ADMX: (r)evolutions in pursuit of the QCD axion.

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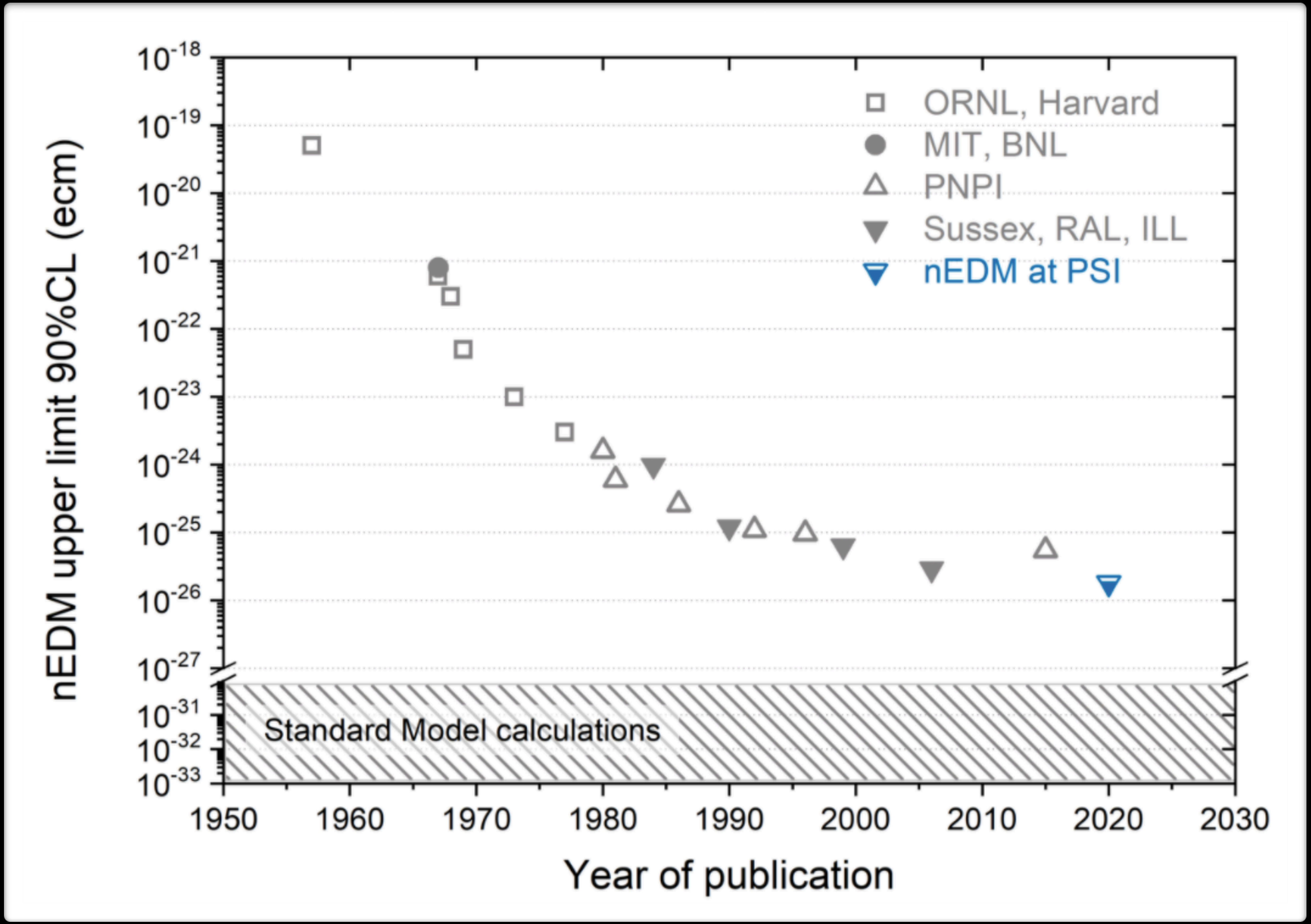
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Strong CP Problem

Quantum Chromodynamics (QCD) describes the binding of atomic nuclei

- Discrete fundamental symmetries known as Charge (C), Parity (P), and Time (T) and their combination (CP, CPT) describe symmetries in particle physics interactions.
- P and CP symmetries could be violated with term in QCD Lagrangian
- Search for an neutron electric dipole moment also search for violations of CP.



Strong CP Problem

No neutron electric dipole moment (n-EDM) has been observed so far!

Most recent search for the neutron electric dipole moment

C. Abel et al.

Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26} e \bullet cm \longrightarrow \theta_{QCD} < 10^{-10}$

Peccei Quinn Mechanism

Solution to the Strong CP problem

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

Θ becomes a dynamical variable that relaxes to zero at the critical temperature.

Implies the existence of the axion

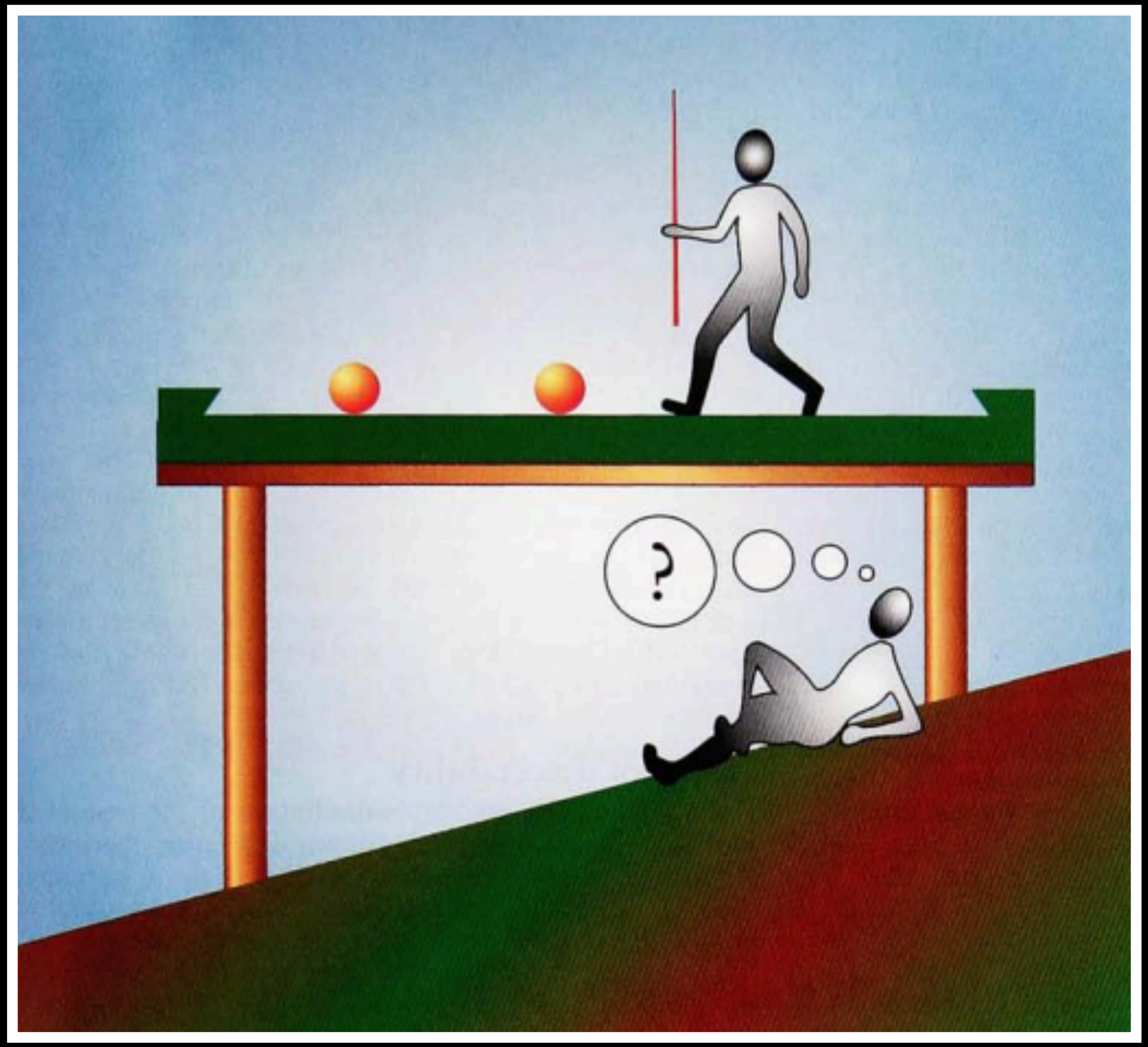
Helen Quinn

Roberto Peccei

The Pool Table Analogy

A story by Pierre Sikivie, 1996

- One imagines a pool table that appears *perfectly* horizontal.
- The occupants of the room realize one day that the room itself is slanted.
- Why is the pool table perfectly horizontal? This seems like an odd coincidence.



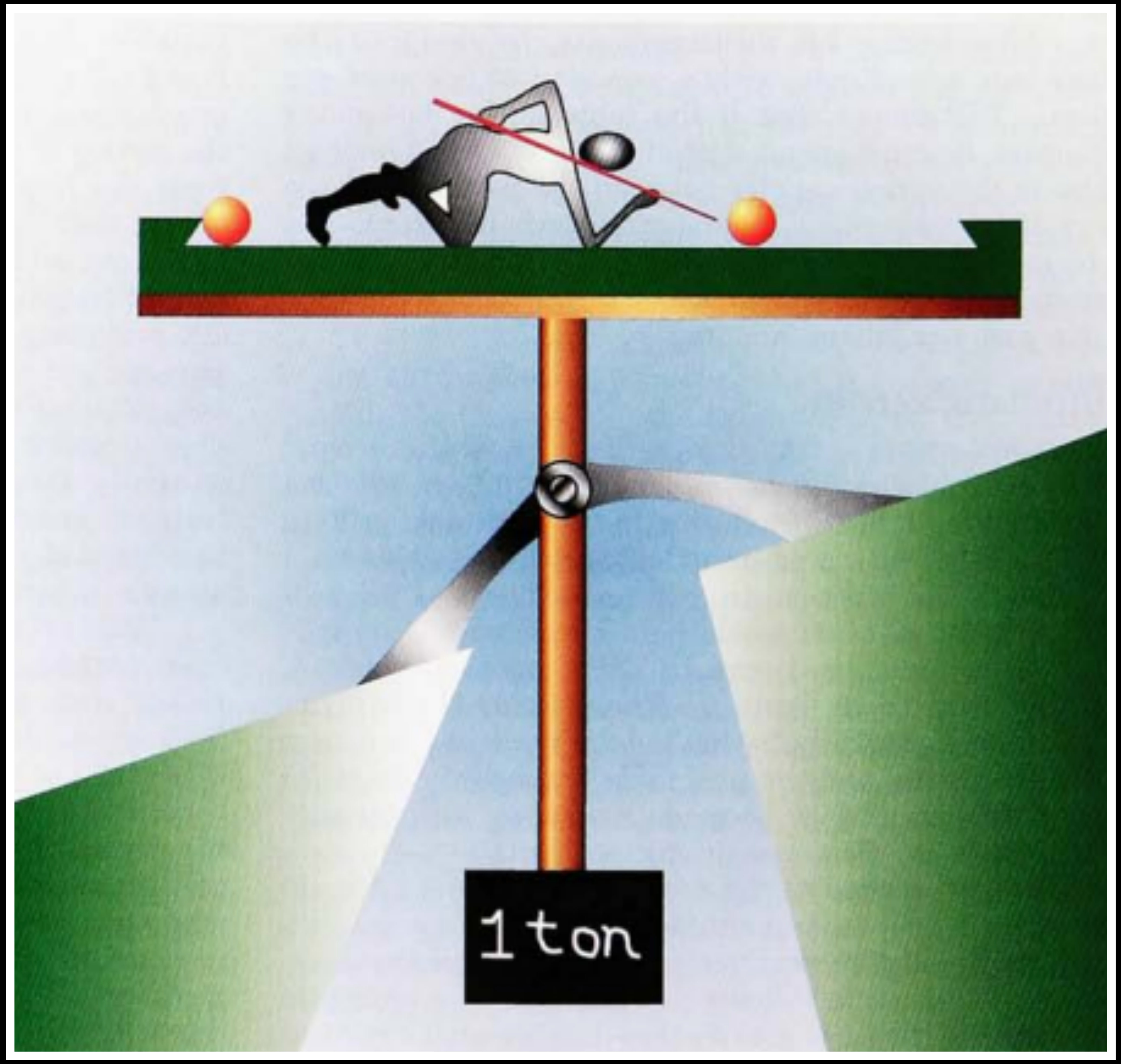
Sikivie, Pierre. "The Pool-Table Analogy with Axion Physics." *Physics Today* 49.12 (1996): 22-27.

The incline of the table is described by a made-up symmetry analogous to CP symmetry. The symmetry is perfectly preserved.

Solution to Strong CP problem?

Perhaps there is a mechanism that uses gravity to level the pool table.

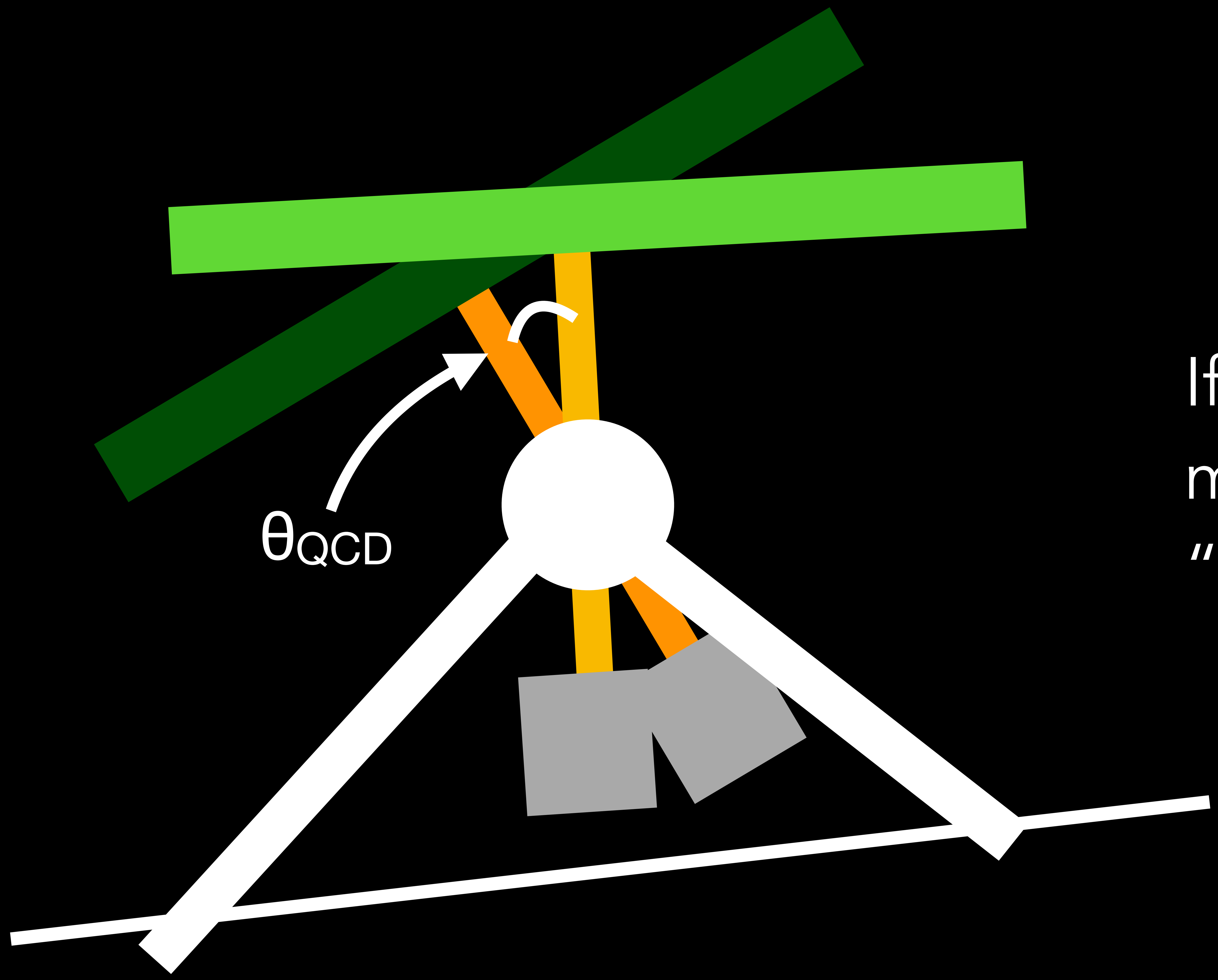
- Angle of pool table tilt = θ_{QCD}
- Physics of pool table = physics of QCD
- Gravity = Nonperturbative effects that make QCD depend on θ_{QCD}



Sikivie, Pierre. "The Pool-Table Analogy with Axion Physics." *Physics Today* 49.12 (1996): 22-27.

Angle θ_{QCD}

θ_{QCD} might be a dynamical variable (moving with time)

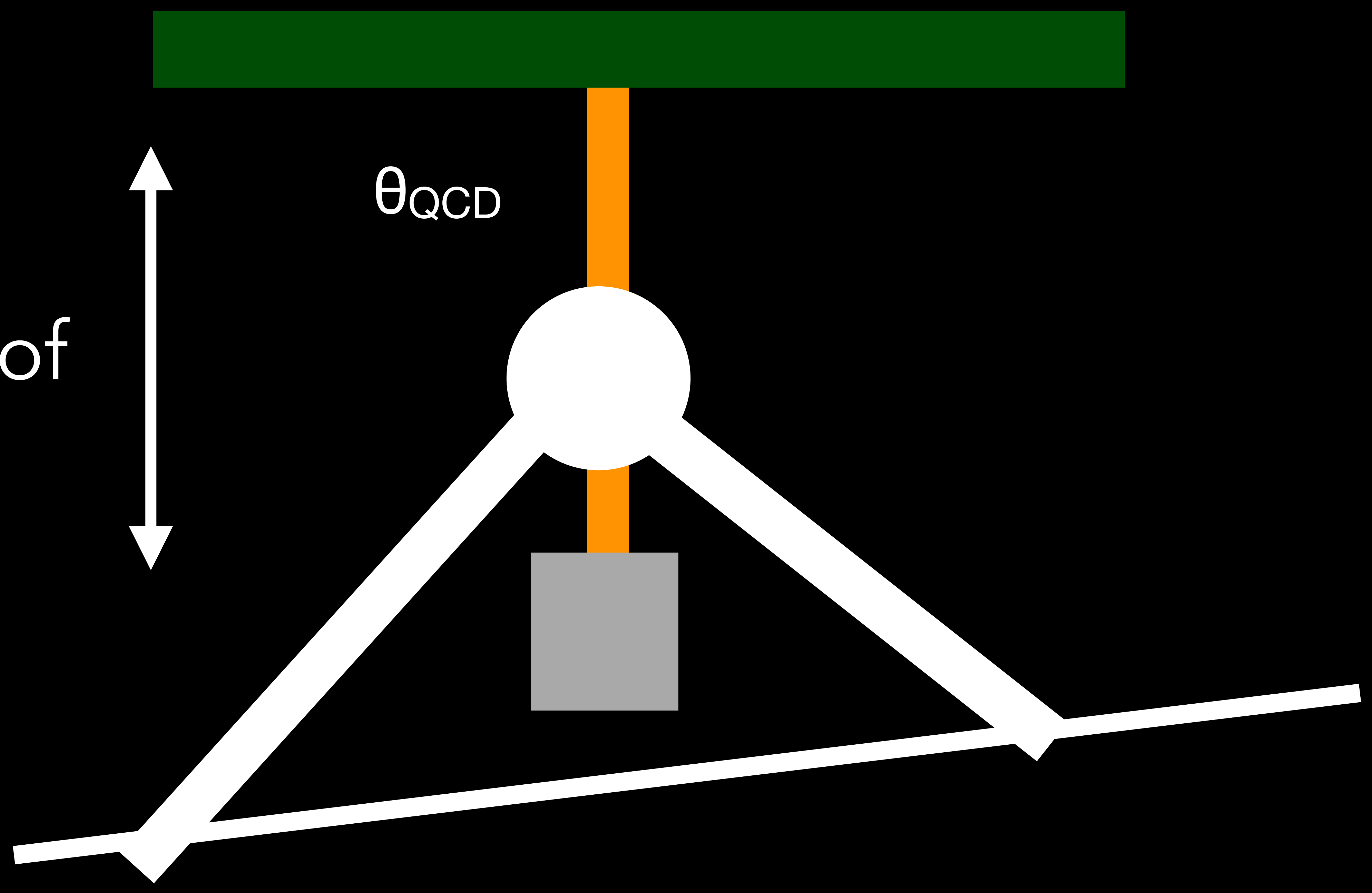


If θ_{QCD} dynamical, mechanism is akin to "Peccei-Quinn Mechanism"

How to test the hypothesis?

"Relic oscillation" that would depend on when gravity "turned on"

Length of lever arm determines strength of oscillation

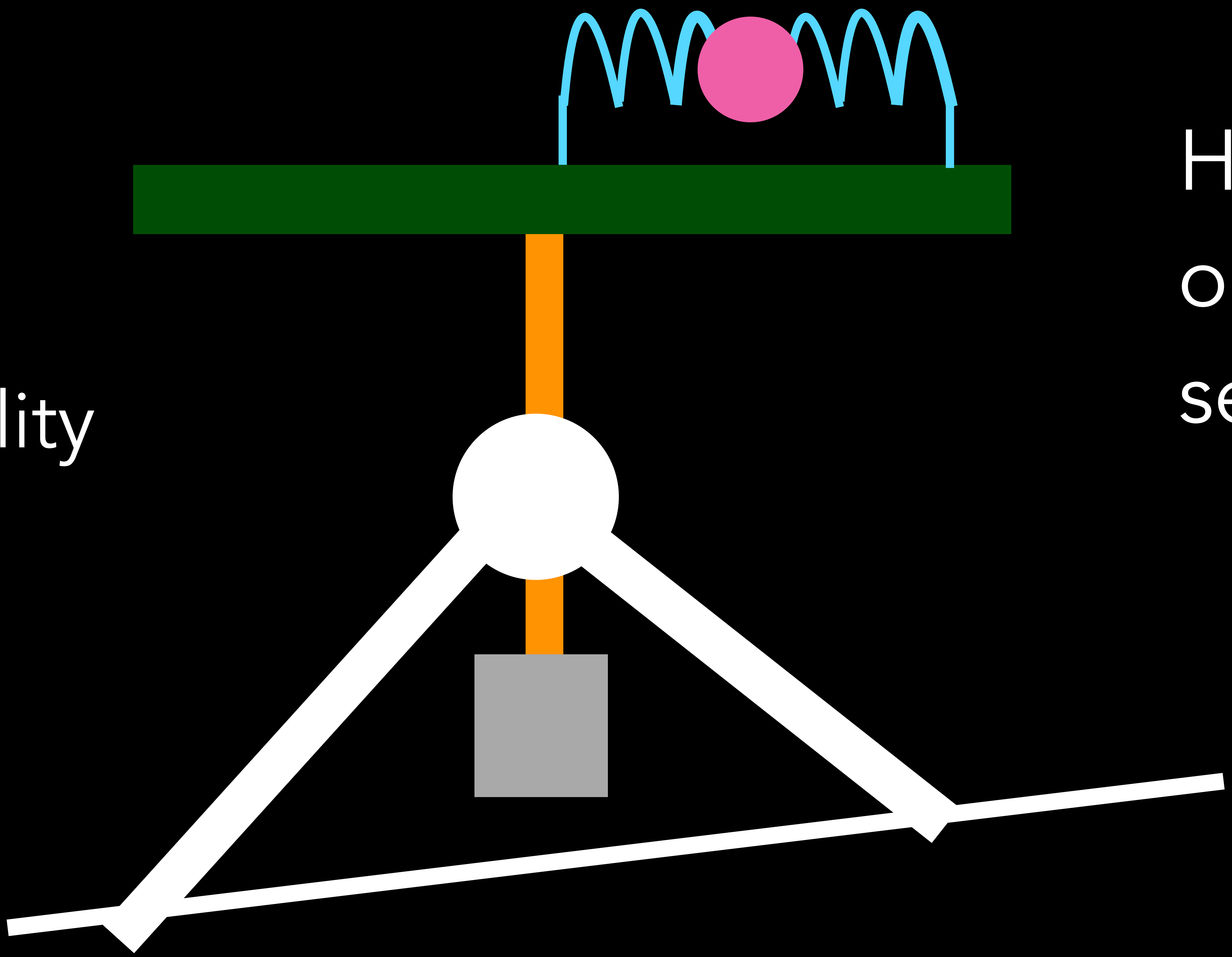


Maybe it's really long and the oscillation is hard to measure?

Equivalently maybe the coupling is extremely small

The pool table analogy

Associated quantum of oscillation = a particle call the axion!

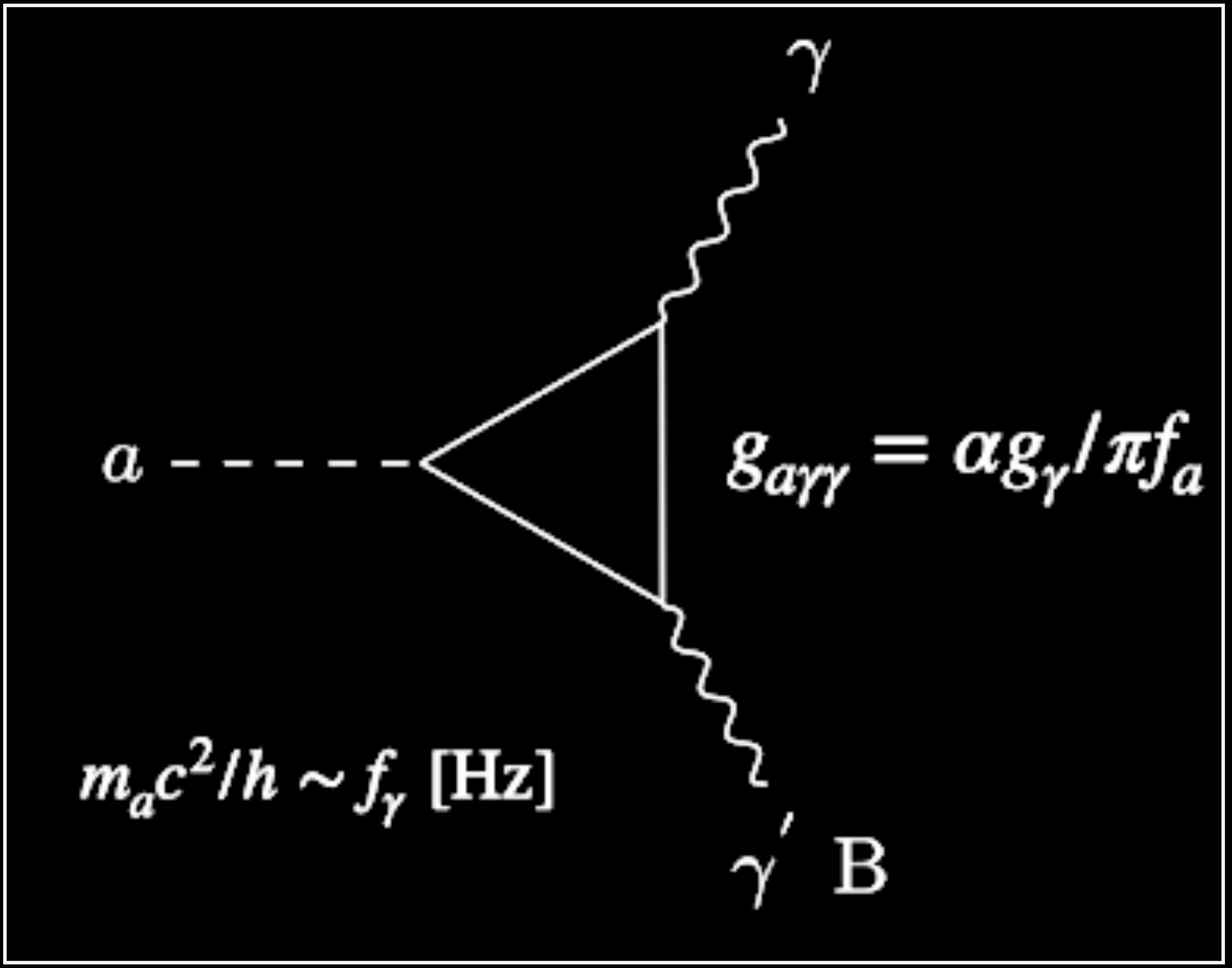


High quality oscillator on the table could sense this!

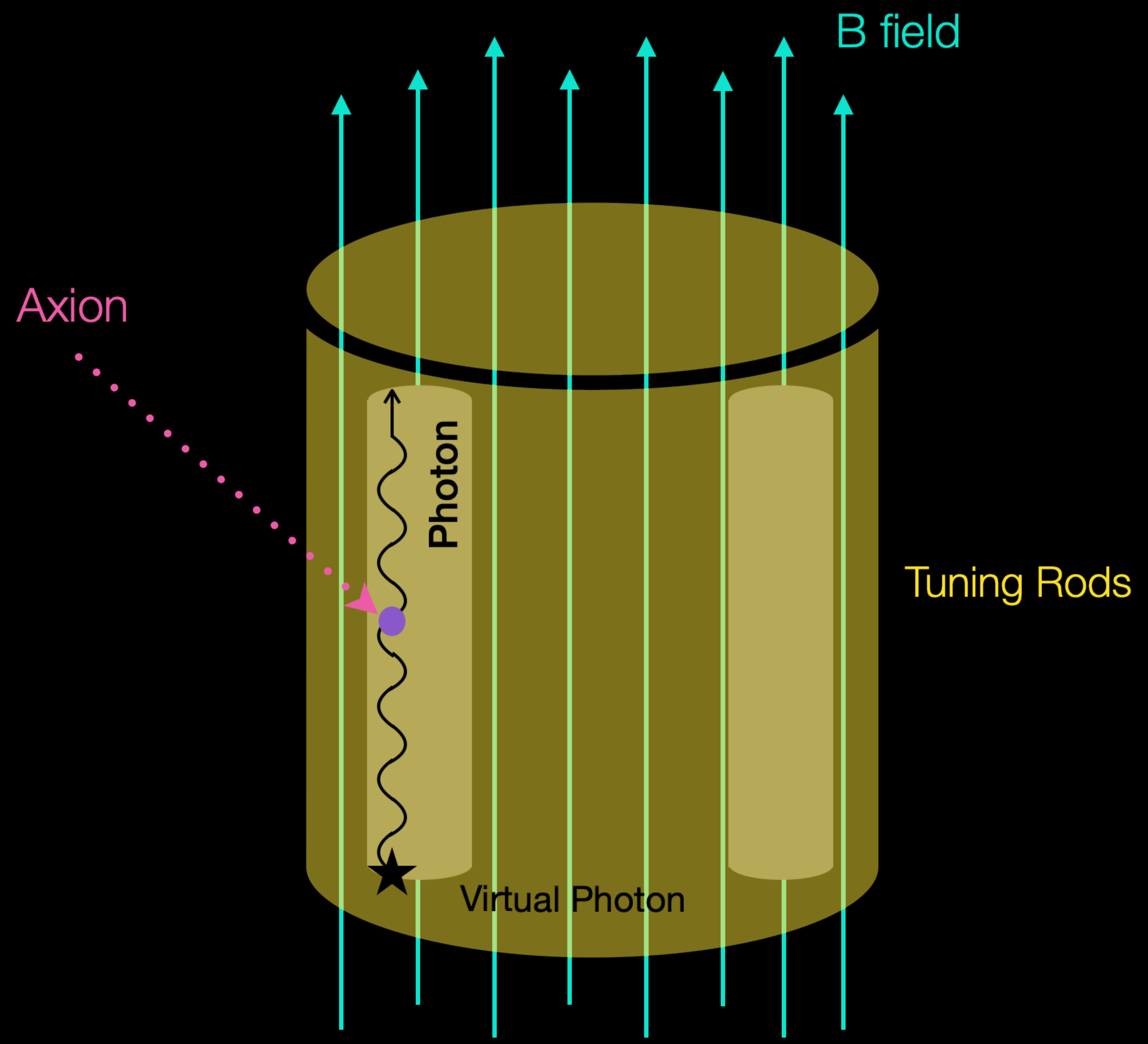
More on high quality oscillators later…

Detection: Axion Haloscope

Photon coupling: cleanest channel for discovery



Inverse Primakoff Effect

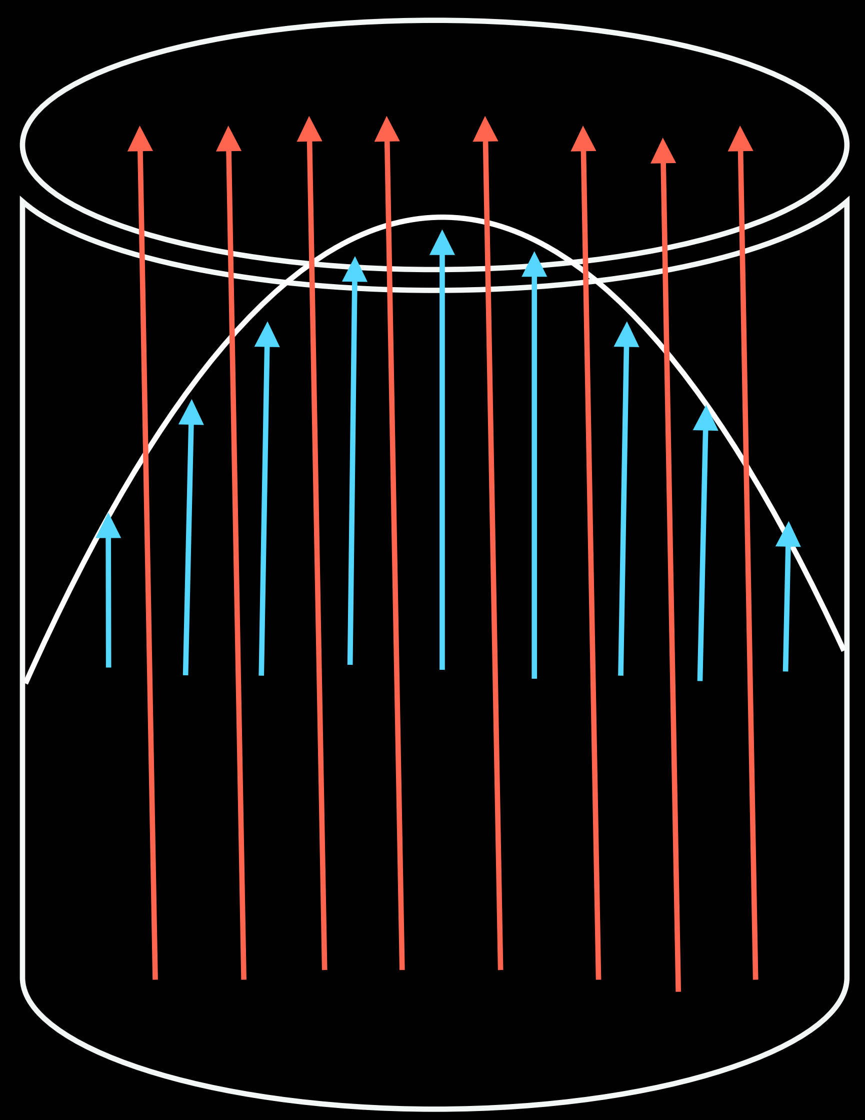


Resonant microwave cavity

Wanted: Very high-Q resonator

Cavity Haloscope

Form factor describes coupling of the axion to the mode

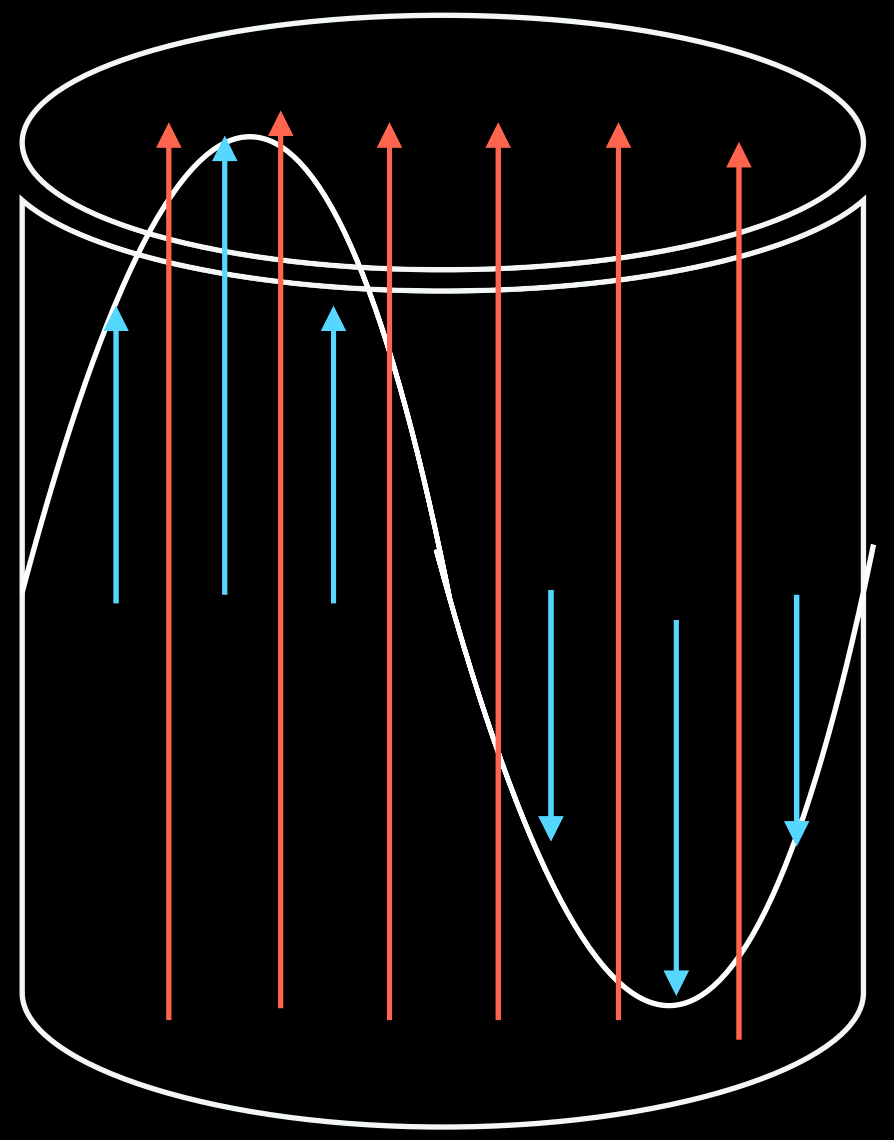


Non-zero form factor

Red is static magnetic field

Blue is axion electric field

$$C_{010} = \frac{\left|\int dV\, \vec{B}_{\mathrm{ext}} \cdot \vec{E}_{\mathrm{a}}\right|^2}{B_{\mathrm{ext}}^2 \int dV\, \epsilon_{\mathrm{r}} |\vec{E}_{\mathrm{a}}|^2}$$

