ADMX Collaboration Meeting
May 4-6, 2022

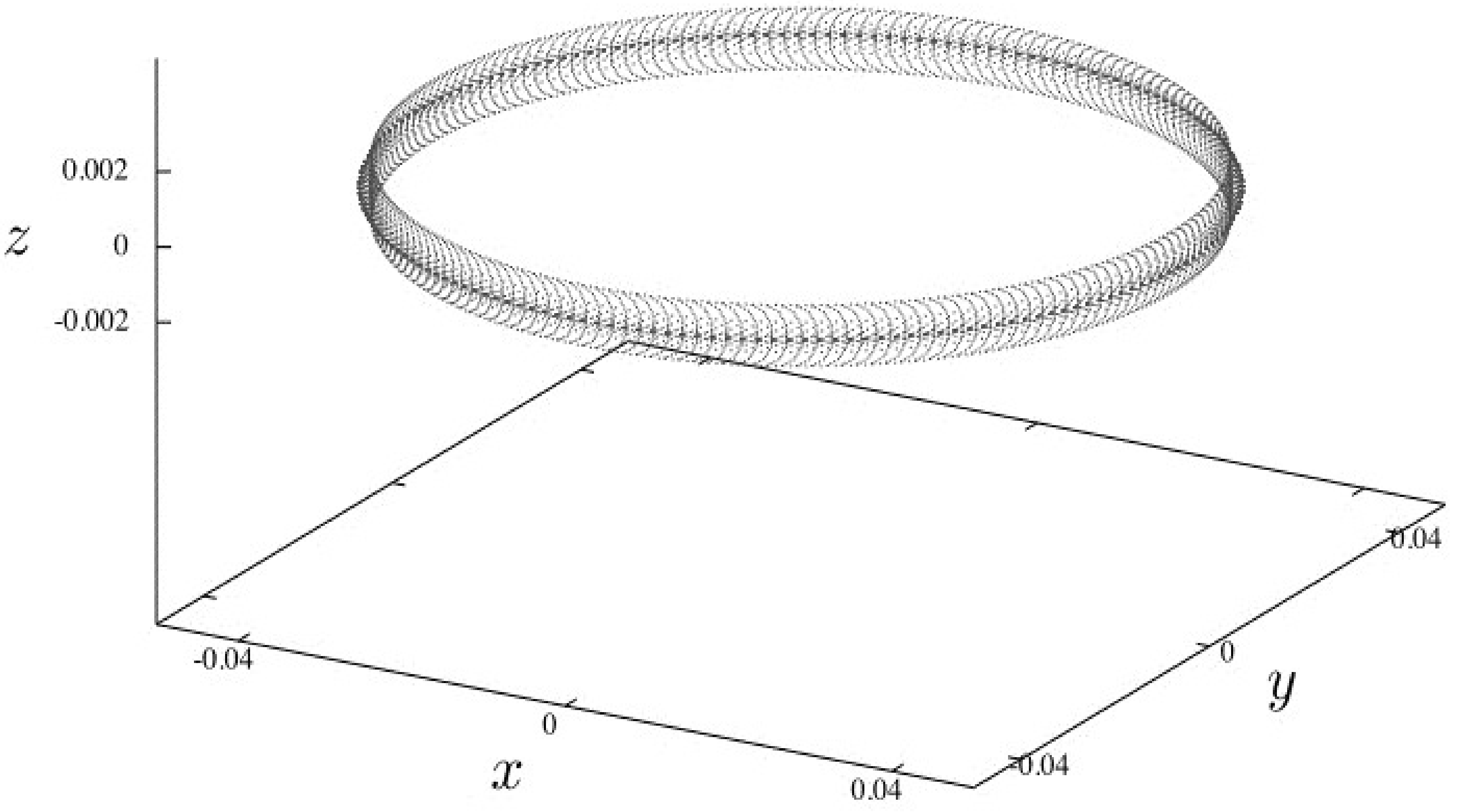
Low Frequency Project

Pierre Sikivie

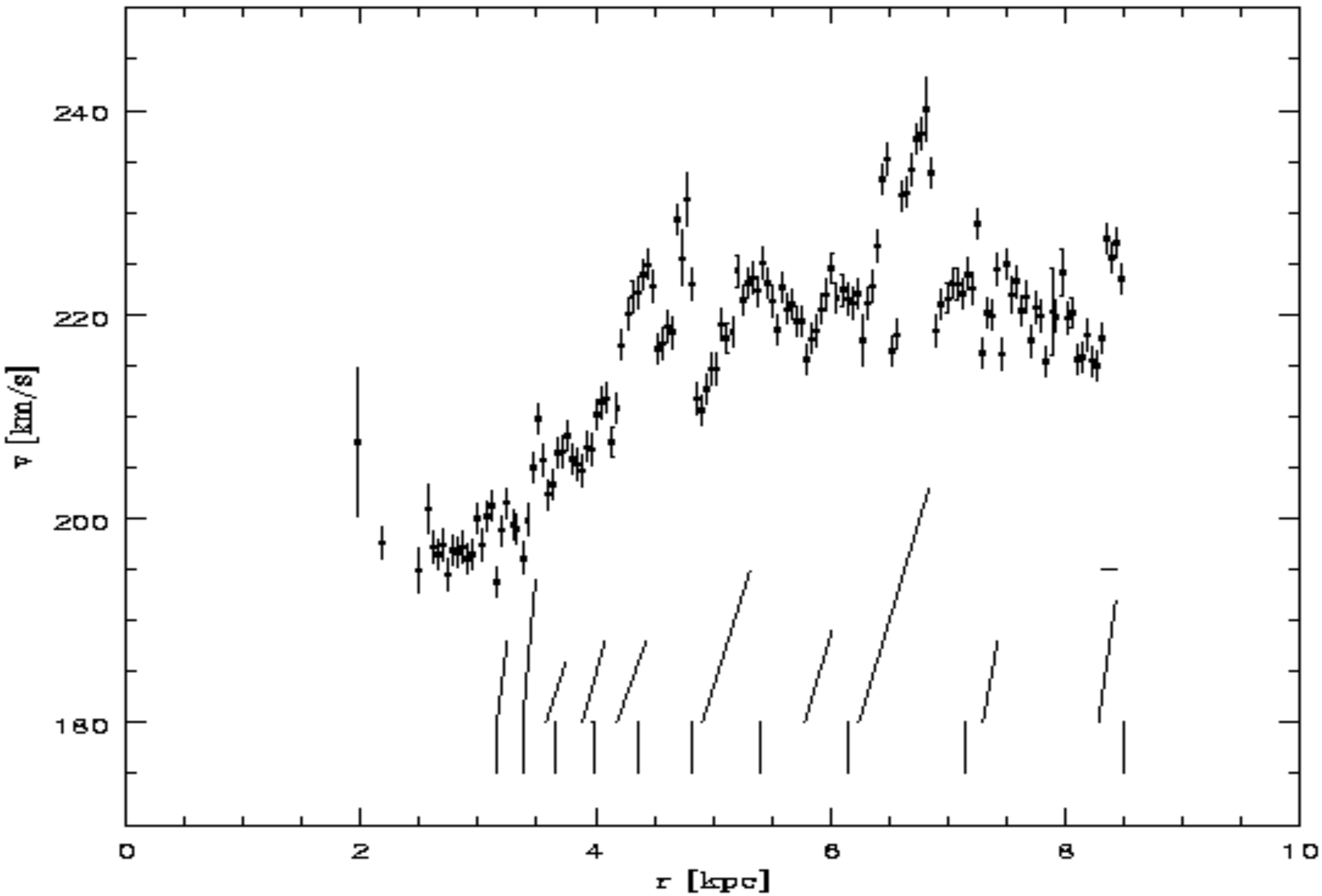
- Motivation
- Reentrant Cavity simulations
- Prototype reentrant cavity

Sankha Chakrabarty
John Clarke
Yaqi Han
Joe Gleason
Alexander Hipp
Stefan Knirck
Mohamed Hassan
Elrina Hartman
Ben McAllister
Mitchell Solano
Andrew Sonnenschein
David Tanner
Michael Tobar
Neil Sullivan

caustic ring

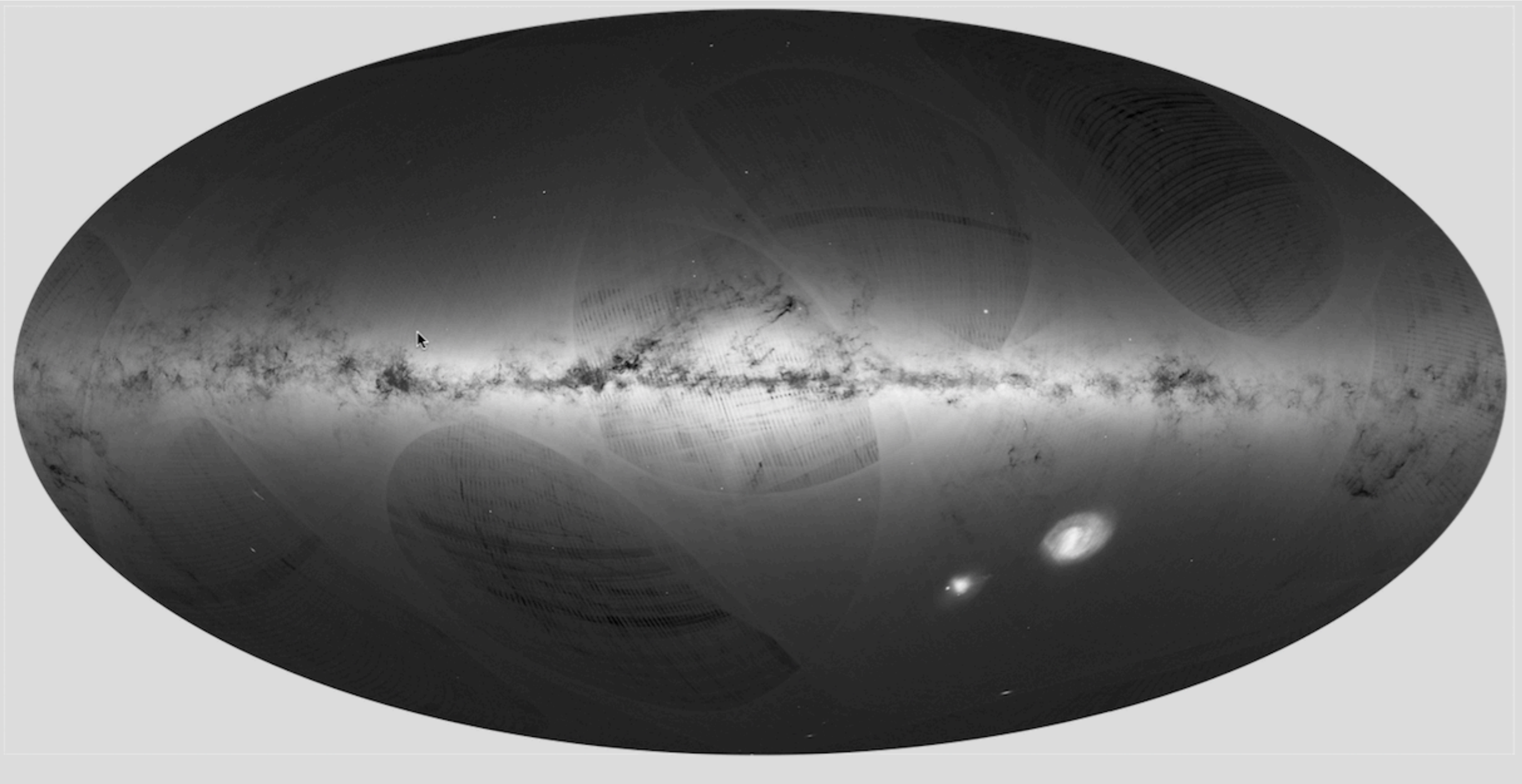


Inner Galactic rotation curve



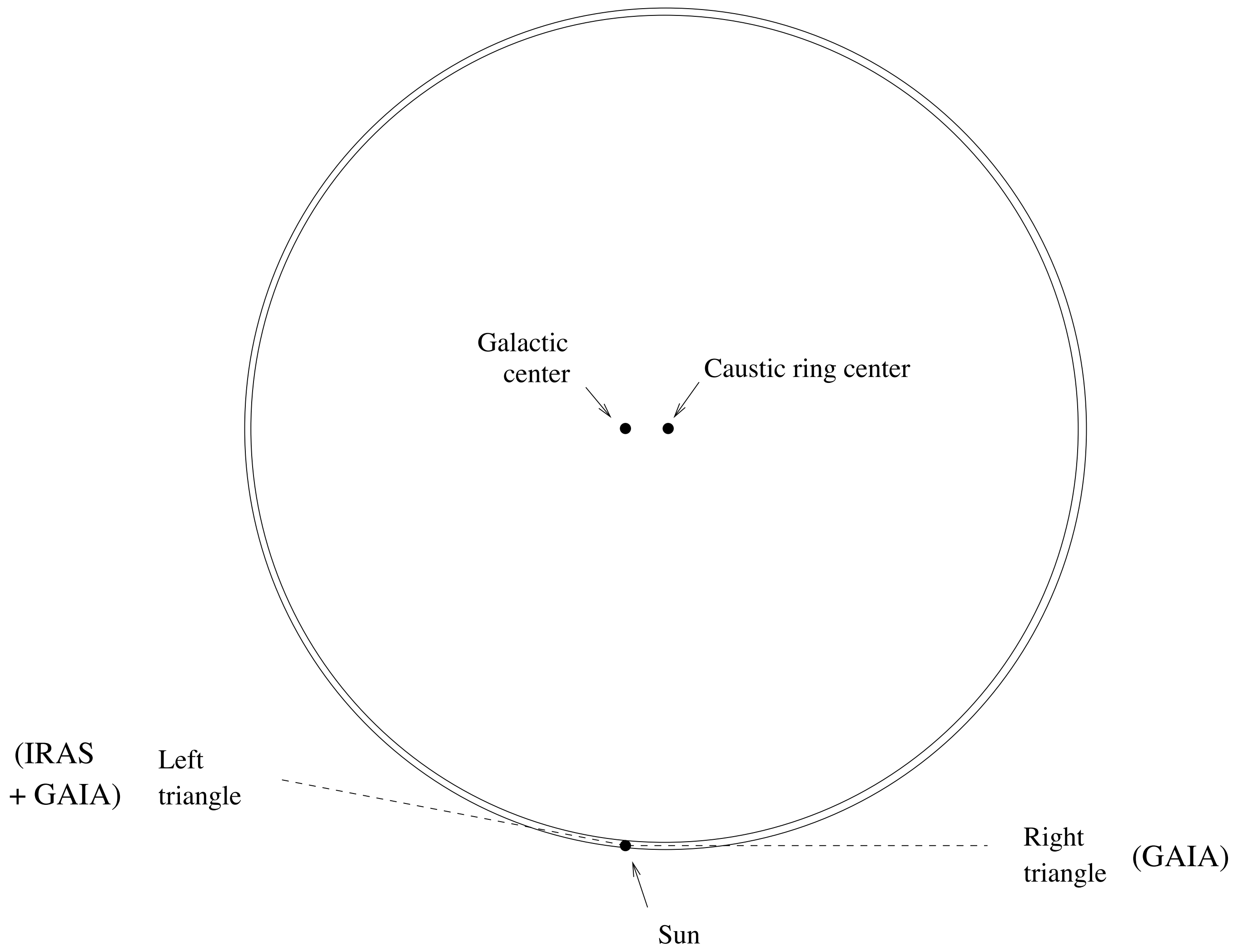
from Massachusetts-Stony Brook North Galactic Pane CO Survey (Clemens, 1985)

