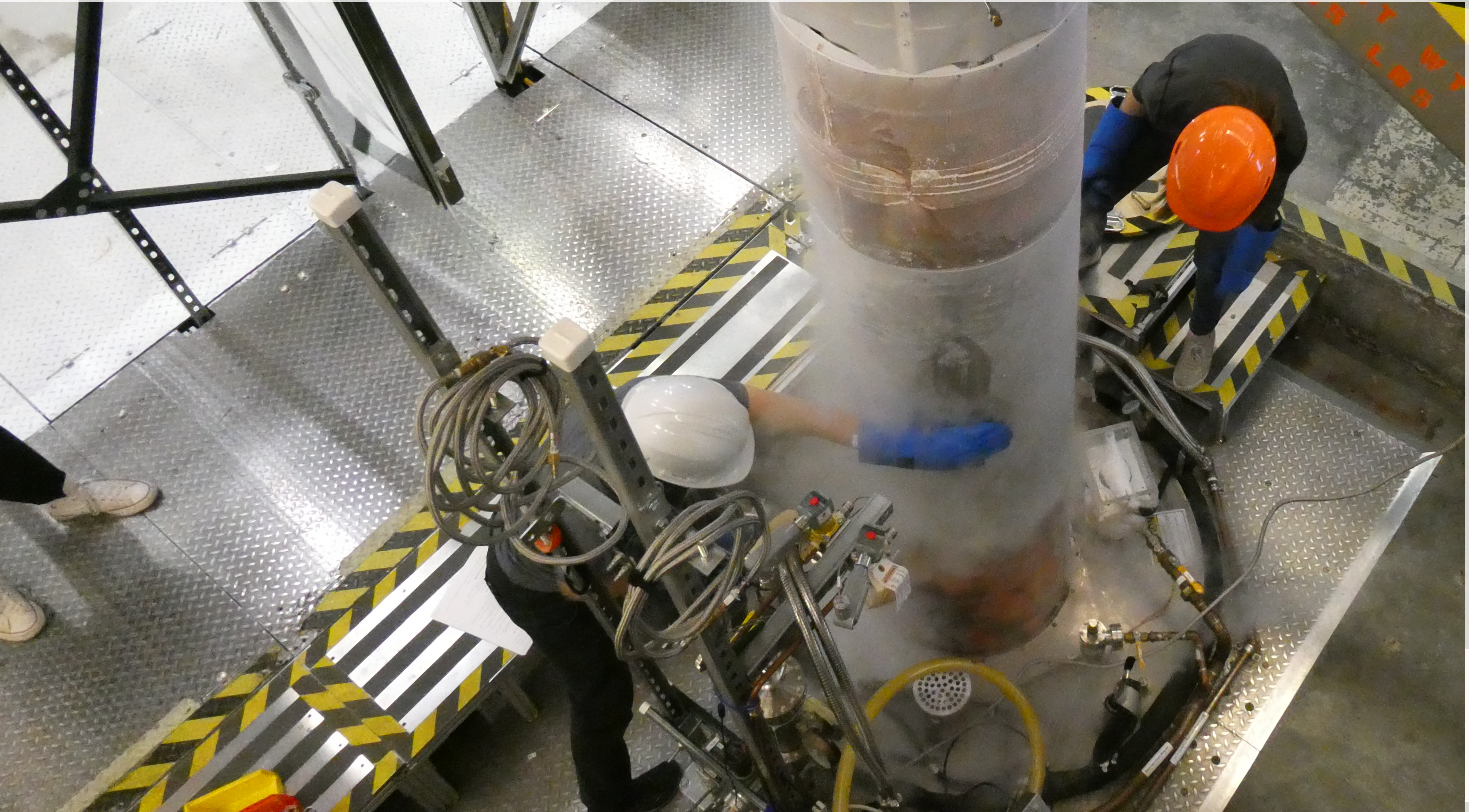
(Halo) Scoping out the axion parameter space

Chelsea Bartram
University of Washington



PATRAS
06/18/201

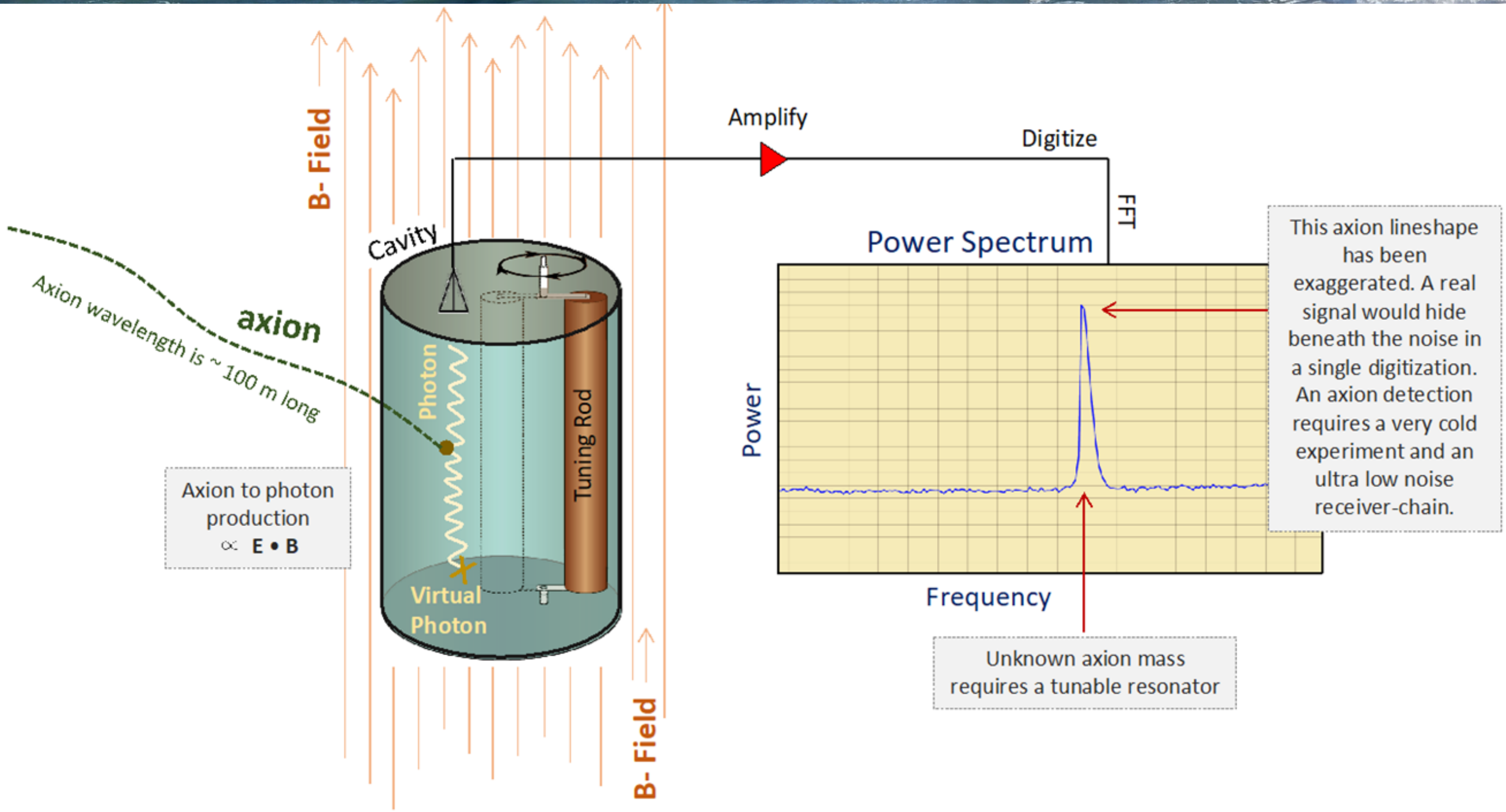
AXION DARK MATTER EXPERIMENT


Can explain *all* the dark matter
Solve the Strong CP Problem
Wave-like Dark Matter
de Broglie wavelength
~100s of meters
QCD Axion


KSVZ
(Kim-Shifman-Vainshtein-Zakharov)
DFSZ
(Dine-Fischler-Srednicki-Zhitnitsky)


KSVZ
DFSZ

Resonant Cavity Haloscope



Scan Rate

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

Maximize	Defined by nature	Minimize

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

Axion Dark Matter eXperiment (ADMX)

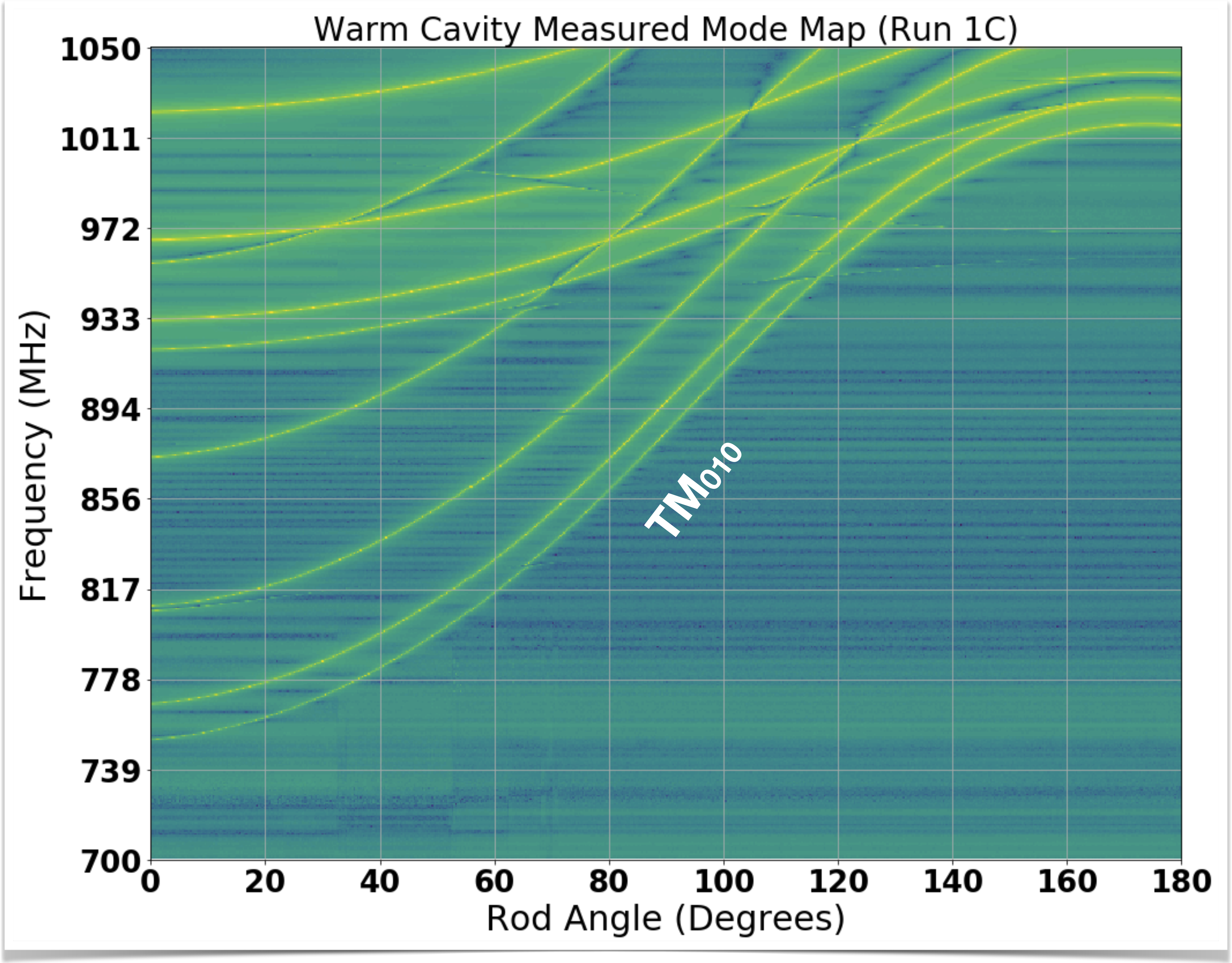
- Built and operated at Livermore (1994-2010)
- Operating at CENPA, University of Washington (2010-Now)
- Most sensitive resonant cavity haloscope experiment. Sensitive to DFSZ axions.
- One of 3 “Gen-2” Dark Matter Projects
- Global collaboration of 11 institutions