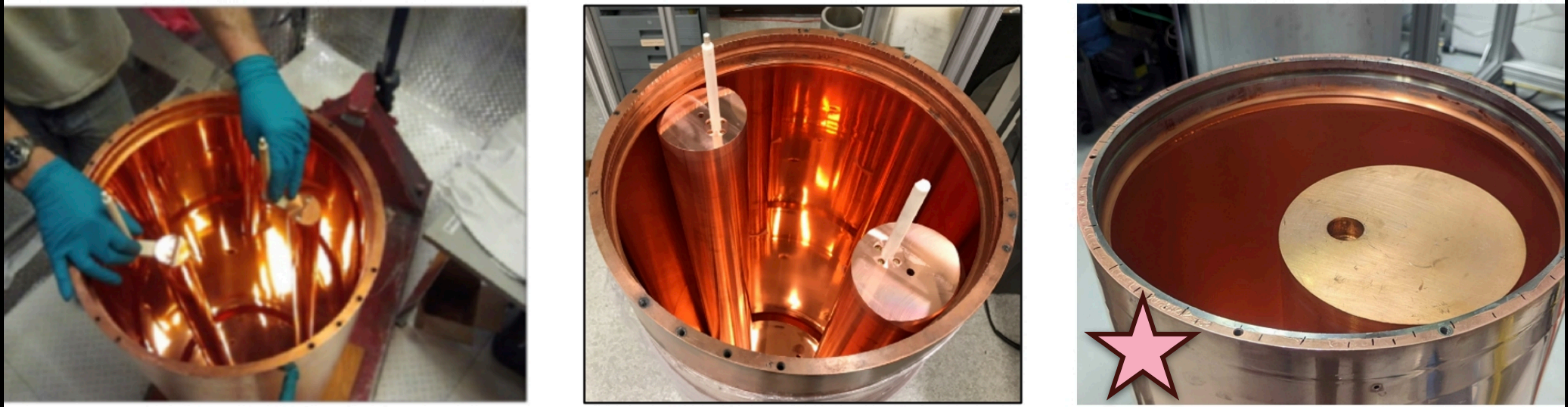


Zero form factor

ADMX: Axion couples most strongly to TM010 mode

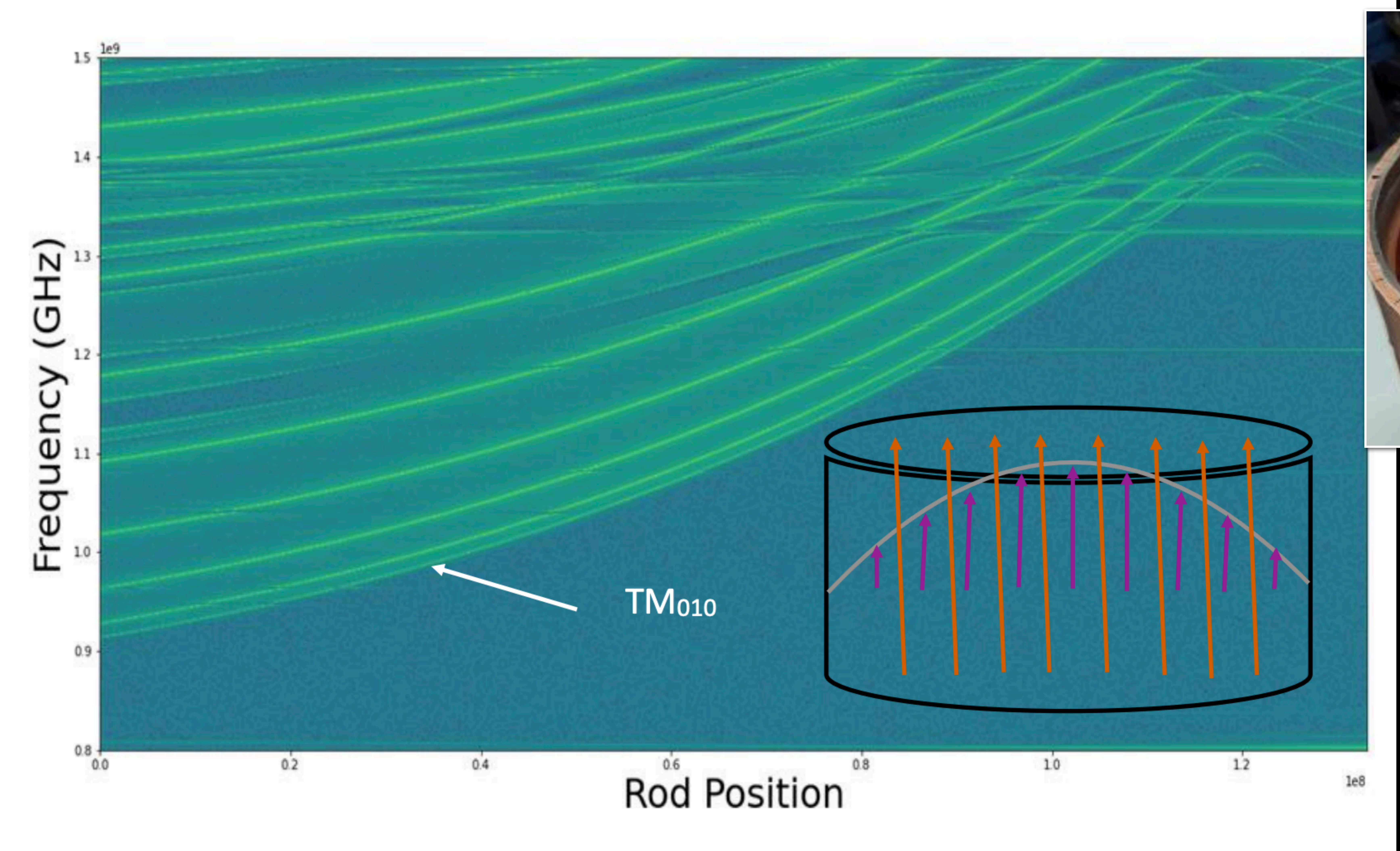
Cavity Haloscope

Recent tuning rod configurations



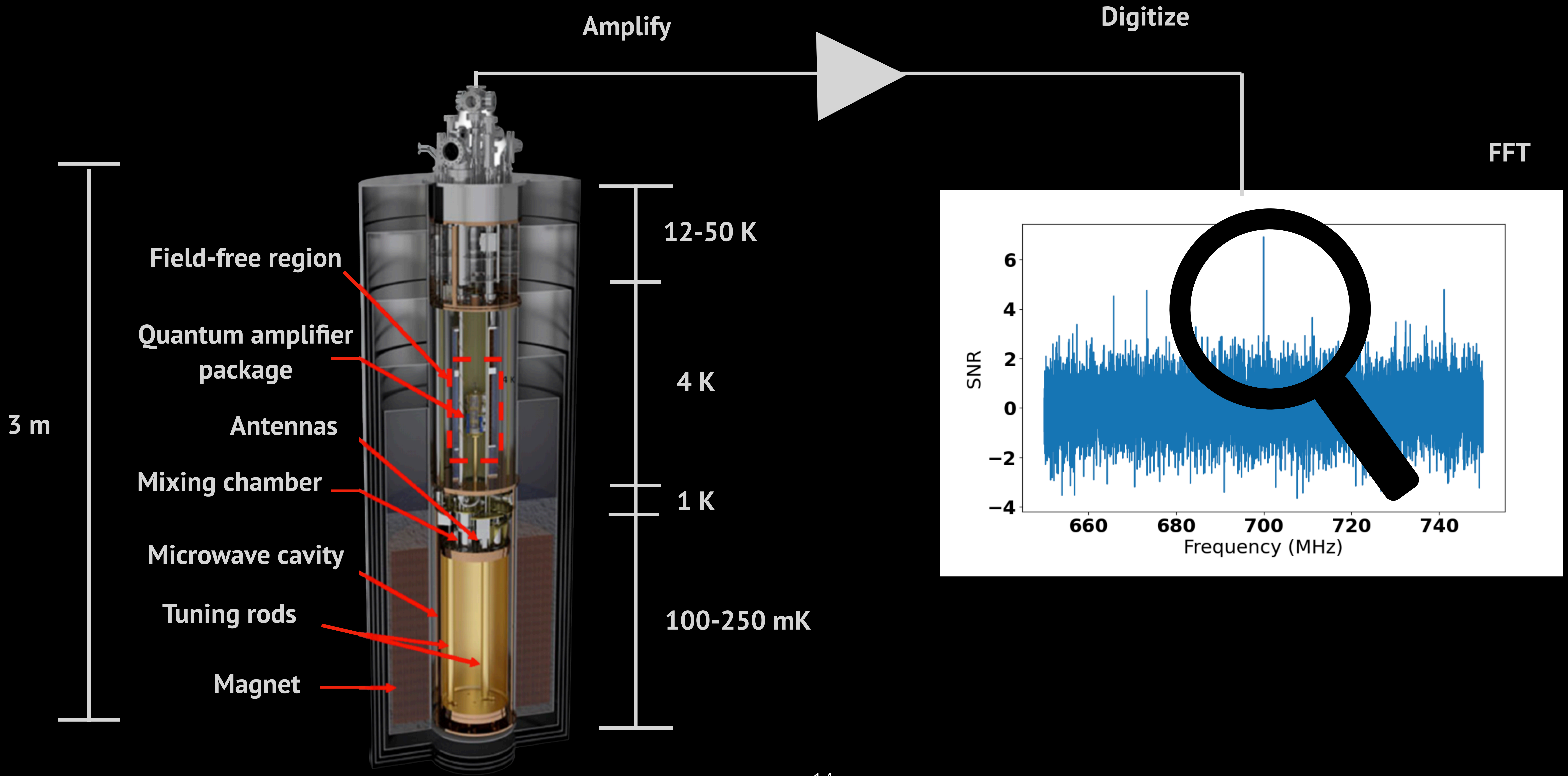
Run 1A+1B | Run 1C | Run 1D

Run 1D Cavity Haloscope

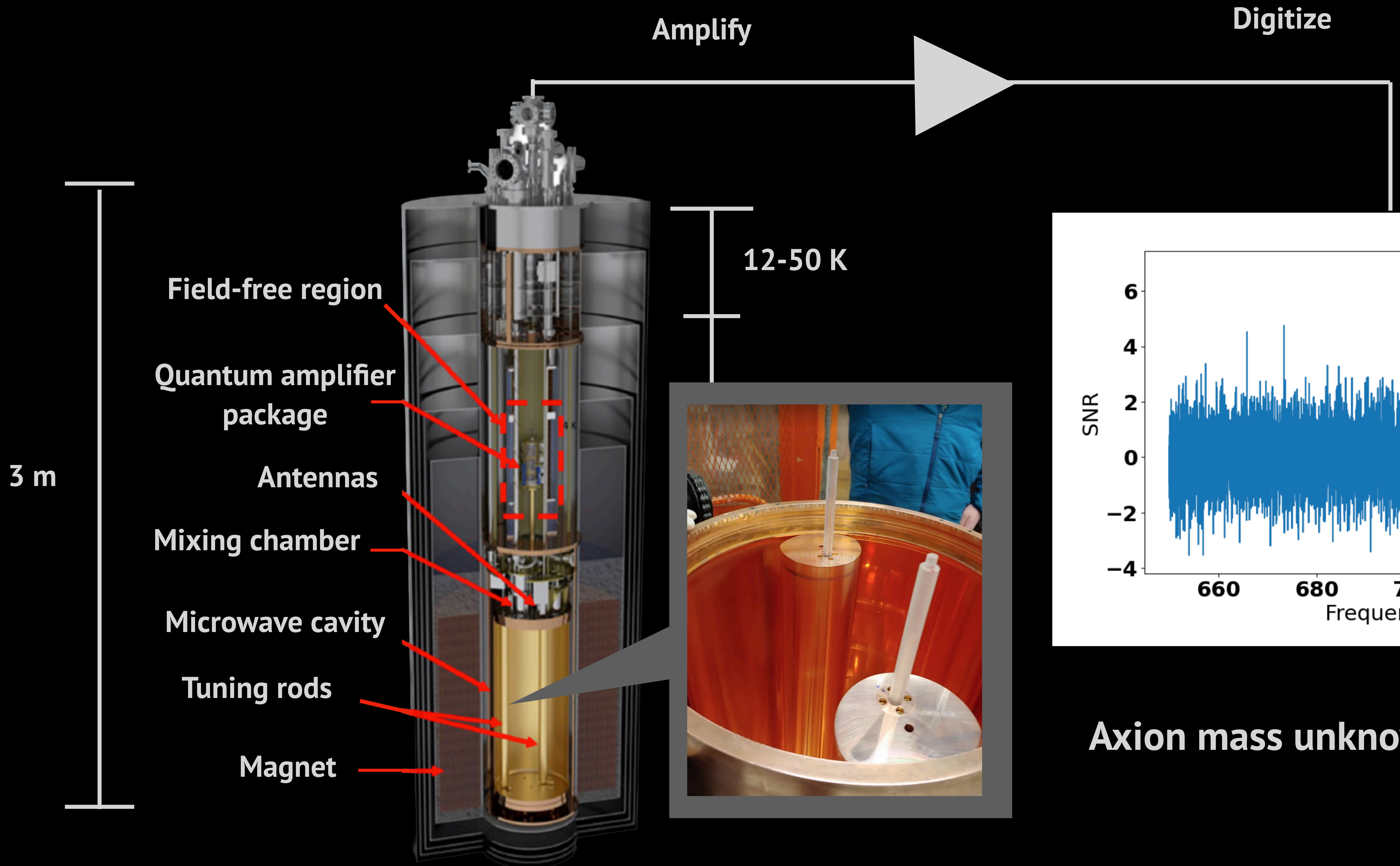


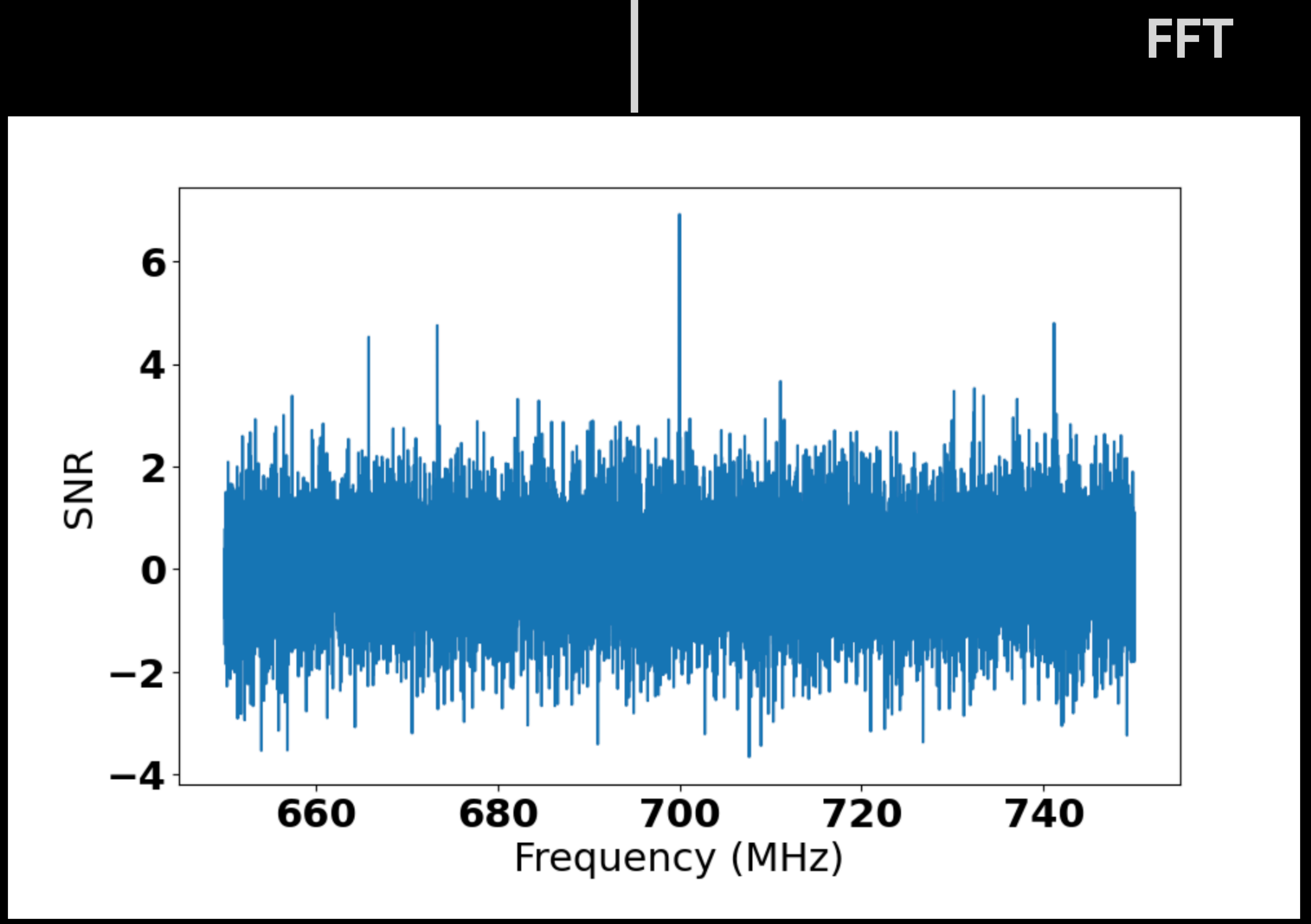
Run 1D cavity with tuning rod

Cavity Haloscope



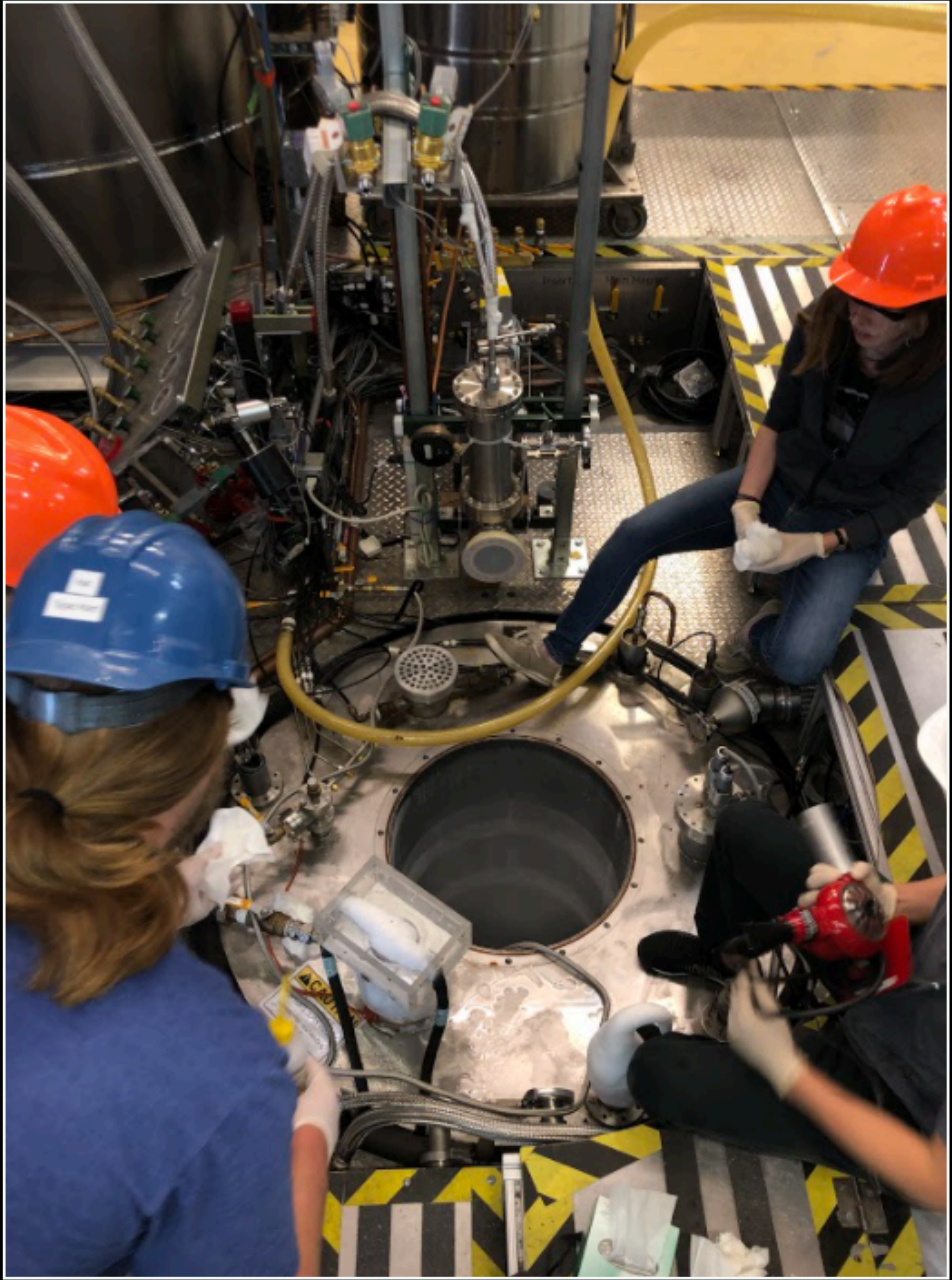
Cavity Haloscope



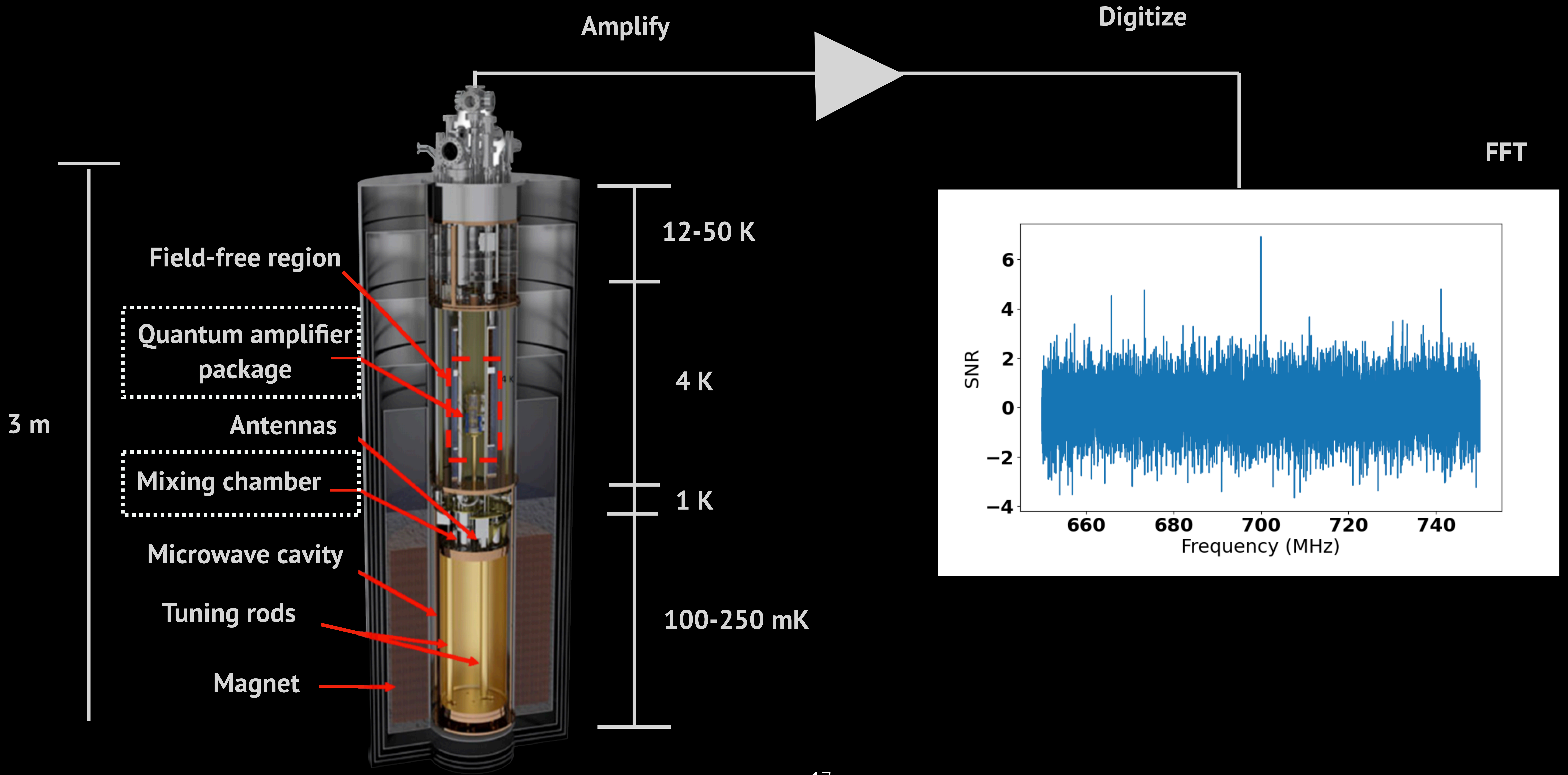


Axion mass unknown: tuning rods required

Cavity Haloscope



Ultra low noise receiver

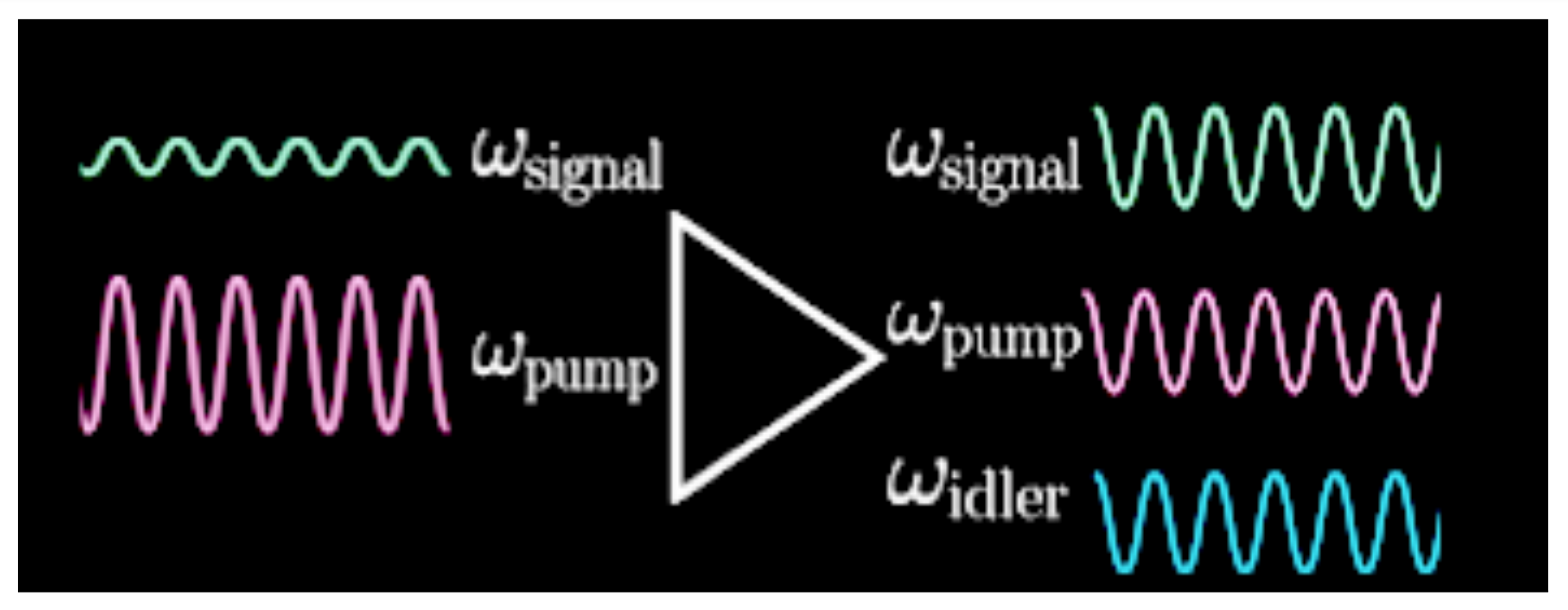


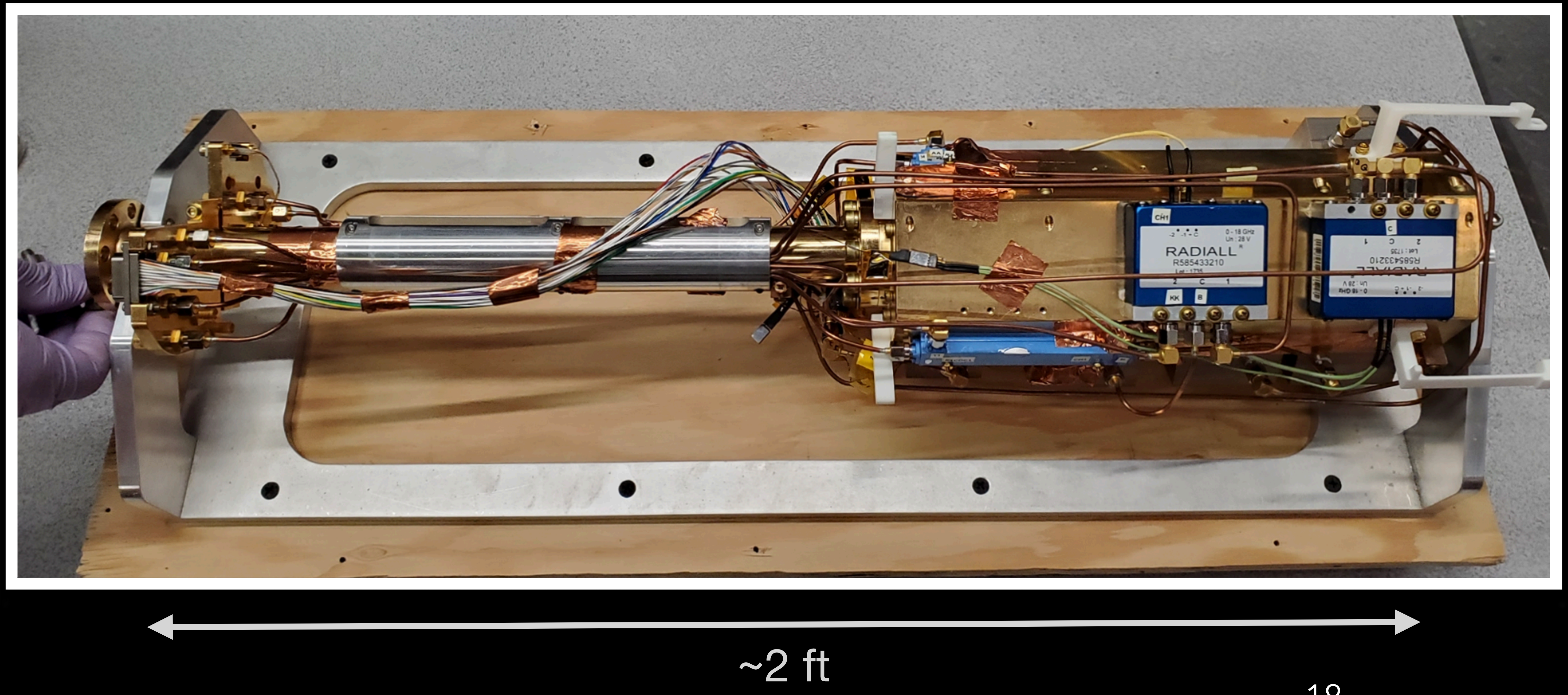
Quantum Amplification

- Microstrip SQUID Amplifier (2017)
- Josephson Parametric Amplifier (2018–today)
  - Anharmonicity leads to energy transfer from pump to signal
  - Josephson Junction is non-linear element

