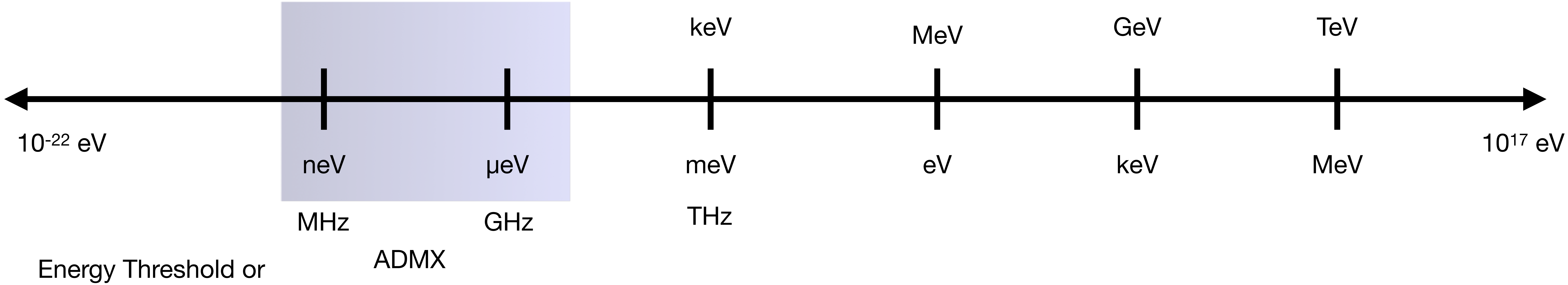
To see 85% of the World in a Grain of Sand: Search for wave-like dark matter in the ADMX Run1C dataset

Joint Workshop Session for the Australian Research Council Centre of Excellence for Engineered Quantum Systems and Dark Matter Particle Physics

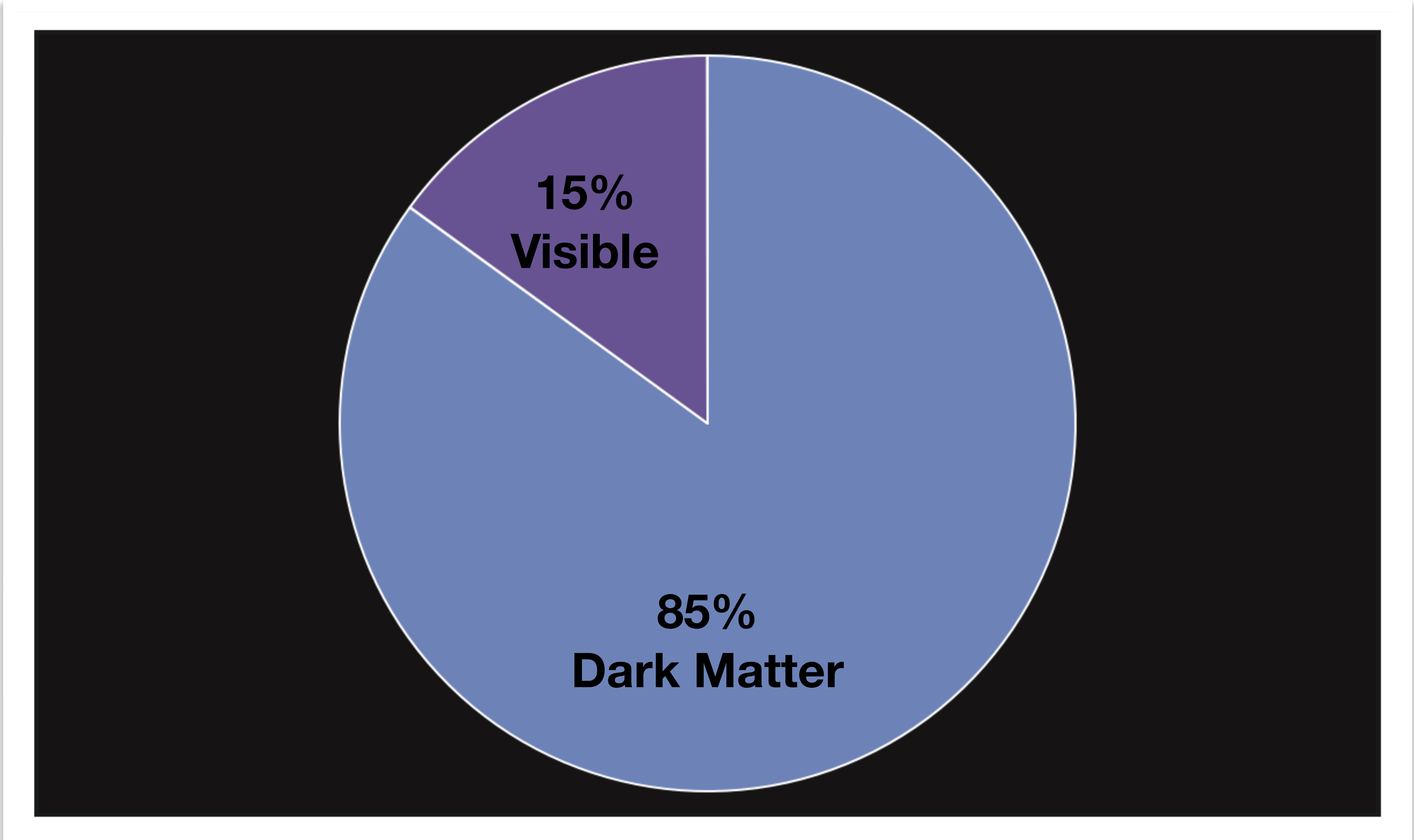
Chelsea Bartram

Sense of scale

DM Scattering Mass



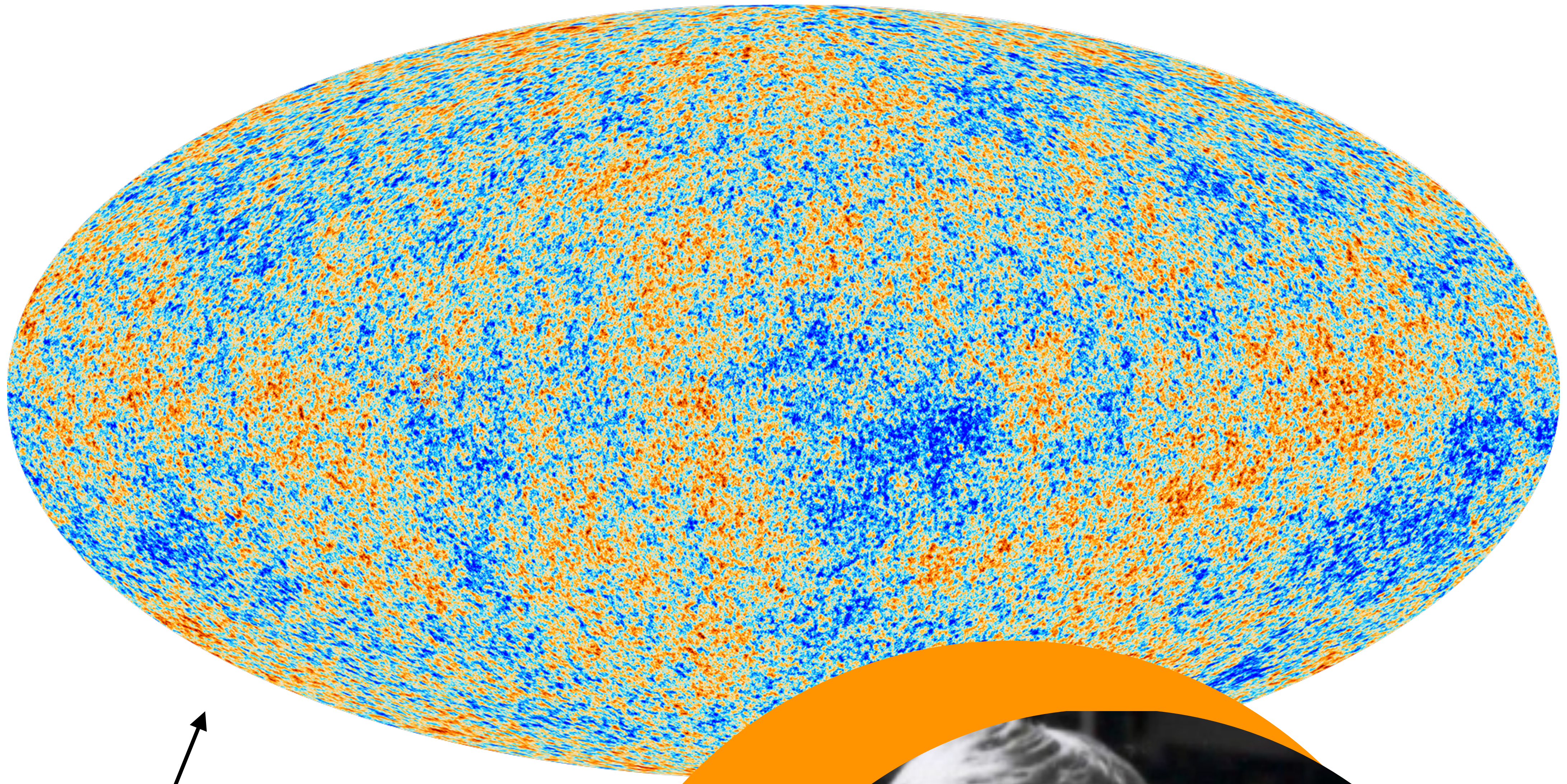
Energy Threshold or
Absorbed DM Mass



What is the dark matter?

'Invisible' matter that would be able to explain:

- Anisotropies in the cosmic microwave background
- Rotation curves of galaxies
- Behavior of galaxy cluster collisions
- Matter Radiation Fluctuations
- Primordial nucleosynthesis
- Gravitational lensing
- Baryon Acoustic Oscillations



ESA and the Planck Collaboration

Characteristics of the dark matter:

- Cold (non-relativistic)
- Feebly-interacting
- Non-baryonic
- Gravitationally-interacting
- Very stable

Vera Rubin

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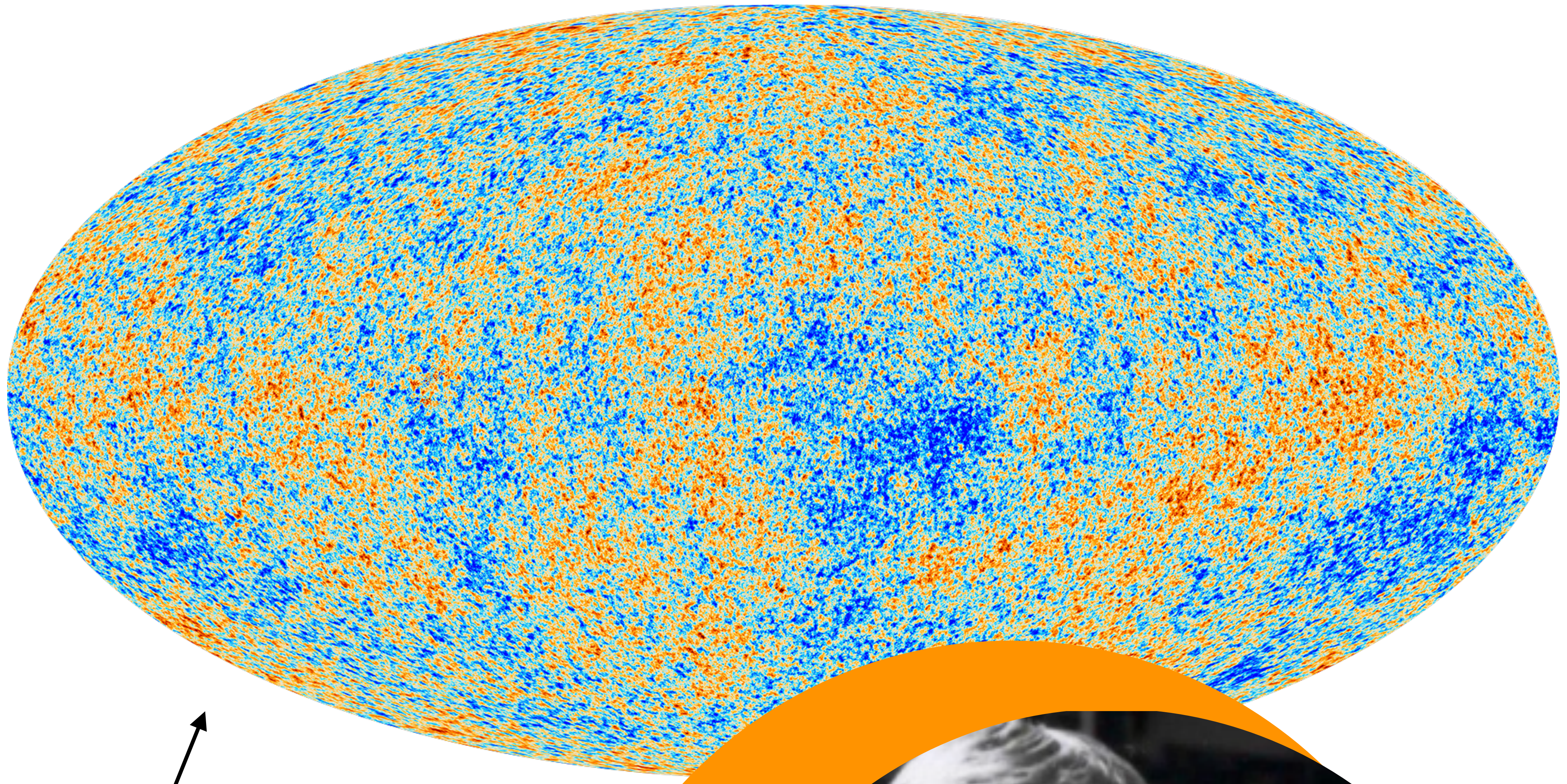

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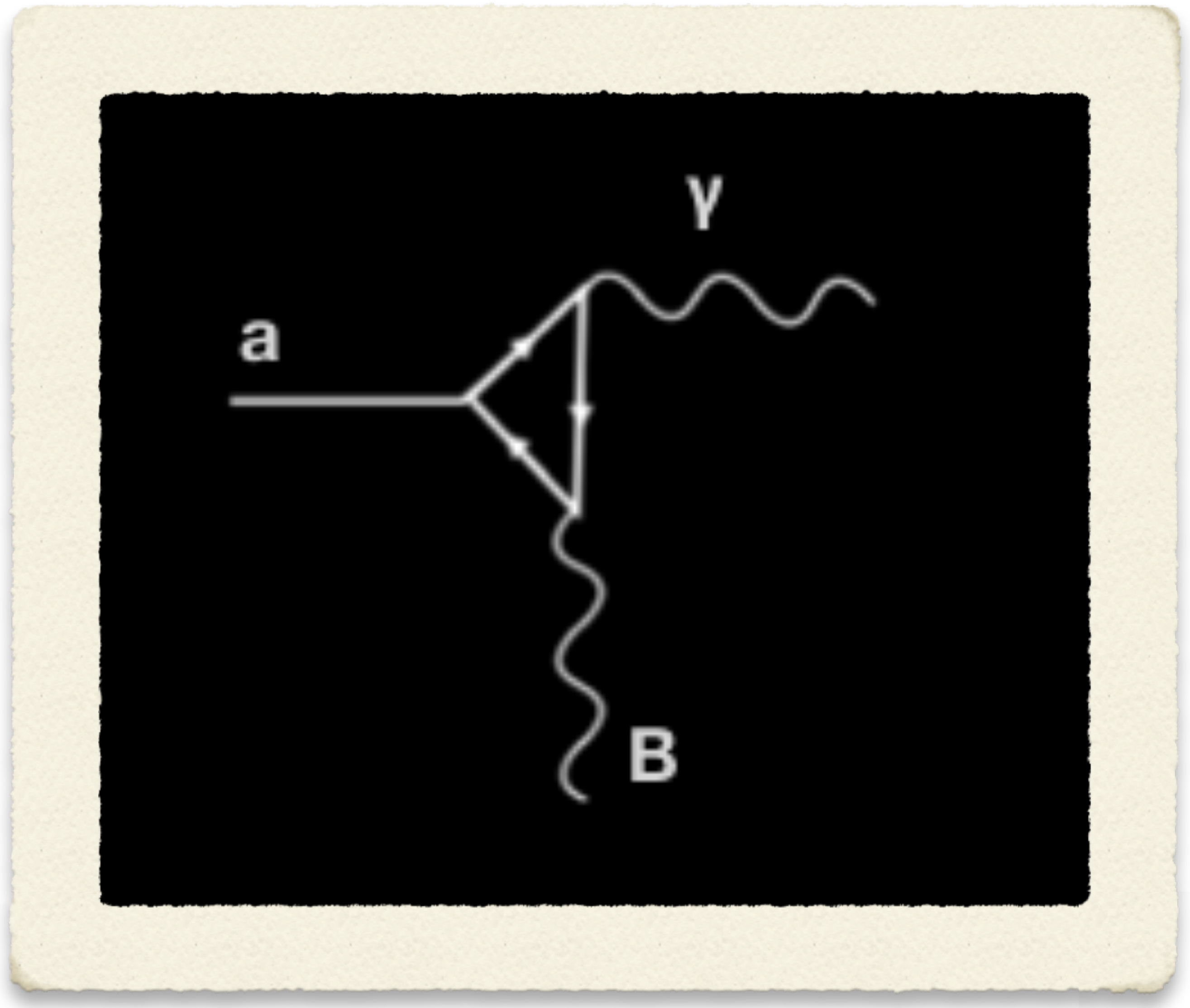
Axions as the dark matter

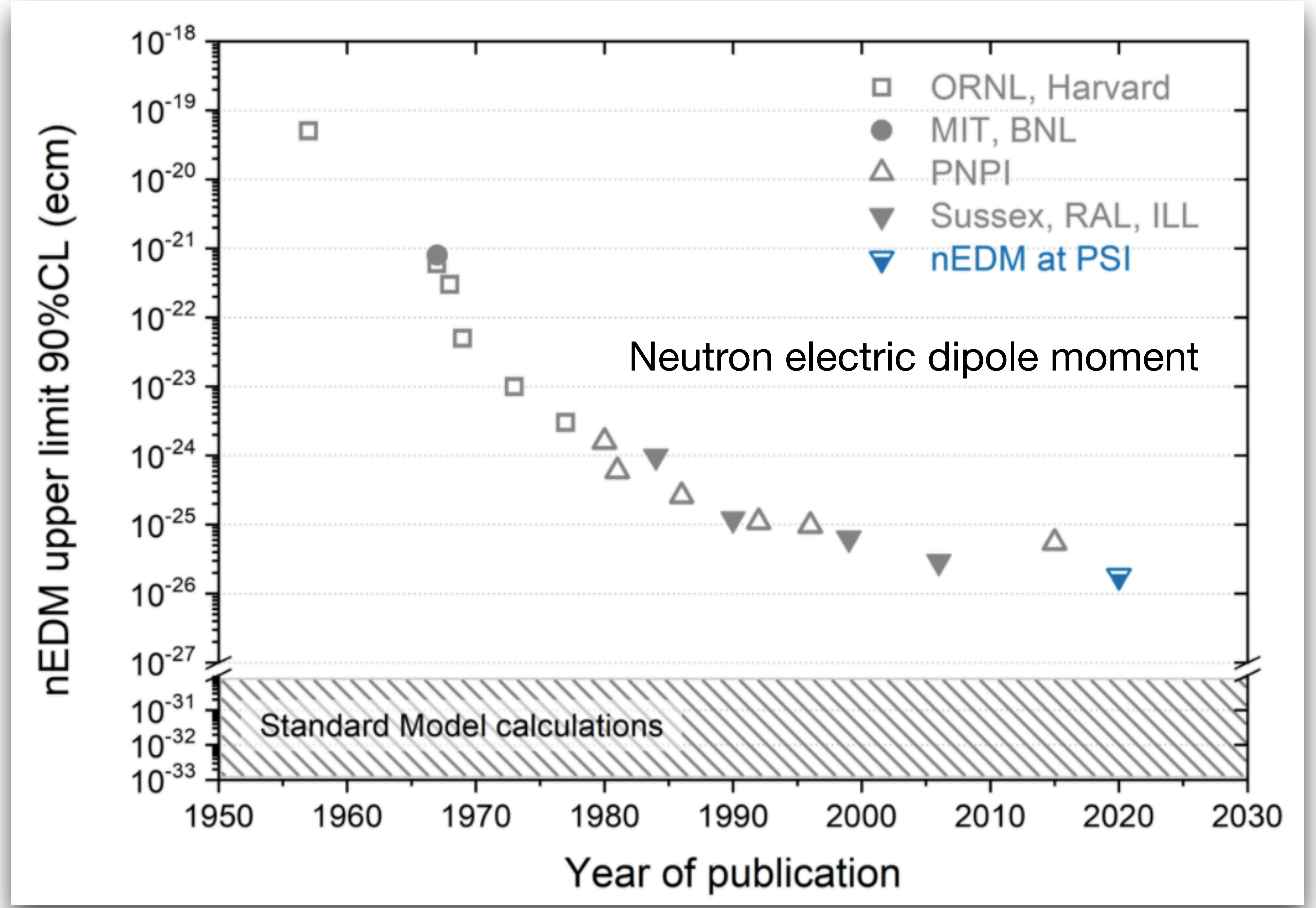
- 1-100 μeV mass range to constitute entirety of dark matter

- 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

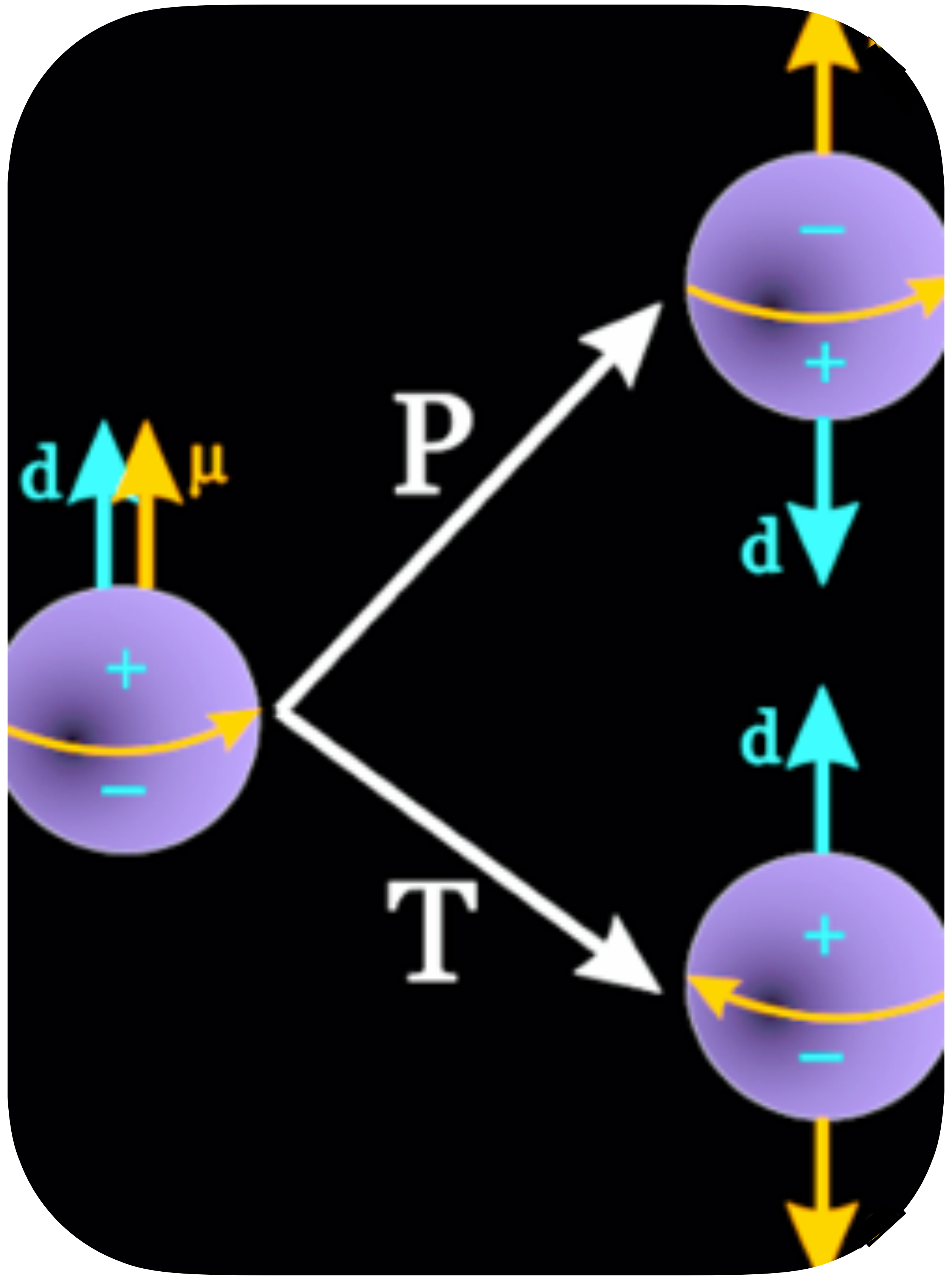


strong CP problem

Standard Model predicts CP-violation in strong interactions
…but none seen so far!



