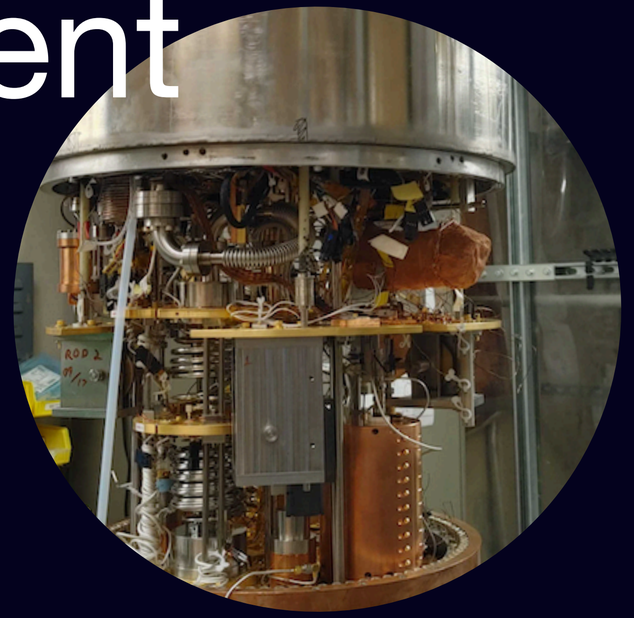
Venturing a glimpse of the dark matter halo with ADMX

Cambridge Workshop on Axion Physics
Chelsea Bartram
July 27 2021

ADMX
AXION DARK MATTER EXPERIMENT

UNIVERSITY OF WASHINGTON
LVX · SIT
1861

Axion Dark Matter eXperiment



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

Funding Agencies

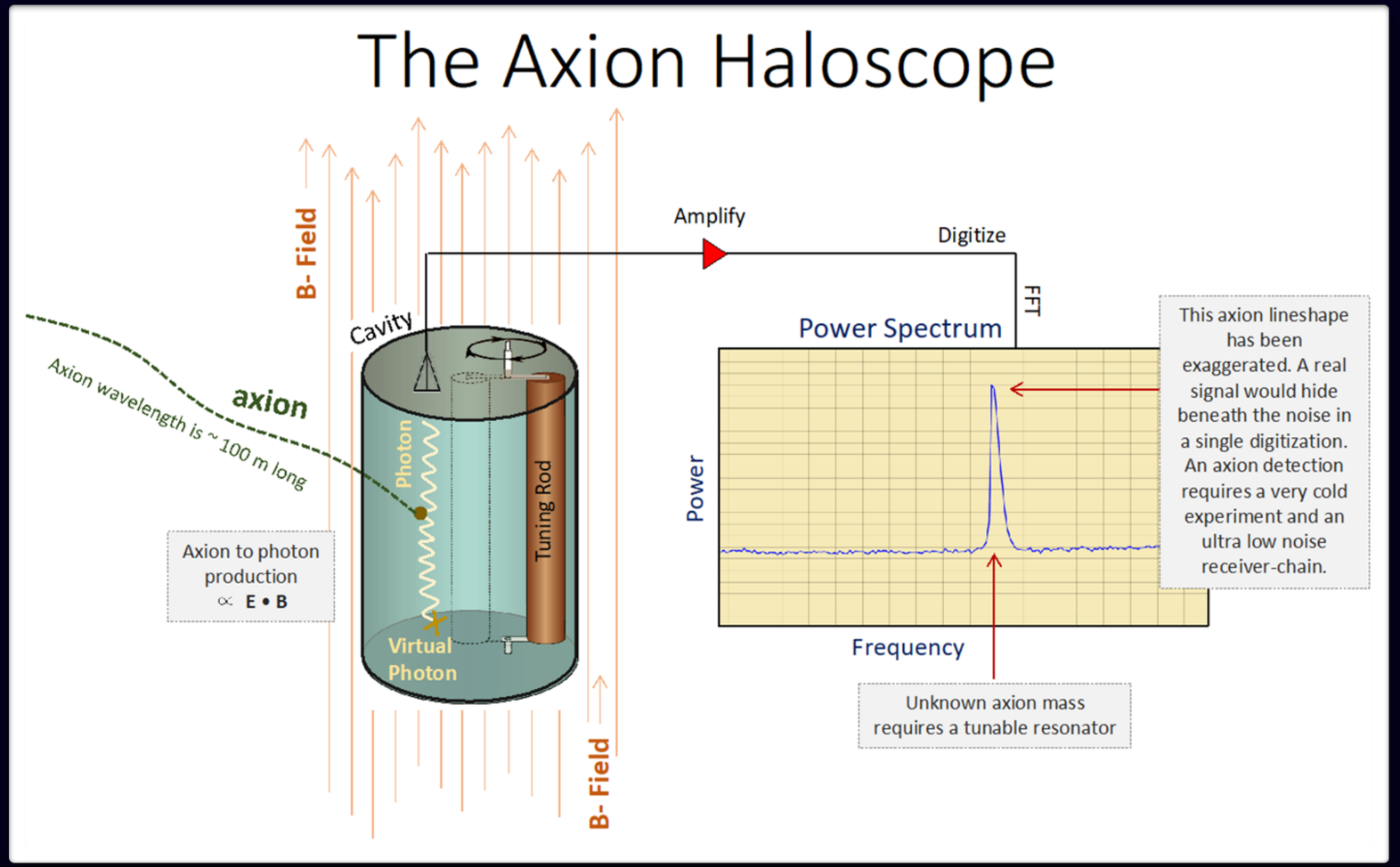
Guided by the QCD Axion

- 1-100 μeV mass range can constitute all the dark matter.
- Can also solve the strong CP problem.

