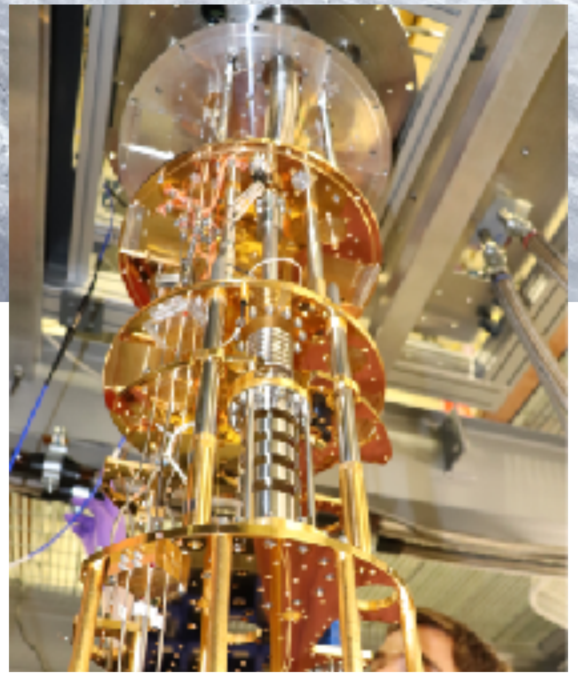
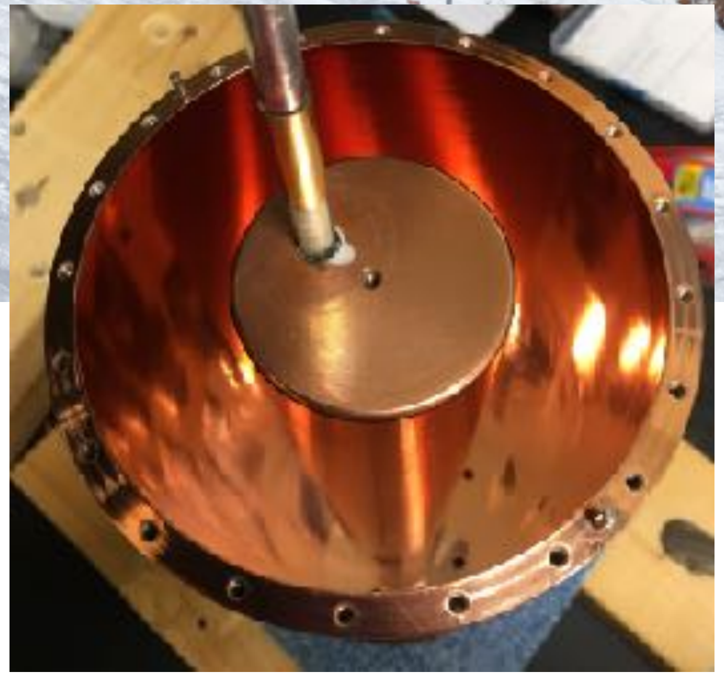
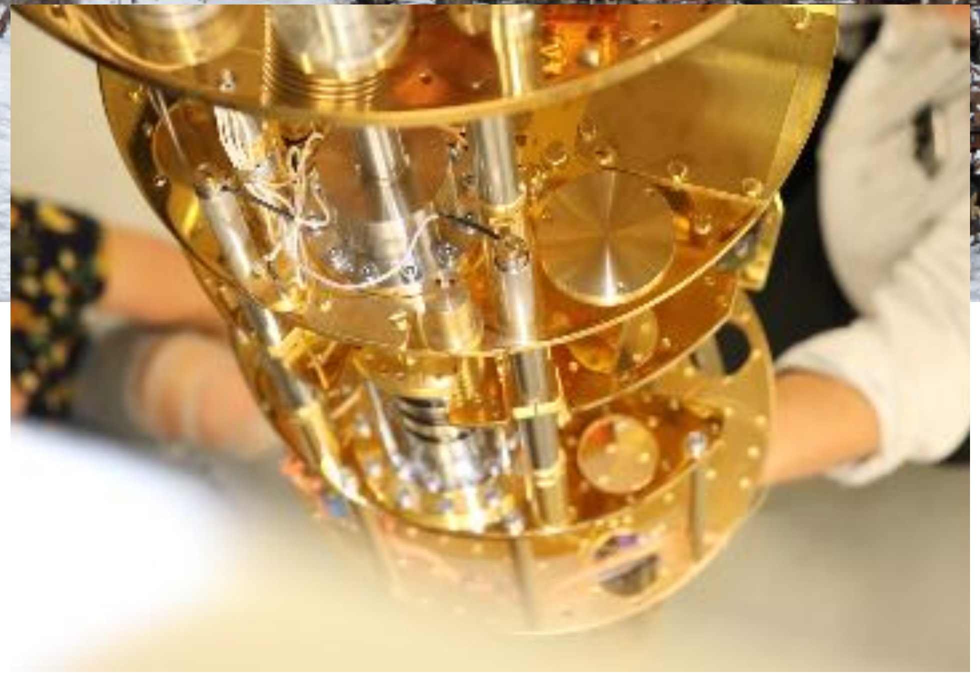
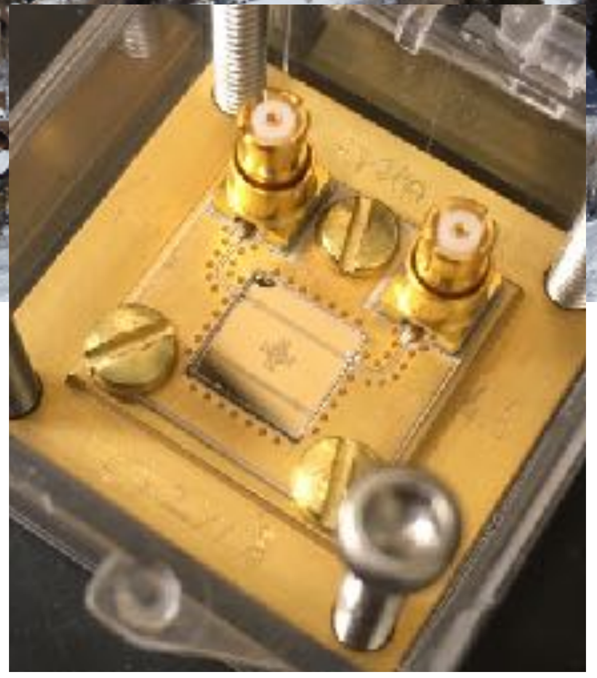
