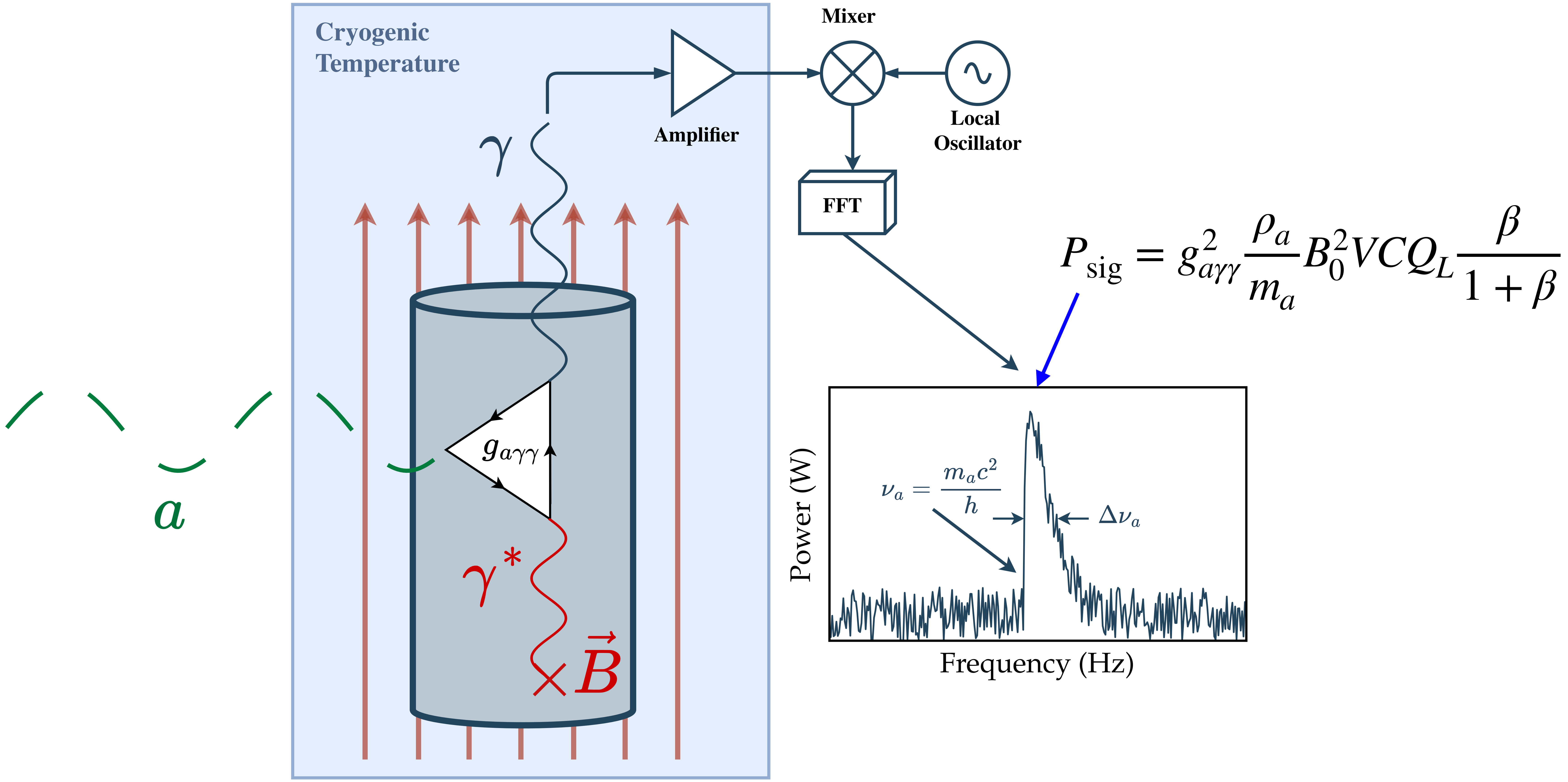
The ORGAN Experiment: Phase 1 results

Aaron Quiskamp

The Axion Quest, Rencontres du Vietnam

How to detect axions?

- Detect photons with resonant cavity → **Axion Haloscope** (P. Sikivie 1983)



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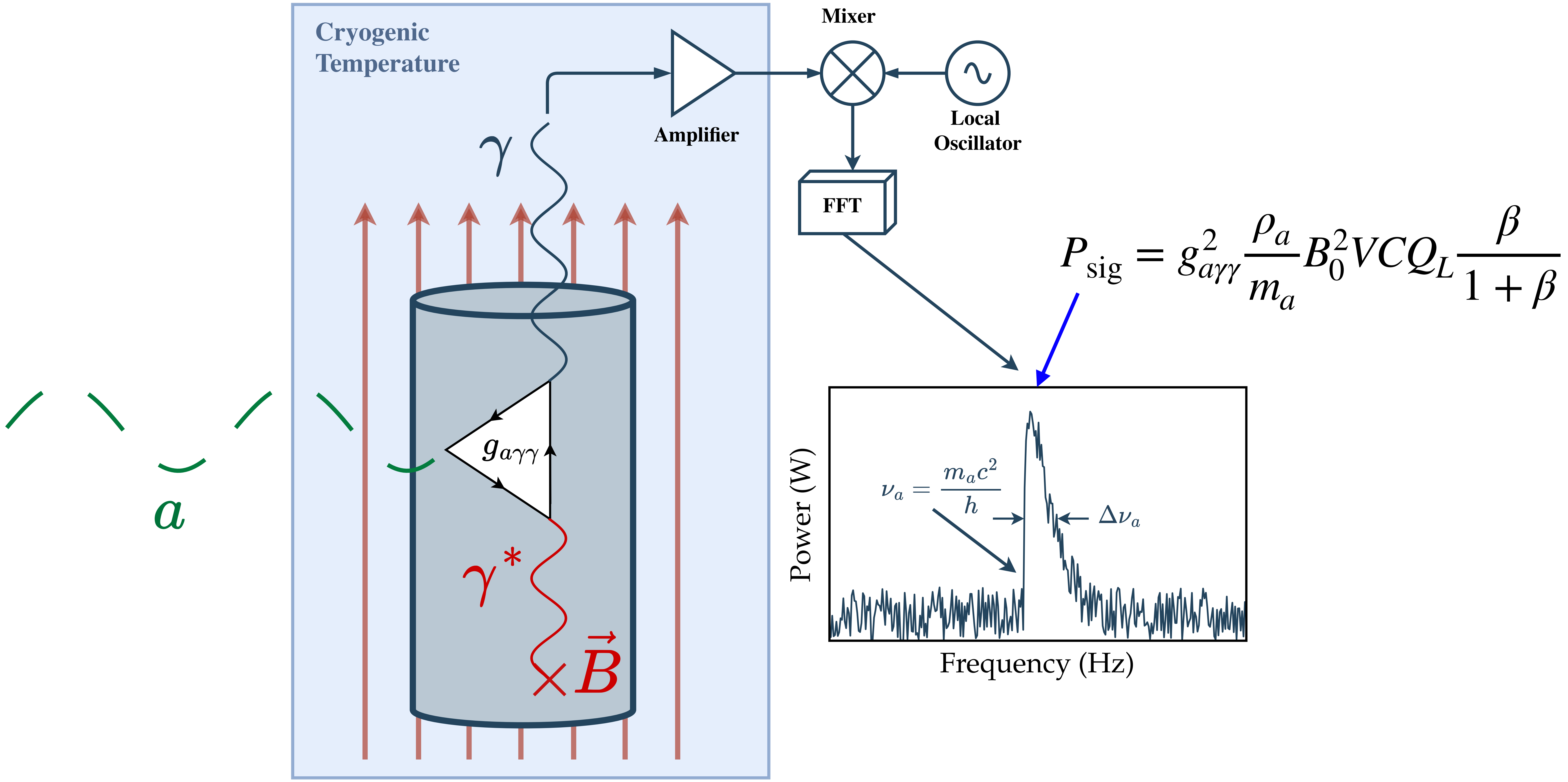

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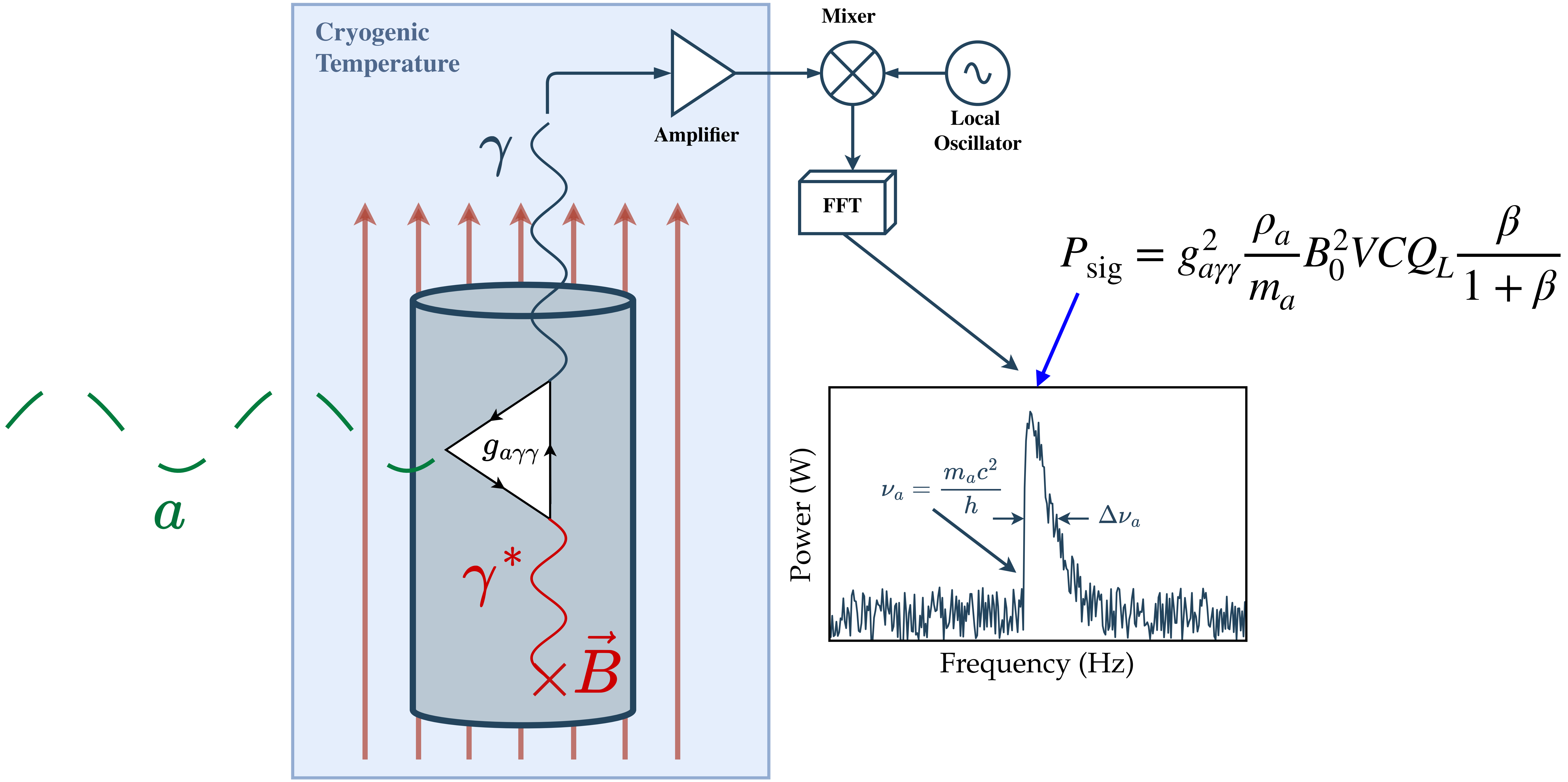
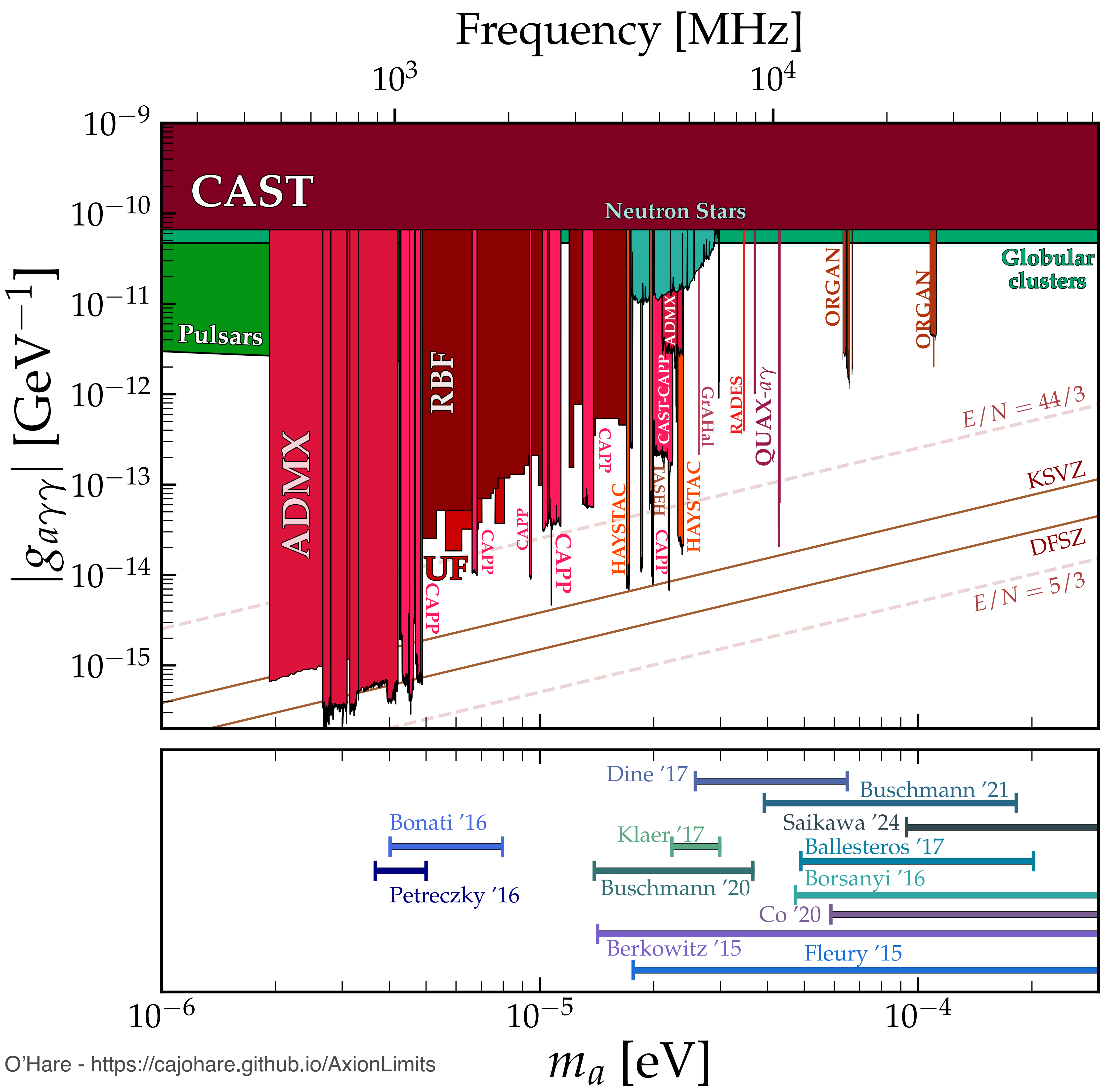


Cavities are narrow-band so must be tunable!

ORGAN: Oscillating Resonant Group AxioN Experiment

- High-mass (frequency) axion haloscope at UWA



Ciaran O'Hare - https://cajohare.github.io/AxionLimits

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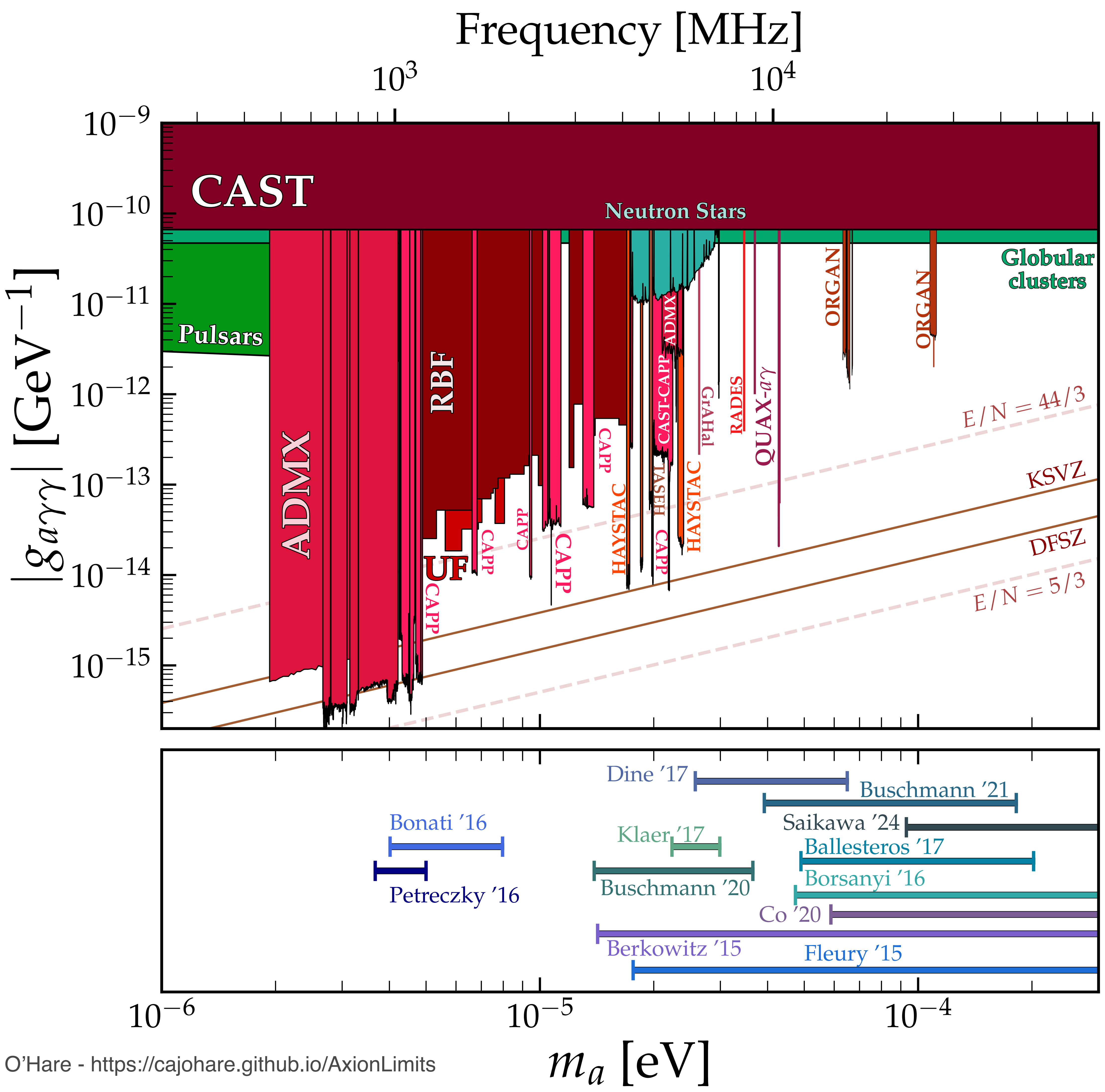

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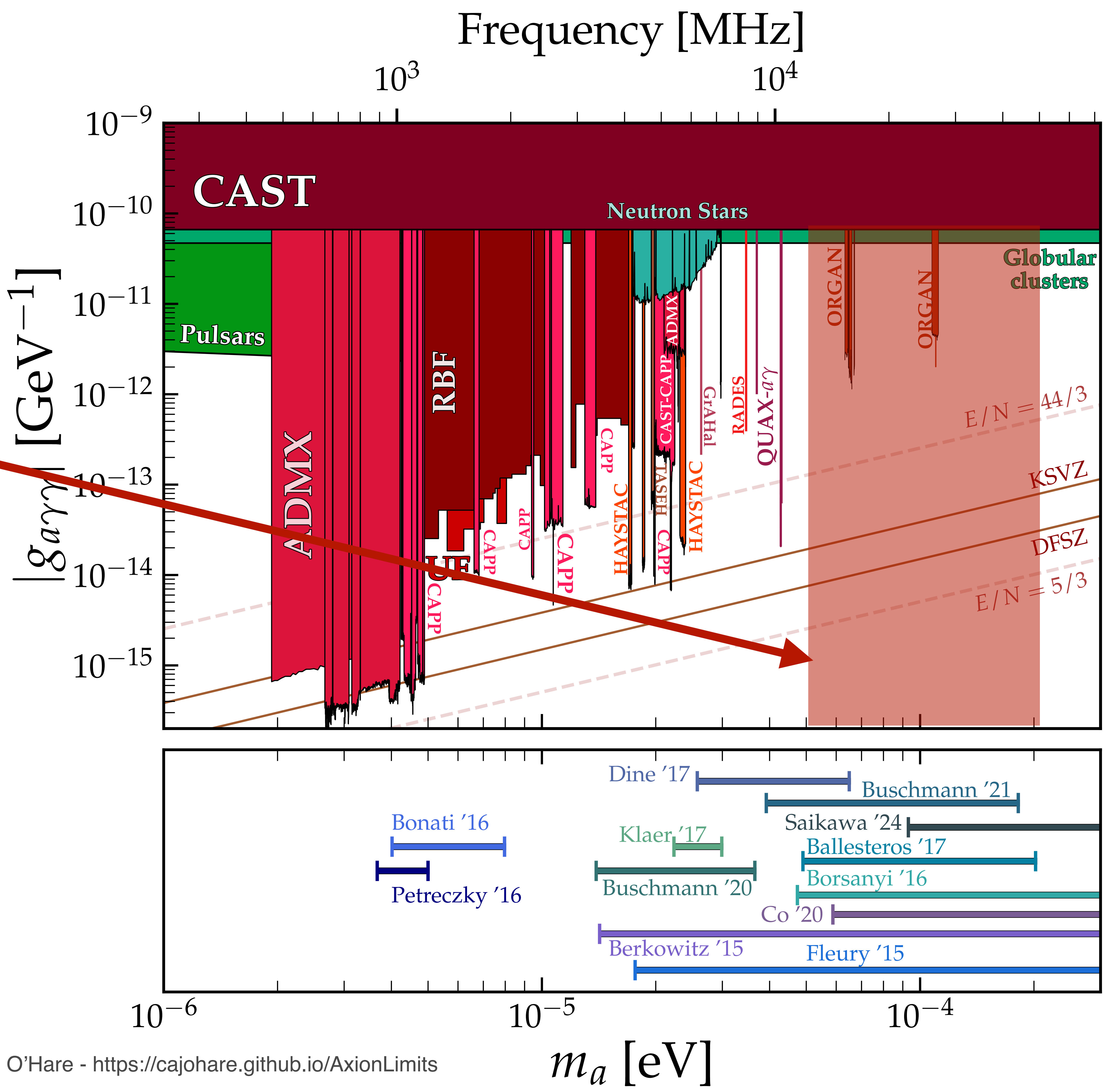

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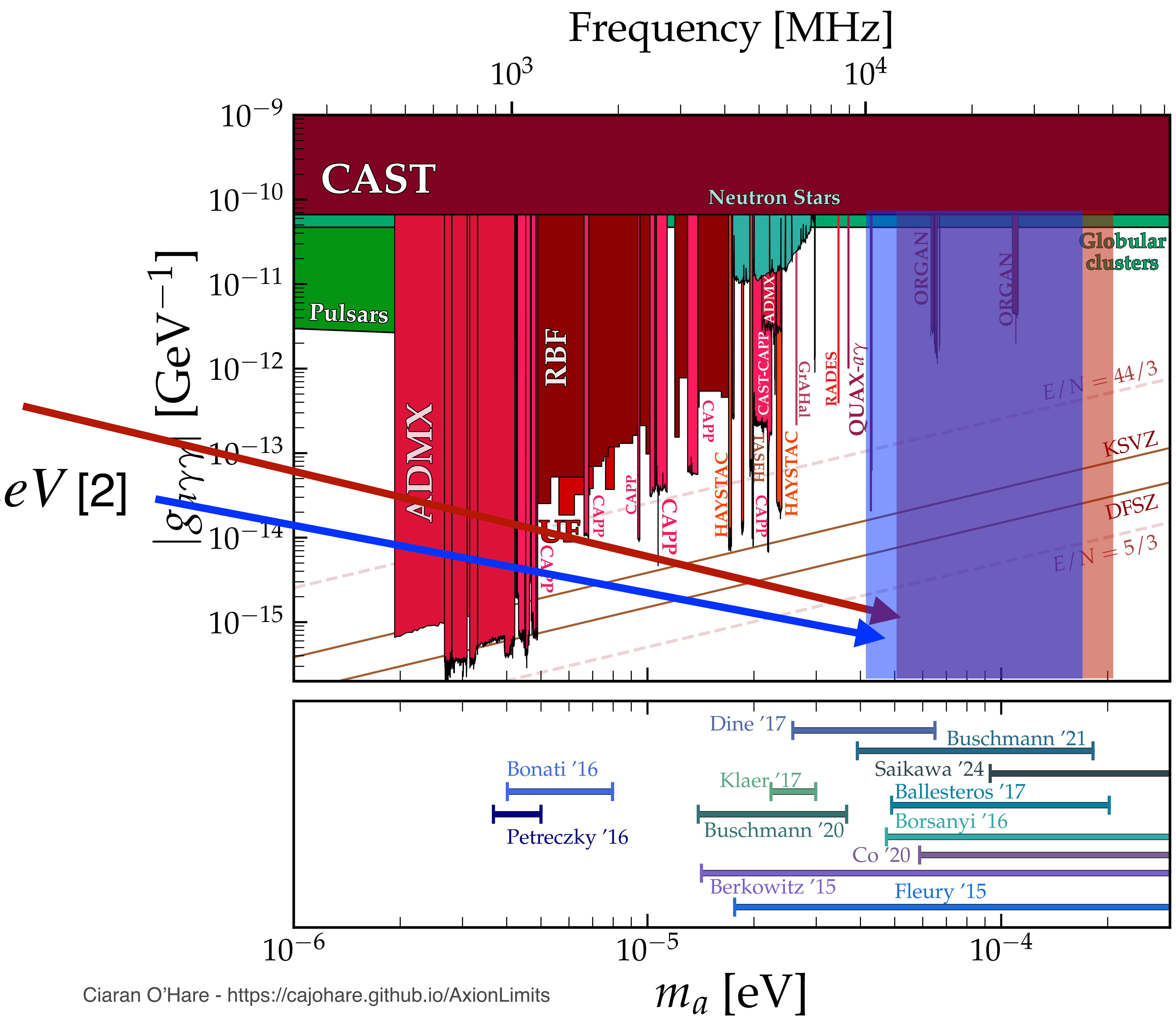

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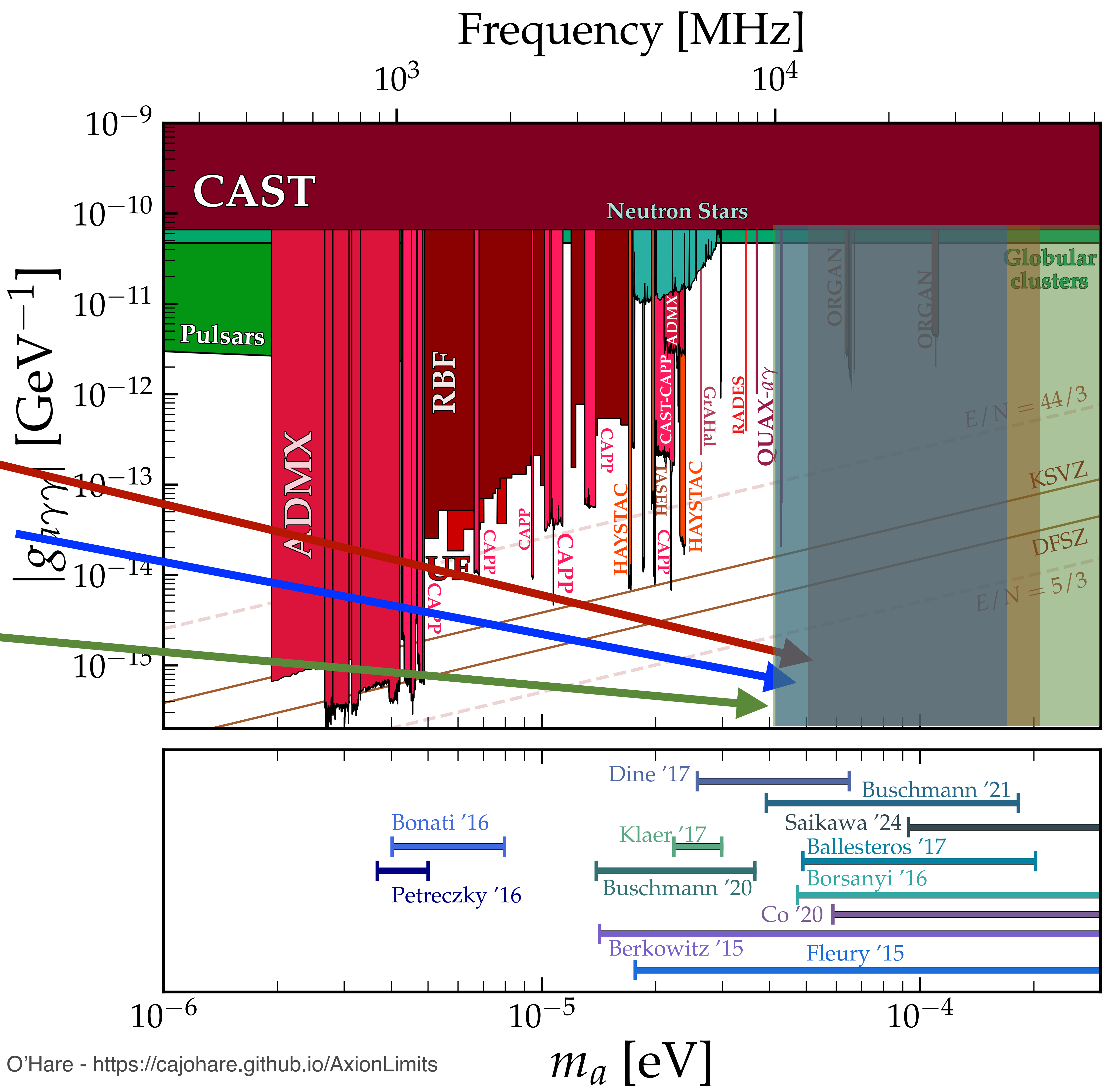

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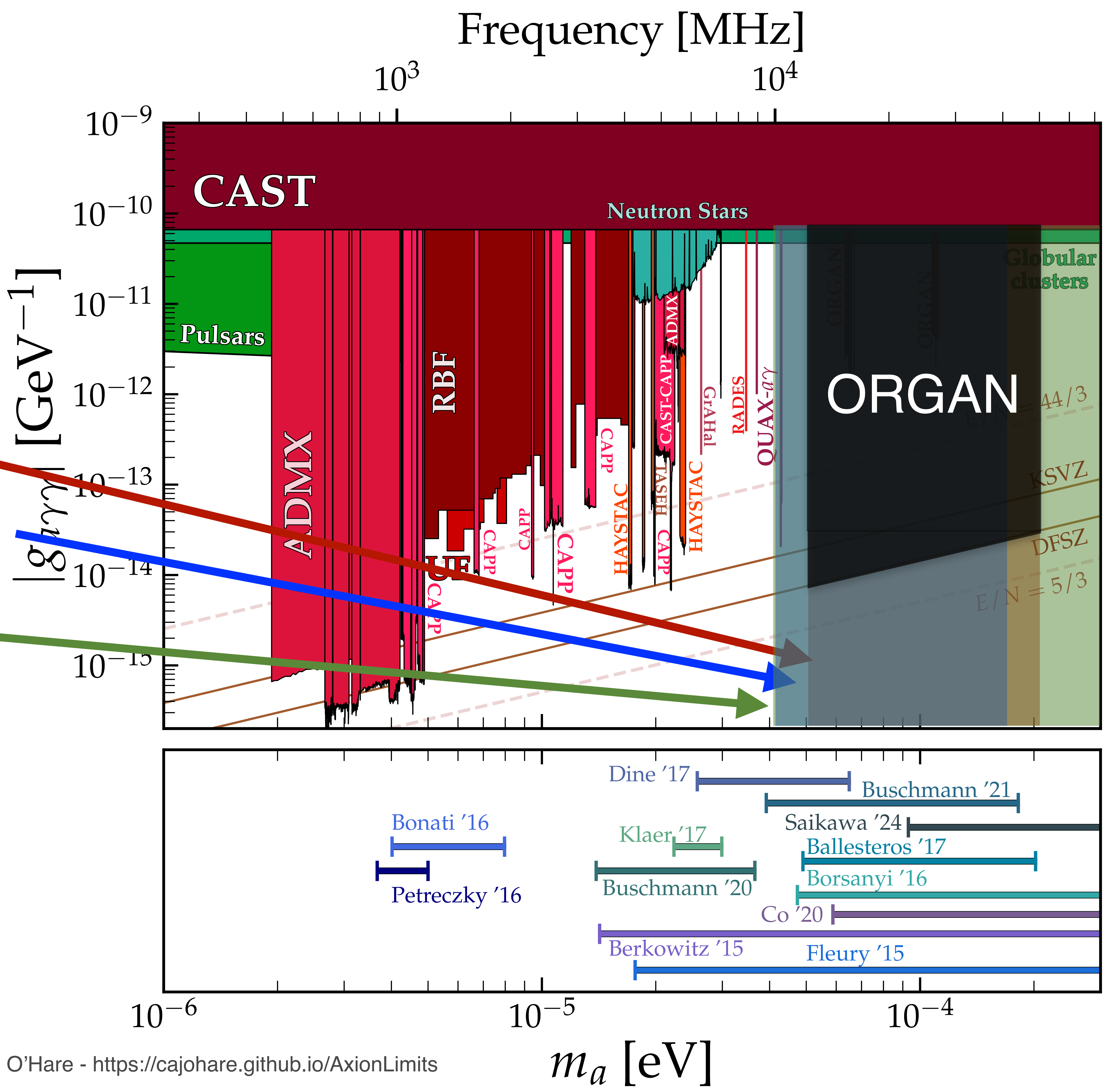

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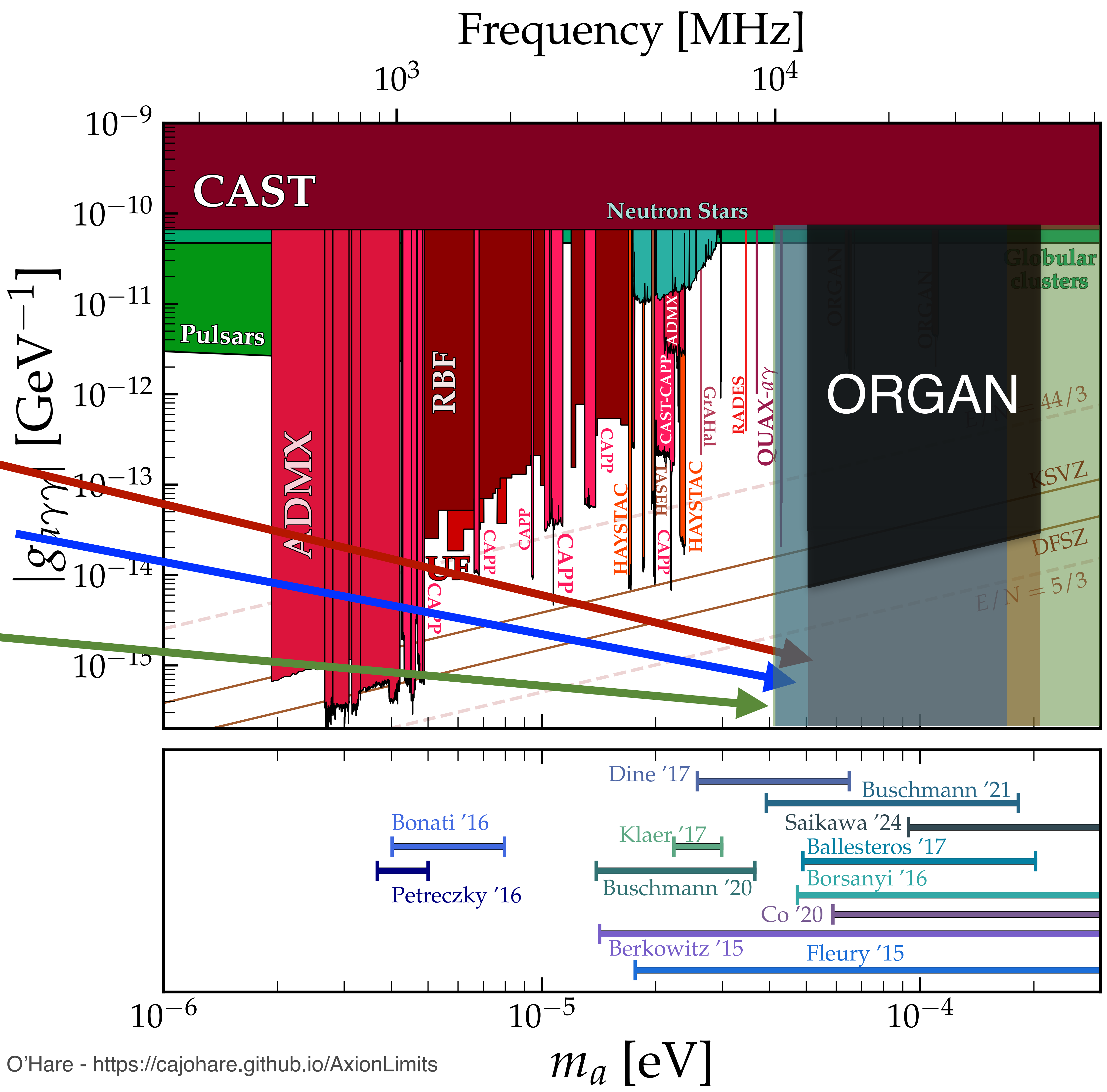
- $\frac{df}{dt} \propto f^{-14/3} \rightarrow$ Falling off a sensitivity cliff..



