# Wave-like Dark Matter on the Horizon: Searching for the DFSZ axion with the ADMX Haloscope

## Run 1C Data-Taking Operations and Beyond

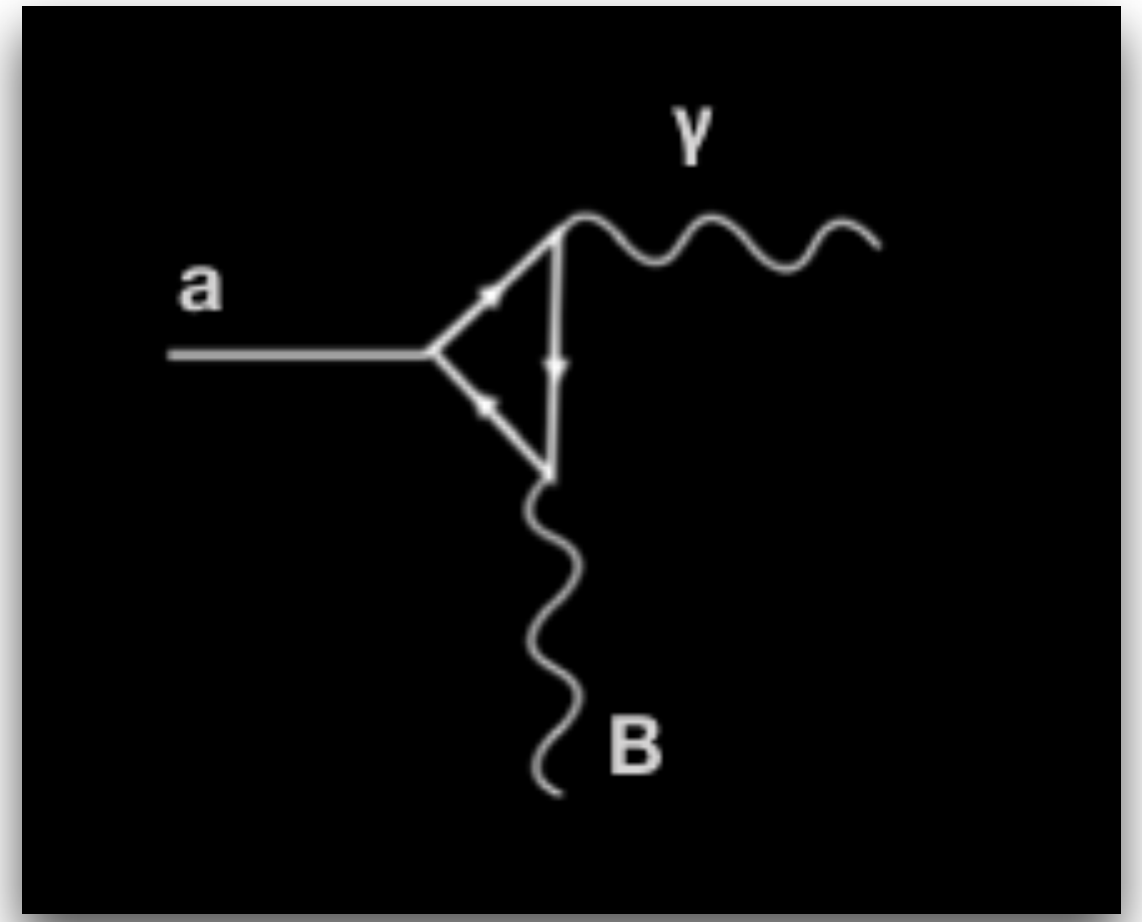
Chelsea Bartram 01/27/2021
University of Washington

# The QCD Axion


- Subset of wave-like dark matter.
- Solves the Strong CP Problem.
- 1-100 μeV mass range can to constitute entirety of dark matter.
- Two classes of models:
  - **KSVZ (Kim-Shifman-Vainshtein-Zakharov)**:
    - couples to quarks
    - Range of $g_\gamma$ values, typically $g_\gamma$=-0.97 used
  - **DFSZ (Dine-Fischler-Srednicki-Zhitnitsky):**
    - couples to quarks and leptons
    - Range of $g_\gamma$ values, typically $g_\gamma$=0.36 used

Helen Quinn

Roberto Peccei
1942-2020




Inverse Primakoff Effect

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**Hardest to detect!**

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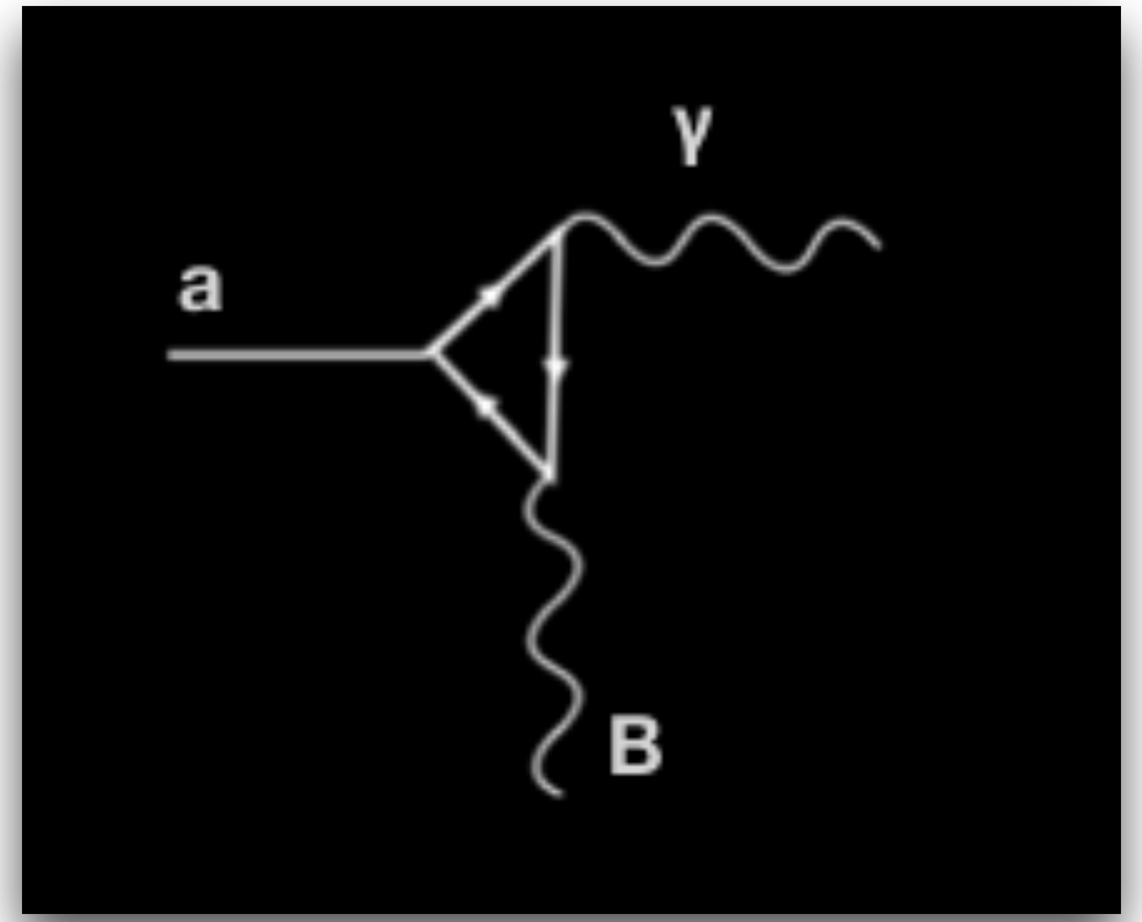
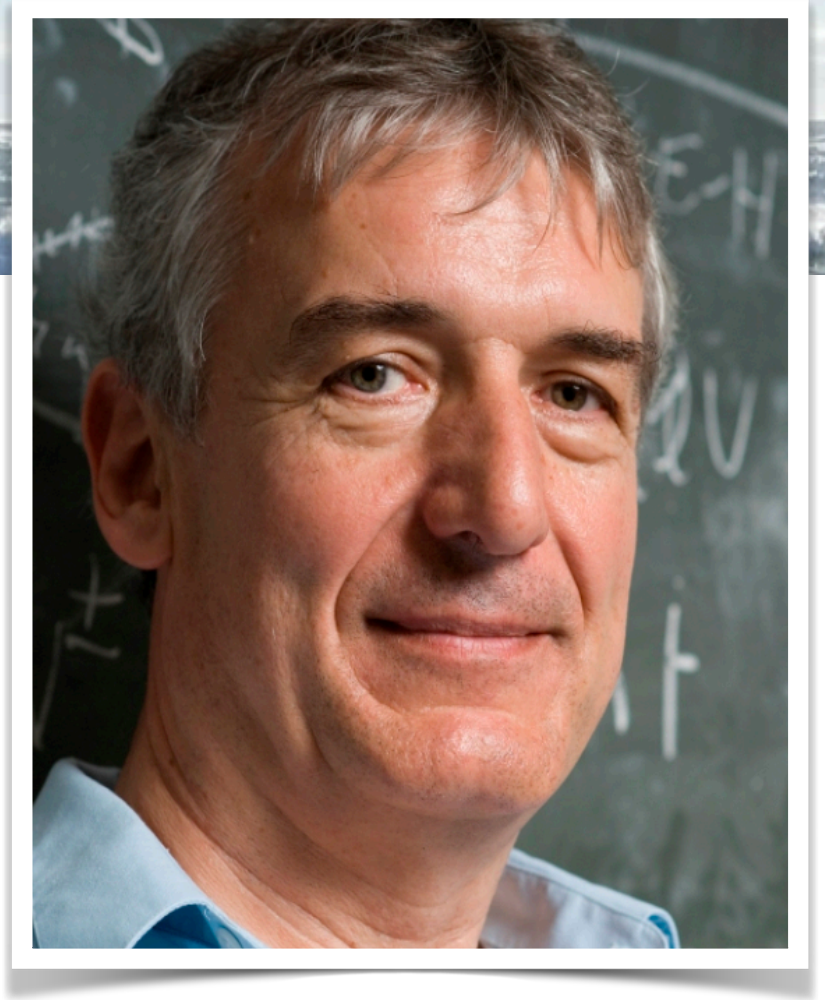



Inverse Primakoff Effect

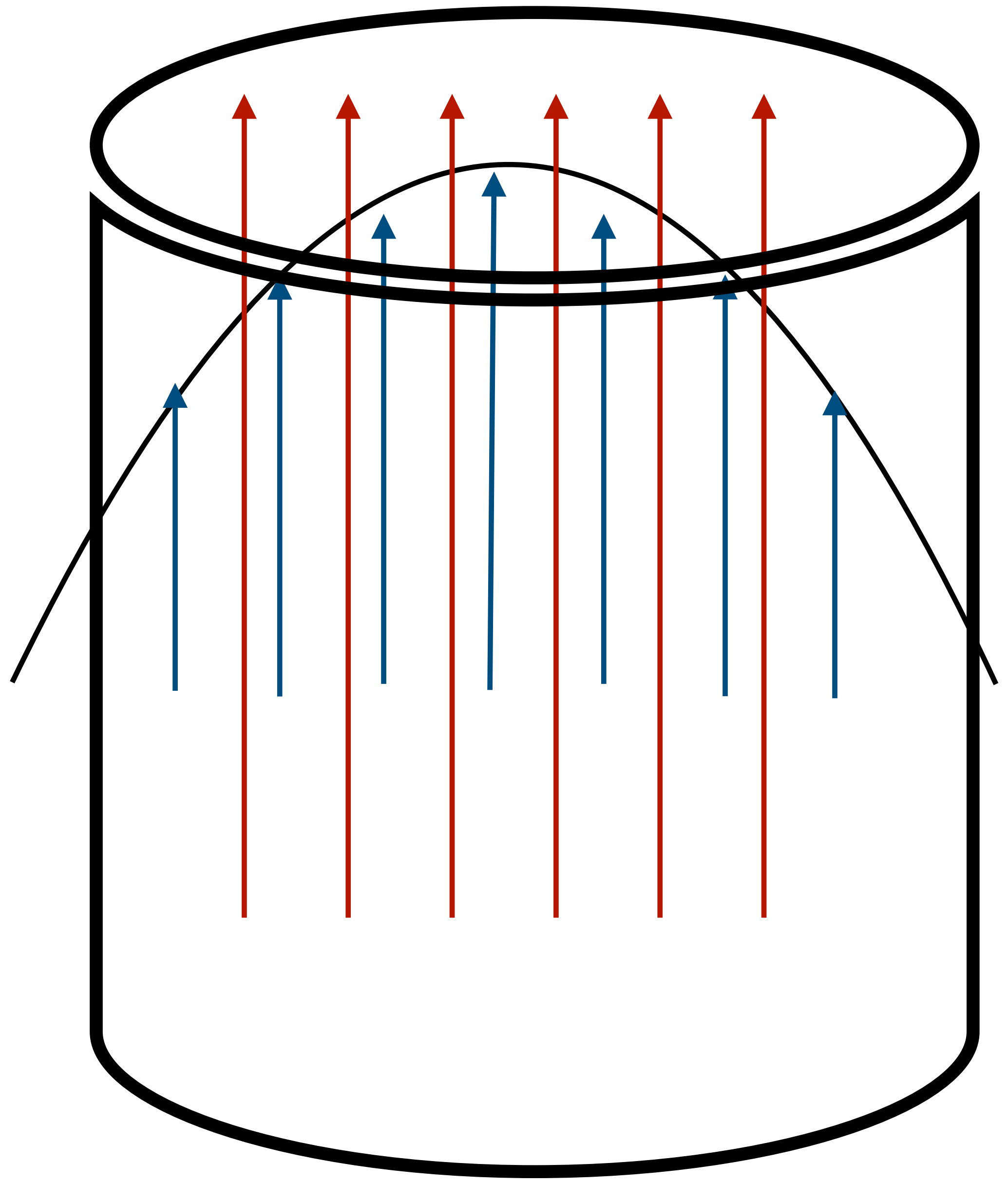
# How to detect them?



## Resonant cavity axion haloscope

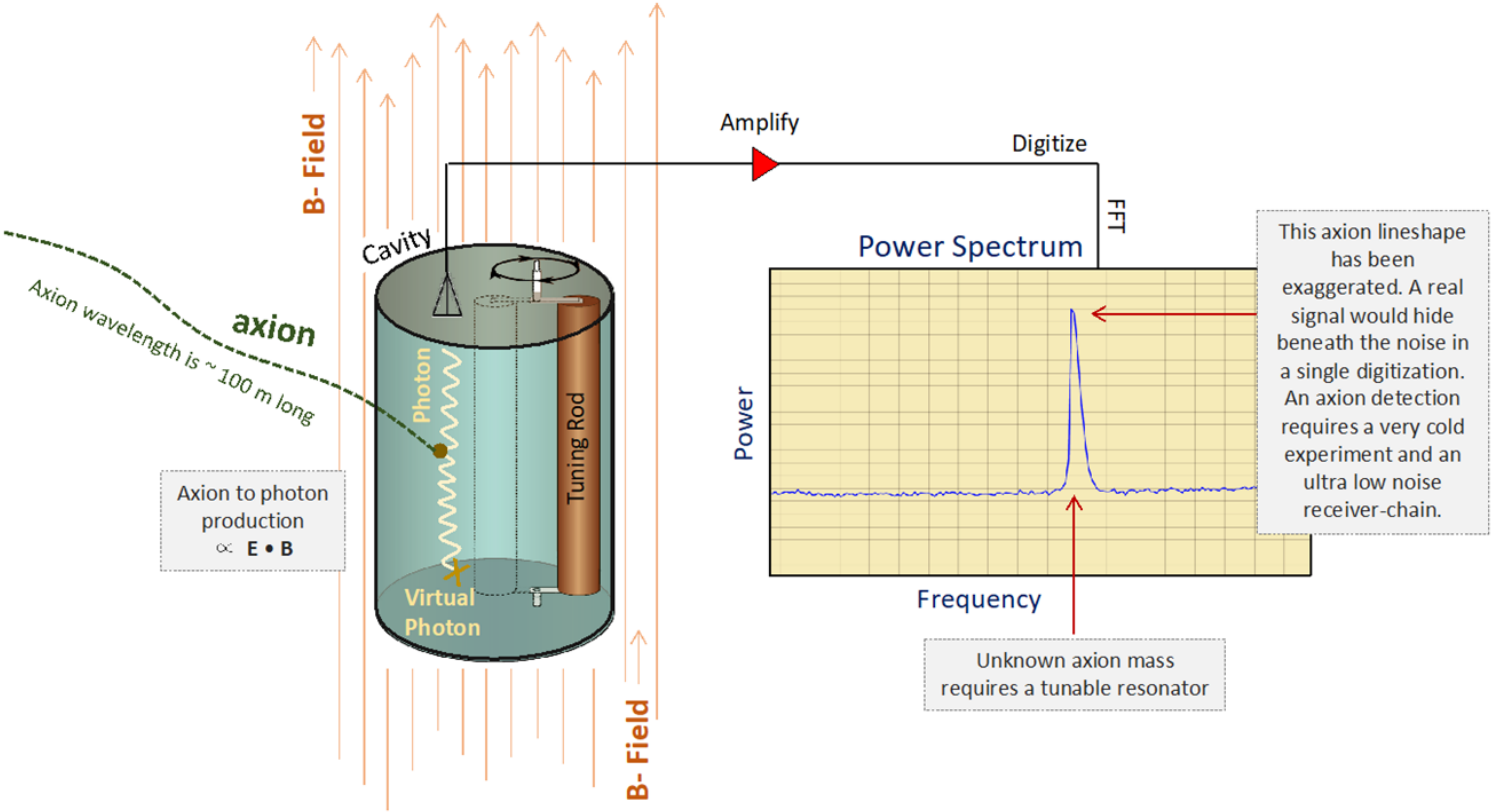
- Proposed by Pierre Sikivie.
- Uses the Inverse Primakoff effect.
- High quality factor ⟶ higher chance of axion to photon conversion.
- High overlap of magnetic and electric fields.

"Form Factor" $$C_{010} = \frac{|\int dV \vec{B}_{ext} \cdot \vec{E}_a|^2}{B_{ext}^2 \int dV \epsilon_r |\vec{E}_a|^2}$$



Red is cartoon magnetic field
Blue is cartoon electric field

# Resonant Cavity Axion Haloscope



# Axion Dark Matter eXperiment (ADMX)

- Extremely sensitive AM receiver attached to microwave resonator in a magnetic field [7].
- ADMX is the only haloscope that is sensitive to DFSZ axions!
- One of 3 “Gen-2” Dark Matter Projects.
- ADMX is currently a global collaboration of 11 institutions.

Sponsors

Primary Sponsor

HEISING - SIMONS FOUNDATION

THE UNIVERSITY OF WESTERN AUSTRALIA

Pacific Northwest NATIONAL LABORATORY

Berkeley UNIVERSITY OF CALIFORNIA

Lawrence Livermore National Laboratory

UF UNIVERSITY of FLORIDA

The University Of Sheffield.

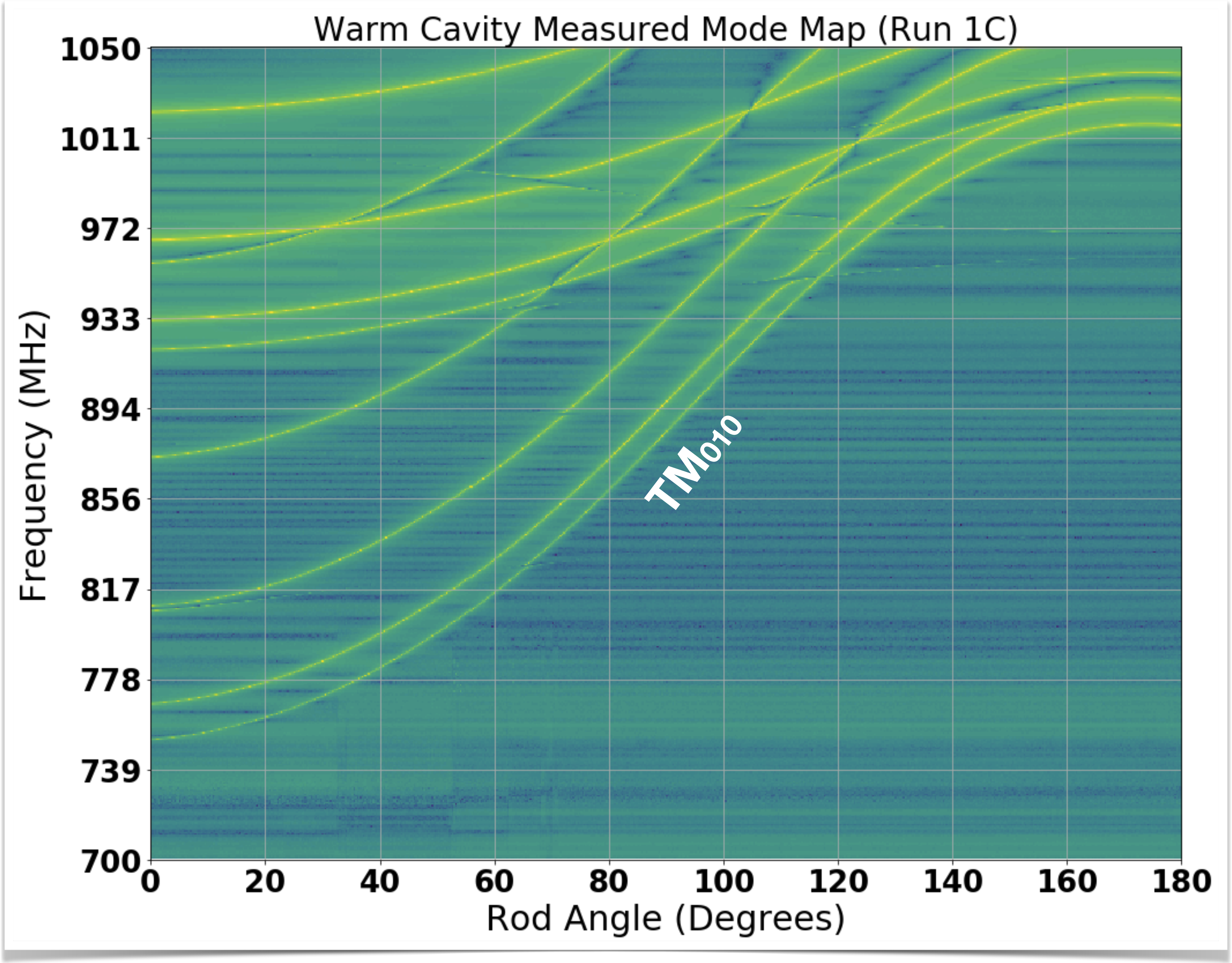
Fermilab

Los Alamos NATIONAL LABORATORY

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

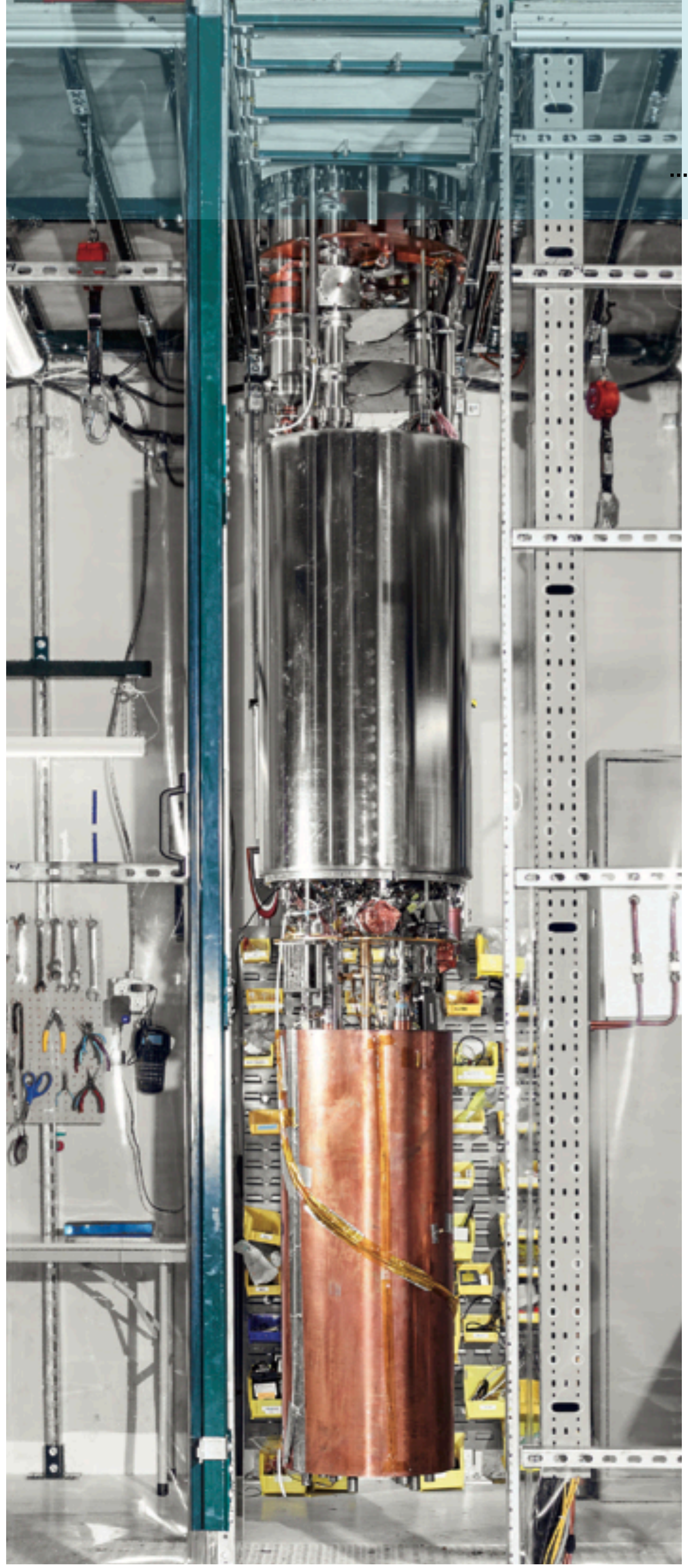
# Run 1C Science Goals

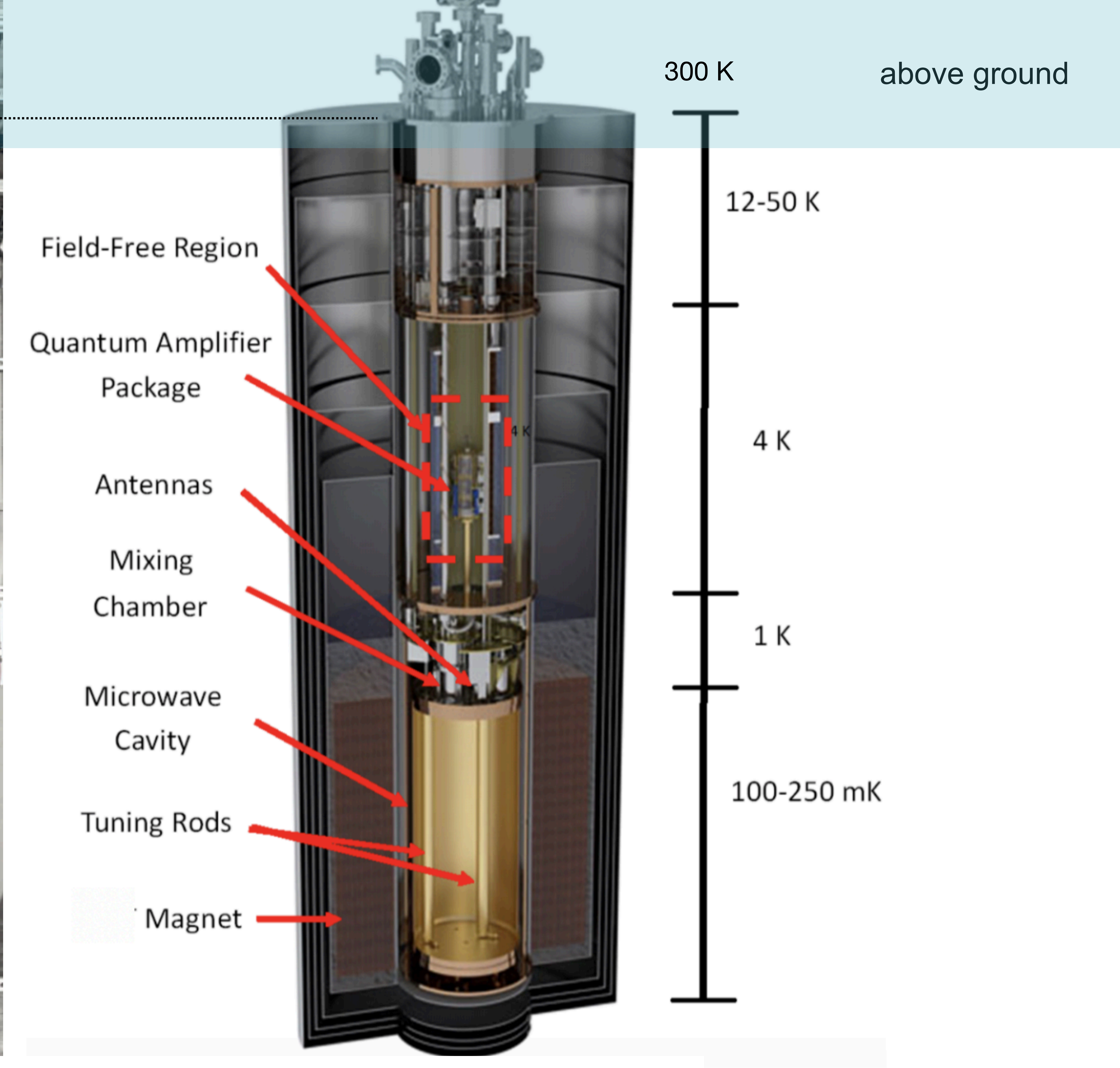
- Target Frequency (Mass) Range: 780-1010 MHz (3.2—4.2 μev)
- Continued DFSZ sensitivity
  - Improve quality factor.
  - Improved understanding and operation of quantum amplifiers.
  - Improved noise temperature.
- Other upgrades:
  - Improved synthetic axion capabilities
  - New digitizer
  - Upgraded RF software