Initial JPAs provided by UC Berkeley
New JPAs produced by Washington University St. Louis

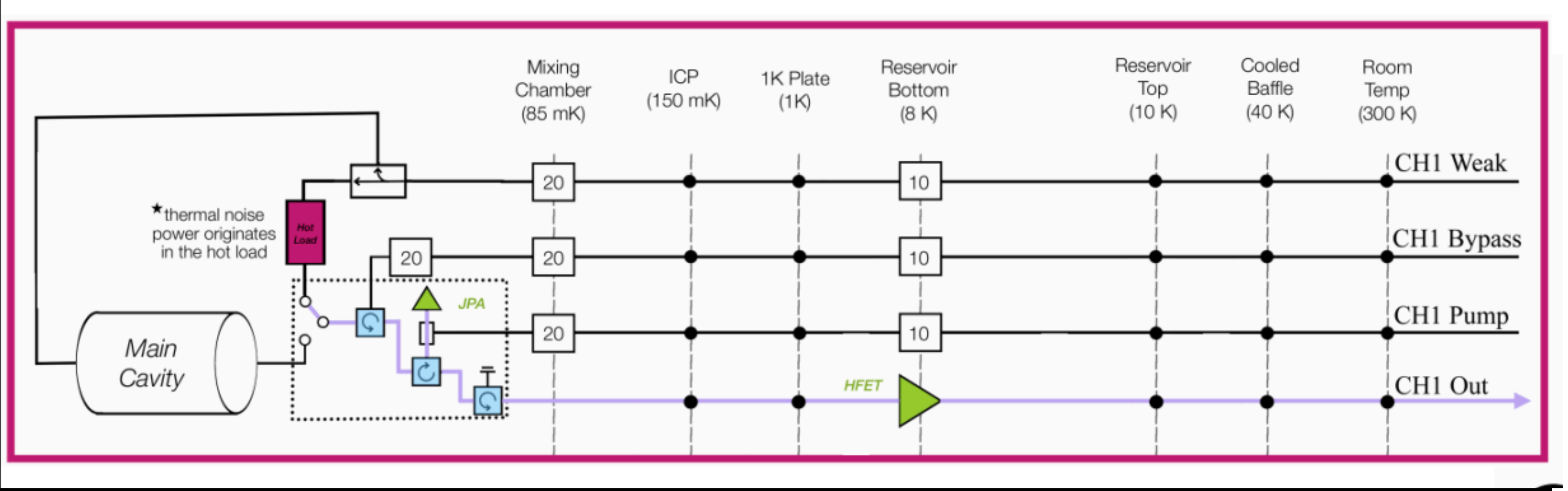
Figures courtesy of Shahid Jawas

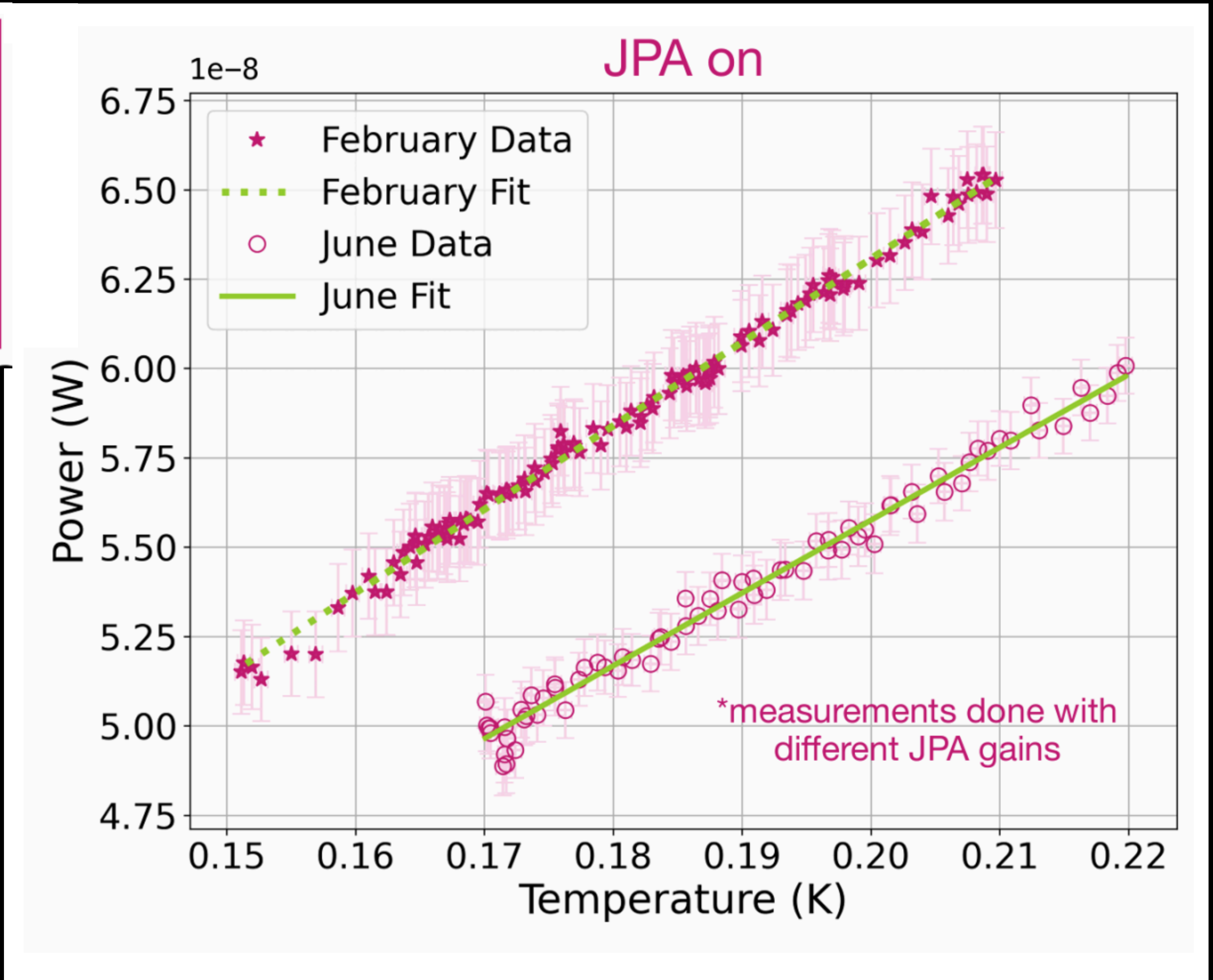




Field cancellation coil + Mu-metal shielding required for optimal performance

Noise Temperature

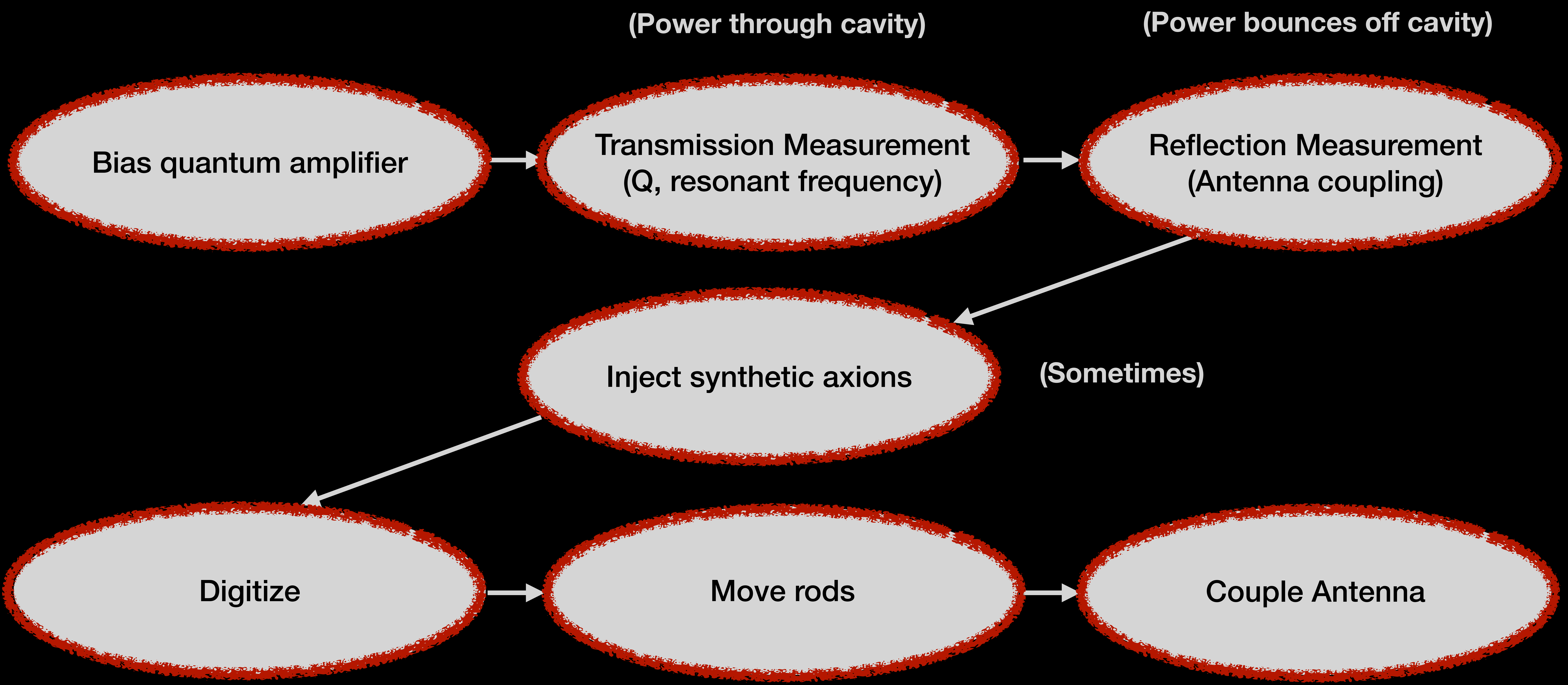




- Improved understanding and calibration of the system noise.
- Two methods very consistent with each other over time (within 5%).

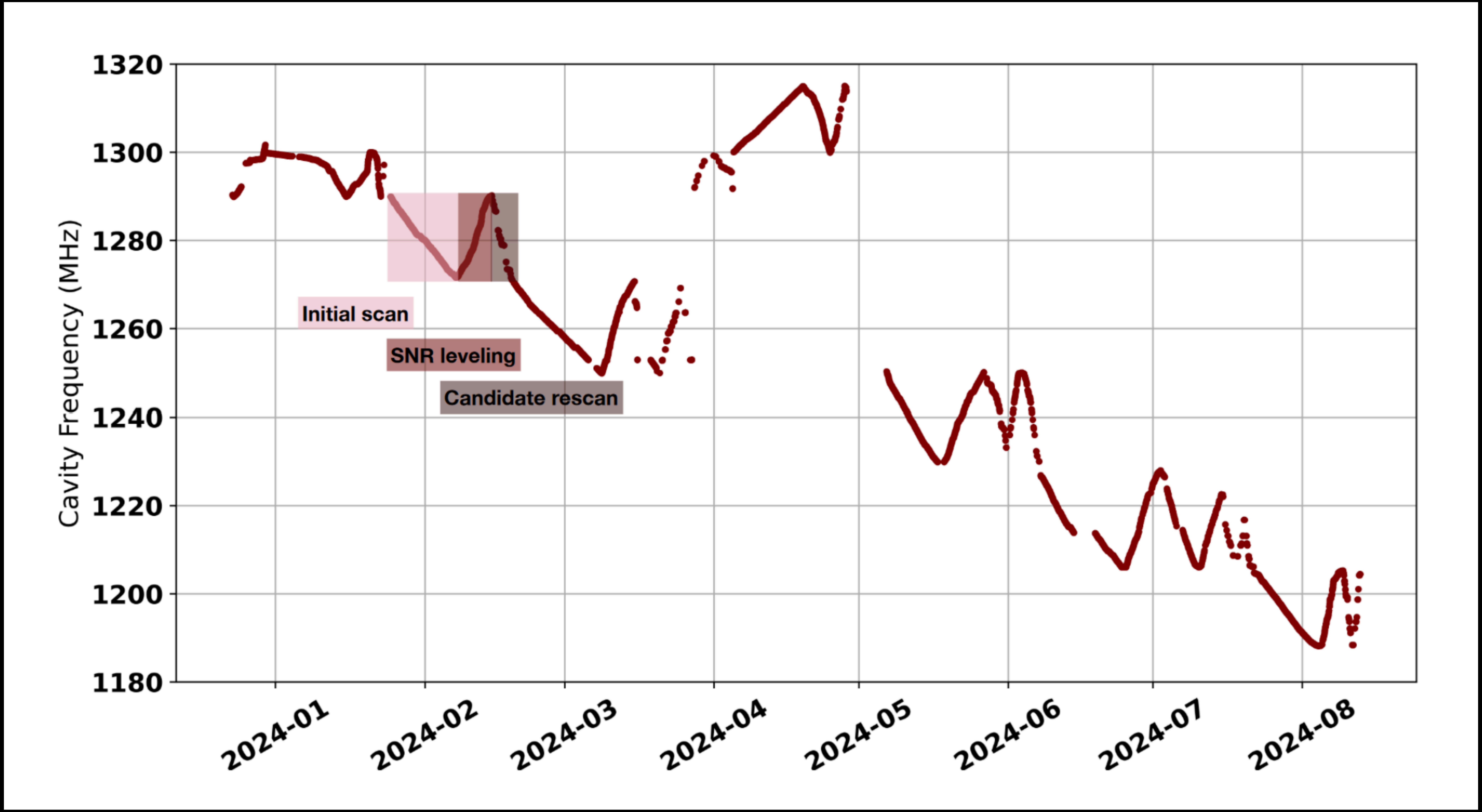
Improved receiver noise calibration for ADMX axion search: 4.54 to 5.41 μeV
Guzzetti, M. et al.

Data-taking operations



Axion Search Data!

Data-taking in 2024



Data Acquisition System

Medium Resolution

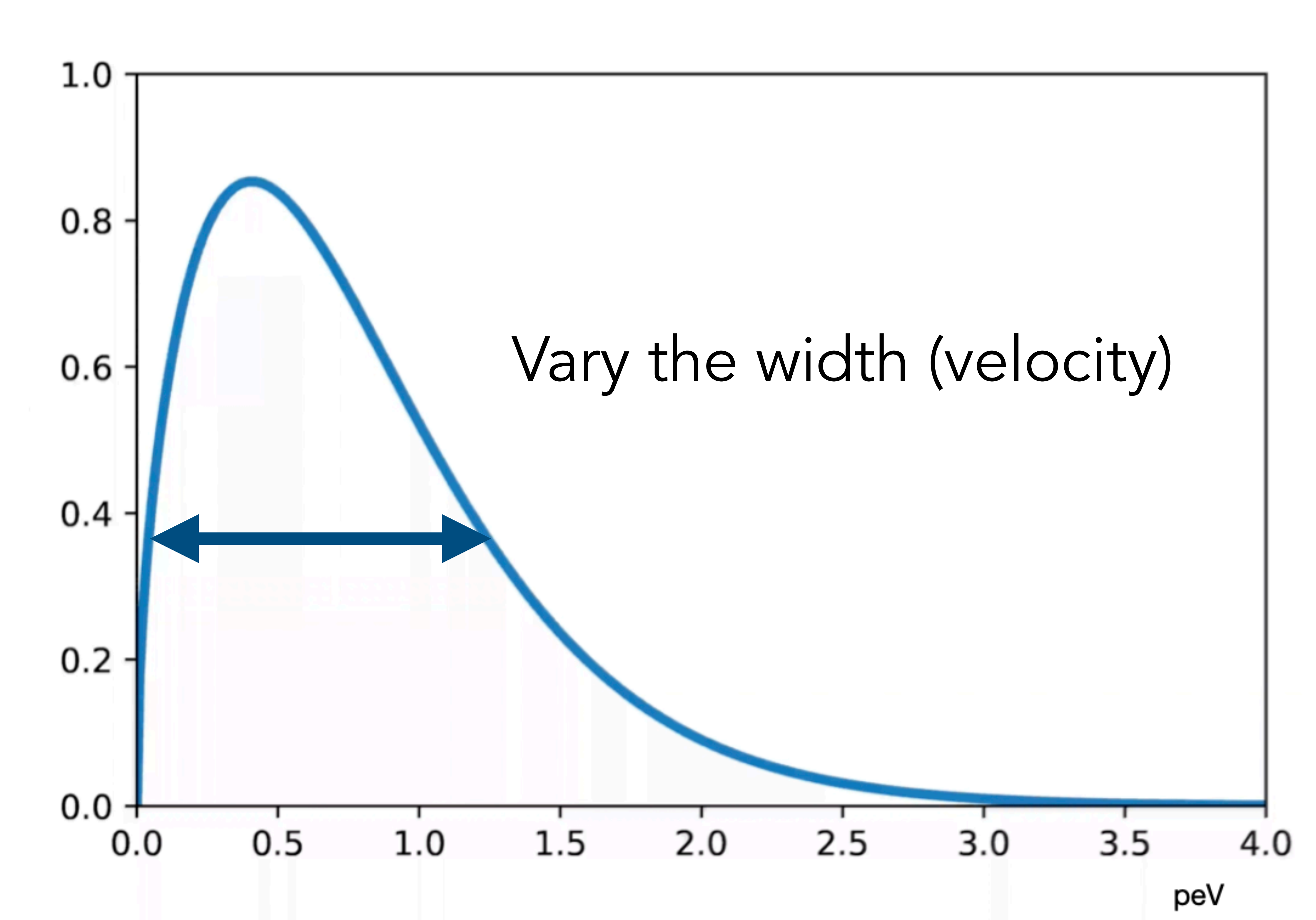
- Isothermal halo model
- Bin width optimized for expected axion lineshape
- Saved as power spectra
- 100 Hz bin width

High Resolution

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

How do we know if a signal is real?

Synthetic injection system provides verification of detection capability.



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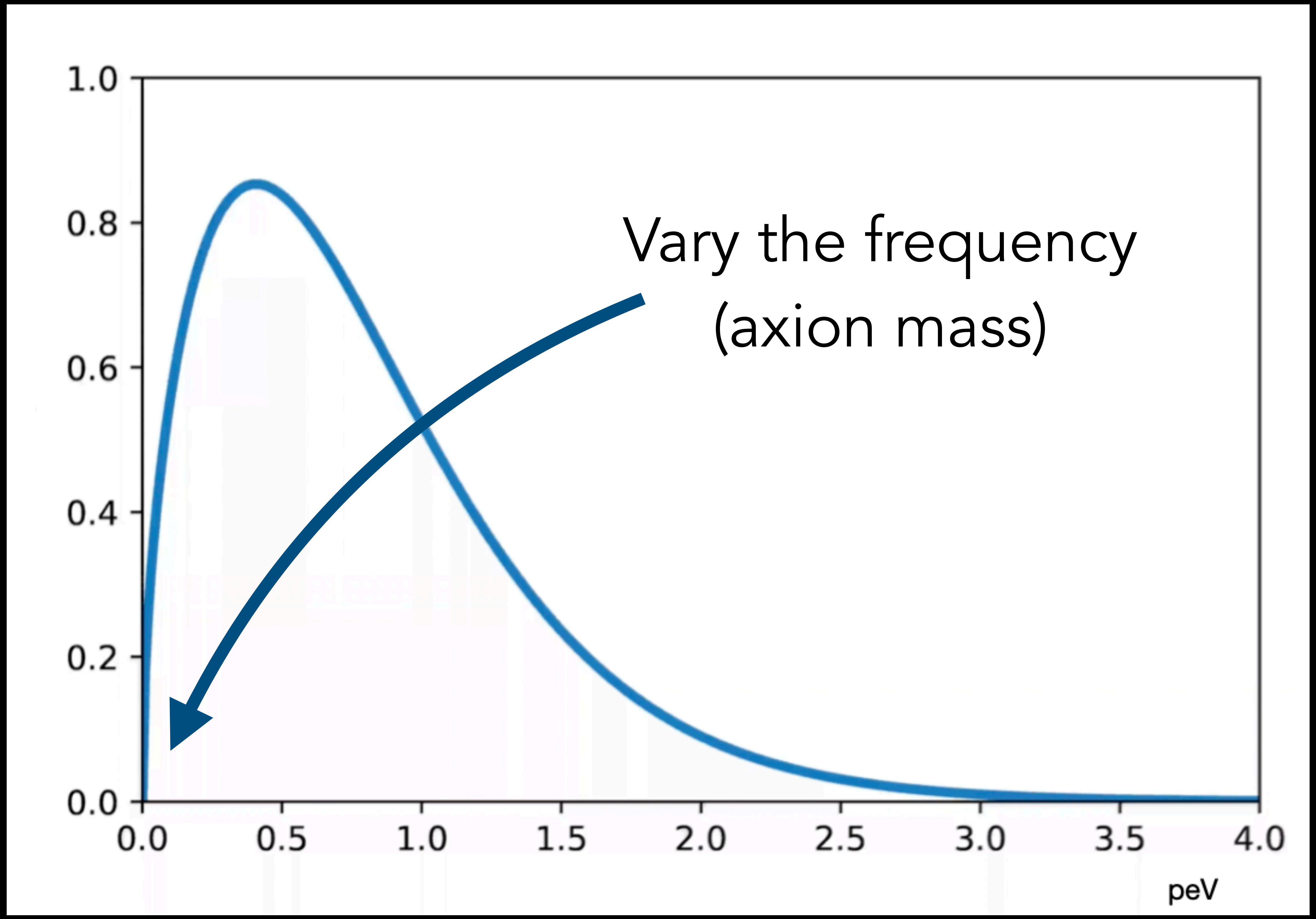

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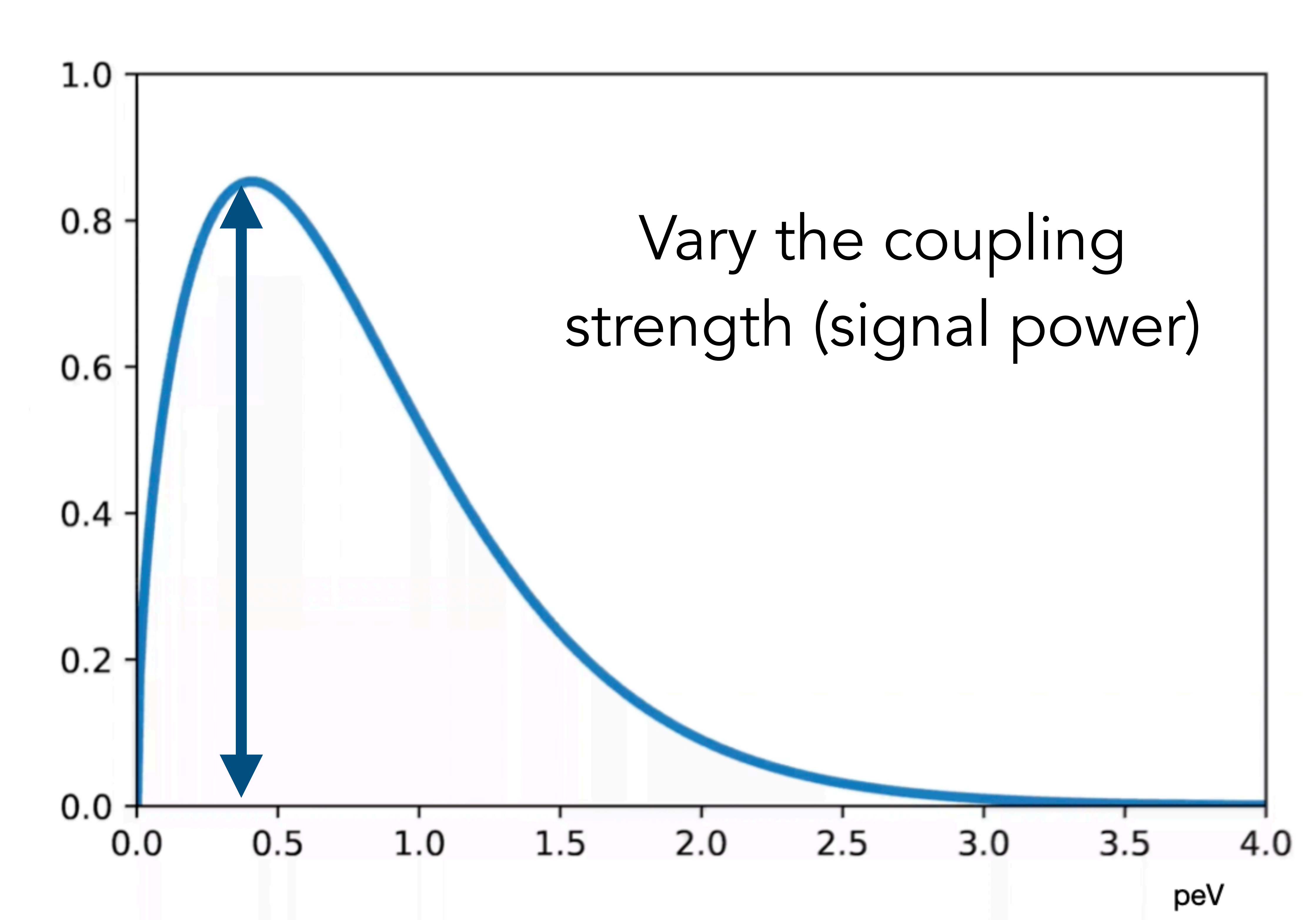

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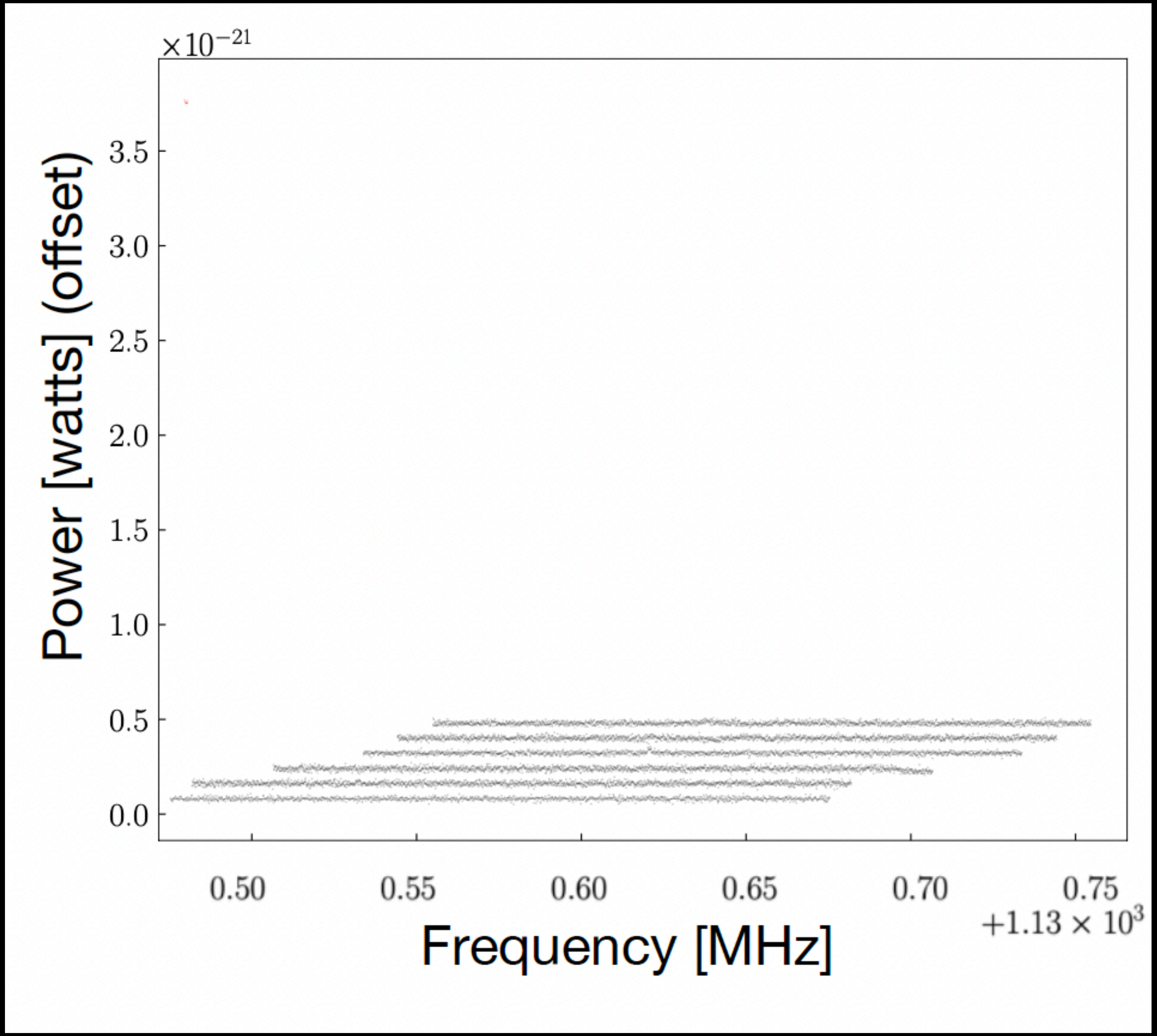

- Take data in chunks of frequency space while tuning at a steady rate

Courtesy of Dan Zhang

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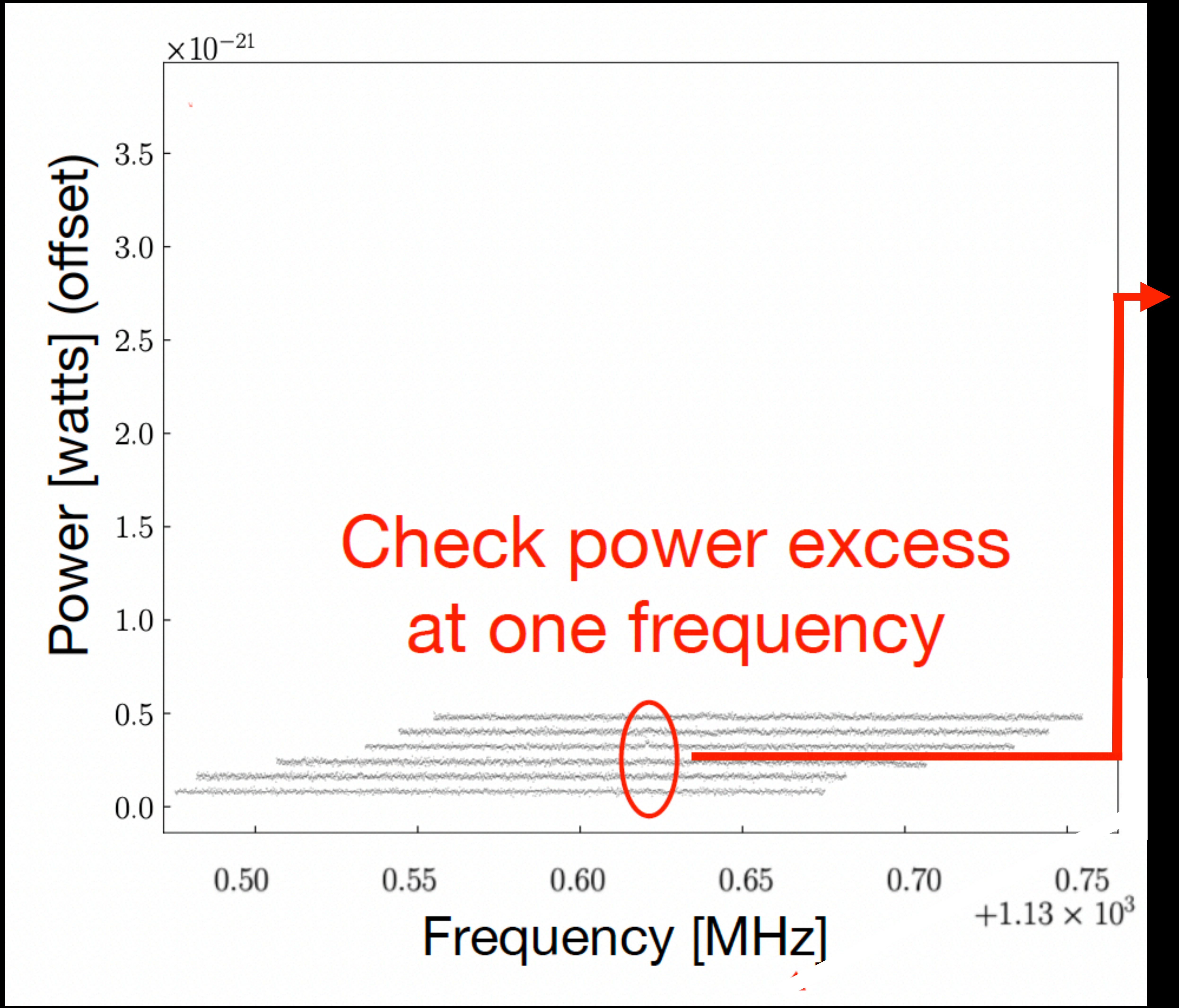

- Take data in chunks of frequency space while tuning at a steady rate
- Flag any candidates above some power threshold