Primary Sponsor

Sponsors

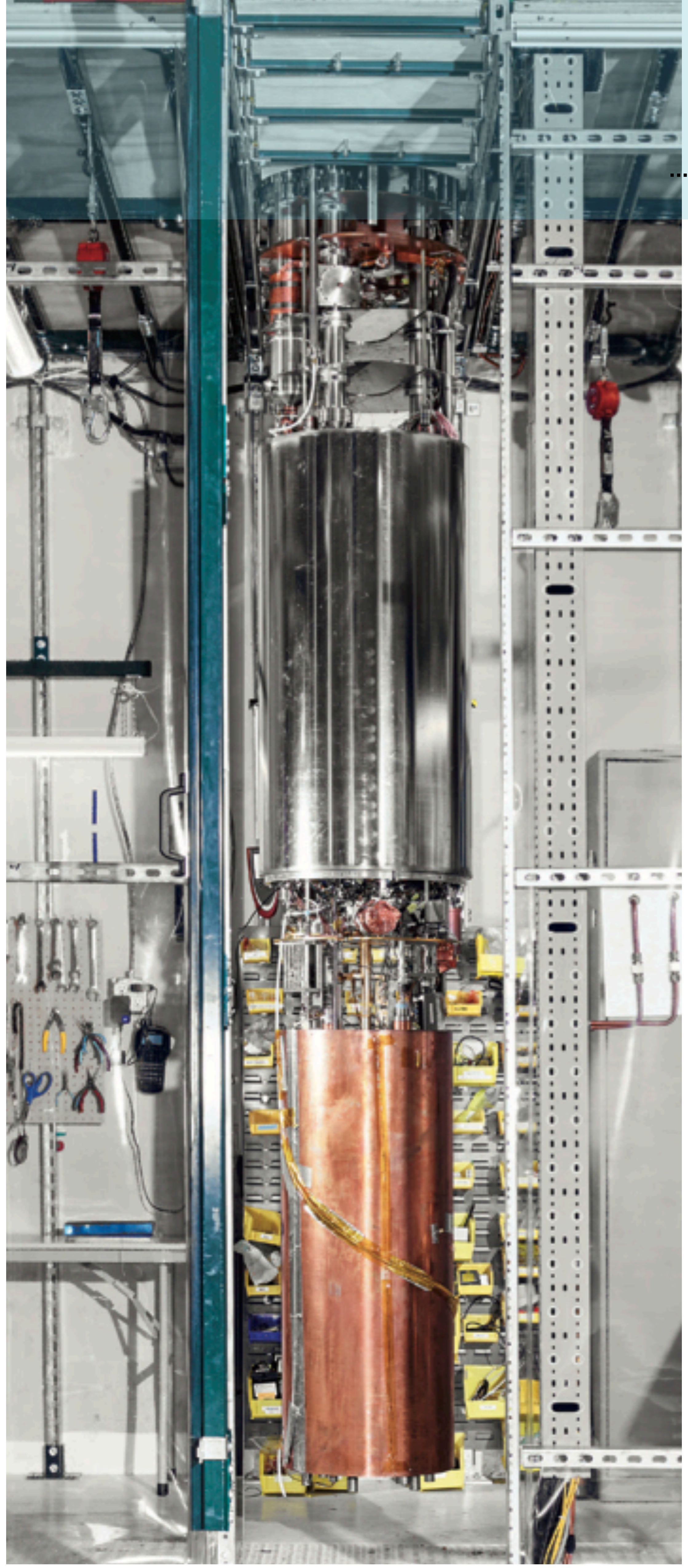
Run 1C Science Goals

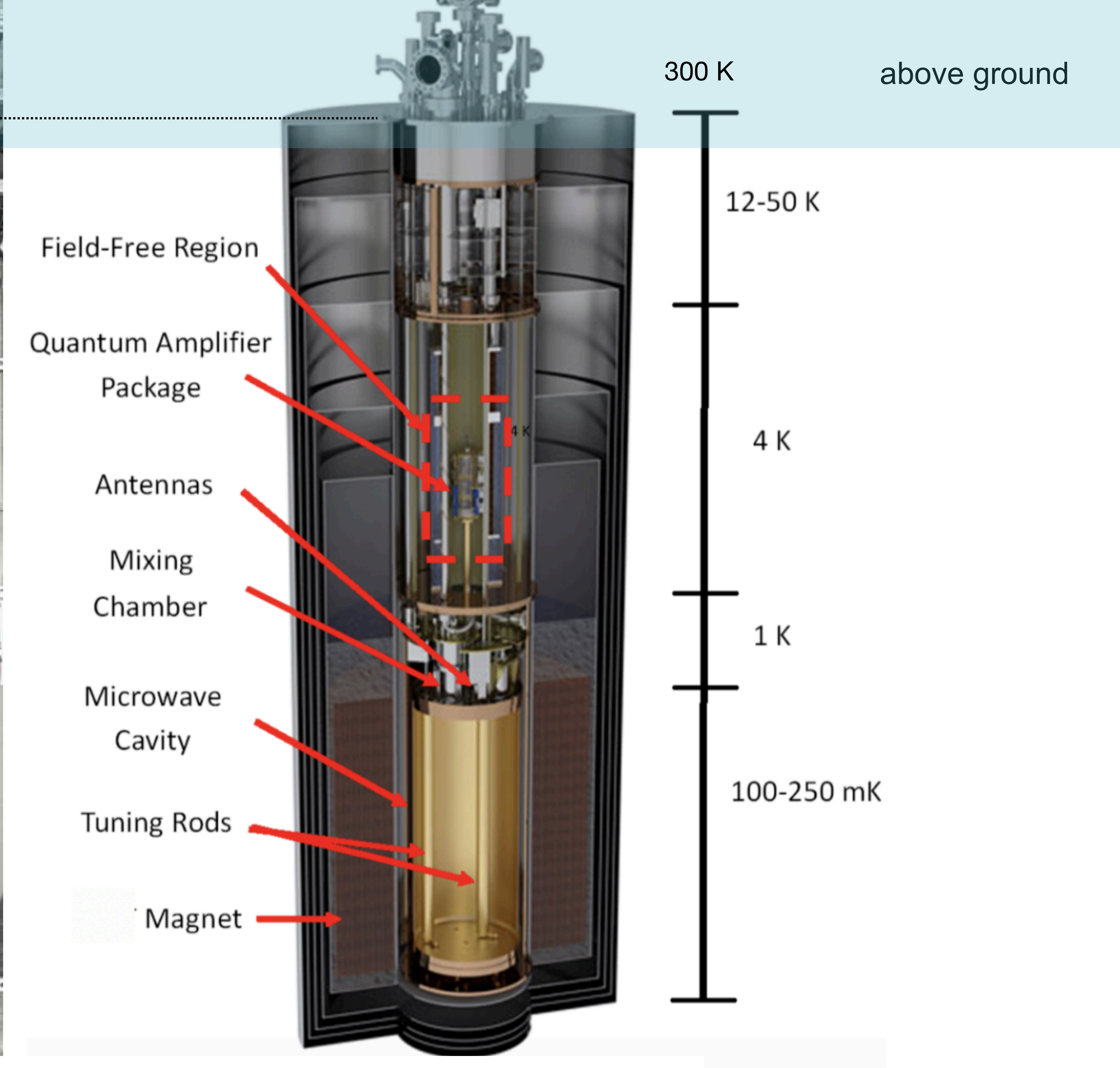
- Target Frequency (Mass) Range: 800-1020 MHz (3.3—4.2 μeV)
- Medium Resolution and High Resolution data sets
- Goal of DFSZ sensitivity
  - Improve quality factor.
  - Improved understanding and operation of quantum amplifiers.
  - Improved noise temperature.
- Other upgrades:
  - New digitizer
  - Upgraded RF software
  - Improved synthetic axion capabilities



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-G2 Run 1C

Period

- Commissioning at UW started March 2019
- October 2019 - May 2021 —> 2x $g_{a\gamma\gamma}$ DFSZ
- Fall 2021 - ? —> 1x $g_{a\gamma\gamma}$ DFSZ

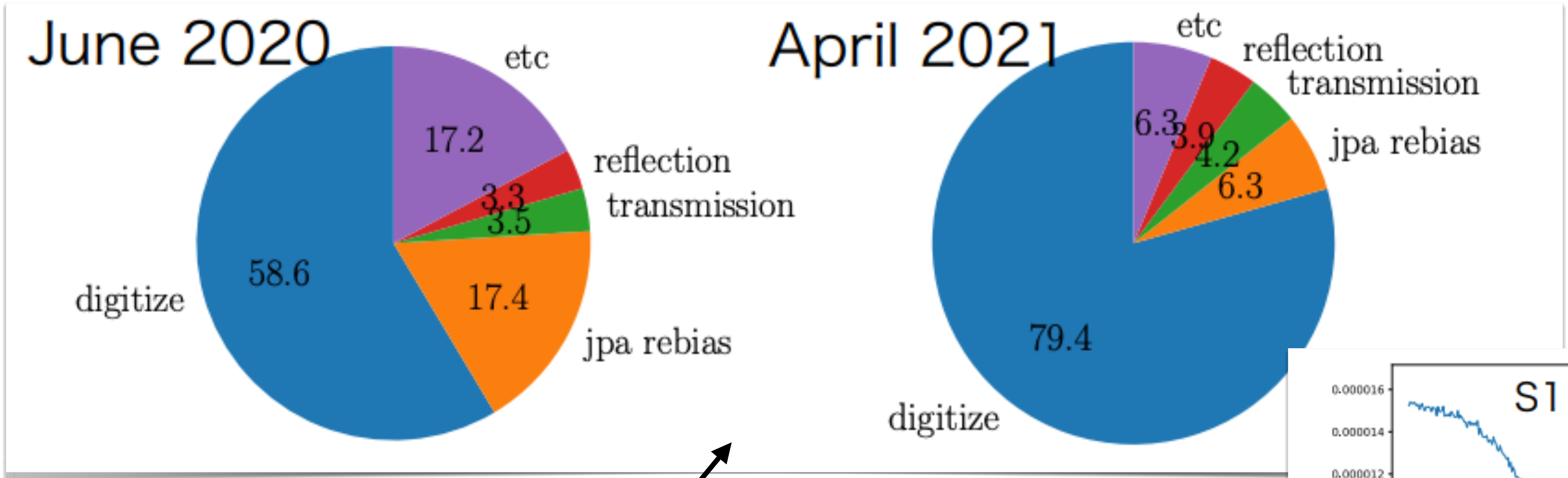
Frequency Range

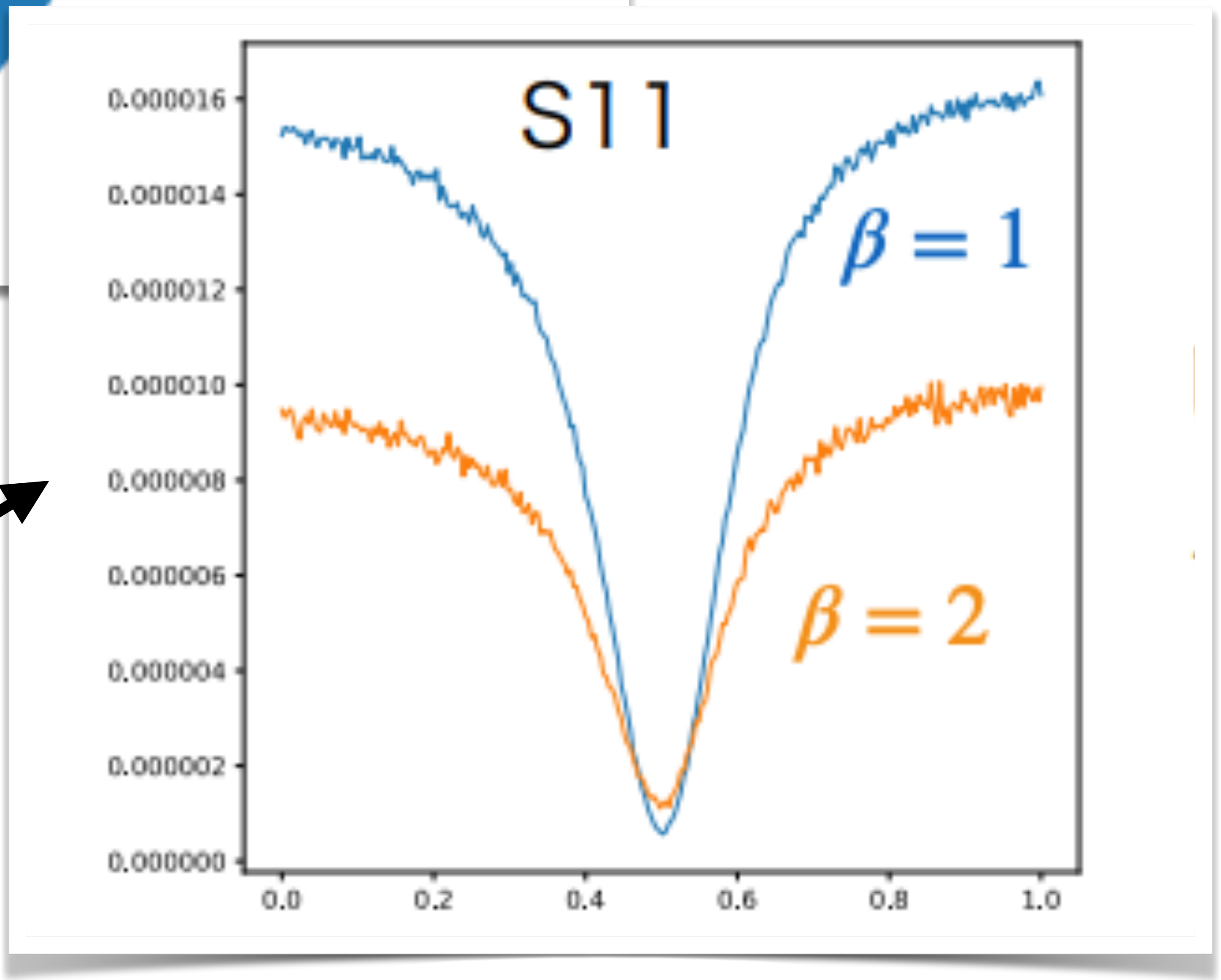
- 800-1020 MHz
- Widest run period for a DFSZ search

Typical System Noise

- 600 mK (includes cavity->JPA attenuation)

