Axion dark matter search with DFSZ sensitivity at CAPP

Saebyeok Ahn

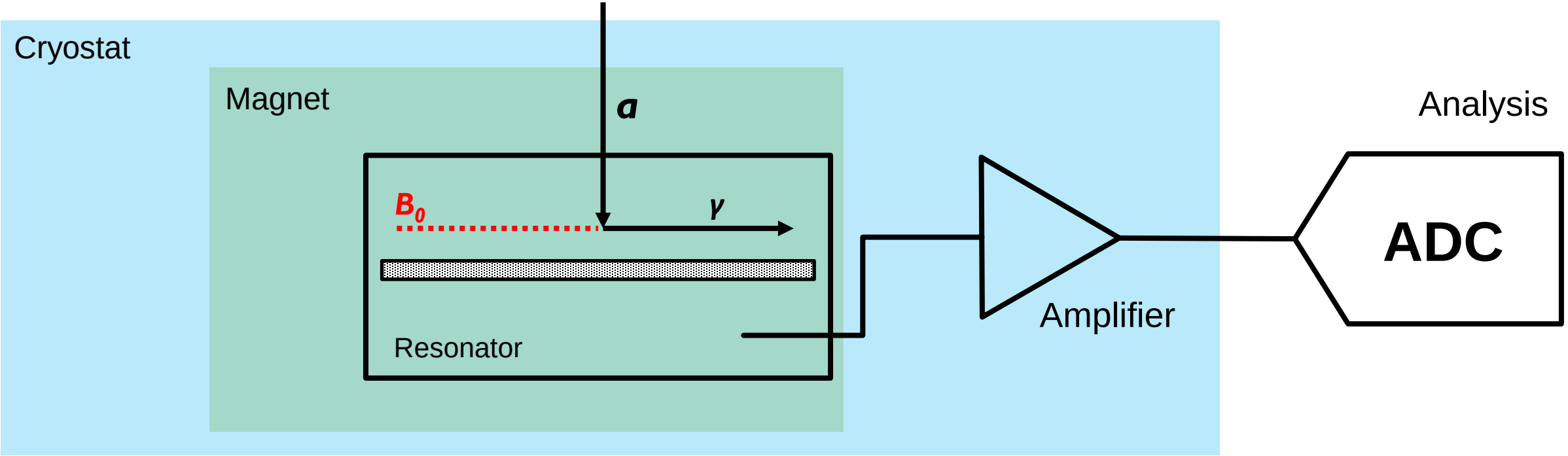
On behalf of
IBS-CAPP in KAIST
South Korea

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

The CAPP-MAX experiment

Principle

- Detection of resonant axion-photon conversion in a microwave cavity in a static magnetic field (Sikivie effect)



Sketch of a conceptualized axion haloscope experimental setup

The CAPP-MAX experiment

Goal

- Search for axion dark matter around 1 – 2 GHz with DFSZ sensitivity

The CAPP-MAX experiment

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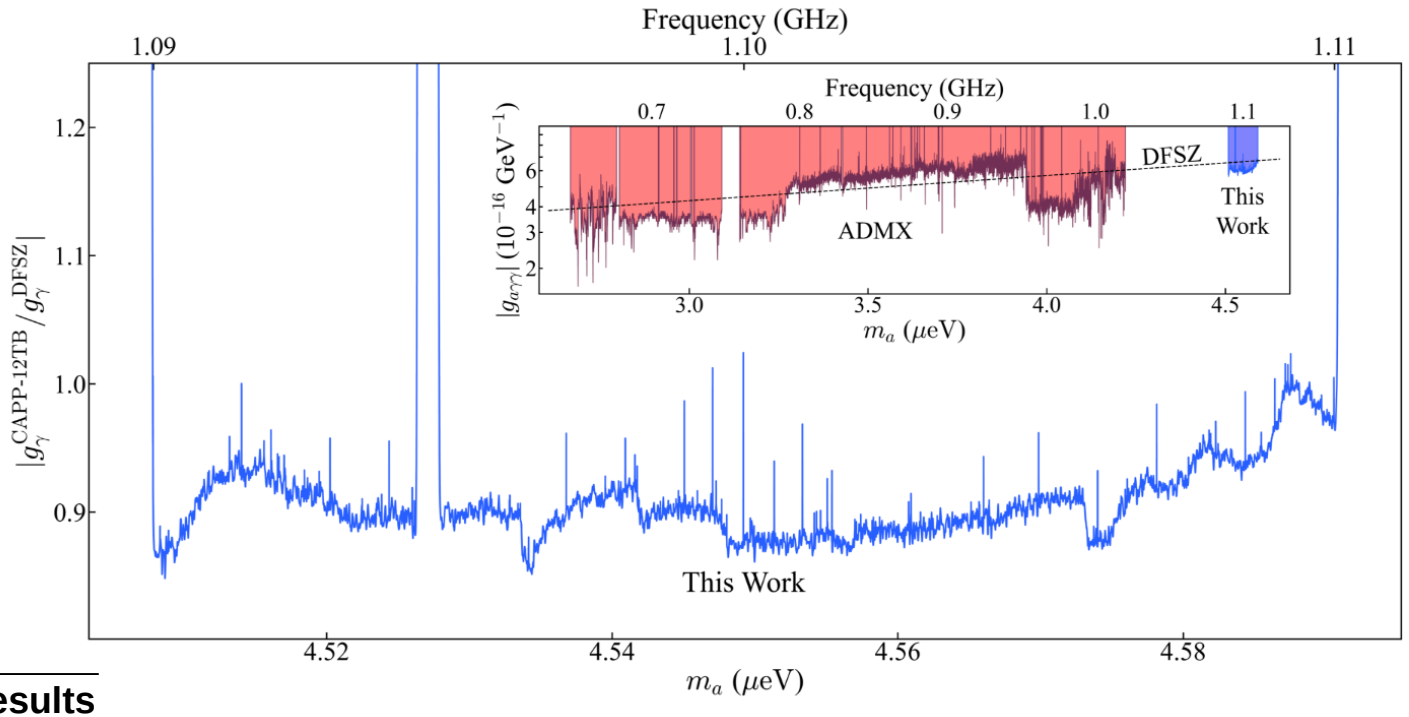
- Search for axion dark matter around 1 – 2 GHz with DFSZ sensitivity

Achieved

- 1st physics run / 1.09 – 1.11 GHz / DFSZ sensitivity



Phys. Rev. Lett. 130, 071002

The CAPP-MAX experiment

Goal

- Search for axion dark matter around 1 – 2 GHz with DFSZ sensitivity

Achieved

- 1st physics run / 1.09 – 1.11 GHz / DFSZ sensitivitv

First Search for the Sagittarius Tidal Stream of Axion Dark Matter around 4.55 μeV

Andrew K. Yi,[1,2] Saebyeok Ahn,[1,2] Çağlar Kutlu,[1,2] JinMyeong Kim,[1,2] Byeong Rok Ko,[2,*] Boris I. Ivanov,[2] HeeSu Byun,[2] Arjan F. van Loo,[3,4] SeongTae Park,[2] Junu Jeong,[2] Ohjoon Kwon,[2] Yasunobu Nakamura,[3,4] Sergey V. Uchaikin,[2] Jihoon Choi,[2,†] Soohyung Lee,[2] MyeongJae Lee,[2,‡] Yun Chang Shin,[2] Jinsu Kim,[1,2] Doyu Lee,[2,§] Danho Ahn,[1,2] SungJae Bae,[1,2] Jiwon Lee,[1,2] Younggeun Kim,[2] Violeta Gkika,[2] Ki Woong Lee,[2] Seonjeong Oh,[2] Taehyeon Seong,[2] DongMin Kim,[2] Woohyun Chung,[2] Andrei Matlashov,[2] SungWoo Youn,[2] and Yannis K. Semertzidis[2,1]

[1] *Dept. of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea*
[2] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*
[3] *RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351-0198, Japan*
[4] *Dept. of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*

We report the first search for the Sagittarius tidal stream of axion dark matter around 4.55 μeV using CAPP-12TB haloscope data acquired in March of 2022. Our result excluded the Sagittarius tidal stream of Dine-Fischler-Srednicki-Zhitnitskii and Kim-Shifman-Vainshtein-Zakharov axion dark matter densities of $\rho_a \gtrsim 0.15$ and $\gtrsim 0.02$ GeV/cm^3, respectively, over a mass range from 4.51 to 4.59 μeV at a 90% confidence level.

arXiv:2302.01502

The CAPP-MAX experiment

Goal

- Search for axion dark matter around 1 – 2 GHz with DFSZ sensitivity

Achieved

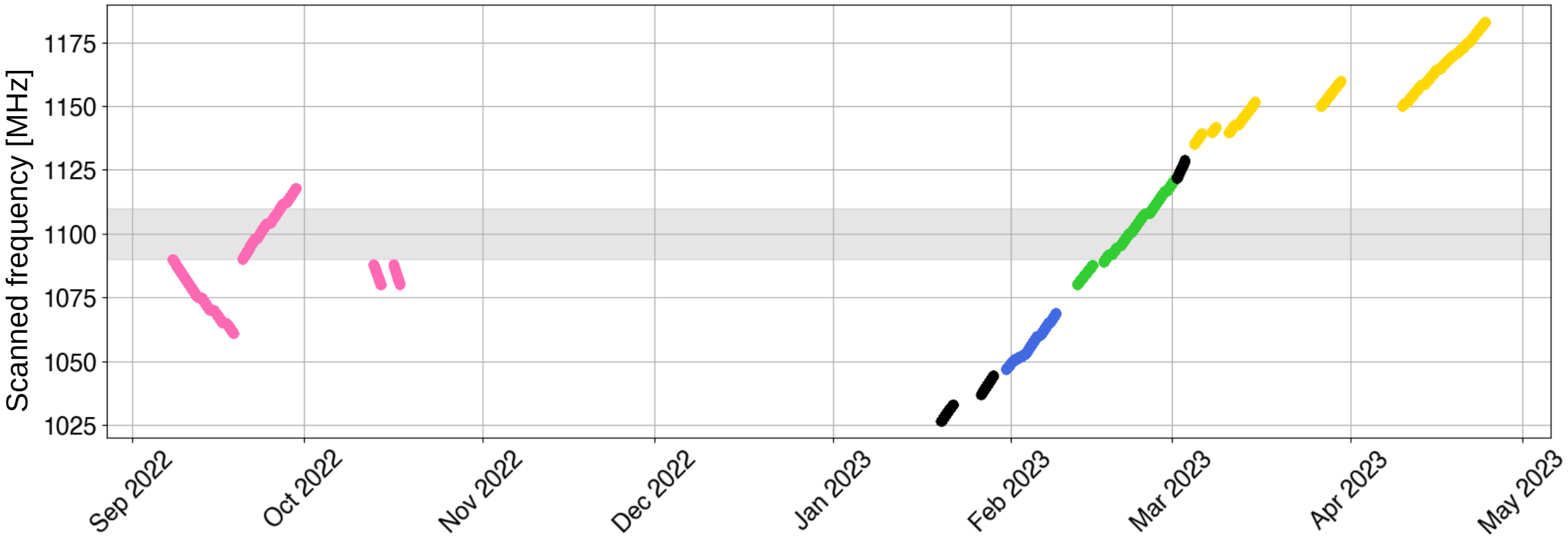
- 1st physics run / 1.09 – 1.11 GHz / DFSZ sensitivity

Recent progress

- 2nd physics run / 1.06 – 1.12 GHz
  - Same system, different scanning speed
- 3rd physics run / 1.025 – 1.18 GHz
  - Parallel/serial JPAs in the system

