Results and Status of the Axion Dark Matter Experiment

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AXION DARK MATTER EXPERIMENT

Outline

- Background
- Haloscope Detectors
- ADMX Design
- ADMX Results
- Future Work

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Why we look for axions

- There is compelling evidence for dark matter, but we don't know what it is
- Axions may make up the dark matter
- Axions are a well motivated dark matter candidate because they arise from solving the strong CP problem

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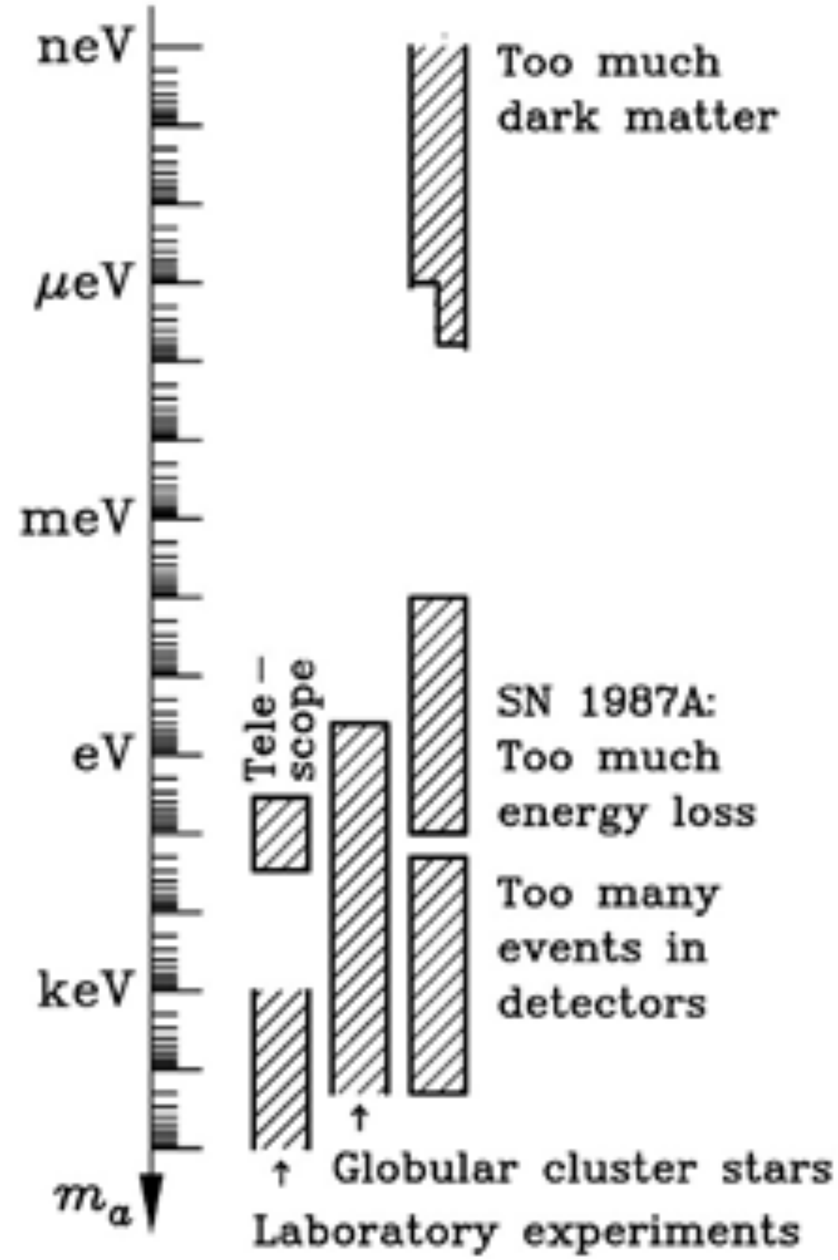
Invisible axions

- For QCD axions that solve strong CP, coupling and mass are interdependent
- Strongly coupled axion are not observed
- Weakly coupled axions make up the the dark matter window
- Elusive invisible axions in μeV mass range



G G Raffelt, arXiv:hep-ph/0611118

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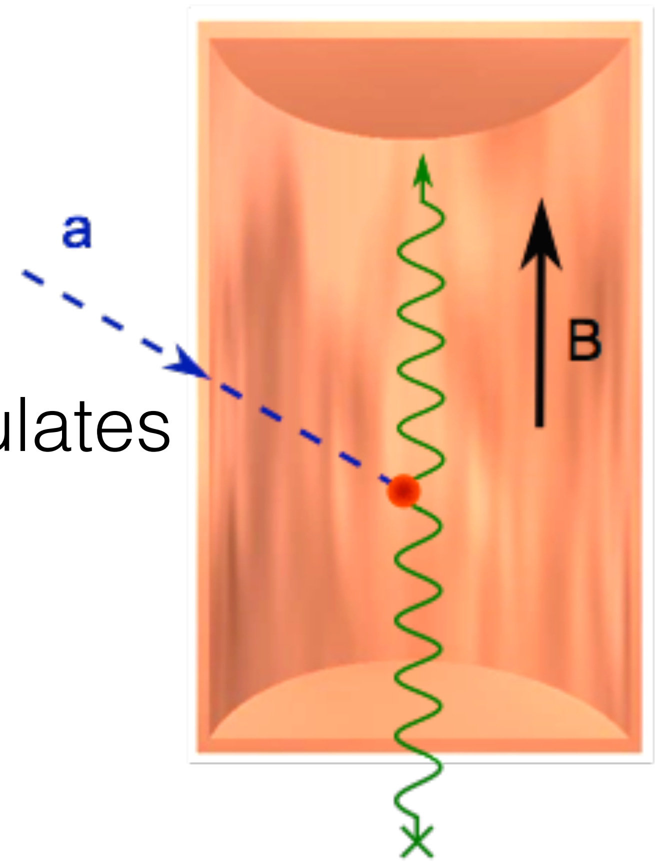
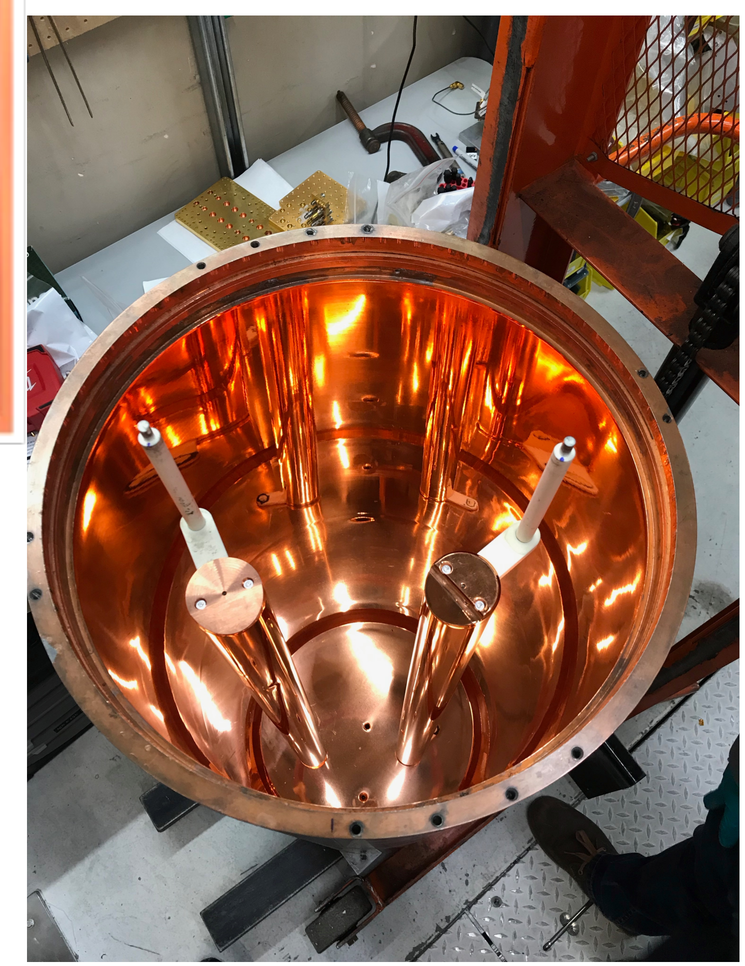
How we look for axions

- Detection through the Sikivie Haloscope
- An external magnetic field stimulates conversion to real photons
- The photon signature of axion conversion is faint
- Resonant enhancement is needed
- Axion mass is unknown so we must scan possible resulting photon frequencies





