JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SUPA0X

A superconducting axion search experiment @ Mainz

Kristof Schmieden, Tim Schneemann, Matthias Schott

With invaluable help from the RADES group, in particular Jessica Golm

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

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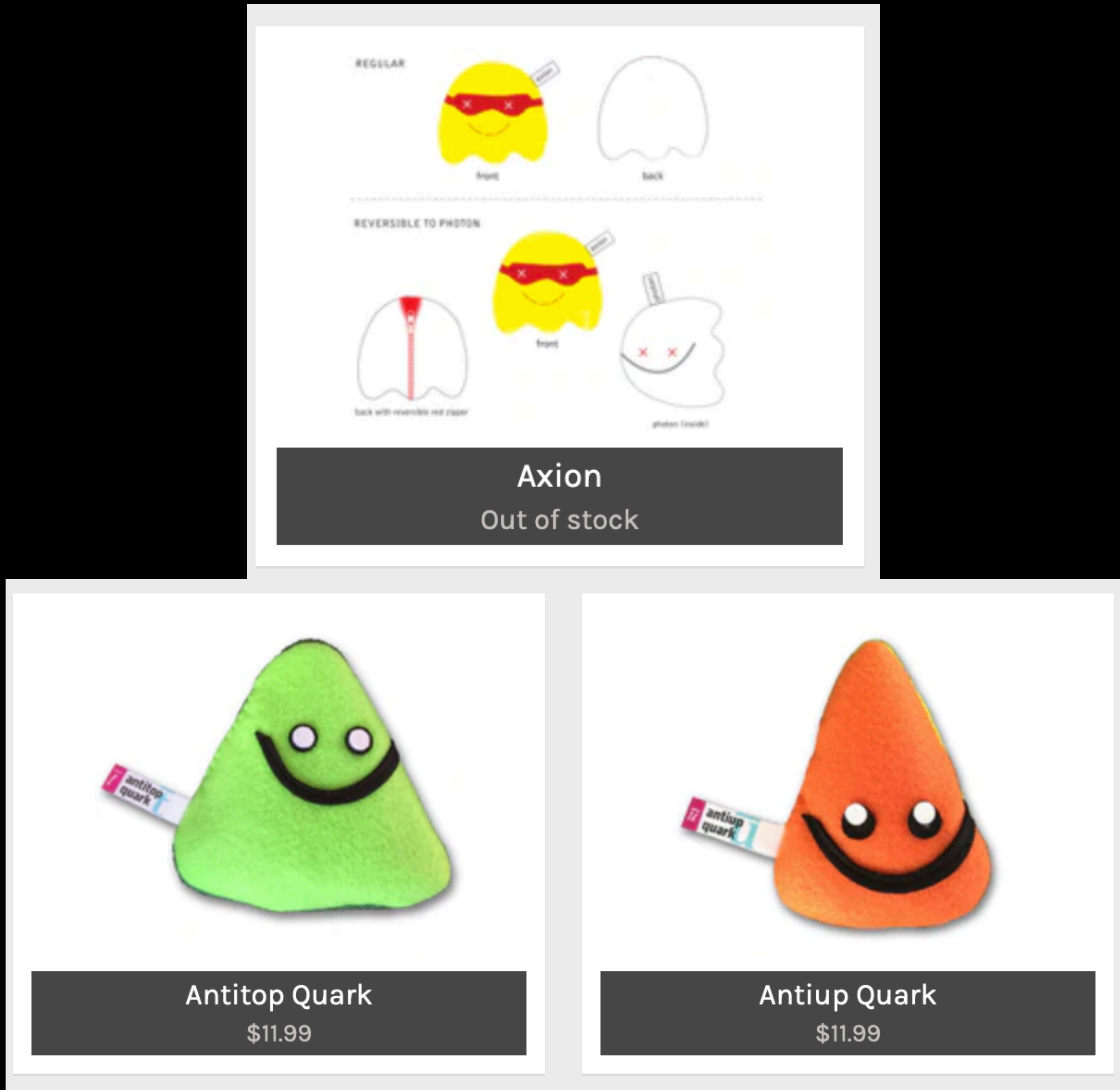
Why Axions?

- Axions are very likeable
  - Very polpular
  - (Presently out of stock)



[https://www.particlezoo.net/collections/all]

Why Axions?

- Axions are very likeable
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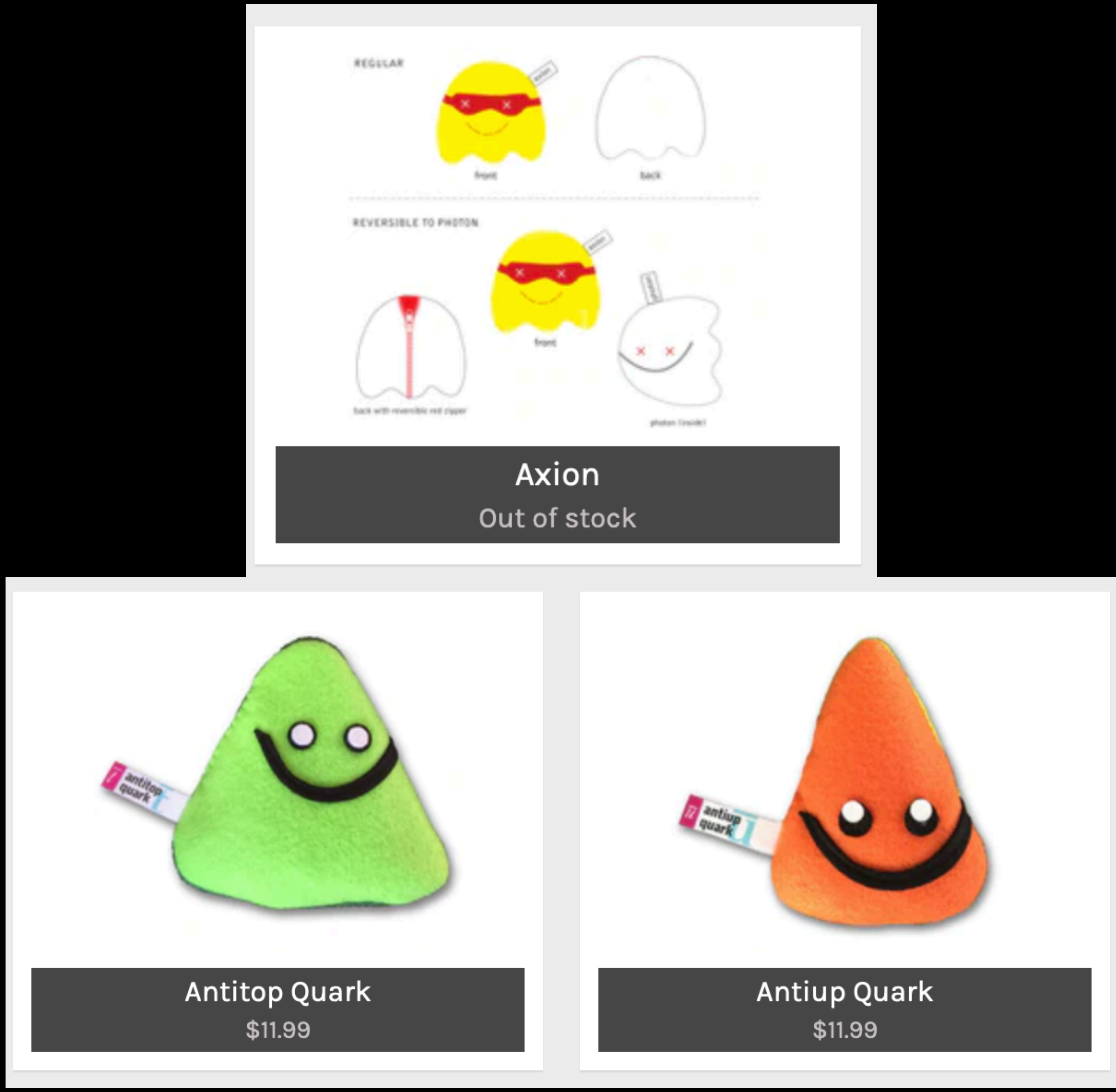
- Clean up the strong CP problem

- Axion (-like particles) appear in many BSM theories!
  - String theories, GUT, SUSY
- Axions can be dark matter



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Axions as Dark Matter

- Axions follow Bose-Einstein statistics
- Ensemble of light axions:
  macroscopic, wave-like behaviour
  - **Acts as cold dark matter**
- $m_a > 10^{-22}$ eV
  otherwise no structure formation possible
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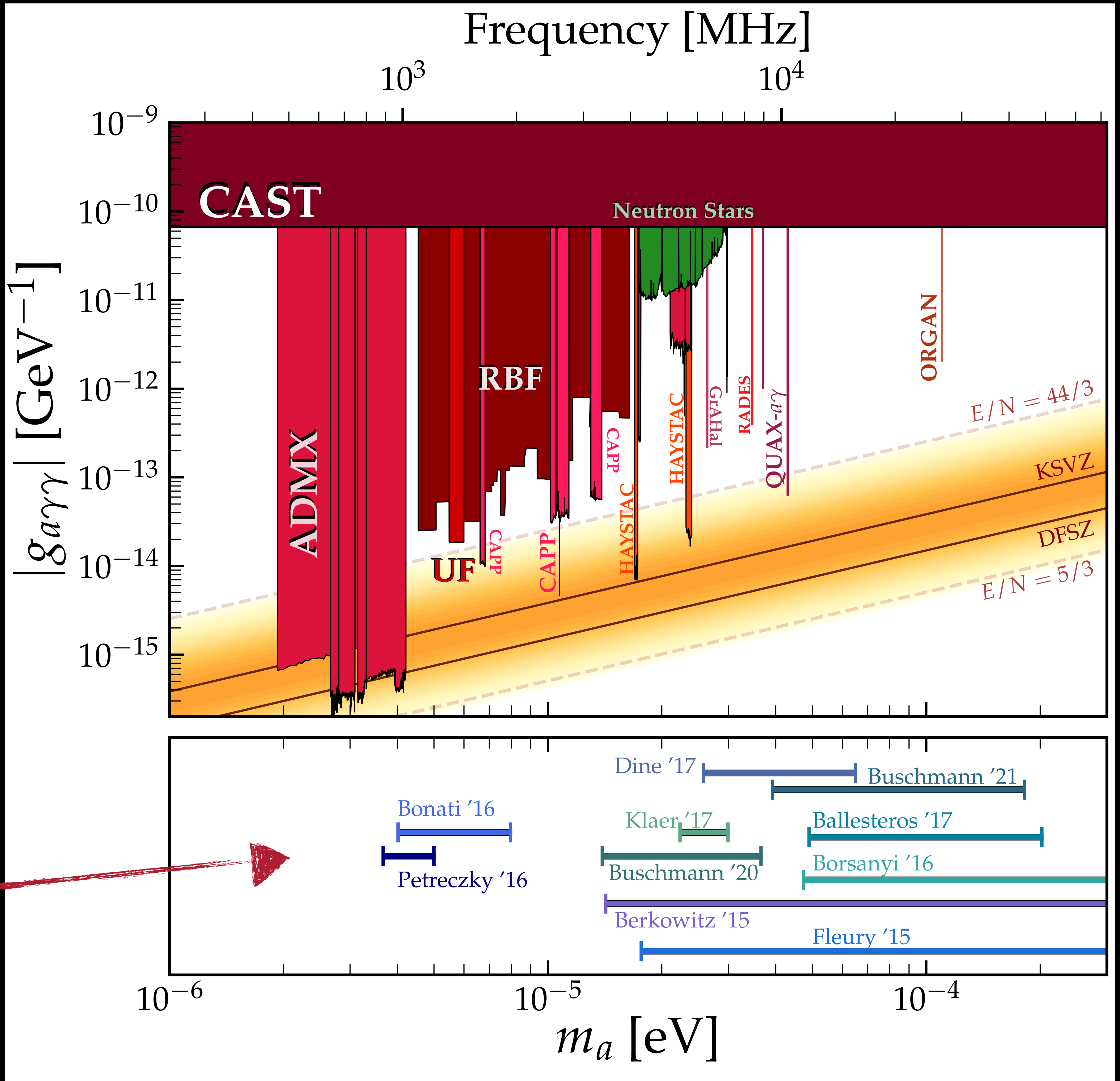
- Assuming all of DM is QCD Axions: Predict it's mass
  - Depends on production mechanism
  - Generation in strings and domain walls
    - Computationally difficult:
      - no ab initio calculation possible
    - ➡ **model dependent results**



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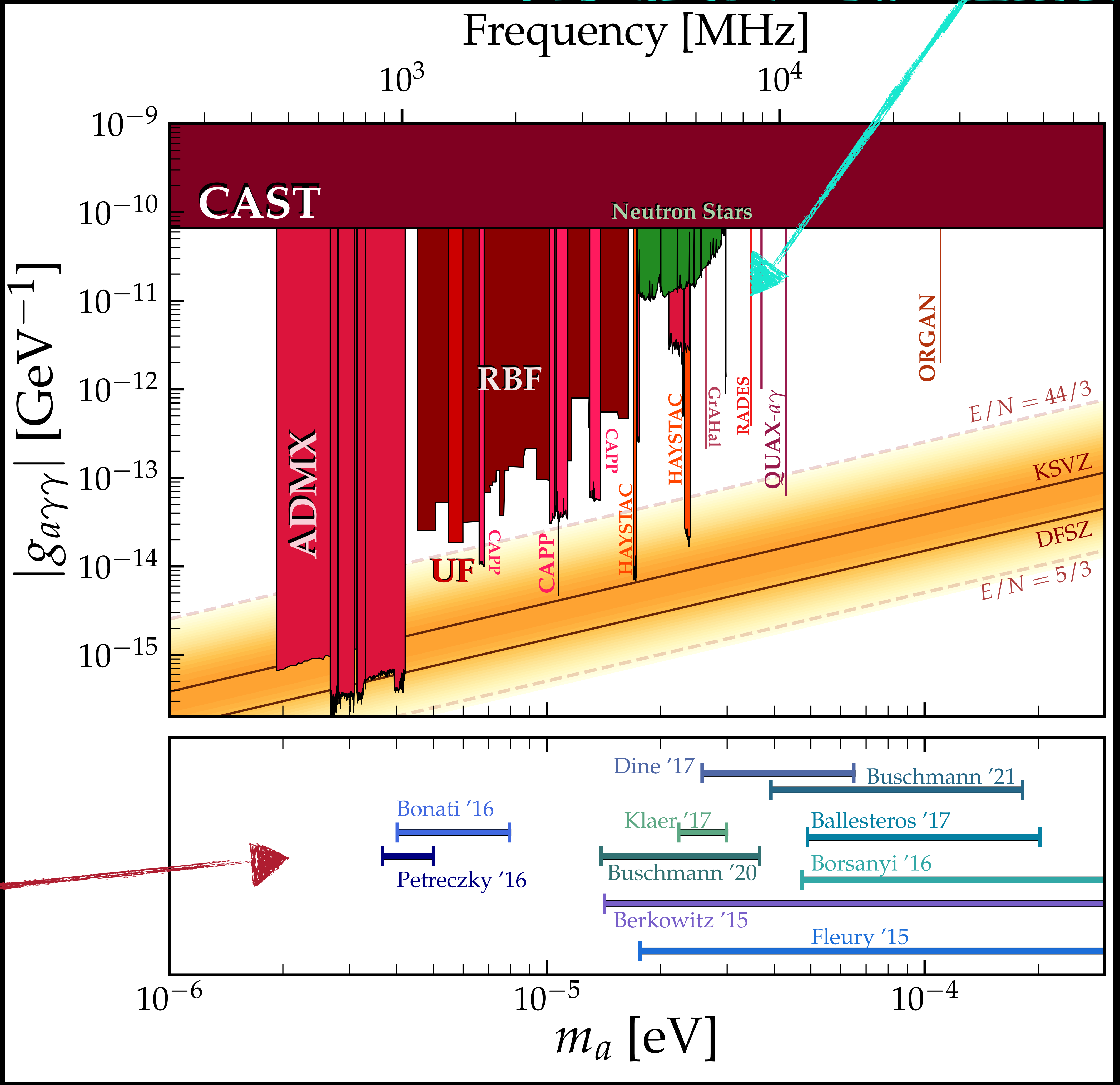
Physics results from the CAST-RADES run published
J. High Energ. Phys. 2021, 75 (2021)