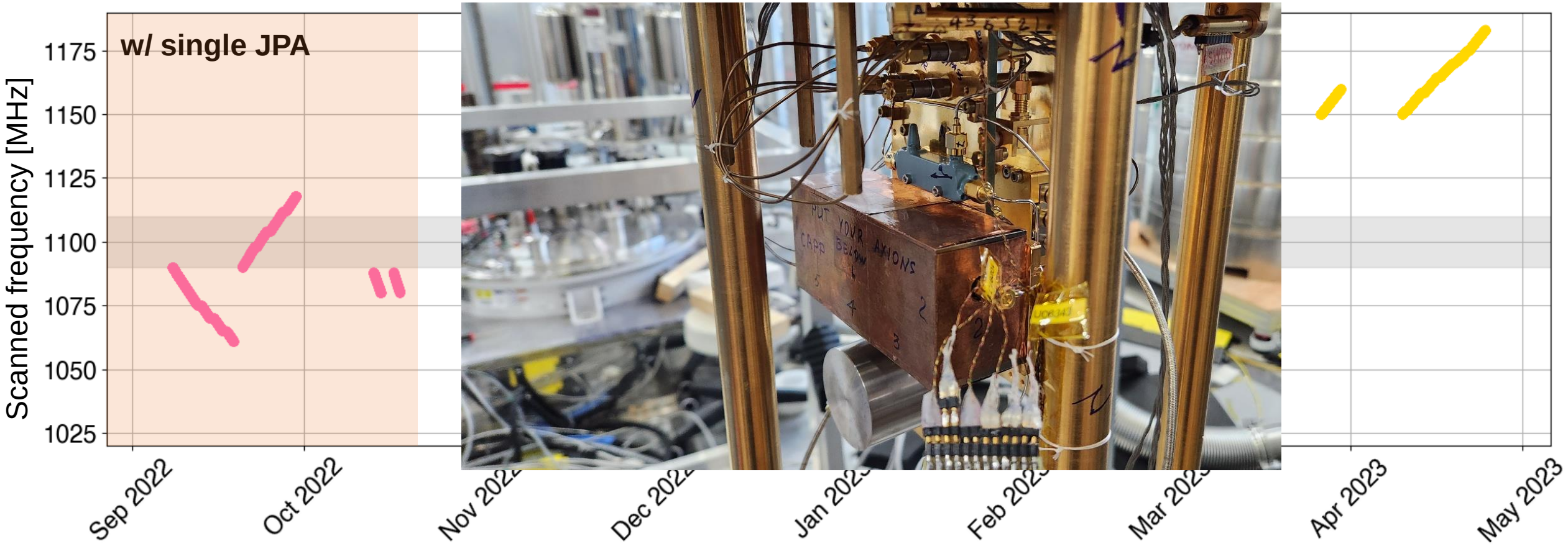
Physics run calendar

Grey band: 1st run



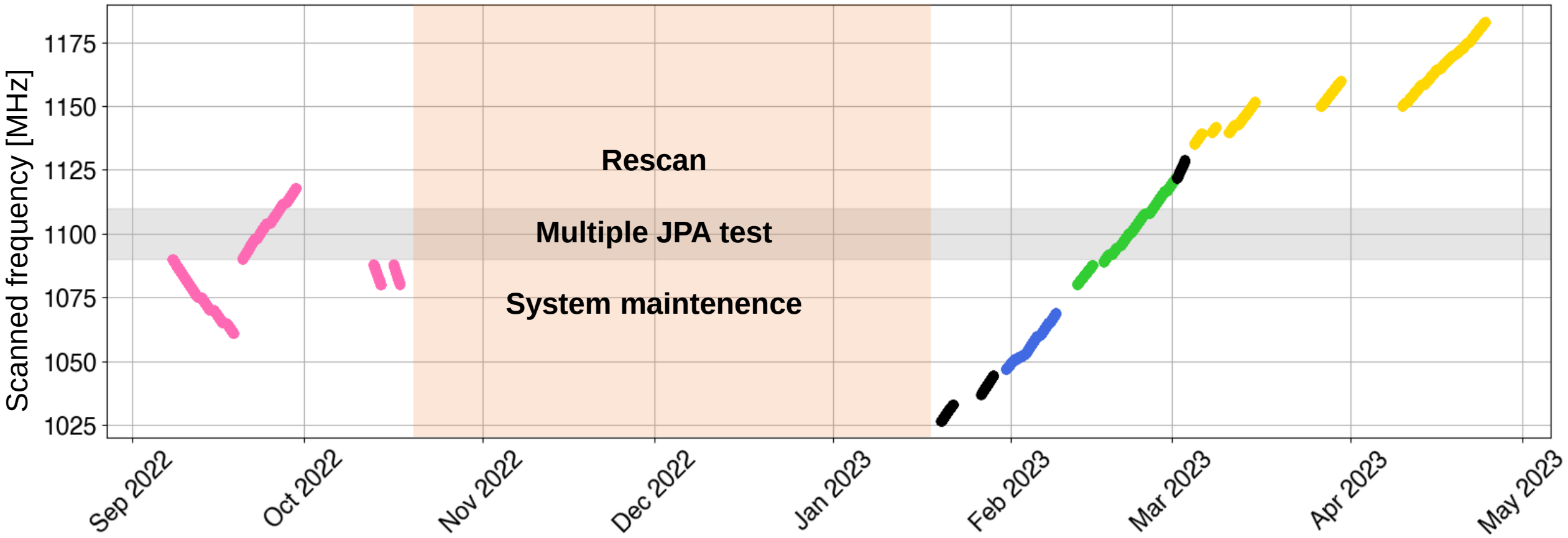
Physics run calendar

Grey band: 1st run



Physics run calendar

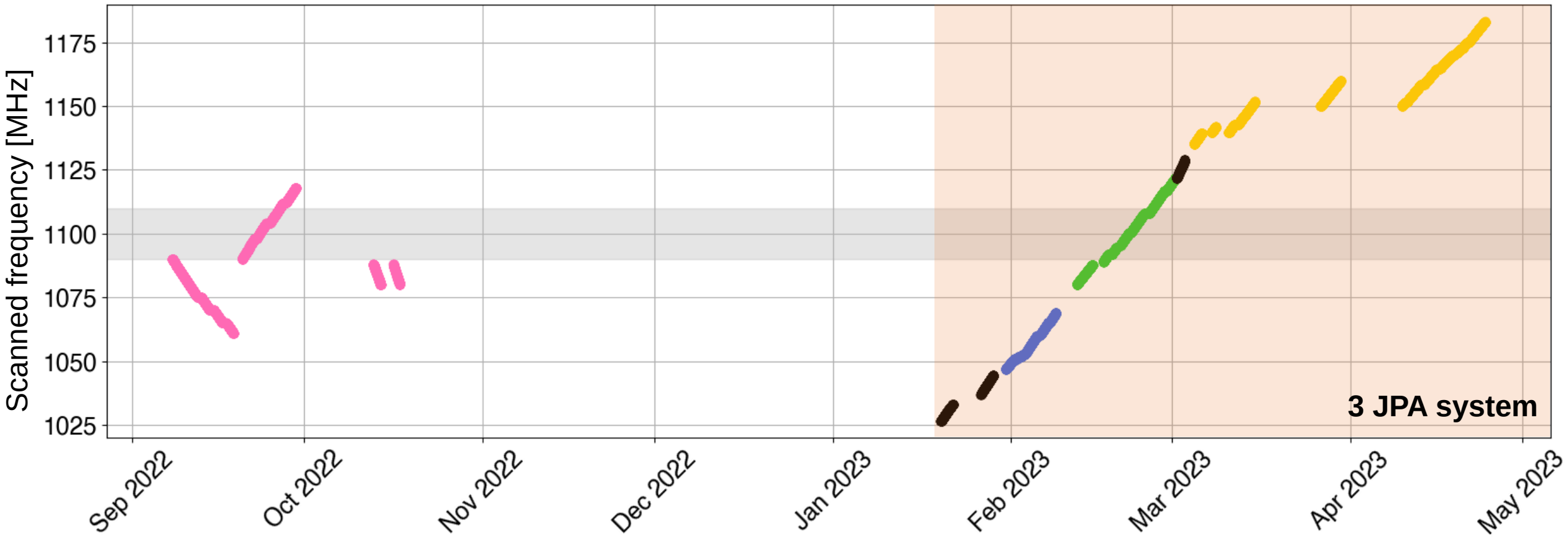
Grey band: 1st run



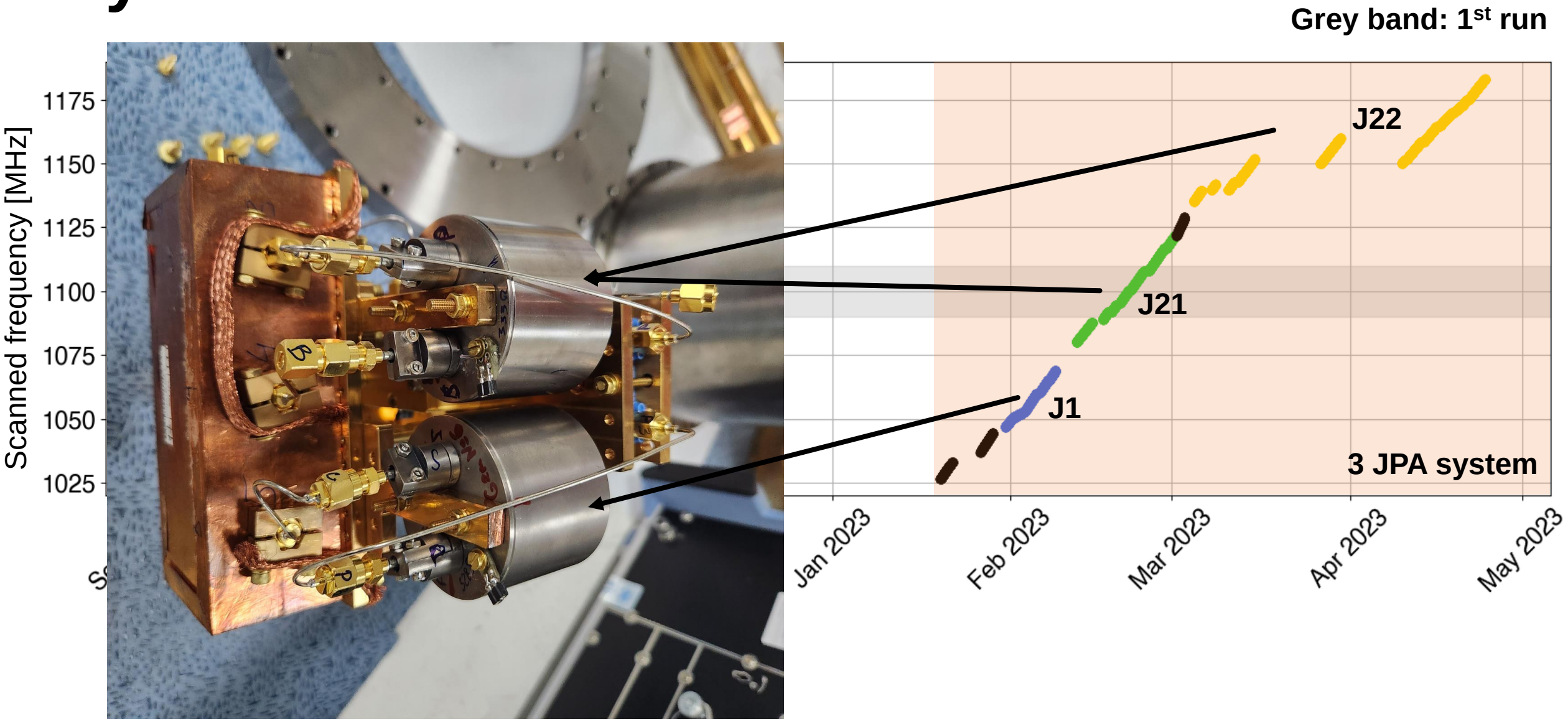
Got my degree
☺

Physics run calendar

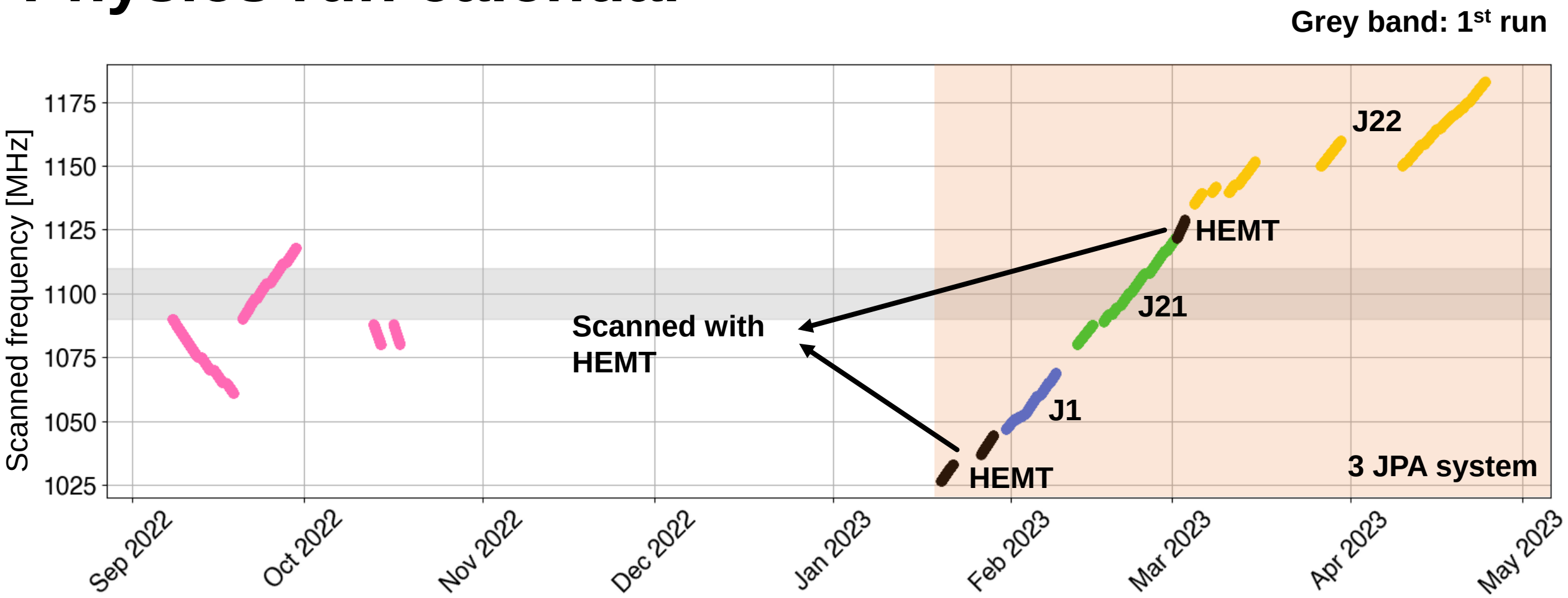
Grey band: 1st run



Physics run calendar



Physics run calendar



Experimental parameters

Axion-photon conversion power

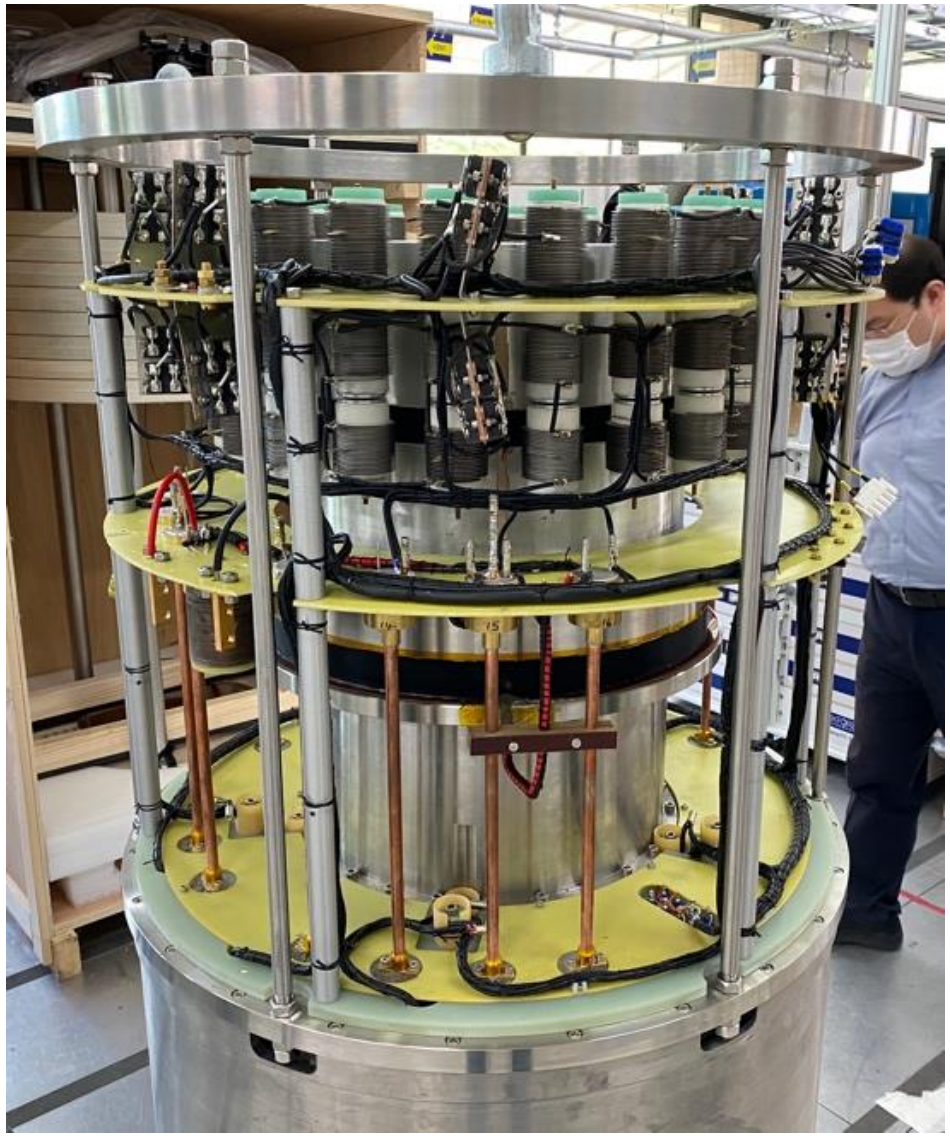
$$P_a^{a\gamma\gamma} = 22.51 \times 10^{-24}\ [\mathrm{W}] \left(\frac{g_\gamma}{0.36}\right)^2$$

DFSZ model

Experimental parameters

Axion-photon conversion power

$$P_a^{a\gamma\gamma} = 22.51 \times 10^{-24}\ [\mathrm{W}] \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{B_{\mathrm{avg}}}{10.31\ \mathrm{T}}\right)^2$$



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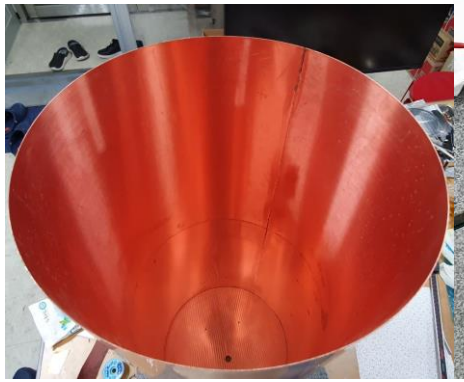
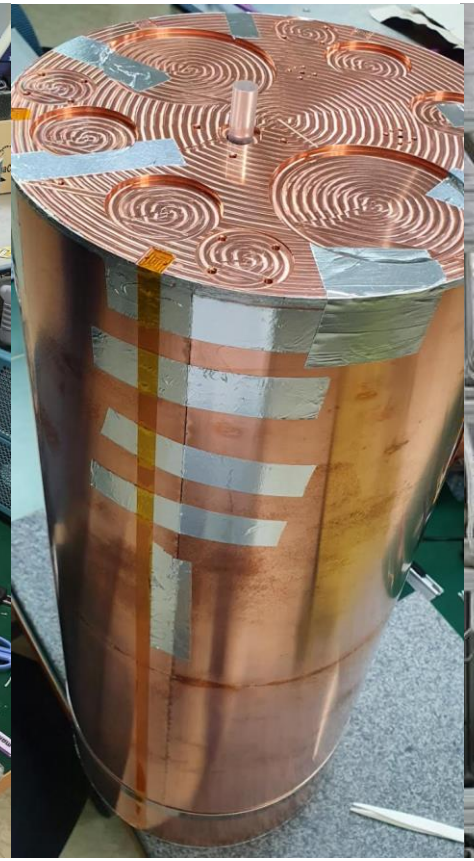
Home-made light cavity with OFHC copper sheet (ULC)

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





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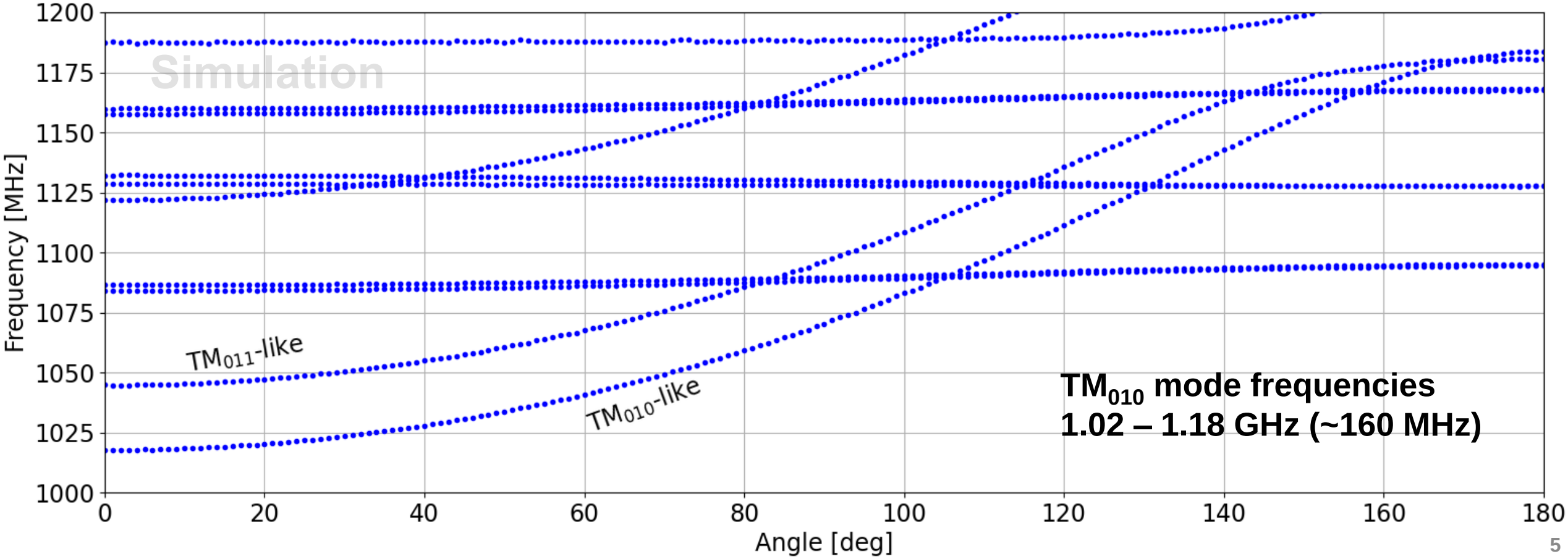

TM_{010} mode frequencies
1.02 – 1.18 GHz (~160 MHz)

Experimental parameters

Axion-photon conversion power

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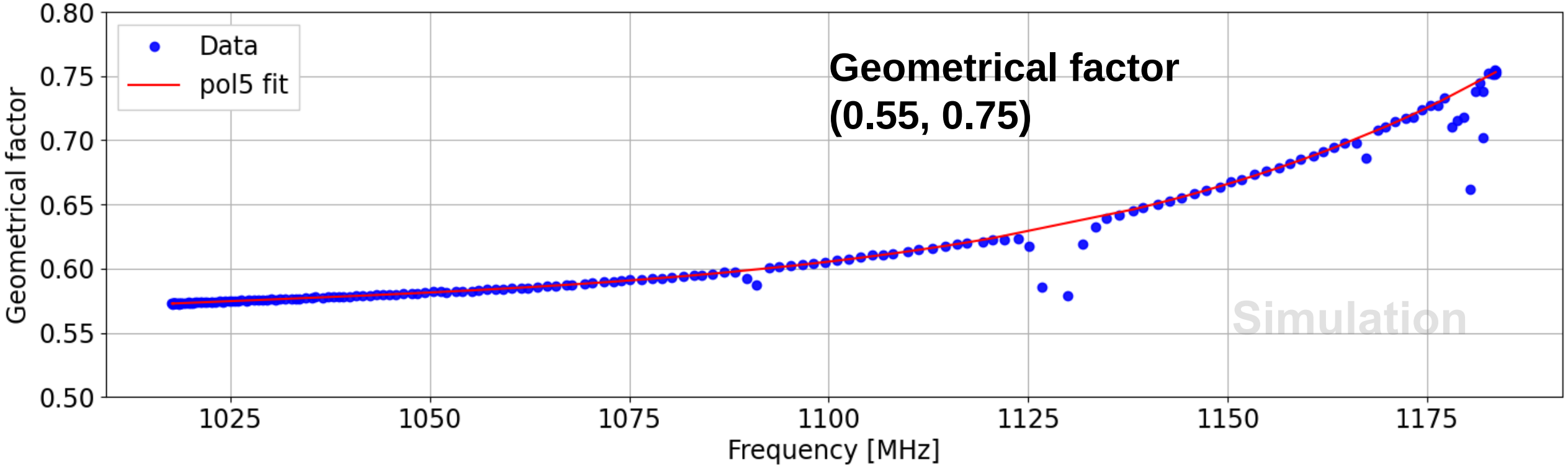
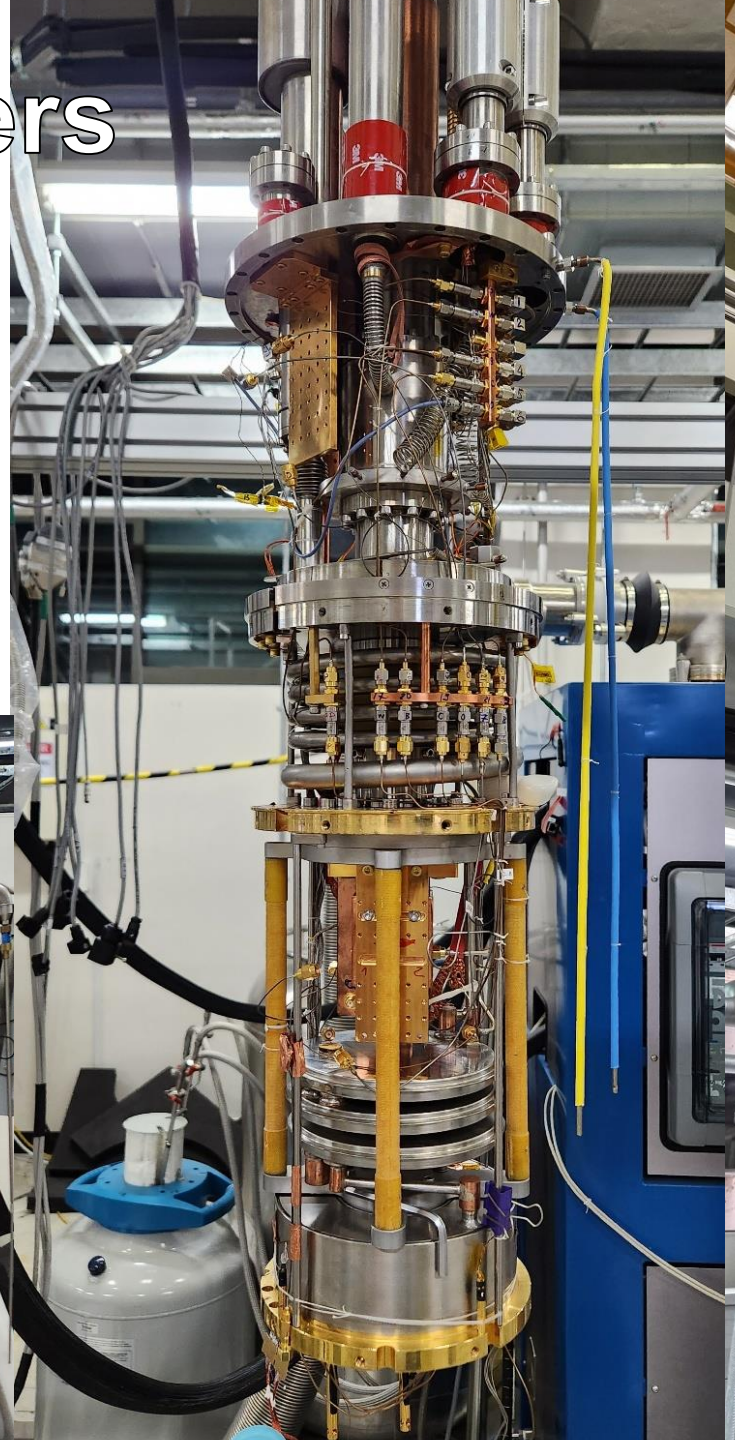


Experimental parameters

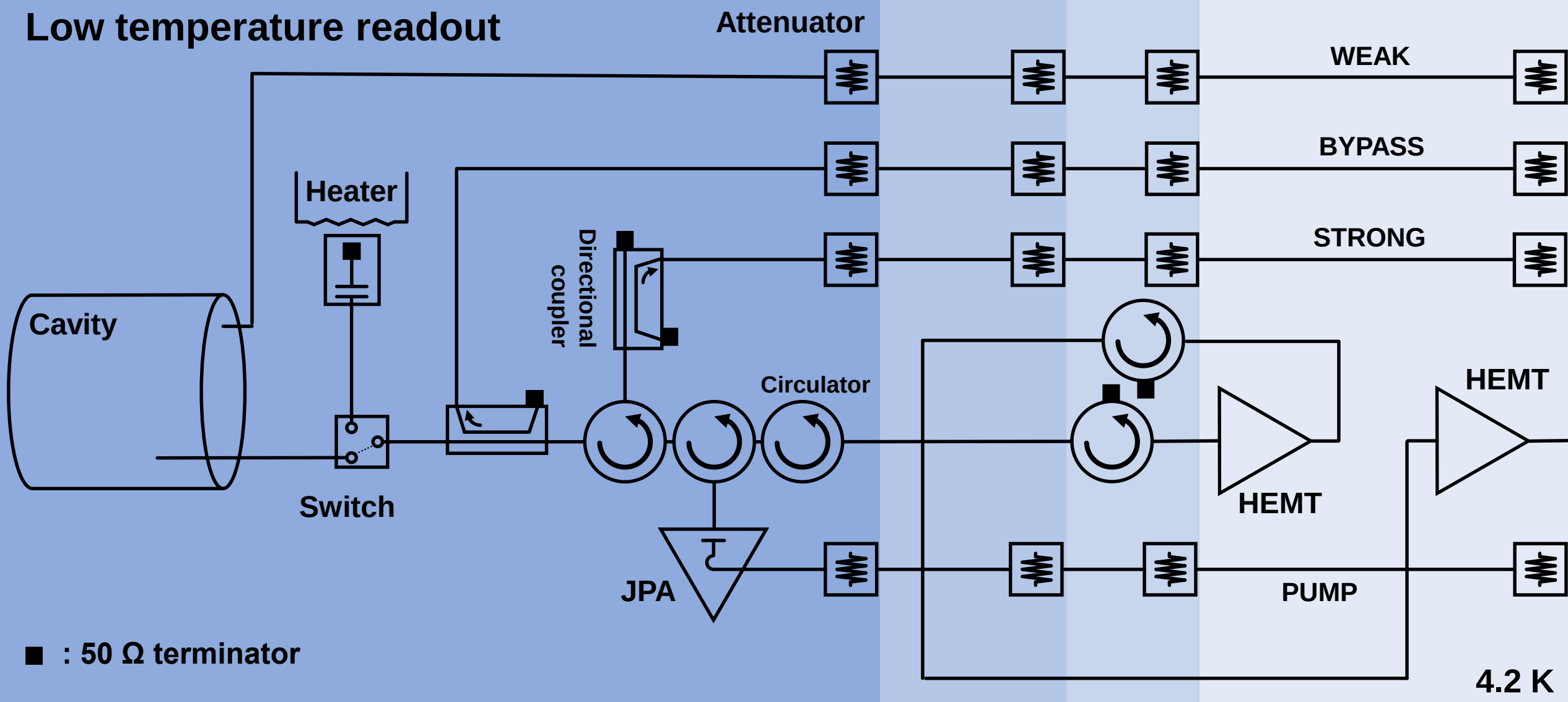
The cryogenic system

- Wet-type LEIDEN dilution fridge
  - Base temperature of 5.4 mK (bare)
  - Typical MXC temp. of < 30 mK (physics run)
- Liquid Helium liquefier/Re-liquefier loop



