Status and Plans of ADMX

PPC 2024, Hyderabad

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SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

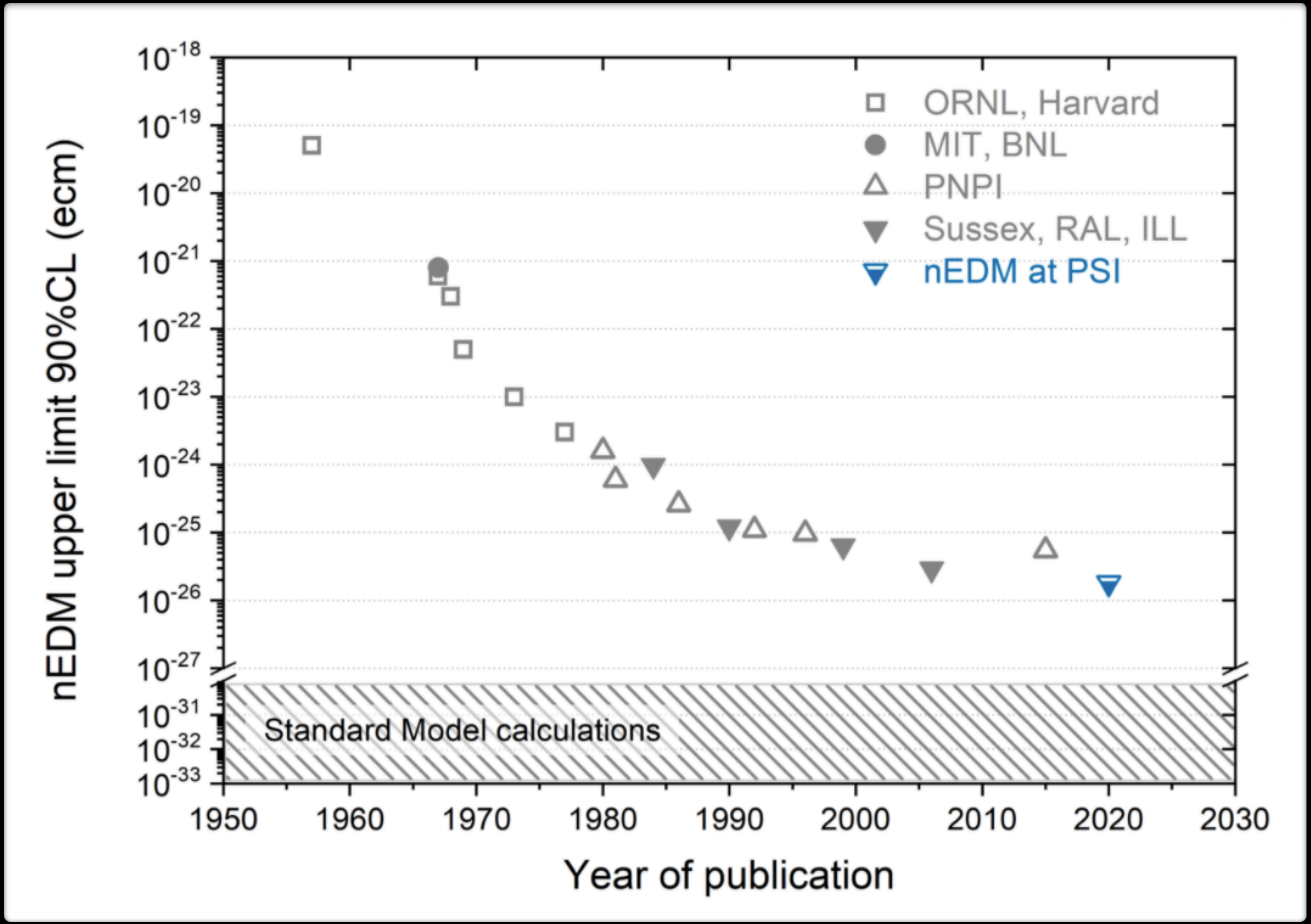
Why dark matter waves?

Story begins with physicists trying to solve other problems…

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.

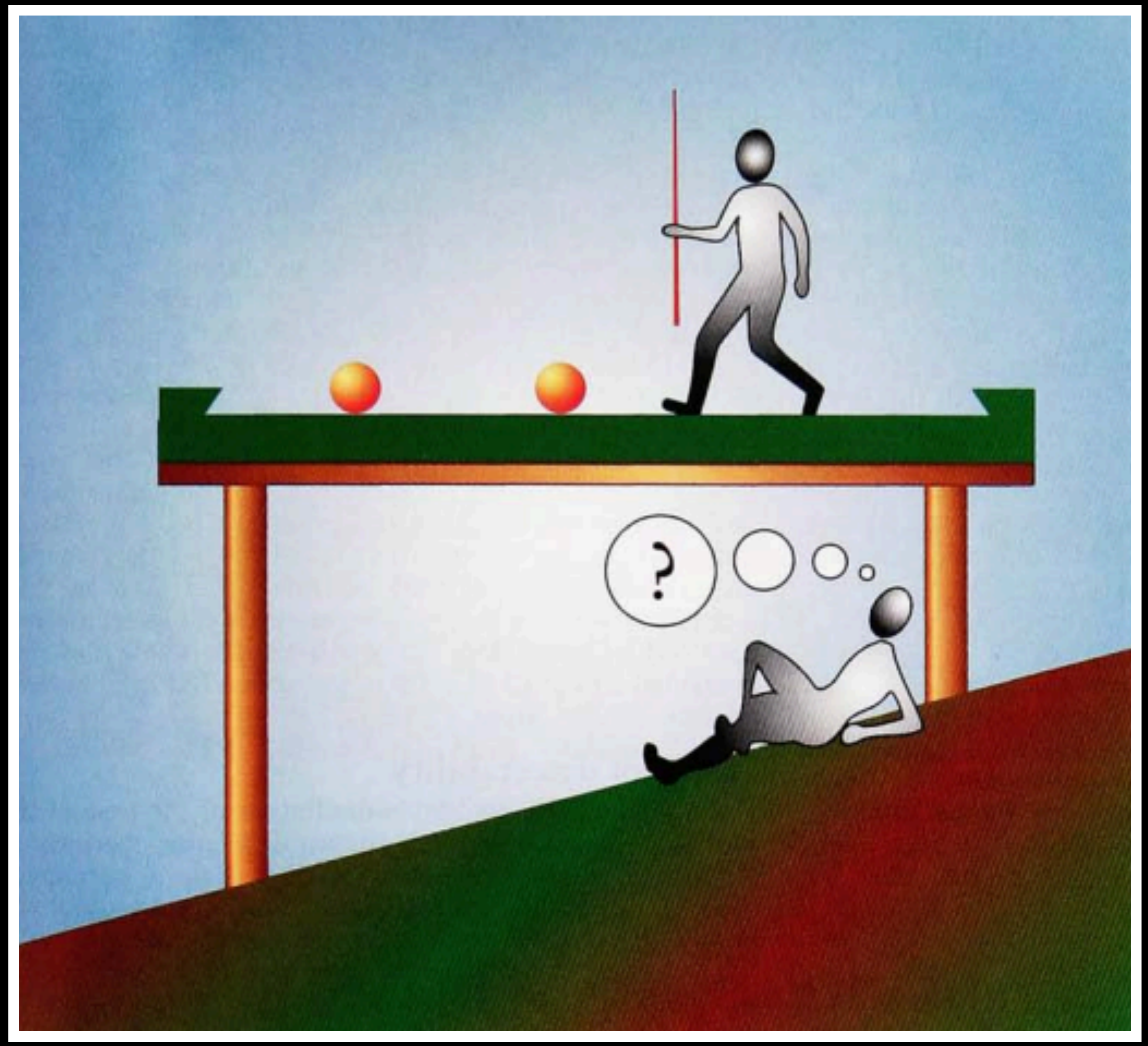
Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

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

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.



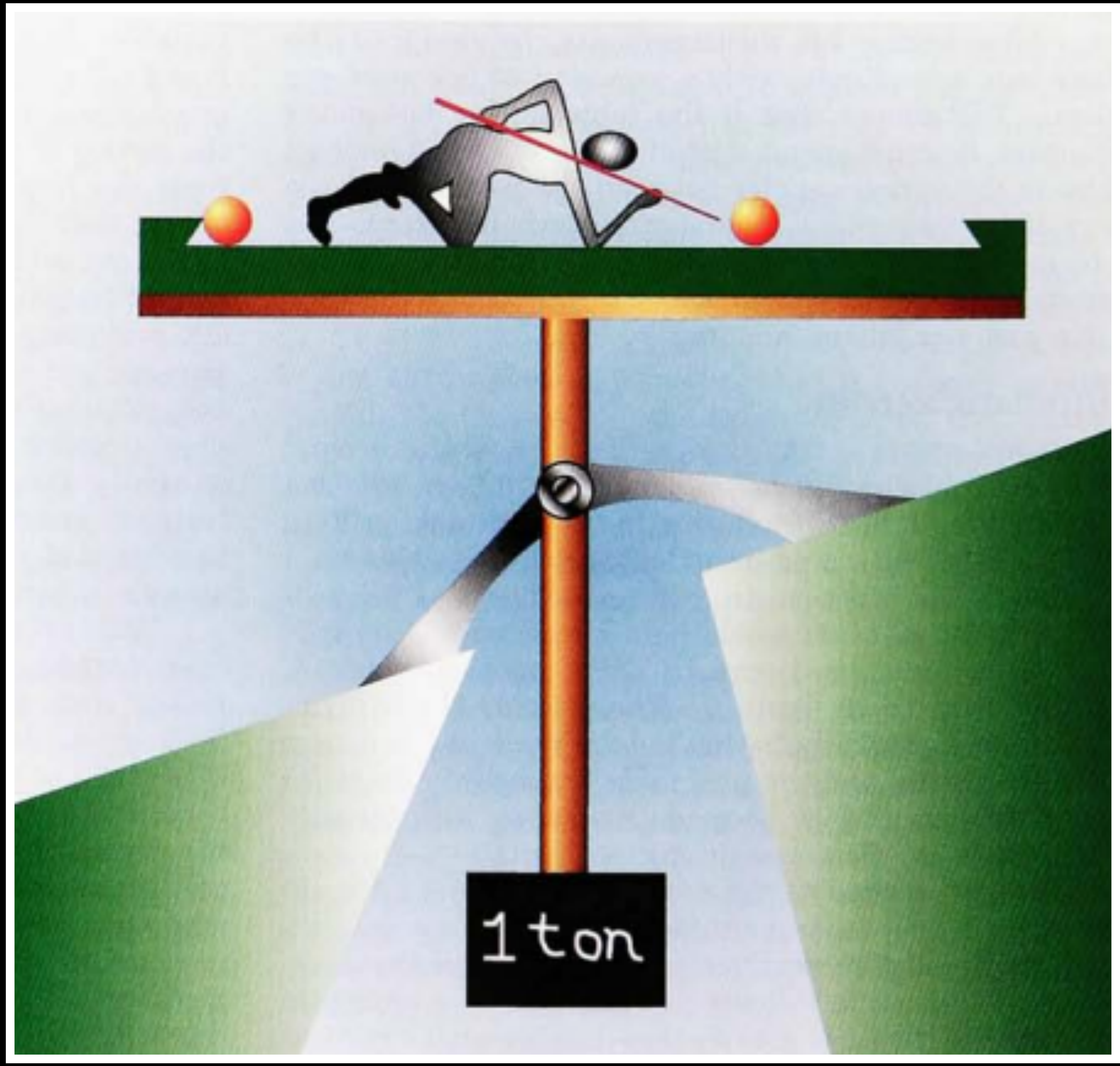
Sikivie, Pierre. "The Pool-Table Analogy with Axion Physics." *Physics Today* 49.12 (1996): 22-27.

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.

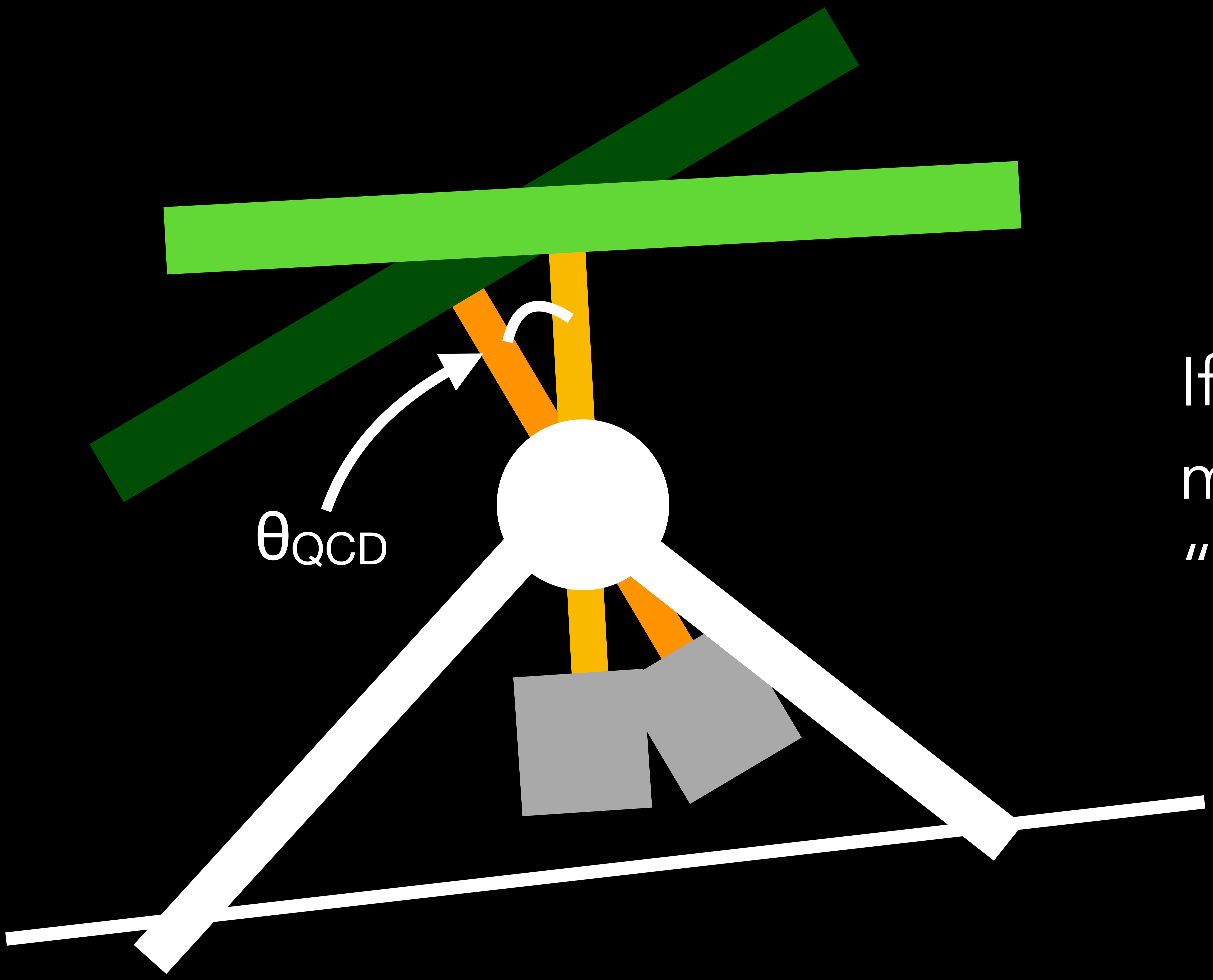
- Angle of pool table tilt = θ_{QCD}
- Physics of pool table = physics of QCD
- Gravity = Nonperturbative effects that make QCD depend on θ_{QCD}



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)

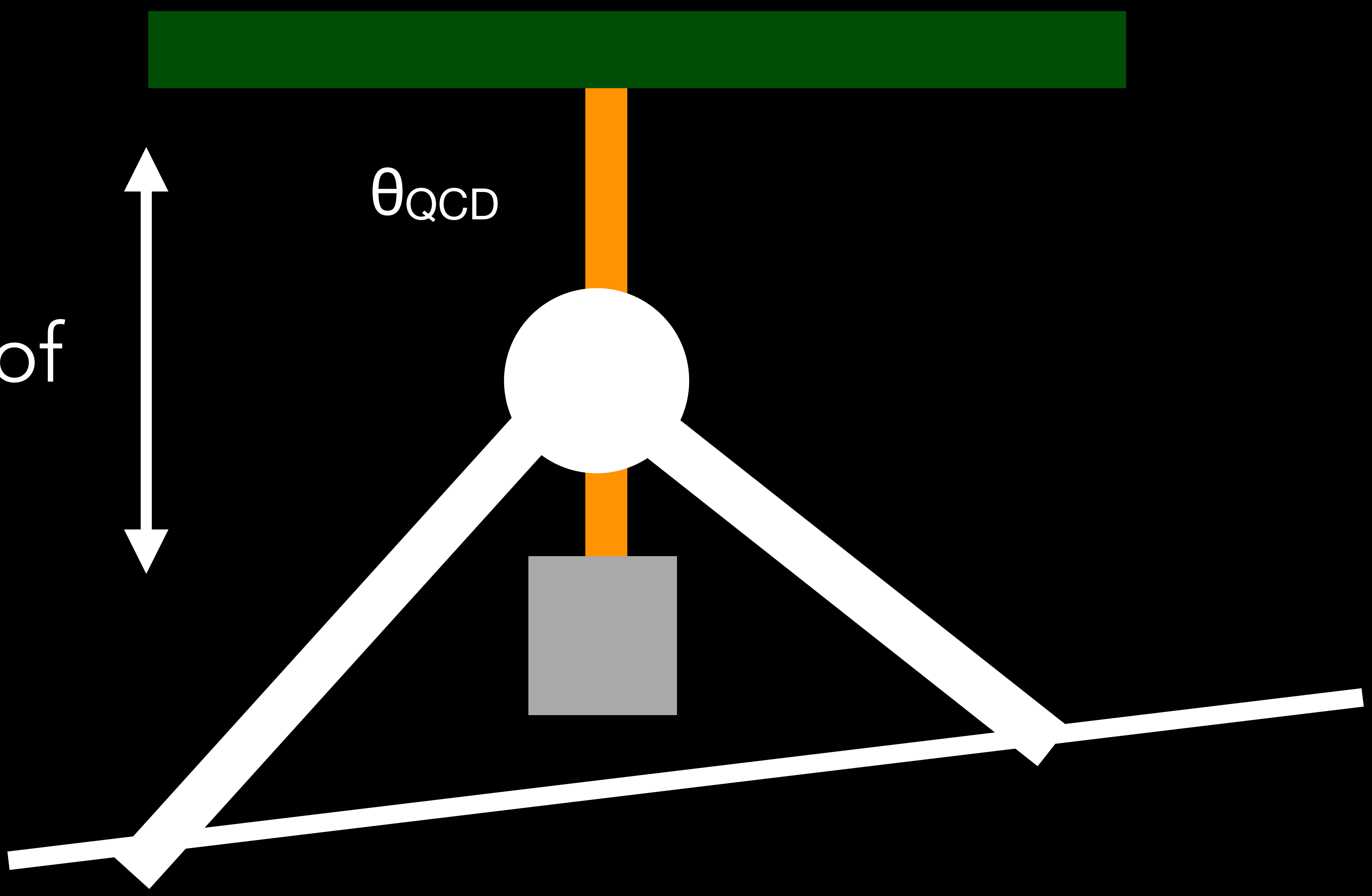


If θ_{QCD} dynamical, mechanism is akin to "Peccei-Quinn Mechanism"

How to test the hypothesis?

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

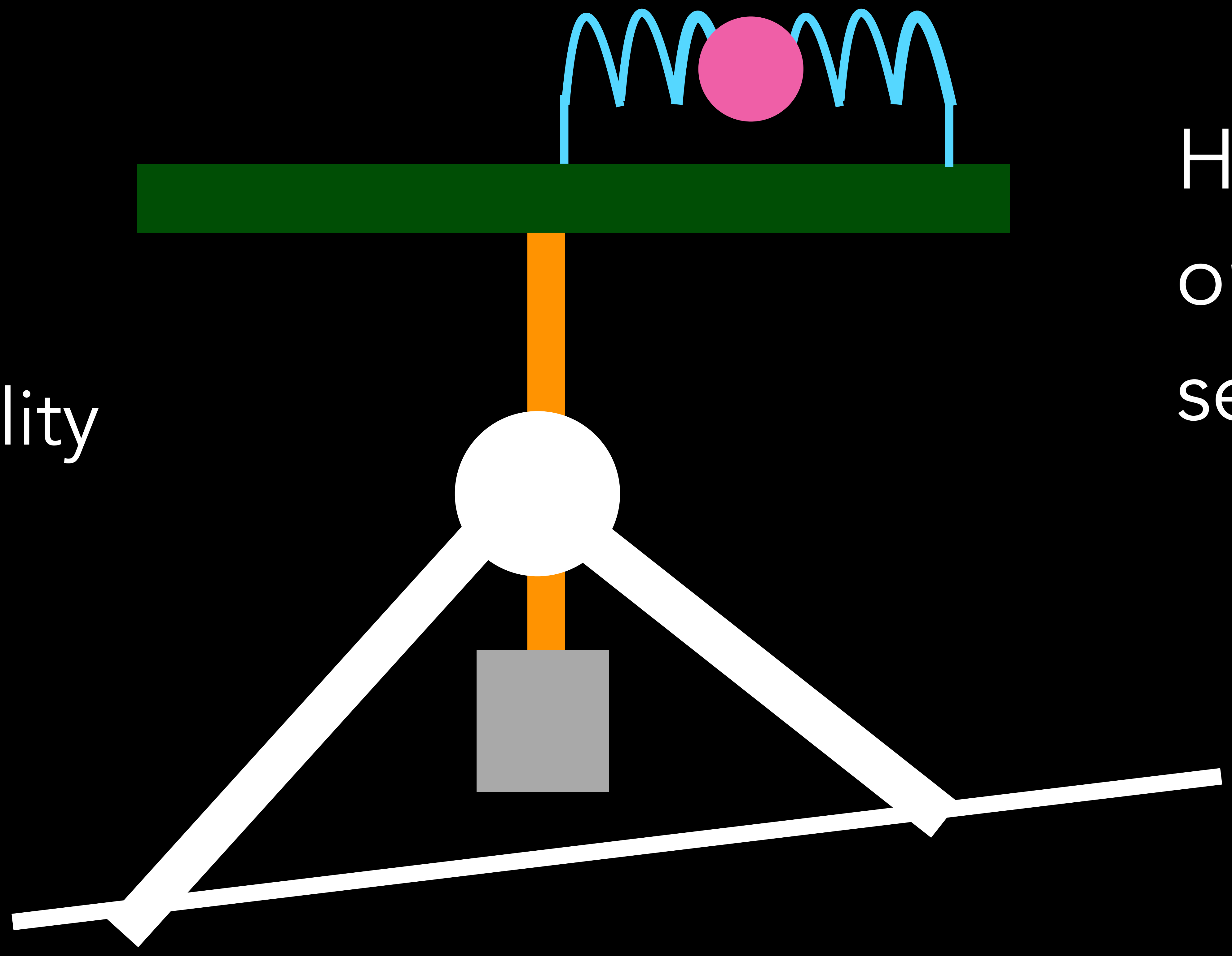
Length of lever arm determines strength of oscillation



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…

Axions as the dark matter

…"the most exciting phrase to hear in science…is not *Eureka* but *That's funny…*"

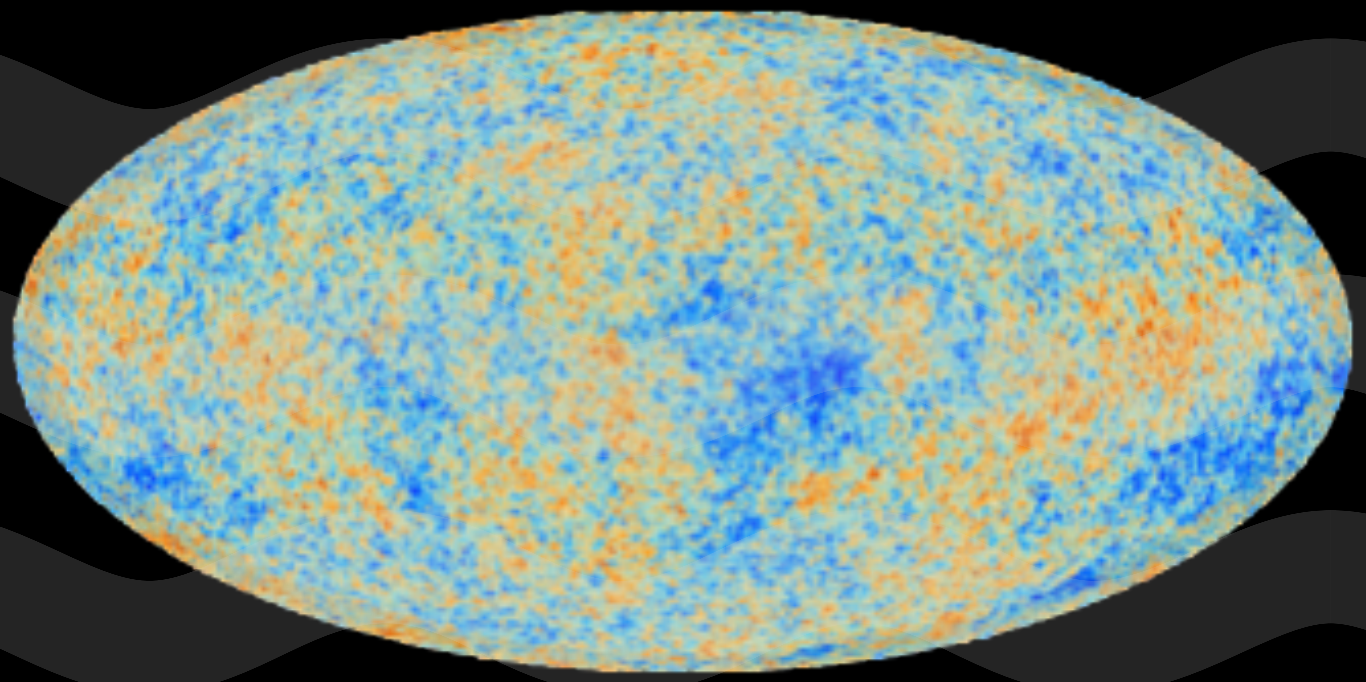
-Isaac Asimov

Dark Matter

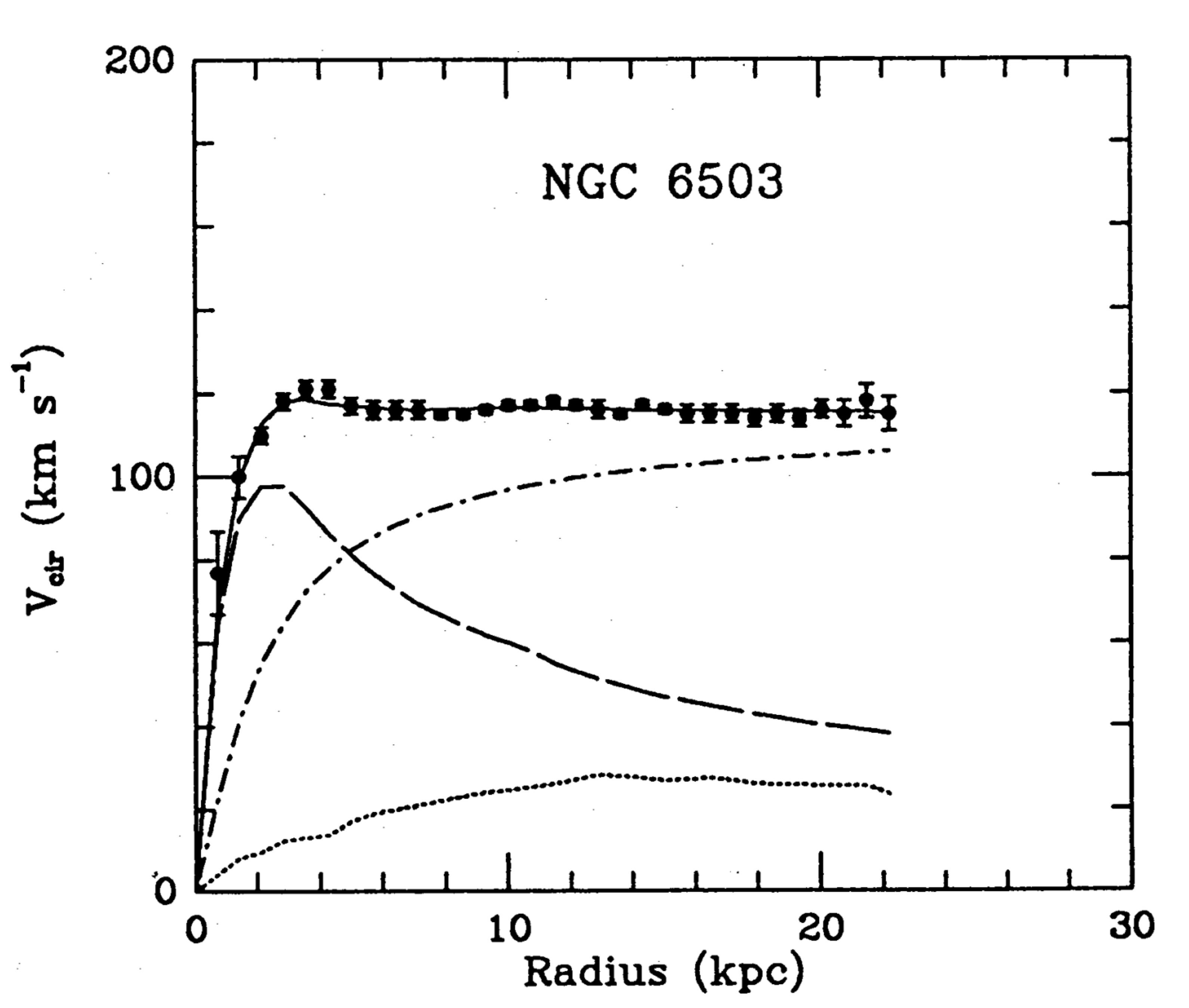
85% of the matter content of the universe. Likely to be non-relativistic, collisionless, dissipation less and non-baryonic.

Evidence coming from:

- Anisotropies in the Cosmic Microwave Background
- Rotation curves of galaxies
- Behavior of galaxy cluster collisions
- Primordial nucleosynthesis
- Gravitational lensing
- Baryon Acoustic Oscillations



ESA and the Planck Collaboration



Monthly Notices of the Royal Astronomical Society 249, 523–537 (1991)

Axions: why are they wave-like?