# ADMX

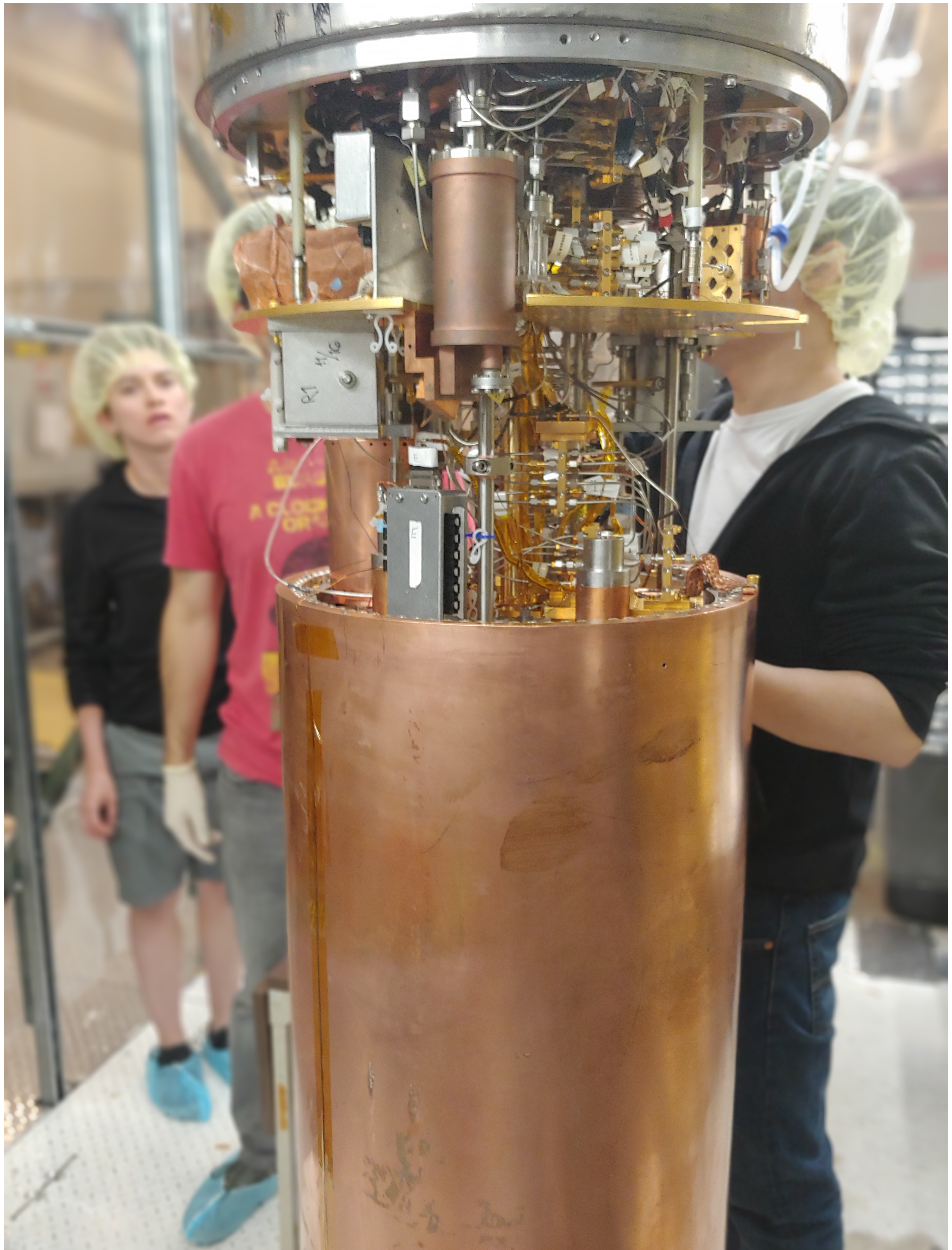
- Dil Fridge: Reaches ~100 mK
- Superconducting magnet:
  ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics





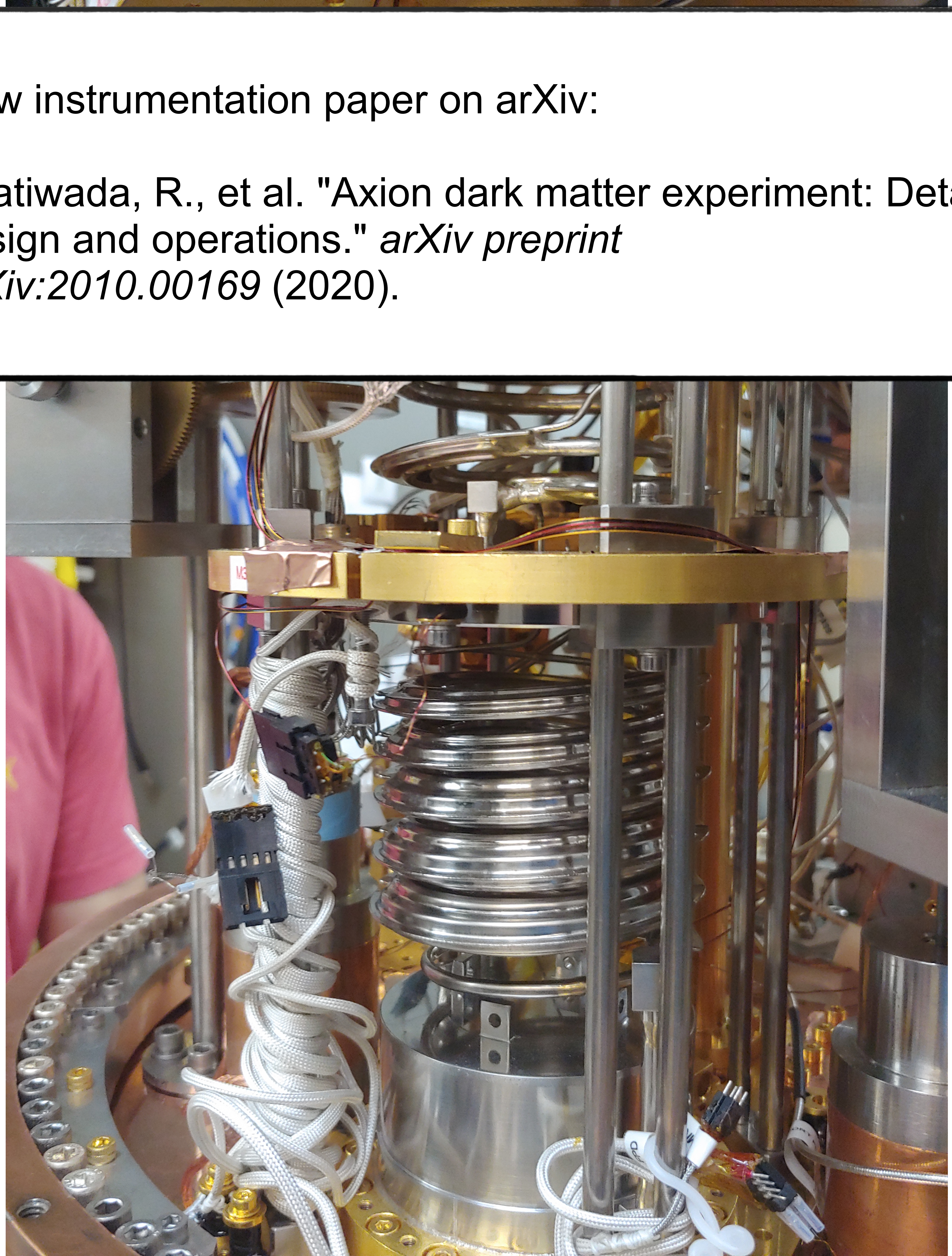

# ADMX Run 1C Commissioning

- Started in March 2019.
- “Insert” is developed on site in a clean room.
- Hardware builds off previous run.
- ~2 months commissioning, followed by rigging operation
- Extraction, debugging
- Continuous data-taking starting in March 2020 until recently



New instrumentation paper on arXiv:

Khatiwada, R., et al. "Axion dark matter experiment: Detailed design and operations." *arXiv preprint arXiv:2010.00169* (2020).




Calvin Klein
WASHINGTON

# Resonant Haloscope Scan Rate

$$\frac{df}{dt} \approx 543\,\frac{\mathrm{MHz}}{\mathrm{yr}} \left(\frac{B}{7.6\,\mathrm{T}}\right)^4 \left(\frac{V}{136\,\ell}\right)^2 \left(\frac{Q_l}{30000}\right) \left(\frac{C}{0.4}\right) \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{740\,\mathrm{MHz}}\right)^2 \left(\frac{\rho}{0.45\,\mathrm{GeV/cm^3}}\right)^2 \left(\frac{0.2\,\mathrm{K}}{\mathrm{T_{sys}}}\right)^2 \left(\frac{3.5}{\mathrm{SNR}}\right)^2$$

| Maximize | Can't Control | Minimize |
|---|---|---|
| • B Field<br>• Volume<br>• Quality Factor<br>• Form Factor | • Frequency<br>• Coupling<br>• Dark Matter Density | • System noise:<br>• Amplifier Noise<br>• Physical Noise |

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| • Form Factor | | |

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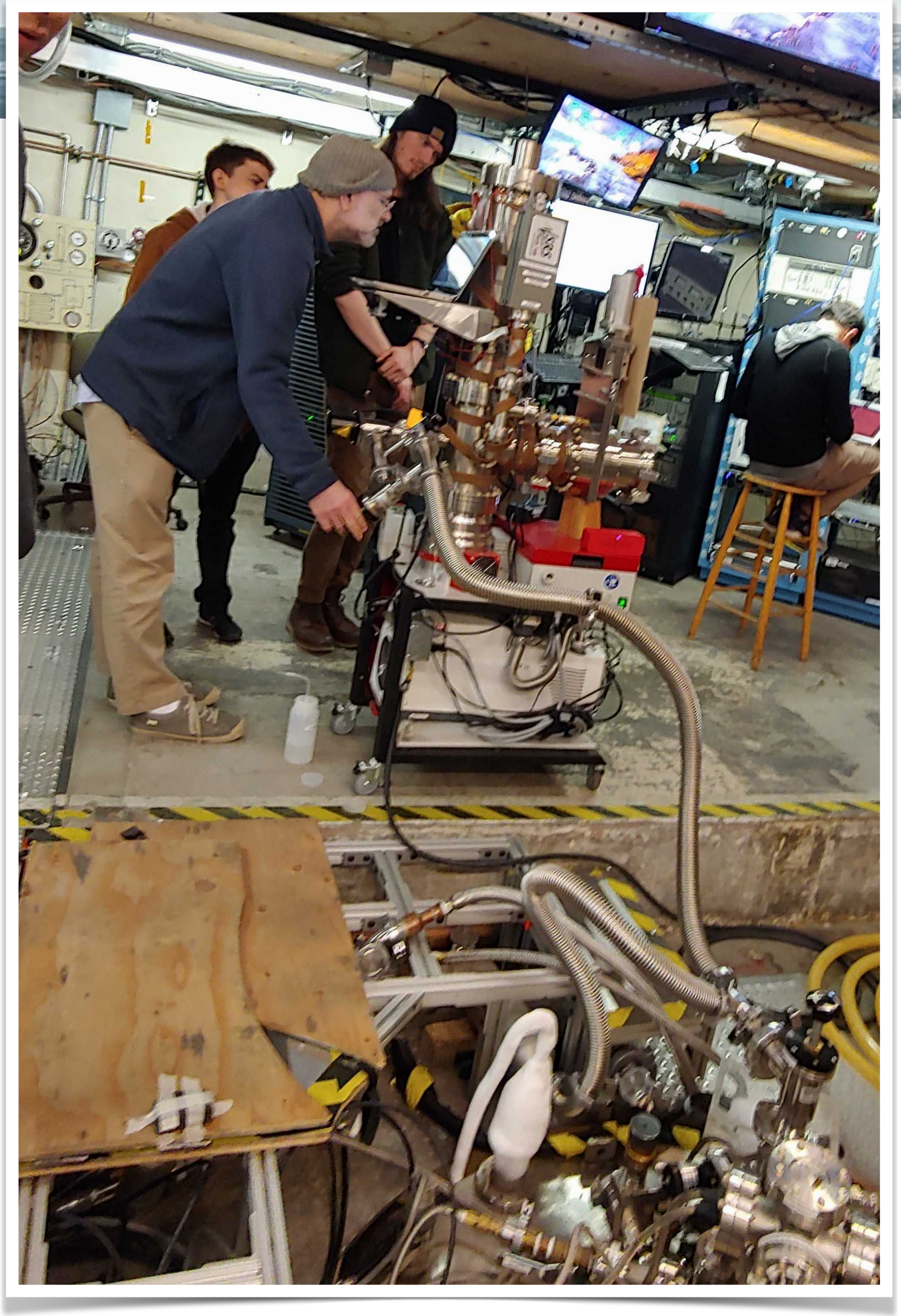
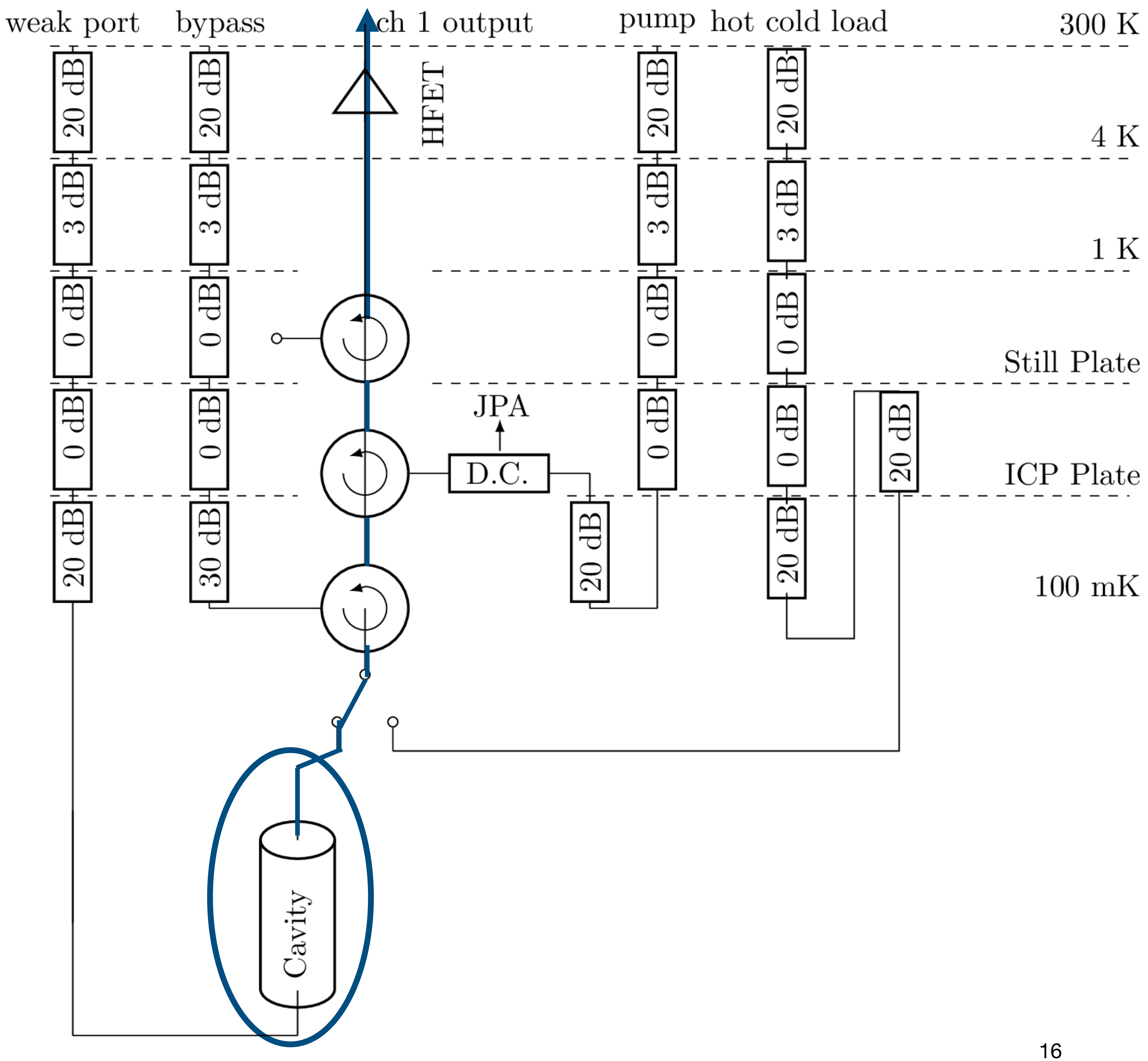
# Other Design Considerations

- Important design factors
  - Limit the attenuation on the line coming out
  - Add attenuation on the lines going in
  - Robust means of characterizing the RF
  - Robust means of determining system noise
  - As many diagnostic tools as possible!



Leslie troubleshooting cryogenics :)

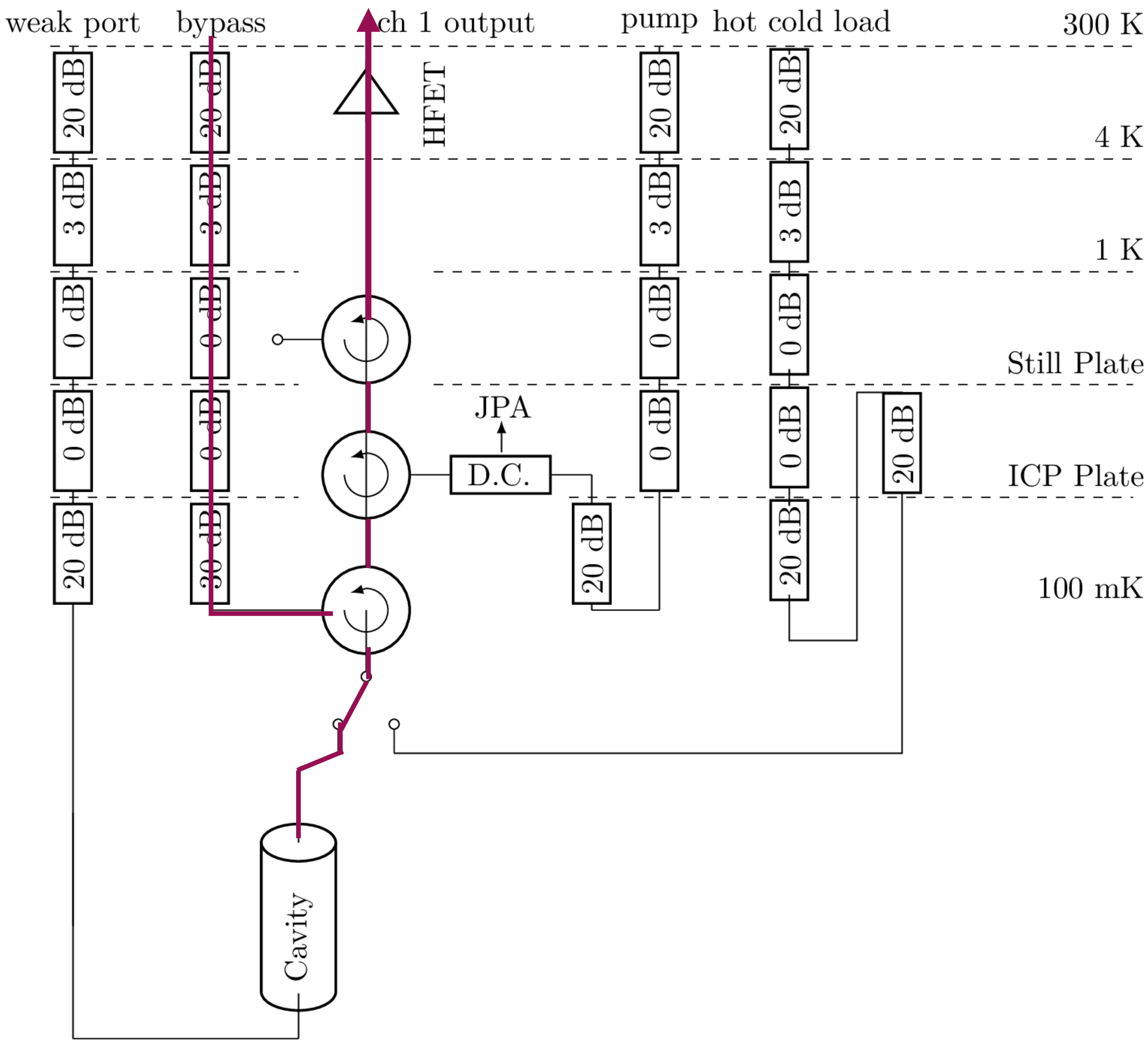
# Run 1C RF Receiver Chain



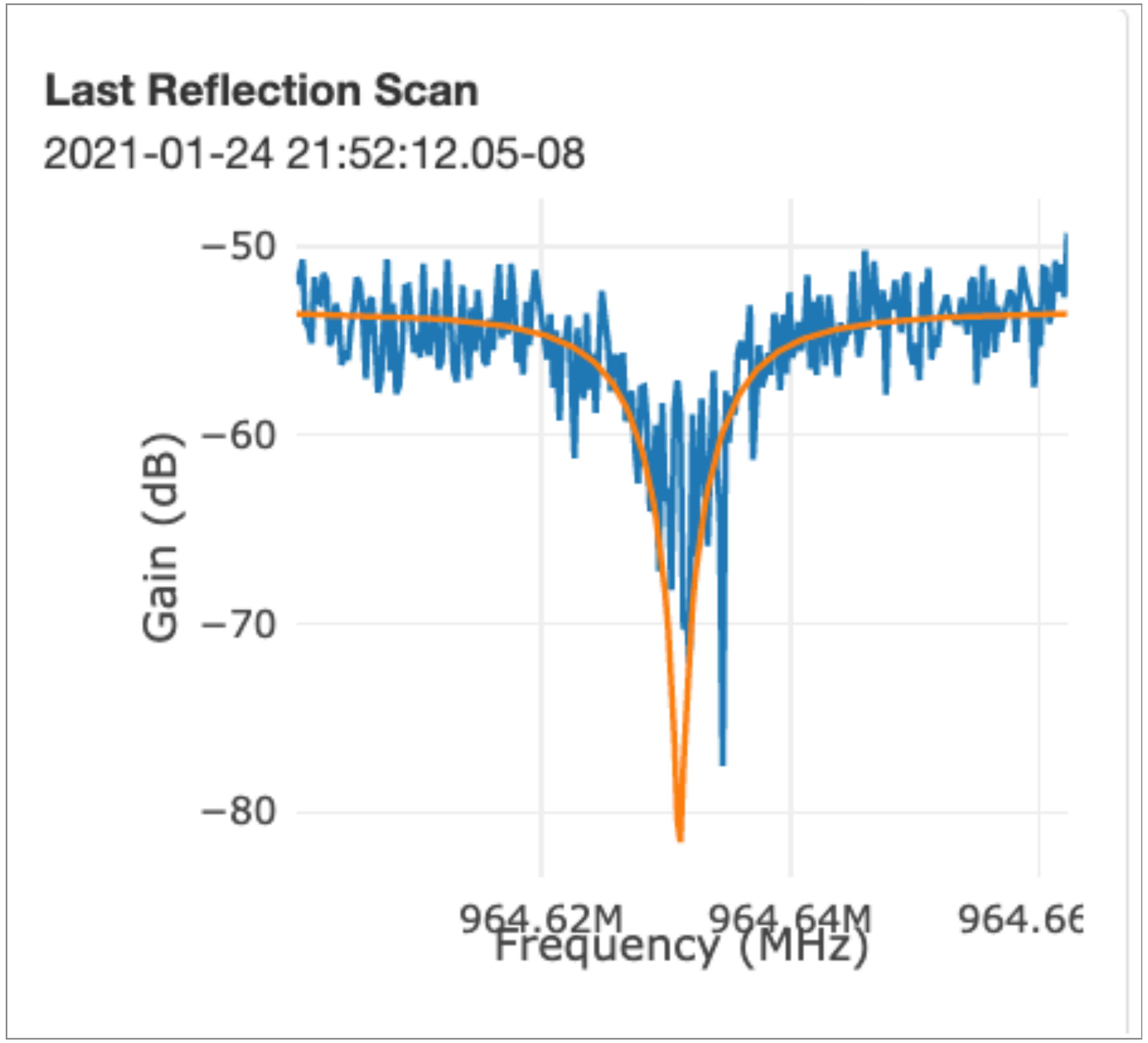

## Data-Taking Mode

- Lowest attenuation on the output line
- Highest attenuation on the input lines
- Signal path in blue. Weak port is terminated unless SAG is being injected.