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Phase 1a

- Scan between 15 - 16 GHz
- Tuning rod cavity

Off-axis tuning rod

Rotation stage

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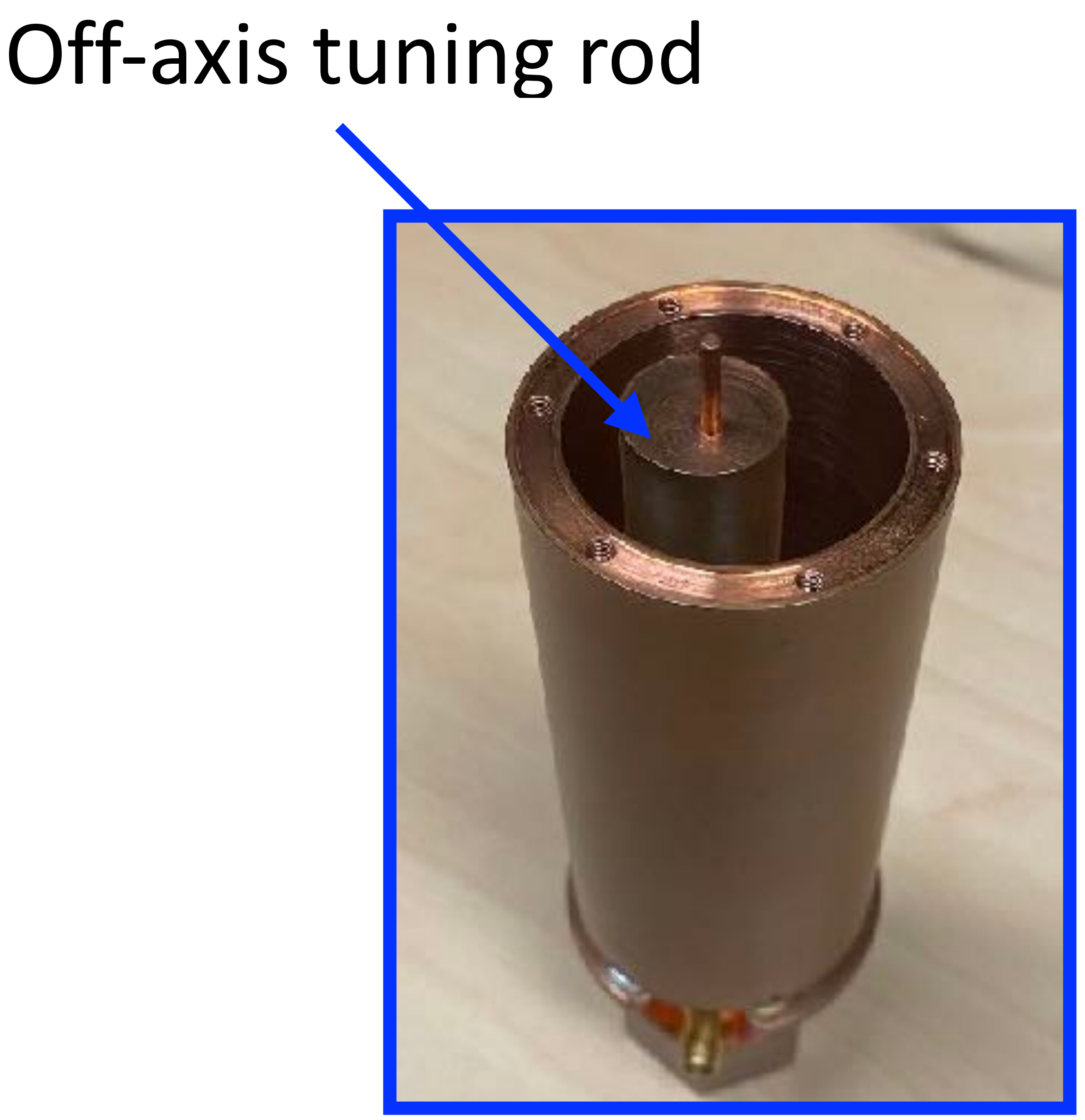
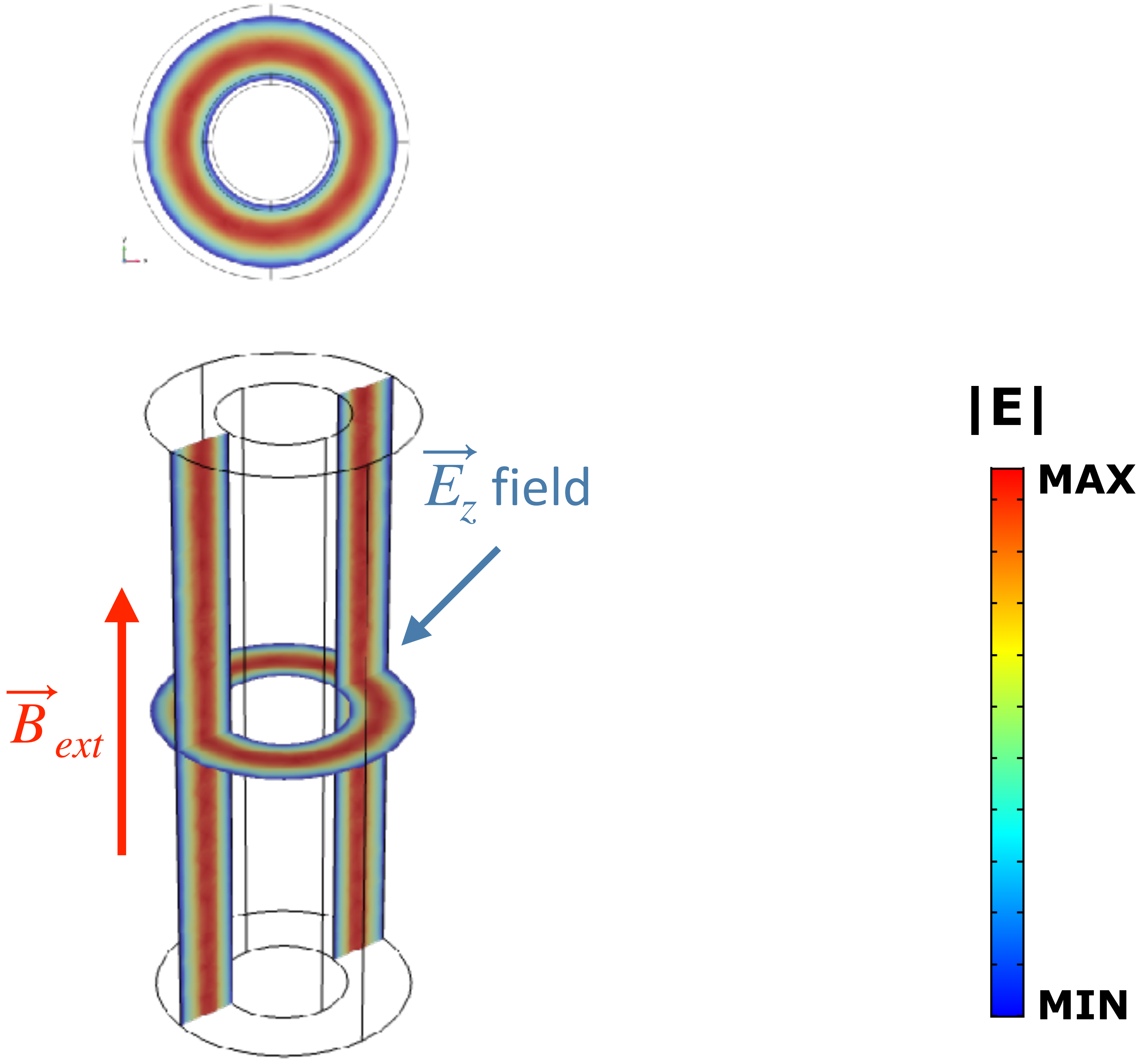


Rotation stage

$\vec{E}_{cav} \bullet \vec{B}_{ext} \neq 0$



TM010 mode

Phase 1a

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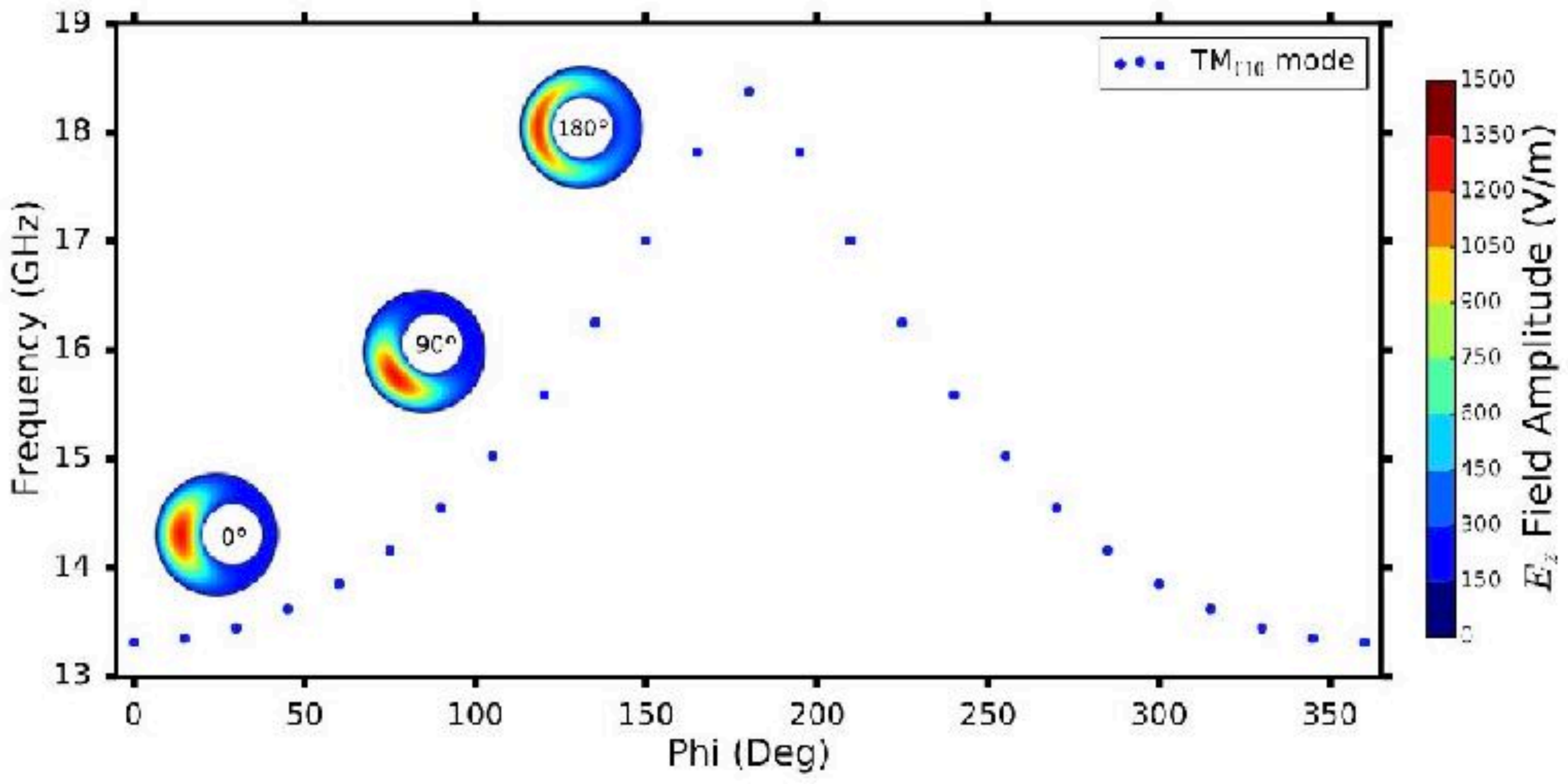
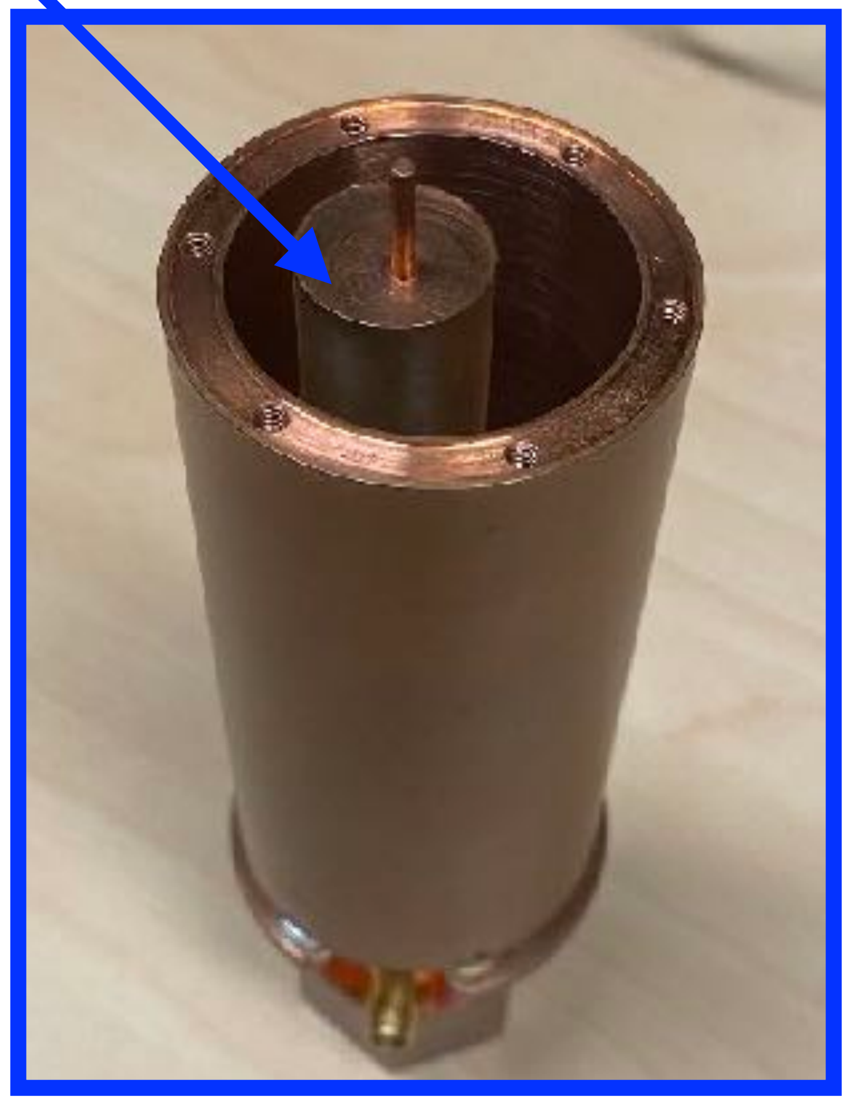
- Tuning rod cavity
- Moving the rod radially **“tunes”** the mode frequency



Off-axis tuning rod



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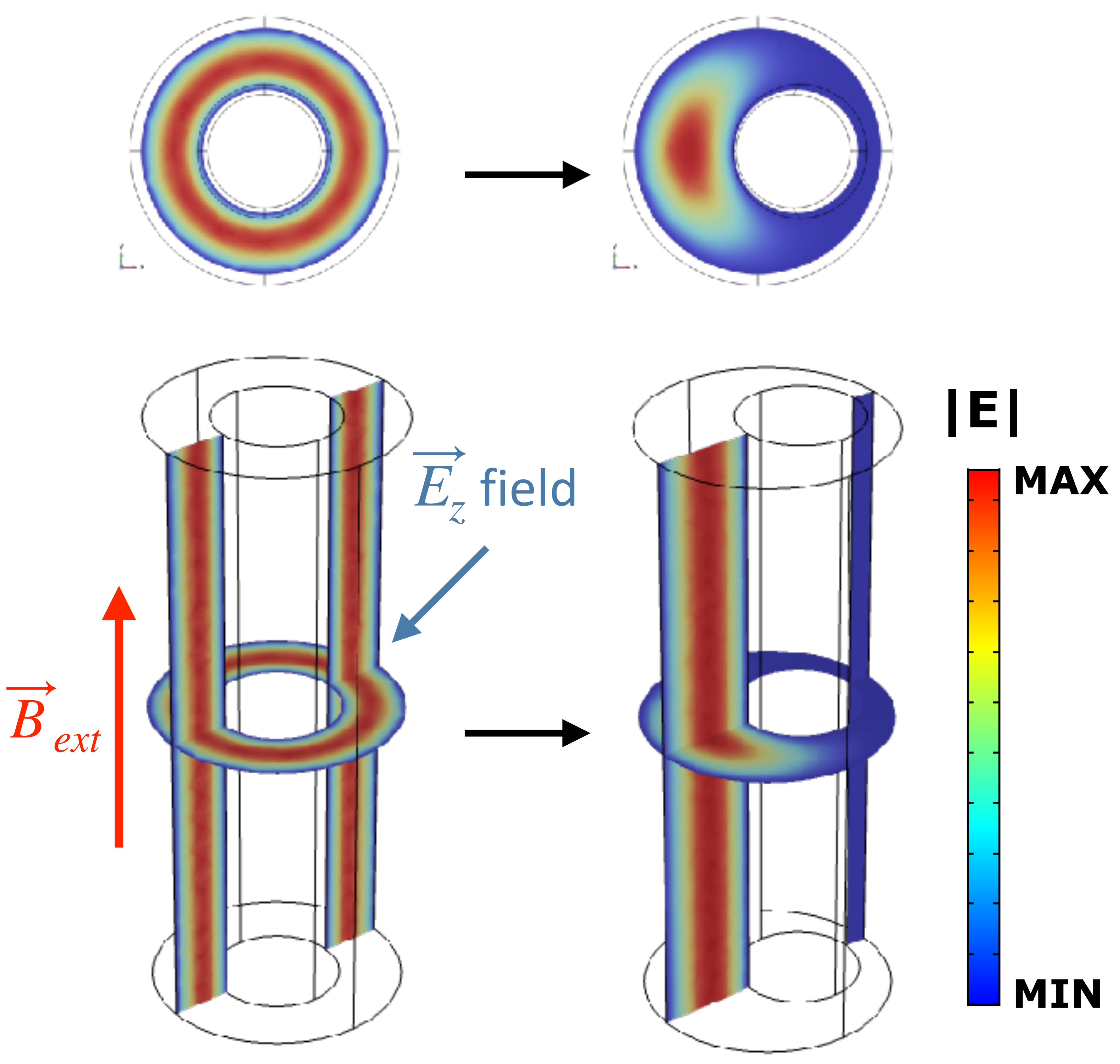
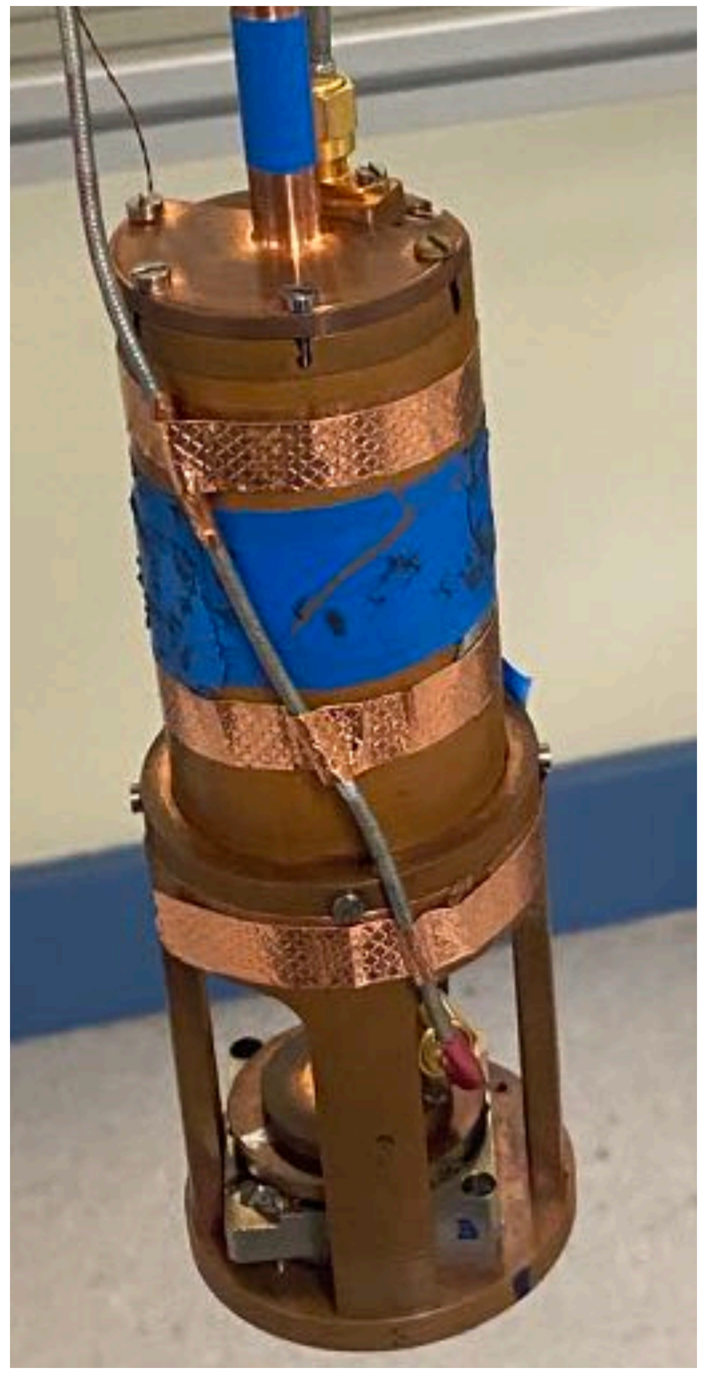


TM_{010} mode

Phase 1a

Phase 1a cavity



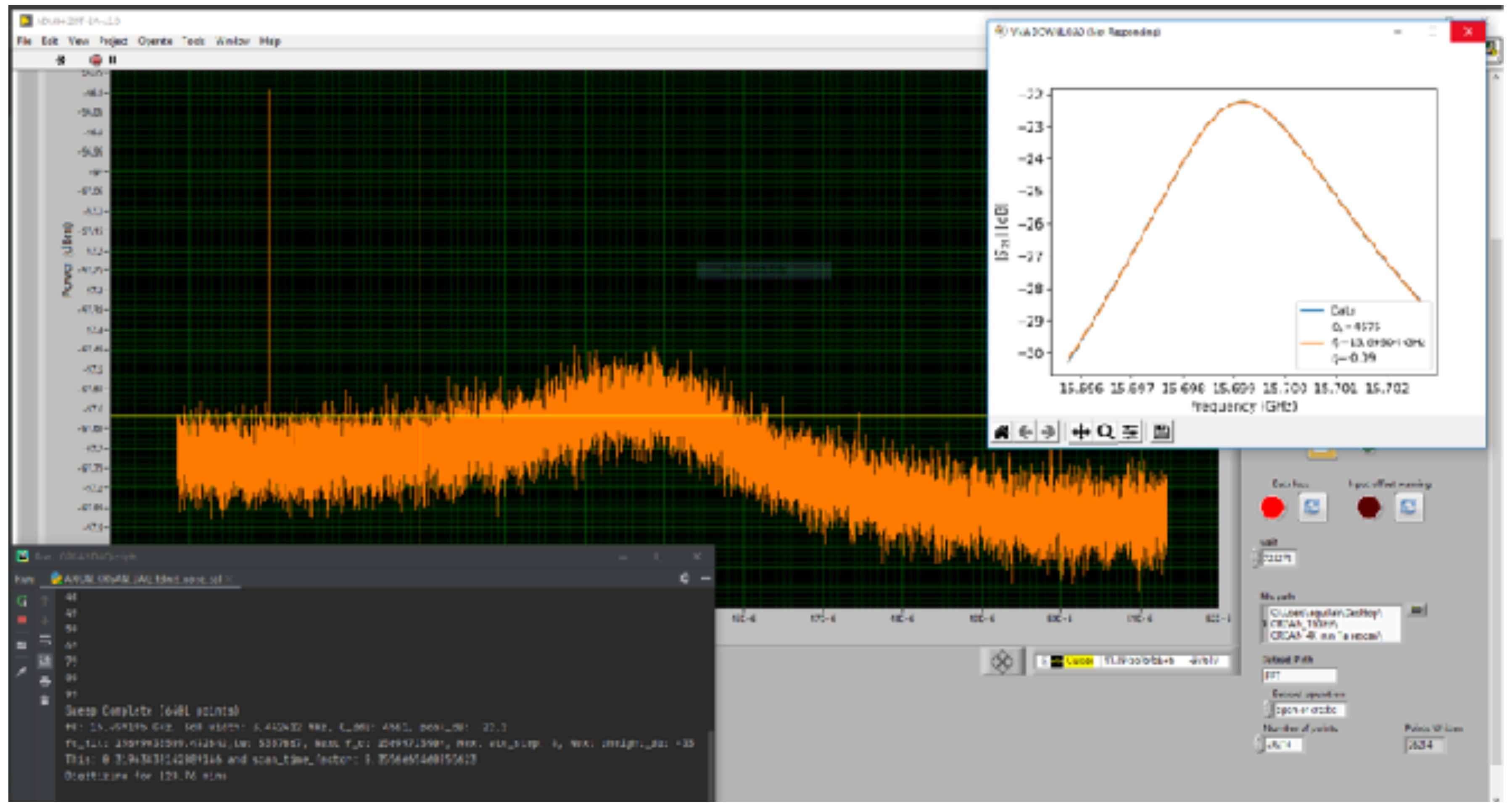
Dilution fridge

Phase 1a

- Zero-dead-time FFT on FPGA
- Python and LabVIEW based DAQ
- Operated at 5K with LNF HEMT amp

Paul Altin (ANU)

ORGAN DAQ



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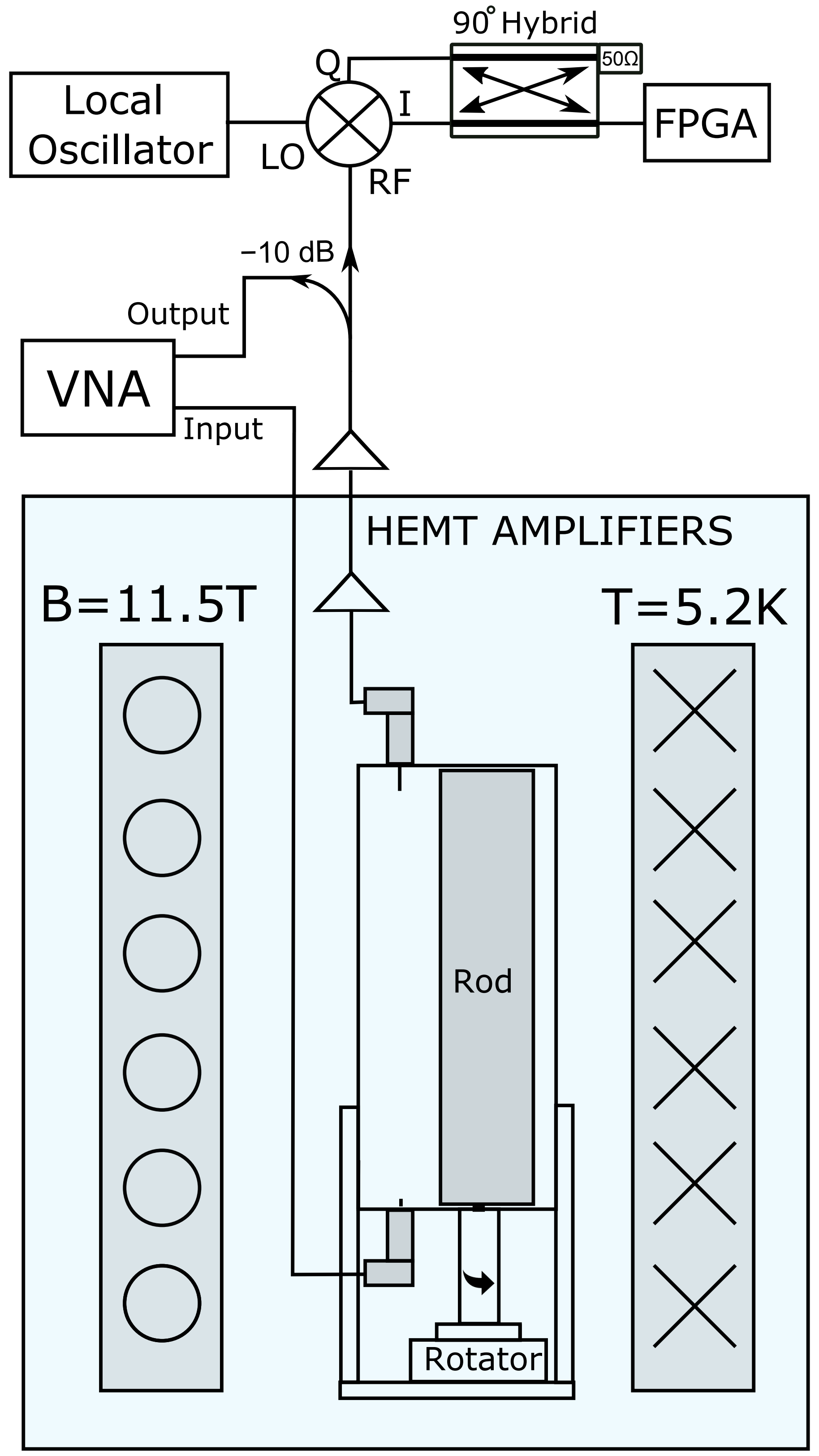
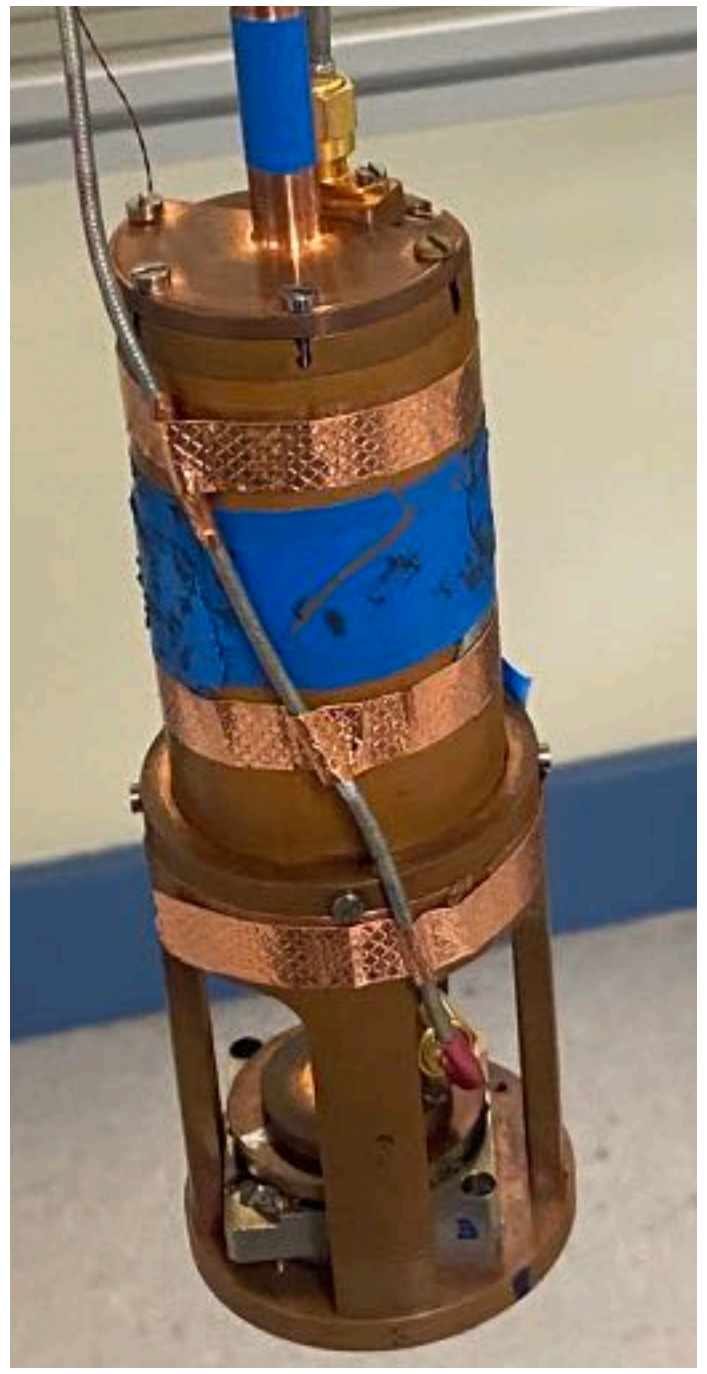


Phase 1a cavity



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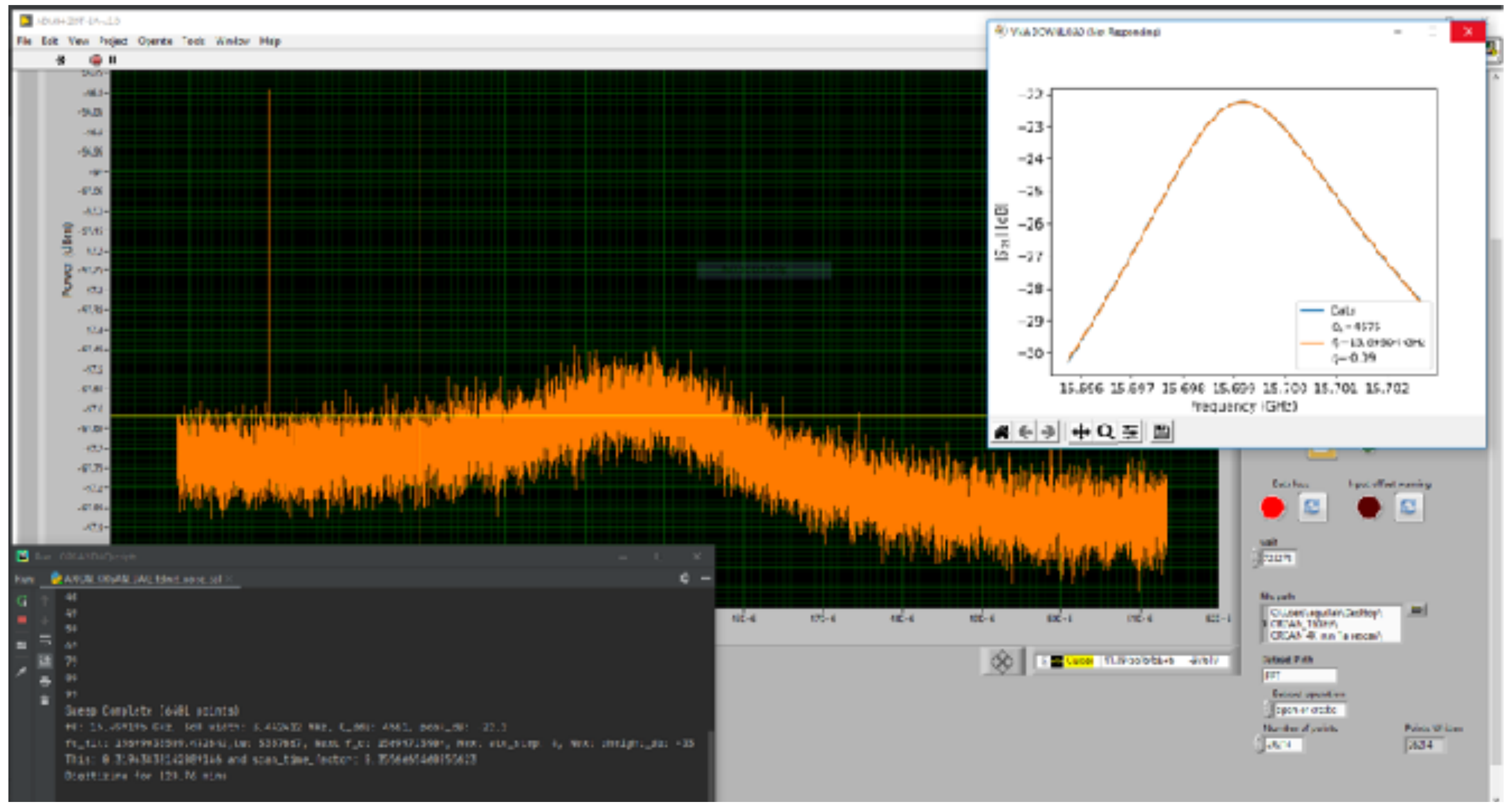

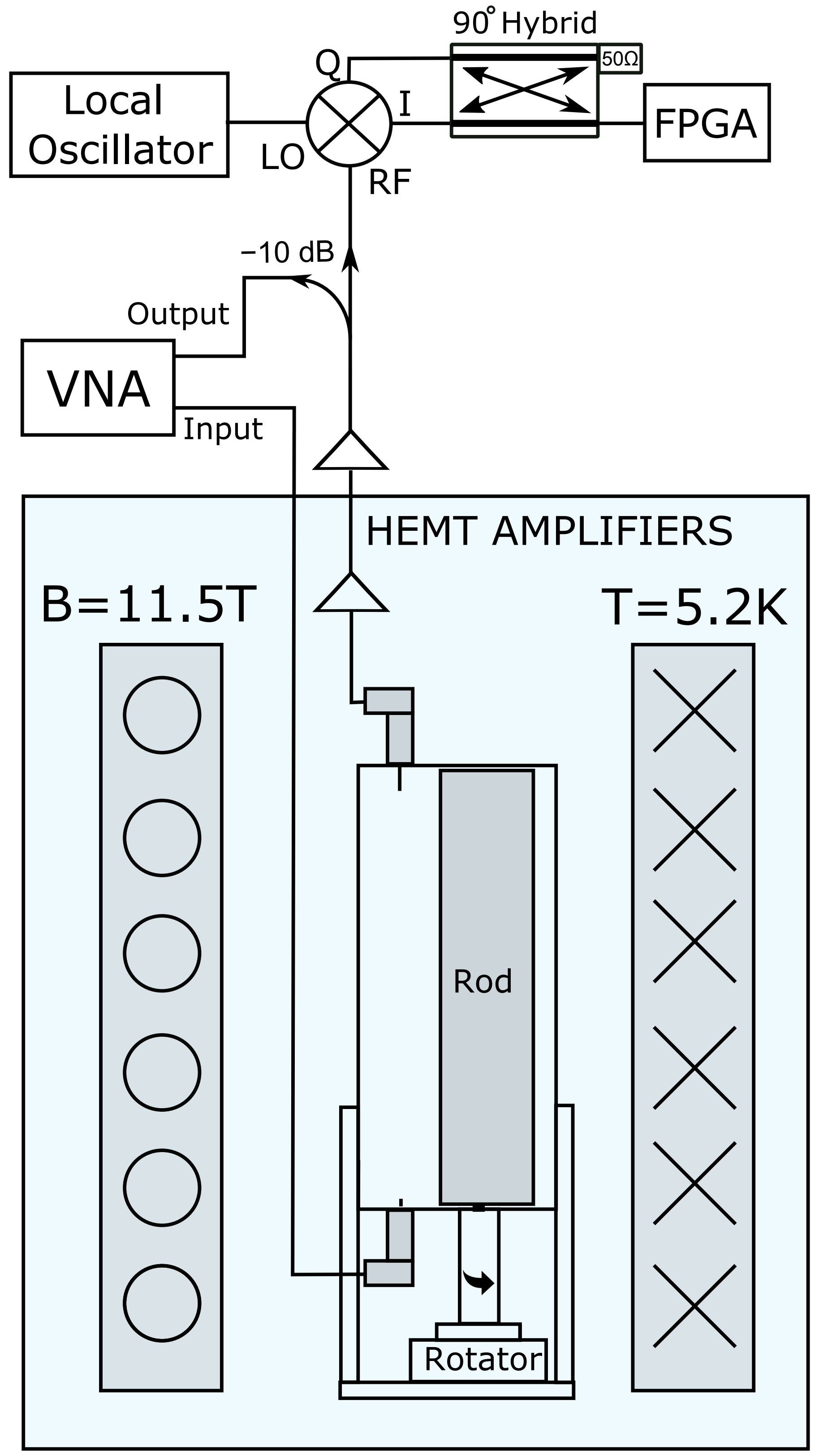

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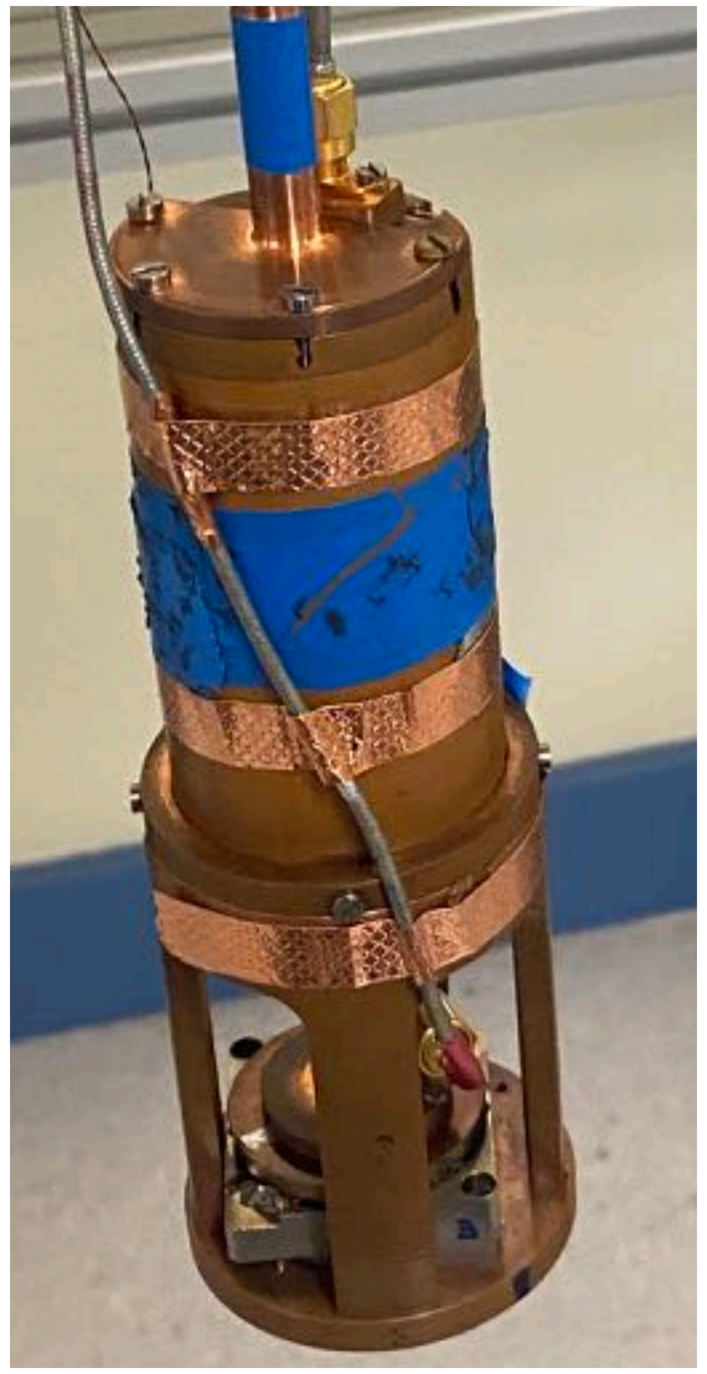
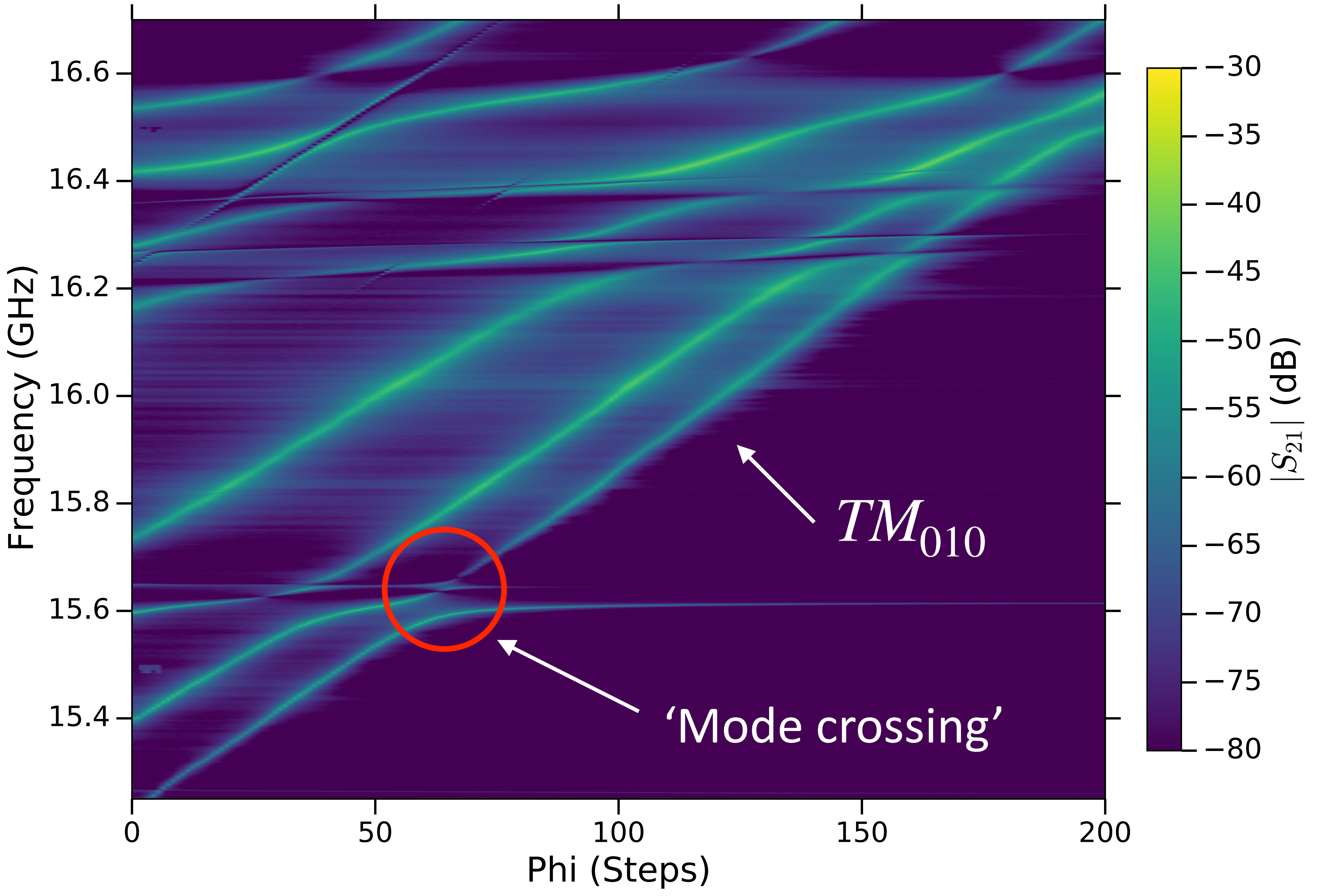


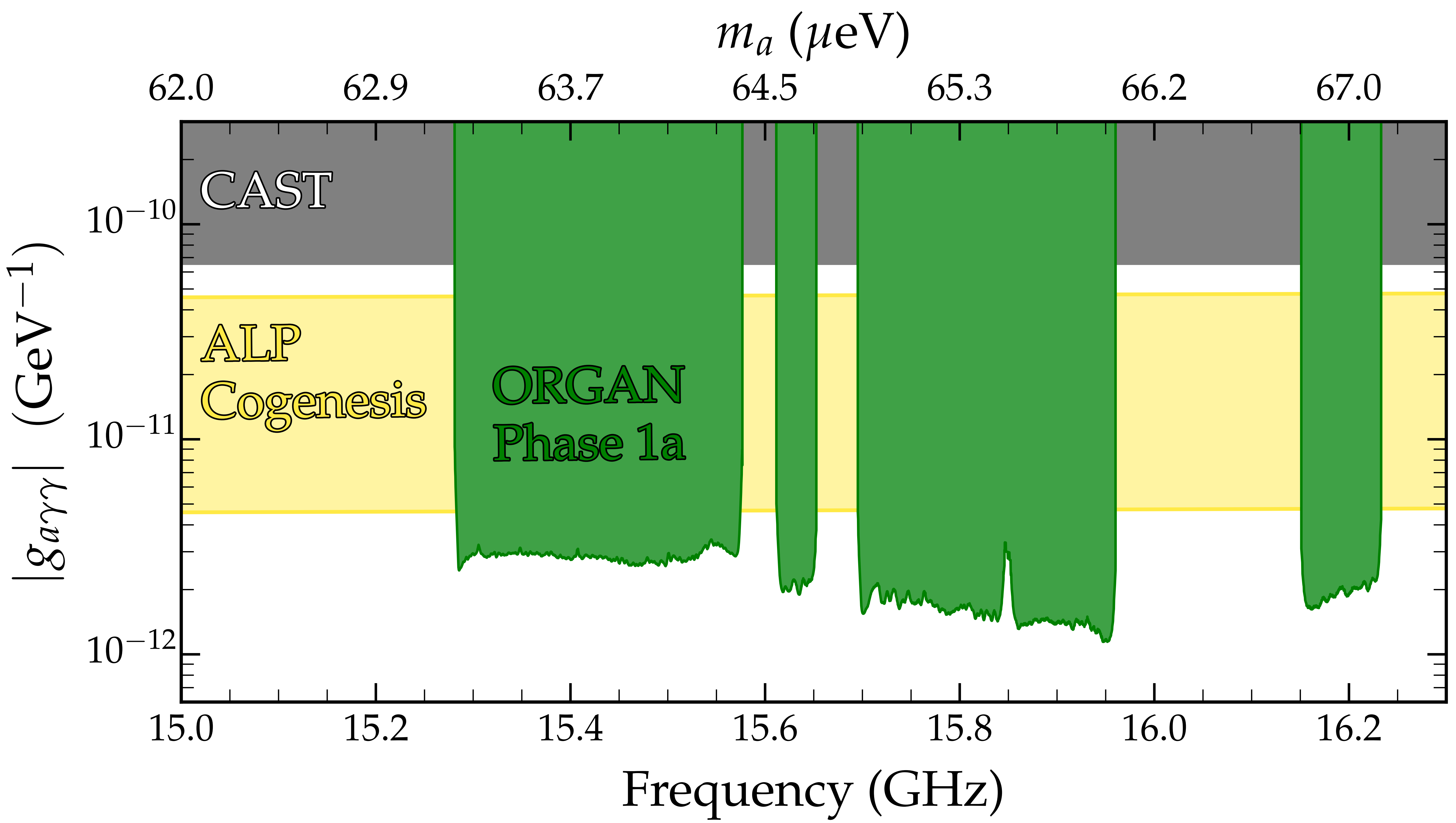
Dilution fridge

"Mode Map"



