ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

EQUS

# The ORGAN Experiment ...and some other stuff

Ben McAllister

Swinburne University of Technology

Australian Government
Australian Research Council

THE UNIVERSITY of ADELAIDE

Australian National University

THE UNIVERSITY OF MELBOURNE

SWINBURNE

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF WESTERN AUSTRALIA

# ORGAN Team

- UWA:
  Michael Tobar, Maxim Goryachev,
  Aaron Quiskamp, Graeme Flower,
  Steven Samuels
- Swinburne:
  Ben McAllister, Geoff Brooks
  Raj Singh, Dylan Dance,
  Paige Taylor, Ned Sullivan
- Other collaborators:
  Ciaran O’Hare (USyd), Paul Altin (ANU)

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WESTERN
AUSTRALIA

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BUR
NE

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UNIVERSITY OF
TECHNOLOGY

# Overview

- ORGAN Experiment
    - ORGAN Main
    - ORGAN Low
    - ORGAN Q
- Other candidate searches (dark photons, scalars, etc)
- A cool new thing that is sort of related

# Axion Direct Detection

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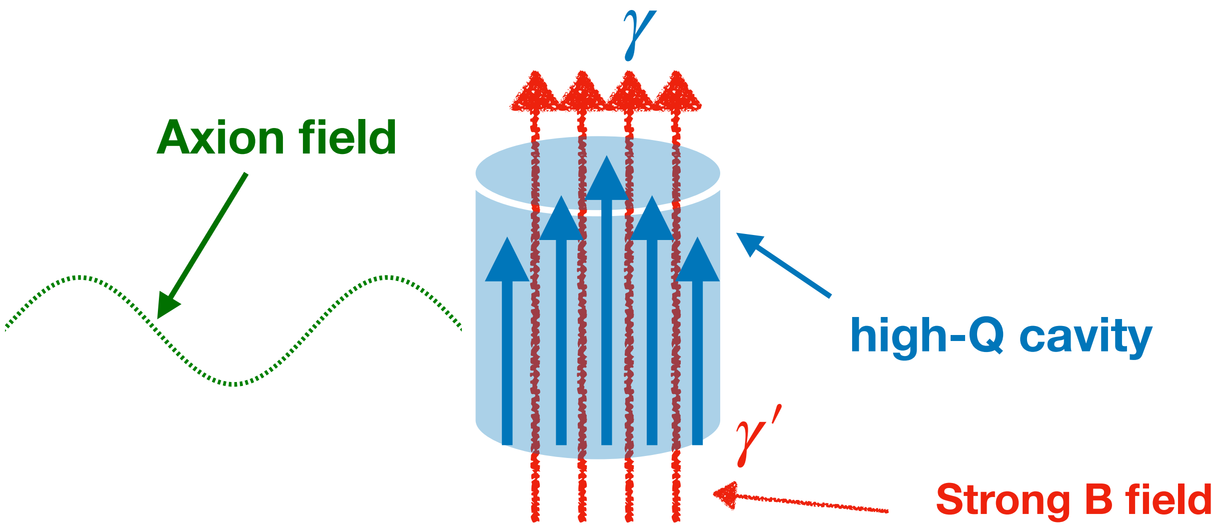
# Axion Direct Detection



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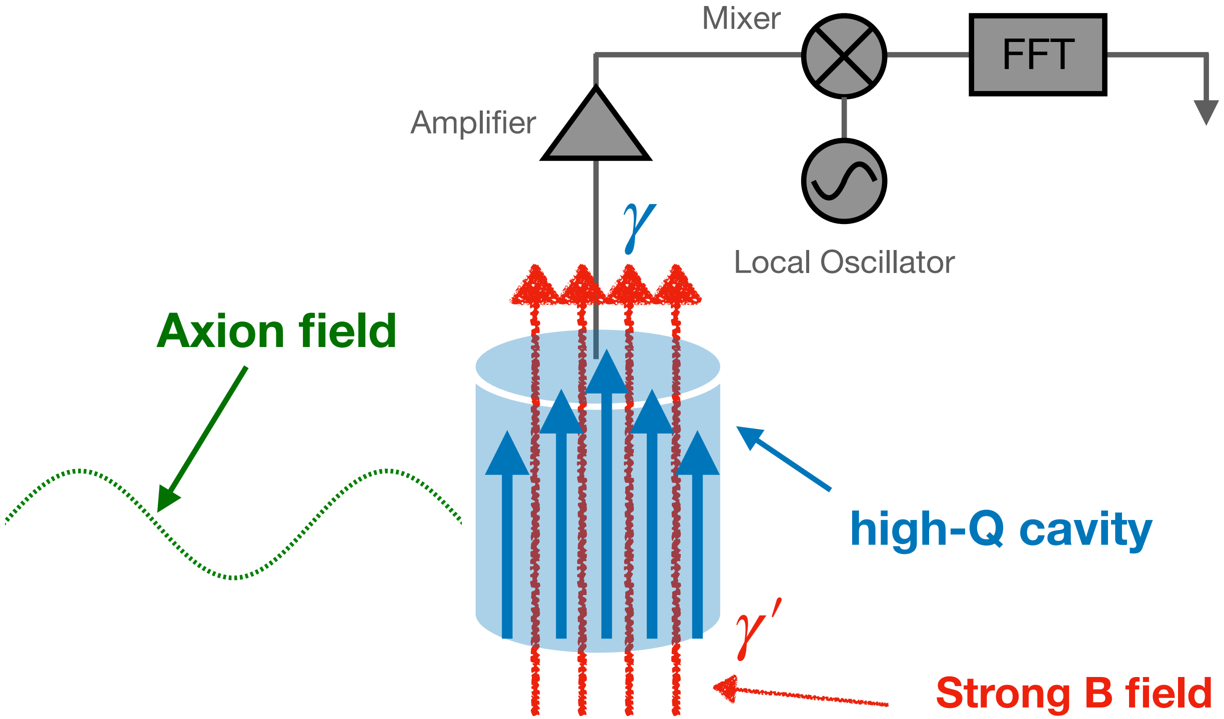

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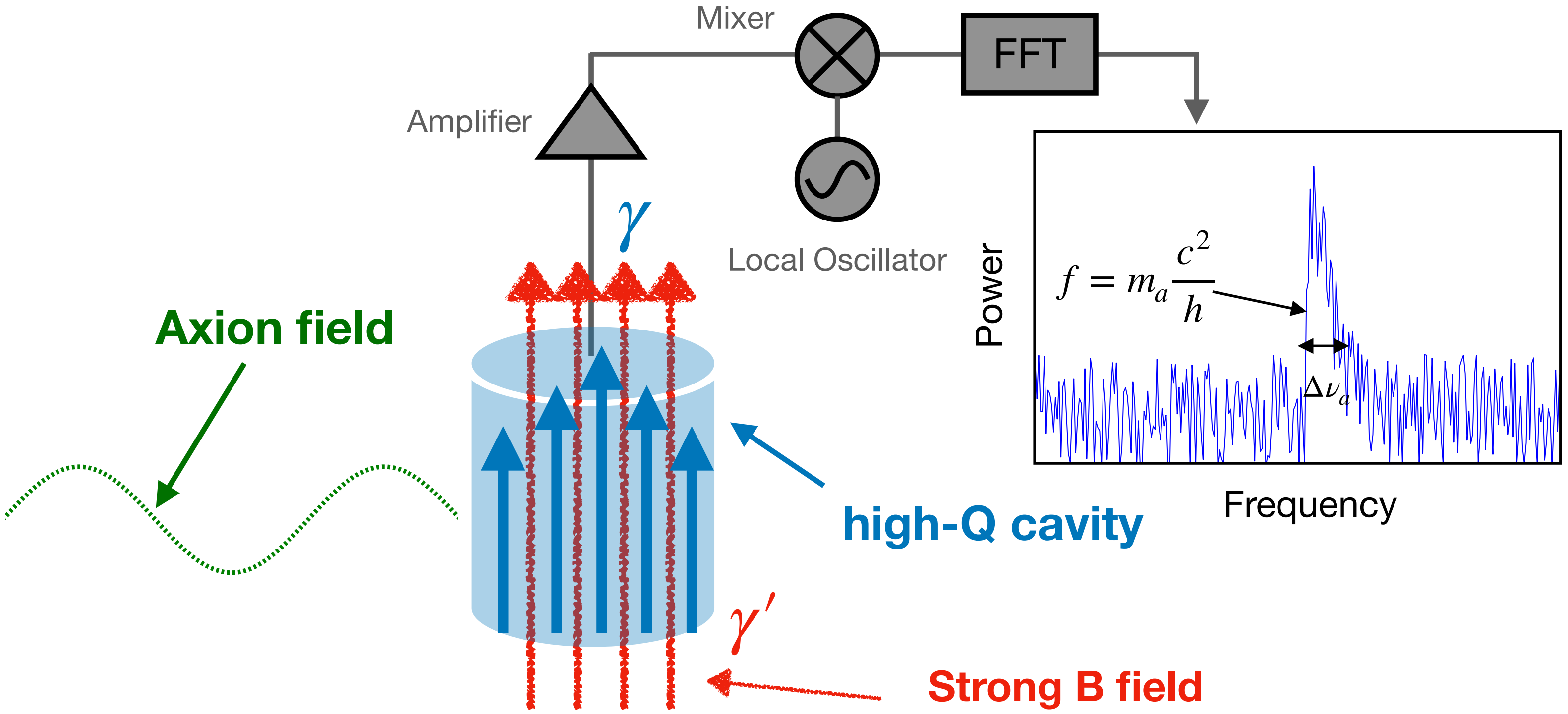

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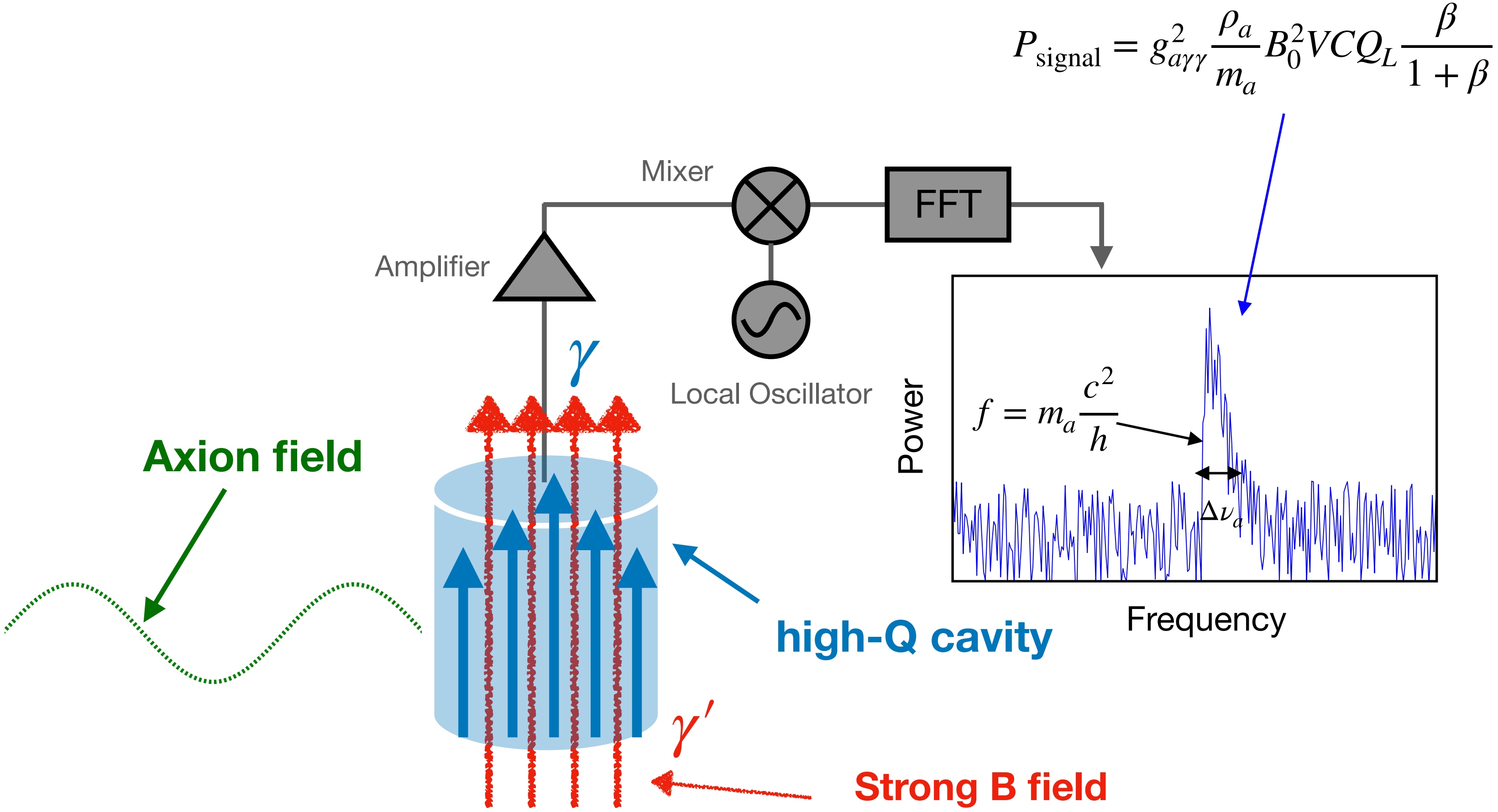

$$P_{\text{signal}} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C Q_L \frac{\beta}{1+\beta}$$

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- Axion converts to photon in strong magnetic field
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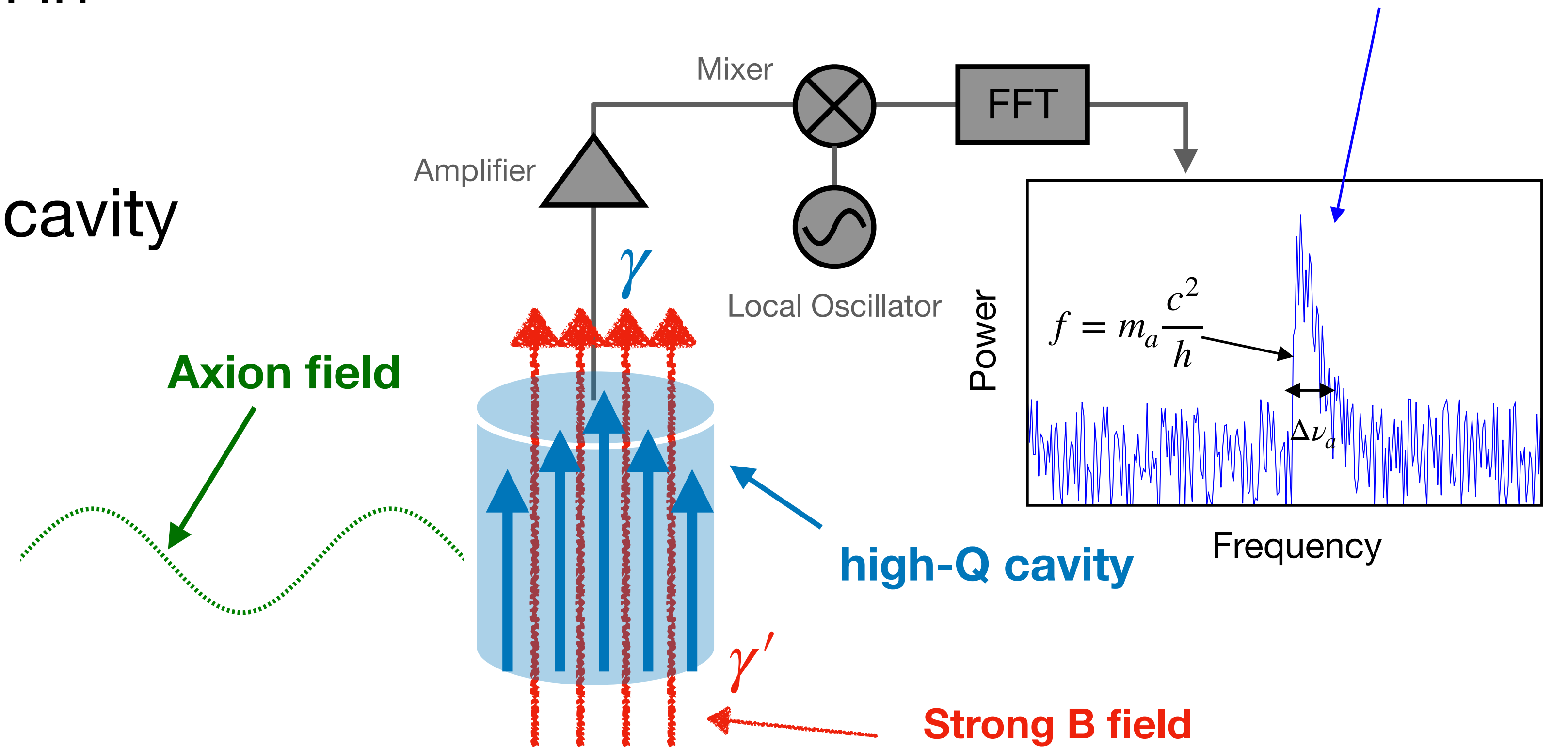

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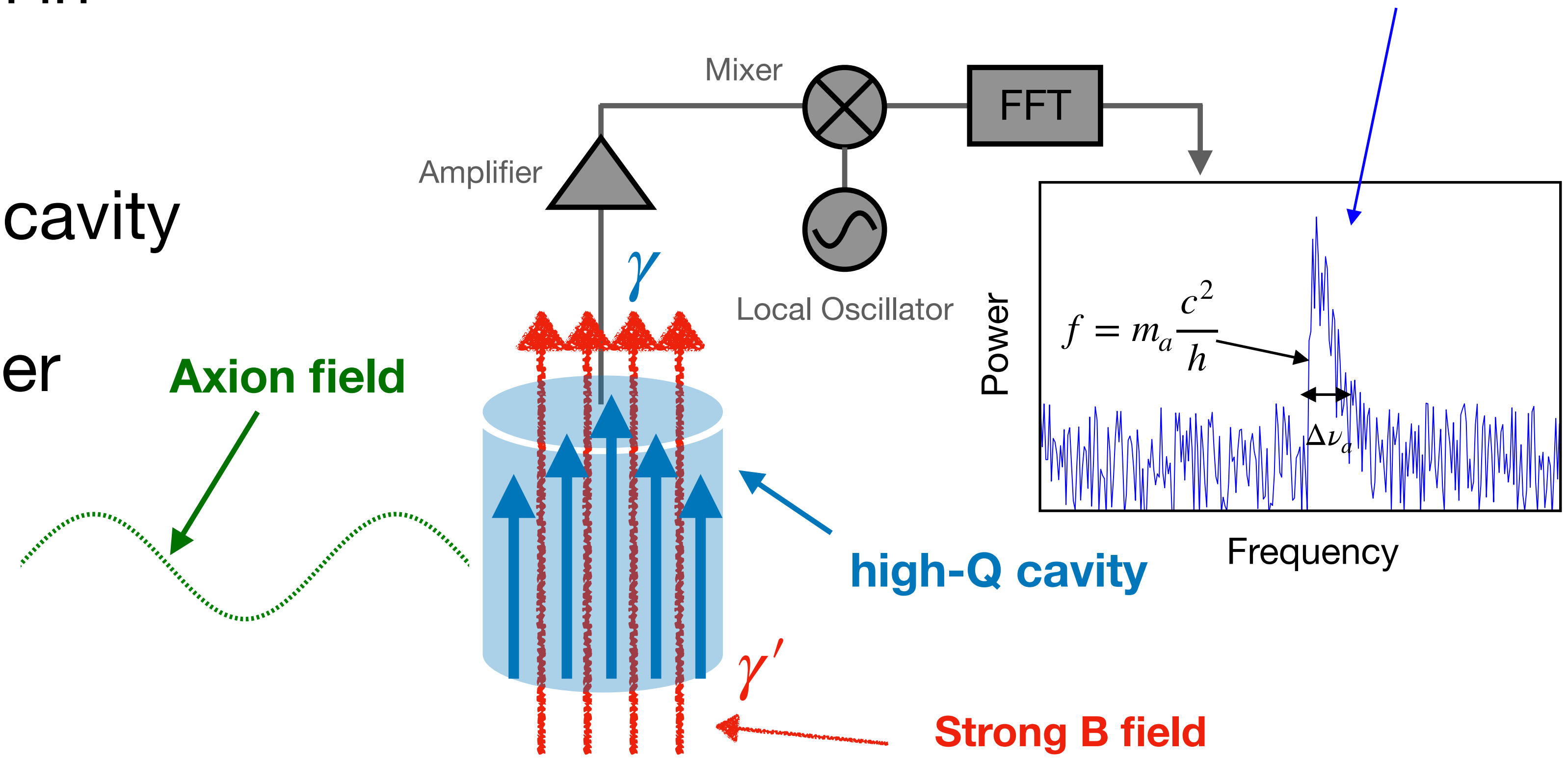

Mixer

FFT

Amplifier

Local Oscillator

$\gamma$

Axion field

high-Q cavity

$\gamma'$

Strong B field

Power

Frequency

$f = m_a \frac{c^2}{h}$

$\Delta\nu_a$

# Axion Direct Detection

- Axion converts to photon in strong magnetic field
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$$f = \frac{m_a}{h}c^2 + \frac{1}{2}\frac{m_a}{h}v^2$$

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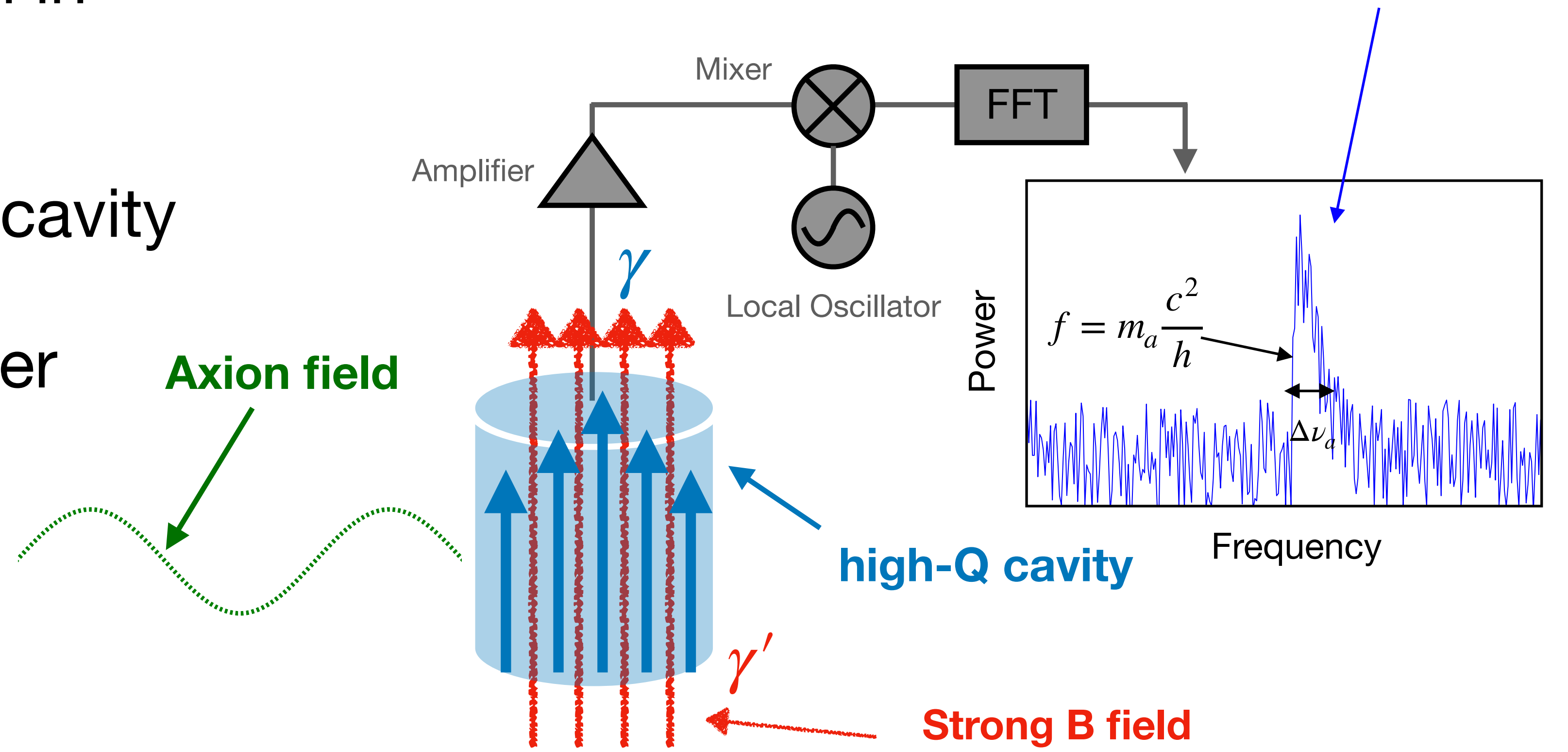

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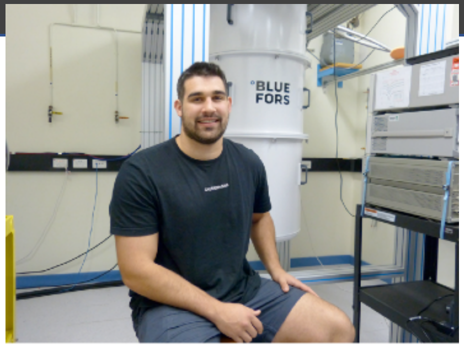

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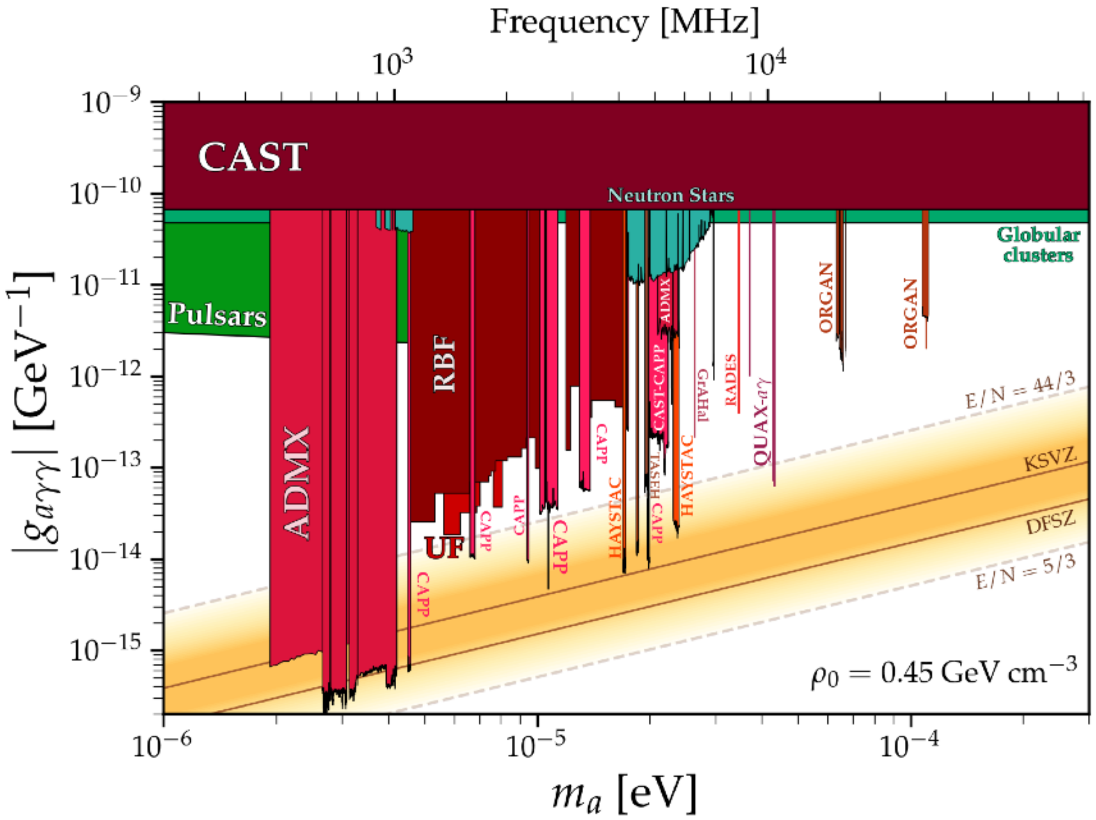

cajohare.github.io/AxionLimits

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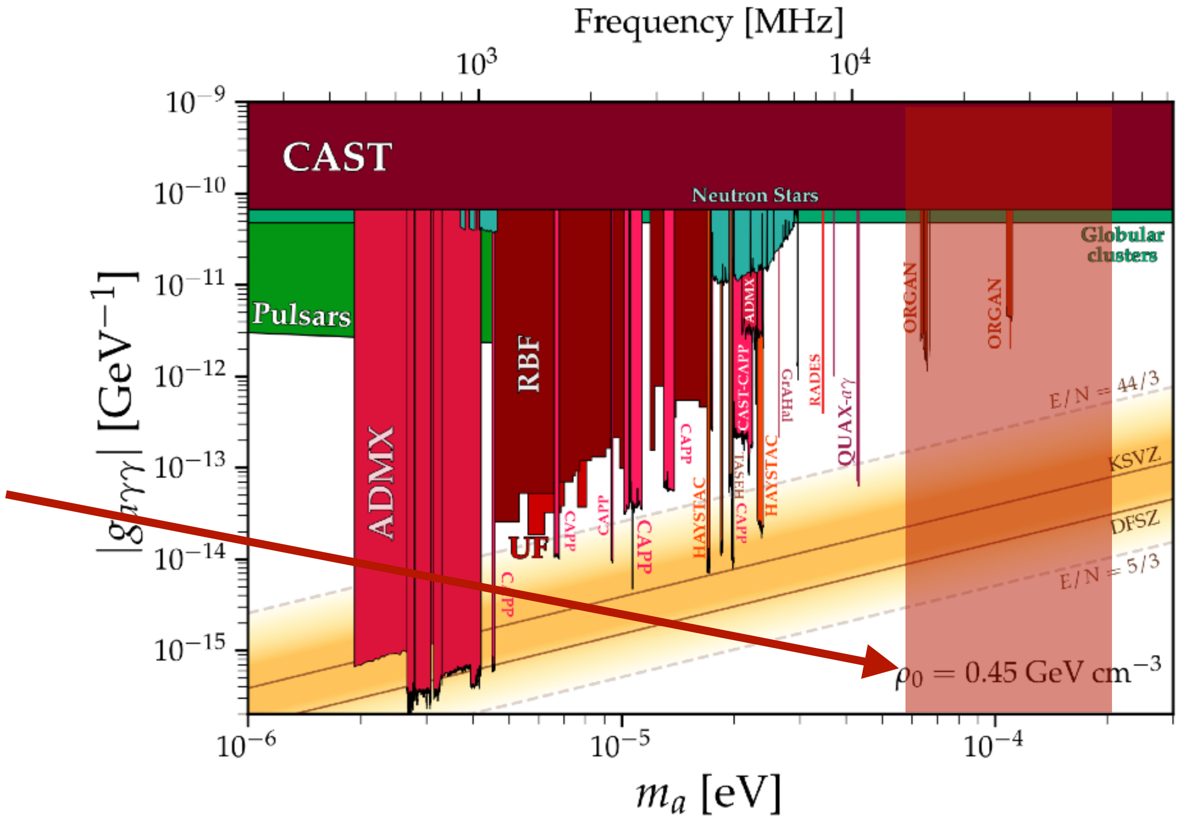

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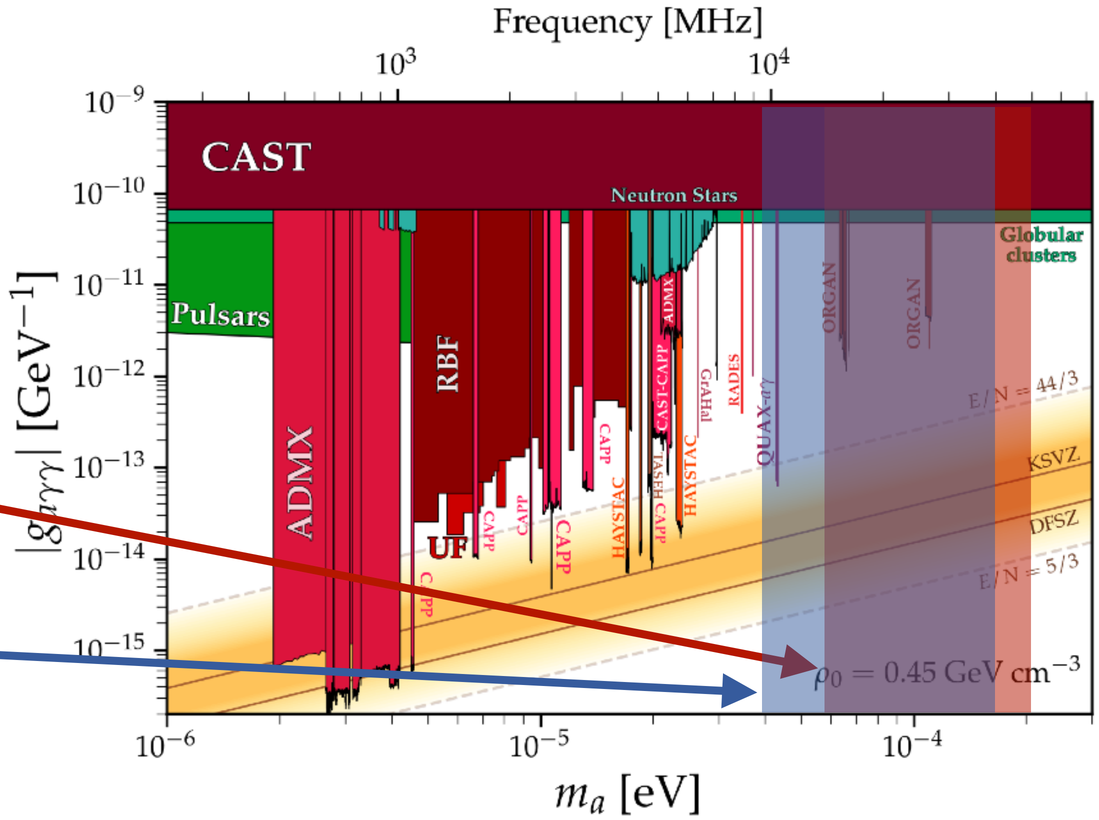

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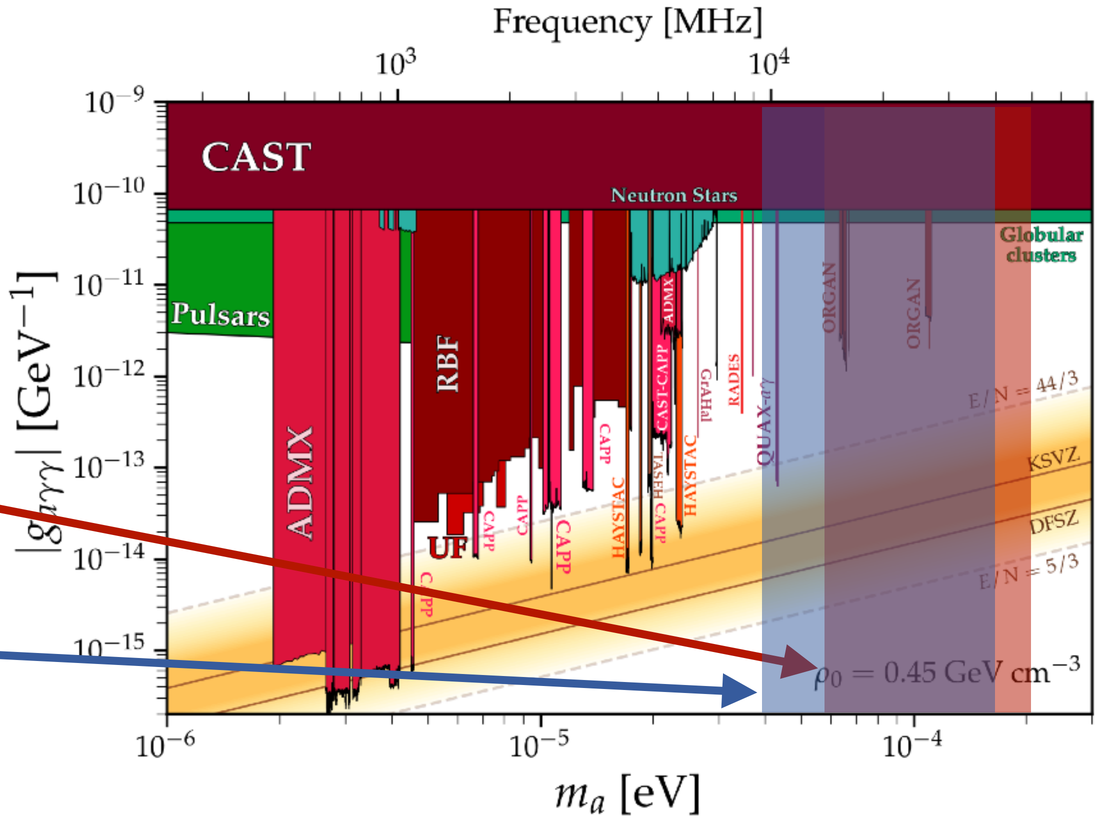
- **Why "high mass" (>60$\mu$eV)?**
- The high mass parameter space is largely unexplored with **many predicitons..**
- **SMASH** model predicts $50 \leq m_a \leq 200\,\mu eV$
- **QCD lattice** simulations favour $40 \leq m_a \leq 180\,\mu eV$



