NOVEL SPIRAL TUNING TECHNIQUE FOR METAMATERIAL BASED CAVITY IN AXION DARK MATTER SEARCHES.

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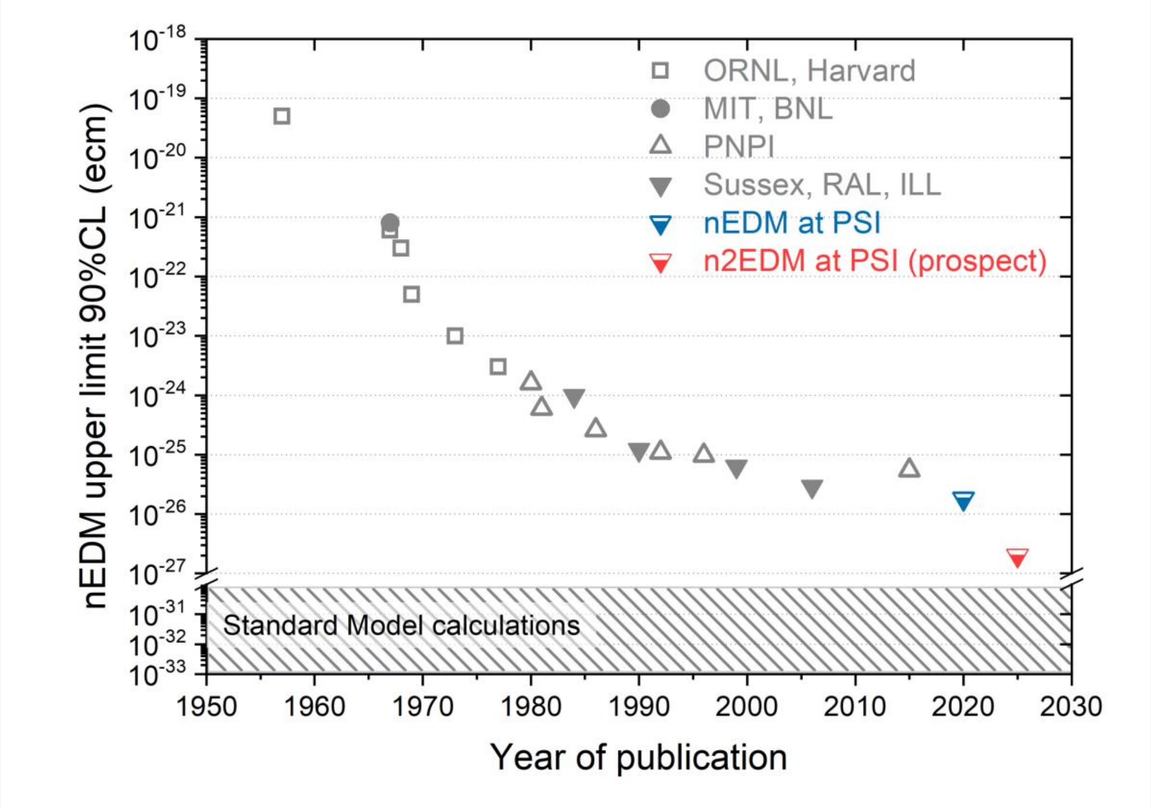
OUTLINE OF TALK

- Why the Axion?
- Haloscopes
- Why Higher Mass?
- Plasma Haloscopes
- The Spiral Design
- Prototype and Results
- Dark Photon Run

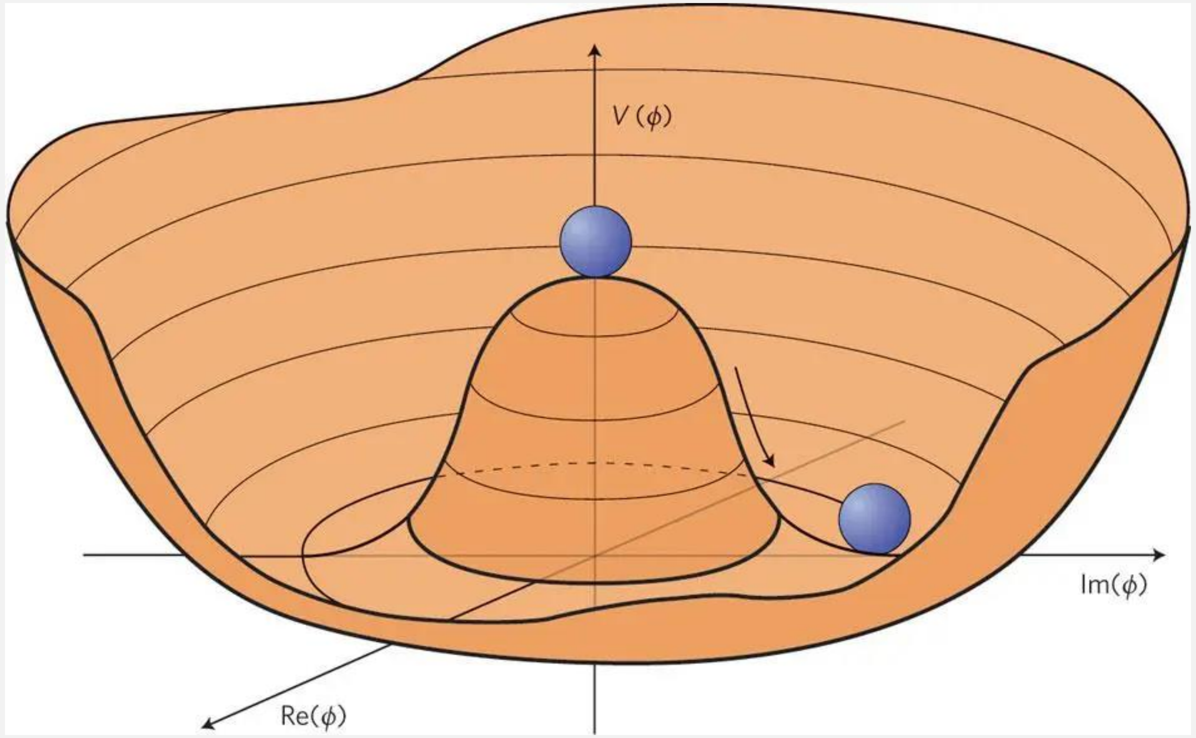
WHY THE AXION?

Neutron Electron Dipole Moment (nEDM)



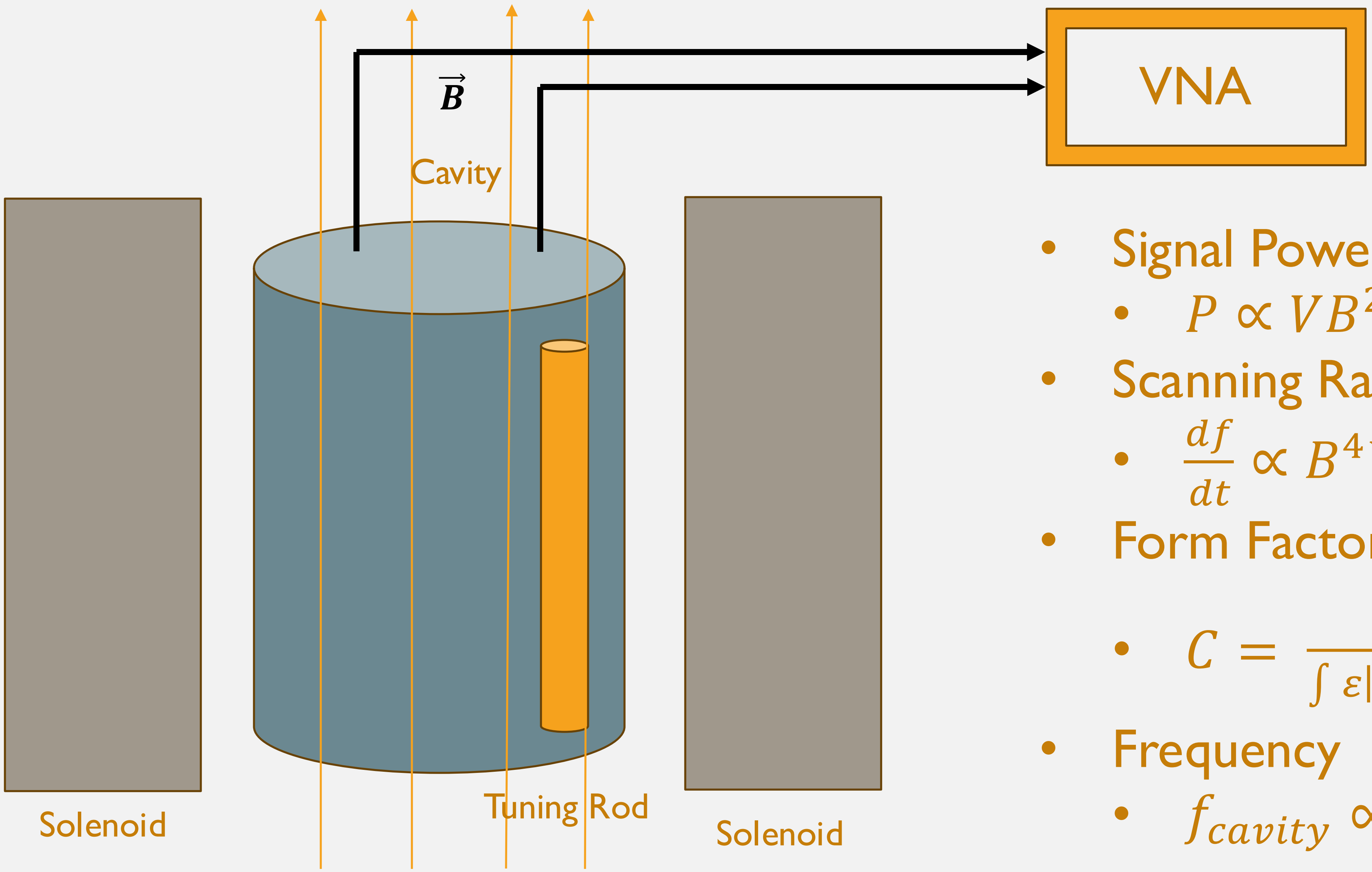
Credit: nEDM Search Collaboration at PSI