# Run 1C RF Receiver Chain

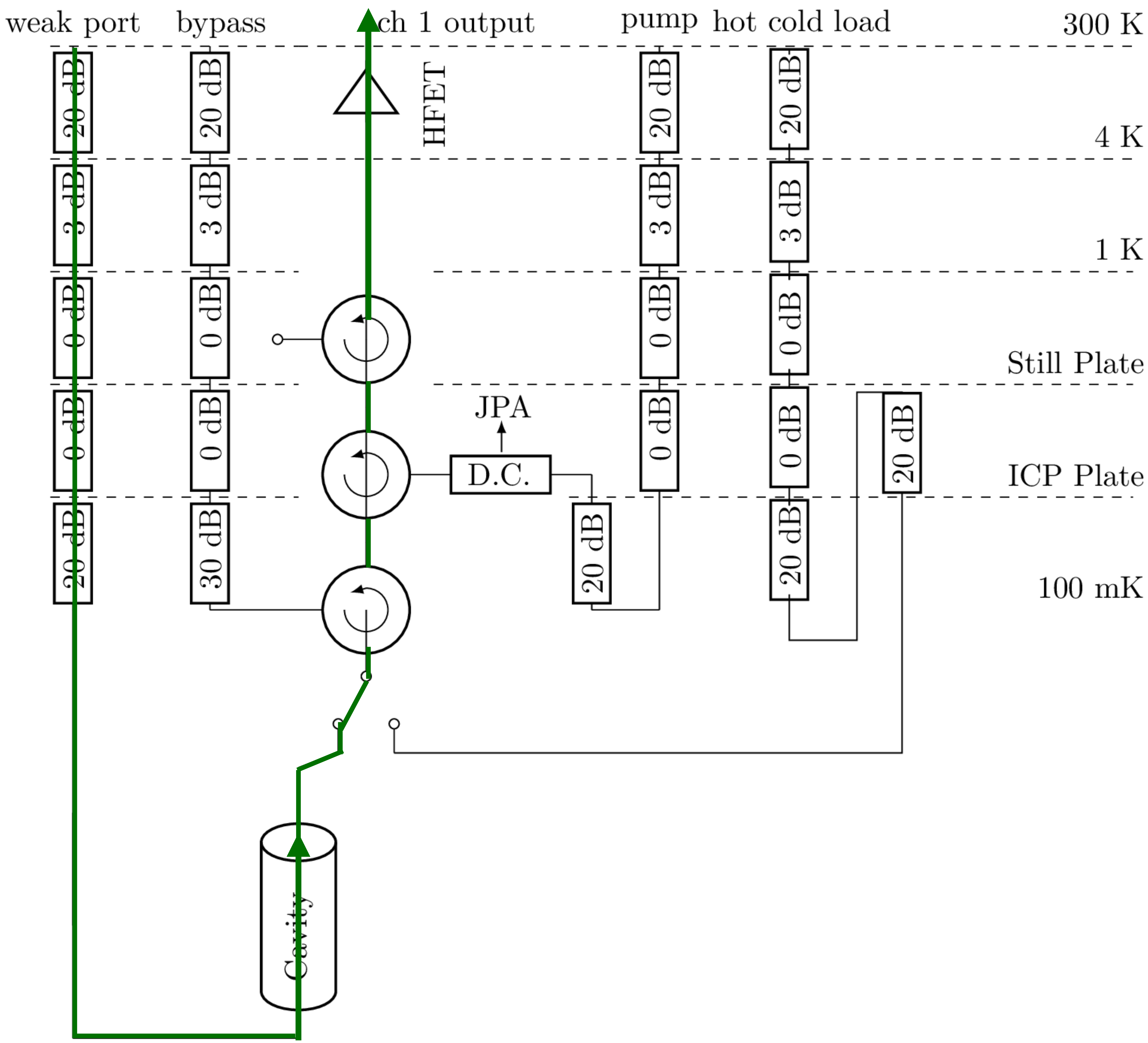



## Reflection Measurements

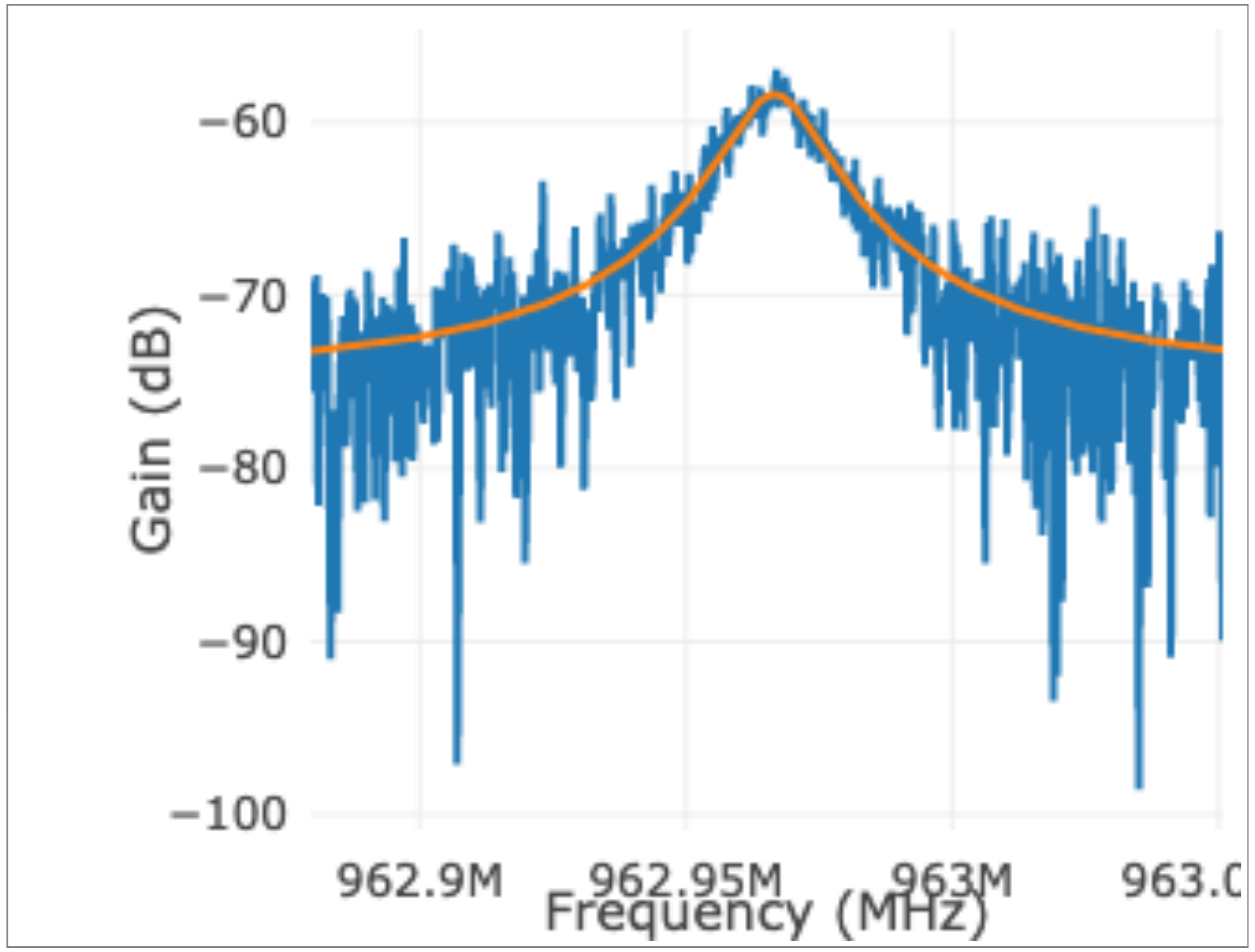



Gives antenna coupling

# Run 1C RF Receiver Chain

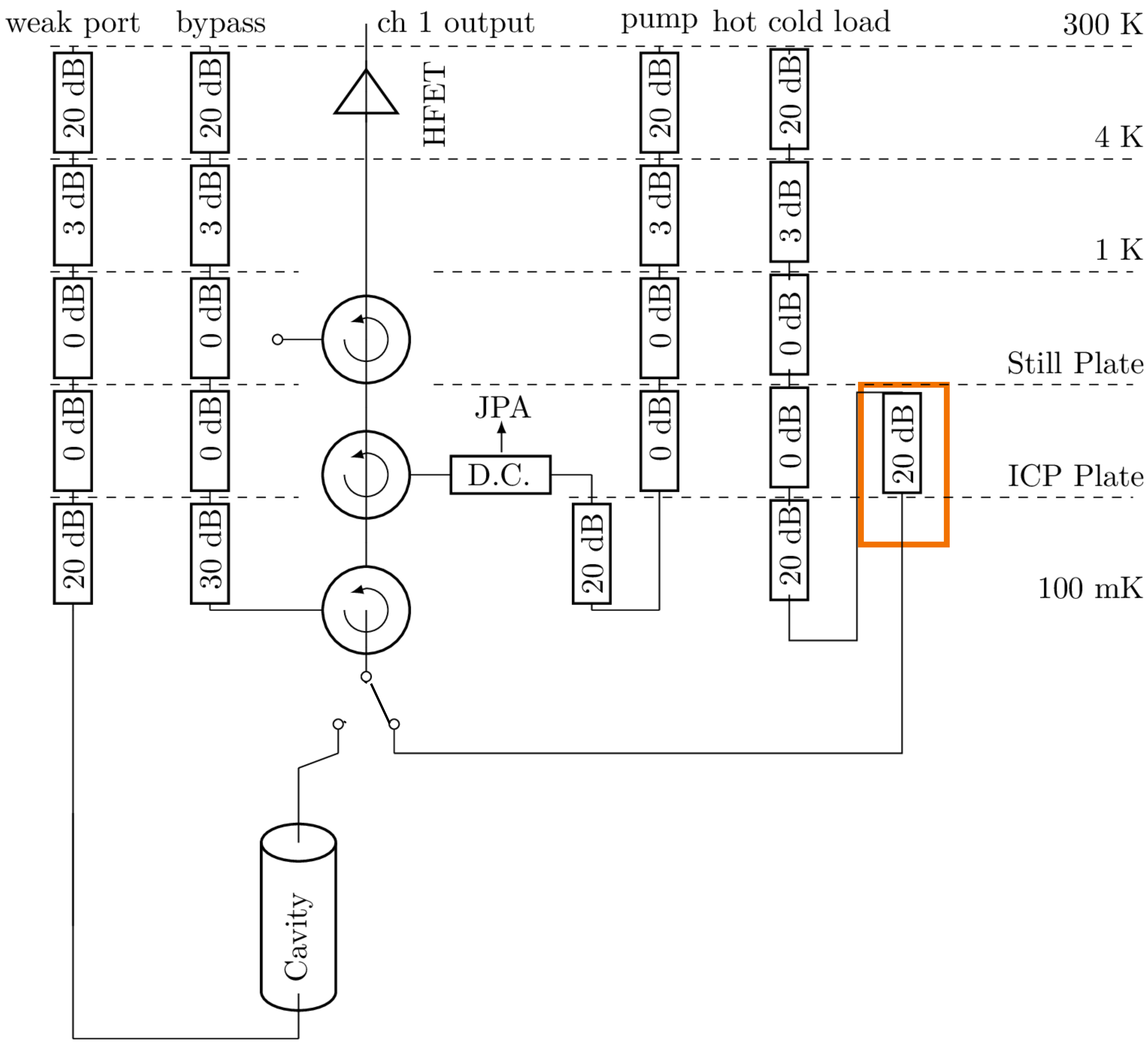



**Transmission Measurements**




Gives quality factor and resonant frequency

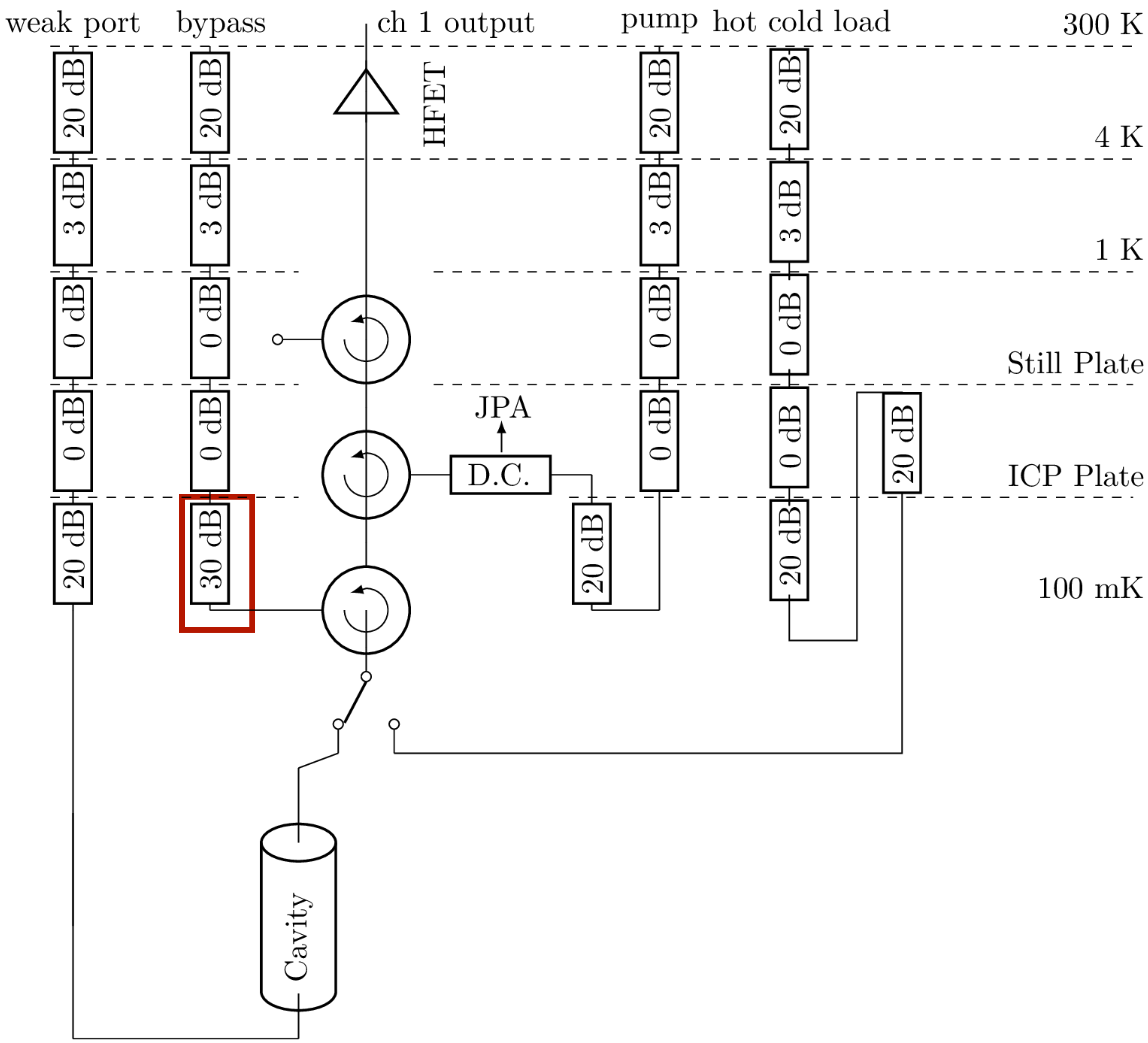
# Run 1C RF Receiver Chain




## Noise Calibration Mode

- Receiver chain provides means for measuring key RF parameters, such as quality factor
- Two types of noise measurement
- 1) Heating of the 'hot-load' via dc current (by design)
- 2) Heating of the quantum amplifier package via an RF switch

# Run 1C RF Receiver Chain

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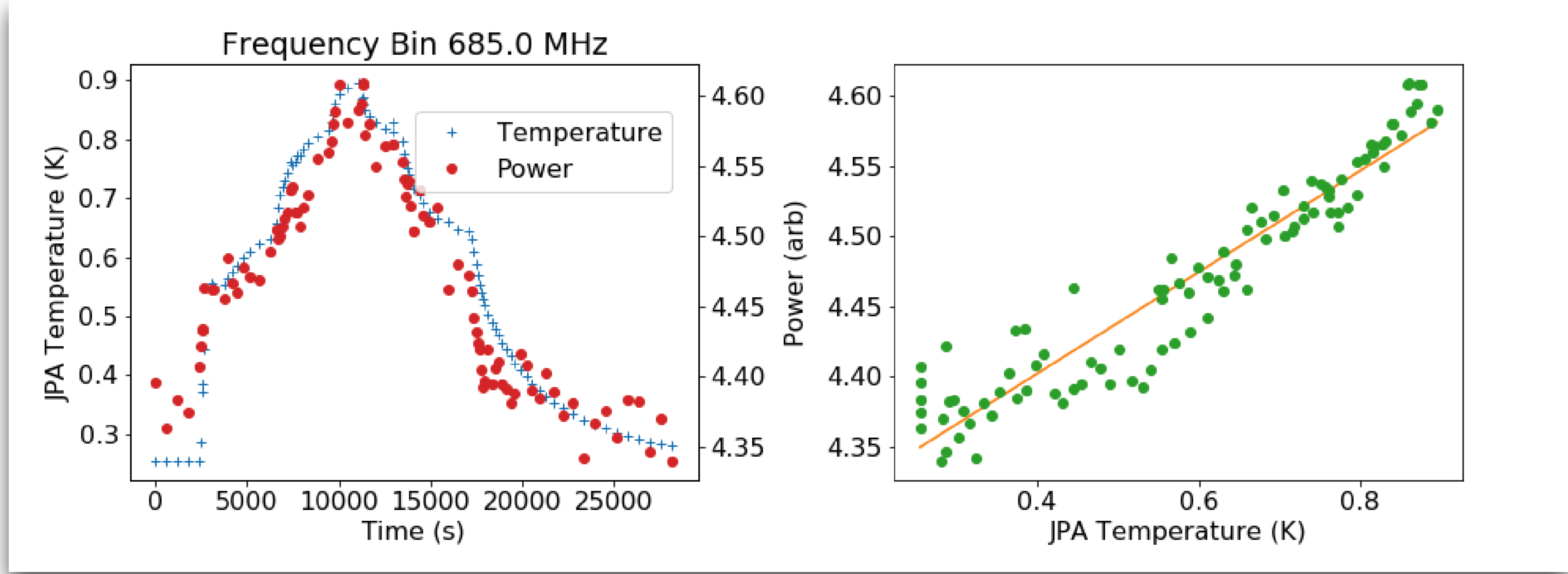
# Receiver noise temperature




$$P = G_{\mathrm{HFET}} k_B \left[T_{\mathrm{JPA}}(1-\epsilon) + T_{\mathrm{cav}}\epsilon + T_{\mathrm{HFET}}\right]$$

$$T_{\mathrm{sys}} = \frac{T_{\mathrm{HFET}}}{\epsilon(\mathrm{SNRI})}$$

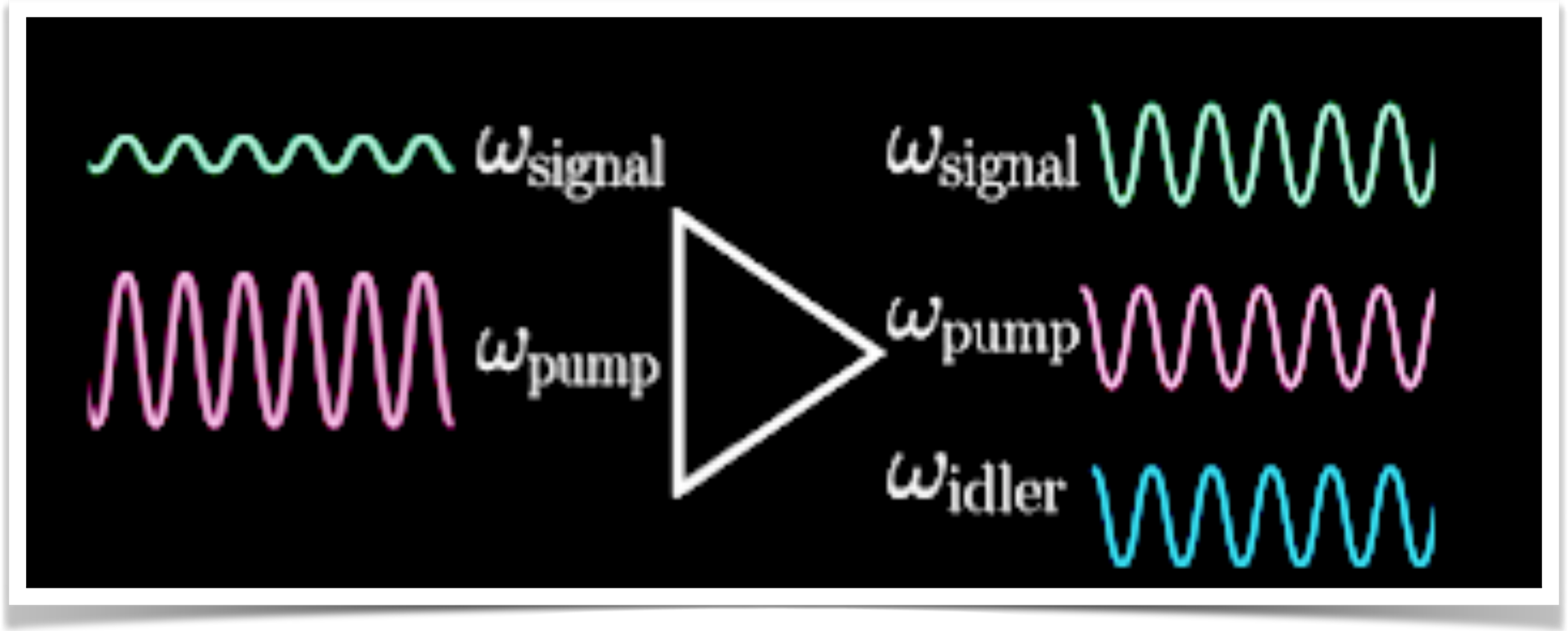
Fit parameters:

- Attenuation from cavity to HFET amp
- Receiver Temperature

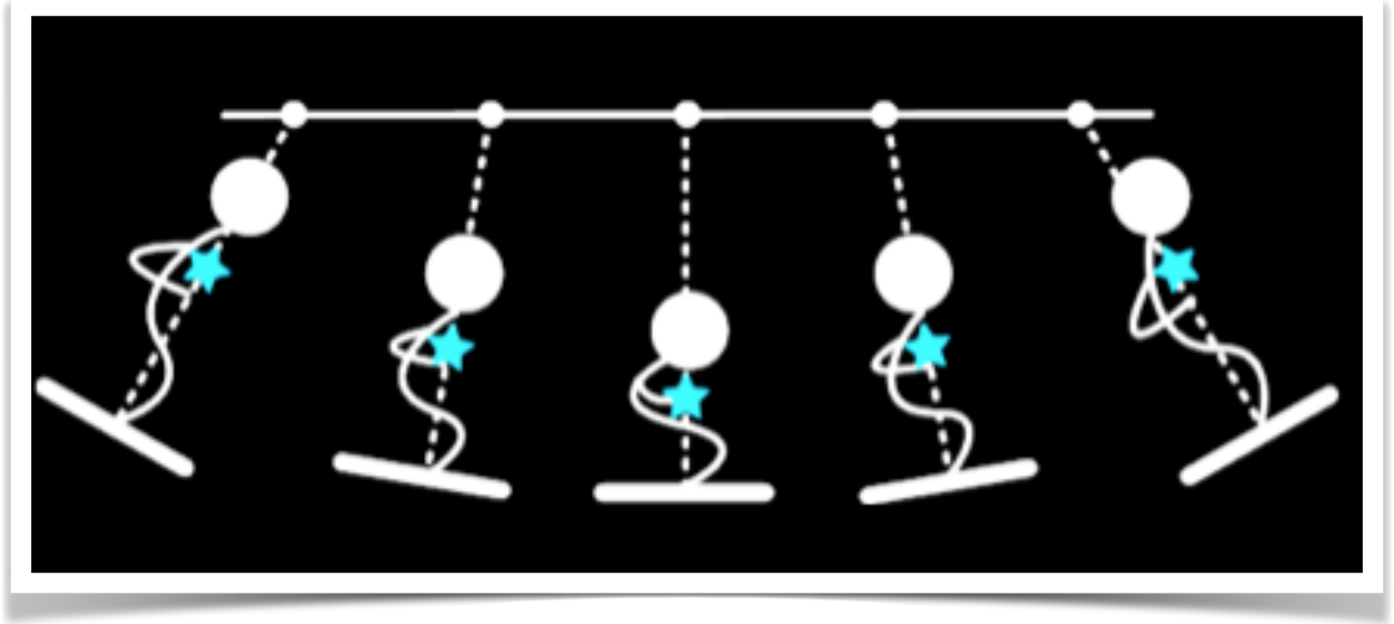
JPA Rebiasing Procedure Gives our SNRI!

# Josephson Parametric Amplifier

- Critical to obtaining low amplifier noise
- How does a parametric amplifier work?
    - Classic example is child on a swing
    - Anharmonicty leads to energy transfer from the pump tone to the signal tone
    - Requires some non-linear element, in this case, the Josephson Junction
- Must be protected from magnetic fields and continuously rebased

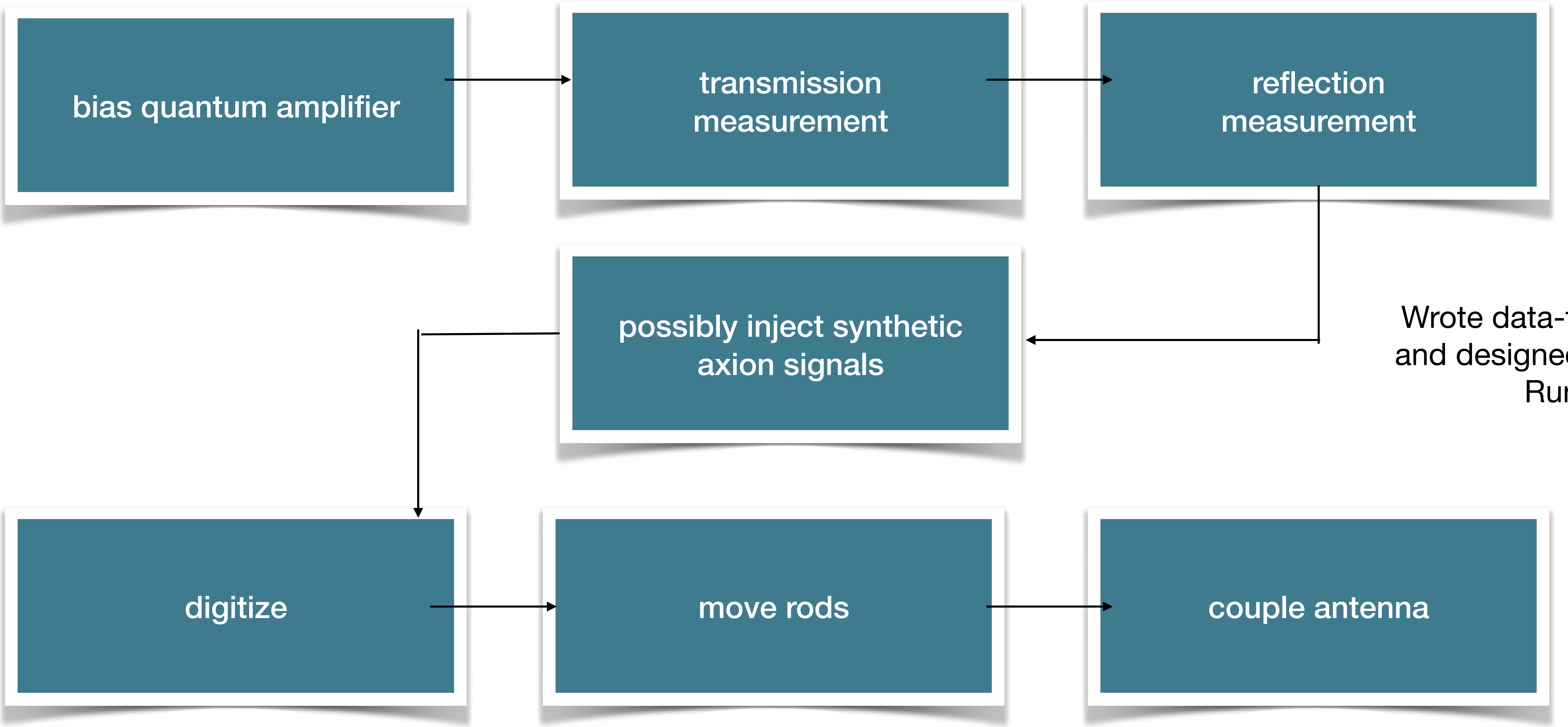



Figures courtesy of Shahid Jawas



# ADMX Run 1C Run Cadence

System state characterization measurements performed every iteration of data-taking cycle

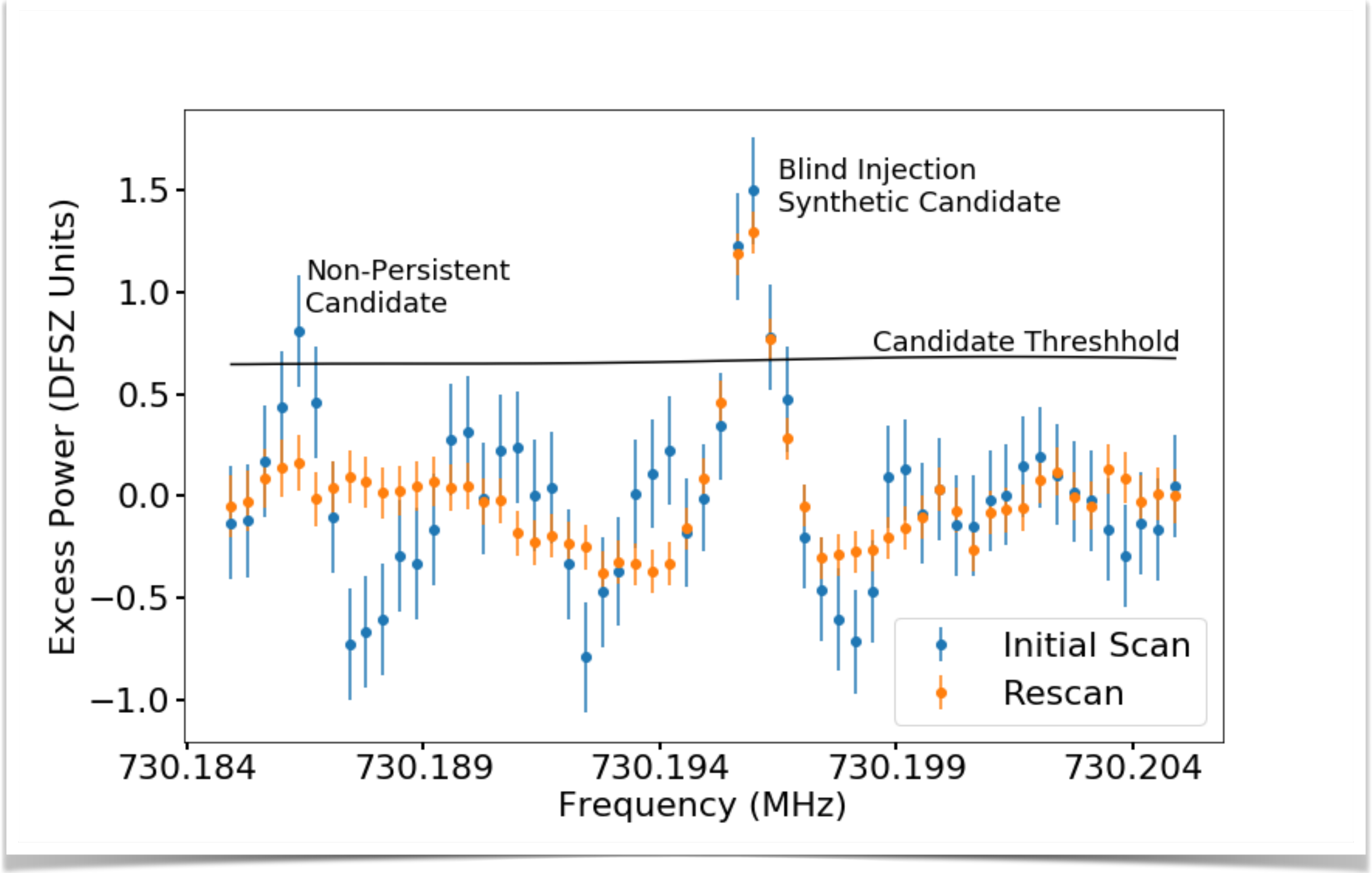



Wrote data-taking scripts and designed interface for Run 1C

Ongoing throughout: Acquisition of physical temperature data

# Synthetic Axion Generator (SAG): Run 1B

- Arb output at low frequency maxwellian-like signal
- Signal mixed up to axion frequencies
- Grad student placed appropriate attenuation
- SAG signal sent to weak port

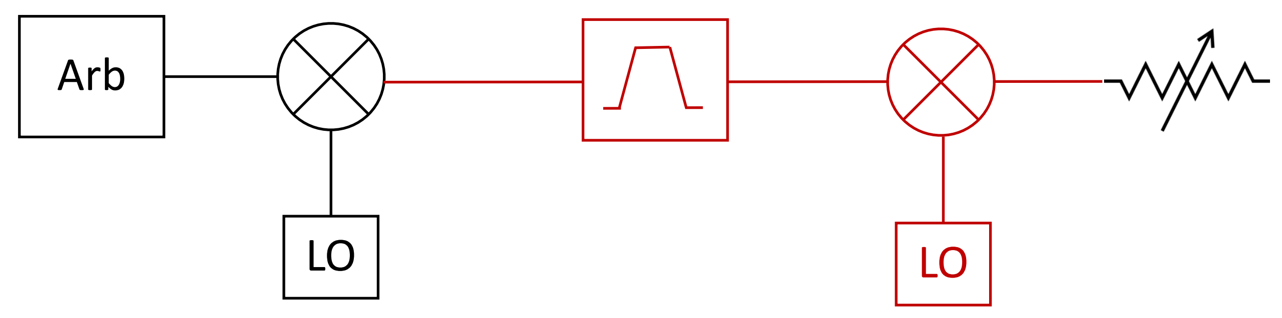



January 2018, ScientificAmerican.com **55**

# Synthetic Axion Generator (SAG): Run 1C

- Extra stage of mixing/filtering to improve signal purity
- New enclosure separate from the main DAQ
- New 0-90 dB programmable attenuator for increased automation. Fully automated and integrated with dripline/lua.

