Searching for the QCD axion with the ADMX Receiver

UCSB Seminar

Chelsea Bartram 12/07/2020

85% of the matter content in the universe is unknown!

Cold (non-relativistic)

Non-Baryonic

85% of the matter content in
the universe is unknown!

Feebly-interacting

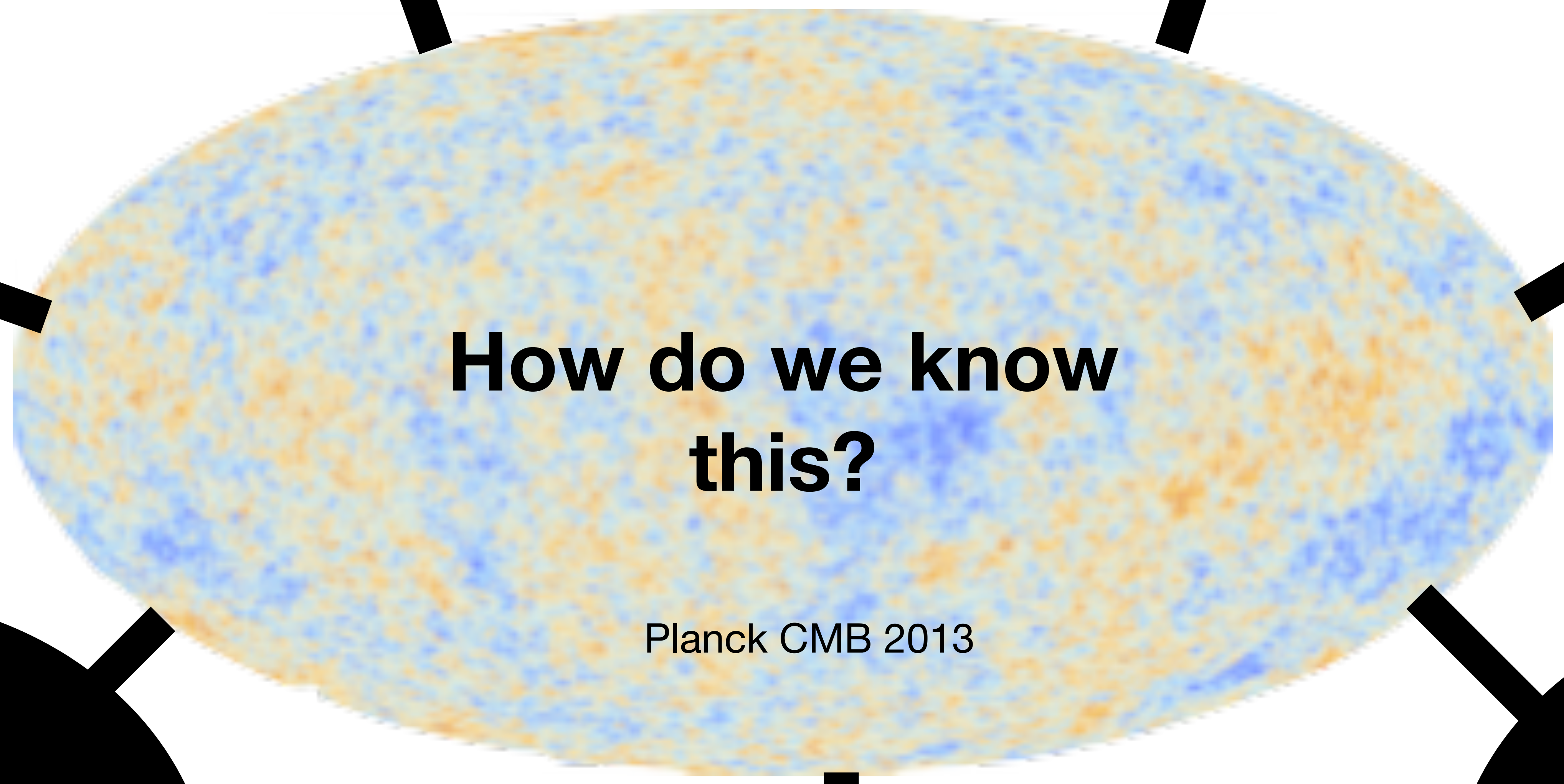
Gravitationally-interacting

Very stable

Matter Radiation Fluctuations

Cosmic Microwave Background

Galaxy Cluster Collisions



Rotational Curves of Galaxies

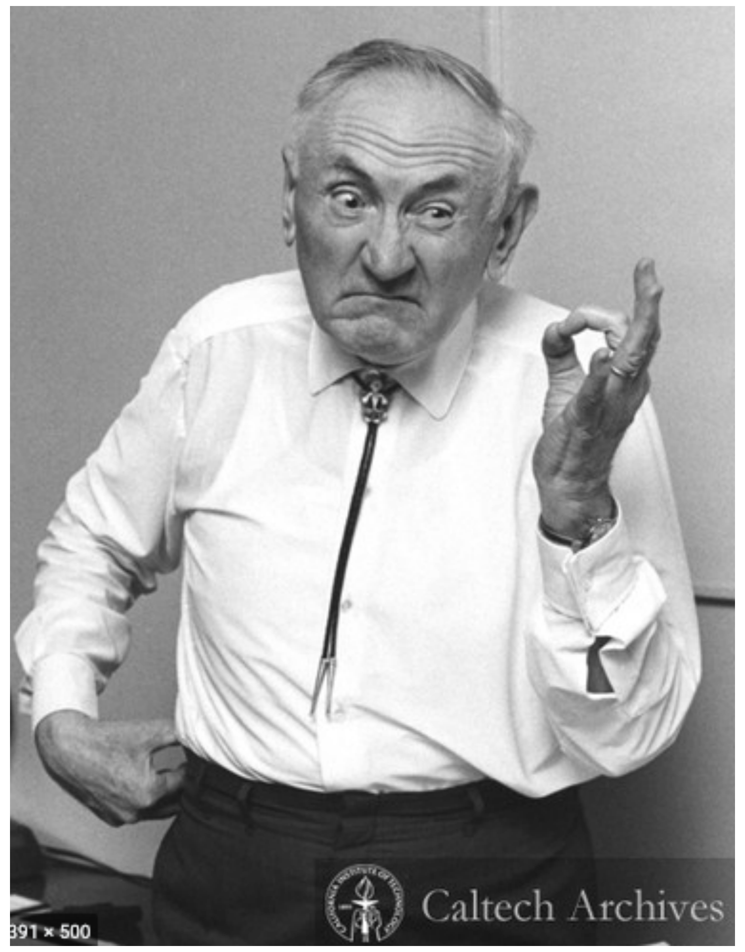
Primordial Nucleosynthesis

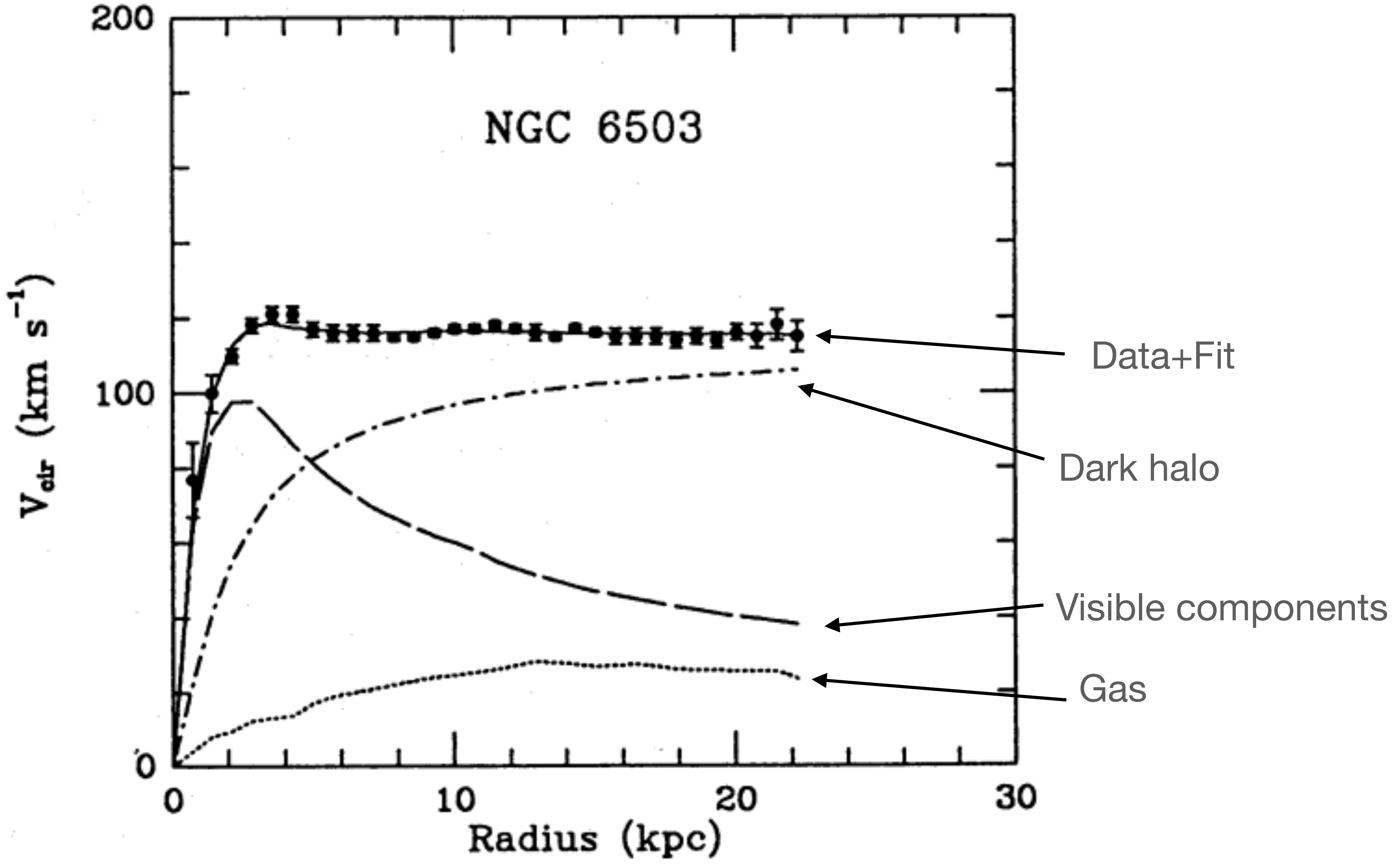
Baryon Acoustic Oscillations

Gravitational Lensing

Galactic Rotation Curves

Naively, velocity should asymptote to constant value.





Zwicky, Fritz. "On the Masses of Nebulae and of Clusters of Nebulae." *The Astrophysical Journal* 86 (1937): 217.

Faber, Sandra M., and J. S. Gallagher. "Masses and mass-to-light ratios of galaxies." *Annual review of astronomy and astrophysics* 17.1 (1979): 135-187.

Rubin, Vera C. "Rotation curves of high-luminosity spiral galaxies and the rotation curve of our galaxy." *Symposium-International Astronomical Union*. Vol. 84. Cambridge University Press, 1979.

K. G. Begeman, A. H. Broeils, R. H. Sanders, Extended rotation curves of spiral galaxies: dark haloes and modified dynamics, *Monthly Notices of the Royal Astronomical Society*, Volume 249, Issue 3, April 1991, Pages 523–537, https://doi.org/10.1093/mnras/249.3.523

Axion Dark Matter

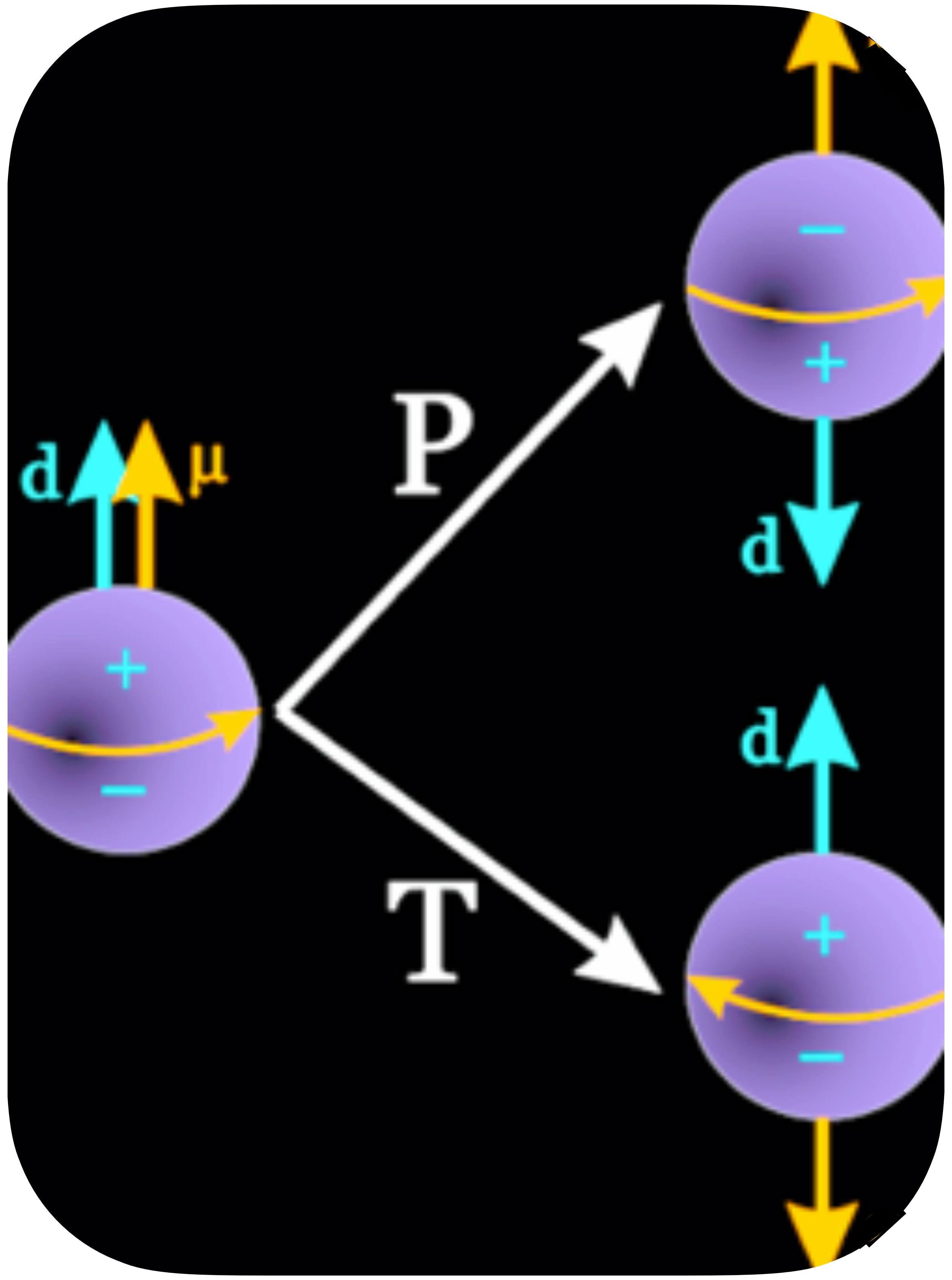
Solving Both Dark Matter and the Strong CP Problem!

What is the Strong CP Problem?

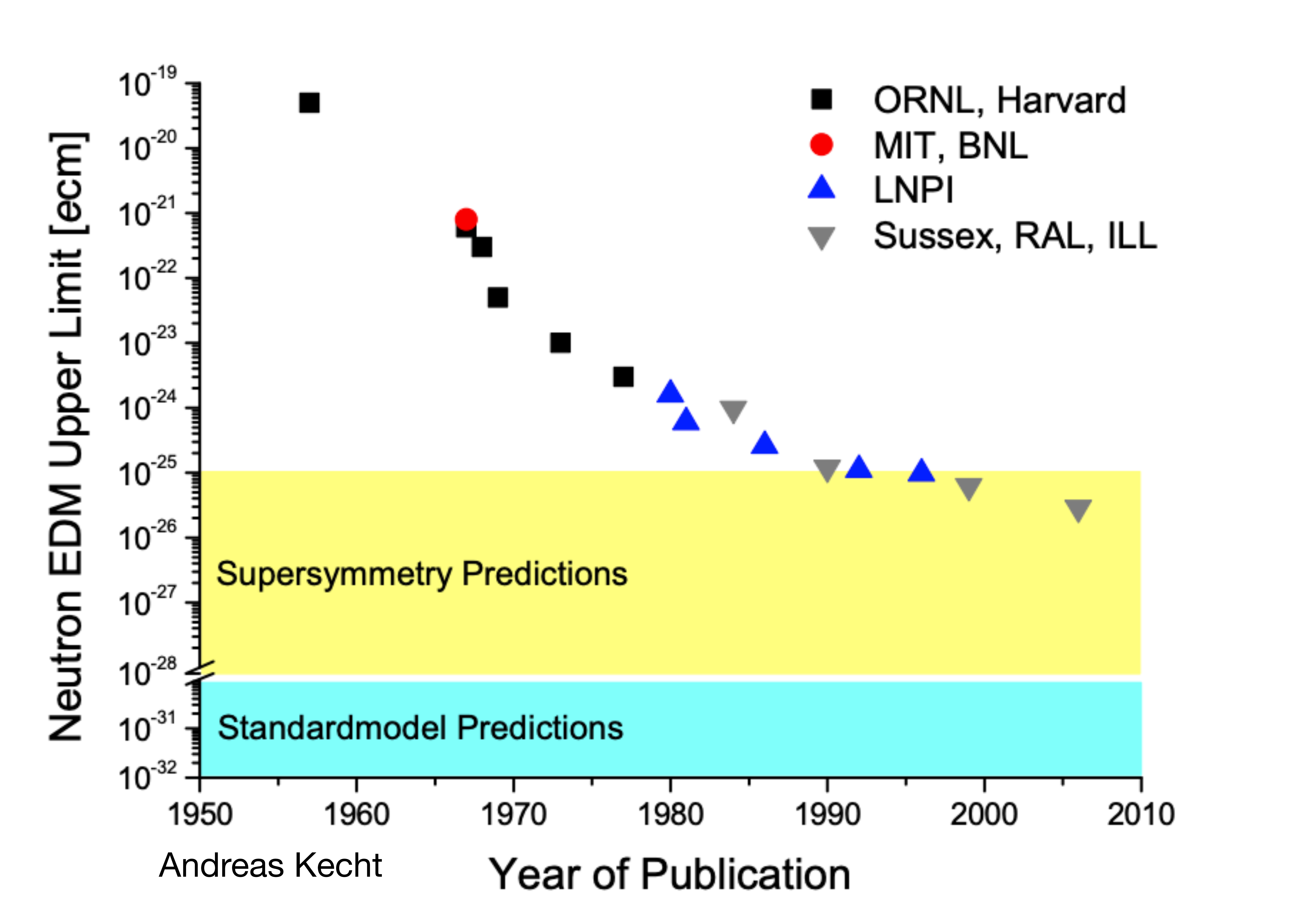
Strong Interactions -should- violate CP due to term in QCD Lagrangian

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

CP-violation in strong interactions not found!



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



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

C. Abel et al.

Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

Axions as wave-like dark matter candidates

What does this mean?

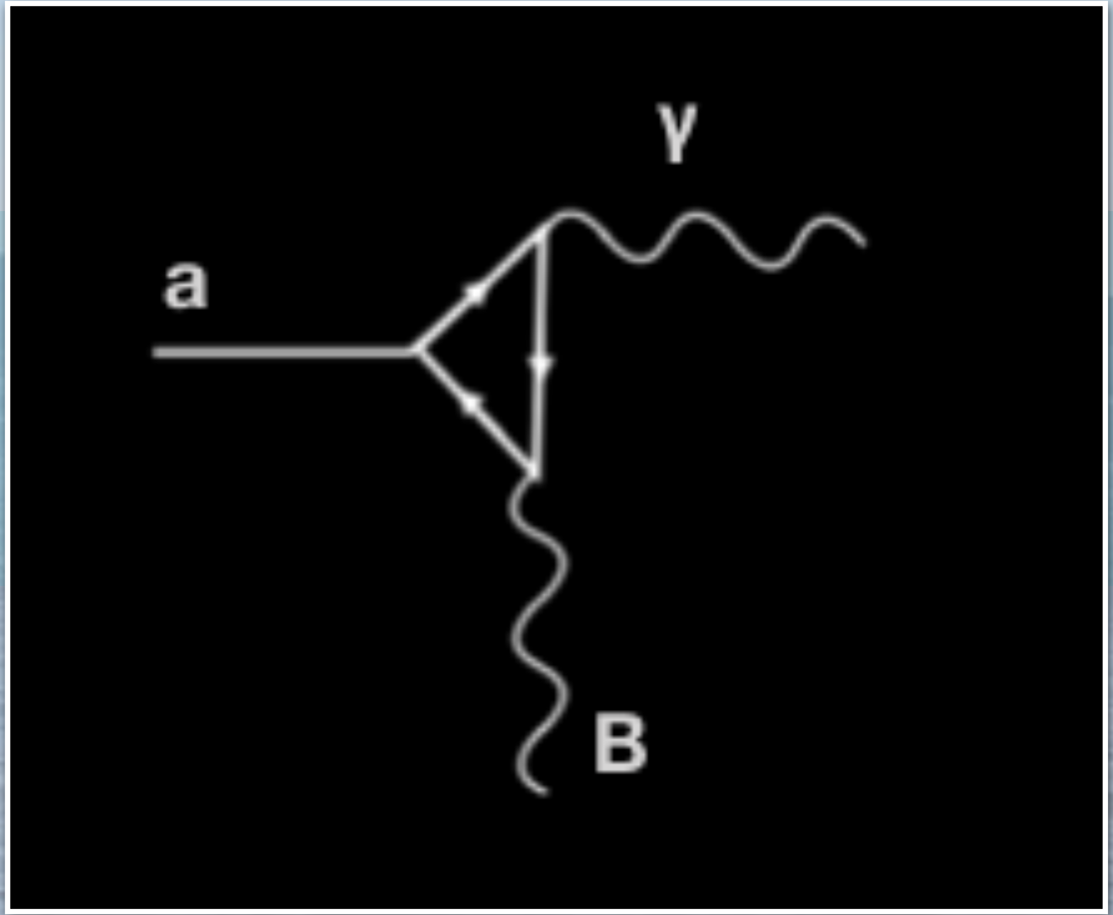
$$a(\vec{x},t) = \frac{\sqrt{(2\rho_{DM})}}{m_a}\cos\left(m_a t + \mathcal{O}(\nu_{DM})\vec{x}\right)$$

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

Calculate de Broglie wavelength of axions:

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

Wavelength of the Conversion Photon: ~meter



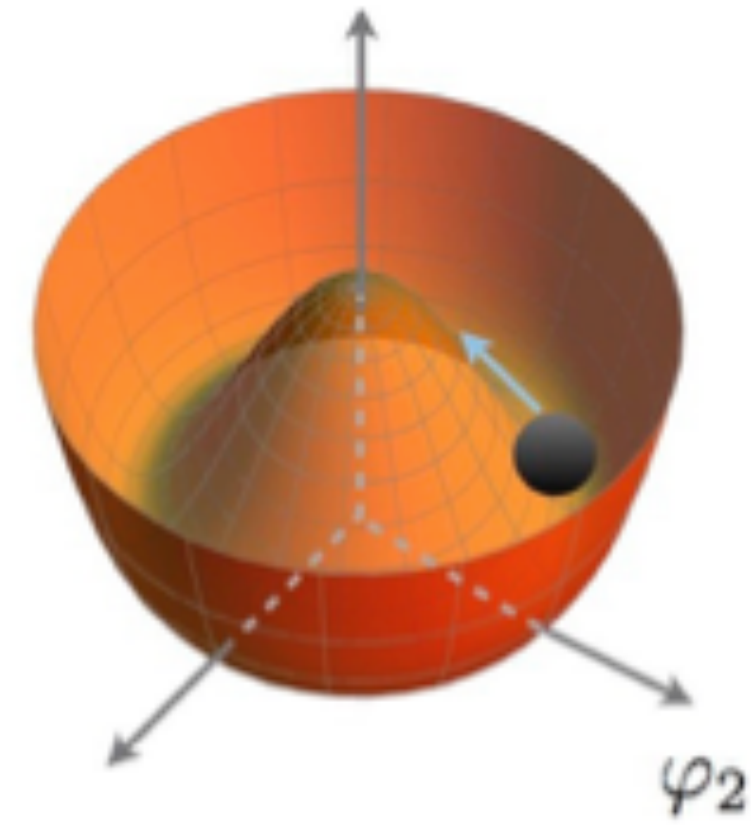
Inverse Primakoff Effect
Axion Decay to Photon in a Magnetic Field

Axions and the Strong CP Problem

- Peccei-Quinn Solution to Strong CP Problem: Propose new global U(1) chiral symmetry that was spontaneously broken in the early universe
- Made Θ_{QCD} a dynamical variable which relaxes to zero at critical temperature, when the wine-bottle potential tips
- PQ Mechanism predicts a pseudo scalar boson which is the axion! (Weinberg, Wilçek)