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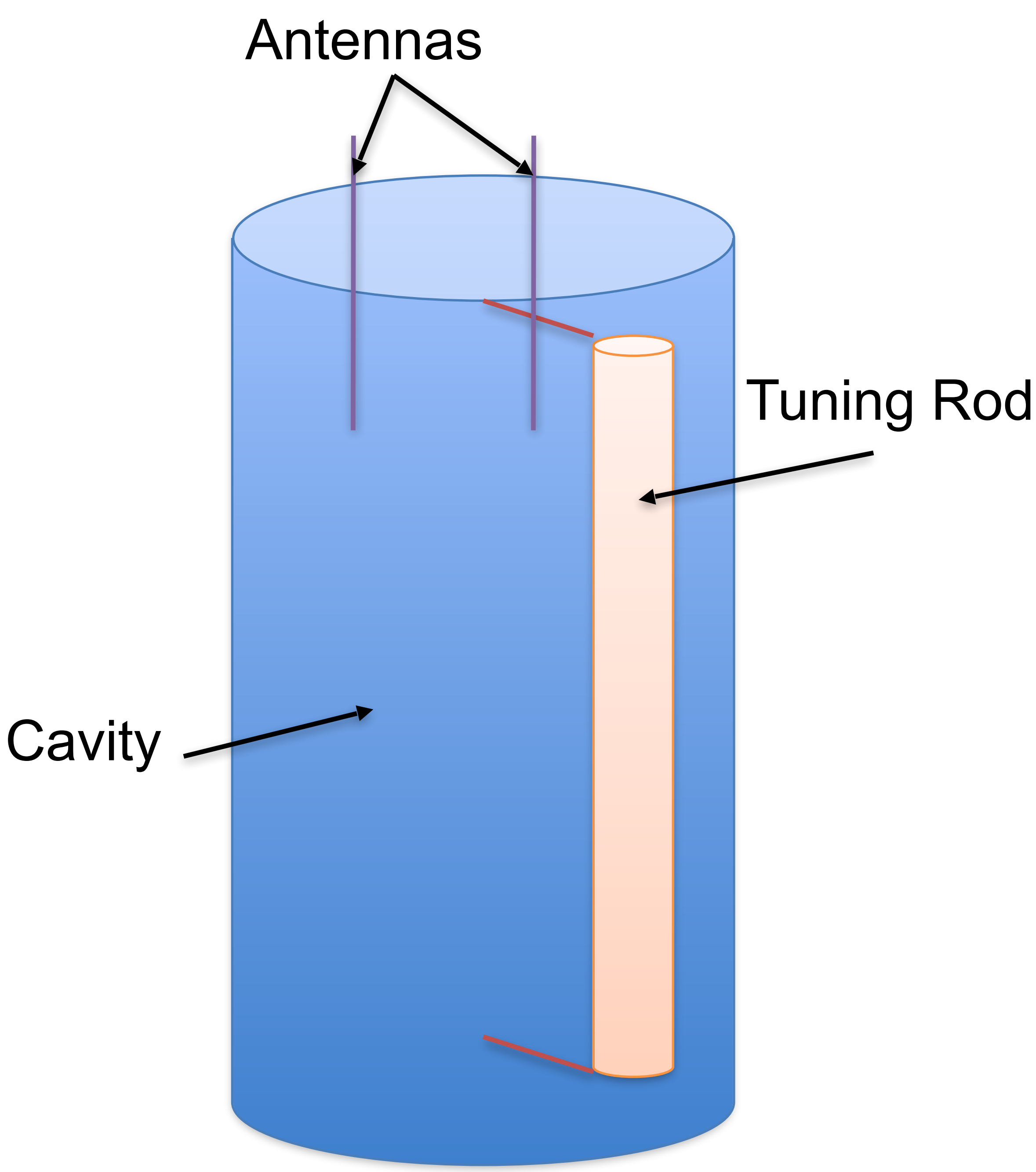
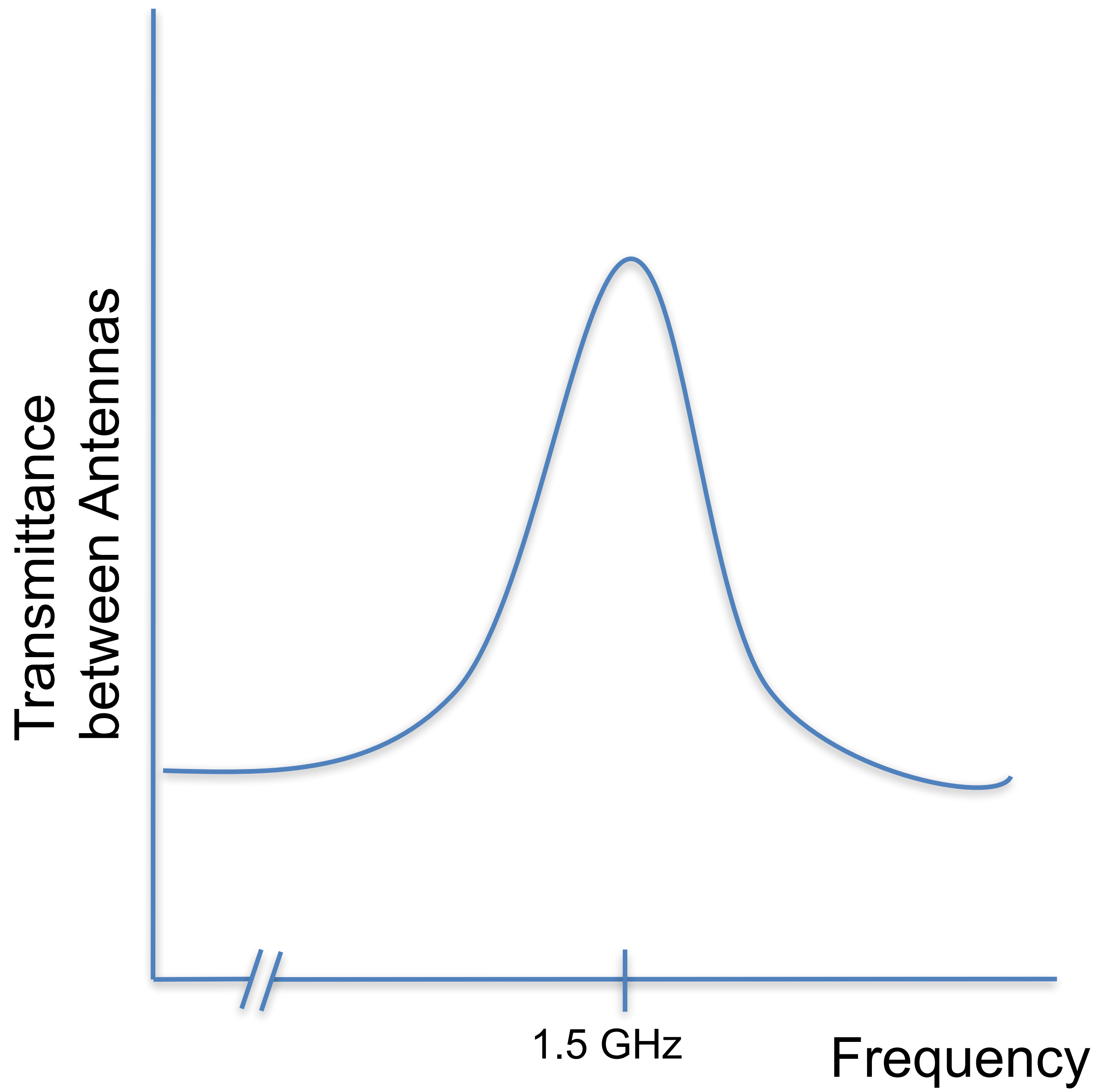
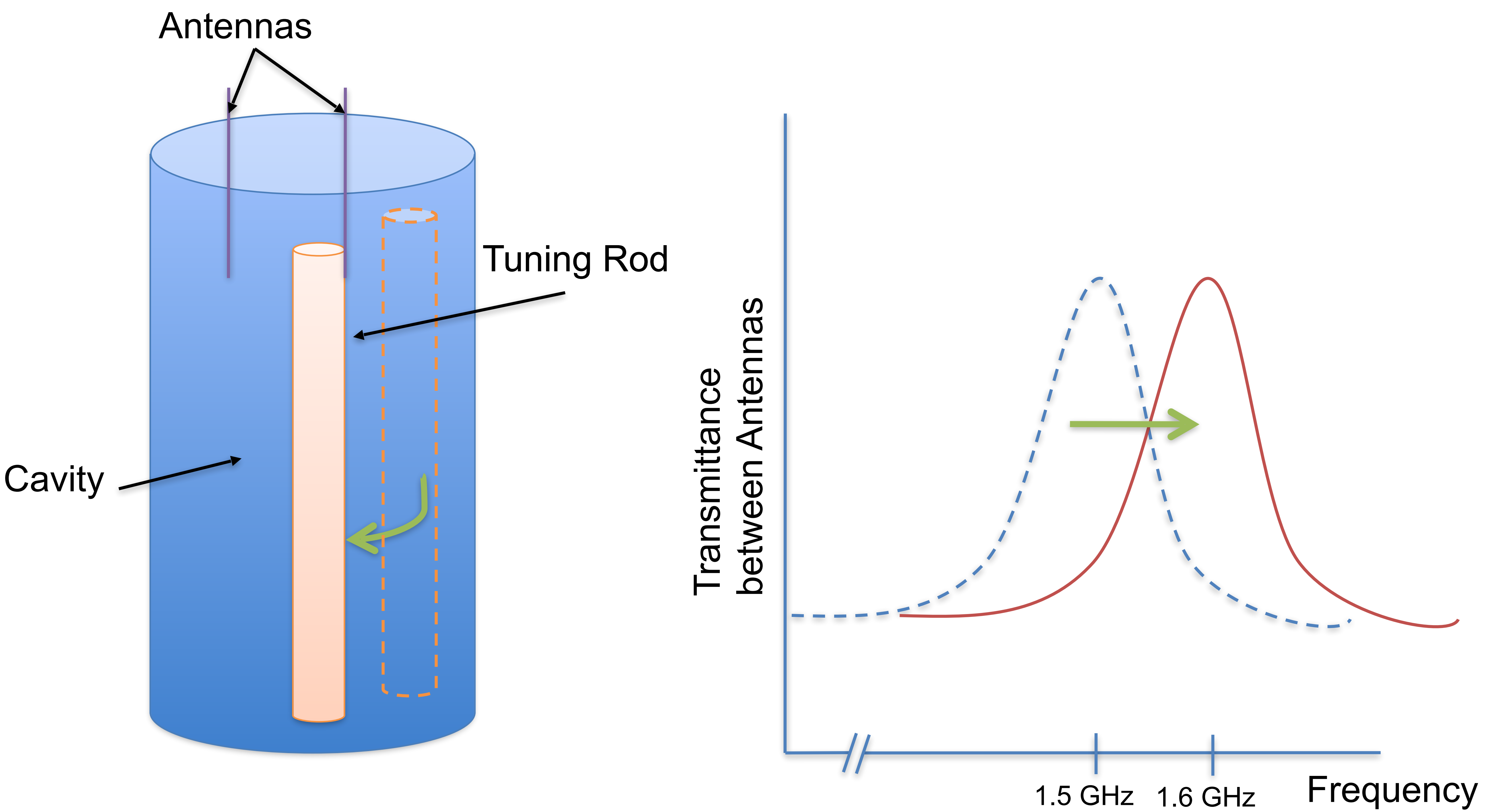
Cavity Tuning





Cavity Tuning



Power

$$P_{axion} = 1.9\times10^{-22}\ \mathrm{W} \left(\frac{V}{136\ \mathrm{L}}\right)\left(\frac{B}{6.8\ \mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_a}{0.45\ \mathrm{GeV\ cm^{-3}}}\right)\left(\frac{f}{650\ \mathrm{MHz}}\right)\left(\frac{Q}{50,000}\right)$$

- V is cavity volume
- B magnetic field
- C_{nl} is a form factor, overlap of cavity mode and applied magnetic field
- g_γ ~ 0.36 (DFSZ) while g_γ ~ -0.97 (KSVZ)
- ρ is local axion halo density
- 650 MHz ⇔ 2.7 μeV
- Q resonator quality factor, how long cavity rings coherently with conversion photon

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Radiometer

- Signal to Noise Ratio from the radiometer equation
  - $\frac{s}{n} = \frac{P}{k\,T_n}\sqrt{\frac{t}{\Delta f}}$
- System temperature
  - $T_n = T_{phys} + T_{amp}$
- Scan rate

$$\frac{df}{dt} \approx 750\ \mathrm{MHz/year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{5}{\mathrm{SNR}}\right)^2 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4$$
$$\left(\frac{V}{100\ \mathrm{L}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{\rho_a}{0.45\ \mathrm{GeV\ cm^{-3}}}\right)^4 \left(\frac{0.2\ \mathrm{K}}{T_{sys}}\right)^2$$

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Engineering Parameters

- High quality factor resonator -> copper plated microwave cavity resonator
- Strong magnetic field ->large superconducting solenoid magnet
- Low system noise temperature
  - Low physical temperature -> dilution refrigerator
  - Low amplifier noise temperature -> quantum electronics

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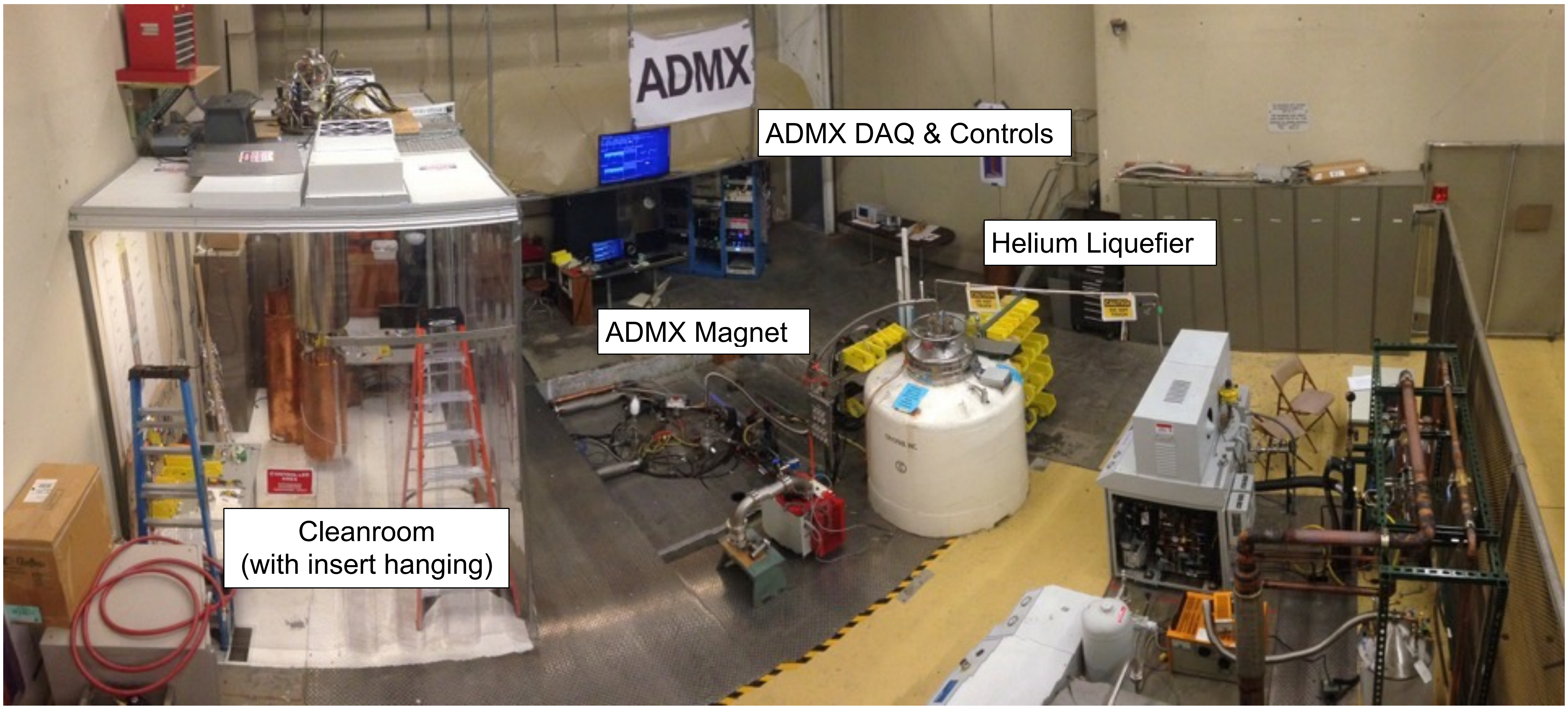
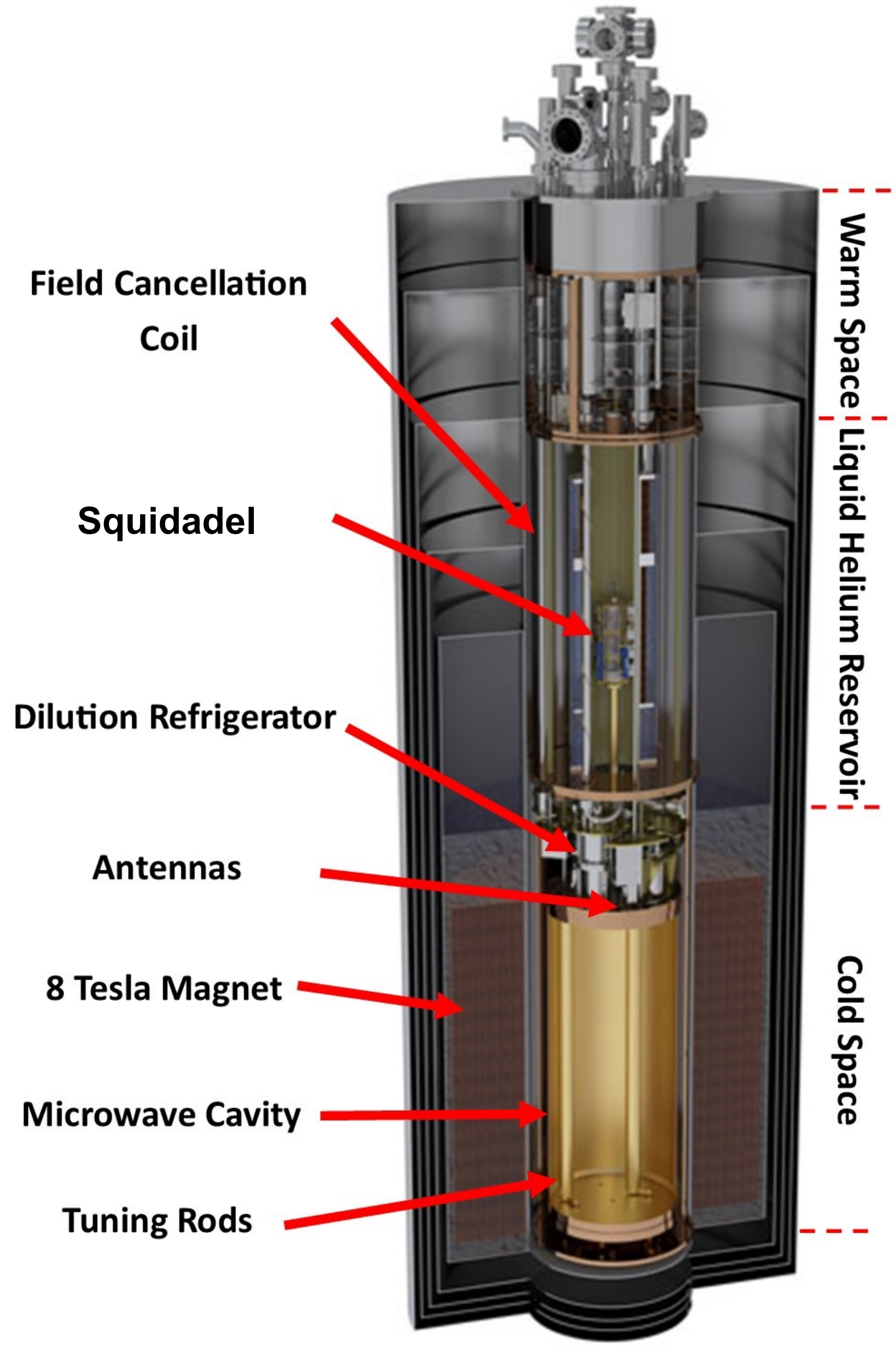
ADMX Site