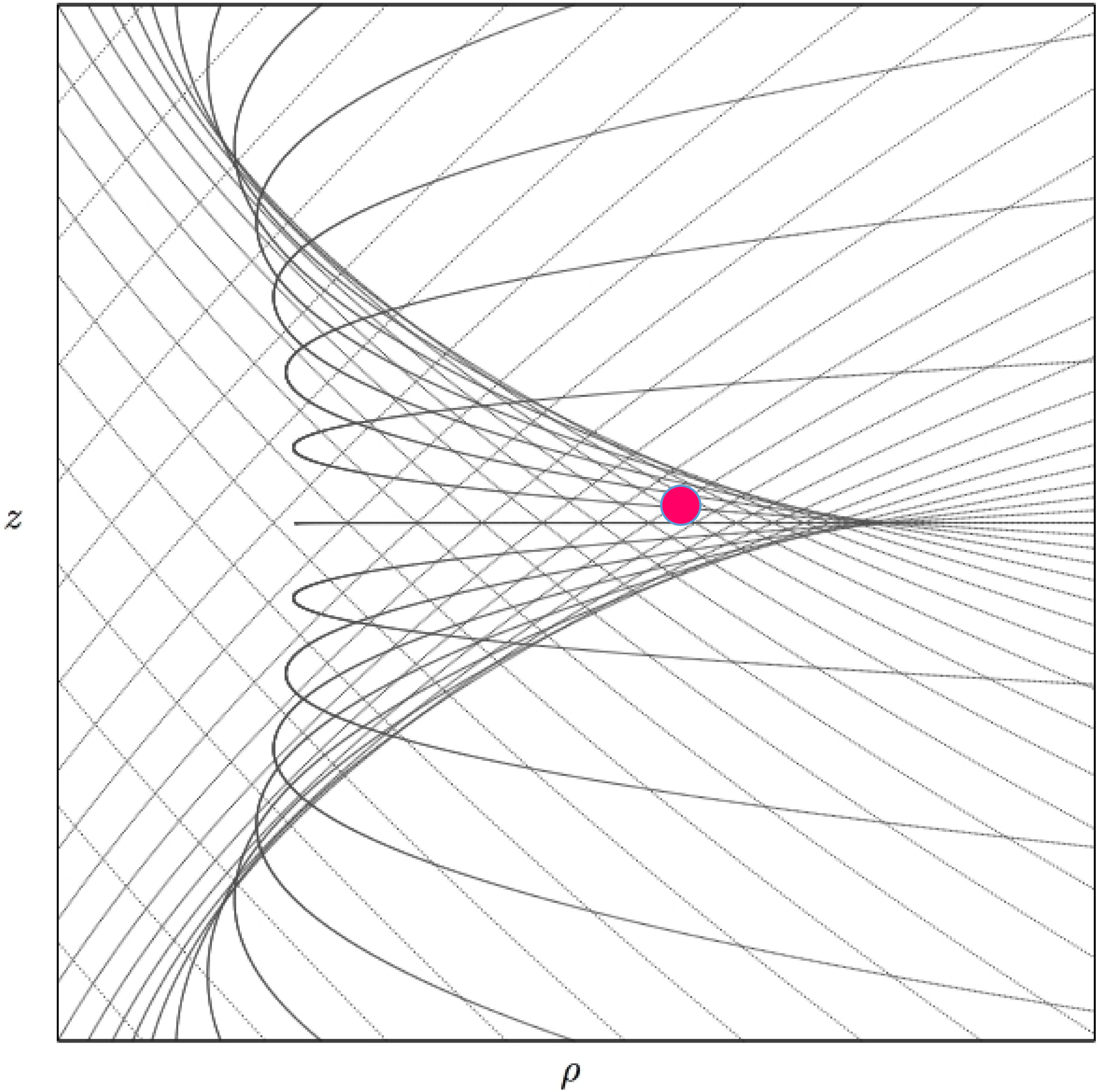
GAIA sky map



L. Duffy and PS, 2008

S. Chakrabarty, Y. Han, A. Gonzalez & PS, 2007.10509





z
ρ

S. Chakrabarty, Y. Han, A. Gonzalez & PS,
2007.10509

with respect to a non-rotating Galactic reference frame

Flow	d [10^{-24} g/cm^3]	v_ρ^G [km/s]	v_ϕ^G [km/s]	v_z^G [km/s]
Big	20.0	−104.4	509.4	6.1
Little	2.0	−0.2	520.0	4.5
Up	9.6	−115.3	505.1	44.8
Down	8.4	−116.4	505.4	−38.1

$\hat{z}$ is toward the North Galactic Pole
$\hat{\phi}$ is in the direction of Galactic rotation
$\hat{\rho}$ is in the direction away from the Galactic Center

Uncertainties on the densities are large but

$$d_{\rm Big} > 10.0 \times 10^{-24} \frac{\rm gr}{\rm cc} = 6 \frac{\rm GeV}{\rm cc}$$

- The evidence for caustic rings requires that the dark matter has vorticity
- Ordinary cold dark matter, such as WIMPs and sterile neutrinos, cannot have vorticity. Their velocity field is curl free.
- Axion dark matter acquires vorticity because it forms a rethermalizing Bose-Einstein condensate. Indeed the lowest energy state for given angular momentum is a state of rotation.

- The axion dark matter fluid first thermalizes (by gravitational self-interactions) and forms a BEC when the universe is approximately 1 year old (Q. Yang and PS, 2009; O. Erken et al., 2012)

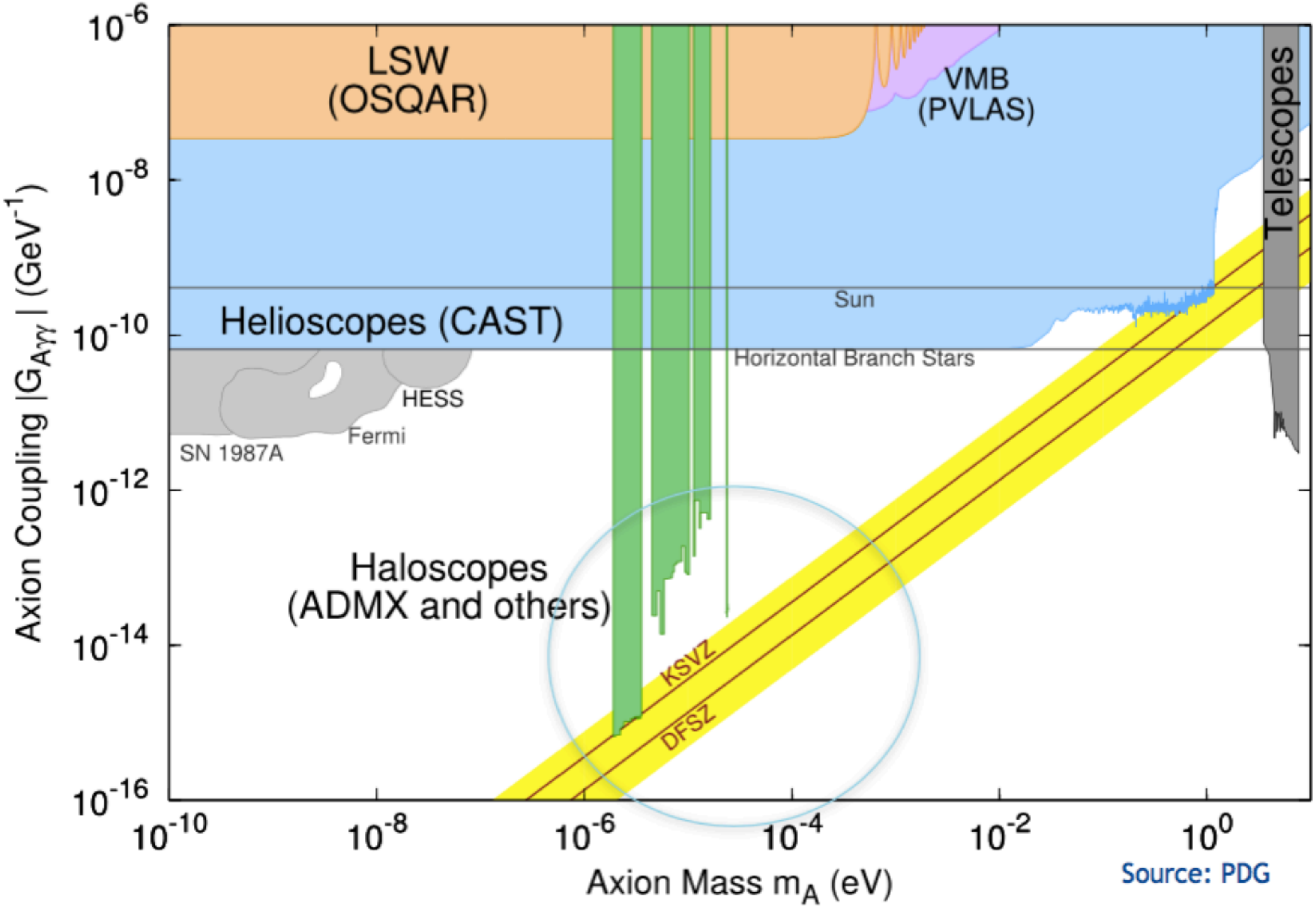
- The horizon at age of one year expands to the size of the largest disk galaxies today.

- Assuming the above is not an accident, we have a new handle on the axion mass.

$$m_a \sim \mu\mathrm{eV}\left(\frac{0.27}{\Omega_a}\right)^{\frac{3}{2}}$$

242 MHz

$$(2\pi)\ 120\ \mathrm{MHz} \lesssim m_a \lesssim (2\pi)\ 3\ \mathrm{GHz}$$



Rybka - ICHEP July 2018

A reentrant cavity search for axion dark matter

ADMX Letter of Intent

August 20, 2020

Abstract:

We propose to search for axion dark matter in the frequency range 100 - 625 MHz ($0.4 < m_a < 2.6$ μeV) using a reentrant cavity haloscope. First a small prototype will be built and tested in data-taking mode inside the magnet of the 1980's UF Axion Project. Based on this experience, a larger reentrant cavity haloscope will be built for the ADMX site at UW and operated there.

Higher Order Reentrant Post Modes in Cylindrical Cavities

Ben T. McAllister,[1, a)] Yifan Shen,[2] Graeme Flower,[1] Stephen R. Parker,[1] and Michael E. Tobar[1, b)]
[1)] *ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, 35 Stirling Highway, Crawley 6009, Western Australia, Australia*
[2)] *Kuang Yaming Honors School, Nanjing University, 22 Hankou Rd, Gulou Qu, Nanjing Shi, Jiangsu Sheng, China, 210000*

(Dated: 4 December 2018)

Reentrant cavities are microwave resonant devices employed in a number of different areas of physics. They are appealing due to their simple frequency tuning mechanism, which offers large tuning ranges. Reentrant cavities are, in essence, 3D lumped LC circuits consisting of a conducting central post embedded in a resonant cavity. The lowest order reentrant mode (which transforms from the TM_{010} mode) has been extensively studied in past publications. In this work we show the existence of higher order reentrant post modes (which transform from the TM_{01n} mode family). We characterize these new modes in terms of their frequency tuning, filling factors and quality factors, as well as discuss some possible applications of these modes in fundamental physics tests. The appendix contains a comment on a paper related to this work.

I. INTRODUCTION

The cylindrical reentrant cavity is a device that can provide high-Q microwave modes with large tuning ranges. It consists of a metal cavity with a conducting post or ring located centrally within the cavity. The gap between the top of this post or ring and the top of the cavity adjusts the mode frequency and at certain gap spacings traps the electric field within the gap. Such cavity designs have been extensively studied and allow for a standard reentrant mode tuning range on the order of GHz without the need for physically large cavities.[1–6]

Since this structure was first investigated in connection with the development of klystrons, it has been widely used in the construction of microwave oscillators and particle accelerators[7,8], and is often chosen as a structure in the study of metamaterials[9,10]. Some recent work has discussed potential applications in telecommunications[11], and detection of gravitational waves[12,13] and dark matter[14]. It is an interesting perspective to view the standard reentrant mode as a perturbed TM_{010} mode. The standard reentrant mode transforms into the empty cavity TM_{010} mode as the central post is removed from the cavity[15]. In a similar way, there exist higher order reentrant modes, which can be viewed as perturbed TM_{01n} modes.

In this work we unequivocally demonstrate the existence of these higher order reentrant modes and characterize them in terms of their tuning range, and quality factor. Section II presents a theoretical study of these modes based on finite element analysis, and experimental data follows in Section III.