Peccei-Quinn Theory



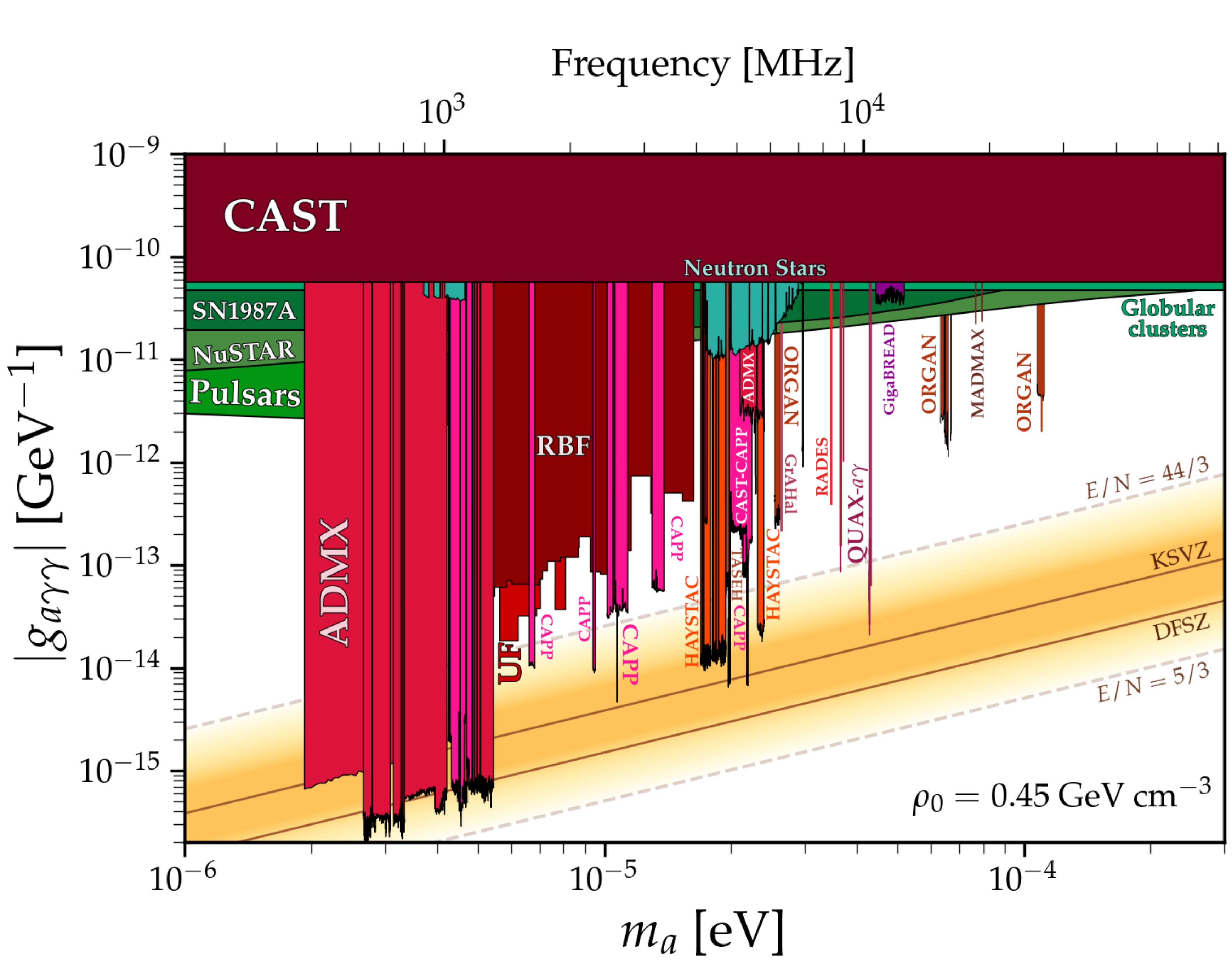
Credit: L. Albarez-Gaume & J. Ellis, Nature Physics, 2011

HALOSCOPES



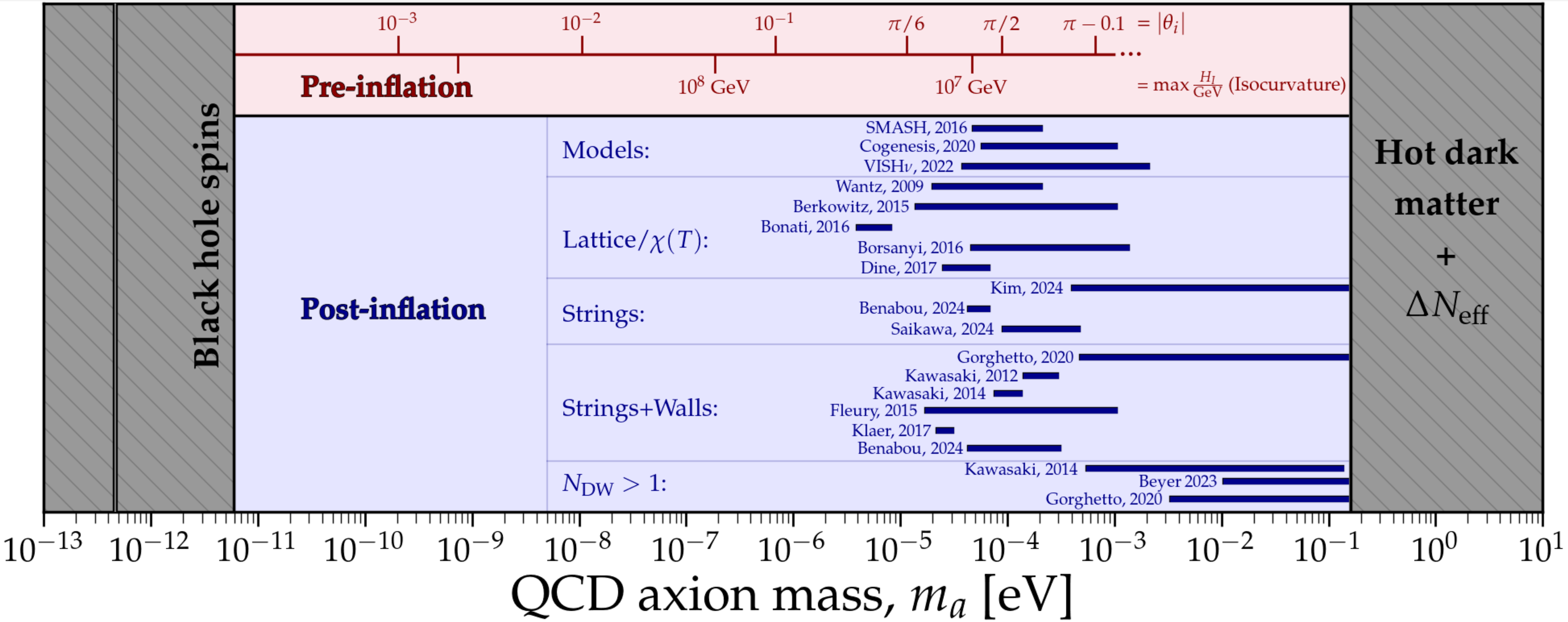
Example Traditional Haloscope

- Signal Power
  - $P \propto VB^2CQ$
- Scanning Rate
  - $\frac{df}{dt} \propto B^4V^2C^2Q$
- Form Factor
  - $C = \frac{\left|\int \mathbf{E} \cdot \boldsymbol{B}_{\text{ext}} dV_c\right|^2}{\int \varepsilon |\mathbf{E}|^2 dV_c \int |\mathbf{B}_{\text{ext}}|^2 dV_c}$
- Frequency
  - $f_{cavity} \propto V^{-2}$



Credit: Ciaran O'Hare. cajohare/axionlimits: Axionlimits. https://cajohare.github.io/AxionLimits/, July 2020

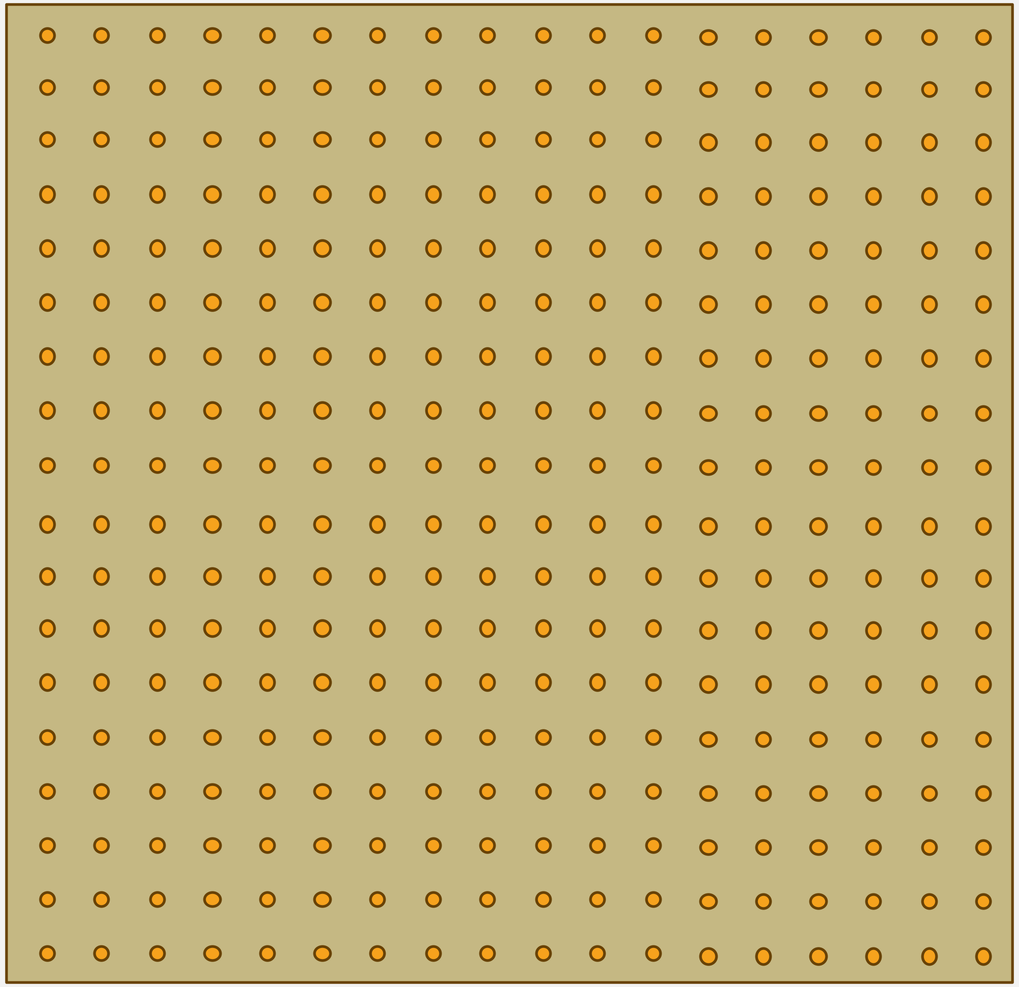
WHY HIGHER MASS: POST-INFLATION



Credit: Ciaran O'Hare. cajohare/axionlimits: Axionlimits. https://cajohare.github.io/AxionLimits/, July 2020

