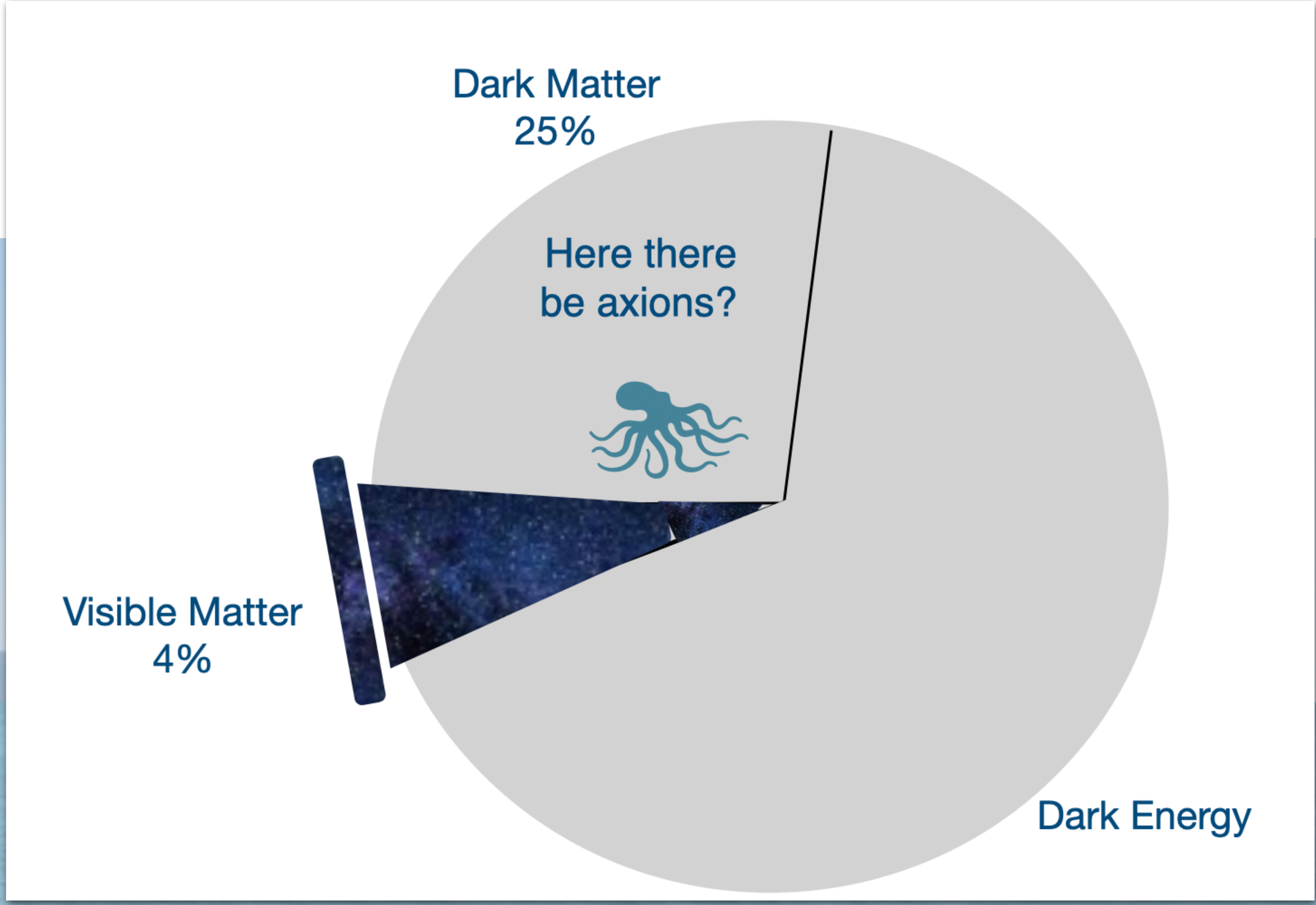
Finding the signal in the noise: an exploration of the Axion Dark Matter eXperiment analysis

Chelsea Bartram

10/28/2020

What are axions?



Wave-like dark matter

- What does this mean?

$$a(\vec{x}, t) = \frac{\sqrt{(2\rho_{DM})}}{m_a} \cos\left(m_a t + \mathcal{O}(\nu_{DM})\vec{x}\right)$$

ρ_{DM}: dark matter density
m_a: axion mass

Calculate de Broglie wavelength of axions:

$$\lambda \approx \frac{2\pi}{mv} \approx \text{10 m - 100 km}$$

Wavelength of the Conversion Photon: ~meter

11/9/20

Axions and Strong CP Problem

Strong Interactions -should- violate CP due to term in QCD Lagrangian

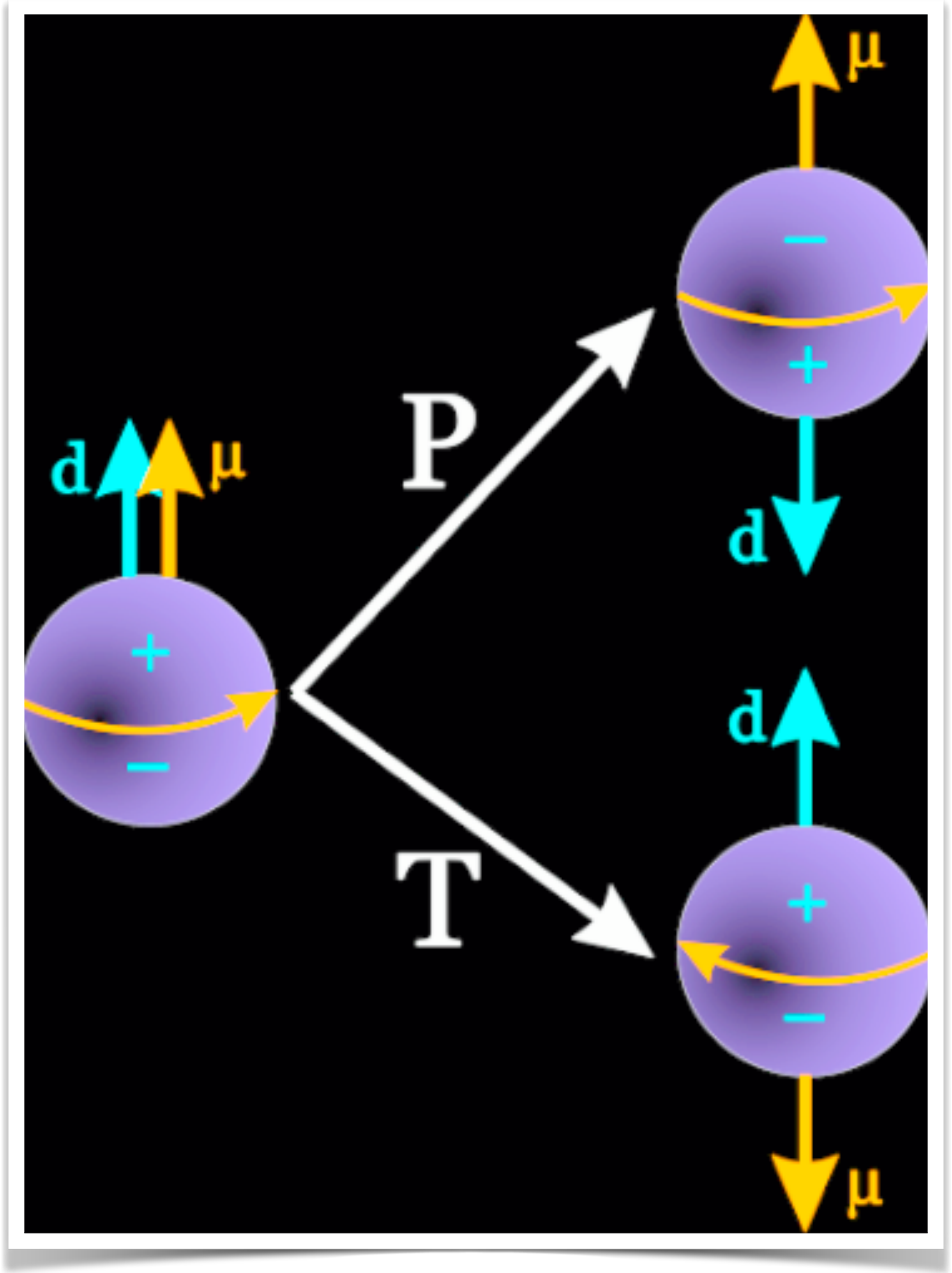
$$L_\theta = \frac{g^2}{32\pi^2}\theta_{QCD} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

CP-violation in strong interactions $\longrightarrow$ Neutron EDM

- New limit on neutron EDM published this year!
- After many years searching: Still no neutron EDM!

$$\mathrm{d_n} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26} \mathrm{e{\cdot}cm}$$

C. Abel et al.
Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

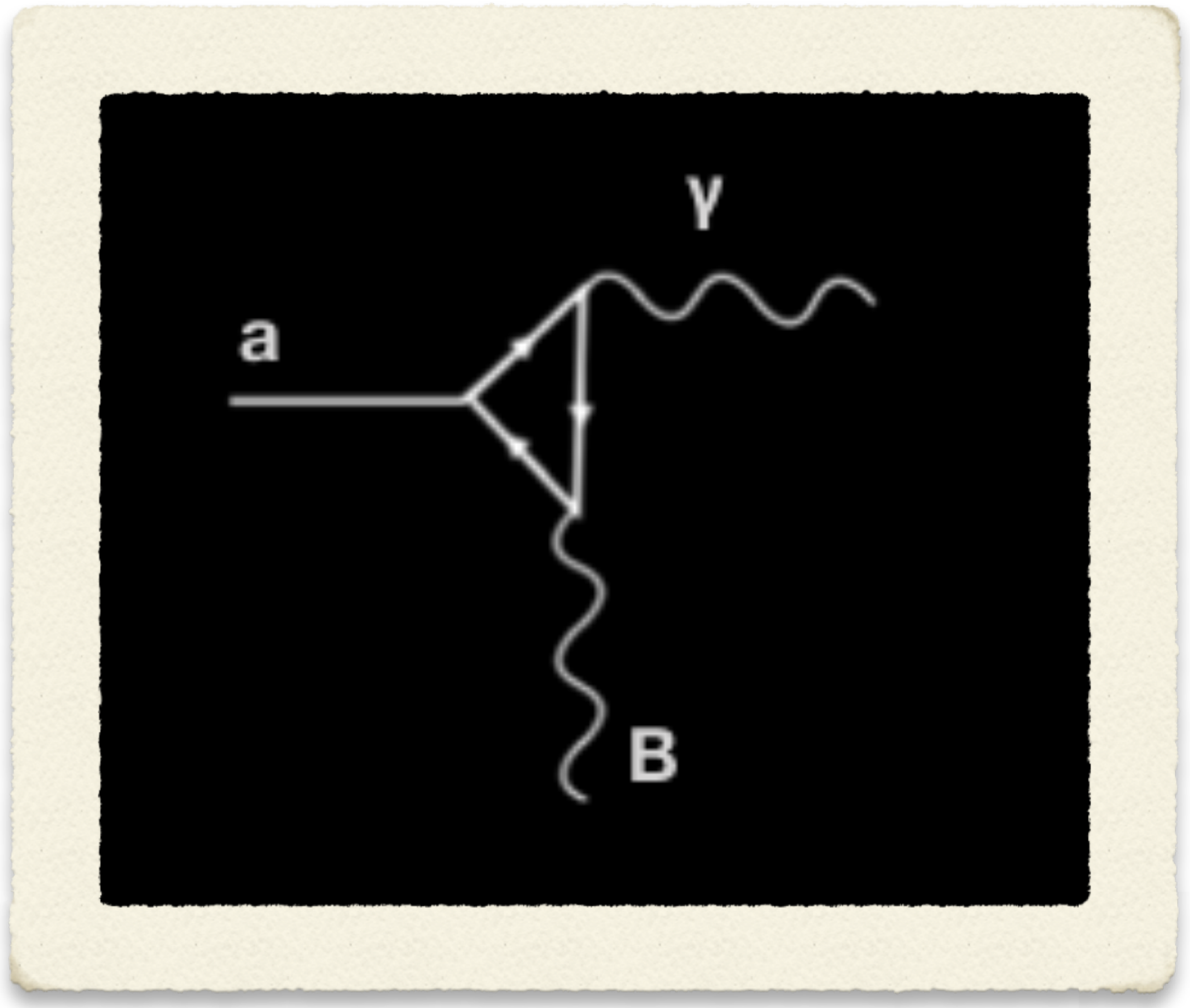


https://www.physics.uoguelph.ca/radon-electric-dipole-moment

Axion Benchmarks

- 1-100 μeV mass range to constitute entirety of dark matter

- Two classes of models:
  - **KSVZ (Kim-Shifman-Vainshtein-Zakharov)**:
    - couples to leptons
    - Range of g_γ values, typically g_γ=-0.97 used
  - **DFSZ (Dine-Fischler-Srednicki-Zhitnitsky):**
    - couples to quarks and leptons
    - Range of g_γ values, typically g_γ=0.36 used



Axion Benchmarks

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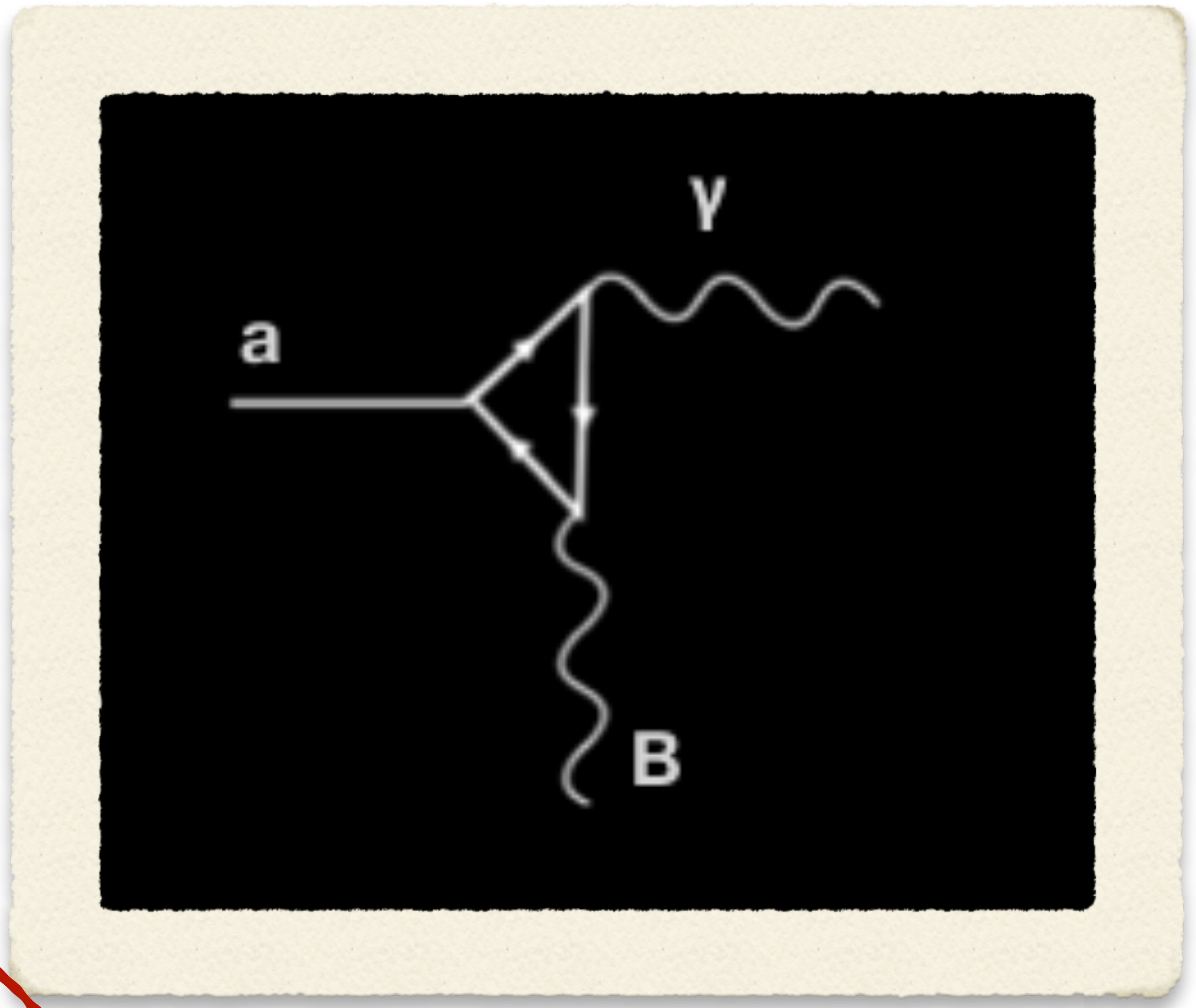


Hardest to detect!

Some more numbers…

Just how small is our signal?
“Yoctowatts” or 10^{-23} watts!

This is the smallest named unit by the SI International Standard of Units

This implies some other small numbers

- 100 mK temperatures. Colder than interstellar space! (~3 K).
- 8 T magnet field. Stronger than your typical MRI magnet! (~3T).

ADMX Collaboration

- Founded in 1994 at LLNL
- One of 3 “Gen-2” Dark Matter Projects
- Now located at University of Washington

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

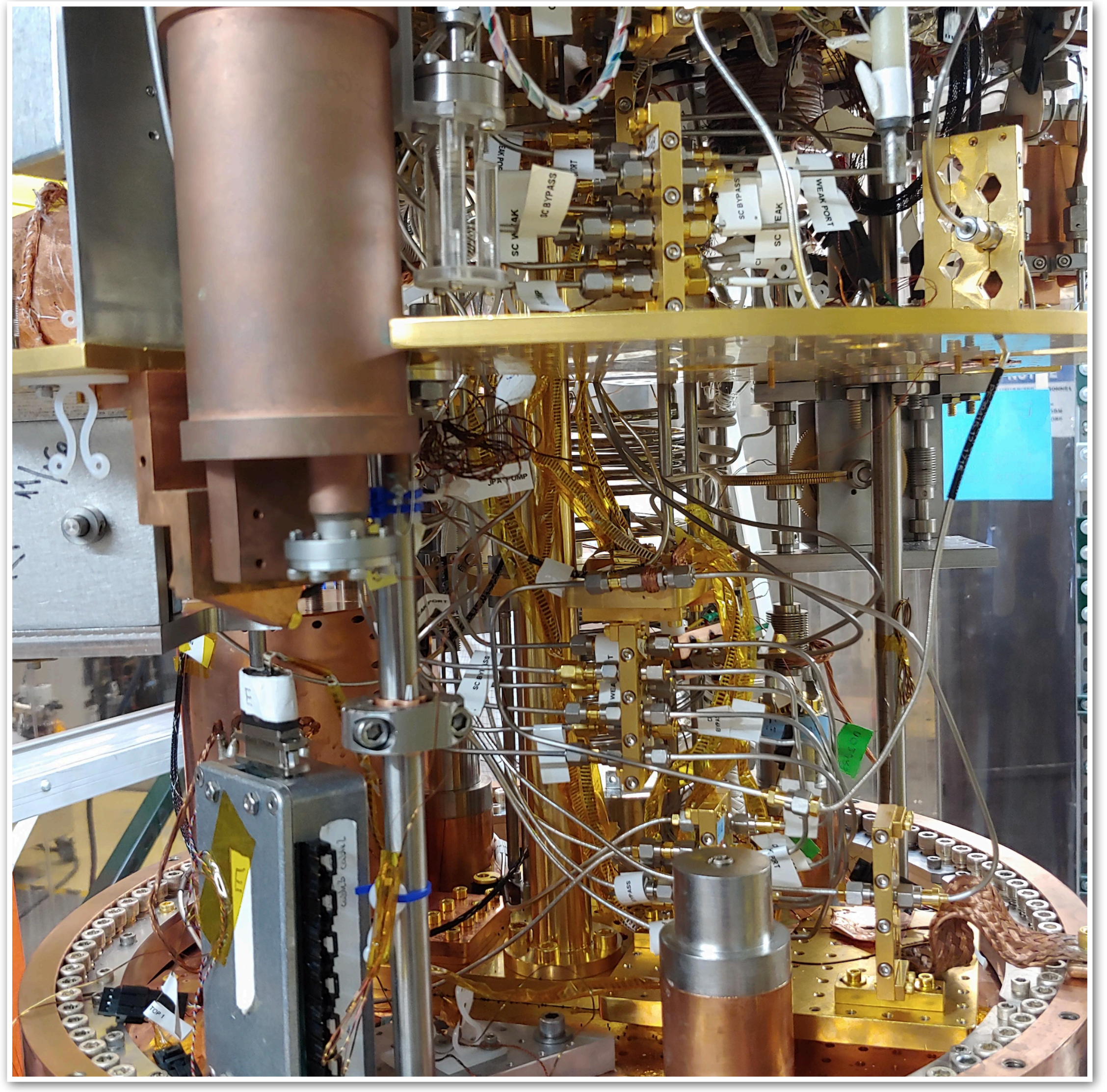
How to detect an axion

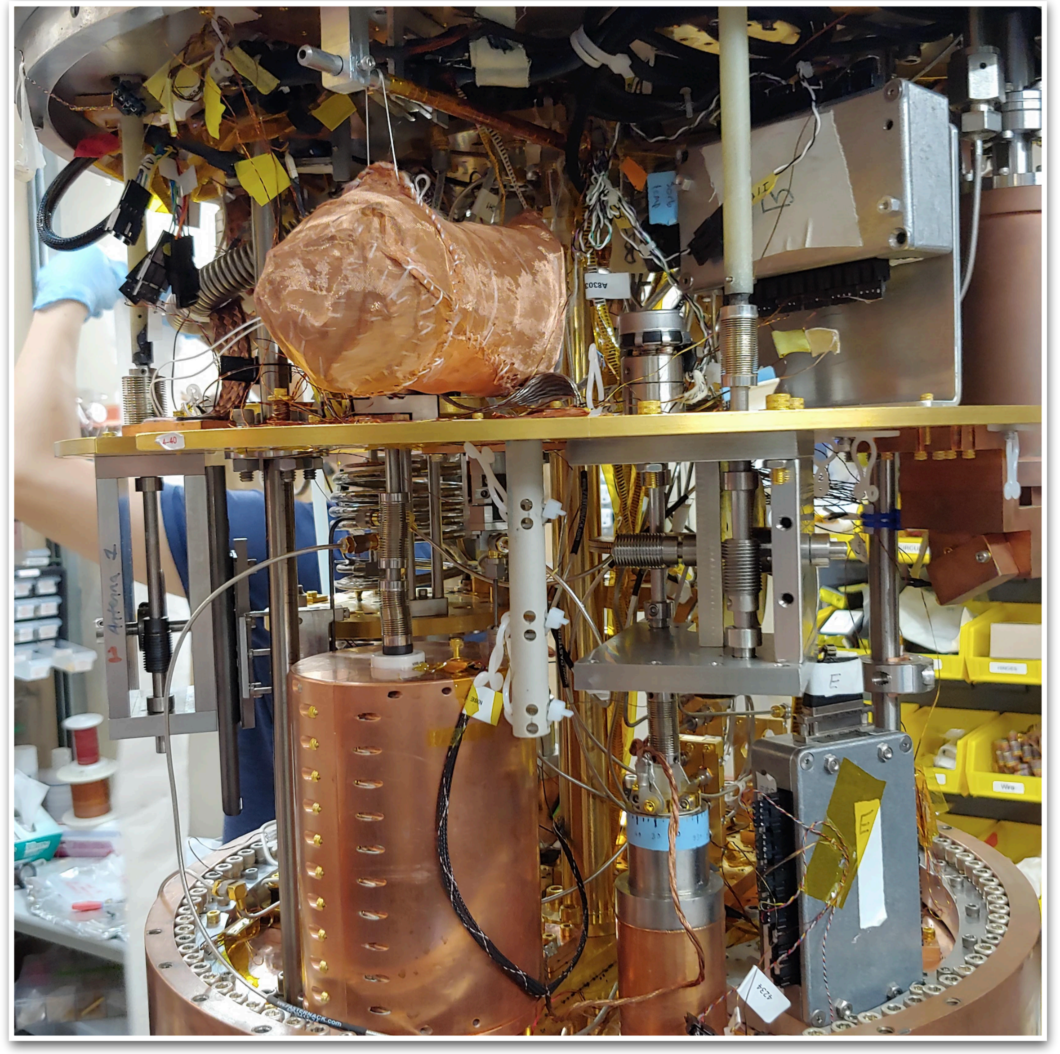
Axion Haloscope

- Extremely sensitive AM receiver in a magnetic field.
- Microwave resonator approach.
- Uses a dilution refrigerator and ultra-low noise amplifiers to reduce background.