II. FINITE ELEMENT ANALYSIS OF THE REENTRANT CAVITY

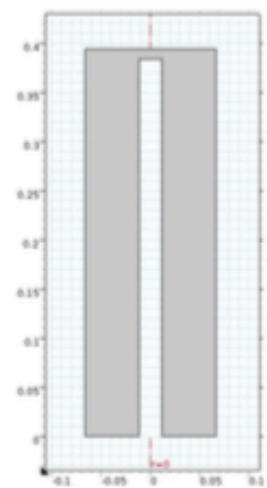
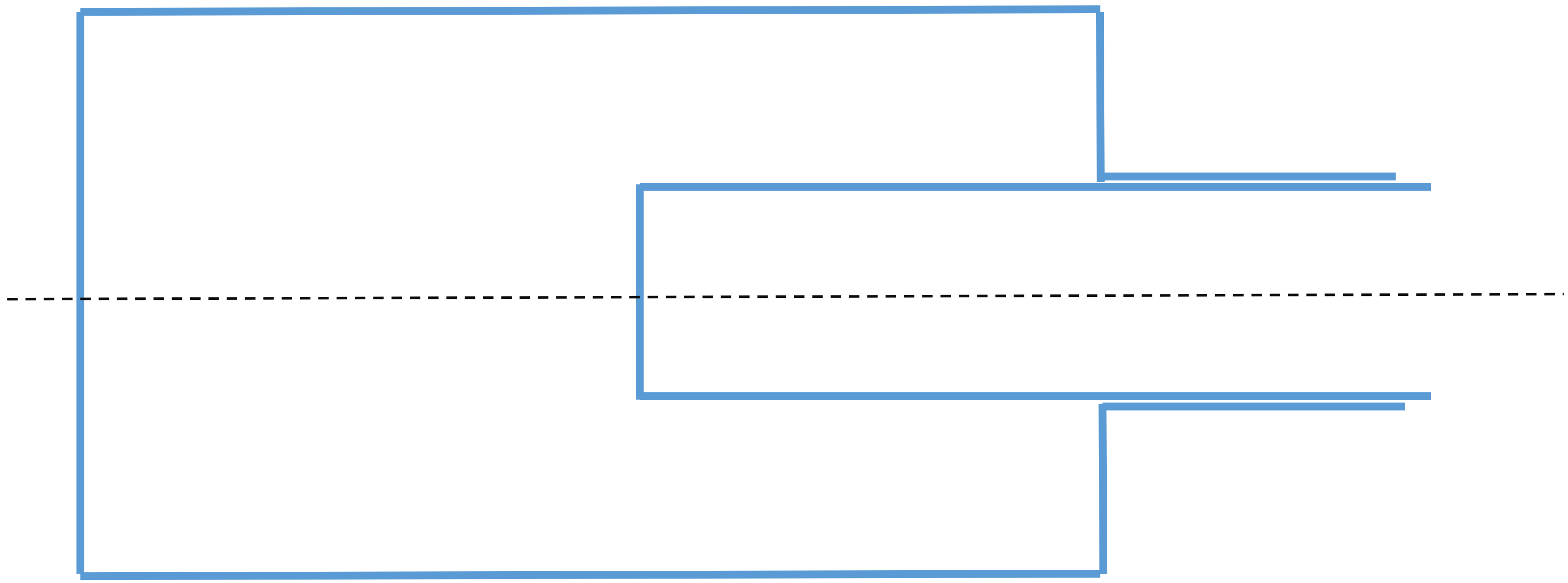
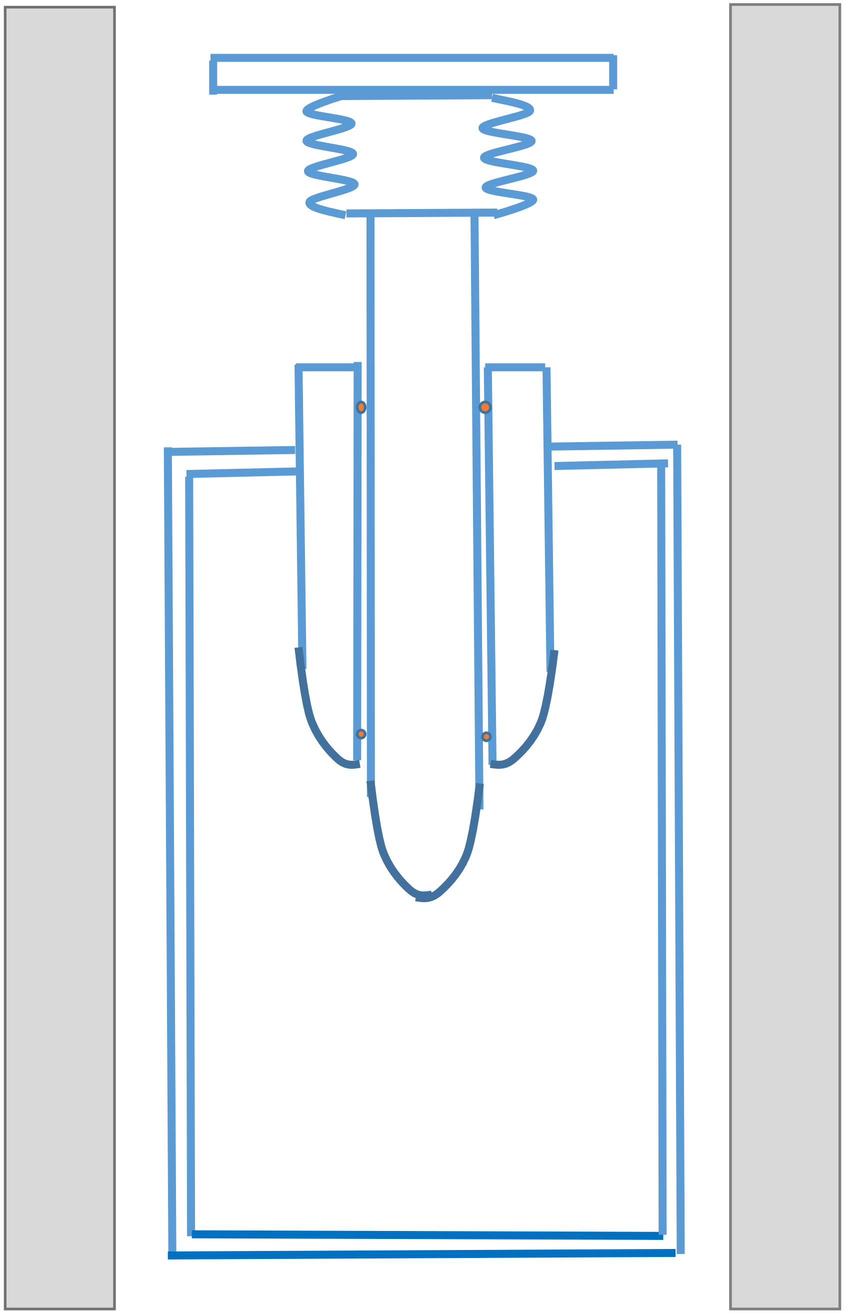


FIG. 1: Cylindrical cross-section of the cavity from the COMSOL model in the r-z plane (encompassing the origin) in cylindrical coordinates. Grey represents the empty cavity space, while the metallic cavity region is represented by grid-lined white area. The height of cavity is ~0.4 m and the diameter of the inner wall is 0.1337 m. The diameter of the central post is 0.024 m.

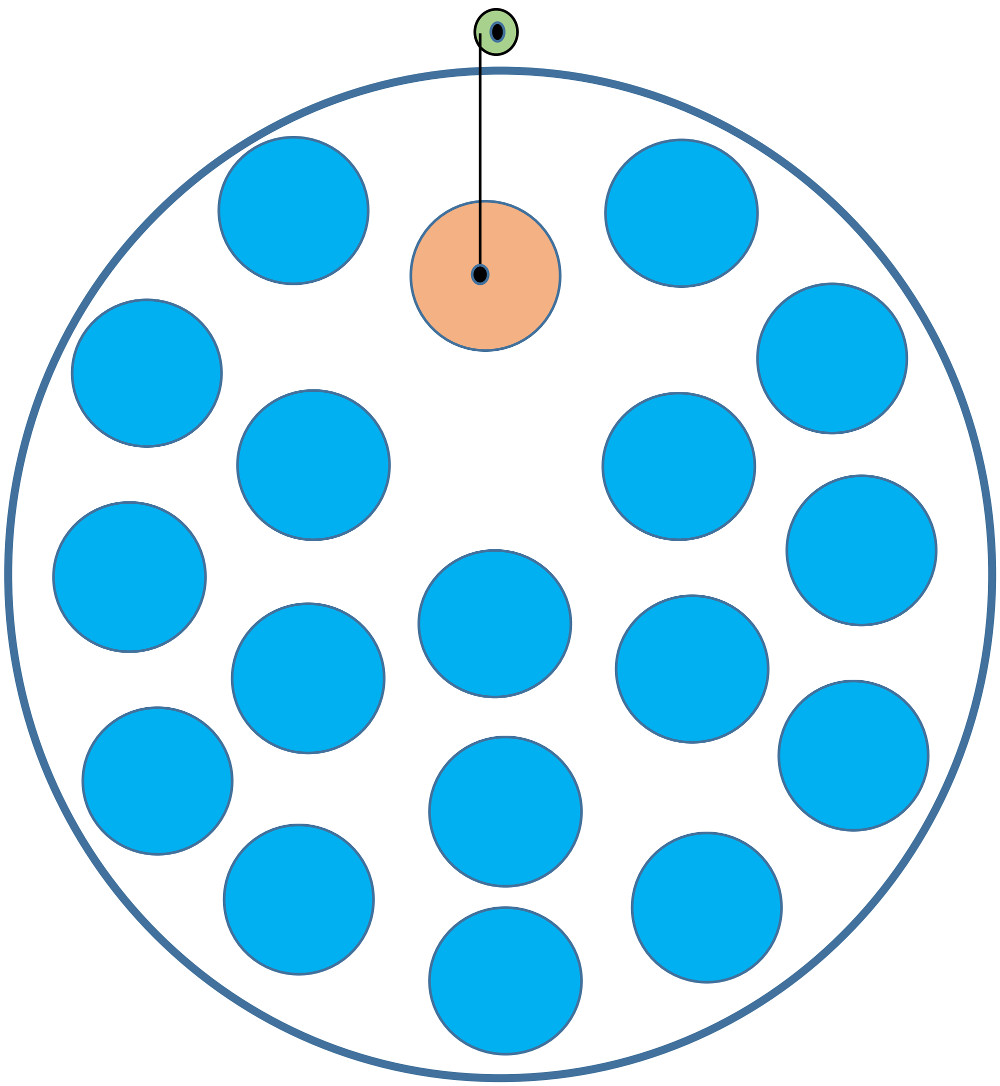
a) Electronic mail: ben.mcallister@uwa.edu.au
b) Electronic mail: michael.tobar@uwa.edu.au

Reentrant Cavity





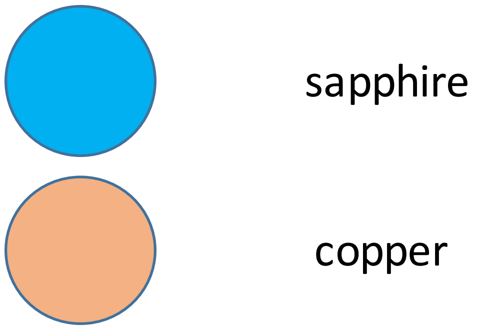
Possible Reentrant Cavity Design



Dielectrically loaded cavity

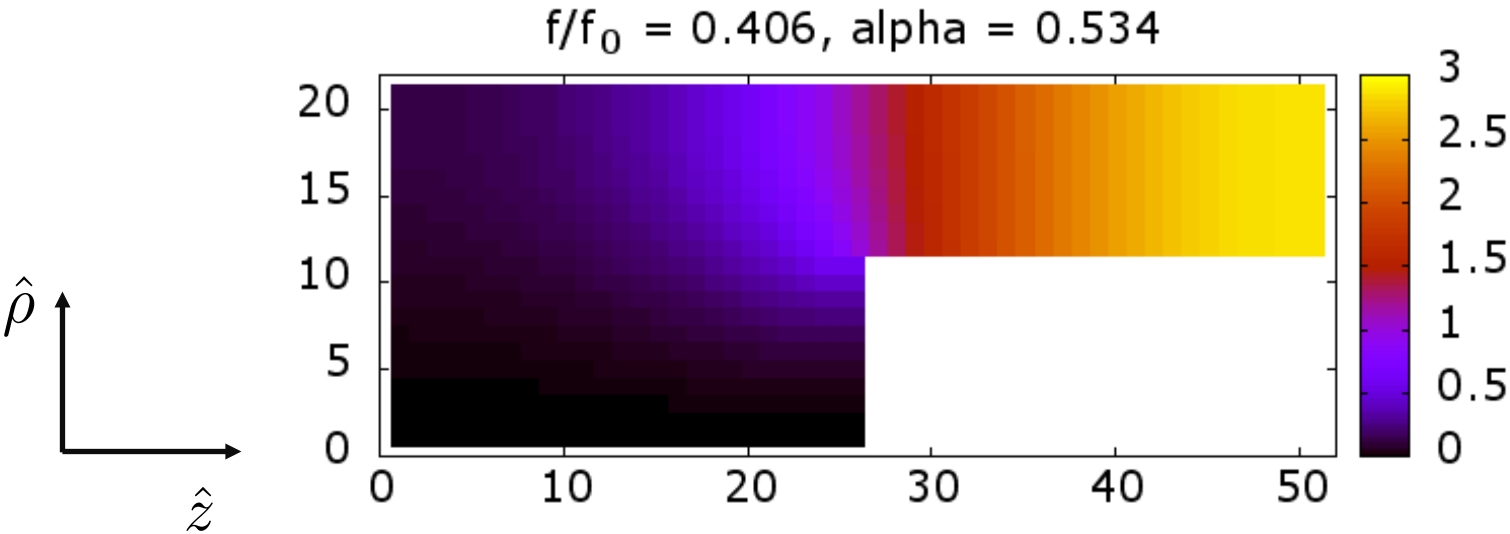
simulations by Mohamed

see Ben’s talk



Axially symmetric reentrant cavities simulations

relax2a2.f, relax2a6.f, relax2a7.f, relax2a8.f, relax2a9.f



$$a(\rho, z) = \rho B(\rho, z)$$

$$\vec{B} = B(\rho, z)\hat{\phi}$$

$$\vec{E} = \frac{i}{\omega}\left[\left(\frac{\partial B}{\partial \rho} + \frac{B}{\rho}\right)\hat{z} - \frac{\partial B}{\partial z}\hat{\rho}\right]$$