Courtesy of Dan Zhang

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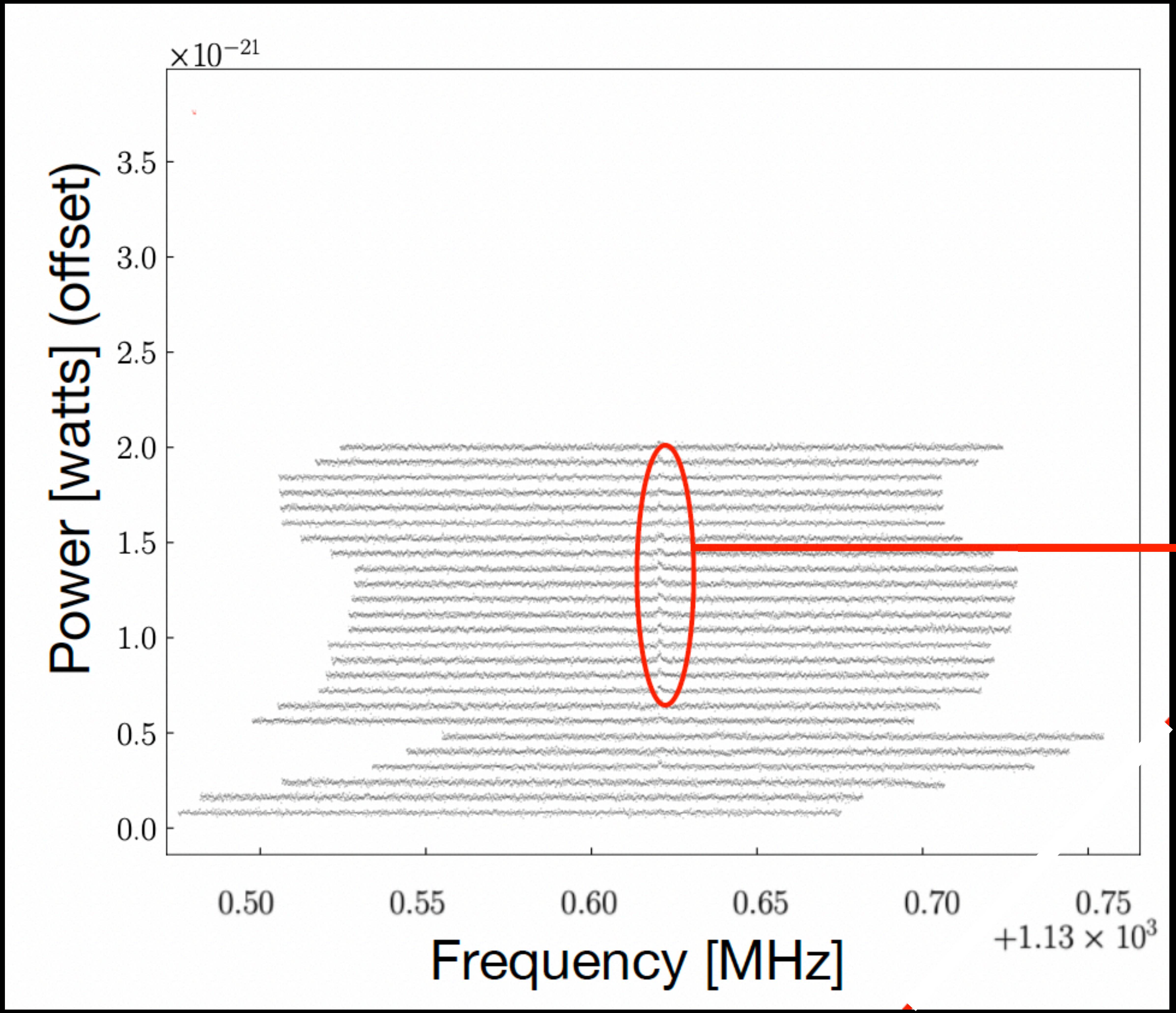

- Take data in chunks of frequency space while tuning at a steady rate
- Flag any candidates above some power threshold
- Rescan the flagged candidate to verify persistence

Courtesy of Dan Zhang

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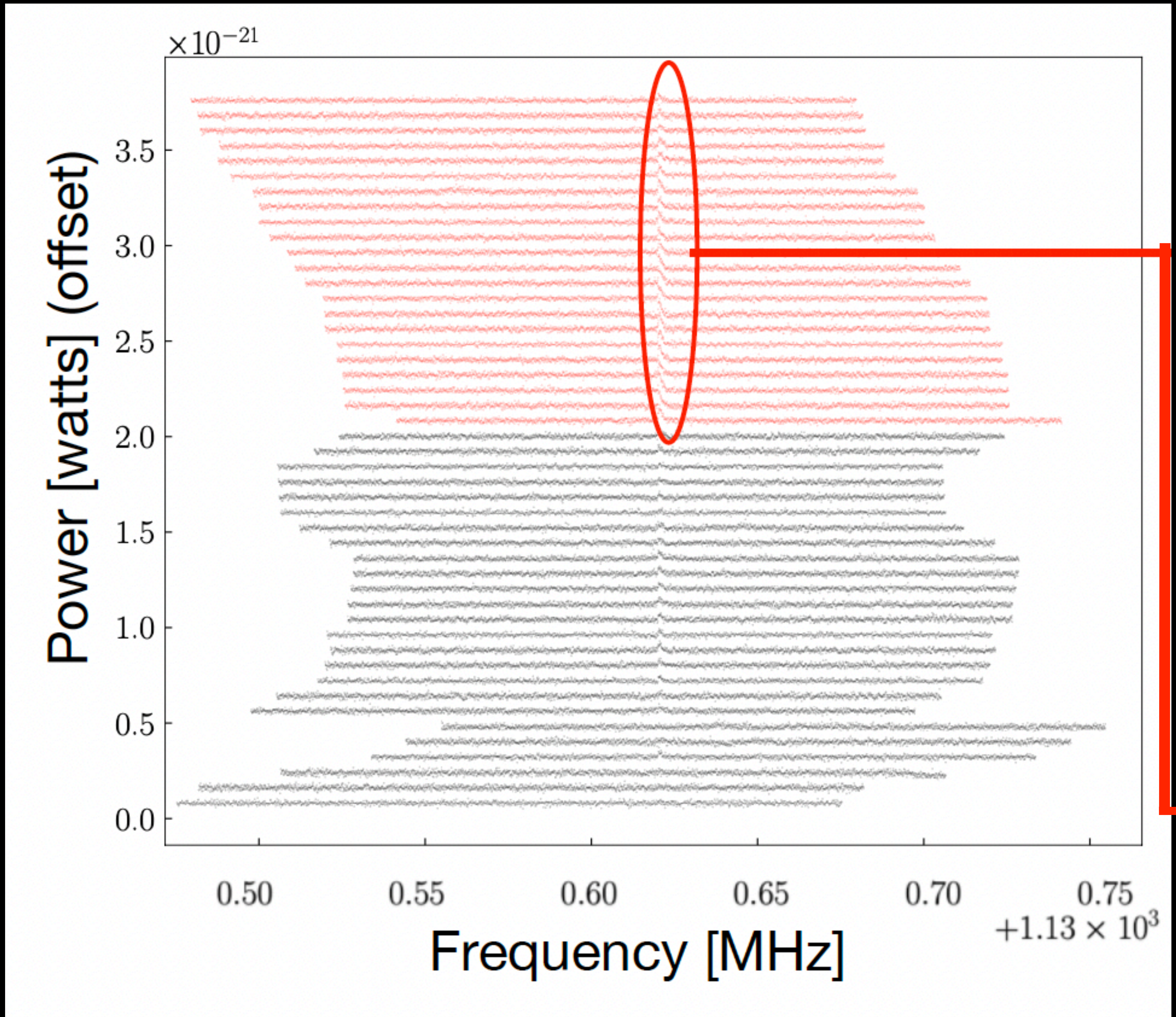
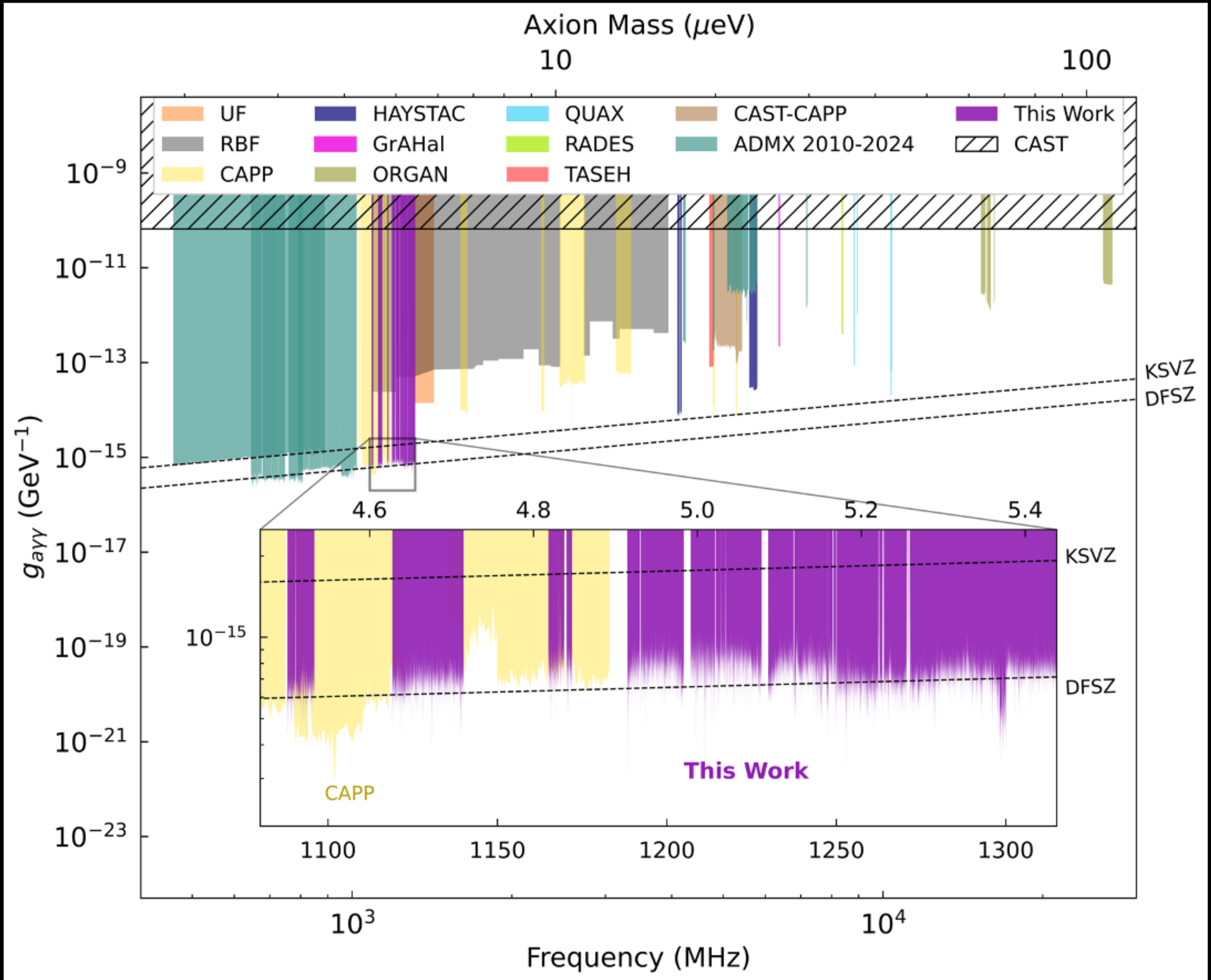


- Take data in chunks of frequency space while tuning at a steady rate
- Flag any candidates above some power threshold
- Rescan the flagged candidate to verify persistence
- Verify that the candidate does not couple to the TM011 mode

Courtesy of Dan Zhang

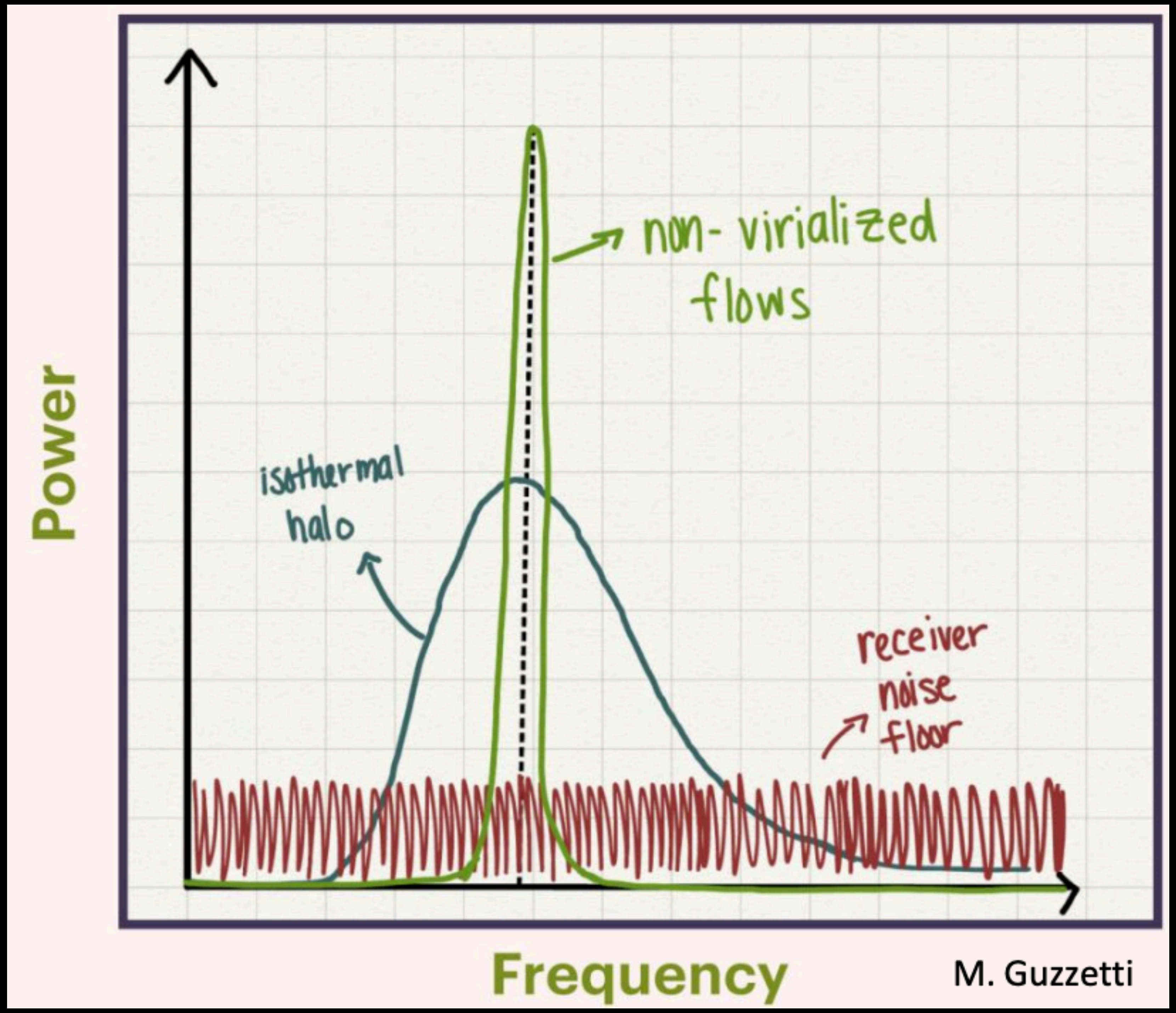
Recent Exclusion Limit

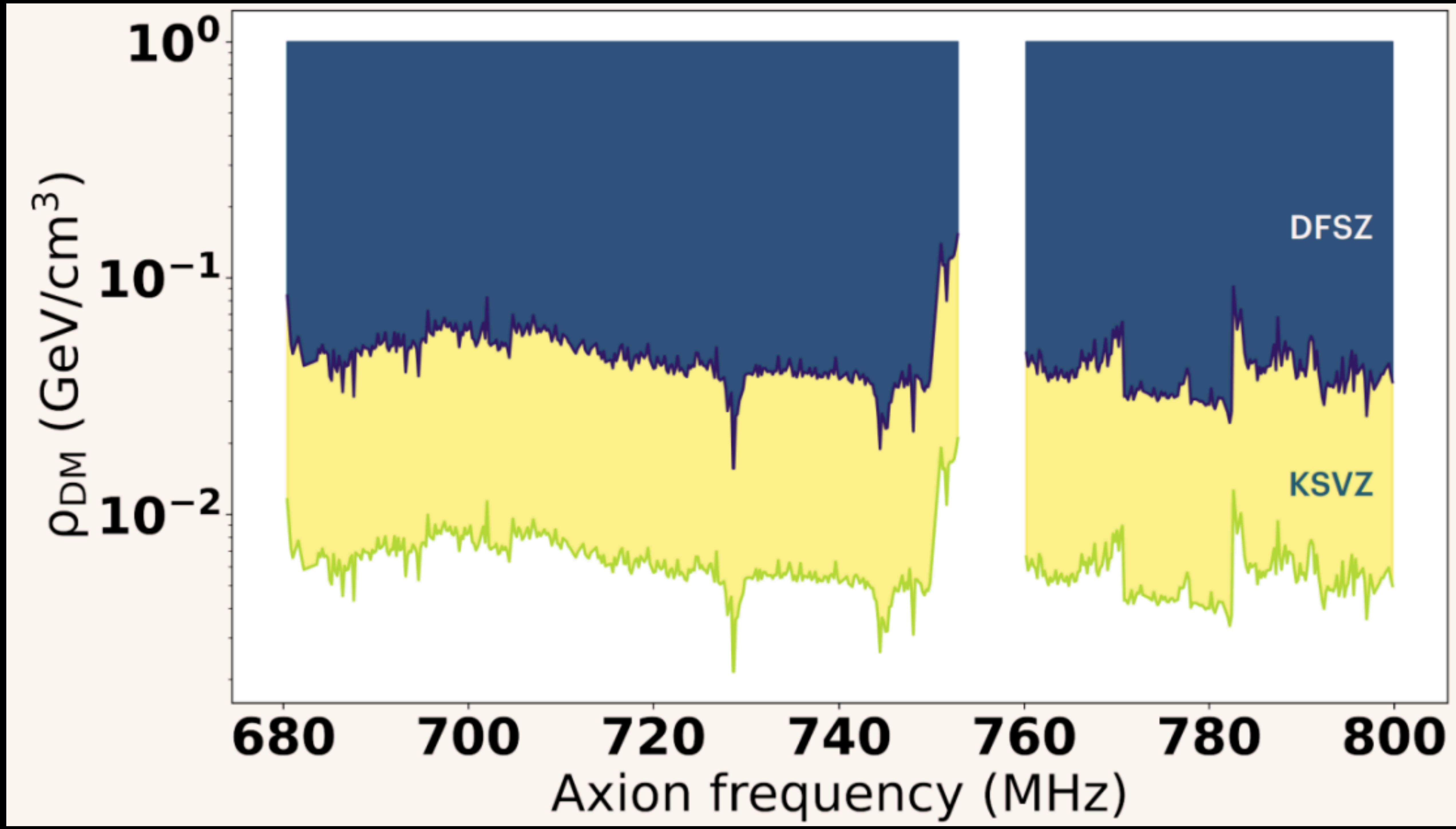
- Exclusion limit from Run 1D shown in purple
- ADMX + CAPP together resulting in excellent coverage
- ρ=0.45 GeV/cc,
- Maxwellian line shape
- Operations improvements lead to smoother tuning and limits



https://arxiv.org/pdf/2504.07279

Ancillary Analyses: High resolution search





No line-shape implied; monochromatic tone only

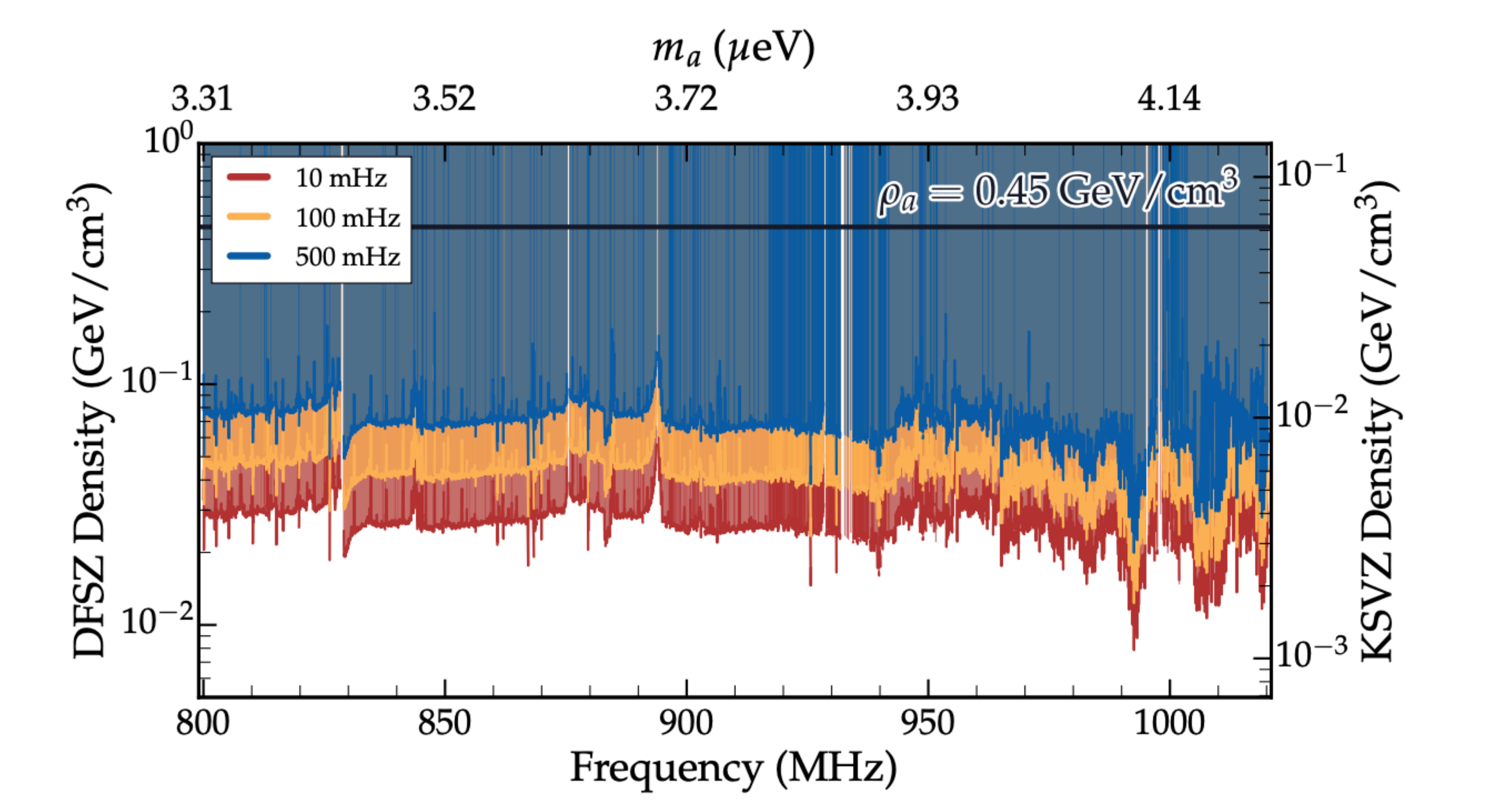
Sensitive to non-virialized axions and frequency modulation.

Teal: DFSZ assumed
Yellow: KSVZ assumed

Michaela Guzzetti, General Exam

Bartram et al. Phys. Rev. D 109, 083014 (2024)

Ancillary Analyses: High resolution search

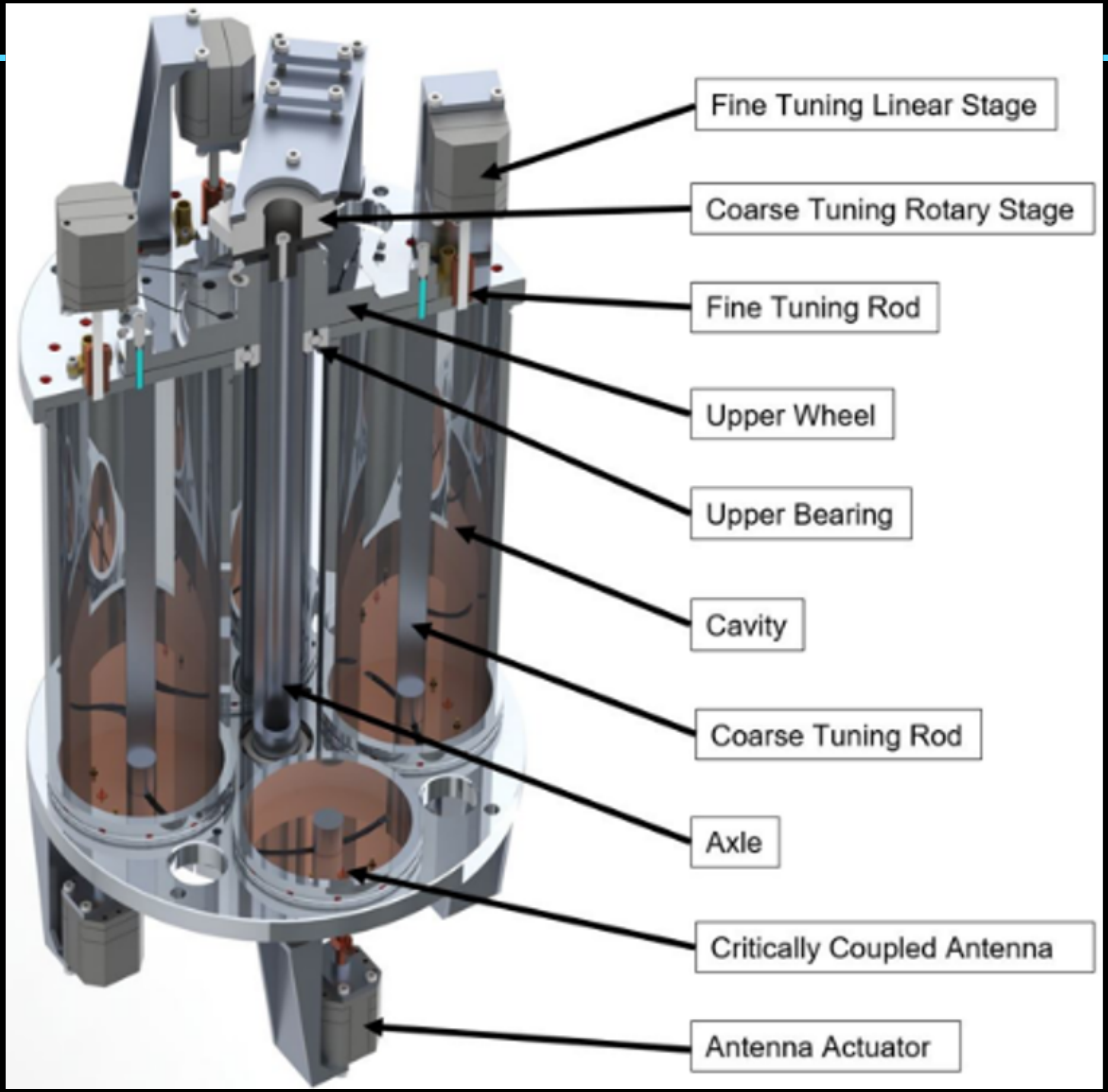


- Run 1C high resolution search results
- Non-virialized search with different frequency resolutions
- Optimized for different axion linewidths

https://arxiv.org/abs/2410.09203 Alex Hipp and Aaron Quiskamp

ADMX Run 2A

- Synchronous tuning of four separate cavities
  - Capable of fine and course tuning
- Full complex data set will be digitally combined outside the receiver chain
- Phase differences monitored via tone injection
- New analysis that accounts for complex data and candidate evaluation with multiple cavities



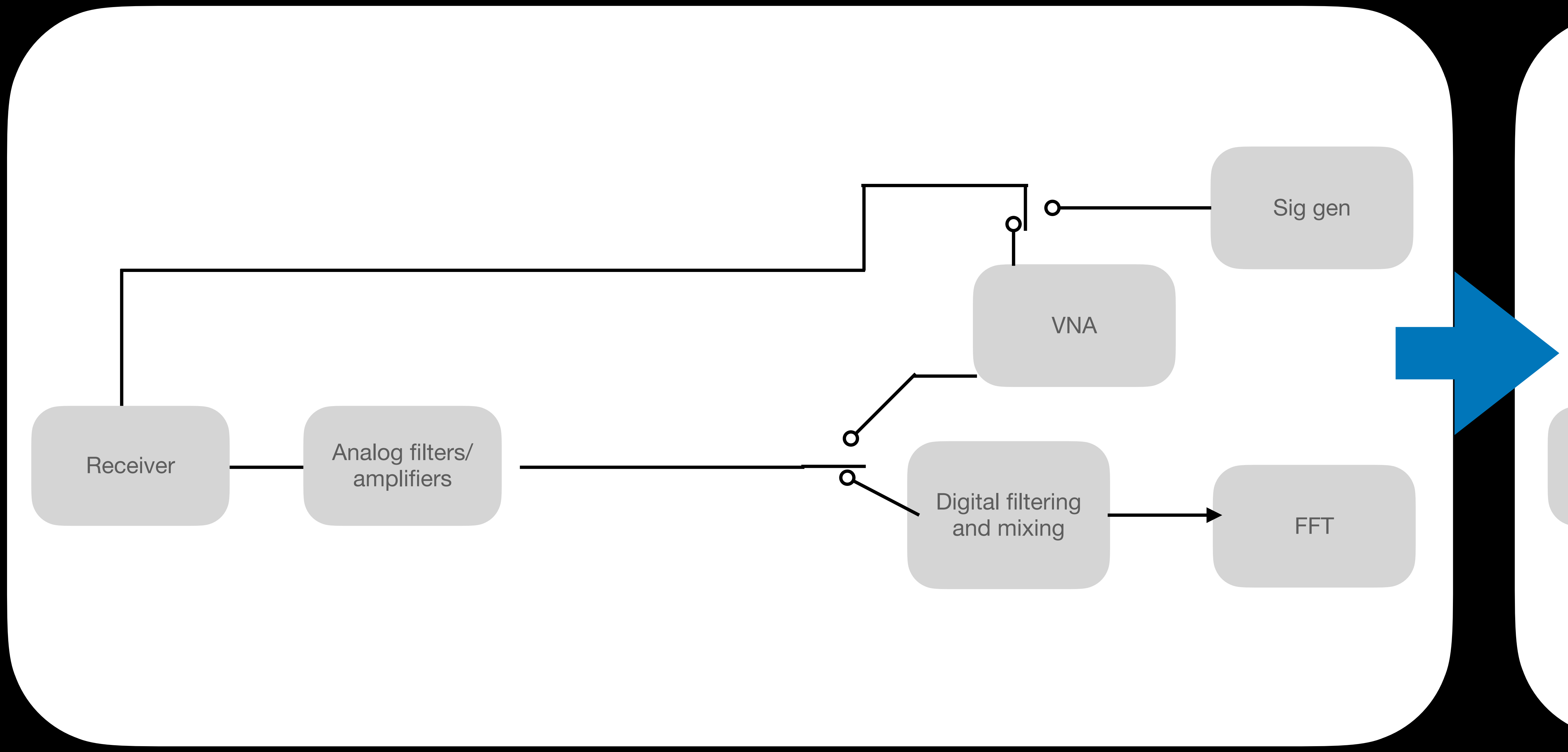
To be operated in the UW magnet

ADMX Run 2A

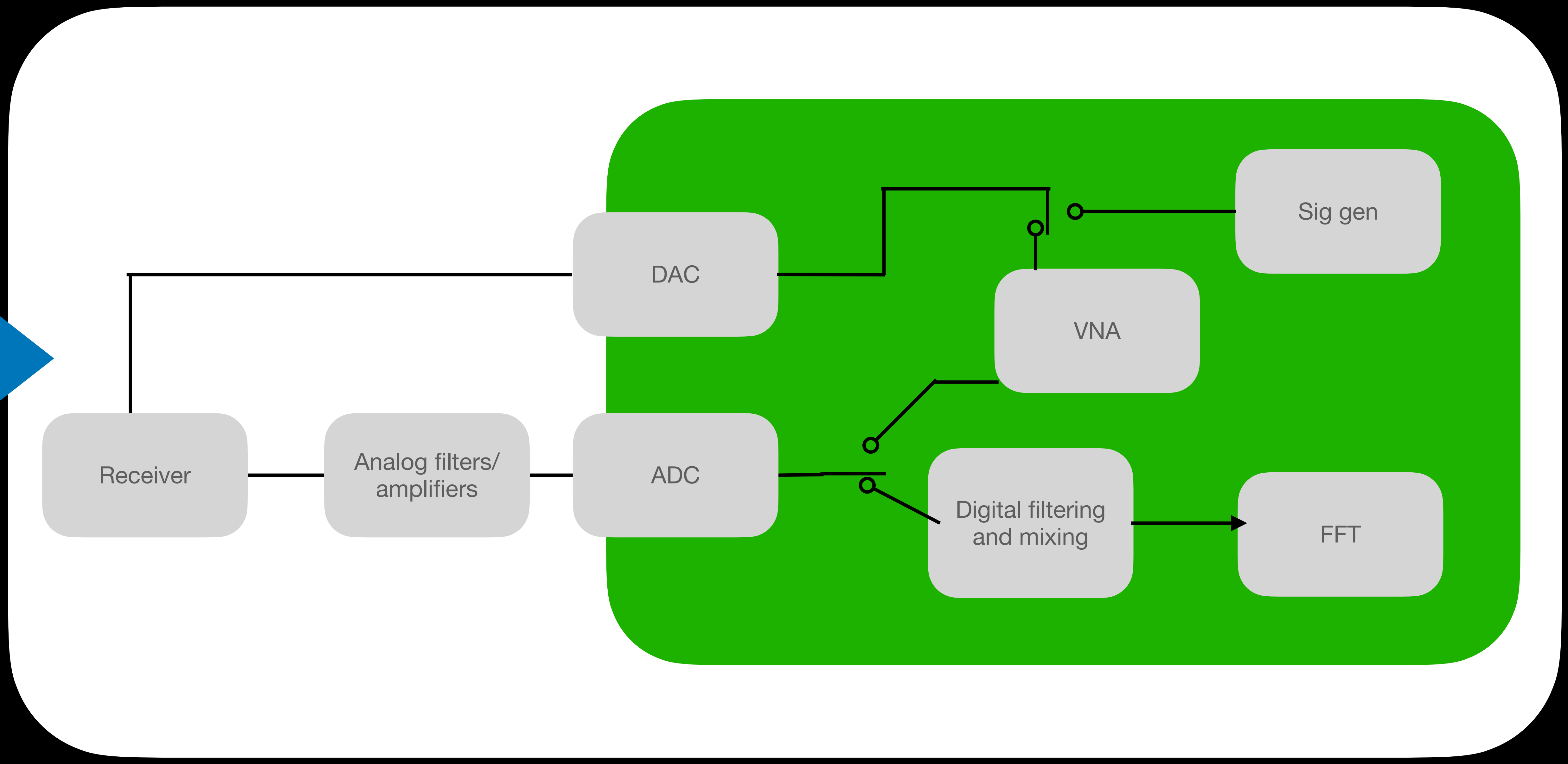
Development of receiver chain using RF "System on a Chip" or RFSoC