EDM would violate T (CP) symmetry



Peccei-Quinn Mechanism

- Peccei-Quinn devised solution that upgraded theta to dynamical variable

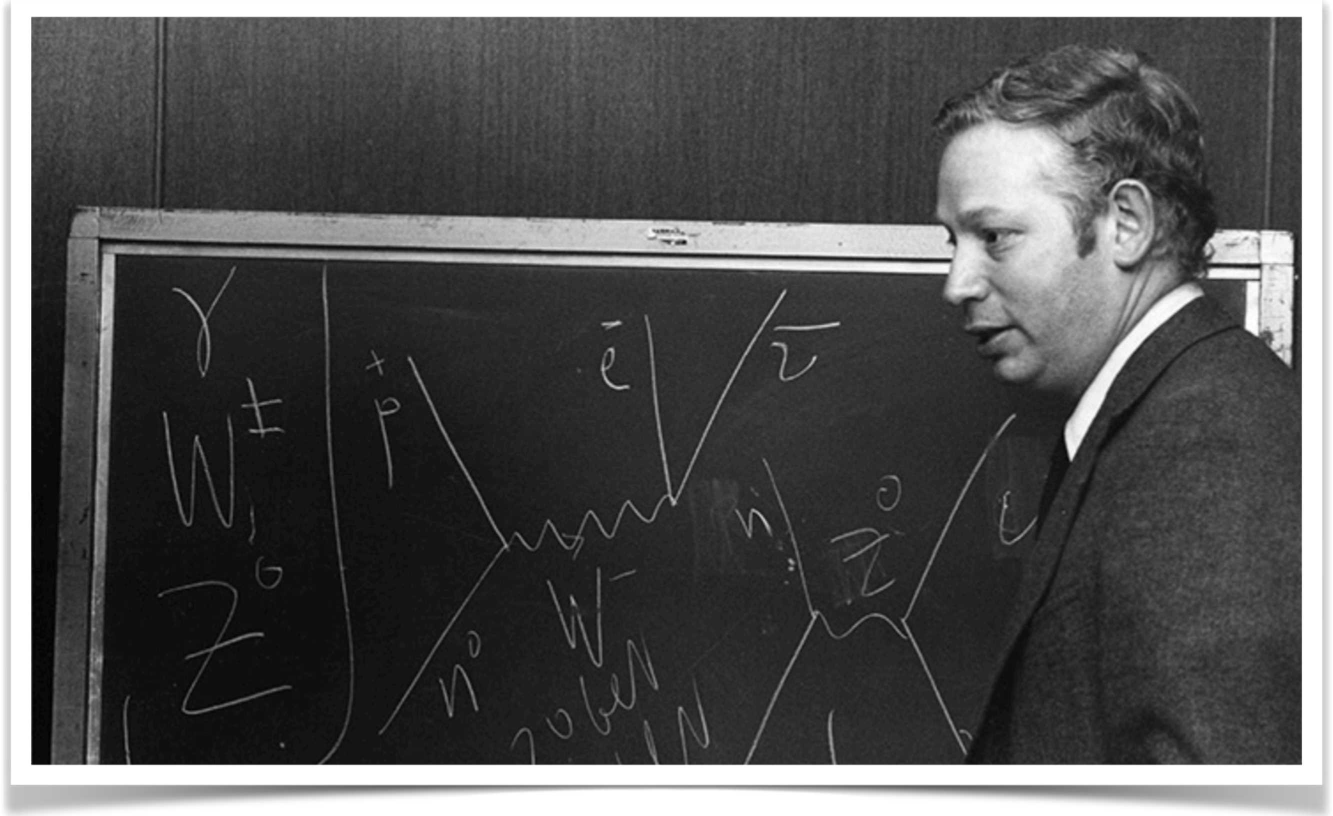
- Tips the wine-bottle potential so that lowest energy configuration precludes existence of neutron EDM

- ‘PQ’ mechanism —> pseudo scalar boson (axion)

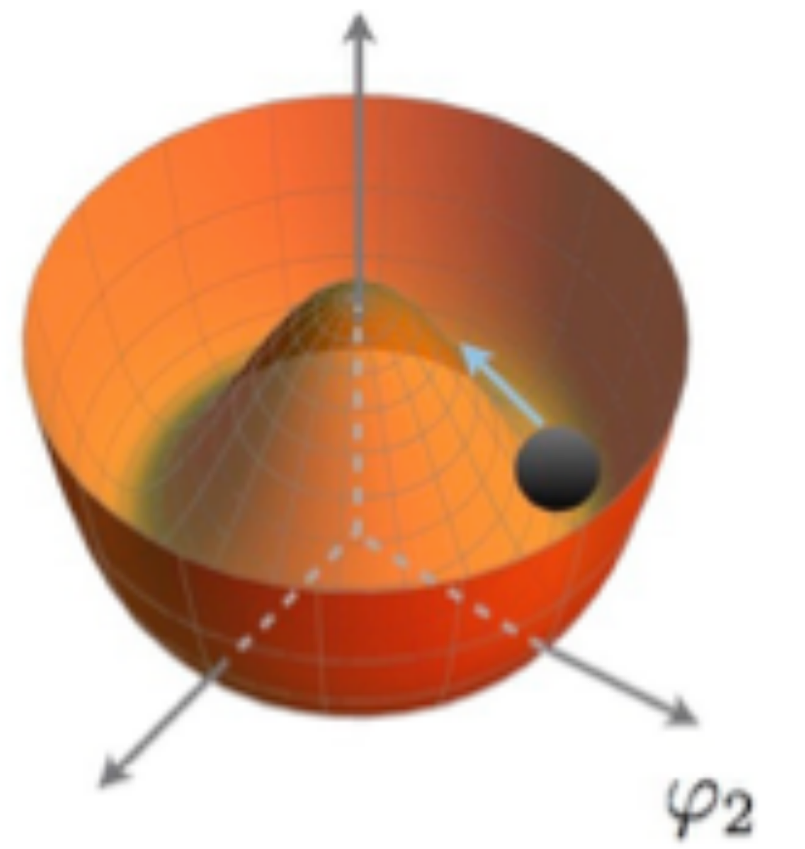
Frank Wilçek

Helen Quinn

Roberto Peccei
1942-2020



Steven Weinberg (1933-2021)



Oscillation about the QCD minimum – *Daniel Grin*

Wave-like Dark Matter Mass Range

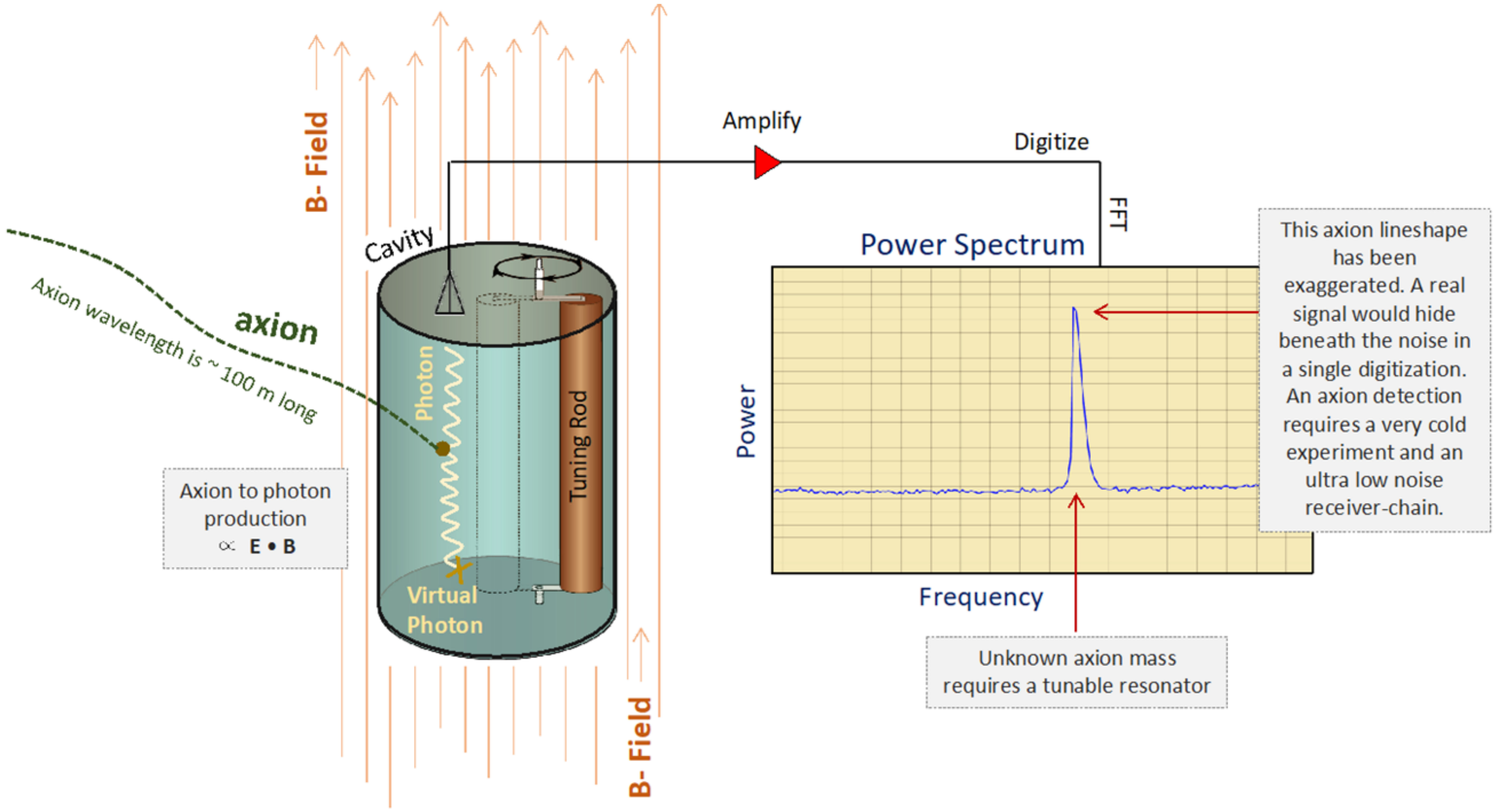
Lower bound set by size of dark matter halo size of dwarf galaxies

Upper bound set by SN1987A and white dwarf cooling time

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

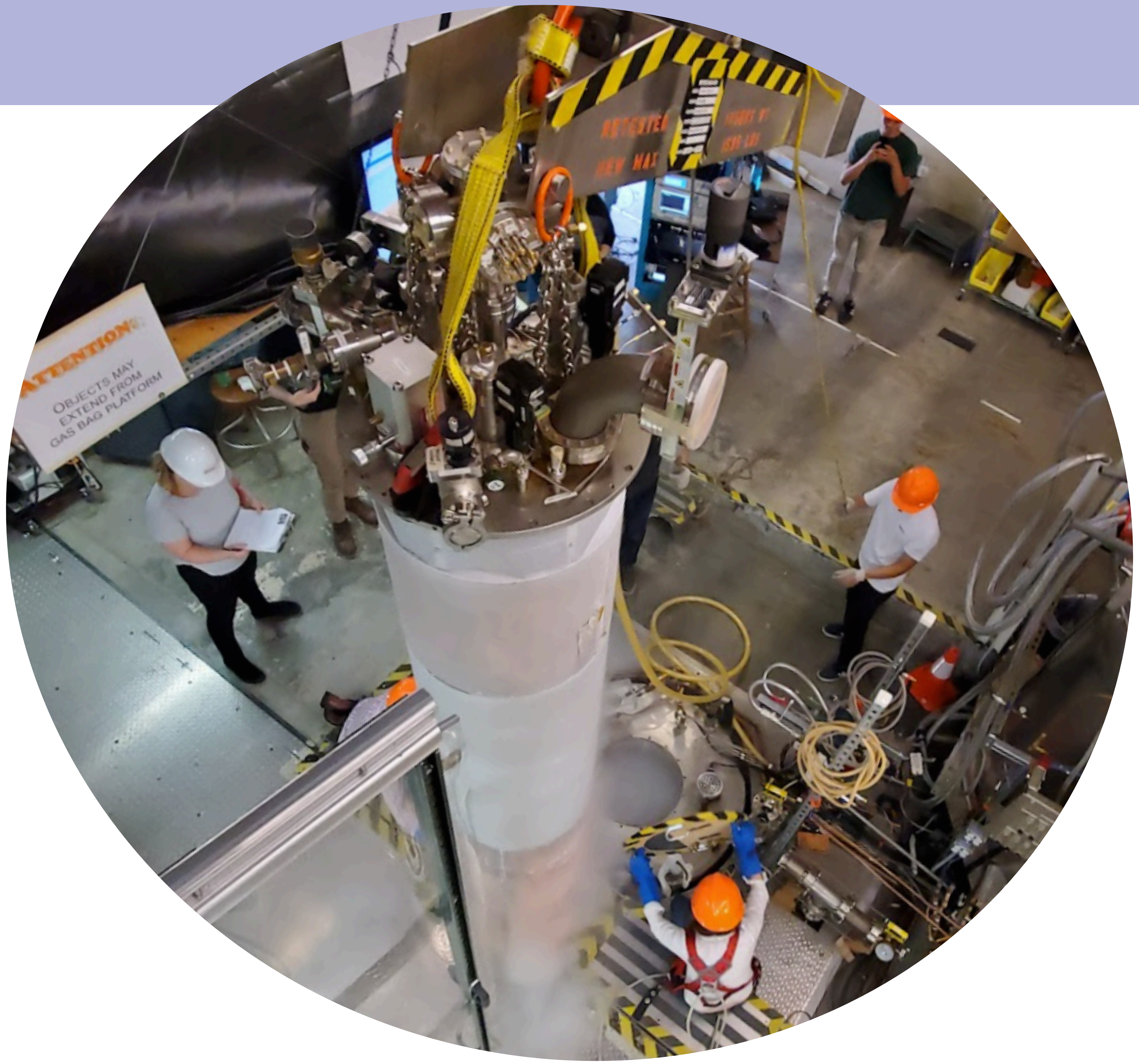
Adaptation of L. Winslow DPF Slide

The Axion Haloscope



Axion Dark Matter eXperiment

- Resonant cavity in a magnetic field (‘haloscope’)
- Relying on inverse Primakoff effect
- High-Q —> Higher probability of axion to photon conversion
- Have reached DFSZ benchmark sensitivity with the ADMX detector



Berkeley UNIVERSITY OF CALIFORNIA

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

University of Washington

THE UNIVERSITY OF WESTERN AUSTRALIA

Washington University in St. Louis

Pacific Northwest NATIONAL LABORATORY

Lawrence Livermore National Laboratory

UF UNIVERSITY of FLORIDA

The University Of Sheffield.

Fermilab

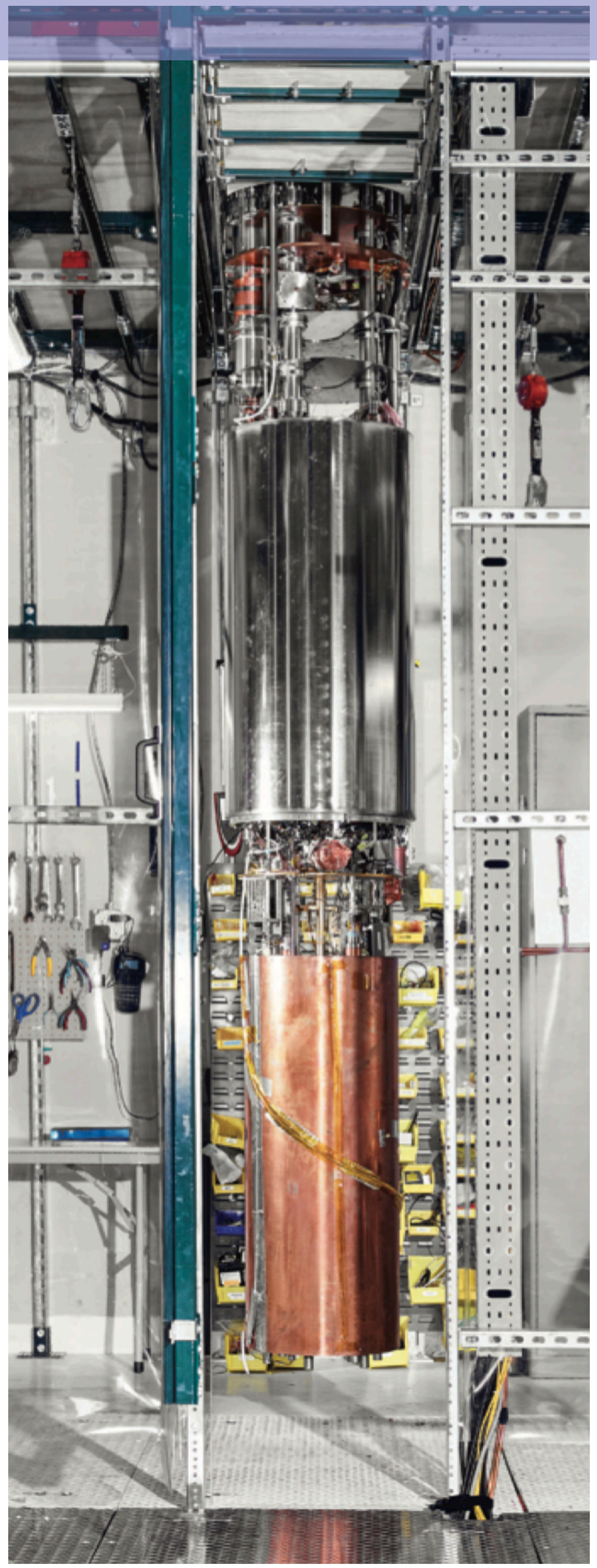
Los Alamos NATIONAL LABORATORY

NSF

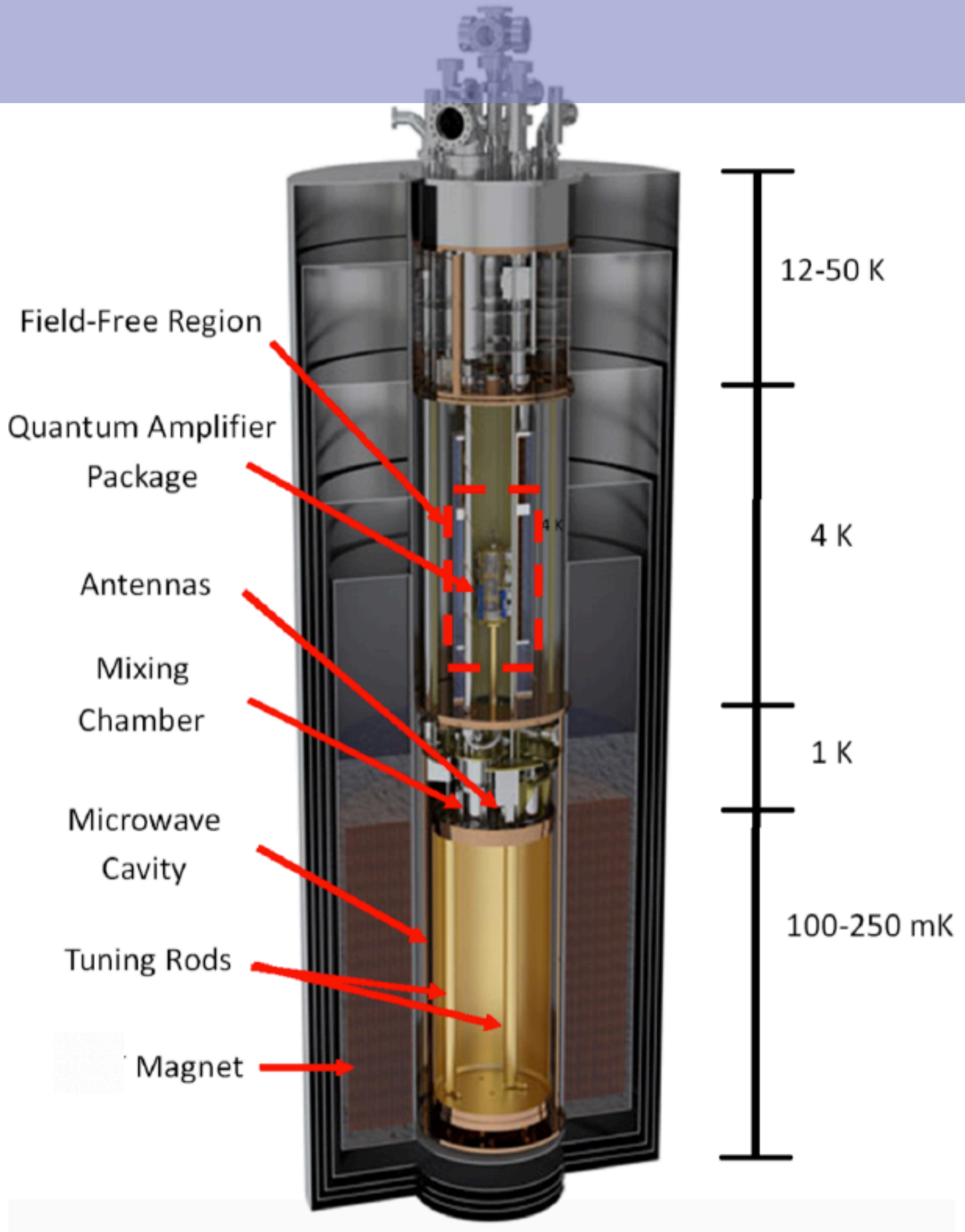
HEISING - SIMONS FOUNDATION

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



In cleanroom



In magnet bore

Data-taking operations 2019-2021

Medium-res

- 100 Hz bin width
- Saved as power spectra
- Isothermal halo model
- Bin width optimized for expected axion lineshape

High-res

- 10 mHz native bin width
- Saved as time-series
- Non-virialized axions
- Sensitive to frequency modulation from orbital and rotational motion

Data-taking operations 2019-2021

Medium-res

Driving the data-taking operations!