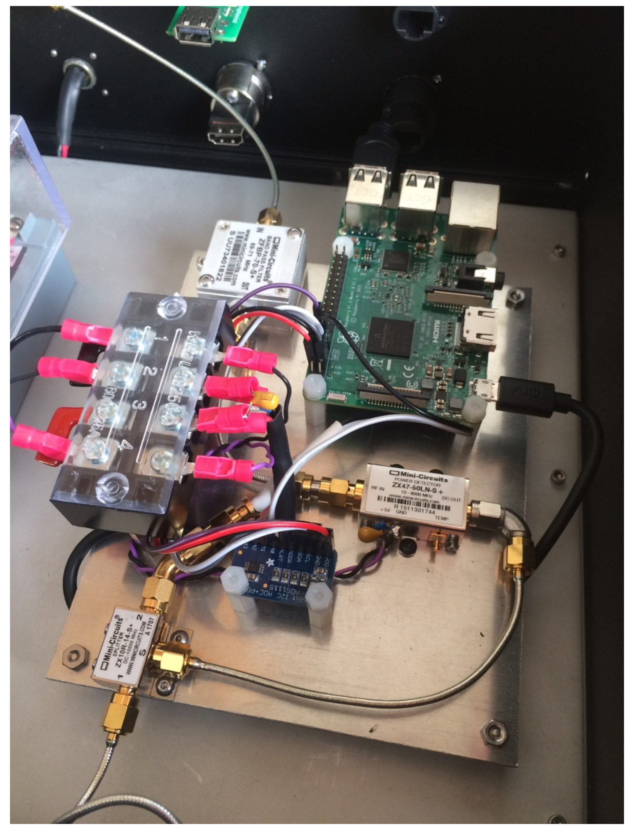
Extra stage of mixing/filtering

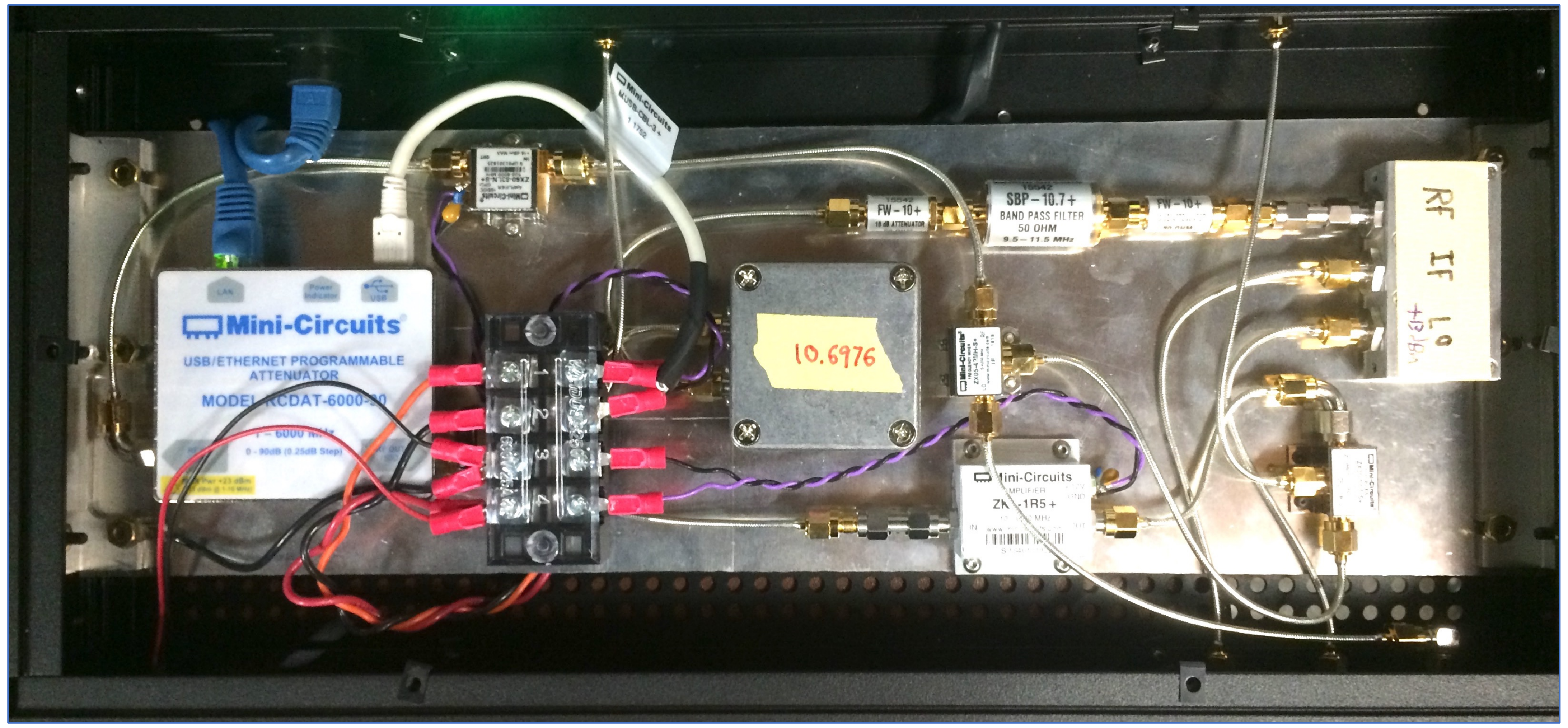



Programmable attenuator

New Enclosure

Power detector + ADC + RPi





# ADMX Run 1C Analysis

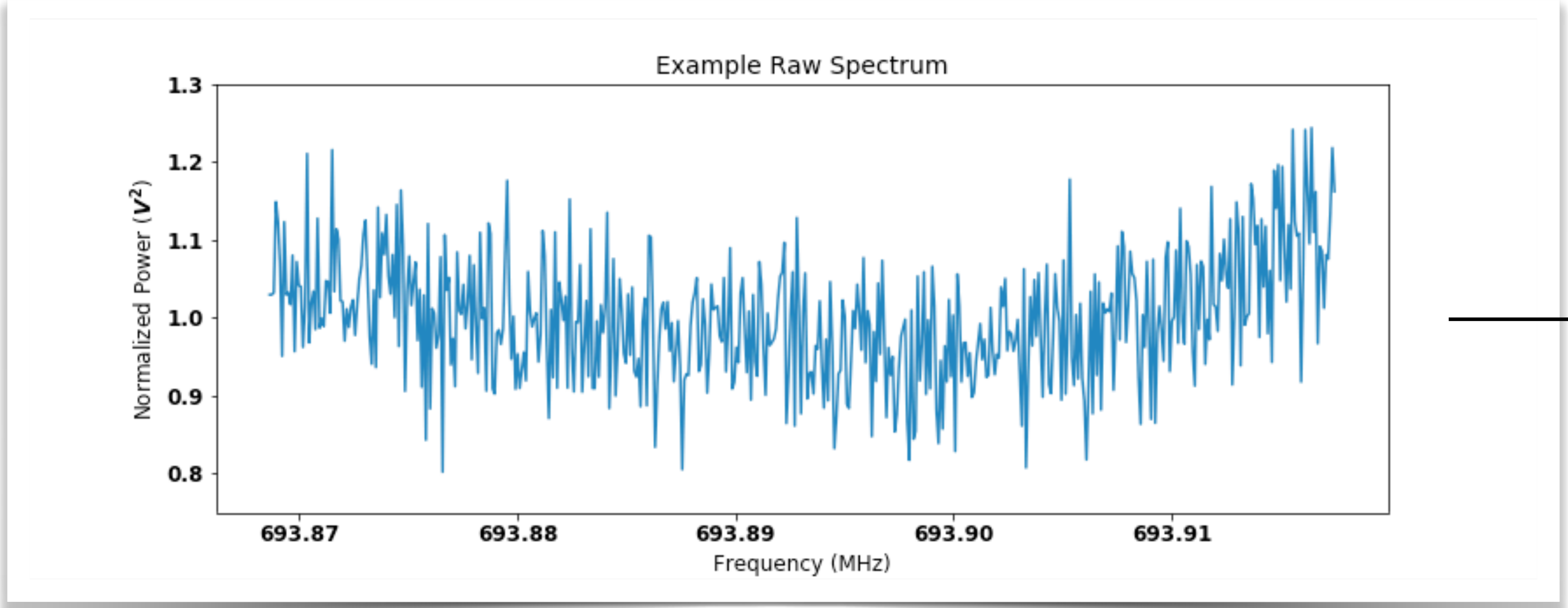
**Two types of analysis:**

- **Medium-resolution analysis (described here):**
  - Can detect persistent axion signal.
  - Assumes isothermal velocity distribution.
  - 100 Hz bin width.

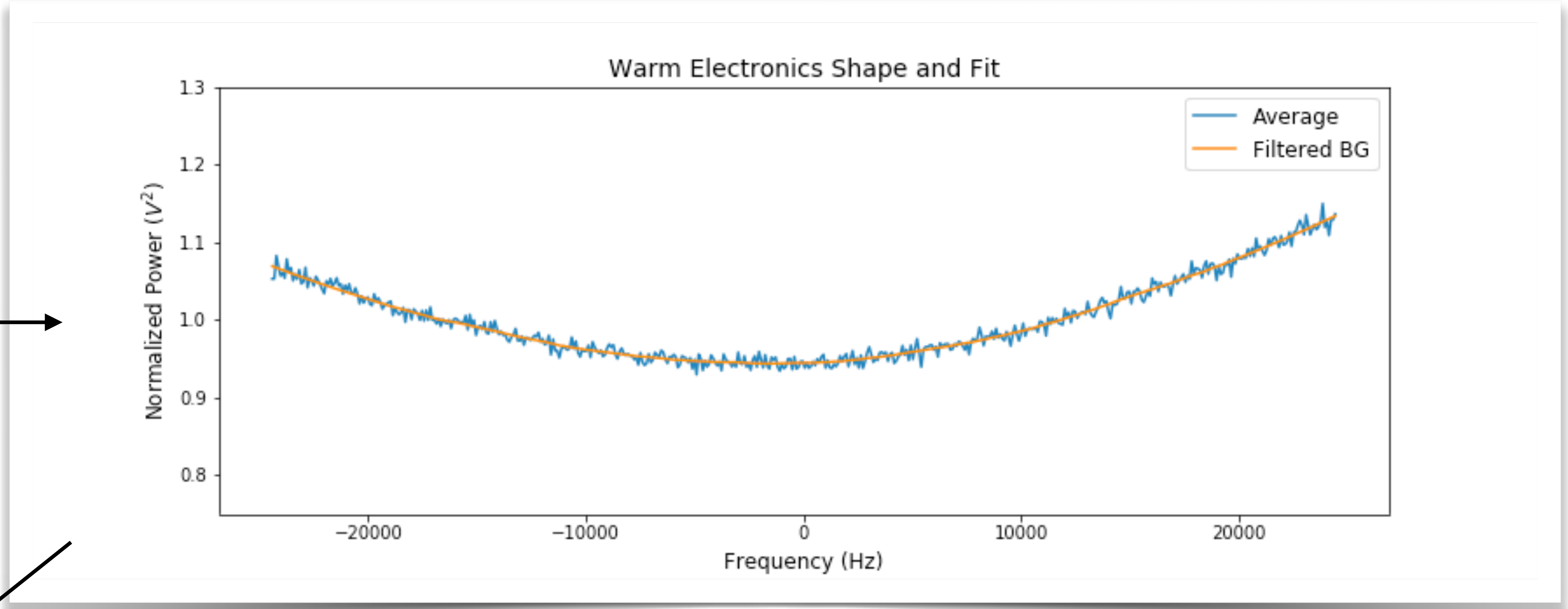
- **High-resolution analysis:**
  - Can search for much narrower peak due to discrete axion flow.
  - Can detect annual and diurnal modulation of the axion, if detected.
  - 10 mHz bins width.

# Spectrum Processing

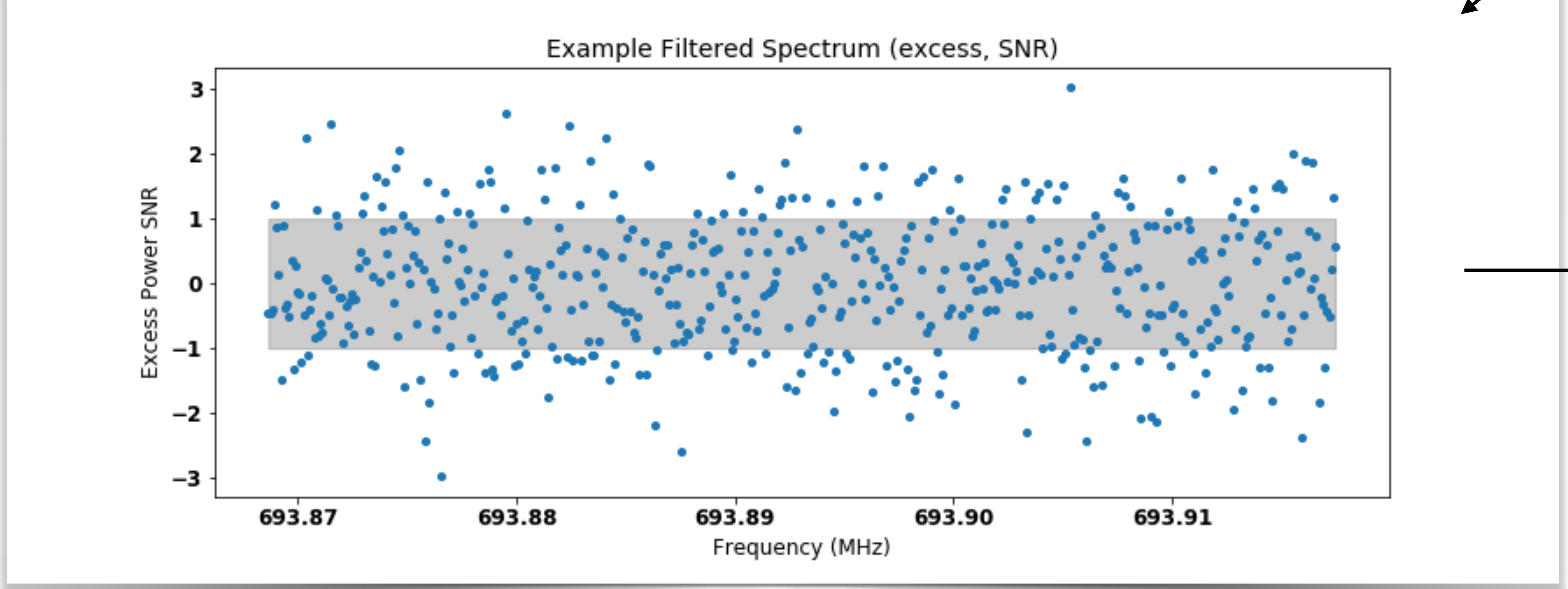
## Acquiring Raw Spectrum



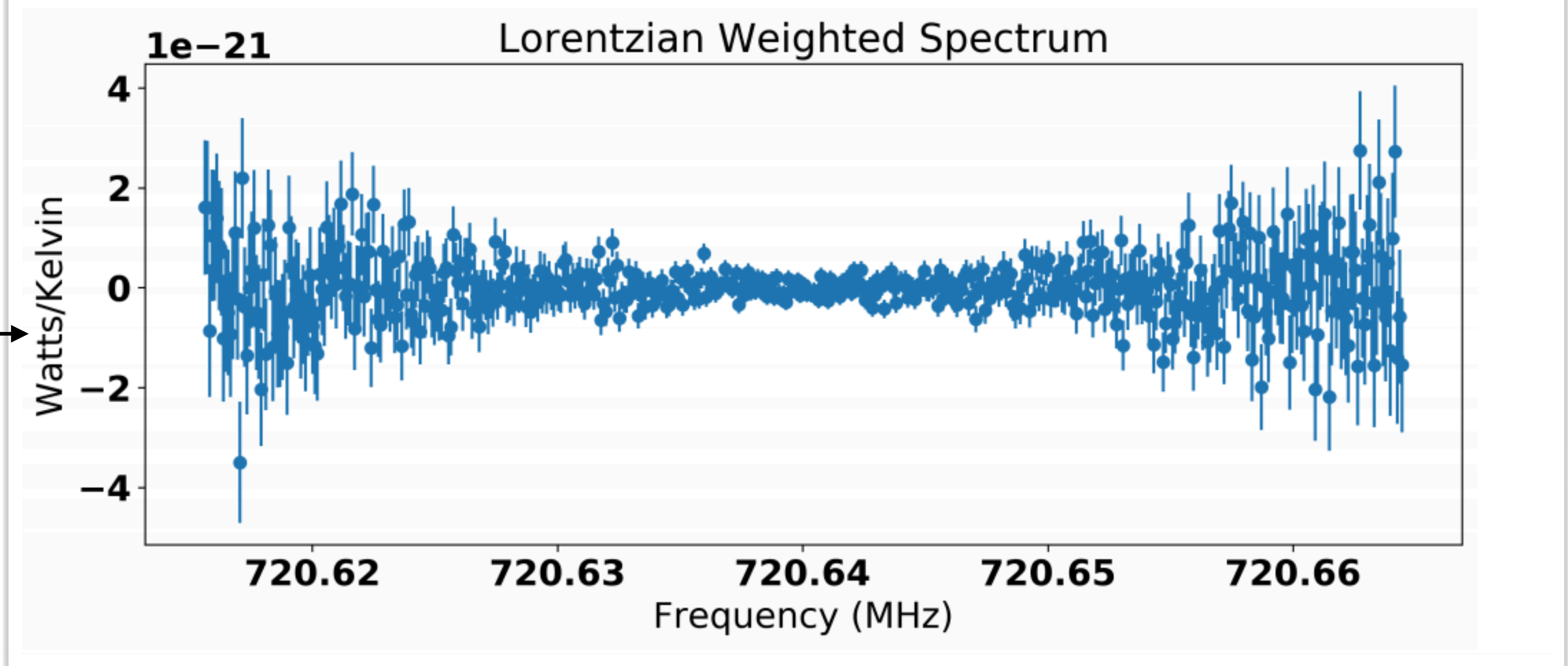

## Determine the shape of the receiver chain



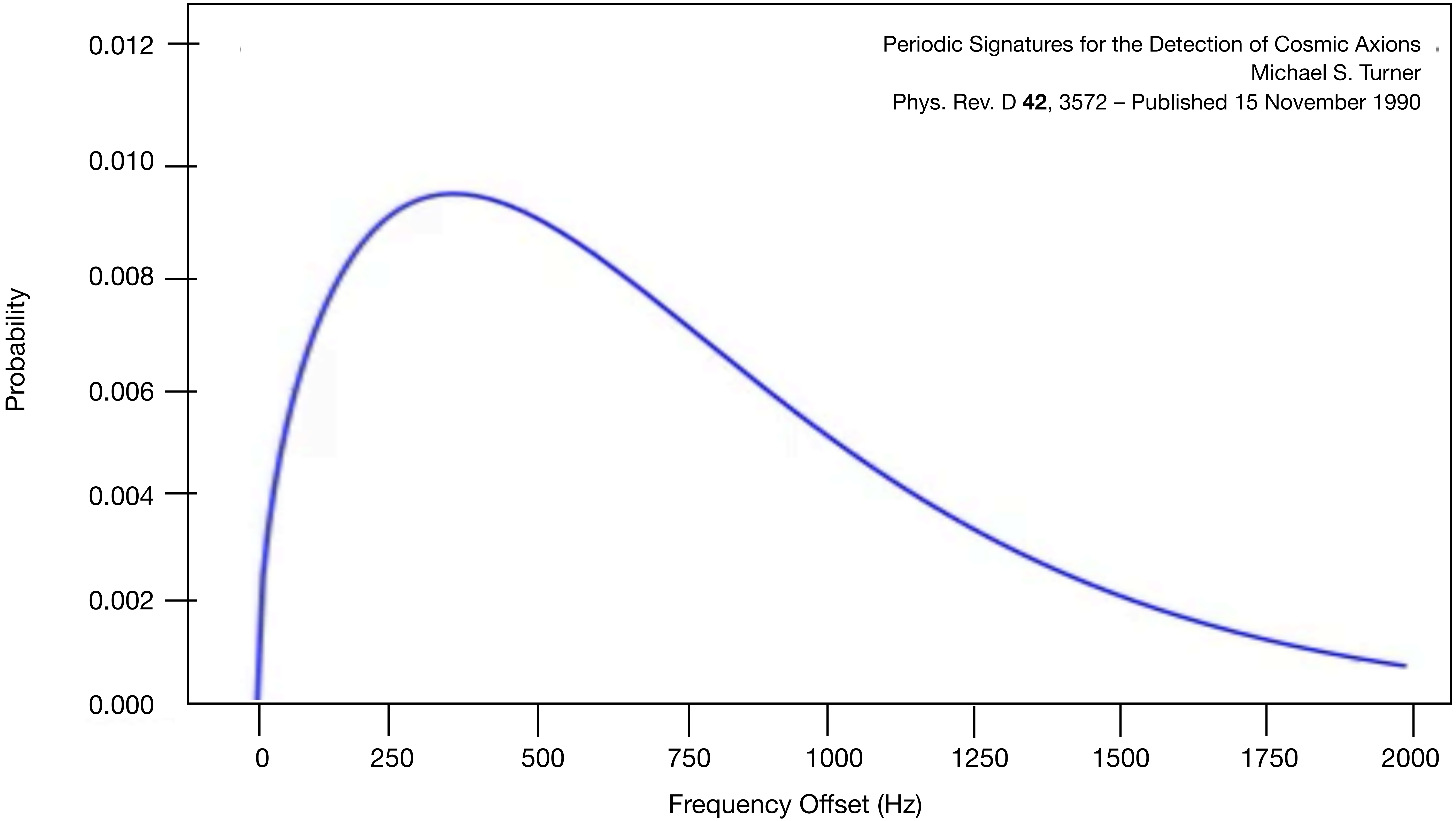

## Remove the shape of the receiver chain




## Weight according to Lorentzian



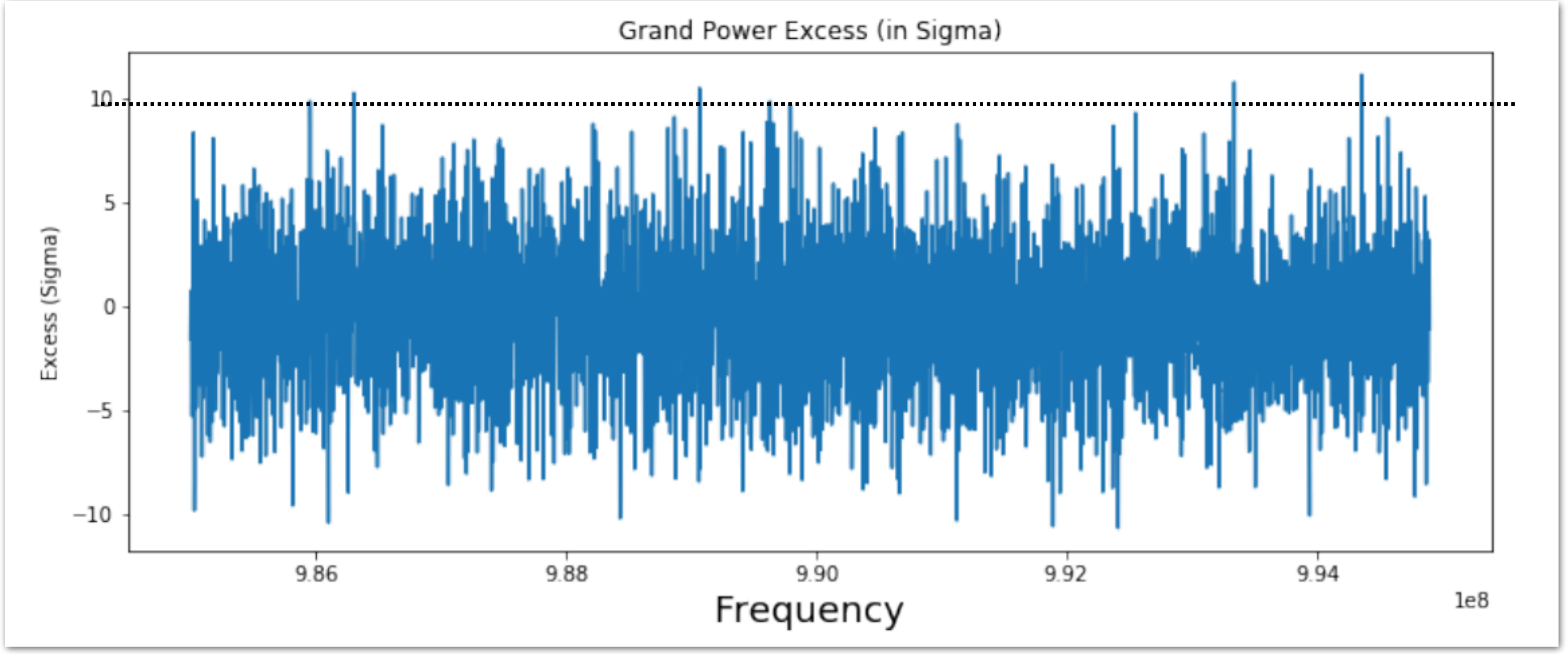
# Axion velocity distribution ("line shape")



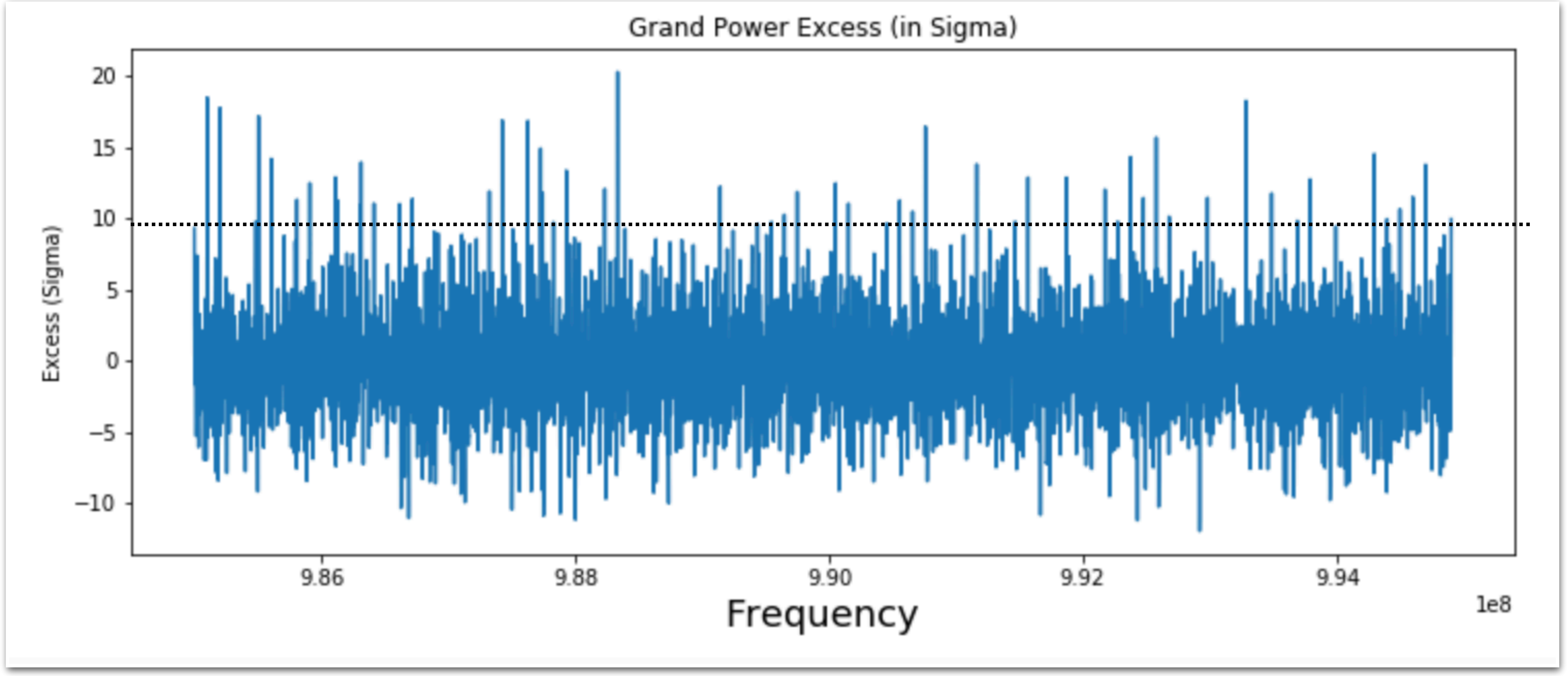

Detectable with High Resolution Search (10 mHz)

# Software synthetics

**SIMULATED DATA!**




**NO SYNTHETICS**




**SYNTHETICS**

- Used to determine our detection efficiency and verify our analysis
- Developed by undergraduate student Hima Korandla, with my supervision
  - Simulated analysis data
  - Software synthetic injections for Run 1C
- Developed a new technique to mitigate sensitivity reduction due to baseline removal.

