Searching for Axion Dark Matter with the ADMX Haloscope

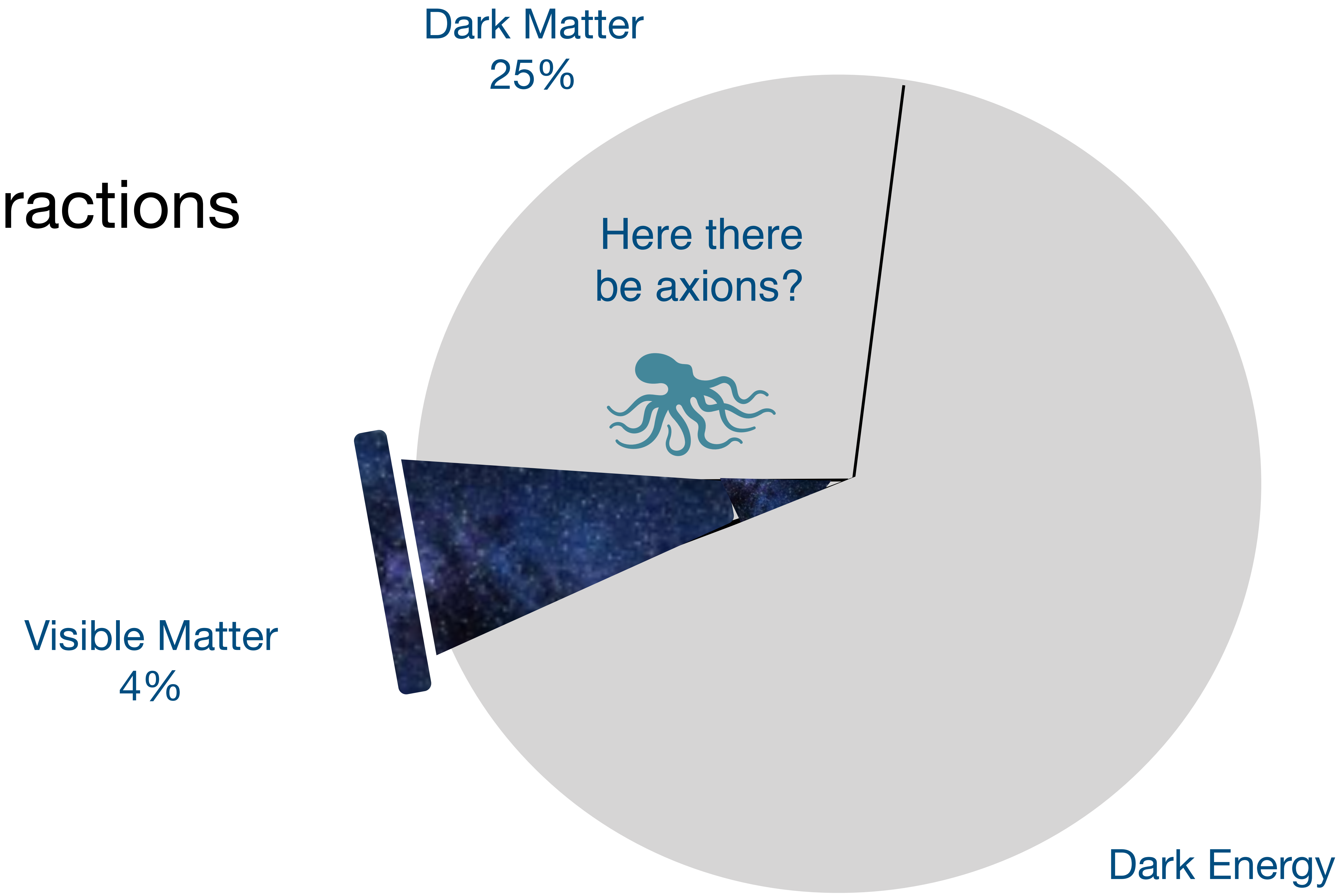
Chelsea Bartram

09/25/2020

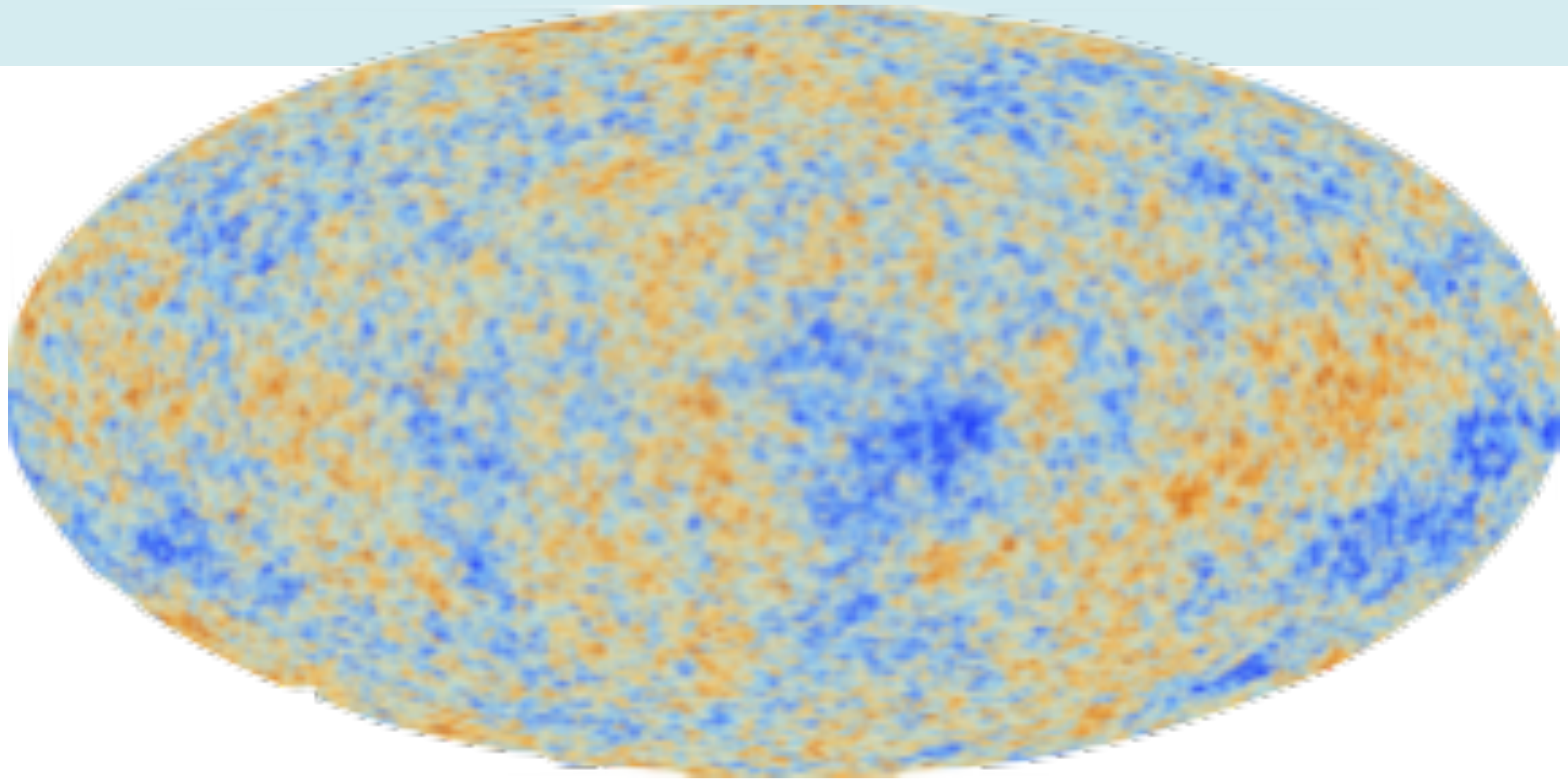
Dark Matter, a mystery

85% of the matter content of the universe is unknown

- How do we know? Indirect observations
- Dark matter concentrated near galaxies
- Interacts via gravity, unclear if other interactions
- Cold (non-relativistic)
- Feebly (non) interacting
- Very stable
- Non-baryonic



Indirect Evidence for Dark Matter



Cosmic Microwave Background
Planck CMB 2013

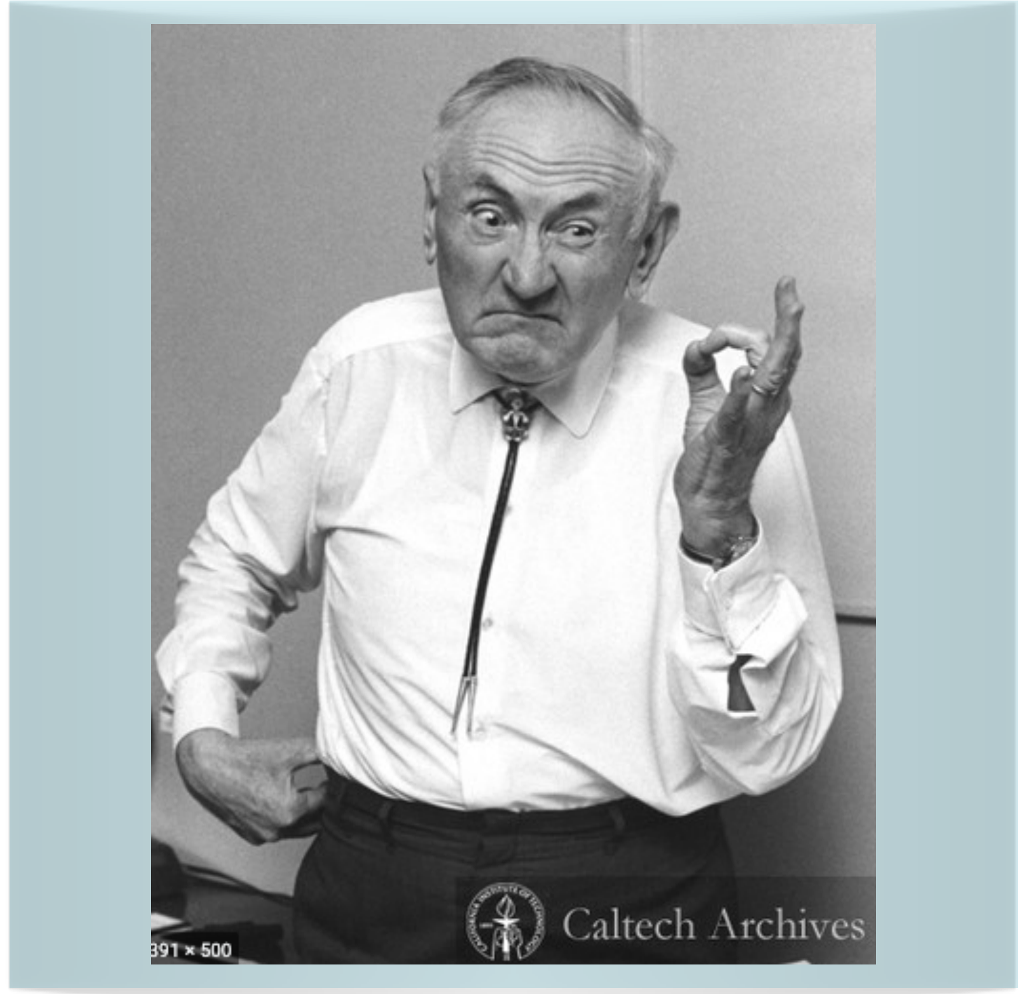
What is the evidence?

- Rotation curves of spiral galaxies
- Gravitational Lensing
- Galaxy Cluster Collisions
- Primordial Nucleosynthesis
- Matter-Radiation Fluctuations
- Cosmic Microwave Background
- Baryon Acoustic Oscillations

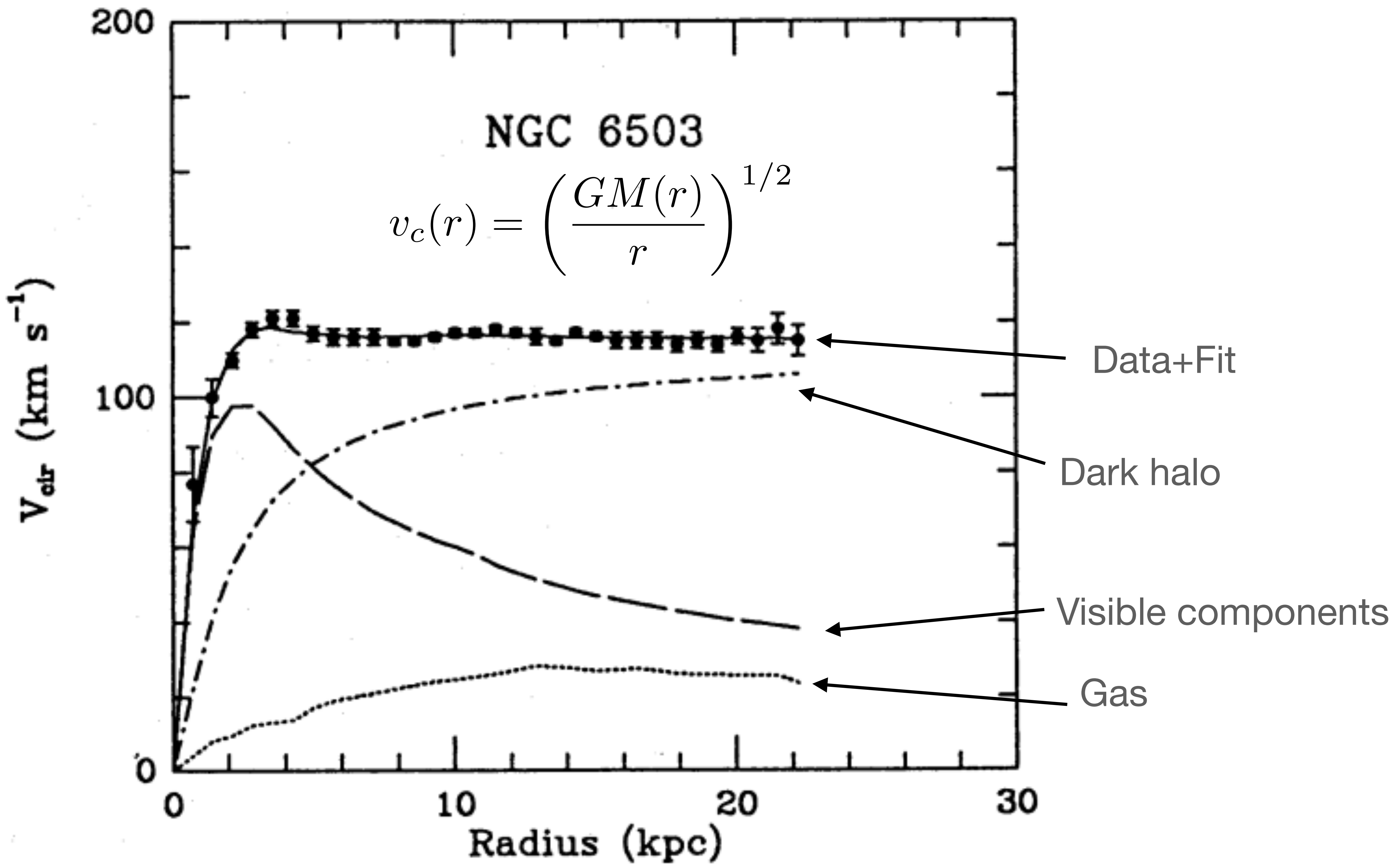
Bullet Cluster
Composite: NASA,
Markevitch etal.,
Clowe et al

Galactic Rotation Curves

Vera Rubin



Fritz Zwicky



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.

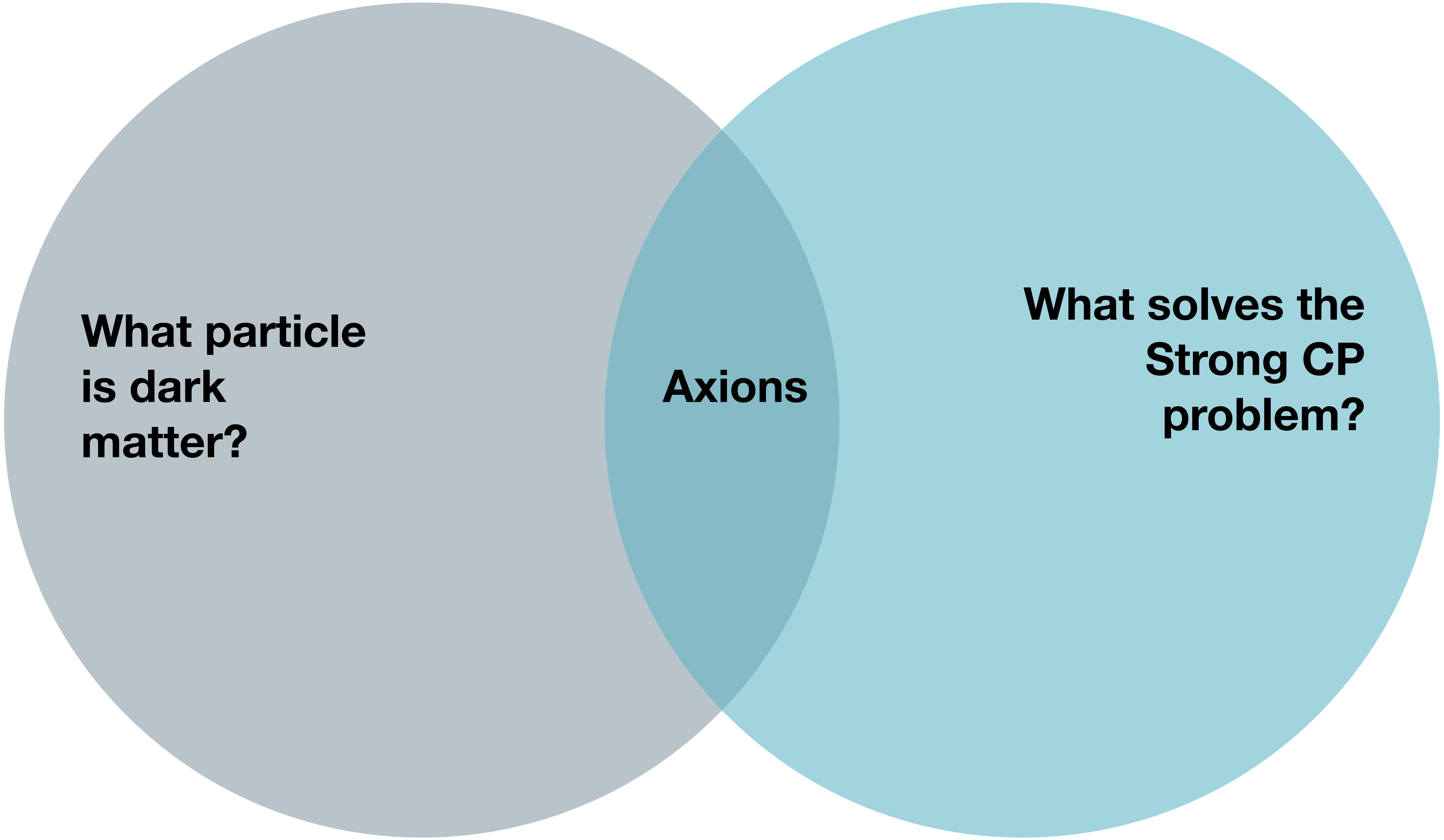
Faber, Sandra M., and J. S. Gallagher. "Masses and mass-to-light ratios of galaxies." *Annual review of astronomy and astrophysics* 17.1 (1979): 135-187.

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

What could this dark matter be?