Scanning improvements



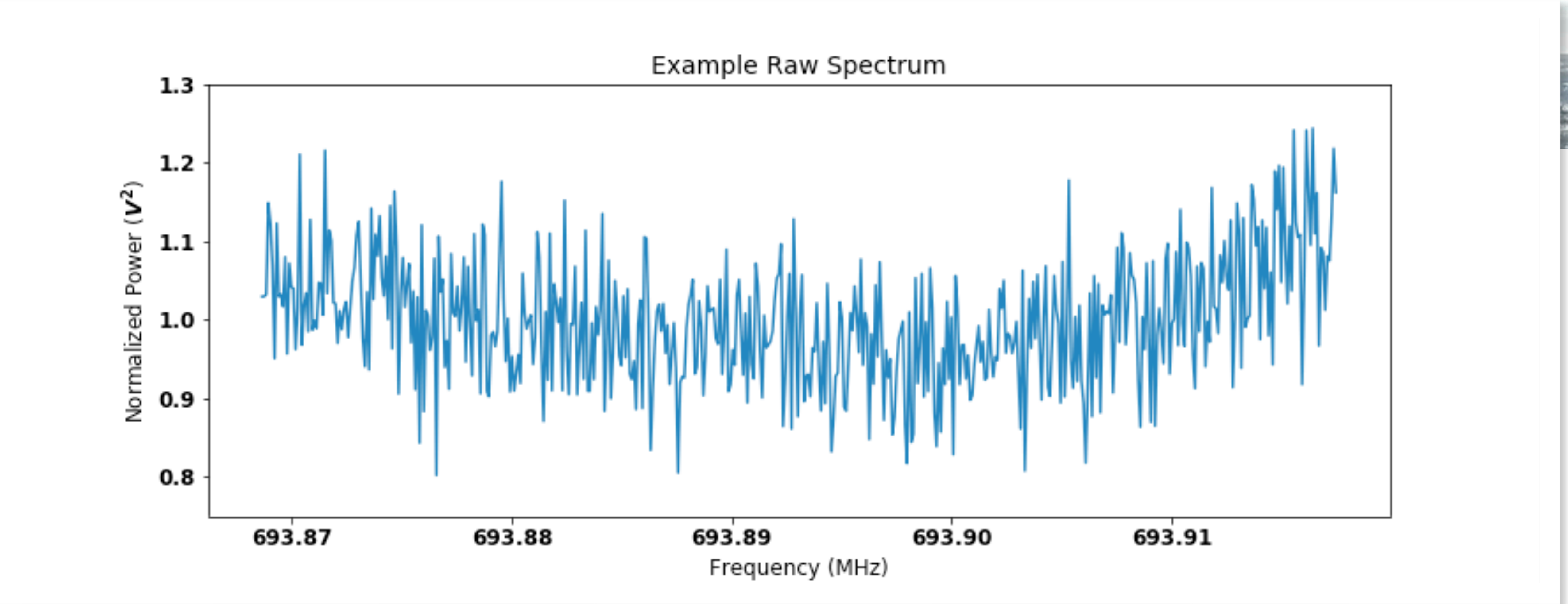


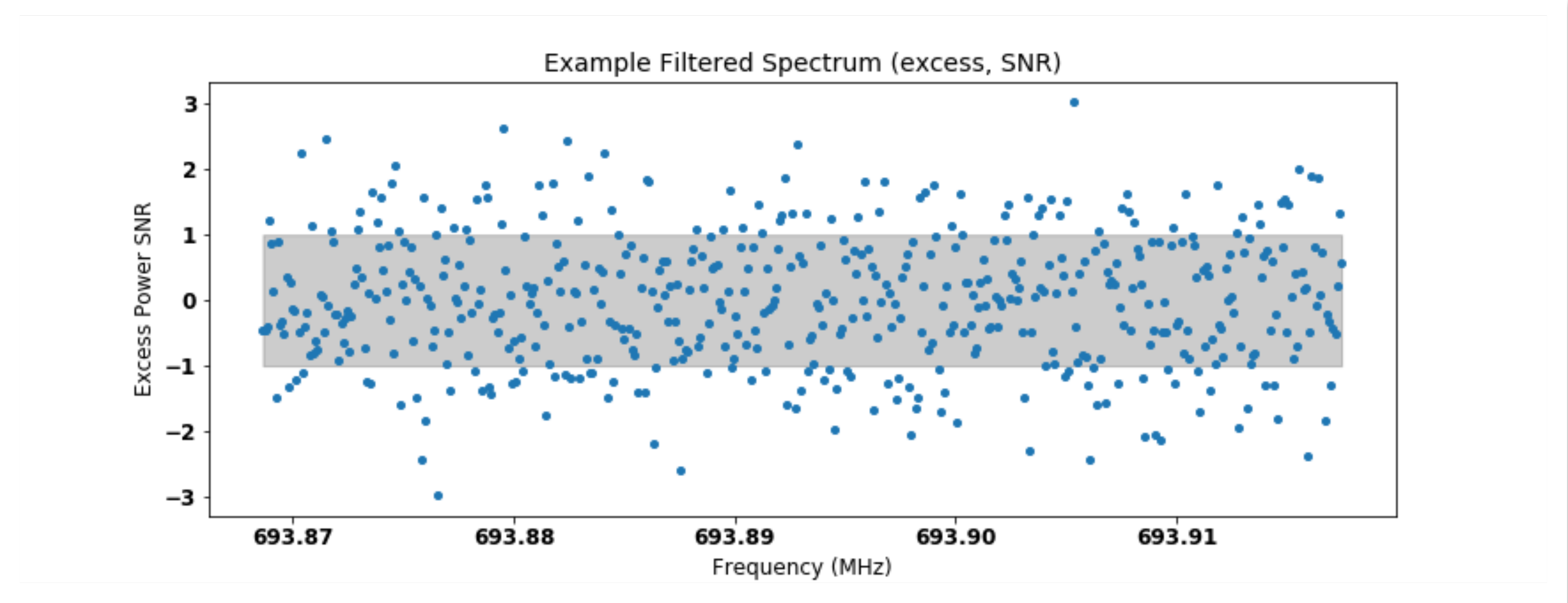
Optimizing the JPA rebiasing

Adjust coupling to cavity (beta = 2): 20% scan rate increase

Analysis

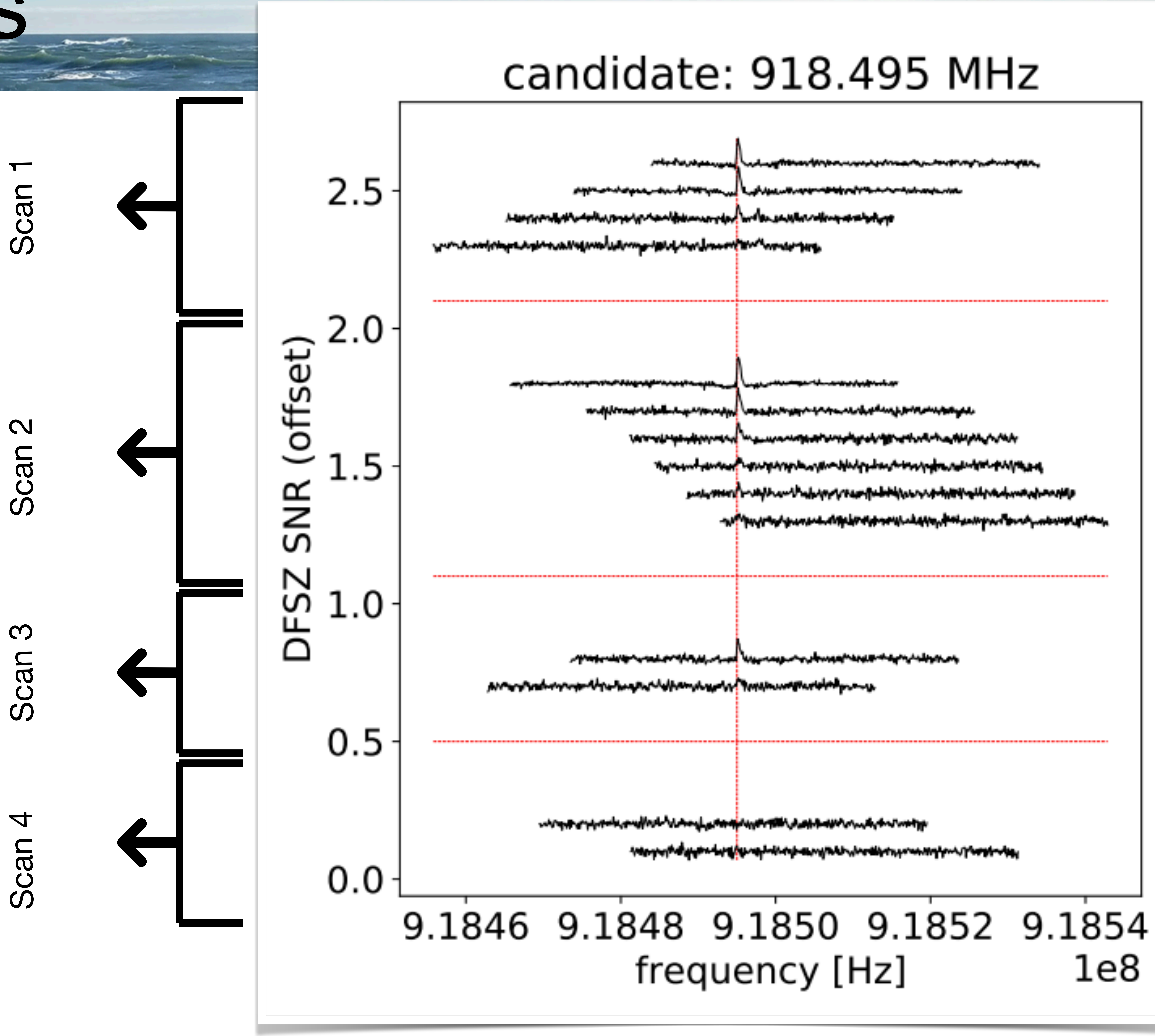
- Data set of > 100,000 spectra.
- Spectra are processed by removing the receiver shape
- Obtain roughly Gaussian noise centered around zero in the absence of an axion signal
- Combine individual spectra into grand spectrum and apply line-shape filter
- Search for candidates
- In general, rescan for 3 conditions
    - Too low SNR (need more data)
    - 3-sigma excess
    - Excess at DFSZ axion power or above





Persistence Checks

- Virialized axion signal is persistent.
- RFI that comes and goes is clearly not an axion.
- Time between scans typically 2 weeks or less. Important details for high-res search.
- Distinguish between synthetic axion signals and real signal.

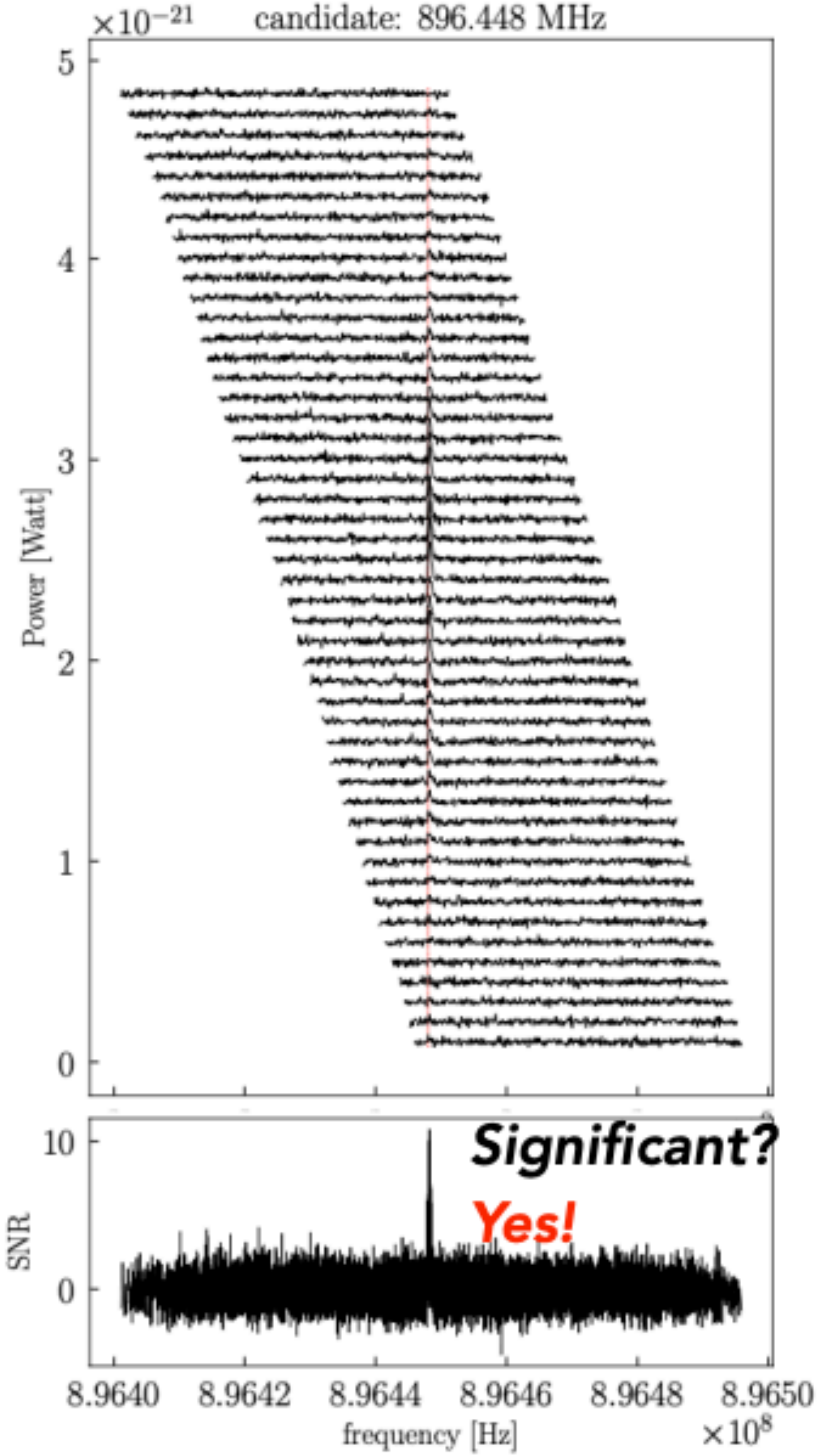


Synthetic Axion Detection (SAG)

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

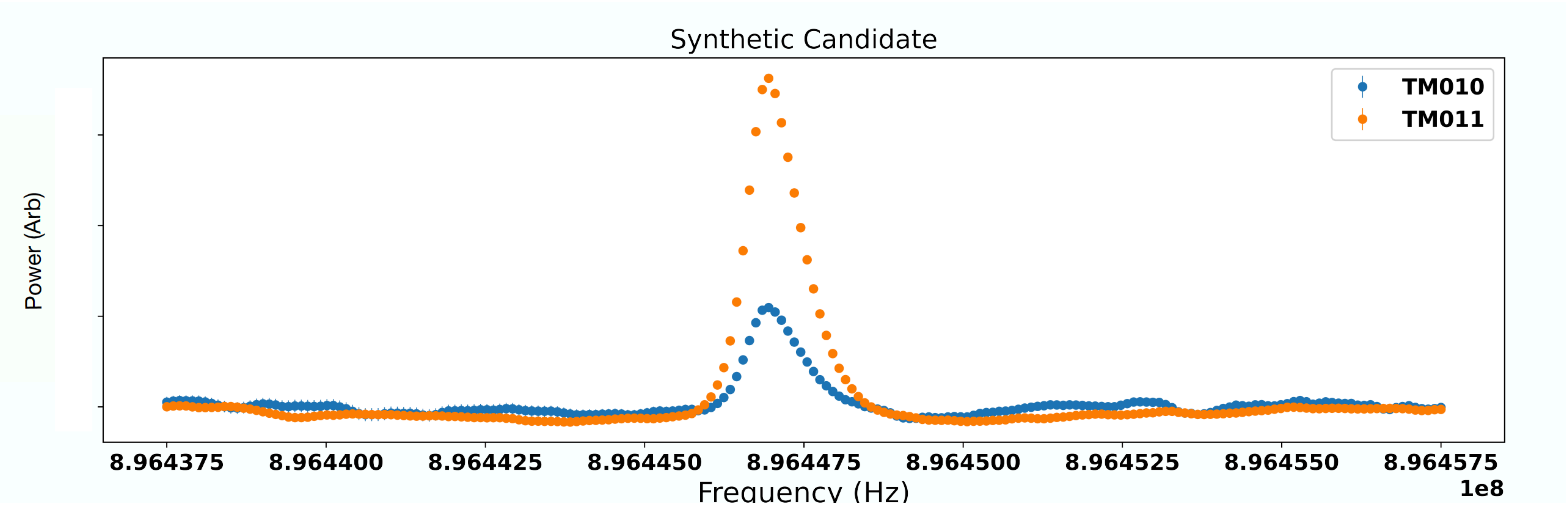
Synthetic Axion Generator Rack Installation for Run 1C

- Extra stage of mixing/filtering to improve signal purity
- New enclosure separate from the main DAQ
- New 0-90 dB programmable attenuator for increased automation. Fully automated and integrated with dripline/lua.
- Axion line shape is simulated but not perfect. Will be improved in future runs.