Limits on $g_{a\gamma\gamma}$

- ~24 days of data-taking
- Limits set between 15.28 - 16.23 GHz at $g_{a\gamma\gamma} \sim 3 \times 10^{-12}$ (ALP cogenesis)



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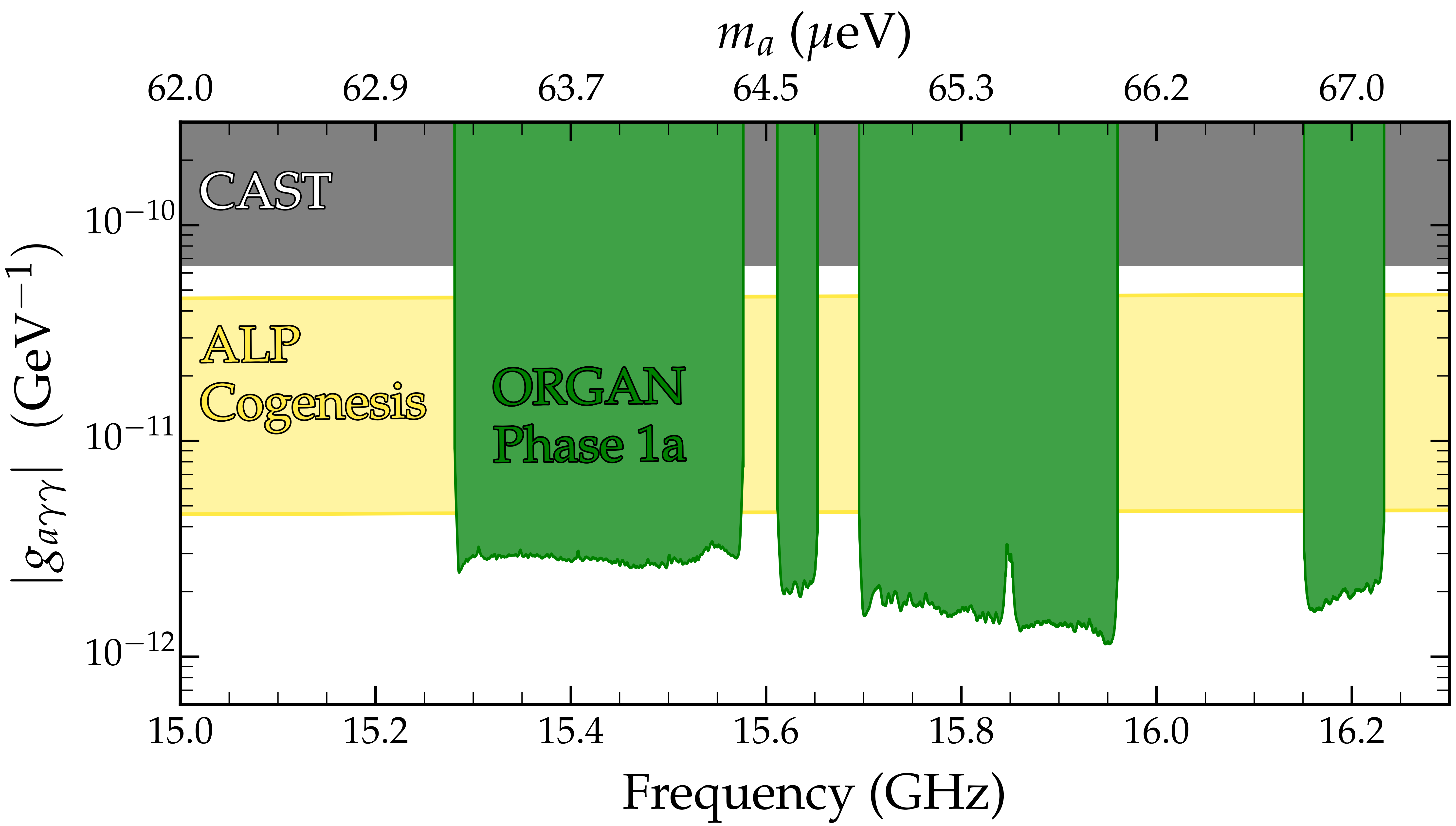

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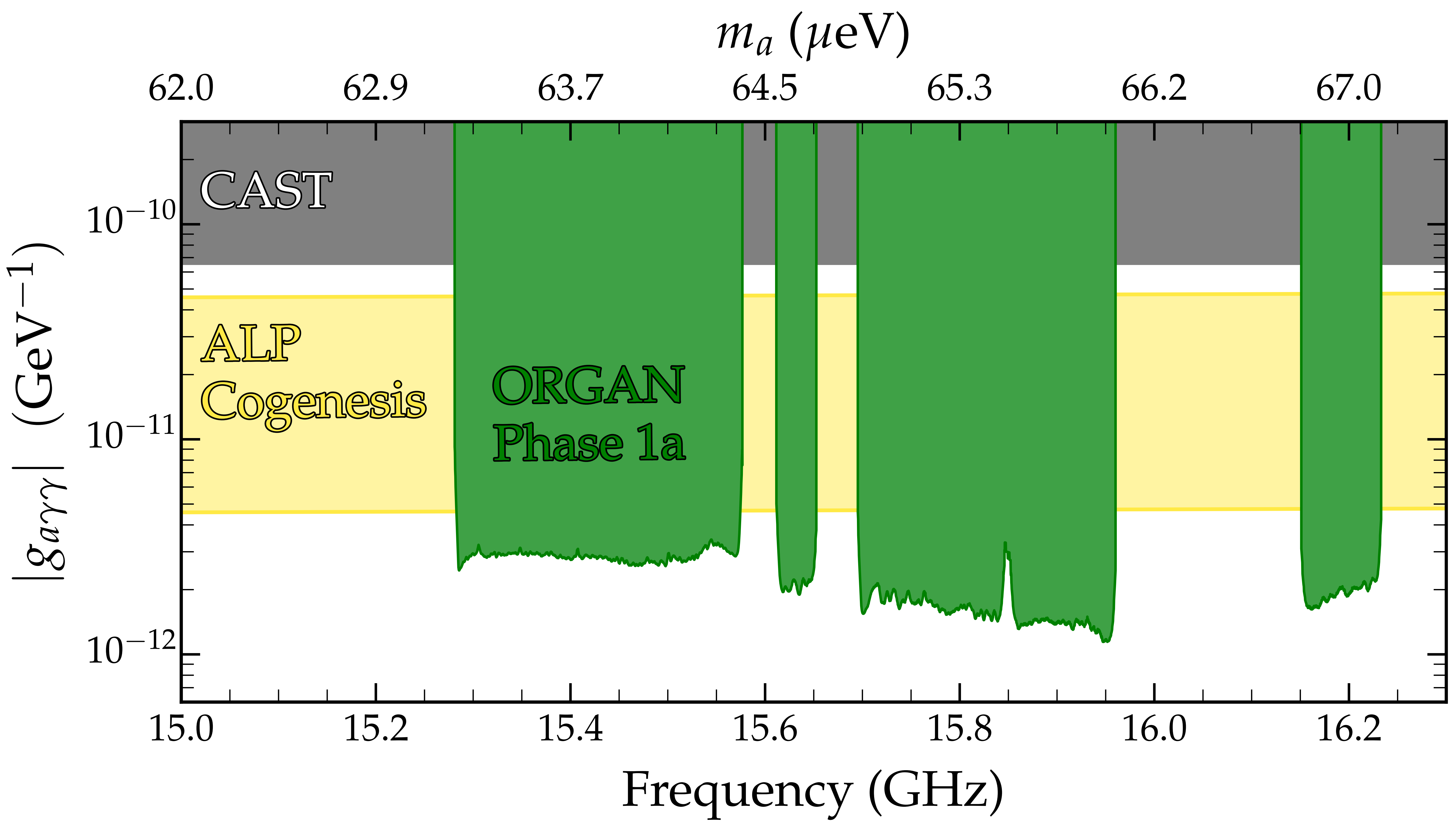

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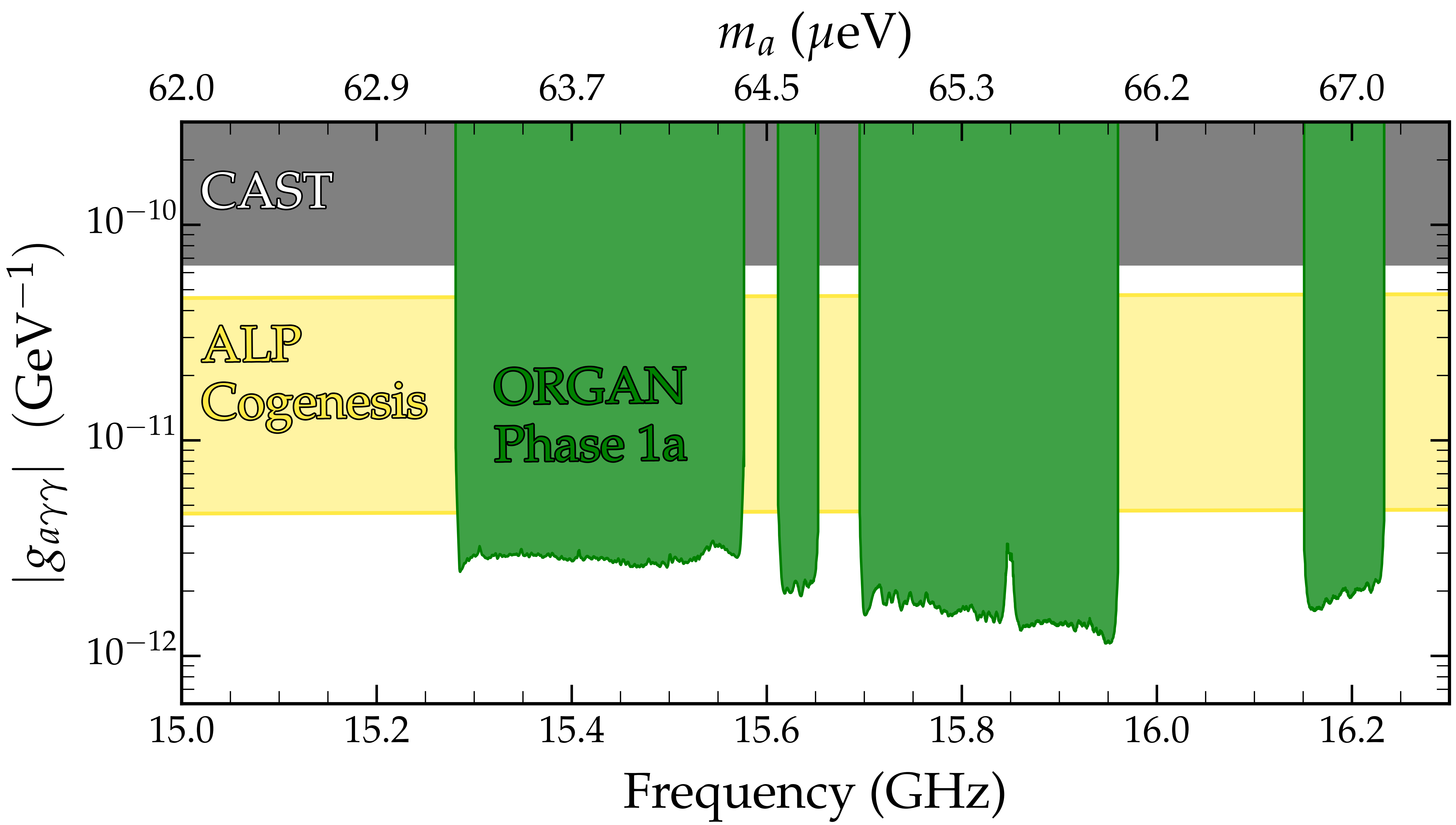
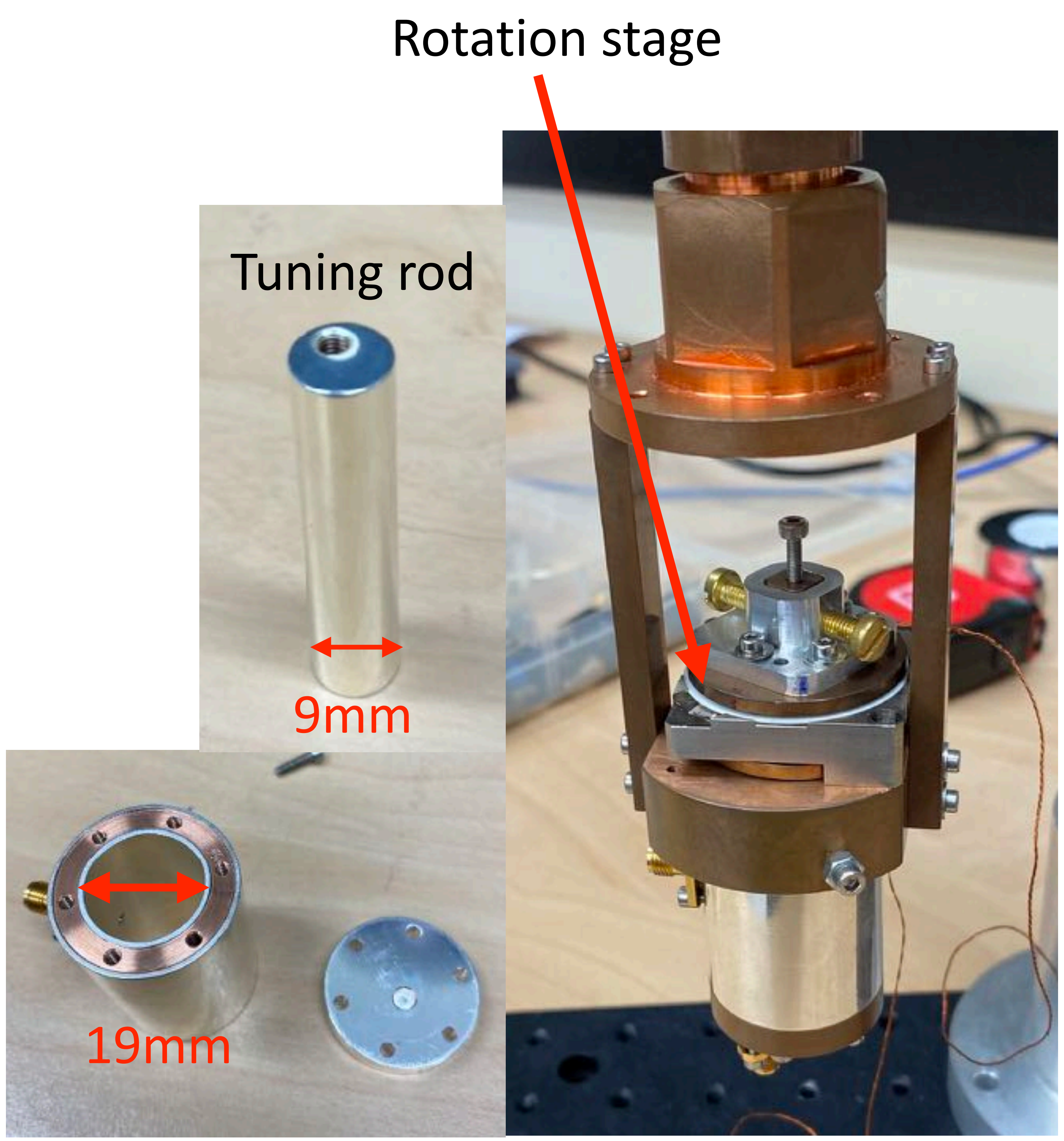
- Gaps to be filled in phase 2 of ORGAN



Phase 1b

- 26 - 27 GHz target range
- Remember resonator is **necessarily** small, $\nu_c \propto R_c^{-1}$



26 GHz tuning-rod cavity

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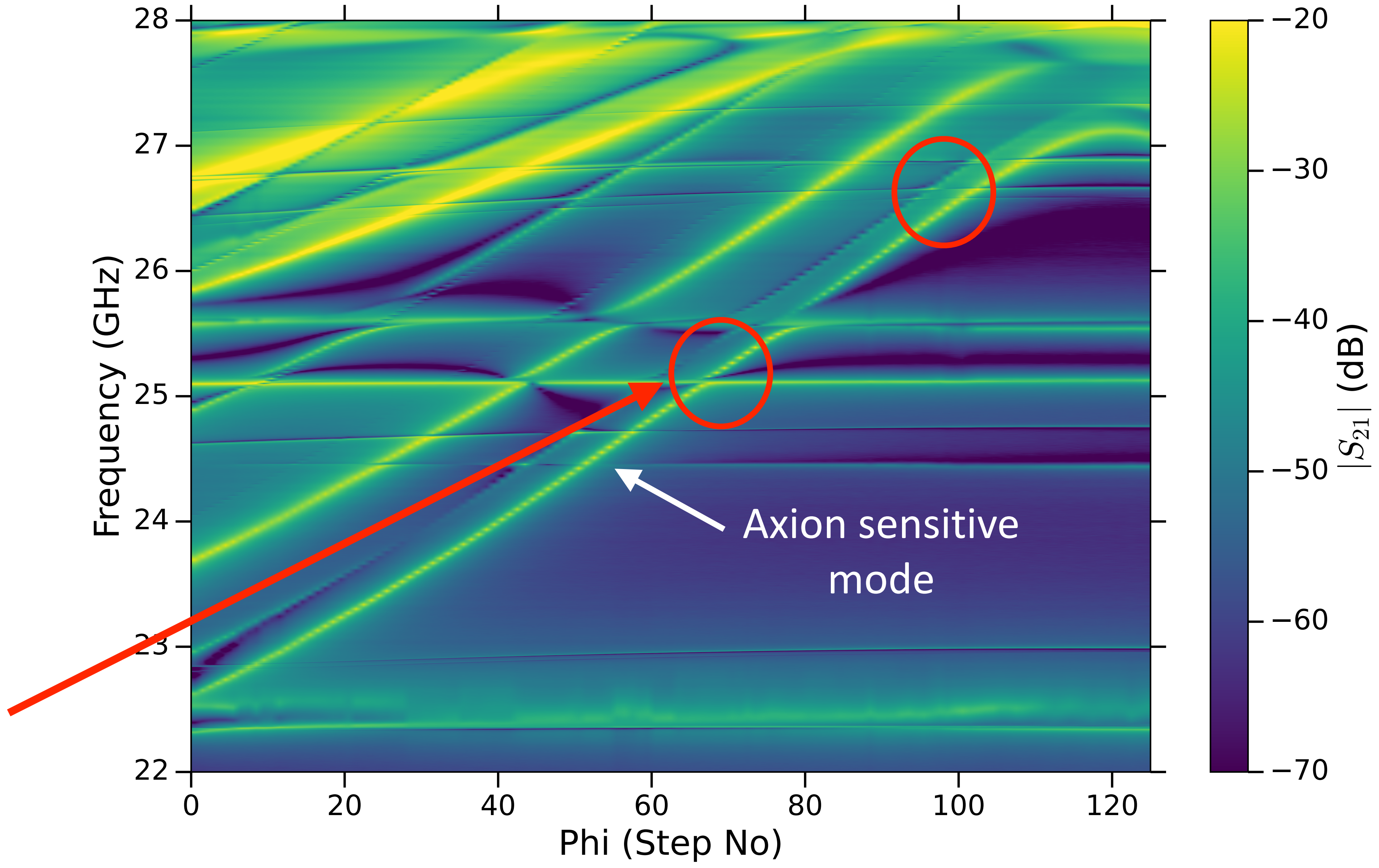

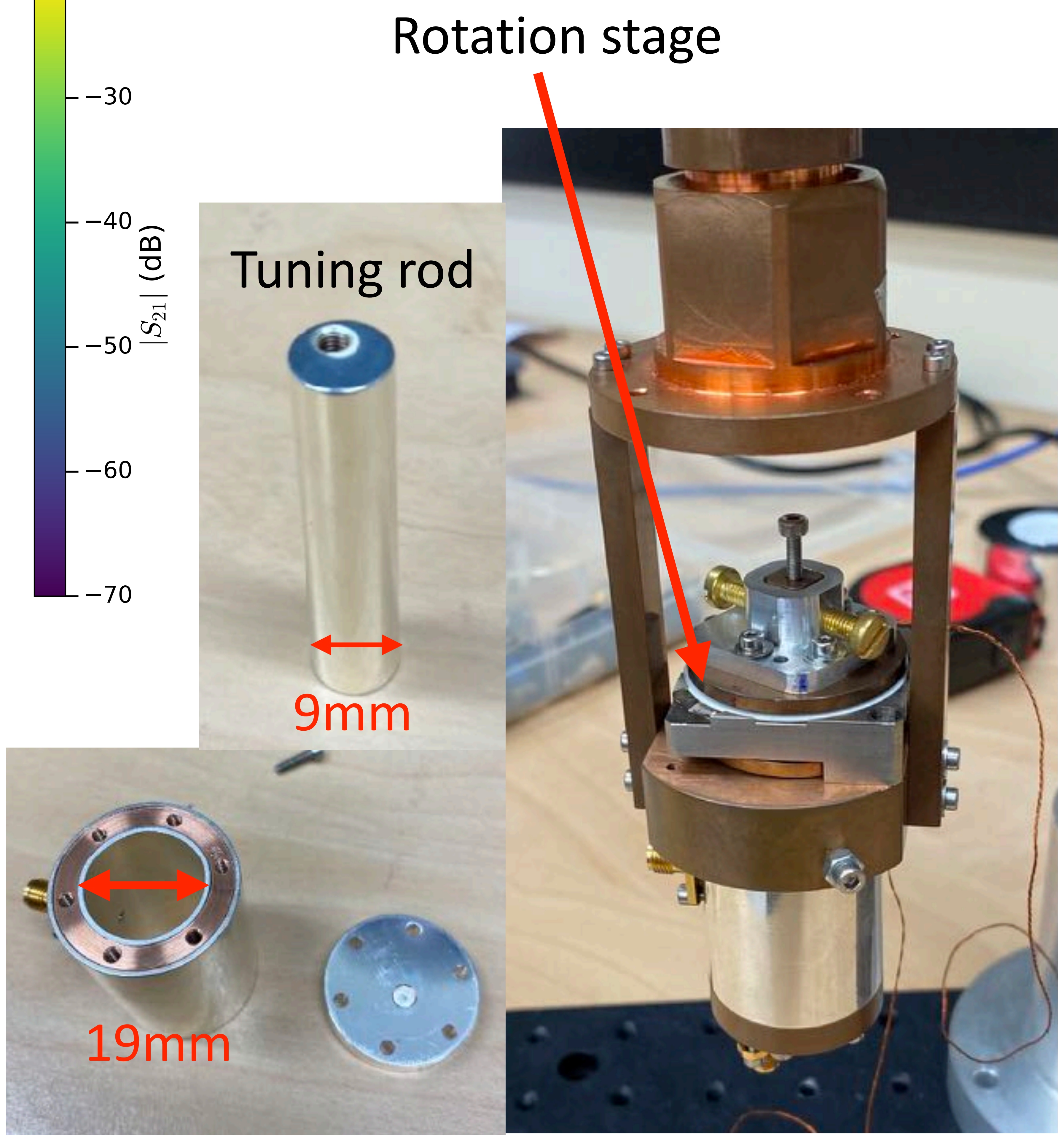

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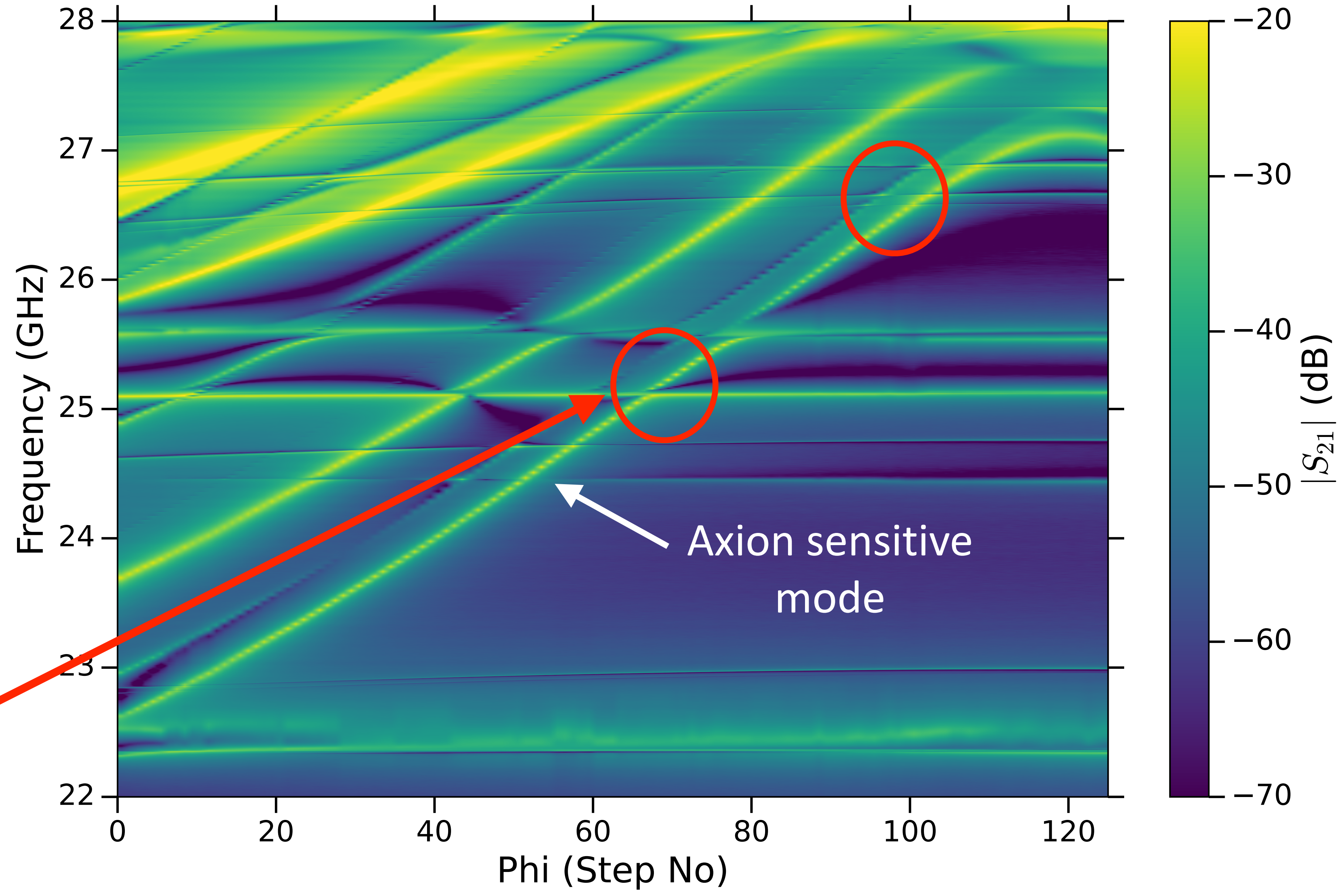

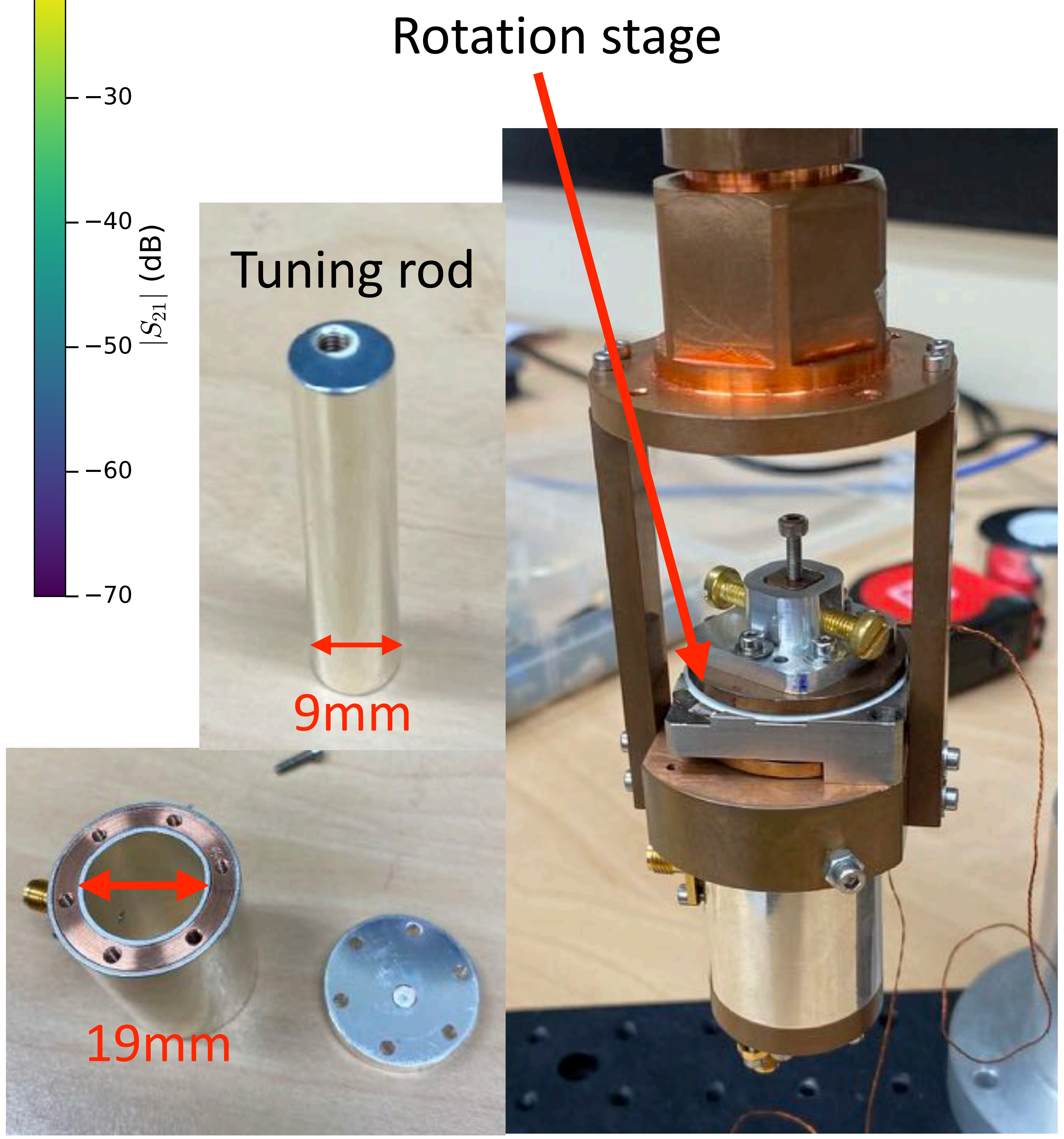

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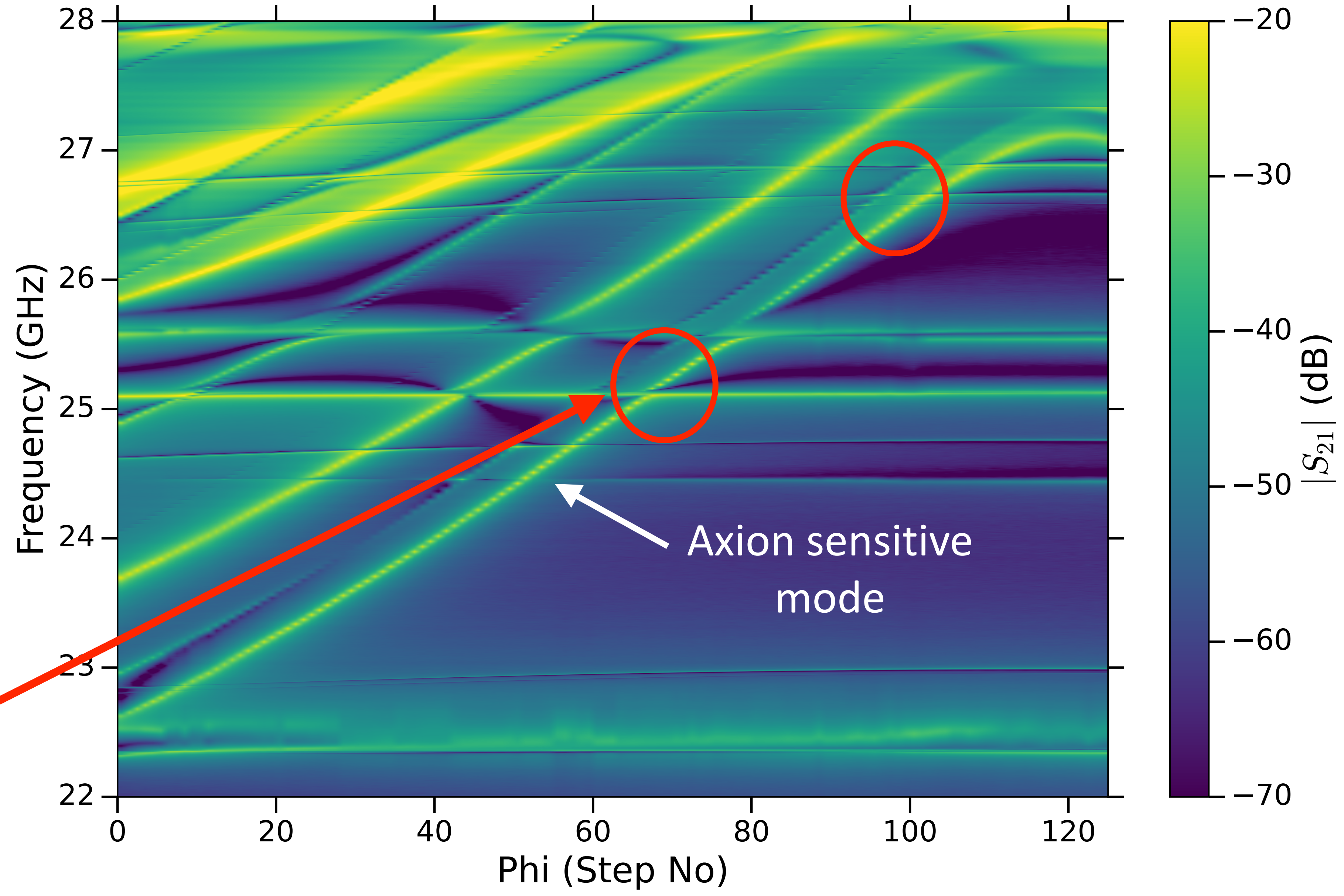

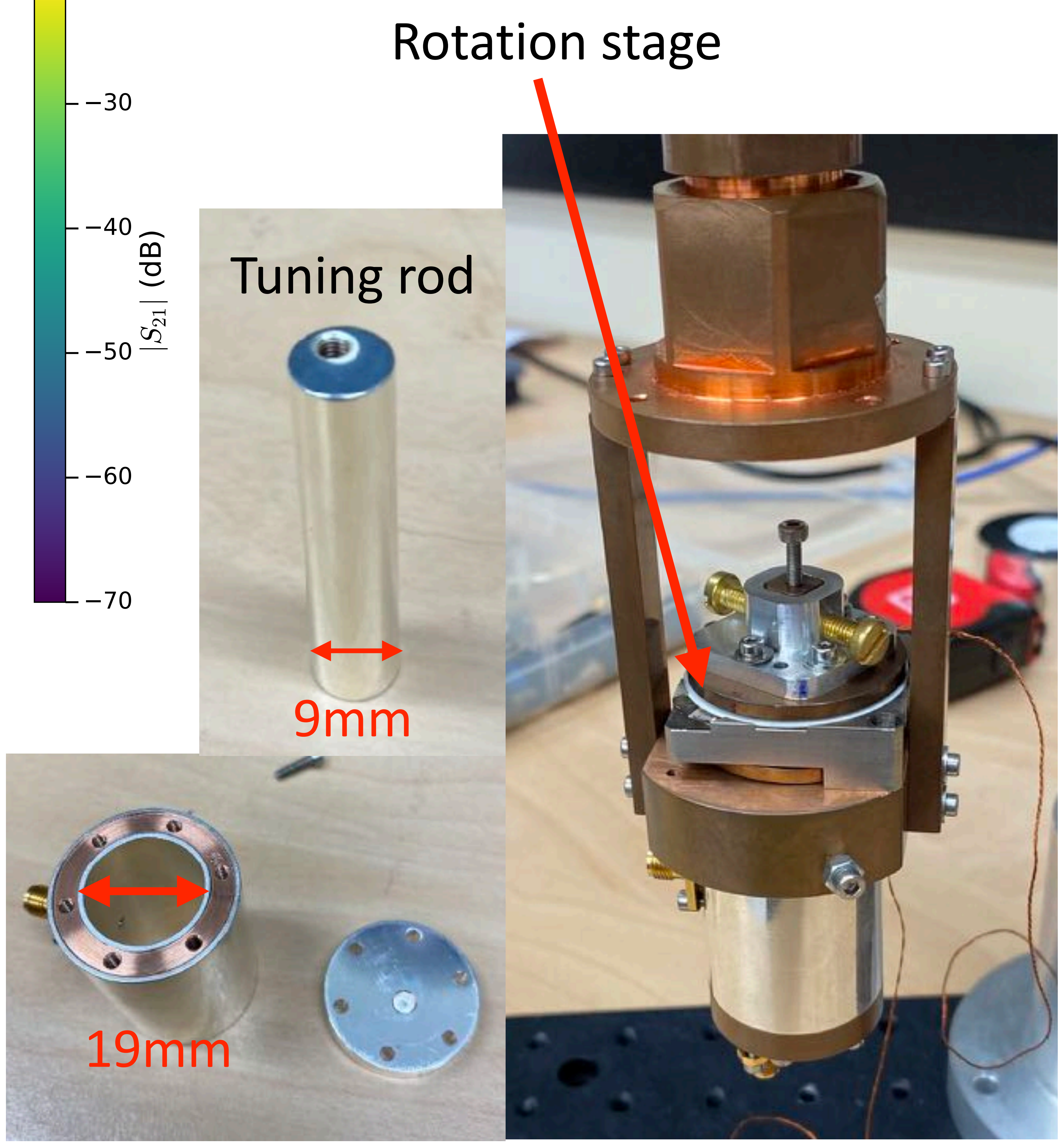

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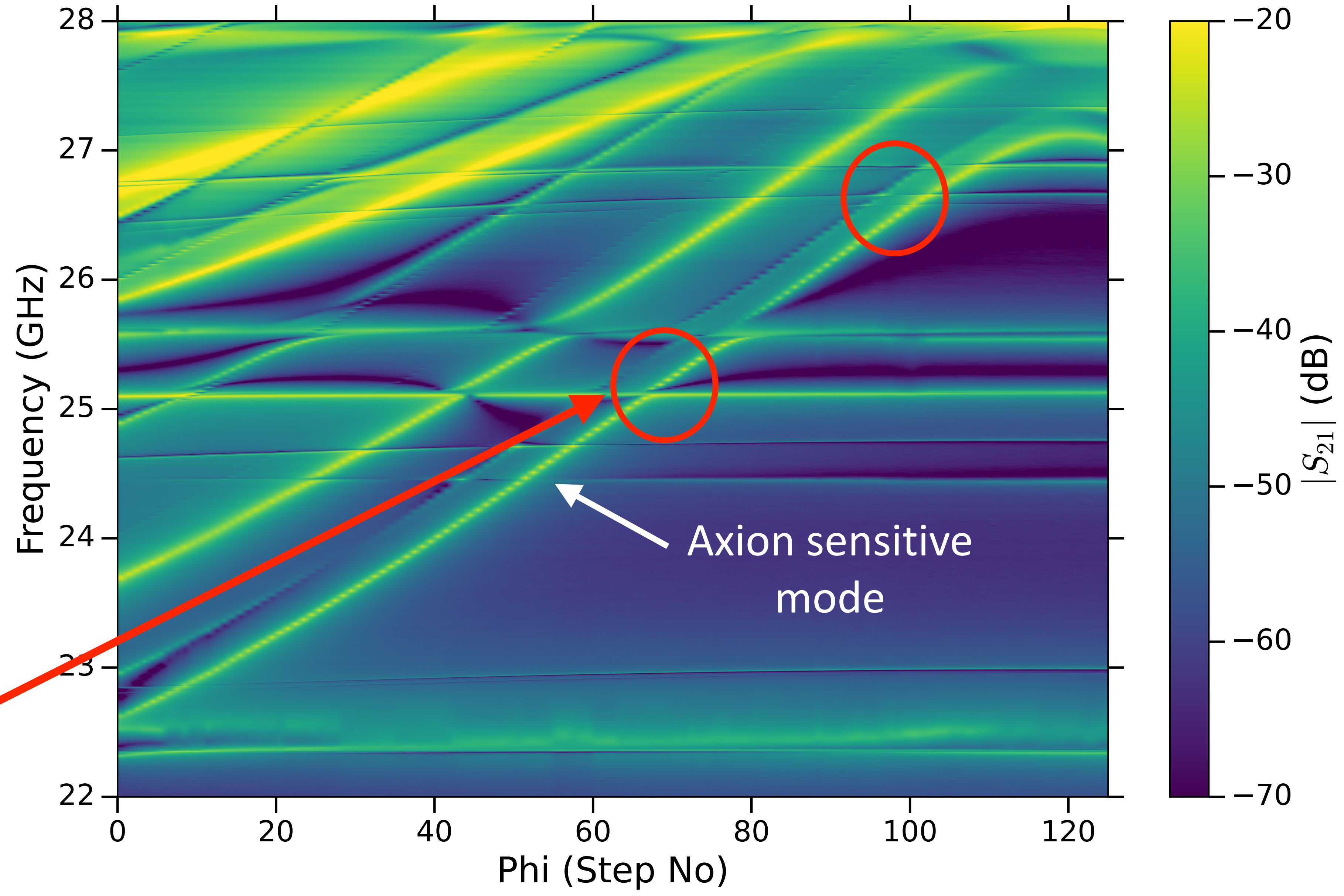