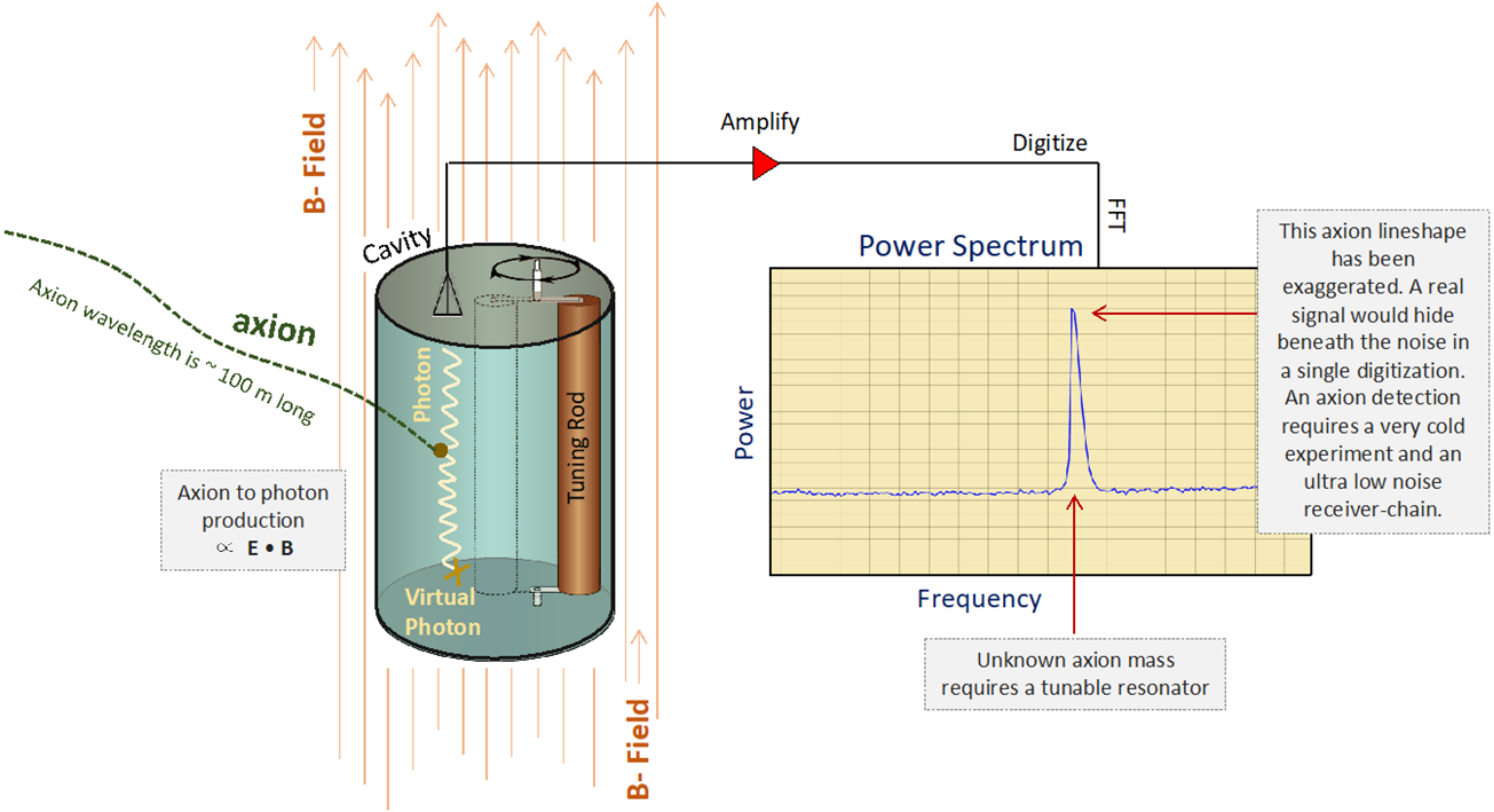
Sikivie, Pierre. "Experimental tests of the" invisible" axion." *Physical Review Letters* 51.16 (1983): 1415.

Pierre Sikivie



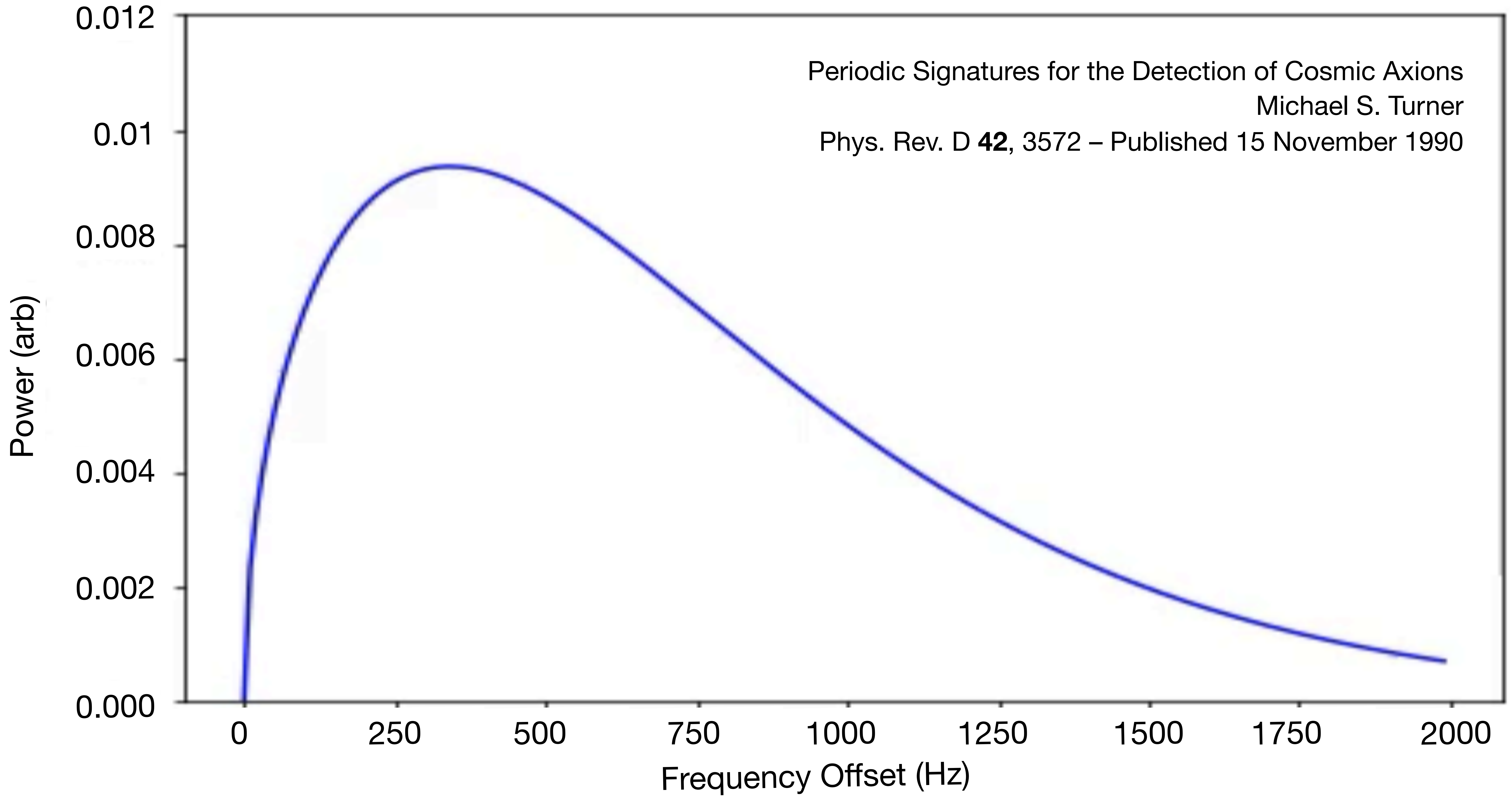


ADMX Haloscope



Axion Lineshape (Velocity Distribution)

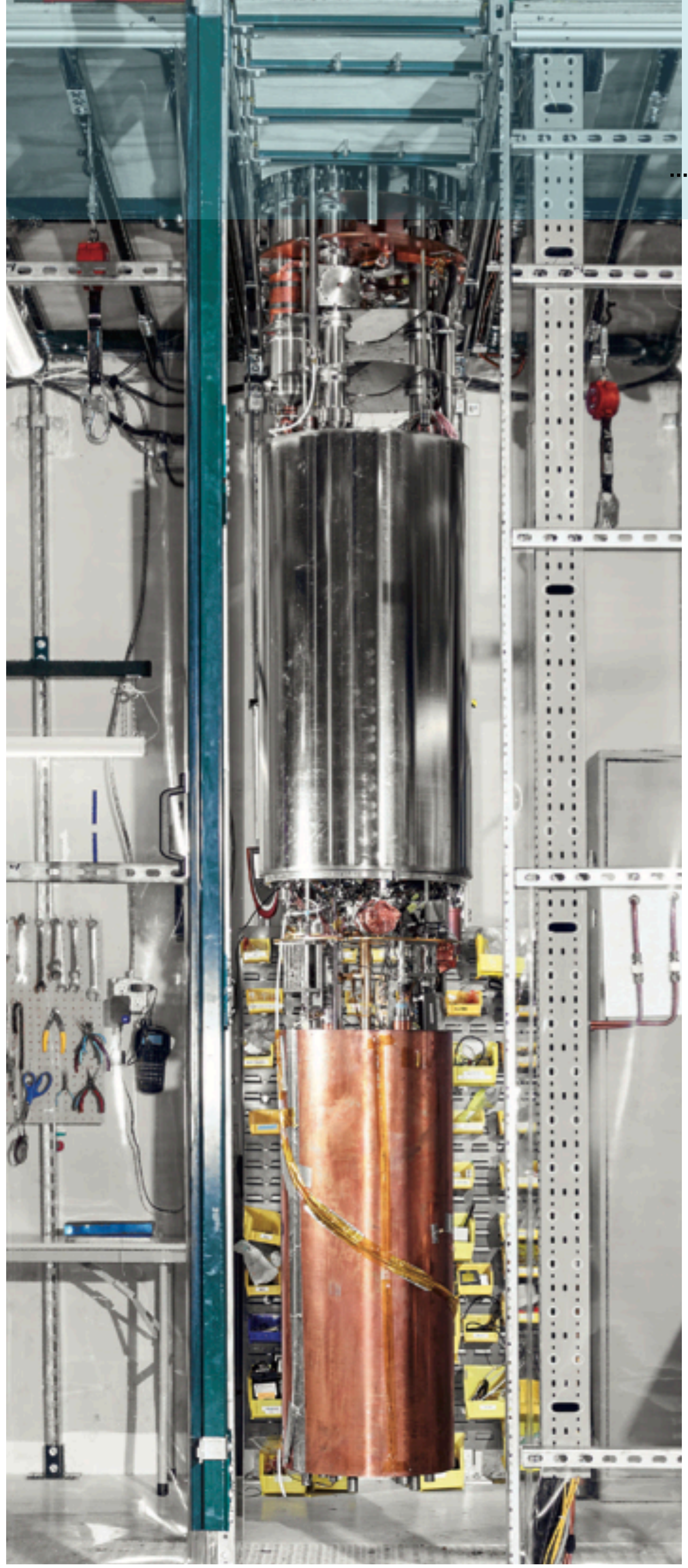
Maxwell-Boltzmann Distribution with annual and diurnal signal modulation

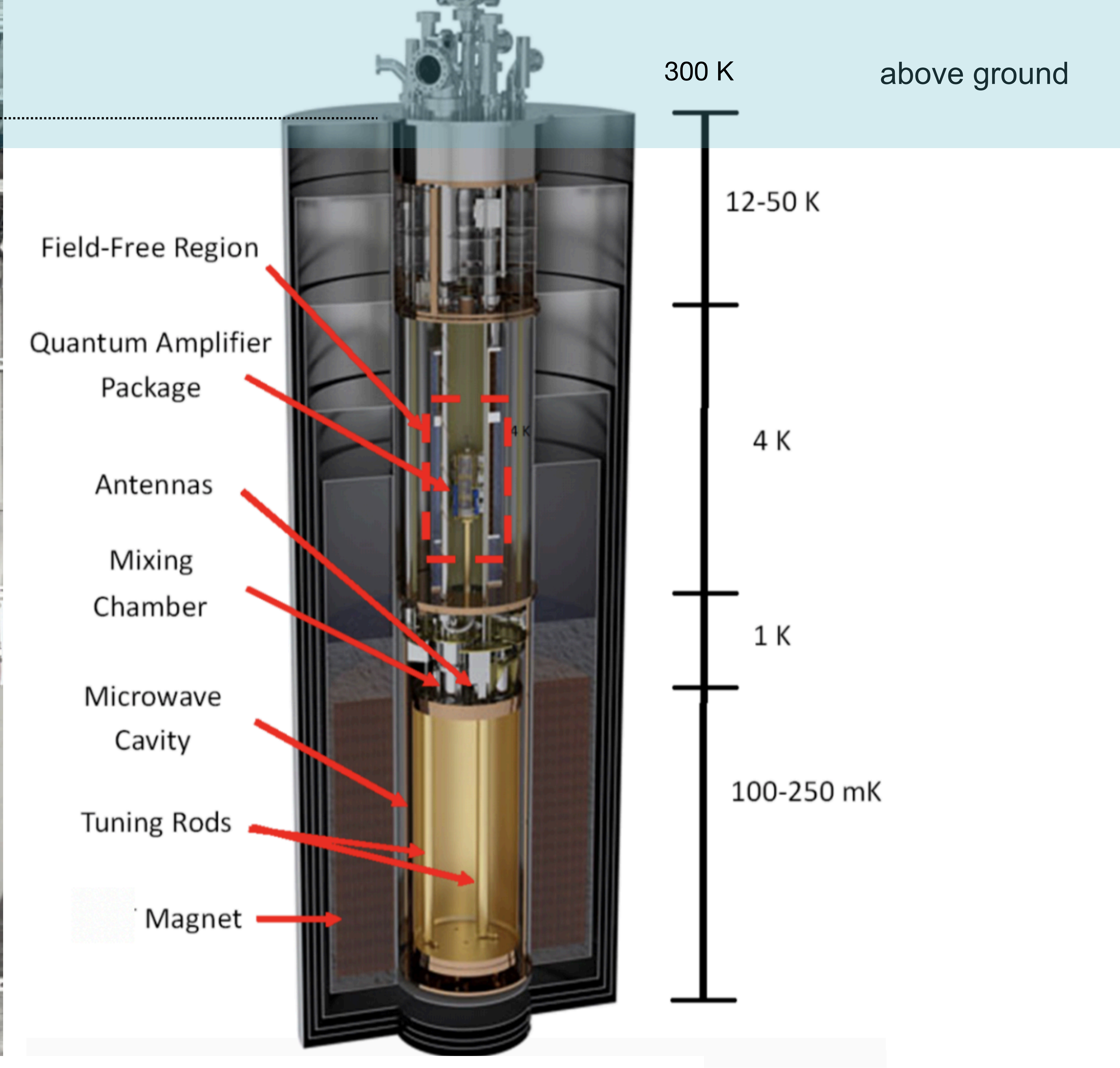


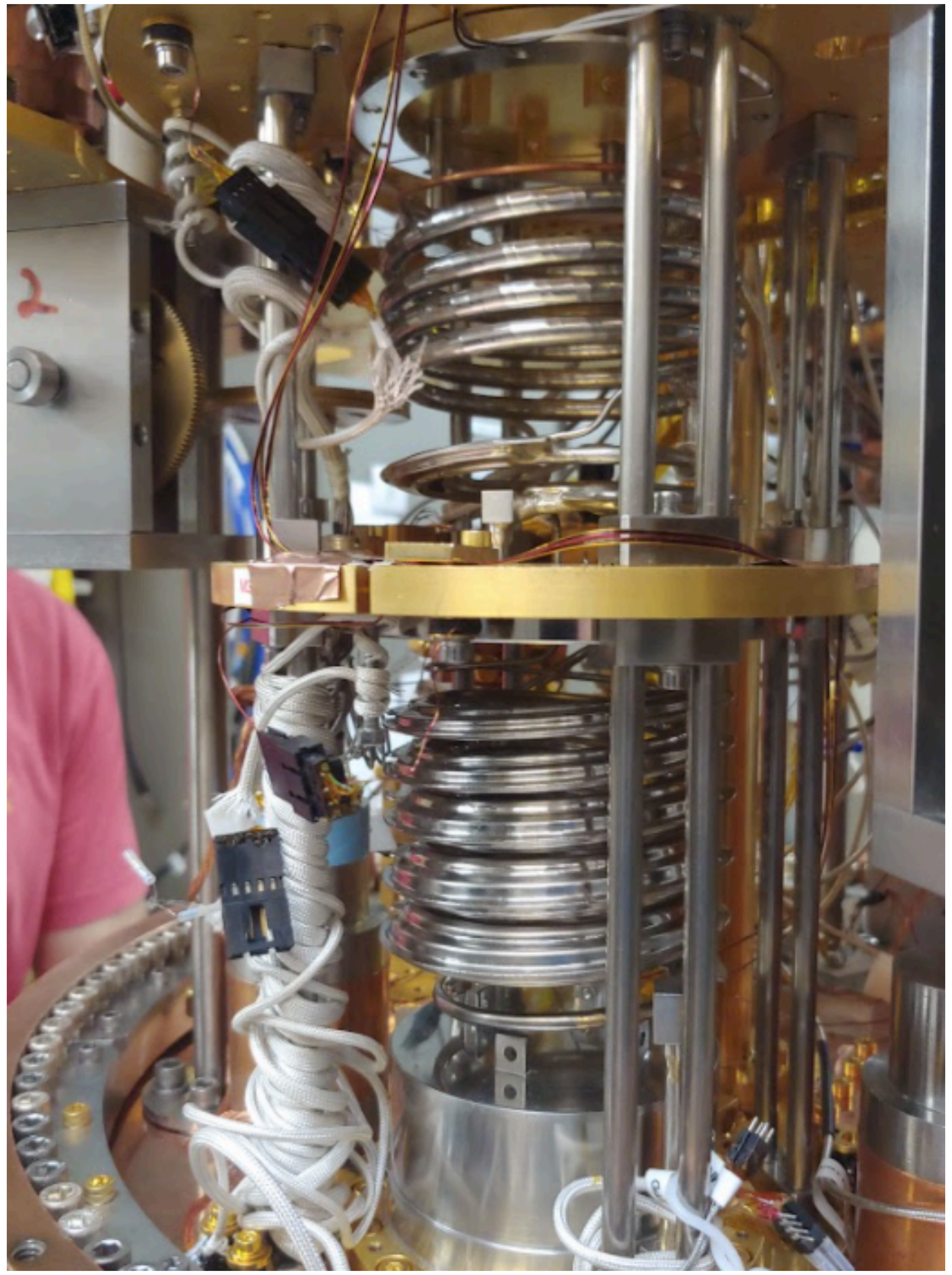
Other lineshapes possible, such as ’N-body’ lineshape

ADMX

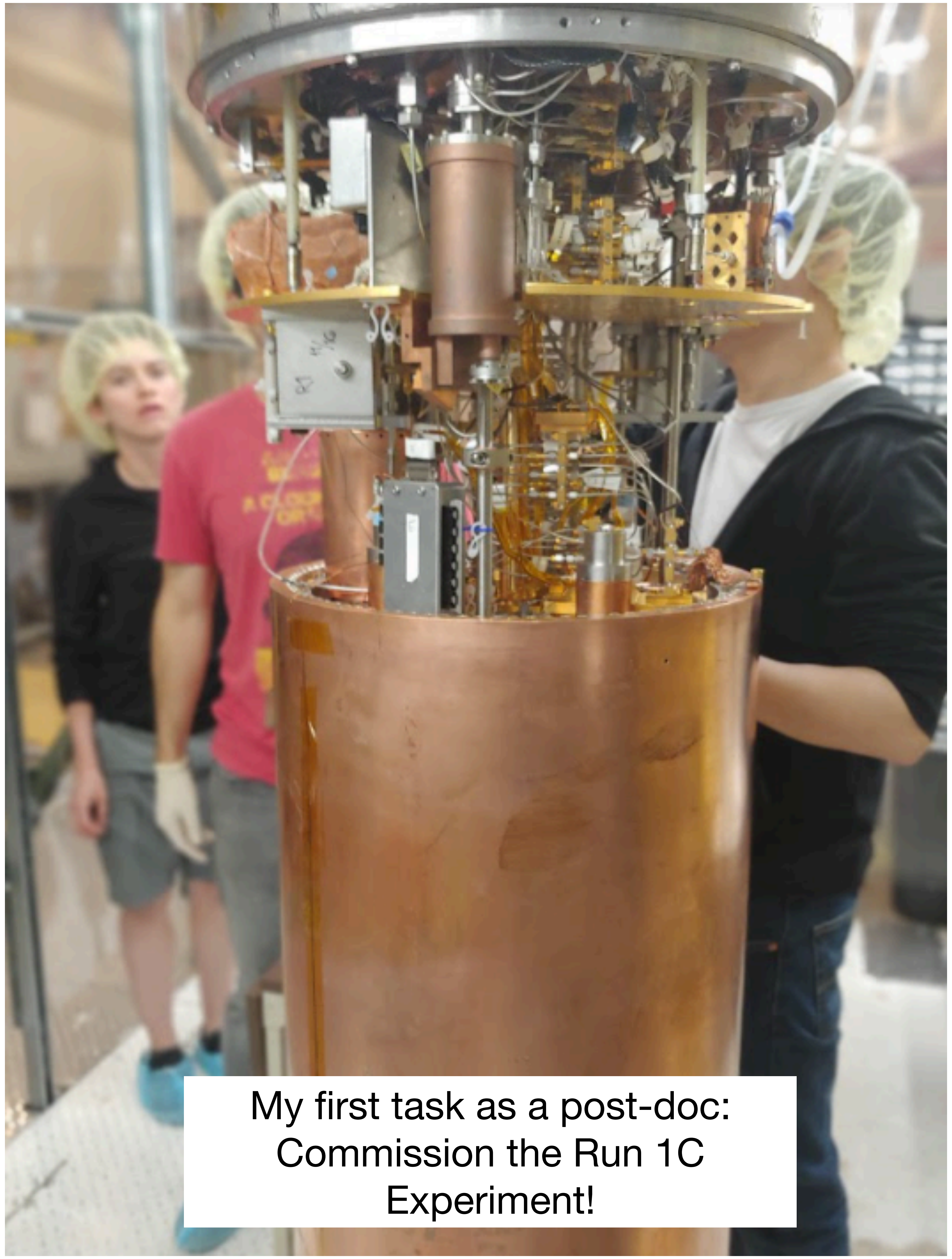
- Dil Fridge: Reaches ~100 mK
- Superconducting magnet:
  ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics







Dilution Refrigerator Mounted to Cavity

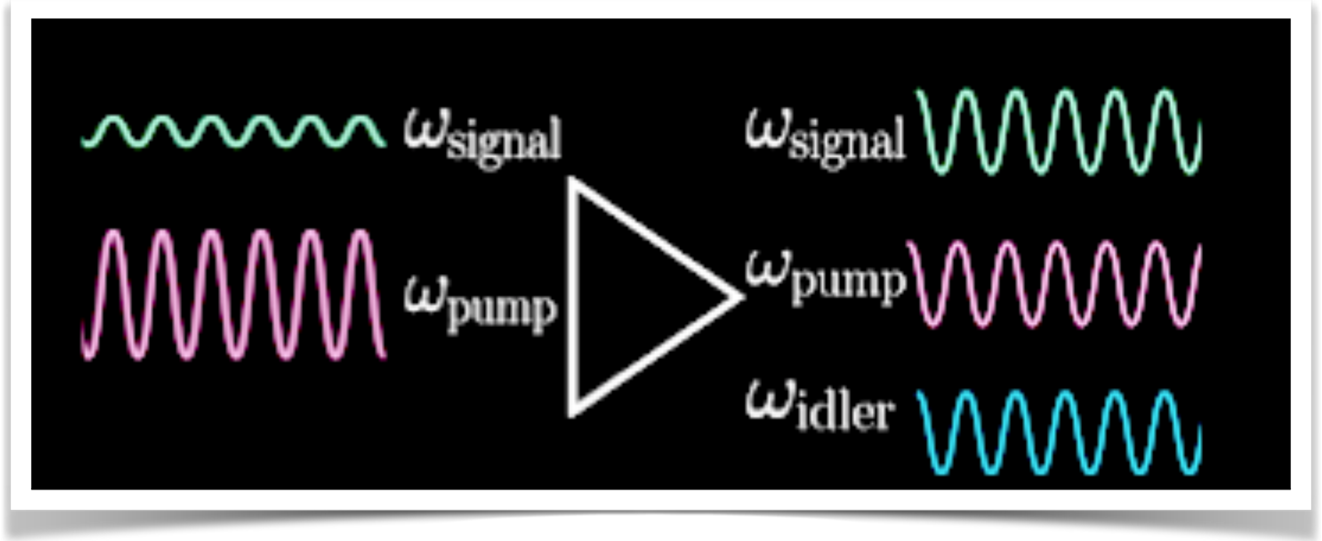


My first task as a post-doc: Commission the Run 1C Experiment!