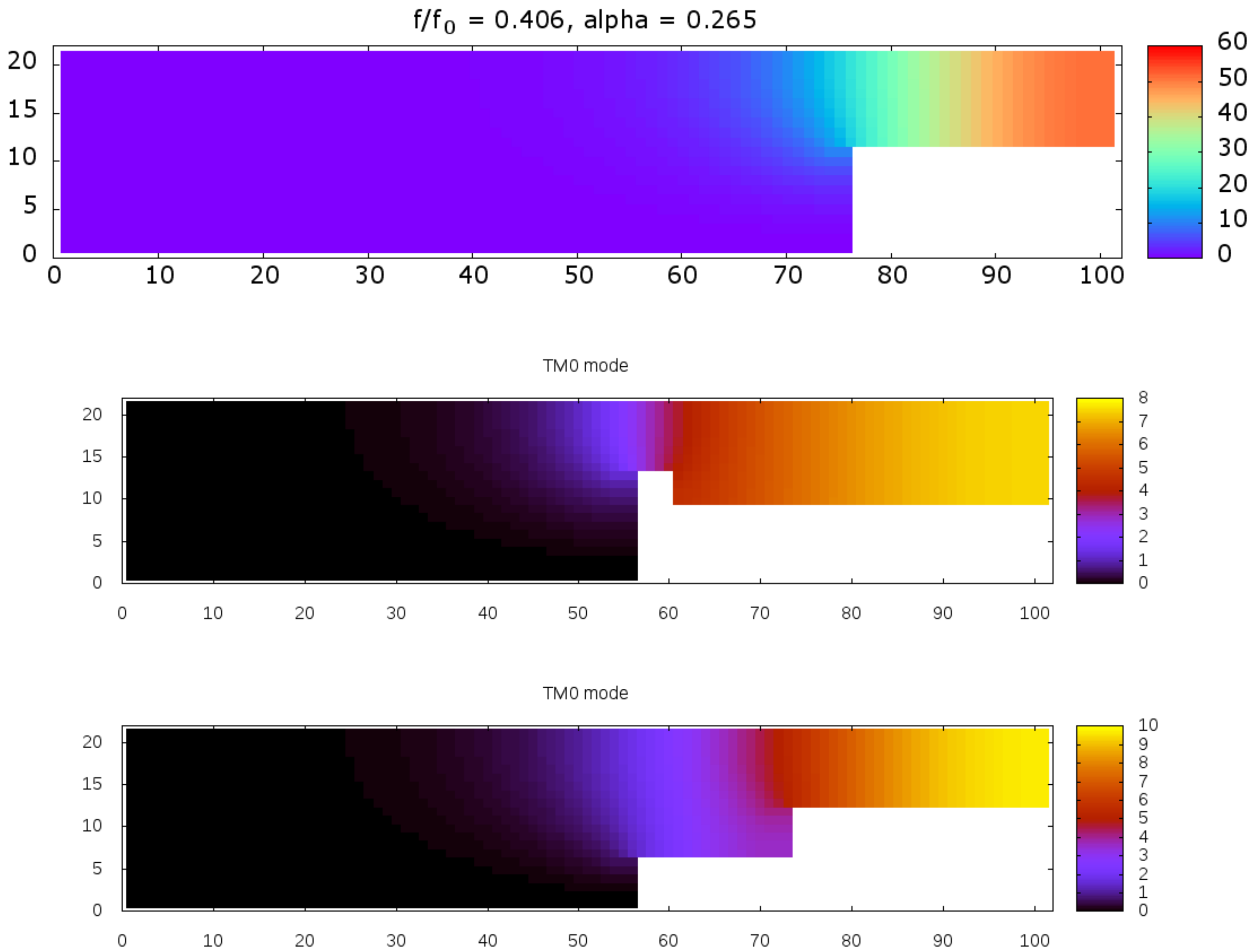
Reentrant Cavity Form factor

$$C(f) = C_0 \left(\frac{f}{f_0}\right)^2 \alpha(\frac{f}{f_0})$$

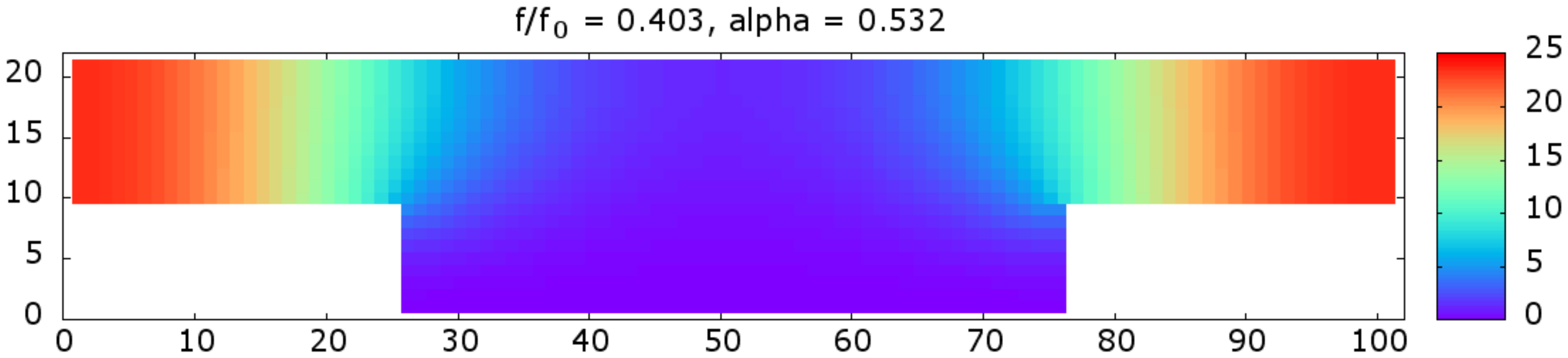
$$C_0 = 0.692 \qquad\qquad f_0 = \frac{2.4048}{2\pi R}$$

$$0.25 \lesssim \alpha \lesssim 0.95$$

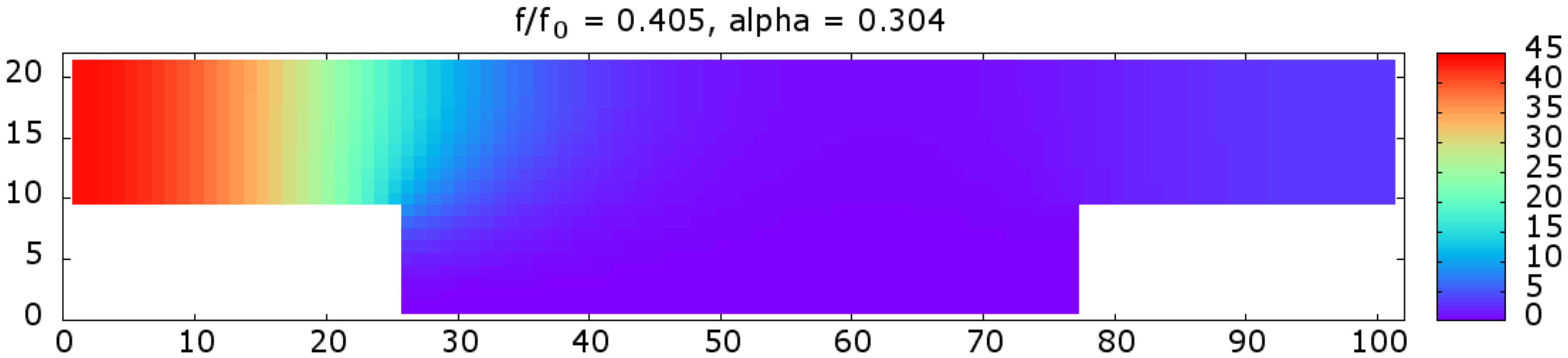
$f = 230$ MHz $f_0 = 570$ MHz $\alpha = 0.4$ $C = 0.045$


f/f0 = 0.406, alpha = 0.265
TM0 mode
TM0 mode

For posts both of length 25 cm:



For posts of lengths 25 cm on the left, 24 cm on the right:



Sensitivity of an ADMX reentrant cavity search

$$P = g^2\rho \; B^2 V \; C \; \frac{1}{m} \; Q$$

$$P = P_0 \; Q$$

$$\frac{d \; log(f)}{dt} = \frac{1}{f} \; \frac{1}{(s/n)^2} \; \left(\frac{P_0}{T_n}\right)^2 \frac{4}{9} \; Q_a \; Q$$

$$\delta v < 70 \text{ m/s} \simeq 2 \times 10^{-7} c$$

$$\frac{\delta f}{f} \sim \frac{v \; \delta v}{c^2} < 2 \times 10^{-10}$$

For example

$$f = 300 \text{ MHz}$$

$$\delta f < 60 \text{ mHz}$$

No mode crossings.

With the ADMX magnet at CENPA, how low can we go?

$$f_0 = 574 \text{ MHz}$$

$$C(f) = 0.4 \left(\frac{f}{f_0}\right)^2$$

$$Q(f) \sim \frac{R}{\delta} \propto f^{\frac{1}{3}}$$

$$T_n \sim f^0 \quad \text{(constant)}$$

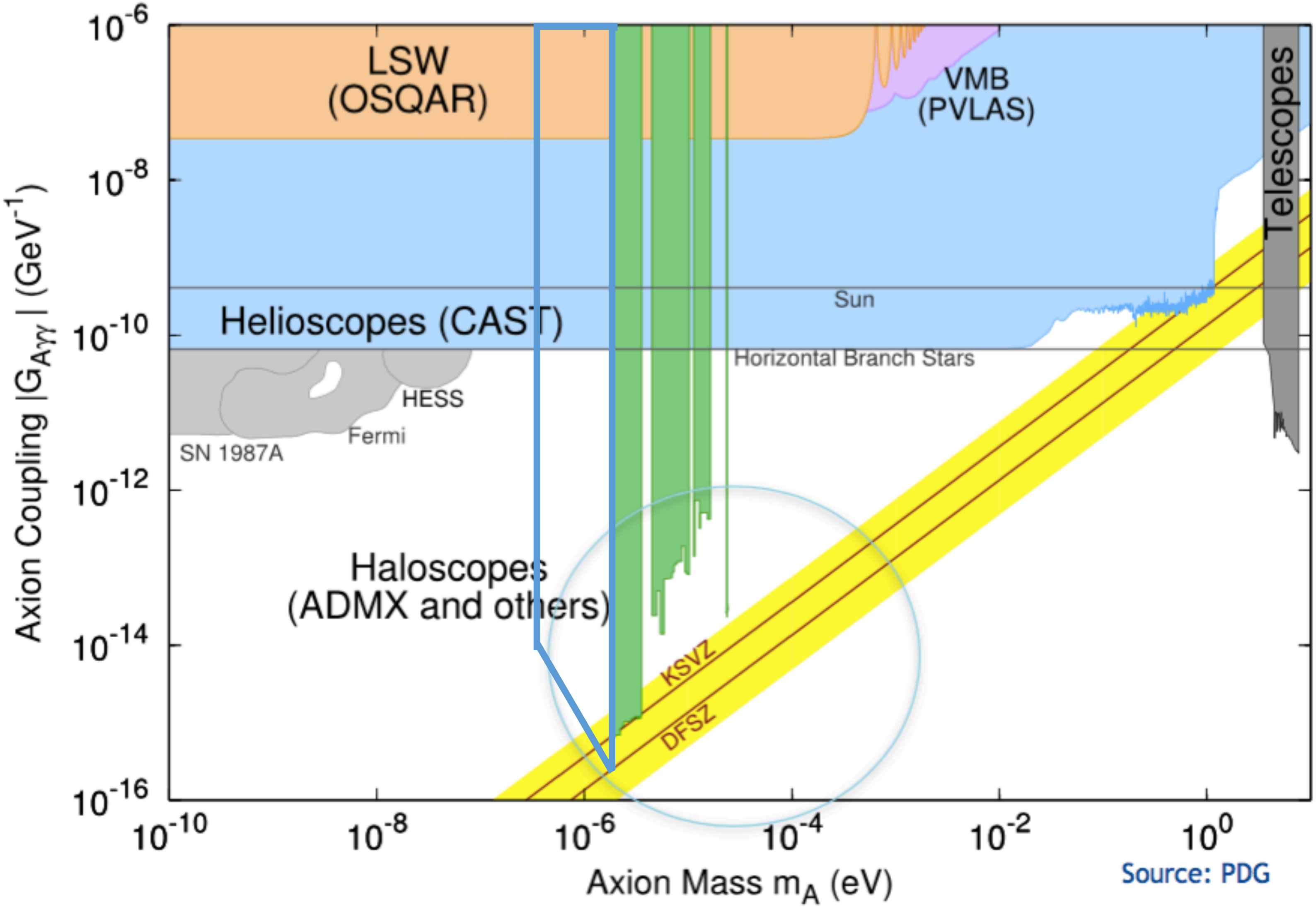
$$\text{sensitivity} \propto \frac{g^2}{m_a}\,\rho\,\frac{\sqrt{Q_a}}{s/n}\,C$$

