ADMX-VERA (Volume-Enhanced Resonating Axion) Experiment

Chao-Lin Kuo

Stanford / SLAC

ADMX-VERA (Volume-Enhanced Resonating Axion) Experiment

A working group within the ADMX collaboration developing high-volume haloscopes above 4 GHz

Chelsea Bartram
Taj Dyson
Chao-Lin Kuo
Noah Kurinsky
Sephora Ruppert
Maria Salatino
Chiara Salemi
Matt Withers
} Stanford University/SLAC

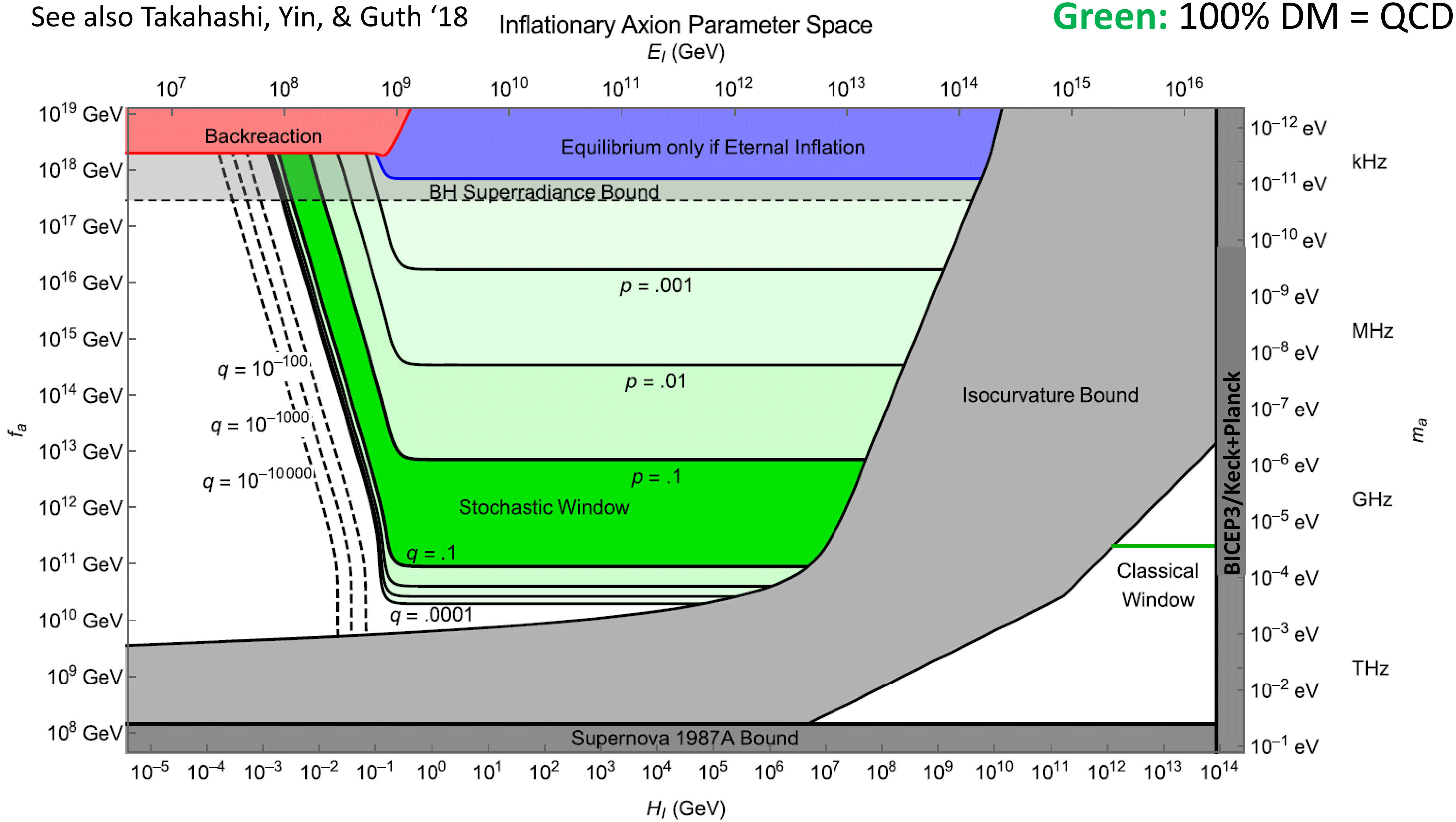
James Sinnis
Gray Rybka
} University of Washington

Gianpaolo Carosi
} LLNL

Vera Rubin

Plot from Graham and Scherlis ’18
See also Takahashi, Yin, & Guth ‘18

Green: 100% DM = QCD axion



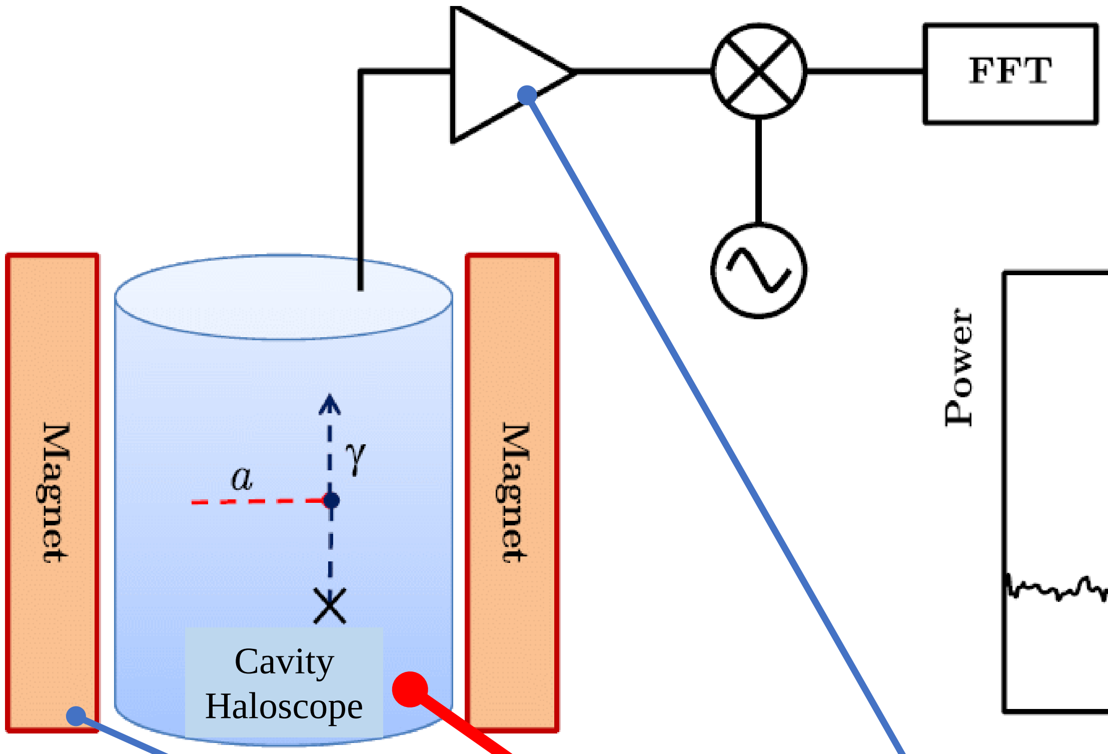
Cornering some axions

Isocurvature Bound

Inflation Bound

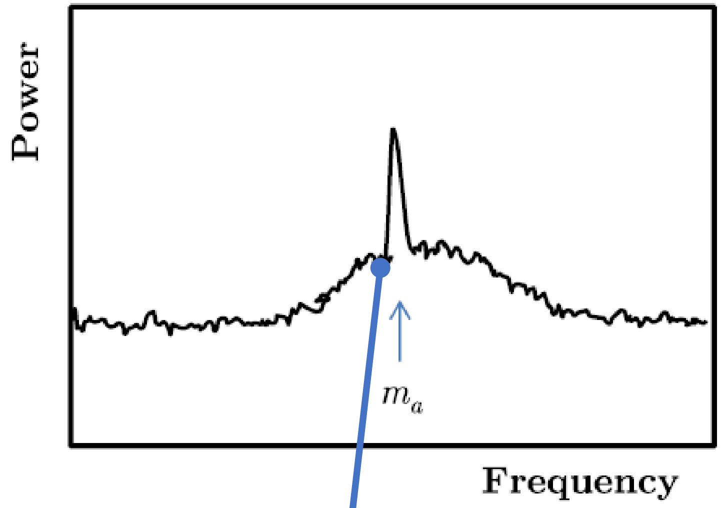
Haloscope Searches

An axion "Haloscope"



P. Sikivie

Figure adapted from Irastorza & Redondo 2018



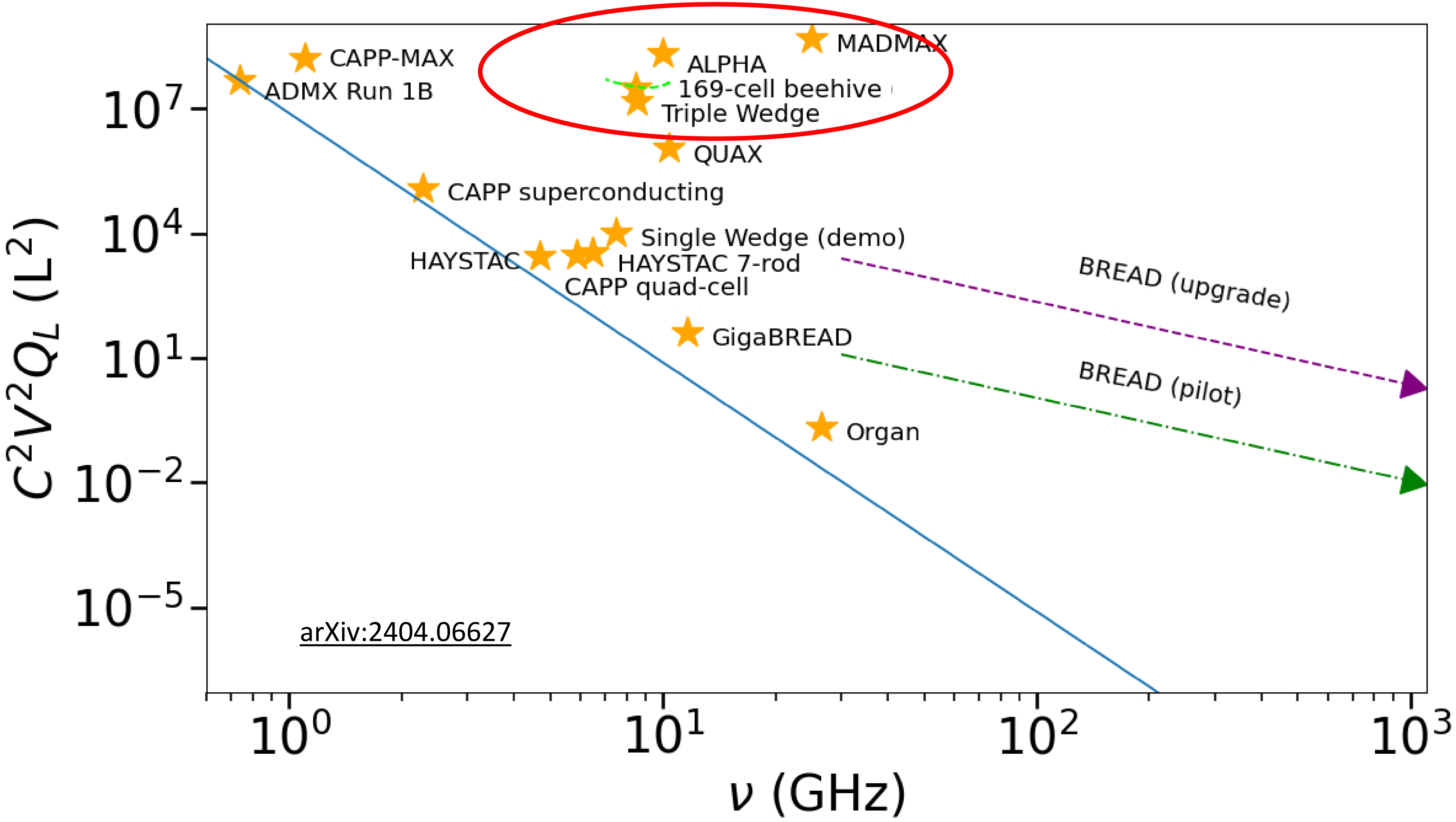
ADMX-EFR , High Tc magnets

Quantum amplifiers (JPA, JTWPA)

Nb superconductive coating

Scan Rate for Axion DM : $\frac{d\nu}{dt} \propto B_0^4 \cdot V^2 \cdot T_{sys}^{-2} \cdot Q$