Technology developed in telecommunications industry

Migrate analog devices onto single digital board

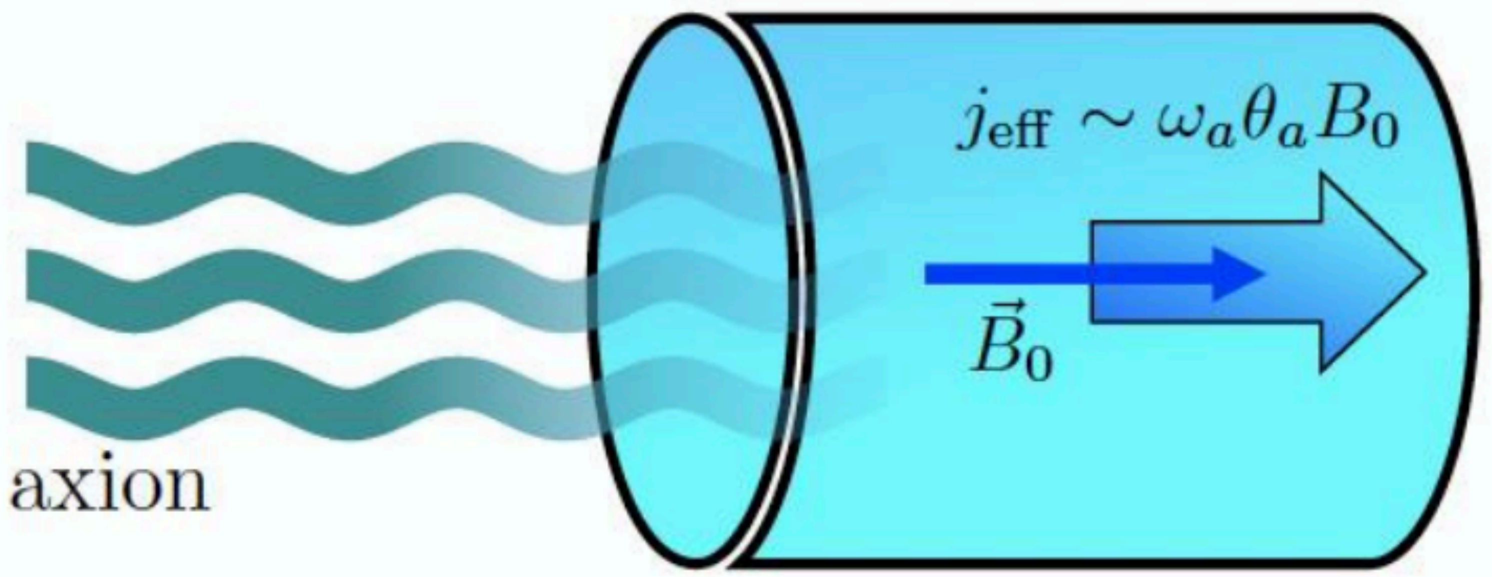


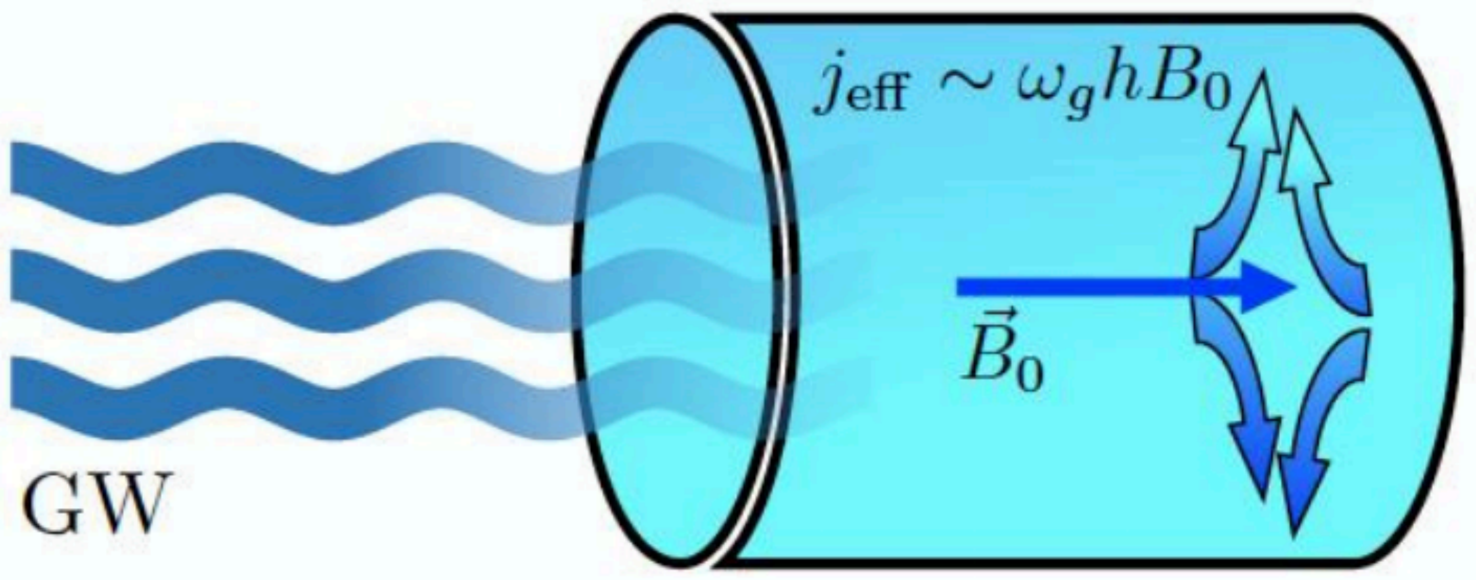
Existing receiver chain design



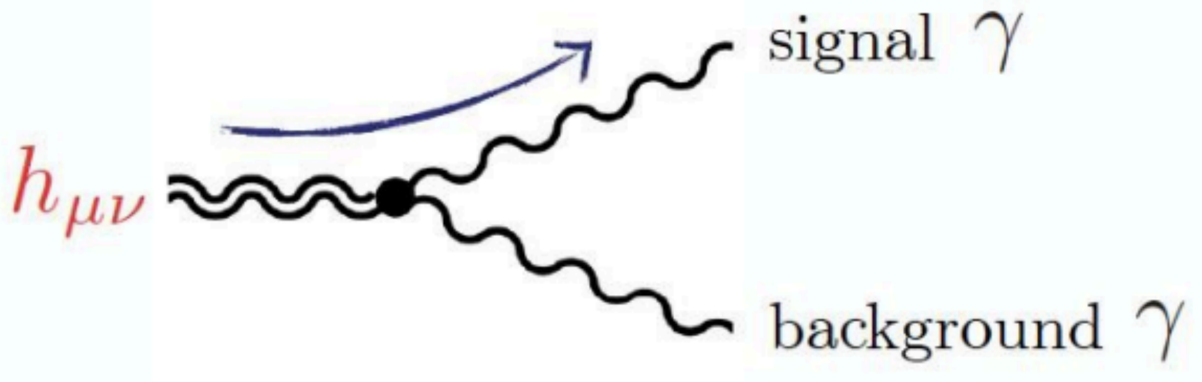
RFSoC receiver chain design

Gravitational Waves





"Inverse-Gertsenshtein Effect" : j^{μ}_{eff} is an "**effective current**" that sources small oscillating EM fields in the presence of background EM fields.



(graviton-to-photon conversion)

Characteristic strain sensitivity: h ~ 10^{-21}
Characteristic frequency: GHz

Experimental issues:

- Not quite the same resonant mode as the axion-> photon (but calculable and buildable)
- Transient or broadband signals require radically different analysis from DM axions

A. Berlin et al. https://doi.org/10.1103/PhysRevD.105.116011

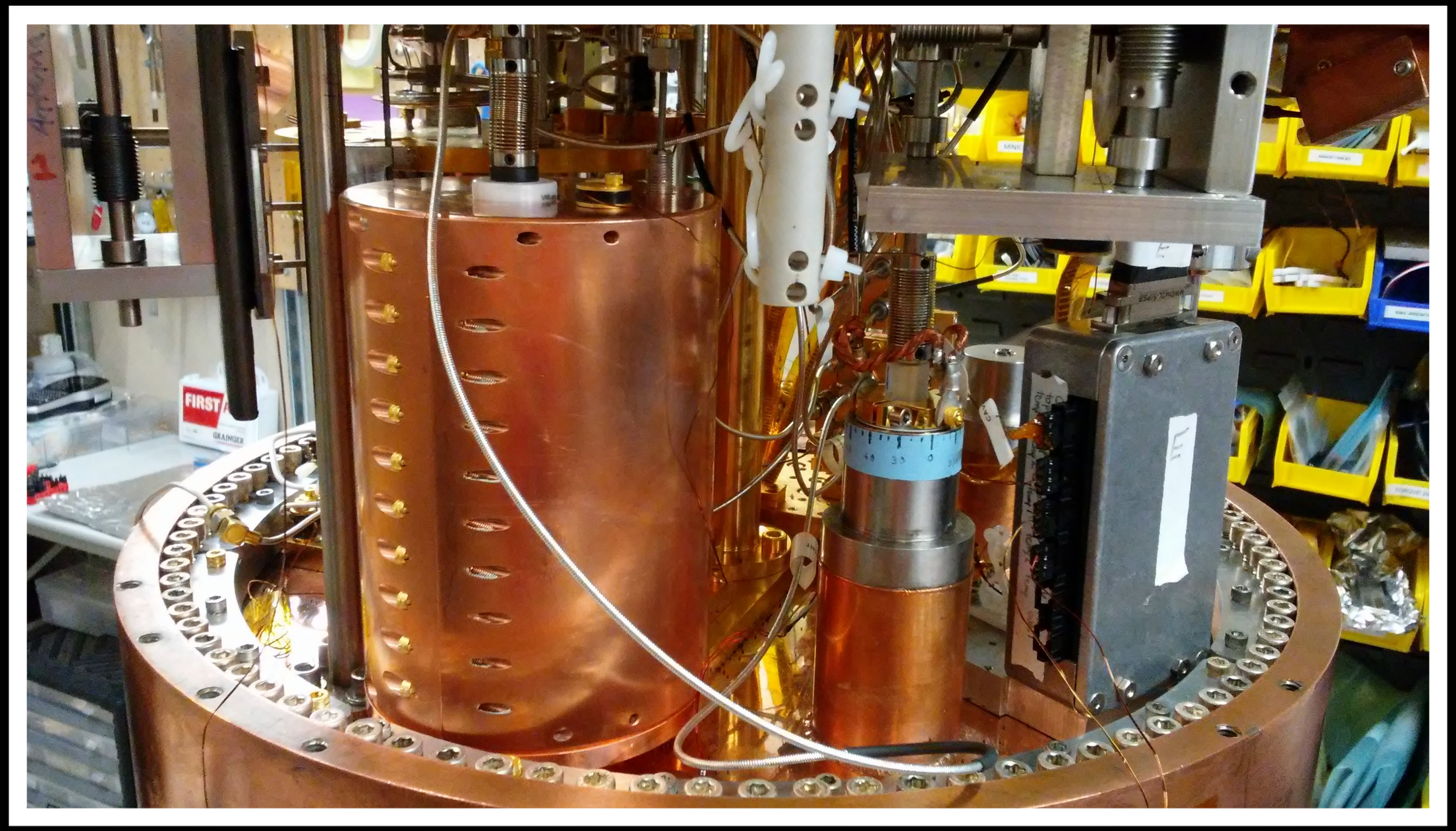
Courtesy of Gray Rybka and Stefano Profumo

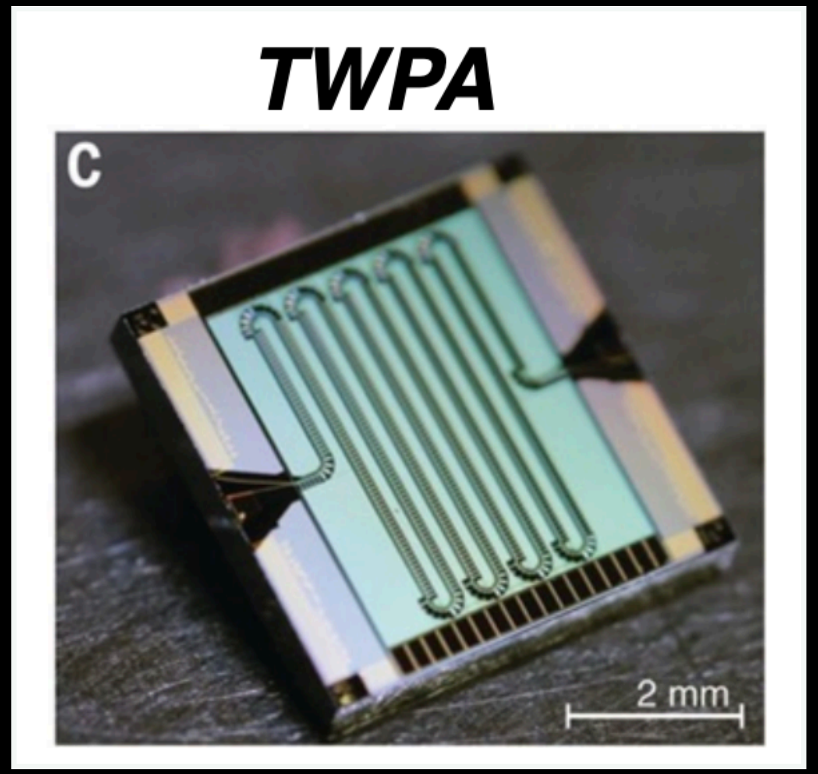
Gravitational Waves

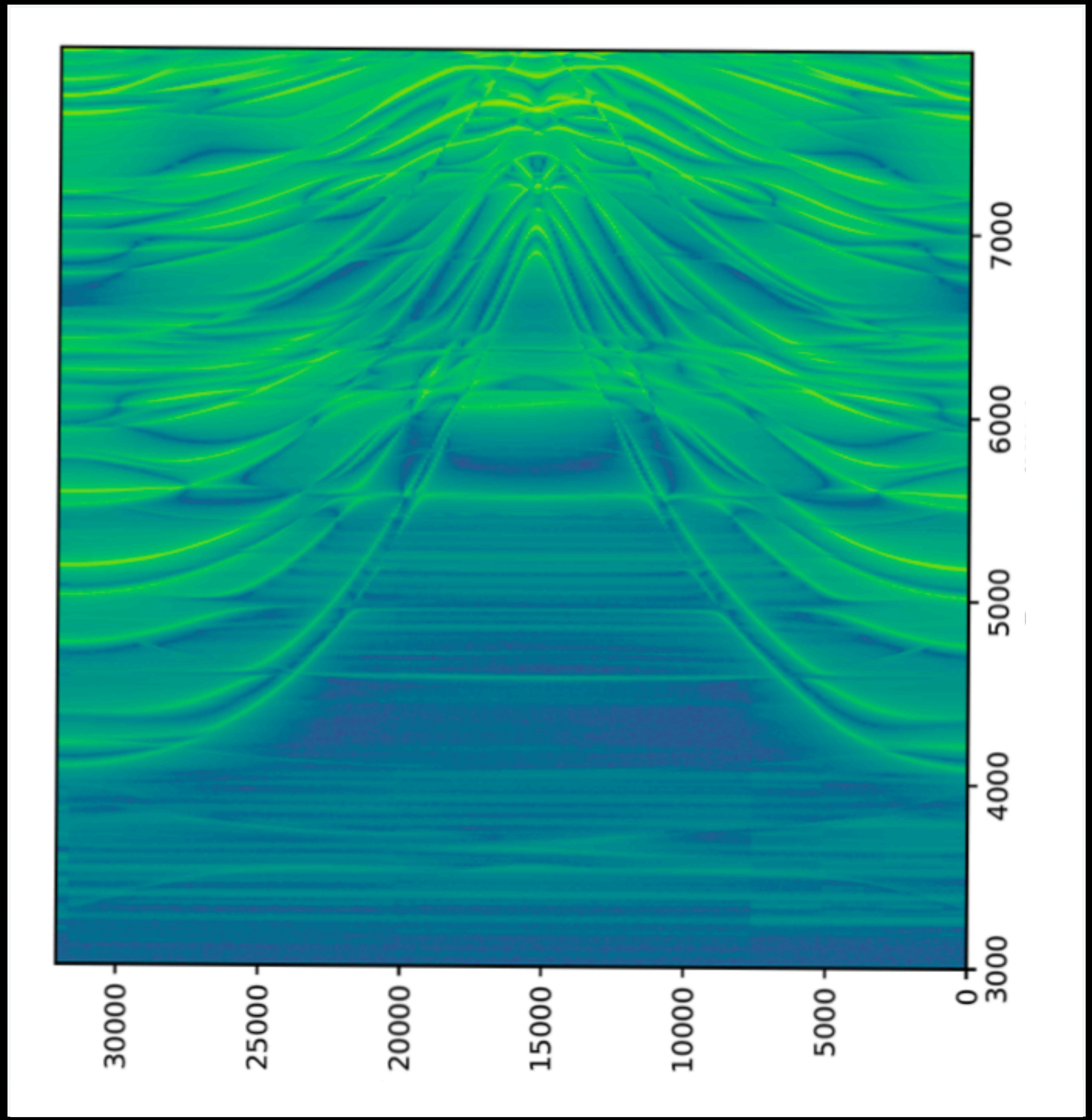
Speculative Source	What's its deal?	Caveats
Primordial Black Holes	Asteroid mass PBHs can be 100% of dark matter, radiate GHz GWs when in binary inspirals	Merger rate low, haloscope detectable range is solar-system sized
Stochastic Background	Early universe events (PBH evaporation, inflation relics, KK gravitons, etc) may leave a GHz GW background.	Resonant detection is particularly bad at broadband searches. Most sources are well below detectability, or violate N_{eff} already.
Black Hole Superradiance	Light bosons suck angular momentum out of black holes and explode into gravitational waves	Broadband signal, requires a new boson, needs to be tuned to get GHz waves

Courtesy of Gray Rybka and Stefano Profumo

ADMX high frequency prototype





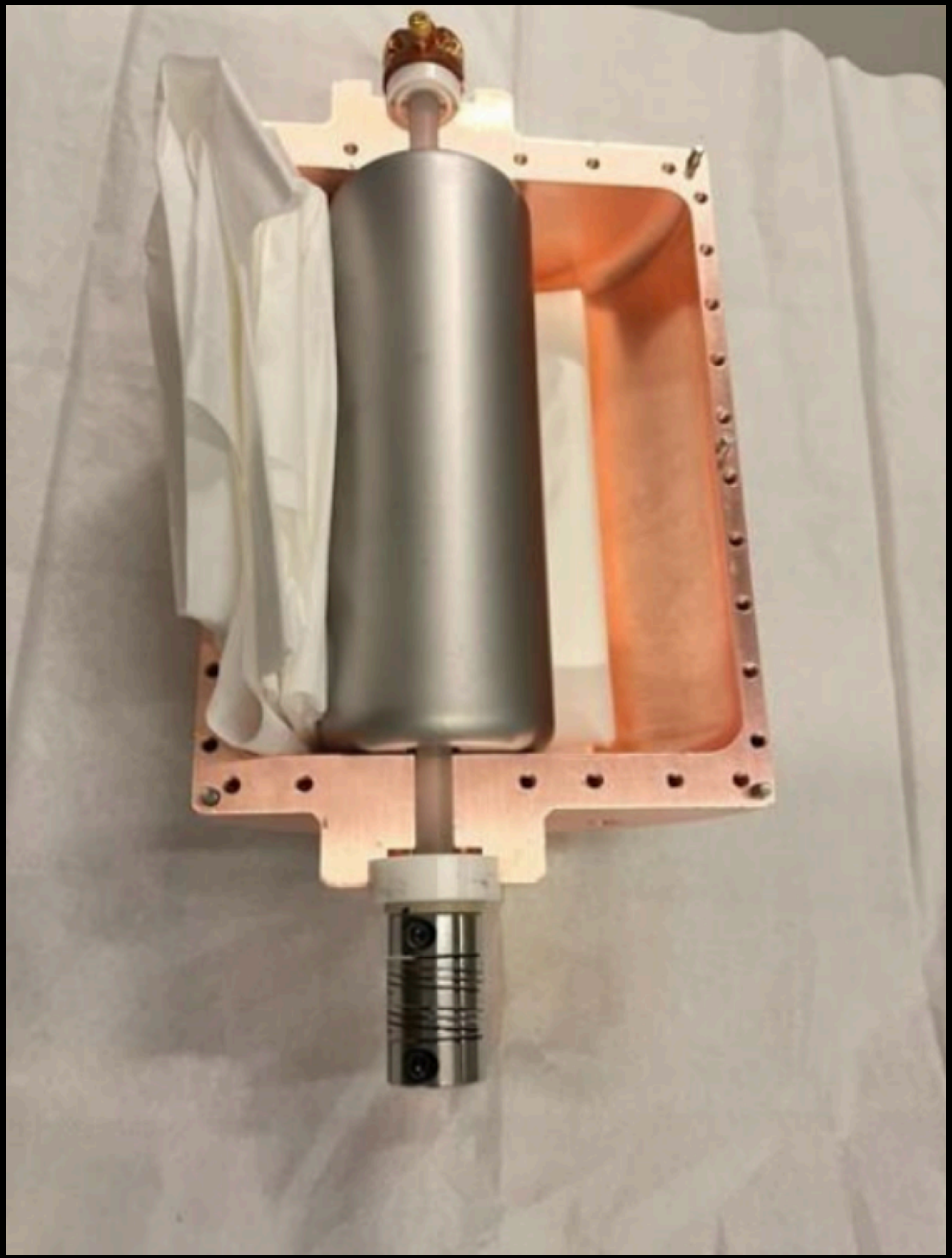


Sidecar mode map

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

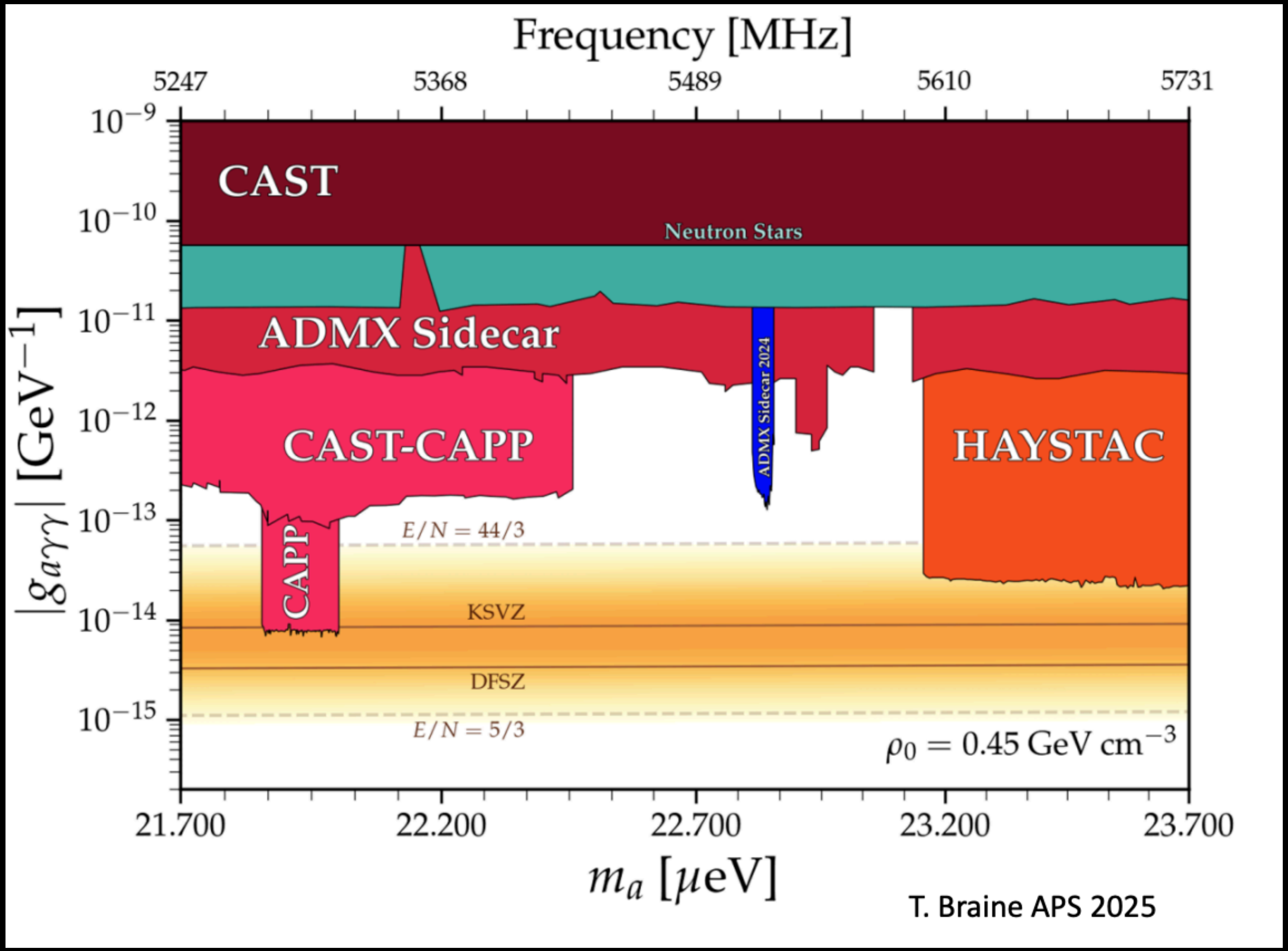
- Traveling Wave Parametric Amplifier (TWPA)
- Clamshell cavity design
- Piezo motors for antenna and tuning rod
- Superconducting films

Sidecar Cavity Haloscope



- O(1) μm Nb3Ti on Nb substrate
- At zero magnetic field, the Q was lower than expected
- Studies with aluminum cavity + indium seal at University of Sheffield
- Next run will add indium seal to clam shell cavity
- Recoating Nb3Ti

Sidecar Cavity Haloscope



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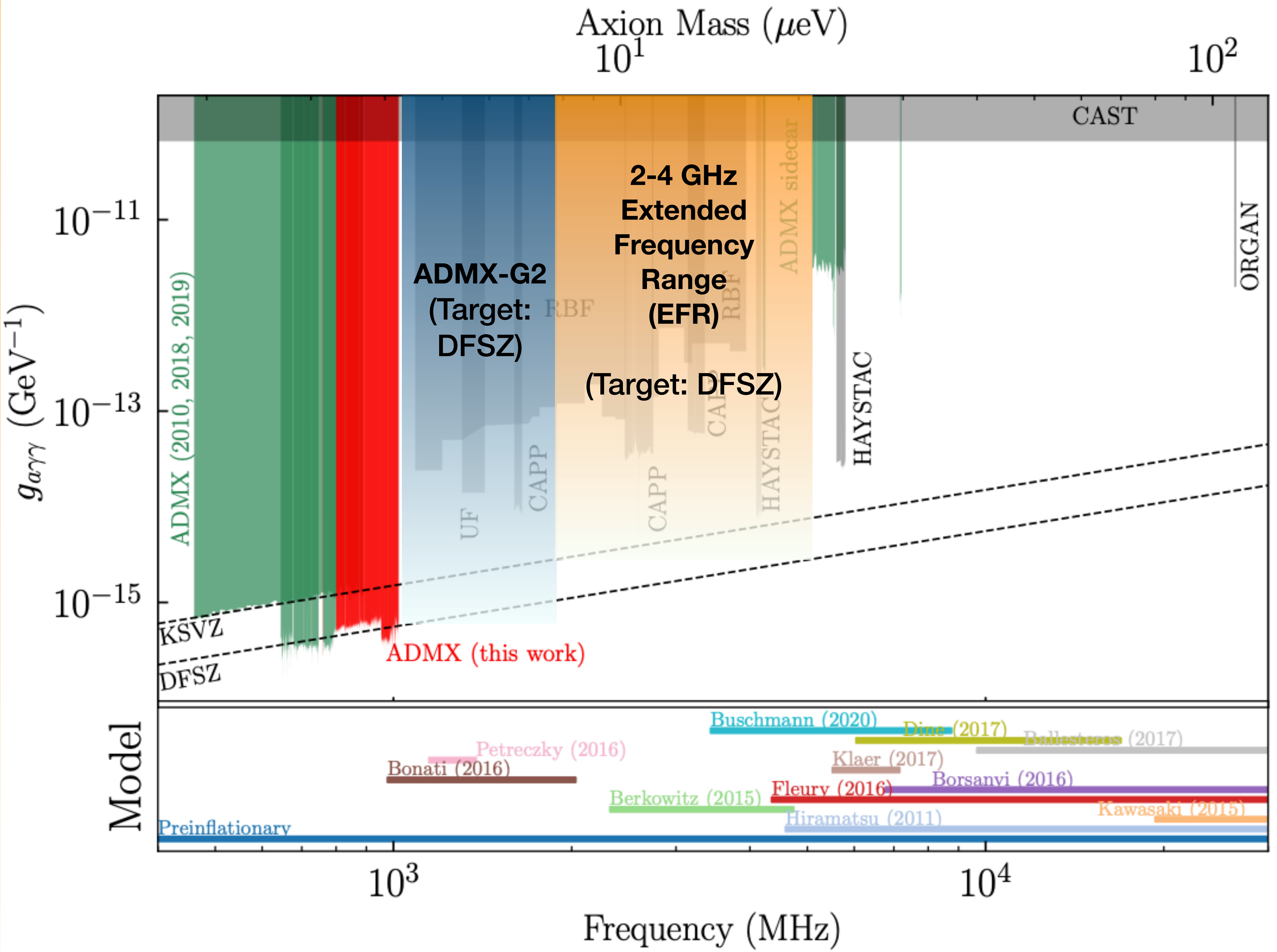
ADMX-EFR



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

Scan speed for cavity haloscope

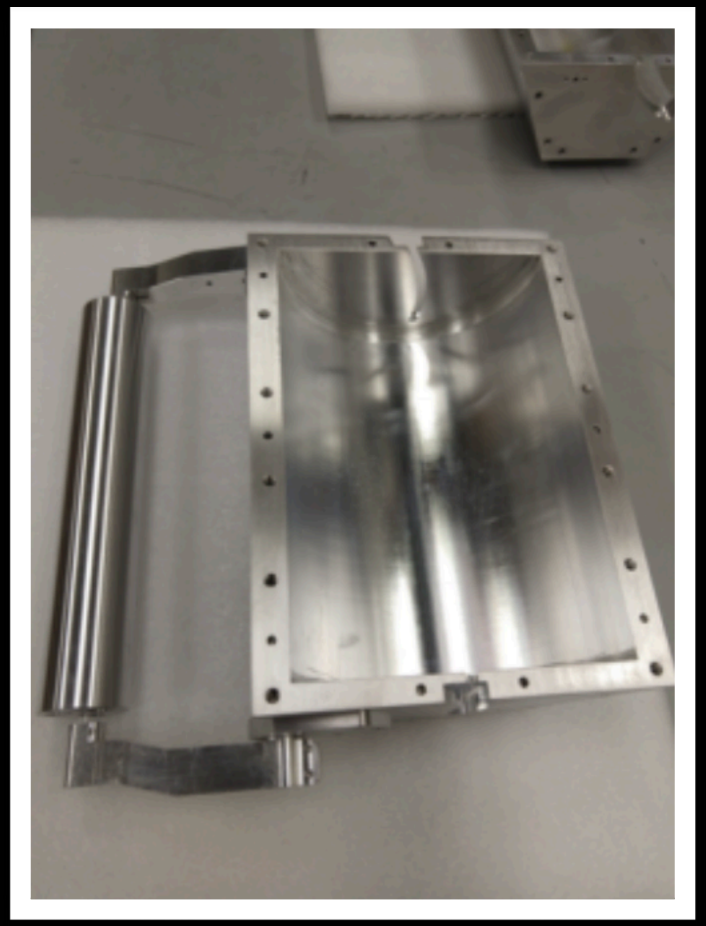
$$\frac{df}{dt} \approx 323 \frac{\text{MHz}}{\text{yr}} \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho}{0.45\,\text{GeV/cm}^3}\right)^2 \left(\frac{f}{1\,\text{GHz}}\right)^2 \left(\frac{3.5}{\text{SNR}}\right)^2 \left(\frac{B_0}{7.6\text{ T}}\right)^4 \left(\frac{V}{136\ \ell}\right)^2 \left(\frac{Q_L}{30,000}\right) \left(\frac{C_{lmn}}{0.4}\right)^2 \left(\frac{0.35\text{ K}}{\text{T}_{\text{sys}}}\right)^2$$

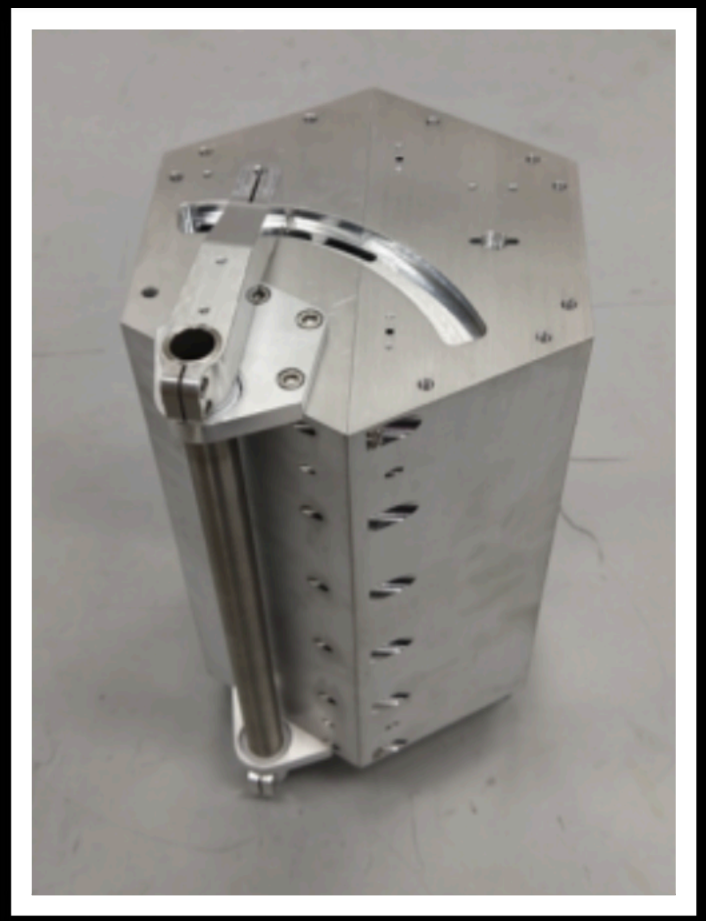
Maximize	Can't Control	Minimize

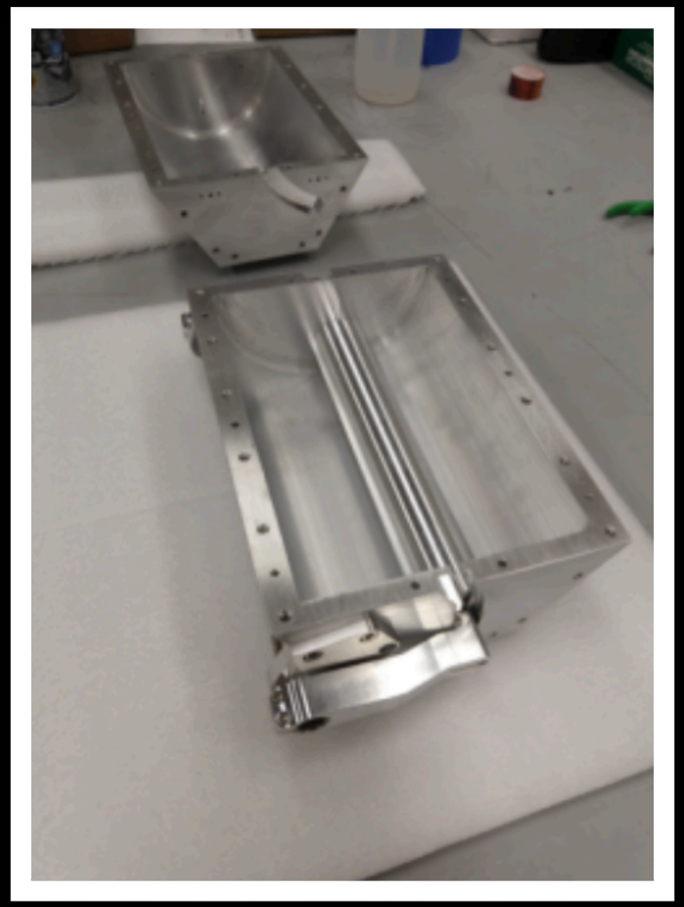
• B Field
• Volume
• Quality Factor
• Form Factor
	• Frequency
	• Coupling
	• Dark Matter Density
		• System noise:
		  • Amplifier Noise
		  • Physical Noise