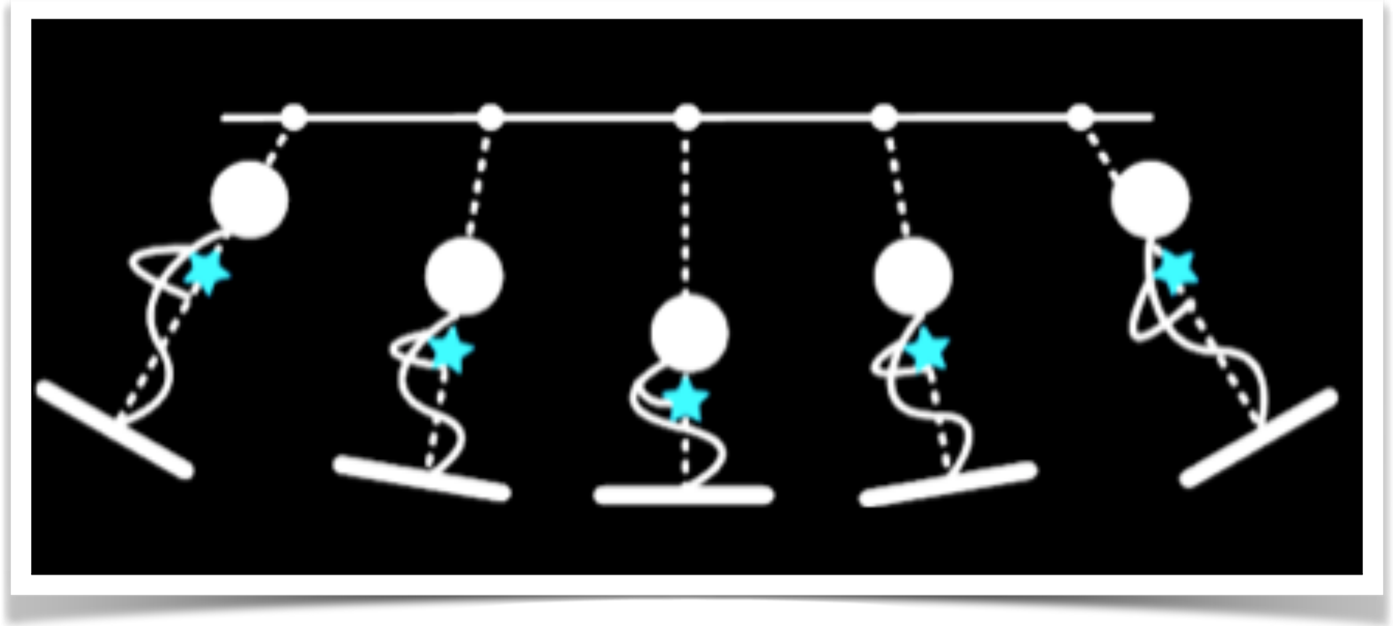
Quantum Electronics Package

Josephson Parametric Amplifier (JPA)

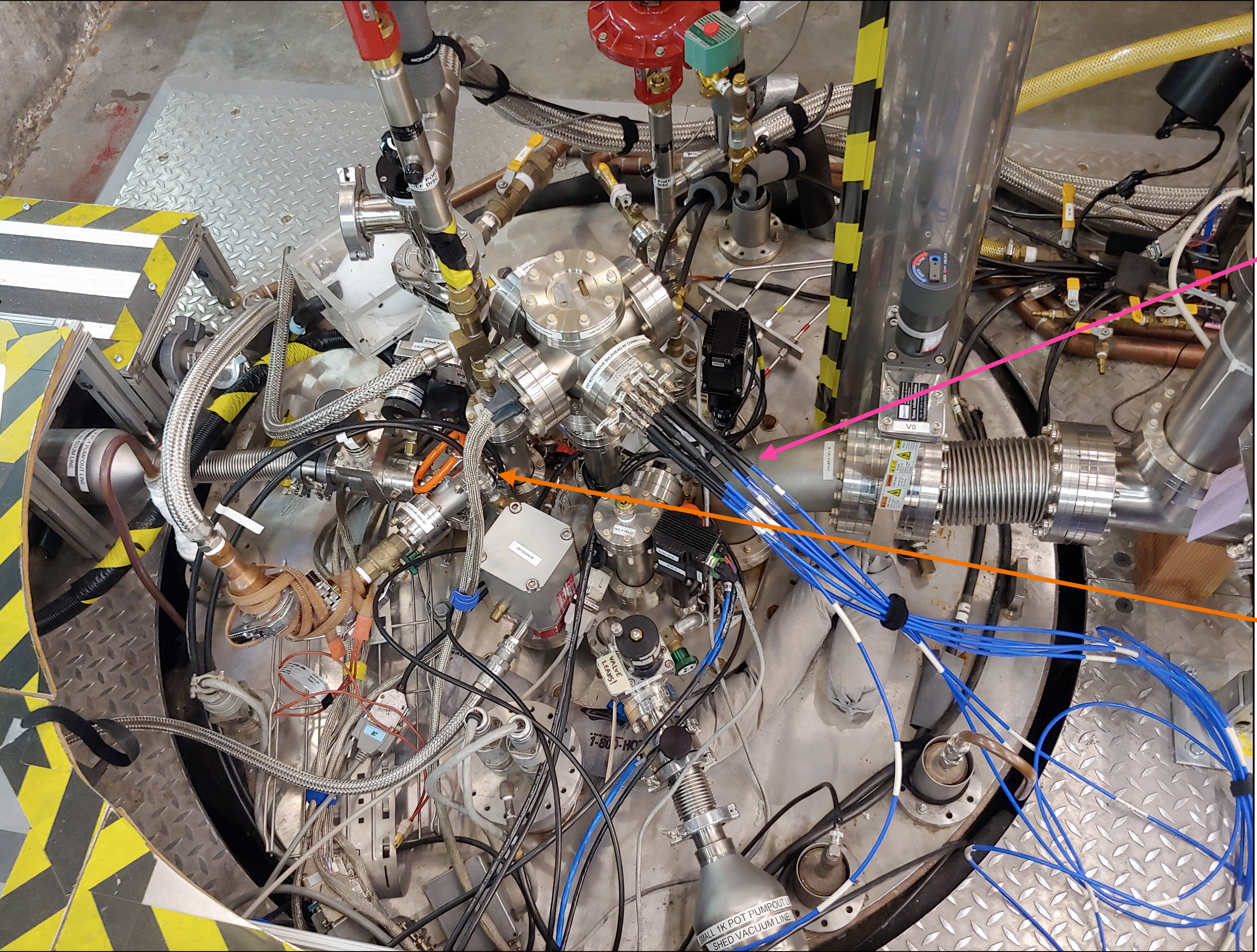
- Critical to obtaining low amplifier noise
- How does a parametric amplifier work?
  - Classic example is child on a swing
  - Anharmonicty leads to energy transfer from the pump tone to the signal tone
  - Requires some non-linear element, in this case, the Josephson Junction



Figures courtesy of Shahid Jawas



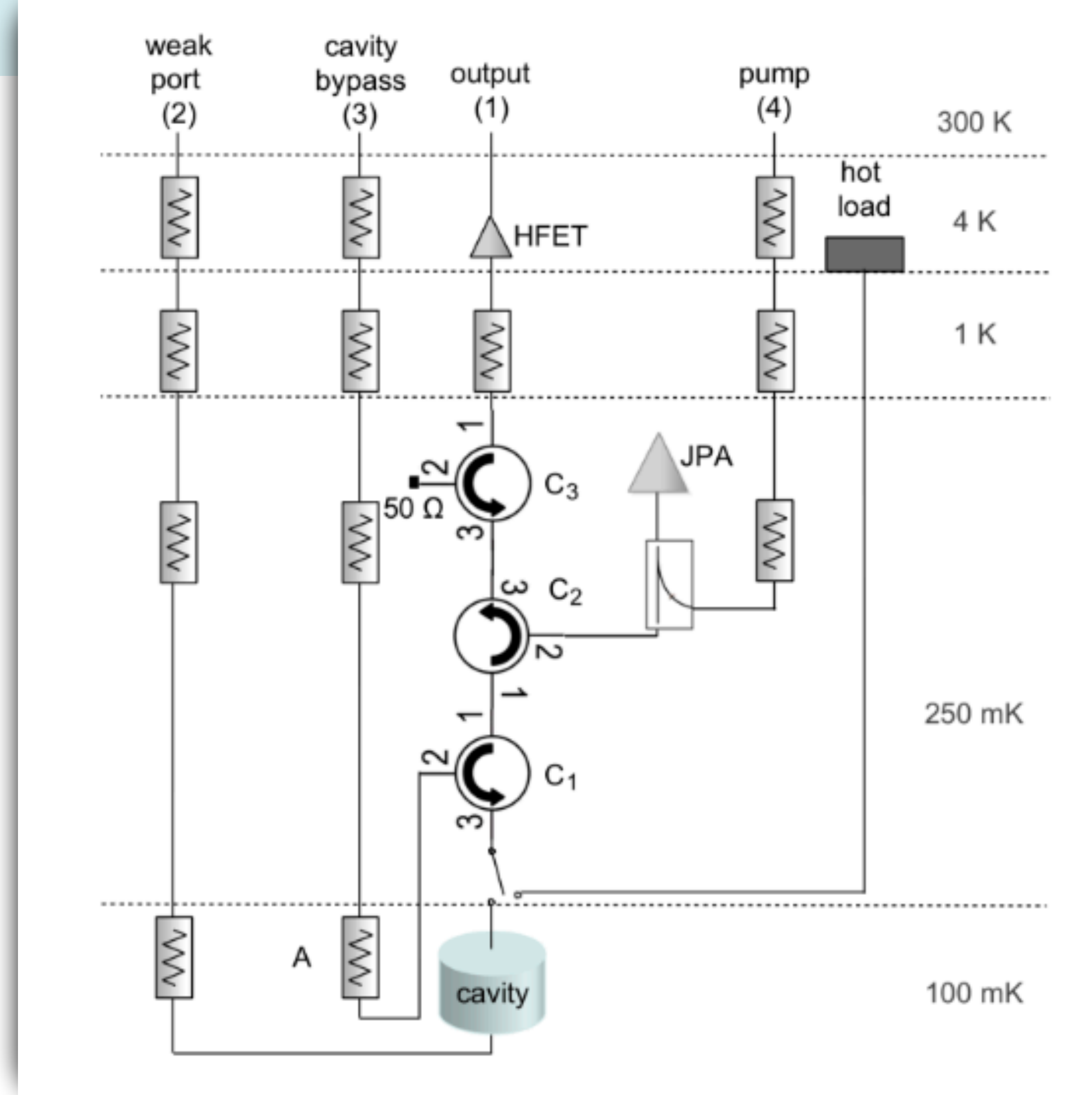
ADMX Rigging Operation



Top of the ADMX "insert" after being moved into the magnet bore

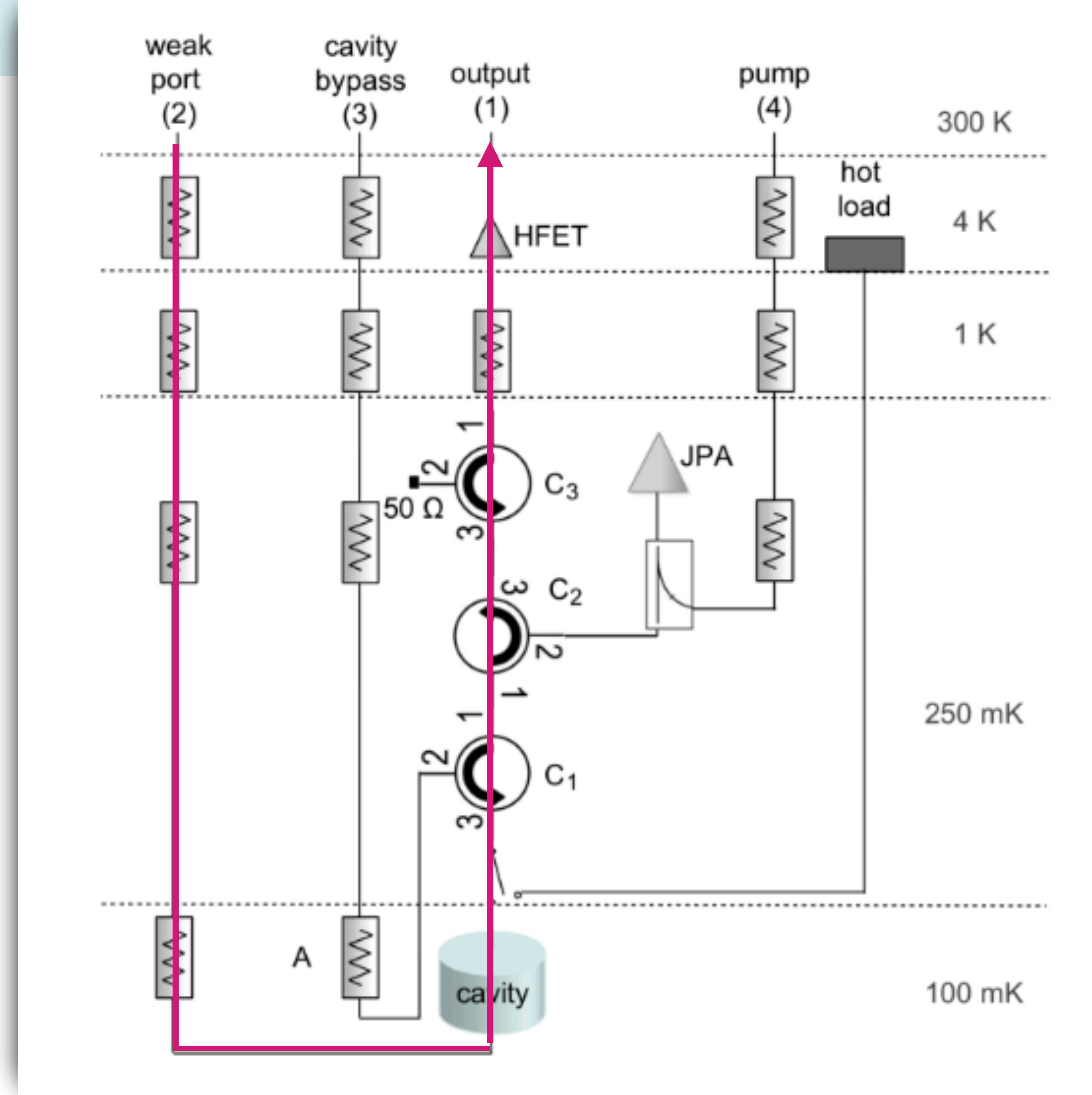
RF cables

DC cables for sensors



ADMX RF Schematic

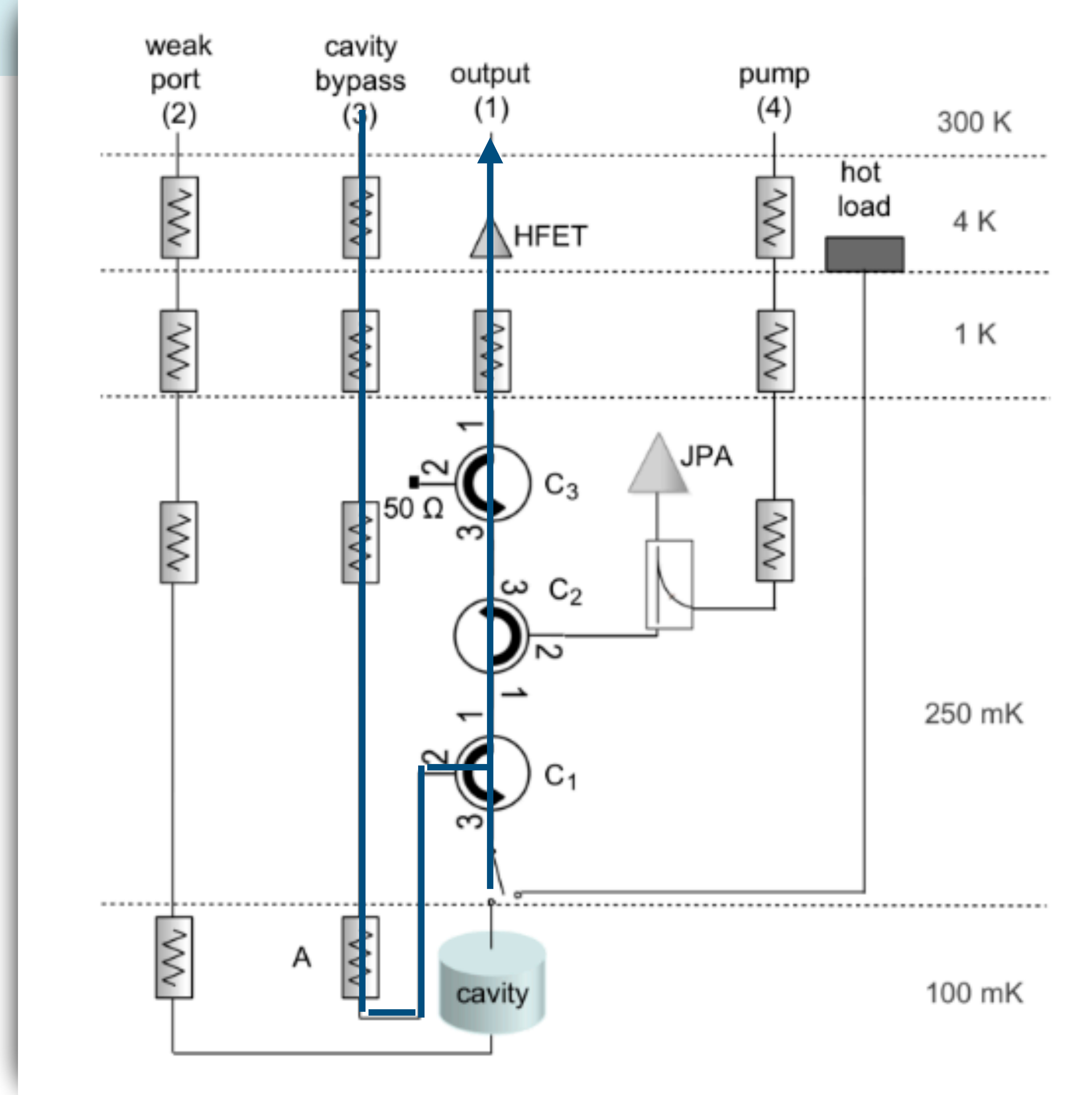
3 important RF paths to highlight!



