Axion dark matter search with DFSZ sensitivity at CAPP

Saebyeok Ahn

On behalf of
IBS-CAPP in KAIST
South Korea

collaborating with
Yasunobu Nakamura, Arjan F. van Loo
RIKEN Superconducting Quantum Electronics Research Team
University of Tokyo
Japan

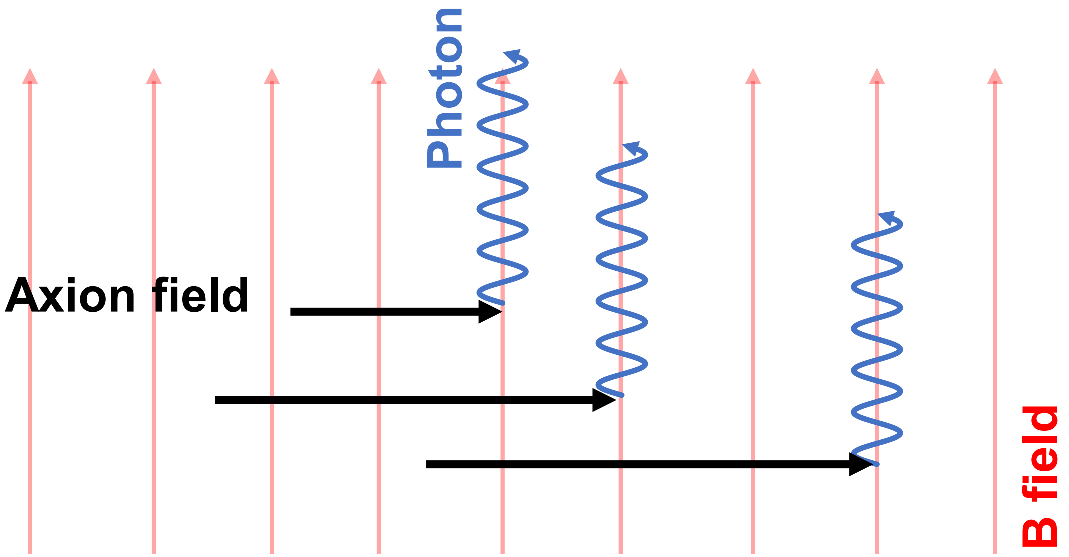
International workshop on Multi-probe approach to wavy dark matter, Korea University

Axion

- Neutron EDM → CP violation in QCD
  - $\theta < 10^{-10}$ where θ scales the CP violating term
- Why CP violation is too small in QCD?
  - **The strong CP problem**
- Solution
  - New global chiral symmetry by Peccei and Quinn
  - Spontaneously breaking → new boson, called **axion**
  - m_a in $10^{-6} – 10^{-3}$ eV
- Axion property
  - Long lifetime, long lived, light enough
  - **Dark matter candidate**

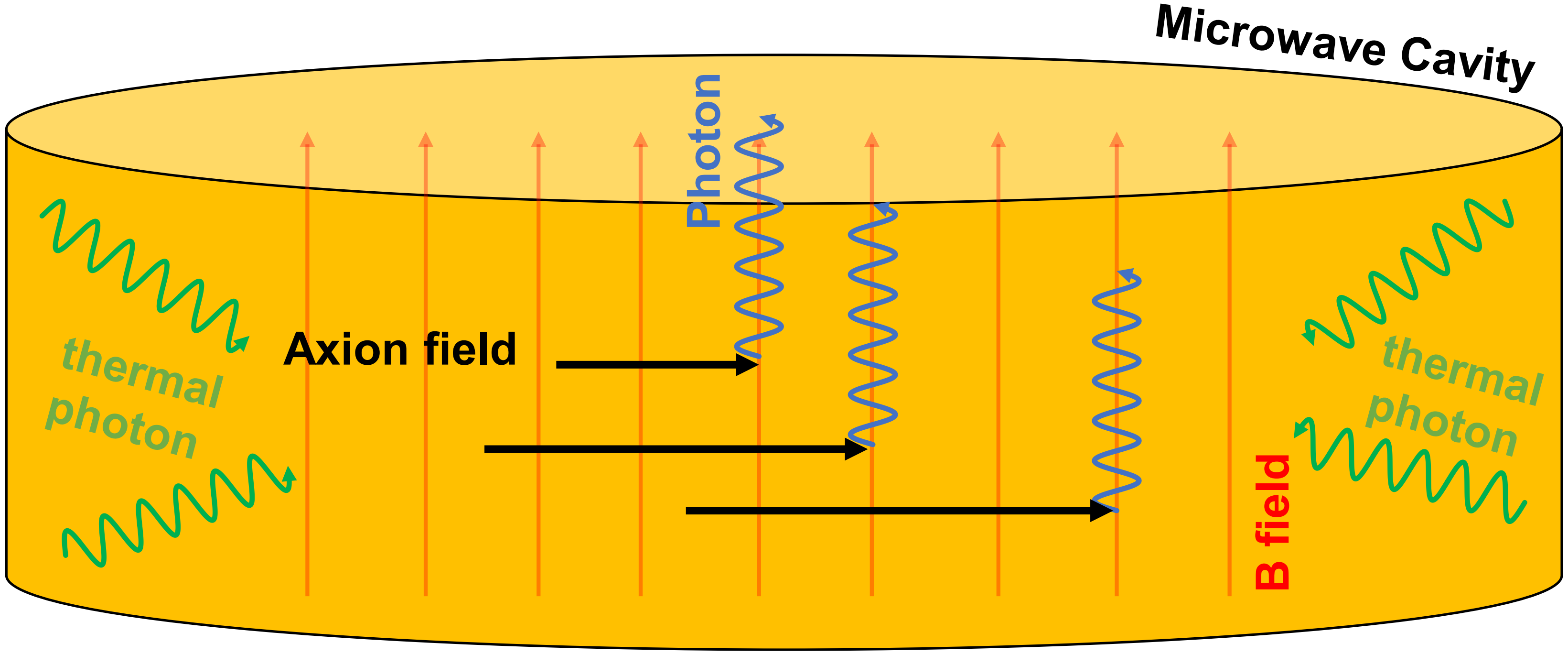
Axion in the haloscope

- Axion to photon conversion in a strong magnetic field



Axion in the haloscope

- ❏ Axion to photon conversion in a strong magnetic field
- ❏ **Resonance in a microwave cavity (matched resonance frequency)**



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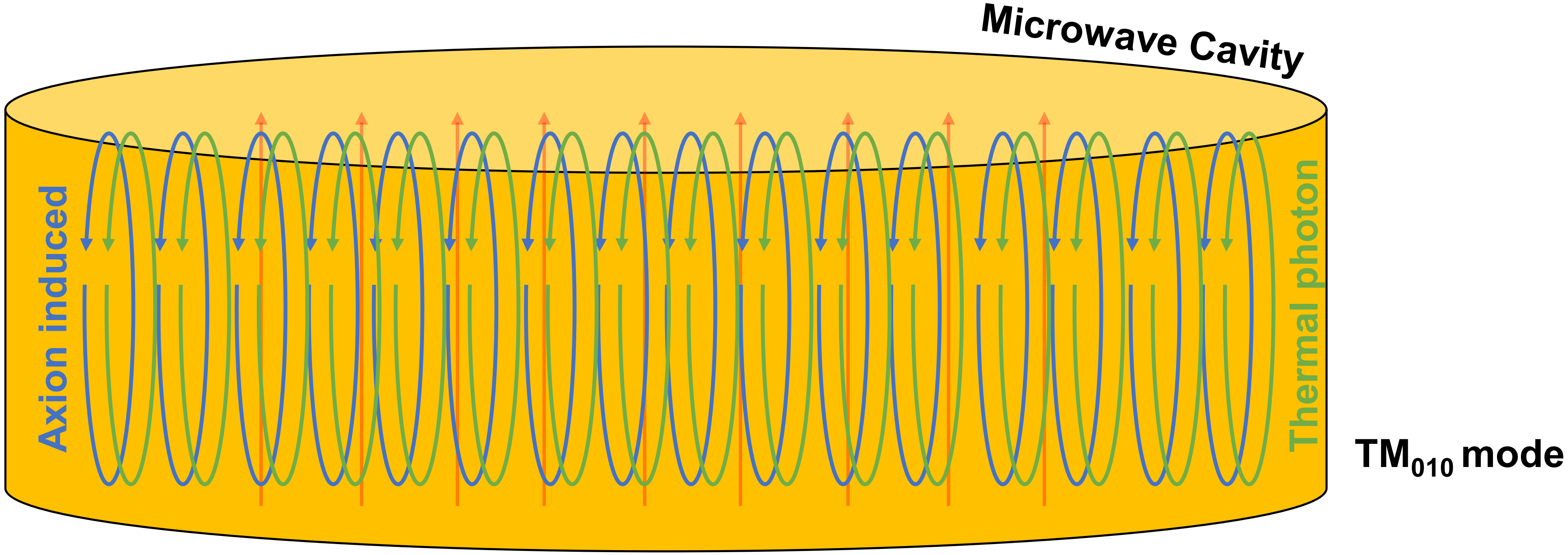
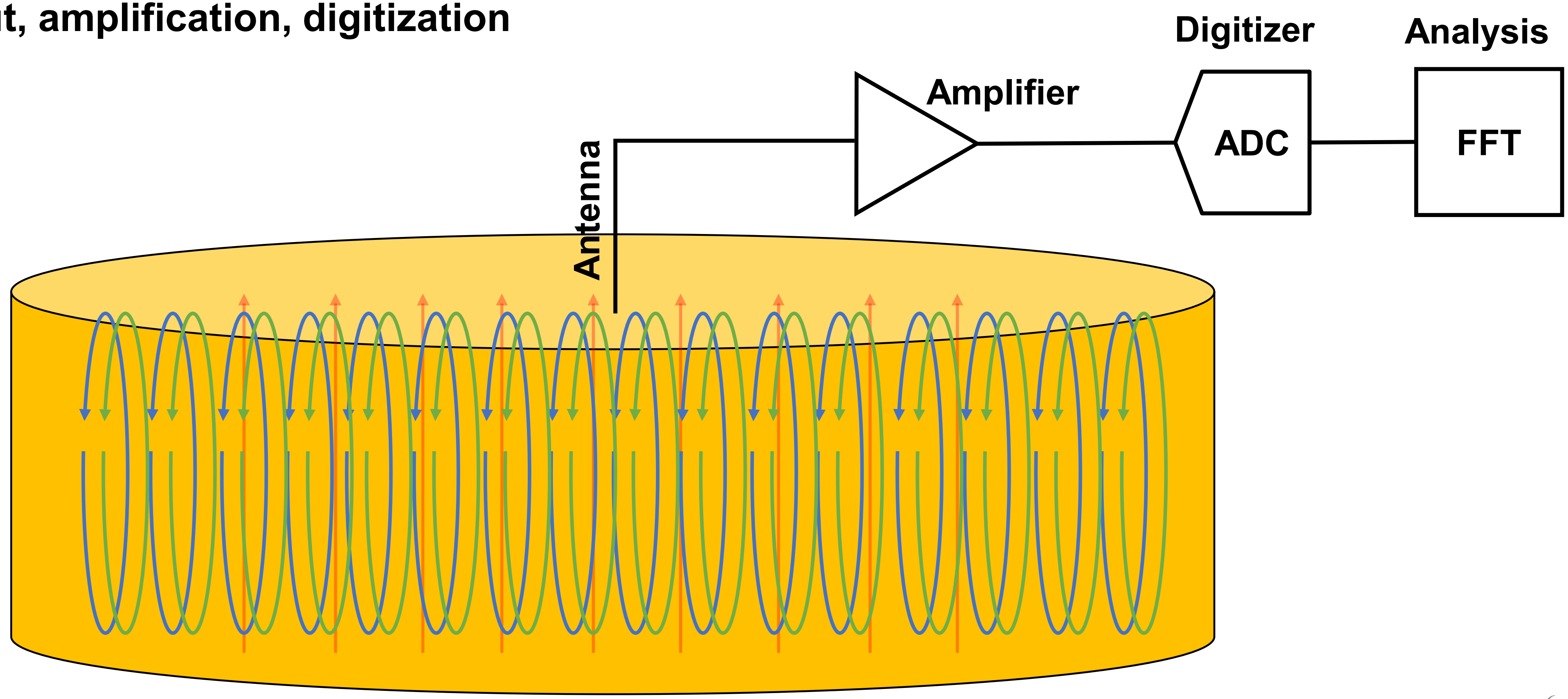


Axion in the haloscope

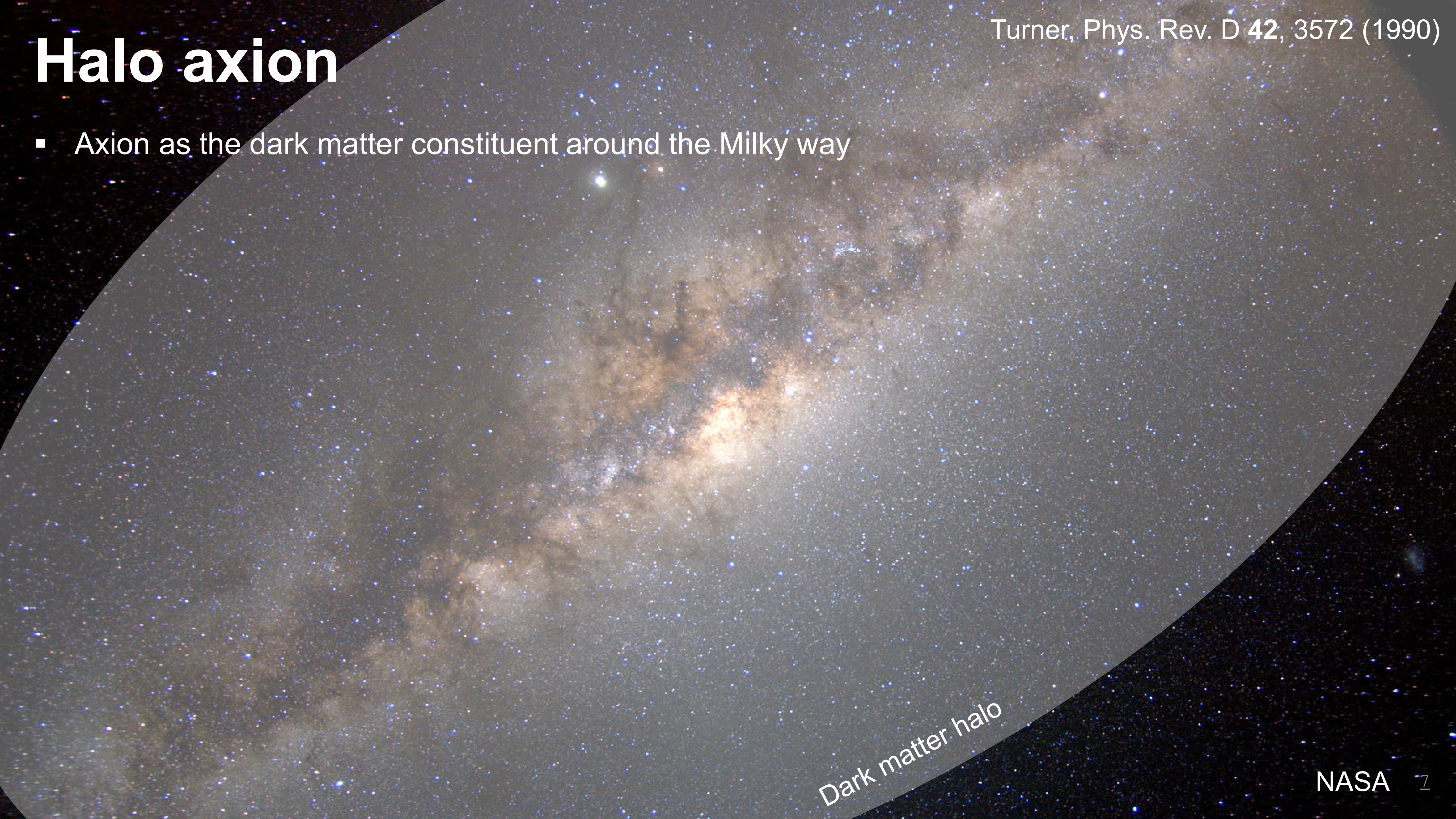
- ❑ Axion to photon conversion in a strong magnetic field
- ❑ Resonance in a microwave cavity (matched resonance frequency)
- ❑ **Reading out, amplification, digitization**



Turner, Phys. Rev. D **42**, 3572 (1990)

