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ADMX
AXION DARK MATTER EXPERIMENT

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Development of Iris-Connected Multicell Cavities for Axion Searches

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8/5/2022

DETECTOR R&D
NEW INITIATIVES

Outline

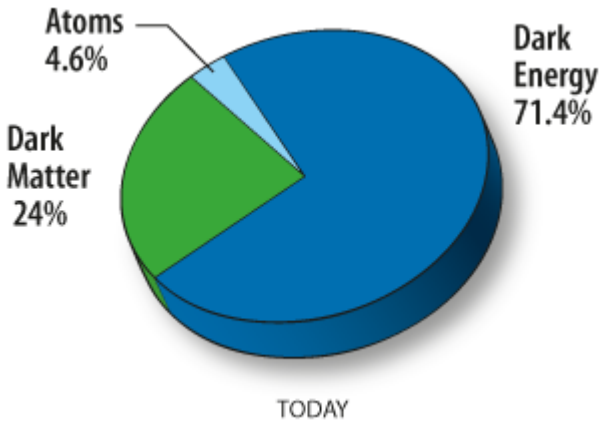
- Introduction to Axion Searches
  - Dark Matter
  - History Timeline of Axions
  - Axion Detection Techniques
  - Inverse Primakoff Effect
  - Invisible Axion Models
  - Cavity-Based Haloscope Detectors
- Iris-Connected Multicell Cavities
  - Basic Idea
  - Electromagnetic Design
  - 4-Cell Prototype
  - Science Reach
  - Outlook

What is the Universe Made of?

- Until about thirty years ago, astronomers thought that the universe was composed almost entirely of "baryonic matter", ordinary atoms
- However, in the past few decades, there has been ever more evidence accumulating (gravitational lensing, cosmic microwave background, supernovae, …etc) that suggests there is something in the universe that we can not see, perhaps some new form of matter

Gravitational Lensing

Supernova



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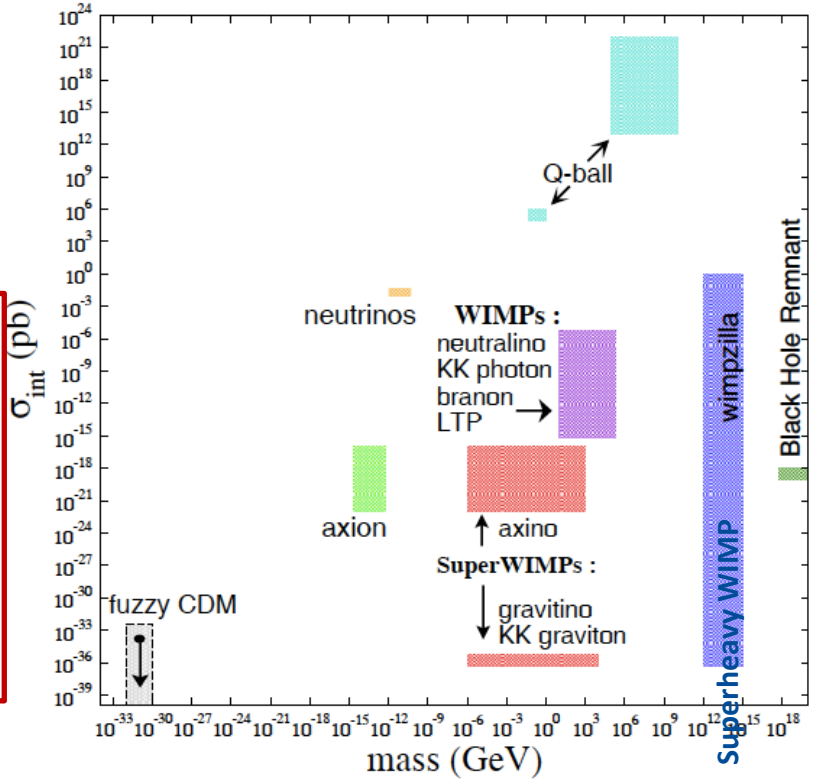
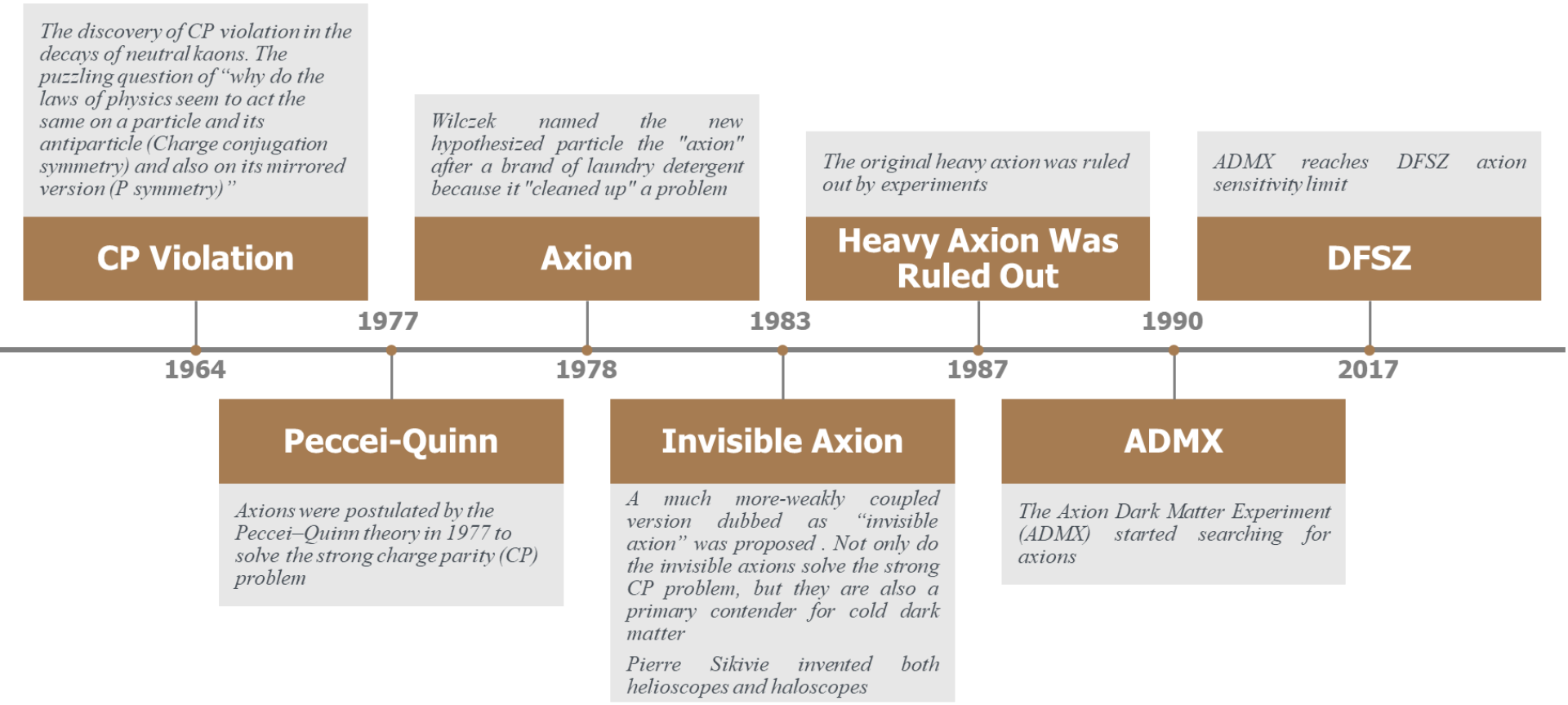
Dark Matter Particles: WIMPs vs WISPs

- Extensions of the Standard Model predict candidate particles classified as either
  - weakly-interacting massive particles (WIMPs) with a typical mass of GeV–TeV
  - weakly-interacting slim particles (WISPs) with μeV–eV (0.2428 GHz-242.8 THz)
    - Axions
    - Hidden/Dark Photons

Despite the tremendous effort that was put by several experiments to find WIMPs over the past few decades, no evidence for WIMPs has been found so far
This gave their rival lightweight counterparts more traction – WISPs and especially axions



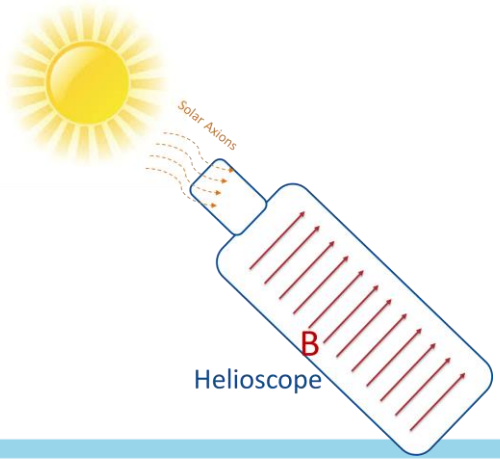
History Timeline of Axions

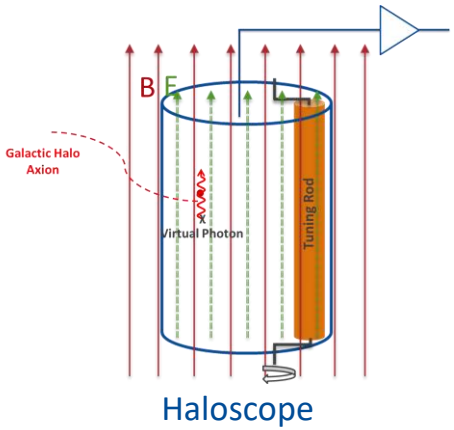


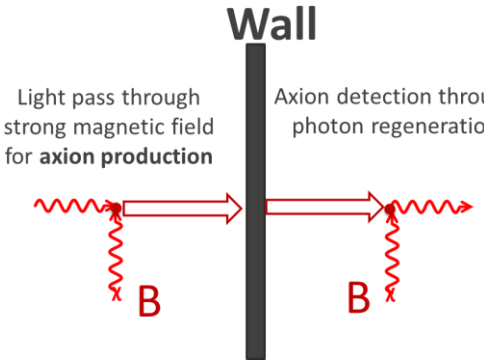
Axion Detection Through Photon Coupling

Axion **detection techniques** rely on the presence of a strong magnetic field to convert either: solar axions into x-rays in **helioscopes** or galactic halo axions into photons in **haloscopes**

Helioscopes	Haloscopes	Light Shining Through Walls
• Point towards the sun for streams of solar axion • CAST	• Look for ambient axions from the Milky Way's matter halo • ADMX, CAPP, Haystac, QUAX, ORGAN, KLASH	• Axions are produced within the first section of the experiment by shining light in the presence of a magnetic field that converts photons to axions. • Then these axions are detected on the other side of the experiment after a wall. • OSQAR







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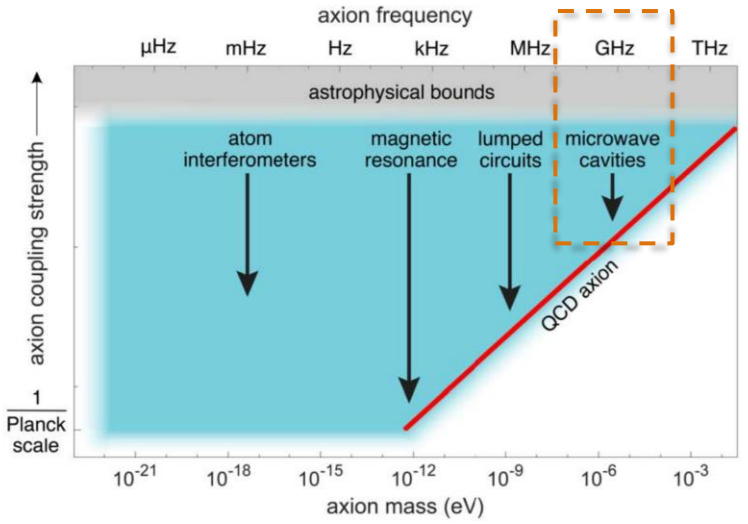
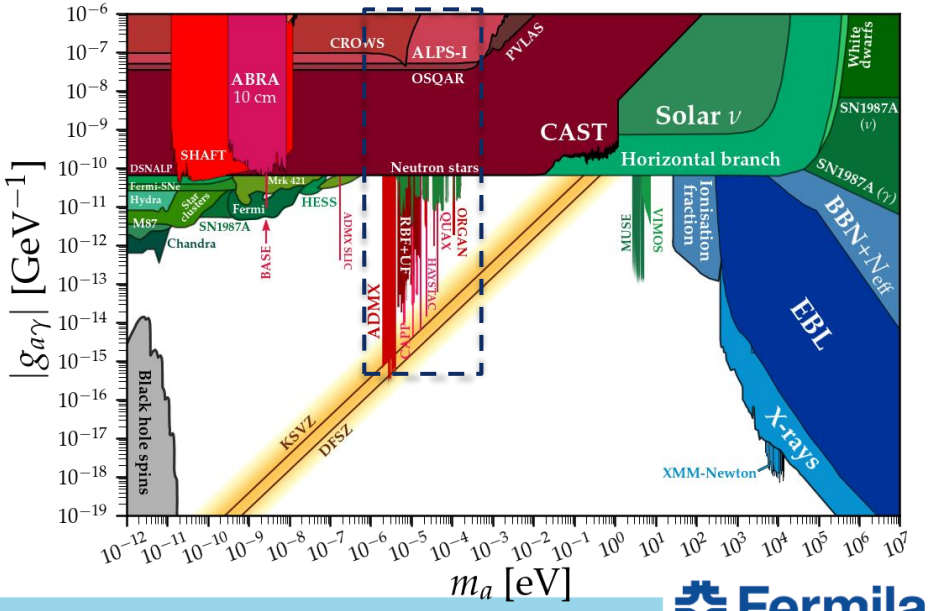
Inverse Primakoff Effect

- Named after Henry Primakoff
- In the presence of a magnetic field, the axion can mix with a virtual photon (borrowed from the magnetic field), resulting in a real photon
- The result is a real photon emitted at a frequency equal to the converted axion's mass
- The electromagnetic signal is expected to be eminently weak, with typical values lying around the range of 10^{-21}W (-180 dBm)
- Haloscopes routinely operate in cryogenic temperatures for reduced noise

Hurdles in the Way to Finding Axions

- Very large parameter space which will prolong the search process for decades if it is done at the same current pace
- Beyond few GHz, significant technical hurdles need to be overcome to maintain the detection sensitivity





Significant advancements in the technology of haloscope detectors are critically needed

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Invisible Axion Models

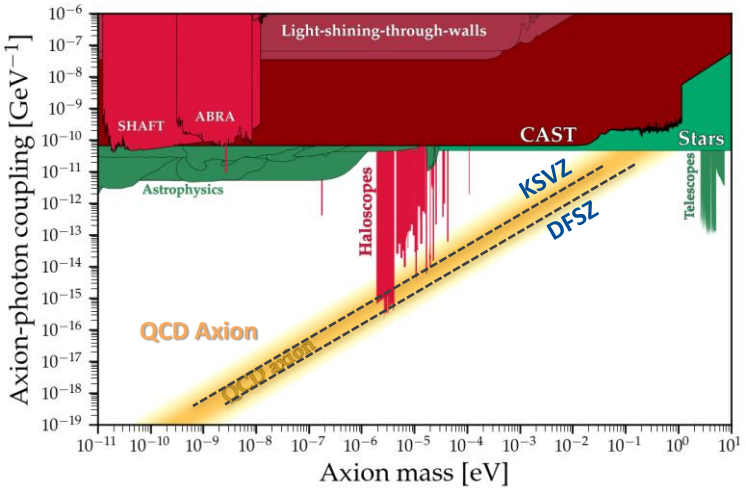
- Named so for their extremely weak couplings
- The Peccei–Quinn (PQ) symmetry is decoupled from the electroweak scale and is spontaneously broken at a much higher temperature, decreasing the axion mass and coupling strength