Wave-particle duality

Proton: $\lambda \sim 10^{-12}$ m

WIMP dark matter: $\lambda \sim 10^{-13}$ m → Recoil experiments

Axion Dark Matter ($m \sim 10^{-6}$ eV): $\lambda \sim 100$ m → Something completely different…

Axion dark matter is associated with a huge wavelength!
No longer behaves like a particle.

So the axion could solve multiple problems in physics!

Strong CP probler

Axion:
wave-like dark matter
candidate

5% of the matter
unknown.

…and has intriguing implications

Maxwell's equations

$$\nabla \times \mathbf{B_a} = \frac{\partial \mathbf{E_a}}{\partial t} - g_{a\gamma\gamma}\mathbf{B_0}\frac{\partial a}{\partial t}$$

Effective current oscillating at the frequency of the axion

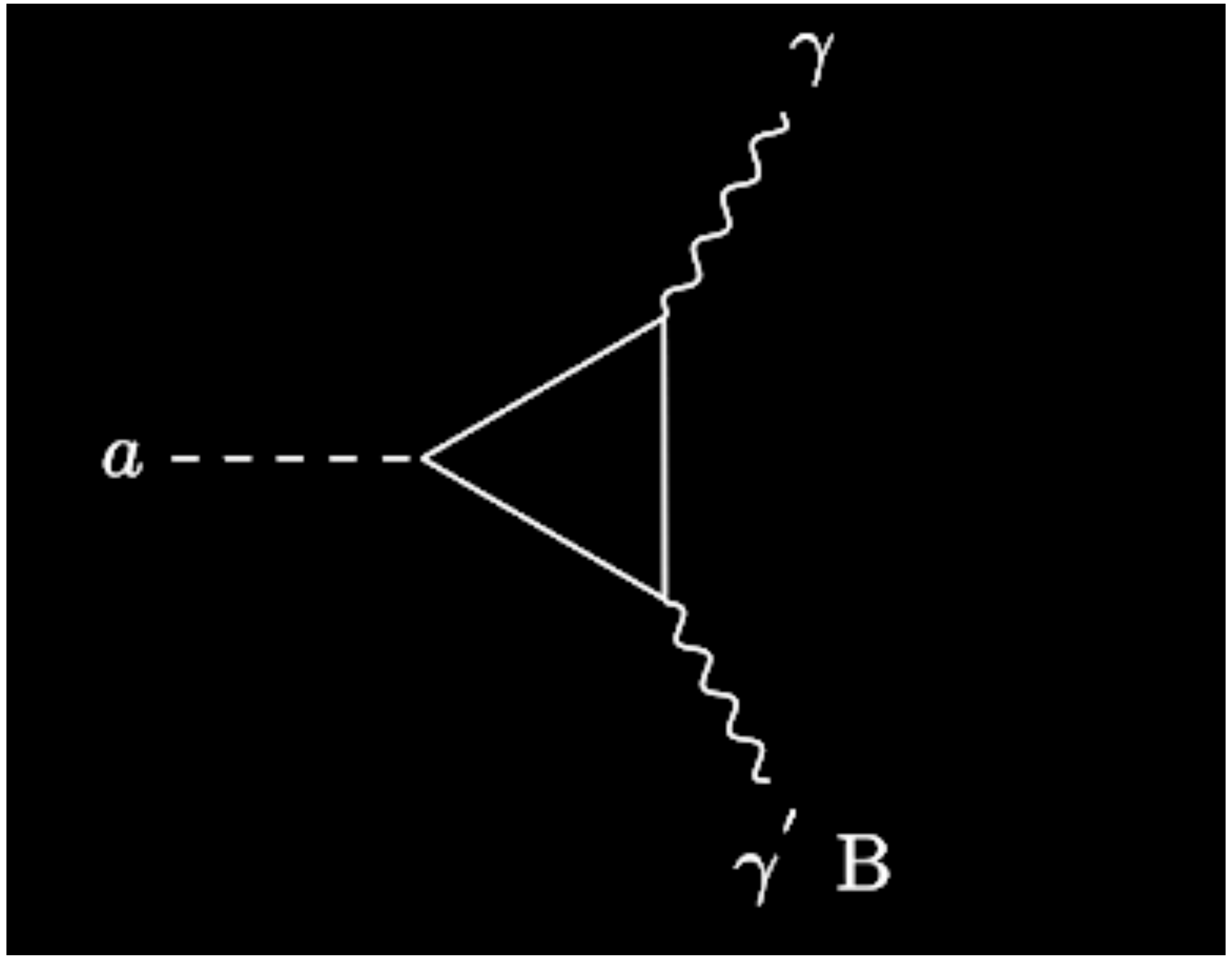
$$\vec{J}_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\vec{B}_0 \cos\left(m_a t\right)$$

Key Detection Mechanism

Axion turns into a photon (light particle) in a magnetic field!

Two key parameters:

$g_{a\gamma\gamma}$	Likelihood or 'strength' of interaction Units: 1/GeV
m_a	Mass of the axion Units: eV



Axion Mass Range

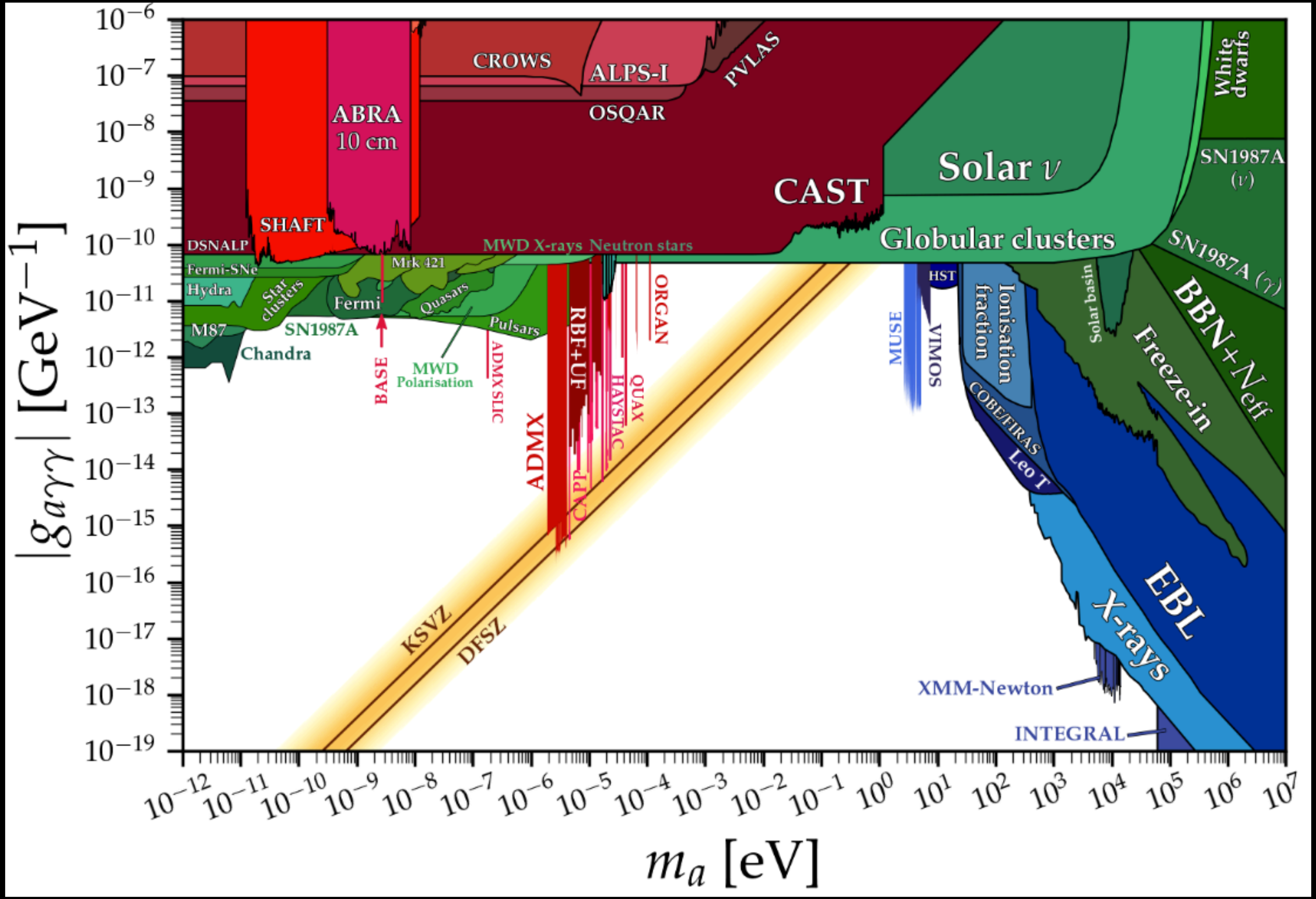
Lower bound set by size of dark matter halo size of dwarf galaxies

Upper bound set by SN1987A and white dwarf cooling time

What frequency (mass) exactly? We don't know.

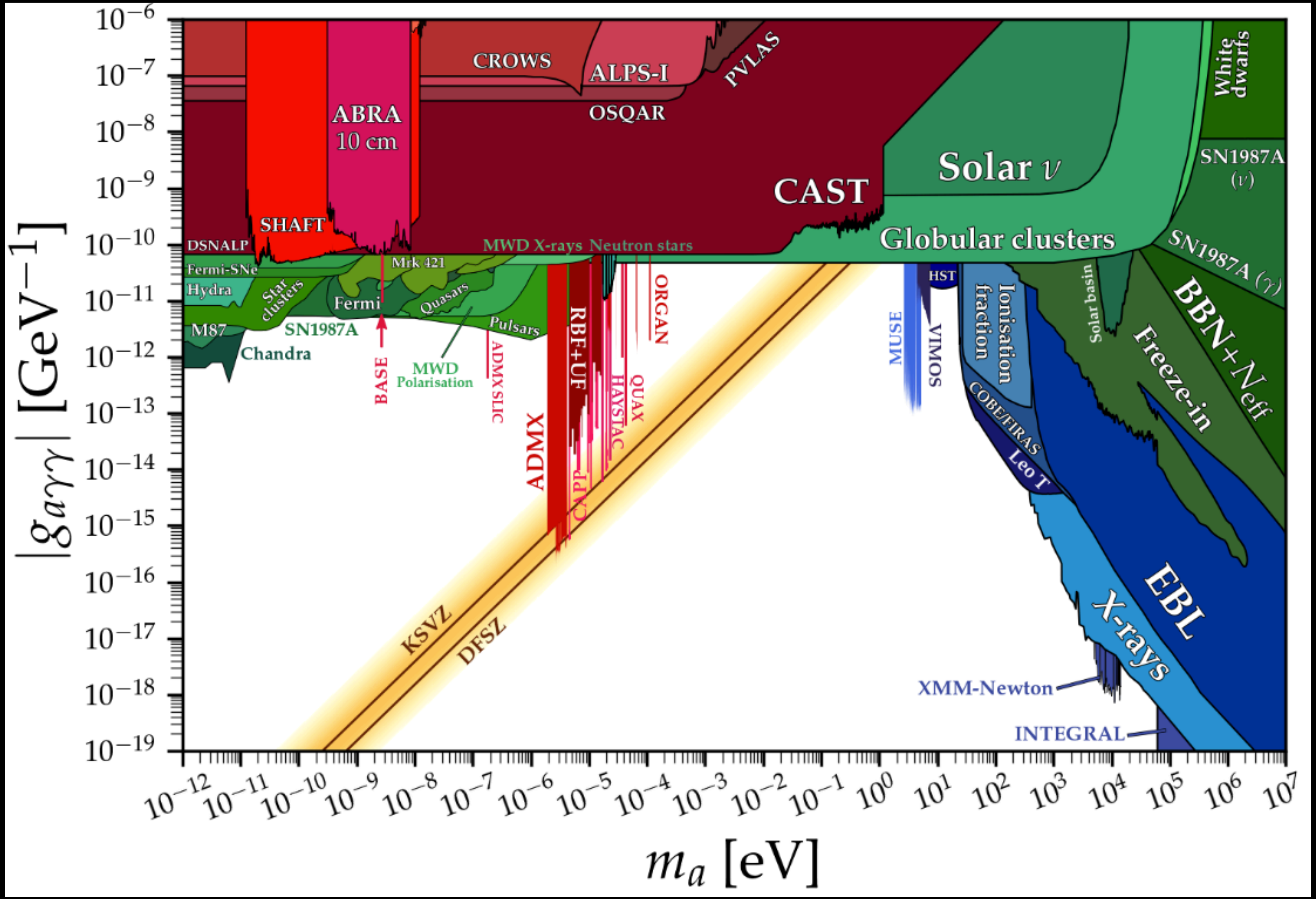
Adaptation of L. Winslow DPF Slide

Red, green and blue show places we looked!



Plot courtesy of Ciaran O'Hare

Yellow shows a special type of axion: the QCD axion!



Plot courtesy of Ciaran O'Hare

QCD axion: Product of the Peccei-Quinn Mechanism

Two classes of models:

- **KSVZ:**
- **DFSZ:**

Helen Quinn

Roberto Peccei

Steven Weinberg

Frank Wilczek

QCD axion: Solves longstanding nuclear physics problem

Two classes of models:

- **KSVZ:**

- **DFSZ:**

  Most difficult to detect but also most compelling because it can be included in Grand Unified Theories (GUT)

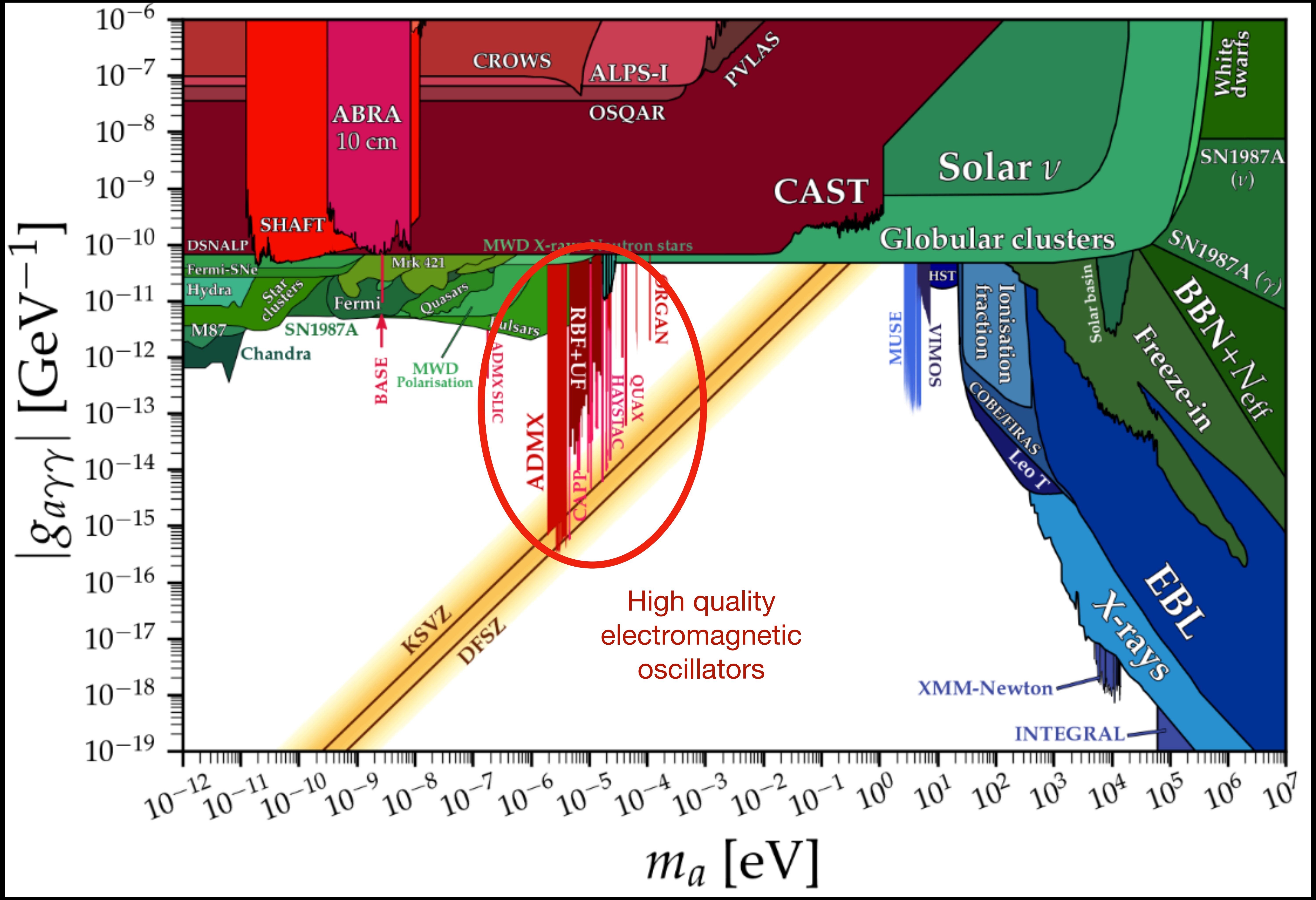
Helen Quinn

Roberto Peccei

Steven Weinberg

Frank Wilczek

QCD axion band is exceedingly difficult to reach



Plot courtesy of Ciaran O'Hare

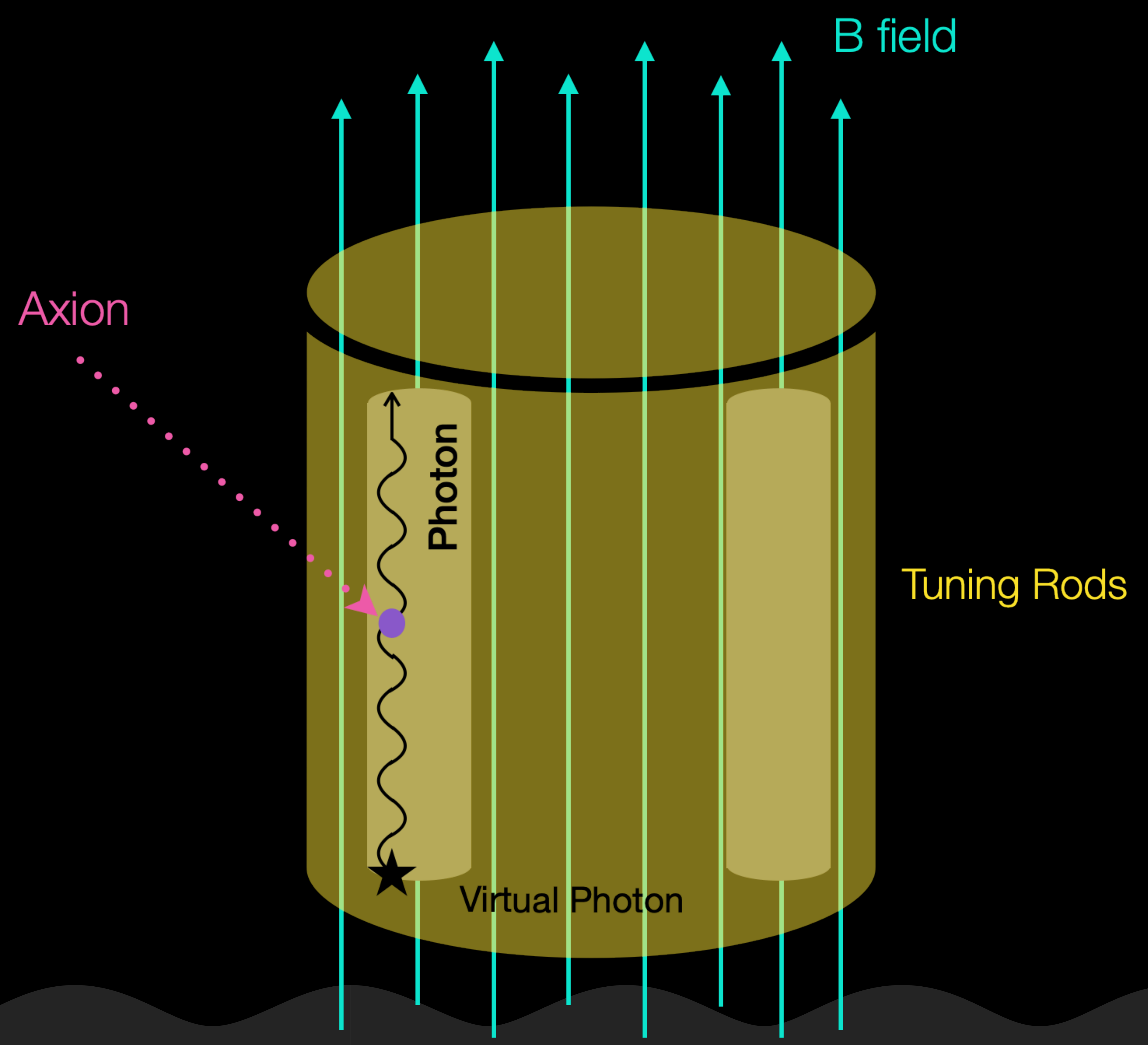
How do you detect this?

How to detect low frequency electromagnetic waves?

Detector that senses the electric current resulting from the axion conversion to photon in a magnetic field.

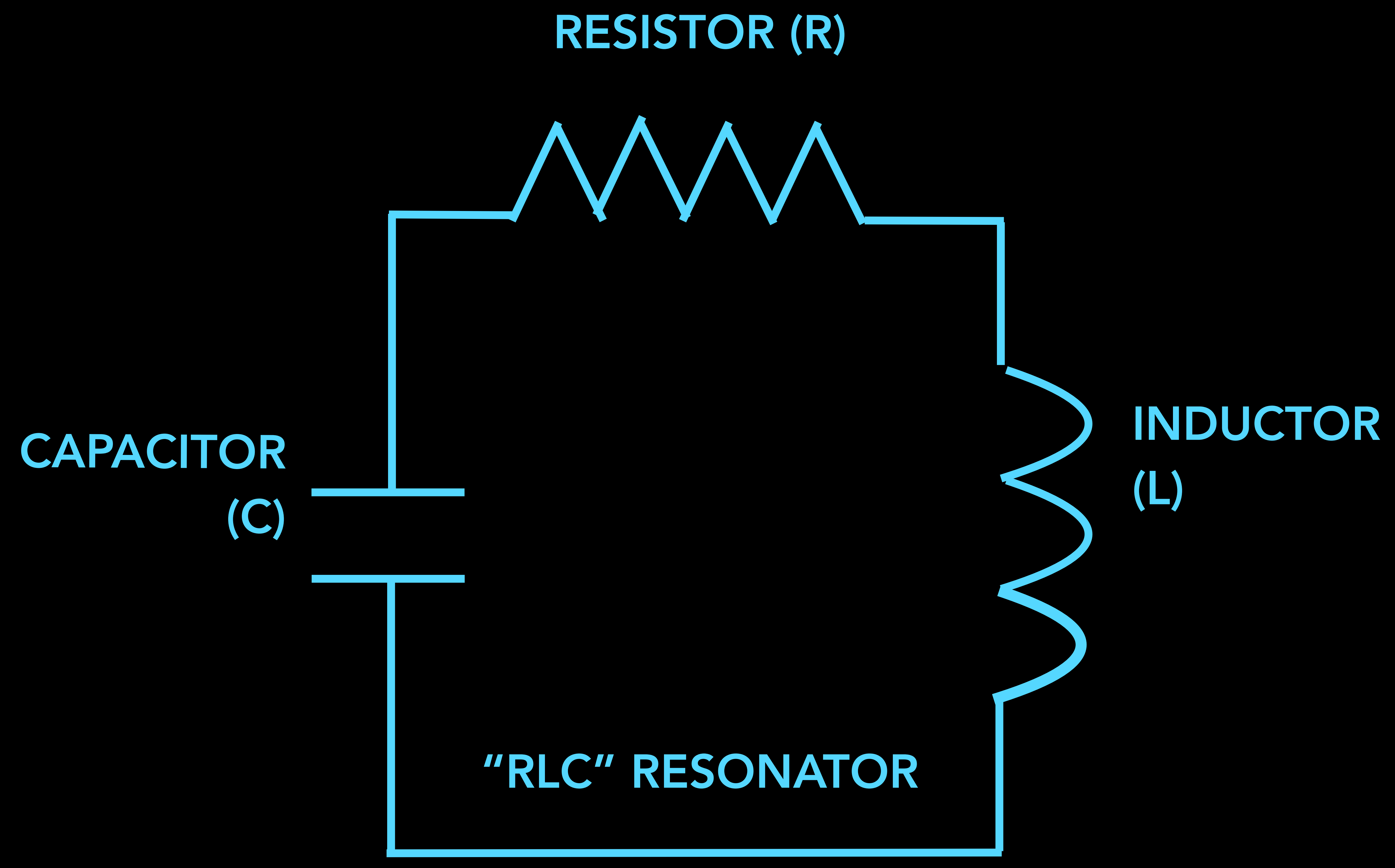
High quality electromagnetic oscillators (resonators) are the most sensitive detectors.

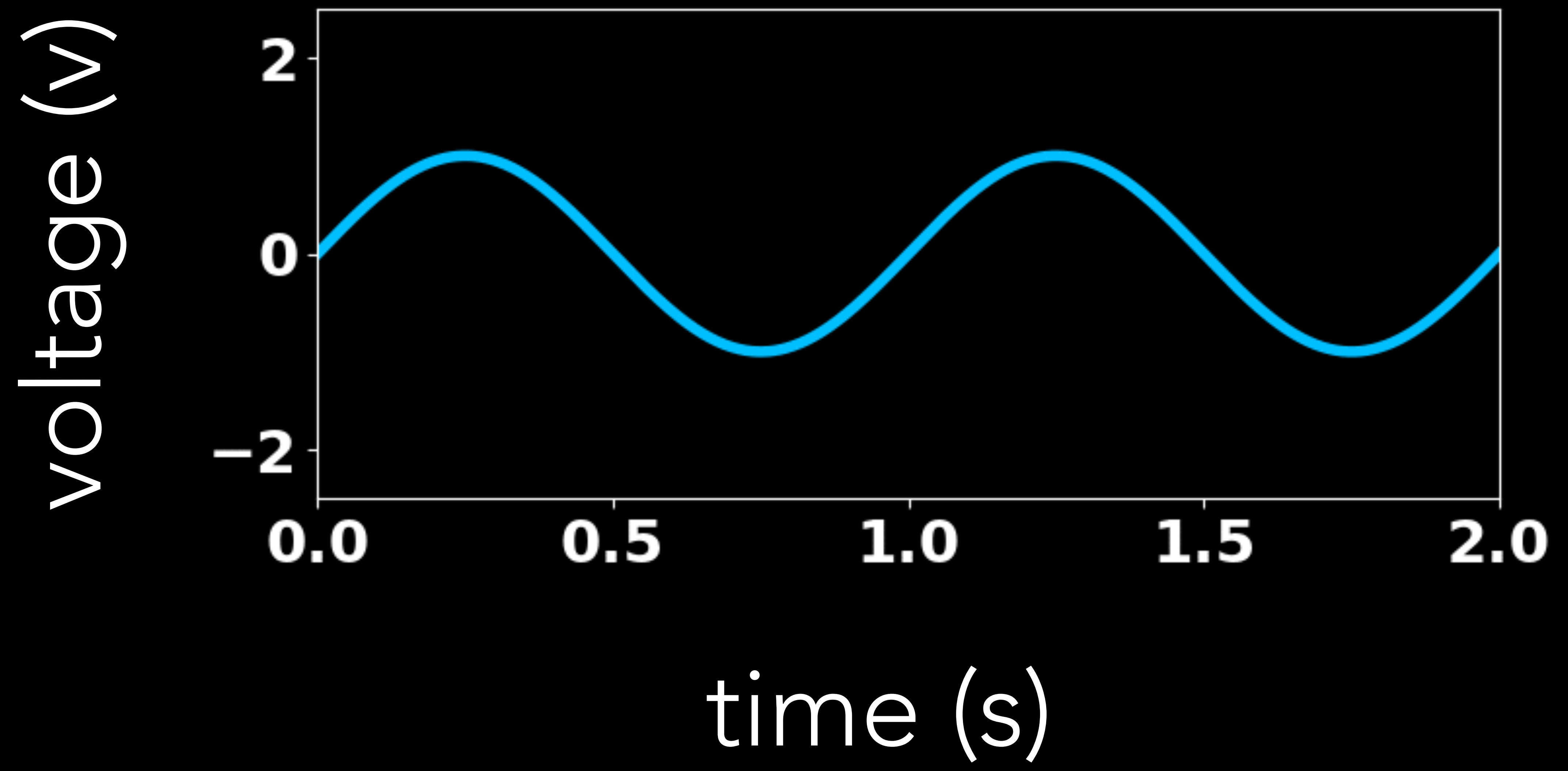
"Axion Haloscope"