@ 5 GHz the scan rate is down compared to 1 GHz by more than 4 orders of magnitude



MADMAX
CAPP-MAX
ALPHA
ADMX Run 1B
169-cell beehive
Triple Wedge
QUAX
CAPP superconducting
Single Wedge (demo)
HAYSTAC
HAYSTAC 7-rod
CAPP quad-cell
BREAD (upgrade)
GigaBREAD
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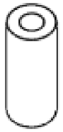
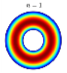
Organ
arXiv:2404.06627
10^7
10^4
10^1
10^{-2}
10^{-5}
$C^2V^2Q_L$ (L^2)
10^0
10^1
10^2
10^3
ν (GHz)

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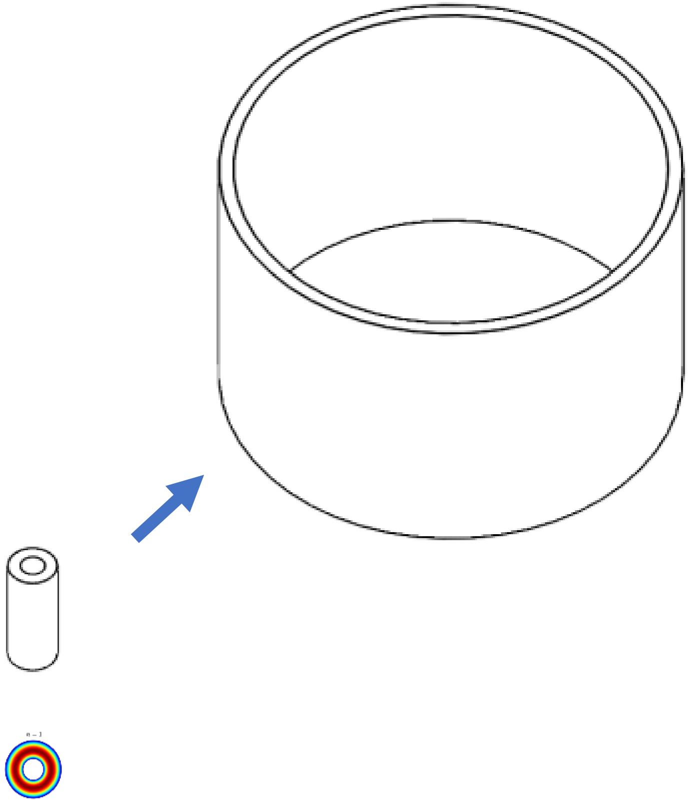
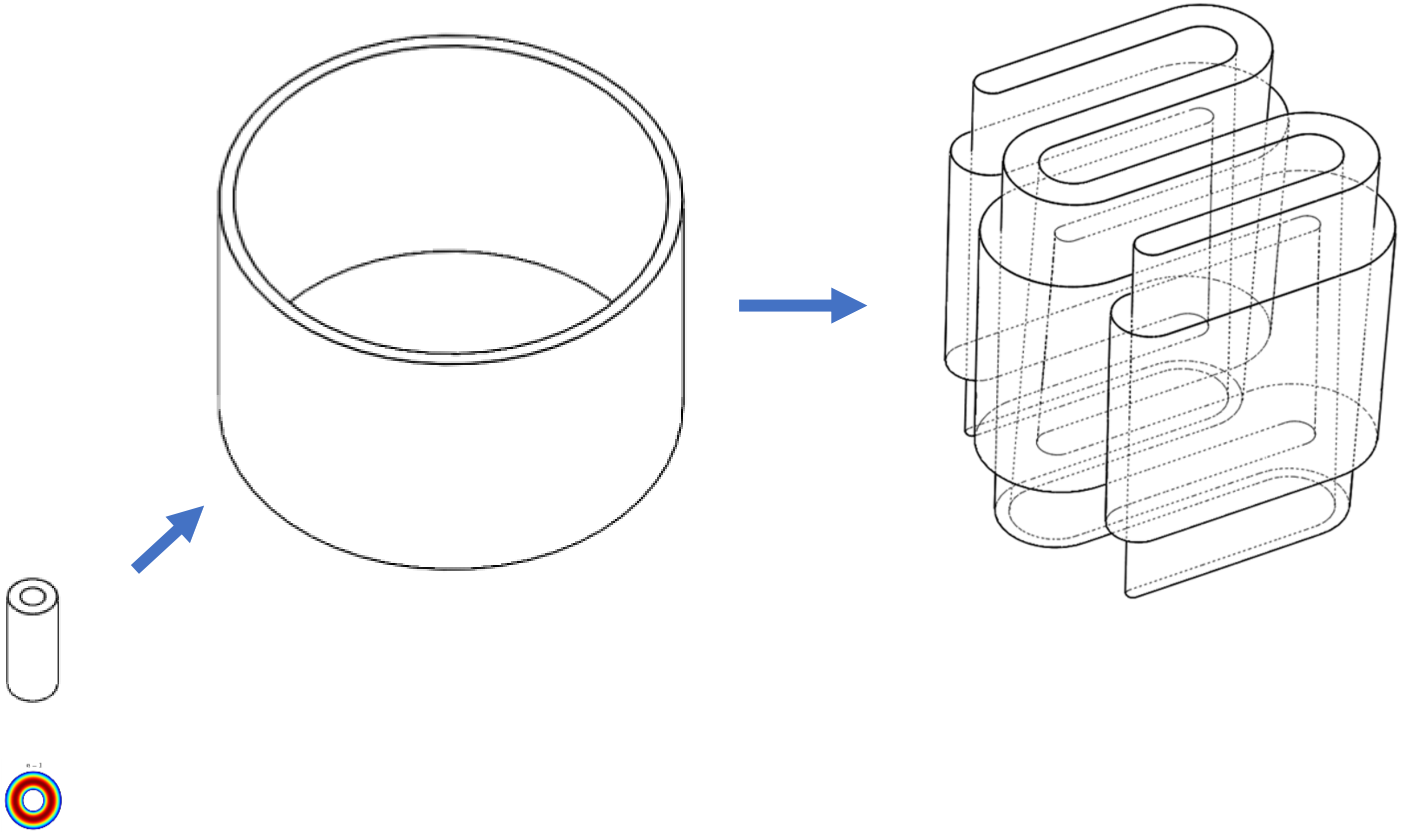
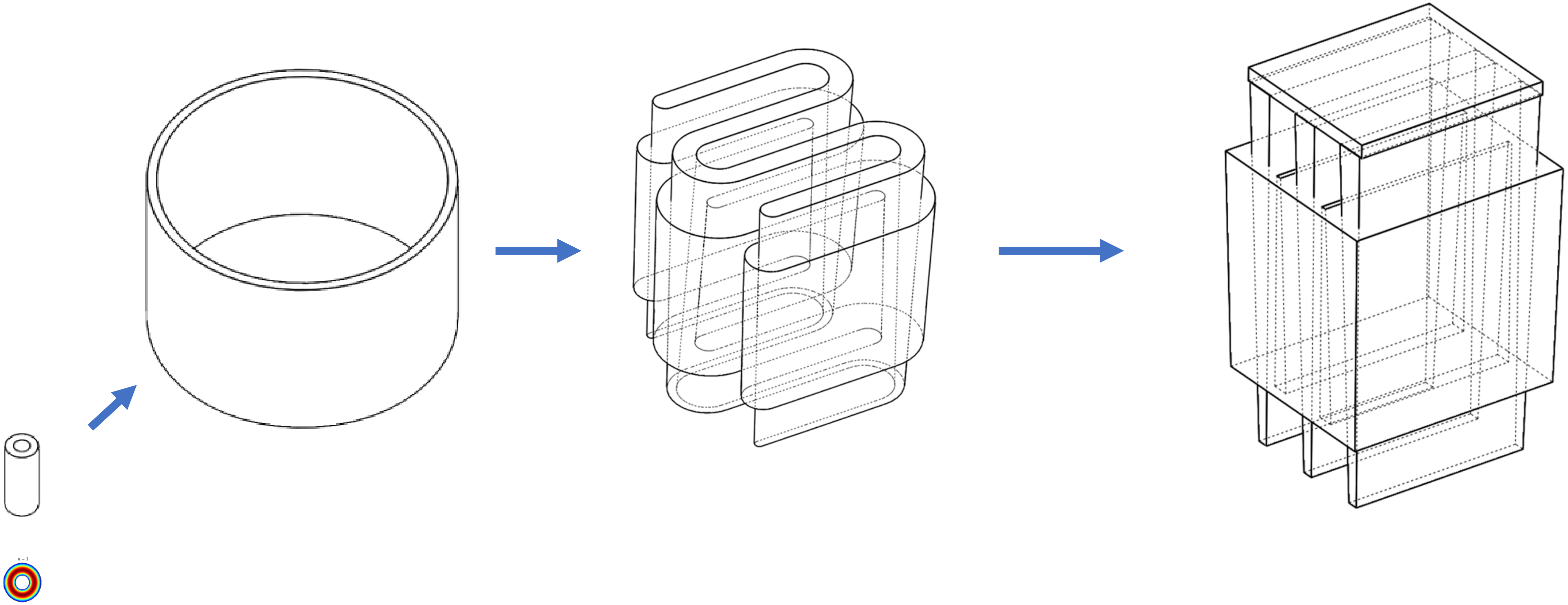
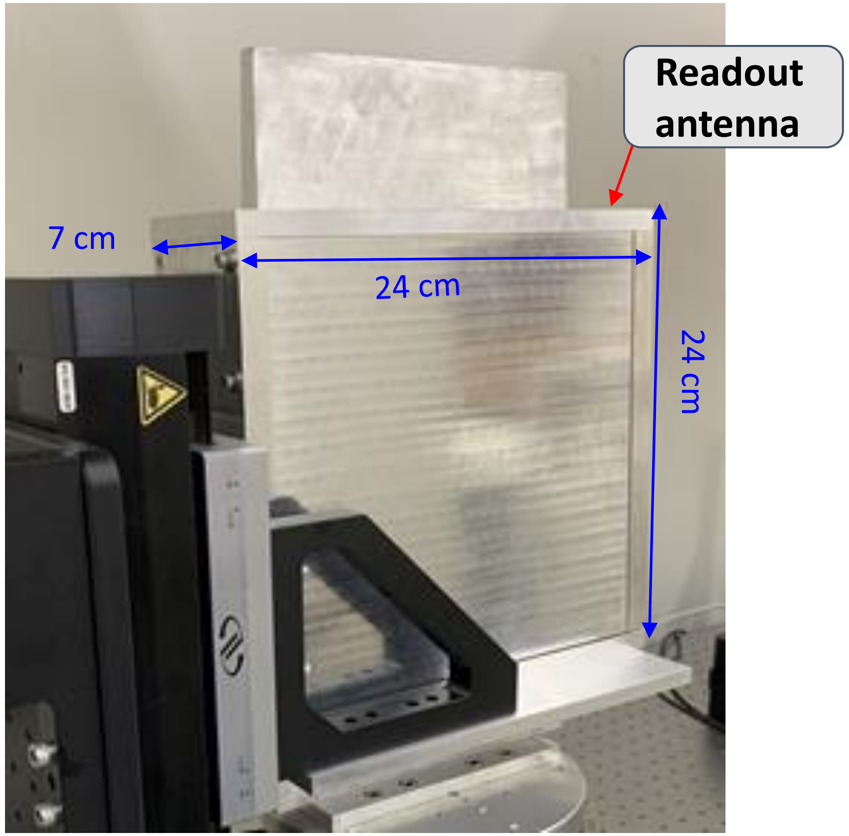