Experimental parameters

Low temperature readout



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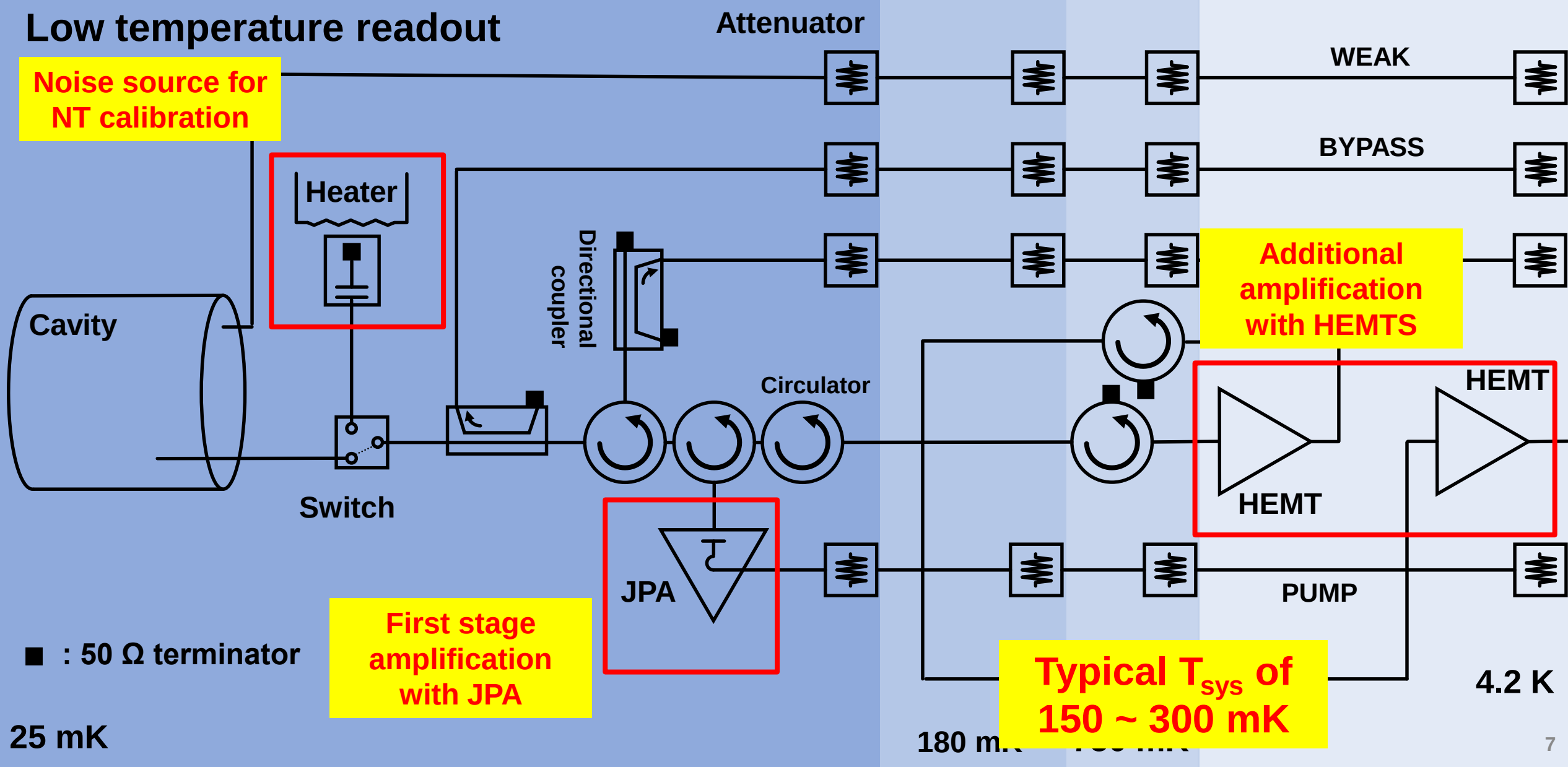
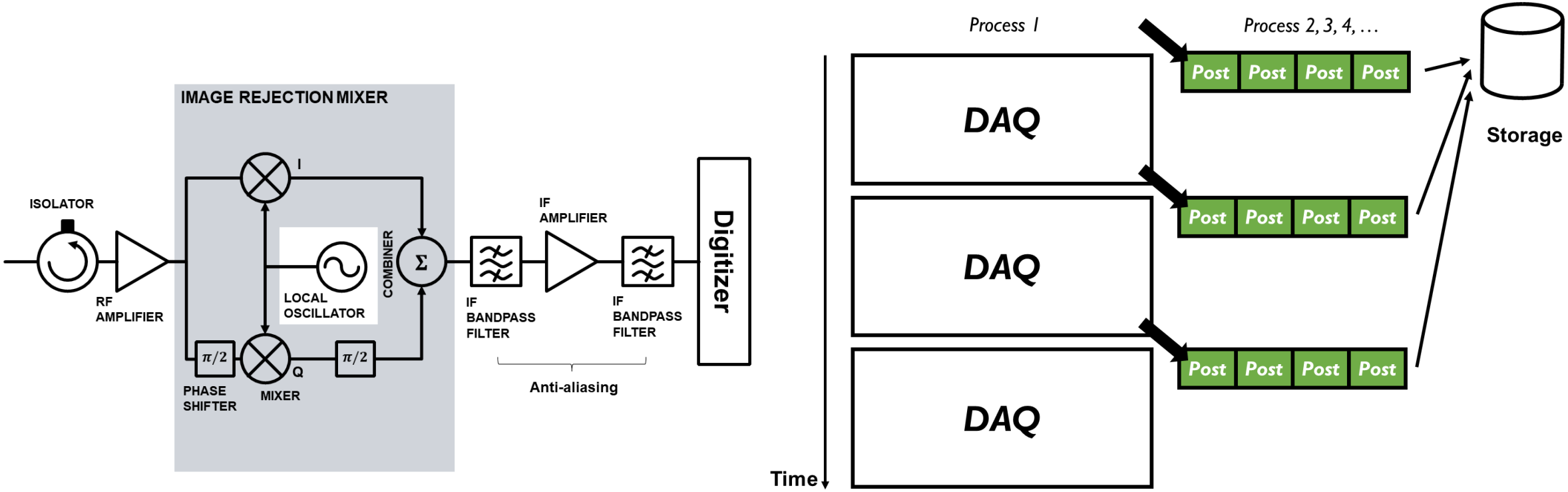


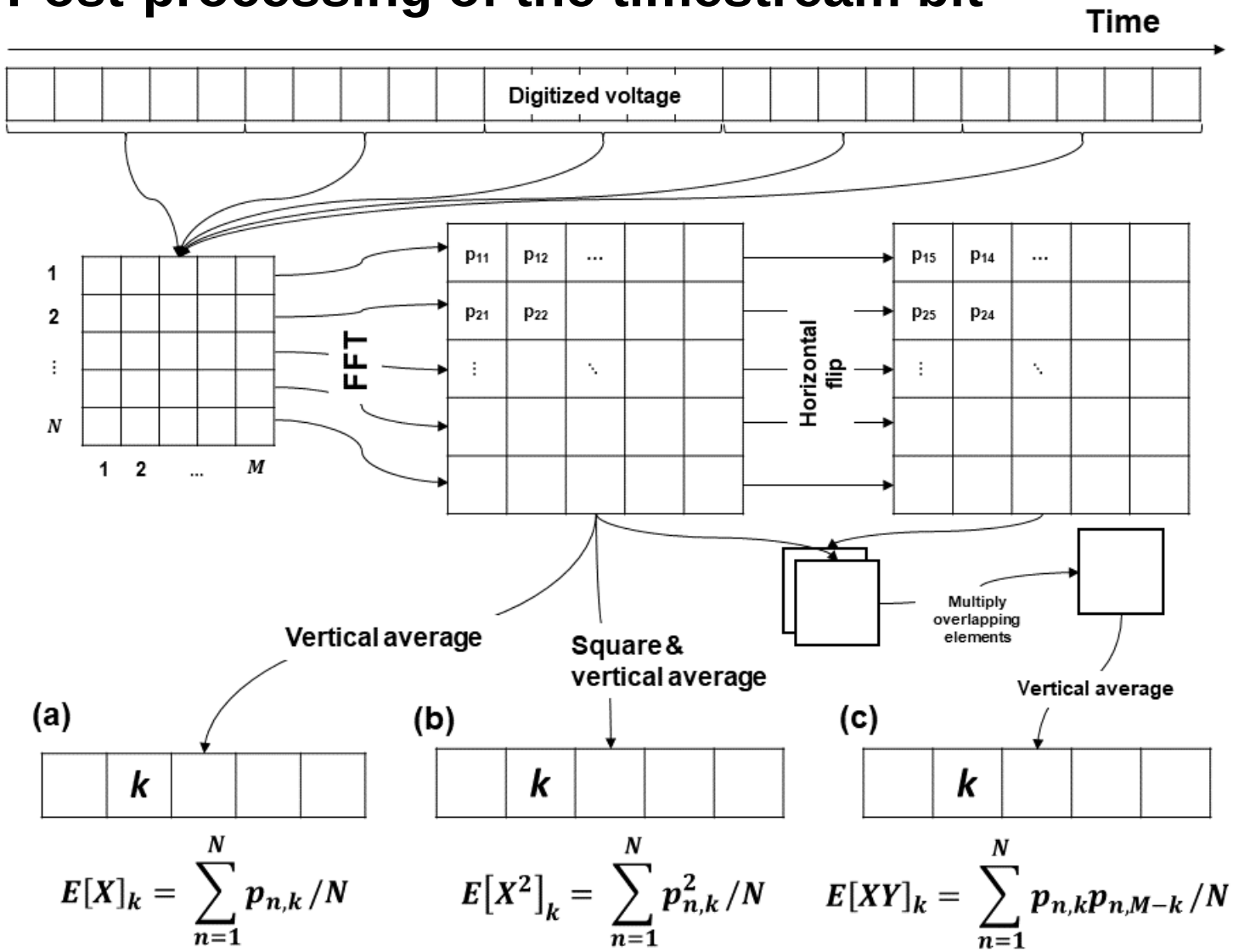
Experimental parameters

Room temperature chain / Digitizer



Digitizer DAQ

Post-processing of the timestream bit



$$E[X]_k = \sum_{n=1}^{N} p_{n,k}/N \qquad E[X^2]_k = \sum_{n=1}^{N} p_{n,k}^2/N \qquad E[XY]_k = \sum_{n=1}^{N} p_{n,k}p_{n,M-k}/N$$

- Chopping the digitized voltage into spectrum unit (based on target RBW)
- FFT each voltage sequence

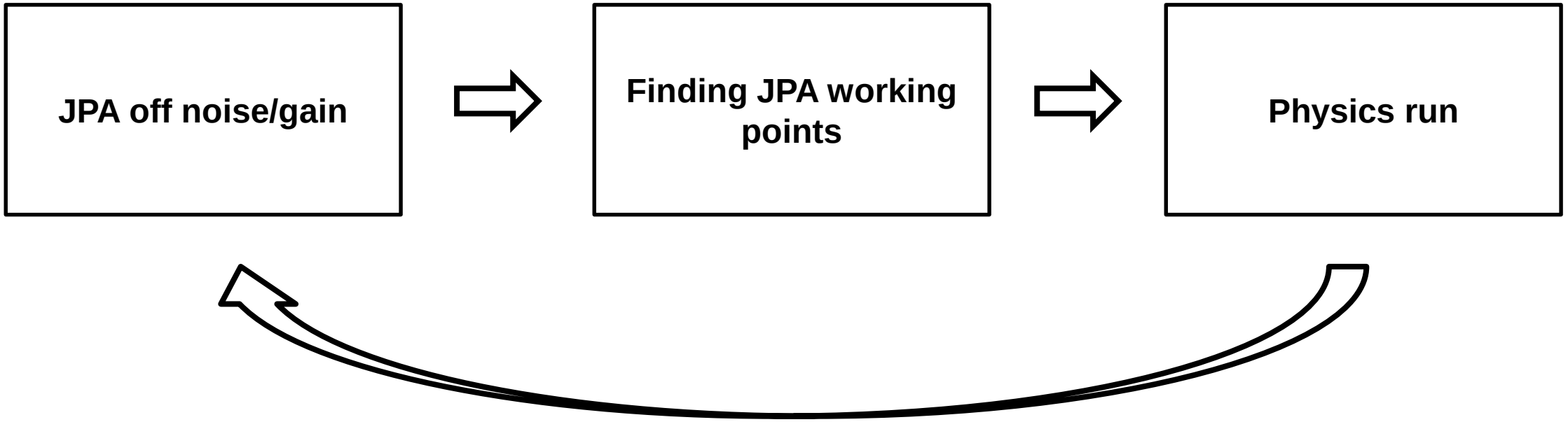
(a) Mean of the spectrum
- Used for the main analysis of axion signal hypothesis testing

(b) Mean of squared spectrum
- Used for variance estimation

(c) Mean of product of mirror pairs
- Used for estimation of **JPA induced correlation**