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High-res

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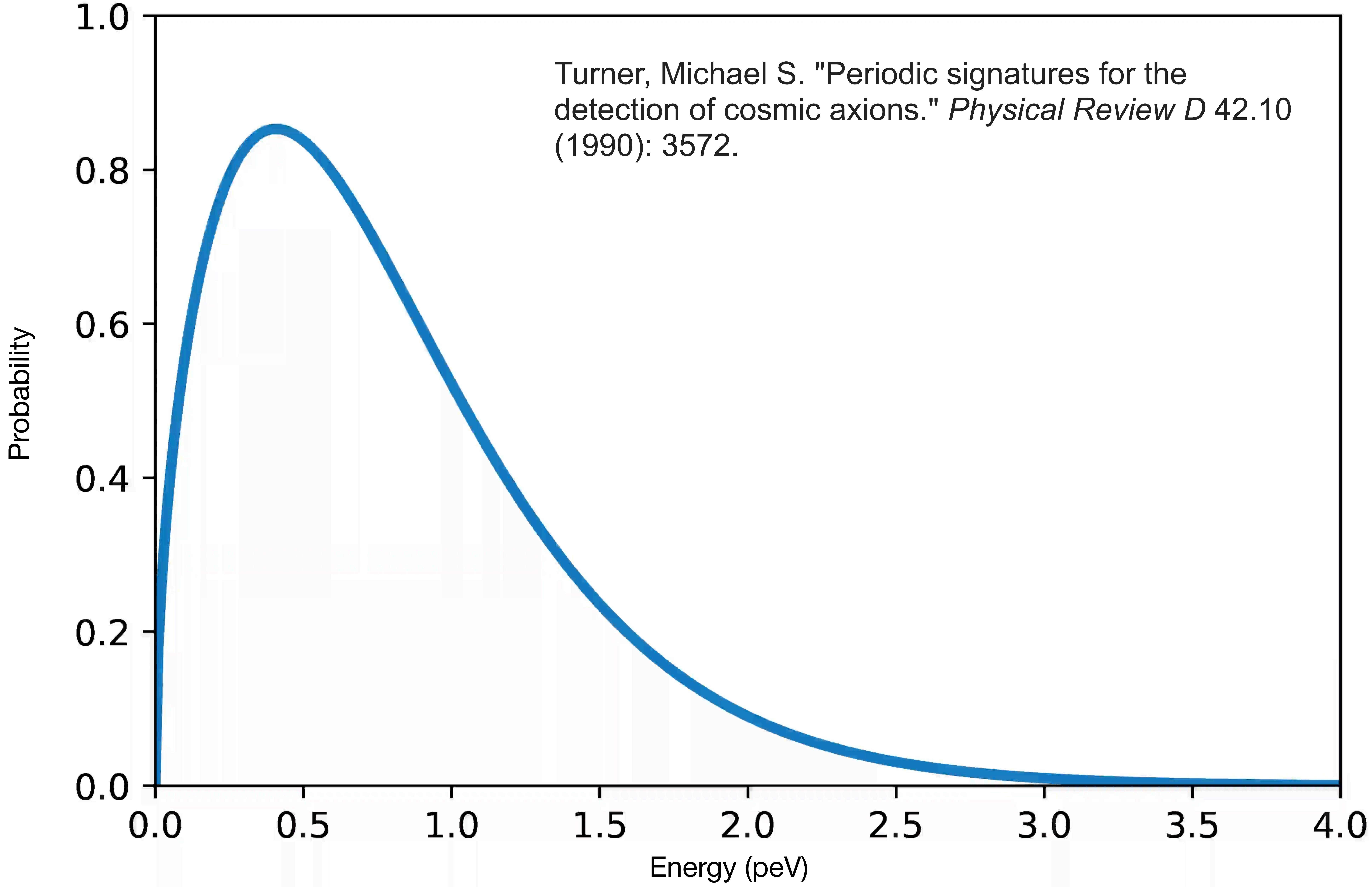
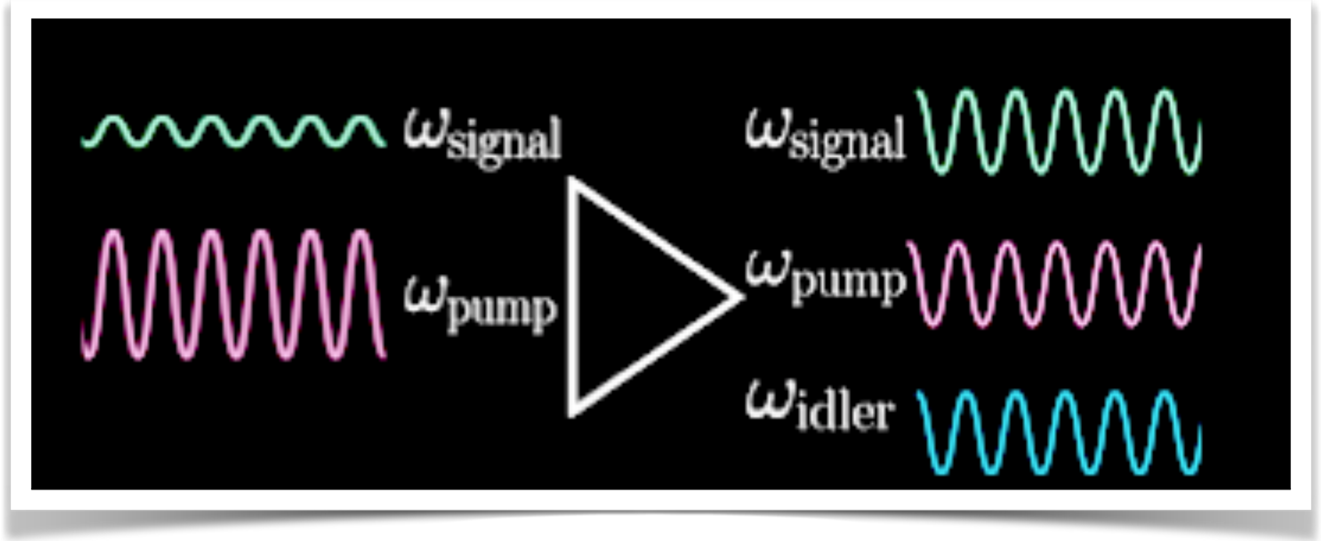
Axion Doppler Shift

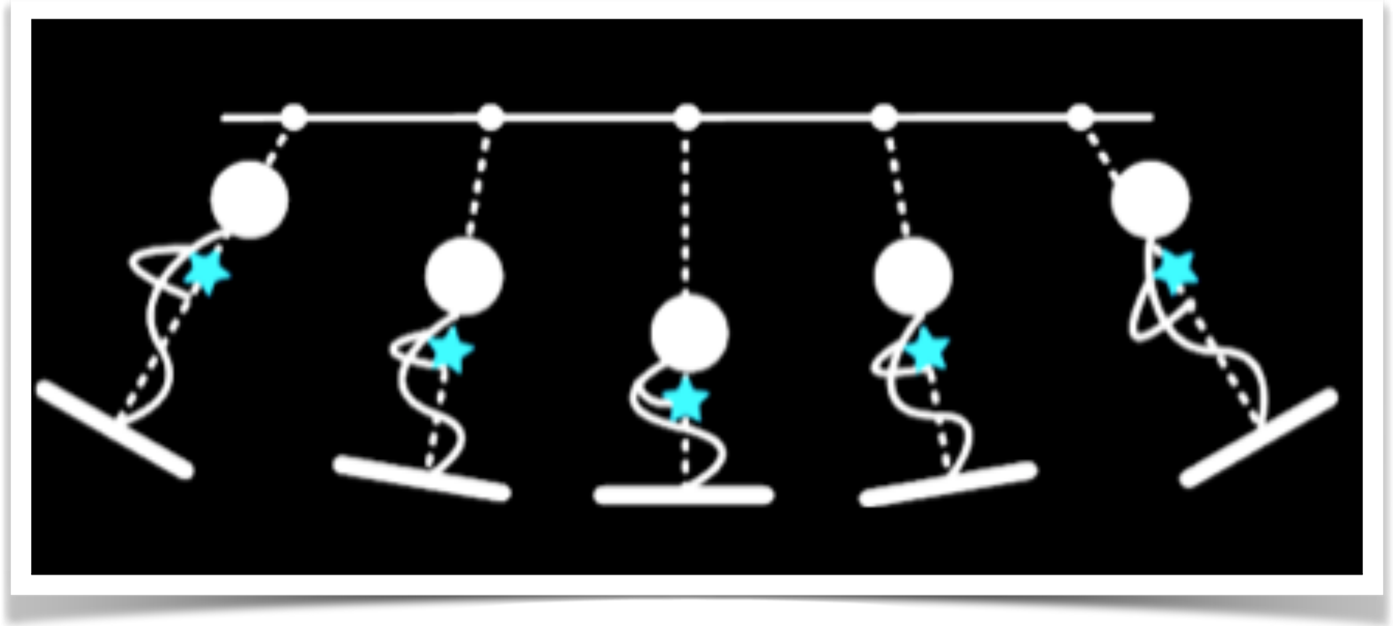


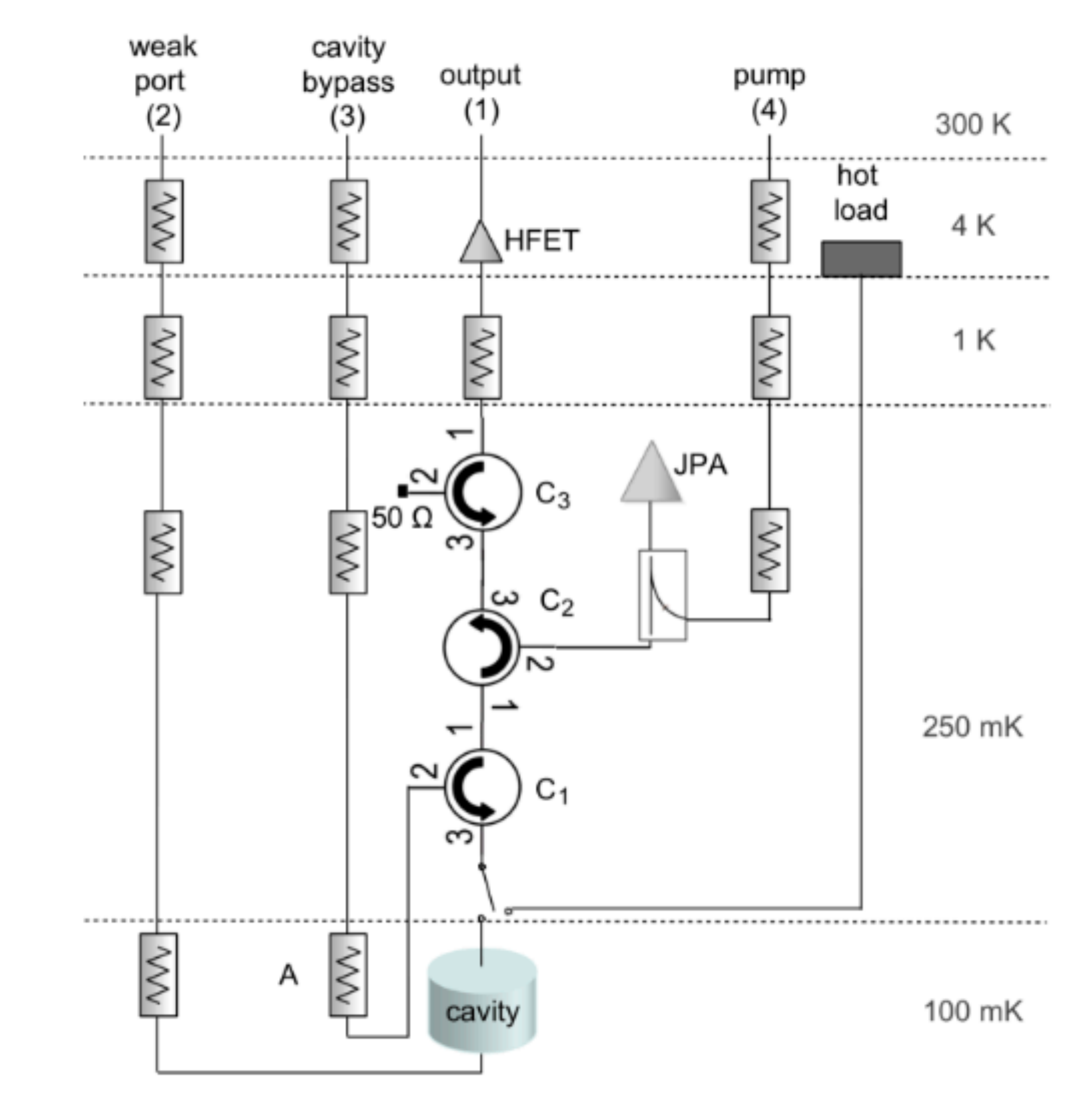
Josephson Parametric Amplifier (JPA)

- 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



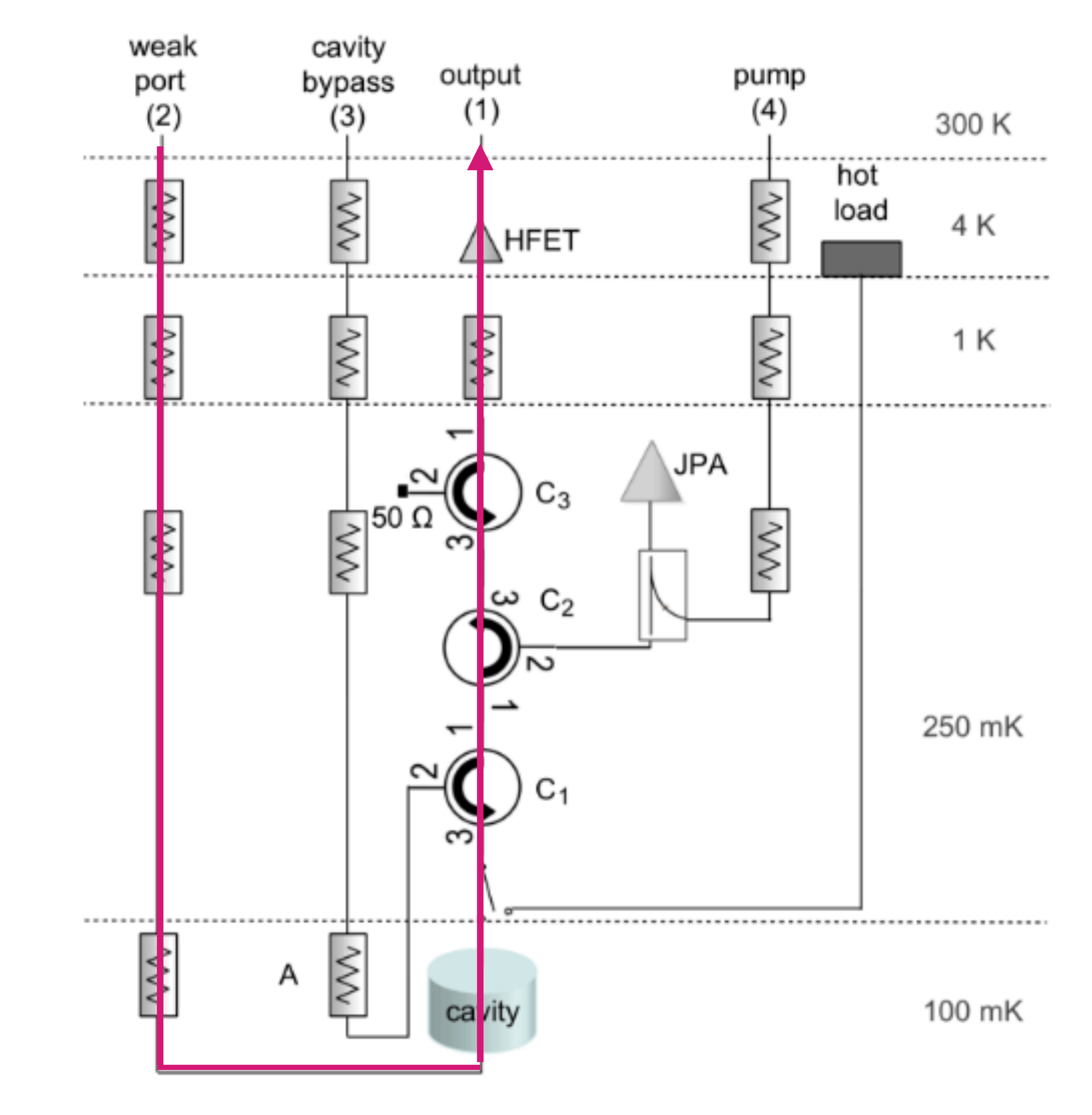
Figures courtesy of Shahid Jawas





ADMX RF Schematic

3 important RF paths to highlight!

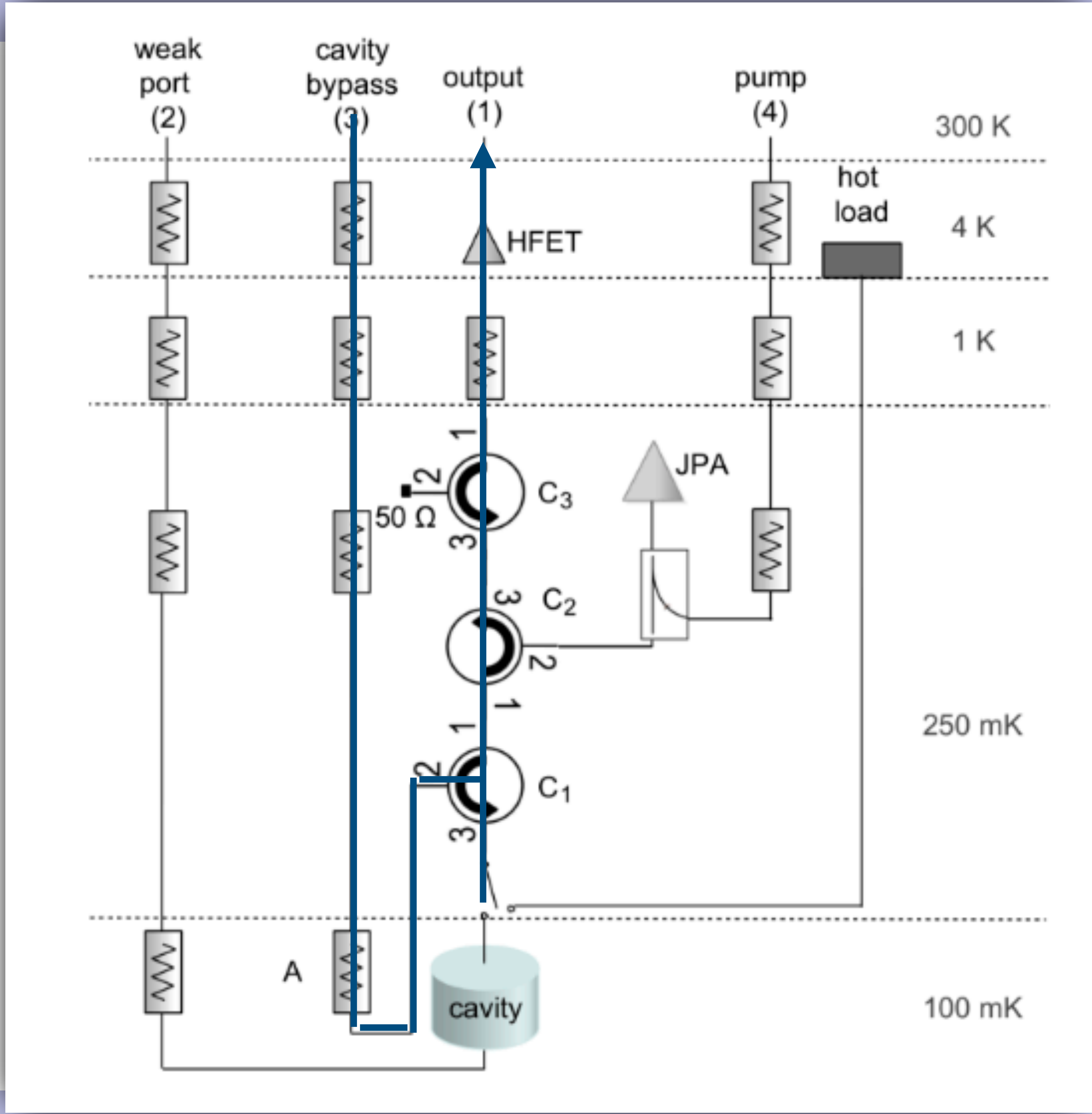


Transmission Measurement RF Path

Transmission Measurement Gives:

- Resonant frequency
- Quality factor

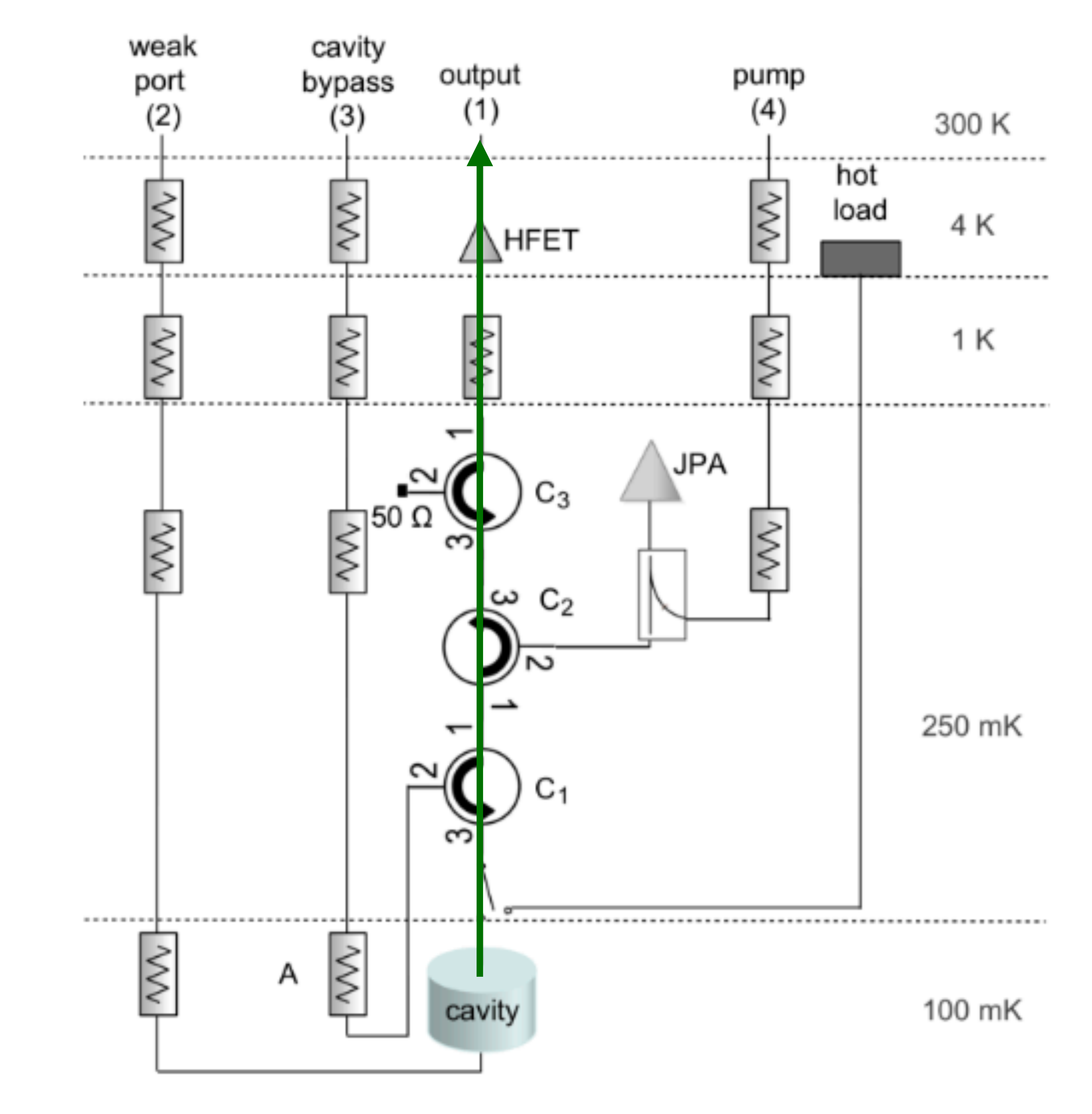
Same path is used to inject synthetic axion signals



Reflection Measurement RF Path

Reflection Measurement gives:

- Antenna Coupling

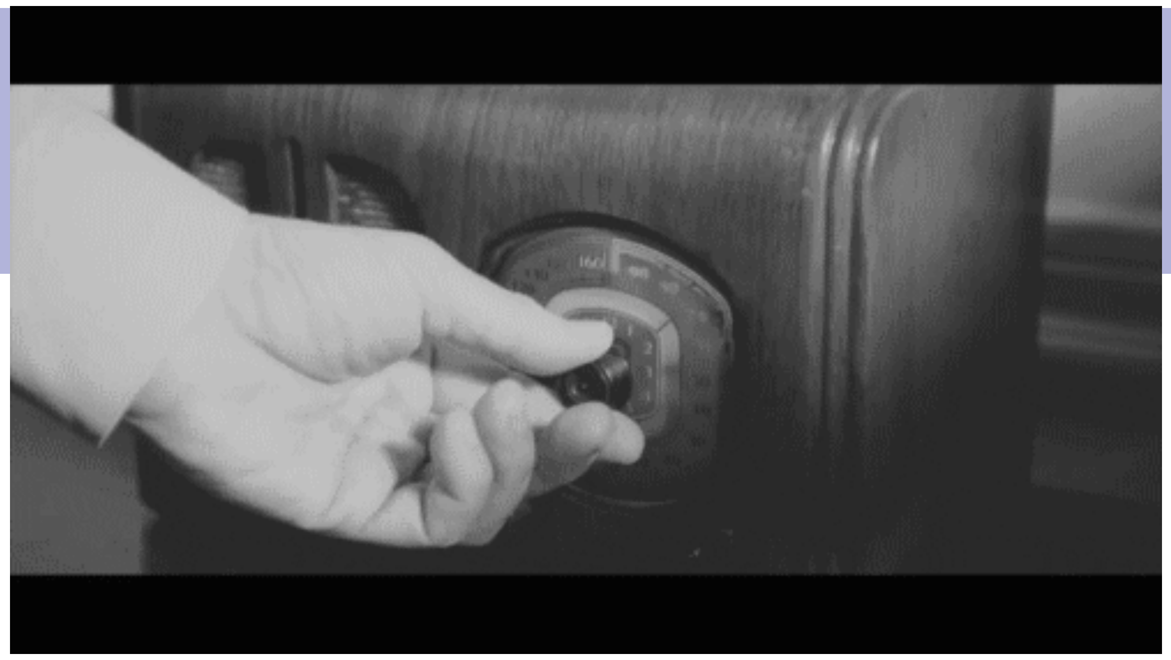


Ch 1 Signal Path

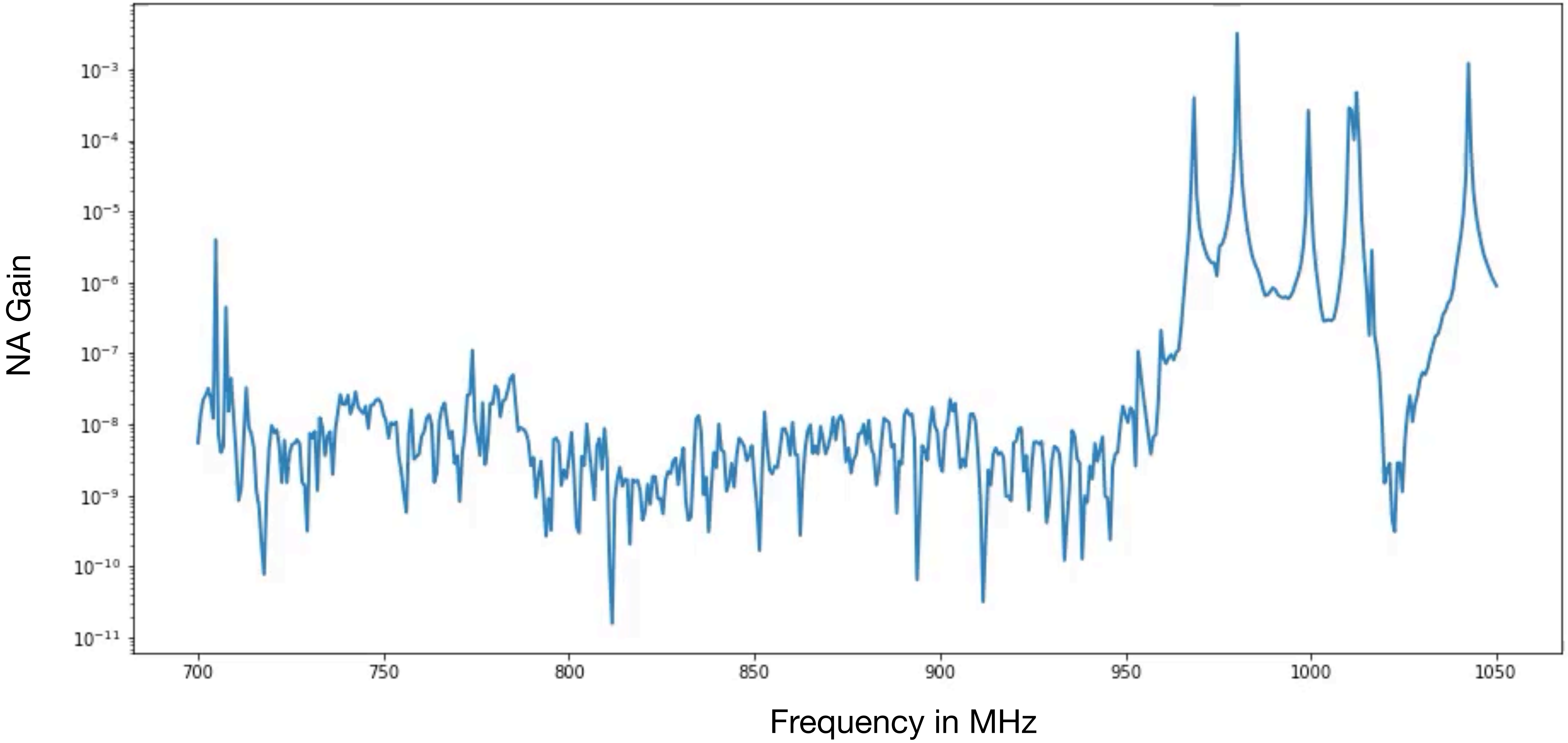
Weak port line is terminated. Signal read out directly from the cavity.