$$373\left(\frac{f}{f_0}\right)^{2+1+\frac{1}{6}} = 1$$

for Big Flow density of 6 GeV/cc

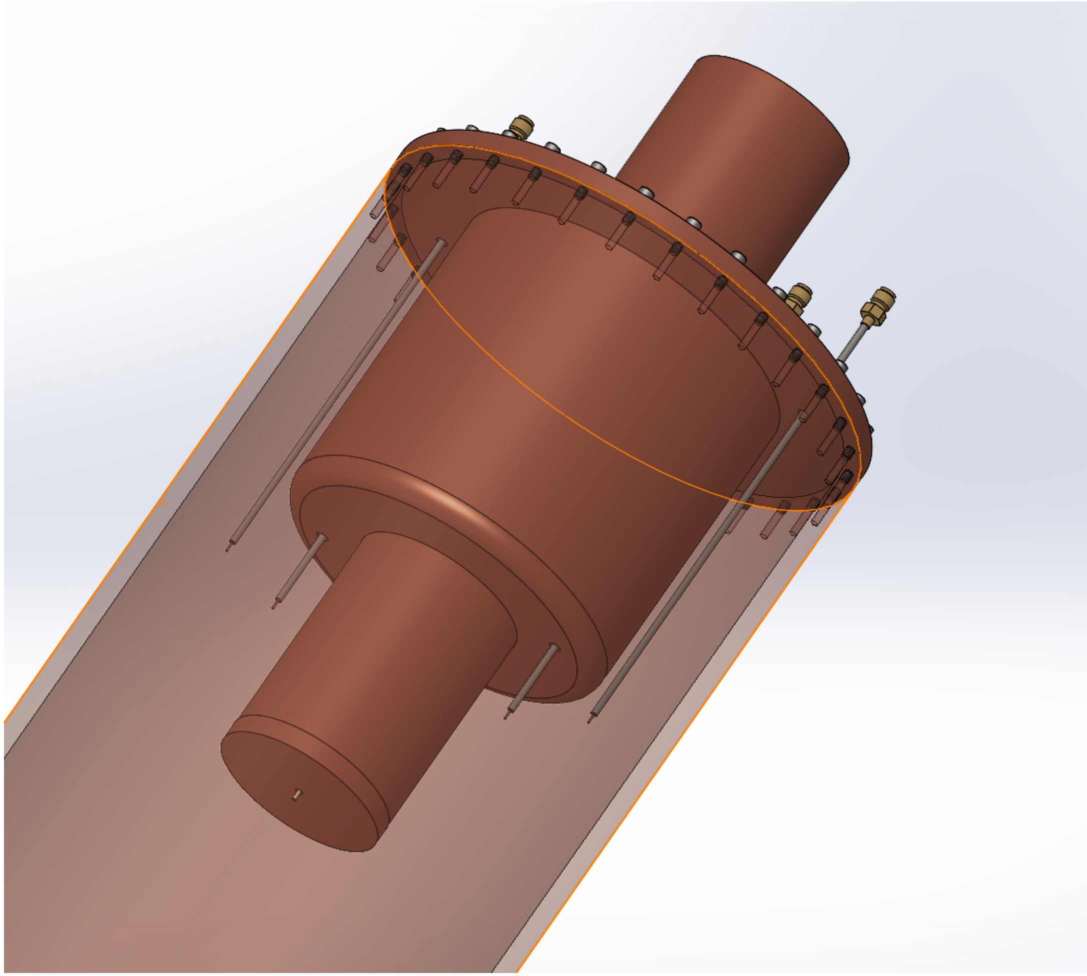
$$f = 88.5\ \text{MHz}$$

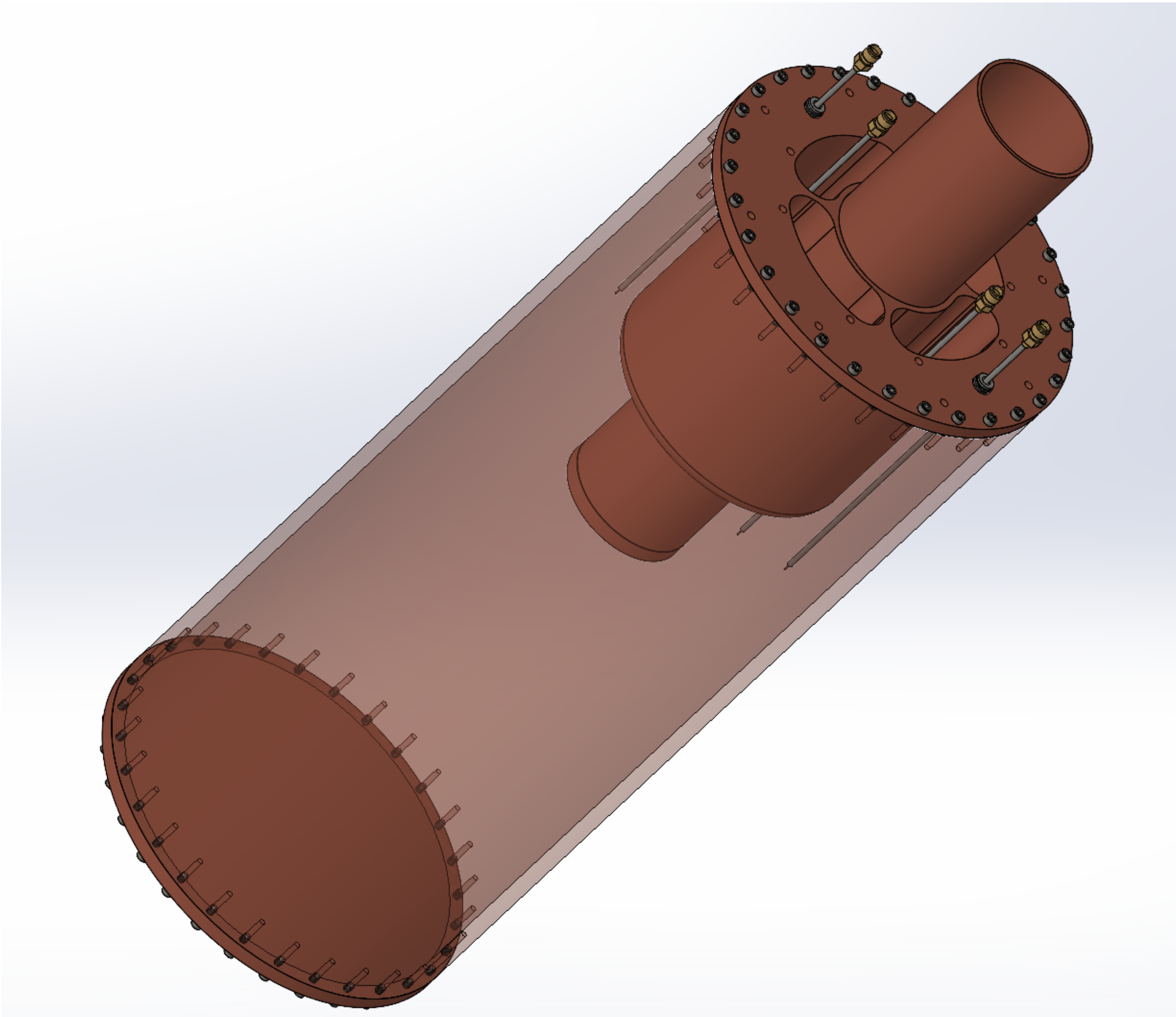
Medres sensitivity for our standard 0.45 GeV/cc density

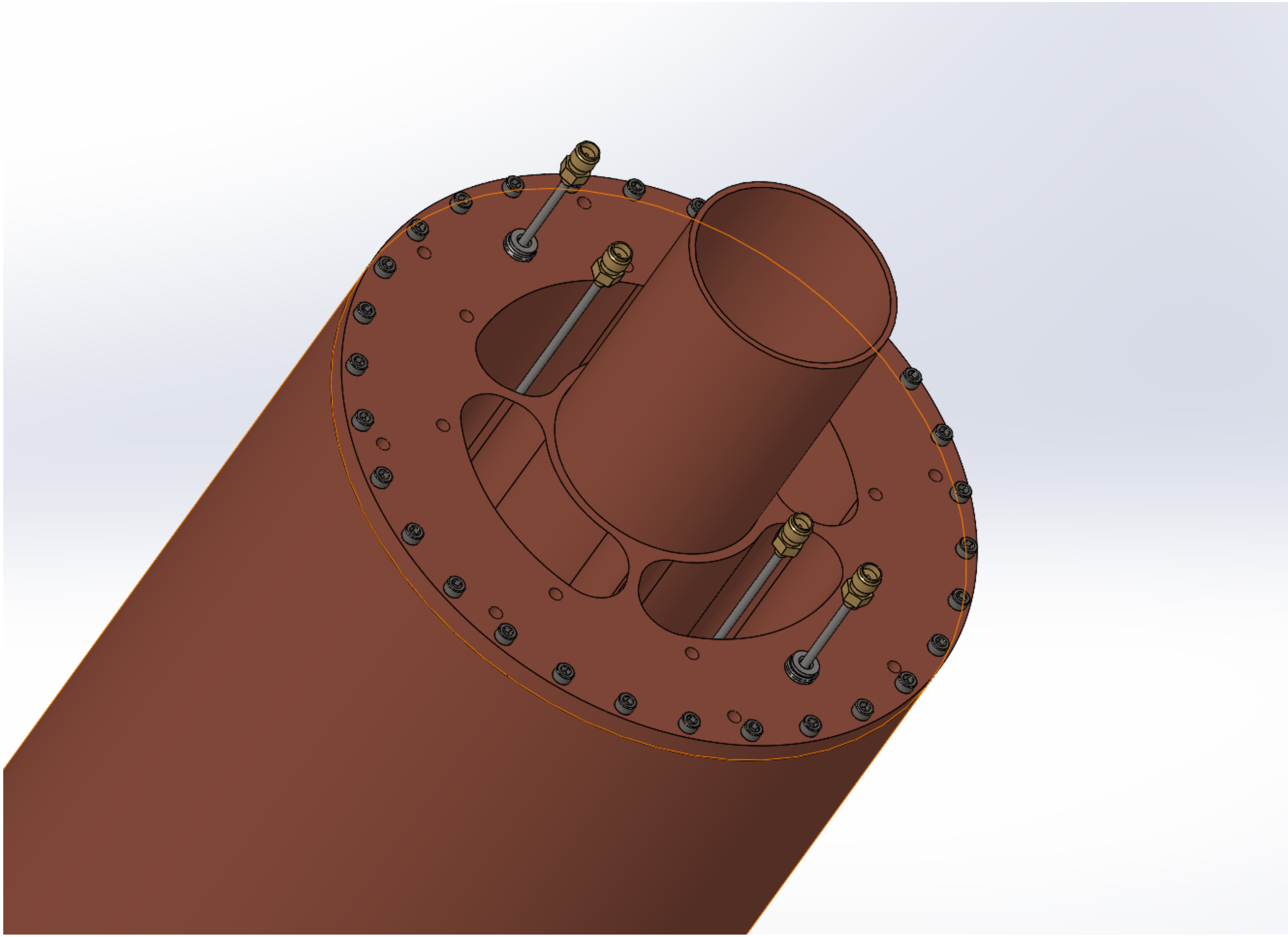


Rybka - ICHEP July 2018

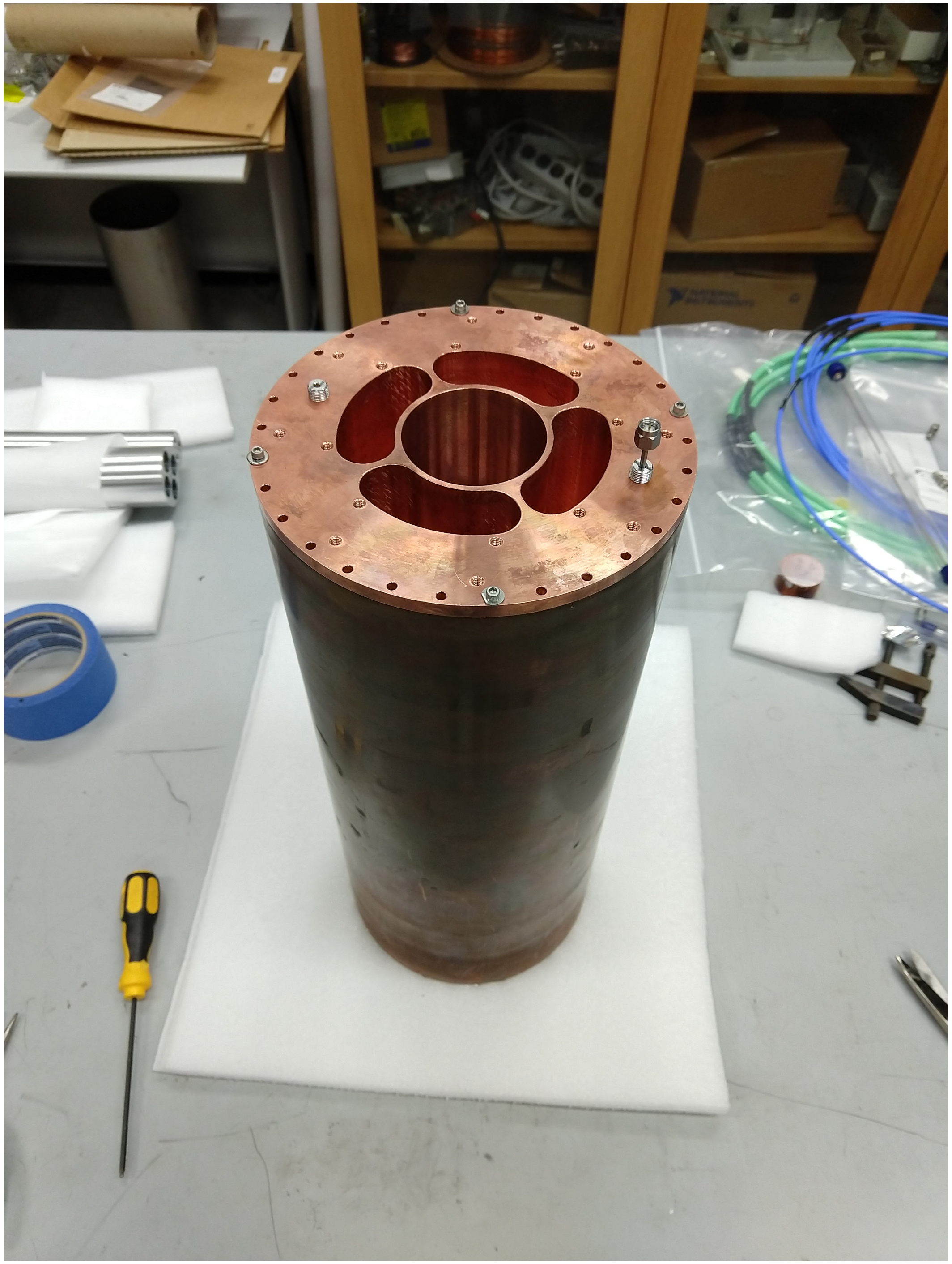
Prototype reentrant cavity design by Joe Gleason

