The ORGAN Experiment, and other axion detection techniques

THE UNIVERSITY OF WESTERN AUSTRALIA

SEEK WISDOM

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

EQUS: Who Are We?

THE UNIVERSITY OF WESTERN AUSTRALIA

- ARC Centre of Excellence for Engineered Quantum Systems
- Five Australian Universities

THE UNIVERSITY OF WESTERN AUSTRALIA

THE UNIVERSITY OF SYDNEY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Australian National University

MACQUARIE University SYDNEY·AUSTRALIA

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

EQUS: Who Are We?

- University of Western Australia
- Located in Perth, Western Australia

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

EQUS: Who Are We?

- Key Axion People:
  - Mike Tobar (talking tomorrow)
  - Ben McAllister (me)
  - Maxim Goryachev (talking thursday)
  - Graeme Flower
  - Catriona Thomson
  - Jeremy Bourhill

EQUS: Who Are We?

THE UNIVERSITY OF WESTERN AUSTRALIA

- Diverse research program
- Centre renewal – focus on quantum machines
  - Designer quantum materials
  - Quantum-enabled diagnostics and imaging
  - Quantum engines and instruments
- Other fundamental physics
- **Axion dark matter detection headed up by UWA node**
- Assistance from other nodes in developing quantum tech, etc

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

EQUS: Who Are We?

- Quantum systems expertise necessary in future
- Development of JPAs, etc
- Applications of quantum technologies to axion/other dark matter detection techniques
- The centre is interested in doing more in this area
- But also…

Australian Research Council Centre of Excellence for Engineered Quantum Systems

EQUS: Who Are We?

- A second connected ARC COE bid is underway!
- CDaMPP – Centre for DArk Matter Particle Physics
- Australian Centre focused on dark matter detection (all flavours)
- Wide mass range – light axions and scalar particles to WIMPs
- **Both EQUS and CDaMPP have room for collaborators**
- There are some pots of funding up for grabs...

EQUS: Axion Detection

- Various experiments targeting high and low mass axions
  - **ORGAN – high masses**
  - BEAST – low masses
  - Yet to be named Dual Oscillator Experiment (both)
  - Some other things…(stay tuned)
- Make use of quantum technology and EQUS collaborators where possible

Australian Research Council Centre of Excellence for Engineered Quantum Systems

ORGAN: A reminder

THE UNIVERSITY OF WESTERN AUSTRALIA

- High frequency haloscope at UWA (>15 GHz), known as the **ORGAN Experiment**
- **O**scillating **R**esonant **G**roup **A**xio**N Experiment**
- Multi-stage project:
  →Narrow Search around 26-27 GHz (Phase I)
  → Wider scan at high frequencies: 15-50 GHz (Phase II)
- Lots of motivation for high frequency searches:
  →SMASH model
  →Lattice QCD Simulations
  →**No one is looking there with a haloscope**

EQUS
Australian Research Council
Centre of Excellence for
Engineered Quantum Systems

ORGAN: A reminder

- Designing a haloscope at high frequency is difficult

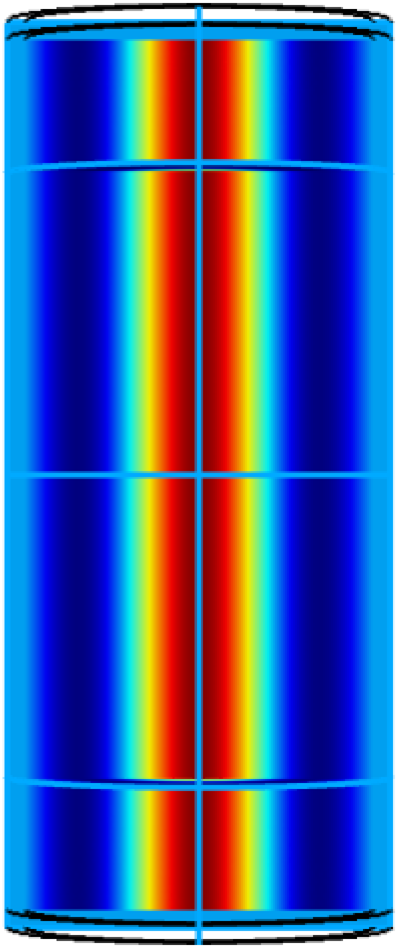
$$P_a \propto g_{a\gamma\gamma}^2 \; B^2 \; C \; V \; Q \frac{\wp_a}{m_a}$$

- TM Mode frequency inversely proportional to cavity size
  → Lower volume
  → Lower sensitivity
  → Lossier material
- **Quantum noise limit increases**
- Our first step (2016): ORGAN Pathfinder Project

Australian Research Council Centre of Excellence for Engineered Quantum Systems

ORGAN Pathfinder

- Cavity dimensions:
- ~1 cm radius
- ~5 cm length
- TM_{020} Mode frequency ~26.5 GHz
- First "path-finding run" complete
- Stationary frequency, single cavity
- Traditional HEMT amplification
- 4 K
- 7 T
- Commercial Vector Signal Analyzer
- Successful test of entire system



ORGAN Pathfinder

Mode	C	V (cm^3)	G
TM010	0.69	1.45	386.5
TM020	0.13	7.783	744.6
TM030	0.053	18.87	1244.3

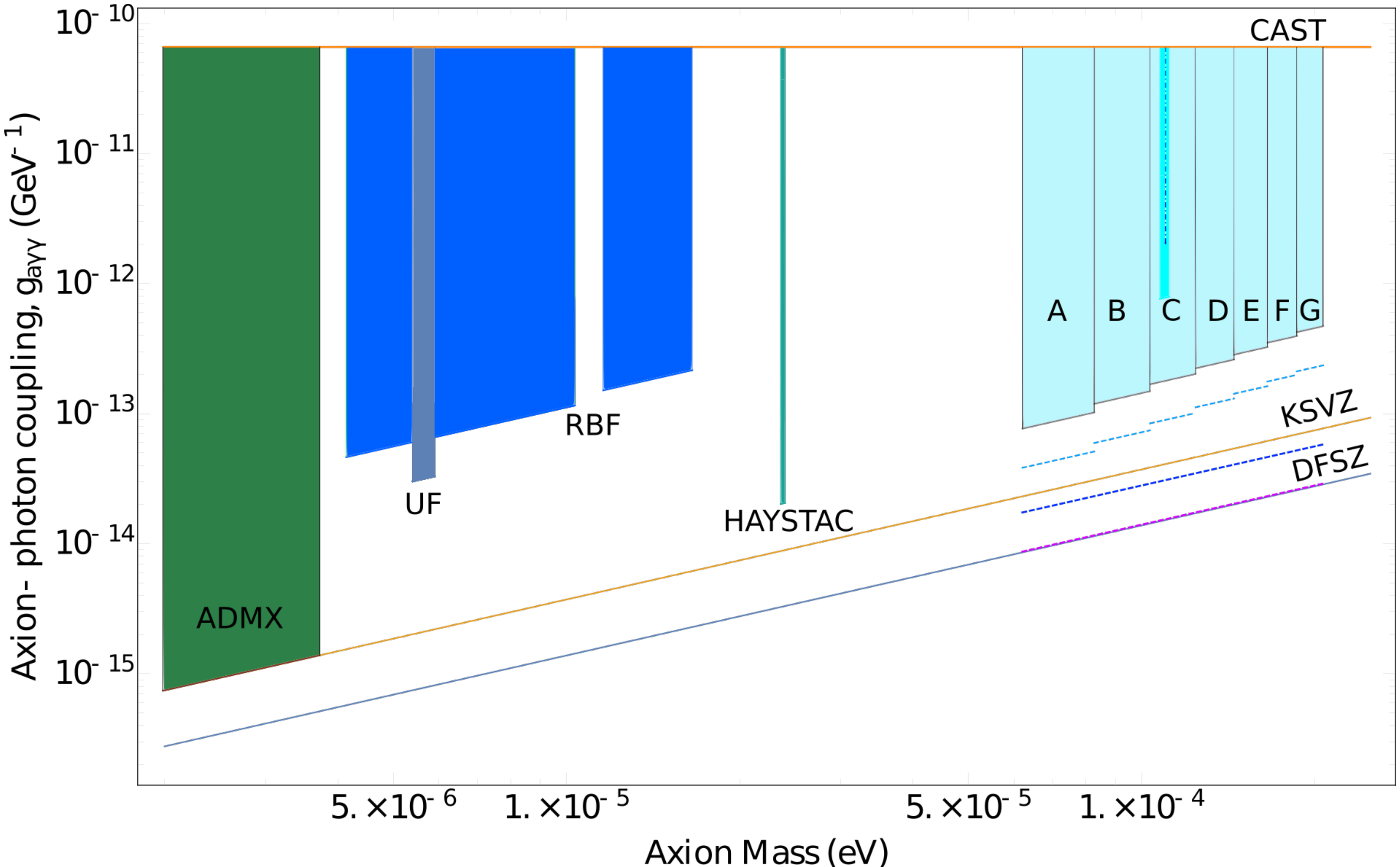
- Mode crowding gets worse, but there is a trade off to consider
- More on higher order modes later

ORGAN Phase I and II

- Federal funding for 7 years → can scale up experiment
- EQUS connections
- New 14 and 3 T magnets
- Dedicated dilution refrigerator
- Multiple cavity search
- Quantum or near-quantum limited amplification (JPAs, NQL HEMTs)
- **Novel resonator design**

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems

Sensitivity Limits/Projections



- Narrow bar is pathfinder result
- Wider aqua bar is Phase I – 26-27 GHz (more coming)
- A→G are the Phase II runs, with 14 T magnet and SQL Amps
- Dashed limits depend on new technology and R&D ie Squeezed vacuum to beat SQL, upgrade magnet again to 28 T

ORGAN Resonator Design

THE UNIVERSITY OF WESTERN AUSTRALIA

- Scan rate of a haloscope

$$\frac{df}{dt} \propto \frac{1}{SNR_{goal}^2} \frac{g_{a\gamma\gamma}^4 B^4 C^2 V^2 \rho_a^2 Q_L Q_a}{m_a^2 (k_B T_n)^2}$$

- We use $C^2 \; V^2 \; G$ as a figure of merit for resonator design
- G is geometry factor, proportional to Q
- Higher frequency → Lower V
- Can use higher order modes!
- Keeps V high, but lowers C
- Or does it...