This is our configuration for data acquisition (digitization).

Tuning our cavity

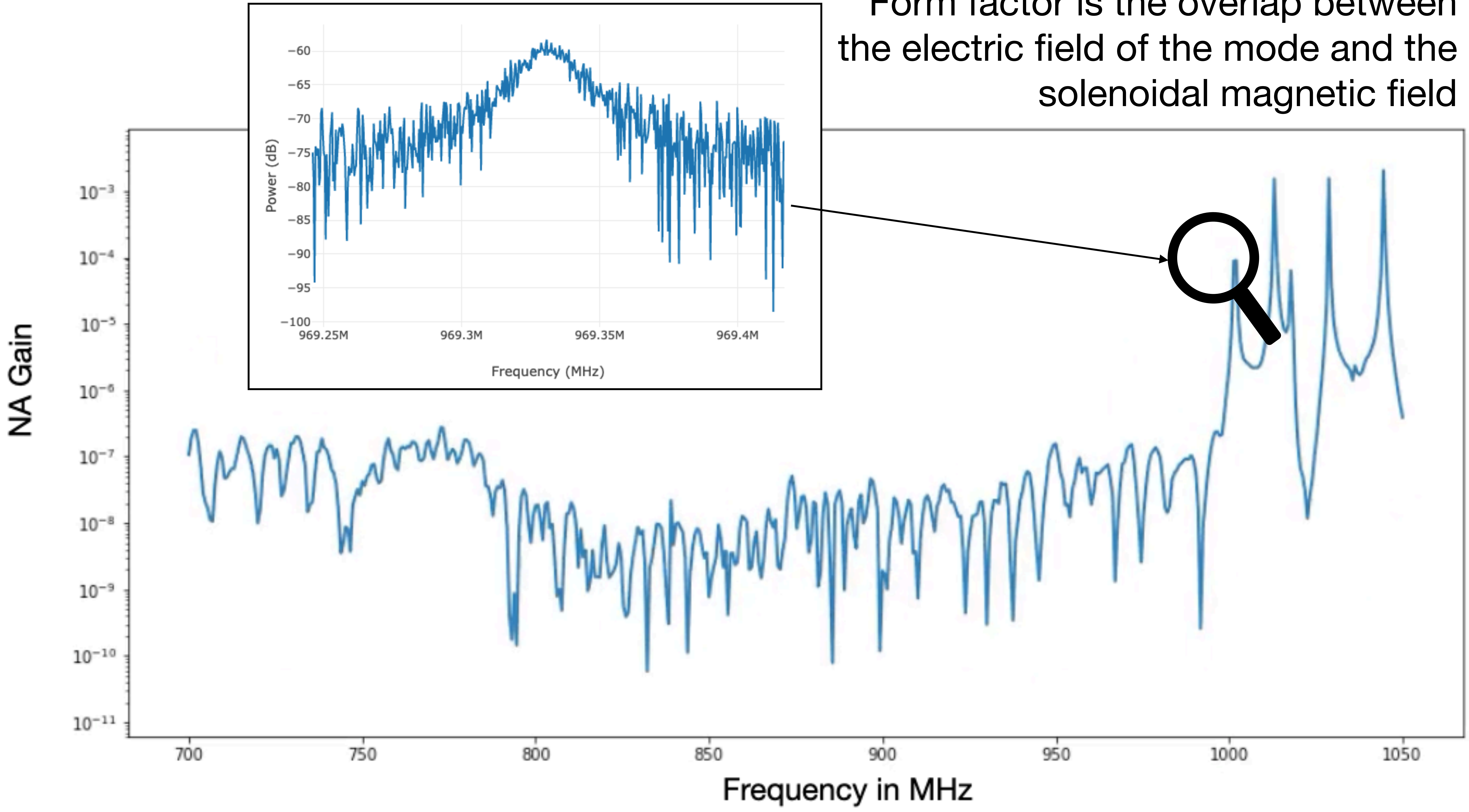


As we tune, we track the TM010 mode
Axion couples most strongly to this mode
Note occasional mode-crossings

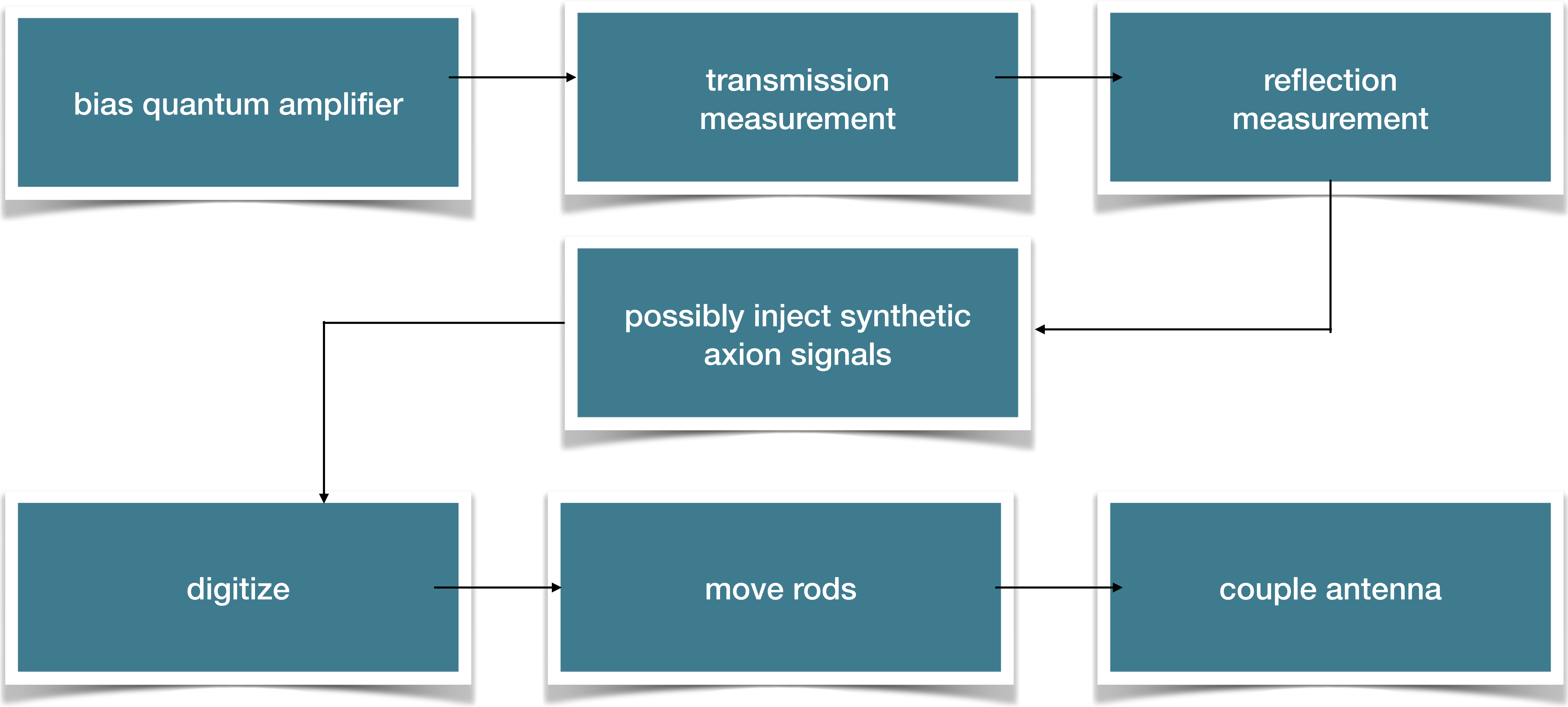


Zooming in on a single mode

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



ADMX Run 1C data-taking?



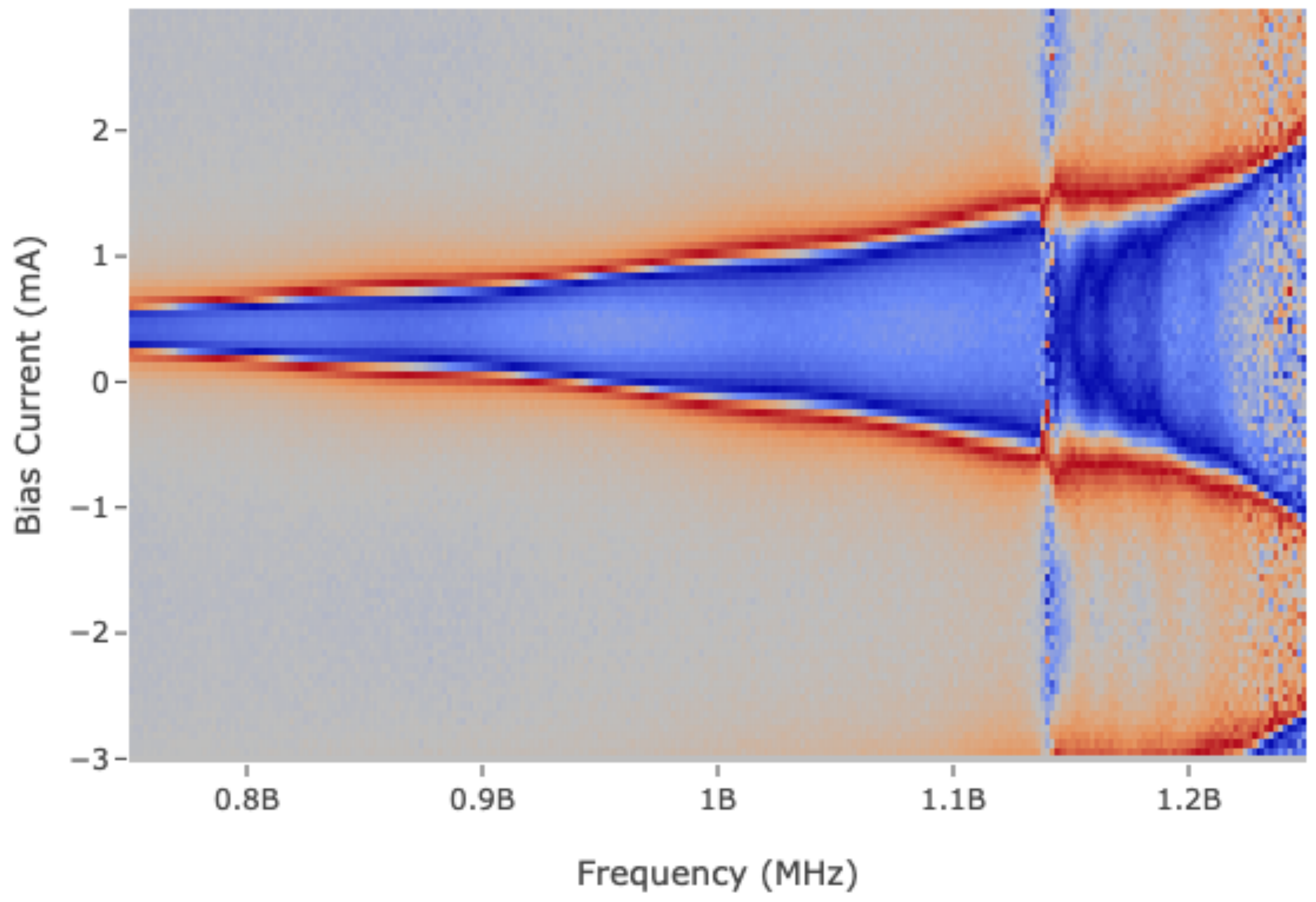
ADMX Run 1C data-taking?

bias quantum amplifier

transmission measurement

reflection measurement

possibly inject synthetic axion signals



move rods

couple antenna

ADMX Run 1C data-taking?

bias quantum amplifier

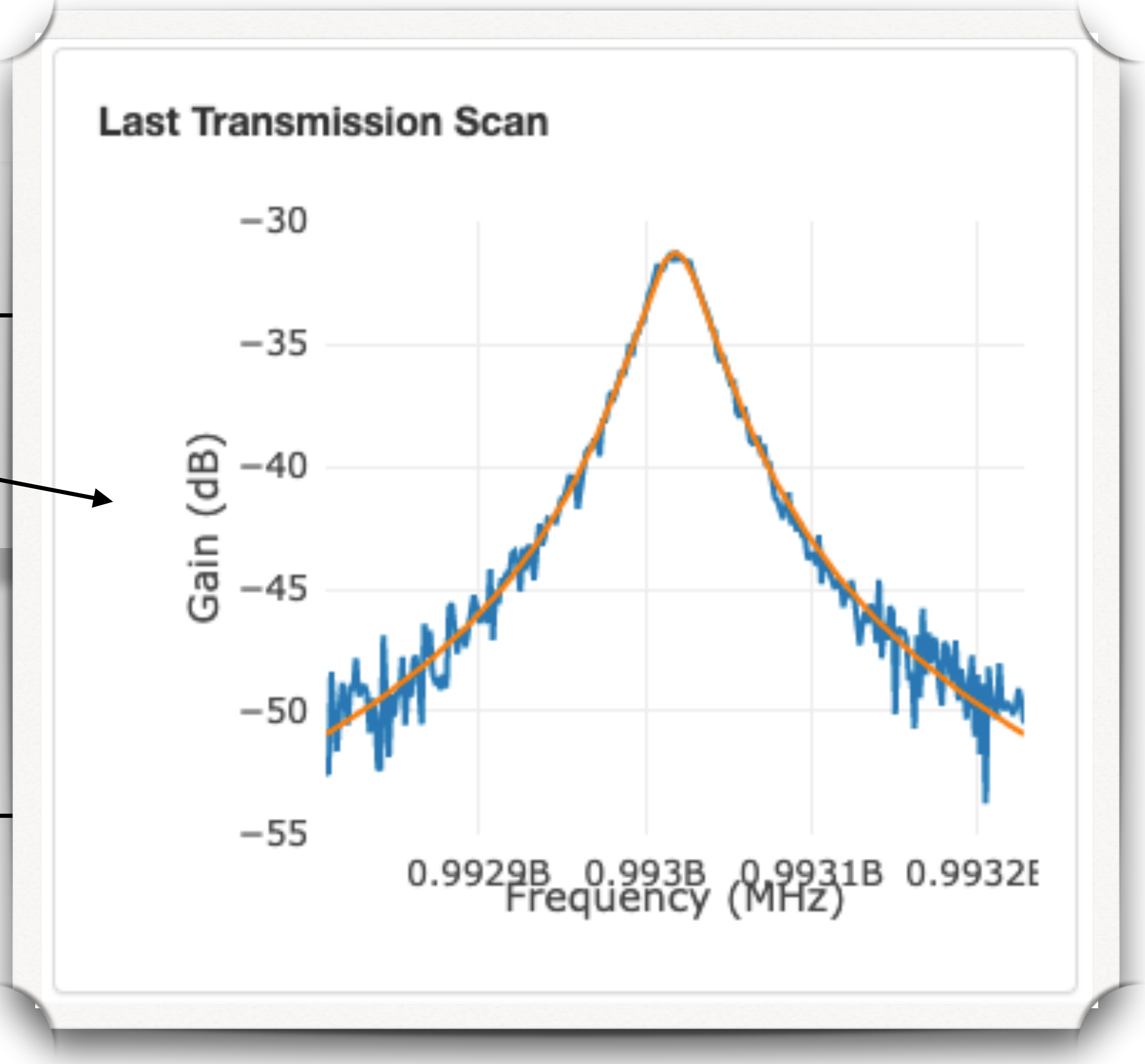
transmission measurement

possibly inject synthetic axion signals

digitize

move rods

couple antenna



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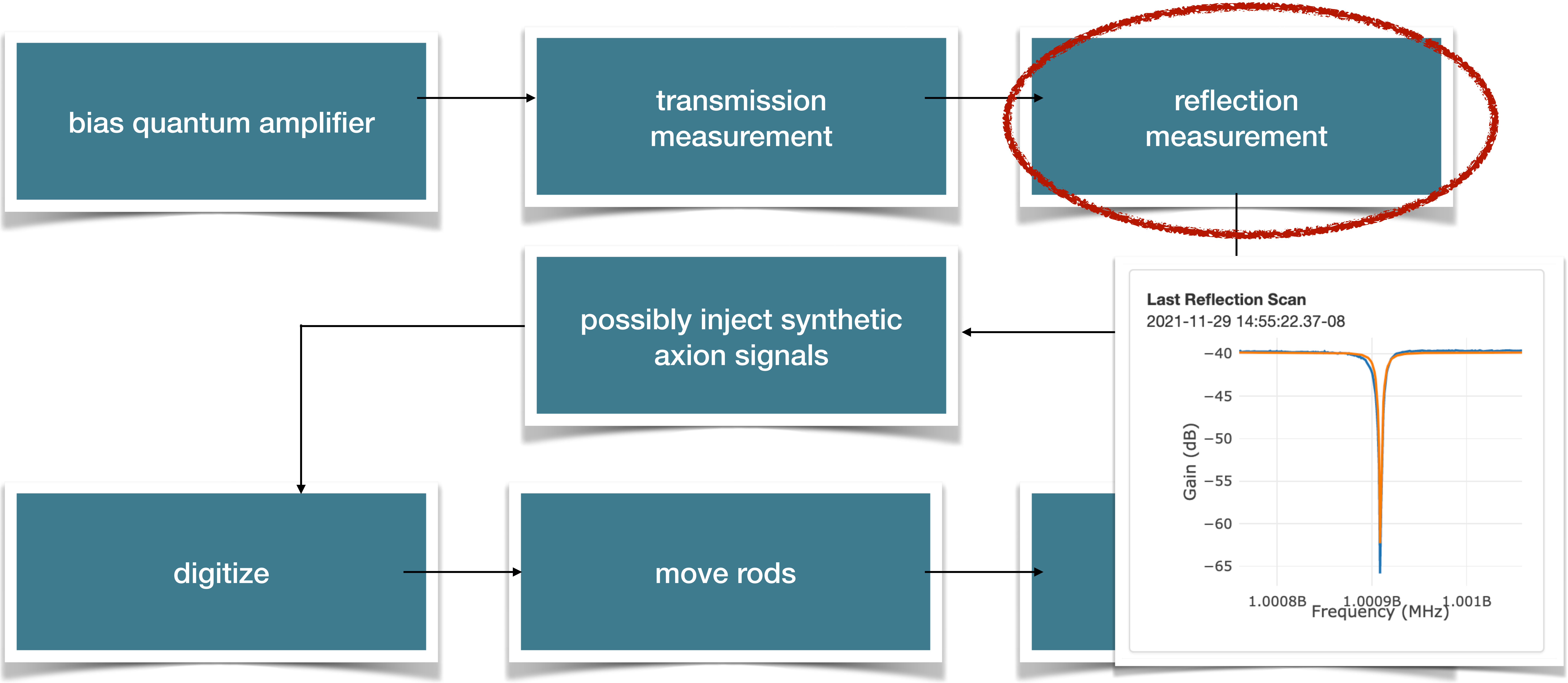

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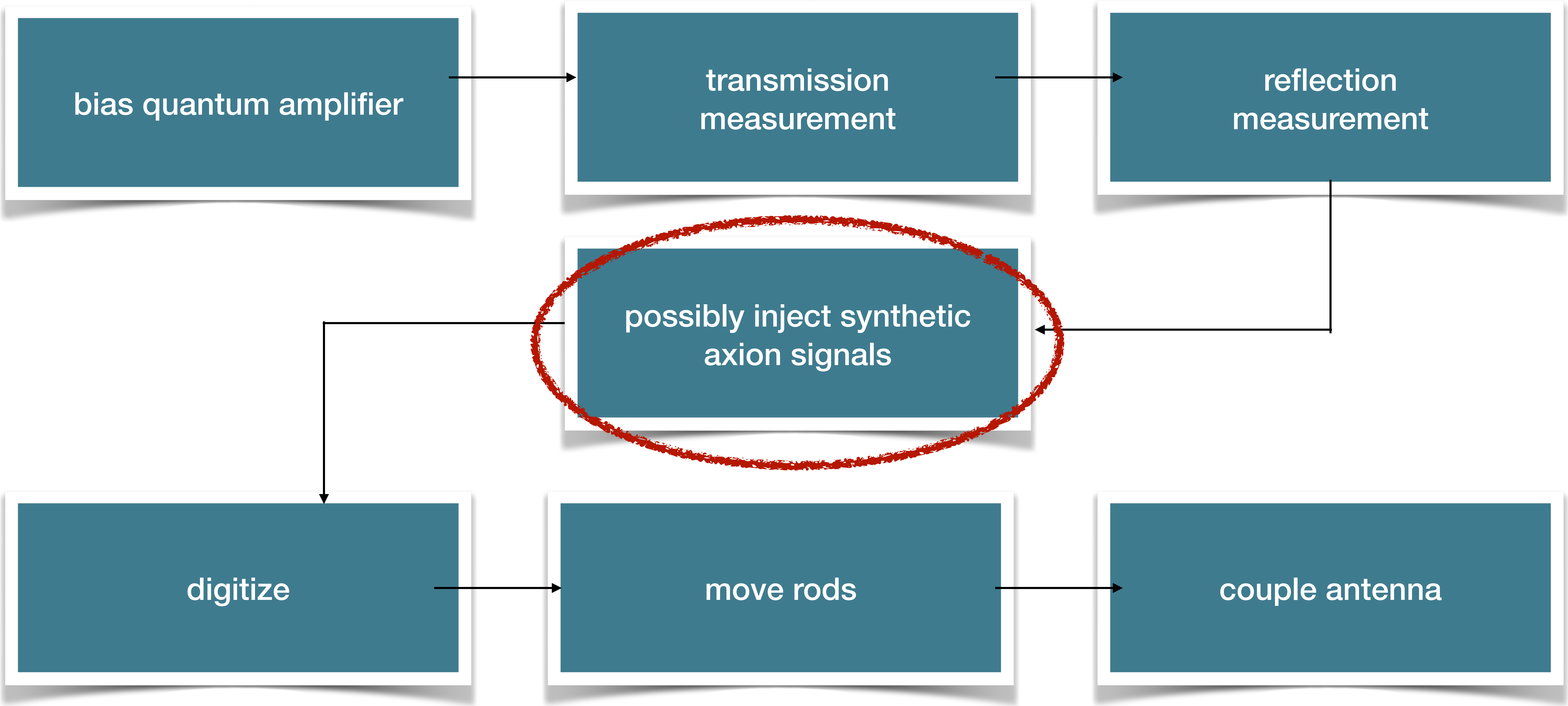


Synthetic Axion Generator

Type 1:

Injections that we use to verify the integrity of the receiver chain and sensitivity

- Turned off in final sweep through frequency range; verified as synthetics.

- 10-12 per 10 MHz.