Transmission Measurement RF Path

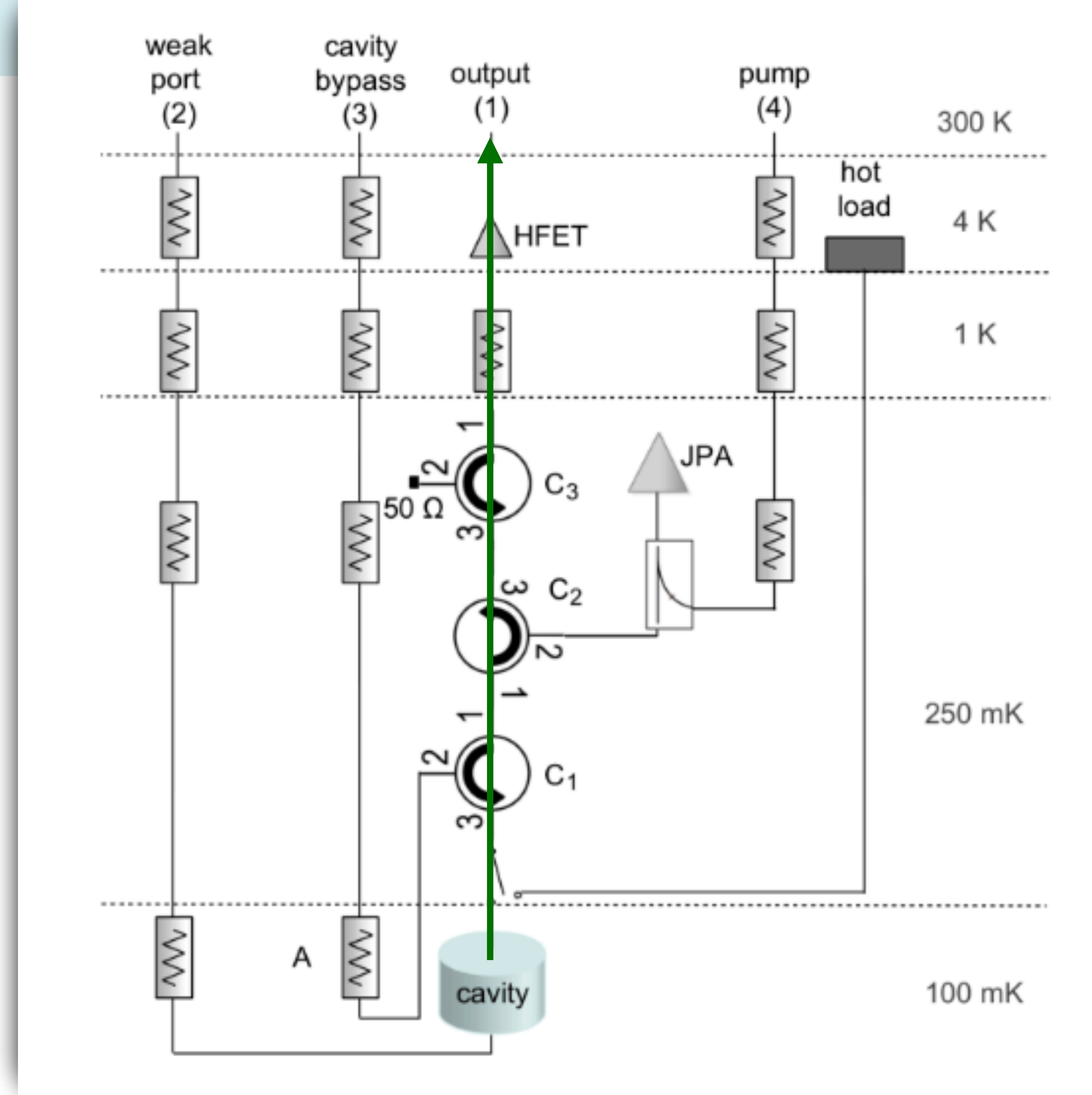
Transmission Measurement Gives:
- Resonant frequency
- Quality factor

Same path is used to inject synthetic axion signals



Reflection Measurement RF Path

Reflection Measurement gives:
- Antenna Coupling

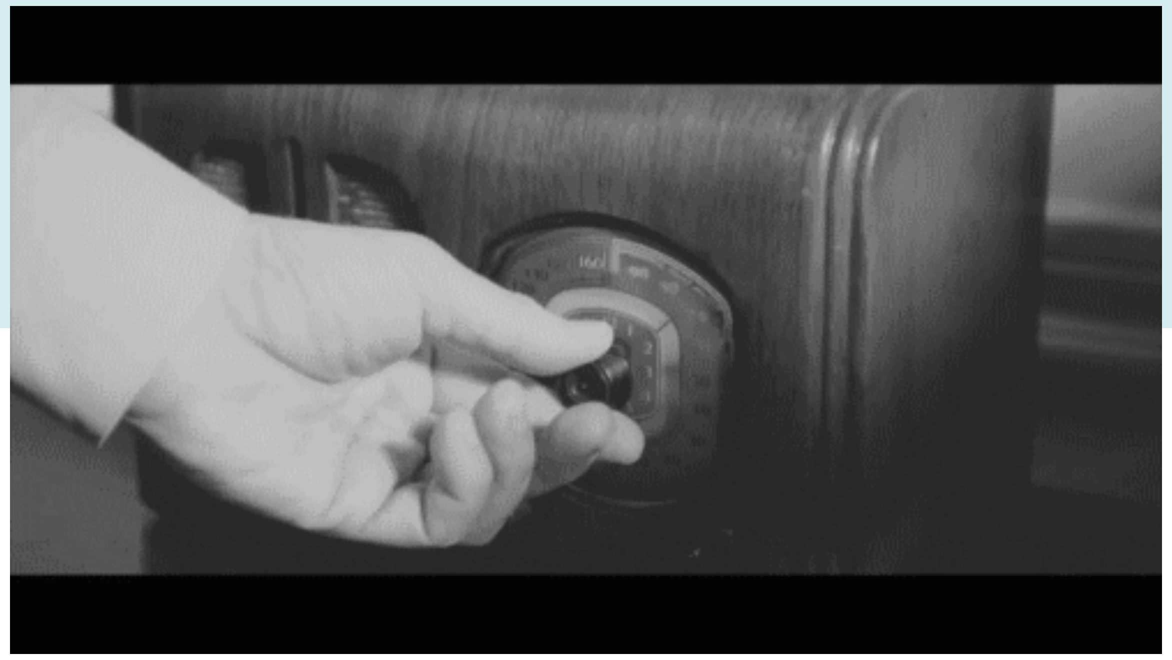


Ch 1 Signal Path

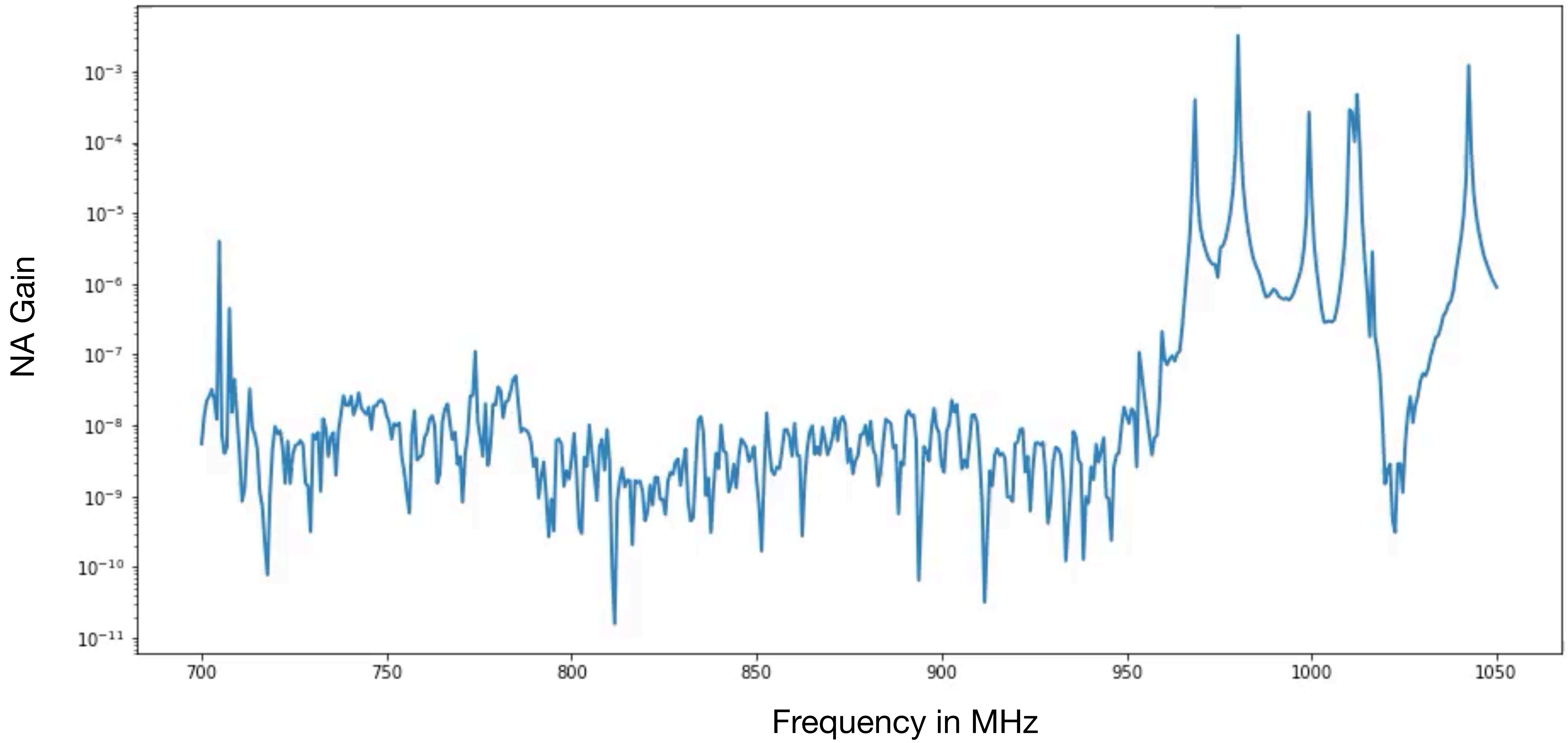
Weak port line is terminated. Signal read out directly from the cavity.

This is our configuration for data acquisition (digitization).

Tuning our cavity

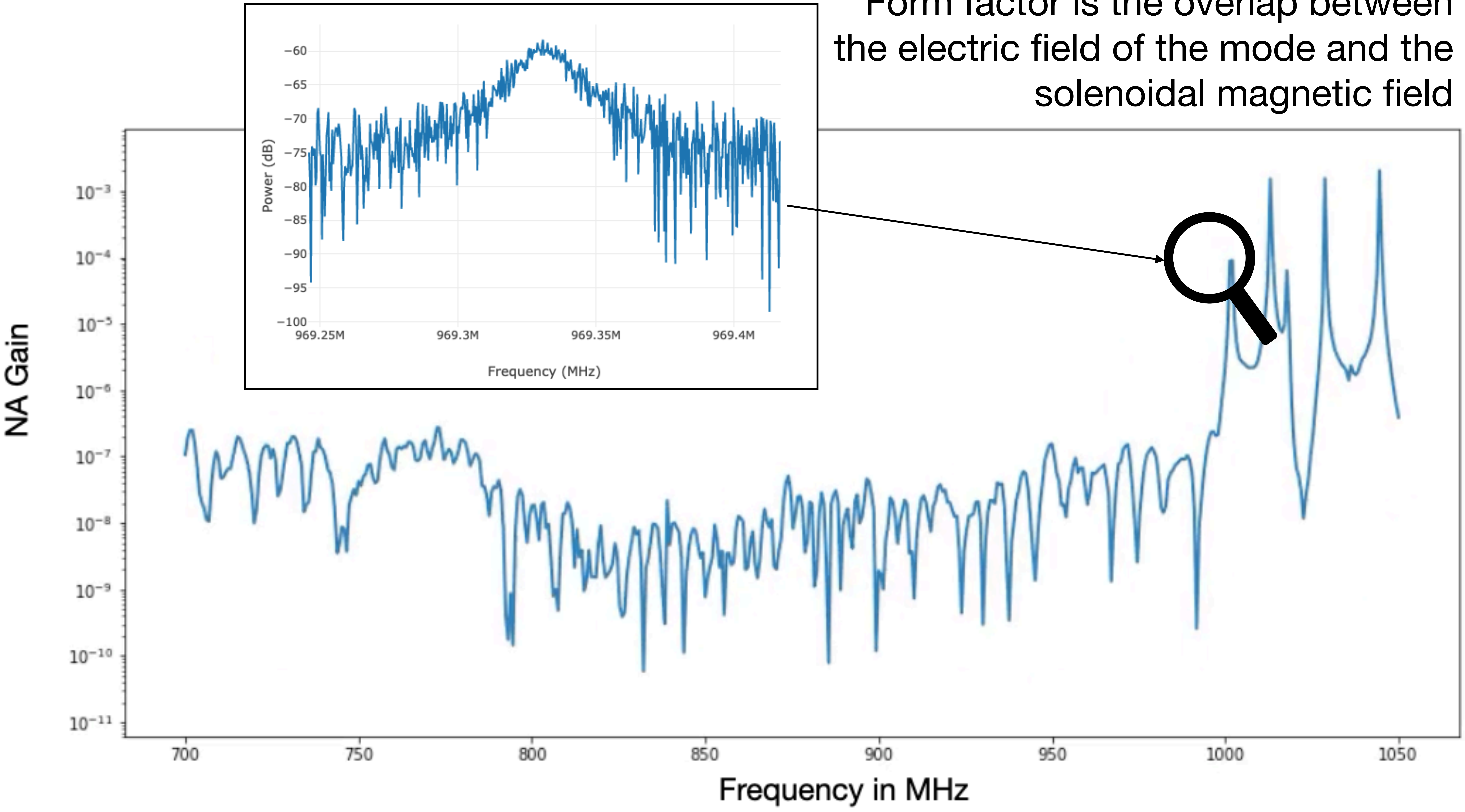


As we tune, we track the TM010 mode
Axion couples most strongly to this mode
Note occasional mode-crossings

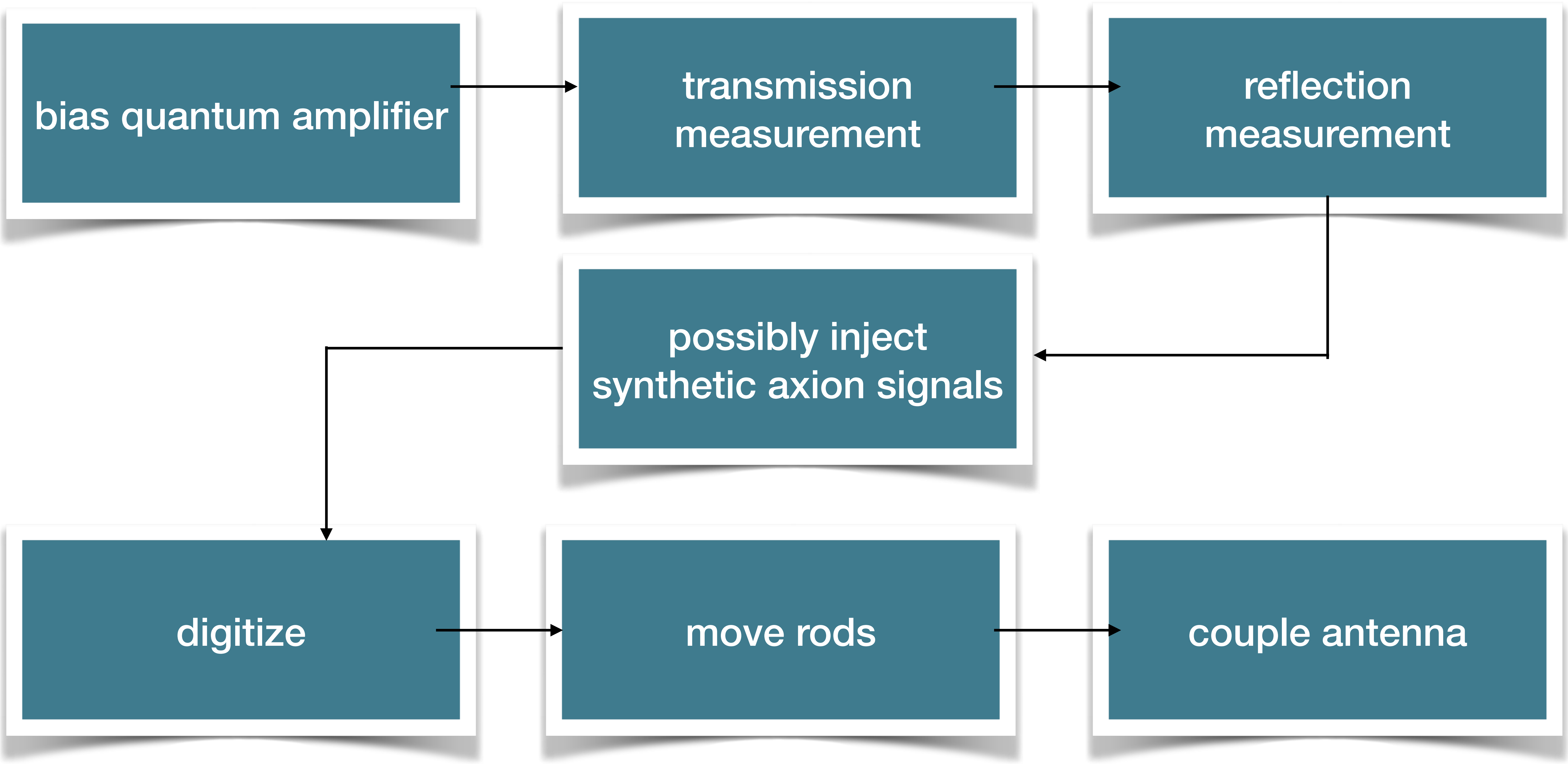


Zooming in on a single mode

Form factor is the overlap between the electric field of the mode and the solenoidal magnetic field



Run Cadence



Data-taking operations:

- 1st pass through—determine if we rescan
- Interrupted by noise temperature measurements
- 2nd pass through to achieve necessary sensitivity, or eliminate rescan regions

Scan Rate: Figure of Merit for Haloscopes

$$\frac{df}{dt} \approx 157\,\frac{\mathrm{MHz}}{\mathrm{yr}}\left(\frac{g_\gamma}{0.36}\right)^4\left(\frac{f}{740\ \mathrm{MHz}}\right)^2\left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)^2\left(\frac{3.5}{\mathrm{SNR}}\right)^2\left(\frac{B}{7.6\ \mathrm{T}}\right)^4\left(\frac{V}{136\ \ell}\right)^2\left(\frac{Q_\mathrm{L}}{30{,}000}\right)\left(\frac{C}{0.4}\right)\left(\frac{0.2\ \mathrm{K}}{T_\mathrm{sys}}\right)^2$$

Maximize

- B Field
- Volume
- Quality Factor
- Form Factor

Can't Control

- Frequency
- Coupling
- Dark Matter Density

Minimize

- System noise:
- Amplifier Noise
- Physical Noise

Some Typical Values

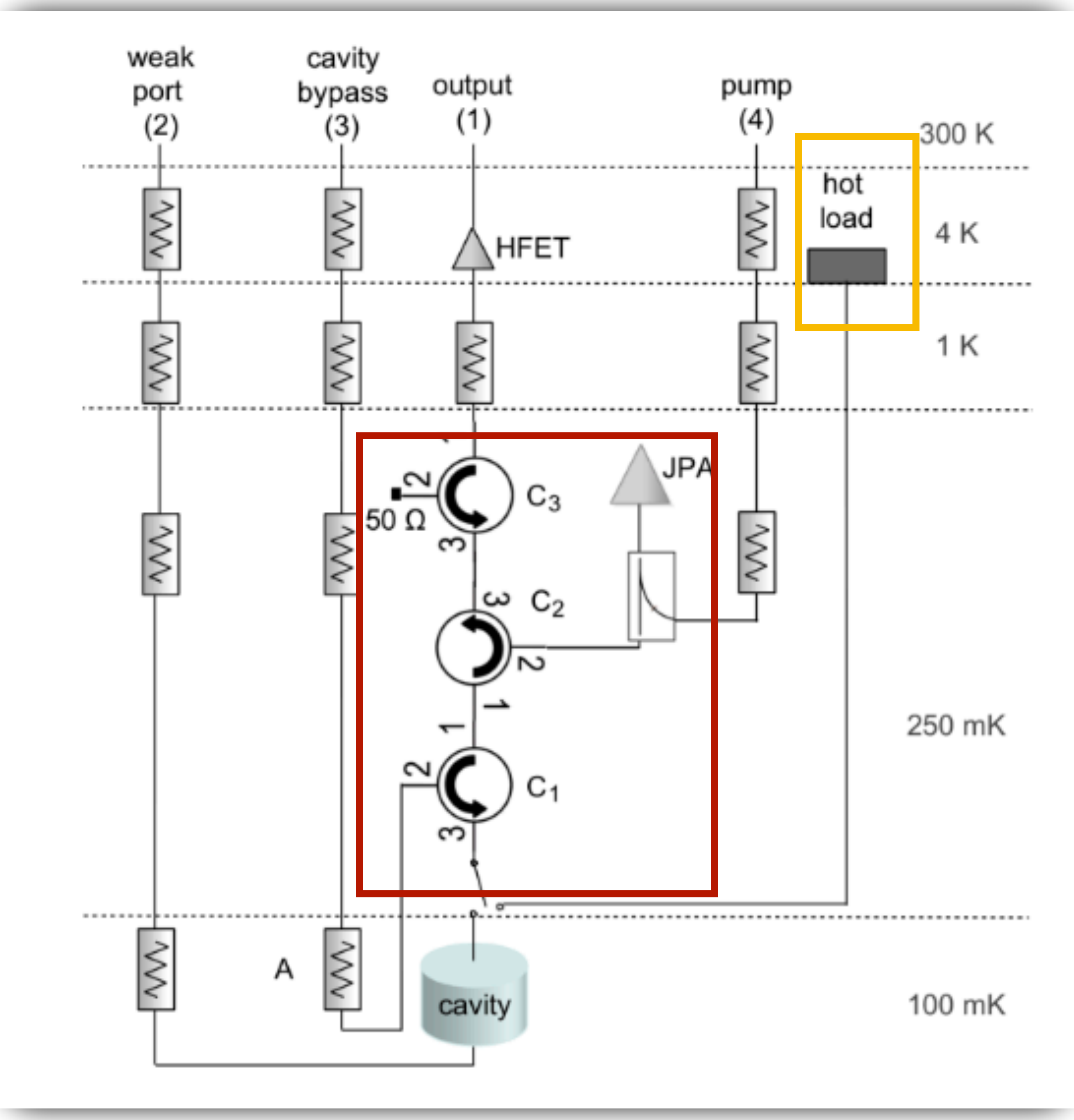
$$\frac{df}{dt} \approx 157\ \frac{\mathrm{MHz}}{\mathrm{yr}} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{740\ \mathrm{MHz}}\right)^2 \left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)^2 \left(\frac{3.5}{\mathrm{SNR}}\right)^2 \left(\frac{B}{7.6\ \mathrm{T}}\right)^4 \left(\frac{V}{136\ \ell}\right)^2 \left(\frac{Q_\mathrm{L}}{30{,}000}\right) \left(\frac{C}{0.4}\right) \left(\frac{0.2\ \mathrm{K}}{T_\mathrm{sys}}\right)^2$$

Some Typical Values:

Run 1B (shown in the denominator):	Run 1C (current run):
Q ~ 30,000-40,000	Q ~ 50,000-80,000
B ~ 7.6 T	B ~ 7.8 T
Tsys ~ 0.2-0.7 K	Tsys ~ 0.2-0.7 K
C_{010} ~ 0.4	C_{010} ~ 0.4

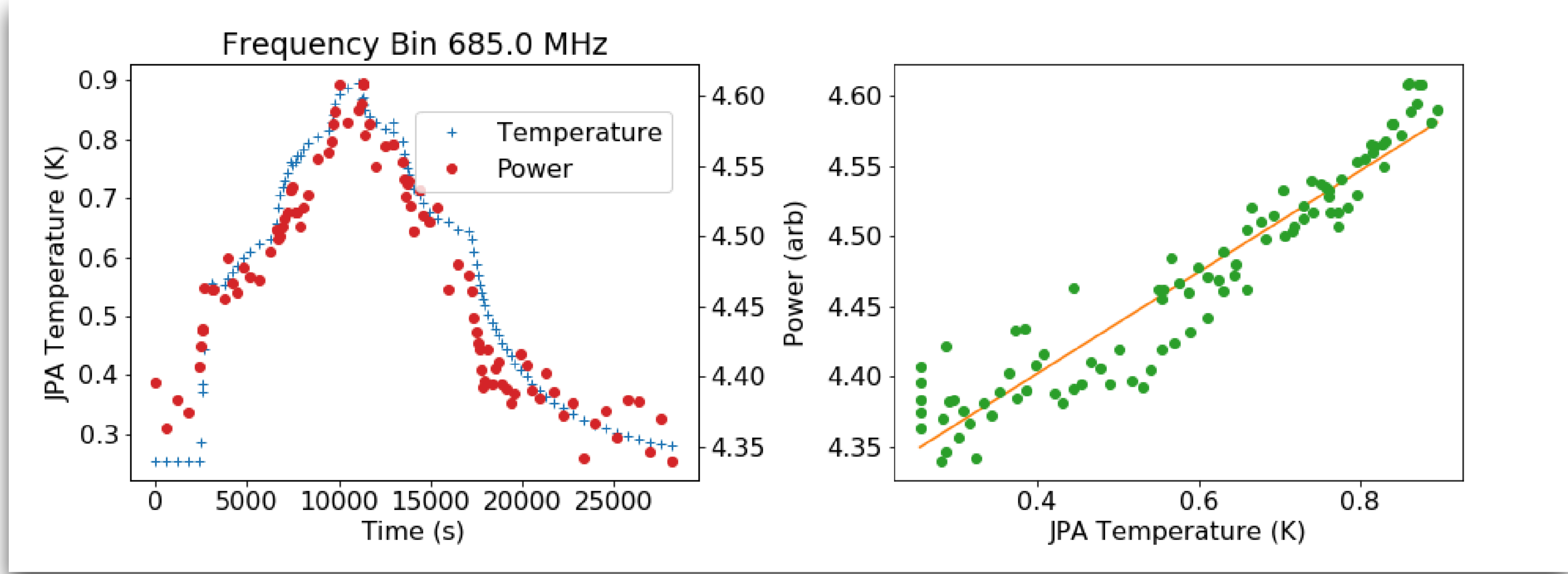
Always striving to improve this!