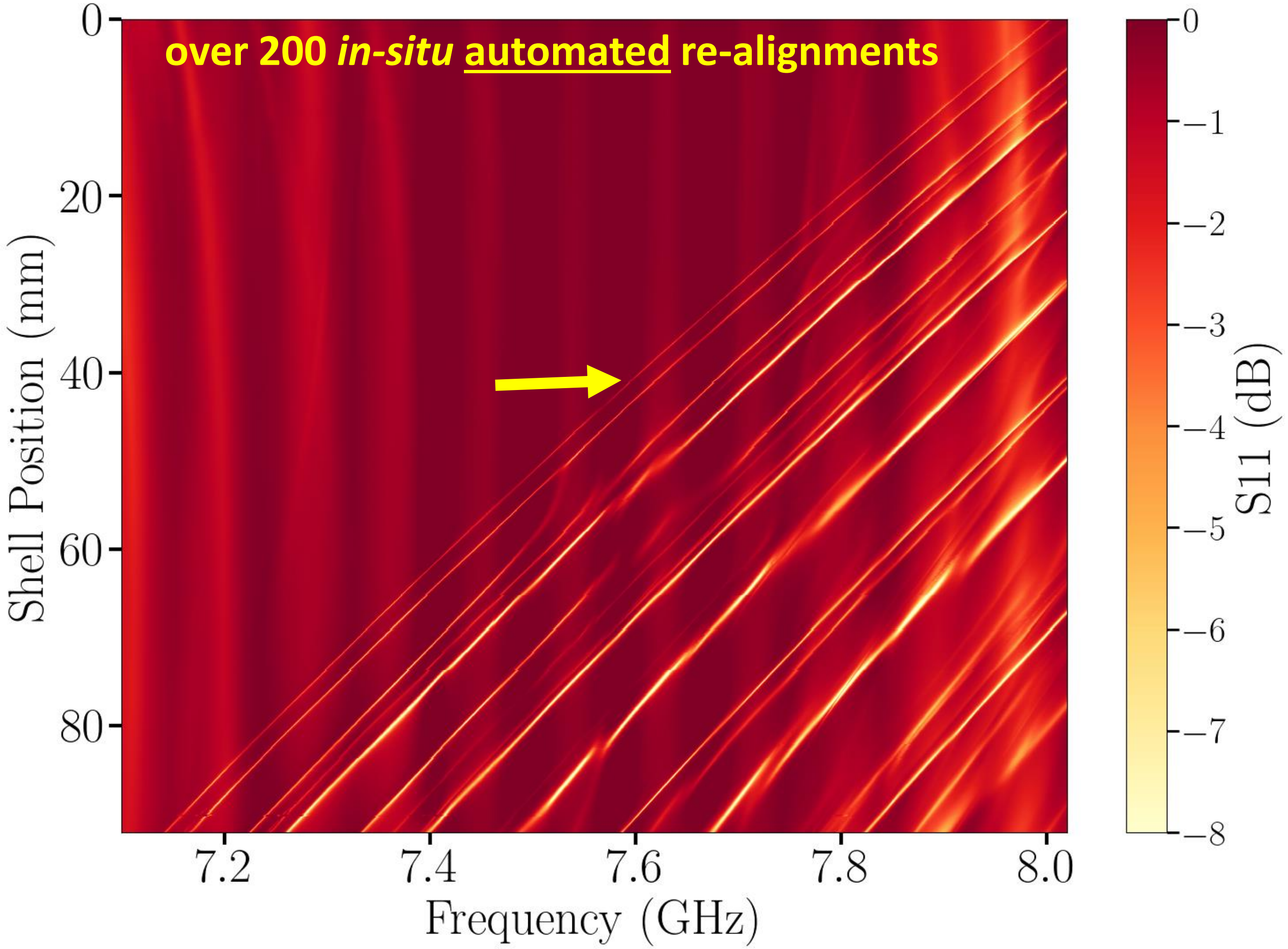
A prototype tunable single-wedge cavity ($V = 40\lambda^3$)

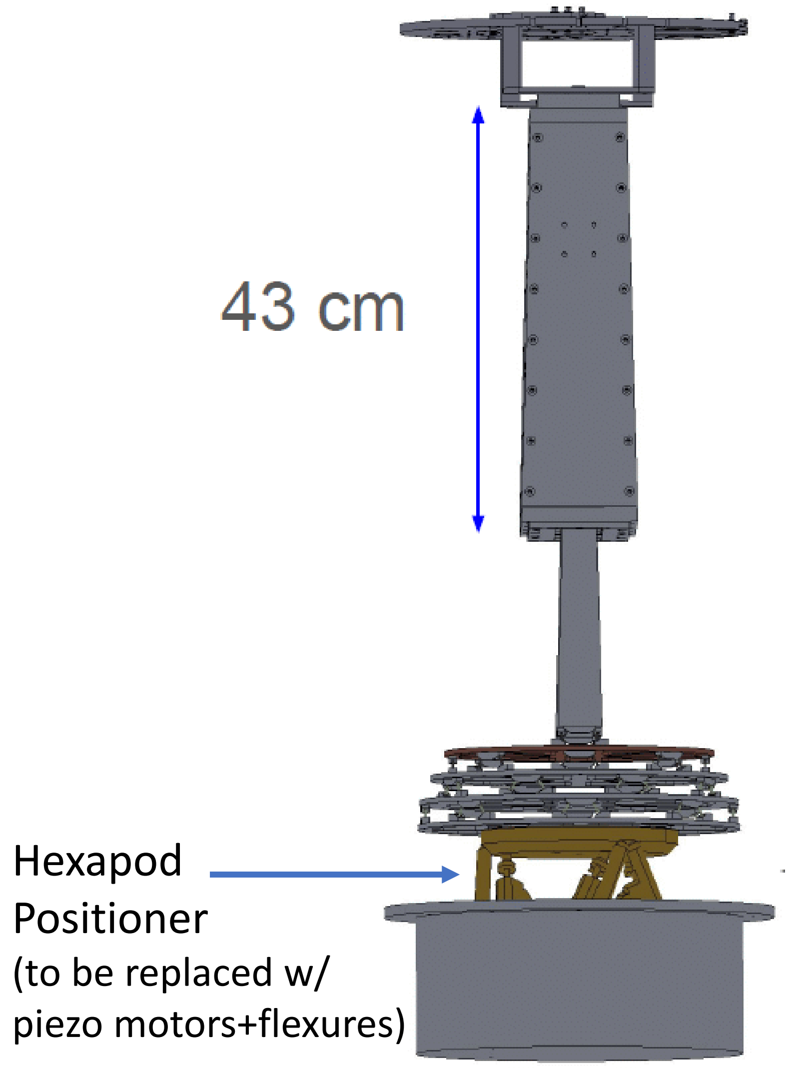
First prototype , w ~ 2.0 cm



Taj Dyson et. al.
arXiv:2402.01060

to appear in *Physical Review Applied*





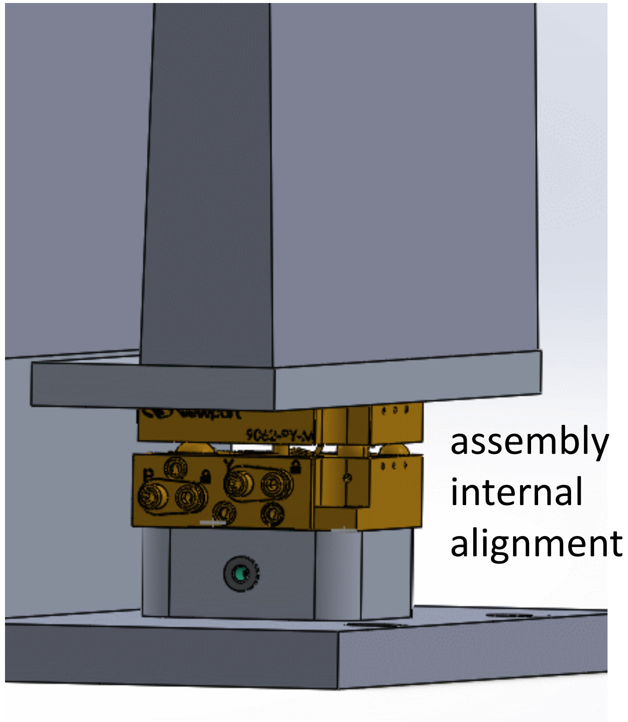
Taj+Sephora + VERA team

A larger, single-wedge prototype will be tested @ 100 mK

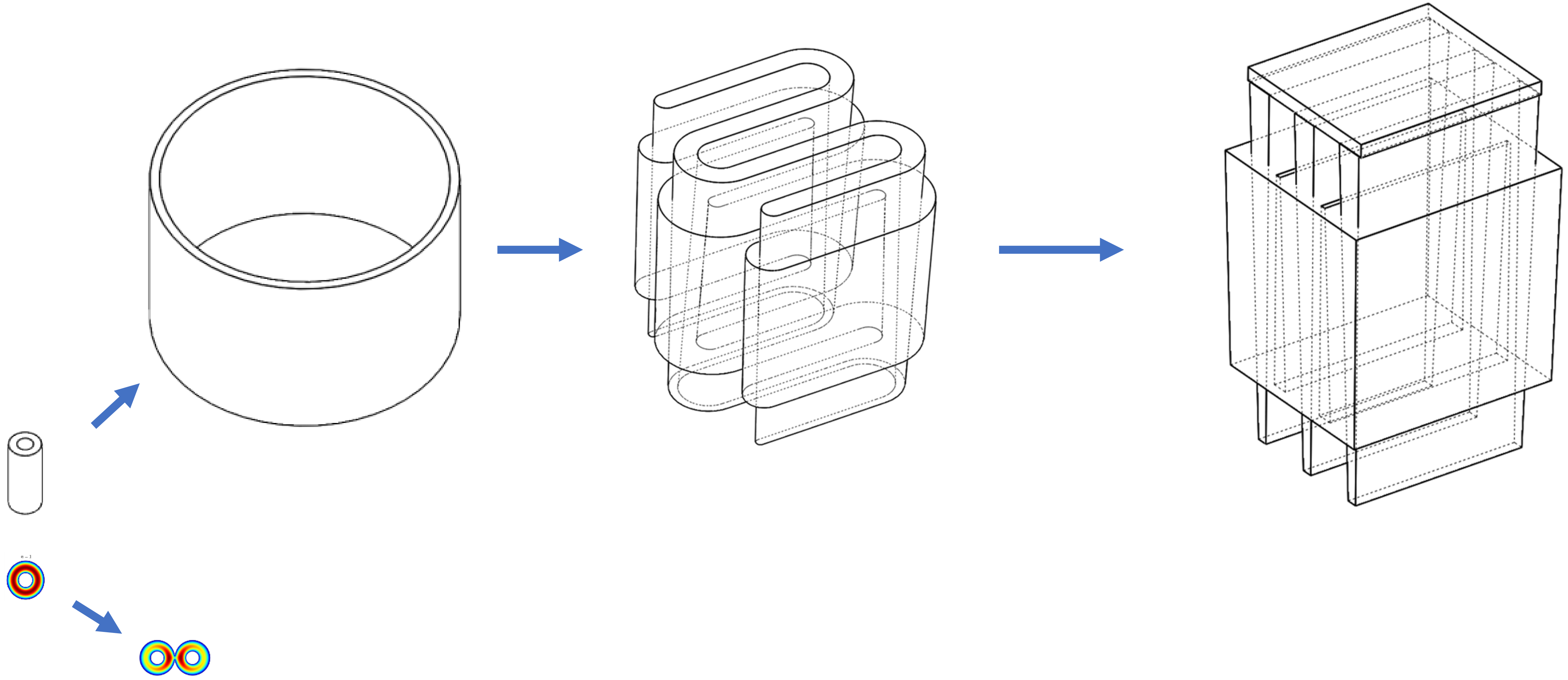
- 5.5-7 GHz
- Verification of high-Q
- Verification of in-situ alignment
- Design complete, ~5 months to results
- Cryogenic testbed for piezo-based tuning/alignment mechanisms, or other ADMX related testing
- Integration with quantum amplifiers/microwave sensors
  (collaboration with Noah Kurinsky and Dave Schuster)