Halo axion

- Axion as the dark matter constituent around the Milky way

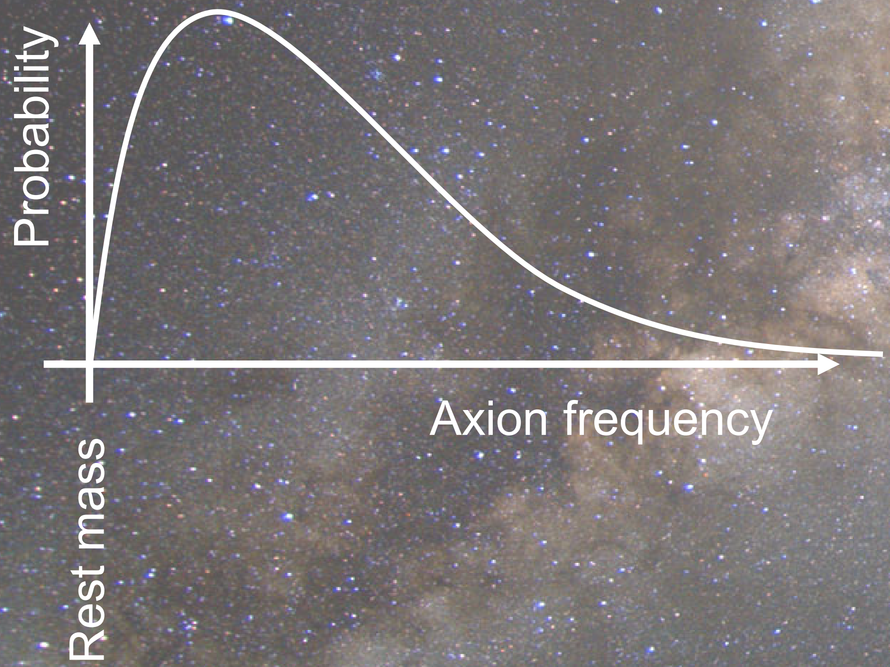


NASA

Turner, Phys. Rev. D **42**, 3572 (1990)

Halo axion

- Axion as the dark matter constituent around the Milky way
- Virialized, Maxwell-Boltzmann distribution



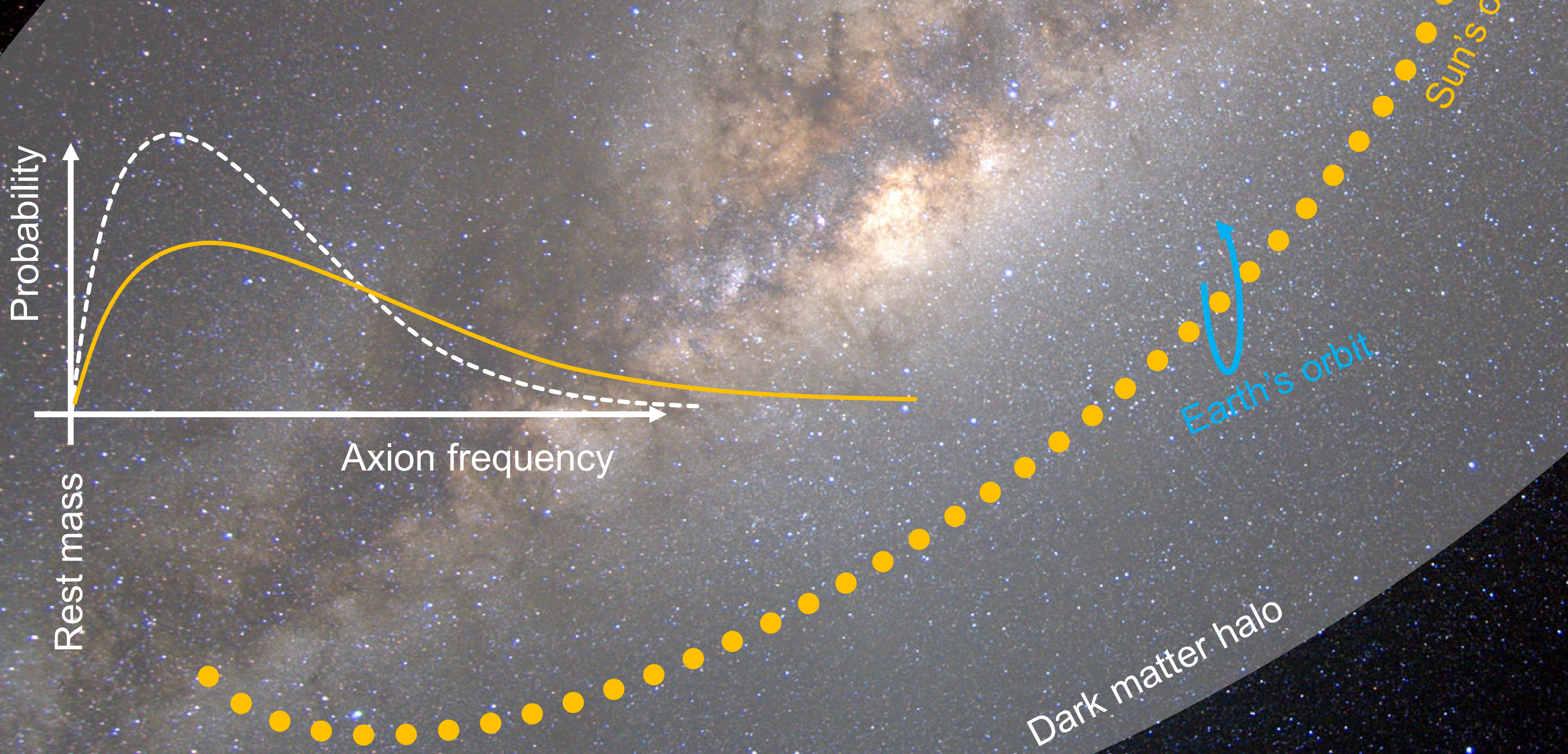
Dark matter halo

NASA

Turner, Phys. Rev. D **42**, 3572 (1990)

Halo axion

- Axion as the dark matter constituent around the Milky way
- Virialized, Maxwell-Boltzmann distribution
- Observation in laboratory: broader lineshape

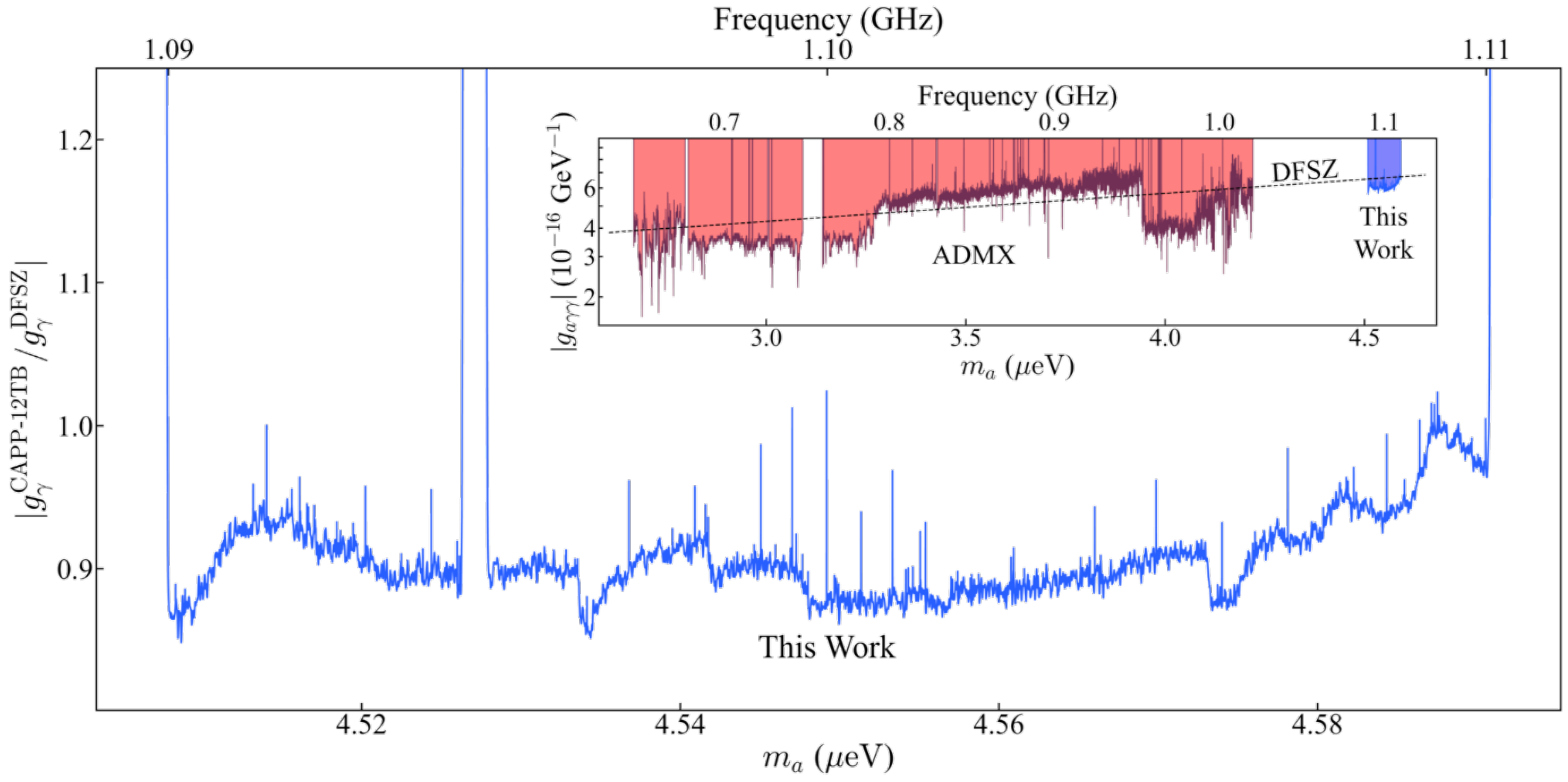


NASA

The CAPP-MAX experiment

Achieved

- Run 4 / 1.09 – 1.11 GHz / DFSZ sensitivity



Phys. Rev. Lett. 130, 071002

The CAPP-MAX experiment

Achieved

- Run 4 / 1.09 – 1.11 GHz / DFSZ sensitivity

Recent progress

- Run 5 / 1.06 – 1.12 GHz
- Run 6 / 1.025 – 1.18 GHz
  - Parallel/series JPAs in the system

Conversion power

- **Axion converted photon in the strong magnetic field**

$$P_a^{a\gamma\gamma} = 23.57 \times 10^{-24}\ [\mathrm{W}] \left(\frac{g_\gamma}{0.36}\right)^2$$

DFSZ model

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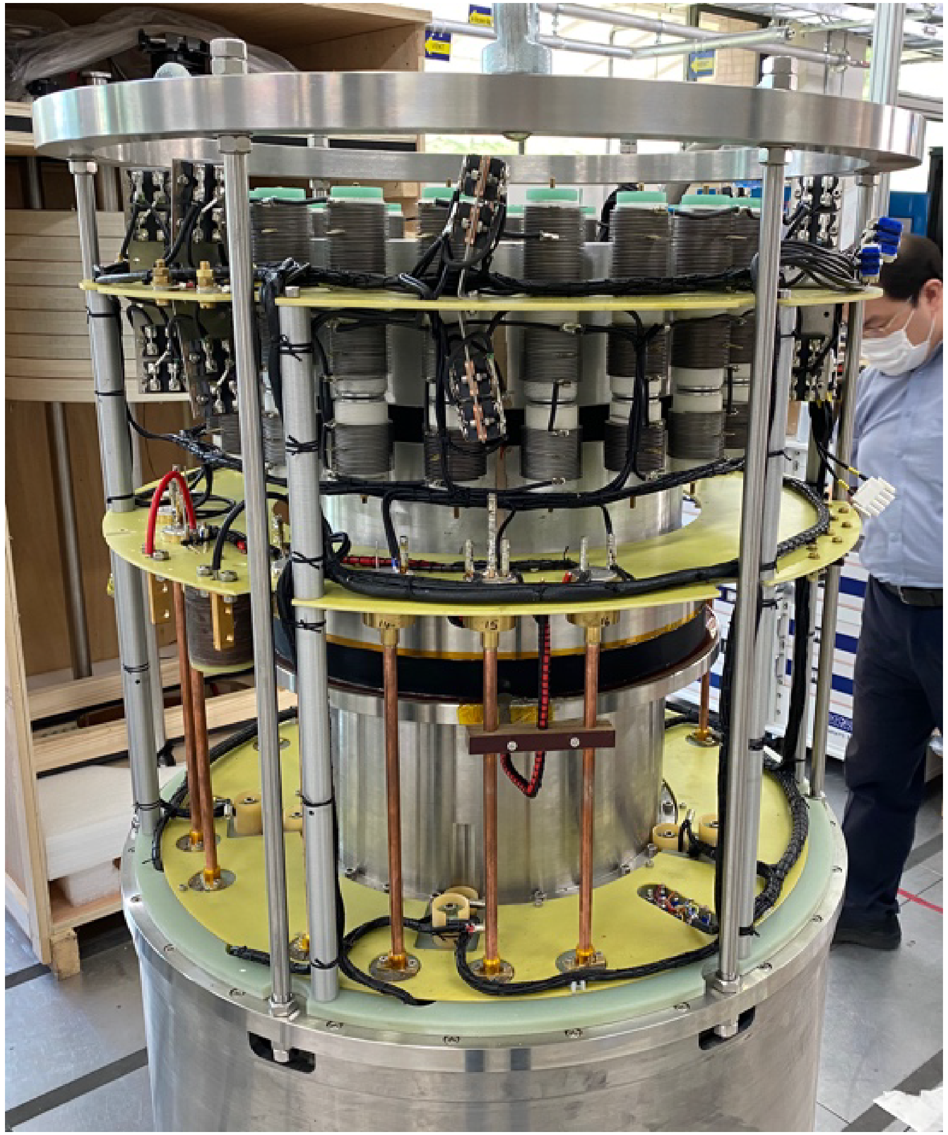

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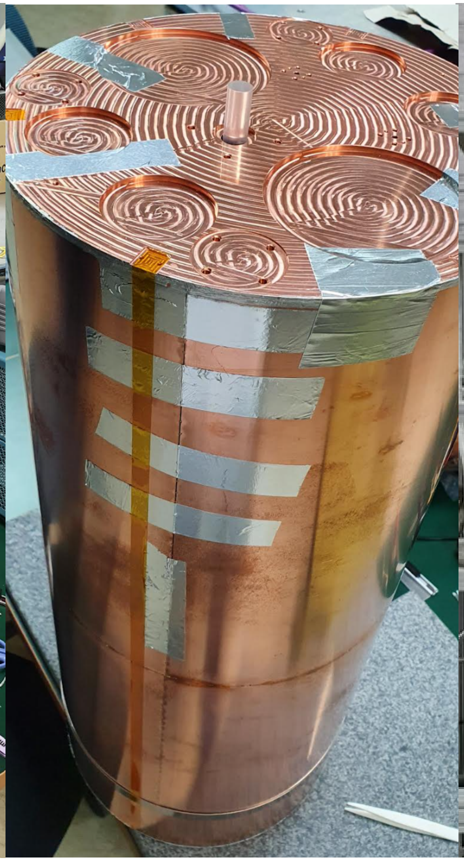
Home-made light cavity with OFHC copper sheet (ULC)

- ❑ Low weight (totally ~ 5 kg)
- ❑ Easy to tune
- ❑ Gain volumes (thin walls)
- ❑ Low cost