Helen Quinn

Roberto Peccei
1942-2020



Oscillation about the QCD minimum – *Daniel Grin*

Theoretical Constraints

Lower bound set by size of dark matter halo size of dwarf galaxies

Upper bound set by SN1987A and white dwarf cooling time

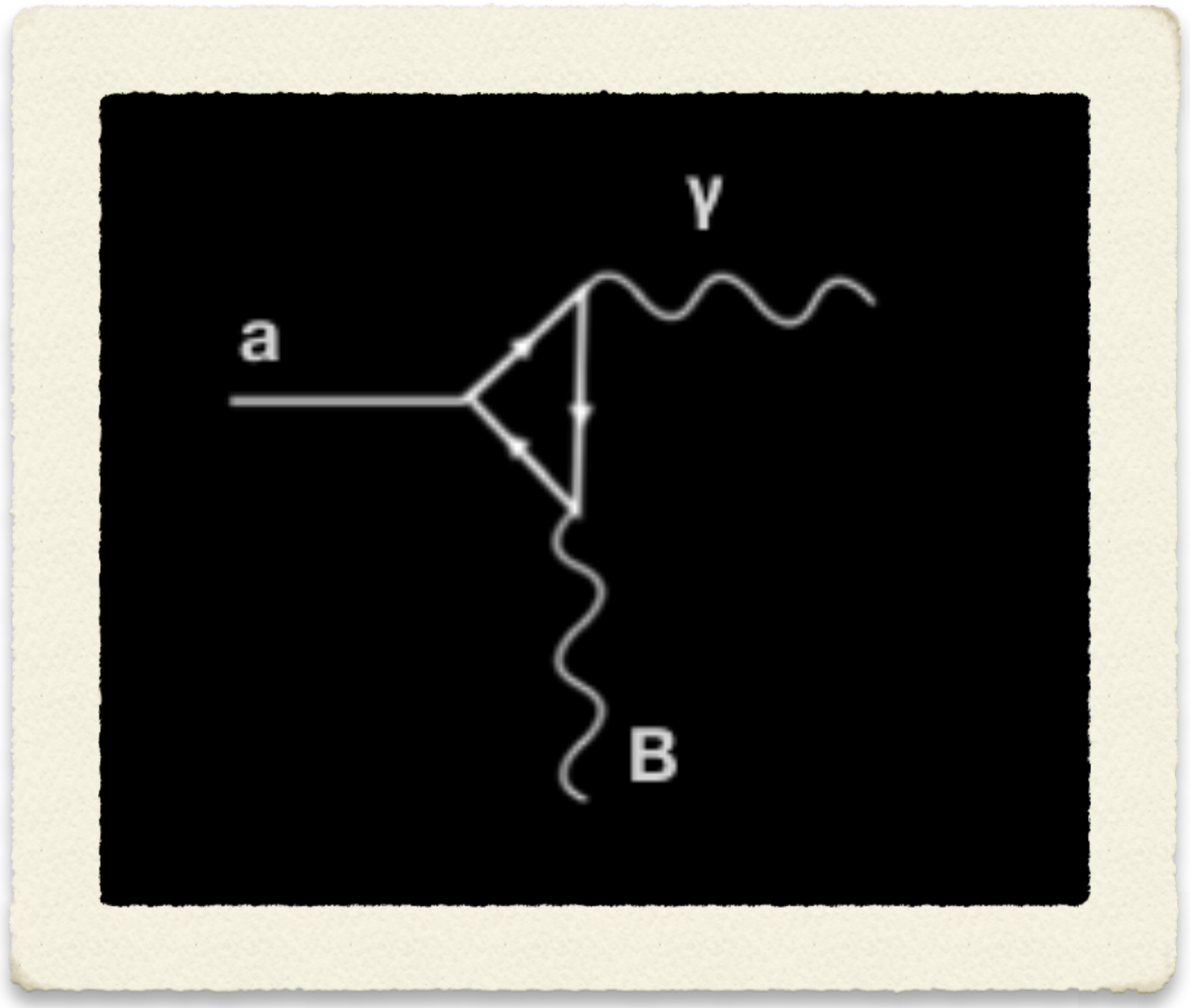
PDG https://arxiv.org/pdf/1710.05413.pdf

Adaptation of L. Winslow DPF Slide

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



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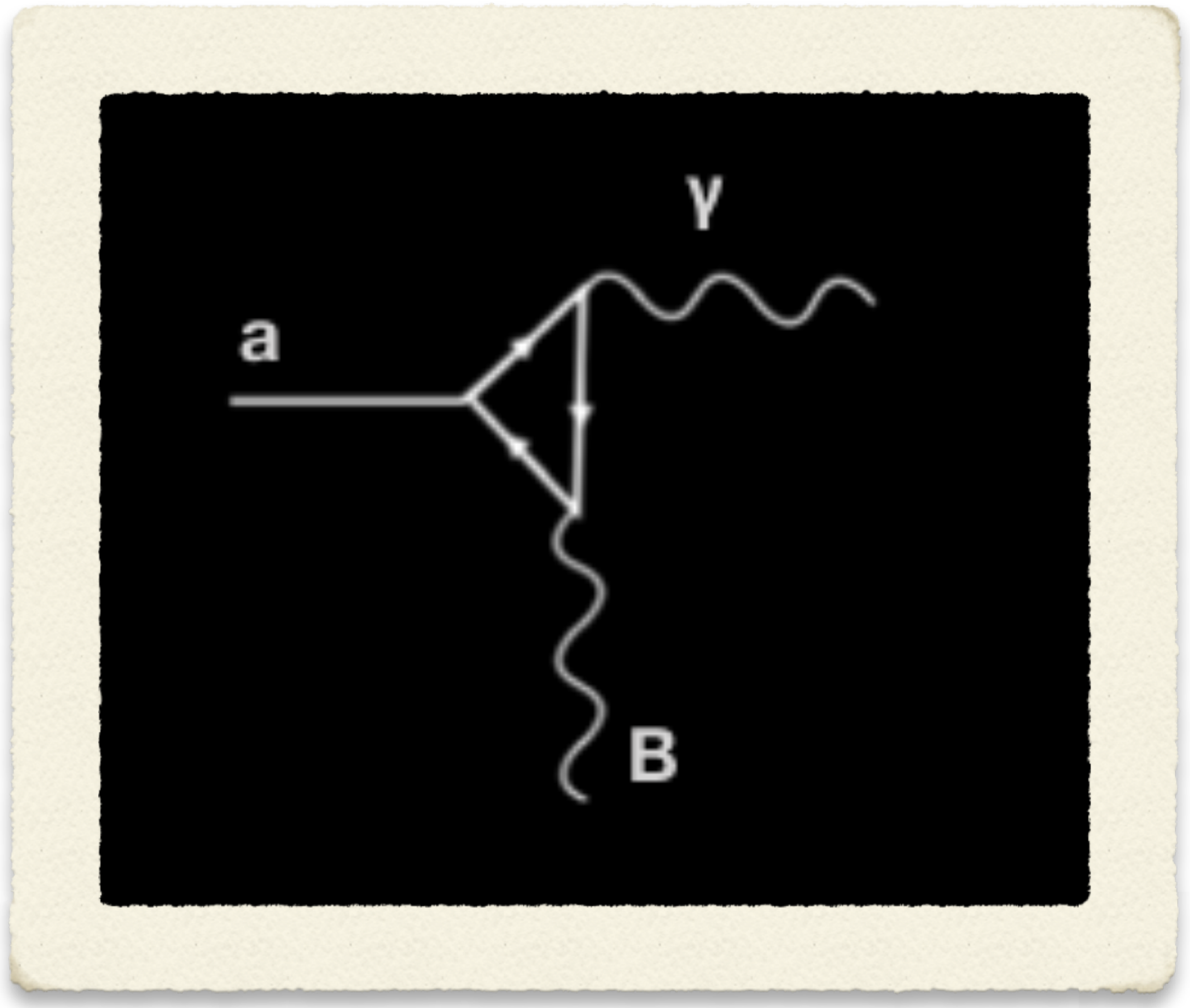
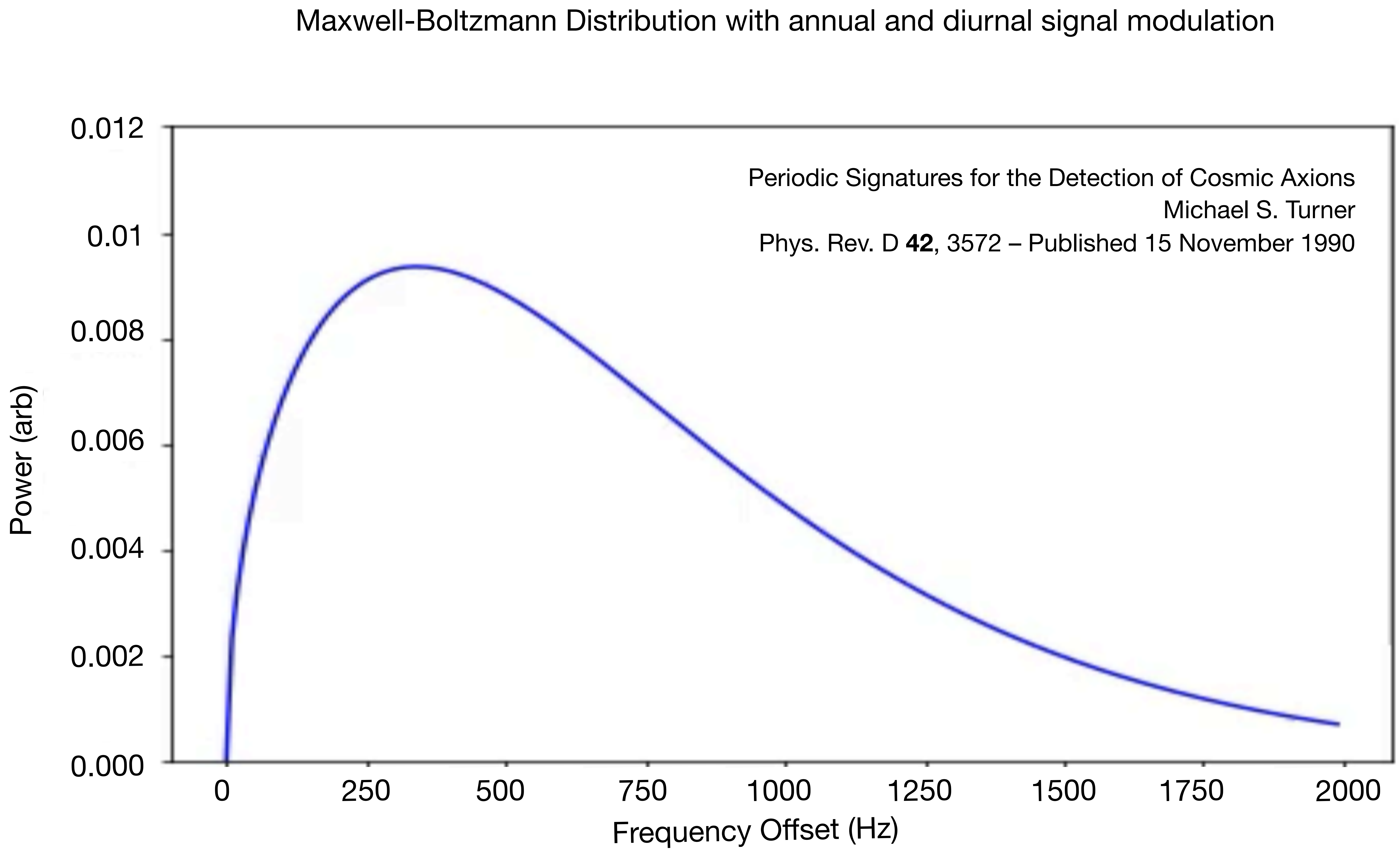


Hardest to detect!

Axion Lineshape (Velocity Distribution)



How to detect an axion

Pierre Sikivie

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.

Axion Dark Matter eXperiment (ADMX) founded in 1994!

