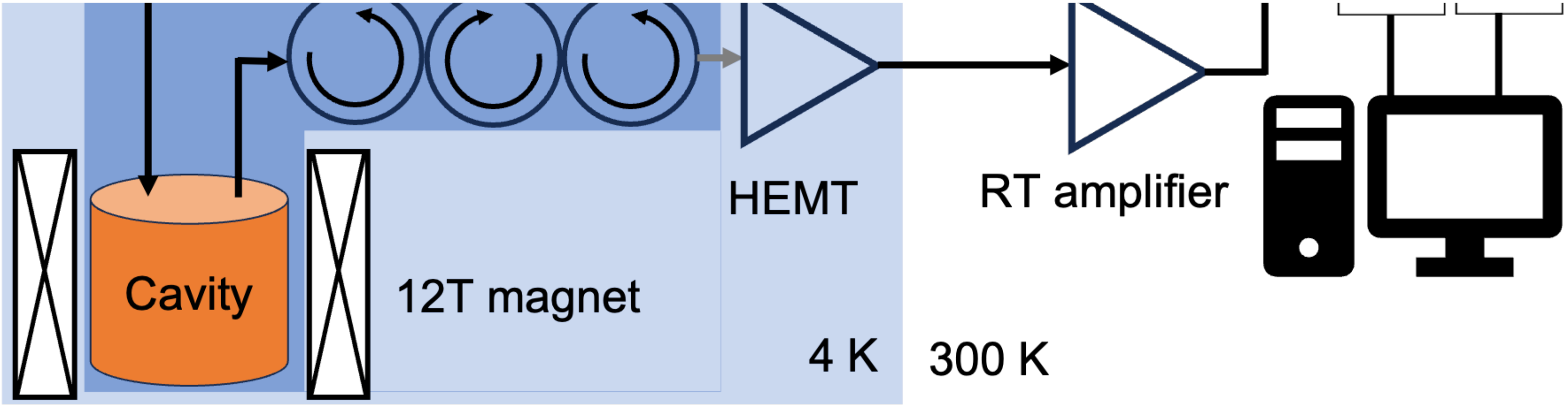
Made by Dr. Junu

Data acquisition & analysis

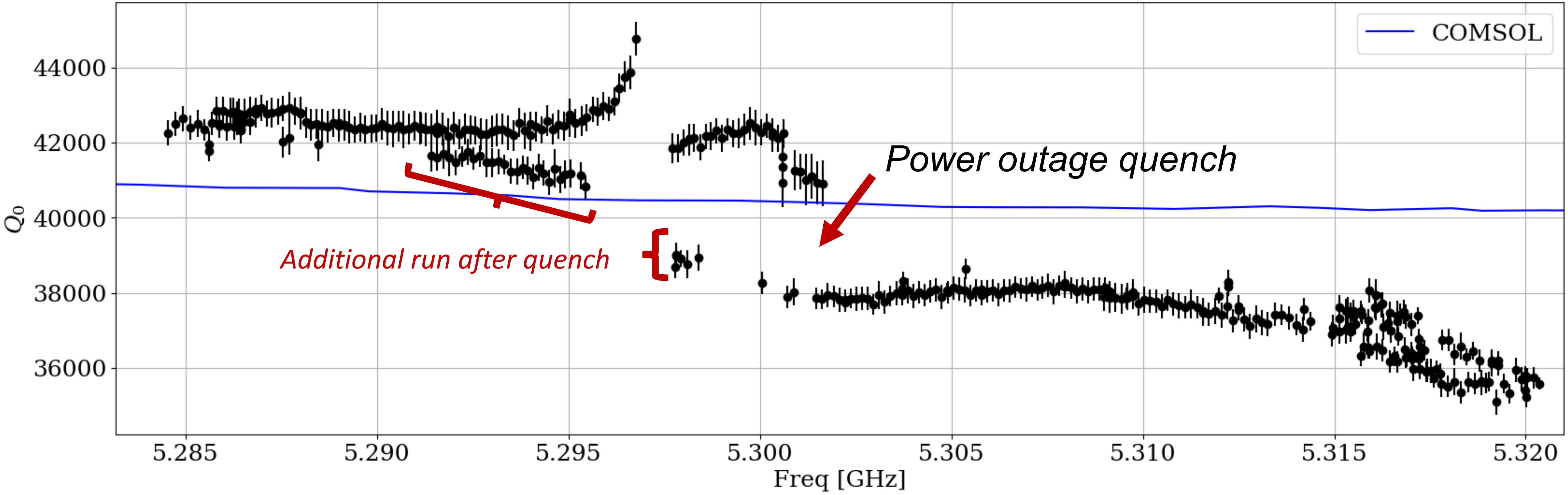
CAPP-12T circuit



Data acquisition: 23.07.01 ~ 23.11.15



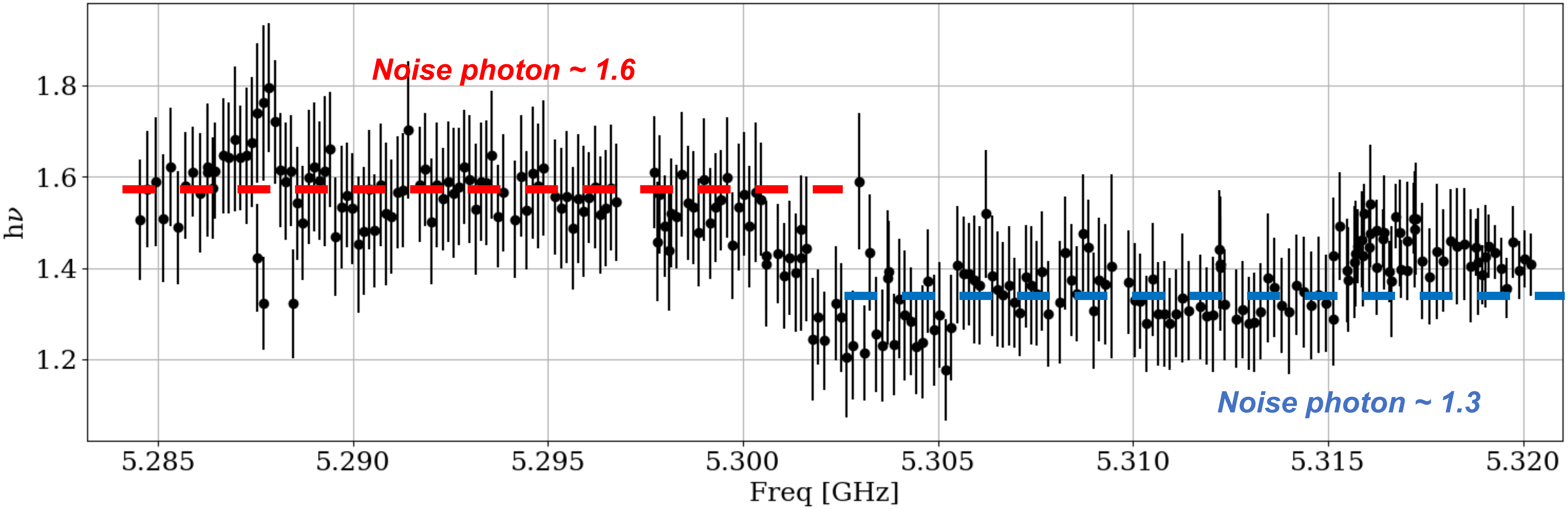
CAPP-12T : Q-factor log



*There was no cavity deformation after quench.