Ohjoon, Heesu, Danho, Jiwoon

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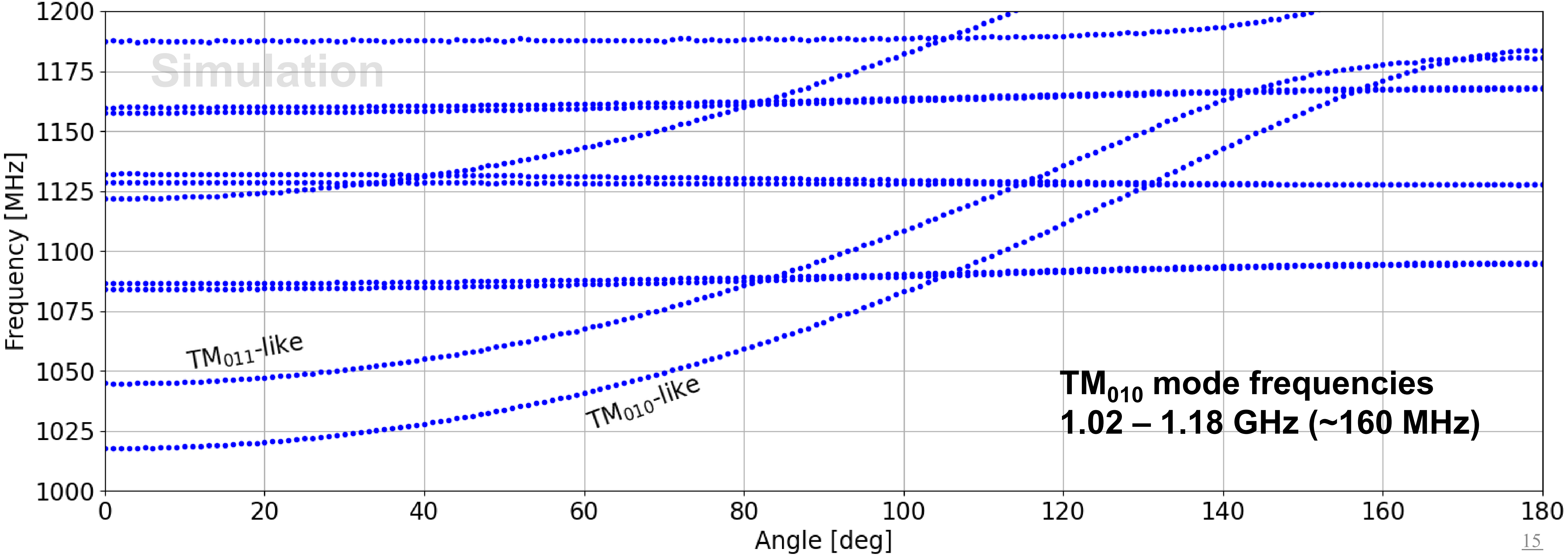
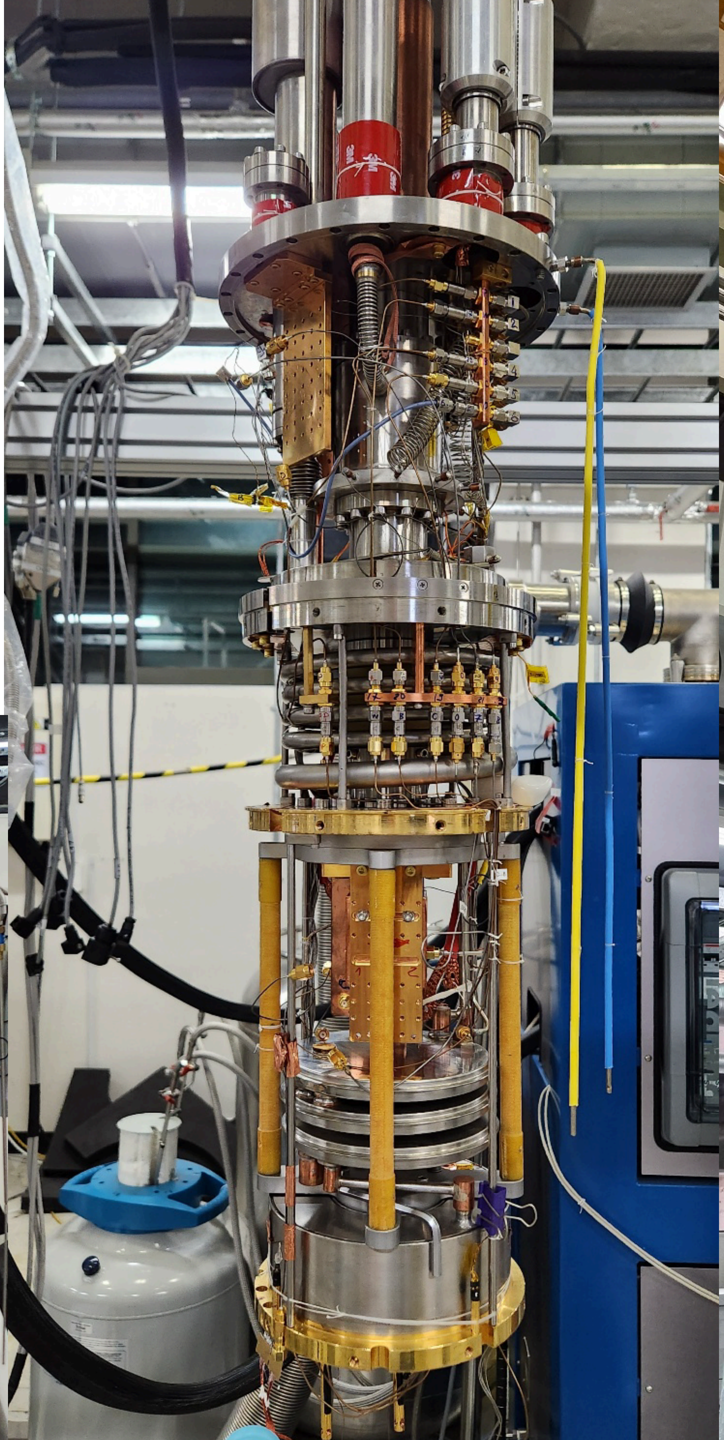
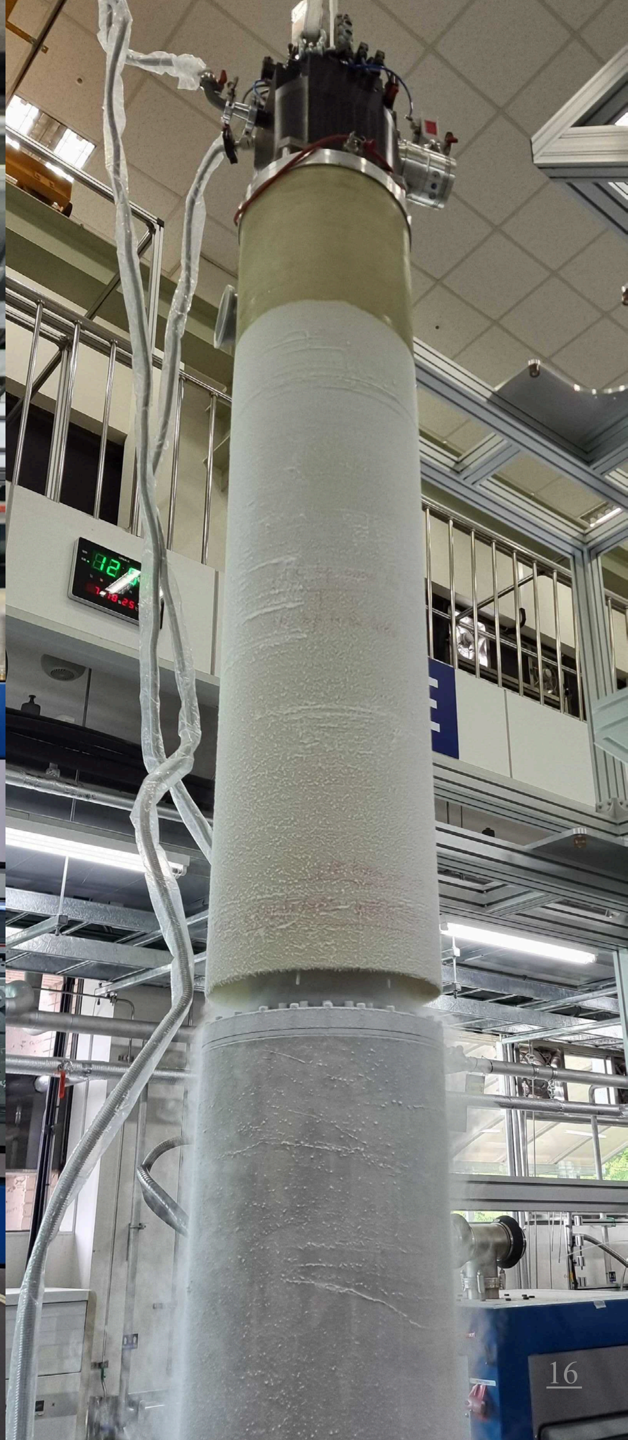


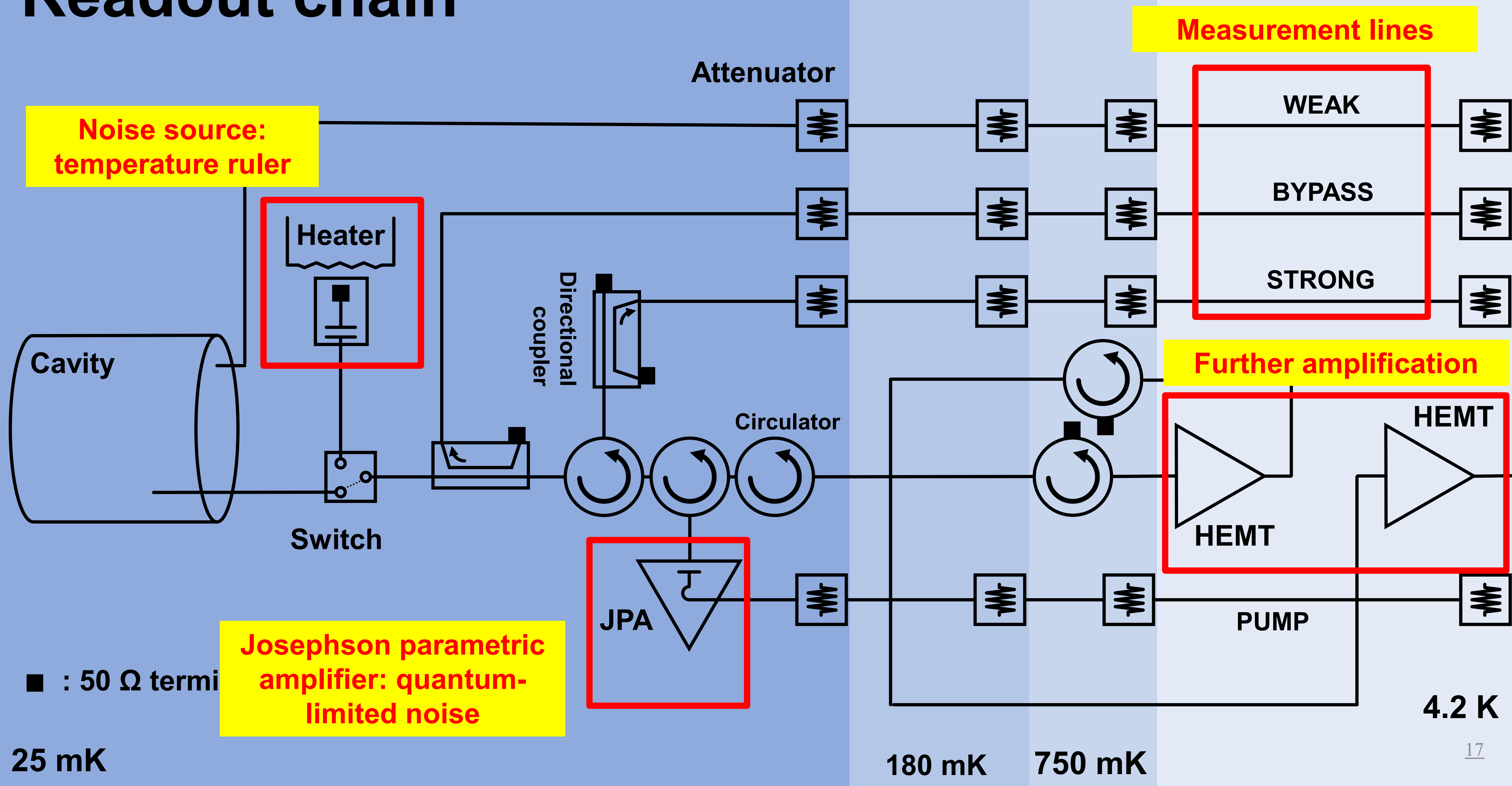
The cryogenic system

- Wet-type LEIDEN dilution fridge
  - Base temperature of 5.4 mK (bare)
  - Average MXC temp. **~ 30 mK (science run)**
- Liquid Helium liquefier/Re-liquefier loop





Readout chain



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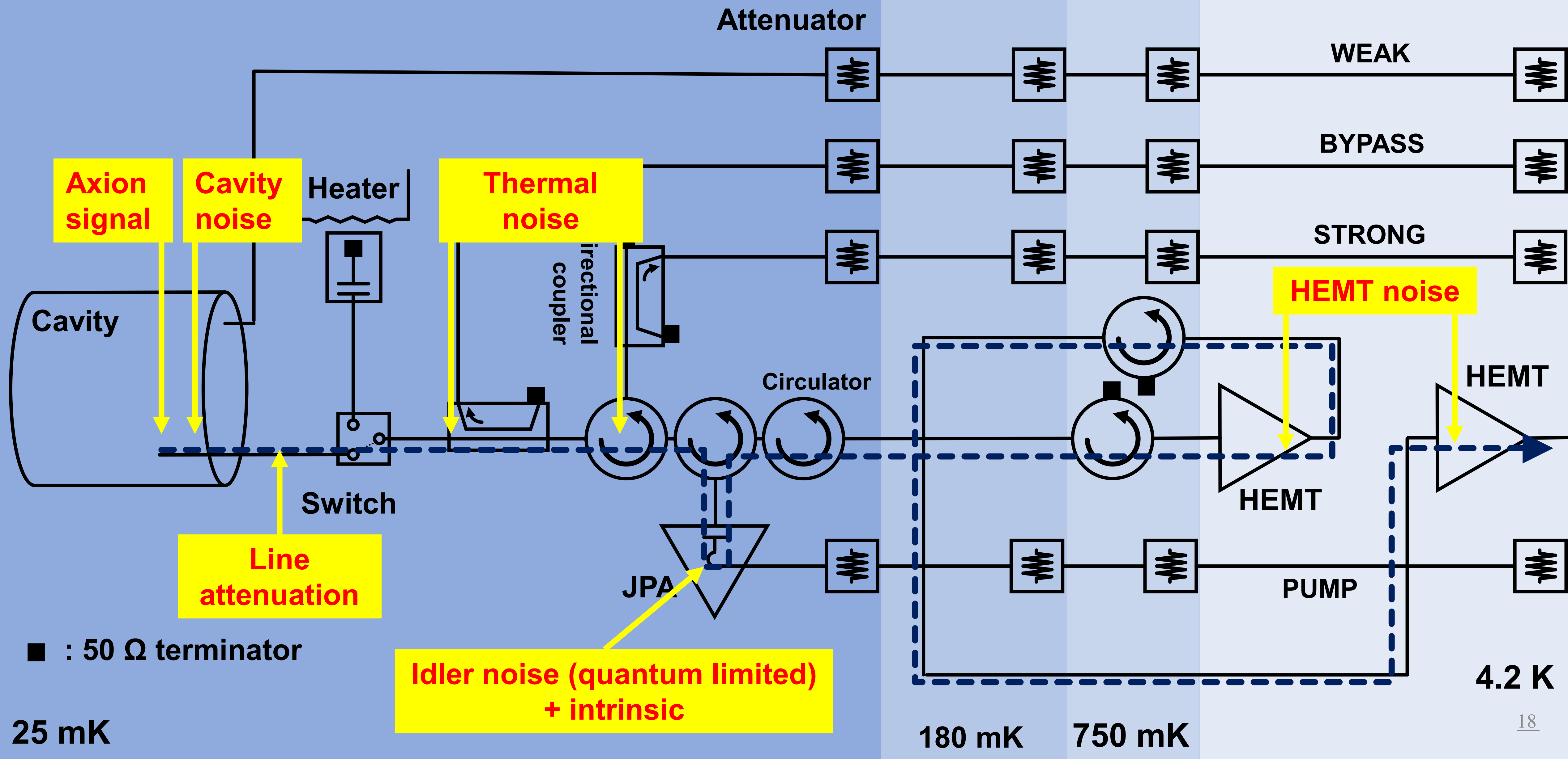
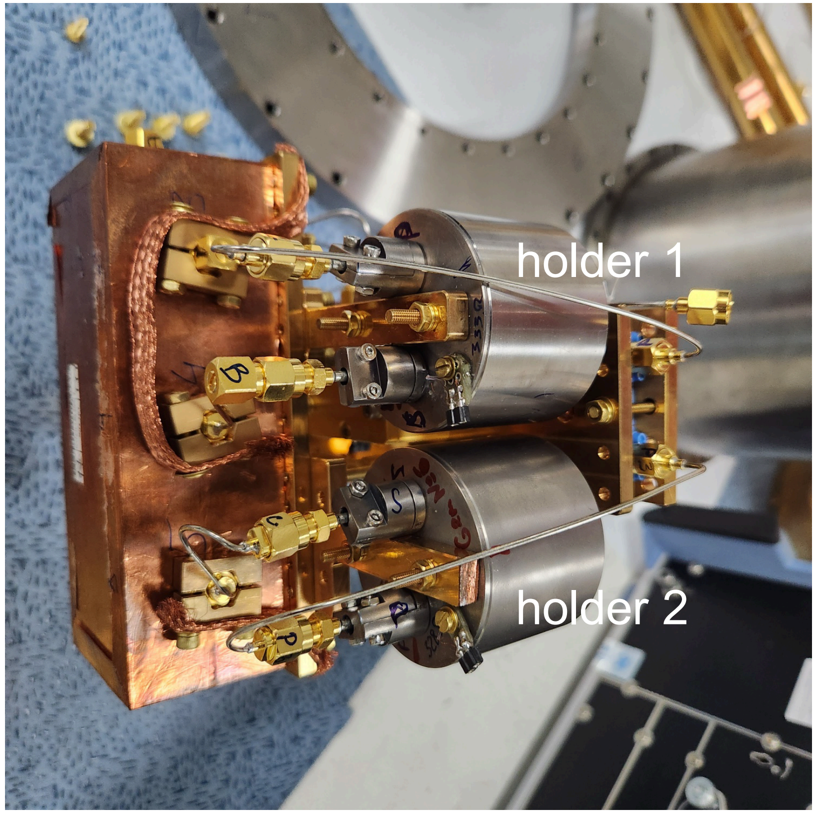
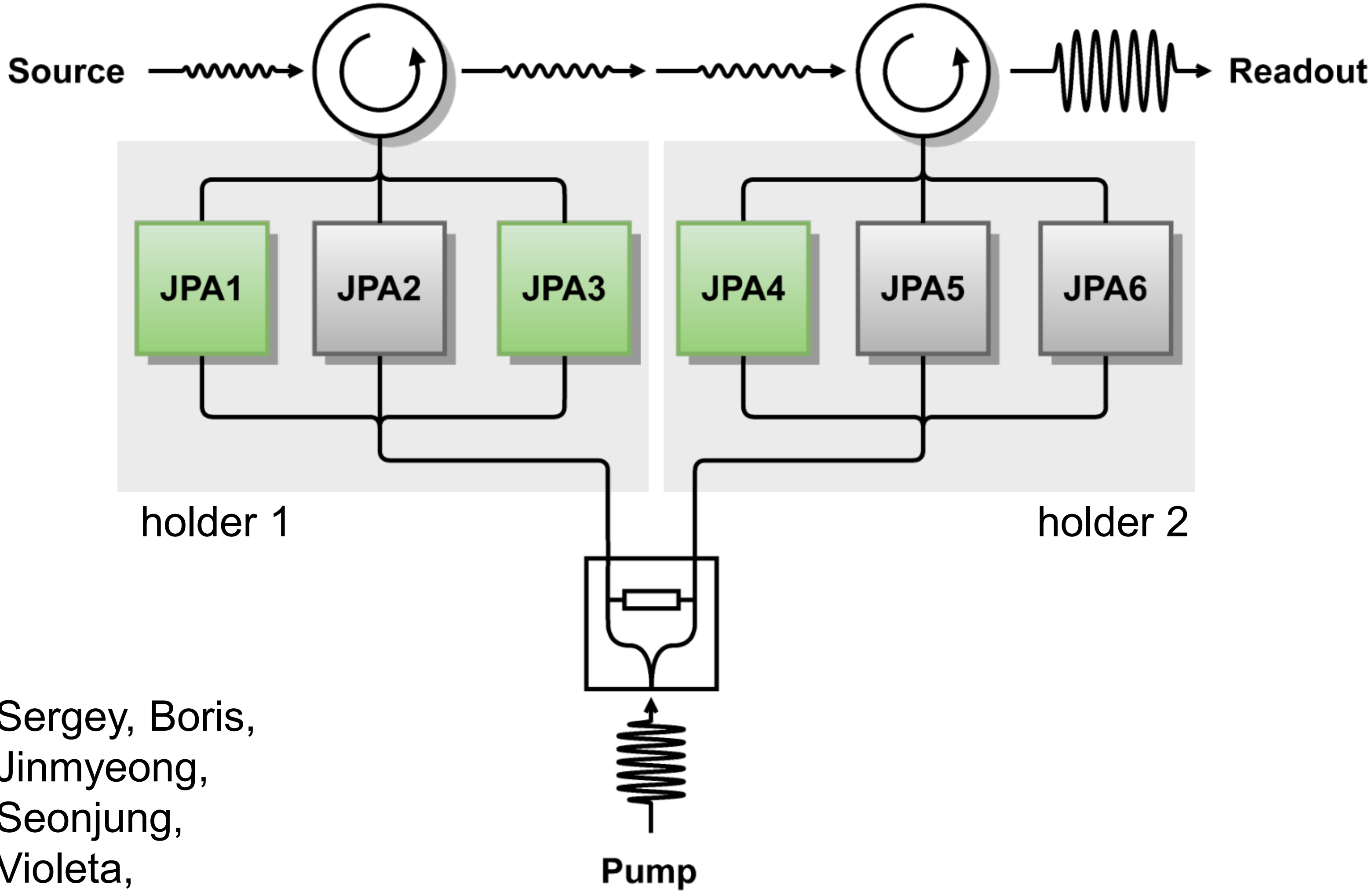