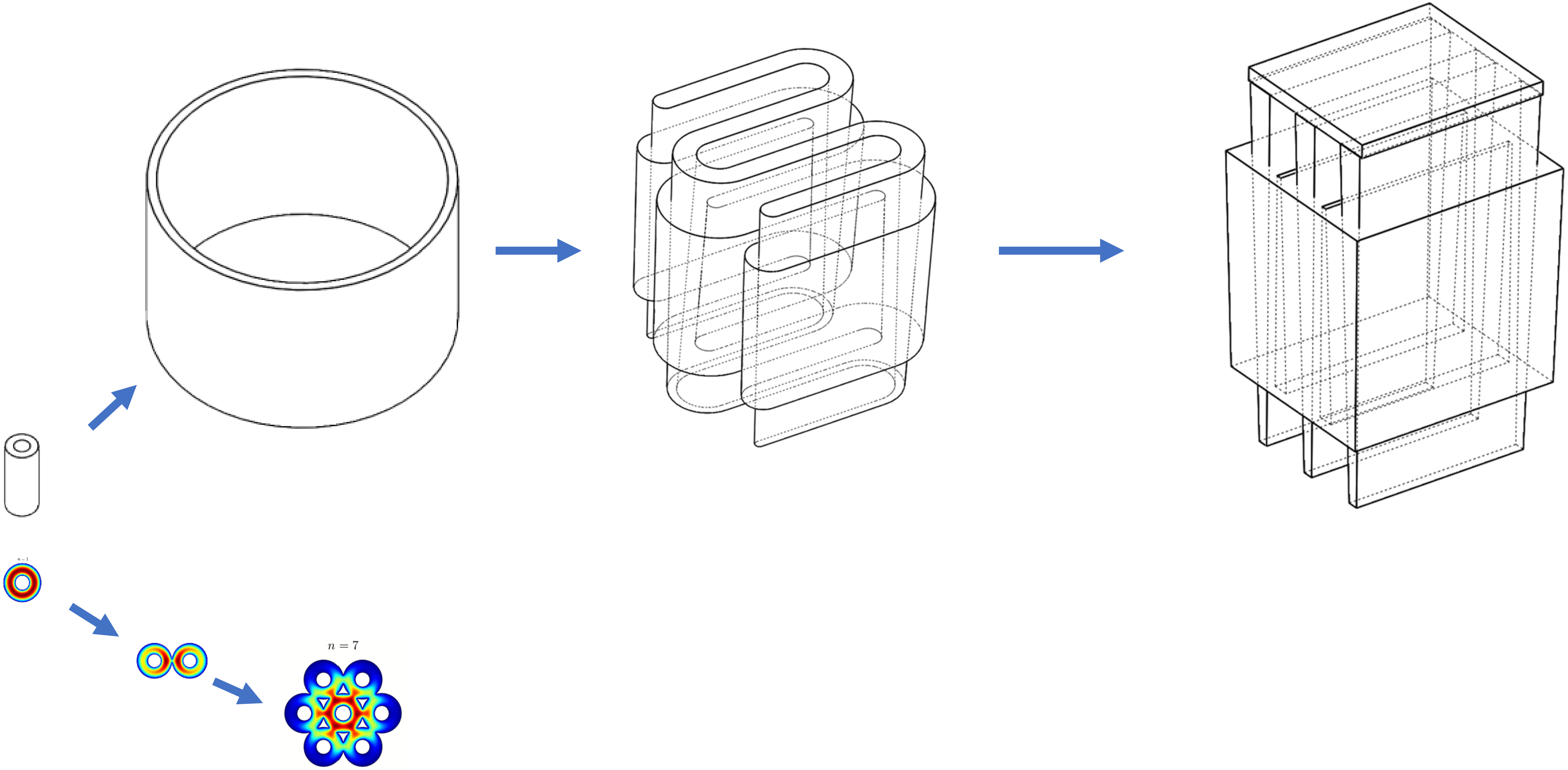
Triple Wedge Prototype

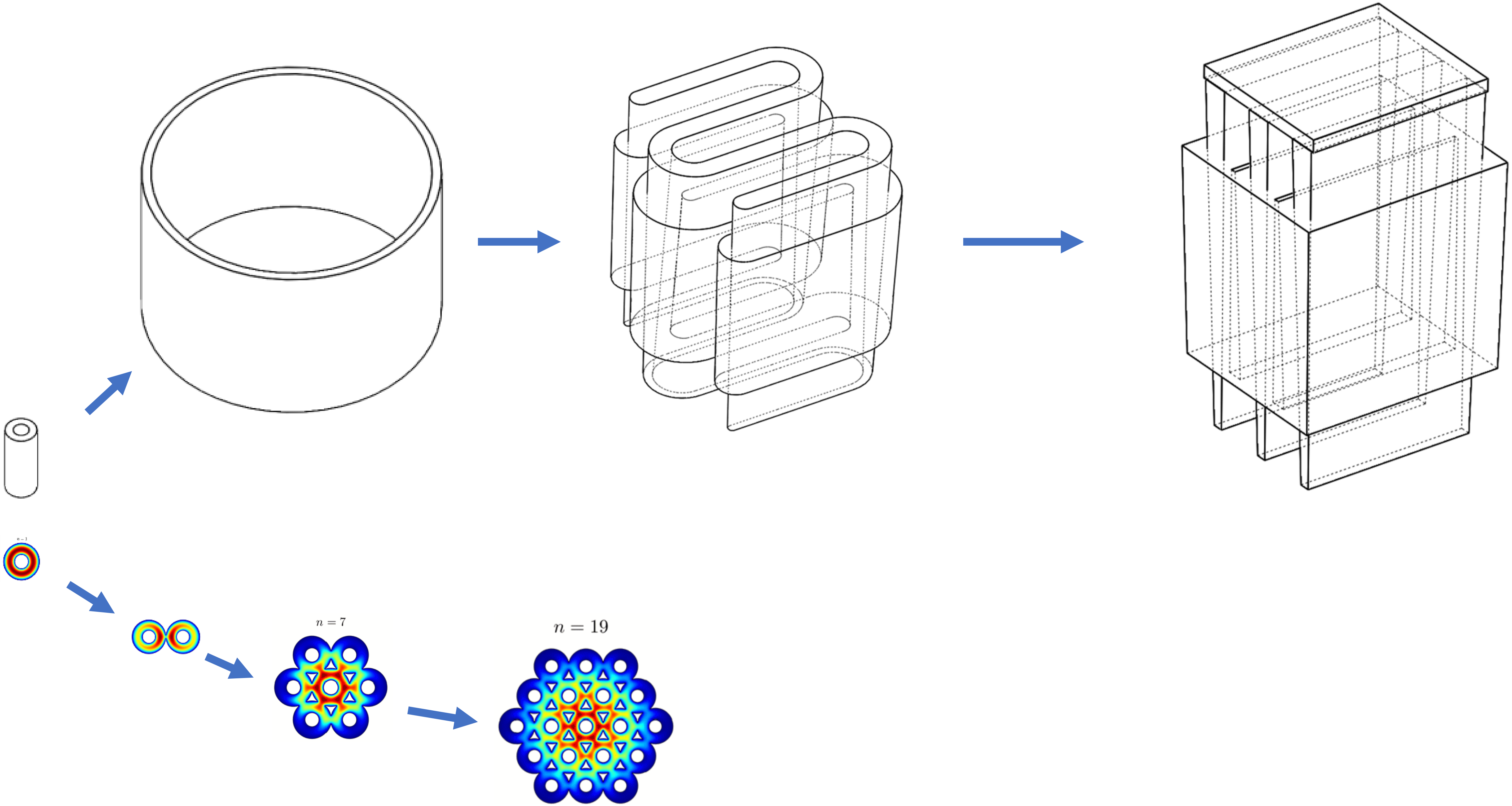
- Fabricated, now being assembled using precision metrology + flexure based fine adjustments
- The three wedges move together, so there remains only five parameters to align.



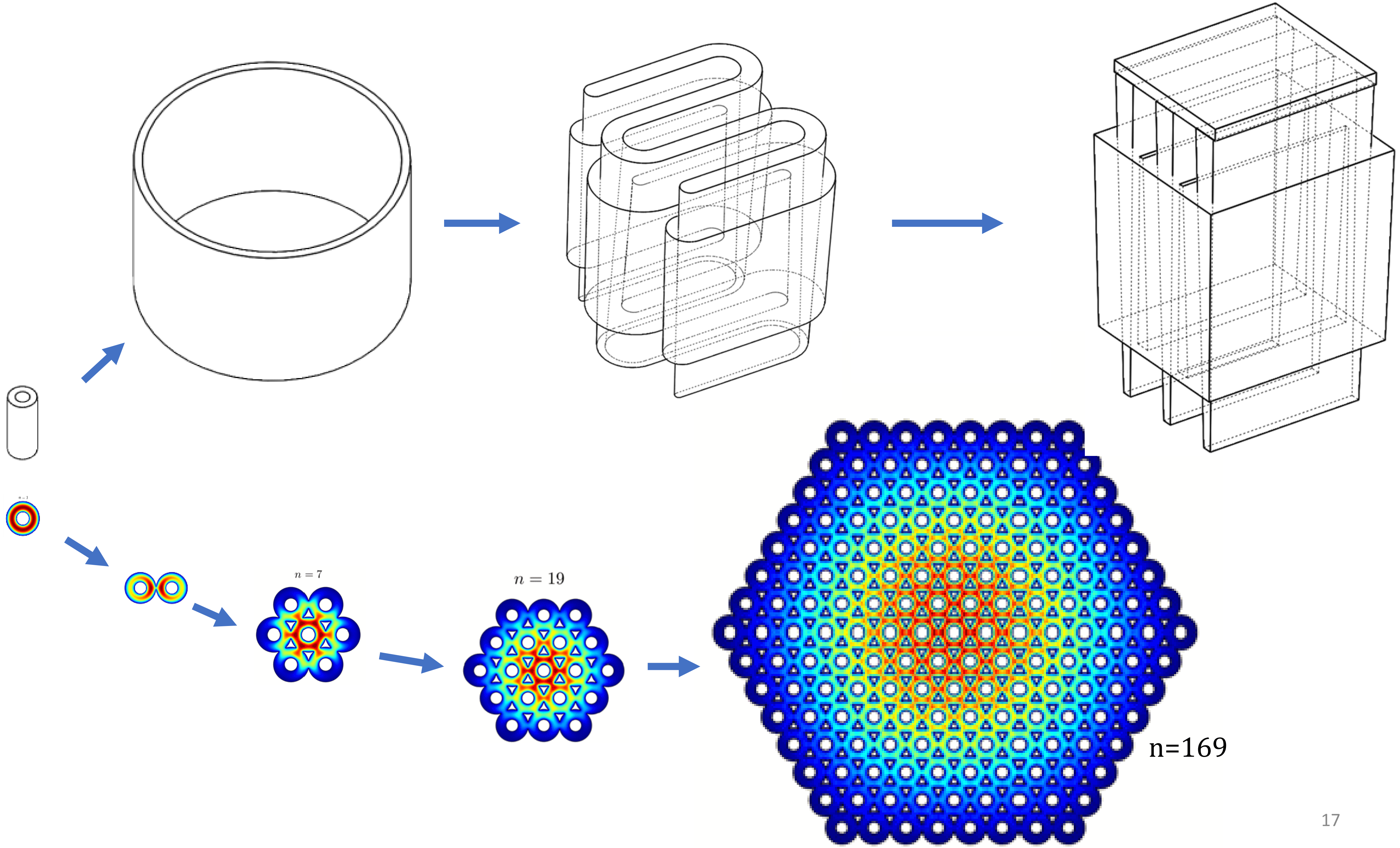
Sephora Ruppert




$n = 7$



n = 7
n = 19


n = 7
n = 19
n=169

A Beehive Haloscope for High-mass Axion Dark Matter

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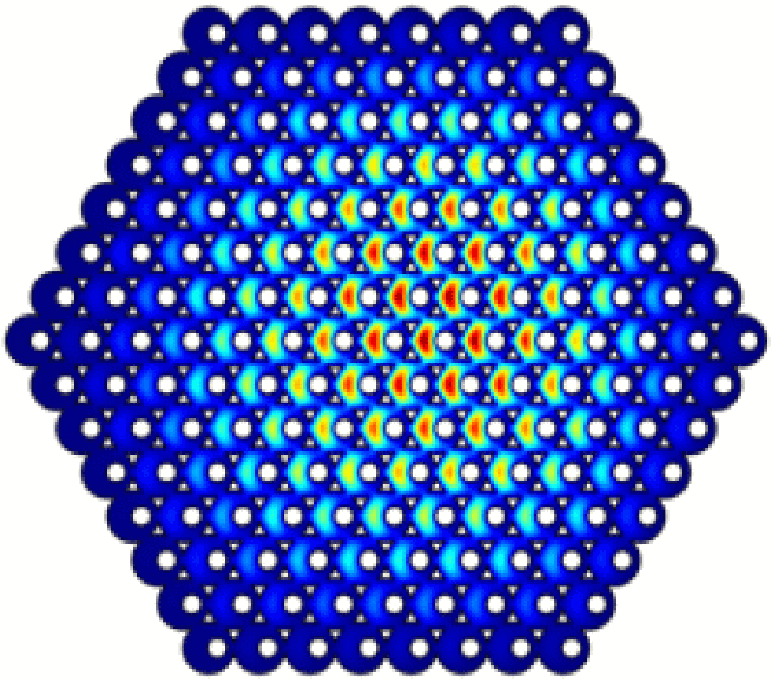
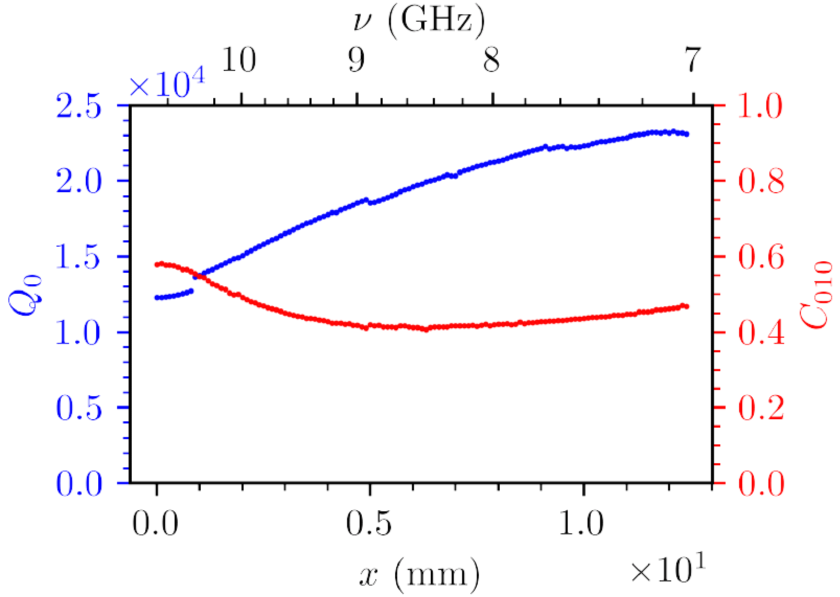
SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
(Dated: April 11, 2024)