***Similar equation for quasistatic haloscope**

ADMX EFR (2-4 GHz)



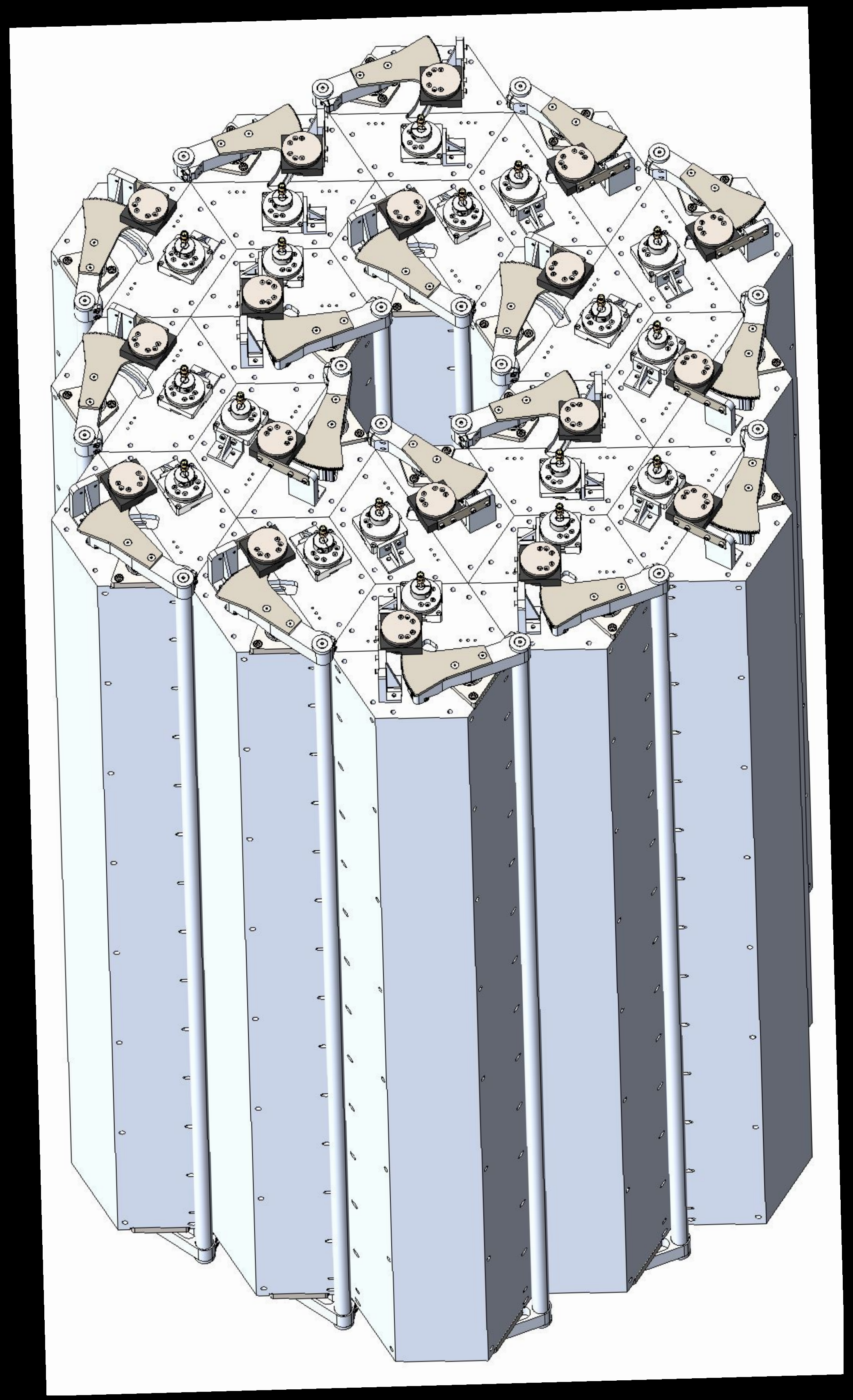




Prototype cavity testing

18-JPA receiver

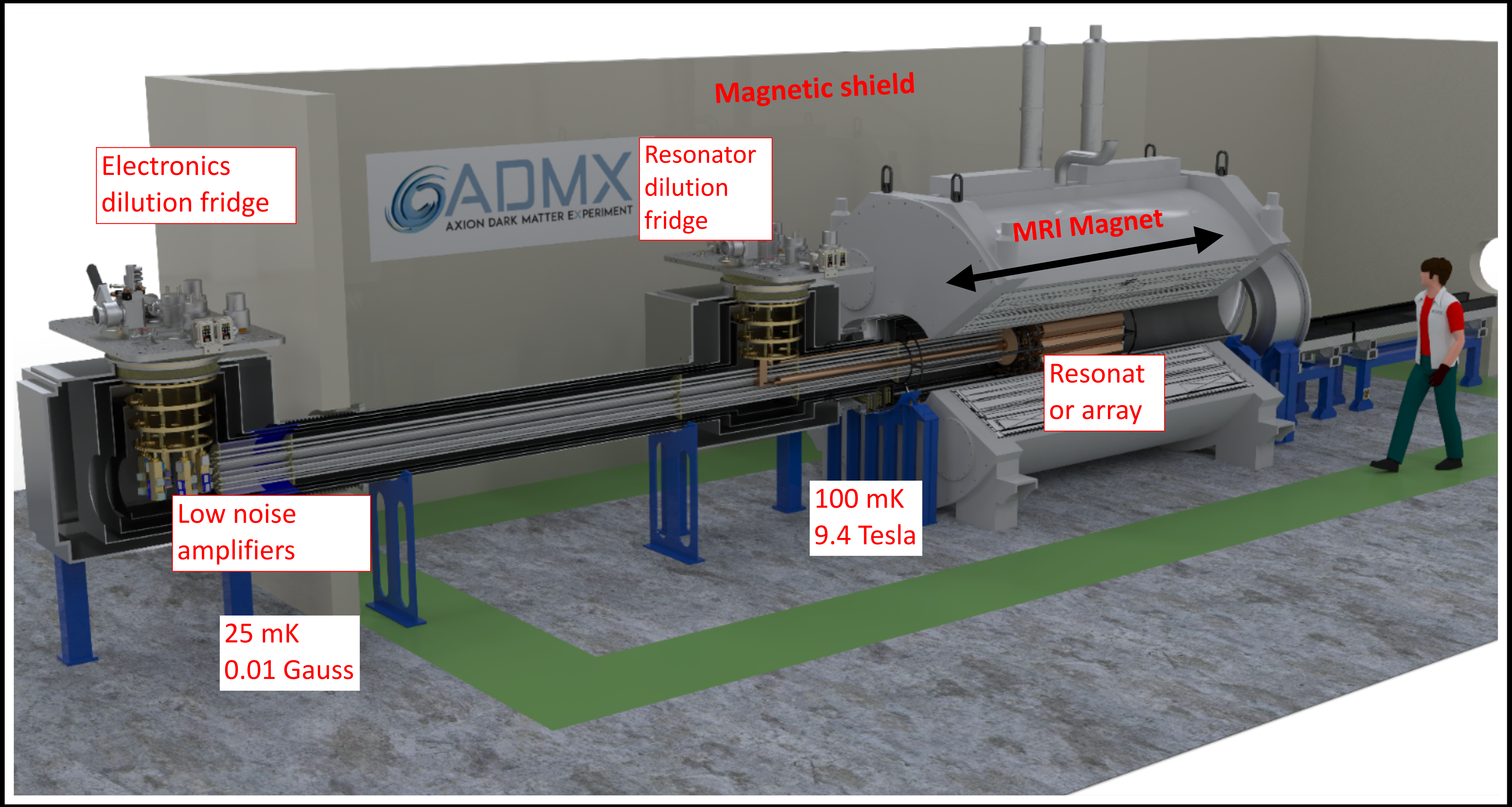
9.4 T Magnet



18-cavity array simulations

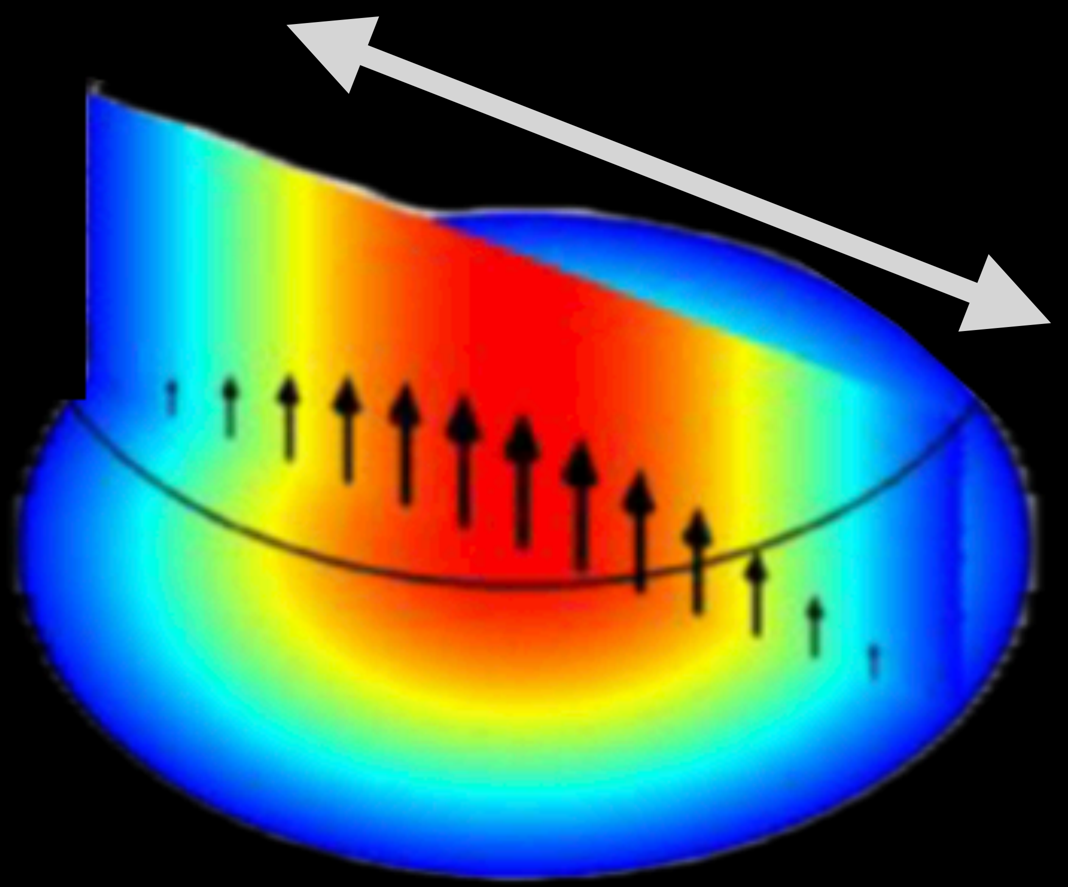
ADMX EFR (2-4 GHz)

- Horizontal magnet bore
- Extra modularity: cavity electronics are separate from magnet bore
- Large magnet volume: 258 liters
- Other: Squeezing? Superconducting cavities?

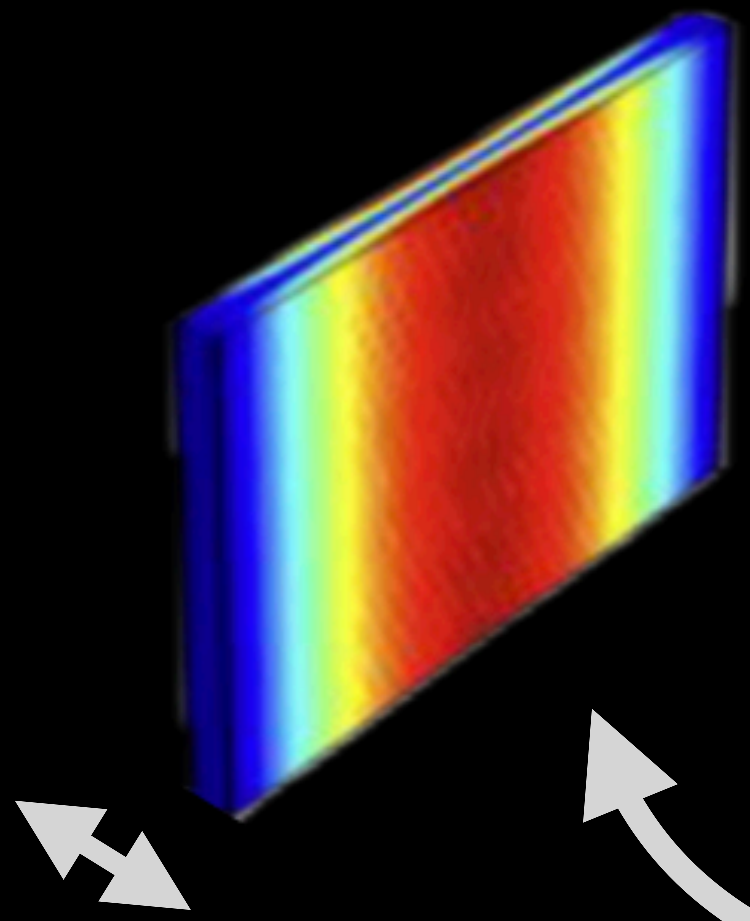


(ADMX EFR Design)

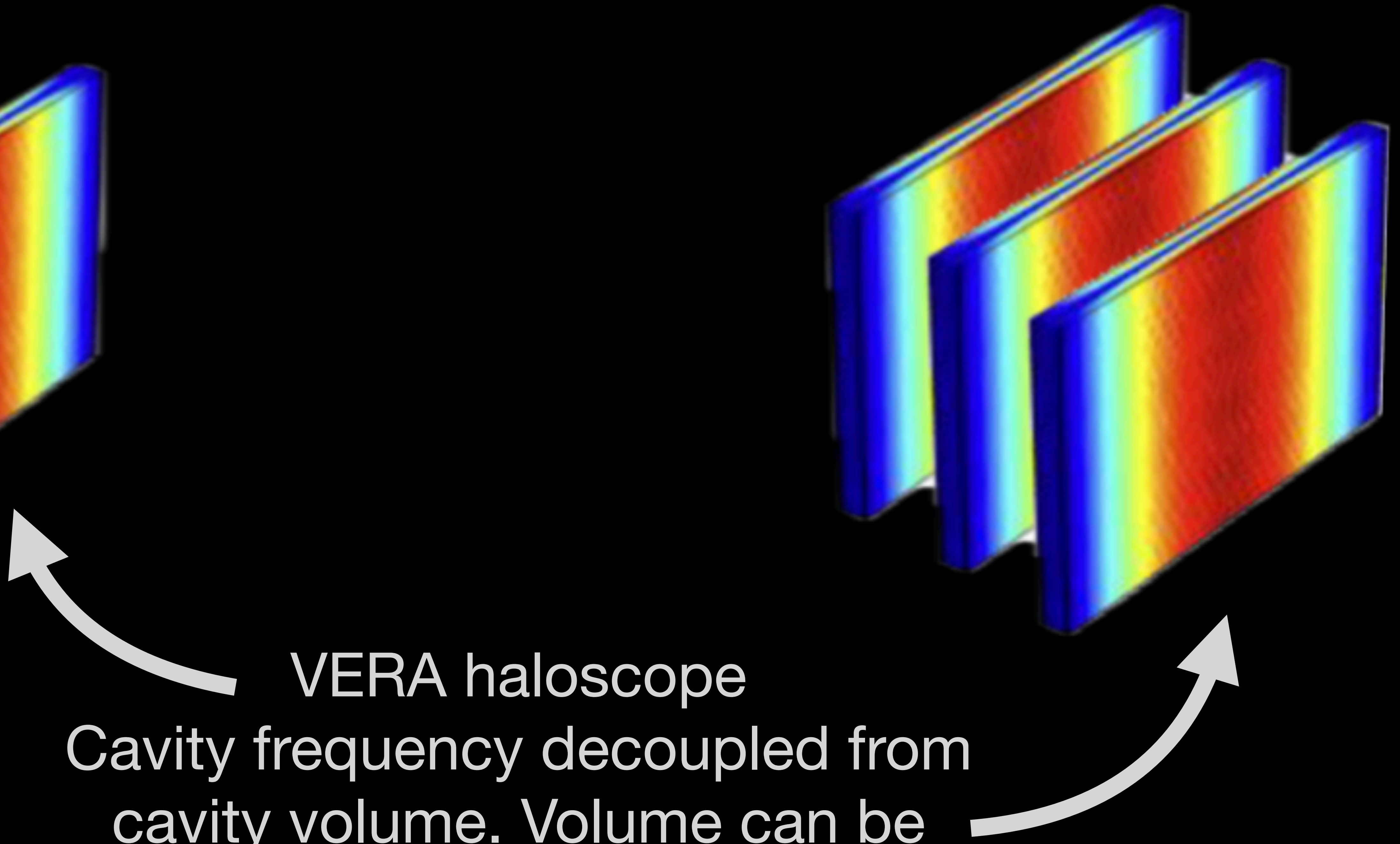
ADMX-VERA



Cavity haloscope
Cavity frequency determines cavity volume.



Width sets frequency of TM010 mode.



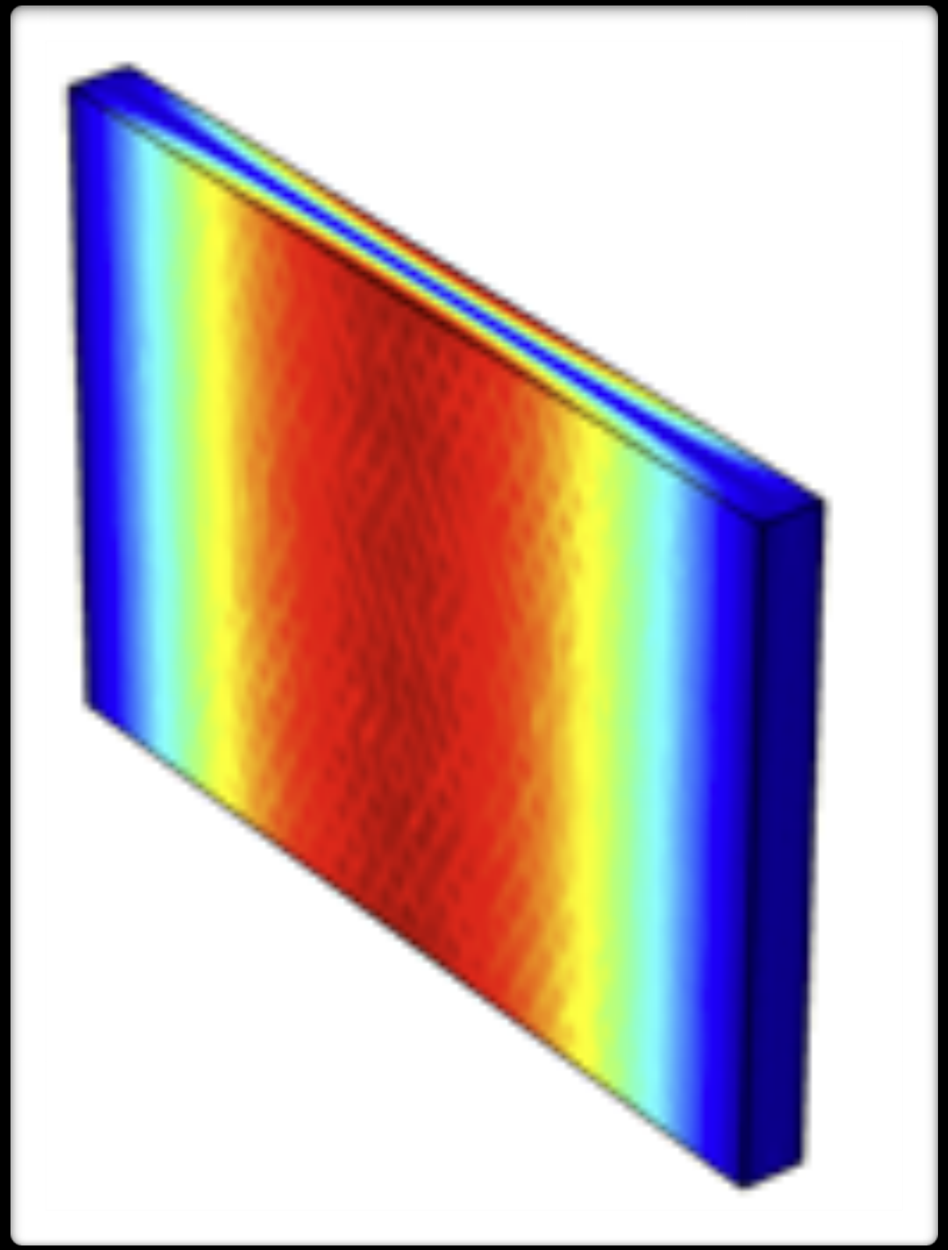
VERA haloscope
Cavity frequency decoupled from cavity volume. Volume can be scaled arbitrarily in other dimensions.

ADMX-VERA

Width sets frequency of fundamental (TM_{010}) compatible with **solenoid B field**

Decouple frequency and volume.

TM010 mode still supported.



Wrap

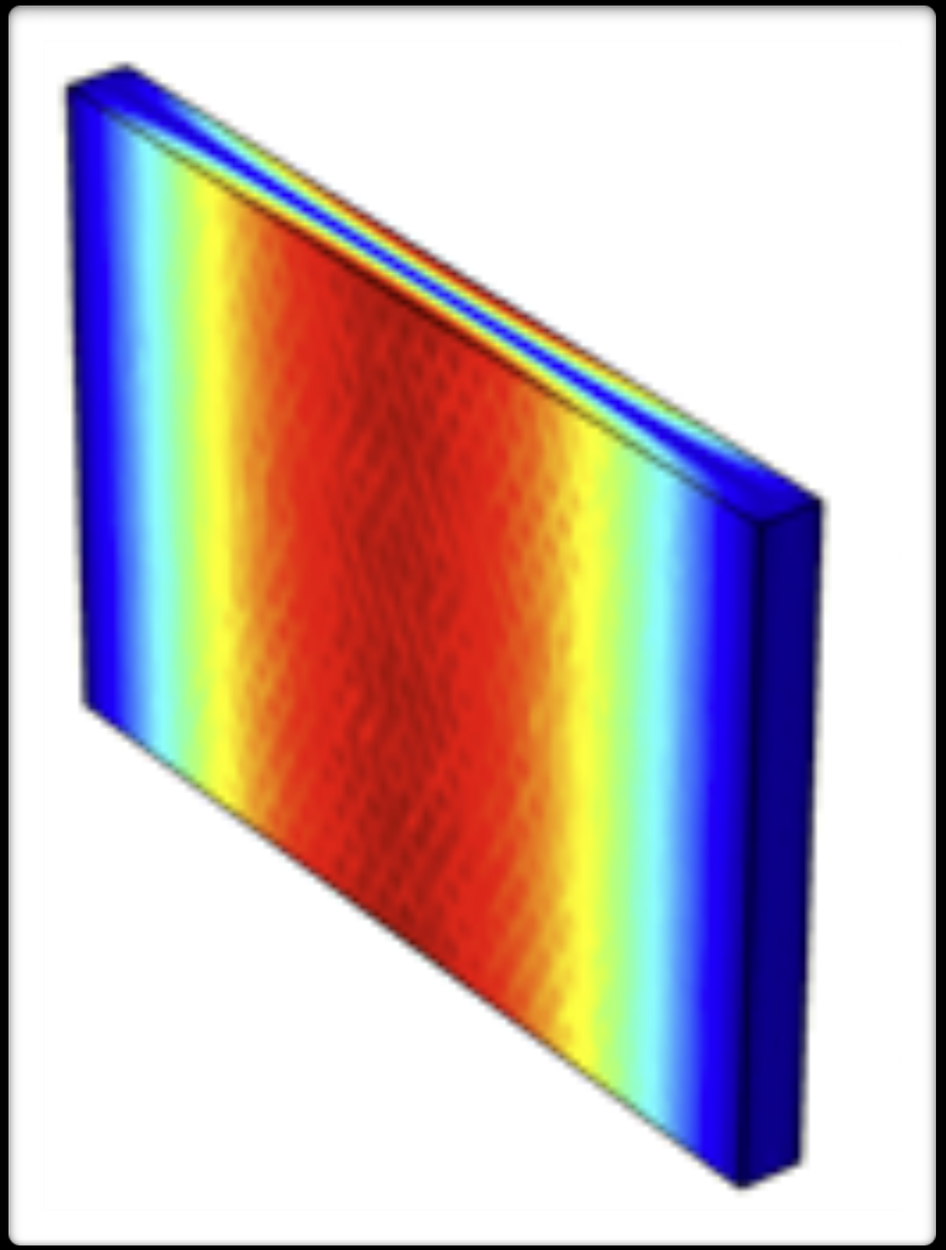
Volume can be scaled arbitrarily in other dimensions

ADMX-VERA

Decouple frequency and volume.

Width sets frequency of fundamental (TM_{010}) compatible with **solenoid B field**

Volume can be scaled arbitrarily in other dimensions

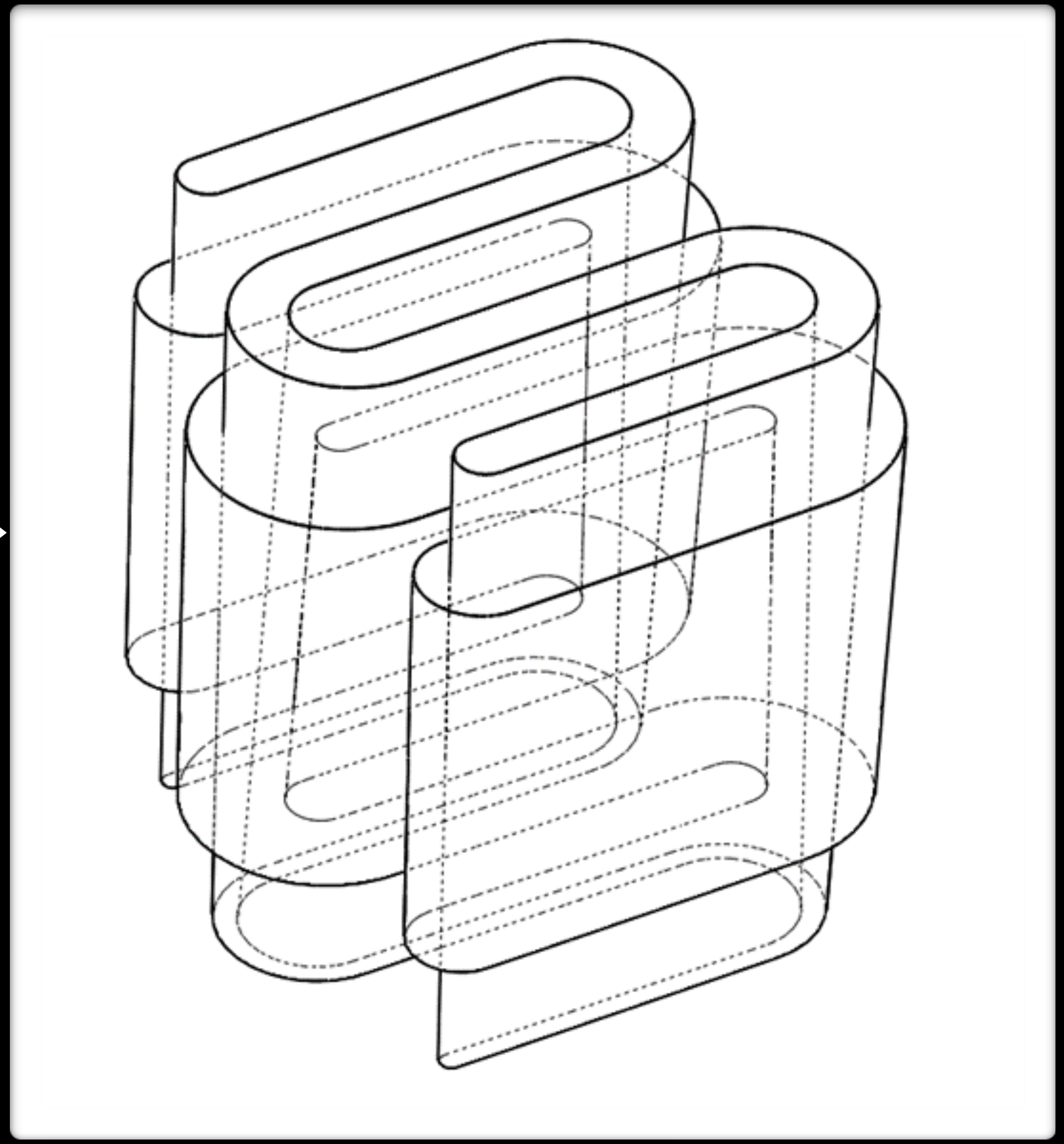


Wrap

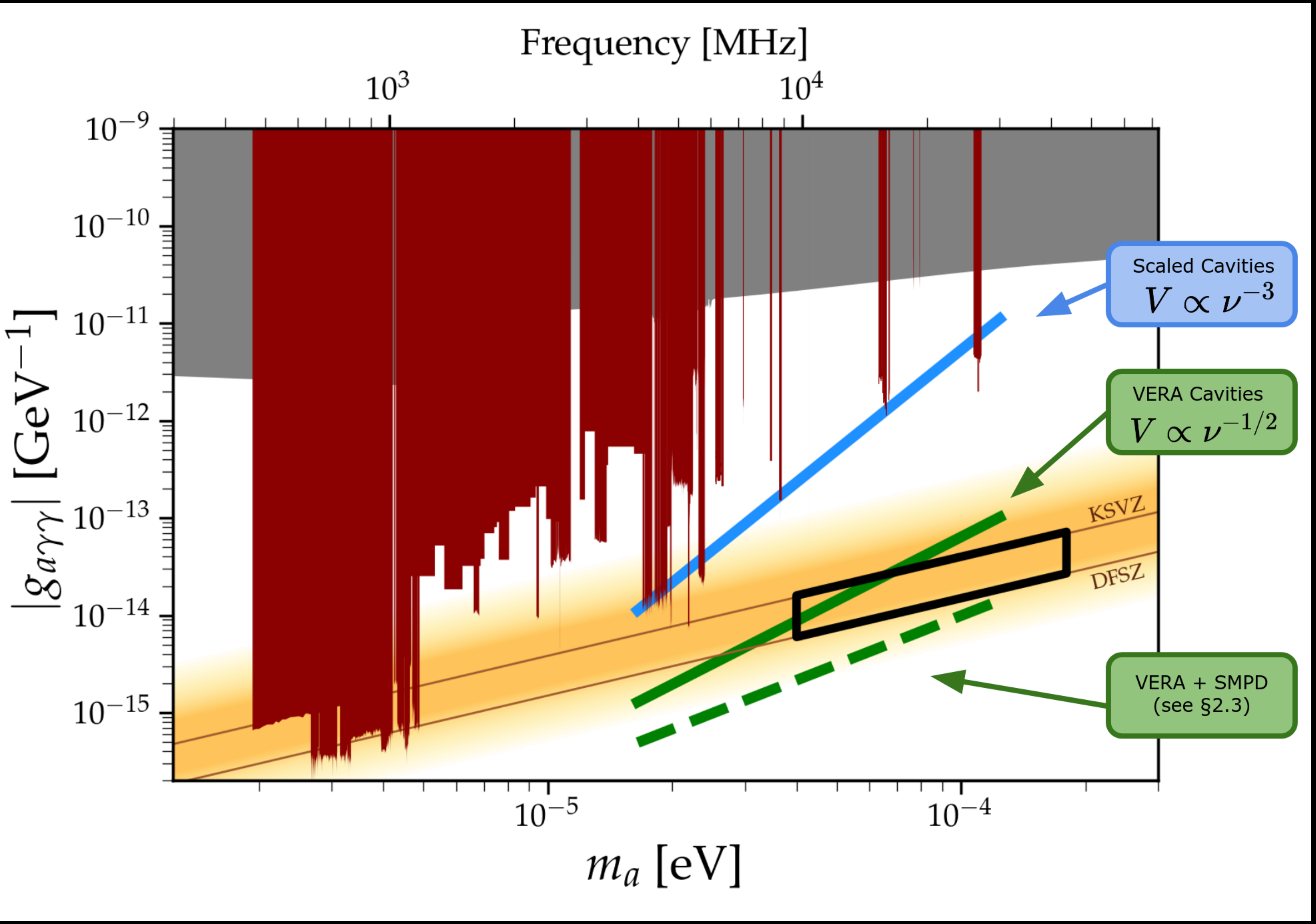
TM010 mode still supported.