ADMX Collaboration

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

Sponsors

Primary Sponsor

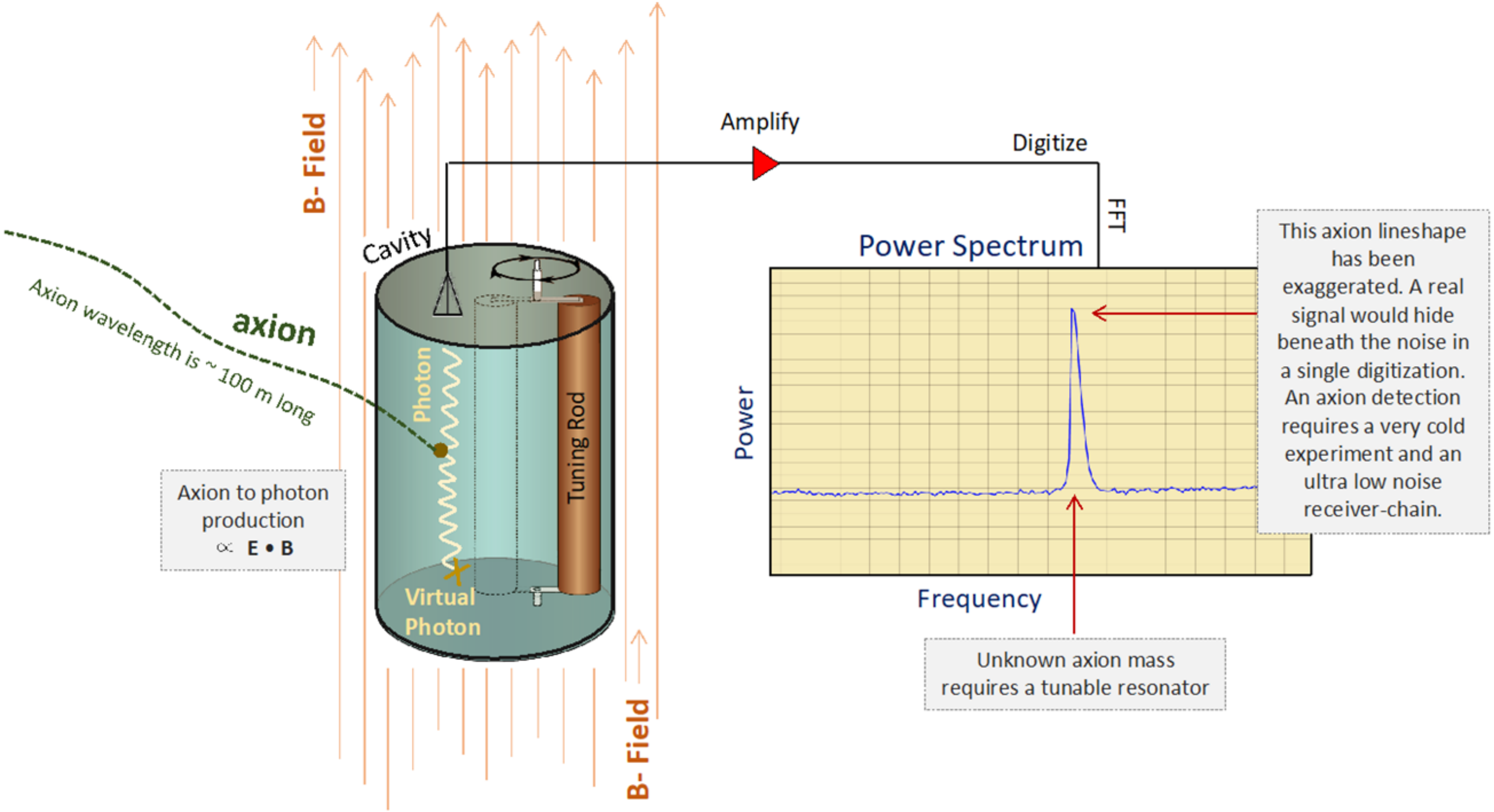
Quantum Computing

Cryogenics

Microwave Electronics

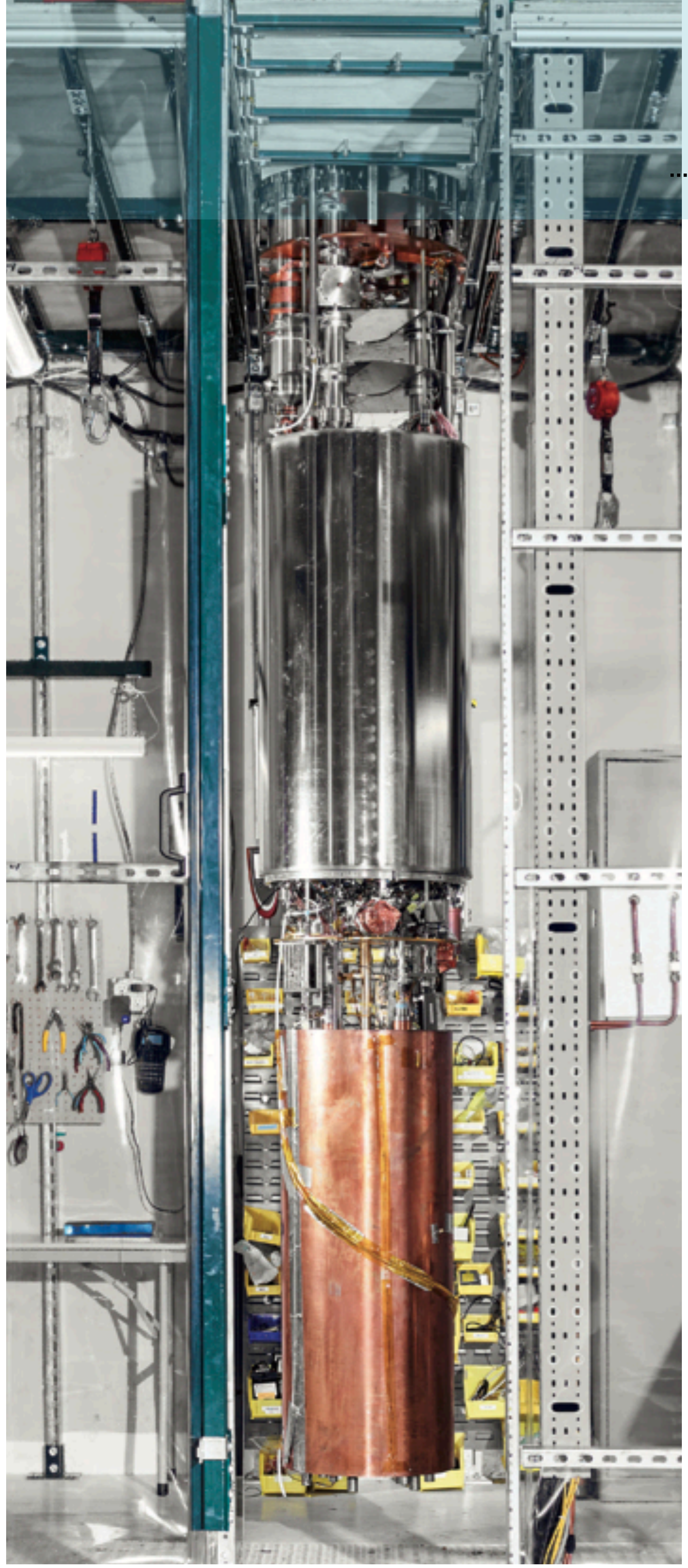
High Magnetic Fields

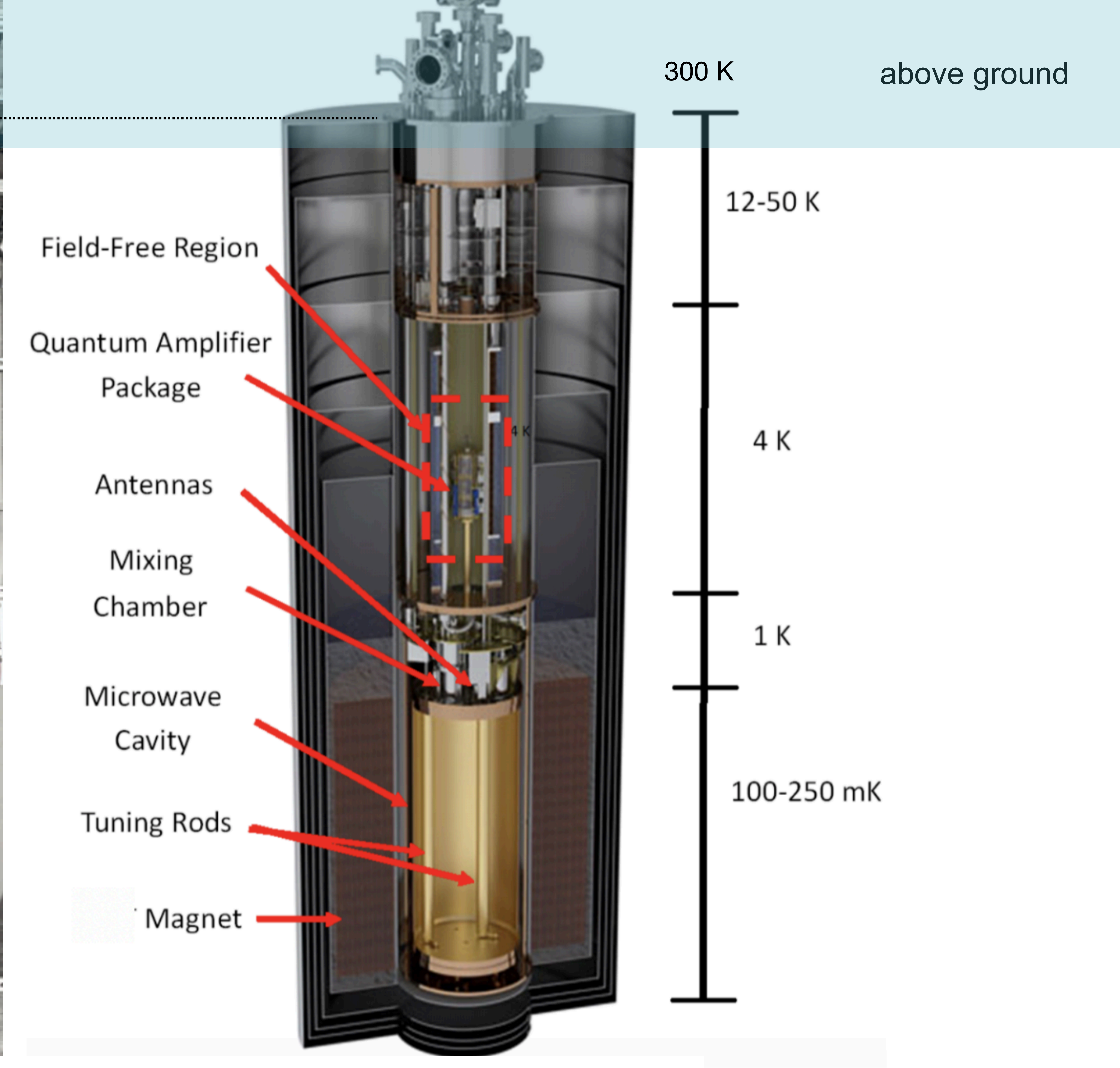
ADMX Haloscope



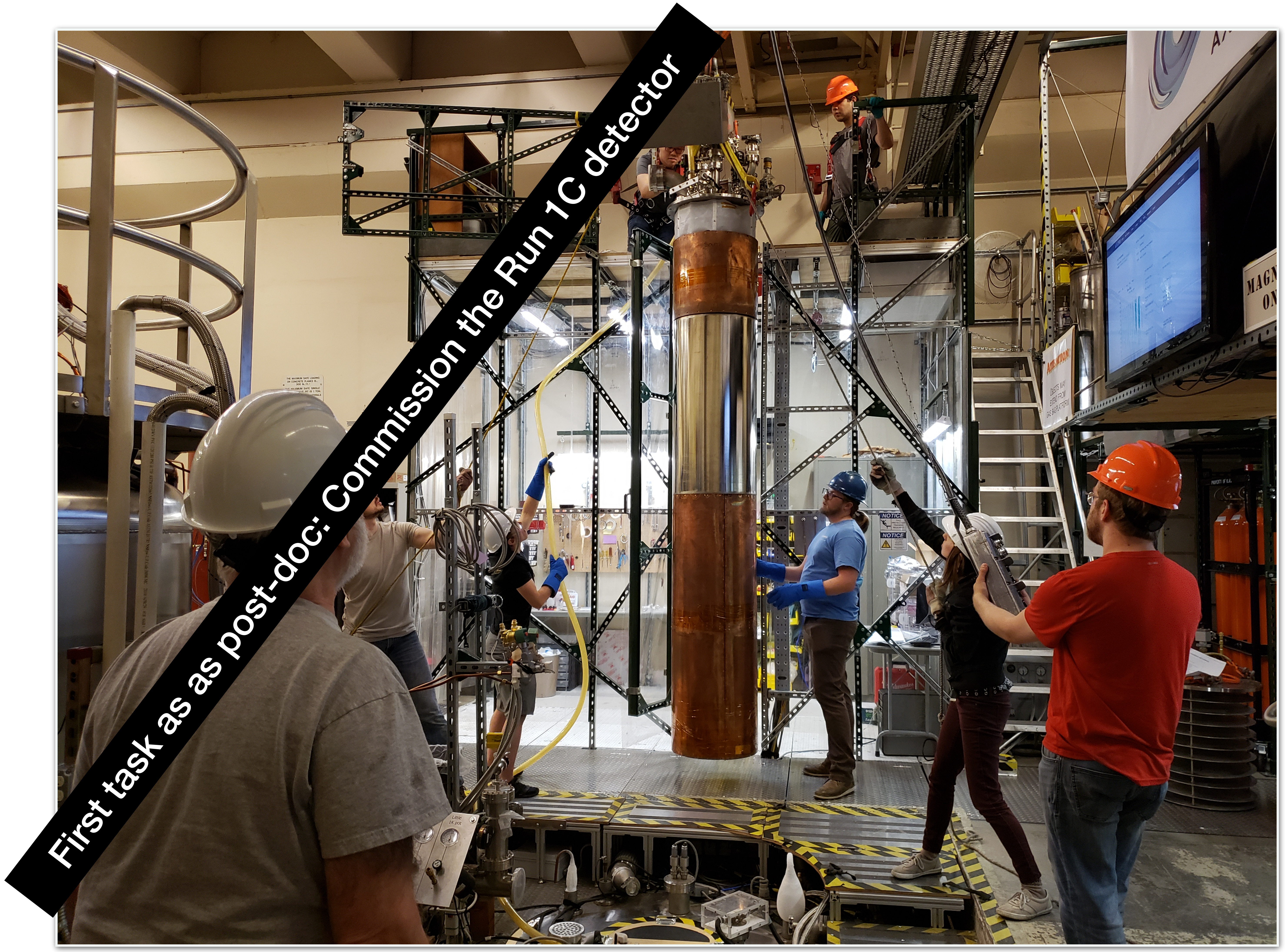
ADMX

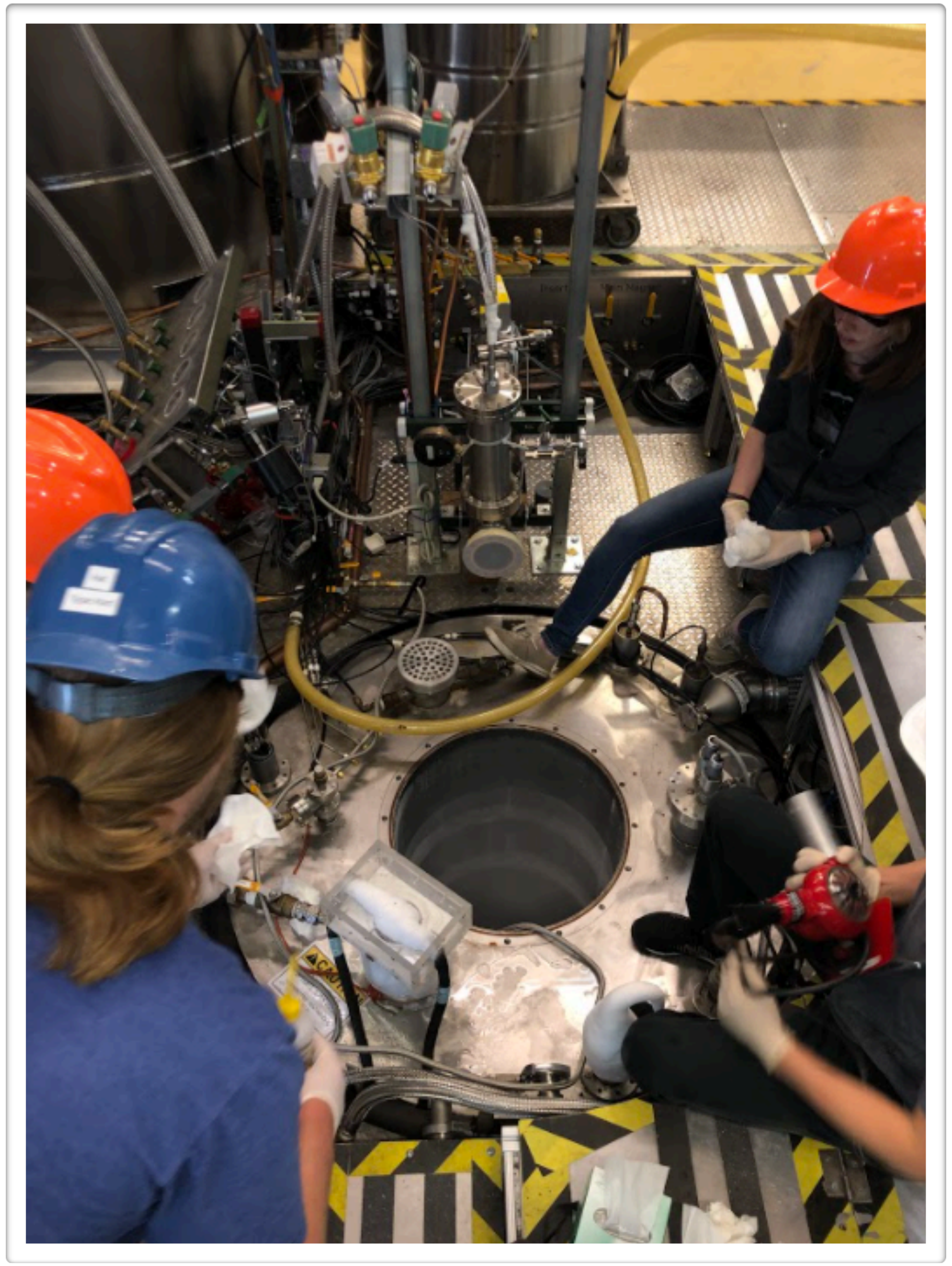
- Dil Fridge: Reaches ~100 mK
- Superconducting magnet:
  ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics



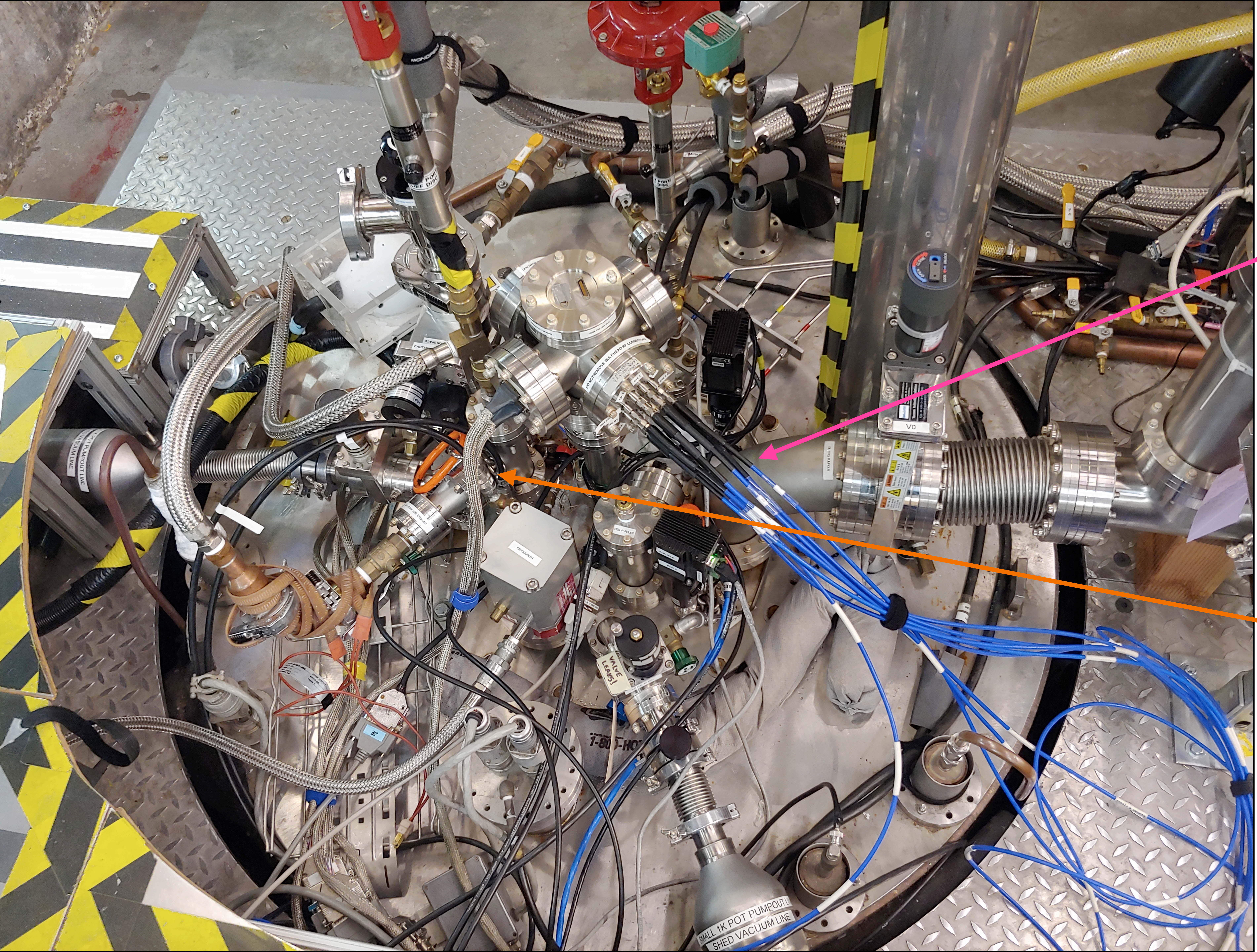


ADMX Rigging Operation





Top of the ADMX “insert” after being moved into the magnet bore



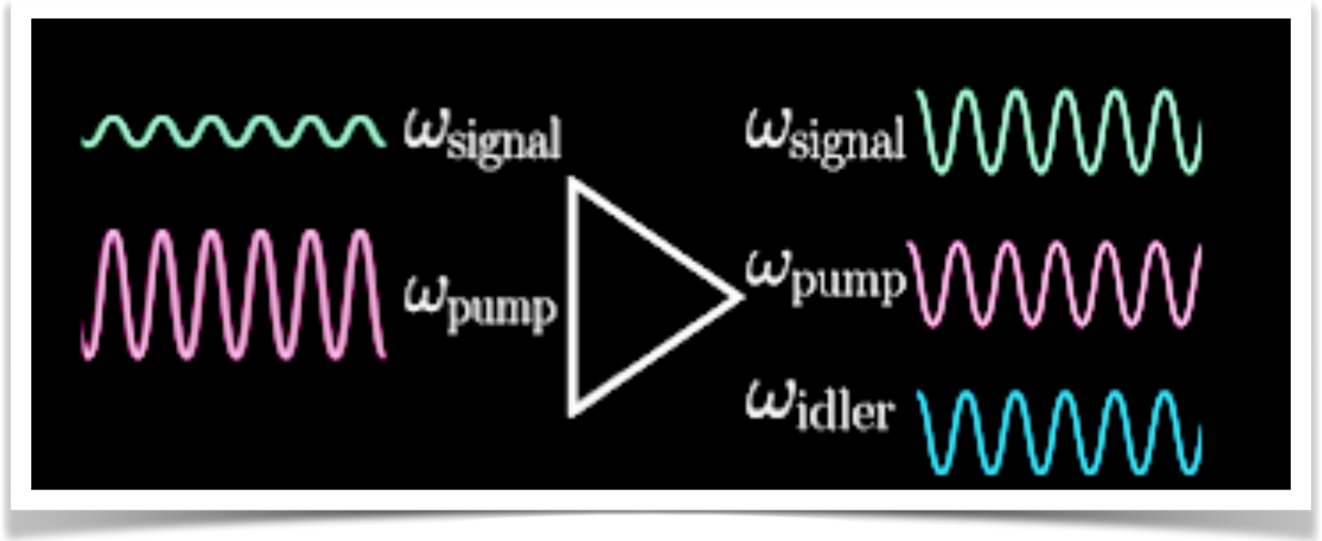
RF cables

DC cables for sensors

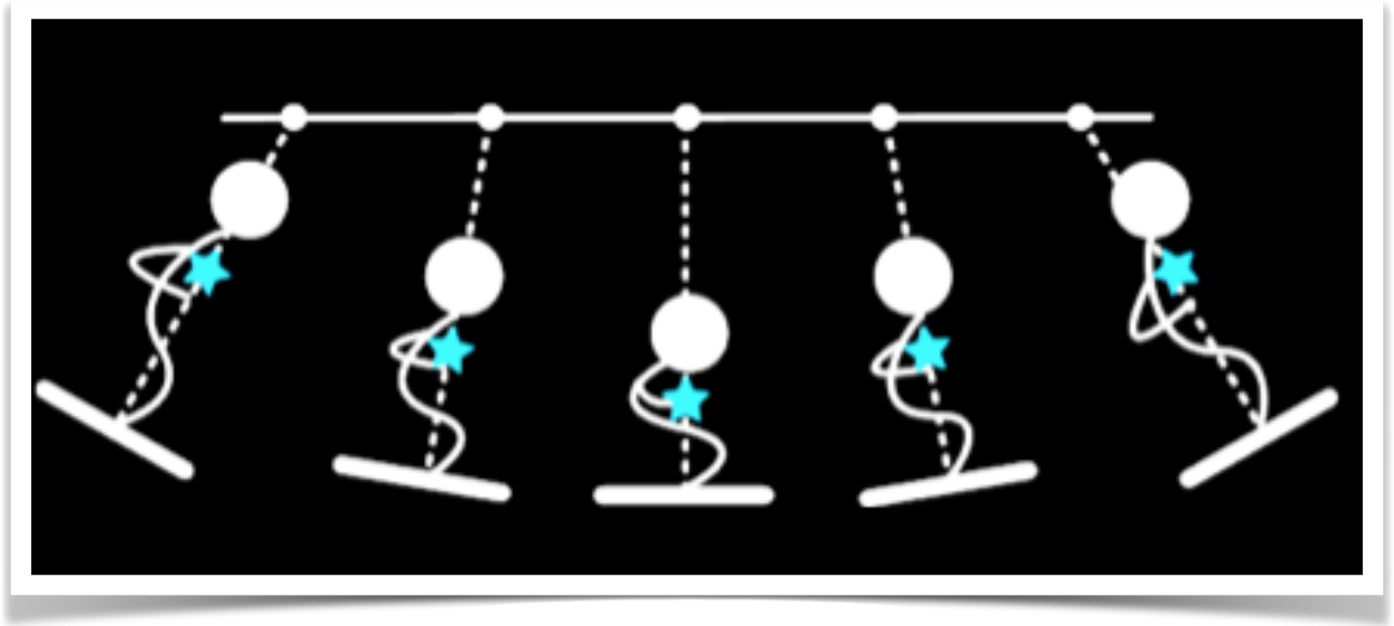
12/6/20

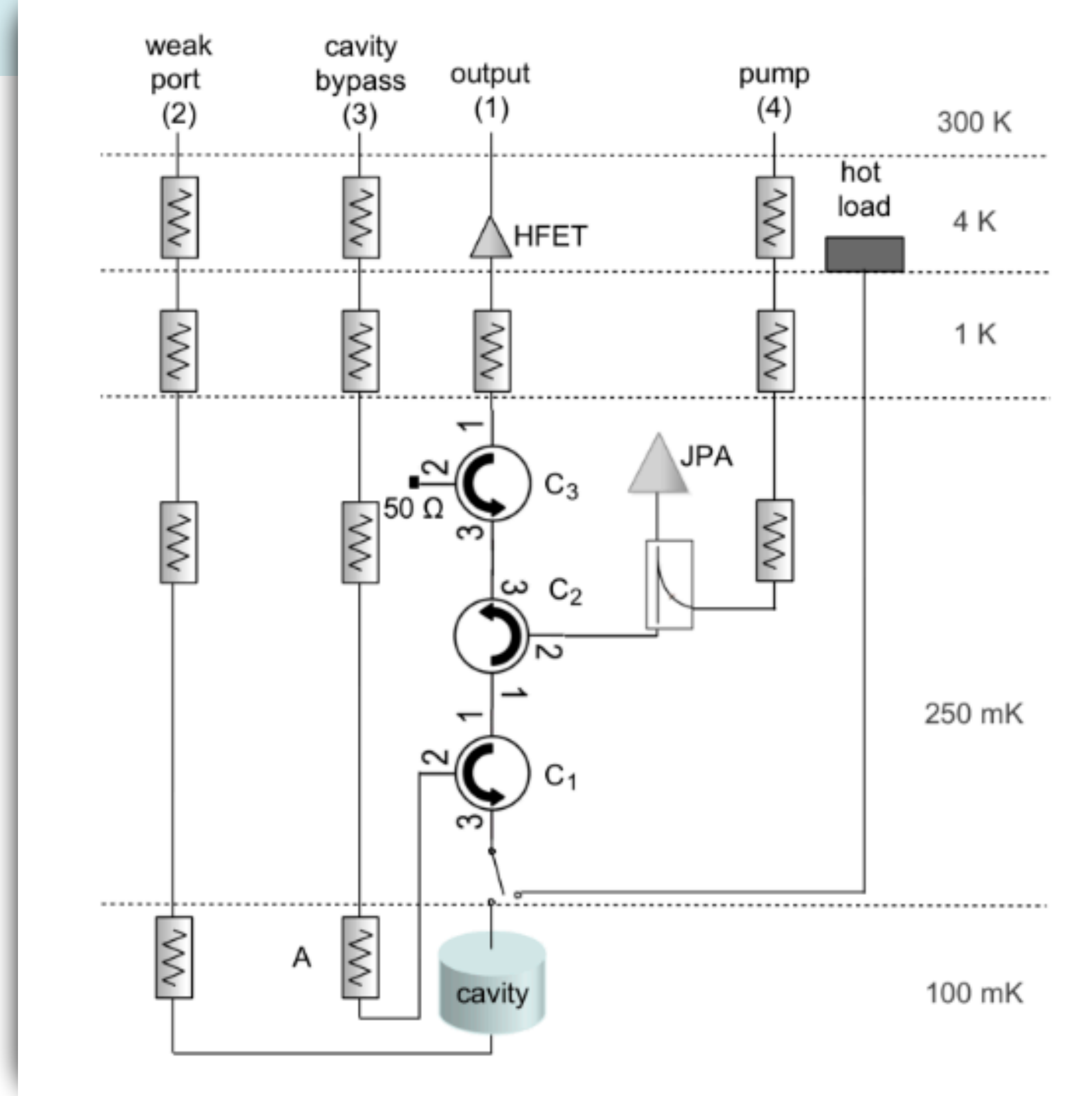
Josephson Parametric Amplifier (JPA)

- 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



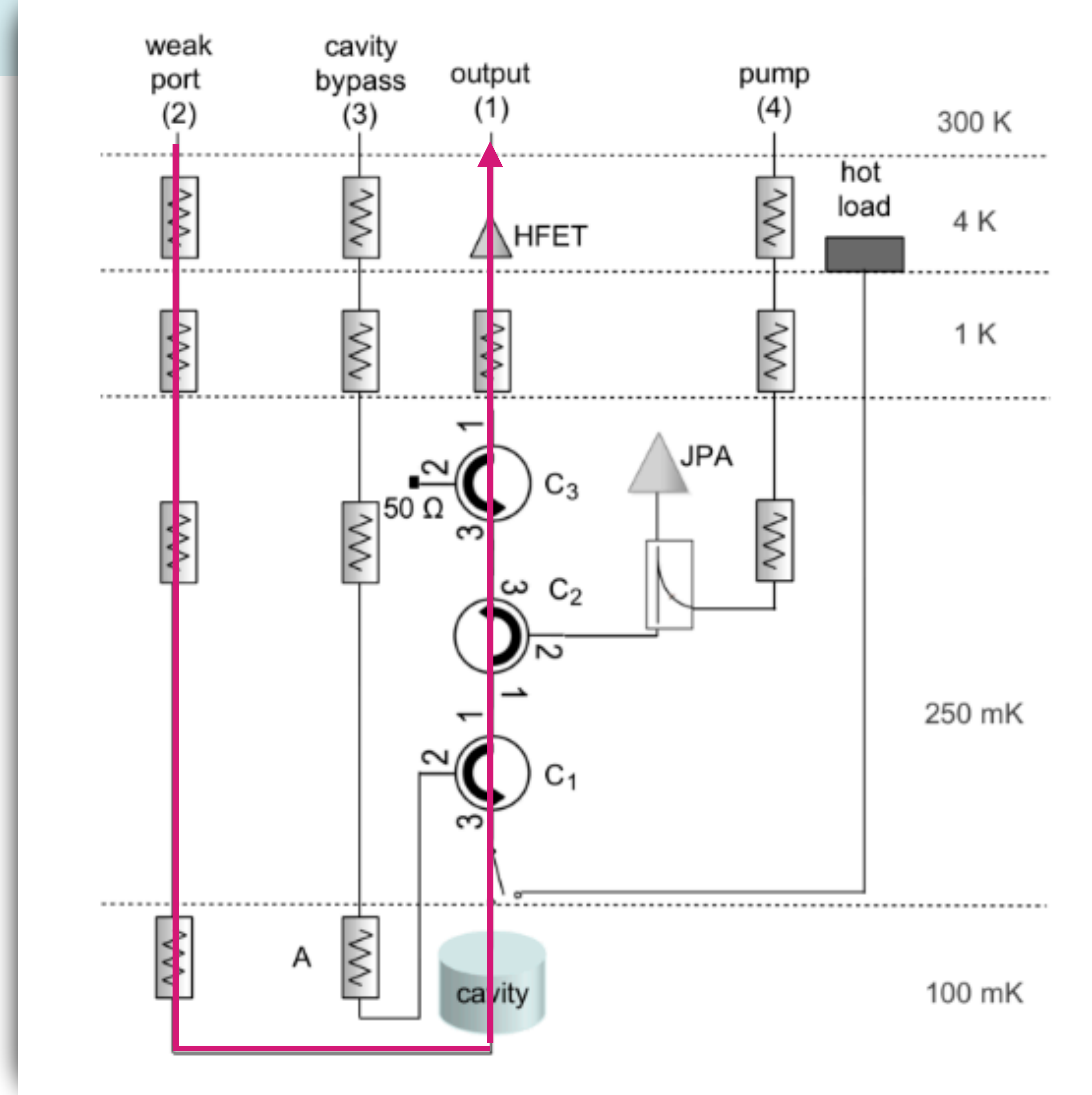
Figures courtesy of Shahid Jawas





ADMX RF Schematic

3 important RF paths to highlight!

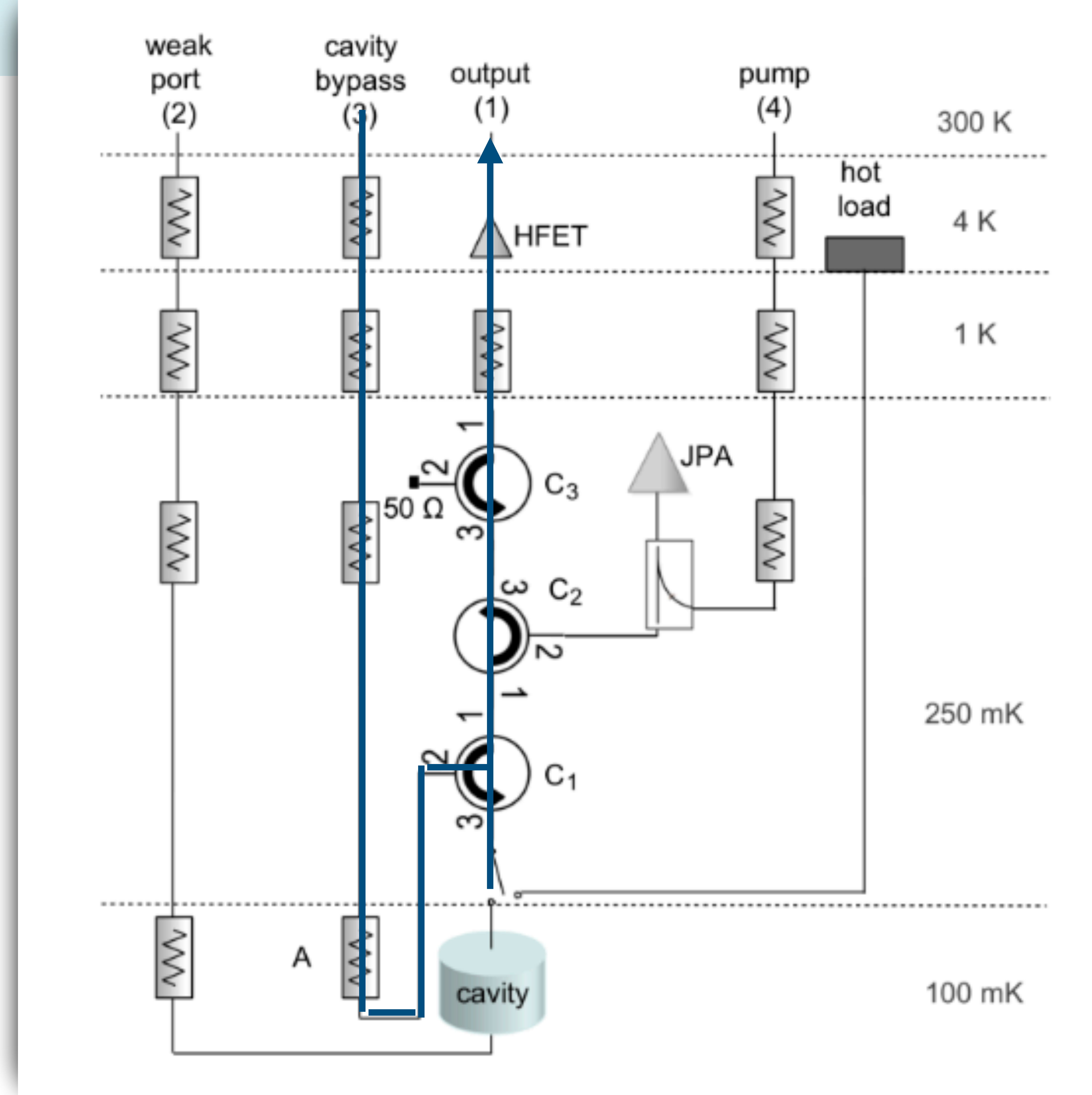


Transmission Measurement RF Path

Transmission Measurement Gives:

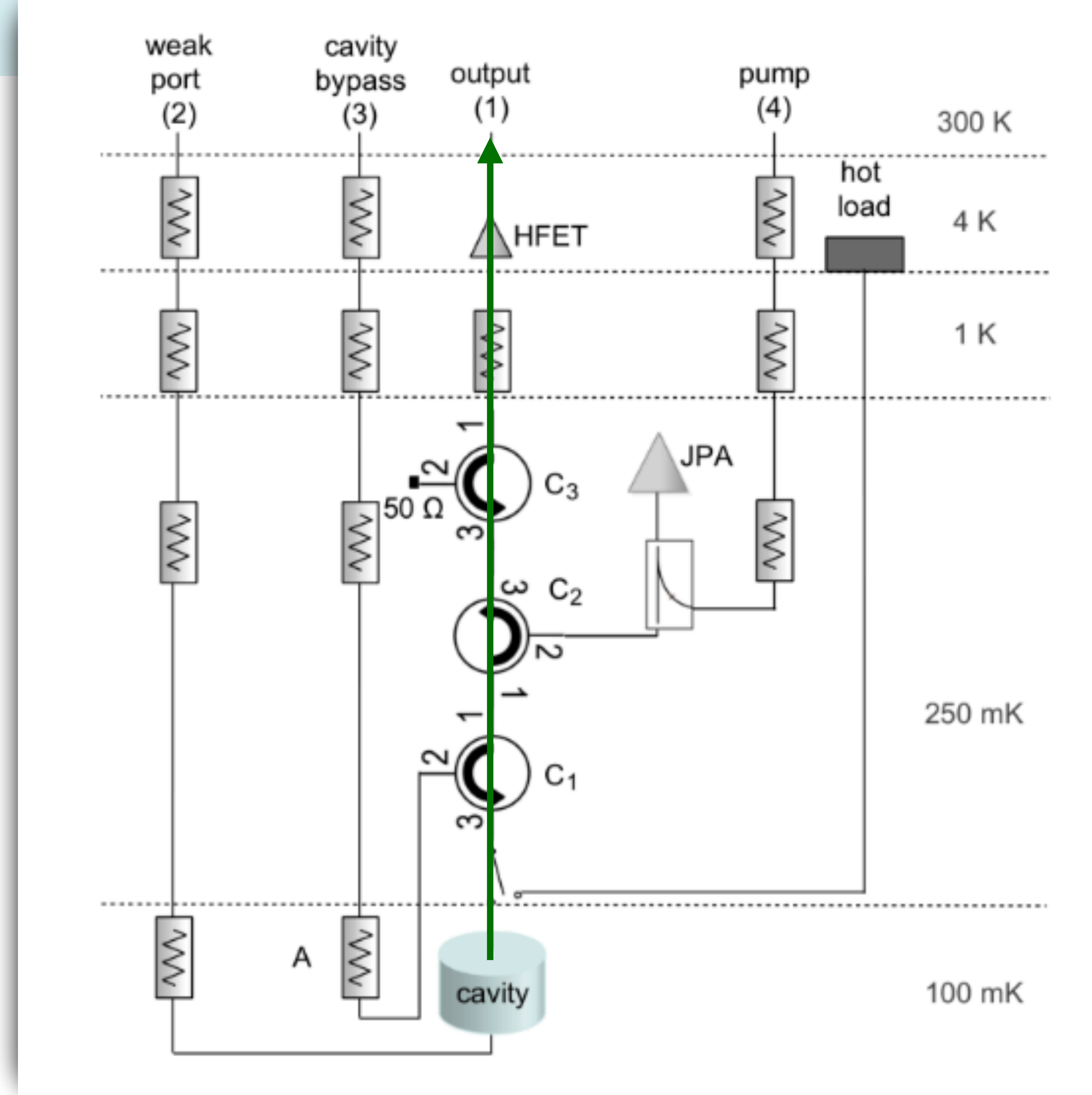
- Resonant frequency
- Quality factor

Same path is used to inject synthetic axion signals



Reflection Measurement RF Path

Reflection Measurement gives:
- Antenna Coupling

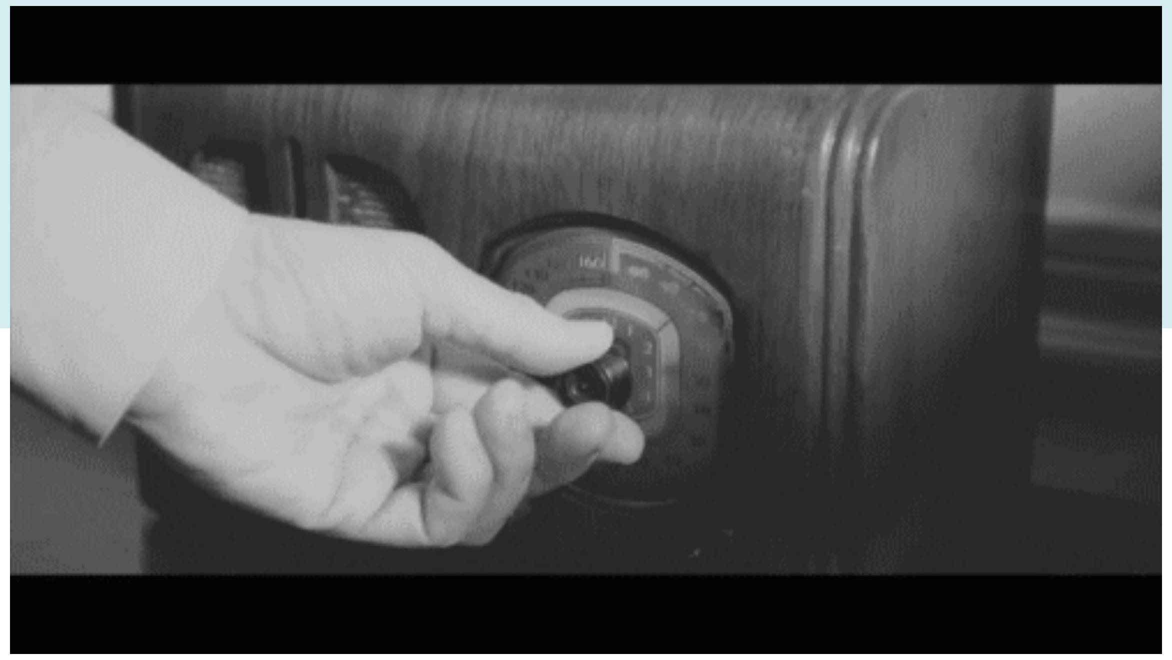


Ch 1 Signal Path

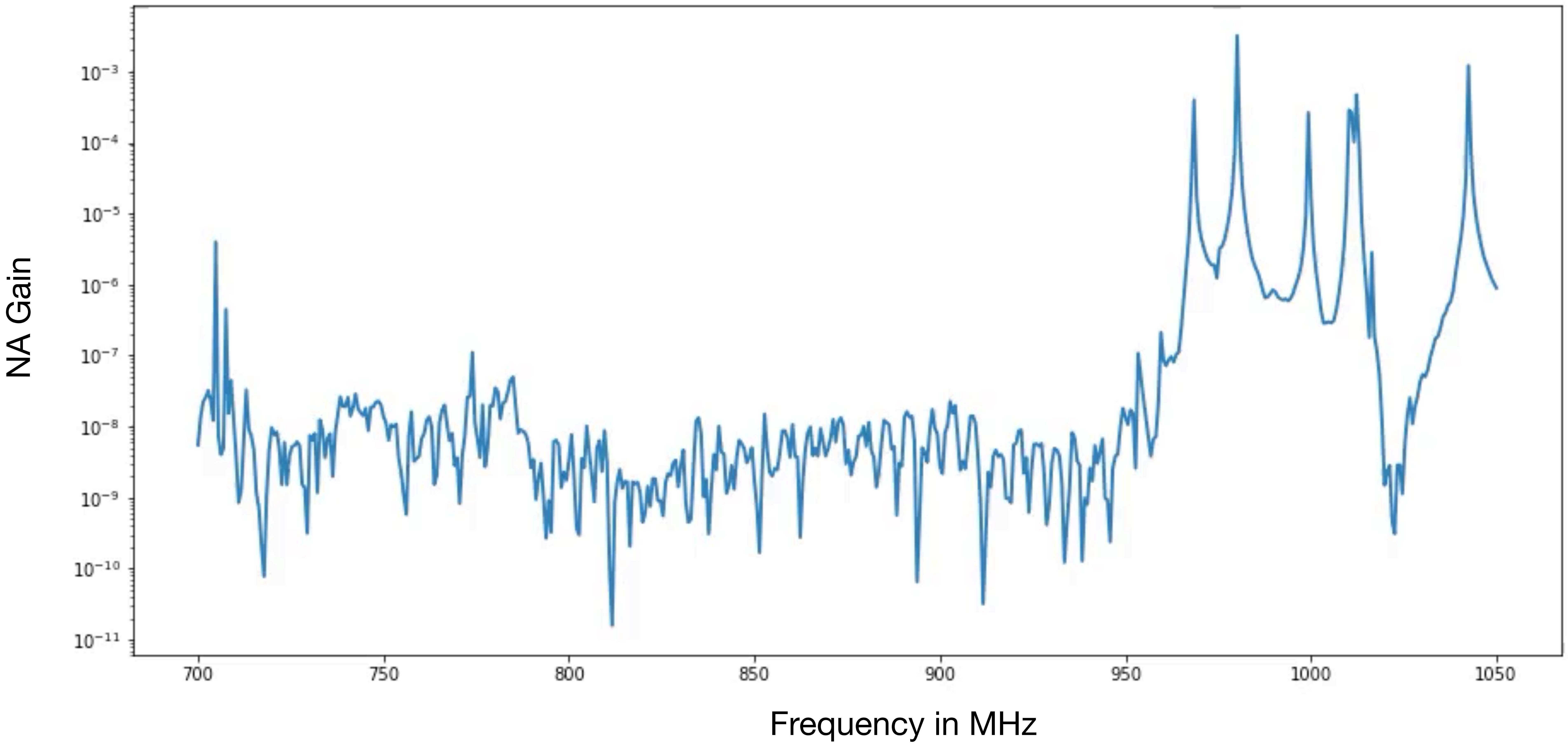
Weak port line is terminated. Signal read out directly from the cavity.

This is our configuration for data acquisition (digitization).

Tuning our cavity

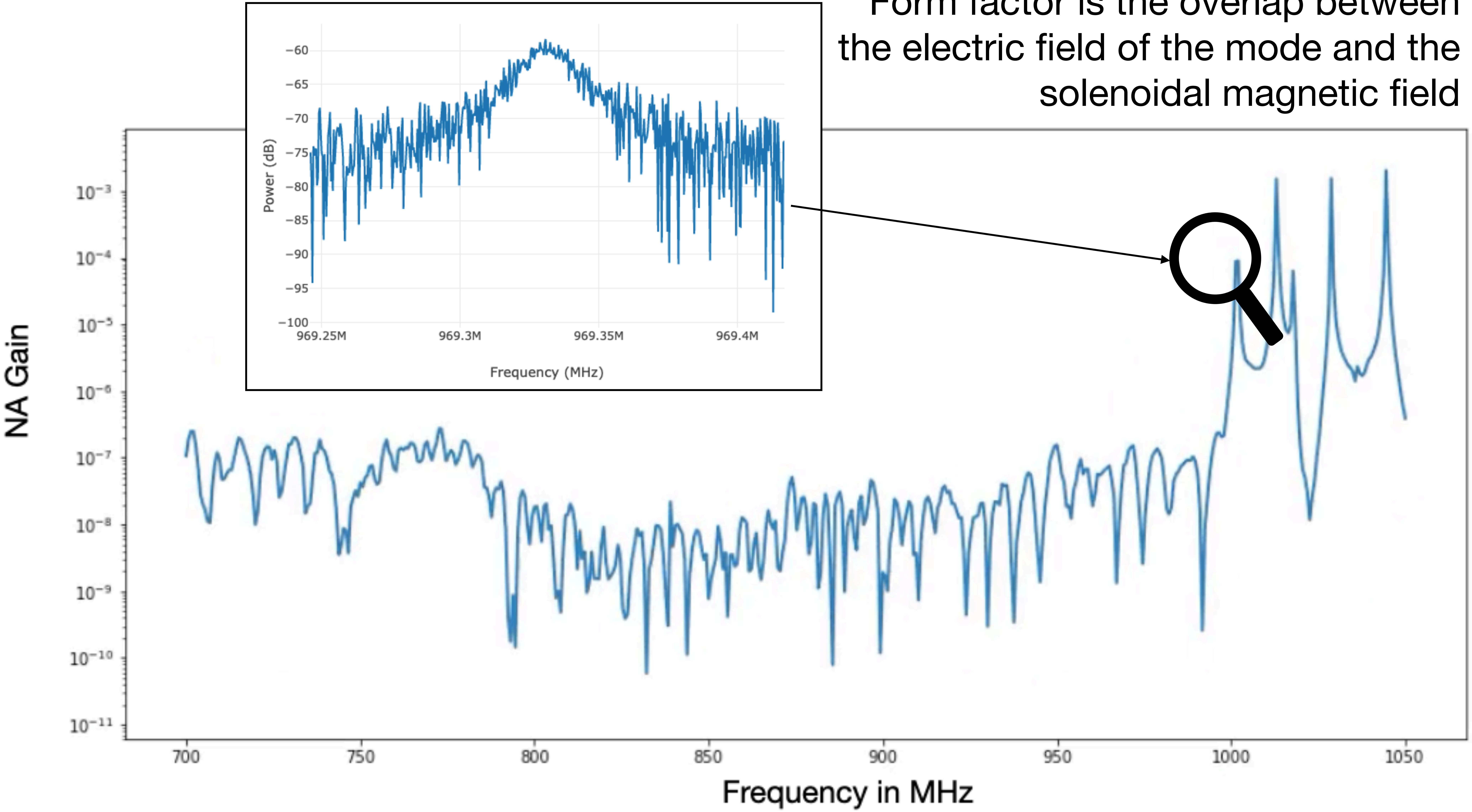


As we tune, we track the TM010 mode
Axion couples most strongly to this mode
Note occasional mode-crossings

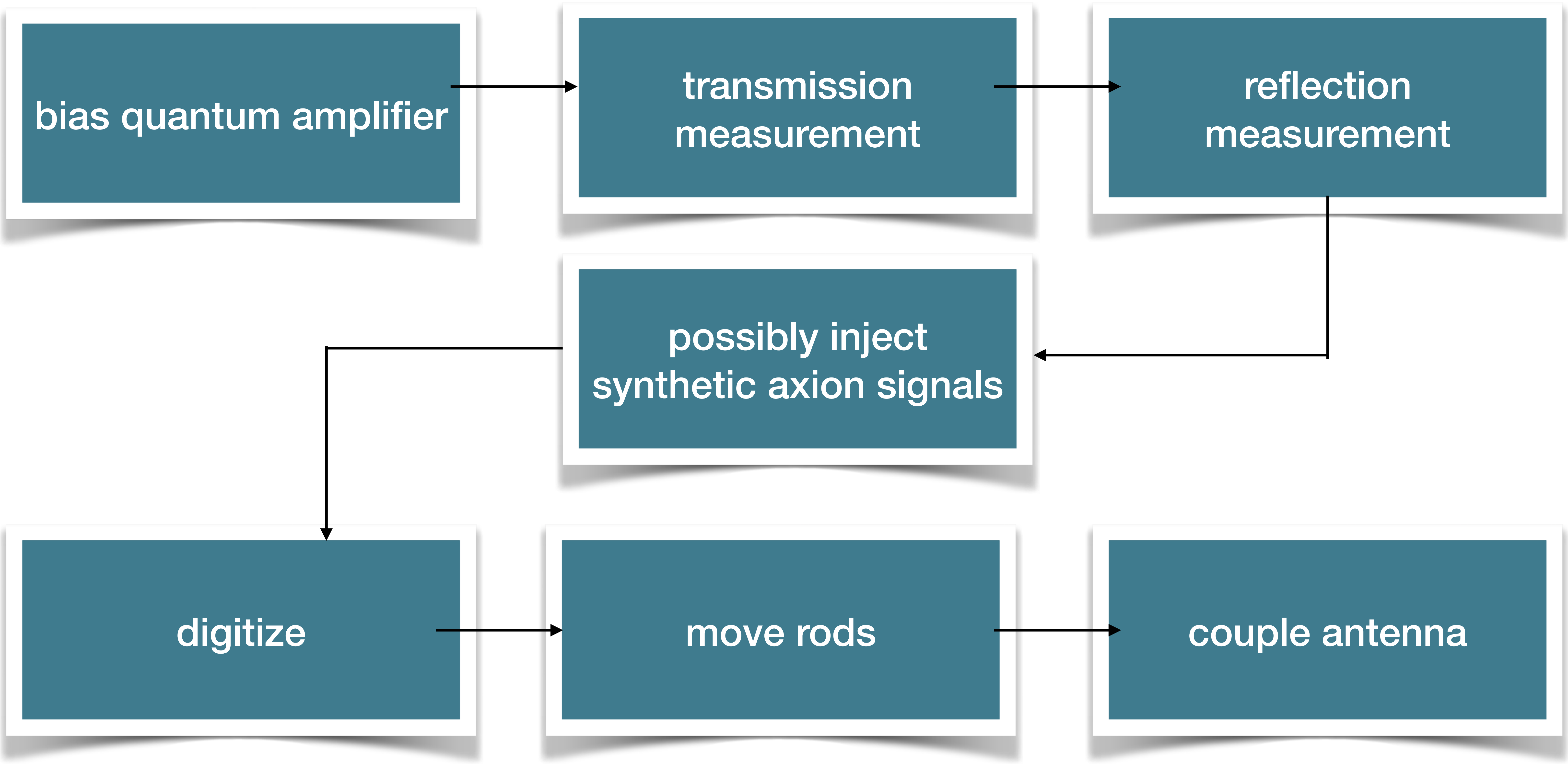


Zooming in on a single mode

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

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

Maximize	Can't Control	Minimize

• B Field
• Volume
• Quality Factor
• Form Factor
	• Frequency
	• Coupling
	• Dark Matter Density
		• System noise:
		  • Amplifier Noise
		  • Physical Noise

Some Typical Values

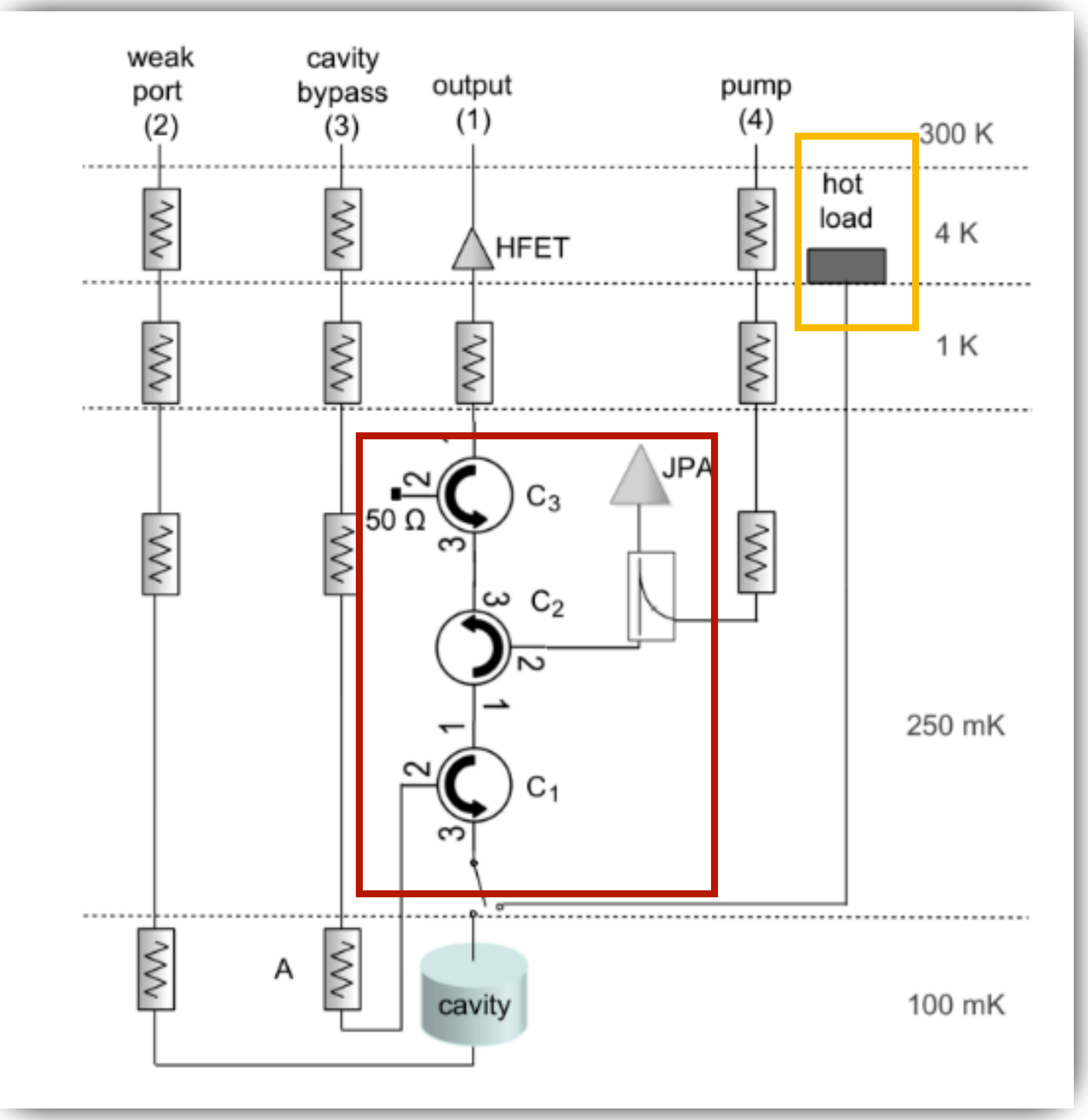
$$\frac{df}{dt} \approx 157\,\frac{\mathrm{MHz}}{\mathrm{yr}}\left(\frac{g_\gamma}{0.36}\right)^4\left(\frac{f}{740\ \mathrm{MHz}}\right)^2\left(\frac{\rho}{0.45\ \mathrm{GeV/cm^3}}\right)^2\left(\frac{3.5}{\mathrm{SNR}}\right)^2\left(\frac{B}{7.6\ \mathrm{T}}\right)^4\left(\frac{V}{136\ \ell}\right)^2\left(\frac{Q_\mathrm{L}}{30{,}000}\right)\left(\frac{C}{0.4}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

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!

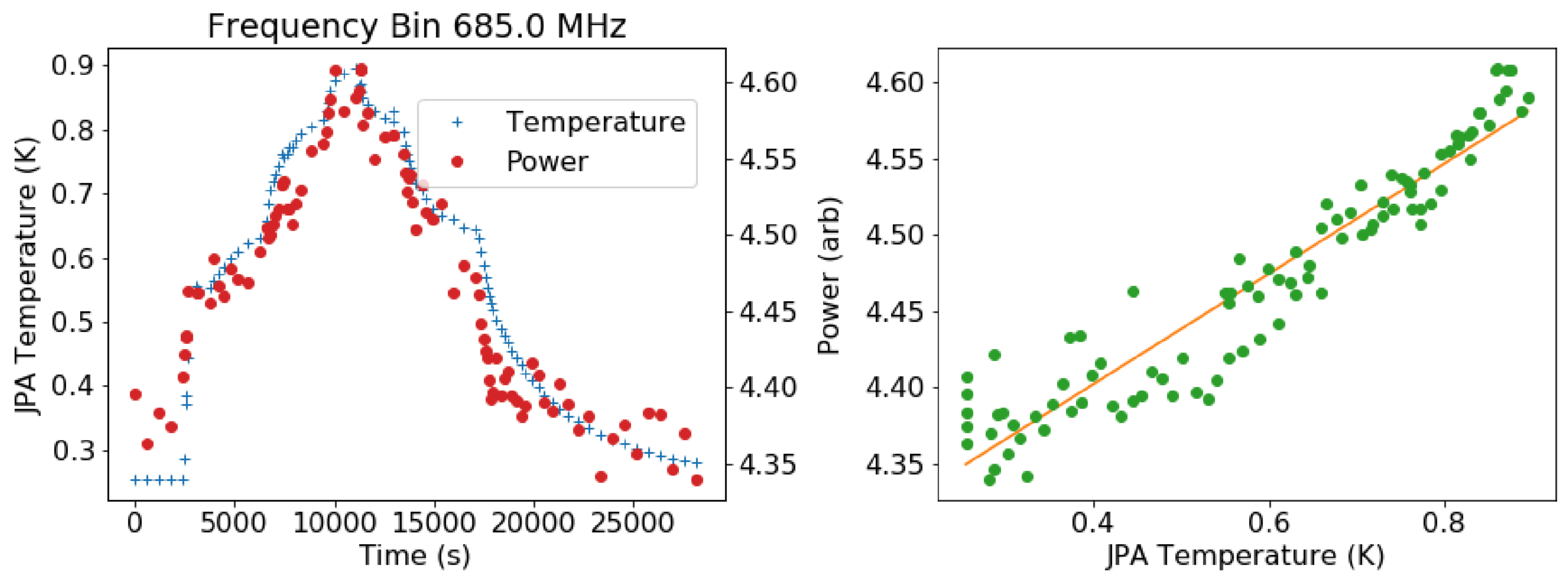
Noise Characterization



- 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



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

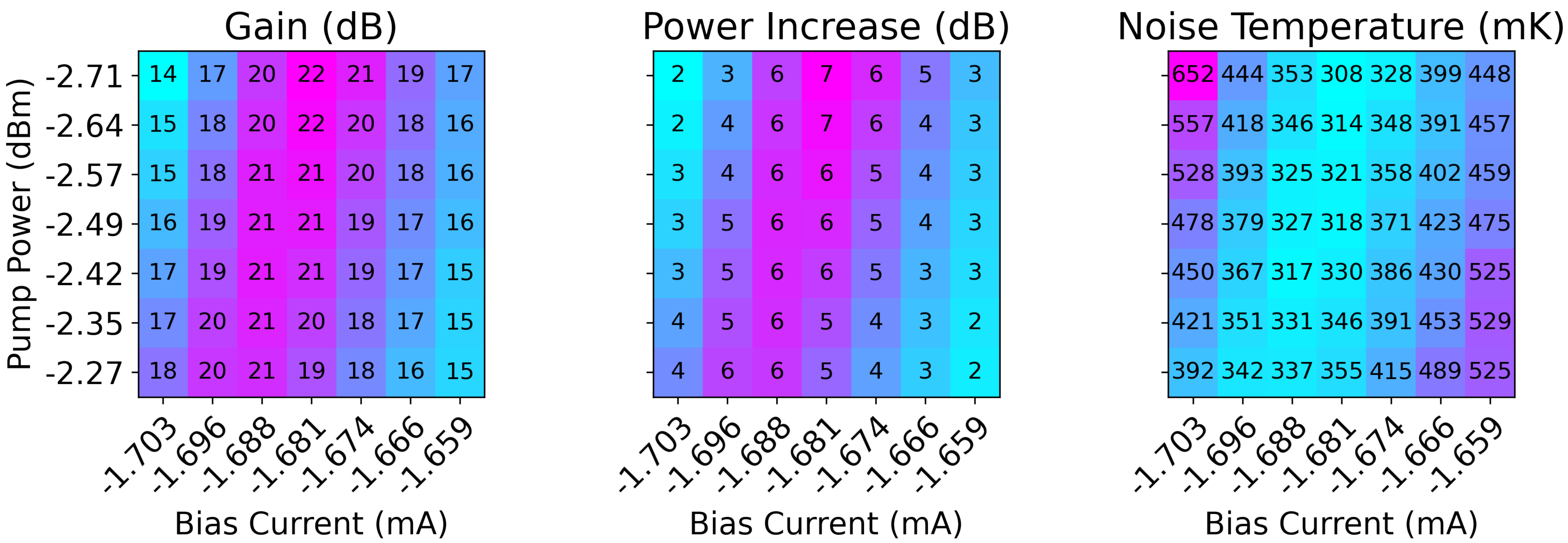
$$T_{\mathrm{sys}} = \frac{T_{\mathrm{HFET}}}{\epsilon(\mathrm{SNRI})}$$

Fit parameters:

- Attenuation from cavity to HFET amp
- Receiver Temperature

JPA Rebiasing Procedure Gives our SNRI!