Kim-Shifman-Vainshtein-Zakharov (KSVZ)

- The PQ symmetry is realized in the context of a heavy quark
- KSVZ axions are a factor of 8/3 stronger than the DFSZ ones

Dine-Fischler-Srednicki-Zhitnitsky (DFSZ)

- The PQ symmetry is realized in the context of a two-Higgs-doublet



Halsoscopes: Resonant vs. Non-Resonant Detection

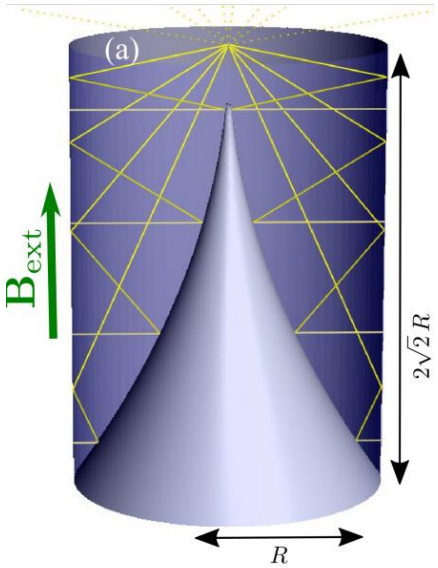
Resonant Halsoscopes

- Based on closed EM structures (cavities, sometimes LC circuit)
- Has the advantage of signal enhancement with the cavity Q (enhanced sensitivity)
- Narrow bandwidth
- Needs tuning

Non-Resonant Halsoscopes

- Based on open EM structures (reflectors)
- Wide bandwidth on the price of lower sensitivity

ADMX,
Haystac,
CAPP, …



BREAD

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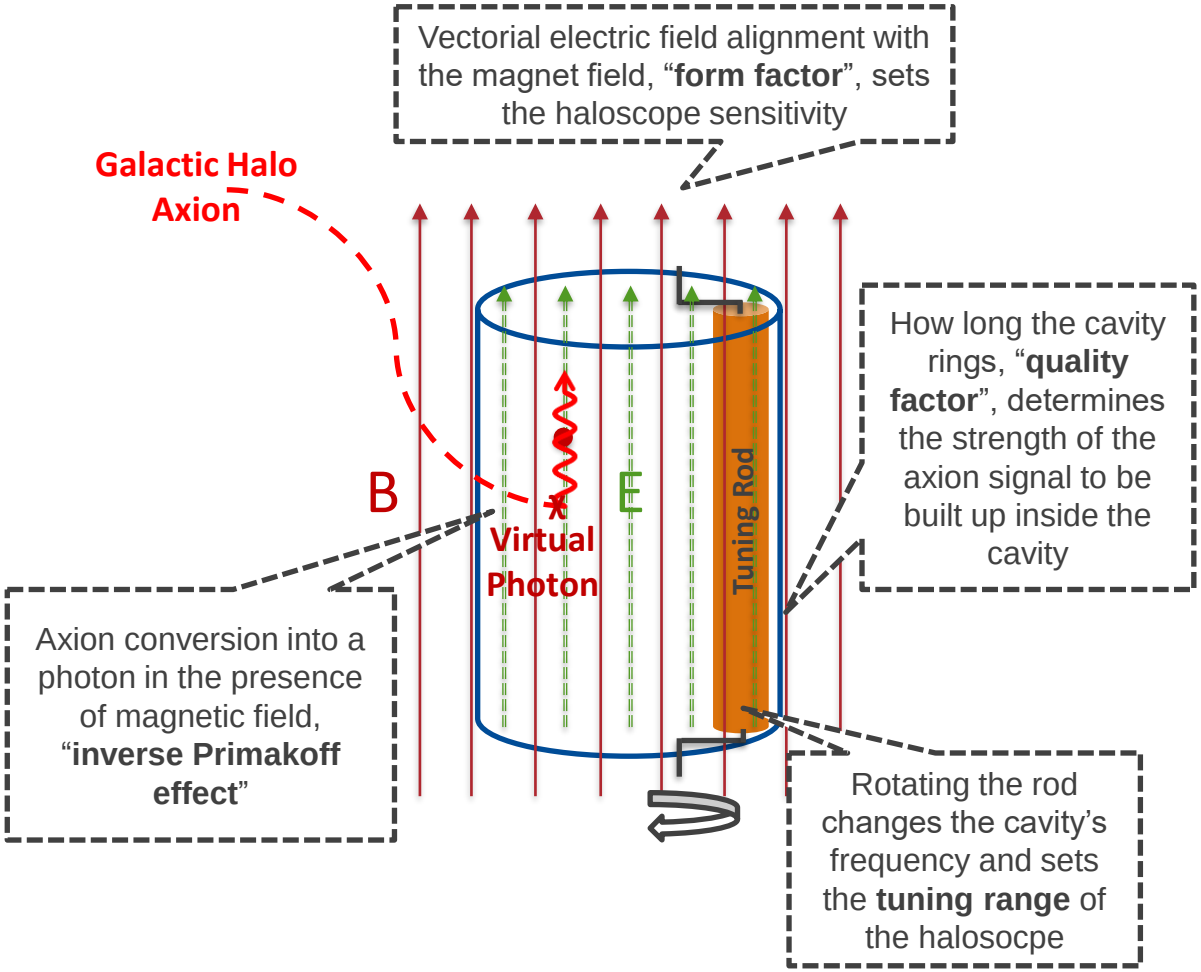
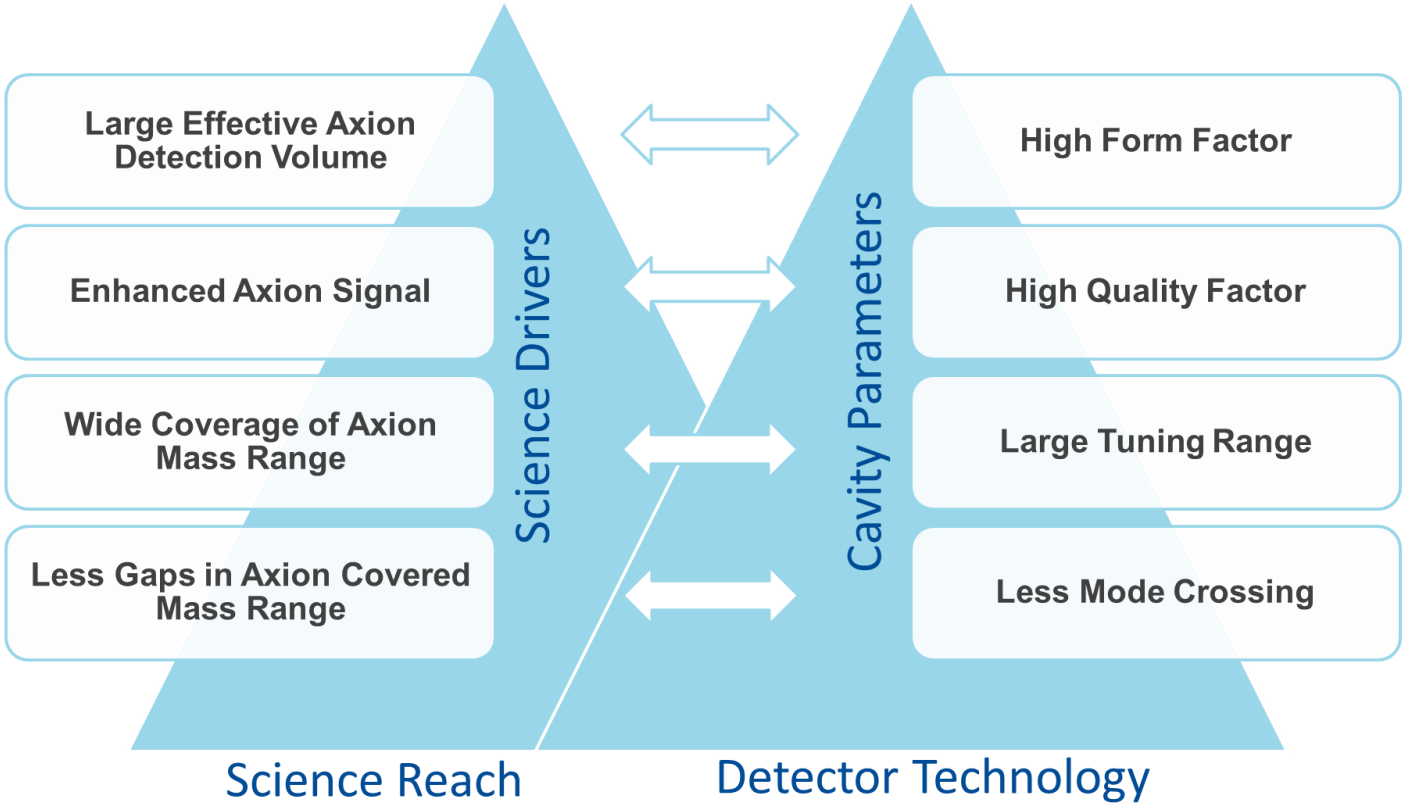
Cavity-Based Haloscope Detector



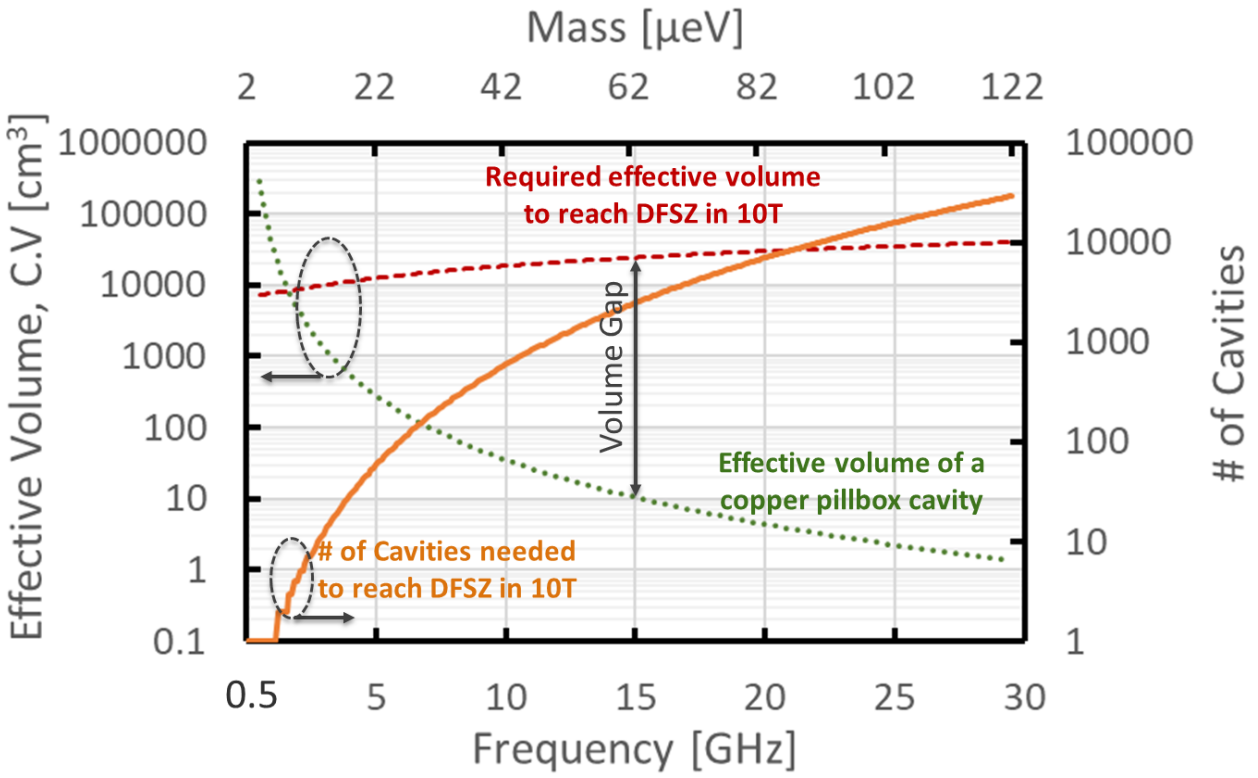
$$df/dt \approx 1.68\ GHz/year \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1GHz}\right)^2 \left(\frac{\rho_0}{0.45GeV/cc}\right)^2 \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8T}\right)^4 \left(\frac{V}{100L}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2K}{T_{sys}}\right)^2$$

Cavity is the Heart of Resonant Haloscope Detectors



Detector Technology and Especially the Cavity Determines the Science Reach of the Haloscope Detector

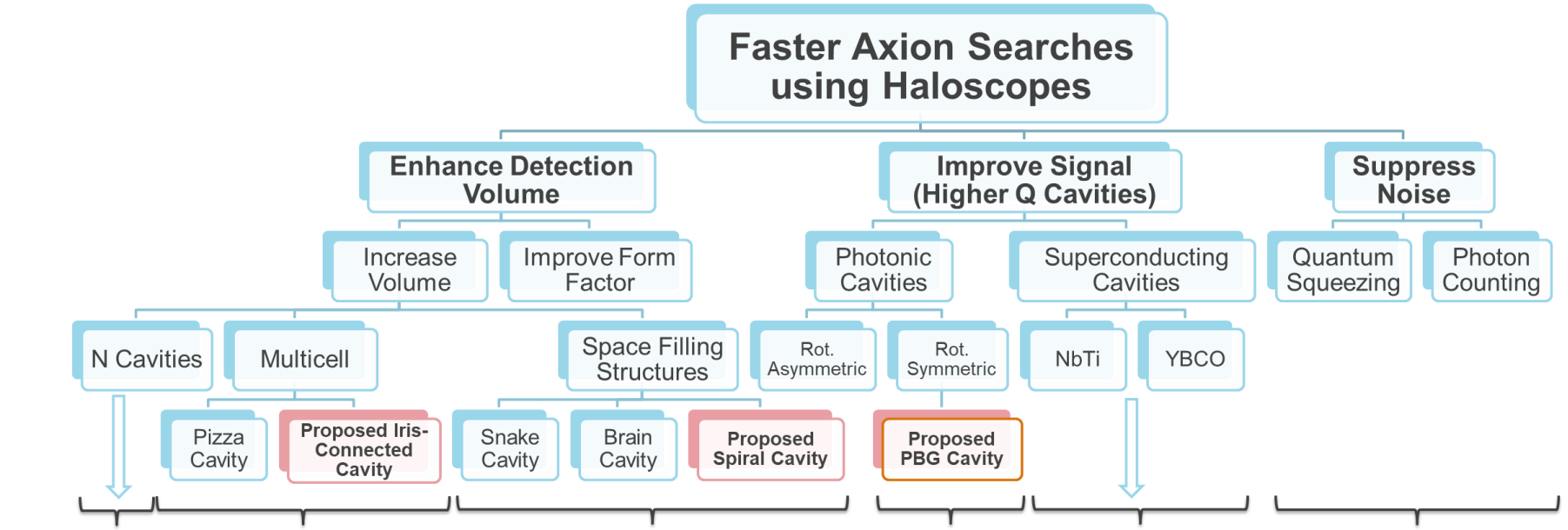
Haloscope Detector Technology: "Volume Gap" Problem



BRN: There is a need for new types of **tunable**, **large volume** (i.e. many times λ^3 resonators at high frequency (> 1 GHz)

Haloscope detectors will face a volume gap problem at higher mass ranges – How to scale number of cavities beyond ~100 cavities?