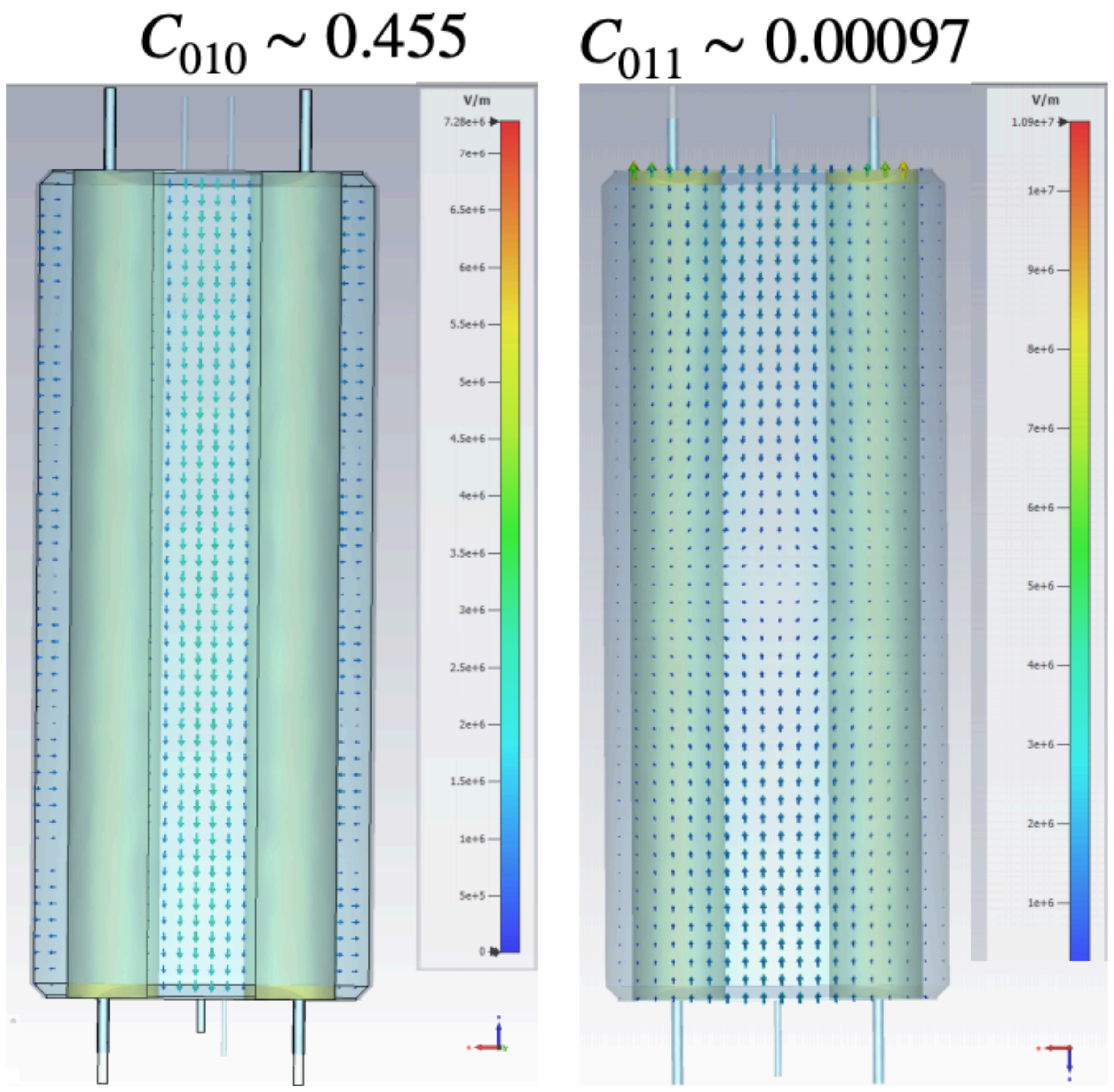
Synthetic Axion Detection

Check on our ability to detect axions+understanding of experiment



Example candidate that proceeded to the detection committee for rigorous evaluation.

- Candidate Evaluation Sequence:
  - Persistence checks
  - RFI test with lab antenna+spectrum analyzer
  - On-off resonance test
  - Mode Test
  - Field ramp (final step!)

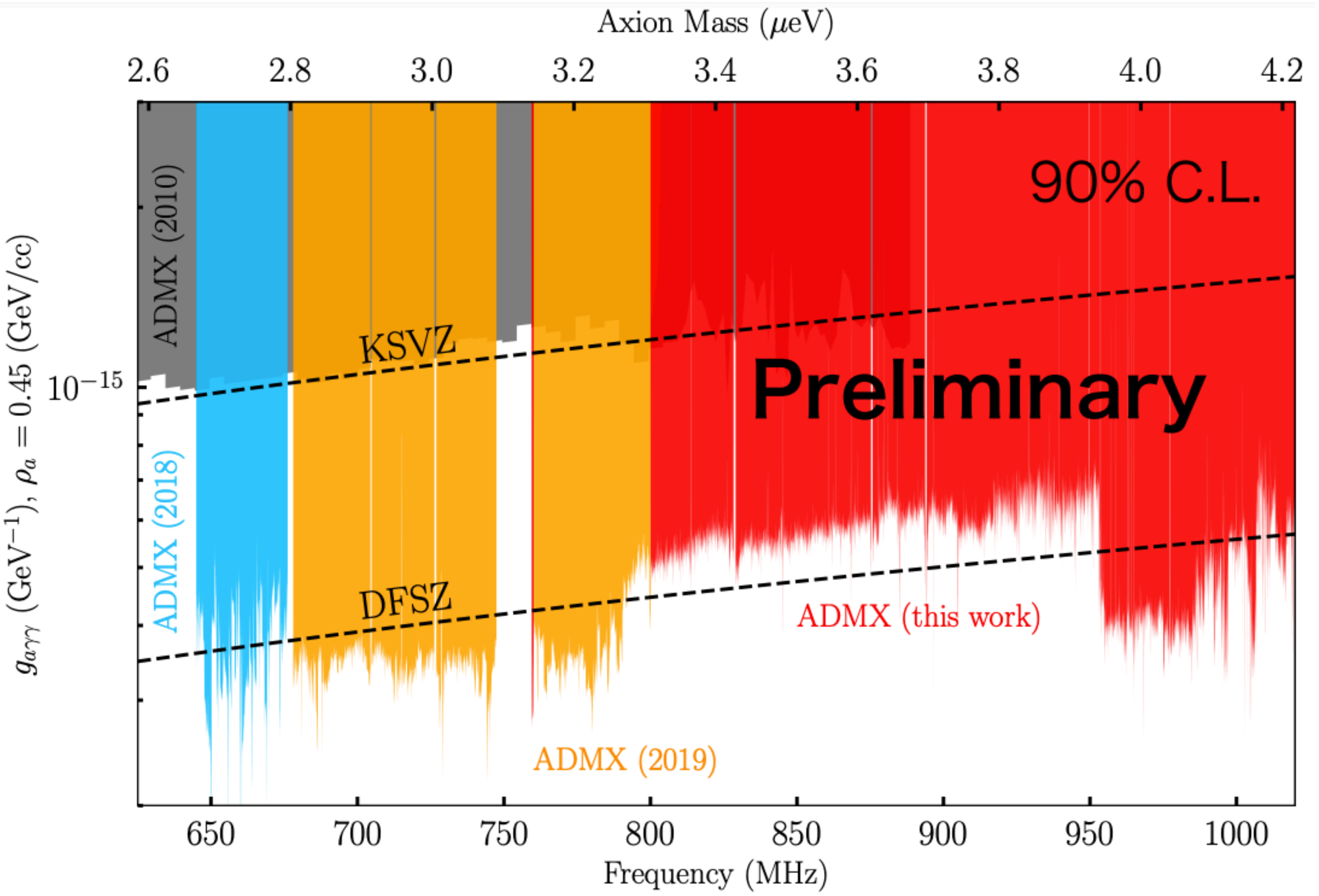


TM010 mode **TM011 mode**

Form Factor Simulations in HFSS

Run 1C Sensitivity

- Sensitive to KSVZ: 800-970 MHz
- Sensitive to DFSZ 970-1020 MHz
- Covered 2x prior frequency range



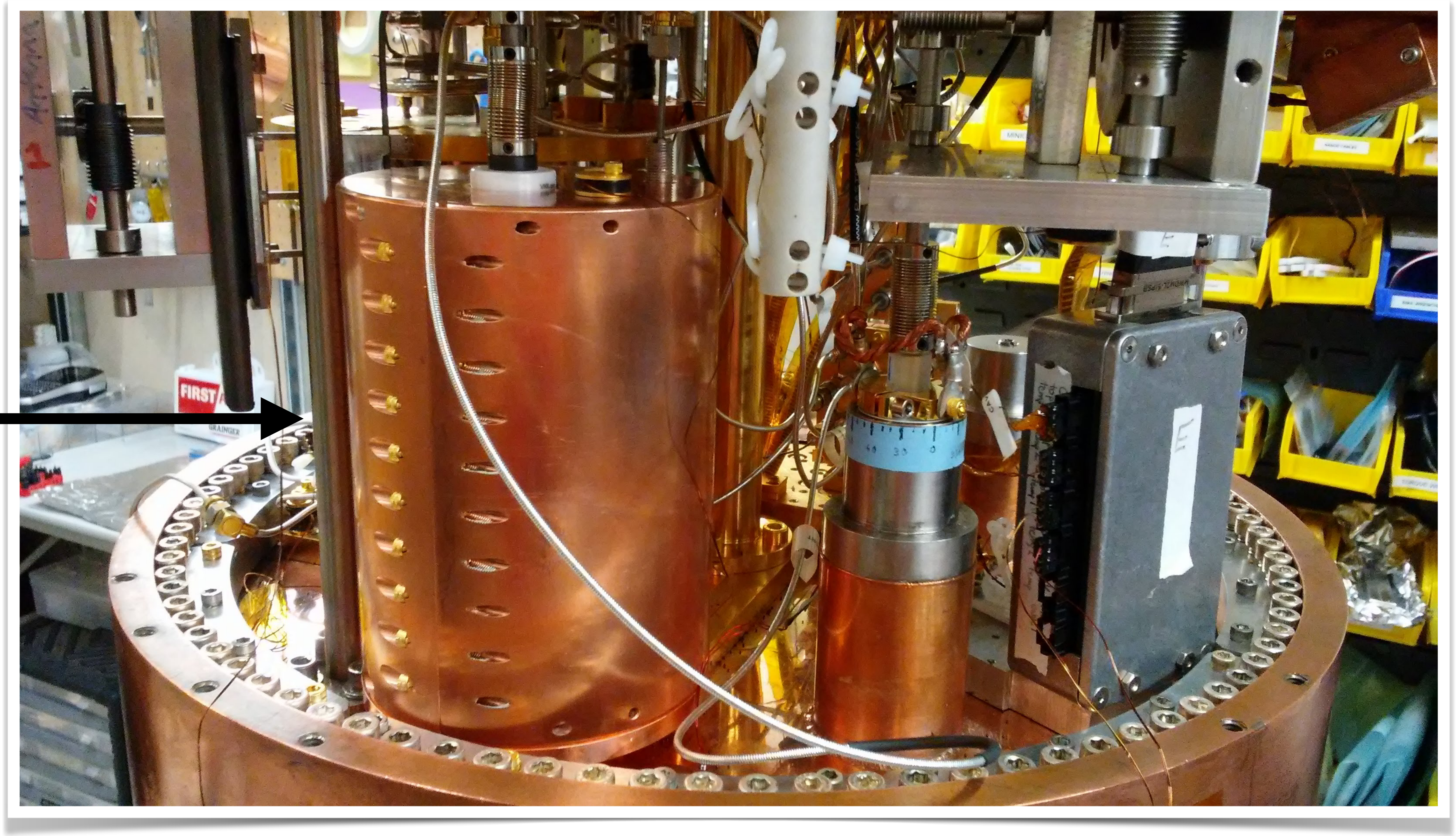
For analysis details

- Prior paper:
  Bartram, Chelsea, et al. "Axion dark matter experiment: Run 1B analysis details." *Physical Review D* 103.3 (2021): 032002.
- Results for Run 1C Forthcoming