EQUS
Australian Research Council Centre of Excellence for Engineered Quantum Systems

Dielectric Boosted Axion Sensitivity Resonators

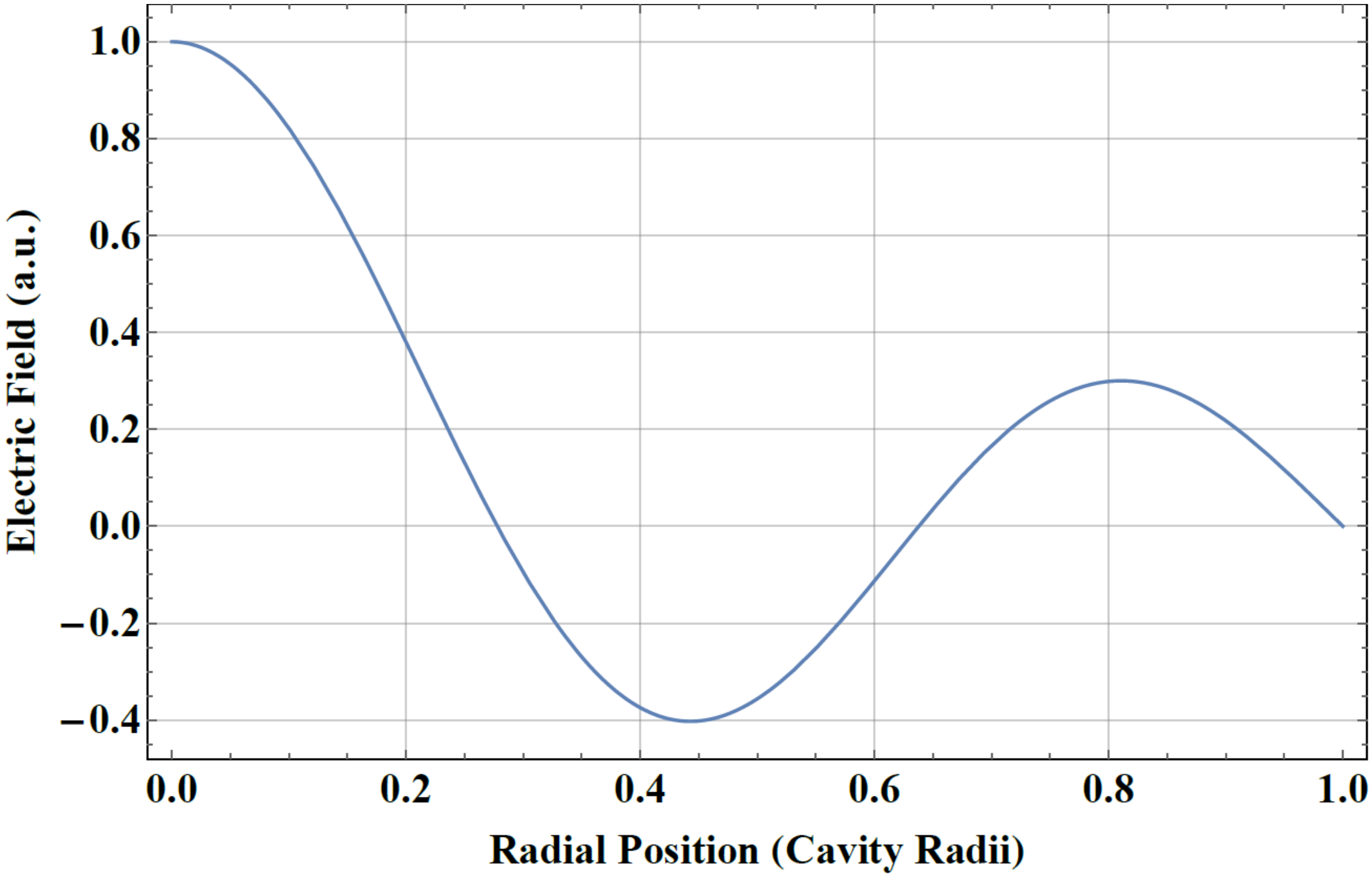
- Boost in axion form factor with careful placement of dielectric in higher order modes

$$C = \frac{\left| \int dV_c \vec{E}_c \cdot \vec{\hat{z}} \right|^2}{V \int dV_c \epsilon_r \mid E_c \mid^2}.$$

- Dielectric materials suppress electric field
- Reduce the electric field where there are out of phase field lobes
- We can Apply this to TM modes → Dielectric Rings
- Tuning mechanisms naturally included

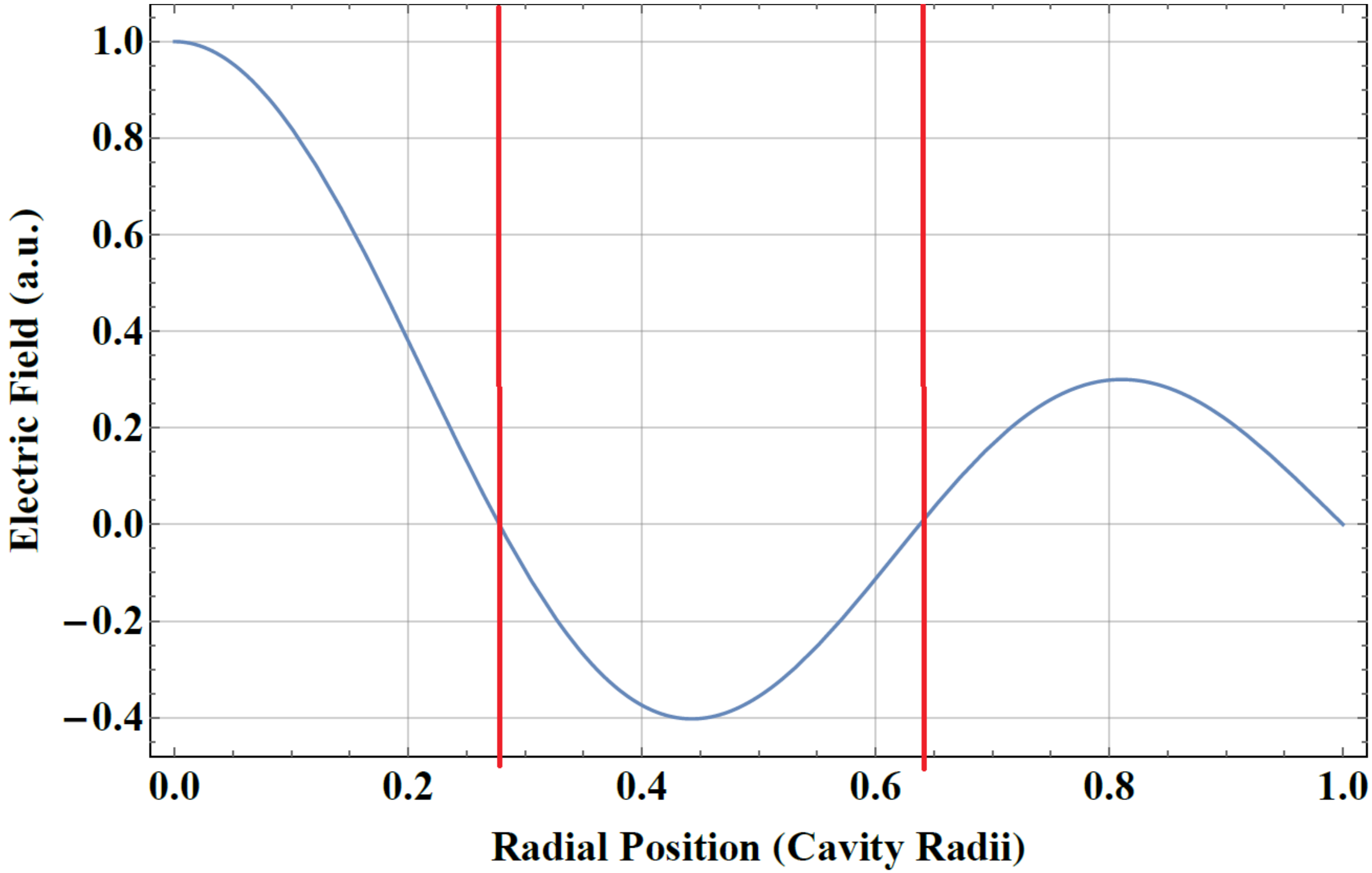
Dielectric Boosted Axion Sensitivity Resonators

- TM030 mode Ez looks like this:



Dielectric Boosted Axion Sensitivity Resonators

- TM030 mode Ez looks like this:



Dielectric Boosted Axion Sensitivity Resonators

- We can calculate the location and thickness of this region
- Electric field looks like:

$$\vec{E}_c(r) = E_0\ e^{i\omega t}\ J_0(\frac{\zeta_{0,n}}{R}r)\ \hat{z}$$

- So the region should have thickness:

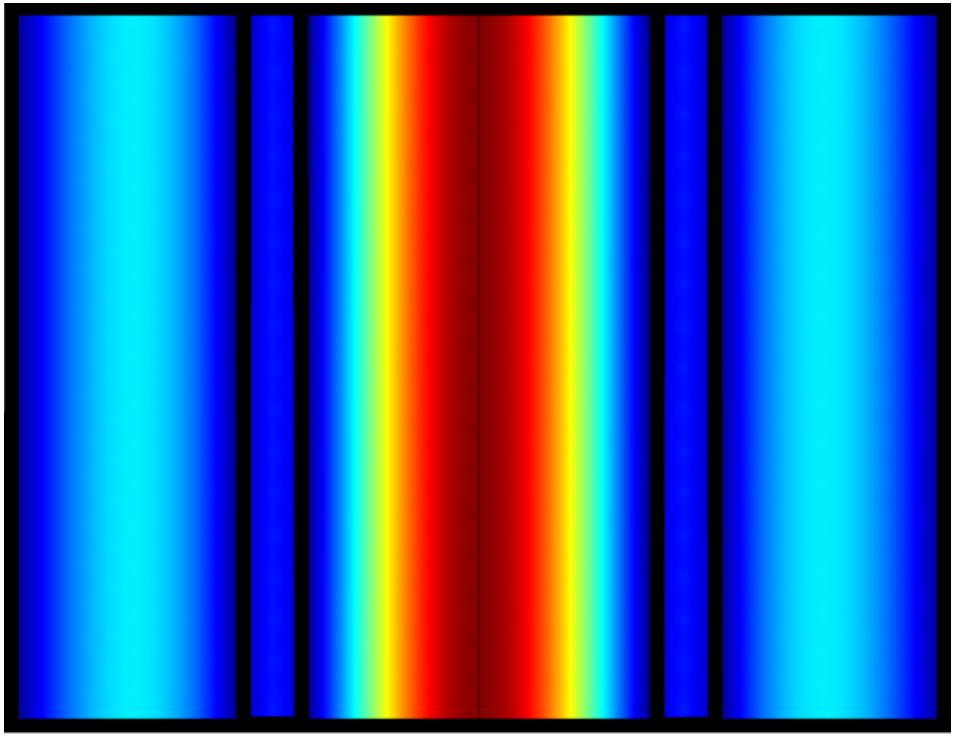
$$\frac{\zeta_{0,2} - \zeta_{0,1}}{\zeta_{0,3}\sqrt{\epsilon_r}}R$$

- Beginning at:

$$r = \frac{\zeta_{0,1}}{\zeta_{0,3}}R$$

Dielectric Boosted Axion Sensitivity Resonators

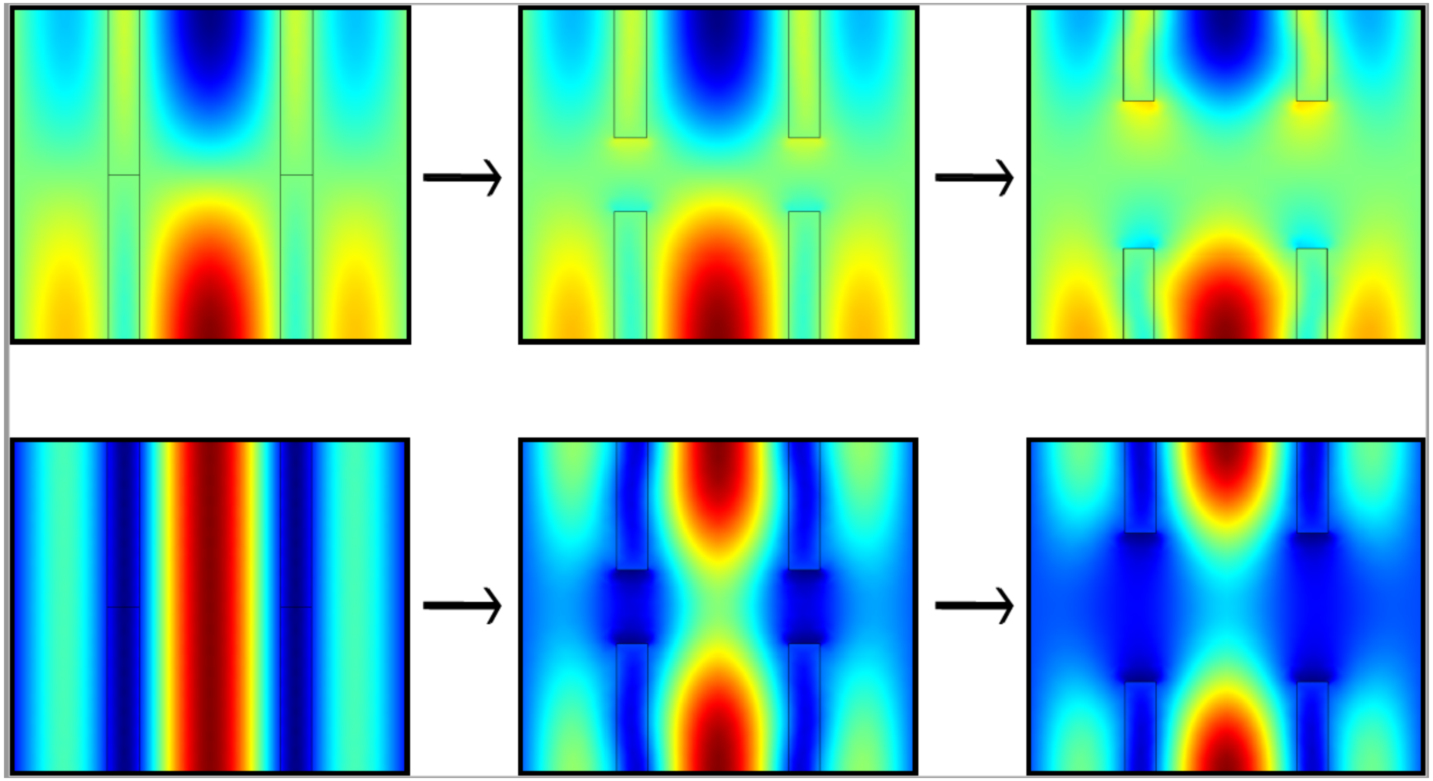
- When these conditions are met we get the following field structure