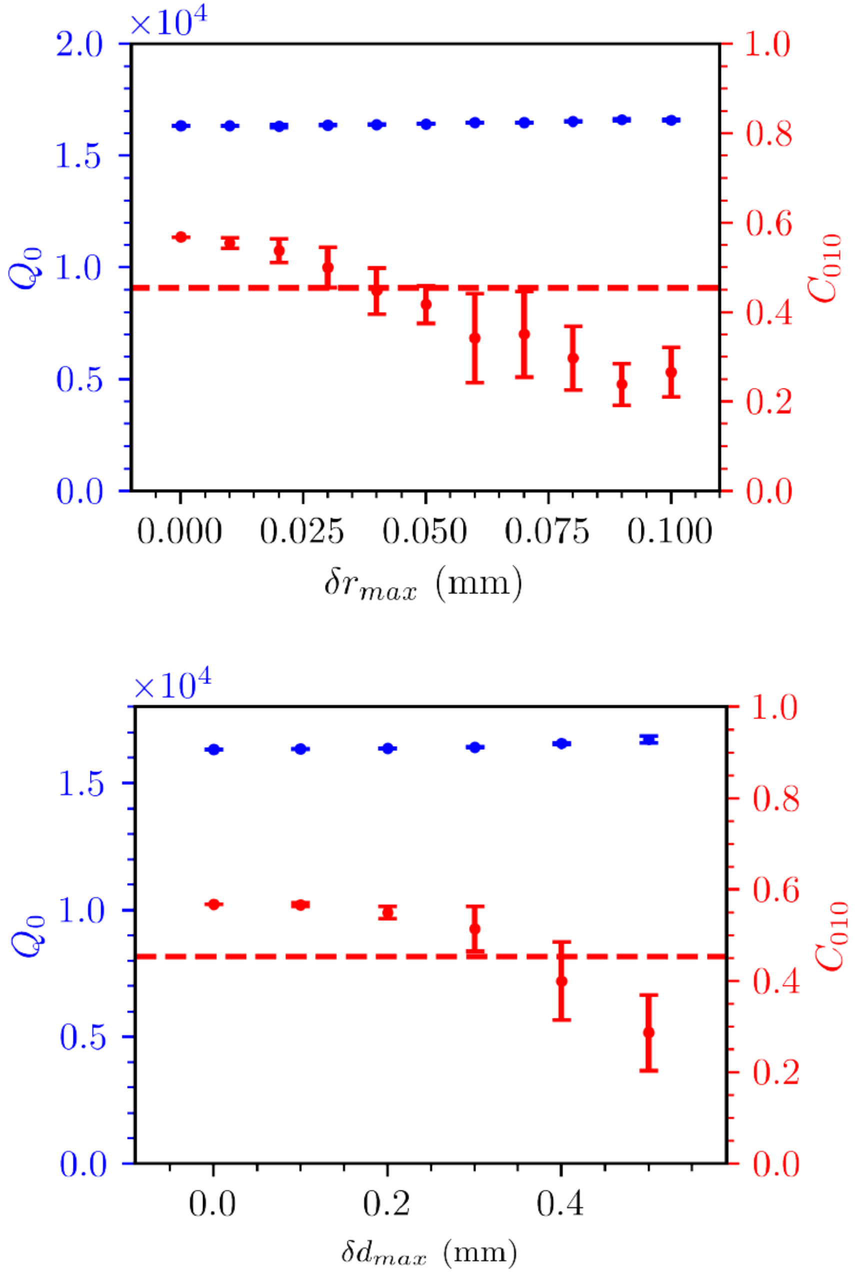
We propose a new haloscope geometry that can arbitrarily increase the resonator volume for a given target axion mass. This geometry consists of closely packed, *overlapping* coaxial cavities operating as a single resonator. While the resonant frequency is still determined by the dimensions of the individual "cells," the strong interactions between the cells encourage the entire "beehive" to oscillate *in phase*, a phenomenon expected of tightly coupled harmonic oscillators. This synchronization behavior allows the construction of a singly connected large-volume resonator at the high frequency by simply increasing the number of the cells. Using direct numerical simulations, we verify the existence of a global eigenmode that has a high (40%) form factor in a 169-element beehive resonator. The resonant frequency of the eigenmode is tunable by moving the center rods laterally in unison. The form factor is very tolerant to dimensional deviations and misalignment, as a result of mode hybridization due to strong coupling. The beehive haloscope inherits many appealing properties from the conventional coaxial cavity: a high quality factor, compatibility with a solenoid magnet, ease of fabrication, tuning, and coupling. We argue that this geometry is an excellent candidate for high-mass axion searches covering the post-inflationary parameter space (>5 GHz).

arXiv:2404.06627

$x = 6.3$ mm







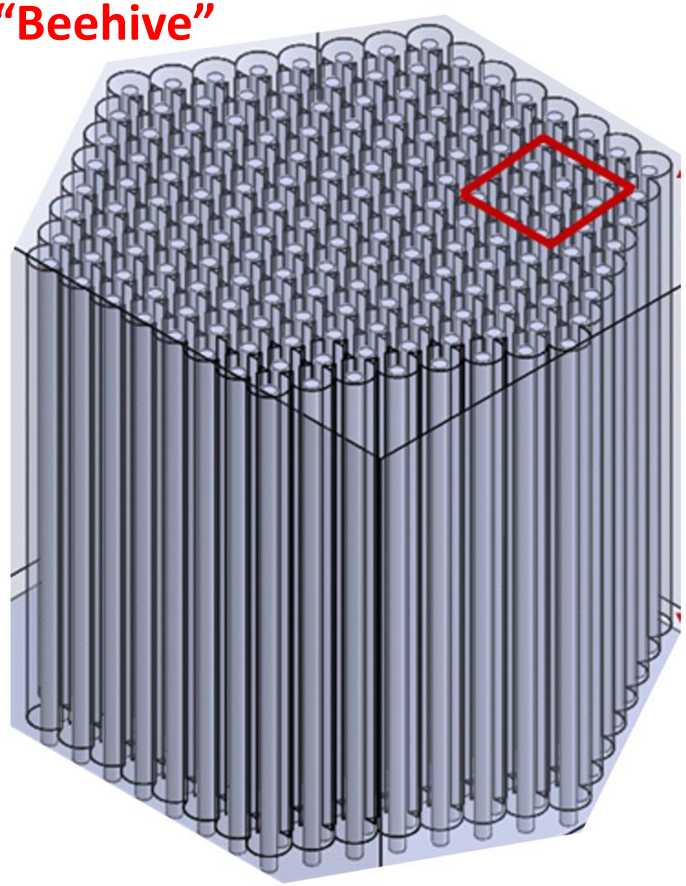
Significantly relaxed mechanical tolerances

- The inter-cell interactions encourage cells to oscillate ***in phase***
- With overlapping cells, the tolerance to variations in
  - rod radii relaxed from $\delta r < 5 \times 10^{-4}$ mm to $\delta r < 0.039$ mm
  - rod centers relaxed from $\delta d < 1.5 \times 10^{-3}$ mm to $\delta d < 0.35$ mm

arXiv:2404.06627

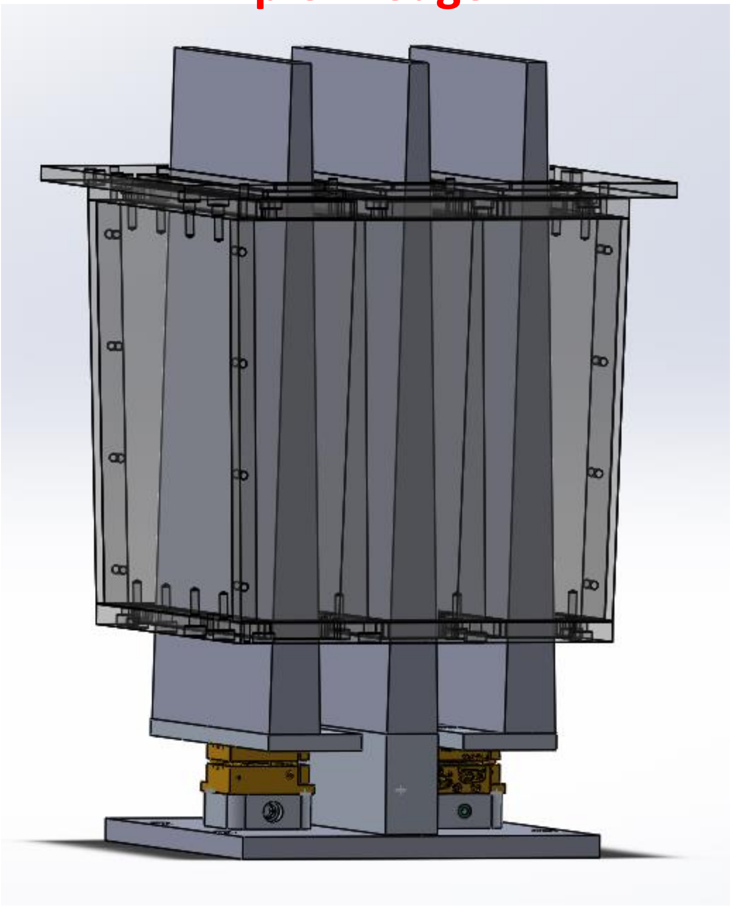
Tunable volume-filling cavities with $V > 100\lambda^3$

"Beehive"

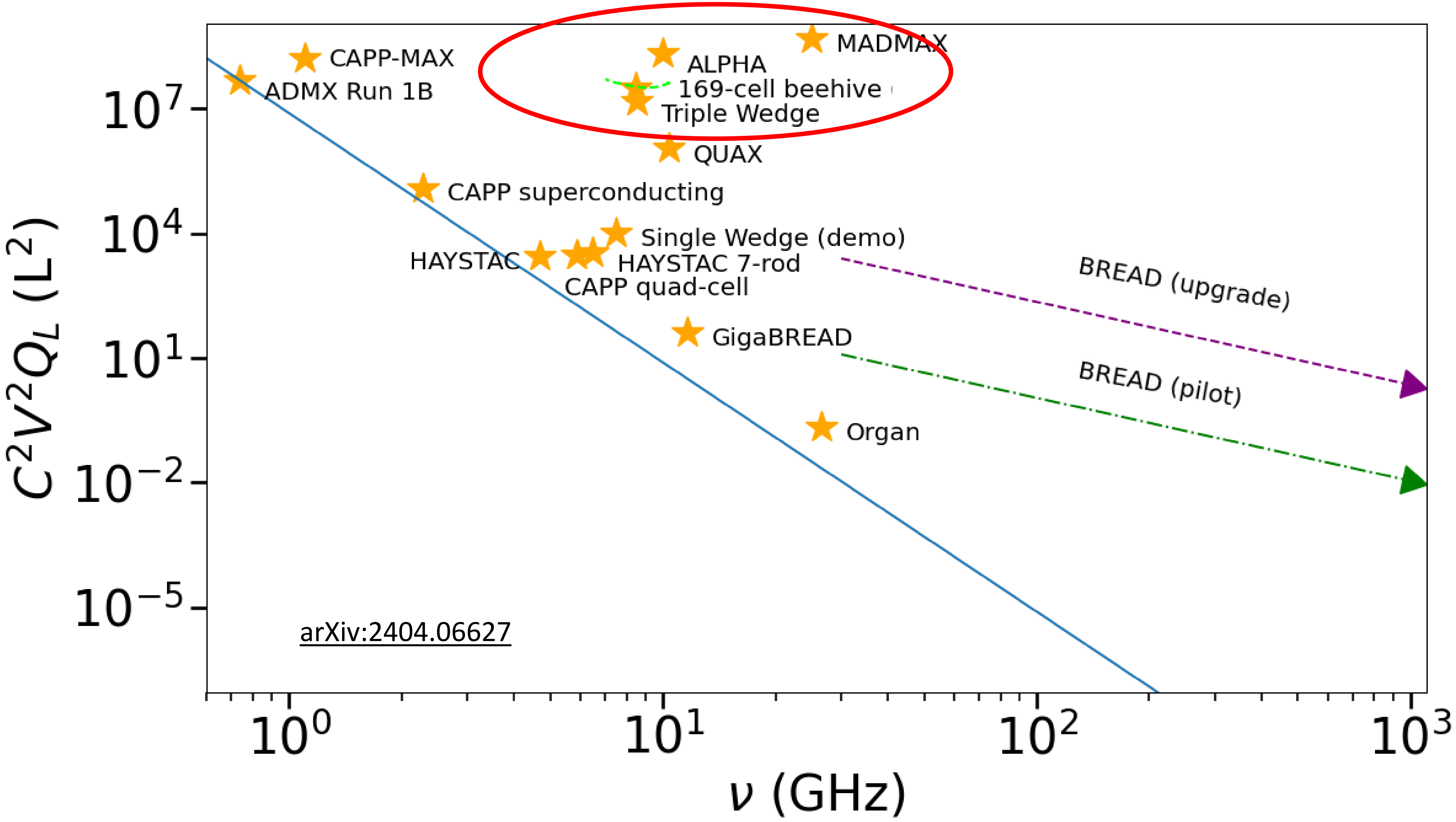


Matt Withers

"Triple Wedge"