# ADMX Rescans

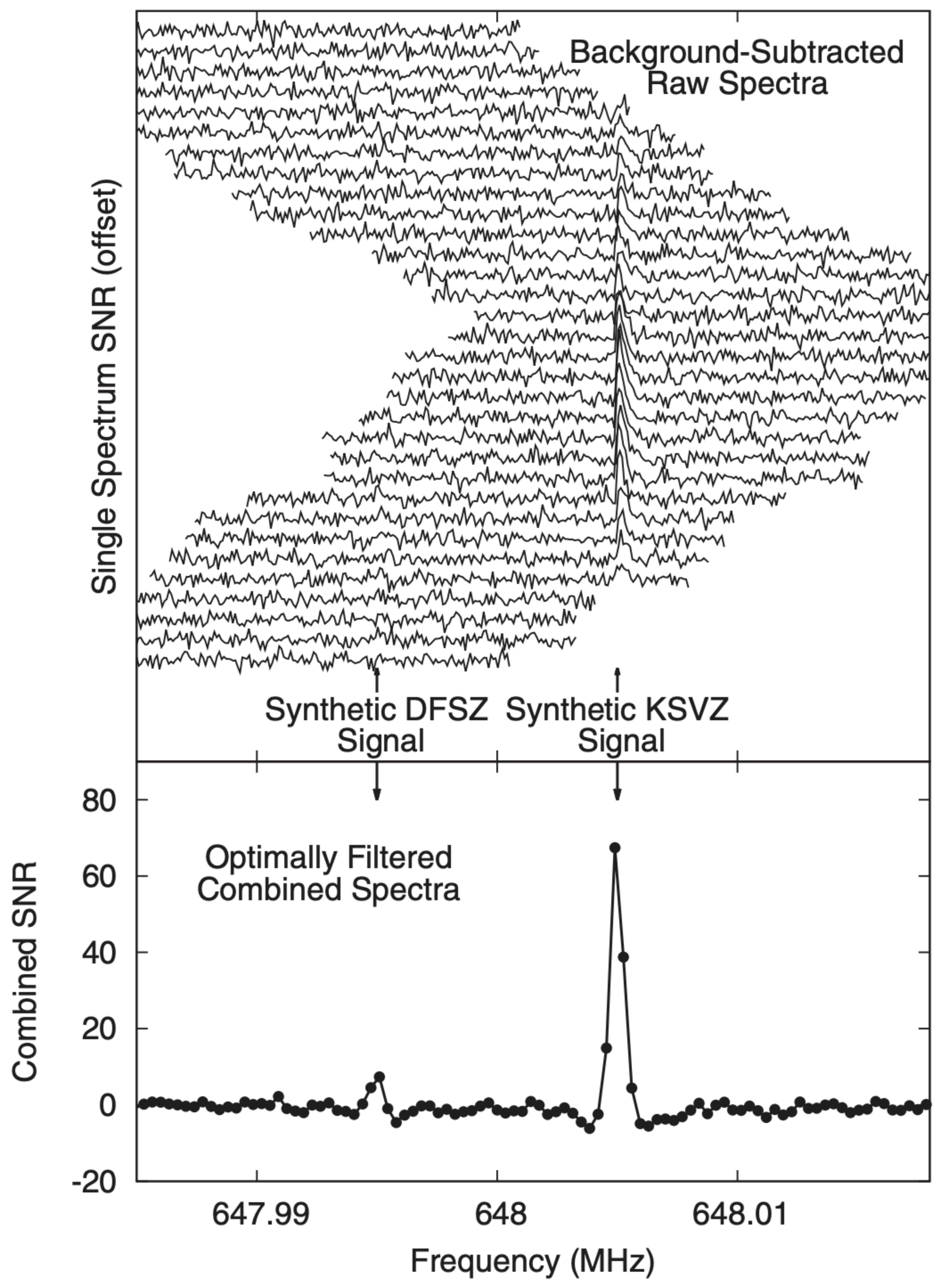
When do you decide to rescan?

3 conditions:

- Not enough data (low SNR): min SNR of 3
- 3.4σ excess
- Excess at DFSZ threshold or above

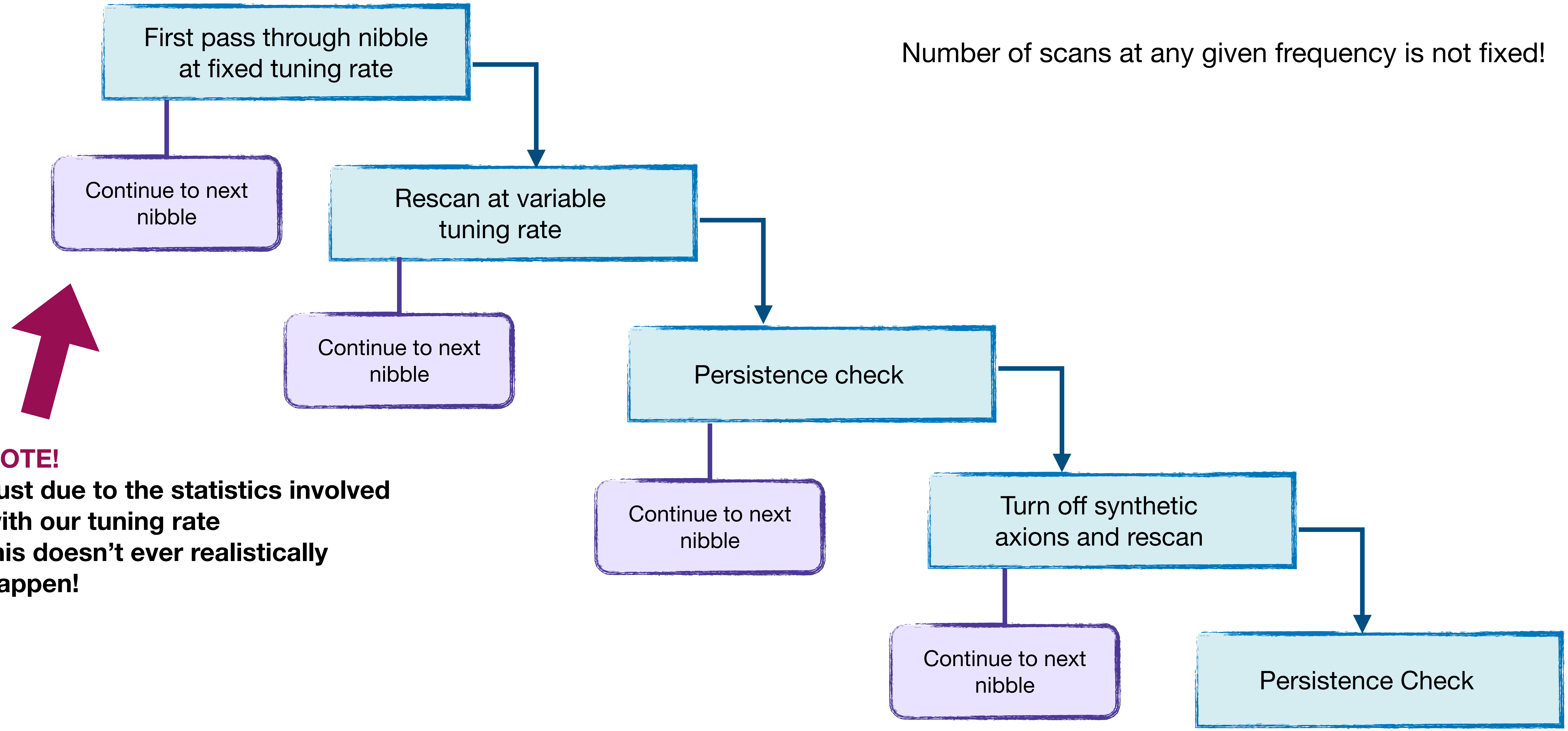
$$P_{\text{measured}} + 0.85\sigma > P_{\text{DFSZ}}$$

There will always be some of these remaining just due to statistics!



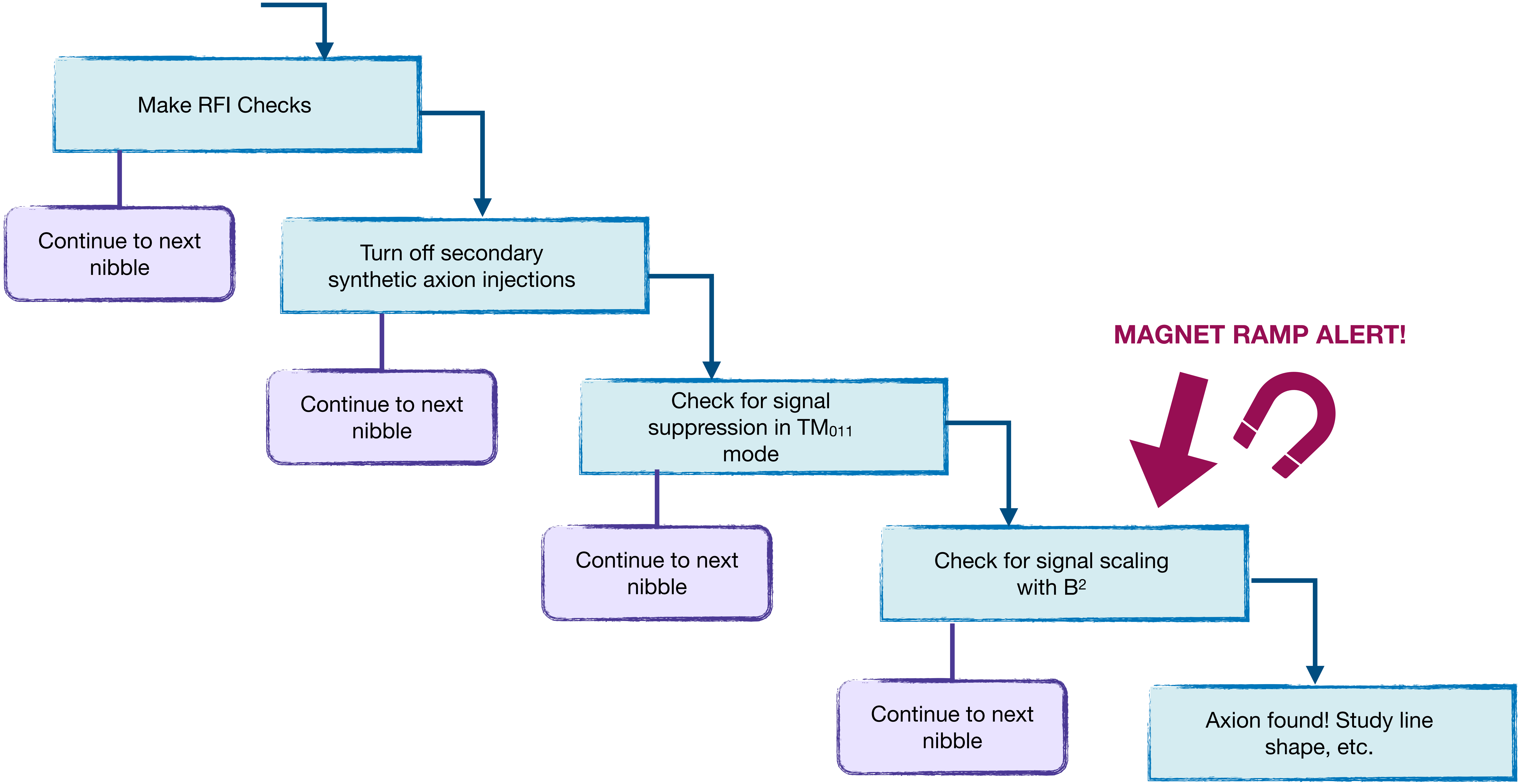
# Axion Search Decision Tree

Number of scans at any given frequency is not fixed!




**NOTE!**
**Just due to the statistics involved with our tuning rate this doesn’t ever realistically happen!**

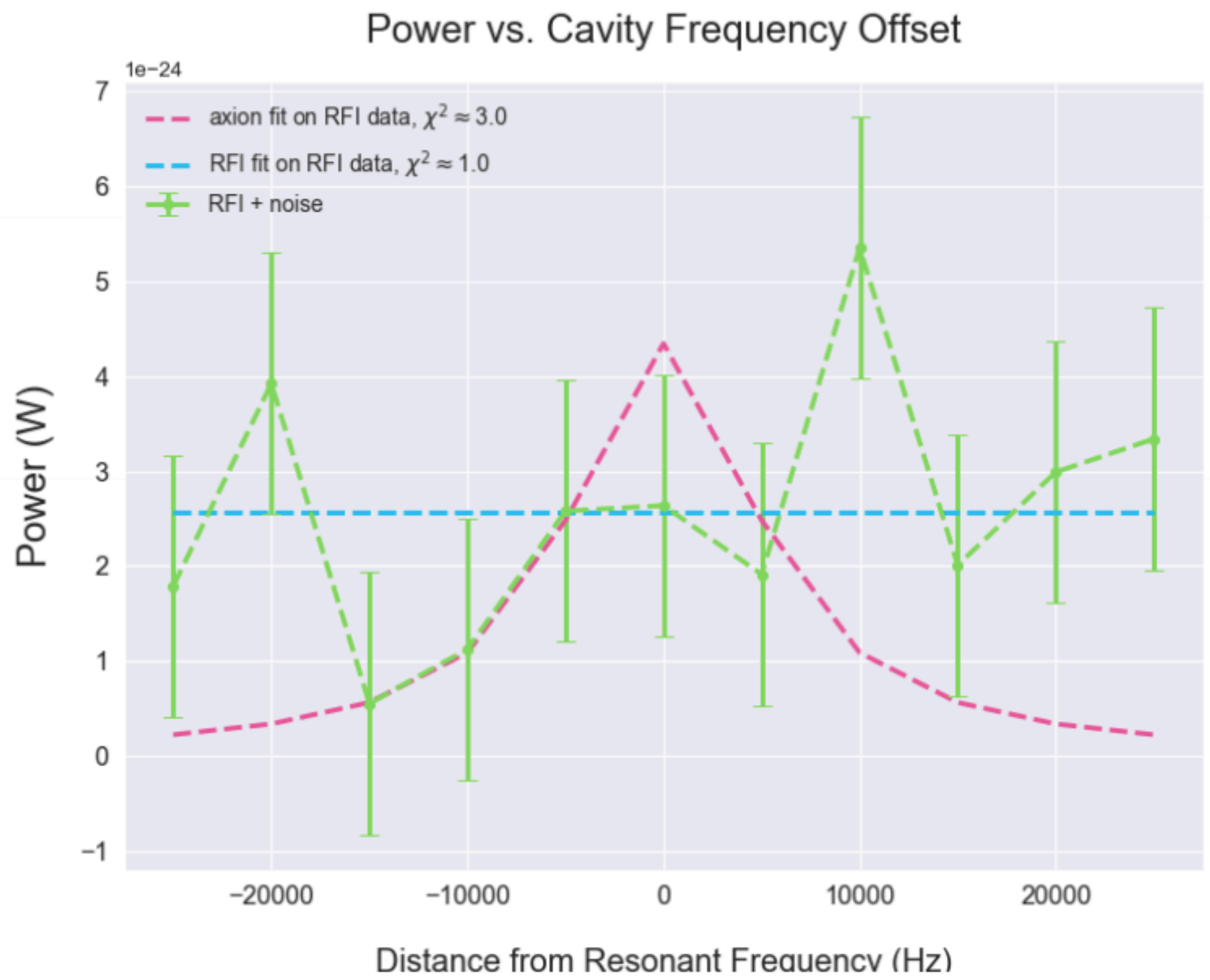
# Axion Search Decision Tree



# ADMX Run 1C Data Analysis

## Raw Data Processing: Eliminating RFI

- Developing tools to distinguish between RFI and real axion signals.
- Came from project with undergrad Michaela Guzzetti in the summer REU.
- Plans to develop this technique in the future.




Plot courtesy of Michaela Guzzetti


REU students Michaela Guzzetti and Nicole Man (2019)

# ADMX Exclusion Limit

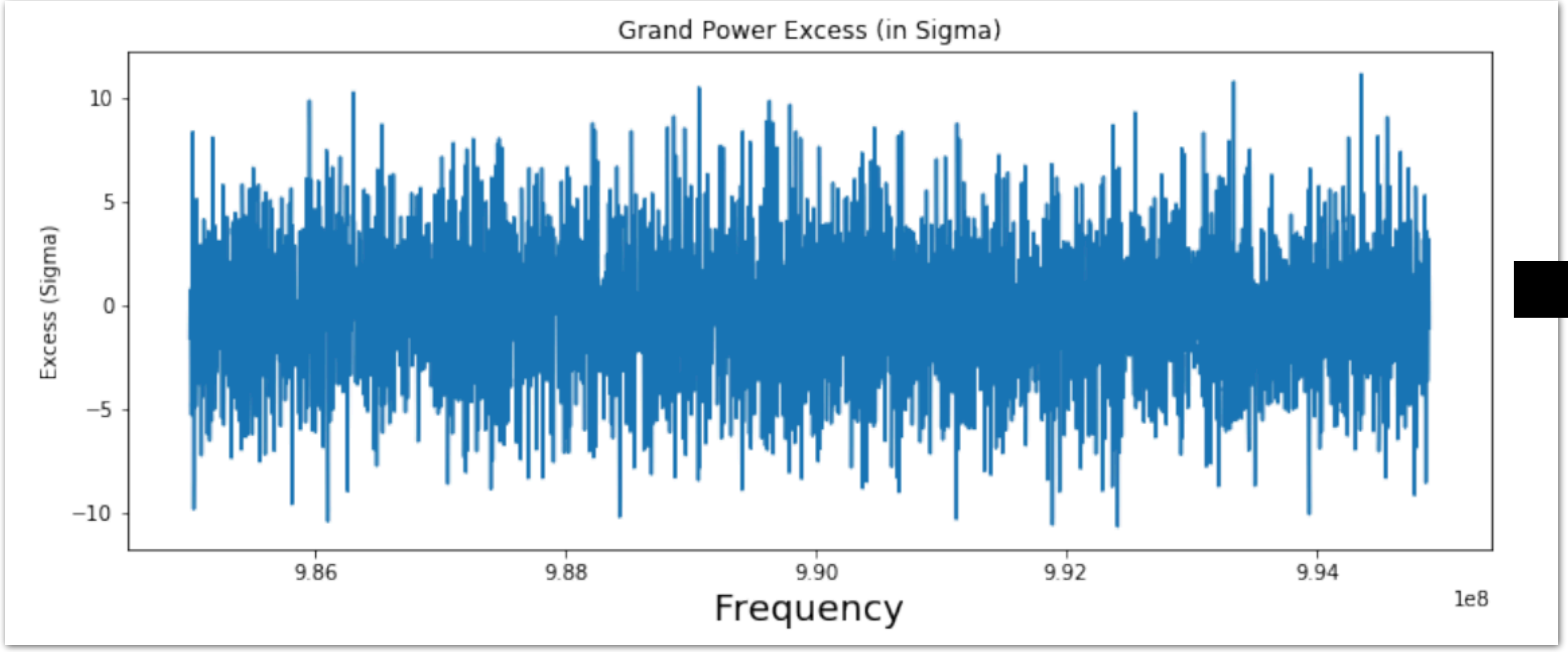
How to go from grand spectrum to an exclusion limit?

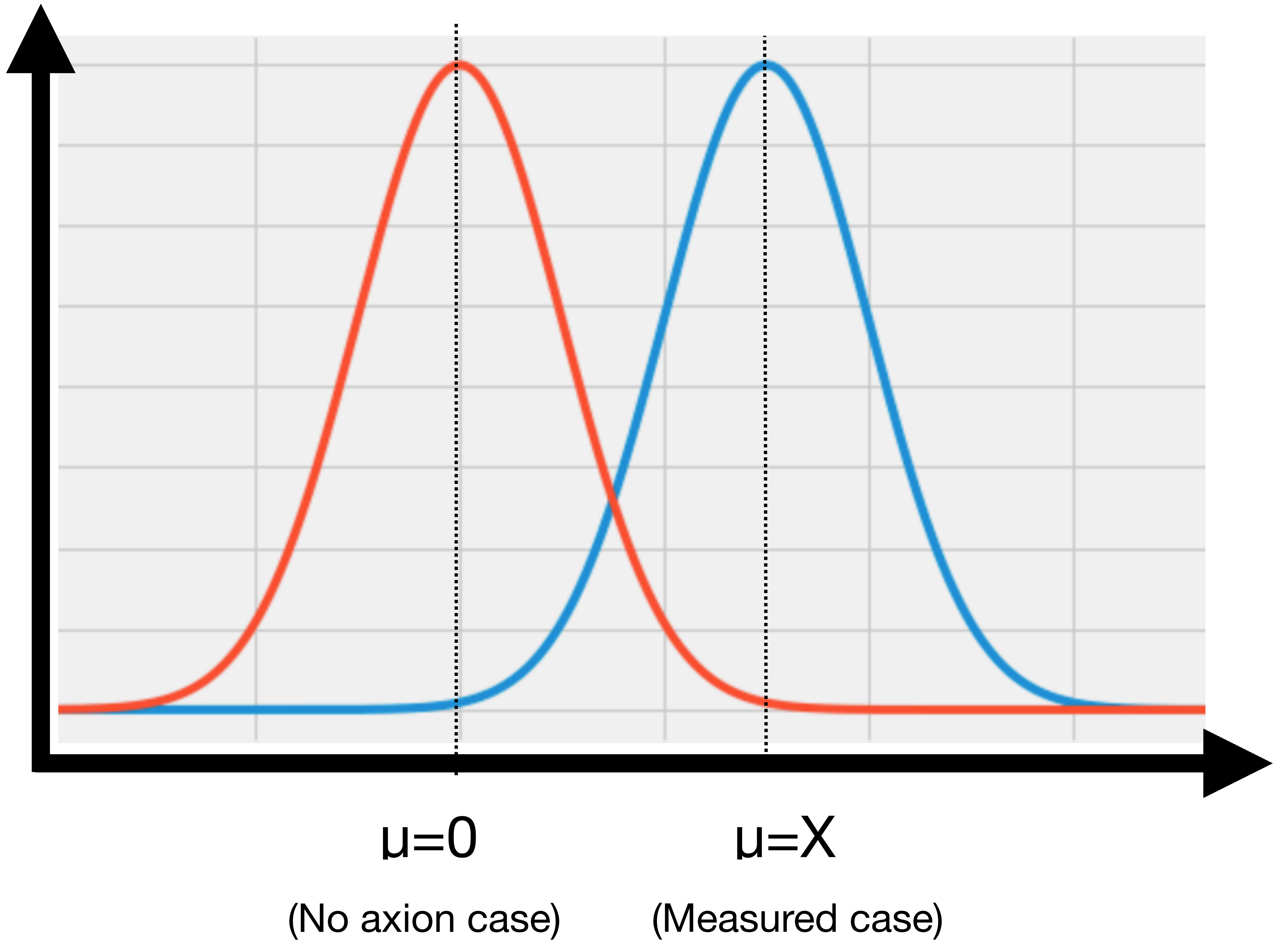
Given a measured SNR, find the μ which corresponds to 90% confidence level, where

$$\mu = g_{\gamma}^{2}\eta$$

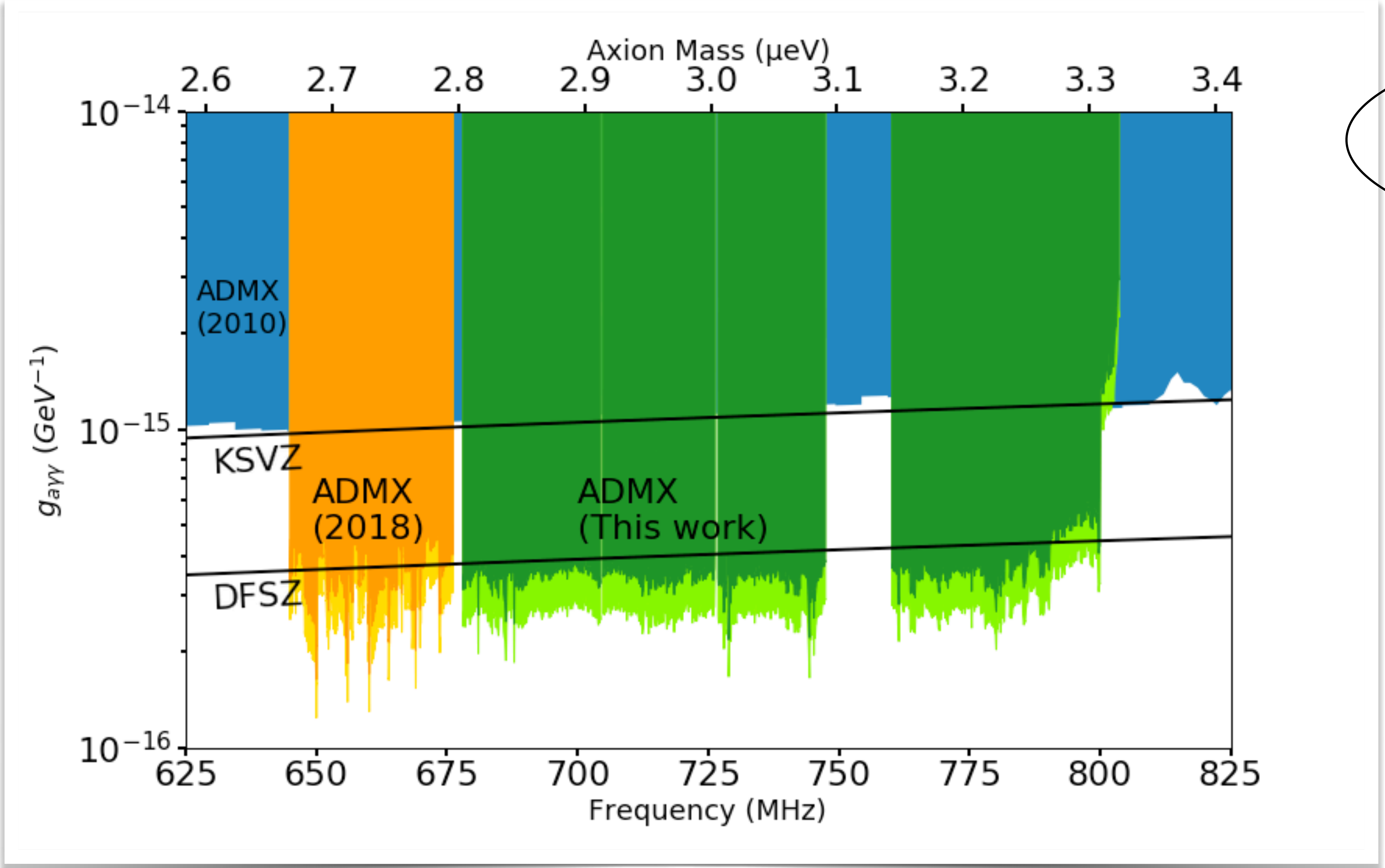
Axion photon coupling ($g_{\gamma}$)