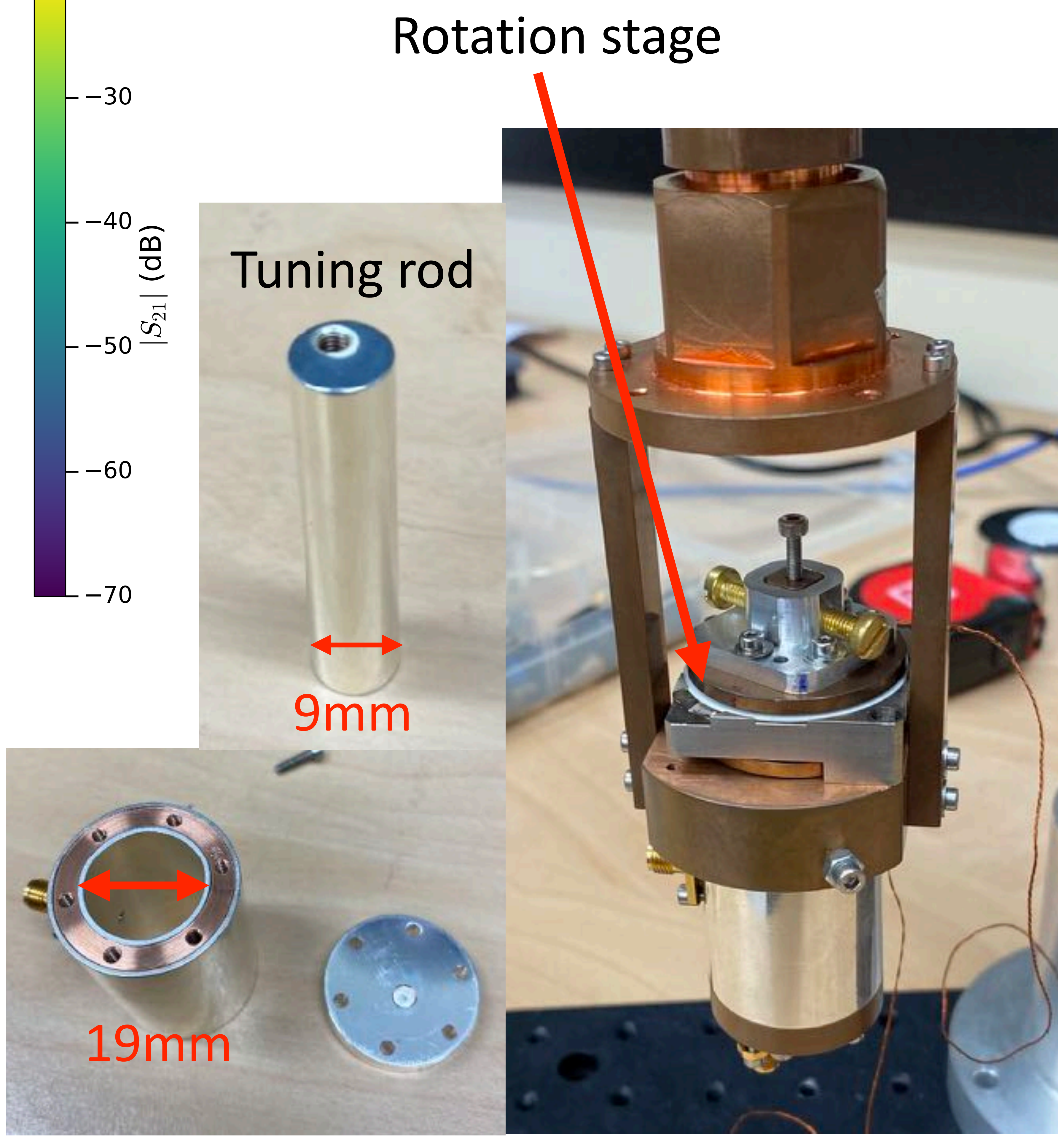

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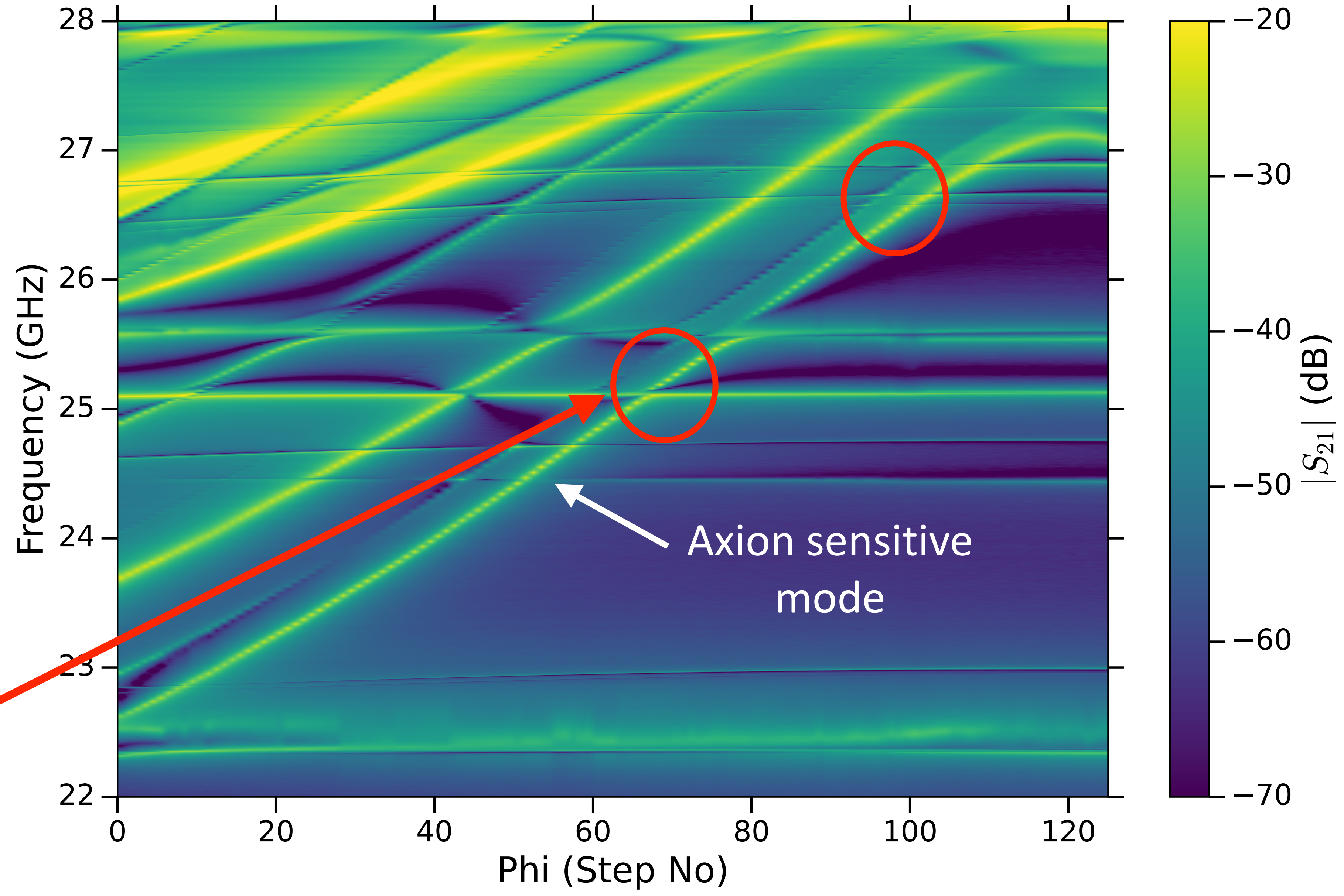
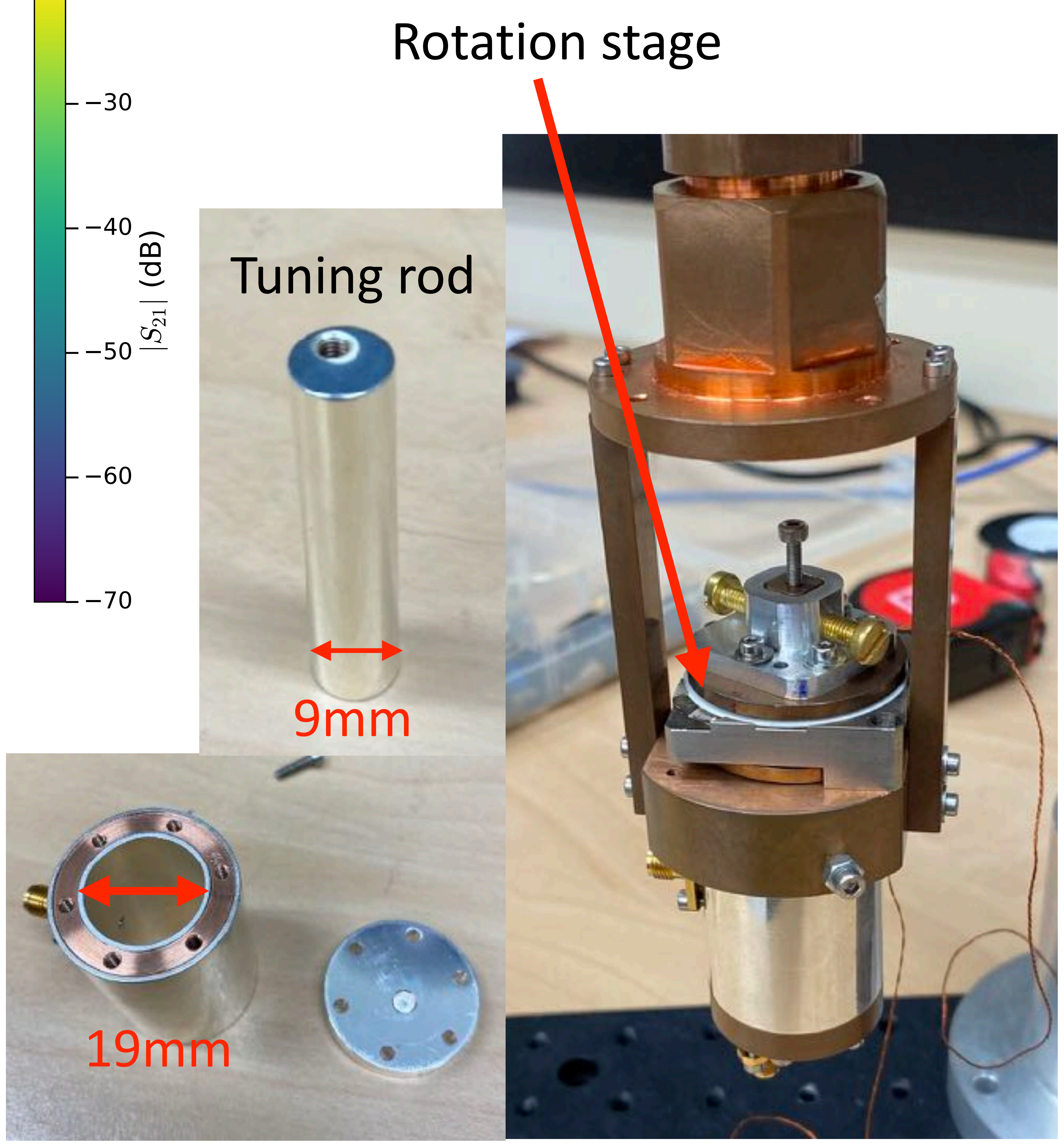
- Novel resonator needed..





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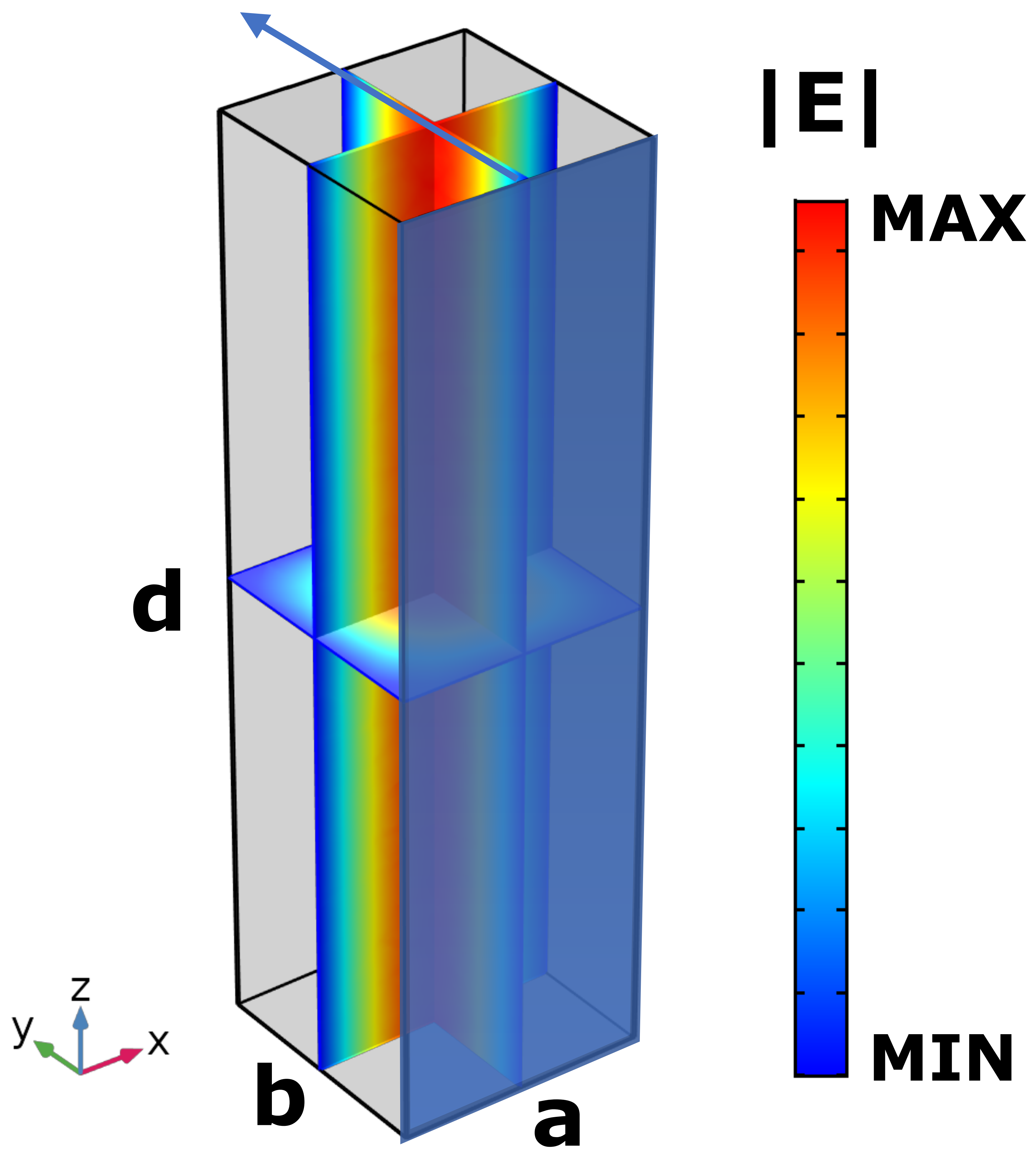
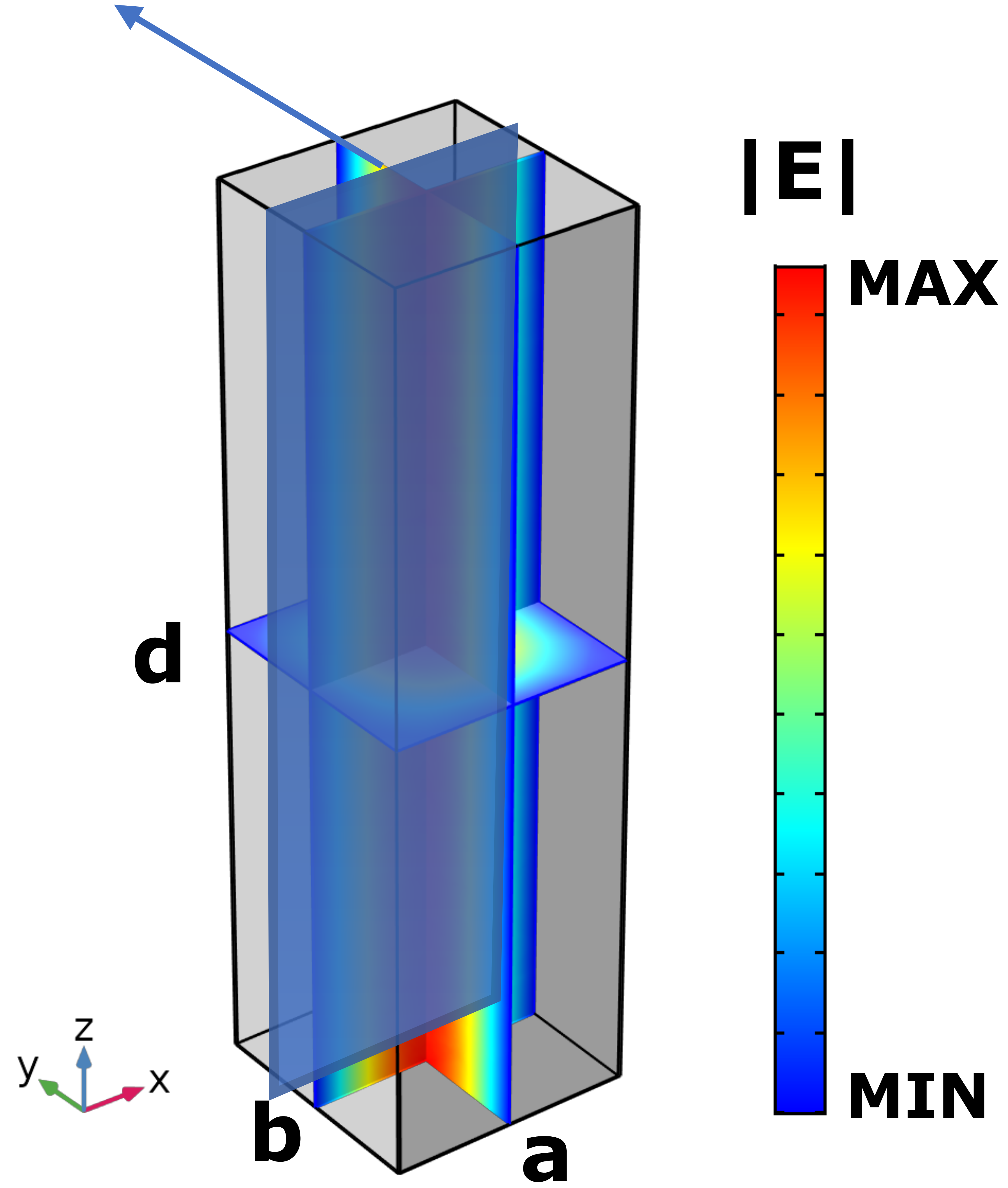
Rectangle vs Tuning-rod



TM_{110} mode

Rectangle vs Tuning-rod

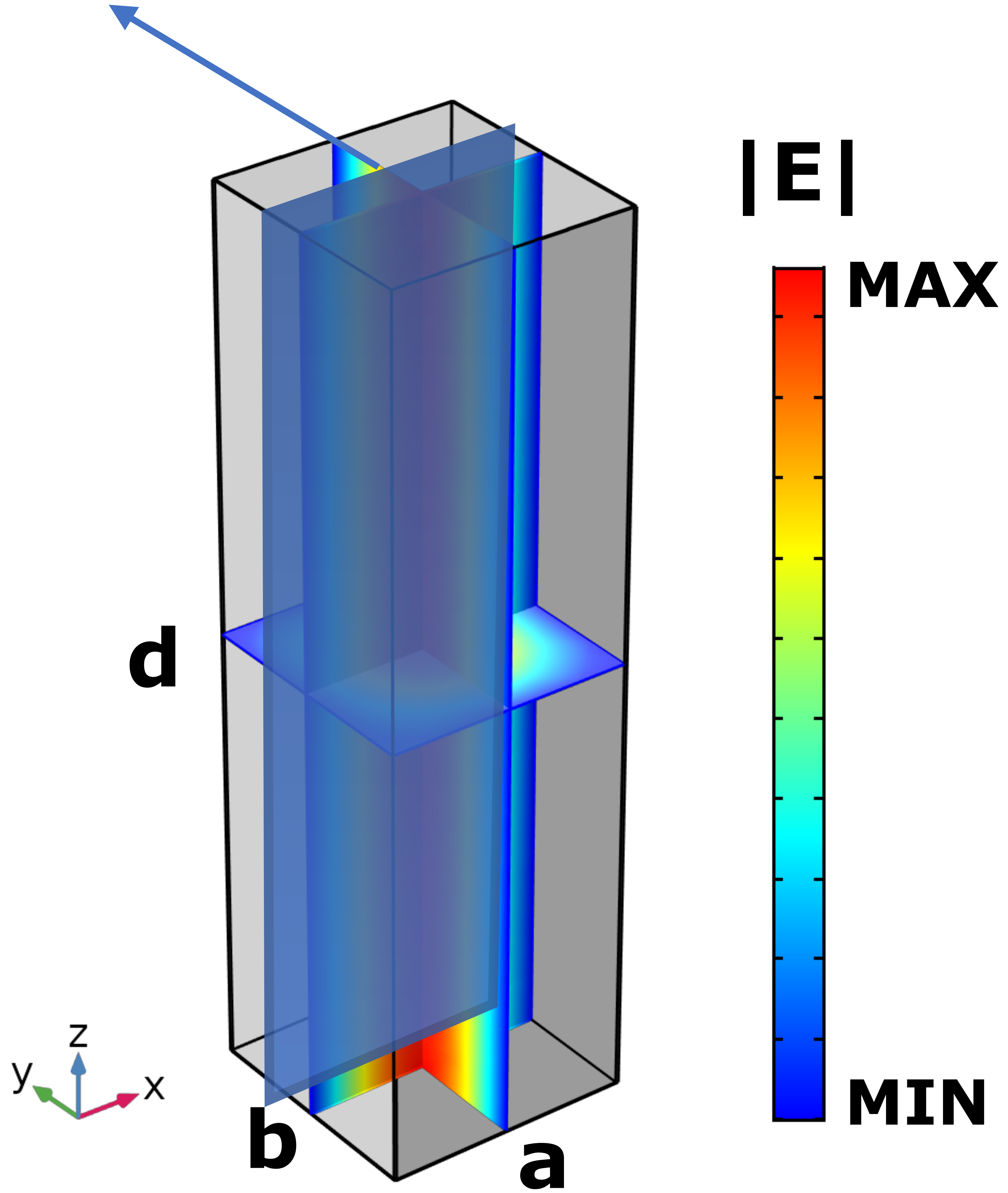
- Rectangular cavity with a tunable wall



TM$_{110}$ mode

Rectangle vs Tuning-rod

- Rectangular cavity with a tunable wall
- New tunable rectangular cavity solves many problems!



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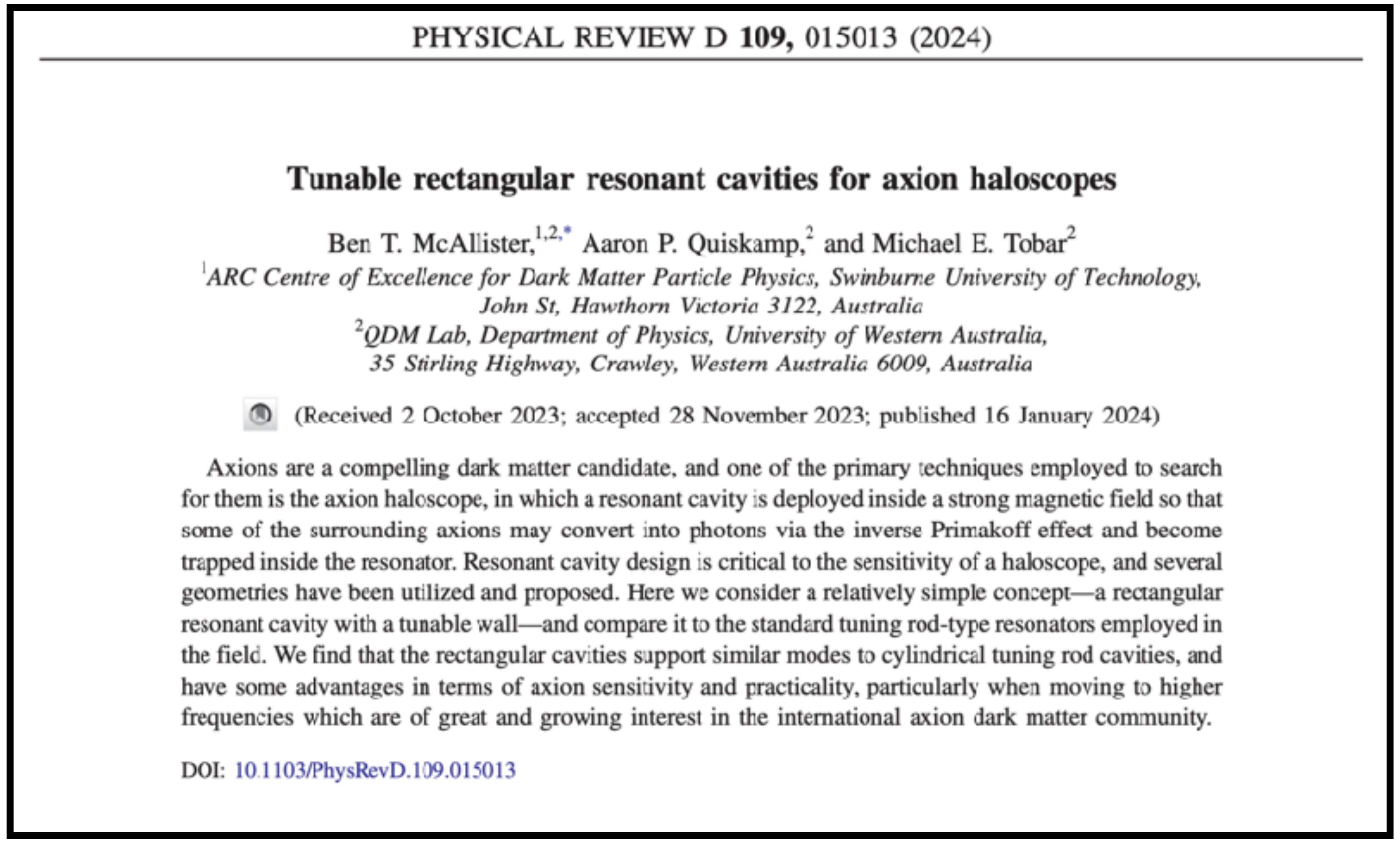
- Rectangle cavity VS Tuning rod cavity



PHYSICAL REVIEW D **109,** 015013 (2024)

Tunable rectangular resonant cavities for axion haloscopes

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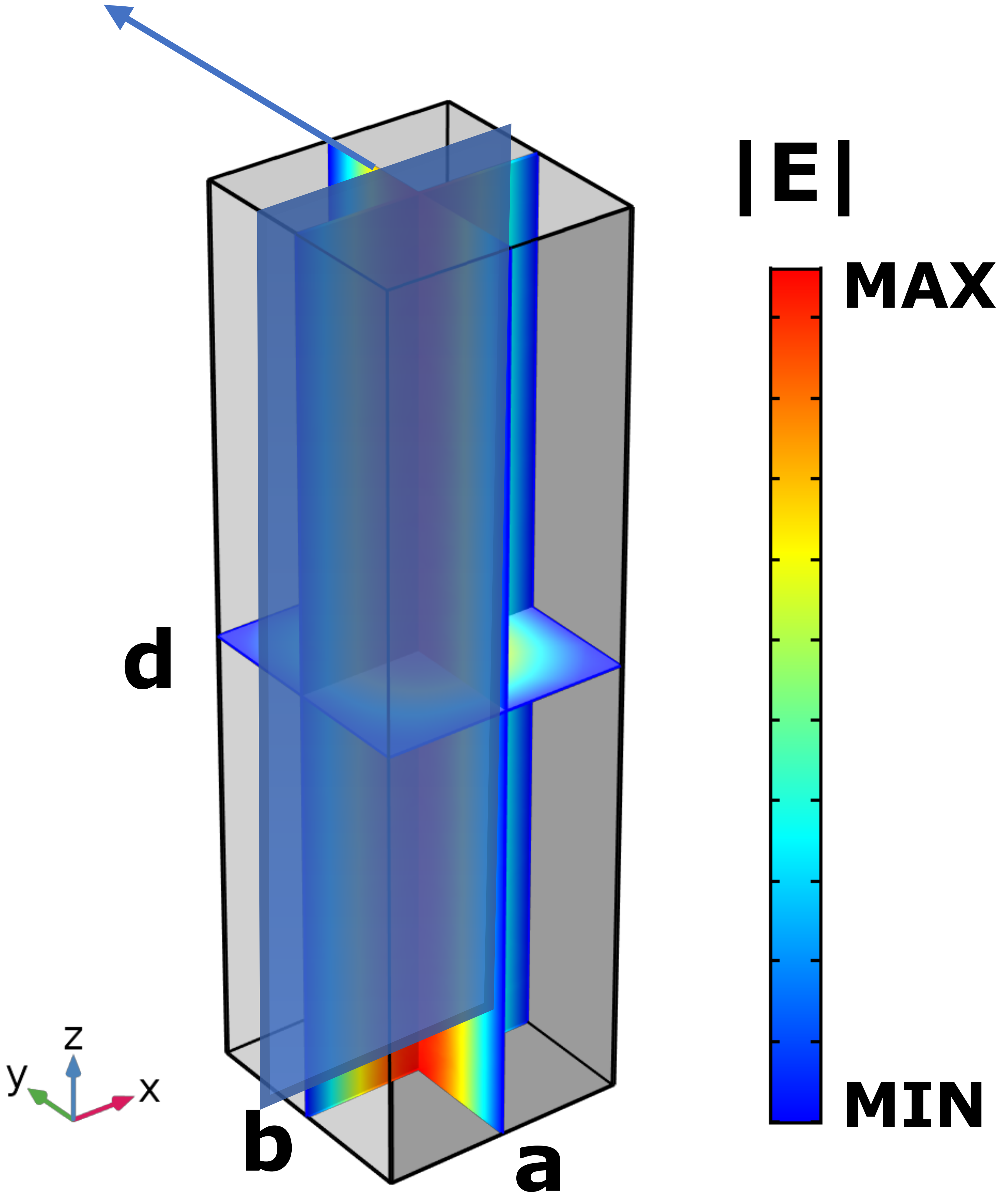
[2]*QDM Lab, Department of Physics, University of Western Australia, 35 Stirling Highway, Crawley, Western Australia 6009, Australia*

(Received 2 October 2023; accepted 28 November 2023; published 16 January 2024)

Axions are a compelling dark matter candidate, and one of the primary techniques employed to search for them is the axion haloscope, in which a resonant cavity is deployed inside a strong magnetic field so that some of the surrounding axions may convert into photons via the inverse Primakoff effect and become trapped inside the resonator. Resonant cavity design is critical to the sensitivity of a haloscope, and several geometries have been utilized and proposed. Here we consider a relatively simple concept—a rectangular resonant cavity with a tunable wall—and compare it to the standard tuning rod-type resonators employed in the field. We find that the rectangular cavities support similar modes to cylindrical tuning rod cavities, and have some advantages in terms of axion sensitivity and practicality, particularly when moving to higher frequencies which are of great and growing interest in the international axion dark matter community.

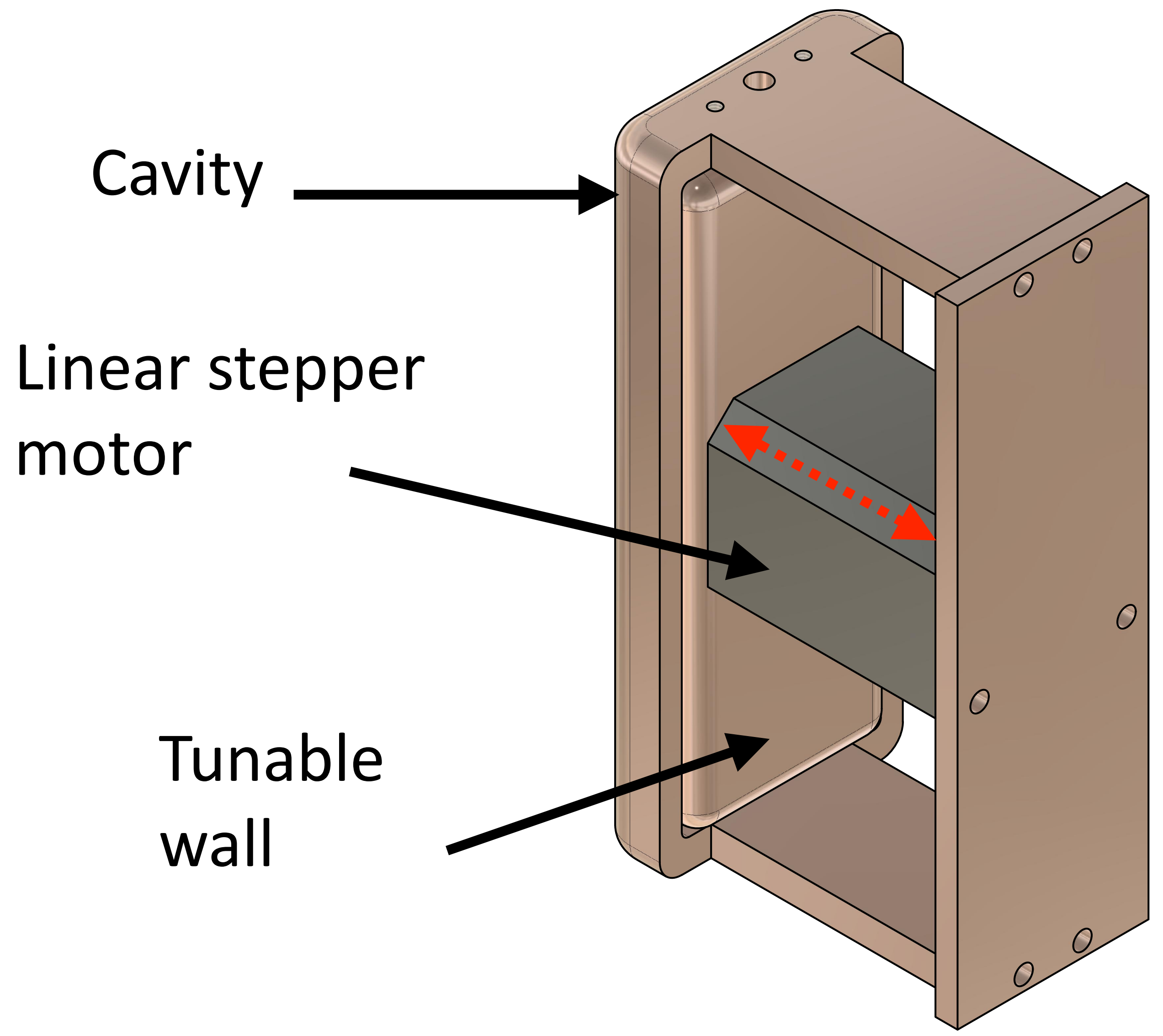
DOI: 10.1103/PhysRevD.109.015013

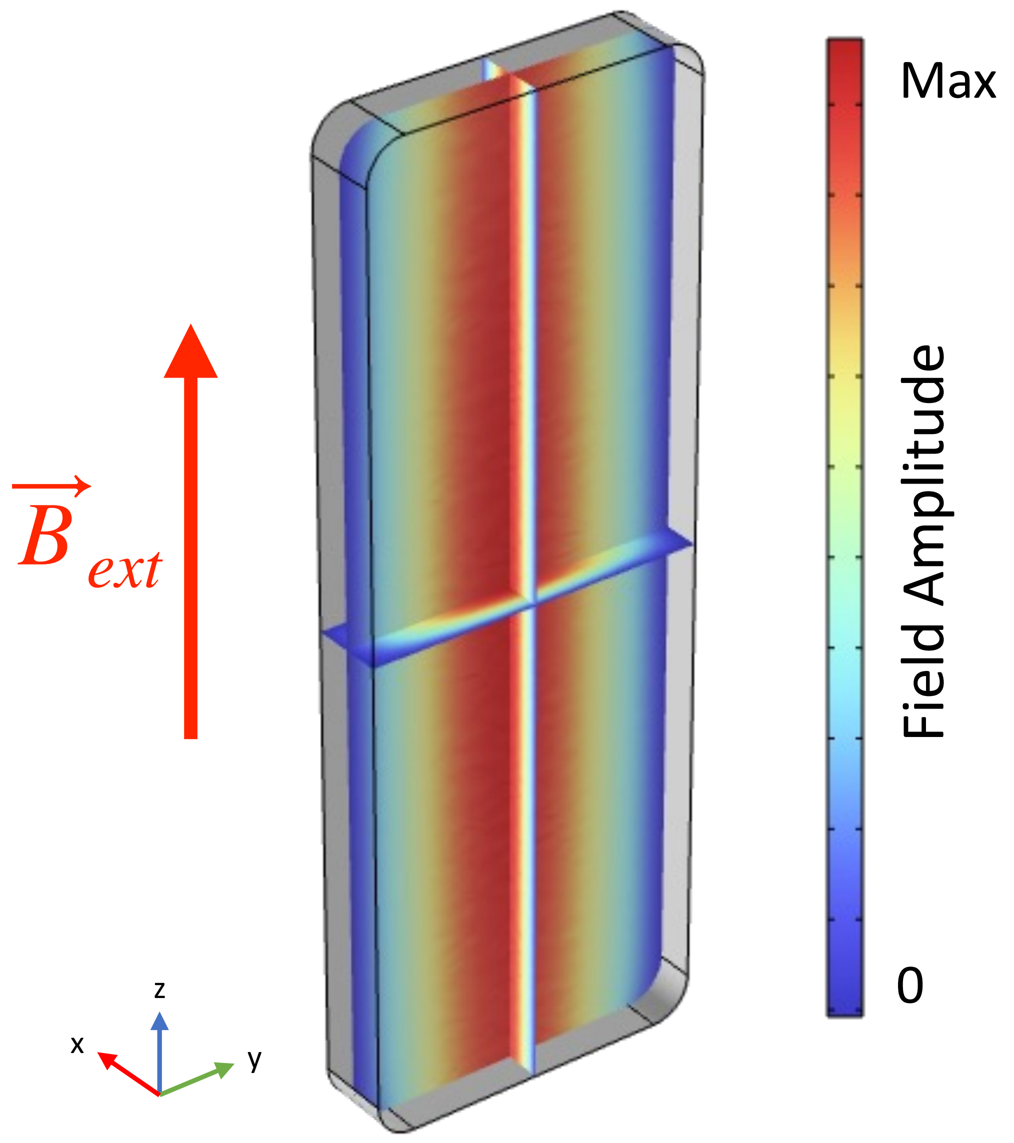


TM_{110} mode

Phase 1b

- Using materials on-hand





E^z Field

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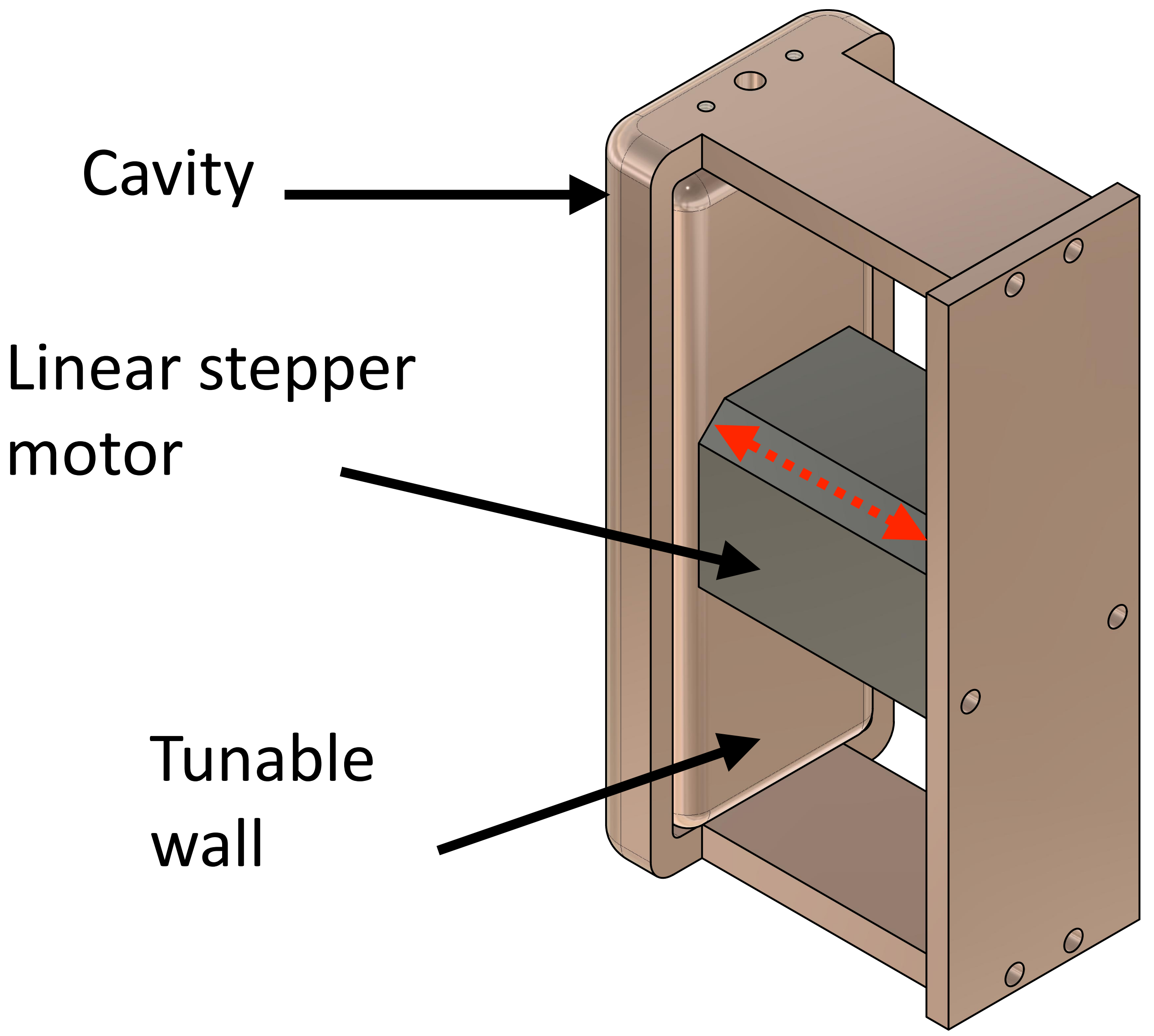
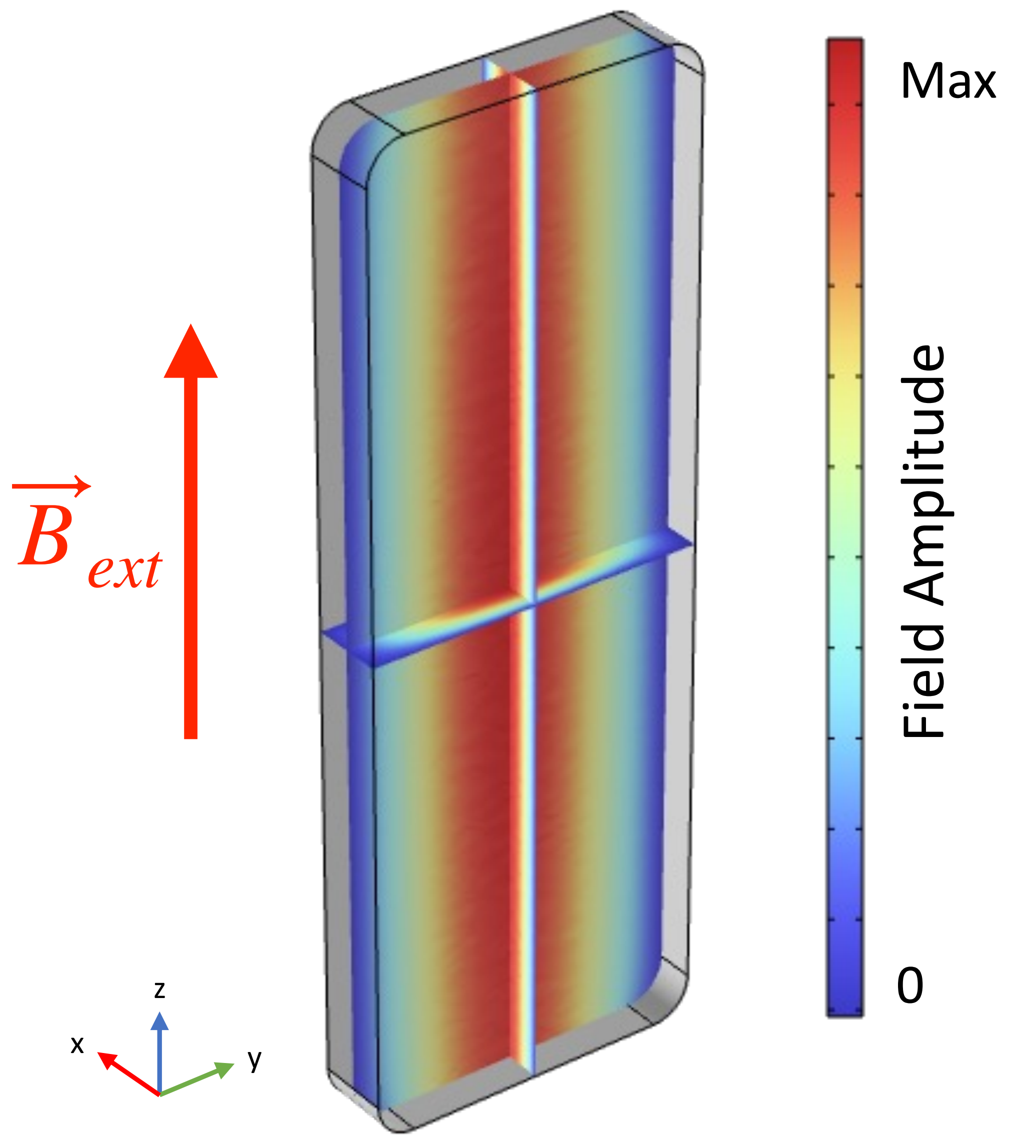
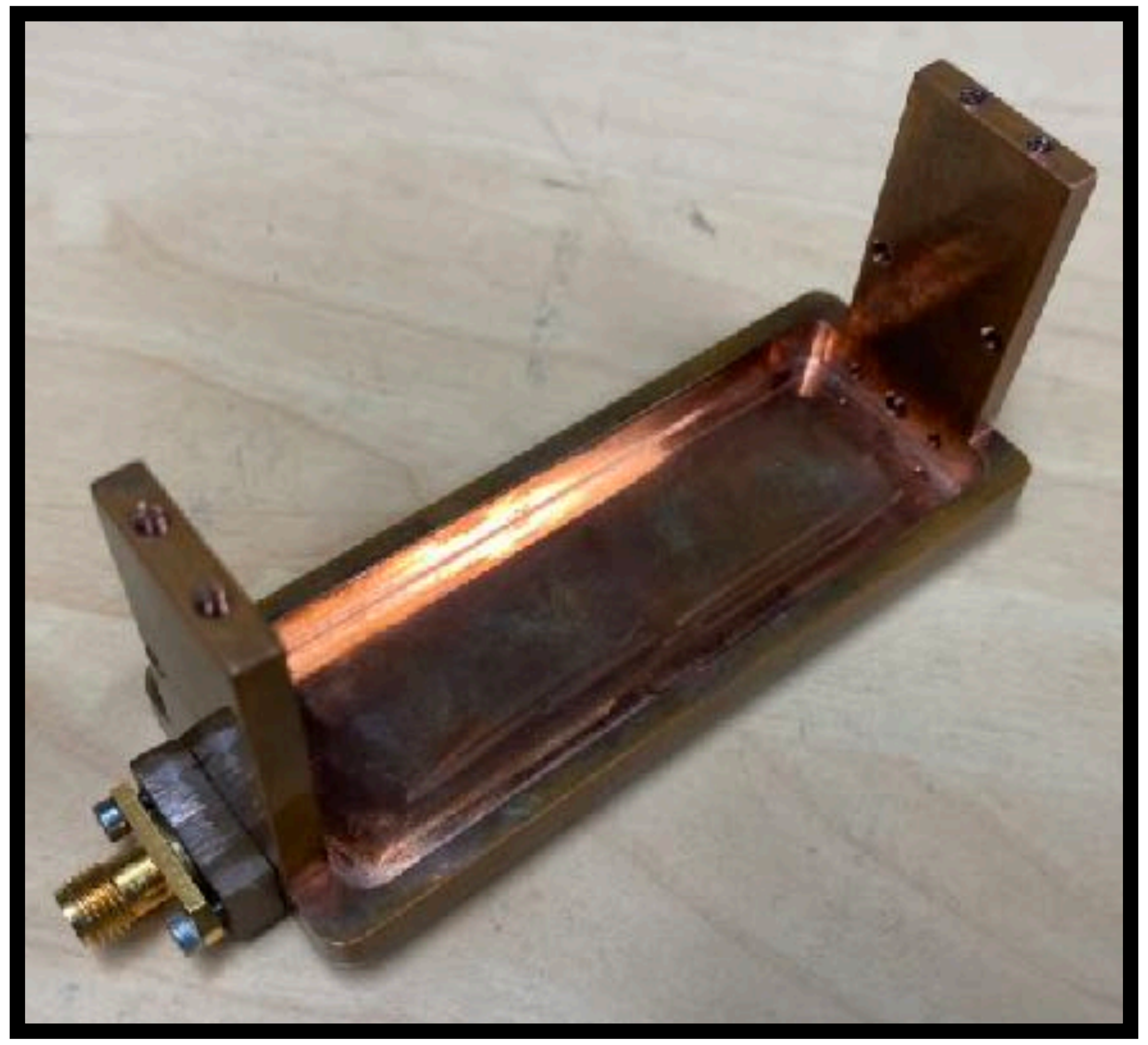
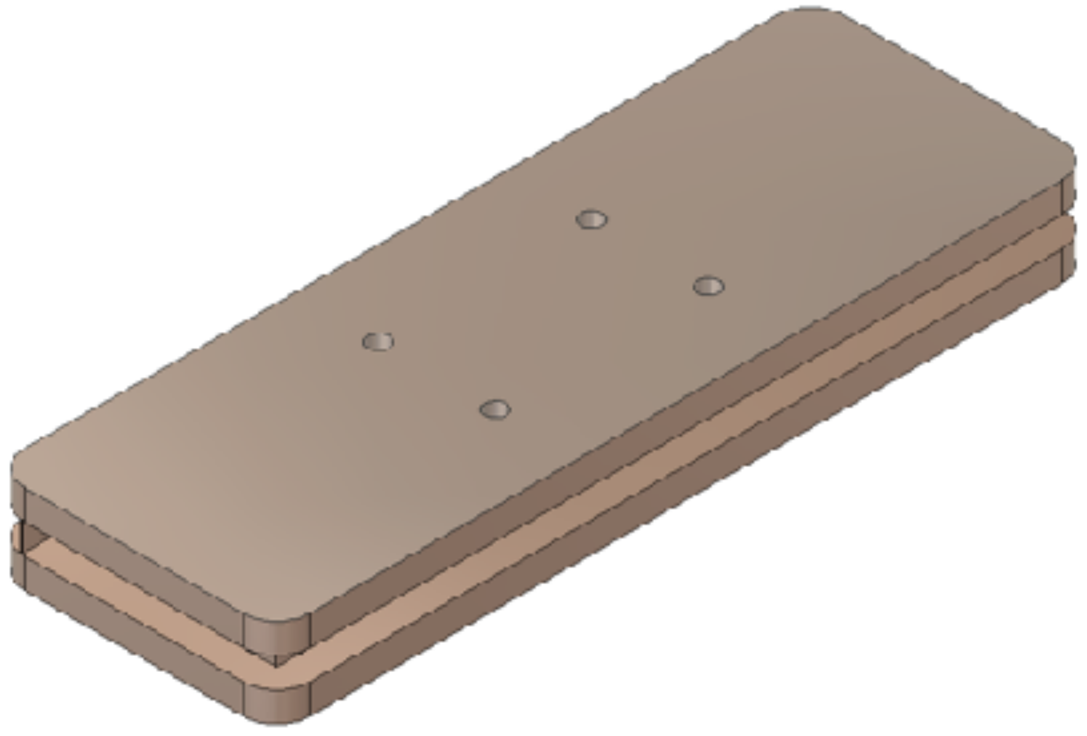
- Using materials on-hand