Resonant microwave cavity

HOW TO BUILD A RESONATOR

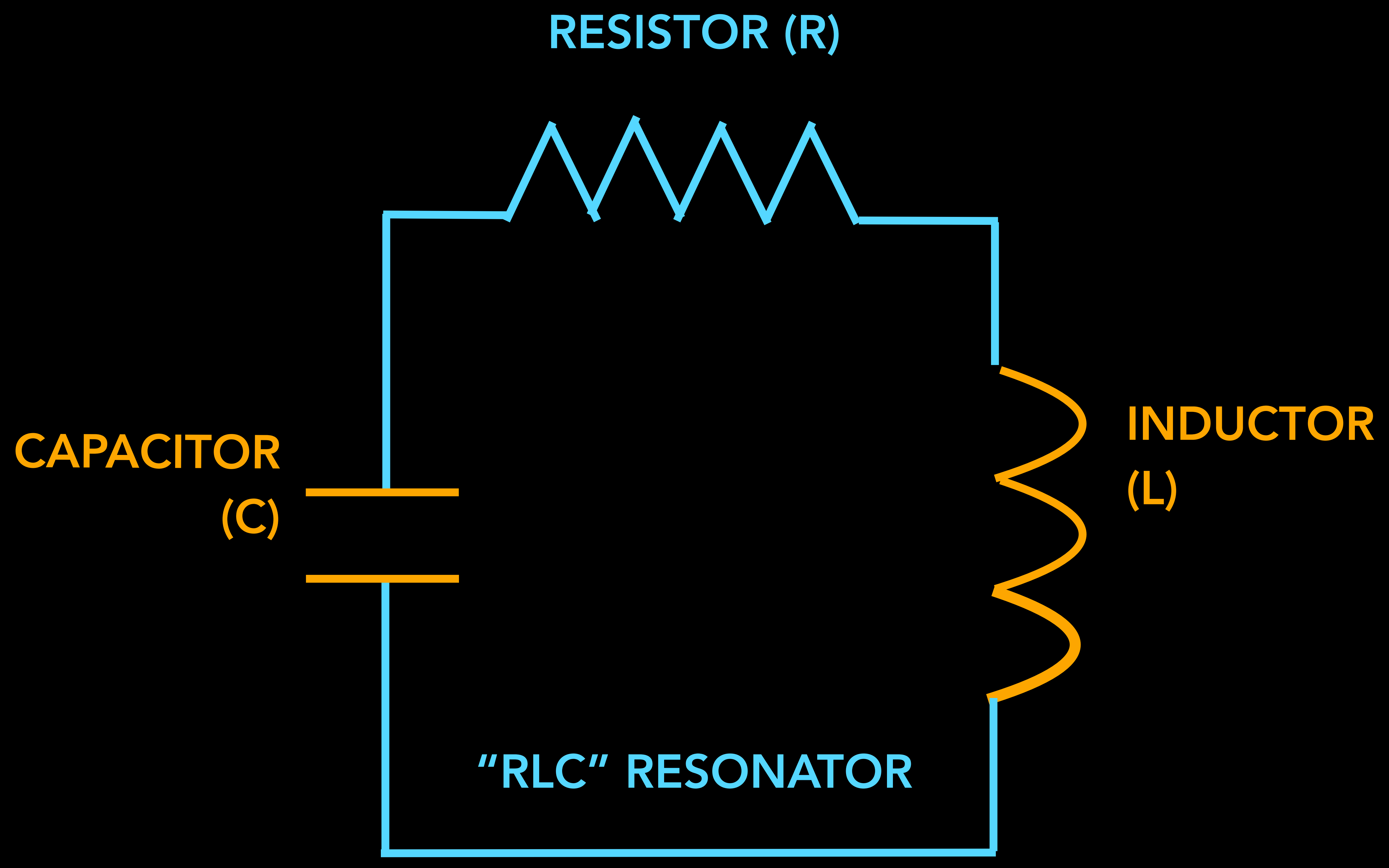


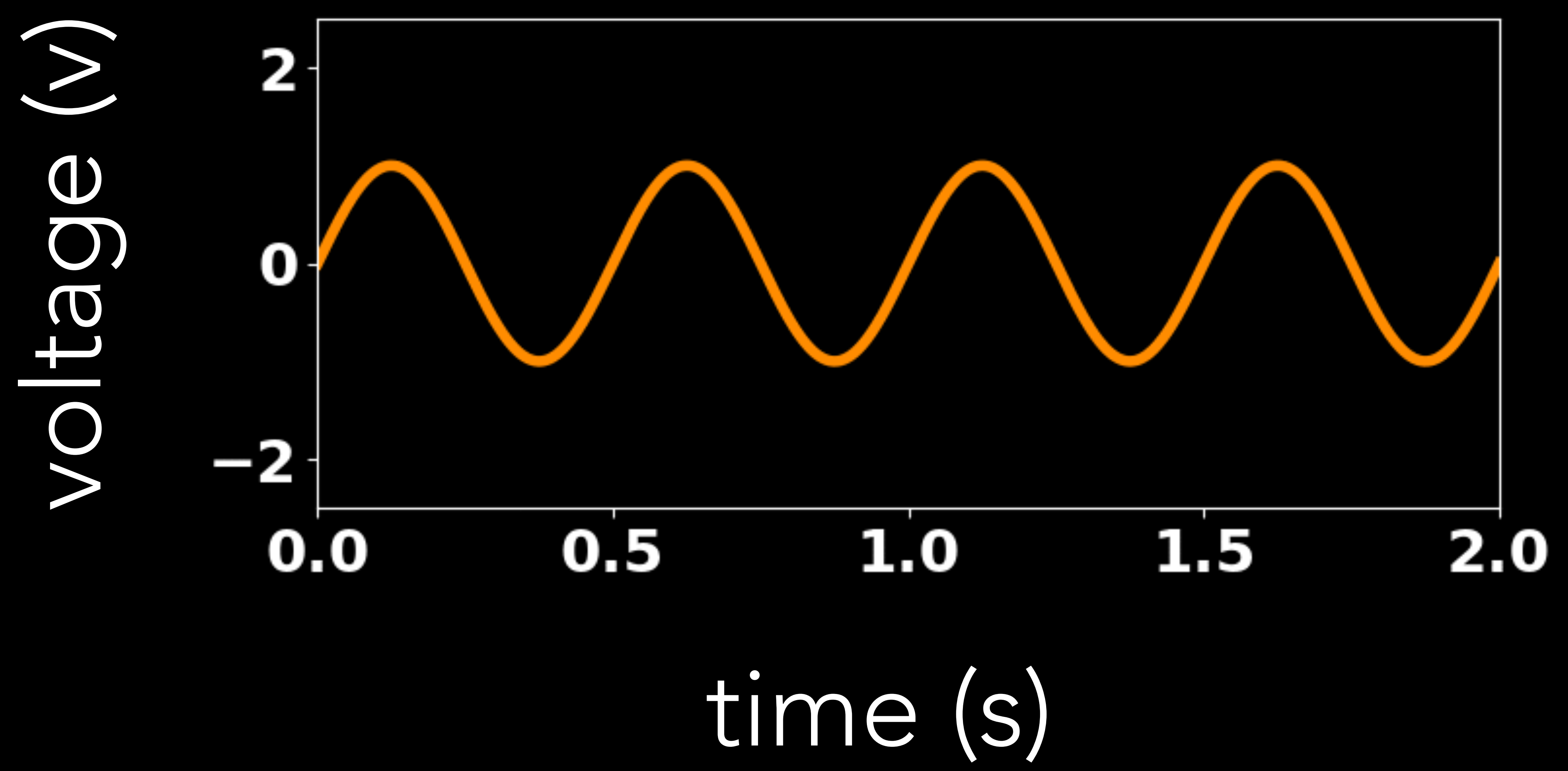


Most sensitive to sine waves at the resonant frequency

$$\omega_0 = 1/\sqrt{LC}$$

HOW TO BUILD A RESONATOR

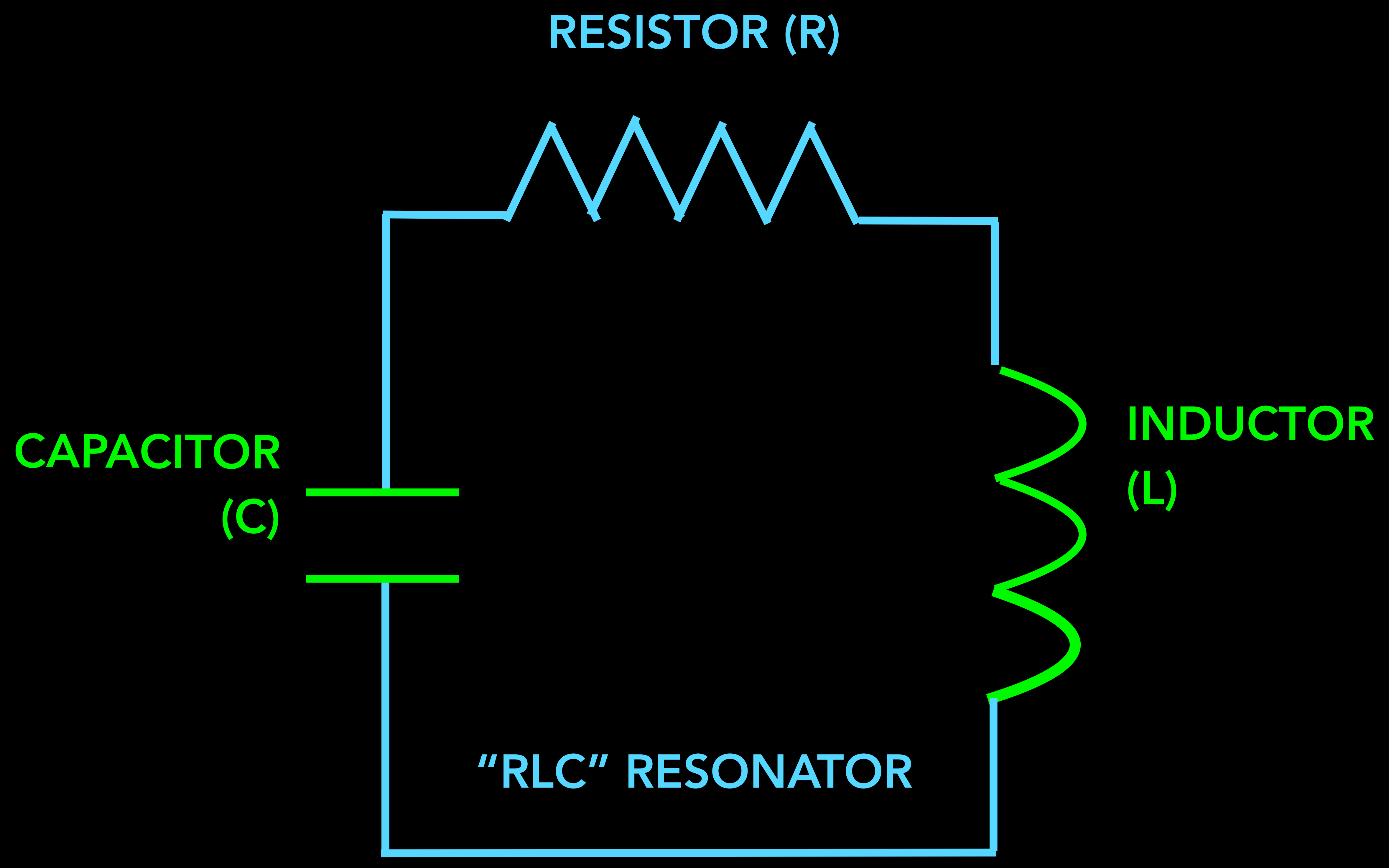


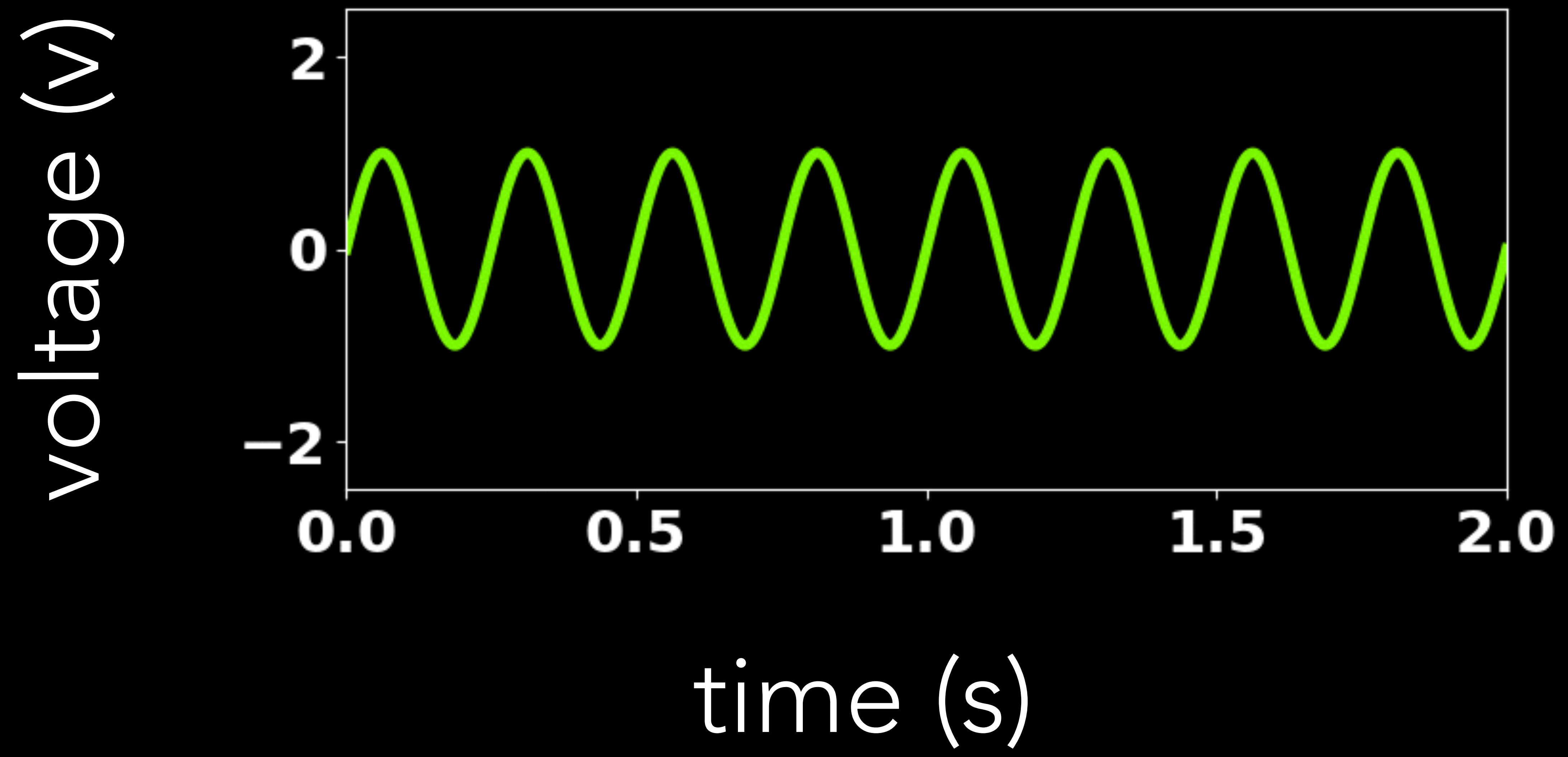


Most sensitive to sine waves with frequency

$$\omega_0 = 1/\sqrt{LC}$$

HOW TO BUILD A RESONATOR

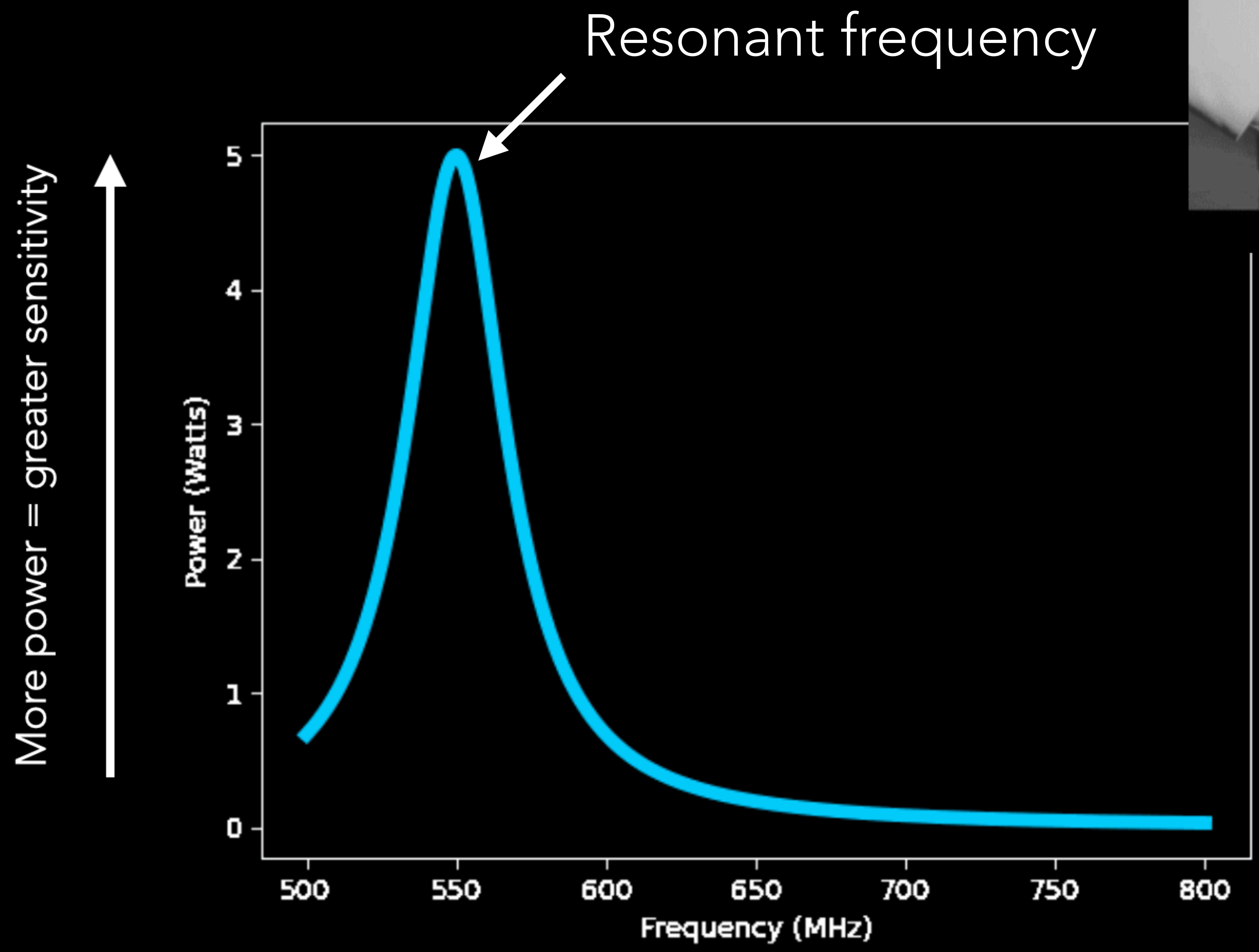


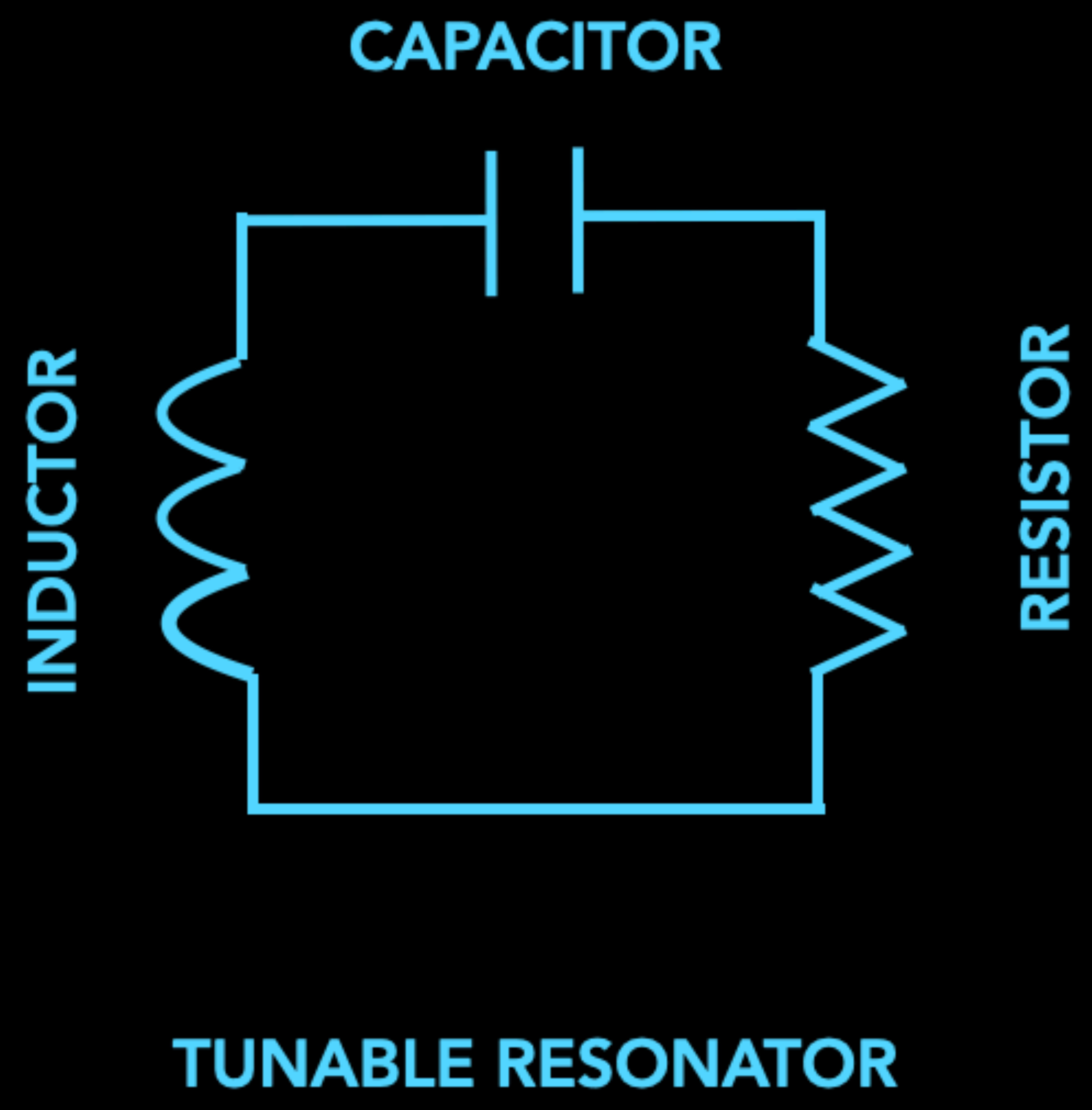


Most sensitive to sine waves with frequency

$$\omega_0 = 1/\sqrt{LC}$$

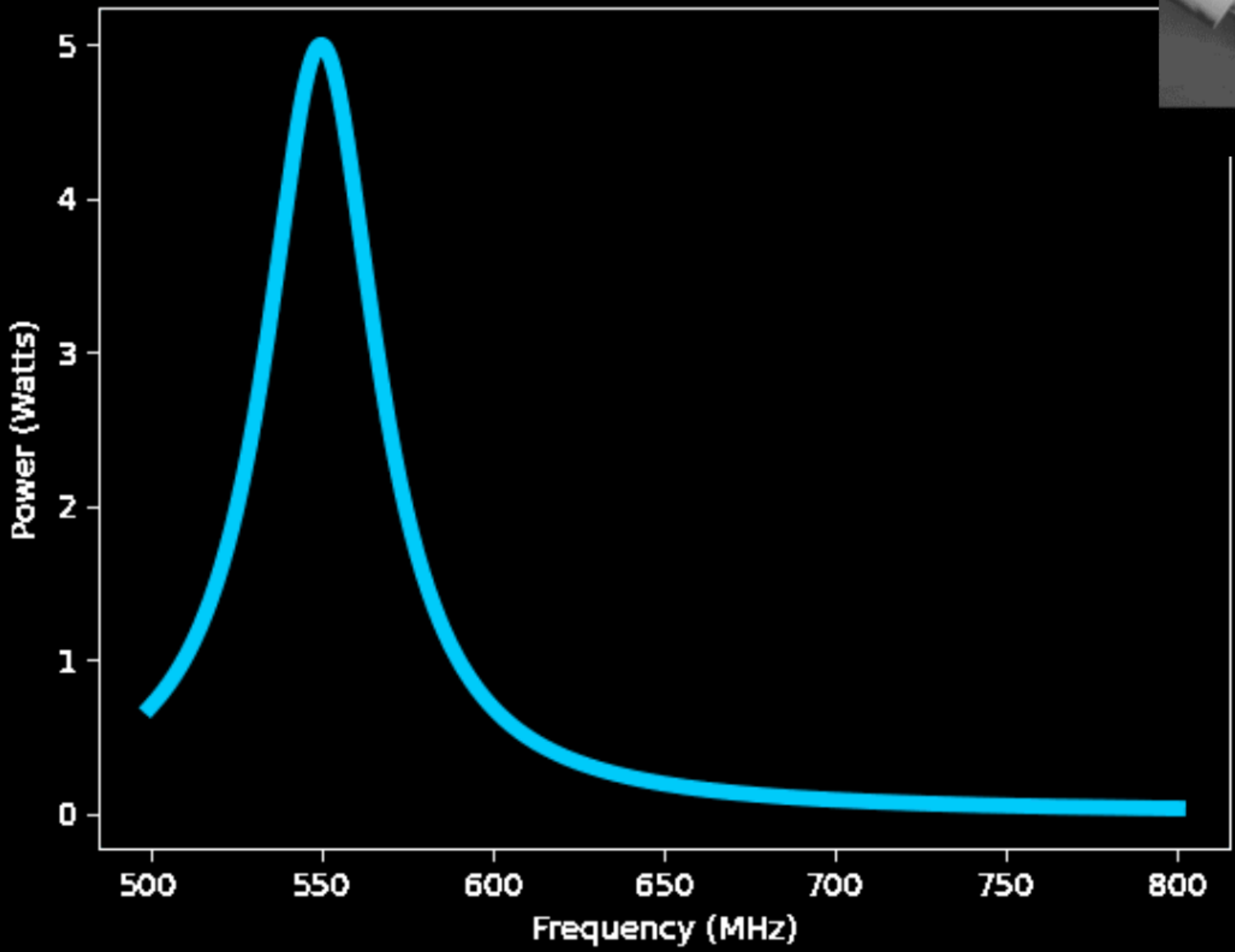
TUNING A RADIO





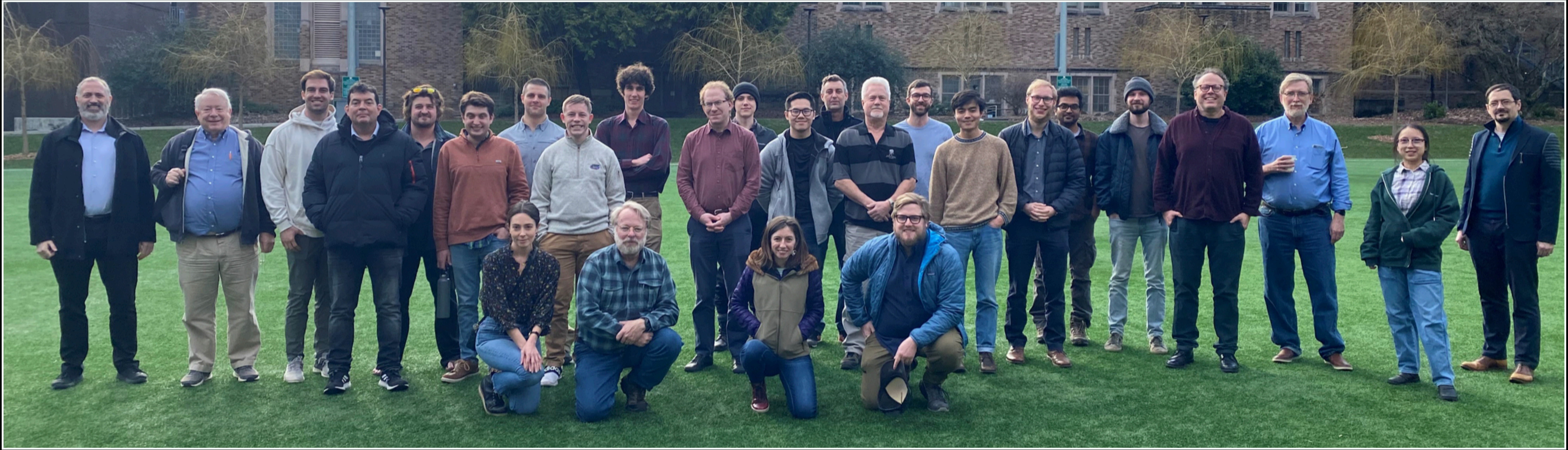
TUNING A RADIO

More power = greater sensitivity



EVEN A COFFEE CAN IS A RESONATOR!

ADMX Collaboration



University of Washington
Lawrence Livermore National Laboratory
Berkeley University of California
The University of Chicago
Fermilab
Pacific Northwest National Laboratory
Washington University in St. Louis
UF University of Florida
The University Of Sheffield.
The University of Western Australia
Illinois Institute of Technology
Los Alamos National Laboratory EST. 1943

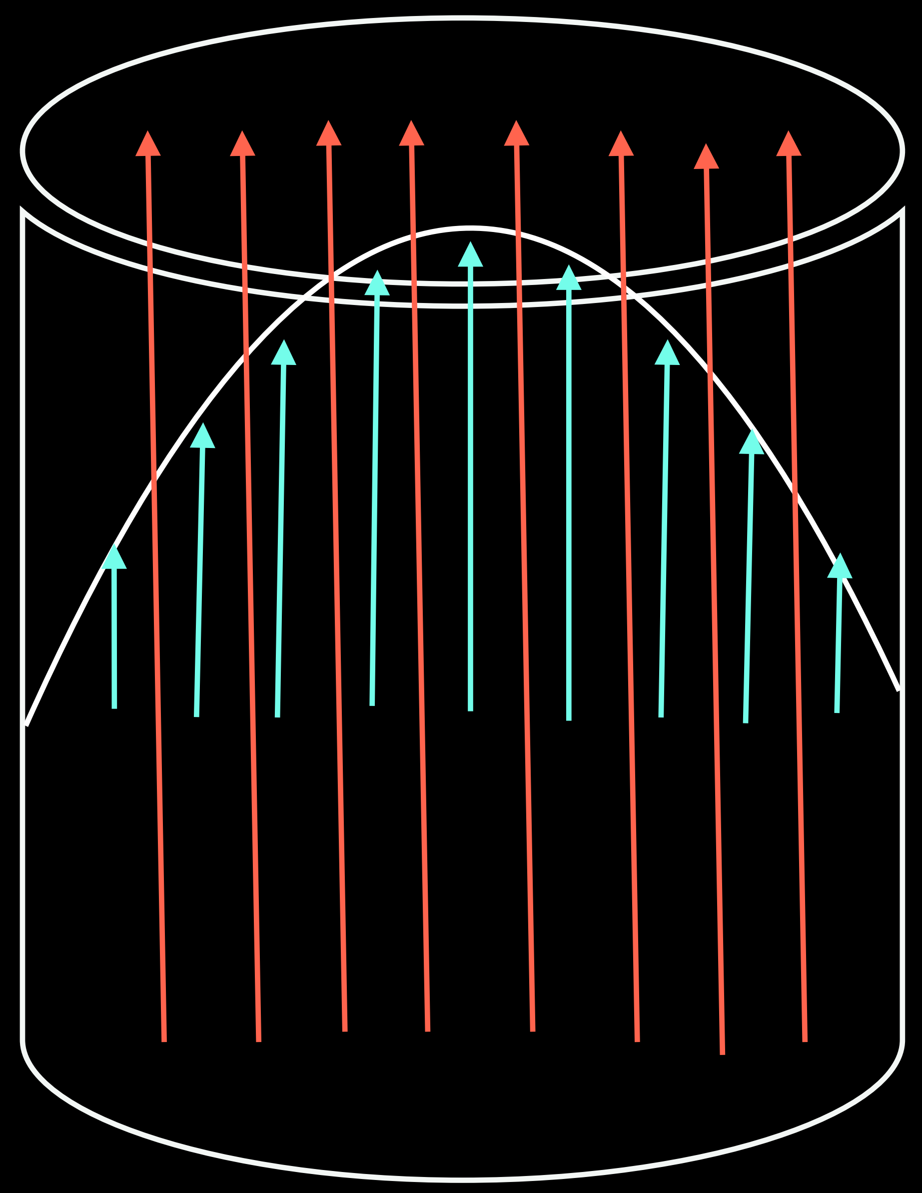
Axion Dark Matter eXperiment (ADMX)

Experiment that looks for dark matter at the University of Washington.