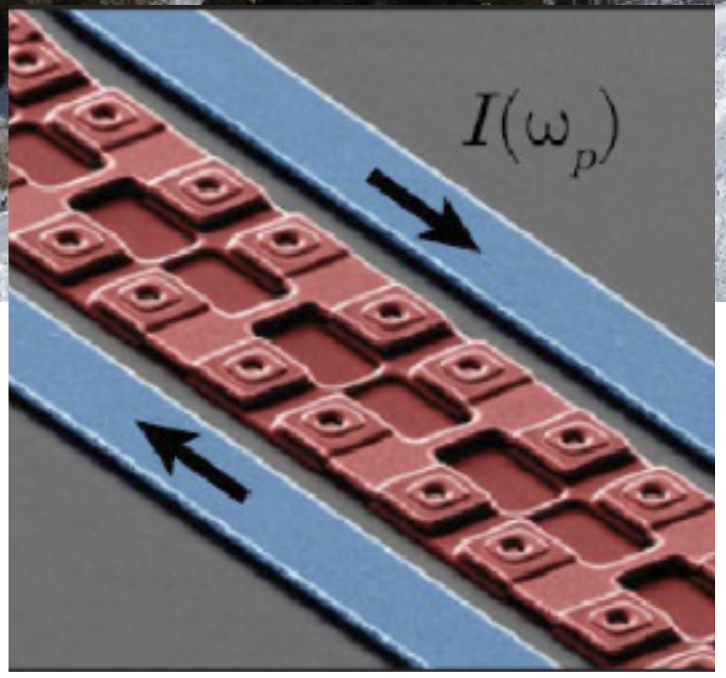
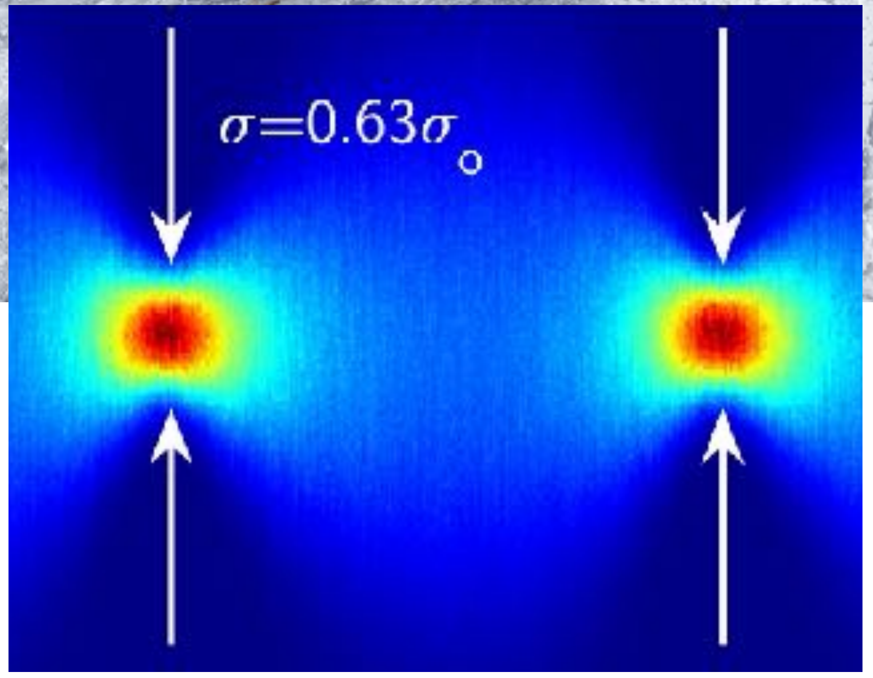
Search for Axions: HAYSTAC & ALPHA