Axions are one solution that happens to solve multiple problems



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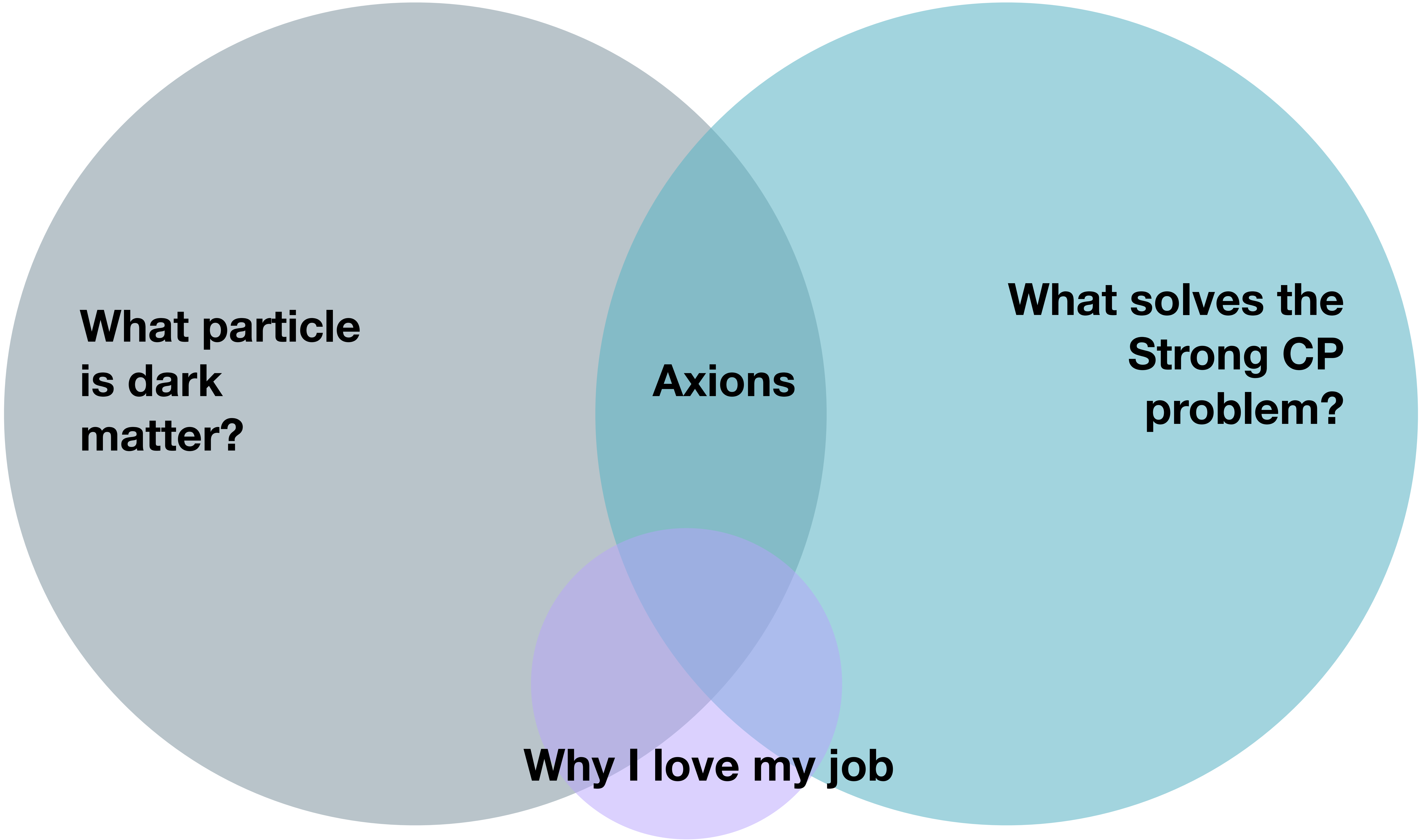


Axions and Strong CP Problem

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

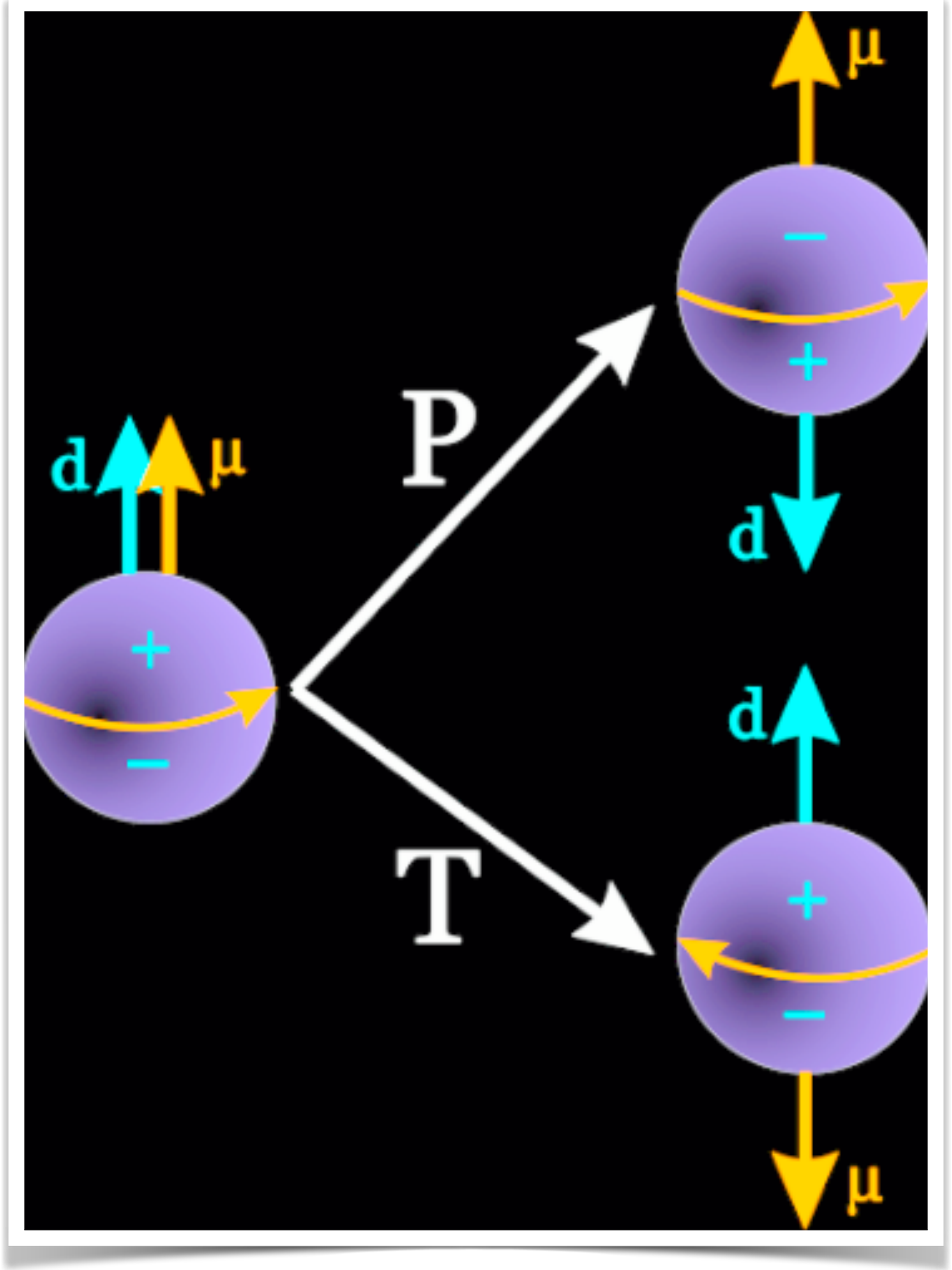
$$L_\theta = \frac{g^2}{32\pi^2}\theta_{QCD}F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

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

Axions and the Strong CP Problem

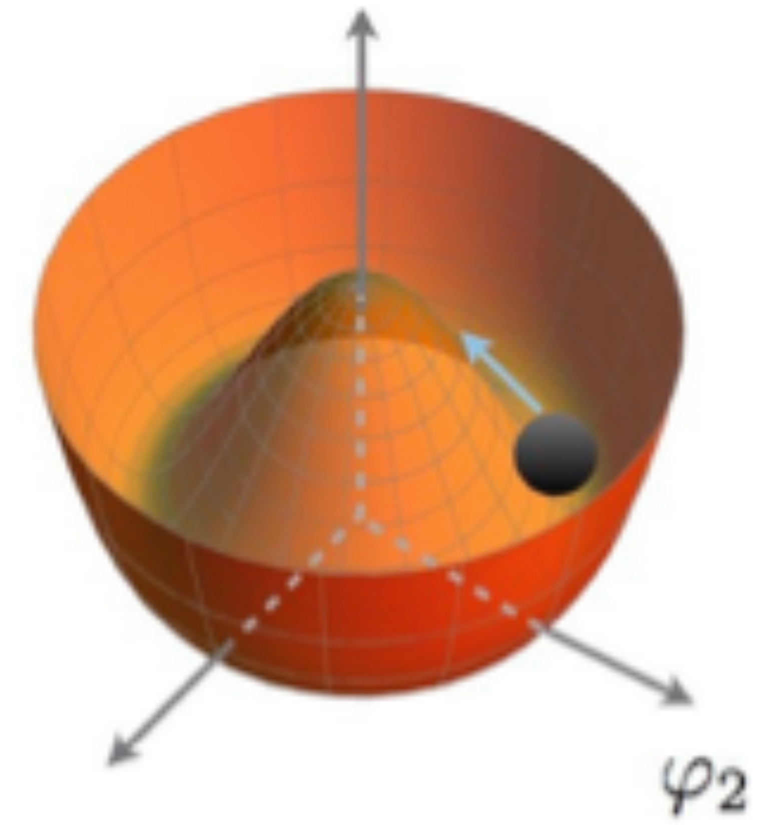
- Peccei-Quinn Solution to Strong CP Problem: Propose new global U(1) chiral symmetry that was spontaneously broken in the early universe

- 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*

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Where do axions fit in?

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

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

Pre-inflation PQ phase transition

Post-inflation PQ phase transition

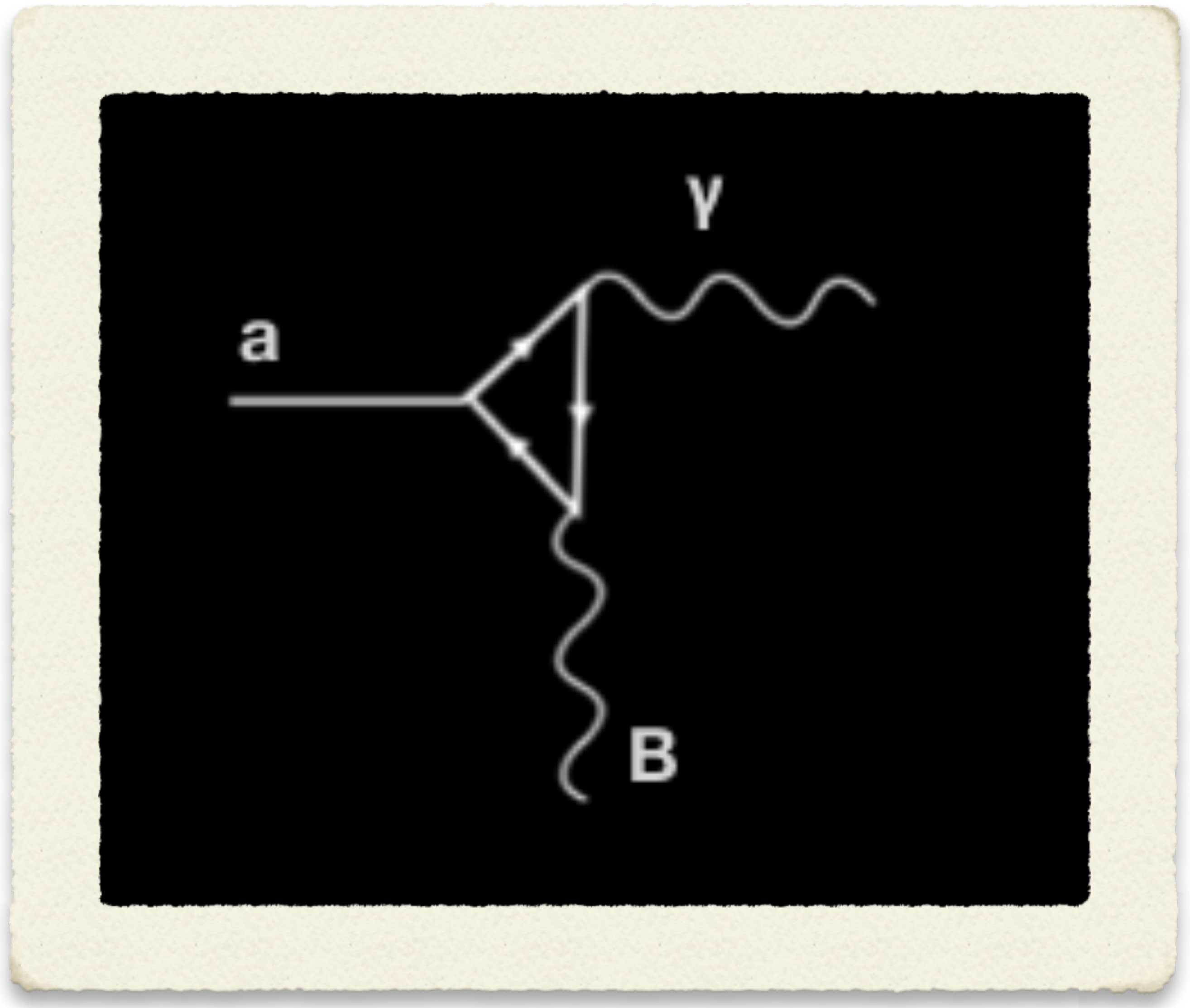
PDG https://arxiv.org/pdf/1710.05413.pdf

Adaptation of L. Winslow DPF Slide

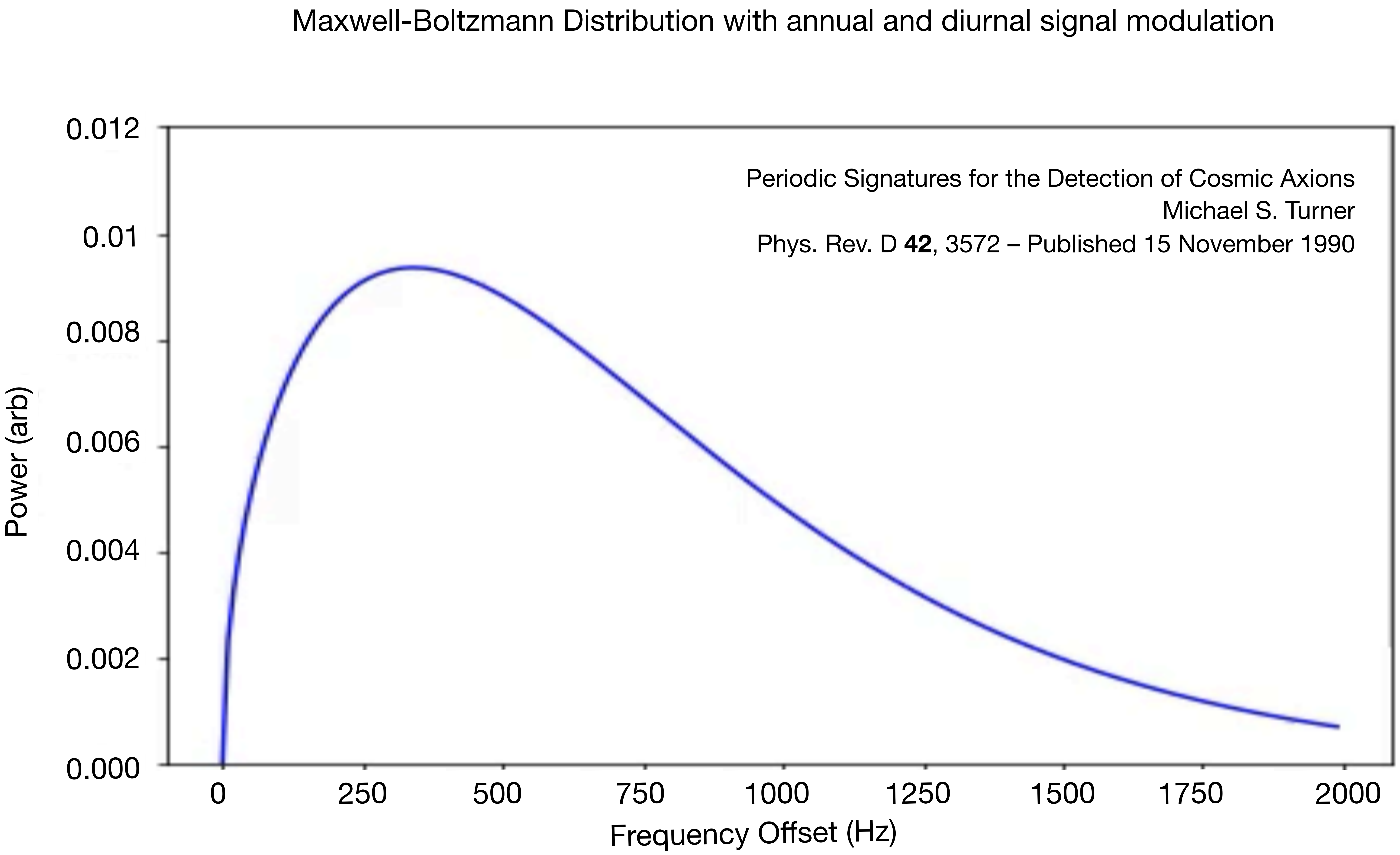
Axion Benchmarks

- 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



Axion Lineshape (Velocity Distribution)



Detecting the axion

$$L = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{i}{2}g_d a\bar{N}\sigma_{\mu\nu}\gamma_5 N F_{mu\nu} + g_{aNN}(\partial_\mu)\bar{N}\gamma^\mu\gamma_5 N + g_{aie}(\partial_\mu)\bar{e}\gamma^\mu\gamma_5 e$$

Coupling to photons

Coupling to nucleon EDM

Causes electric dipole moments (EDMs) in nuclei/atoms/molecules

Coupling to axion nuclear moment

Creates spin-dependent energy shifts/spin precession in fermions

Coupling to axial electron moment

Axioelectric effect, Analogous to photoelectric effect

Adapted from L. Winslow DPF slide and Y. Kahn, See Graham and Rajendran, Phys.Rev. D88 (2013) 035023

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.

Quantum Computing

Cryogenics

Microwave Electronics

High Magnetic Fields

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.

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Los Alamos NATIONAL LABORATORY

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

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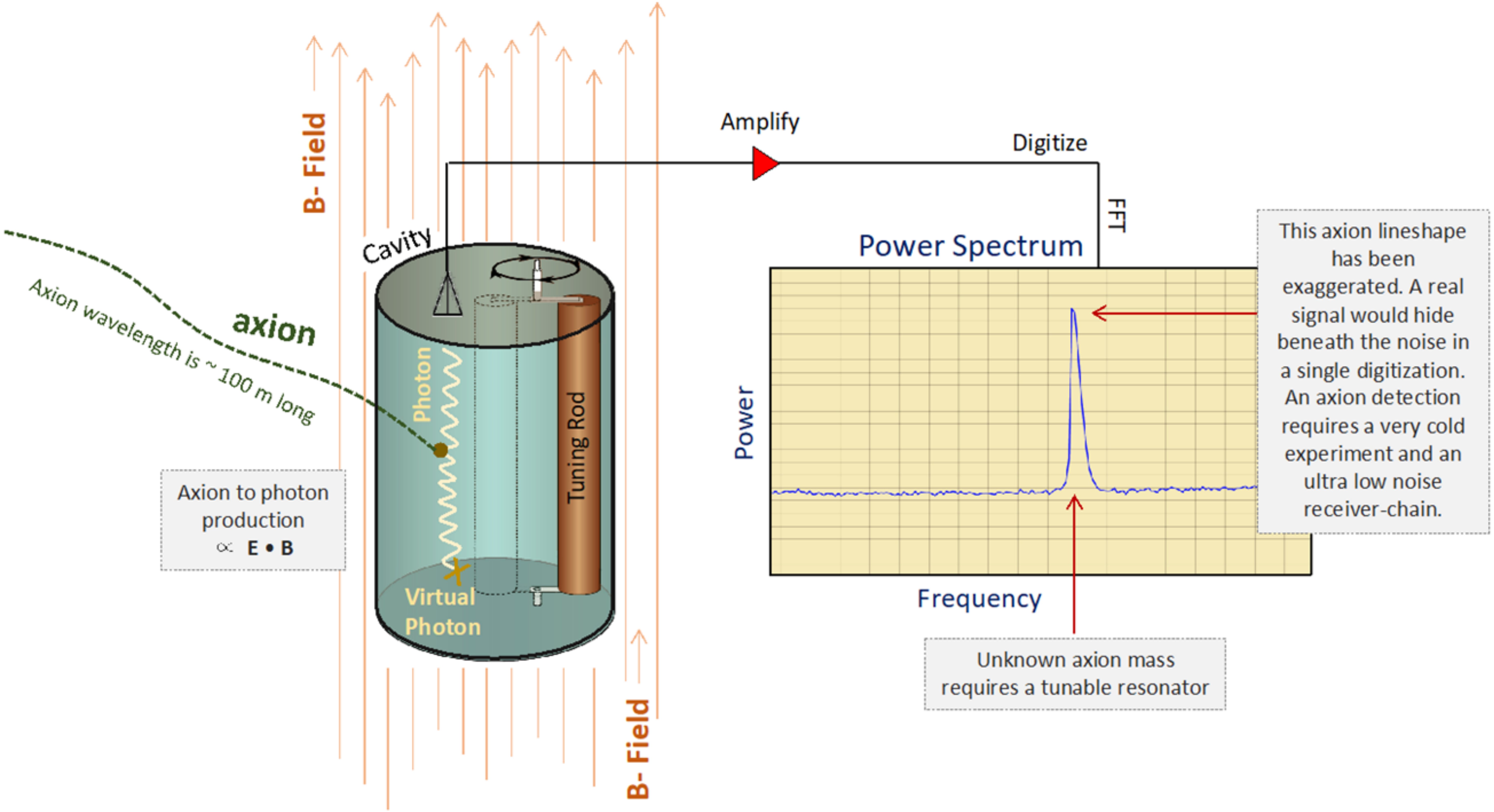
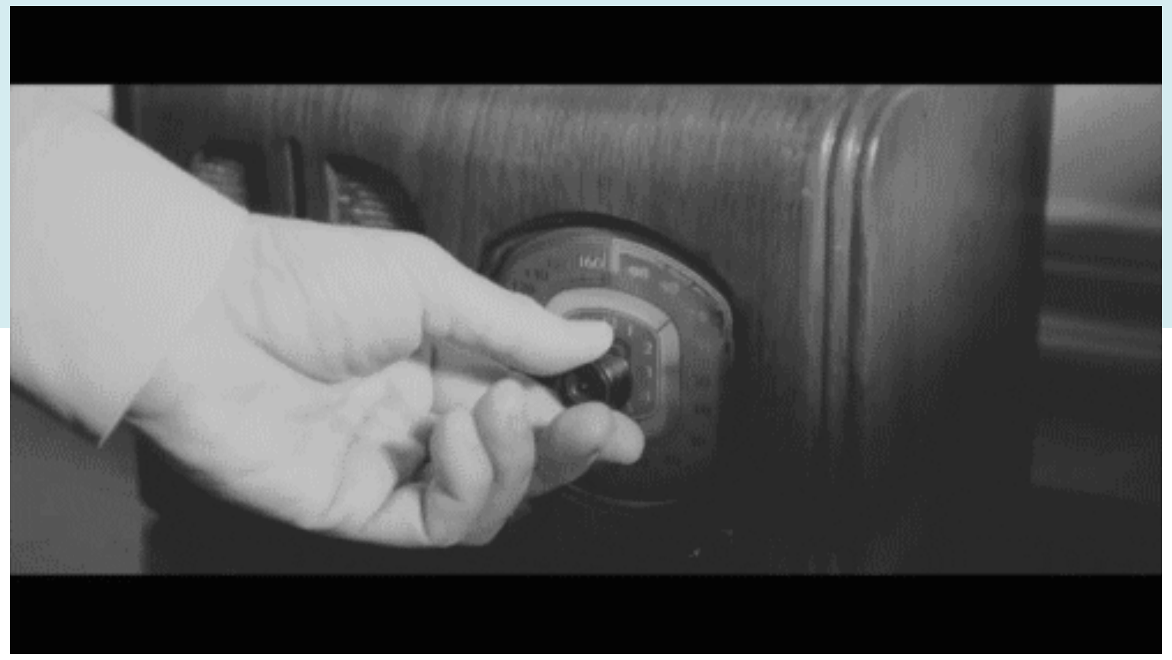
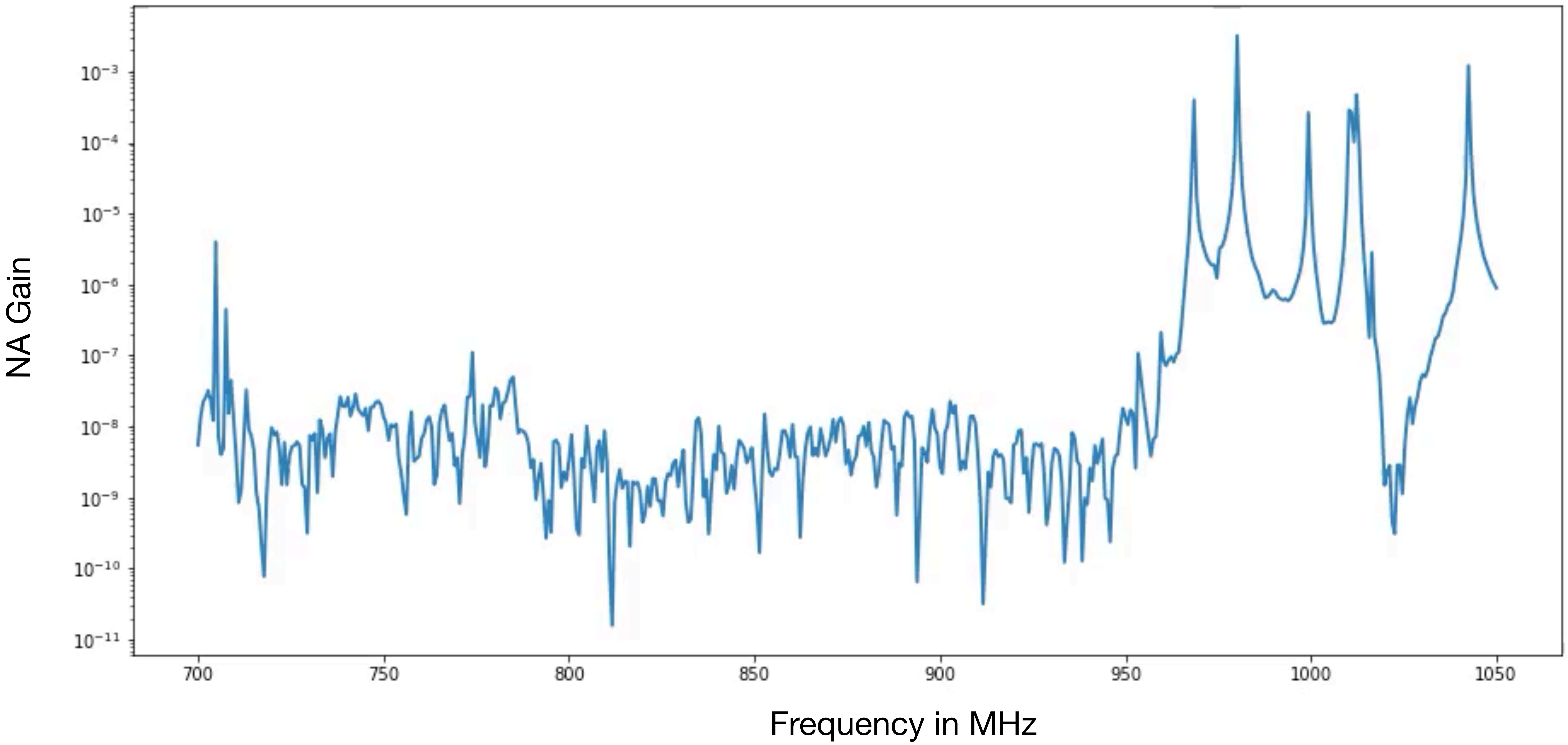
ADMX Haloscope