ADMX
ADMX DAQ & Controls
Helium Liquefier
ADMX Magnet
Cleanroom
(with insert hanging)

Experiment Layout



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Magnet

- Superconducting solenoid magnet
- 53 cm bore
- 100 cm height
- Up to 8 Telsa
- 230 Amps

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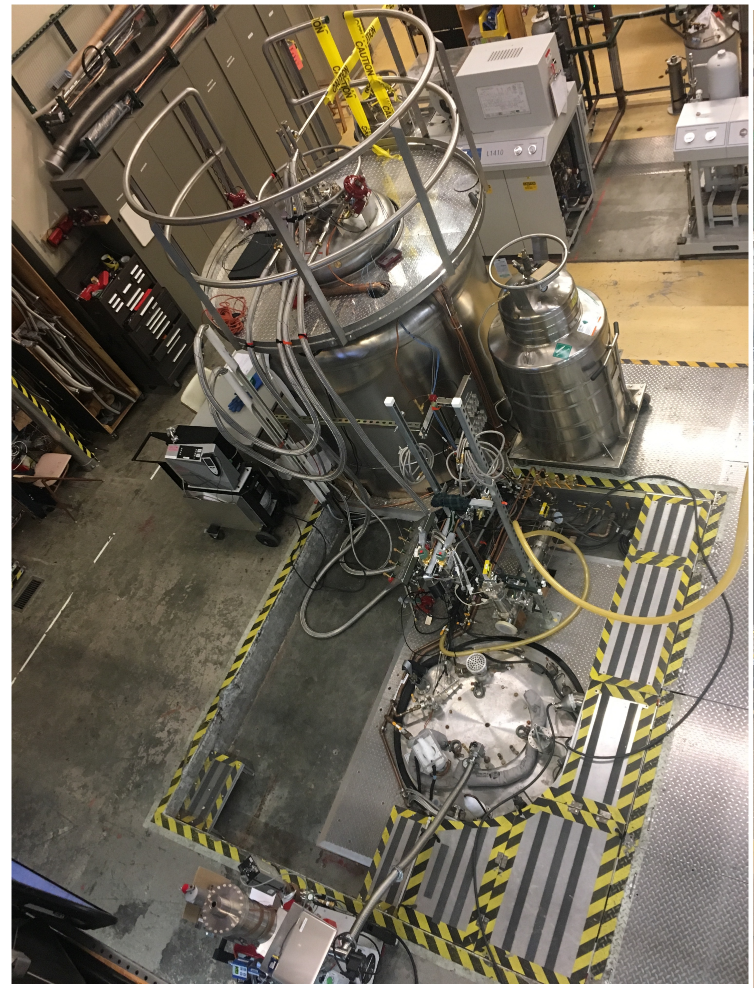
Helium Plant

- Major ^{4}He consumption
  - Magnet fills
  - Insert reservoir fills
- Capture and re-liquify ^{4}He
- Recent Plant Upgrades
  - Mother Dewar volume increase
  - Production rate increase
  - Autofill System



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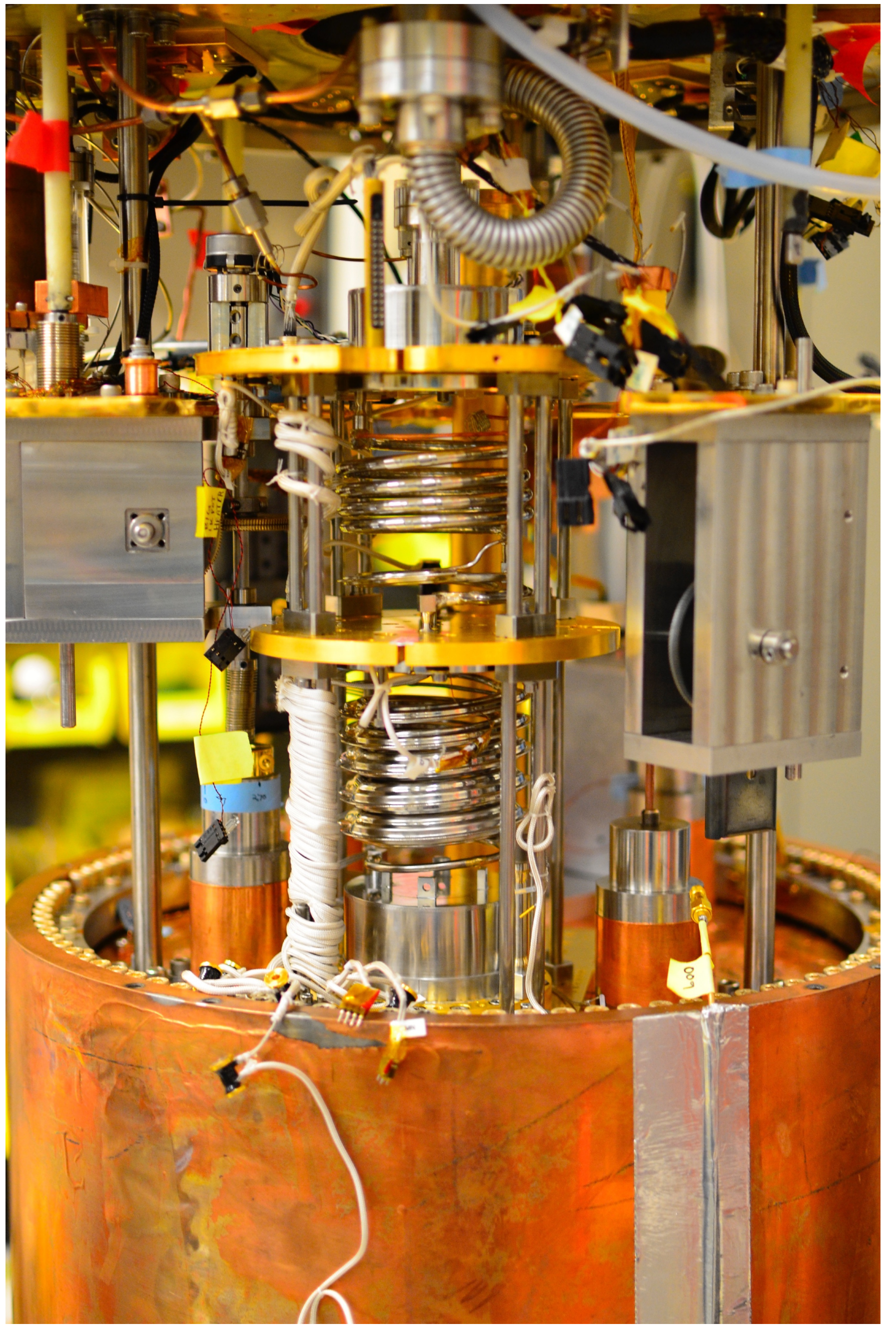
Dilution Refrigerator

- Cooling through of mixing ^3He and ^4He
- Allows persistent miliKelvin temperatures
- Substantial cooling power 800 µwatts @ 100 mK
- Physical noise becomes lower than noise temperature of classically limited amplifiers
- Sets the stage for quantum limited amplifiers



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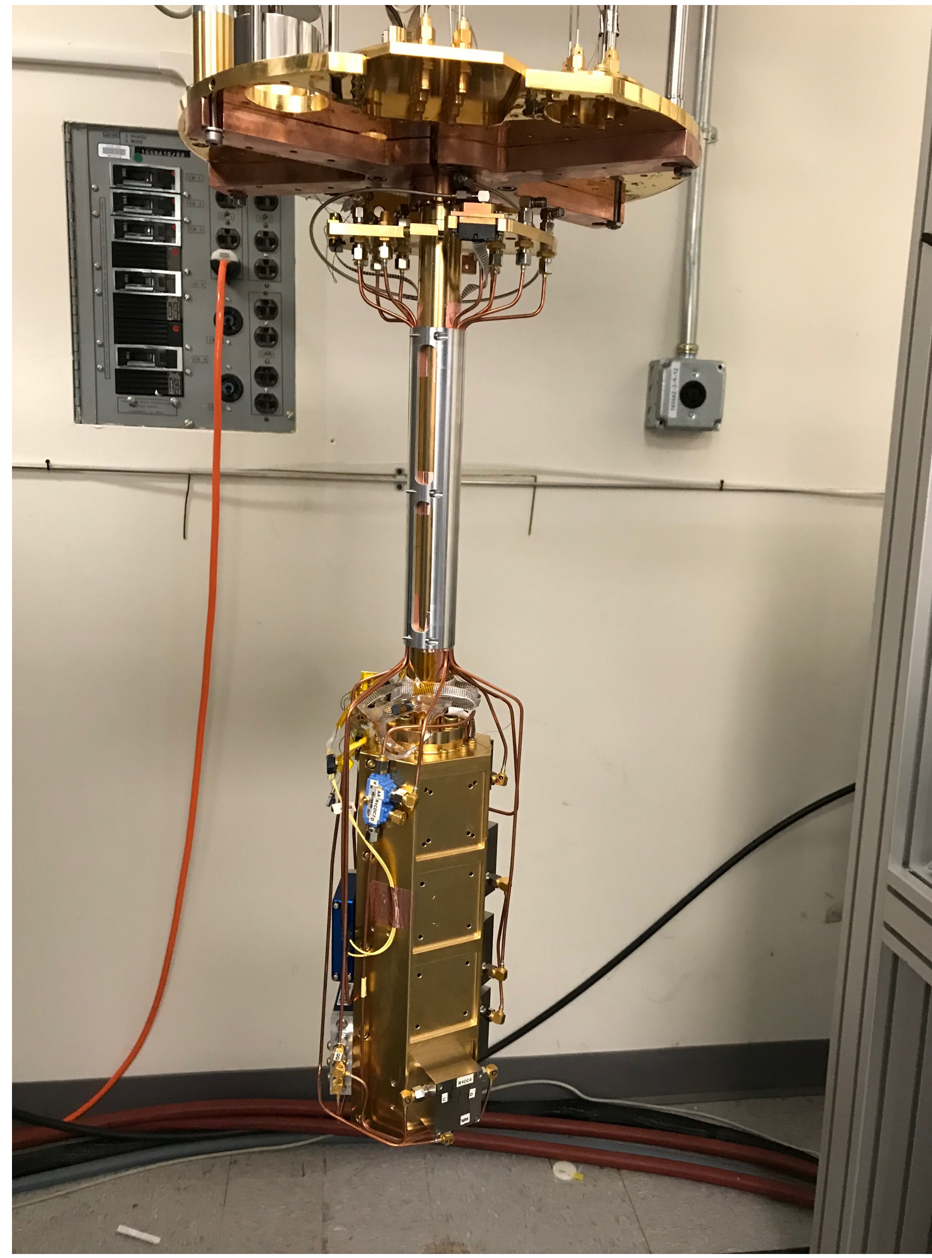
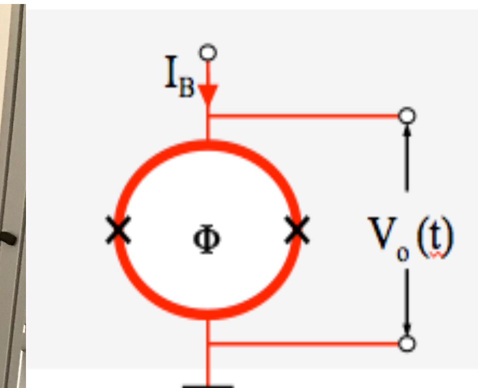
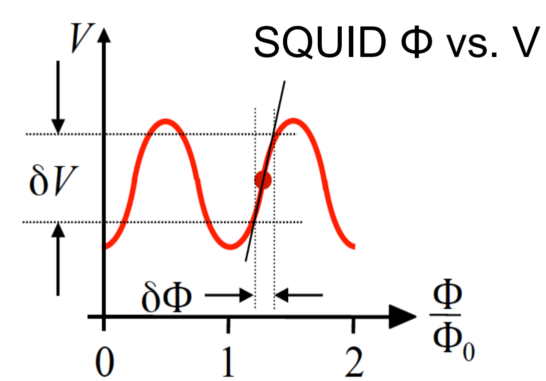
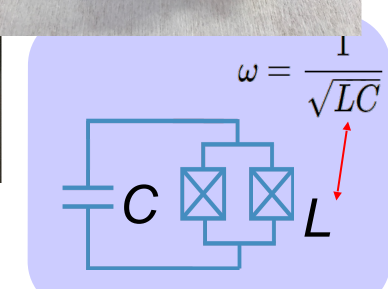
Quantum Electronics

- Superconducting Quantum Interference Devices (SQUIDs)
  - Flux to voltage transducers
- Josephson Parametric Amplifiers (JPAs)
  - “pumped” oscillator
- Amplifiers that approach the quantum limit
- Allow for low noise temperature
- Live in a field free region “squidadel”