Measurements

Measurement routines

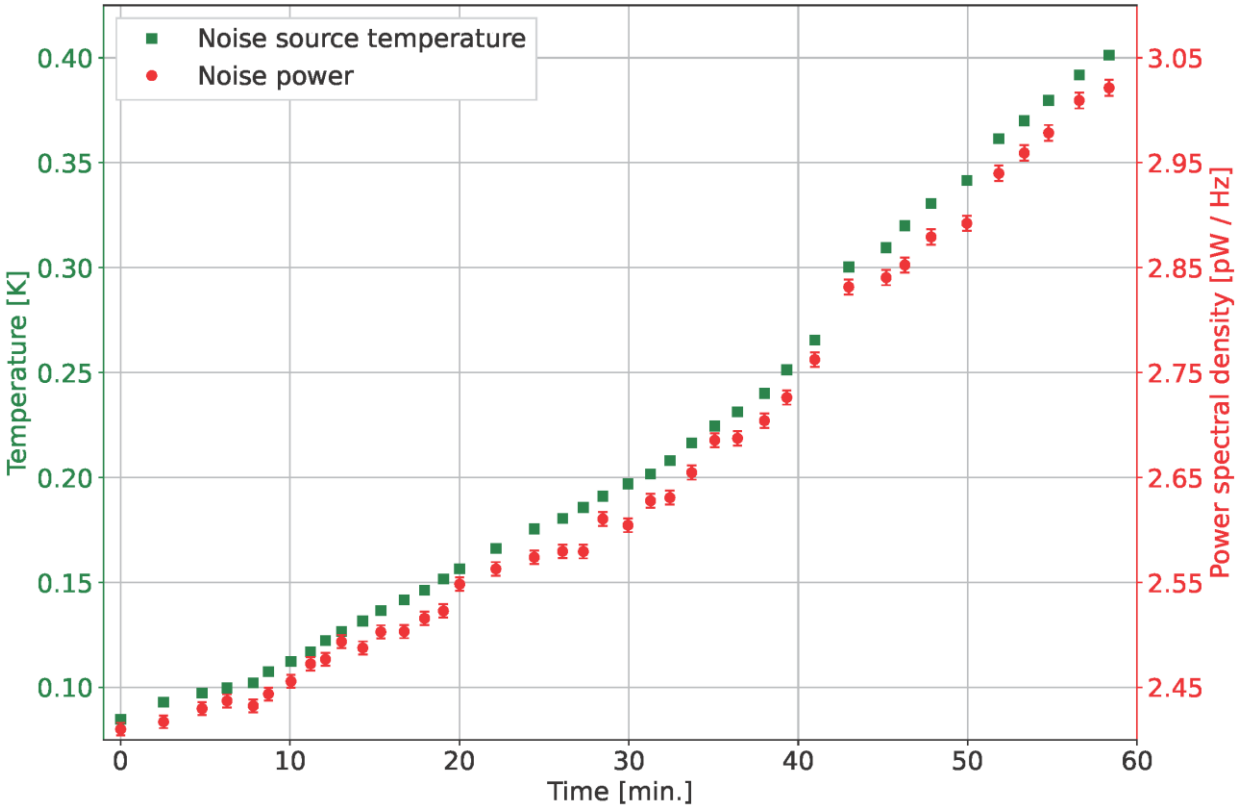


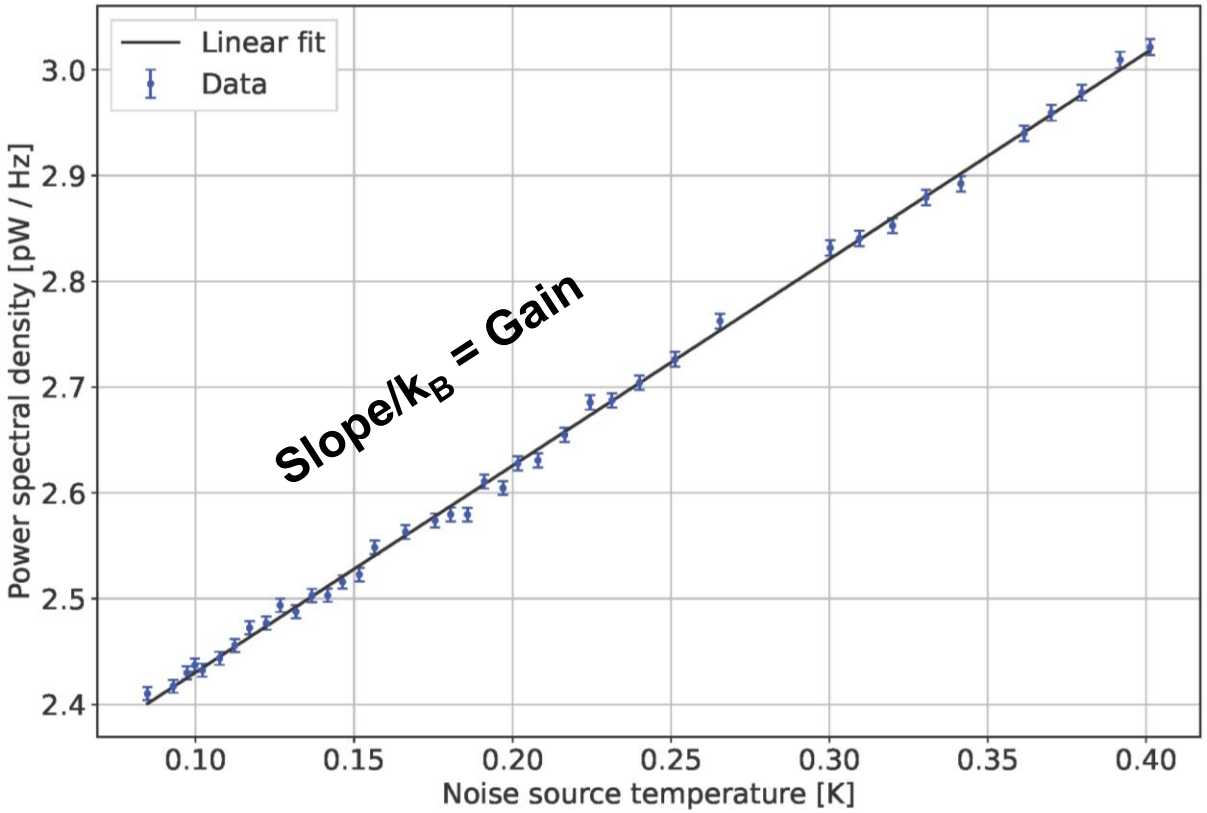
Iterating every 5 – 10 MHz

- Possible HEMT/JPA drifts
- Discussion on data

Measurements

JPA off noise measurement

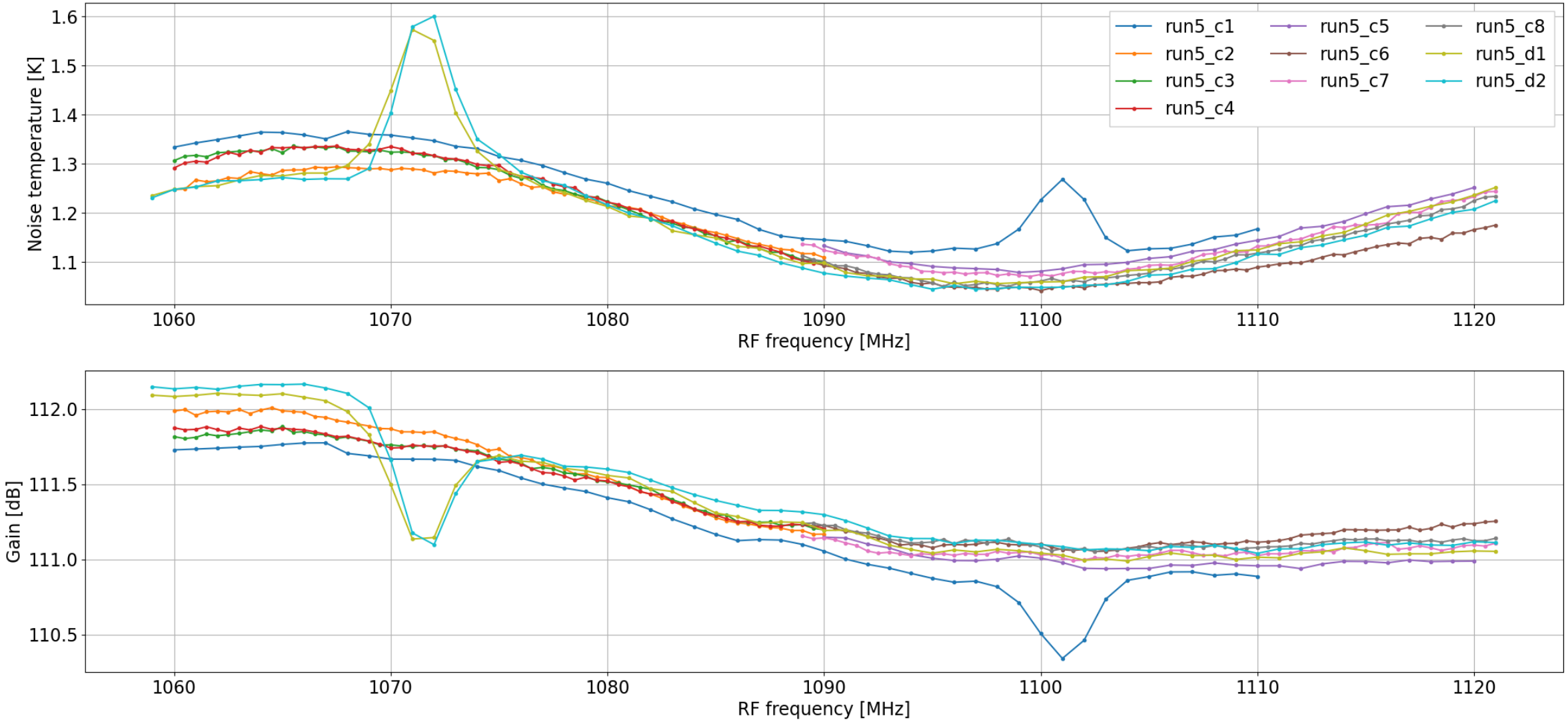




Measurements

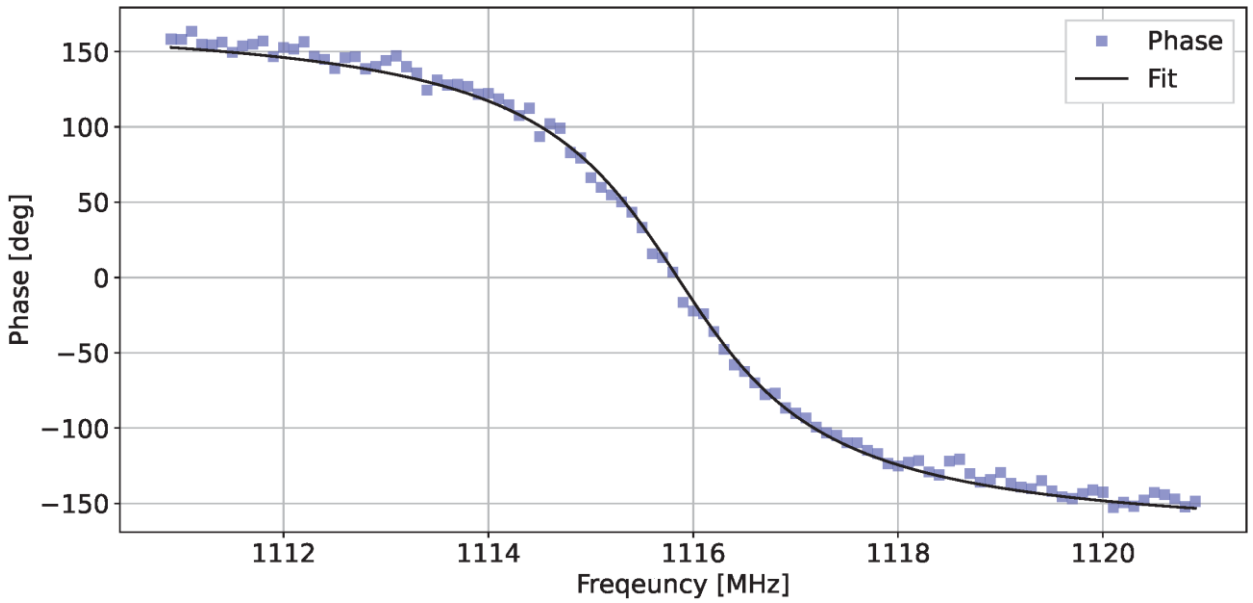
JPA's passive resonances on the peaks

JPA off noise measurements

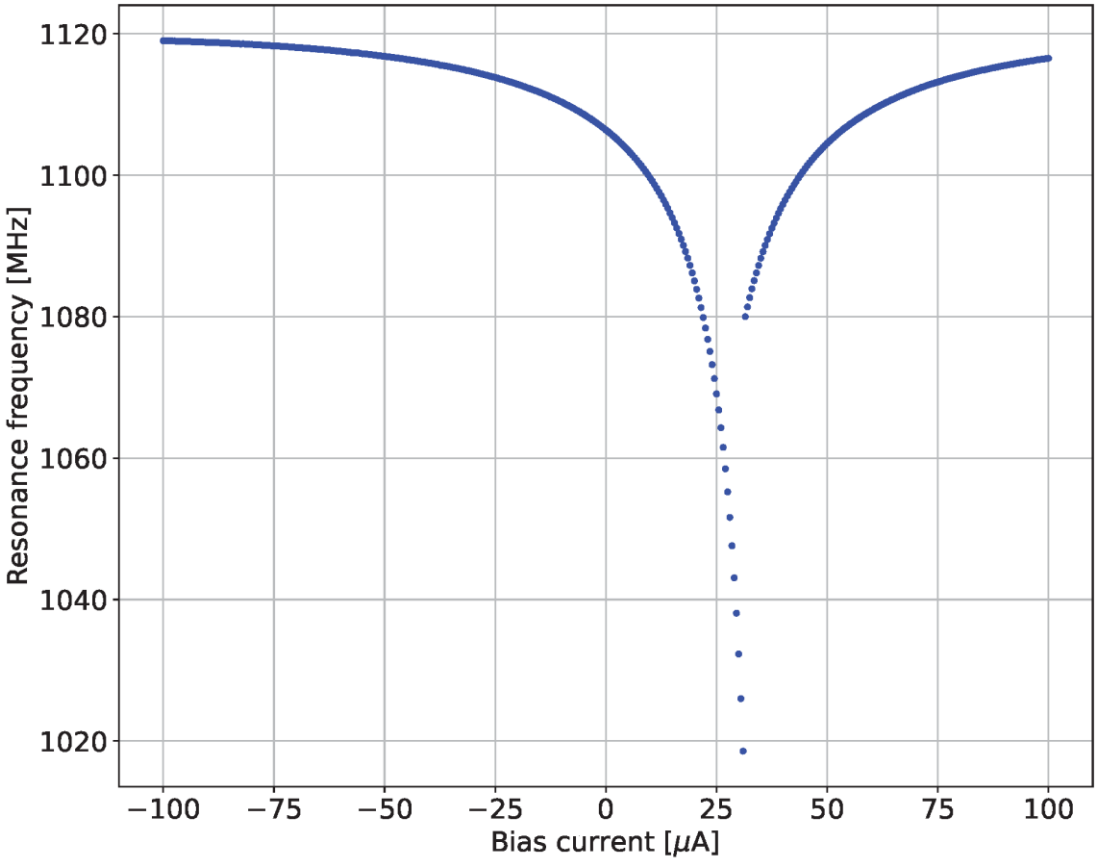


Measurements

JPA working point calibration



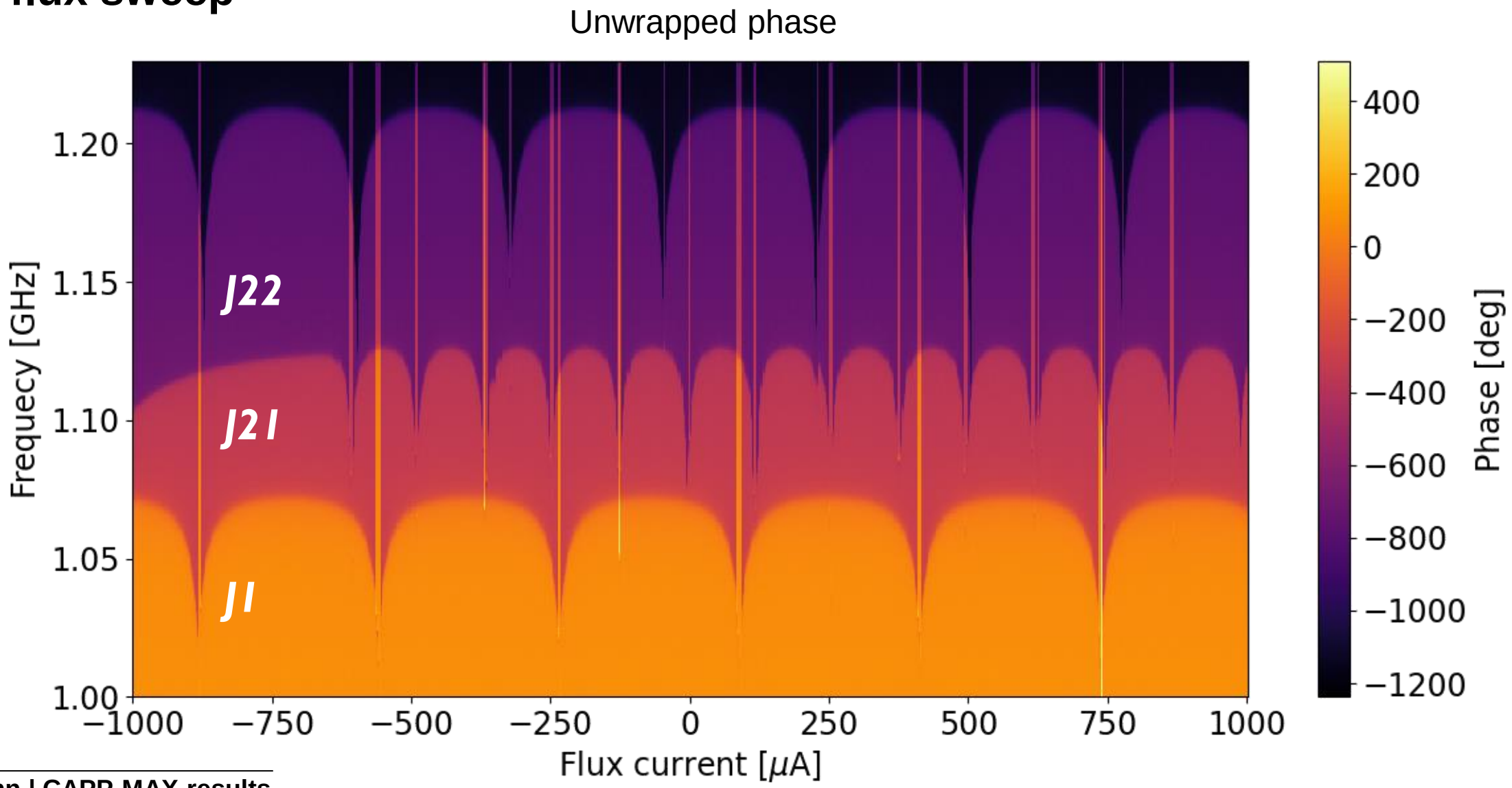
$$\phi = \phi_0 + \phi_1 - 2\theta = \phi_0 + \frac{2\pi L}{c} f \; - 2\tan^{-1}\left[\frac{2(f - f_j)}{\Gamma_j}\right]$$



(Flux bias – passive resonance) mapping

Measurements

3 JPA flux sweep

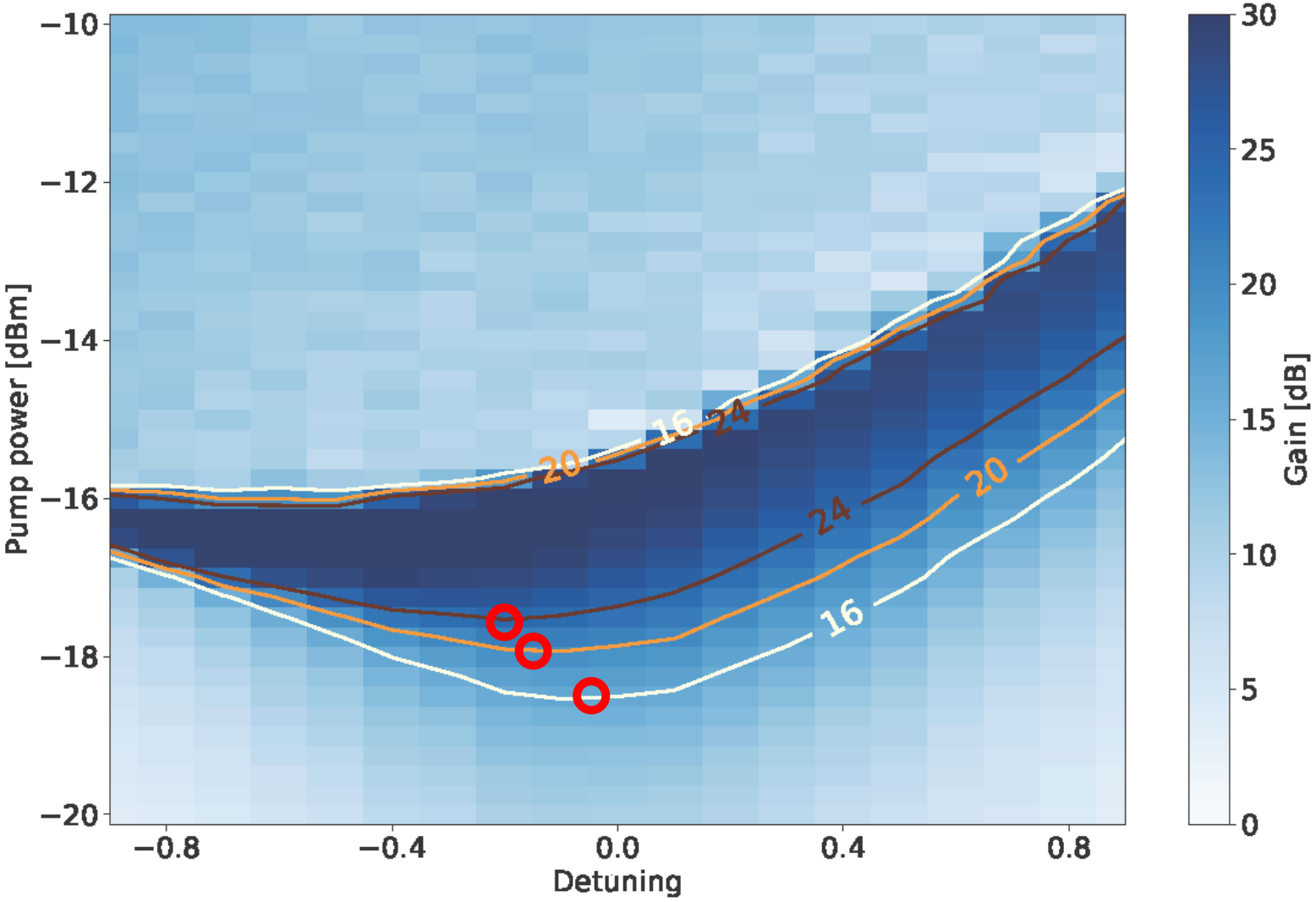


Measurements

JPA working point calibration

Corresponding to a fixed $f_{passive}$, **preliminarily measured**

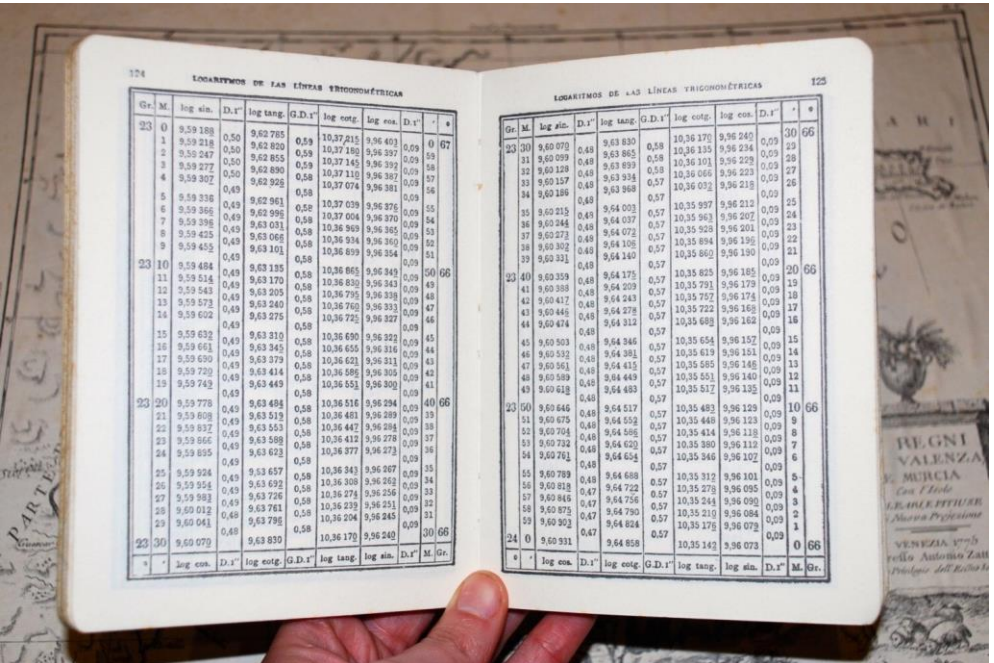
- Sweeping the frequency/power of the pump tone
- Calibrating the gain of the JPA at a fixed offset frequency
- Given target gain -> lowest pump tone power

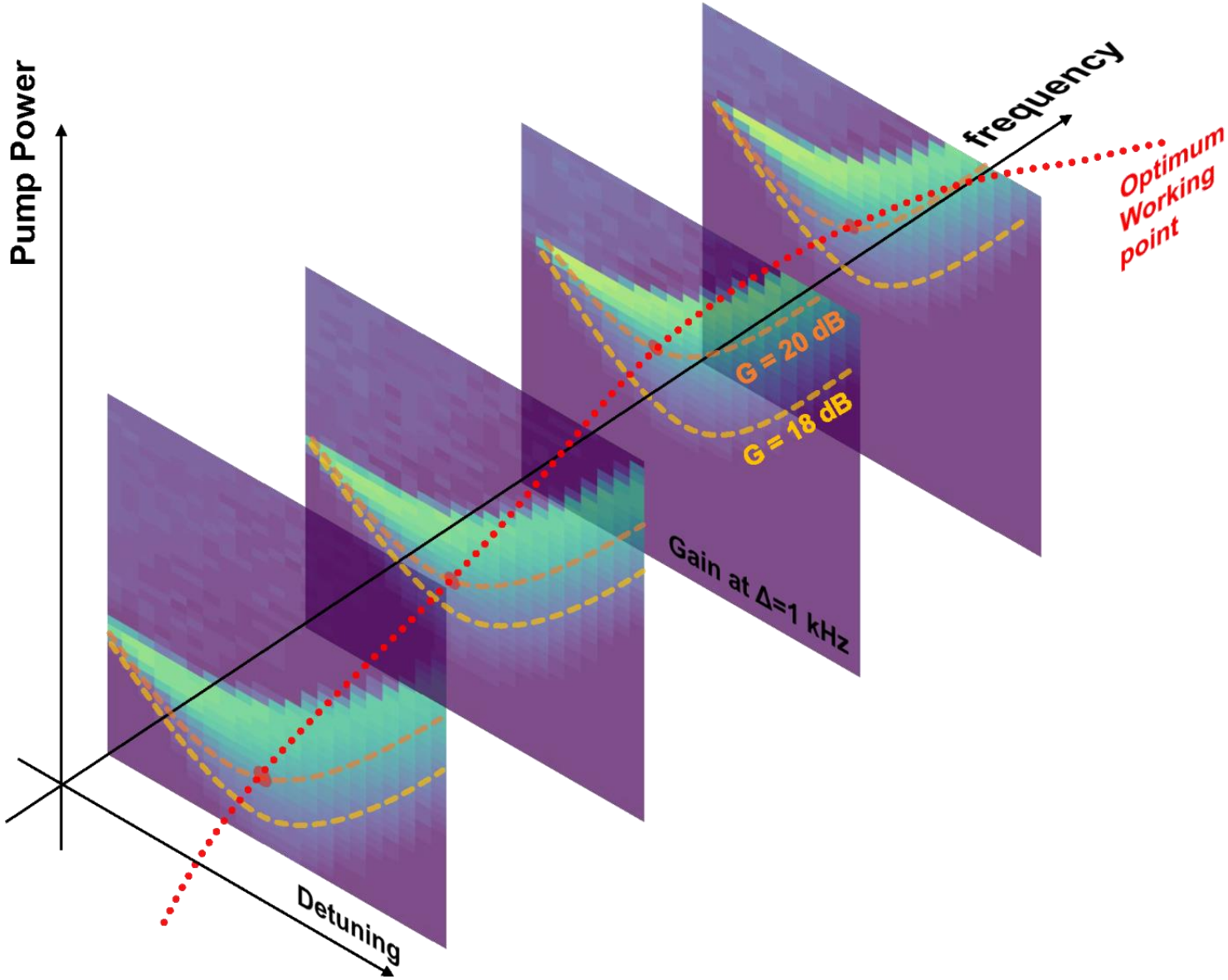


Measurements

JPA working point calibration

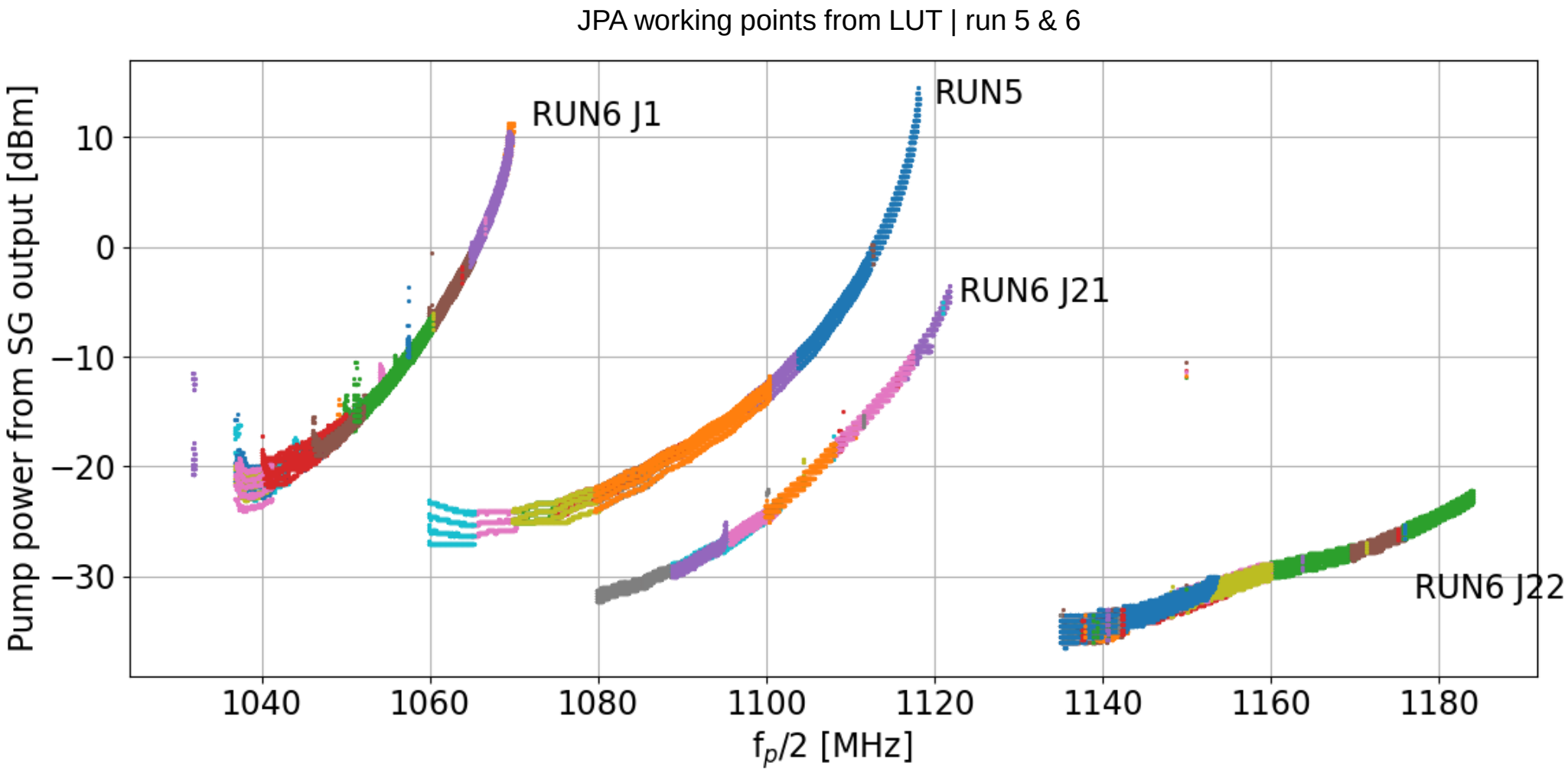
- Iteration over some picked-up target frequencies (typically 1:20 sampling)
- Up-sampling at each target scanning frequencies to generate a **look-up table**
- arXiv:2305.08866