Helen Quinn

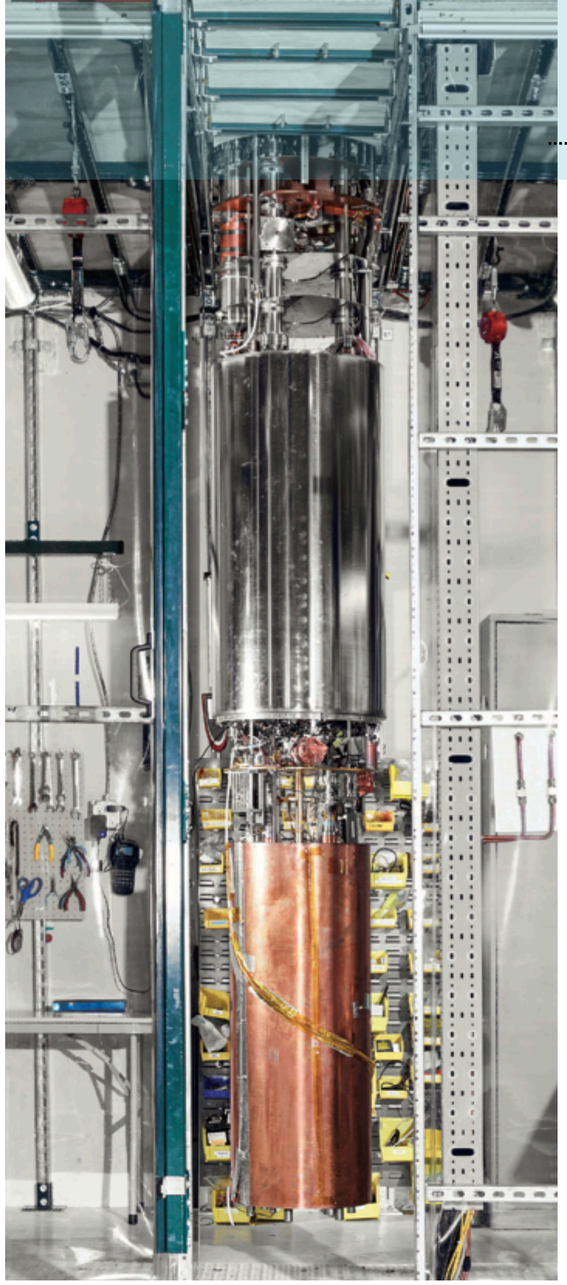
Roberto Peccei
1942-2020

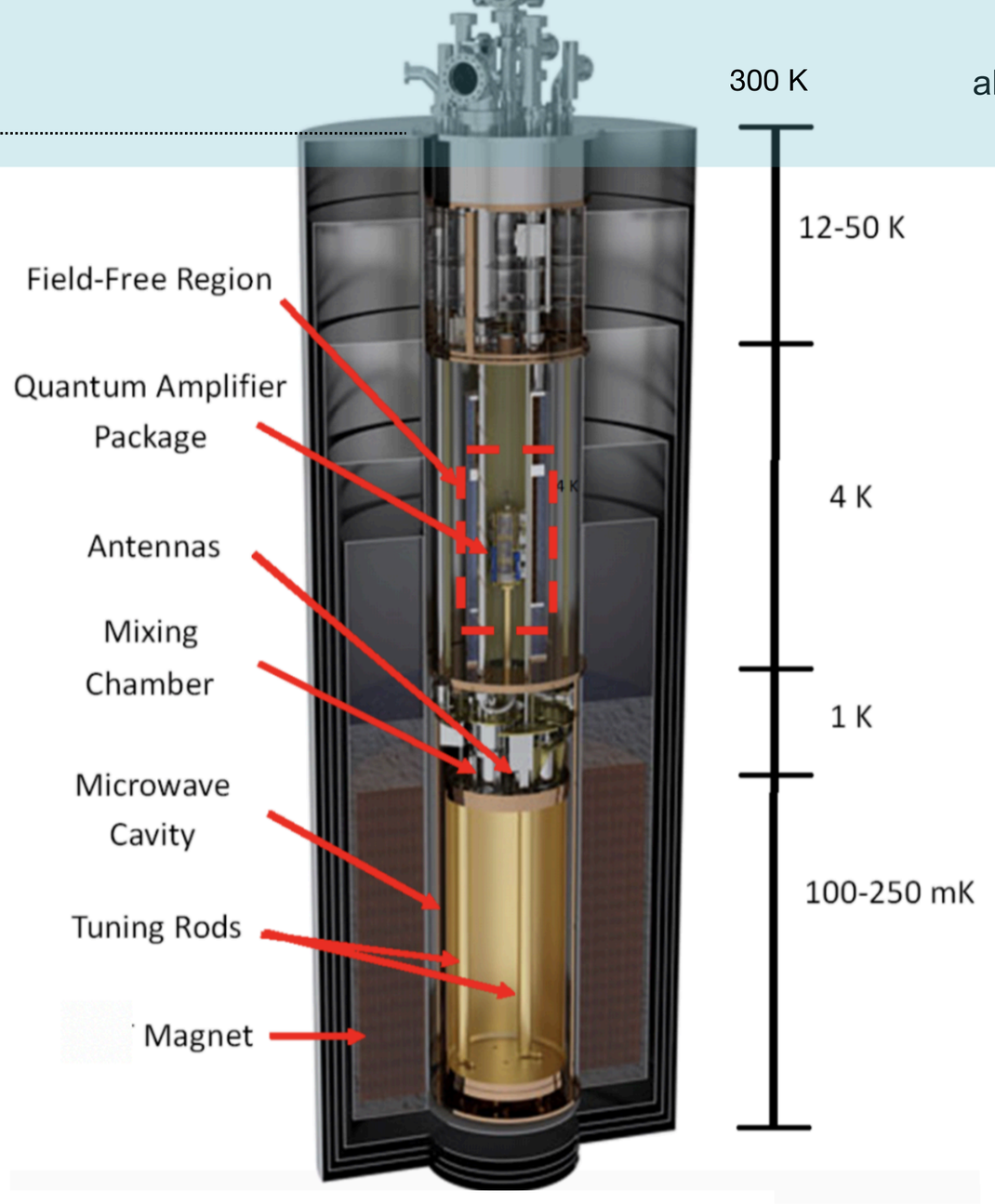
- Two classes of models: KSVZ, DFSZ



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





Two main analyses

Medium-res

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

High-res

- 10 mHz native bin width
- Saved as time-series
- Non-virialized axions
- Sensitive to frequency modulation from orbital and rotational motion
- Not (yet) integrated into rescan procedure

What is a candidate?

Medium-res

- Must be persistent in every spectrum
- Must follow cavity line-shape (enhance on resonance)
- Not a hardware synthetic

High-res

- Persistent in some fraction of spectra
- Frequency must not drift beyond what is predicted from Doppler shift

Must not exist in the lab or warm receiver chain as ambient RFI

Must be suppressed in TM011 mode

Must scale accordingly with the magnetic field

Synthetic Candidates

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.

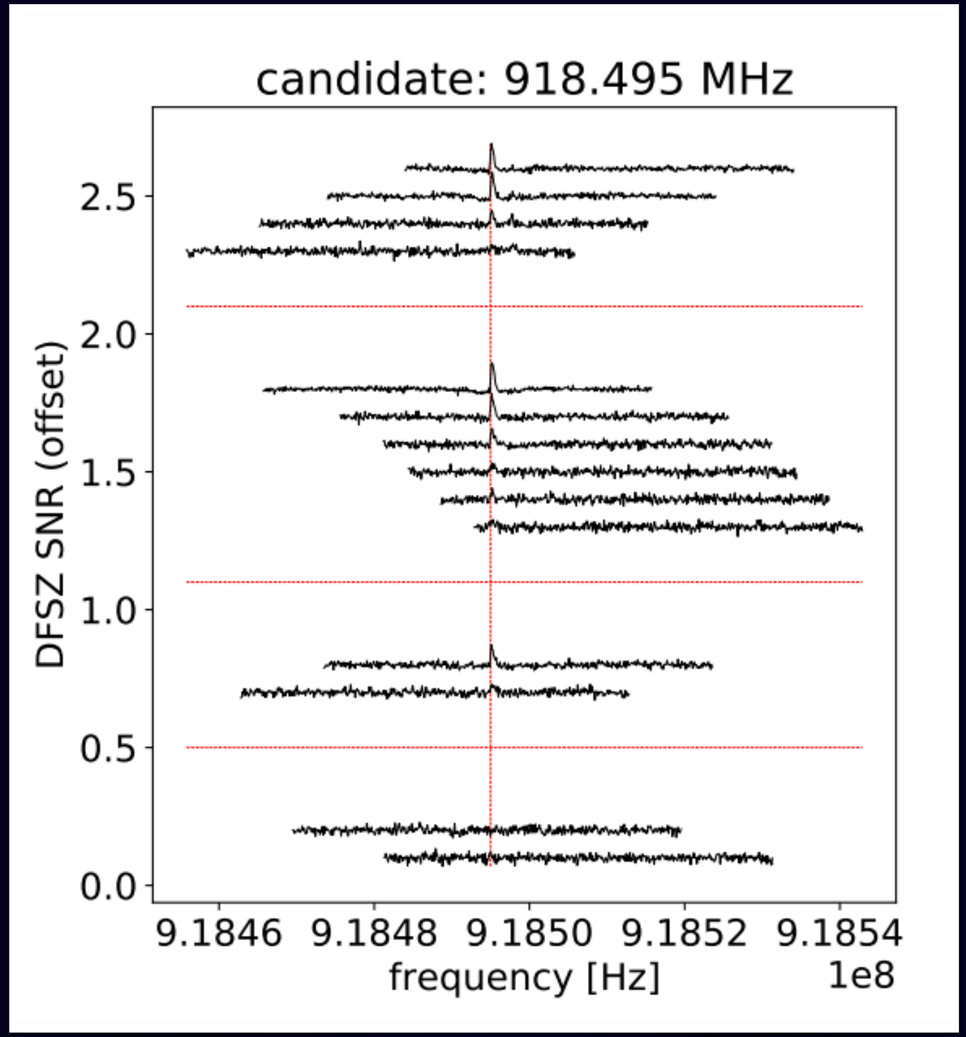
- 10-12 per 10 MHz.

Type 2:

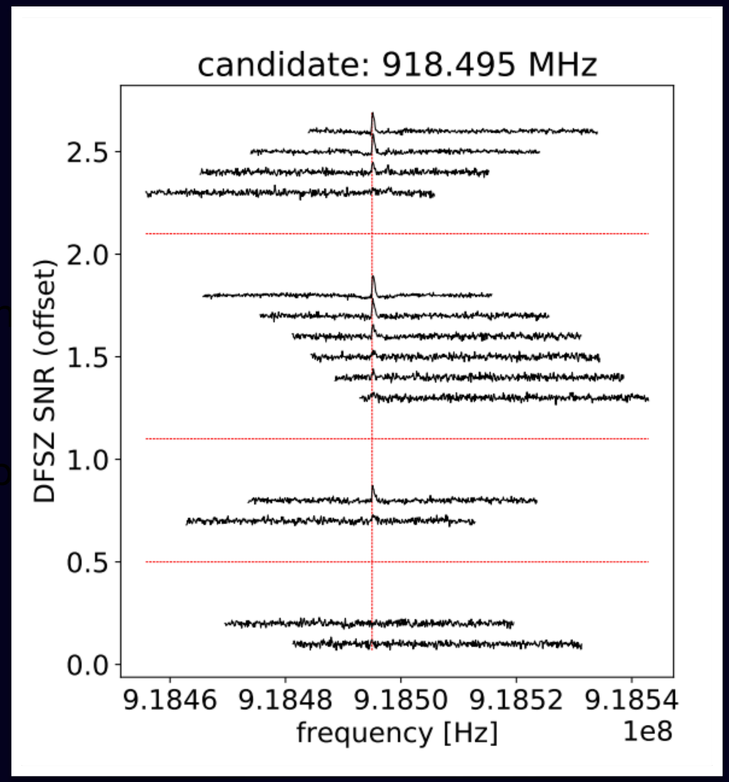
Injection used to practice full axion detection procedure

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

- 1-2 per run.