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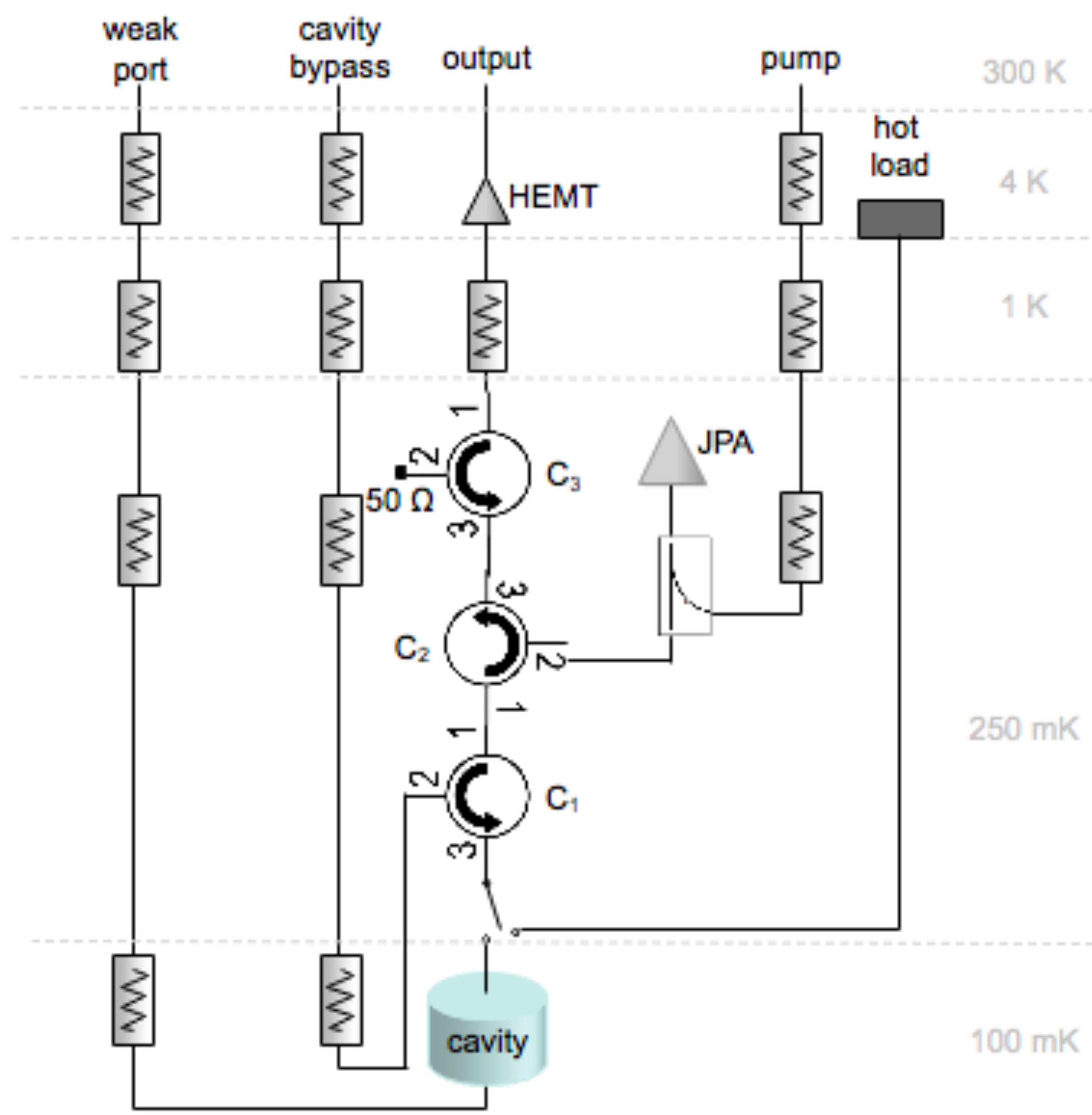
*jpa figures courtesy of Shahid Nawaz

Receiver Chain

- Receiver chain progress through warmer regions
- Additional HEMT amplification
- Double heterodyne mixing
- FFT to digitize and record



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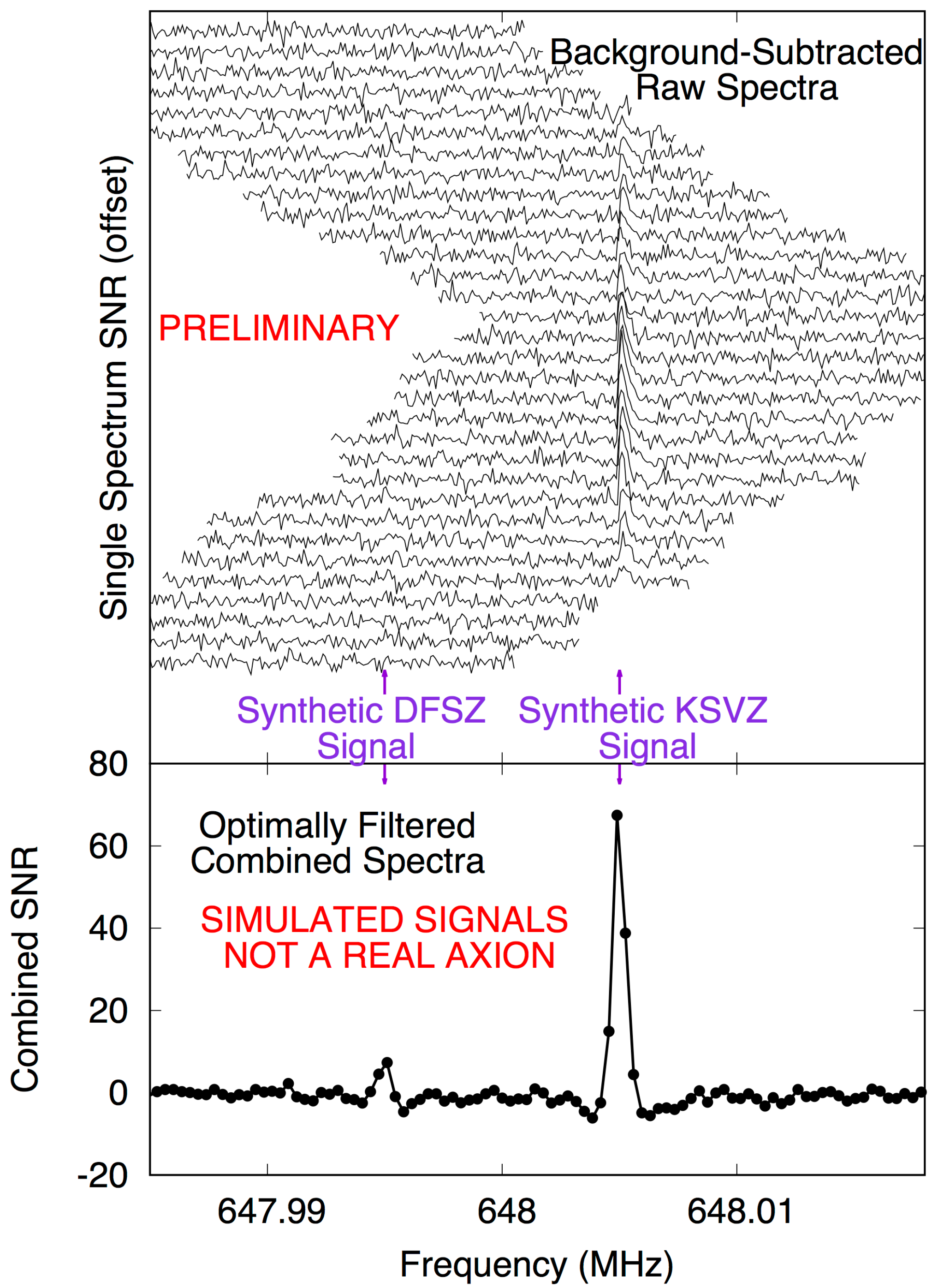
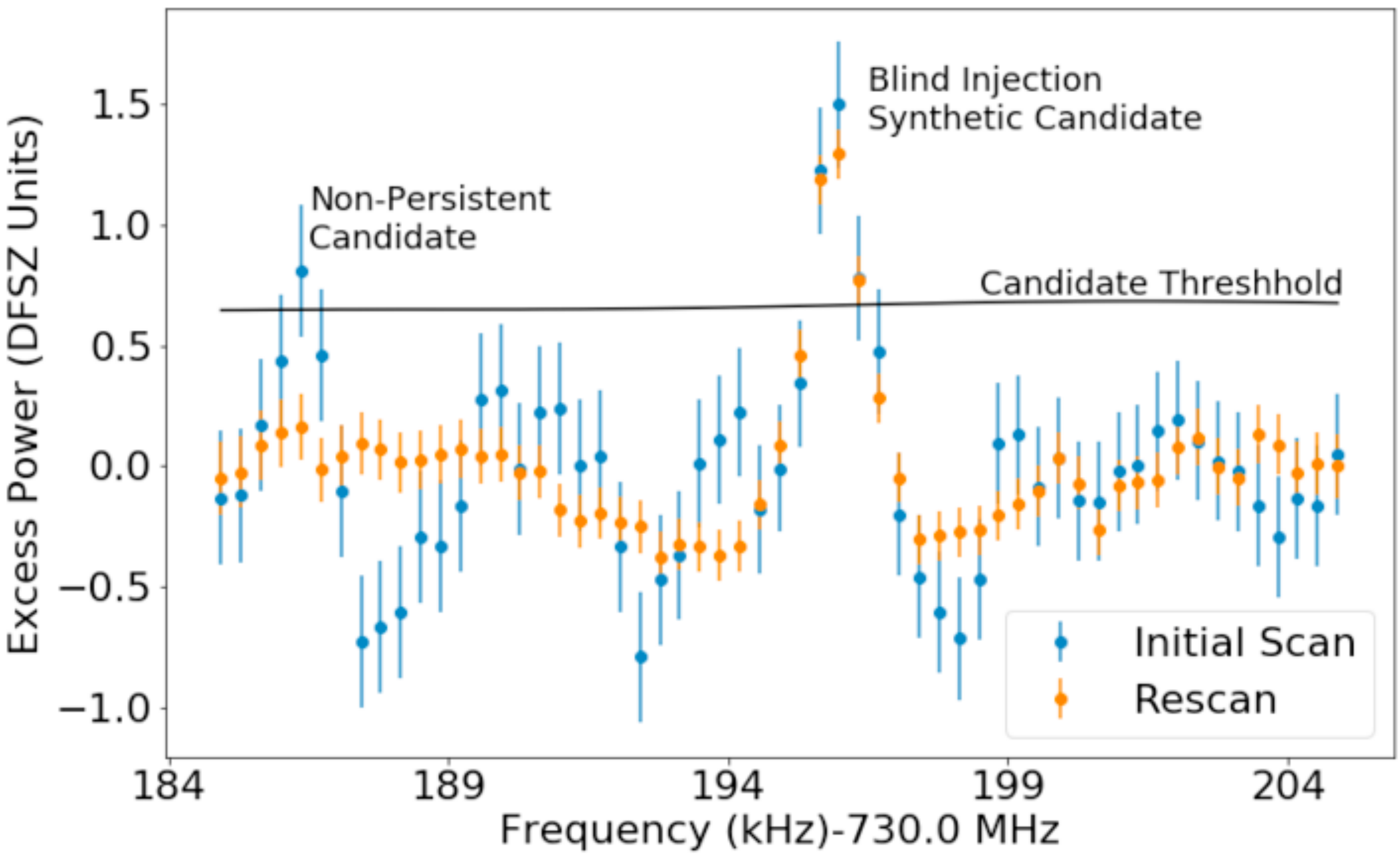
Synthetic Axion Injection



- How do we know we are capable of detection?
- Synthetic test signals are periodically injected
- Confirm in live analysis and remove from actual search data

Synthetic signal candidate for ADMX Run1b



Run 1a

- Operated from January- June 2017
- Scanned frequency range: 645-680 MHz (2.66-2.81 μeV)
- Magnetic field: 6.8 T
- Temperature: ~150 mK
- DFSZ sensitivity attained for the first time!

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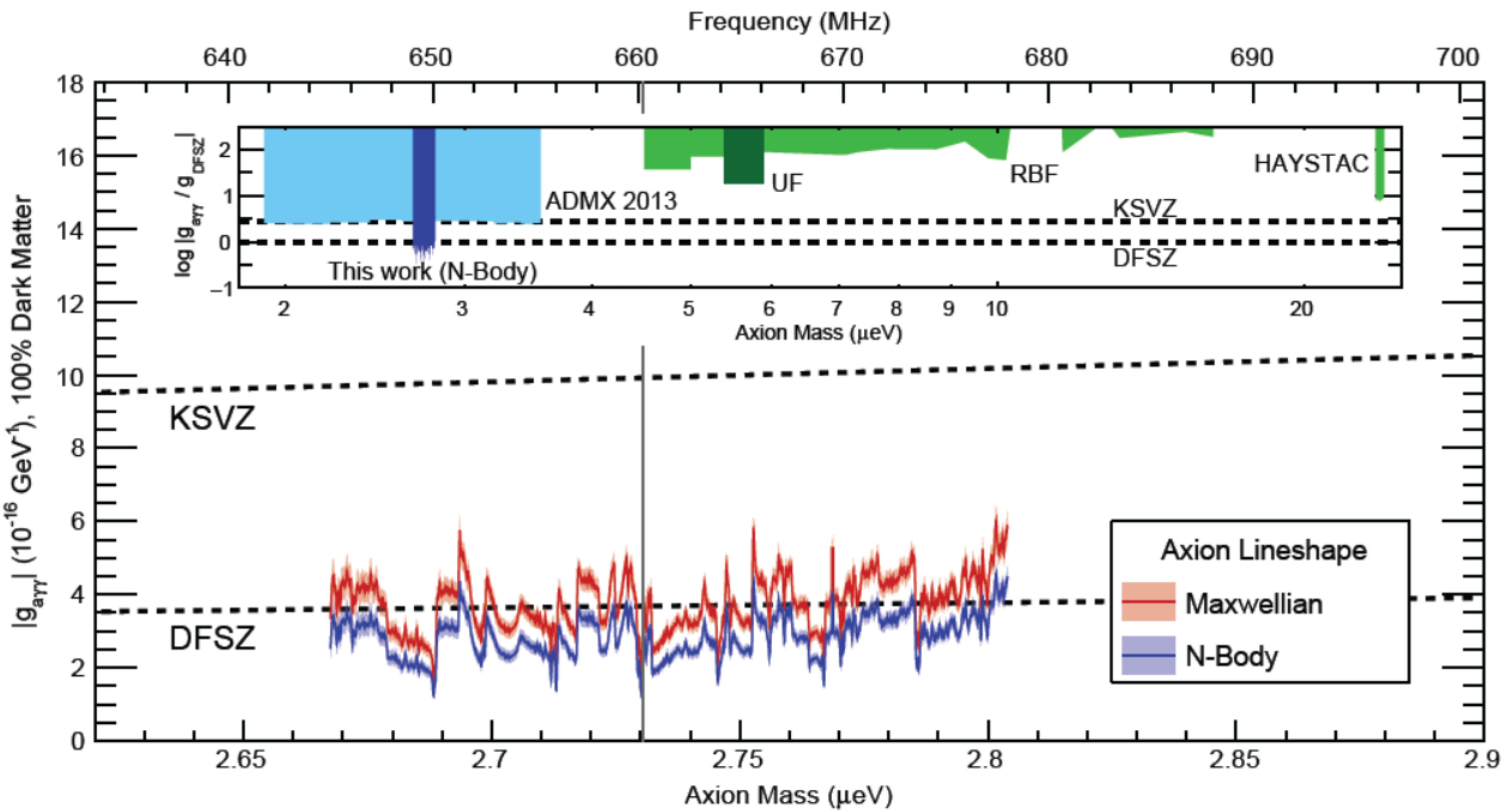
Run 1a Limits



Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment
PRL 120, 151301 (2018)

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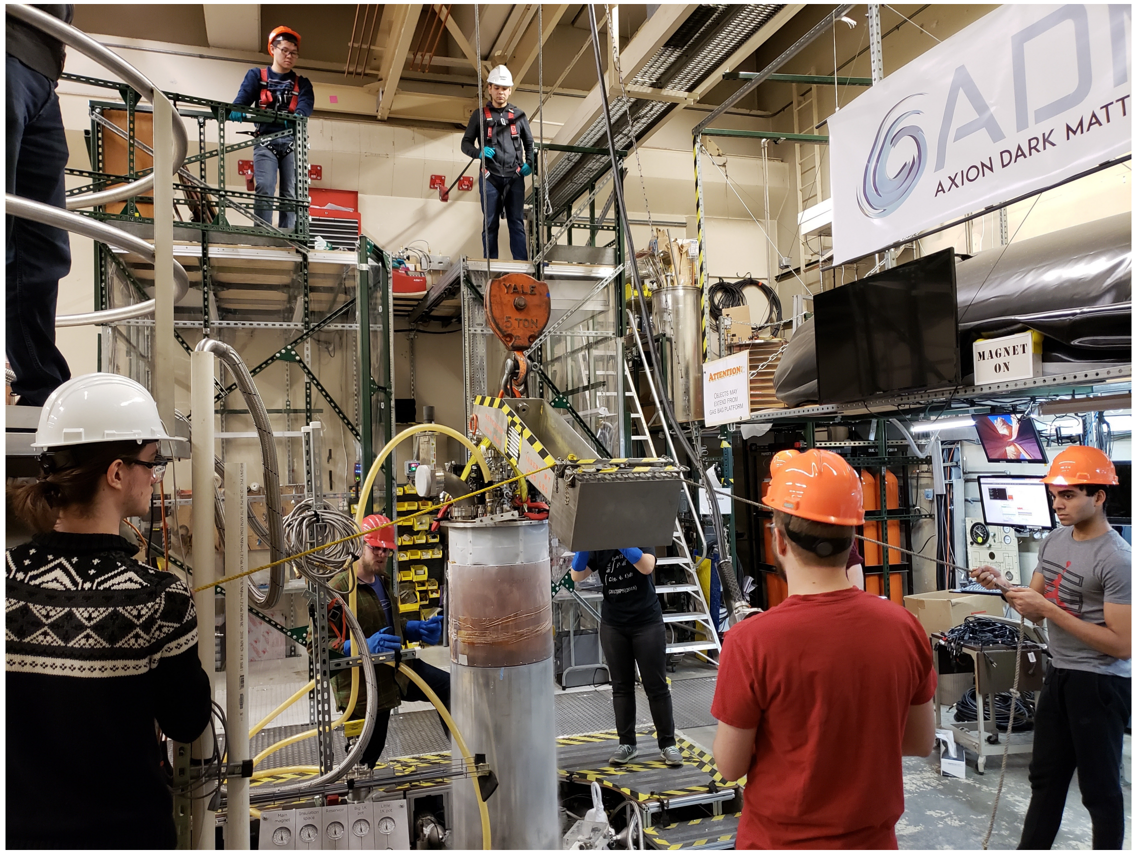
Run 1b

- Operated from January - October 2018
- Higher magnetic field 7.6 T
- Colder temperature ~90 mK
- Extended searched mass frequency range 680 - 800 MHz (2.81 -3.31 μeV)



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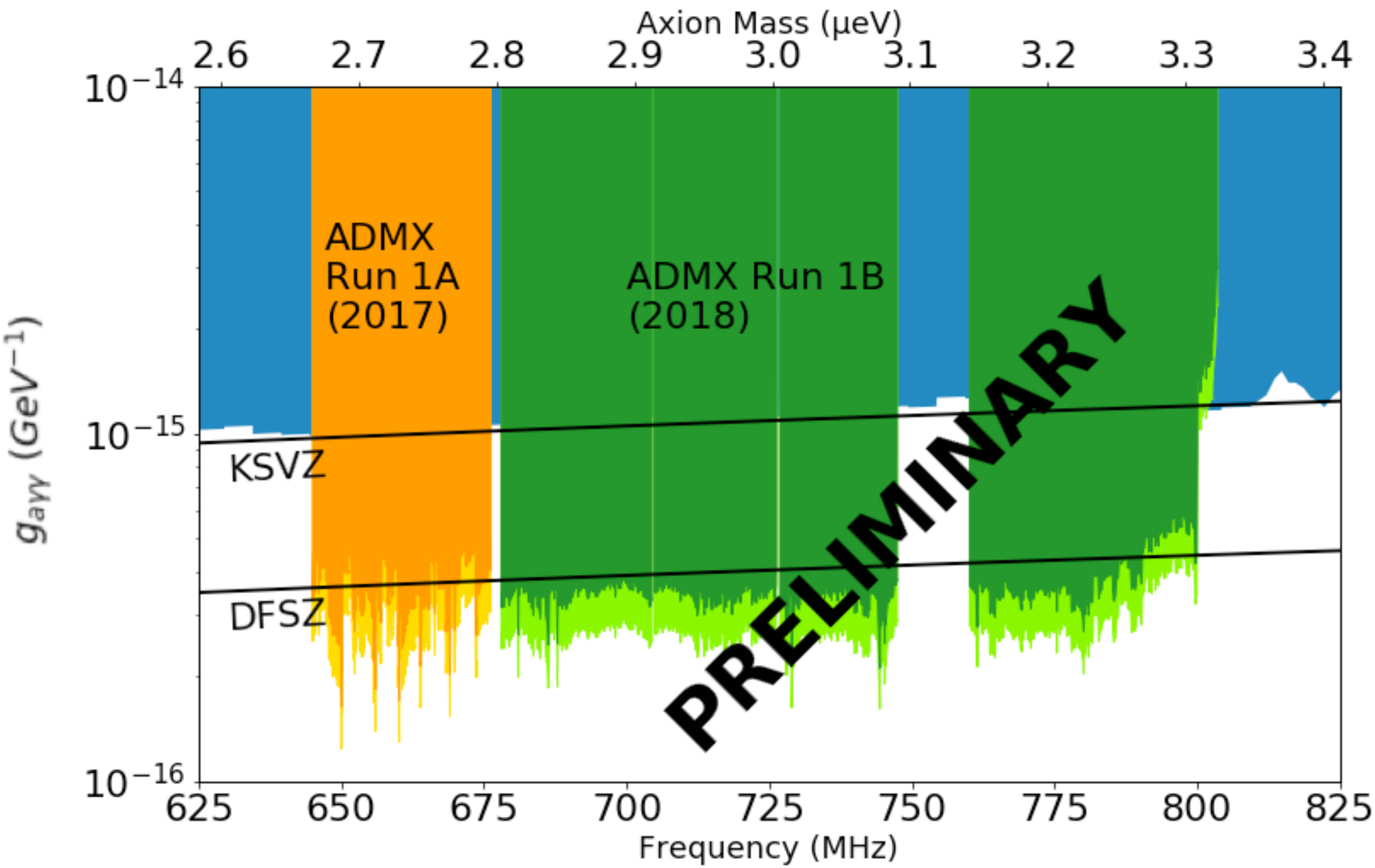
Run 1b Limits



Run 1c: On-going search

- An axion has not yet been found, the search continues
- Tuning Rod and Quantum Electronics Changed
- Planned Frequency Range: 800 - 1,000 Mhz

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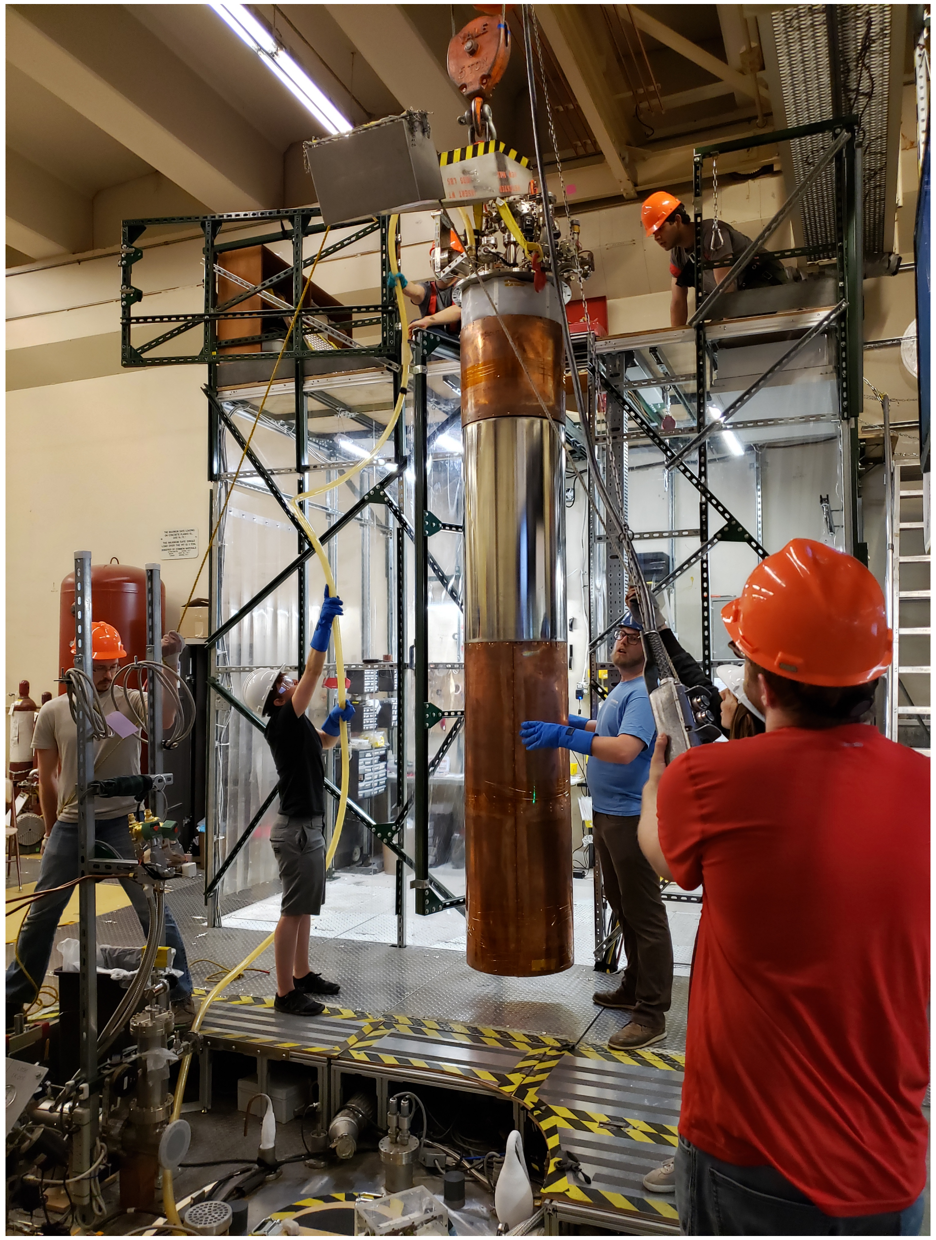
Run 1c: On-going search

- Expected Improvements
  - smaller mode crossings
  - better cryogenics and noise temperature
  - lower dead time/more efficient operation
  - wider tuning range
- Stay tuned for progress updates!



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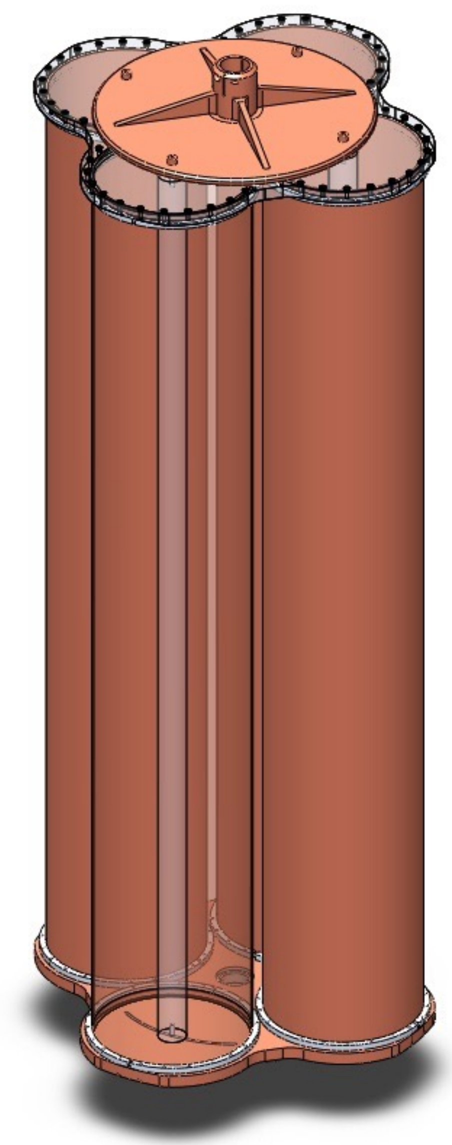
Searching Higher Masses

- Smaller cavity radius for higher frequency
- Loss of volume => less power out
- Combine an array of cavities!