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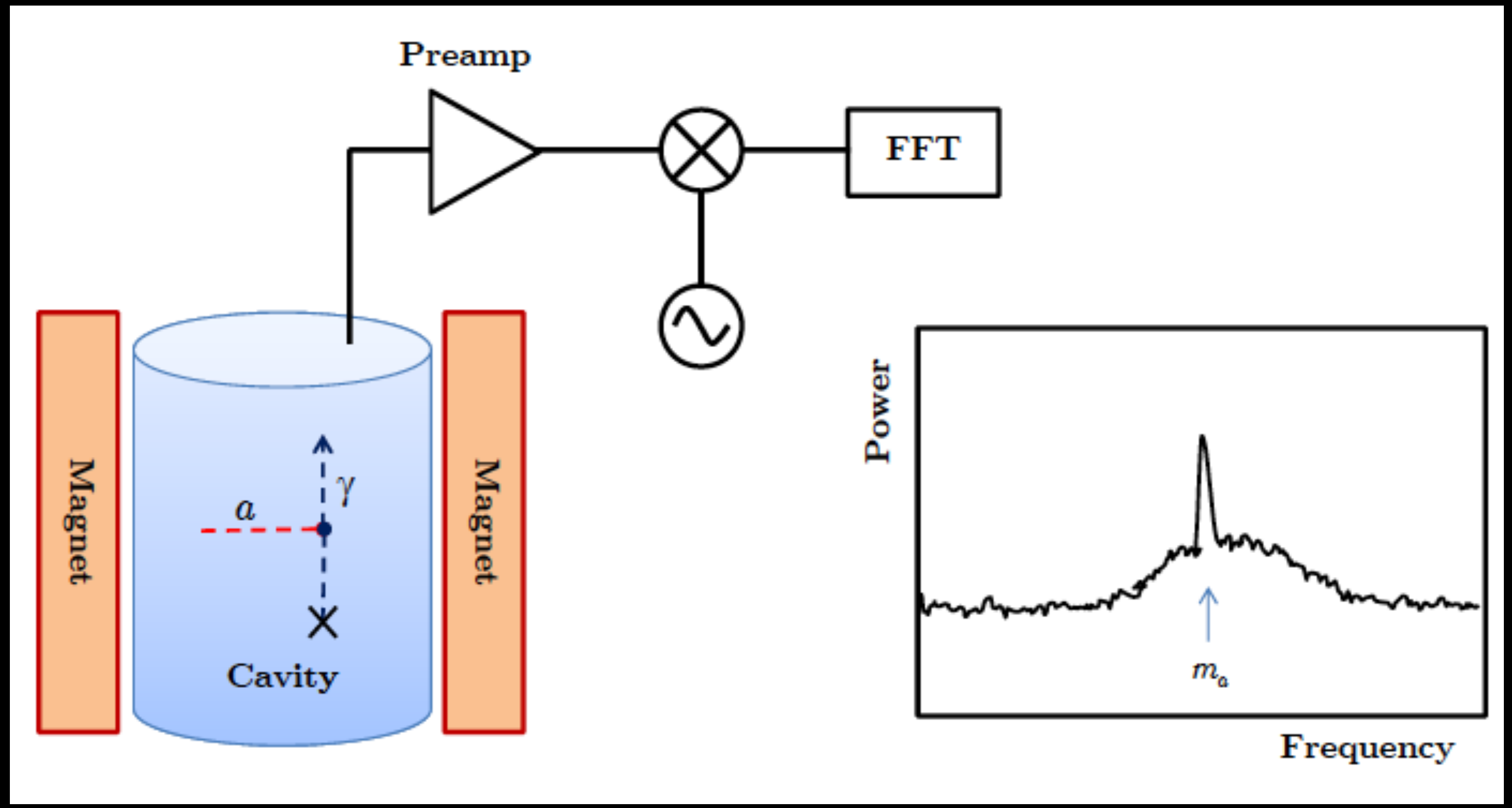
Axion detection in RF cavities

- Axion conversion to photons in B-field
- Using RF resonators to enhance the signal
- Sensitivity: ~µeV - meV

- Several magnitudes in frequency
  - Various designs of resonators & DAQ
  - Many experiments!



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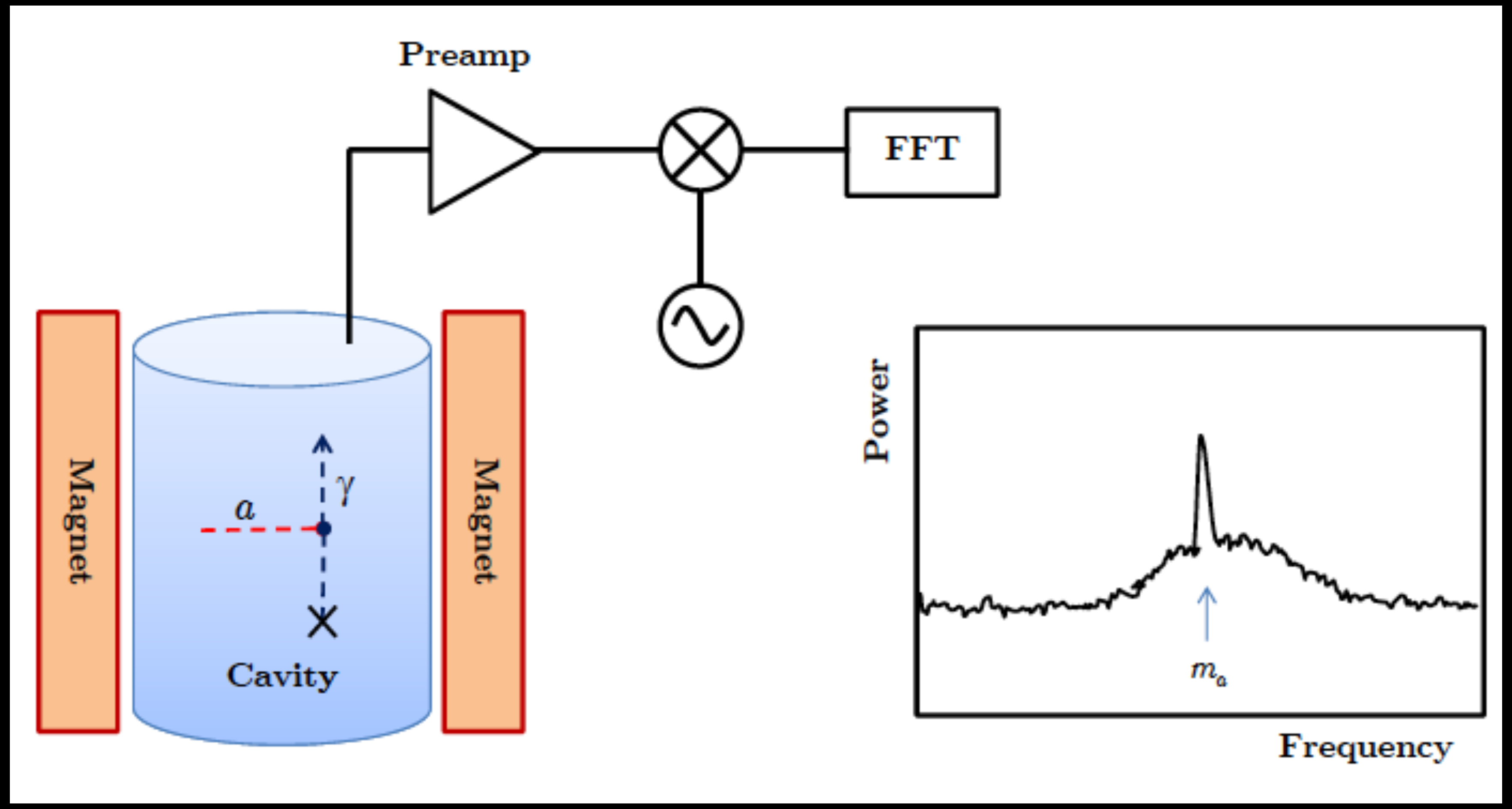

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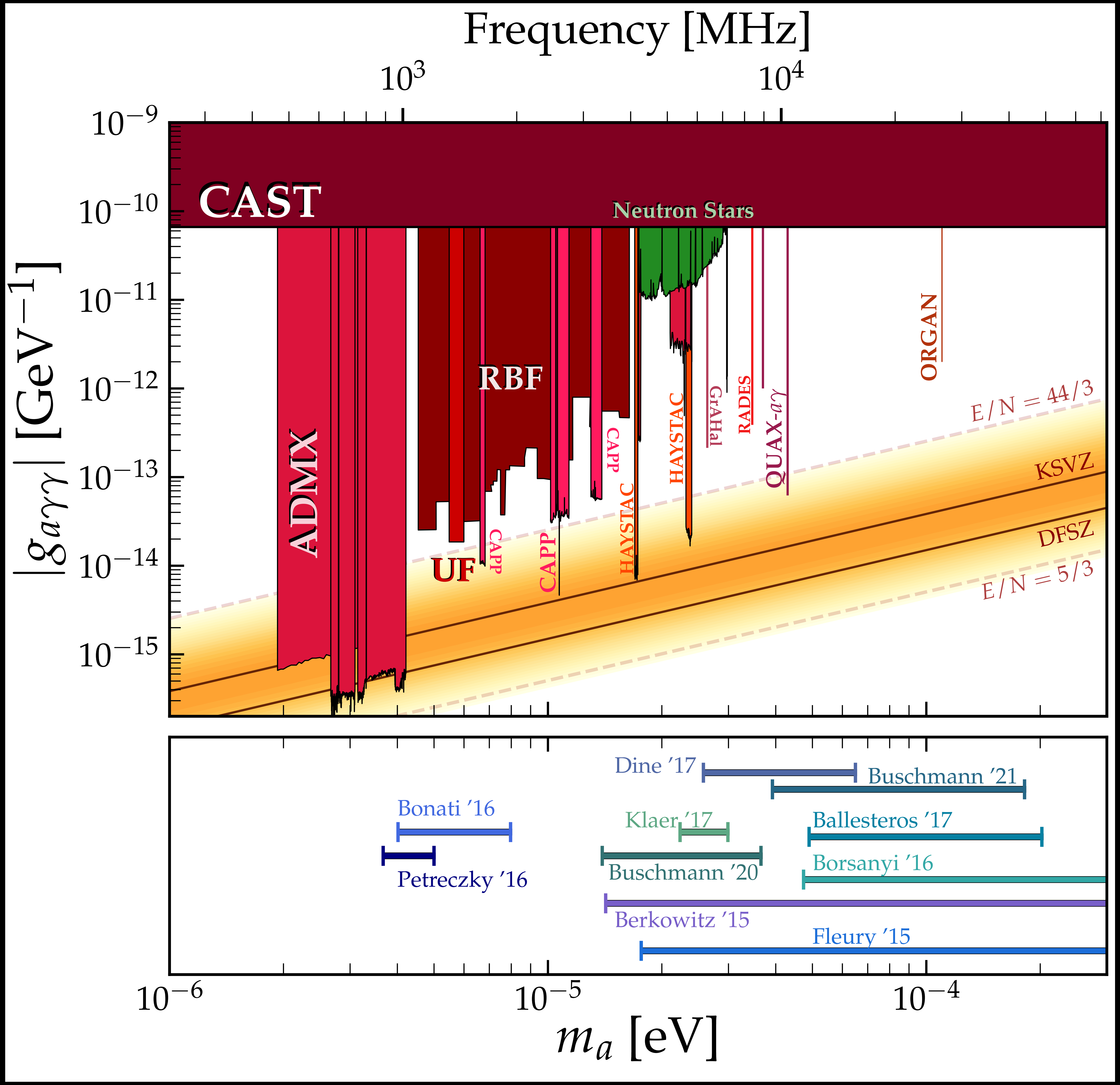

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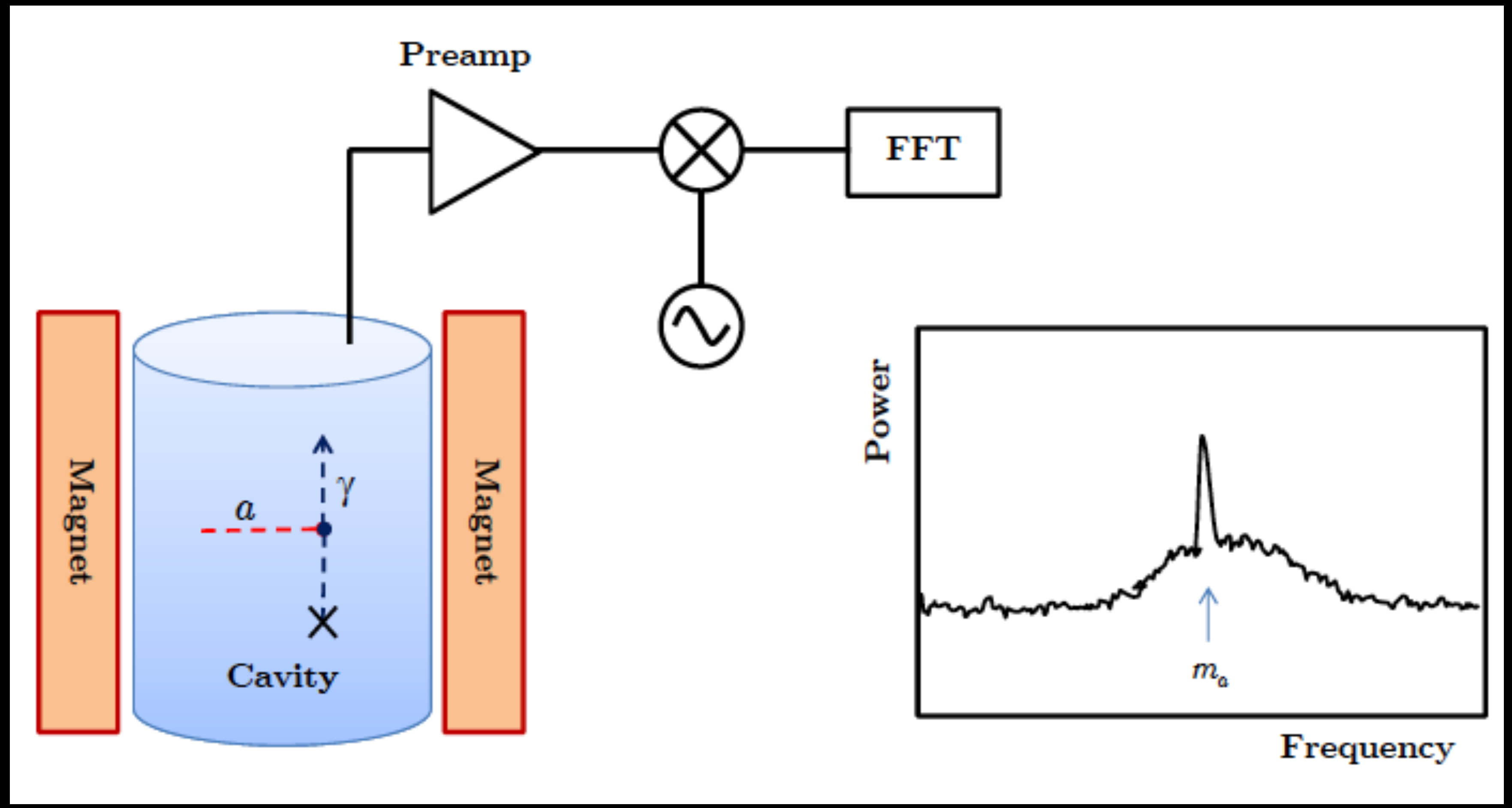

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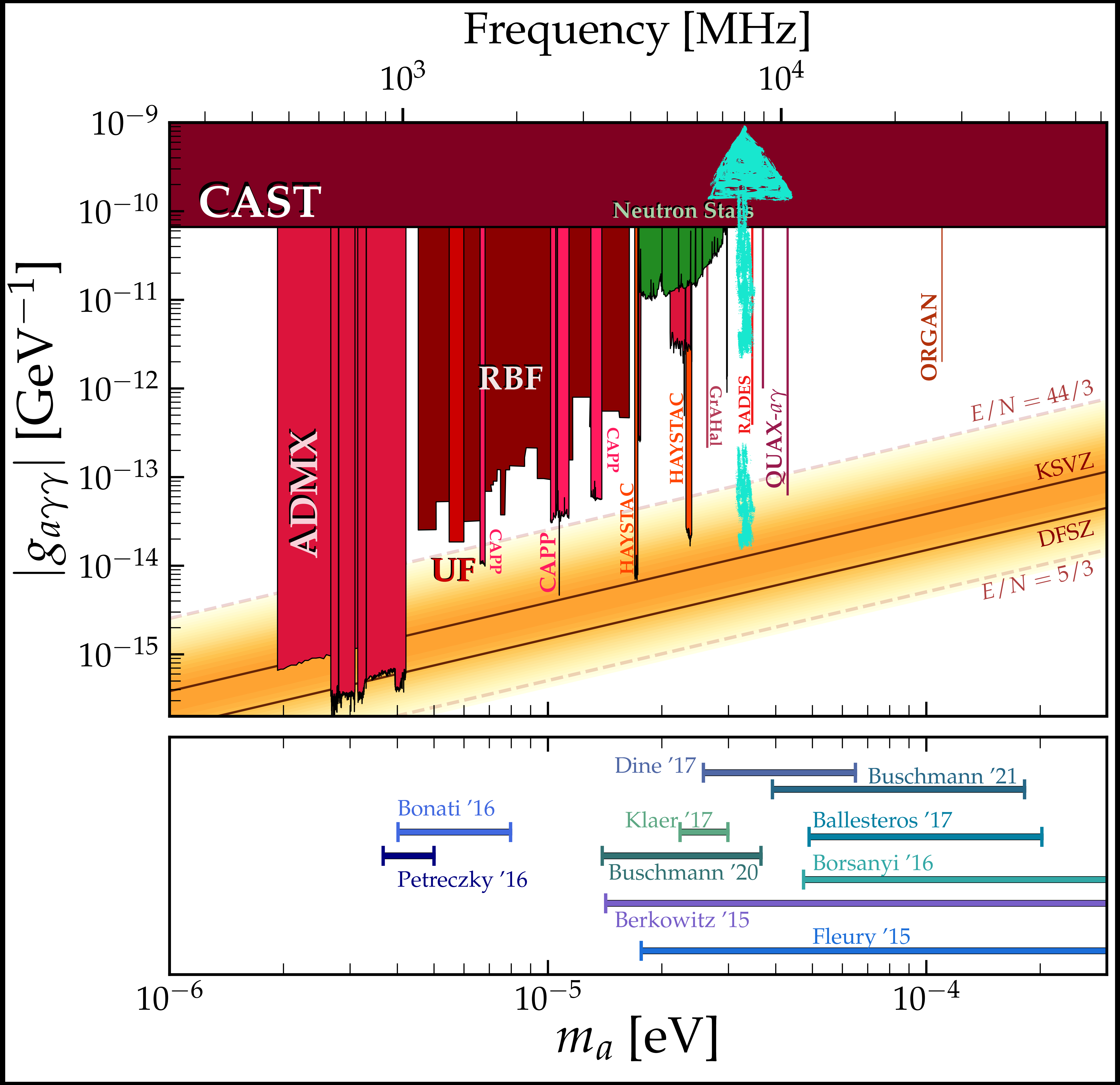