Candidate Decision Tree



First pass through nibble at fixed tuning rate

Continue to next nibble

Rescan at variable tuning rate

Continue to next nibble

Persistence check

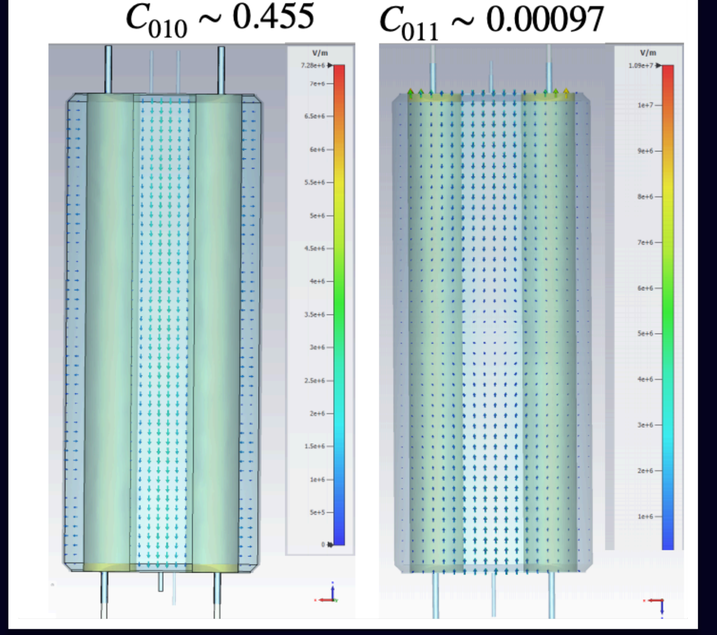
Continue to next nibble

Turn off synthetic axions and rescan

Continue to next nibble

Persistence Check

Candidate Decision Tree



Make RFI Checks

Continue to next nibble

Check for signal suppression in TM_{011} mode

Continue to next nibble

Turn off secondary synthetic axion injections

Continue to next nibble

Check for signal scaling with B^2

Continue to next nibble

Axion found! Study line shape, etc.

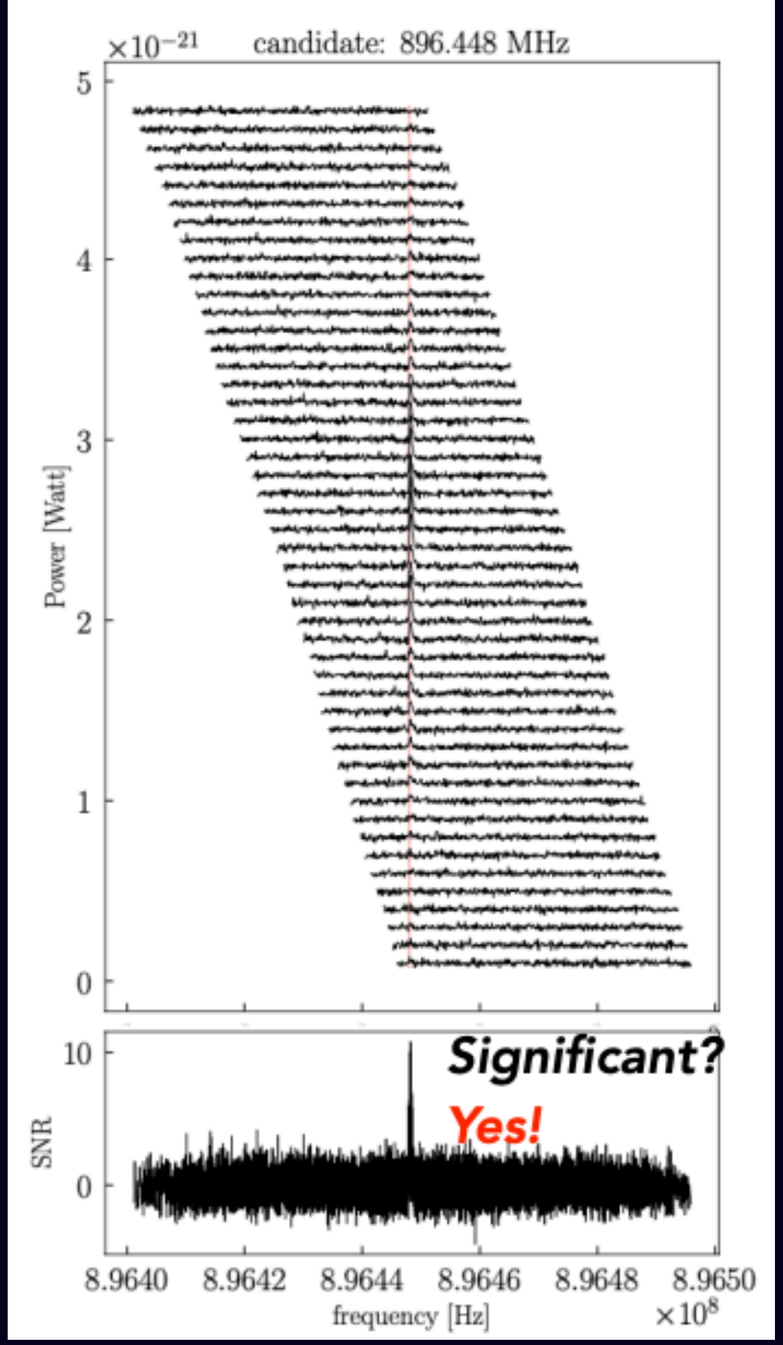
MAGNET RAMP ALERT!

Synthetic Axion Generator

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.