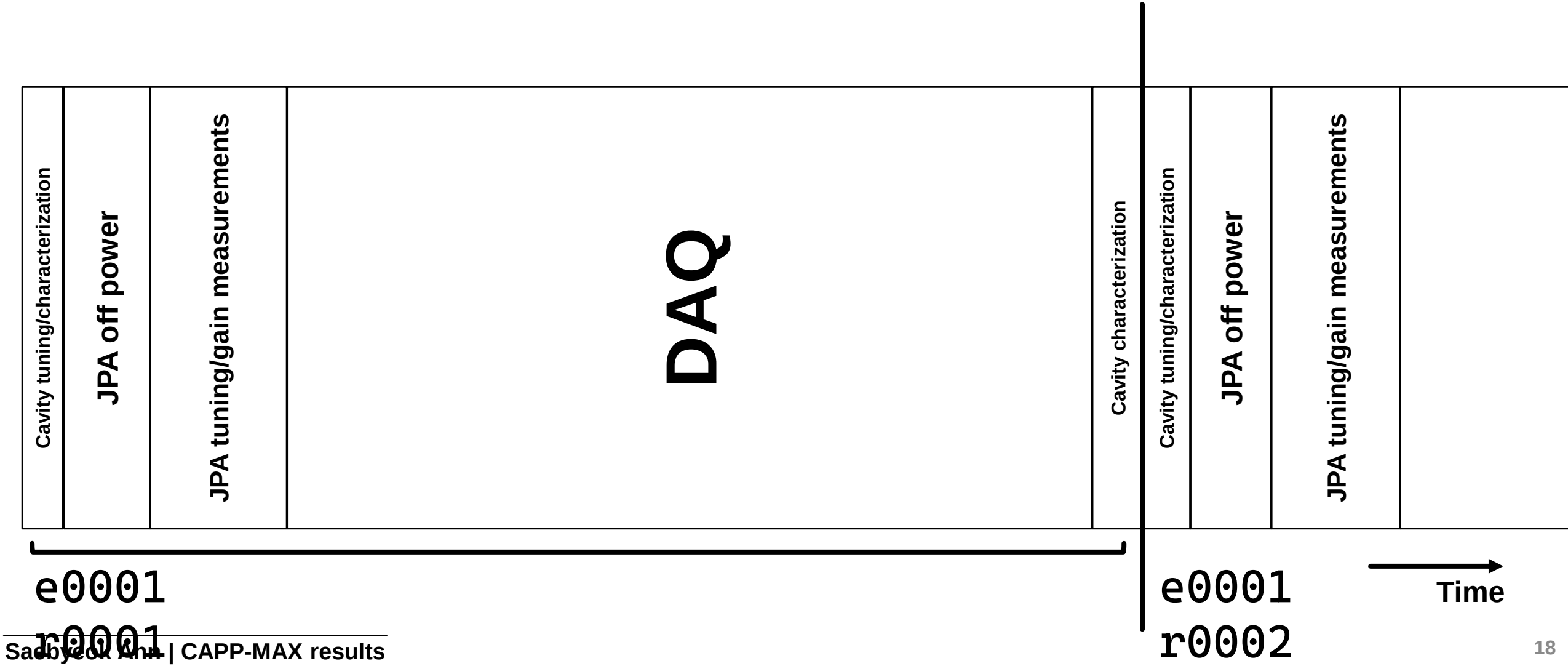
Measurements

JPA working point calibration



Measurements

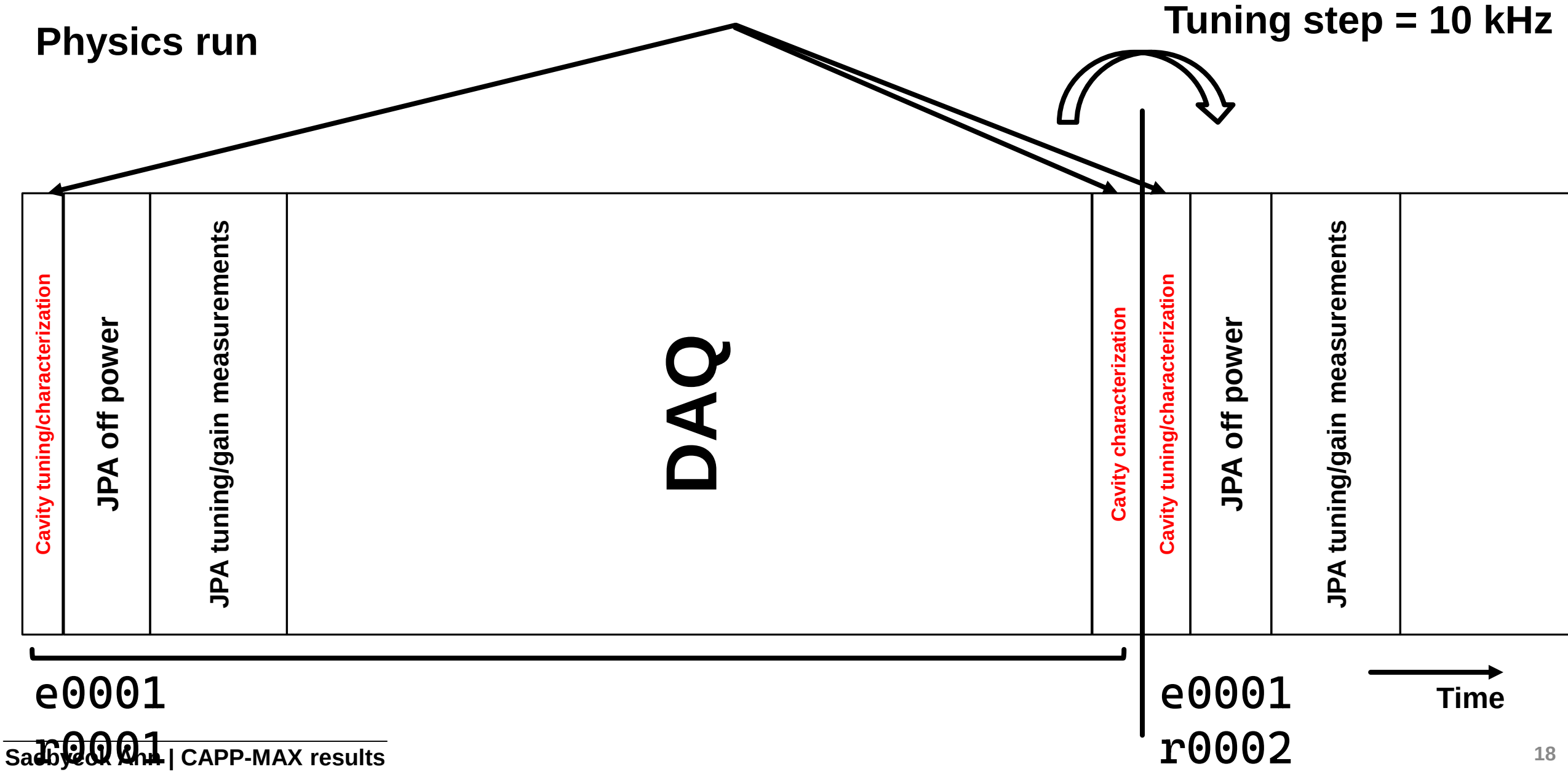
Physics run



Measurements

Cavity resonance tuning
Transmission/reflection measurements.

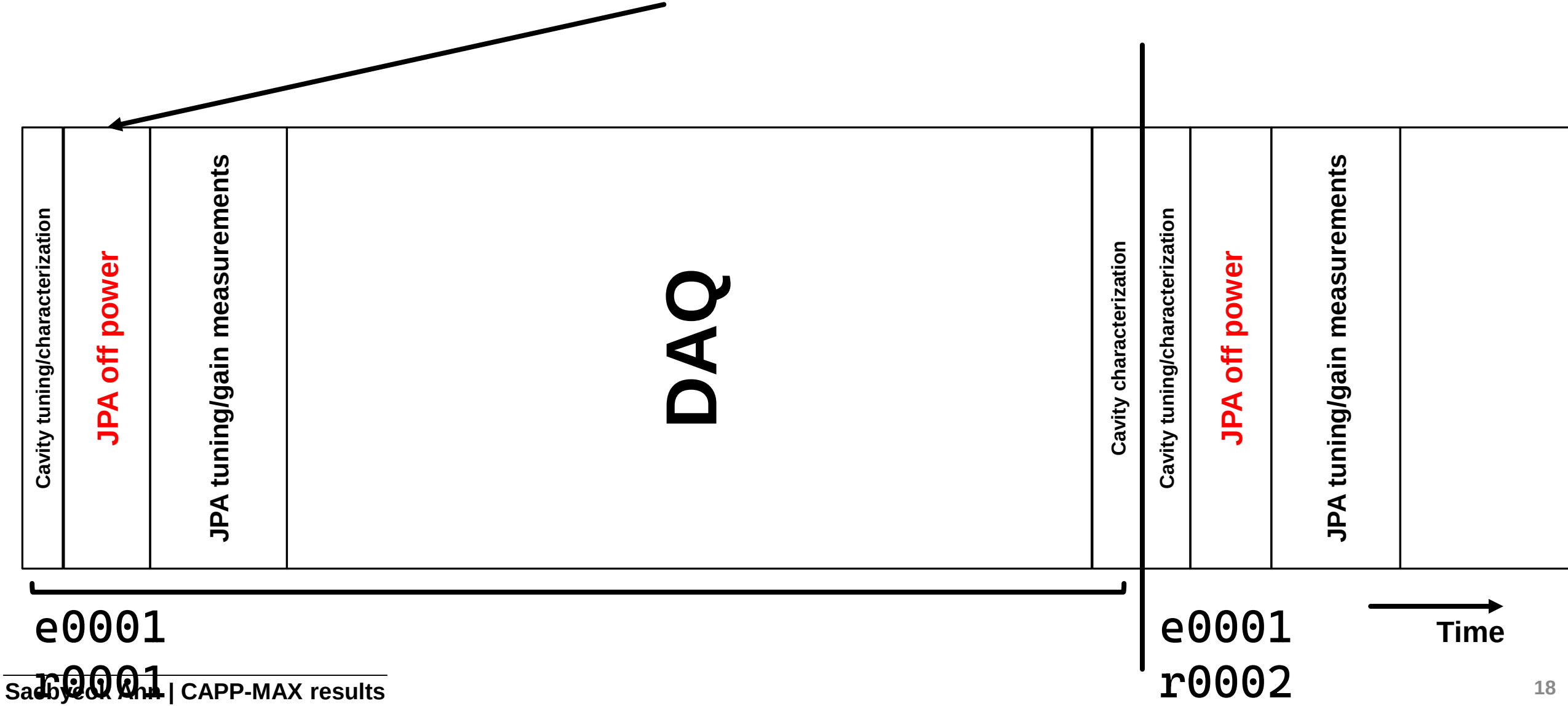
Physics run



Measurements

Physics run

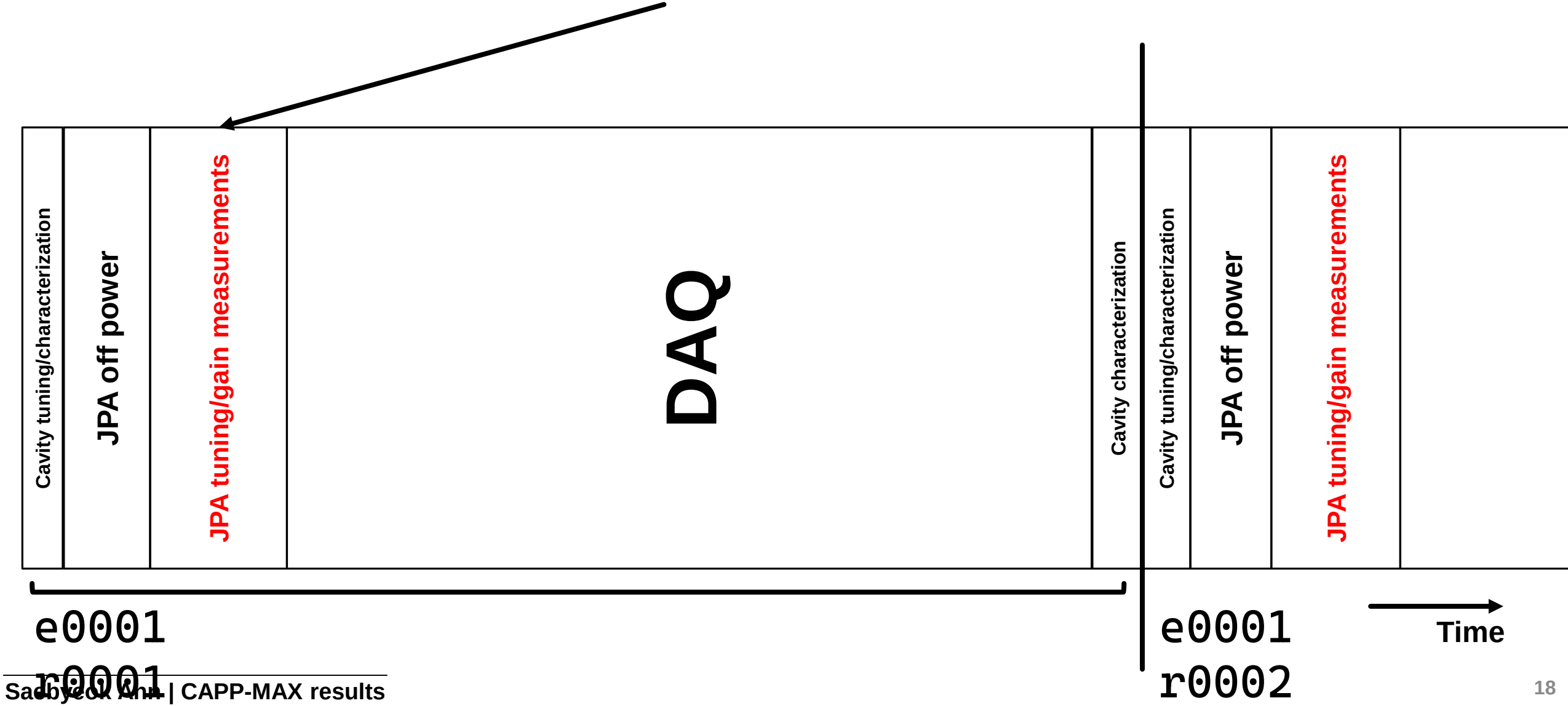
JPA off power baseline measurement
for NT calibration (~ 1/20 data acquisition time)



Measurements

Physics run

JPA gain tuning with LUT/fine tuning
JPA gain characterization (on/off)
JPA target gain of 16 – 22 dB depending on the range

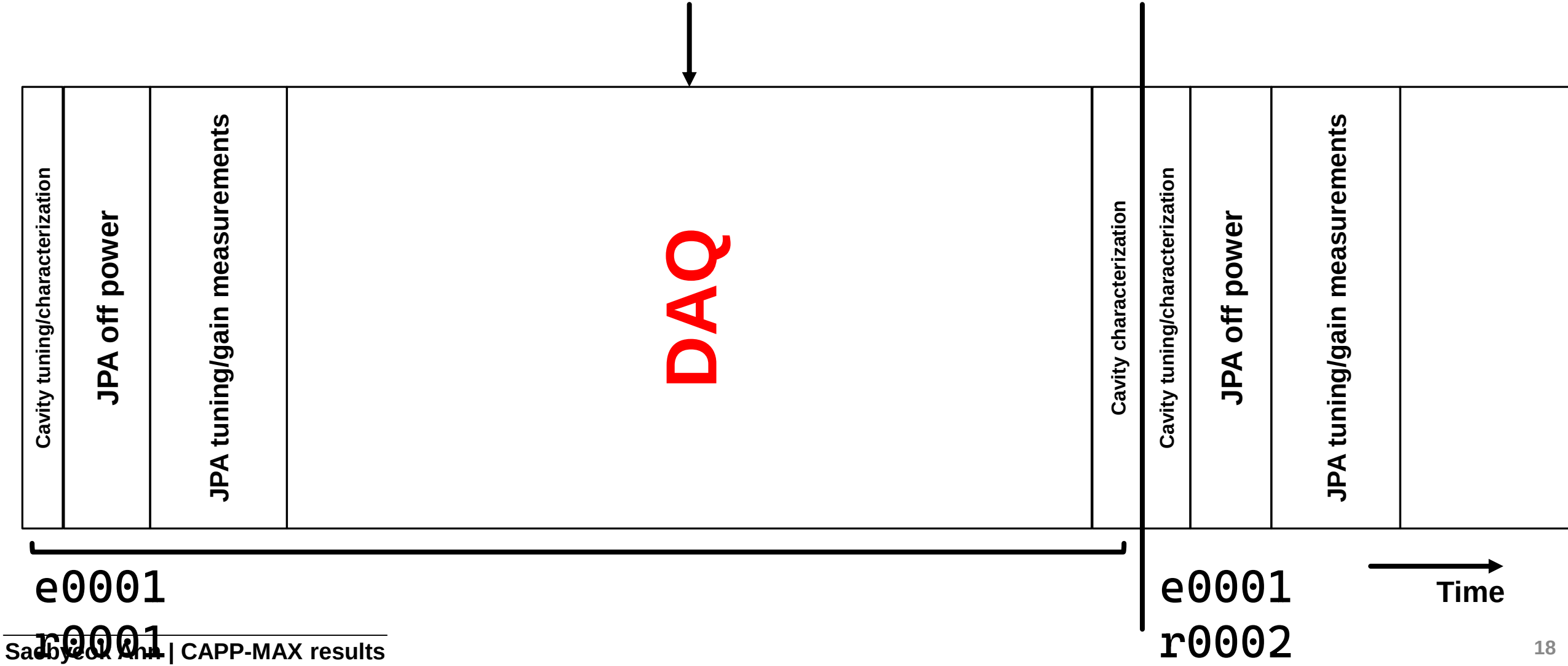


Measurements

Physics run

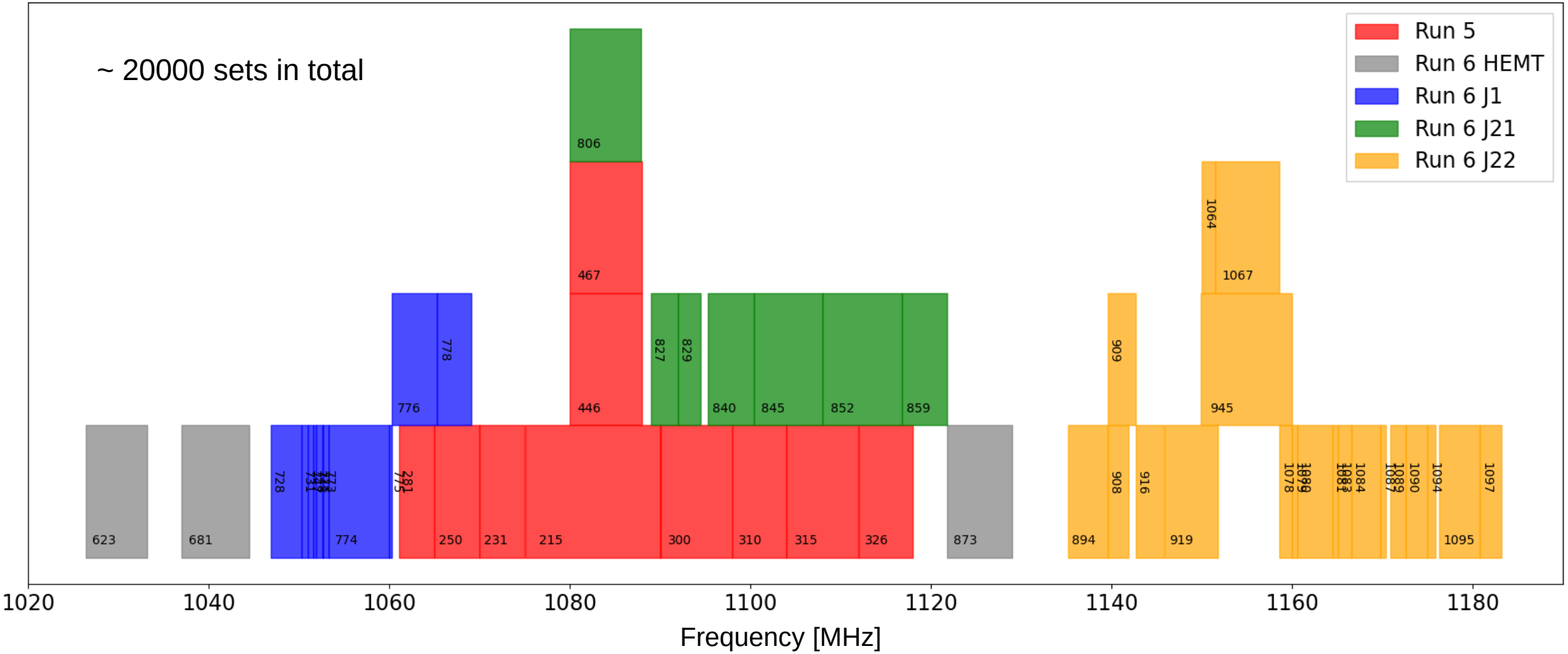
Physics data taking:192 s of acquisition

- 1920 total spectra with RBW = 10 Hz = 192 s
- 128 average sub-spectra x 15 sets = 1920