Tuning our cavity

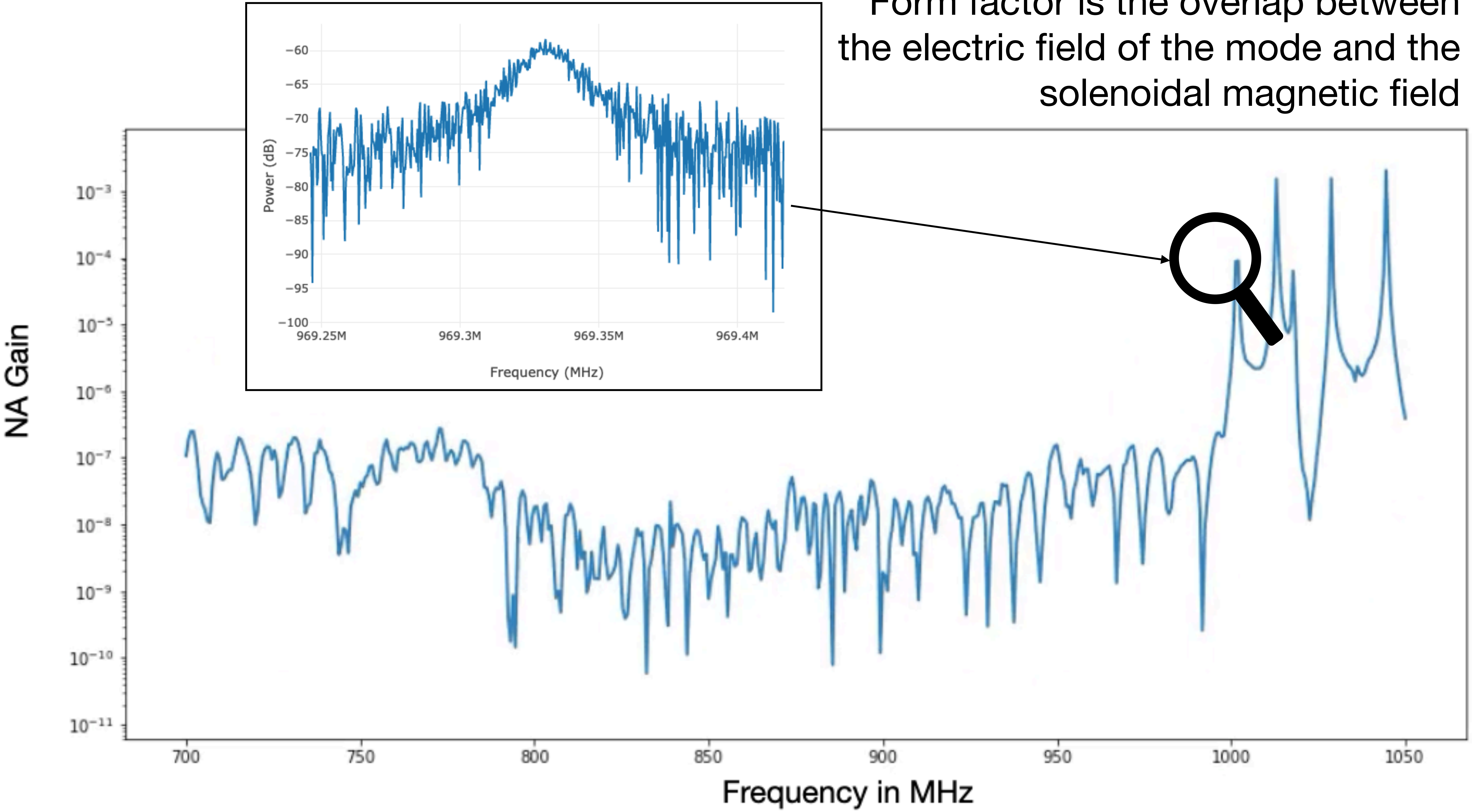


As we tune, we track the TM010 mode
Axion couples most strongly to this mode
Note occasional mode-crossings



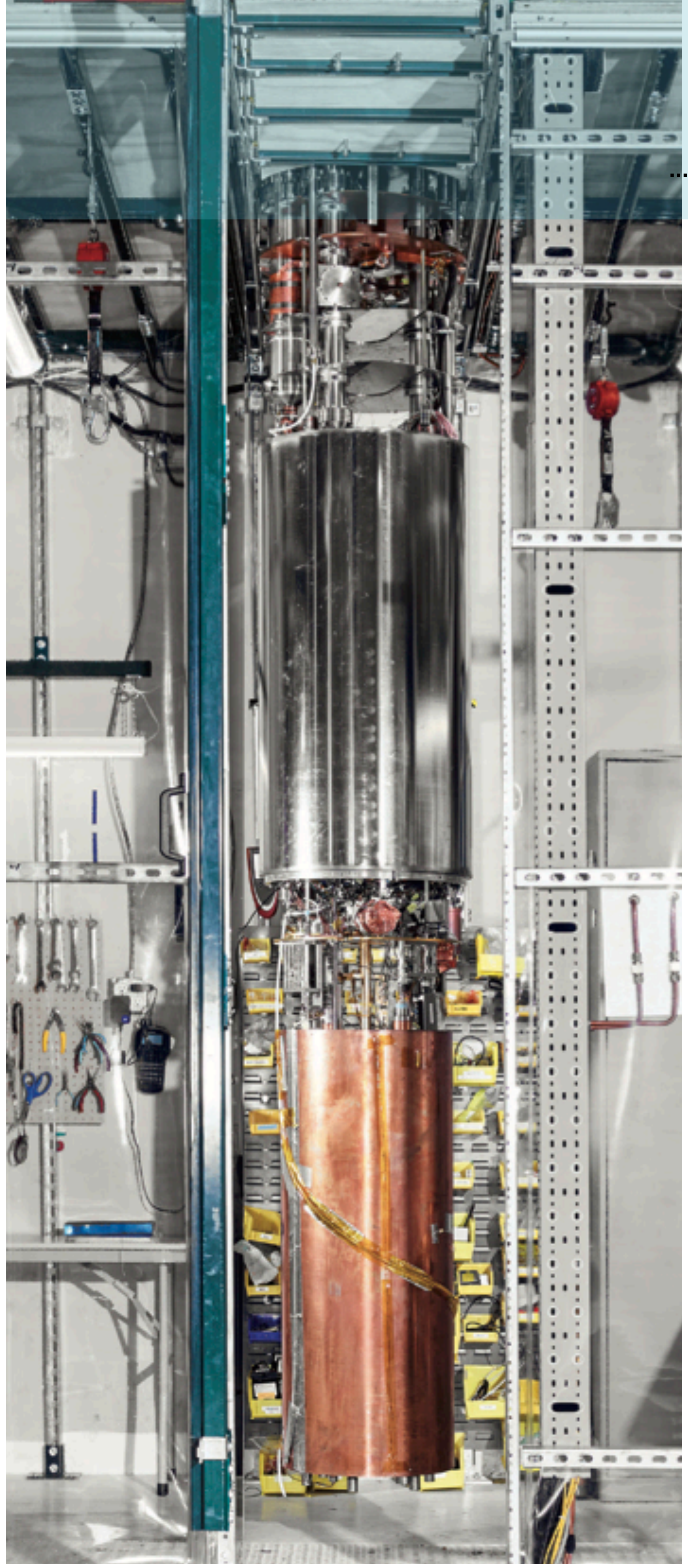
Zooming in on a single mode

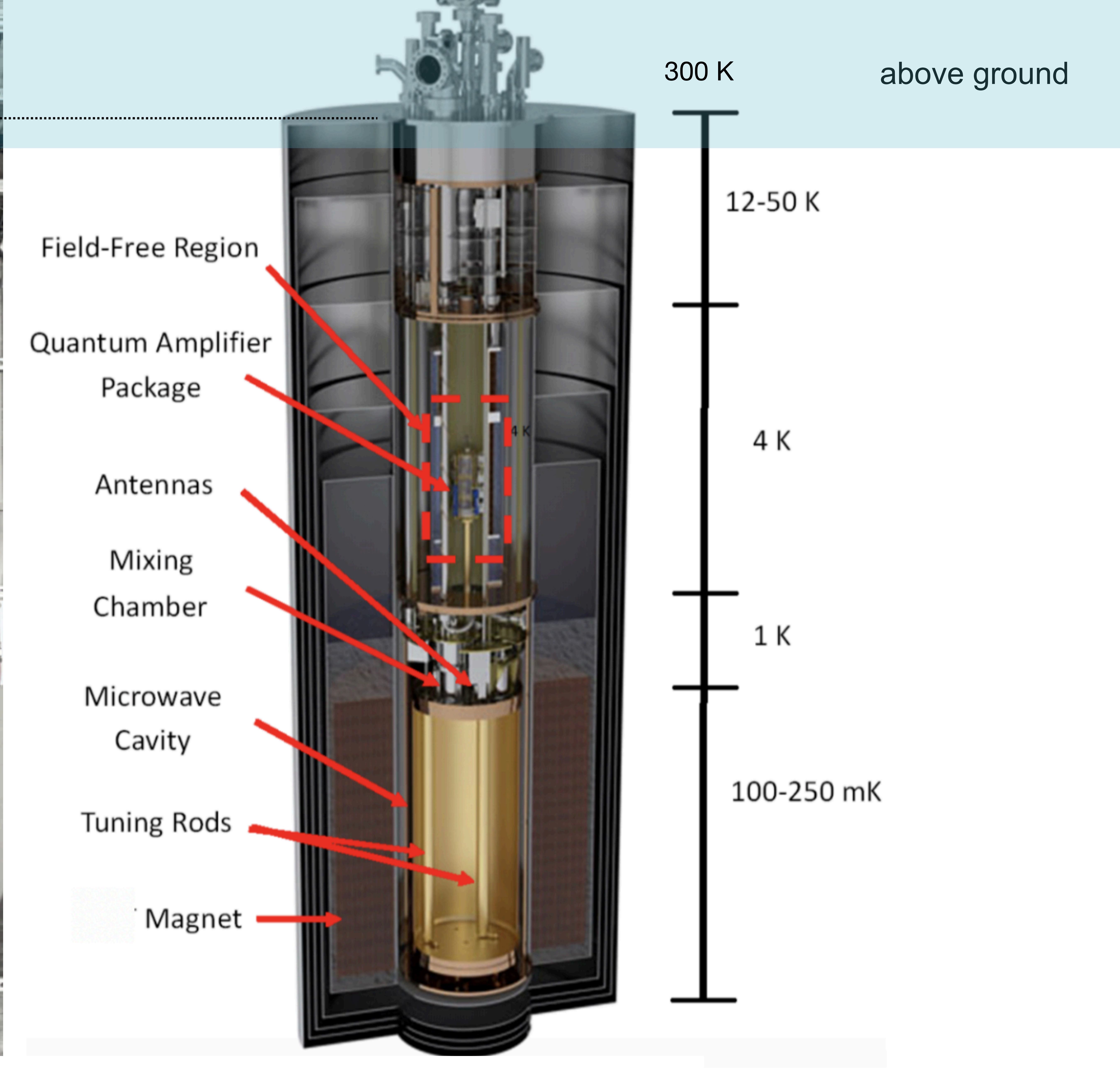
Form factor is the overlap between the electric field of the mode and the solenoidal magnetic field

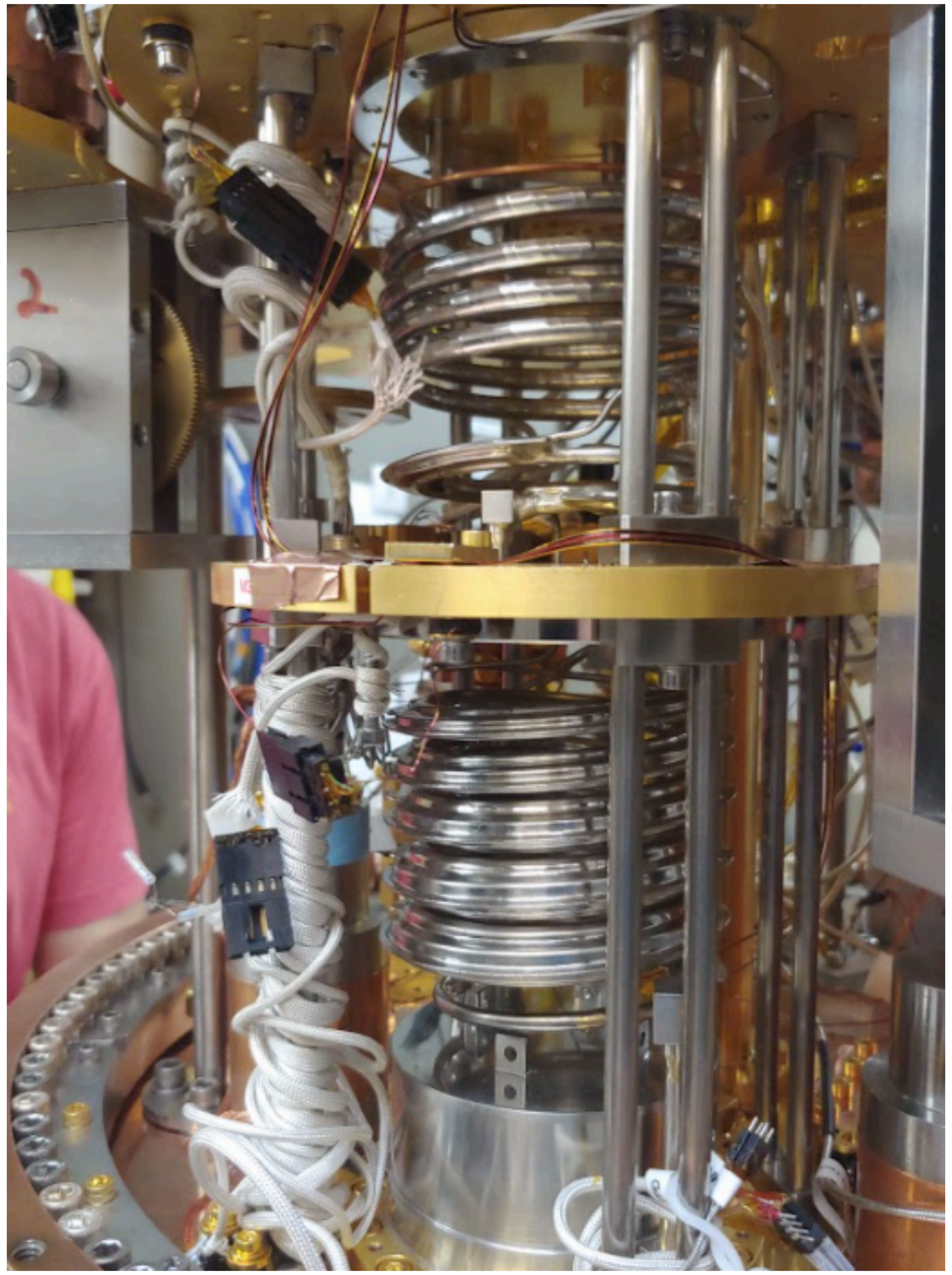


ADMX

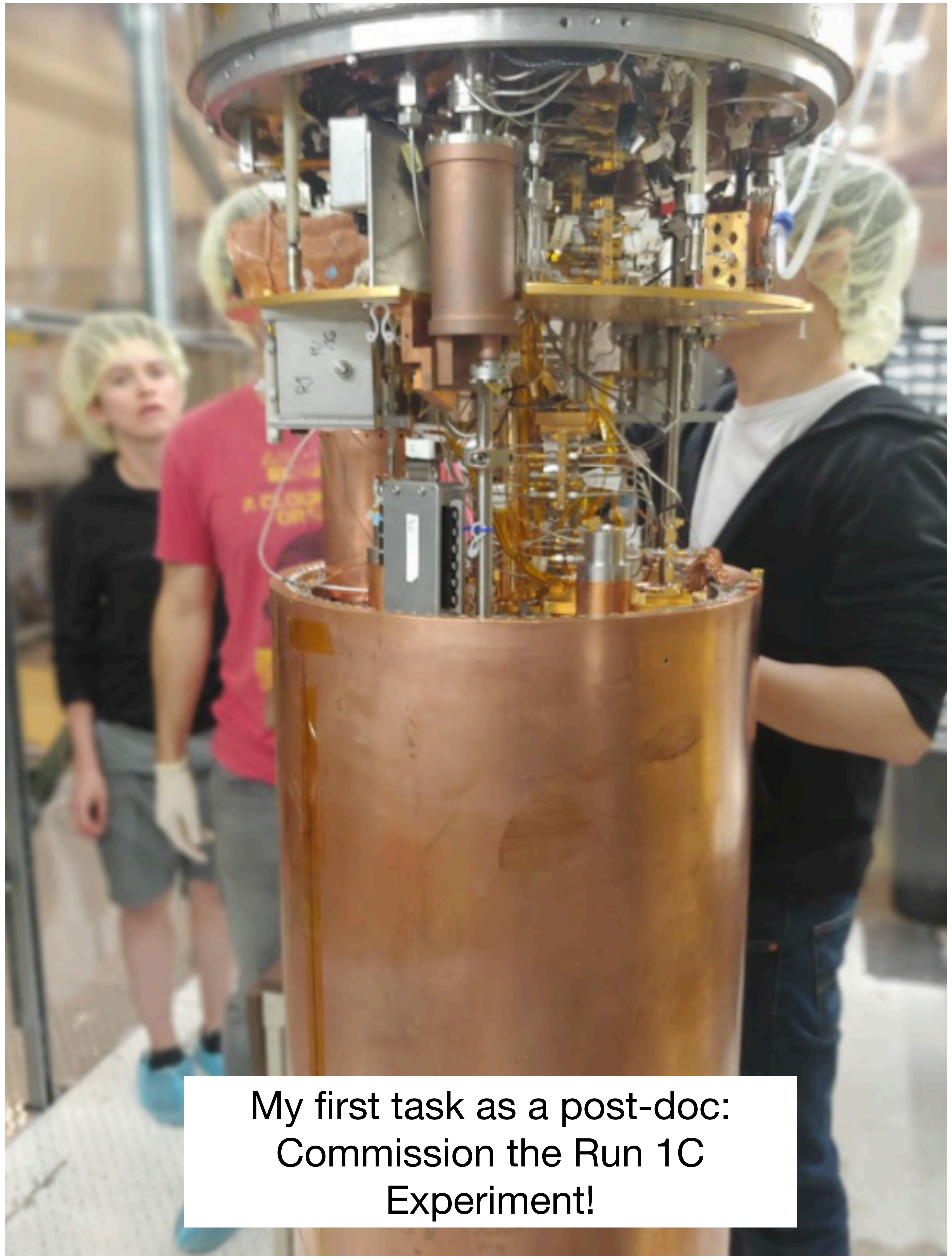
- Dil Fridge: Reaches ~100 mK
- Superconducting magnet:
  ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics







Dilution Refrigerator Mounted to Cavity

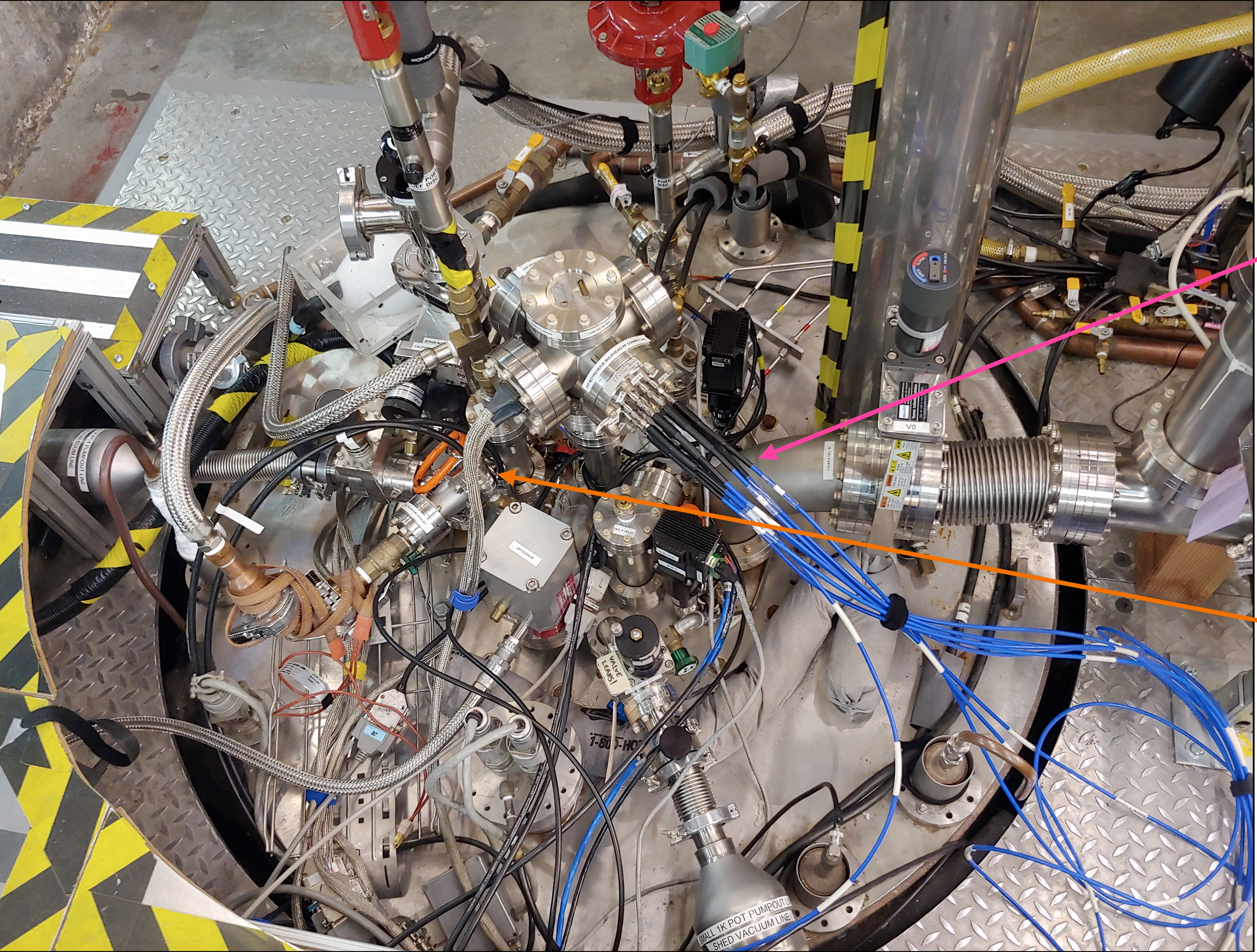


My first task as a post-doc: Commission the Run 1C Experiment!

Quantum Electronics Package

ADMX Rigging Operation

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



RF cables

DC cables for sensors

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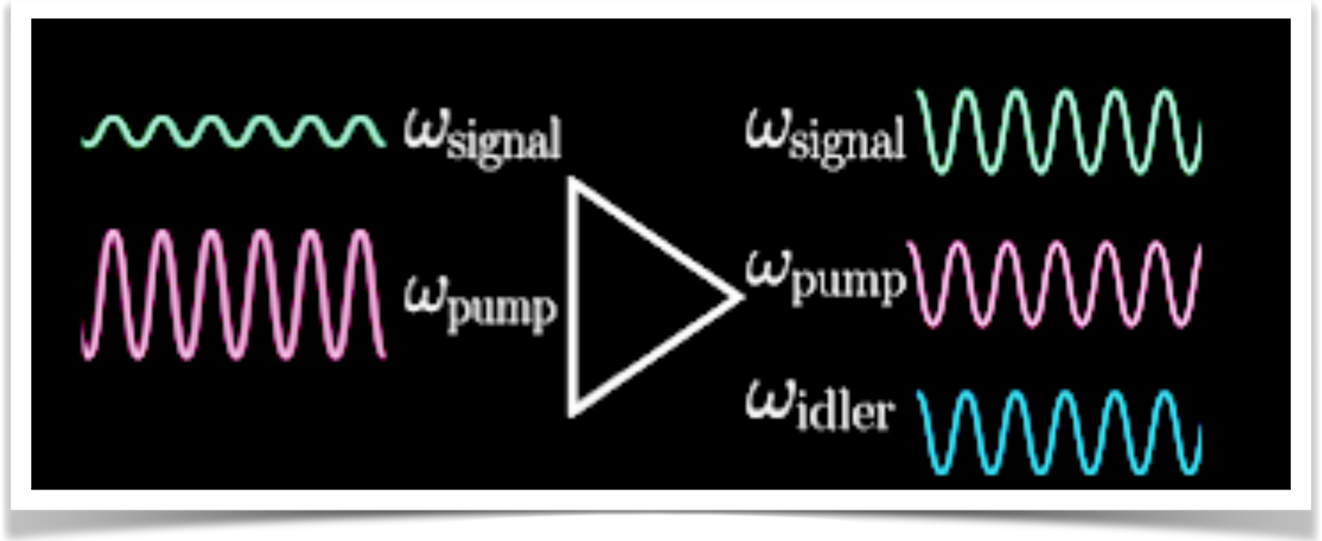
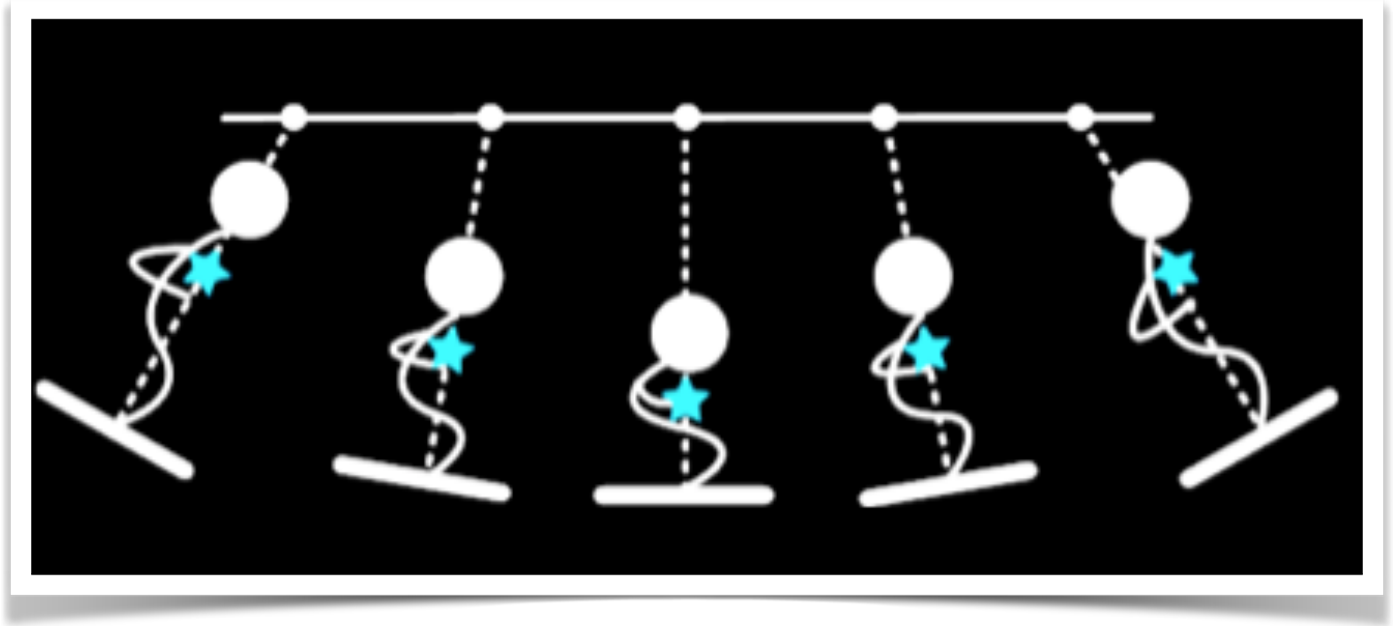
Josephson Parametric Amplifier (JPA)

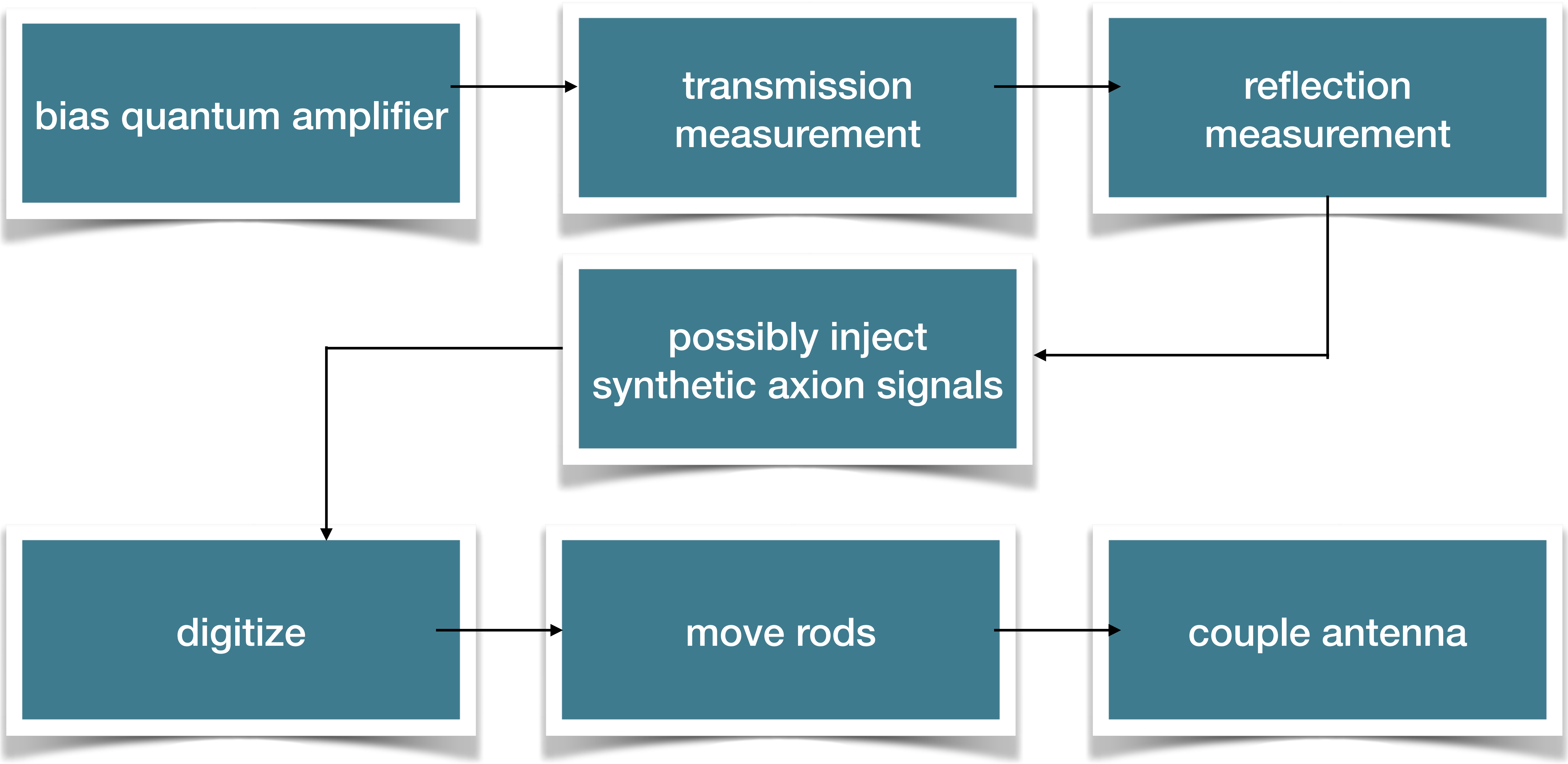
- Critical to obtaining low amplifier noise
- How does a parametric amplifier work?
- Classic example is child on a swing
- Anharmonicty leads to energy transfer from the pump tone to the signal tone
- Requires some non-linear element, in this case, the Josephson Junction



Figures courtesy of Shahid Jawas



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

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

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

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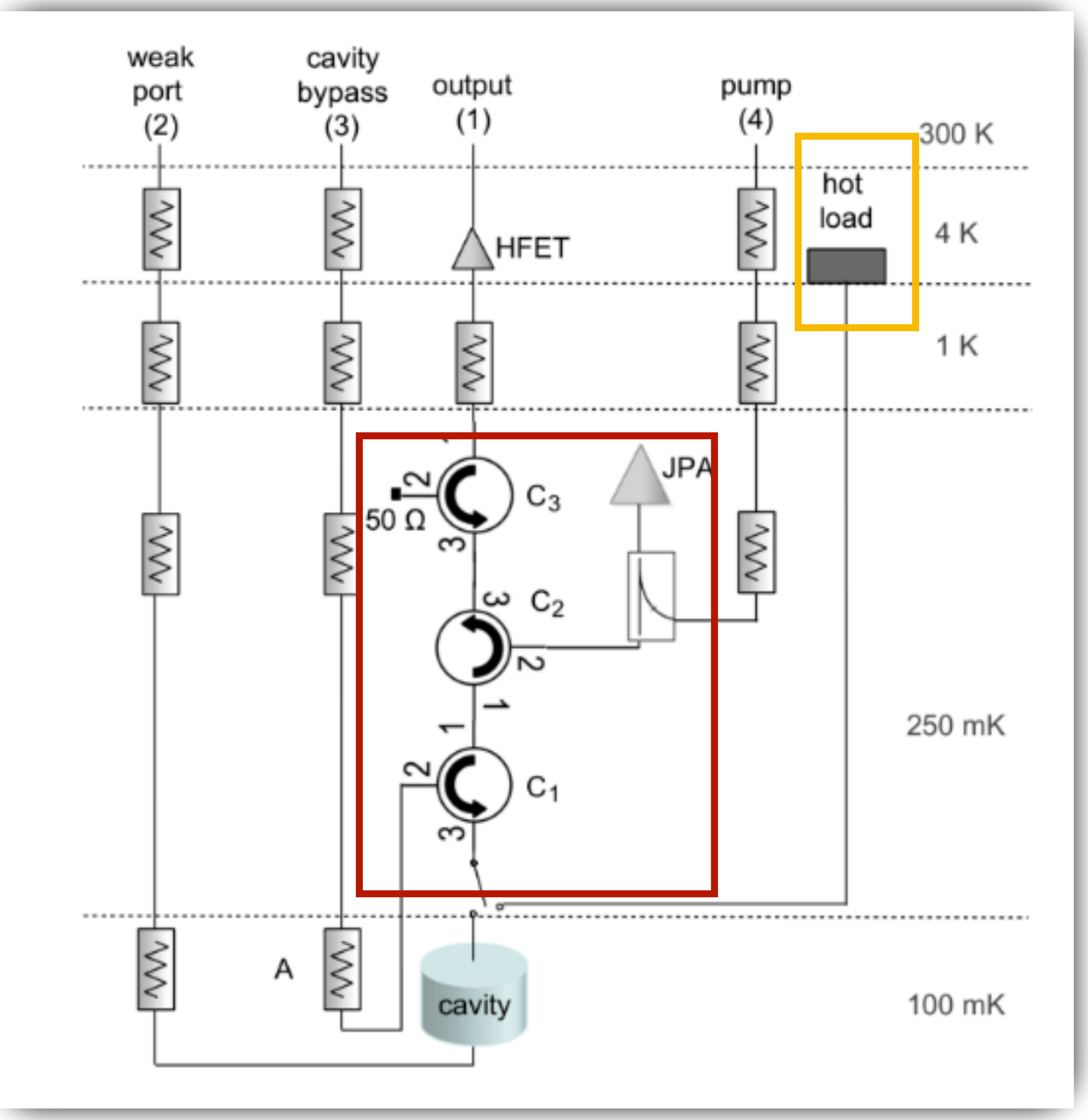
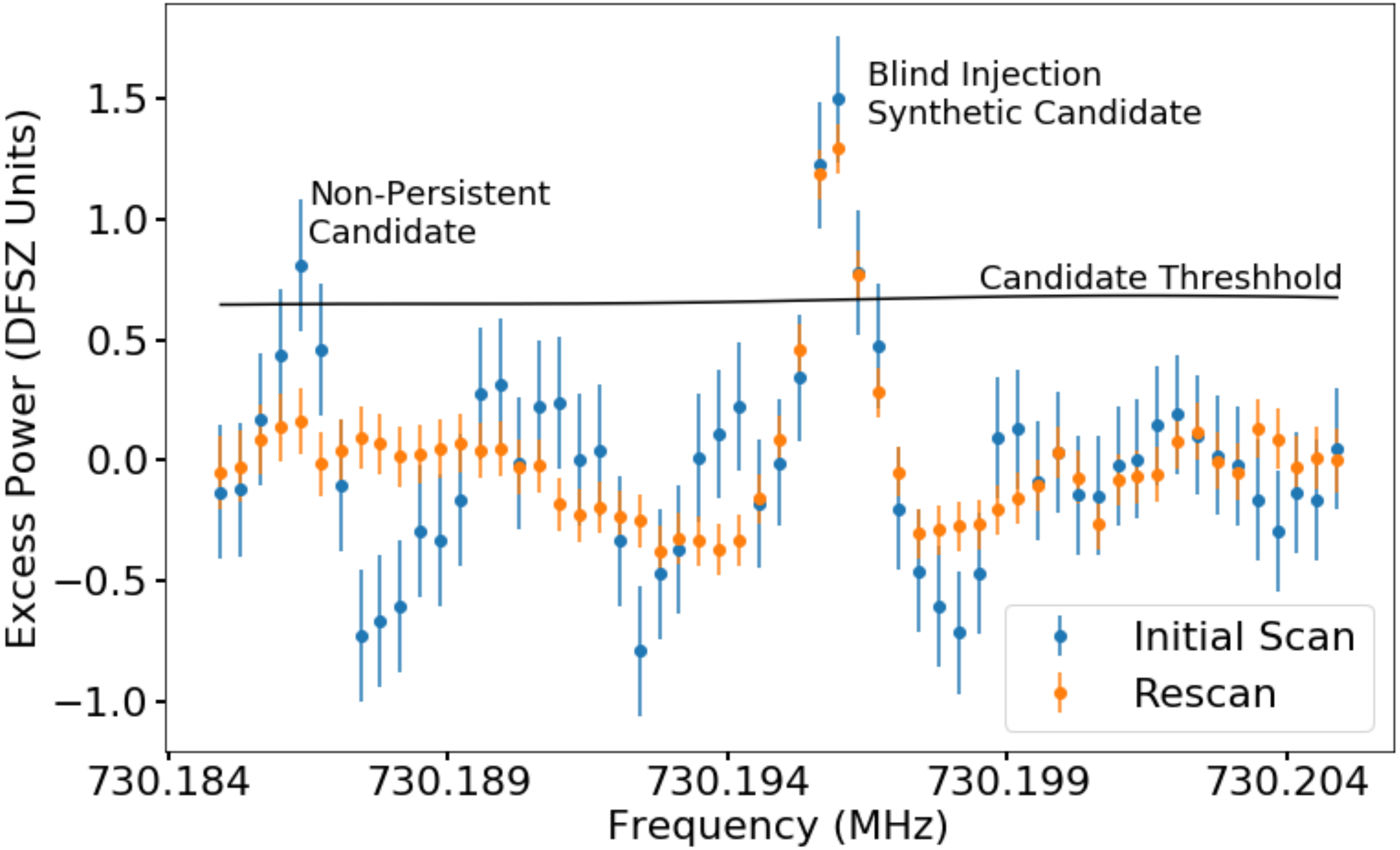
Noise Characterization



- 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

Hardware Synthetic Axion Injections



Analysis

Two types of analysis:

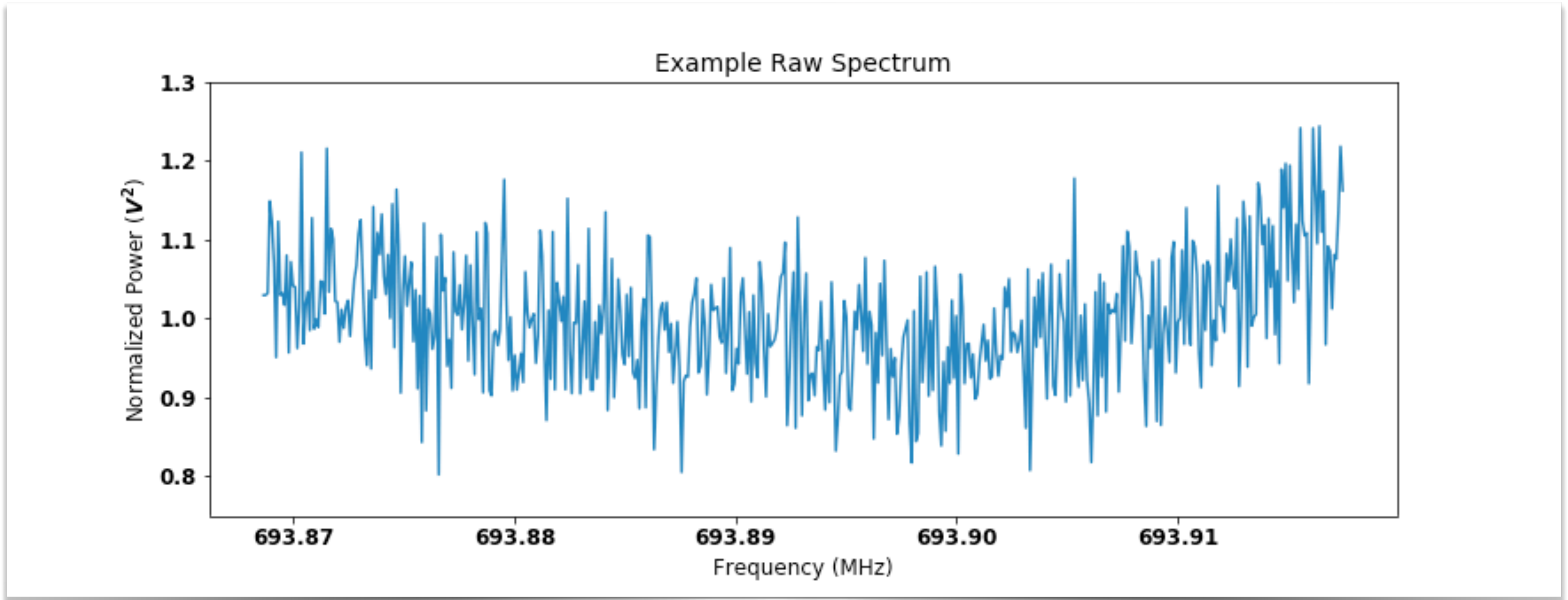
- Medium-resolution analysis (described here):
  - Can detect persistent axion signal.
  - Assumes isothermal velocity distribution.
  - 100 Hz bin width.