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Axion detection in RF cavities

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- Up to 14T magnets in use
  - Up to 20T envisioned
- Larger fields - smaller volume

- Depends on cavity material:
  - High purity copper: ~$5 \cdot 10^4$
  - Superconducting: difficult in high magnetic field!
    - Target: 10^6
    - Demonstrated: $3 \cdot 10^5$ (CAPP, non tunable)
      - Materials under study: Nb_3Sn, HTS materials (YBCO)

$$P_{sig} \propto B^2 Q_0 V g_\gamma^2$$

- Volume limited by
  - Magnet aperture
  - Resonance frequency
  - Tuning elements

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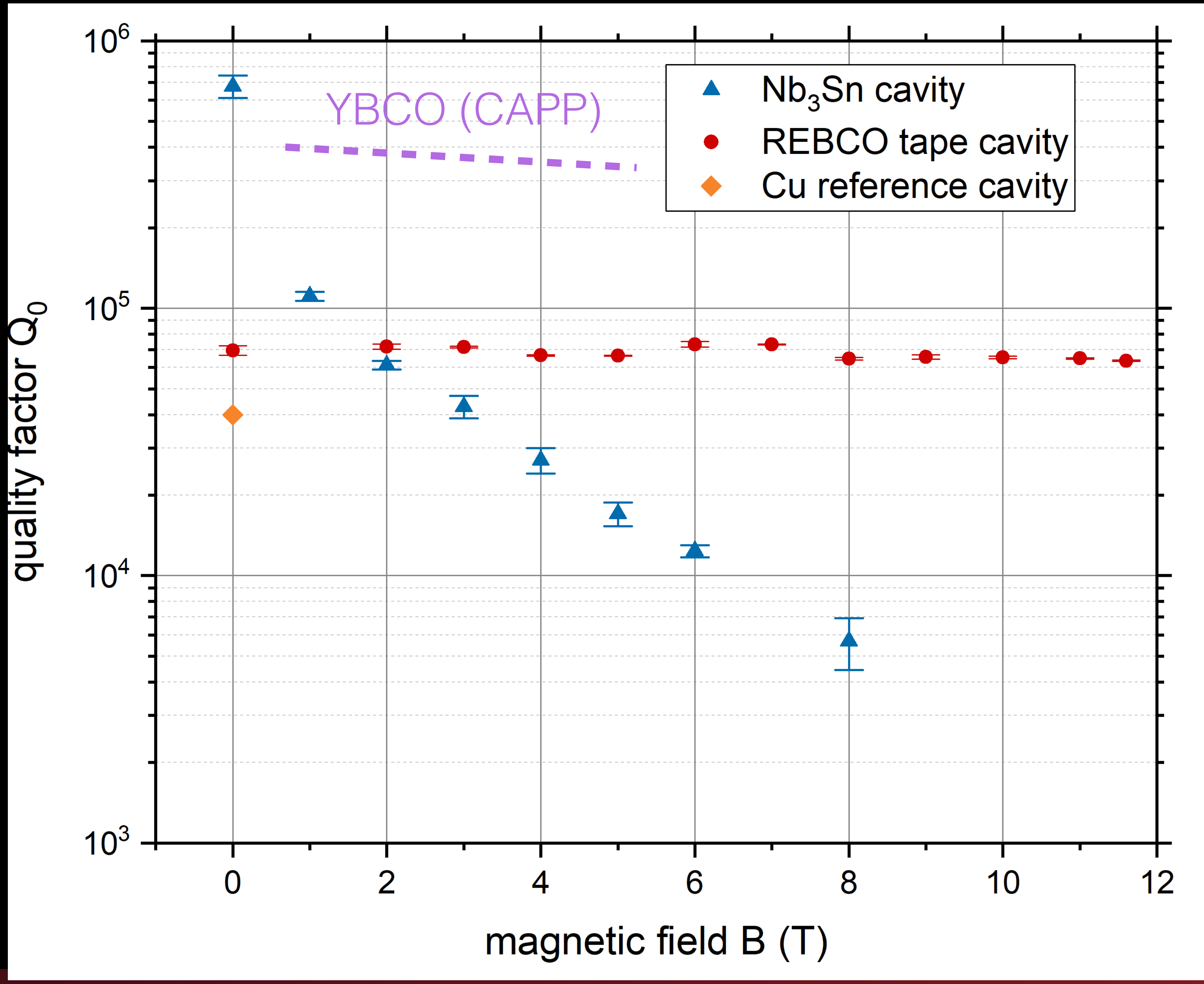
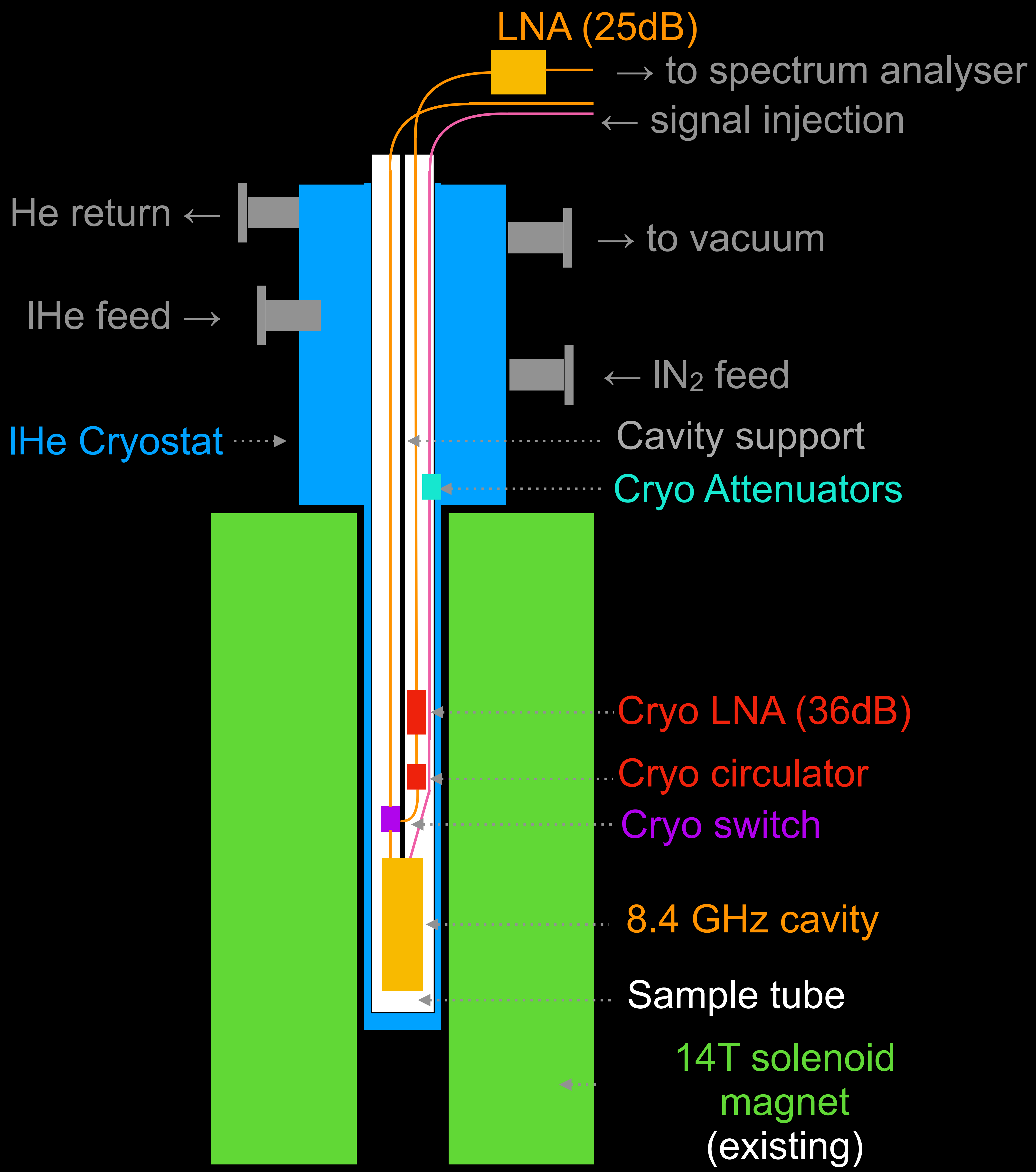


- D. Ahn et. al (CAPP), ~7 GHz https://arxiv.org/abs/2002.08769
- J. Golm et. al (RADES), ~8 GHz https://arxiv.org/abs/2110.01296

The Mainz Setup

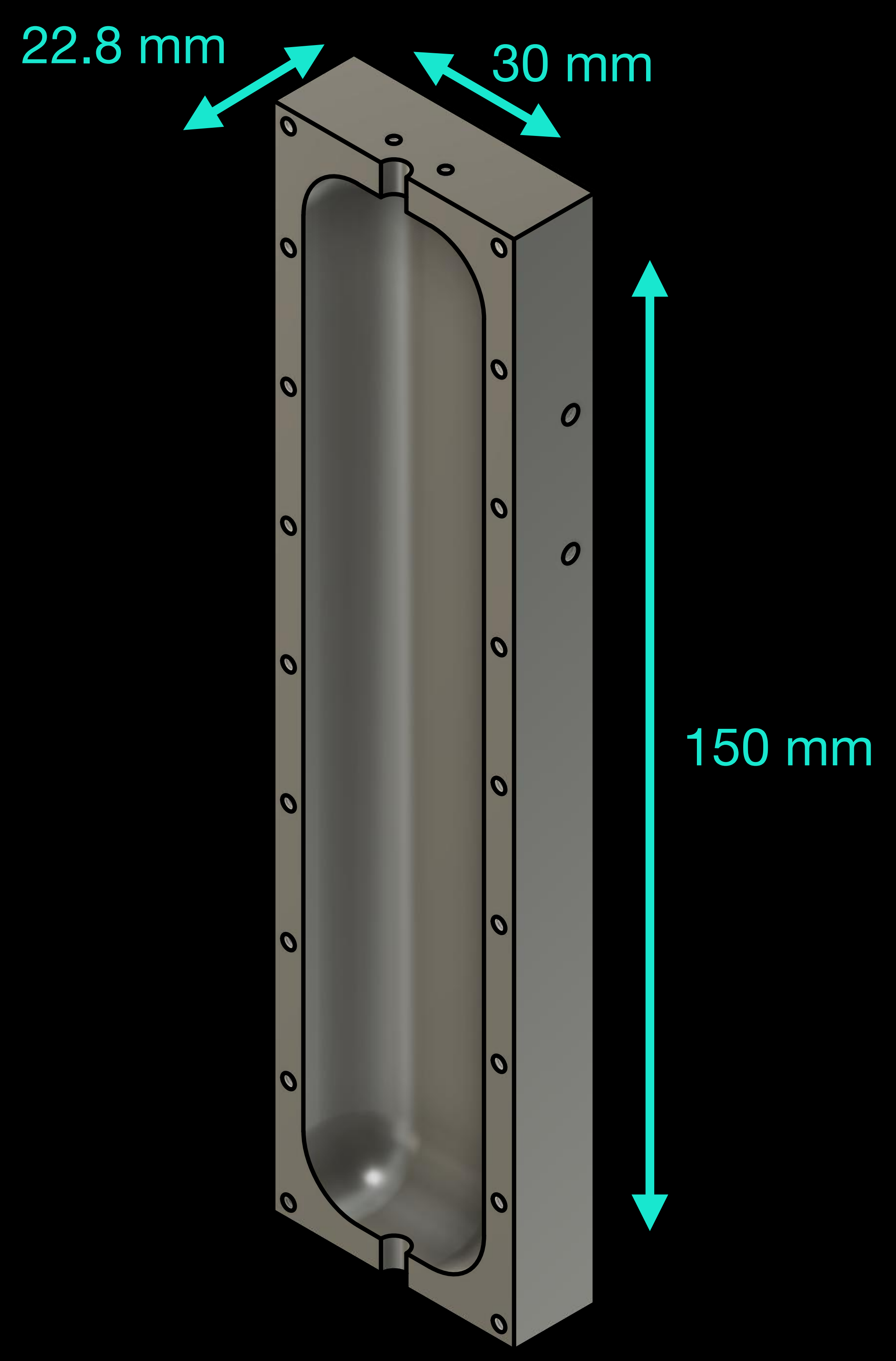


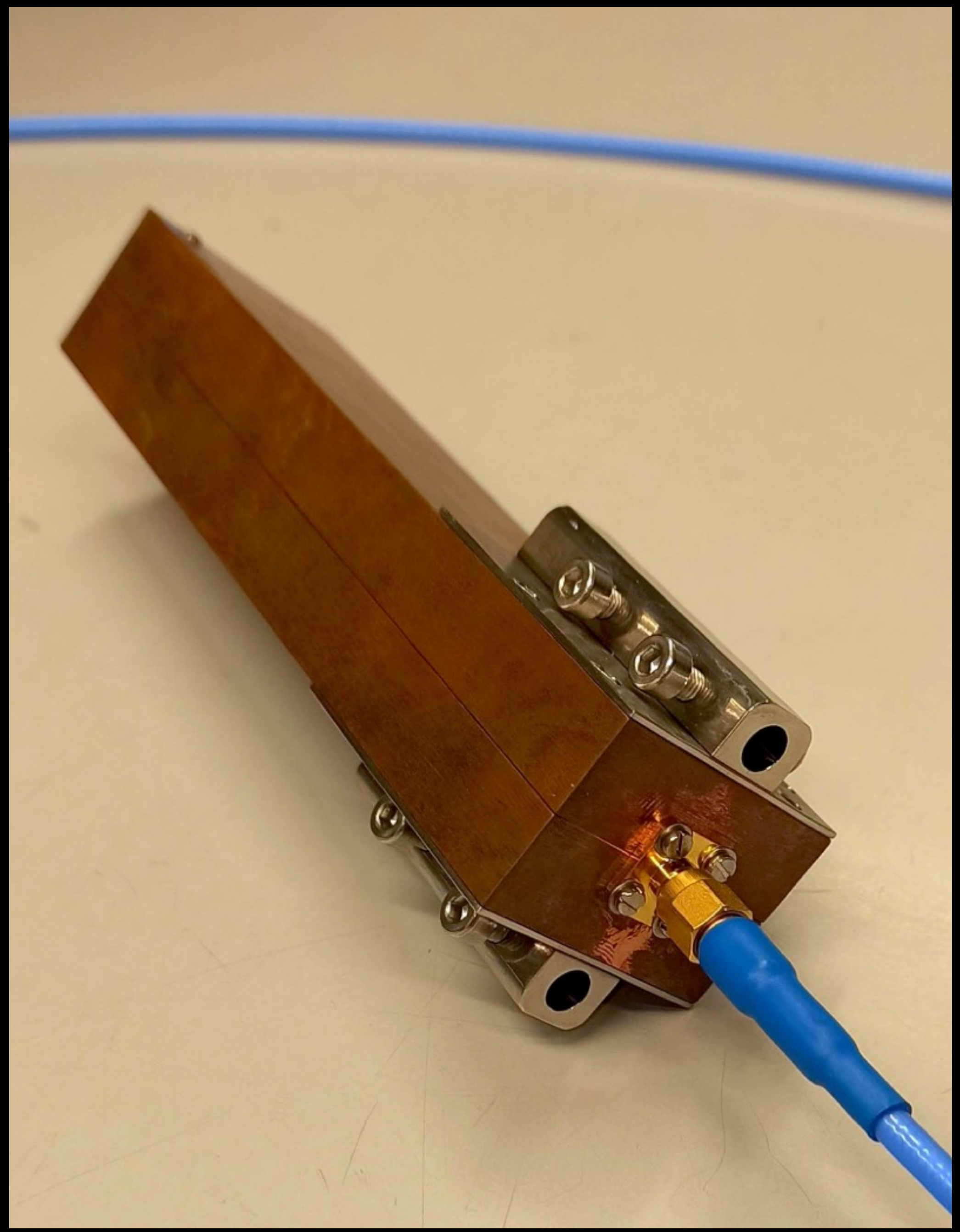
- Magnet:
  - Thanks to D. Budker's group at HIM
  - Bore: 89mm
    Inner cryostat diameter: 50 mm
- Isolator (Circulator) before Preamp
  - Reduction of residual RF reflection
- Cryo Preamp @ 4K, 10GHz:
  - Gain: 36 dB
  - Noise: 3.6K (0.05dB)
- DAQ system complete
- Cryostat delayed