Readout chain

Multi-JPA system

- ❑ Each JPA ~ 50 MHz tuning range
- ❑ 3 combination ~ 150 MHz coverage





Sergey, Boris,
Jinmyeong,
Seonjung,
Violeta,
Andrei

Readout chain

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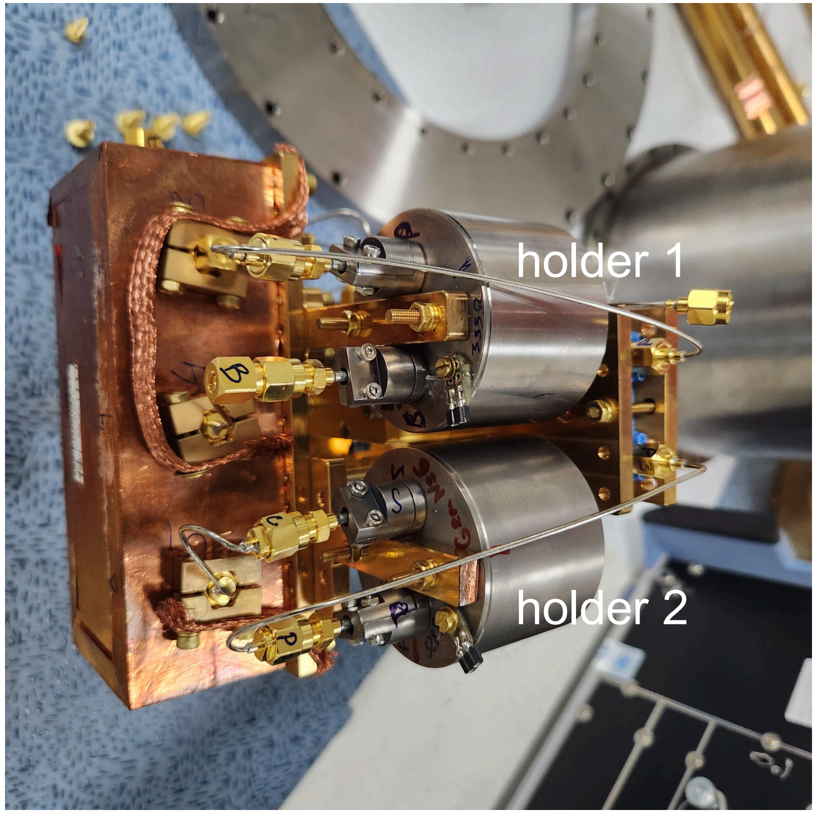
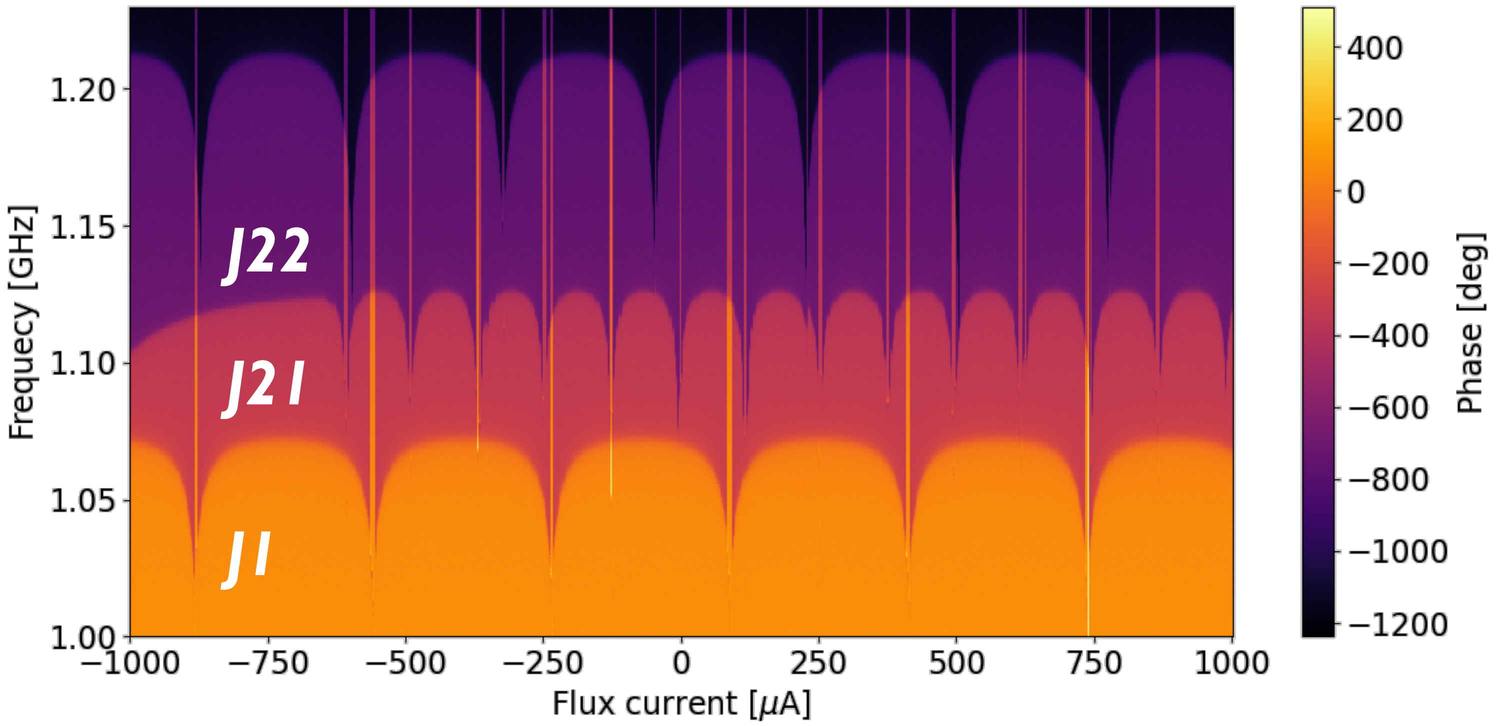
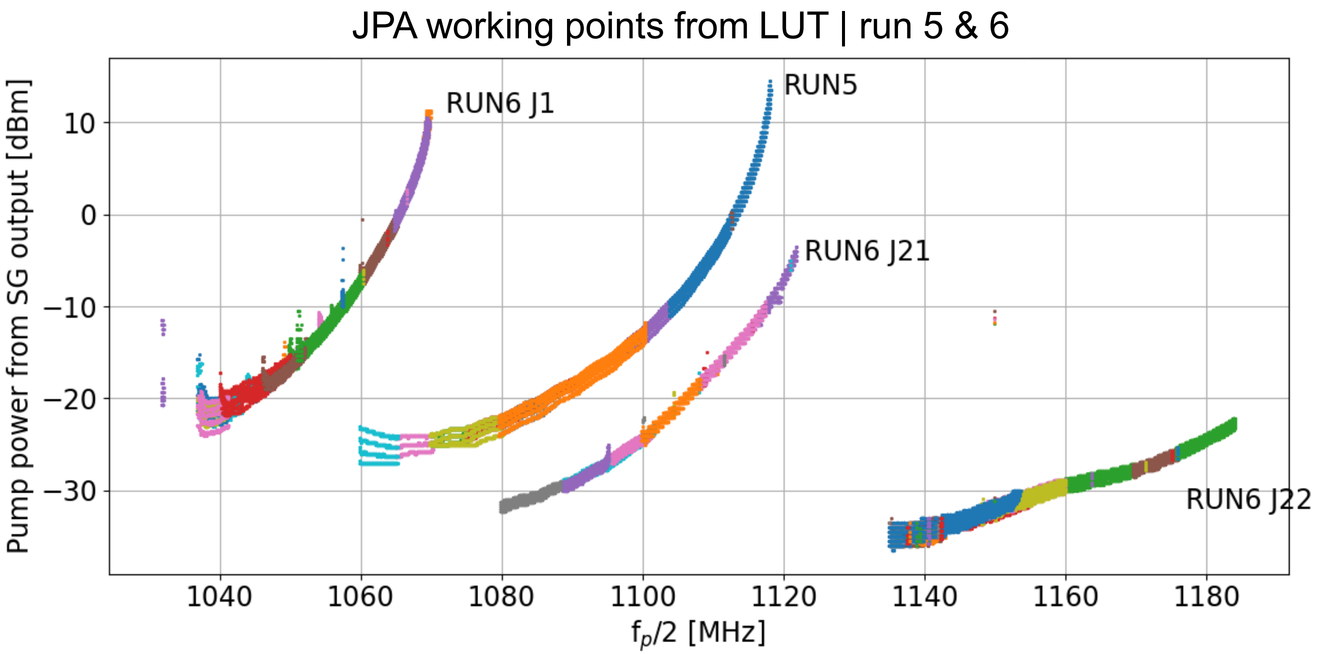
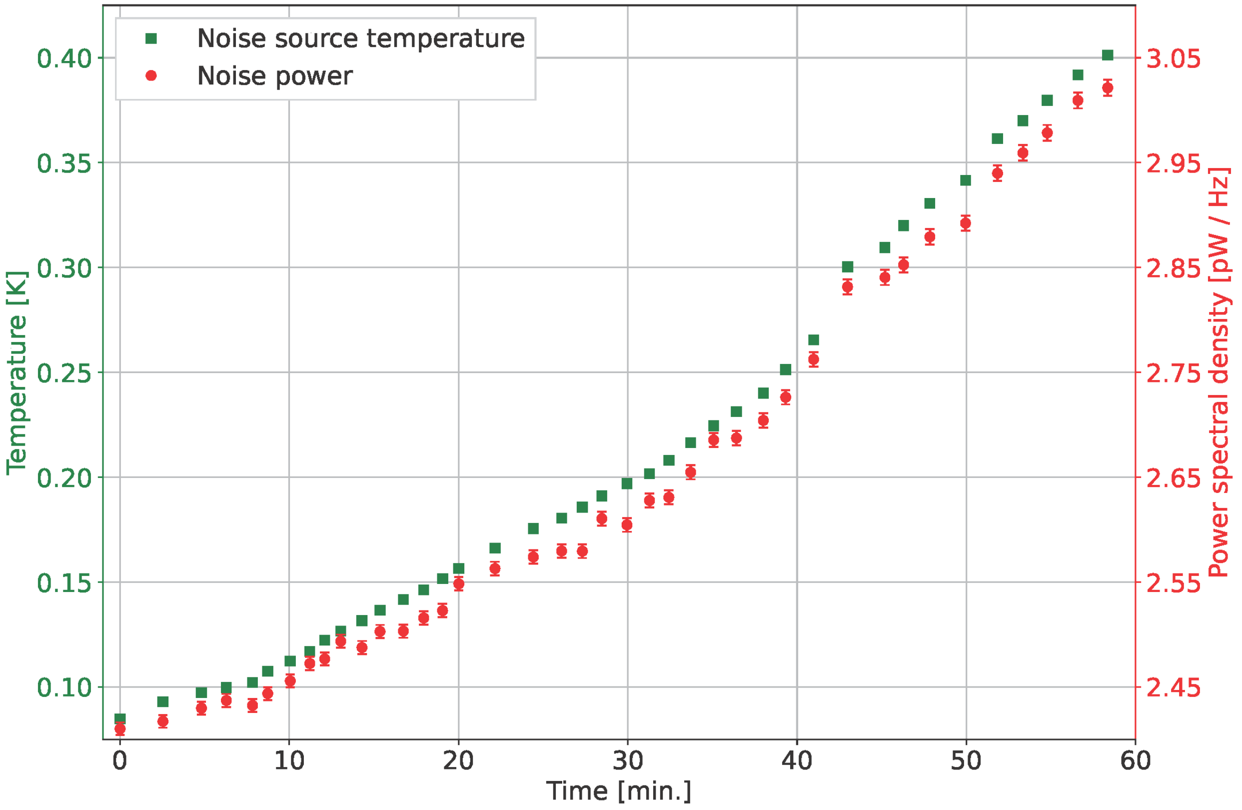