Q drop caused by deep antenna injection, negligible impact on form factor <0.002

JPA noise temperature



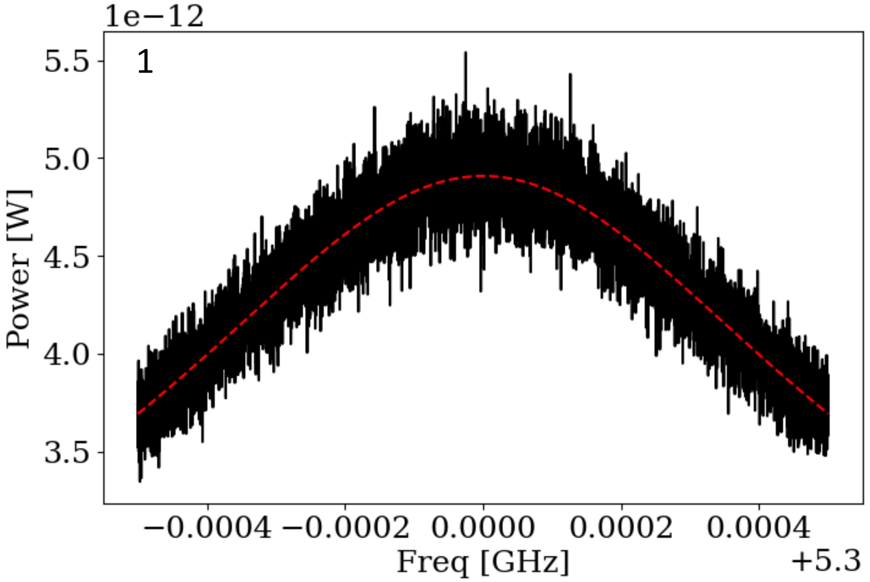
T_{sys}~380 mK

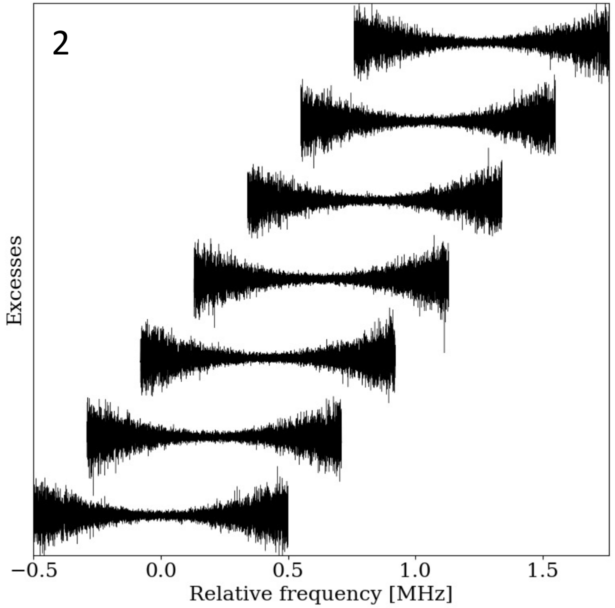
T_{phy}~ 40mK

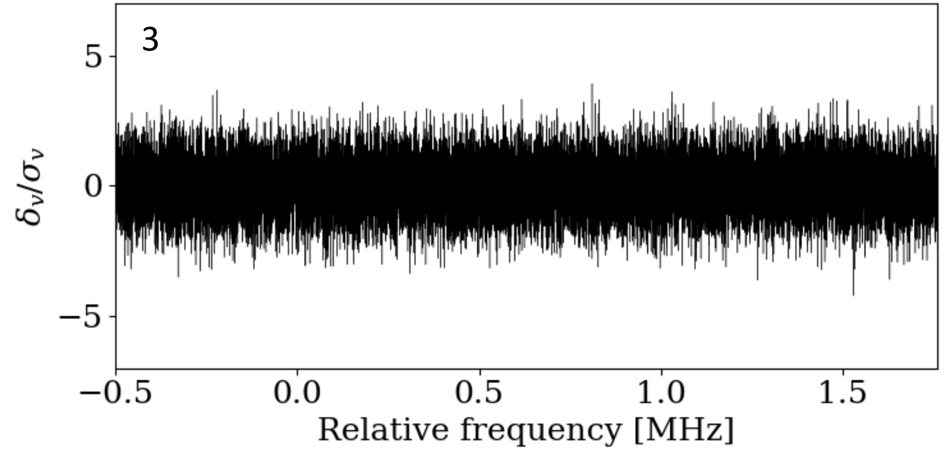
$\delta T^{Y-\text{factor}}$: 7.2mK
δT^{stat}: 30mK