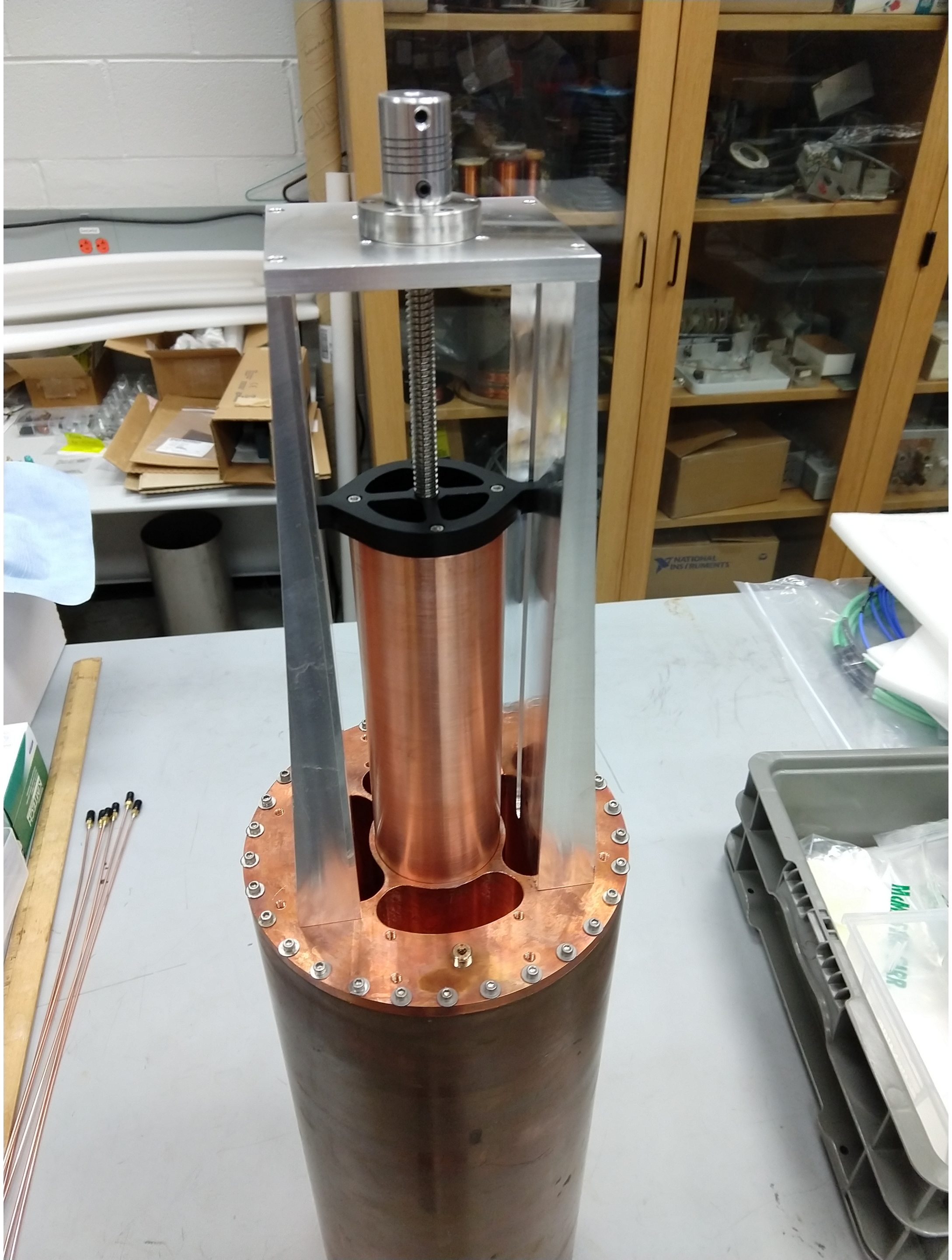


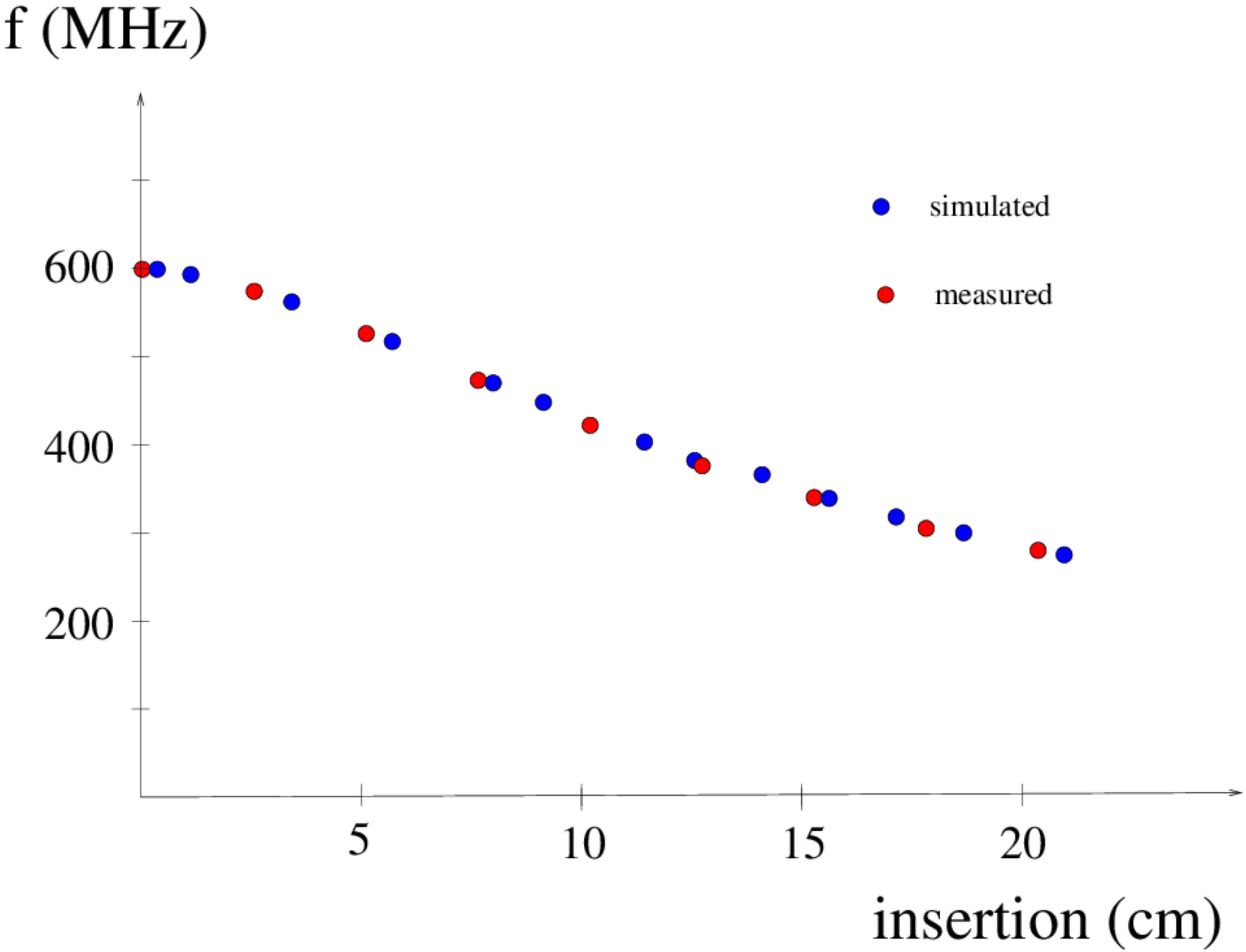


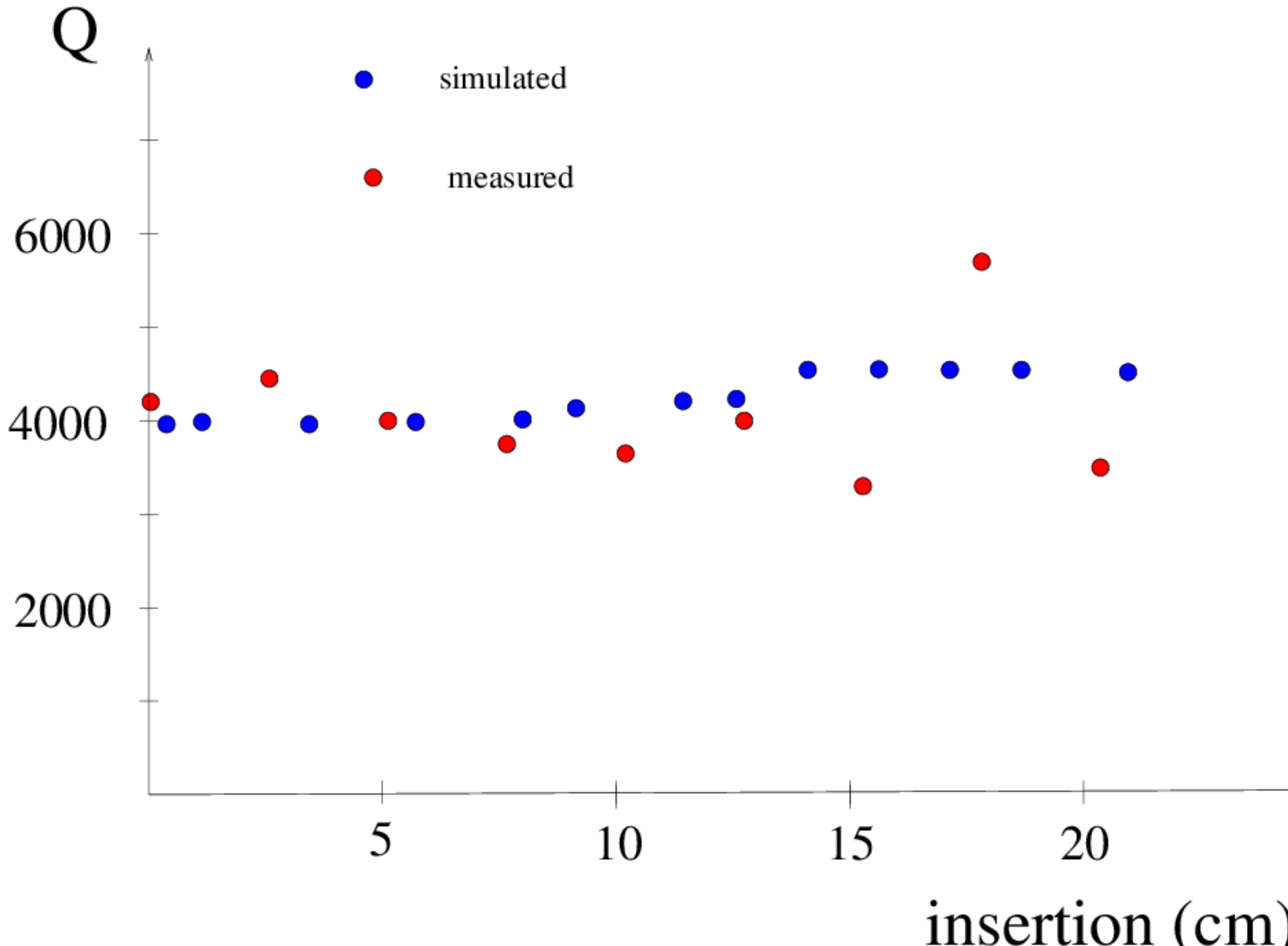


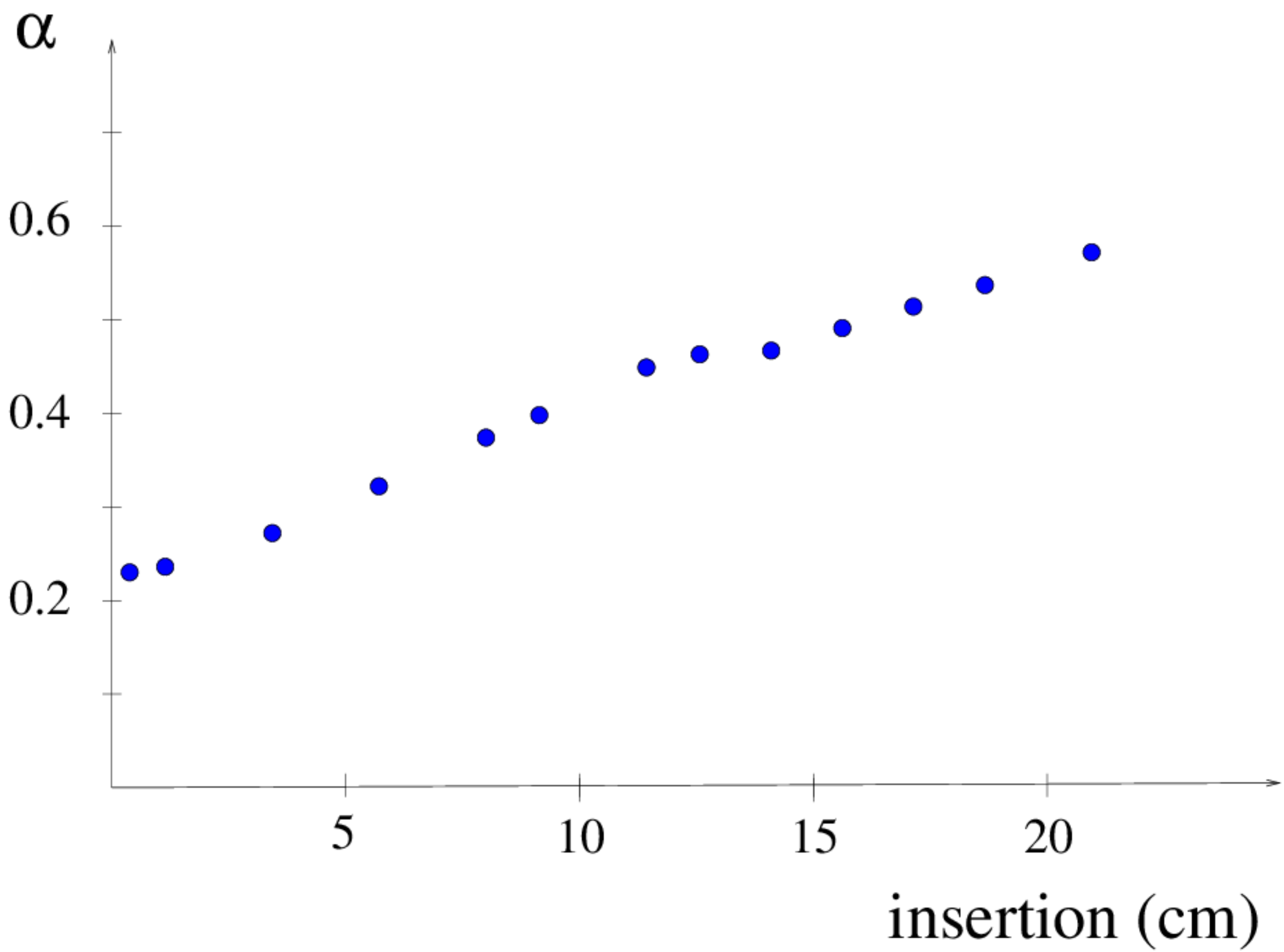

Sontara®
Sontara EC®
engineered-cloth wipers

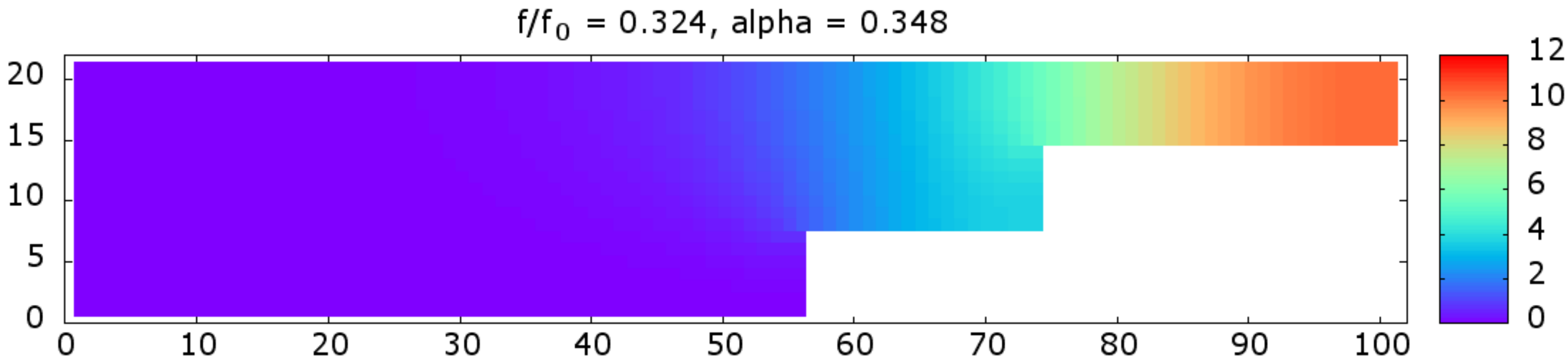


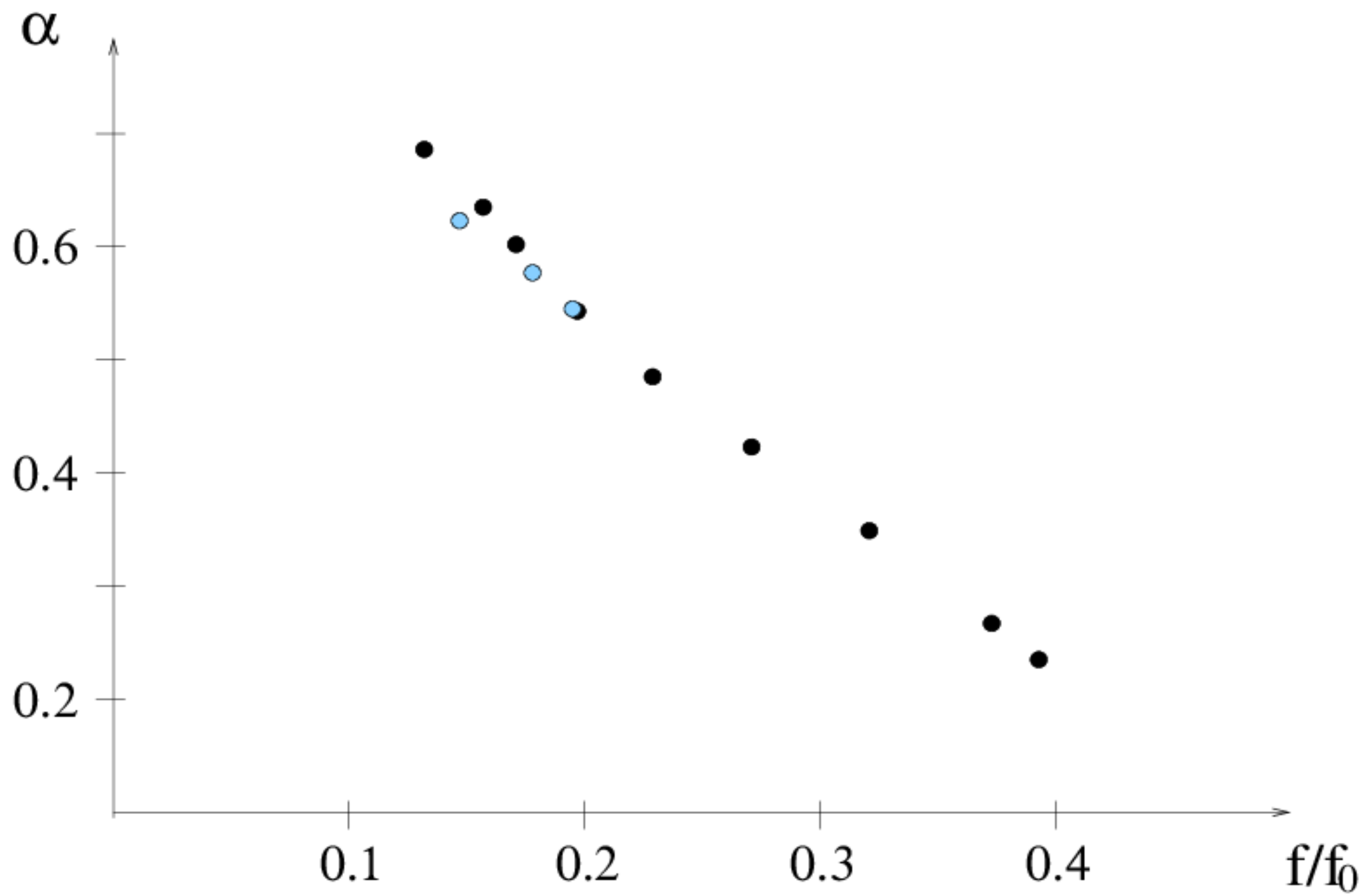

NATIONAL INSTRUMENTS


f (MHz)
600
400