- Finite element simulations → Form factor ~0.45, improved from 0.053
- Can use higher order modes and maintain C while boosting V

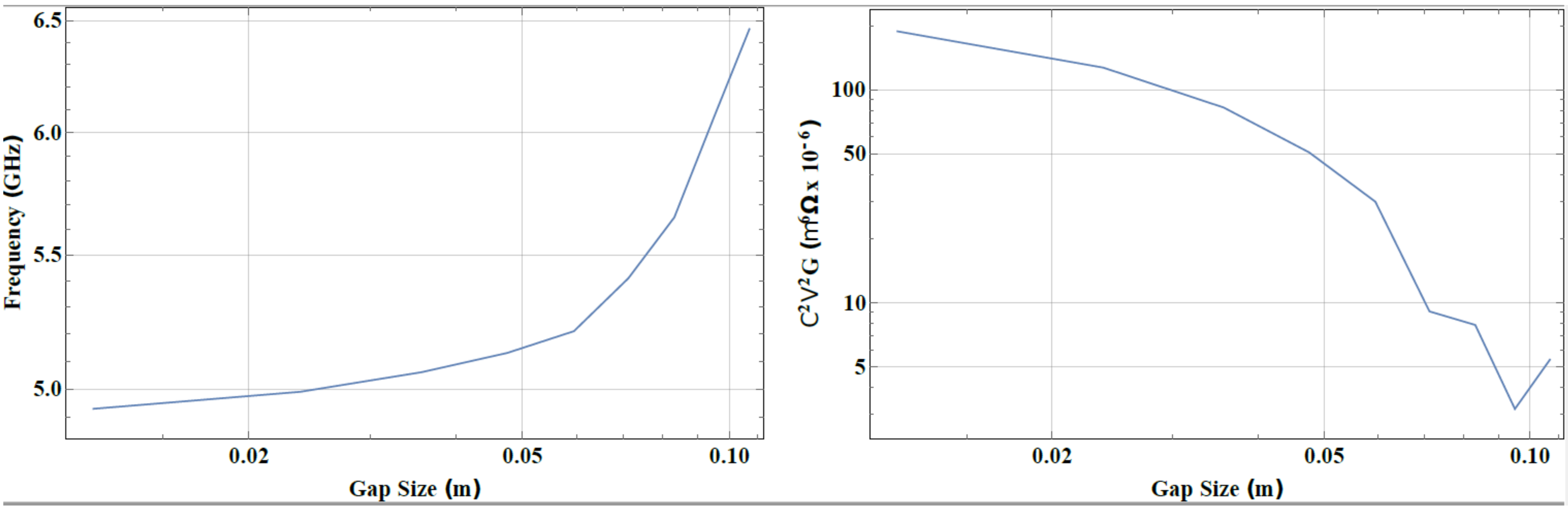
Dielectric Boosted Axion Sensitivity Resonators

- We can tune this structure
- Axial "supermodes"
- TM030 and TM031 modes



Dielectric Boosted Axion Sensitivity Resonators

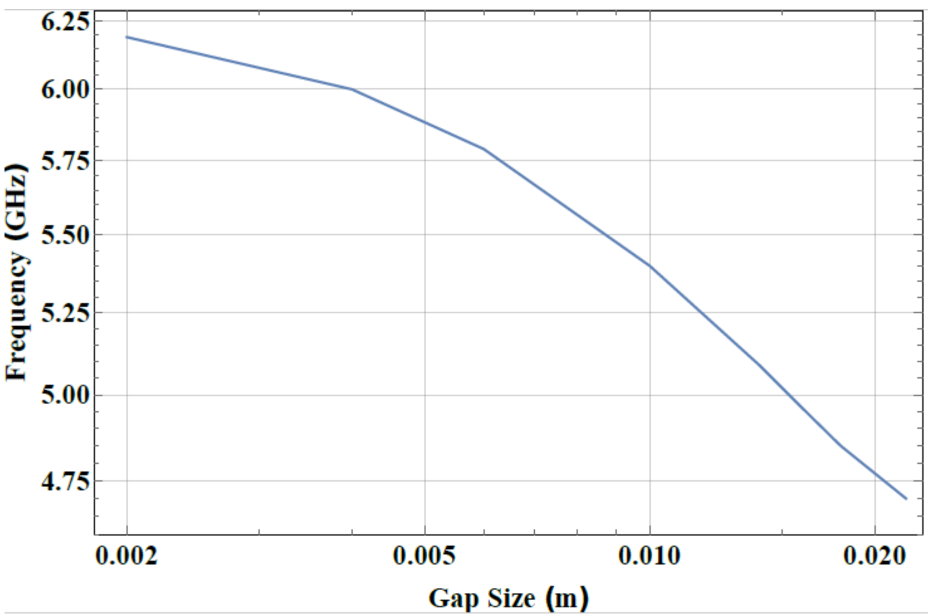
- Most sensitive “symmetric supermode” retains sensitivity as the gap size increases
- Frequency tuning greater than 20% of initial frequency

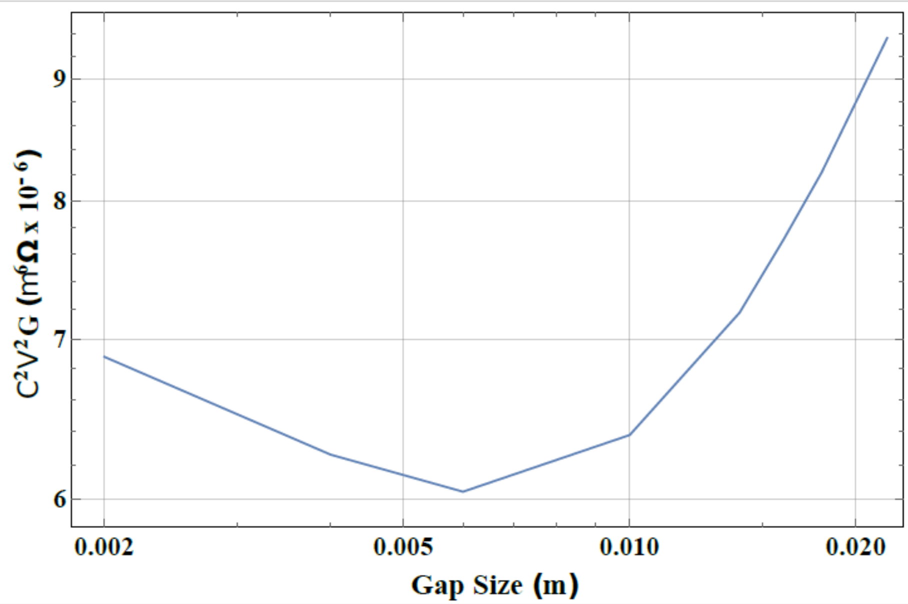


“Traditional” tuning rod

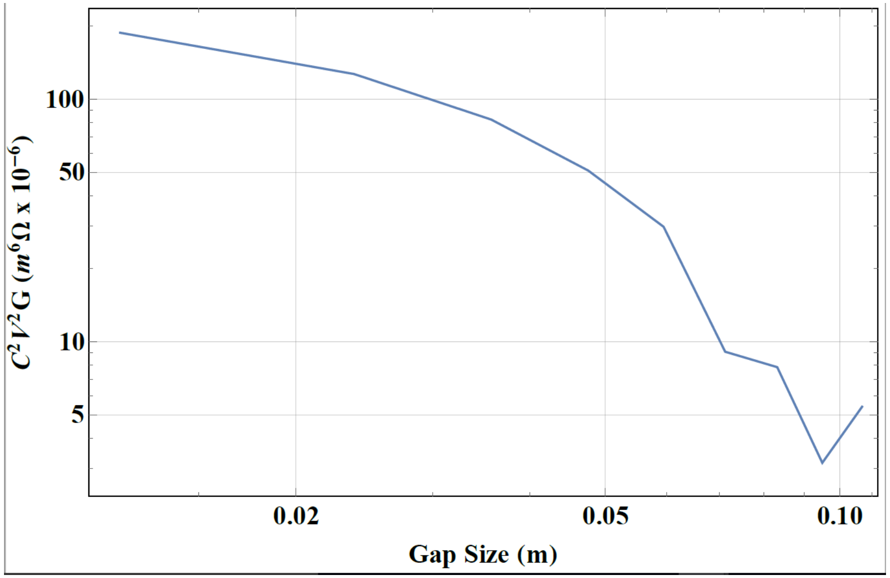
THE UNIVERSITY OF WESTERN AUSTRALIA

- Modelled a TM010 mode with a tuning rod sliding radially for a point of comparison
- Frequency tuning roughly the same