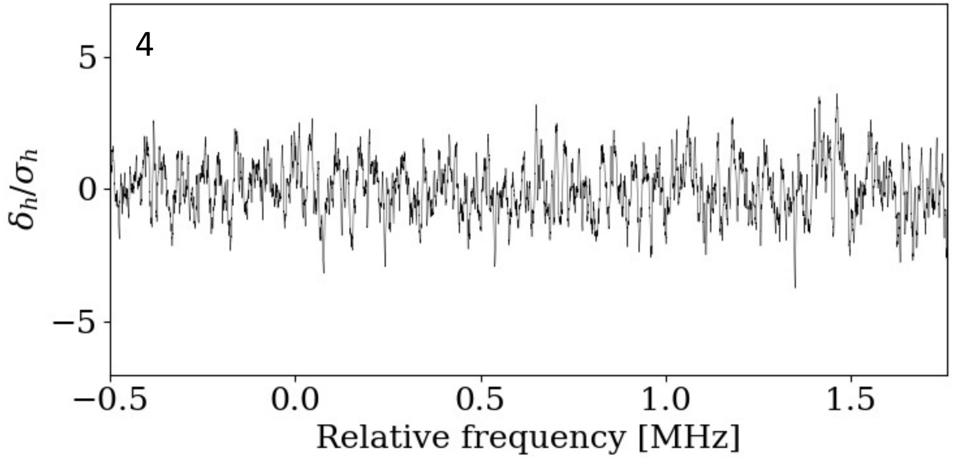
Analysis procedure

1. Baseline removing
2. Scaling spectrum
3. Vertical combination
4. Horizontal combination

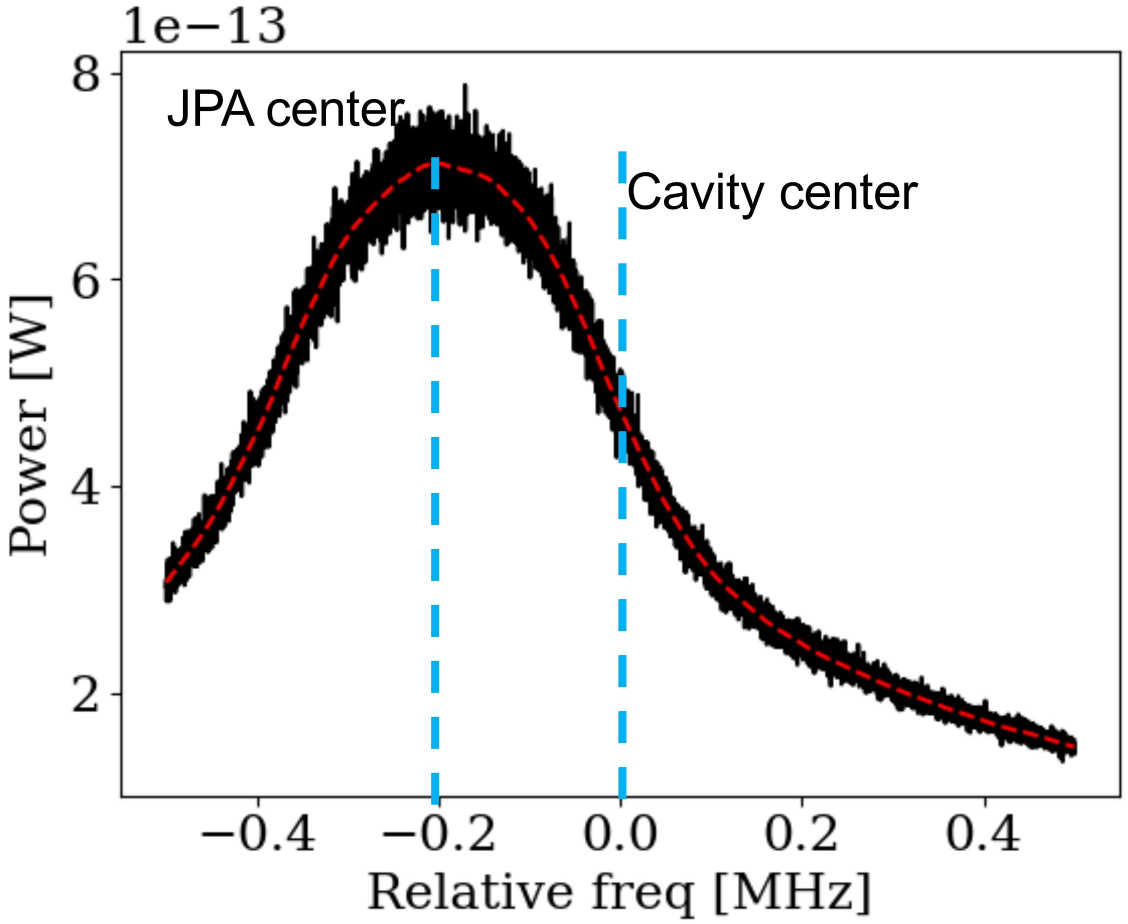








Data analysis – Baseline removing

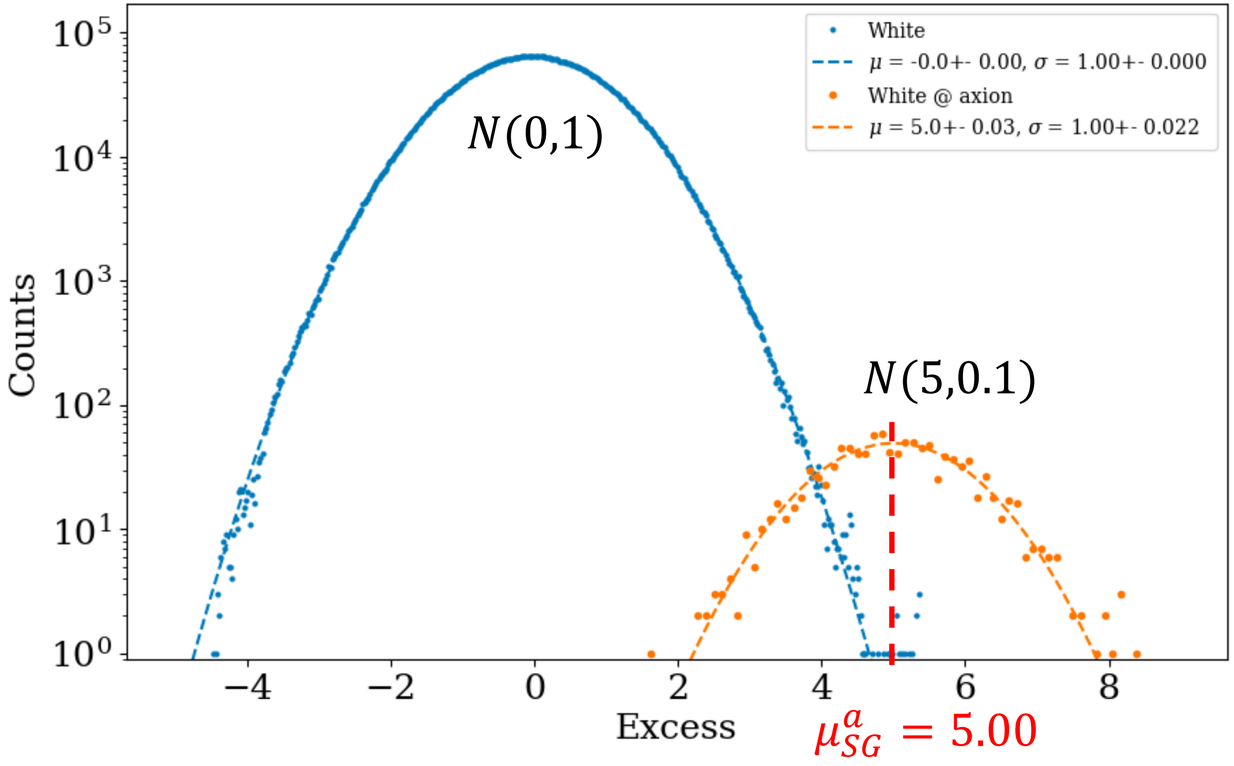


- Example of CAPP-12T experiment
- Impedance mismatch:
  - Non-linearity of JPA and non-perfect circulator,
- Fit spectrum using Savitzky-Golay filter
- Filter does not distinguish “axion” or “noise”
- Monte-Carlo simulation requires to estimate reduction due to filter