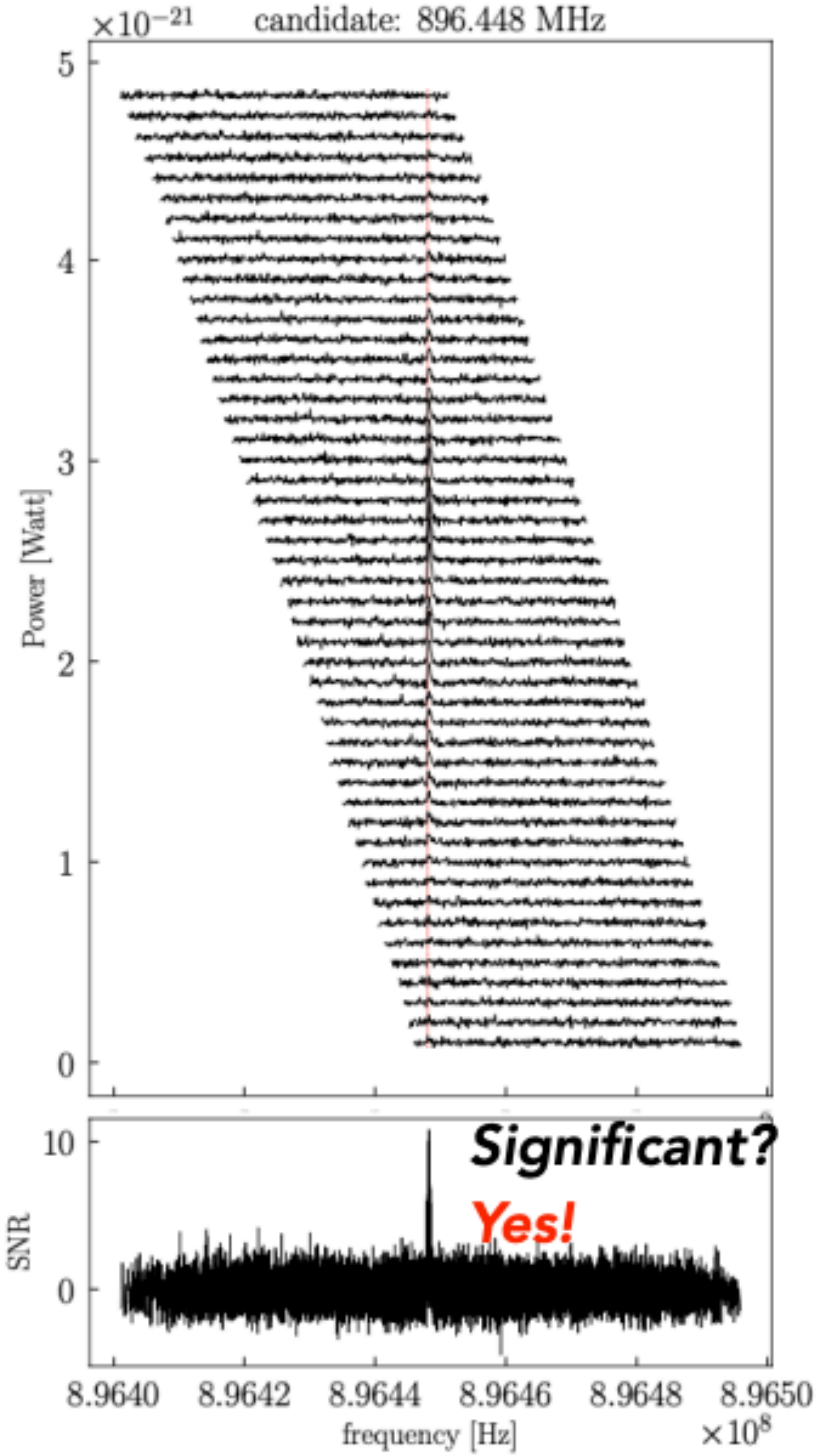
Type 2:

Injection used to practice full axion detection procedure

- Stay on until the ADMX operators determine that they are not real signals.

- 1-2 per run.

Upgrades made to Synthetic Axion Generator (SAG) for Run 1C



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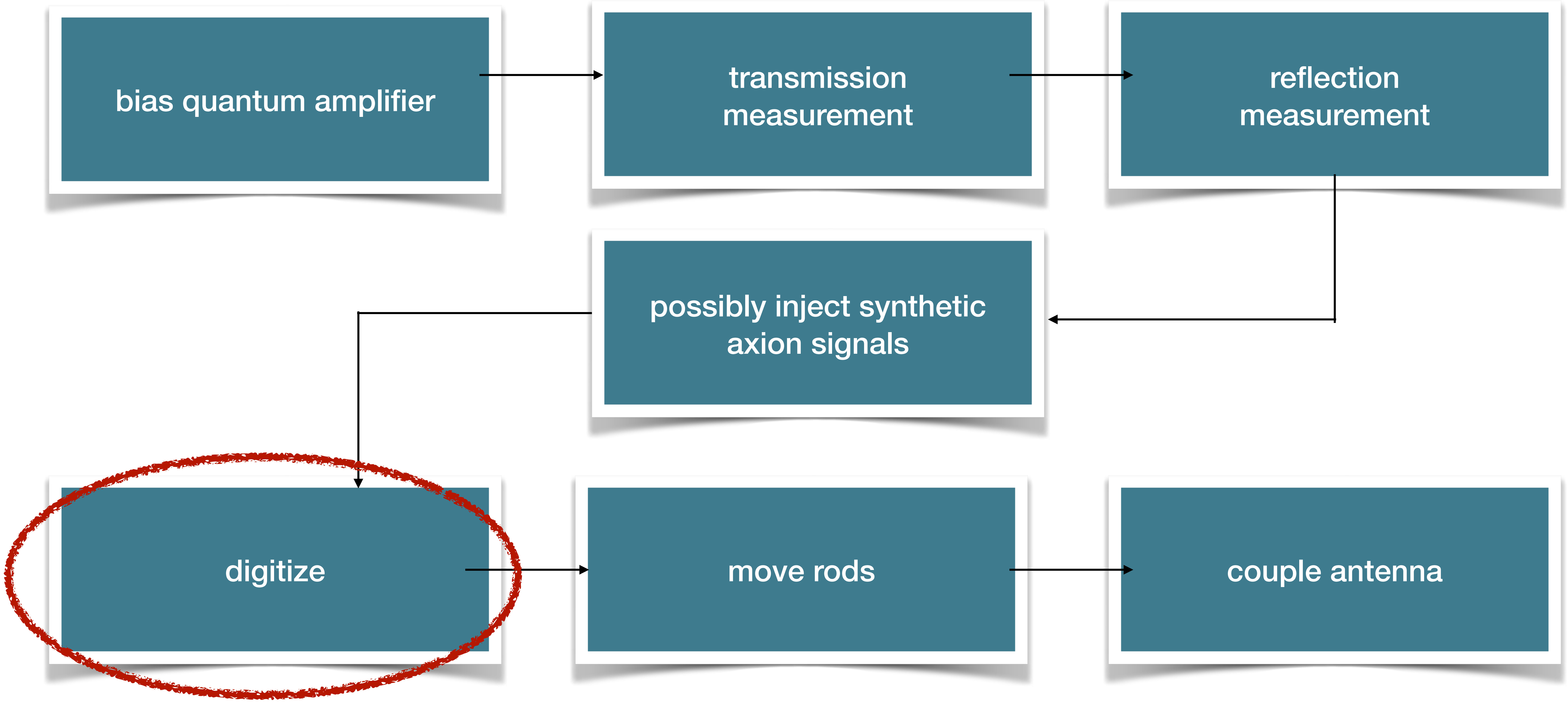

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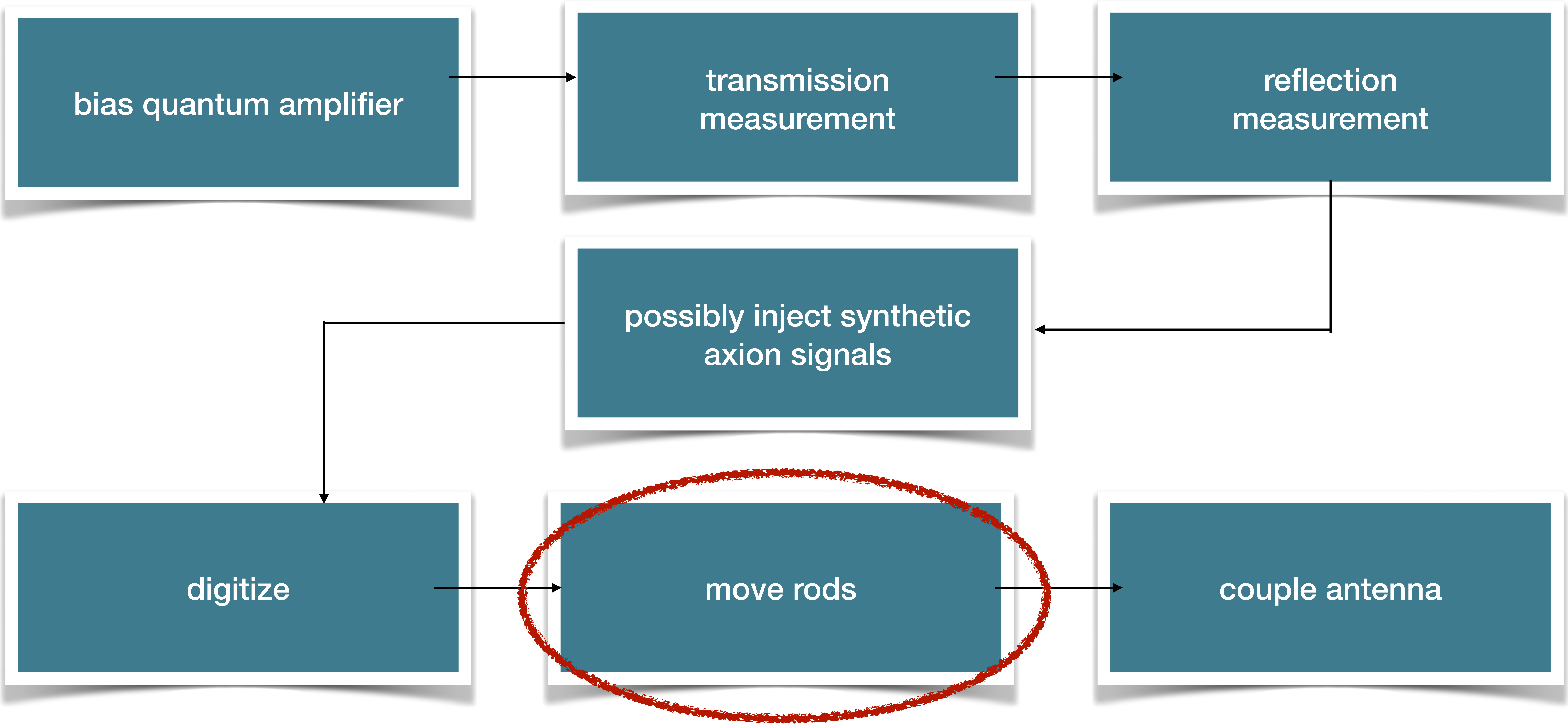

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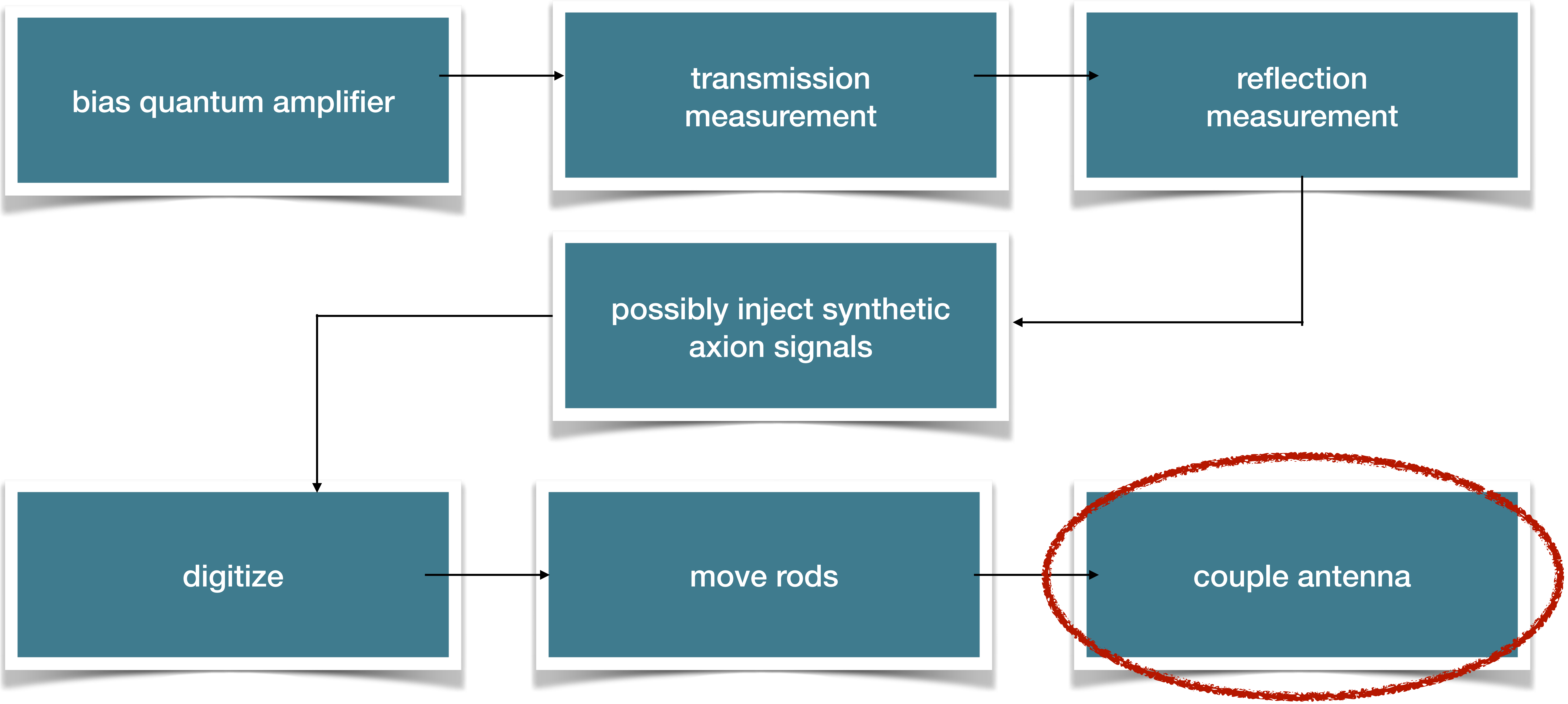
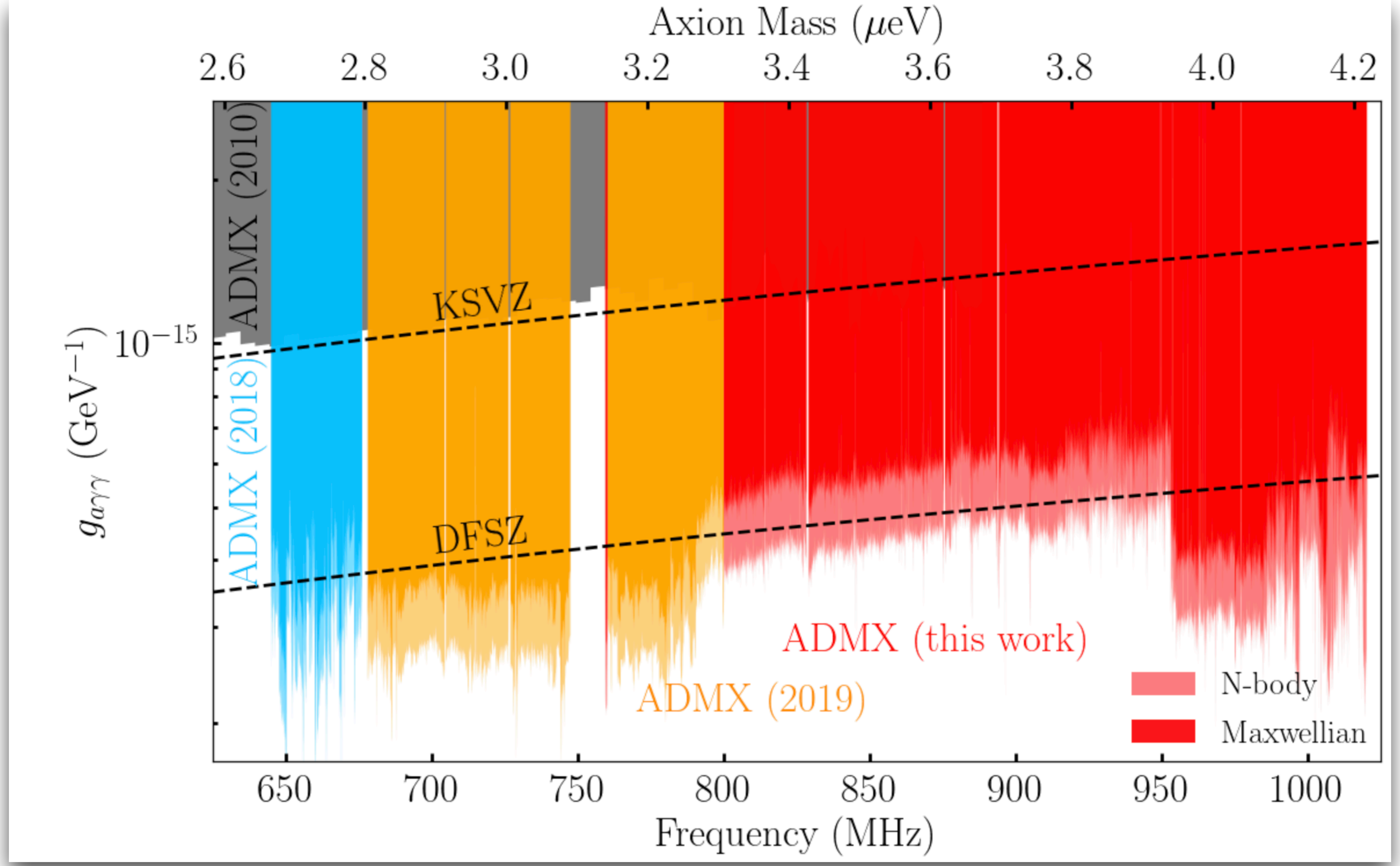


ADMX Run 1C limit

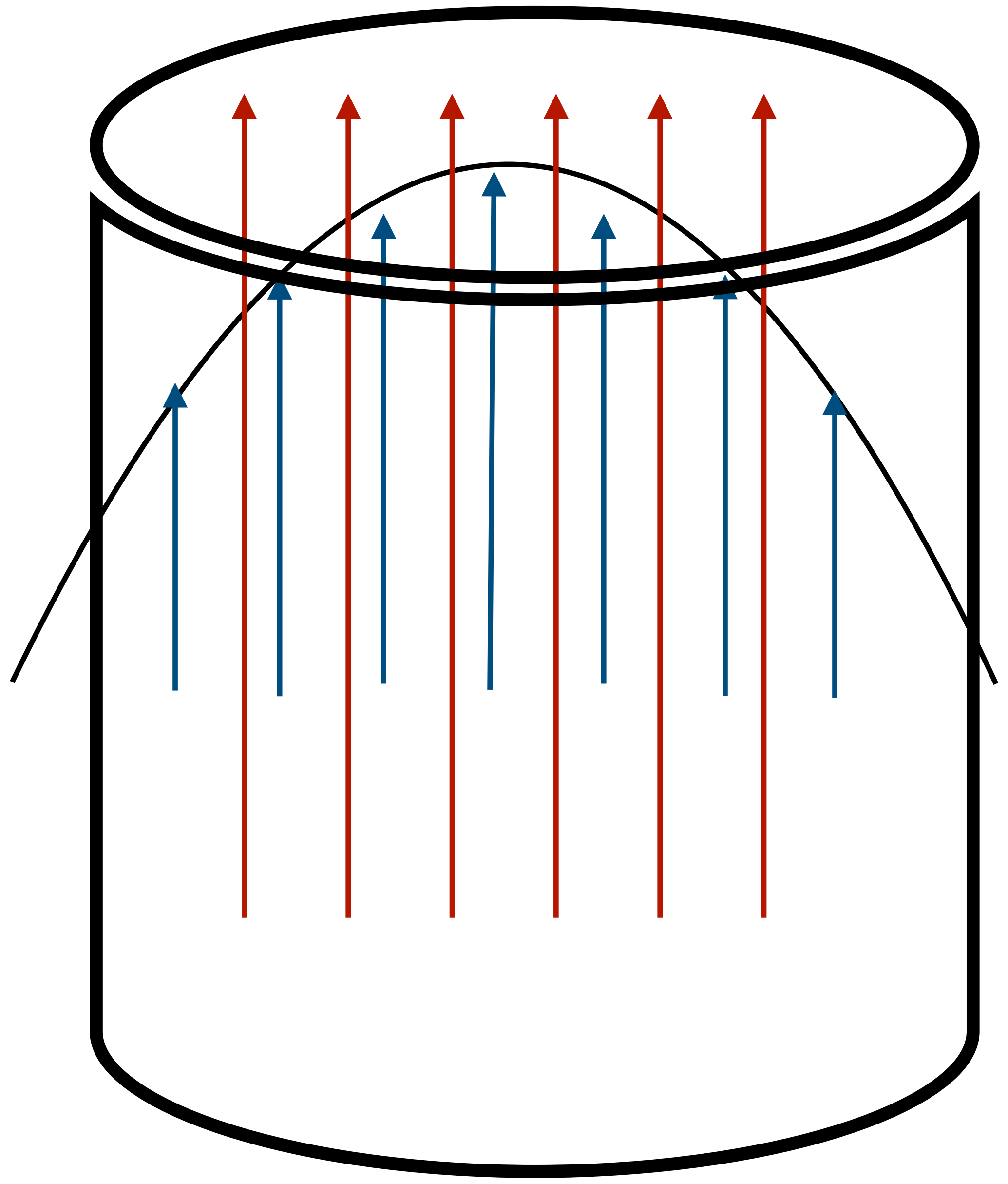
Bartram, C., et al. "Search for 'Invisible' Axion Dark Matter in the 3.3–4.2 μeV Mass Range." *arXiv preprint arXiv:2110.06096* (2021).

Recently accepted by PRL!



Resonant Haloscope Scan Rate

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



Red is cartoon magnetic field
Blue is cartoon axion electric field

Two factors here are inextricably linked…

Small volume

Smaller wavelength of TM010 mode

Higher frequency (mass) of axion you can detect

$$C_{010} = \frac{|\int dV\, \vec{B_{ext}} \cdot \vec{E_a}|^2}{B_{ext}^2 \int dV\, \epsilon_r |\vec{E_a}|^2}$$

"Form Factor"

Where do we go from here?

High Frequency → **Smaller Volume** → **Slower Scan Rate**

We need solutions to this problem if we are going to keep up the search!

