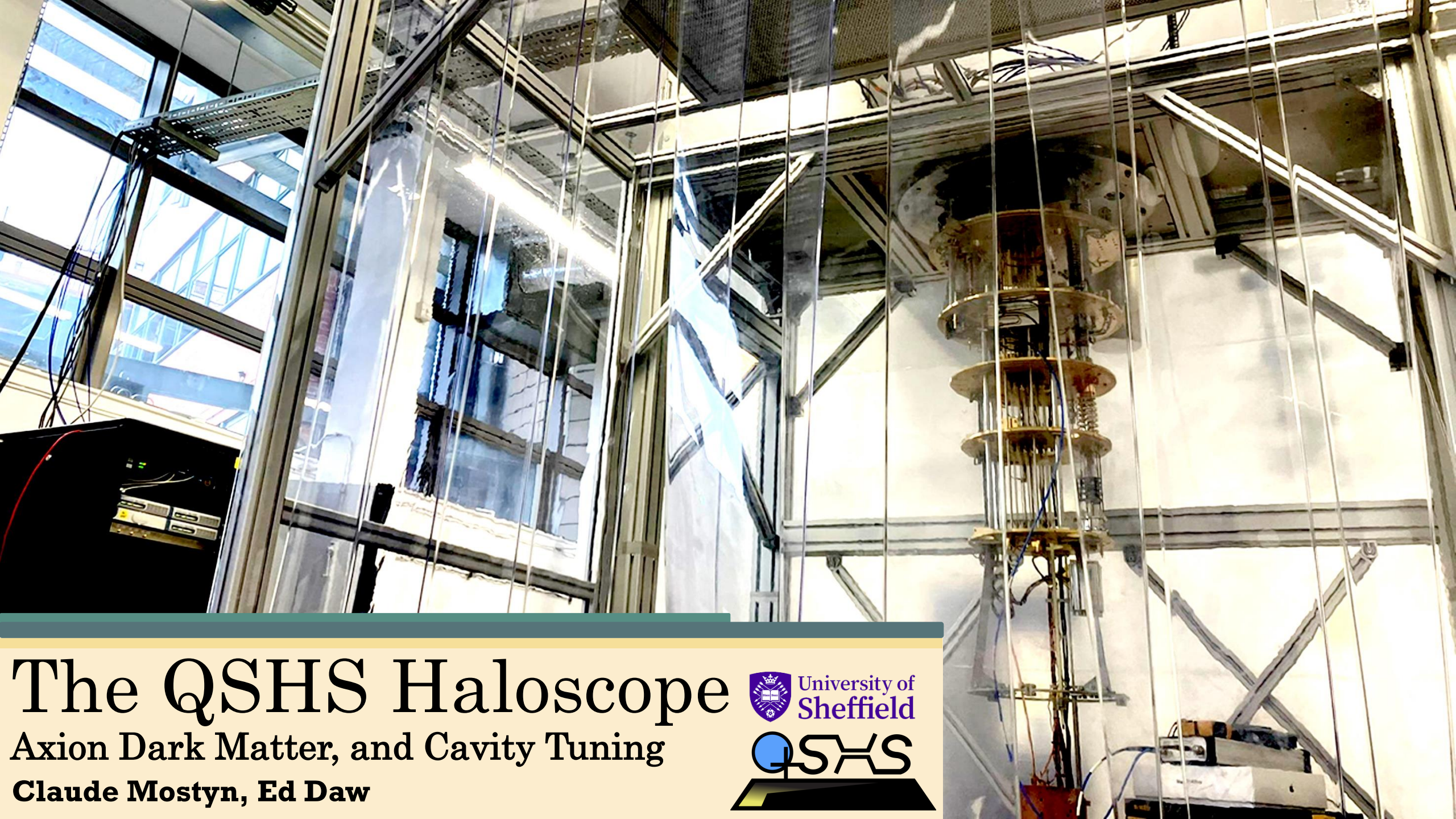

The QSHS Haloscope

Axion Dark Matter, and Cavity Tuning

Claude Mostyn, Ed Daw

University of Sheffield

QSHS

The QSHS Haloscope

Claude Mostyn

1 The Strong CP Problem

- Charge Parity violation in quantum chromodynamics (QCD) can be measured using the neutron electric dipole moment (NEDM)
- No NEDM has been detected, limiting the CP violating angle of the strong force to $\bar{\theta} < 5 \times 10^{-11}$ [1]
- "Fine tuning problem" found in 1970s, requires two CP violating terms in QCD Lagrangian to cancel

NEDM $< 10^{-26}$ e − cm

So, CP Violating Angle of QCD:

$$\bar{\theta} < 5 \times 10^{-11}$$

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Standard model symmetry groups:

QCD		Electroweak		EM
$SU(3)$	$\times$	$SU(2)$	$\times$	$U(1)$
Non-Abelian		**Non-Abelian**		**Abelian**
CP Conserving?		CP Violating		CP Conserving

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Also, Two Independent CP Violating Terms in QCD Lagrangian

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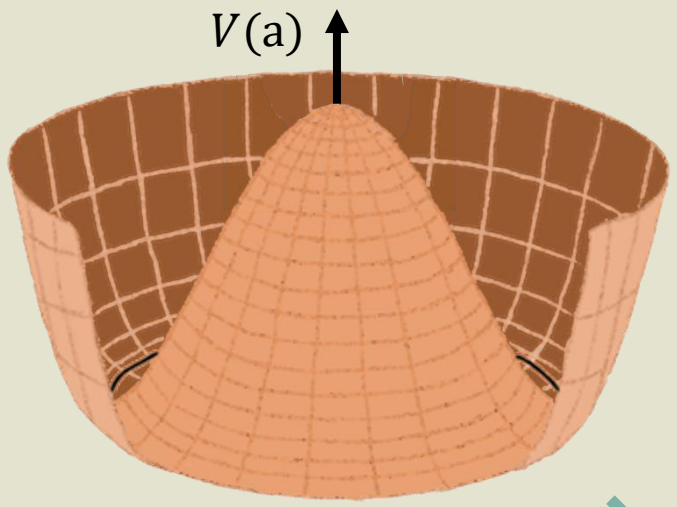
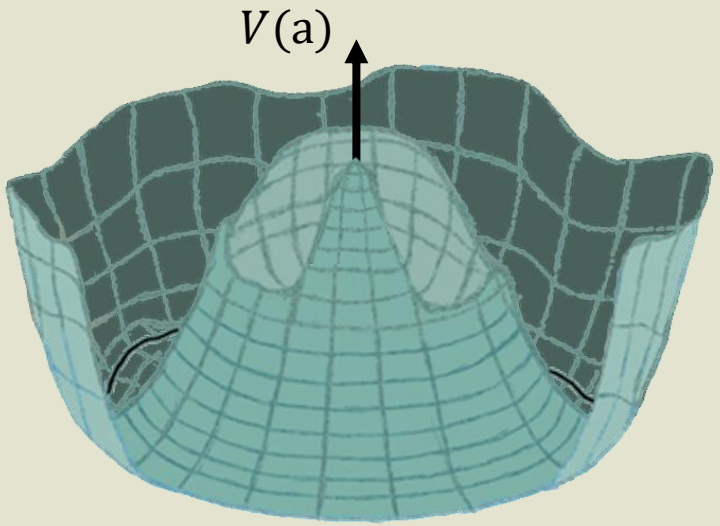
2 Peccei Quinn Theory

- Peccei and Quinn (PQ) propose promoting $\bar{\theta}$ to a dynamic variable with associated new pseudoscalar PQ/axion field
- In the very early universe, the field's potential is symmetric and CP violation spontaneously occurs in QCD
- U(1) symmetry then breaks and field takes on minimum energy value setting $\bar{\theta}$ to 0, oscillations of the field about that minima create axions



At a lower (but still early universe) energy f_a, the PQ field symmetry breaks
The potential now has many sharp minima

Symmetry breaks at f_a



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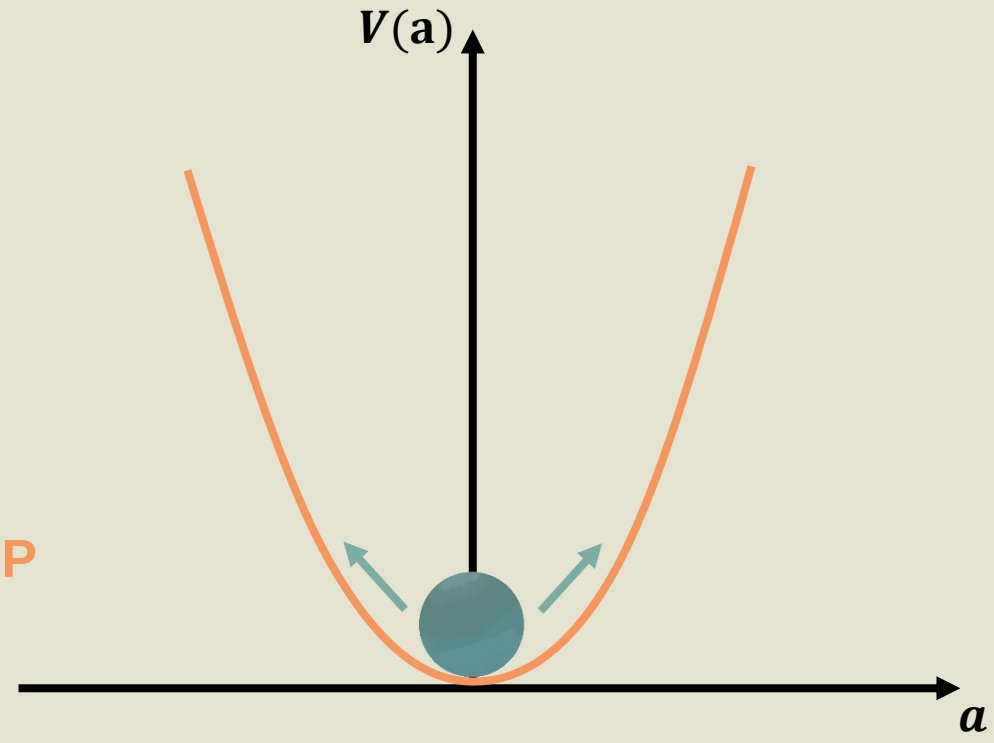
Oscillations about the minima create

Pseudo Nambu-Goldstone Bosons

Associated with pseudoscalar field

Scientists who discovered this type of boson

Axions!



The field rolls into one of these minima, naturally setting $\bar{\theta}$ to zero

QCD has to conserve CP symmetry!

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- ***Weak Coupling to Other Particles!***

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Could be Dark Matter Too!

The QSHS Haloscope

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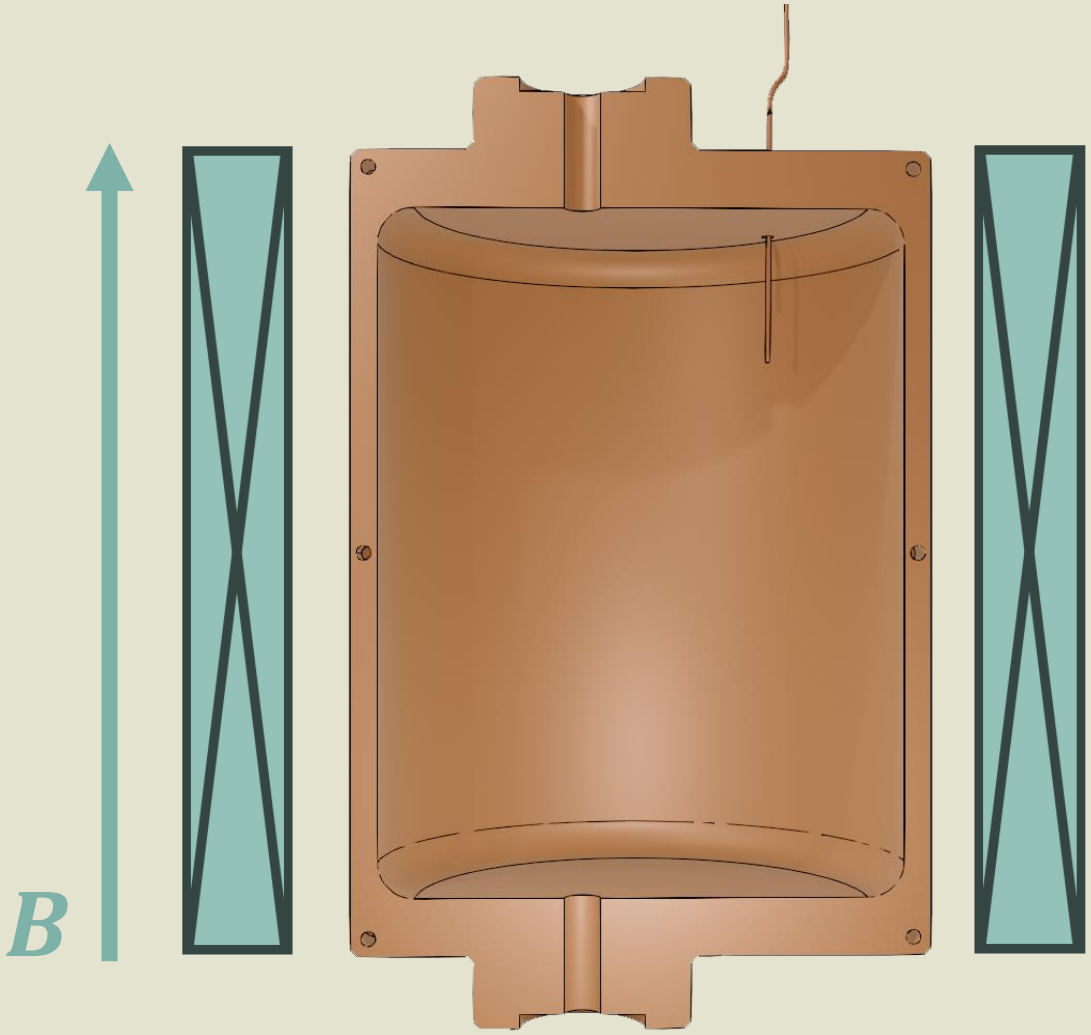
3 Axion Haloscopes

- An axion haloscope uses a cavity with resonant frequencies in the microwave region placed in uniform magnetic field
- Axions can decay into photons within the field in a Primakoff-effect-like process
- If the axion-mass dependent photon frequency matches the cavity's the signal will be resonantly amplified



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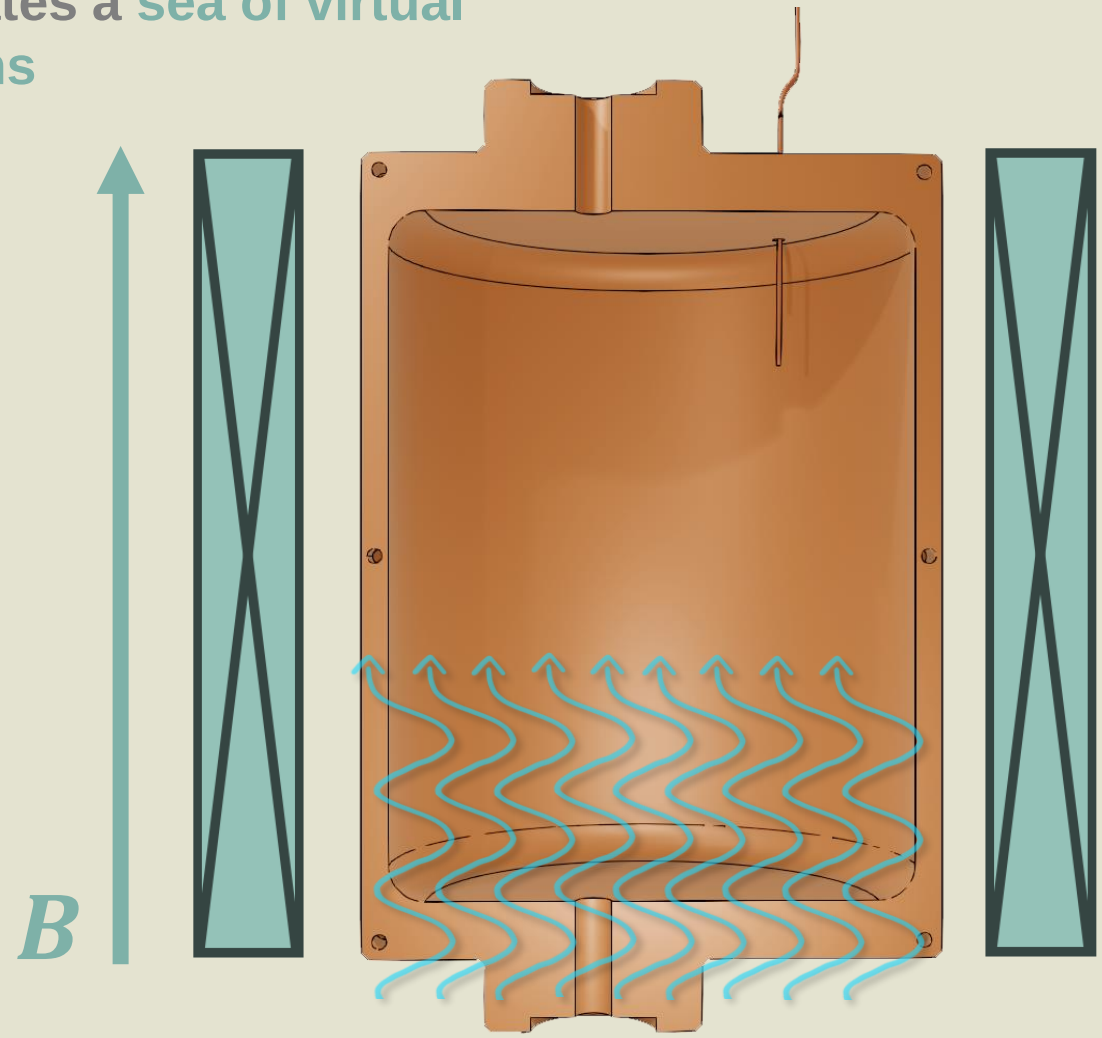
External magnetic field generates a sea of virtual photons



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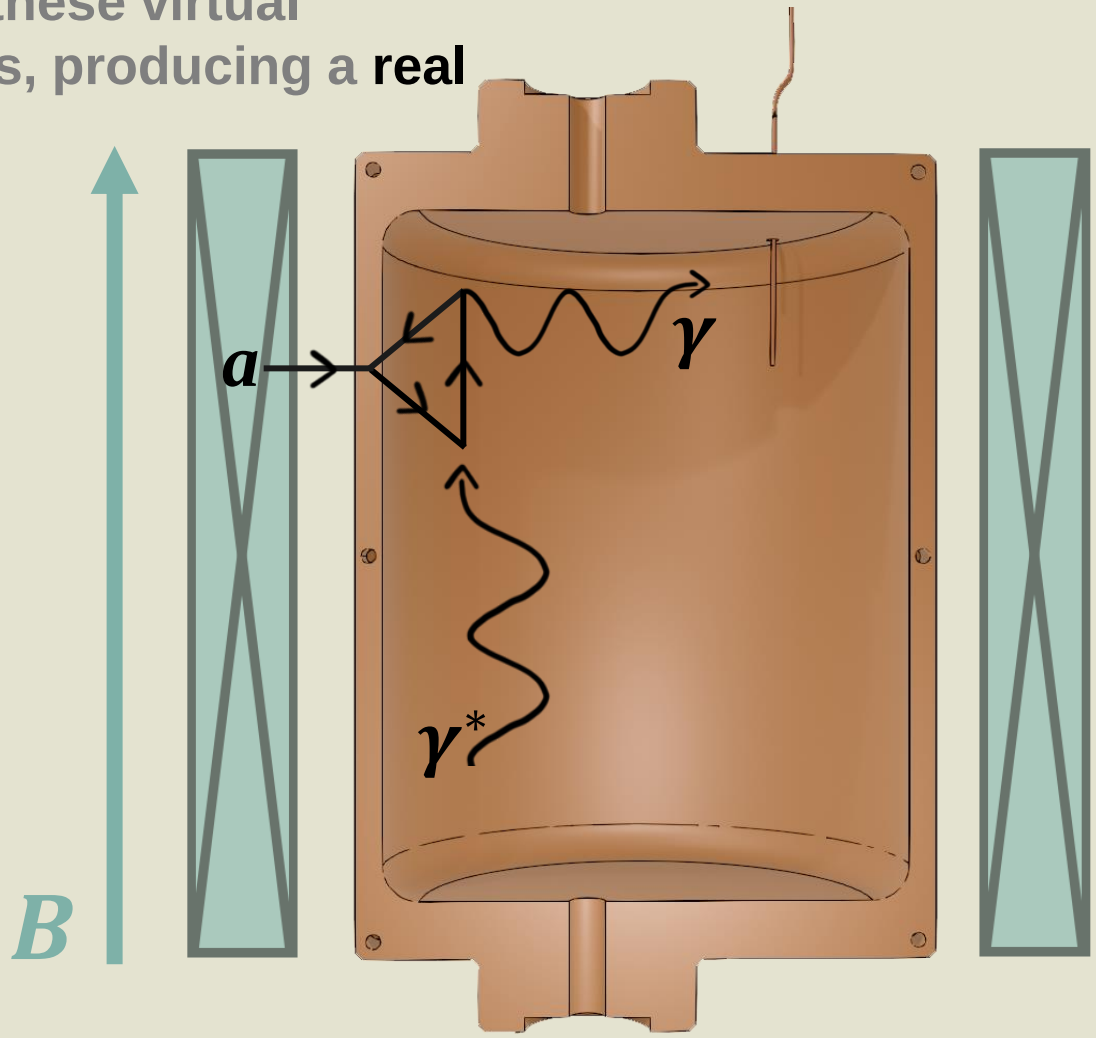
An **axion** can interact with one of these virtual photons, producing a **real photon**