- 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:

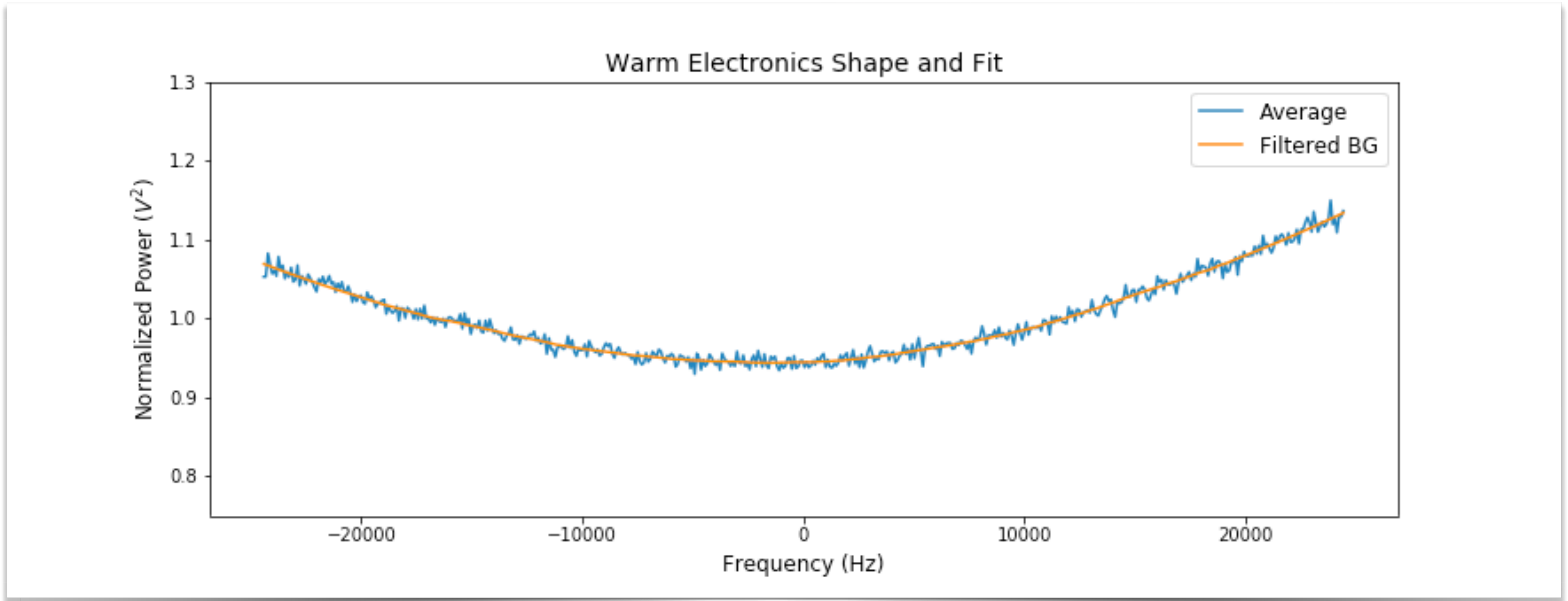
- ~50 kHz wide raw spectra, 100 Hz bins



Analysis

Baseline Removal:

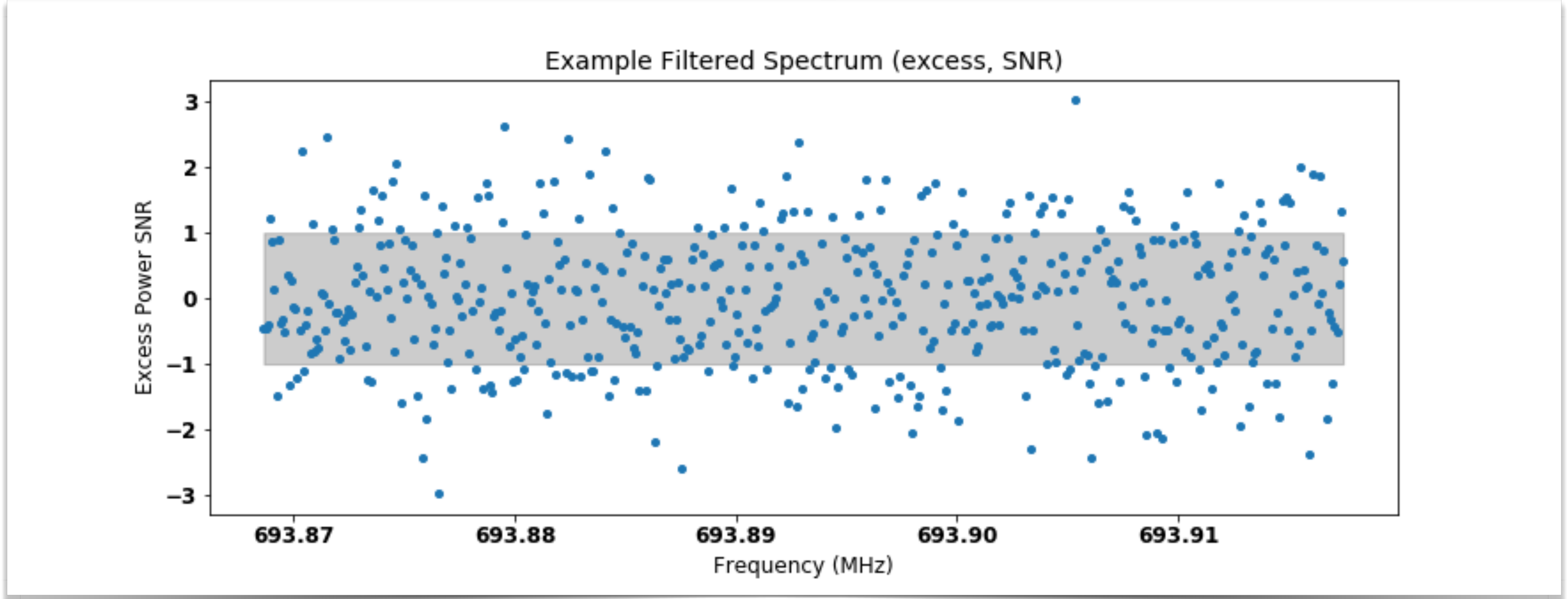
- The warm electronics shape is identified by averaging and filtering off-resonance scans.



Analysis

Raw spectrum processing:

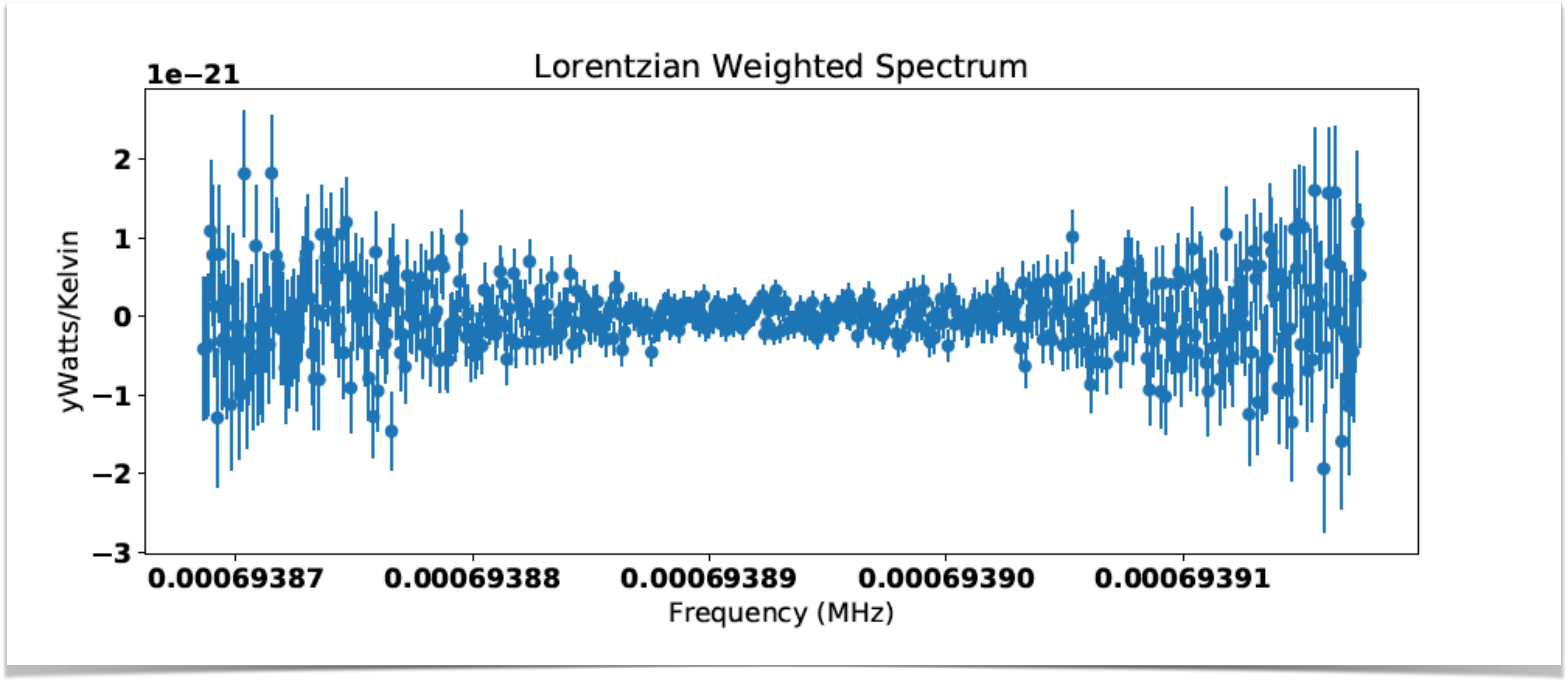
- Raw spectra are divided by the receiver shape and filtered
- Subtract 1 from each bin to obtain ~Gaussian white noise



Analysis

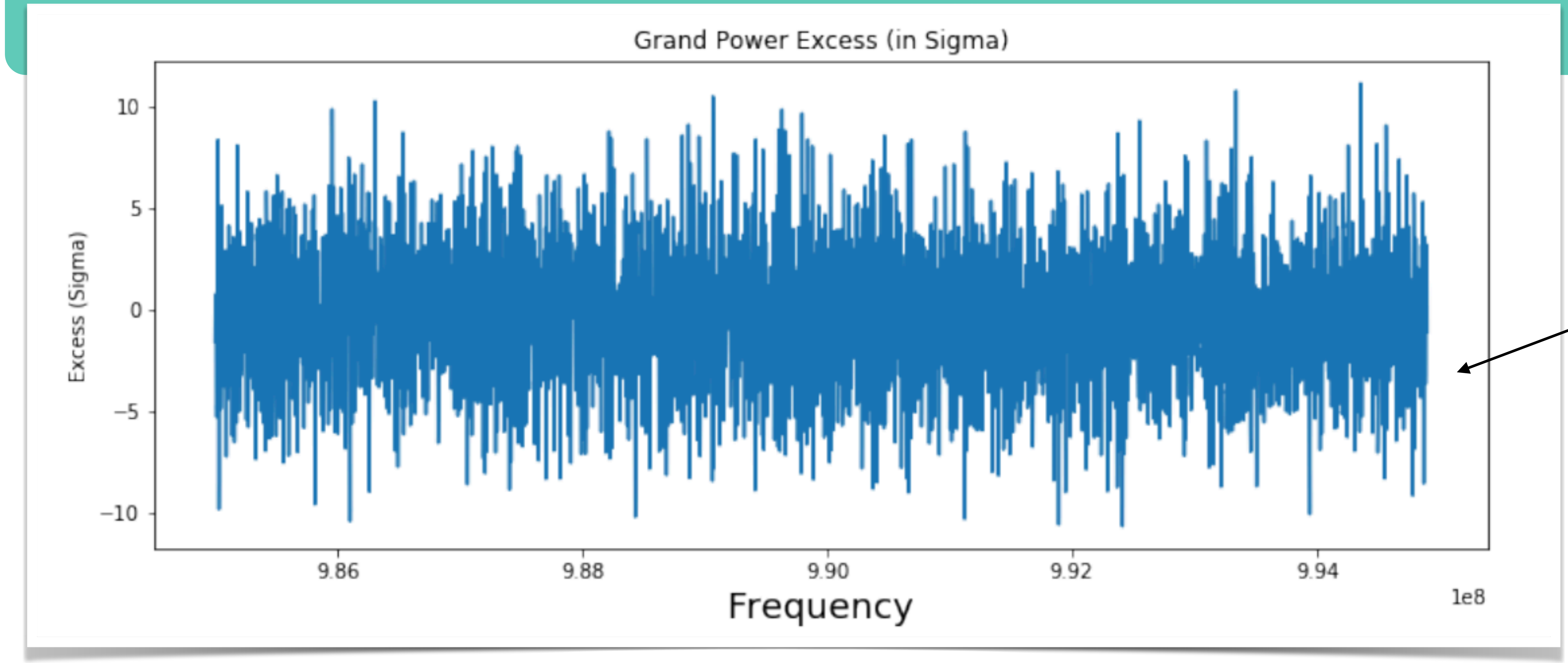
Raw spectrum processing:

- 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

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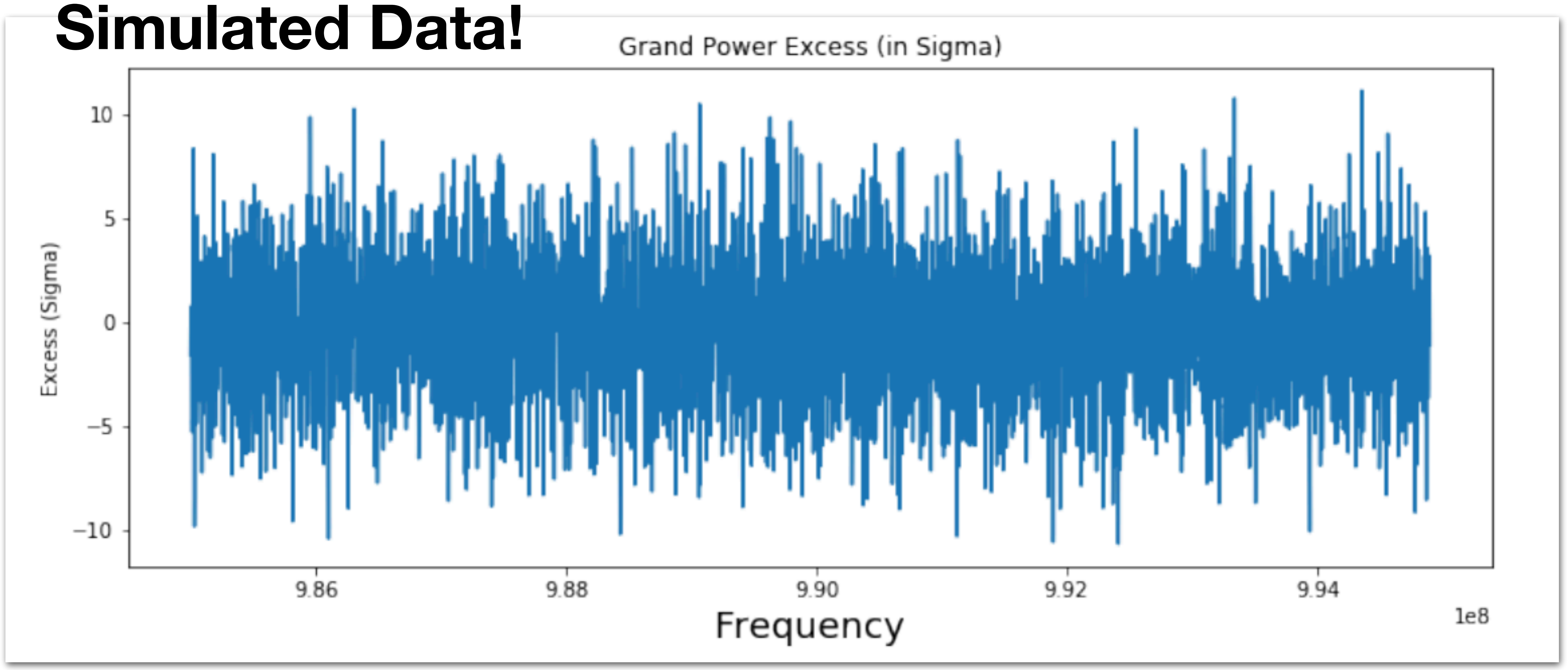
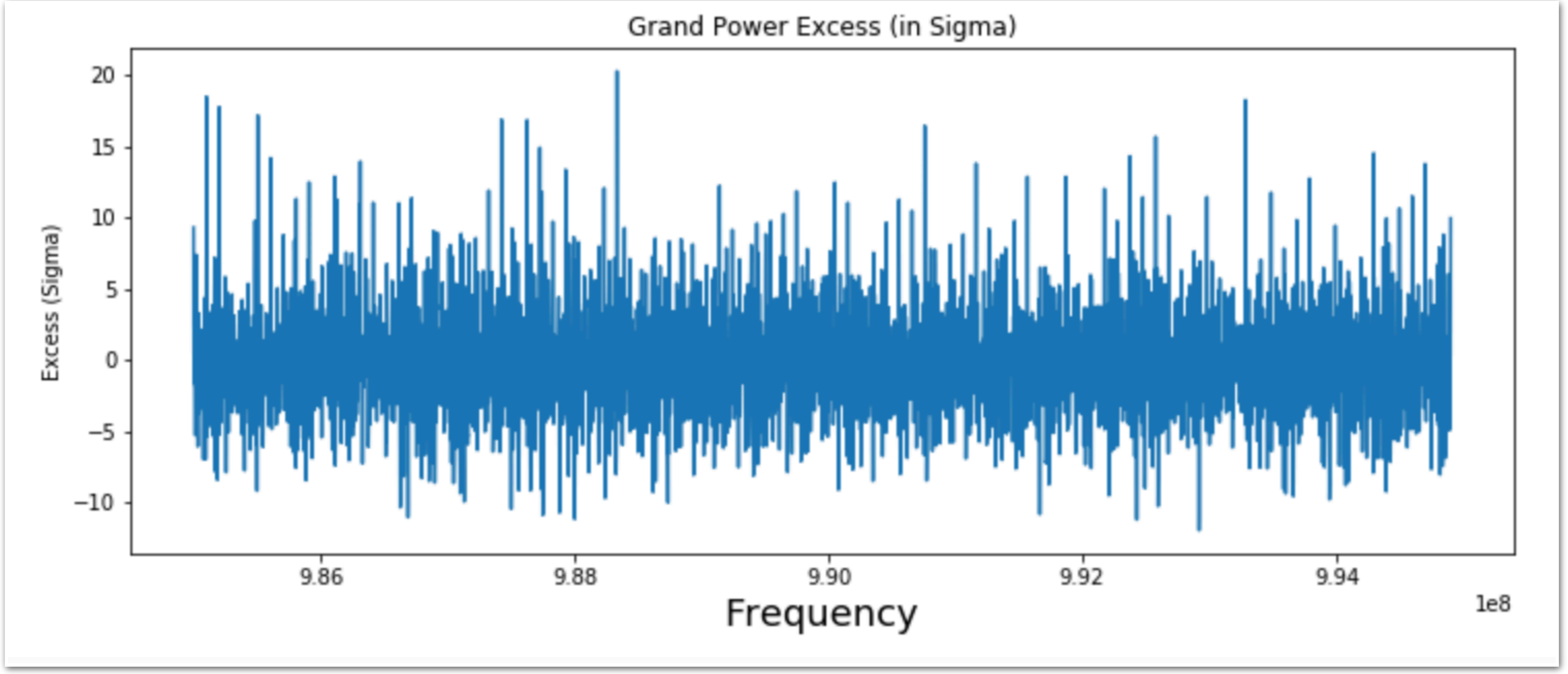
Software Synthetic Injections

Simulated Data!