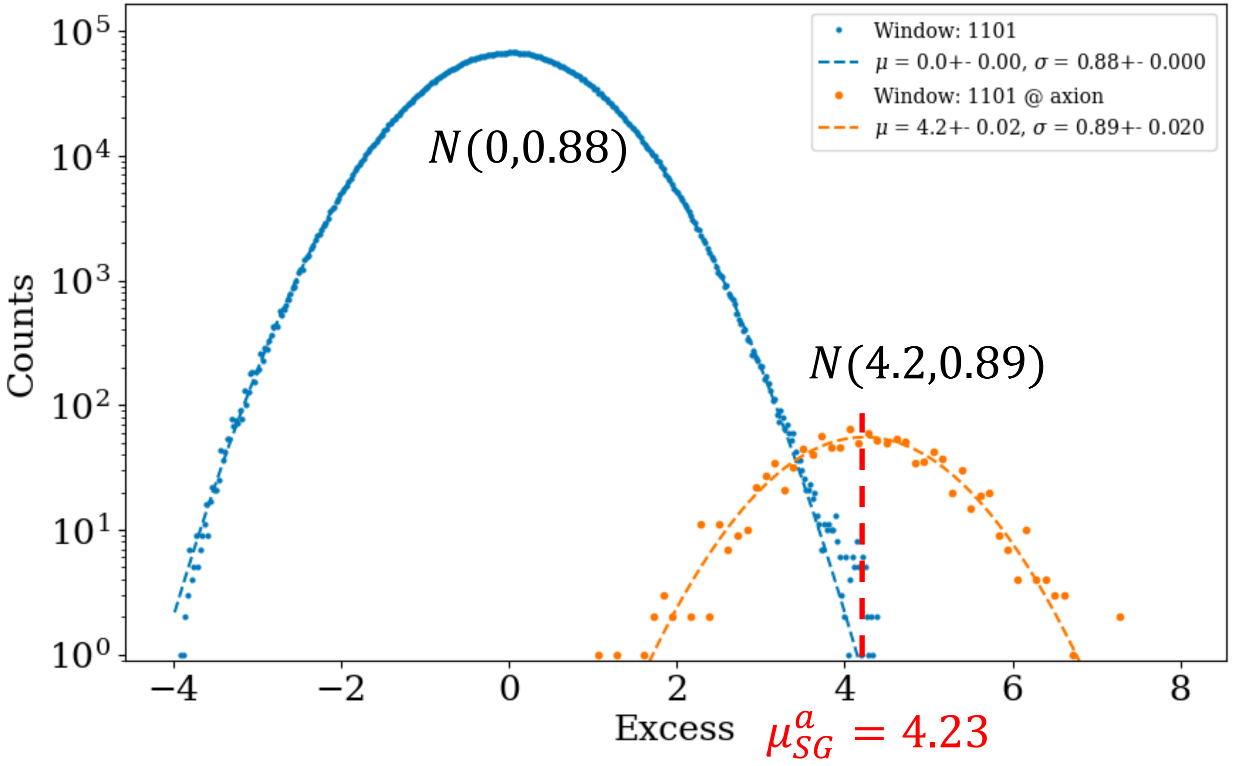
$$\text{Normalized excess} = \frac{spectrum}{baseline} - 1$$