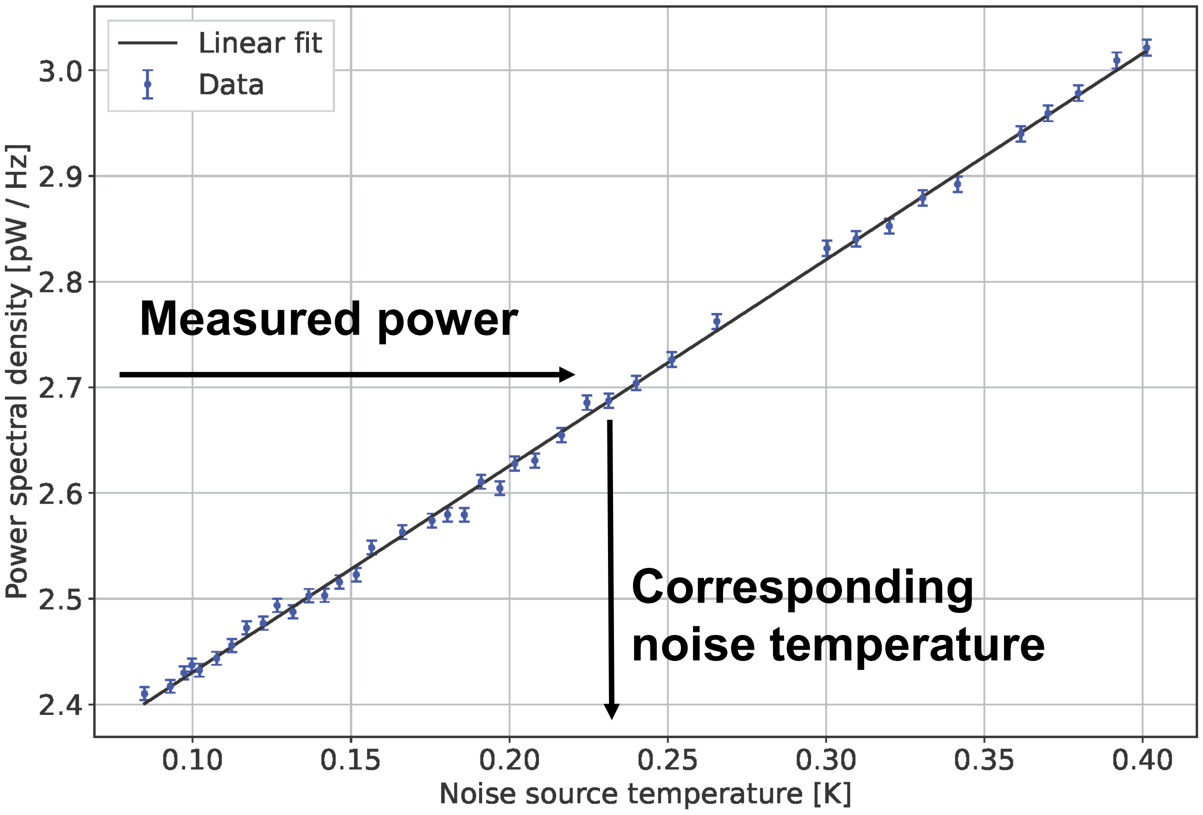




Readout chain

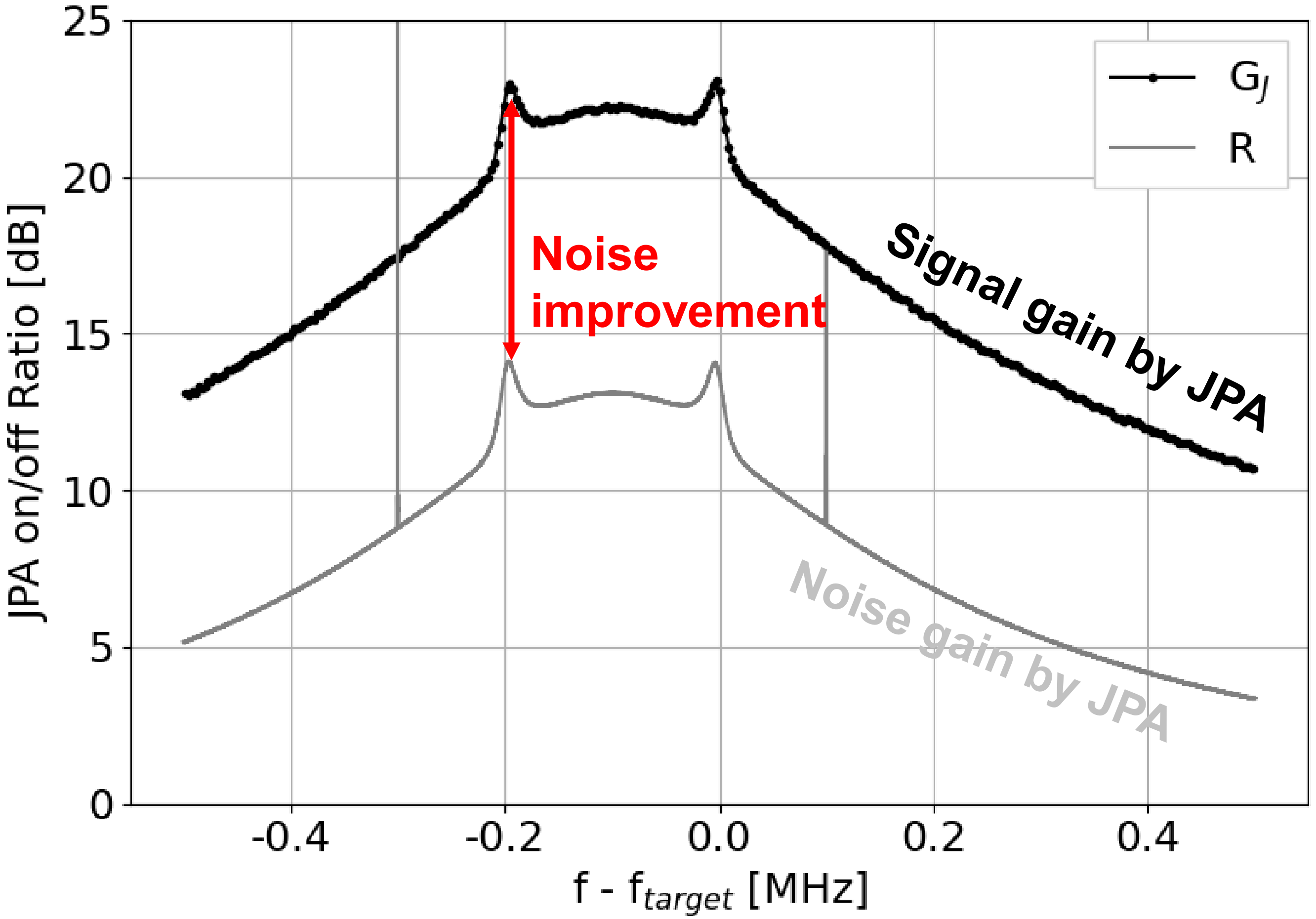
JPA off noise measurement

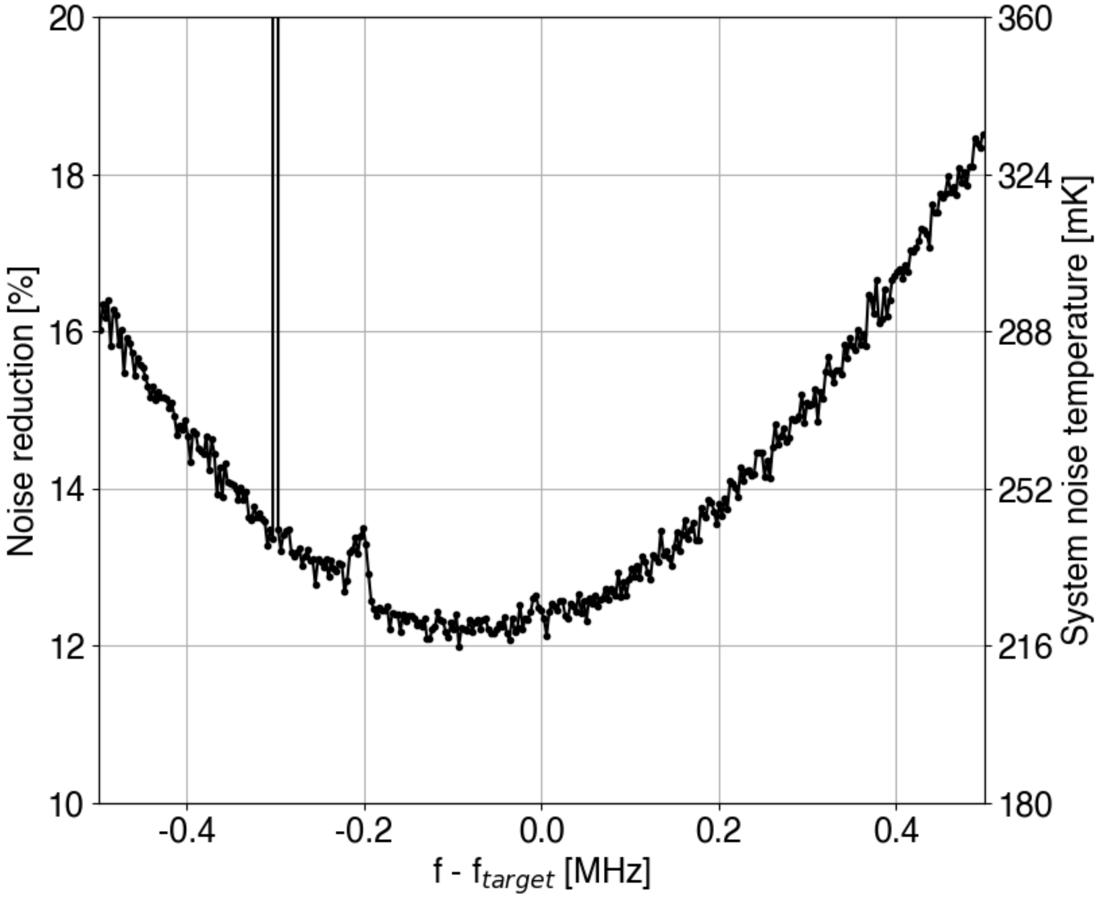




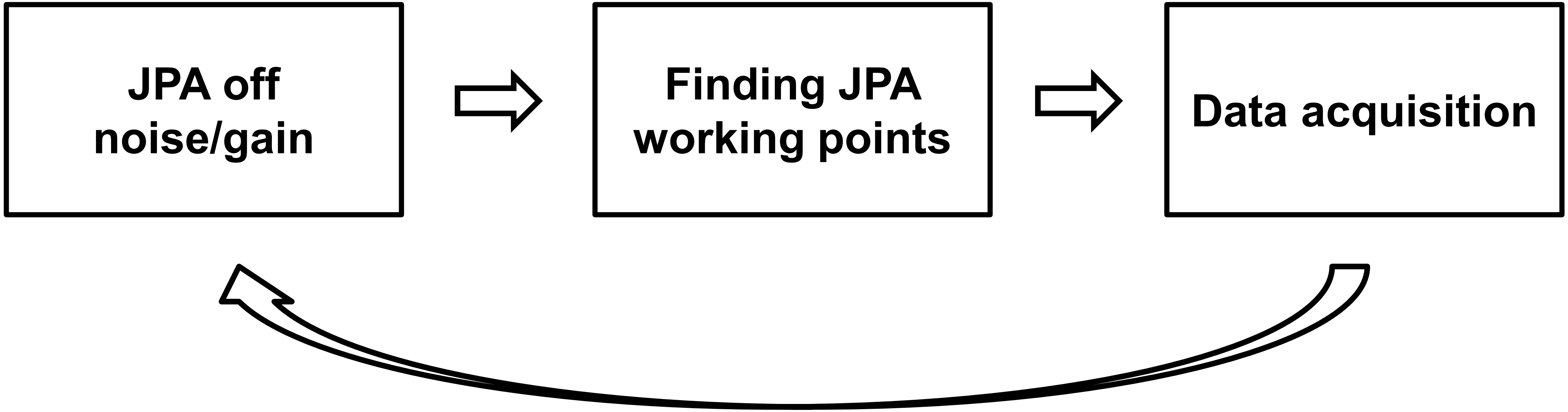
Readout chain

JPA on noise temperature





Experiment routine

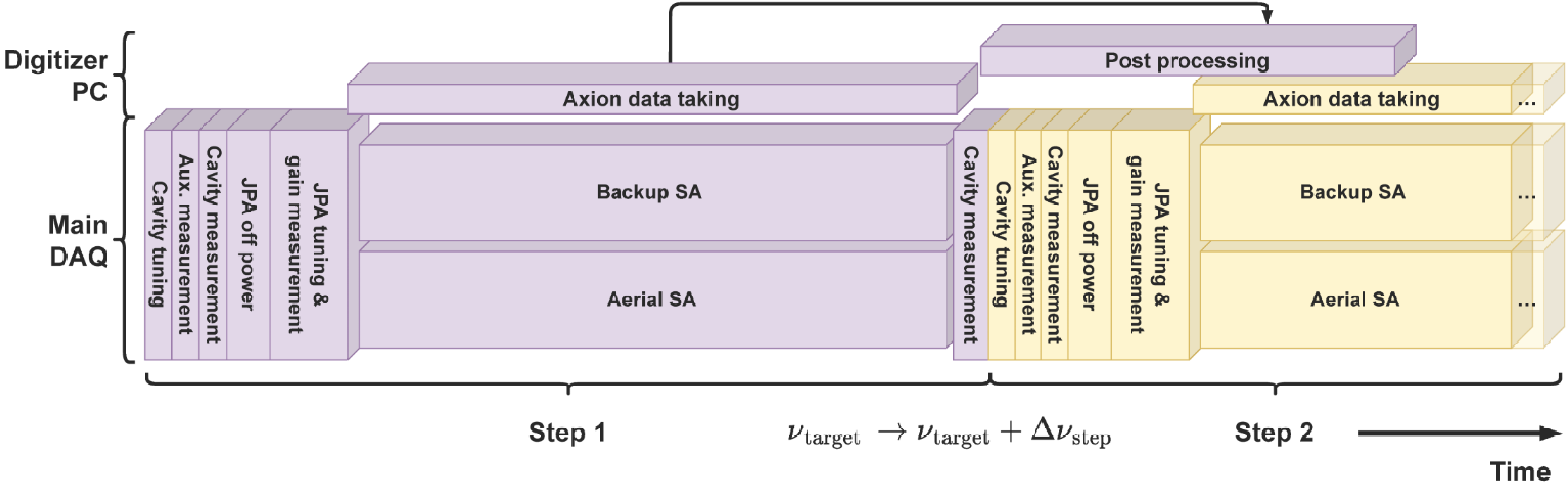


Iterating every 5 – 15 MHz

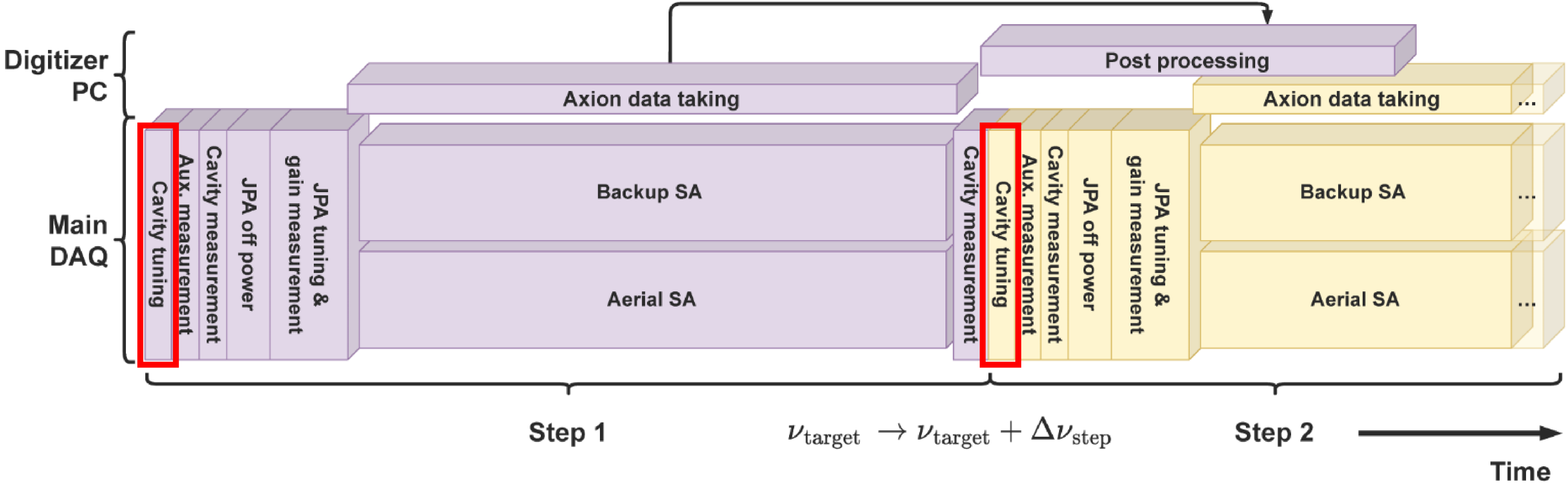
- ❑ Possible HEMT/JPA drifts
- ❑ Discussion on data / plan

DAQ cadence

Soohyung, Saebyeok, ByeongRok



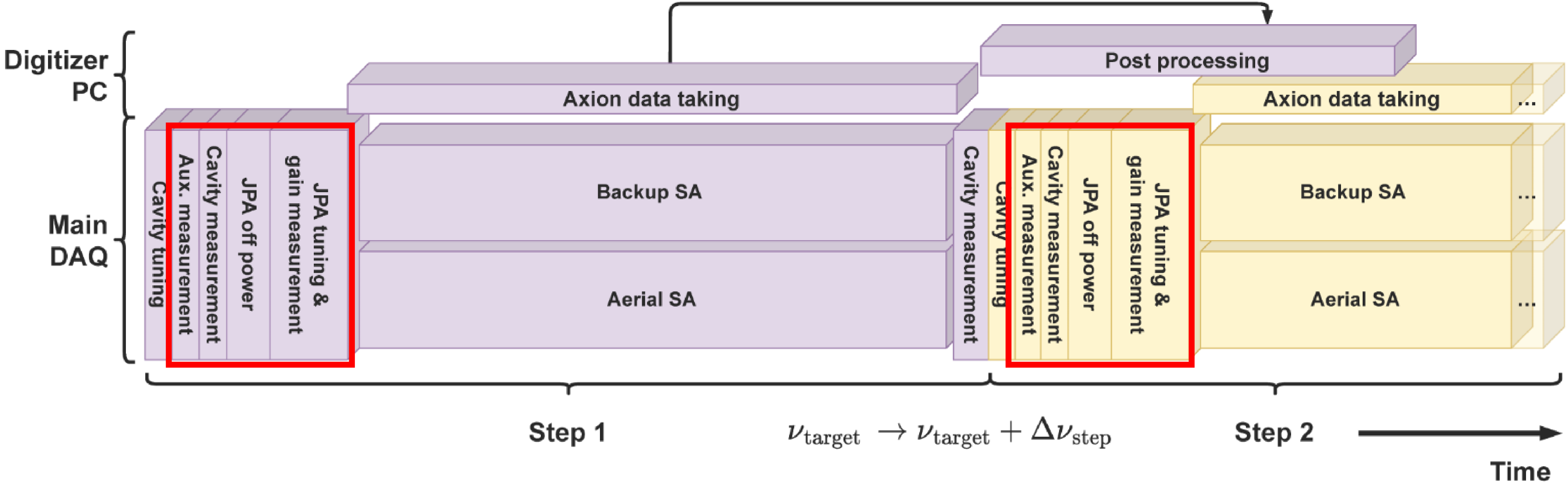
DAQ cadence



Cavity tuning

- Data acquisition at every 10 kHz step
- Overlapping the cavity resonance bandwidth