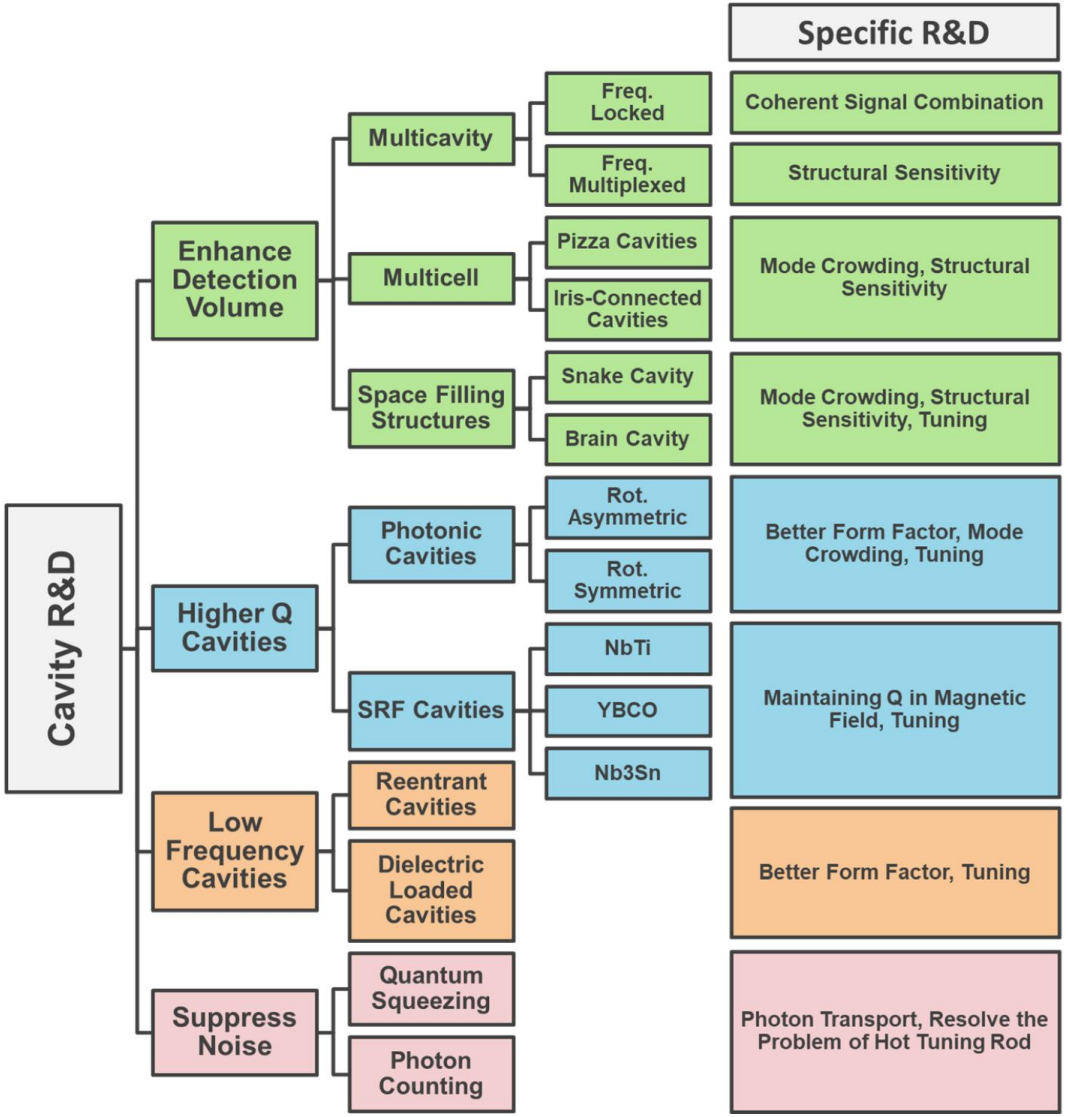
Haloscope Detectors: State of the Art



Many Technological Challenges and Opportunities

Haloscope Detectors: State of the Art (Snowmass White Paper)

- Contributed this graph to Snowmass white paper
- It explains the challenges facing cavity-based haloscope detectors and highlight the needed R&D



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High Frequency Haloscope Detectors: The Challenge

- For relatively low axion mass ranges (<1GHz), a single cavity was used for axion detection to reach the DFSZ limit (ADMX Run1)
- However, to scan at larger mass ranges the cavity physical dimension will scale down with frequency necessitating the use of multiple cavities in order to maintain the detection volume which in turn controls the sensitivity and the scan rate of the haloscope detector
- Working with multiple cavities adds a significant complexity to the detector because of the need to lock the cavities together and then coherently combine the output signal from the multiple cavities

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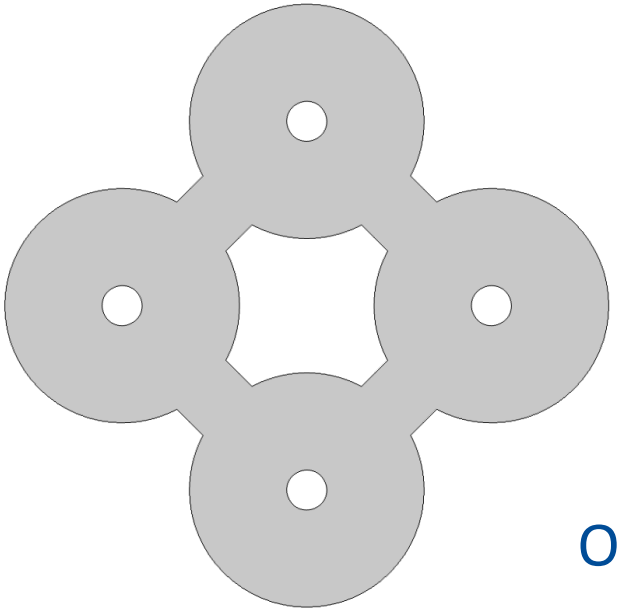
Iris-Connected Multicell Cavities

Iris-Connected Cavities: Motivation

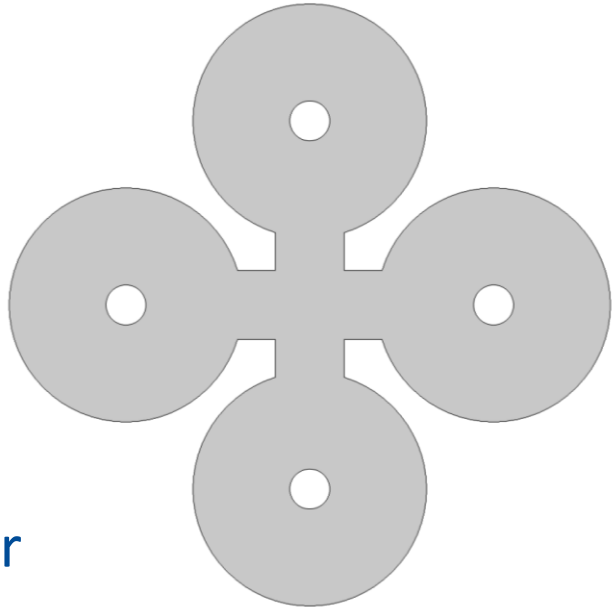
- With iris-connected cavities, we end up with a structure that have modes residing in the cavities collectively with the following benefits
  - Eliminate/minimize the technical challenge of locking cavities on each other
  - Eliminate/minimize the technical challenge of coherent signal combination

Peripherally connected

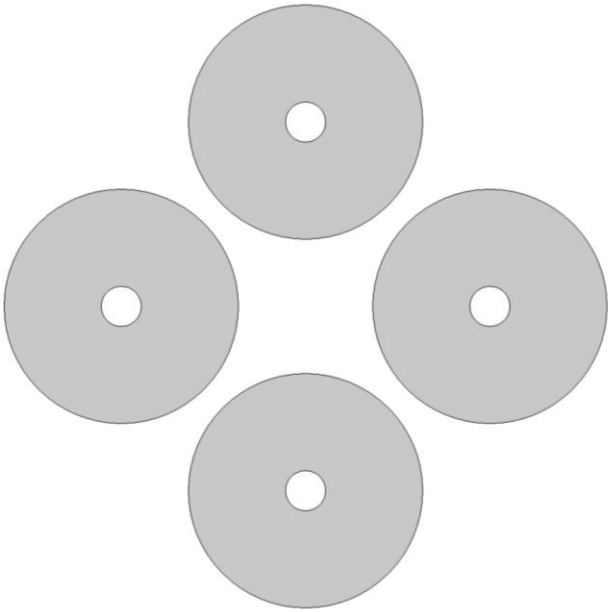


Or

Centrally connected



Conventional Cavity Array



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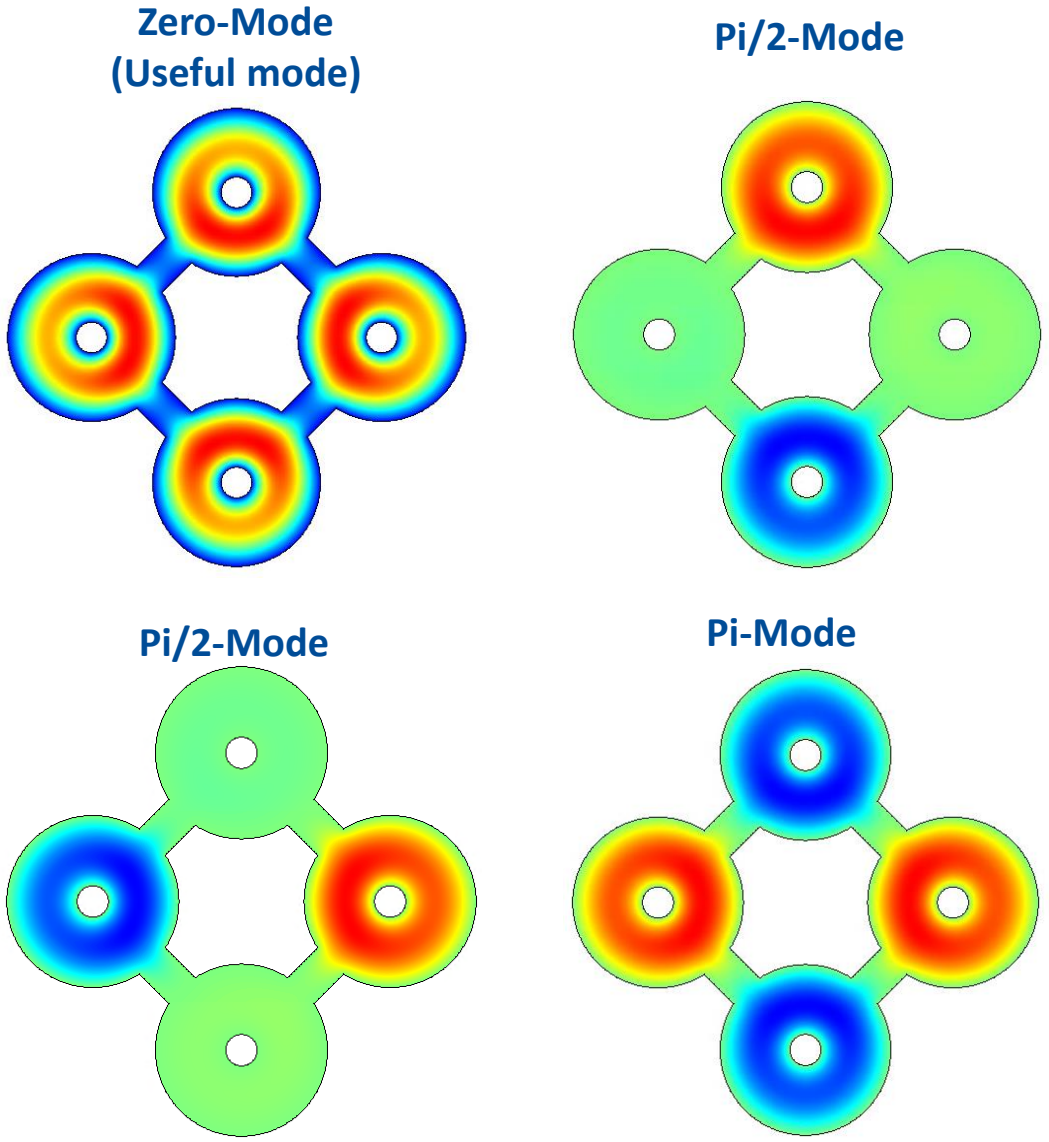
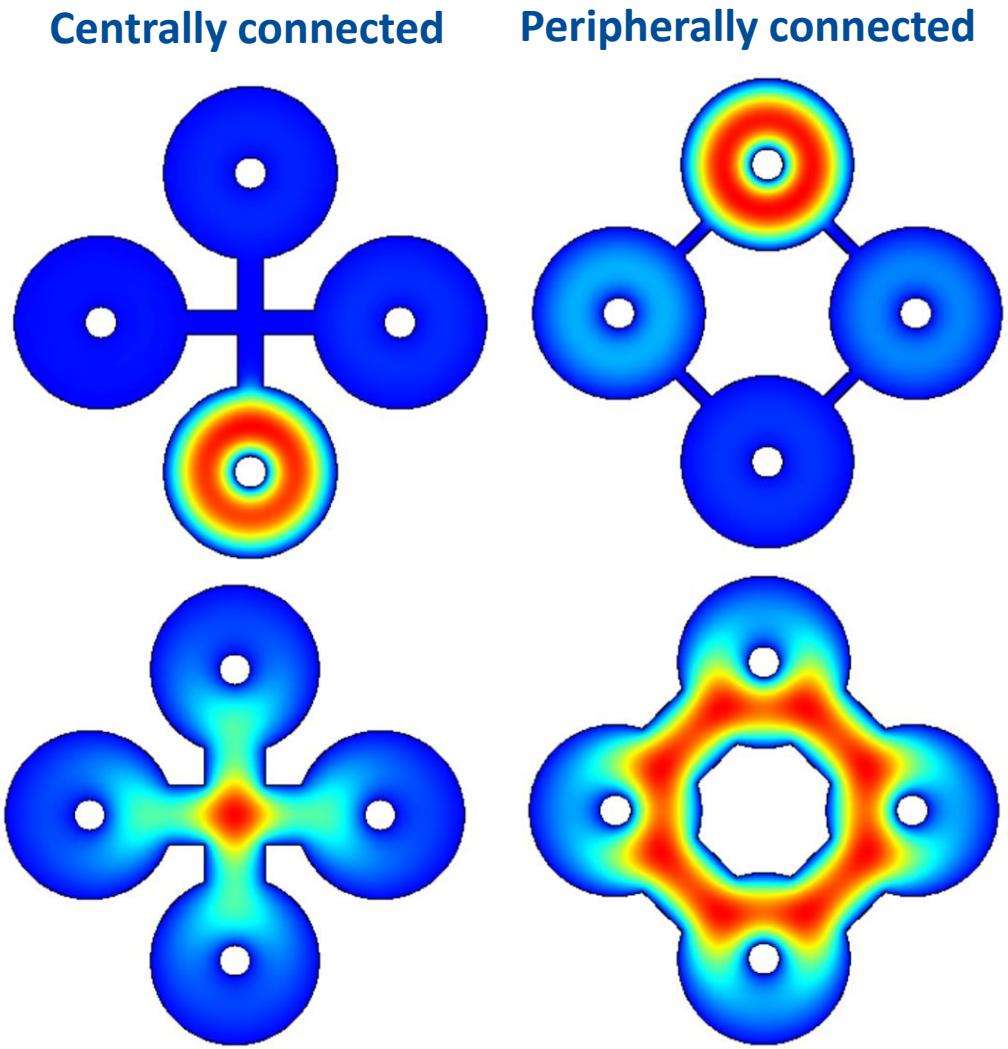
Mode Hybridization