Sephora Ruppert



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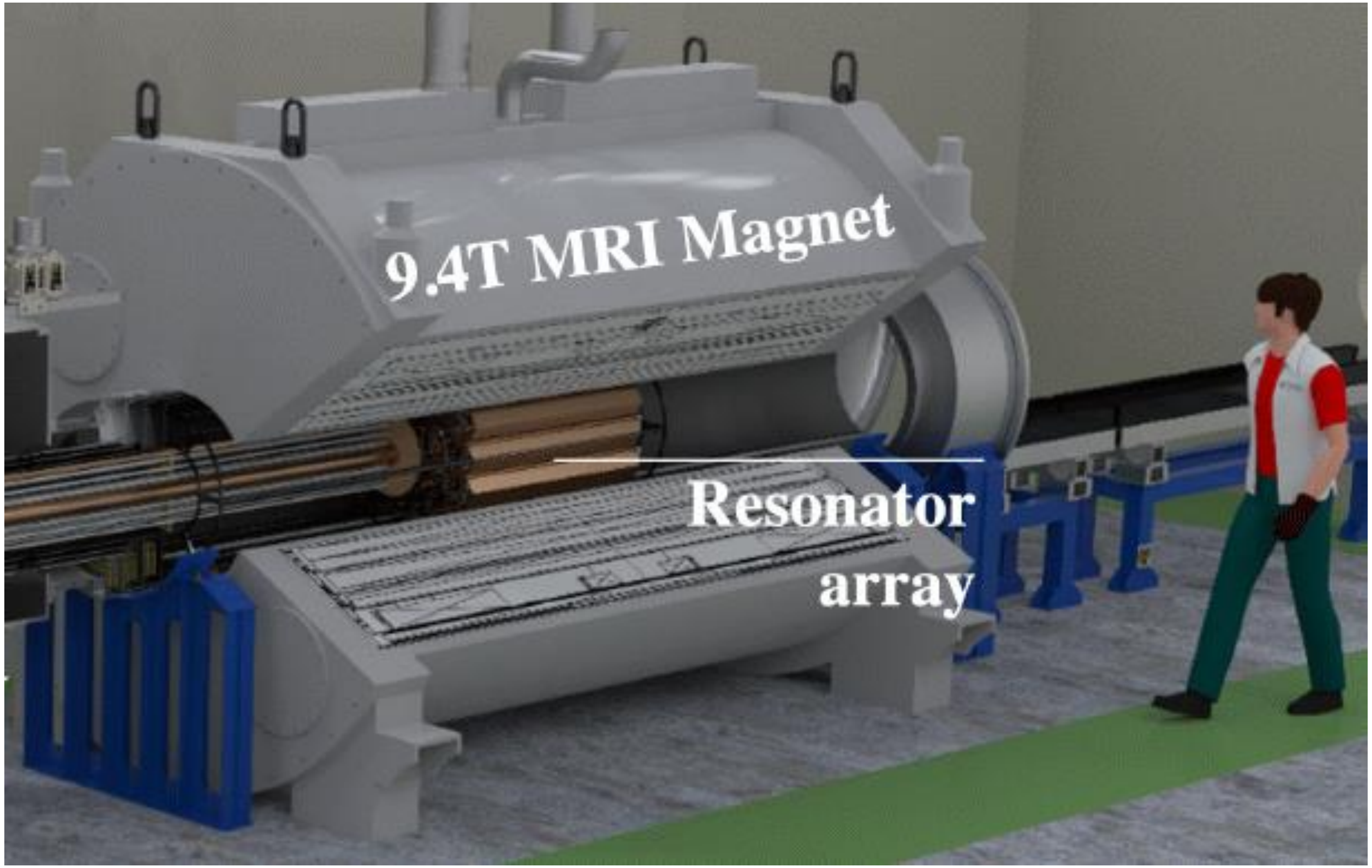
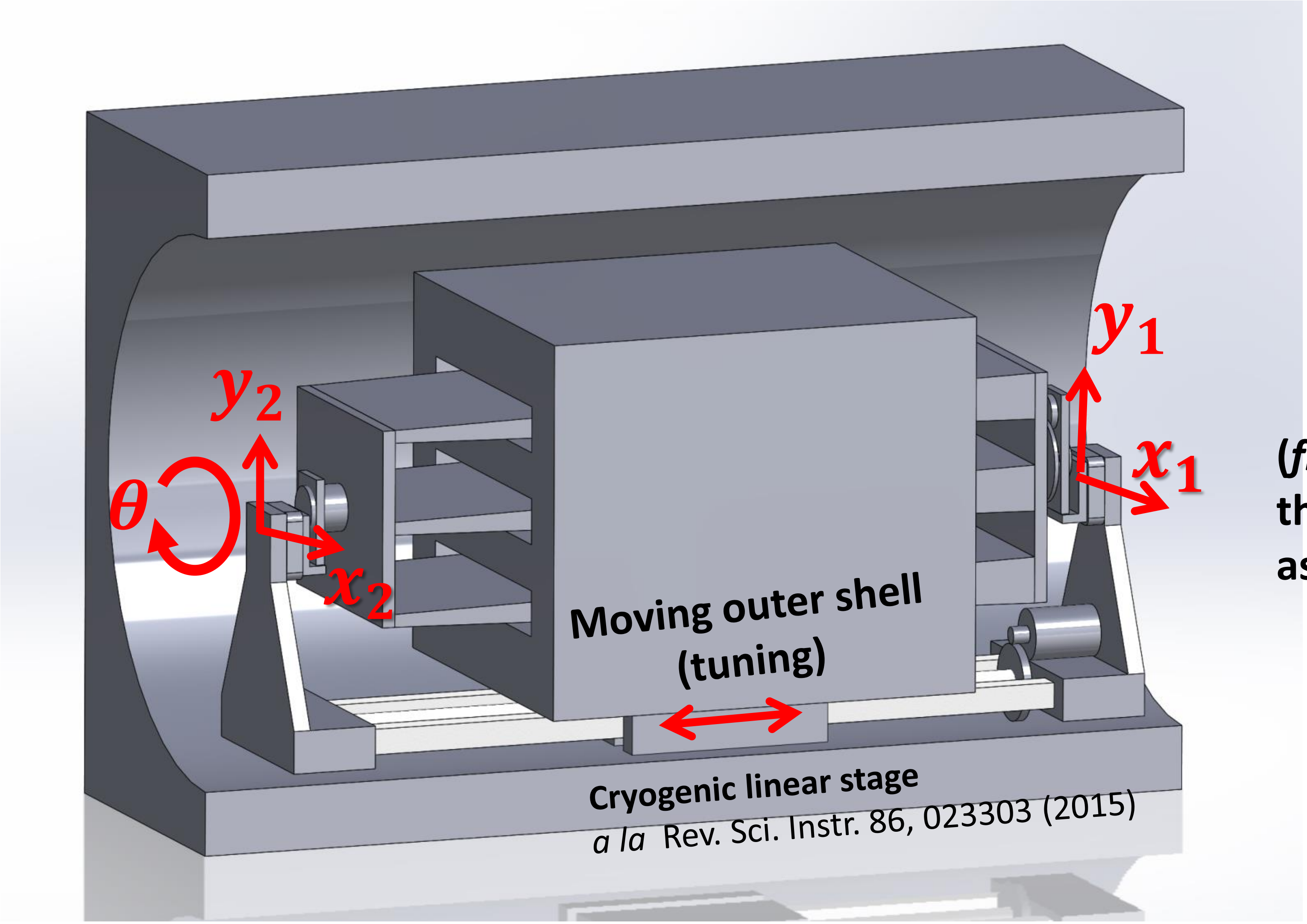
10^7
10^4
10^1
10^{-2}
10^{-5}
$C^2V^2Q_L$ (L^2)
10^0
10^1
10^2
10^3
ν (GHz)

The Dark Wave Lab

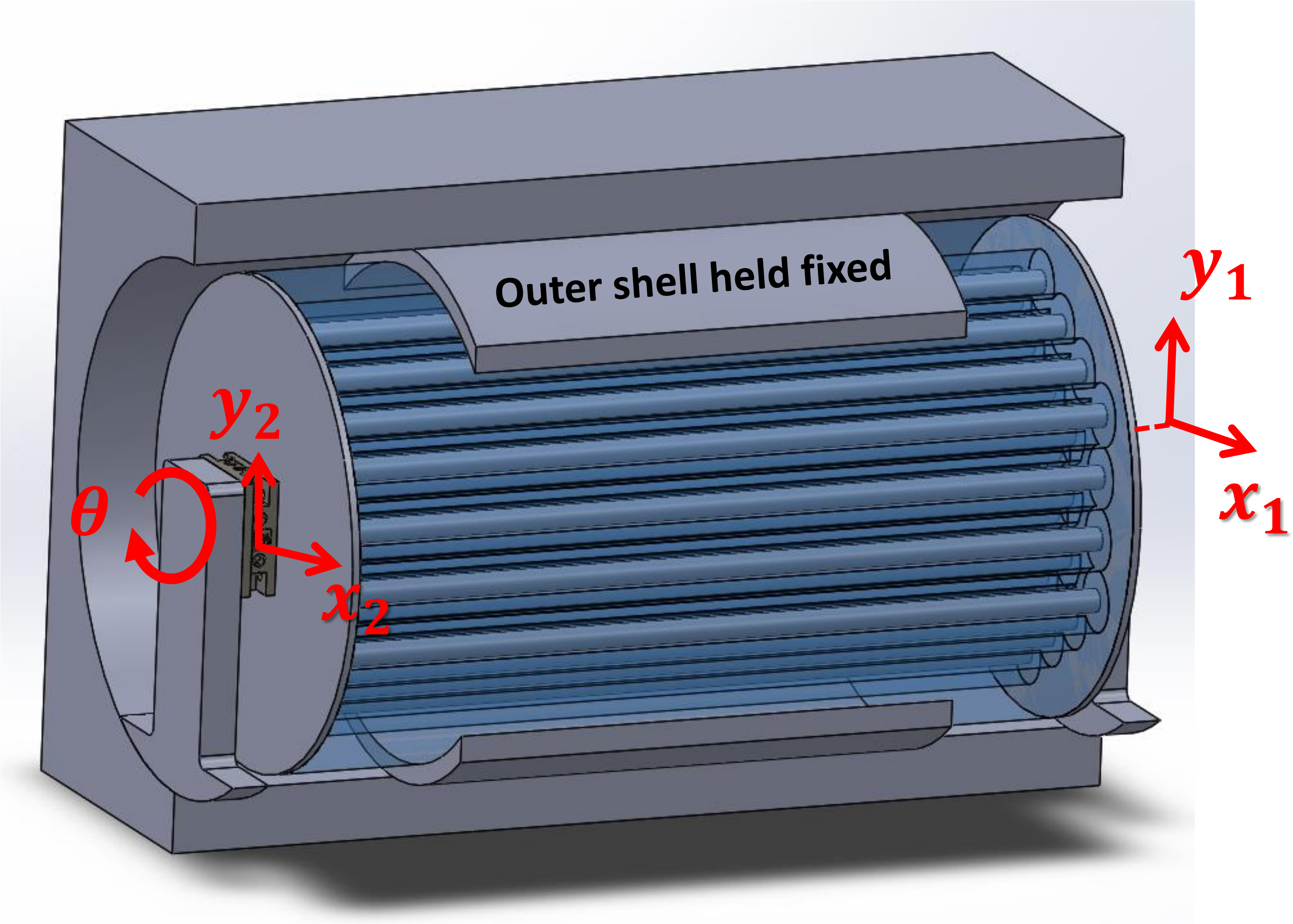


Triple Wedge in the DWL



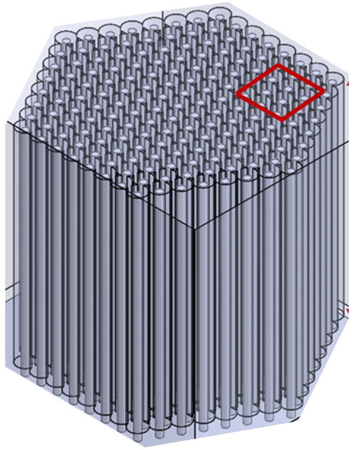
(*fine*-) aligning the wedge assembly

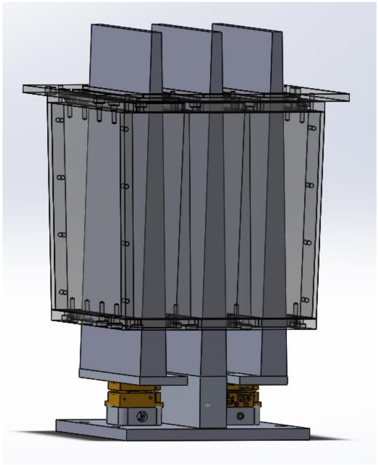
Beehive in the DWL



aligning and tuning
(rod array)