PLASMA HALOSCOPE: WIRE METAMATERIAL

- M. Lawson et al (2019)
- Wire Metamaterial → Artificial Plasma
- $\omega_p^2 = \frac{2\pi}{s^2 \log(s/d)}$
  - s: spacing
  - d: diameter
- Frequencies: 10 GHz and upwards
- P and $\frac{df}{dt}$ same as Haloscope



Conducting rods inside resonator

PLASMA HALOSCOPE: ELECTRICAL FIELD

- M. Lawson et al (2019)
- Wire Metamaterial → Artificial Plasma
- $\omega_p^2 = \frac{2\pi}{s^2 \log(s/d)}$
  - *s*: spacing
  - *d*: diameter
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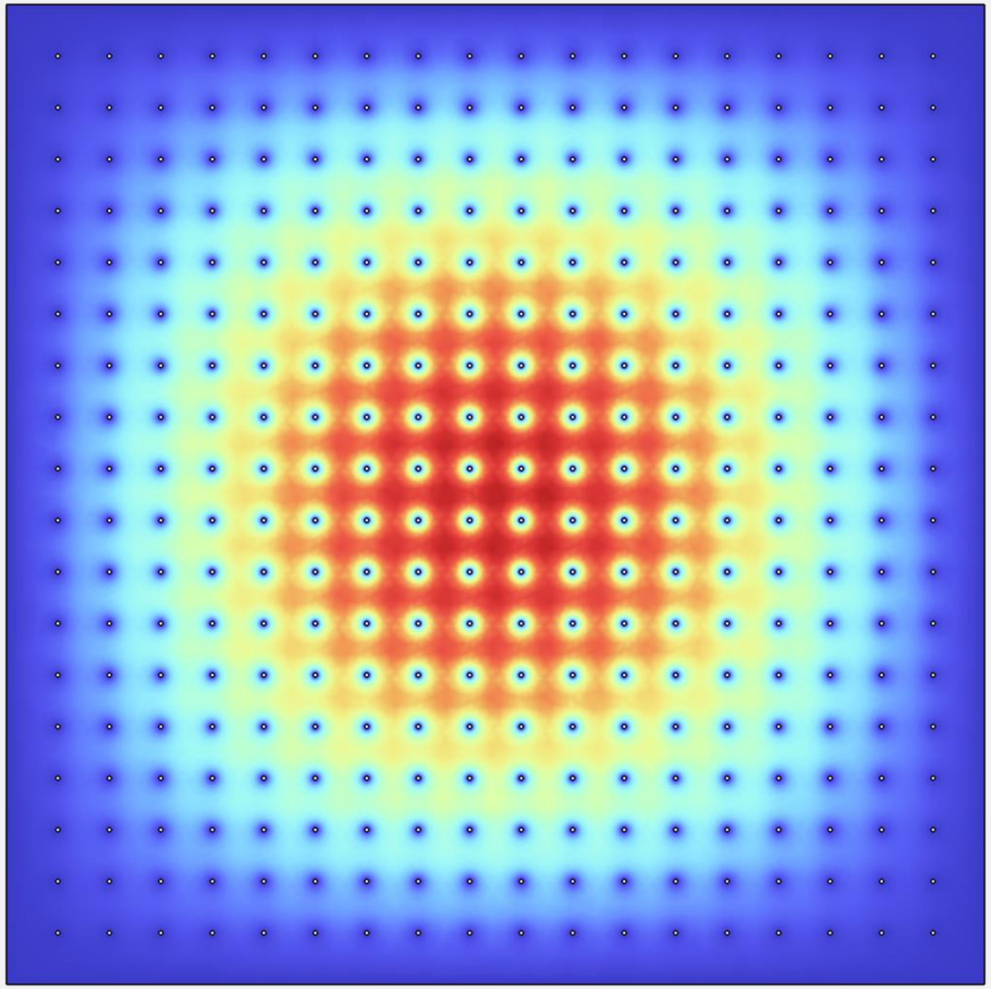
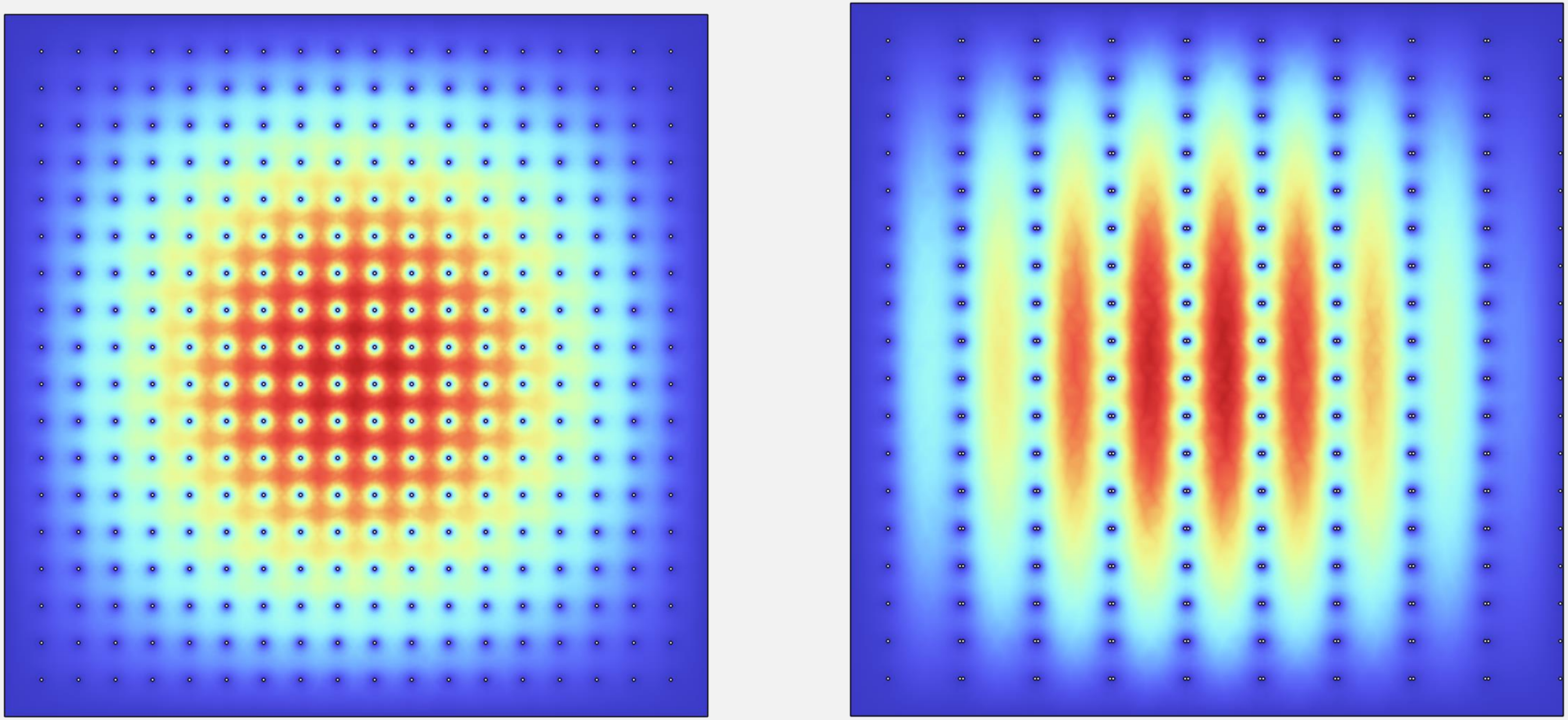


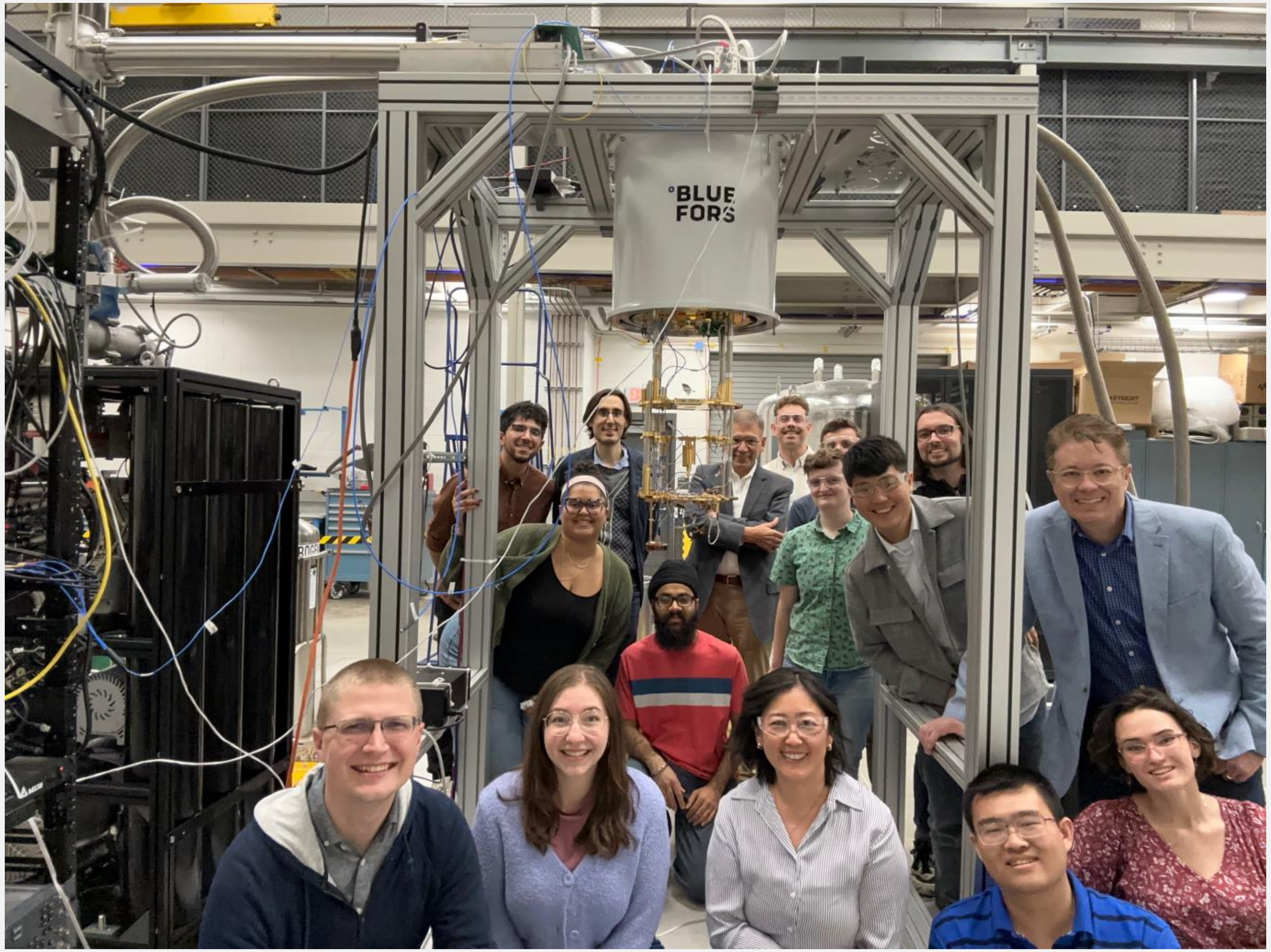
Electrical Field [Credit: Junu Jeong]