- Each TM like mode in the original geometry splits into four modes (for four cells)
- Iris-connected cavities will have a challenge in engineering the mode spectrum to avoid mode crowding
- Good news: the useful mode (zero-mode) is lowest in frequency among the four



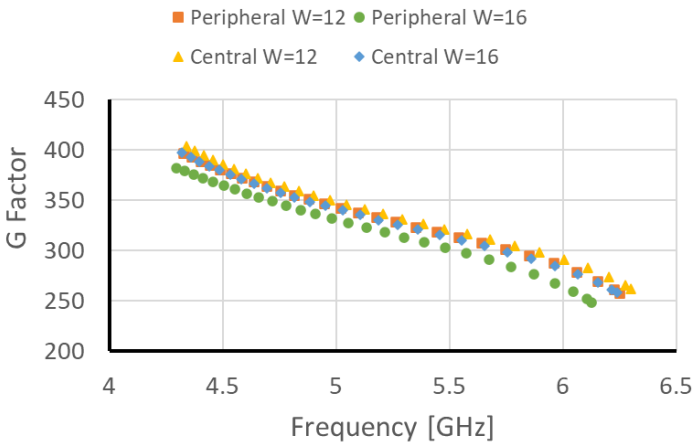
Effect of Iris Width on Multi-cell Cavity Performance

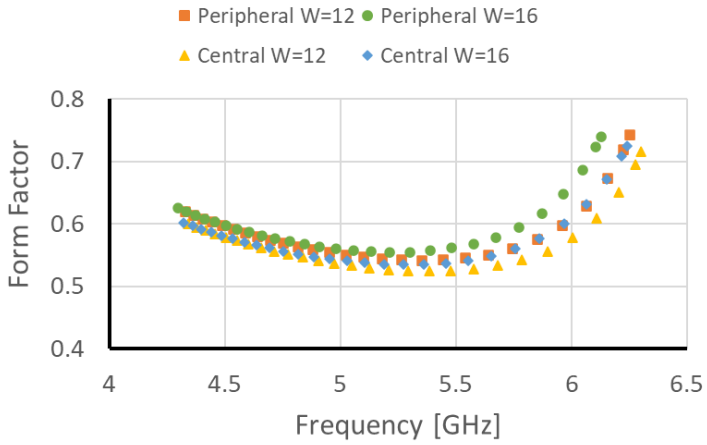
- We have studied the two extremes of iris coupling
- Lesson learnt:-
  - Closing the iris eliminates mode hybridization causing the modes to live isolated in each cell
  - Opening the iris strengthen mode hybridization but eventually causes the mode to leak outside the cells degrading form factor
  - Peripherally connected configuration has stronger mode hybridization for the same iris width when compared to the centrally connected configuration

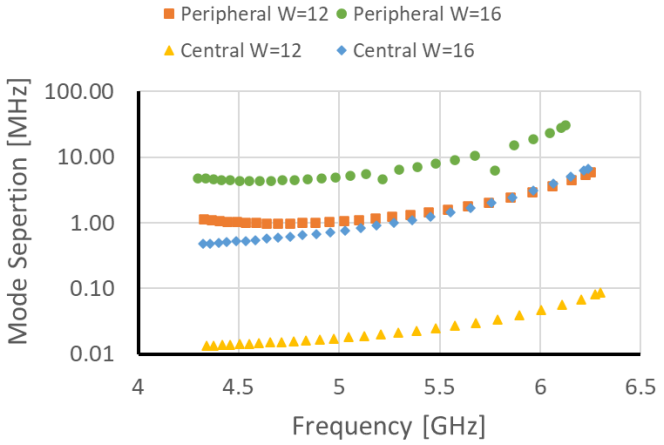


Effect of Iris Width on Multi-cell Cavity Performance Cont.

- We have completed a parametric study for the effect of the iris width on cavity performance
- Lesson learnt:-
  - G-factor (Q) decreases with increasing the width of the irises between cavities
  - Form factor eventually degrades upon opening the irises
  - Mode separation can be increased by opening the irises
  - Peripherally connected cavity has better performance on terms of mode separation when compared to a centrally connected cavity for the same iris width
- For this cavity design, we will aim for 2MHz mode separation (10*cavity BW)

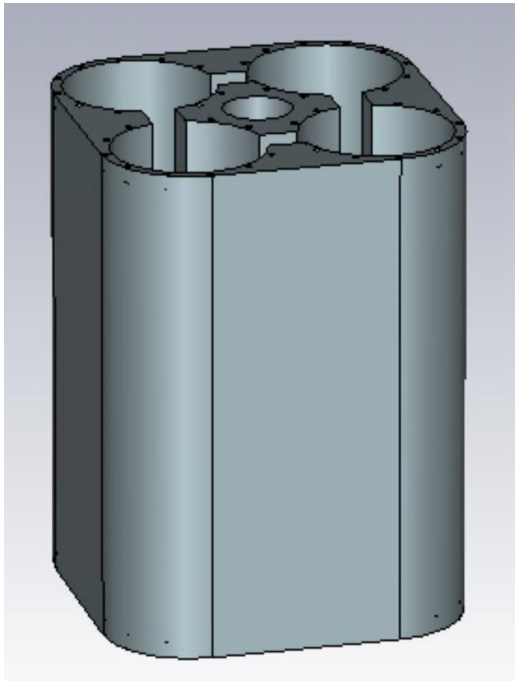






Mechanical Design of 4-Cell Cavity

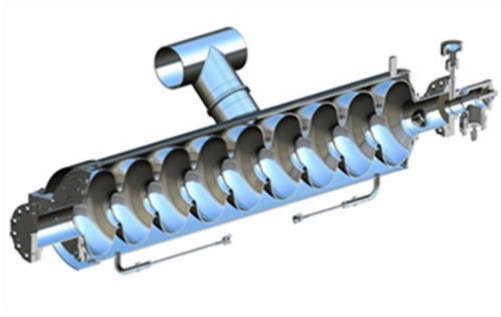
- For this cavity design, we will aim for 2MHz mode separation (10*cavity BW)
- We decided to proceed with peripherally connected configuration for the following reason:-
  - Better separation between the resonance modes
  - More tolerance to fabrication errors
- Initial mechanical model for the cavity body is completed
- Currently working on the top and bottom plates



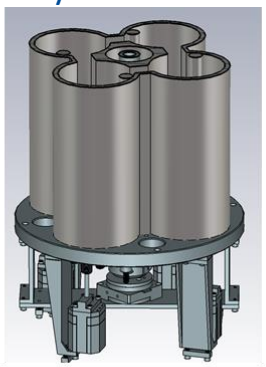
Mechanical model of peripherally connected 4-cell cavity

Development of 4-Cell Cavity

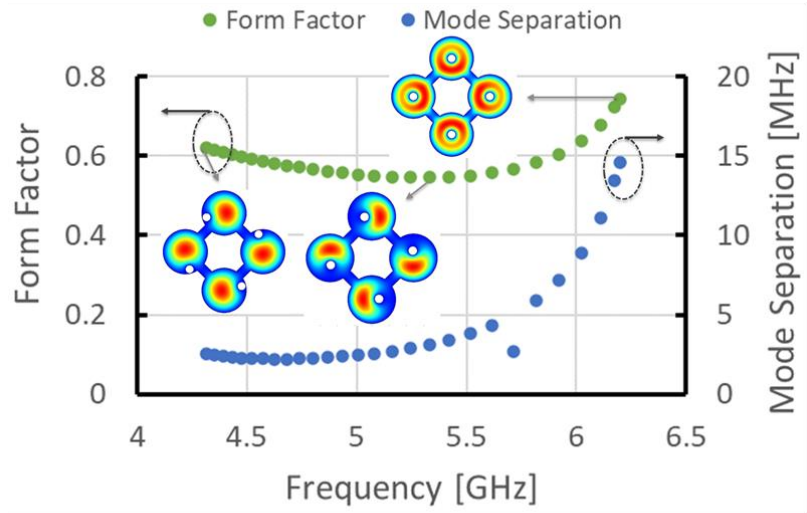
Mechanical system design
by J. Gleason



(a) 9-cell accelerator cavity that inspired the PI

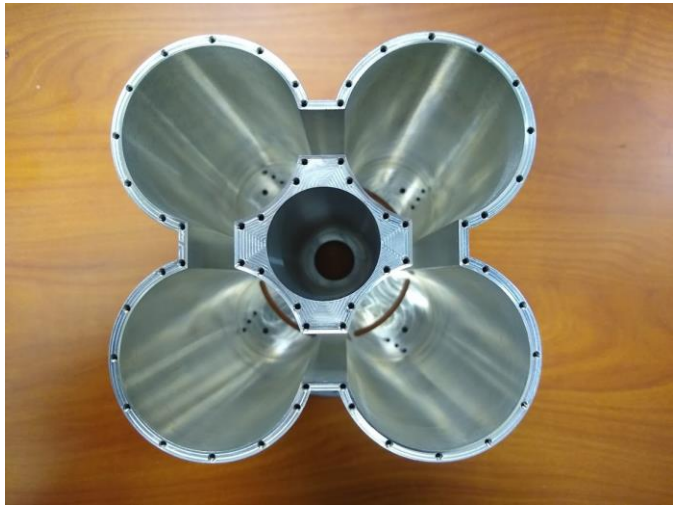


(b) Proposed 4-cell axion cavity



(c) Tuning of the proposed 4-cell axion cavity

Mechanical cavity design
by O. Pronitchev



Fabricated Cavity Prototype

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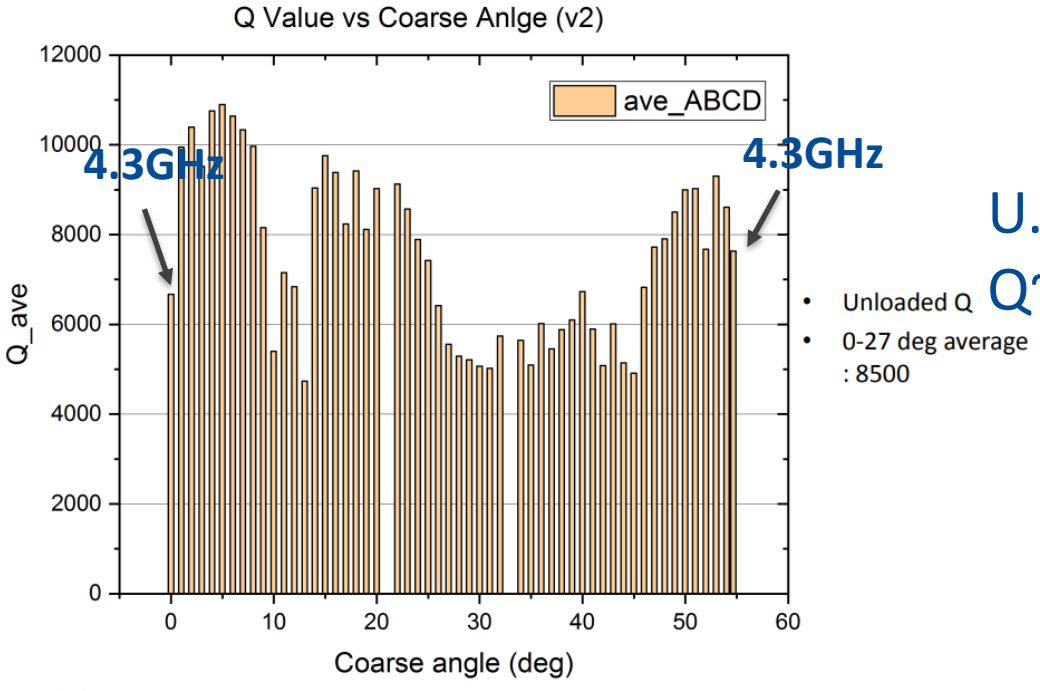
Expectation for Quality Factor

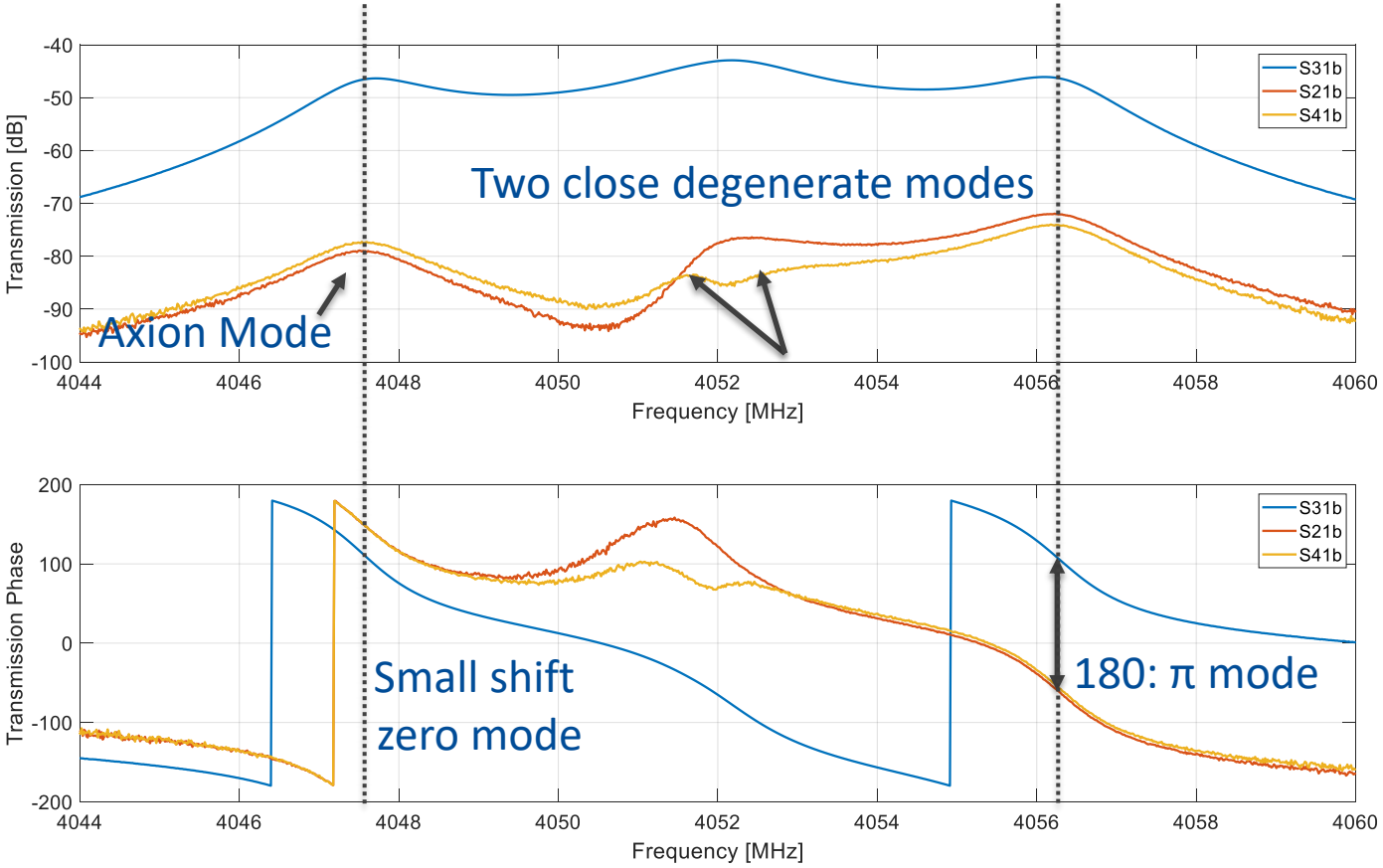
- Aluminum 6061-T6, sigma=2.5e7 at room temperature, Q~11800
- Surface Roughness 32uin, sigma~1.3e7 at 4GHz, Q~8500
- Surface Roughness 64uin, sigma~8.4e6 at 4GHz, Q~6800