Noise Characterization



- 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

Noise Characterization



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

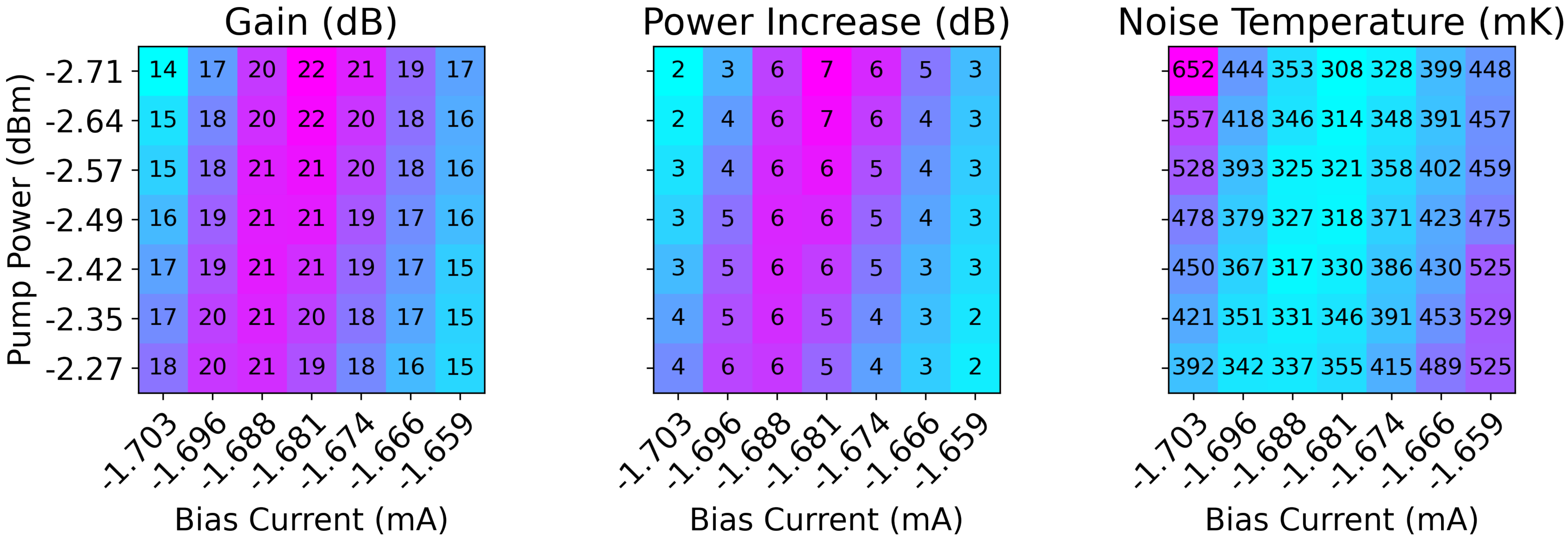
$$T_{\mathrm{sys}} = \frac{T_{\mathrm{HFET}}}{\epsilon(\mathrm{SNRI})}$$

Fit parameters:

- Attenuation from cavity to HFET amp
- Receiver Temperature

JPA Rebiasing Procedure Gives our SNRI!

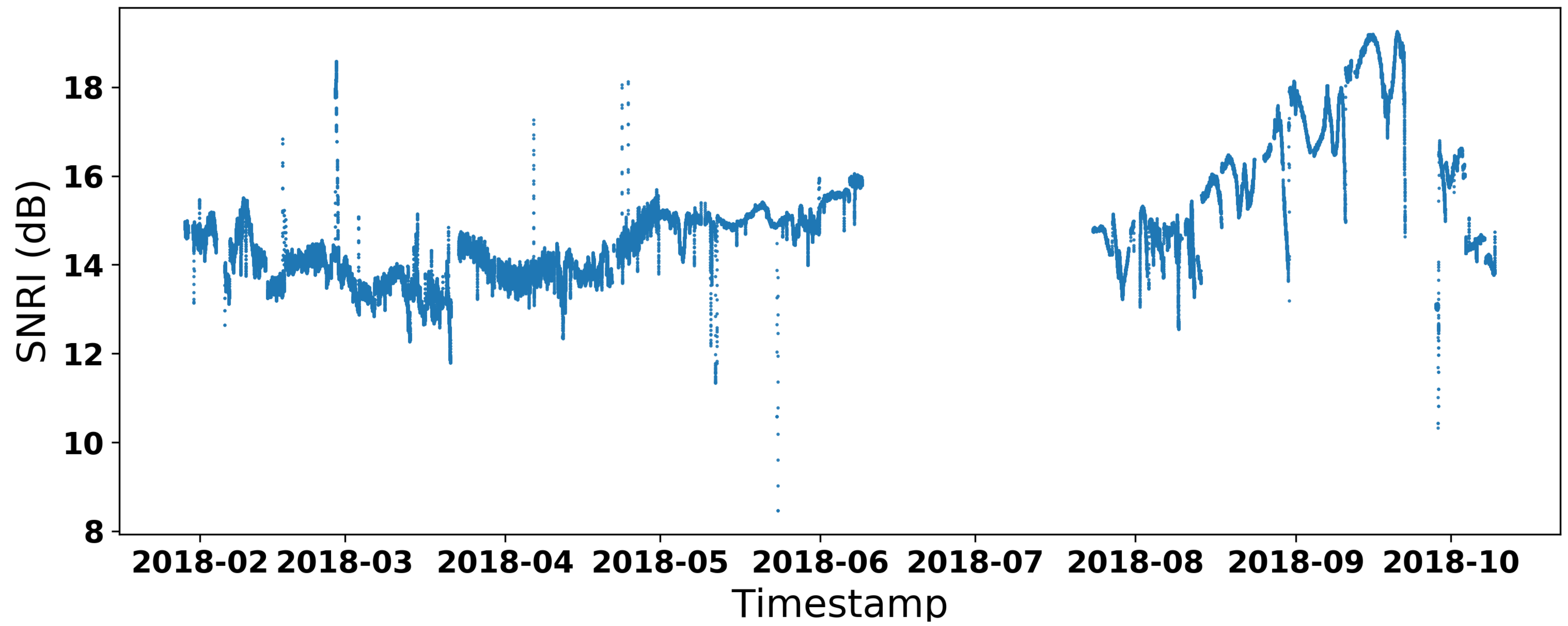
JPA Biasing



$$\mathrm{SNRI} = \frac{G_{\mathrm{on}}}{G_{\mathrm{off}}}\frac{P_{\mathrm{off}}}{P_{\mathrm{on}}}$$

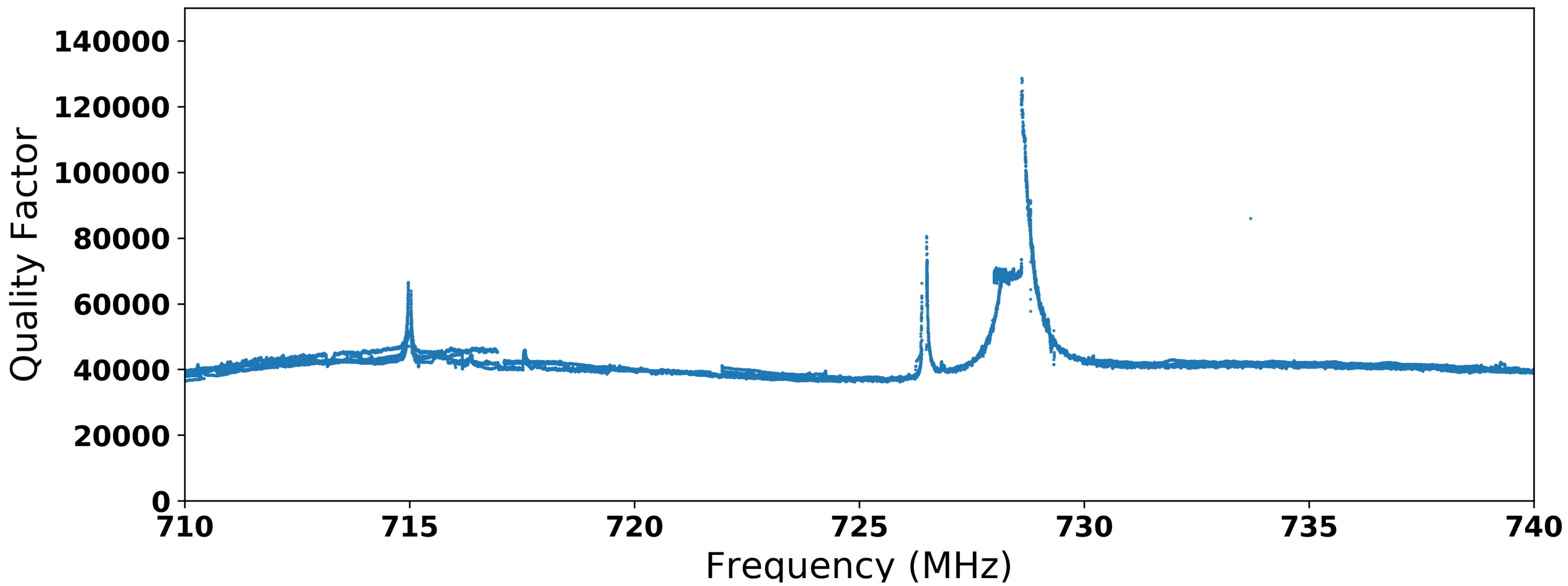
$$T_{\mathrm{sys}} = \frac{T_{\mathrm{HFET}}}{\epsilon(\mathrm{SNRI})}$$

Some Typical Parameter Values



SNRI as a function of time

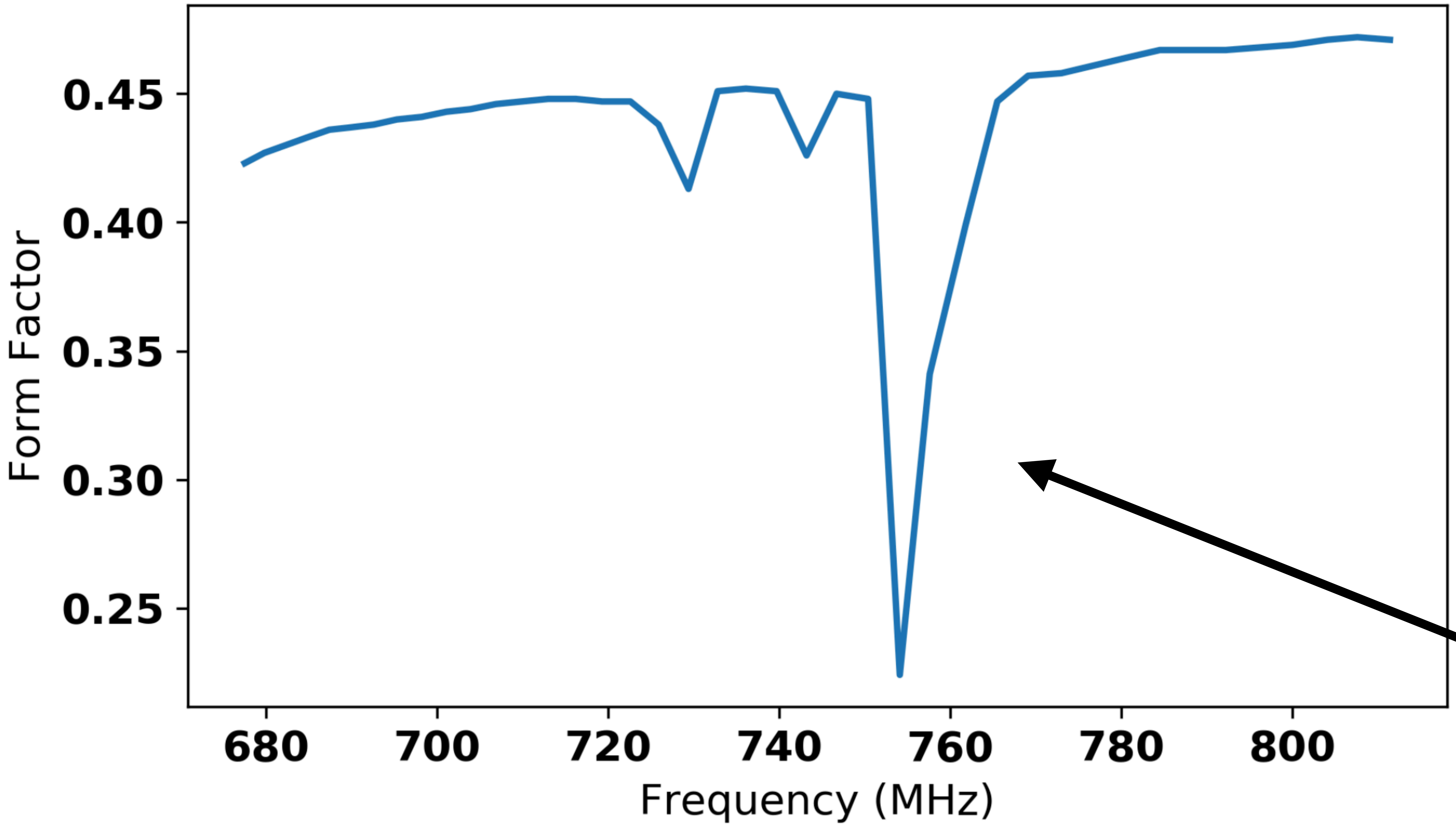
- Aberrations could be due to gain compression, etc.
- Removed with data quality cuts.



Quality factor as a function of frequency

- Aberrations usually the result of a fit.
- Removed with data quality cuts.
- Smoothed over 30 min time period

Some Typical Parameter Values



- Form factor is simulated via CST Microwave Studio
- Existence of tuning rods means changing with frequency

Mode Crossing

Form factor: Overlap of Magnetic and Electric Fields

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

Analysis

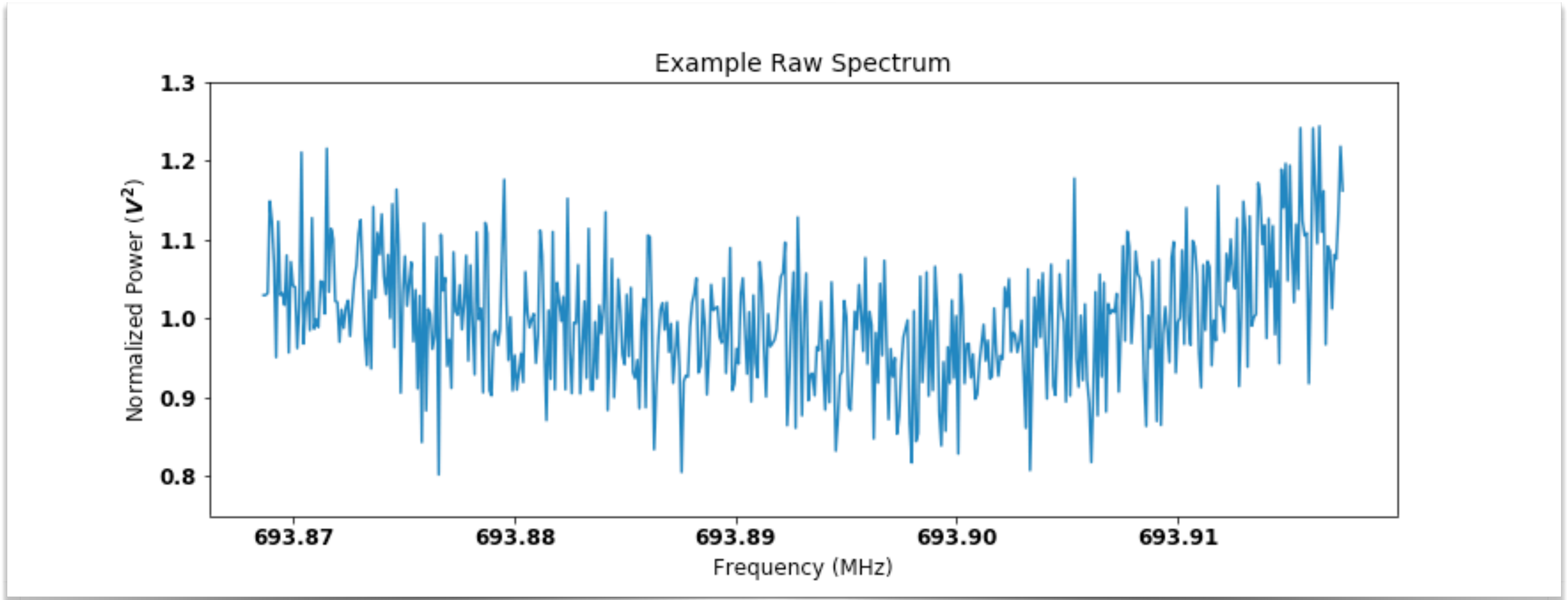
Two types of analysis:

- **Medium-resolution analysis (described here):**
  - Can detect persistent axion signal.
  - Assumes isothermal velocity distribution.
  - 100 Hz bin width.
- **High-resolution analysis (not described here):**
  - Can search for much narrower peak due to discrete axion flow.
  - Can detect annual and diurnal modulation of the axion, if detected.
  - 0.01 mHz bins width.

Analysis

Raw spectrum processing:

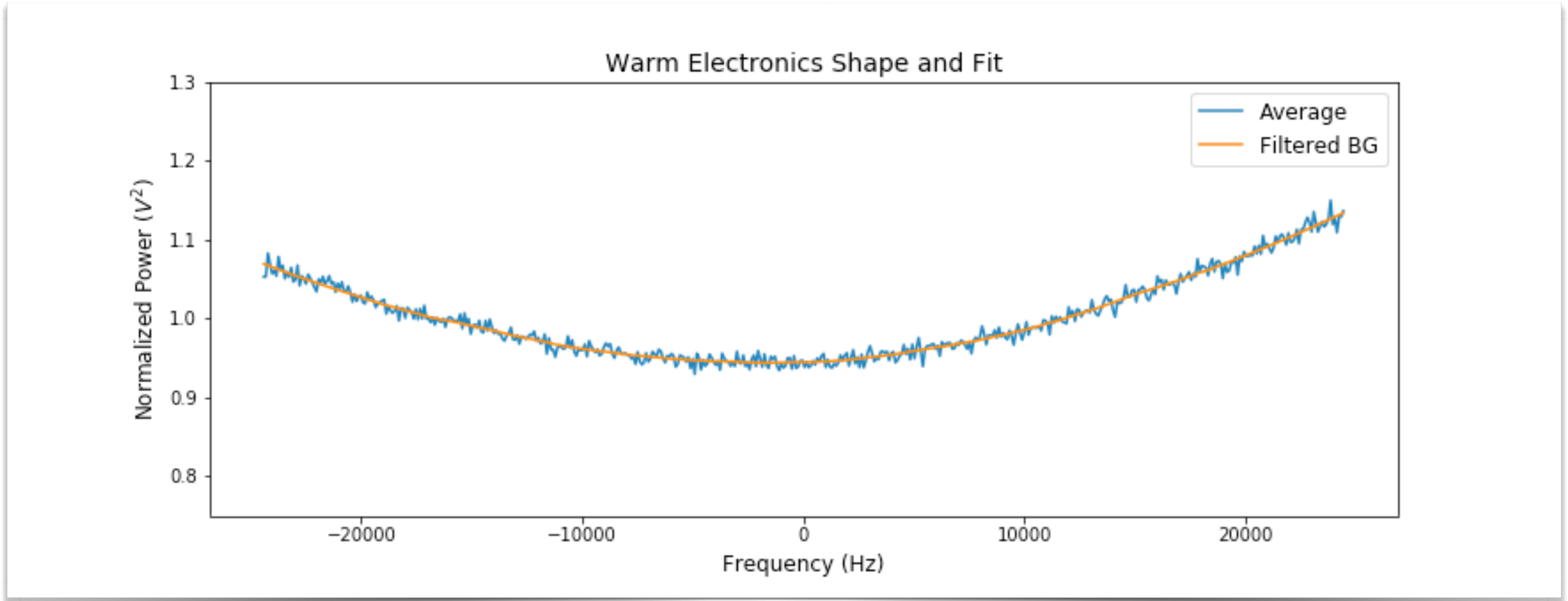
- ~50 kHz wide raw spectra, 100 Hz bins



Analysis

Baseline Removal:

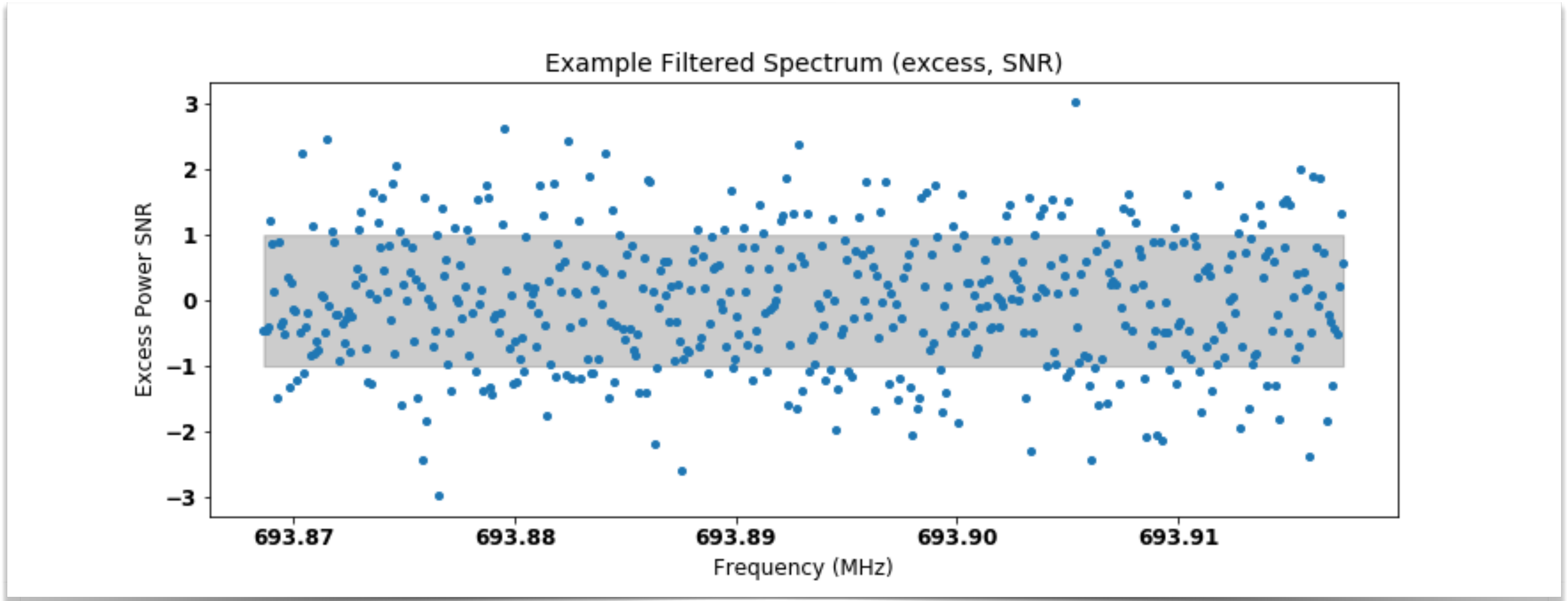
- The warm electronics shape is identified by averaging and filtering off-resonance scans.