Cavity Haloscope

Search for axions with wavelength similar in scale to the cavity dimensions

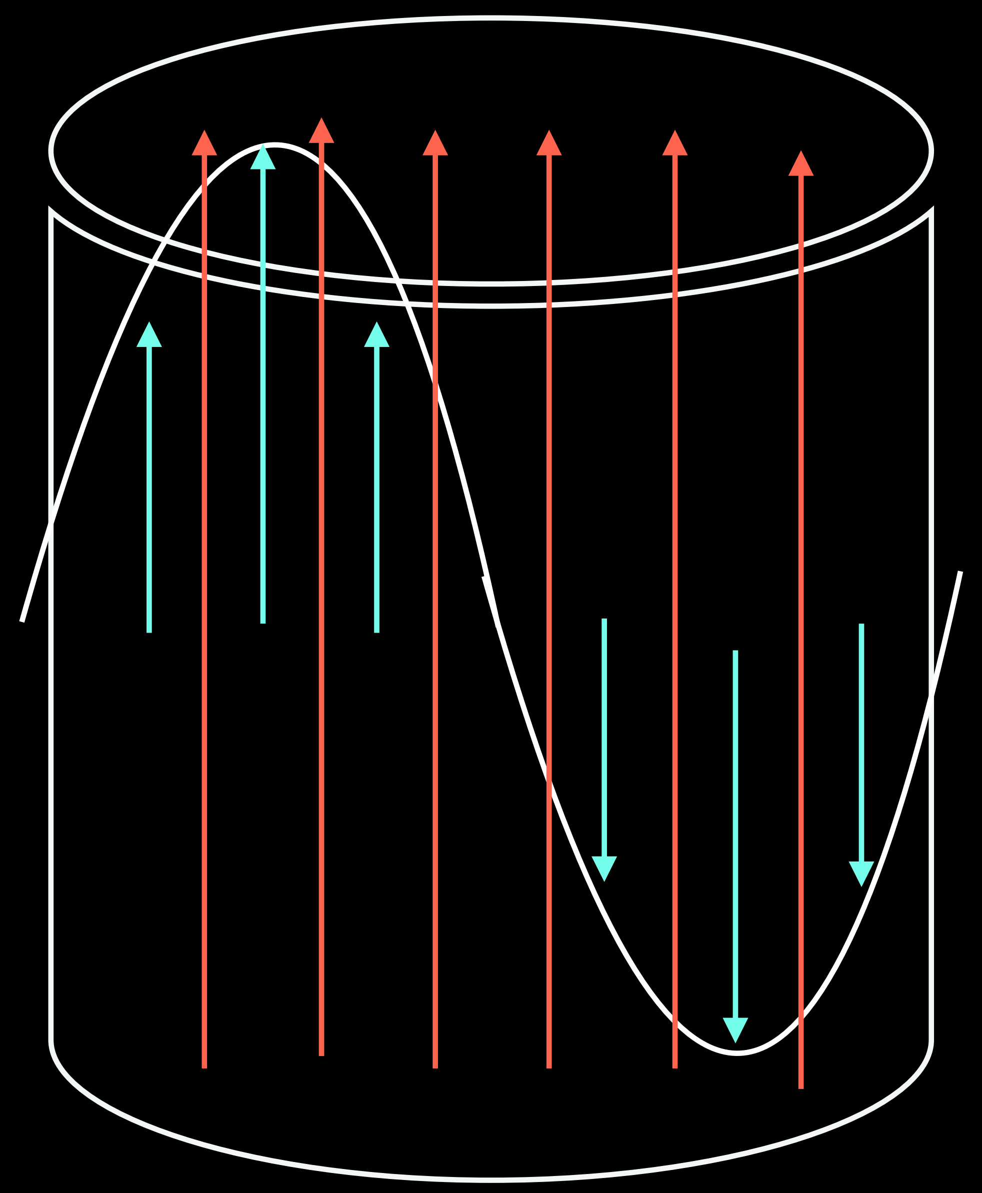
Form Factor == overlap of axion E field with static B field



Red is static magnetic field

Blue is axion electric field

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

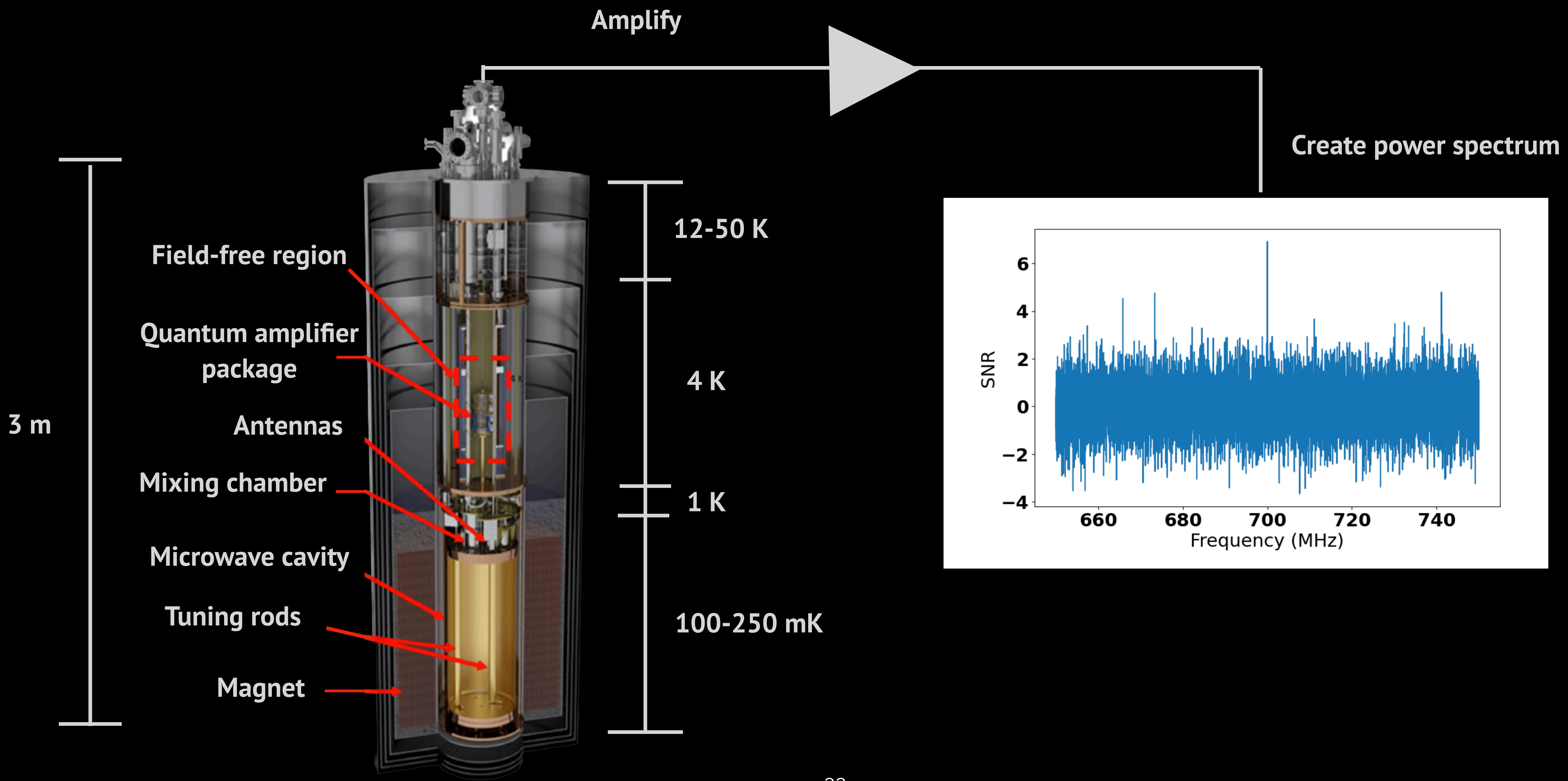


Non-zero form factor

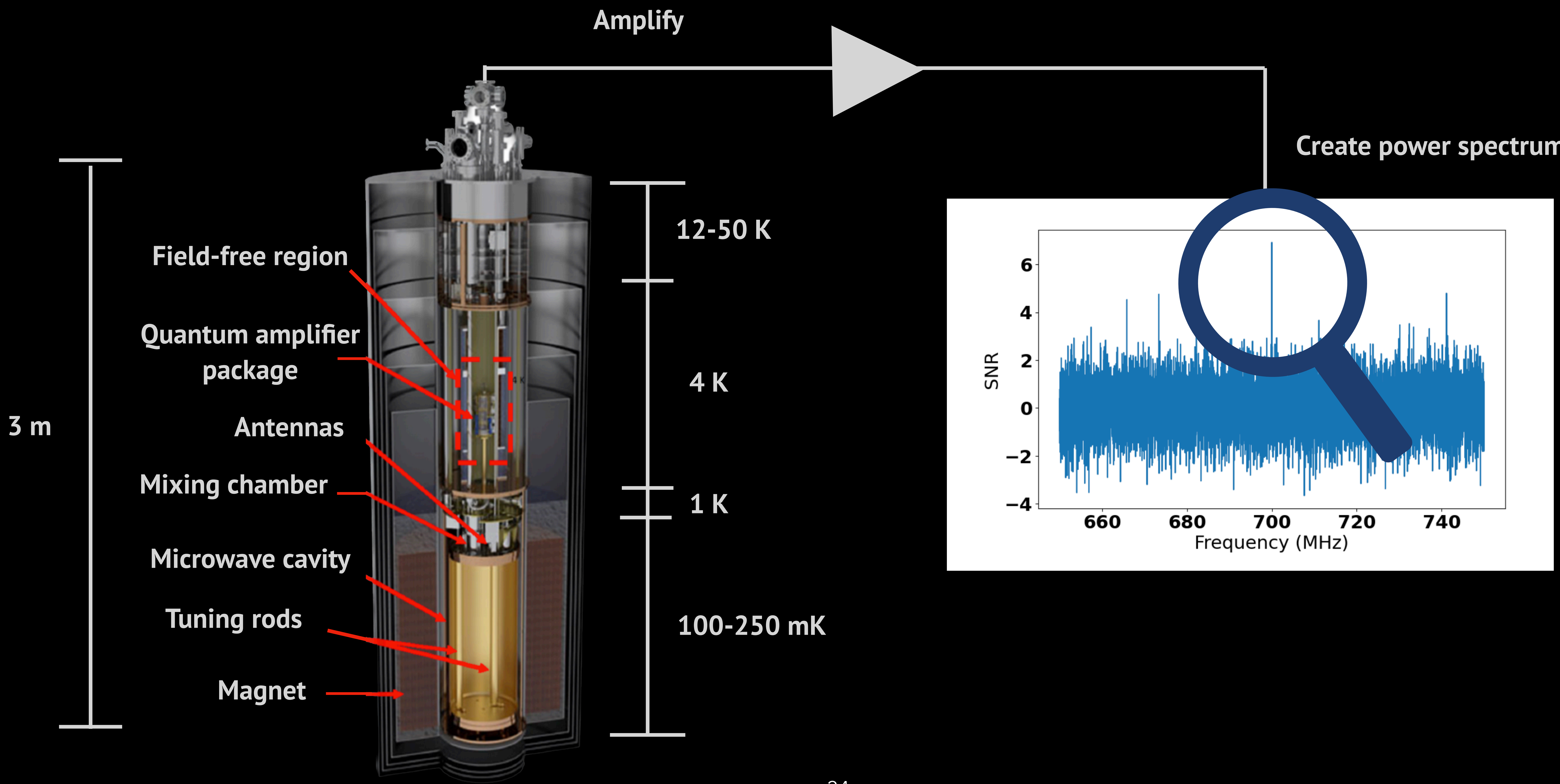
Zero form factor

In ADMX: Axion couples most strongly to TM010 mode

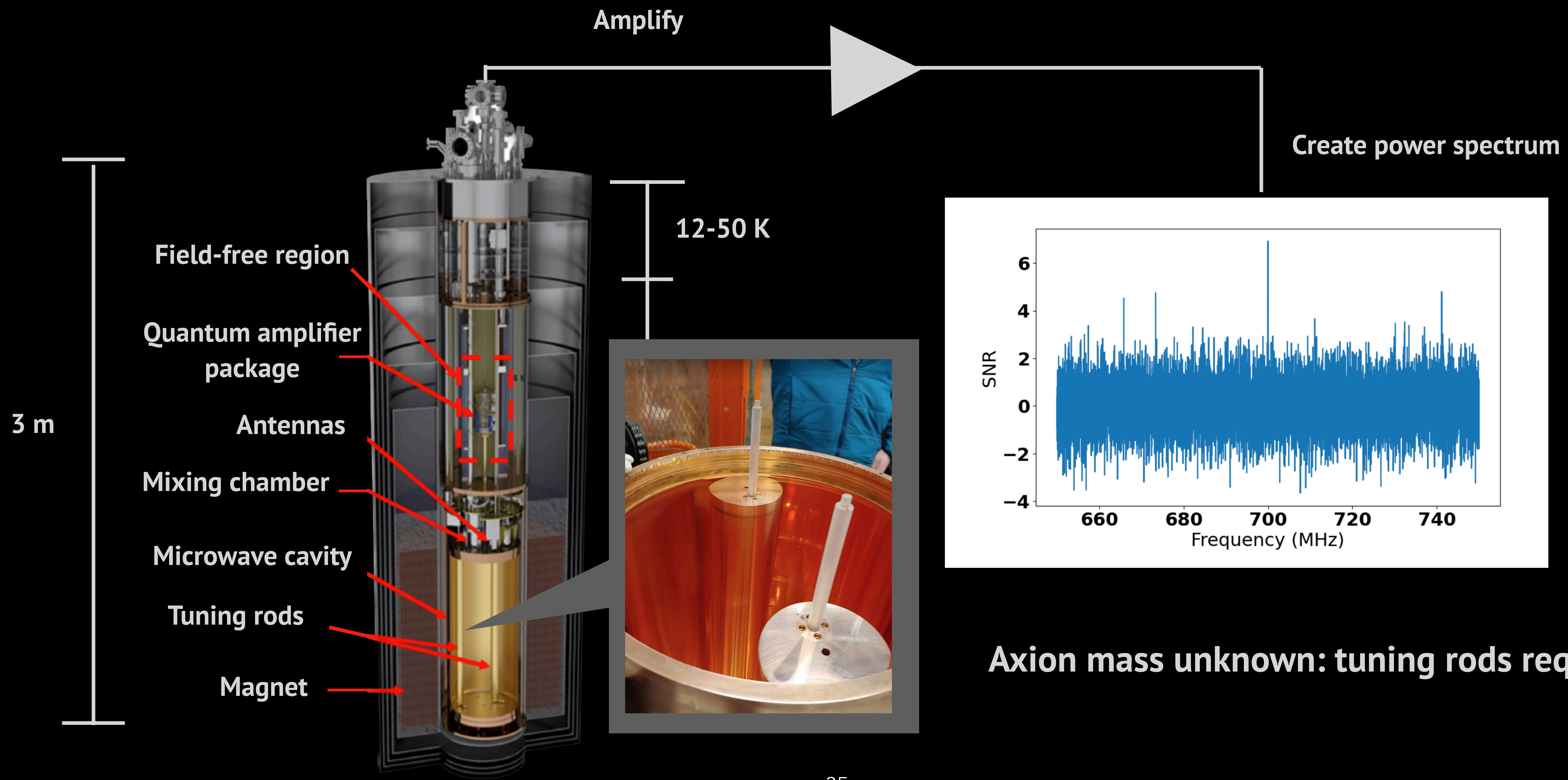
Cavity Haloscope



Cavity Haloscope

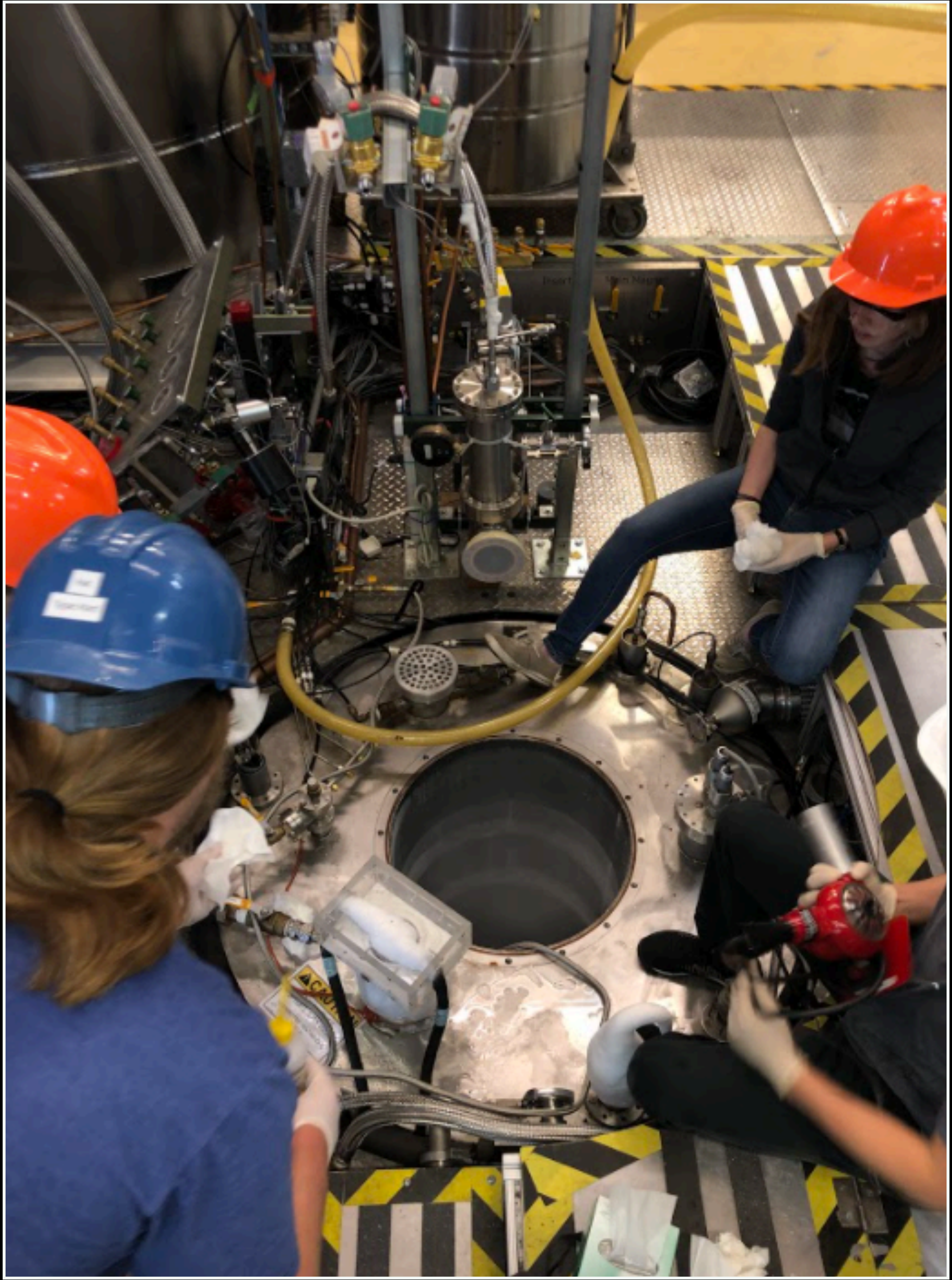


Cavity Haloscope

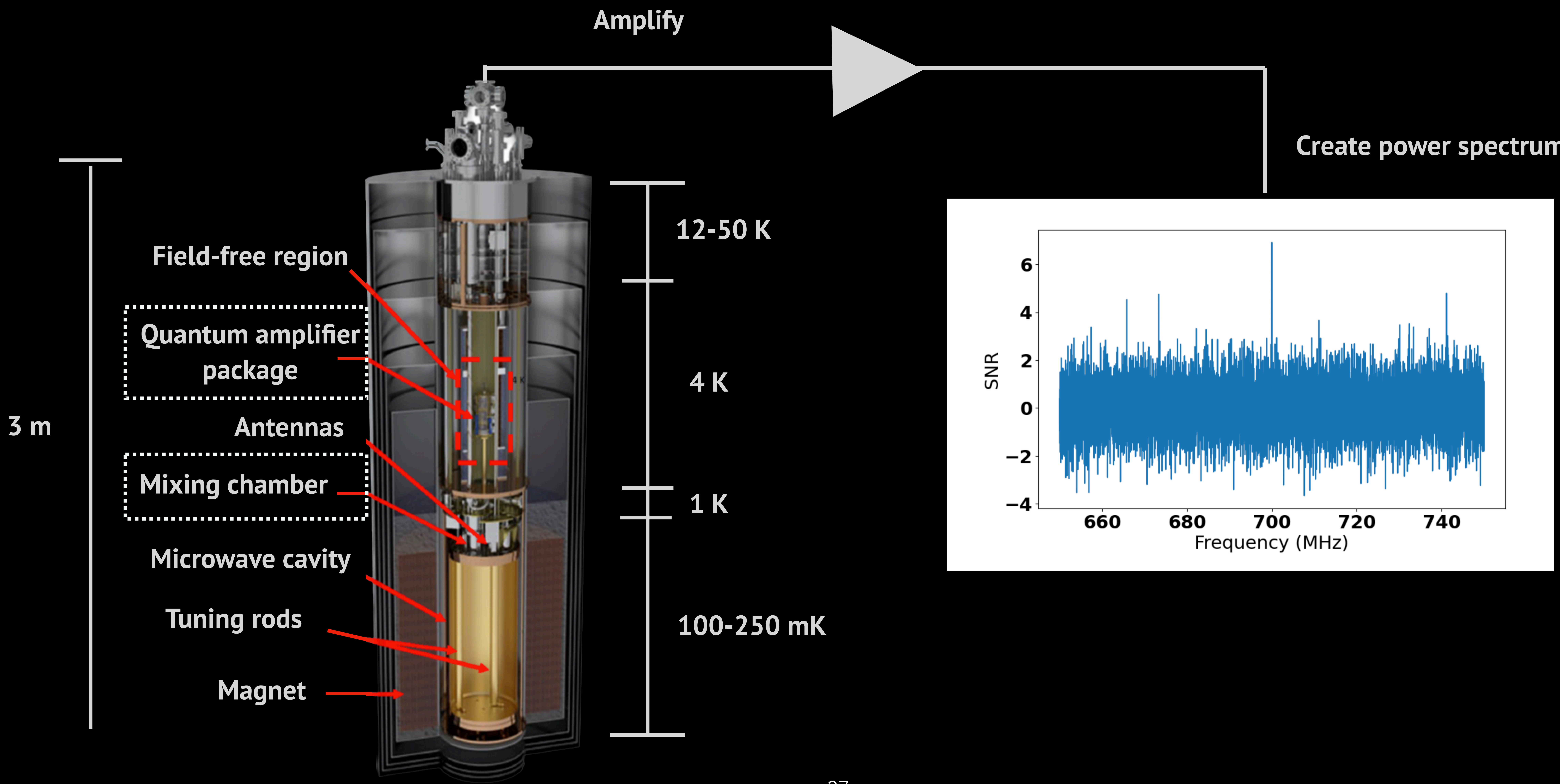


Axion mass unknown: tuning rods required

Cavity Haloscope

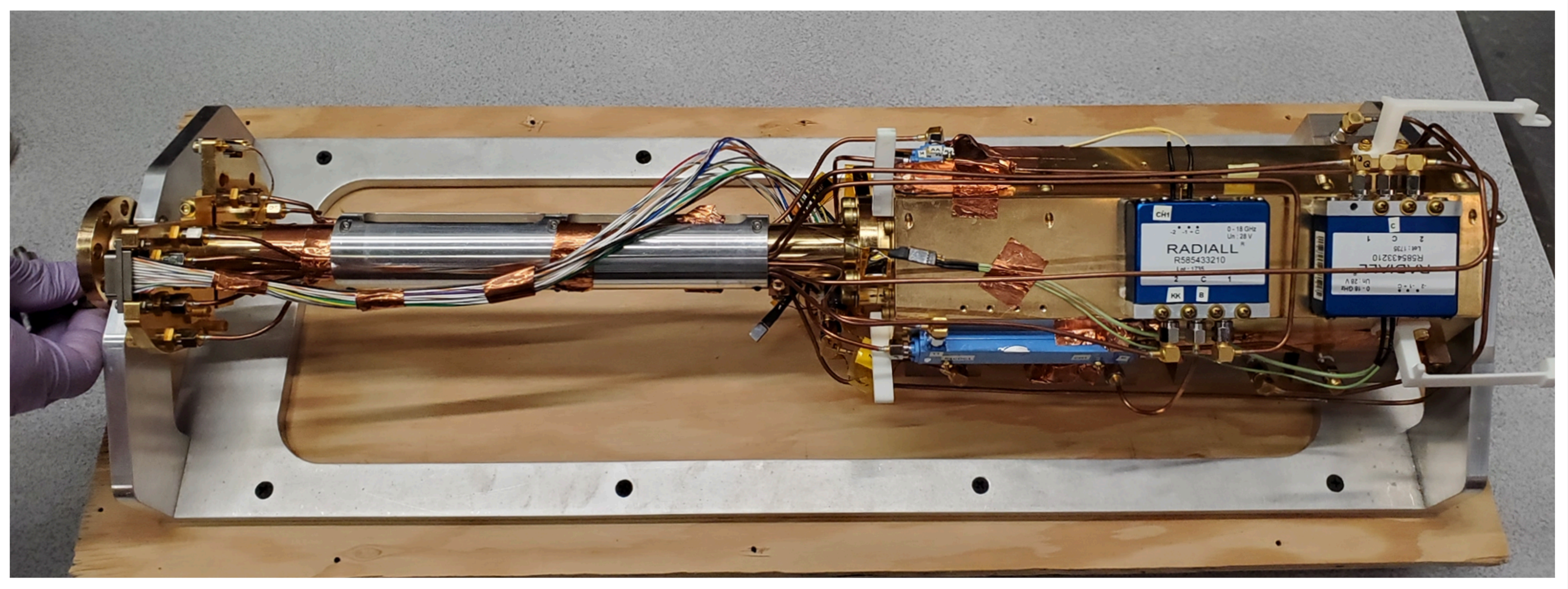


Ultra low noise receiver



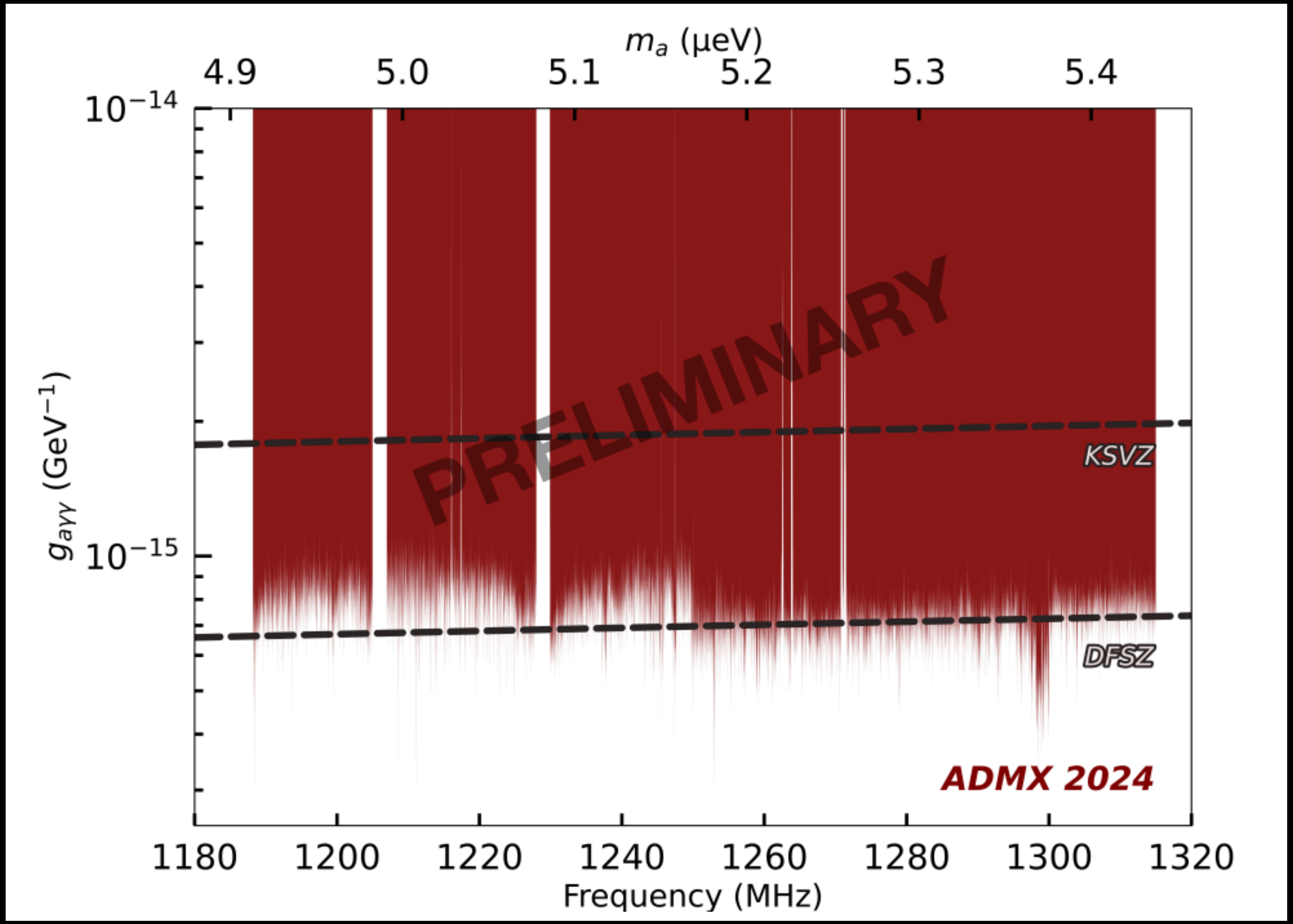
Josephson Parametric Amplifiers (JPAs)