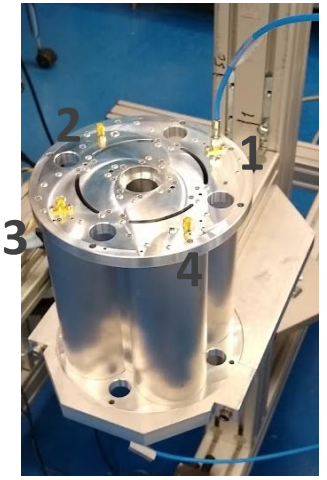


Credit to Jihee Yang

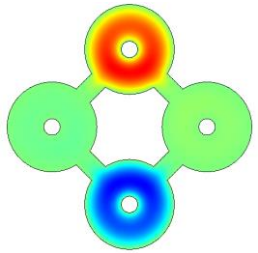
U. Florida 4-Cavity System
Q~7000 at 4.3 GHz

Transmission through the 4-Cells Top to Bottom

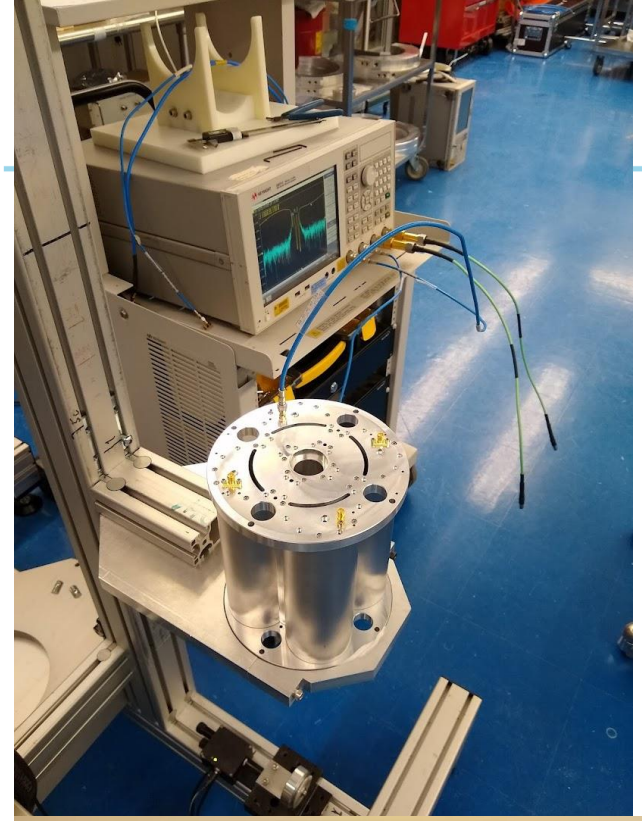


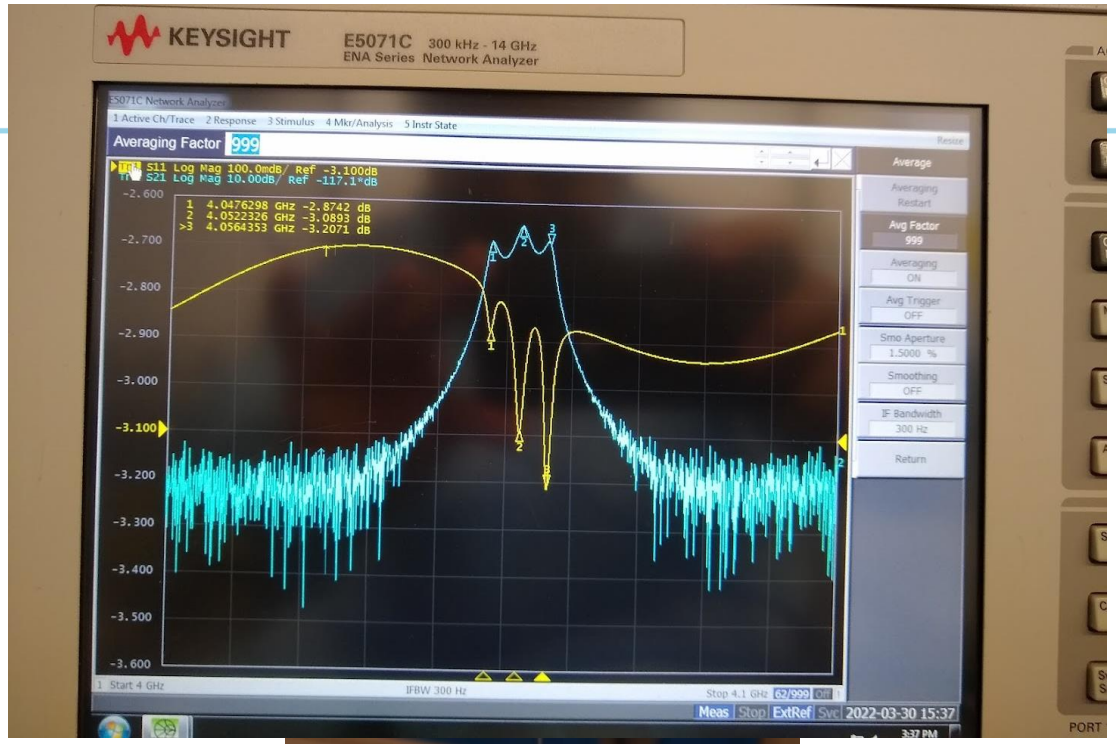


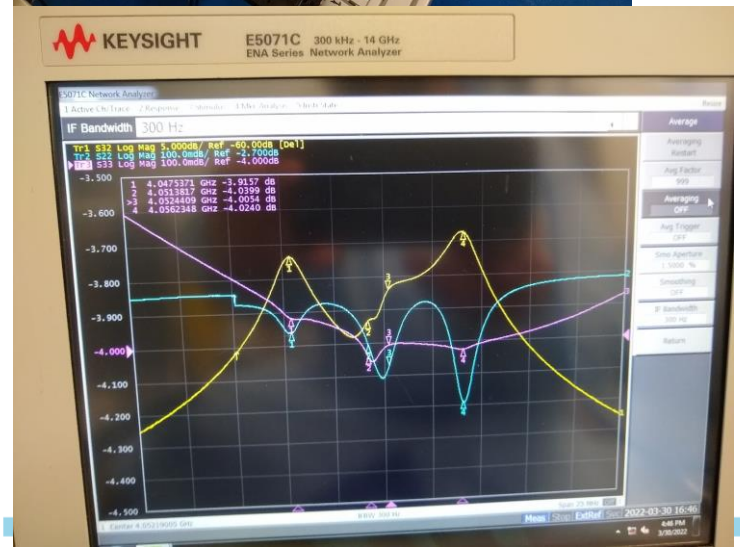
P3 antenna is slightly stronger than P2 and P4

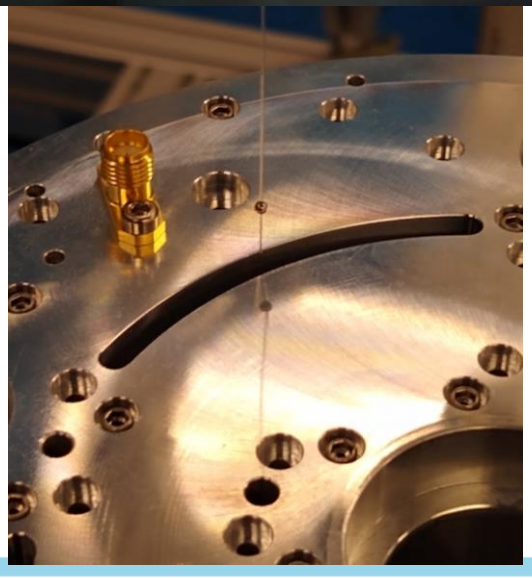


- Axion sensitive mode at 4047.53 MHz, Q~3000
- Antenna at the bottom of cell 3 is stronger than the one of cell 2, and 4



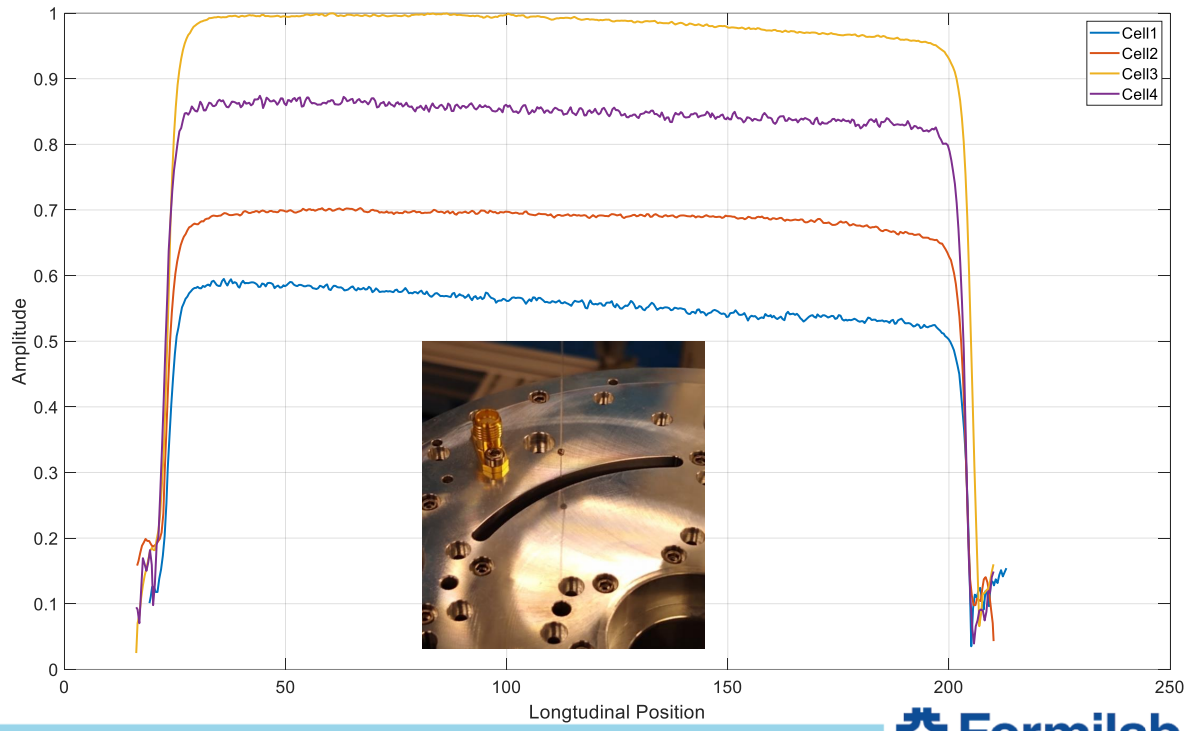

KEYSIGHT
E5071C 300 kHz - 14 GHz
ENA Series Network Analyzer
Averaging Factor 999
Tr1 S11 Log Mag 100.0mdB/ Ref -3.100dB
Tr2 S21 Log Mag 10.00dB/ Ref -117.1*dB
1 4.0476298 GHz -2.8742 dB
2 4.0522326 GHz -3.0893 dB
>3 4.0564353 GHz -3.2071 dB
Start 4 GHz
IFBW 300 Hz
Stop 4.1 GHz
2022-03-30 15:37


KEYSIGHT
E5071C 300 kHz - 14 GHz
ENA Series Network Analyzer
IF Bandwidth 300 Hz



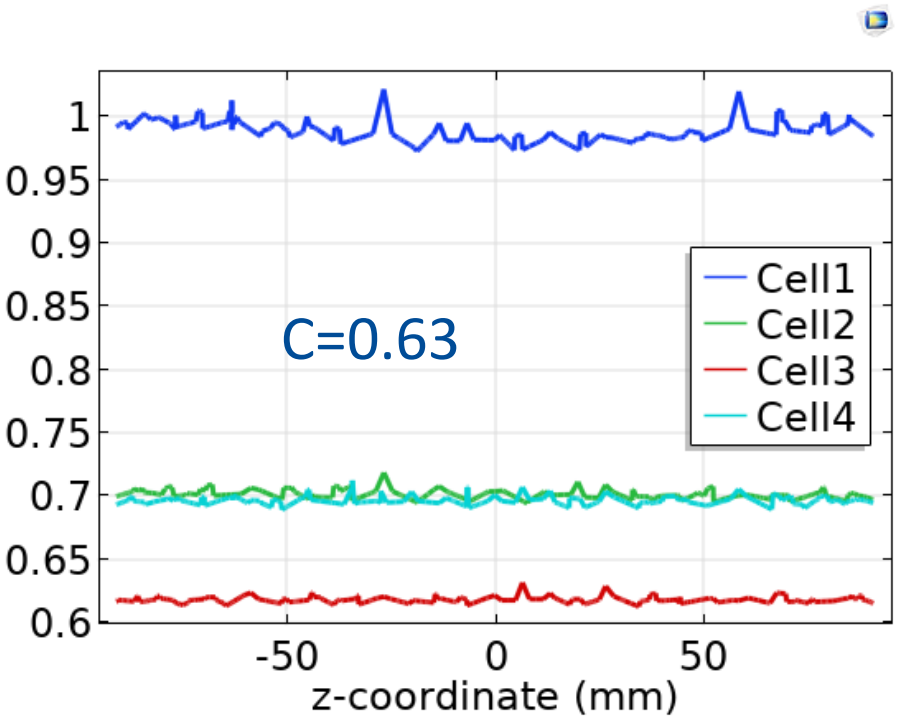
Bead-Pull Measurements

- Successfully measured the field inside the 4-cells using bead pull technique
  - Visually aligned the bead wire to the middle of the tuner slot
  - Rotated the whole cavity to measure the various cells after removing then inserting the bead
- Axion mode is filling the full cavity but not equally distributed
- Projecting a penalty on the form factor of 10%
- It seems manageable