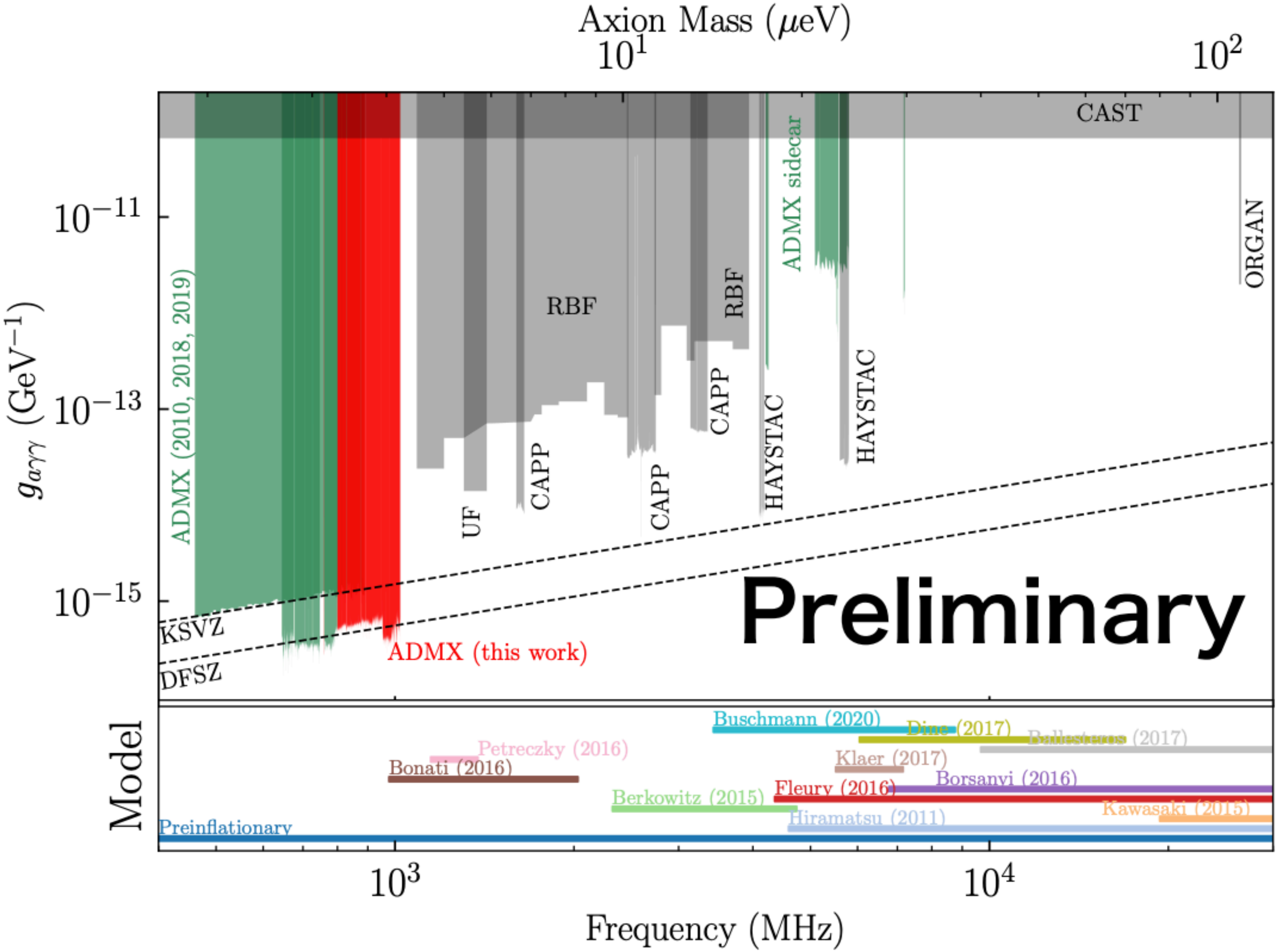
ADMX Near-Term Solution: Coherently combine the power from multiple small cavities

3 Planned Multi-Cavity Searches:

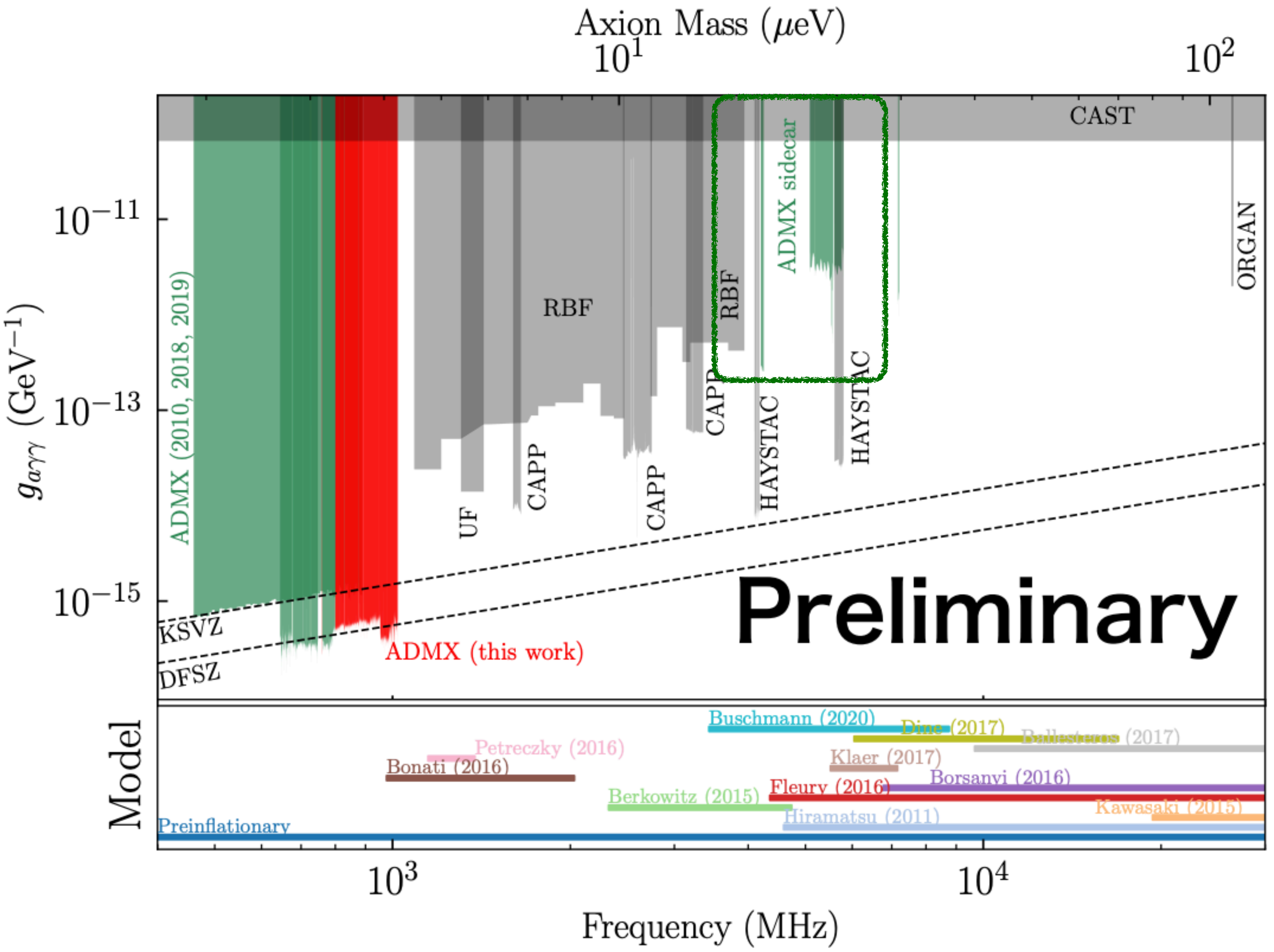
Run 2A/B (1.4–2.2 GHz)
2–4 GHz

Where do we go from here?

Near-Term **Longer-Term** **Future**



Axion Mass (μeV)
10^1
10^2
CAST
10^{-11}
10^{-13}
10^{-15}
$g_{a\gamma\gamma}$ (GeV^{-1})
ADMX (2010, 2018, 2019)
RBF
RBF
ADMX sidecar
ORGAN
UF
CAPP
CAPP
CAPP
HAYSTAC
HAYSTAC
KSVZ
DFSZ
ADMX (this work)
Preliminary
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)



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Sidecar Experiment

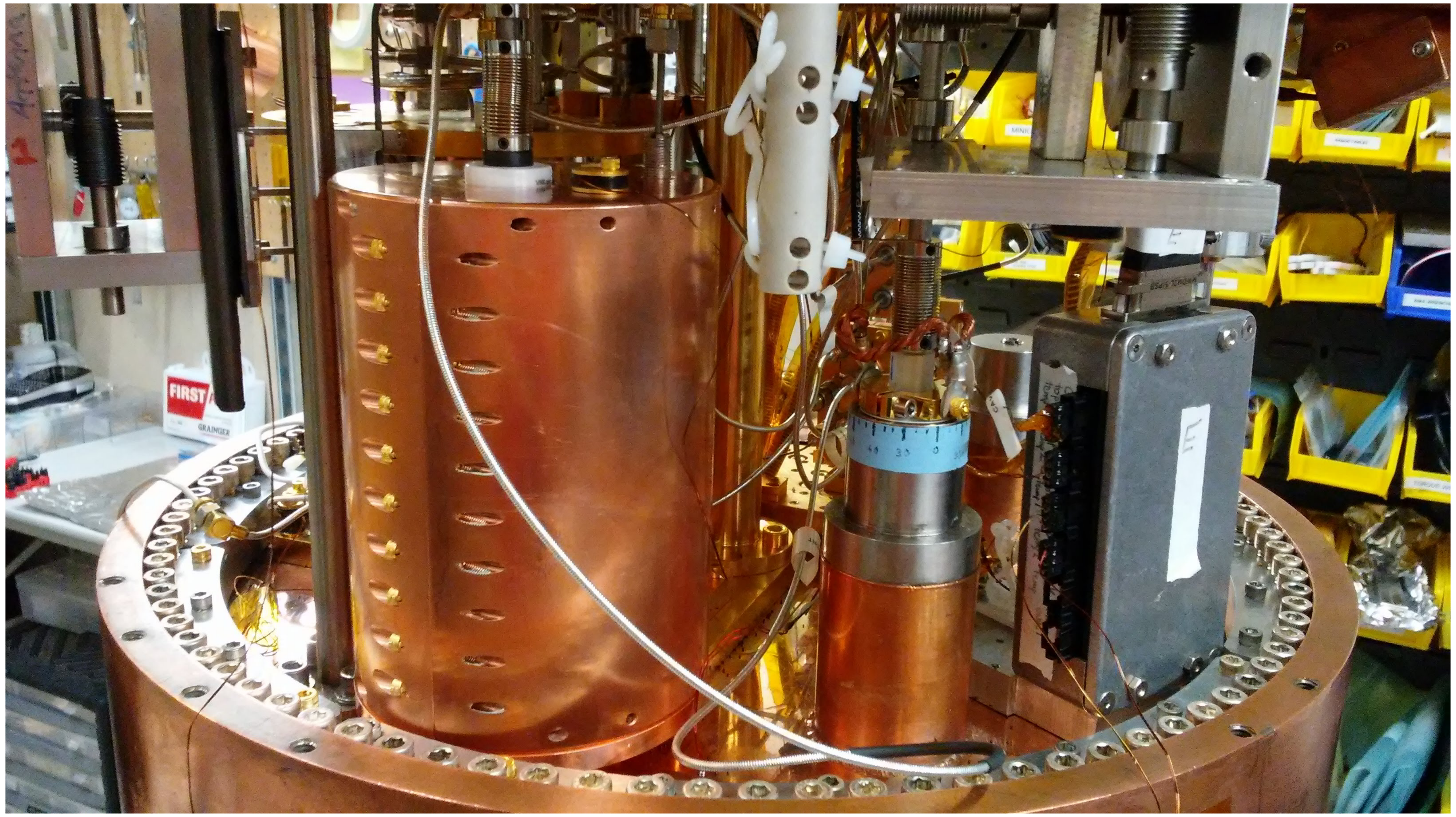
- Sidecar is a small prototyping cavity that sits on top of the main cavity.

- This iteration of sidecar is testing:

  - Traveling Wave Parametric Amplifier (TWPA)

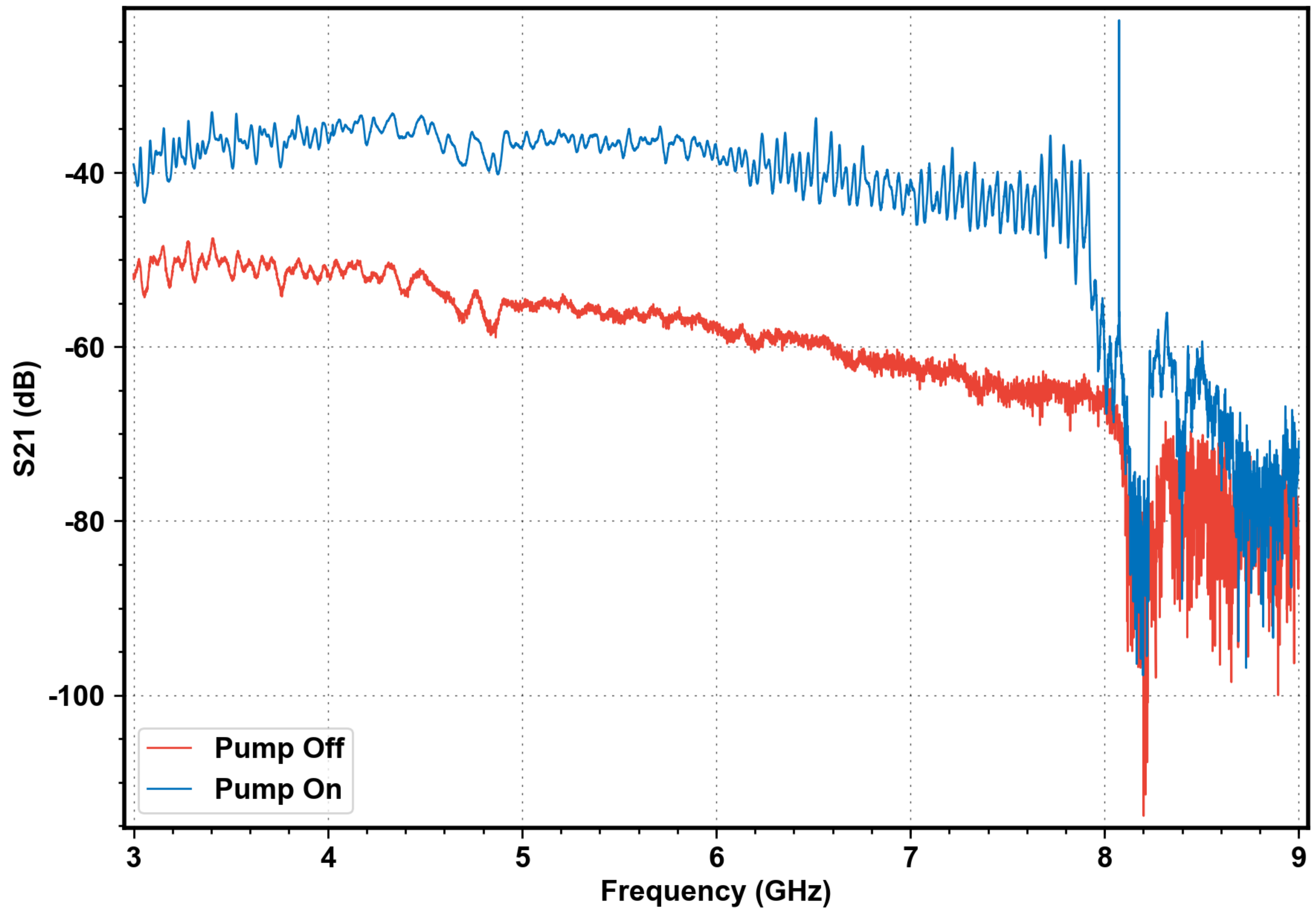
  - Clamshell cavity design

  - Piezo motors for antenna and tuning rod

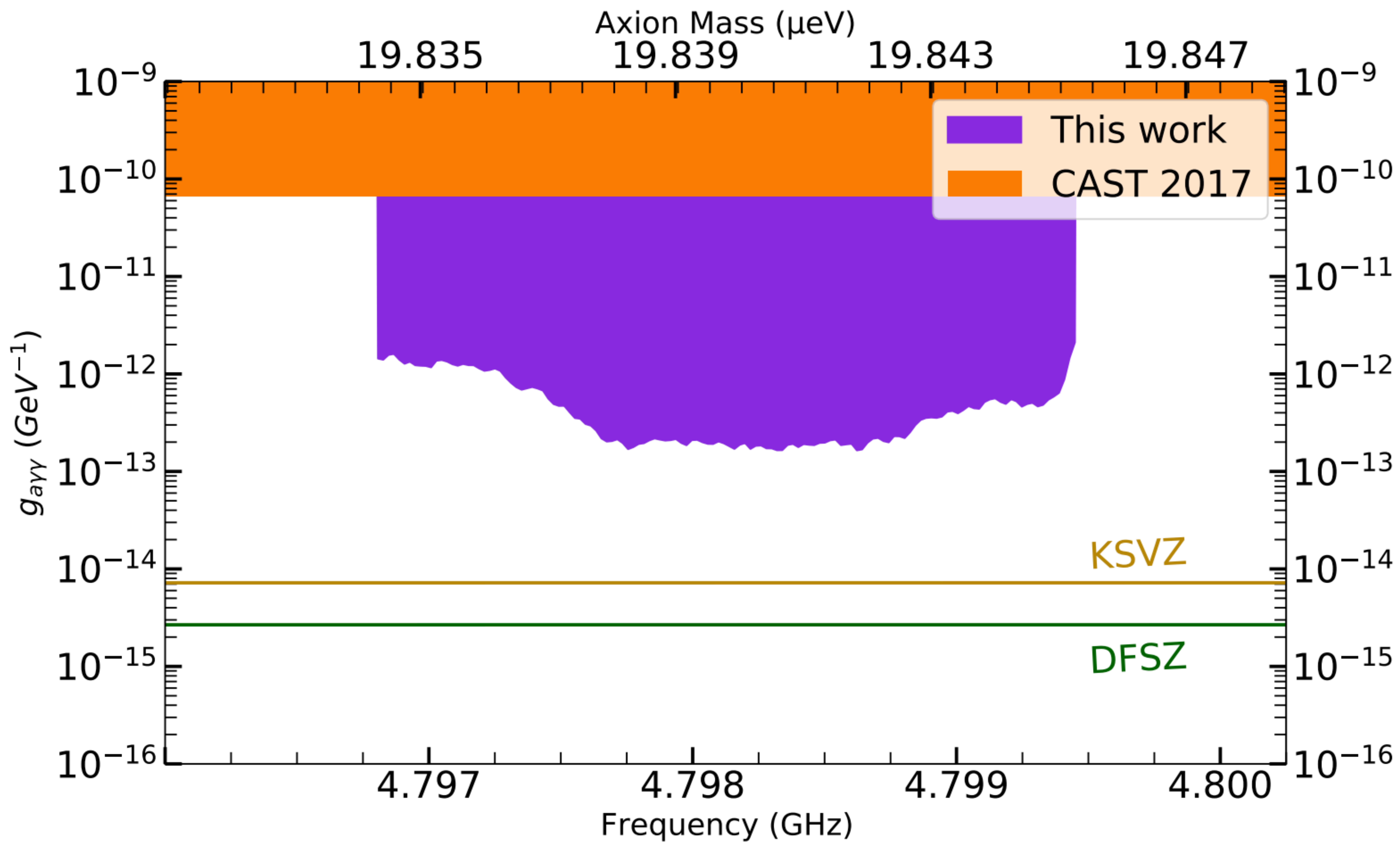


Traveling Wave Parametric Amplifier

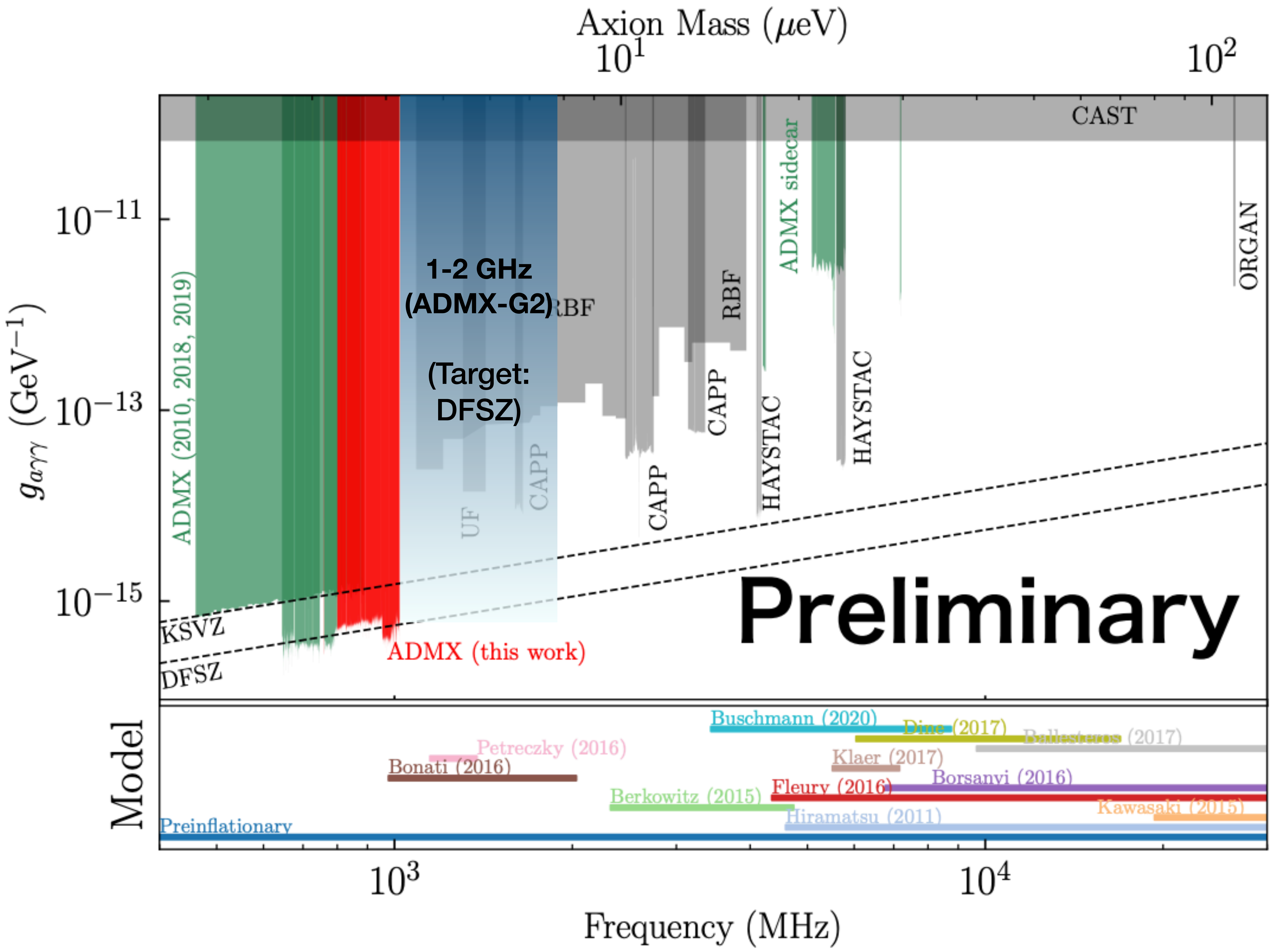
- Benefits of TWPA include
  - Broadband gain spans several GHz.
  - Eliminates need for an additional circulator (Less loss, more space)
  - Reasonable noise performance
- ADMX Sidecar Demonstration
  - Operated TWPA for several weeks in magnetic field
  - Reasonable performance (achieved ~8 dB SNR)



Sidecar Exclusion Plot



Bartram, C., et al. "Dark Matter Axion Search Using a Josephson Traveling Wave Parametric Amplifier." *arXiv preprint arXiv:2110.10262* (2021).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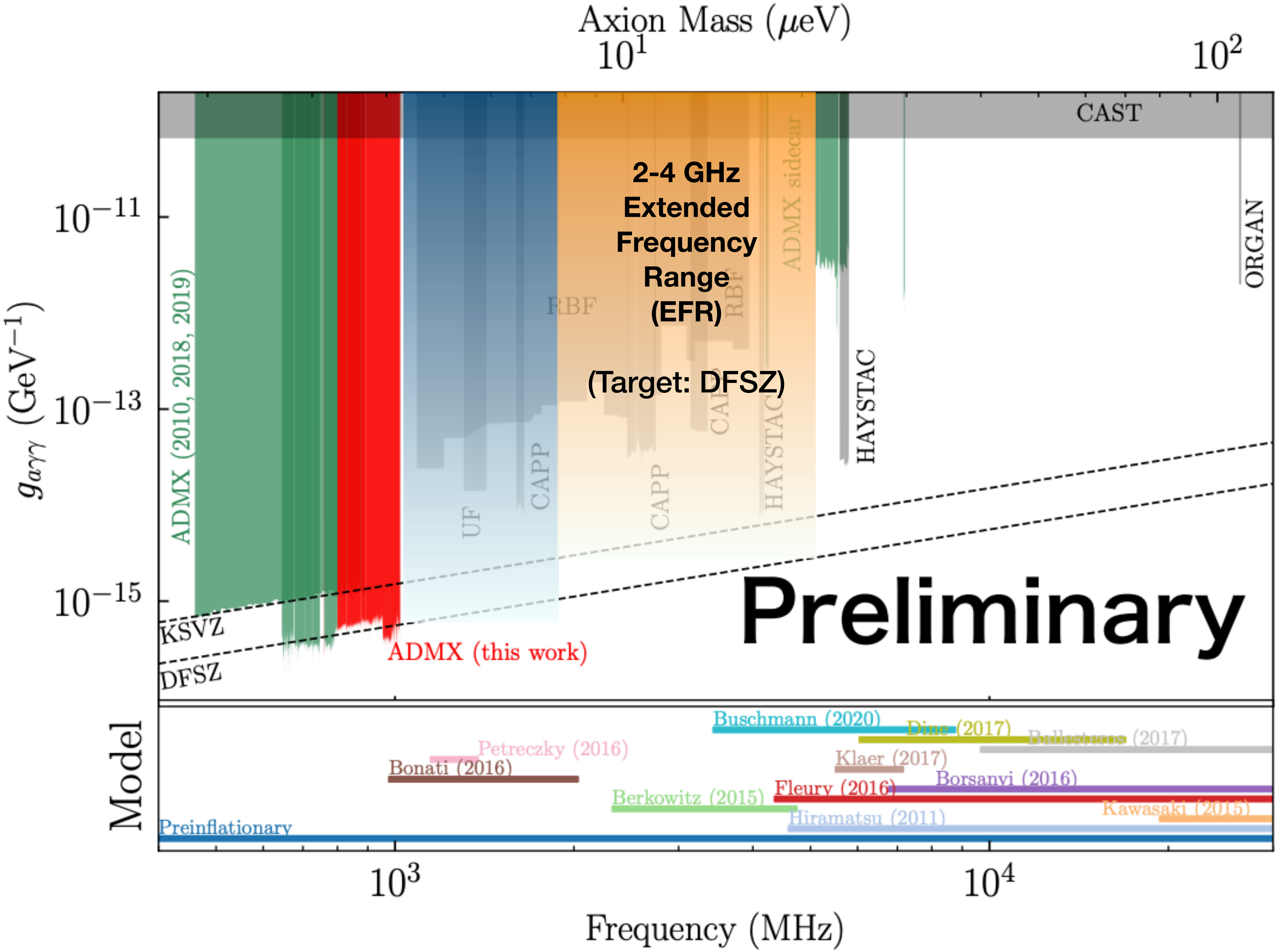