E^z Field



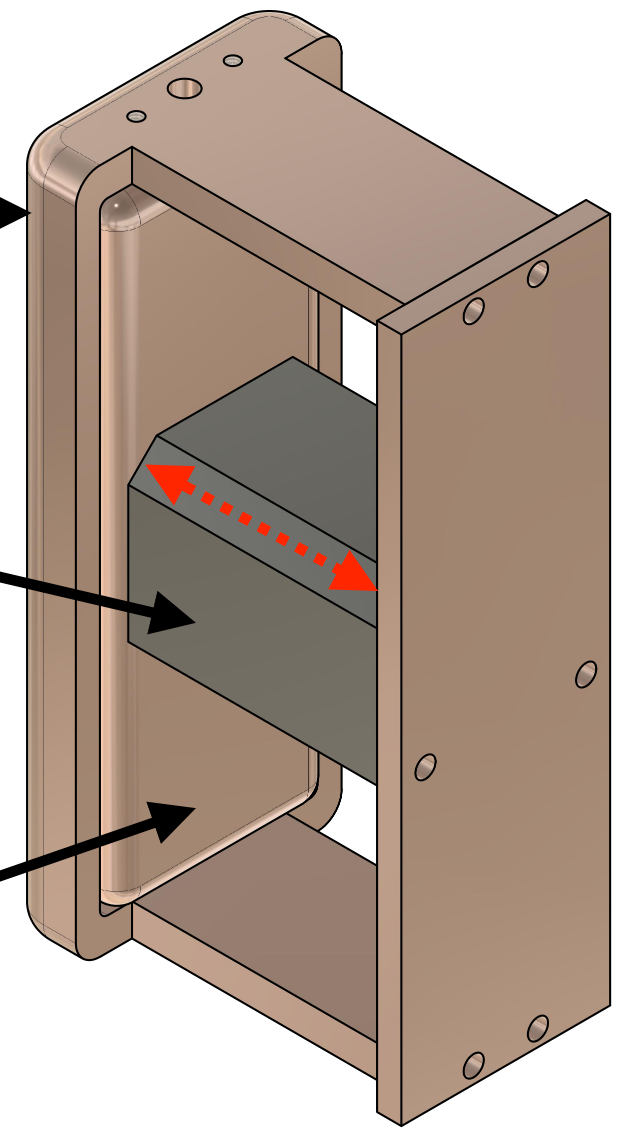


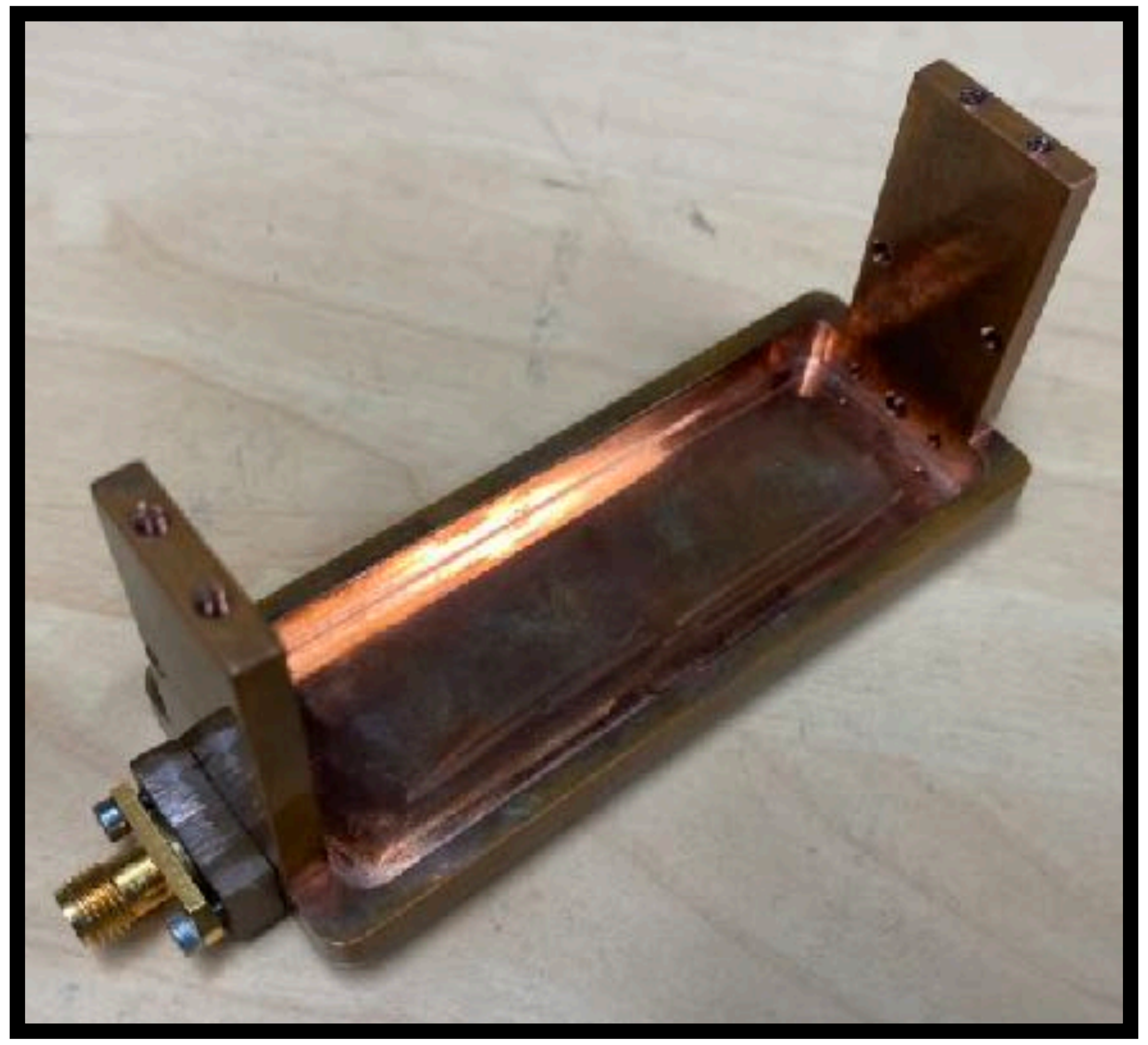
RF choke lid

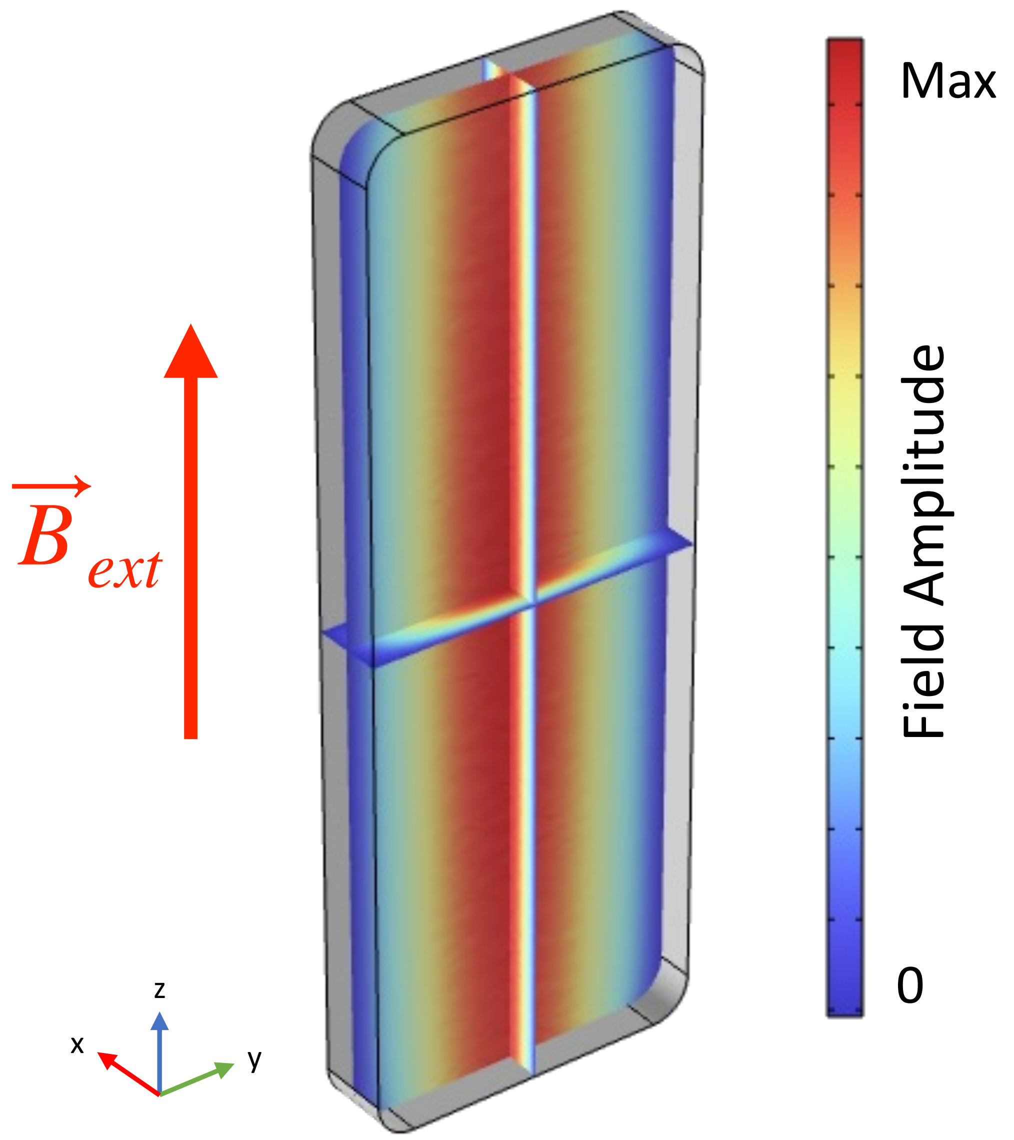
$Q_L :\sim 1000 \rightarrow 4000$

Phase 1b

- Using materials on-hand
- **<u>NO</u>** mode crossings between 26 - 27 GHz







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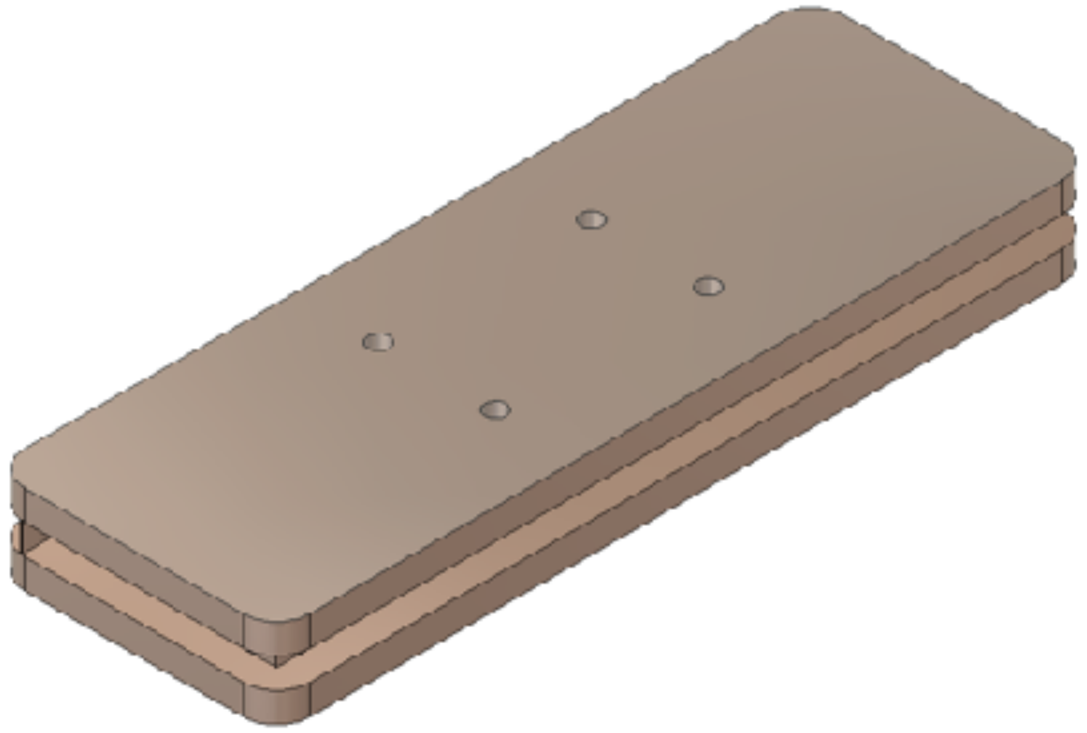
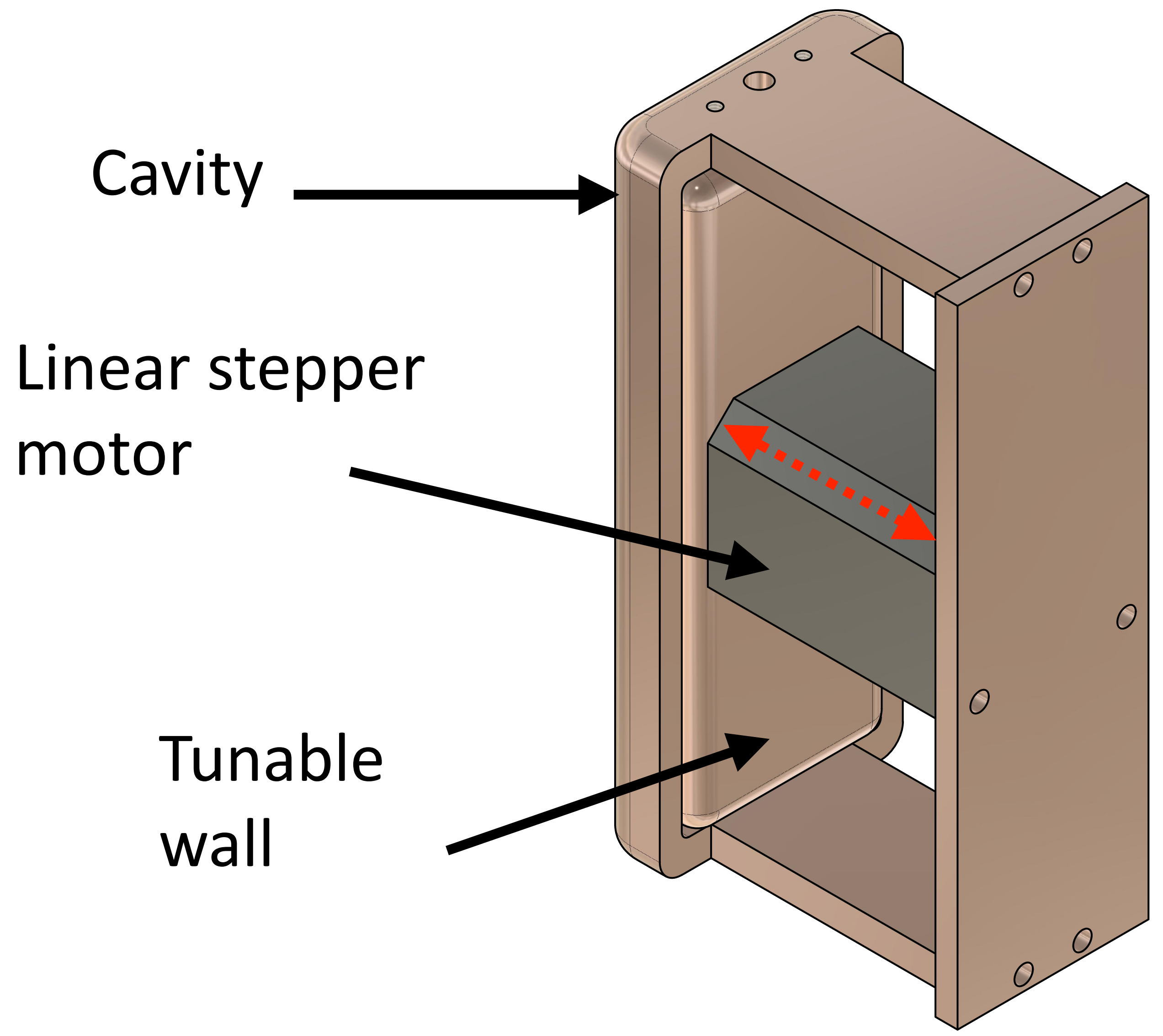


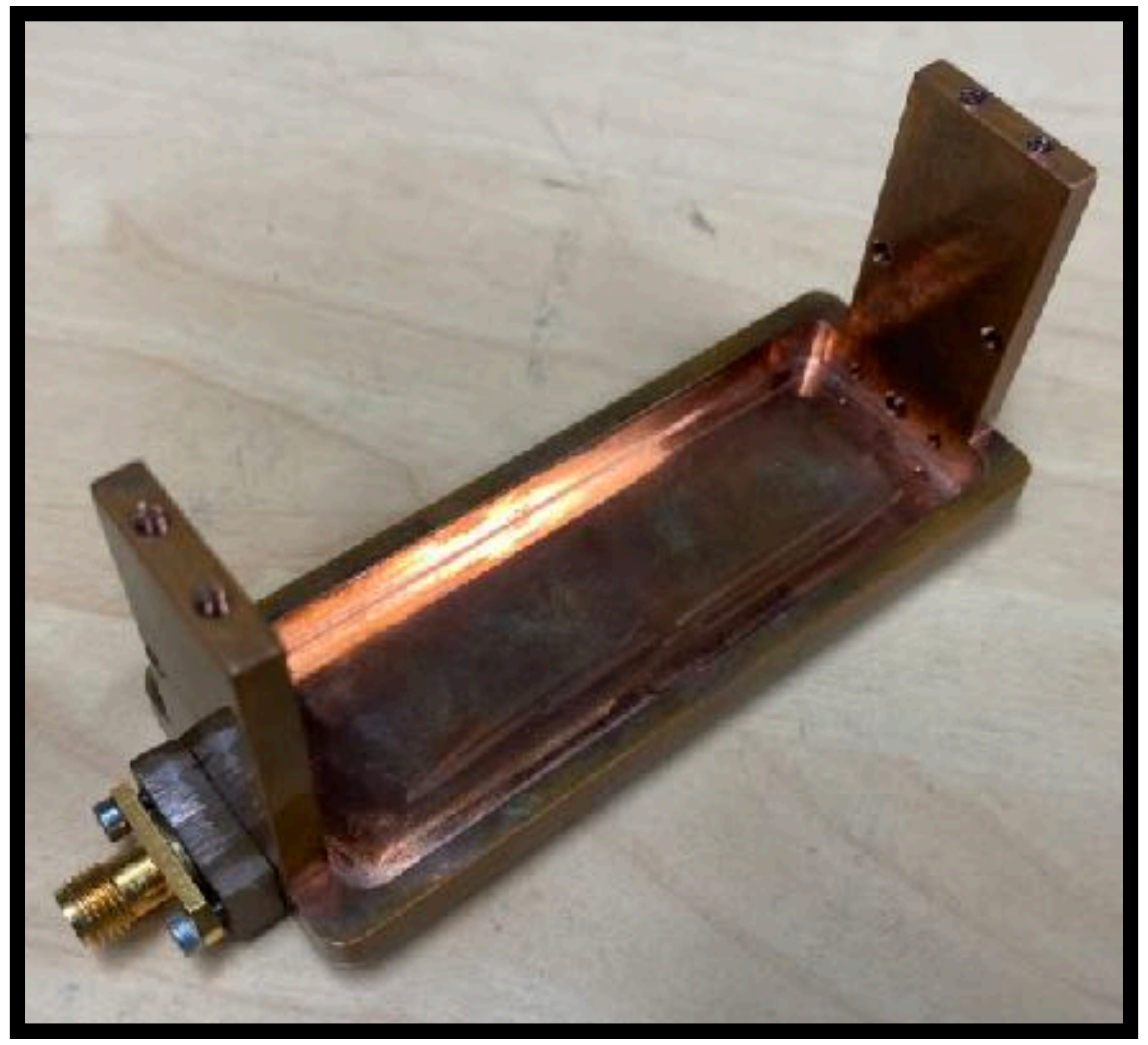
RF choke lid

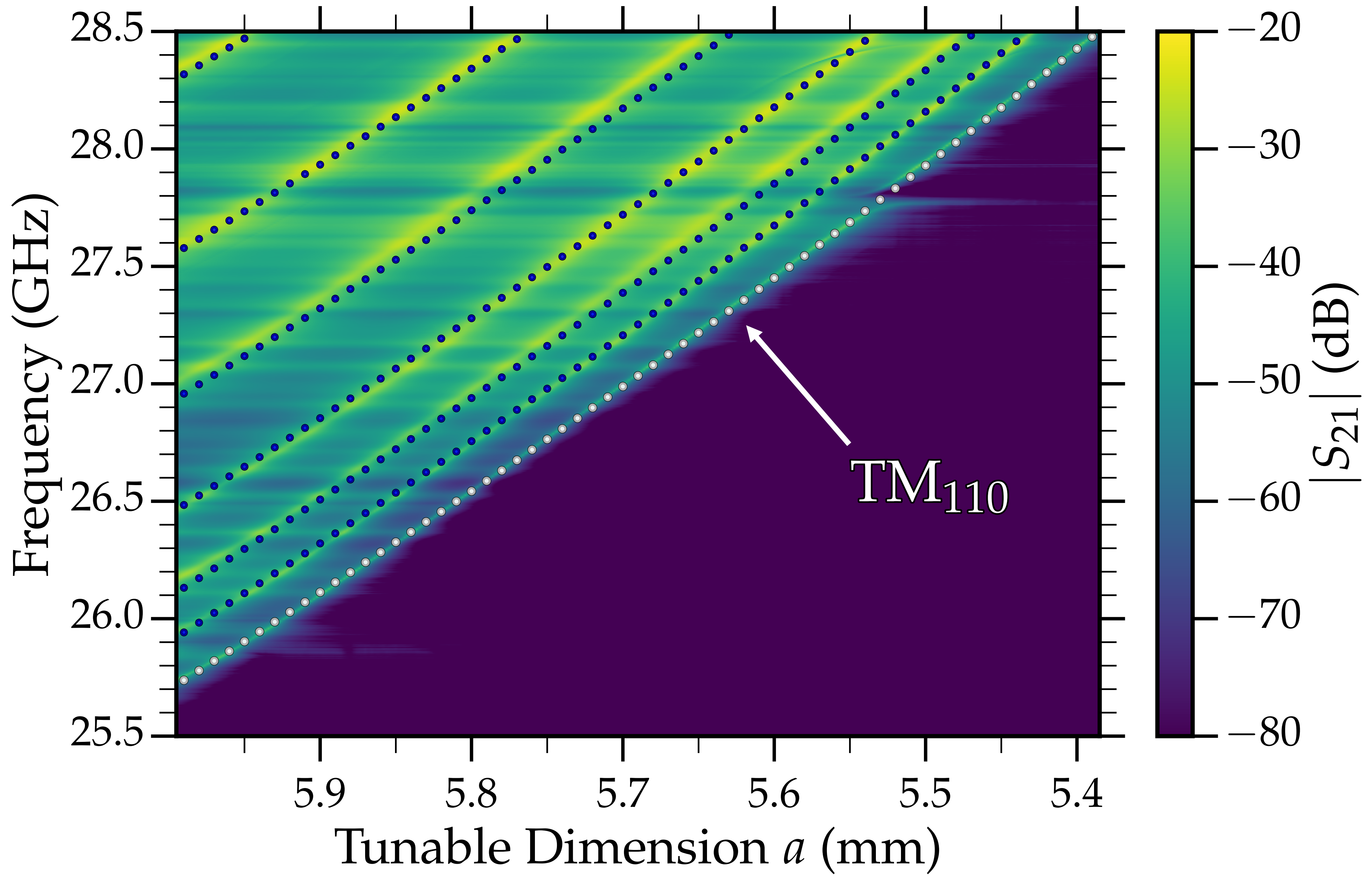
$Q_L :\sim 1000 \rightarrow 4000$

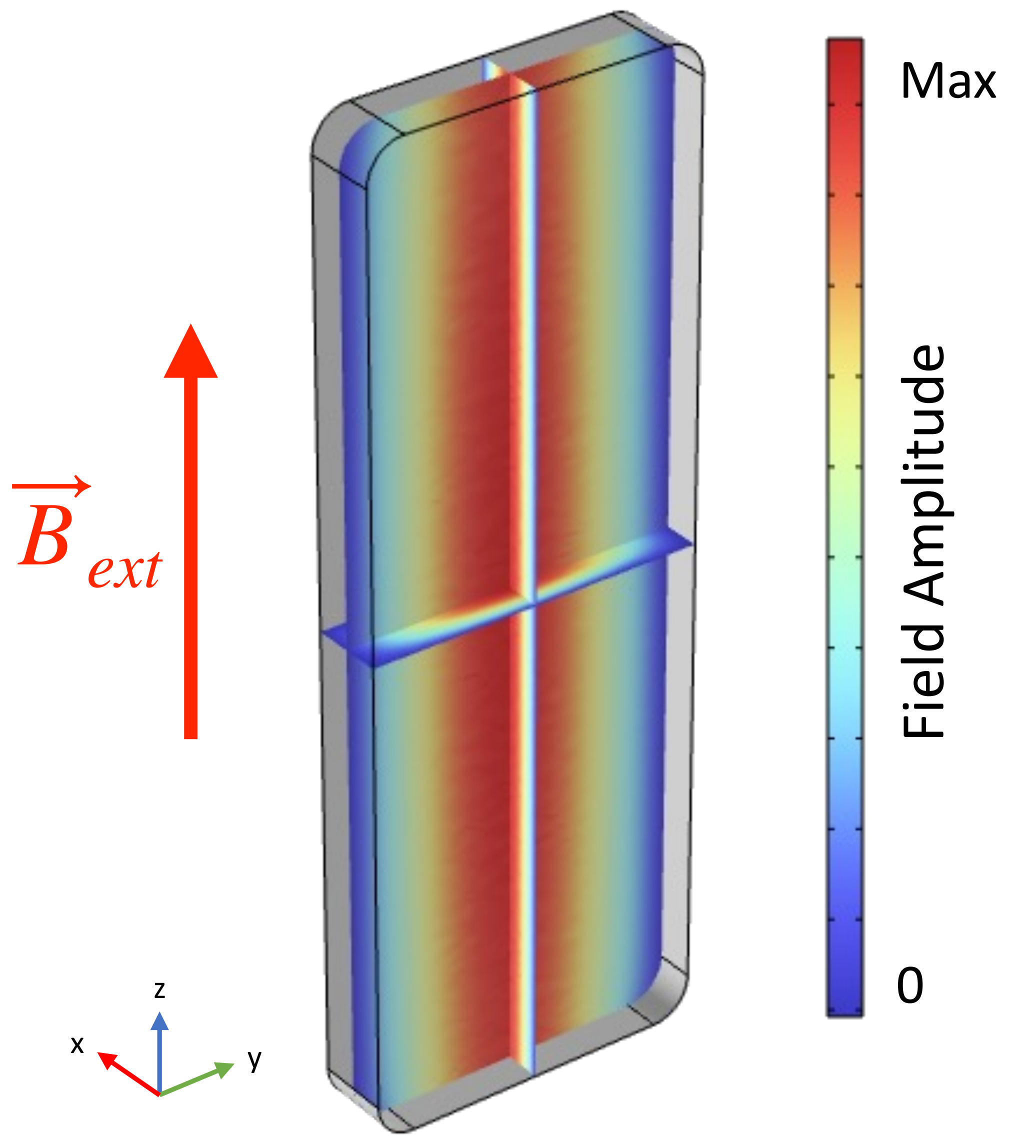
Phase 1b

- Using materials on-hand
- **NO** mode crossings between 26 - 27 GHz
- **Very easy to tune** - minimal motor steps required → reduced cryogenic heat load









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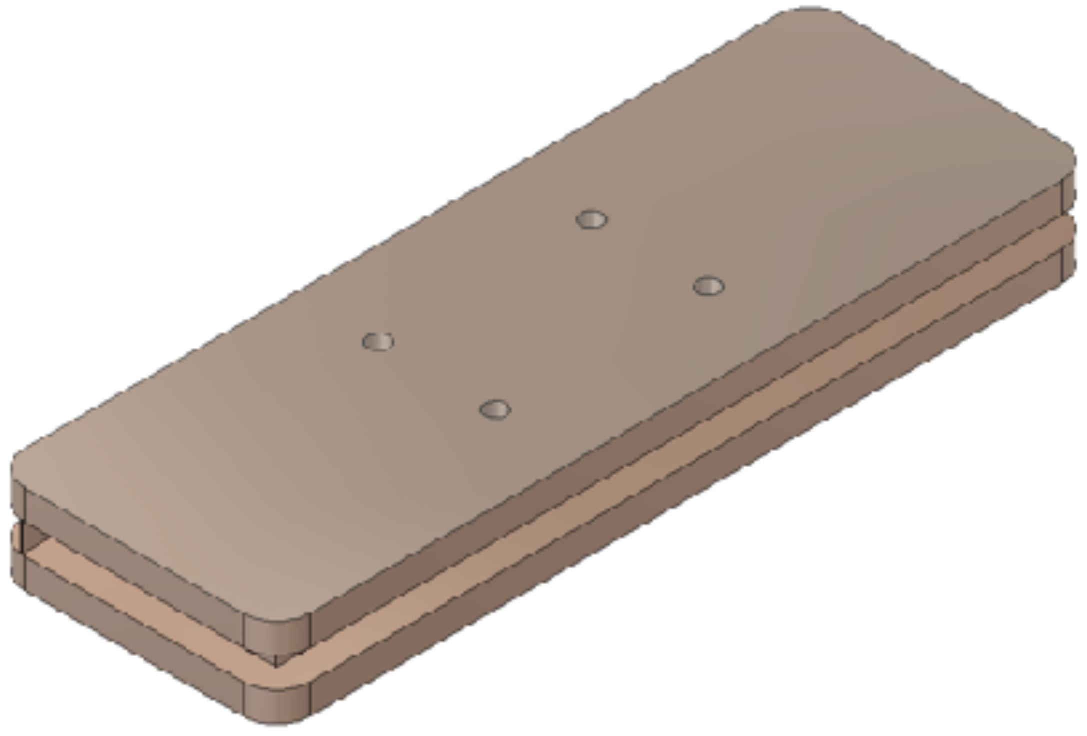

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Phase 1b

- Lets compare the options for Phase 1b

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Parameter	Rectangle	Tuning-rod
C	~ 0.4*	~ 0.43

Phase 1b

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Due to gaps between rod-endcap

Parameter	Rectangle	Tuning-rod
C	~ 0.4*	~ 0.43
Q_0 (RT)	~ 4000	~ 2000

Phase 1b

- Lets compare the options for Phase 1b

Parameter	Rectangle	Tuning-rod
C	~ 0.4*	~ 0.43
Q_0 *(RT)*	~ 4000	~ 2000
V	~ 12 mL	~ 9.5 mL

Due to gaps between rod-endcap

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C	~ 0.4*	~ 0.43
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Mode Xs	0	2

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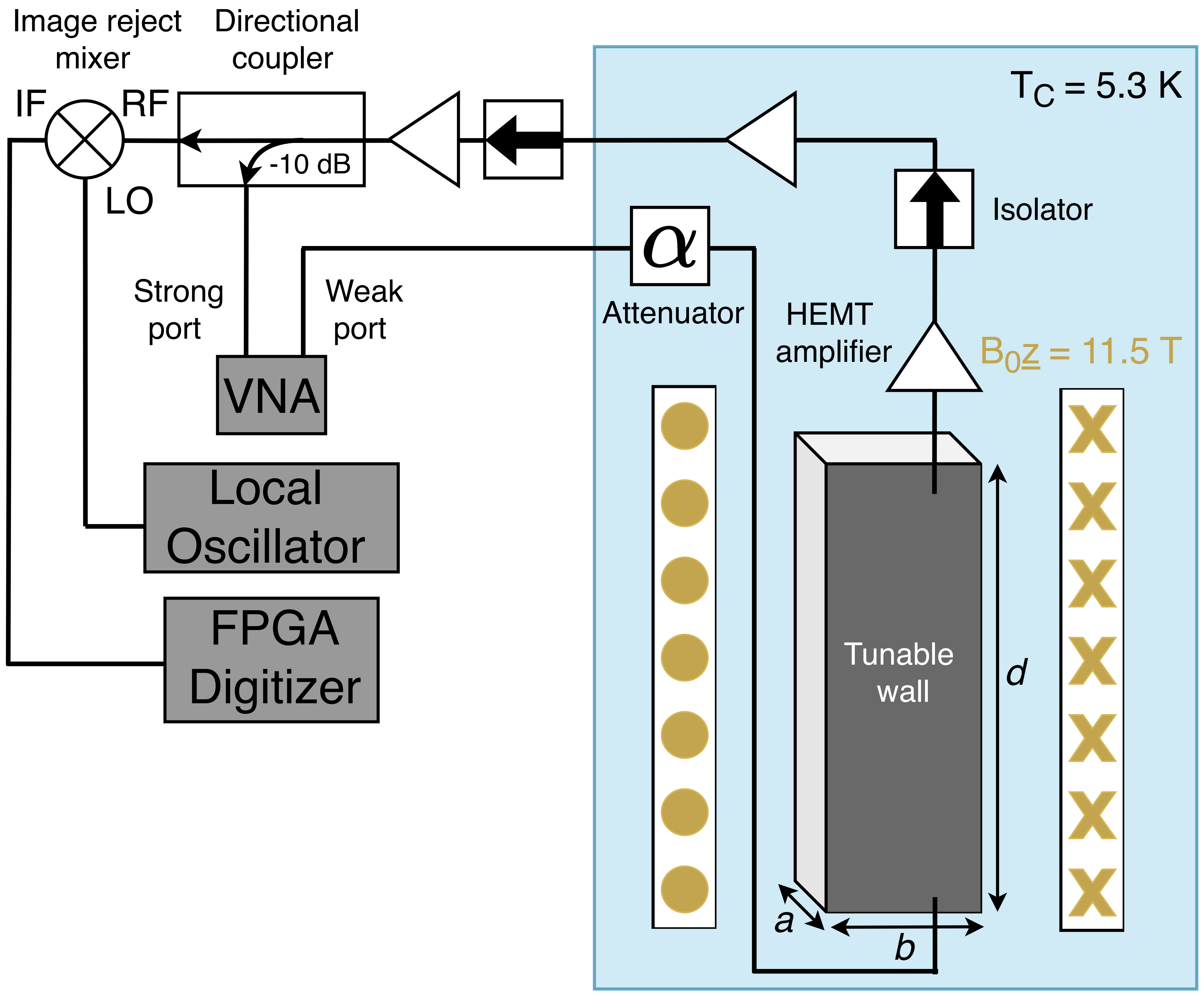
Bore Util.	-	-
Tuning	✅ Actually tuned	❌ Difficulty tuning
Scan rate (C^2V^2Q)	~ 2.76x	1x
Antenna Coupling	✅ Relatively easy	❌ Challenging