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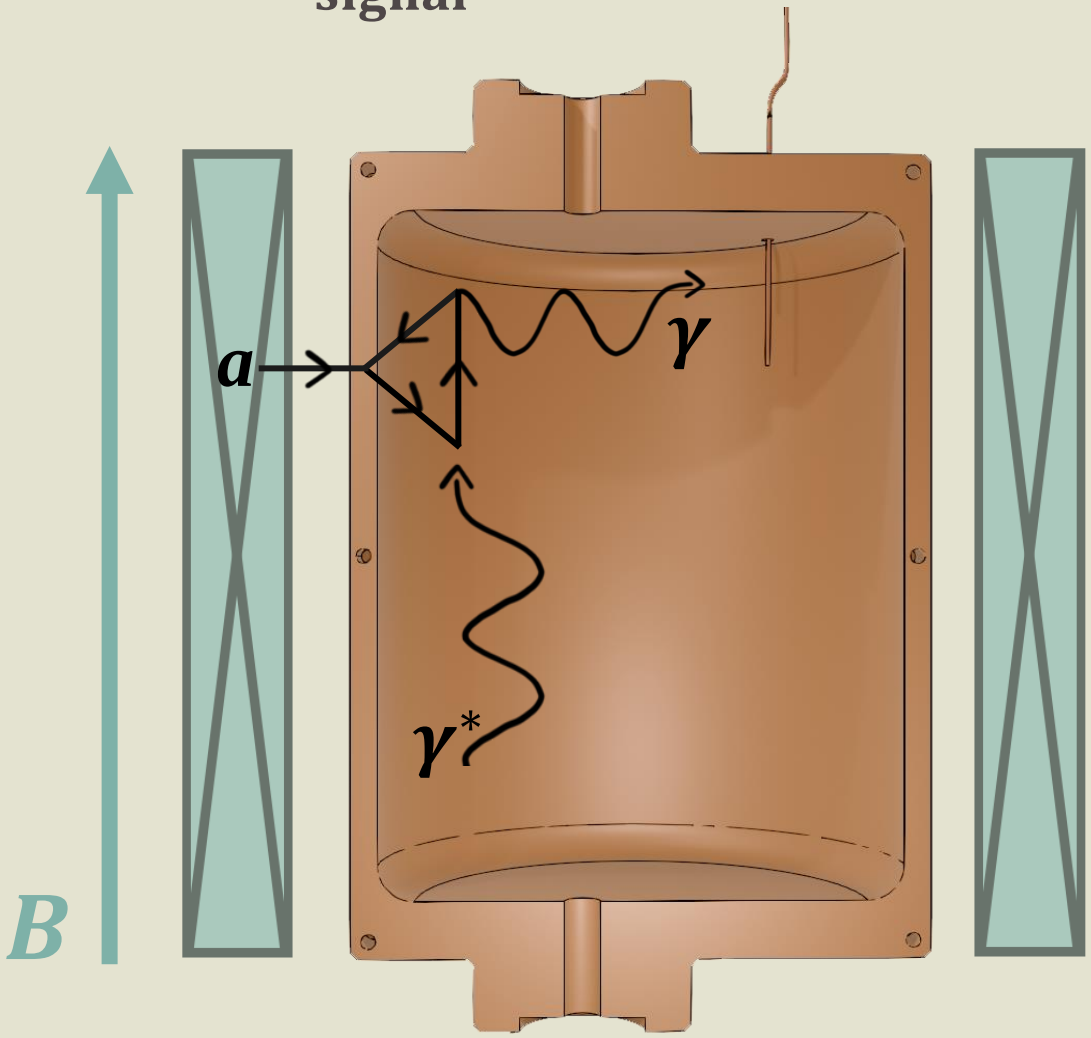
$$P_{\text{signal}} \approx 10^{-22} \text{ to } 10^{-24}\text{W}$$



The QSHS Haloscope

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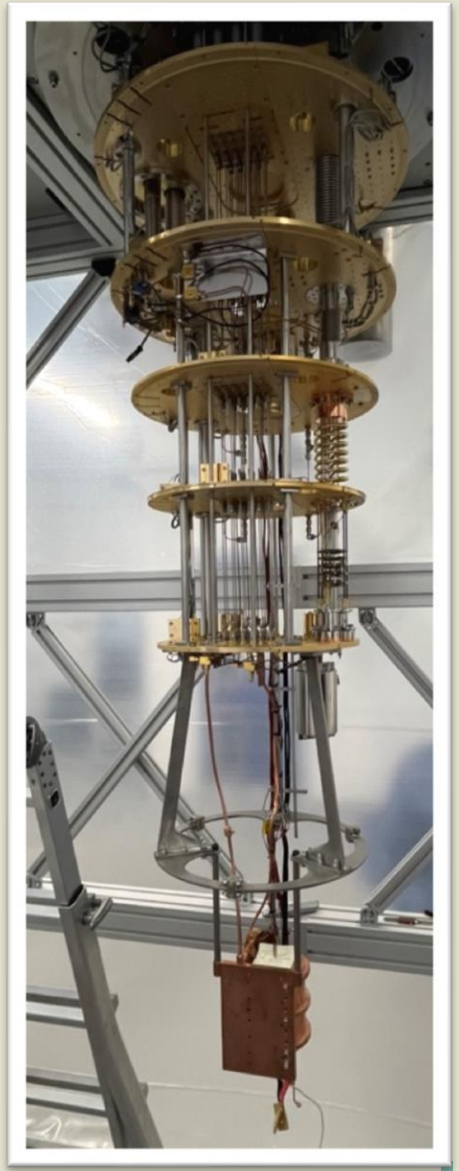
4 The Dilution Refrigerator

- A dilution refrigerator with minimum temperature 8.5 mK was installed at the University of Sheffield in February 2024
- A He3-He4 mixture separates into a liquid-like concentrated He3 phase and a gas-like dilute He3 phase. Evaporation between these phases at the lowest mixing chamber plate creates the low temperatures
- The He3 is then pumped off the mixture at the still, recooled, and recondensed into the mixture

Feb 2024



Jan 2025

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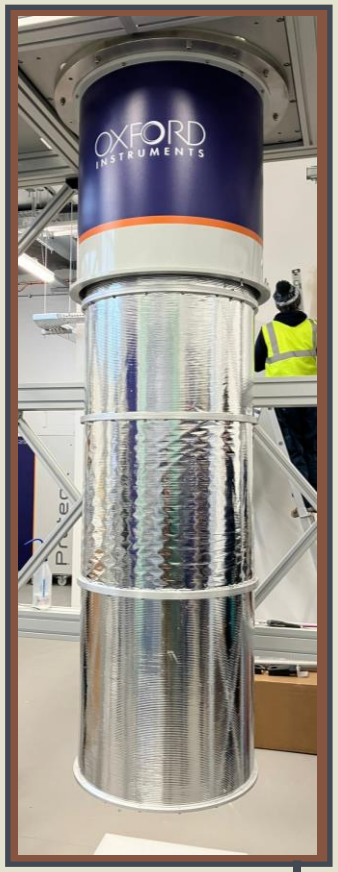

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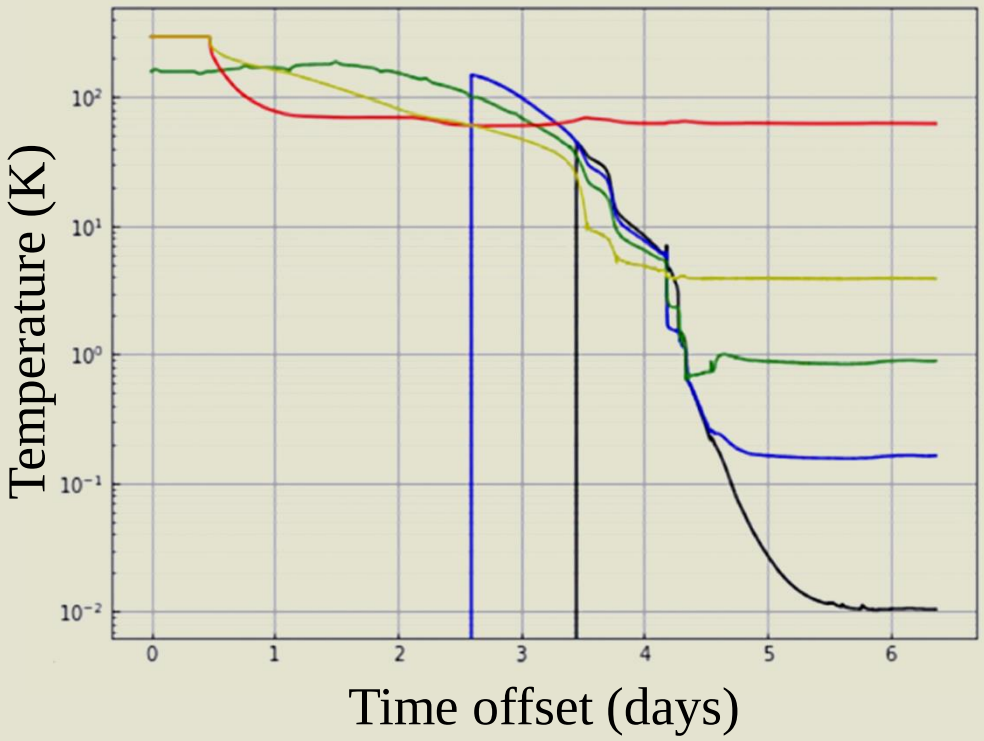

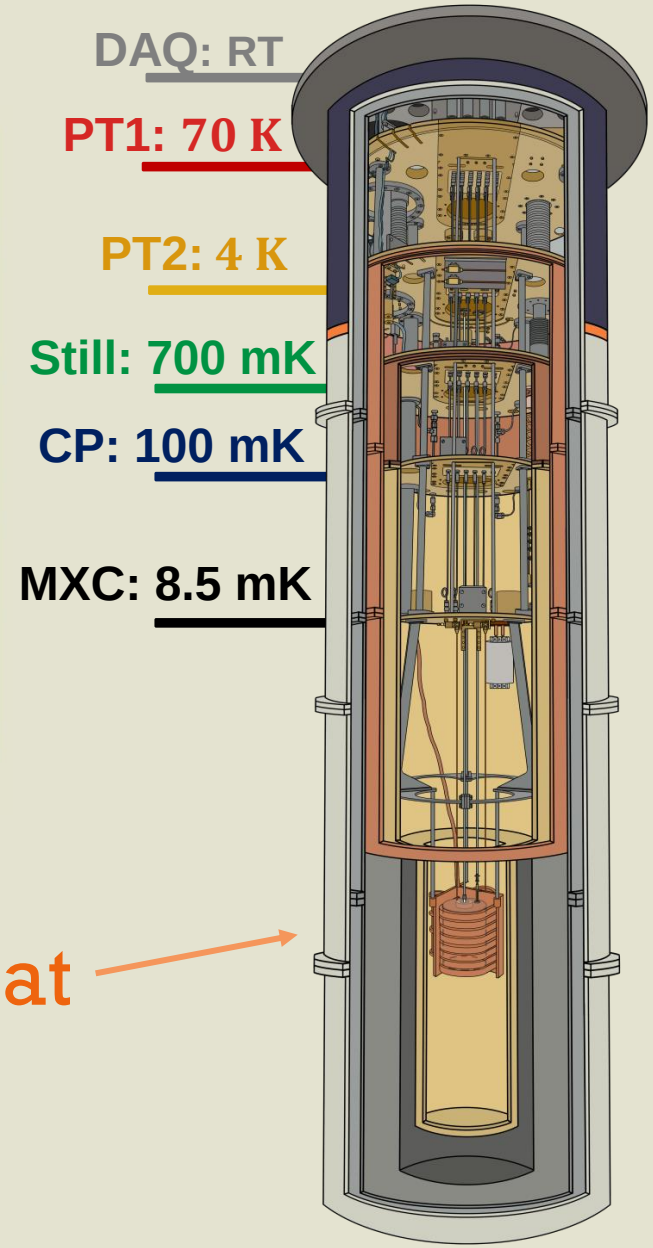

Cavity at 18 mK

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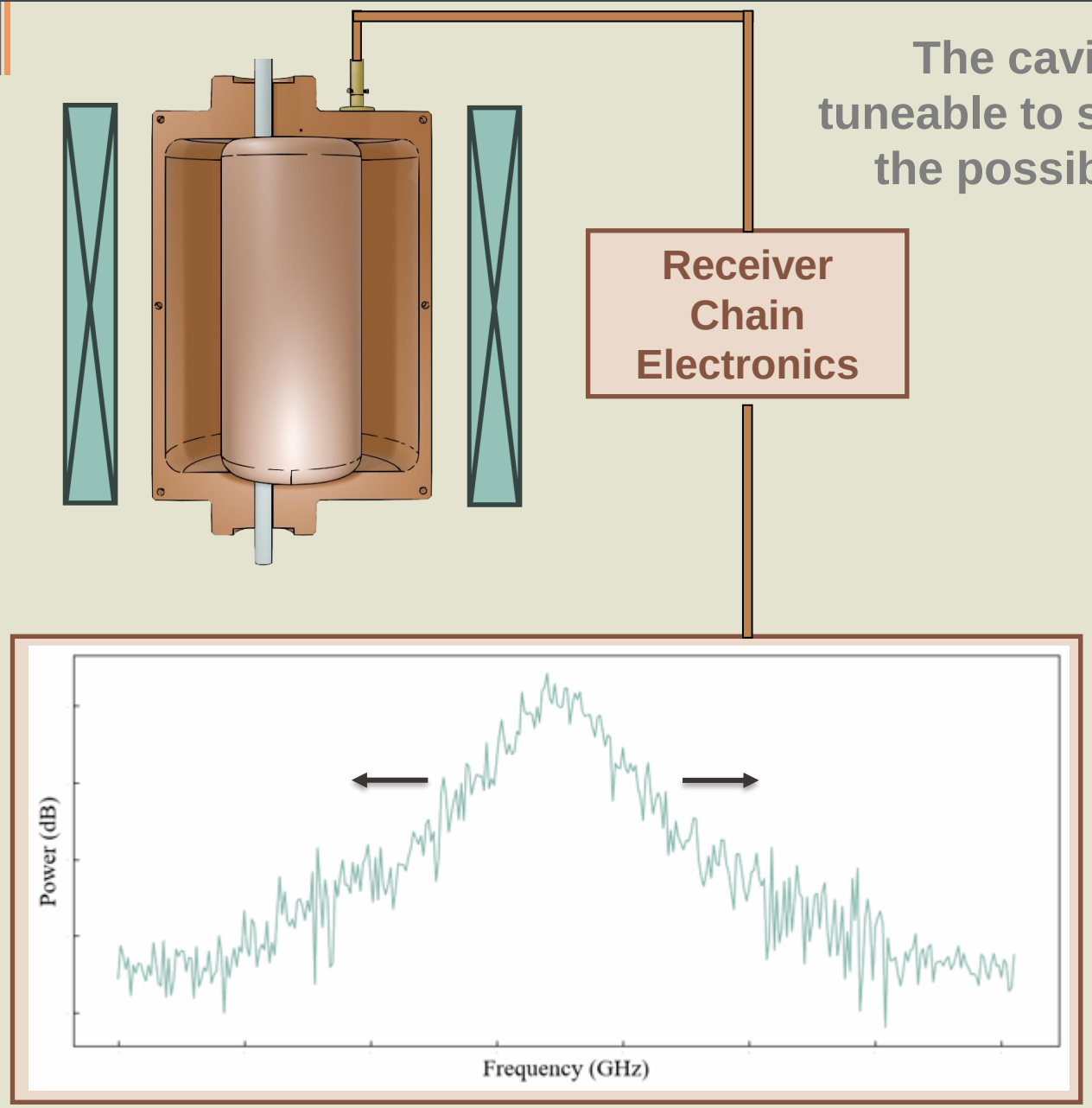
5 Mechanising the Cavity

- PQ theory does not provide a preferred axion mass, so the cavity must be tuneable to allow a range of possible masses/frequencies to be searched
- The tuning rod and an adjustable antenna are controlled by piezomotors mounted on the 4 K plate
- The antenna uses a rotational-to-linear coupler to allow critical coupling to be maintained at cryogenic temperatures without lubrication



The cavity needs to be tuneable to search more of the possible axion mass space

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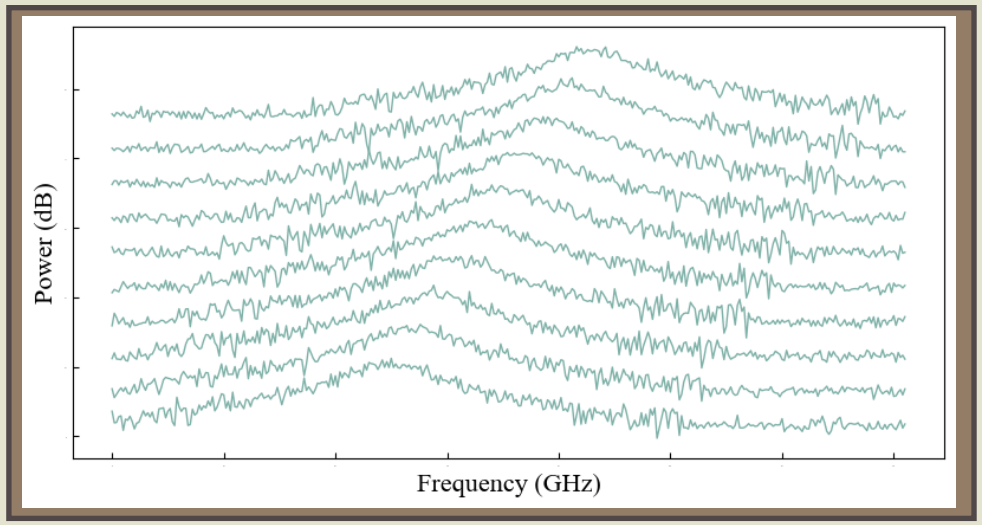