Convolute

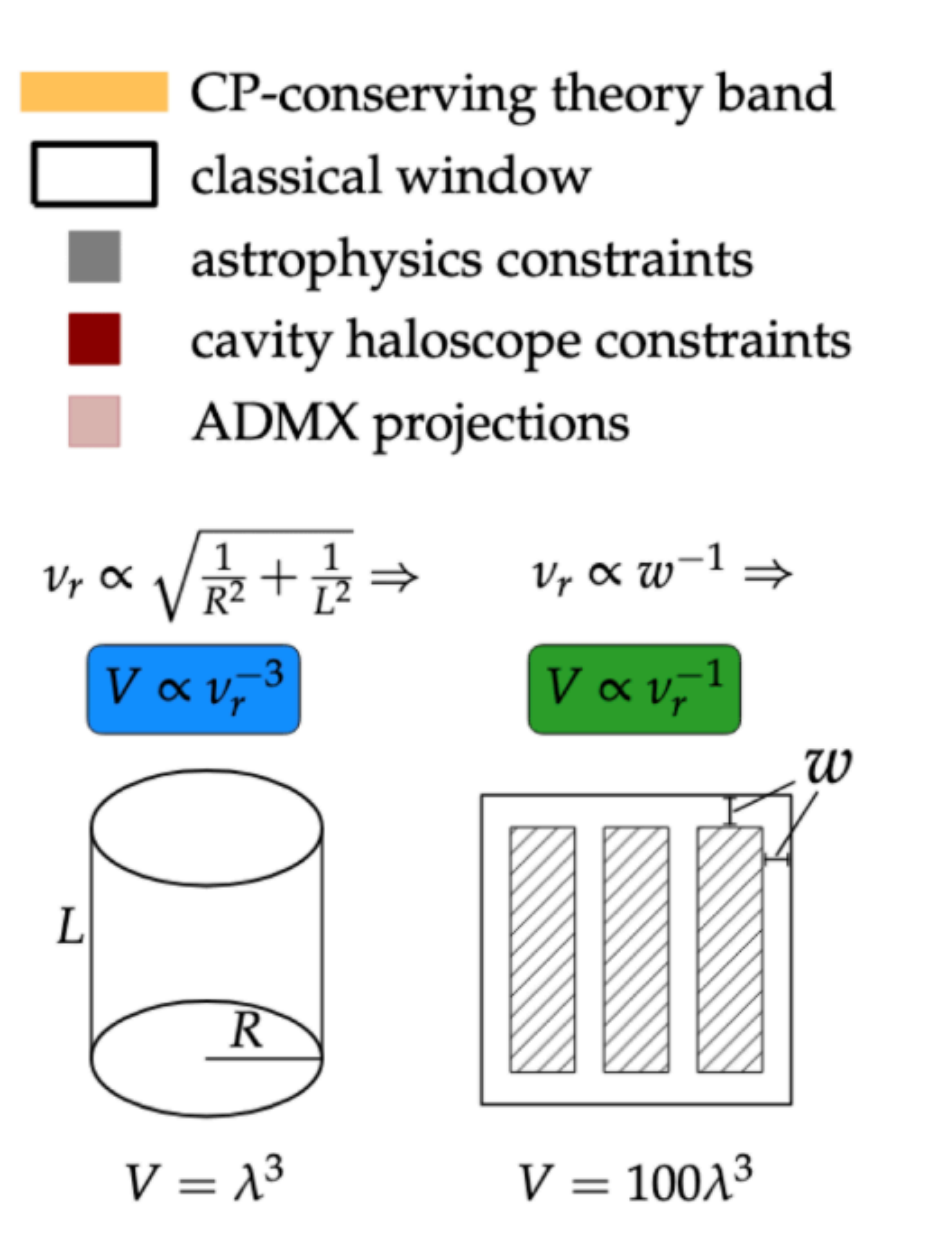
JCAP 02 (2021) 018
JCAP 06 (2020) 010



ADMX-VERA

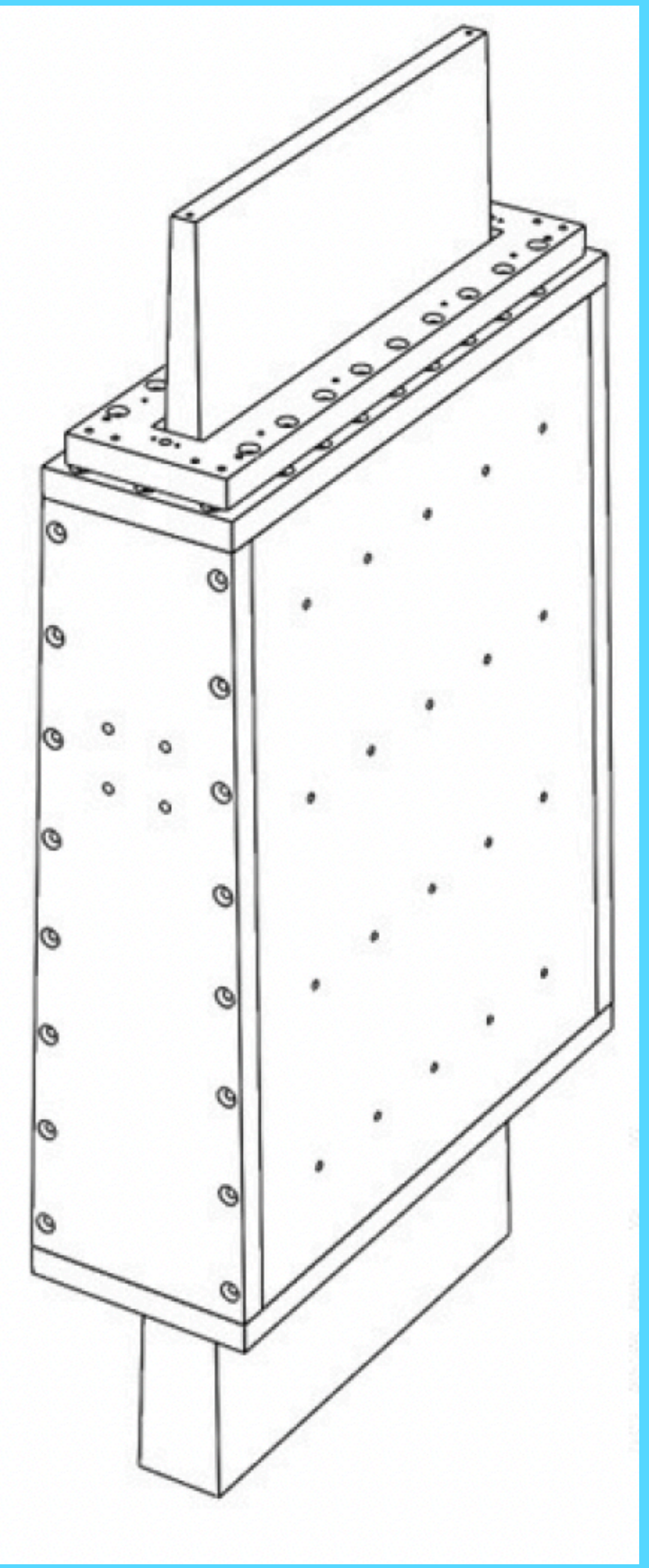


Frequency [MHz]
10^3
10^4
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
10^{-5}
10^{-4}
m_a [eV]
KSVZ
DFSZ
Scaled Cavities
$V \propto \nu^{-3}$
VERA Cavities
$V \propto \nu^{-1/2}$
VERA + SMPD
(see §2.3)



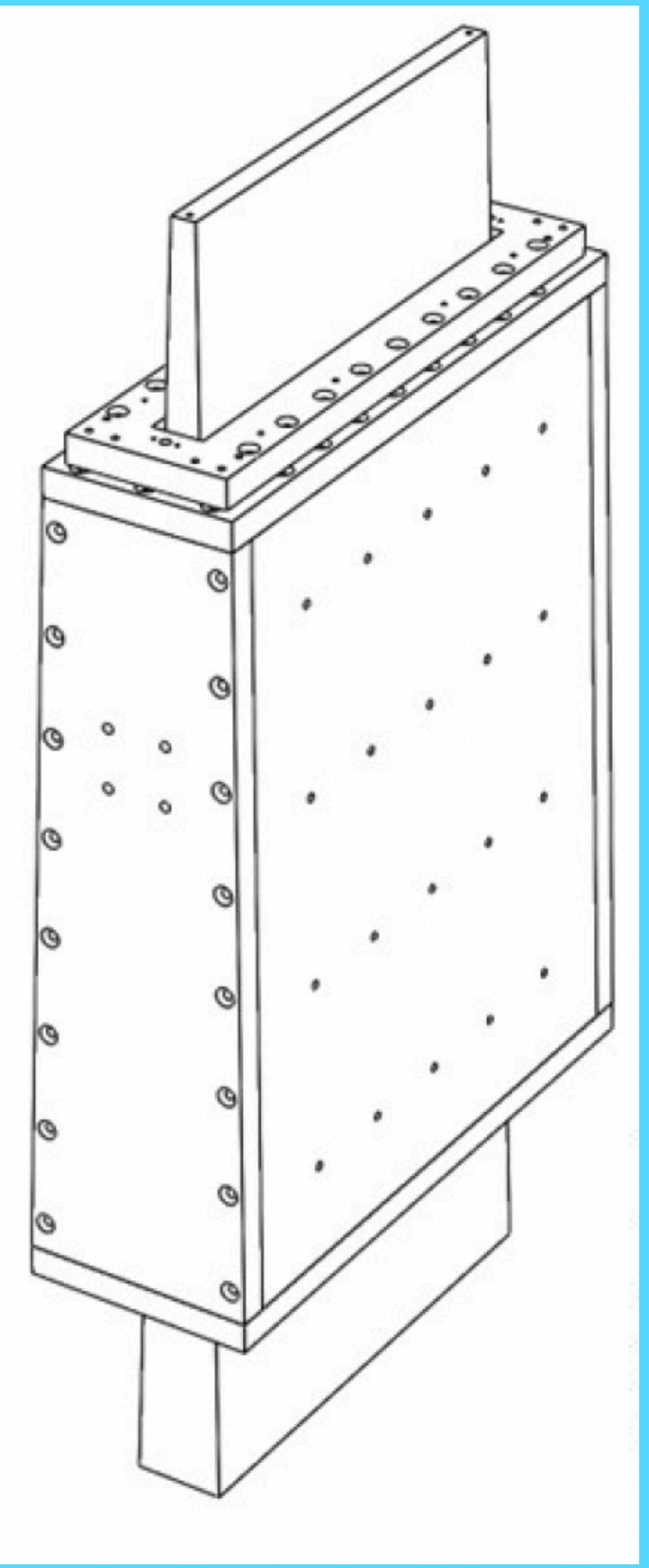
CP-conserving theory band
classical window
astrophysics constraints
cavity haloscope constraints
ADMX projections
$\nu_r \propto \sqrt{\frac{1}{R^2} + \frac{1}{L^2}} \Rightarrow$
$\nu_r \propto w^{-1} \Rightarrow$
$V \propto \nu_r^{-3}$
$V \propto \nu_r^{-1}$
w
L
R
$V = \lambda^3$
$V = 100\lambda^3$

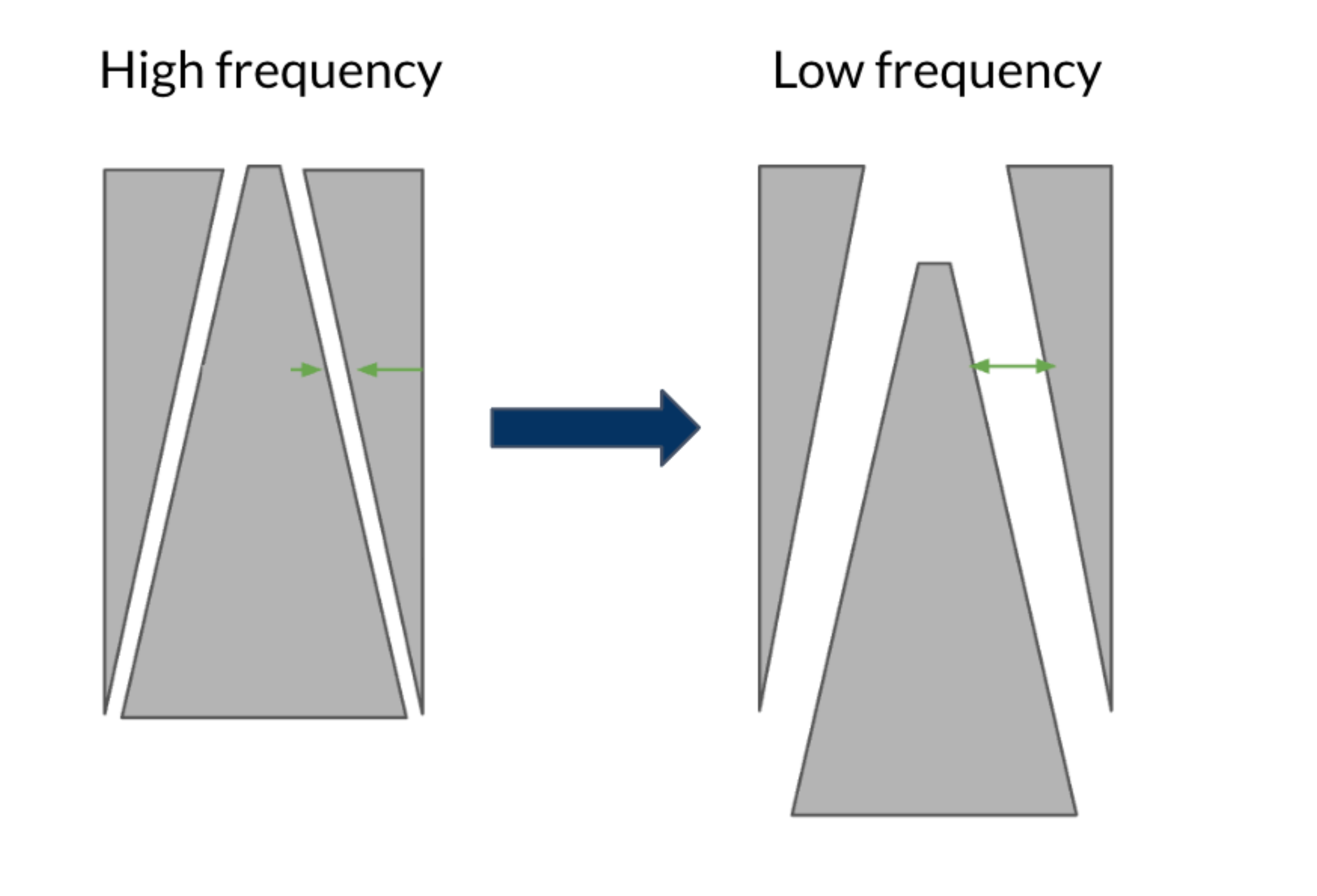
ADMX-VERA



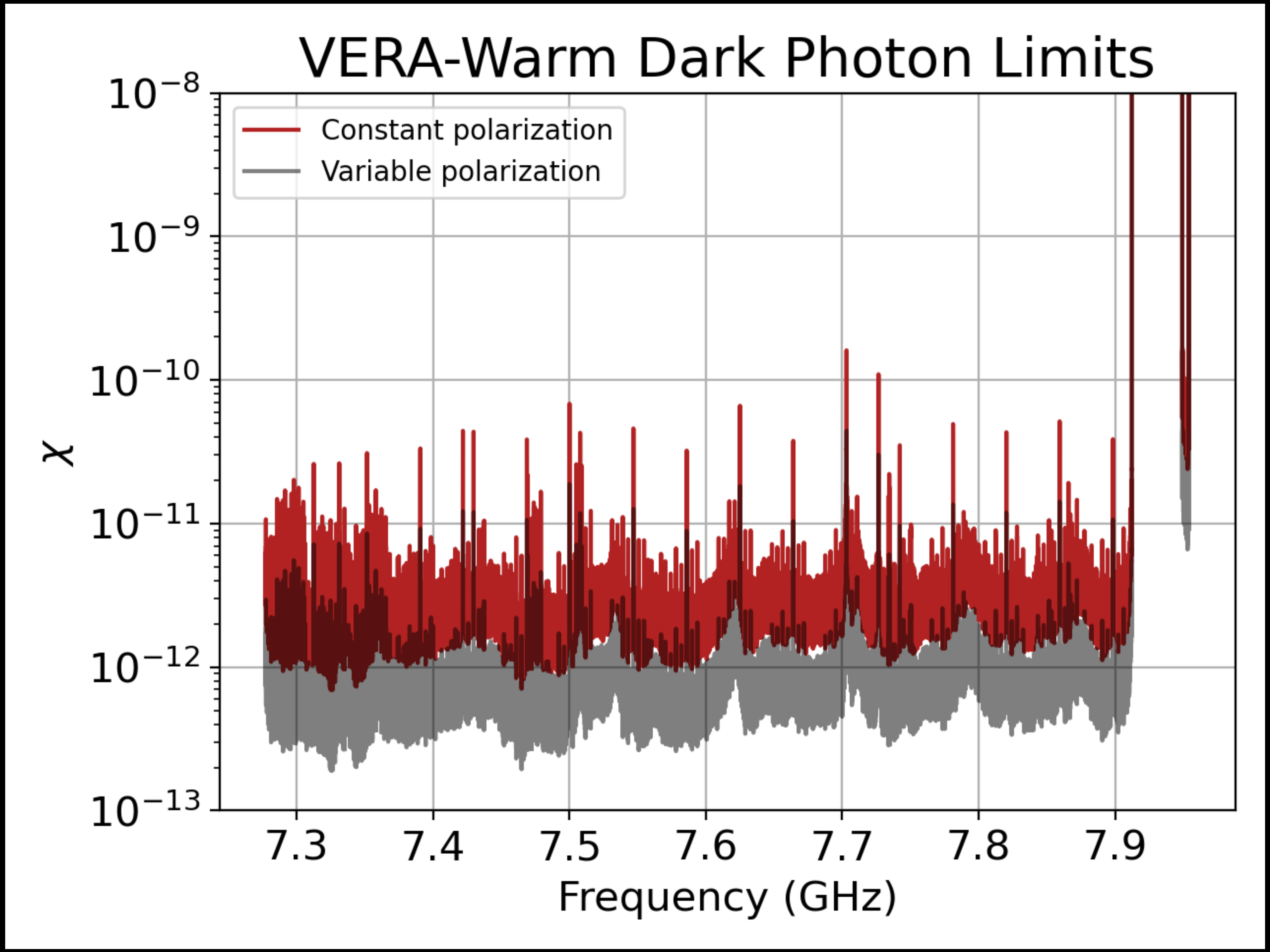
Volume (V)	2.6L (41 λ^3) at 7.5 GHz
Frequency Range	7 to 8 GHz
Quality Factor (Q)	4000
Form Factor (C_{010})	0.57

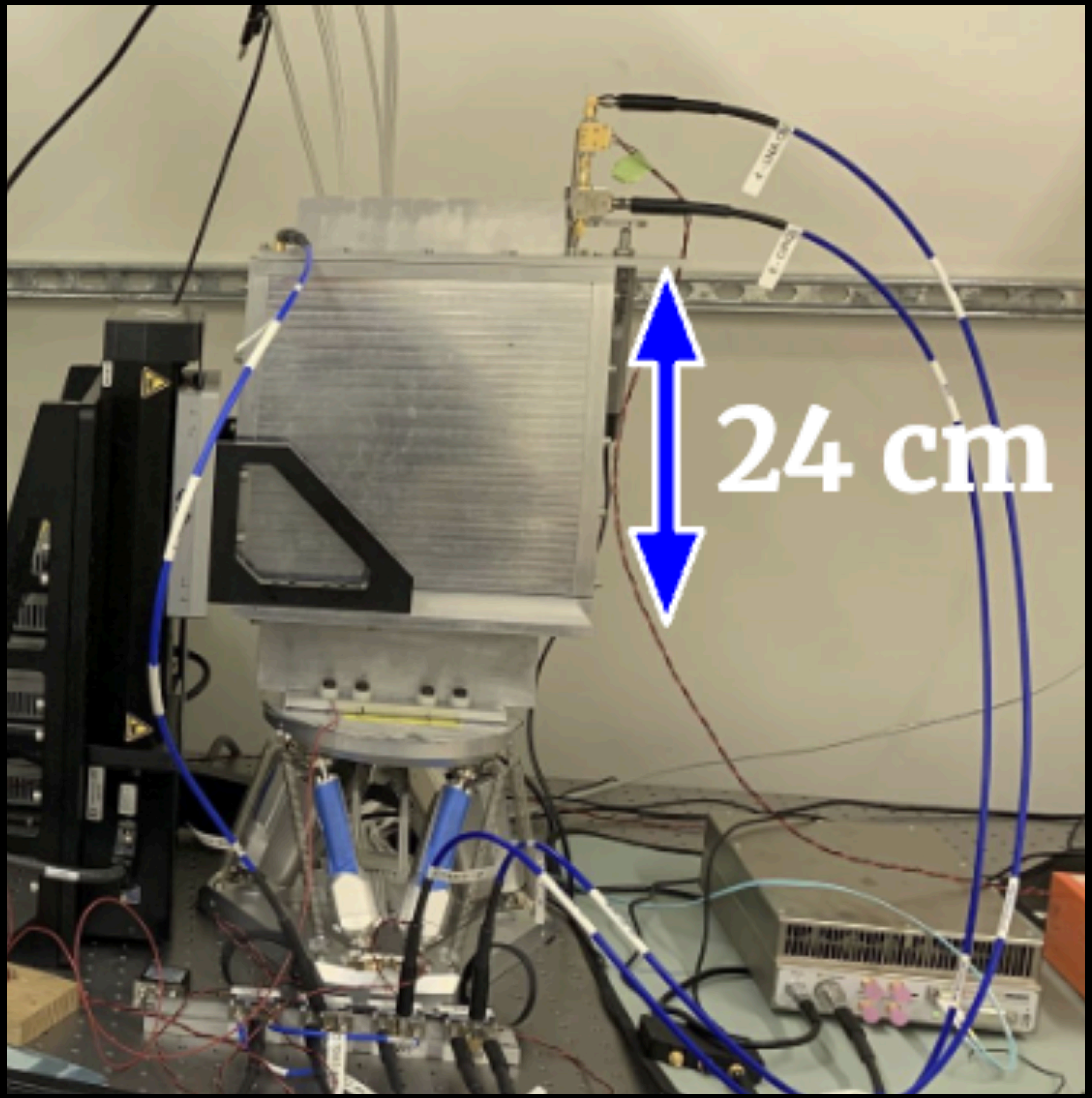
ADMX-VERA





ADMX-VERA



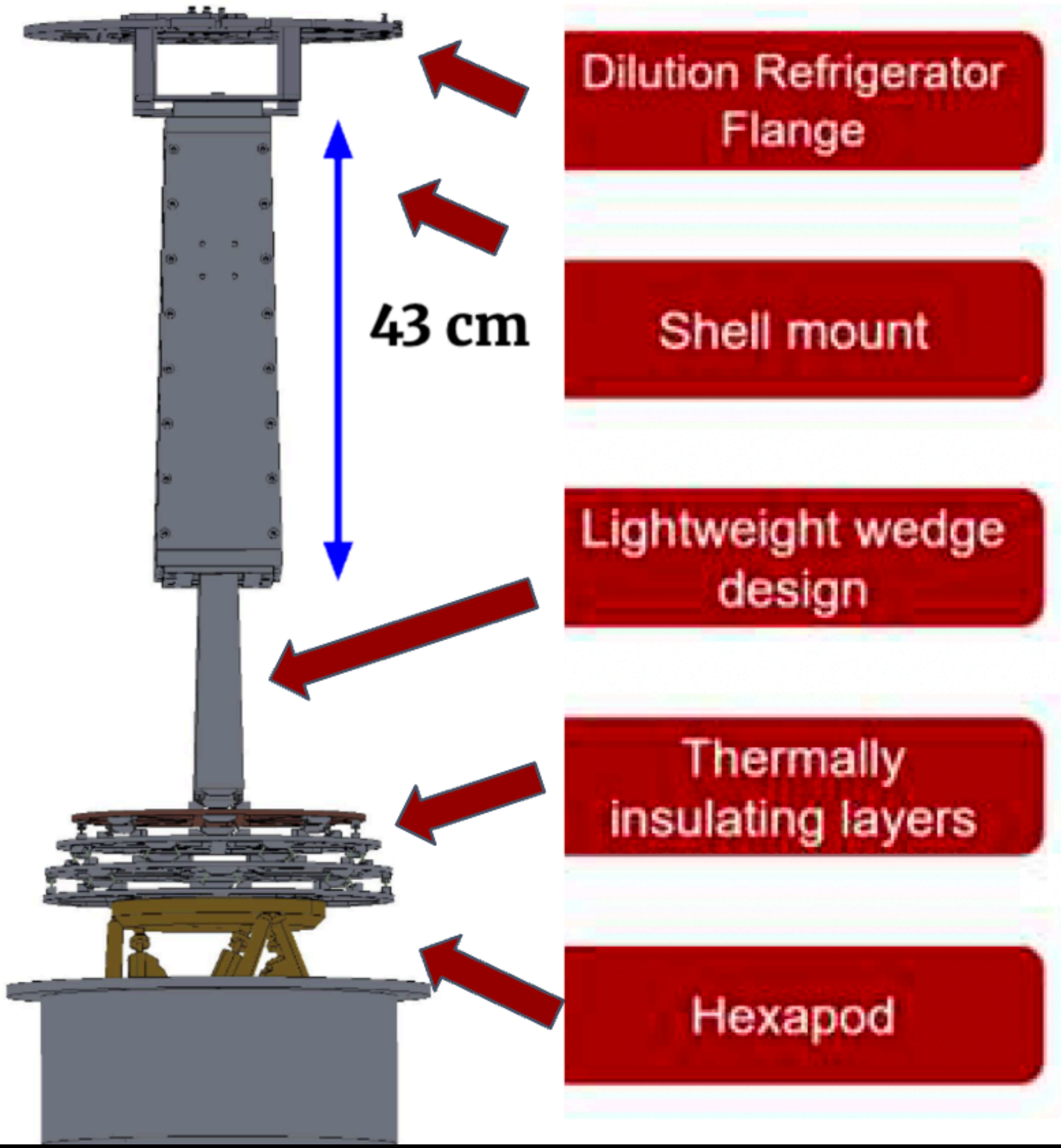


Courtesy of Taj Dyson

ADMX-VERA

Volume (V)	6L (51 λ^3) at 6 GHz
Frequency Range	5 to 7 GHz
Quality Factor (Q)	20,000
Form Factor (C_{010})	>0.5

Simulated!

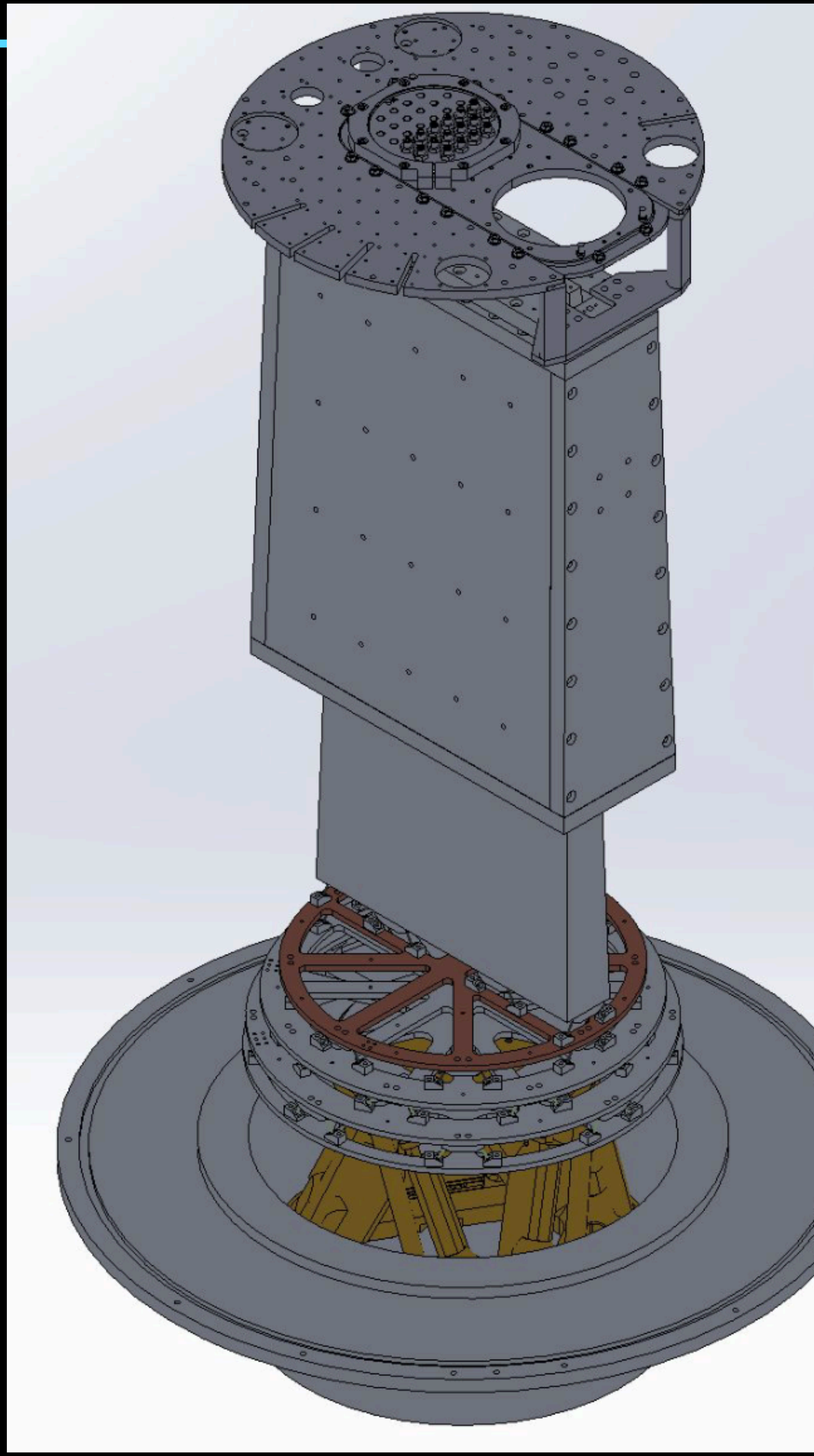


ADMX-VERA

- Leverages “wedding cake” cryostat design from CMB experiments

- Hexapod motion transferred through wedding cake layers for precision alignment

- Designed to mount to Oxford fridge at SLAC milliKelvin Facility (SMF)



ADMX-VERA

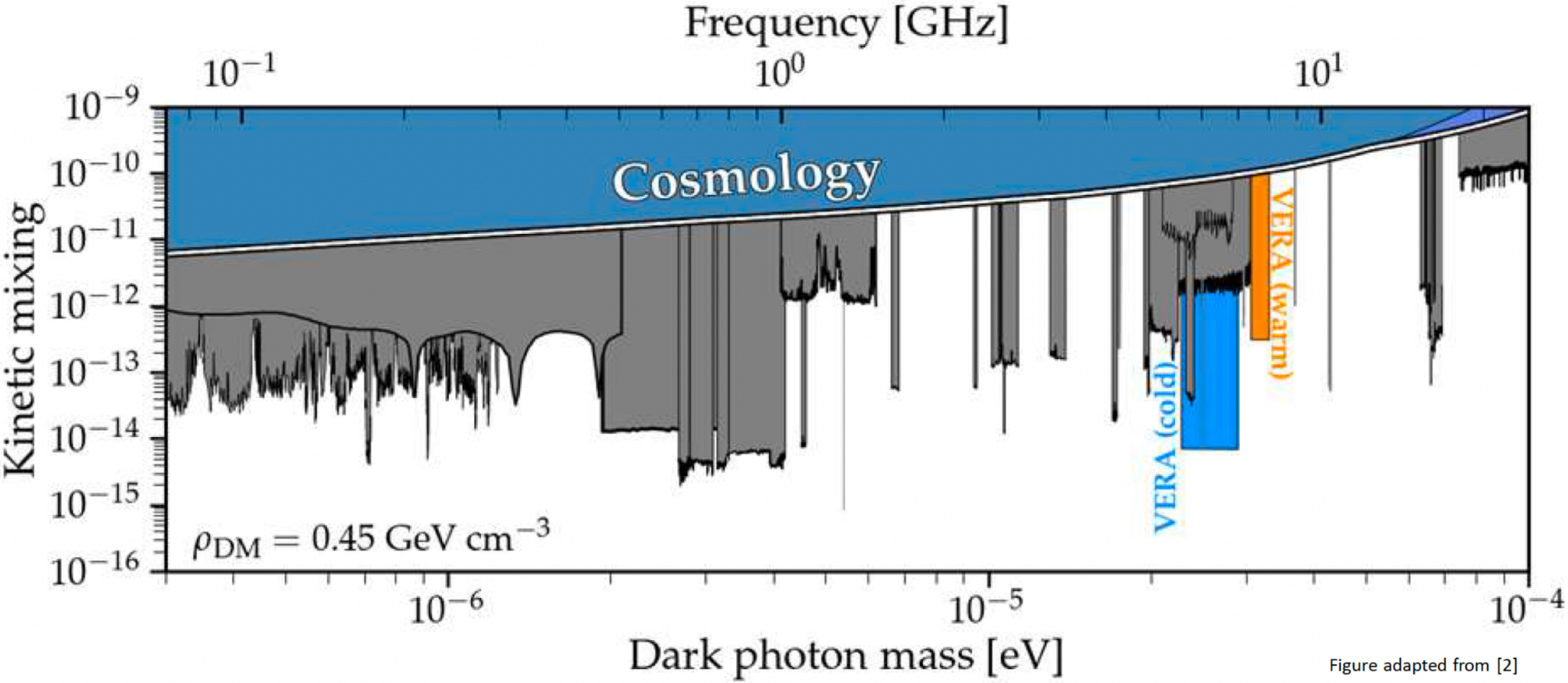
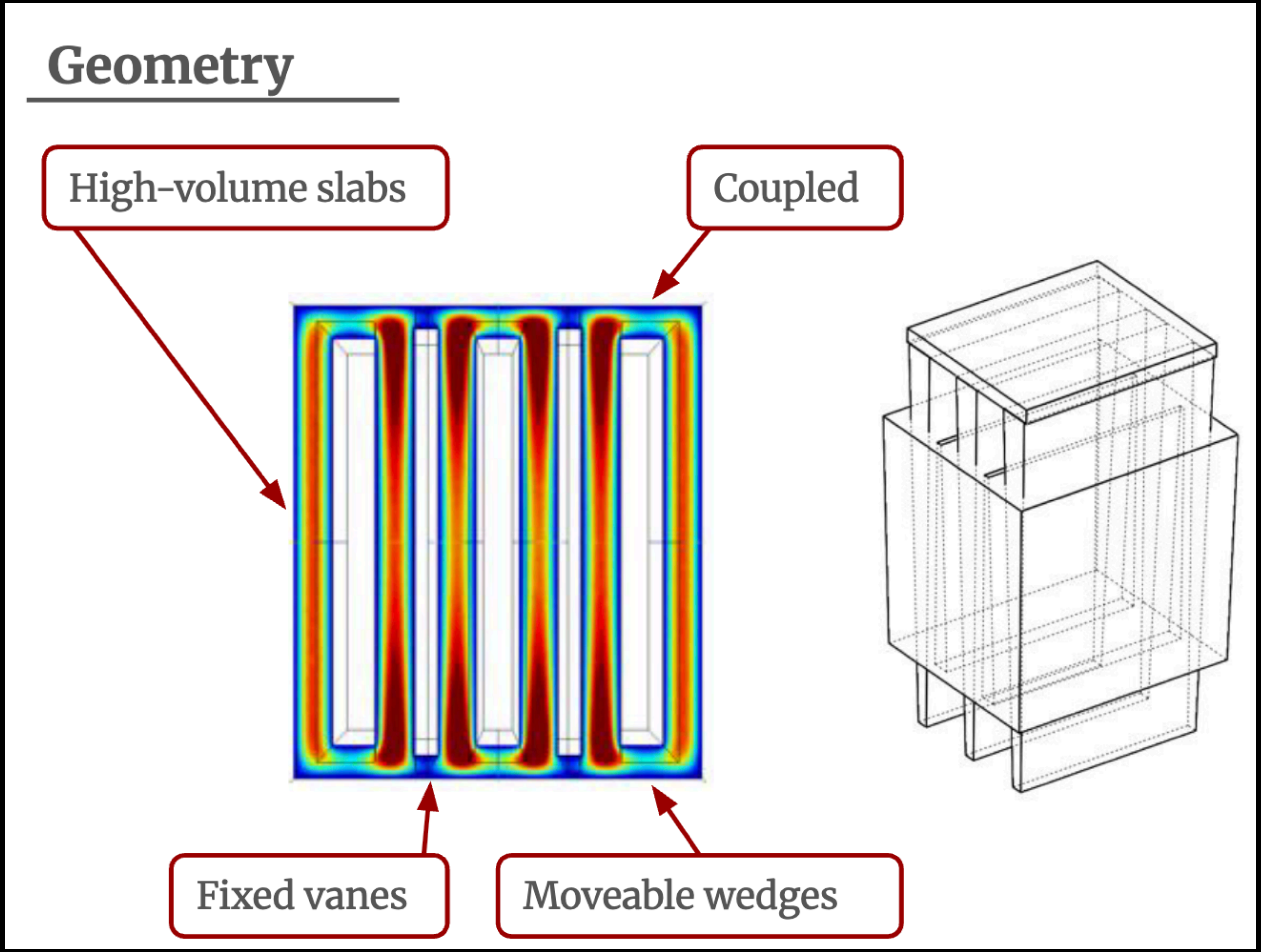
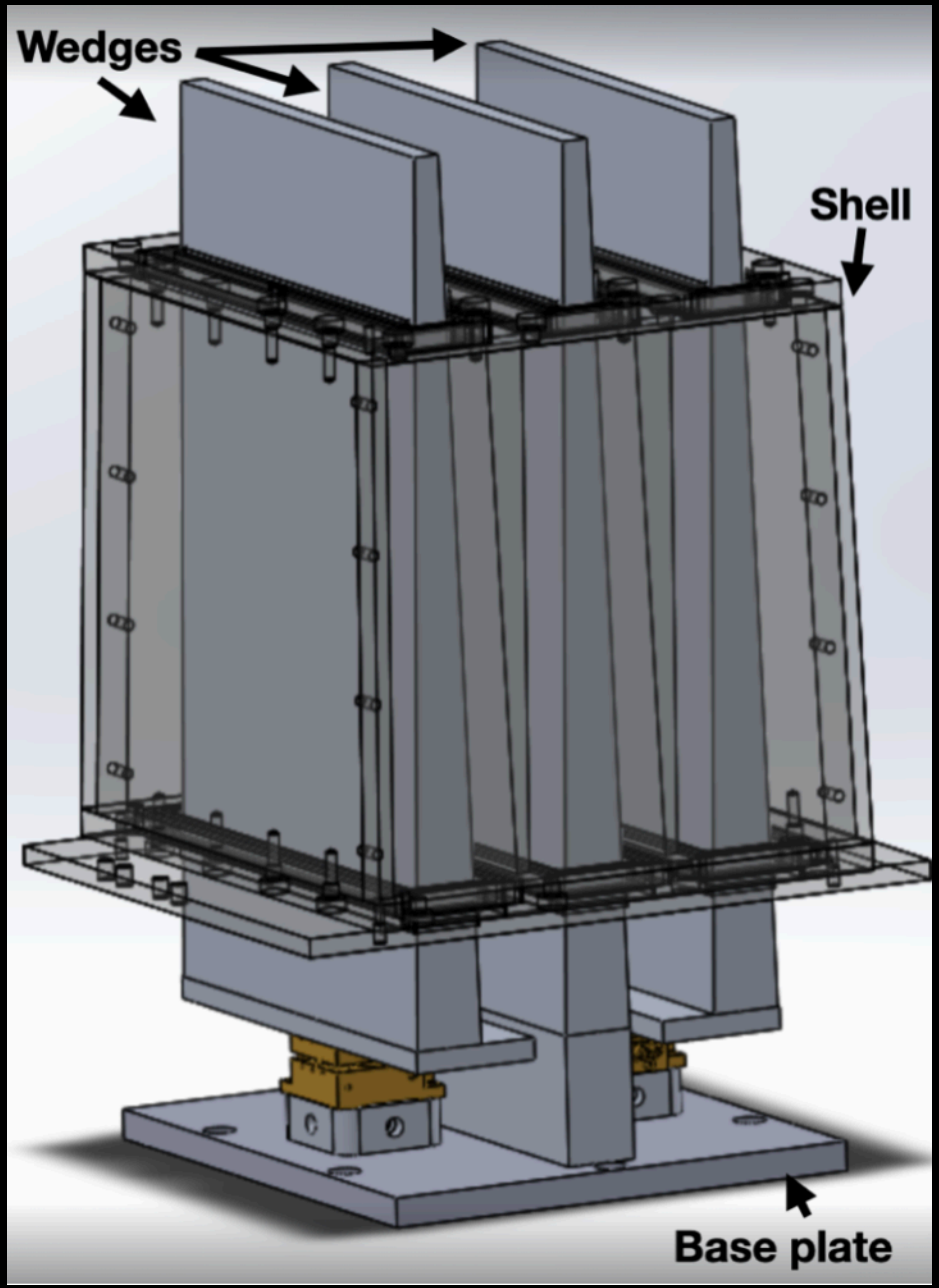