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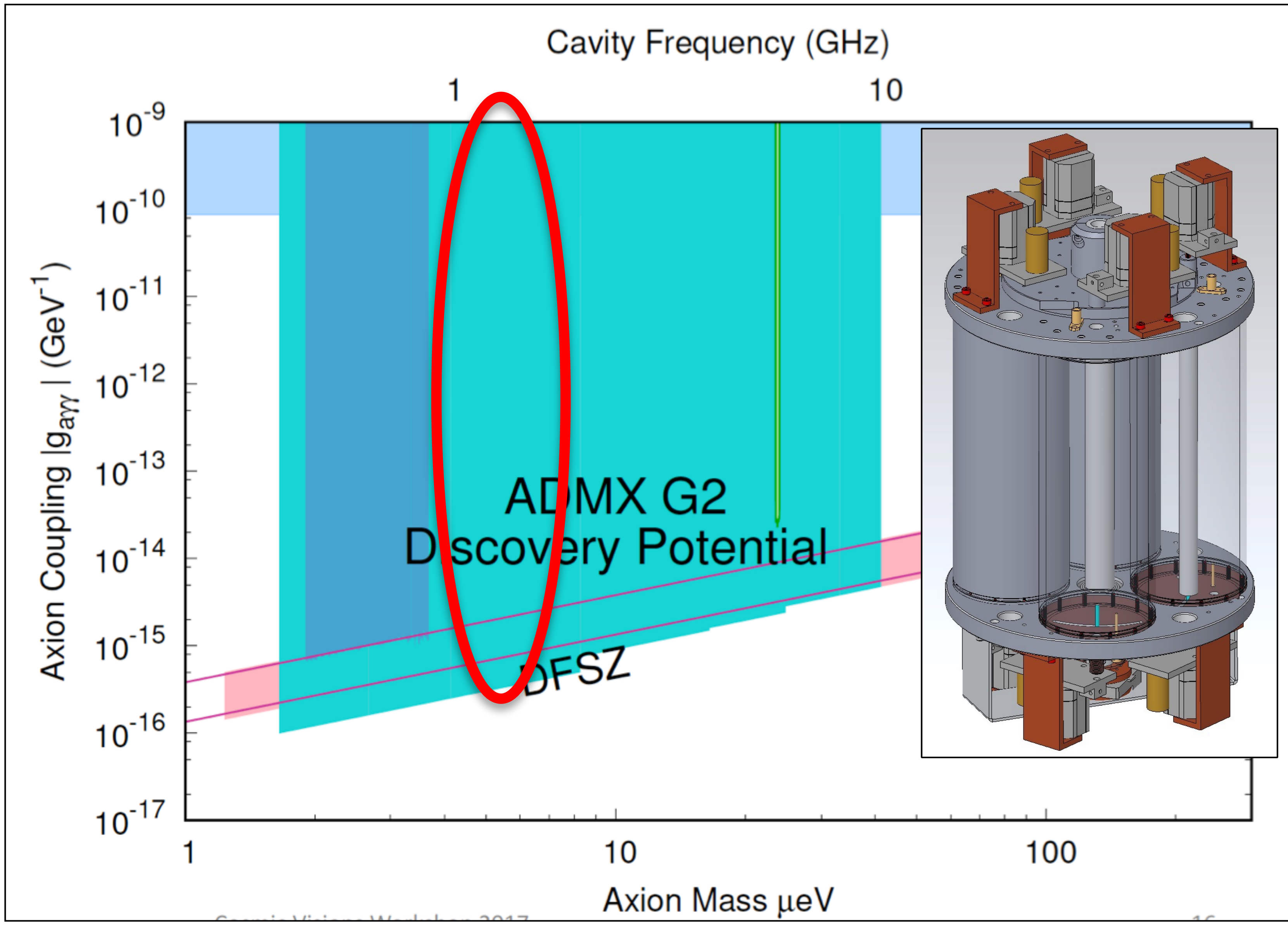
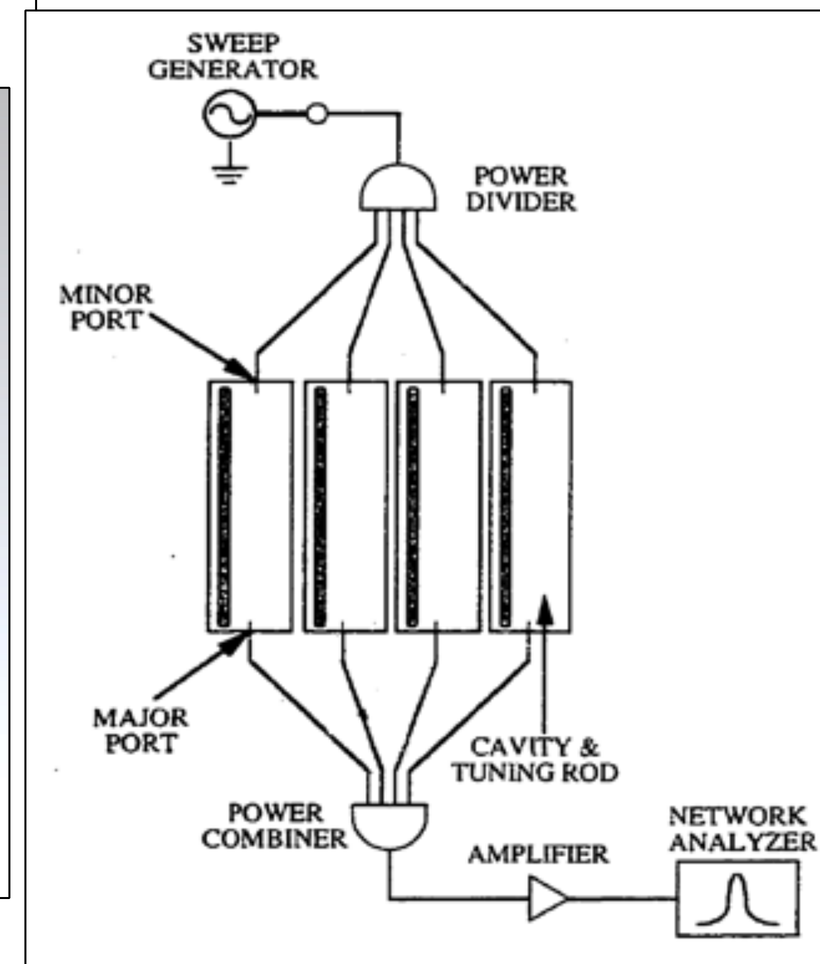
Run 2





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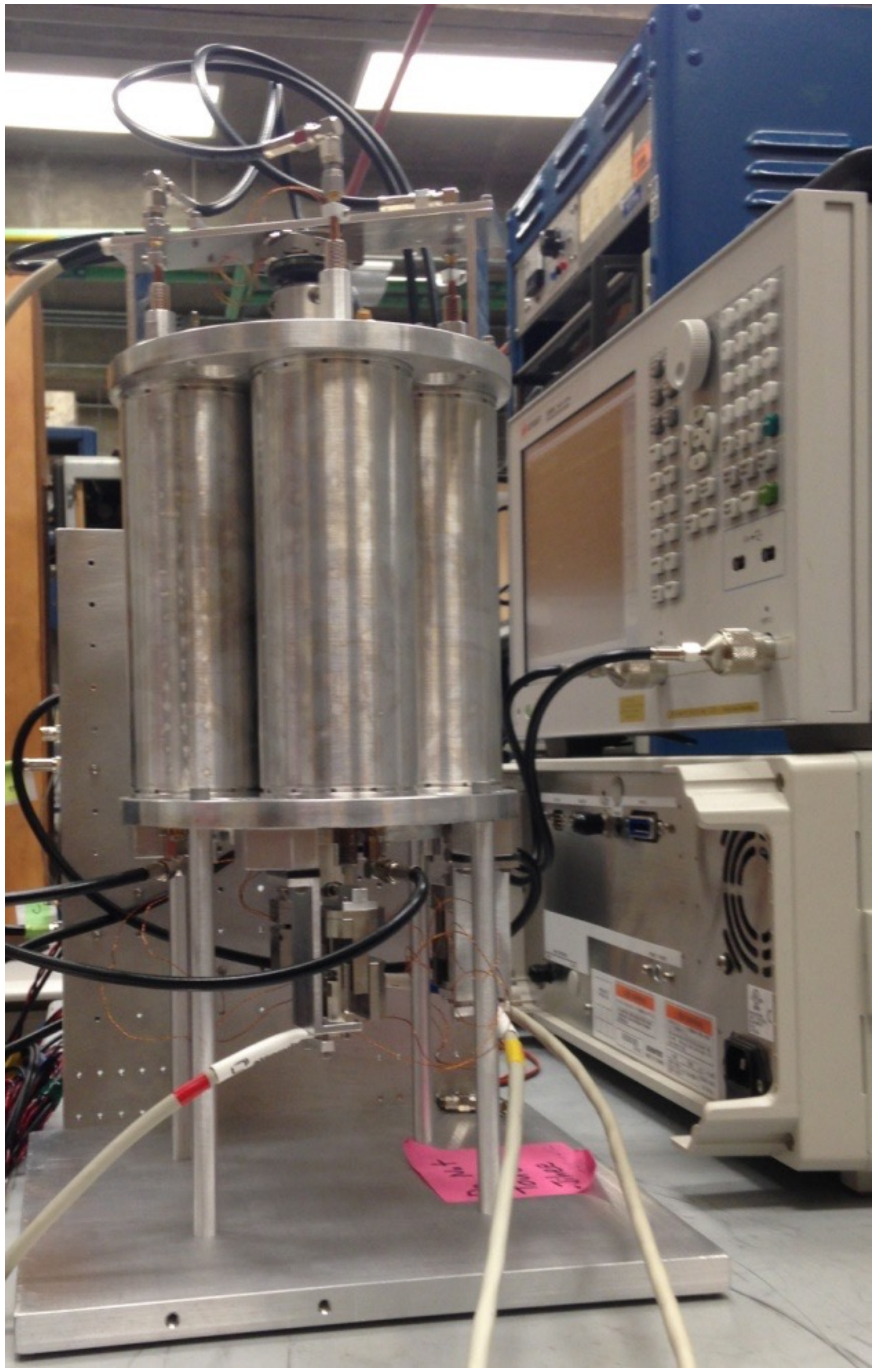
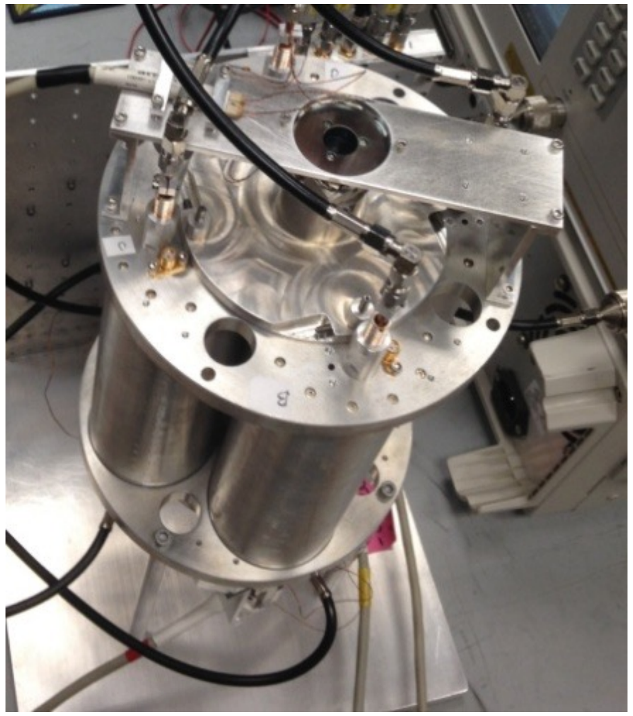
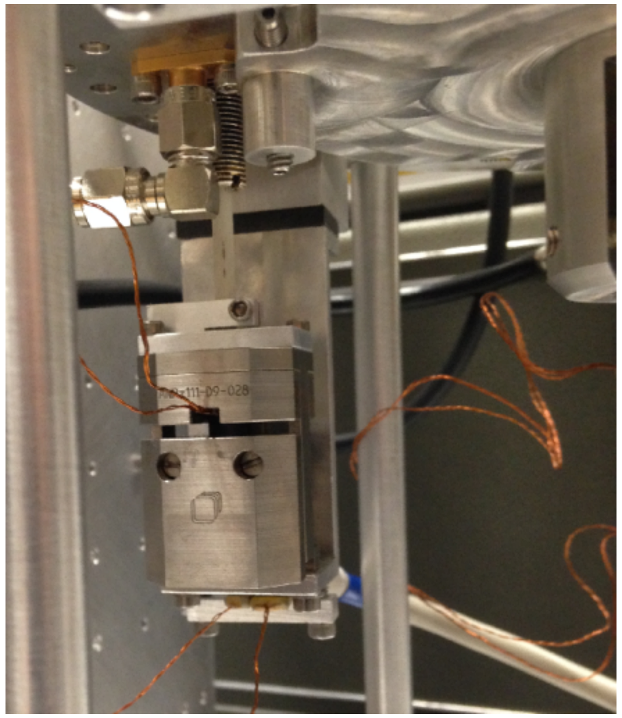
Four-Cavity Array Prototype