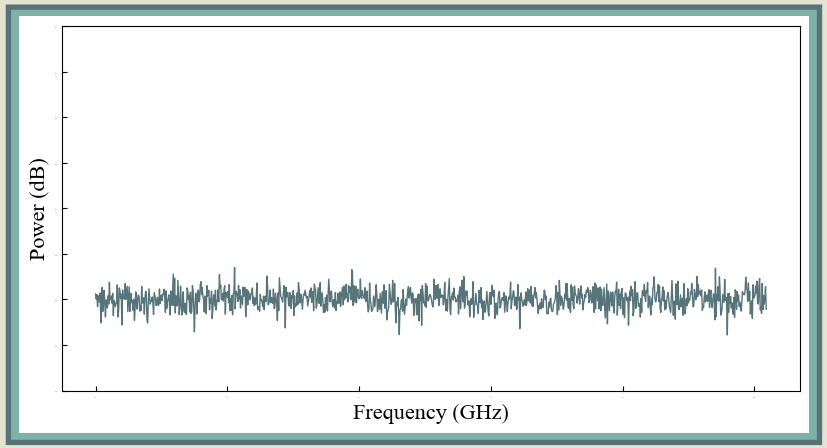

The cavity needs to be tuneable to search more of the possible axion mass space

Slow steps are taken and the powers of the TM010 resonant mode measured at each

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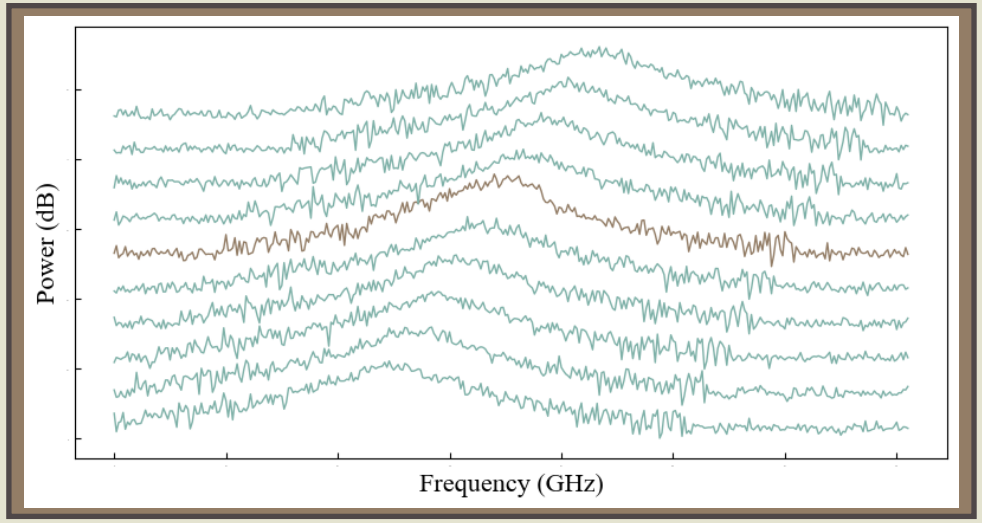

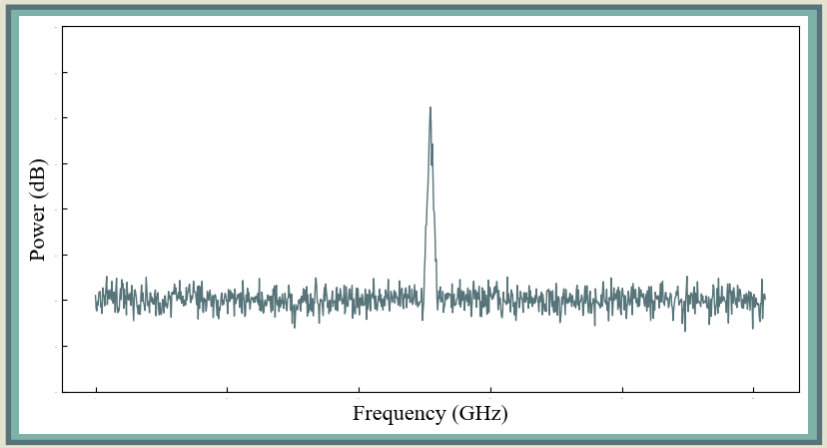

The cavity needs to be tuneable to search more of the possible axion mass space

Slow steps are taken and the powers of the TM010 resonant mode measured at each

An axion signal would appear as a small excess of power at one frequency

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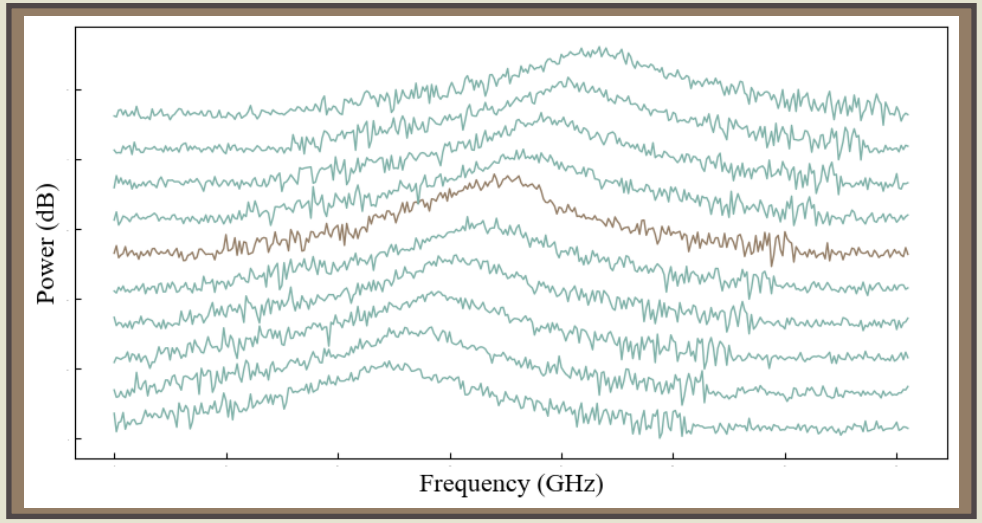

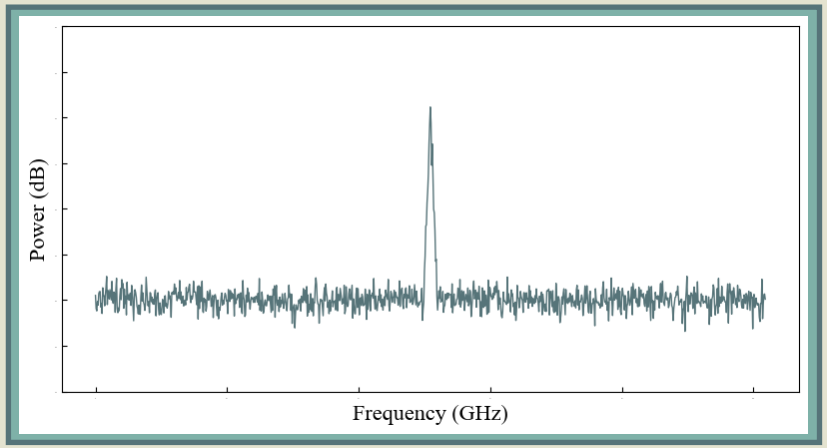

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Need to Mechanise the cavity

Need to be able to identify the TM_{010} mode

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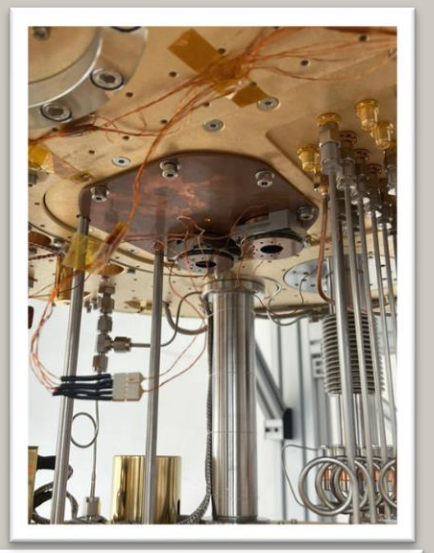

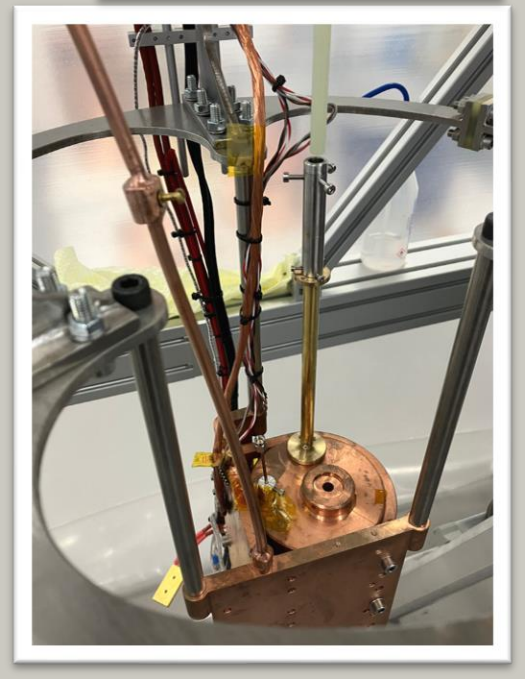

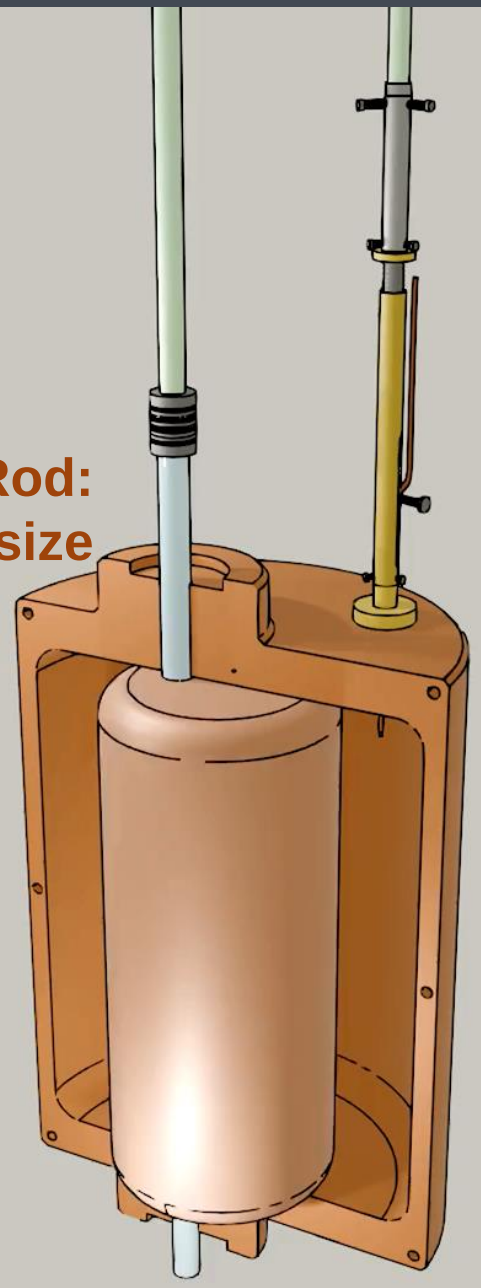

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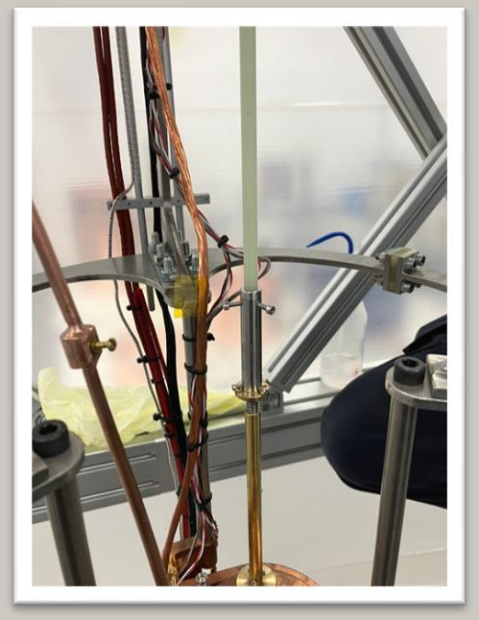
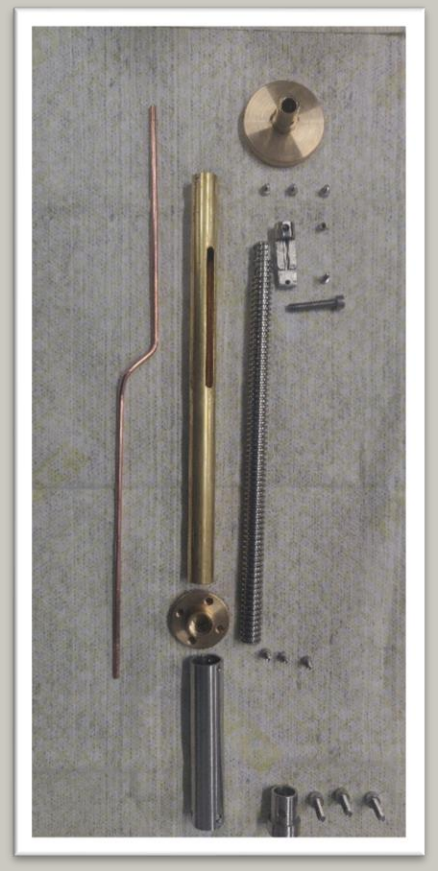
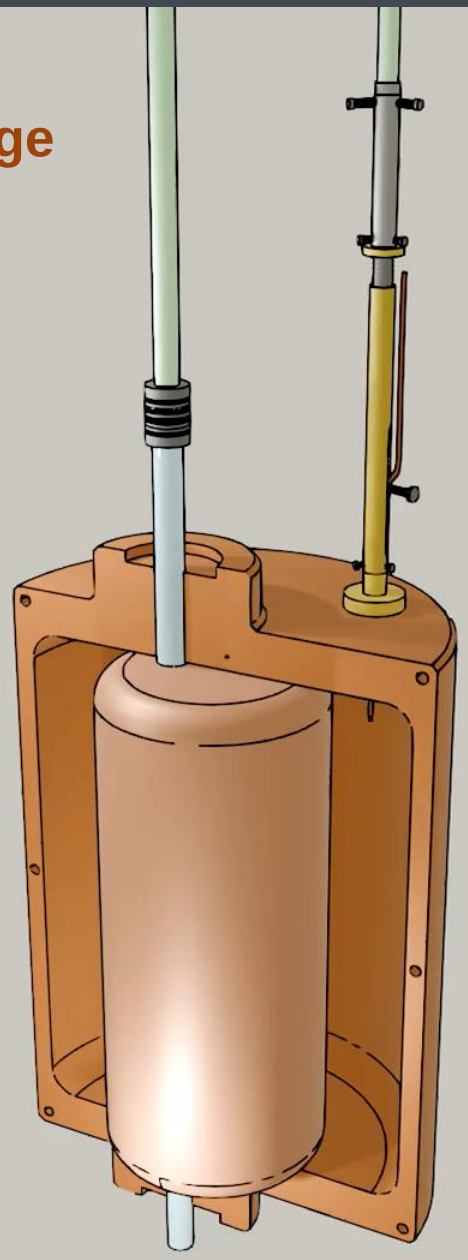


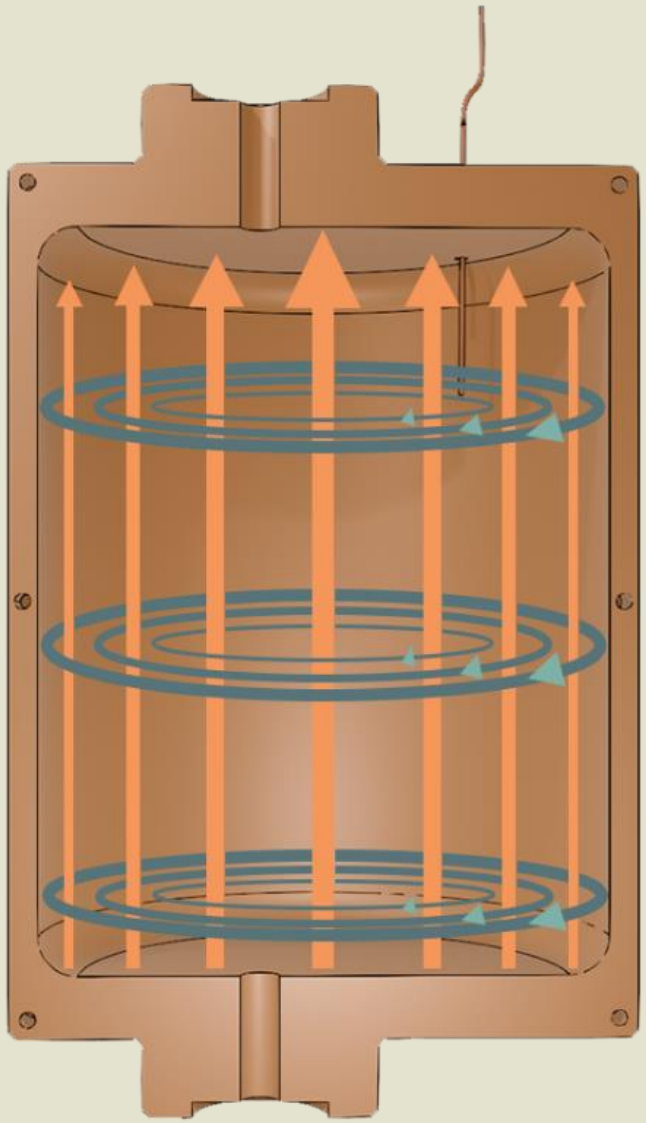
Antenna:
2 mm insertion change per rotation





6 Tracking the TM_{010} Mode

- Axion sensitivity is maximised when the cavity mode's ***E*** field's overlap integral with the external ***B*** field over the cavity's volume is maximised, expressed as a form factor
- During tuning the target mode is affected by stationary-frequency intruder modes
- Careful tracking, ANSYS simulations, and peak fitting are needed to handle mode hybridisation, and distorted modes while accurately calculating the sensitivity



The target resonant mode is the most fundamental transverse magnetic mode TM_{010}

The Lagrangian term for the coupling of the axion to the EM field:

$$\mathcal{L} = -\varepsilon_0 g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

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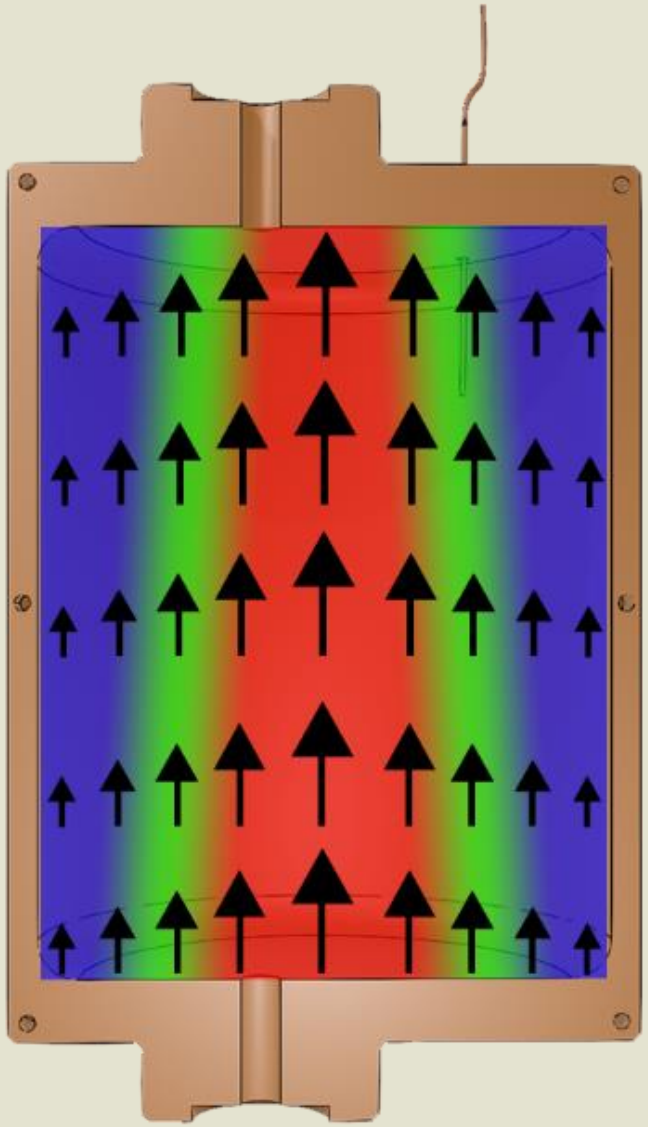