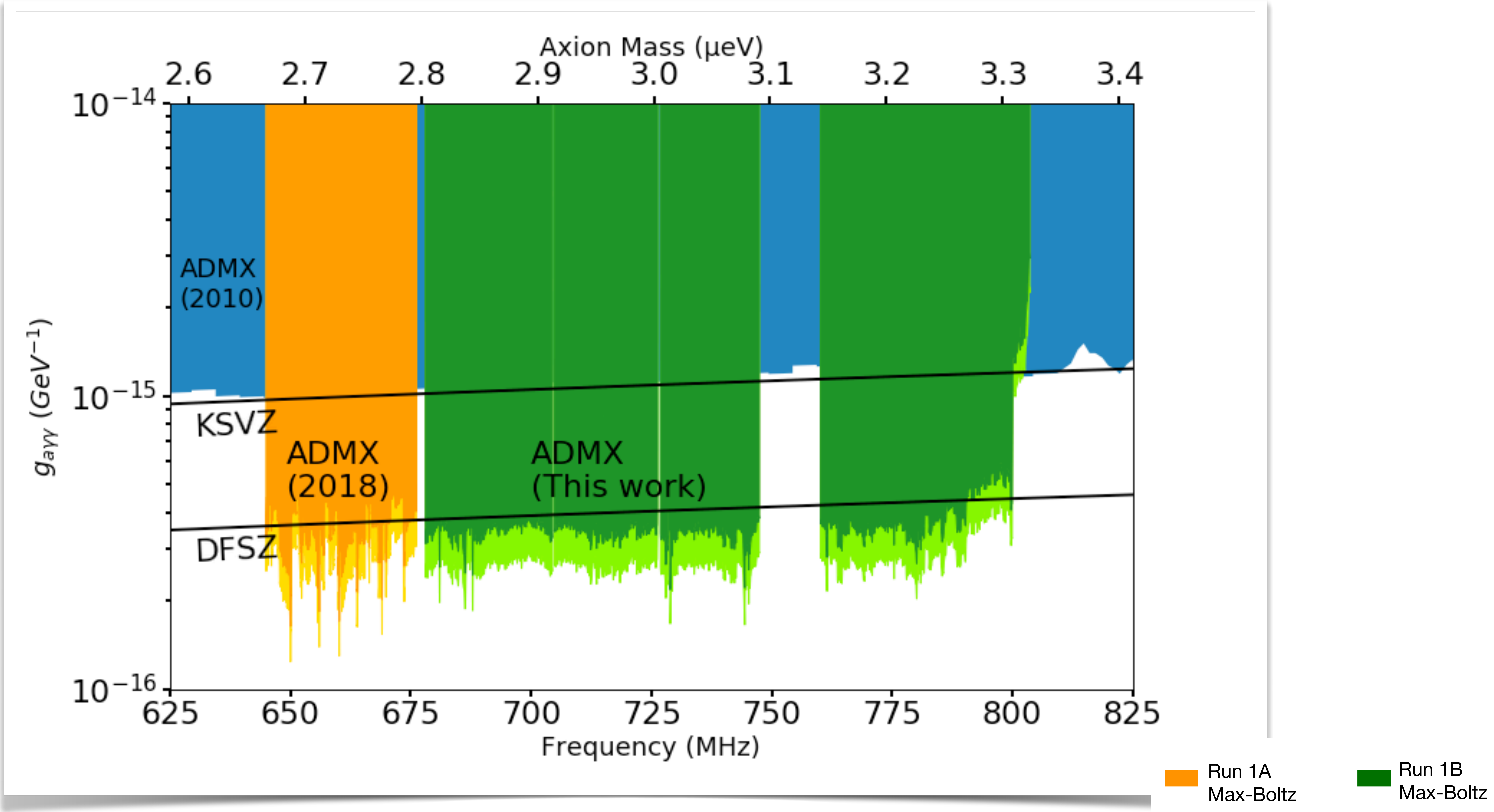


- Used to determine our detection efficiency and verify our analysis
- Developed by undergraduate student Hima Korandla, with my supervision
  - Simulated analysis data
  - Software synthetic injections for Run 1C

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

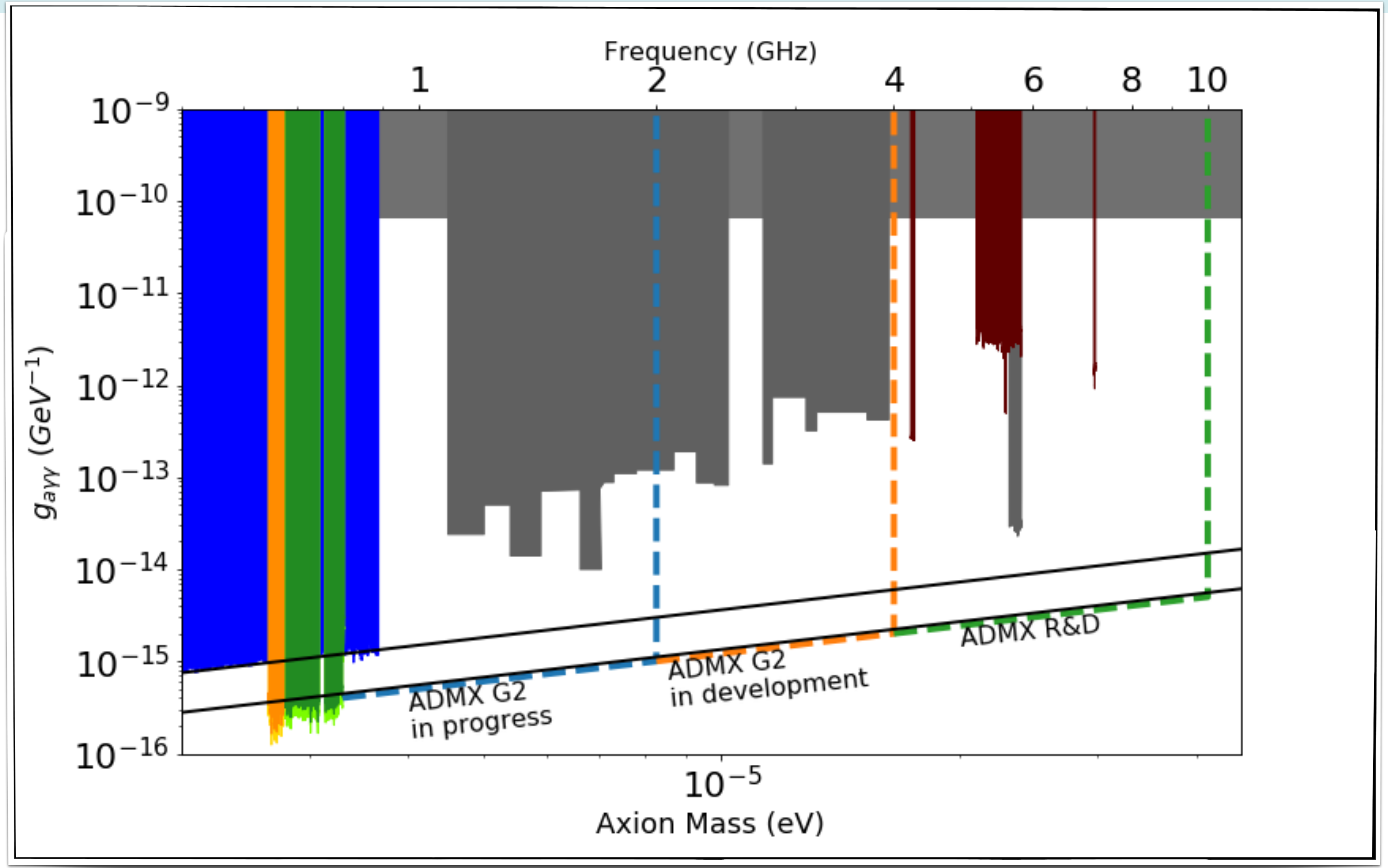


Extended Search for the Invisible Axion with the Axion Dark Matter Experiment

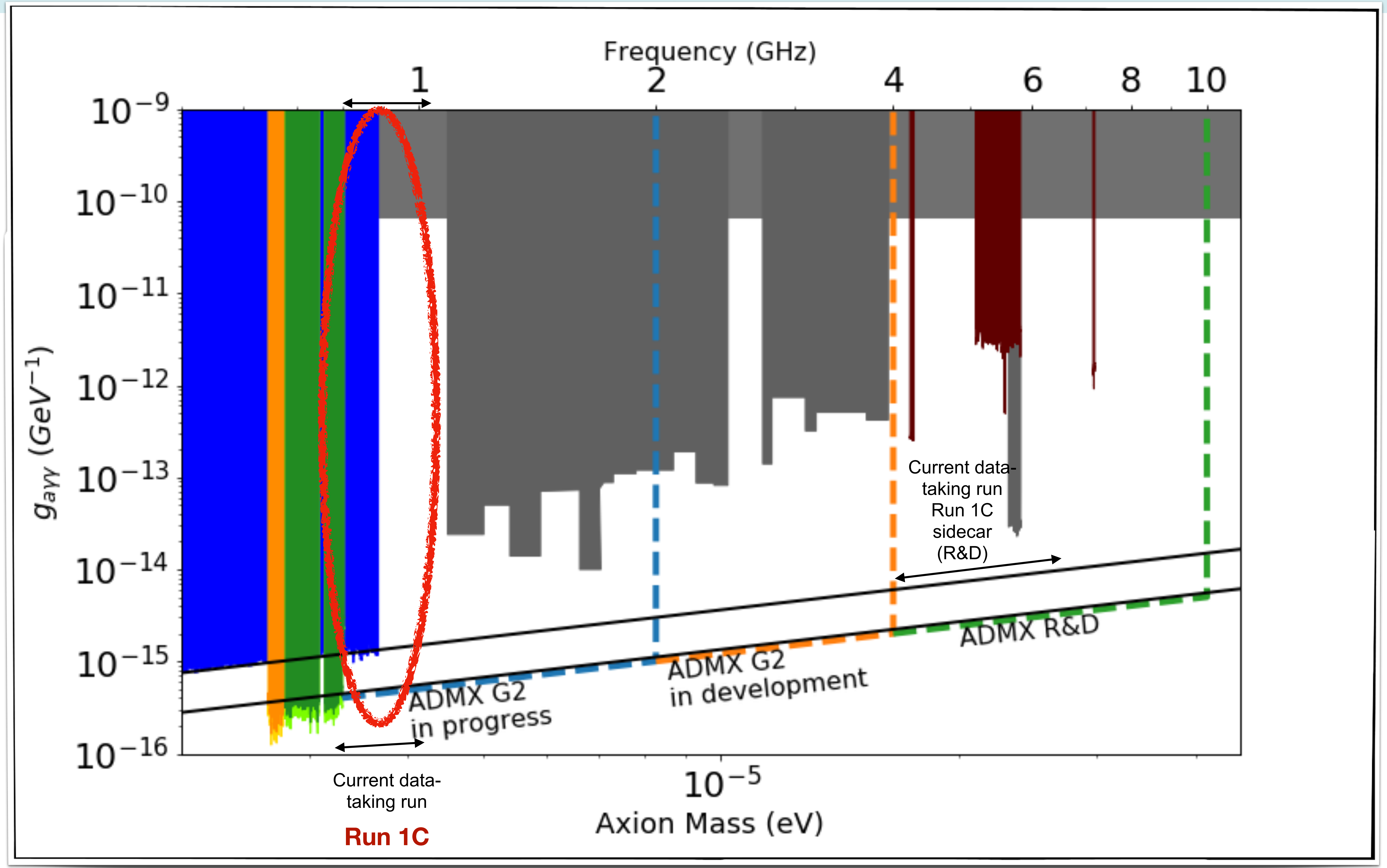
T. Braine et al. (ADMX Collaboration)