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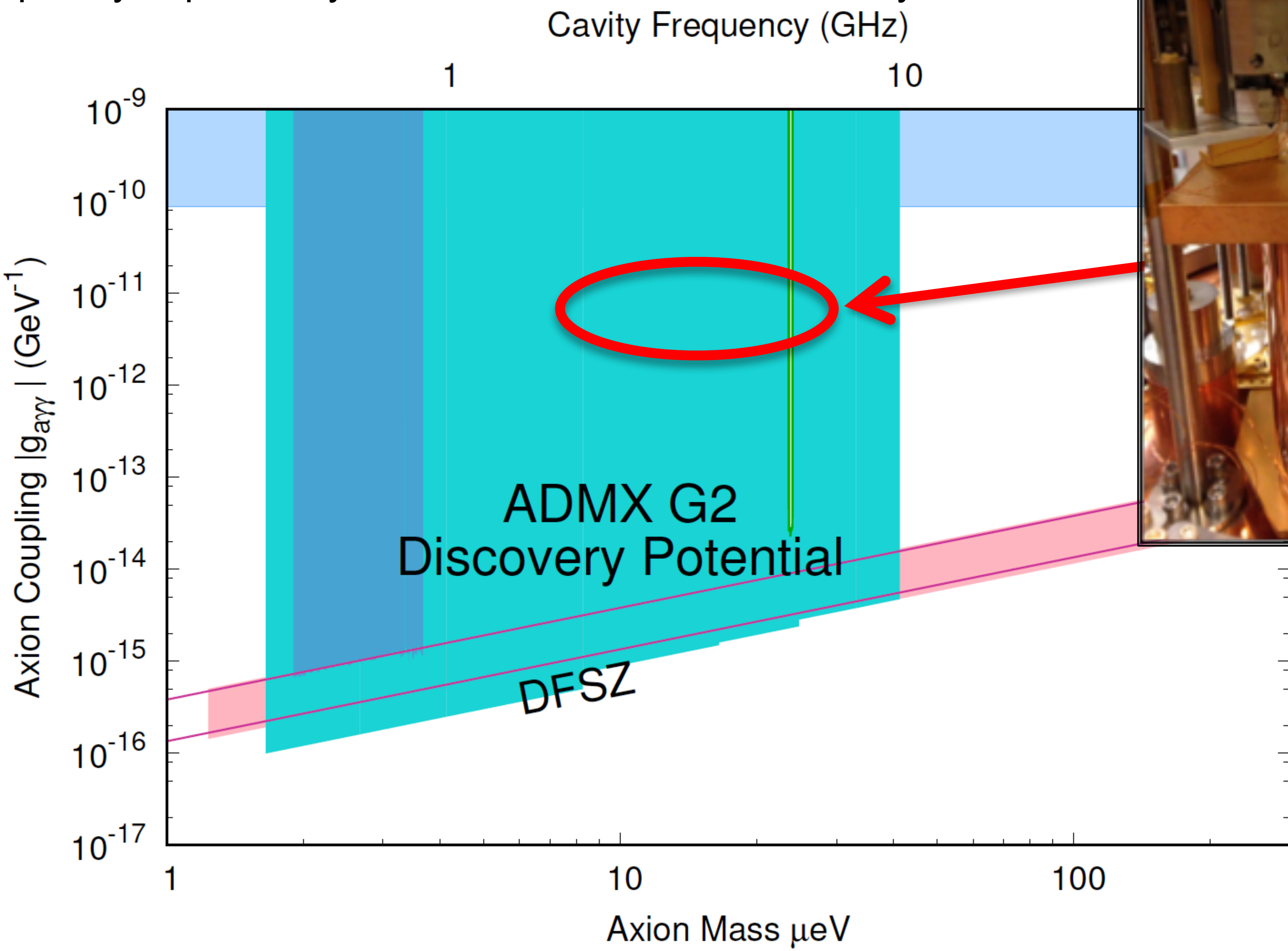
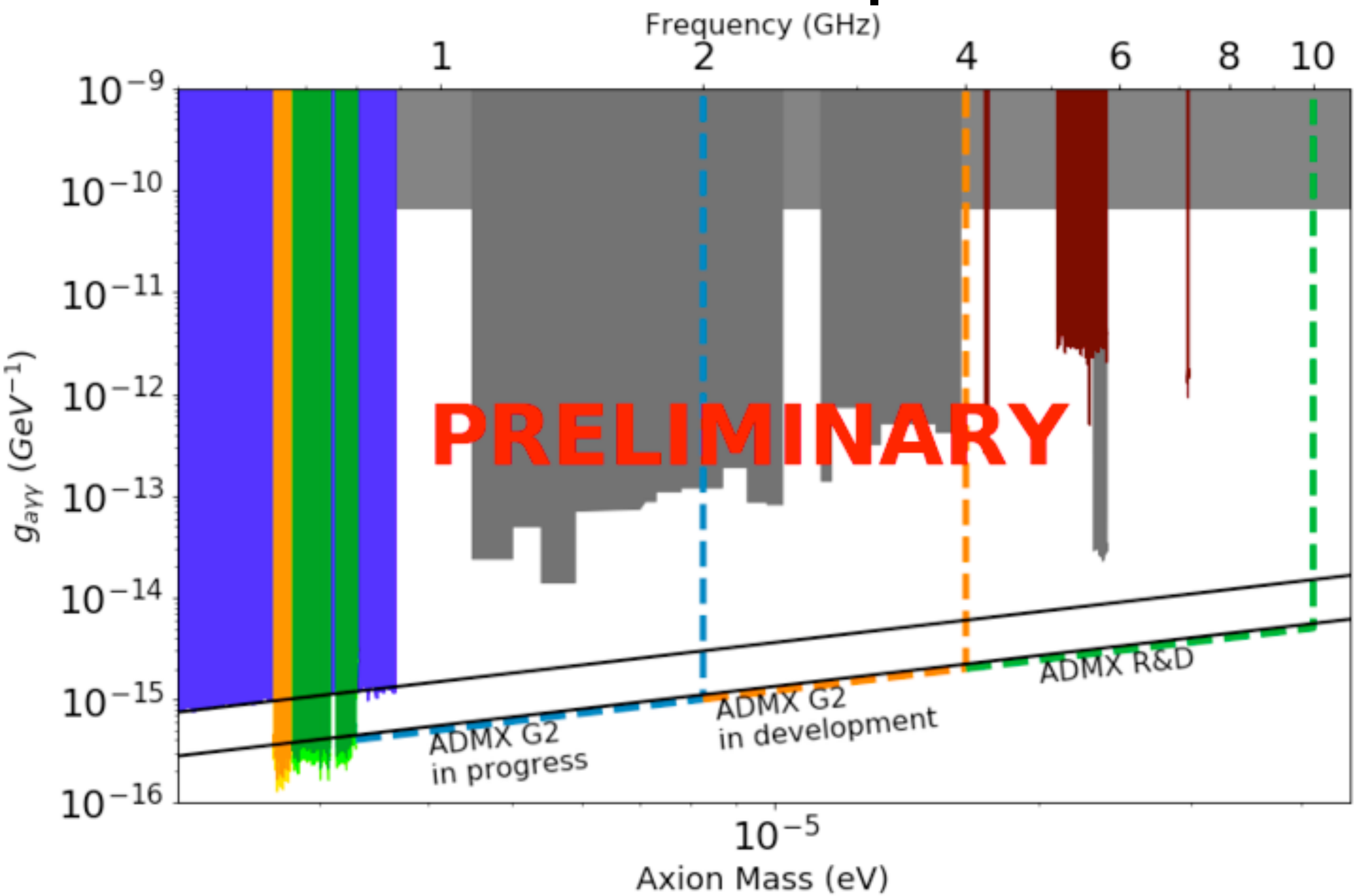
ADMX Sidecar Cavity
4-6 GHz TM_{010} & 6-7 GHz TM_{020}

Completely separate system installed above main cavity



Future Prospectus



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Conclusion

- Axions are a well motivated dark matter candidate, especially of in light of the Strong CP problem
- Axions are hard to detect
- Orchestration of a tuned resonator, large magnet, cryogenics, and quantum electronics gives us a chance at detection!
- ADMX is the first and only experiment to attain DFSZ sensitivity thus far
- Data-taking is to be continued in the near future
- Other resonators are under development to extend searchable axion mass range

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Acknowledgements

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- Thank you ADMX collaborators at:
  - UW, UF, LLNL, FNAL, UCB, PNNL, LANL, NRAO, WU, UWA, & Sheffield

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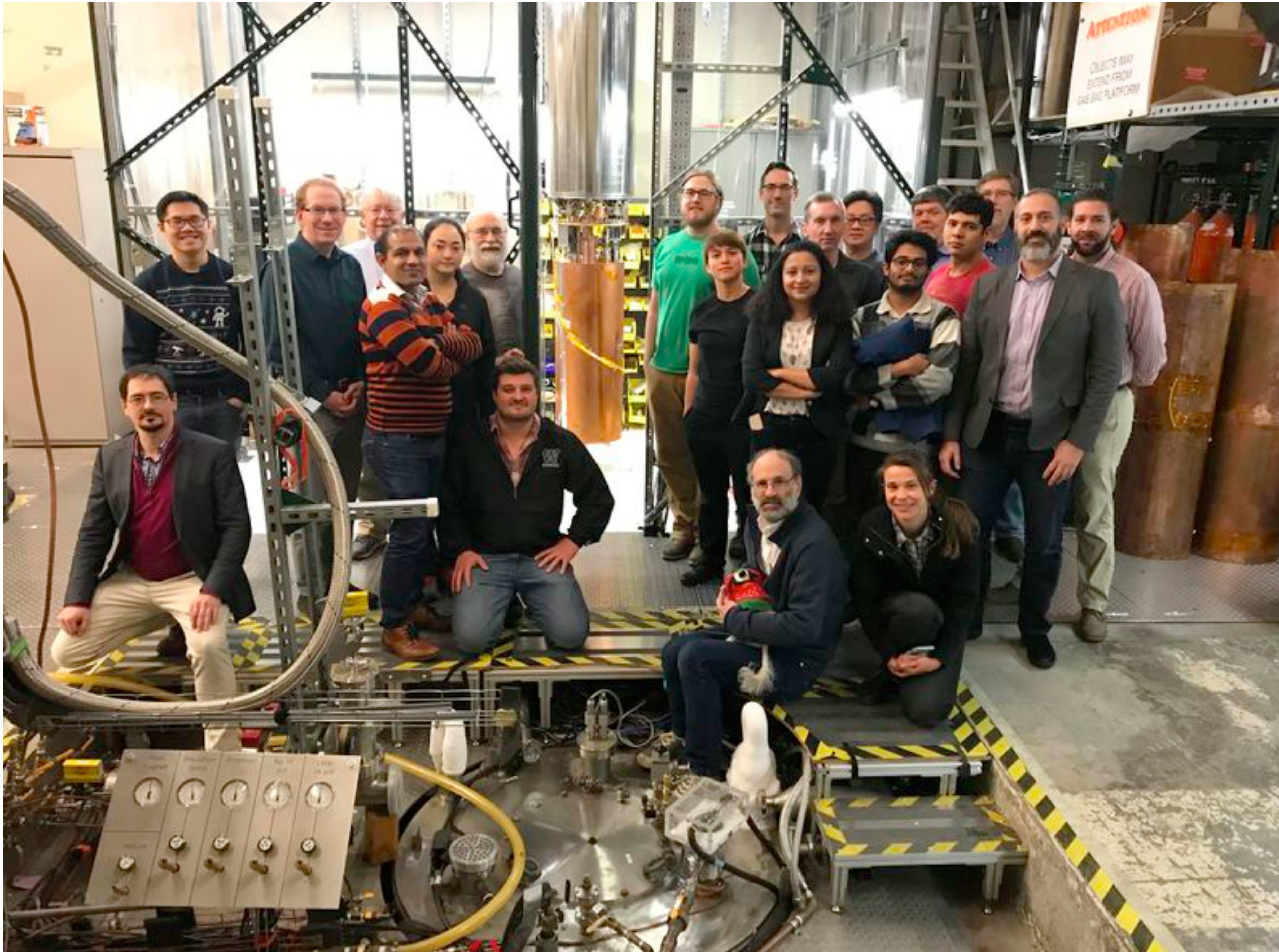
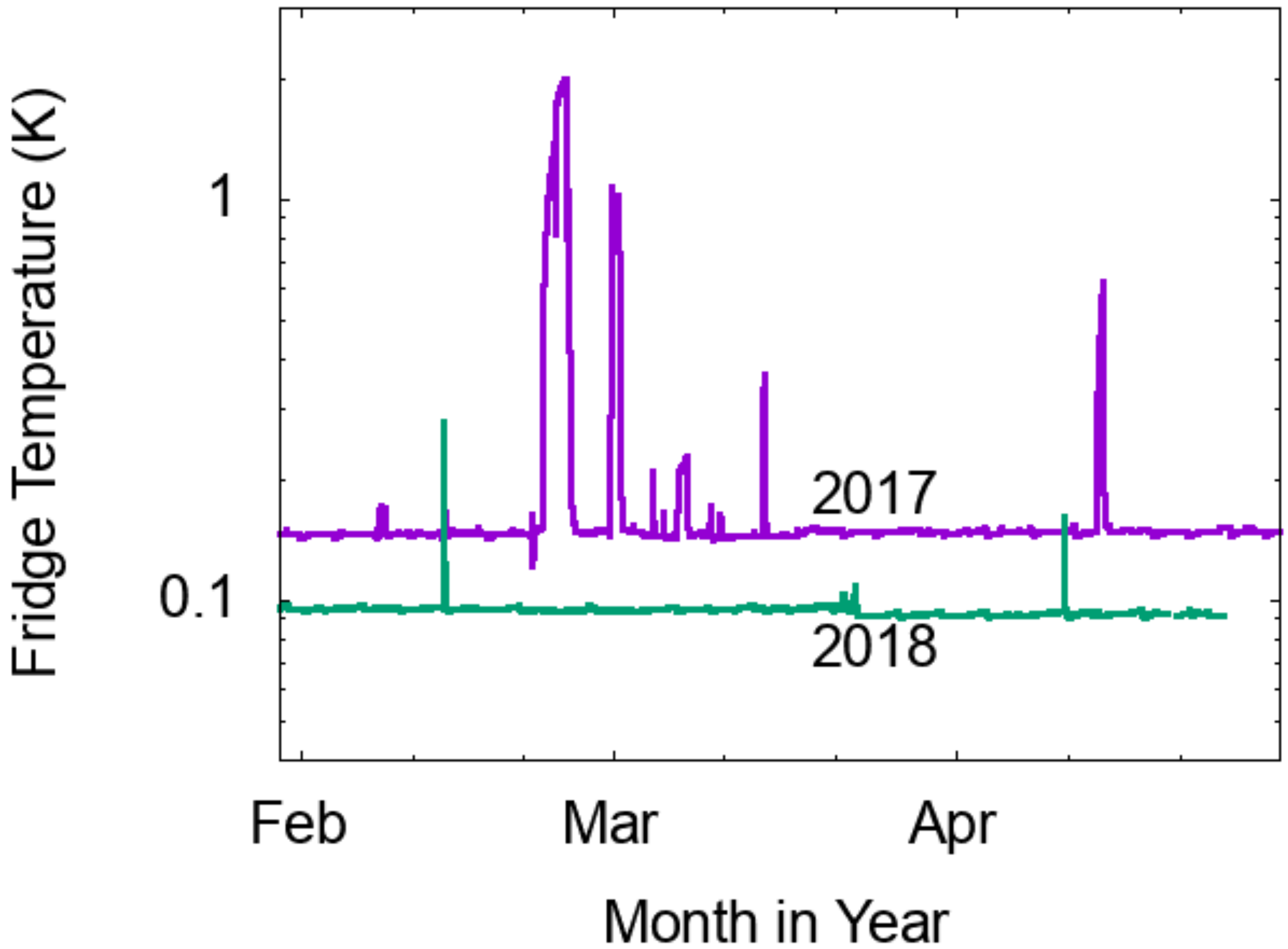
ADMX Collaboration