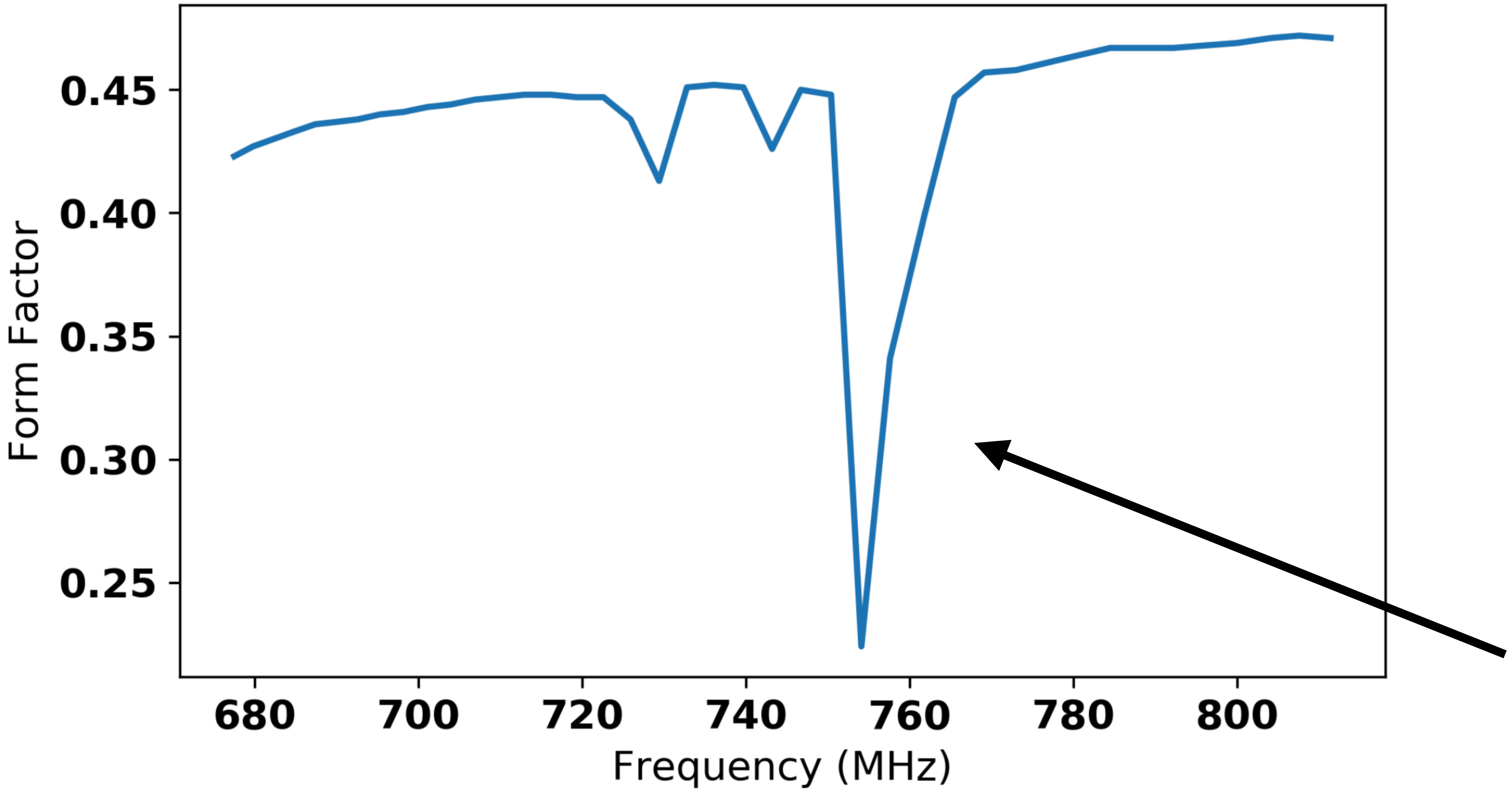
JPA Biasing



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

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

Some Typical Parameter Values



- 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

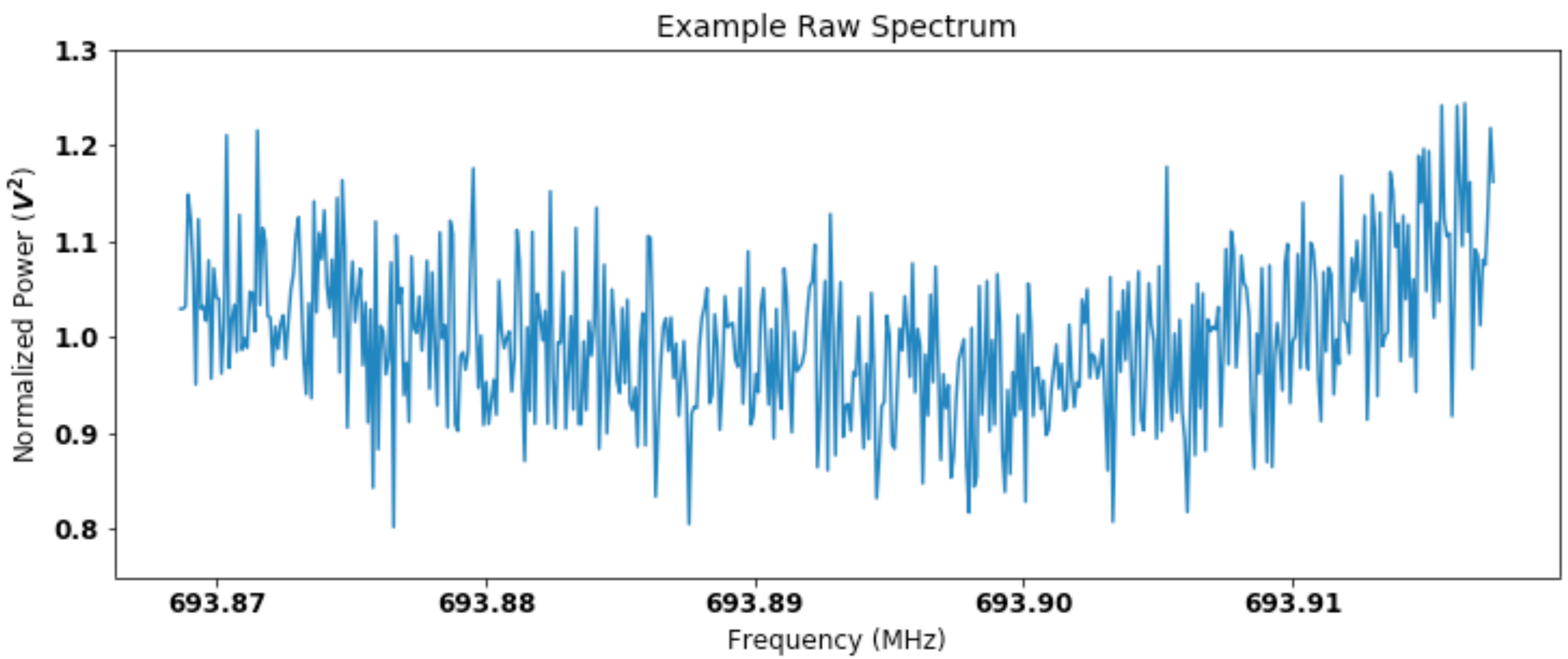
Two types of analysis:

- **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.
  - 10 mHz bins width.

Analysis

Raw spectrum processing:

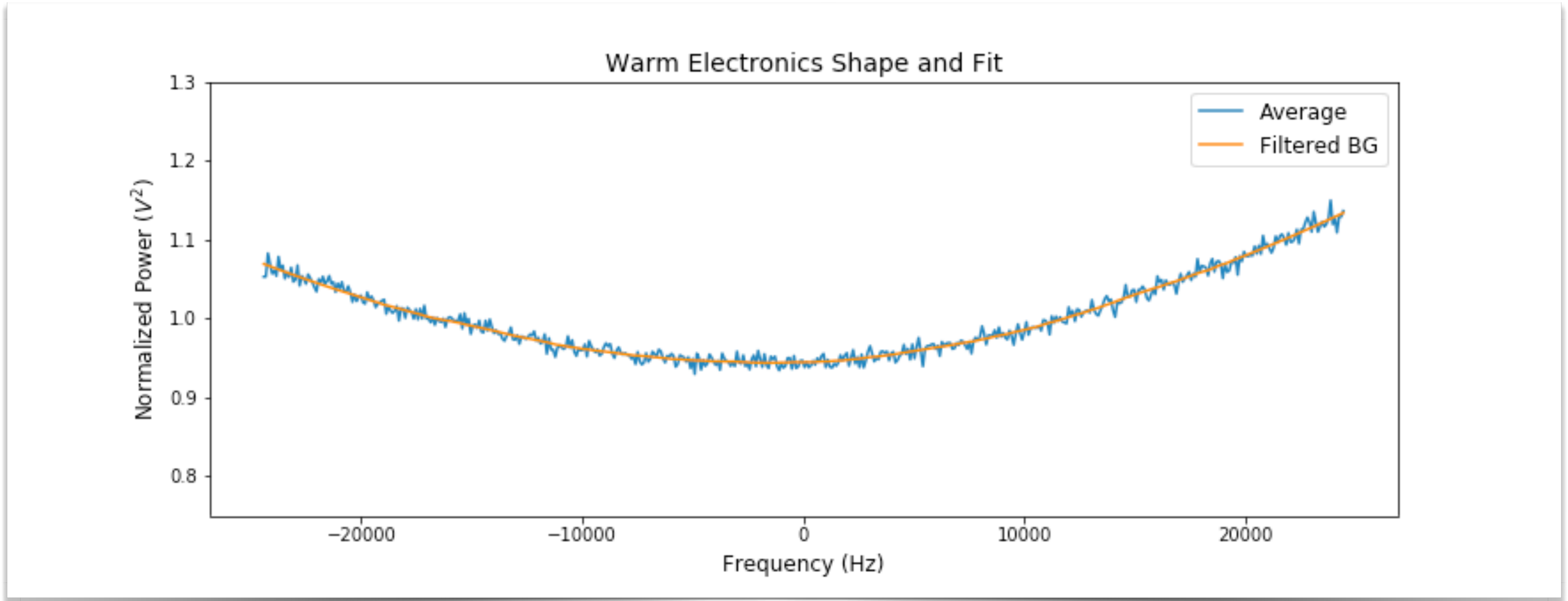
- ~50 kHz wide raw spectra, 100 Hz bins



Analysis

Baseline Removal:

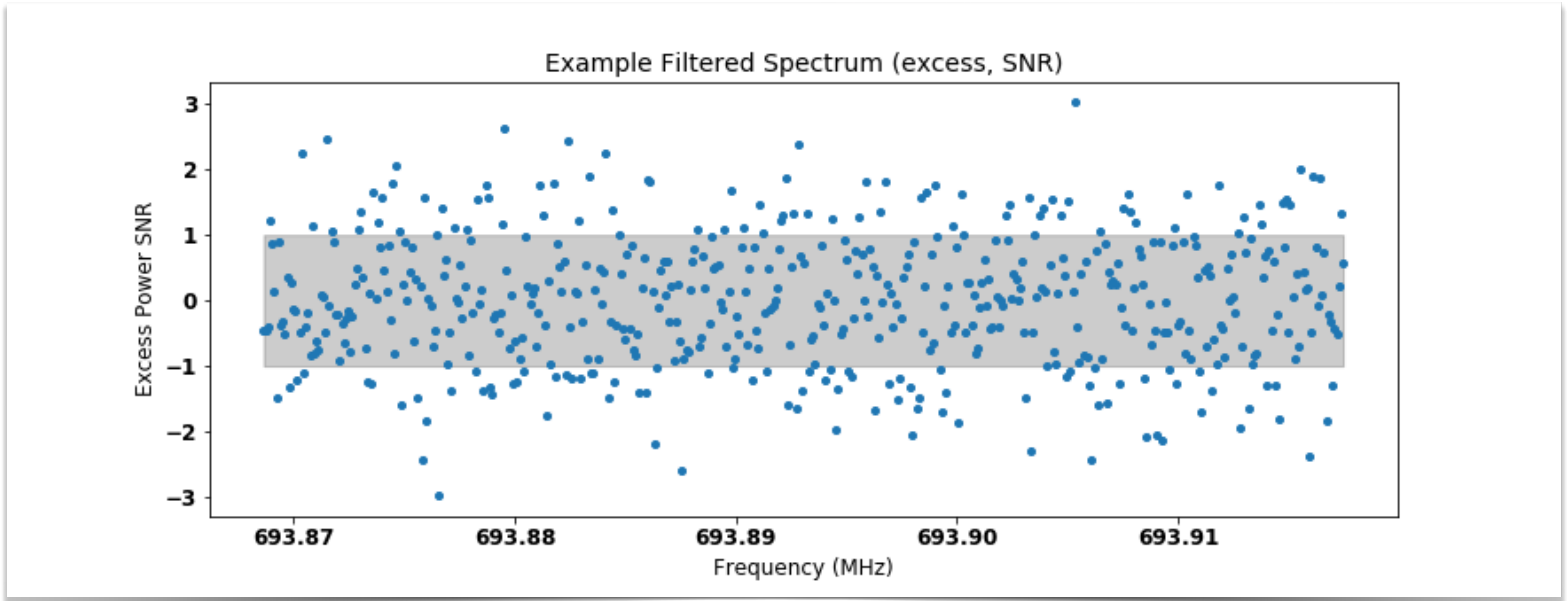
- The warm electronics shape is identified by averaging and filtering off-resonance scans.



Analysis

Raw spectrum processing:

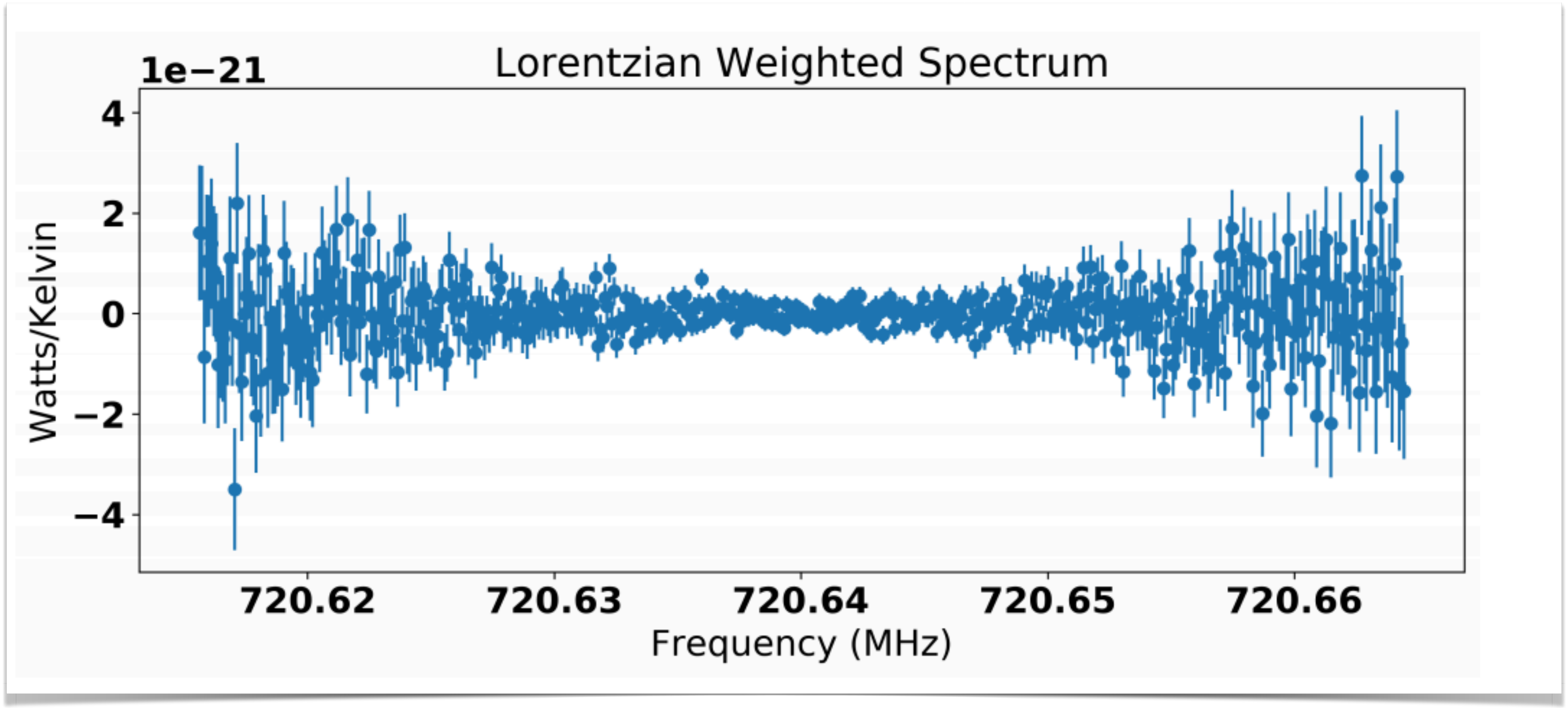
- Raw spectra are divided by the receiver shape and filtered (Padé filter: designed to fit out wide structure and ignore narrow axion-like peaks)
- Subtract 1 from each bin to obtain ~Gaussian white noise



Analysis

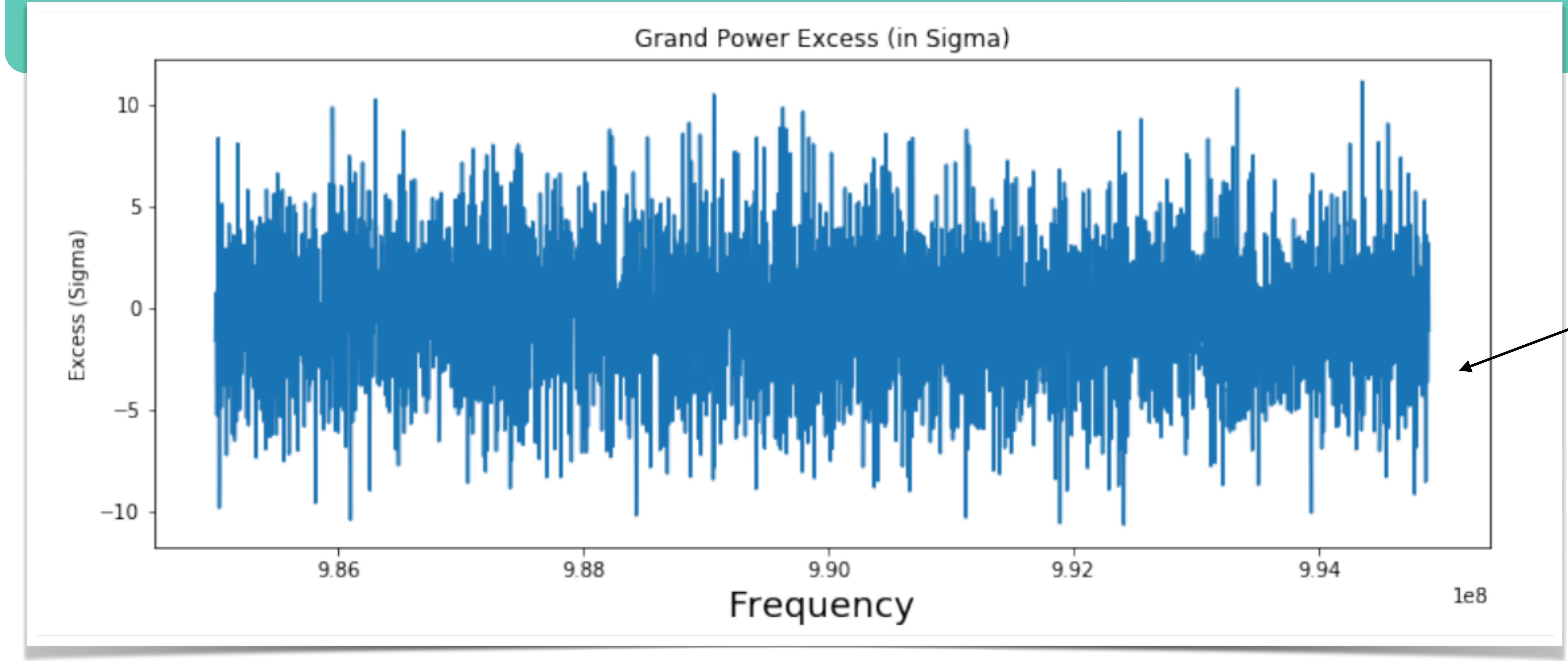
Raw spectrum processing:

- Scale by the Lorentzian (cavity line shape)



Grand spectrum processing

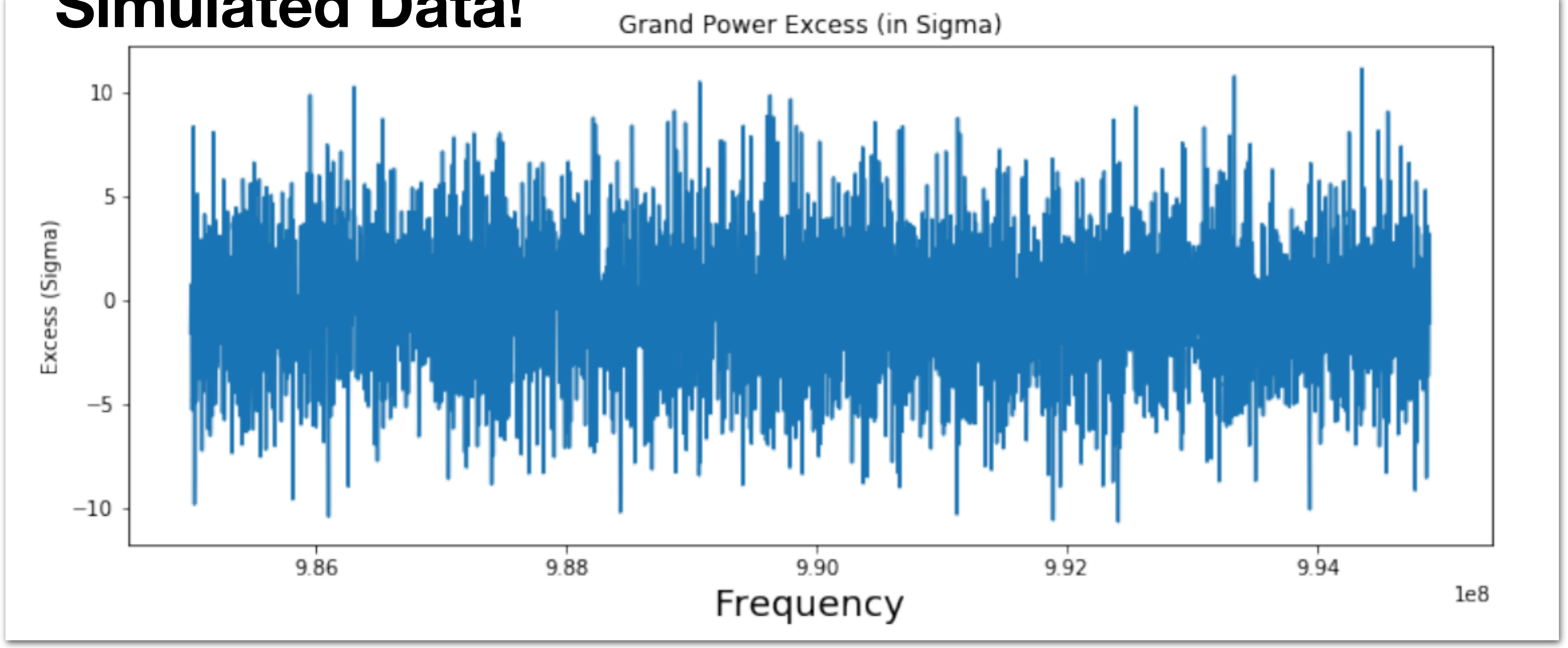
- Scale spectra by the average noise power per bin to achieve signal peaks independent of noise temperature.
- Filter spectra using the expected axion line shape
- Combine spectra using an optimal weighting procedure.