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ORGAN
HAYSTAC
ADMX sidecar
2-4 GHz
Extended
Frequency
Range
(EFR)
(Target: DFSZ)
RBF
CAPP
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ADMX (2010, 2018, 2019)
10^−11
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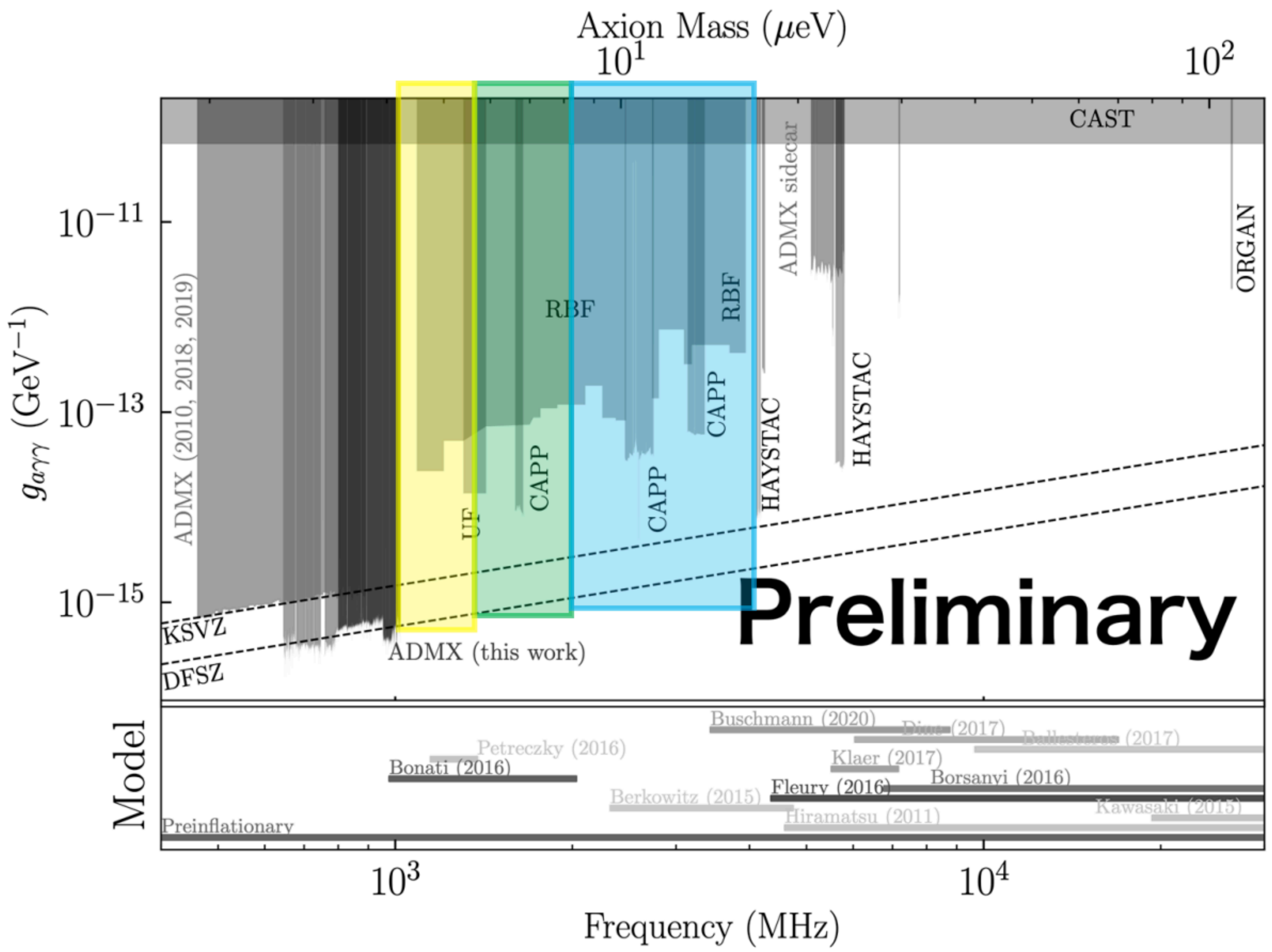
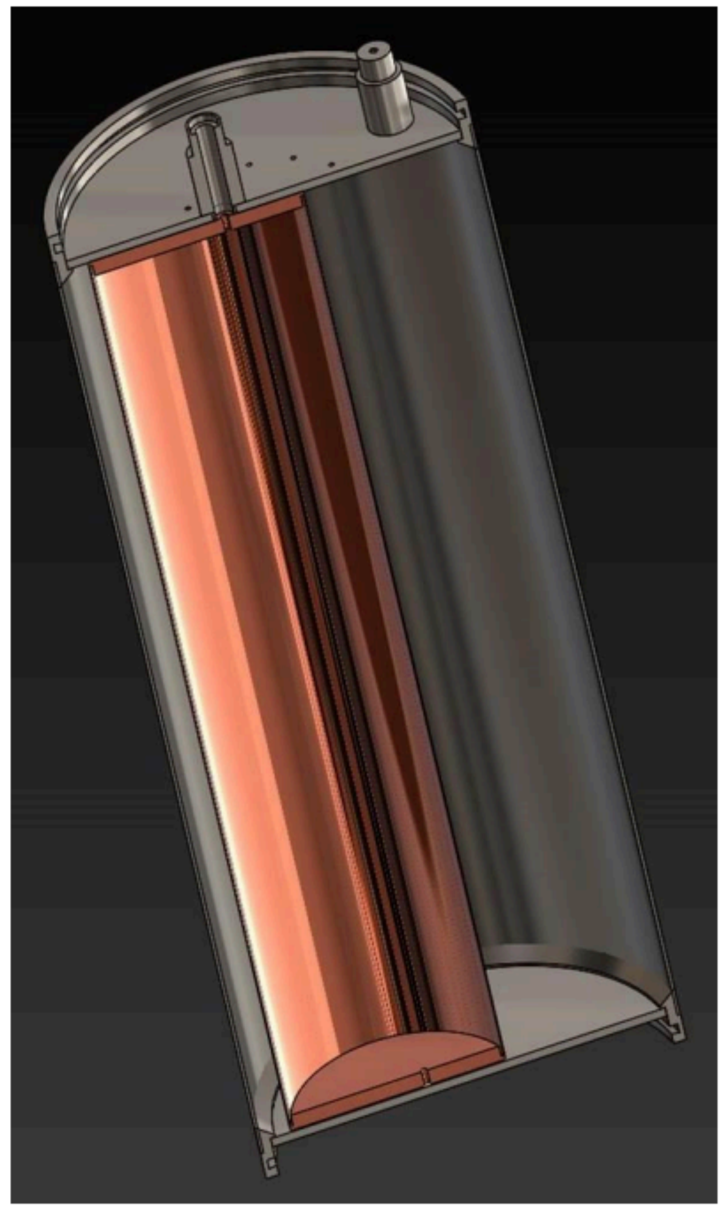
10^3
10^4
Frequency (MHz)

Near-term ADMX strategy



2022--23

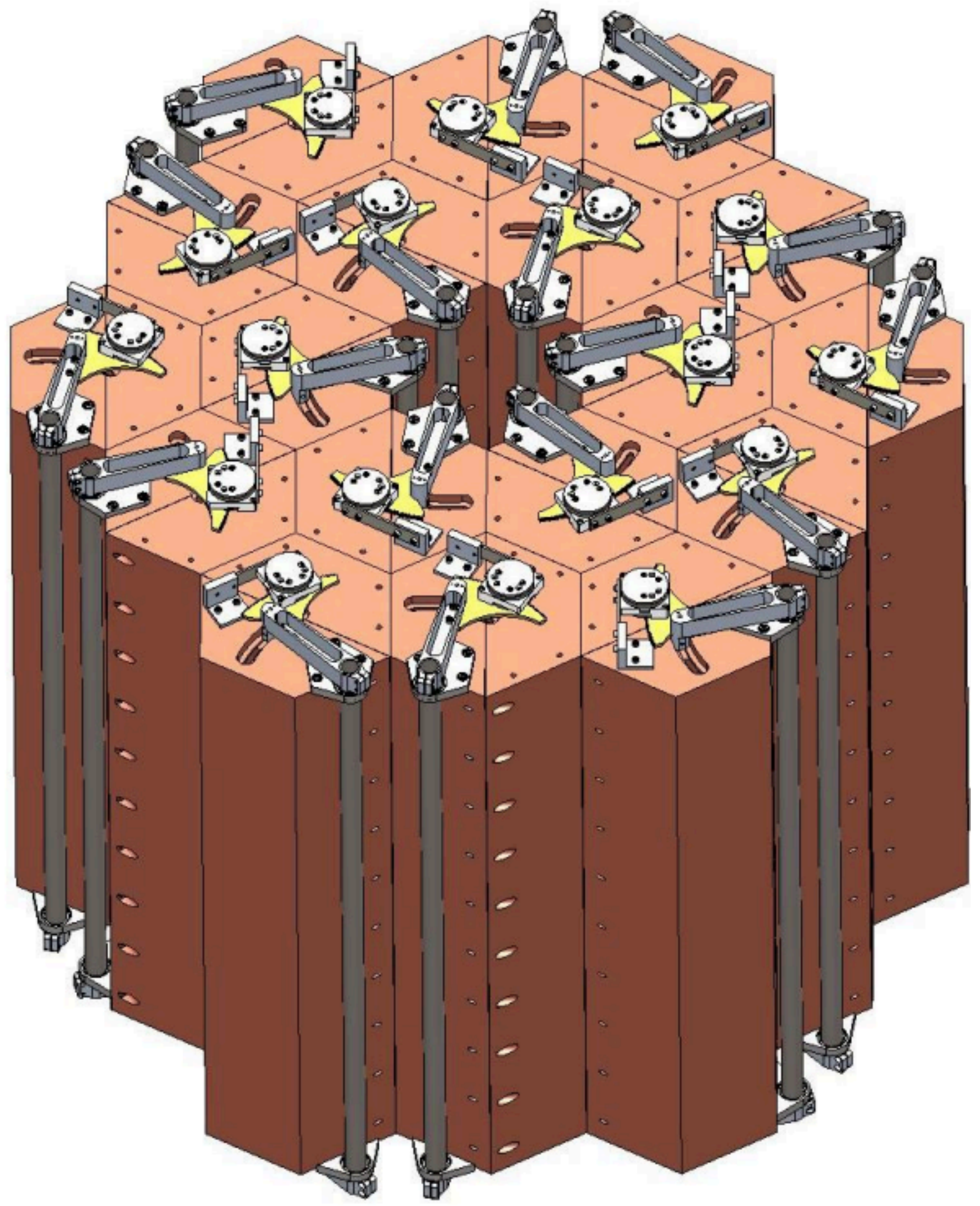


Single cavity
Big tuning rod

2023--25

4-Cavity array

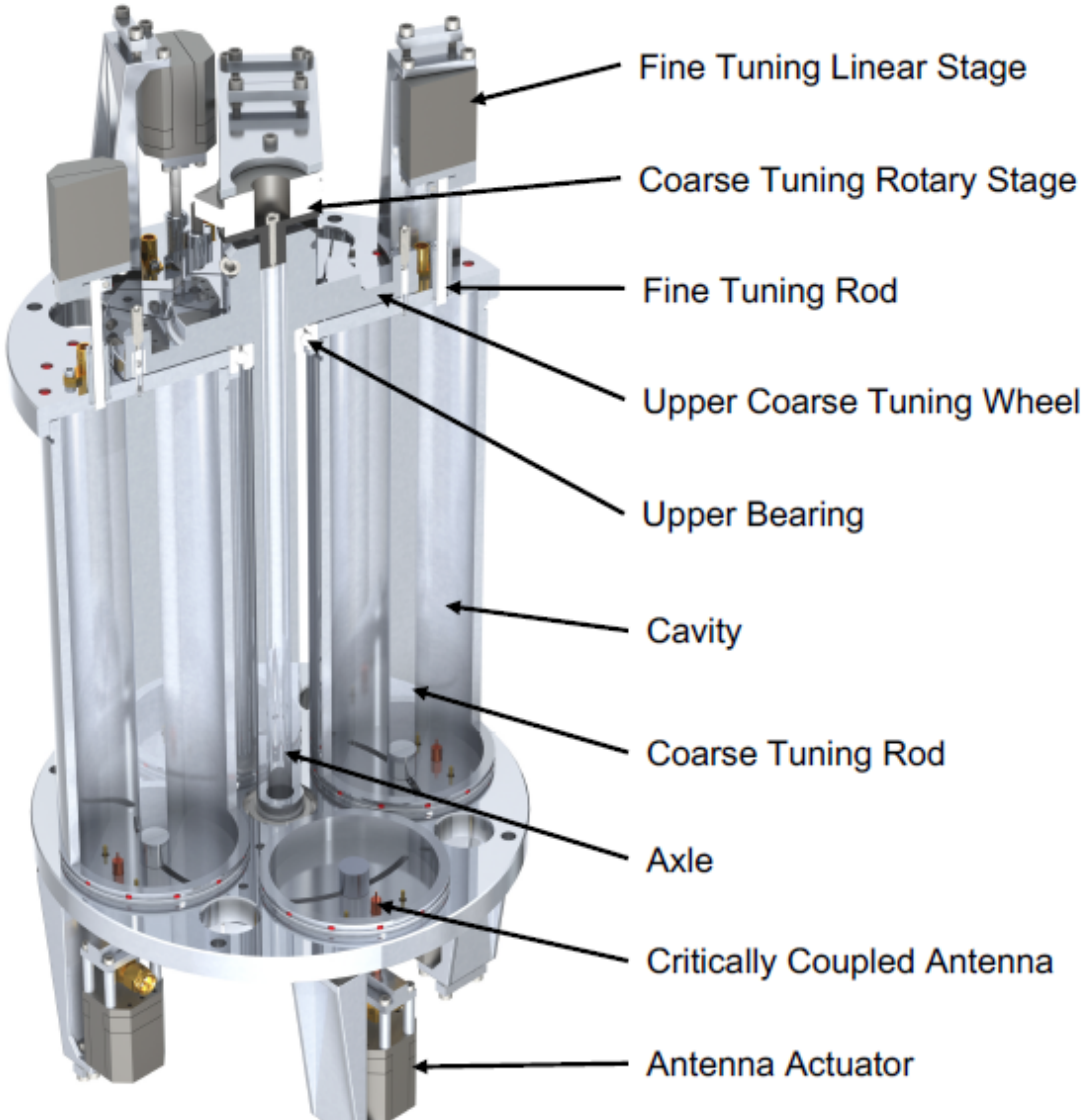
2025--



18-Cavity array

Courtesy of Jihee Yang

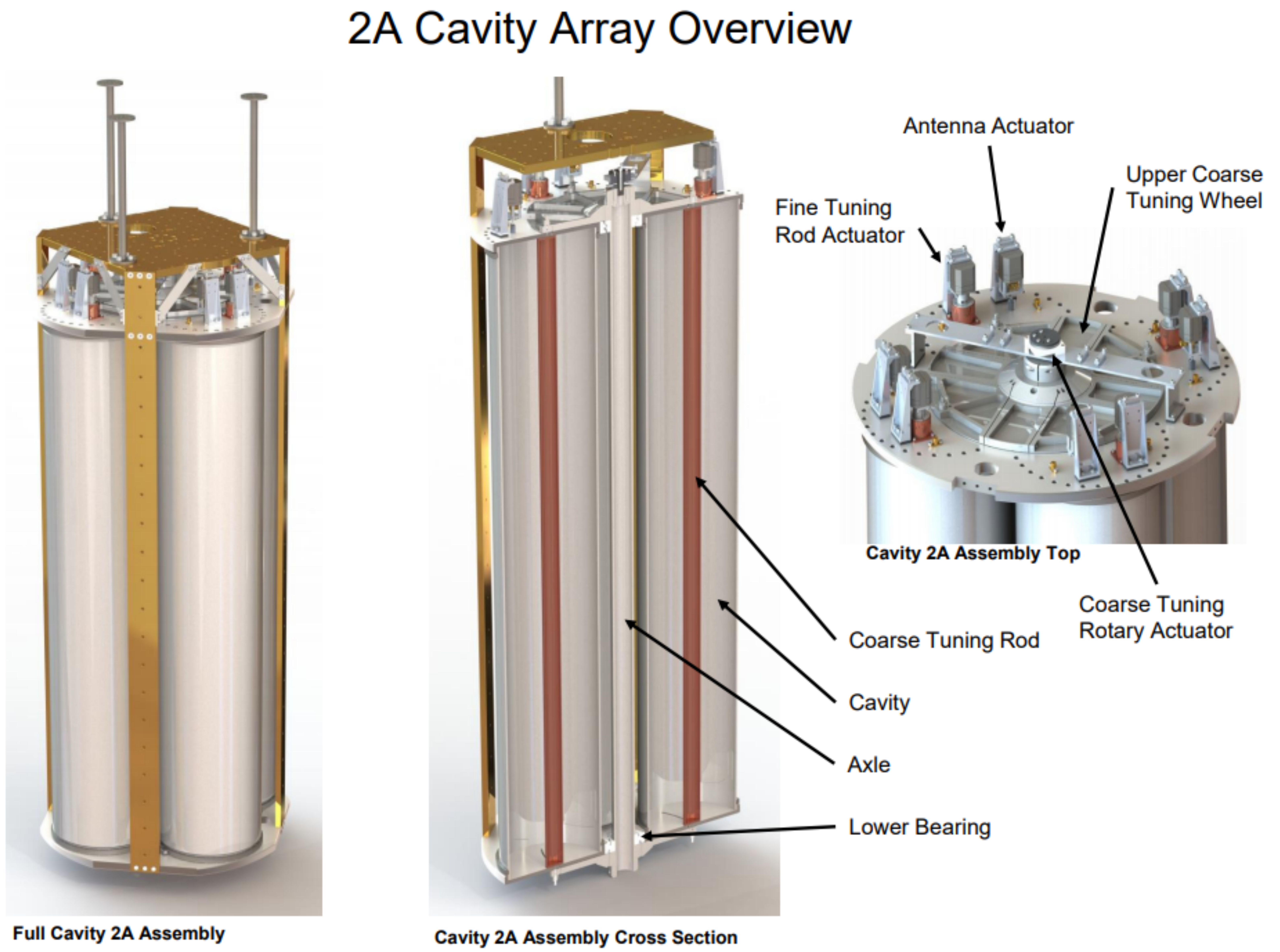
Multi-cavity arrays



4-cavity array planned for University of Washington

- 1.4-2.2 GHz
- Amplitude-combine cavities in phase for improved SNR.
- Scan rate ~ $(N)^2$: N cavities in phase allows factor of N increase in scan rate relative to power combining after the fact
- Setup has common rotor with coarse tuning rods.
- Fine-tuning done by perturbing fields with sapphire mounted to linear stage.

Multi-cavity arrays



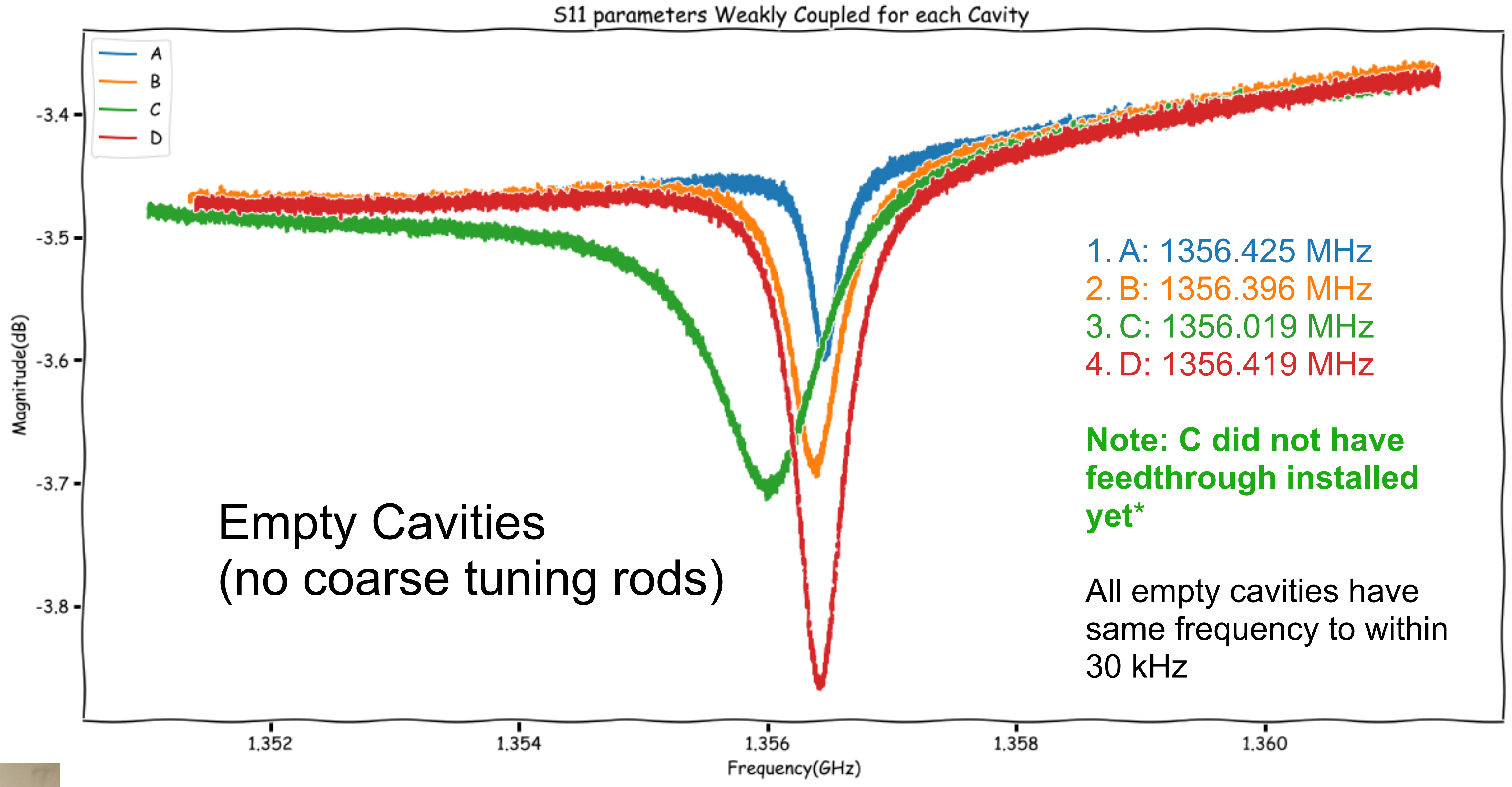
<u>Run 2A & 2B</u>
Frequency range: 1.4-2 GHz
Volume: 76 liters
Anticipated $Q_{unloaded}$ ~ 130k

- Component construction essentially complete (U. of Florida)
- Copper plating completed (LLNL)
- Initial assembly of empty cavity system at LLNL
- Awaiting relaxation of “shelter-in-place” orders to finish room-temperature testing and operations with tuning rods.
- In parallel work on custom power combiners optimized for frequency range (Wash. U. St Louis)