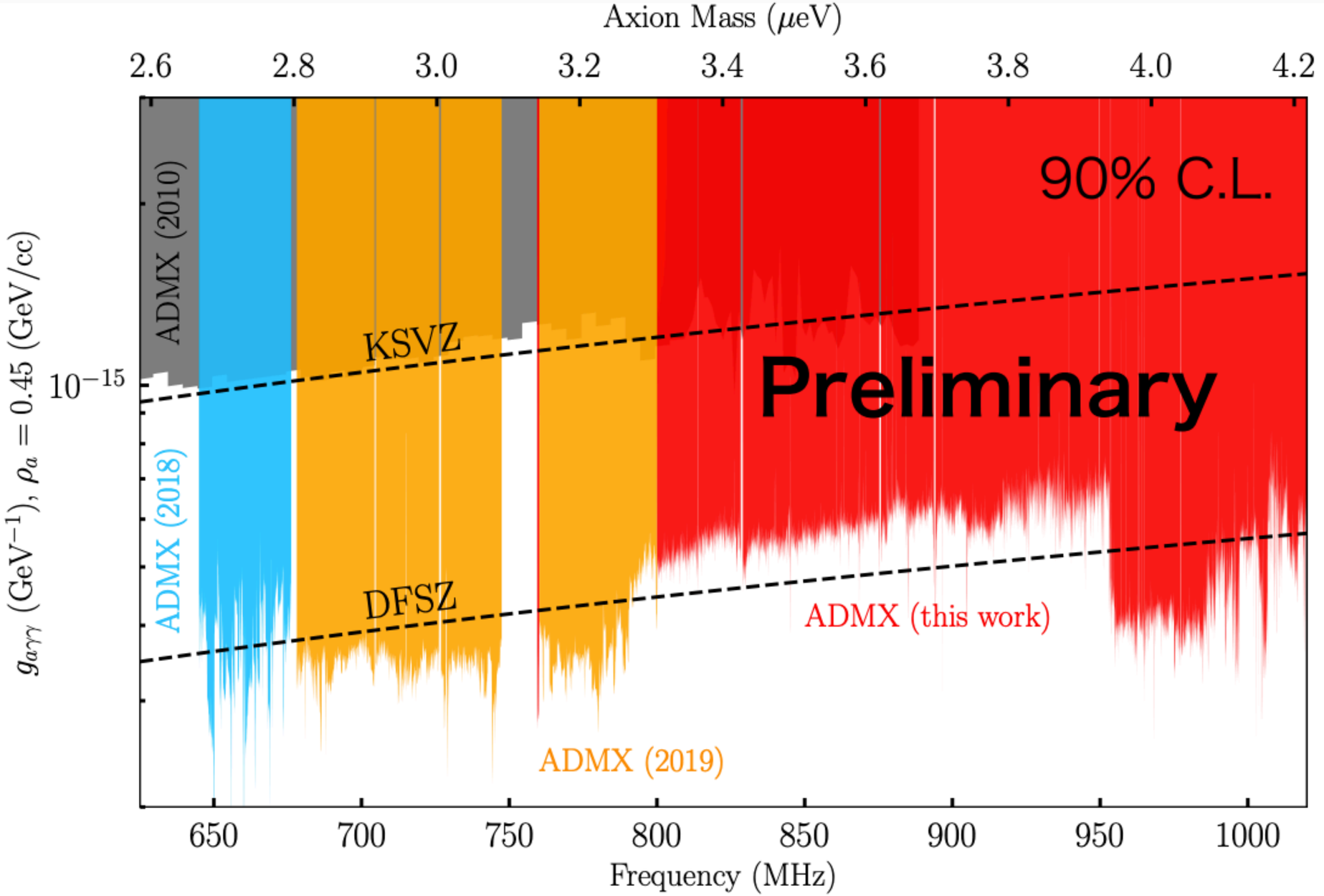


Run 1C Sensitivity

- 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



Sensitivity Plot

Scan speed limitations

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

Maximize

- B Field
- Volume
- Quality Factor
- Form Factor

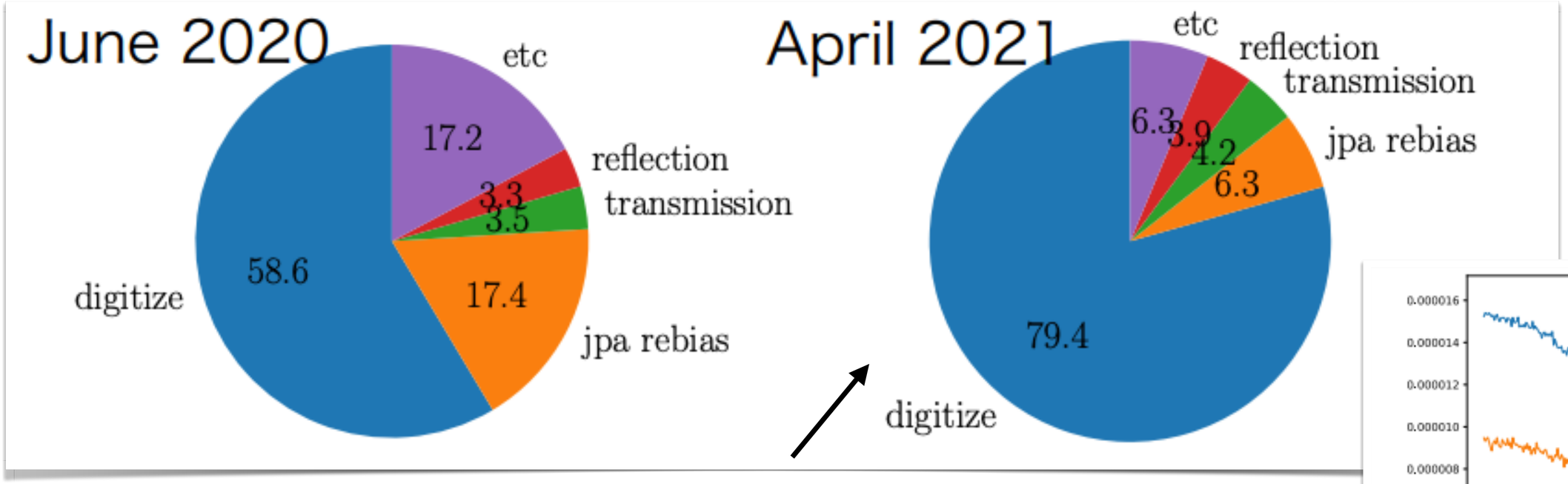
Defined by nature

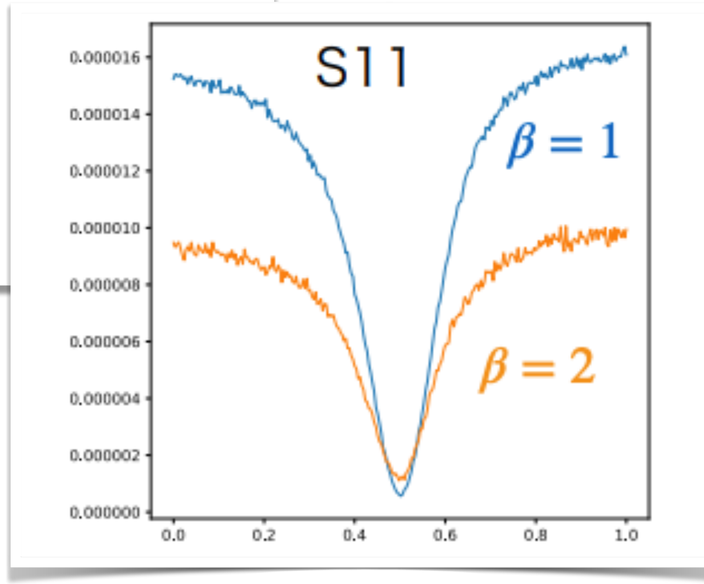
- Frequency
- Coupling
- Dark Matter Density