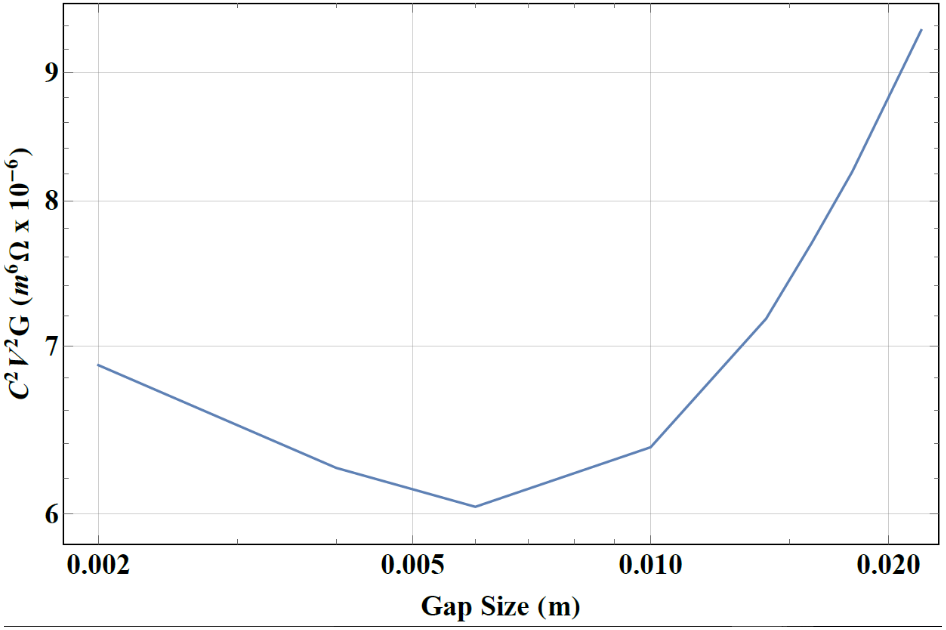


Sensitivity comparison



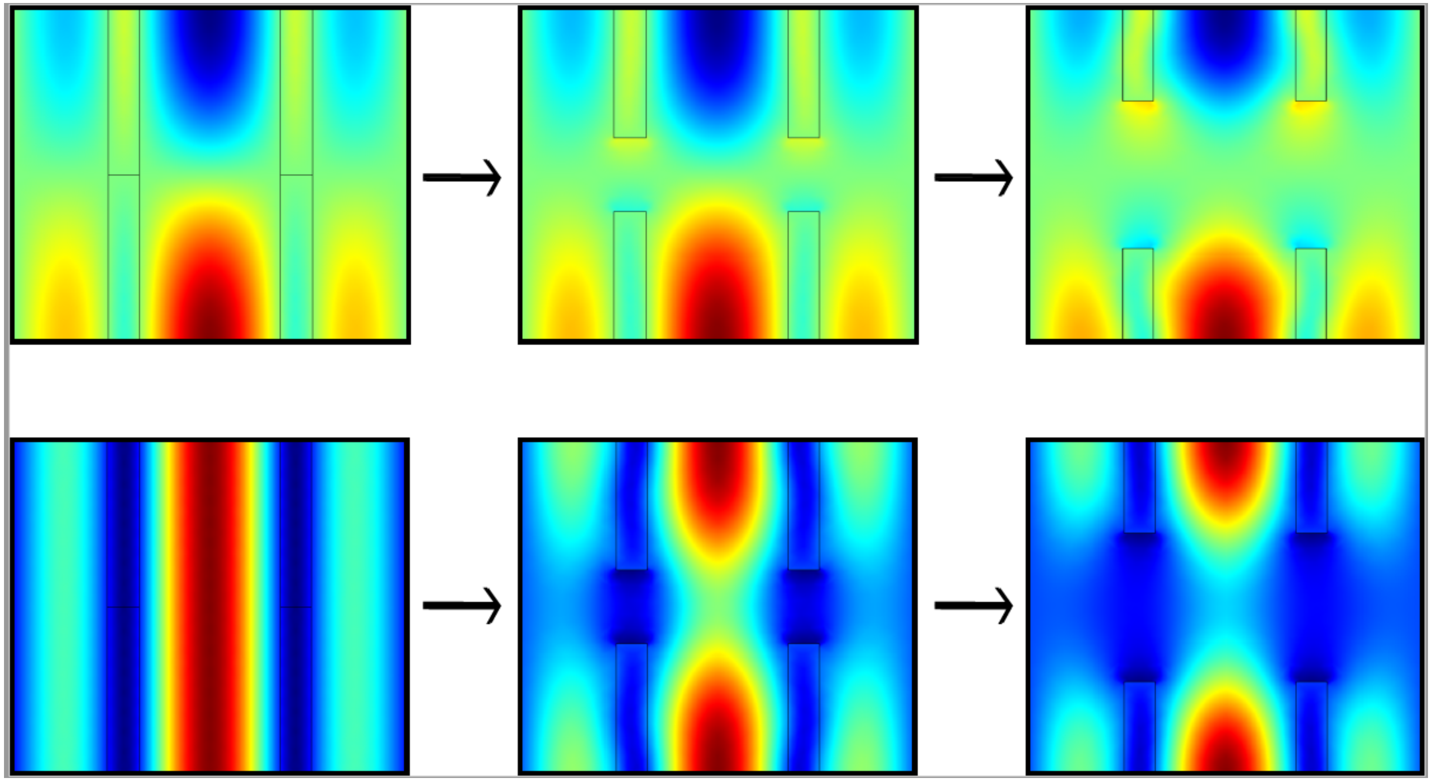
← DBAS Resonator

Tuning Rod →



Higher Mass Experiment

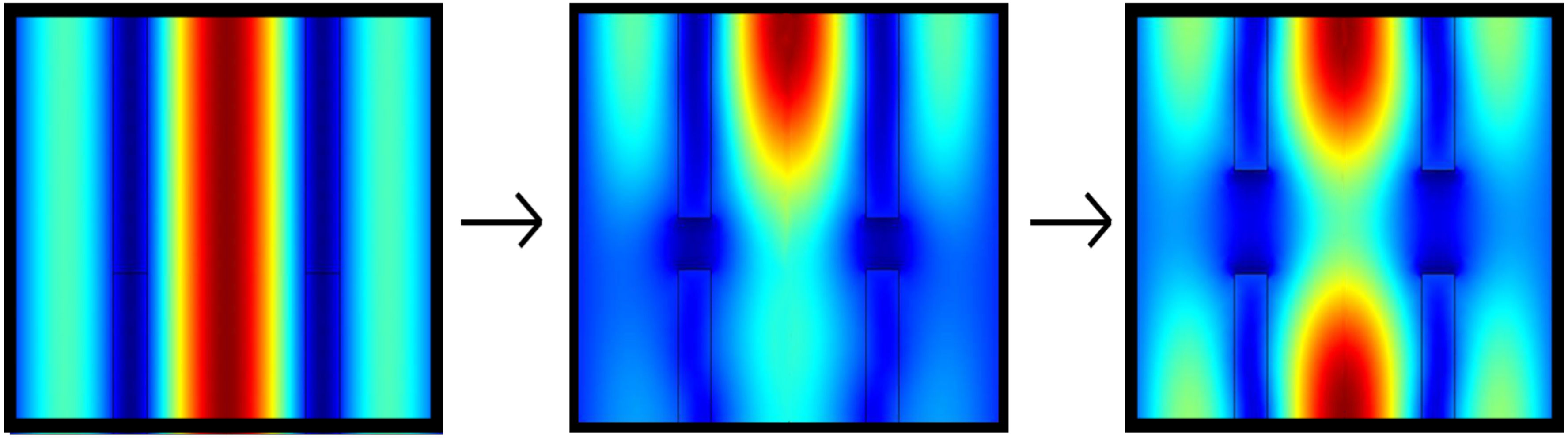
- How do we build one of these things?



- These plots assume a “magical shrinking ring”
- We need to actually pull the ring out

Higher Mass Experiment

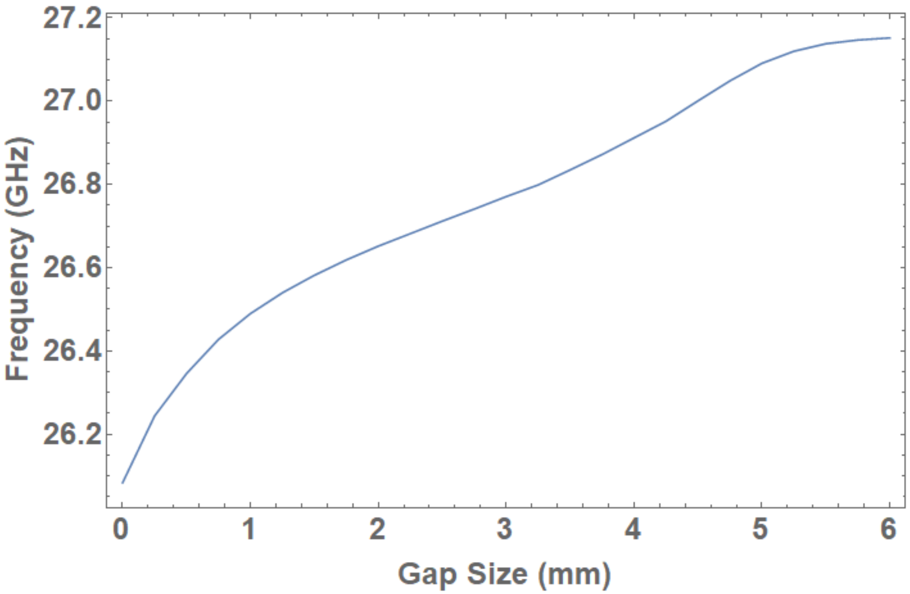
- Leave bottom ring stationary and just pull out the top ring

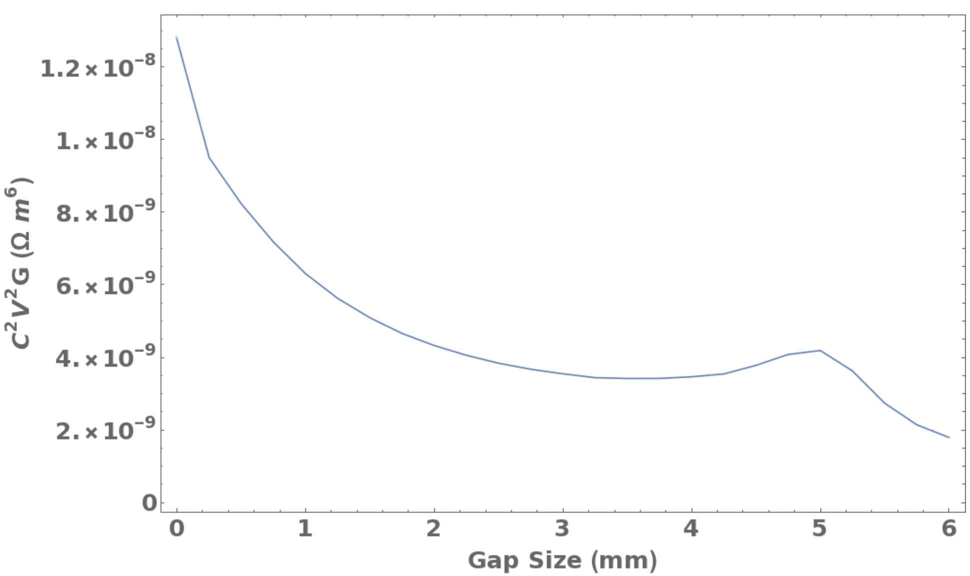


- Bottom ring shorter to increase symmetry in tuning range
- This slightly boosts sensitivity

Higher Mass Experiment

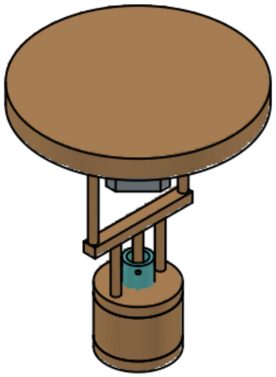
- Expected sensitivity and range for this cavity

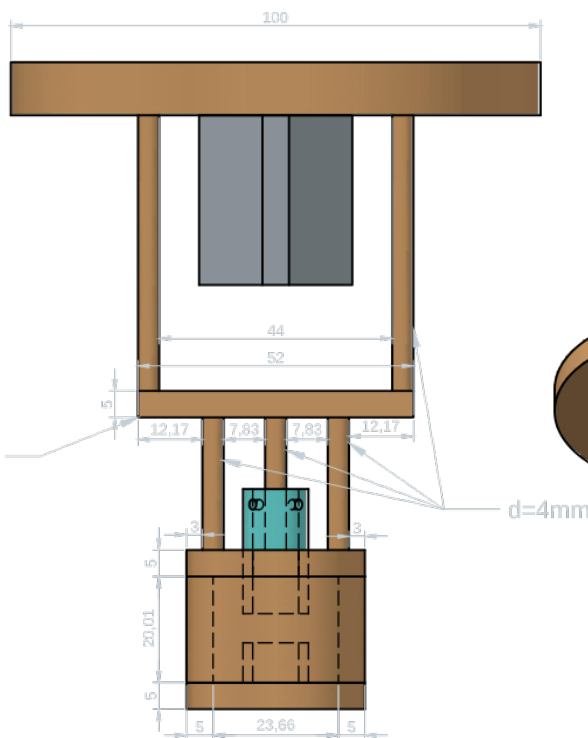


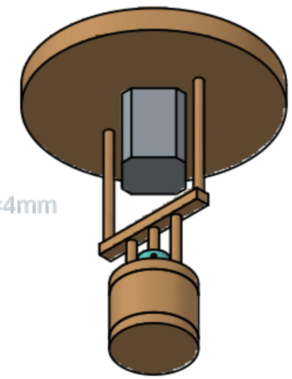


- But how do we actually build this thing? How do we slide the cylinder out of the lid?