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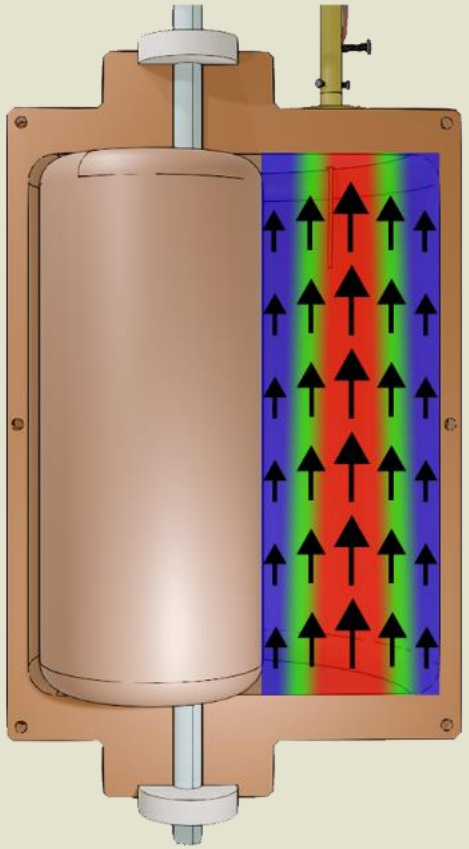

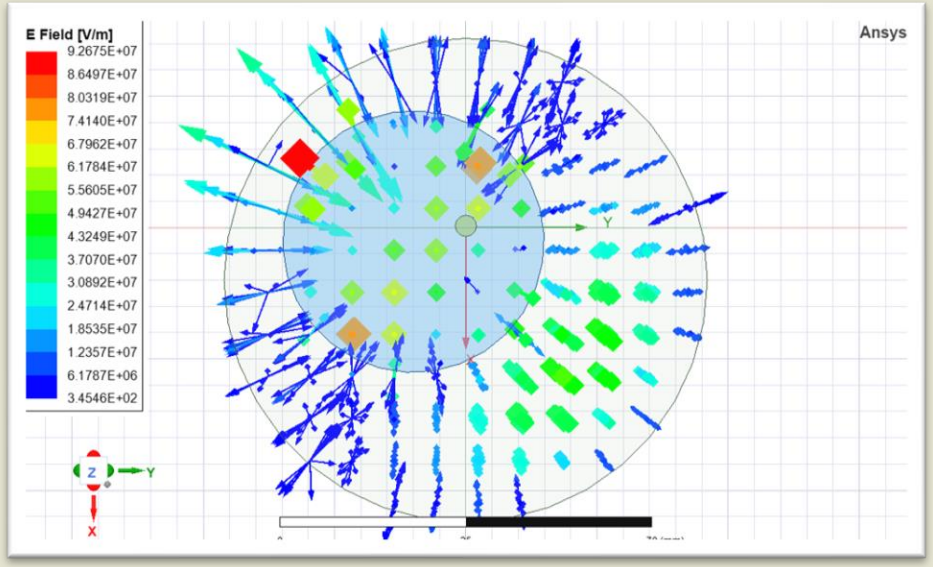

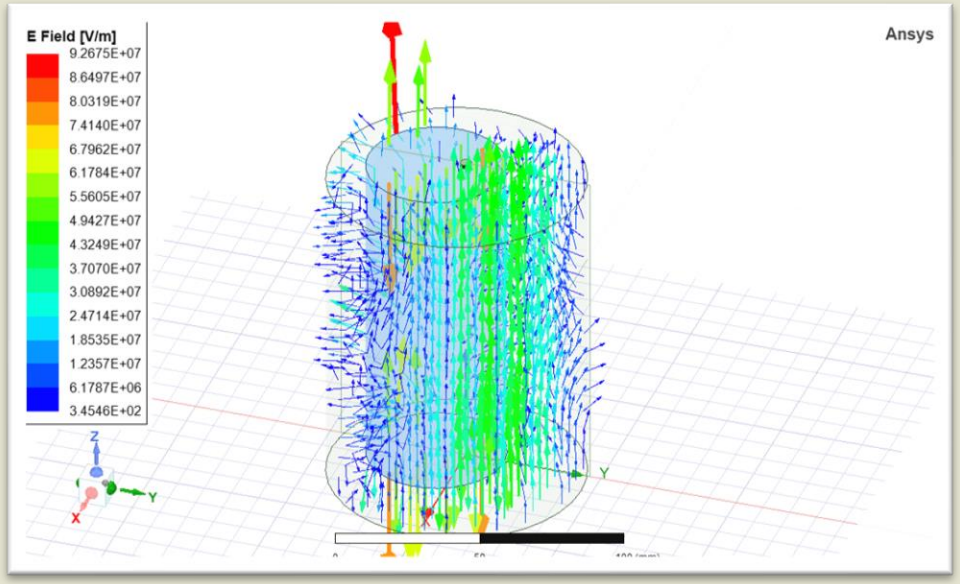

The QSHS Haloscope

Claude Mostyn

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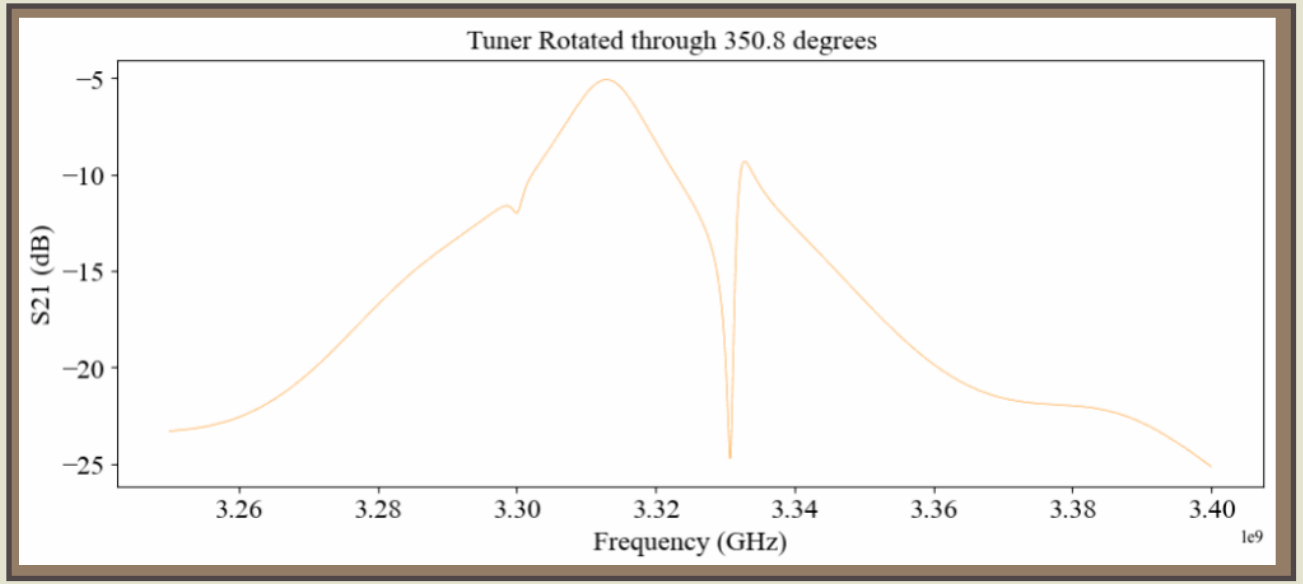

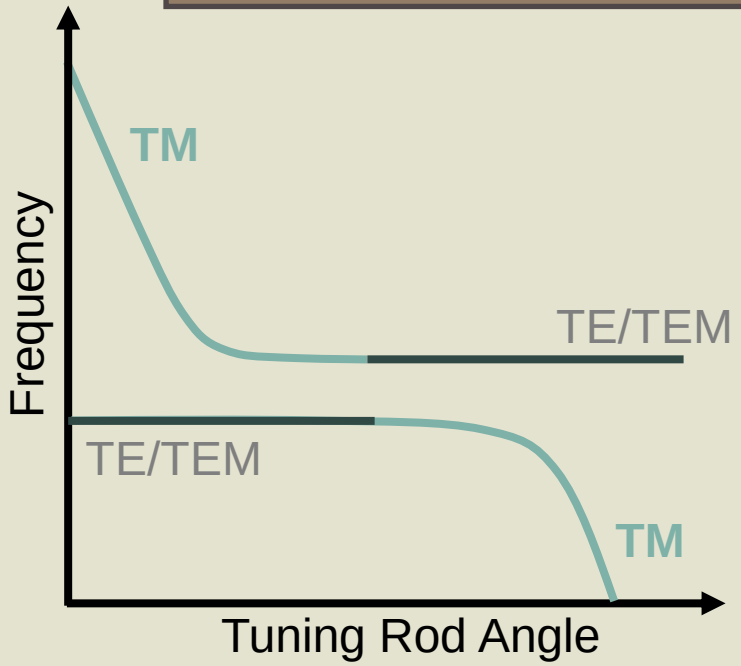

Incoming TM mode mixes with constant frequency TE/TEM mode, becoming less "TM-like"

Eventually the two swap and the TM mode continues moving

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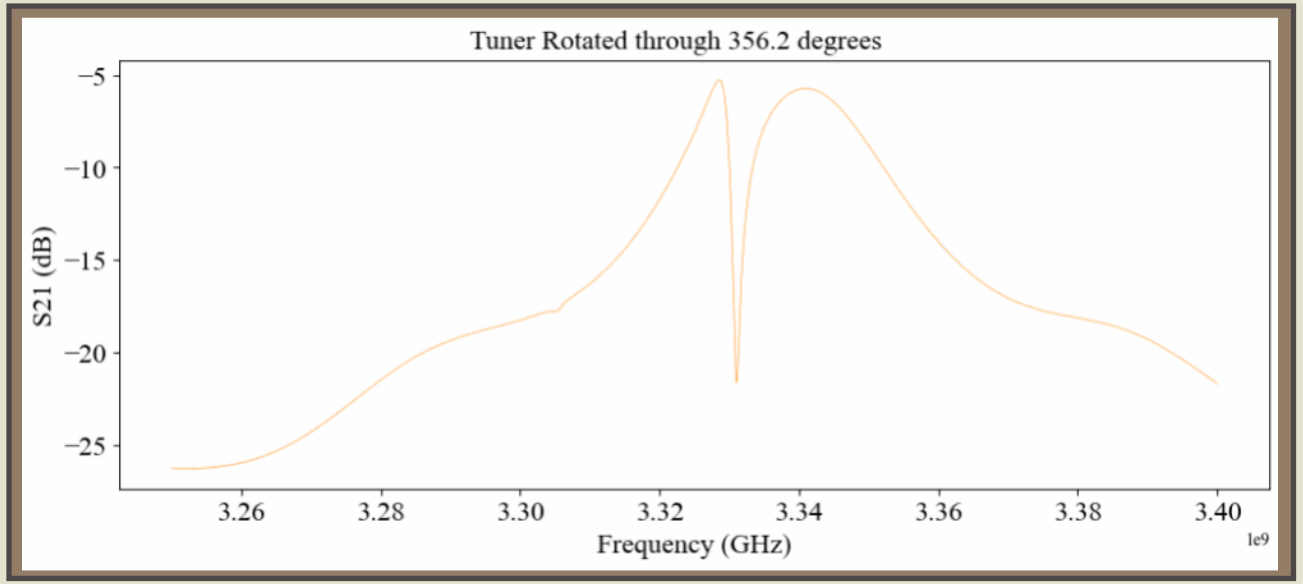

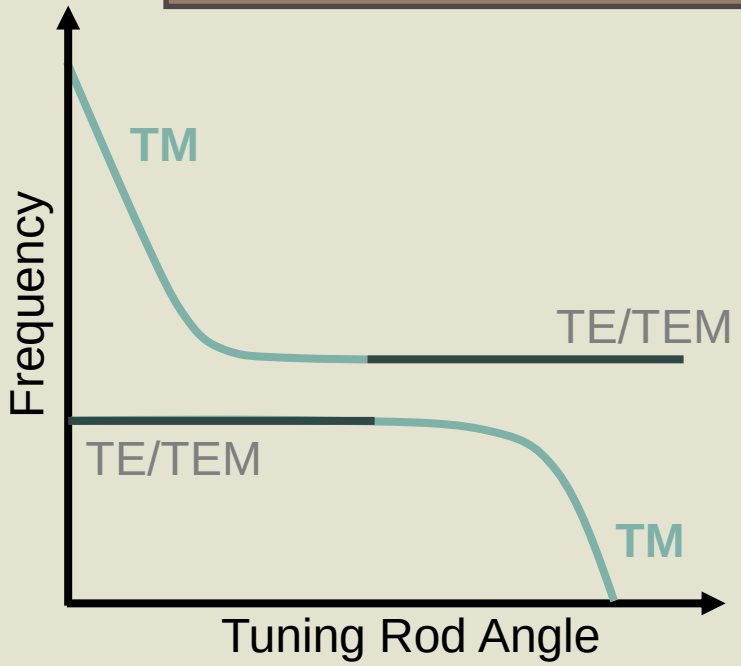

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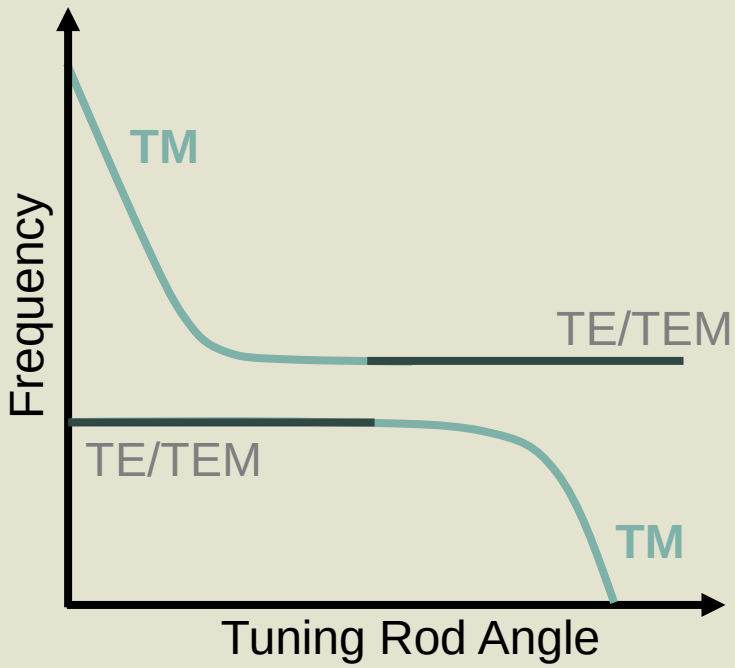

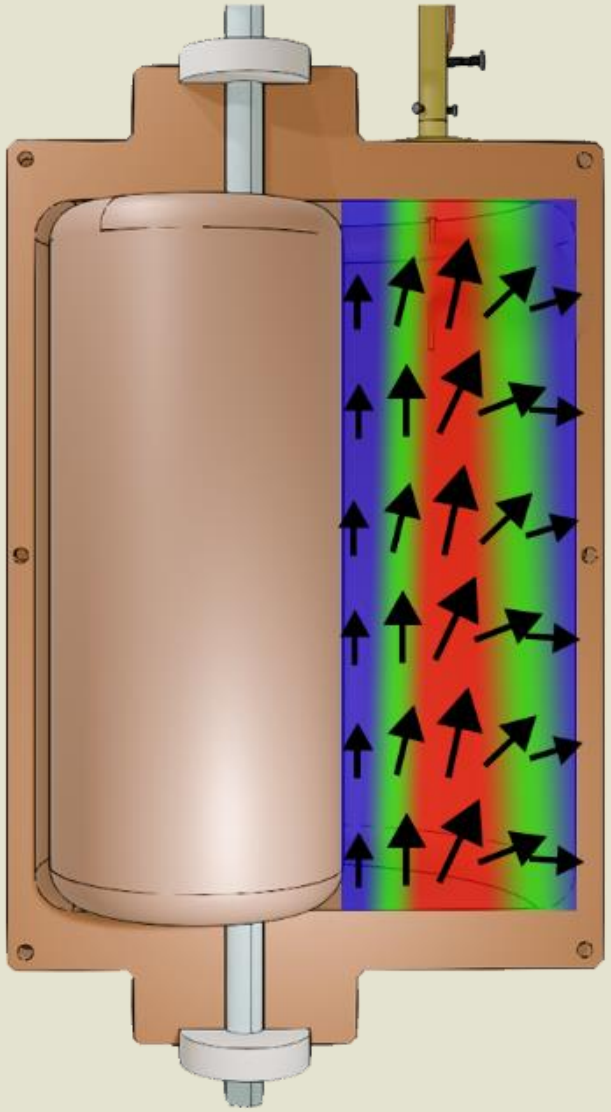

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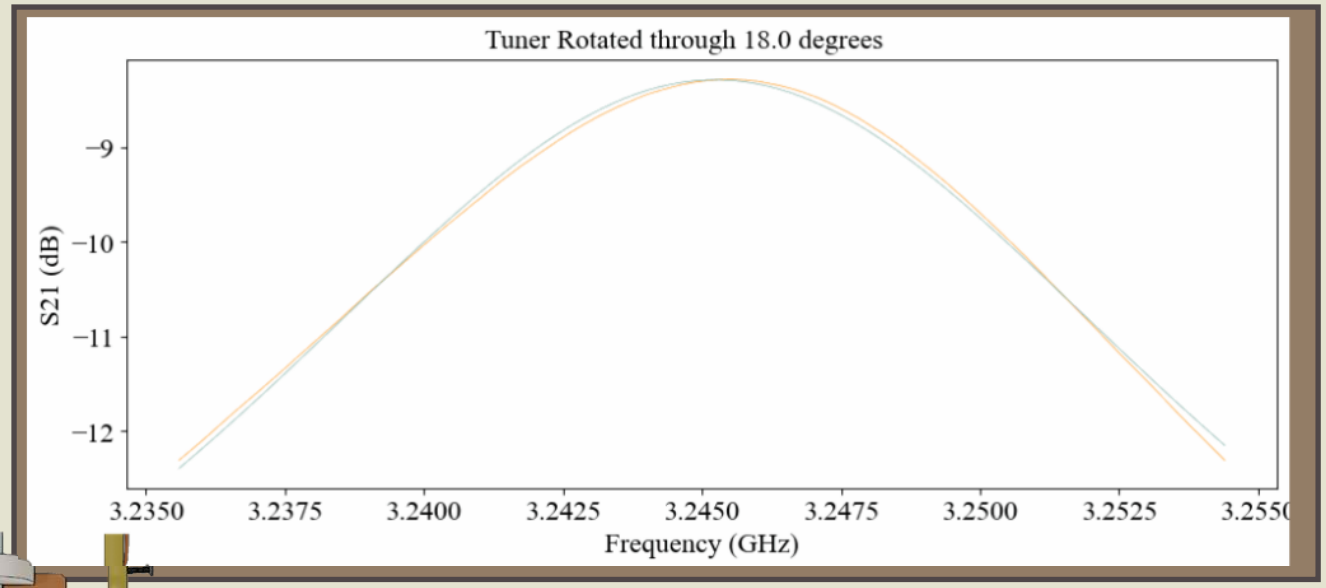