Measured SNR ratio for an axion ($\eta$)



# Prior Analysis (Run 1B)



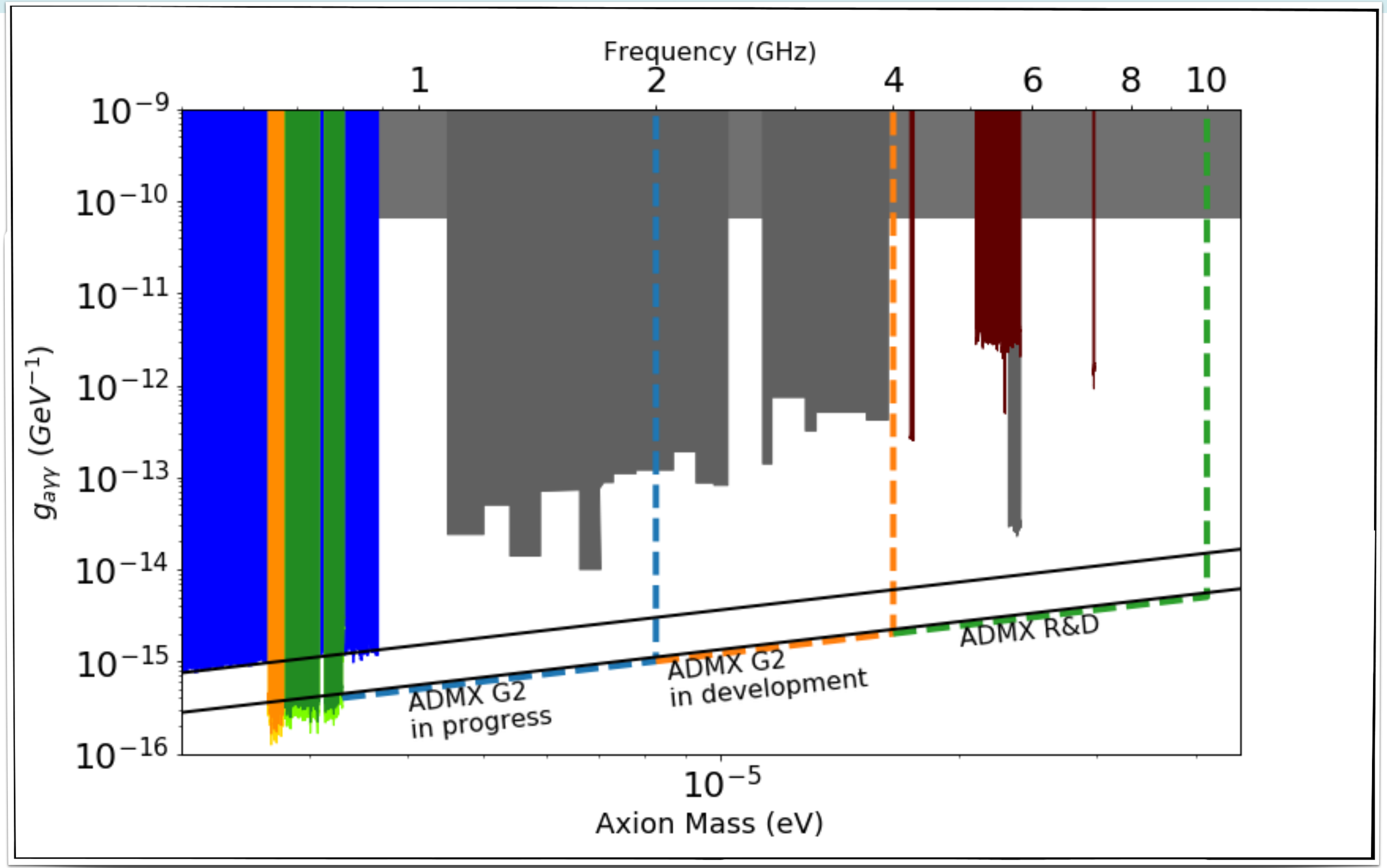

**New paper accepted by PRD!**

Bartram, C., et al. "Axion Dark Matter eXperiment: Run 1B Analysis Details." arXiv preprint arXiv:2010.06183 (2020).

Extended Search for the Invisible Axion with the Axion Dark Matter Experiment
*T. Braine et al. (ADMX Collaboration)*
Phys. Rev. Lett. 124, 101303 — Published 11 March 2020

Run 1A Max-Boltz
Run 1B Max-Boltz
Run 1A N-body
Run 1B N-body

# Projected ADMX Sensitivity



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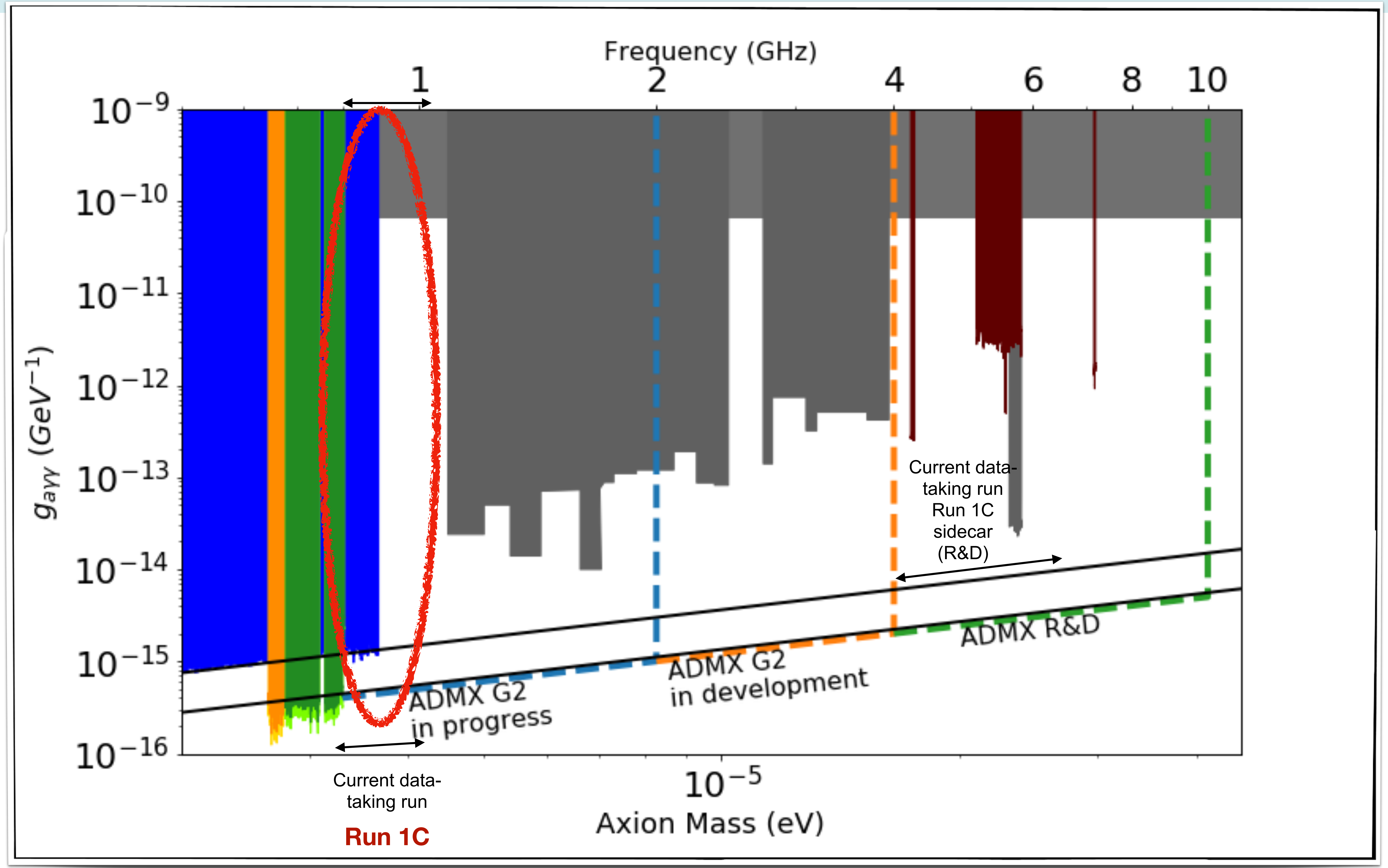

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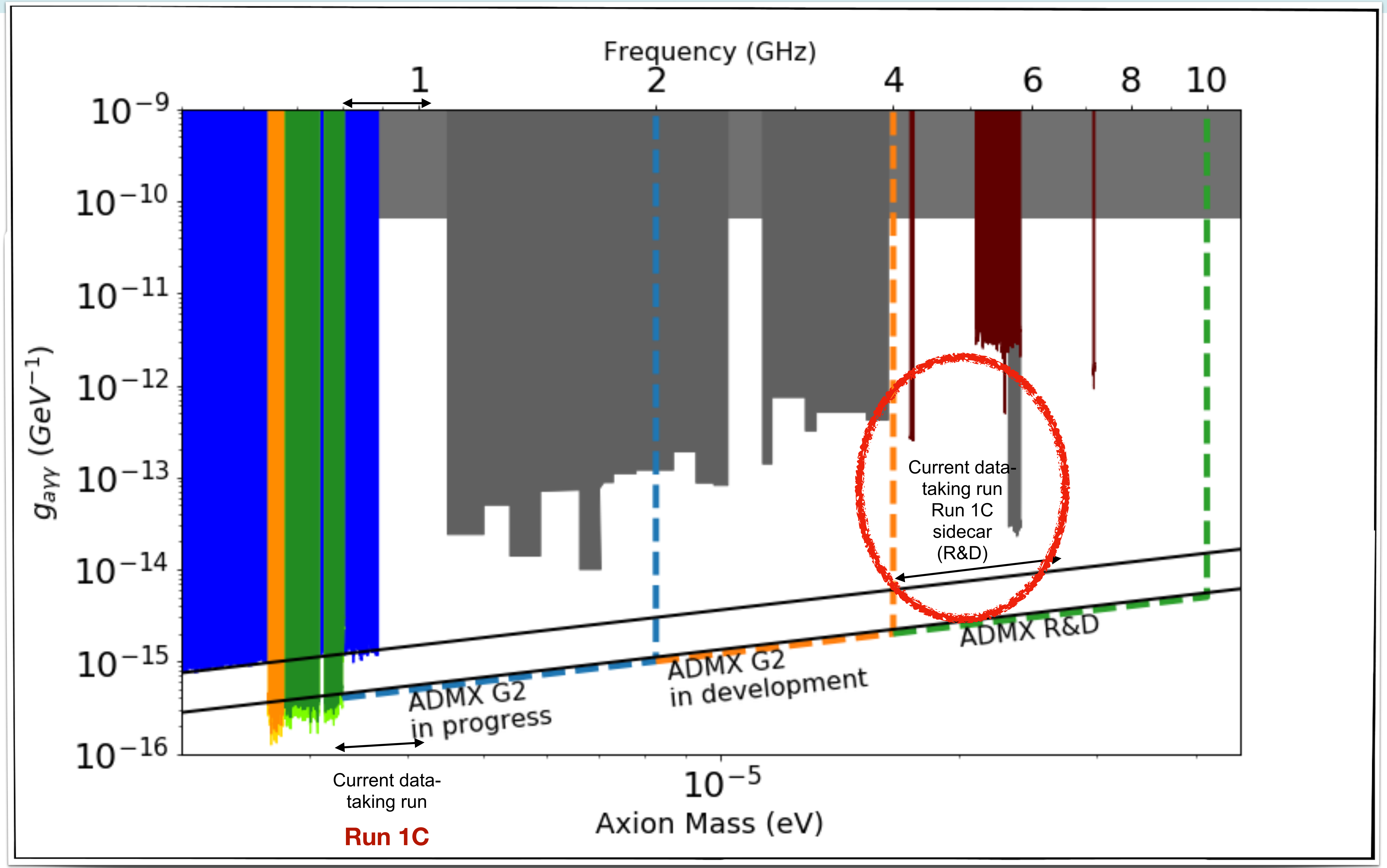
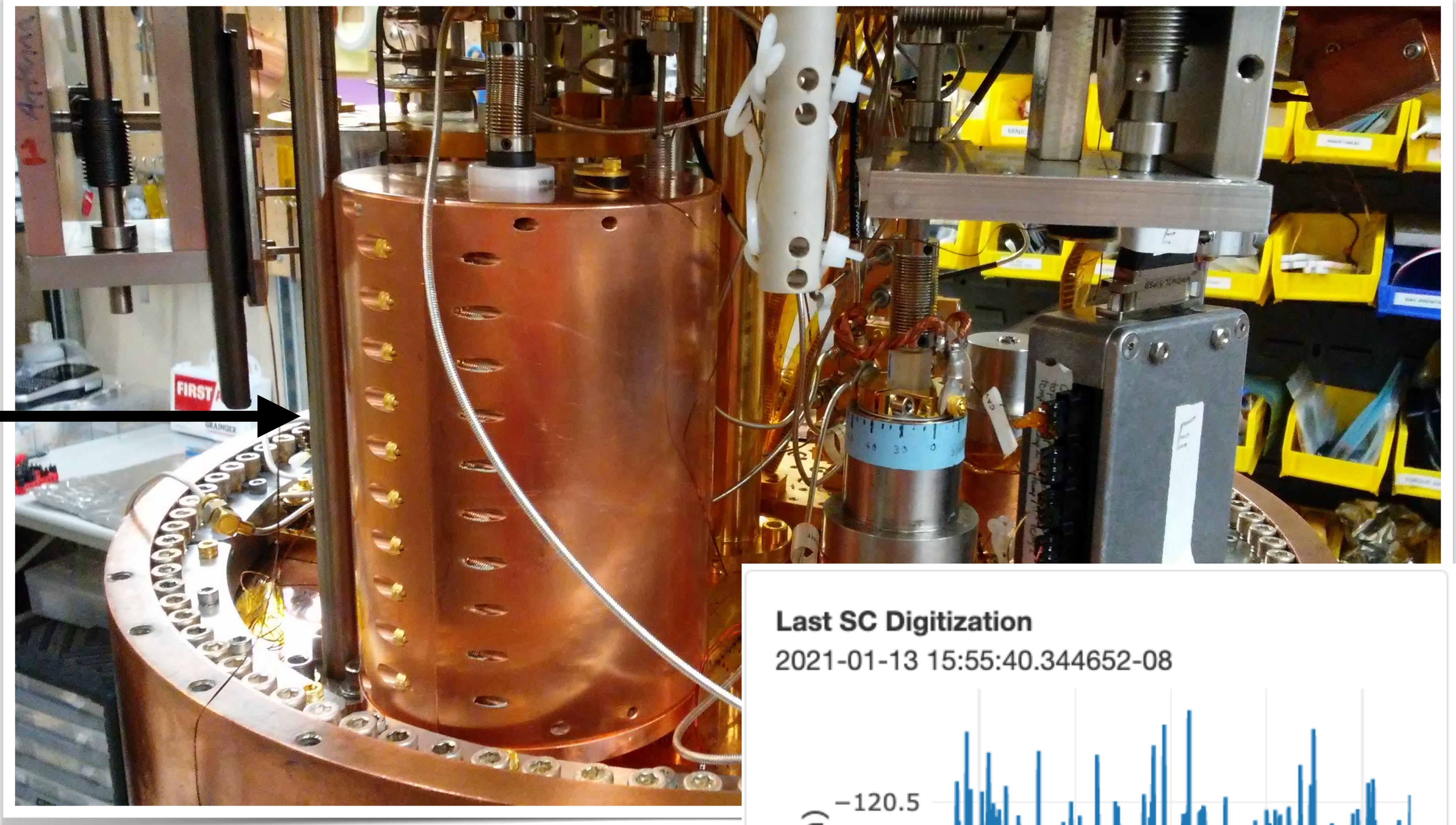
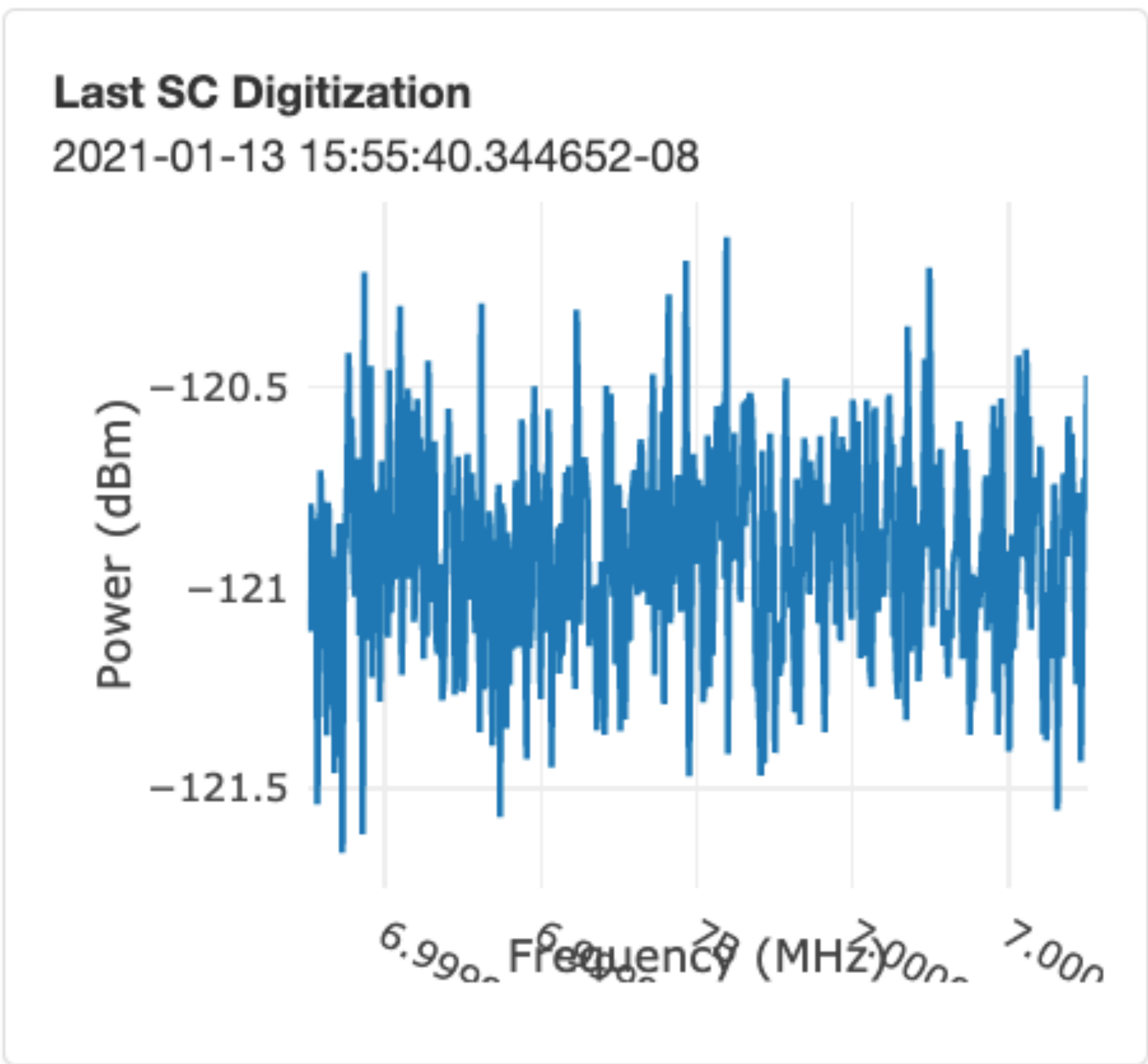


# ADMX R&D

## Sidecar Cavity and Receiver Chain

- Sidecar is a small prototyping cavity that sits on top of the main cavity.
- This iteration of sidecar is testing:
    - Traveling Wave Parametric Amplifier (TWPA).
    - Clamshell cavity design.
    - Piezo motors for antenna and tuning rod.

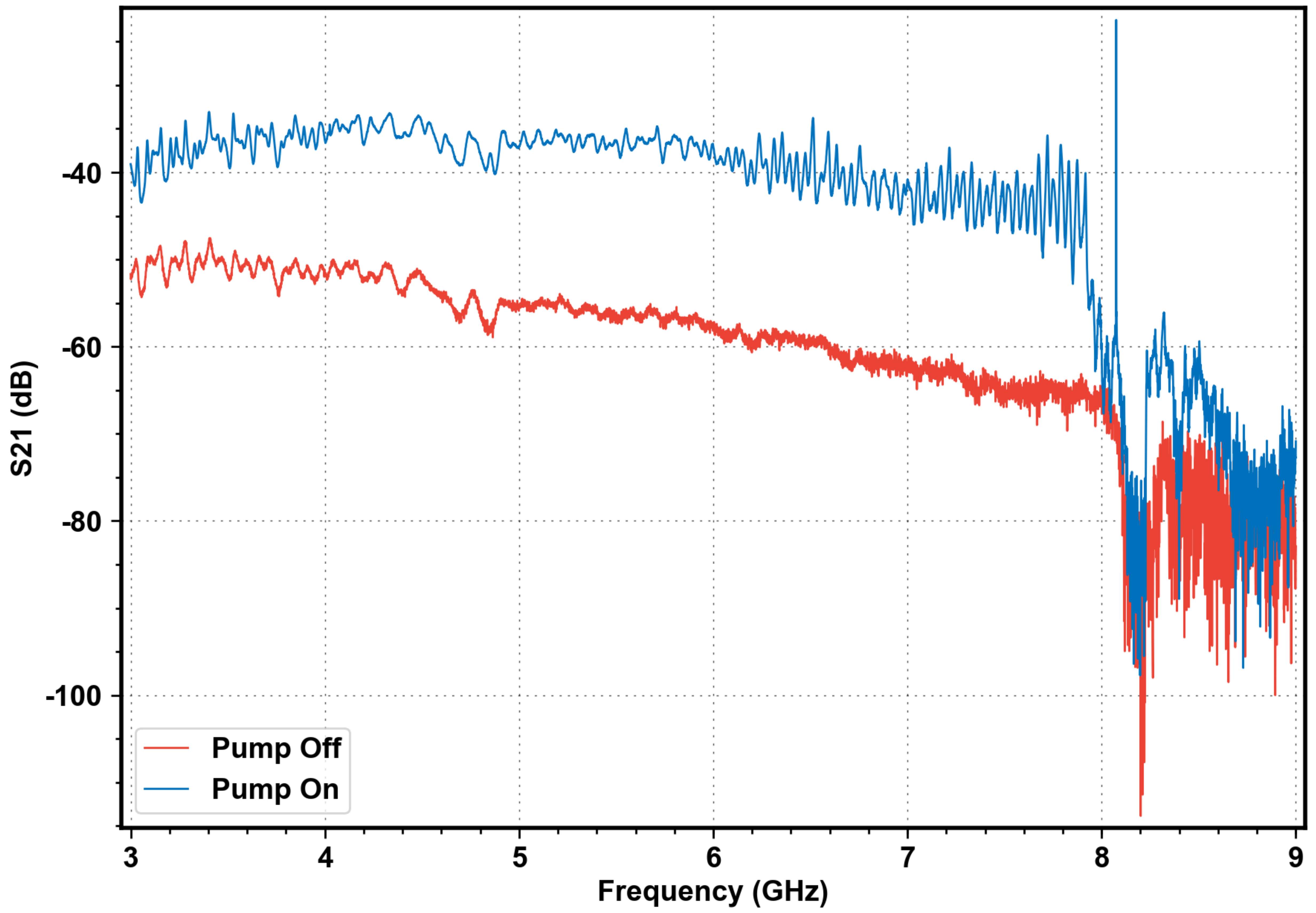




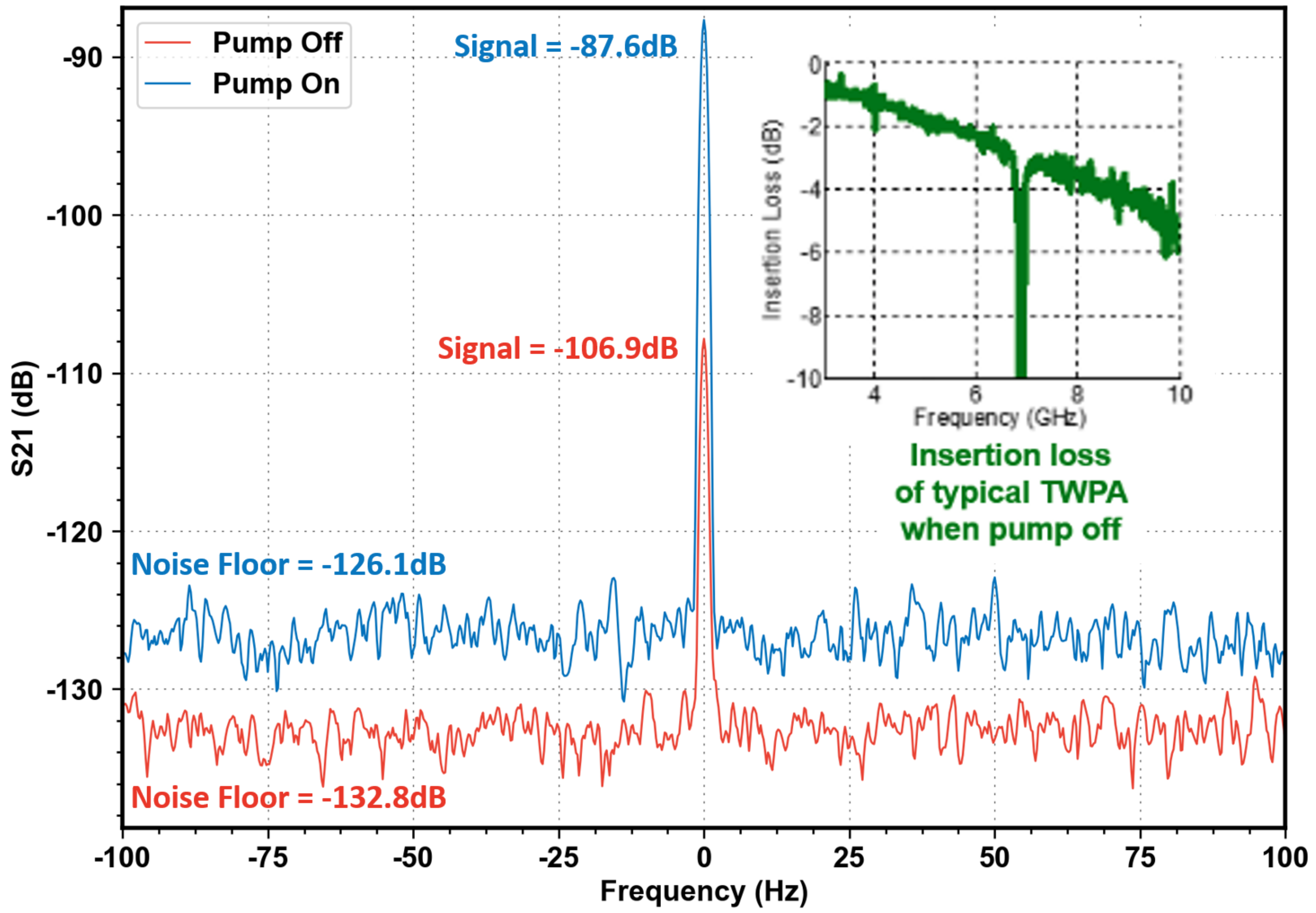

These are possible features of the future data-taking operations.