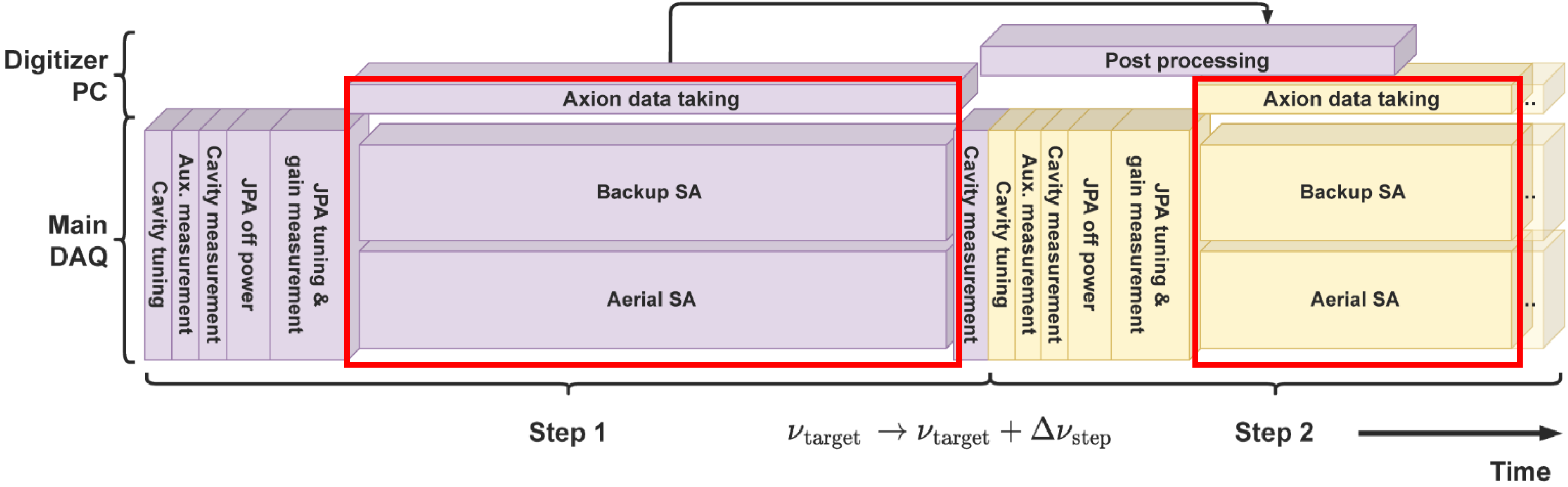
DAQ cadence



Monitoring / calibration / JPA tuning

- Auxiliary data (temperature, gas pressure, …) for monitoring
- Cavity characterization
- Fine tuning the JPA

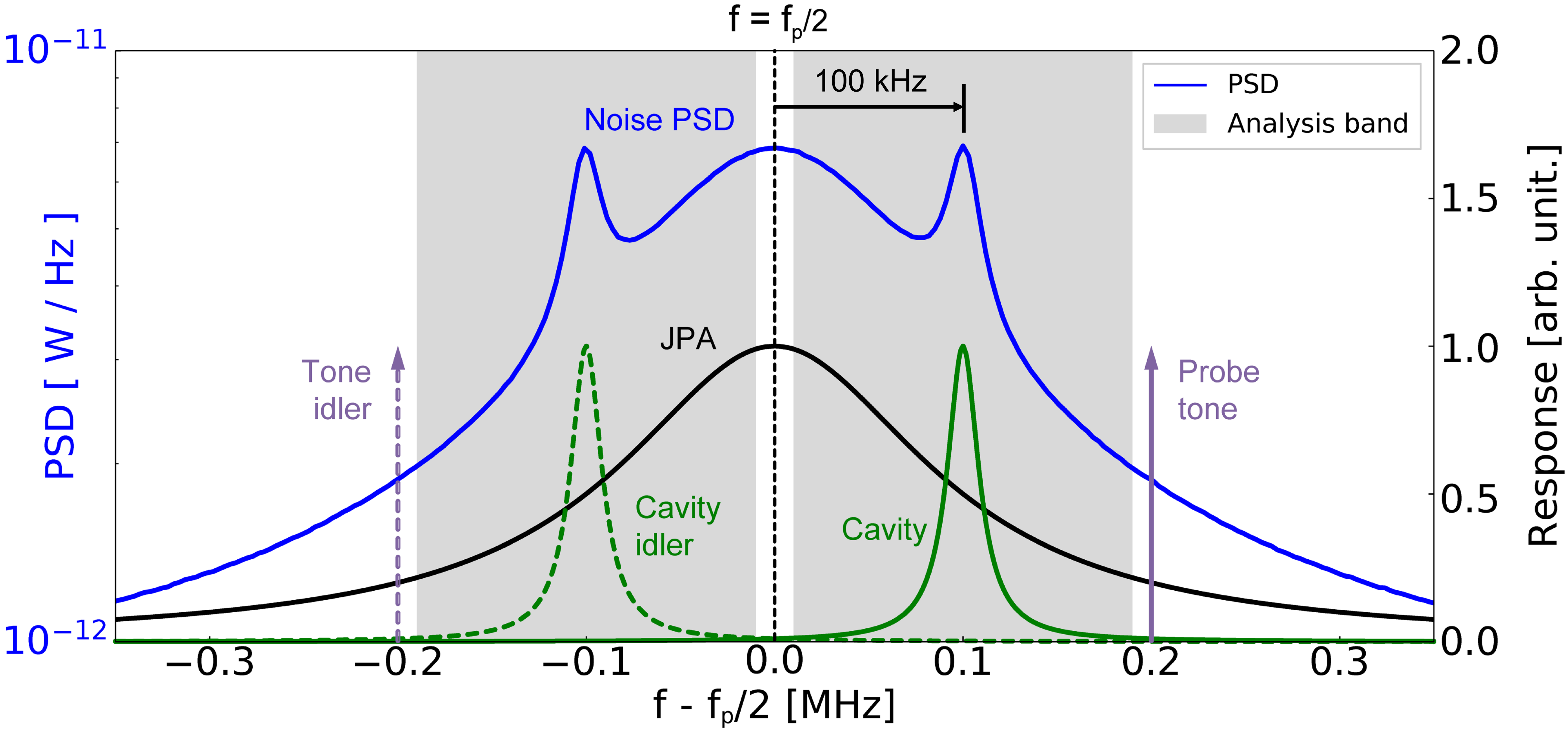
DAQ cadence



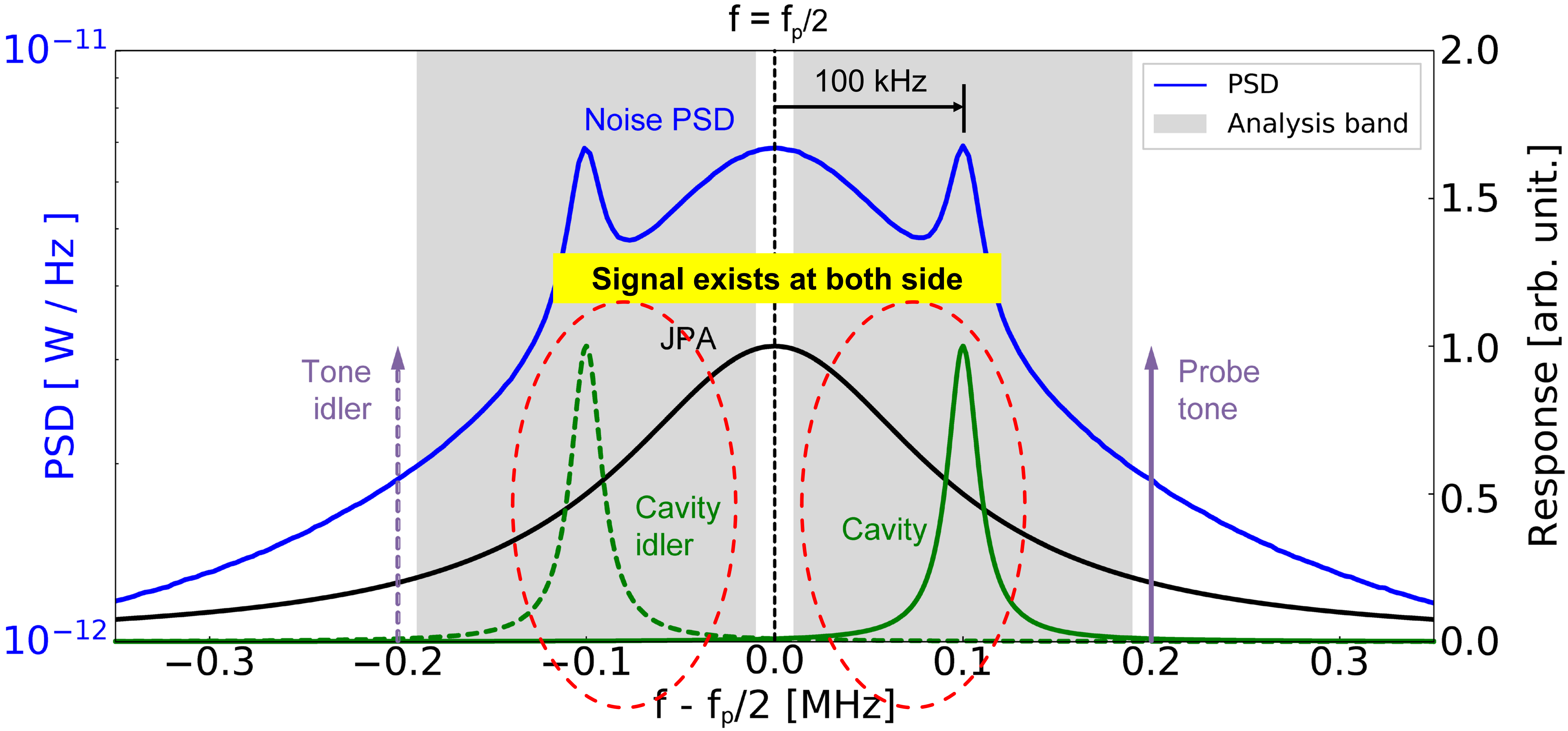
Axion sensitive data taking

- Digitizer / back-up spectrum analyzer / Aerial spectrum analyzer in parallel
- Aerial data check for filtering large non-axion peaks
- Post-processing (FFT, …) during the next DAQ

Data at a glance



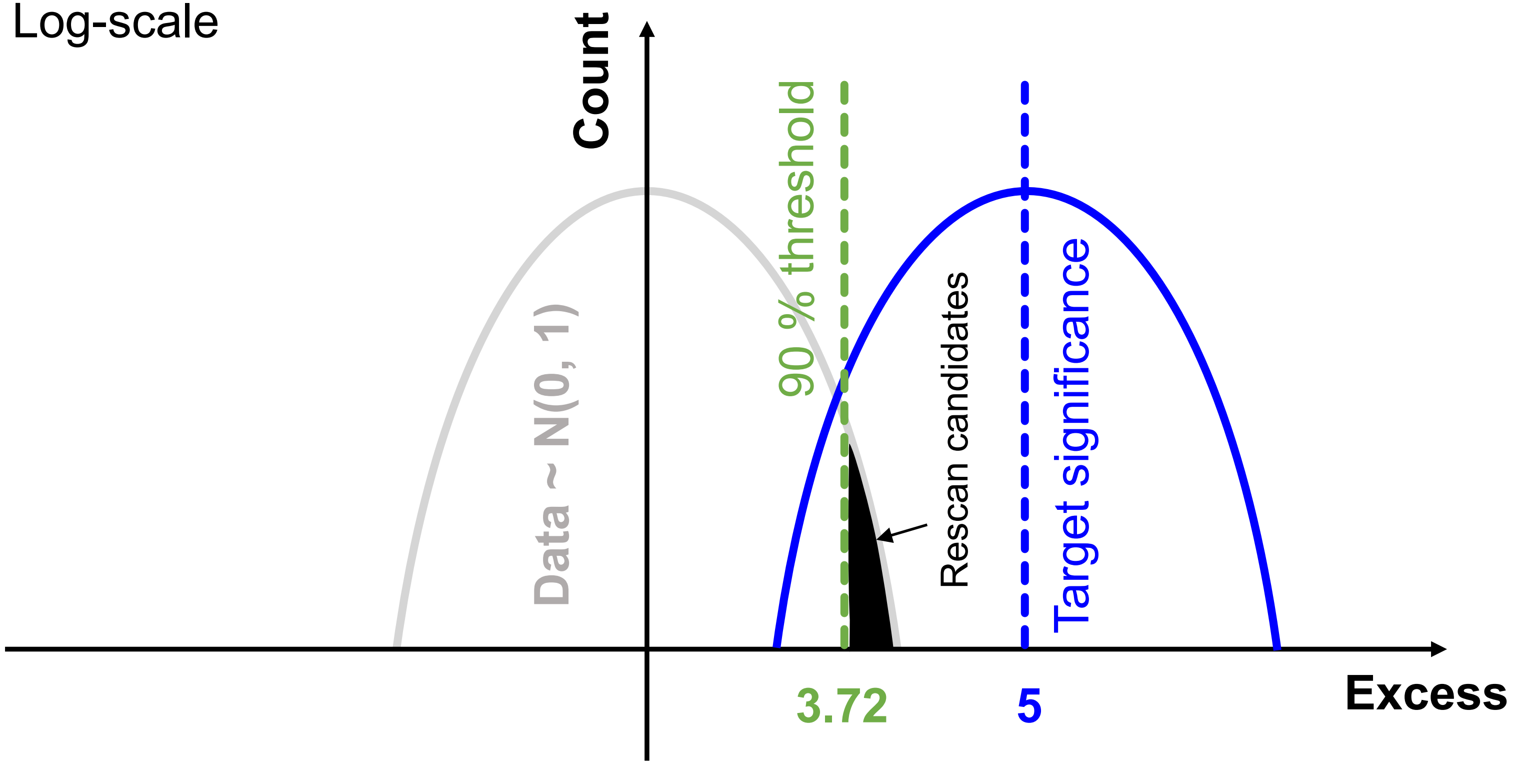
Data at a glance



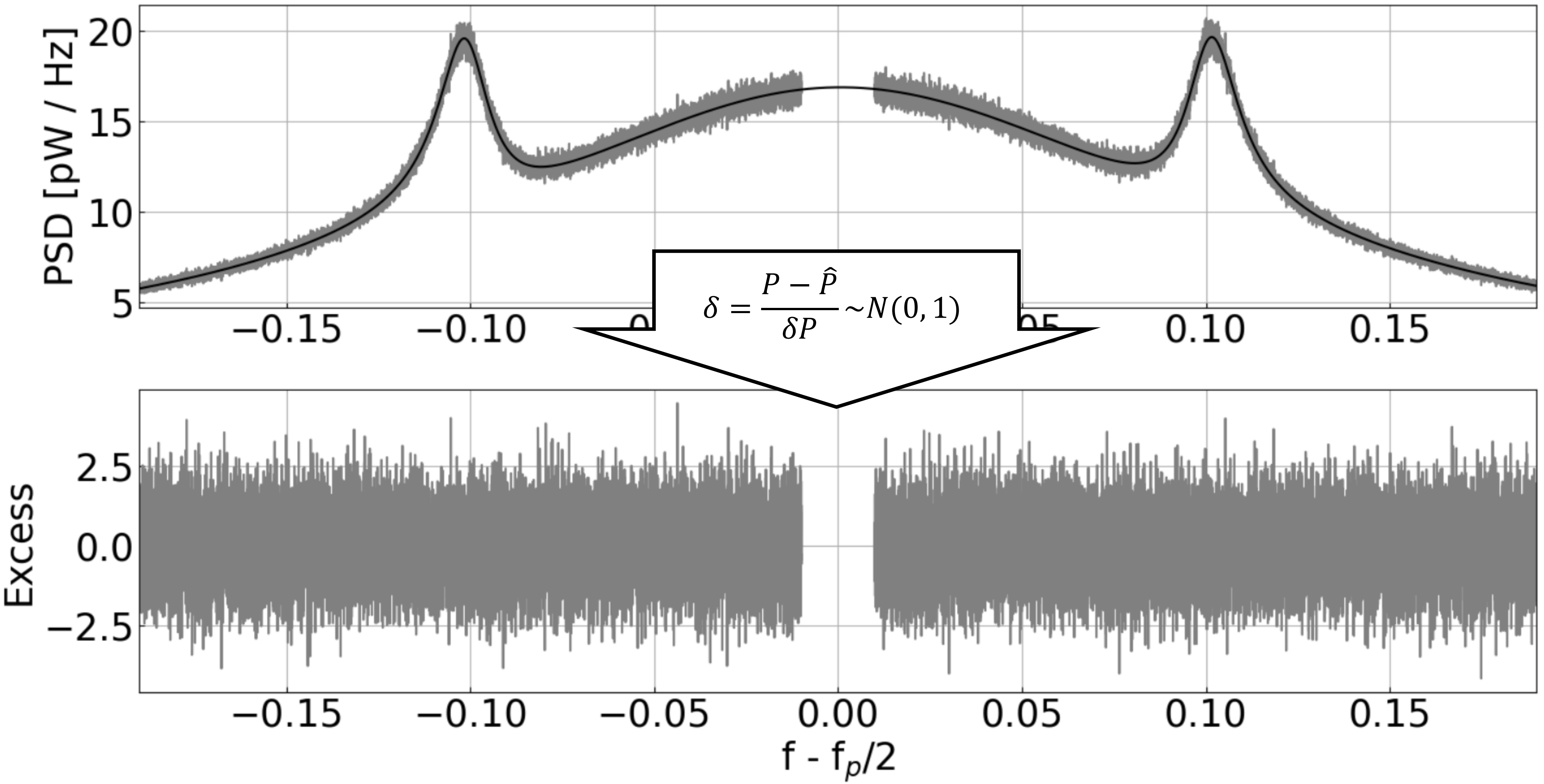
Data analysis

Saebyeok, Seongtae, Andrew,
ByeongRok, Jinsu

- **Gaussian statistics**
- Combining all the data possibly containing the signal
- Re-scan the nibbles above the threshold: 5 sigma / 90 % detection rate