Backup Slides

Fridge Improvement



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Axions and Maxwell's Equations

- Axion field alters Maxwell's Equations

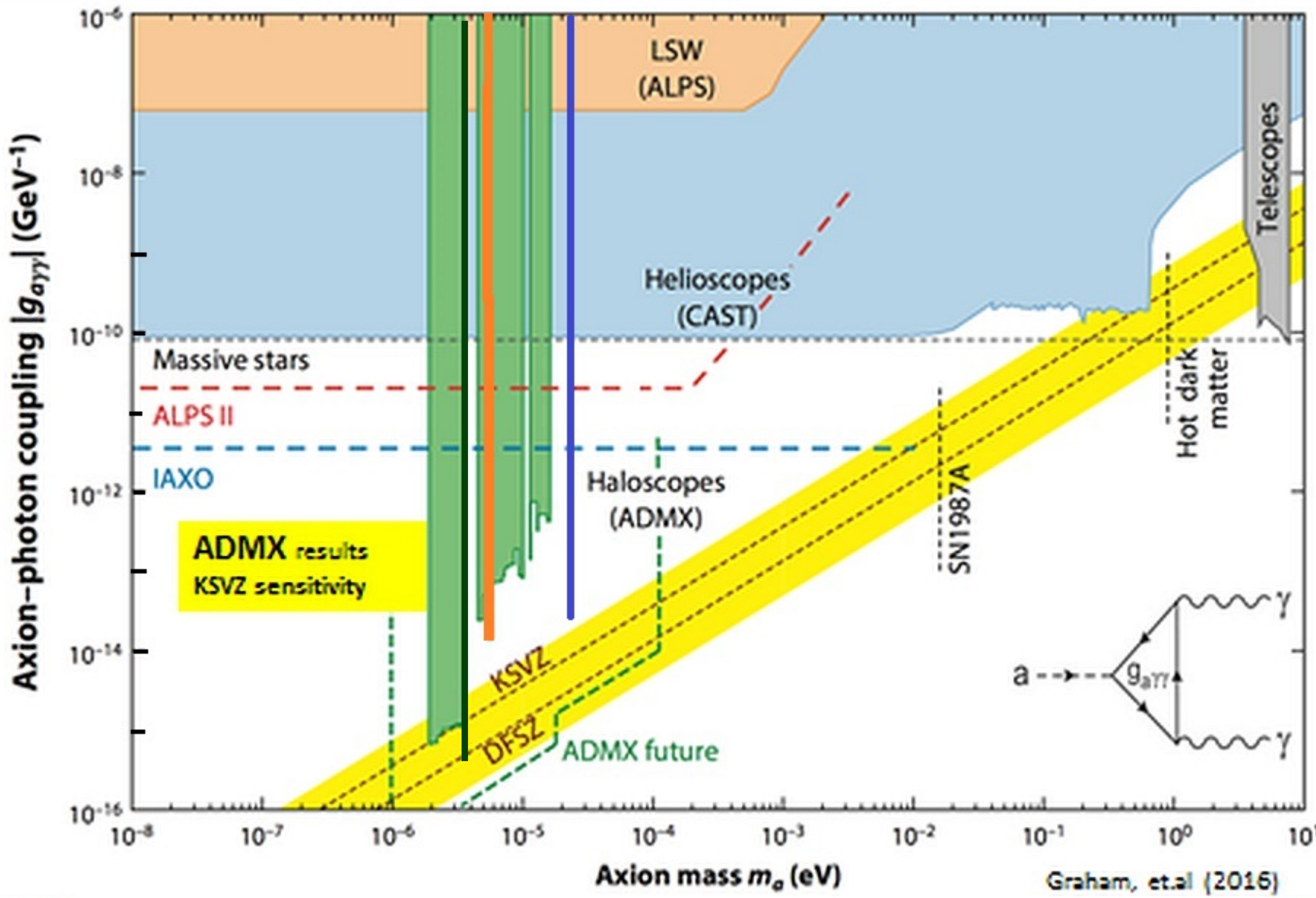
$$\nabla \cdot \vec{E} = g\vec{B} \cdot \nabla a$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = g(\vec{E} \times \vec{\nabla} a - \vec{B}\frac{\partial a}{\partial t})$$

- In the presence of an external magnetic field $\vec{B}_0$,

$$\vec{\nabla} \times \vec{B}_a = \vec{j}_a = -g\vec{B}_0 \frac{\partial a}{\partial t}$$

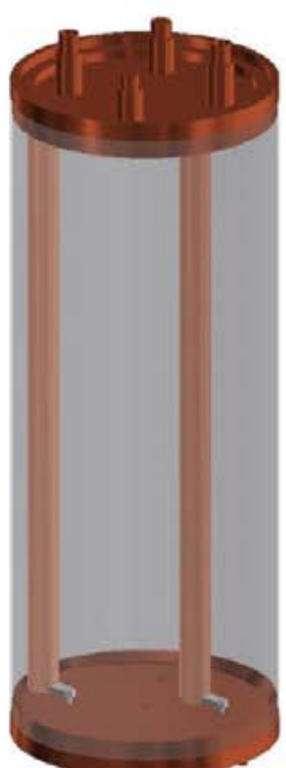
Searches to Date



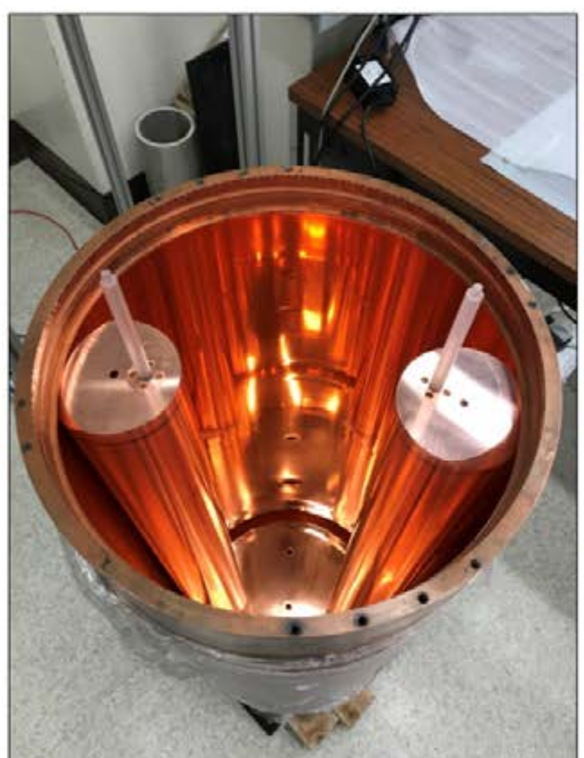
Design and R&D 2

Cavities

- ADMX Gen2 has used a single cavity with metal tuning rods
- Plans to use a 4 cavity array
  - Tuned in concert to a single frequency
  - Output amplitudes added
  - Use metal and dielectric tuning

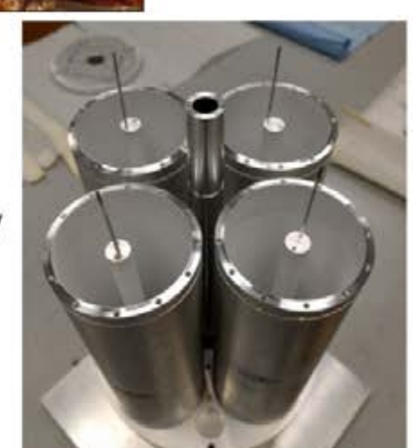


Cavity from run 1a & 1b
Two 2” diameter tuning rods
580 – 890 MHz



Cavity from run 1c & 1d
Larger 4.5” (then 6”) diameter tuning rods
780 – 1200 MHz

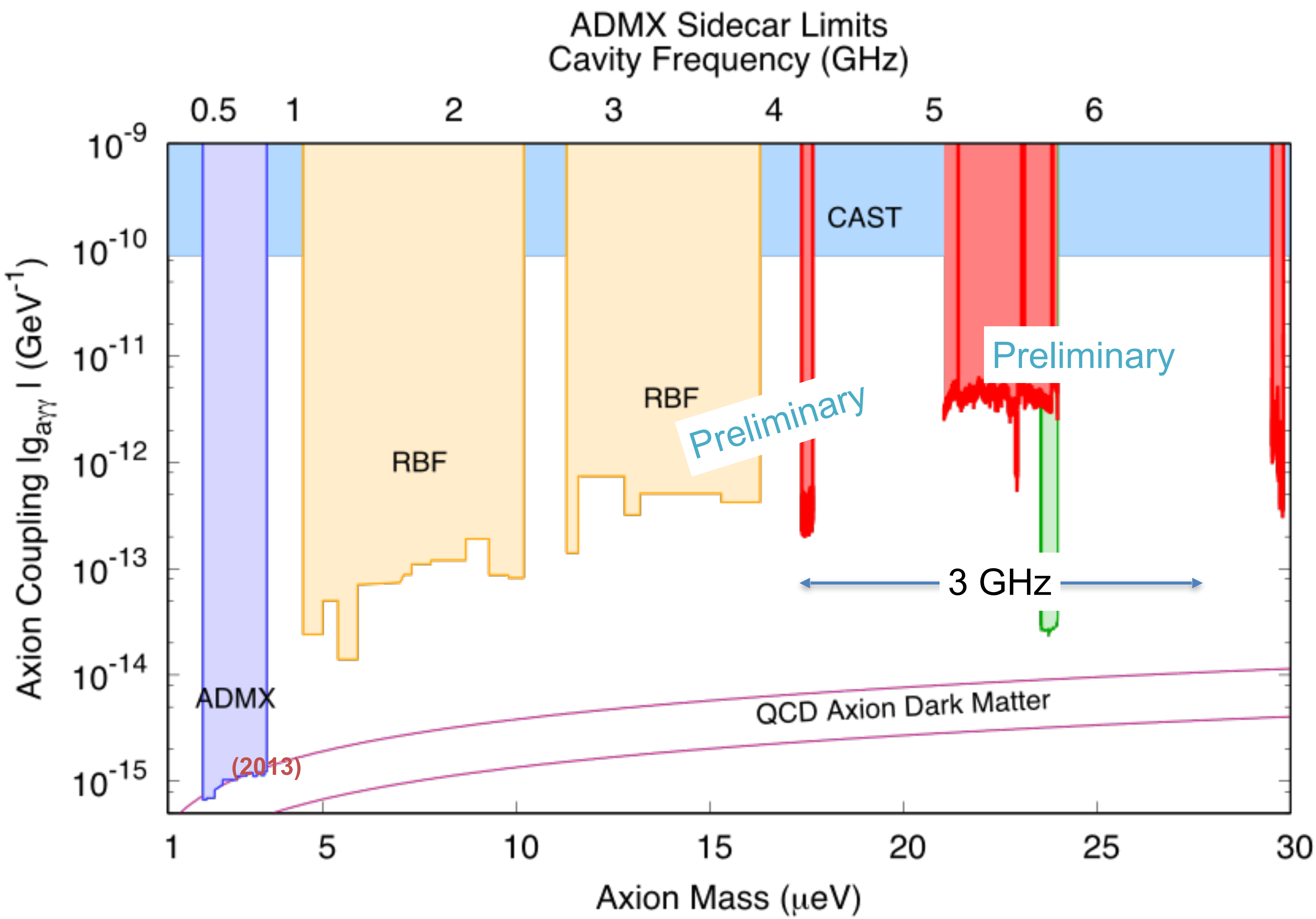
Sidecar Cavity
4-6 GHz TM_{010} mode
> 7 GHz TM_{020} mode



4-cavity array prototype

Cavity system for run 2a
Full sized 4 cavity array
Sapphire (1200 – 1500 MHz)
Metal Rods (1500 – 2000 MHz)

Slide: DB Tanner



*C. Boutan Thesis