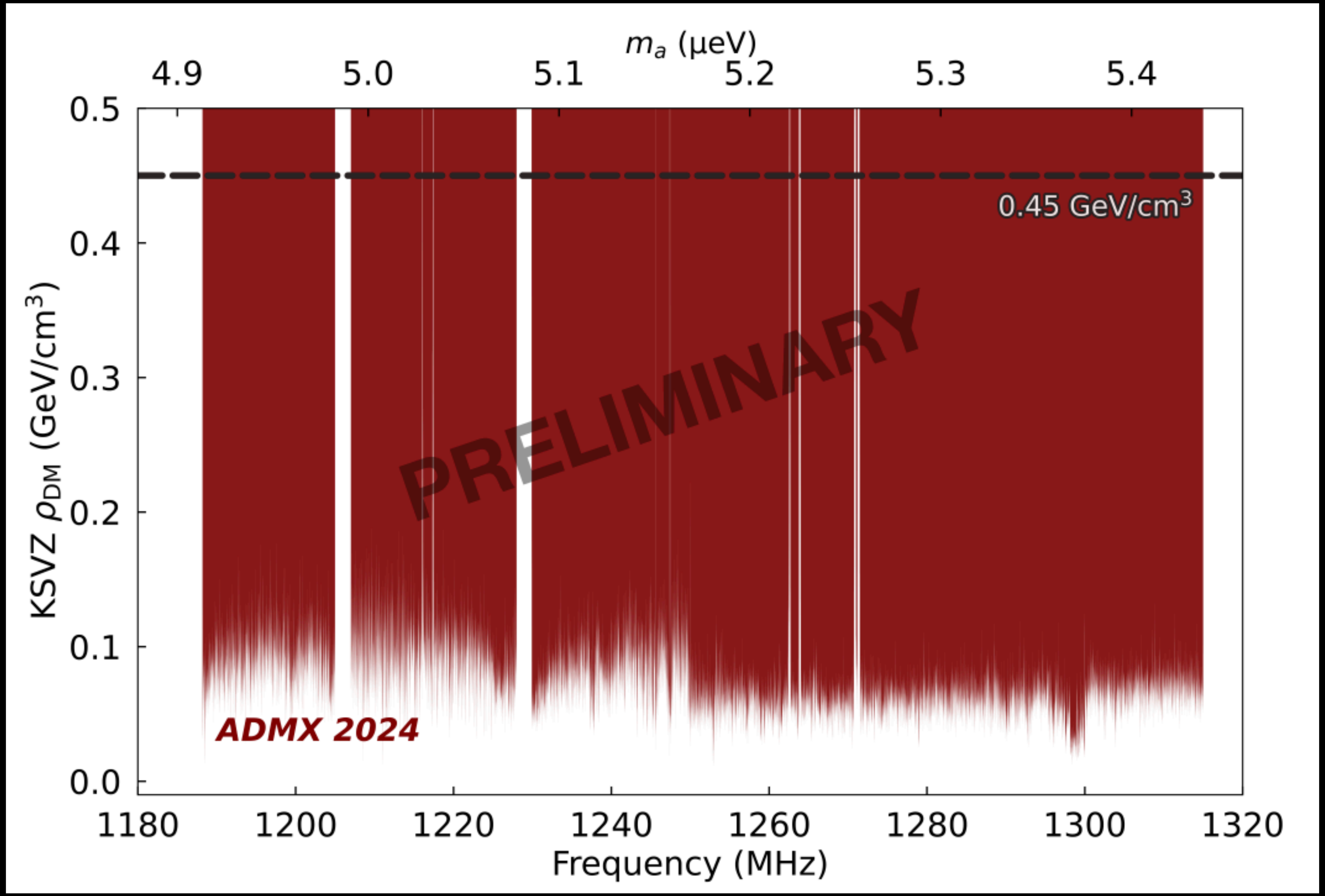
- Josephson parametric amplifiers are quantum amplifiers boost the signal strength while adding minimal noise
  - Made of superconducting circuits
  - Requires nanofabrication



Yanjie Qiu, Siddiqi Group, UC Berkeley

ADMX Recent Exclusion Limits (Preliminary)

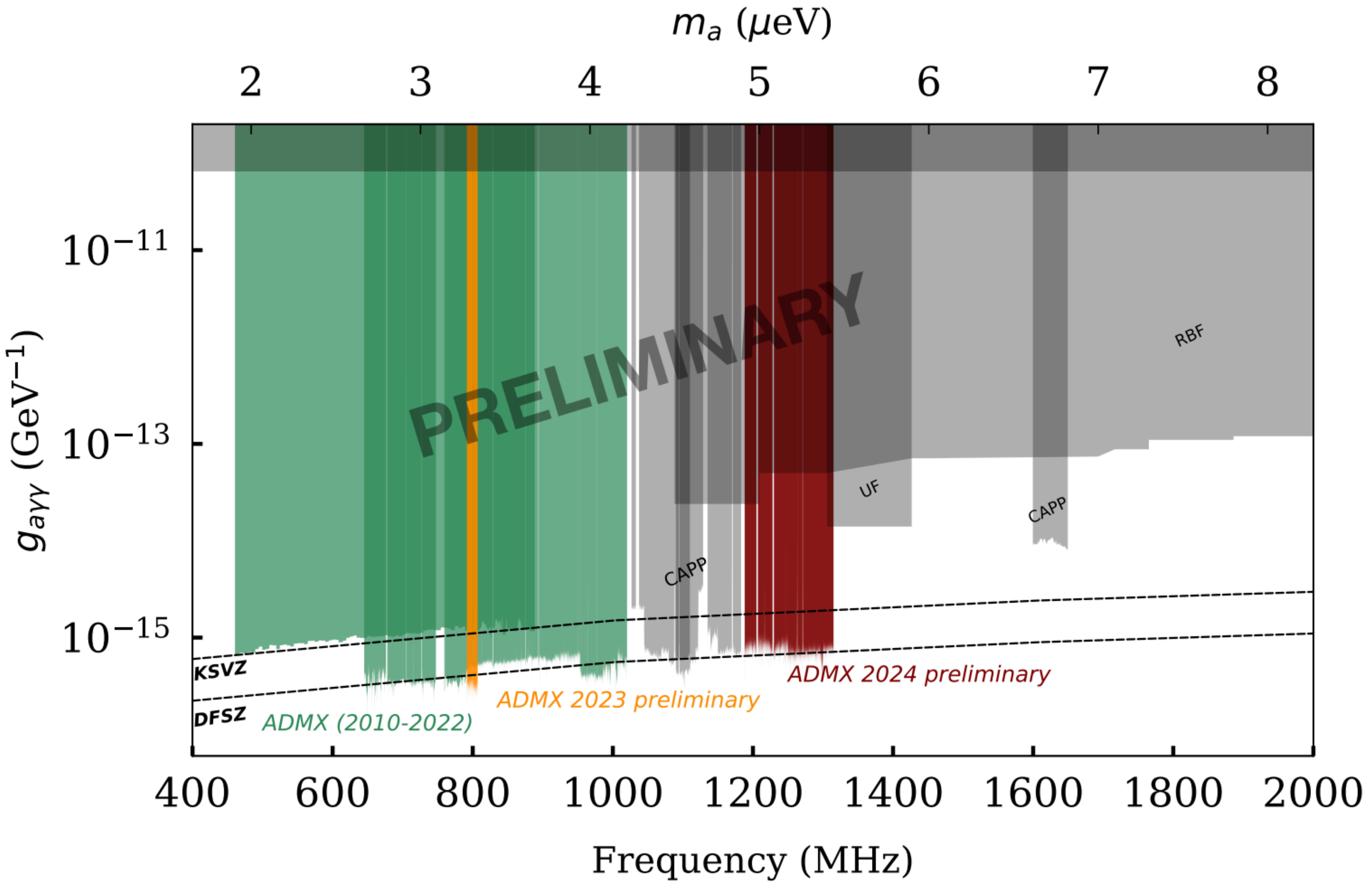




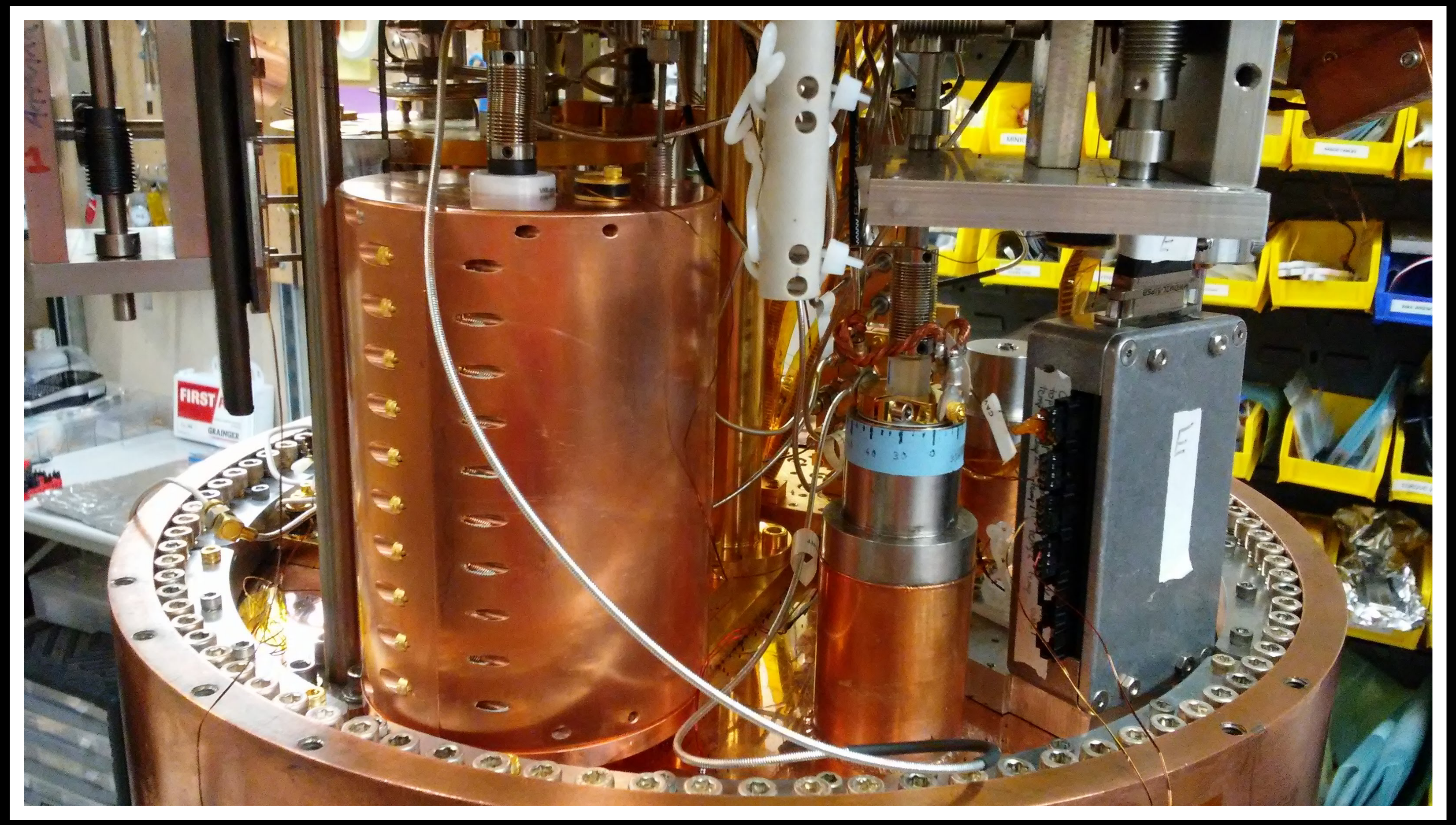
ρ_{DM} = 0.45 GeV^{-1}

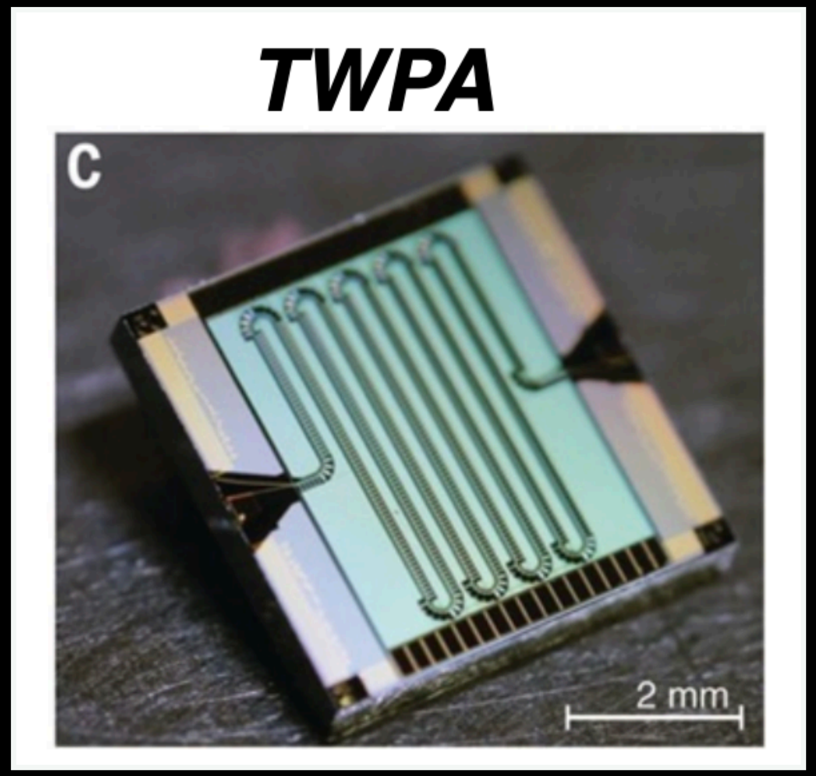
$g_{a\gamma\gamma}$ = -0.97

ADMX Exclusion Limits (in context)

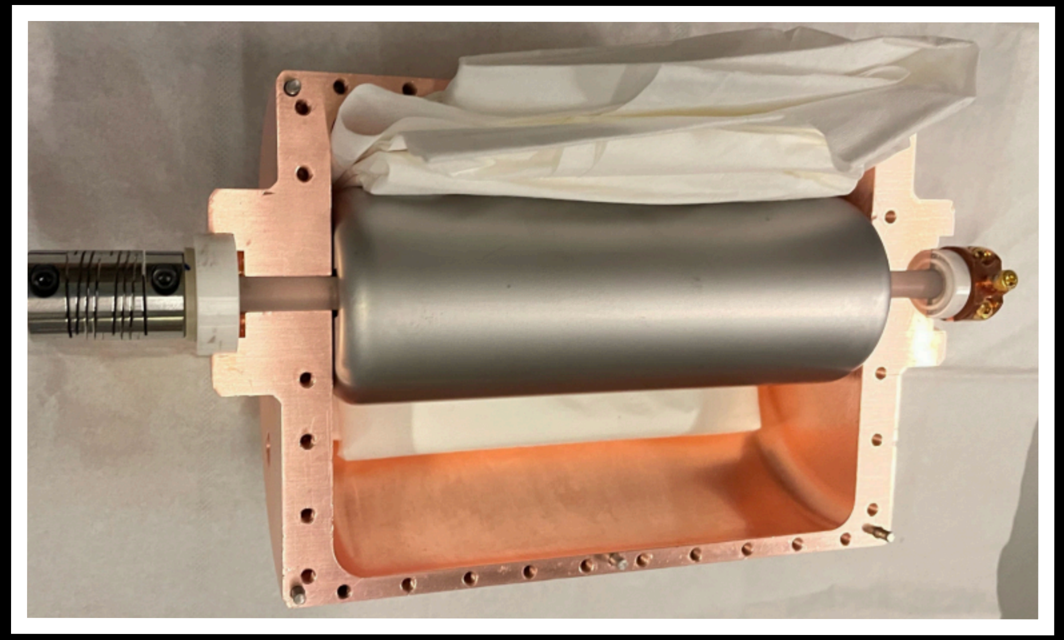


ADMX high frequency prototype

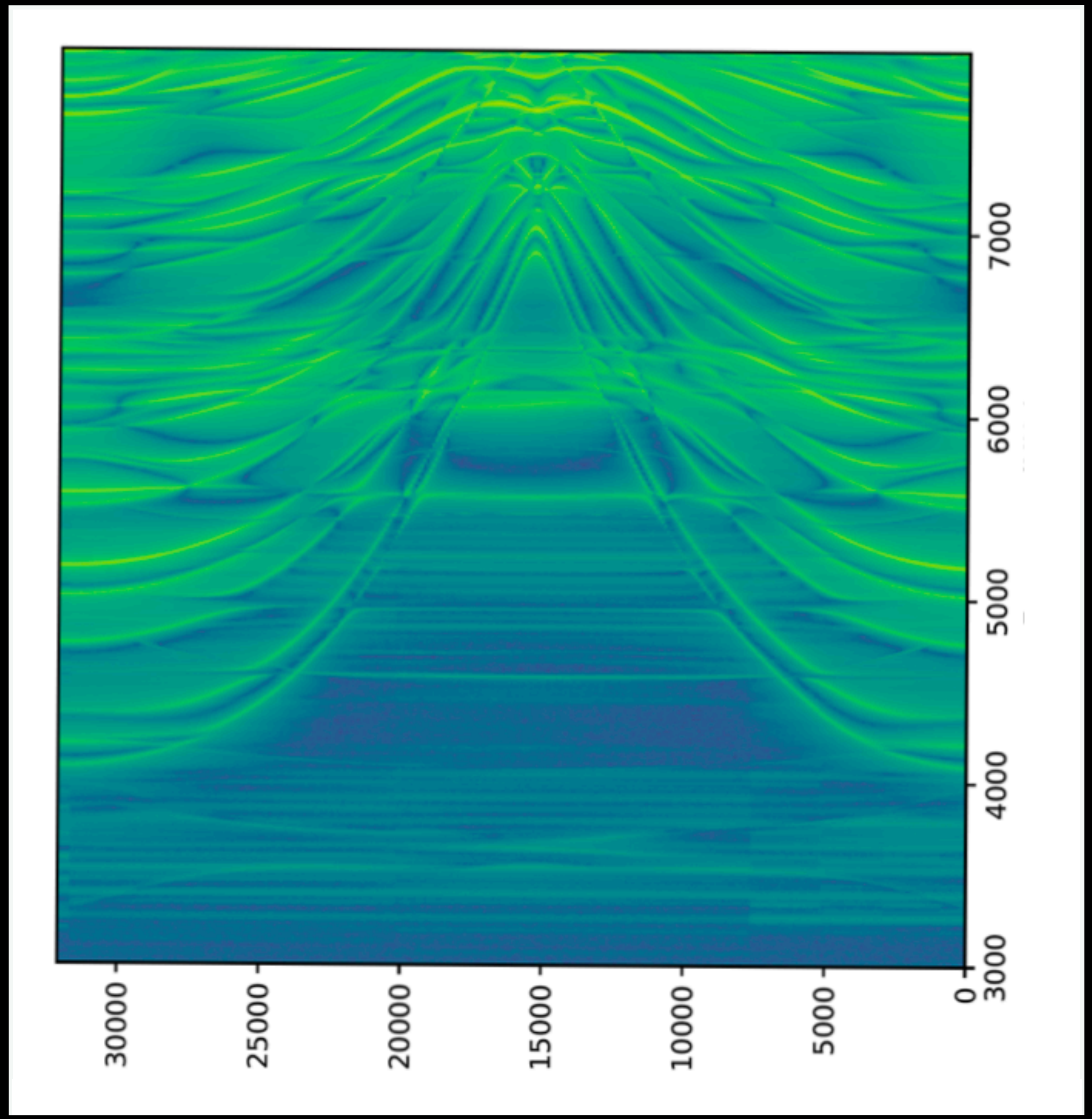




Nb3Sn on Niobium →



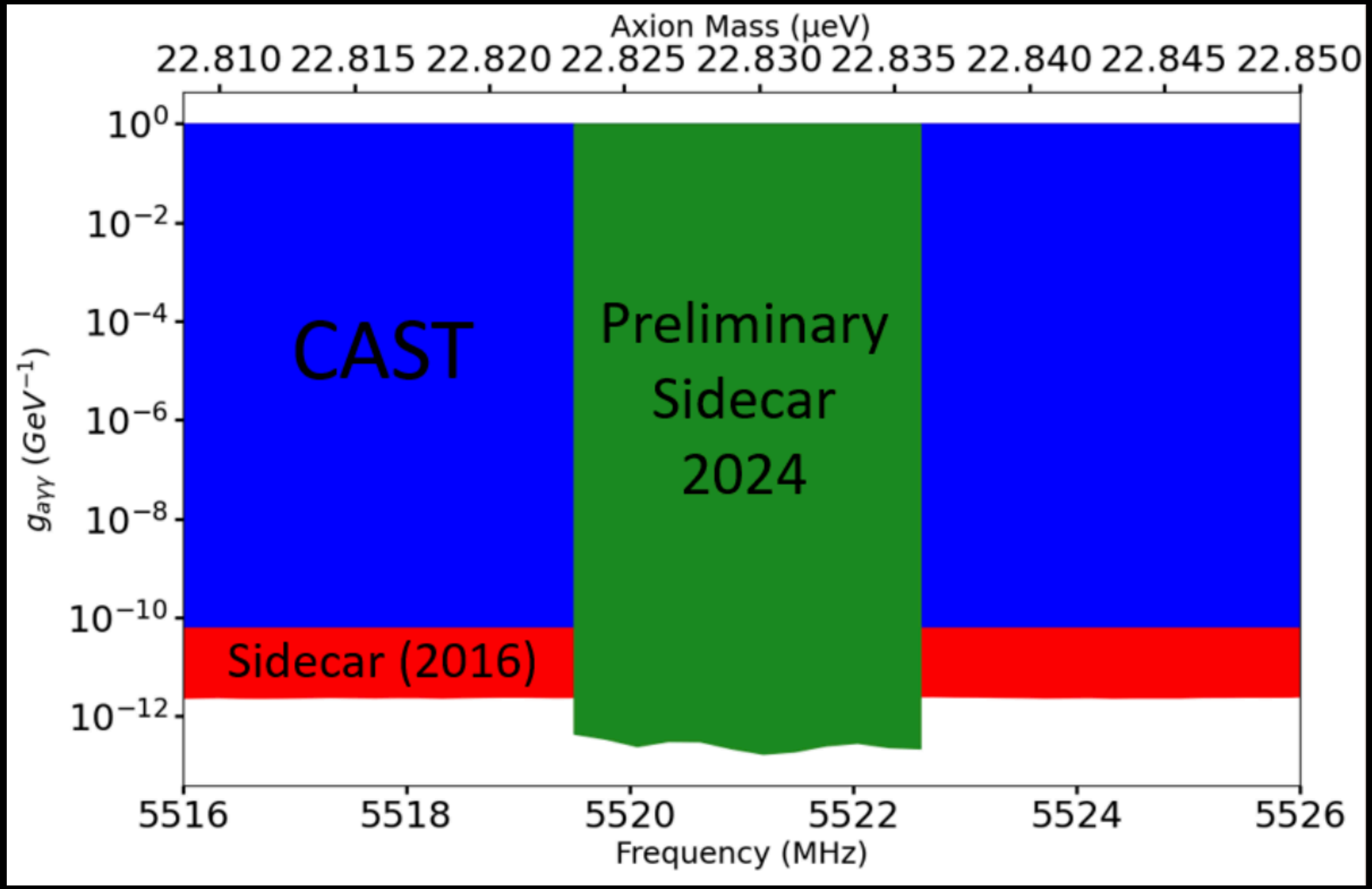
Sidecar mode map



Sidecar is a high frequency (4-6 GHz) prototyping cavity that sits on top of the main cavity.

- Run 1D Testing:
  - Traveling Wave Parametric Amplifier (TWPA)
  - Clamshell cavity design
  - Piezo motors for antenna and tuning rod
  - Nb3Sn film sputtered on pure Niobium substrate by SQMS

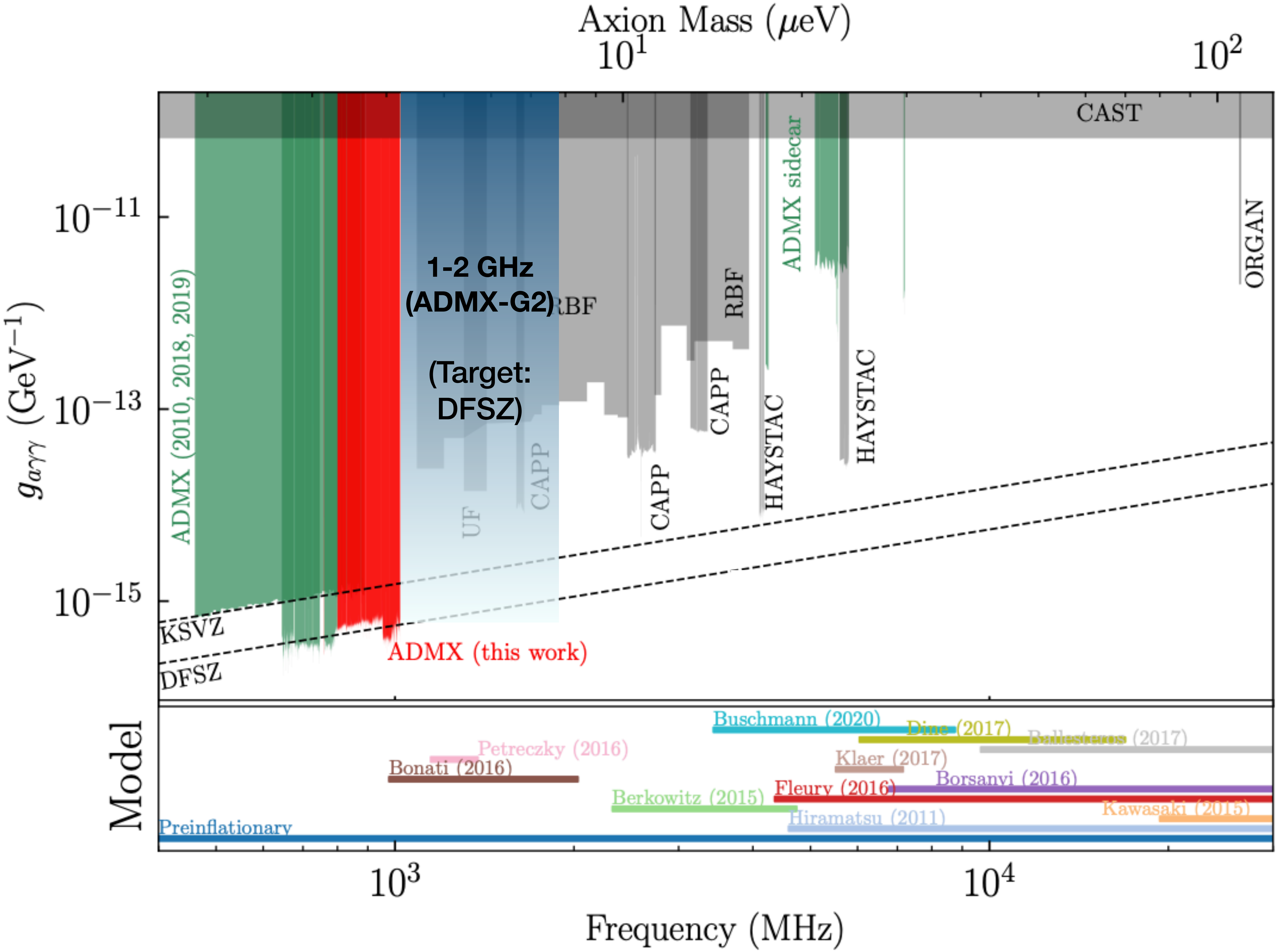
Testing of a superconducting tuning rod in sidecar



Contact: thomas.braine@pnnl.gov

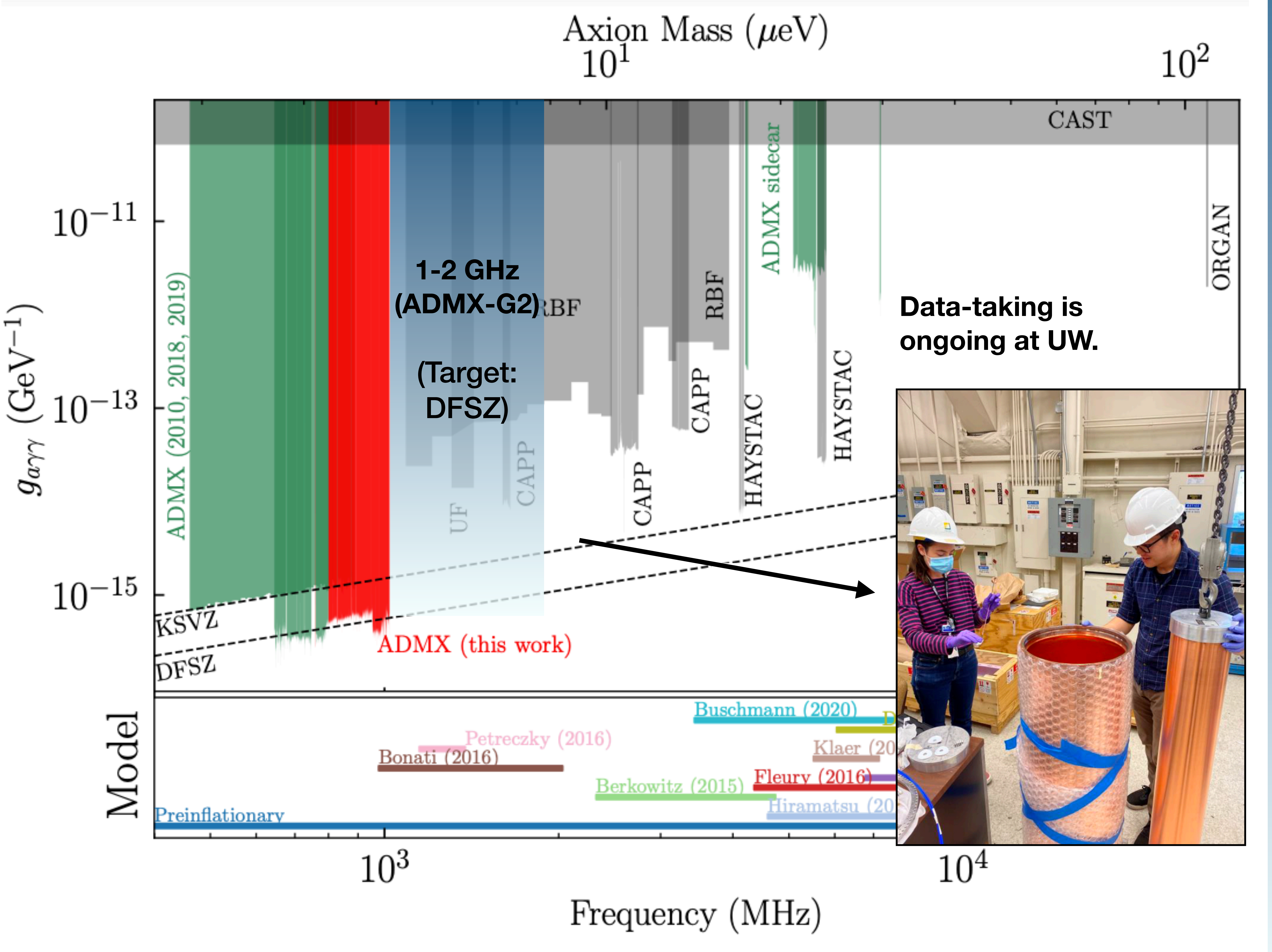
Sidecar continues taking data at 5.2-5.6 GHz at 10x KSVZ with a Nb3Tn superconducting tuning rod!