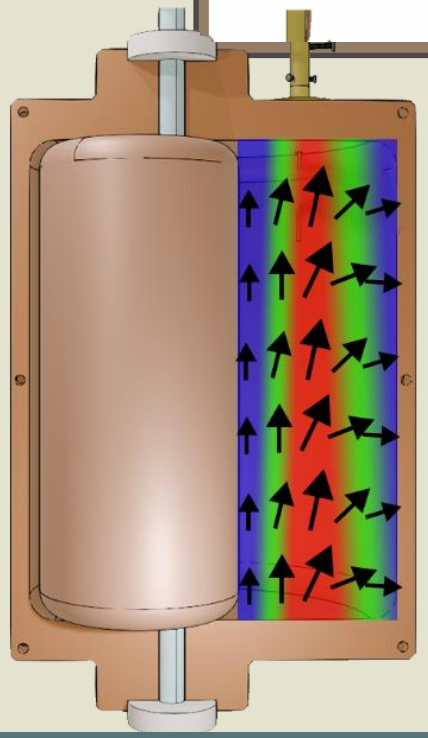

During mode crossings, the TM mode is distorted/pulled down requiring more complicated fits, accurate estimations of mixed mode form factors, and use of multiple modes to maintain sensitivity

The QSHS Haloscope

Claude Mostyn

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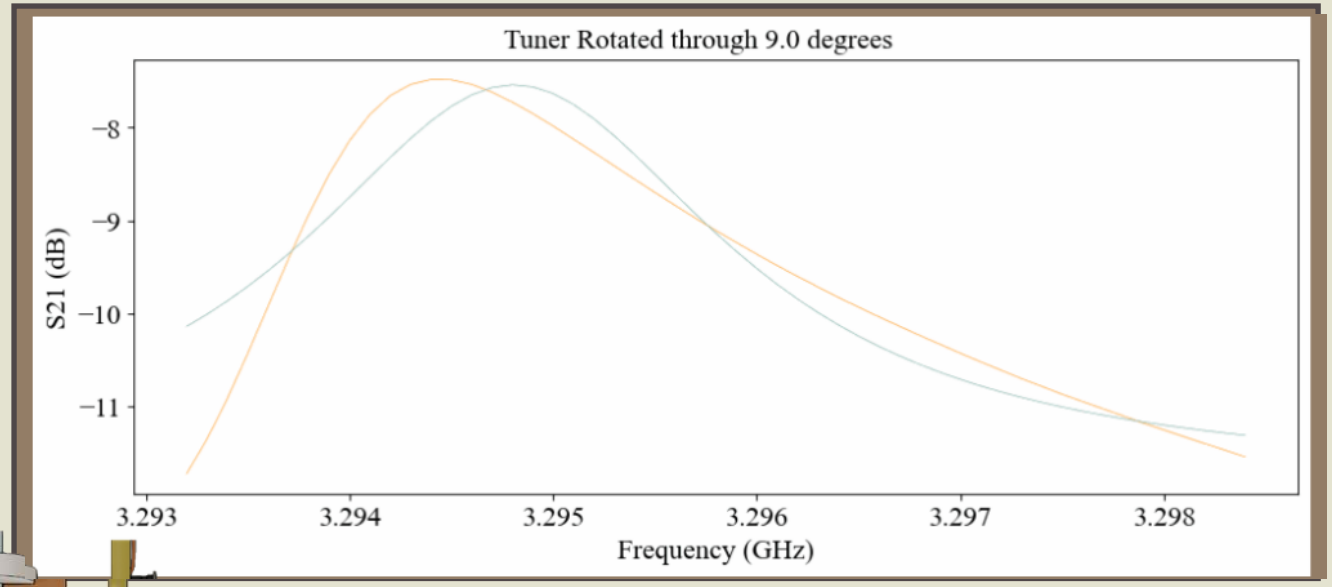

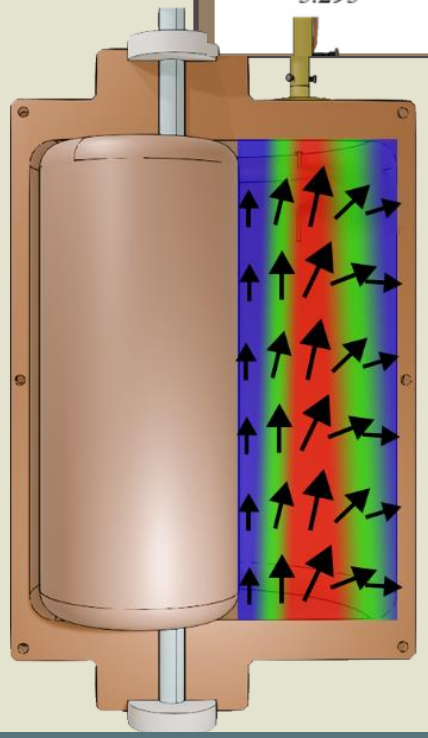

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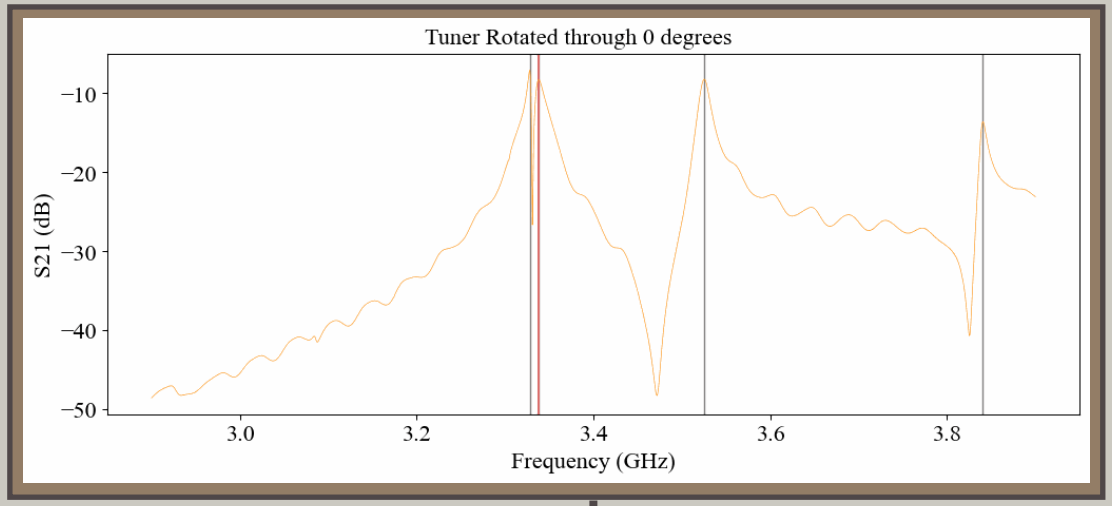

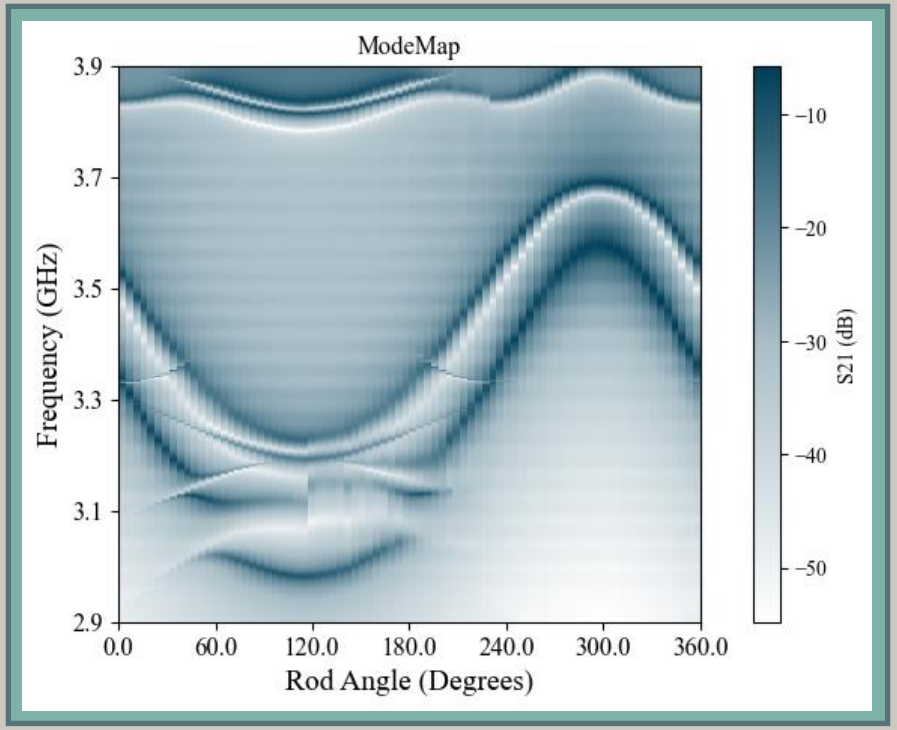

Prototype cavity mode map

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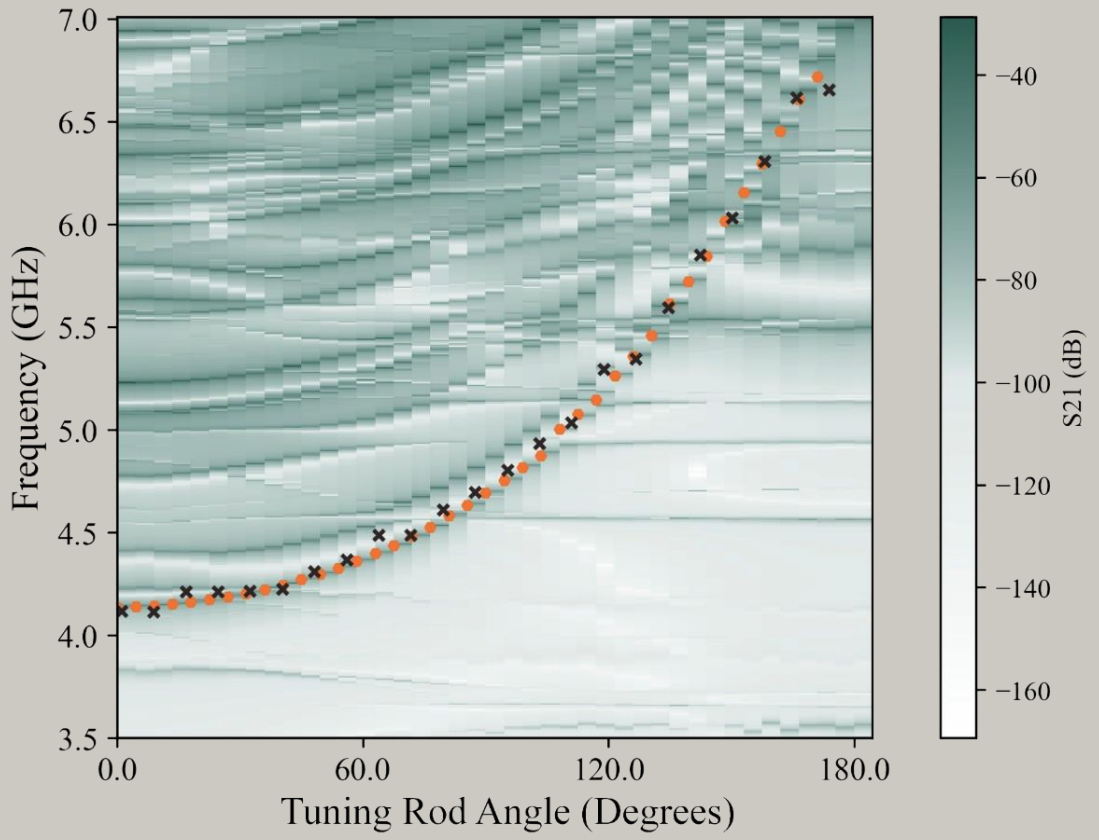
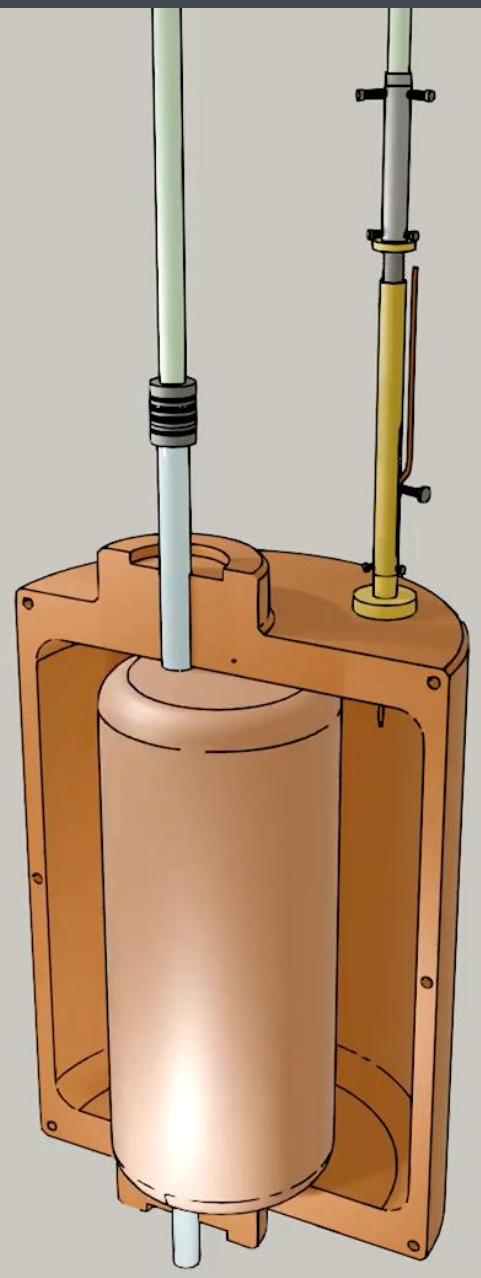


● Eigenmode Simulation Peak Frequencies

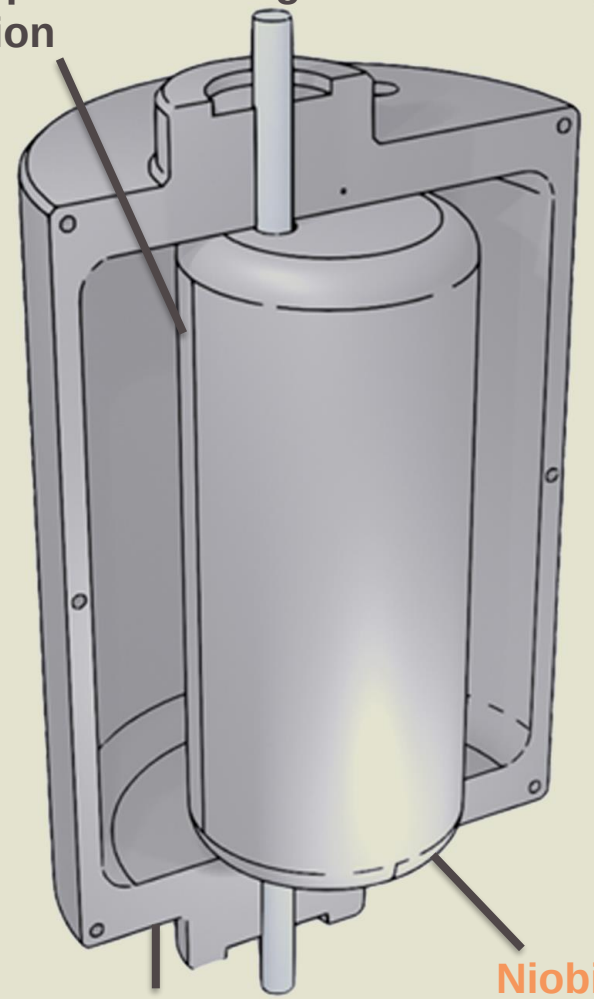
✖ Experimental Room Temperature Peak Frequencies