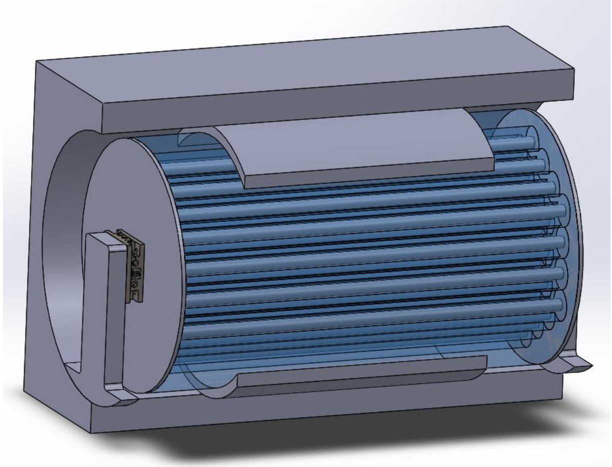
Beehive vs Multiple-Wedge



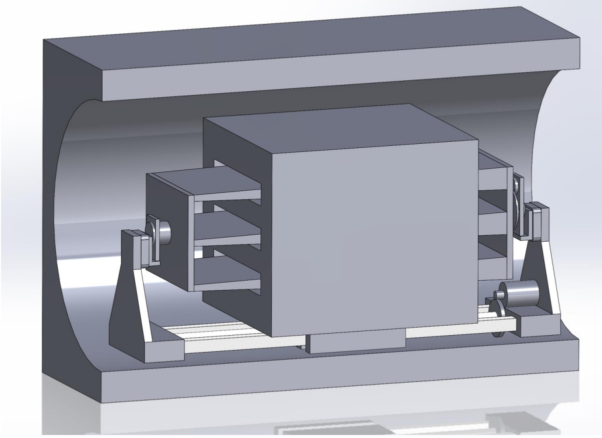


- Shared features
  - 20%~30% tuning range
  - Similar volume , a few $100\ \lambda^3$
  - High-Q (cold copper) $\sim 10^4$
  - Require fine alignment / mechanical tuning (piezo rotors + flexure mounts)
  - Require distributed readout, *i.e.*, multiple antennas + summing tree

- Differences
  - "Wedges" have all flat surfaces, but require one long travel for tuning; easier to implement a low-Q version with high density summing tree
  - "Beehives" might have larger tolerance to errors, but harder to fab/do metrology
  - Beehive 4-8 GHz; Multiple-wedge 8-16 GHz

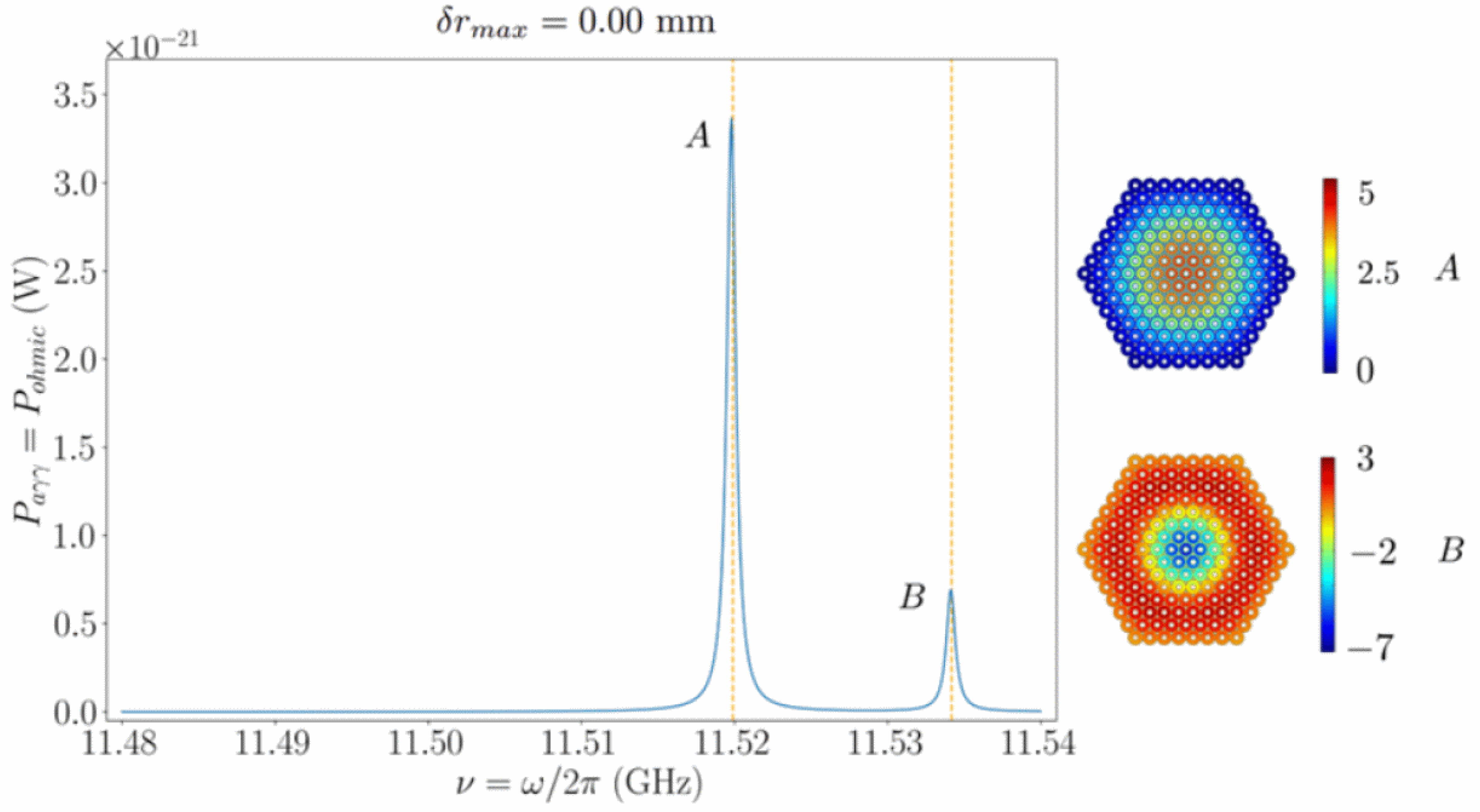


ADMX-VERA in DWL

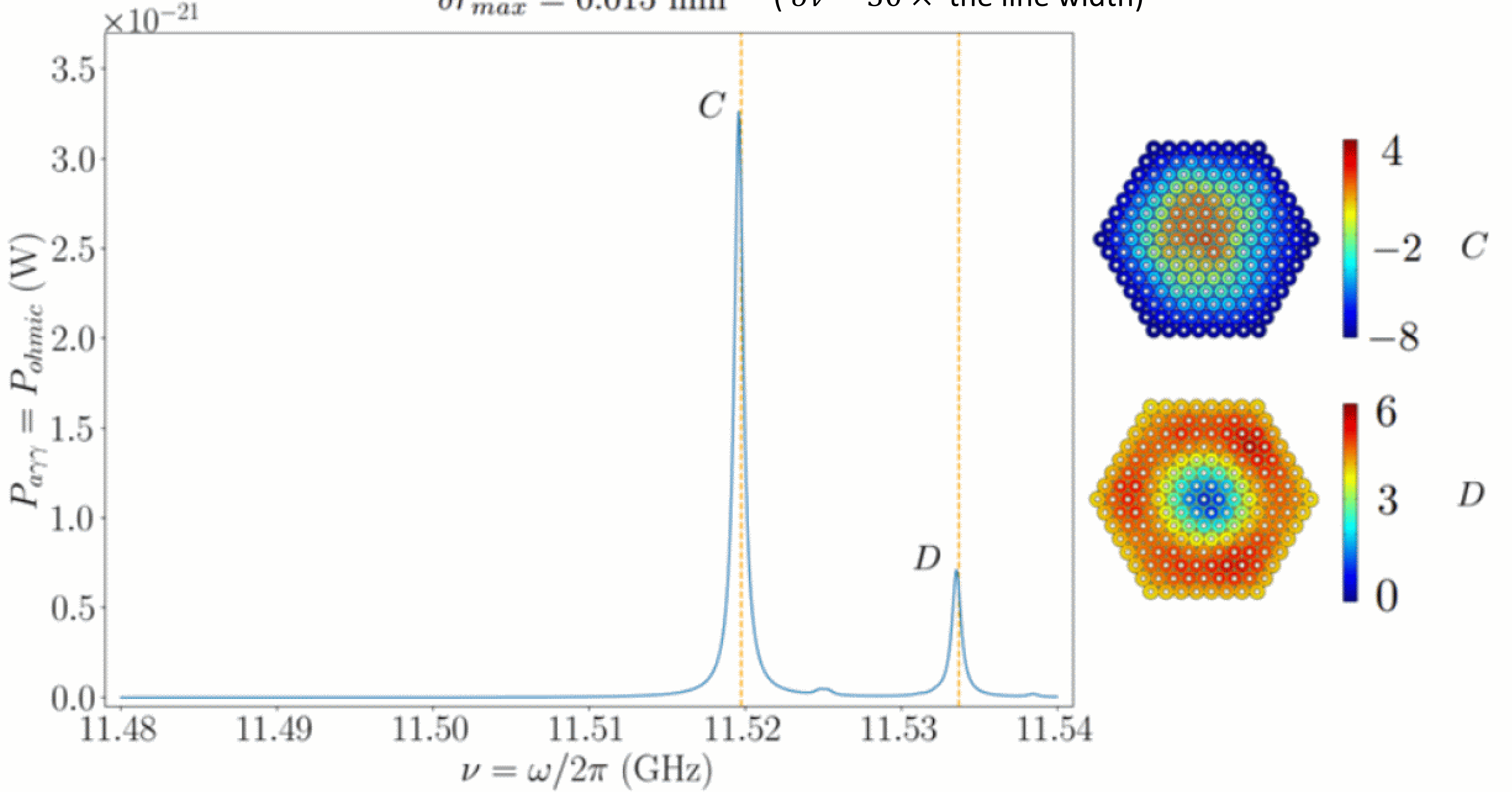


- *Starting today*, an $\mathcal{O}(m^3)$ 4-5.5 GHz/10-13GHz Beehive/Triple-Wedge can be ready for the Dark Wave Lab by **mid-2026.**
- It will be based on a **single HEMT amplifier**, cavity at **4K**
- Projected to run in FY27, with the goal of demonstrating 20% range, automated alignment/tuning, and high-Q expected of cold copper
- Required R&D's: coupling summing tree, piezo motor drive(s)/control system
- Future upgrades: compact He3 sorption or dilution fridges, small region of field cancellation, JPA/TWPA operations, …