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

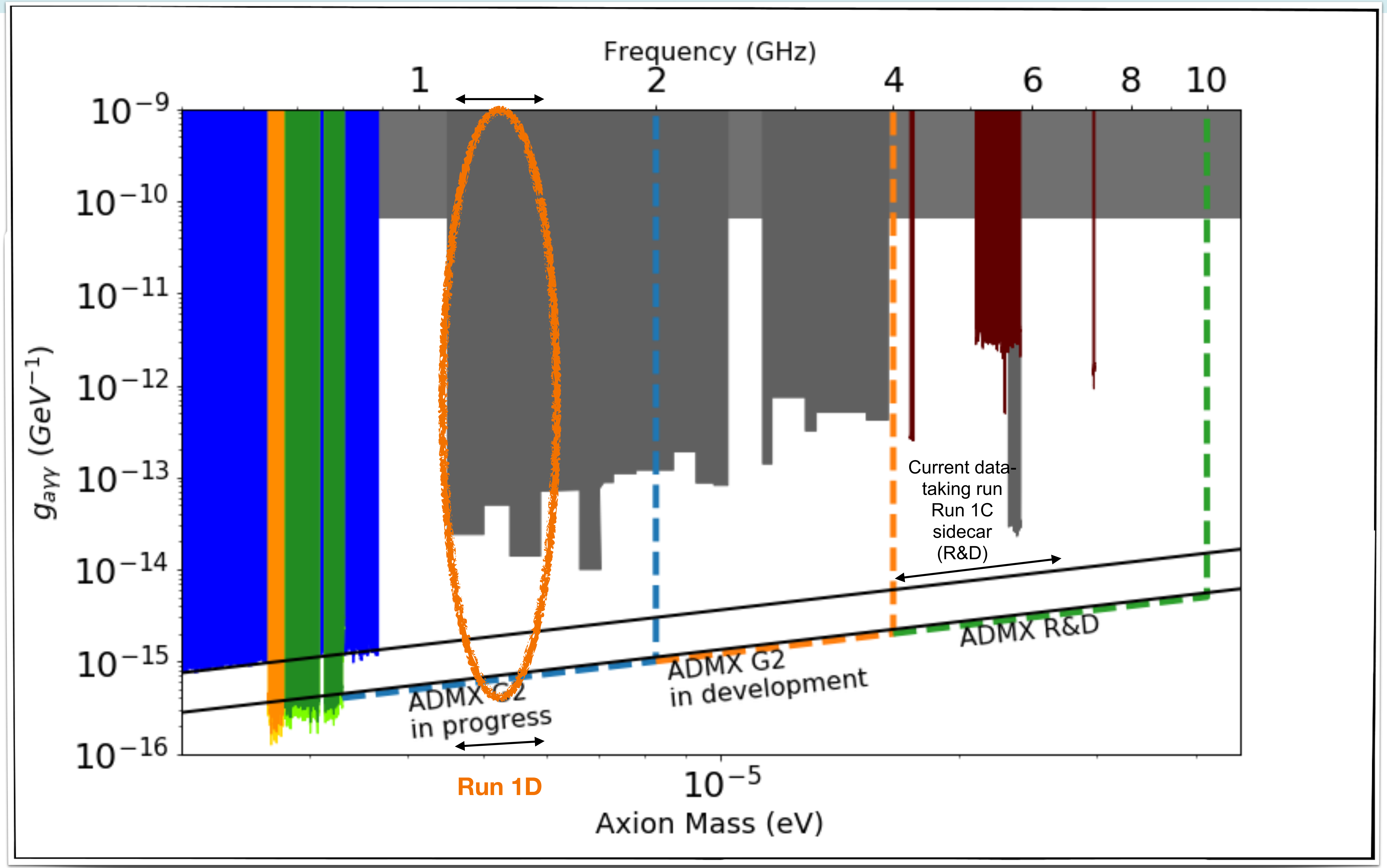
Projected ADMX Sensitivity



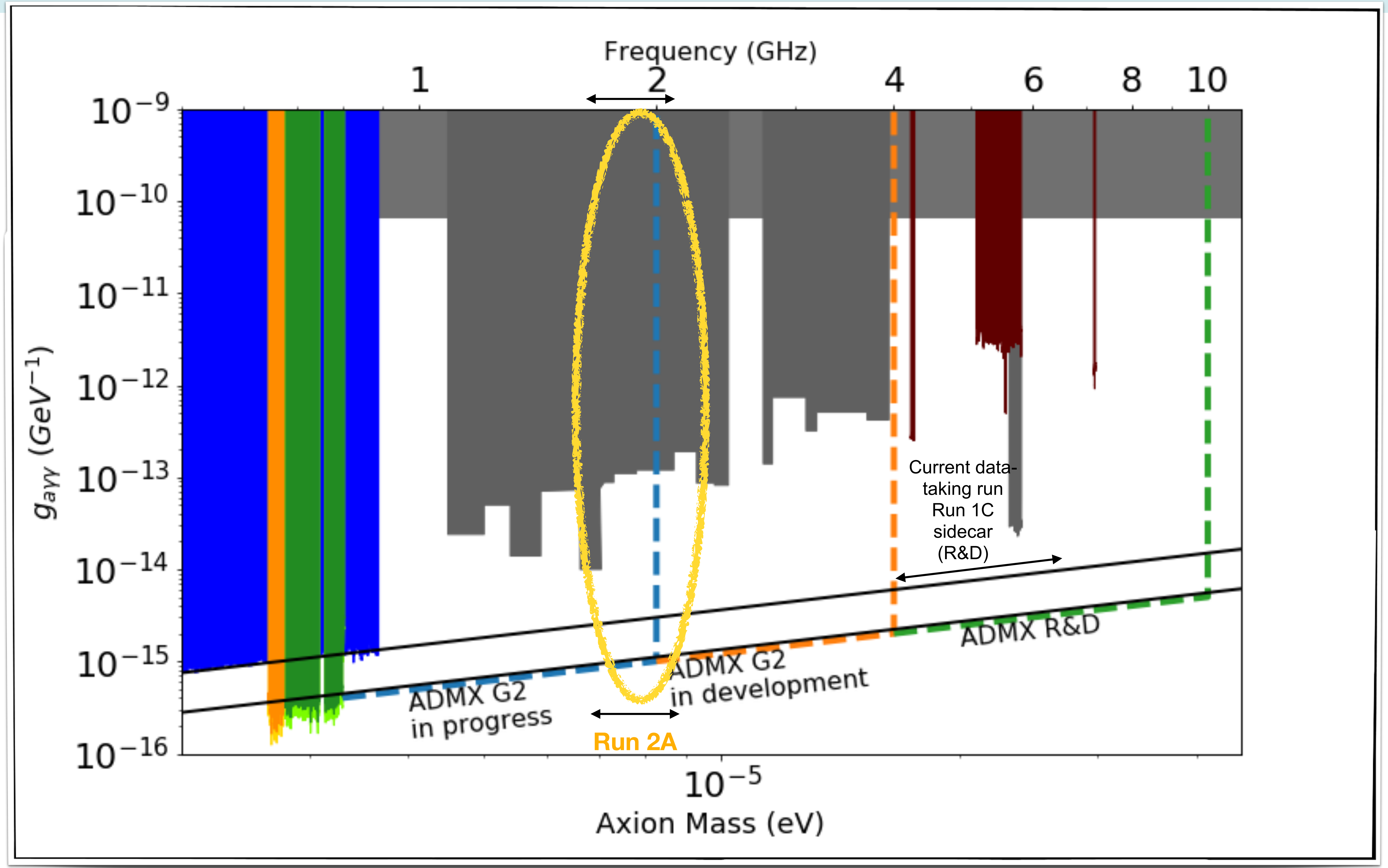
Projected ADMX Sensitivity



Projected ADMX Sensitivity

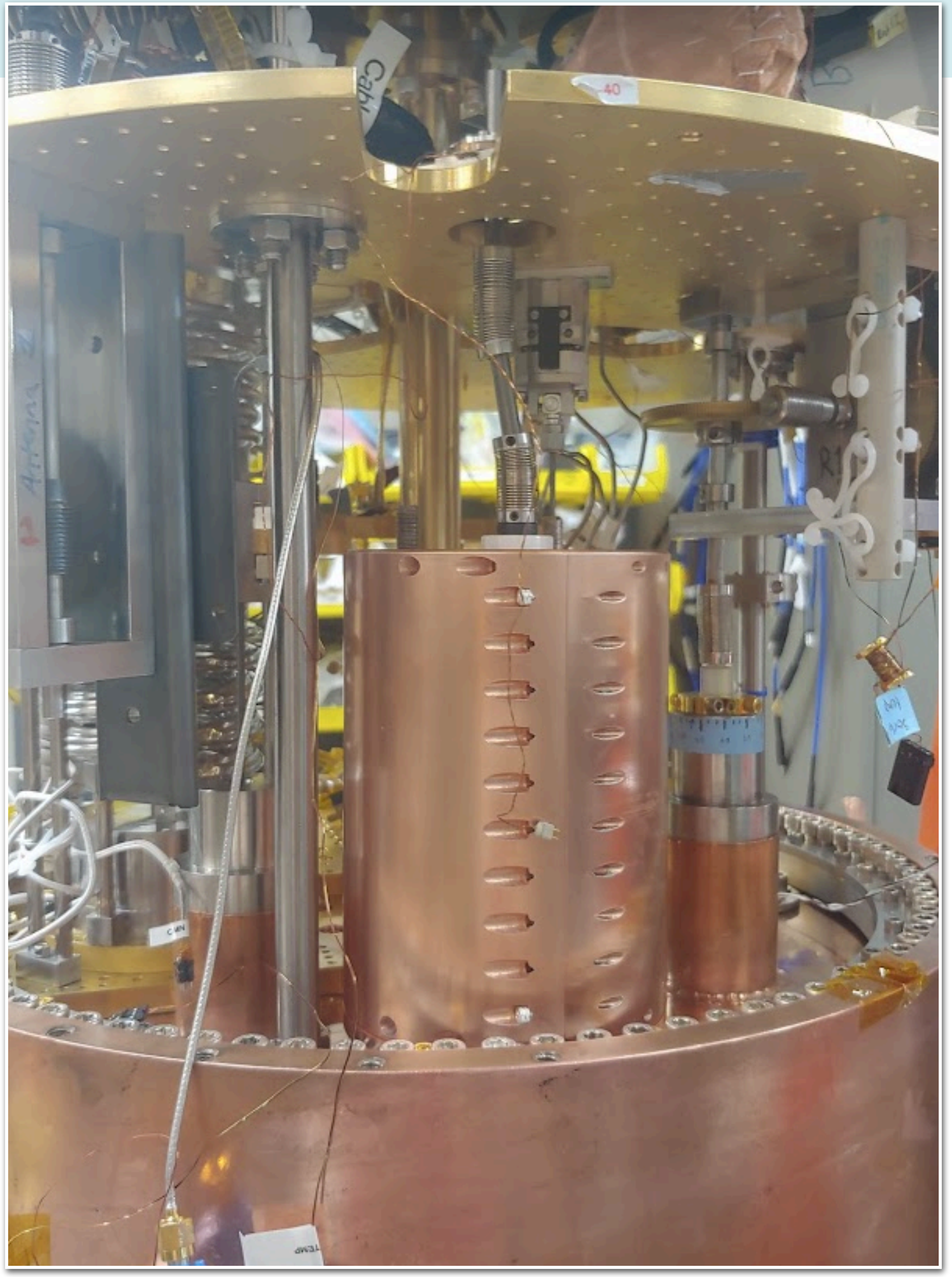


Projected ADMX Sensitivity



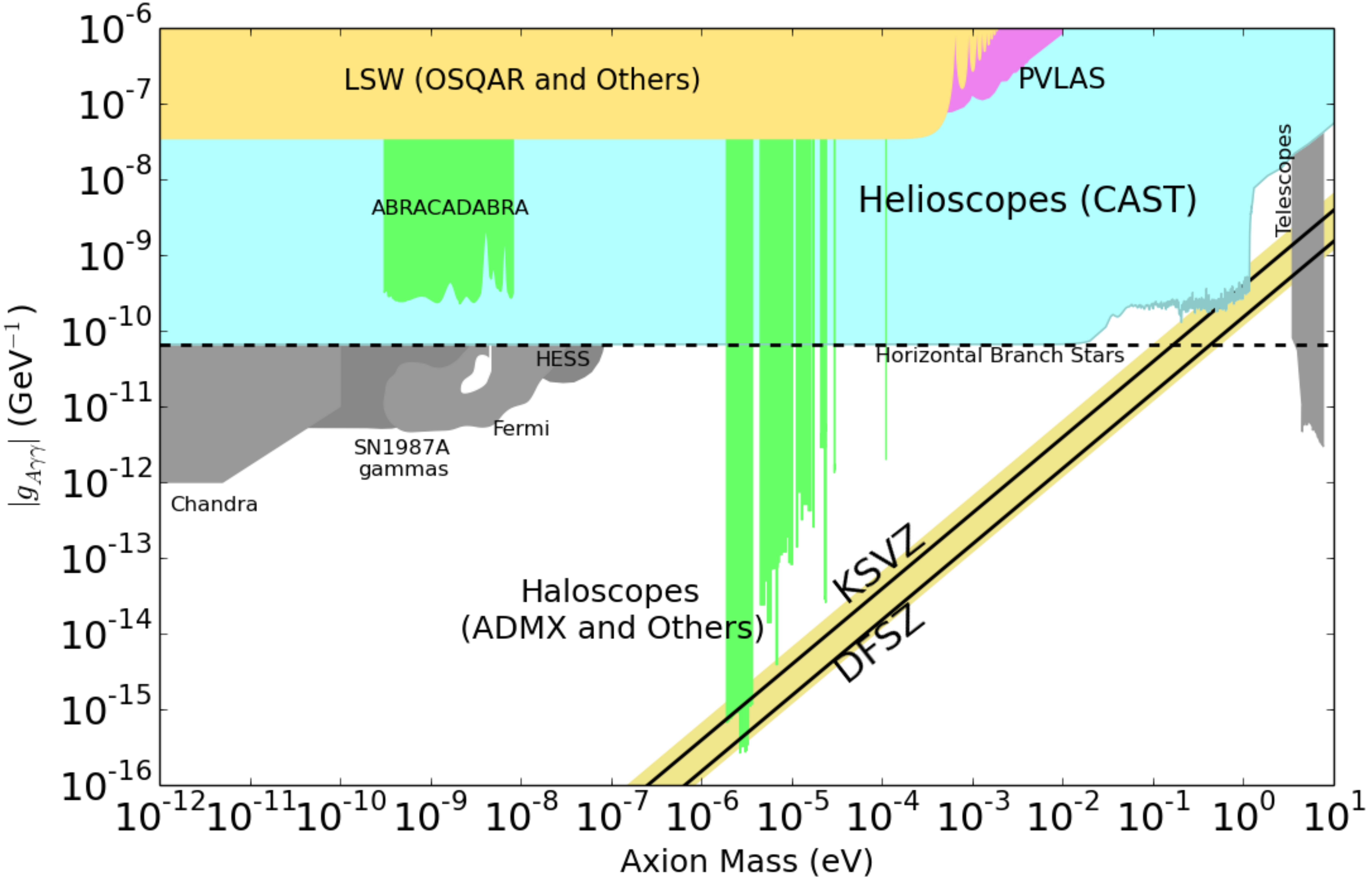
Sidecar Cavity R&D

- Smaller prototype cavity that sits within ADMX insert
- Testbed for new quantum electronics and piezo tuning mechanisms
- Using a traveling wave parametric amplifier (TWPA) in current incarnation
    - Benefits of TWPA: Broadband gain. Reduces need to tune with cavity. No current bias. Pump bias only.



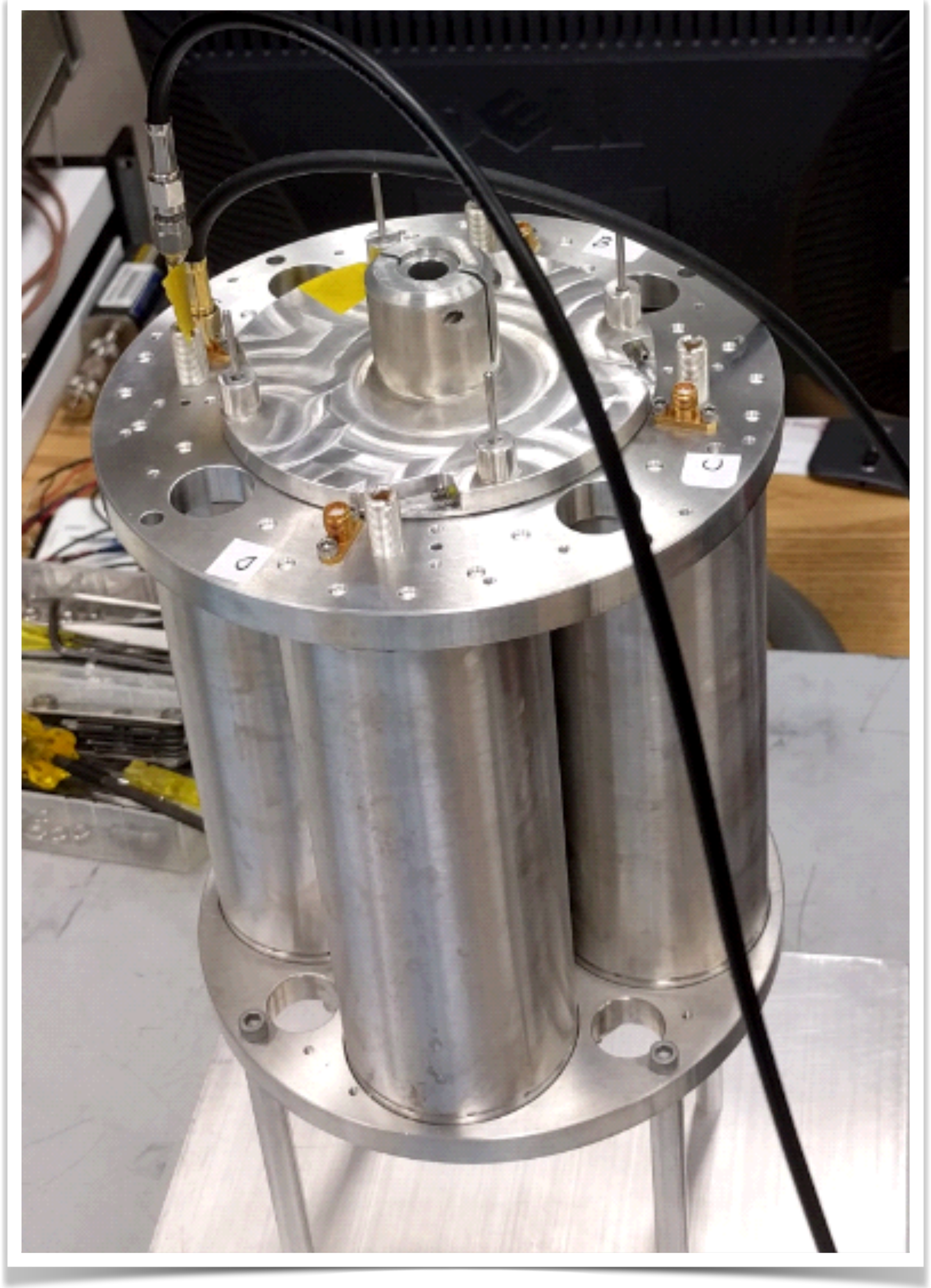
Sidecar sitting on top of the main cavity for Run 1C

DOI: 10.1126/science.aaa8525


LSW (OSQAR and Others)
PVLAS
Helioscopes (CAST)
ABRACADABRA
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}

Higher Frequencies

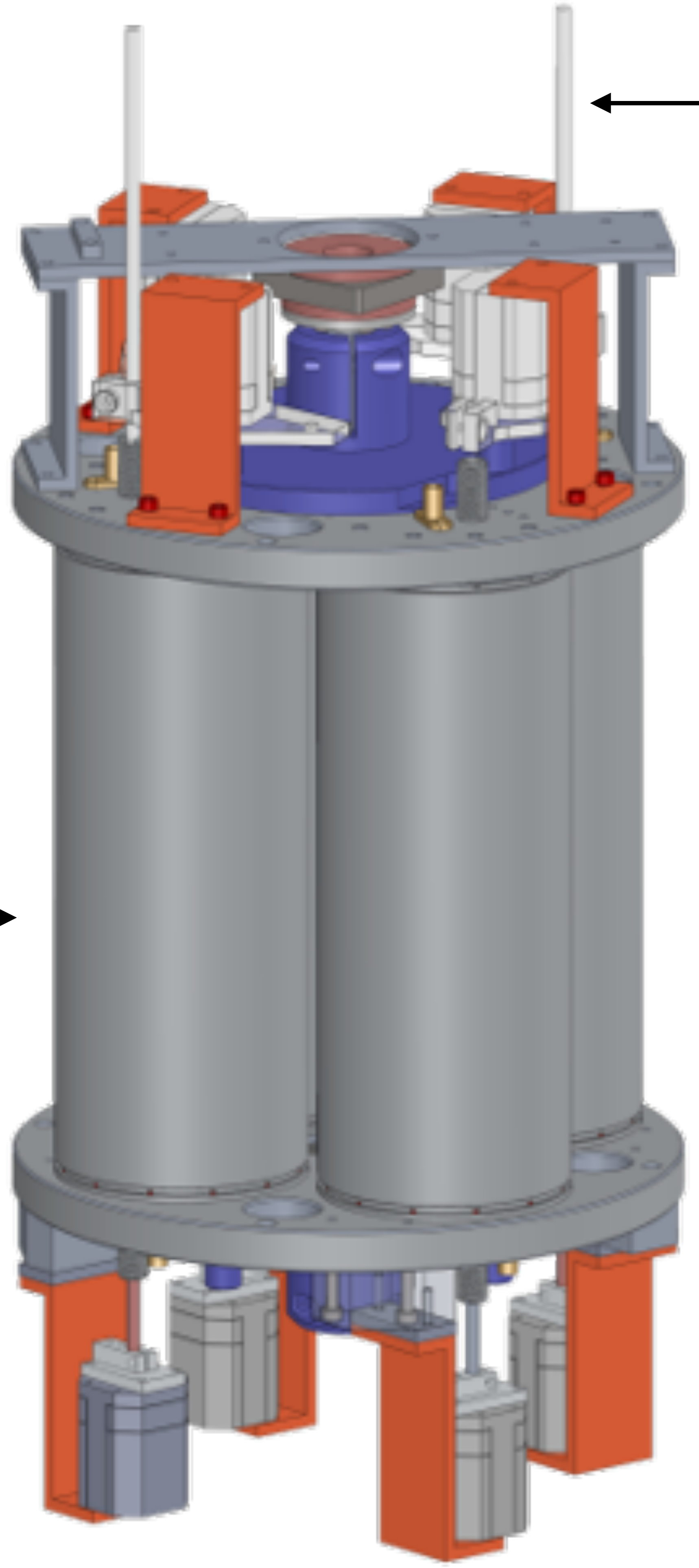
- Scaling gets challenging
- One idea: Power combine multiple cavities and tune synchronously
- Challenges:
    - Cavity frequencies must be locked together
    - Increase in complexity



ADMX Run 2A

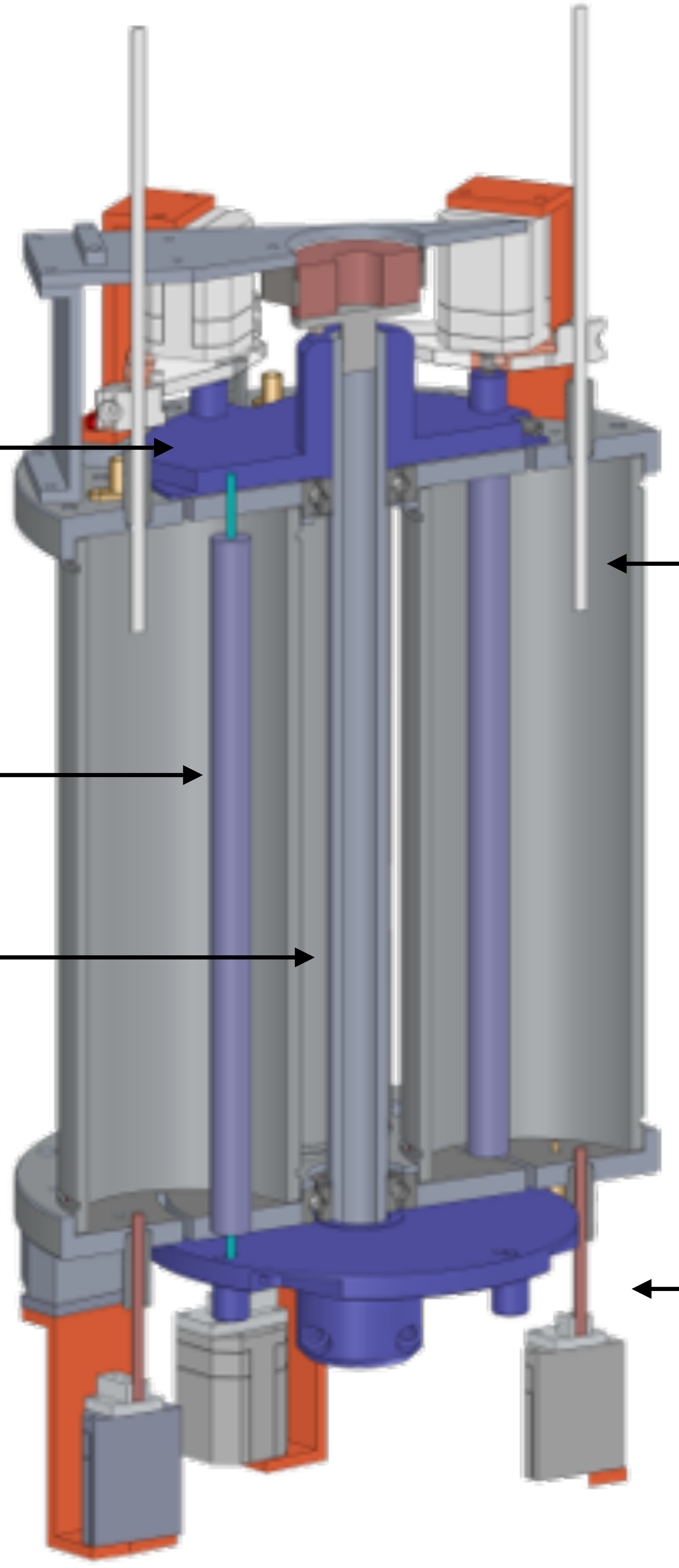
- 4 cavity array with common rotor. Frequency fine-tuned with sapphire mounted to linear stages
- N cavities combined in phase = sqrt(N) SNR improvement
- Scan rate (SNR)^2
- 1.4-1.8 GHz frequency range (Run 2A)
- Volume ~76 liters
- Q~130,000

Prototype Study



Images courtesy of Jihee Yang

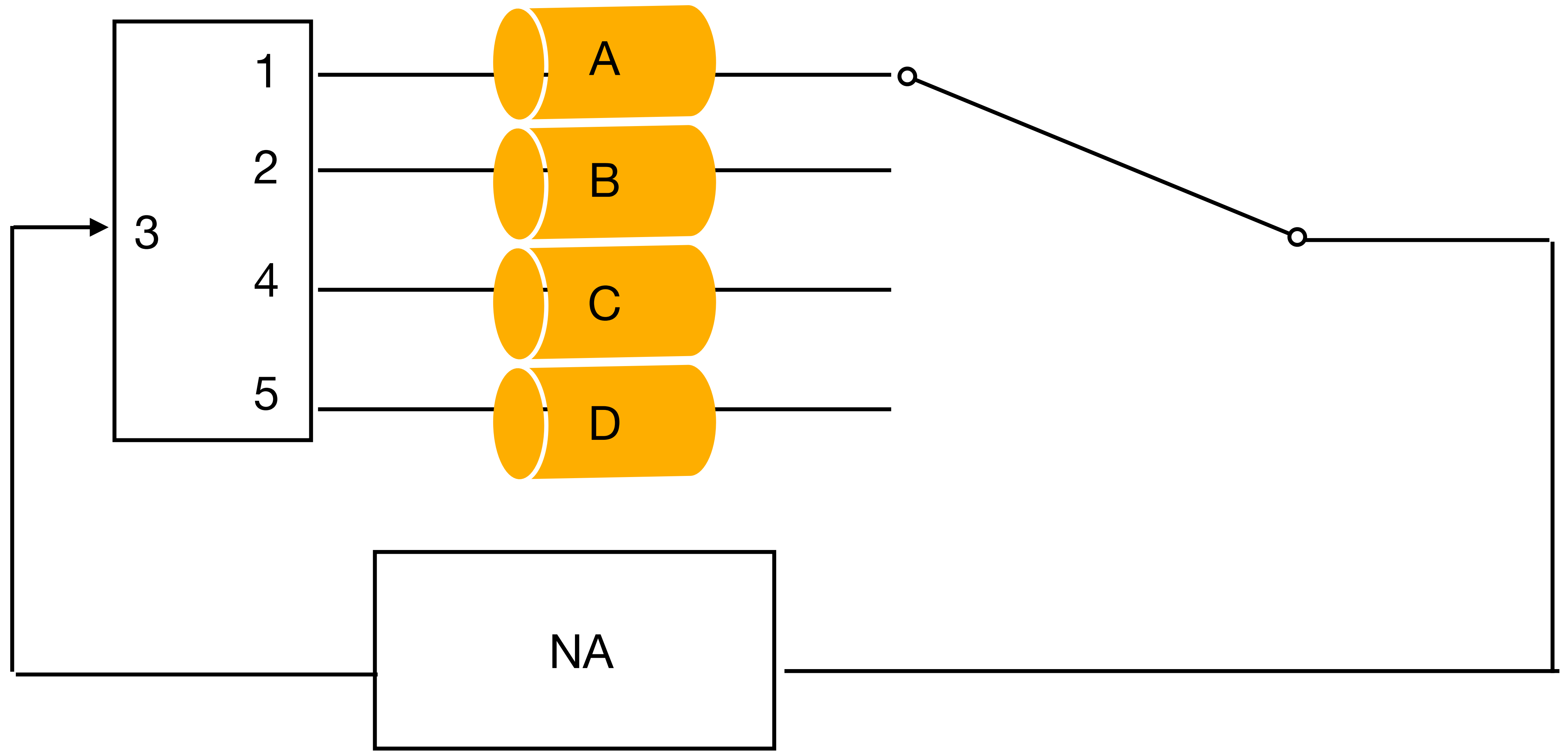
Prototype Study



Images courtesy of Jihee Yang

Run 2A System

- UF Prototype Study
    - Two versions of the 4 cavity design
    - Tested assembly fit/motion
    - Piezo actuator performance
    - Acquire mode map
    - Frequency tuning/locking
    - Antenna tuning
    - Quality Factor