Higher Mass Experiment



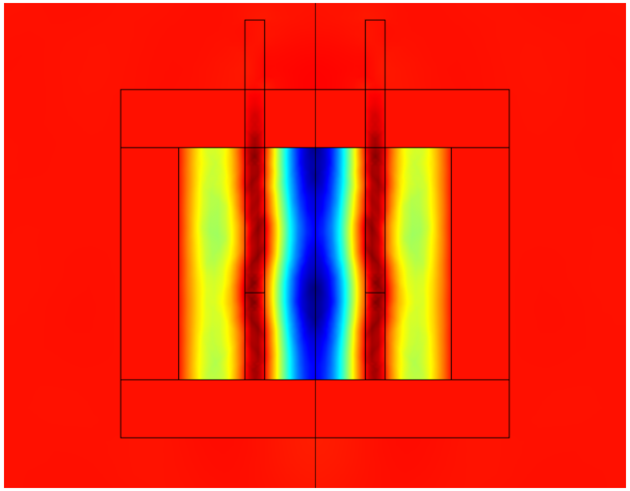


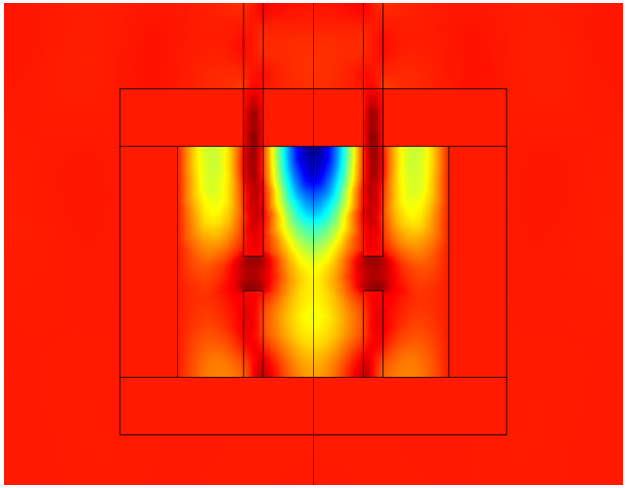


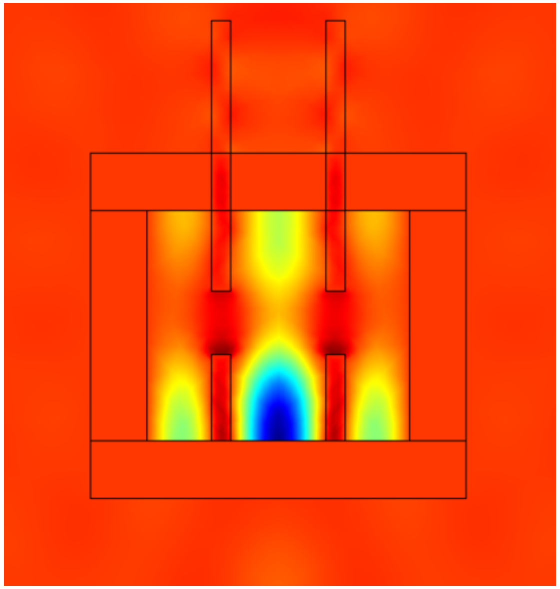
- Designed to be at 26 - 27 GHz for ORGAN Phase-I
- Lid split into two parts so that ring can be removed with attocube translation stage

Higher Mass Experiment

- This is kind of an open resonator
- Simulations suggest the field is quite confined in the cavity



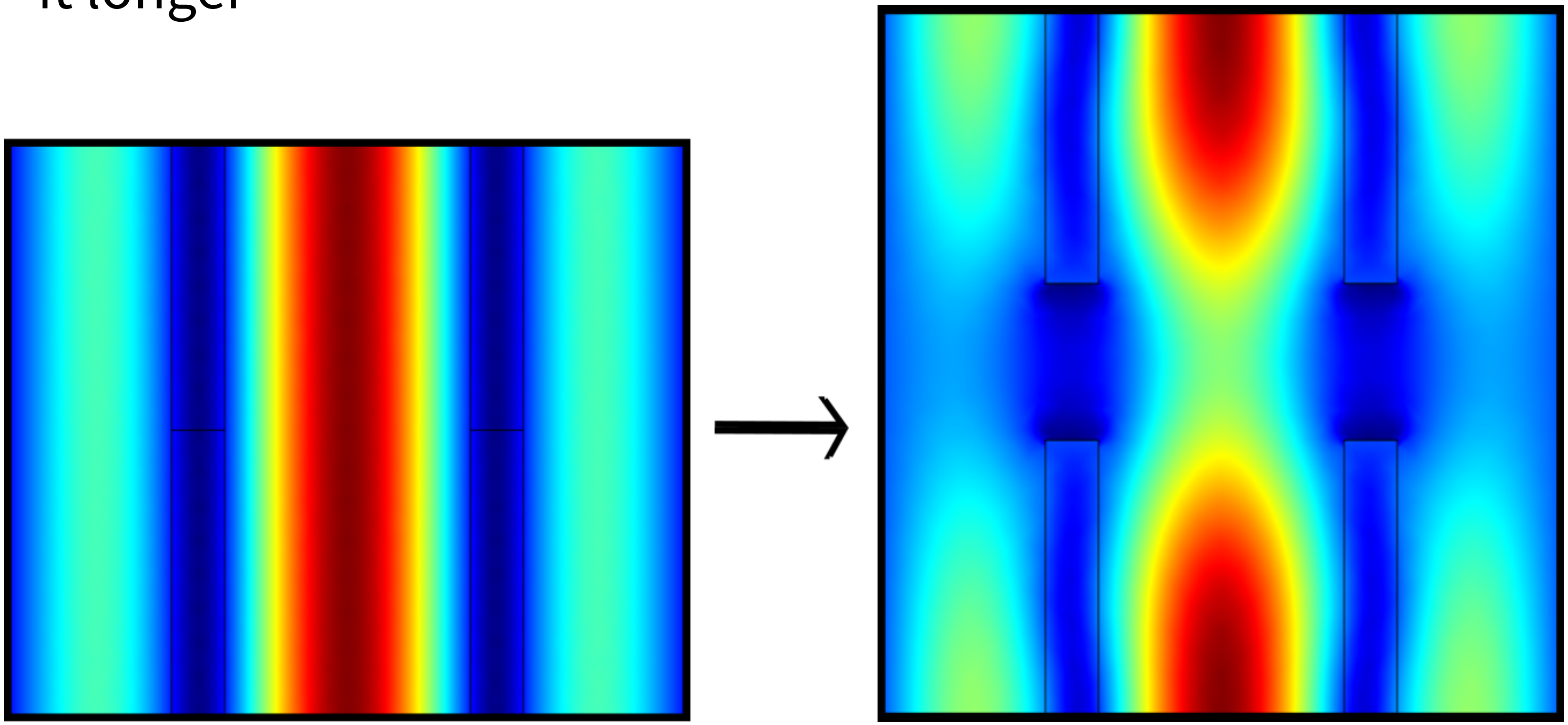




- However this doesn't mean it's easy

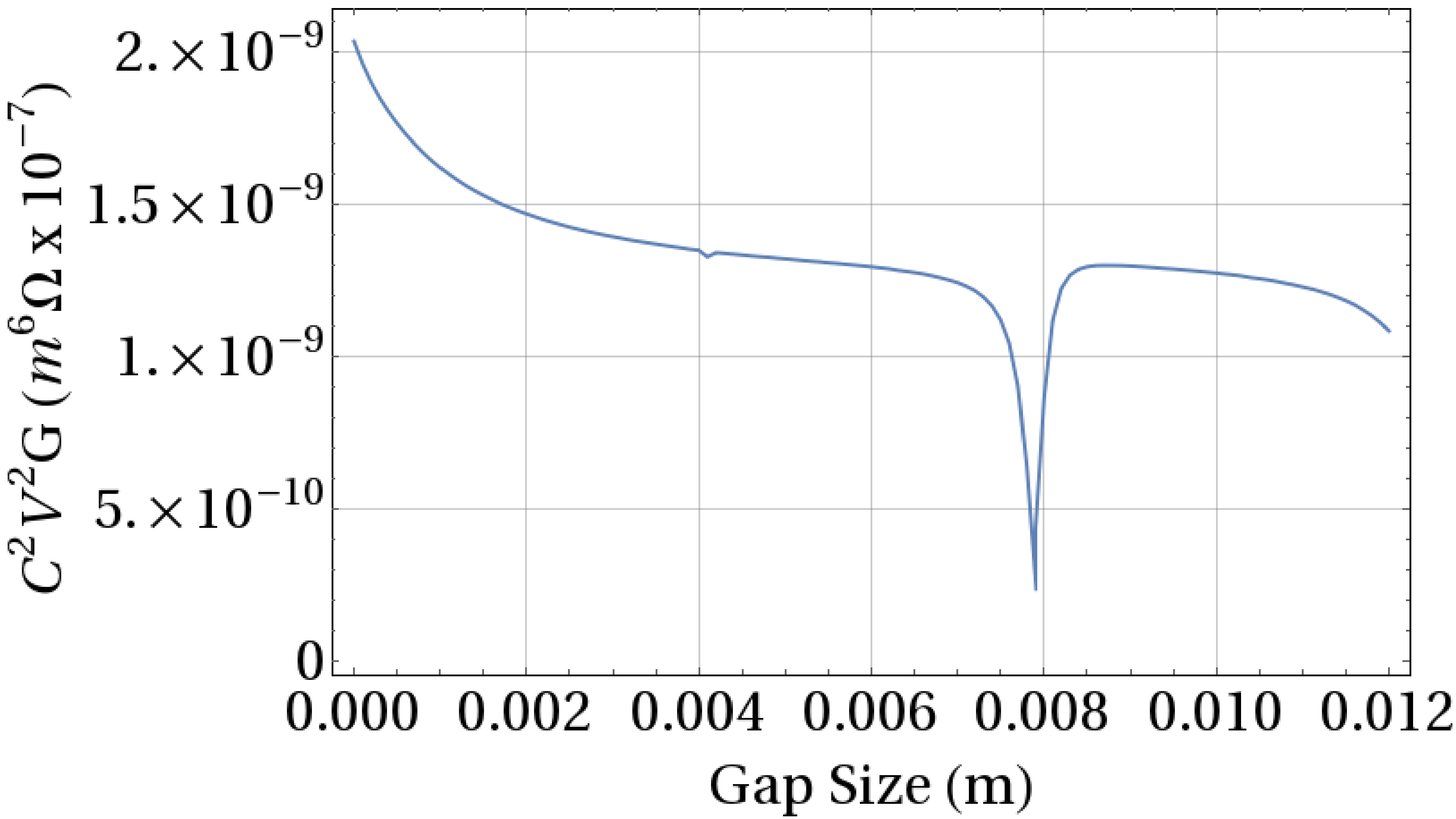
Higher Mass Experiment

- Cavity undergoing testing now – looks promising, but it is challenging
- We have a few backups if we run into too many problems
- Alternative – build a symmetrical cavity where we just make it longer