Cavity Design

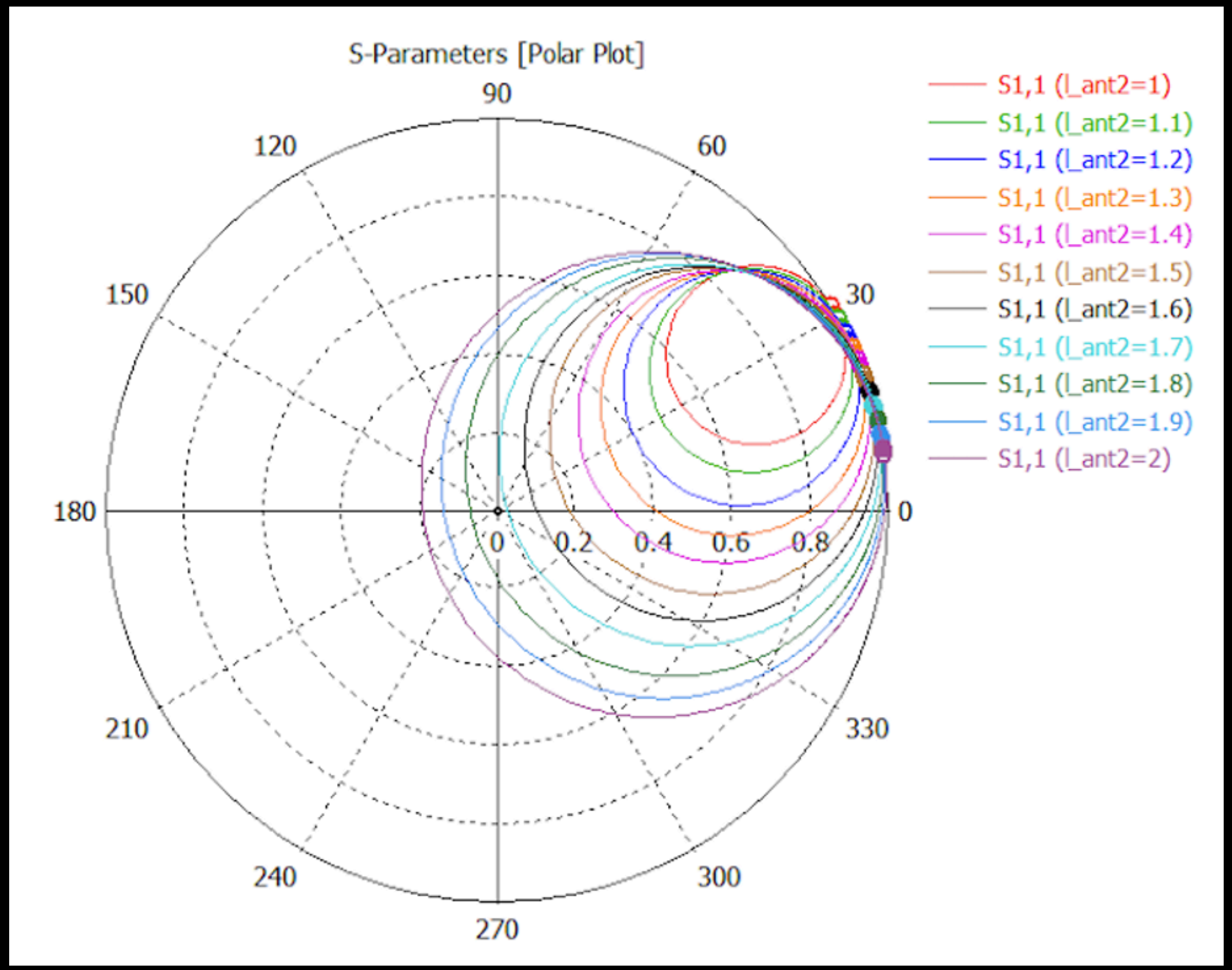
- Custom tailored cavity to fit into the cryostat
  - Manufactured from high purity copper

Inner dimensions (103 ccm):





- Antenna length optimised in simulation



Cavity - Comparison to Measurement

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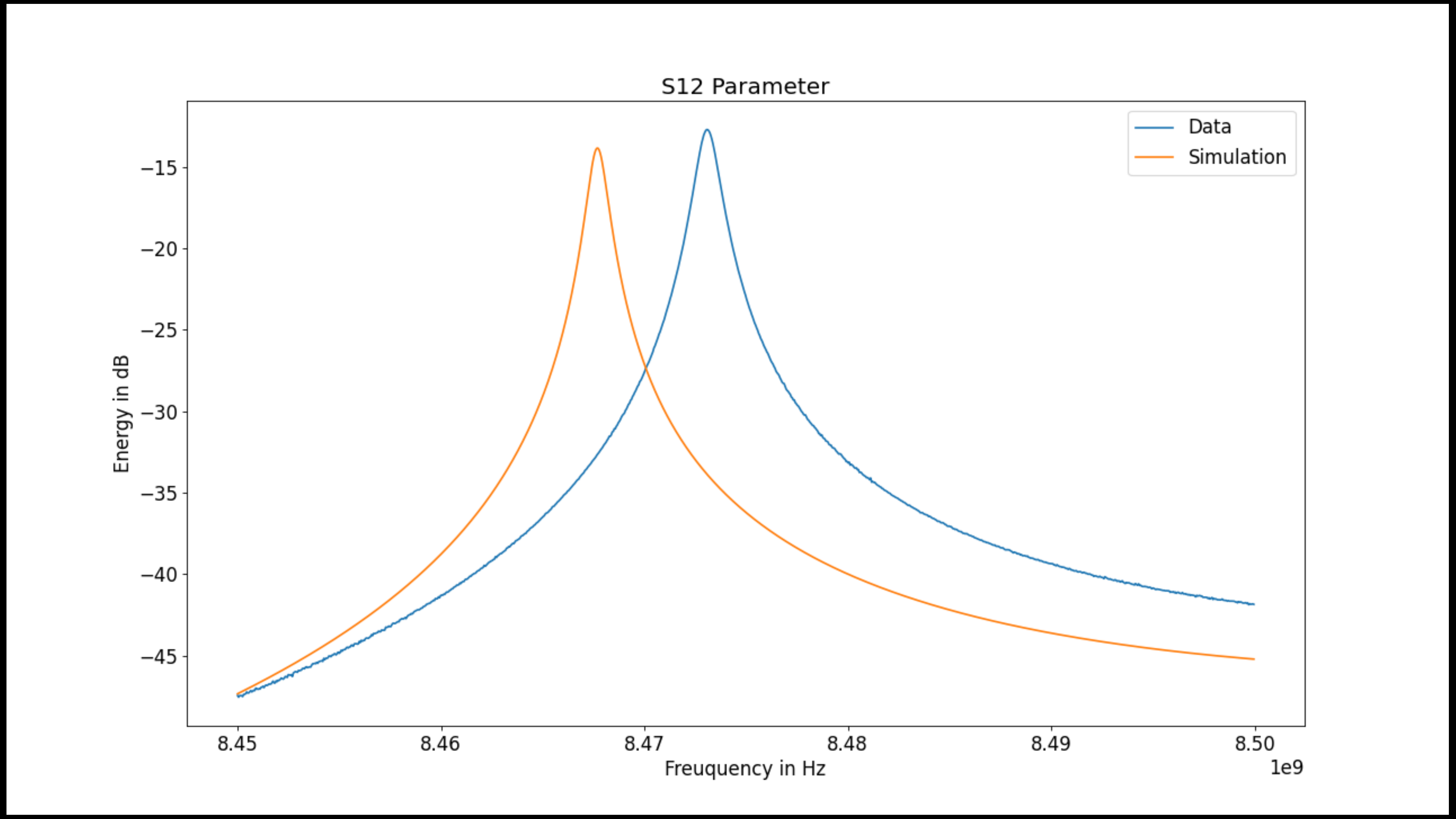
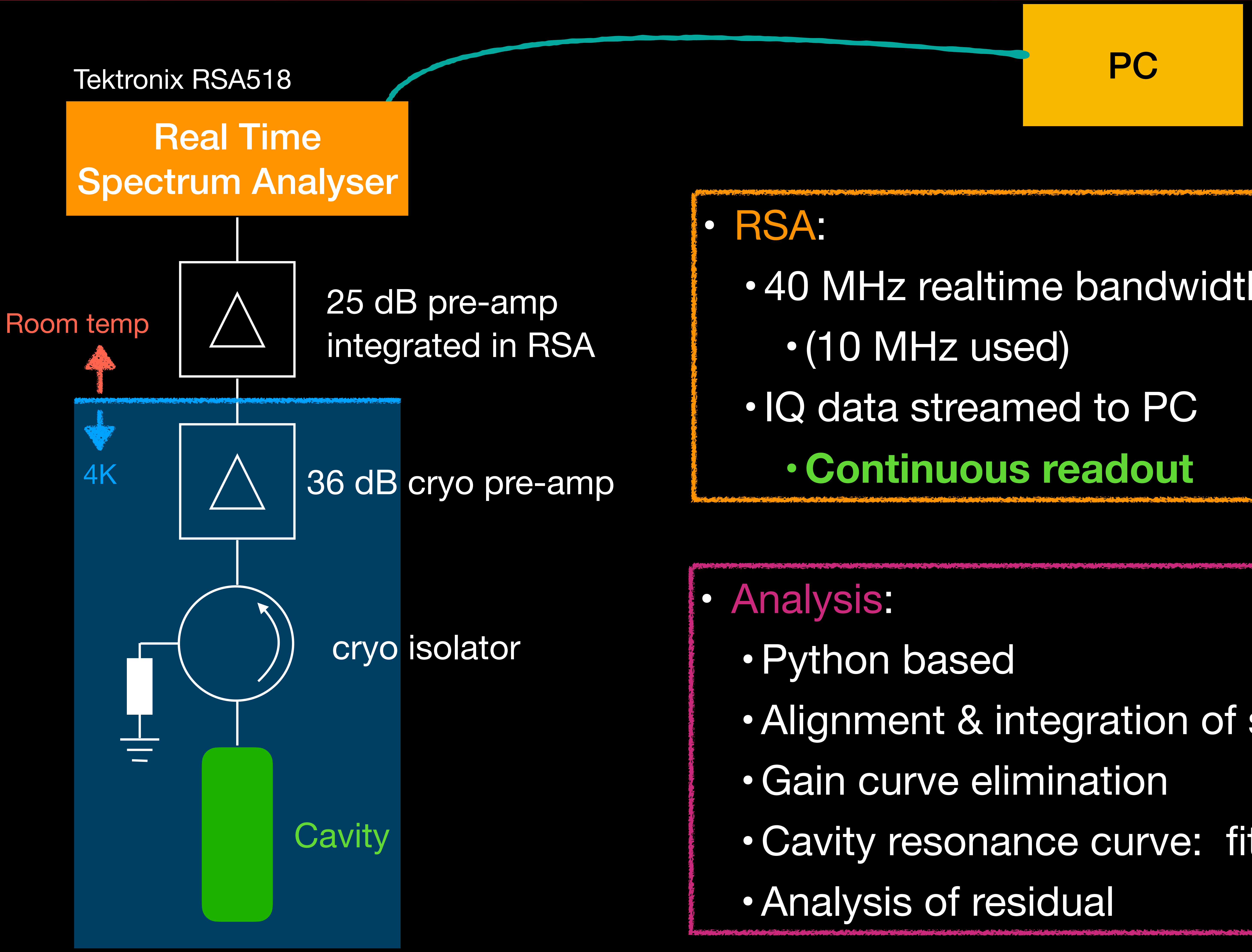
- Cavity characterised at room temperature:
  - Good agreement with simulation



- Δf (meas - sim) = 5.4 MHz
- Q_0 (meas / exp) = 16300 / 18000
  - Expecting factor 4 improvement at 4K:
    - $Q_{0,4K}$ = 65k

Real Time Data Acquisition



- RSA:
  - 40 MHz realtime bandwidth
    - (10 MHz used)
  - IQ data streamed to PC
    - **Continuous readout**

- Software (C++):
  - Realtime conversion to frequency domain
    - 1 kHz readout bandwidth
  - Stacking of 2 second blocks
  - Storage of spectra in root format

- Analysis:
  - Python based
  - Alignment & integration of spectra
  - Gain curve elimination
  - Cavity resonance curve: fit and subtraction
  - Analysis of residual

Status of the DAQ commissioning

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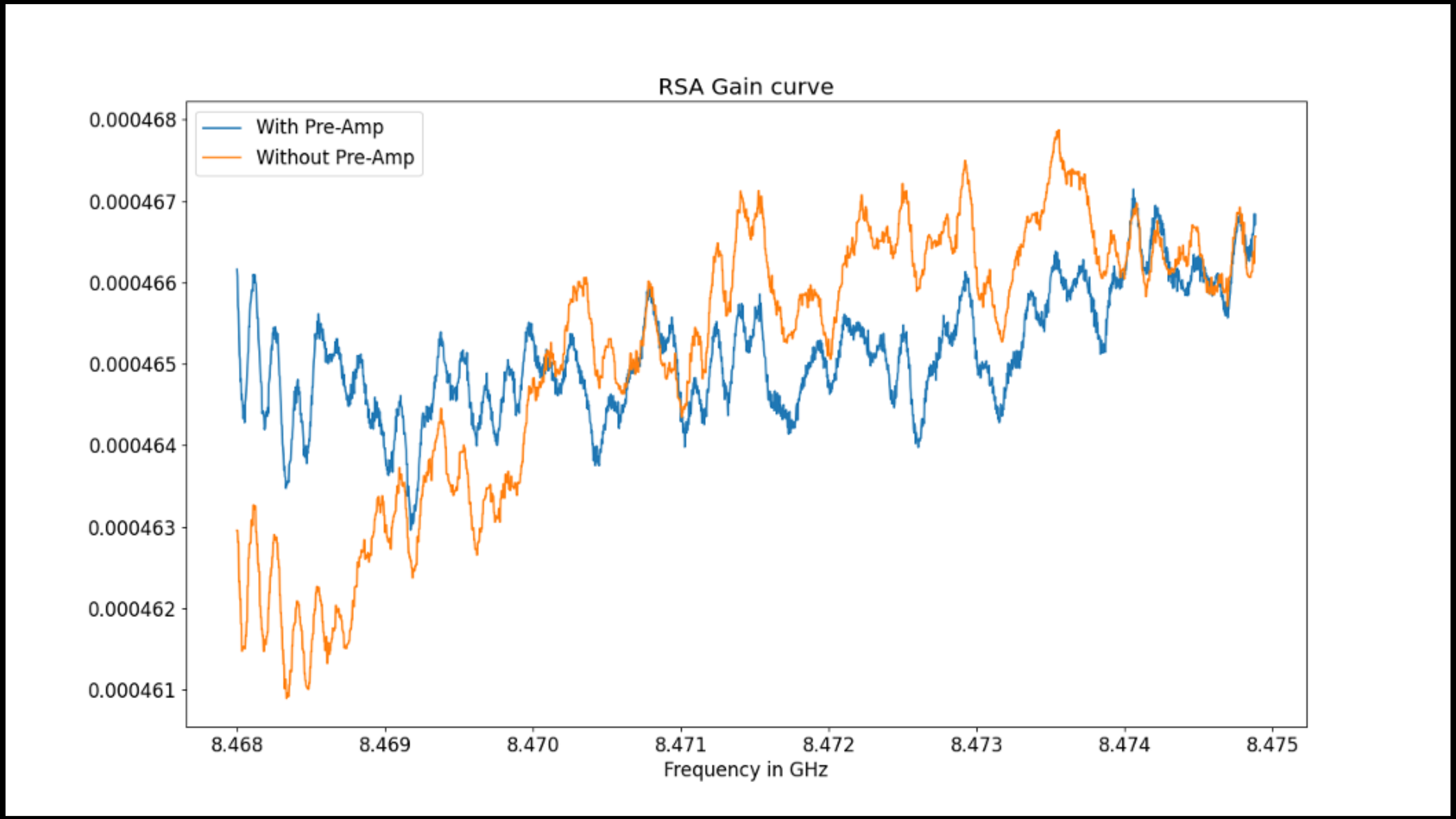
Work of Tim Schneemann

- Noise structure of RSA and cryo pre-amp:
  - Measured with input terminated with 50Ω
- Yields gain curve of DAQ chain