Baseline removal



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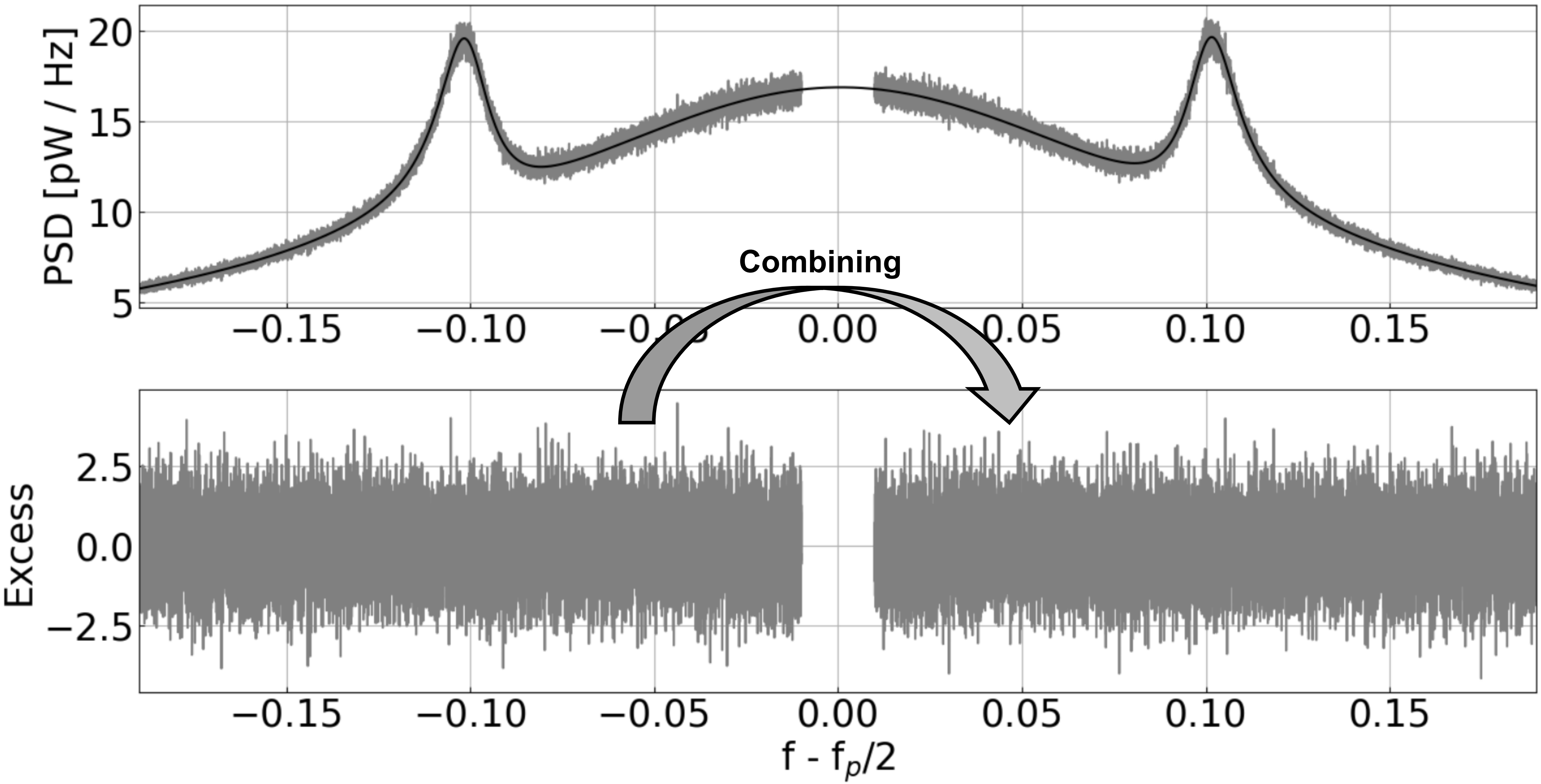
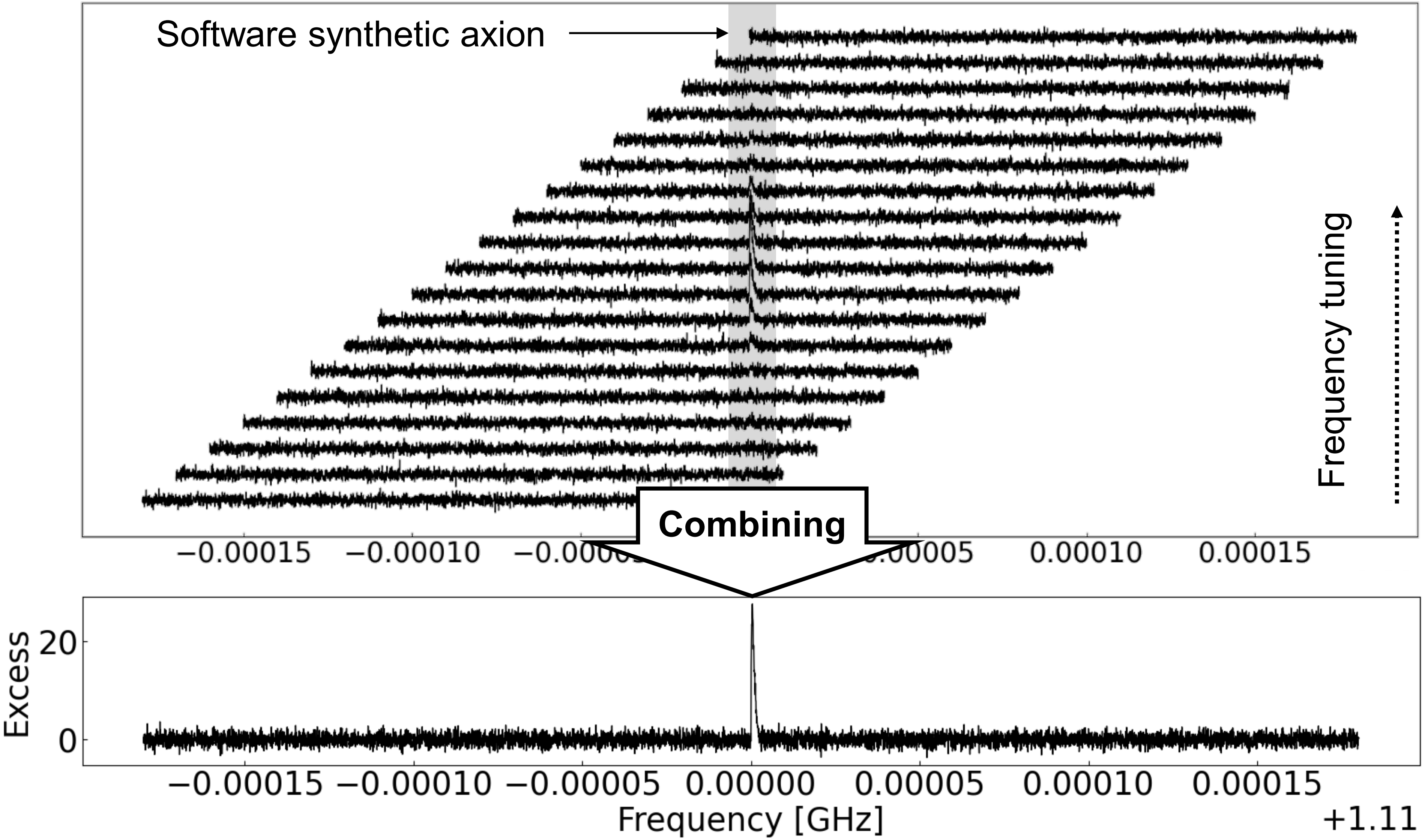
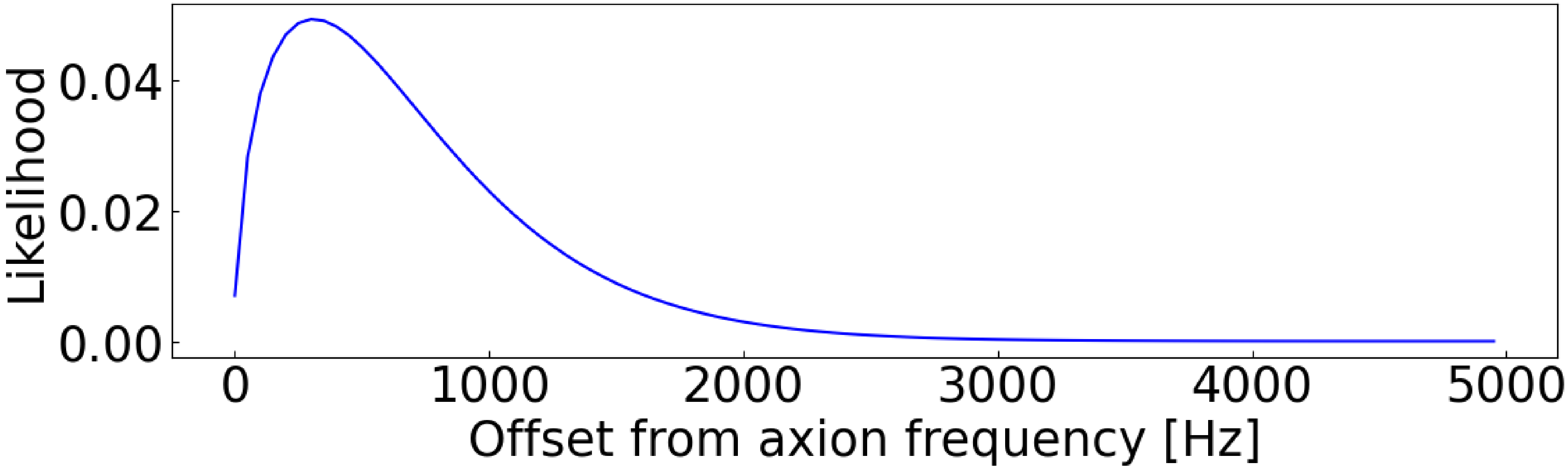


Vertical combination

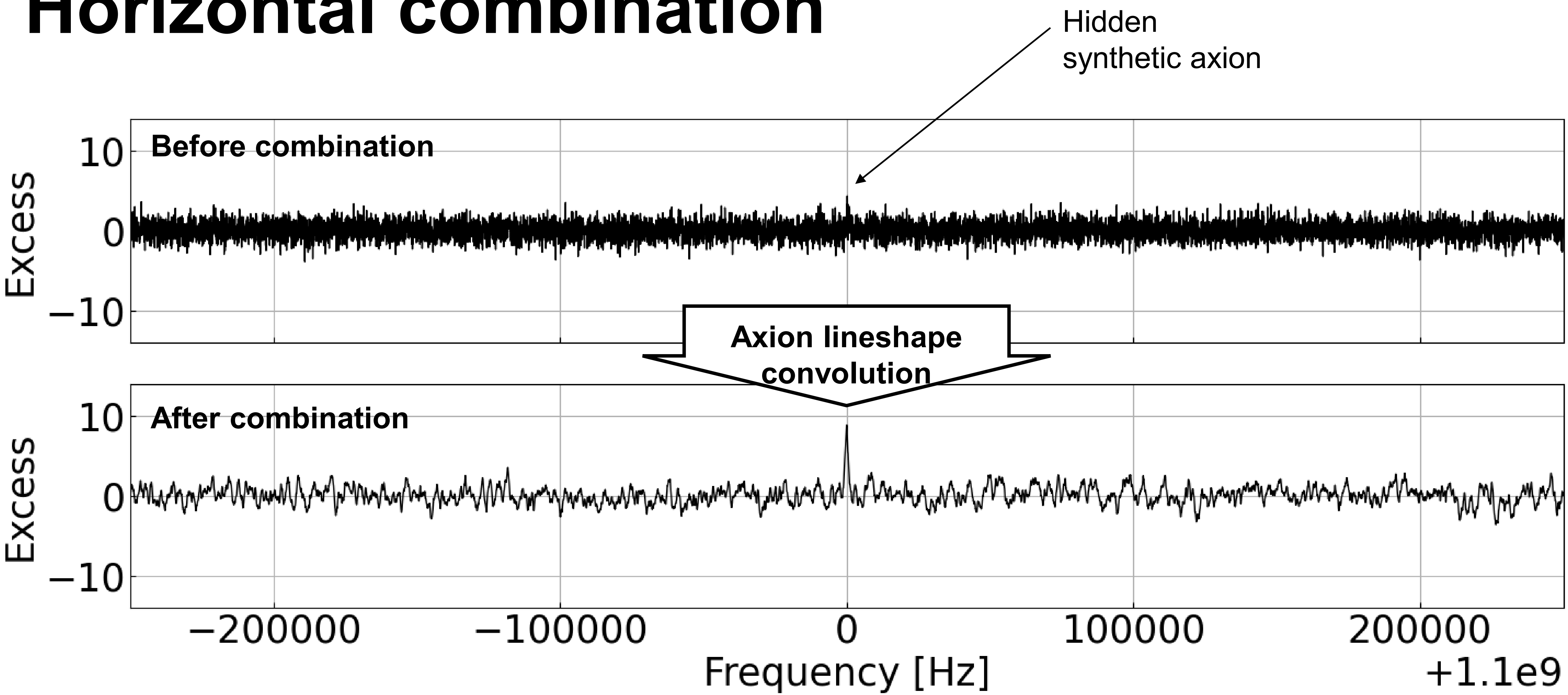


Horizontal combination



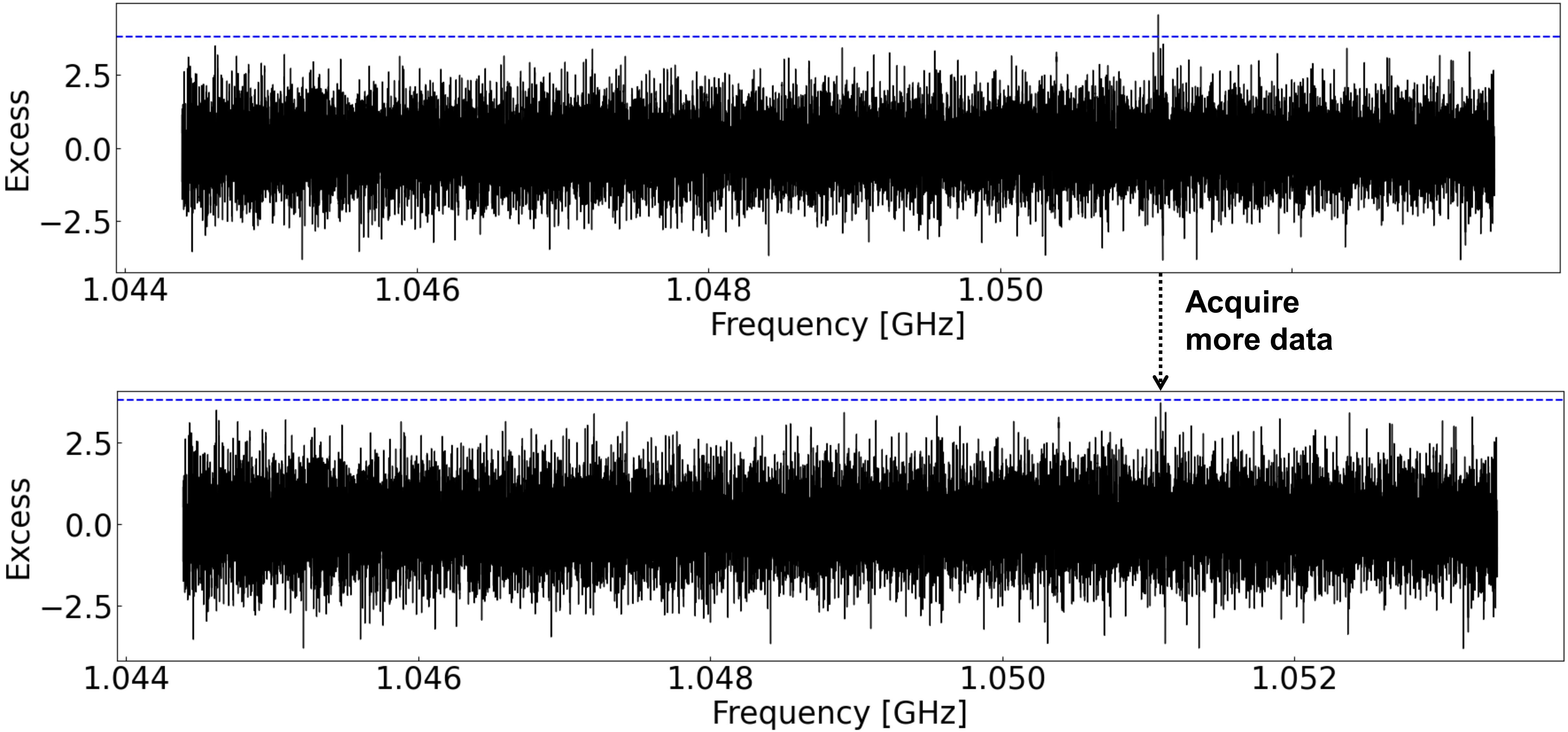
- Signal power is dispersed (~ 2 kHz at f = 1 GHz) → Lower signal-to-noise ratio
- Combining horizontally using the lineshape model (virialized axion)