Analysis

Raw spectrum processing:

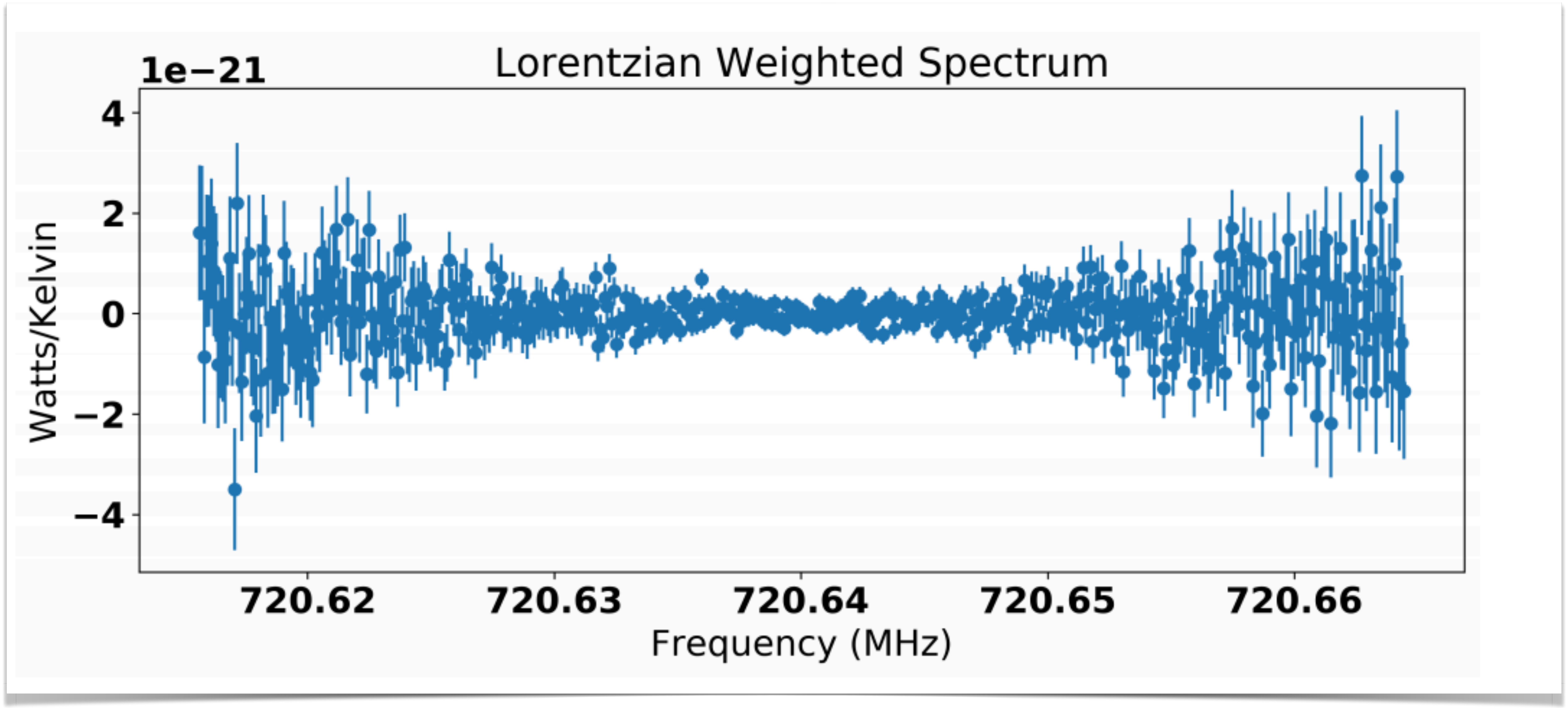
- Raw spectra are divided by the receiver shape and filtered (Padé filter: designed to fit out wide structure and ignore narrow axion-like peaks)
- Subtract 1 from each bin to obtain ~Gaussian white noise



Analysis

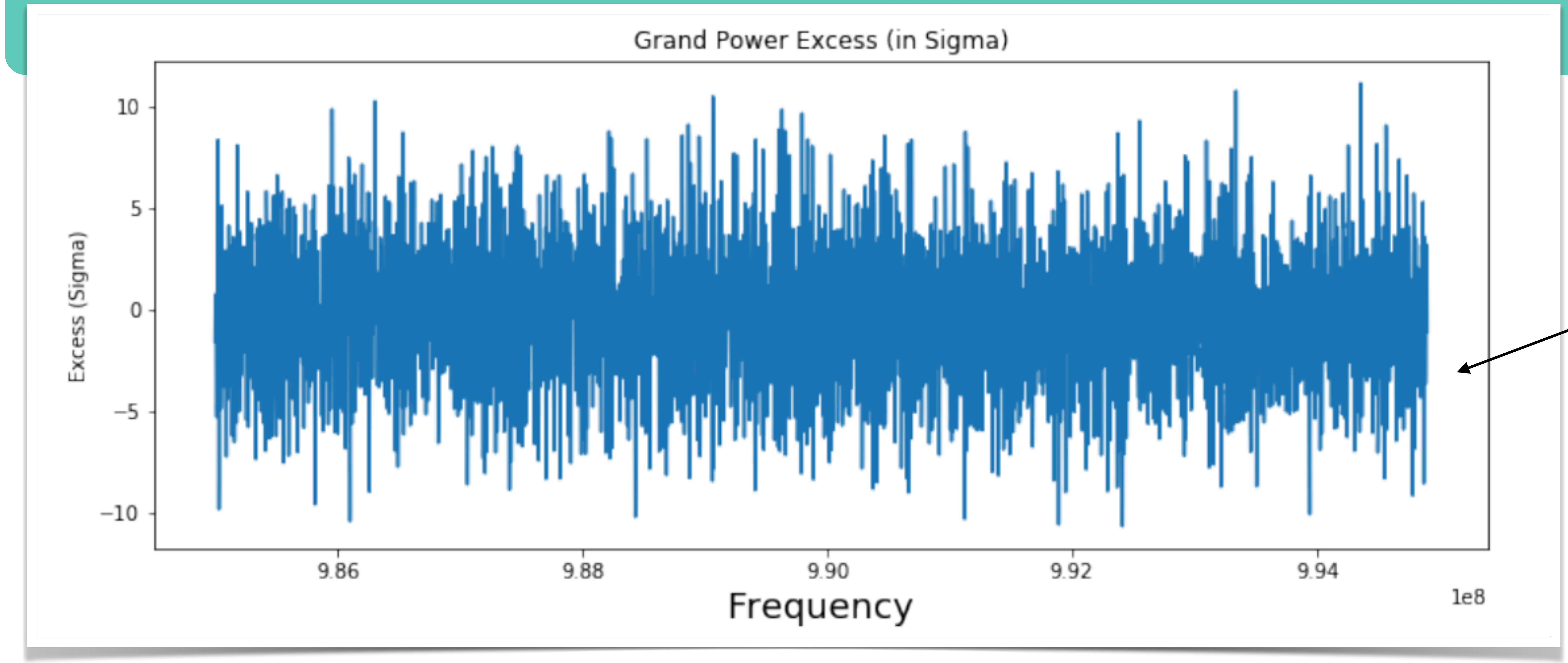
Raw spectrum processing:

- Scale by the Lorentzian (cavity line shape)



Grand spectrum processing

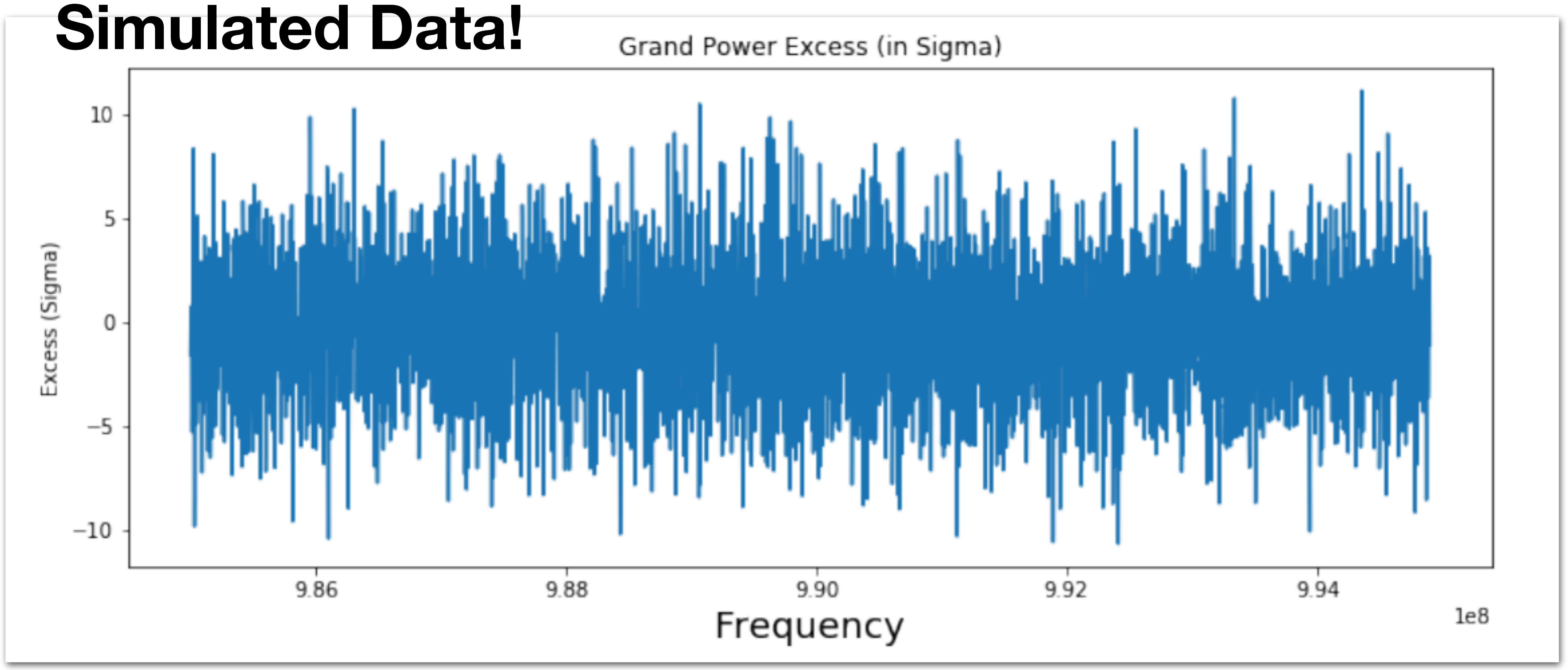
- Scale spectra by the average noise power per bin to achieve signal peaks independent of noise temperature.
- Filter spectra using the expected axion line shape
- Combine spectra using an optimal weighting procedure.

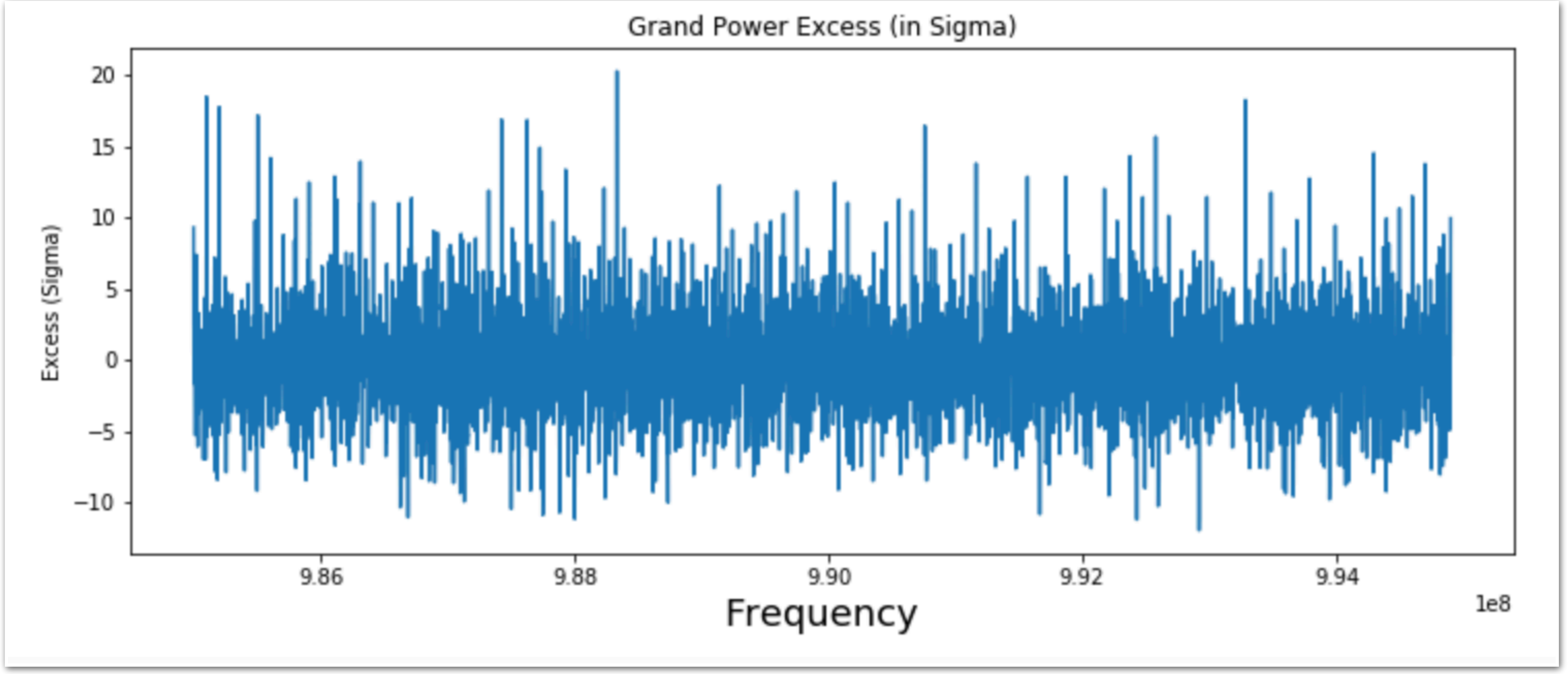


Example: **Simulated Data**
From my undergraduate,
Hima Korandla

Software Synthetic Injections

Simulated Data!





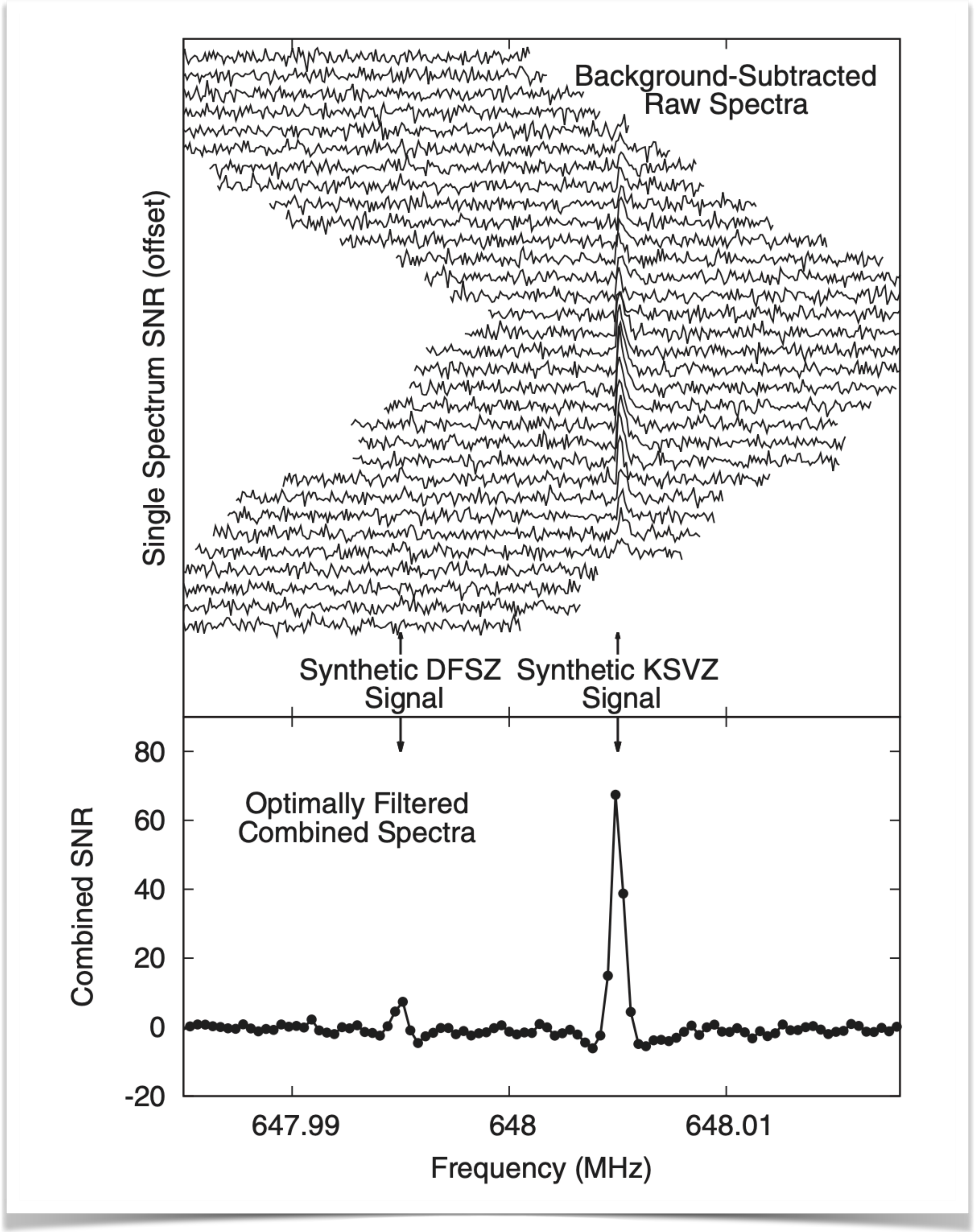
- Used to determine our detection efficiency and verify our analysis
- Developed by undergraduate student Hima Korandla, with my supervision
  - Simulated analysis data
  - Software synthetic injections for Run 1C

Rescan Procedure

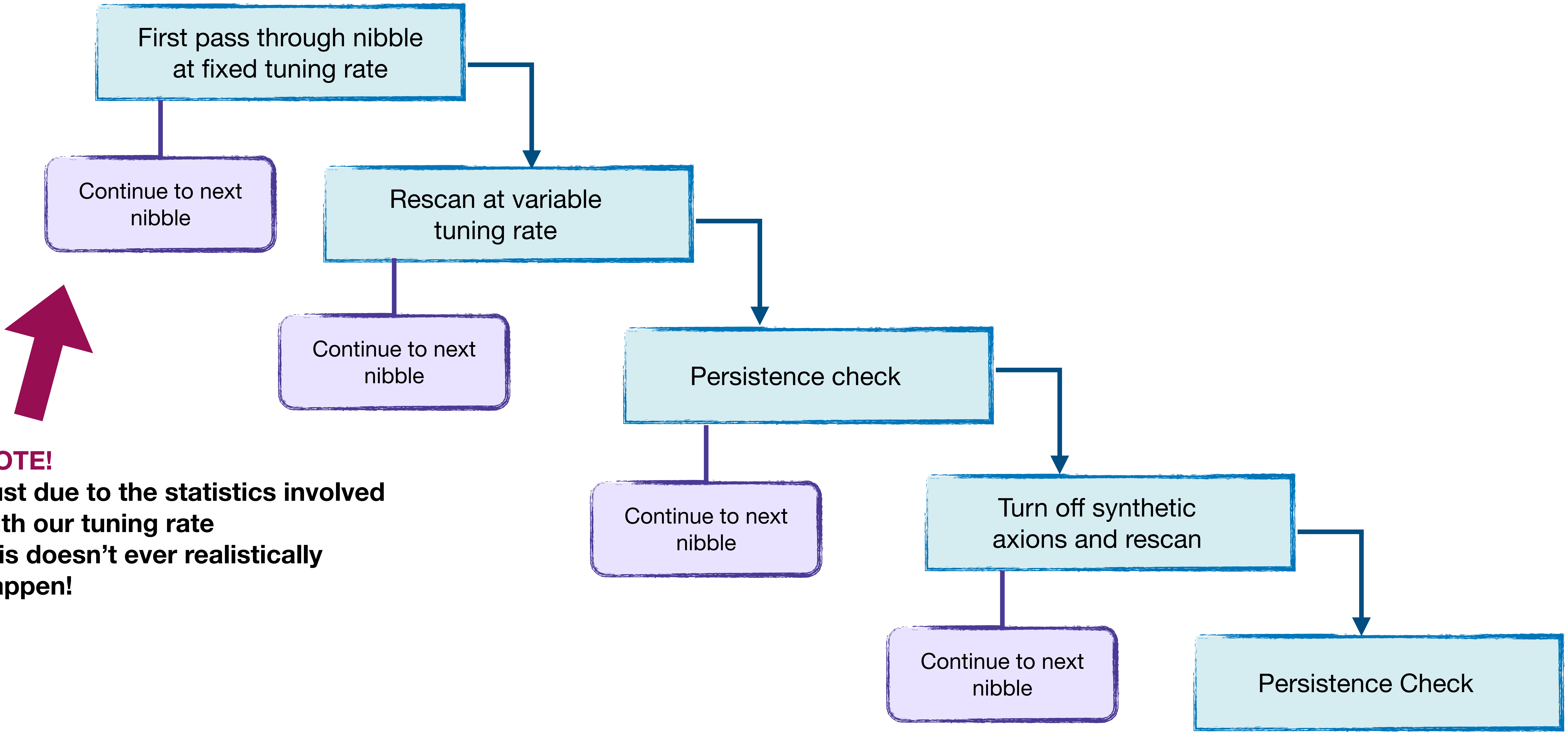
When do you decide to rescan?