Minimize

- System noise:
  - Amplifier Noise
  - Physical Noise

Scanning improvements

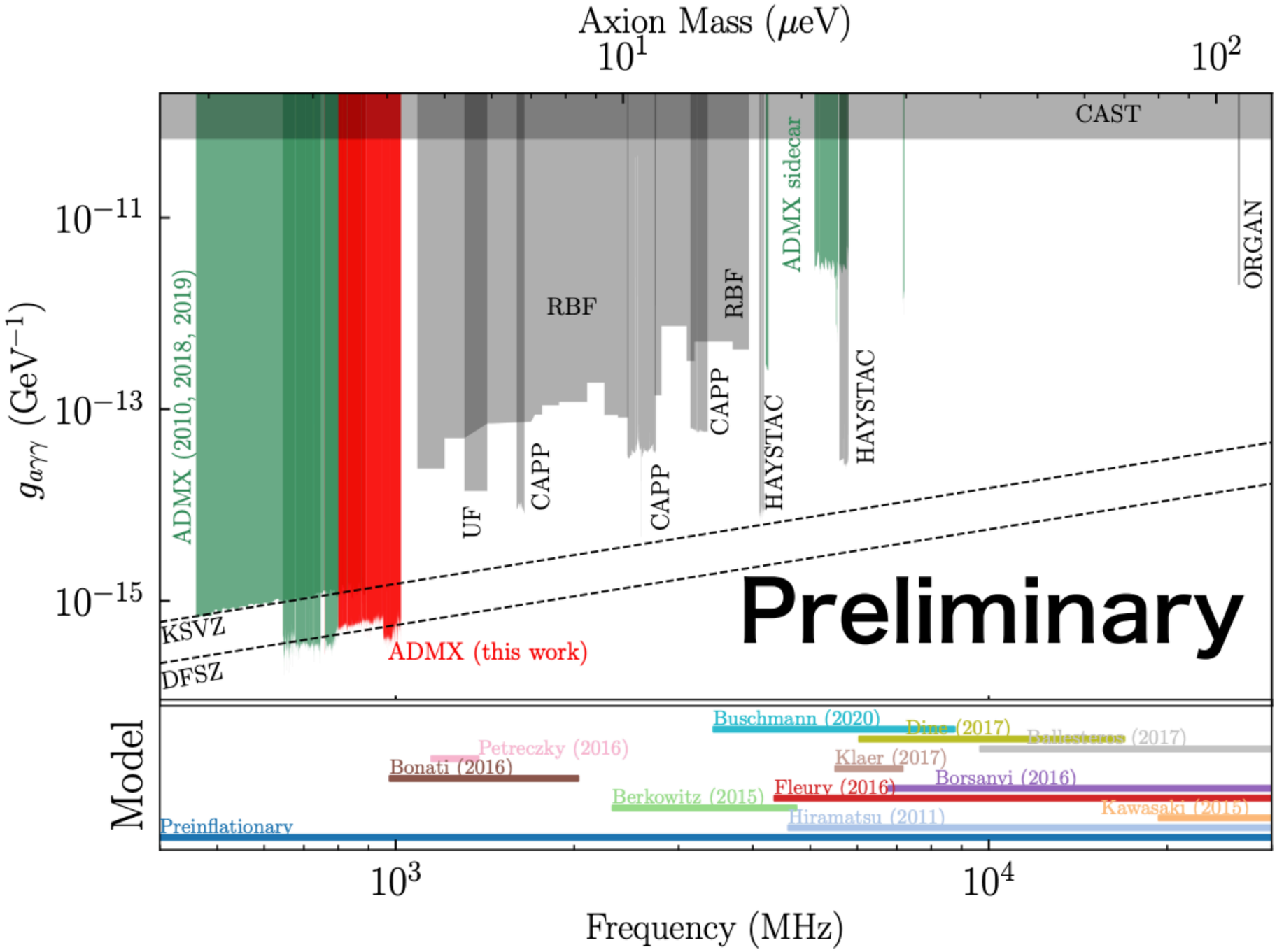


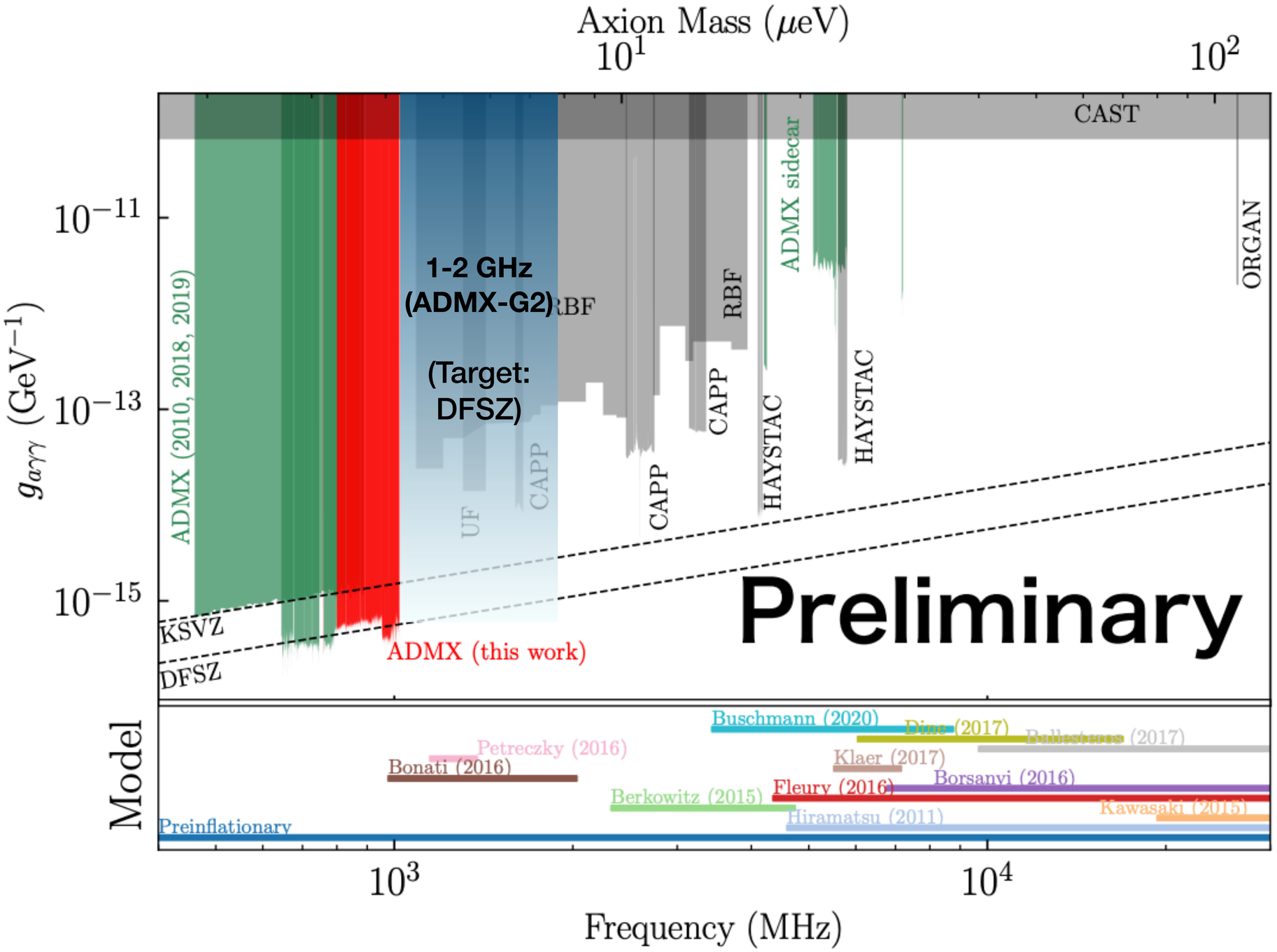


Optimizing the JPA rebiasing

Adjust coupling to cavity: 20% scan rate increase

To do: Improve magnetic shielding, bring cavity temperature down, replace JPA, improve system noise understanding


Axion Mass (μeV)
10^1
10^2
10^{-11}
10^{-13}
10^{-15}
$g_{a\gamma\gamma}$ (GeV^{-1})
CAST
ADMX (2010, 2018, 2019)
RBF
UF
CAPP
CAPP
RBF
CAPP
ADMX sidecar
HAYSTAC
HAYSTAC
ORGAN
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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1-2 GHz
(ADMX-G2)
(Target:
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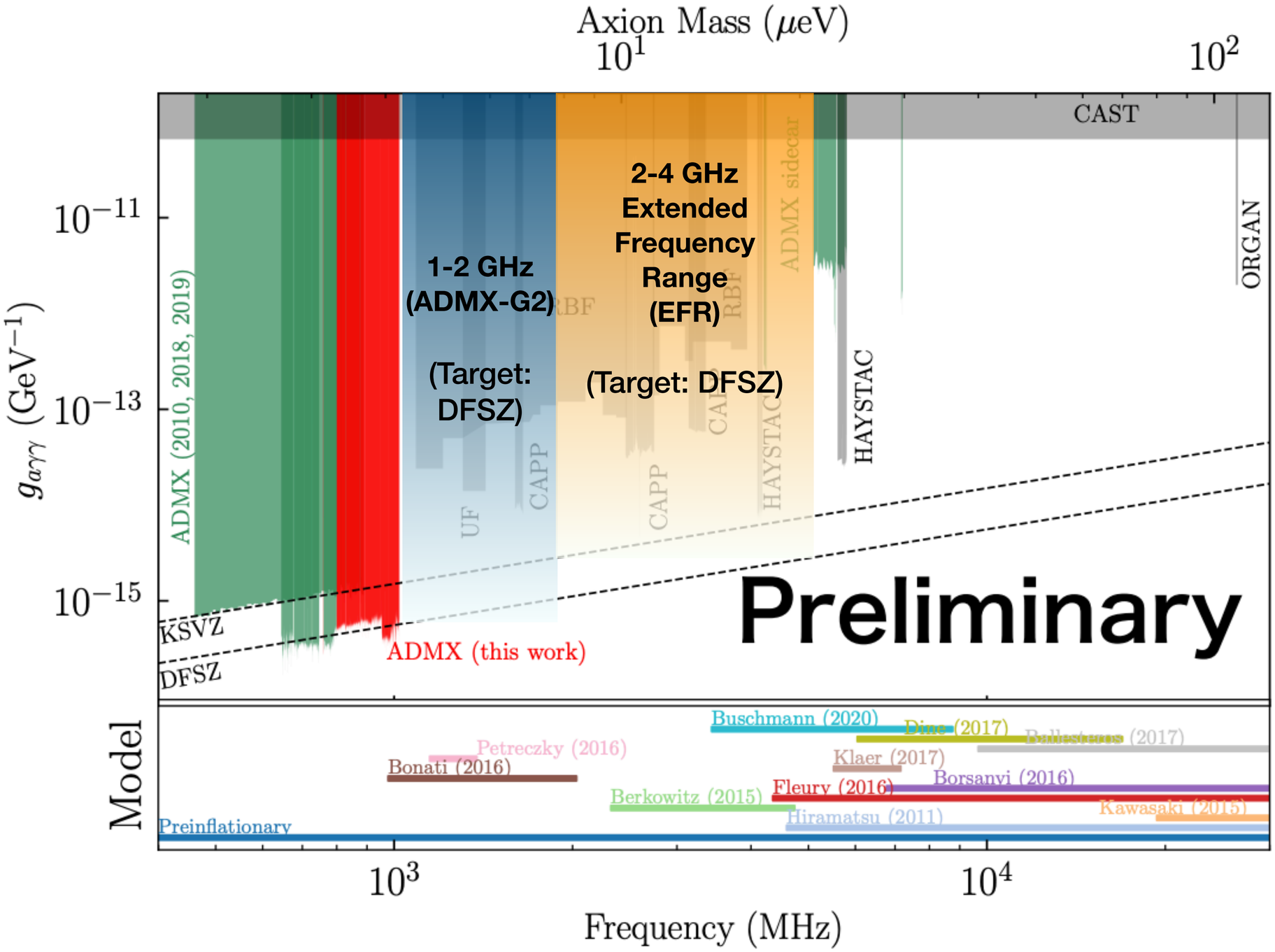
Frequency (MHz)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1-2 GHz (ADMX-G2)
(Target: DFSZ)
2-4 GHz Extended Frequency Range (EFR)
(Target: DFSZ)
KSVZ
DFSZ
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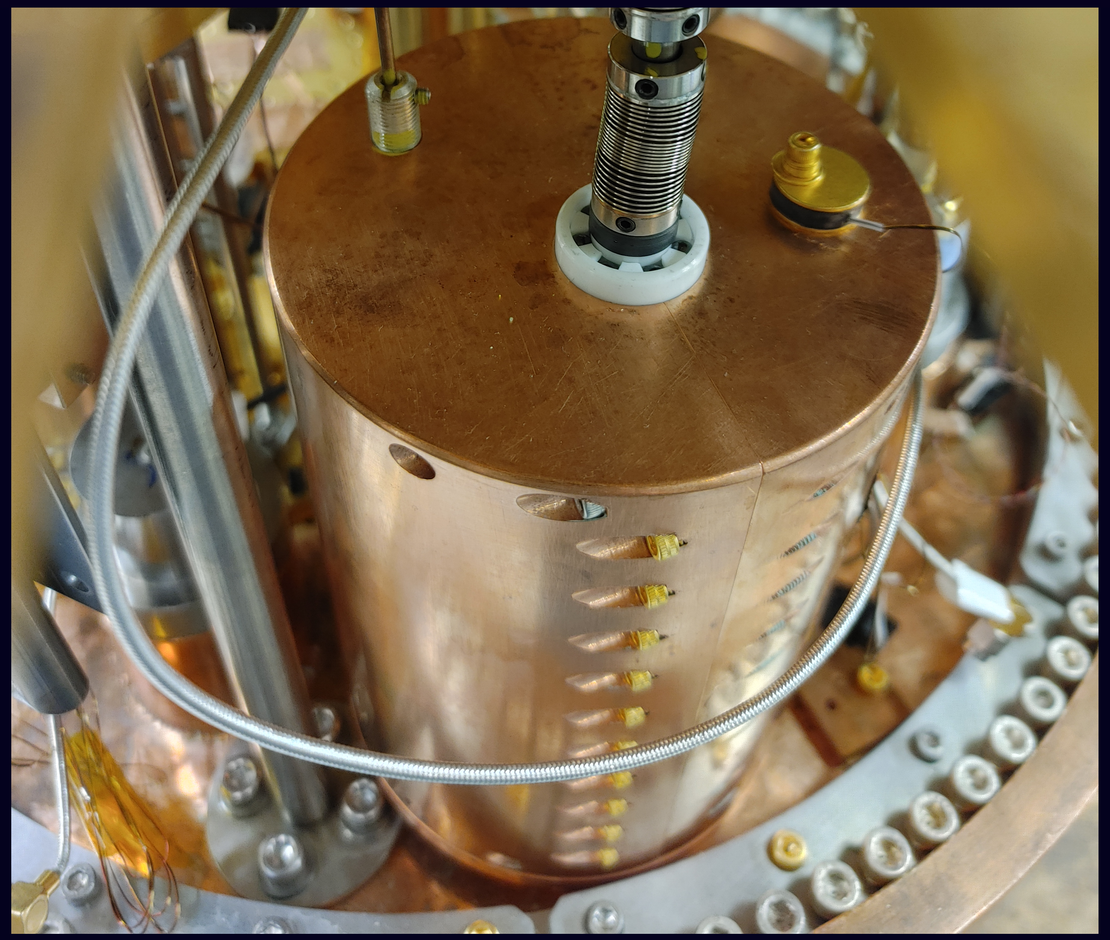
Preinflationary
10^3
10^4
Frequency (MHz)