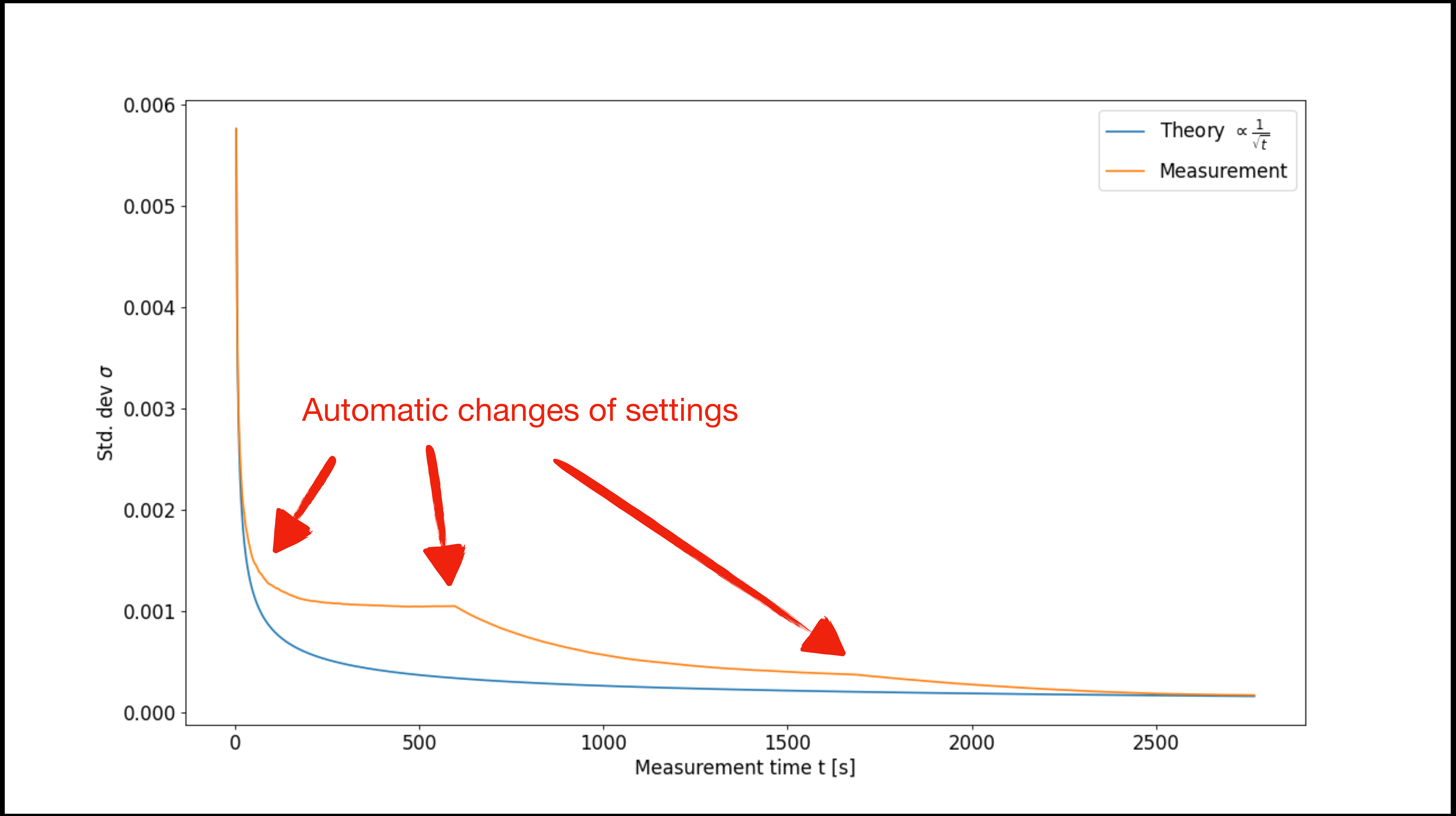
- 10 MHz readout window around 8.47 GHz
  - Measurement at room temperature
  - 1h integration time

- Noise structure stable over ~days
- Cryo-PreAmp does not add additional fine structure

- Variations in noise / gain:
  - Small scale: ~ 0.2 %
  - Full range min-max: < 0.8%

Status of the DAQ commissioning

- Noise evolution over time
  - Integration of noise signal
  - Expect $1/\sqrt{t}$ reduction of RMS of spectrum with integration time
- Manufacturer software:
  - Discontinuous shape
- Custom readout software: OK



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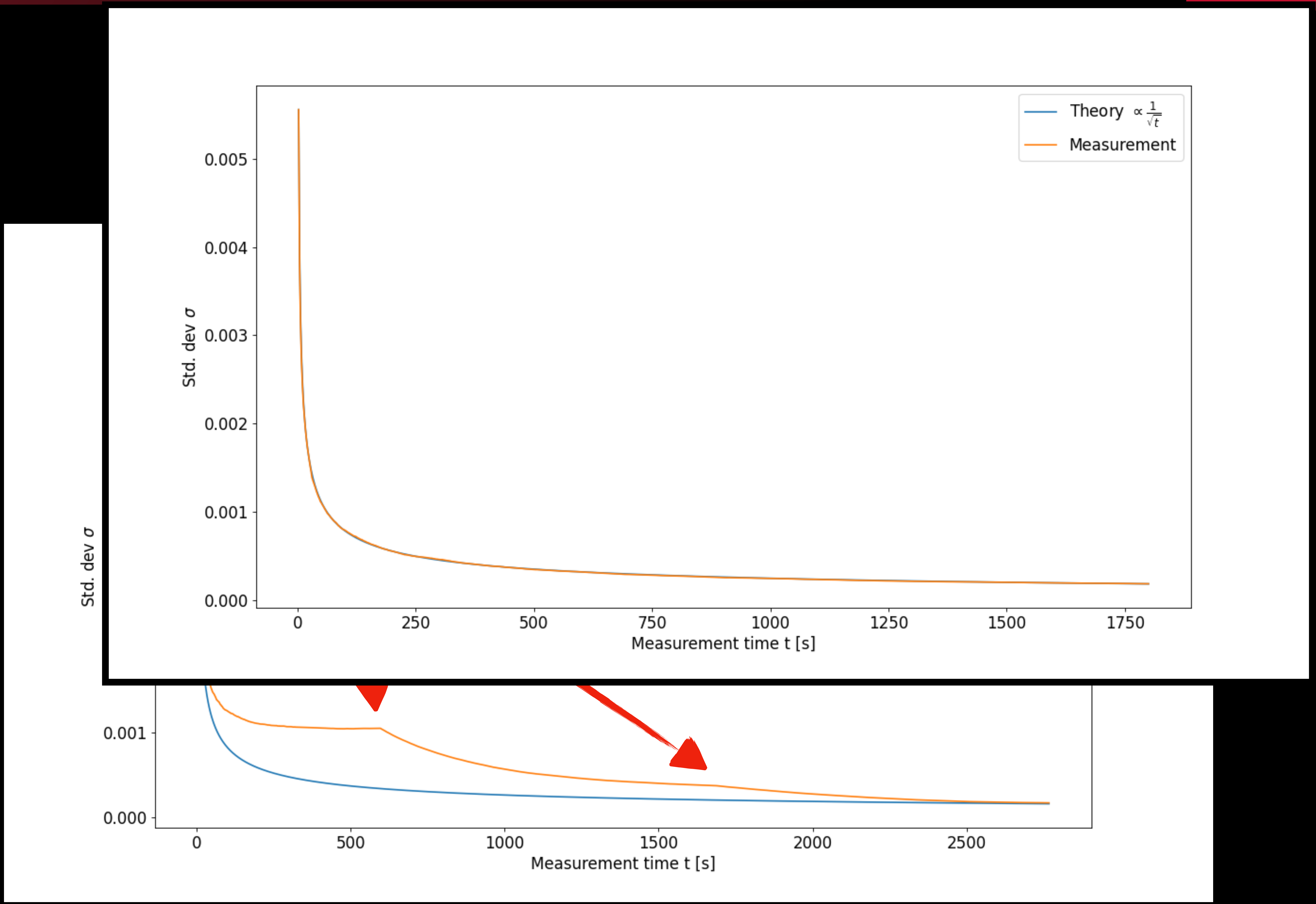

Status of the DAQ commissioning

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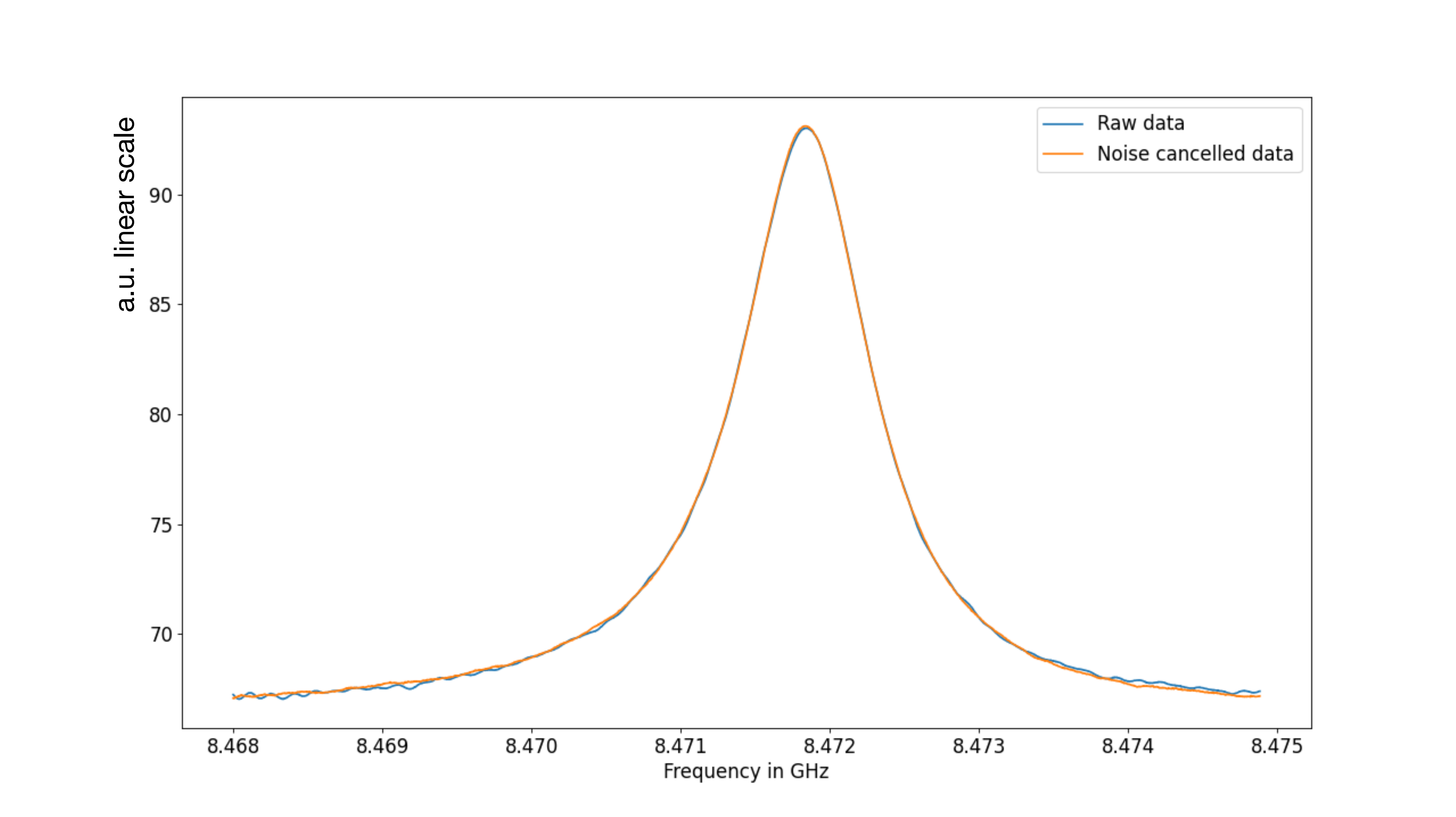
- Cavity noise signal (room temperature)
  - 1.44 times larger than pedestal
- Frequency drifts
  - Up to 175 kHz in 1h, < 0.1 kHz in 2s
    - Attributed to temperature drifts
- Mitigation:
  - During integration: shift frequency axis of every 2 sec block to keep cavity peak position const.



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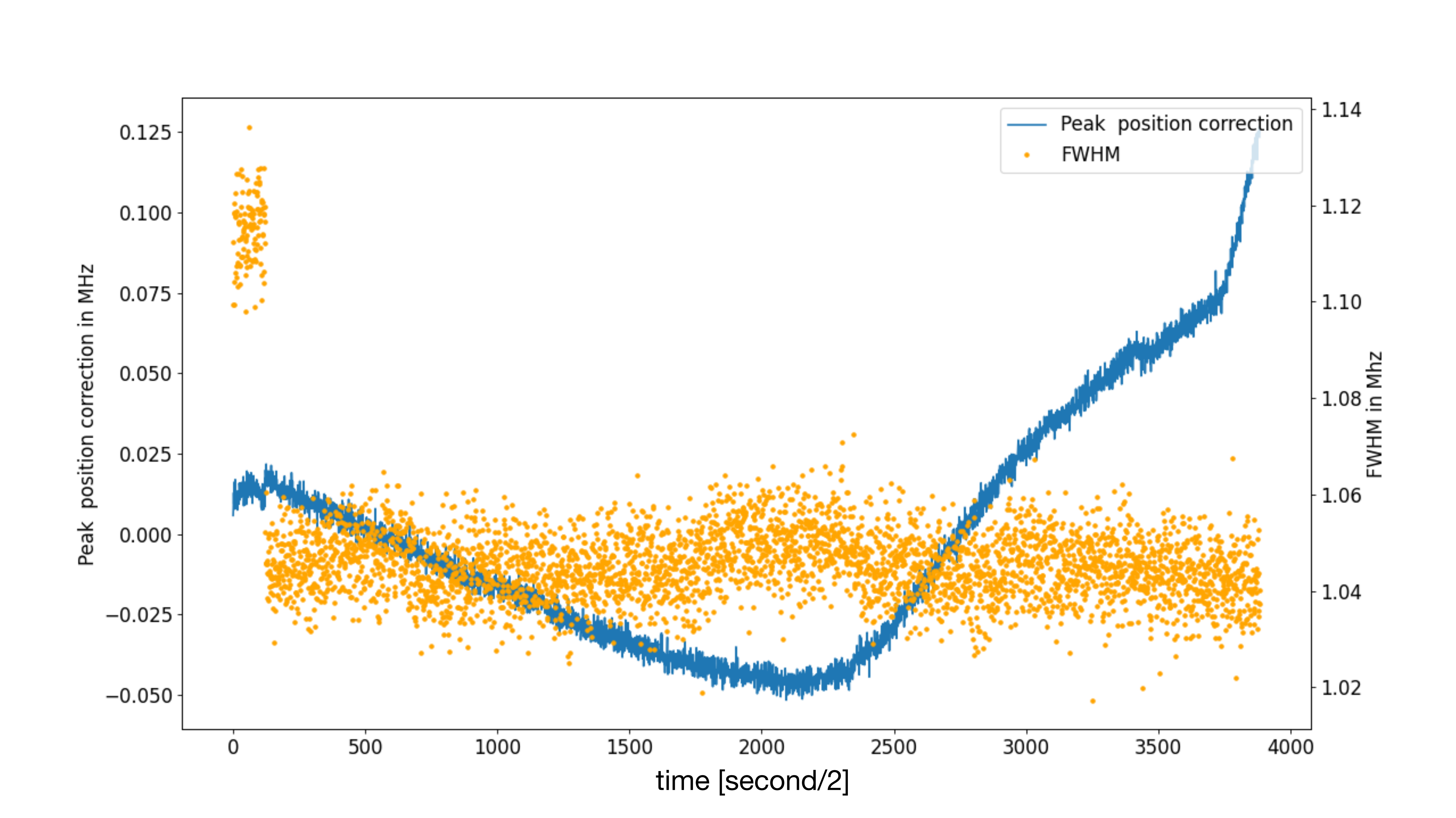


Data Analysis

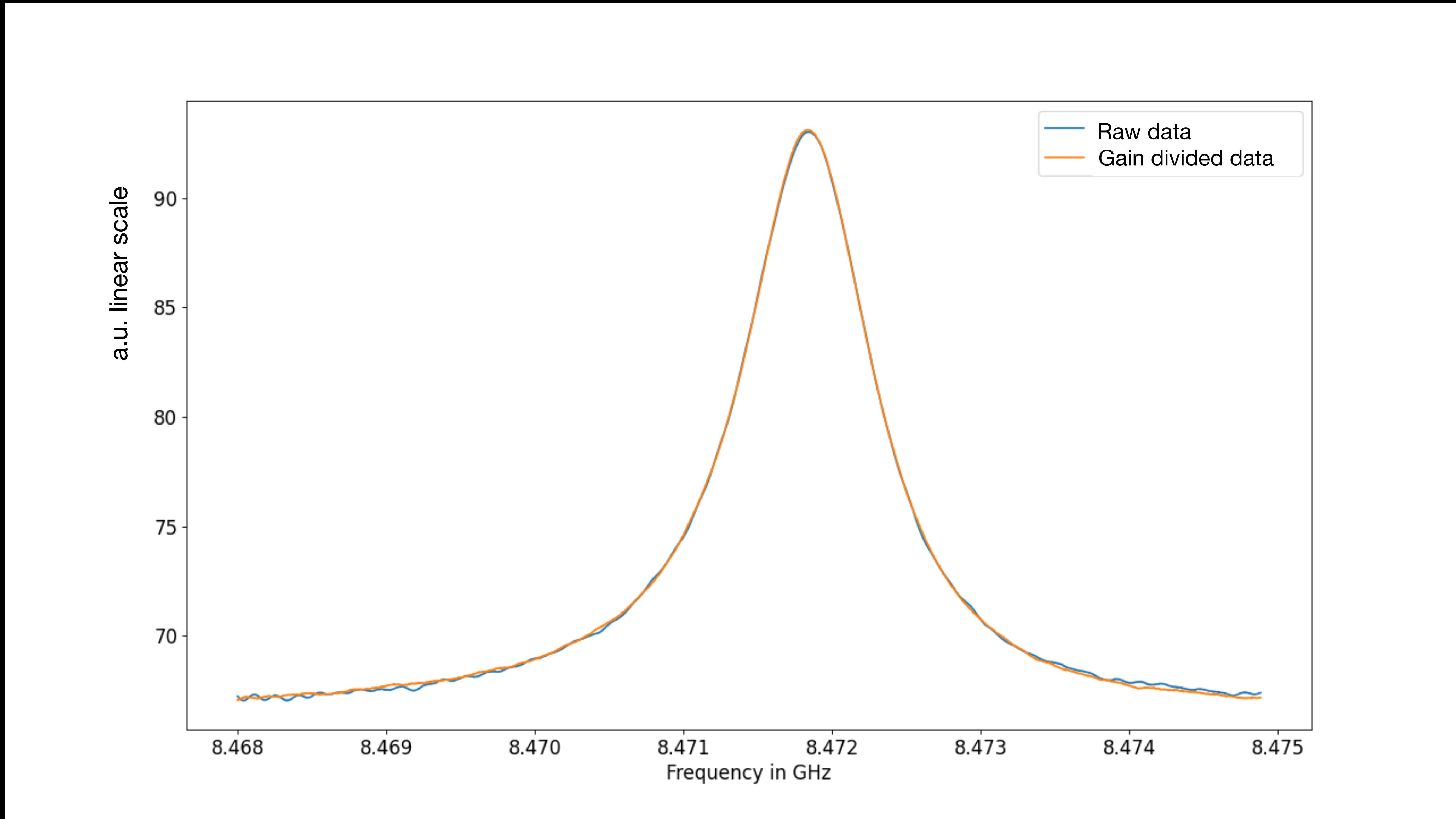
- Basic approach:

  - Integration

  - Division by gain-curve

  - Cavity signal well described by Lorentz function

    - Residual < 10^{-3} at peak



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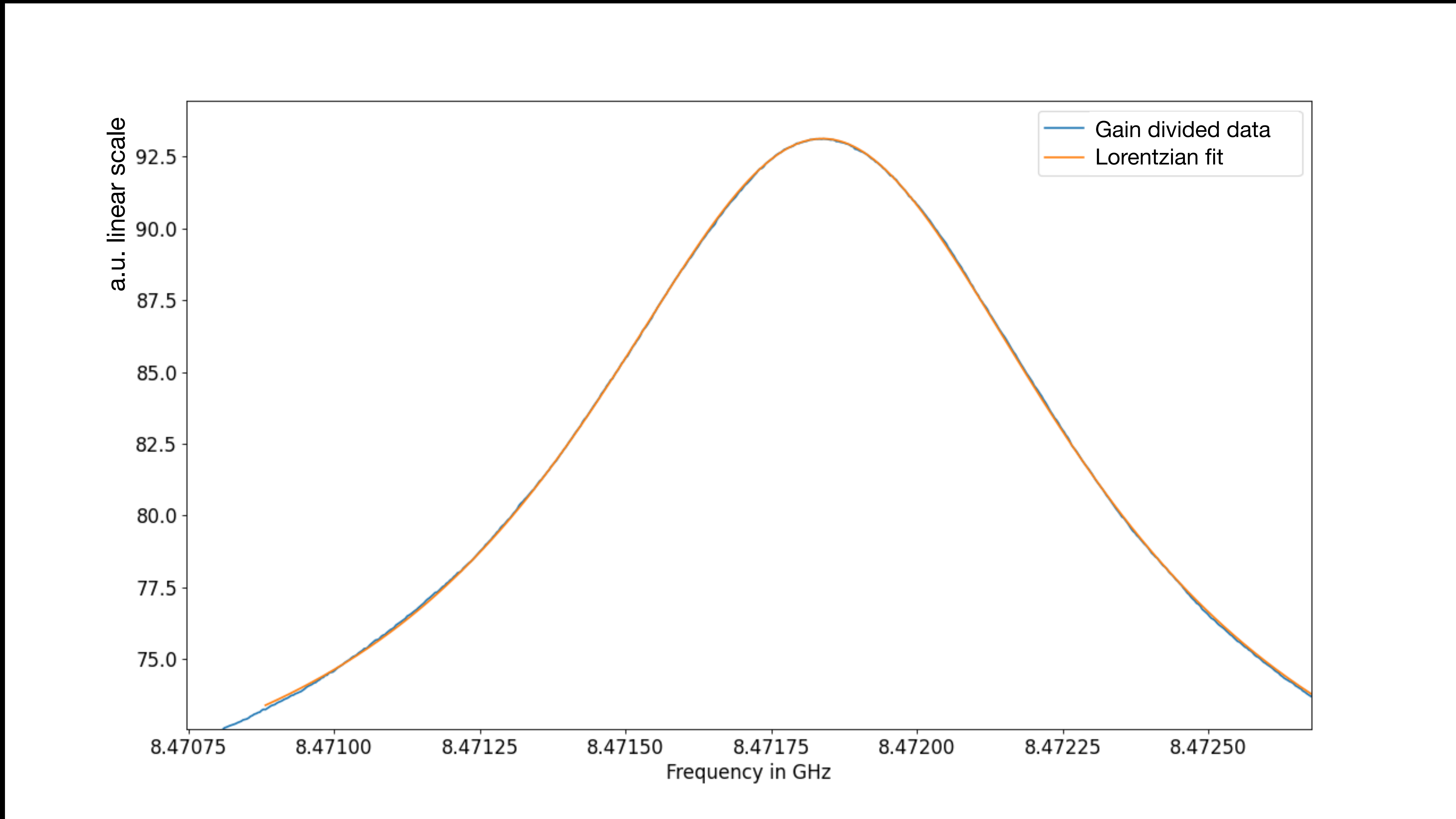

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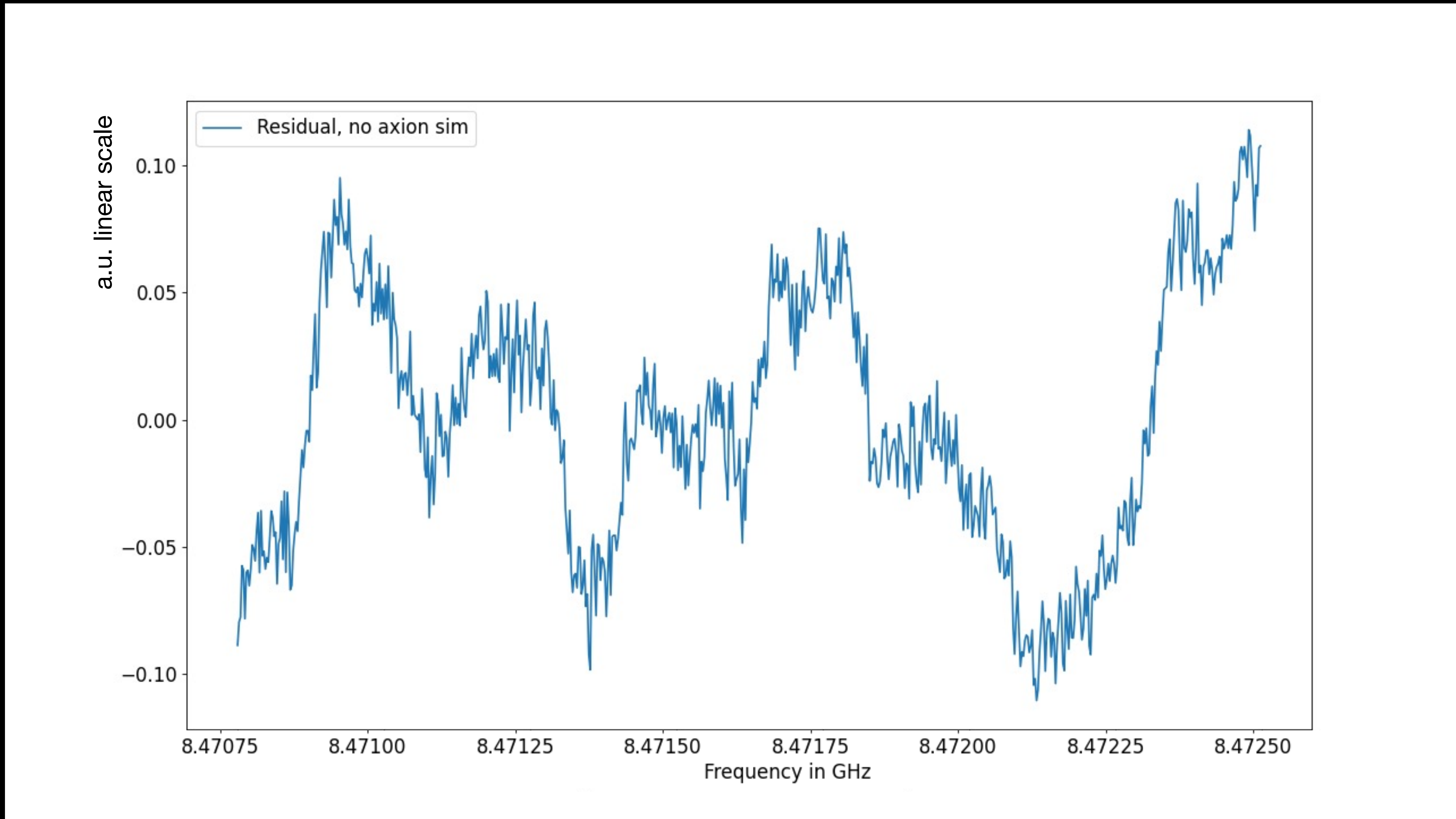
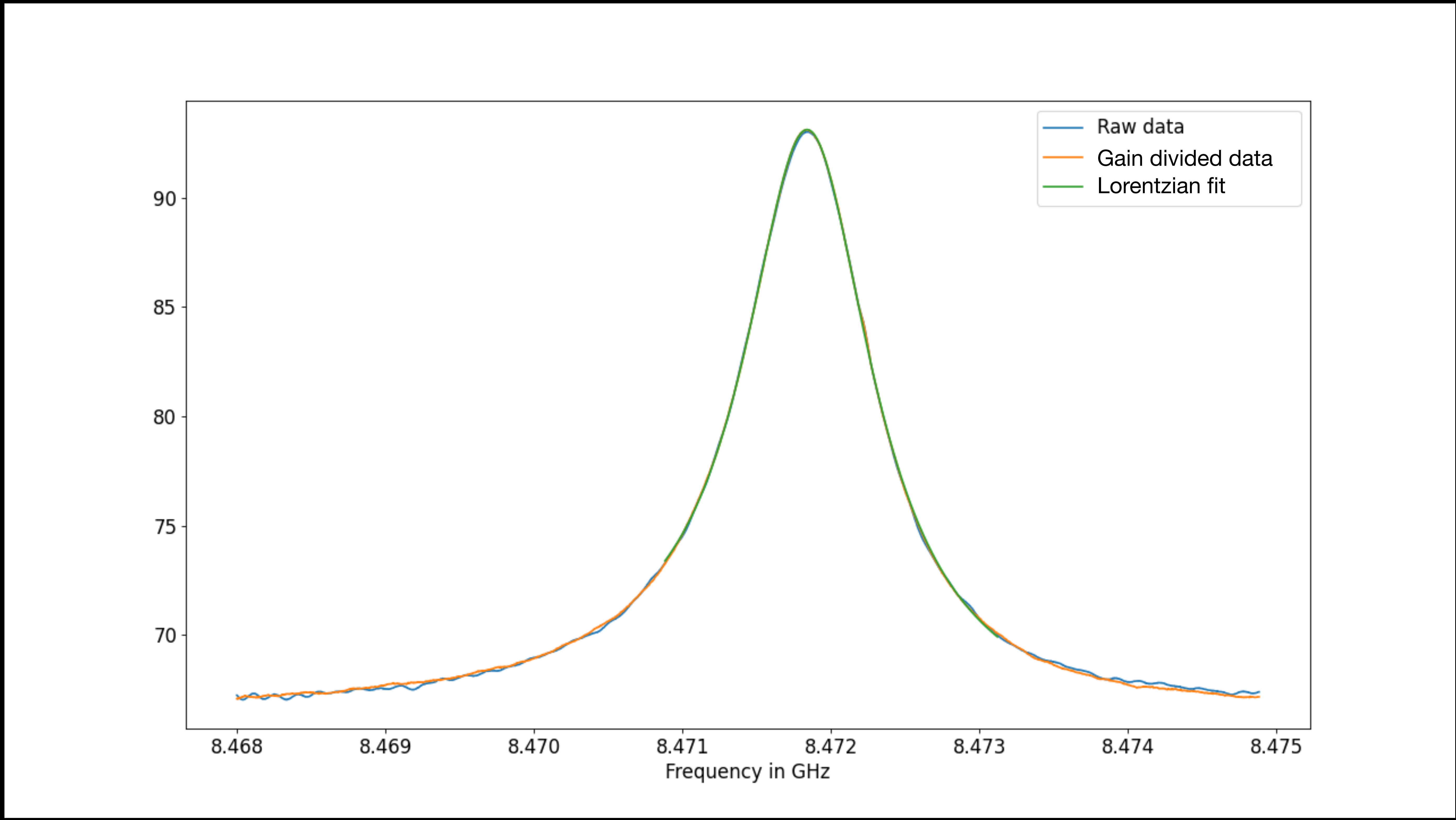


Data Analysis - signal injection

- Axion signal injected into readout data
  - 1% of cavity thermal noise amplitude
- Subtraction of Lorenzian fit from corrected spectra
  - Removing cavity structure
- Peak finding in residual histogram



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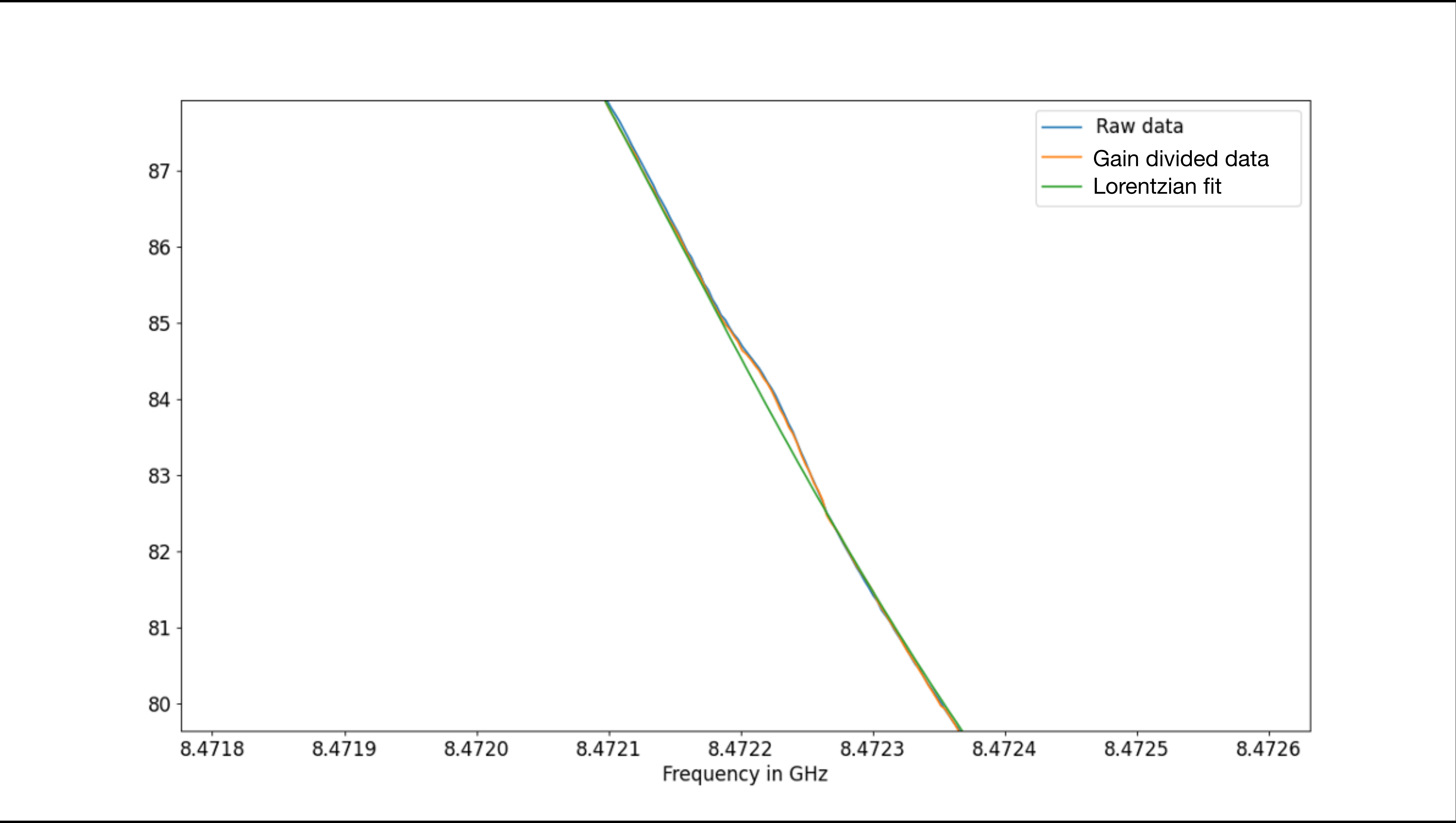