200
simulated
measured
5
10
15
20
insertion (cm)

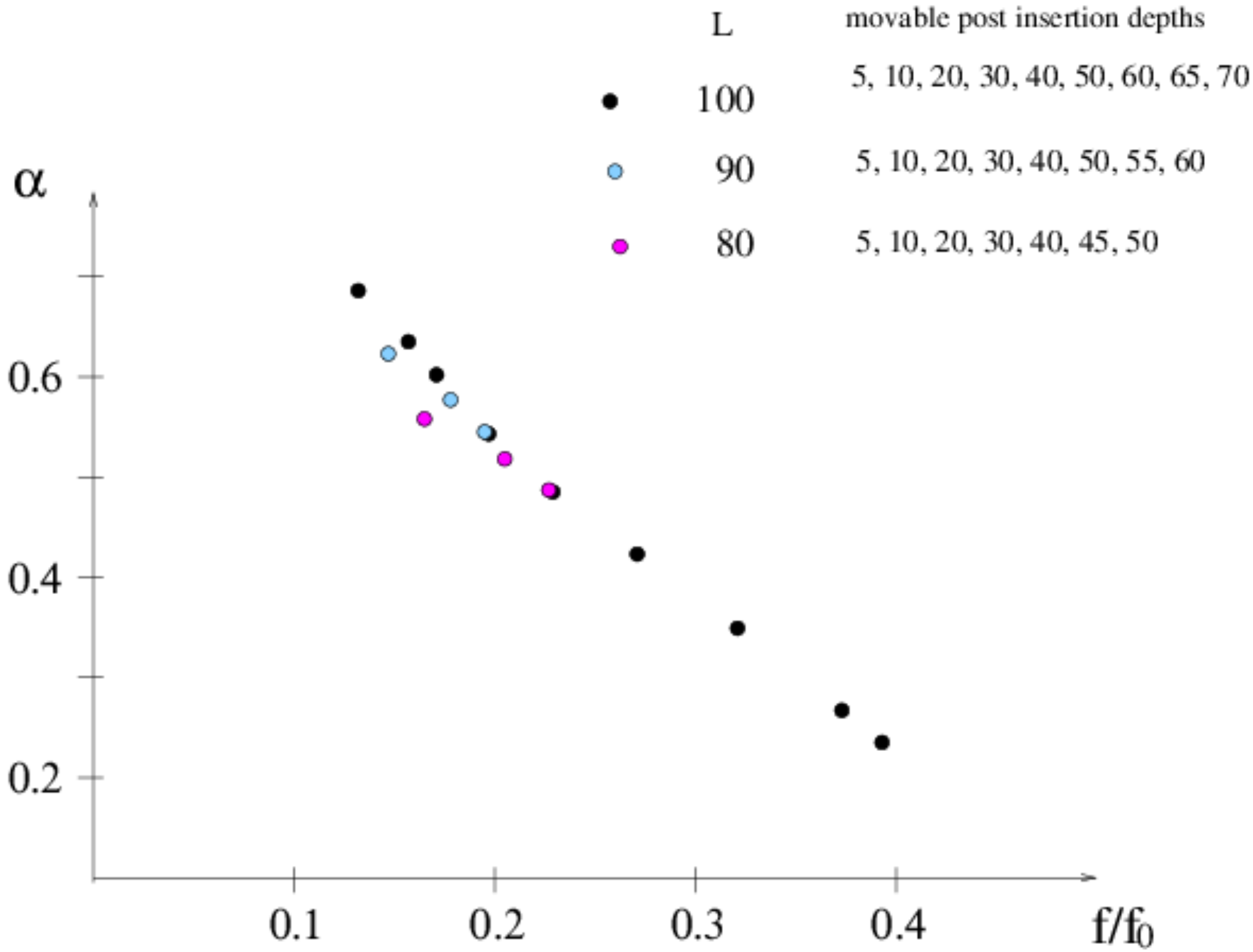

Q
simulated
measured
6000
4000
2000
5
10
15
20
insertion (cm)


α
0.6
0.4
0.2
5
10
15
20
insertion (cm)

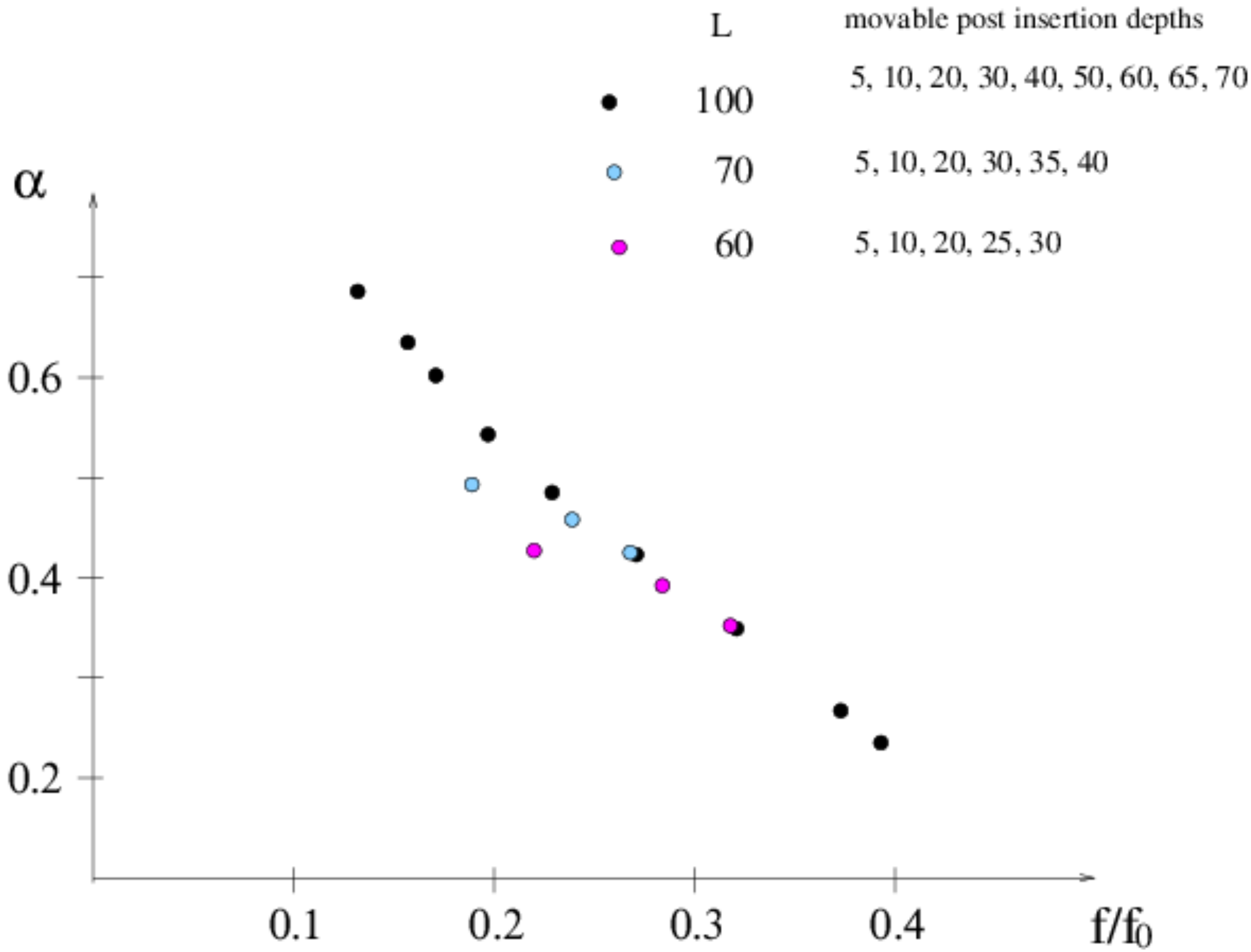

f/f0 = 0.324, alpha = 0.348
0
5
10
15
20
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12