Ongoing Higher Frequency Searches

Sidecar Cavity and Receiver Chain

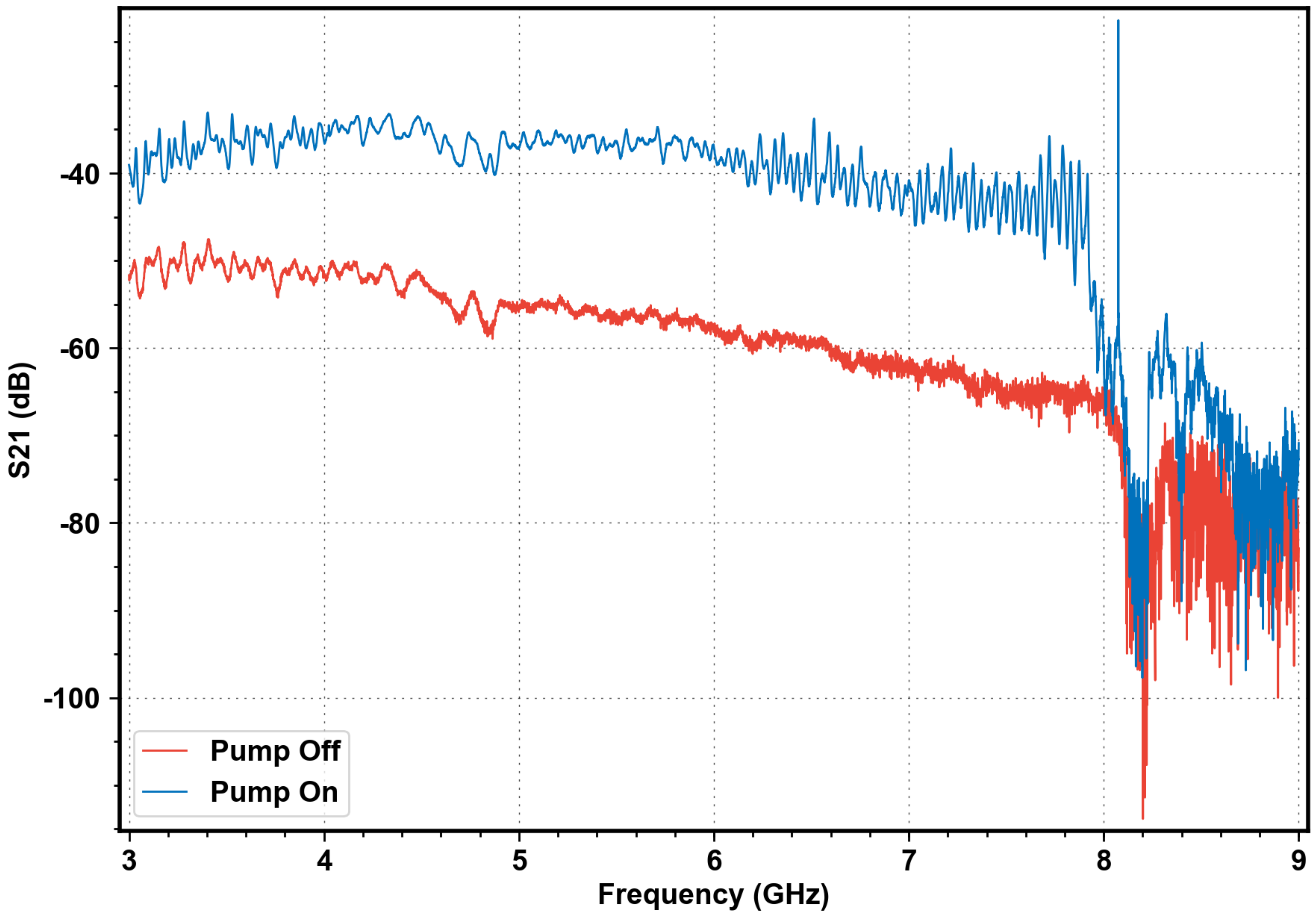
- Sidecar is a small prototyping cavity that sits on top of the main cavity.
- This iteration of sidecar is testing:
  - Traveling Wave Parametric Amplifier (TWPA)
  - Clamshell cavity design
  - Piezo motors for antenna and tuning rod



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

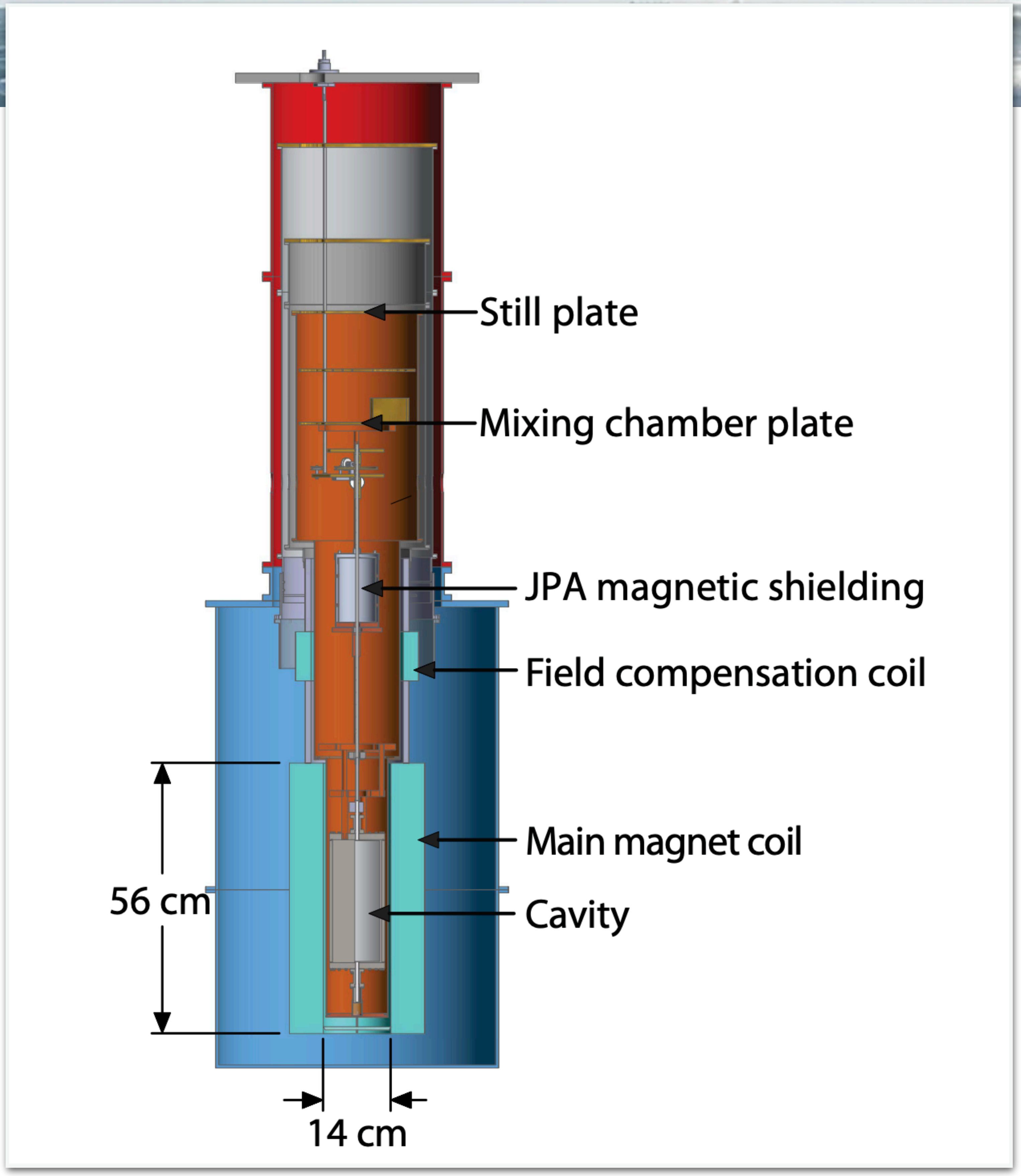
Demonstration of a Axion Search with TWPA

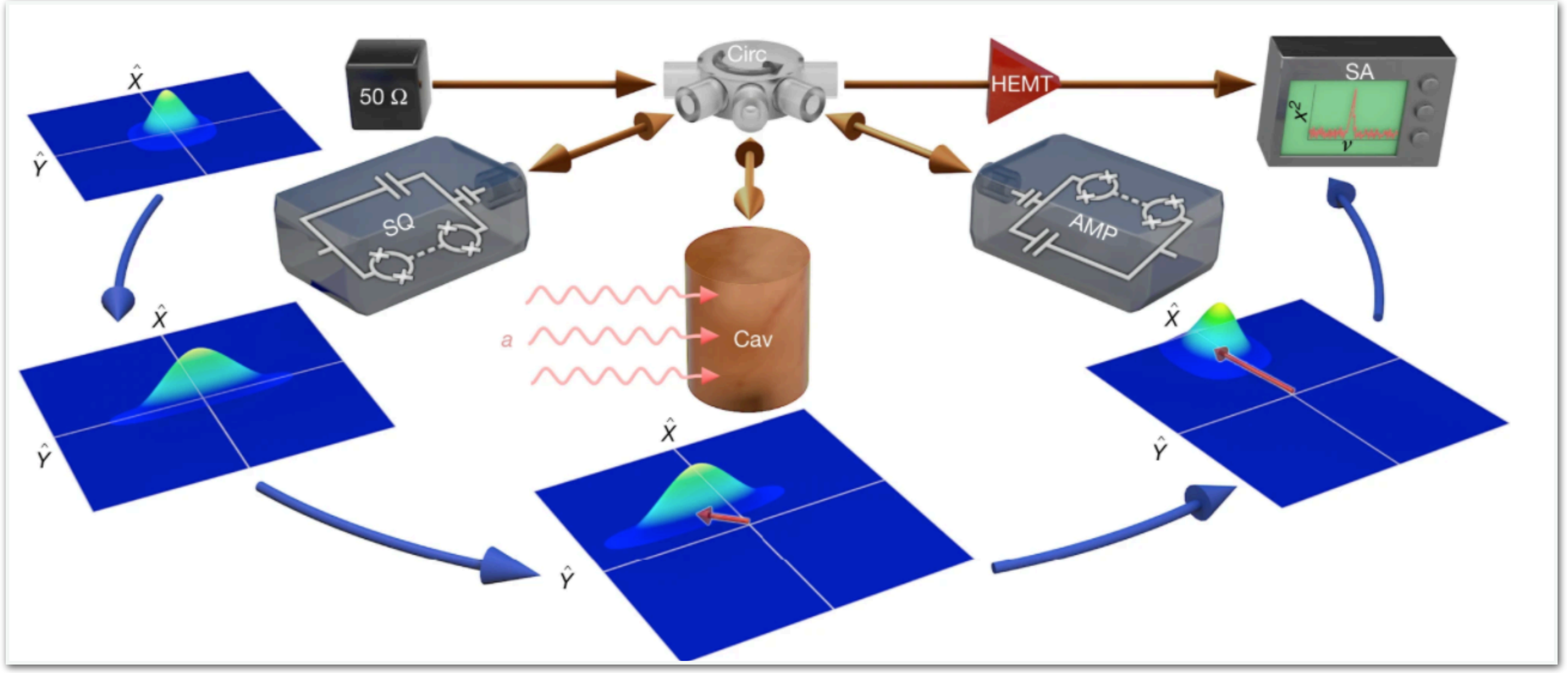
- Benefits of TWPA include
    - Broadband gain spans several GHz.
    - Eliminates need for an additional circulator (Less loss, more space)
    - Reasonable noise performance
- ADMX Sidecar Demonstration
    - Operated TWPA for several weeks in magnetic field
    - Reasonable performance (achieved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



HAYSTAC

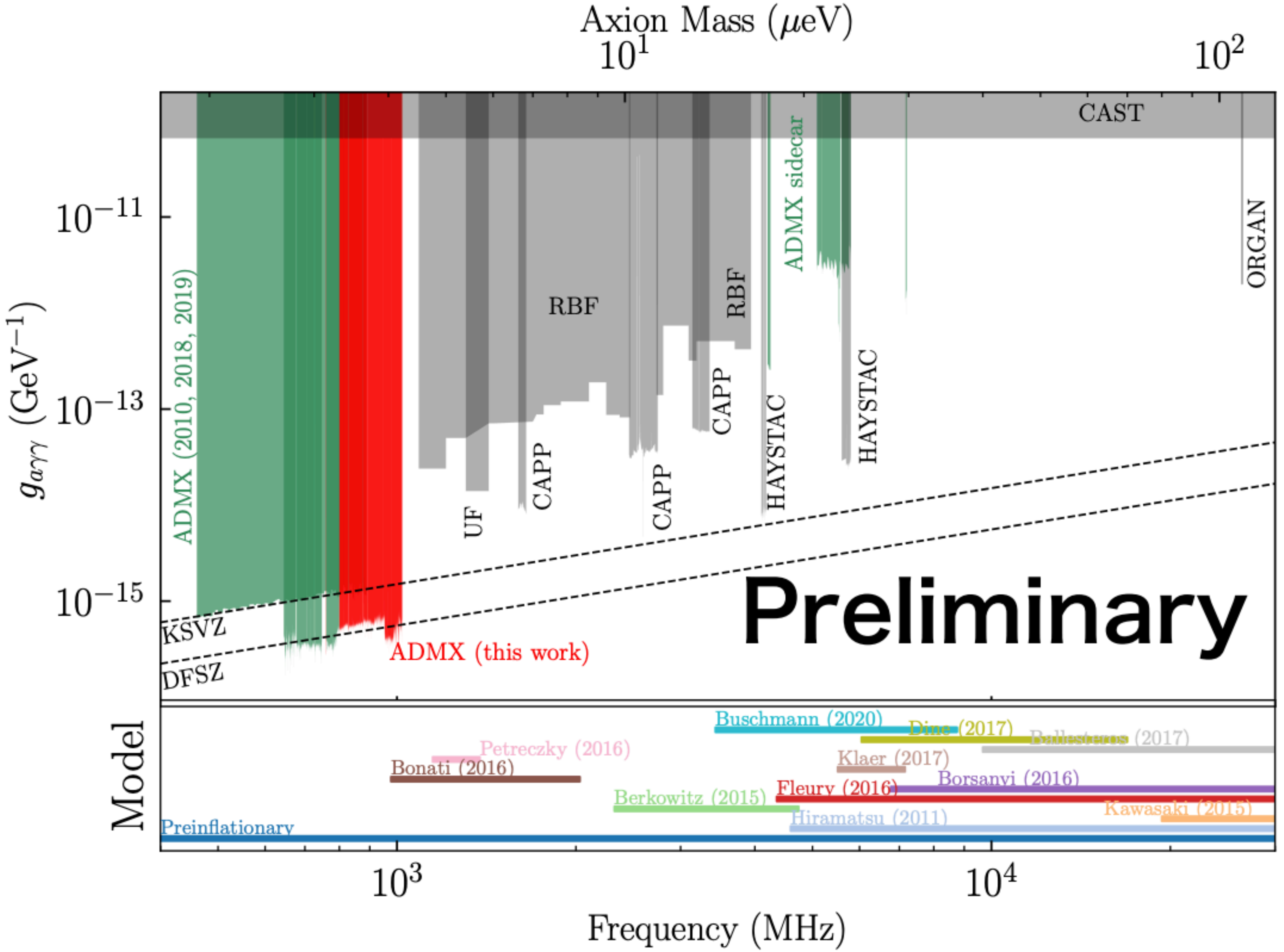
- Exploring higher frequency axions
- Using squeezed state receiver
  - Phys. Rev. X 9, 021023 (2019)
- Exploring Bayesian techniques:
  - Phys. Rev. D 101, 123011 (2020)