Removal efficiency calculation Example

White noise

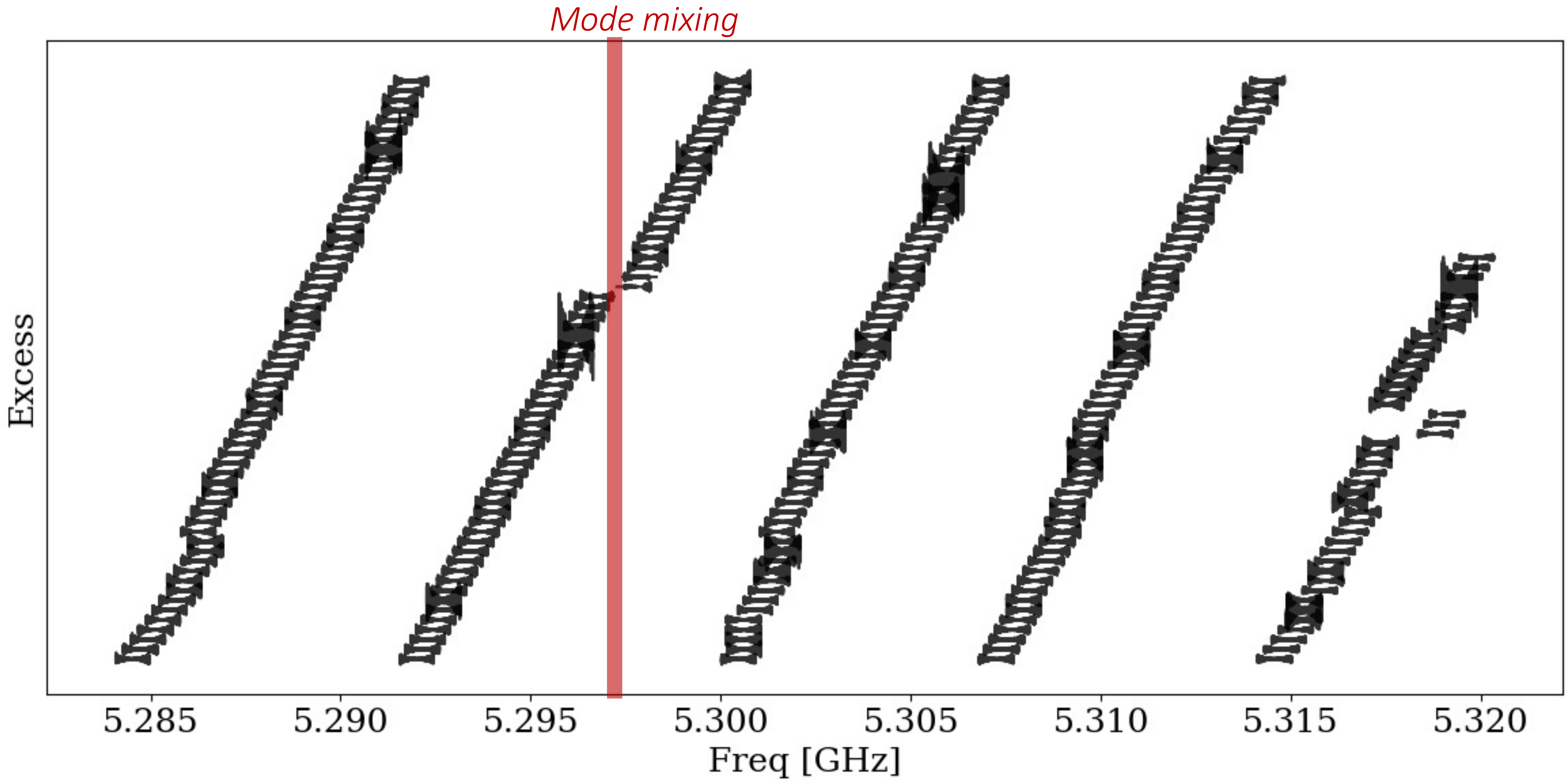


With SG filter