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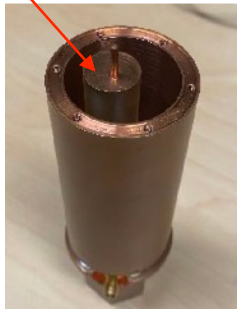
Rotation stage



Tuning rod

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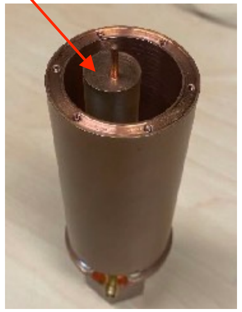

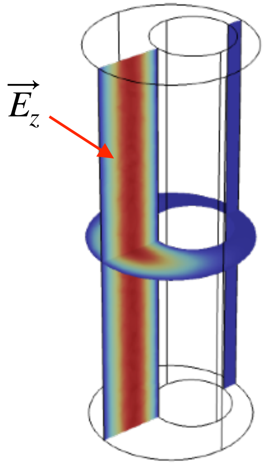

TM$_{010}$ mode

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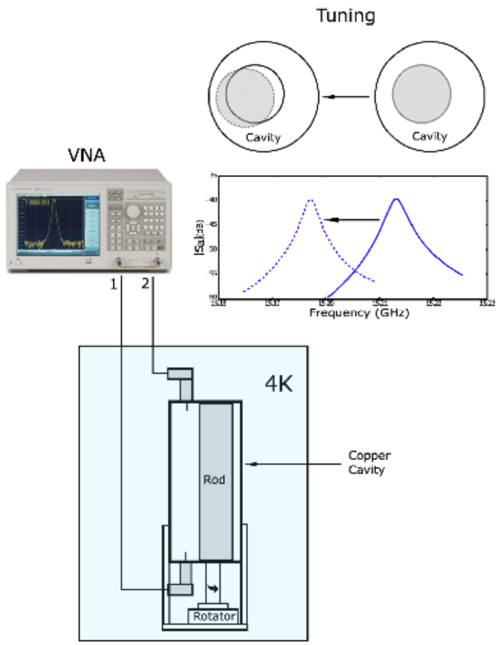
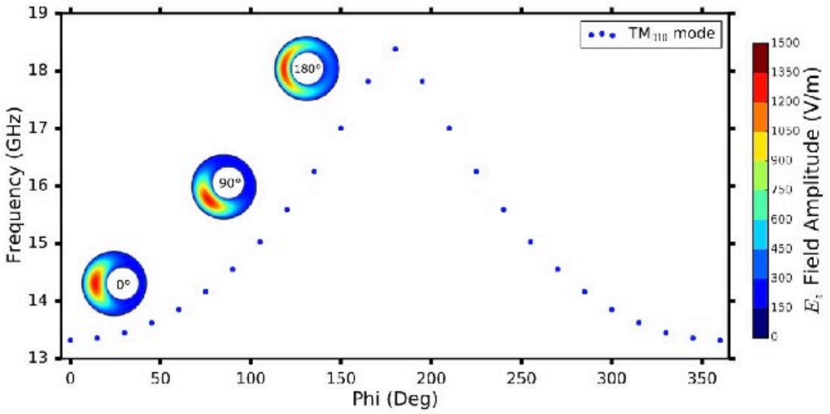
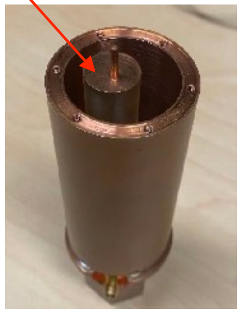
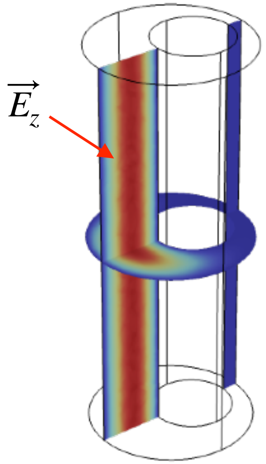




Rotation stage

Tuning rod





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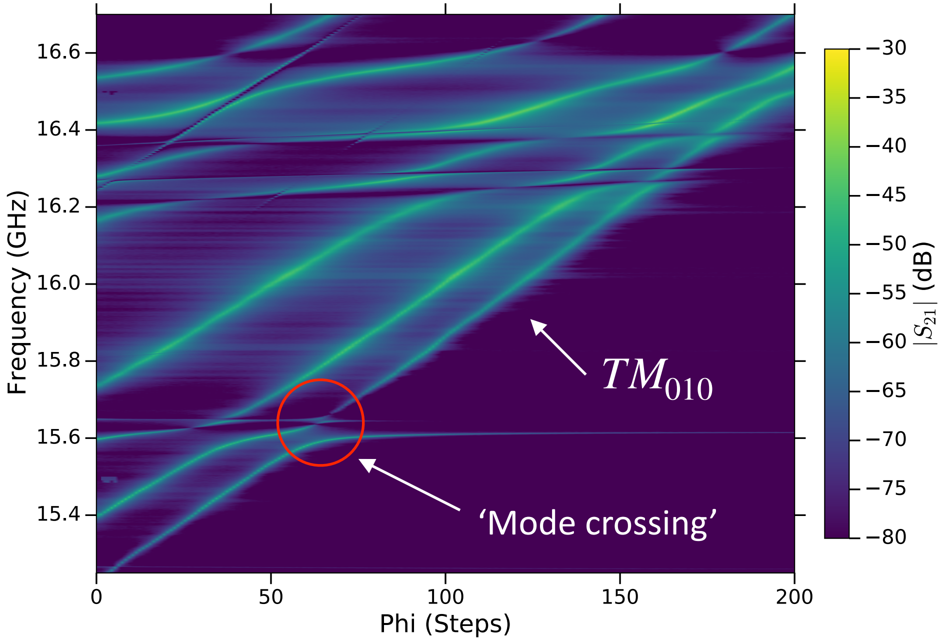

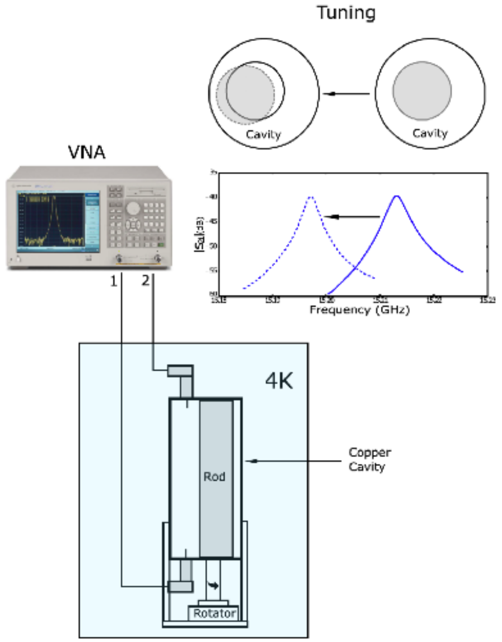

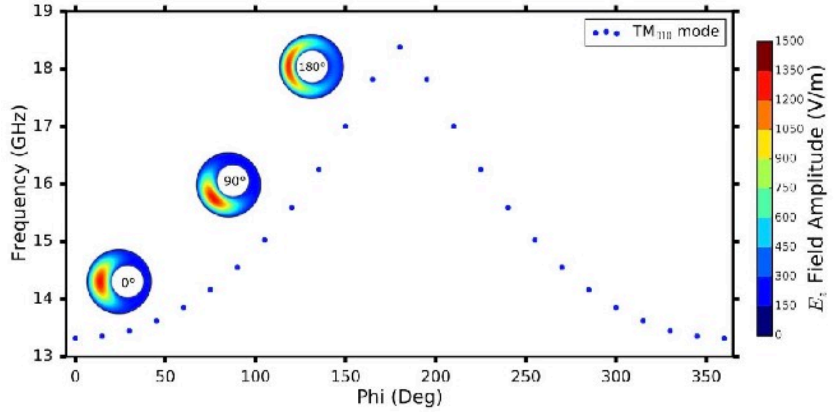

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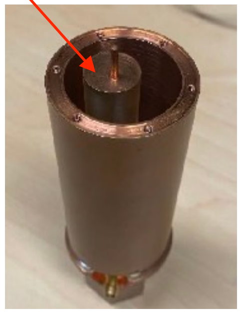

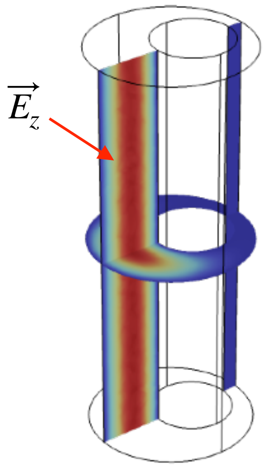

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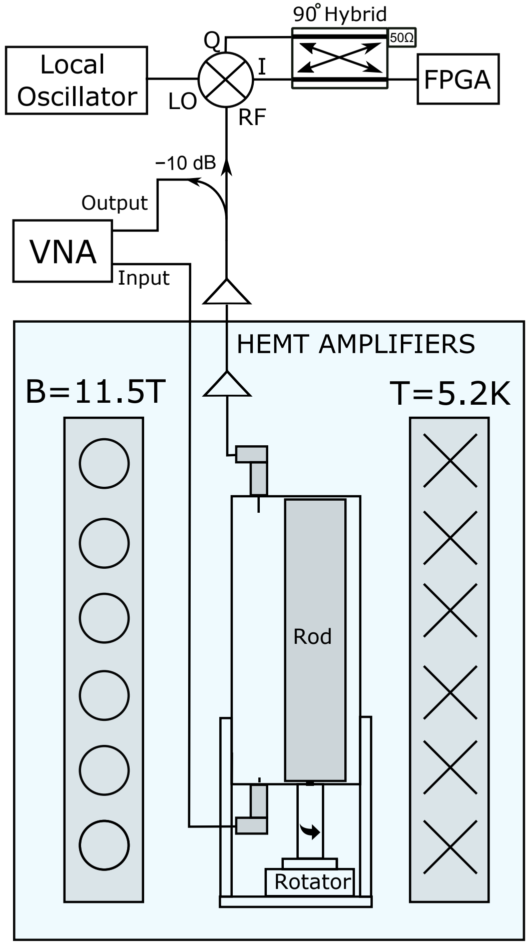
90° Hybrid
50Ω
Q
I
Local Oscillator
LO
RF
FPGA
−10 dB
Output
VNA
Input
HEMT AMPLIFIERS
B=11.5T
T=5.2K
Rod
Rotator

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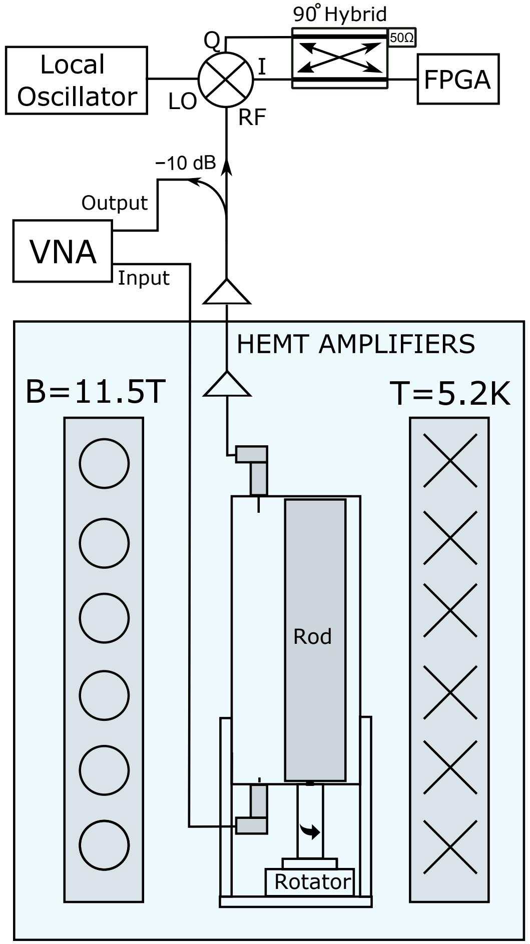
- We scanned for ~ 3.5 weeks (~700MHz)



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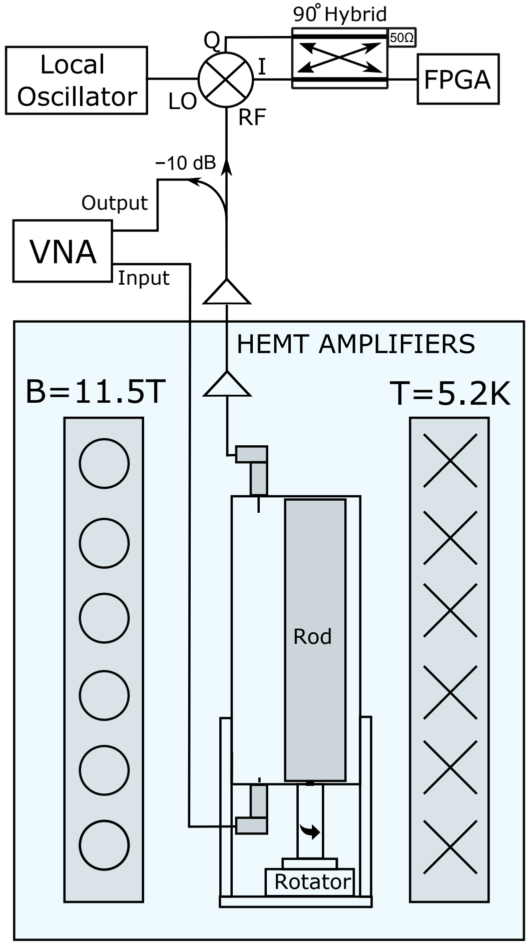
Step motor



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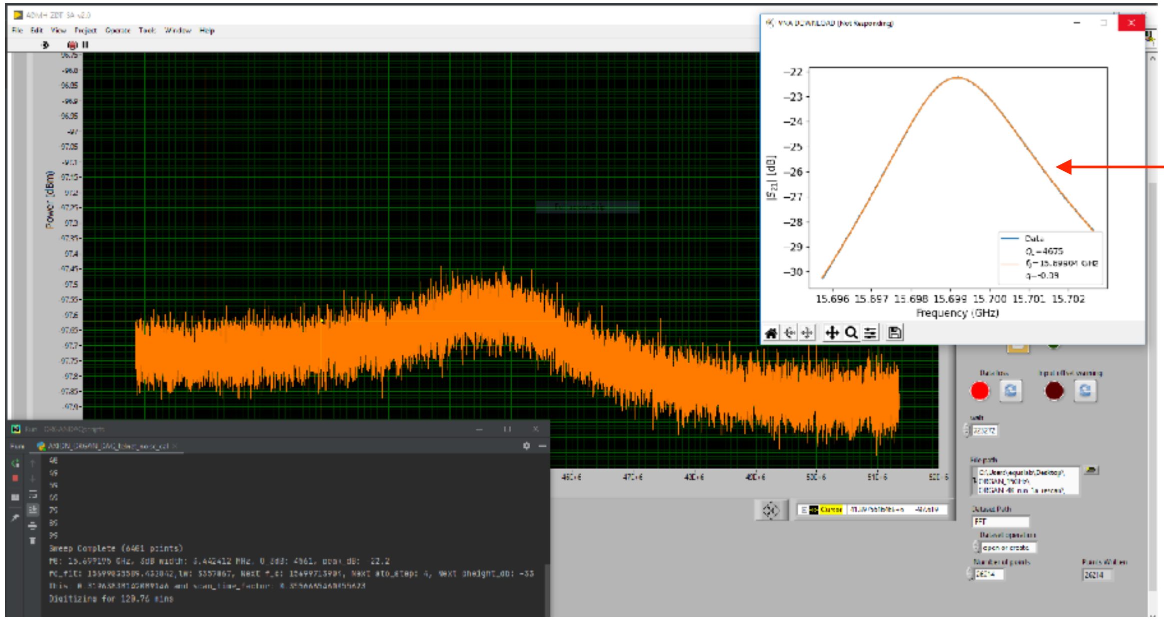
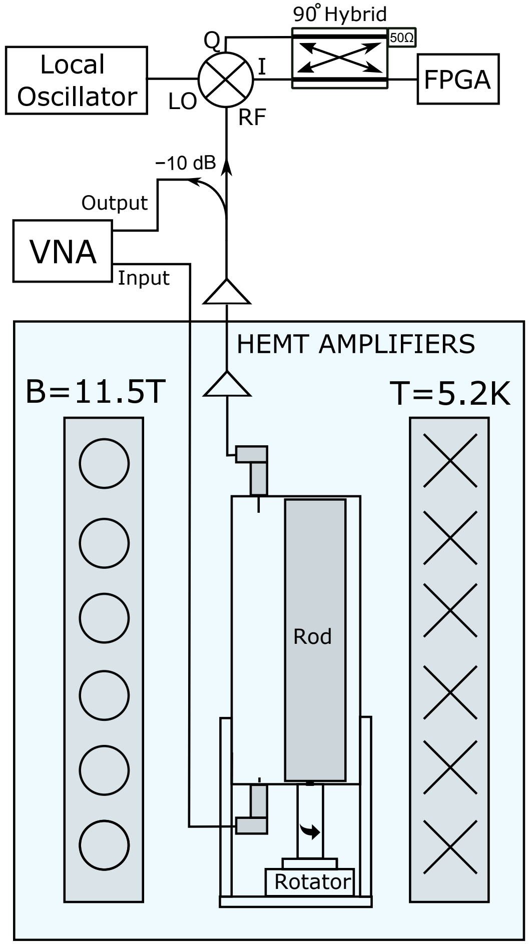


```
Sweep Complete (6461 points)
Digitizing for 120.76 mins
```

DAQ

Step motor

Sweep VNA for



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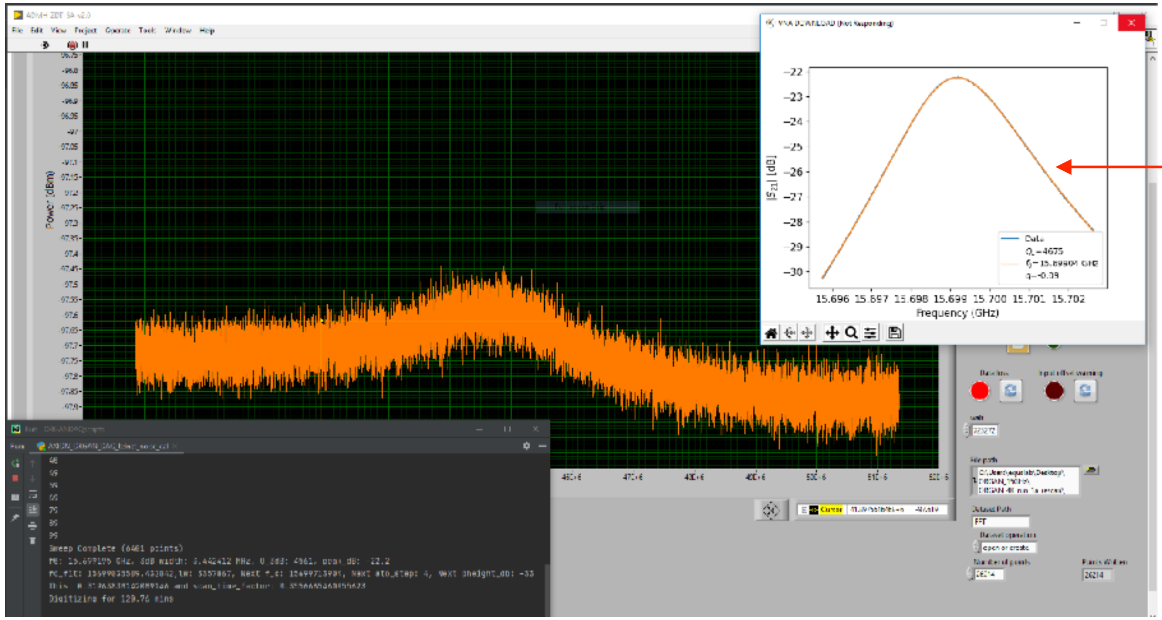

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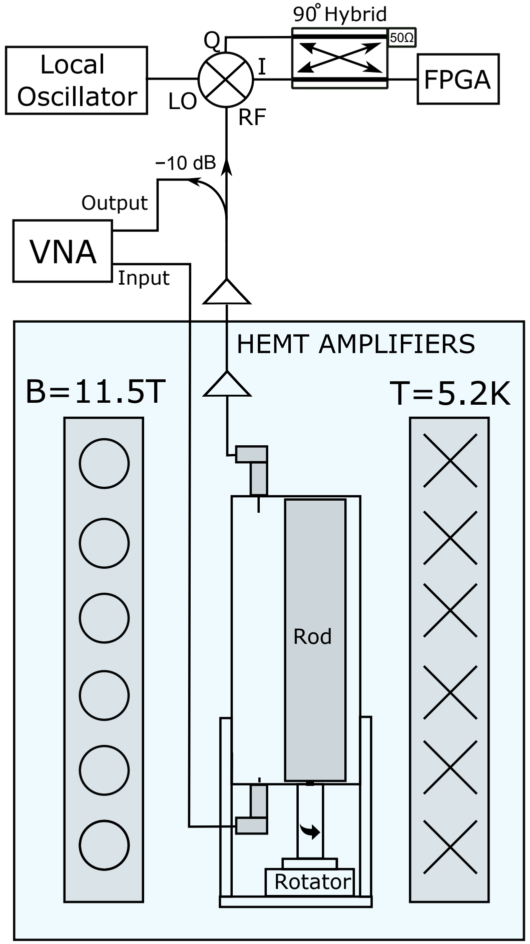
Sweep VNA for

Set demodulation



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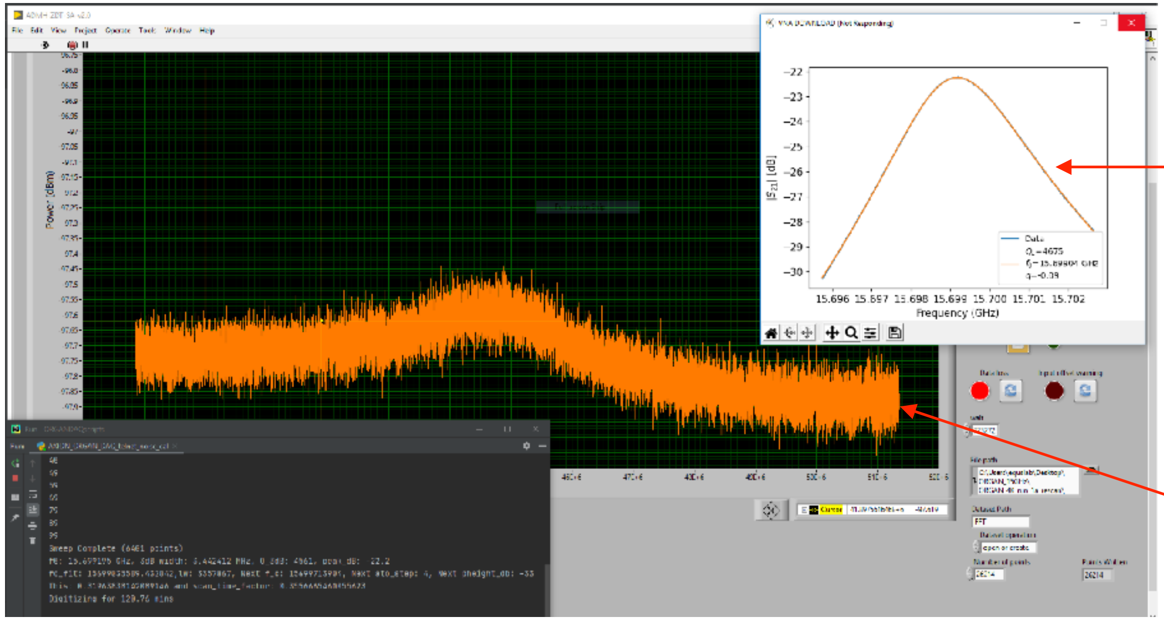

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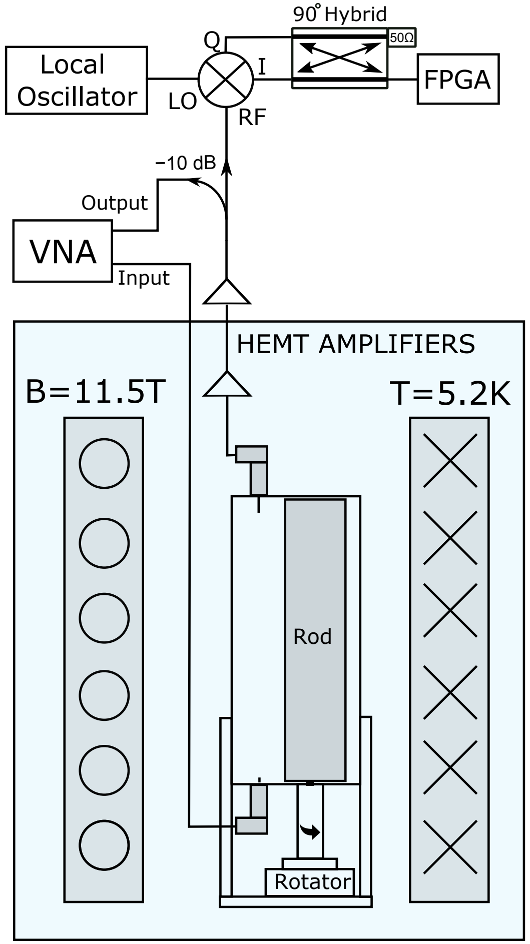

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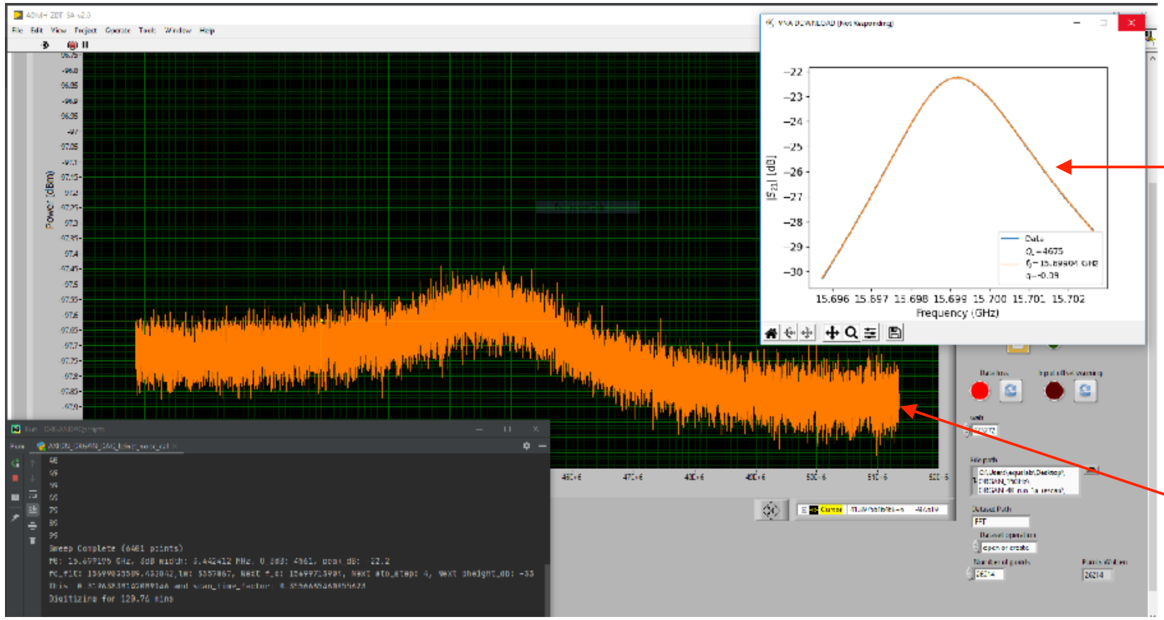

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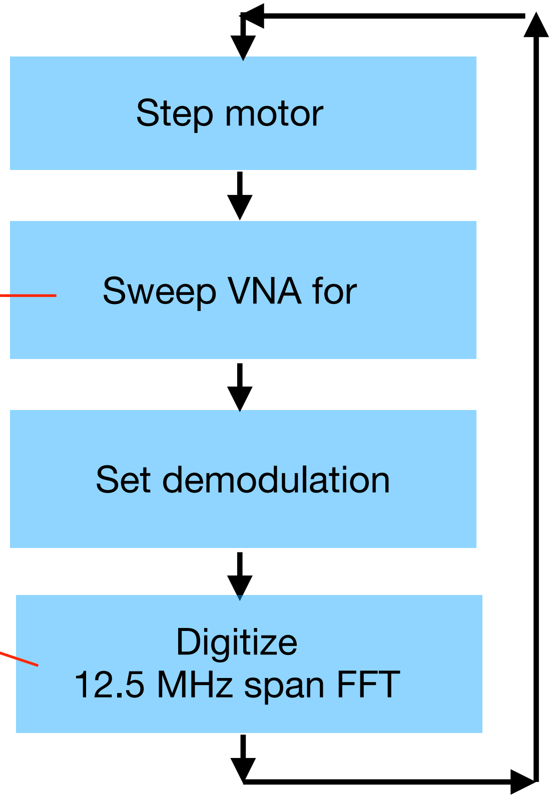

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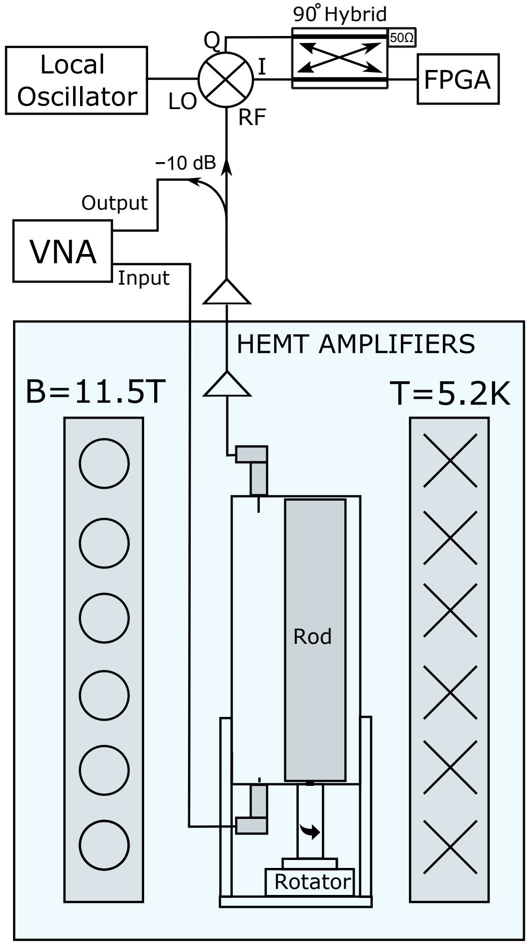

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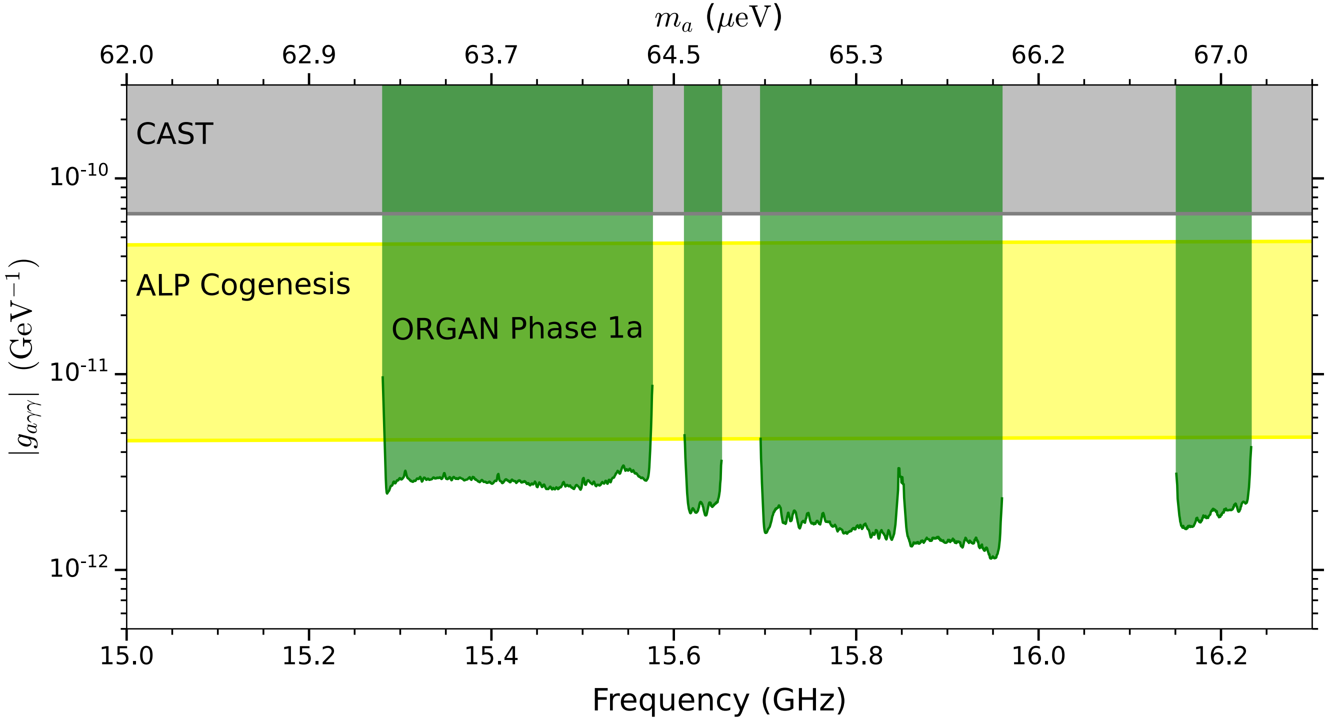

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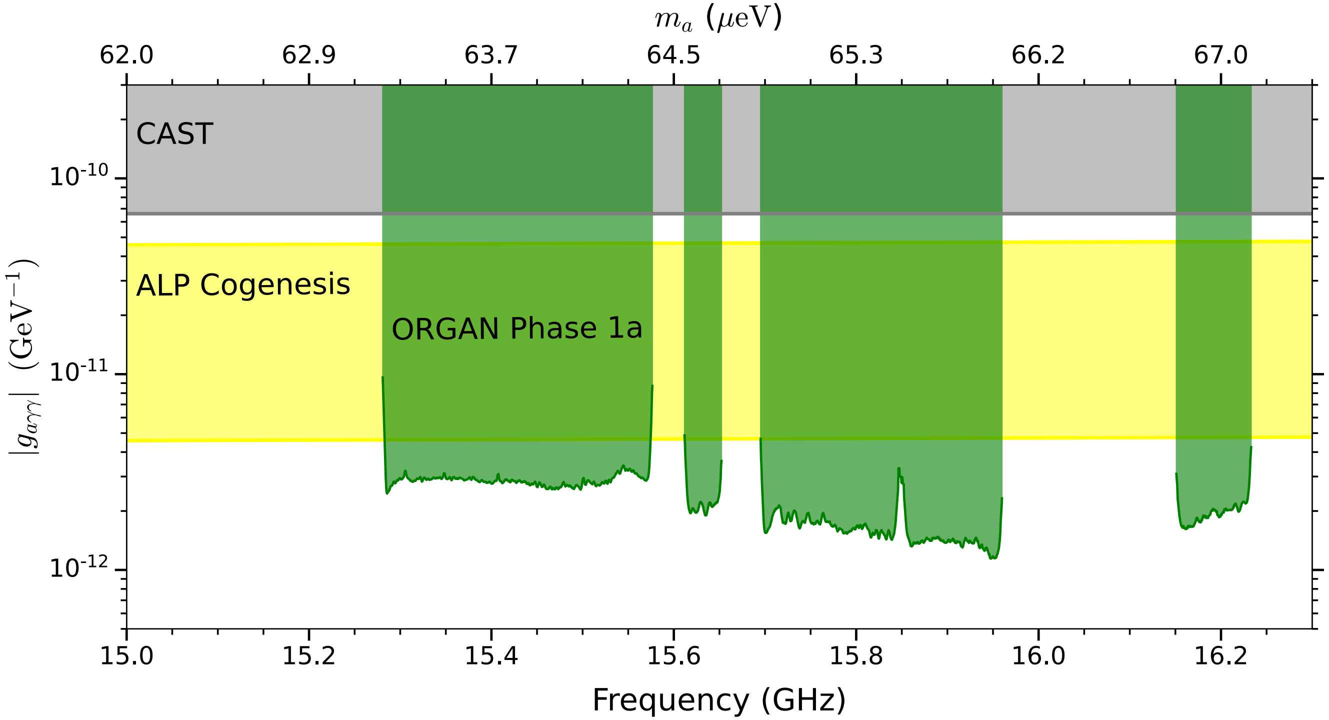