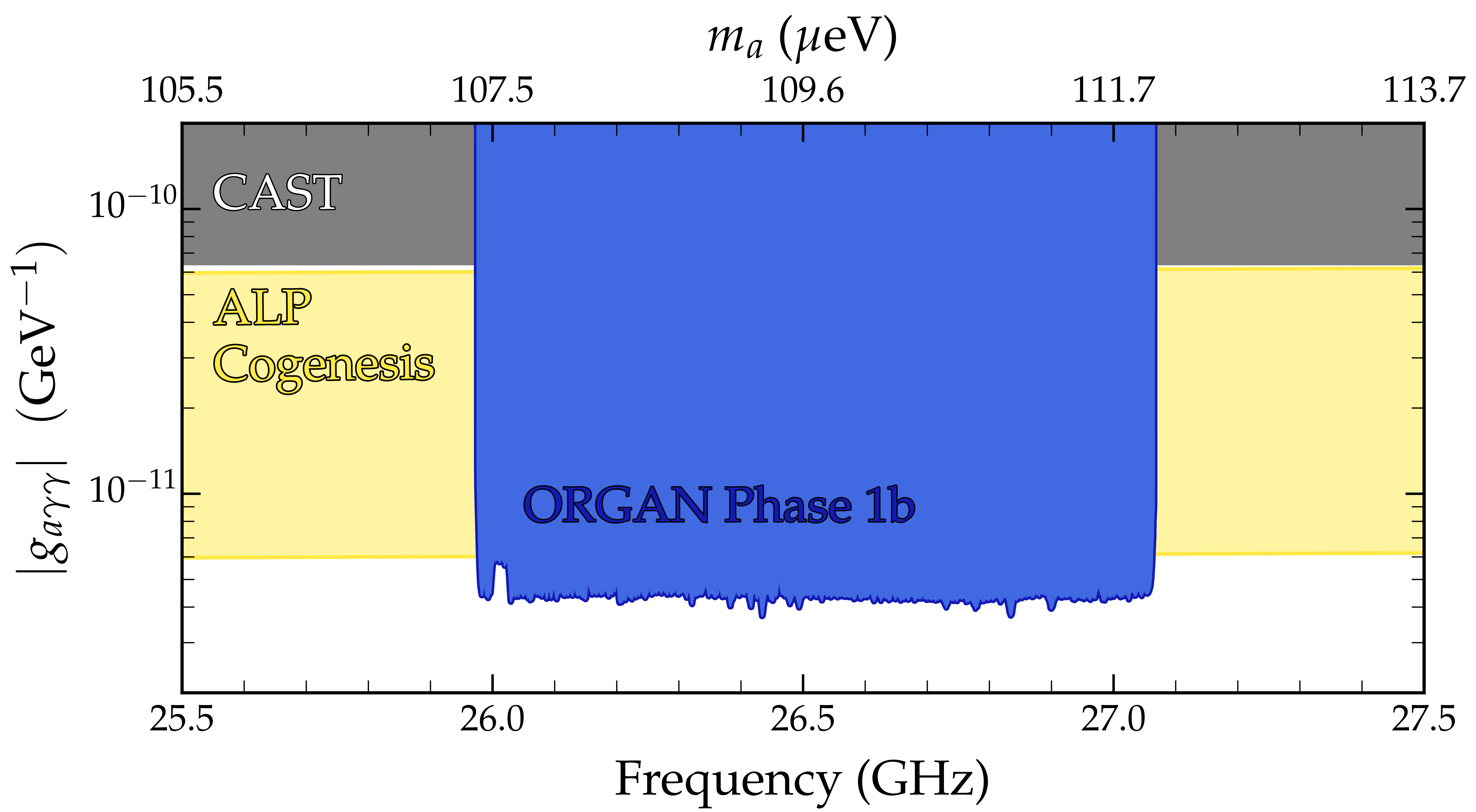
Due to gaps between rod-endcap

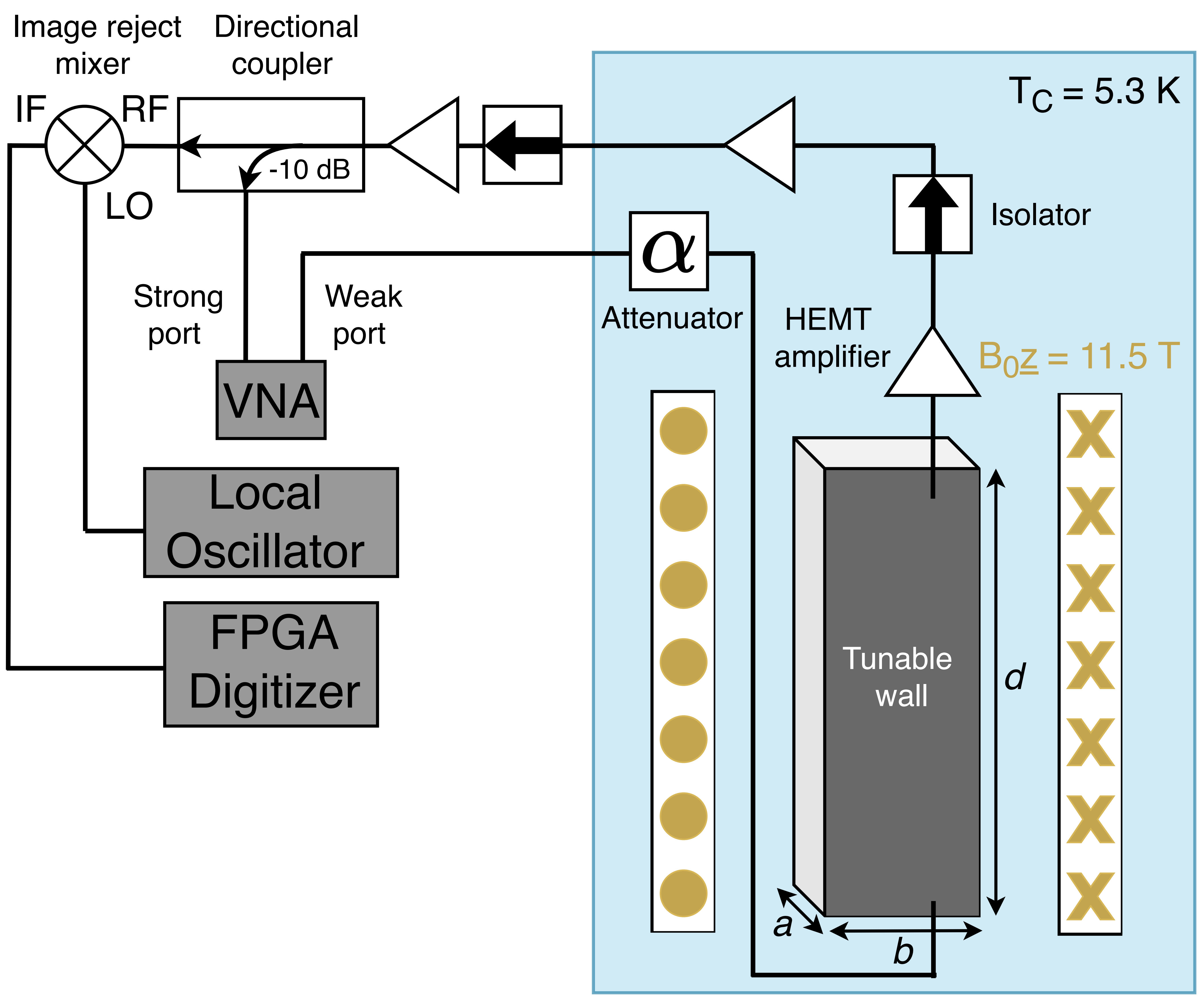
Limits on $g_{a\gamma\gamma}$



Limits on $g_{a\gamma\gamma}$

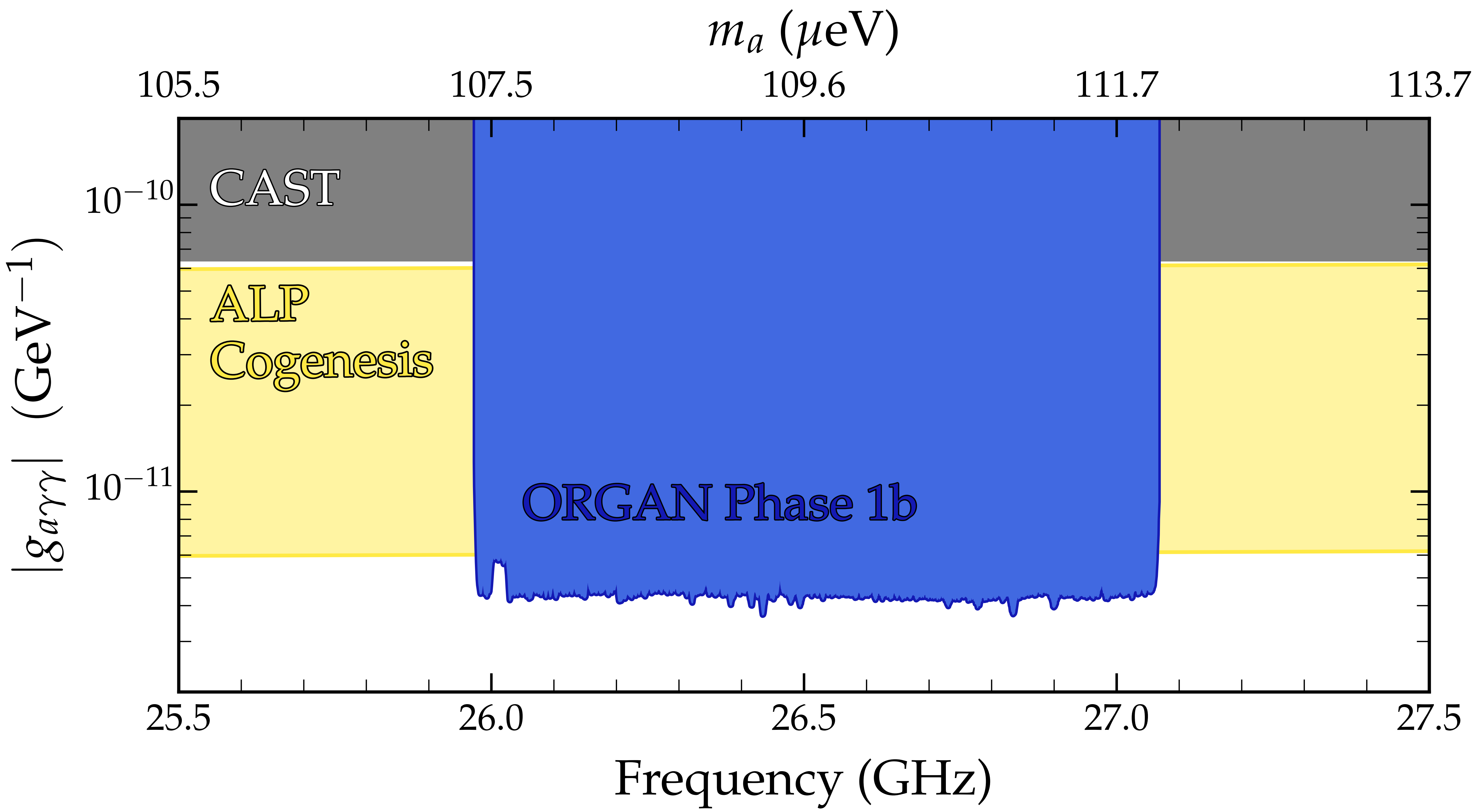
- Can exclude ALP cogenesis with 95% confidence!

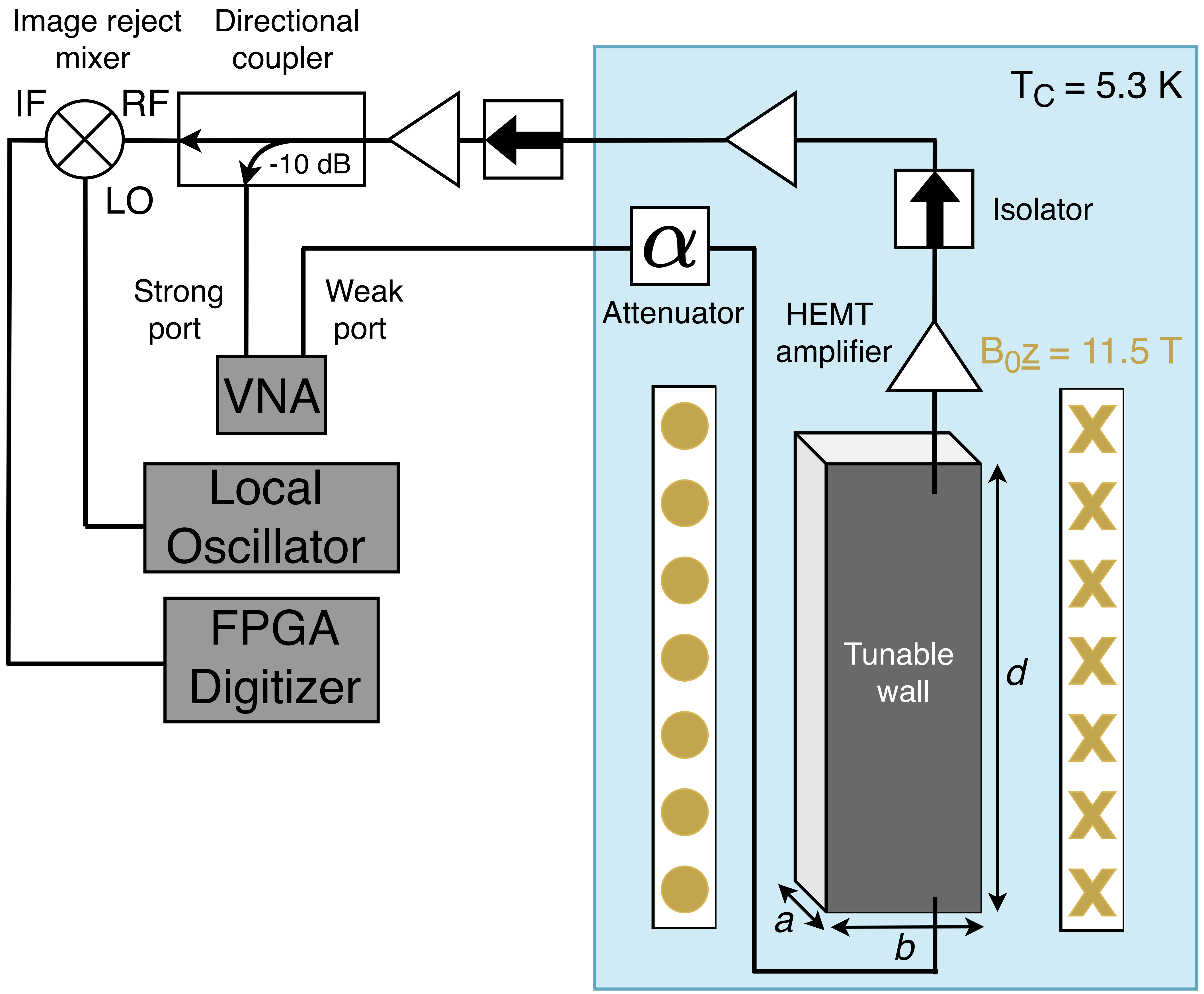




Limits on $g_{a\gamma\gamma}$

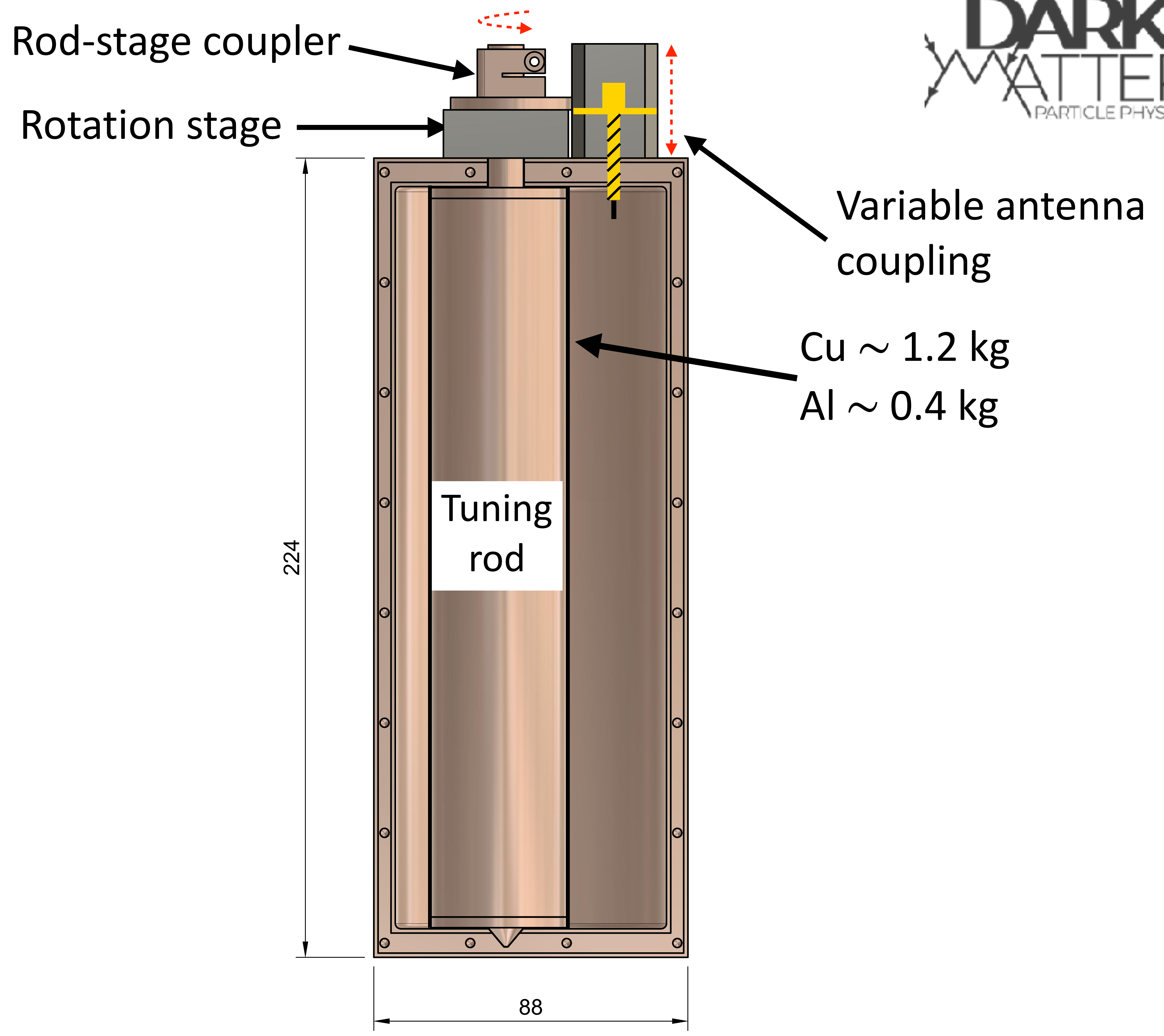
- Can exclude ALP cogenesis with 95% confidence!
- Single photon counters needed to improve sensitivity!





ORGAN-Q

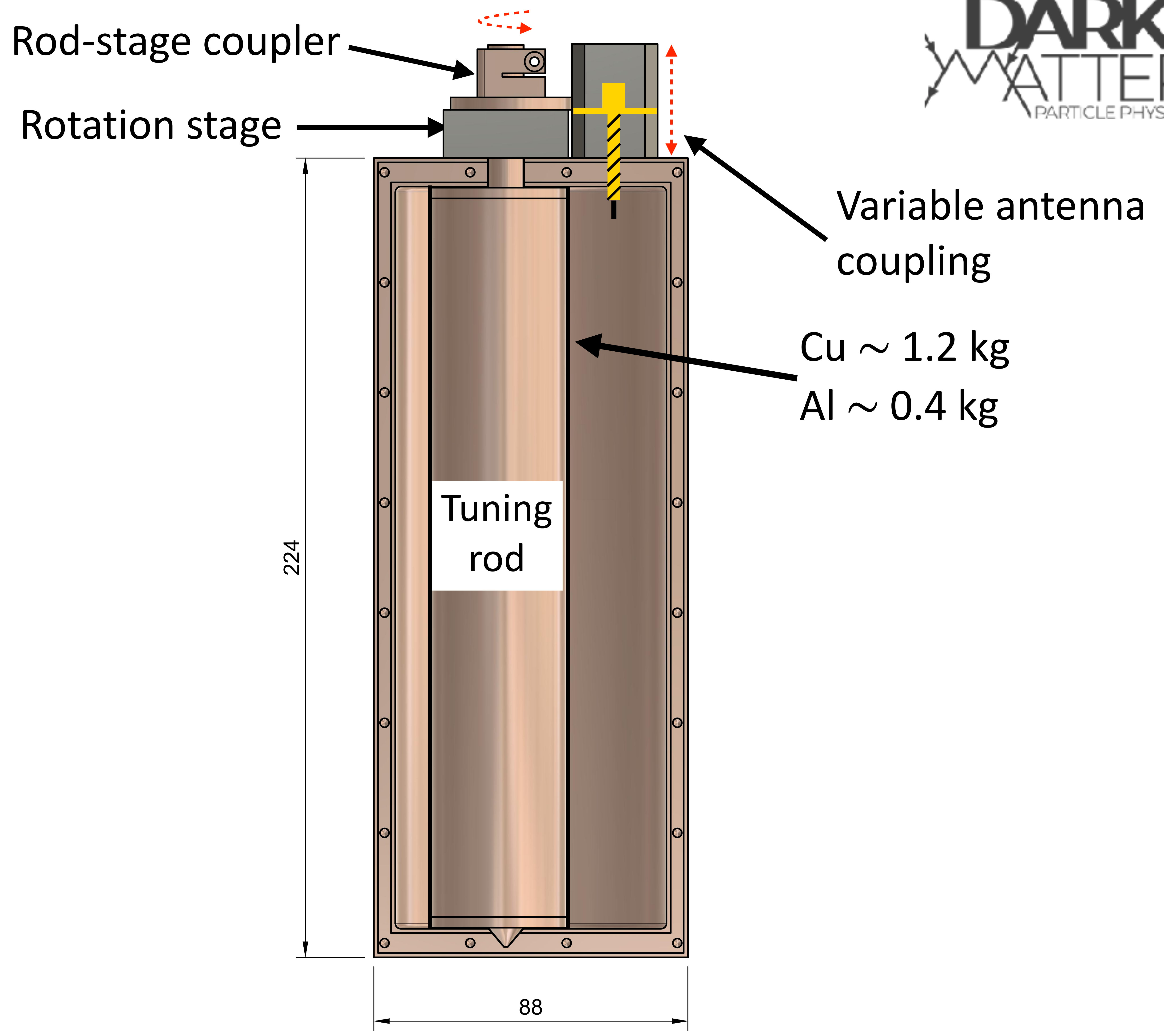
(A quick detour..)



ORGAN-Q

(A quick detour..)

- Q → Quantum



ORGAN-Q

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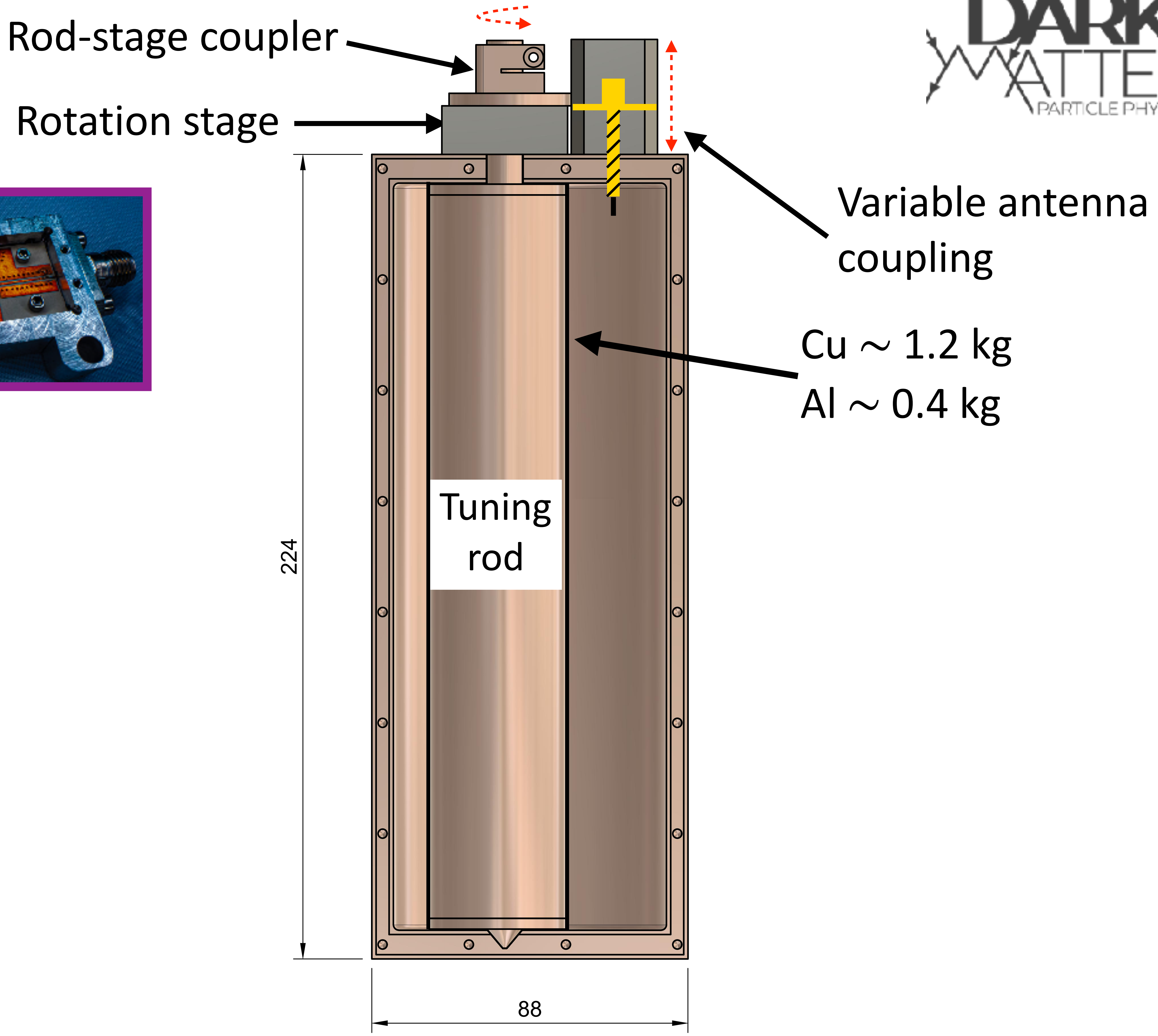
- Q → Quantum
- Search around 6 GHz



ORGAN-Q

(A quick detour..)

- Q → Quantum
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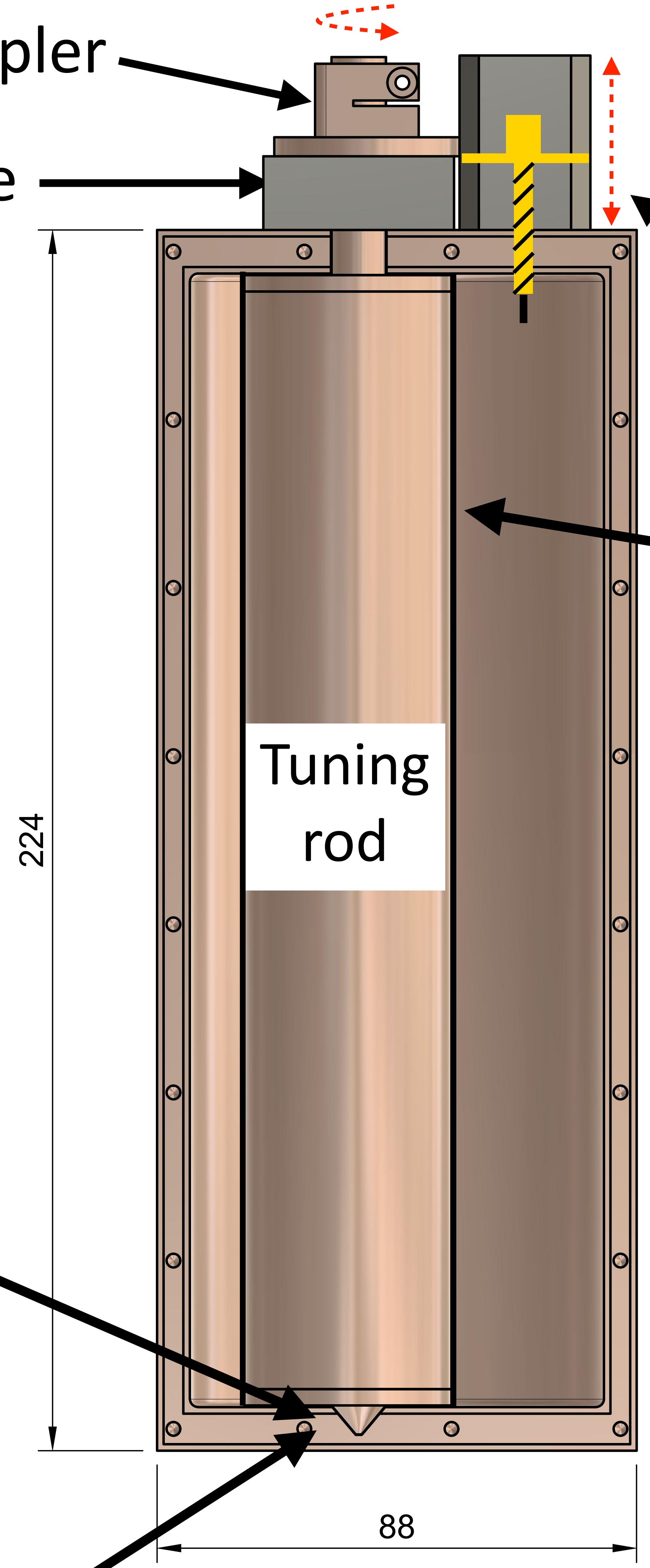
- Uses **Josephson Parametric Amplifier** (JPA): ↓ T_s



Thermalise rod and cavity

$T_{cav} \sim 100\,\mathrm{mK},\ T_{rod} \sim 500\,\mathrm{mK}$ when scanning

ORGAN-Q

(A quick detour..)

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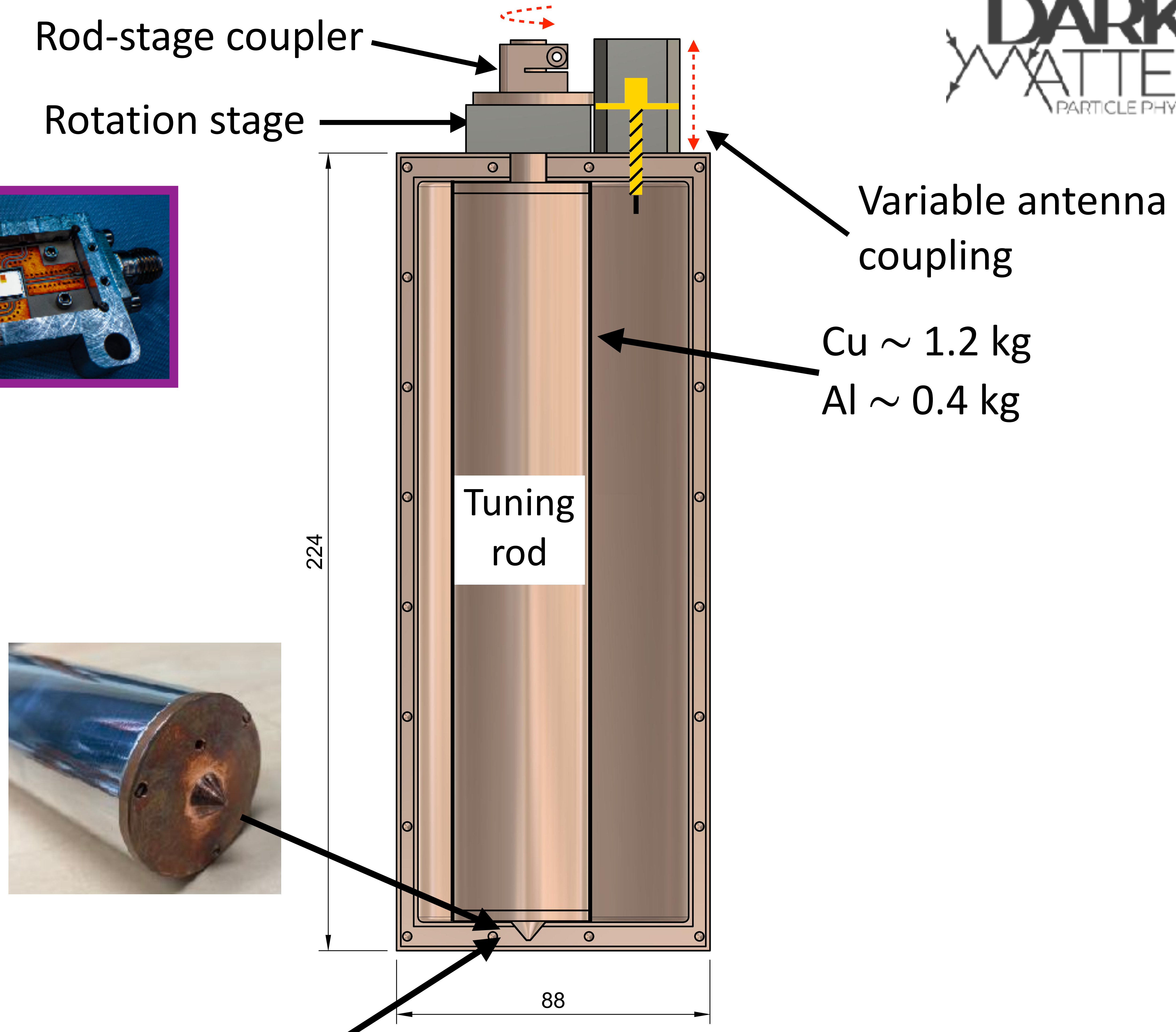
- Uses **Josephson Parametric Amplifier** (JPA): ↓ T_s
- Operates at mK: ↓ T_s
- Variable coupling: ↑ $Q_L \frac{\beta^2}{(1+\beta)^2}$
- Useful R&D for future ORGAN phases



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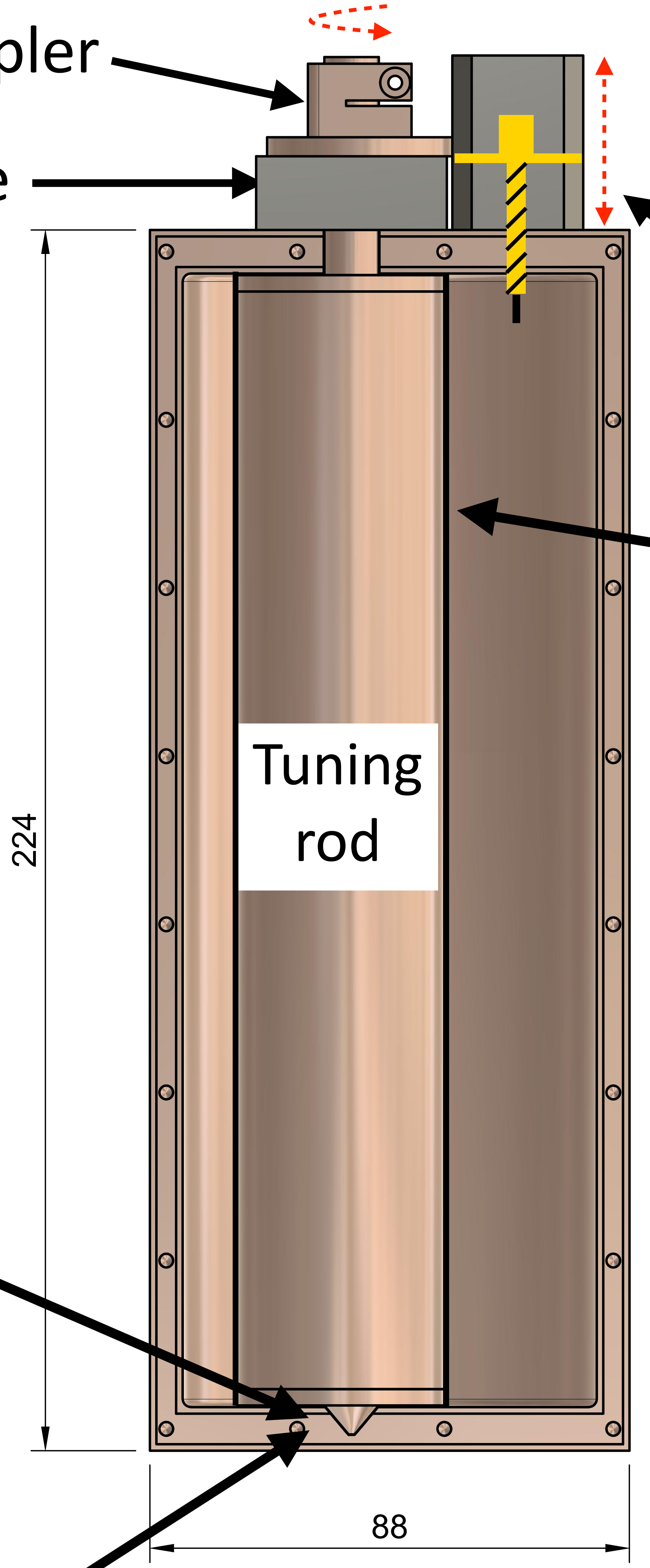
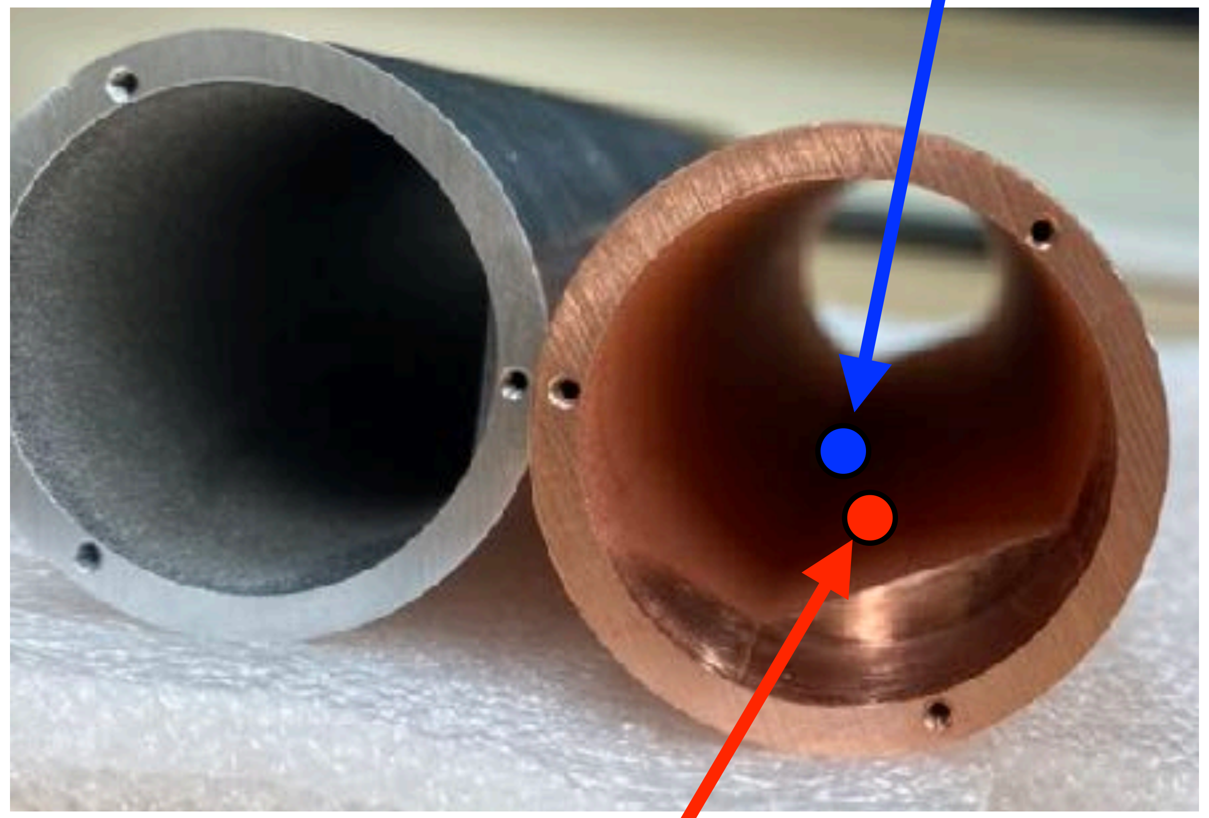




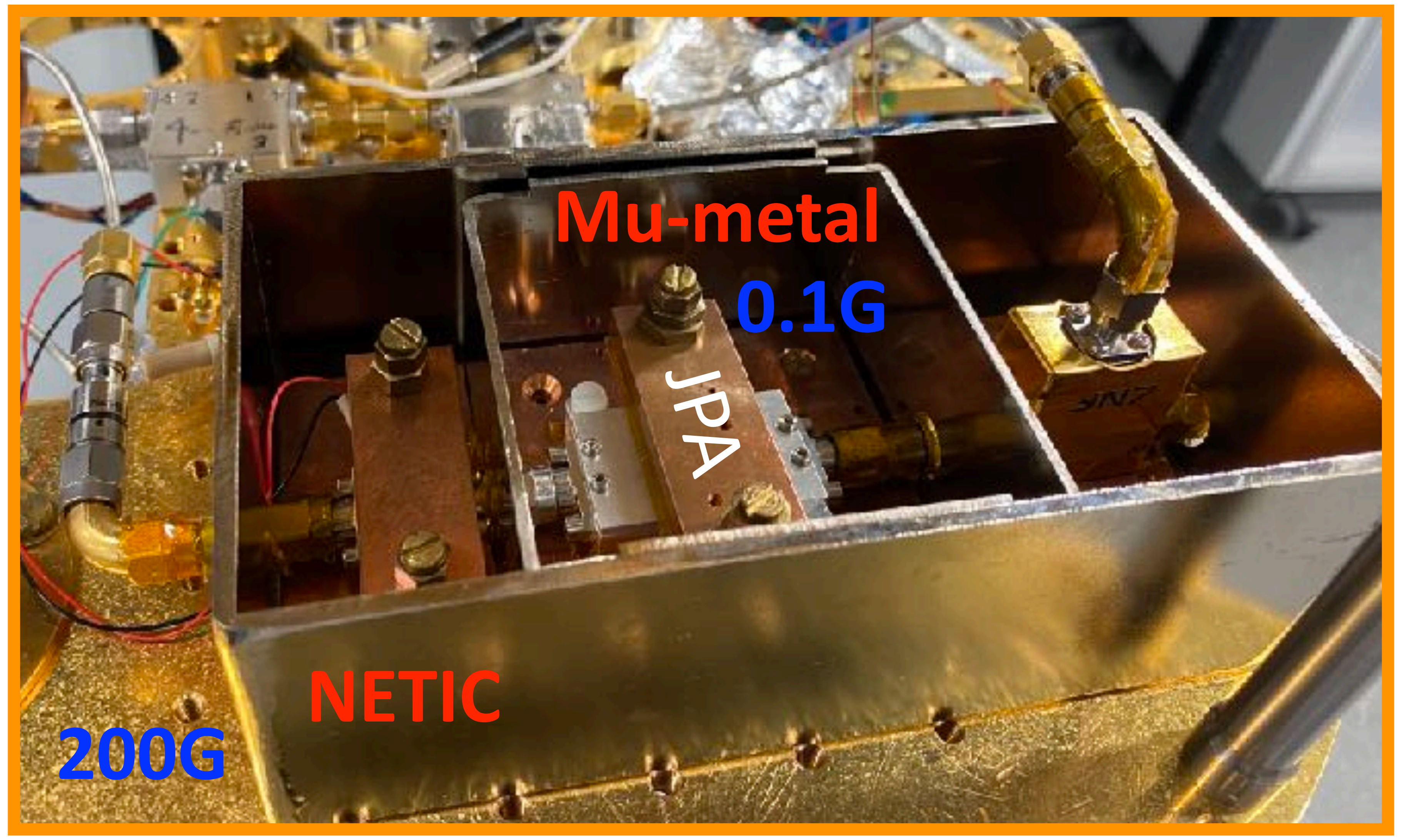
Align CoM and rotation axis for smooth tuning