ADMX-G2



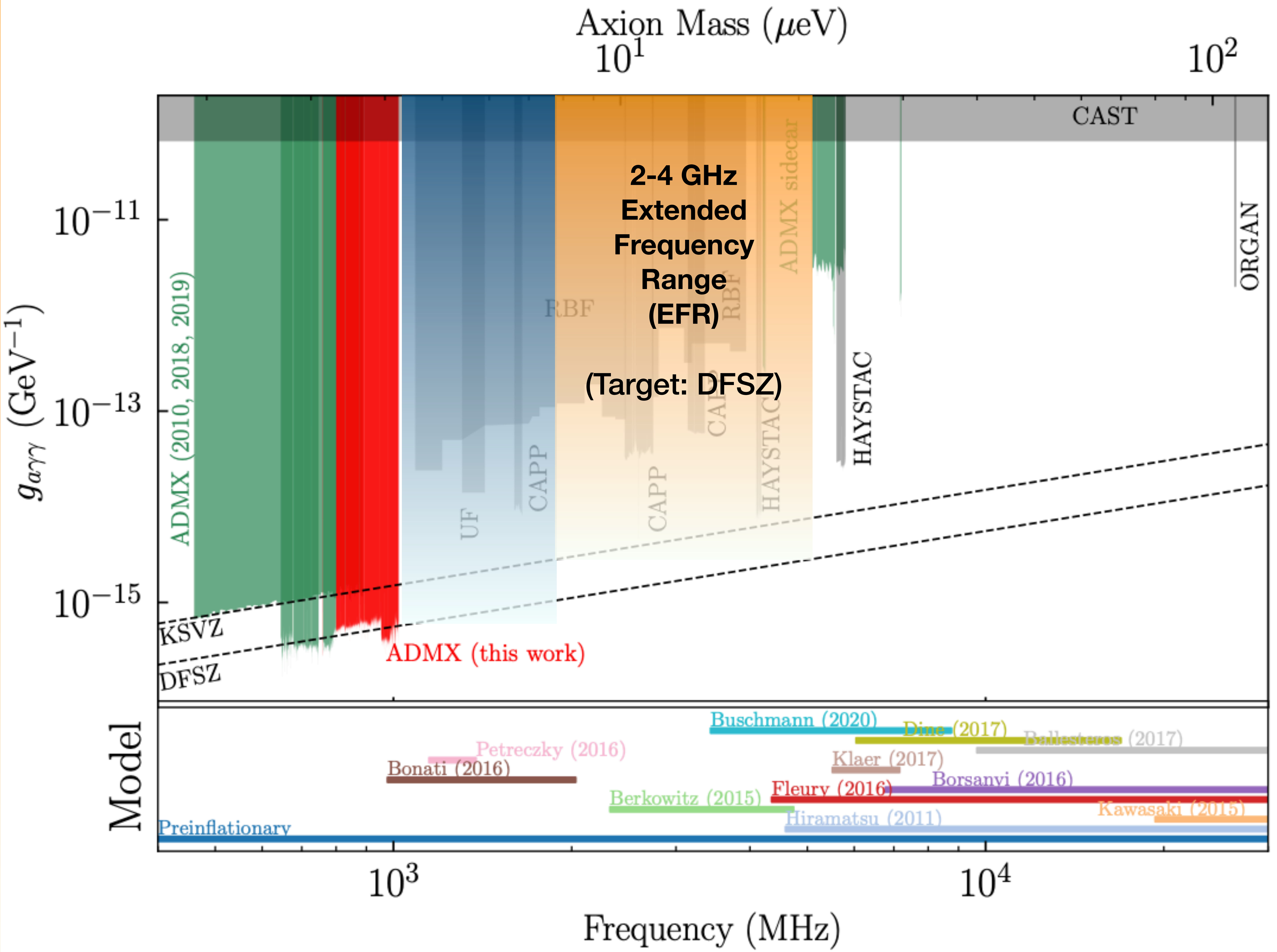
Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
RBF
RBF
ADMX sidecar
CAPP
CAPP
CAPP
UF
HAYSTAC
HAYSTAC
ADMX (2010, 2018, 2019)
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-13}
10^{-15}
KSVZ
DFSZ
ADMX (this work)
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)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

ADMX-G2



Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
ADMX sidecar
RBF
RBF
CAPP
CAPP
CAPP
HAYSTAC
HAYSTAC
UF
ADMX (2010, 2018, 2019)
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
Data-taking is
ongoing at UW.
10^{-11}
10^{-13}
10^{-15}
$g_{a\gamma\gamma}$ (GeV^{-1})
KSVZ
DFSZ
ADMX (this work)
Model
Buschmann (2020)
Petreczky (2016)
Klaer (20
Bonati (2016)
Fleury (2016)
Berkowitz (2015)
Hiramatsu (20
Preinflationary
10^3
10^4
Frequency (MHz)

ADMX-EFR


Axion Mass (μeV)
10^1
10^2
CAST
2-4 GHz
Extended
Frequency
Range
(EFR)
(Target: DFSZ)
ADMX sidecar
ORGAN
HAYSTAC
RBF
UF
CAPP
ADMX (2010, 2018, 2019)
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-13}
10^{-15}
KSVZ
DFSZ
ADMX (this work)
Model
Buschmann (2020)
Dine (2017)
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Bonati (2016)
Borsanyi (2016)
Berkowitz (2015)
Fleury (2016)
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

More scan rate considerations

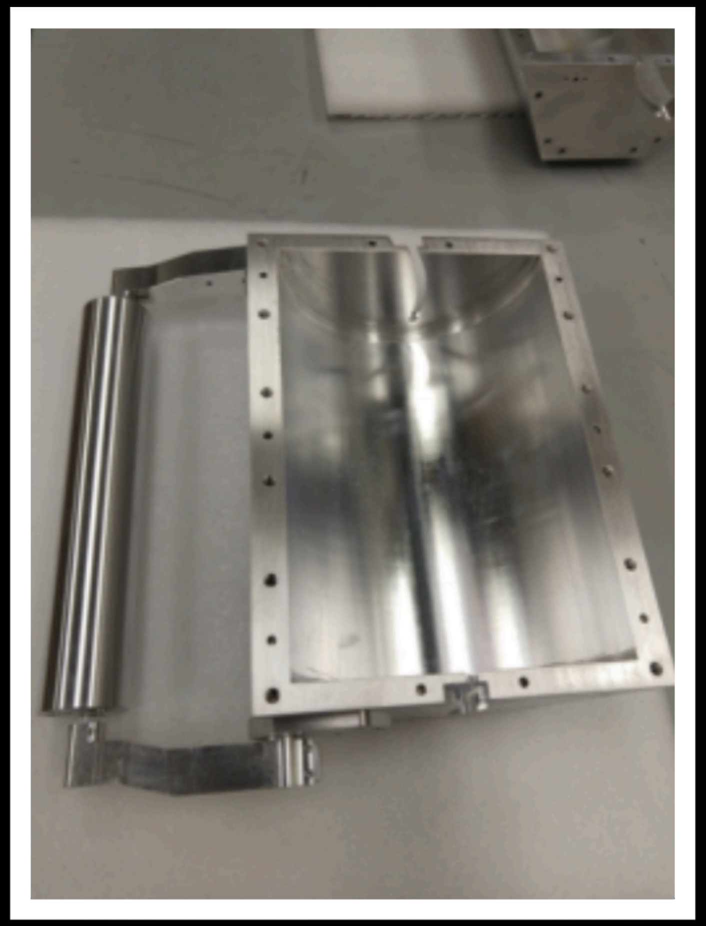
Volume decreases like $V \sim \frac{1}{f^3}$

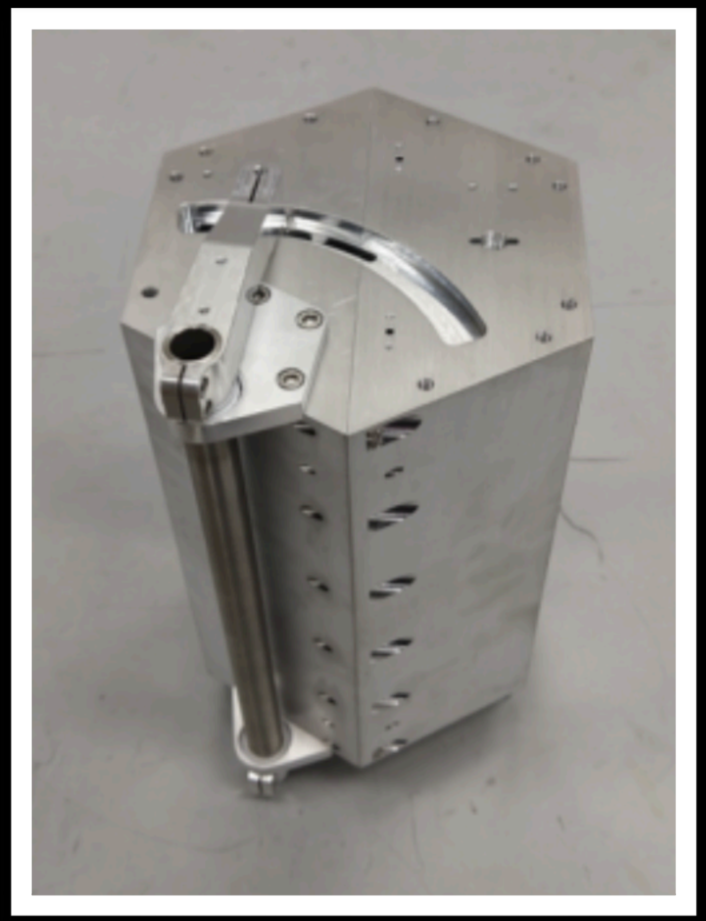
Quality factor decreases like $Q \sim \frac{1}{f^{2/3}}$

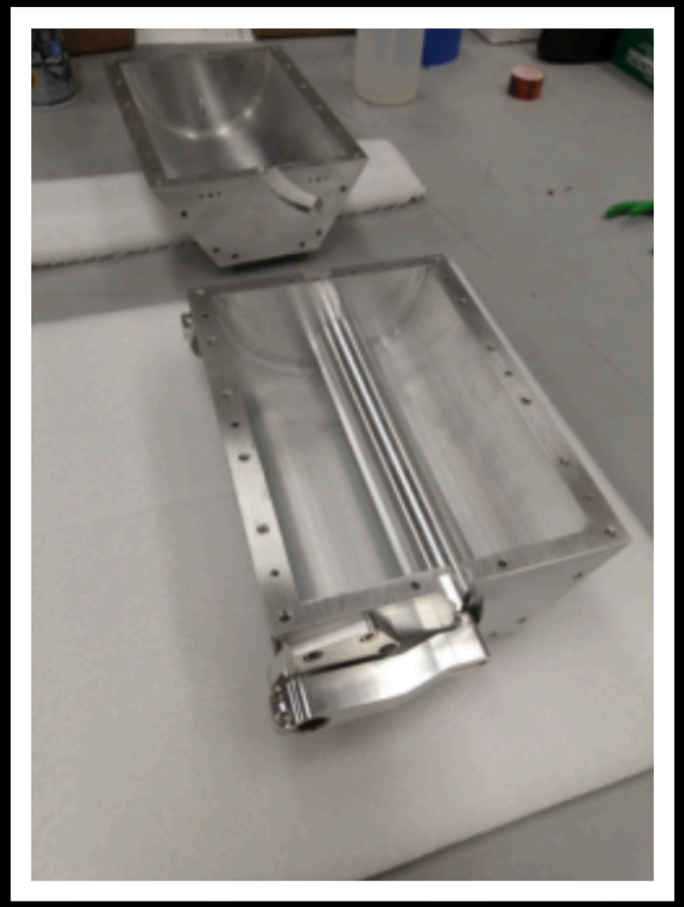
Noise power increases like $T_{\text{amp}} \sim f$

High frequencies are a real challenge!

ADMX EFR (2-4 GHz)



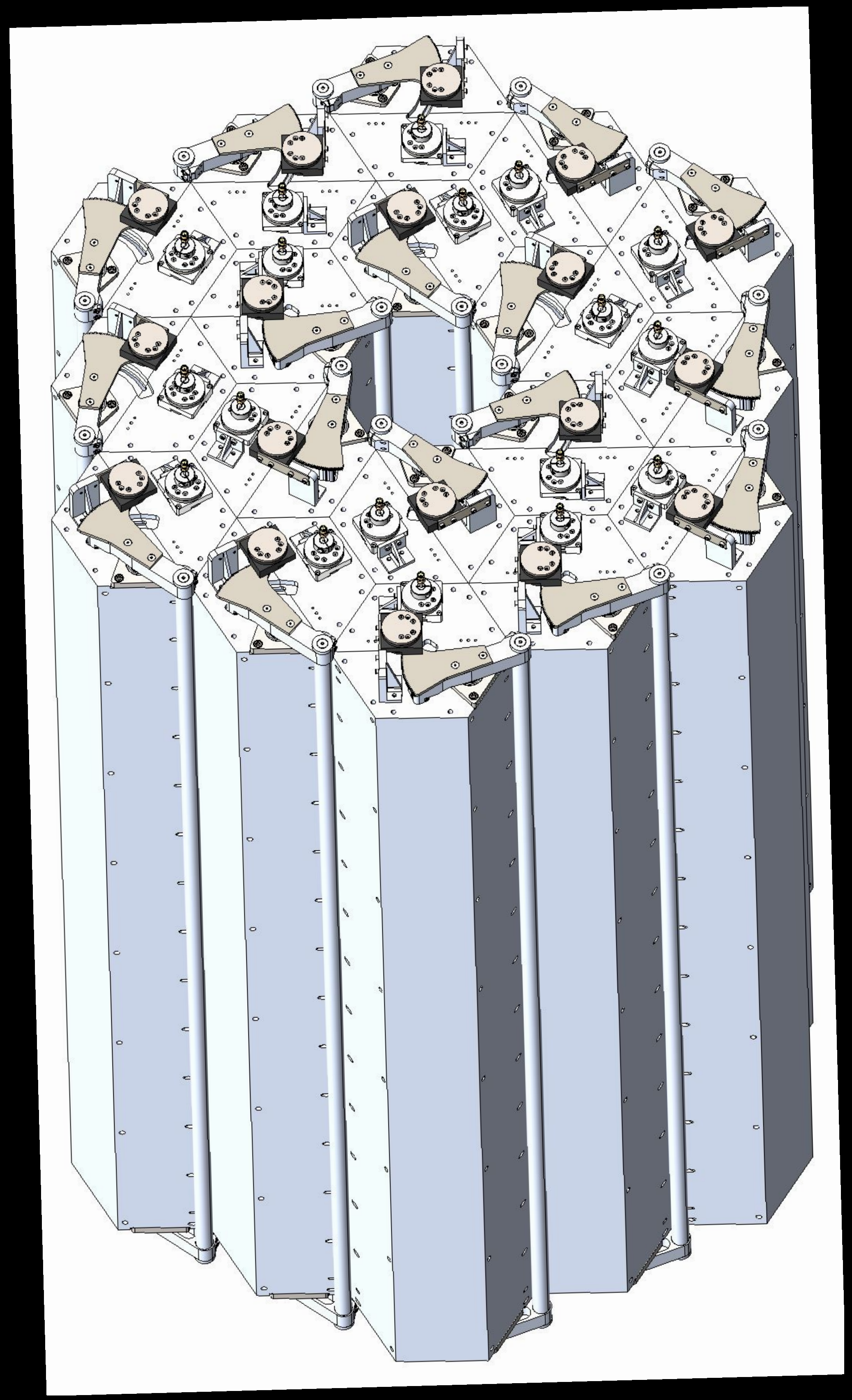




Prototype
cavity
testing

18-JPA receiver

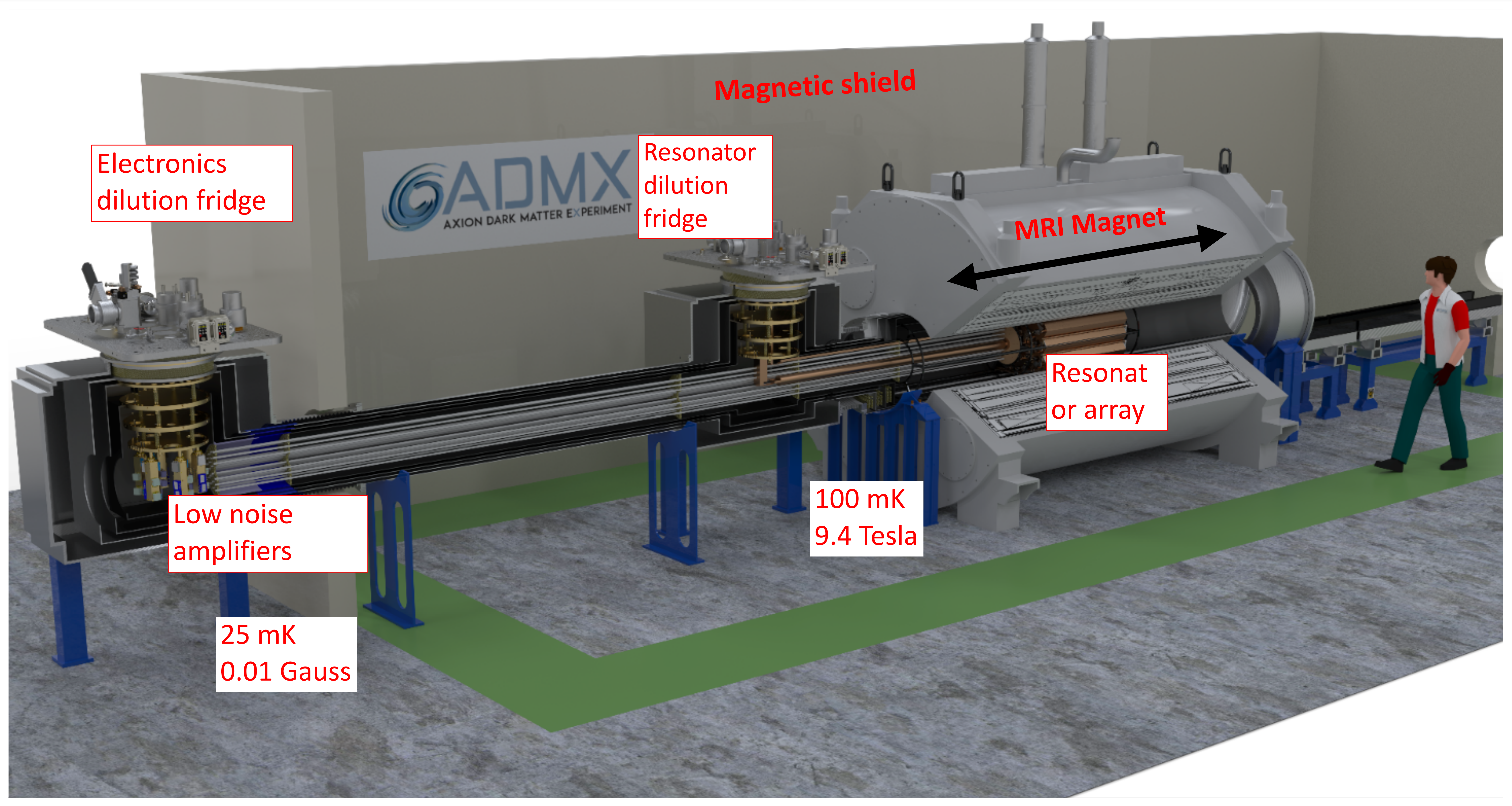
9.4 T Magnet



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?



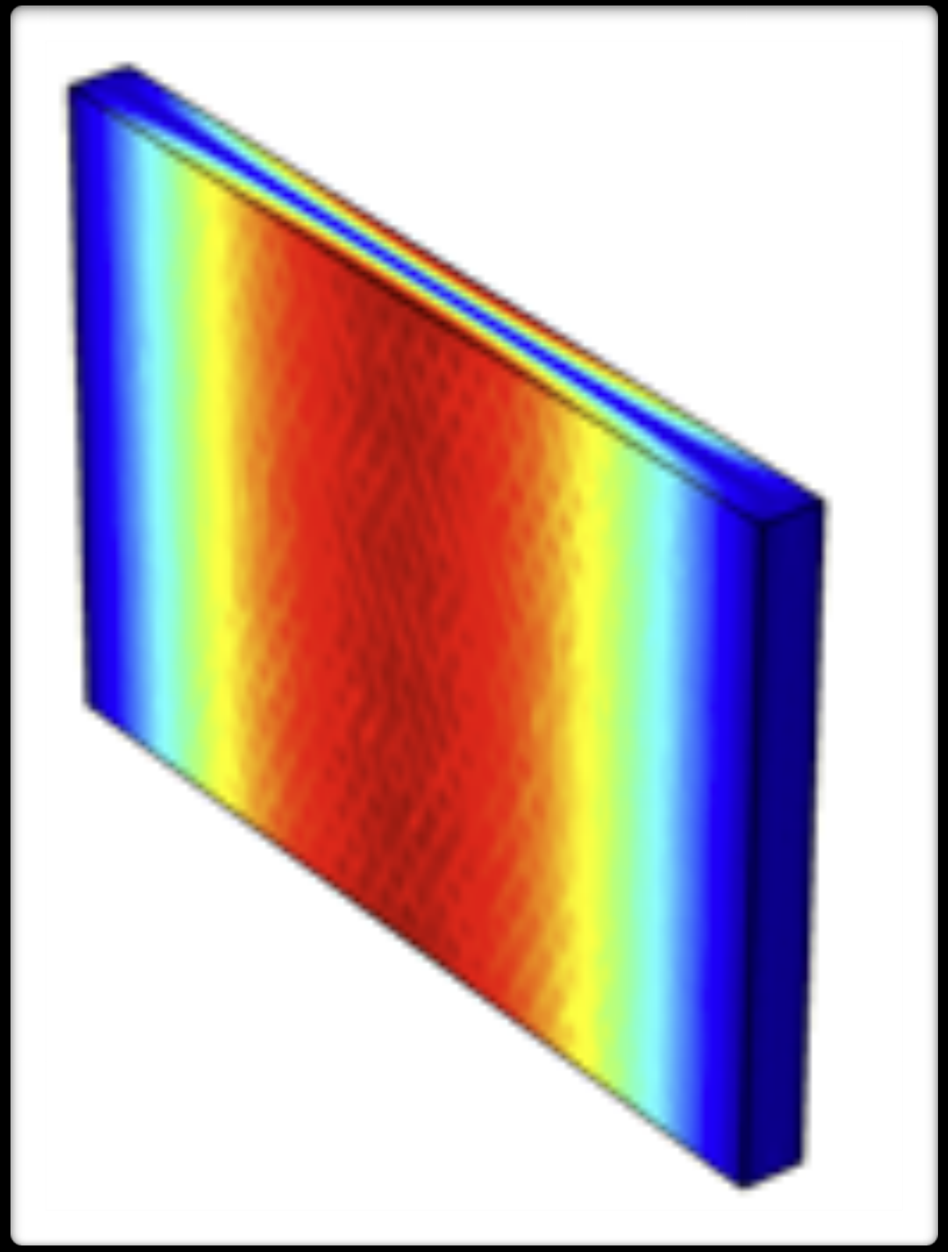
(ADMX EFR Design)

Dark Matter New Initiatives

ADMX-VERA (4-20 GHz)

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

Decouple frequency and volume.



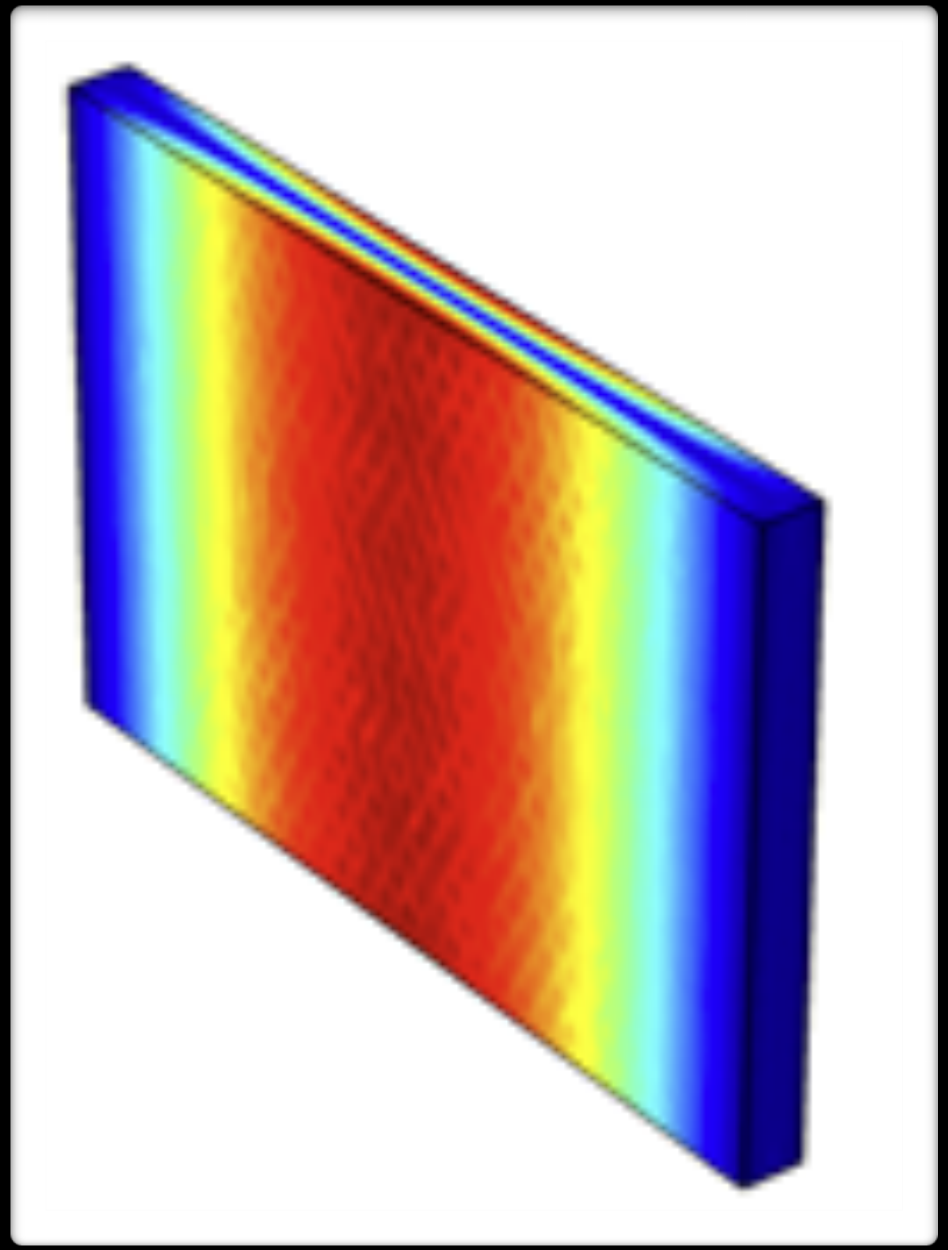
Volume can be scaled arbitrarily in other dimensions

ADMX-VERA (4-20 GHz)

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

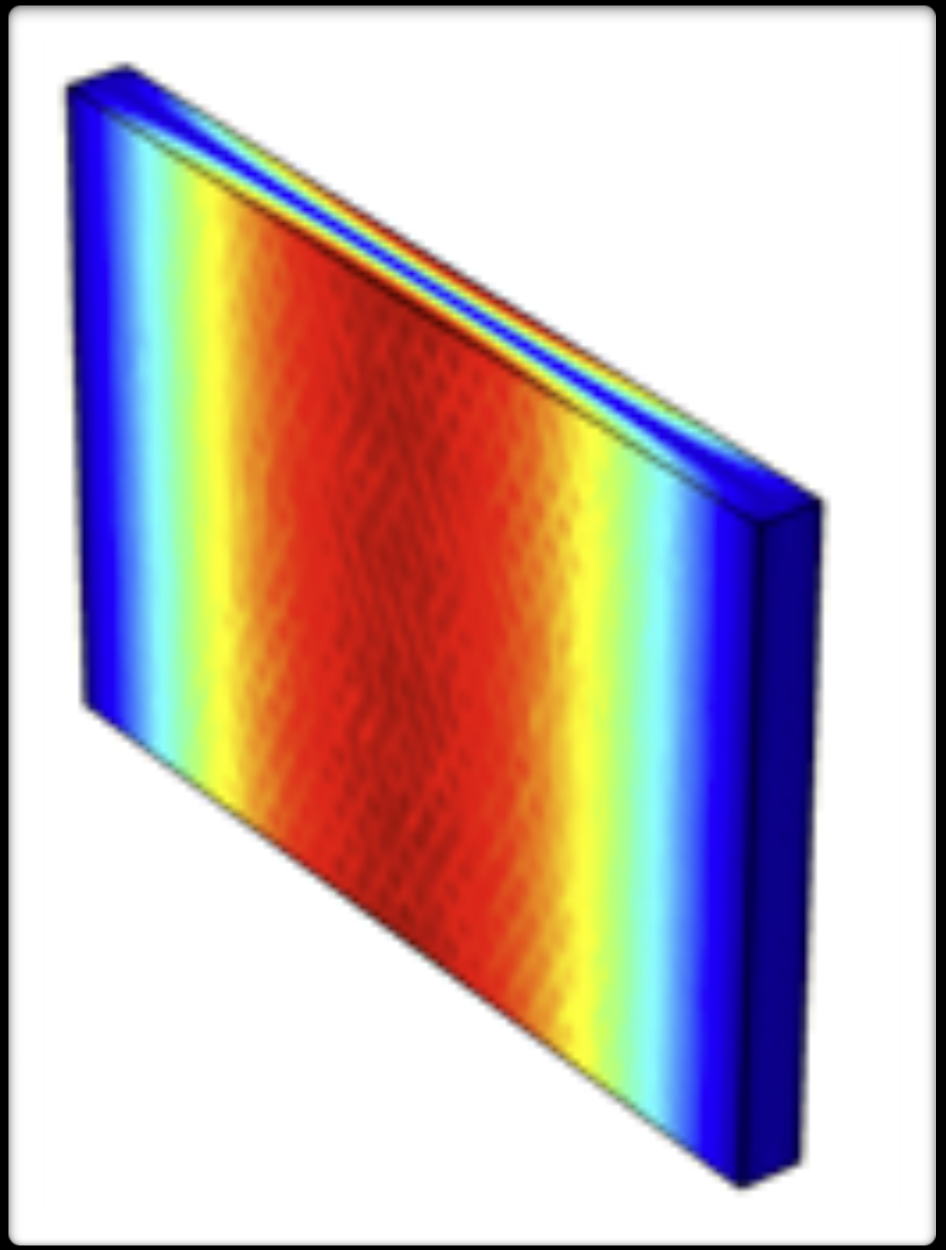
TM010 mode still supported.