The QSHS Haloscope

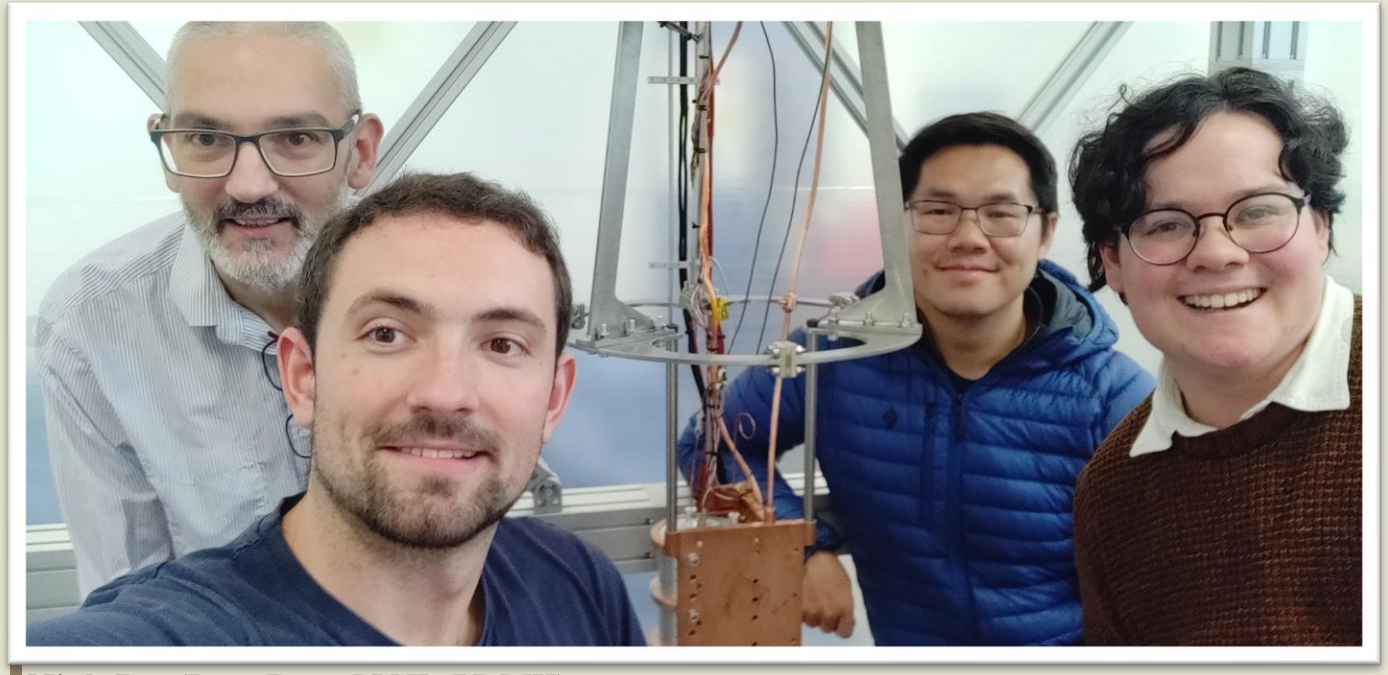
7 ADMX Superconductivity

Niobium Tin Tuning Rod Coating: 11 K Superconducting Transition

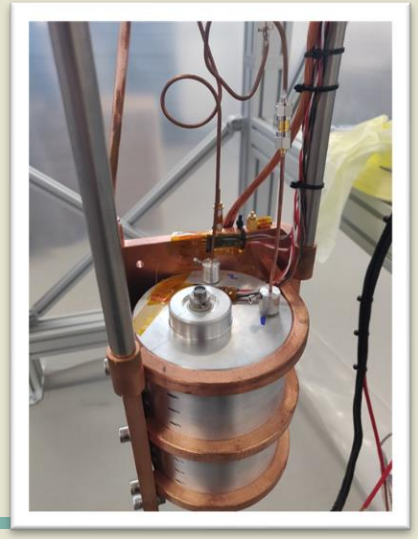


Aluminium Cavity: 1 K SC Transition

Niobium Tuning Rod: 9 K SC Transition

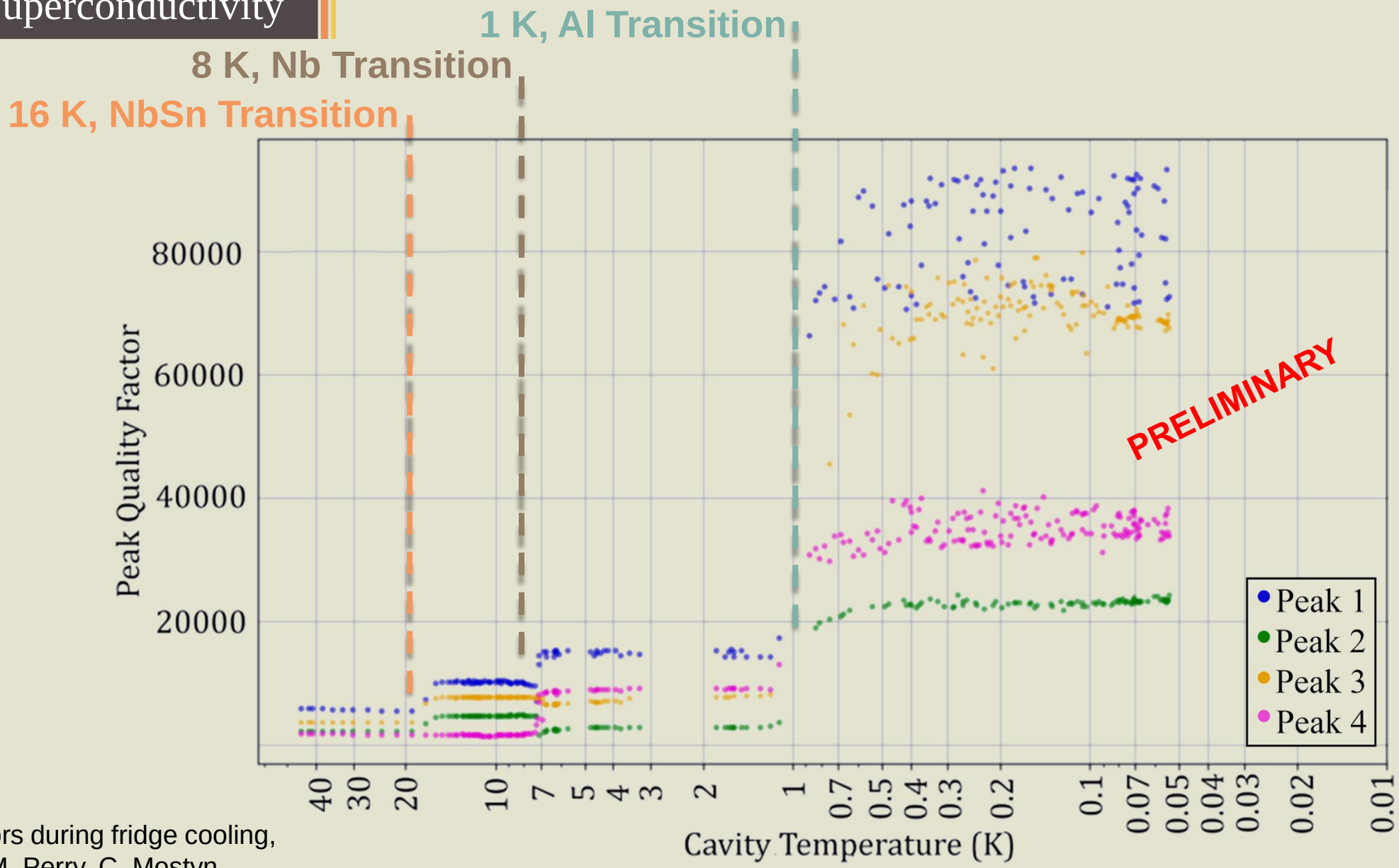


Nick Du (Post Doc, LLNL ADMX), Paul Smith (Post Doc, Sheffield), Mitch Perry and Claude Mostyn (PhD Students, Sheffield)



Tuning Rod Held Static

7 ADMX Superconductivity



During Cooling

Peak quality factors during fridge cooling,
P. Smith, N. Du, M. Perry, C. Mostyn

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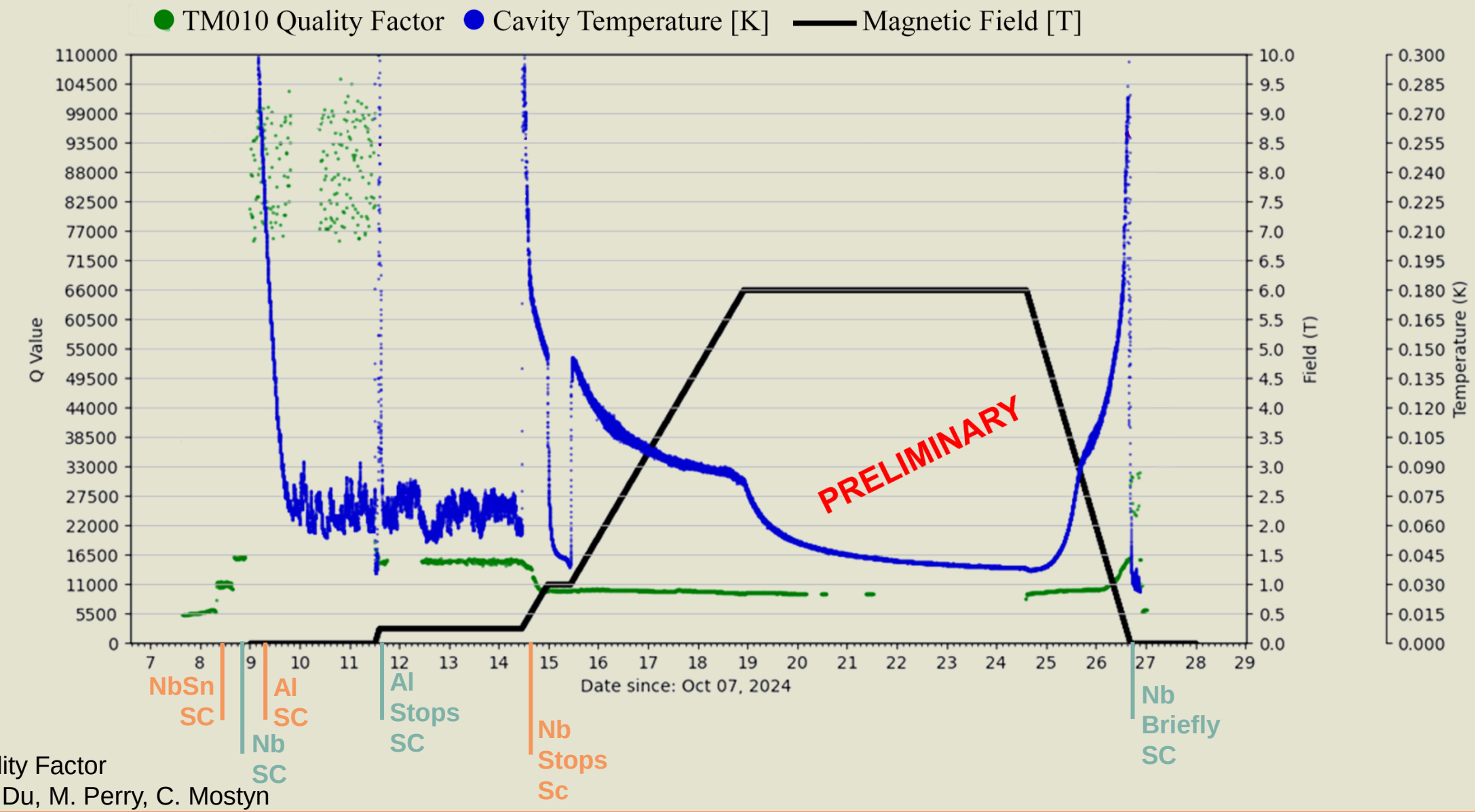
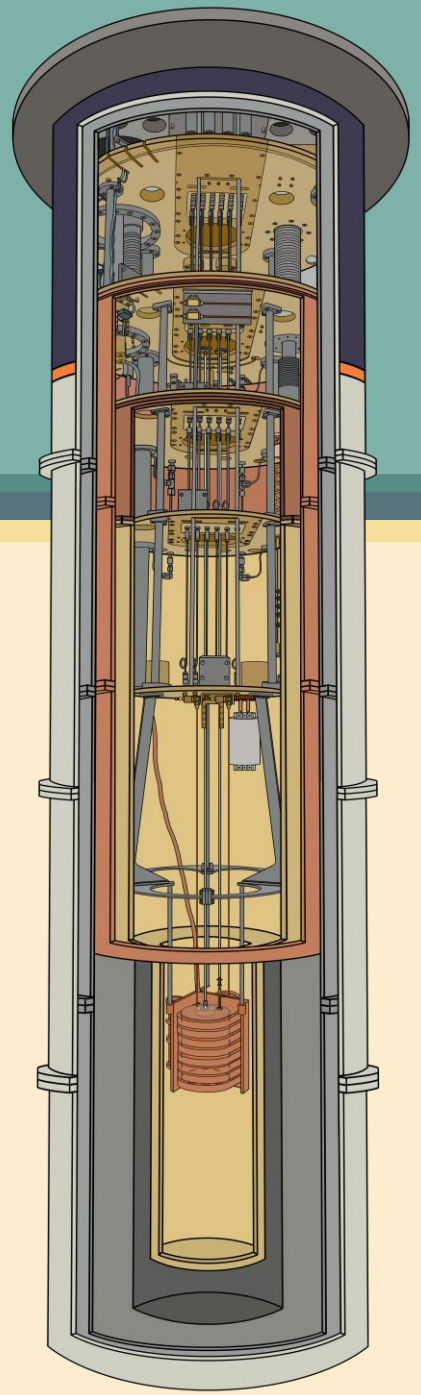


TM010 Quality Factor
P. Smith, N. Du, M. Perry, C. Mostyn

Thank You!



Contact Details:

Claude Mostyn
cfmostyn1@sheffield.ac.uk
Supervisor Ed Daw
e.daw@sheffield.ac.uk

qshs.org

Thanks to STFC for
Supporting my Studentship

Extra Slides

Analysis

1 Data Cuts

Calculate Needed Parameters for Later Calculations and Remove Poor Data

2 Baseline Removal

Remove RF Baseline to Create Spectra as Close to Expected Statistics as Possible

3 Spectra Combination

Rescale Individual Spectra and Combine While Maximising SNR

4 Making the Grand Spectrum

Average Combined Spectra Bins to Maximise SNR, Produce the Axion-Search Grand Spectrum

5 Statistics Correction

Correct Statistics and Quantify Errors to Produce an Accurate SNR

6 Identify Rescan Candidates

Identify a Reasonably Sized List of Candidates for Rescanning

• Rescan Data Taking

7 Rescan Analysis

Similar to Initial Analysis

Some Changes Based on if New Data is Combined with Initial or Used Independently, Some Extra Errors etc.

8 Setting Exclusion Limit

Uses SNR Estimates from Initial Analysis, Can Require Further Analysis/Algebra

8’ Further Candidate Analysis

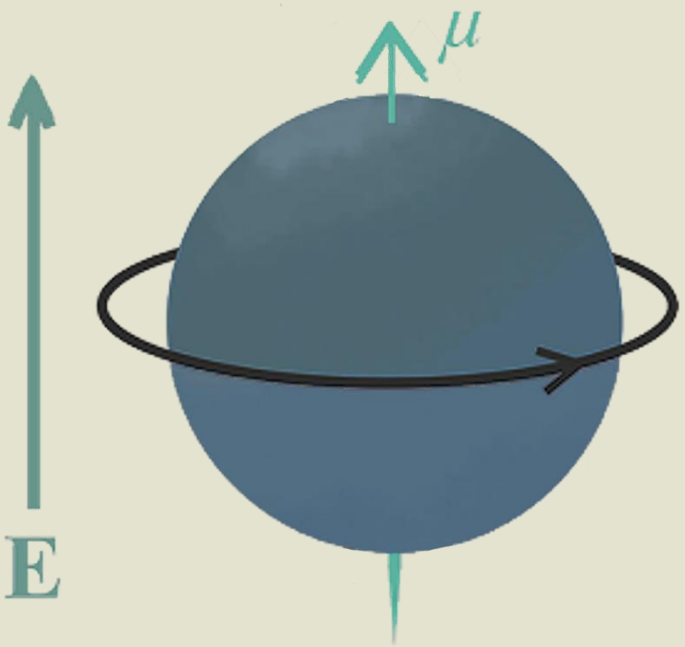
Candidates Persisting After Planned Scans are Interrogated Individually to Identify Source

Claude Mostyn

The Strong CP Problem

- Charge Parity violation in quantum chromodynamics (QCD) can be measured using the neutron electric dipole moment (NEDM)
- No NEDM has been detected, limiting the CP violating angle of the strong force to $\bar{\theta} < 5 \times 10^{-11}$ [1]
- "Fine tuning problem" found in 1970s, requires two CP violating terms in QCD Lagrangian to cancel

If There is Not a Neutron Electric Dipole Moment



Neutron with **spin** and a magnetic dipole moment in an external E field

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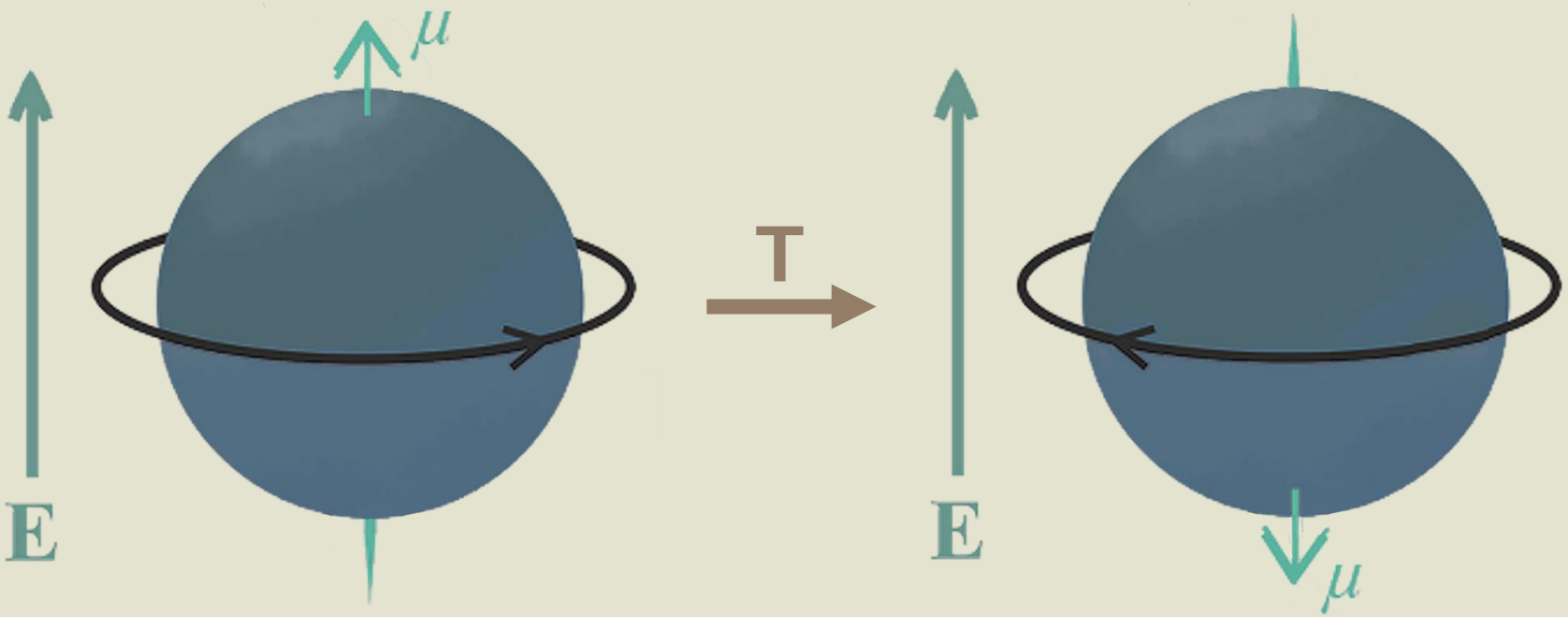
Under Time Inversion



Spin changes direction, so the magnetic dipole moment does too…

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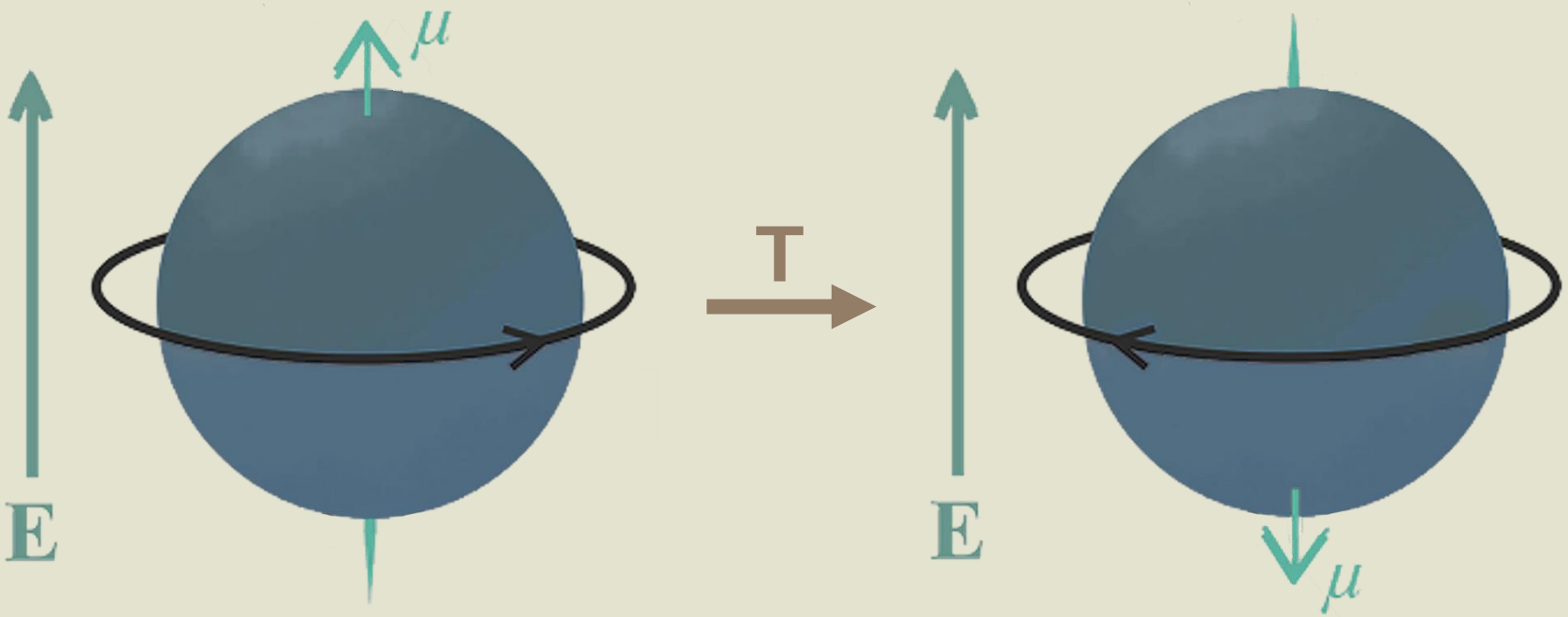

But as the *E* field has no effect the neutron is free to rotate

The QSHS Haloscope

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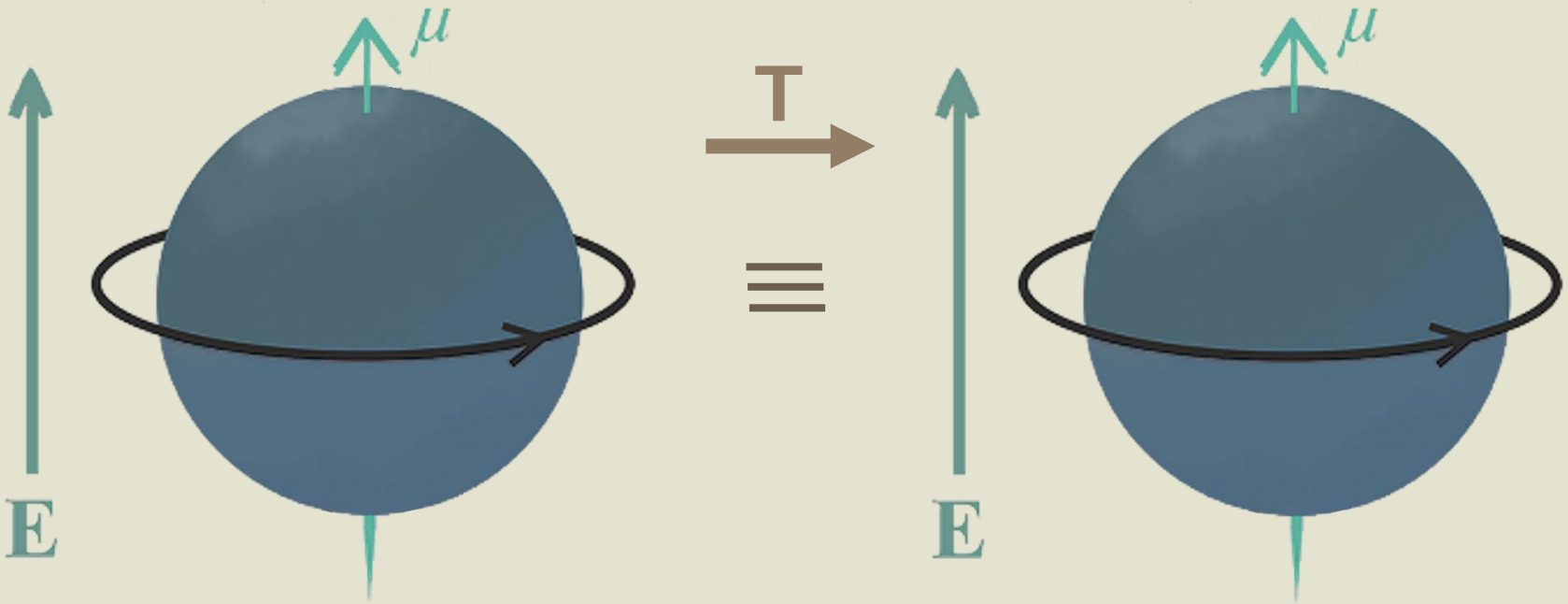

The two are equivalent

T symmetry is conserved

So, CP must be too!