Thermalise rod and cavity

$T_{cav} \sim 100\,\mathrm{mK},\ T_{rod} \sim 500\,\mathrm{mK}$ when scanning

Raytheon JPA

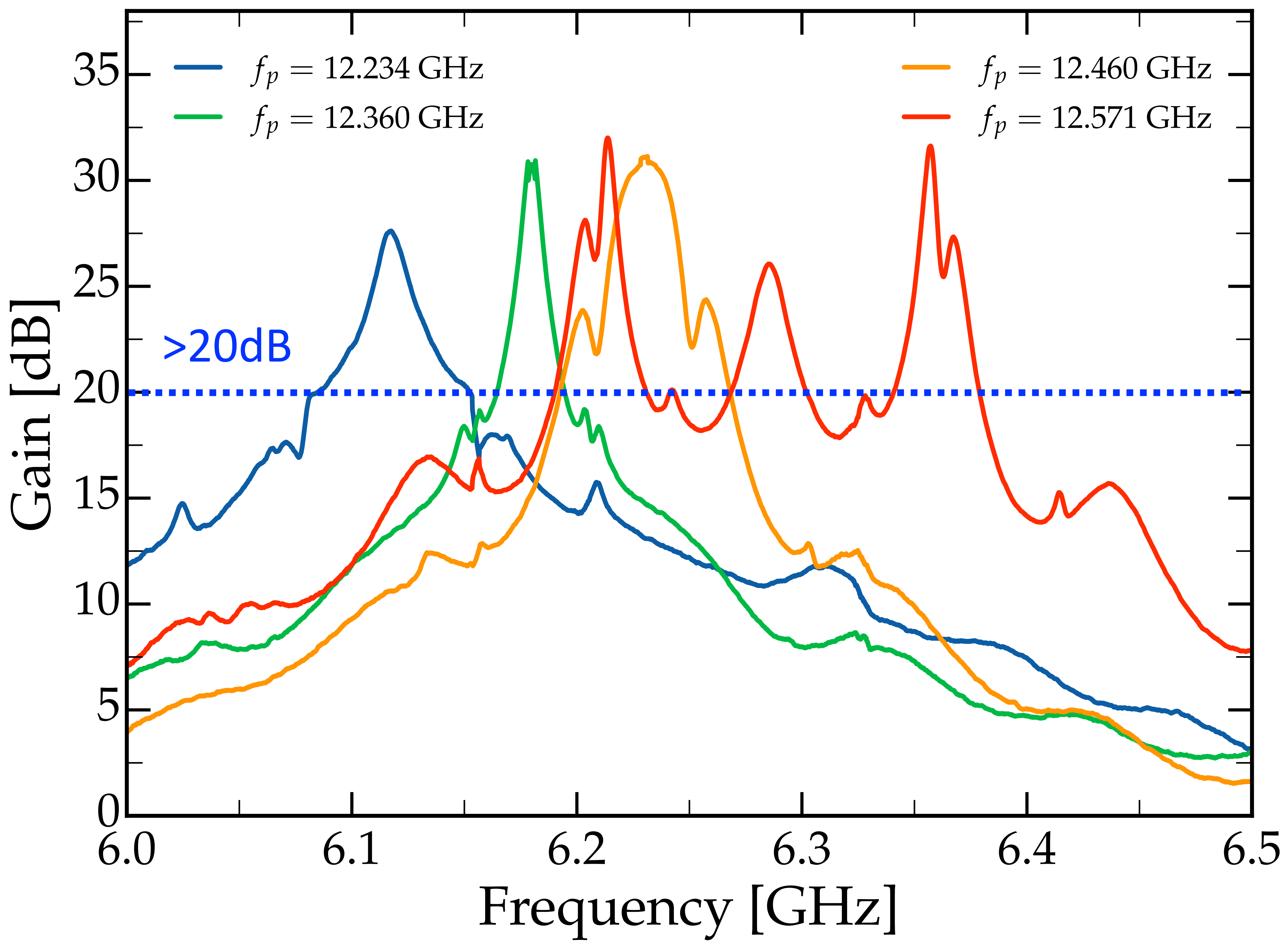
- JPA very sensitive to environment

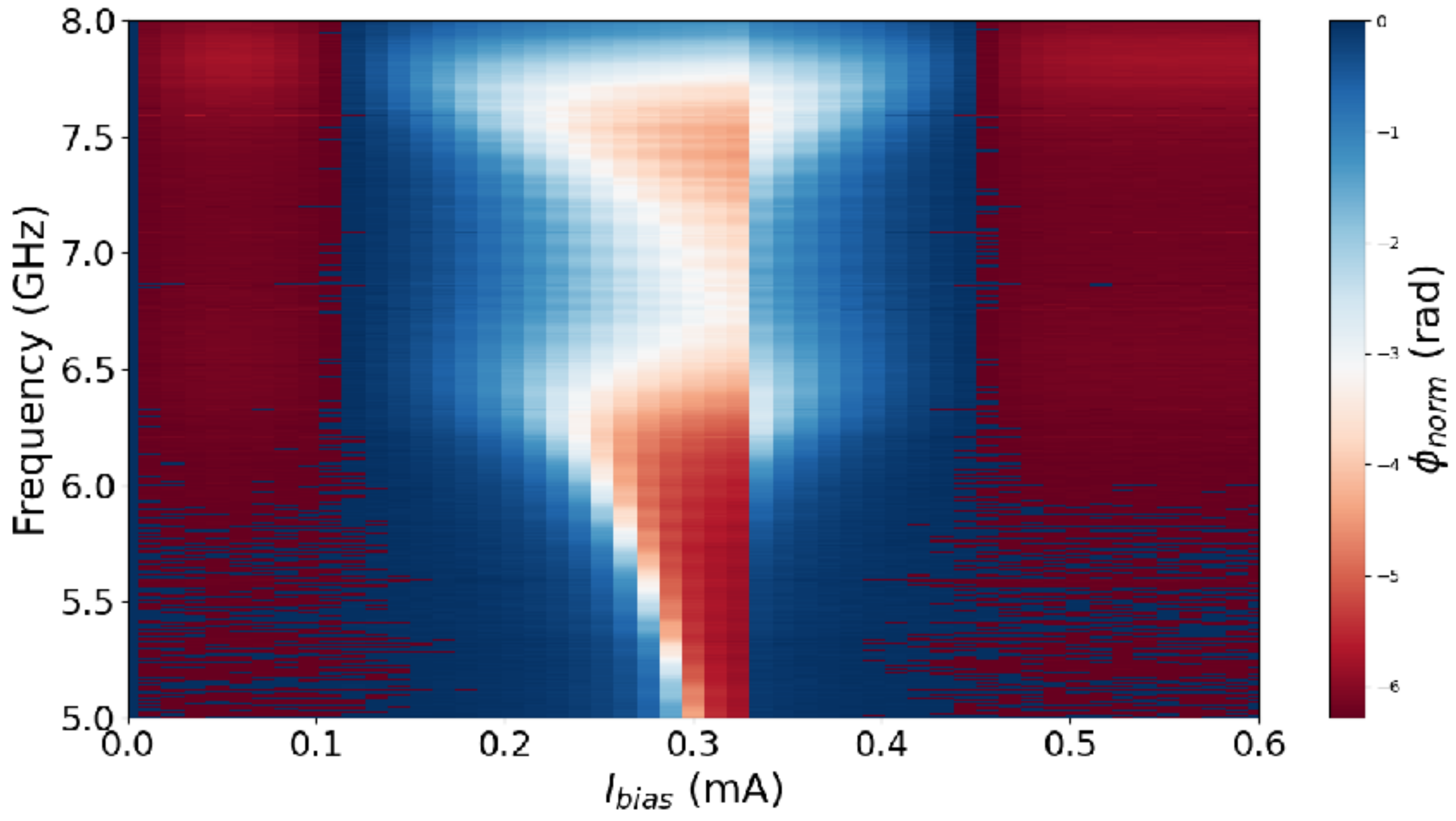


Raytheon JPA

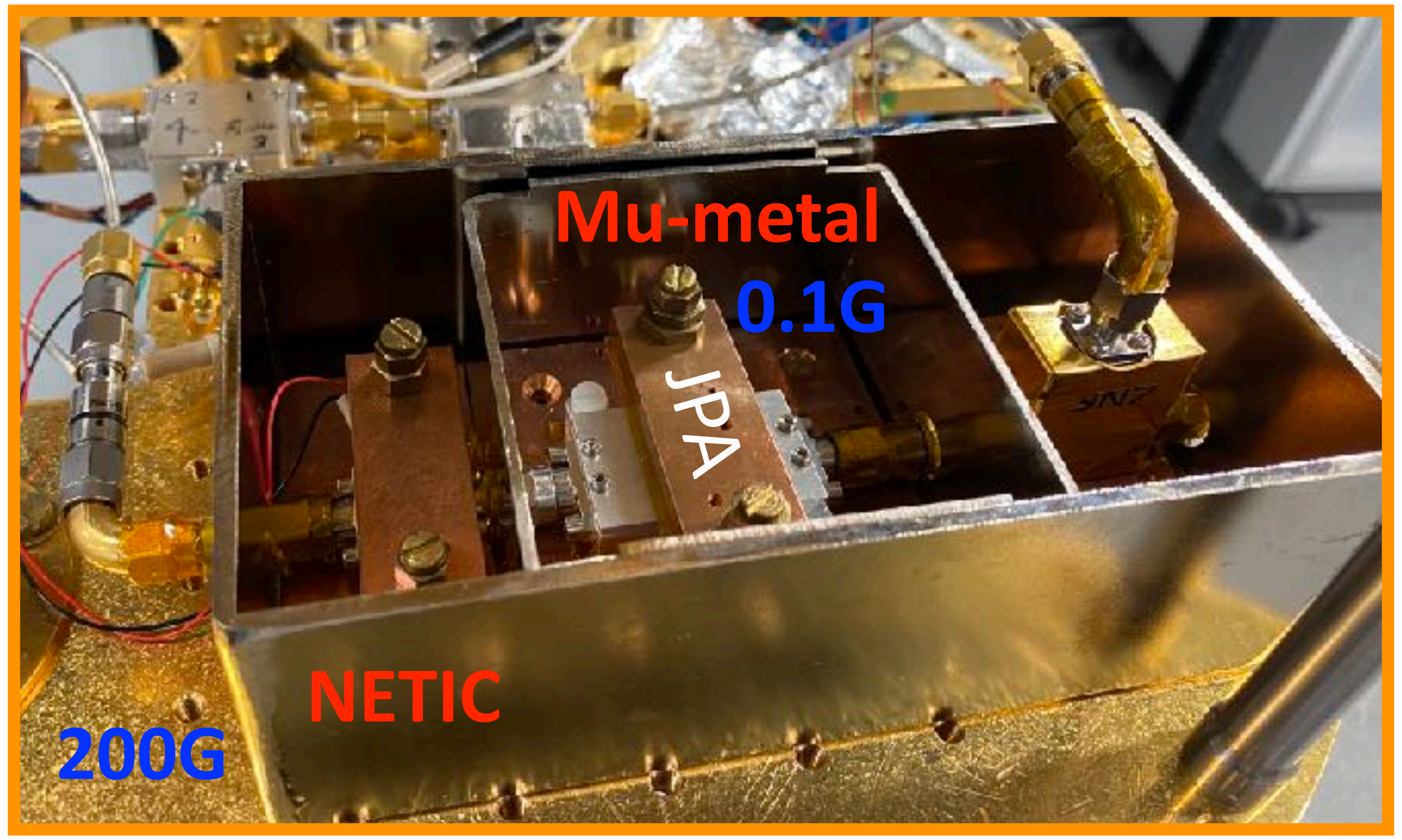
- JPA very sensitive to environment
- Tune the JPA resonance using flux bias

Gain curves

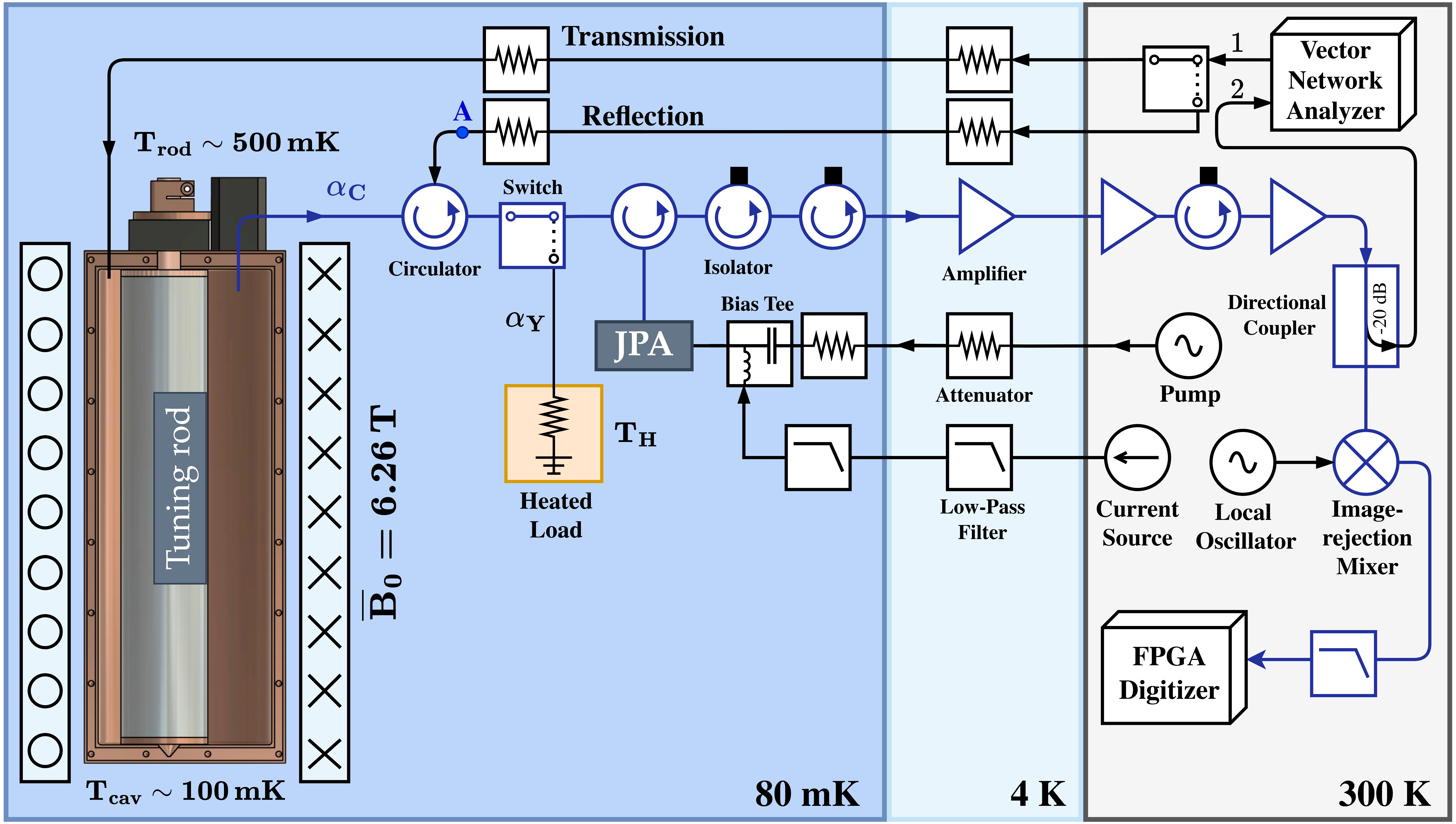




Normalised reflection phase



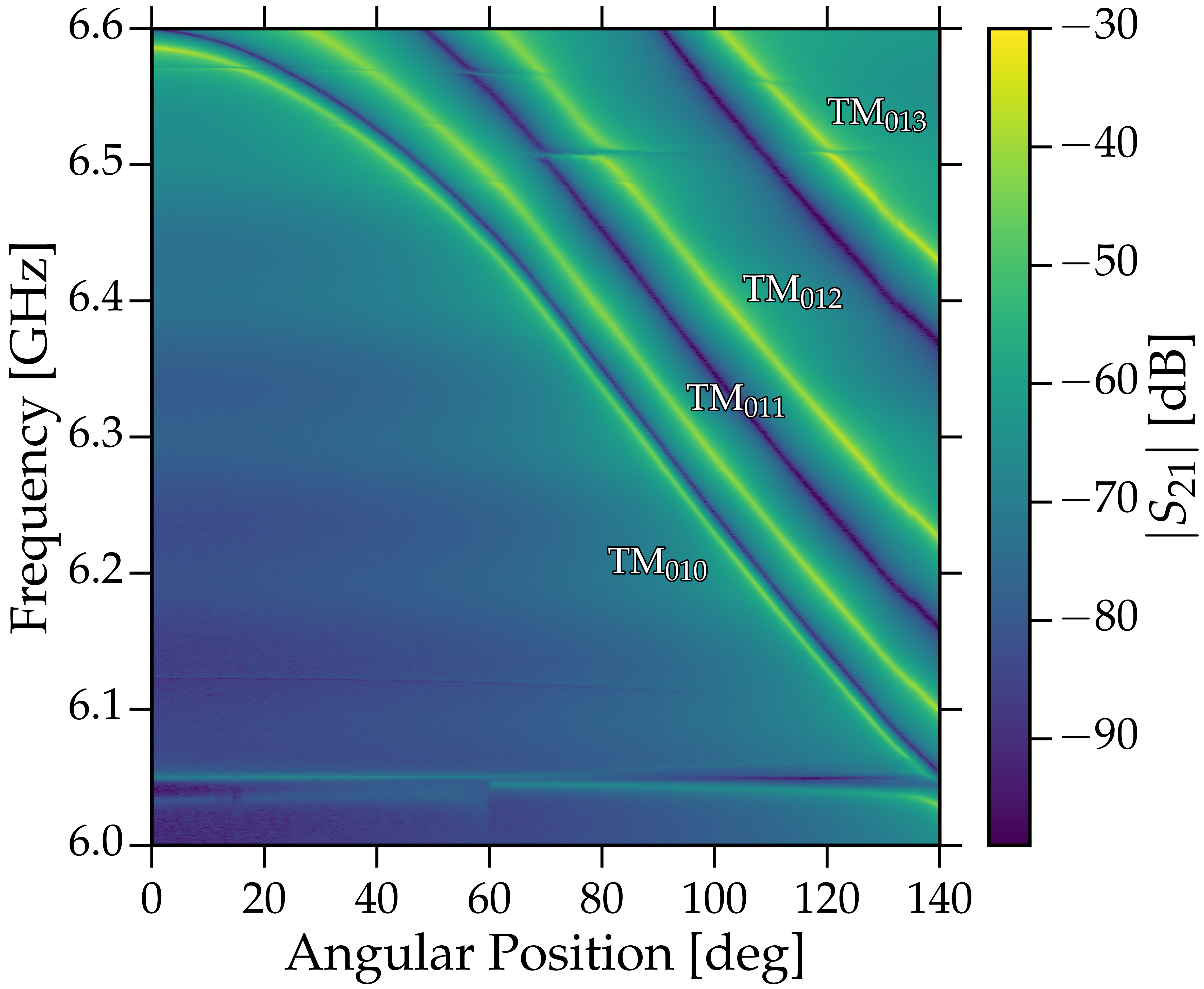
ORGAN-Q Setup



ORGAN-Q Results

- Scanned between 6.15 – 6.35 GHz
- ~17 days of data

Mode Map @ 4K



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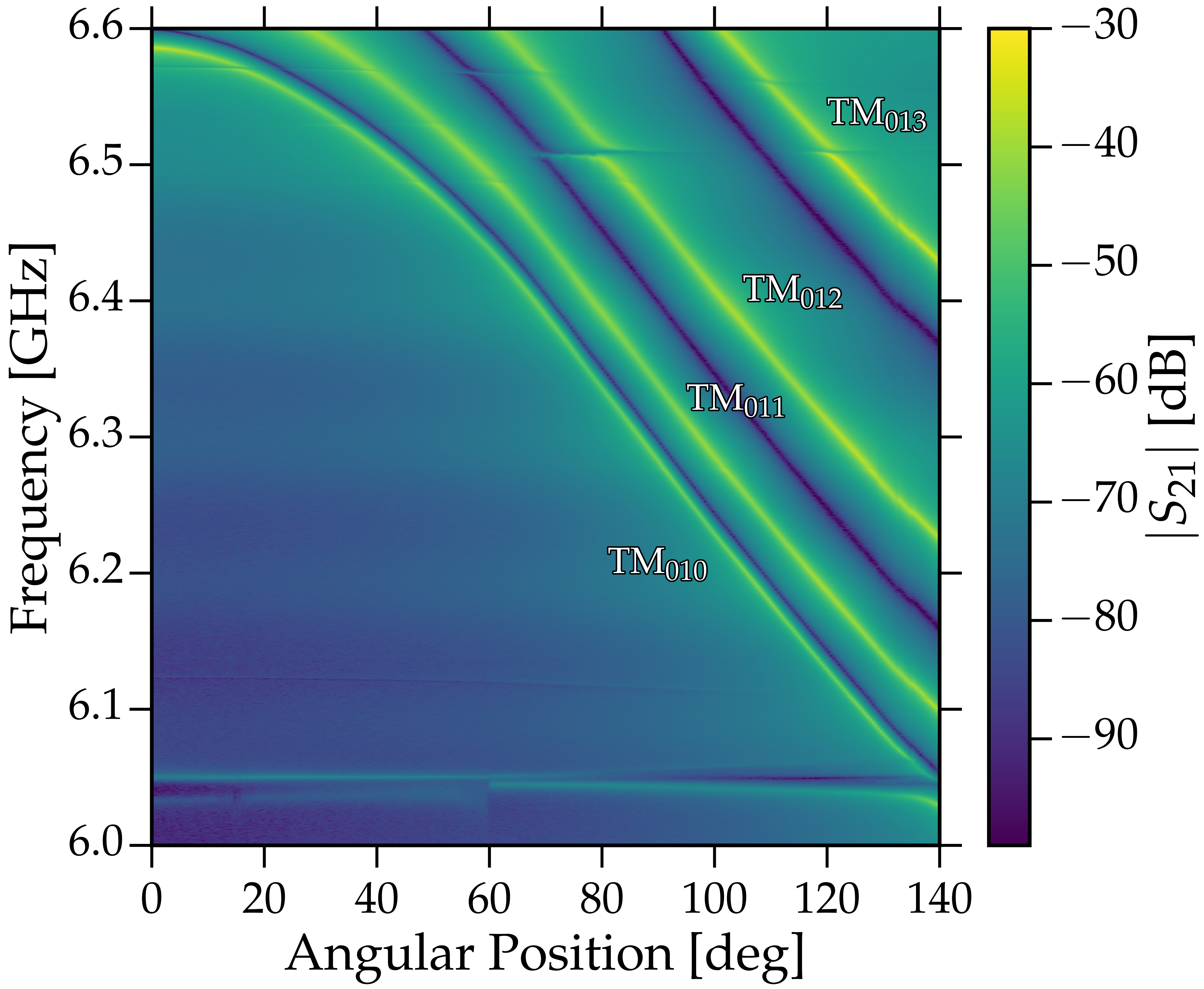

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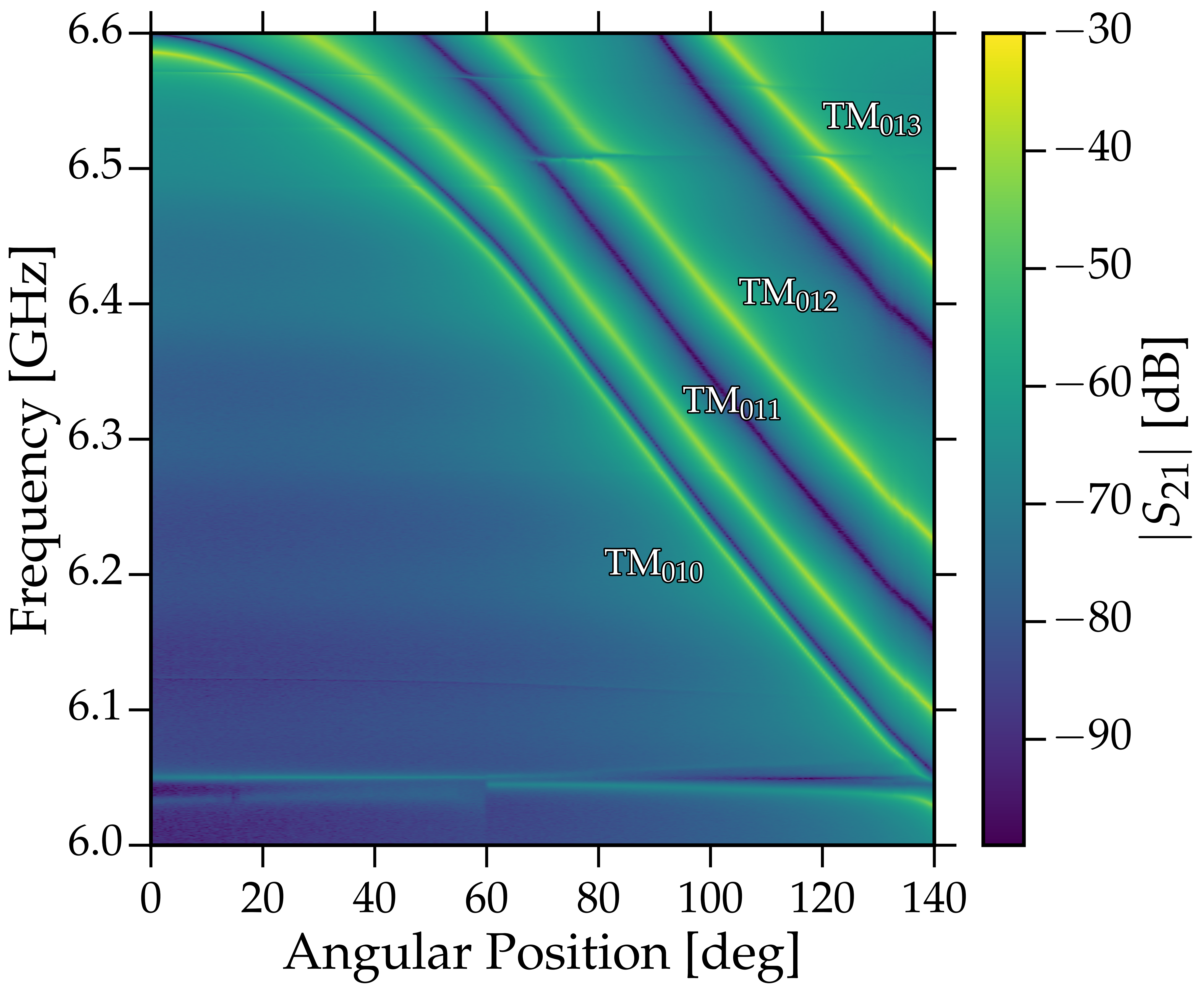

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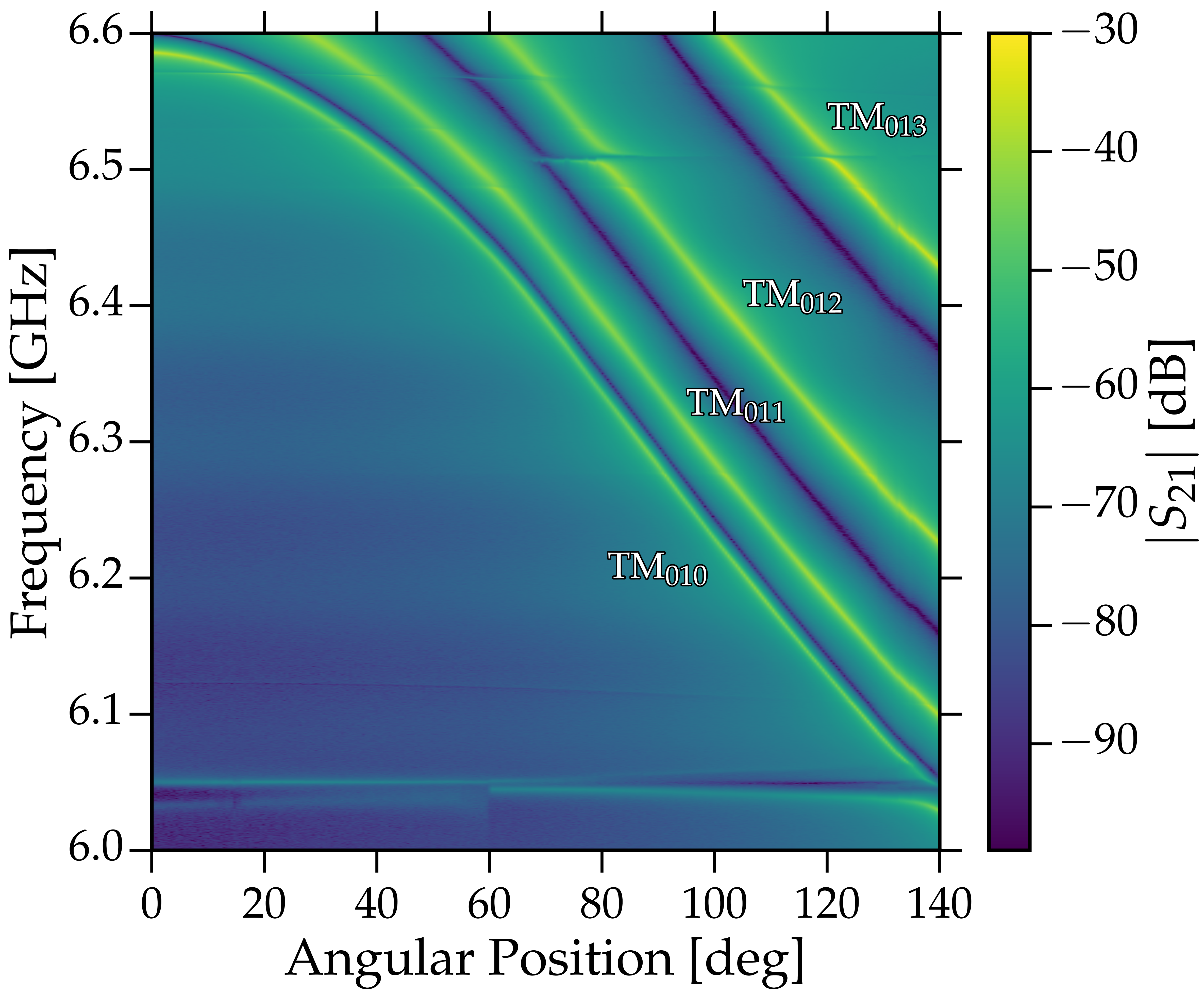
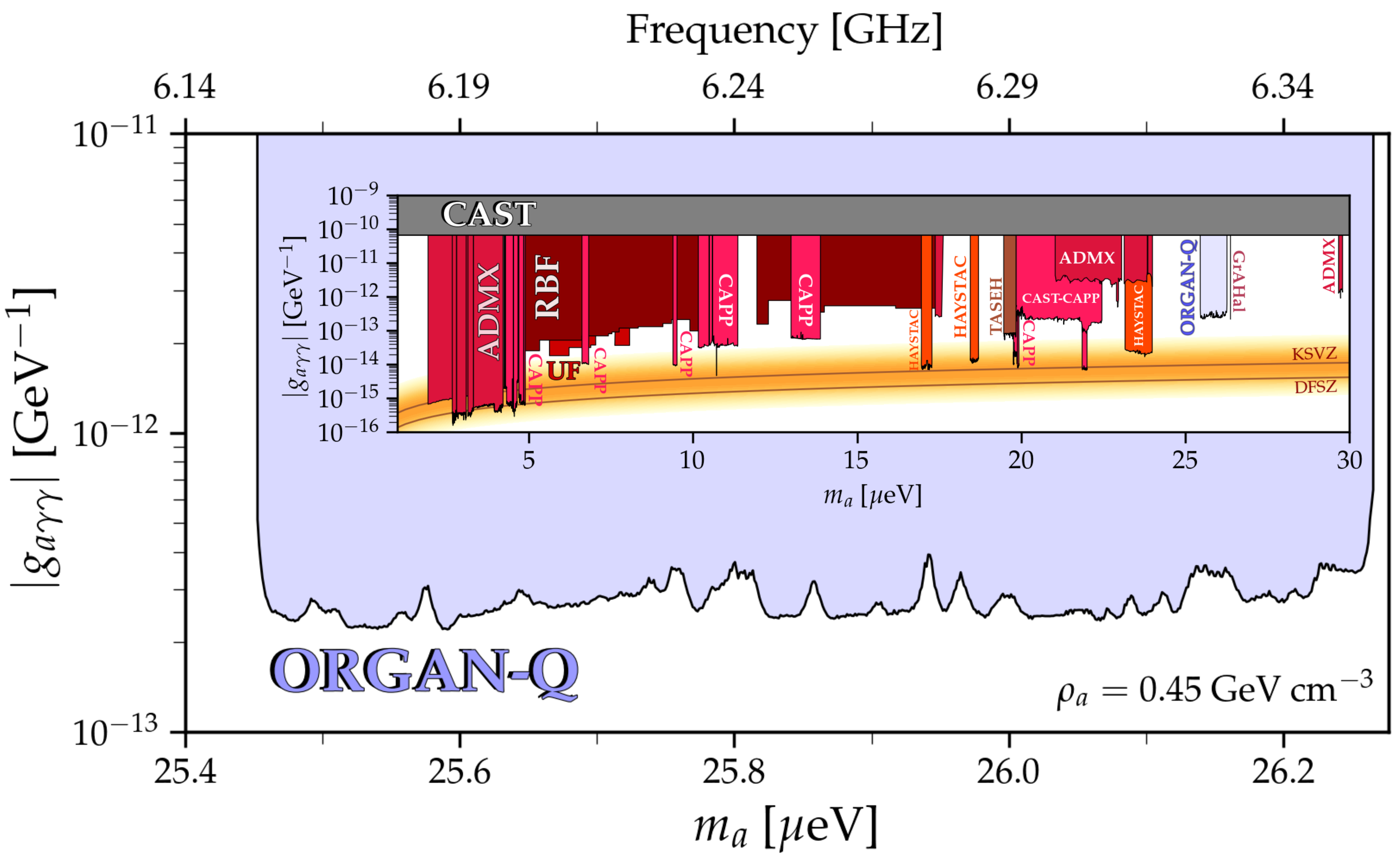
- Initial 4K measurements $Q_0 \sim 14{,}000$
- Degraded to $Q_0 \sim 4{,}000$ over many cools
- Tradeoff between tuning, Q and T_{rod}
- Adjusted antenna coupling $\beta \simeq 1.45 \pm 0.32$
- $T_{sys} \simeq 928 \pm 108\,\mathrm{mK}$ using SNRI method

Mode Map @ 4K



ORGAN-Q Limits

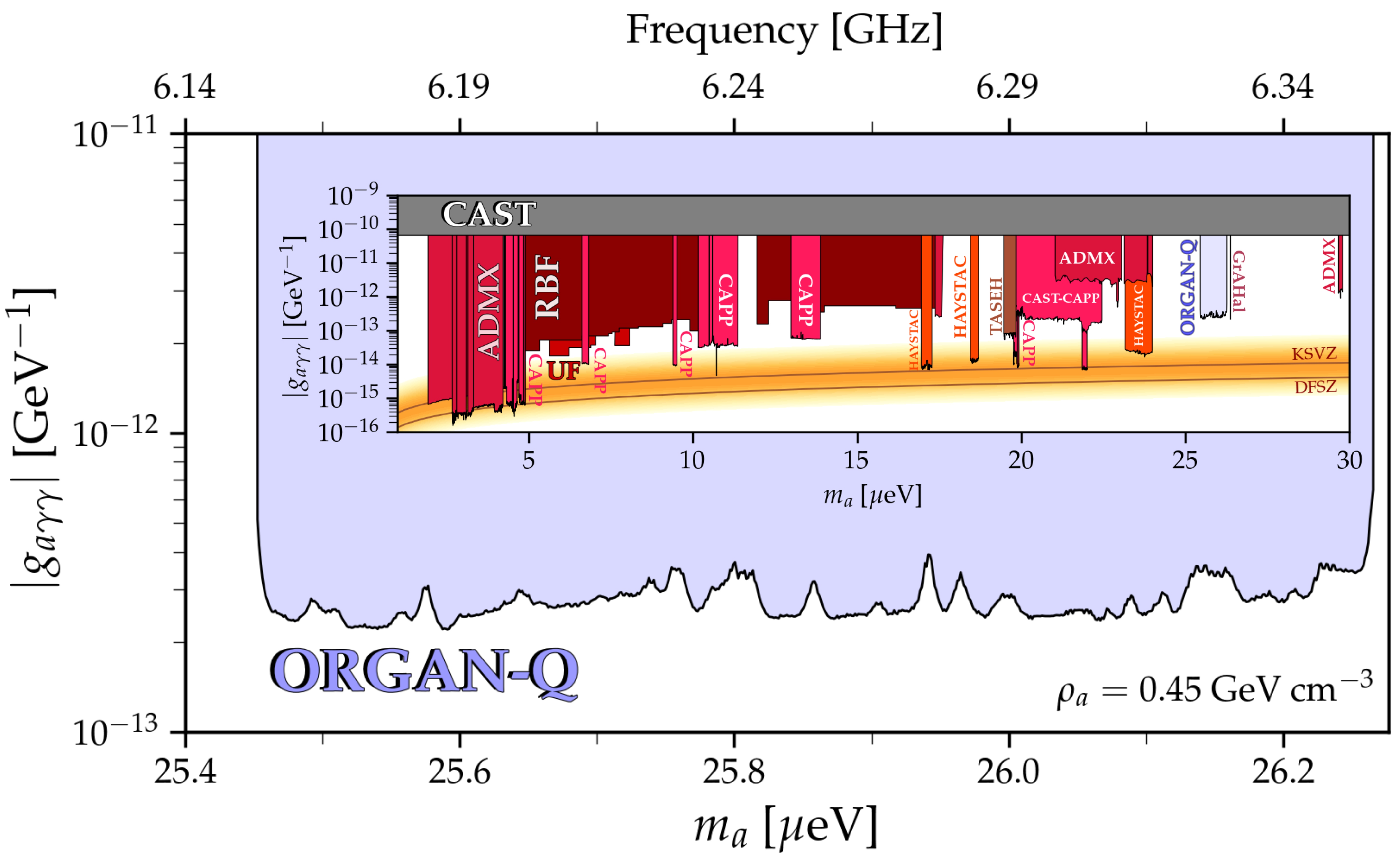
- Most sensitive limits in the region



arXiv:2407.18586

ORGAN-Q Limits

- Most sensitive limits in the region
- Comparable sensitivity to neighbouring experiments



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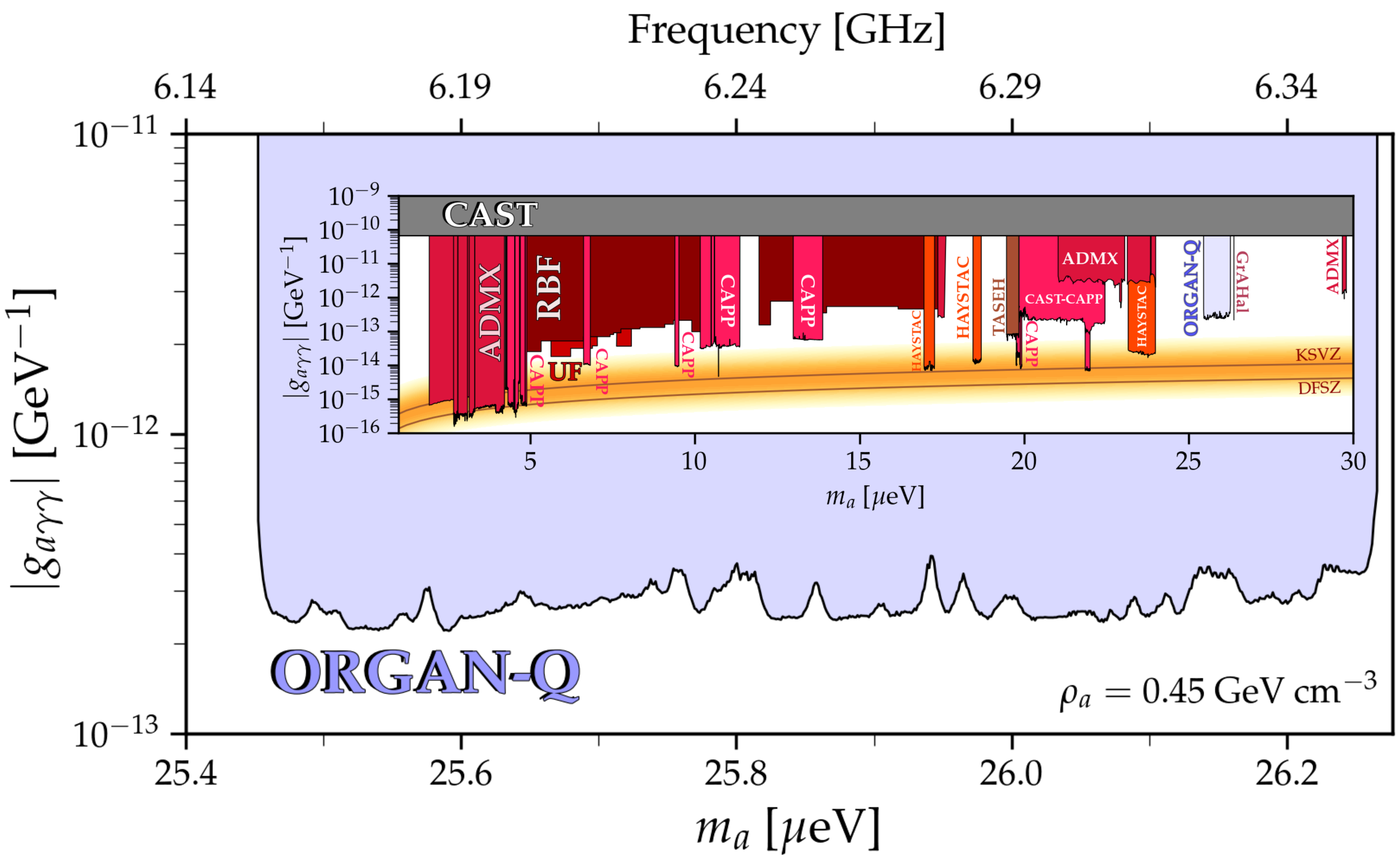
ORGAN-Q Limits

- Most sensitive limits in the region
- Comparable sensitivity to neighbouring experiments
- ORGAN-Q was a successful testbed for future phases of ORGAN
  - Clamshell cavity
  - Millikelvin operation
  - JPA operation and characterisation
  - Cryogenic switch + hot load calibration
  - Adjustable antenna coupling



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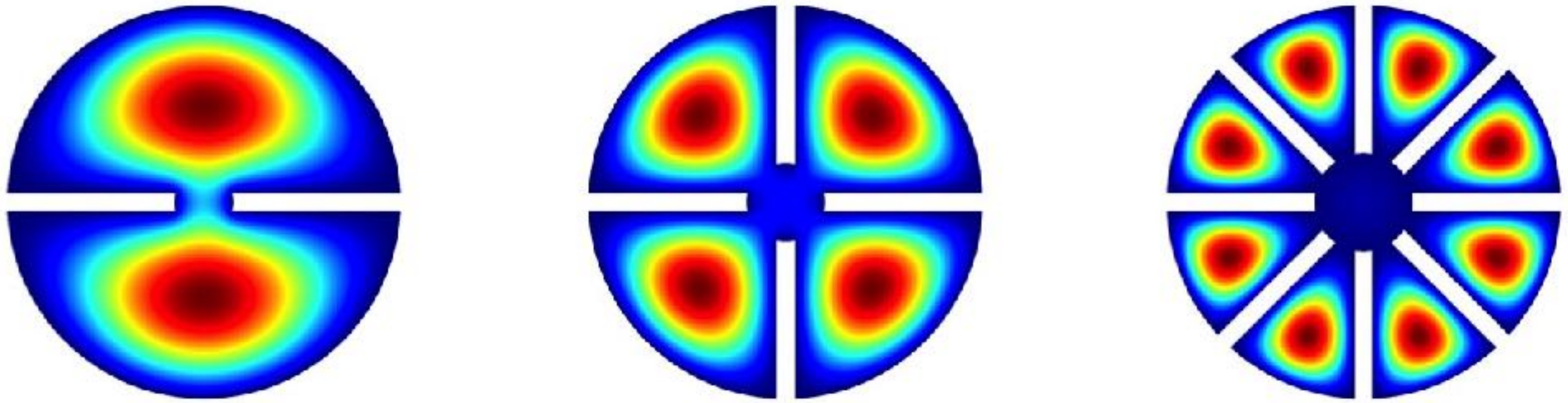
Future (optimistic) Plans

How to increase V?

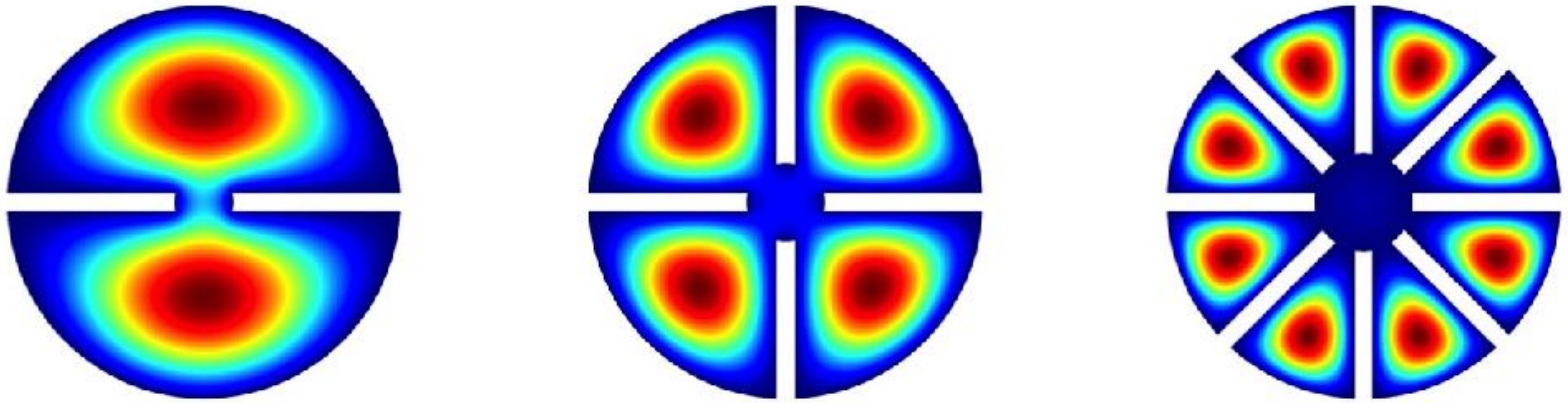


“Pizza cavity”

Jeong, Junu, et al. ‘Search for Invisible Axion Dark Matter with a Multiple-Cell Haloscope’. Physical Review Letters, vol. 125, no. 22, APS, Nov. 2020

How to increase V?