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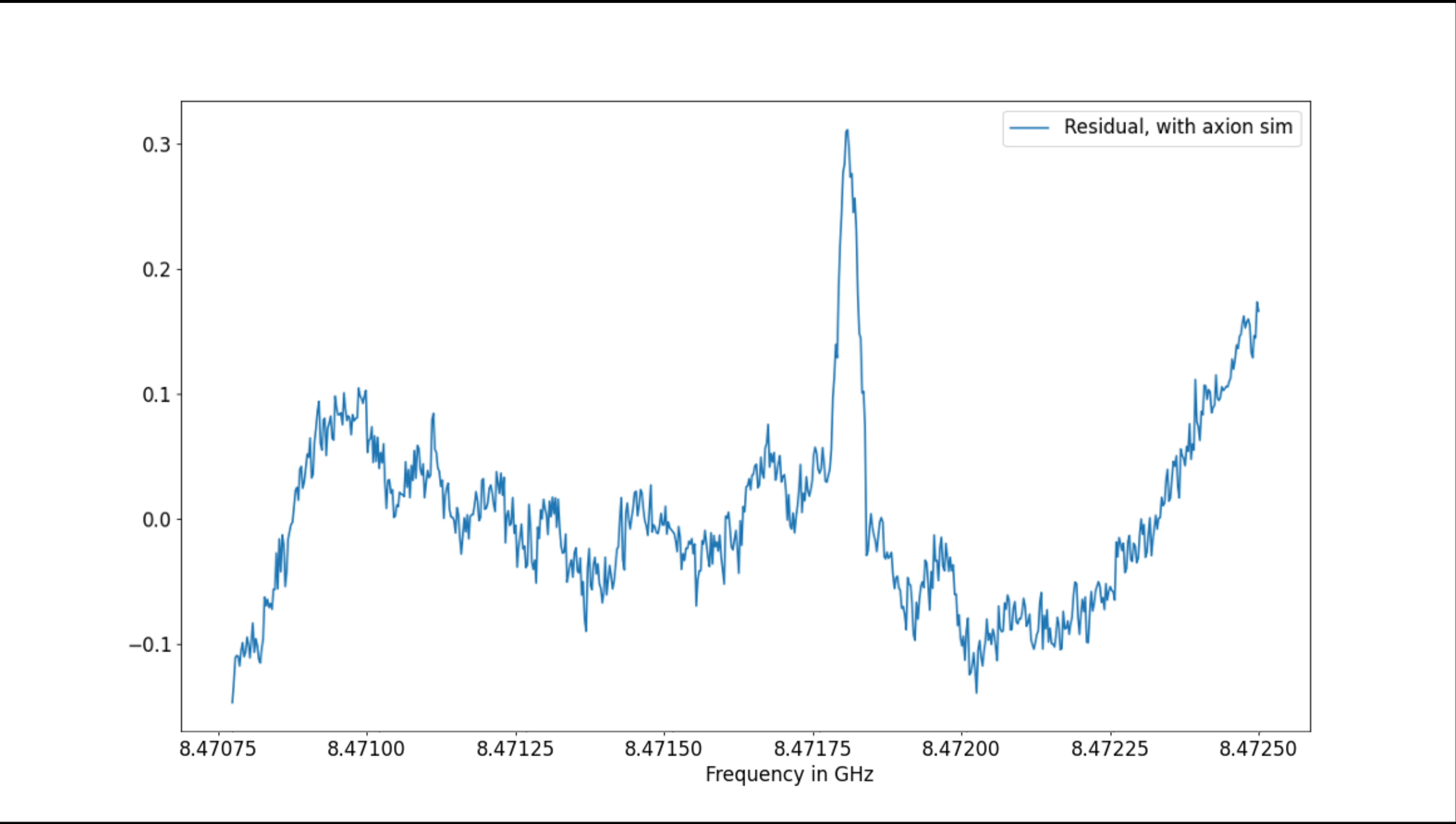

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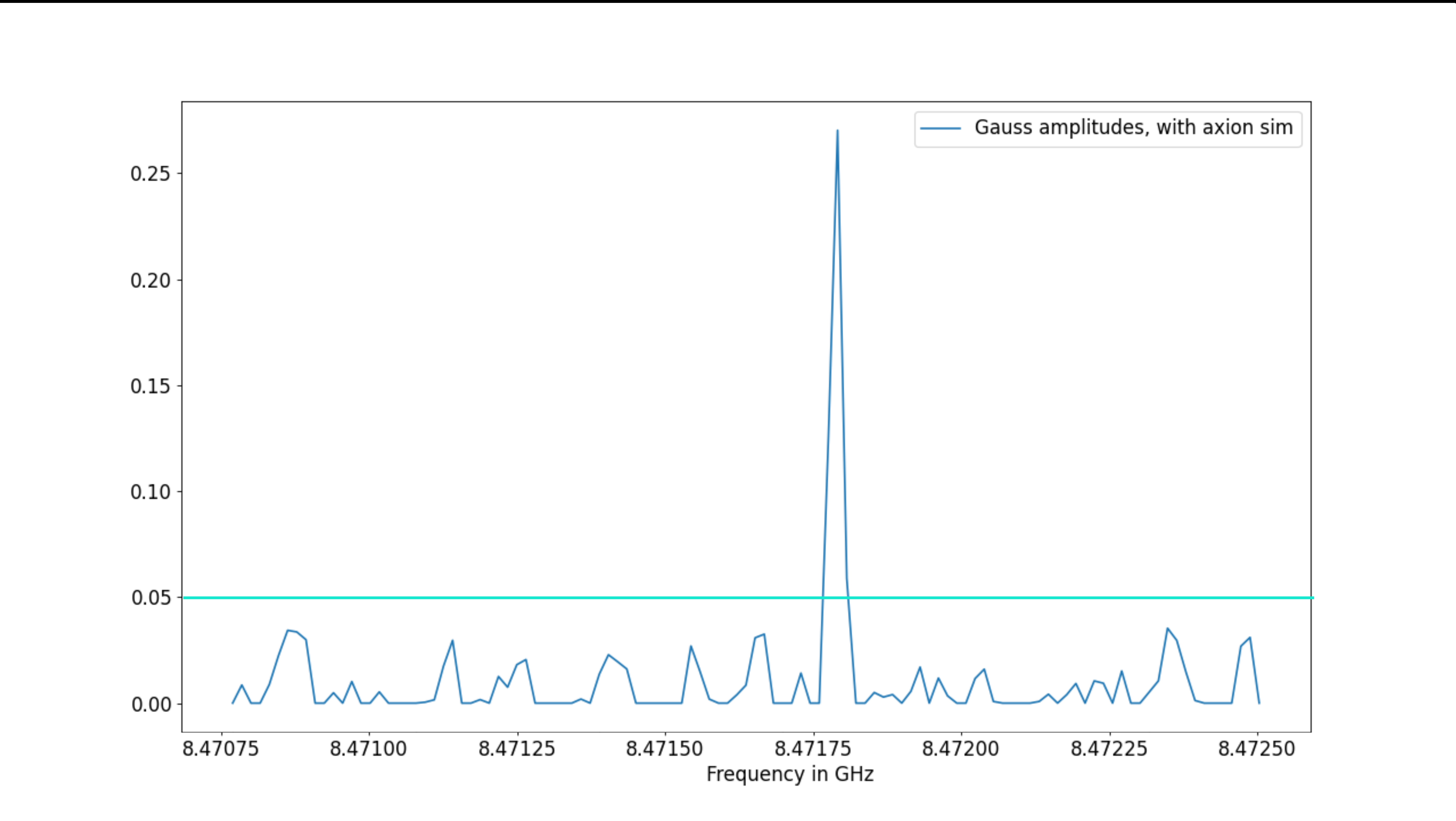
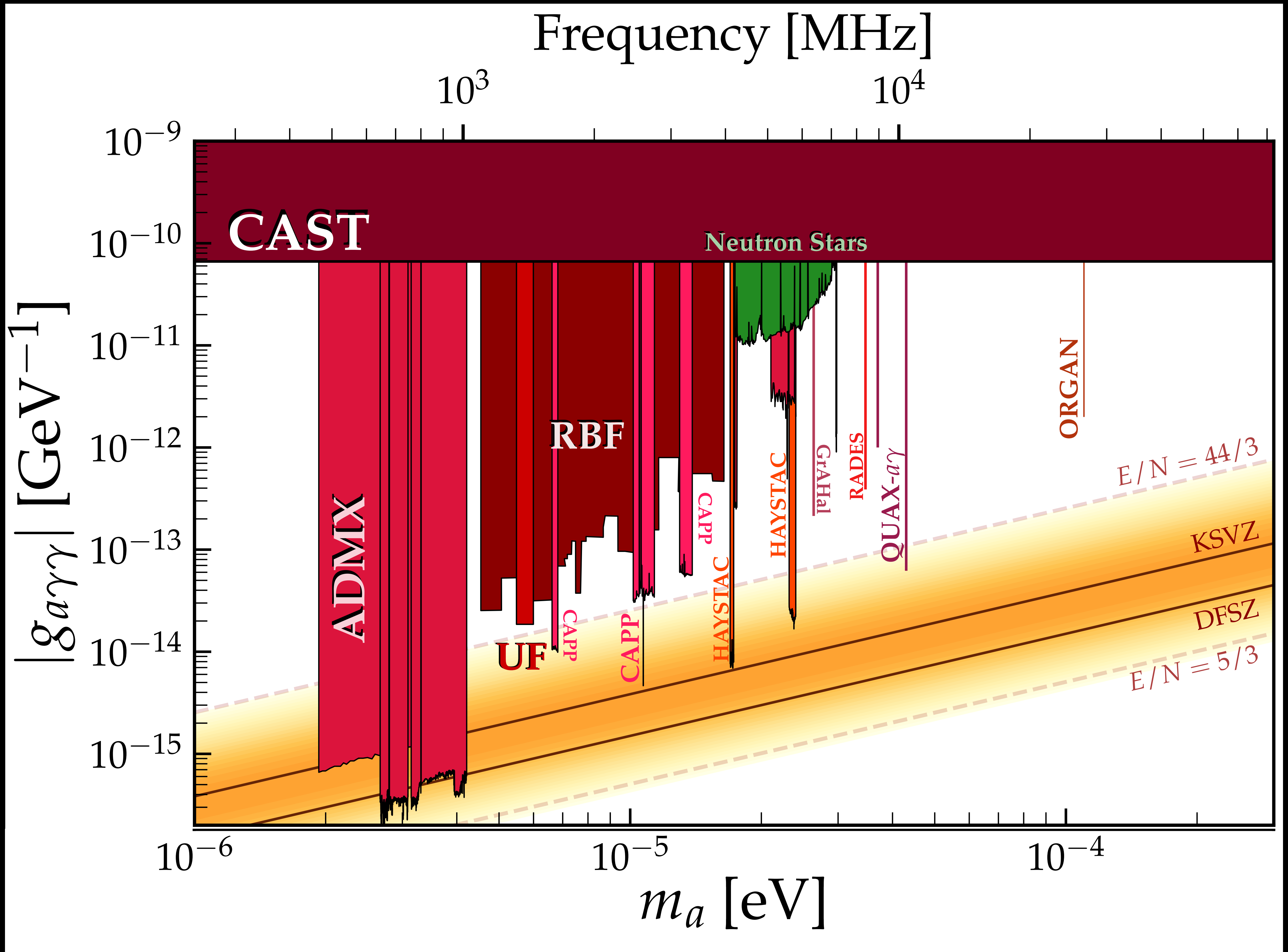


Expected Sensitivity

- First data taking at LHe temperature, non-taxable cavity



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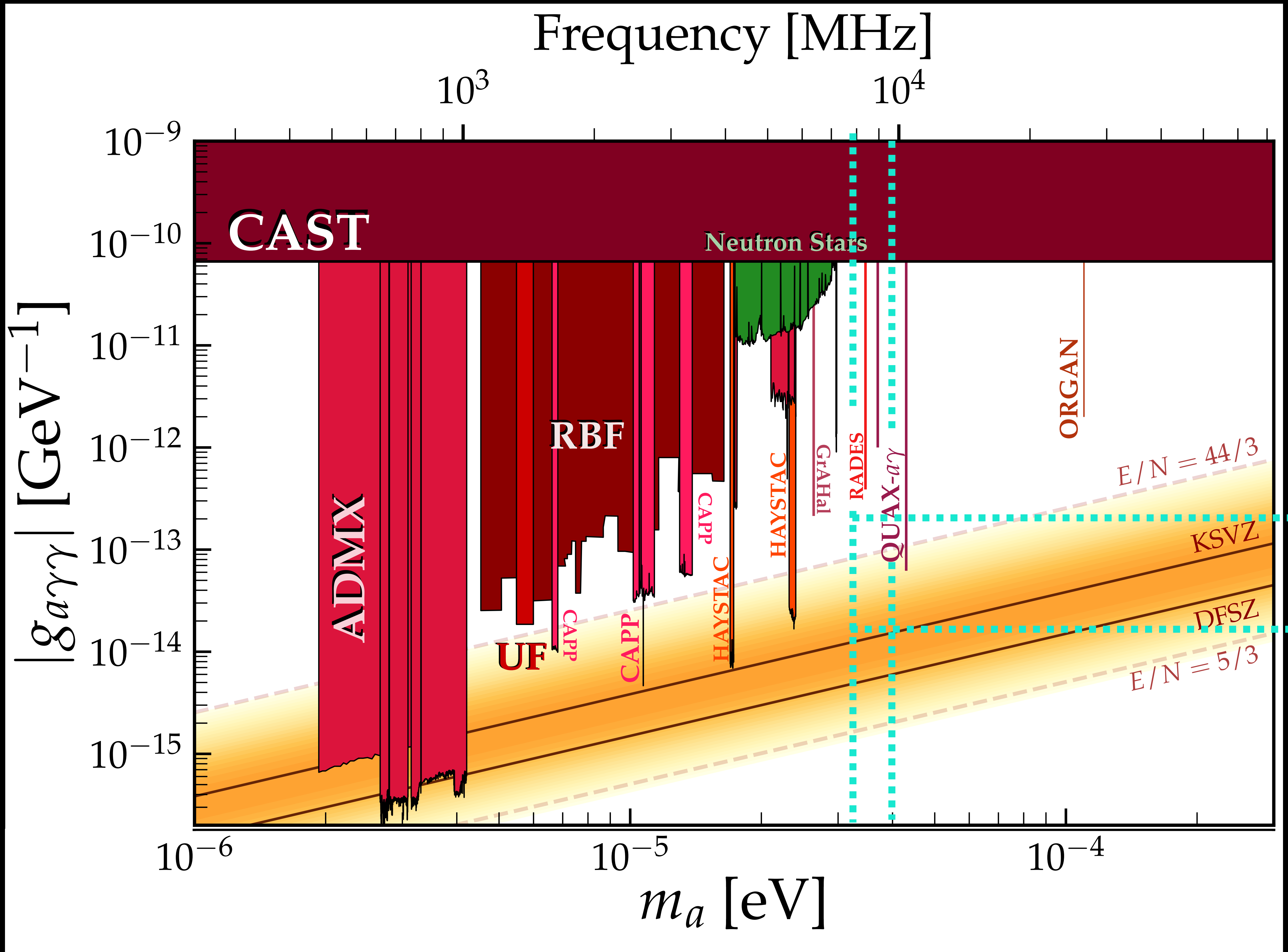
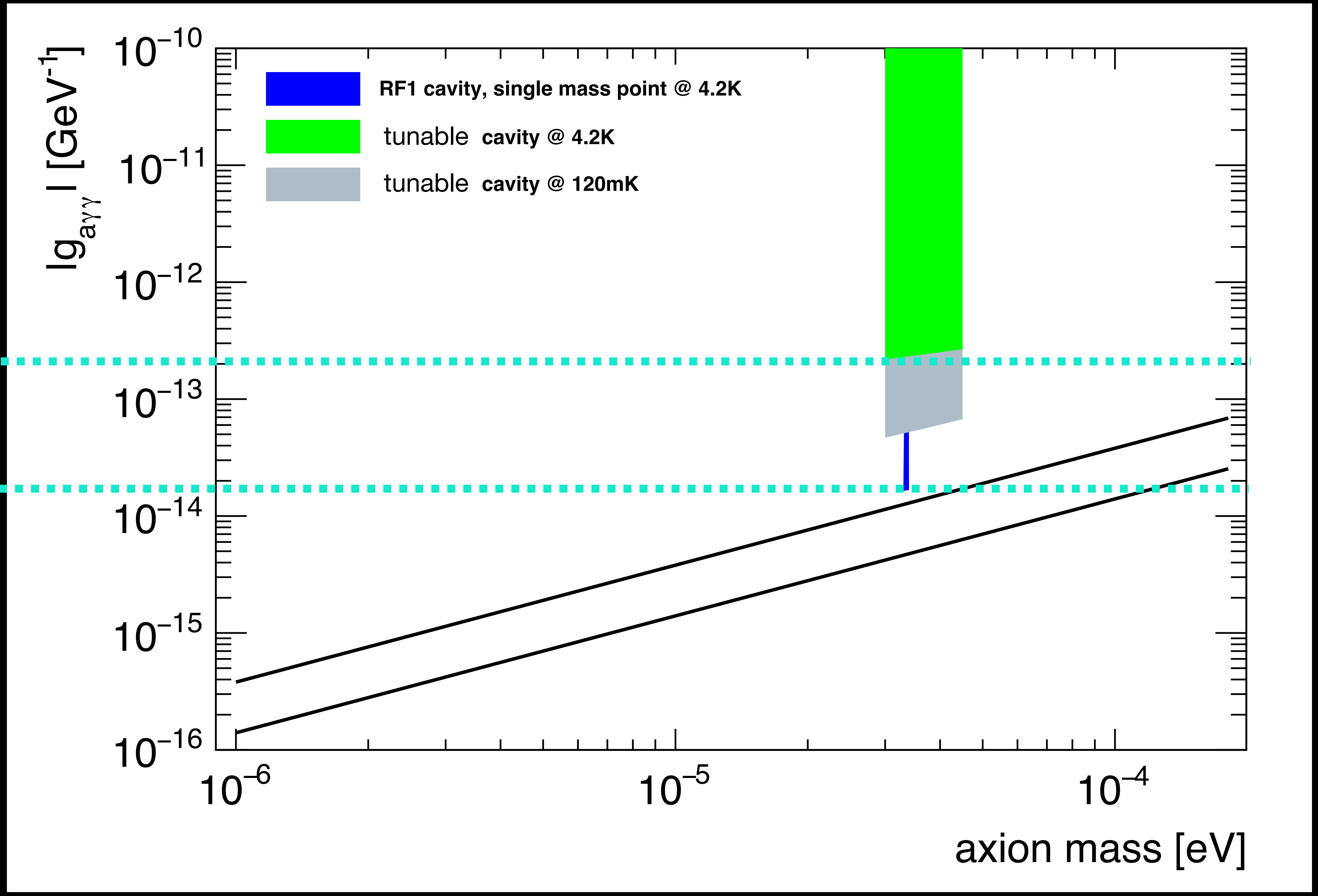