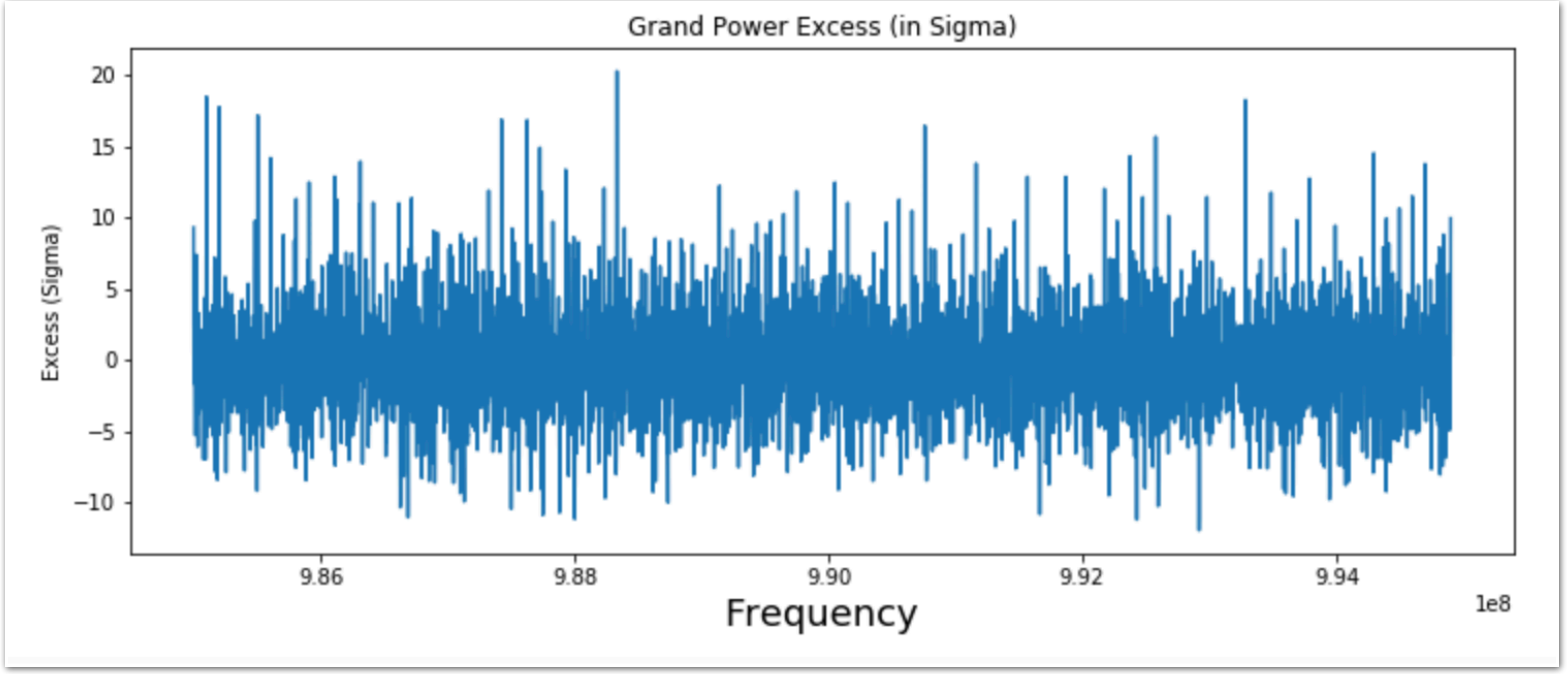


Example: **Simulated Data**
From my undergraduate,
Hima Korandla

Software Synthetic Injections

Simulated Data!





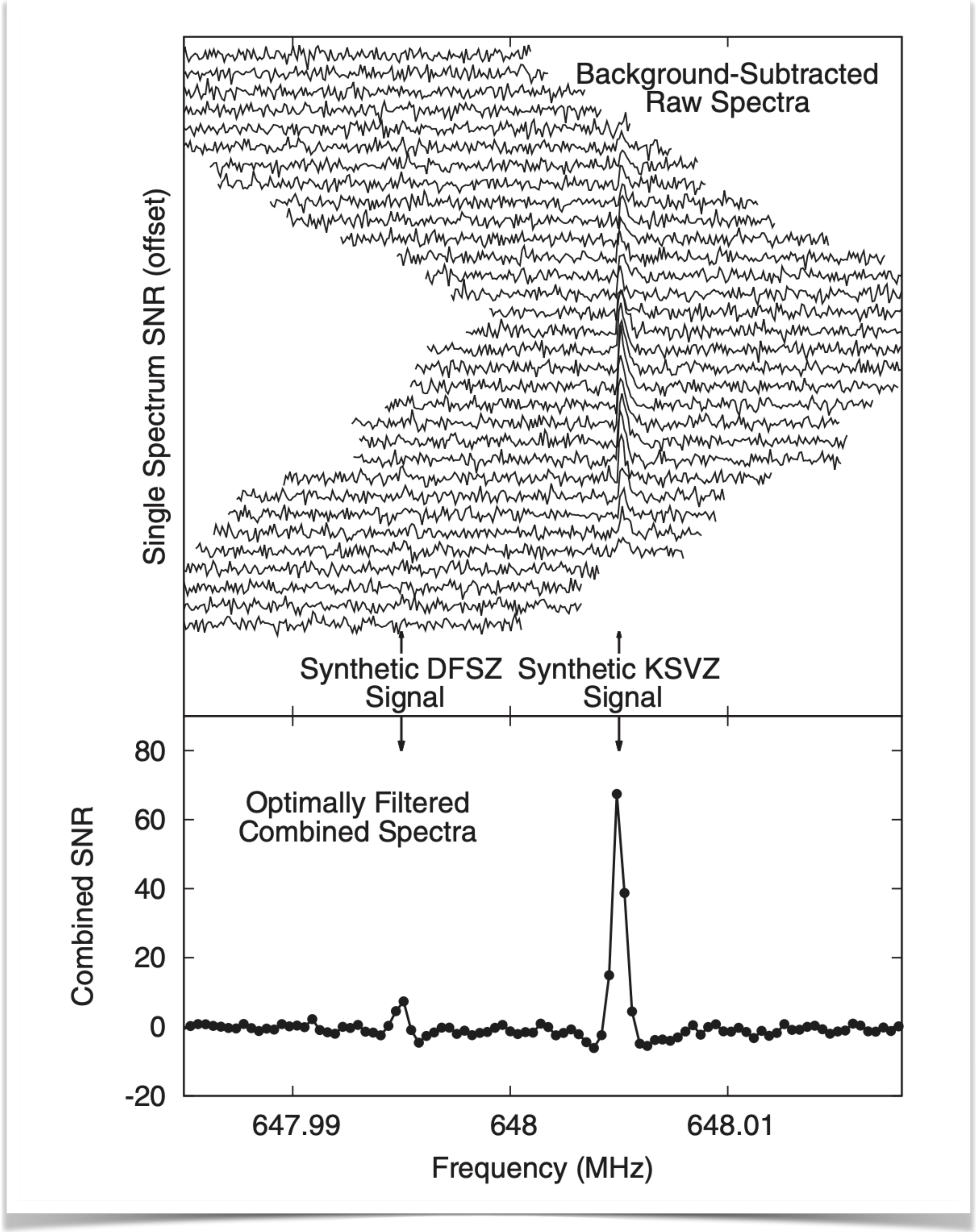
- Used to determine our detection efficiency and verify our analysis
- Developed by undergraduate student Hima Korandla, with my supervision
  - Simulated analysis data
  - Software synthetic injections for Run 1C
- Developed a new technique to mitigate sensitivity reduction due to background subtraction

Rescan Procedure

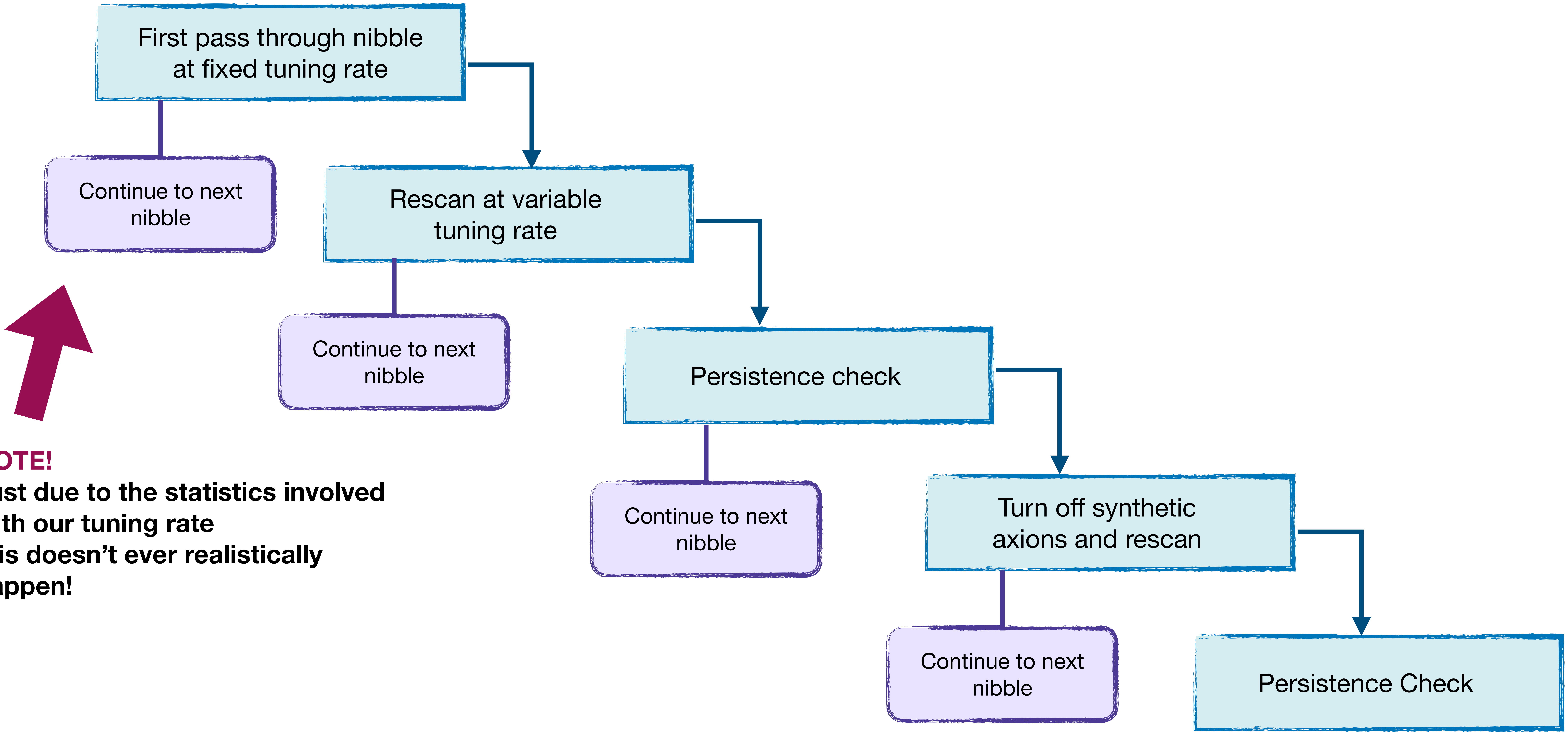
When do you decide to rescan?

3 conditions:

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

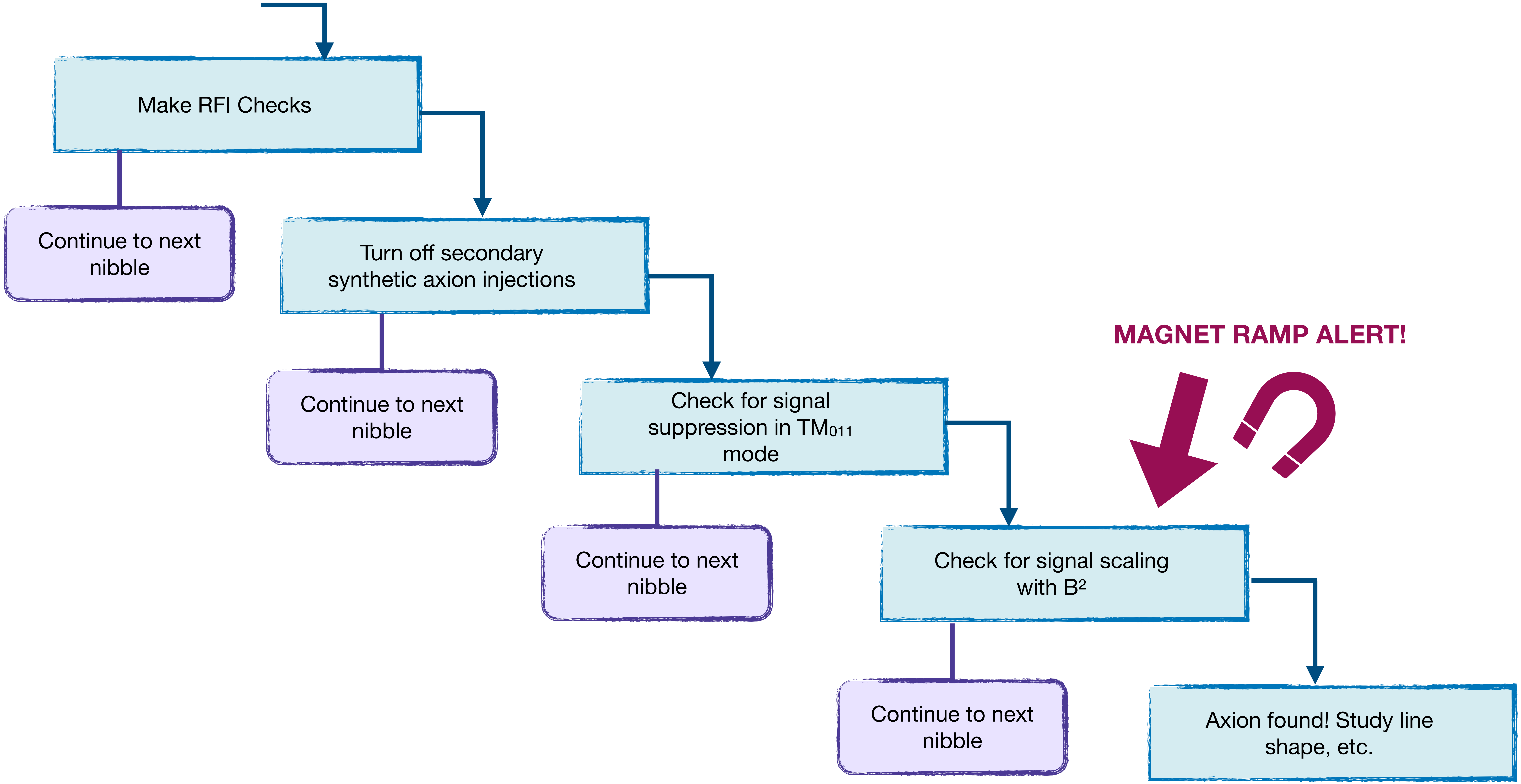


ADMX Search Decision Tree

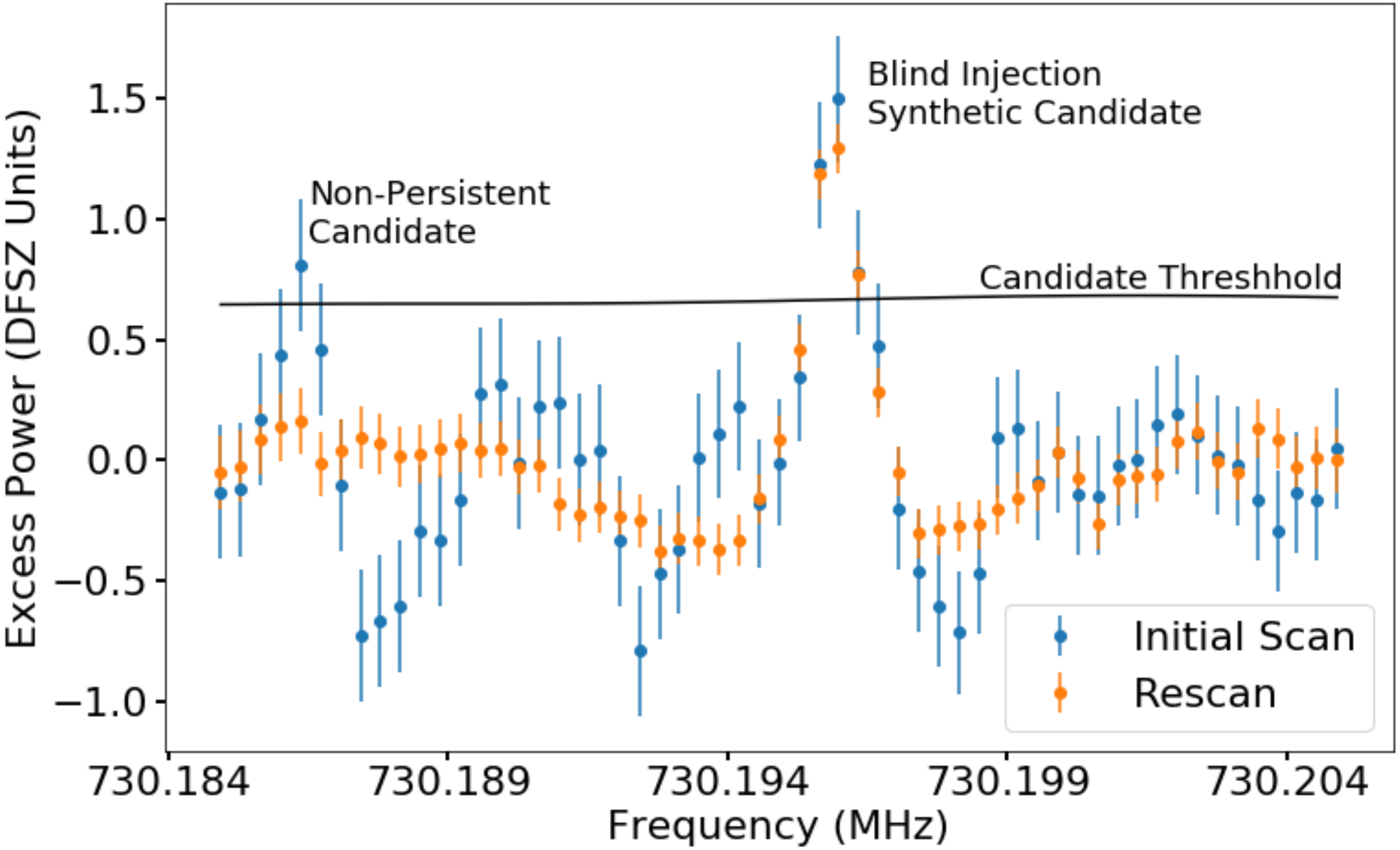


NOTE!
Just due to the statistics involved with our tuning rate this doesn't ever realistically happen!

ADMX Search Decision Tree



Hardware Synthetic Axion Injections

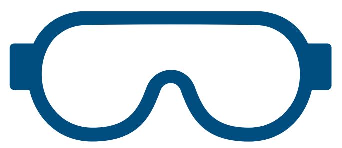


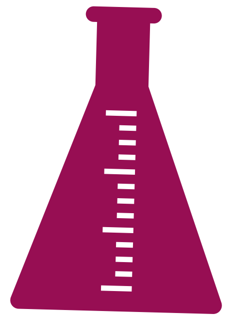
Verifying the axion signal

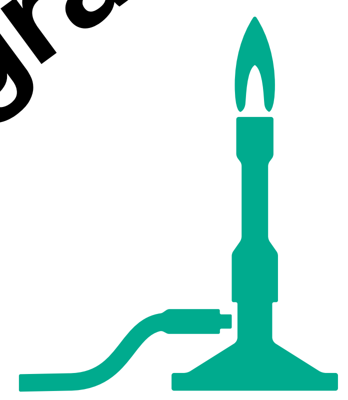
A true axion signal

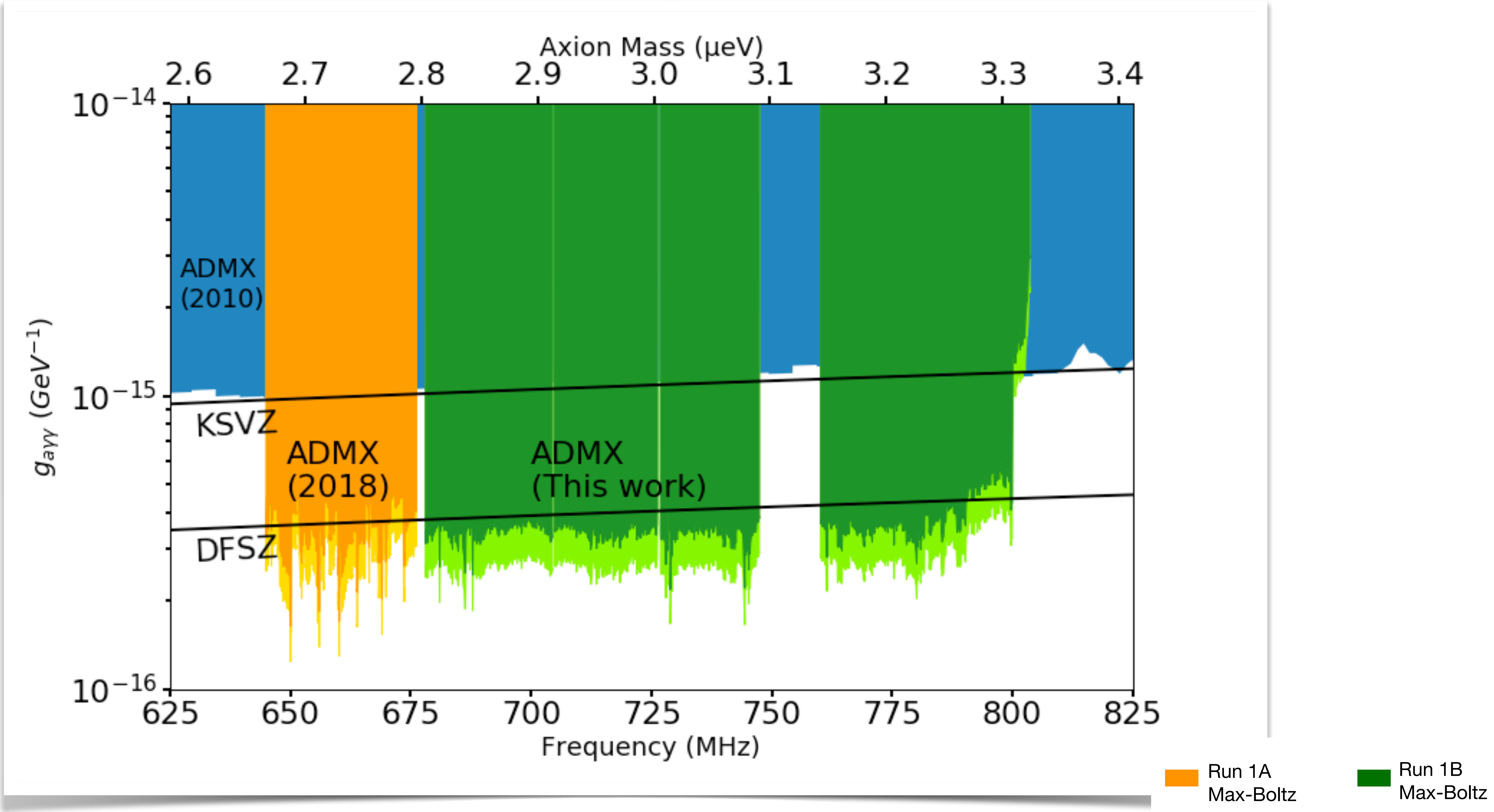
- Only observed within the confines of the cavity and magnetic field
- Persistent
- Remains when the synthetic axion generator is turned off
- Lorentzian line shape that follows that of the cavity
- Suppressed in non-TM010 modes
- Scales as B^2 (where B is the magnetic field)
- Small daily and annual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

Could even be an undergrad lab if found!