Datasets at a glance

Run 5 & 6 frequency coverage



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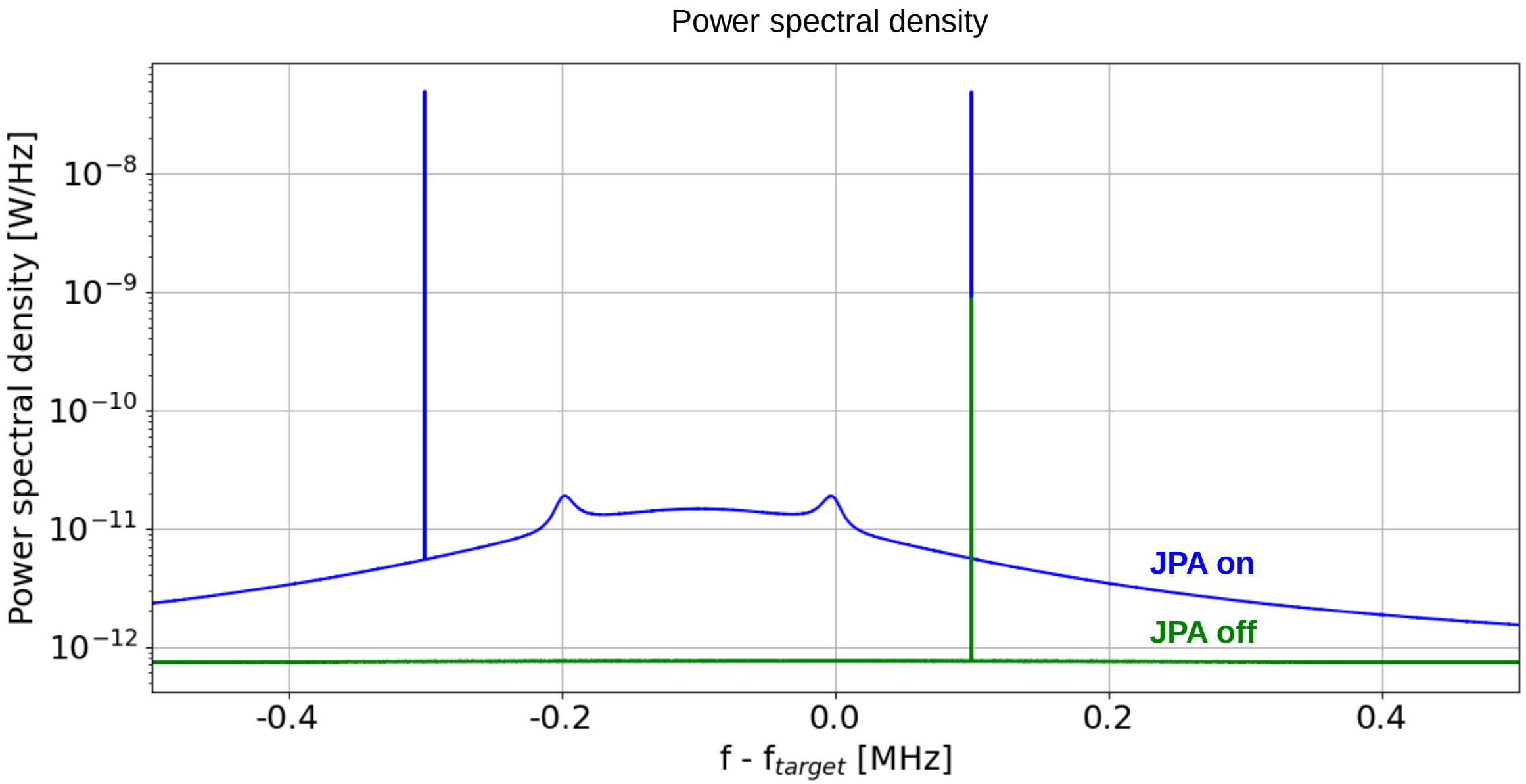

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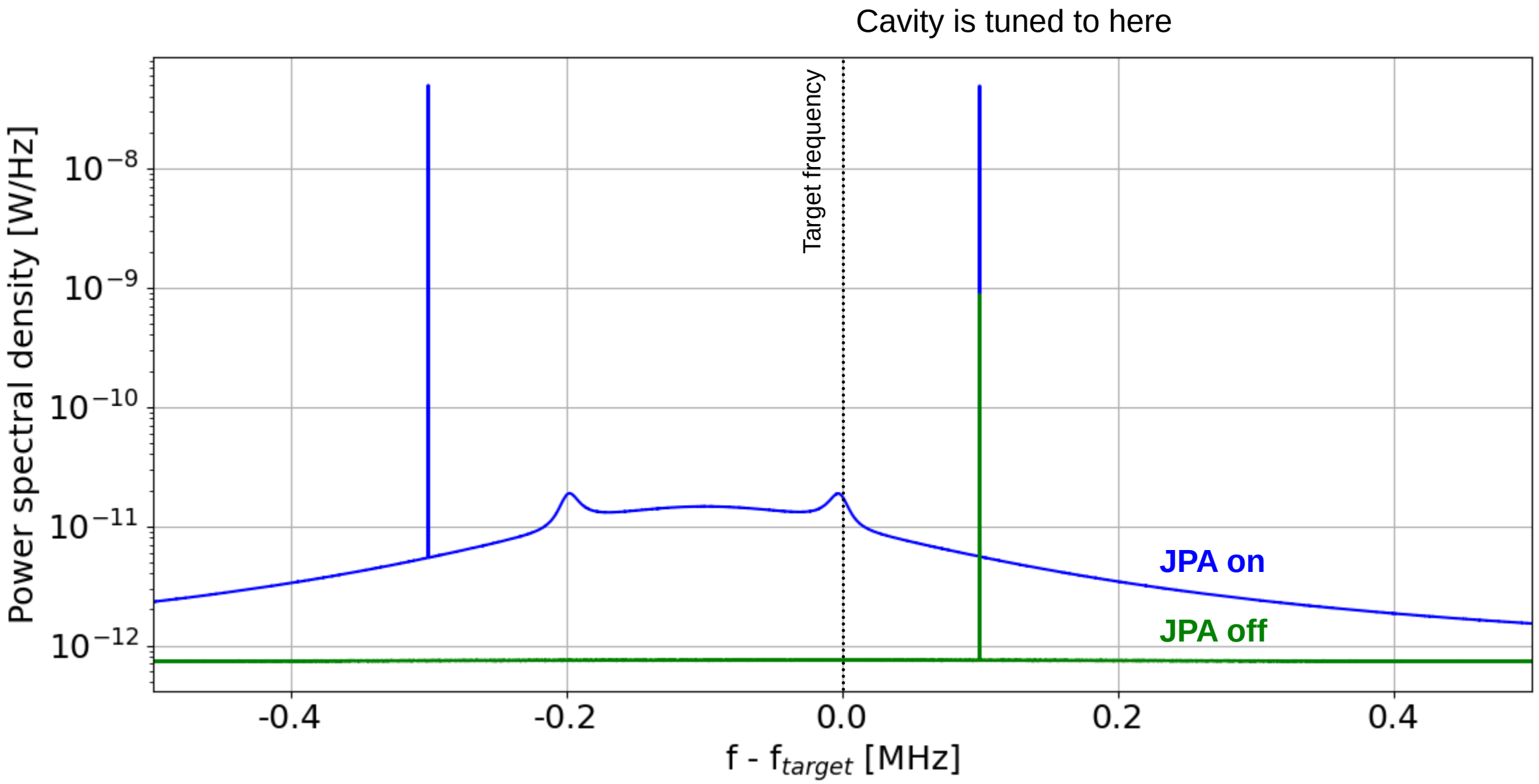

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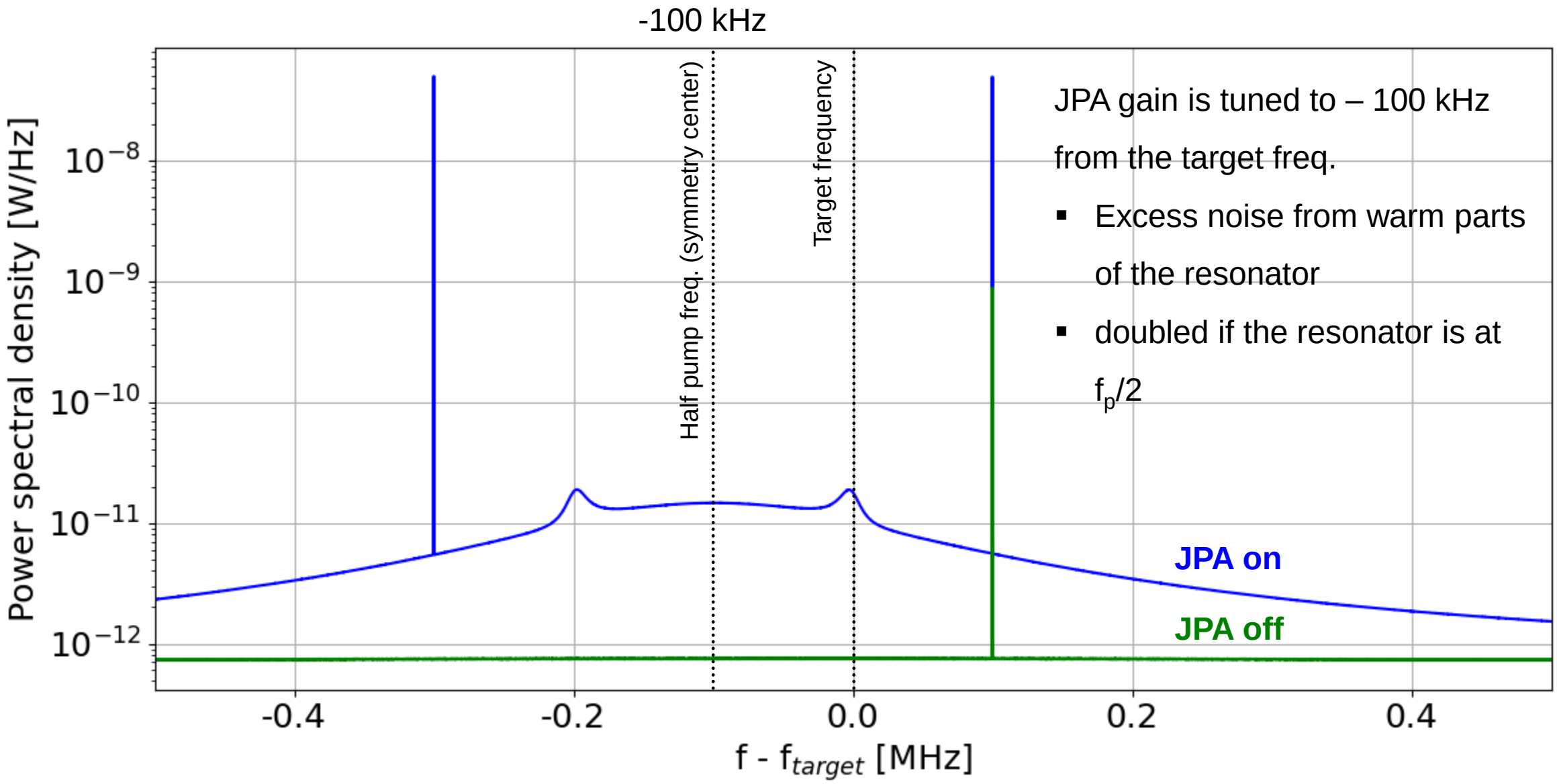
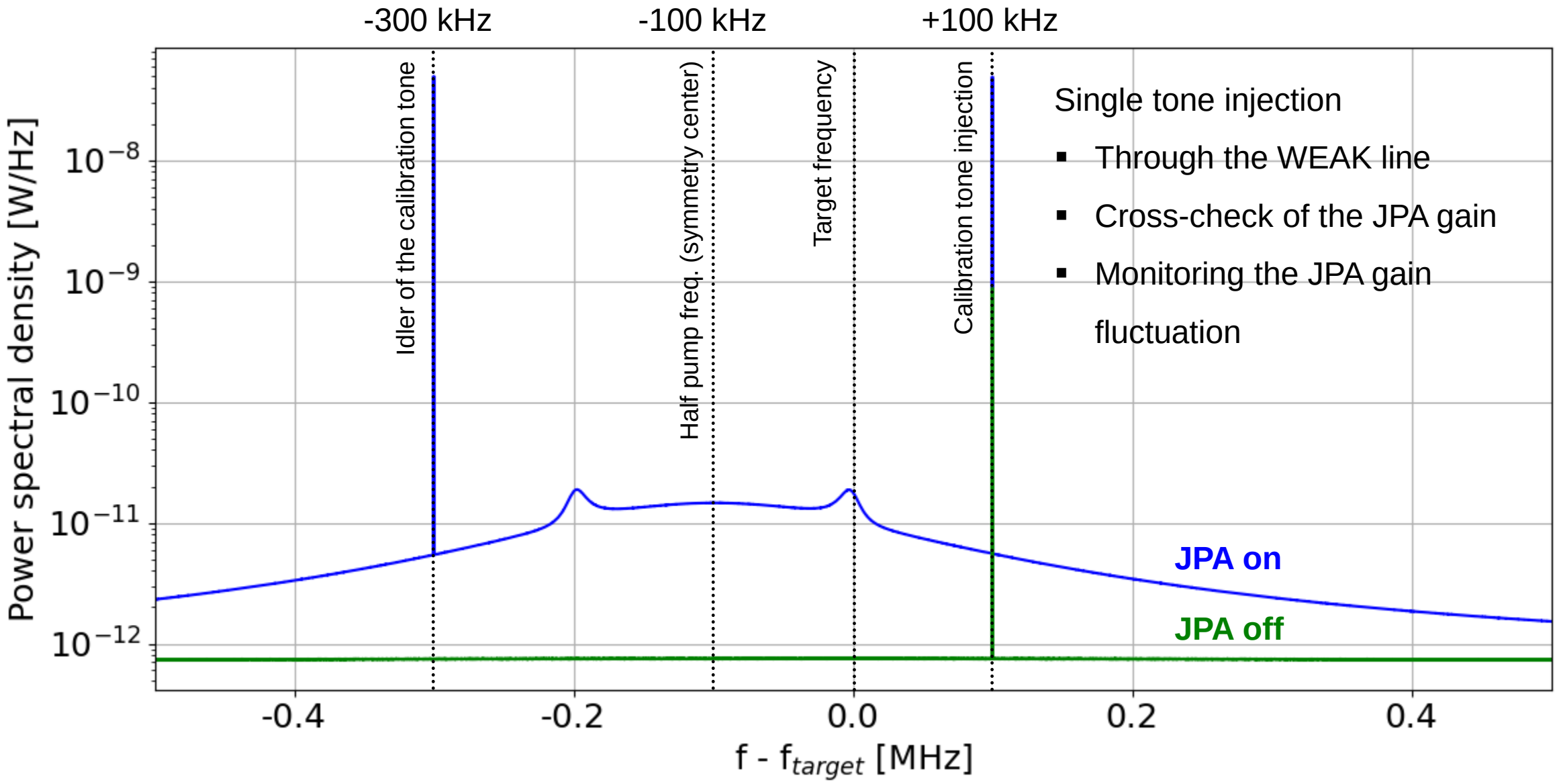
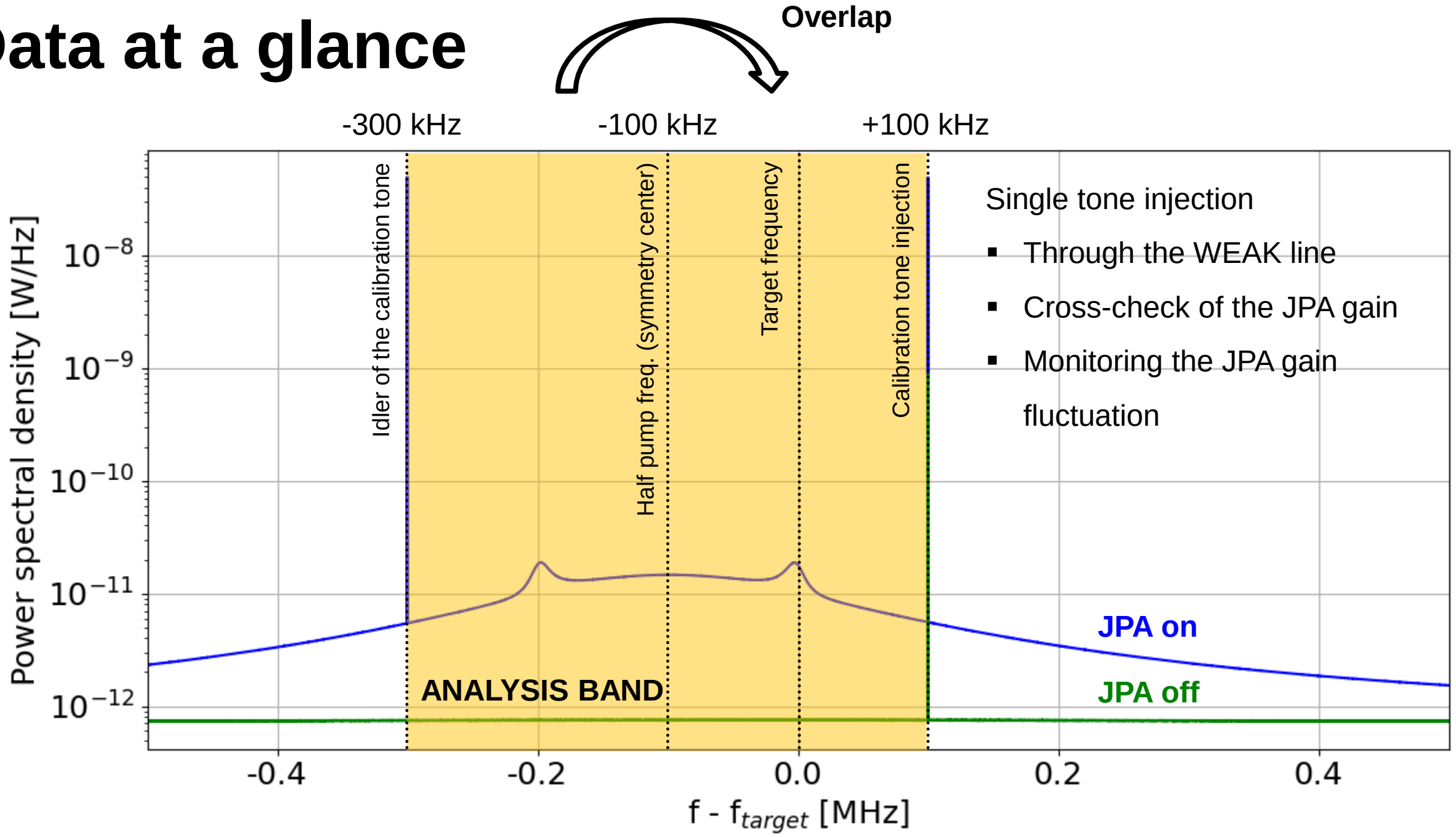


Data at a glance



Data at a glance



Noise temperature calibration

SNRI method, or spectra comparison method

$$\mathrm{SNRI} = \frac{\mathrm{SNR_{on}}}{\mathrm{SNR_{off}}} = \frac{\mathrm{G_{on}}}{\mathrm{P_{on}}} \Big/ \frac{\mathrm{G_{off}}}{\mathrm{P_{off}}} = \frac{\mathrm{G_J}}{\mathrm{R}}$$

G_J: JPA gain (JPA on/off S-parameter ratio)

R: JPA on/off PSD ratio

Noise temperature calibration

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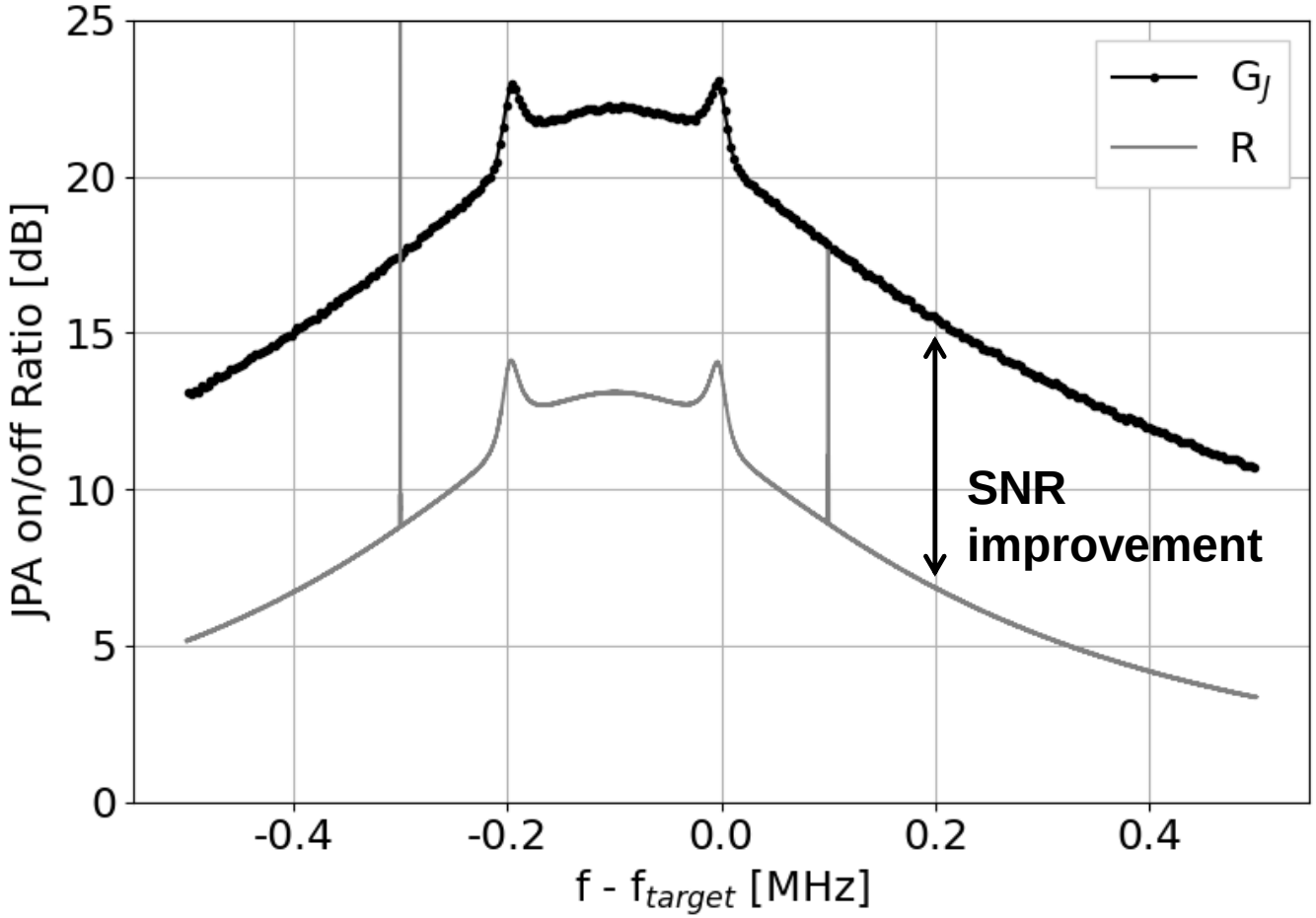