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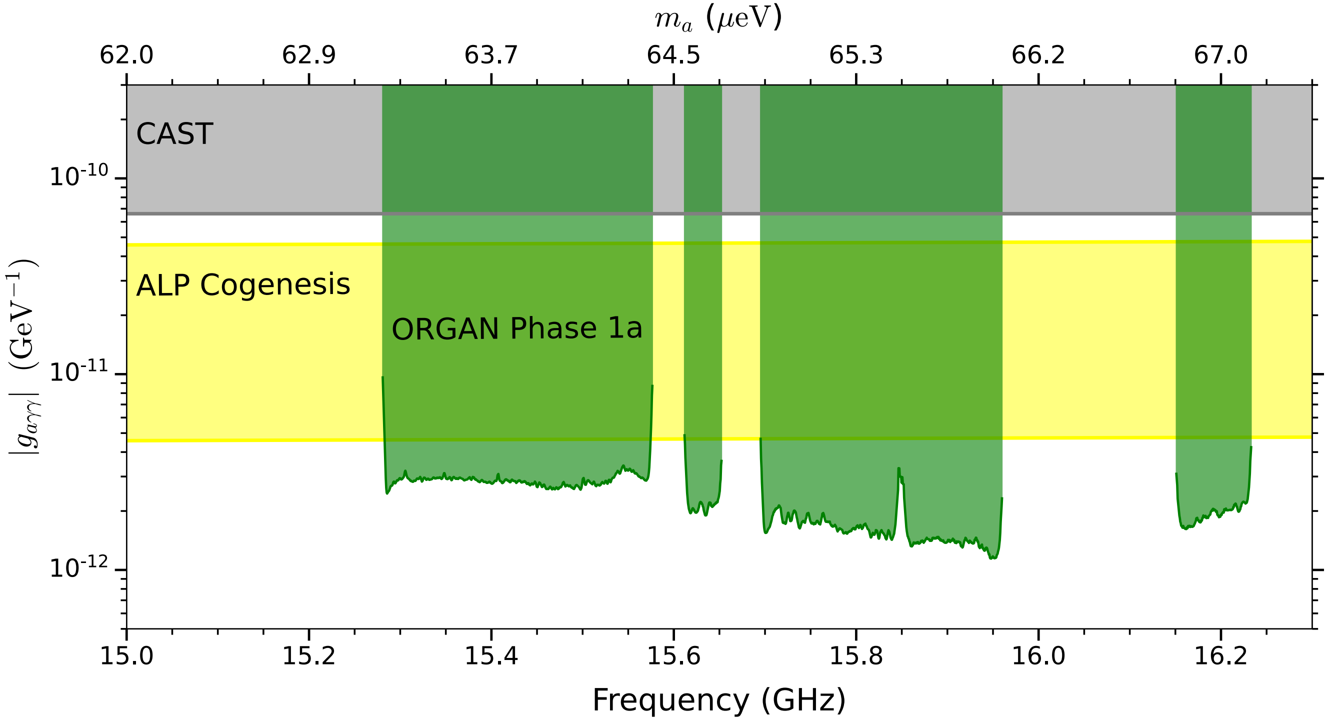

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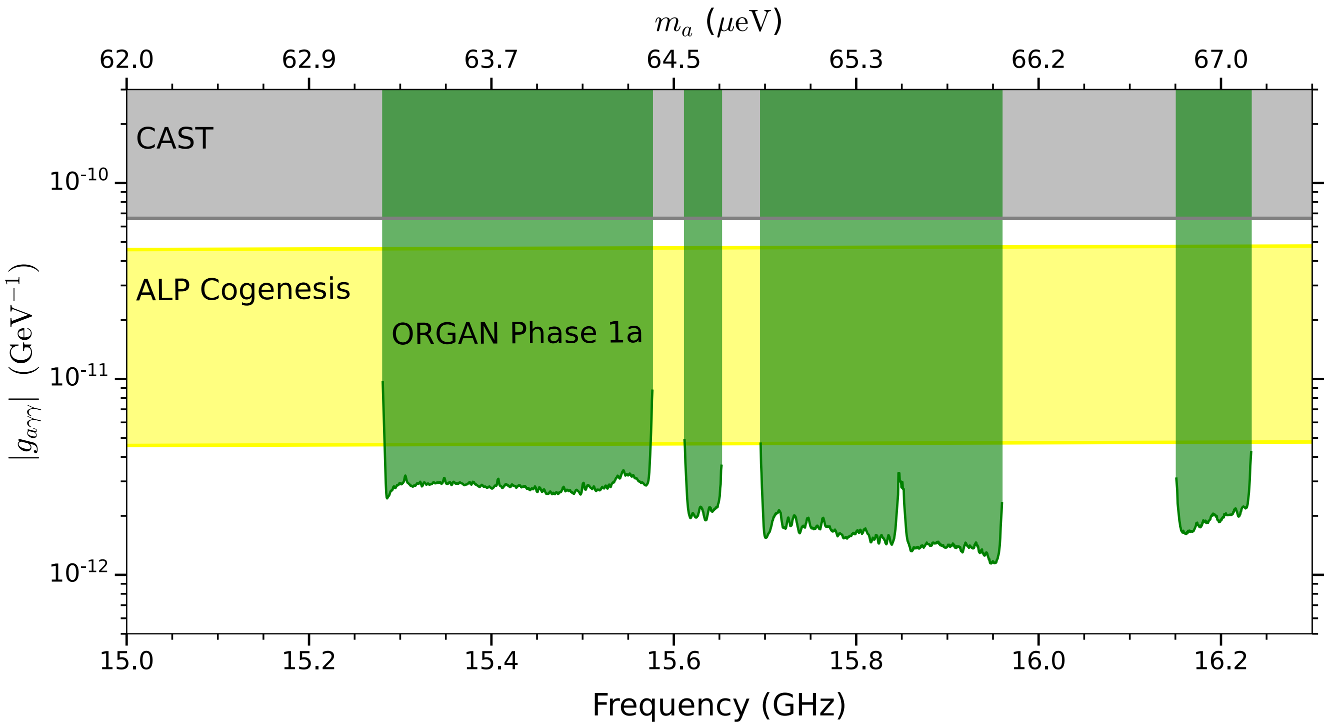
PHYSICS

**Direct search for dark matter axions excluding ALP cogenesis in the 63- to 67-μeV range with the ORGAN experiment**

**Aaron Quiskamp[1]*, Ben T. McAllister[1,2]*, Paul Altin[3], Eugene N. Ivanov[1], Maxim Goryachev[1], Michael E. Tobar[1]***



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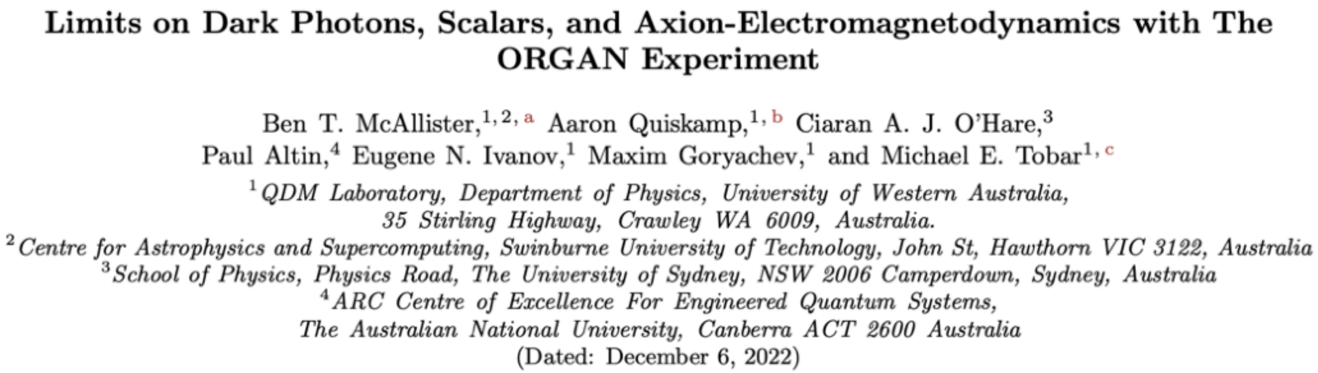

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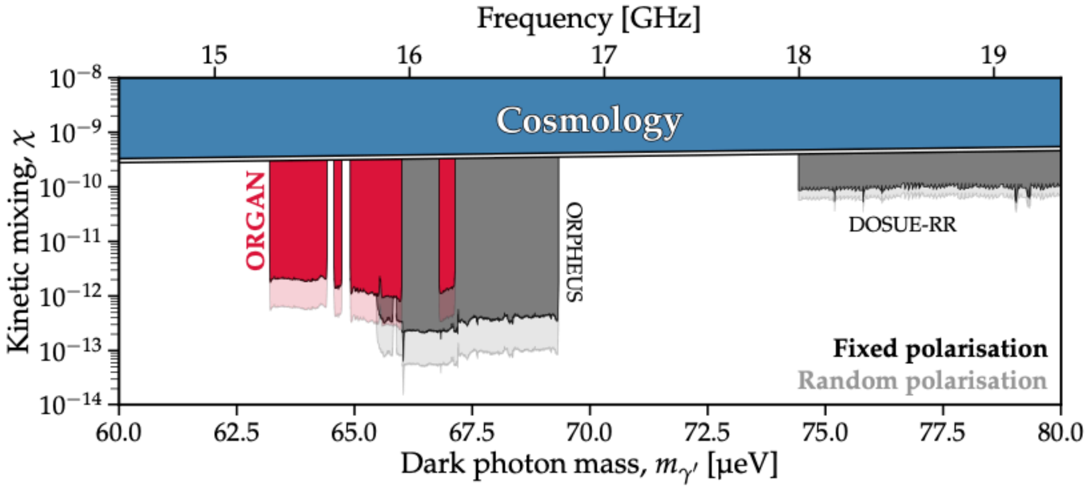
[1] *QDM Laboratory, Department of Physics, University of Western Australia,*
*35 Stirling Highway, Crawley WA 6009, Australia.*
[2] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn VIC 3122, Australia*
[3] *School of Physics, Physics Road, The University of Sydney, NSW 2006 Camperdown, Sydney, Australia*
[4] *ARC Centre of Excellence For Engineered Quantum Systems,*
*The Australian National University, Canberra ACT 2600 Australia*
(Dated: December 6, 2022)



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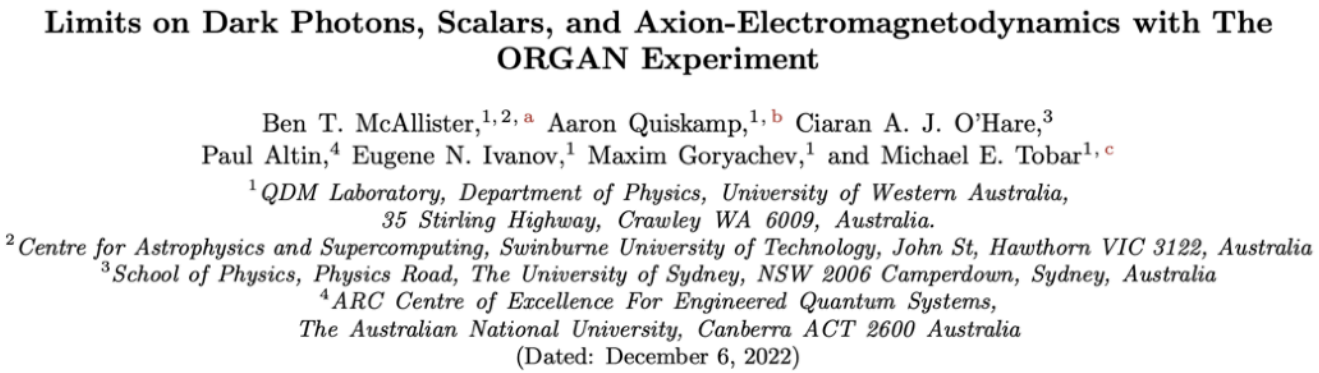
- Placing limits ‘for free’ on other dark matter candidates

- Dark photons convert to detectable photons



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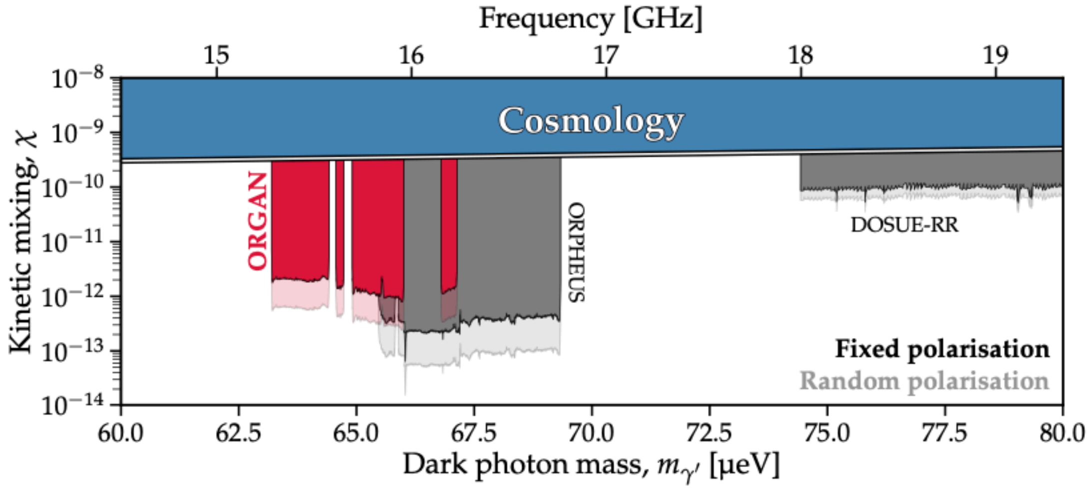

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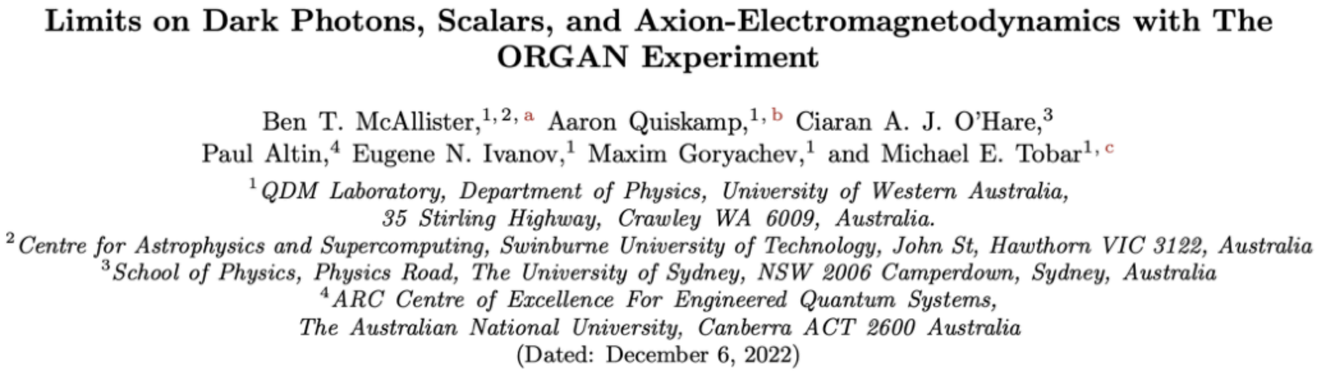
- Placing limits ‘for free’ on other dark matter candidates
- Dark photons convert to detectable photons
- Simple scaling of Axion limits to Dark Photon limits



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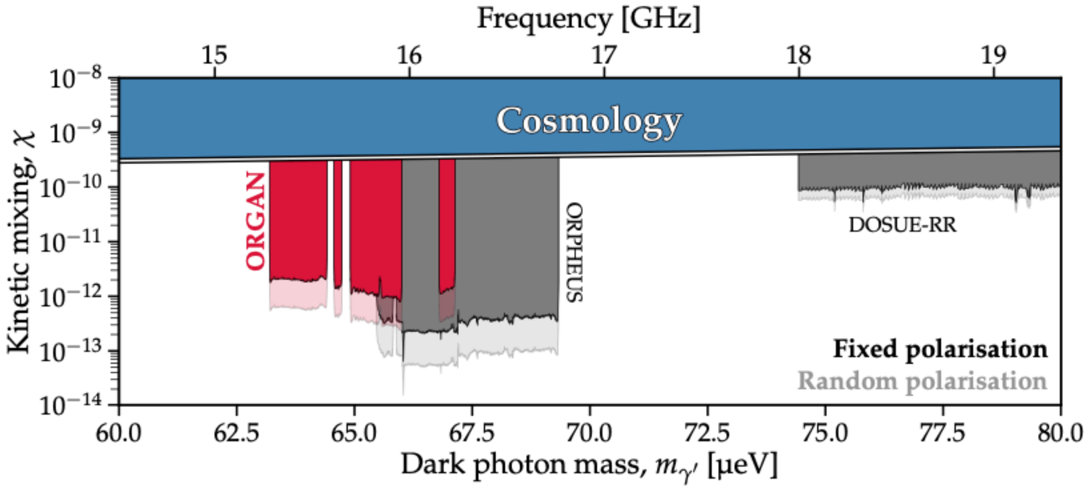
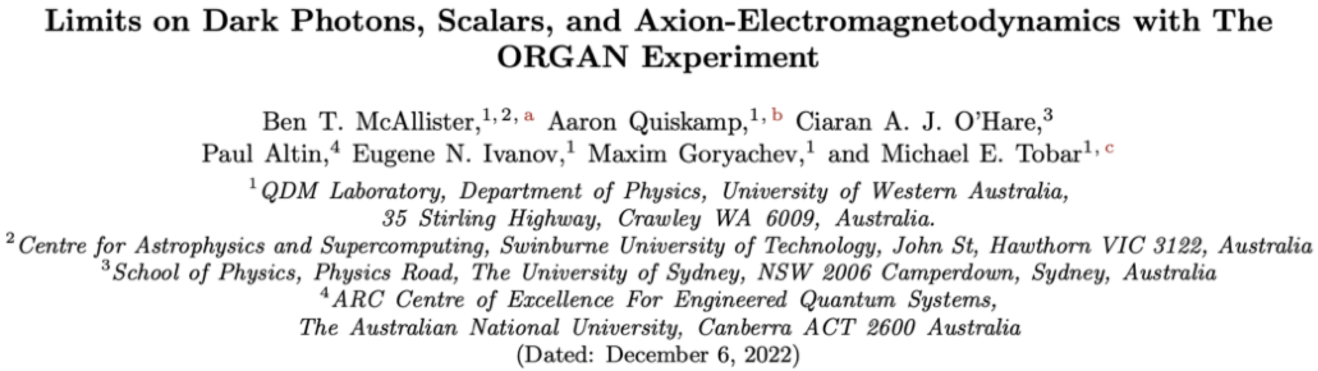
[4] *ARC Centre of Excellence For Engineered Quantum Systems,*
*The Australian National University, Canberra ACT 2600 Australia*
(Dated: December 6, 2022)



# Limits on other Dark Matter Candidates

- Placing limits ‘for free’ on other dark matter candidates
- Dark photons convert to detectable photons
- Simple scaling of Axion limits to Dark Photon limits
- **B-field** non-uniformity -> scalar dark matter (eg. dilaton) limits can also be placed



**Limits on Dark Photons, Scalars, and Axion-Electromagnetodynamics with The ORGAN Experiment**

Ben T. McAllister,[1,2,a] Aaron Quiskamp,[1,b] Ciaran A. J. O'Hare,[3]
Paul Altin,[4] Eugene N. Ivanov,[1] Maxim Goryachev,[1] and Michael E. Tobar[1,c]

[1] *QDM Laboratory, Department of Physics, University of Western Australia,*
*35 Stirling Highway, Crawley WA 6009, Australia.*
[2] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, John St, Hawthorn VIC 3122, Australia*
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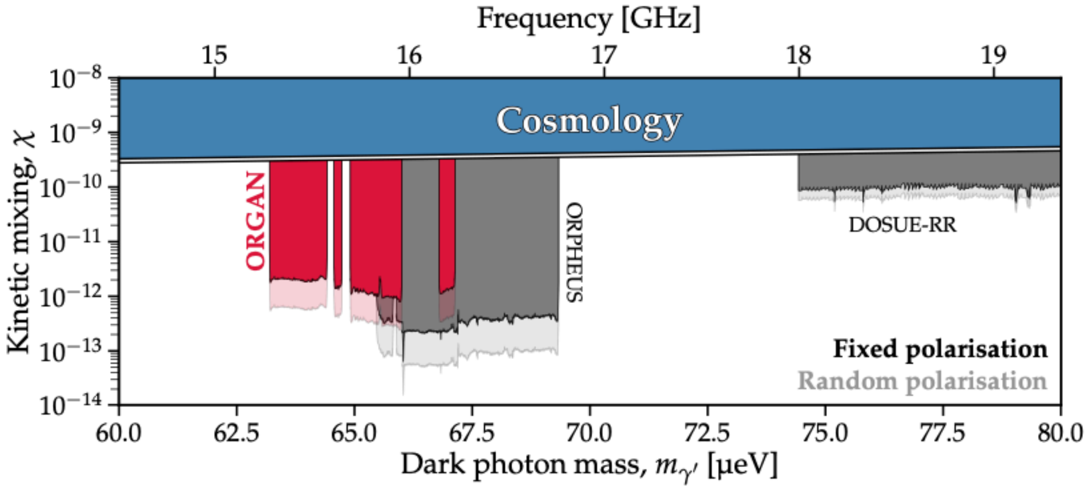


Череп Гребенчатого крокодила
Crocodylus porosus Schneid.
Судя по величине принадлежал крокодилу длиной около 5 м.


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~1 death/year :-(

# Phase 1b

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- Targeted search between ~26-27GHz

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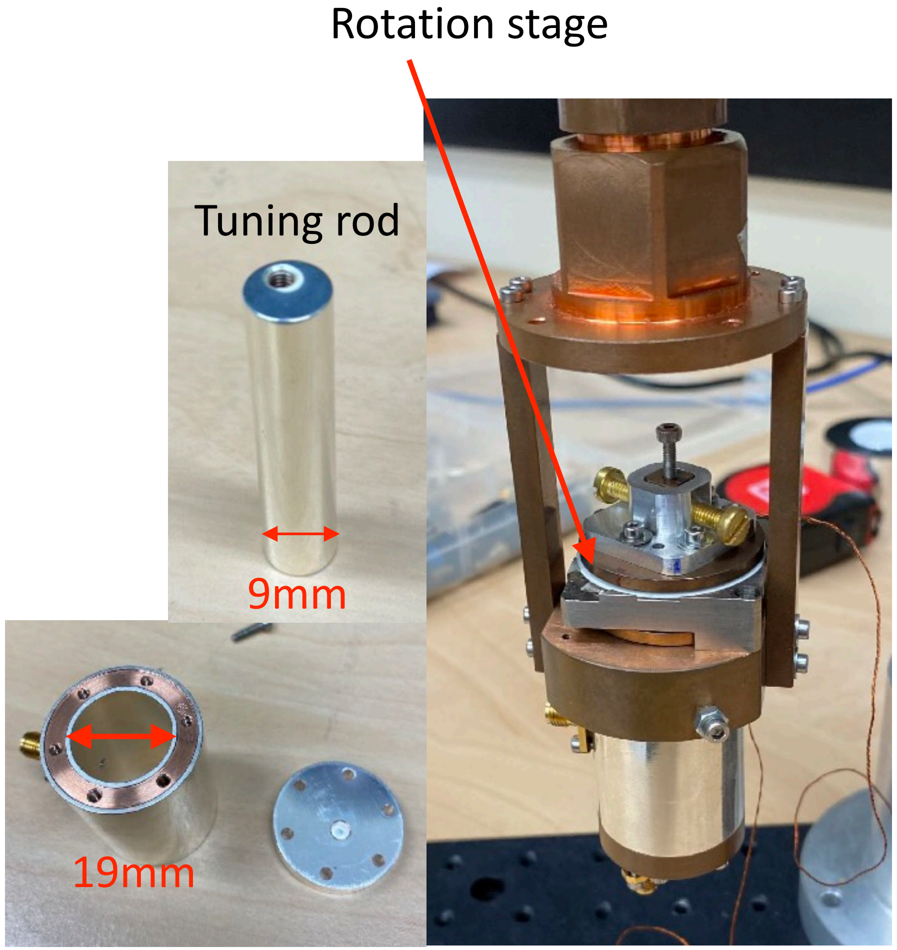
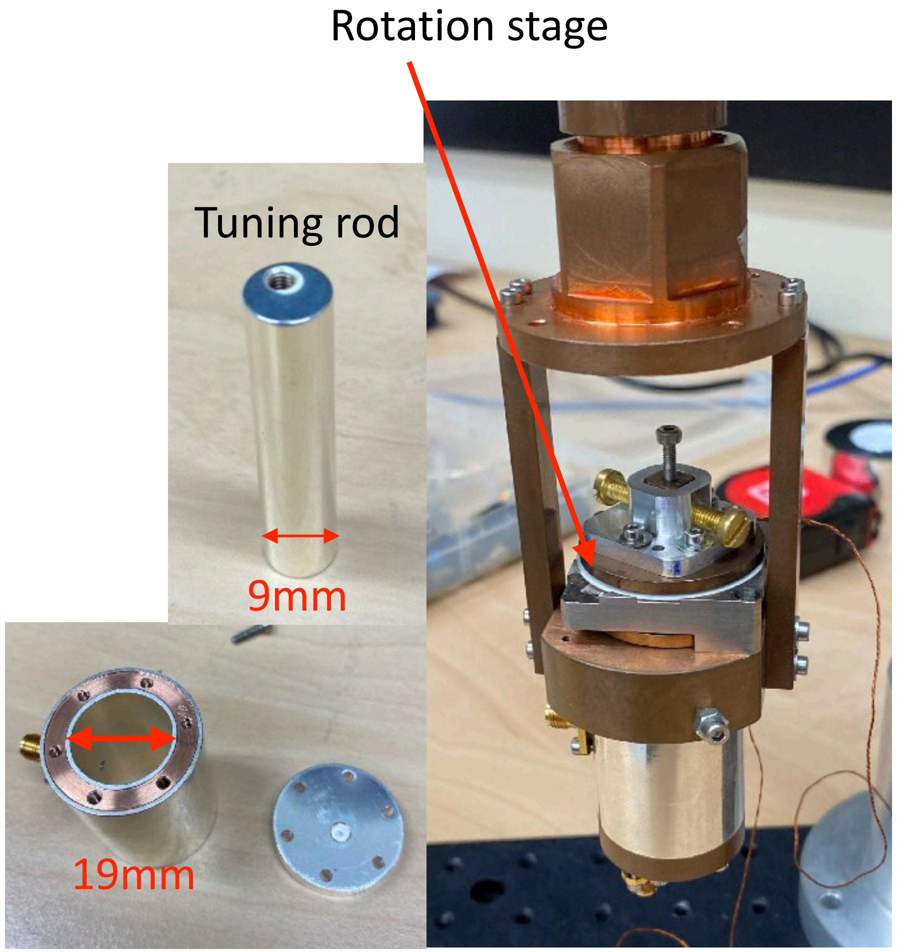
- Length scale ~45% smaller than phase 1a



26GHz tuning-rod resonator

# Phase 1b

- Targeted search between ~26-27GHz
- Length scale ~45% smaller than phase 1a
- High frequency is difficult —> Resonator is **<u>necessarily</u>** small
- Relative tolerances are much bigger



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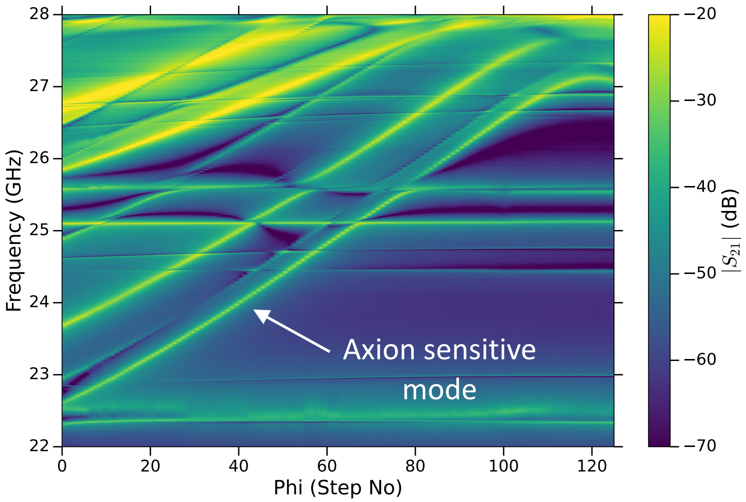

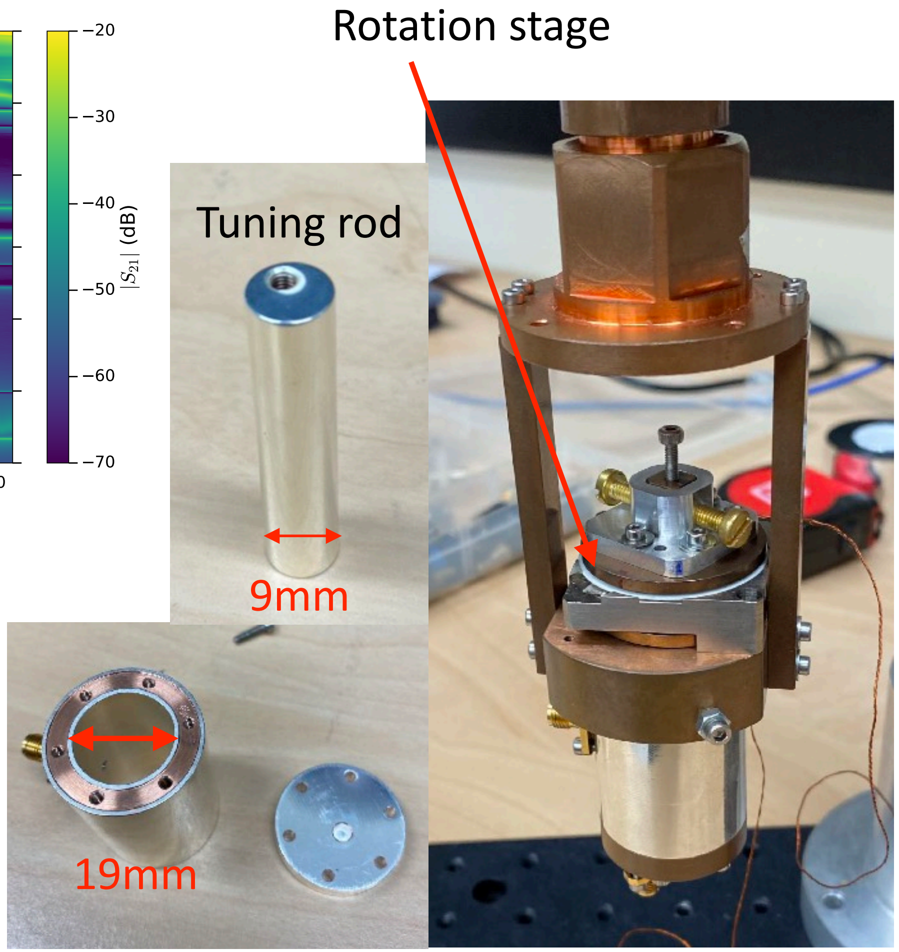

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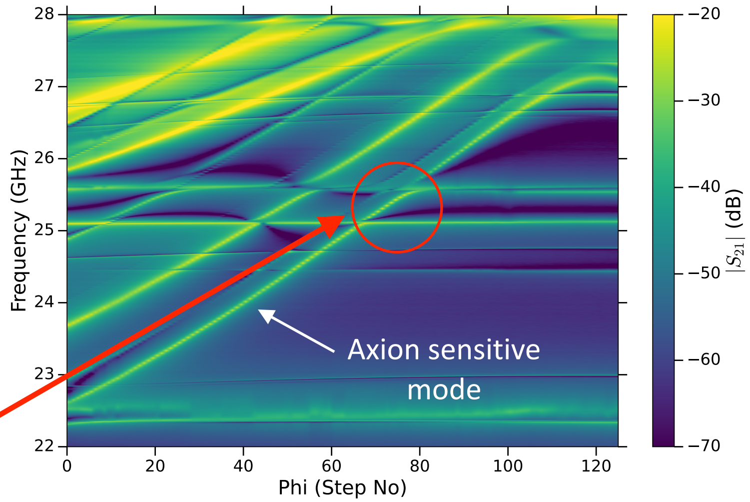

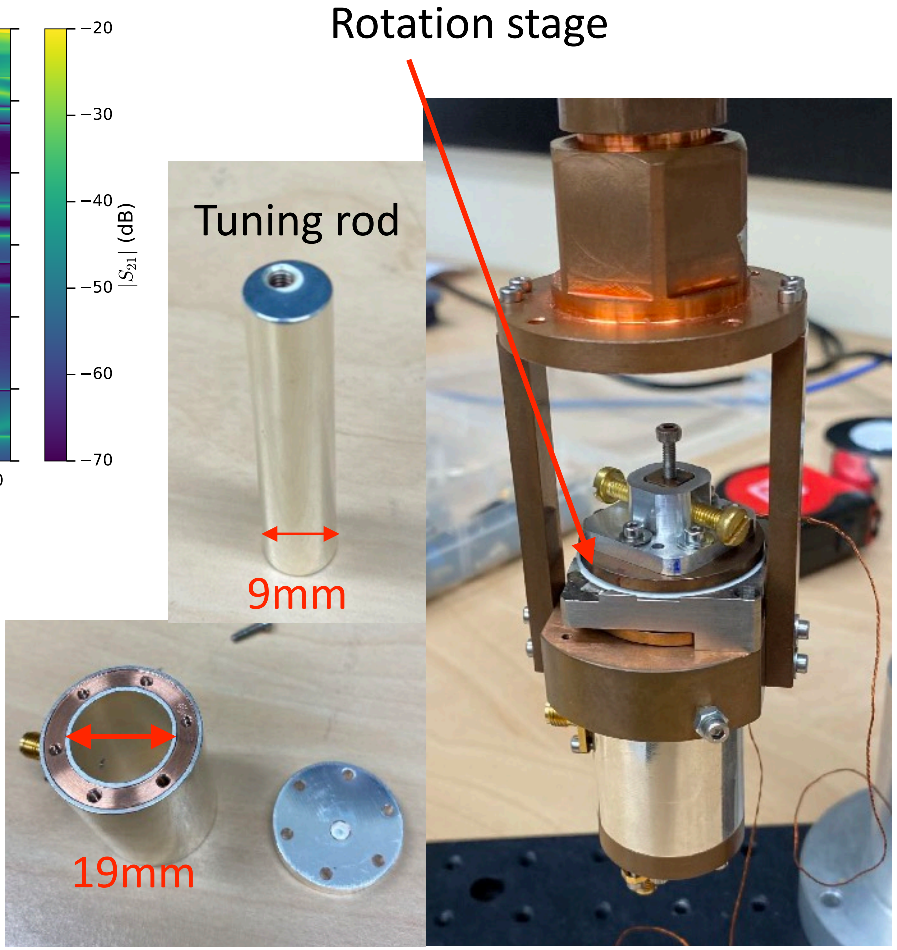

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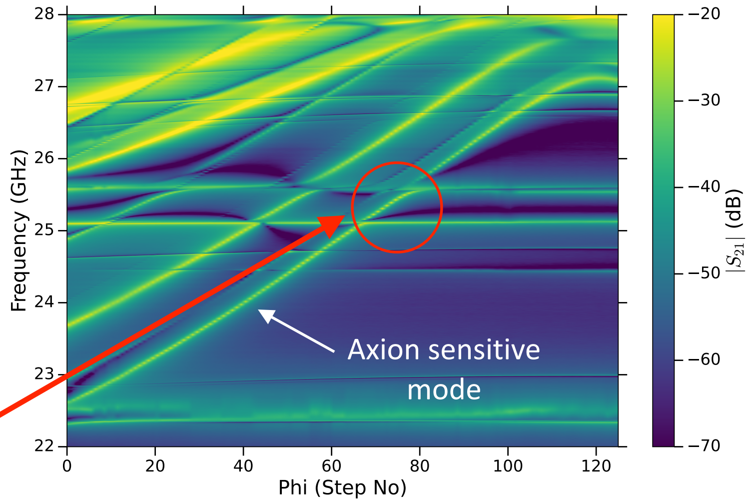