Amplitude Imbalance

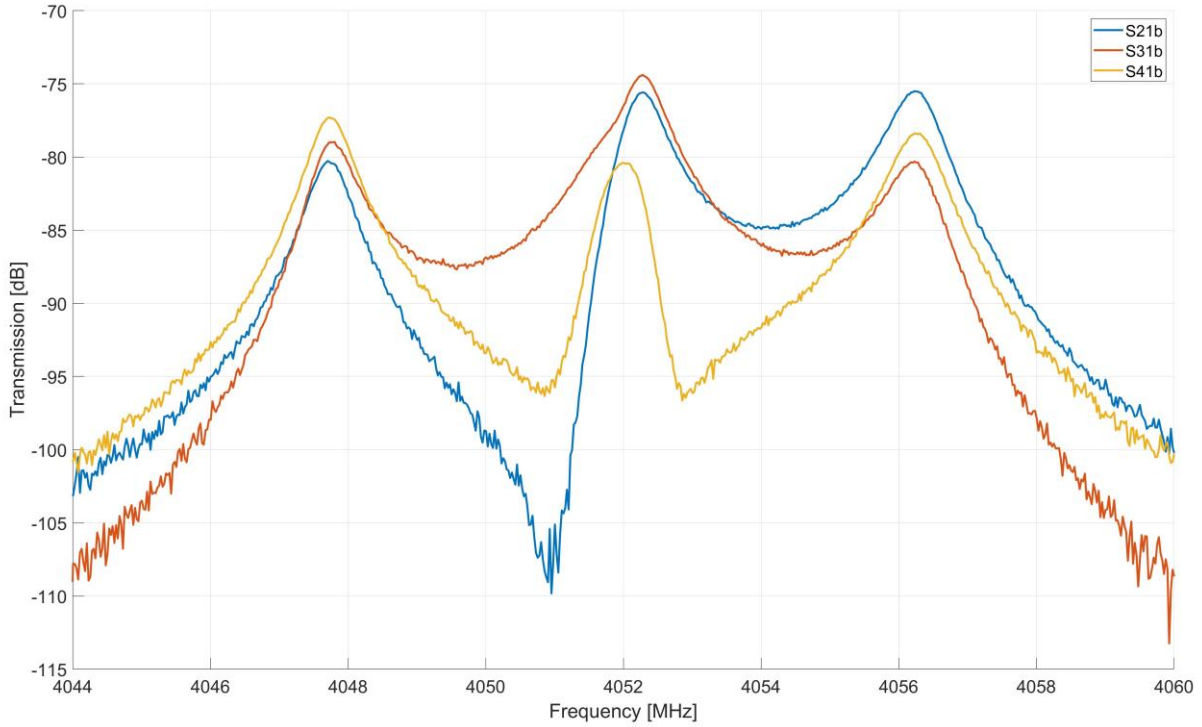
- Simulation shows that with the shown imbalance of the field distribution between the four cells, form factor is still reasonably good ~0.63 (compared to 0.69 for the pillbox)



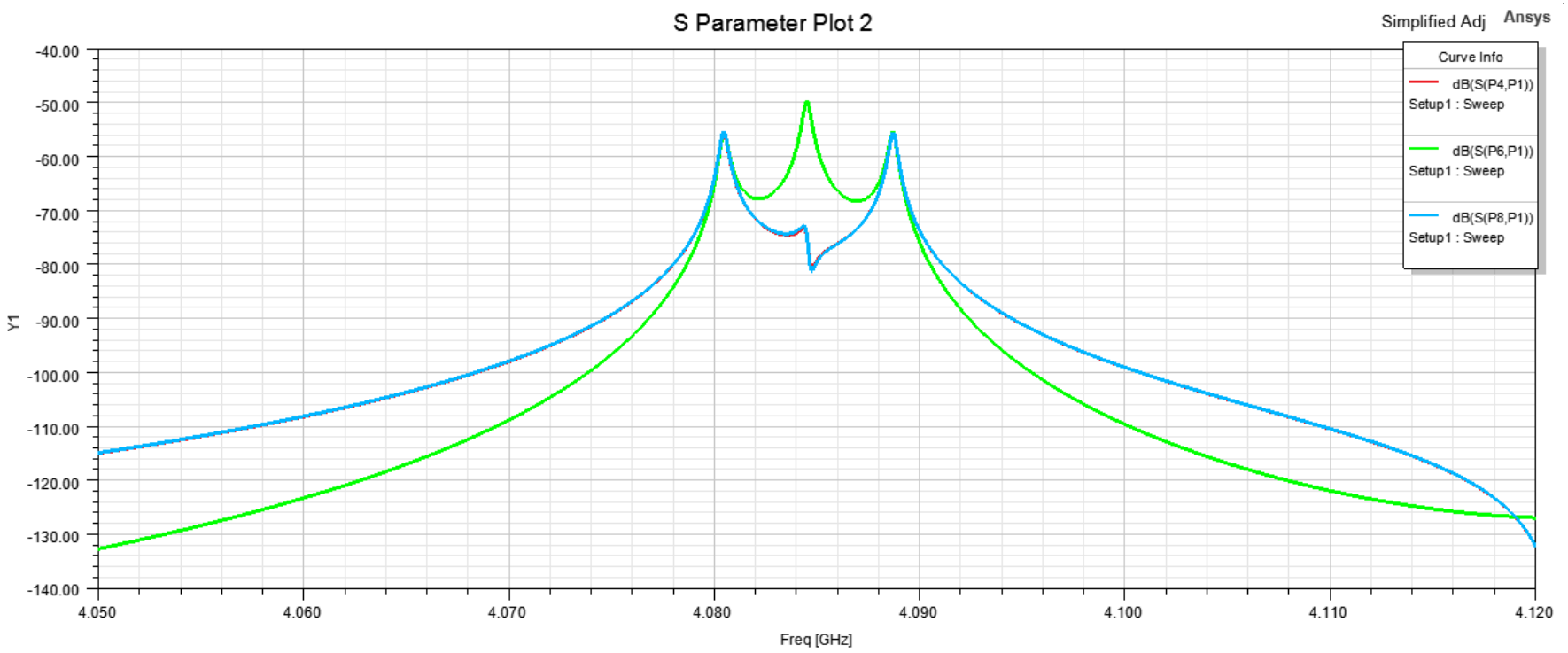
Quality Factor Improvement

- We successfully got the Quality factor to improve by a factor of two to 6200 upon tightening more the top and bottom end plates
  - Likely knife edge engagement

Pickup antennas are of equal length, difference in transmission is indicative of imbalance



Simulated Response

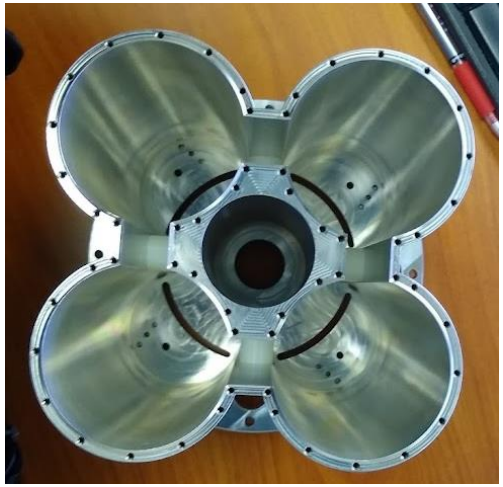


- Overall frequency response is similar to the measured one

Assembling Tunning Rods

- Had some issues procuring the sapphire pin then trimming them
- Managed to get the Sapphire pins from Swiss-Jewel
  - Their standard product doesn't have the beveled ends anymore!
- Successfully got the pins trimmed at Fermilab
- Assembly of Tuning Rods is completed

Aligning the irises

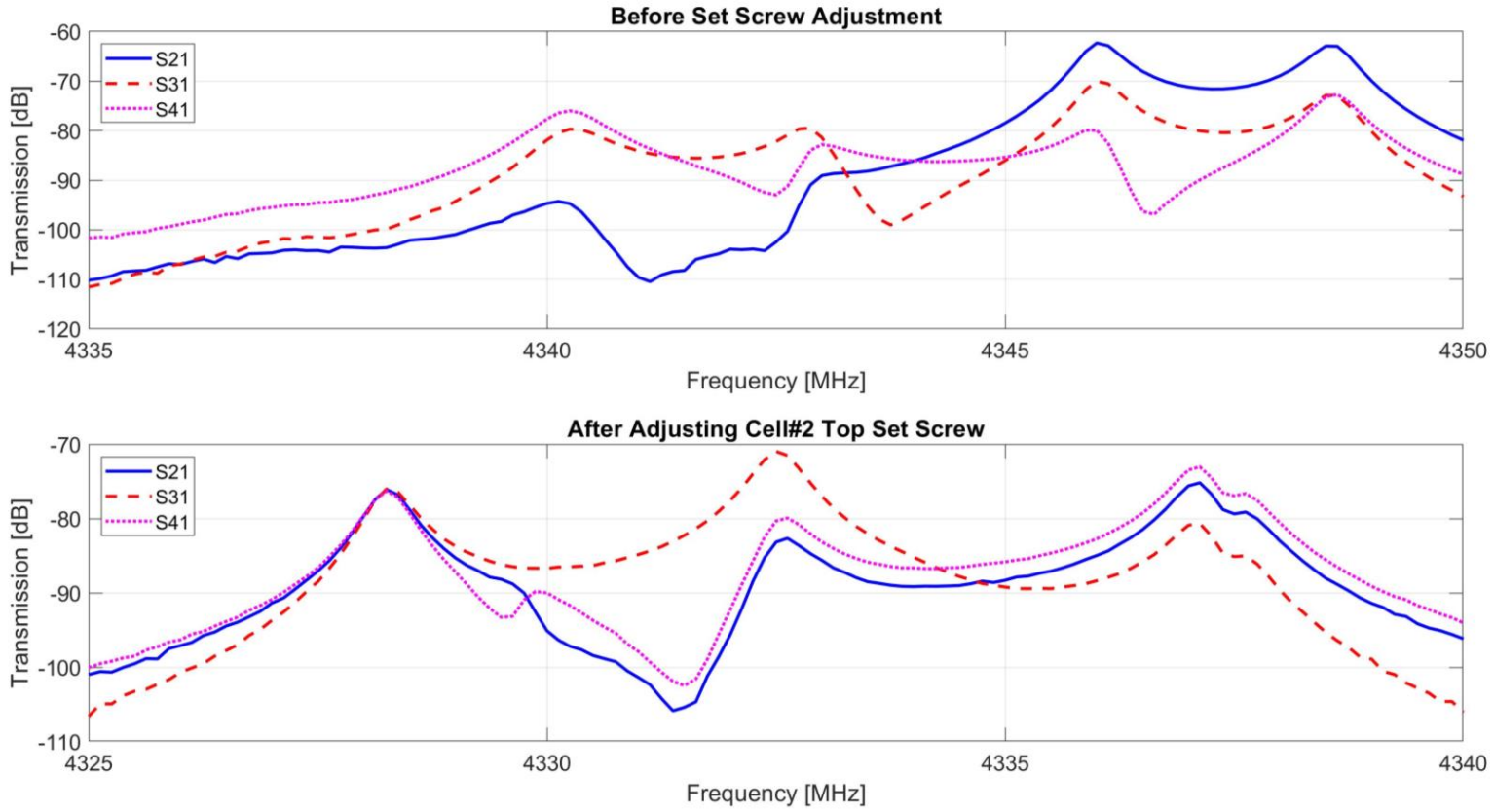


Installing tunning rods

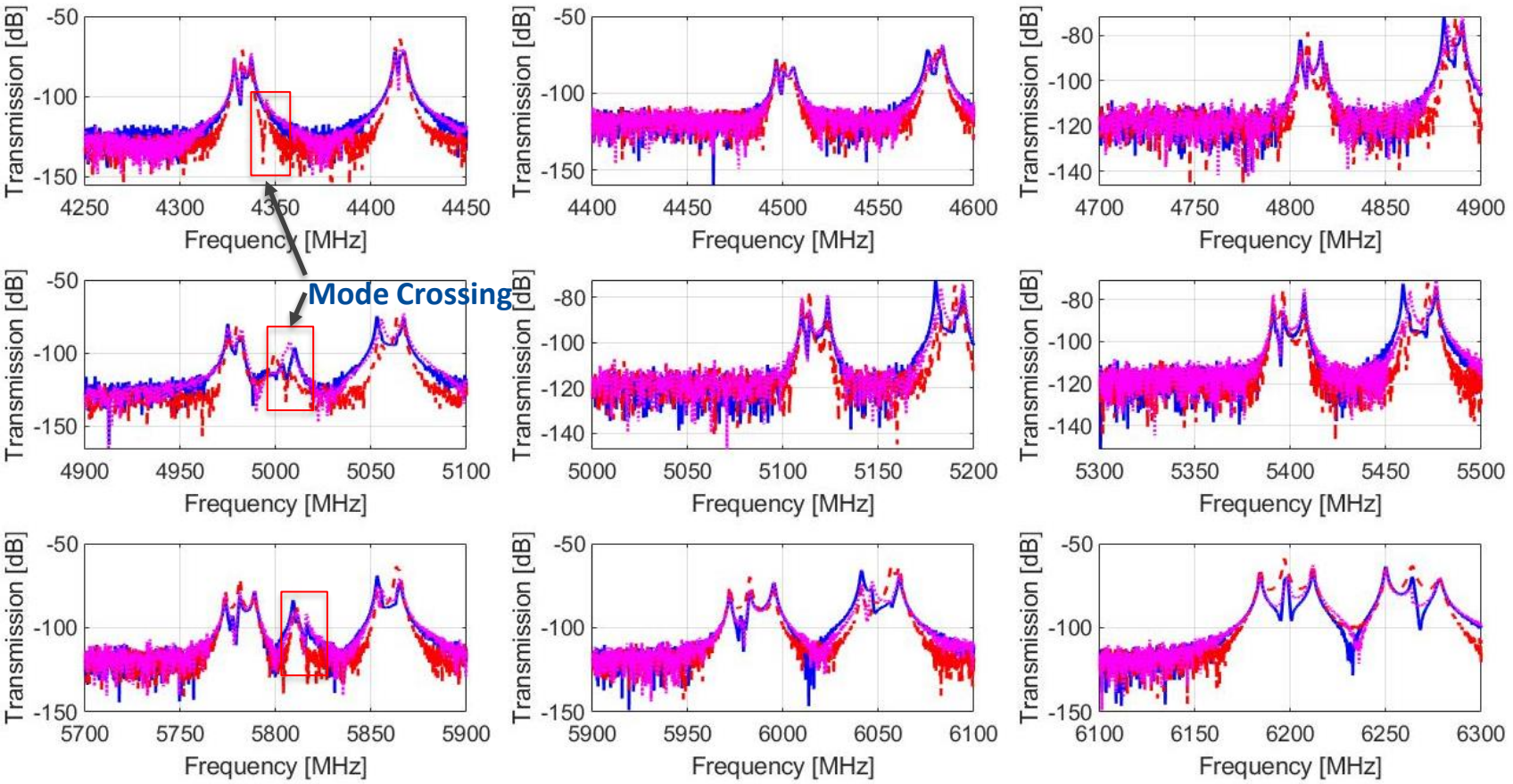
Installing end plates and bearing

Adjustment of Amplitude Imbalance

Amplitude balance between the 4 cells was adjusted using a set screw on the wheel that slightly tilt the tuning rods