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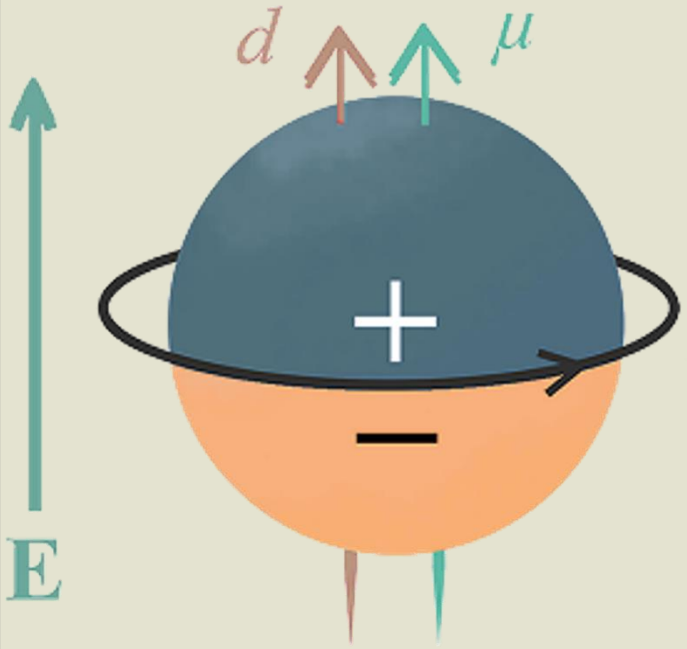

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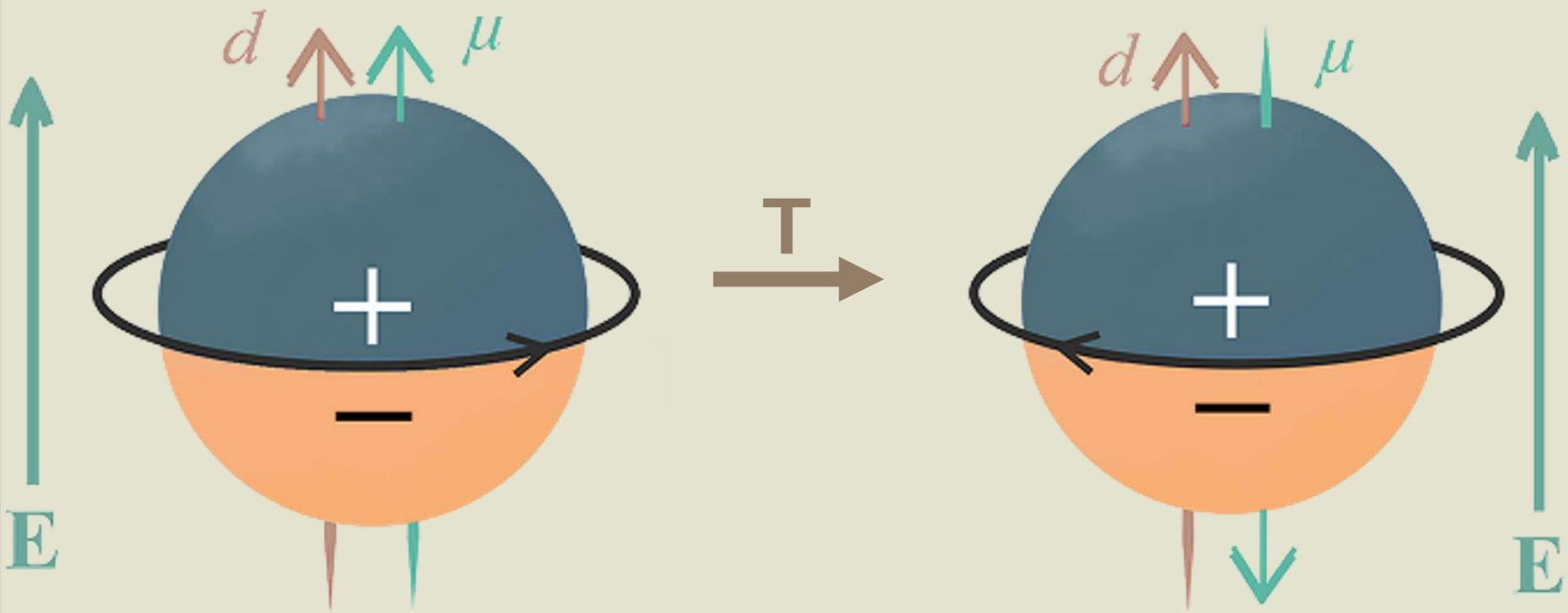

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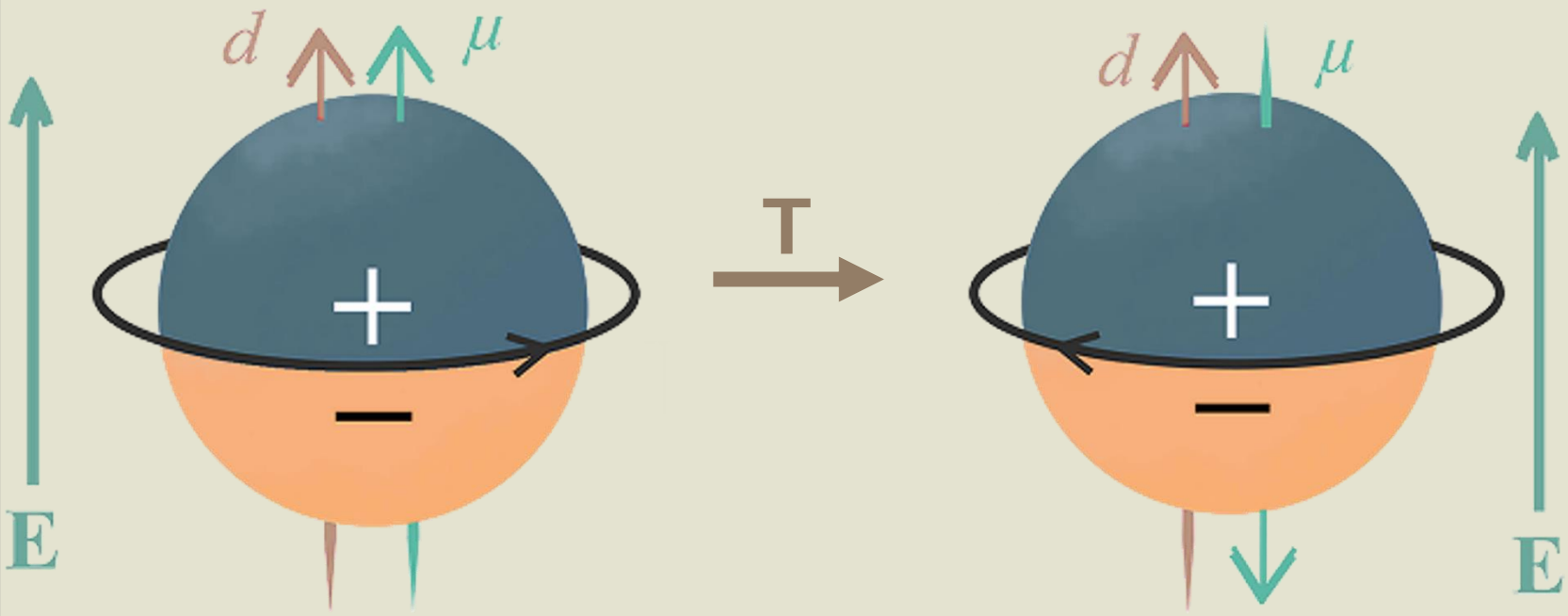

Now the electric dipole moment must align with the *E* field…

The QSHS Haloscope

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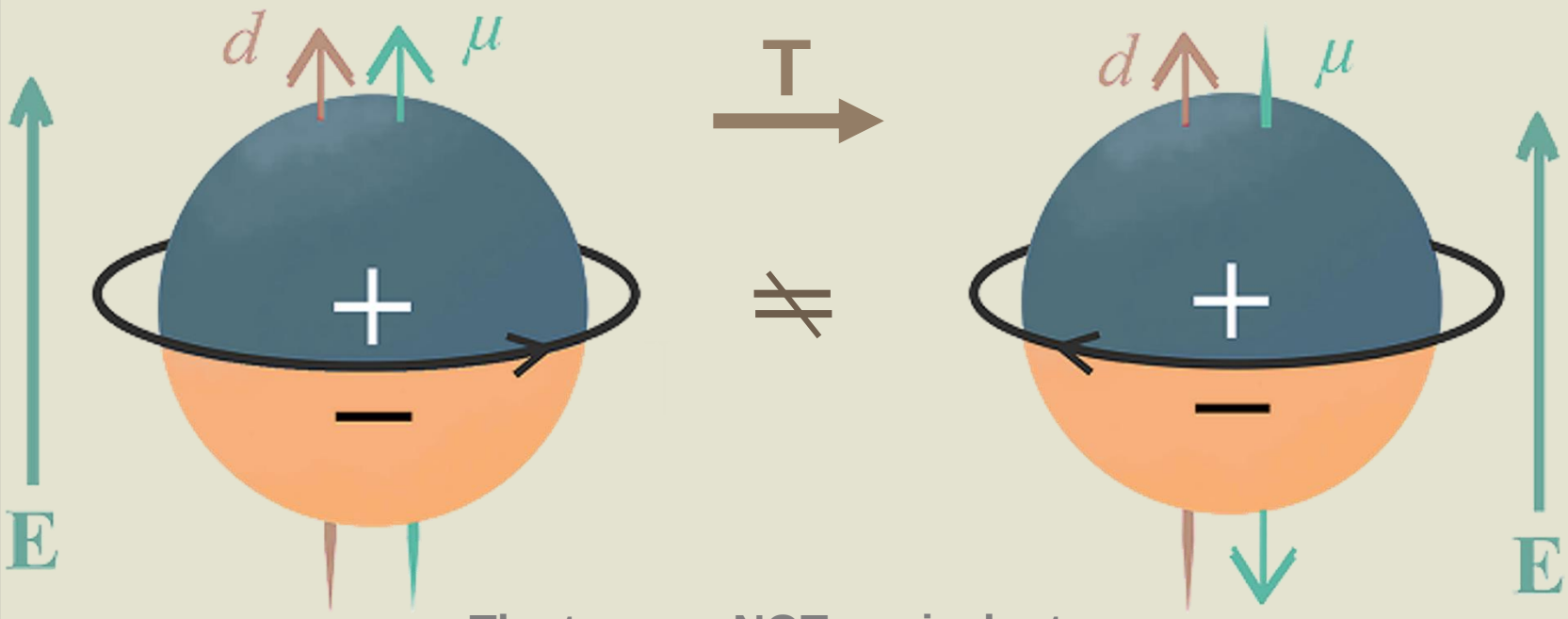

The two are NOT equivalent

T symmetry is violated

So, CP must be too!

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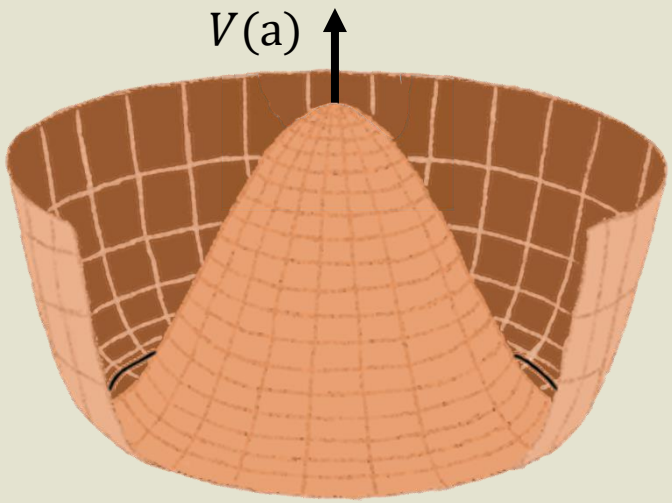
Peccei Quinn Theory

- Peccei and Quinn (PQ) propose promoting $\bar{\theta}$ to a dynamic variable with associated new scalar PQ field
- In the very early universe, the field's potential is symmetric and CP violation occurs in QCD
- U(1) symmetry breaks and field takes on minimum energy value setting $\bar{\theta}$ to 0, oscillations about minima create axions



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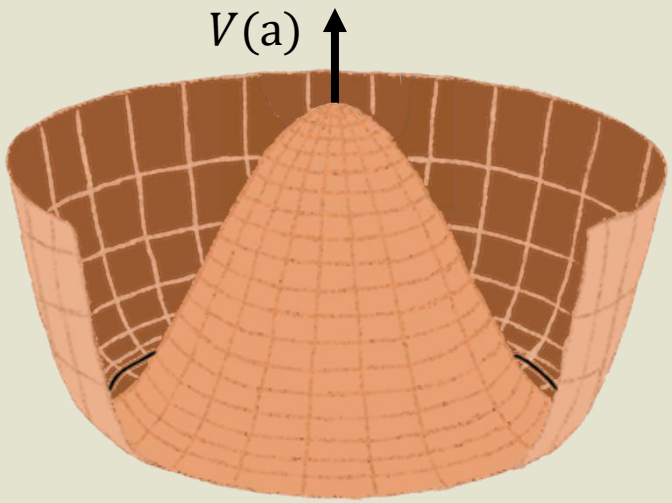
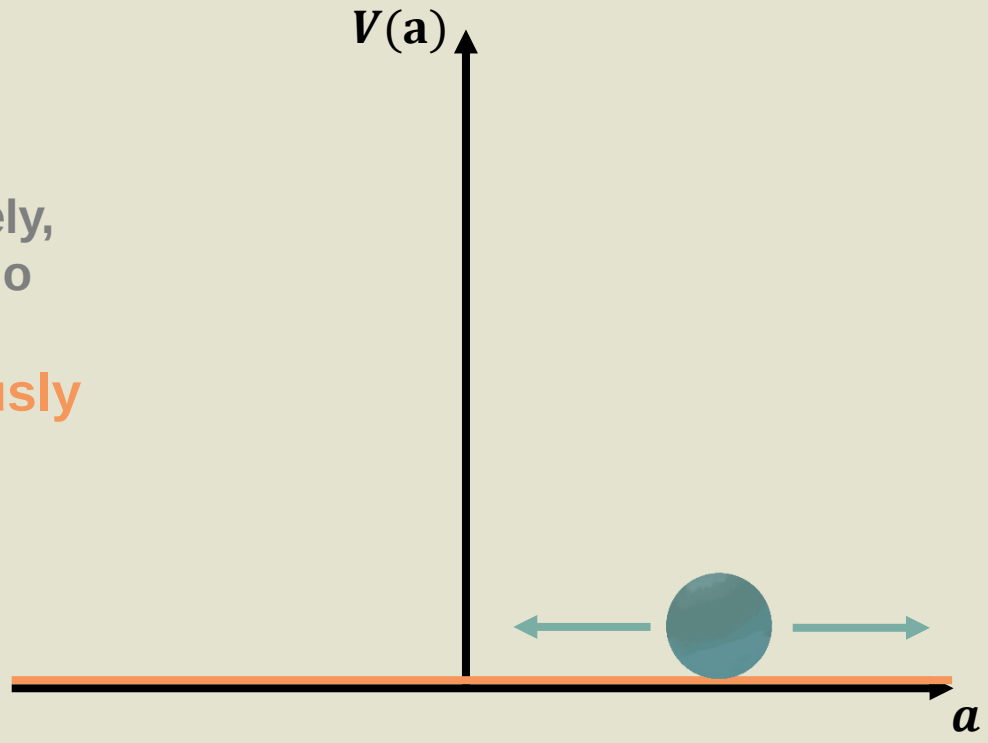


In the very early universe, the PQ field is symmetric

Field can roll about freely, and has the energy to go over the central bump:
QCD can spontaneously break CP symmetry



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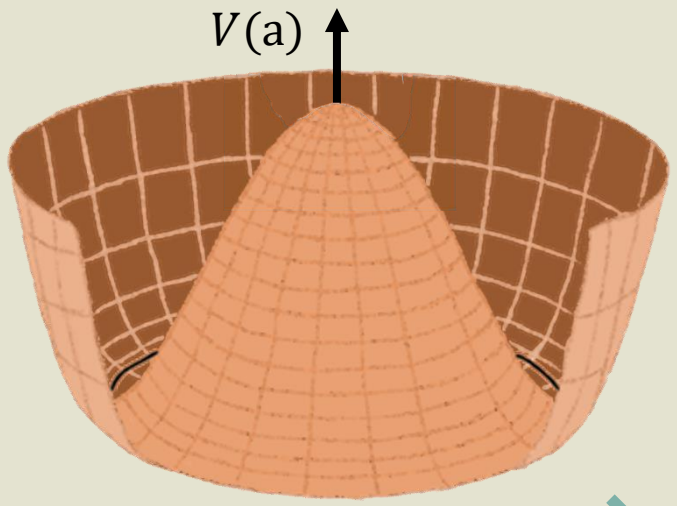
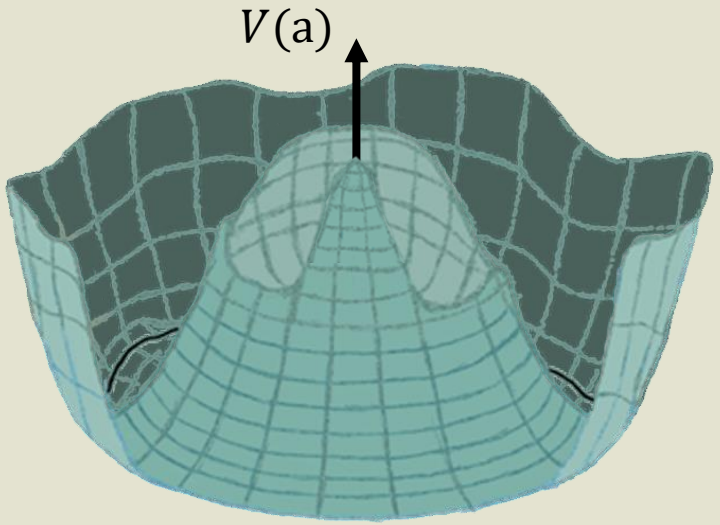