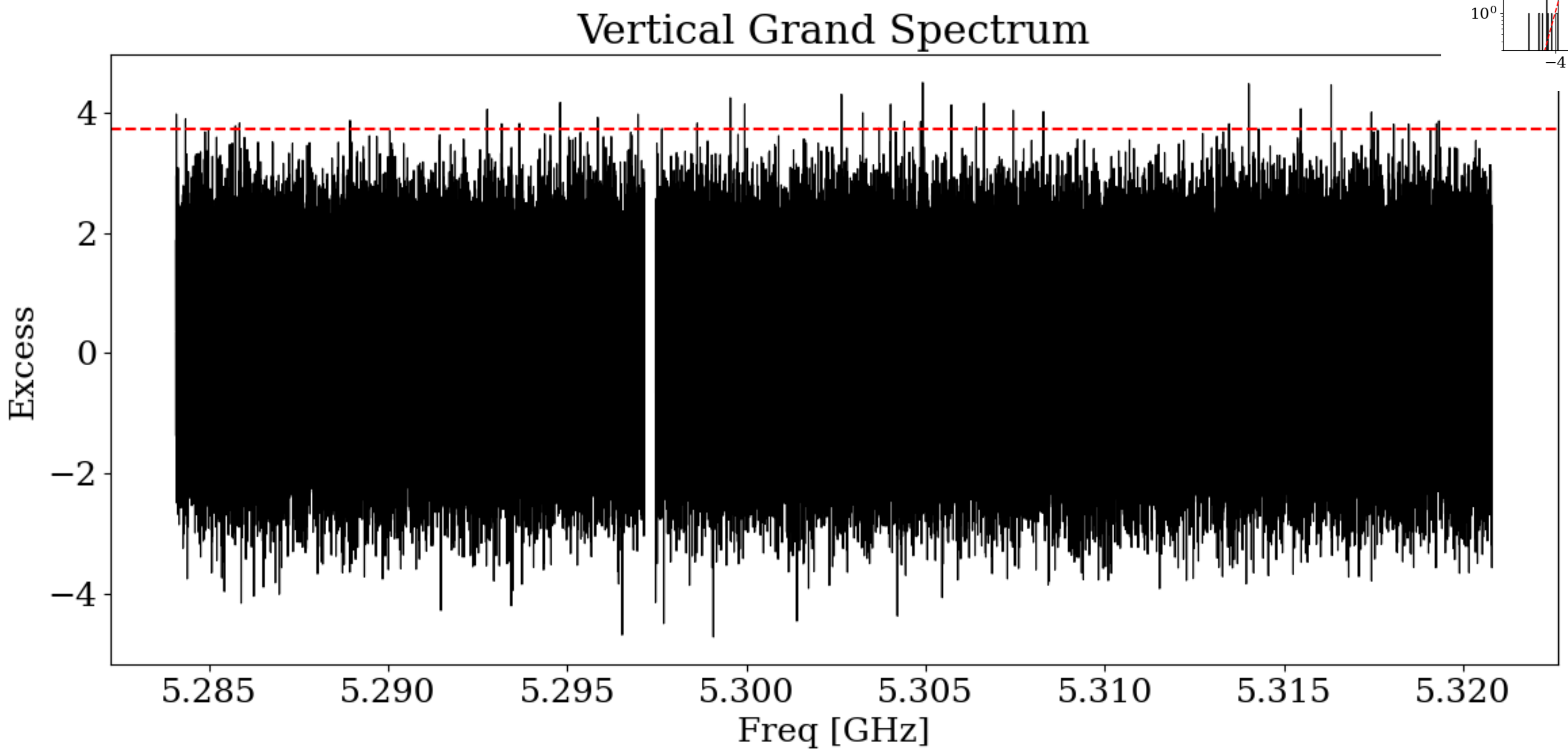


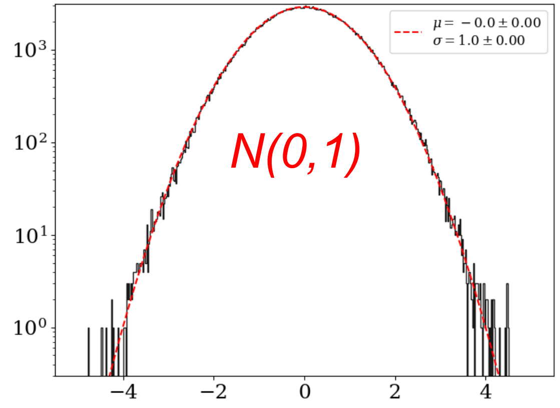
Signal efficiency: $\frac{\mu^a_{SG}}{\mu^a_{W}} \sim 0.845$