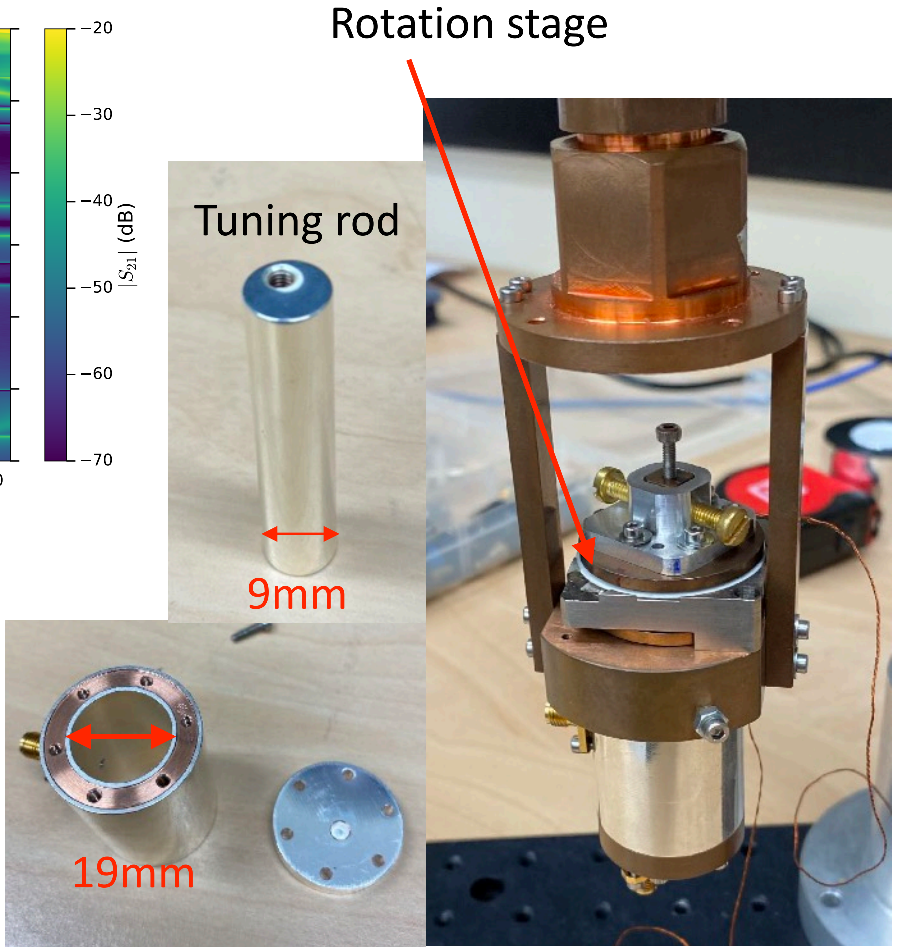

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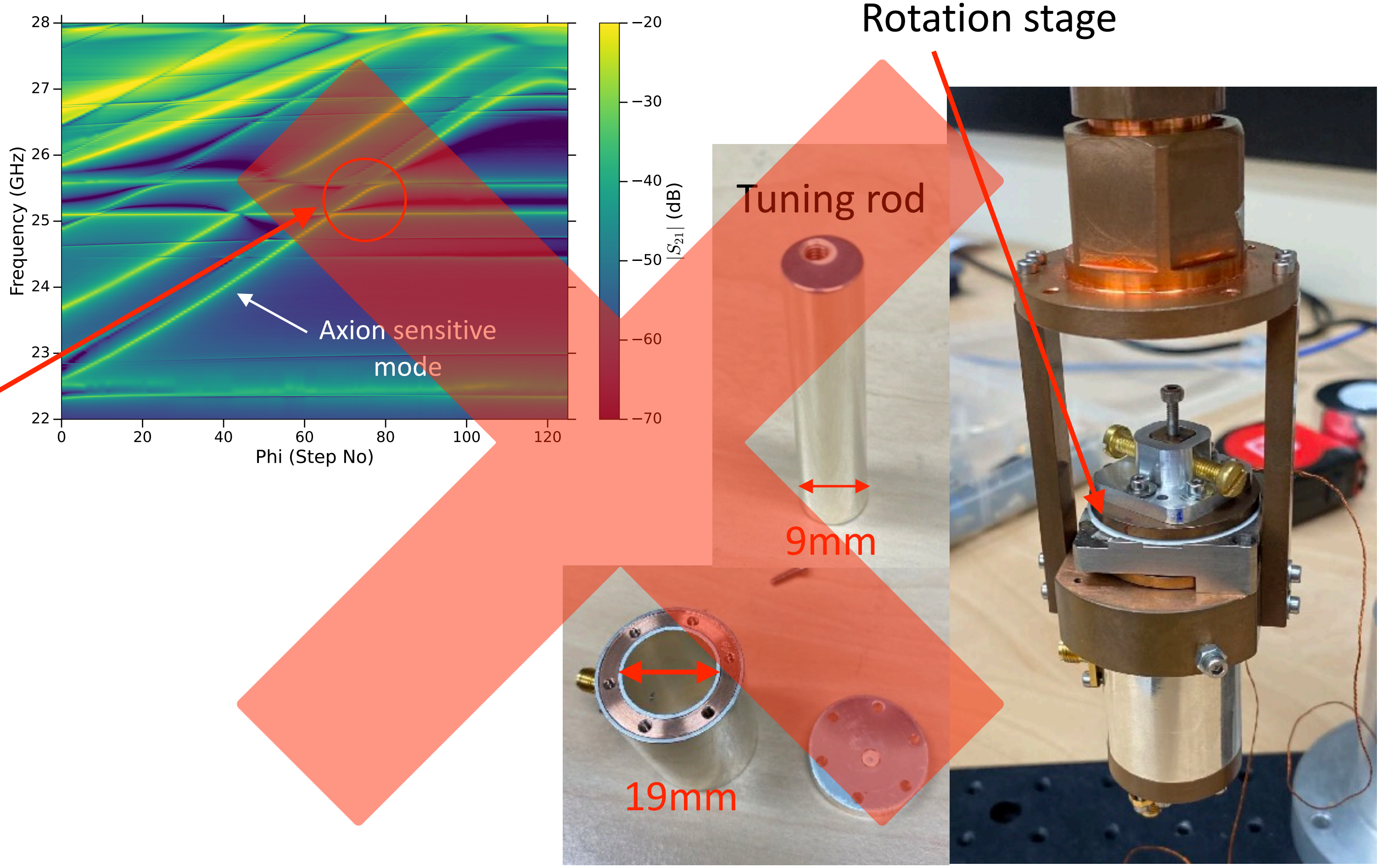
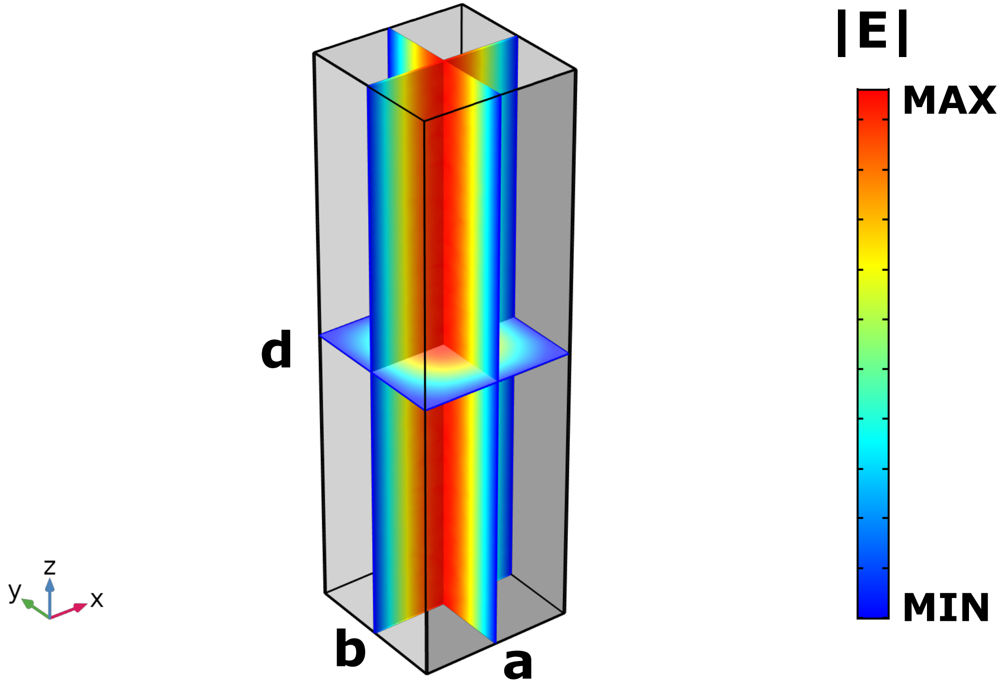
- Greater number of mode crossings
- Extremely sensitive to alignment and rod tilt -> <u>couldn't set antenna coupling reliably</u>
- **Novel high frequency resonator designs are needed!**



26GHz tuning-rod resonator

# Phase 1b

- New tunable rectangular cavity solves many problems!



Tunable rectangular resonant cavities for axion haloscopes

Ben T. McAllister, Aaron P. Quiskamp, and Michael E. Tobar
Phys. Rev. D **109**, 015013 – Published 16 January 2024

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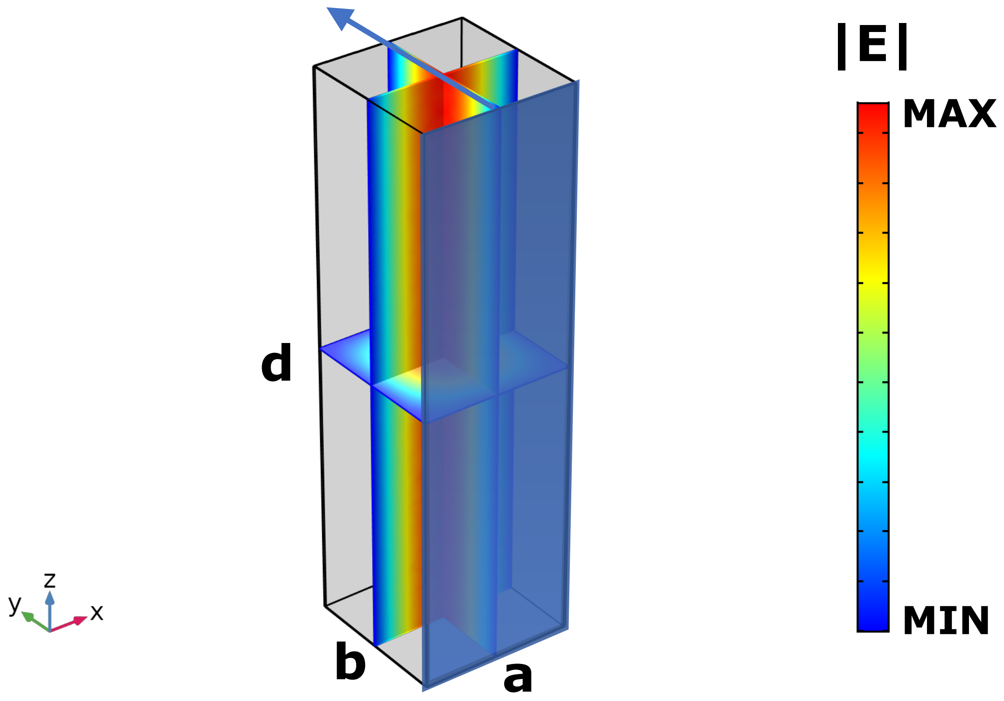

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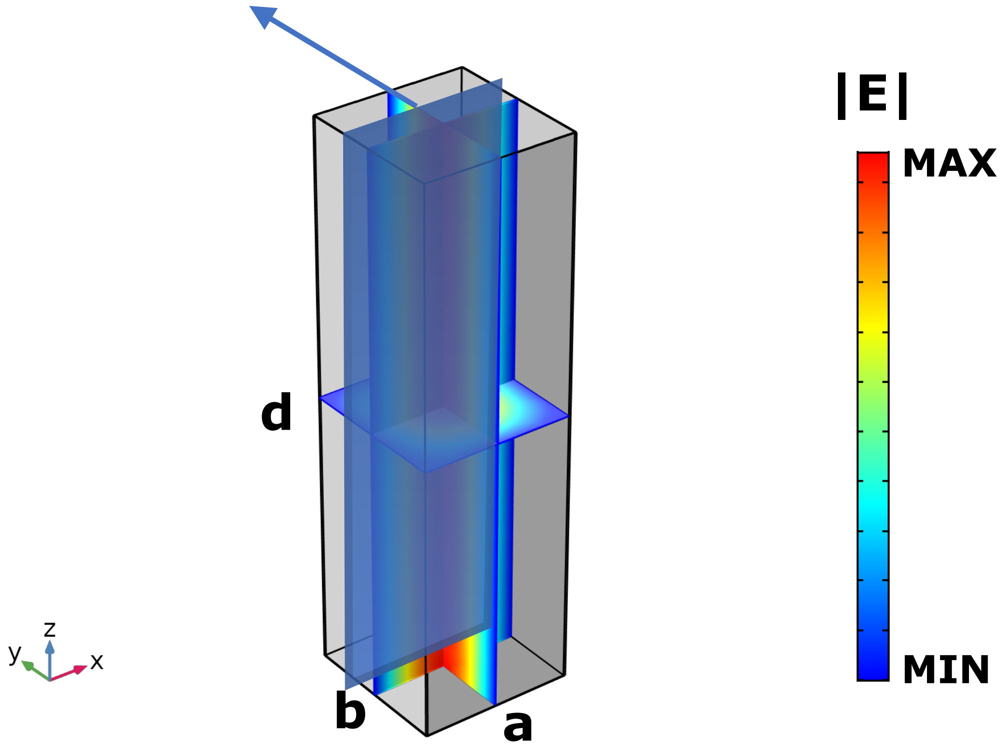

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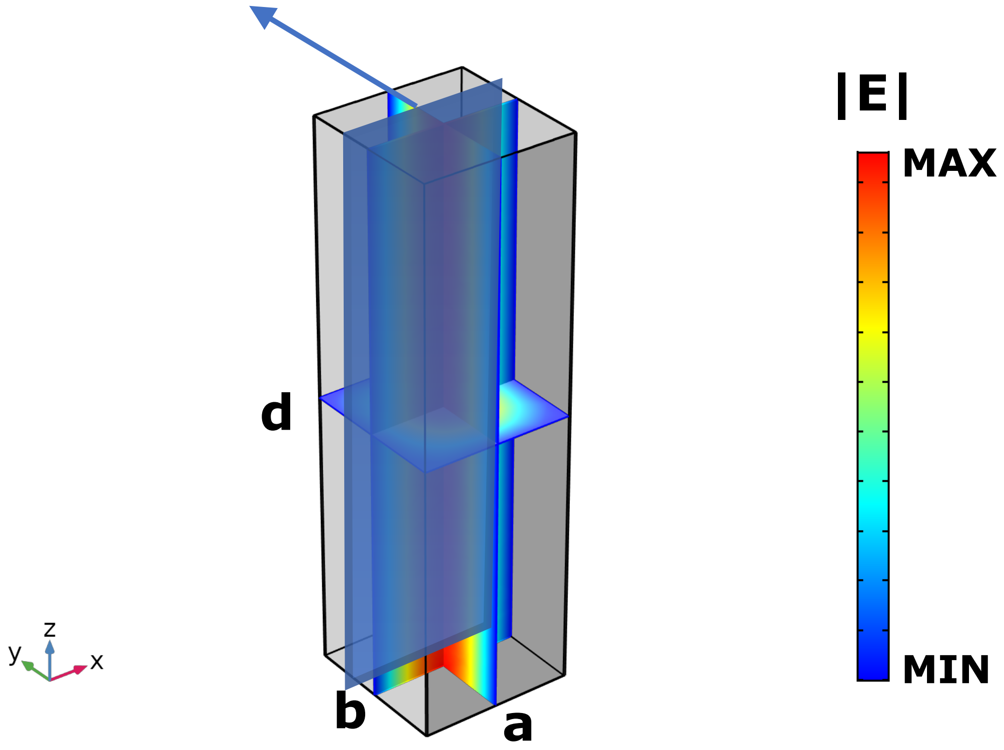
| Parameter | Tuning-rod cavity | Rectangular cavity |
|---|---|---|
| *C* | ❌ | ✅ |



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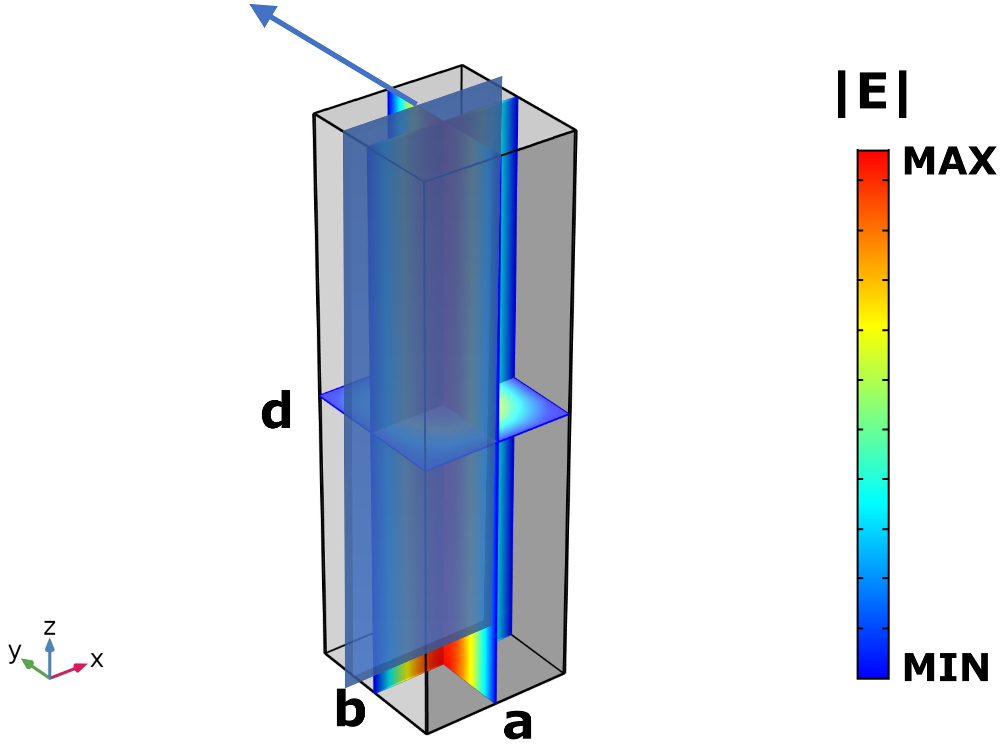
| *Q* | ❌ | ✅ |



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ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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|---|---|---|
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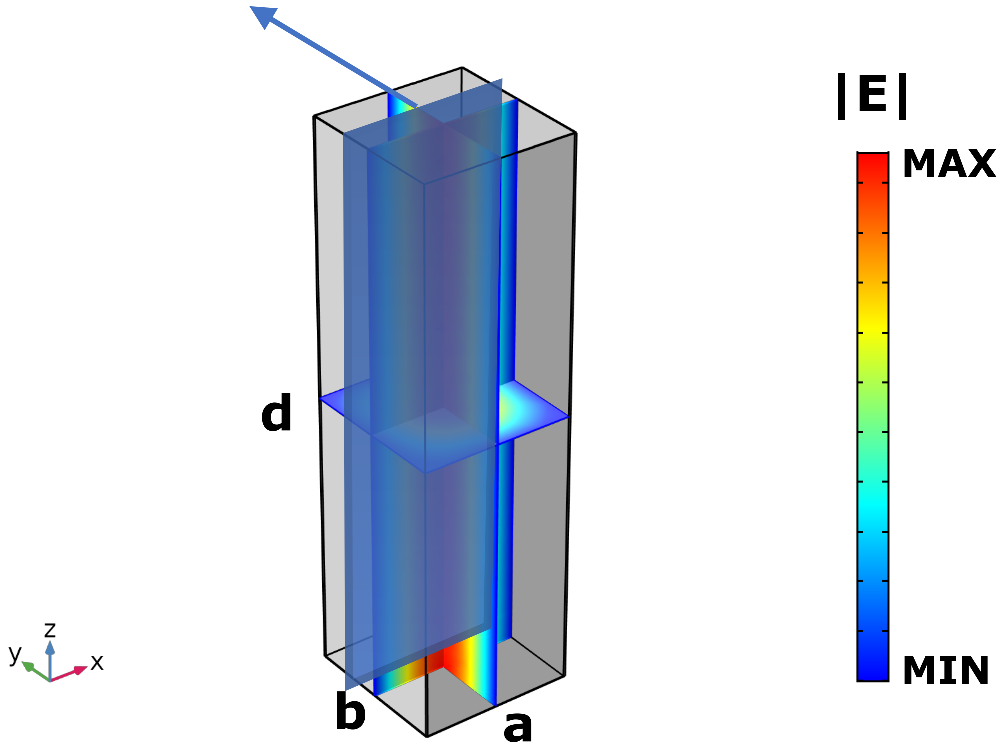
| *Q* | ❌ | ✅ |
| *V* | ✅ | ❌ |



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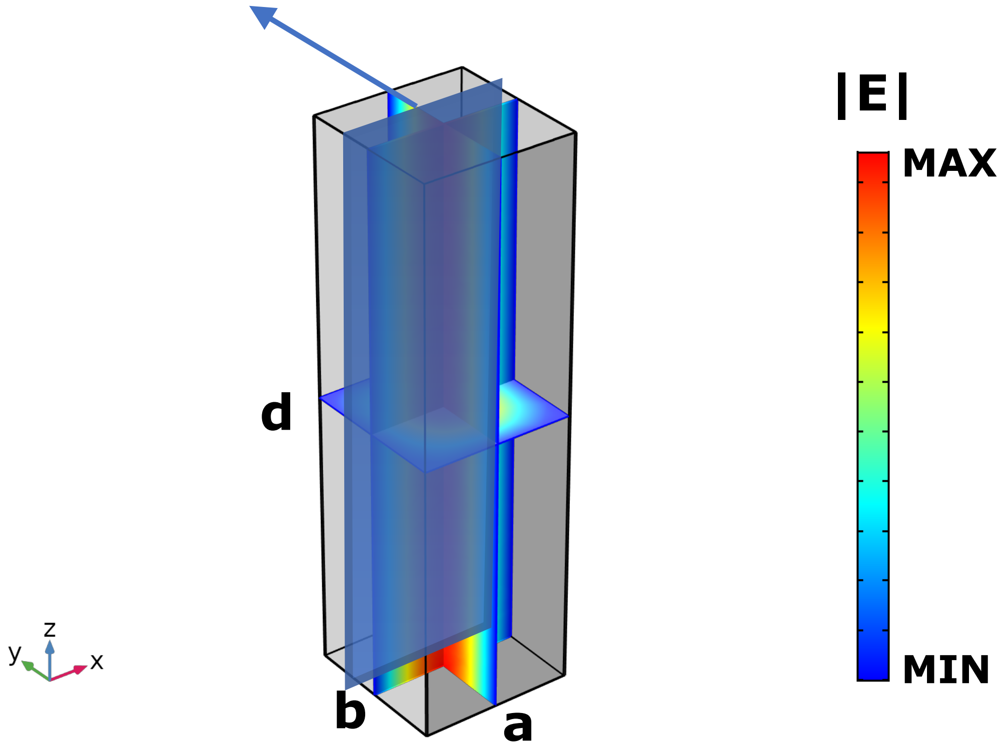
| *Q* | ❌ | ✅ |
| *V* | ✅ | ❌ |
| Mode crossings | ❌ | ✅ |



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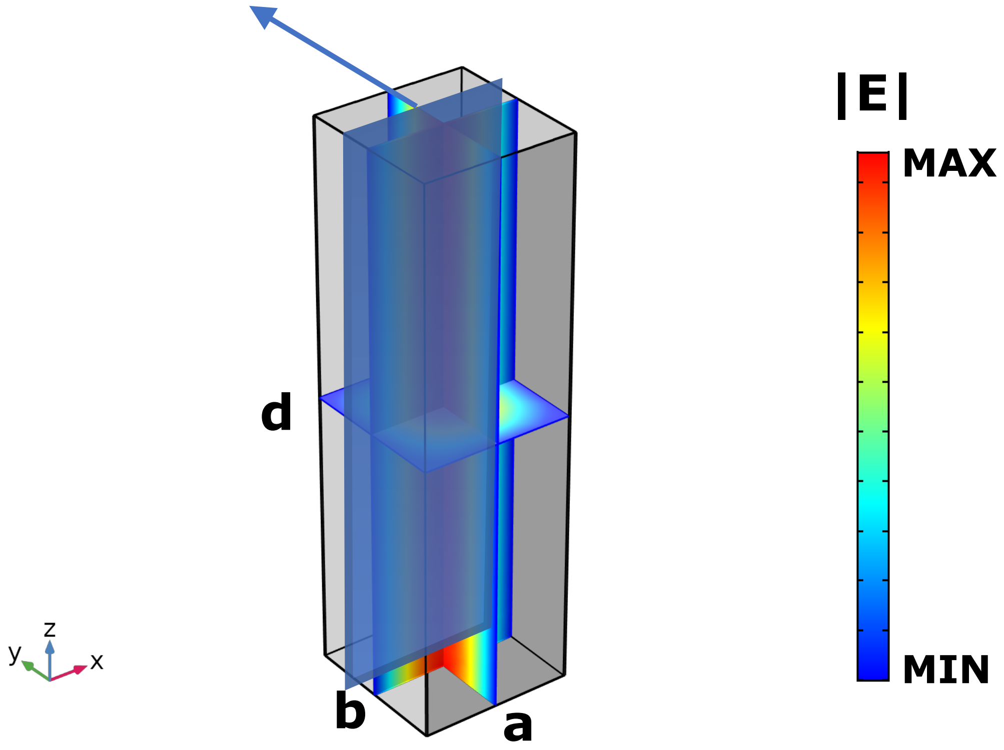
| *Q* | ✗ | ✓ |
| *V* | ✓ | ✗ |
| Mode crossings | ✗ | ✓ |
| Bore utilisation | ✓ | ✗ |



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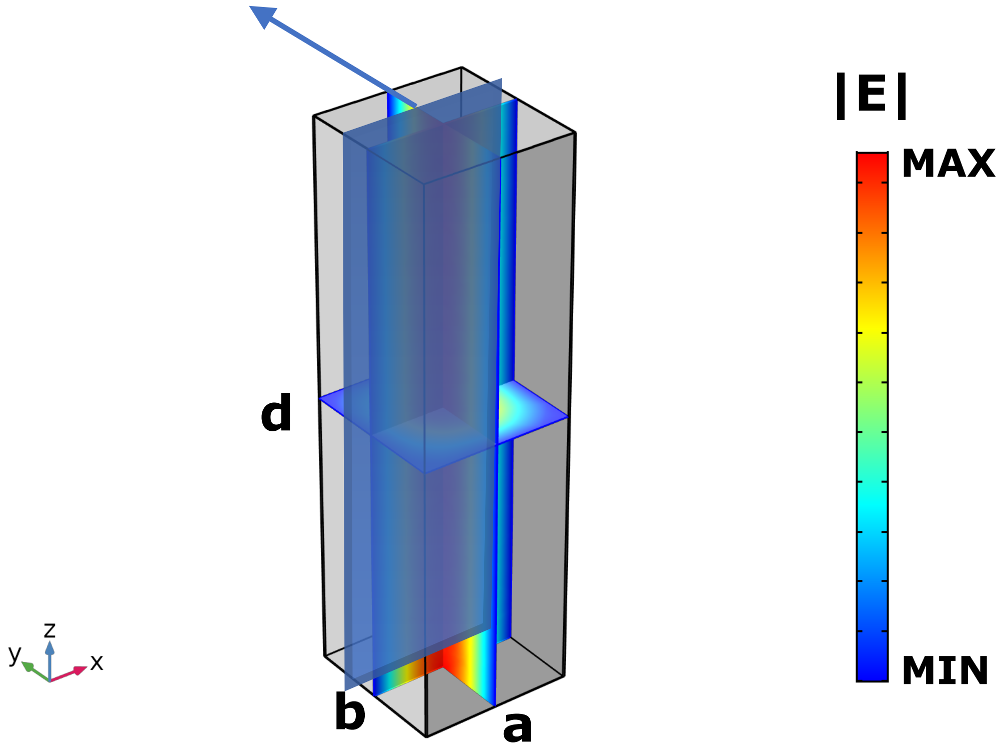
| *V* | ✓ | ✗ |
| Mode crossings | ✗ | ✓ |
| Bore utilisation | ✓ | ✗ |
| Tuning | ✗ | ✓ |



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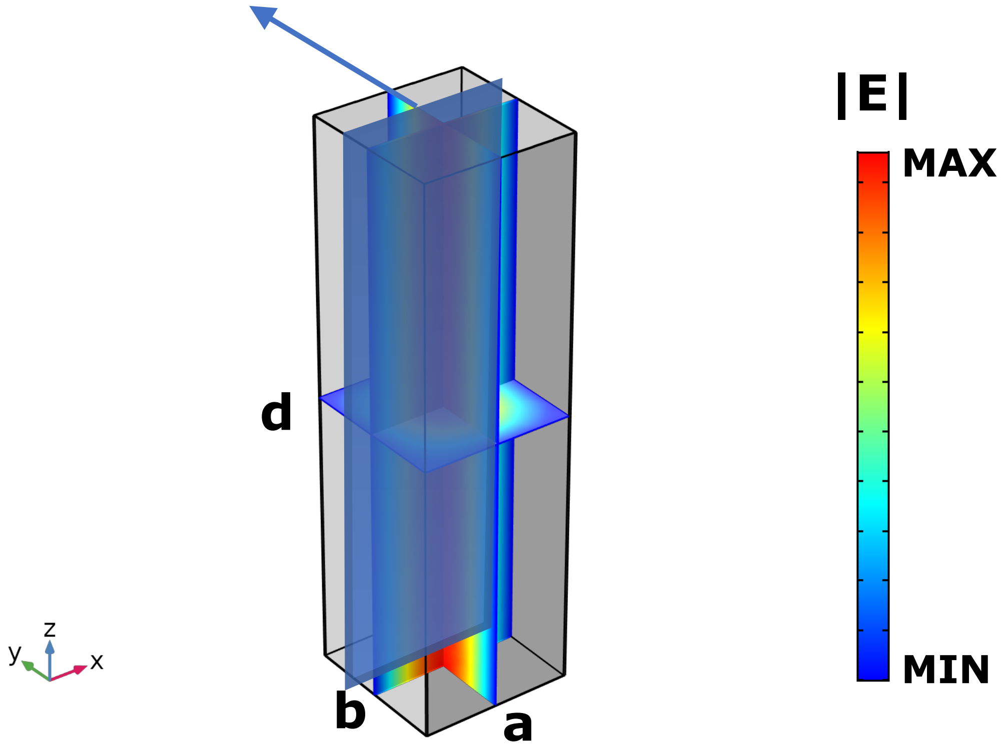
| *Q* | ✗ | ✓ |
| *V* | ✓ | ✗ |
| Mode crossings | ✗ | ✓ |
| Bore utilisation | ✓ | ✗ |
| Tuning | ✗ | ✓ |
| Scan rate | = | =/✓ |



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# Phase 1b

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Exclusion of Axionlike-Particle Cogenesis Dark Matter in a Mass Window above $100\ \mu\text{eV}$

Aaron Quiskamp, Ben T. McAllister, Paul Altin, Eugene N. Ivanov, Maxim Goryachev, and Michael E. Tobar
Phys. Rev. Lett. **132**, 031601 – Published 16 January 2024

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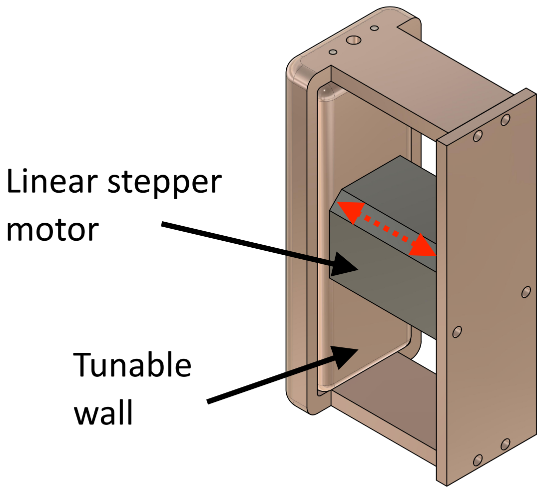
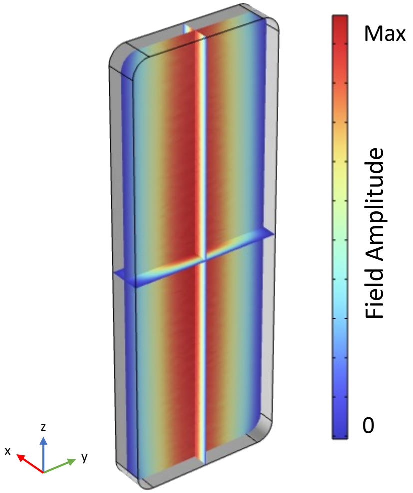
- First search already complete!





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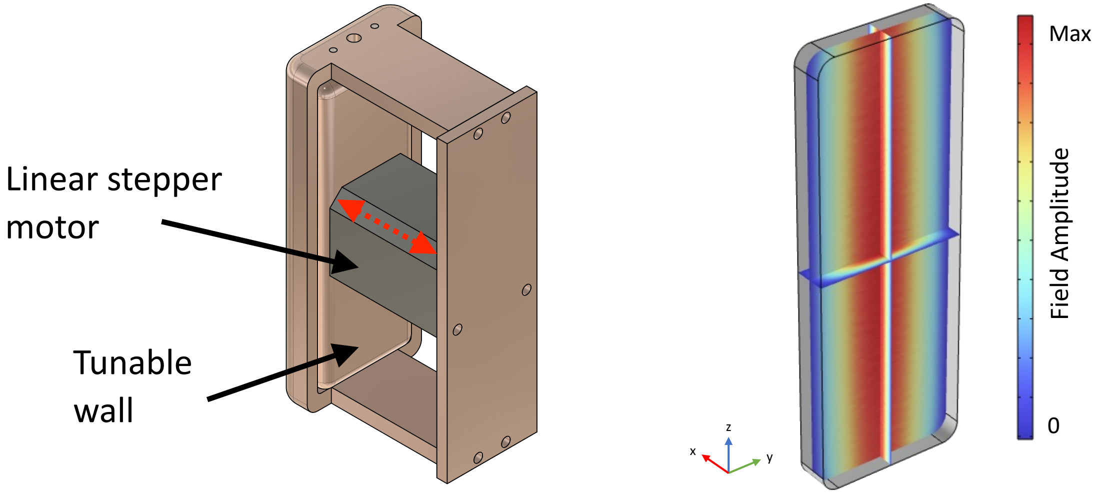
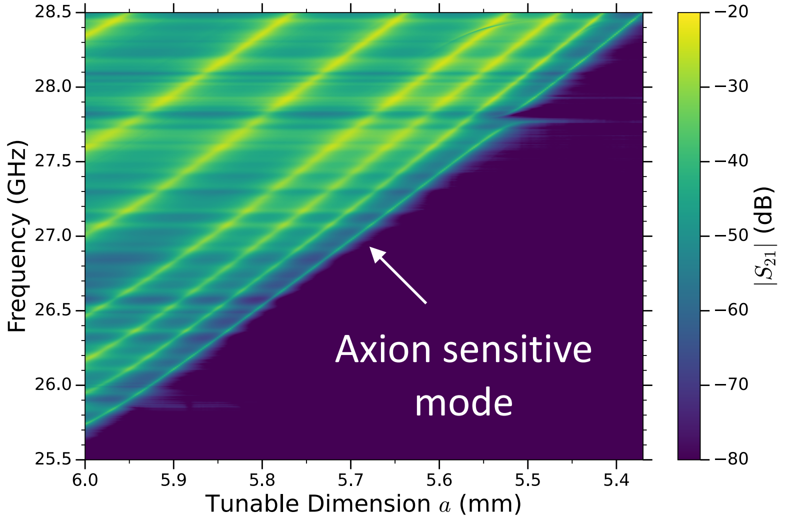
- First search already complete!
- **No** mode crossings in 26-27 GHz target region!