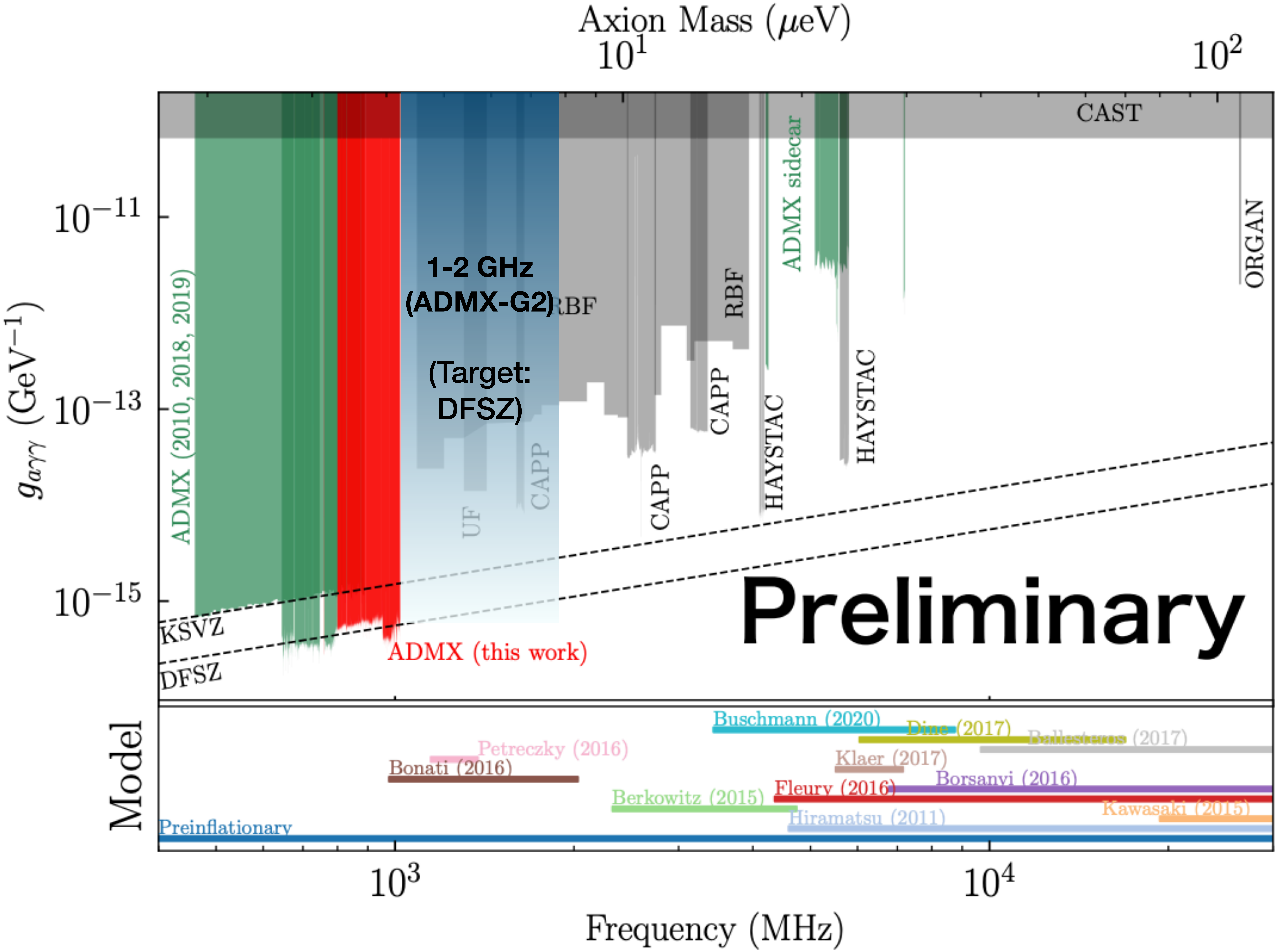


Recent publication from earlier this year

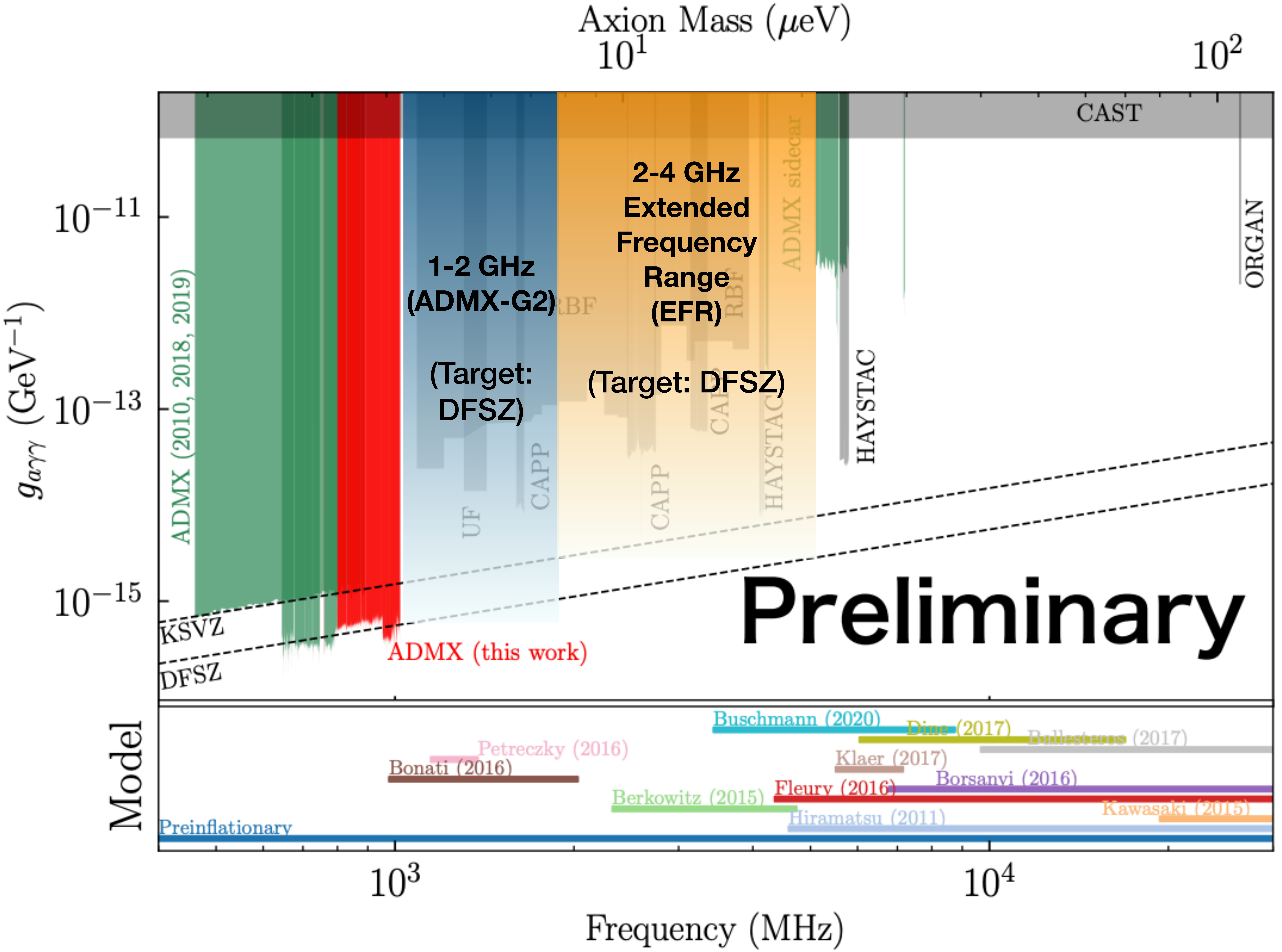
Backes, K.M., Palken, D.A., Kenany, S.A. *et al.* A quantum enhanced search for dark matter axions. *Nature* **590,** 238–242 (2021). https://doi.org/10.1038/s41586-021-03226-



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)

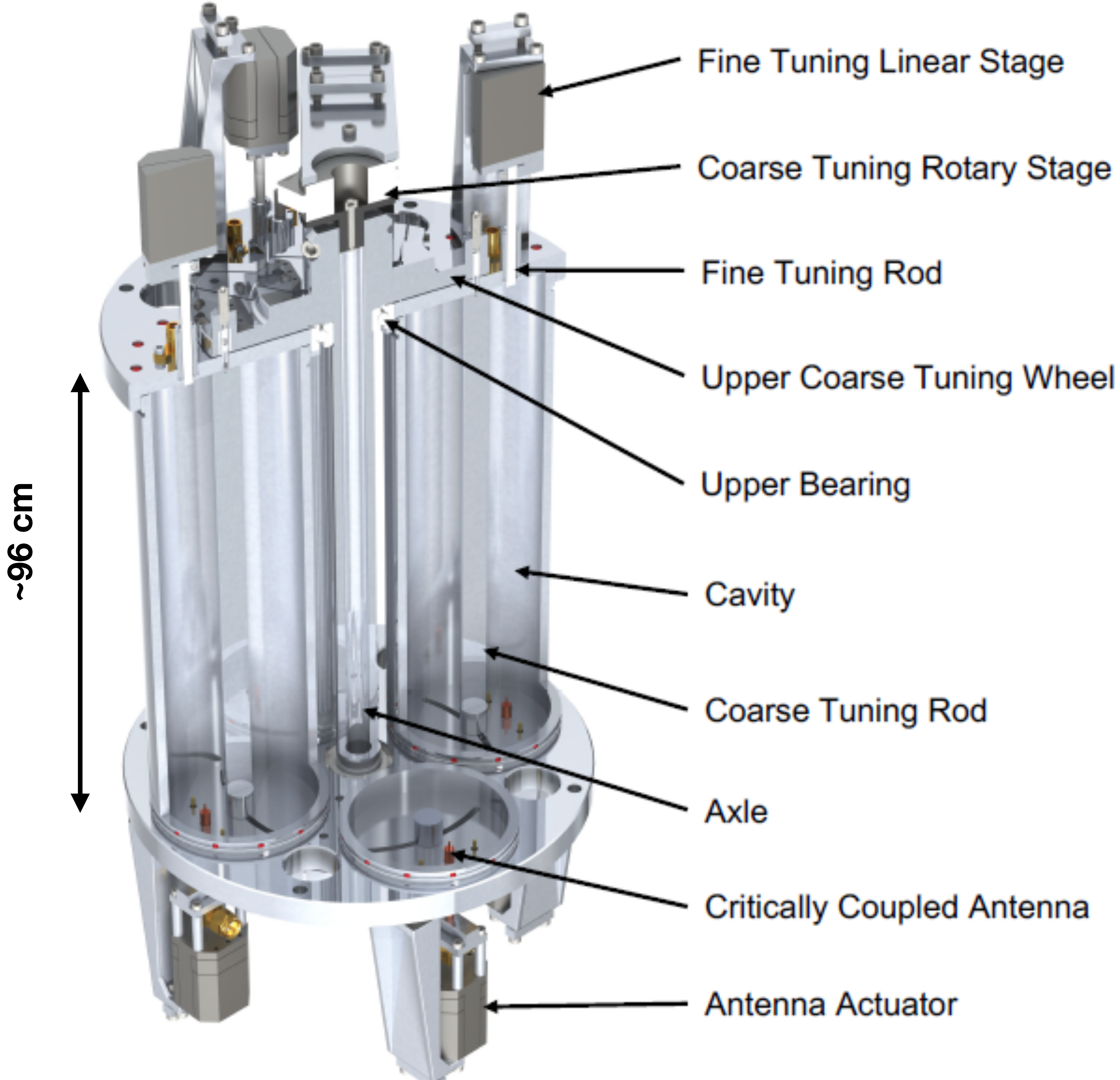


Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
ADMX sidecar
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
RBF
RBF
CAPP
CAPP
CAPP
HAYSTAC
HAYSTAC
UF
ADMX (2010, 2018, 2019)
10^{-11}
10^{-13}
10^{-15}
$g_{a\gamma\gamma}$ (GeV^{-1})
KSVZ
DFSZ
ADMX (this work)
Preliminary
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)



Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
2-4 GHz
Extended
Frequency
Range
(EFR)
(Target: DFSZ)
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
ADMX sidecar
RBF
CAPP
UF
HAYSTAC
ADMX (2010, 2018, 2019)
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-13}
10^{-15}
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)