3 conditions:

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

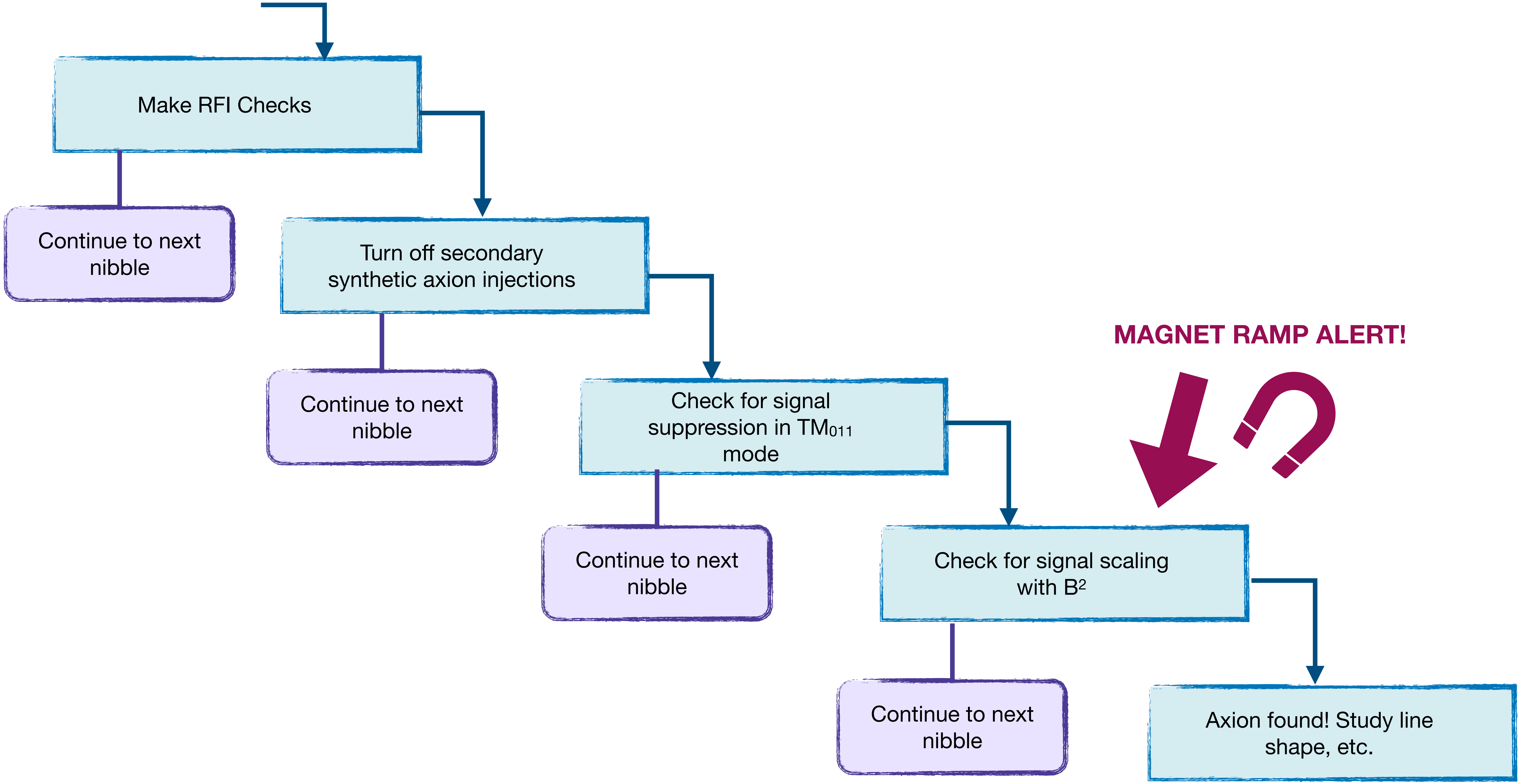


ADMX Search Decision Tree

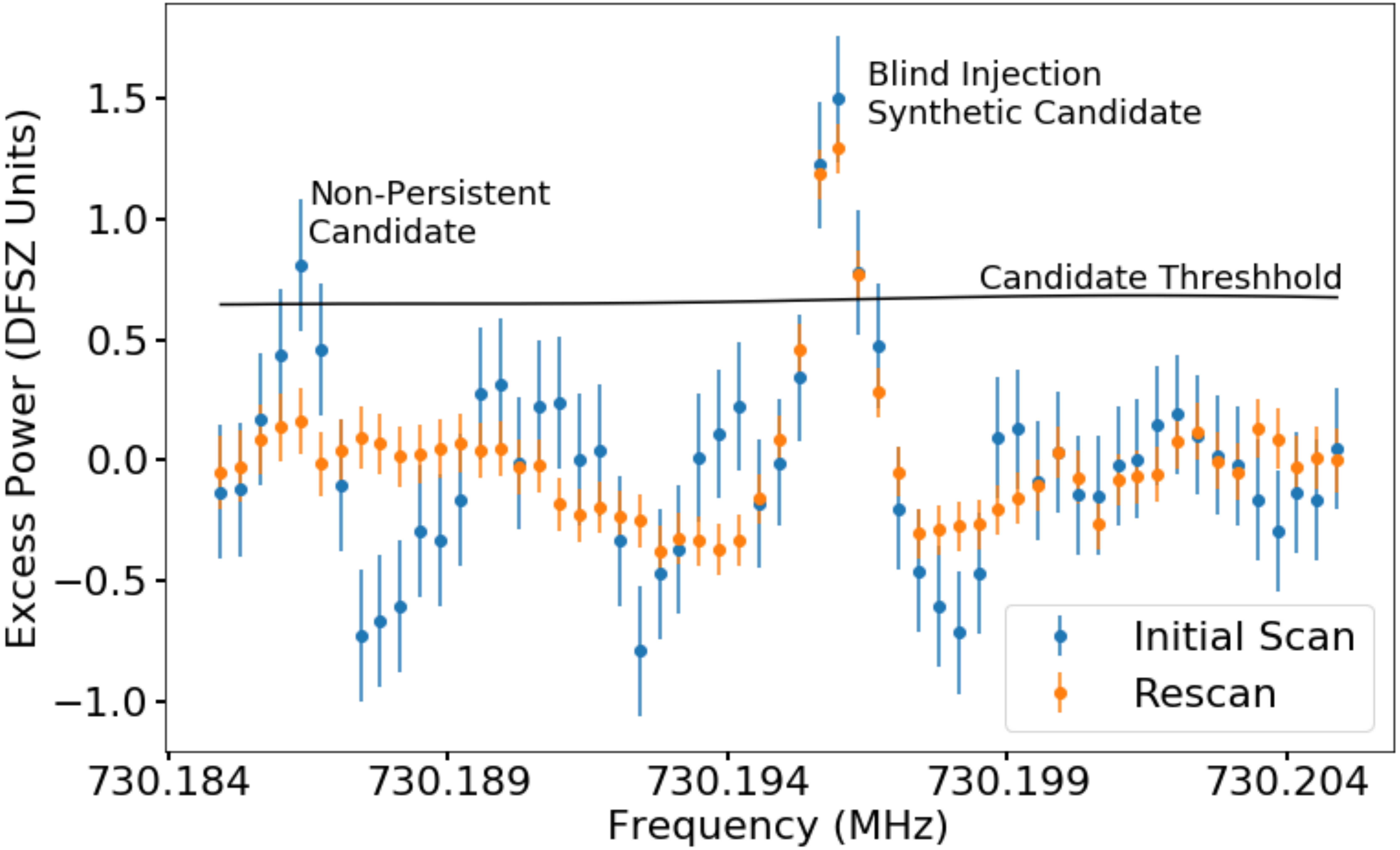


NOTE!
Just due to the statistics involved with our tuning rate this doesn't ever realistically happen!

ADMX Search Decision Tree



Hardware Synthetic Axion Injections

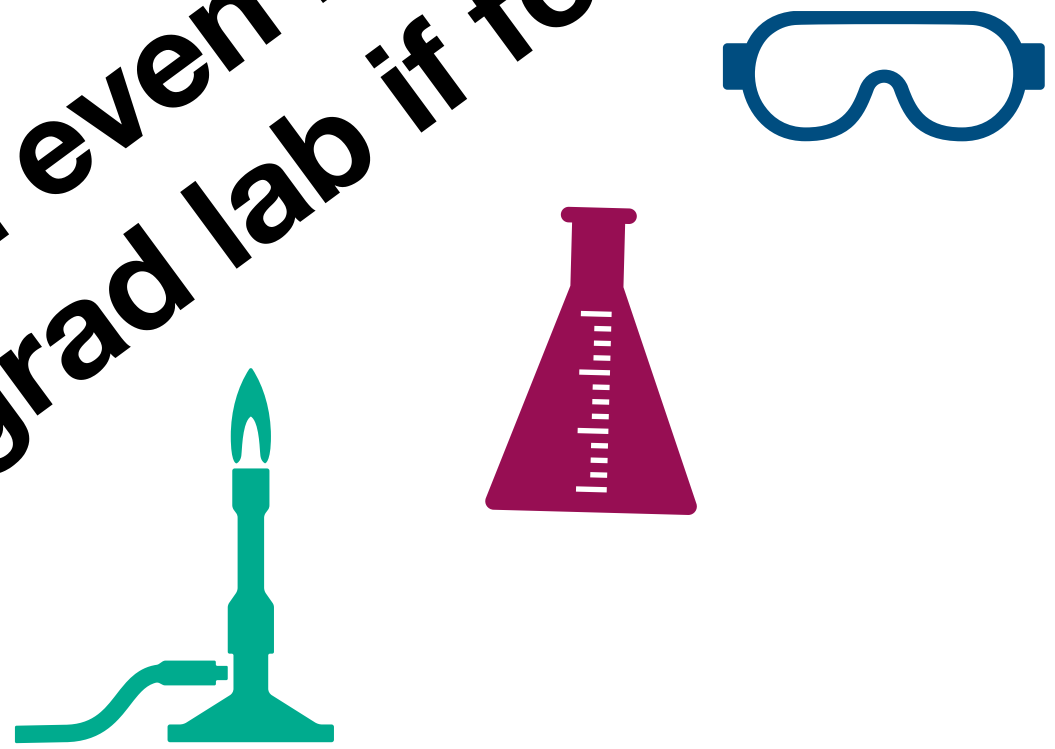


Verifying the axion signal

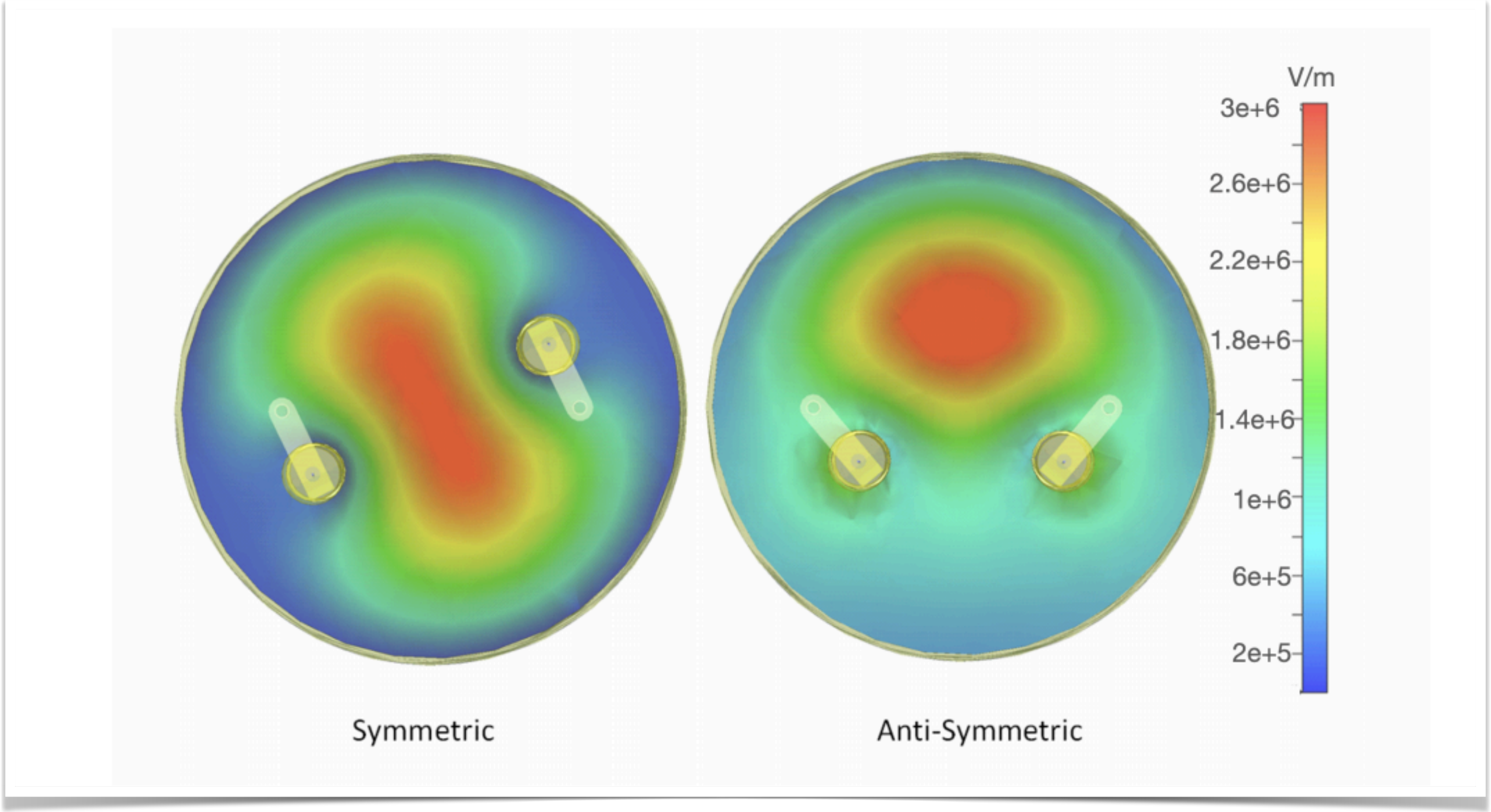
A true axion signal

- Only observed within the confines of the cavity and magnetic field
- Persistent
- Remains when the synthetic axion generator is turned off
- Lorentzian line shape that follows that of the cavity
- Suppressed in non-TM010 modes
- Scales as B^2 (where B is the magnetic field)
- Small daily and annual frequency modulation

Could even be an undergrad lab if found!



Filling in mode-crossings



Rods can be moved in anti-symmetric mode to fill in gaps due to mode-crossings.

This shifts the location of modes within the cavity because the tuning rods change the boundary conditions.

Drawing a Limit

Grand Spectrum consists of

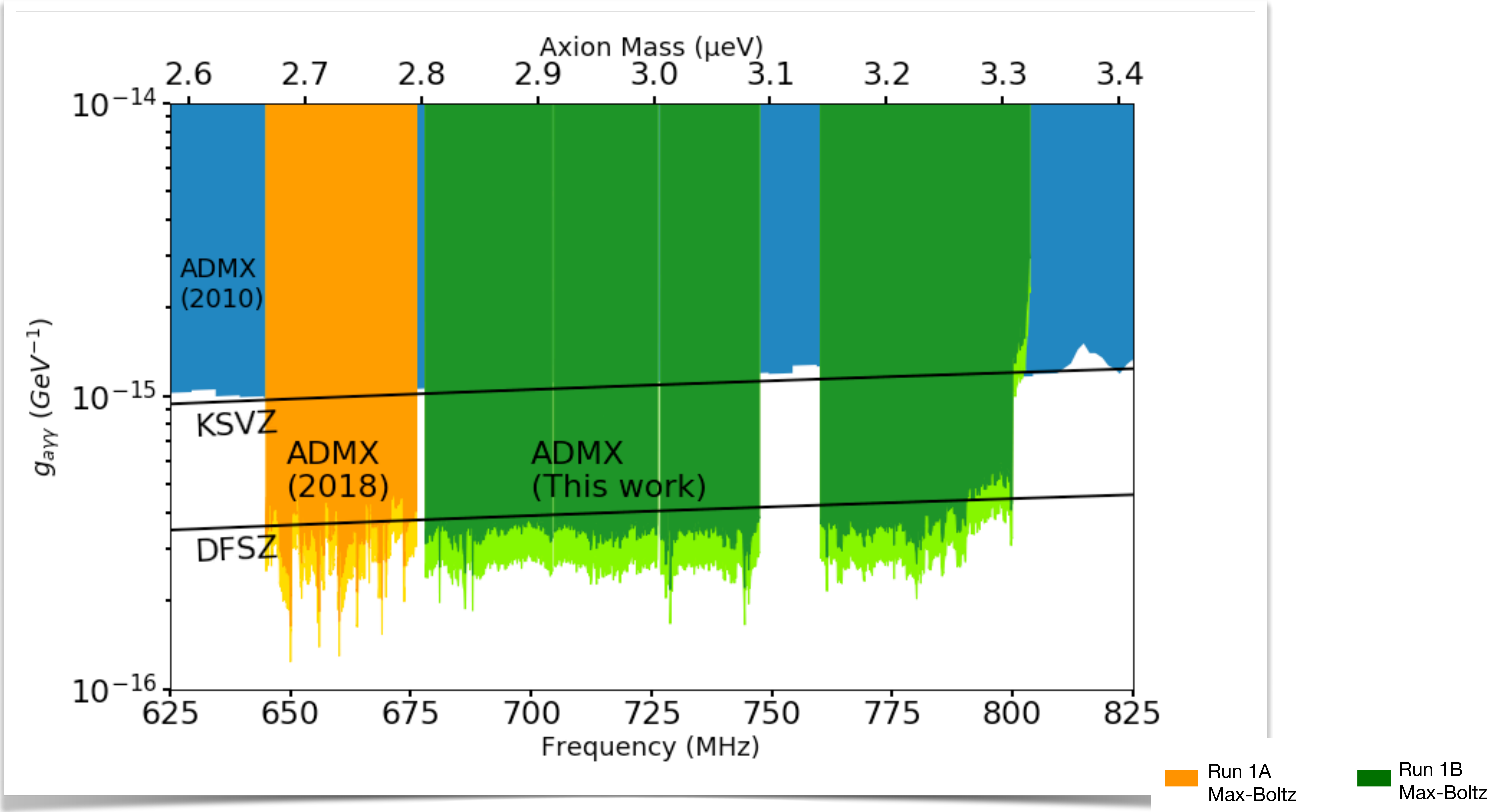
1) measured power
2) measured uncertainties

To convert to a limit:

Find the value for g_γ that gives us the desired C.L. for a particular measured value in the grand spectrum.

For more details, please see:

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

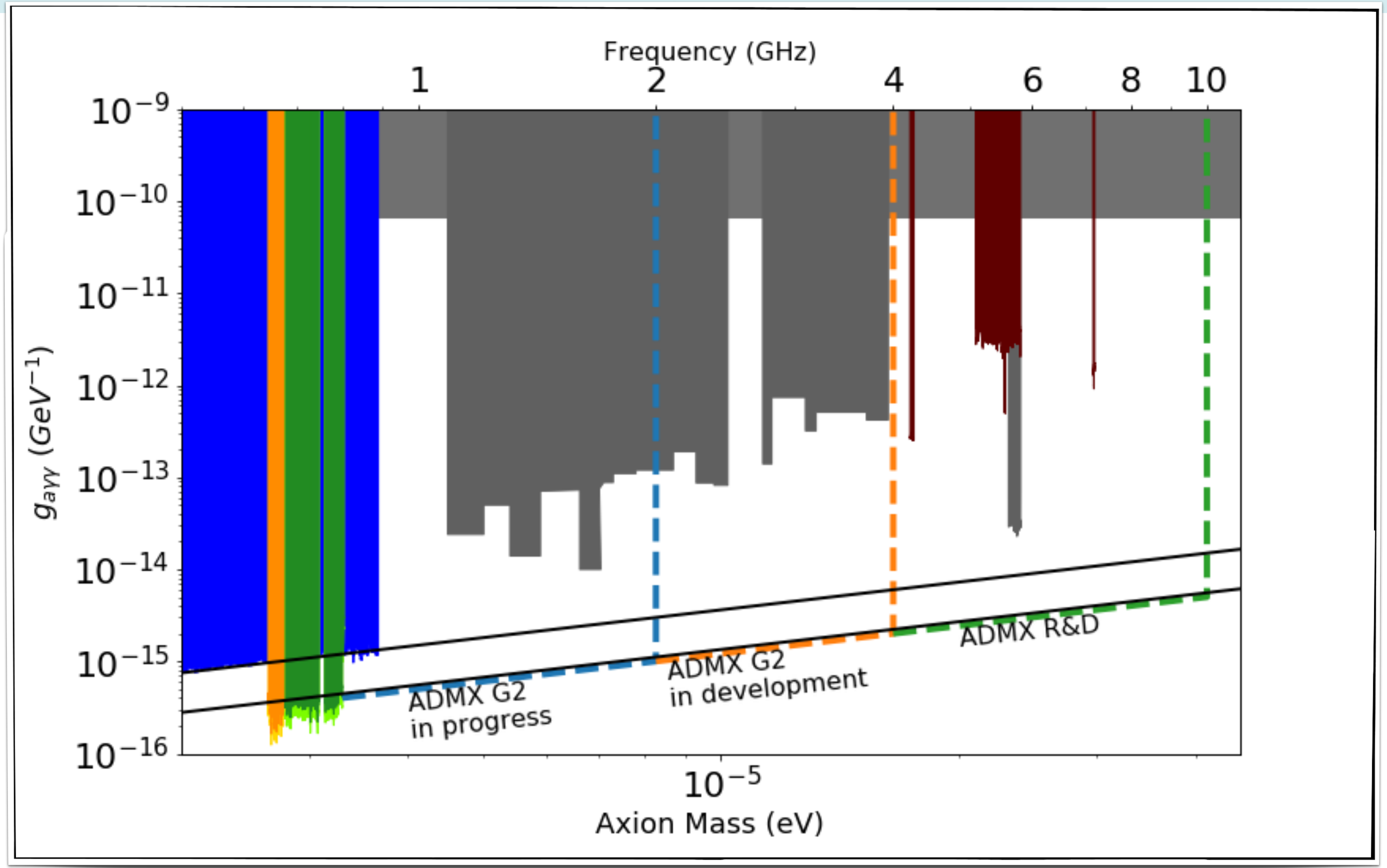


Extended Search for the Invisible Axion with the Axion Dark Matter Experiment

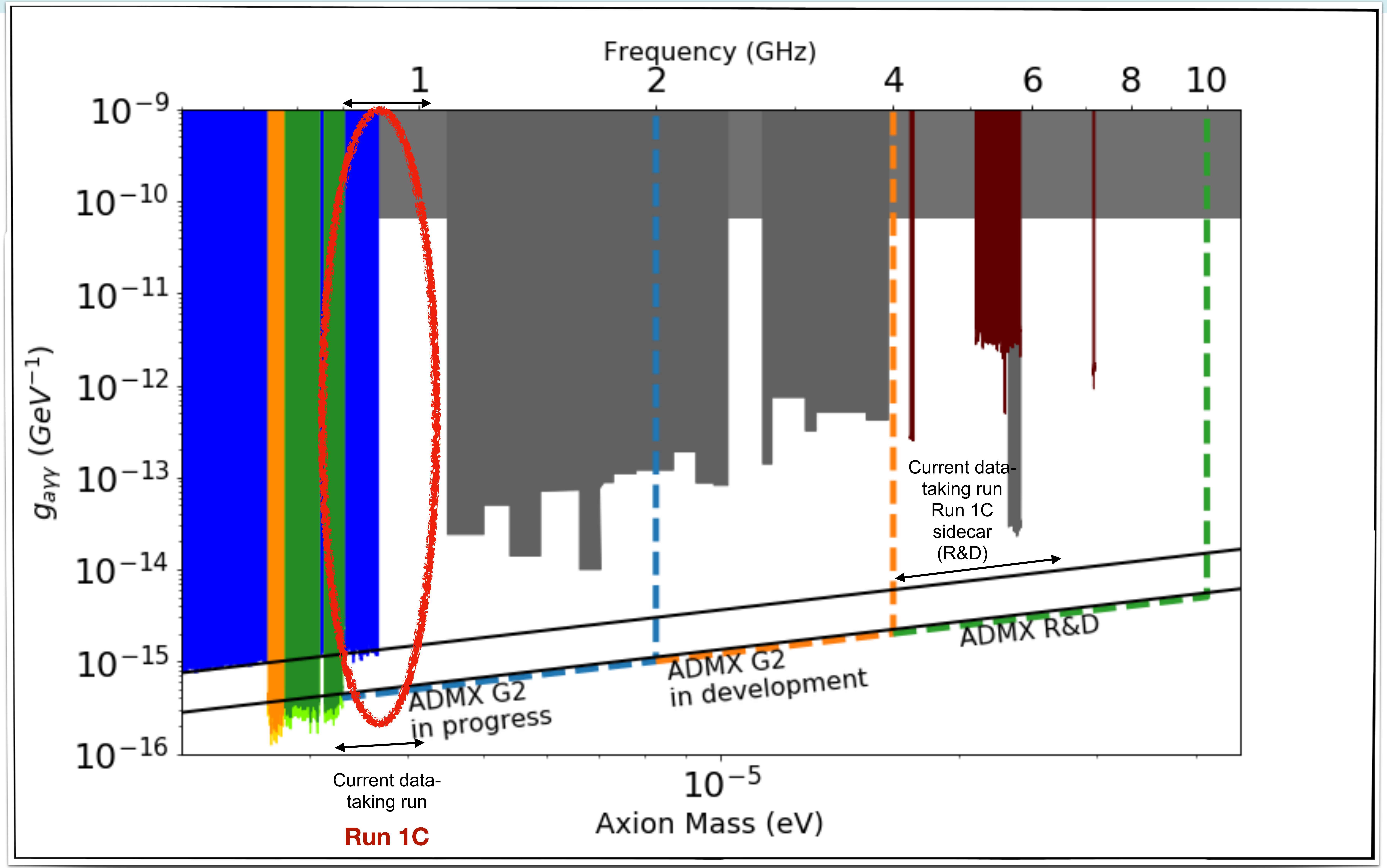
T. Braine et al. (ADMX Collaboration)