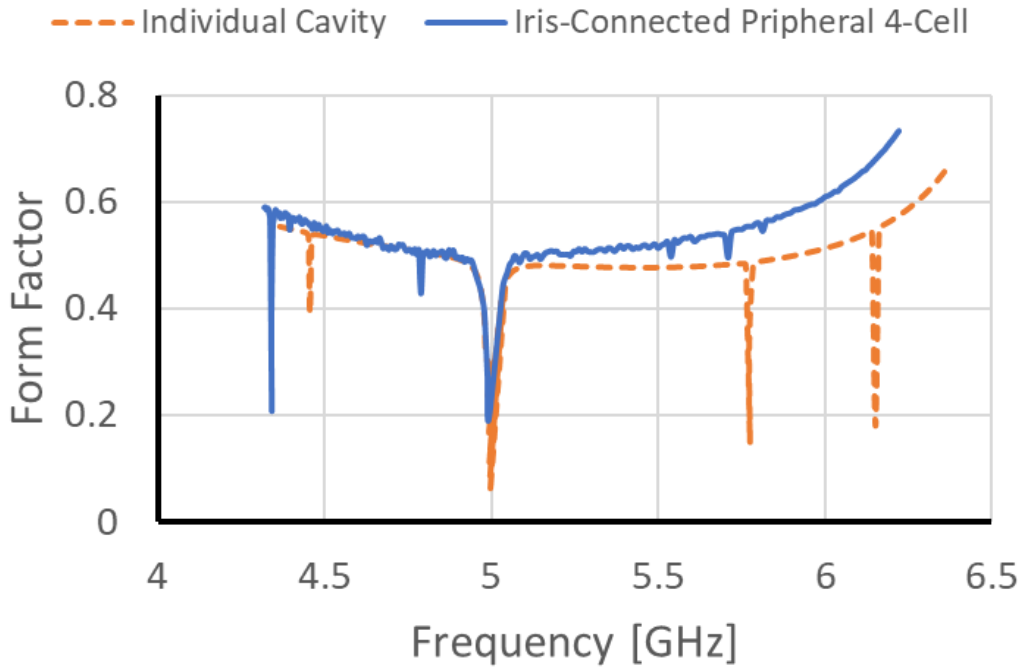


Frequency Tuning



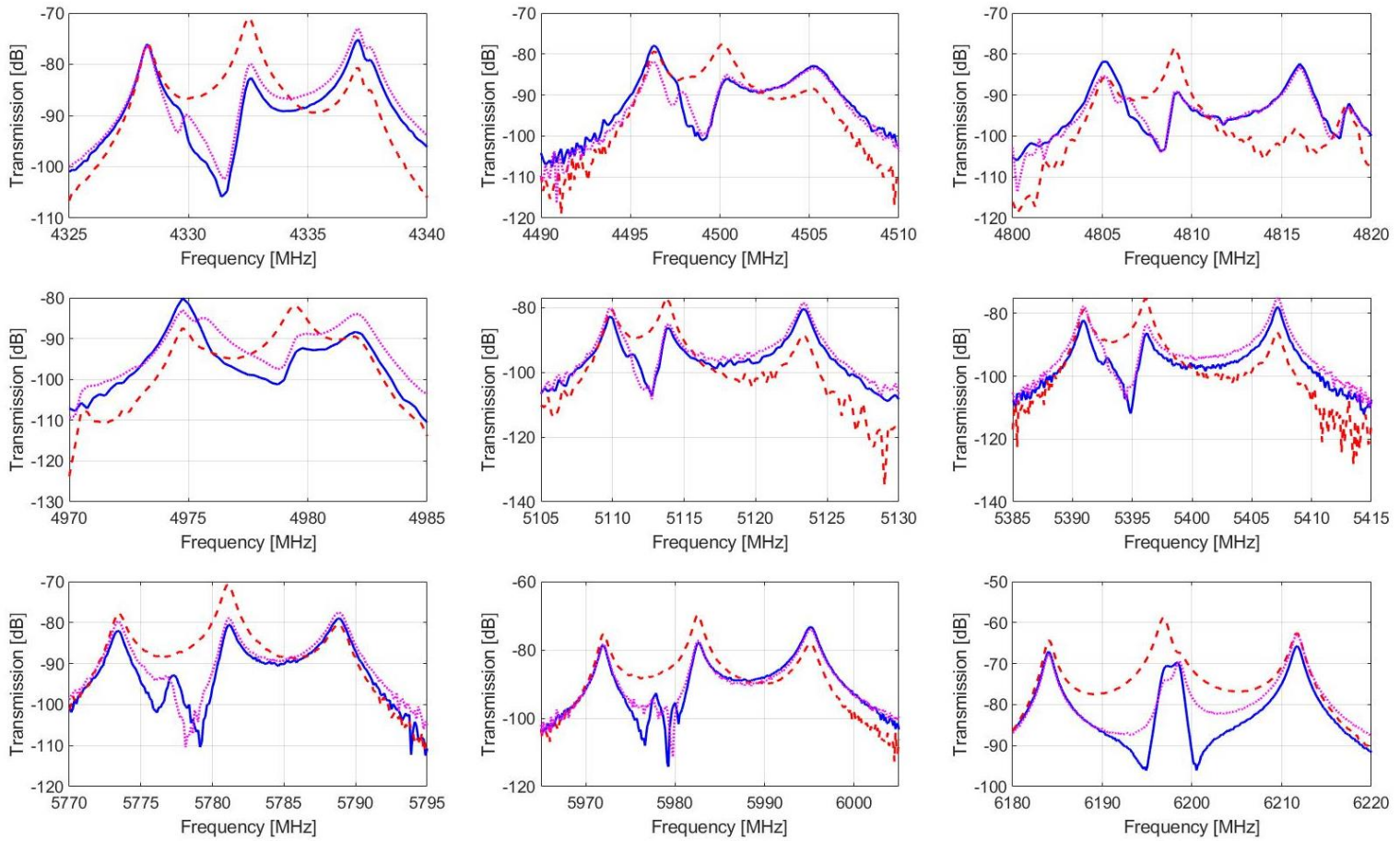
Cavity tunes from 4.3 GHz to 6.3 GHz

Simulated Mode Crossing



- Simulated mode crossings looks good
- Agrees with measurements

Amplitude Balance Across the Frequency Tuning Range



Amplitude balance changes across the band

Can we do better with individual tuning rods?

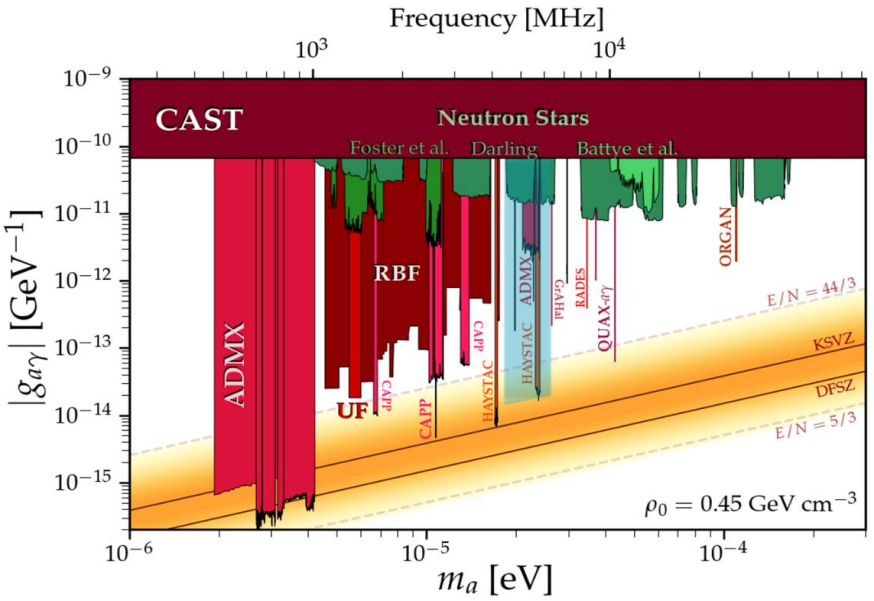
Fermilab

Science Reach

Cavity	Frequency [GHz]	Diameter [mm]	L [mm]	Effective Volume [L]**	B [T]	SNR	Q_L	T_{sys} [mK]	Sensitivity *	Scan Rate [MHz/day]
HAYSTAC Phase1	5.6-5.8	101.6	254	0.96	9	3	60000	821	2.7KSVZ	7.3
Multi-Cell	4.3 to 6.3	55.8	181	1.1	9	3	60000	763	2KSVZ	10.0

*Projected **Effective Volume=Form Factor x Volume

Cavity can be used to potentially search for axions at the 2KSVZ limit

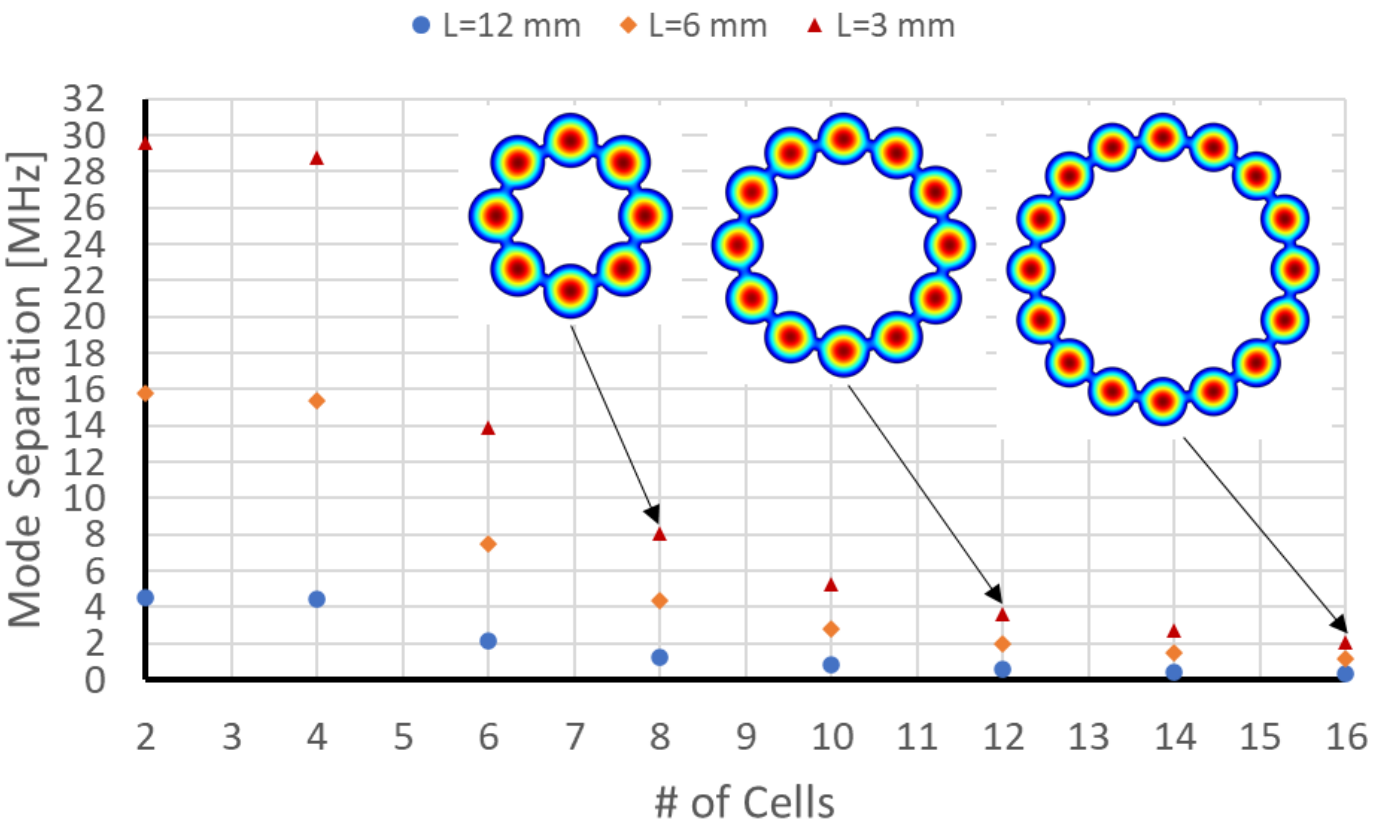


Adapted from
https://github.com/cajohare/AxionLimits

What is next

- Integrating a piezo rotary actuator with the cavity
- Fine resolution mode maps
- Cold test?
- Pilot axion search in the coming 9.4T magnet?

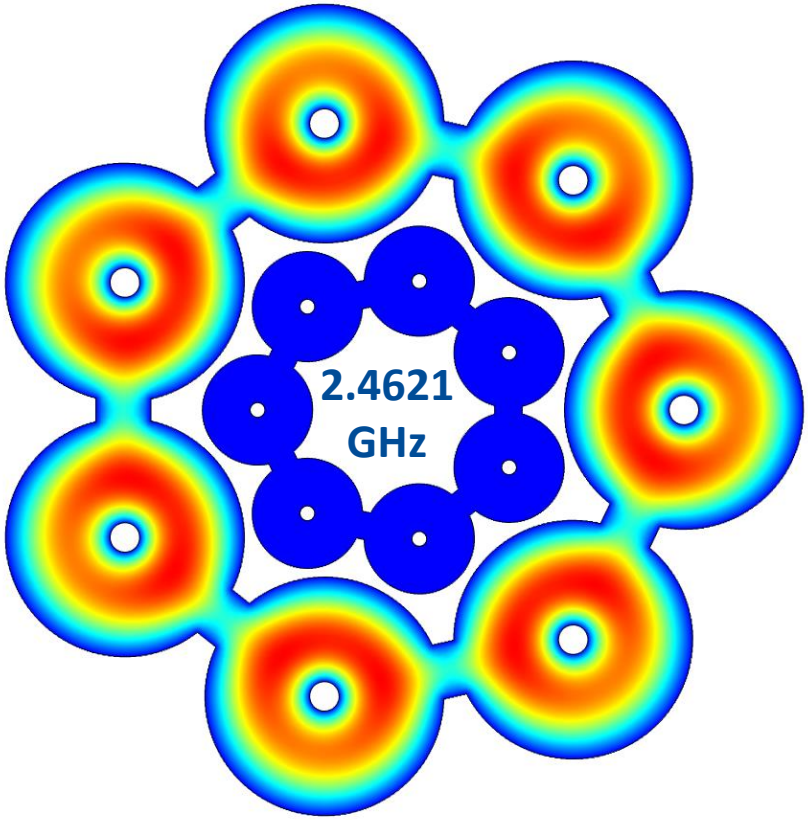
Outlook: On the Number of Cells

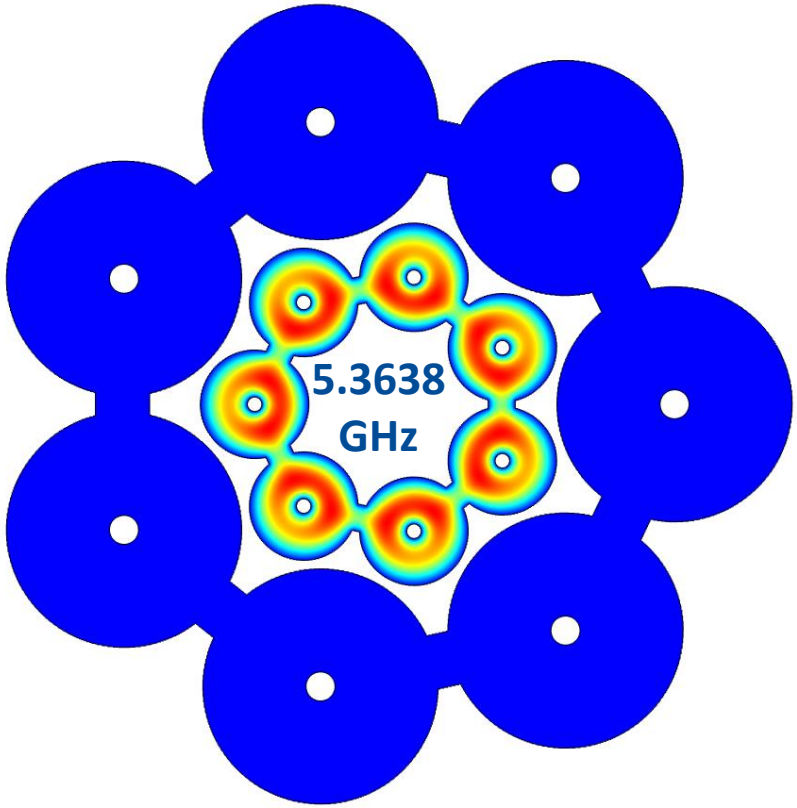


Cavities with a larger number of cells are possible

Fermilab

Outlook: Potential Double Frequency Systems





Double cavity system can better use the magnet space and search simultaneously in two frequency bands