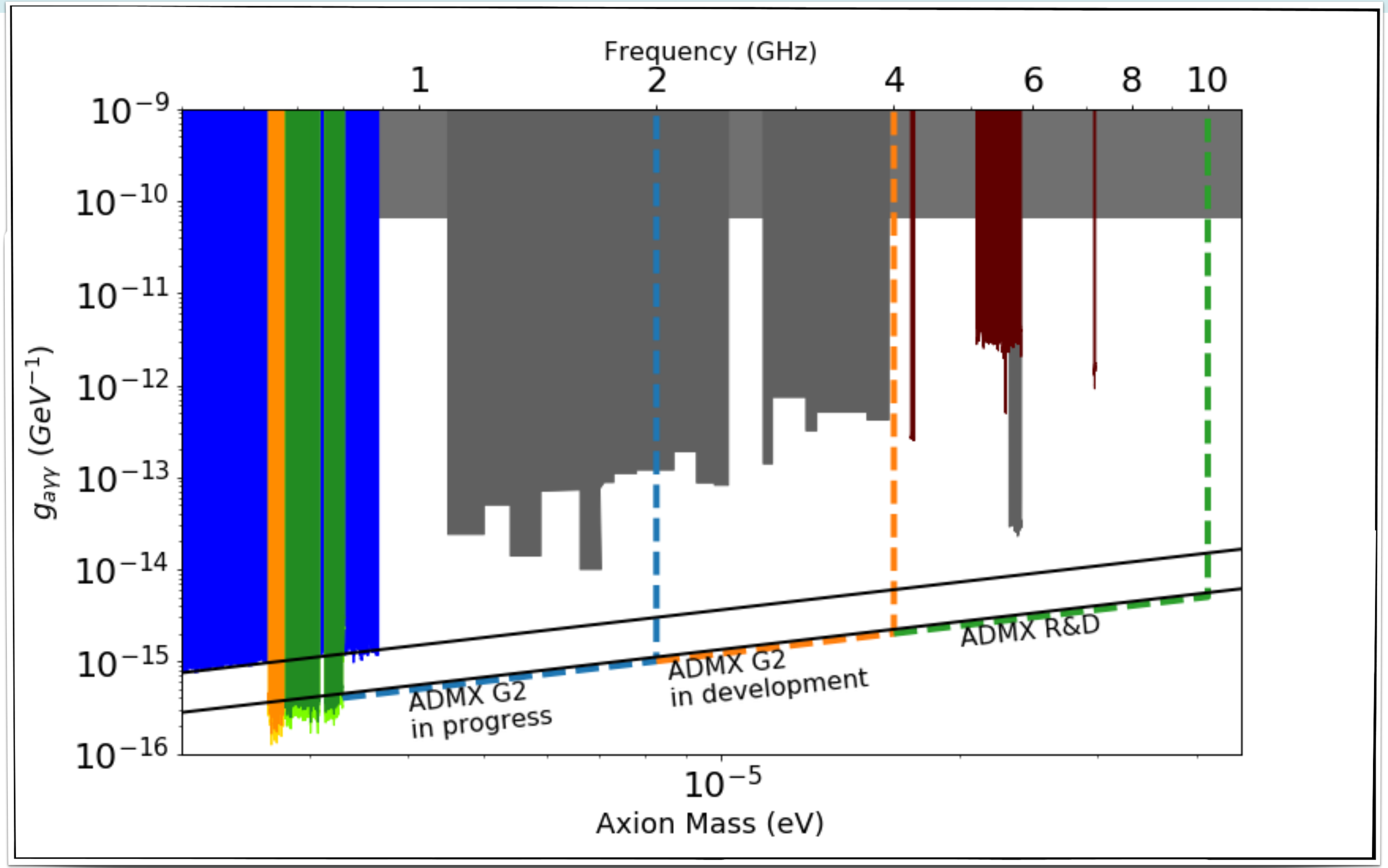


Extended Search for the Invisible Axion with the Axion Dark Matter Experiment

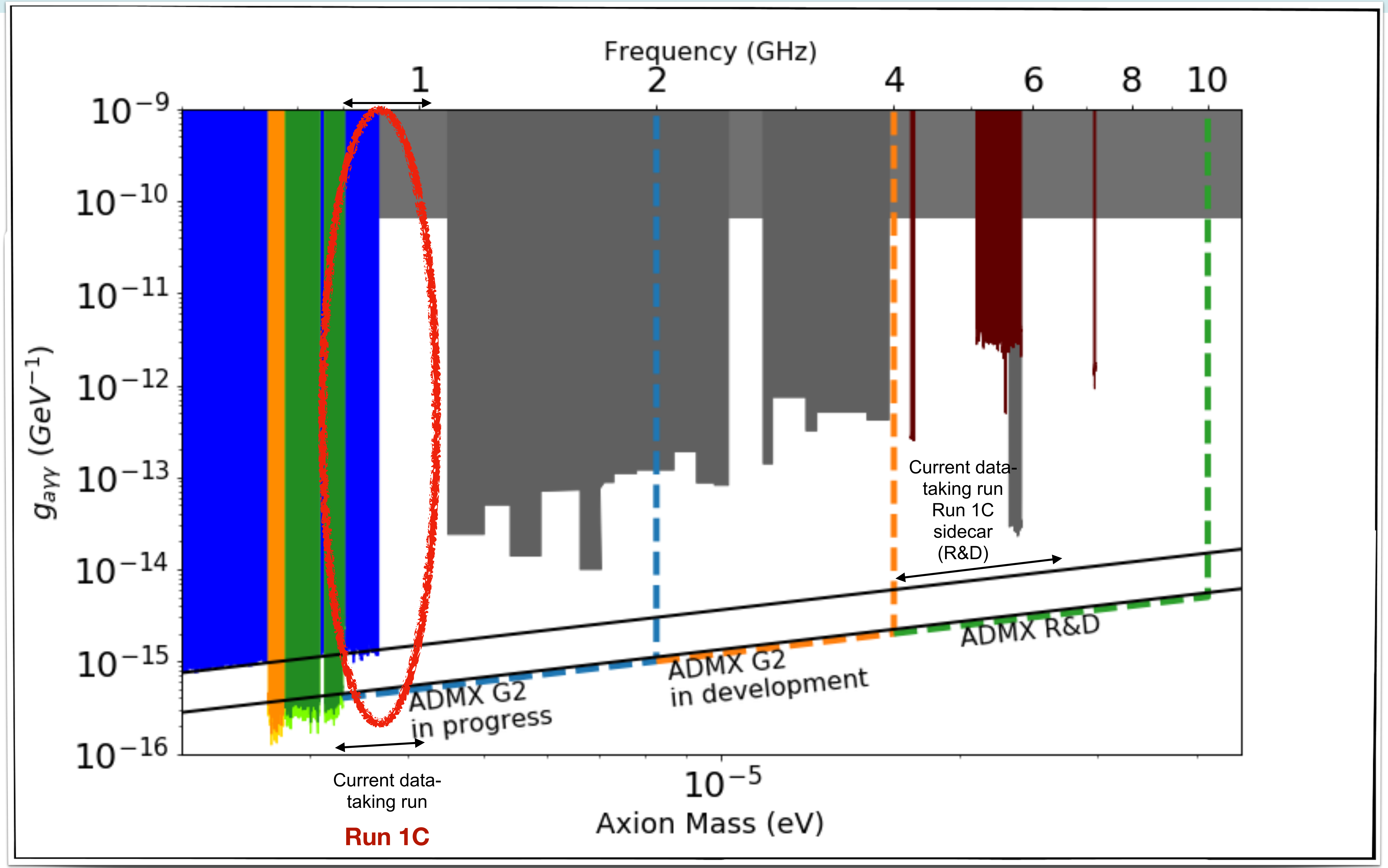
T. Braine et al. (ADMX Collaboration)

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

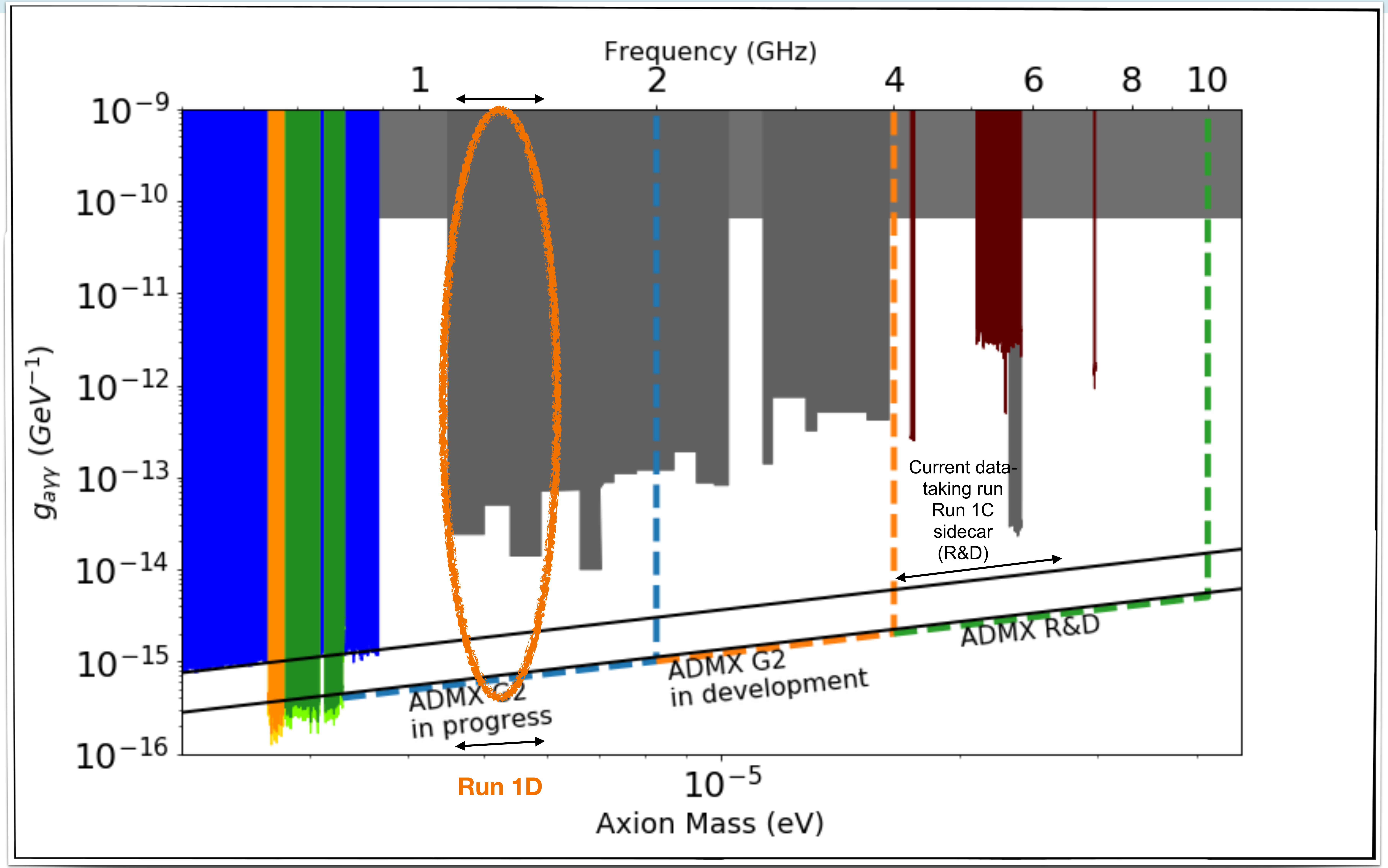
Projected ADMX Sensitivity



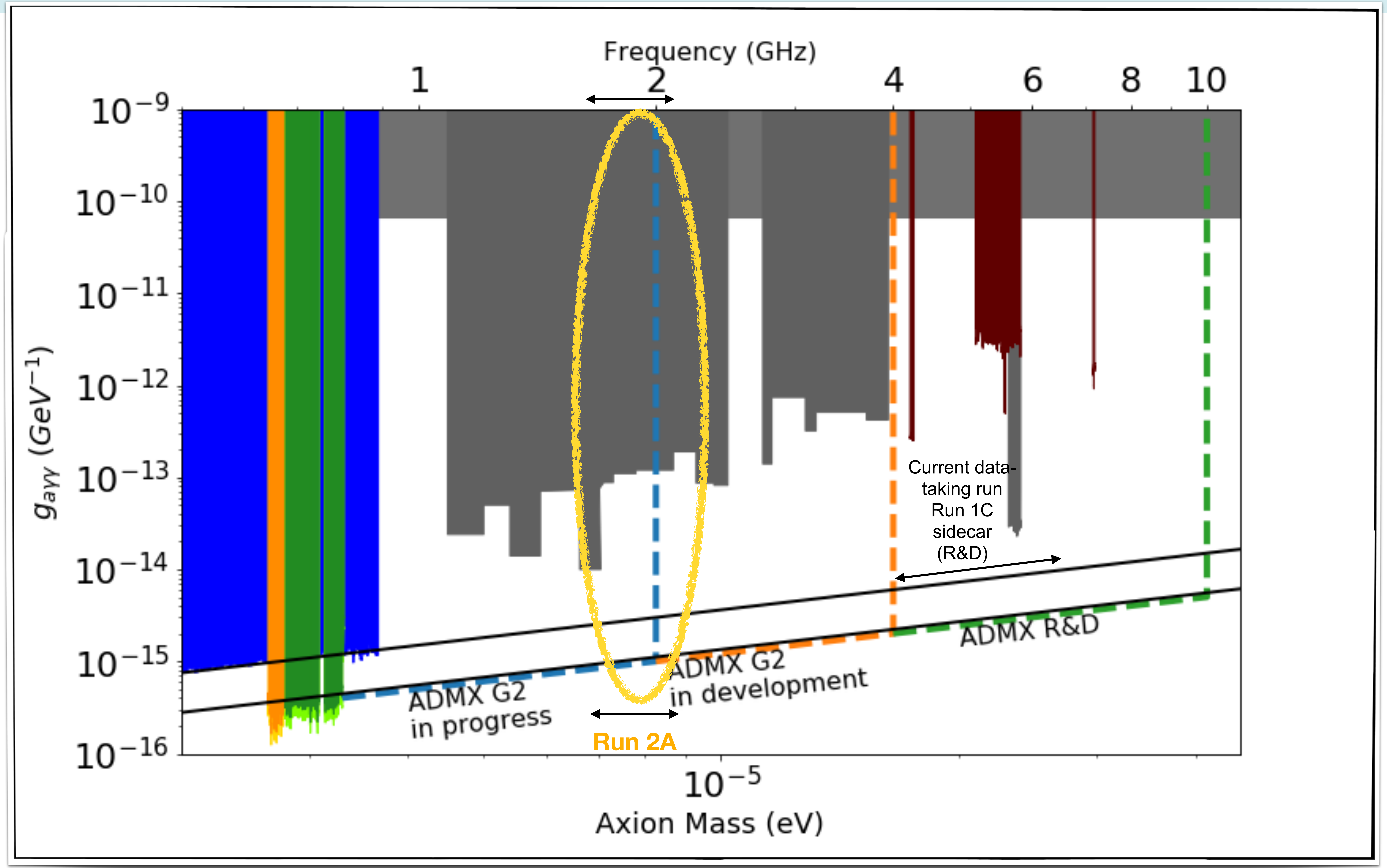
Projected ADMX Sensitivity



Projected ADMX Sensitivity

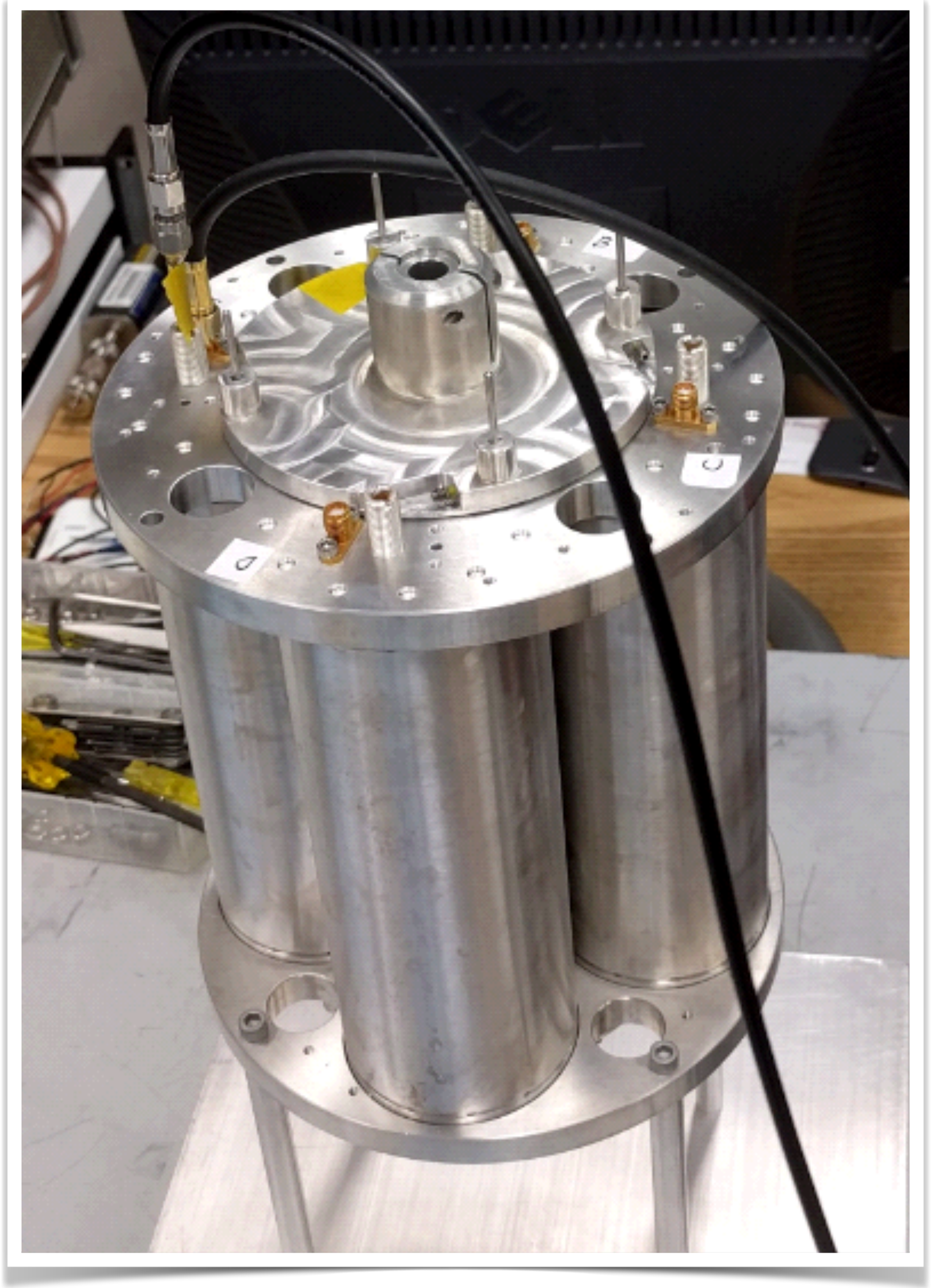


Projected ADMX Sensitivity



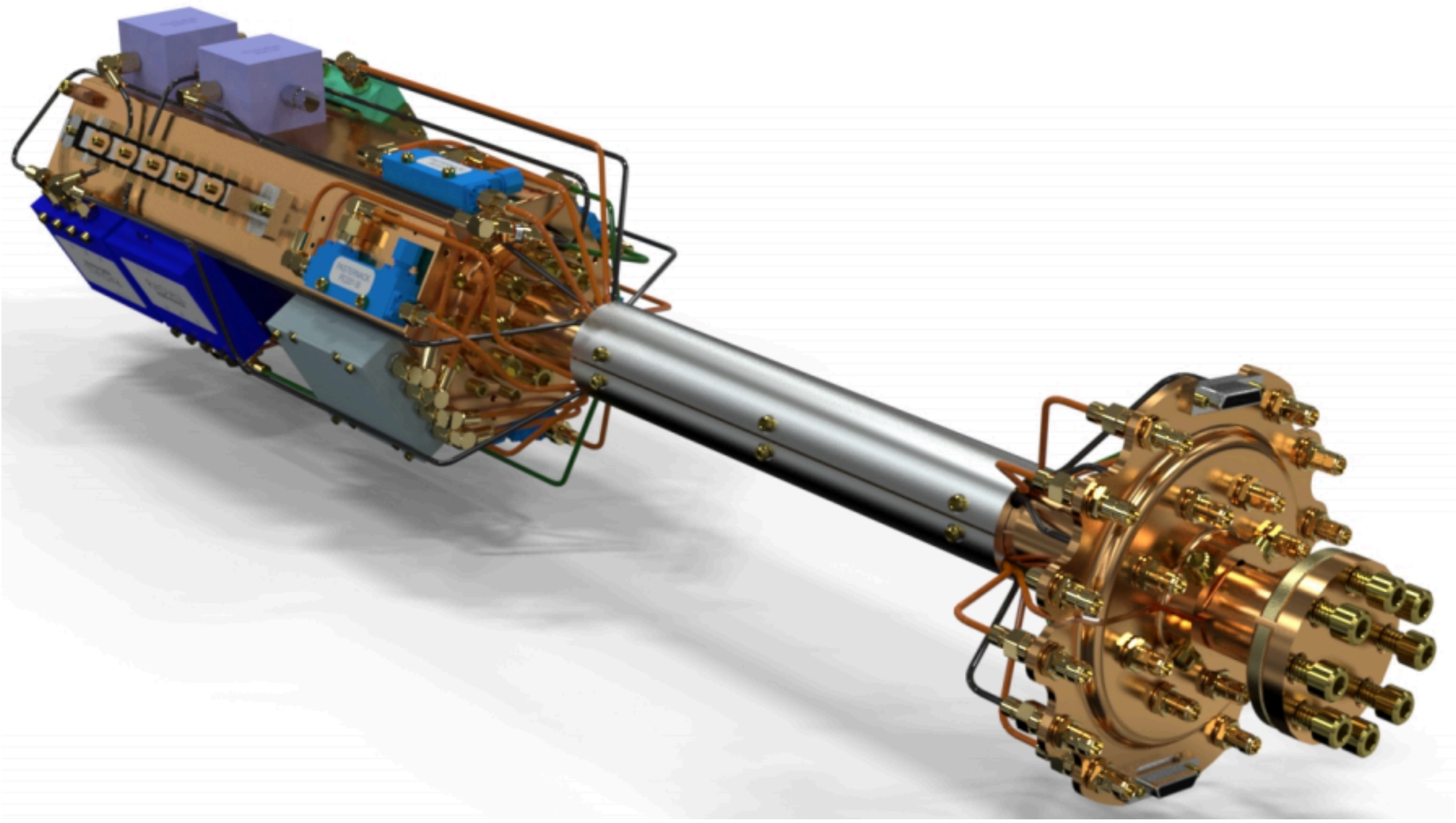
Higher Frequencies

- Scaling gets challenging
- One idea: Power combine multiple cavities and tune synchronously
- Challenges:
    - Cavity frequencies must be locked together
    - Power combining must be performed
    - New piezo motors installed
    - Increase in complexity: cables x N!