Noise temperature calibration

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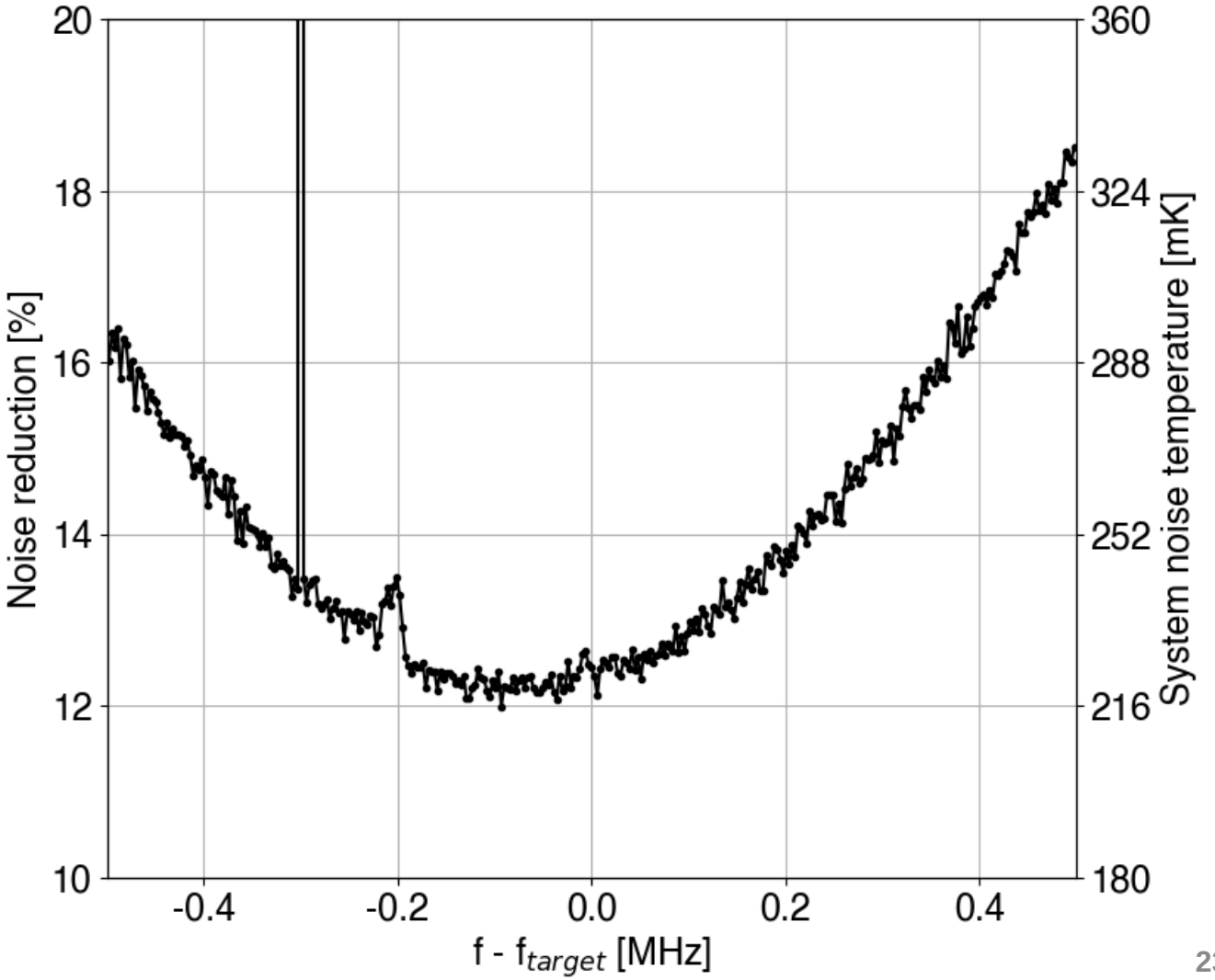
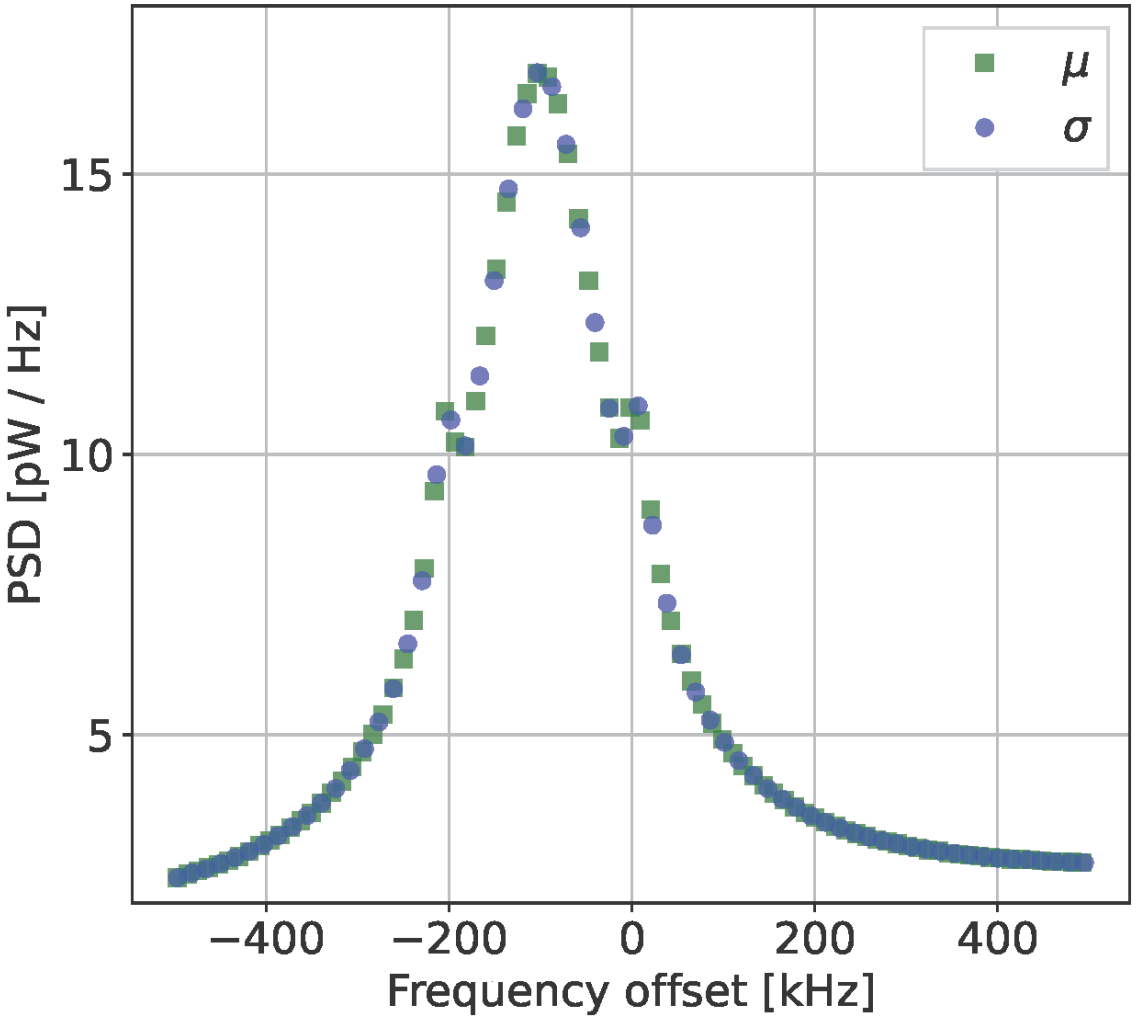
$$\Downarrow$$

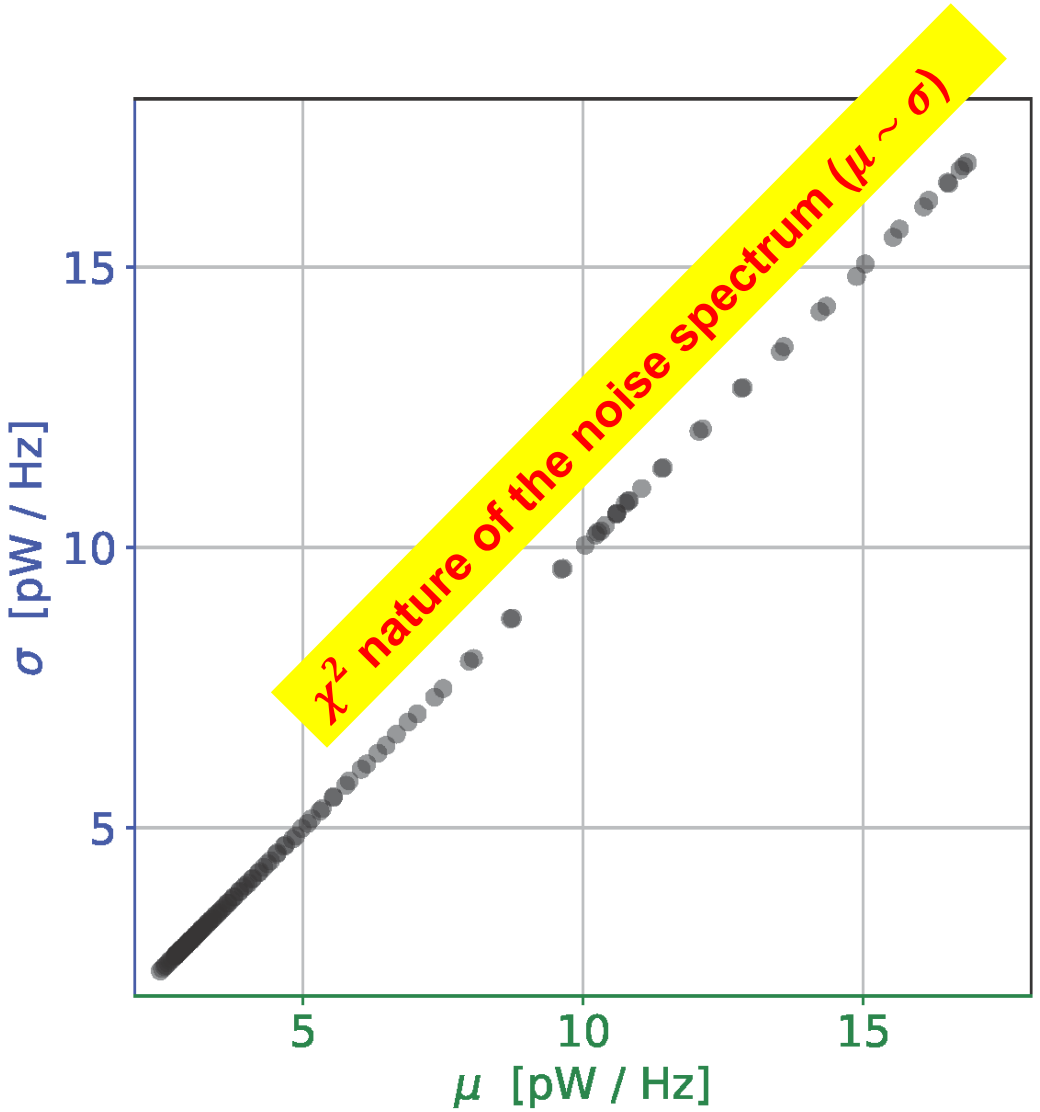
$$\mathrm{T_{sys}^{on}} = \mathrm{T_{sys}^{off}}/\mathrm{SNRI}$$



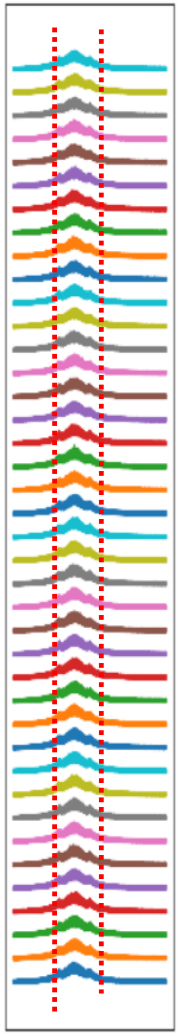
Spectrum statistics

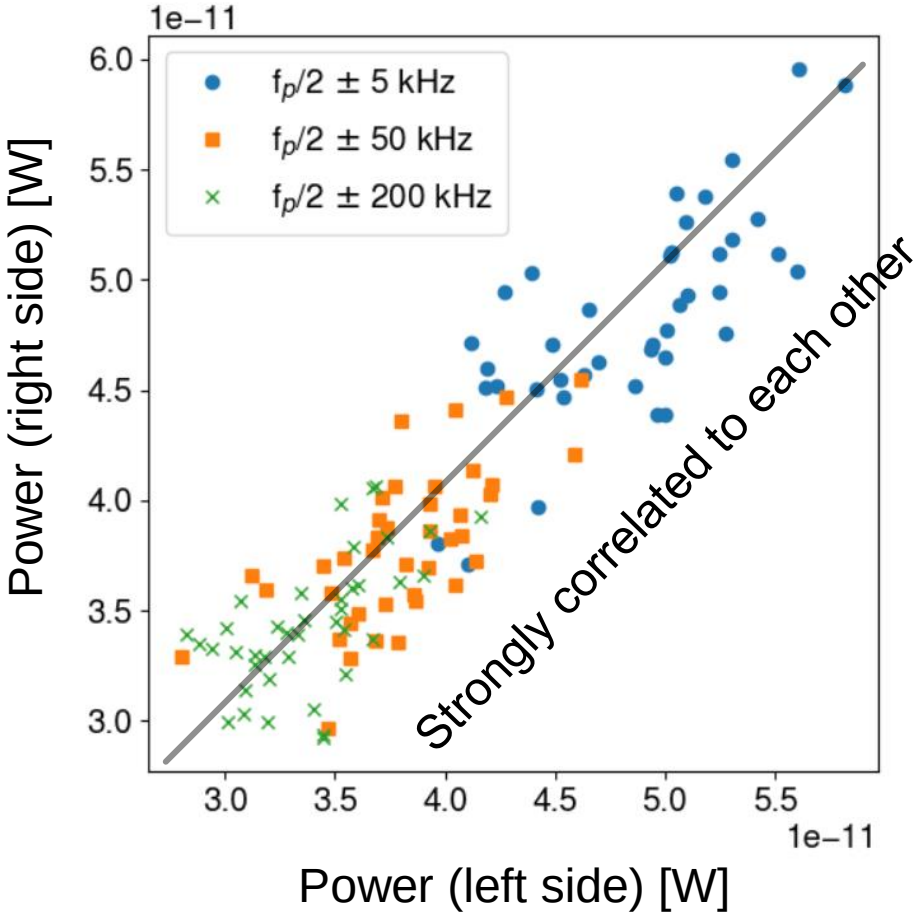
Mean and variance





Spectrum statistics





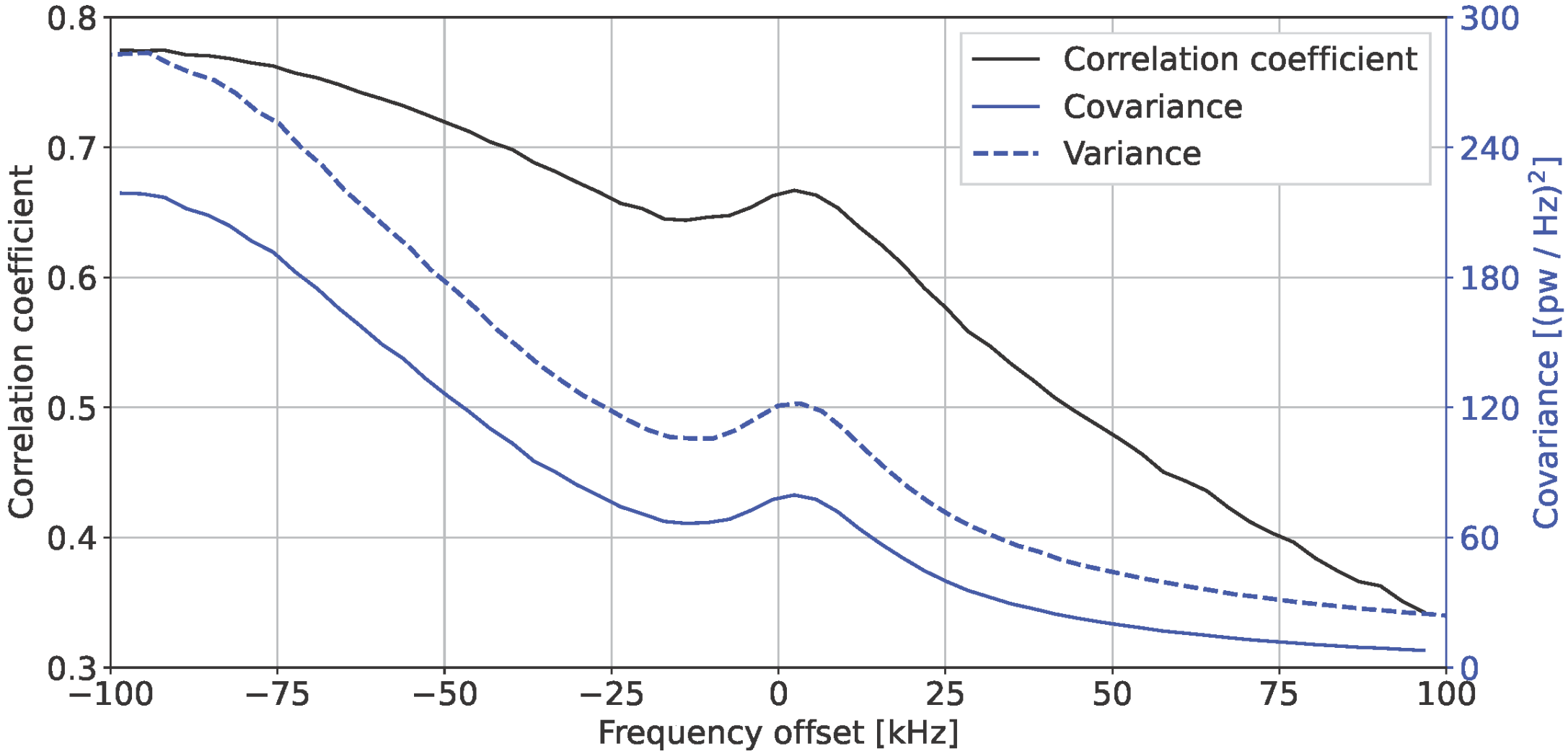
X: signal side || Y: idler pair

$$\mathrm{cov}(XY) = E[XY] - E[X]E[Y]$$

$$\boldsymbol{\rho_{XY} = \frac{\mathrm{cov}(XY)}{\sigma_X \sigma_Y}}$$

- Could gain some statistics from overlapping both sides (from uncorrelated parts)
- Informative (related to the total system noise)
  - $\boldsymbol{\rho = \frac{T_{cl}T_{cr}}{T_l T_r} \sim \left(\frac{T_c}{T_{sys}}\right)^2}$

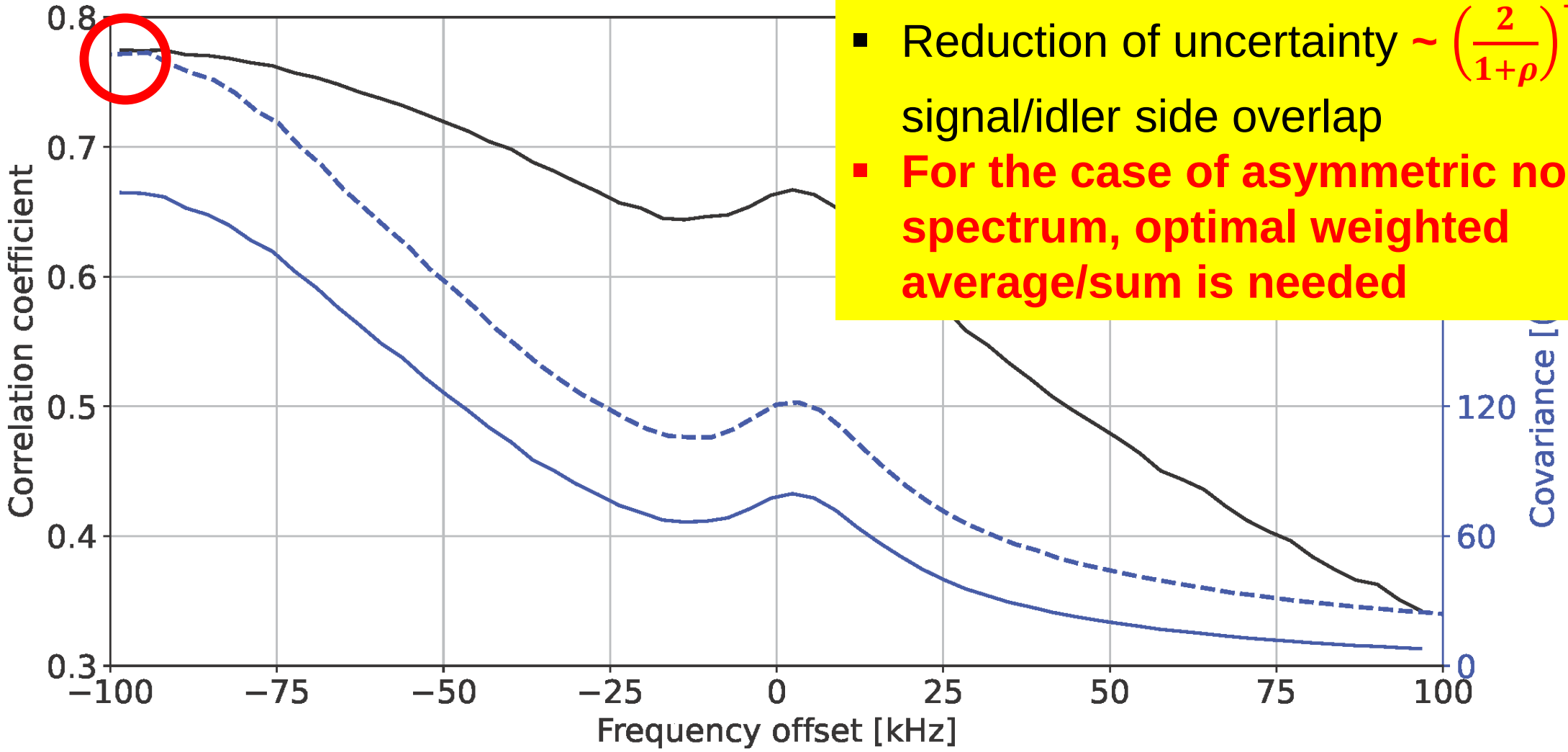
Spectrum statistics



Spectrum statistics

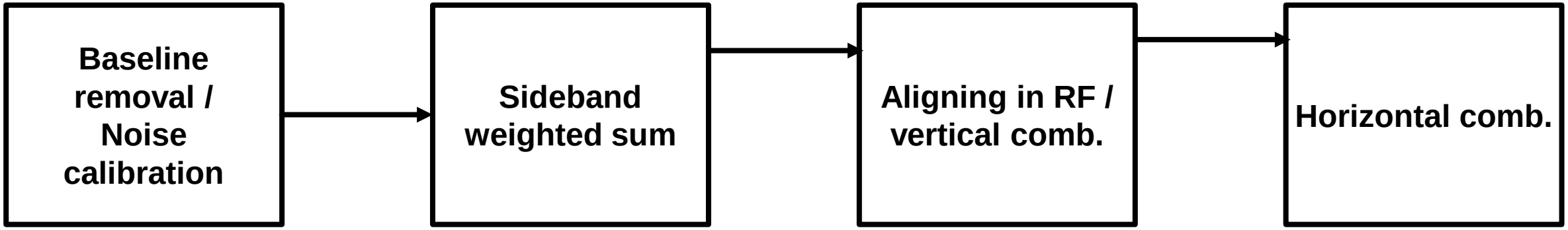
Correlation typically ~ 0.8 at symmetry center, ~0.7 at the target frequency