Horizontal combination



Rescanning

Run 6 J1 group 2



Exclusion limit

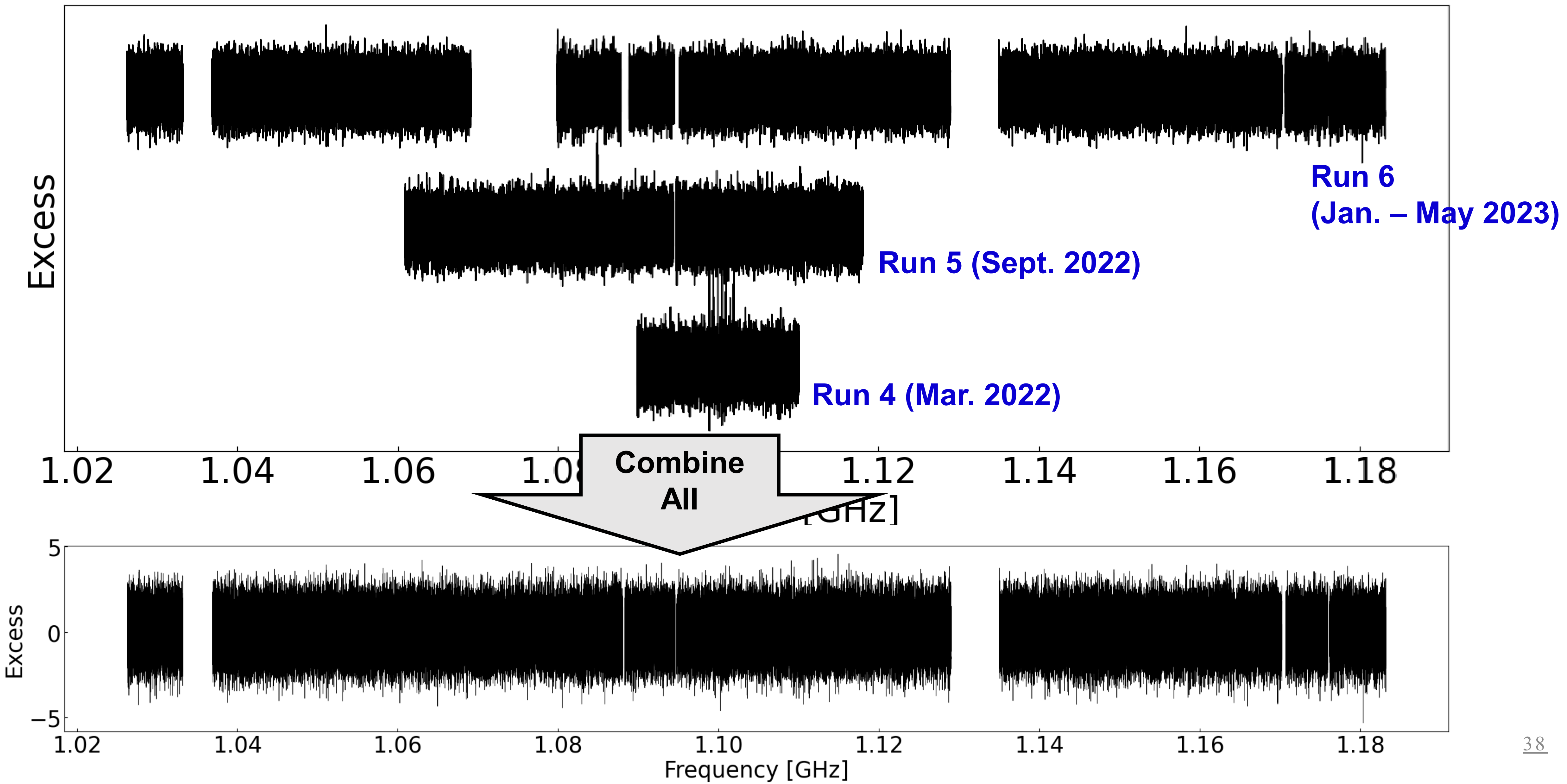
$$P(A|x_1, x_2, x_3, \ldots) \approx P(A)\frac{P(x_1, x_2, x_3, \ldots|A)}{P(x_1, x_2, x_3, \ldots|N)} = P(A) \times U(g_r)$$

Probability of axion existence with a given observation

Bayes factor between Axion existence and Gaussian noise

HAYSTAC, Phys. Rev. D **101**, 123011

Exclusion limit



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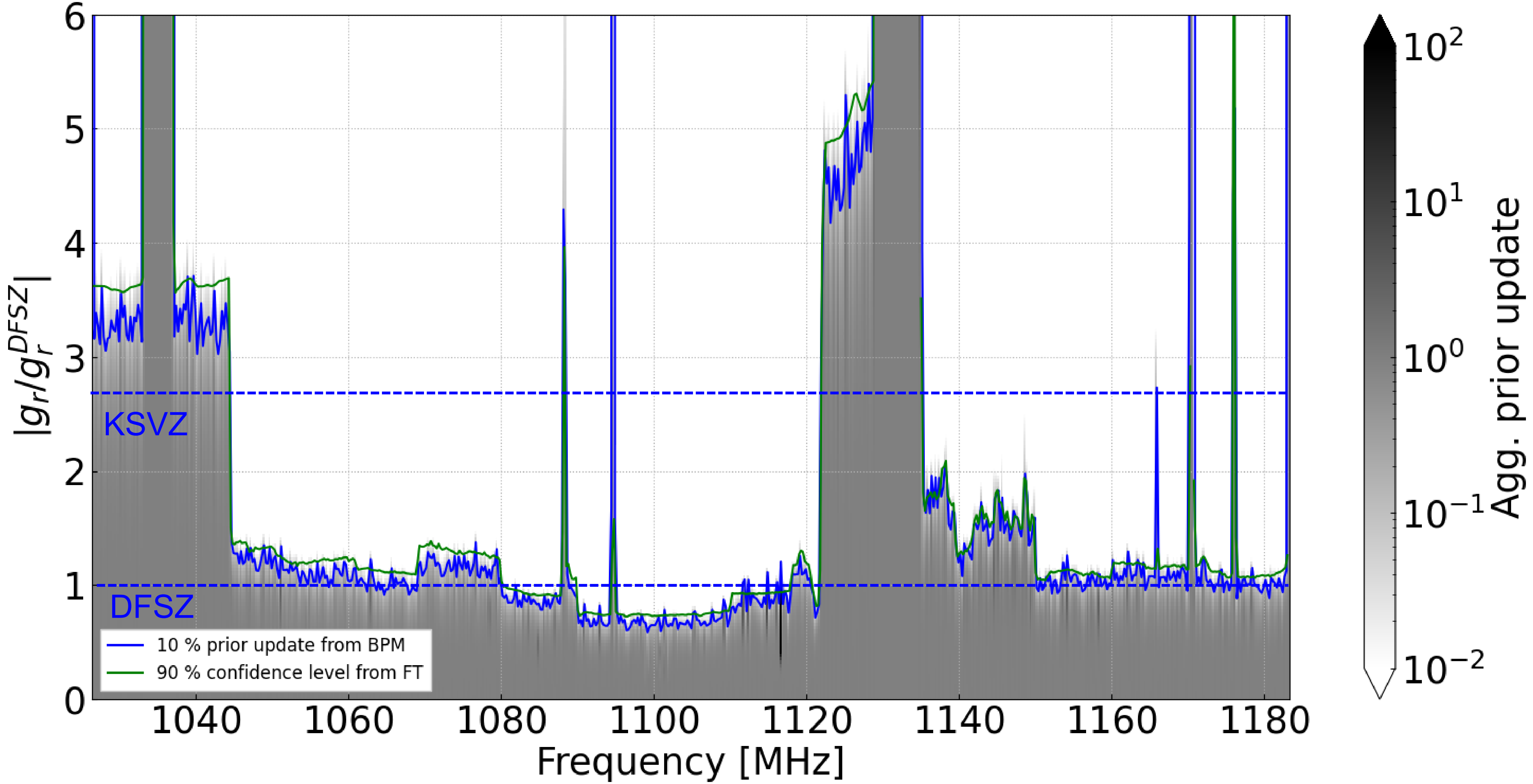

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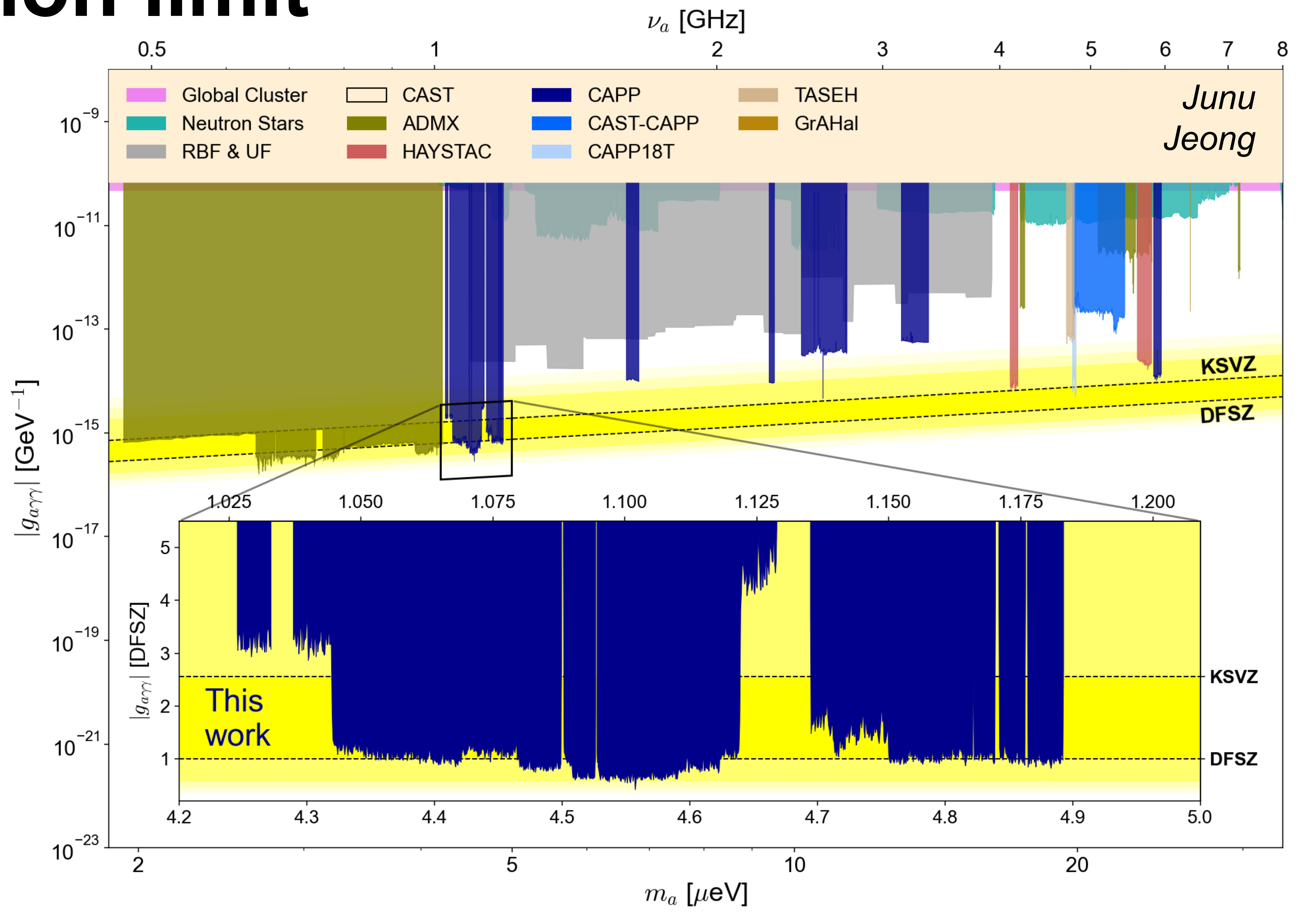


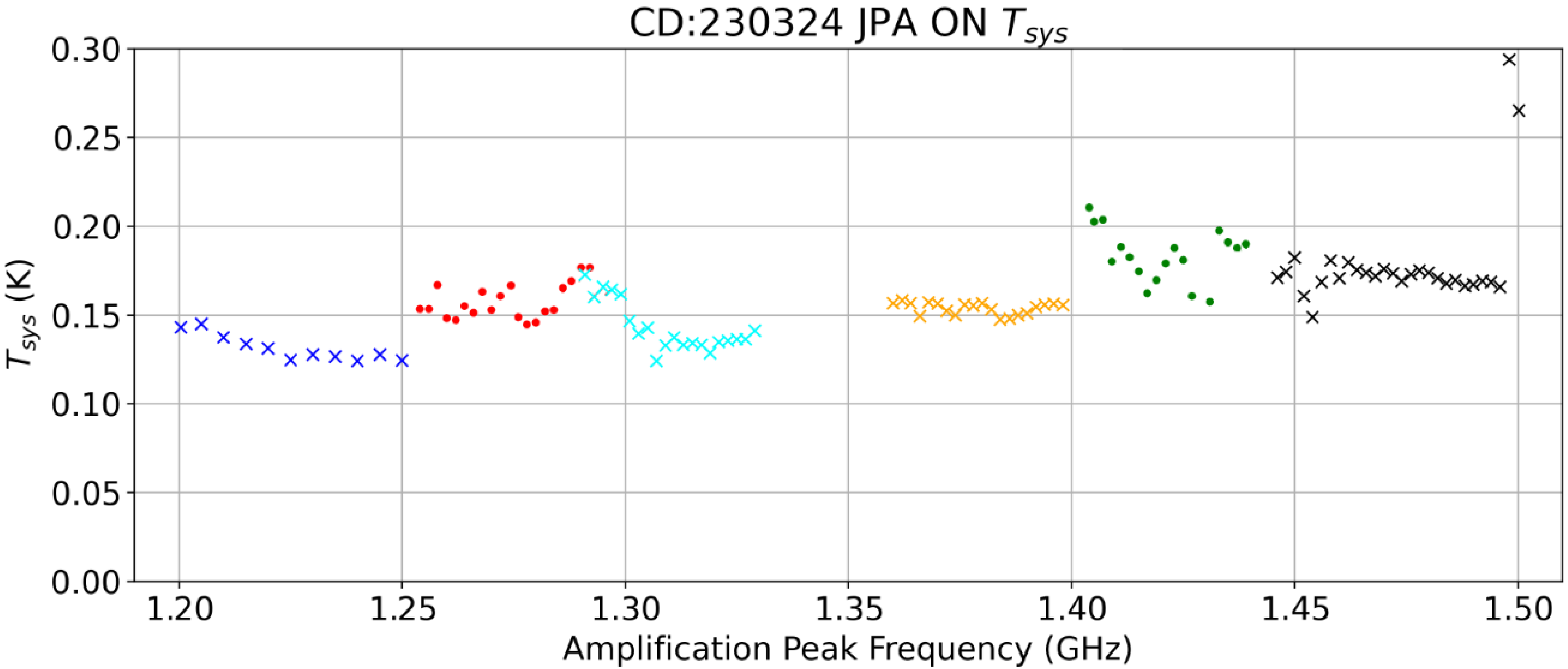
Next experiment

Danho, Jiwon, Ohjoon, Seongtae, Prof. Yum, Woohyun

Superconducting tuning rod

- ❑ Higher Q factor
- ❑ Higher axion conversion power

Next experiment



6 JPA system

- Covering ~ 300 MHz
- Nearly quantum-limited added noise (each of them)

Prospects

Publication

- Wrapping up run 4 – 6, working on the publication (Saebyeok, SungWoo, ByeongRok, Ohjoon, Heesu, Soohyung, Boris, Woohyun, Junu, Yannis)

Ongoing

- SC tuning rod + 6 JPA: 1.2 – 1.5 GHz

Beyond 1.5 GHz

- Full SC cavity (Danho, Jiwon, Ohjoon, Seongtae, Prof. Yum, Woohyun)
- High frequency approach (Junu, Sungjae, **Youngguen**, Sungwoo)
- Heterodyne variance method (Junu)
    - Bolometer (**Boris**)

Summary

- CAPP-MAX is the axion search experiment with DFSZ sensitivity
- Run 4 – 6 for 1.02 – 1.18 GHz scan are finished
- Next data taking run for 1.2 – 1.5 GHz soon
- Beyond 1.5 GHz with integrated new techniques are also being prepared