Phys. Rev. Lett. 124, 101303 — Published 11 March 2020

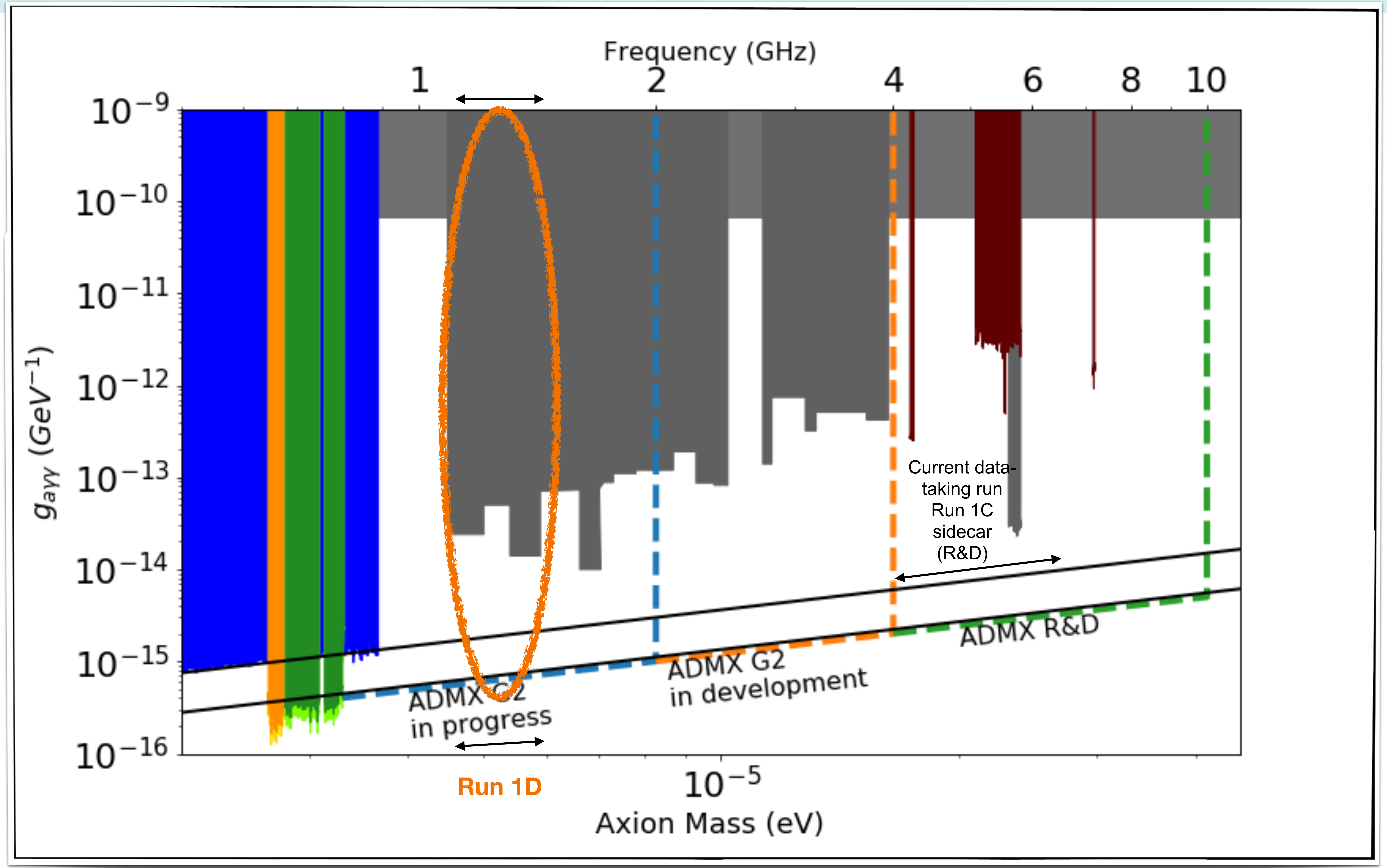
Projected ADMX Sensitivity



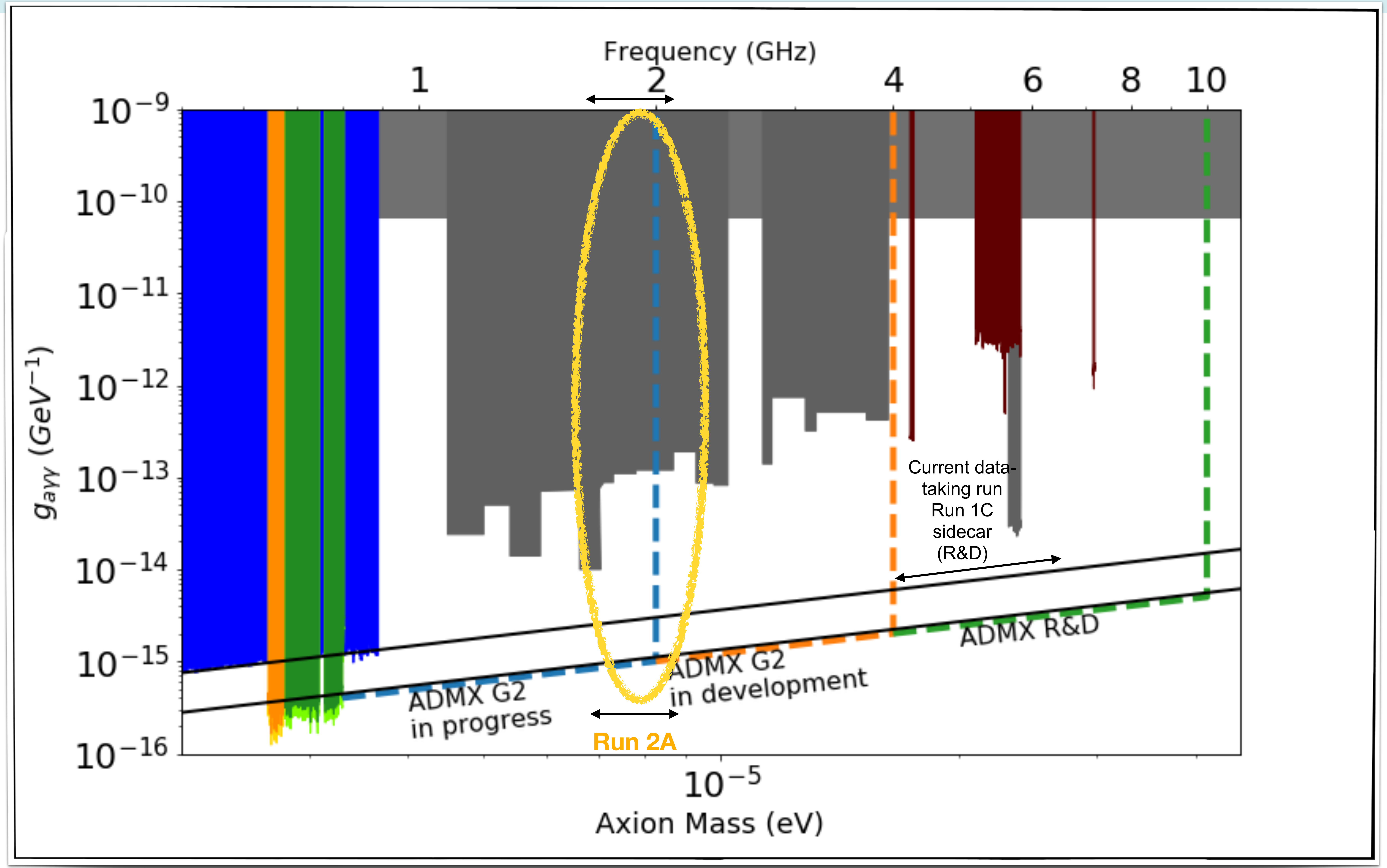
Projected ADMX Sensitivity



Projected ADMX Sensitivity



Projected ADMX Sensitivity



ADMX Collaboration Fermilab Collaboration Meeting in 2018

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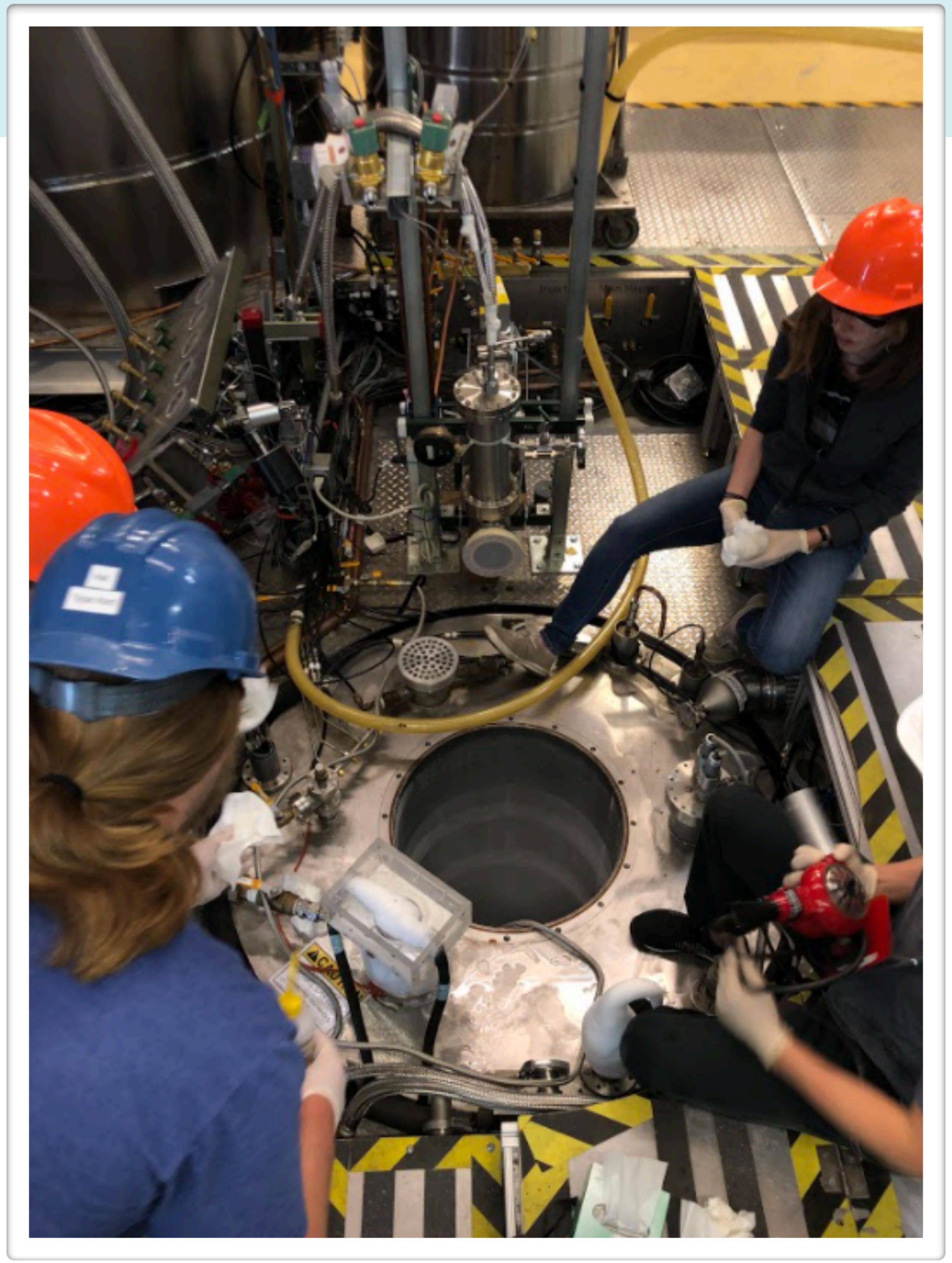
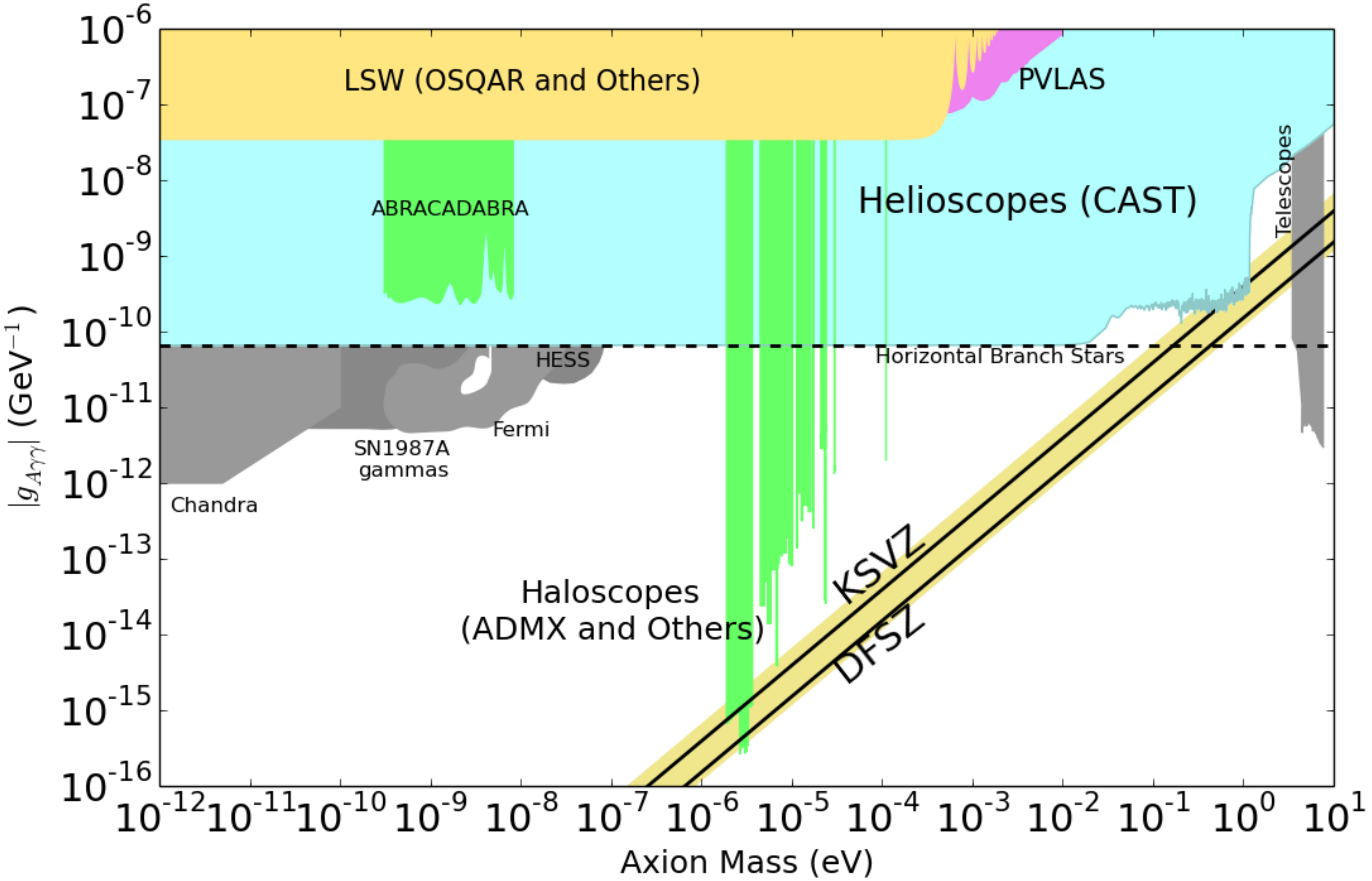
Conclusions

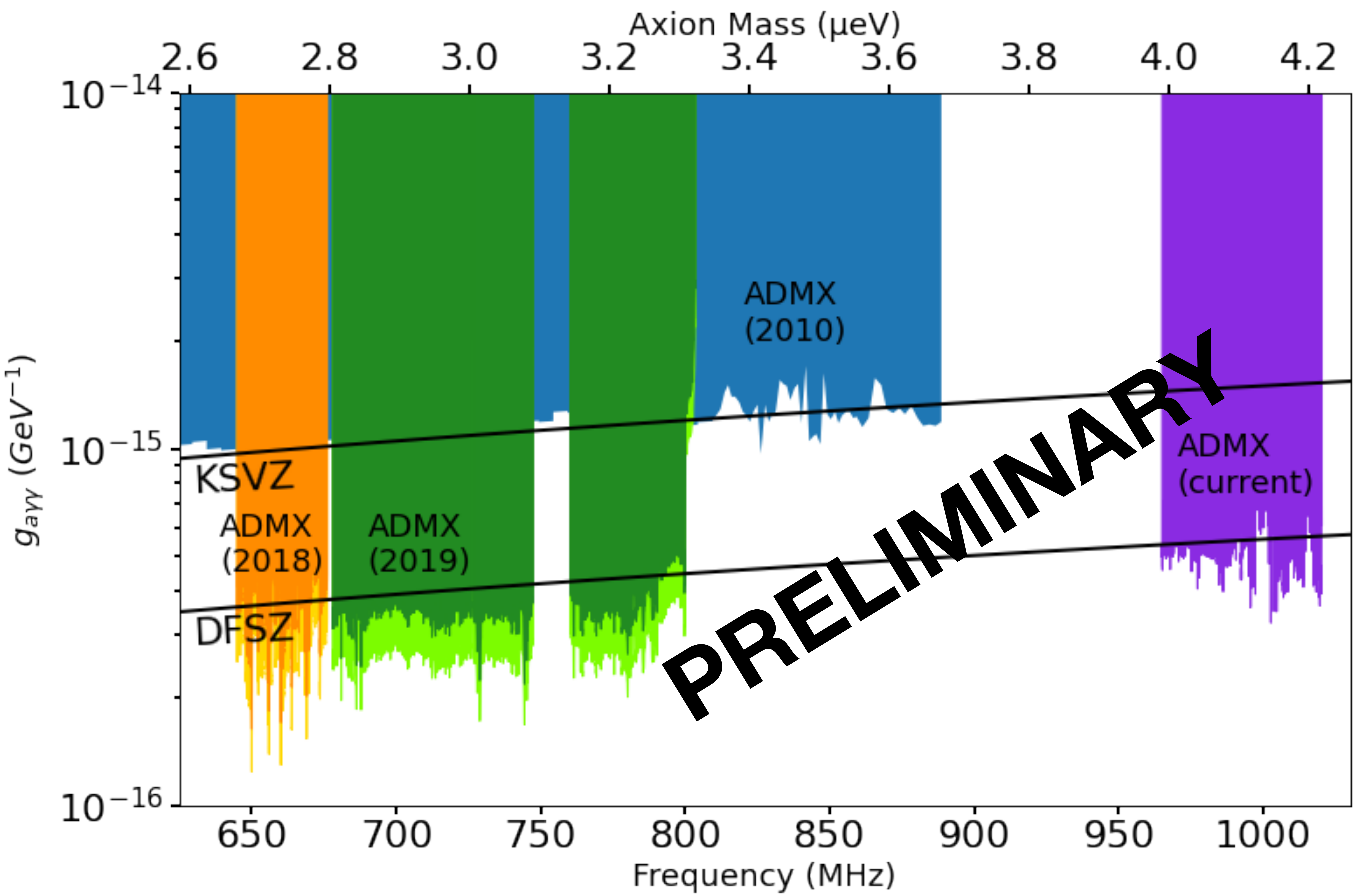
Axions are exciting!

- 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
- ADMX is on track to continue its search for axions. Discovery could happen at any moment!
- Progress being made towards higher frequency searches



Thank you!

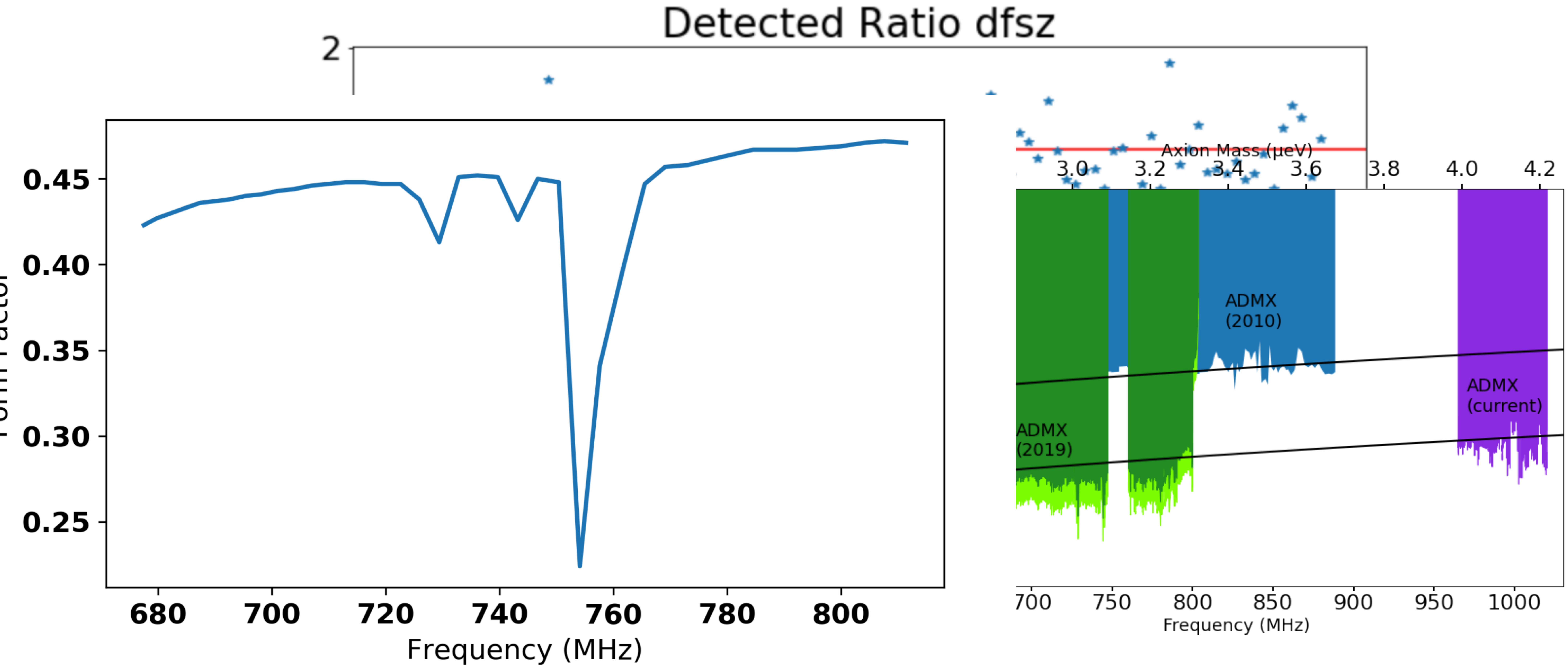

LSW (OSQAR and Others)
PVLAS
ABRACADABRA
Helioscopes (CAST)
Telescopes
HESS
Horizontal Branch Stars
Fermi
SN1987A gammas
Chandra
Haloscopes (ADMX and Others)
KSVZ
DFSZ
$|g_{A\gamma\gamma}|$ (GeV^{-1})
Axion Mass (eV)
10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}



Different types of analyses possible

Current result looks for what value of g_γ gives us the desired C.L. for a particular measured value of μ

Personally interested in discussing other types of analysis, such as Bayesian


Detected Ratio dfsz
2
0.45
0.40
0.35
0.30
0.25
680
700
720
740
760
780
800
Frequency (MHz)
Axion Mass (μeV)
3.0
3.2
3.4
3.6
3.8
4.0
4.2
ADMX
(2010)
ADMX
(current)
ADMX
(2019)
700
750
800
850
900
950
1000
Frequency (MHz)

ADMX Collaboration

- Founded in 1994 at LLNL
- One of 3 "Gen-2" Dark Matter Projects
- Now located at University of Washington

Sponsors

Heising - Simons Foundation

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The University Of Sheffield.

Fermilab

Los Alamos National Laboratory

Georg-August-Universität Göttingen

DFSZ synthetic

$$\frac{df}{dt} \approx 1.68 \frac{\mathrm{GHz}}{\mathrm{yr}} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_o}{0.45\ \mathrm{GeV/cc}}\right)^2 \left(\frac{5}{\mathrm{SNR}}\right)^2 \left(\frac{B_0}{8}\right)^4 \left(\frac{V}{100\ l}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2}{T_{sys}}\right)^2$$