PLASMA HALOSCOPE: MECHANICALLY COMPLEX TUNING



Electrical Field Before and After Tuning [Credit: Junu Jeong]

AXION LONGITUDINAL PLASMA HALOSCOPE

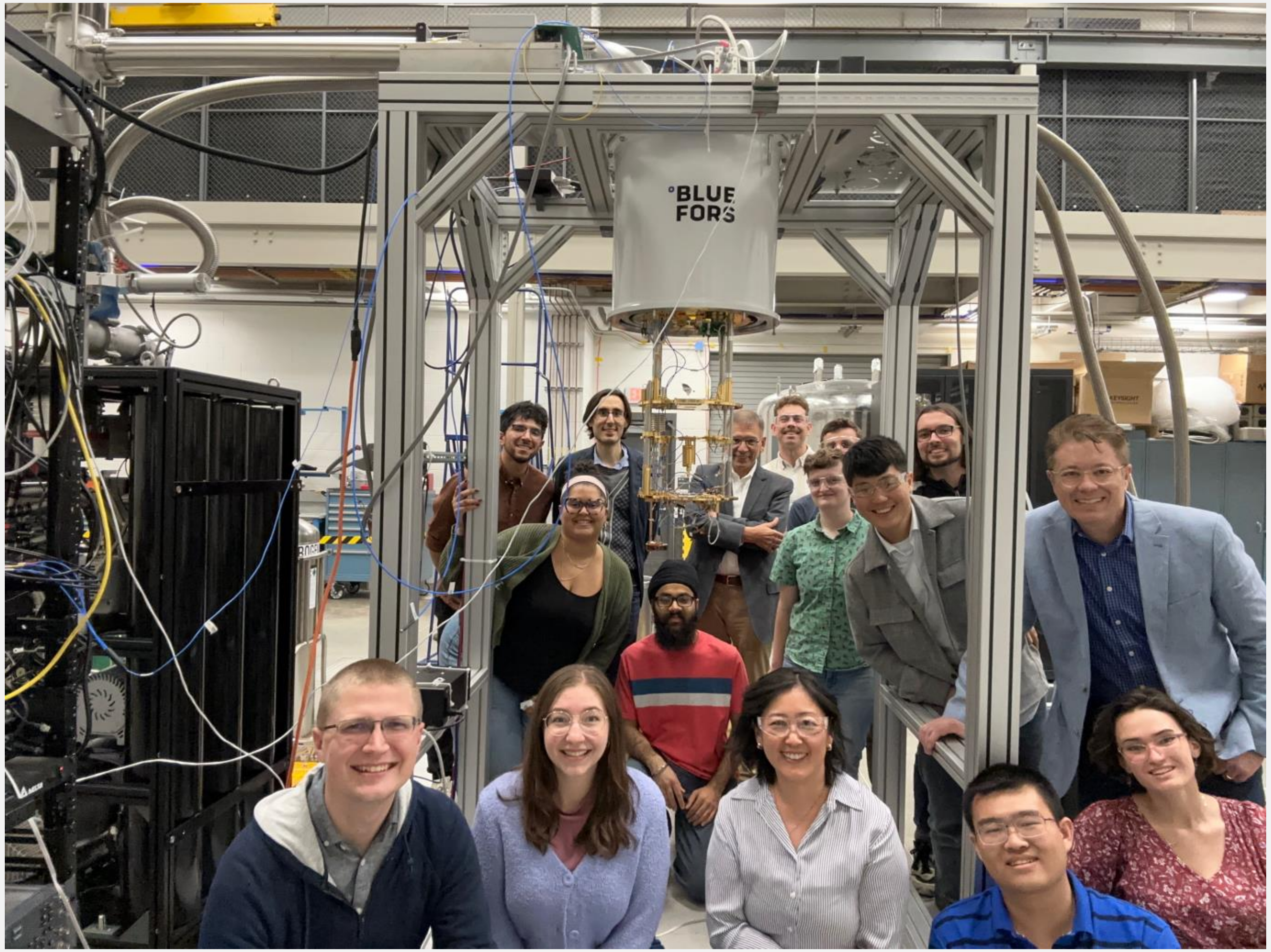


Credit: Reina Maruyama

Collaborating Institutes:

- Yale University (Host University)
- Arizona State University
- University of California, Berkley
- Cambridge University
- Colorado University
- University of Iceland
- John Hopkins University
- Massachusetts Institute of Technology
- Oak Ridge National Laboratory
- Stockholm University
- Wellesley College

AXION LONGITUDINAL PLASMA HALOSCOPE

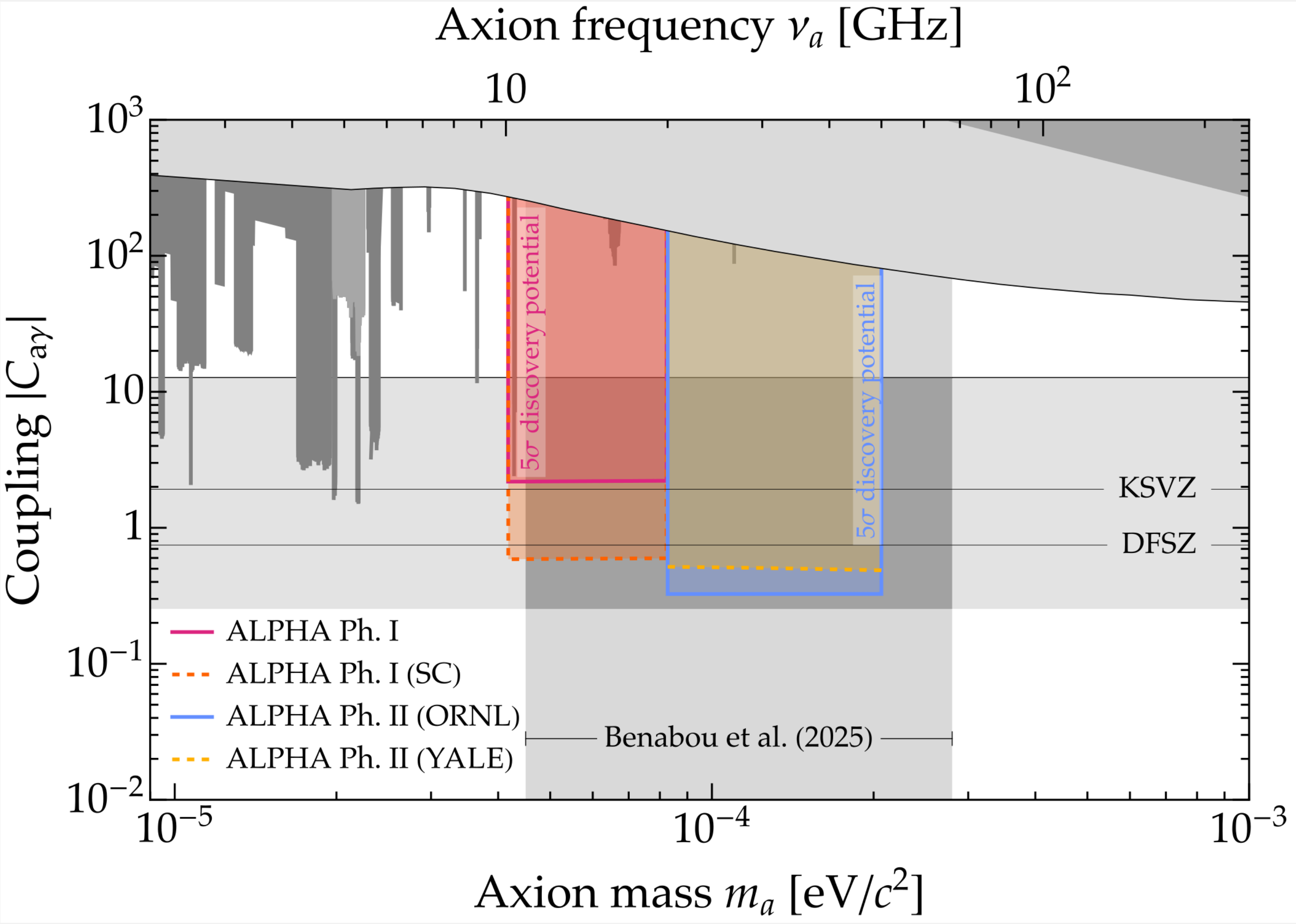


Credit: Reina Maruyama

Stockholm University Group:

- Resonator:
  - Junu Jeong (Resonator co-lead)
  - Jon E. Gudmundsson [former spokesperson](U of Iceland)
  - Rustam Balafendiev (U of Iceland)
  - Gagandeep Kaur
  - Gaganpreet Singh
  - Jianyang Qi
  - Jacob Lindahl
- Analysis:
  - Jan Conrad (Deputy Spokesperson)
  - Andrea Gallo Rosso (Analysis co-lead)
  - Andy Meyer

ALPHA PARAMETER SPACE



ALPHA Ph. I	
Volume:	12 l
Magnetic field:	9 T
Form factor C_{010}:	0.5
Quality factor Q_0:	10^4
Noise quanta N_{sys}:	1.38
Integration time:	2 years

ALPHA Ph. I (SC)	
Volume:	12 l
Magnetic field:	9 T
Form factor C_{010}:	0.5
Quality factor Q_0:	10^6
Noise:	q. limit
Integration time:	2 years