Data analysis – Scaled spectra

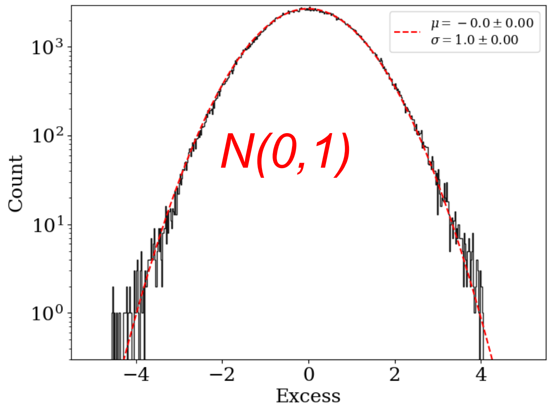


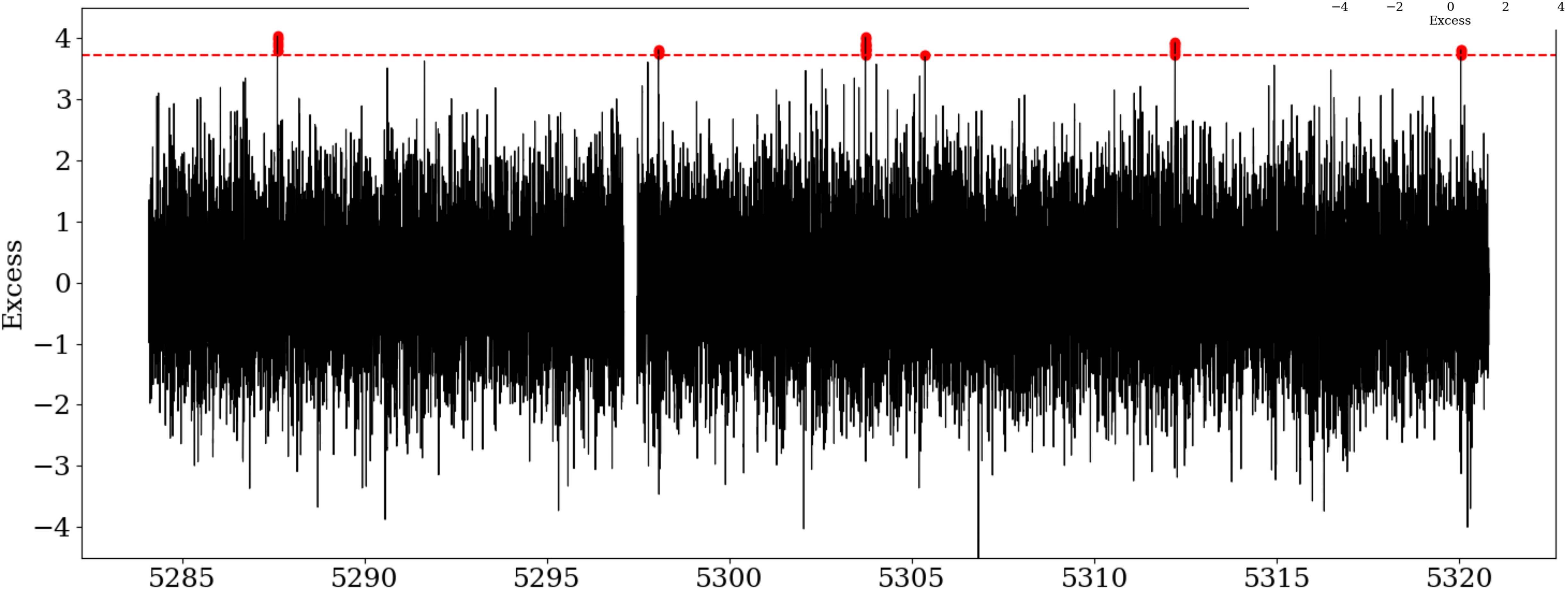
Vertical combined spectrum





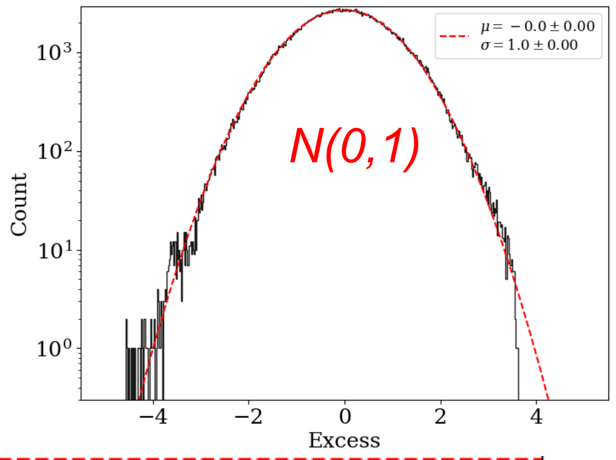
Horizontal combination

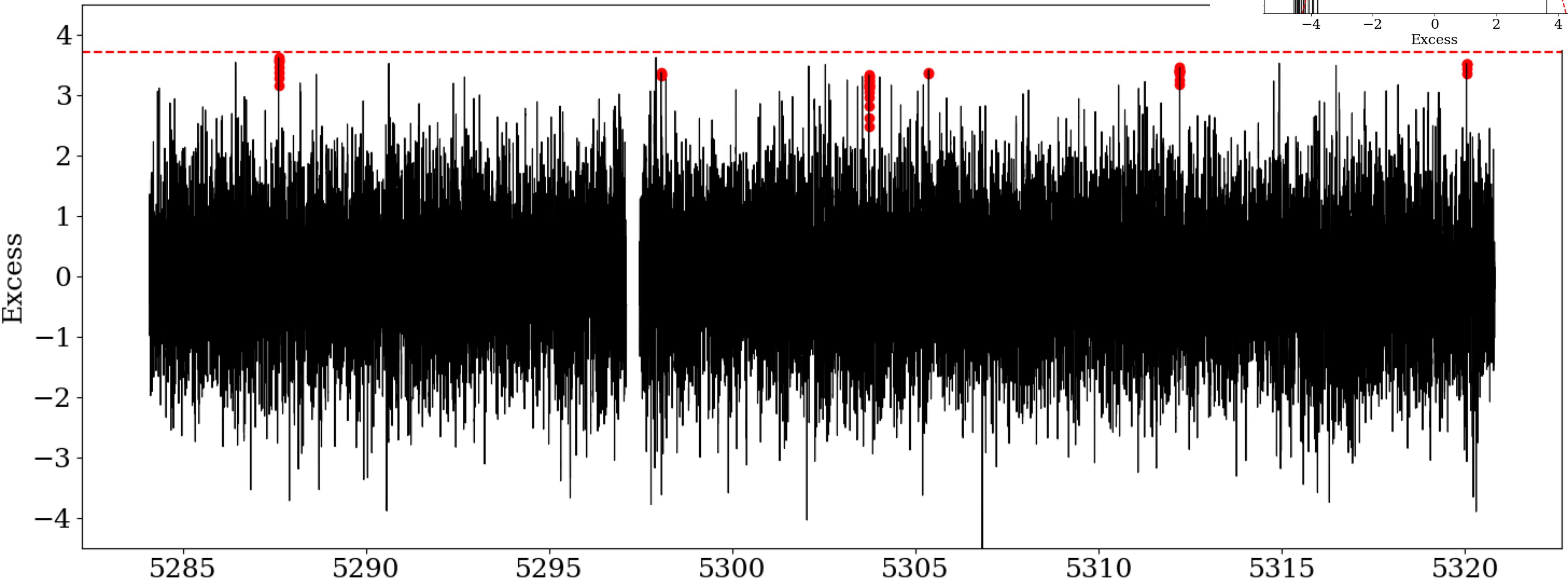




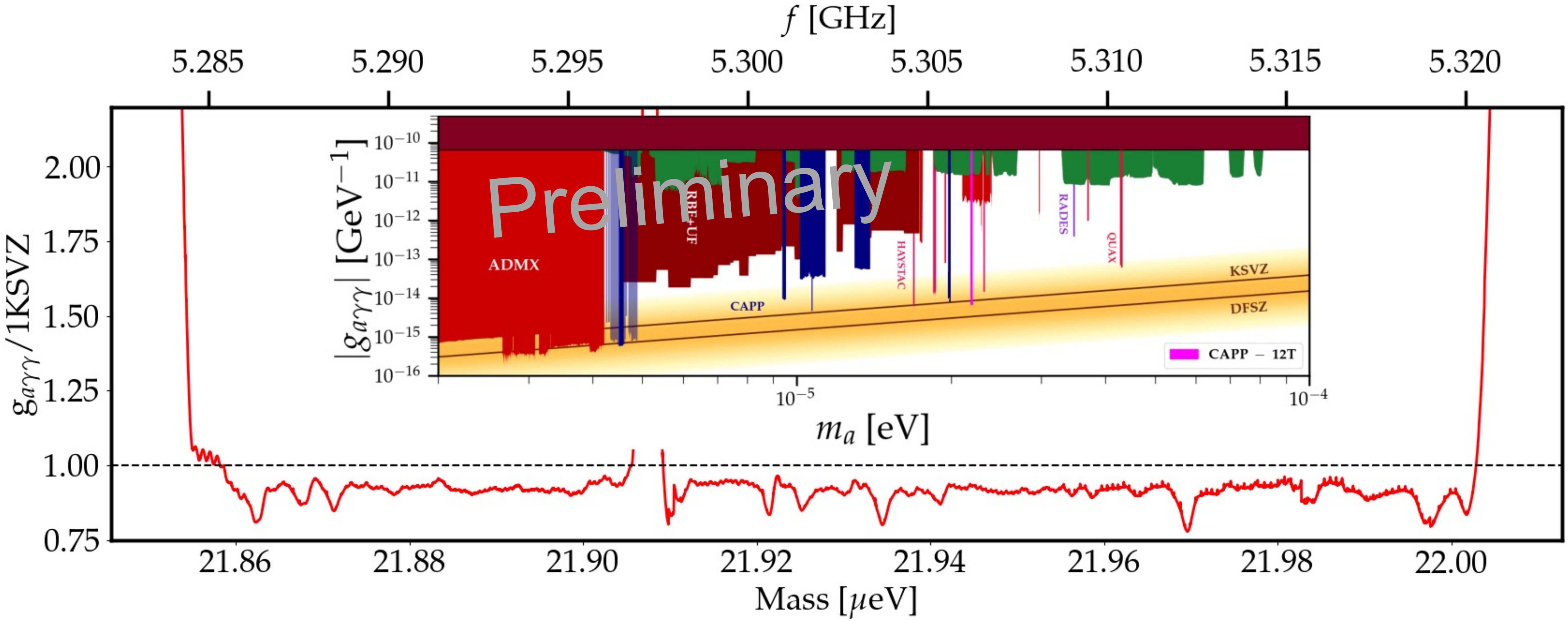
Cosmic axion parameters: $v_{obs} = 230$ [km/s], $v_{rms} = 270$ [km/s]

Horizontal combination-Rescan





Sensitivity



Conclusion

- We experimentally tested the Axion cosmology around 5.3 GHz (22 μeV).
- A multi-cell cavity and a Josephson parametric amplifier were utilized.
- Cavity design: Modified multi-cell cavity to produce a higher form factor.
- JPA working points: The NM algorithm was integrated into DAQ
- DAQ: 5.285 GHz to 5.320GHz, covering a total of 35 MHz.
- **Noise level: ~ 1.5 photons**
- **Sensitivity: < 1 KSVZ sensitivity for the 35 MHz range**
- ***High temperature superconductor tape can increase sensitivity in future***