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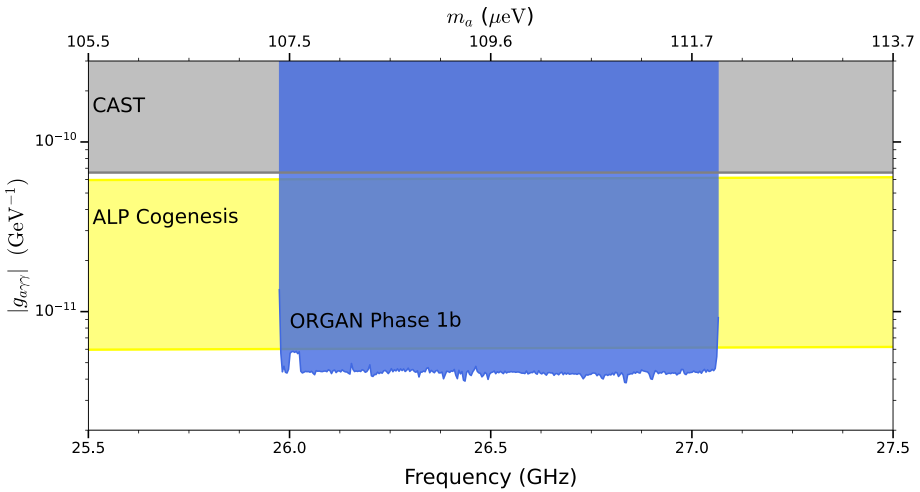
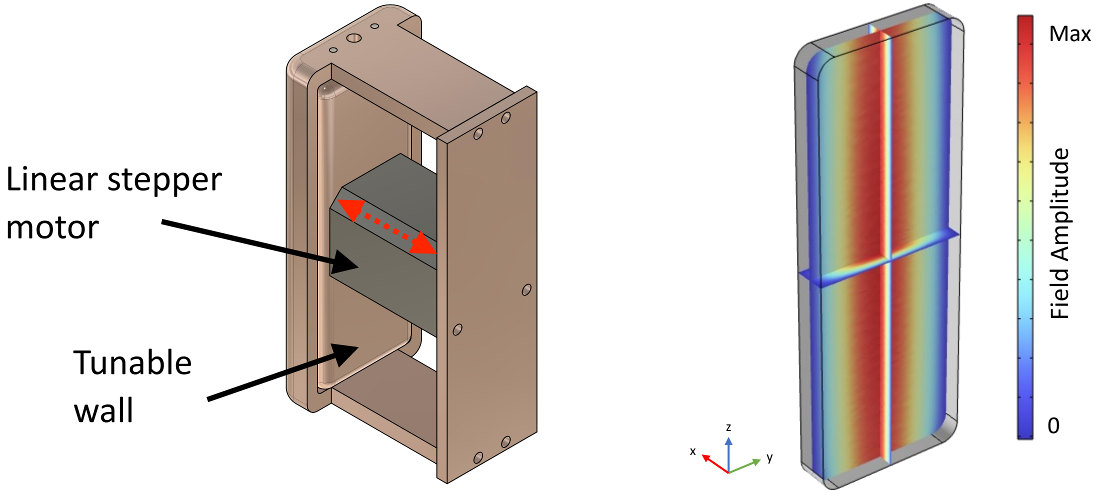
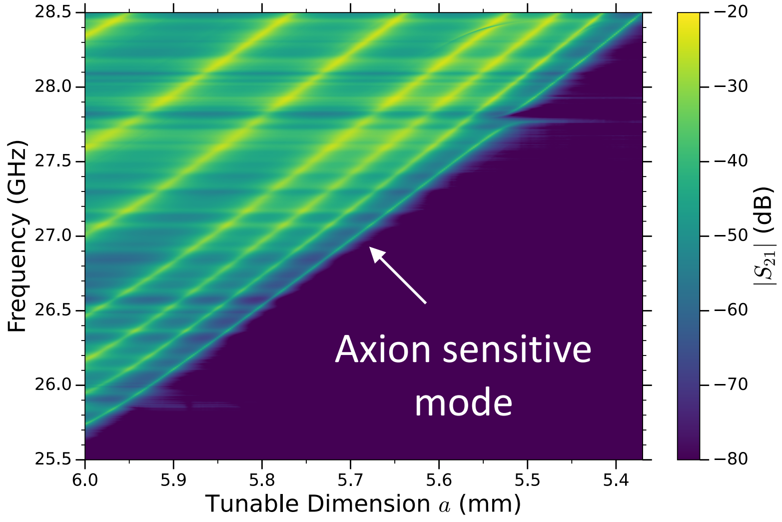
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# Phase 1b

- First search already complete!
- **<u>No</u>** mode crossings in 26-27 GHz target region!
- Most sensitive high mass axion search yet!







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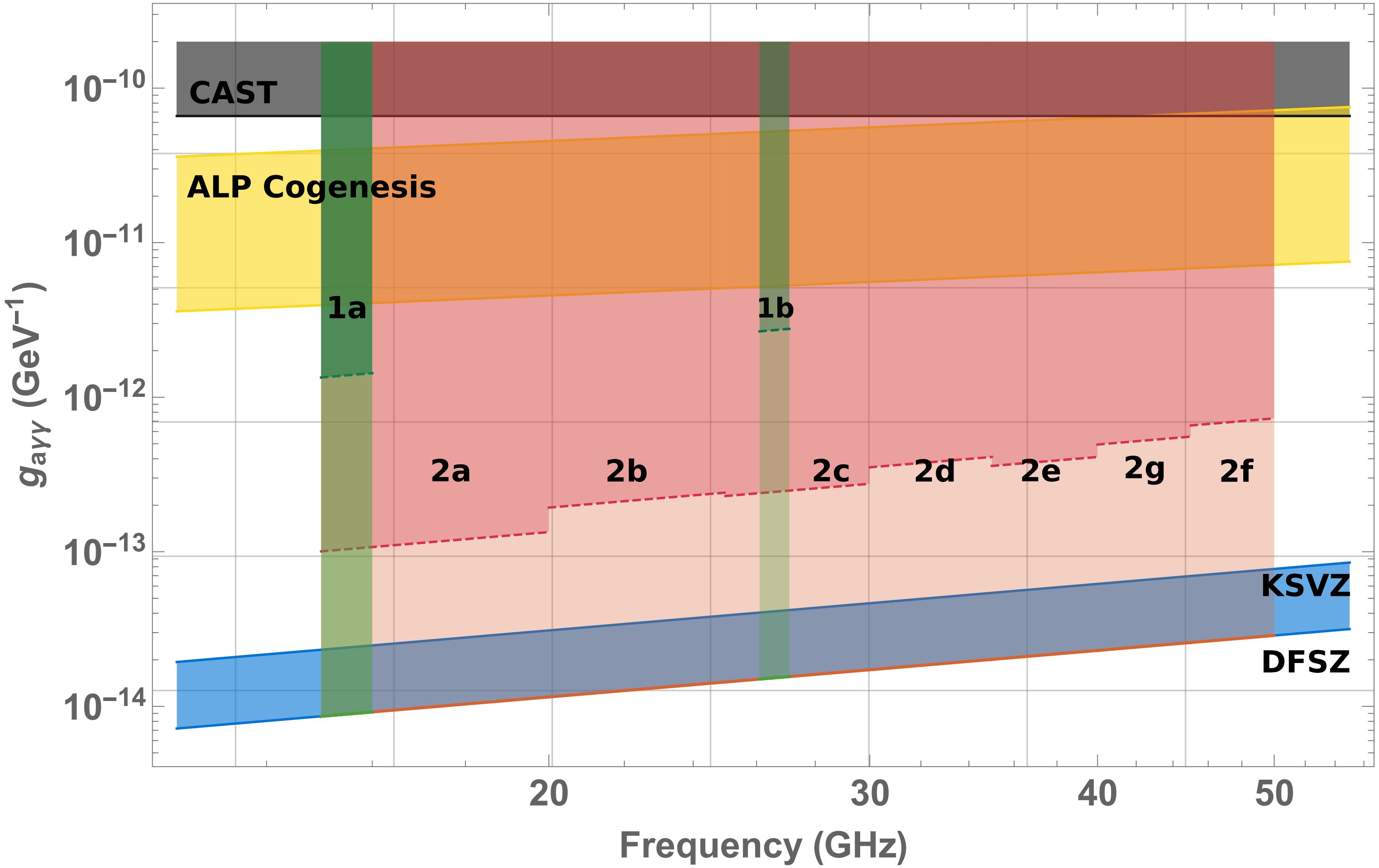
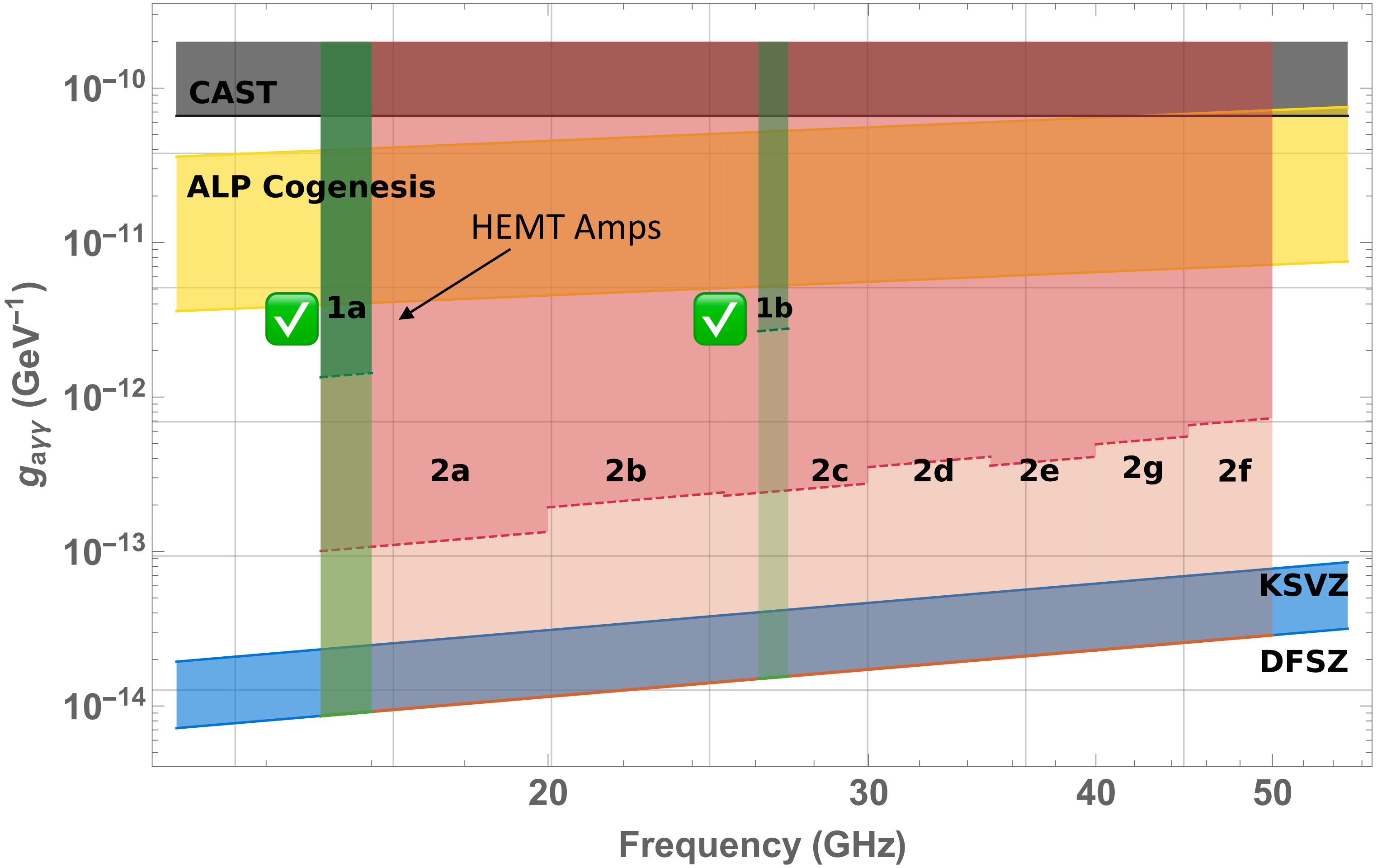


# ORGAN Run Plan

- Phase 1: Targeted searches between 15-16GHz and 26-27GHz ~ month scale search time



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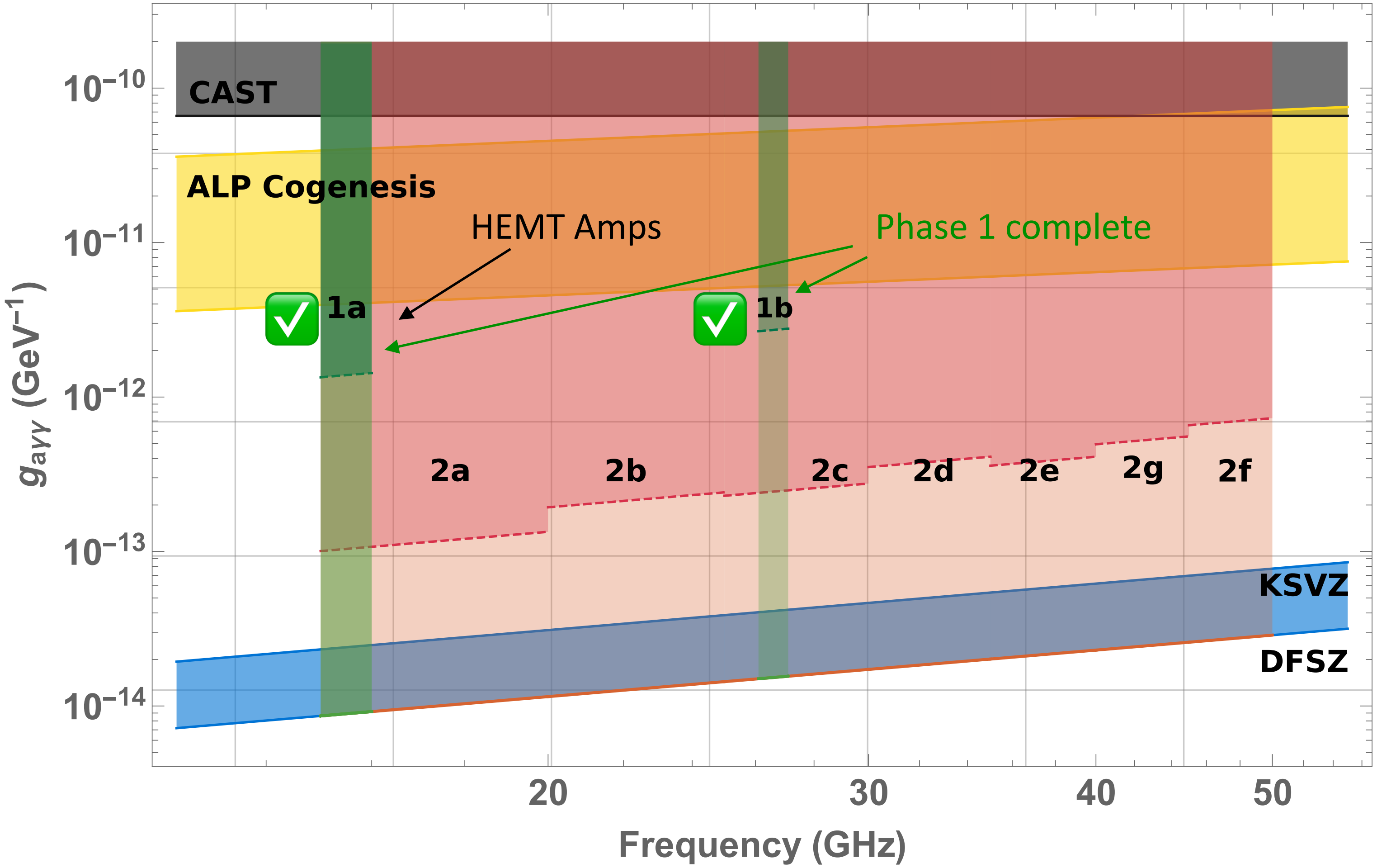

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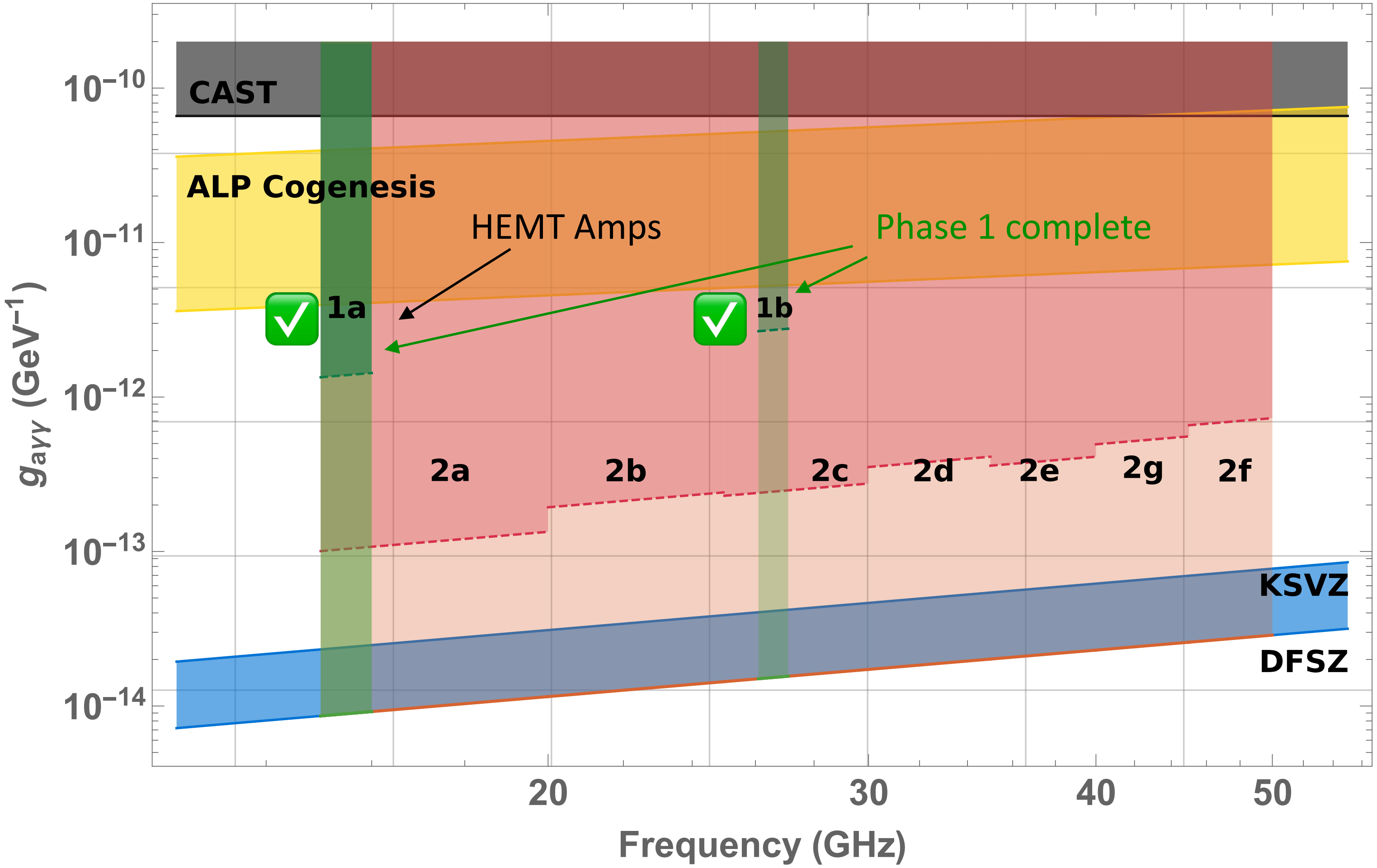

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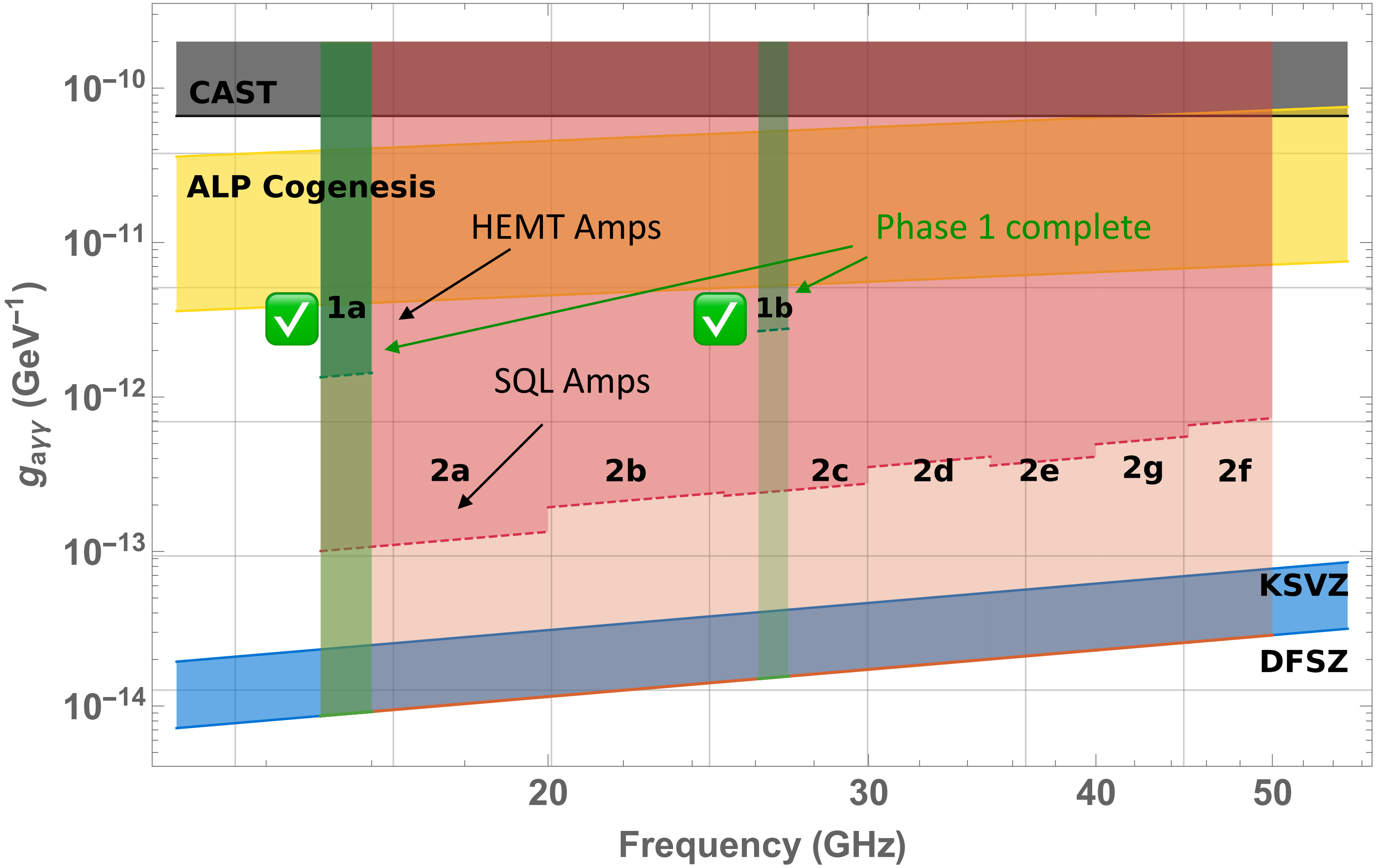
- Phase 2: moving to mK Temperatures, superconducting cavities, and Standard Quantum Limited (SQL) amplifiers (and ideally beyond)



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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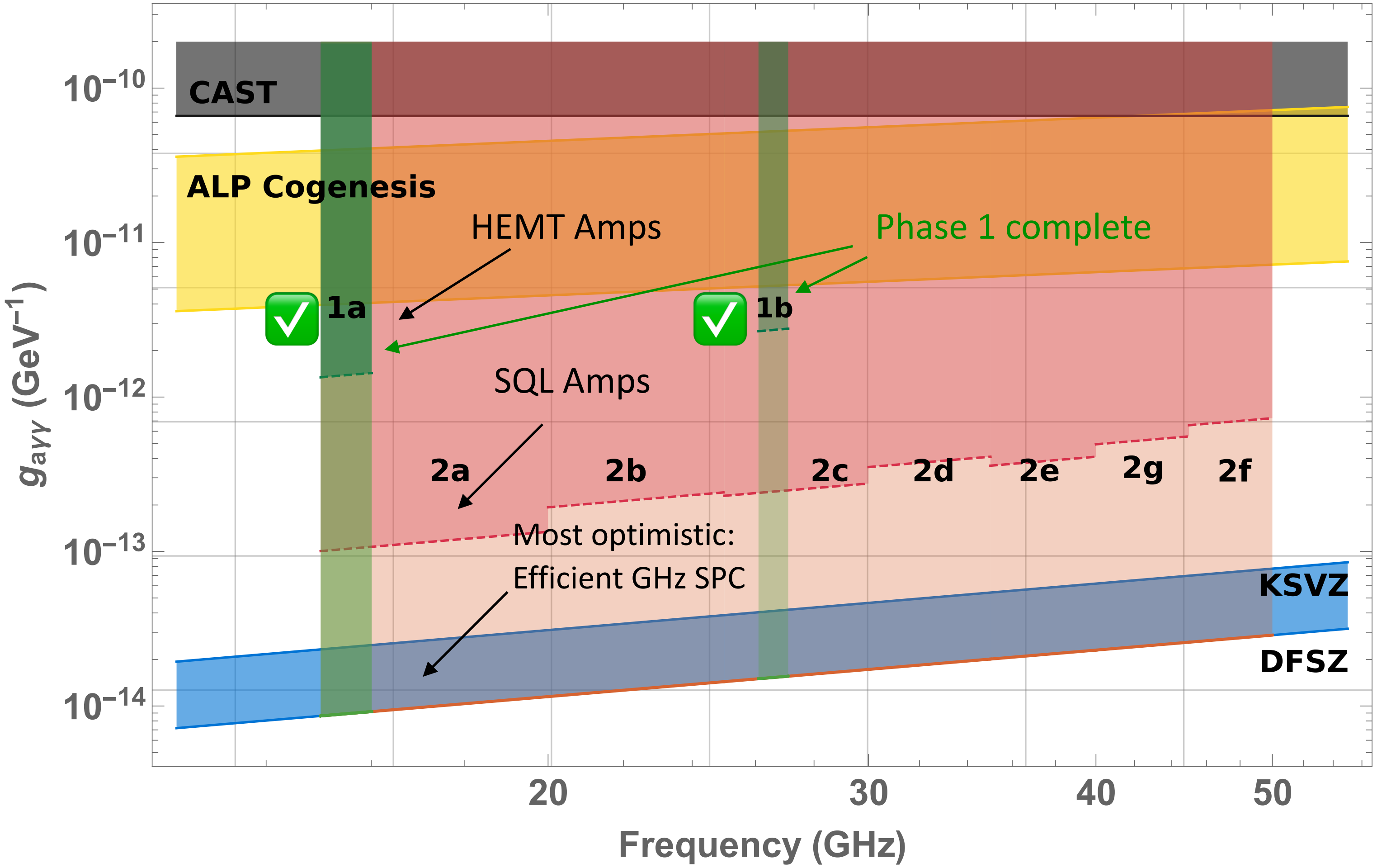
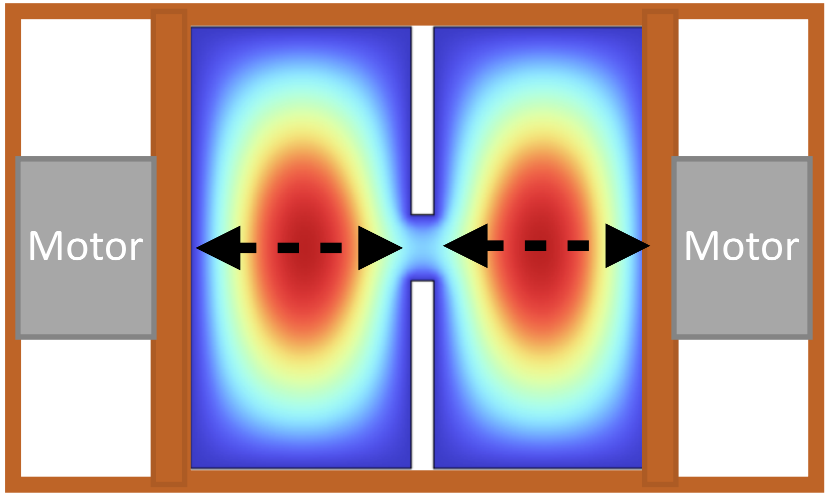
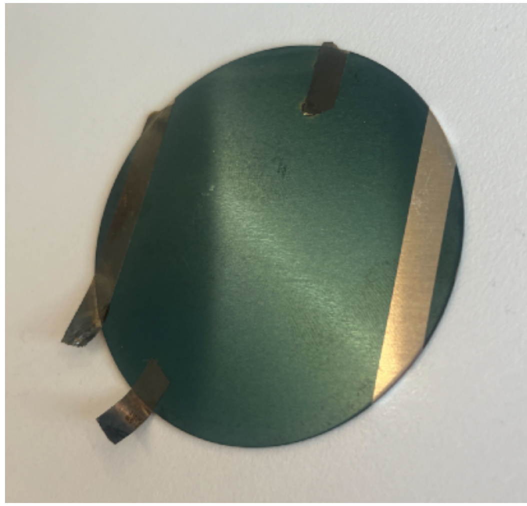
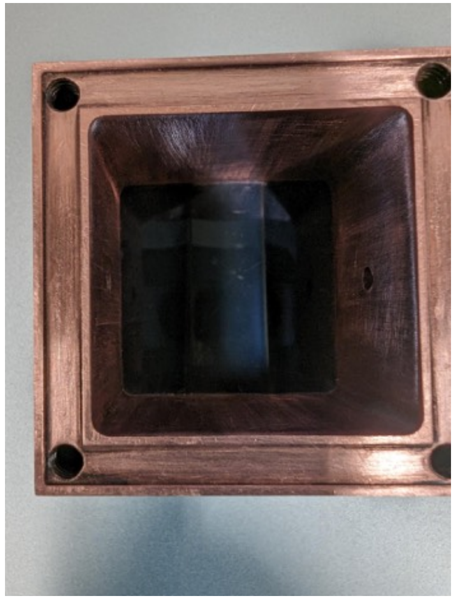


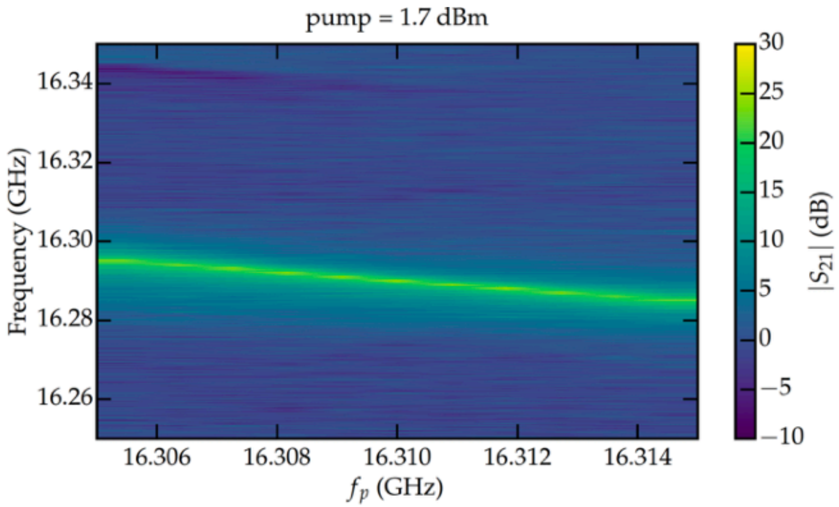
~2-3 deaths/year :-(

# Phase 2









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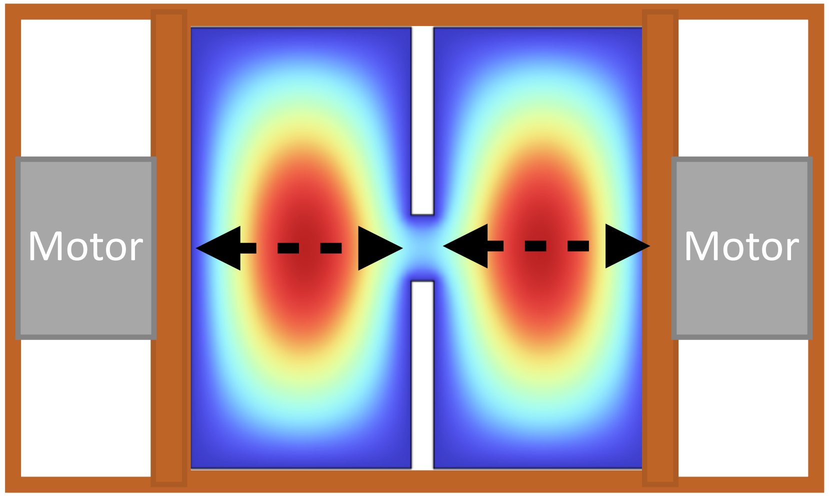
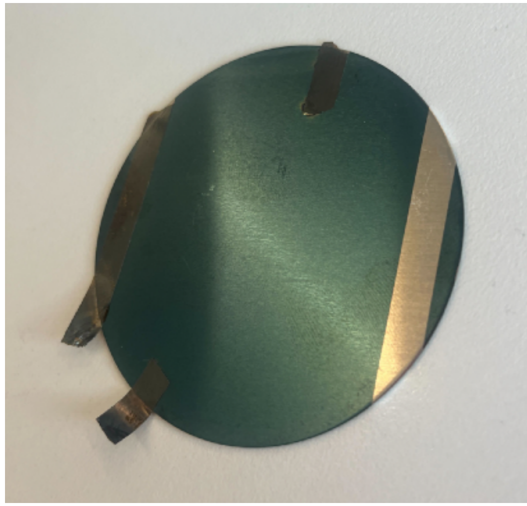
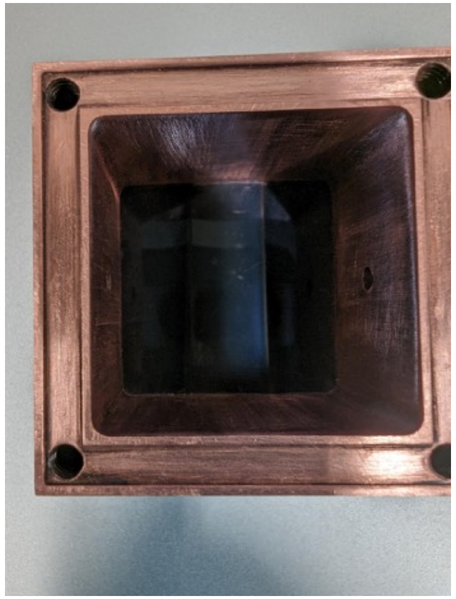
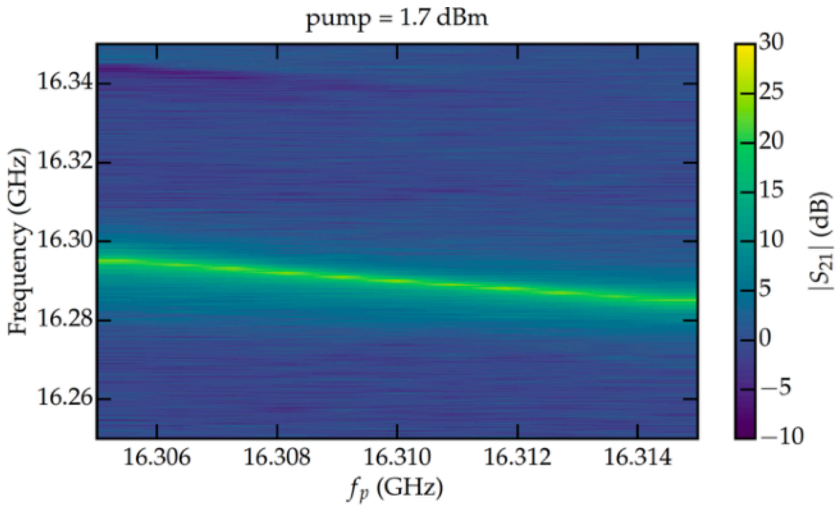
# Phase 2

- Novel cavity designs (rectangular, iris coupled)