- Reduction of uncertainty $\sim \left(\frac{2}{1+\rho}\right)^{-\frac{1}{2}}$ by signal/idler side overlap
- **For the case of asymmetric noise spectrum, optimal weighted average/sum is needed**



Data analysis

- Overall, based on the HAYSTAC analysis procedure
- Baseline removal → Vertical combination → Convolving with normalized axion line shape (boosted Maxwellian)
  - Weighted combination (sum/average) subject to **maximizing the SNR**
  - σ itself represents the expected SNR



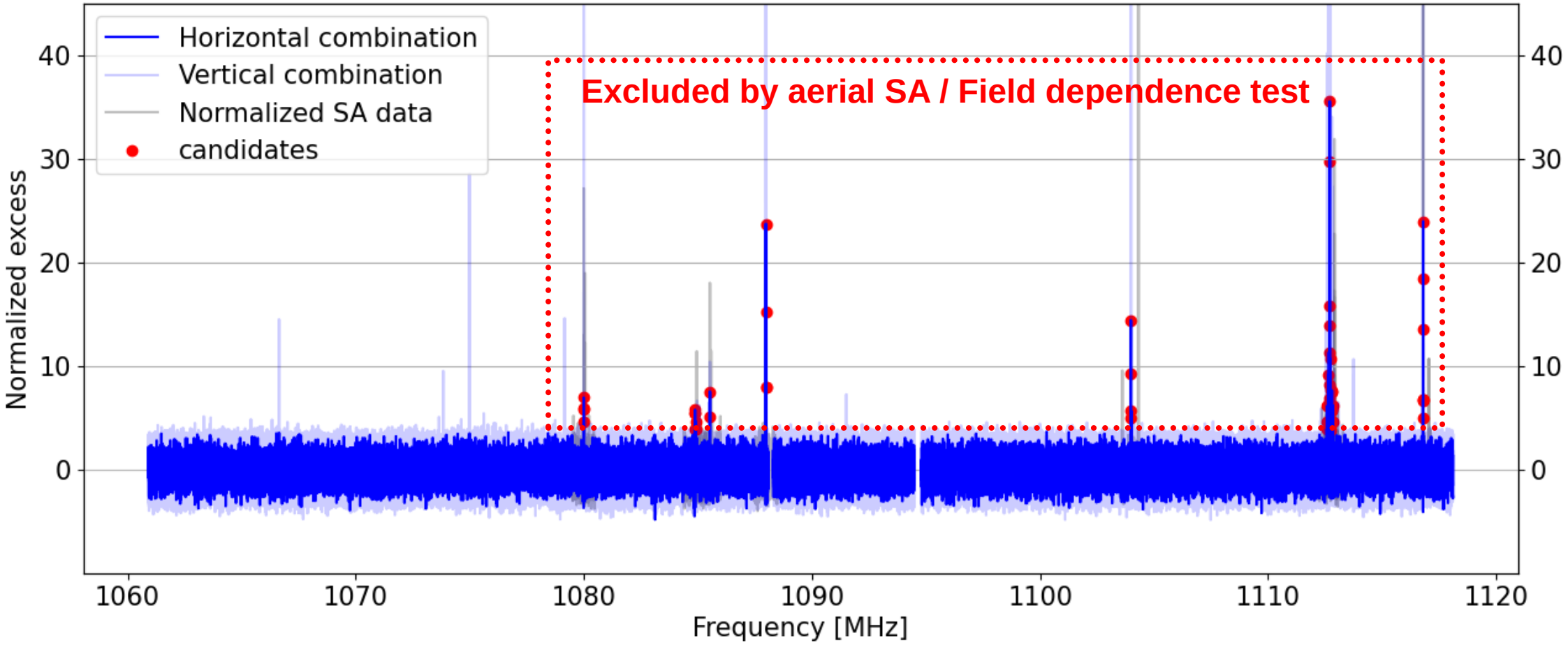
Data analysis

Grand spectrum

Peak exclusion strategy

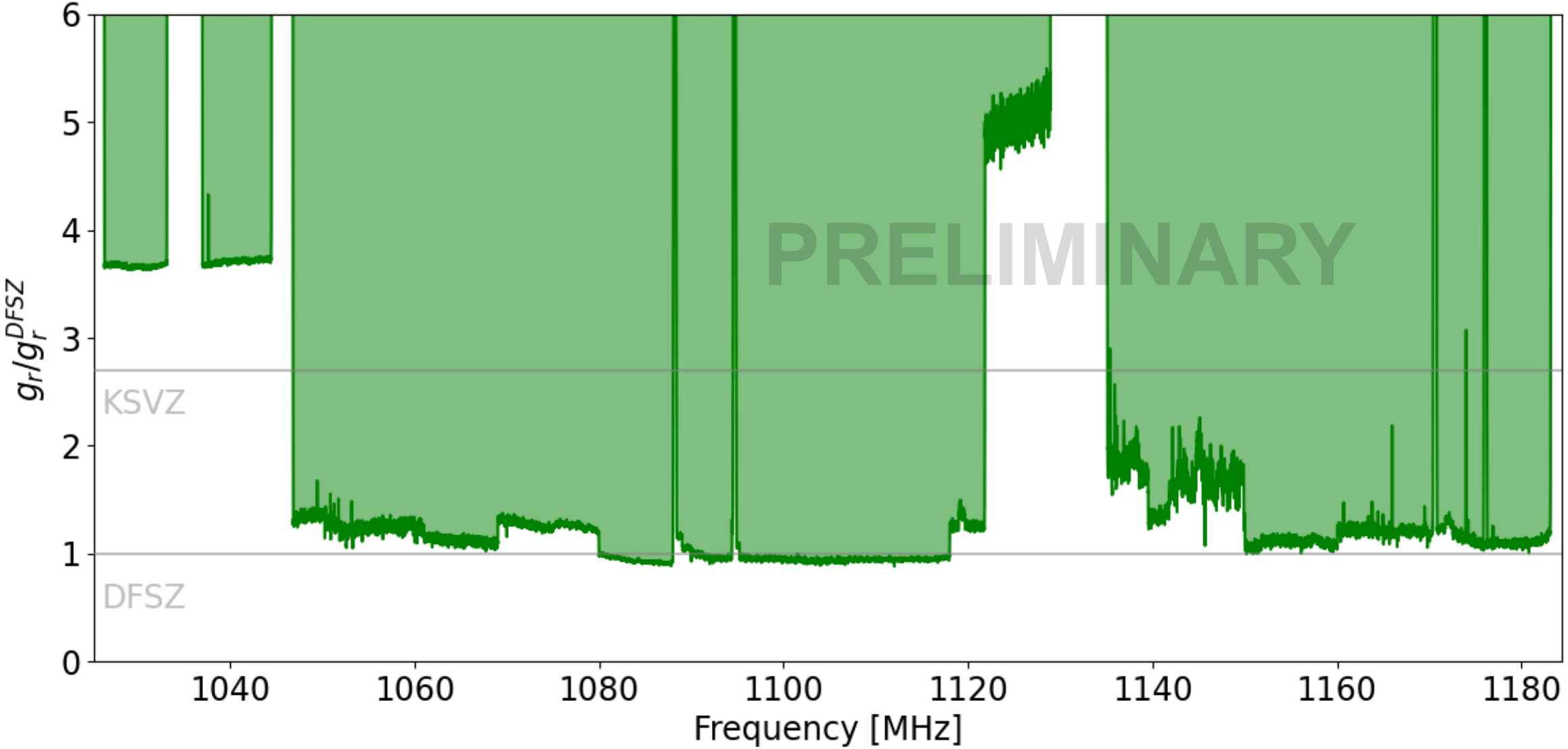
- Use of aerial antenna: taking data with aerial antenna at each DAQ
- Use of higher TM-like modes (C ~ 0)
- Whether it is enhanced at the cavity
- Rescan for the remained peaks

If survived after all, magnetic field dependence test



Sensitivity (preliminary)

2nd / 3rd phys. run combined

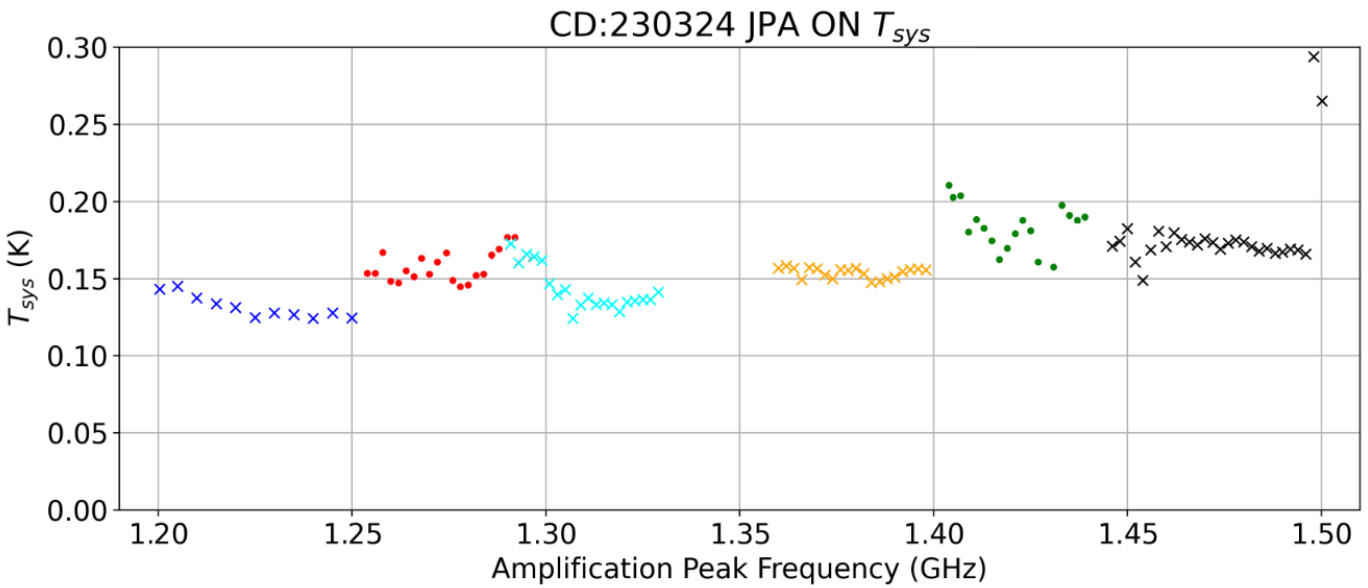


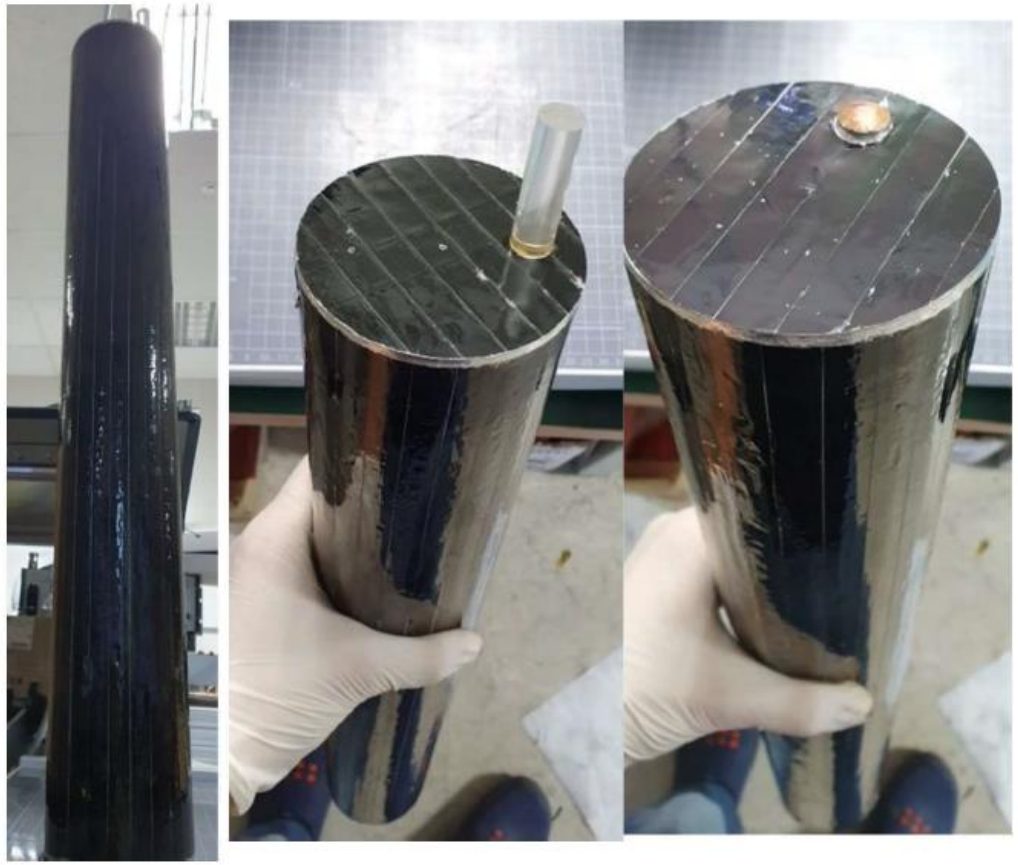
Challenges

- JPA passive resonance vibration / drift
  - Leads to difficulties in JPA tuning / some bad runs due to drift
  - May leads complexities in spectrum statistics
- Overlap of resonances between two series/parallel JPAs
- Warm resonator parts => excess noise at the resonance frequency
  - Getting better with adjustment / careful tuning

Future plan

- 2nd / 3rd physics run (finished)
  - Analysis / simulation / combining data / publication
- 4th in 1.2 – 1.5 GHz
  - With 6 JPAs (2 holders x 3 parallel)
  - With a superconducting tuning rod

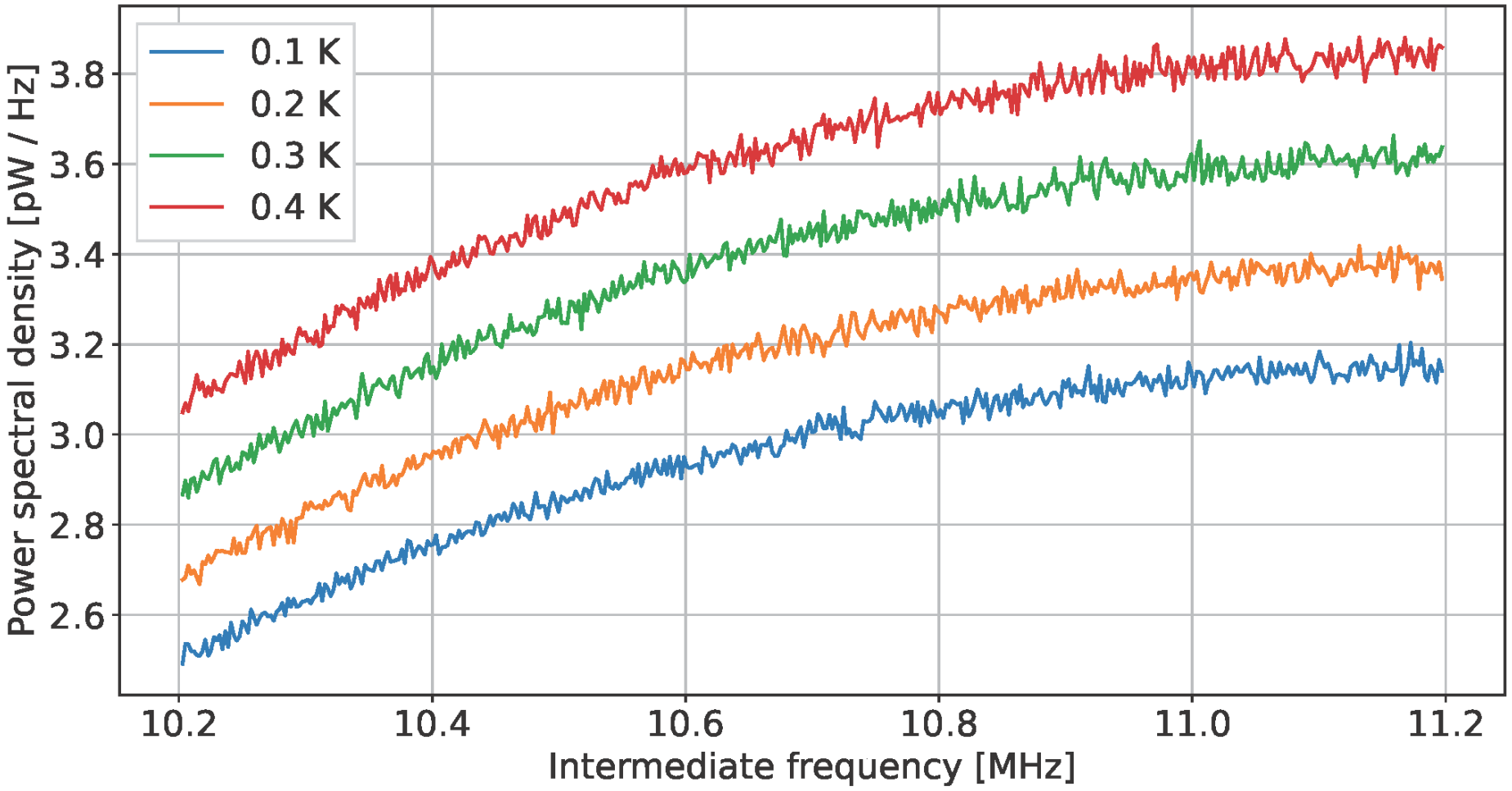


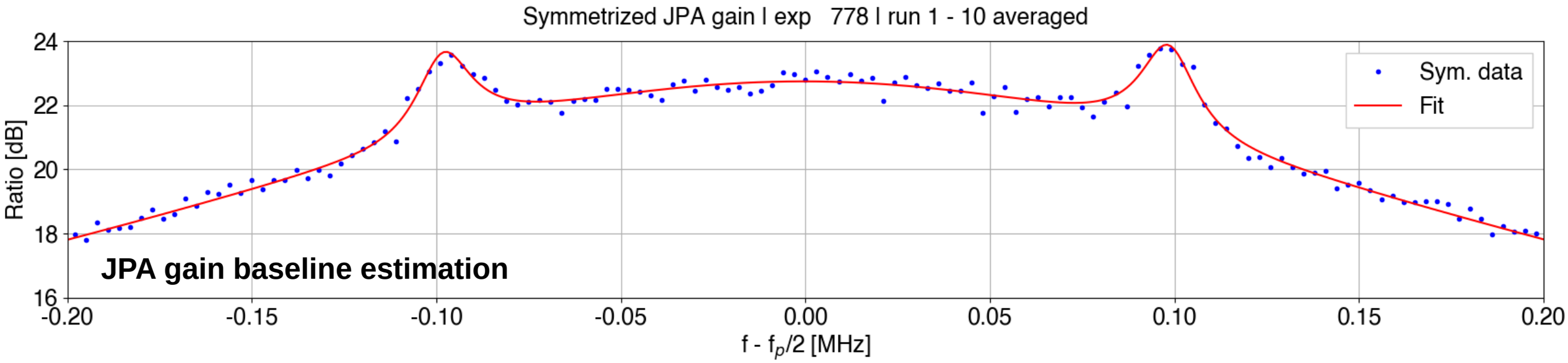
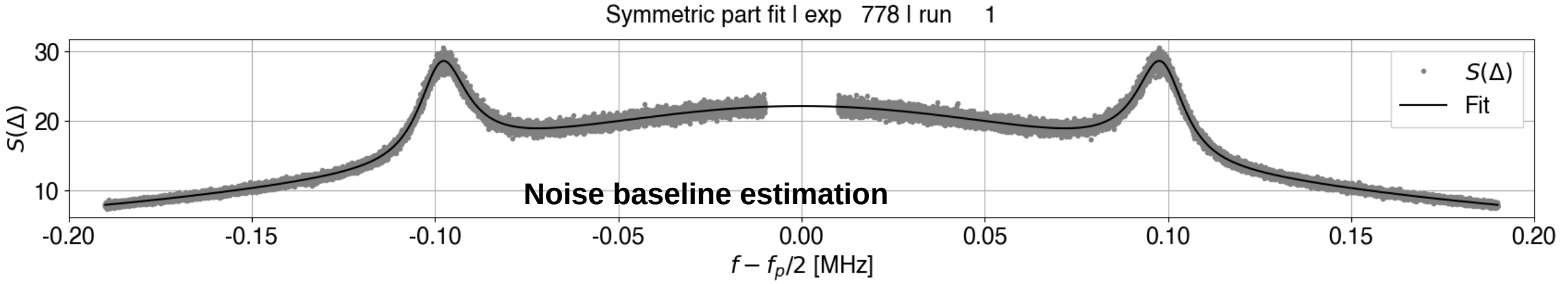


Measurements

JPA off noise measurements

Y factor measurements **at an LO freq.**



Data analysis

JPA gain / baseline estimation