- The rectangle geometry is a natural candidate for a 2-cavity array with iris coupling
- Only 1 readout required
- ~3x increase in scan rate for 2-cavity array
- Easy to tune compared to tuning-rod iris cavity



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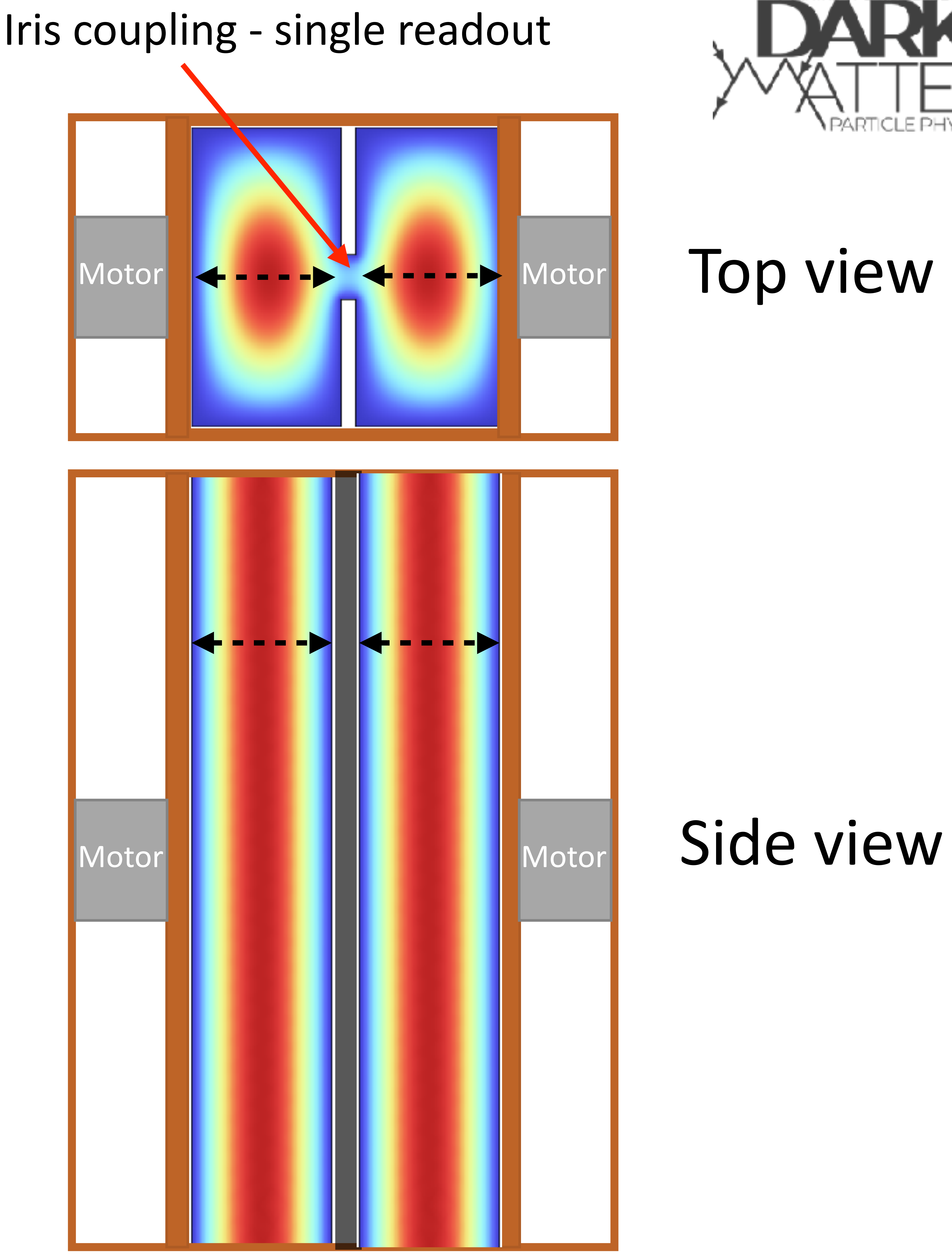
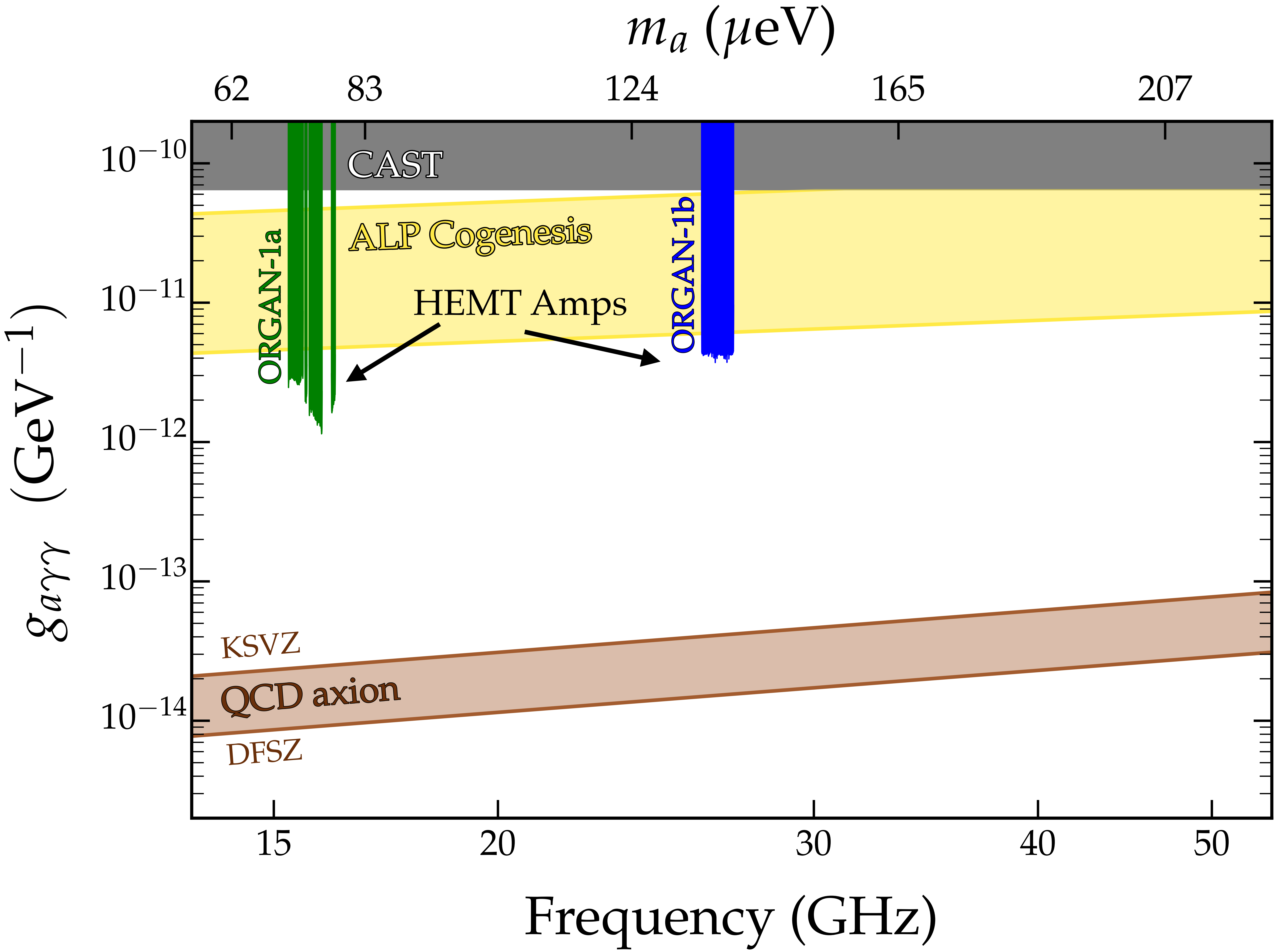


ORGAN Run Plan

<u>Phase 1</u>

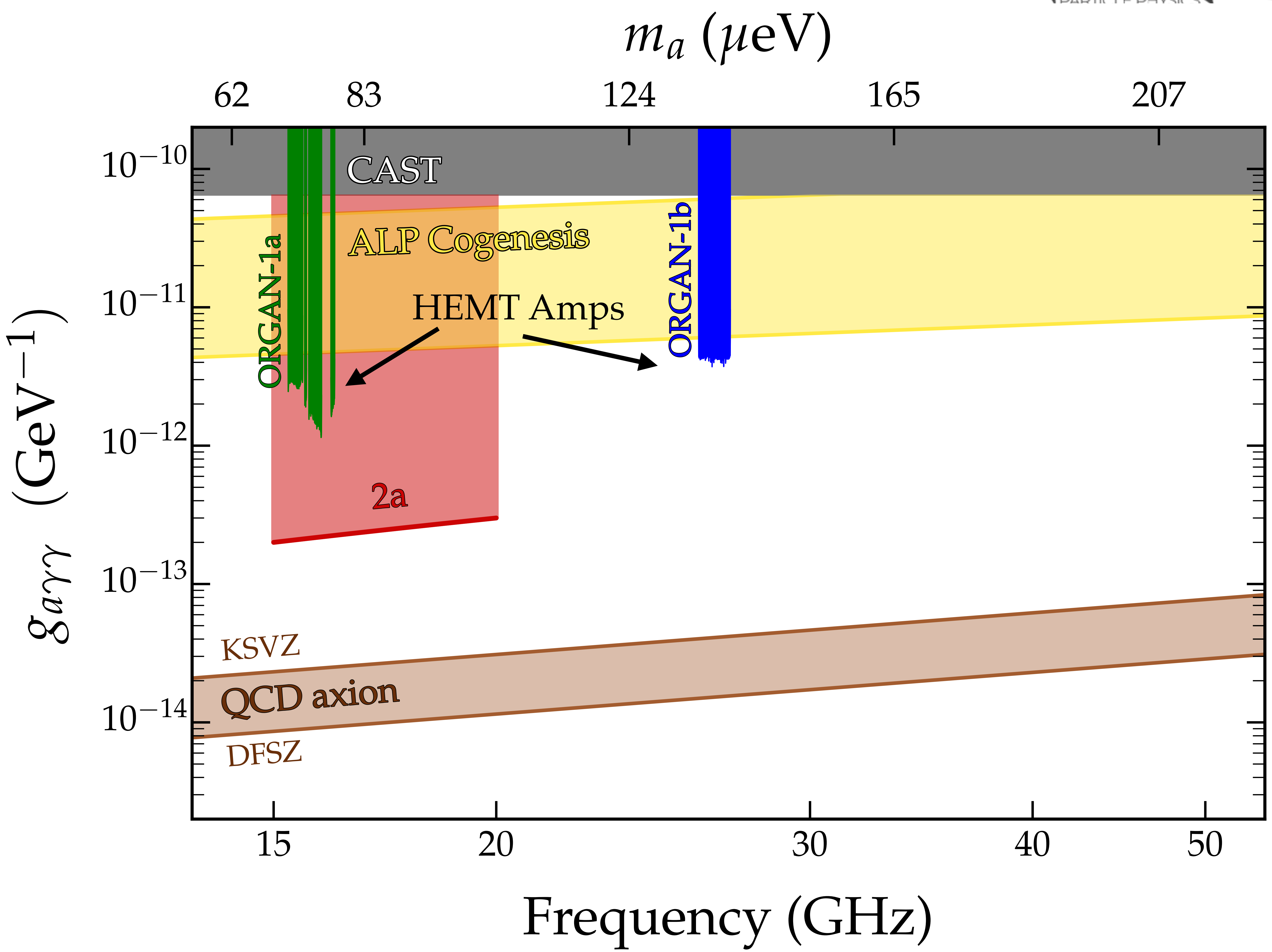
- Targeted searches between 15-16 GHz and 26-27 GHz ~ month scale



ORGAN Run Plan

Phase 2a

- Wider search (15-20 GHz) building on current expertise ~ year scale



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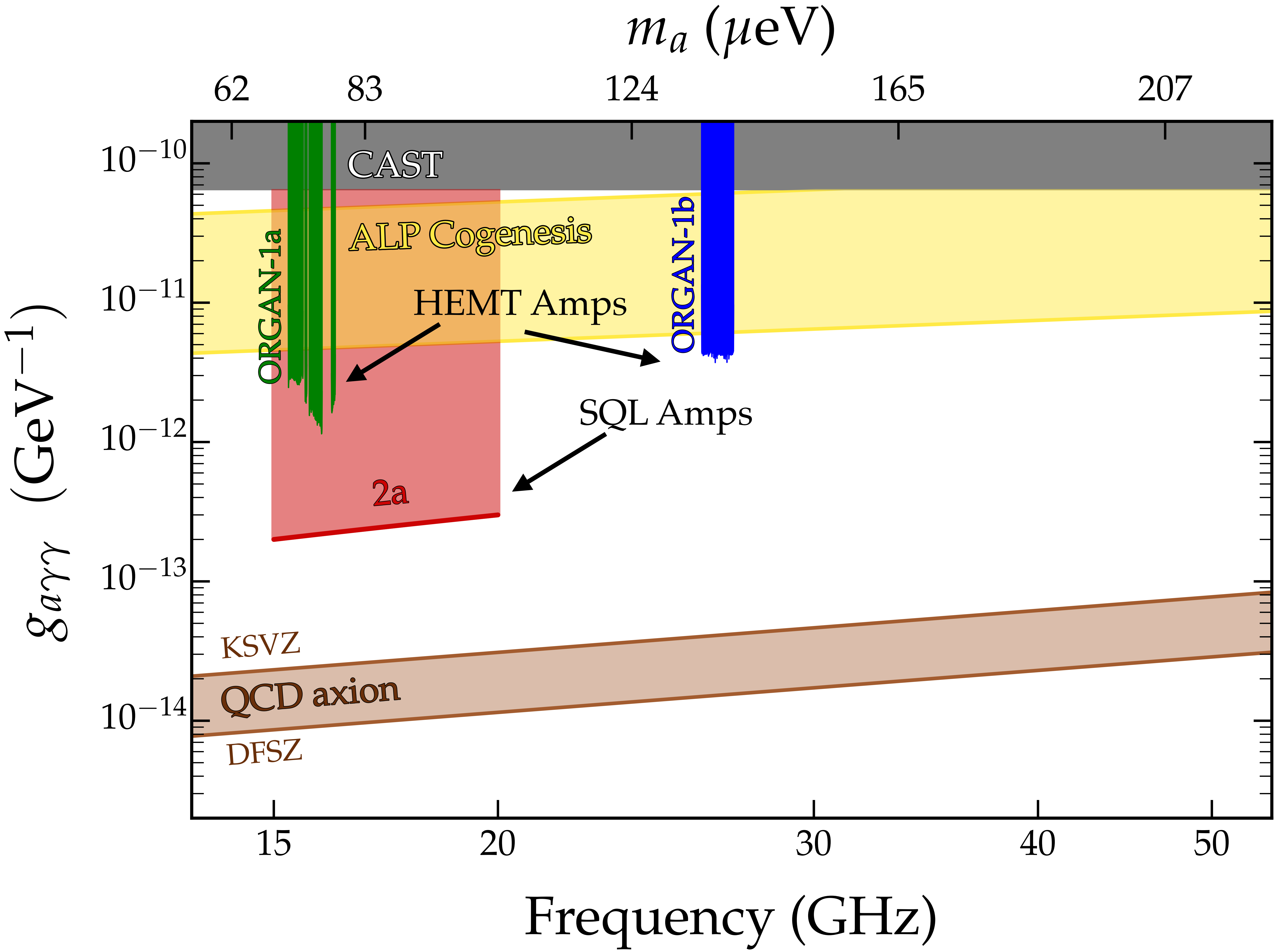

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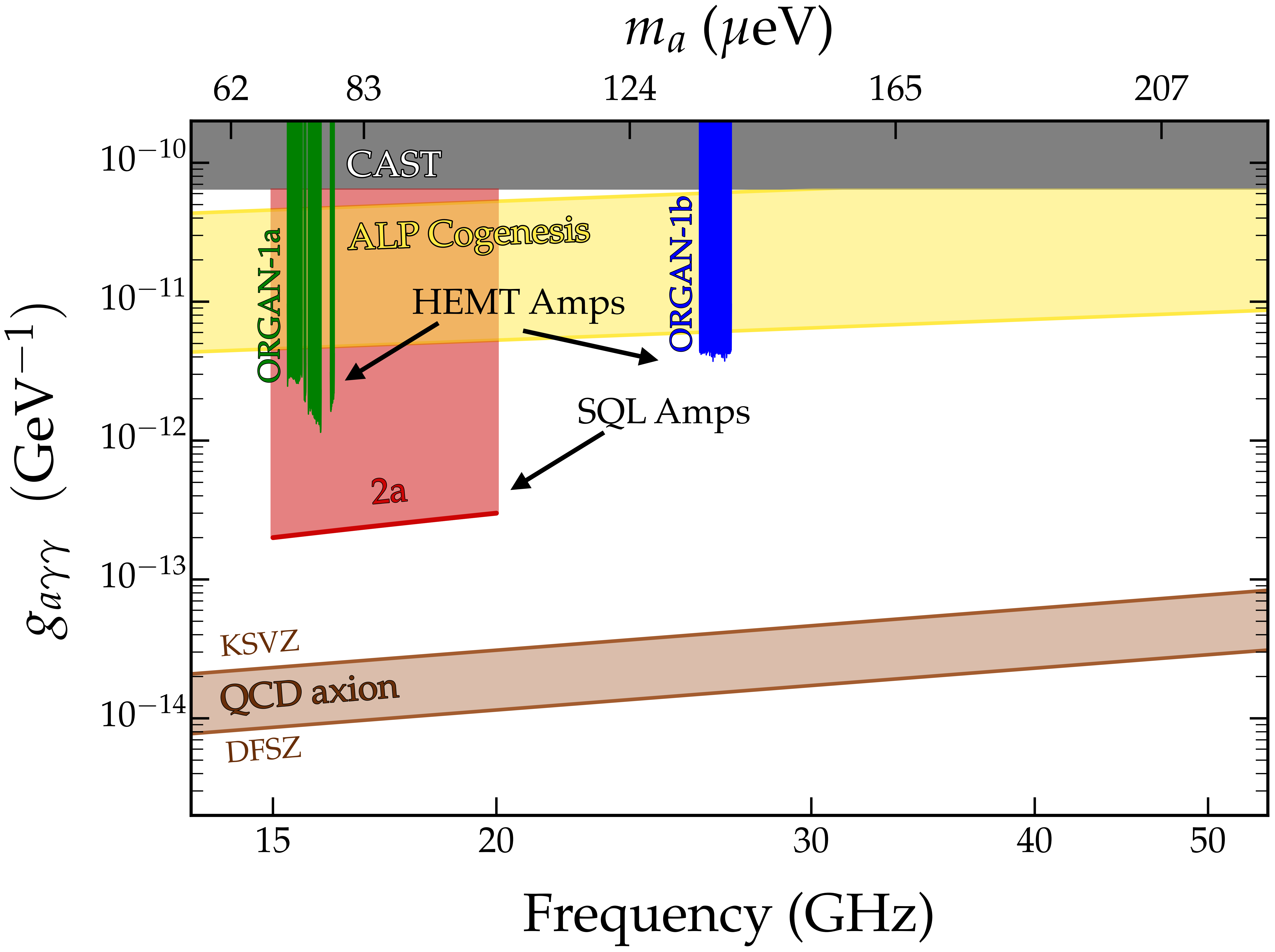

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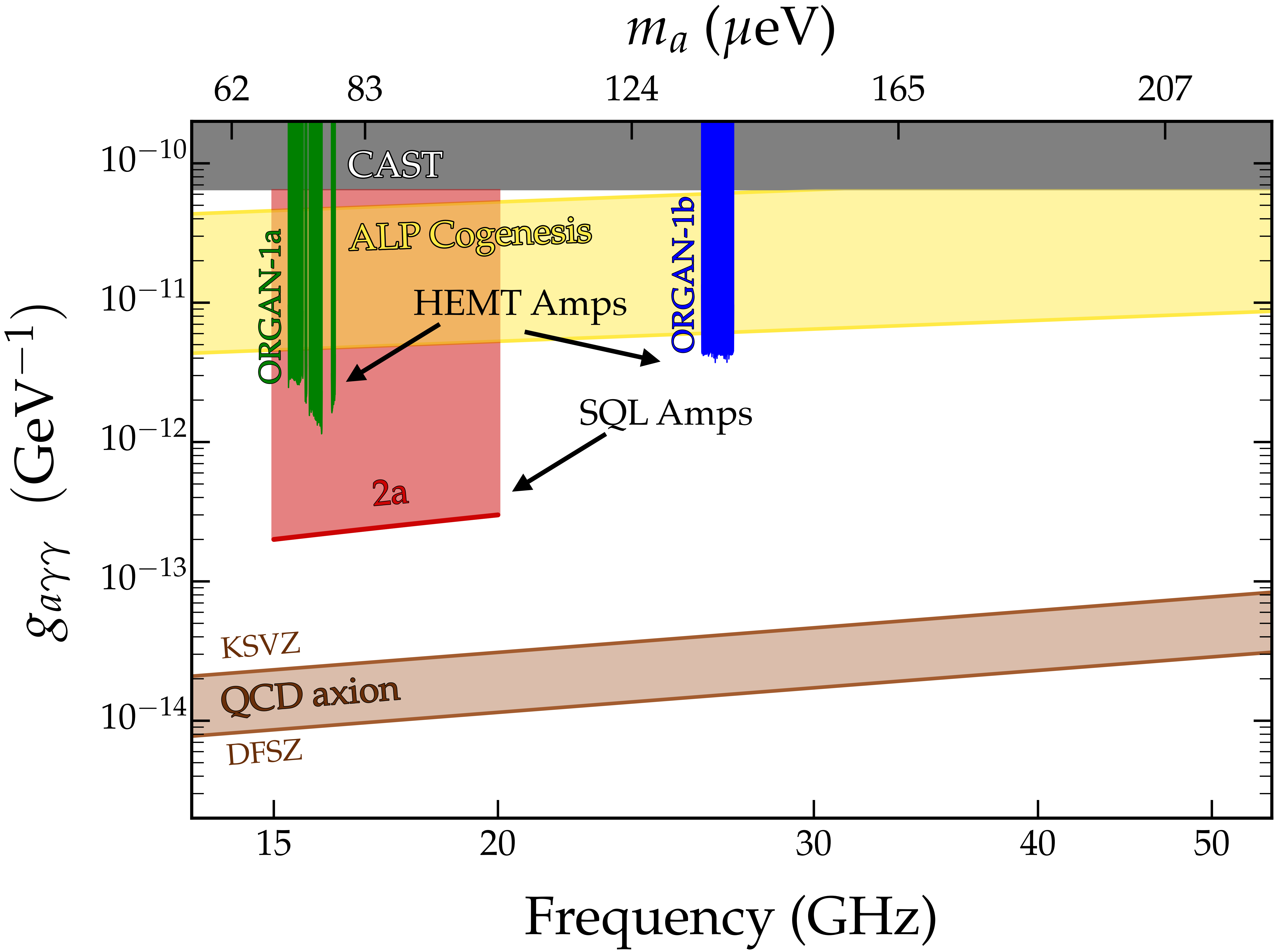

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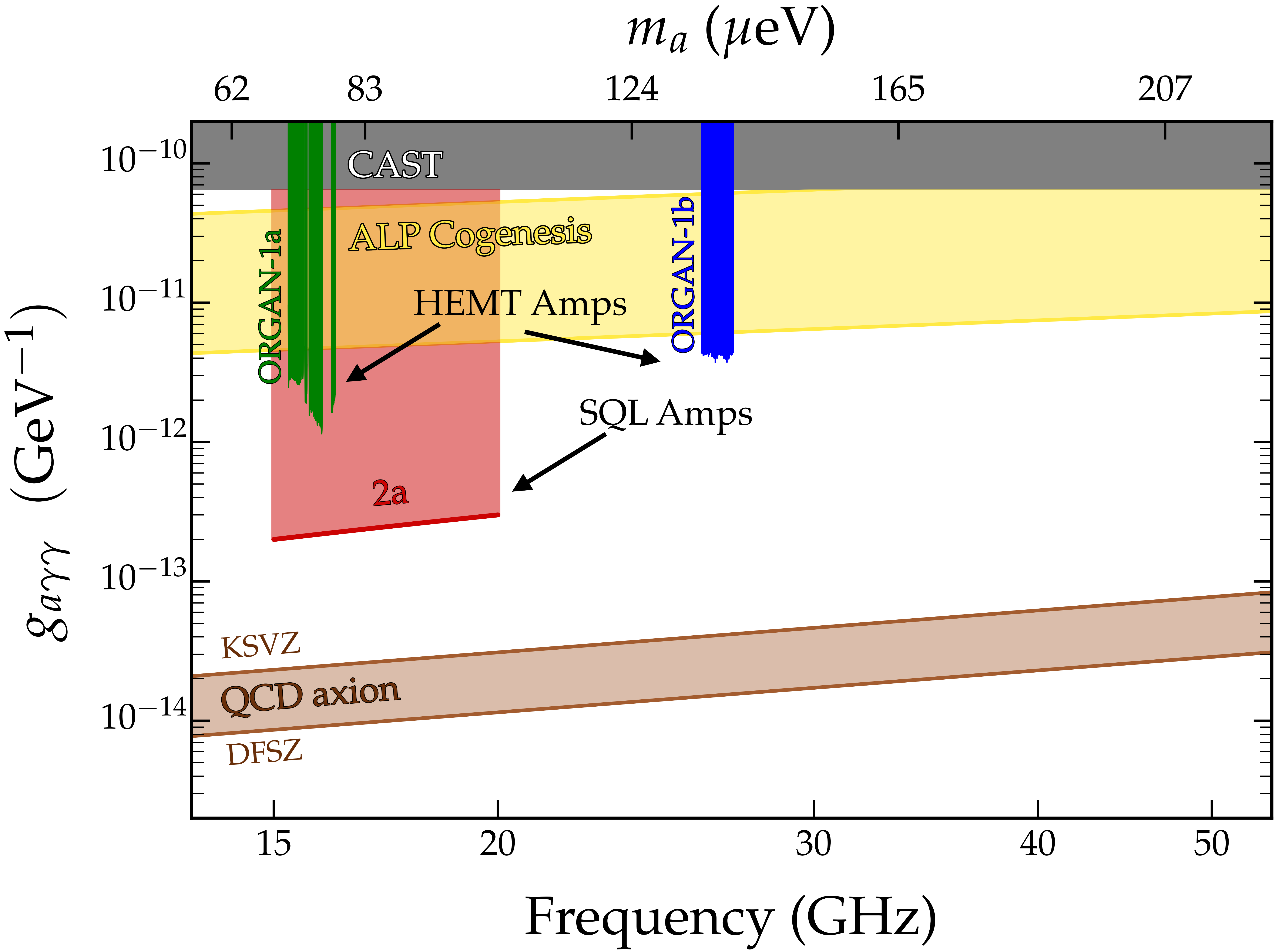

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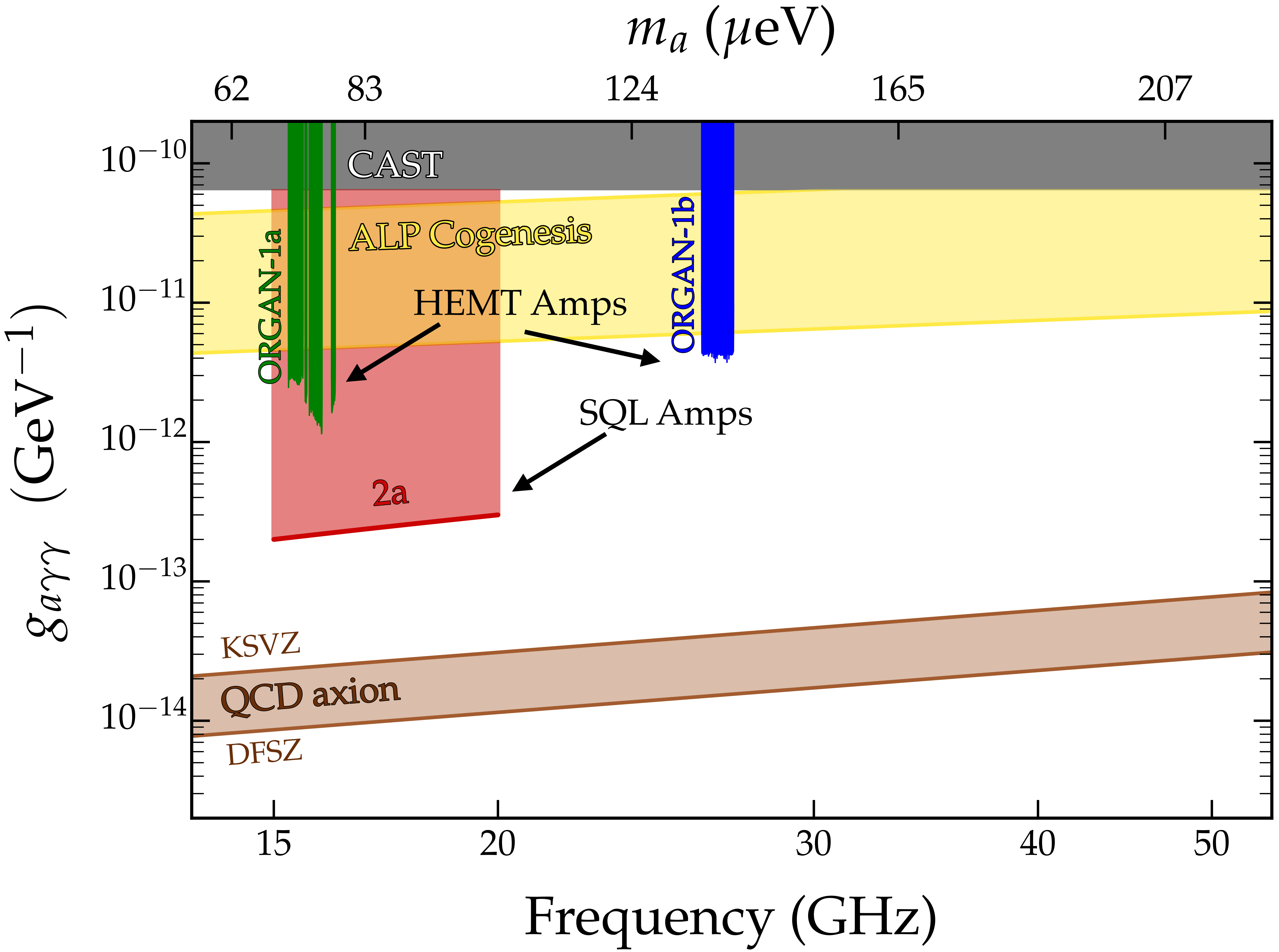
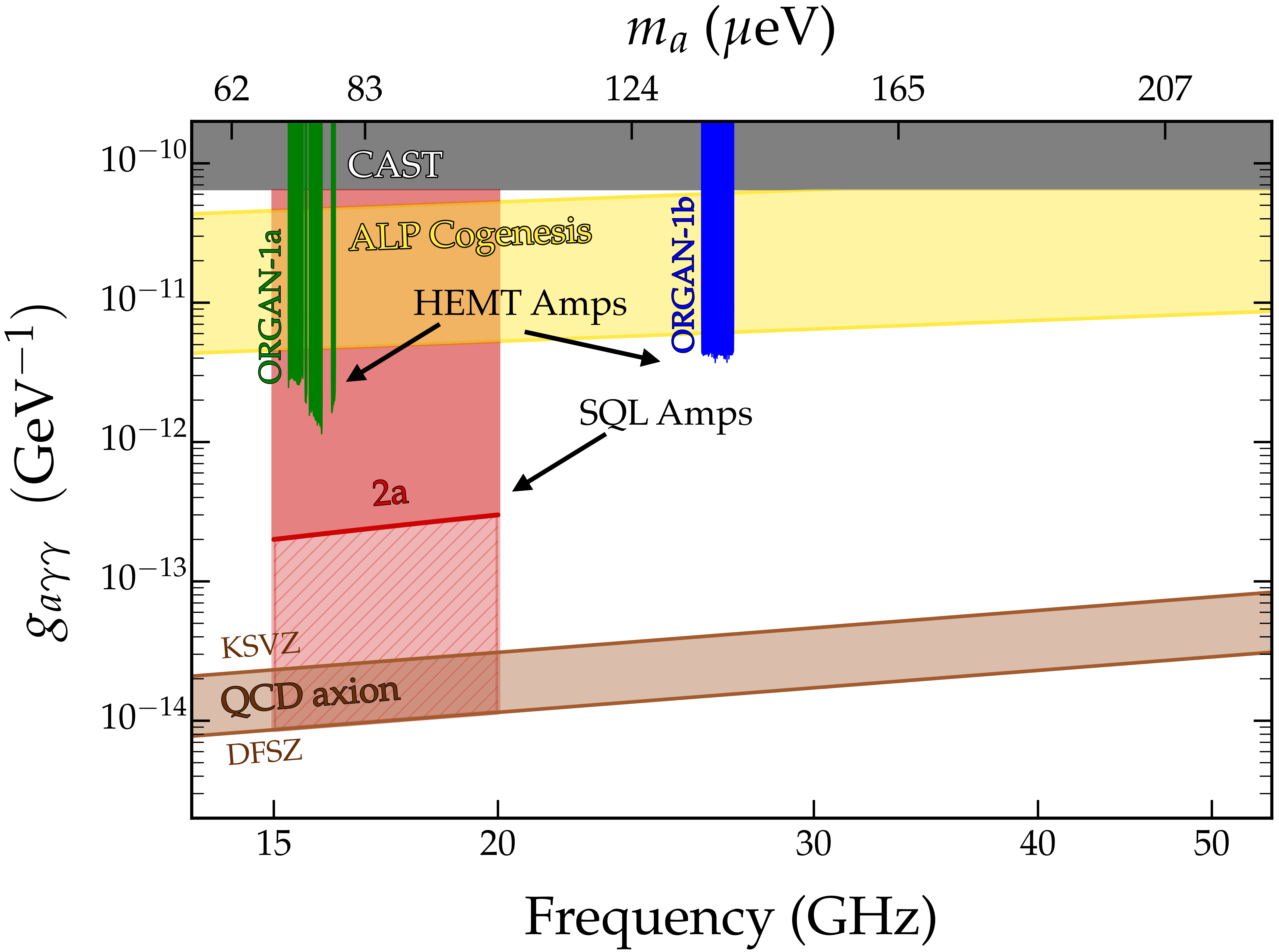
- Larger V: Iris cavity



ORGAN Run Plan

Phase 2a

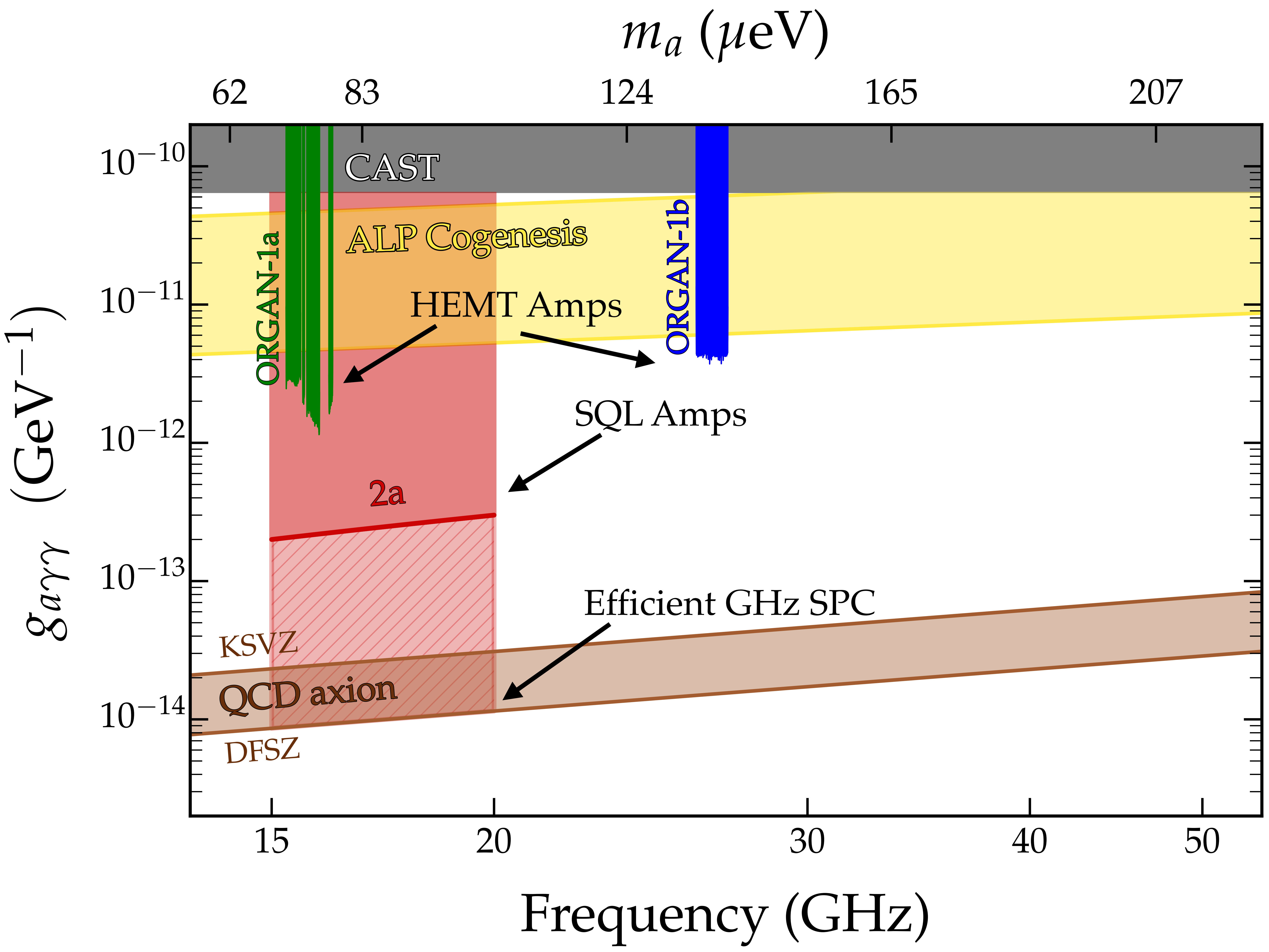
- Develop efficent single photon counting (SPC) devices



ORGAN Run Plan

Phase 2a

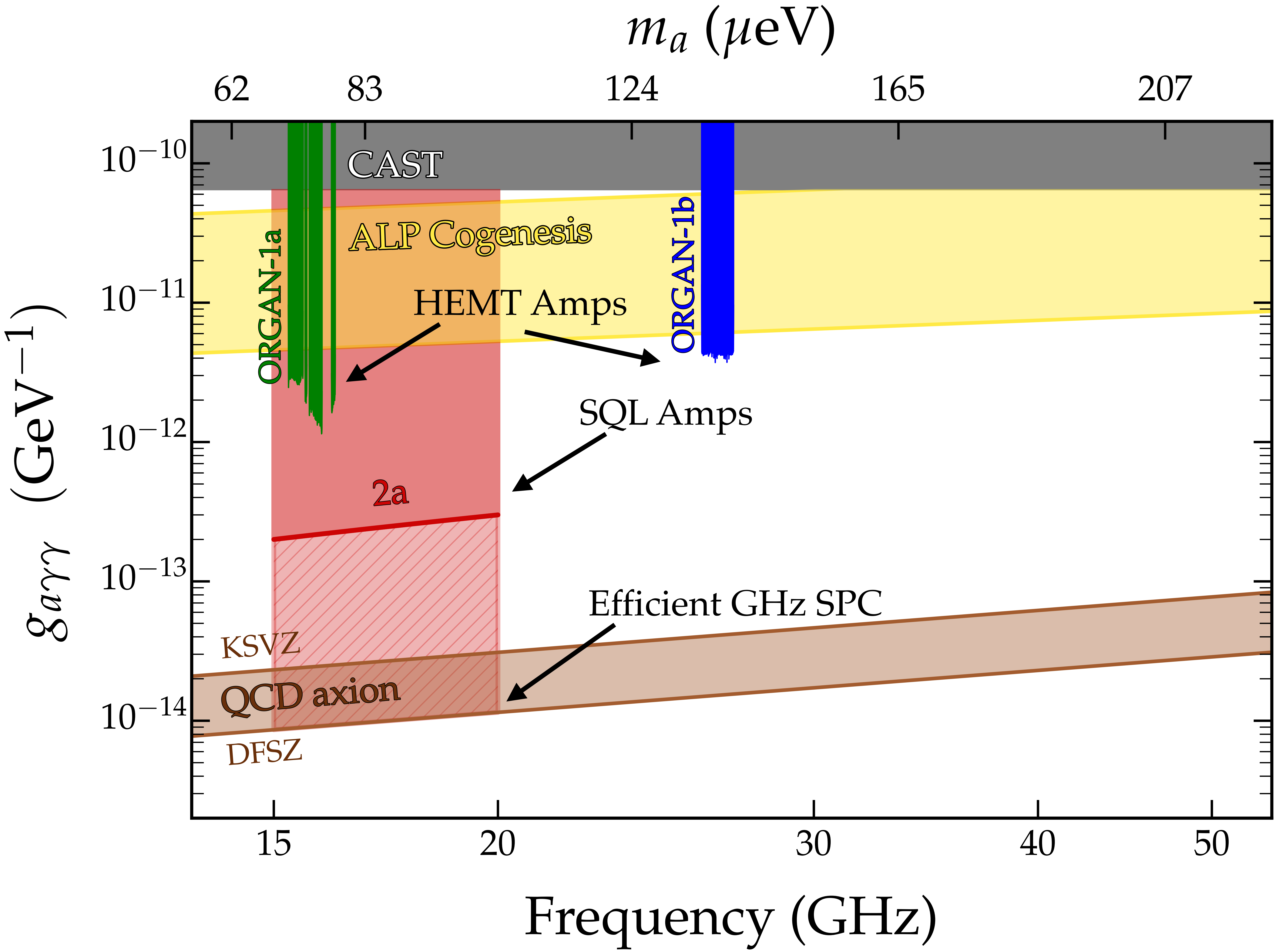
- Develop efficent single photon counting (SPC) devices
- Reach **QCD axion** model bands



ORGAN Run Plan

Phase 2a

- Develop efficent single photon counting (SPC) devices
- Reach **QCD axion** model bands
- $T_{amb} \lesssim 50\text{mk}$



ORGAN Run Plan

Phase 2a

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- Reach **QCD axion** model bands
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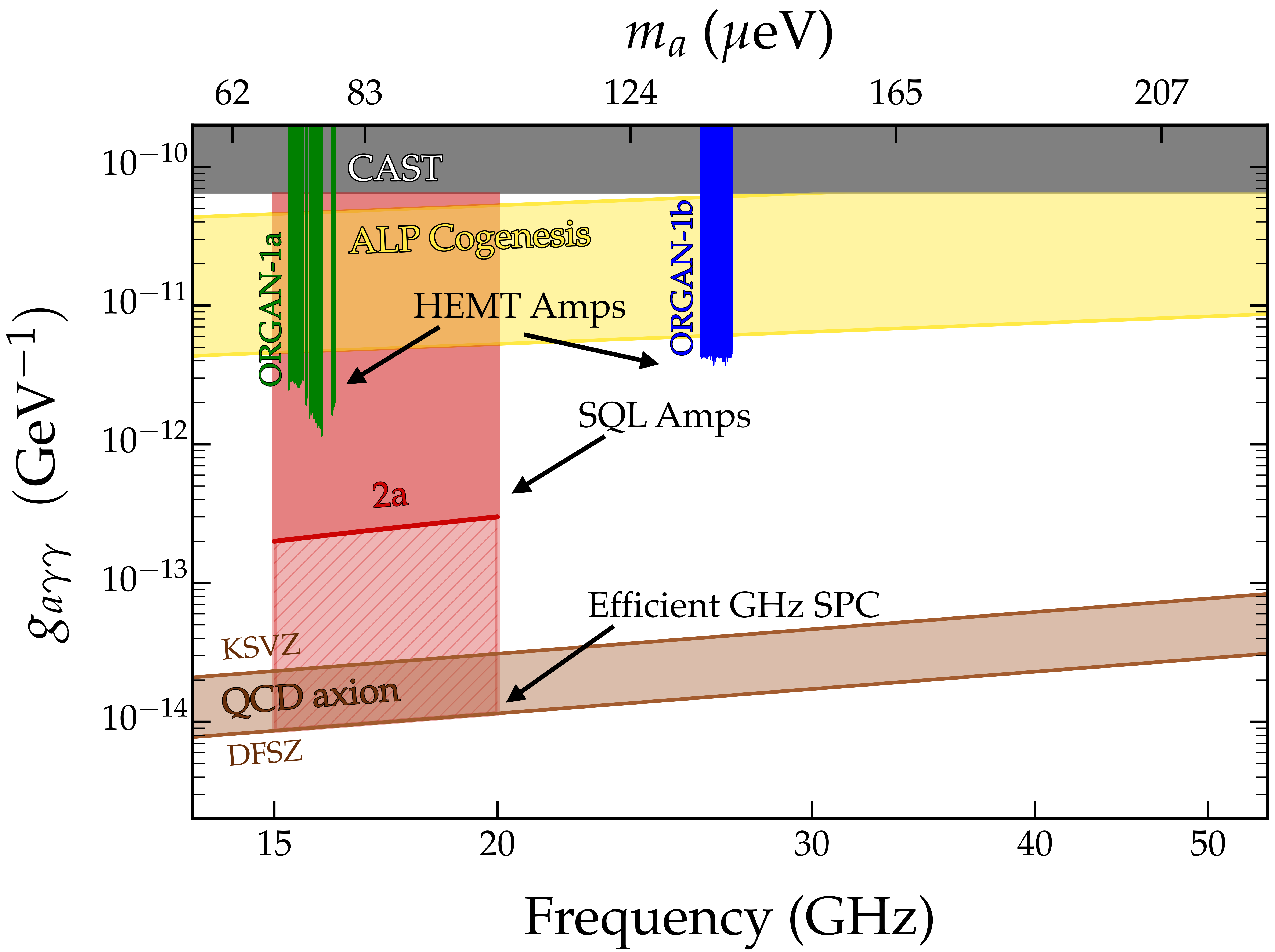
- + All previous upgrades



Summary & Outlook

- Phase 1 of ORGAN complete ✅

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Summary & Outlook

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- Most sensitive limits **above 15 GHz**

Summary & Outlook

- Phase 1 of ORGAN complete ✅
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Questions?

Thank you for your attention!