ADMX Run 2A

- 4 cavity array with common rotor. Frequency fine-tuned with sapphire mounted to linear stages
- N cavities combined in phase = sqrt(N) SNR improvement
- Scan rate $(SNR)^2$
- 1.4-1.8 GHz frequency range (Run 2A)
- Volume ~76 liters
- Q~130,000
- Quantum Electronics Package Upgrades



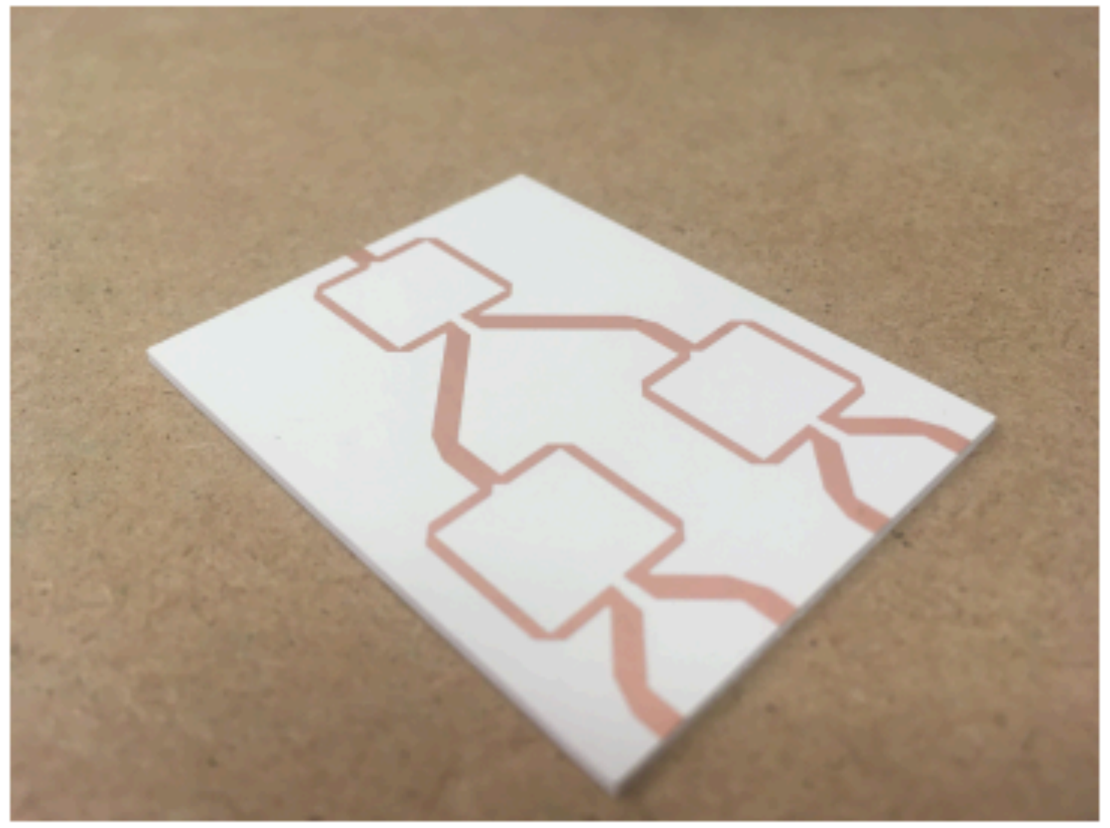
ADMX Run 2A

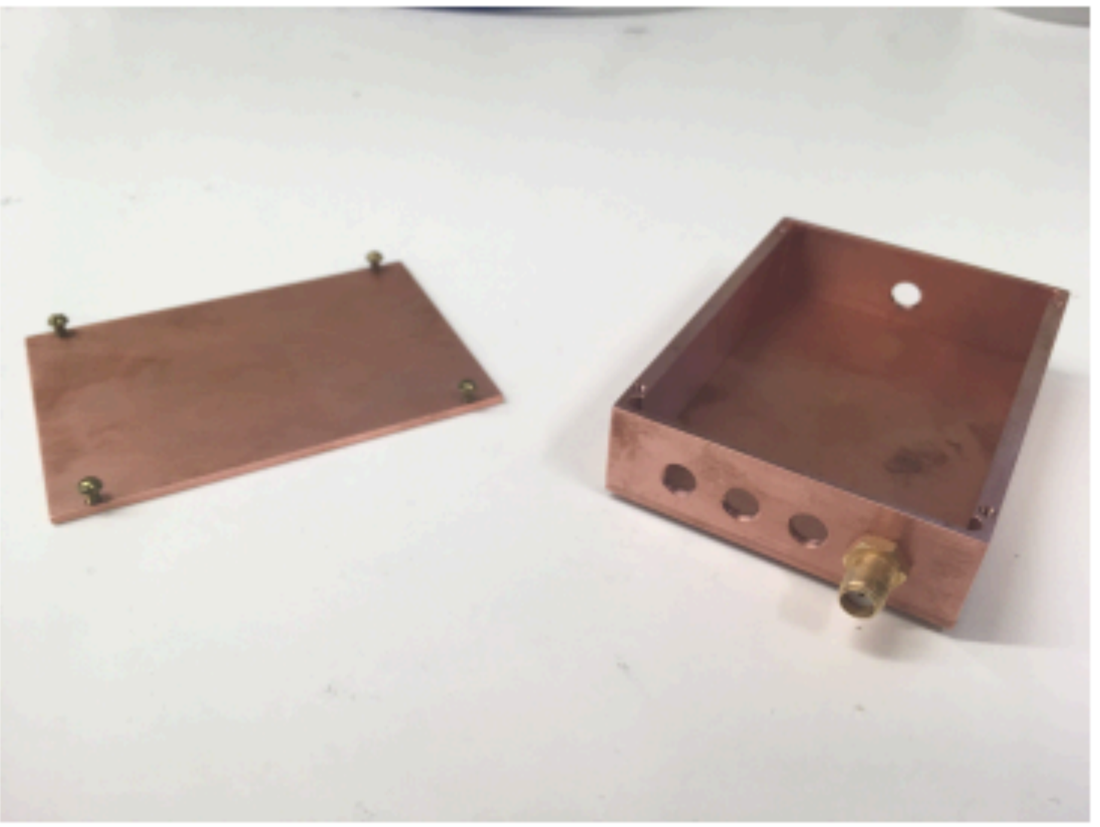
New components require a new quantum electronics package

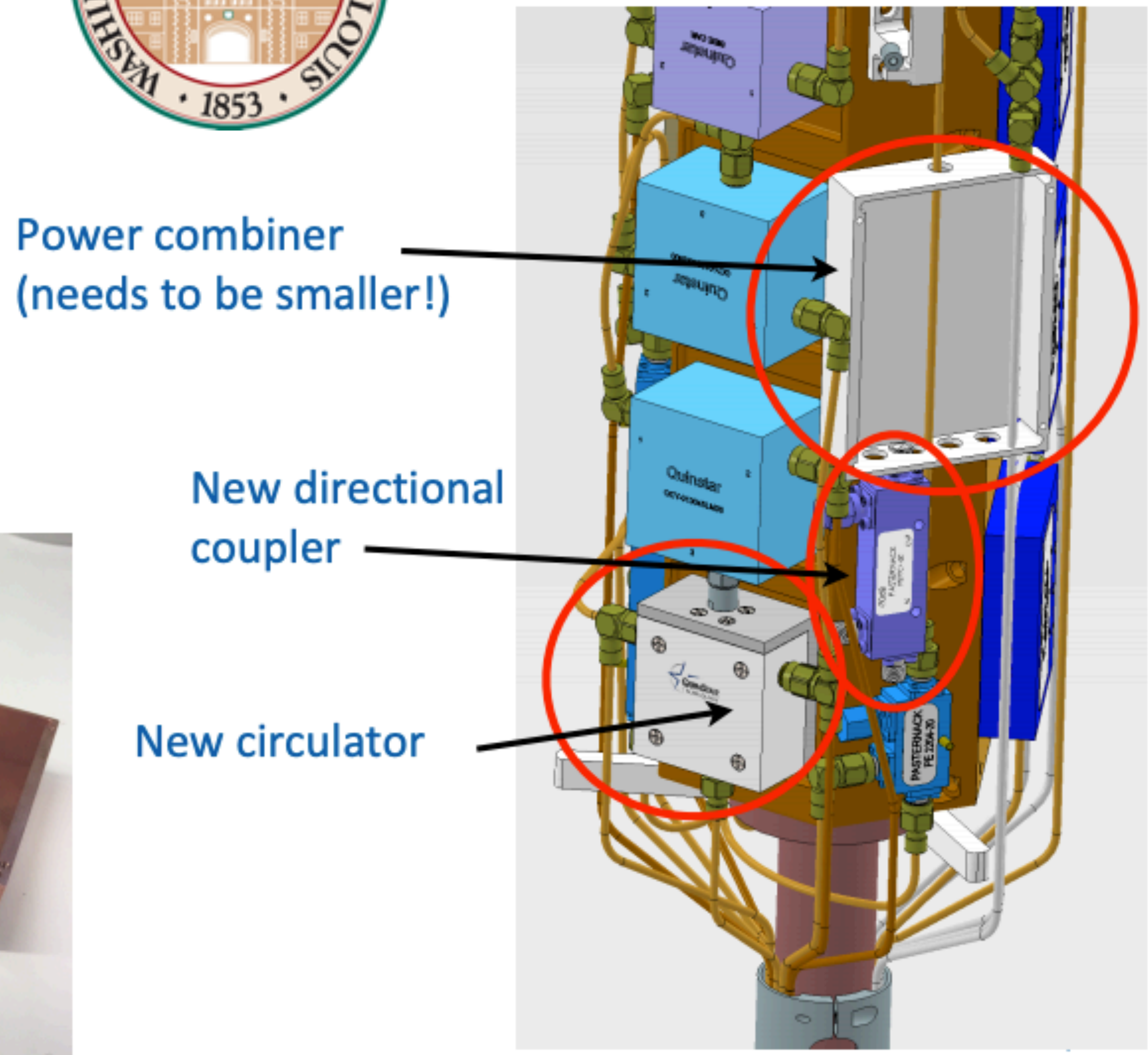
- Wilkinson Power Combiners designed at Washington University of St. Louis

- Ideal transmission is -6 dB, additional insertion loss < 0.4 dB

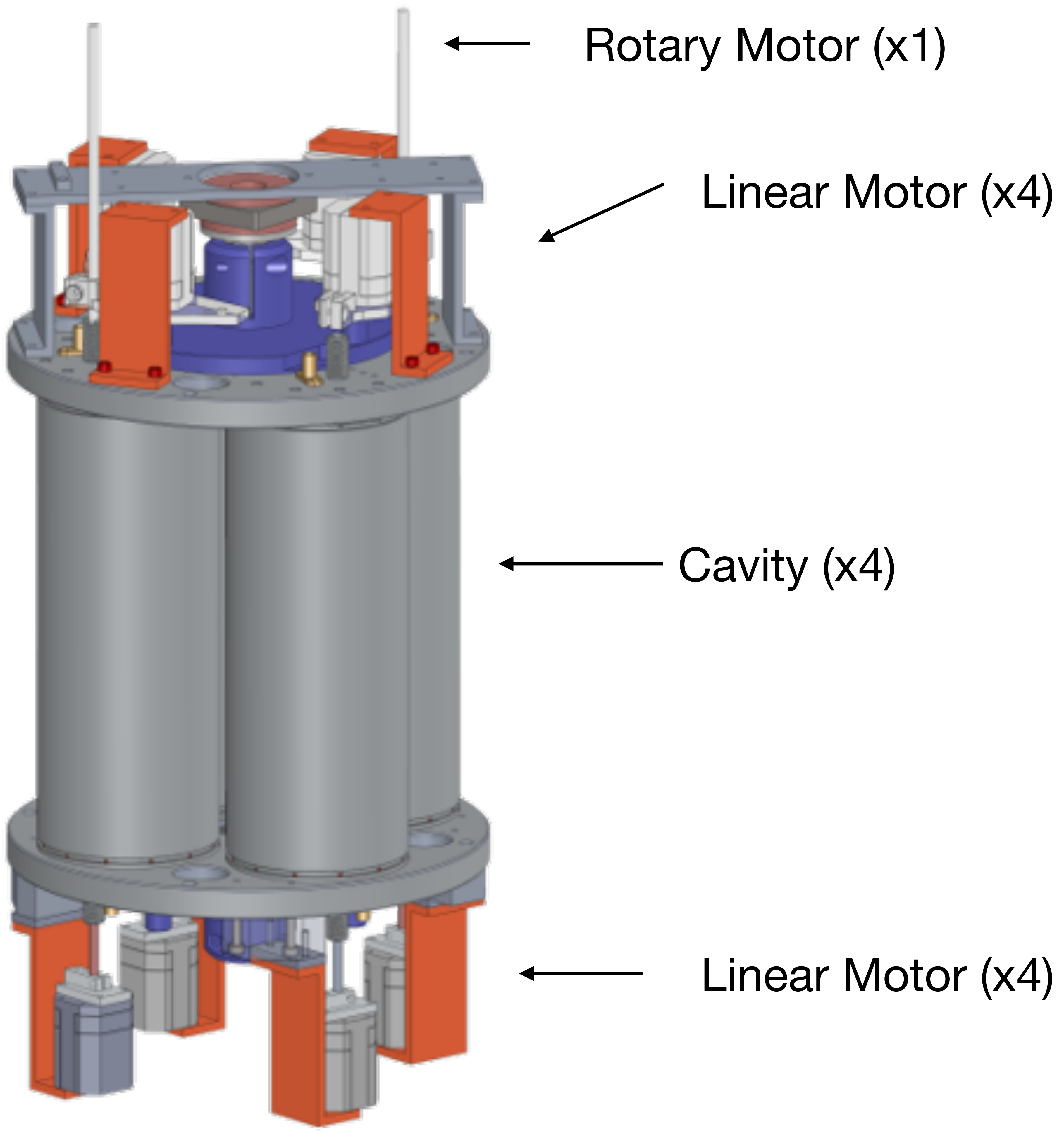
- Testing in agreement with their simulations

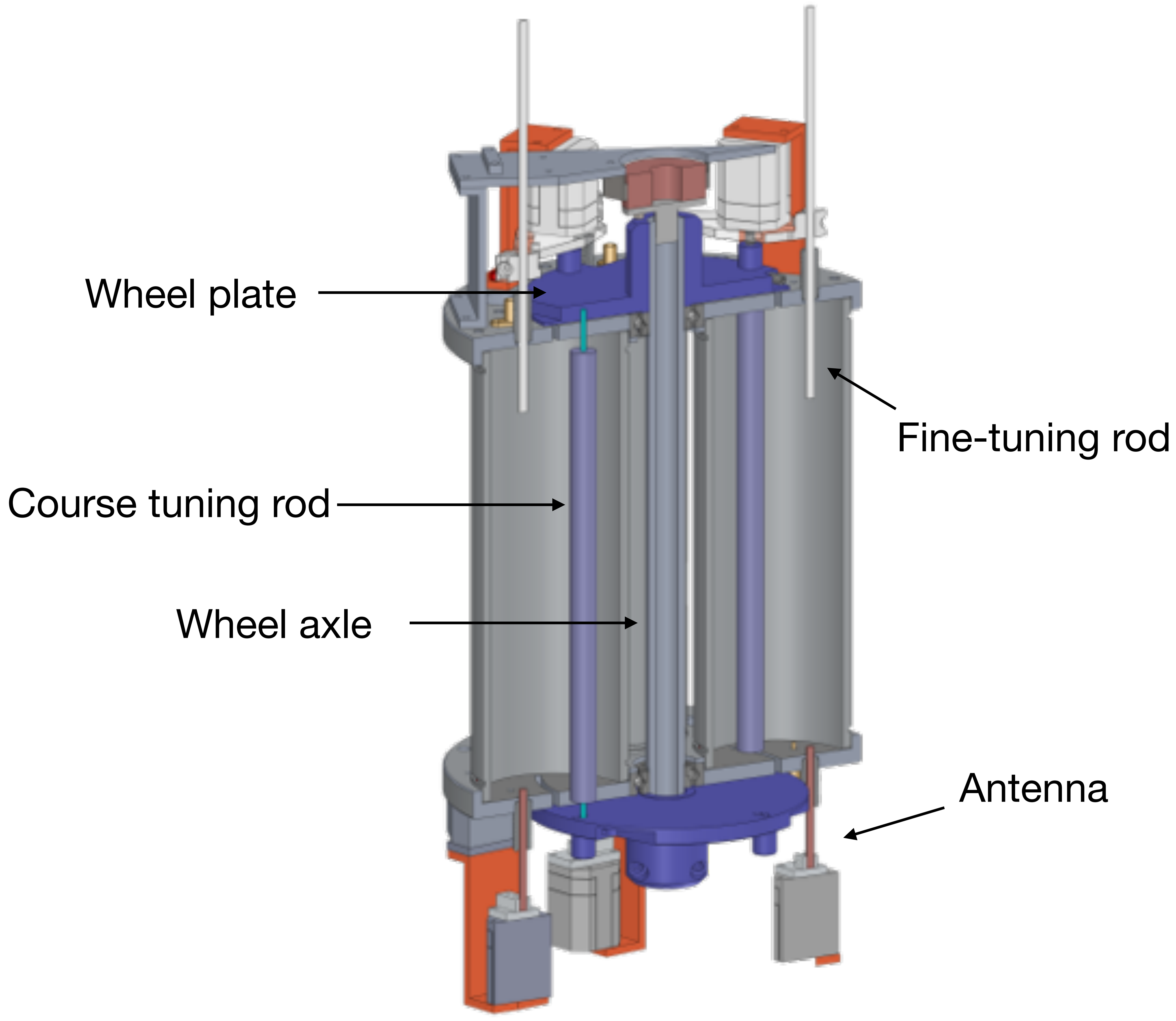






Prototype Study

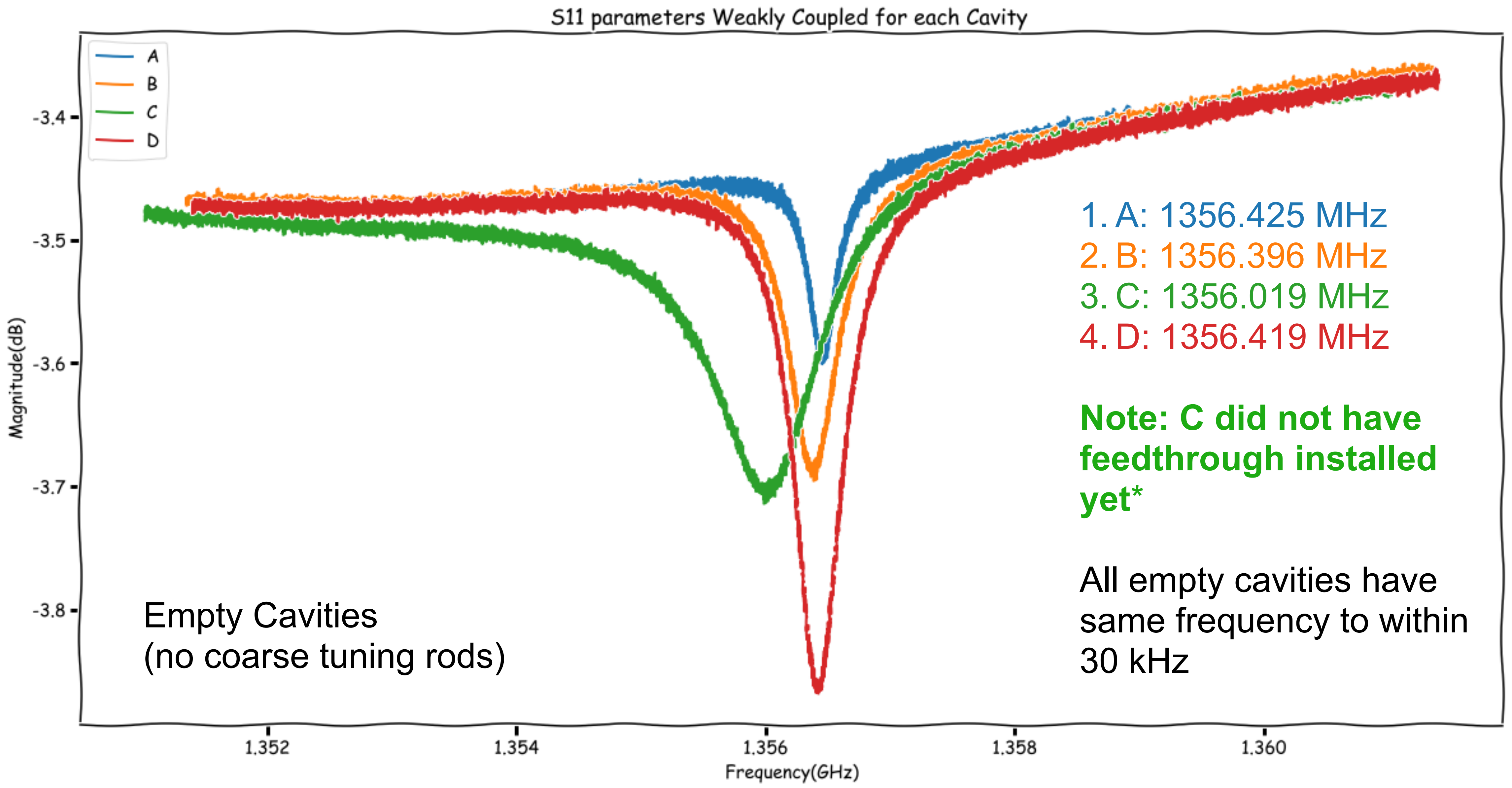




Images courtesy of Jihee Yang

Run 2A System

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

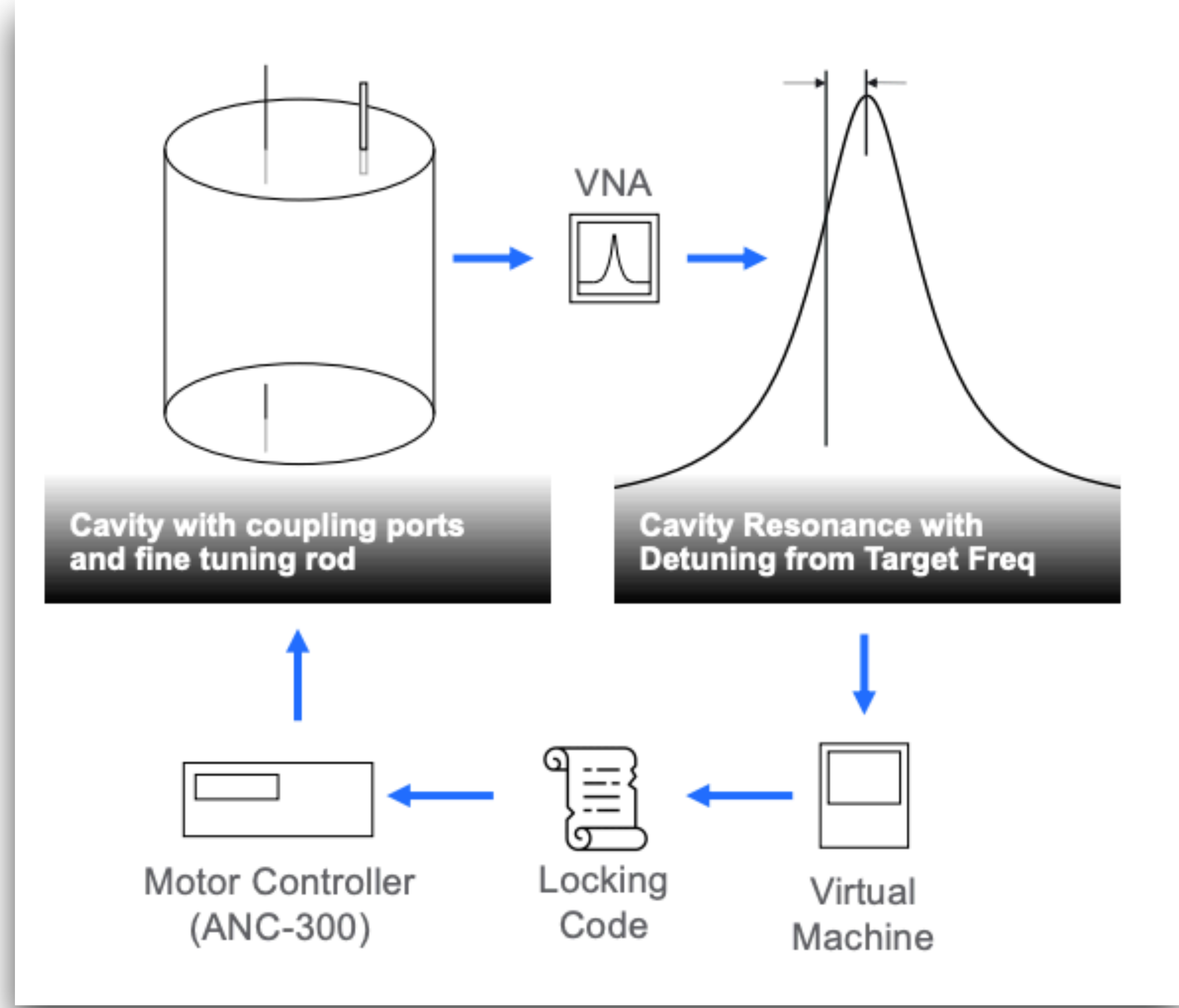


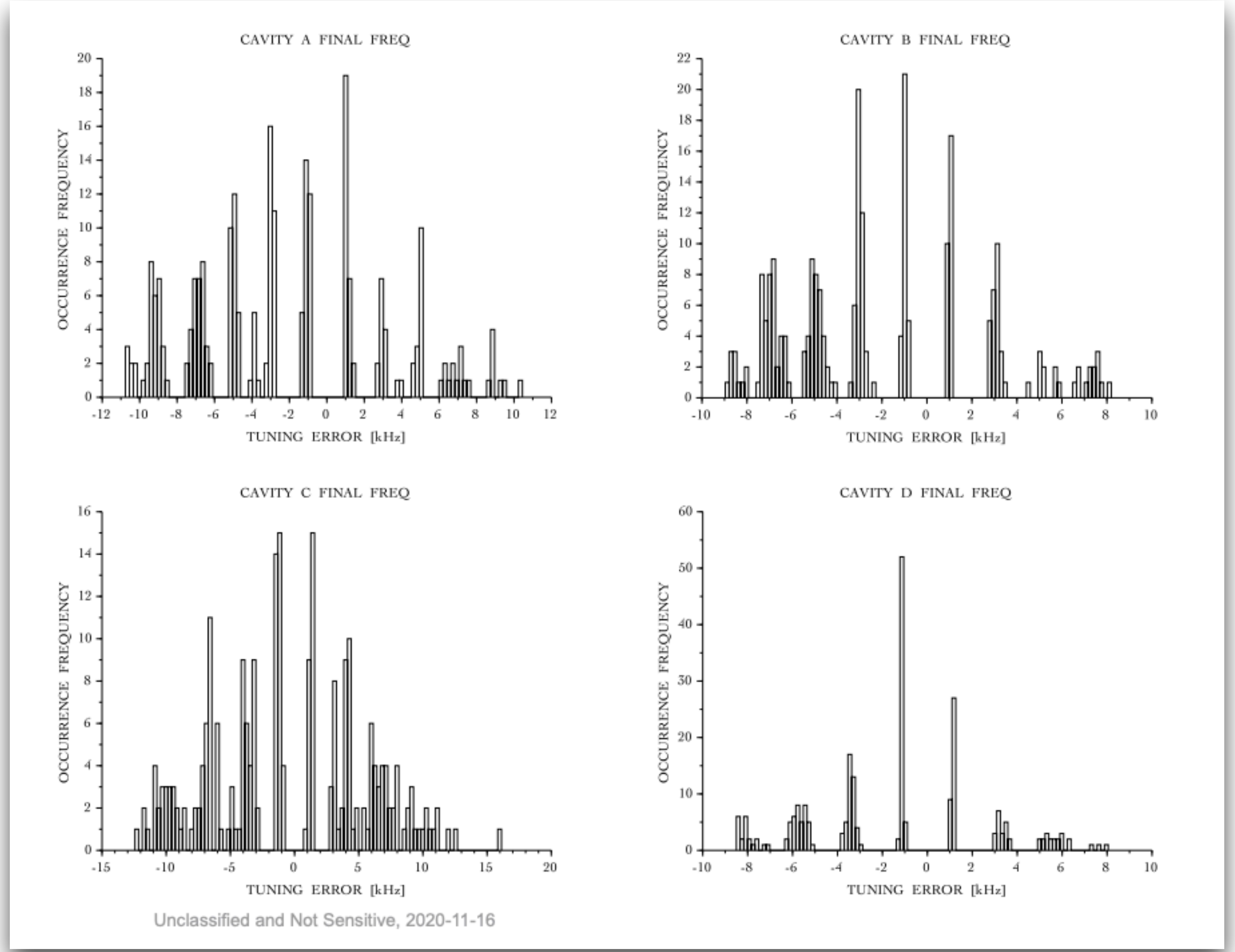
Staff scientist Nathan Woollett ←

Graduate student Tom Braine working on the cavities at Livermore →

Run 2A System

- Locking algorithm being designed at PNNL
  - 1.5% precision
  - Median time to lock < 2.5 s





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