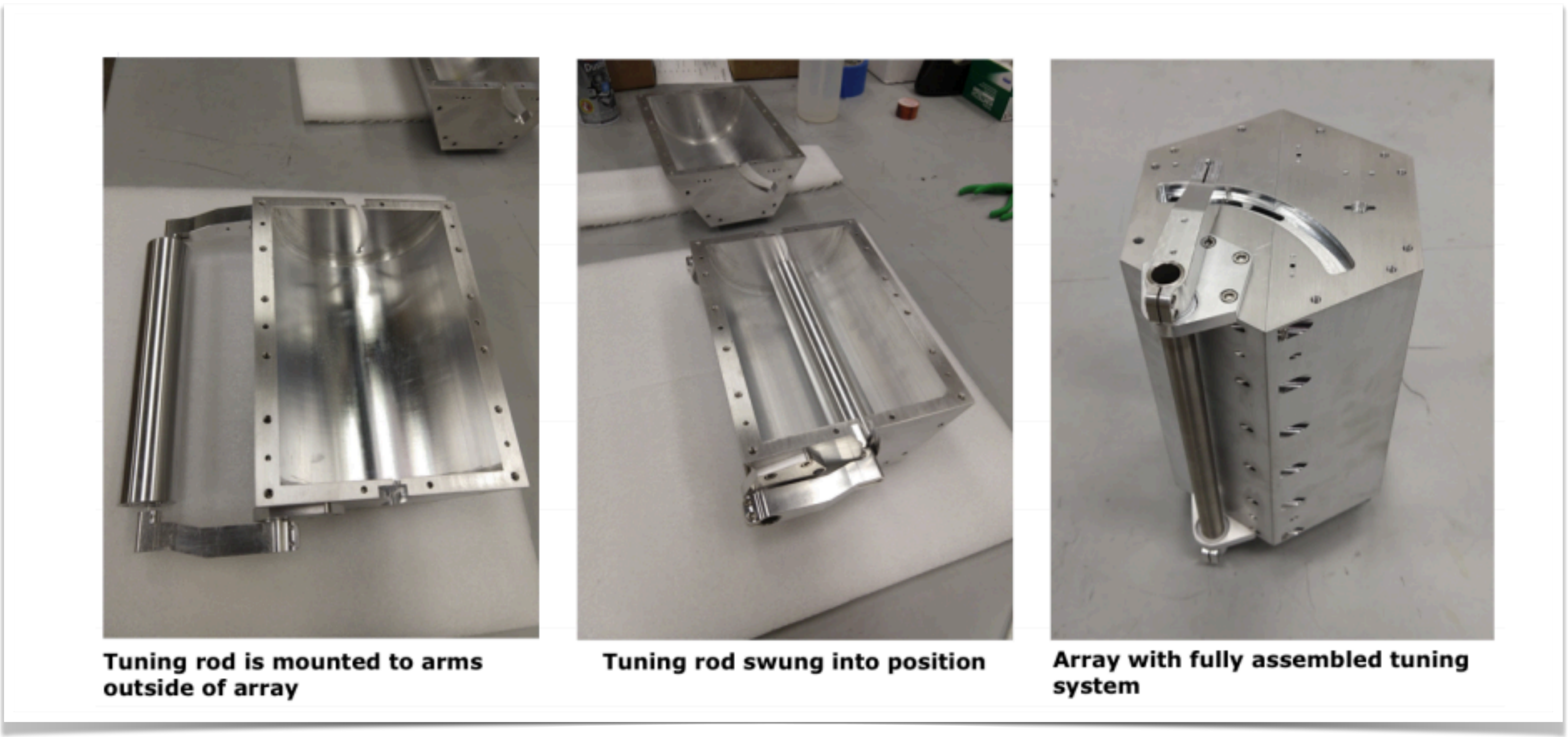
4-cavity array

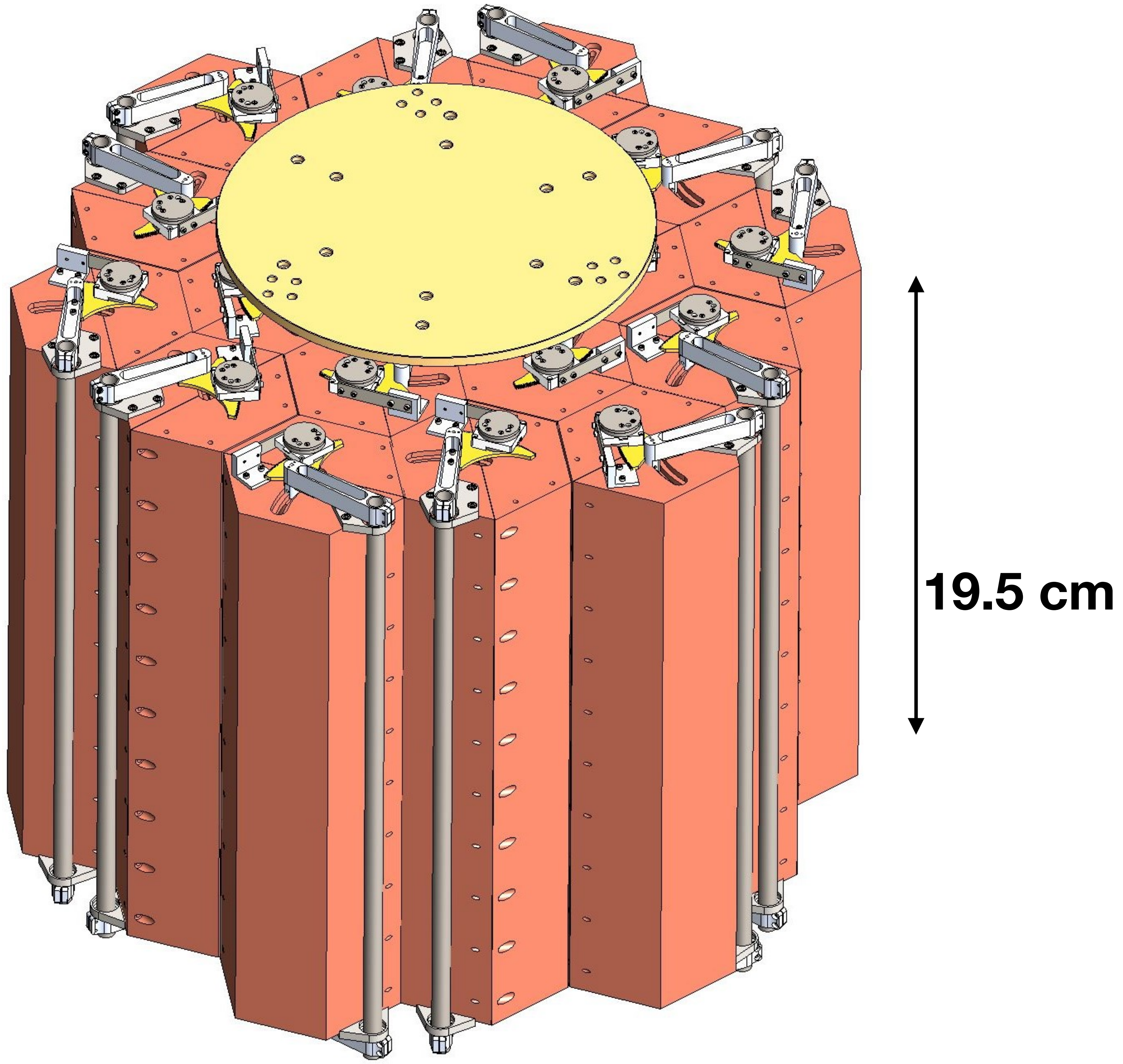


4-cavity array planned for University of Washington

- 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.

ADMX Extended Frequency Range (EFR)





2-4 GHz prototype cavity assembly at University of Florida
Cylindrical cavity formed from two clamshell halves

Possibly ~18 cavities
Simulations underway

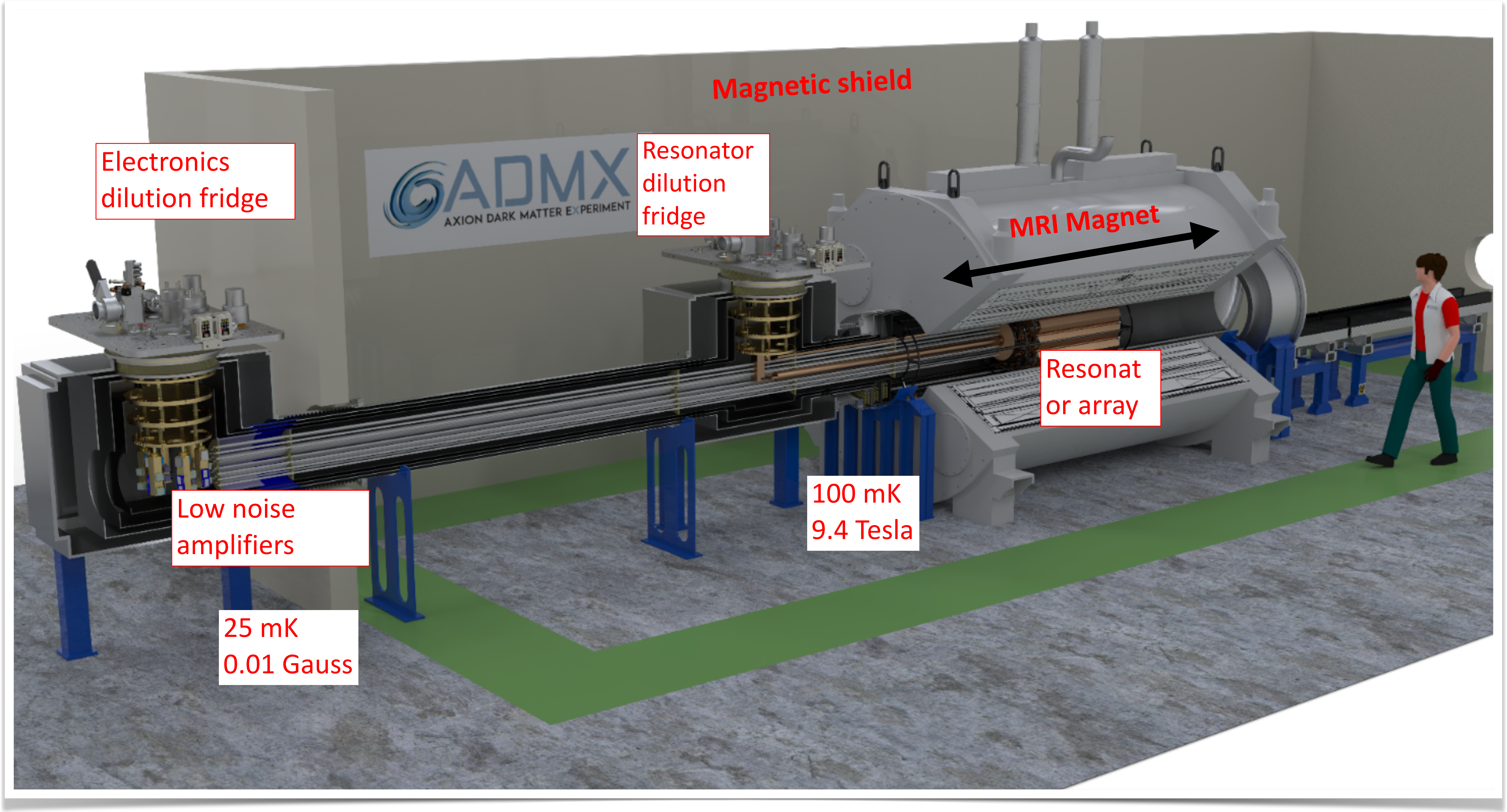
9.4 T MRI Magnet at UIUC

- 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!

ADMX Extended Frequency Range (EFR)

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)

Conclusions

- First pass through Run 1C excludes axion dark matter at roughly half the DFSZ coupling in the mass range of 3.2—4.2 μeV (780–-1010 MHz).

- Second pass through this region in the coming months will bring us to DFSZ.

- ADMX is on track to continue its search for axions. Discovery could happen at any moment!

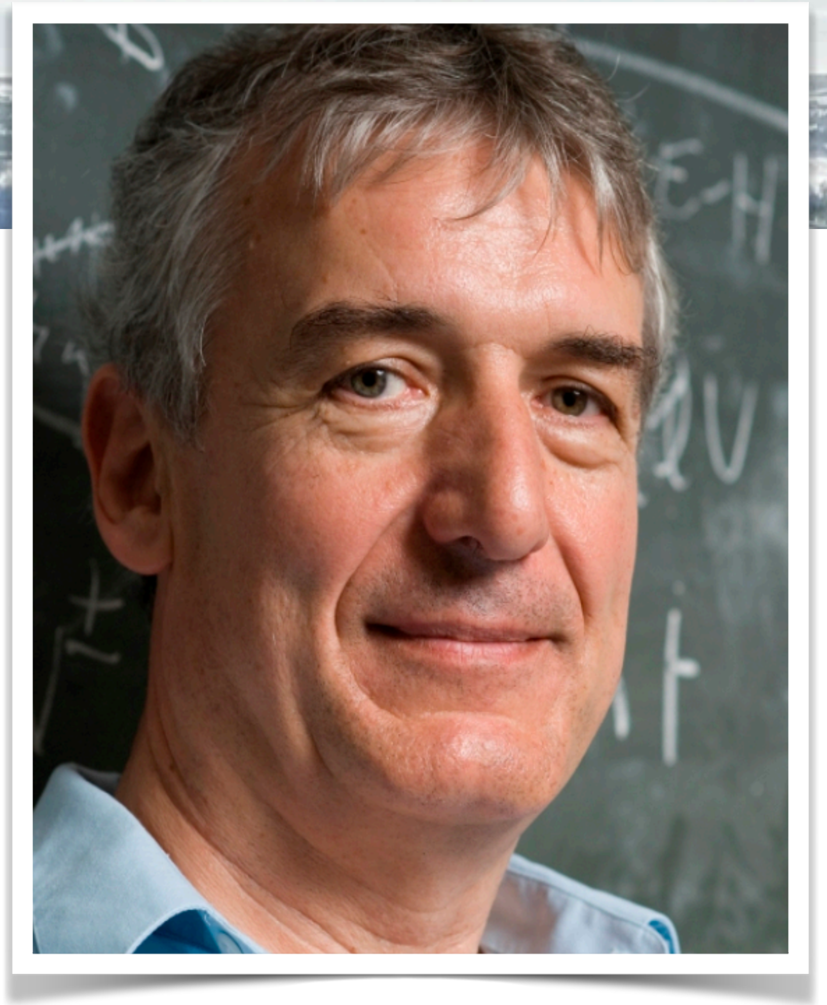
- Progress being made towards higher frequency searches.