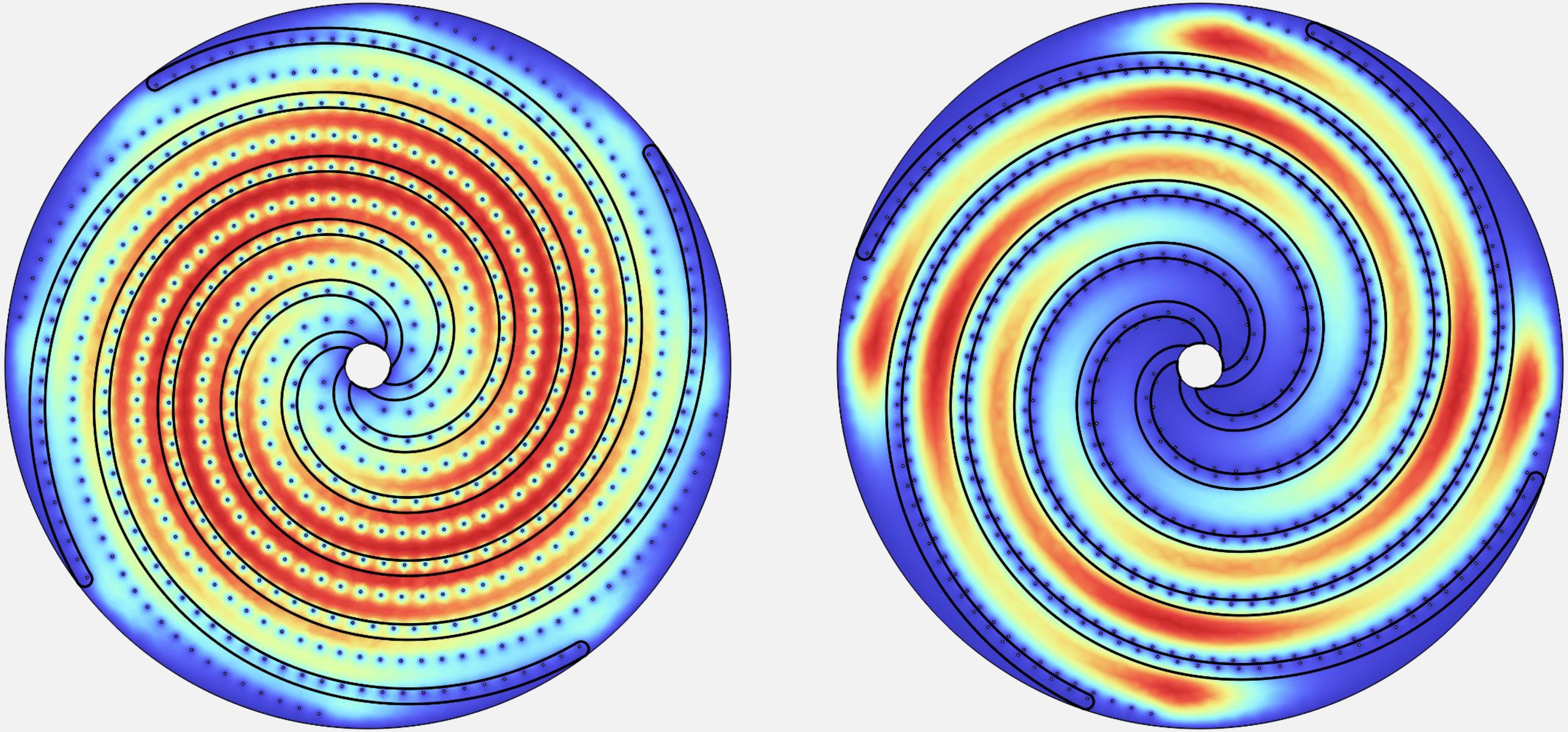
ALPHA Ph. II (ORNL)	
Volume:	295 l
Magnetic field:	13 T
Form factor C_{010}:	0.5
Quality factor Q_0:	10^4
Noise:	q. limit
Integration time:	3 years

ALPHA Ph. II (YALE)	
Volume:	20 l
Magnetic field:	9 T
Form factor C_{010}:	0.5
Quality factor Q_0:	10^5
Noise:	sqzd
Integration time:	3 years

Ph. I: 2027 - (Fully funded)

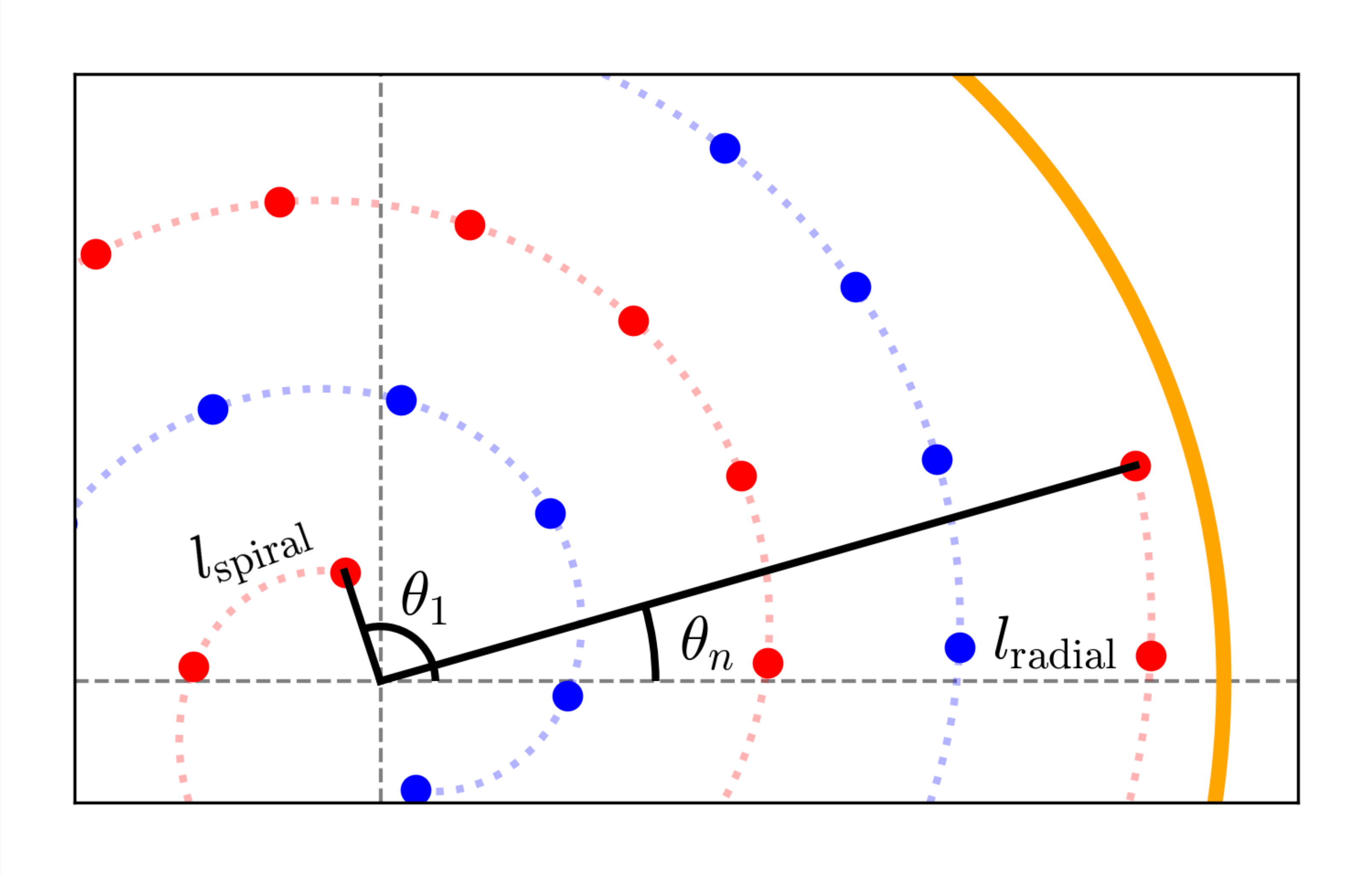
Ph. II: 2029 -

SPIRAL METHOD



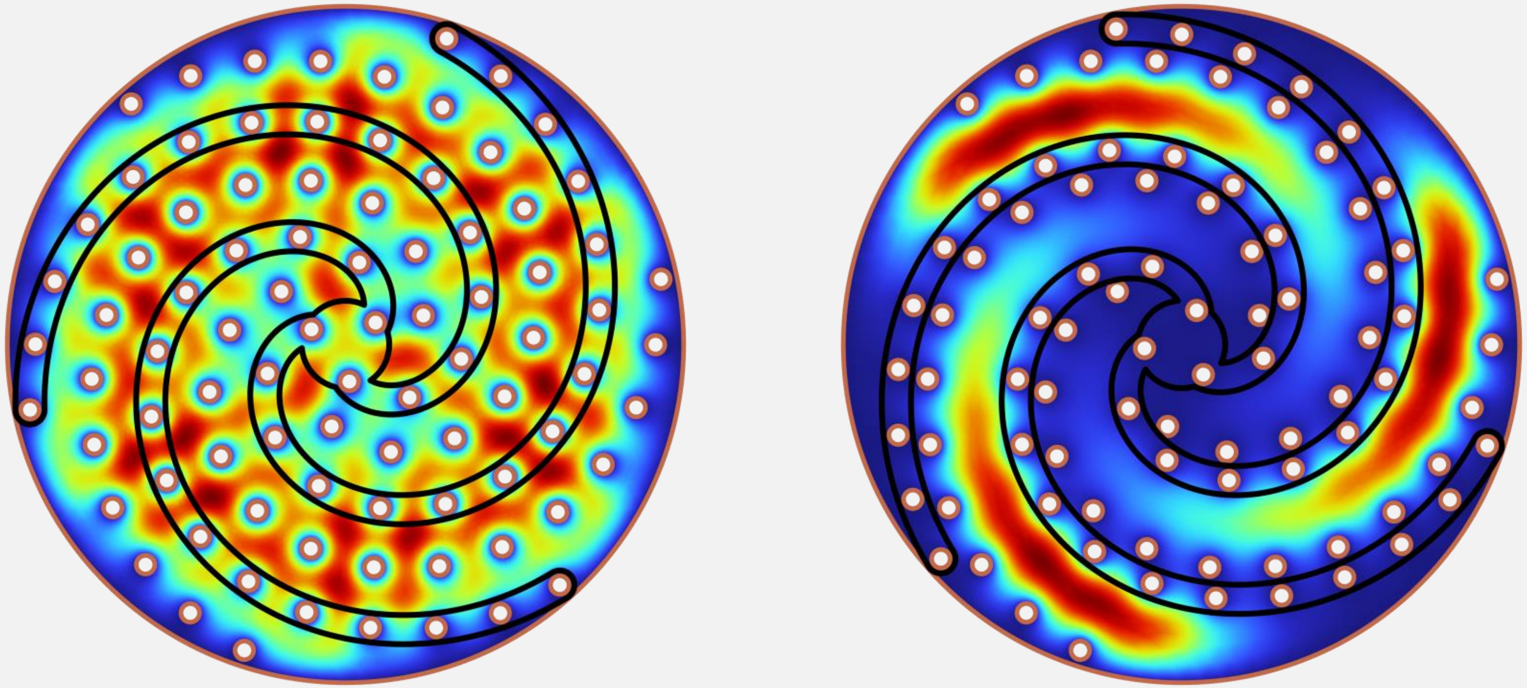
8-arm Spiral Electrical Field [Credit: Junu Jeong]