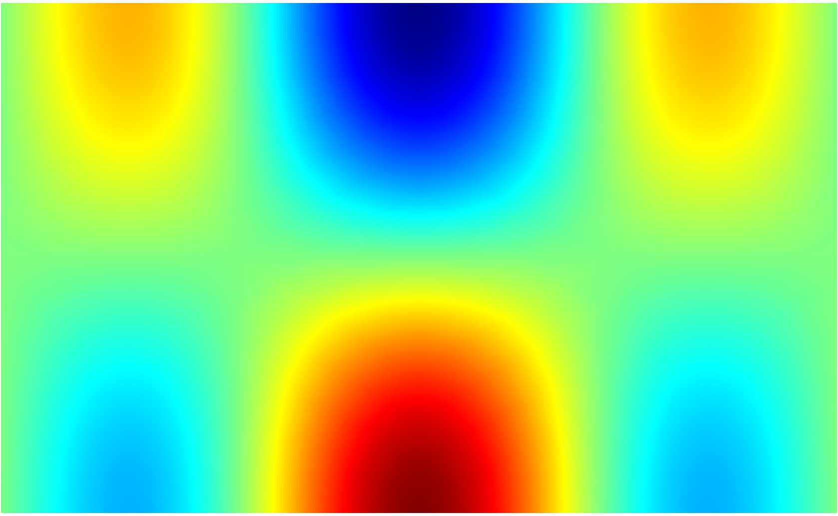
Higher Mass Experiment

- We lose some sensitivity, so we're sticking with plan A for now



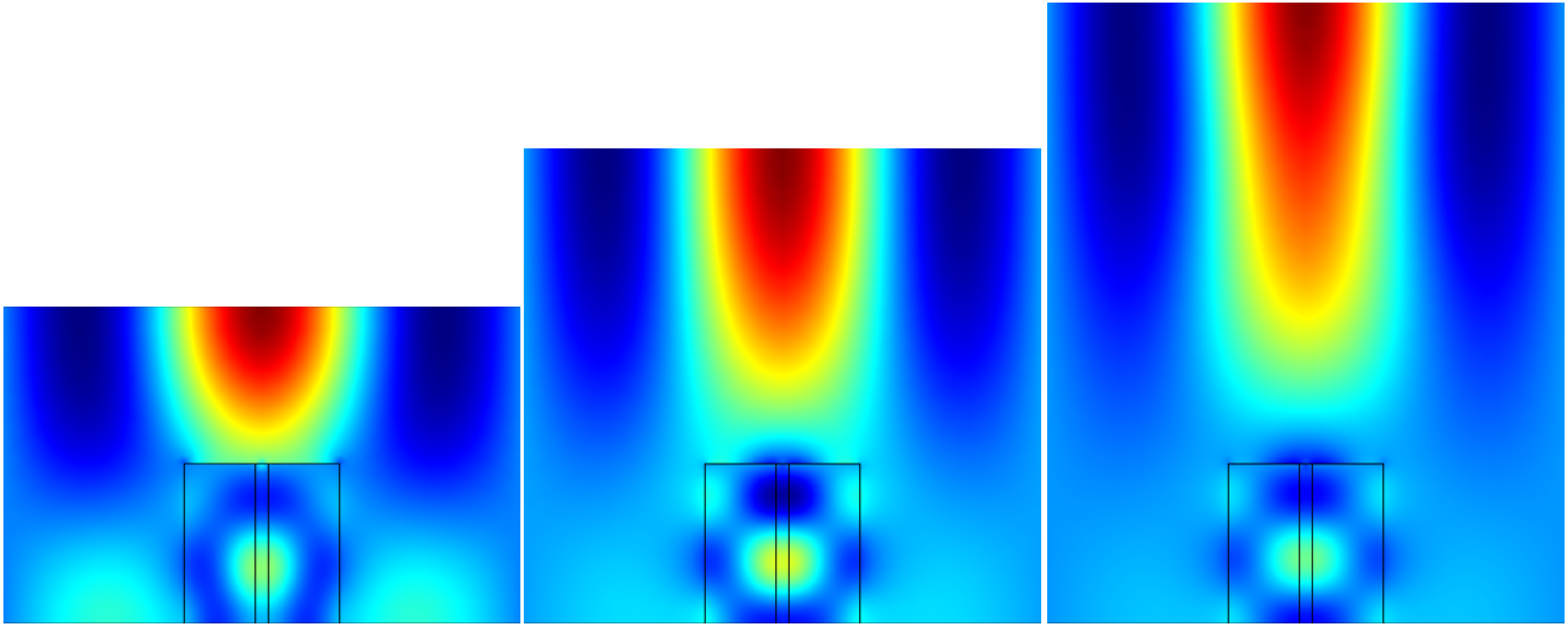
Other Dielectric Ideas

- Can we apply a similar principle to other modes?
- TM011, or TM021, for example



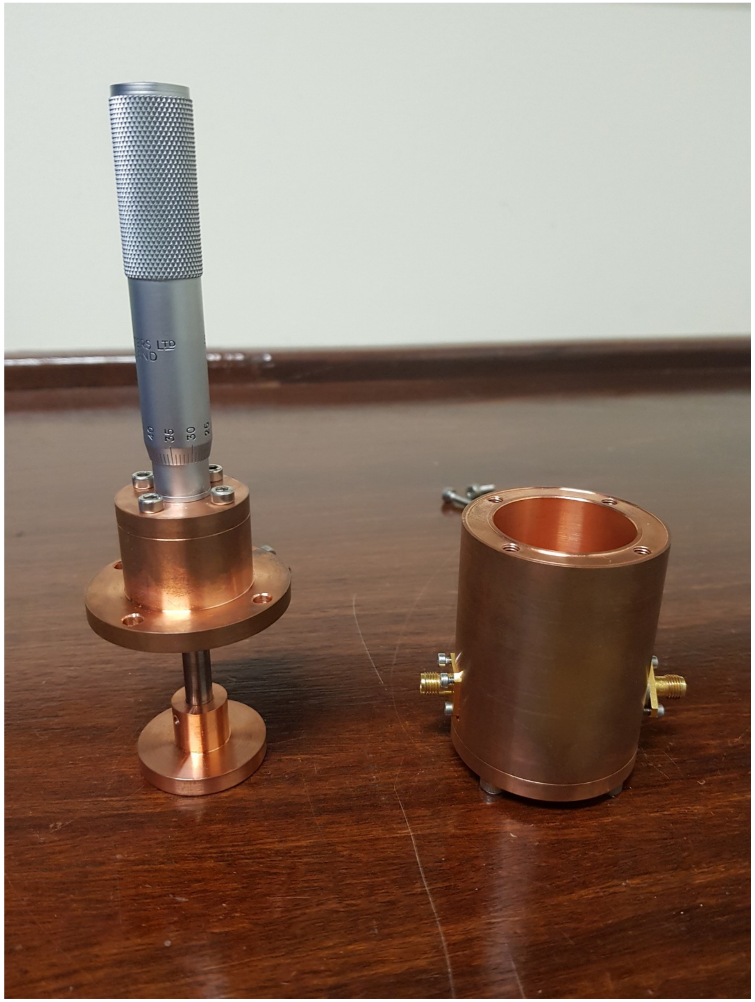
Other Dielectric Ideas

- We can suppress the out of phase field lobes in a similar way
- Very easy to tune, simply adjust length of can