Multi-cavity arrays

4-cavity main cavity assembly at LLNL

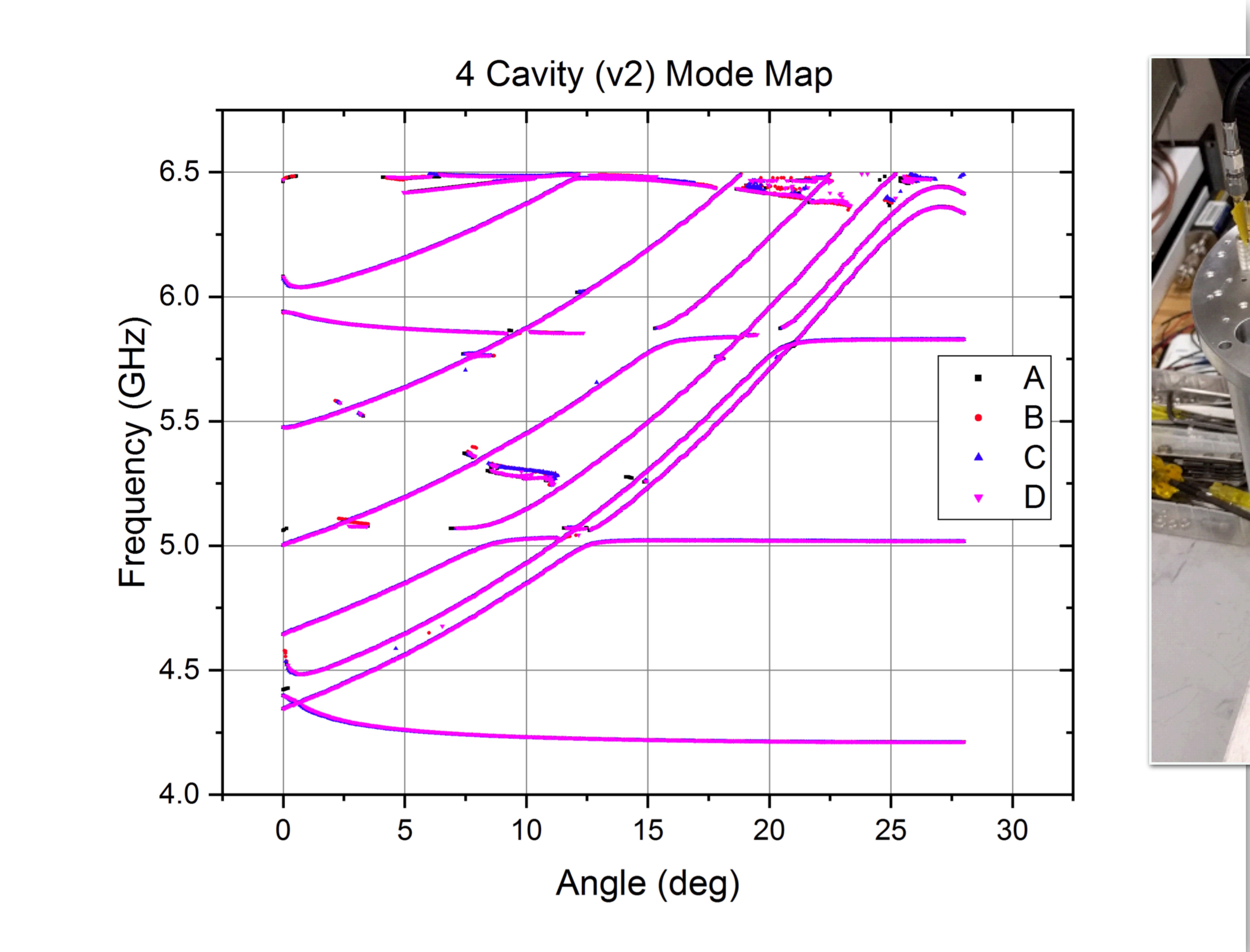
LLNL staff scientist Nathan Woollett (top) and UW grad student Tom Braine (bottom)

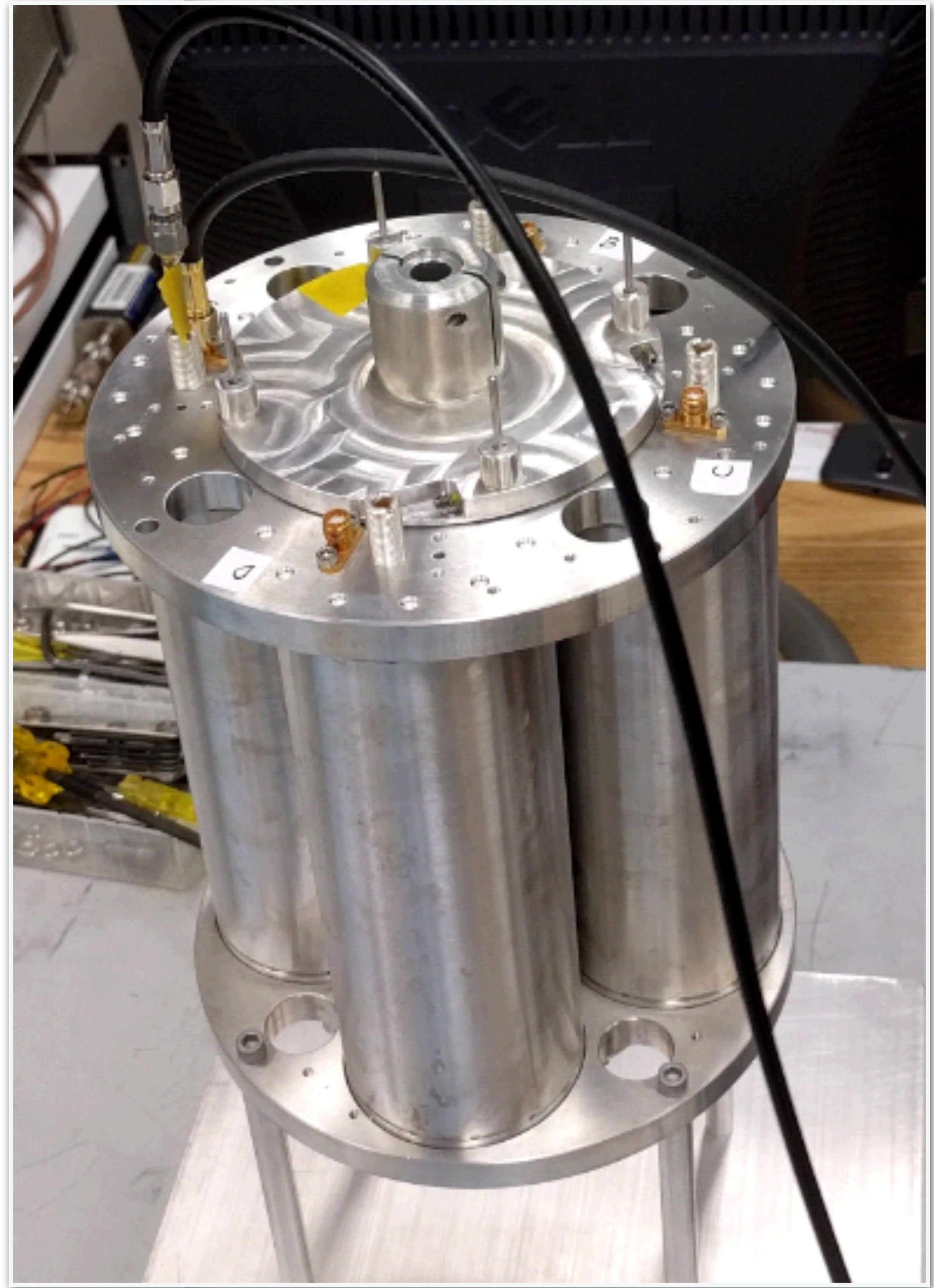


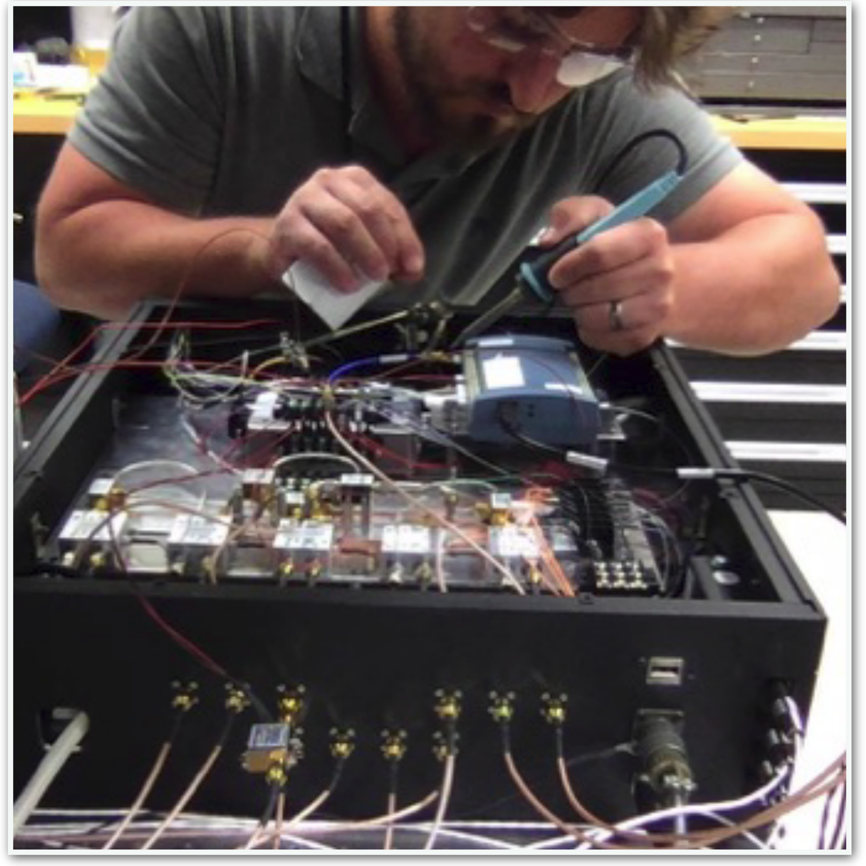
Awaiting relaxation of “shelter-in-place” to continue assembly and testing (including addition of tuning rods)

System then shipped to Fermilab for cryogenic testing.

ADMX Run 2A/B Frequency Locking



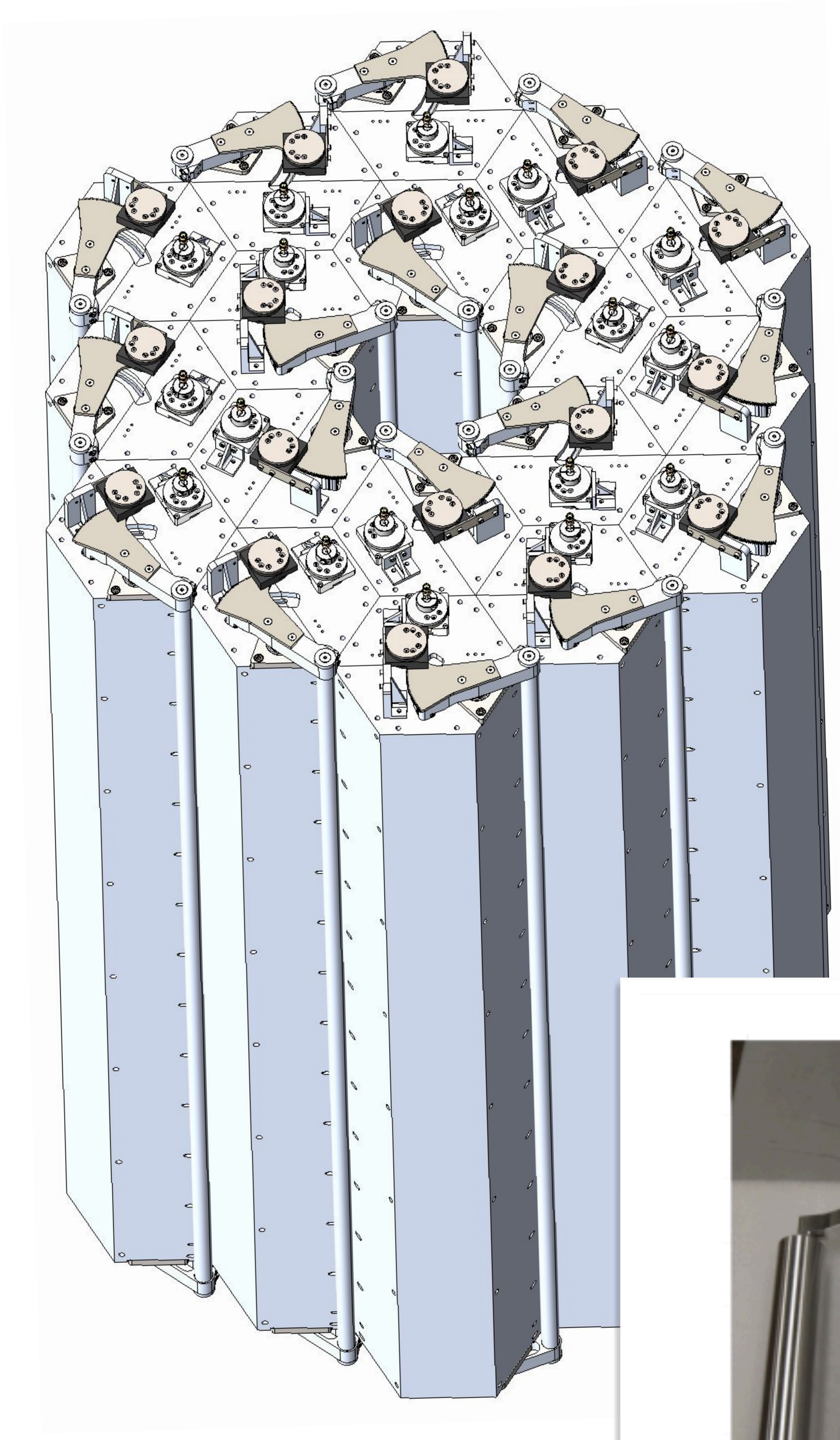


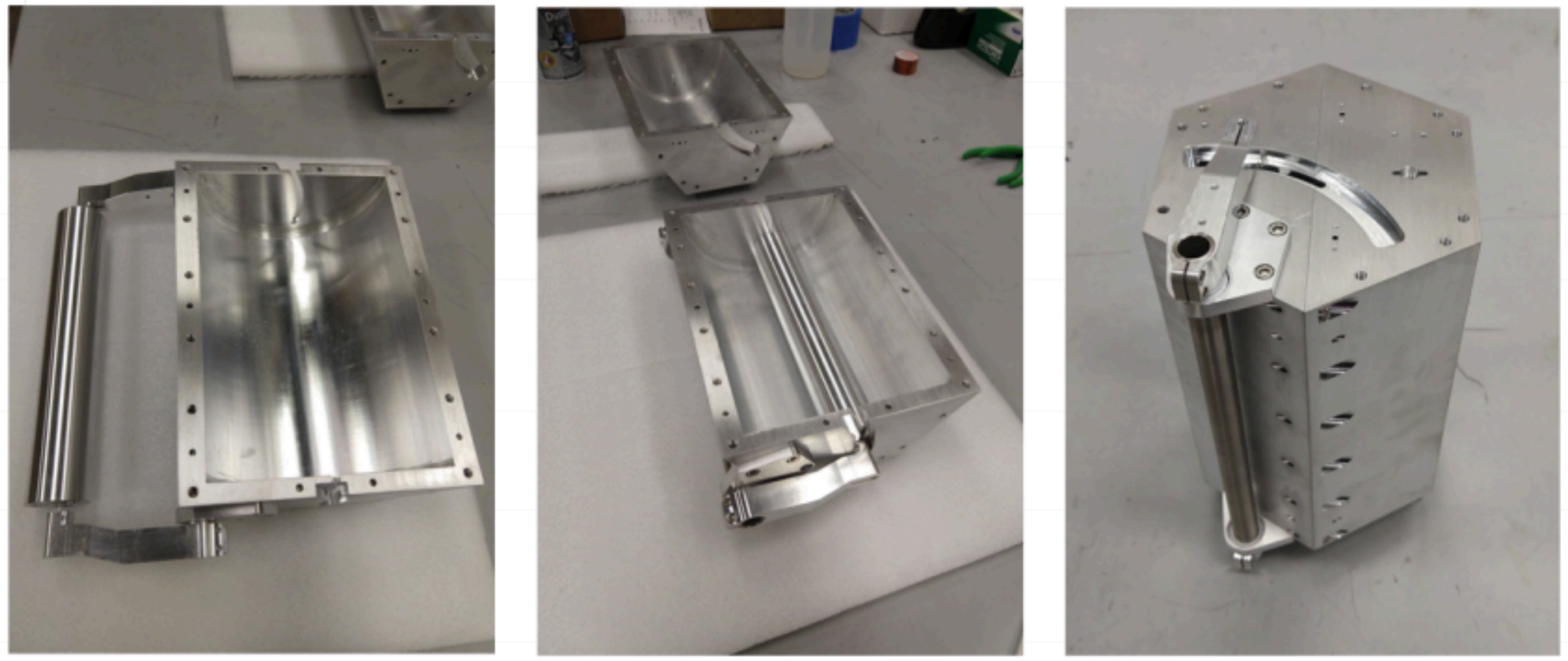


- Prototype Room Measurements down at U. of Florida
- Locking protocol and software implementation by PNNL
- Awaiting cryo-testing at FNAL

ADMX Extended Frequency Range

- Scan rate goes as B^4 = High field critical for future axion searches.
- Scan rate goes as V^2 = Large volume critical for future axion searches.
- ADMX Collaboration plans to use large-bore 9.4 T magnet currently at UIUC.
- Room for R&D work in this magnet as well!





Tuning rod is mounted to arms outside of array

Tuning rod swung into position

Array with fully assembled tuning system

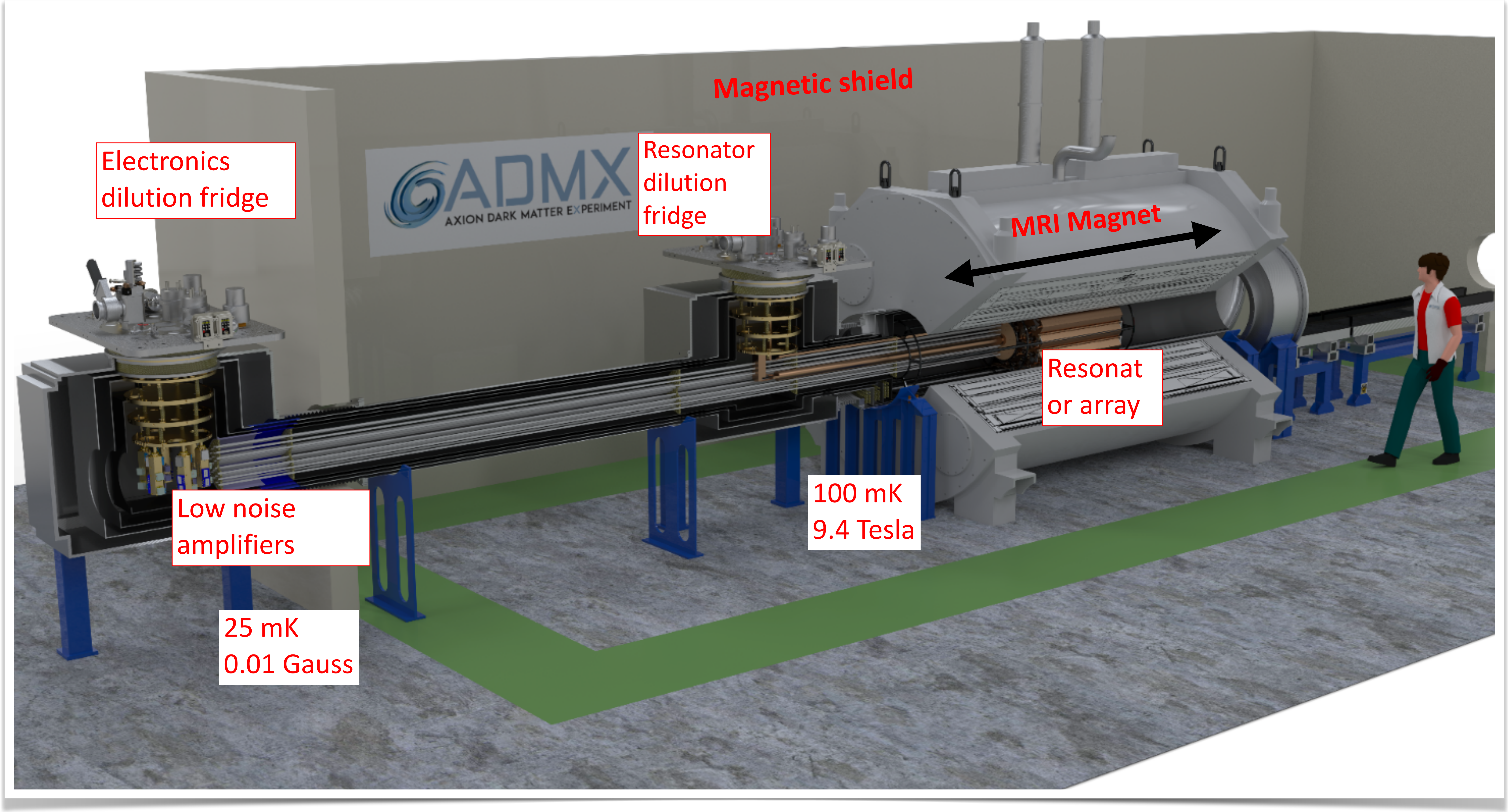
ADMX Extended Frequency Range

	Baseline Requirement	Target Performance	Current Design
Frequency Range	2-4 GHz	2-4 GHz	2-4 GHz
Number of Resonant Cavities	14	14	18
Volume	80 Liters	80 Liters	258 Liters
Q	30,000	90,000	38,000
B Field	7.6 T	12.0 T	9.4 T
Form Factor	0.4	0.4	0.4
Noise Temperature	350 mK	325 mK	425 mK
Amplifier Squeezing	1	1.4	1
Operations Days	1000	1000	1000
Normalized FOM	1	30.3	20.8
Dark Matter Sensitivity for DFSZ Coupling	0.65 GeV/cc	0.12 GeV/cc	0.14 GeV/cc
Dark Matter Sensitivity for KSVZ Coupling	0.15 GeV/cc	0.027 GeV/cc	0.033 GeV/cc

ADMX Extended Frequency Range

New Features

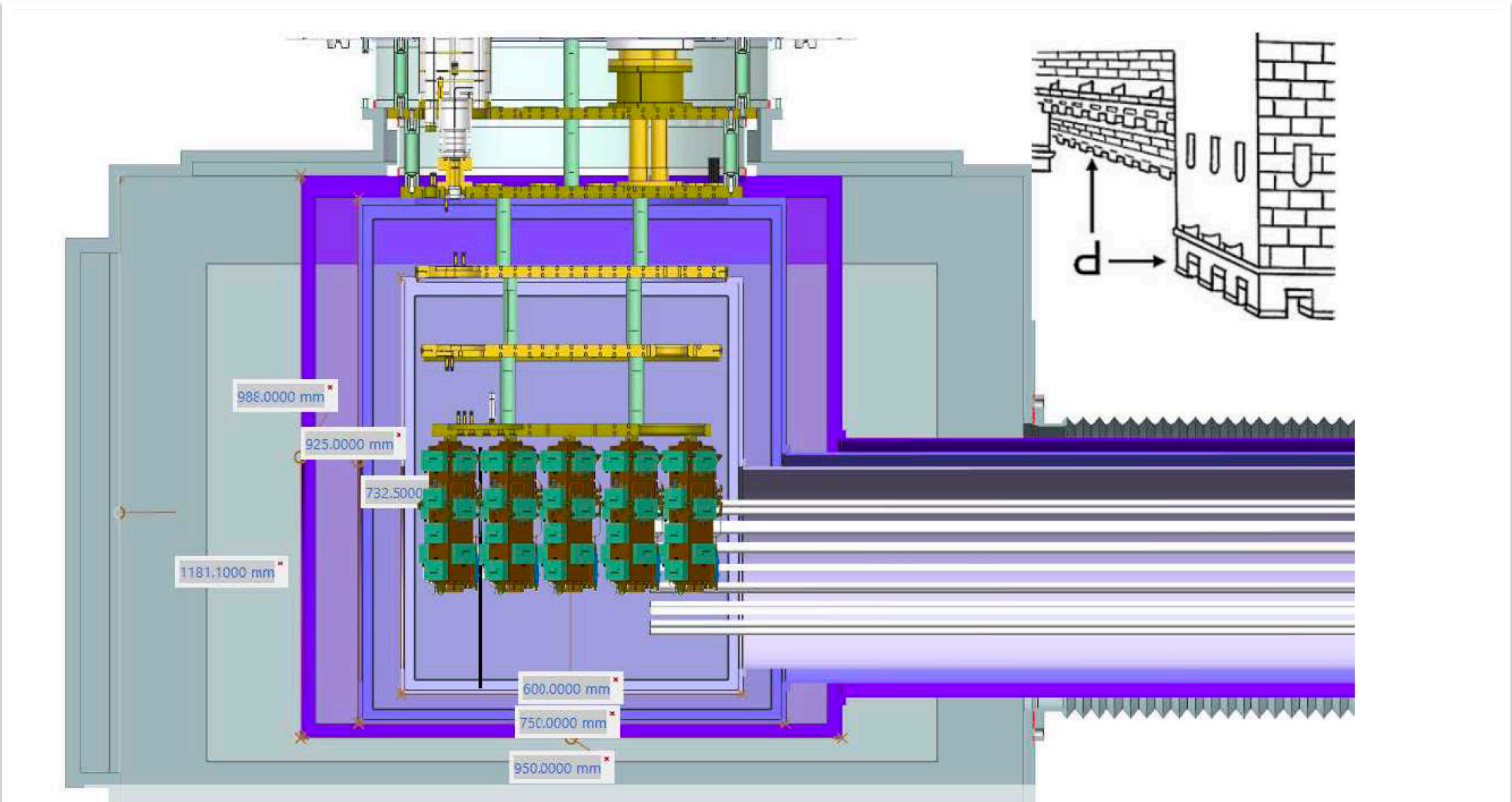
- Horizontal magnet bore
- Extra modularity: cavity electronics are separate from magnet bore
- Large magnet volume: 258 liters
- Preferred site for ADMX-EFR: PW8 Hall at Fermilab
- Other: Squeezing? Superconducting cavities?



(ADMX EFR Design)

ADMX Extended Frequency Range

Squidadel —> Parapet



- Could easily fit 12 parapets or ≈24 channels (with squeezing) in cold space using existing circulator and JPA packaging.

Conclusions

- ADMX Run 1C covered 3.3-4.2 μeV assuming 100% dark matter density
    - 2xDFSZ coupling in the range from 950-1020 MHz
    - 1xDFSZ coupling in the range from 800-950 MHz
- Run 1C part 2 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

Acknowledgements

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