Sidecar Cavity

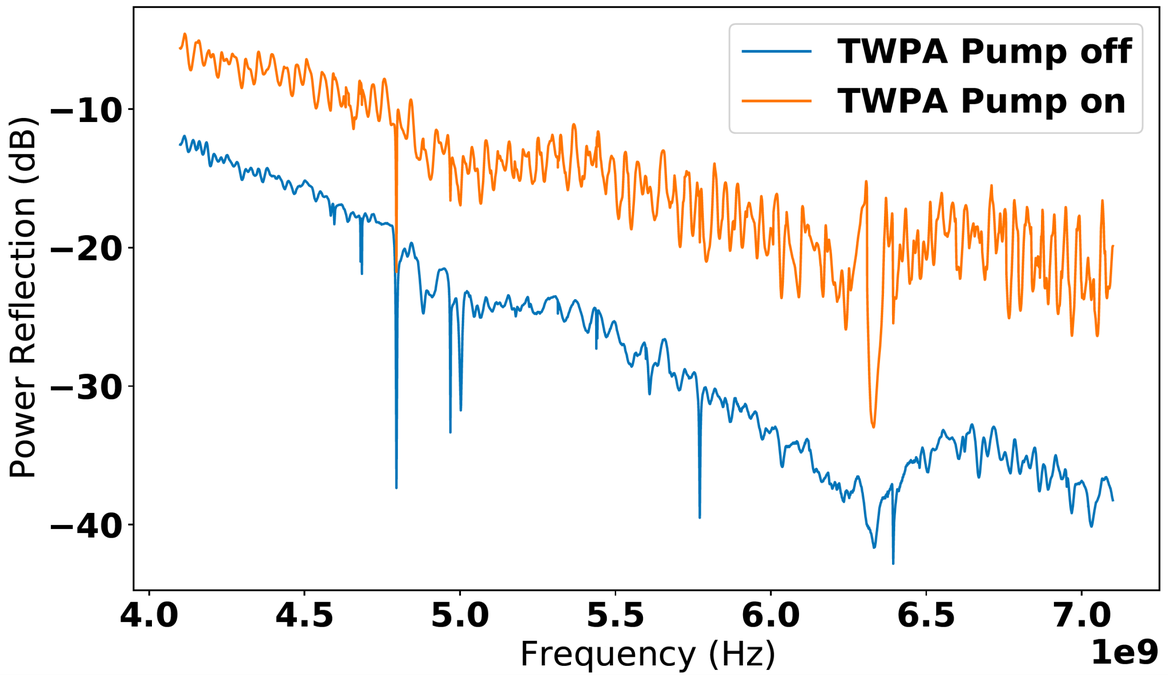
Proof-of-concept for possible features of the future data-taking operations.

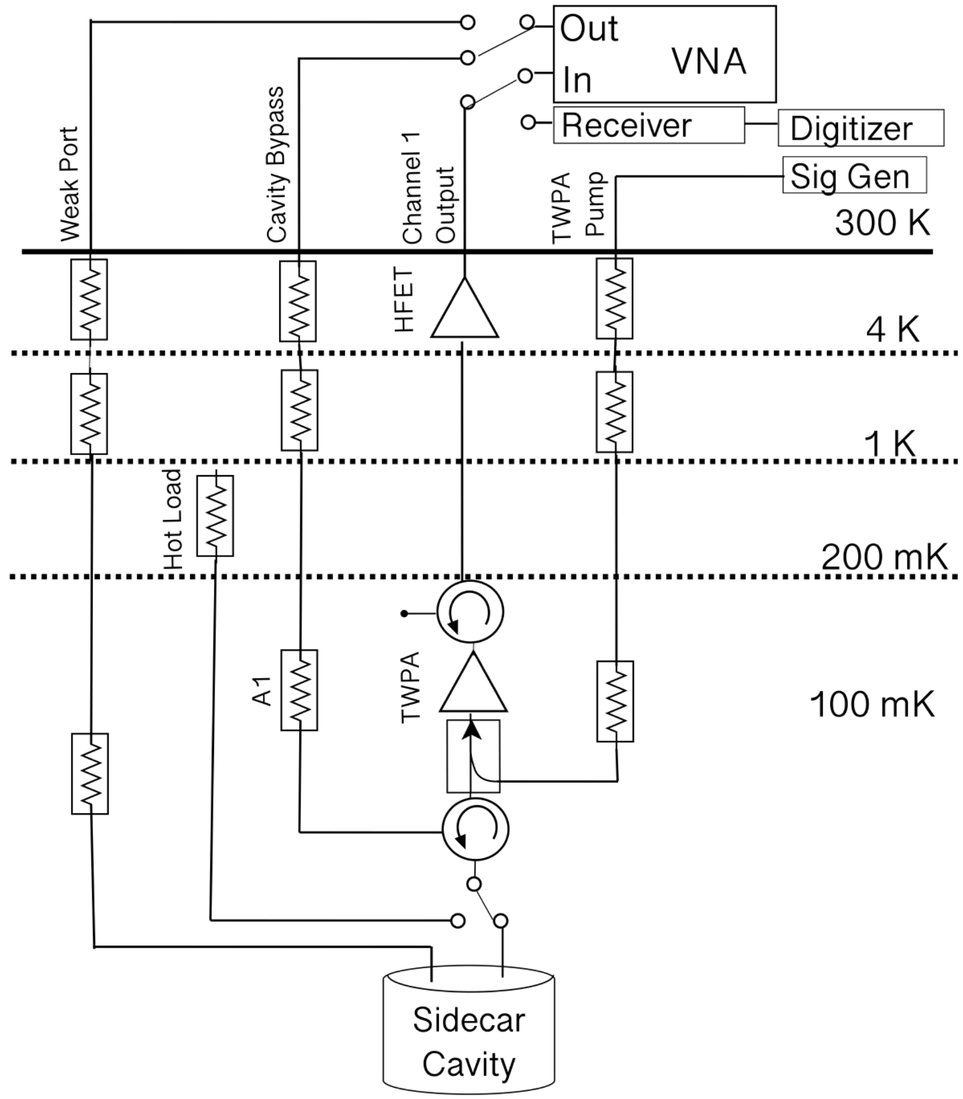
- Sidecar is a small prototyping cavity that sits on top of the main cavity.
- This iteration of sidecar is testing:
  - Traveling wave parametric amplifier
  - Clamshell cavity design
  - Piezo motors for antenna and tuning rod



Bird’s-eye view of sidecar mounted to the main cavity.