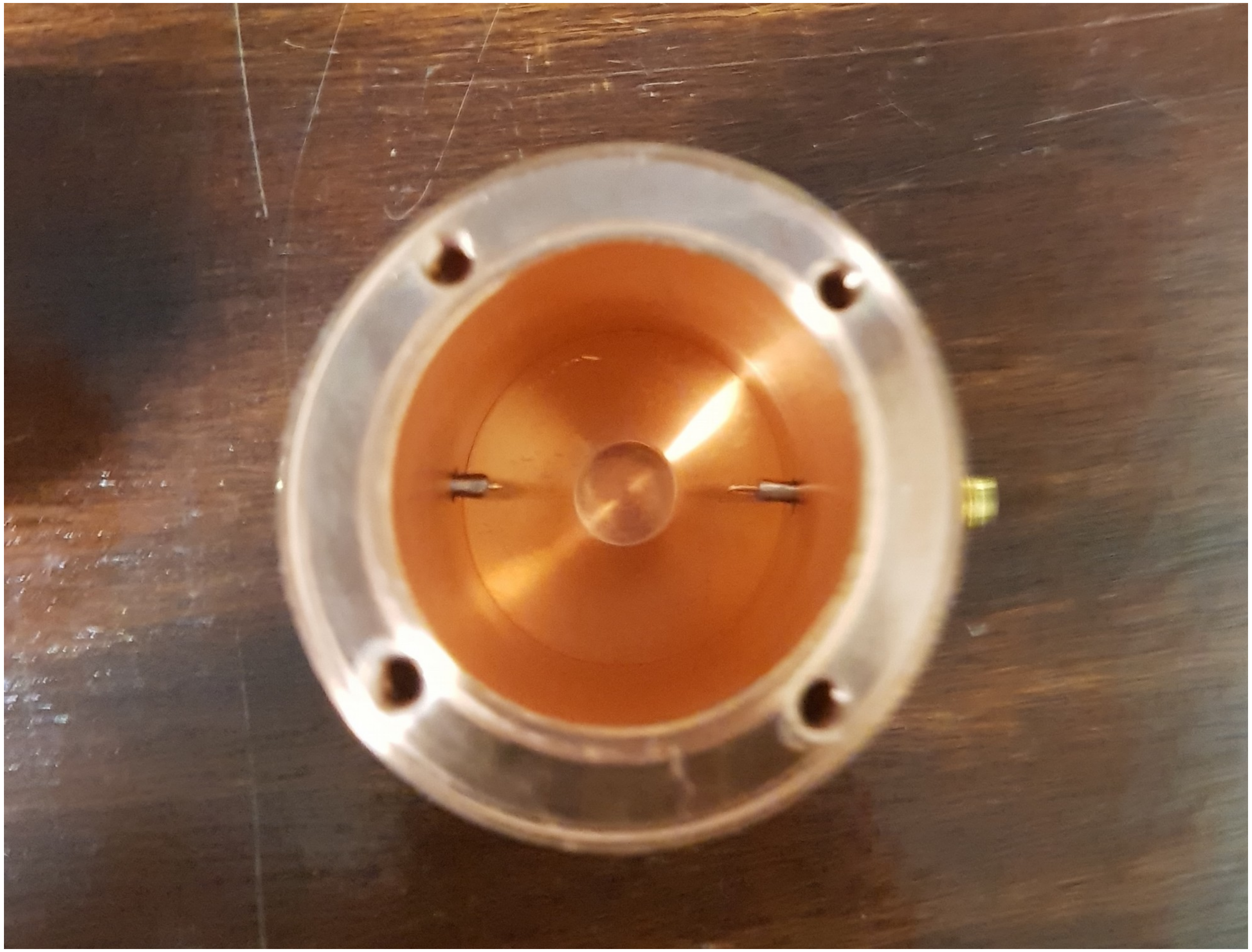
Other Dielectric Ideas

- Prototype has been built



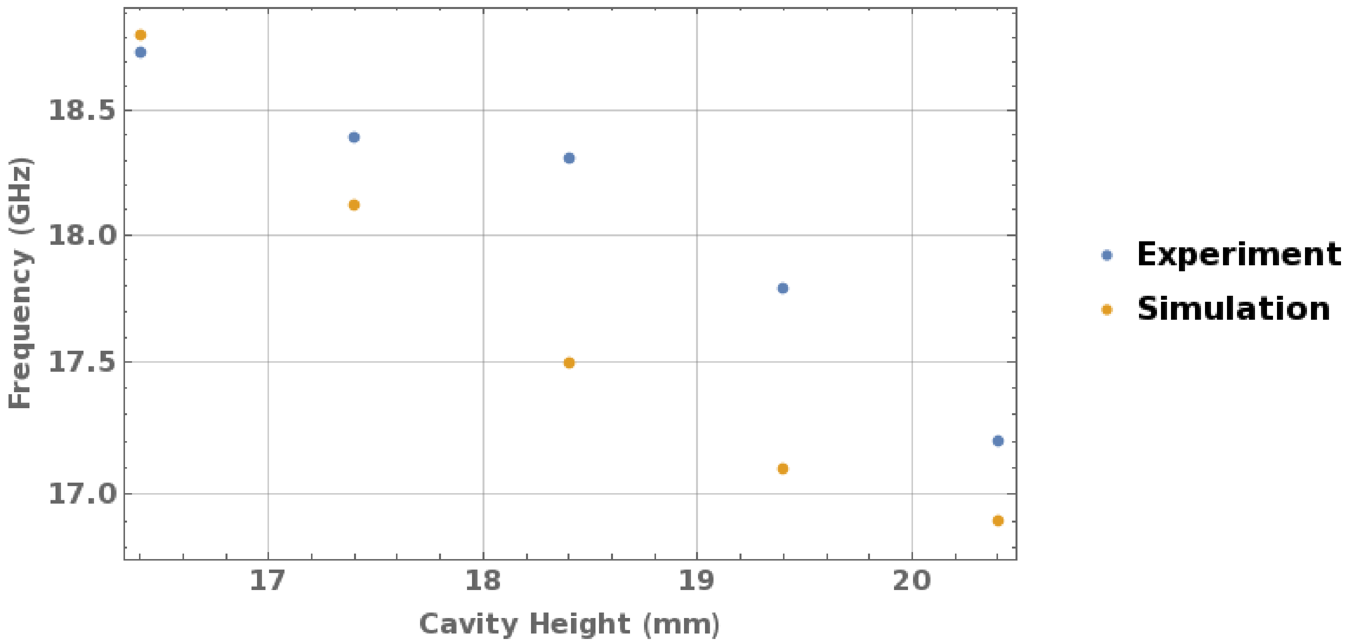
Other Dielectric Ideas

- Prototype has been built



Other Dielectric Ideas

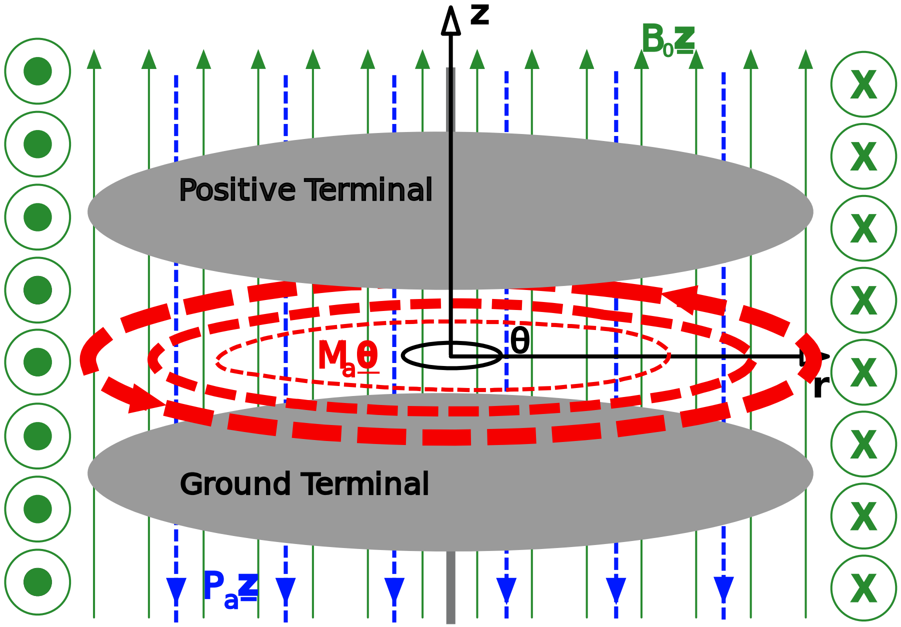
- Initial testing looks promising



- Another alternative, easy to tune

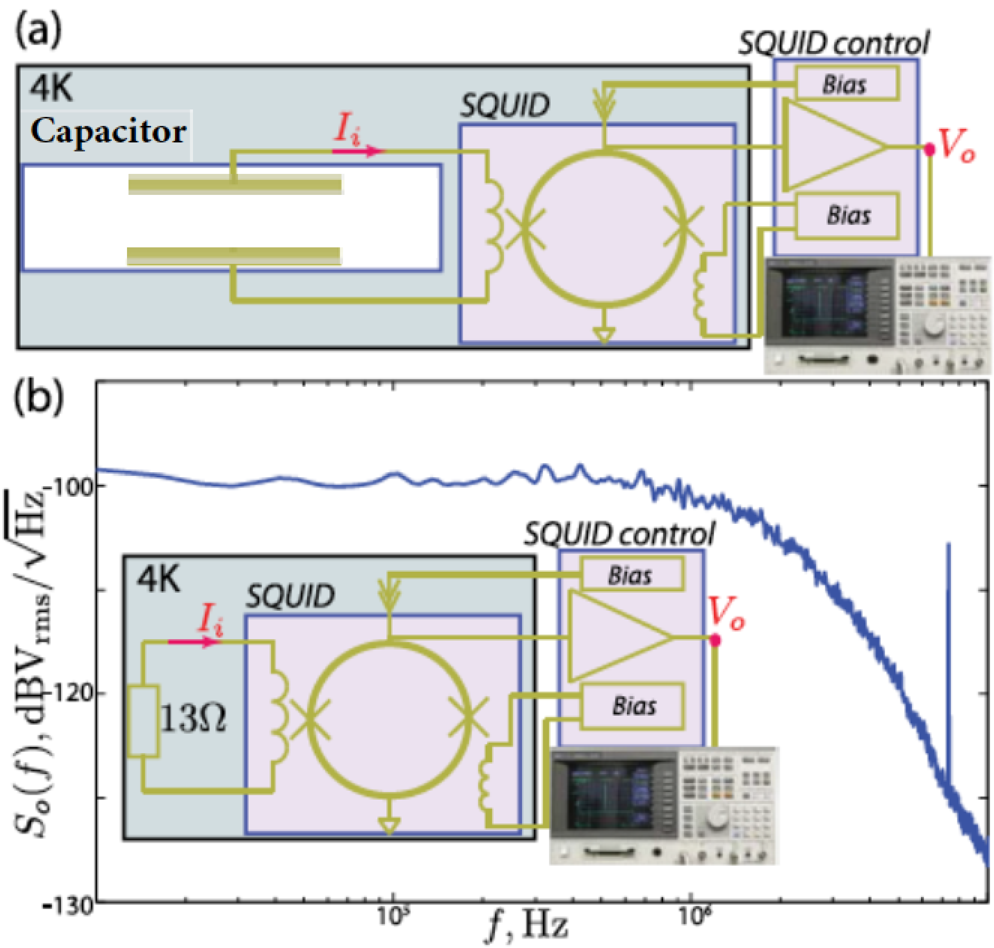
Other Experiments: BEAST

- Directly sense low-frequency electromagnetic field generated by low mass axions
- Broadband experiment
- Use a capacitor, or some other capacitive sensor
- See Mike Tobar's talk



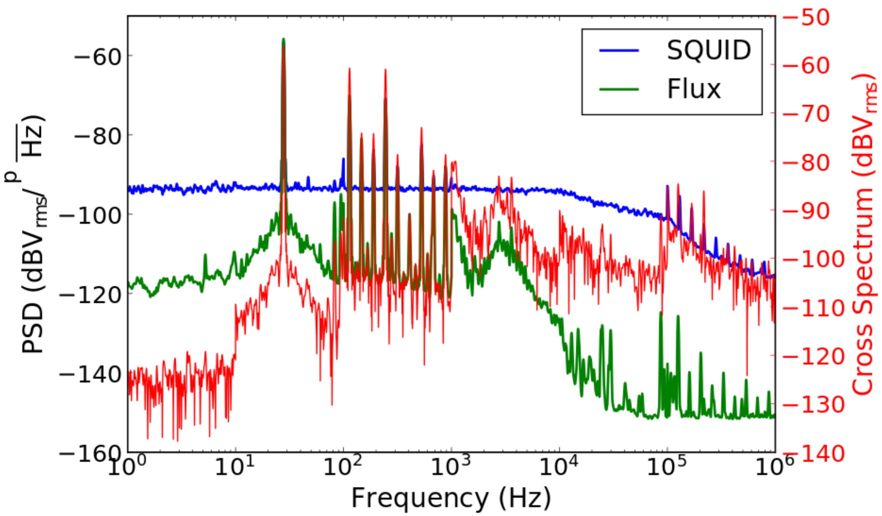
Other Experiments: BEAST

- First experiment was run earlier this year
- Single capacitor
- 7 T magnet
- Coupled to SQUID
- 8 days measurement time

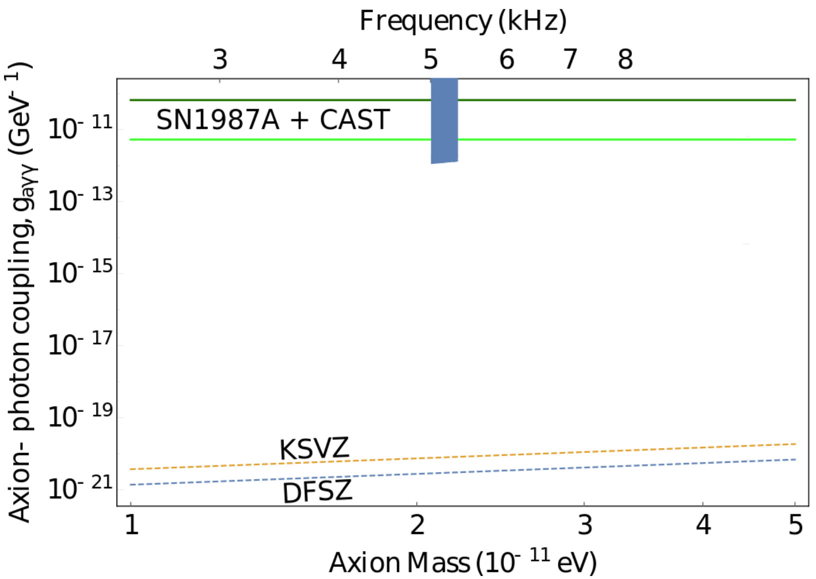


Other Experiments: BEAST

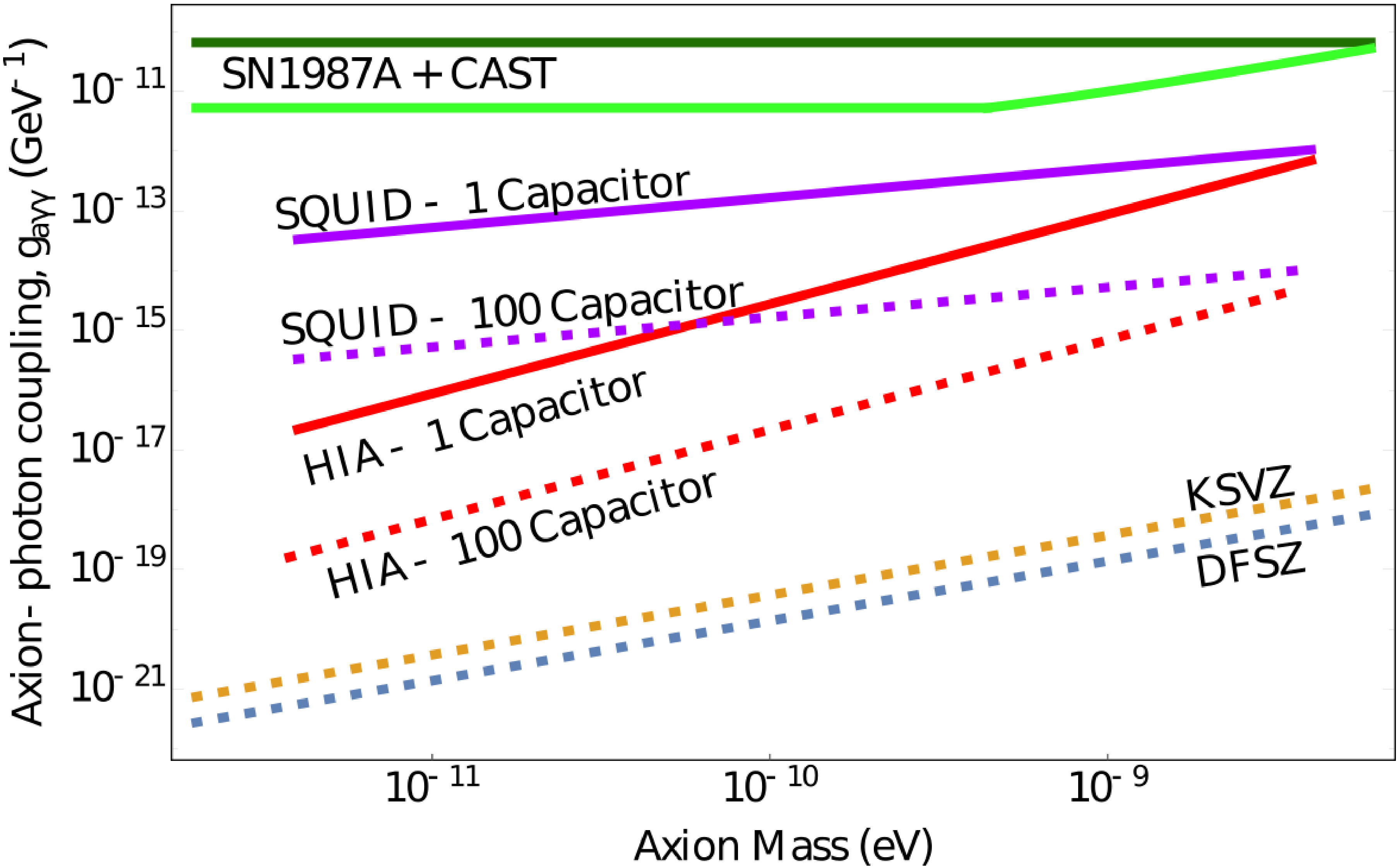
- SQUID spectra
- Can be used to veto candidate signals