Acknowledgements

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

Backup Slides

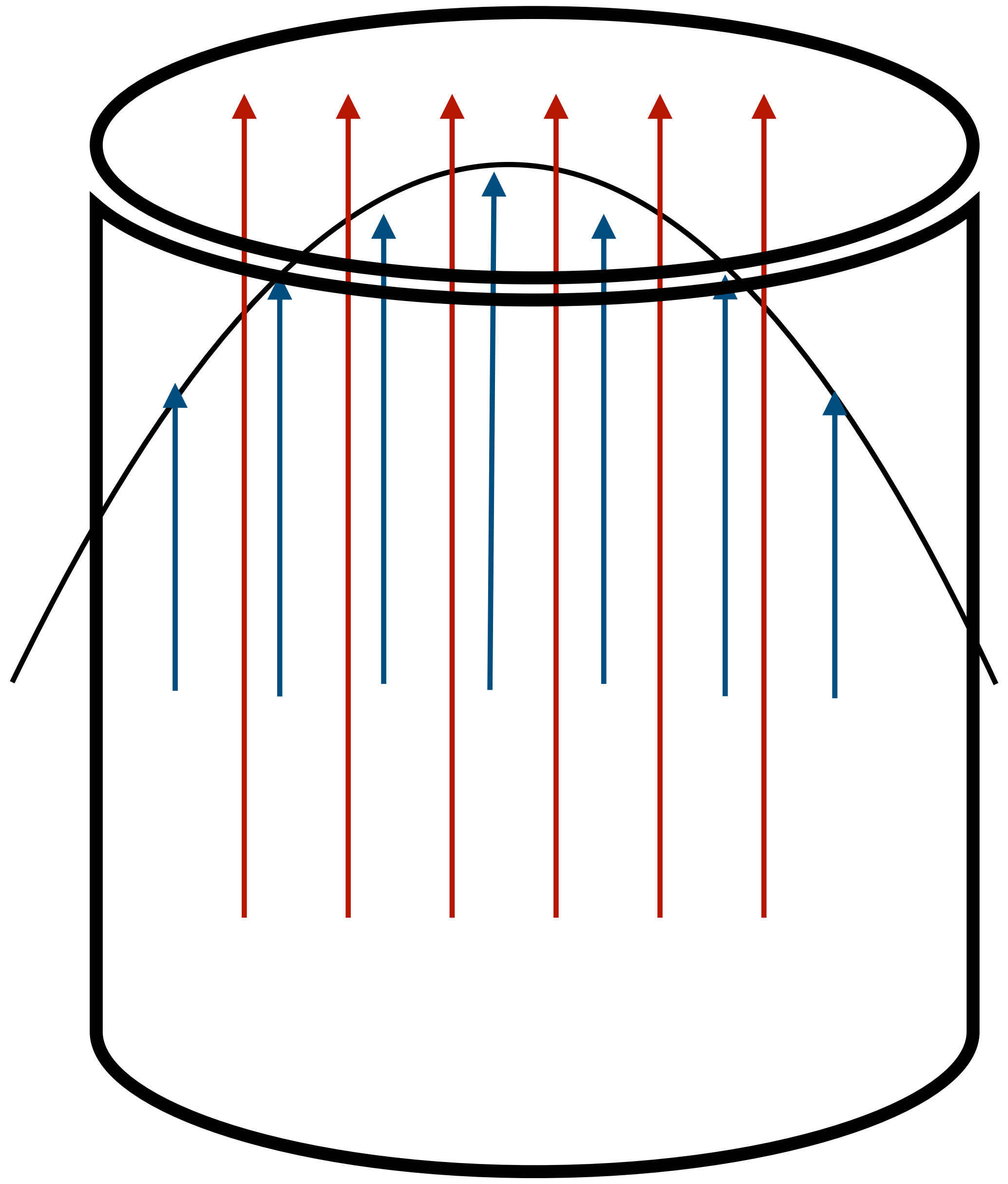
Axion Haloscope



Resonant cavity axion haloscope

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

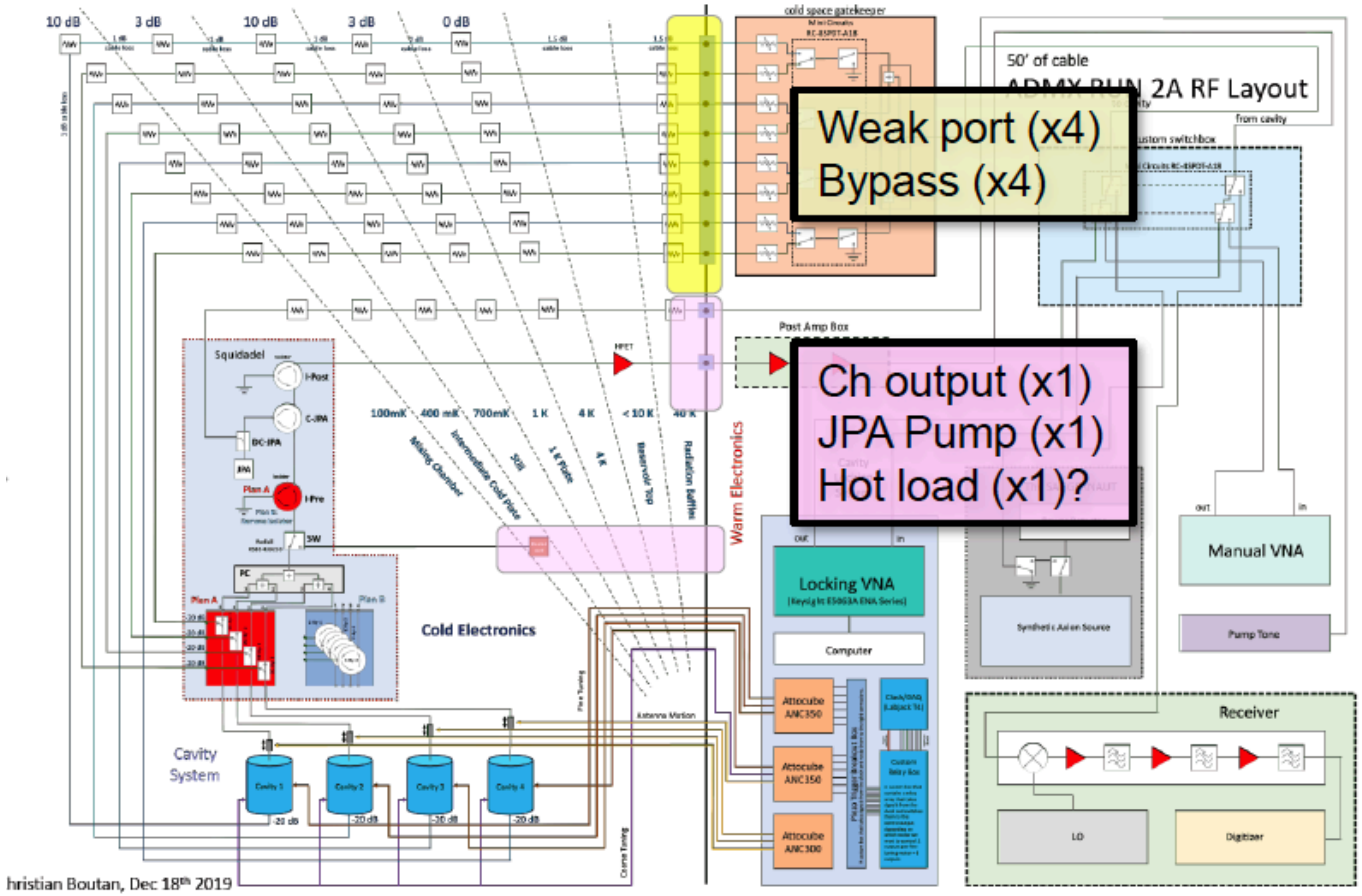
"Form Factor" $$C_{010} = \frac{|\int dV \vec{B_{ext}} \cdot \vec{E_a}|^2}{B_{ext}^2 \int dV \epsilon_r |\vec{E_a}|^2}$$



Red is cartoon magnetic field
Blue is cartoon electric field

Main cavity (x4)

No Sidecar



Weak port (x4)
Bypass (x4)

Ch output (x1)
JPA Pump (x1)
Hot load (x1)?

Piezo
actuators

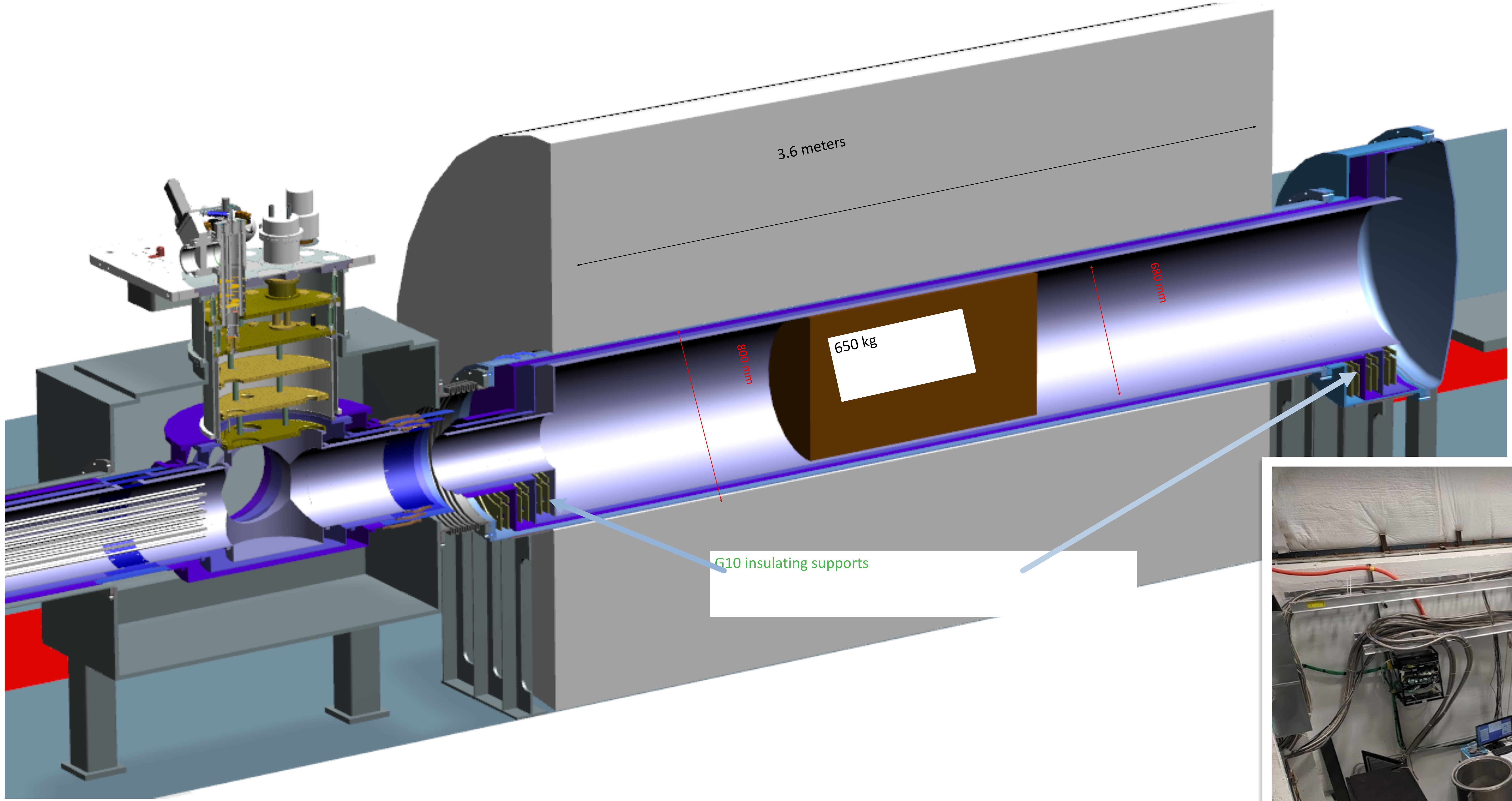
Theoretical Constraints

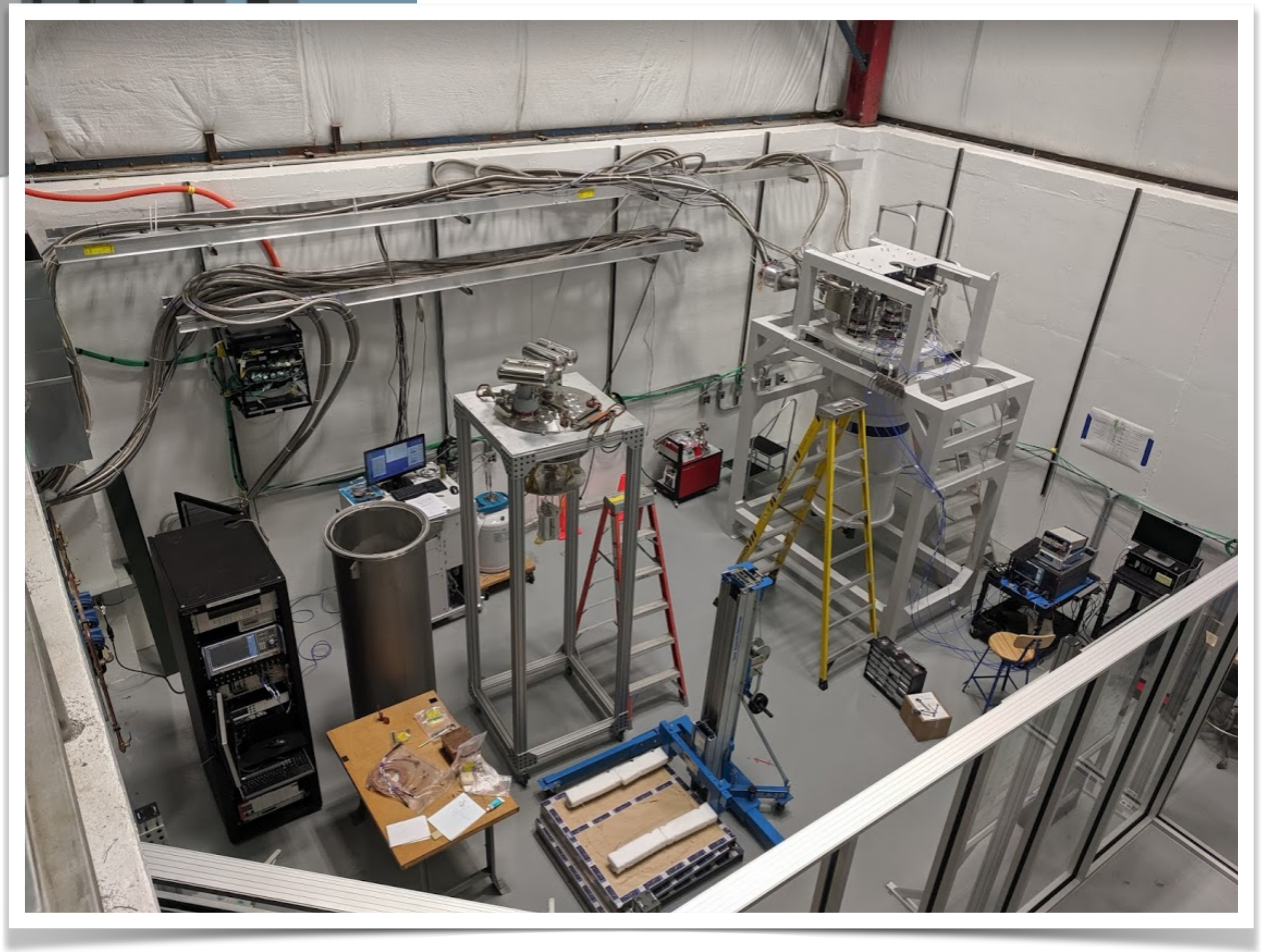
Lower bound set by size of dark matter halo size of dwarf galaxies

Upper bound set by SN1987A and white dwarf cooling time

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

Adaptation of L. Winslow DPF Slide


3.6 meters
650 kg
800 mm
680 mm
G10 insulating supports



Demonstration of a Axion Search with TWPA

- Benefits of TWPA include
  - Broadband gain spans several GHz.
  - Eliminates need for an additional circulator to separate incoming and outgoing modes (less loss, more space for us)
  - Peaks and troughs every 50-MHz could enable new scanning and optimization strategies
  - Reasonable noise performance
- ADMX Sidecar Demonstration
  - Operated TWPA for several weeks in magnetic field
  - Reasonable performance (achieved ~8 dB SNR)
  - System noise meets expectations
  - Definitive results coming soon in paper.