Traveling Wave Parametric Amplifier

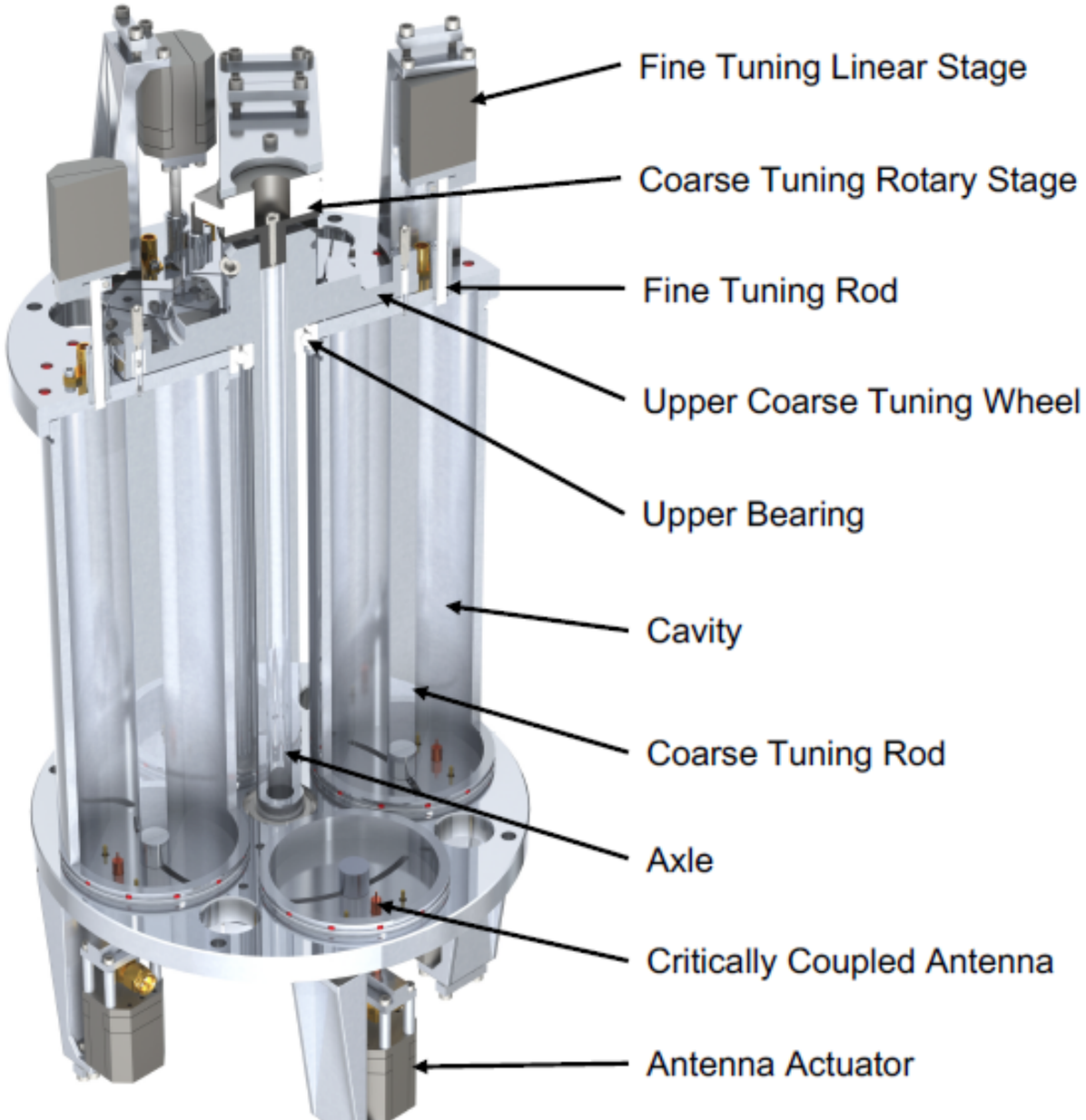




Power gain over 3-GHz wide!
Compact, requires fewer circulators
Off-resonance—> Look for axion mini clusters

Arvanitaki, Asimina, et al. "Large-misalignment mechanism for the formation of compact axion structures: Signatures from the QCD axion to fuzzy dark matter." *Physical Review D* 101.8 (2020): 083014.

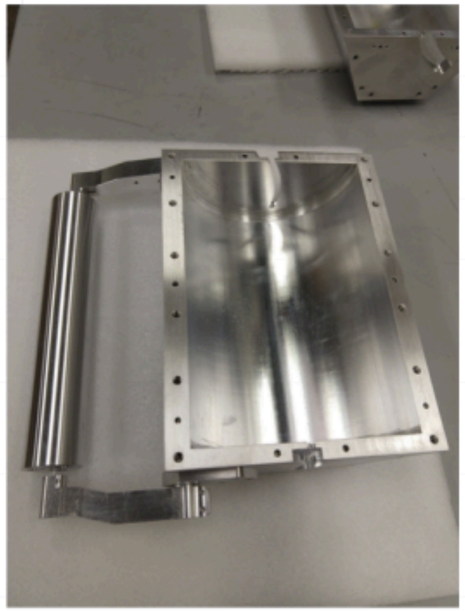
4-cavity array (1-2 GHz)



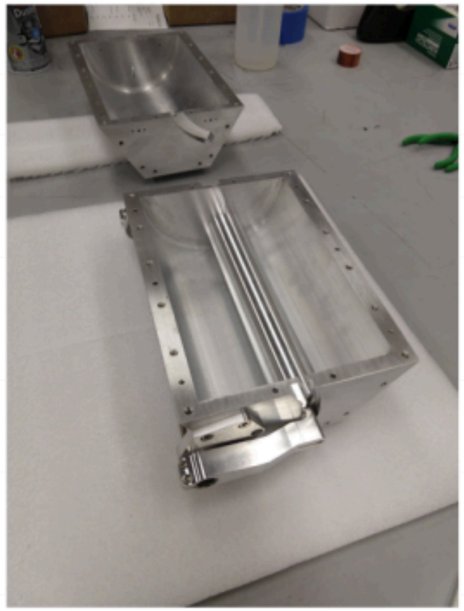
4-cavity array planned for University of Washington

- 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.

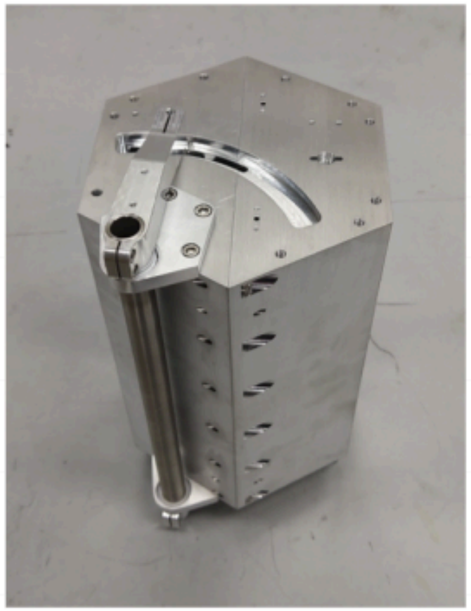
ADMX Extended Frequency Range (EFR)