Images courtesy of Jihee Yang

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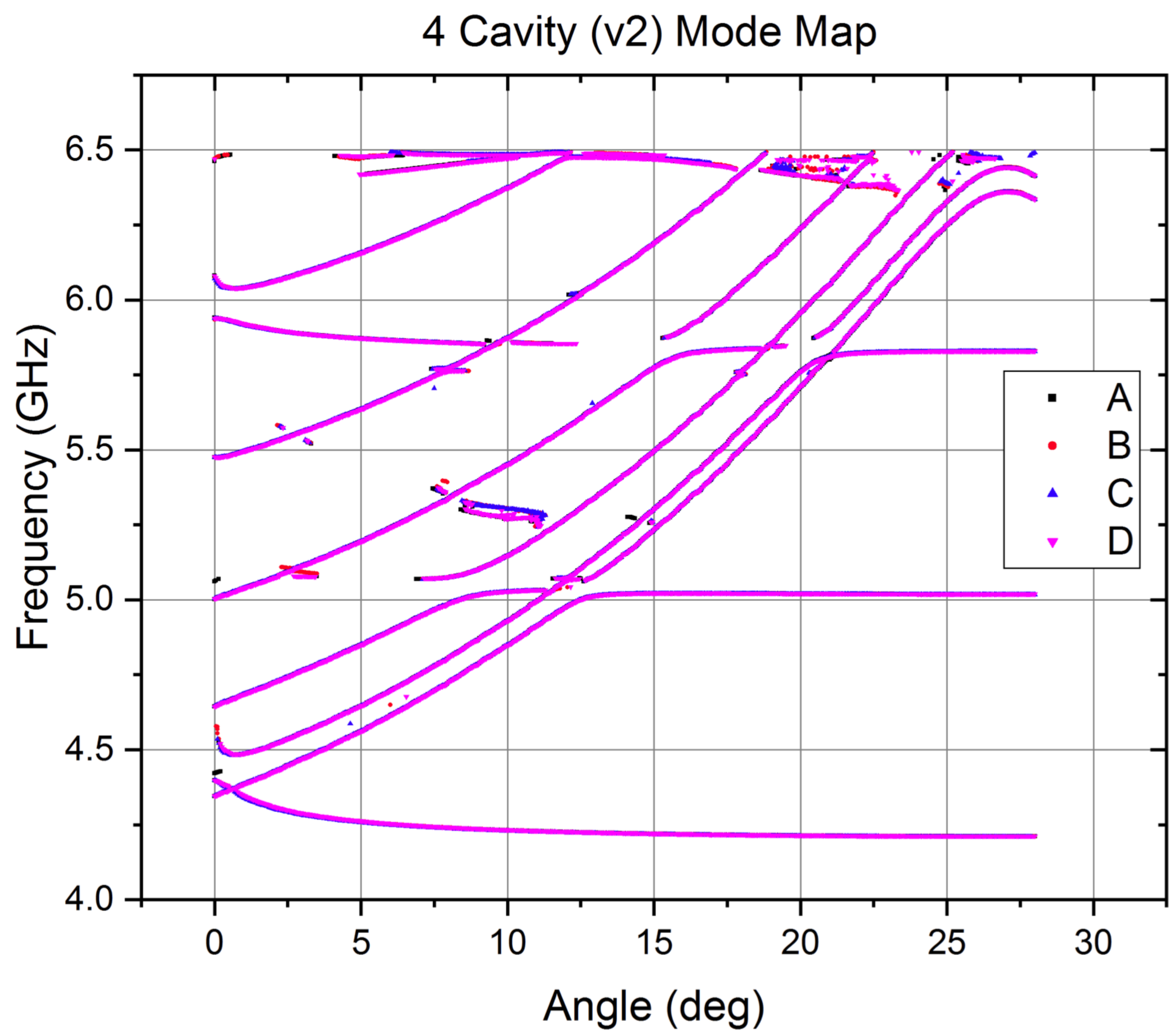
Two Versions Developed

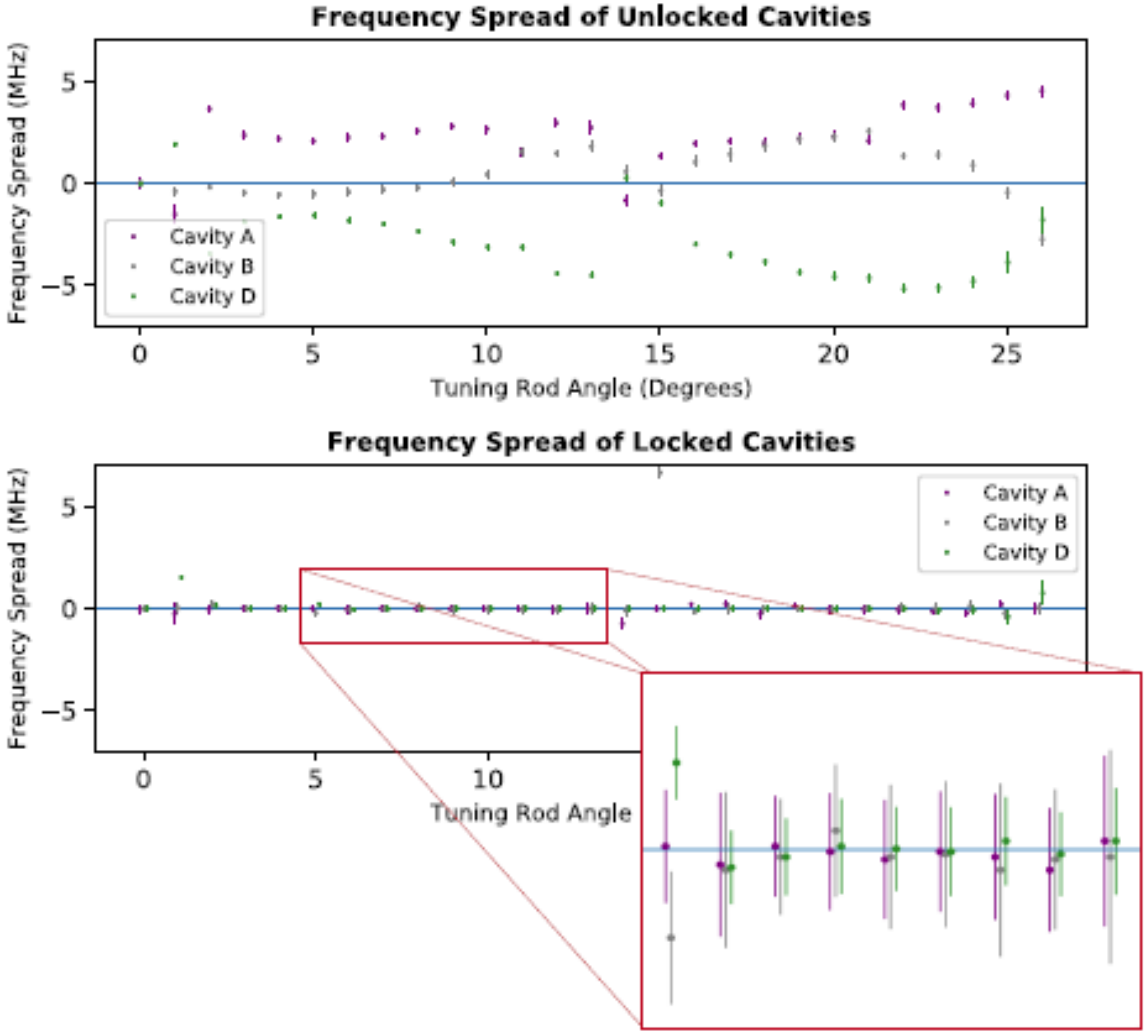
	Prototype V1	Prototype V2
Wheel Plate	No flexures	Flexures
Vertical Gap btw Course Rod and End Cap	0.02” each	0.005” each
Material	Al6061	Al6061+99.99% Al plated
Cavity Length	6.925”	7.126”

Courtesy of Jihee Yang

Run 2A System

- Frequency lock the cavities
- Room measurements at UF
- Locking protocol at PNNL
- Software implementation at PNNL
- Cryo-testing will be at FNAL

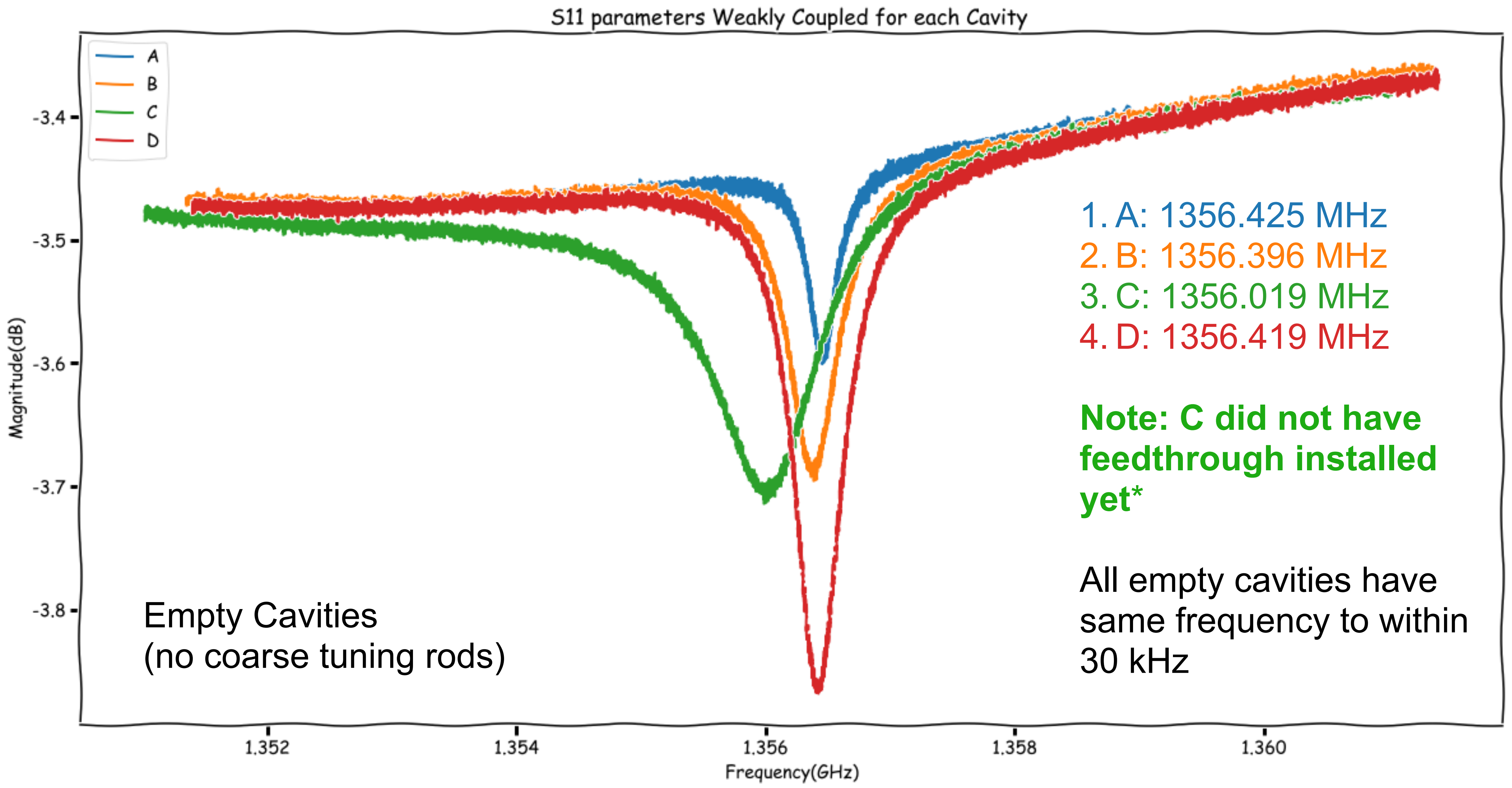




Images courtesy of Jihee Yang

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 →

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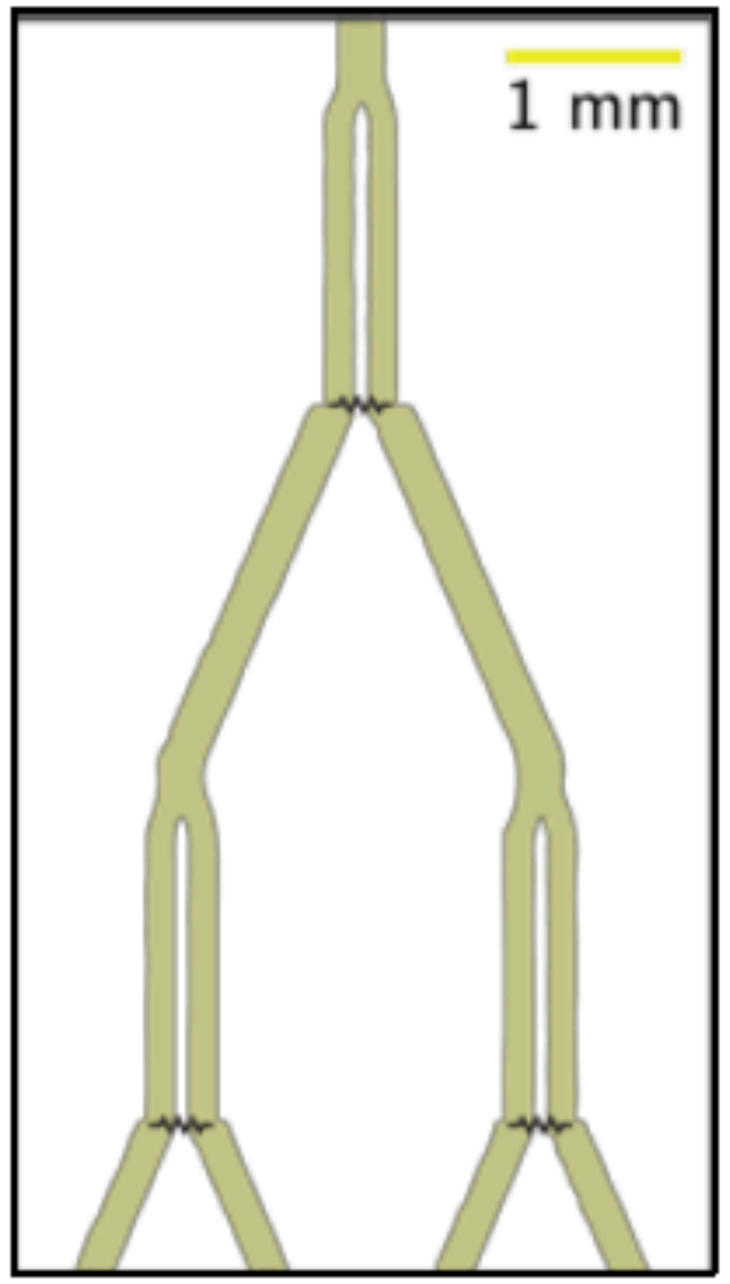
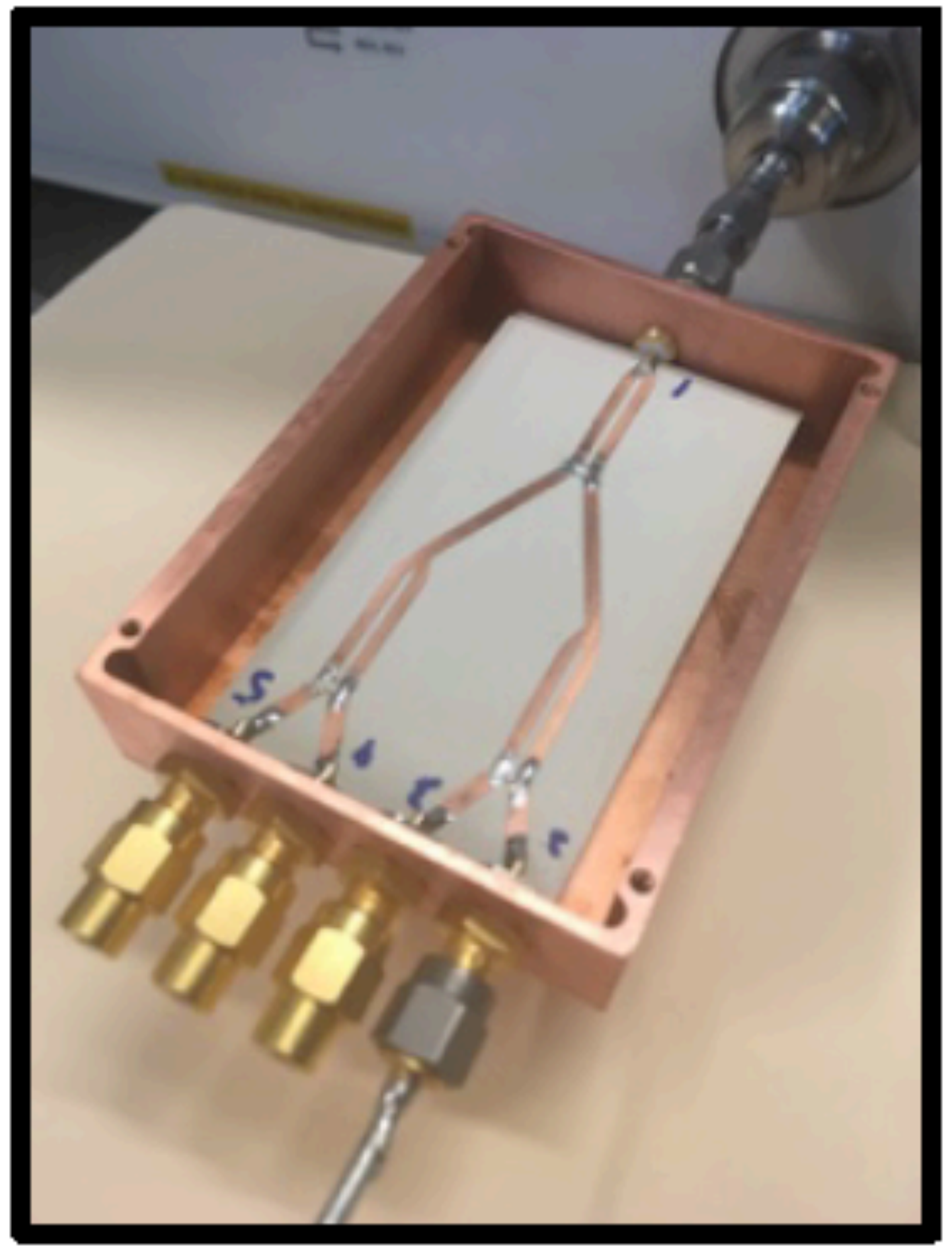
Run 2A System

- Quantum electronics testing at WUSTL
- Circulator Testing, JPA Testing
- Custom Power Combiners
- Updated Quantum Electronics Package
- FNAL Cryo Teststand





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ADMX Collaboration Fermilab Collaboration Meeting in 2018

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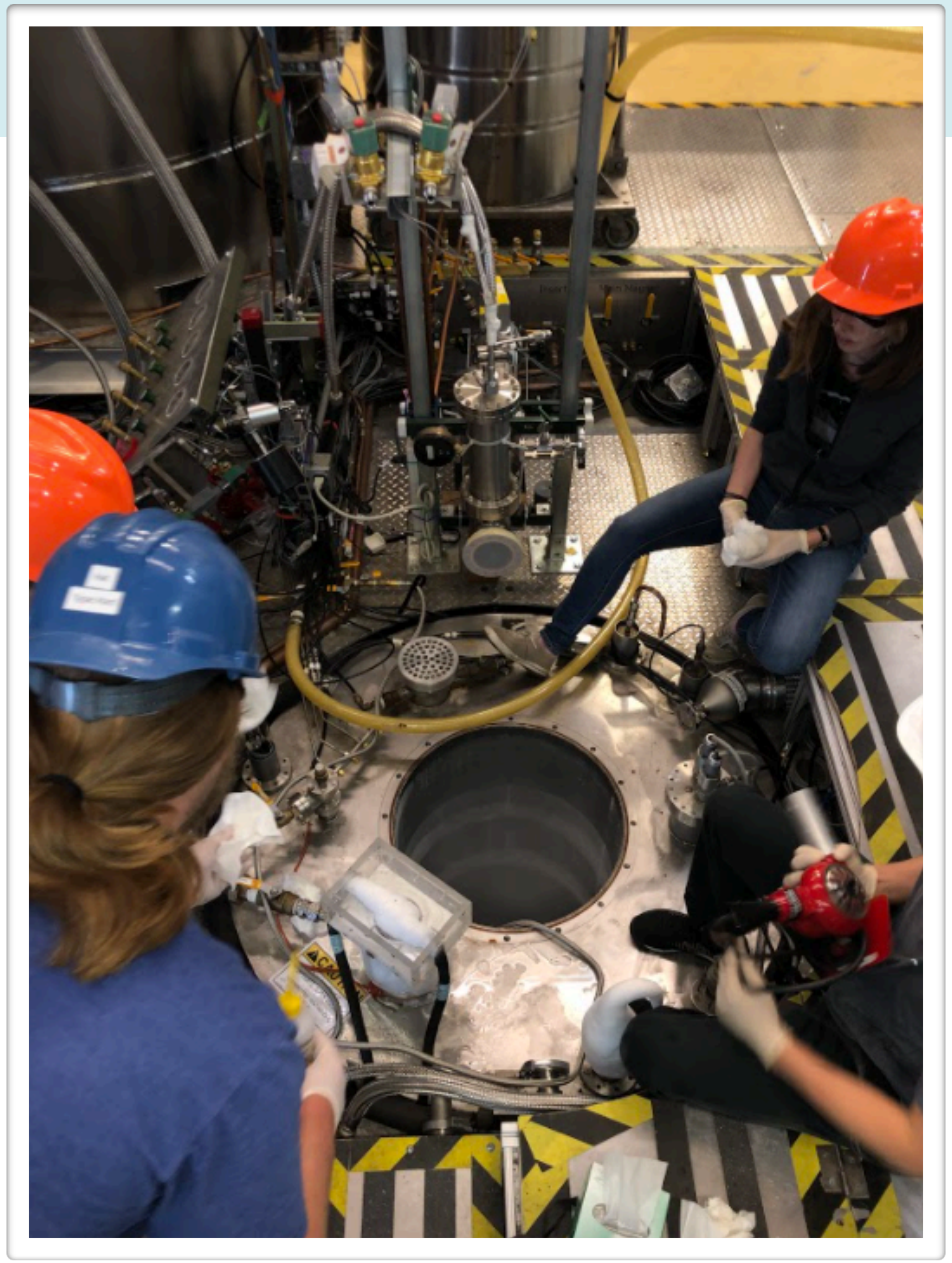
Conclusions

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!