Figure adapted from [2]

ADMX-VERA

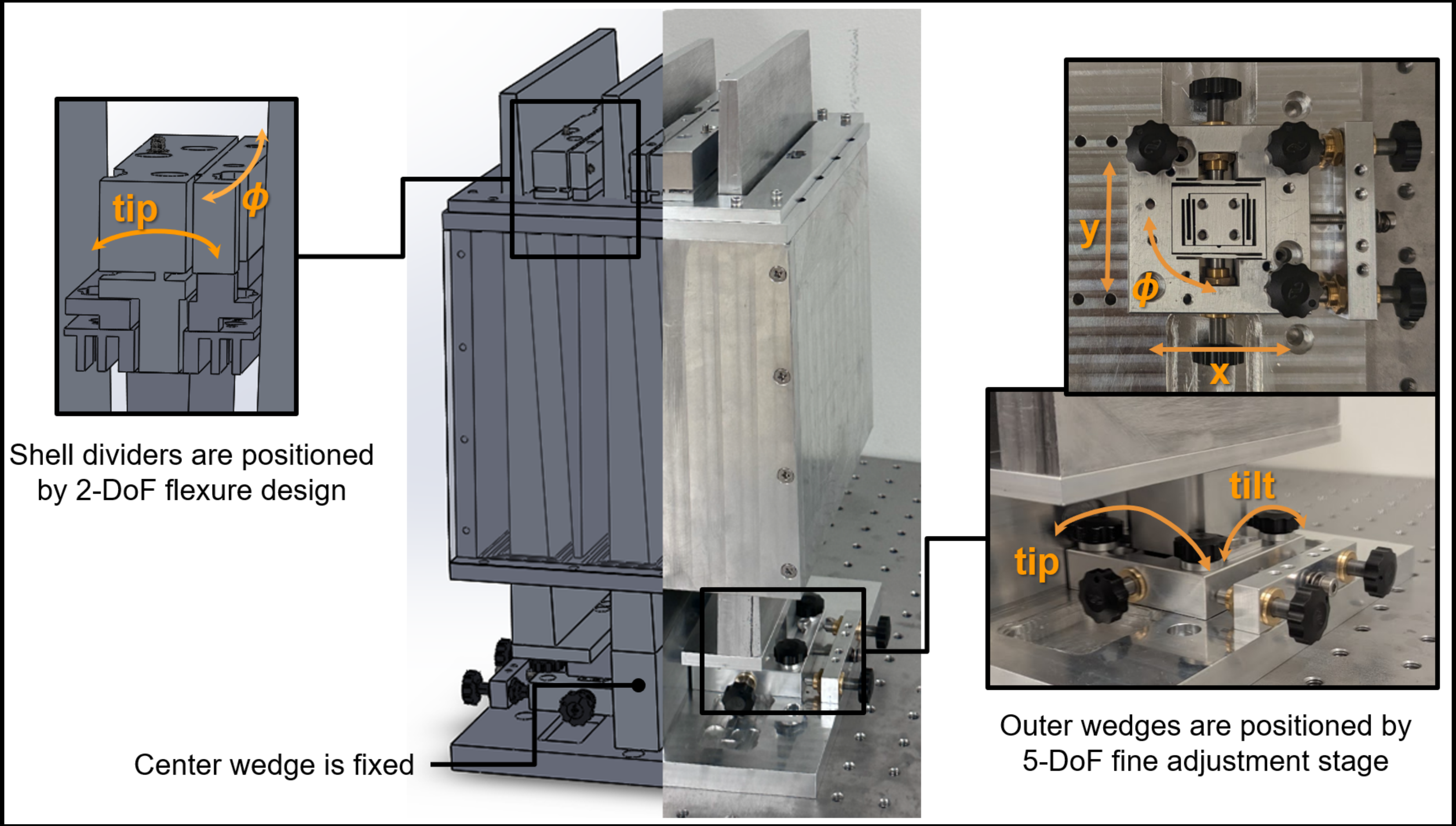


Geometry
High-volume slabs
Coupled
Fixed vanes
Moveable wedges



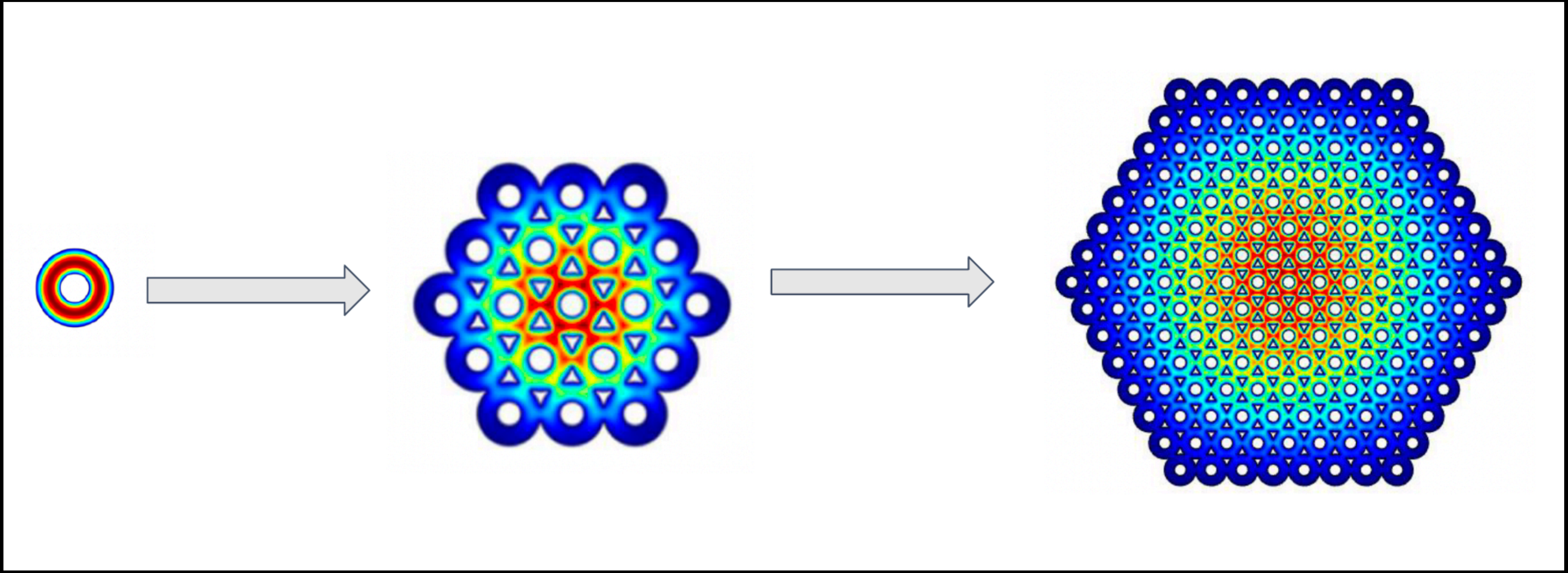
Wedges
Shell
Base plate

ADMX-VERA



Courtesy of Sephora Ruppert

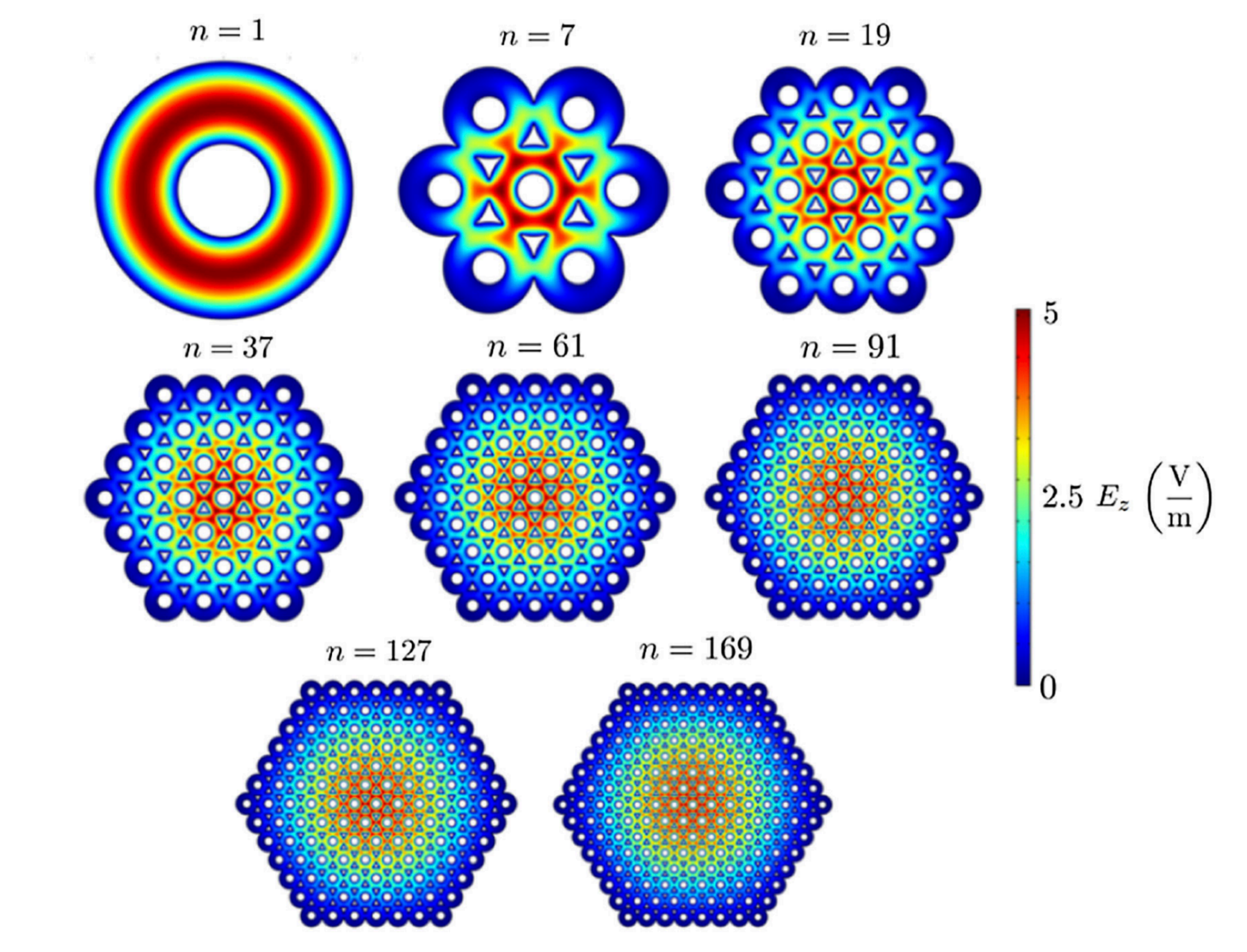
ADMX-VERA



Courtesy of Matt Withers

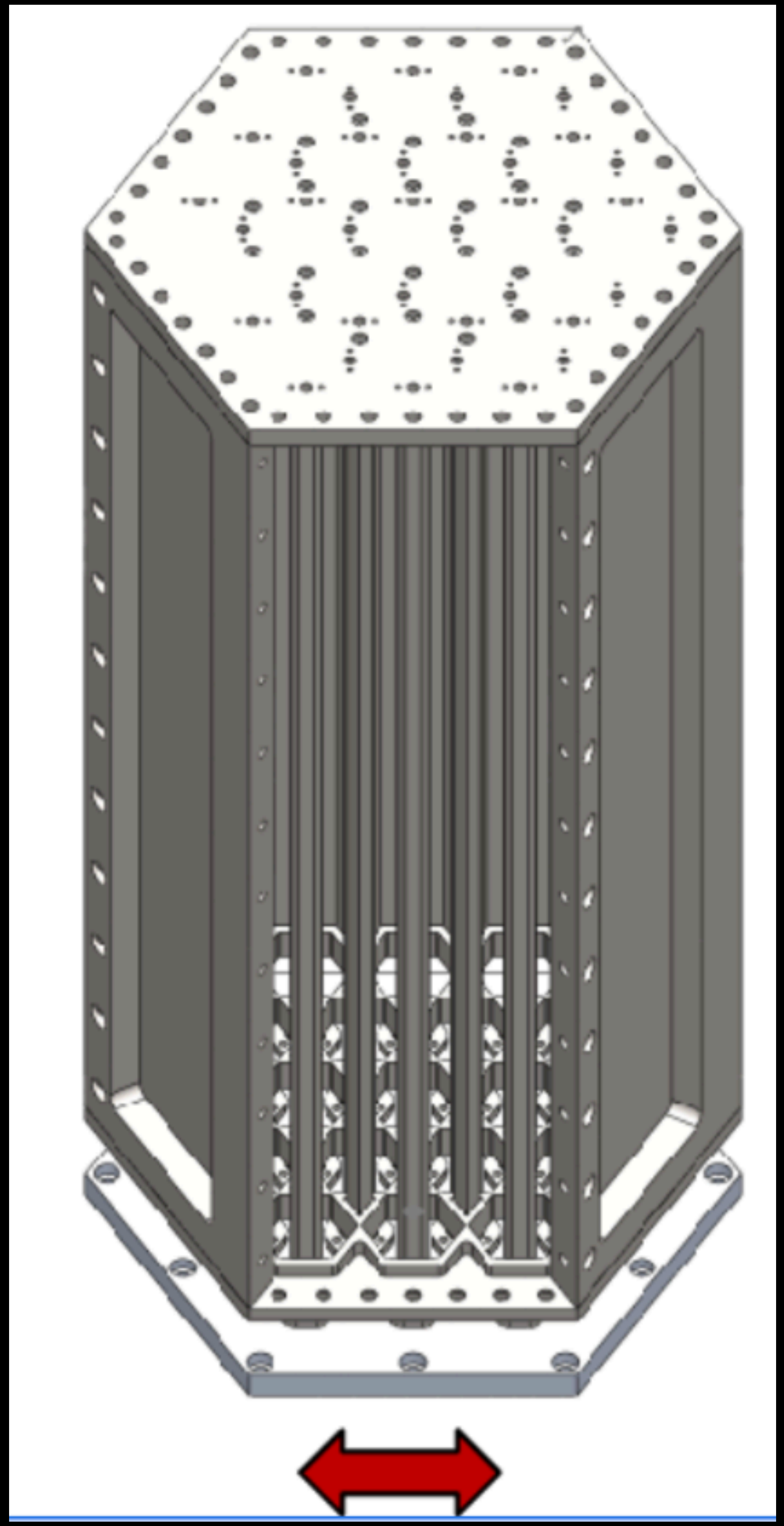
ADMX-VERA

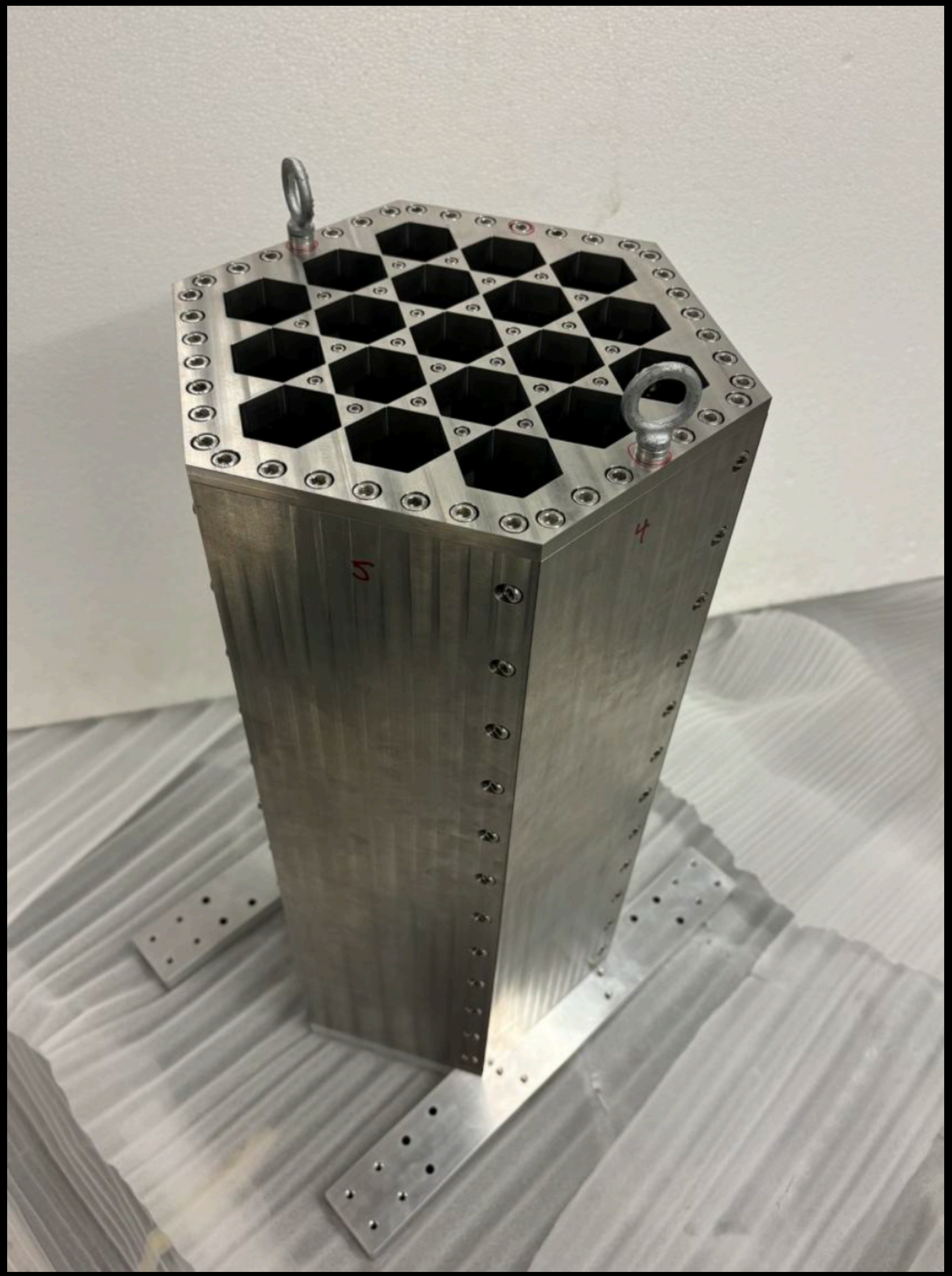
- Closely packed overlapping cavities.
- Resonant frequency determined by cells oscillating in phase.
- Global eigenmode that has high (40%) form factor in a 169-element resonator.
- Tunable by moving center rods laterally in unison.

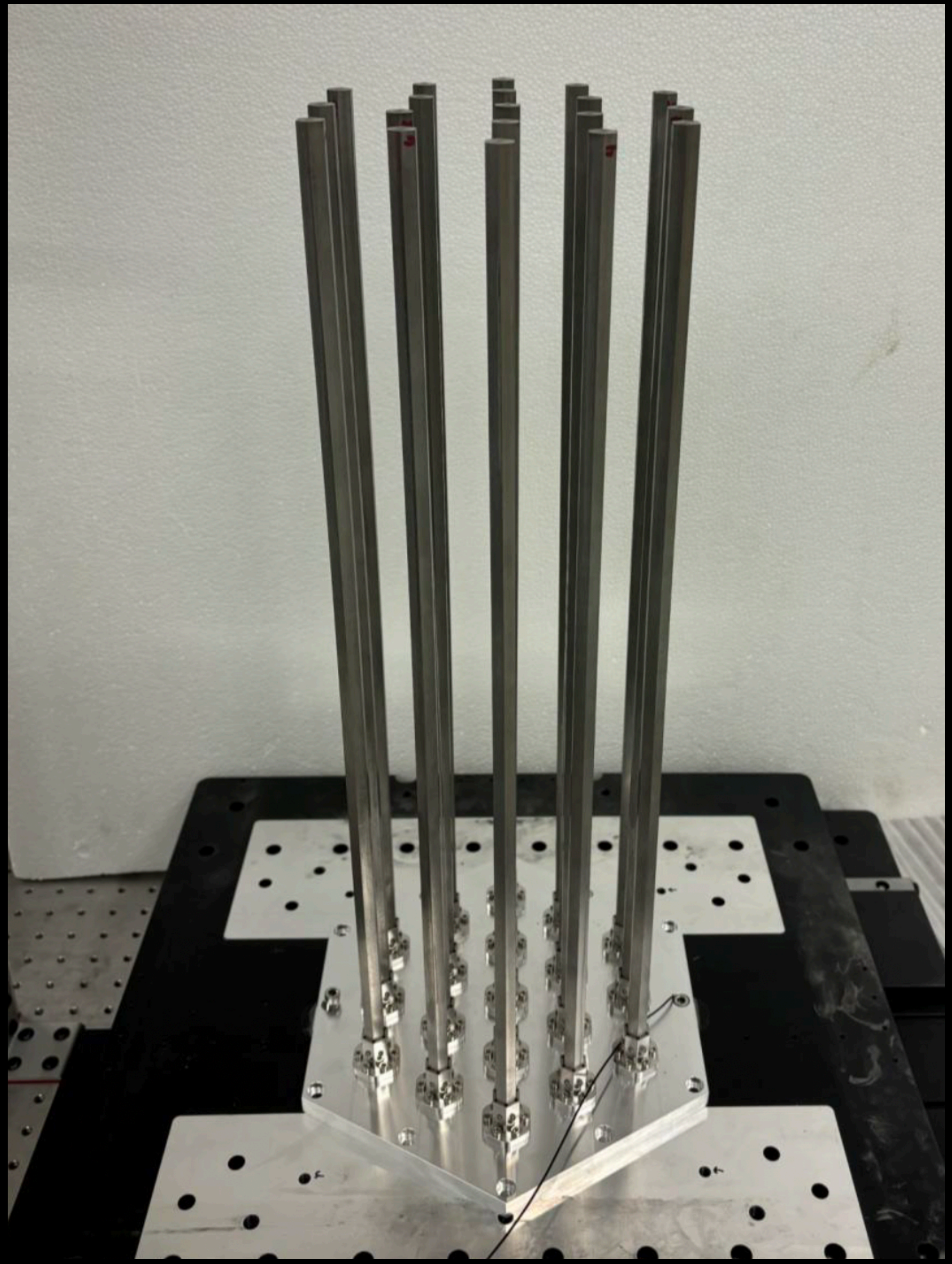


Withers, Matthew O., and Chao-Lin Kuo. "Beehive haloscope for high-mass axion dark matter." Physical Review D 111.7 (2025): 072011.

ADMX-VERA





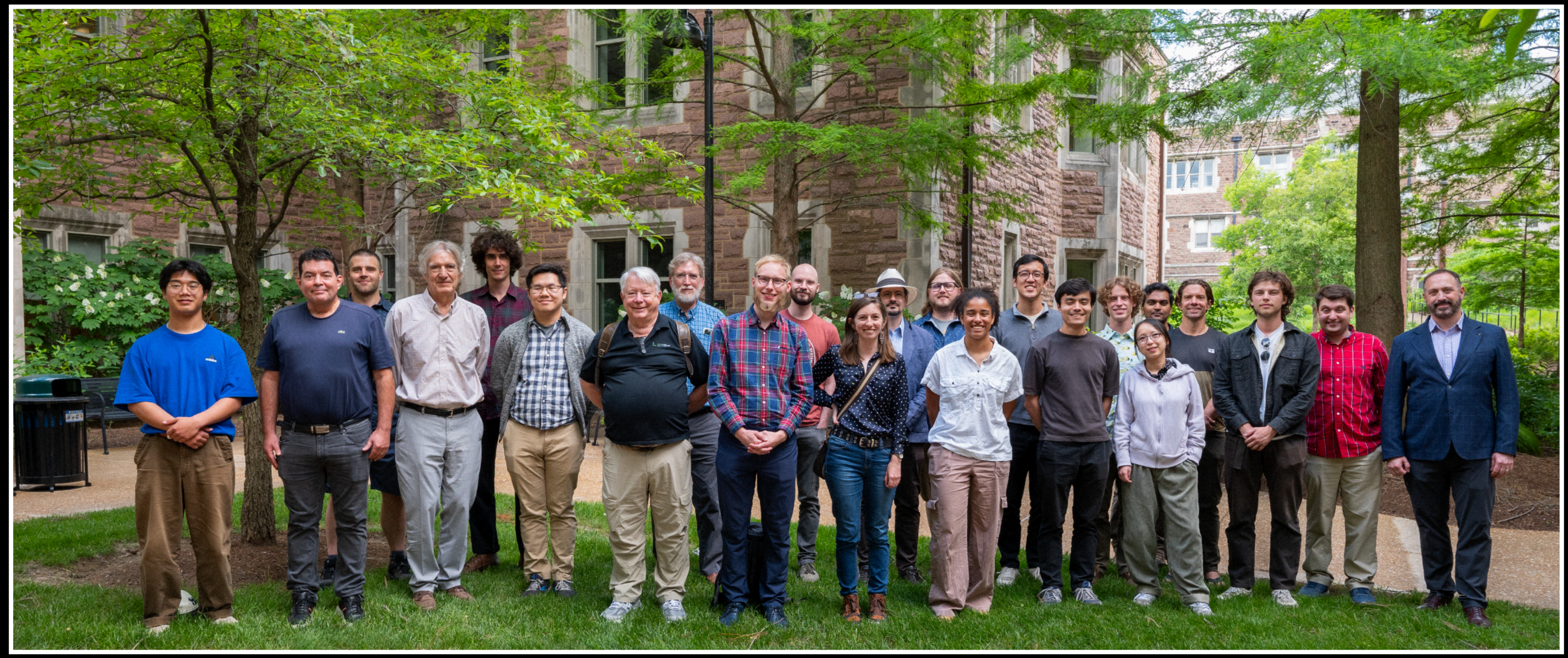


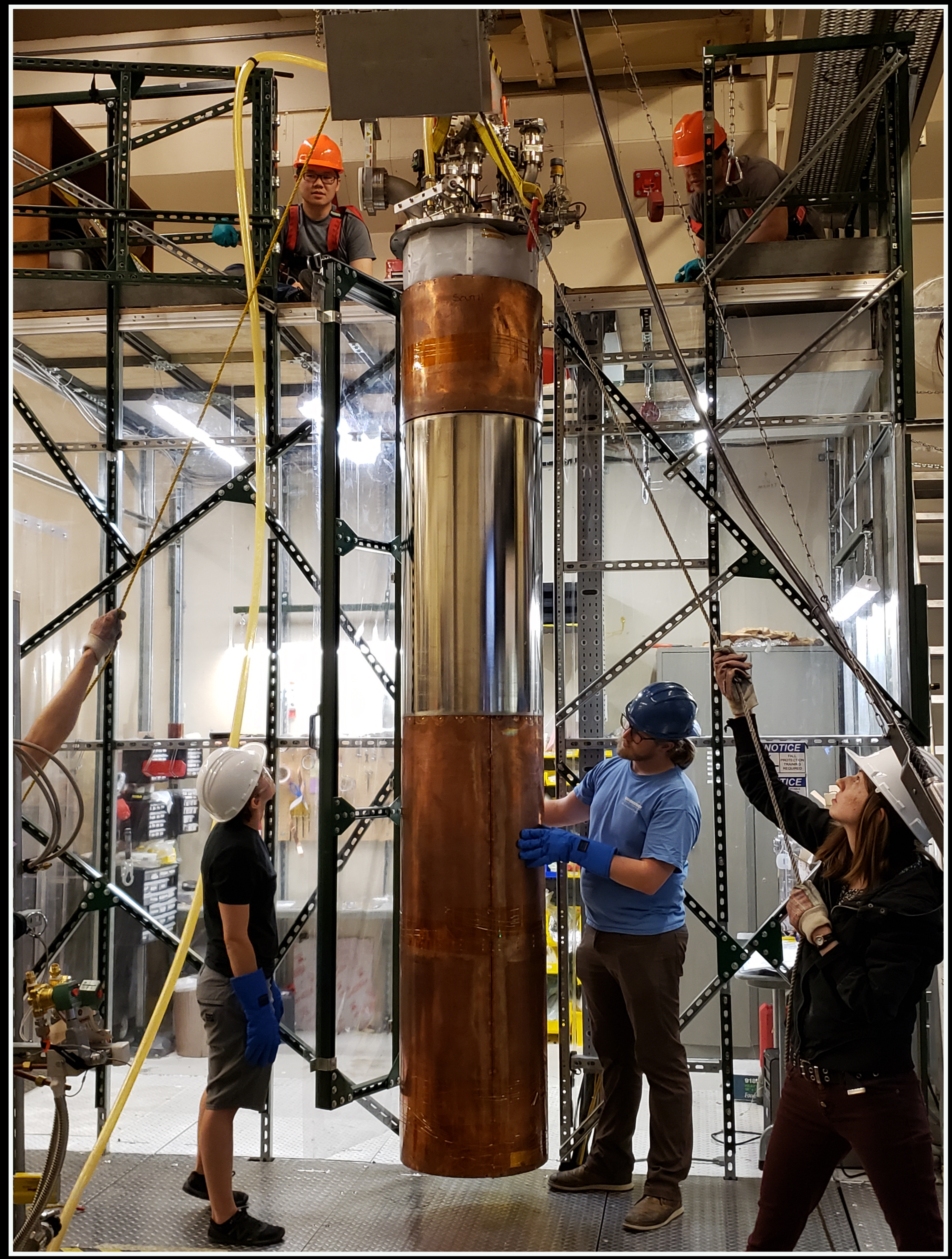
ADMX Collaboration

Lawrence Livermore National Laboratory
Washington University in St. Louis 1853
The University of Western Australia
Pacific Northwest National Laboratory
University of Washington 1861
Illinois Institute of Technology
SLAC National Accelerator Laboratory
The University of California Berkeley 1868
The University Of Sheffield.
Swinburne University of Technology
UF University of Florida
Los Alamos National Laboratory
Fermilab
Harvard

Conclusions

- ADMX continues to make progress at higher frequencies
- Pursuing multi-cavity solutions in the near-term
- Alternative ideas in the long-term
- Synchronously driving the frontier of quantum sensing





Acknowledgements

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