Tuning rod is mounted to arms outside of array

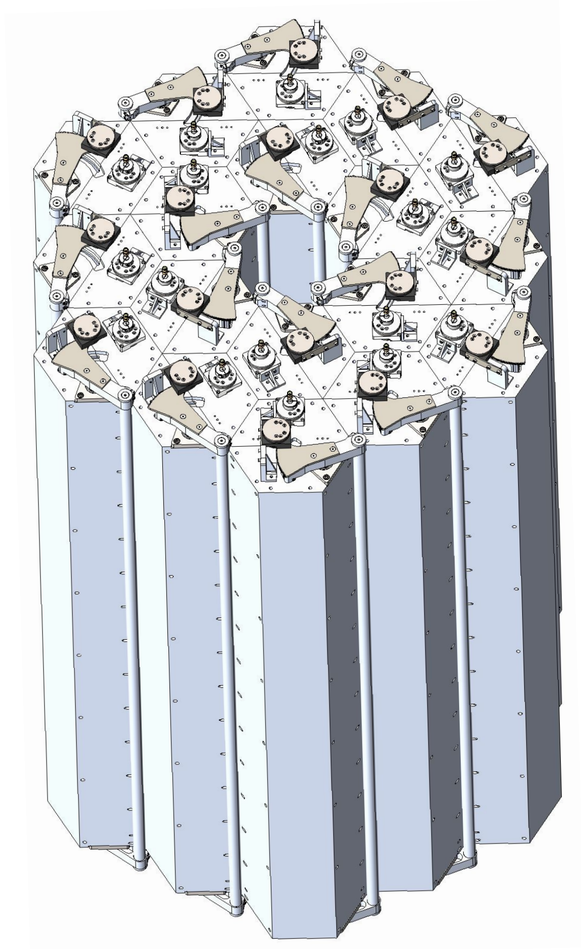


Tuning rod swung into position



Array with fully assembled tuning system

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



19.5 cm

Possibly ~18 cavities
Simulations underway

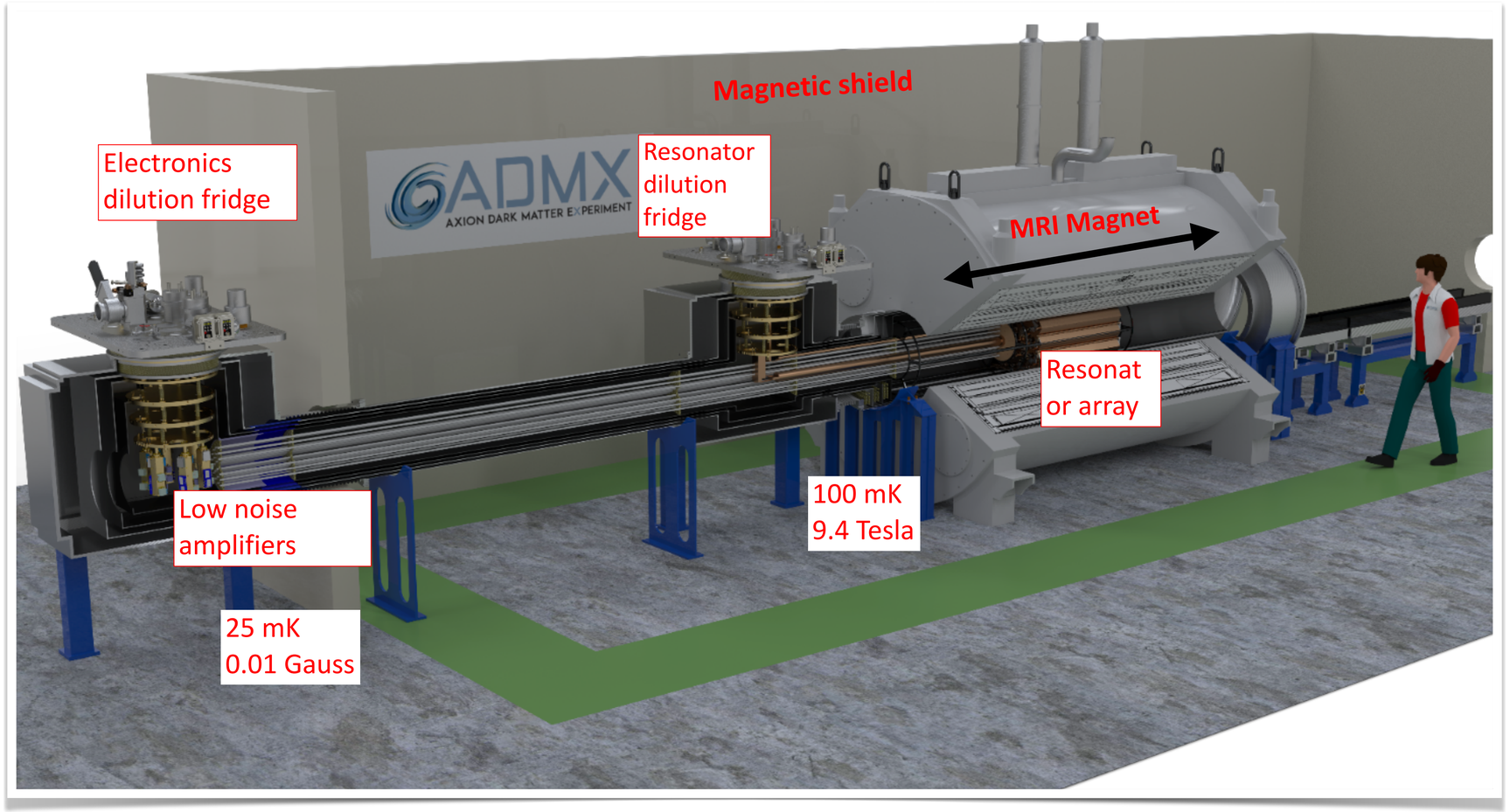
9.4 T MRI Magnet at UIUC

- 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?

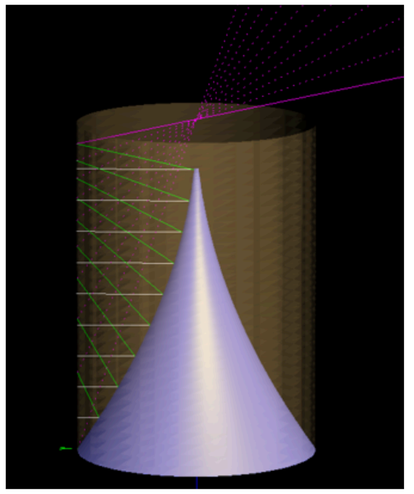


(ADMX EFR Design)

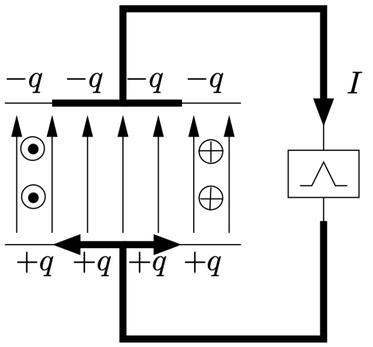
ADMX Extended Frequency Range (EFR)

New ideas being explored with collaborators

- Andrew Sonnenschein: Broadband ‘Lighthouse’ Detector (BREAD collaboration)
  - Coaxial dish antenna concept to focus light
  - Requires single photon counting capabilities
  - Broadband capabilities
- Ed Daw: Resonant Feedback Concept
  - Resonant feedback using FPGA filters
  - Possibility of generating multiple resonances
  - Broadband capabilities
- Akash Dixit: Single photon counting with qubits
  - Need to develop techniques to transport the photon
  - Investigate magnetic field performance
  - Possibility of starting cavity in high N Fock state

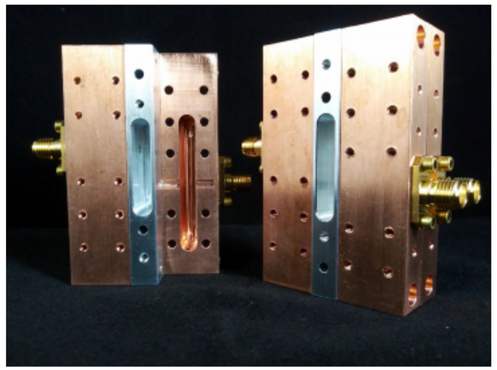


Andrew Sonnenschein



Resonant feedback

Ed Daw



Akash Dixit

Acknowledgements

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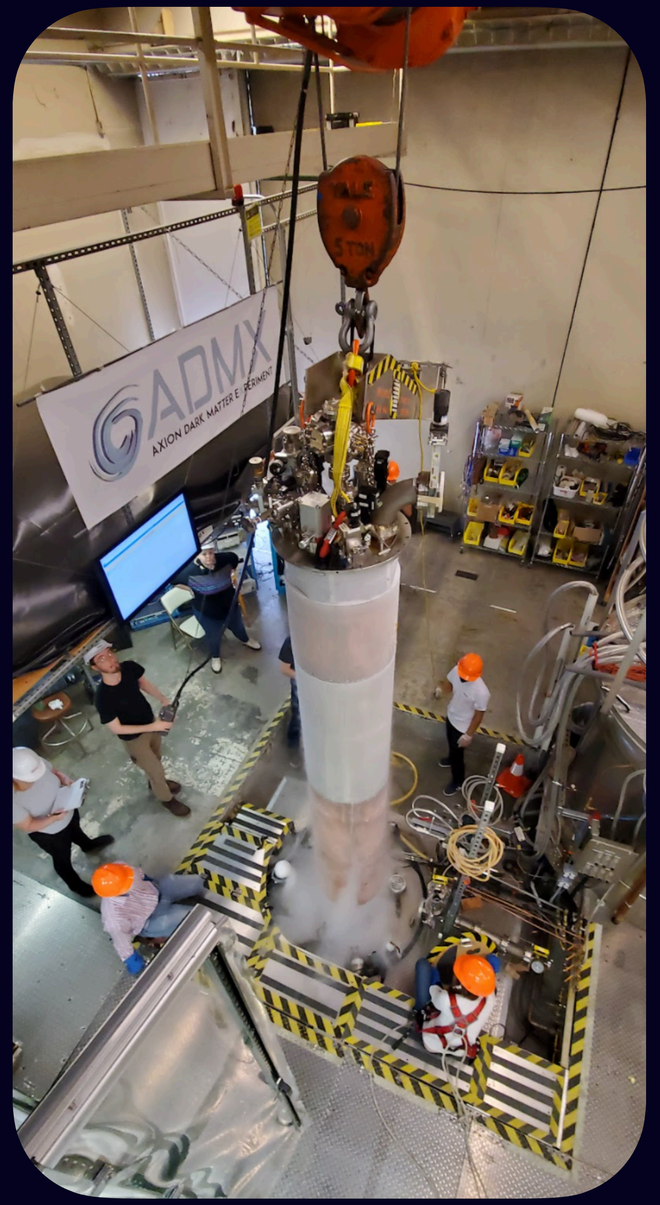
Conclusions

- ADMX has completed the first half of Run 1C data-taking.
- Will resume second half at DFSZ sensitivity after repairs.
- Progress is being made towards higher frequency searches.
- Discovery could happen at any moment.



Thank you!

Any Questions?