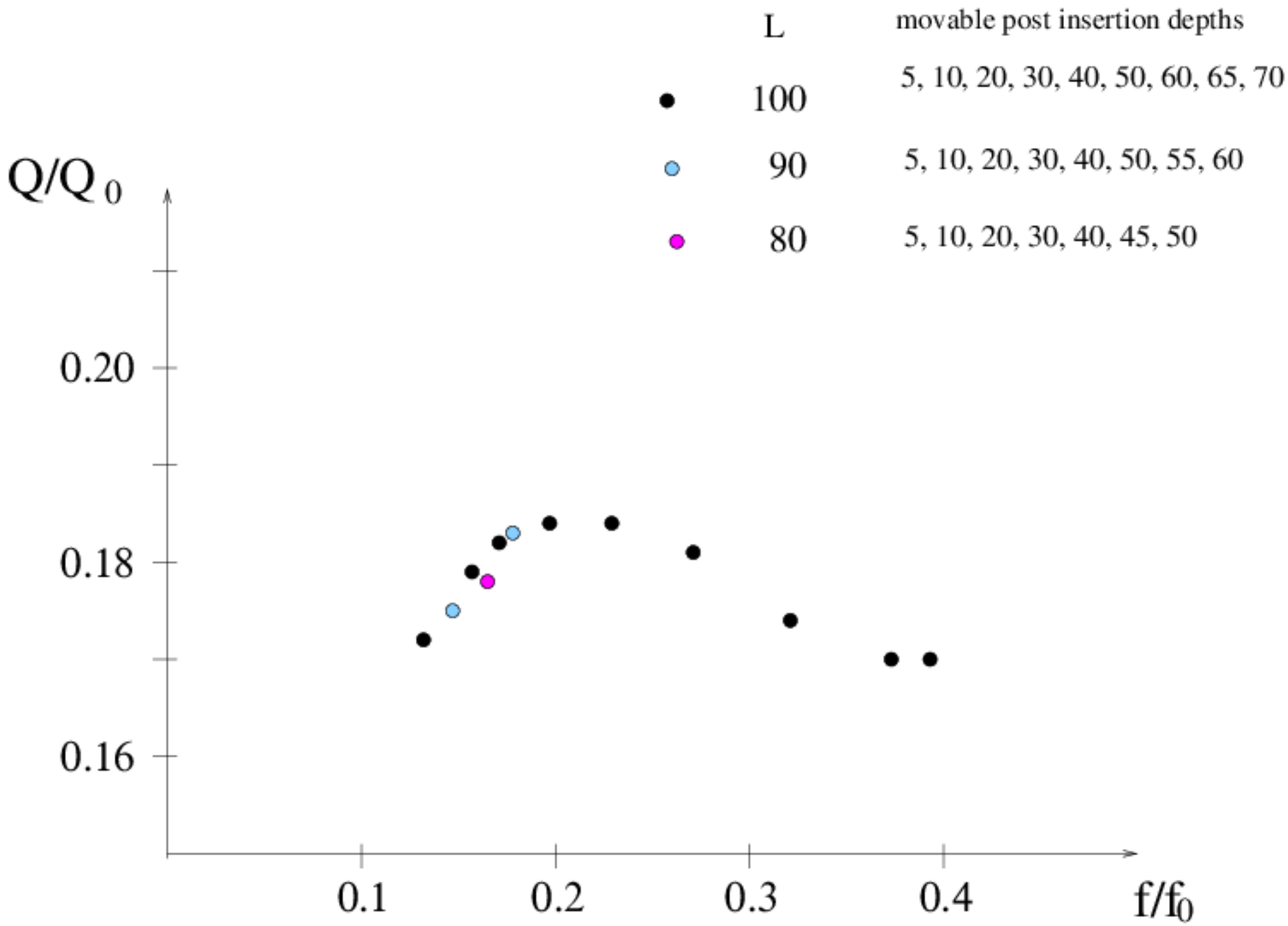
α
0.6
0.4
0.2
0.1
0.2
0.3
0.4
f/f0



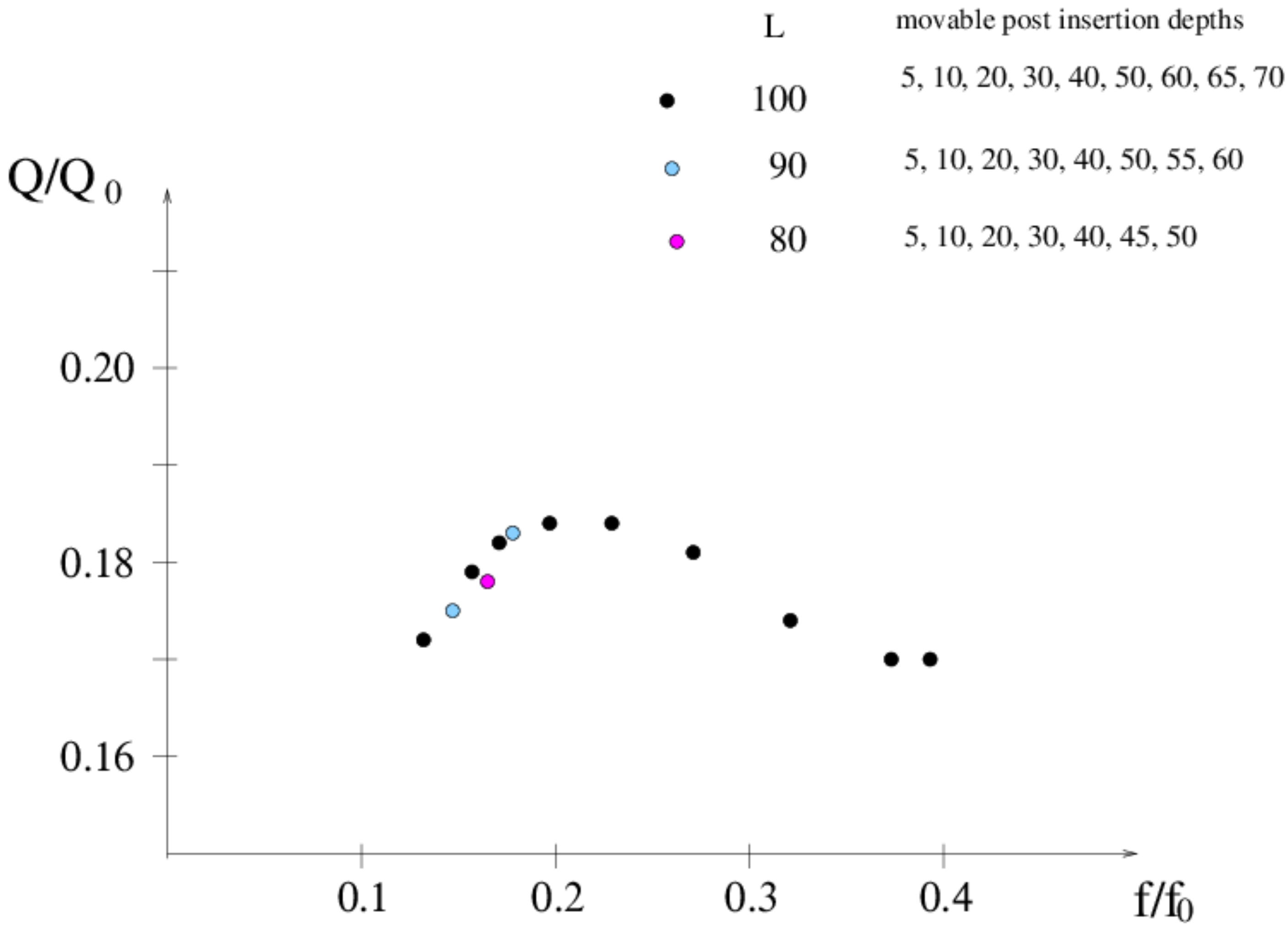
L
movable post insertion depths
100
5, 10, 20, 30, 40, 50, 60, 65, 70
90
5, 10, 20, 30, 40, 50, 55, 60
80
5, 10, 20, 30, 40, 45, 50
α
0.6
0.4
0.2
0.1
0.2
0.3
0.4
f/f0

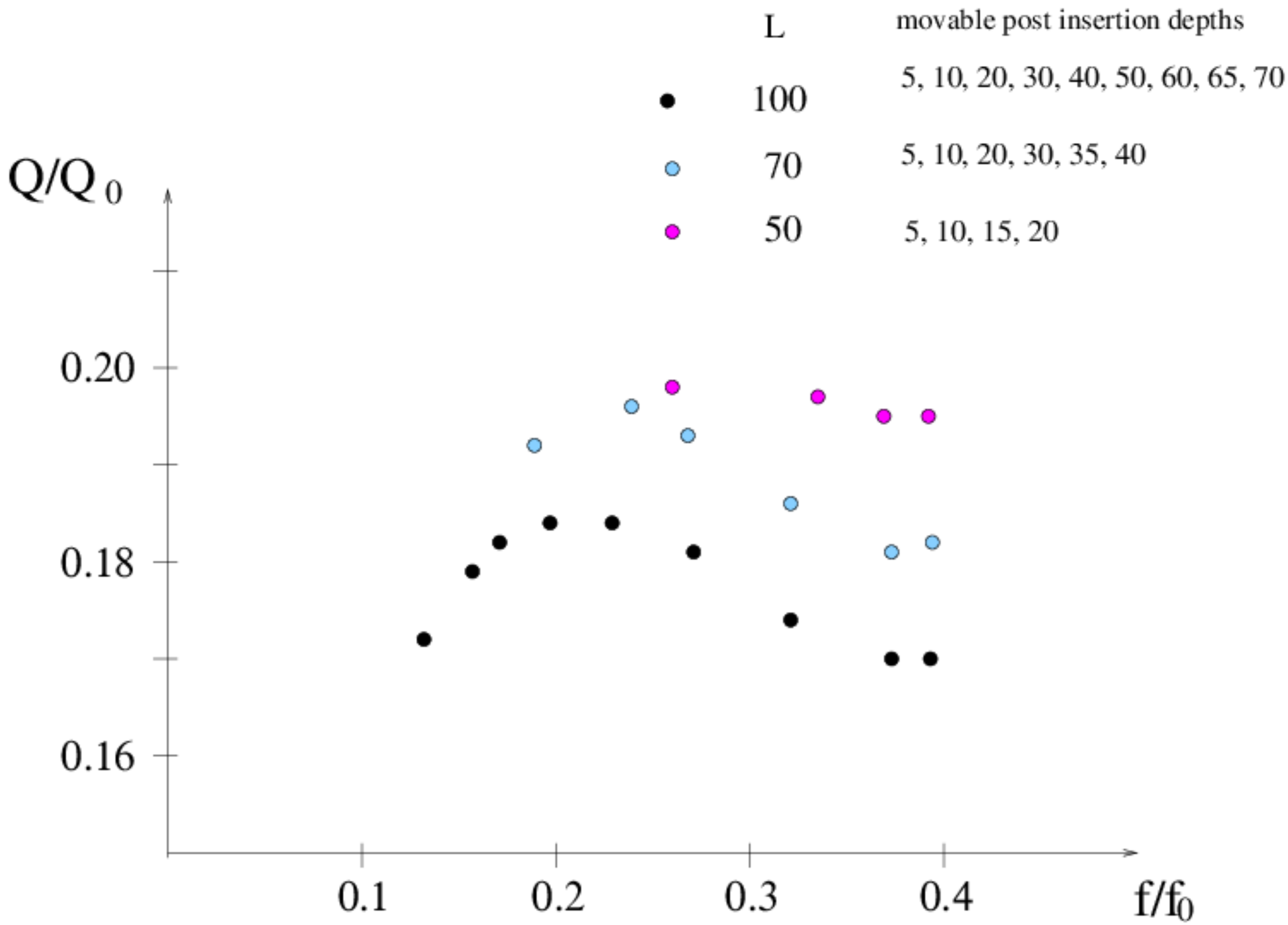


L
movable post insertion depths
100
5, 10, 20, 30, 40, 50, 60, 65, 70
70
5, 10, 20, 30, 35, 40
60
5, 10, 20, 25, 30
α
0.6
0.4
0.2
0.1
0.2
0.3
0.4
f/f0



L
movable post insertion depths
100
5, 10, 20, 30, 40, 50, 60, 65, 70
90
5, 10, 20, 30, 40, 50, 55, 60
80
5, 10, 20, 30, 40, 45, 50
Q/Q 0
0.20
0.18
0.16
0.1
0.2
0.3
0.4
f/f0


L
movable post insertion depths
100
5, 10, 20, 30, 40, 50, 60, 65, 70
90
5, 10, 20, 30, 40, 50, 55, 60
80
5, 10, 20, 30, 40, 45, 50
Q/Q 0
0.20
0.18
0.16
0.1
0.2
0.3
0.4
f/f0



L
movable post insertion depths
100
5, 10, 20, 30, 40, 50, 60, 65, 70
70
5, 10, 20, 30, 35, 40
50
5, 10, 15, 20
Q/Q 0
0.20
0.18
0.16
0.1
0.2
0.3
0.4
f/f0

Conclusion:

a low frequency search
is “low lying fruit”

Thank you