Questions

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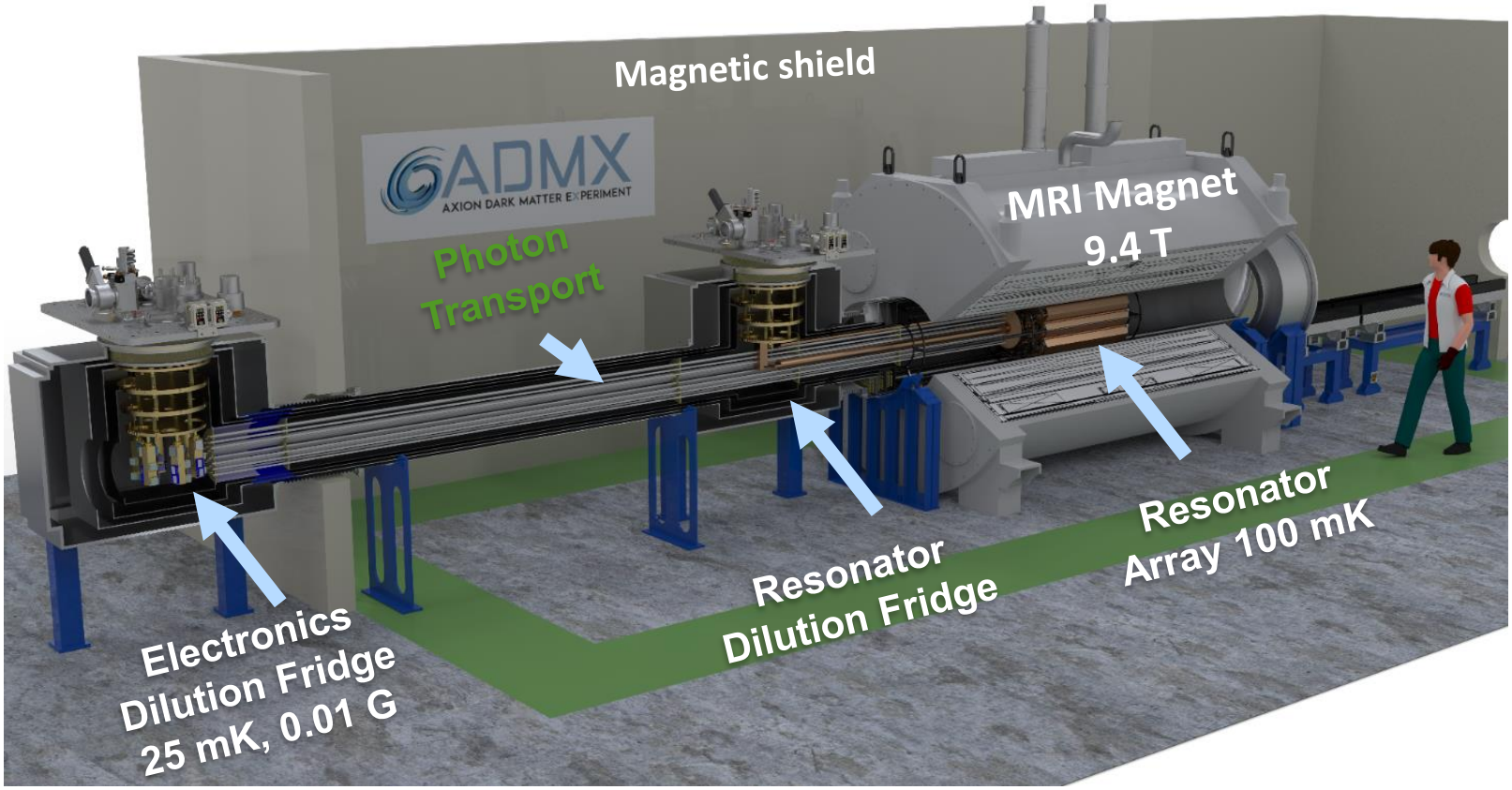
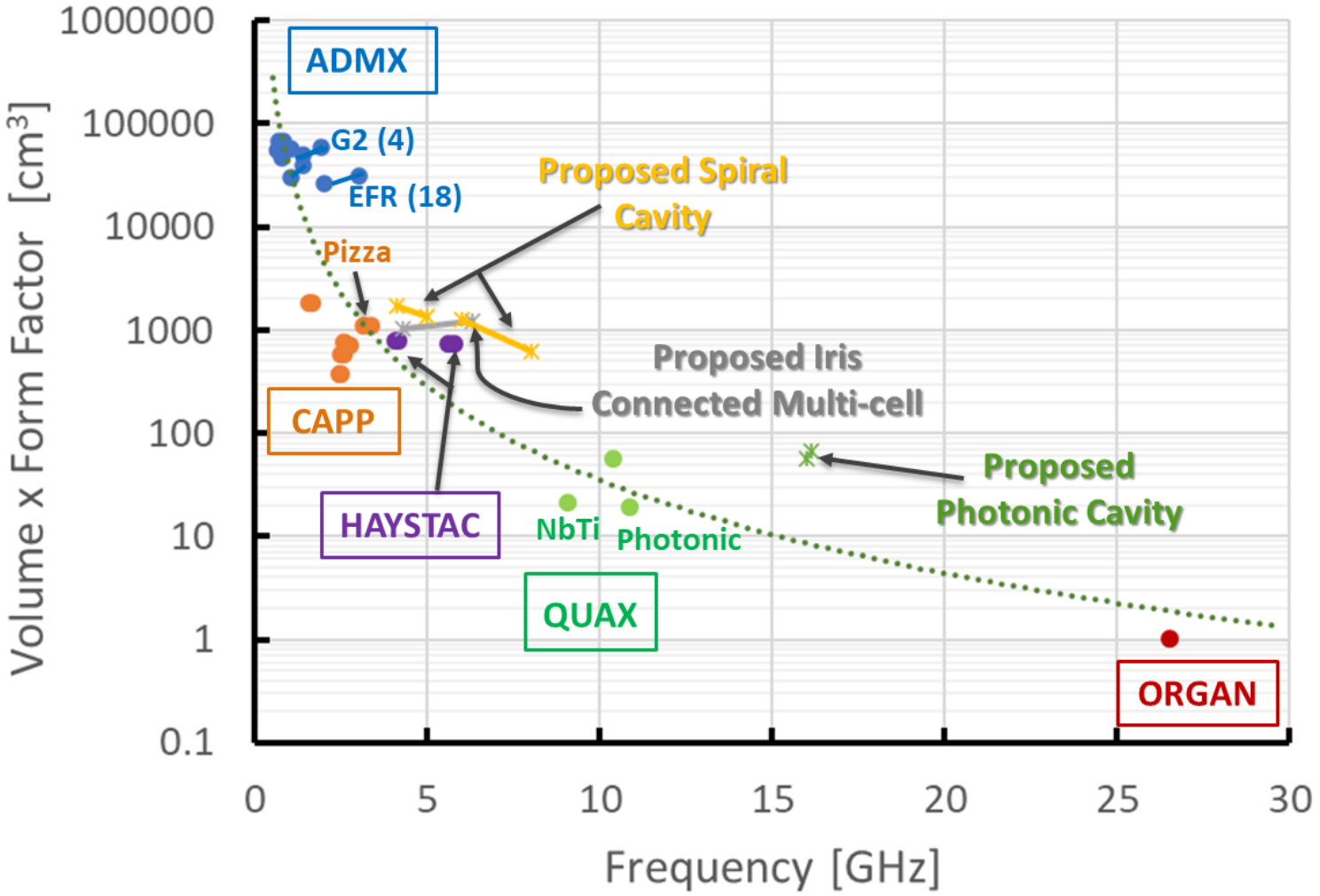
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

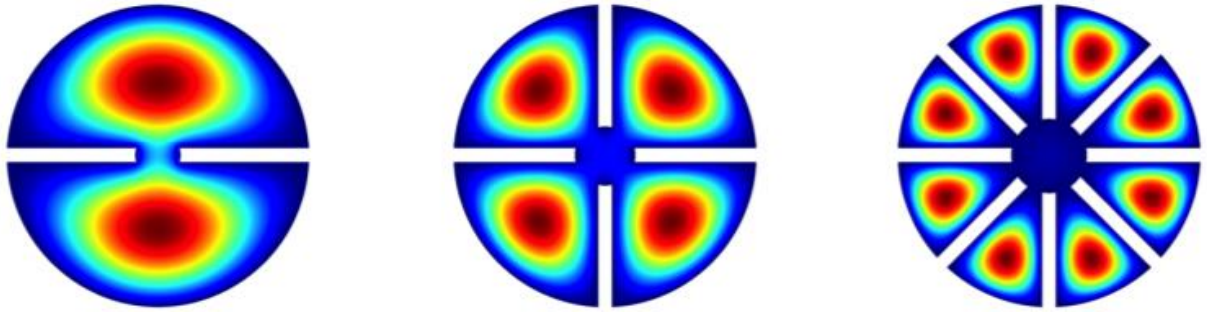
Backup Slides

Fermilab Coming New Infrastructure for Axion Searches




Volume x Form Factor [cm³]
1000000
100000
10000
1000
100
10
1
0.1
0
5
10
15
20
25
30
Frequency [GHz]
ADMX
G2 (4)
EFR (18)
Pizza
Proposed Spiral Cavity
Proposed Iris Connected Multi-cell
CAPP
HAYSTAC
NbTi
Photonic
Proposed Photonic Cavity
QUAX
ORGAN

Proposed Idea vs CAAP Pizza Cavity

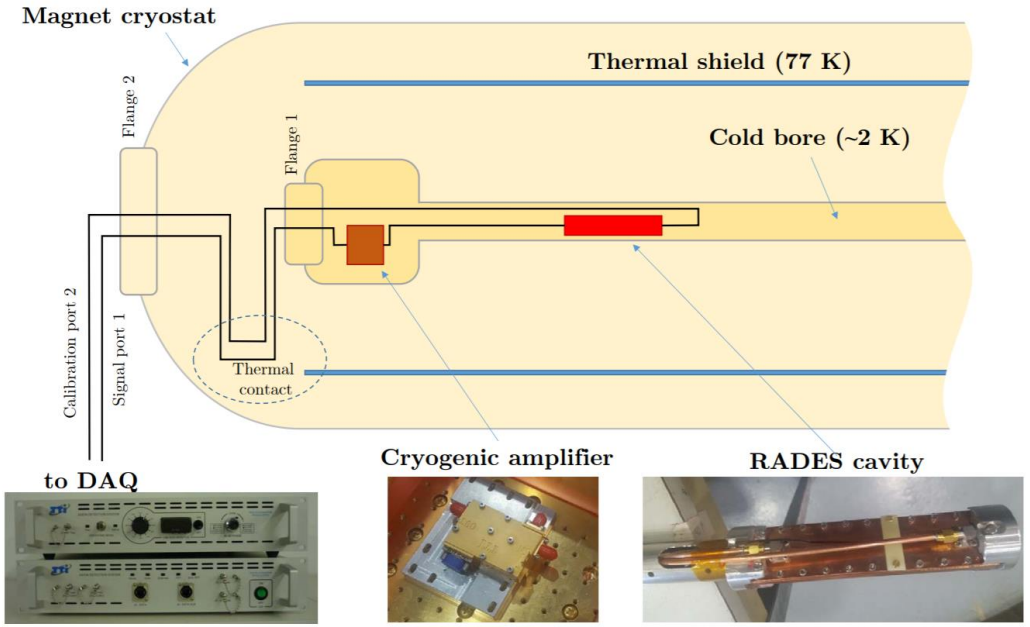


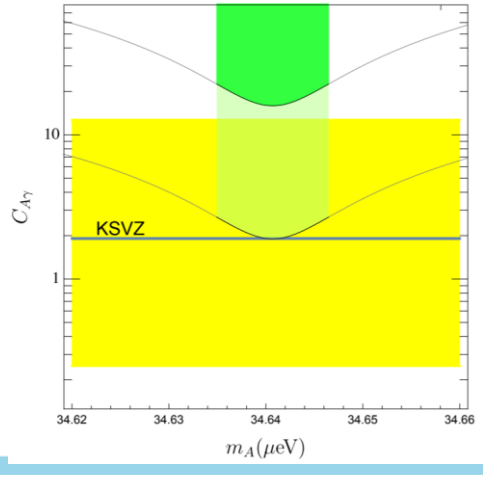
- The CAPP collaboration suggested in some sense a similar idea that I am aware of (the “pizza” cavity), without demonstrating how to tune it
- However, the proposed idea is better for two reasons
  - It maintains the large tuning range of a circular cross-section cavity (35%) even with increasing number of cells in the structure, while the “pizza” cavity ends up sacrificing the tuning range with increased number of cells
  - It is less sensitive to structure asymmetry
  - Mode separation can be engineered up to 16 cells!

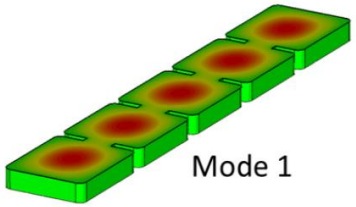
Jeong, Junu, et al. "Search for invisible axion dark matter with a multiple-cell haloscope." Physical Review Letters 125.22 (2020): 221302.

Proposed Idea vs RADES

- Using 9T CAST dipole magnet at CERN (a 10-meter long, 2 ×15 cm^2 aperture)
- Multi-cavity iris coupled structure in a rectangular waveguide WR-90 (TE101)
- Q~4e4 (predicted), 12e3 (measured) at 8.4GHz
- The proposed idea is more versatile
  - Easier to tune (not obvious how Rades structure can be tuned)
  - Less mode crowding







Melcón, A. Á. "Axion searches with microwave filters: the RADES project J. Cosmol." *Astropart. Phys* 5.040 (2018): 1803-01243.