SPIRAL DISTRIBUTION



- $N_{spirals} = N_{fixed} + N_{tunable}$
- $l_{\text{spiral}} \approx l_{\text{radial}}$
- $\theta_i \approx \sqrt{\theta_1^2 + \frac{\theta_n^2 - \theta_1^2}{n-1} \cdot (i-1)}$
- $f \approx \frac{c}{\pi} \sqrt{\frac{N_s \times n}{2 \cdot \text{Cross-sectional Area}}}$

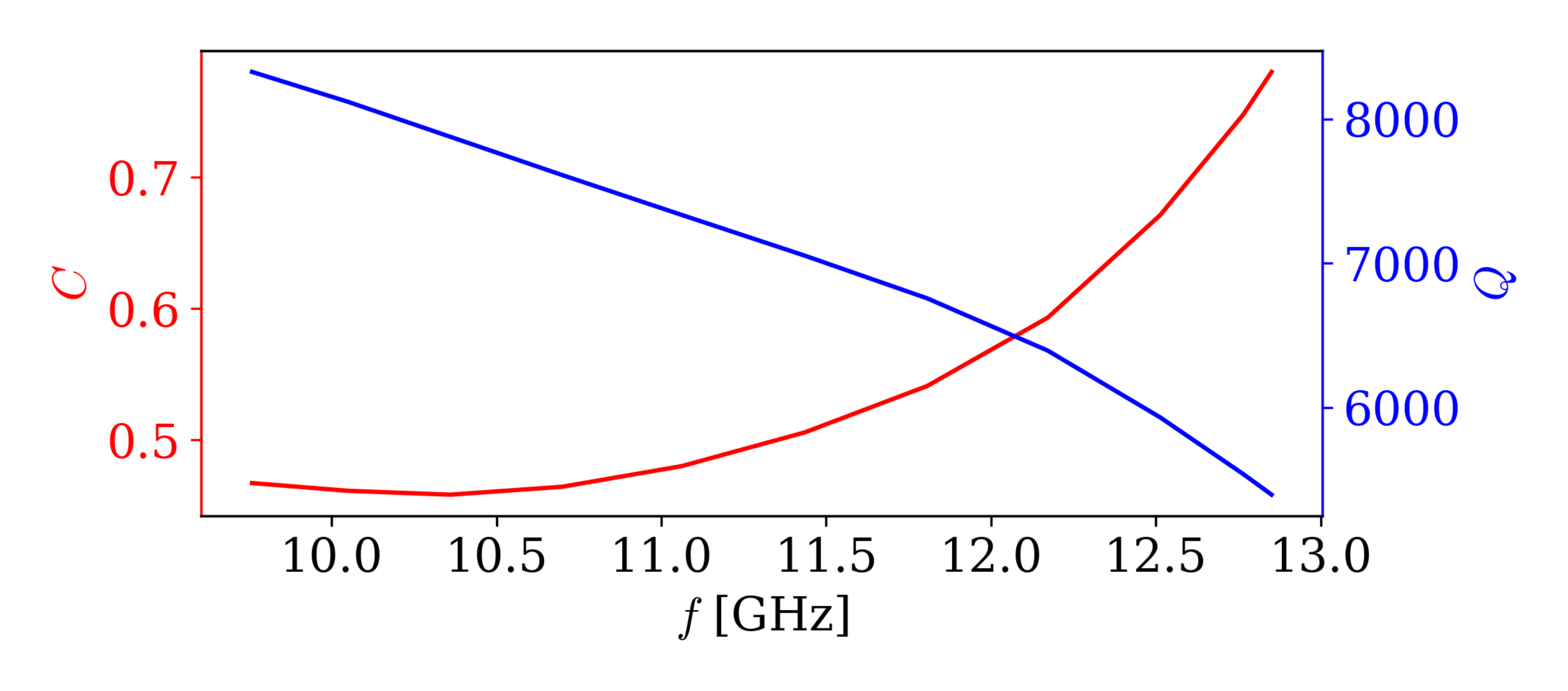
6-ARM PROTOTYPE



0° 30°

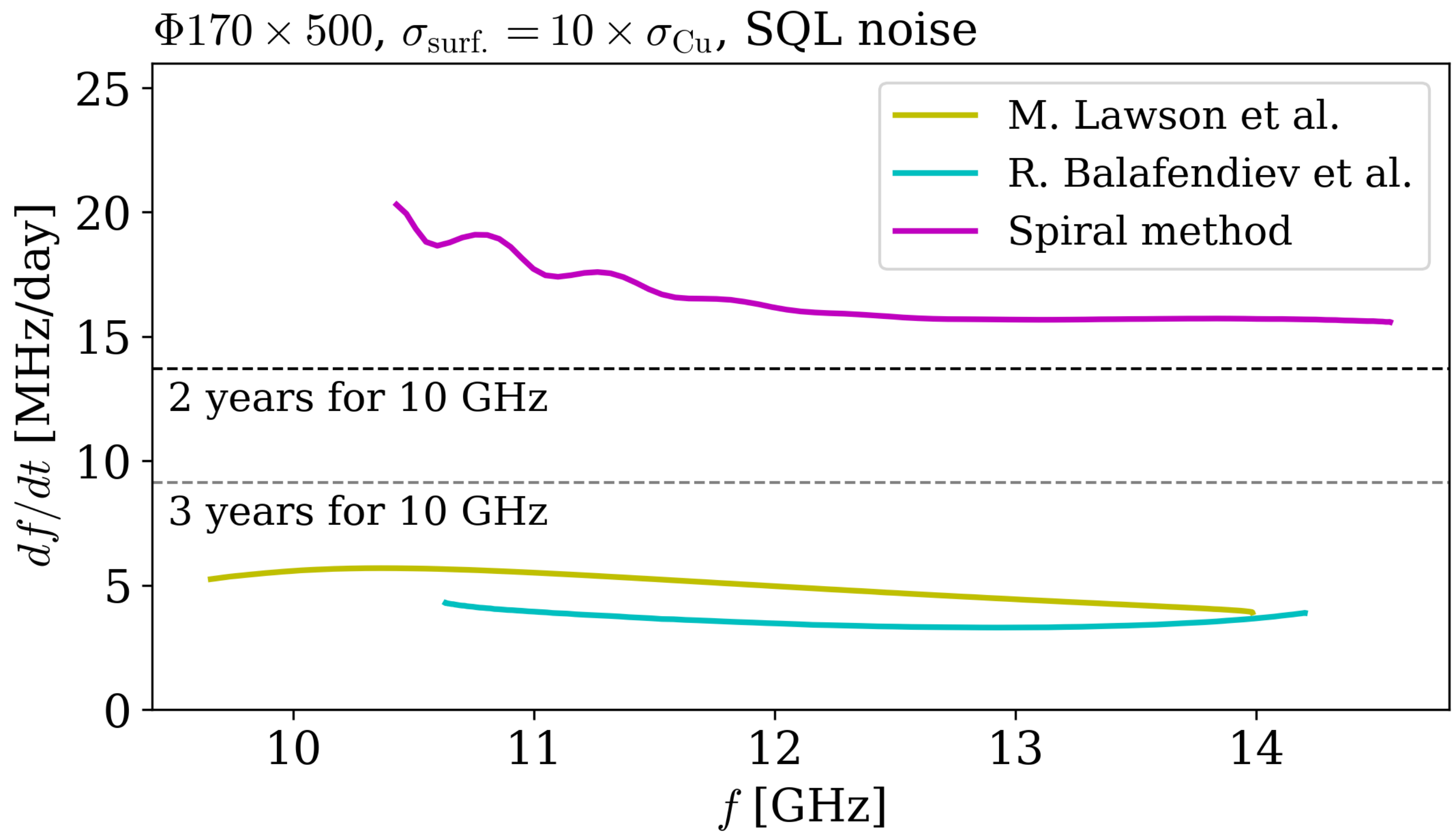
Frequency

2D SPIRAL SIMULATION



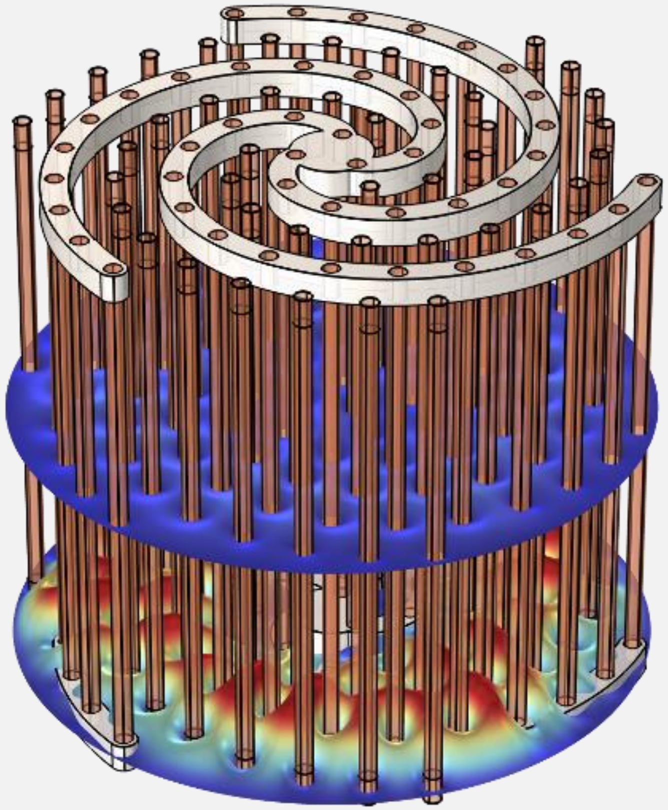
The form factor and quality factor for 2D simulation of a 6-arm Spiral resonator [arXiv:2508.18145]

SCANNING RATES

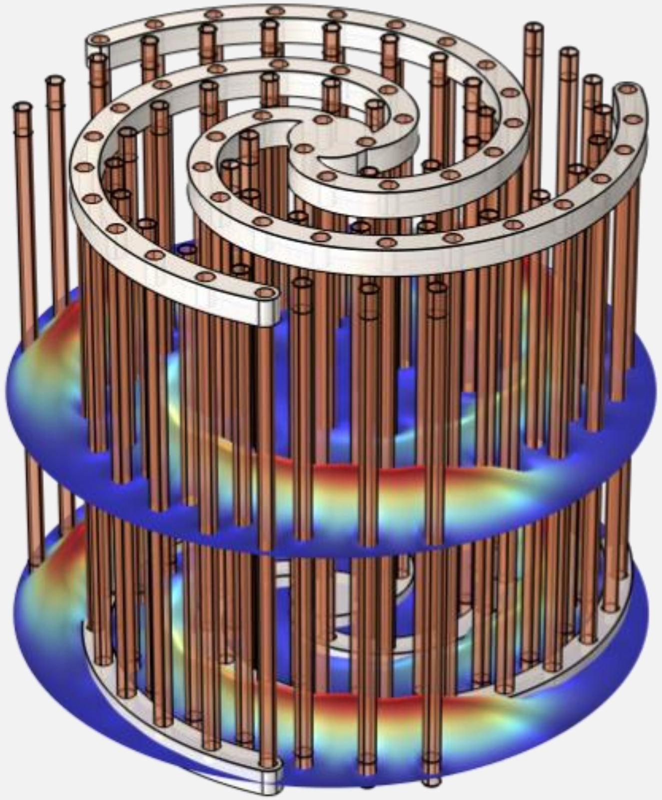


Comparison of Scanning Rates for 8-arm spiral [arXiv:2508.18145]