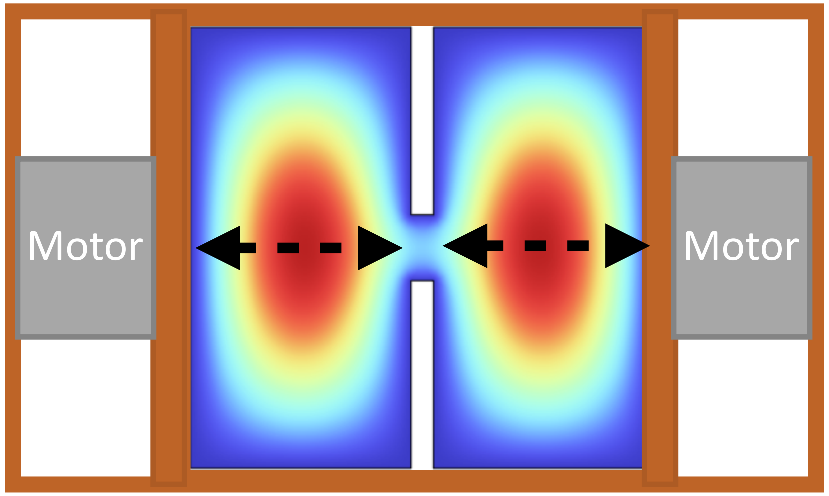


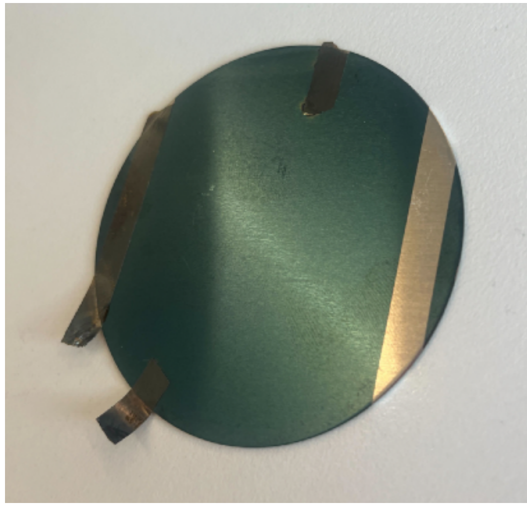


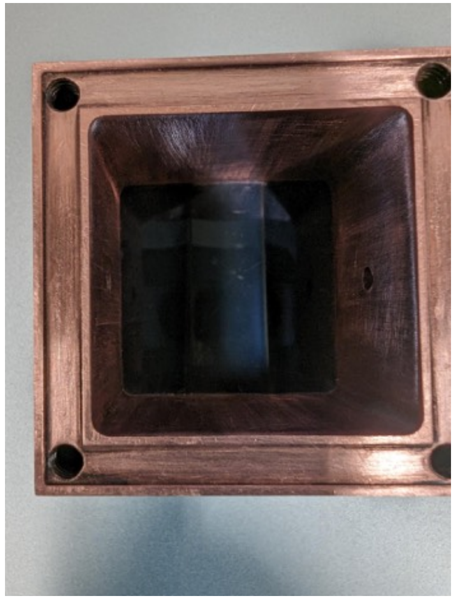
# Phase 2

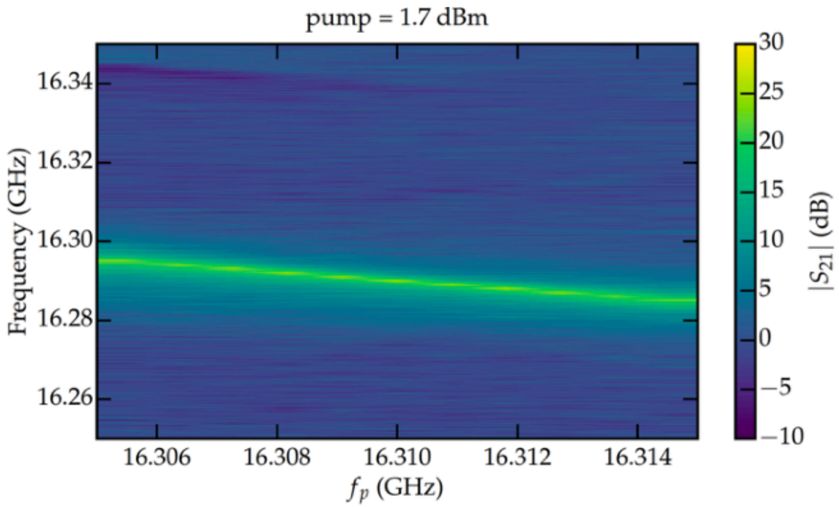
- Novel cavity designs (rectangular, iris coupled)

- Superconducting coatings (BCO materials)



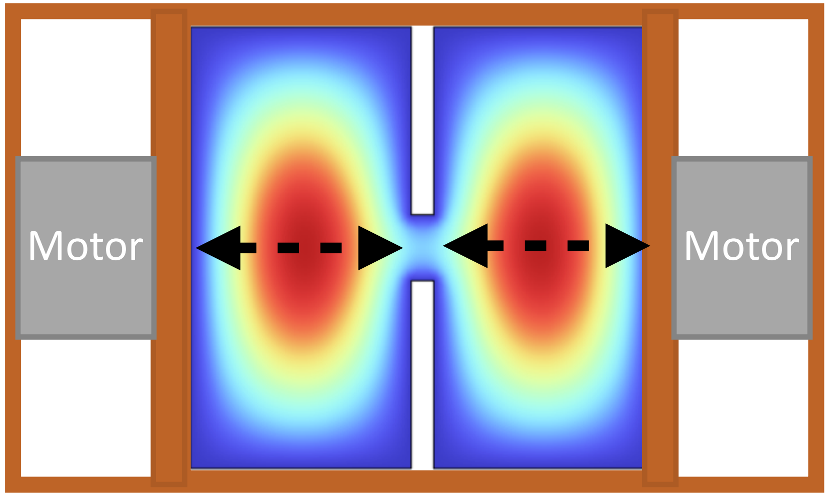


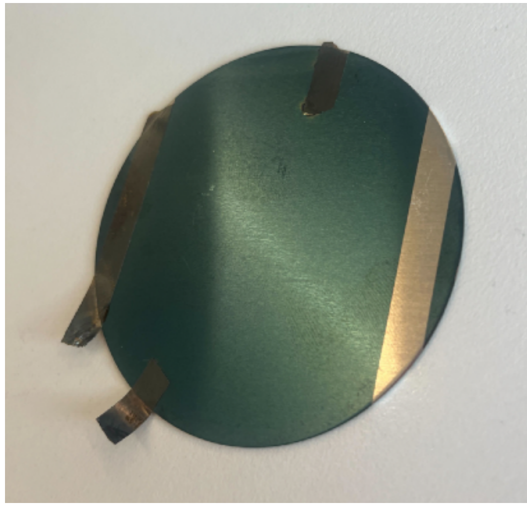


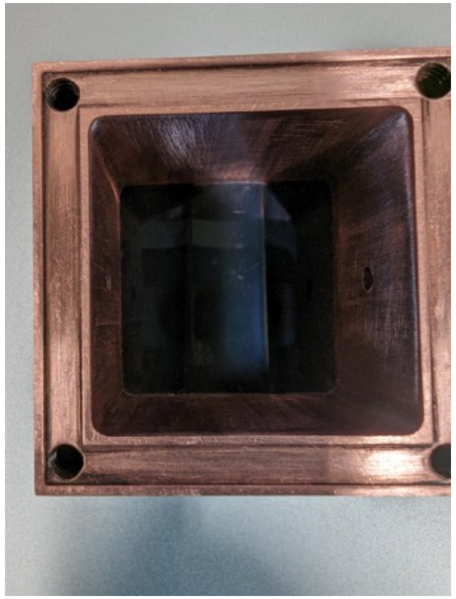


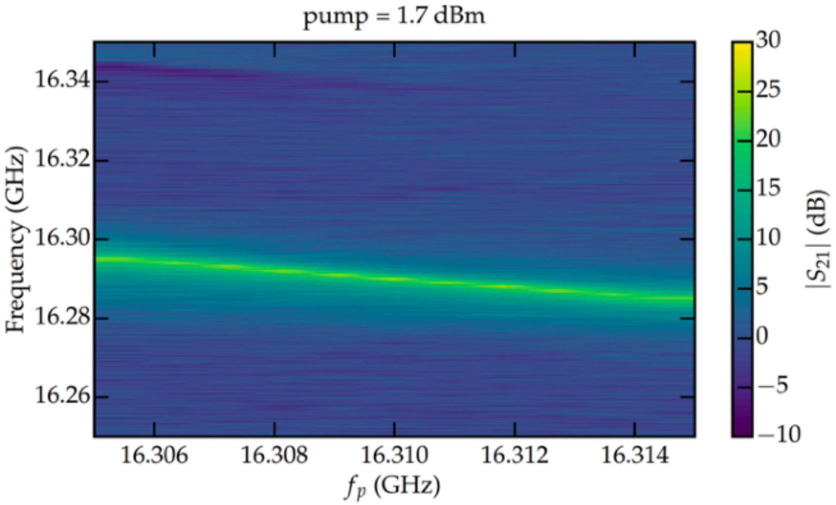
# Phase 2

- Novel cavity designs (rectangular, iris coupled)
- Superconducting coatings (BCO materials)
- Quantum-limited amps (NKPA under testing at the moment)









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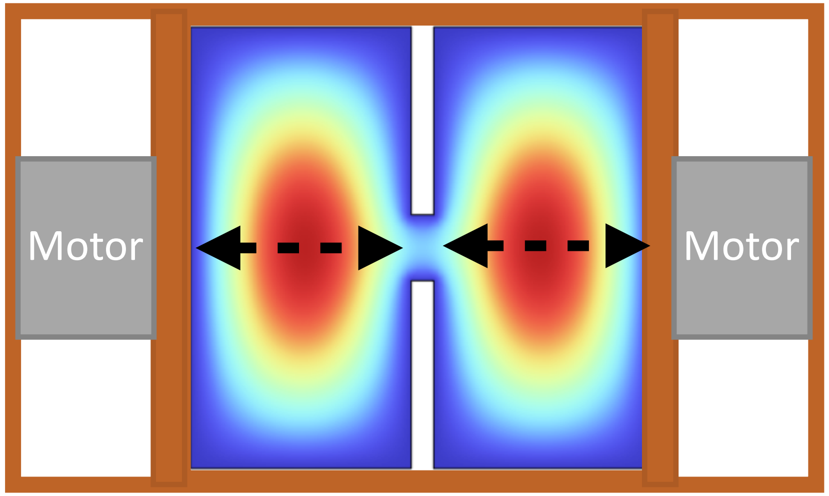

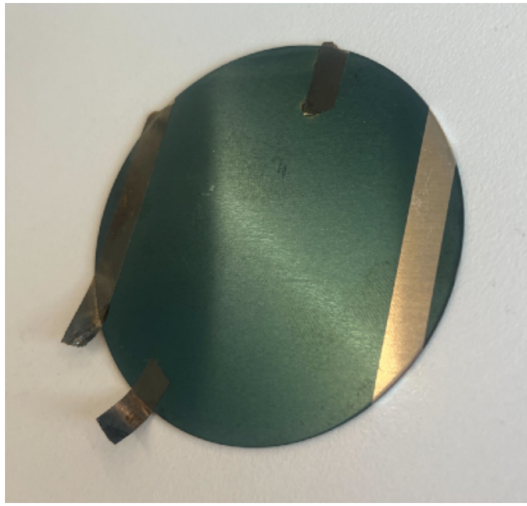

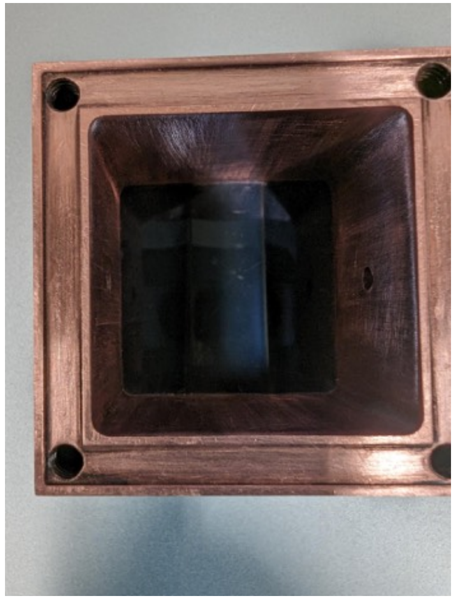

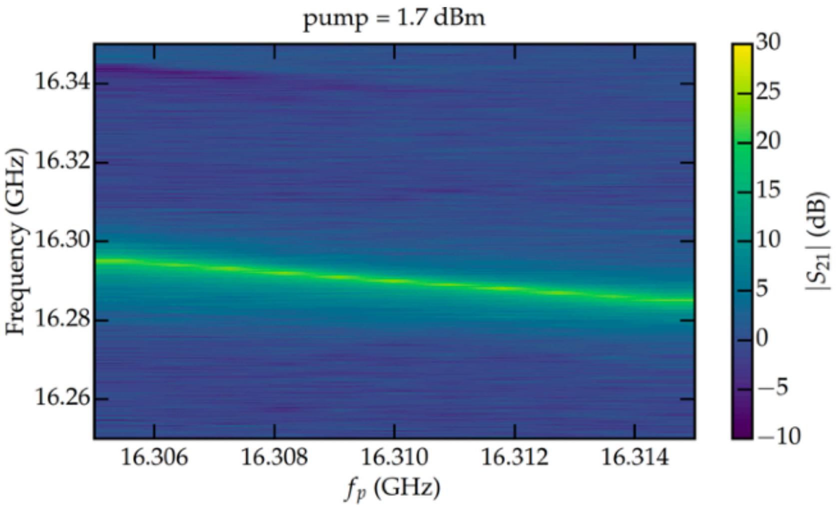

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# Phase 2

- Novel cavity designs (rectangular, iris coupled)
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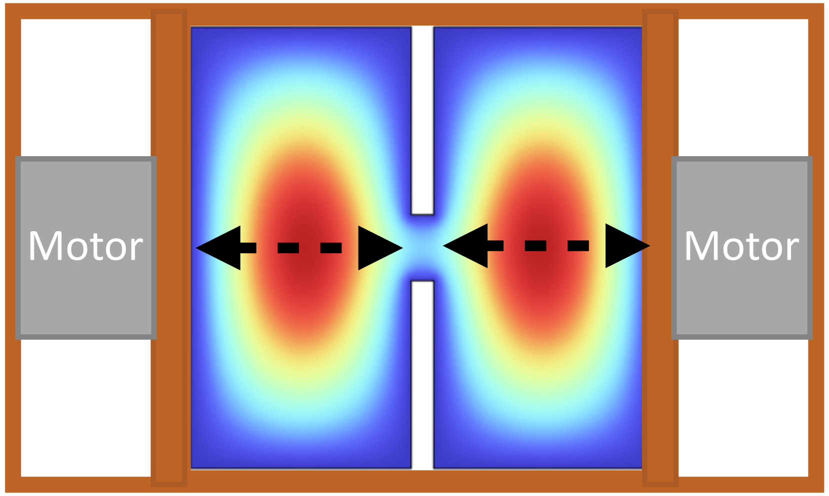
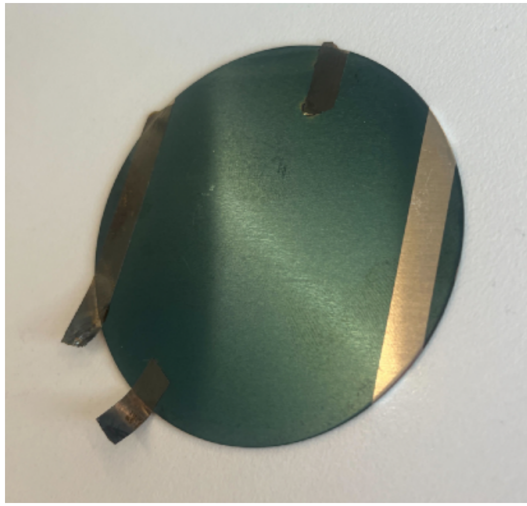
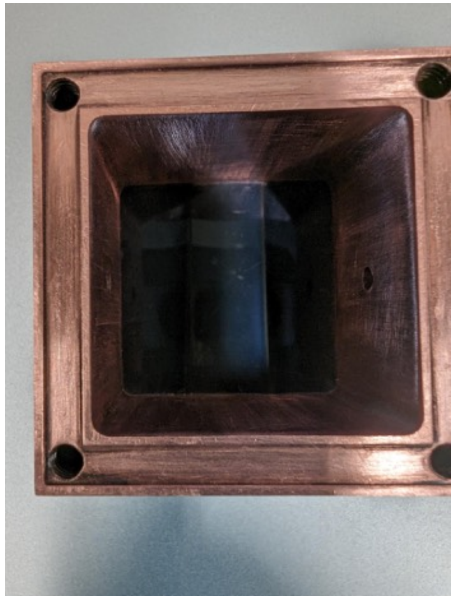
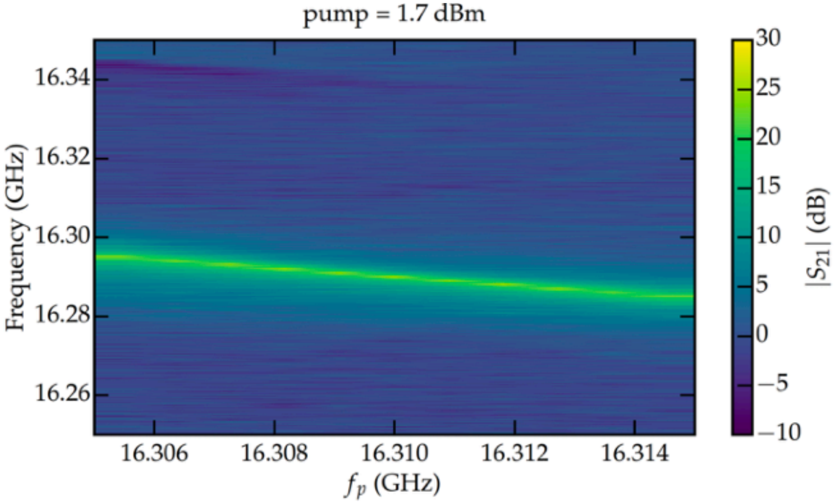
- Single photon counter R&D continues
- Commencing 2025









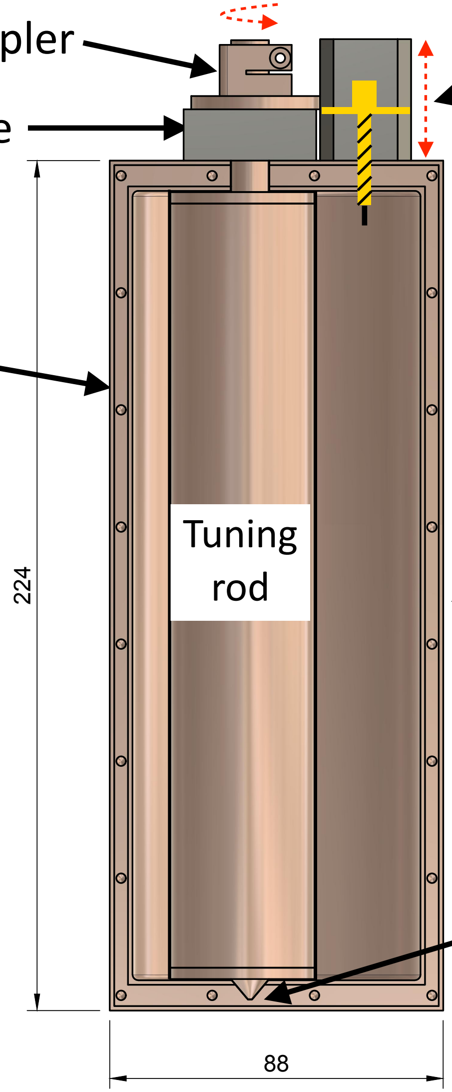
ARC CENTRE OF EXCELLENCE FOR
DARK MATTER
PARTICLE PHYSICS

# ORGAN-Q

# ORGAN-Q


Wide-Band Josephson Parametric Amplifier (WB-JPA)
Superconducting Low-Noise Amplifier for Quantum Computing

# ORGAN-Q



Rod-stage coupler

Rotation stage

Variable antenna coupling

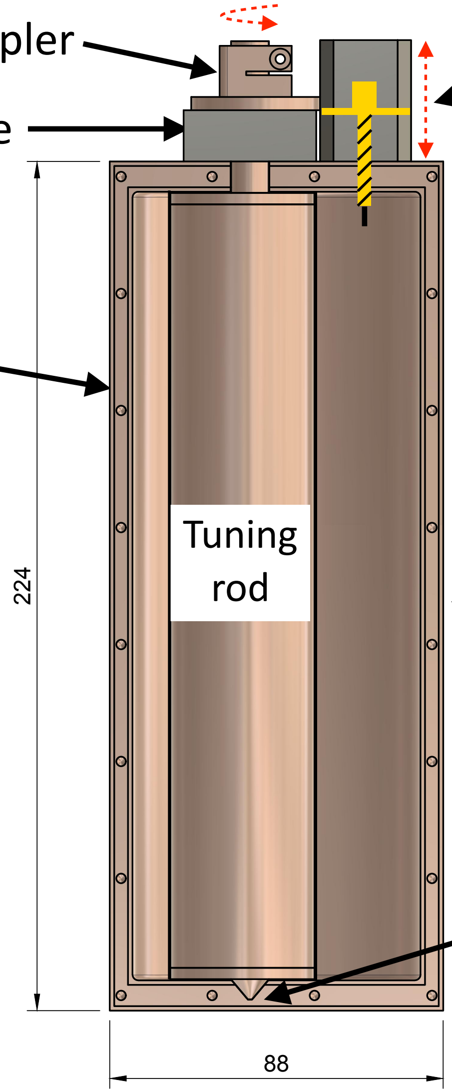
Clamshell design: ↑Q
Spurious modes ↓

Knife edges: ↑Q

Thermalisation: ↓$T_s$

# ORGAN-Q

- Q -> Quantum



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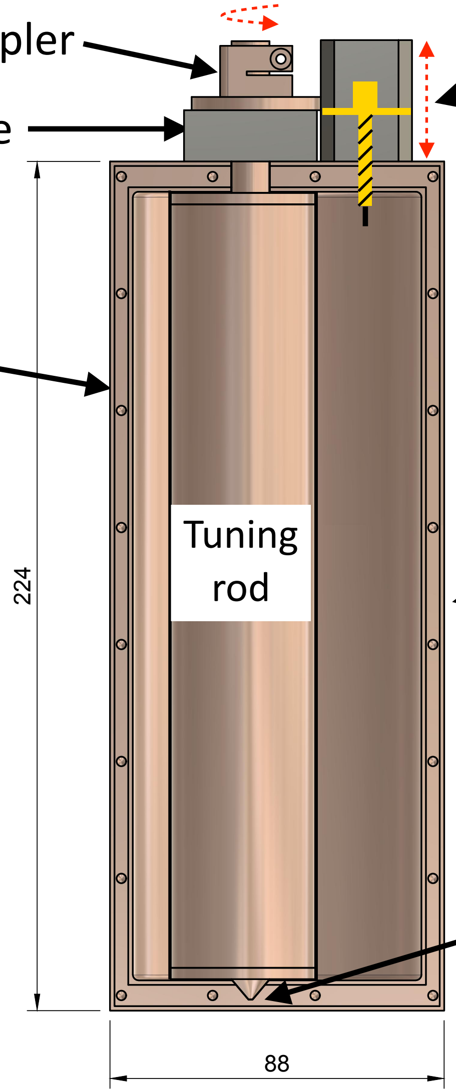

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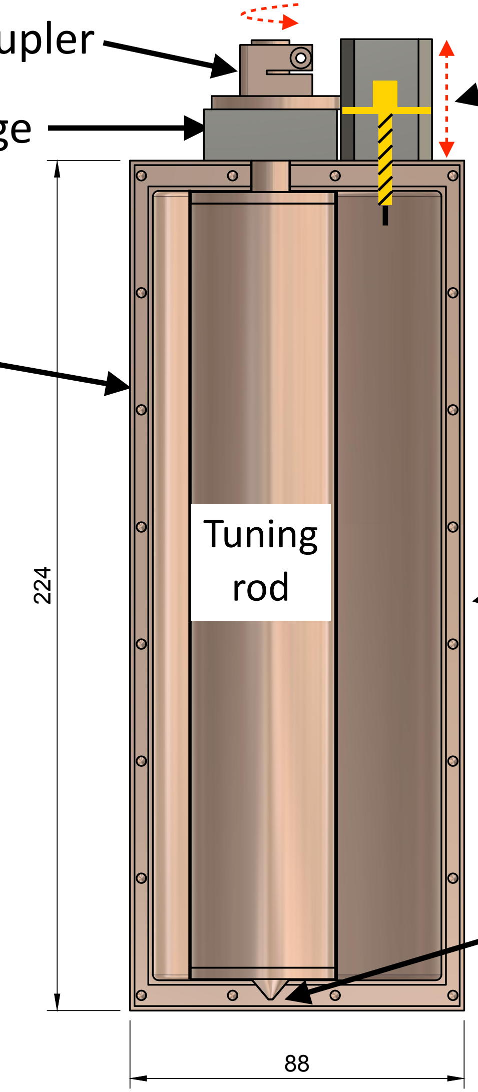

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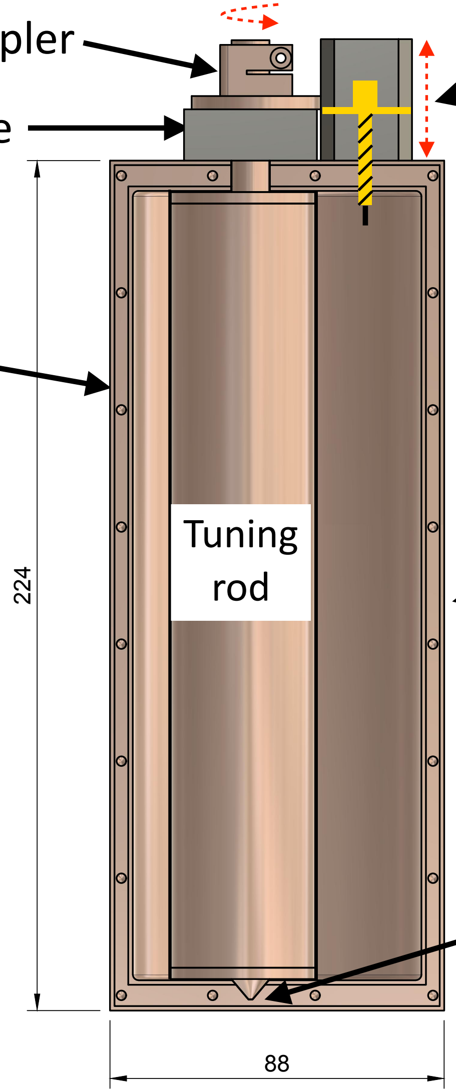

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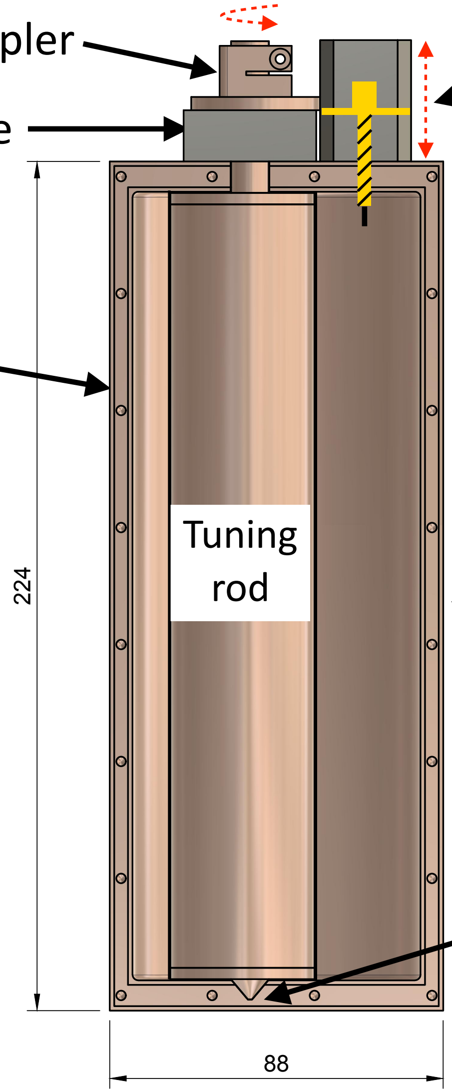
- Operates at mK -> ↓ $T_s$
- Variable coupling -> ↑ $Q_L \dfrac{\beta^2}{(1+\beta)^2}$
- Maximises bore volume completely!



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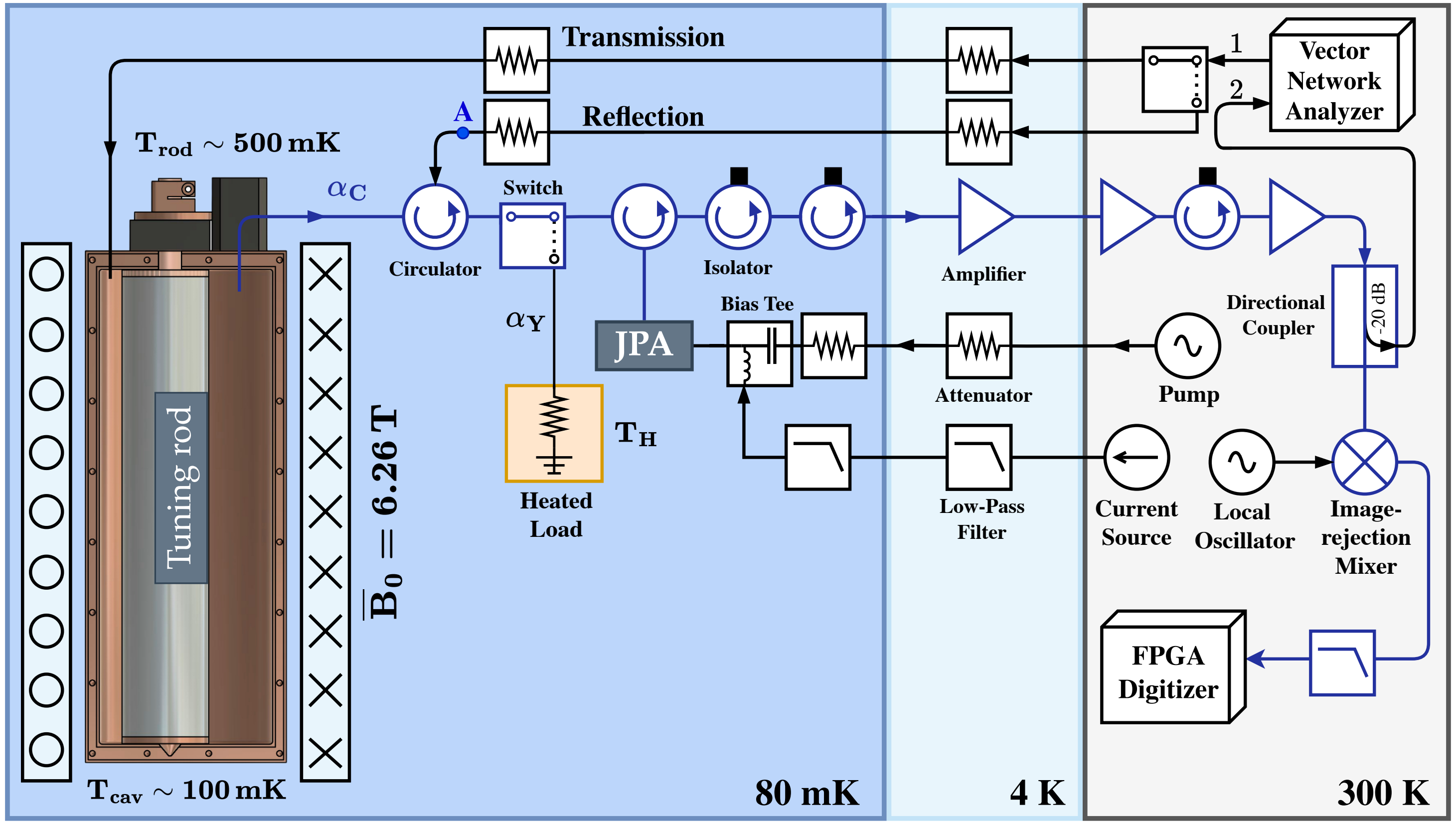
# ORGAN-Q Setup



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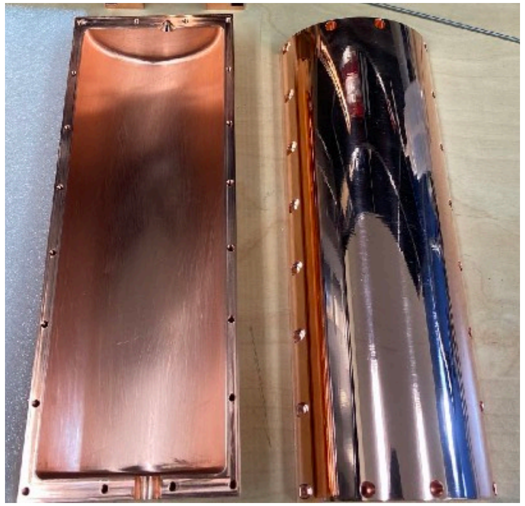

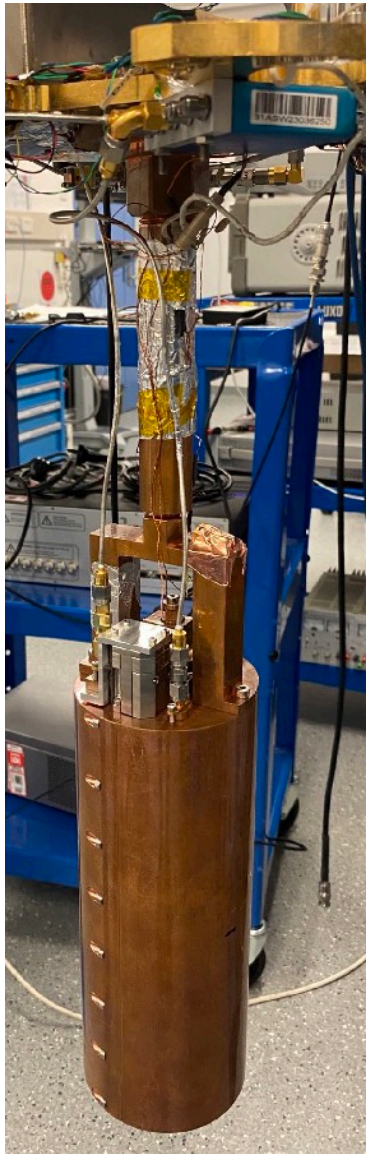

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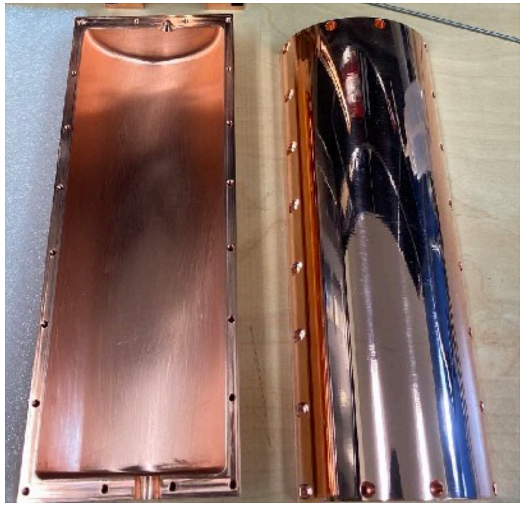

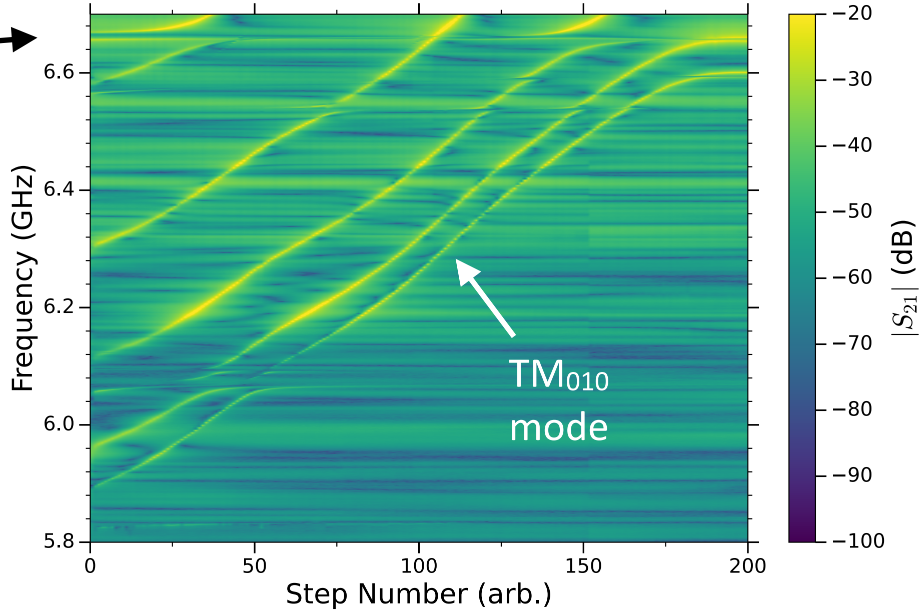

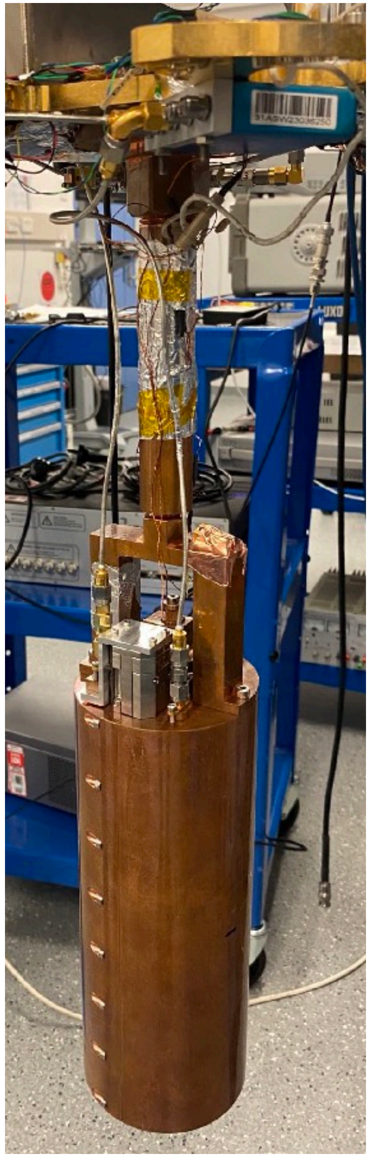

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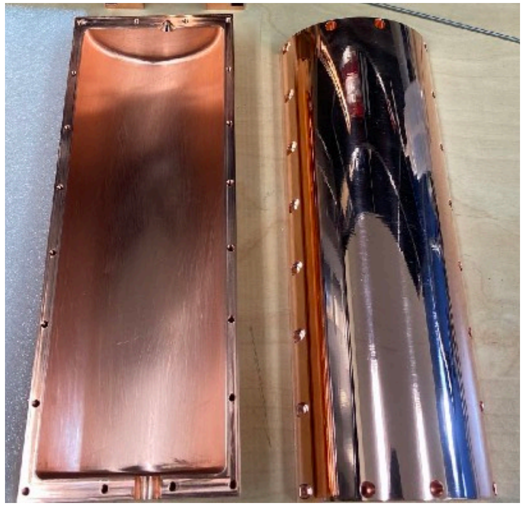