ADMX-VERA (4-20 GHz)

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

Decouple frequency and volume.

Volume can be scaled arbitrarily in other dimensions

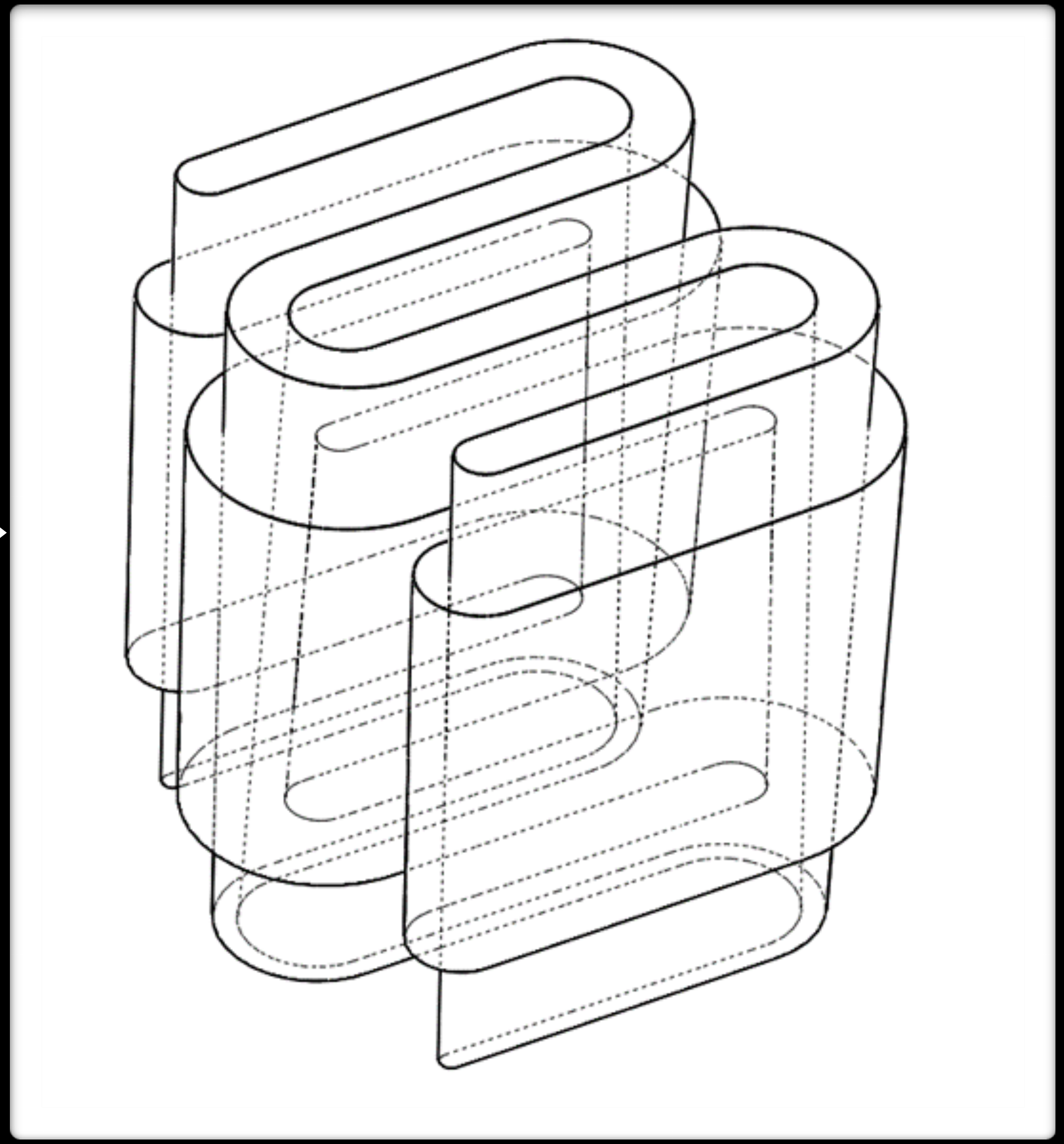


Wrap

TM010 mode still supported.

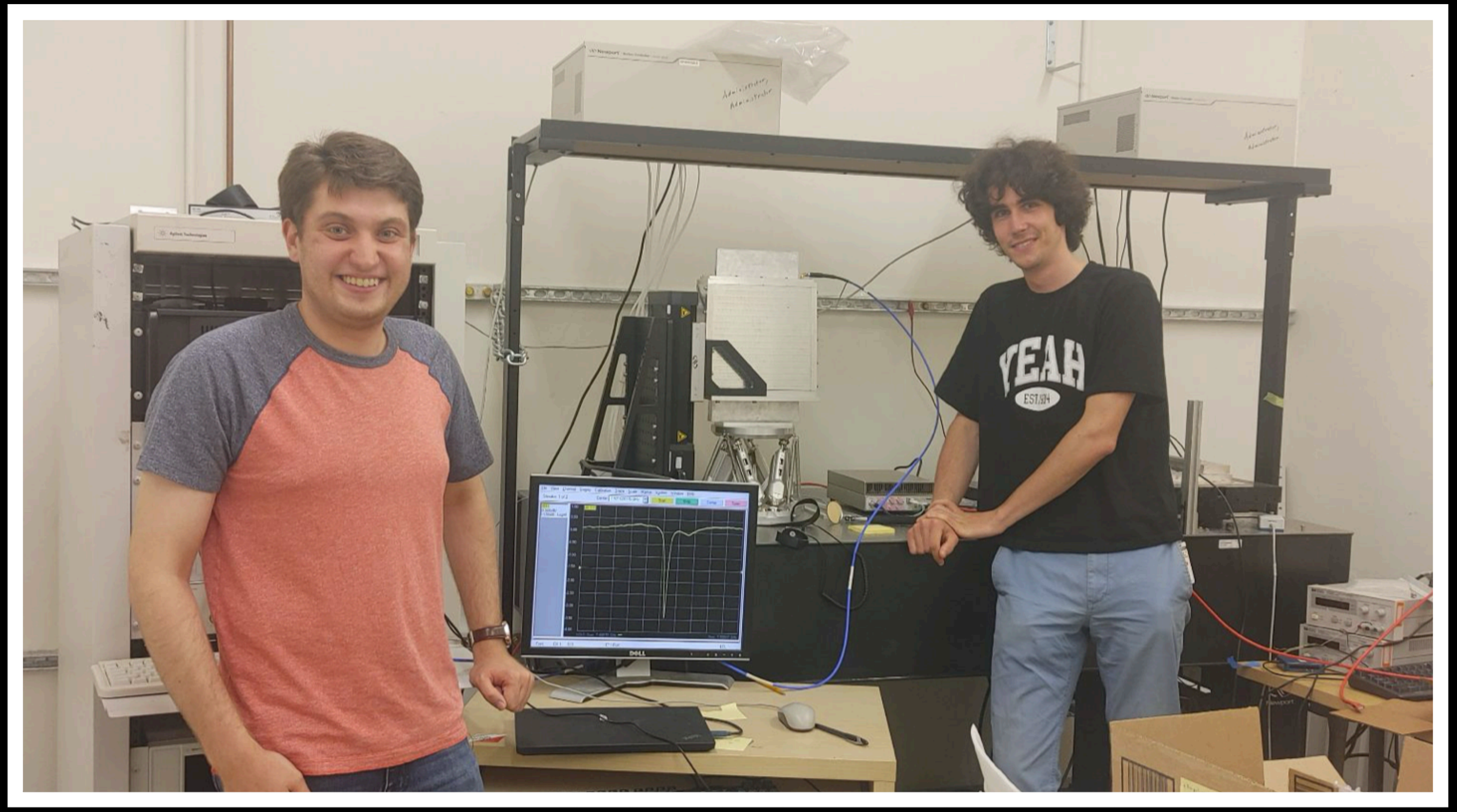
Convolute

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

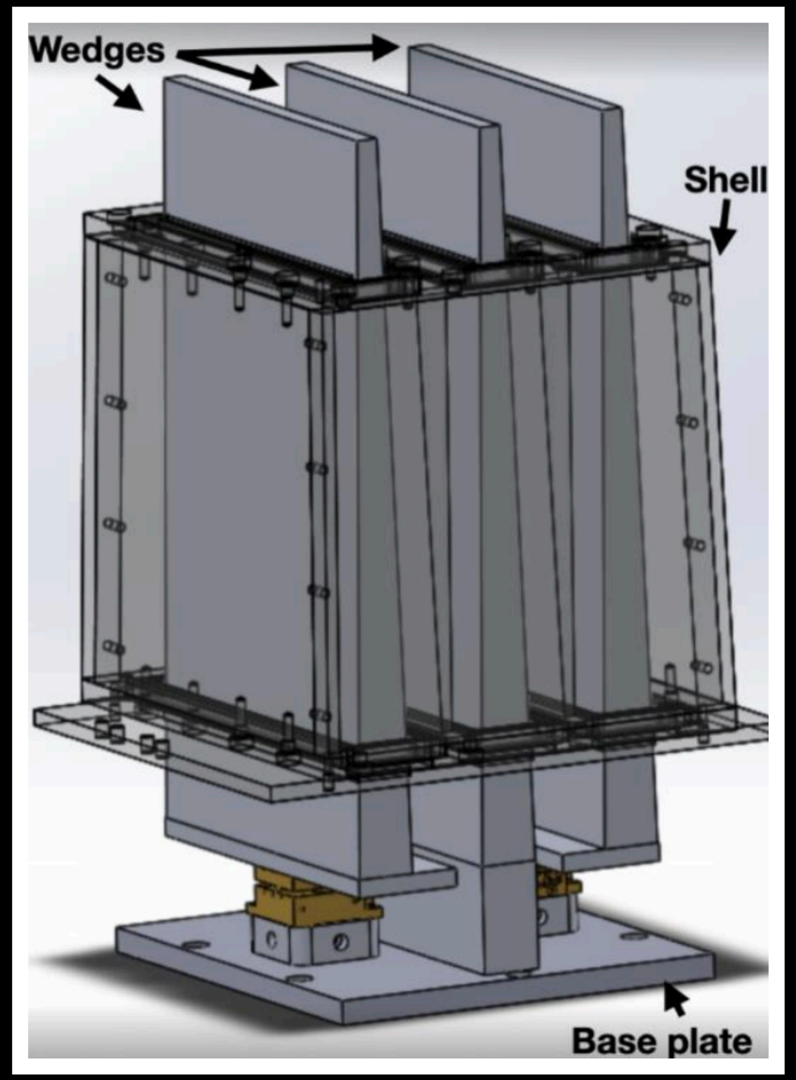


ADMX-VERA (4-20 GHz)

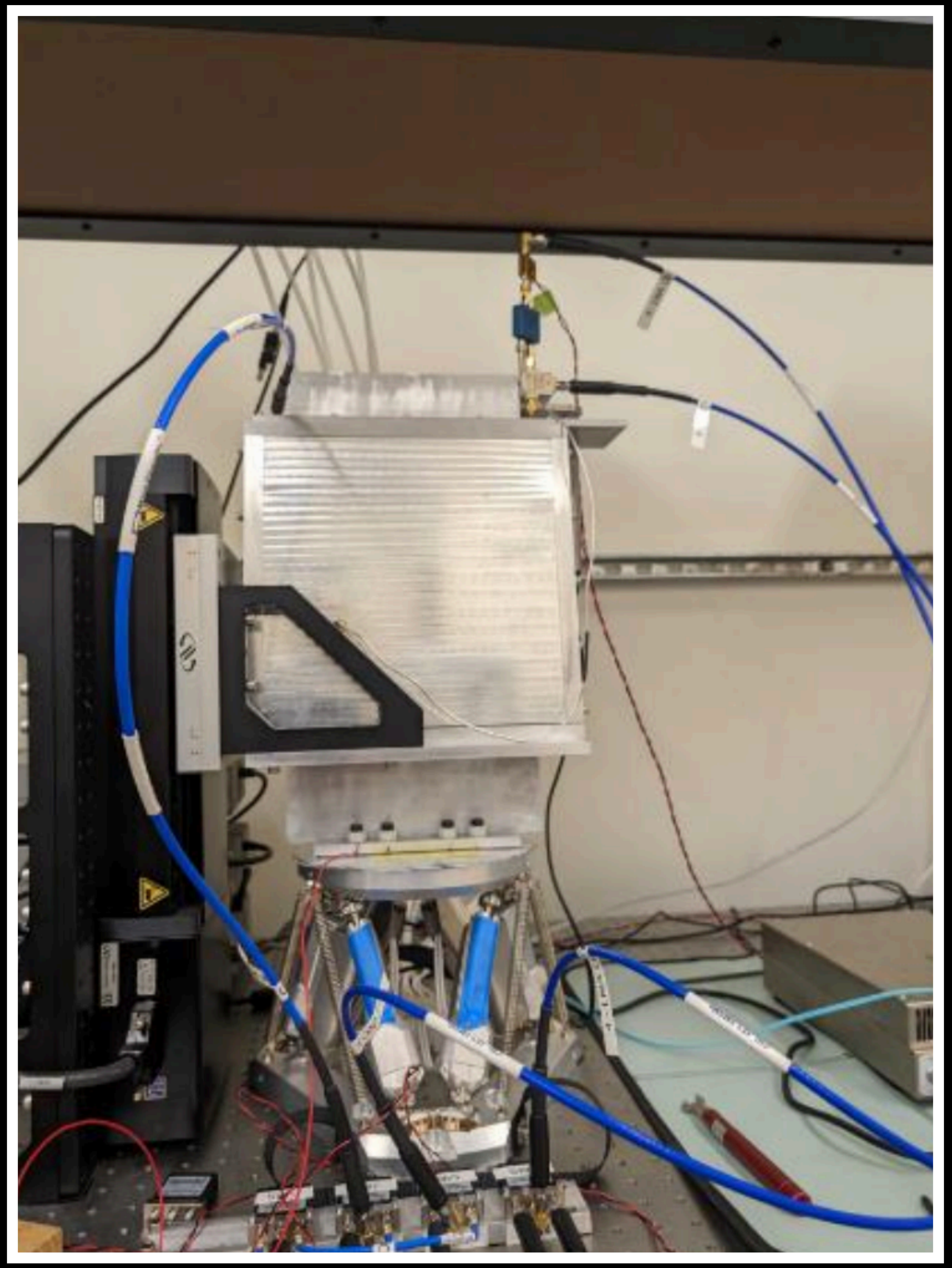
- Warm hidden photon search at Stanford.
- Cryogenic hidden photon search intended for SLAC.
- Opportunity to test new quantum sensors.



Stanford hidden photon search



Triplet wedge by Sephora Ruppert



T. Dyson et al., Phys. Rev. Applied 21, L041002

Suppose we find it!

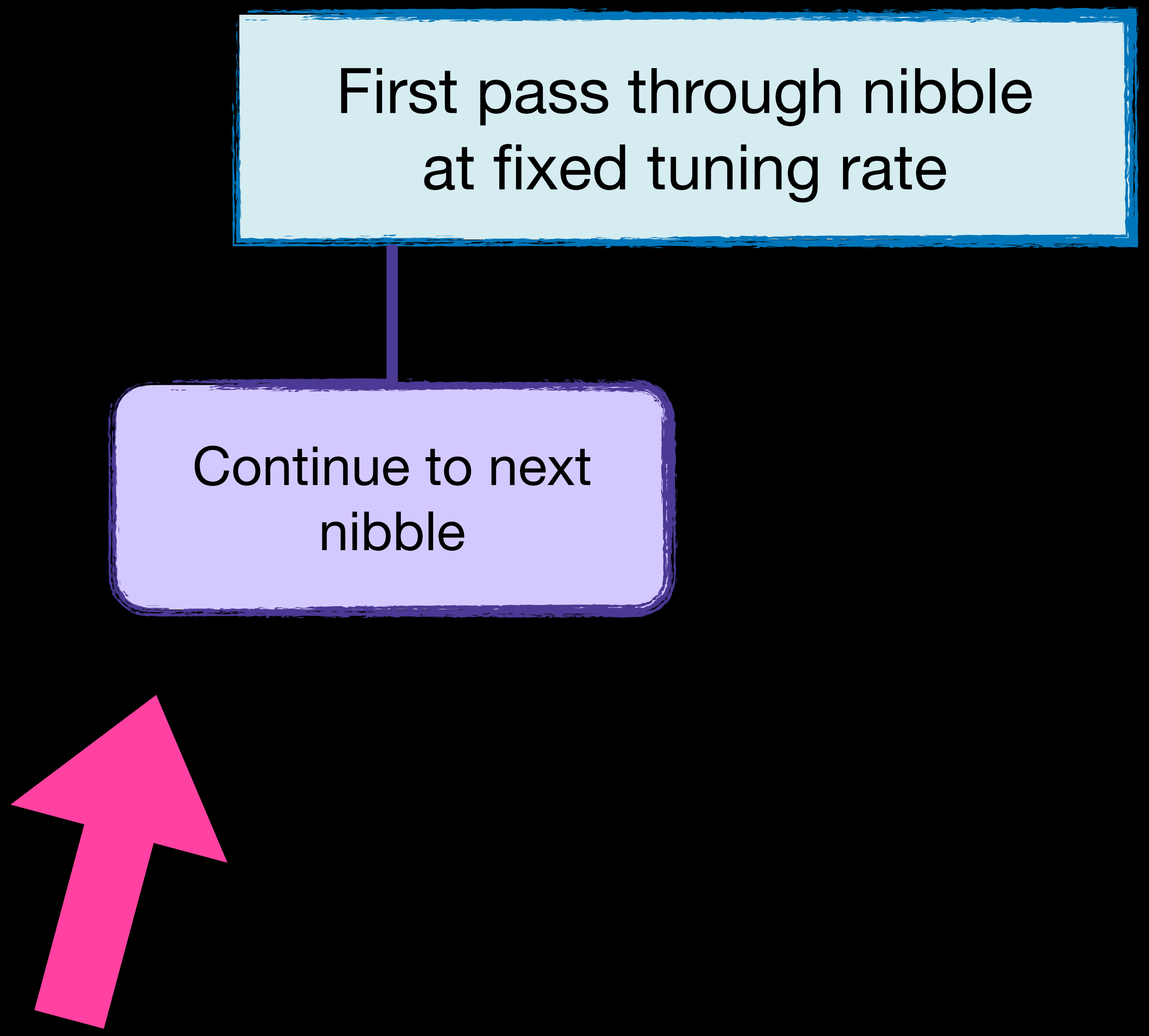
How do we know it is real?

Synthetic injection system provides verification of detection capability.

ADMX: "top secret" synthetic axion generator rack allows for blind injection of signals into the cavity →

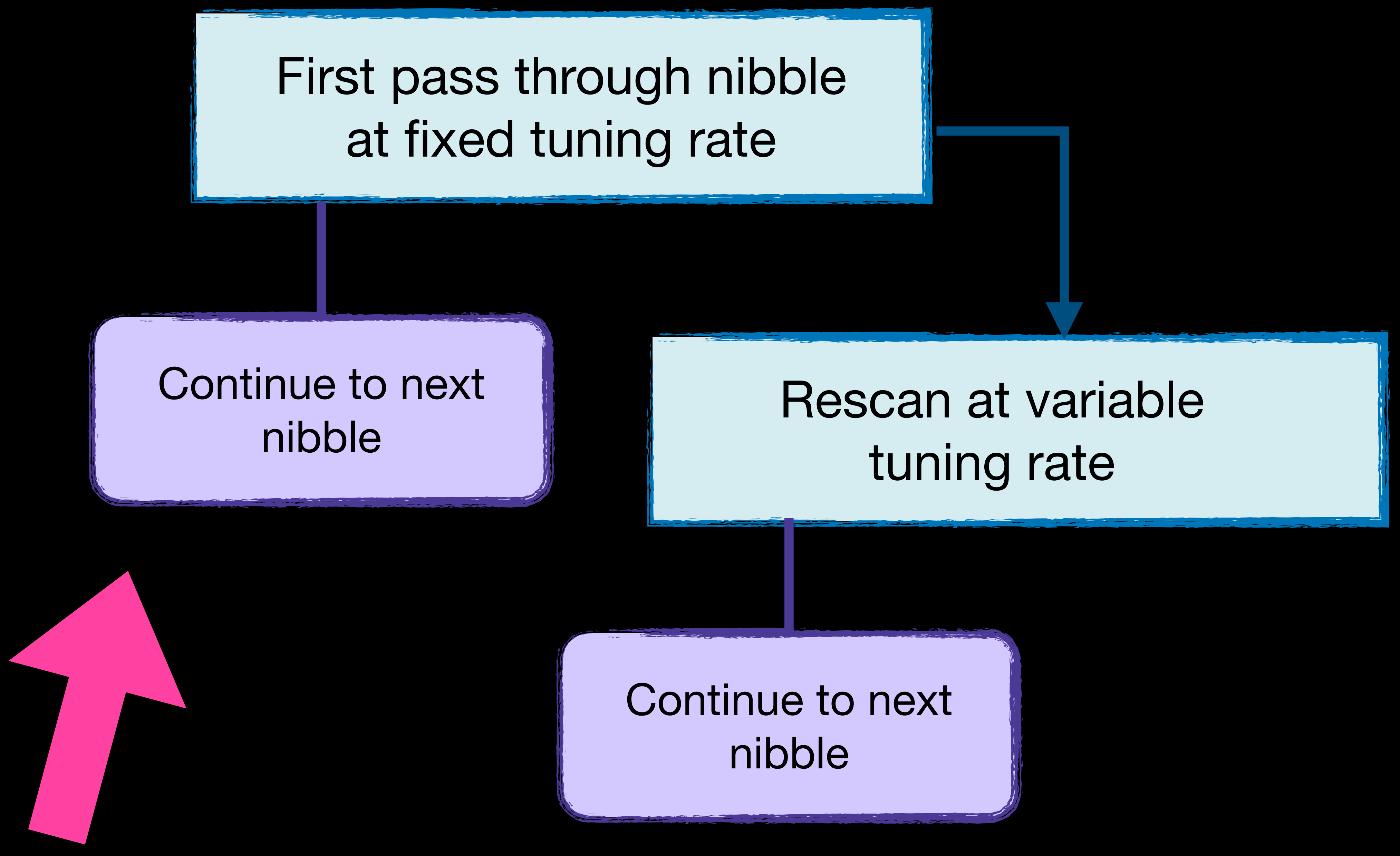
DMRadio: More challenging, but similar tactics forthcoming

Candidate Decision Tree



NOTE!
Just due to the statistics involved with our tuning rate this doesn't ever realistically happen!

Candidate Decision Tree



NOTE!
Just due to the statistics involved with our tuning rate this doesn't ever realistically happen!

Candidate Decision Tree

First pass through nibble at fixed tuning rate

Continue to next nibble

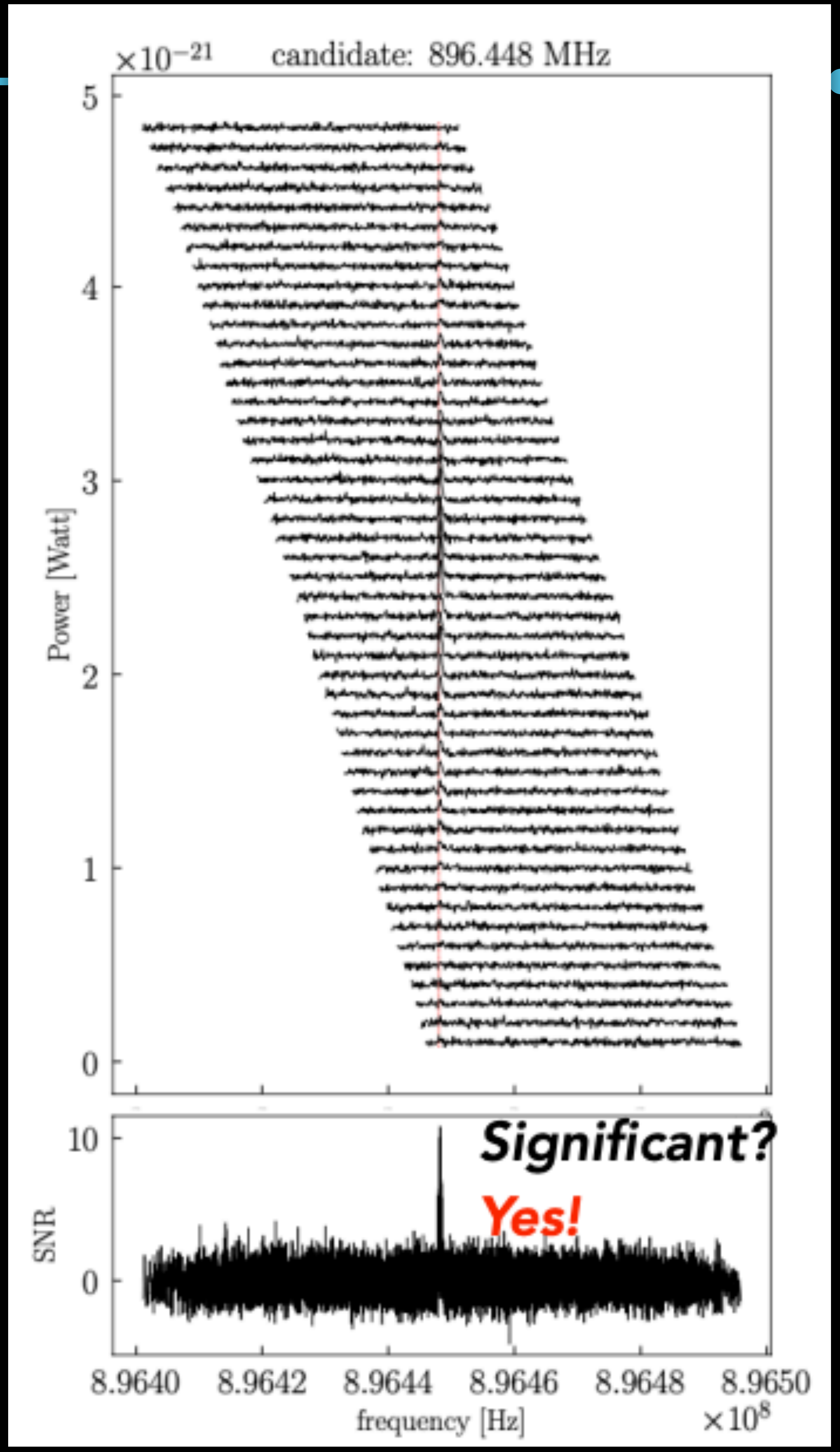
Rescan at variable tuning rate

Continue to next nibble

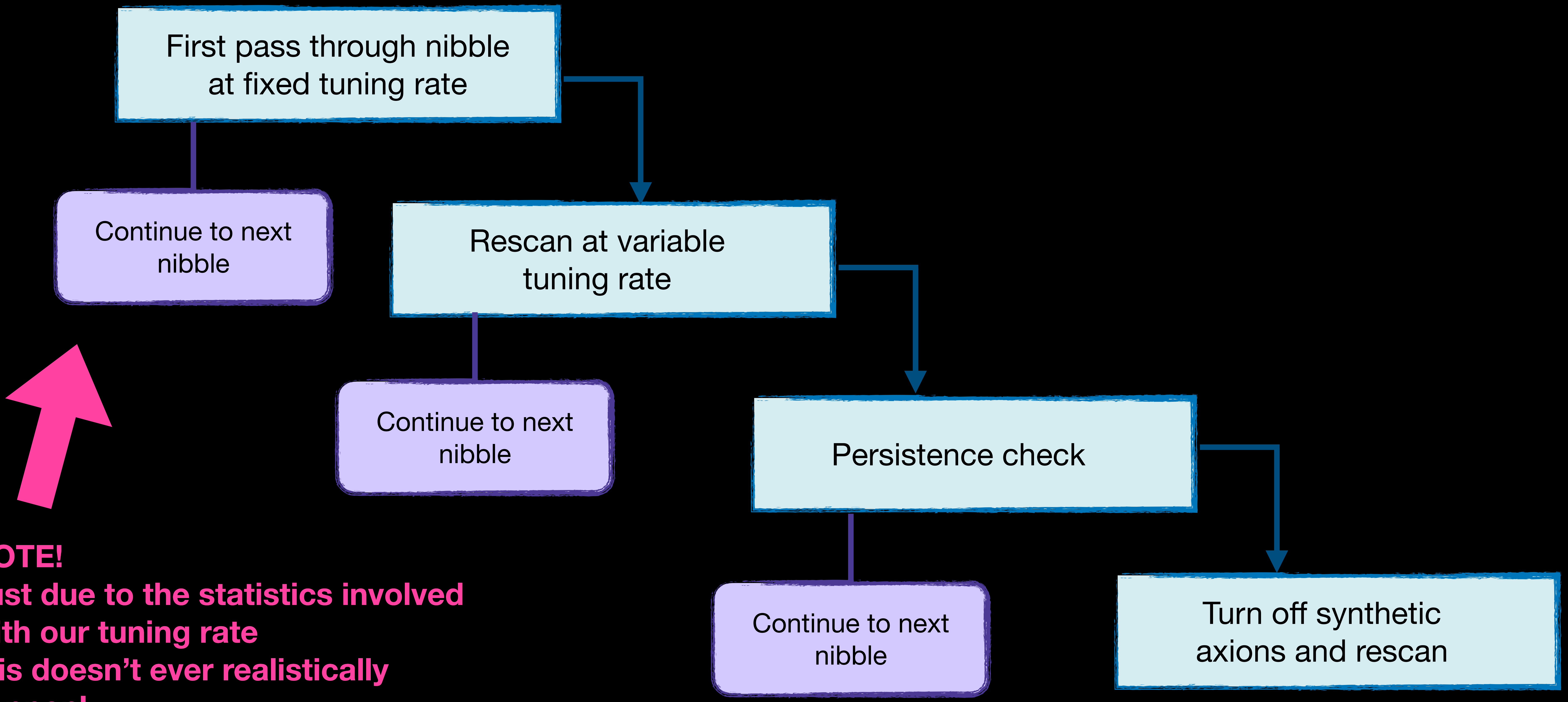
Persistence check

Continue to next nibble

NOTE!
Just due to the statistics involved with our tuning rate this doesn't ever realistically happen!