- Preliminary exclusion limits



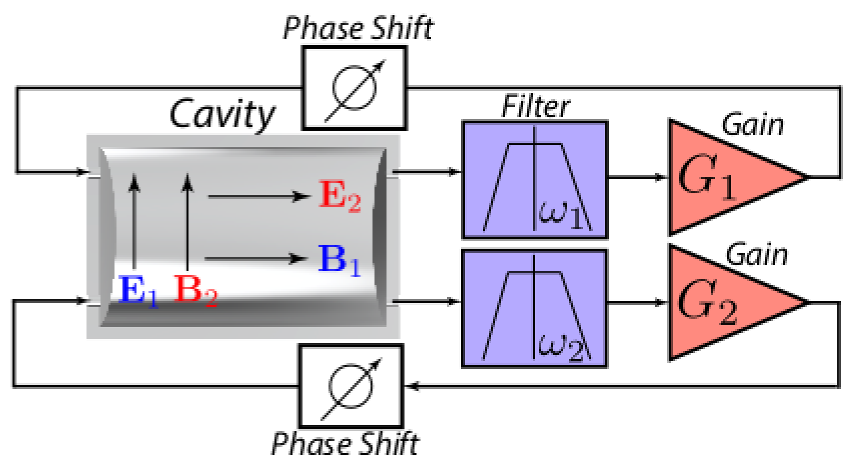
Other Experiments: BEAST



Other Experiments: Dual Mode Oscillator

- New type of axion detector
- Precision phase and frequency noise measurement
- Two orthogonally polarized modes as source of photons to interact with galactic halo axions
- Phase or frequency shifts induced
- First order in coupling constant, g_{ayy}

$$\sqrt{S_{\phi}^{\mathrm{D/U}}} = \sqrt{\left(1+\frac{\gamma_i^2}{f^2}\right)\left(\frac{1}{f^2+\gamma_i^2}\right)}\, g_{a\gamma\gamma}\sqrt{\omega_1\omega_2}\,\xi_{\pm}\left|\frac{\overline{x}_j}{\overline{x}_i}\right|\left|A\right|$$



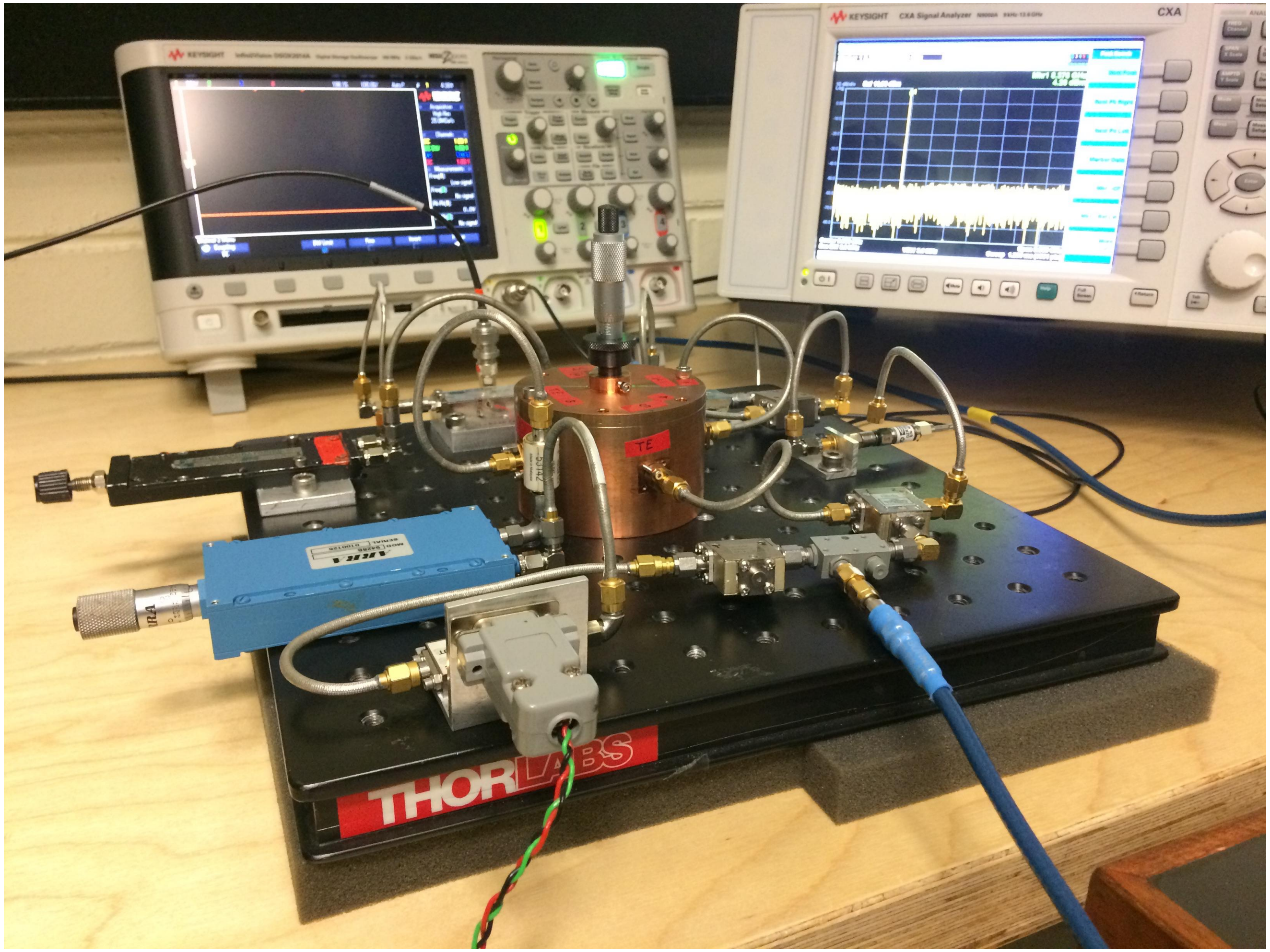
- Detect with low-phase noise measurement system

Other Experiments: Dual Mode Oscillator

- TM020 and TE011 modes employed in first experiment
- Several stages/scale-ups:
  - Free-running oscillator
  - Frequency stabilized oscillator
  - Empty copper cans
  - More exotic ideas…
- Multiple experiments possible: upconversion/downconversion, loops vs pumped resonances
- Some of the nice things about this experiment:
  - No magnet/dil fridge required
  - No quantum amplifiers required

Other Experiments: Dual Mode Oscillator

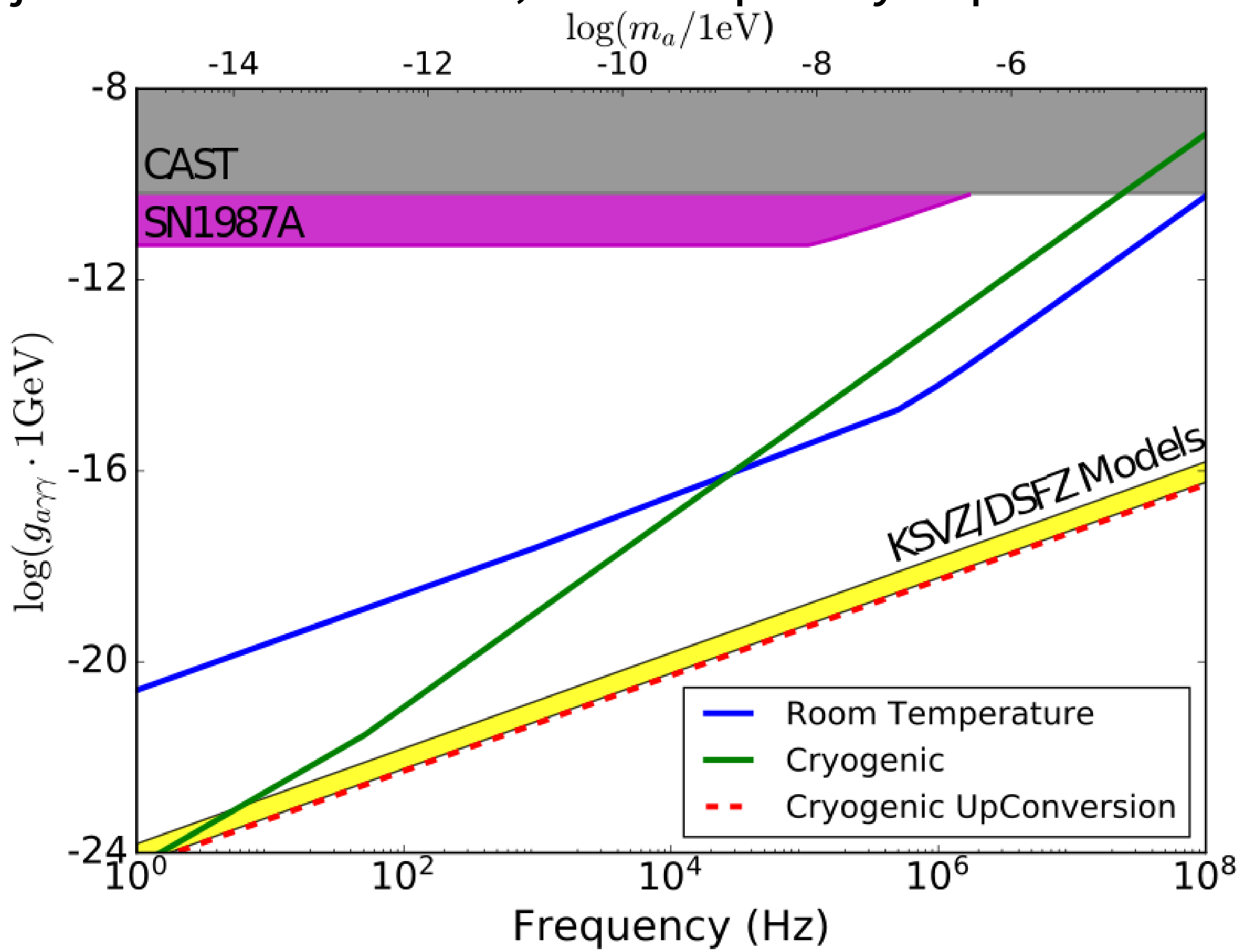
- A few different experiments possible with this technique



- Prototype under construction

Other Experiments: Dual Mode Oscillator

- Projected limits for first, low frequency experiments



- See Maxim Goryachev's talk for more

Conclusions

- Many parallel dark matter detection experiments with EQUS
- ORGAN (see arXiv:1706.00209v2/Physics of Dark Universe and arXiv:1705.06028v3/Physical Review Applied):
  - Purchasing new fridge and magnet
  - Novel resonator design to enhance sensitivity in high mass regime
- BEAST (see arXiv:1803.07755v2):
  - Low mass axion detection
  - Broadband measurement
- Dual Mode Experiment: Acronym pending…(see arxiv:1806.07141):
  - Precision measurement techniques