# ADMX R&D

## TWPA Gain




## TWPA SNR




Optimize the TWPA performance by adjusting the pump power and pump frequency

# Higher Frequencies

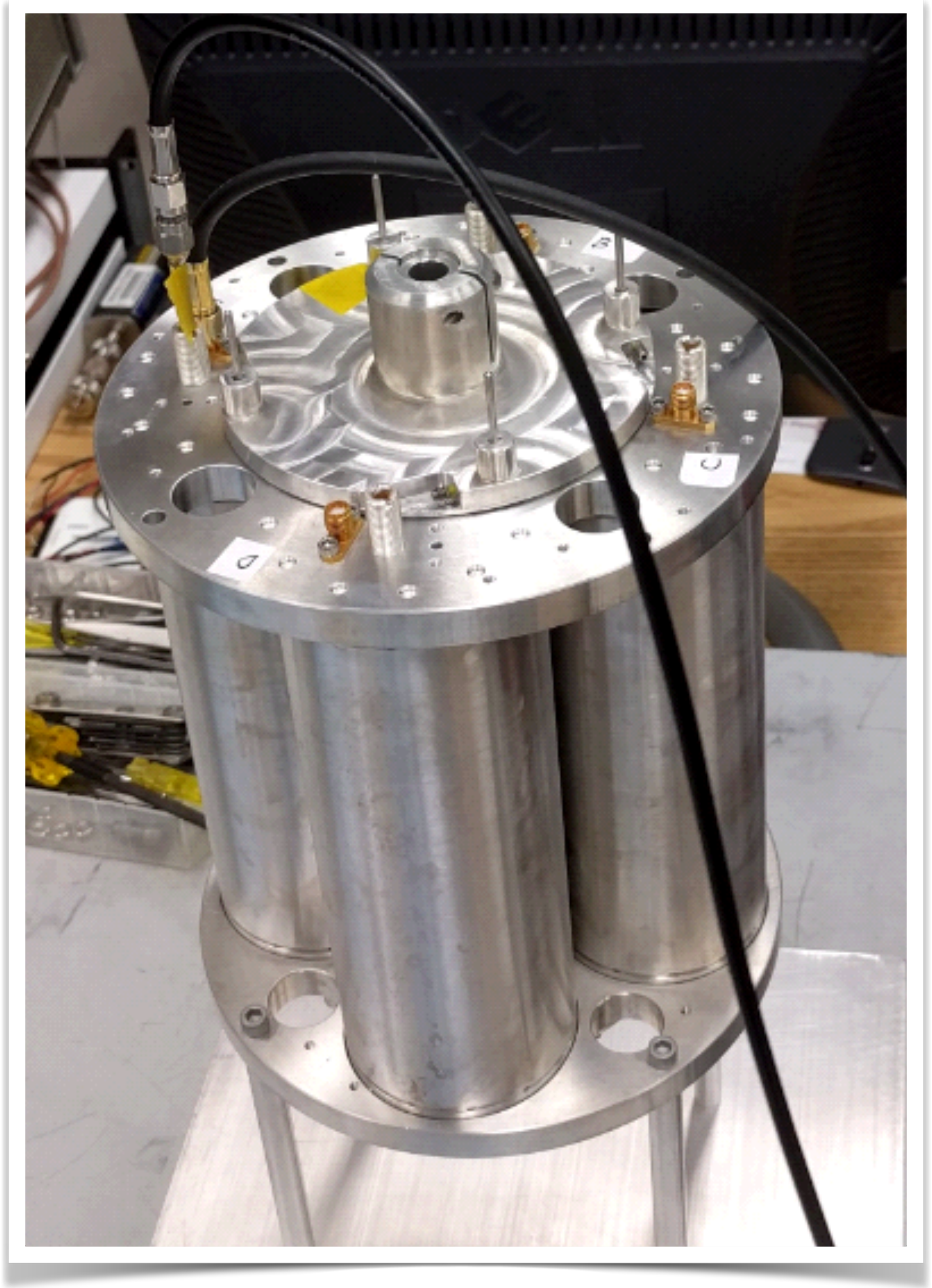
High Frequency → Smaller Volume → Slower Scan Rate

**We need solutions!**

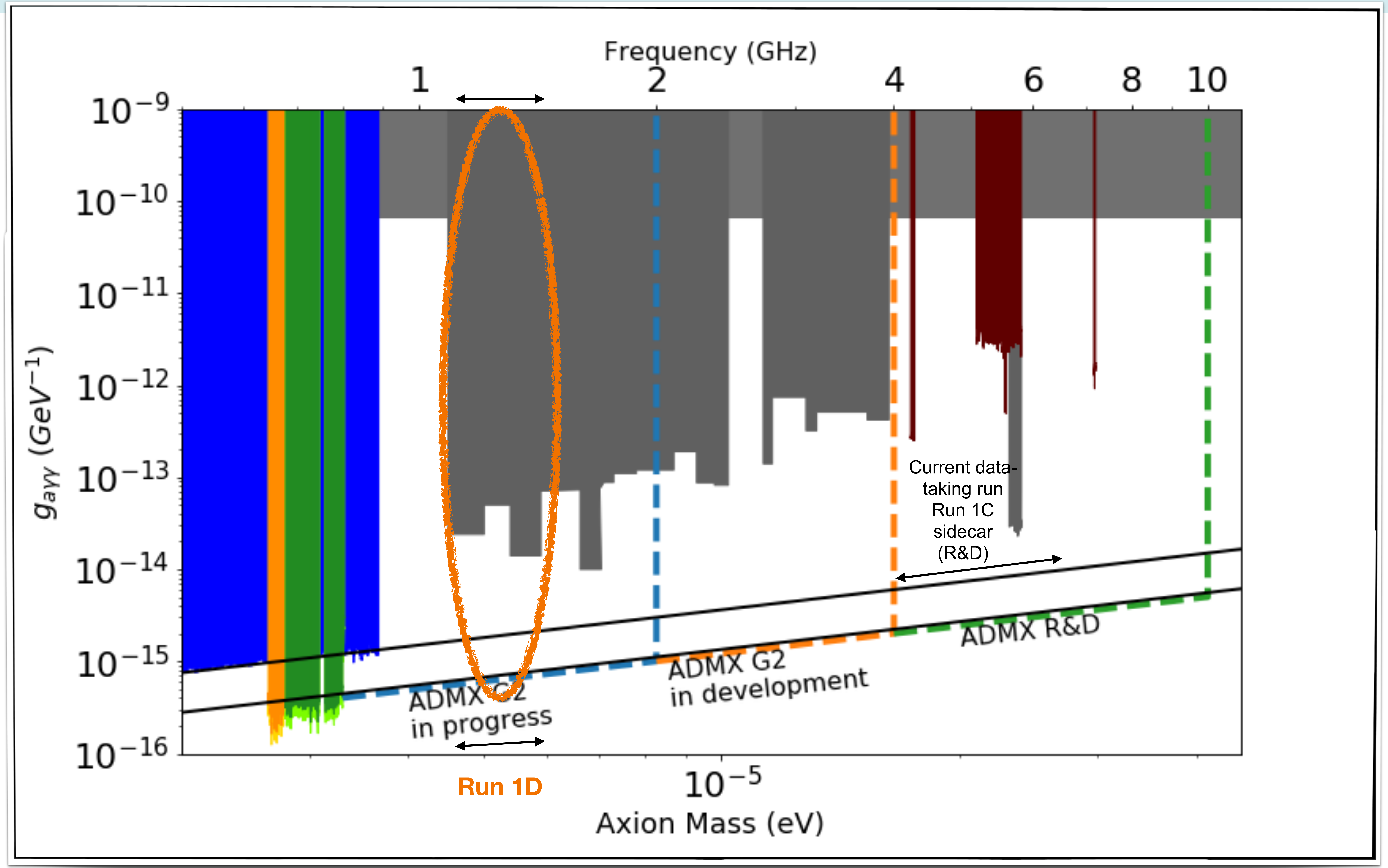
**ADMX:**

Near term: Multi-cavity arrays tuned synchronously
N cavities = sqrt(N) SNR improvement

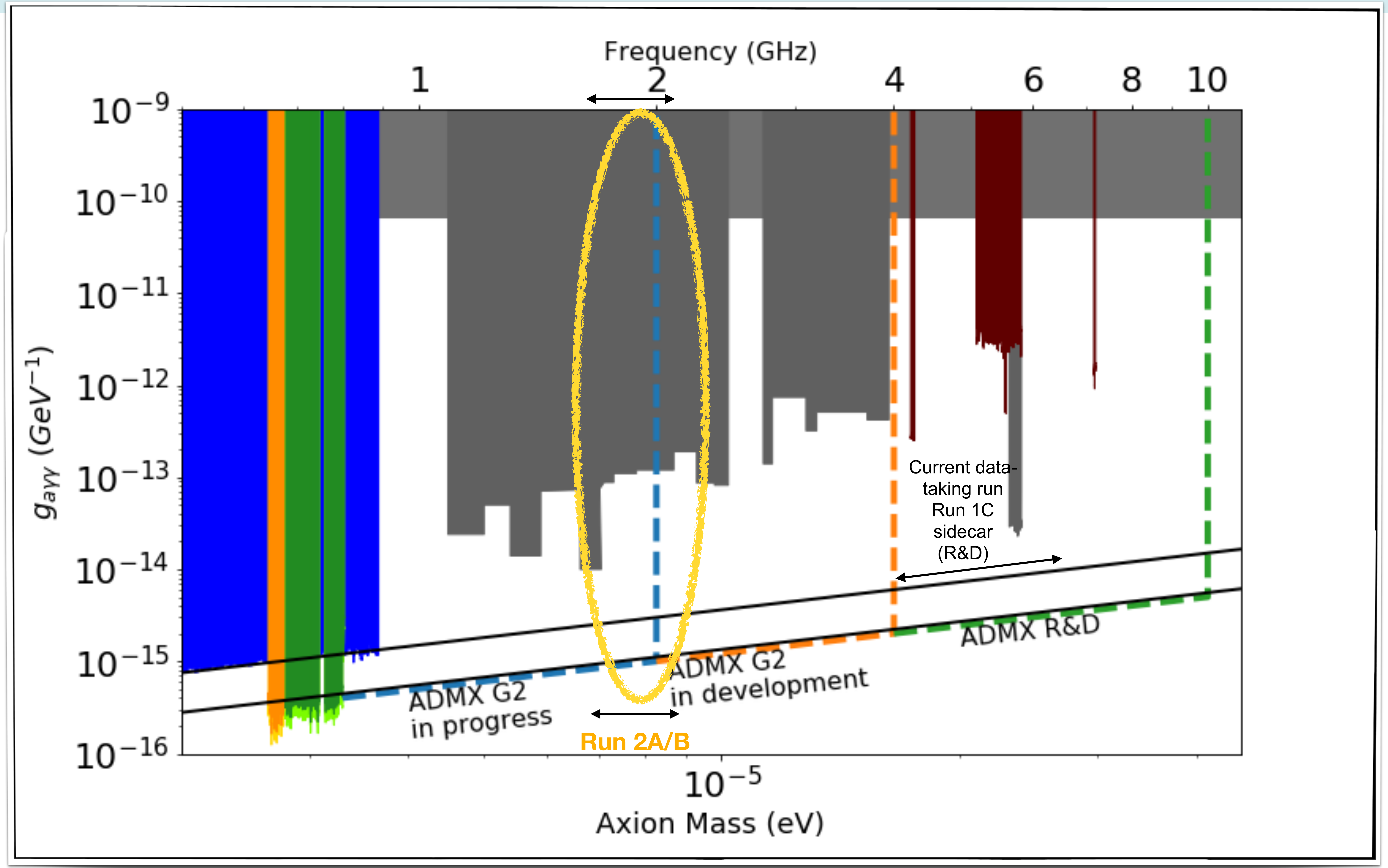
- Challenges:
  - Cavity frequencies must be locked together
  - Power combining must be performed
  - New piezo motors installed
  - Increase in complexity: cables x N!



# Projected ADMX Sensitivity

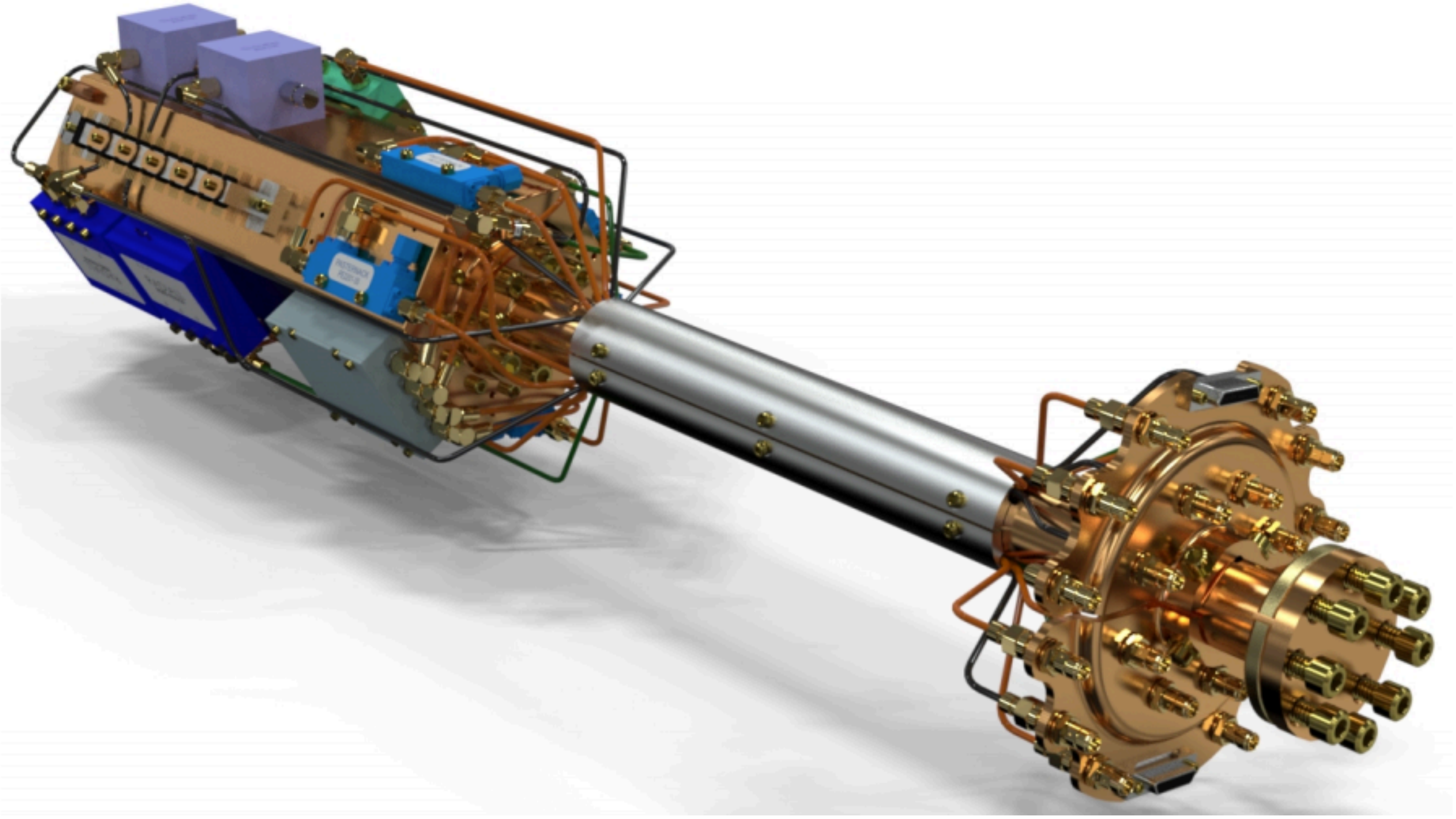


# Projected ADMX Sensitivity



# ADMX Run 2A/B (Sited at UW)

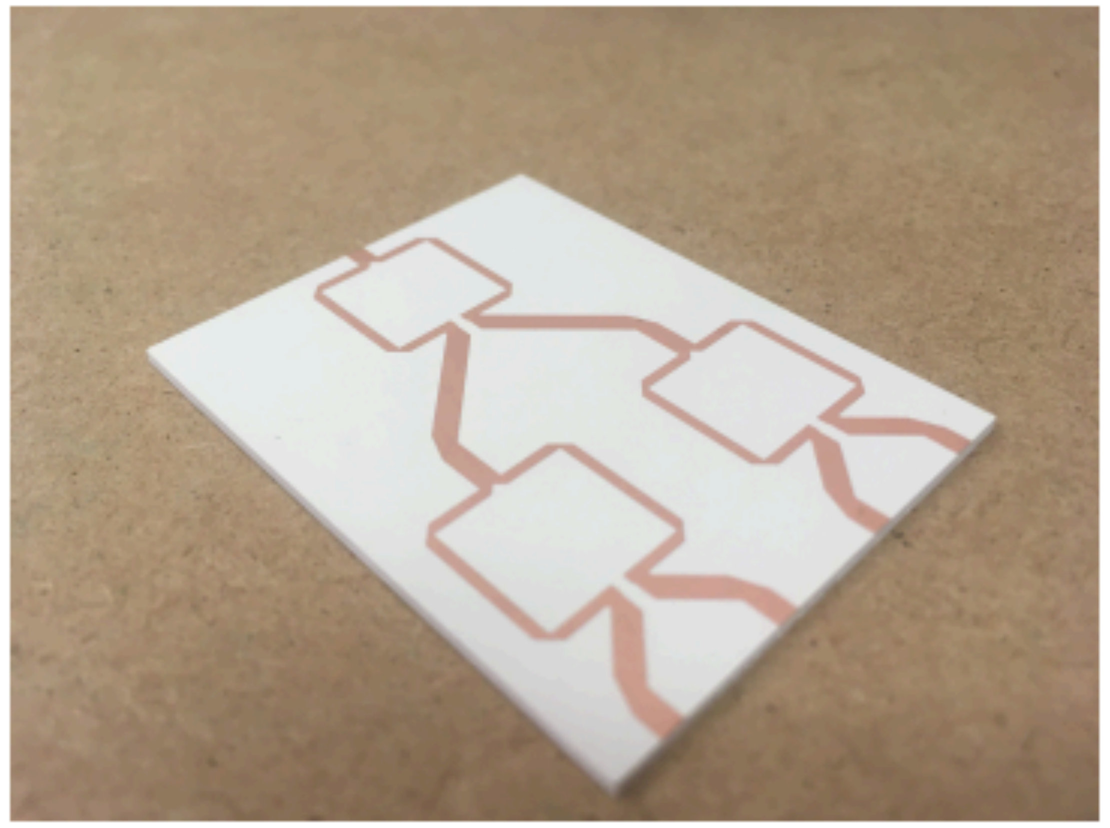
- 4 cavity array with common rotor. Frequency fine-tuned with sapphire mounted to linear stages
- 1.4-1.8 GHz frequency range (Run 2A)
- Volume ~76 liters
- Q~130,000
- Quantum Electronics Package Upgrades

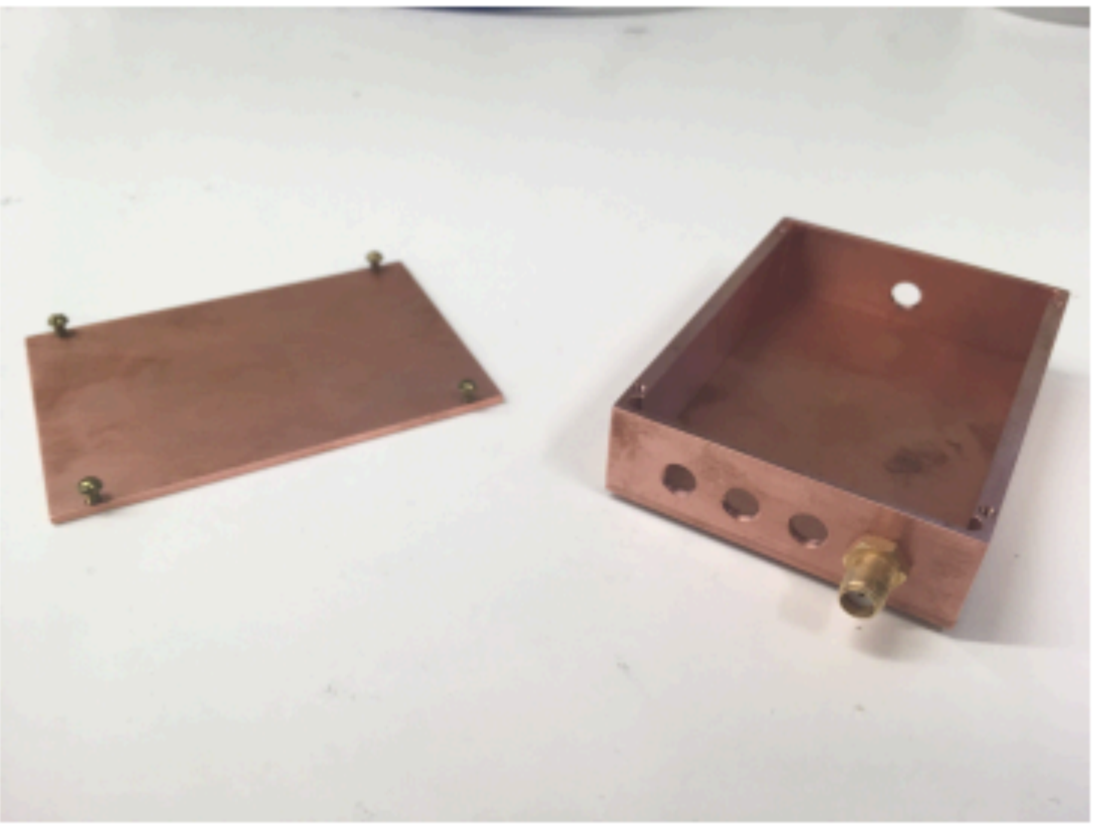


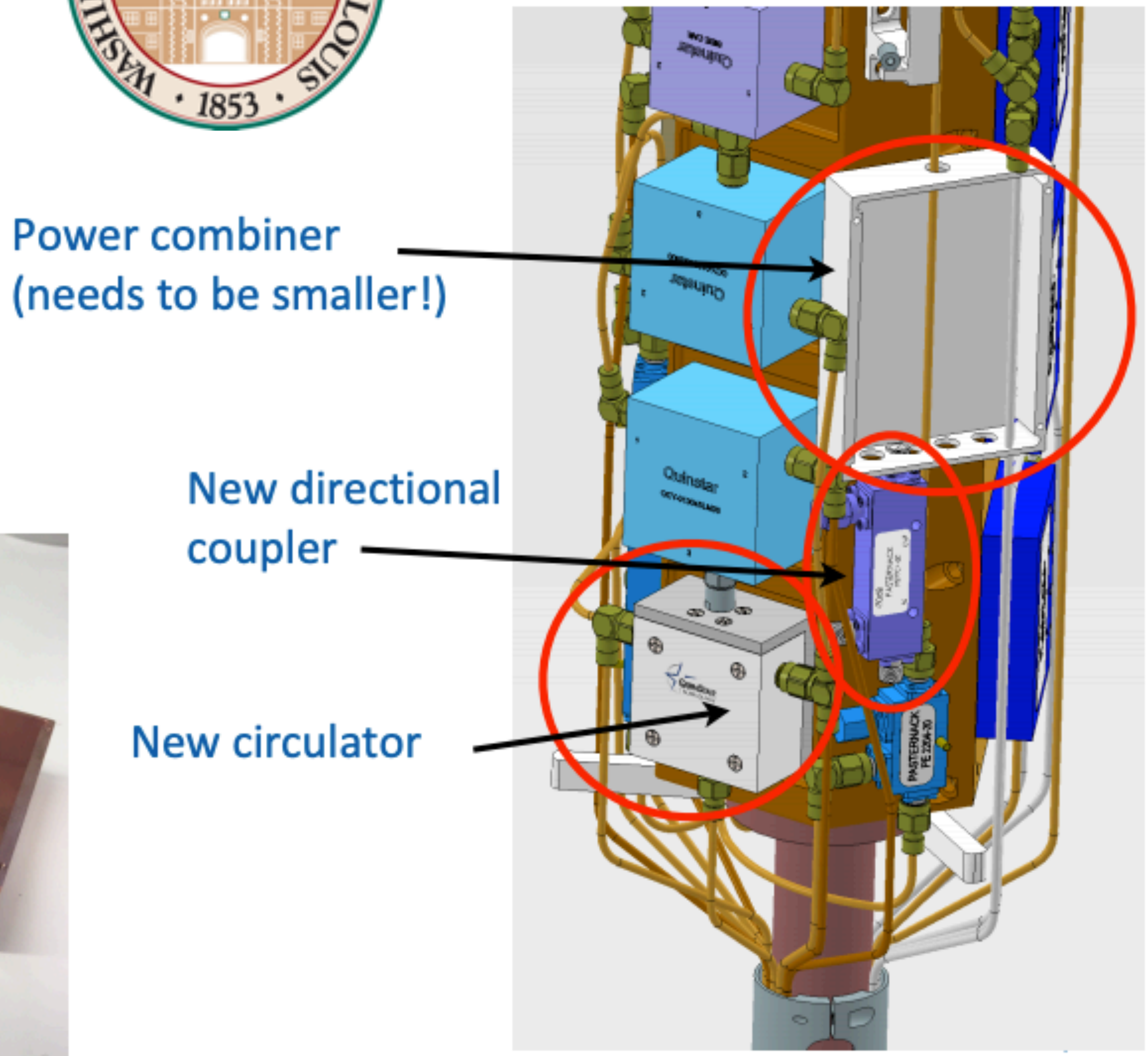
# ADMX Run 2A/B

New components require a new quantum electronics package

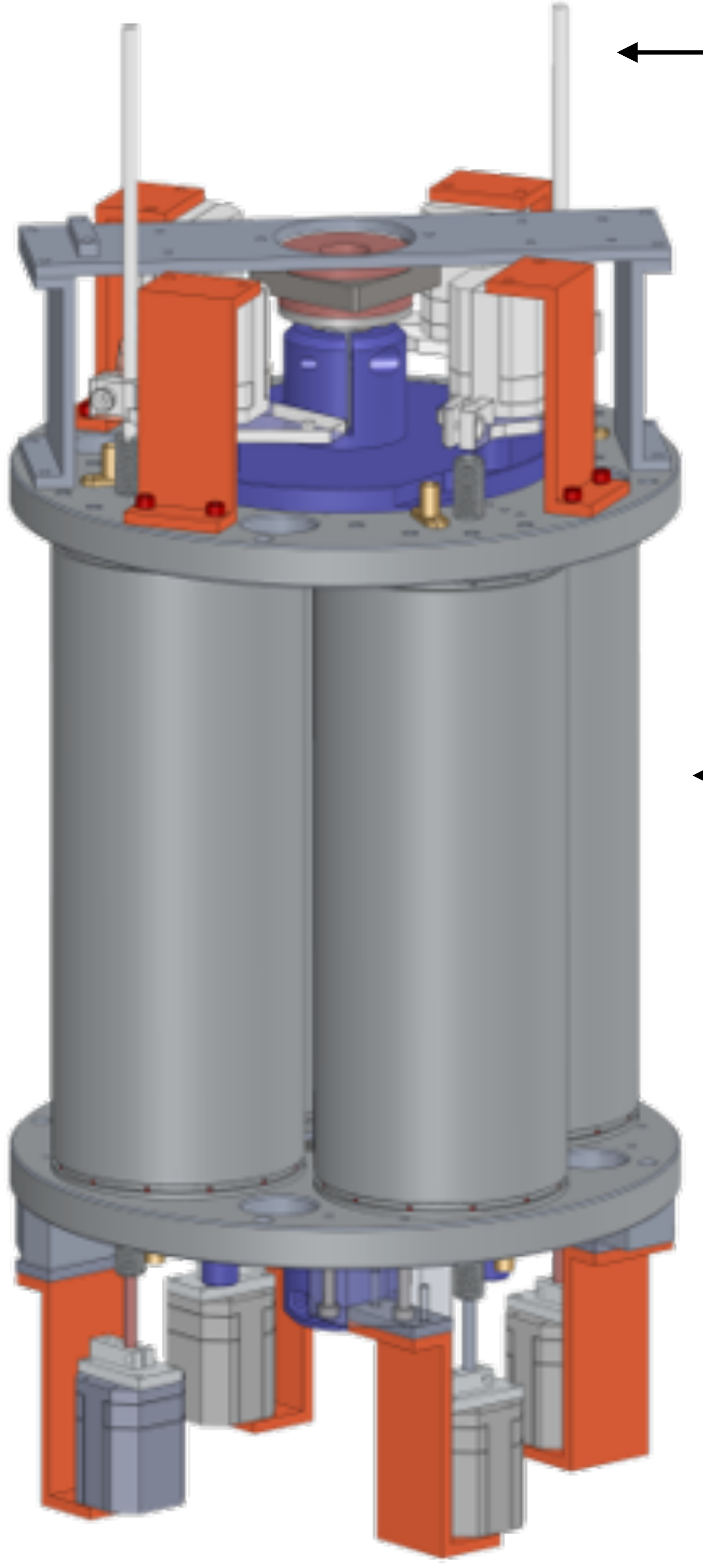
- Wilkinson Power Combiners designed at Washington University of St. Louis
- Ideal transmission is -6 dB, additional insertion loss < 0.4 dB
- Testing in agreement with their simulations