Outlook

- Fast turnaround times:
  - Cavity installation & cool-down: 1/2 day
  - Good setup for cavity R&D

- Study superconducting cavities:
  - Within the **RADES** collaboration
  - Study behaviour of SC cavities in 14T B-Field
  - First SRF cavity expected for Q4 measurement

- Tunable cavities
  - Design of tunable cavity ongoing

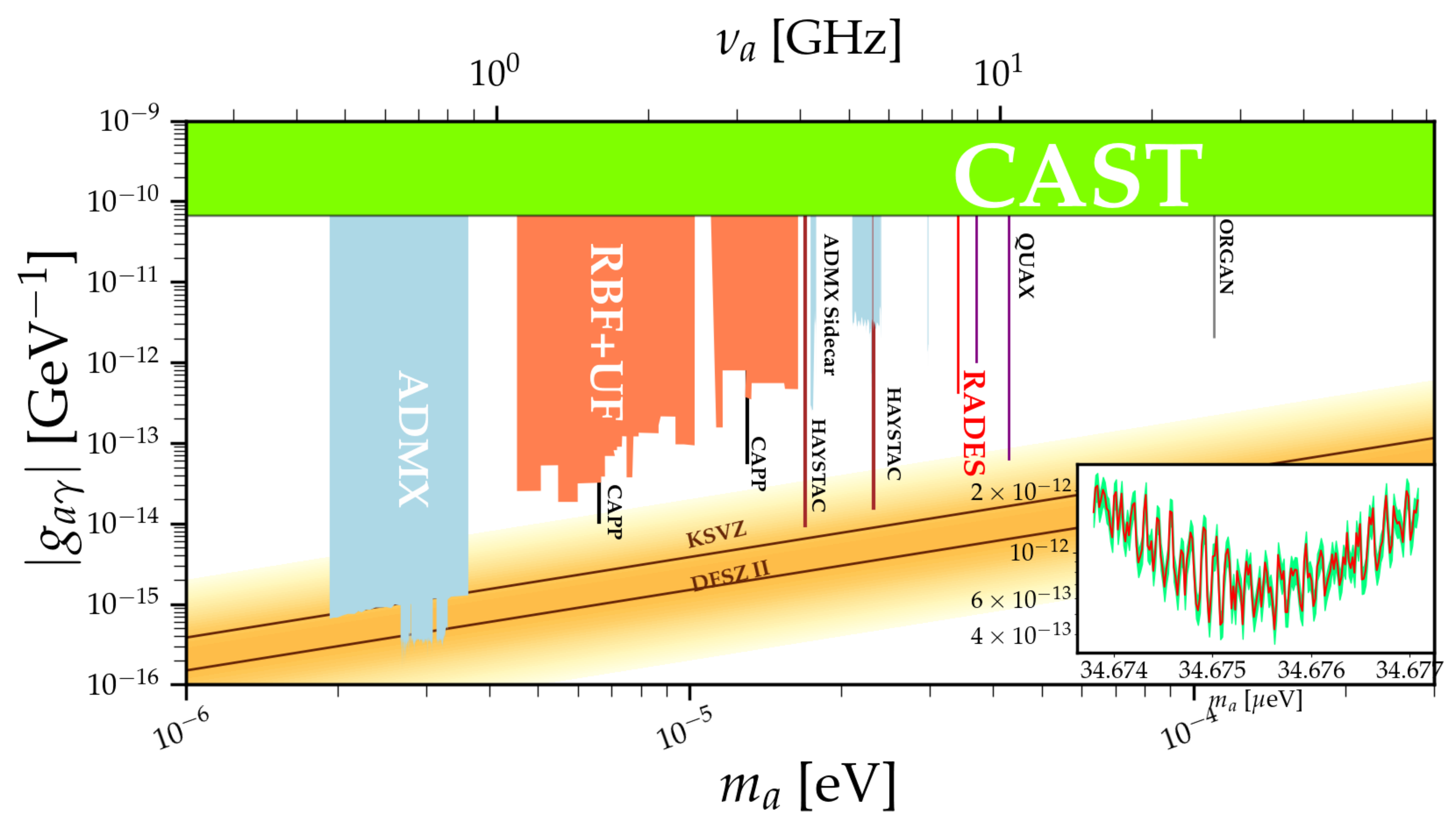
- Magnet and Cryostat operational in Q4
- First physics data taking in December
- First physics result at fixed frequency early next year

BACKUP

RADES Activities

A RADES experiment

- Physics results from the CAST-RADES run published
  J. High Energ. Phys. 2021, 75 (2021)



- More data collected the CERN's SM18 magnet facility:
  - Data analysis ongoing

- Development of new cavities & readout for the BabyIAXO setup

- https://arxiv.org/abs/2204.11919
- https://arxiv.org/abs/2110.01296
- https://arxiv.org/abs/2111.14510

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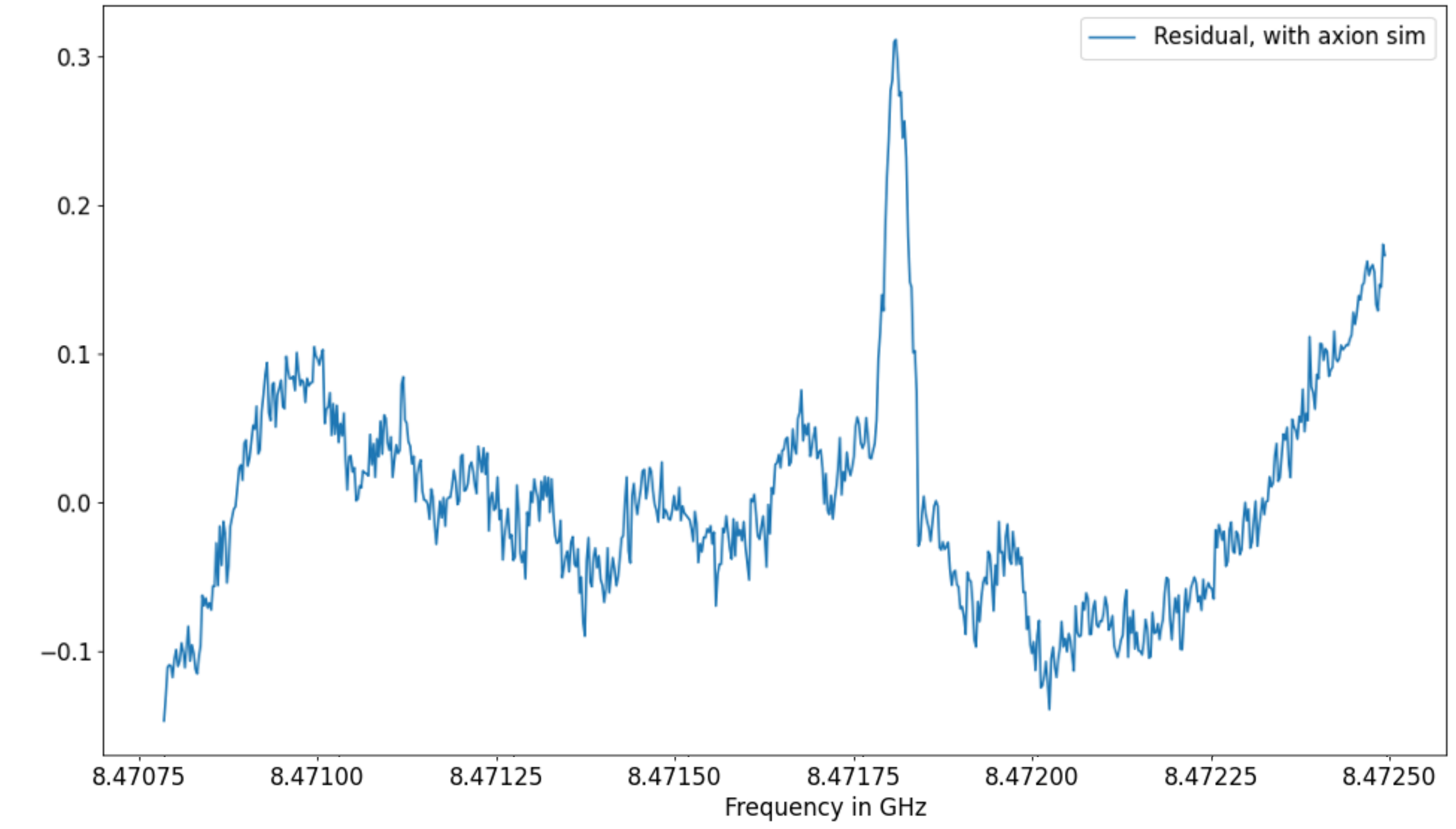
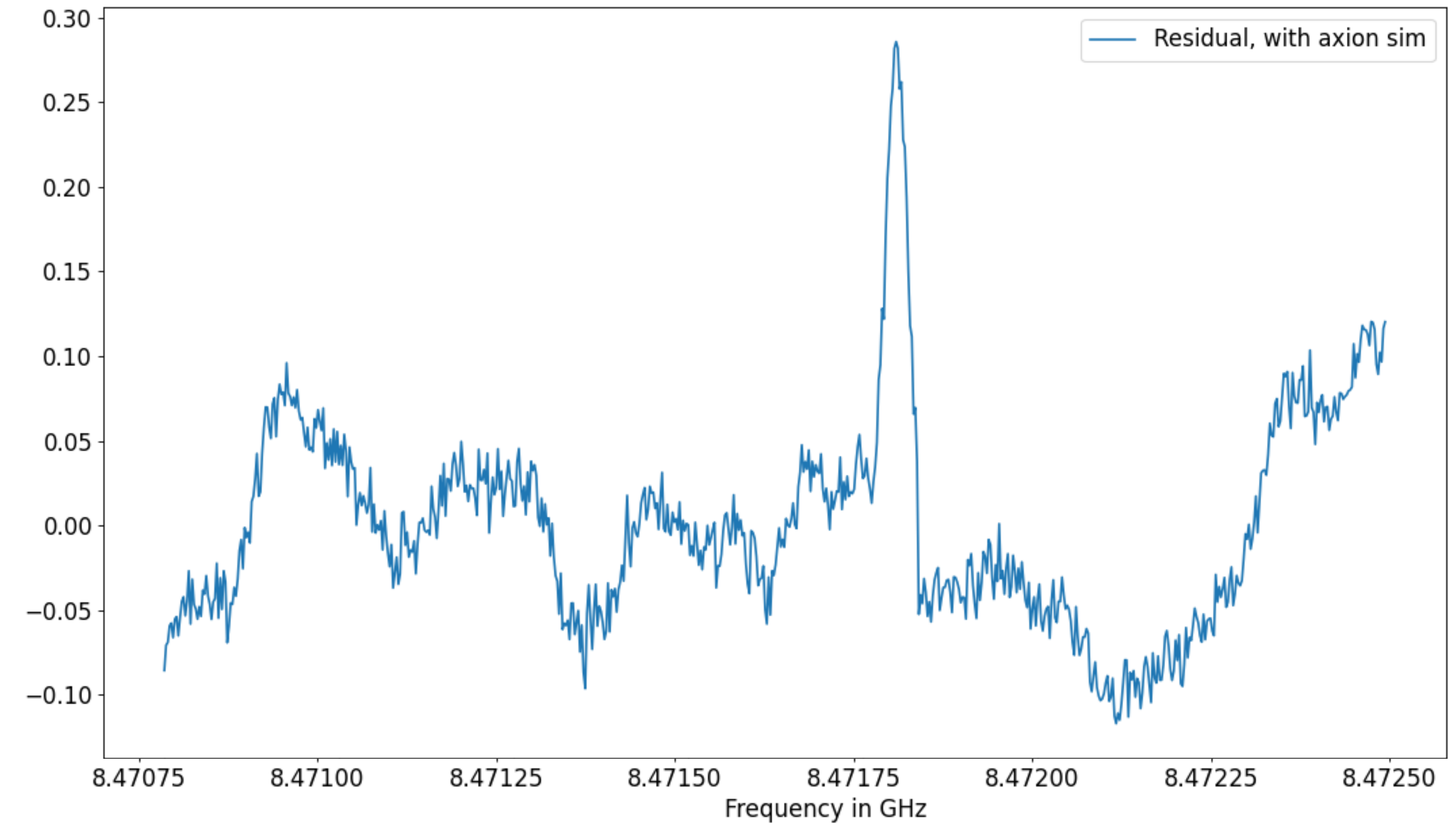


Subtraction of reference run



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- Comparable results
  - Reference spectrum subtraction slightly preferable

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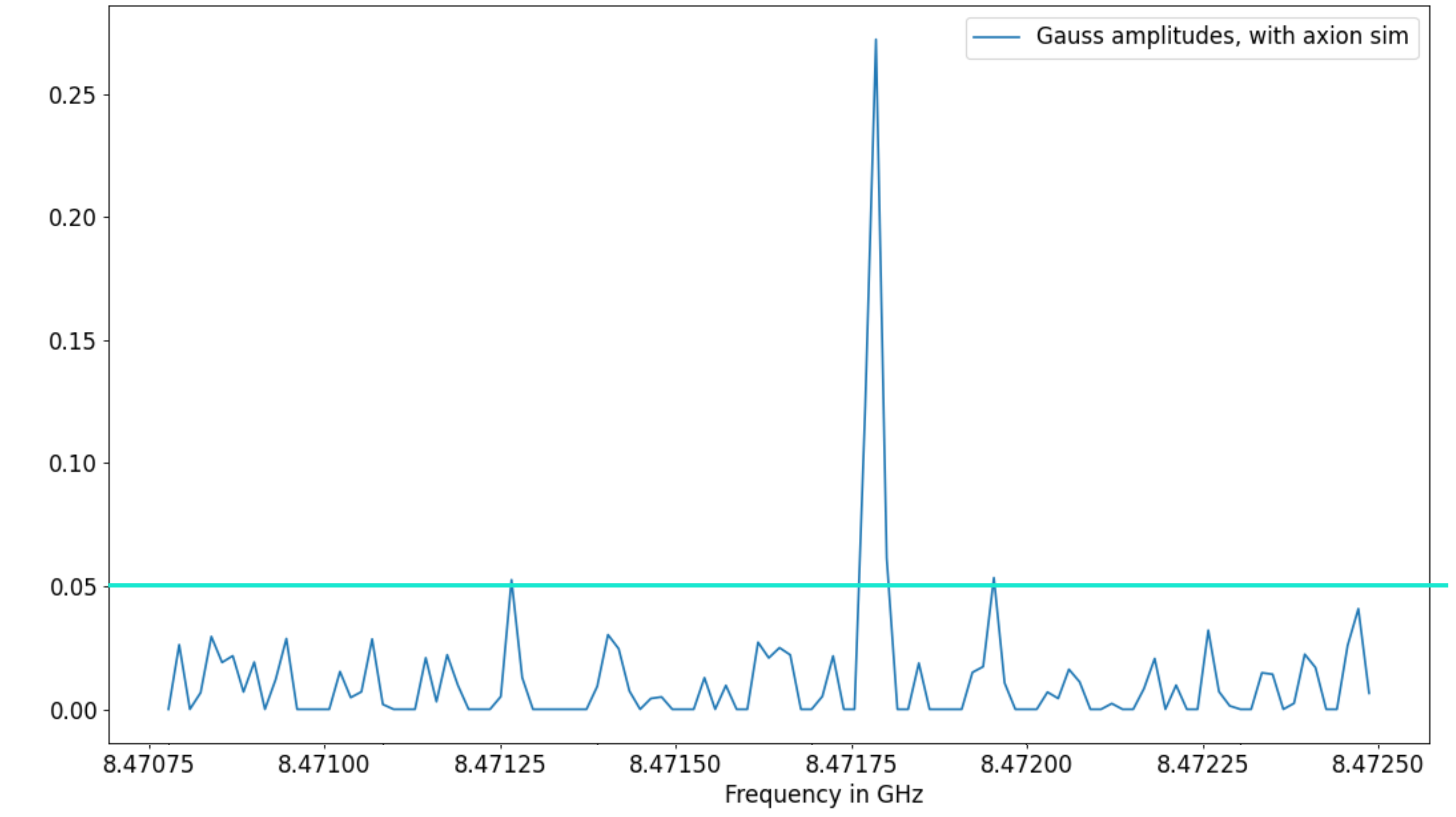

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