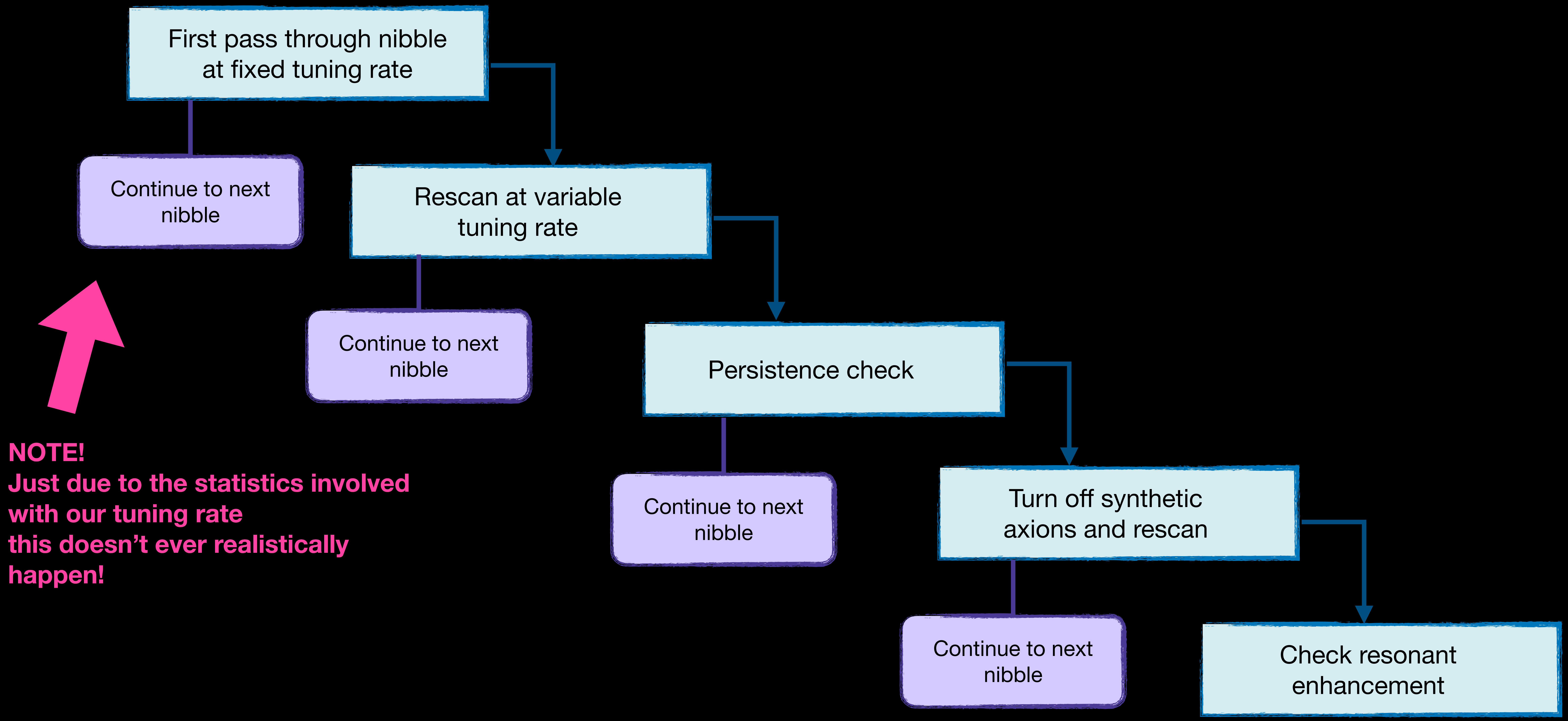


Candidate Decision Tree

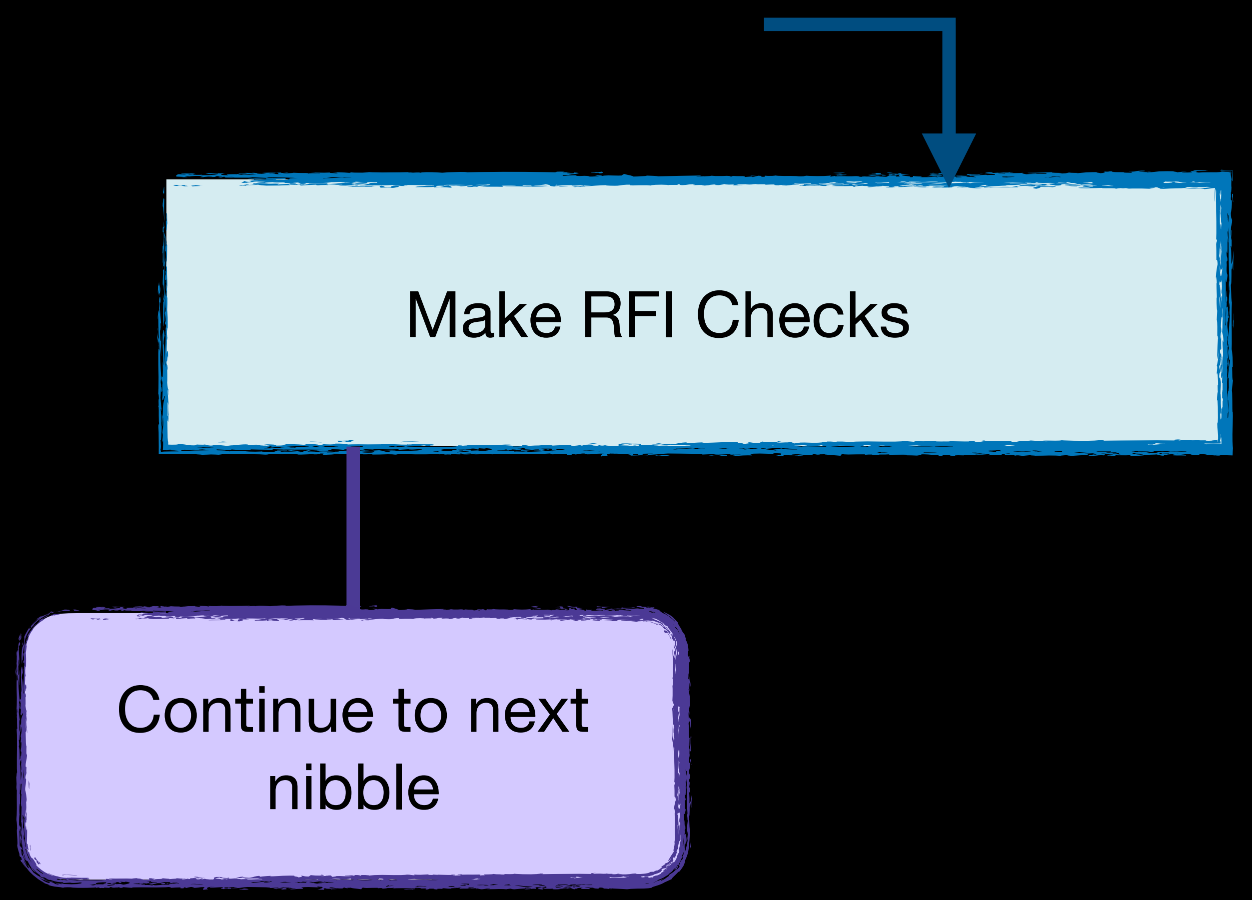


NOTE!
Just due to the statistics involved with our tuning rate this doesn't ever realistically happen!

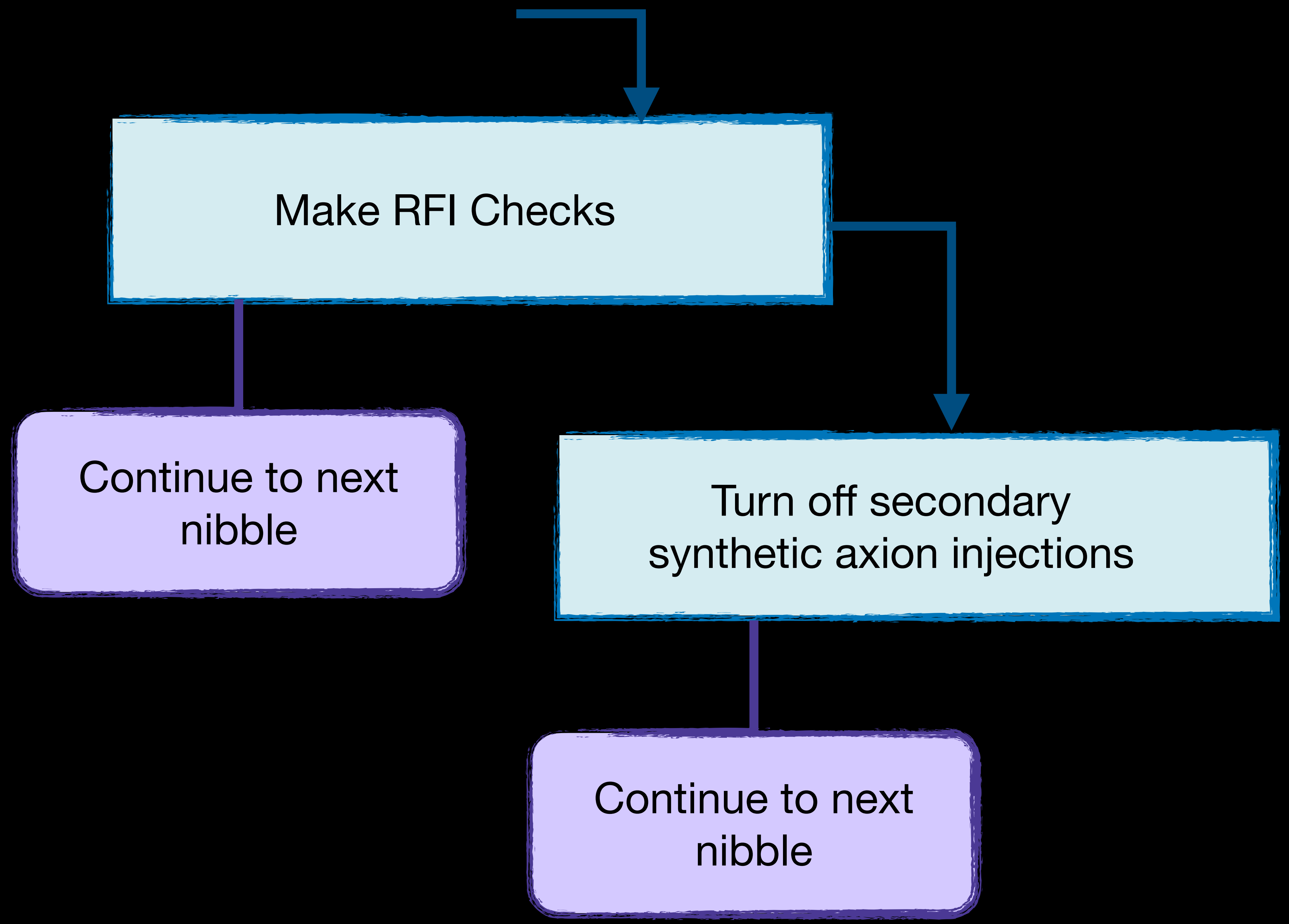
Candidate Decision Tree



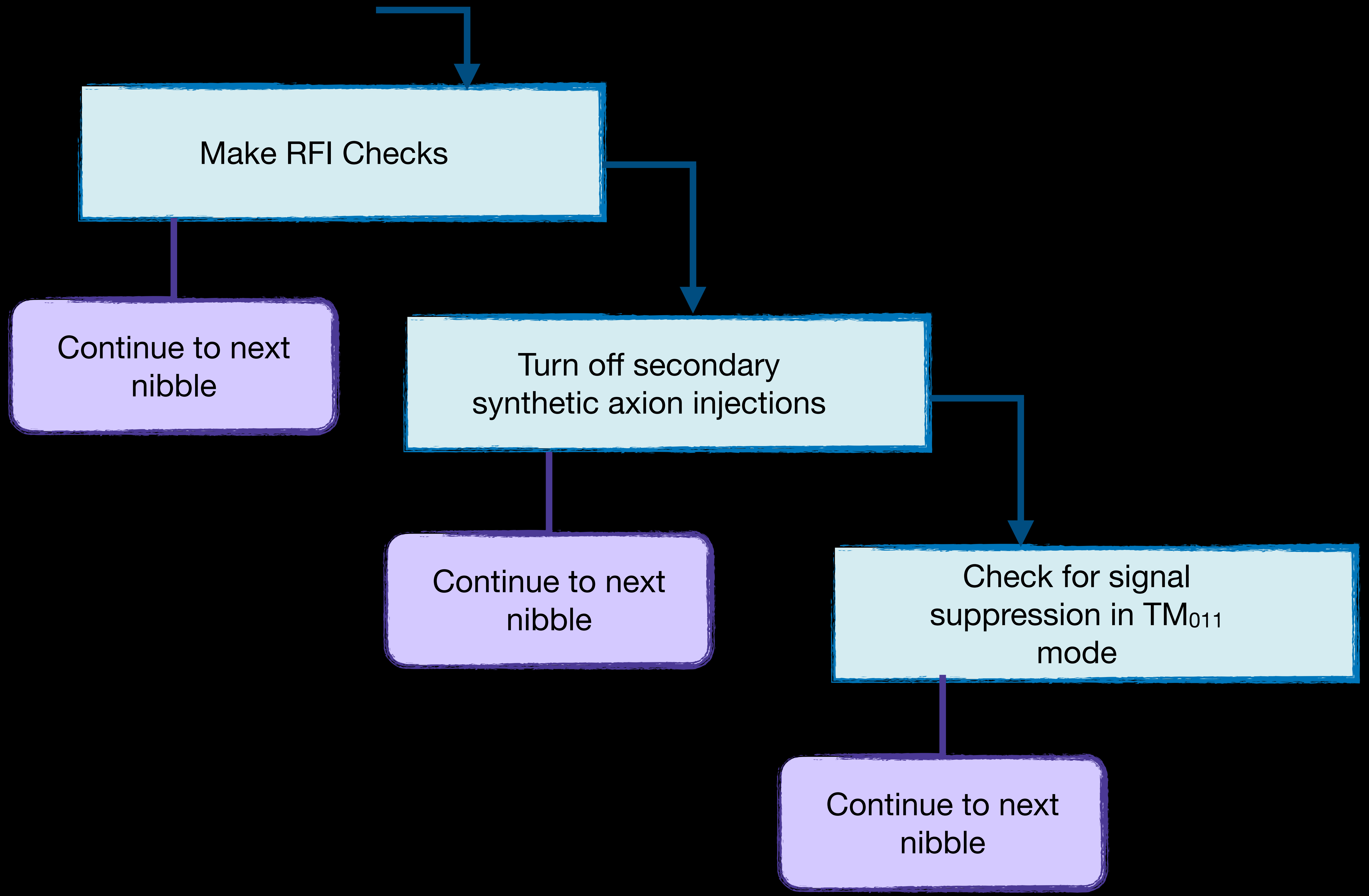
Candidate Decision Tree



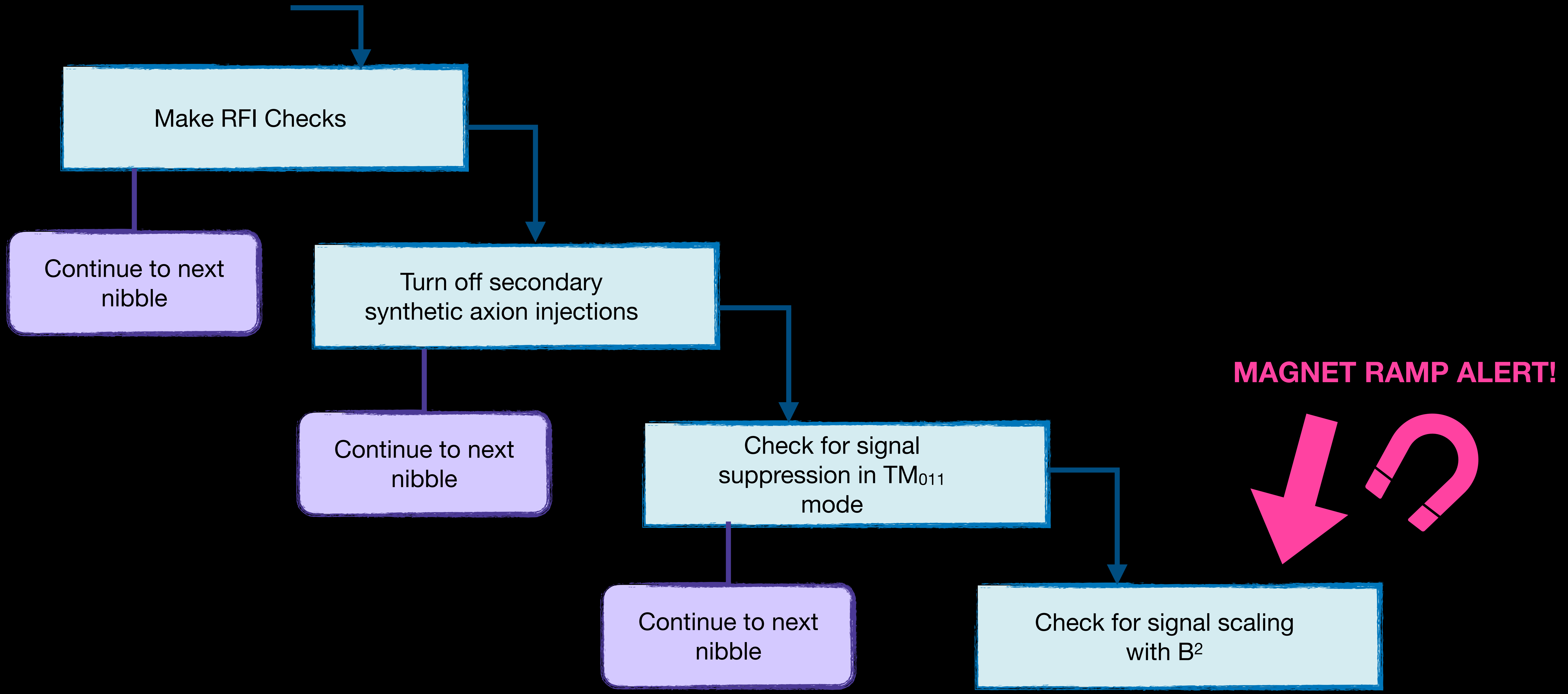
Candidate Decision Tree



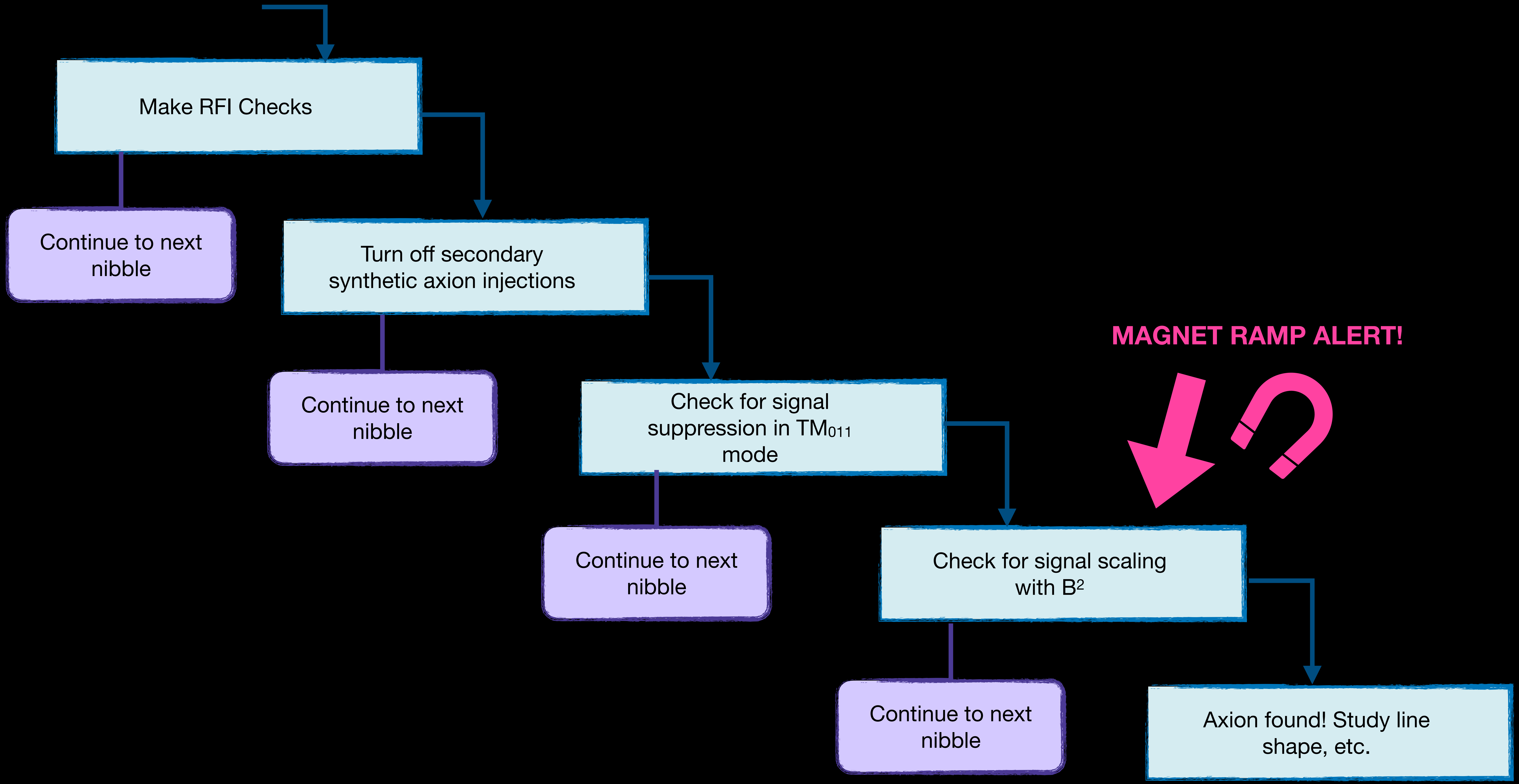
Candidate Decision Tree



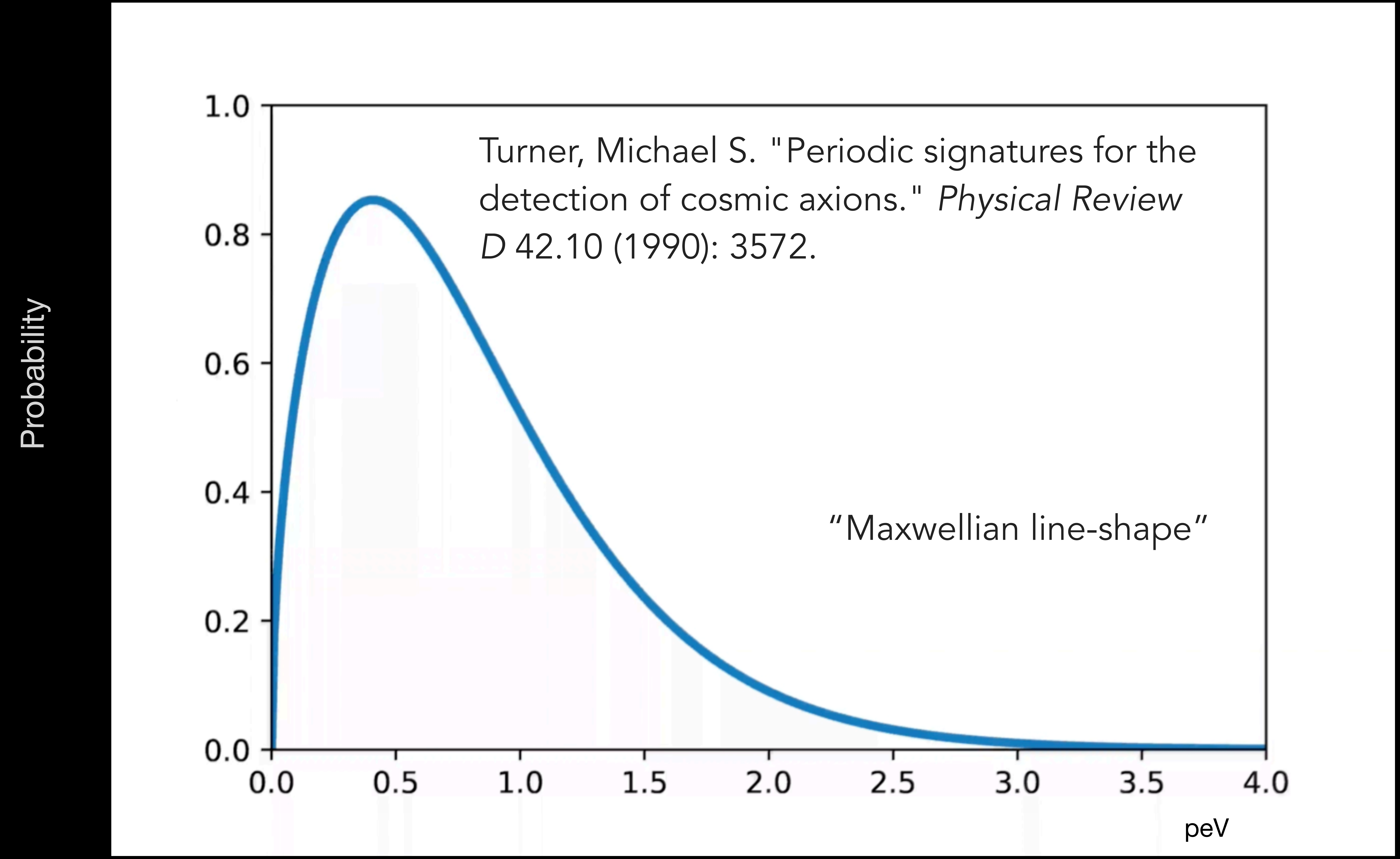
Candidate Decision Tree



Candidate Decision Tree



Axion Doppler Shift

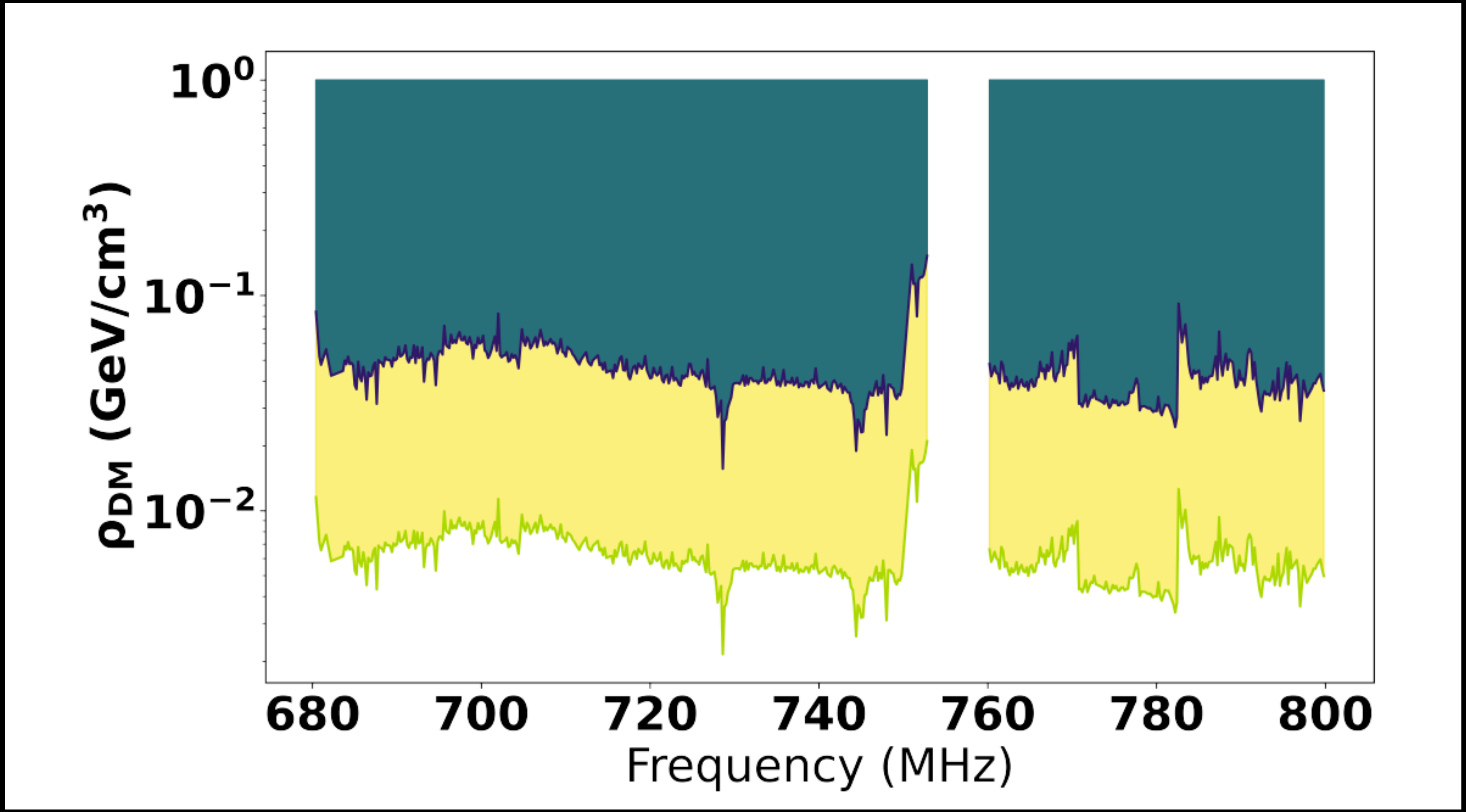


Conclusion

- Radios can be repurposed to look for axion dark matter!
- New techniques from fields of quantum information science and quantum measurement
- A detection could happen at any moment!

Thank you!

High Resolution Search



Legend

- Teal: DFSZ assumed
- Yellow: KSVZ assumed

No line-shape implied; monochromatic tone only