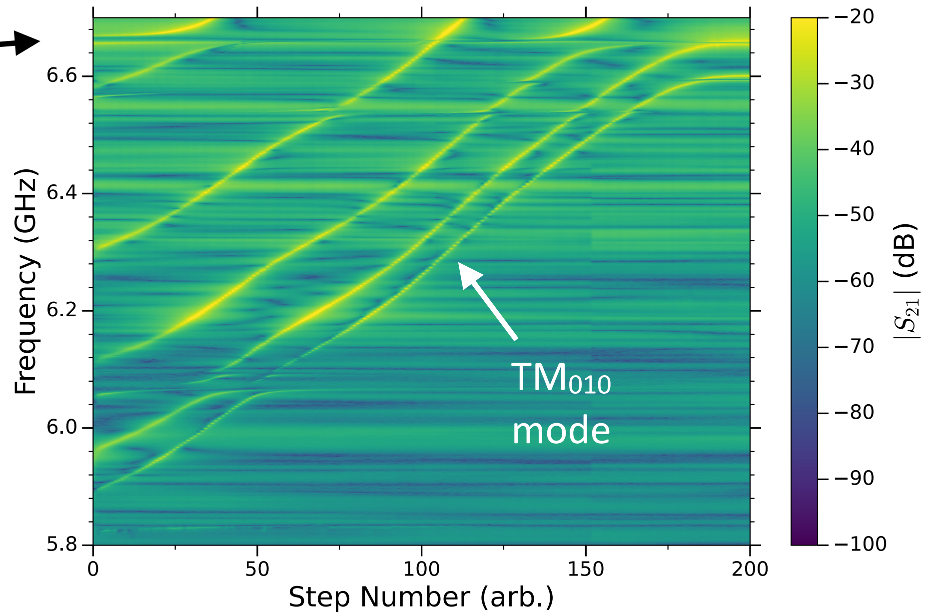

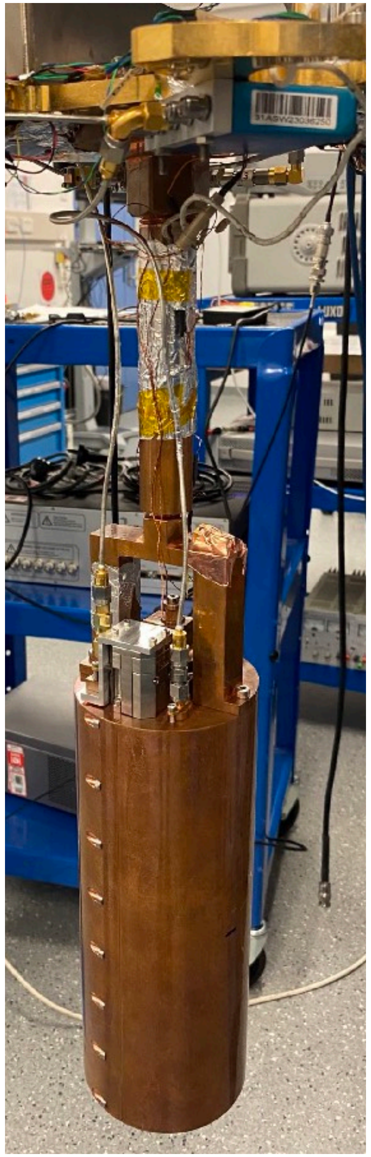

# ORGAN-Q Results

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- Cavity designed for no mode crossings in the region
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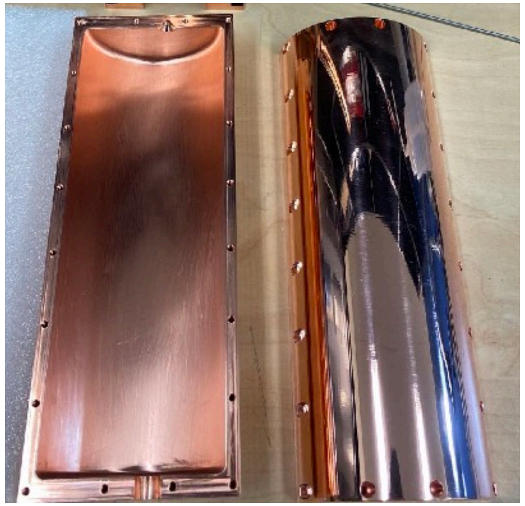
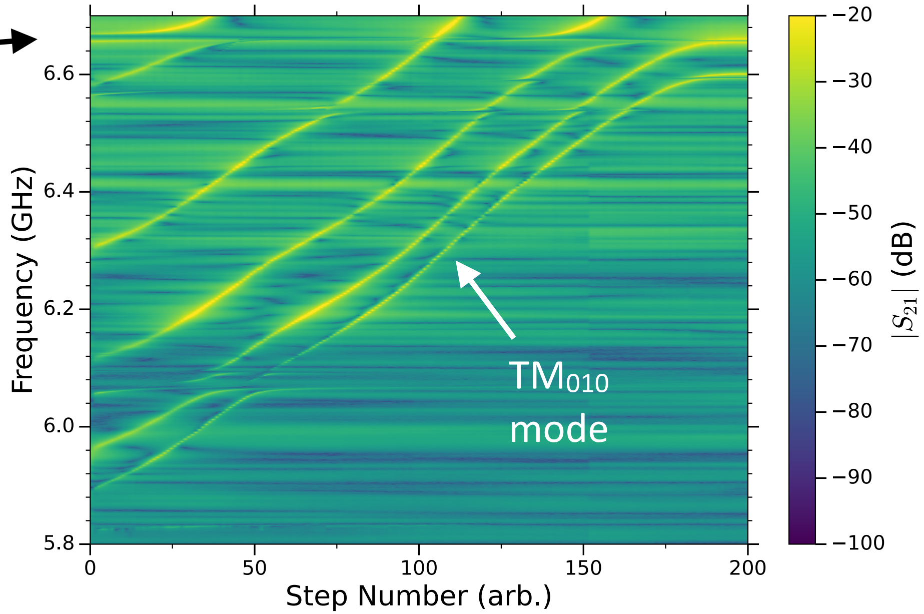
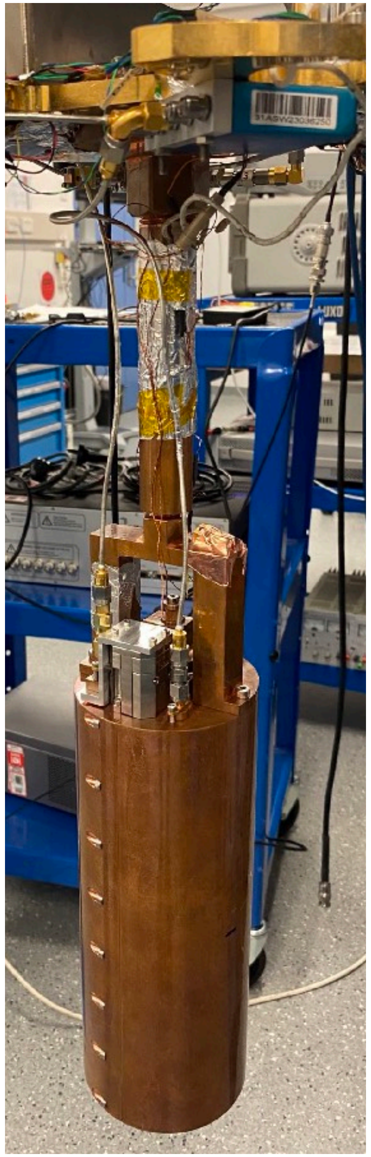
- The first “High-Res” ORGAN search



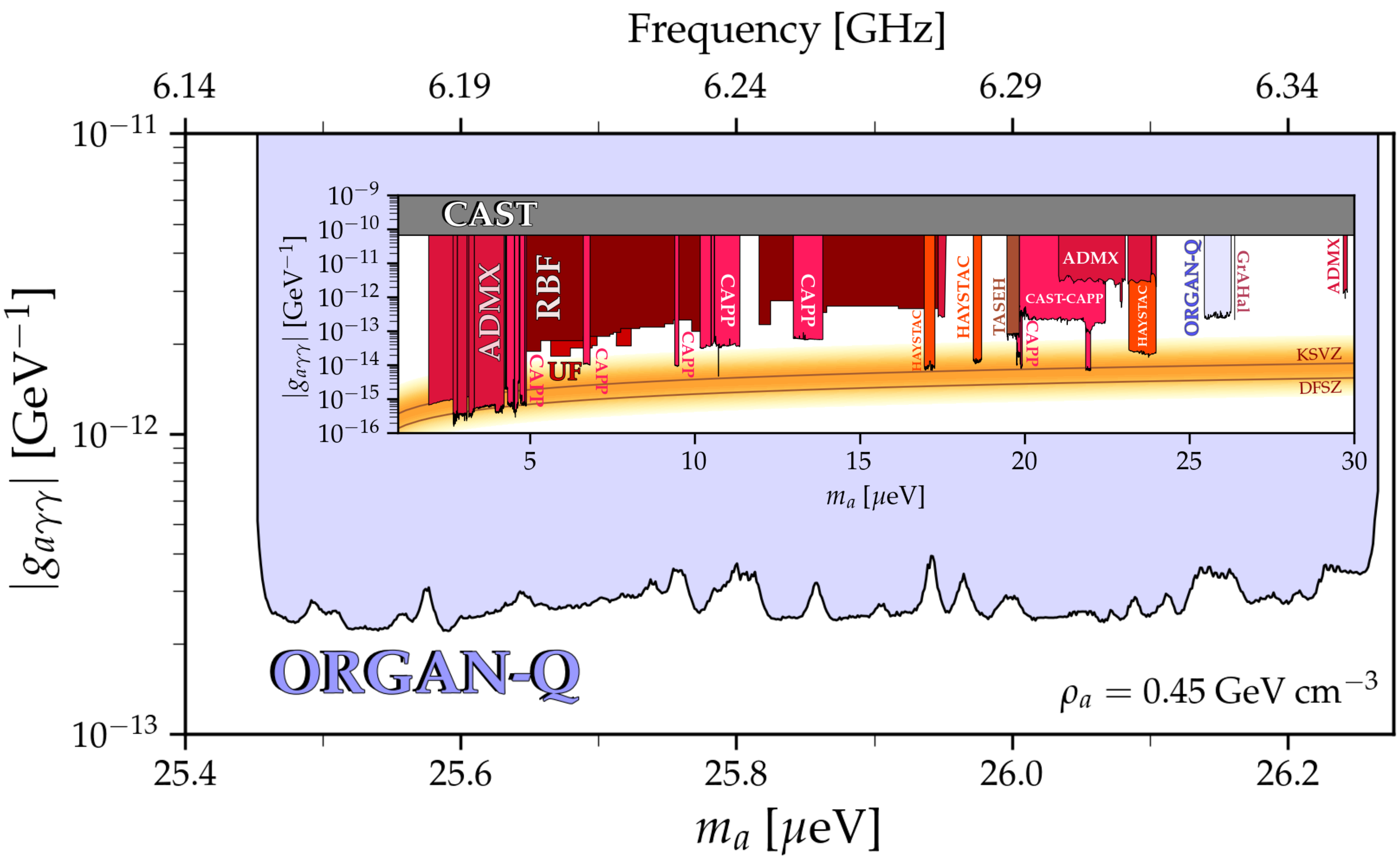


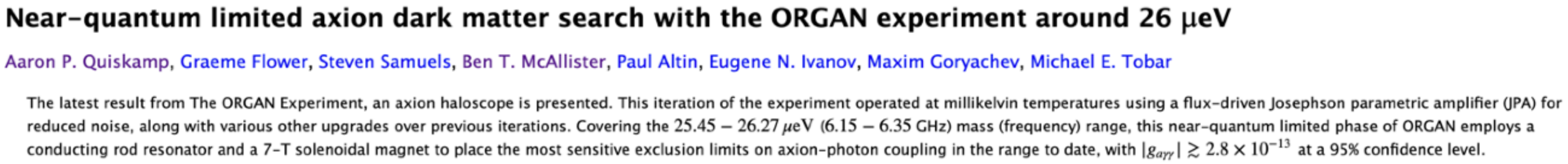


## Near-quantum limited axion dark matter search with the ORGAN experiment around 26 μeV

Aaron P. Quiskamp, Graeme Flower, Steven Samuels, Ben T. McAllister, Paul Altin, Eugene N. Ivanov, Maxim Goryachev, Michael E. Tobar

The latest result from The ORGAN Experiment, an axion haloscope is presented. This iteration of the experiment operated at millikelvin temperatures using a flux-driven Josephson parametric amplifier (JPA) for reduced noise, along with various other upgrades over previous iterations. Covering the $25.45 - 26.27\,\mu\mathrm{eV}$ ($6.15 - 6.35$ GHz) mass (frequency) range, this near-quantum limited phase of ORGAN employs a conducting rod resonator and a 7-T solenoidal magnet to place the most sensitive exclusion limits on axion-photon coupling in the range to date, with $|g_{a\gamma\gamma}| \gtrsim 2.8 \times 10^{-13}$ at a 95% confidence level.





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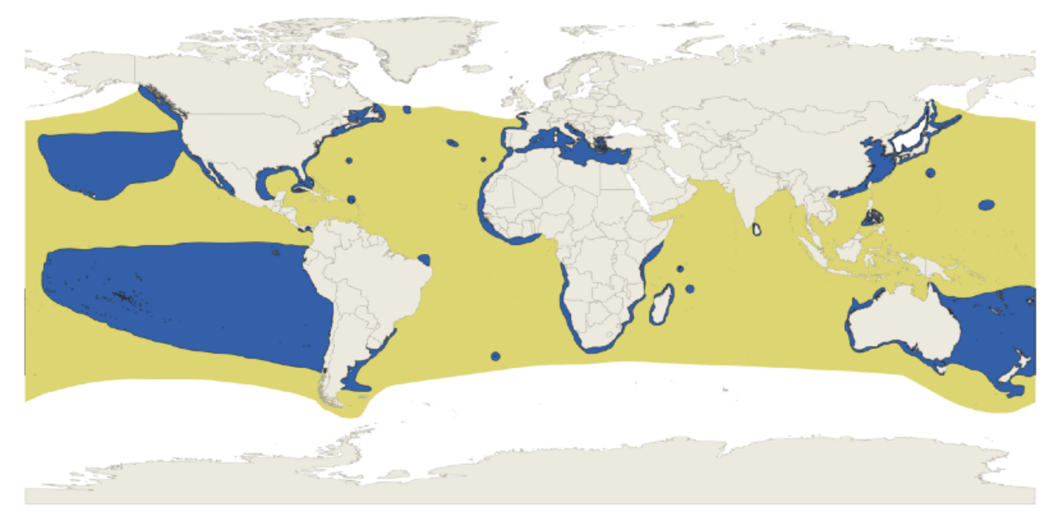

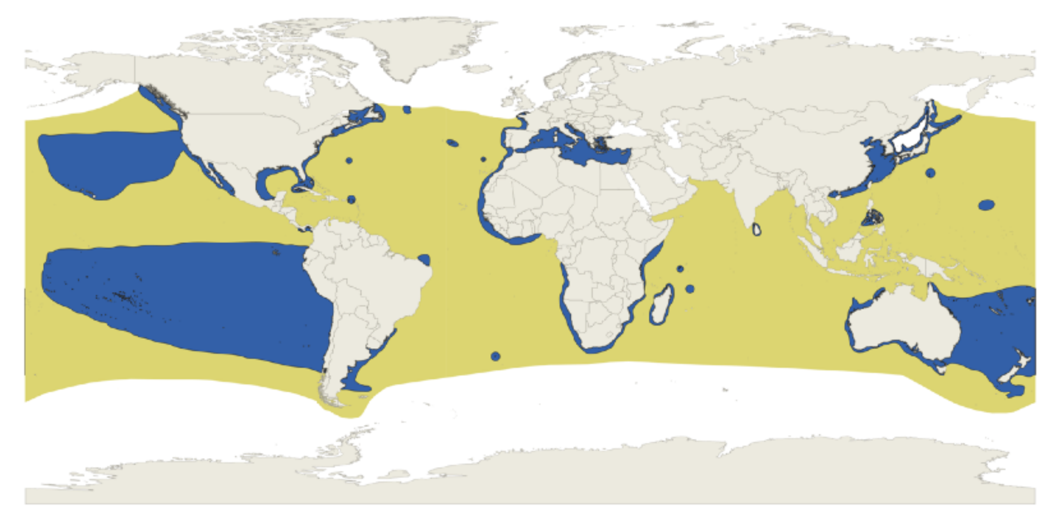

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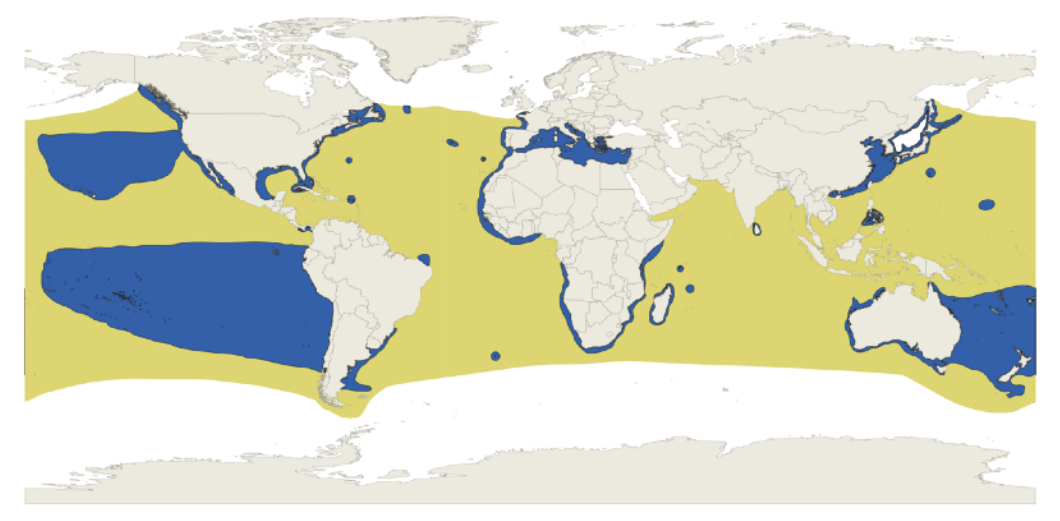

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~5 deaths/year :-(

# ORGAN Low Frequency

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- Various cosmological motivations for such axions

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- Problem: Cavities get HUGE

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# ORGAN Low Frequency

- Re-entrant cavities (lumped LC resonators)

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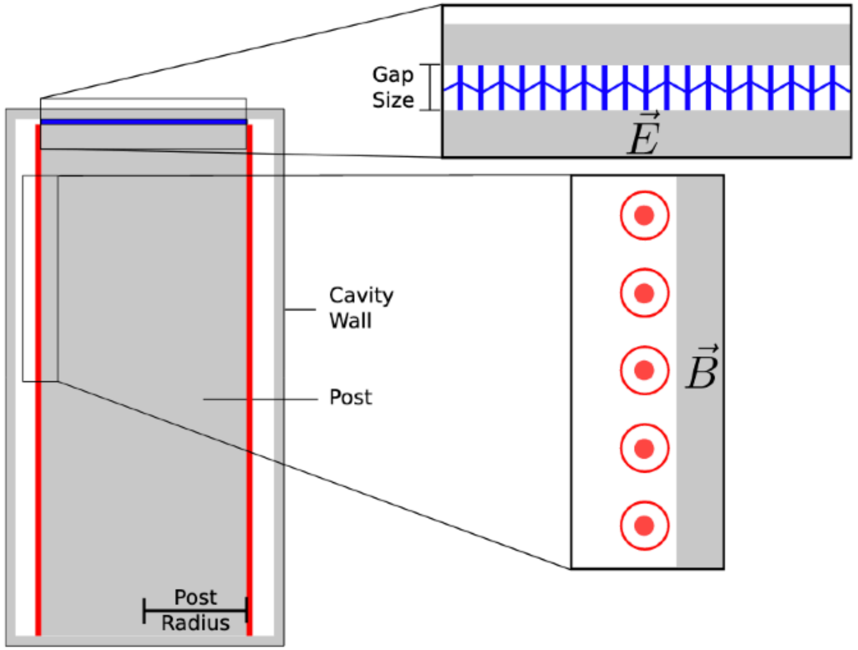
3D lumped LC resonators as low mass axion haloscopes

Ben T. McAllister, Stephen R. Parker, and Michael E. Tobar

Phys. Rev. D **94**, 042001 – Published 11 August 2016



# ORGAN Low Frequency

- Re-entrant cavities (lumped LC resonators)
- Lower frequency, take hit to sensitivity


PHYSICAL REVIEW D

*covering particles, fields, gravitation, and cosmology*

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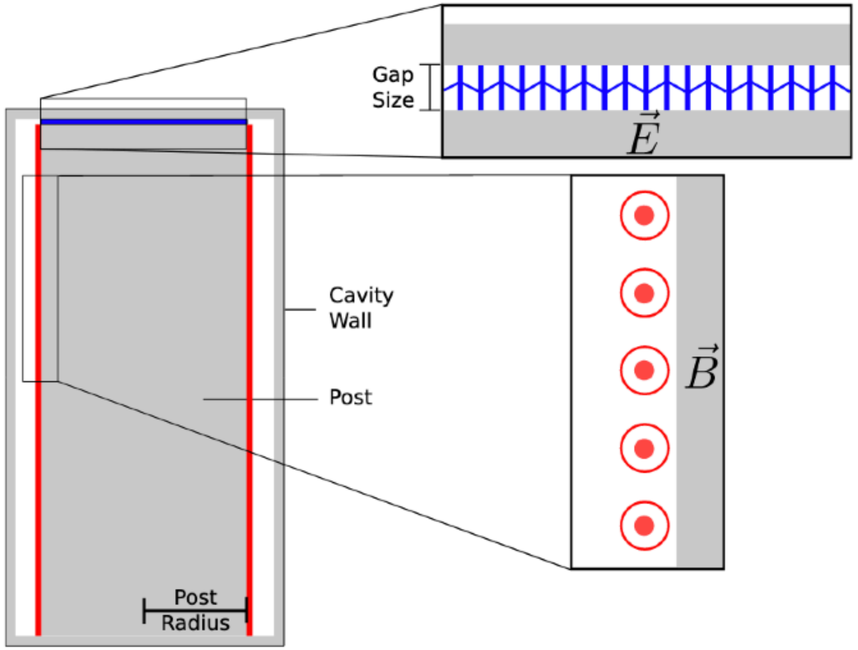

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# ORGAN Low Frequency

- Re-entrant cavities (lumped LC resonators)
- Lower frequency, take hit to sensitivity
- Actually plan to use a novel re-entrant cavity

PHYSICAL REVIEW D

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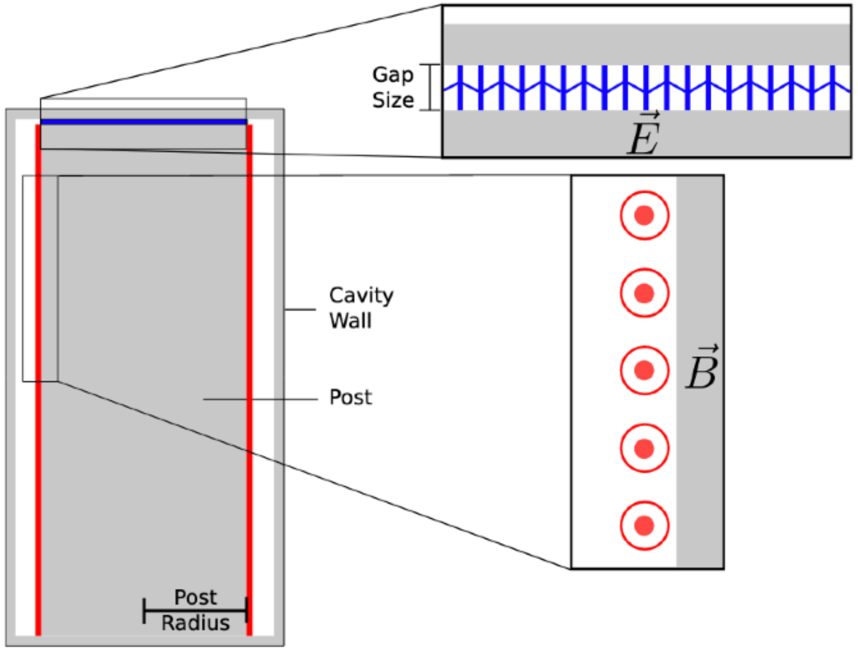

# ORGAN Low Frequency

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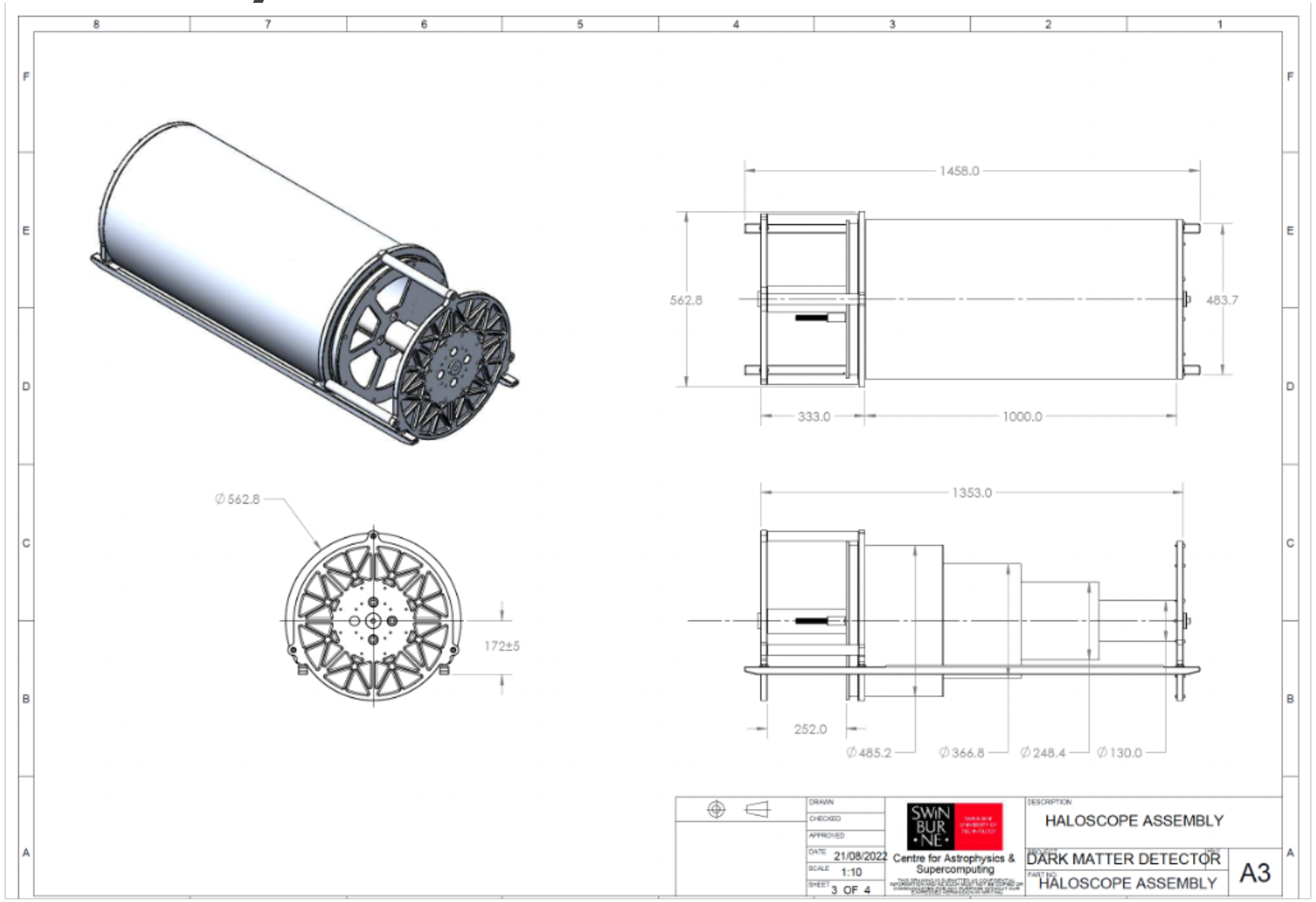

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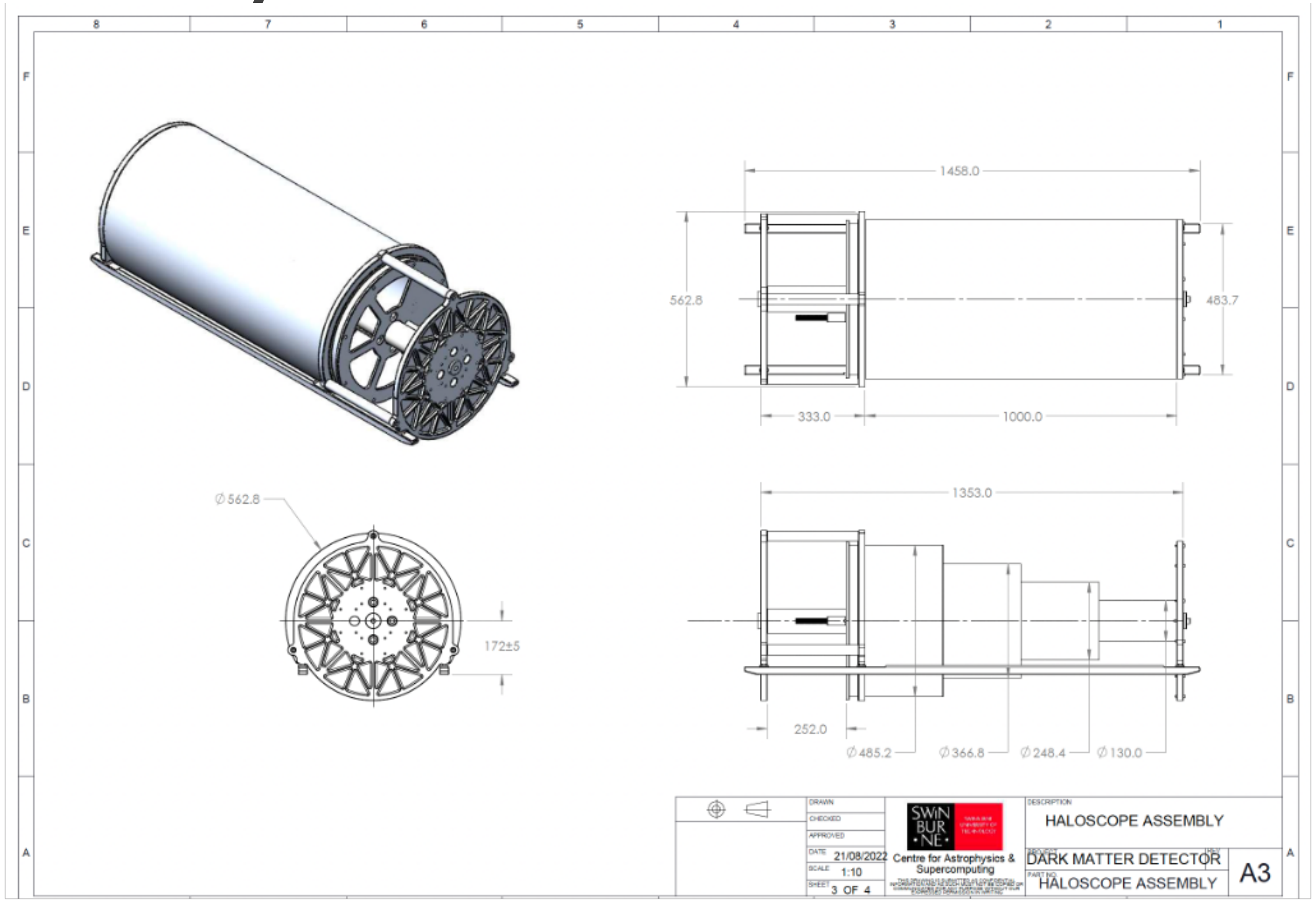
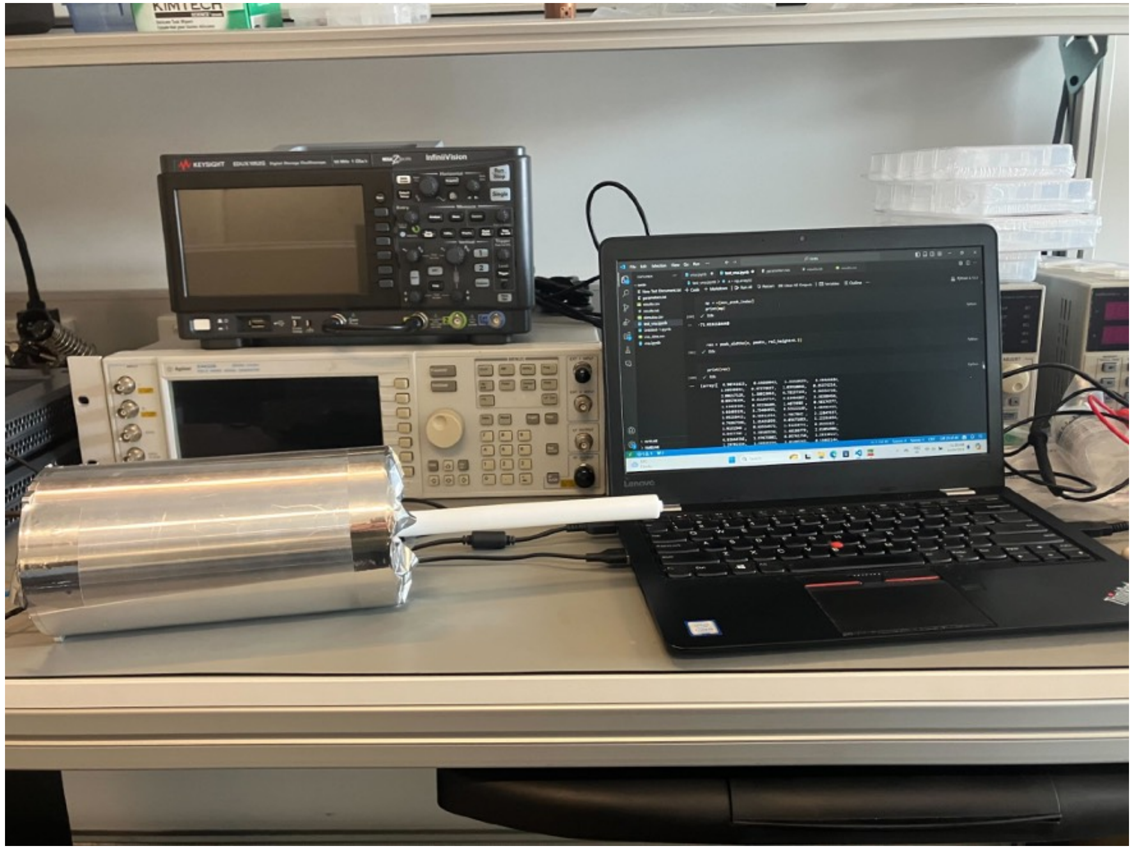


# ORGAN Low Frequency

- Telescopic tuning rod
- Cavity currently being built
- Planning a few ~100 MHz scan
- Prototype resonators have been built and tested…big cavity coming soon



# ORGAN Low Frequency

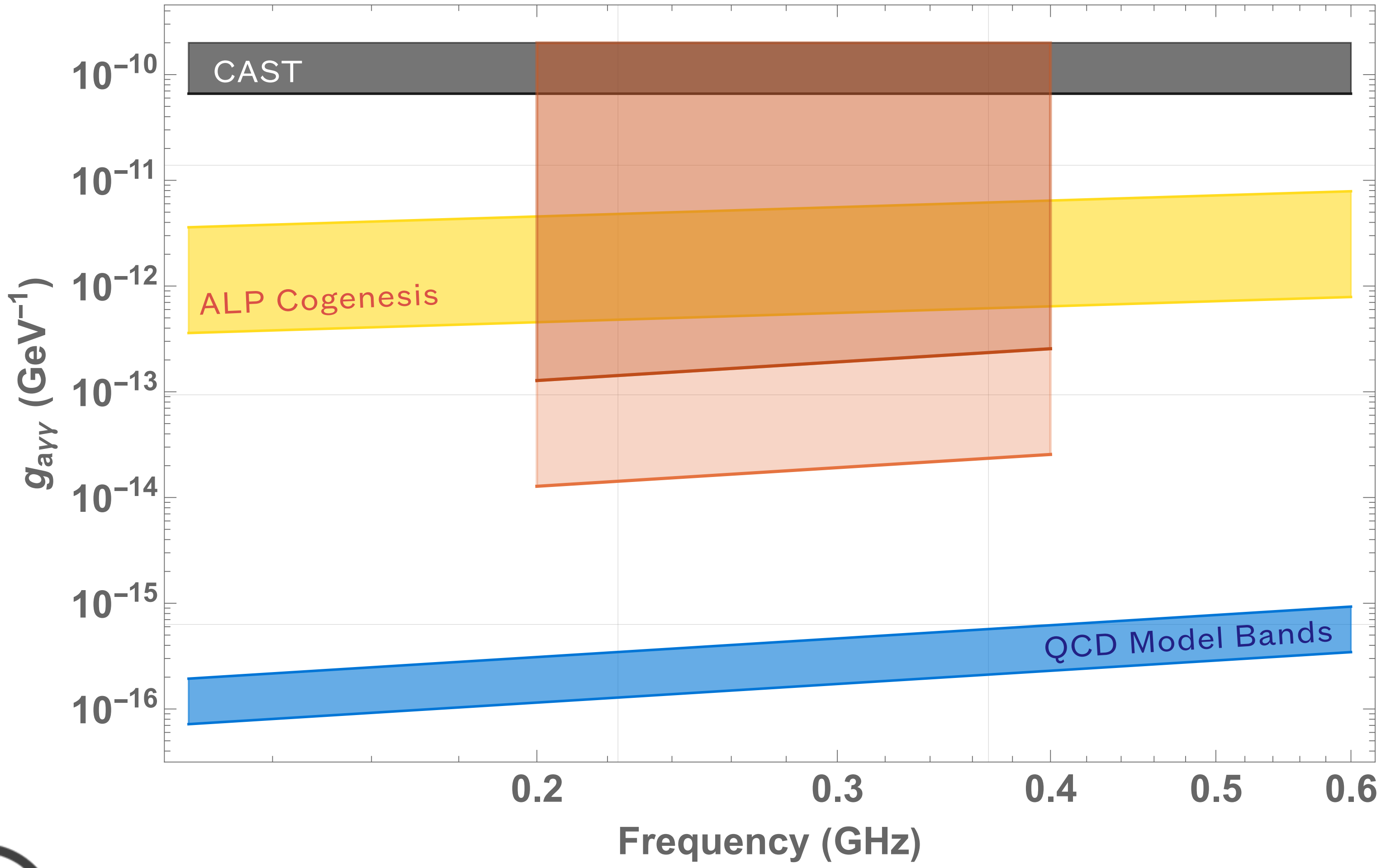
- Where do you put a big re-entrant cavity?