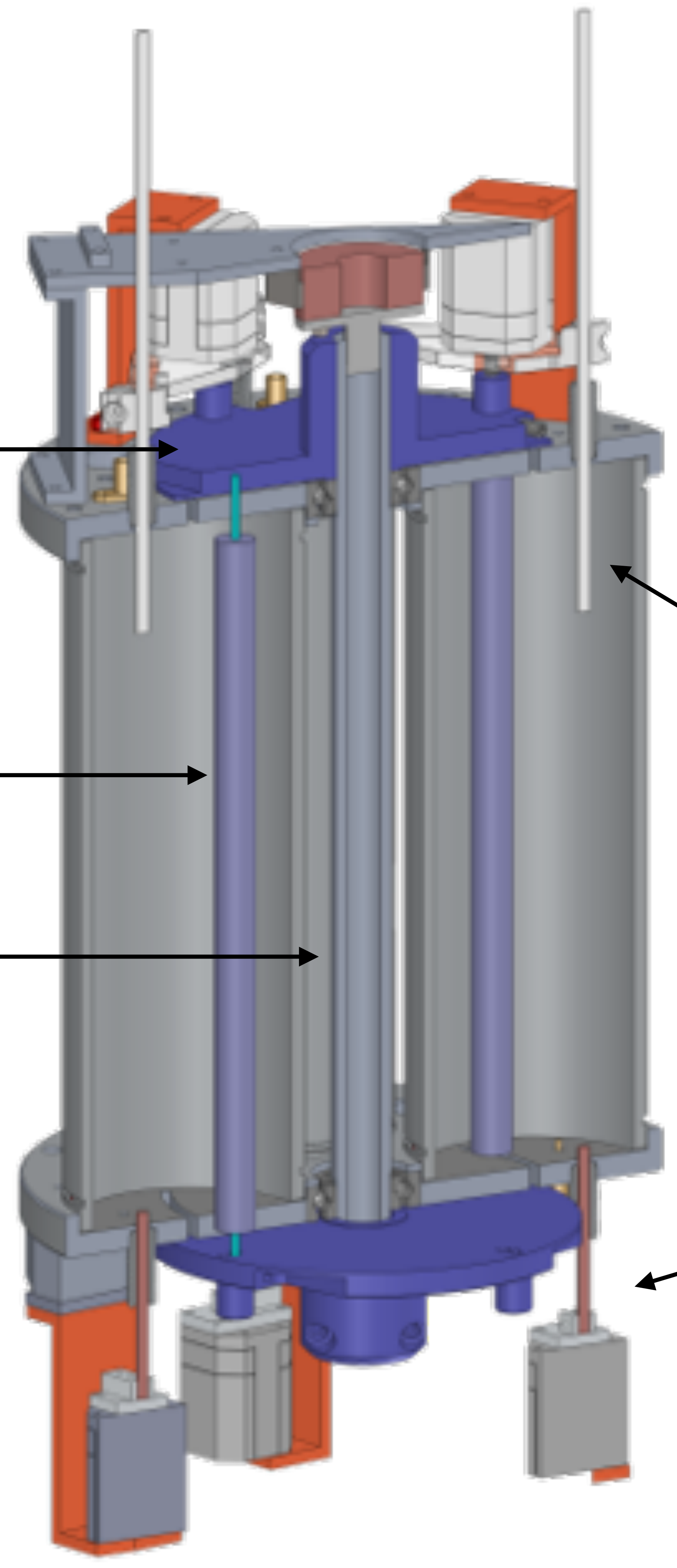






# Prototype Study



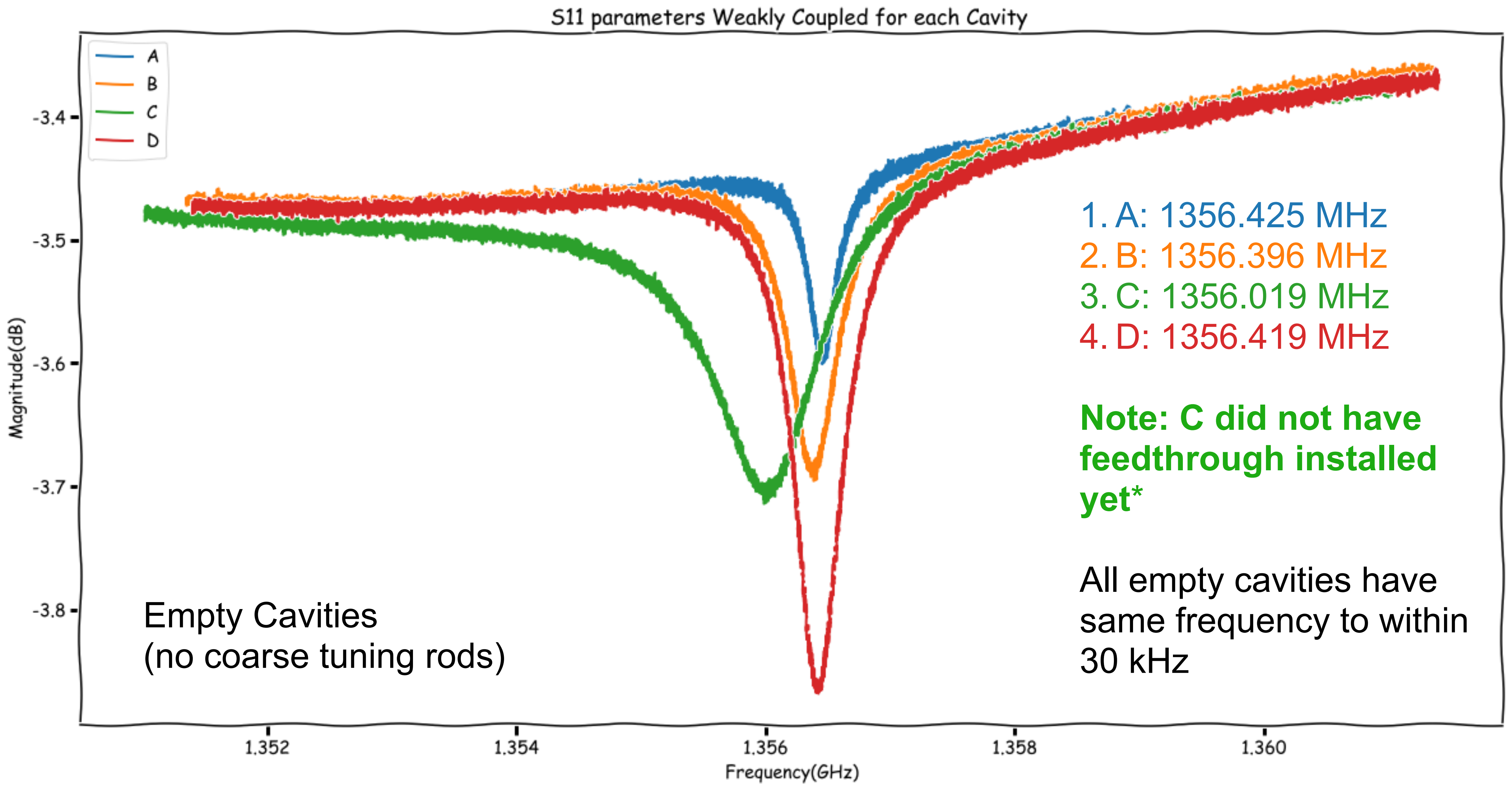

Images courtesy of Jihee Yang

# Run 2A/B System

- 4-Cavity Main Cavity Assembly at LLNL
- Copper Cavity Plating at LLNL

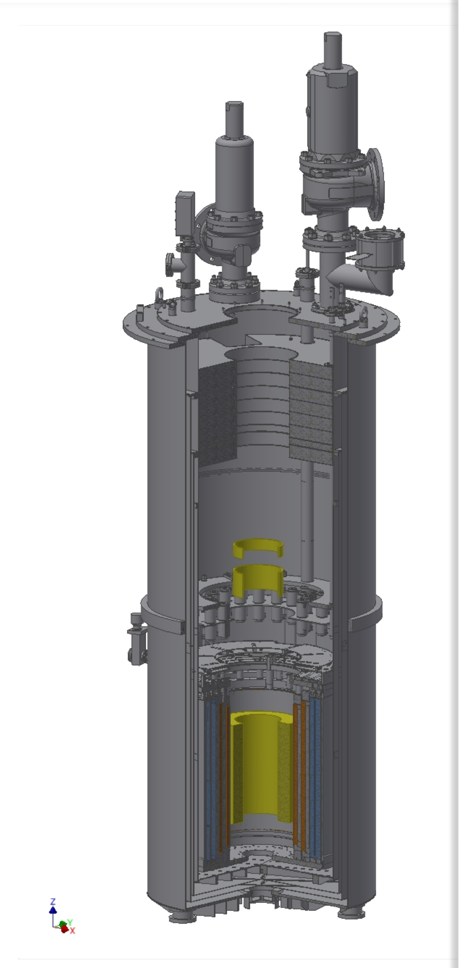
Staff scientist Nathan Woollett ←

Graduate student Tom Braine working on the cavities at Livermore →

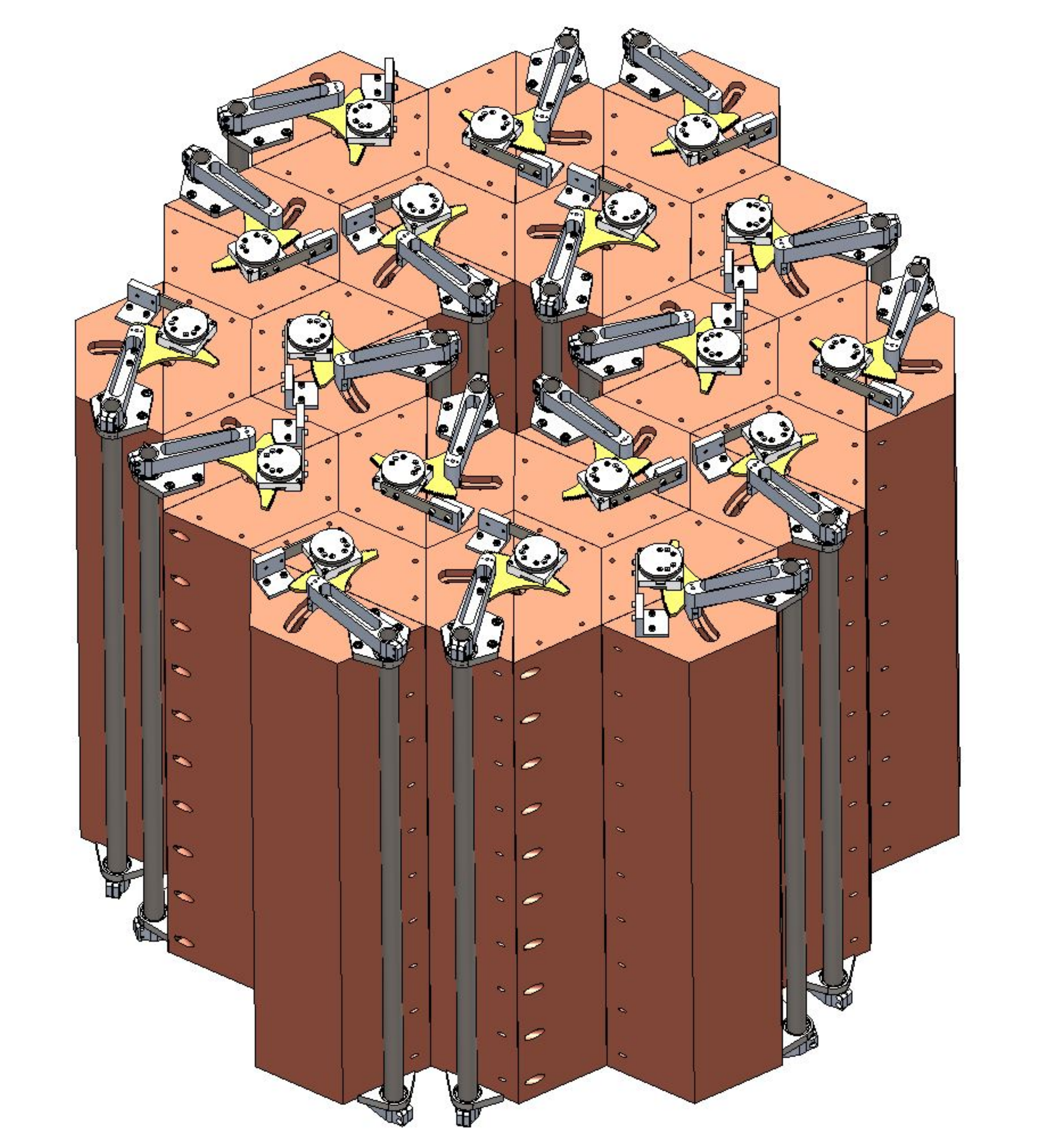


# ADMX 2-4 GHz run (site uncertain)

- **New magnet?**
  - Desirable Properties:
    - High field
    - Large bore
- **New Cavities?**
- Desirable Properties
  - High Tc superconducting walls with higher Q
- **Detector Improvements?**
  - Digital combining
  - Squeezing



Variety of magnets being investigated



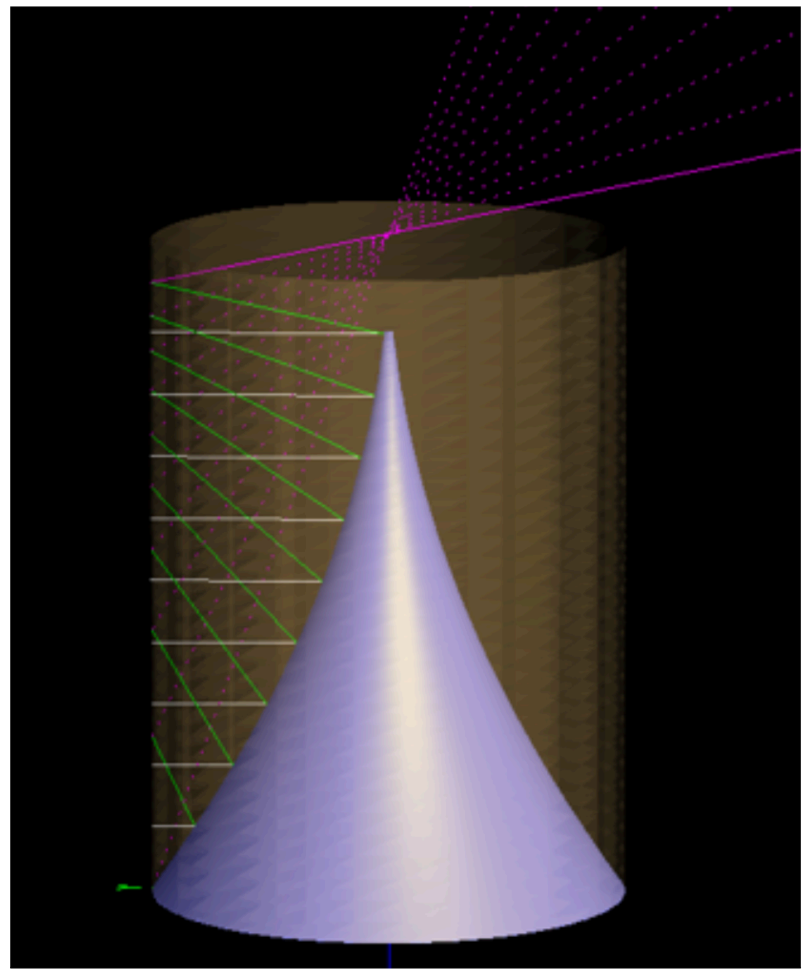
Design still in progress!

Tune in for Mark Bird's talk Thursday morning for more magnet details

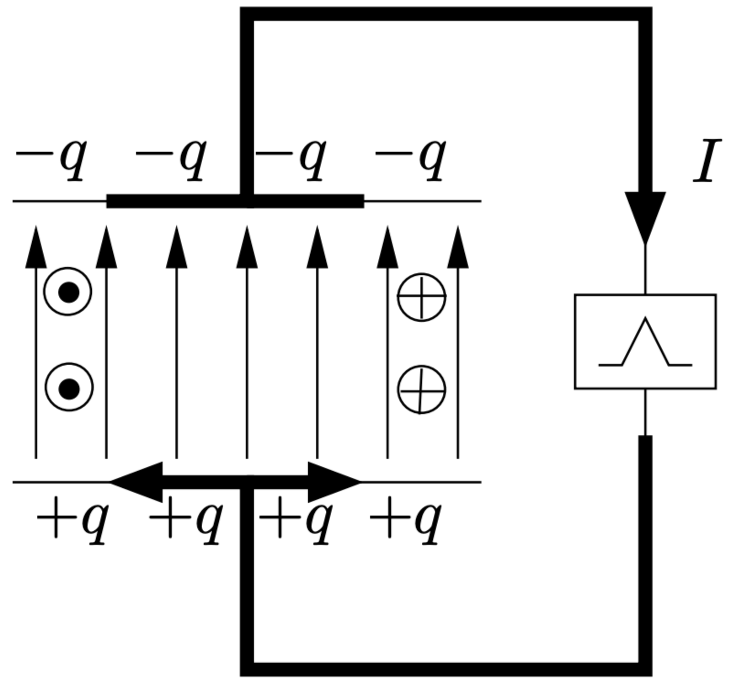
# ADMX Beyond Gen 2

## New ideas being explored with collaborators

- Andrew Sonnenschein: Broadband 'Lighthouse' Detector (BREAD collaboration)
  - Coaxial dish antenna concept to focus light
  - Requires single photon counting capabilities
  - Broadband capabilities
- Ed Daw: Resonant Feedback Concept
  - Resonant feedback using FPGA filters
  - Possibility of generating multiple resonances
  - Broadband capabilities
- Akash Dixit: Single photon counting with qubits
  - Need to develop techniques to transport the photon
  - Investigate magnetic field performance
  - Possibility of starting cavity in high N Fock state

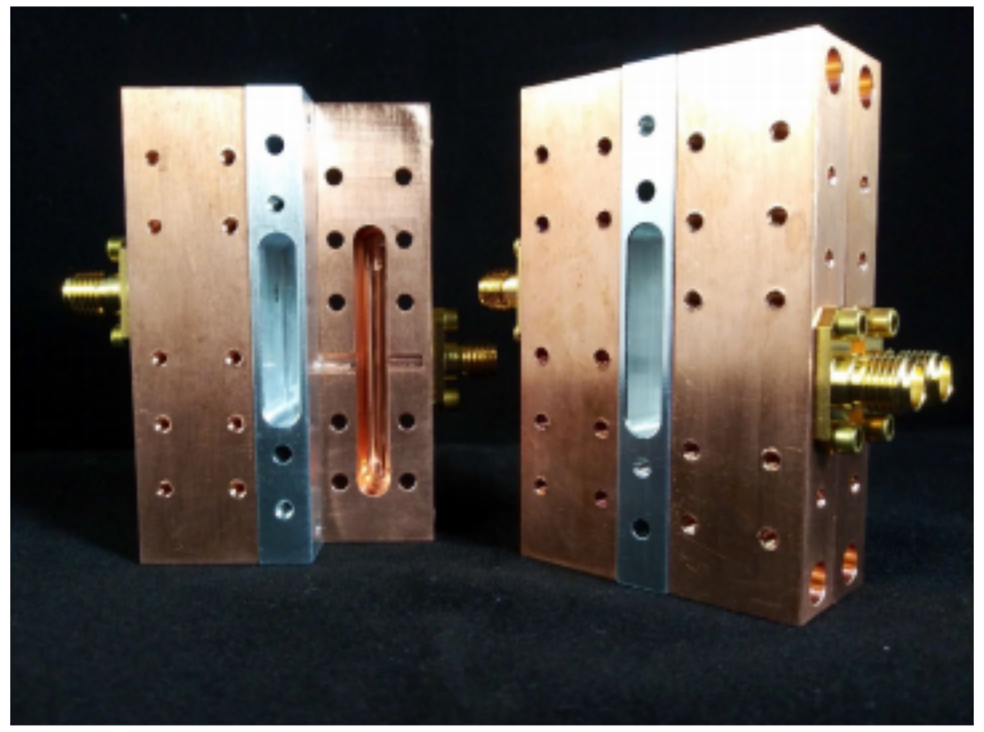


Andrew Sonnenschein




Resonant feedback

Ed Daw



Akash Dixit

# Conclusions

- ADMX Run 1B achieved DFSZ sensitivity for 100% axion dark matter density in the range from 680–800 MHz, corresponding to a mass range from 2.81–-3.31 μeV.
- Run 1C currently underway and aims to exclude axion dark matter in the mass range of 3.2—4.2 μeV (780–-1010 MHz)
- ADMX is on track to continue its search for axions. Discovery could happen at any moment!
- Progress being made towards higher frequency searches.

ADMX Run 1C Commissioning

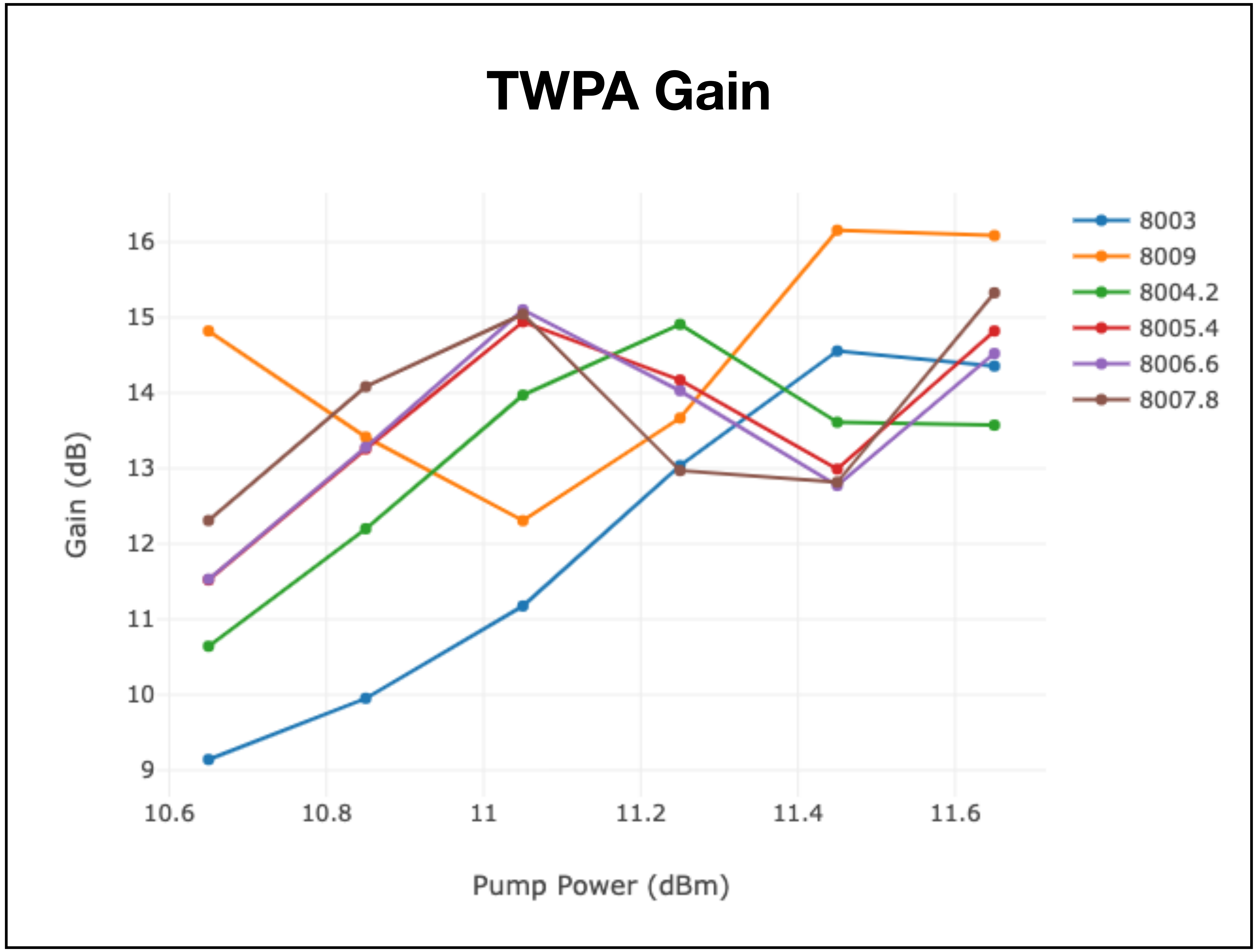

# ADMX Collaboration at Fermilab 2018

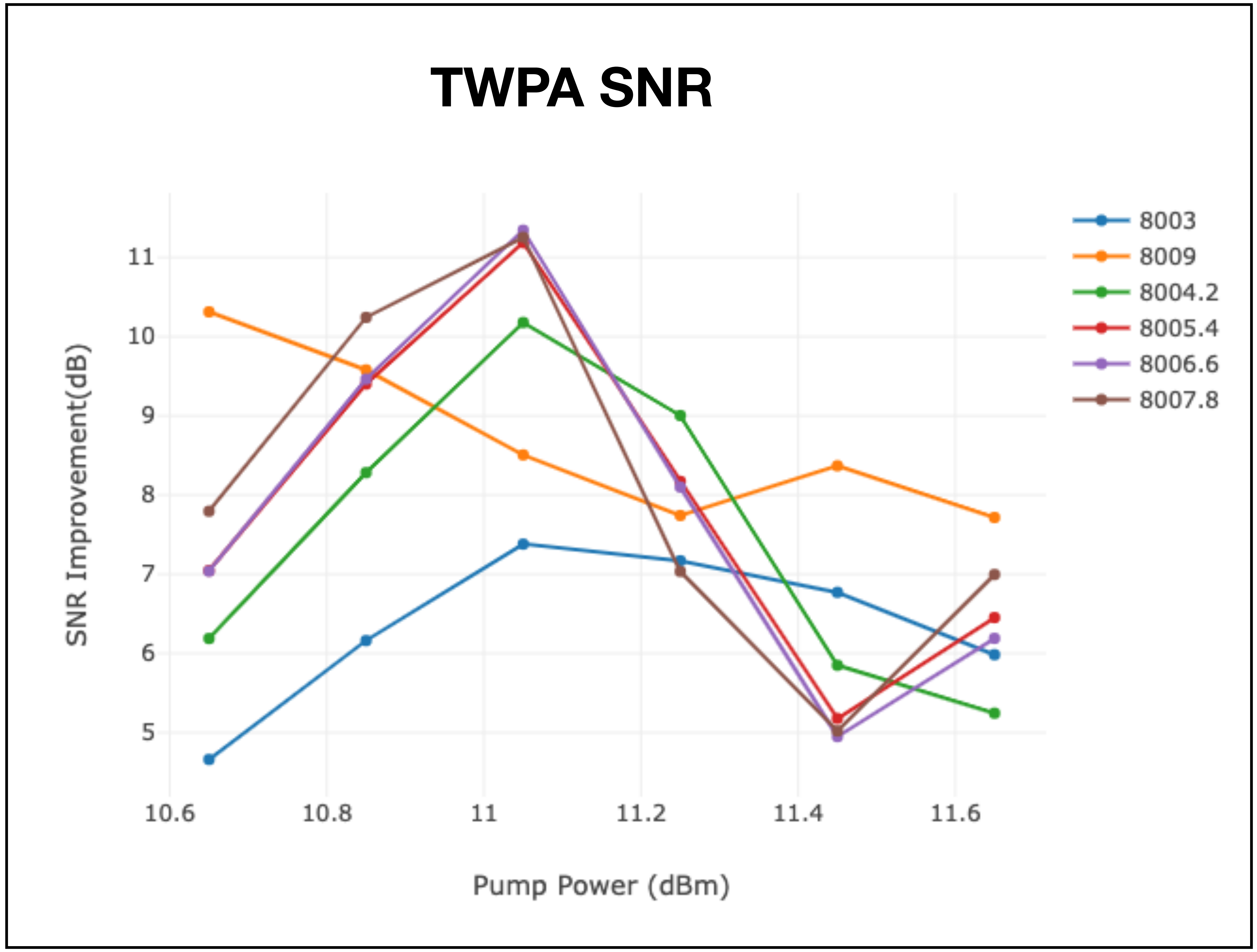
This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

# Thank you!

# Questions?

# ADMX R&D




Optimizing the TWPA performance by adjusting the pump power and pump frequency