At a lower (but still early universe) energy f_a, the PQ field symmetry breaks
The potential now has many sharp minima

Symmetry breaks at f_a



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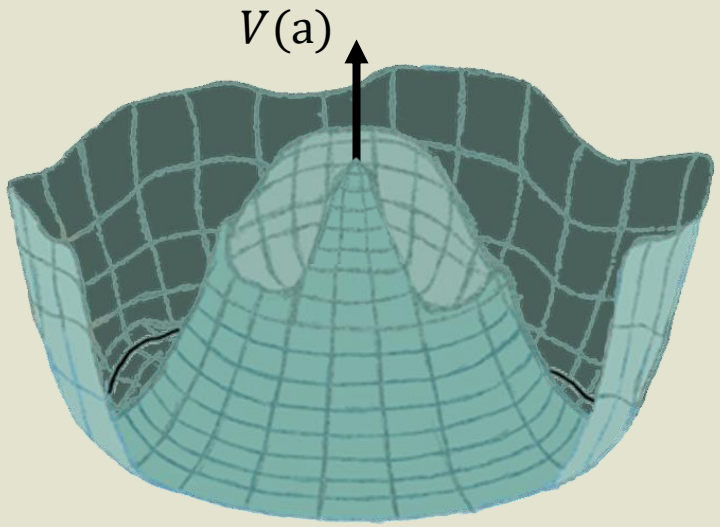
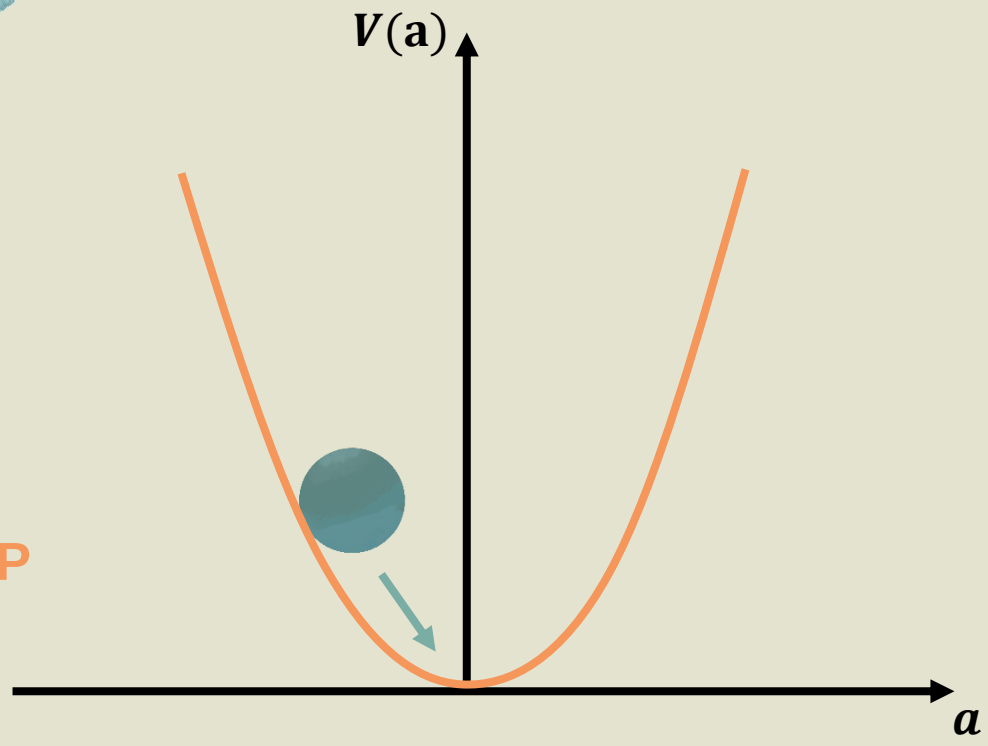


At a lower (but still early universe) energy f_a, the PQ field symmetry breaks
The potential now has many sharp minima



The field rolls into one of these minima, naturally setting $\bar{\theta}$ to zero
QCD has to conserve CP symmetry!

The QSHS Haloscope

Claude Mostyn

Peccei Quinn Theory

- Peccei and Quinn (PQ) propose promoting $\bar{\theta}$ to a dynamic variable with associated new pseudoscalar PQ field
- In the very early universe, the field's potential is symmetric and CP violation occurs in QCD
- U(1) symmetry breaks and field takes on minimum energy value setting $\bar{\theta}$ to 0, oscillations about minima create axions

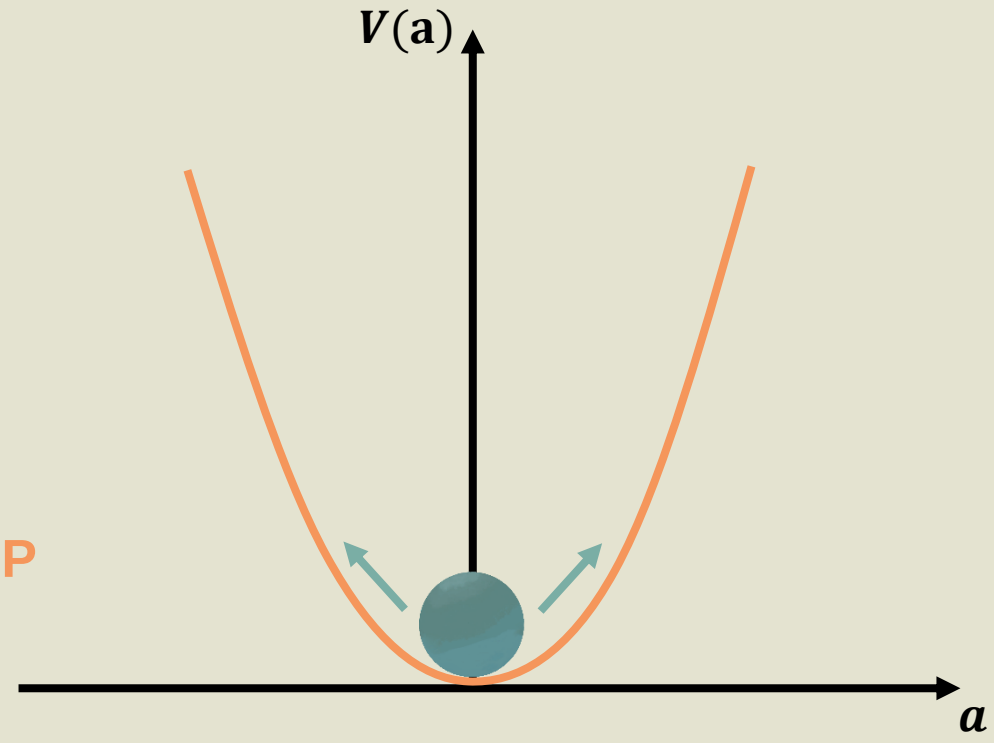
Oscillations about the minima create

Pseudo Nambu-Goldstone Bosons

Associated with pseudoscalar field

Scientists who discovered this type of boson

Axions!

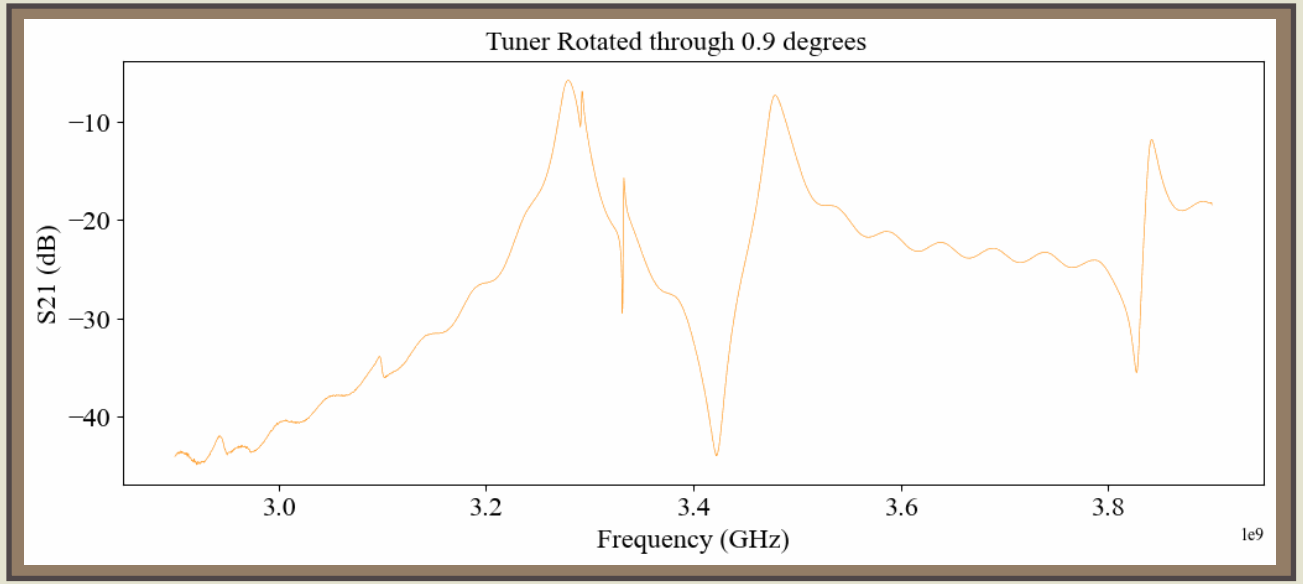


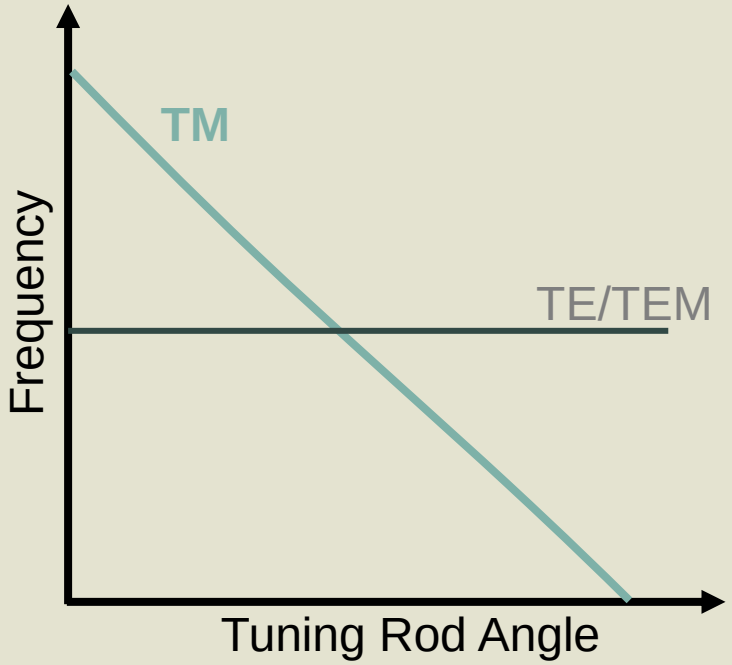
The field rolls into one of these minima, naturally setting $\bar{\theta}$ to zero

QCD has to conserve CP symmetry!

6 Tracking the TM_{010} Mode

- Axion sensitivity is maximised when the cavity mode's ***E*** field's overlap integral with the external ***B*** field over the cavity's volume is maximised, expressed as a form factor
- During tuning the target mode is affected by stationary-frequency intruder modes
- Careful tracking, ANSYS simulations, and peak fitting are needed to handle mode hybridisation, and distorted modes while accurately calculating the sensitivity





Where the quality factors and amplitudes of the target and intruder modes are sufficiently different the TM mode appears to pass through

6 Tracking the TM_{010} Mode

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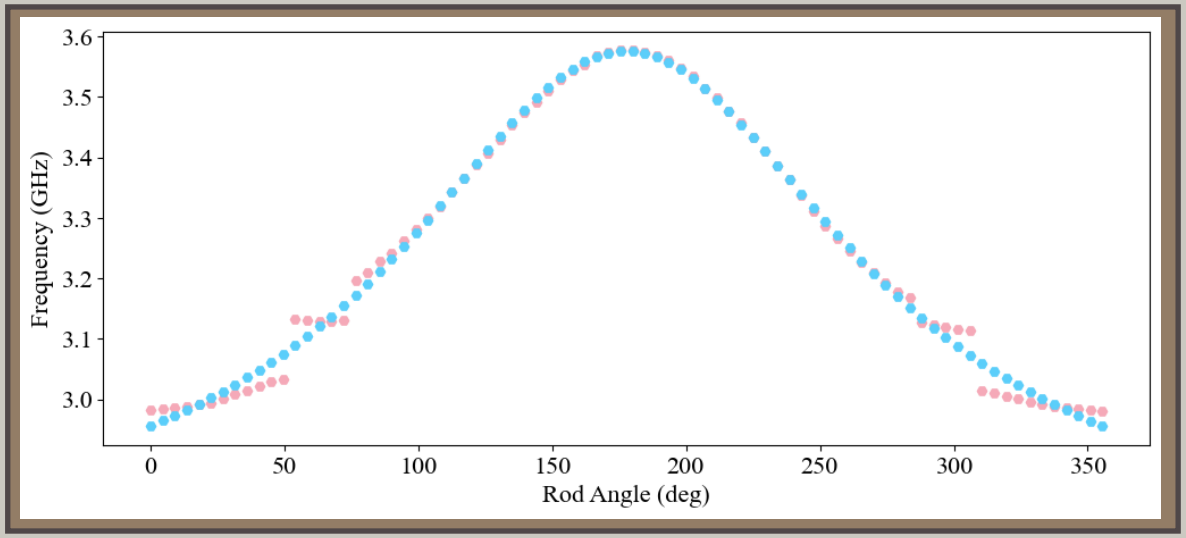
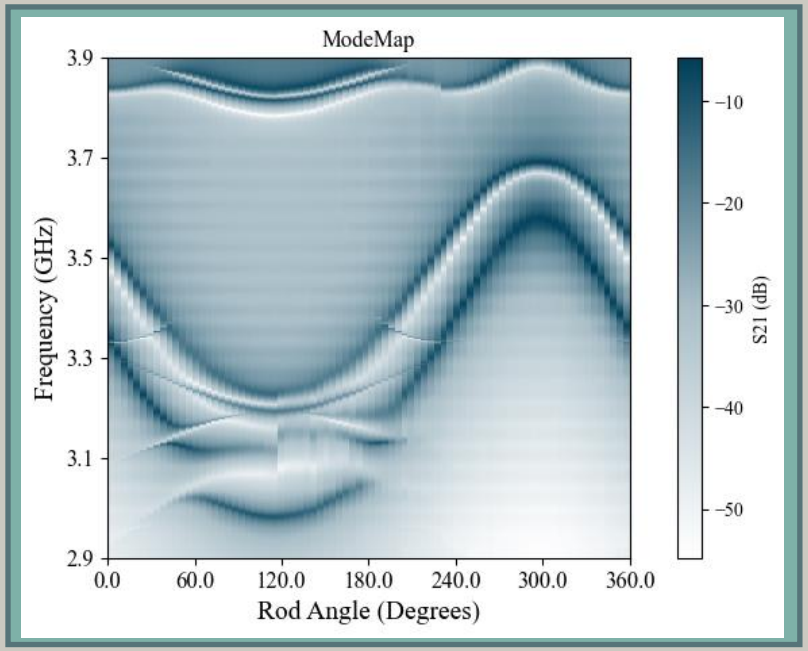
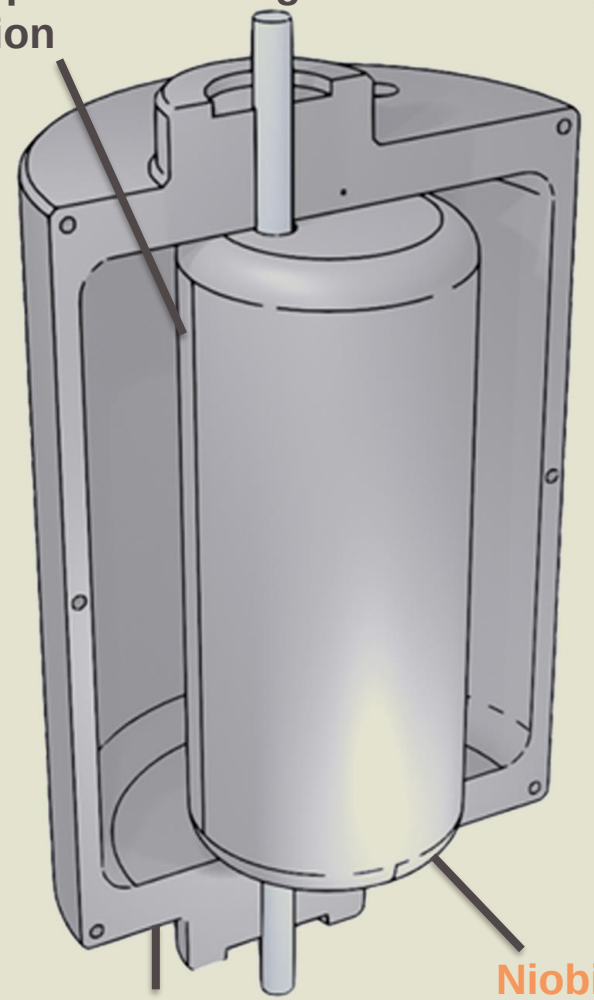




Prototype cavity mode map

7 ADMX Superconductivity

Niobium Tin Tuning Rod Coating:
11 K Superconducting Transition

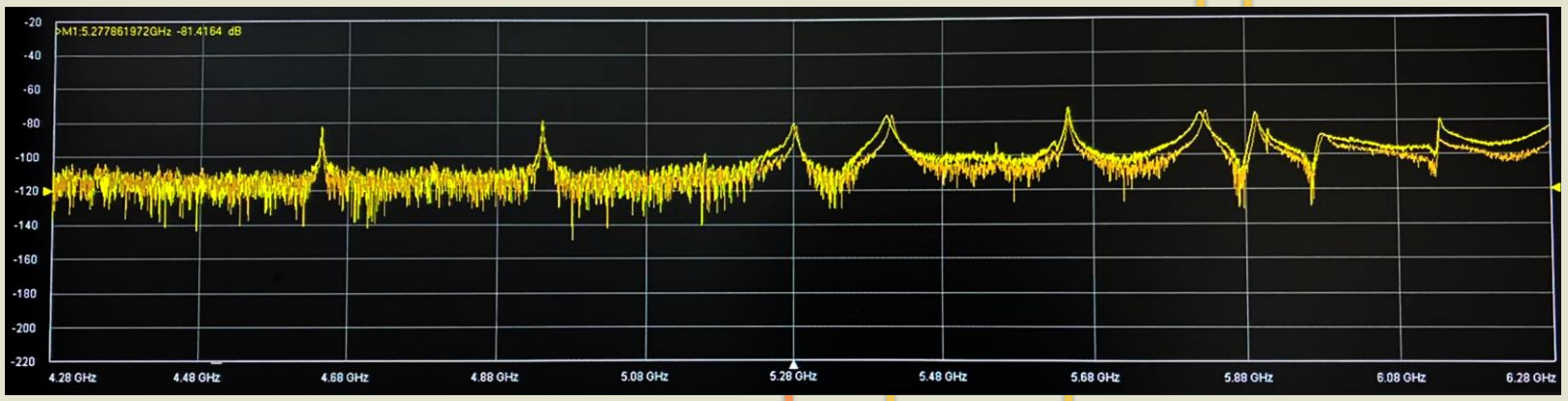


Aluminium Cavity:
1 K SC Transition

Niobium Tuning Rod:
9 K SC Transition

$f_{r4} \approx 5.820$ GHz

$f_{r5} \approx 5.897$ GHz



VNA Spectrum, Before Cool

$f_{r3} \approx 5.691$ GHz

$f_{r2} \approx 5.398$ GHz

$f_{r1} \approx 5.269$ GHz