# ORGAN Low Frequency

- Where do you put a big re-entrant cavity?
- 3 T MRI Machine at Swinburne University

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

# ORGAN Low Frequency



ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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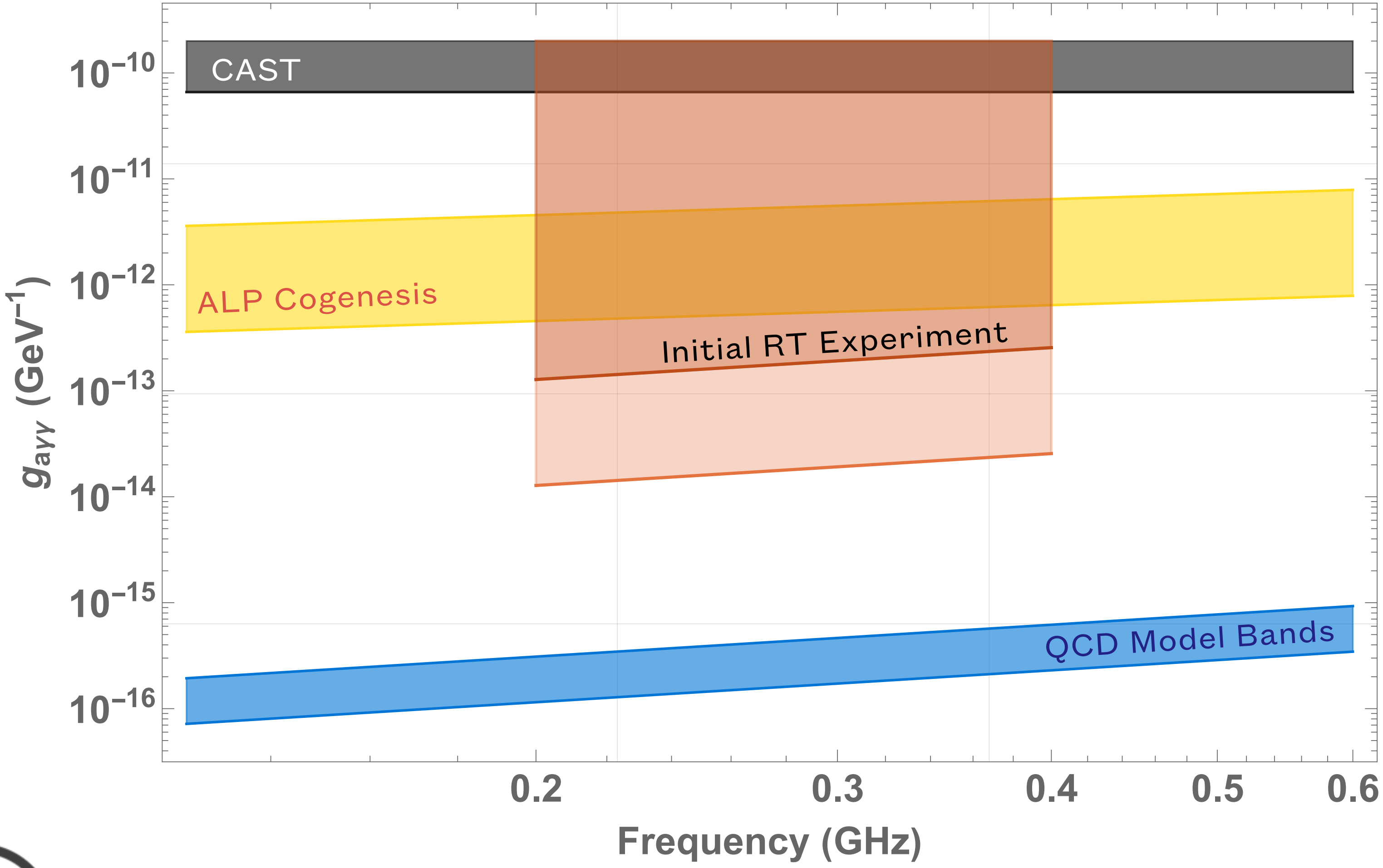
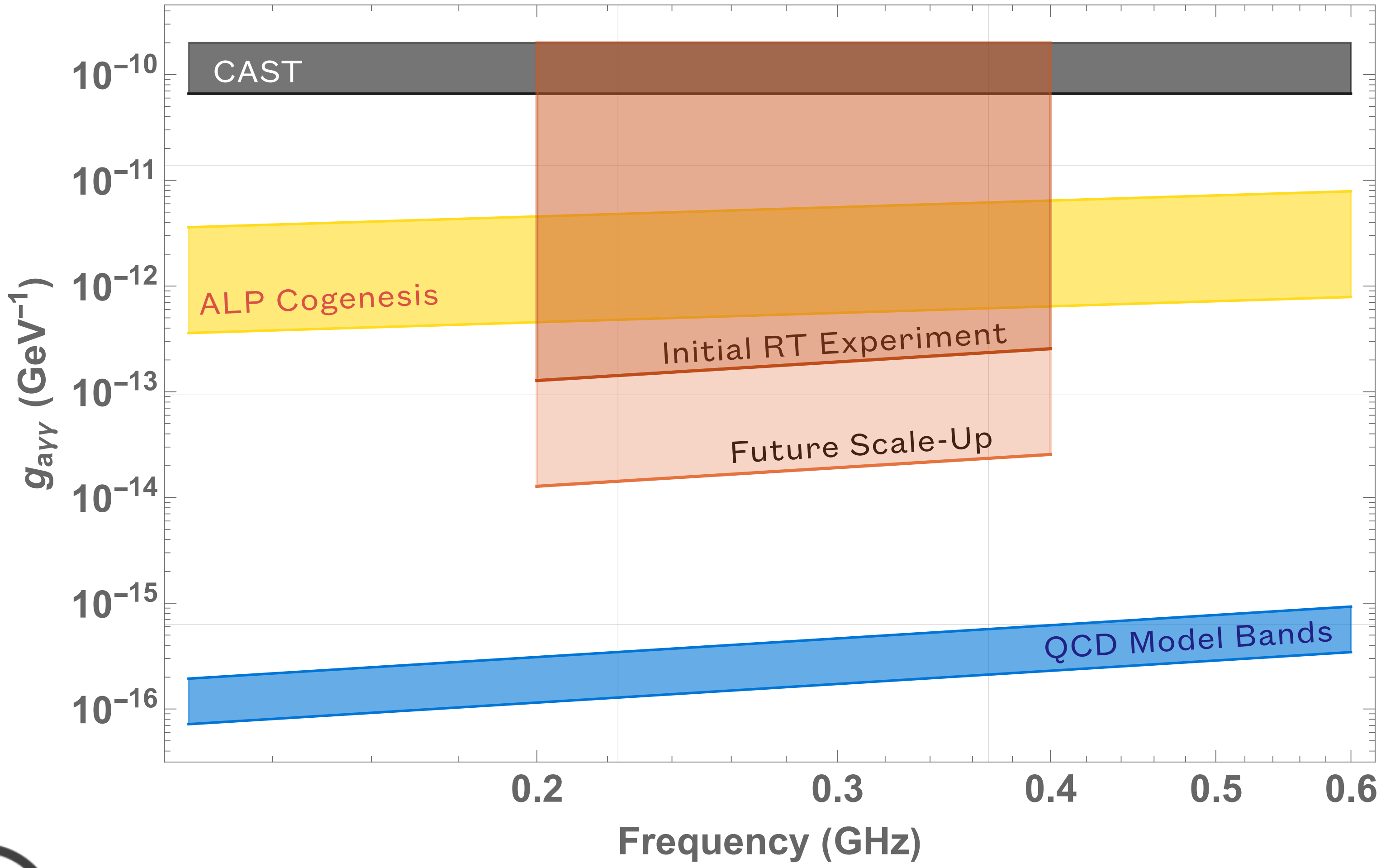


HEMT Amplifier

Room
Temperature

# ORGAN Low Frequency



HEMT Amplifier

Room
Temperature

SQUID
Amplifier

4K System

# Thank you!

# CELLAR

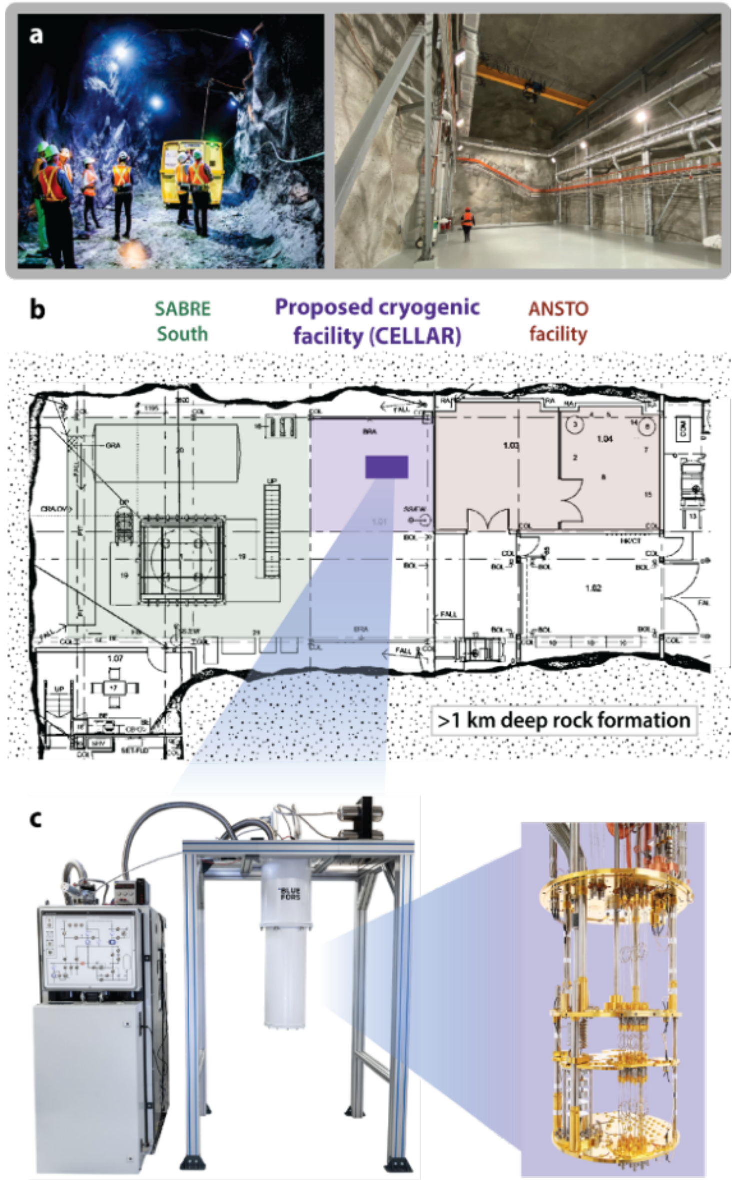
## Cryogenic Experimental Laboratory for Low-background Australian Research

Ben McAllister

Swinburne University of Technology

# CELLAR Summary

- Dilution refrigerator (10 mK base) in SUPL (Stawell Underground Physics Laboratory)
- 1024 m underground (2900 m.w.e)
- Another at Swinburne University of Technology (also 10 mK base)
- Research areas: quantum technology, gravitational waves, dark matter, clocks and oscillators, etc
- Open to collaboration - time is available for people with cool ideas



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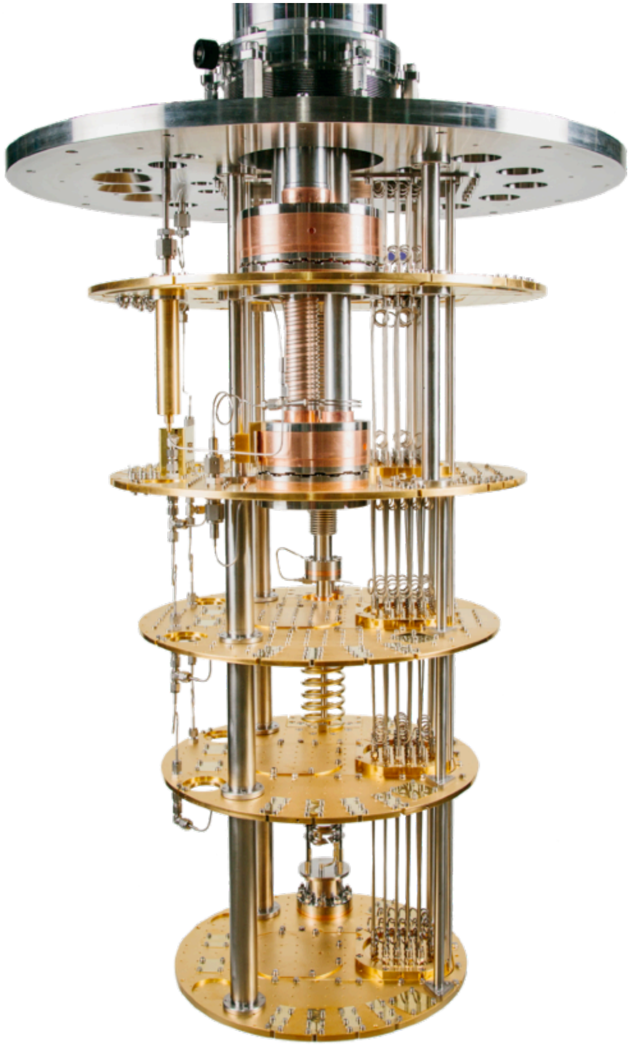
- The number of DULs with cryogenic systems world-wide is very low
- Increased interest in DULs with cryostats globally in recent years
- Evidence for need for such facilities to conduct cutting edge research in some fields (quantum circuits, quantum clocks)
- Can also enhance other kinds of typical DUL research (fundamental physics) by employing cryogenic systems

# Acquisition & Installation

- Proteox MX system underground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines, optical fibre



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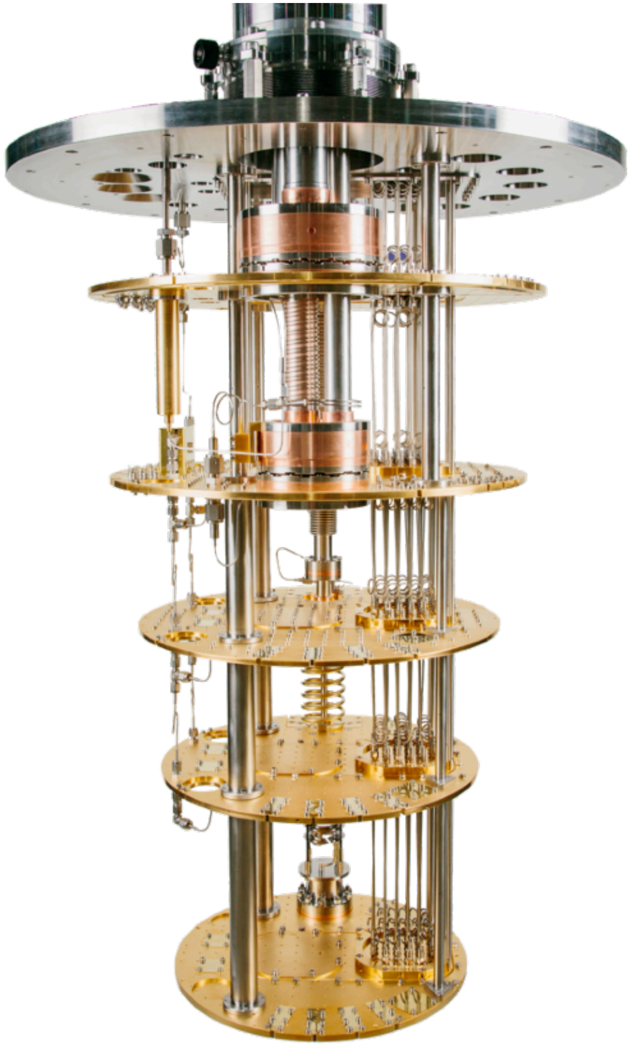

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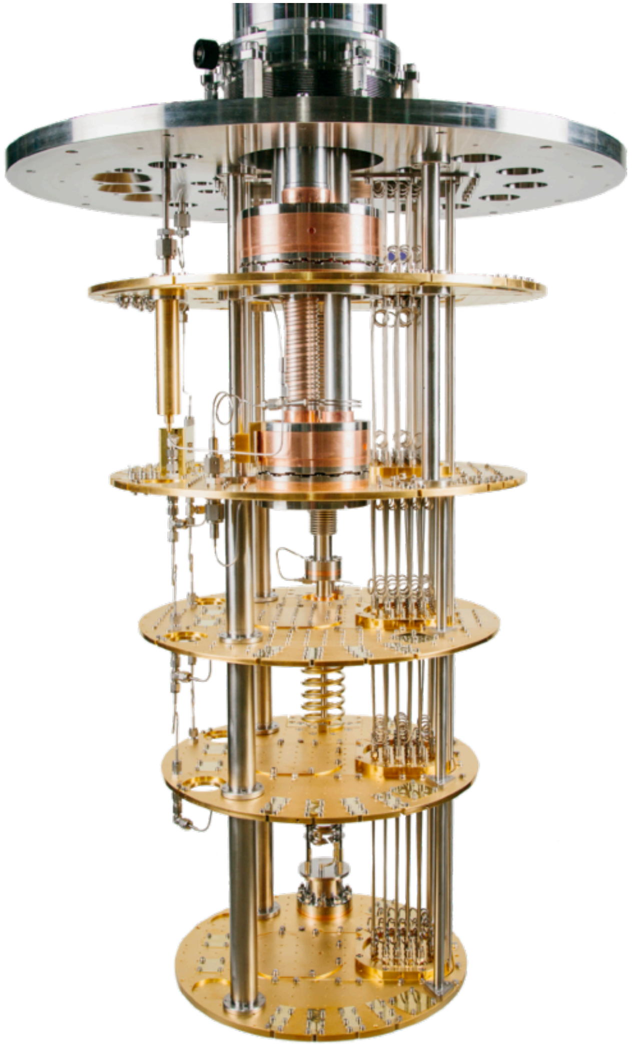
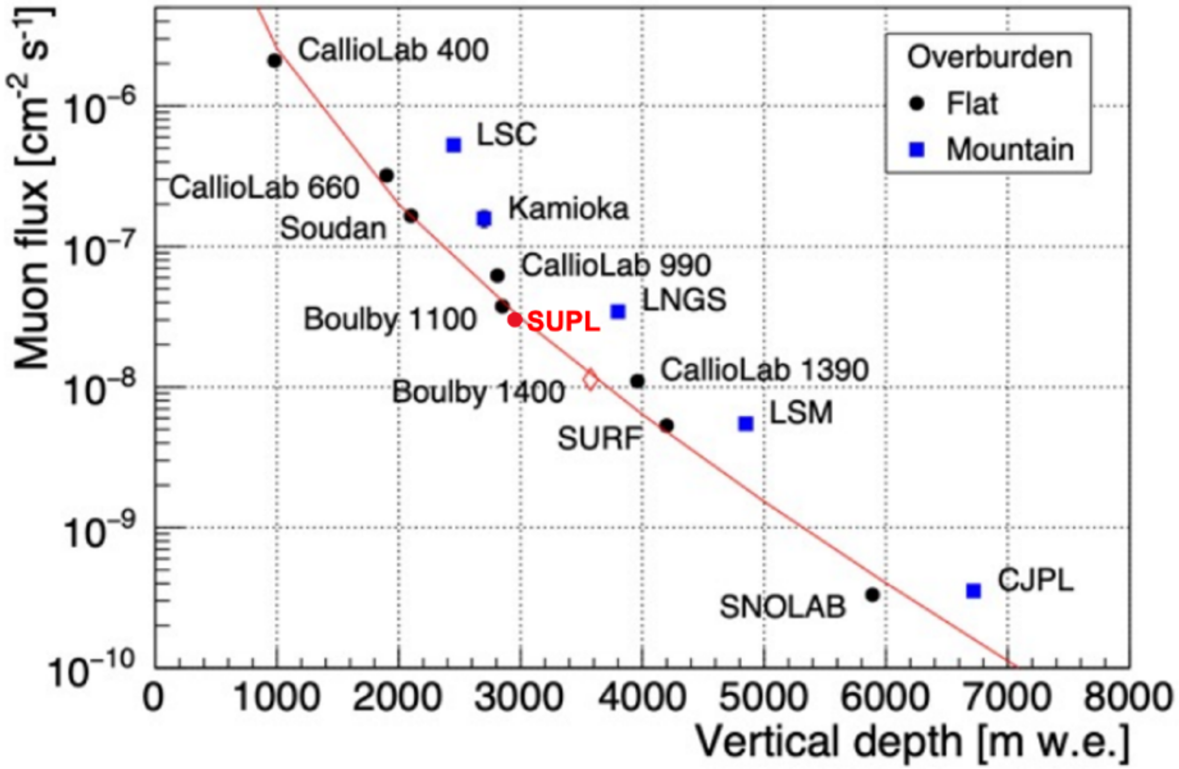
# Acquisition & Installation

- Proteox MX system underground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines, optical fibre
- Proteox S system above ground - 10 mK base, extended tail set, 4+ microwave lines, 24 DC lines
- Working on lead shielding for both systems at the moment



# SUPL - Stawell Underground Physics Laboratory

- Depth of 1025 m gives ~2900 m.w.e
- Flat rock overburden
- Muon flux similar to LNGS, Boulby



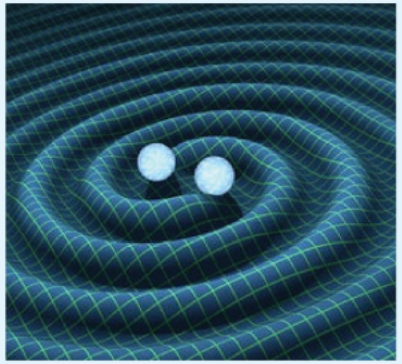
# CELLAR Research

OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

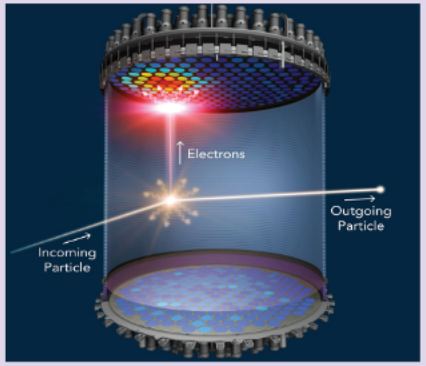
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

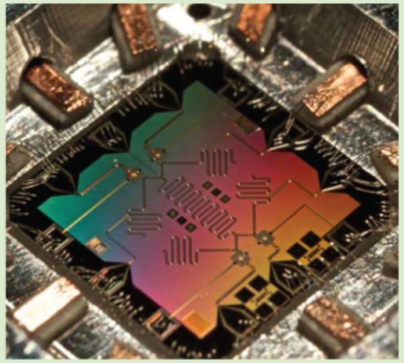
Gravitational wave



Dark Matter



Quantum Tech.



THE UNIVERSITY OF WESTERN AUSTRALIA

THE UNIVERSITY OF MELBOURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

# Dark Matter Research

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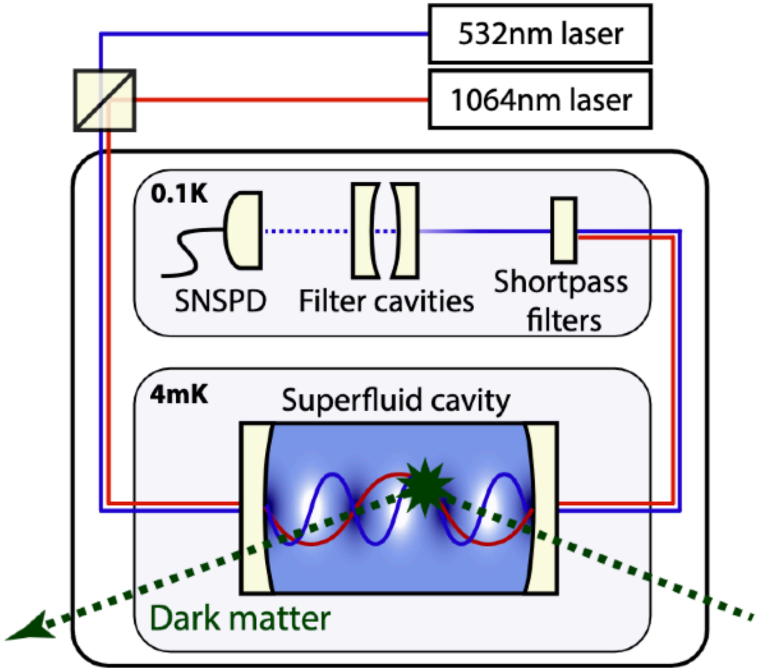
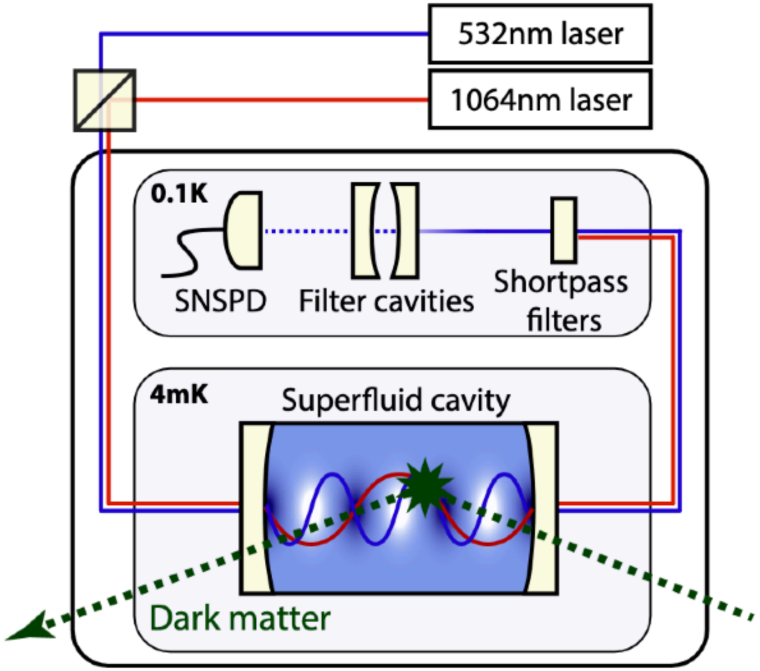


FIG. 1. Schematic diagram of the Optomechanical Dark-matter INstrument (ODIN). Dark matter scatters off a highly populated phonon mode (*scattering mode*), which is optically pumped by a 1064 nm laser. The scattered phonon is converted to an anti-Stokes photon through the optomechanical interaction with a 564 nm laser. The presence of that photon is registered by a single photon detector after passing through a series of optical filters.

https://doi.org/10.48550/arXiv.2306.09726

# Dark Matter Research

- Low mass WIMP regime remains largely unproved (sub 1 GeV)
- Superfluid-based detectors have been identified as a promising platform for dark matter searches in this mass range
- Cannot currently be realised in many underground laboratories owing to the lack of cryogenic facilities
- We plan to demonstrate an underground superfluid-based dark matter detector and probe an interesting region of parameter space



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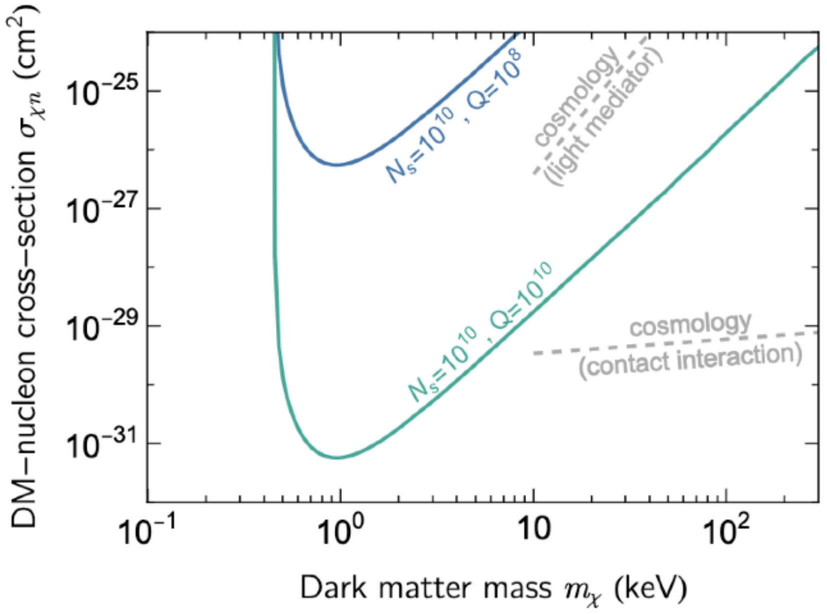

FIG. 4. Projected 90% C.L. upper limits on the dark matter–nucleon cross-section at ODIN, $\sigma_{\chi n}$, assuming a run time of 100 days.

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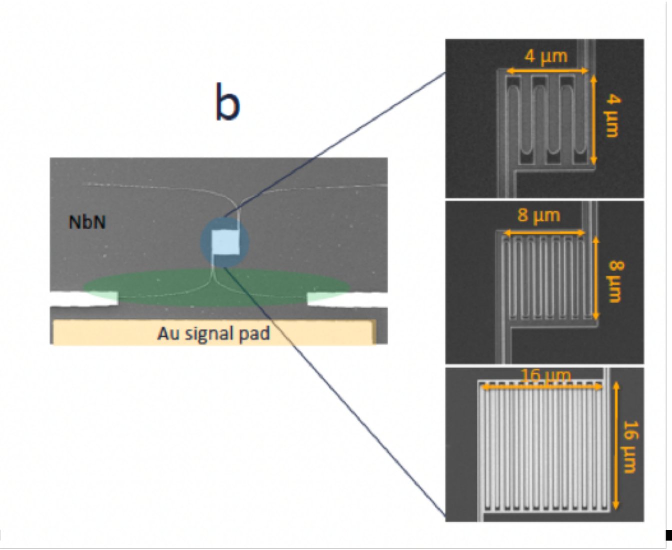
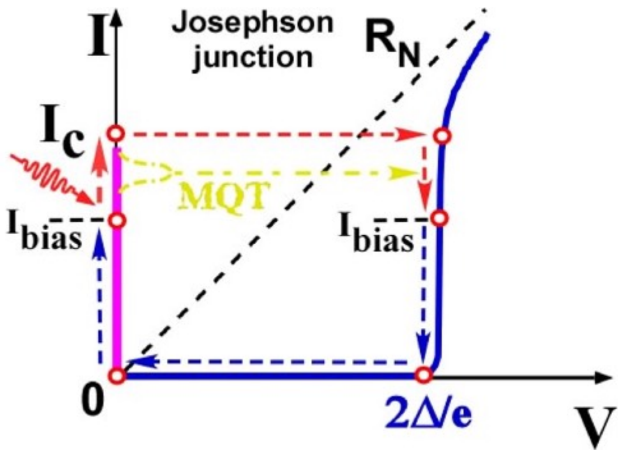
# Dark Matter Research

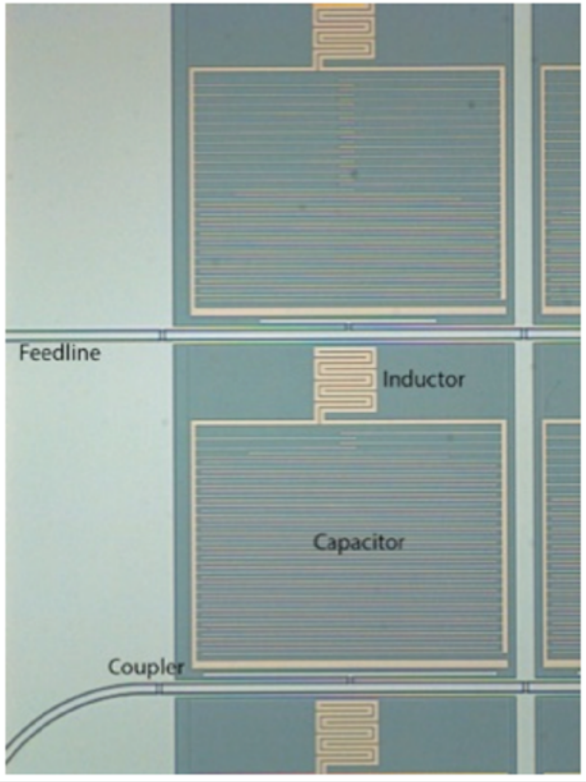
- CELLAR also enables research in new kinds of quantum sensors explicitly for DM detectors, such as new kinds of SNSPDs, MKIDs and TES devices
- This work can largely be done in the surface facility before moving underground
- Could enable new cryogenic WIMP searches in SUPL



Nicolo Petrini, Masters Thesis, MIT, 2019.



L. S. Kuzmin *et al.*, *IEEE Transactions on Applied Superconductivity*, 2018



Mazin Lab, UCSB

# Conclusions

- CELLAR will open in late 2024
- Hosted in SUPL (Victoria, Australia), ~2900 m.w.e
- Plans for research in quantum technology, dark matter, other new physics such as HFGWs
- Two dilution refrigerators, one at Swinburne and one in SUPL
- Very open to domestic international collaboration