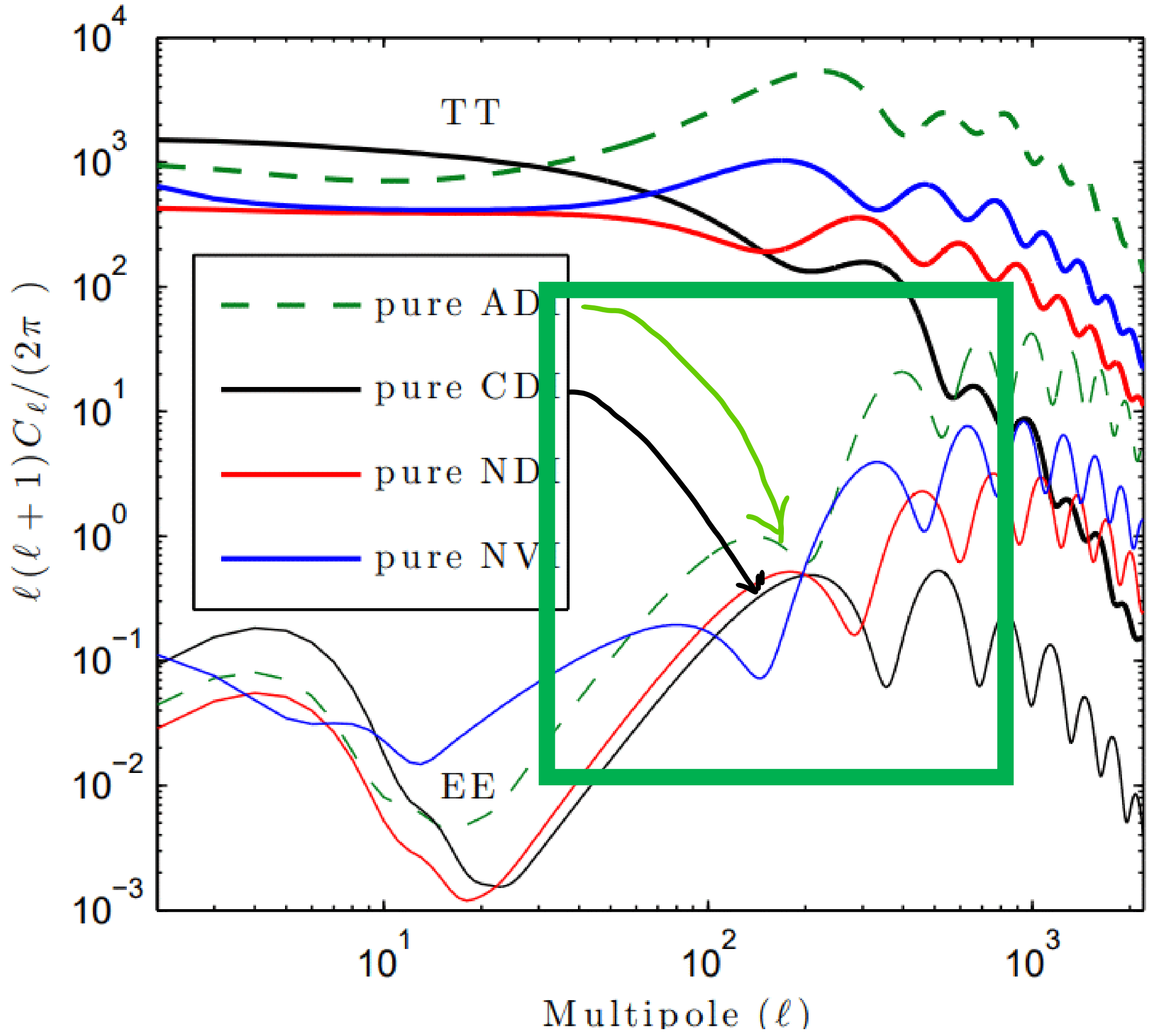
Thank you !

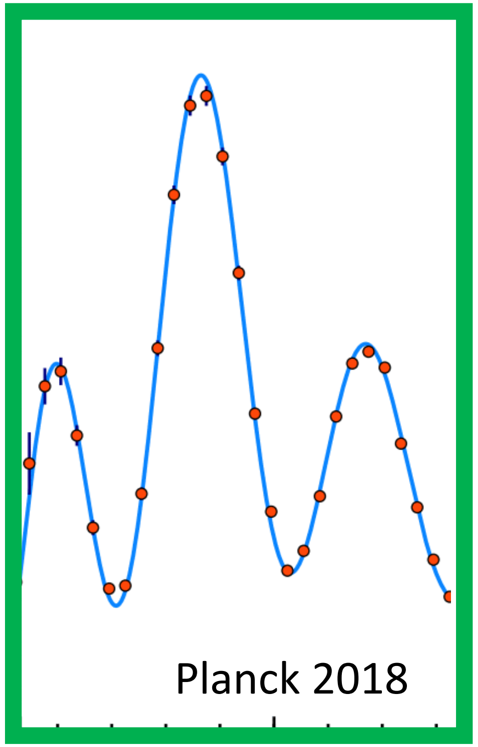

$\delta r_{max} = 0.00$ mm
$\times 10^{-21}$
$P_{a\gamma\gamma} = P_{ohmic}$ (W)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
A
B
11.48
11.49
11.50
11.51
11.52
11.53
11.54
$\nu = \omega/2\pi$ (GHz)
5
2.5
0
A
3
−2
−7
B

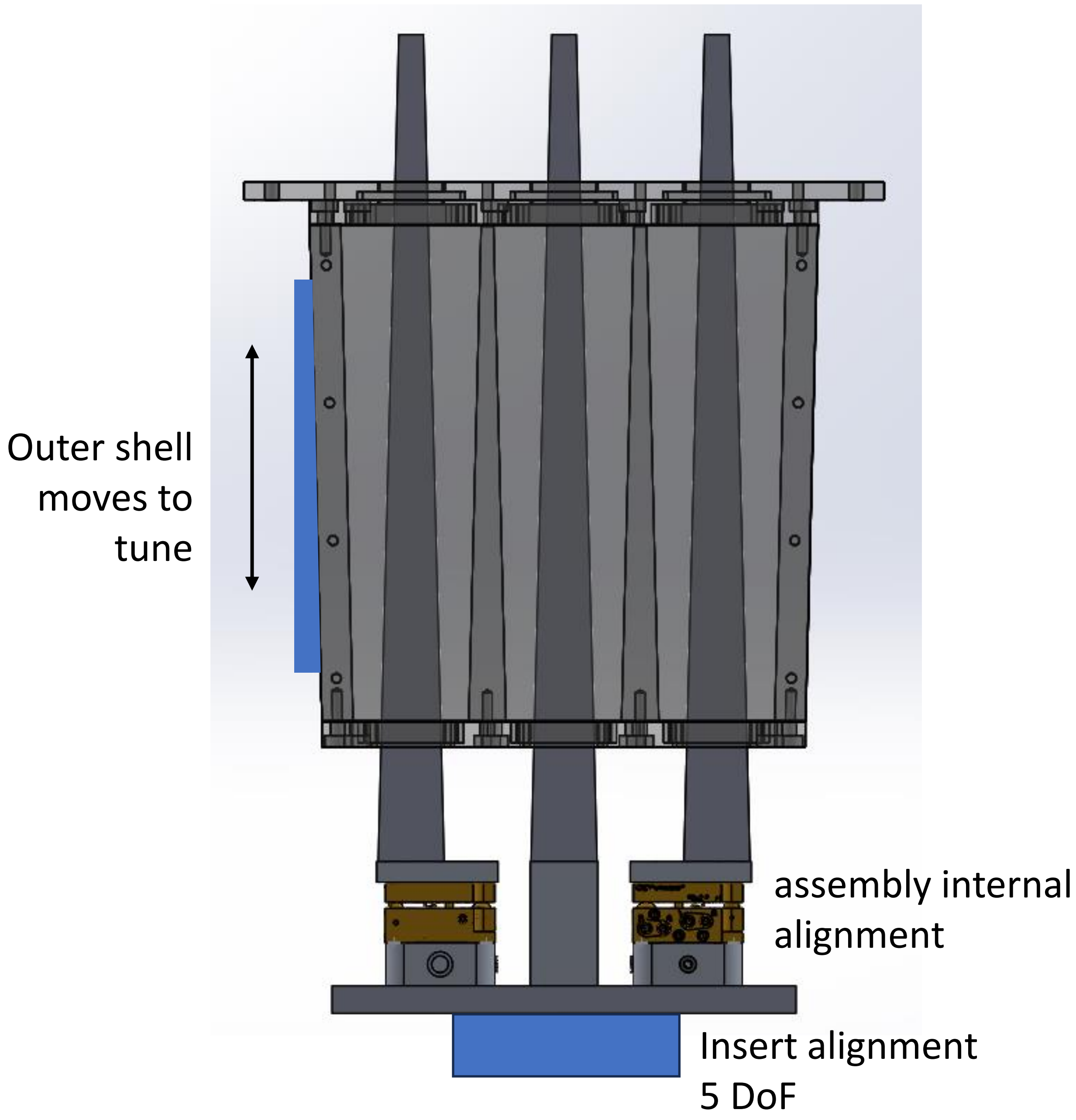
$\delta r_{max} = 0.015$ mm ($\delta\nu \sim 30 \times$ the line width)

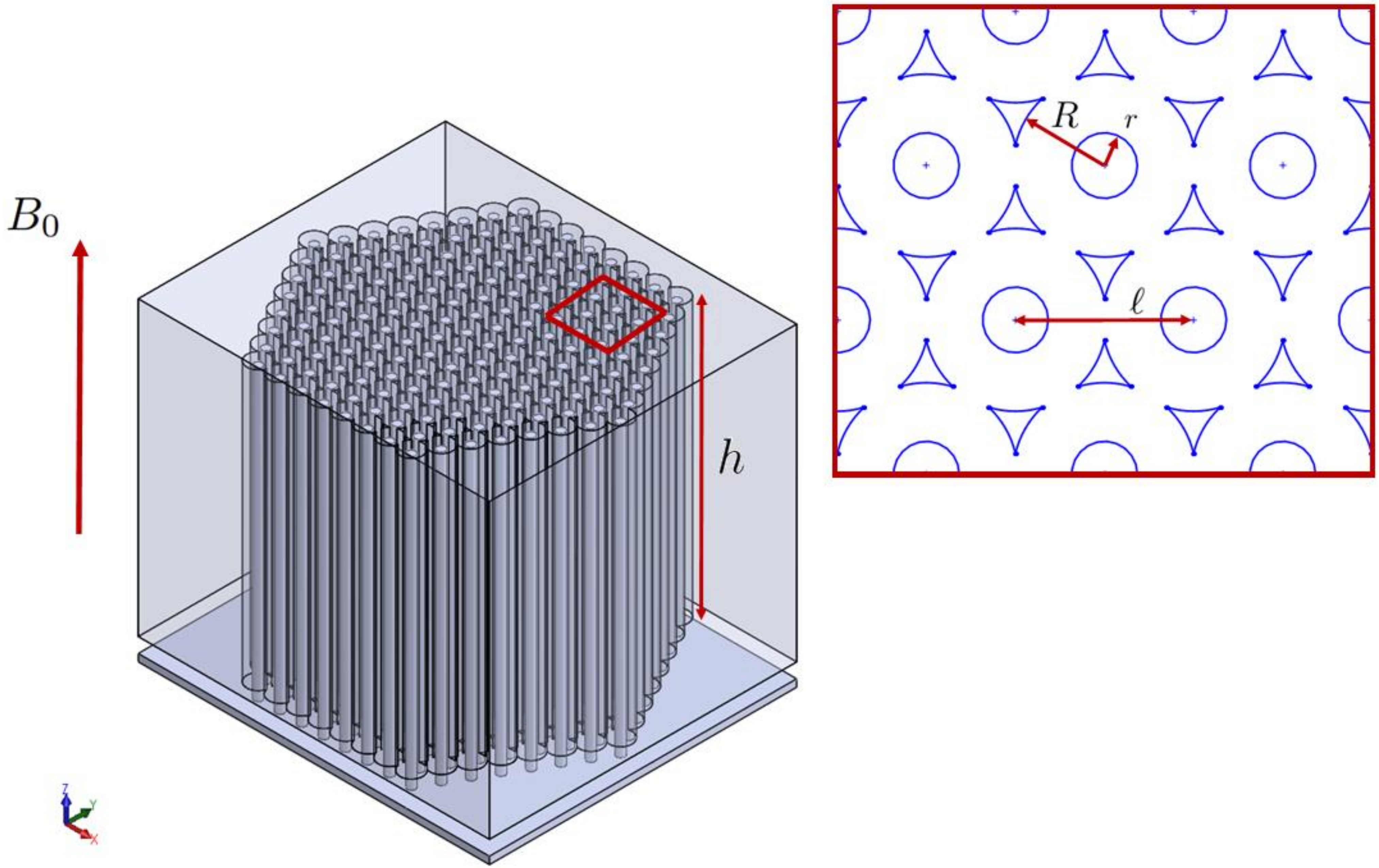


Isocurvature limit from CMB E-mode polarization






Outer shell moves to tune
assembly internal alignment
Insert alignment 5 DoF



B_0
h
R
r
ℓ