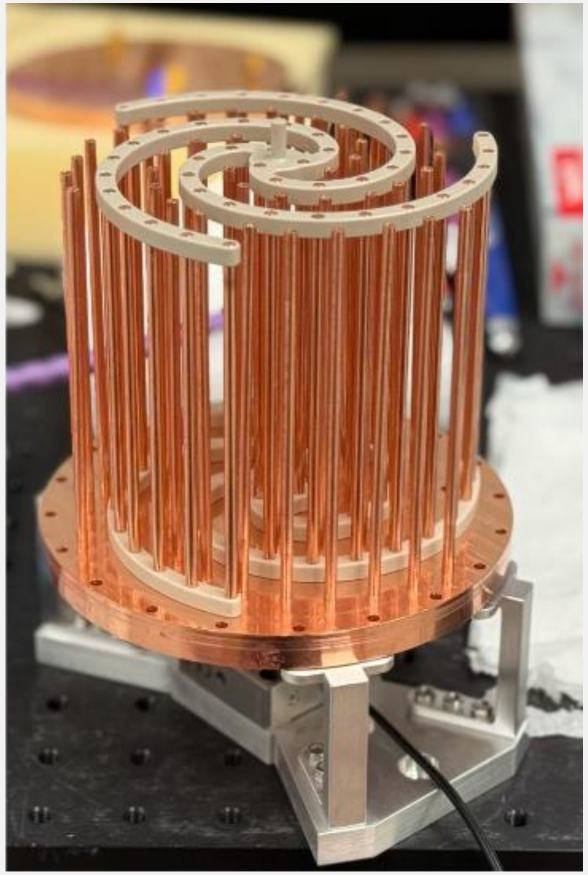
6-ARM PROTOTYPE



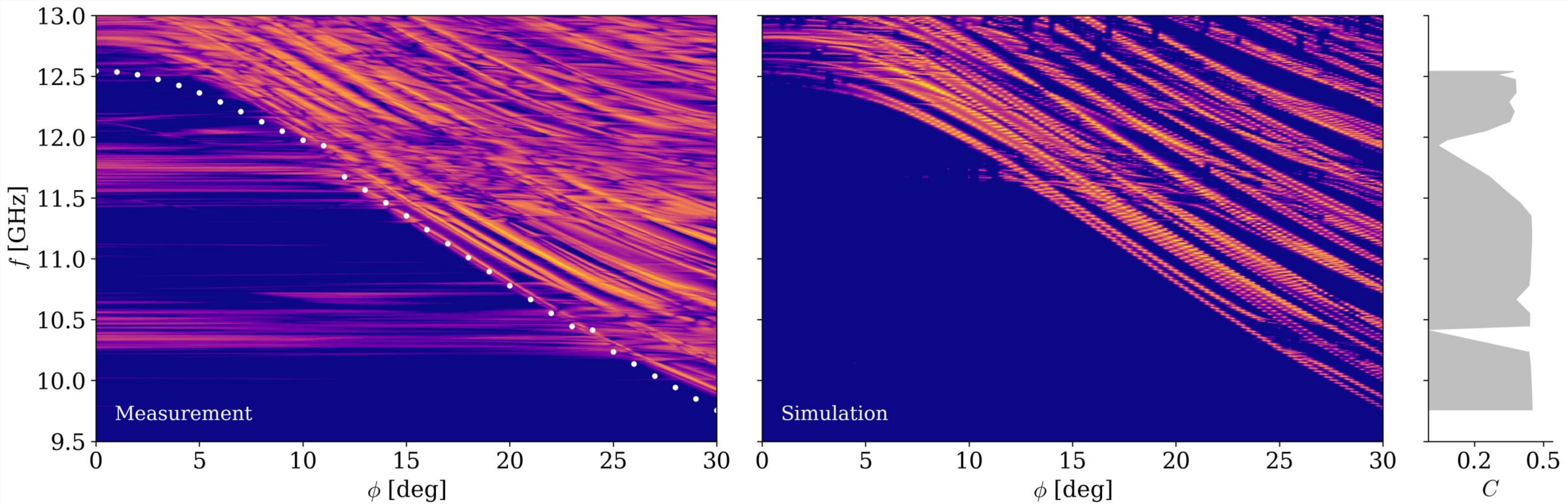
0°



30°

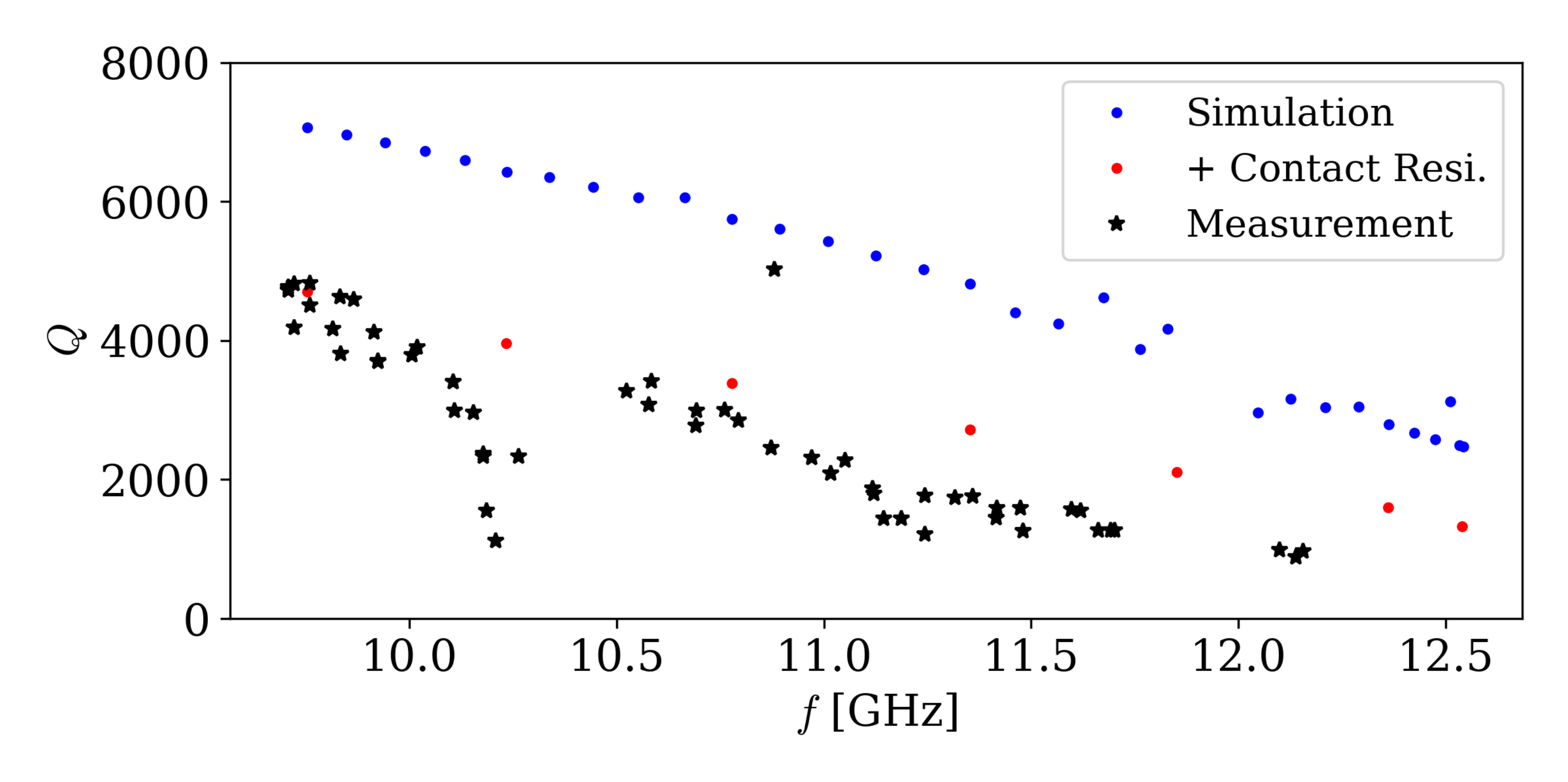


6-ARM MODE MAP



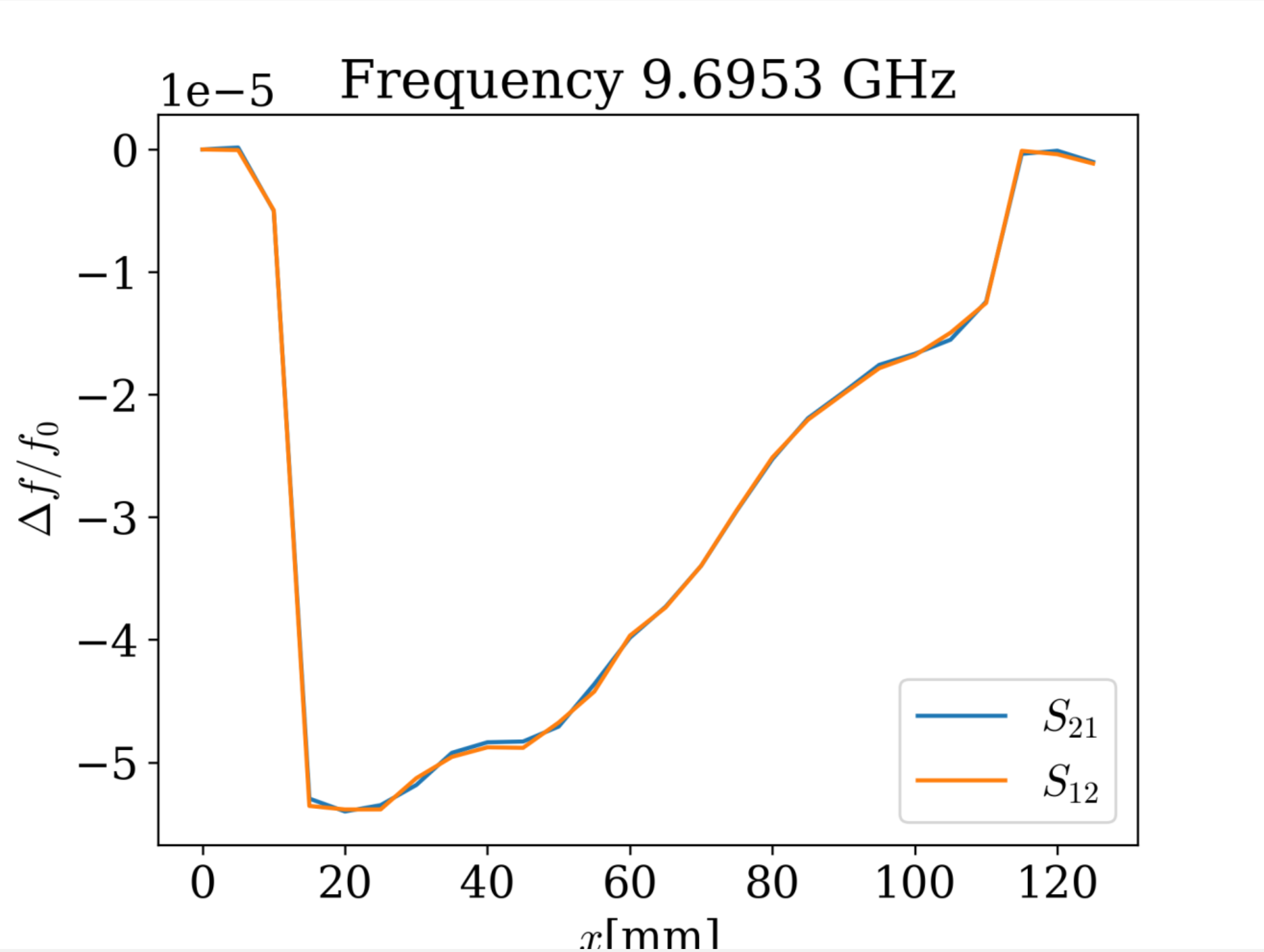
Mode Map and Form Factor of 6-arm prototype

6-ARM QUALITY FACTOR AND BEAD PULL



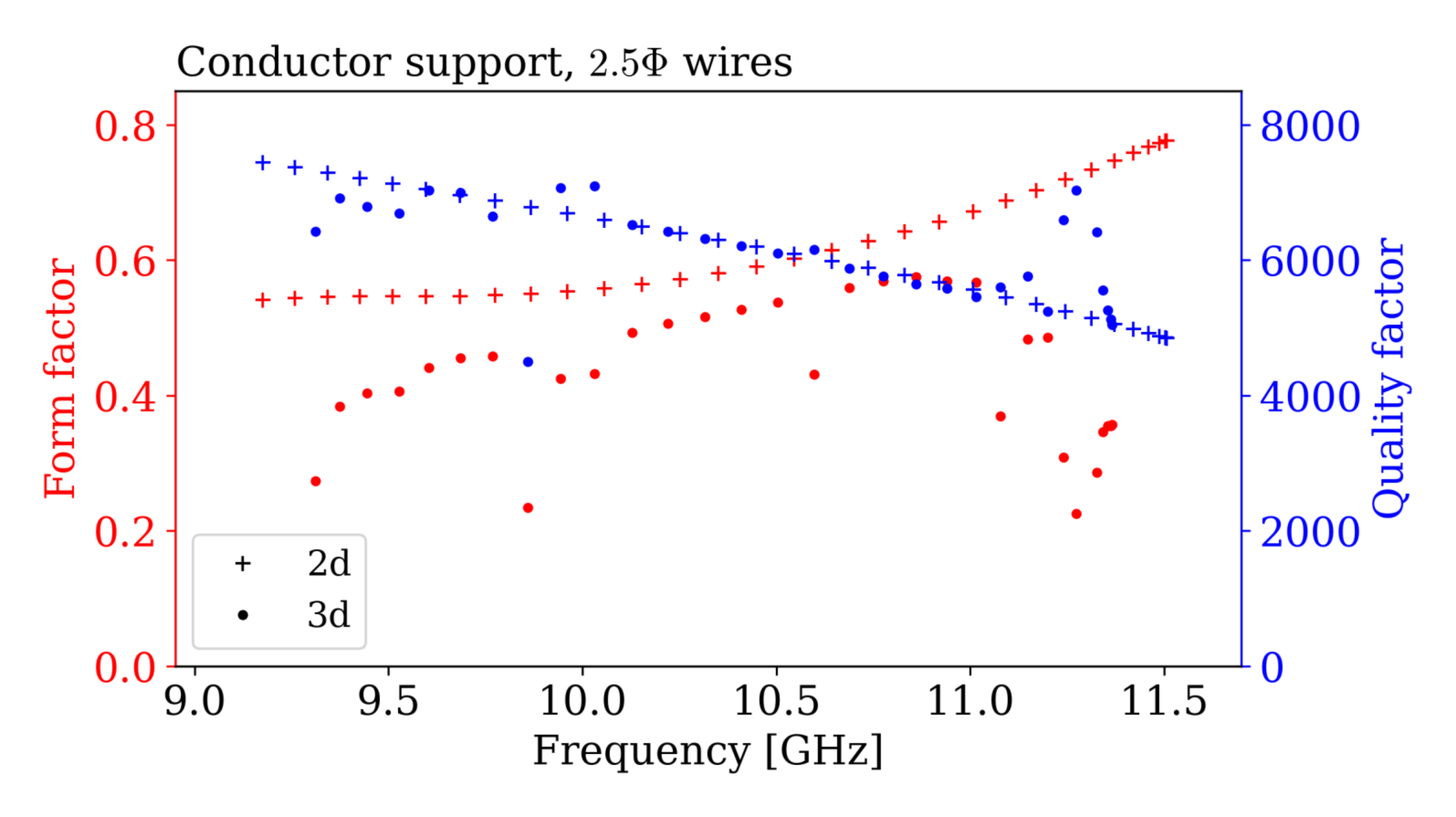
Simulated and Measured Quality Factor of 6-arm

6-ARM QUALITY FACTOR AND BEAD PULL



Bead Pull Measurement of 6-arm Lowest Frequency

DARK PHOTON RUN



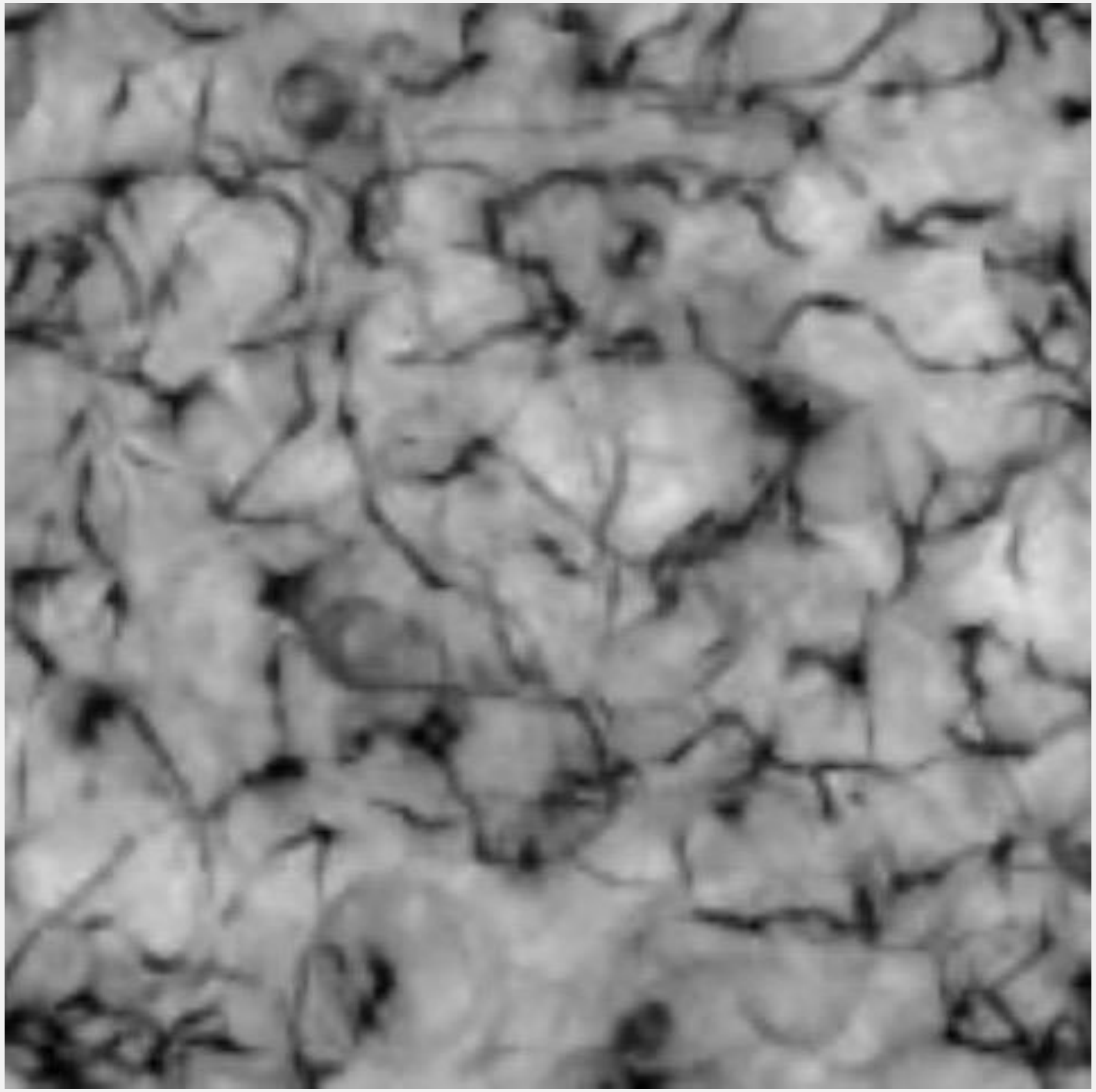
2D and 3D Simulations for the Dark Photon Spiral Resonator

- Using 6-arm design
- Aiming for 2026
- Fully Conductive Support
- 9-12GHz

SUMMARY

- ALPHA is a collaboration dedicated to exploring the high-mass axion range via plasma haloscopes
- The Spiral approach allows for enhanced scanning speed and low mechanical complexity
- The 6-arm prototype has demonstrated its feasibility and convergence between simulation and measurements
- Aiming for a Dark Photon Run next year

BACK UP: PRODUCTION: POST-INFLATION



Buschmann, M., Foster, J.W., Hook, A. *et al.* Dark matter from axion strings with adaptive mesh refinement. *Nat Commun* **13**, 1049 (2022). https://doi.org/10.1038/s41467-022-28669-y