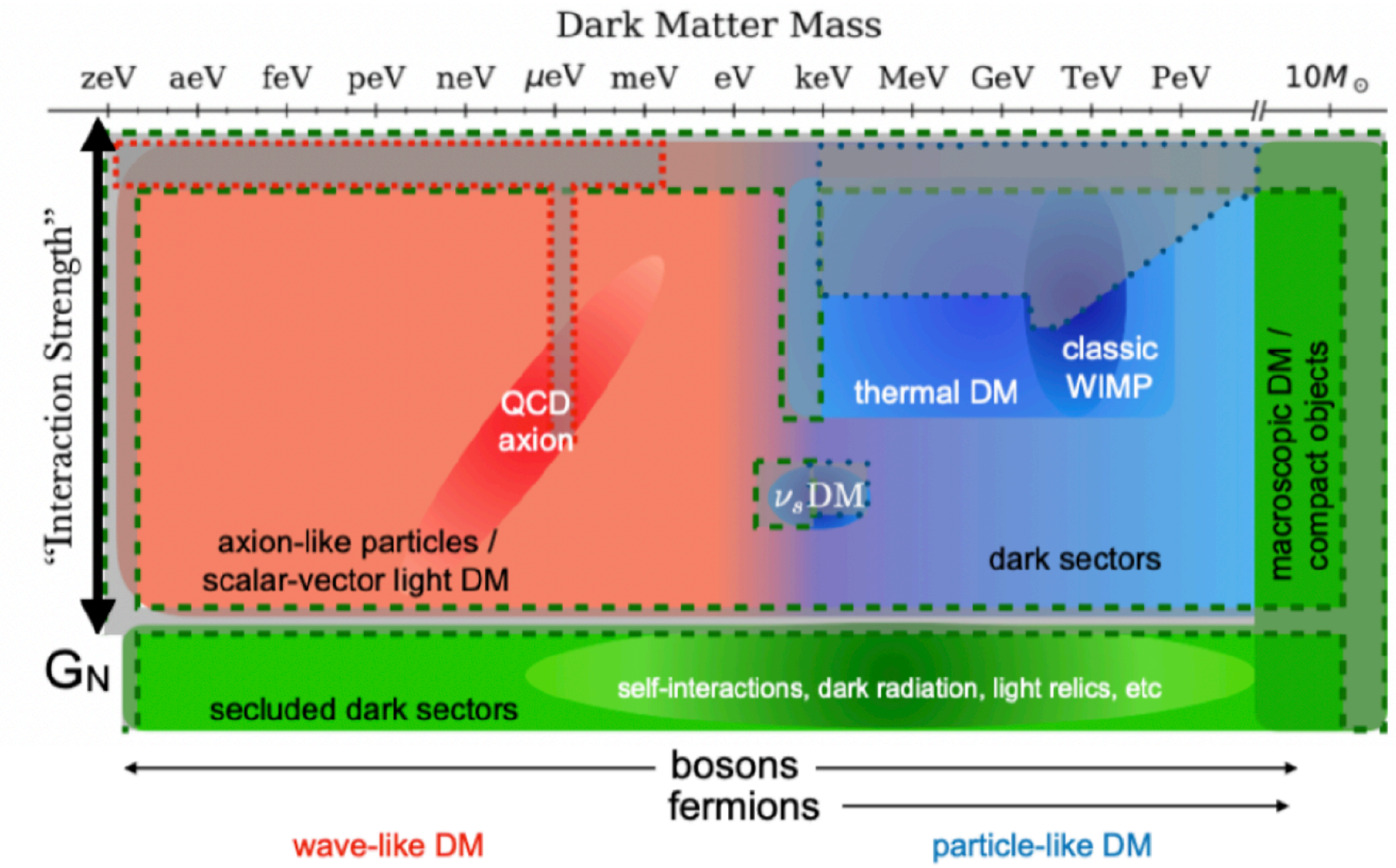








Reina Maruyama (for ALPHA & HAYSTAC Collaborations)
Yale University

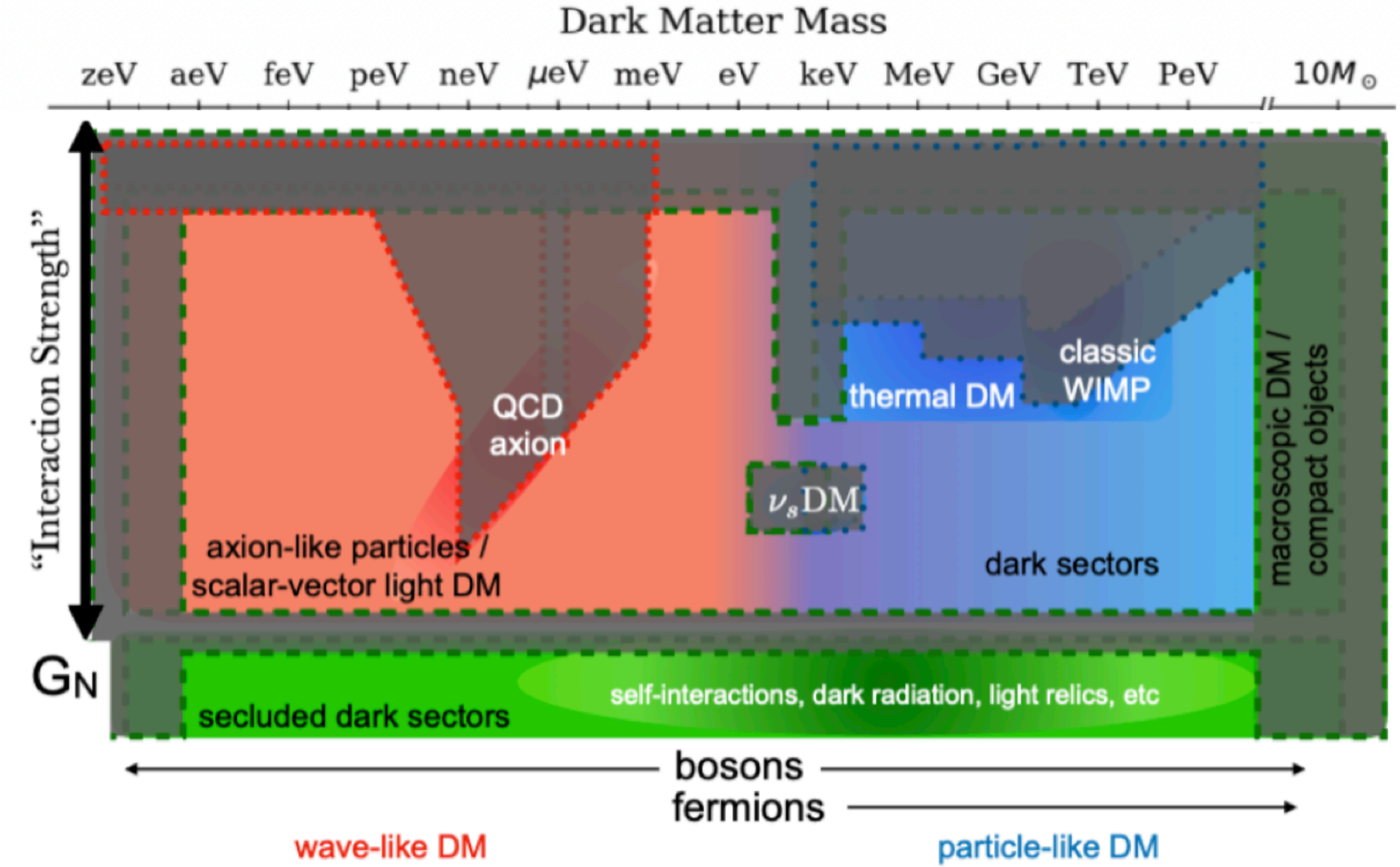
Aspen Winter
The Future of High Energy Physics: A New Generation, A New Vision
March 24 – 29, 2024

“Snowmass 2022”: U.S. Dark Matter Program



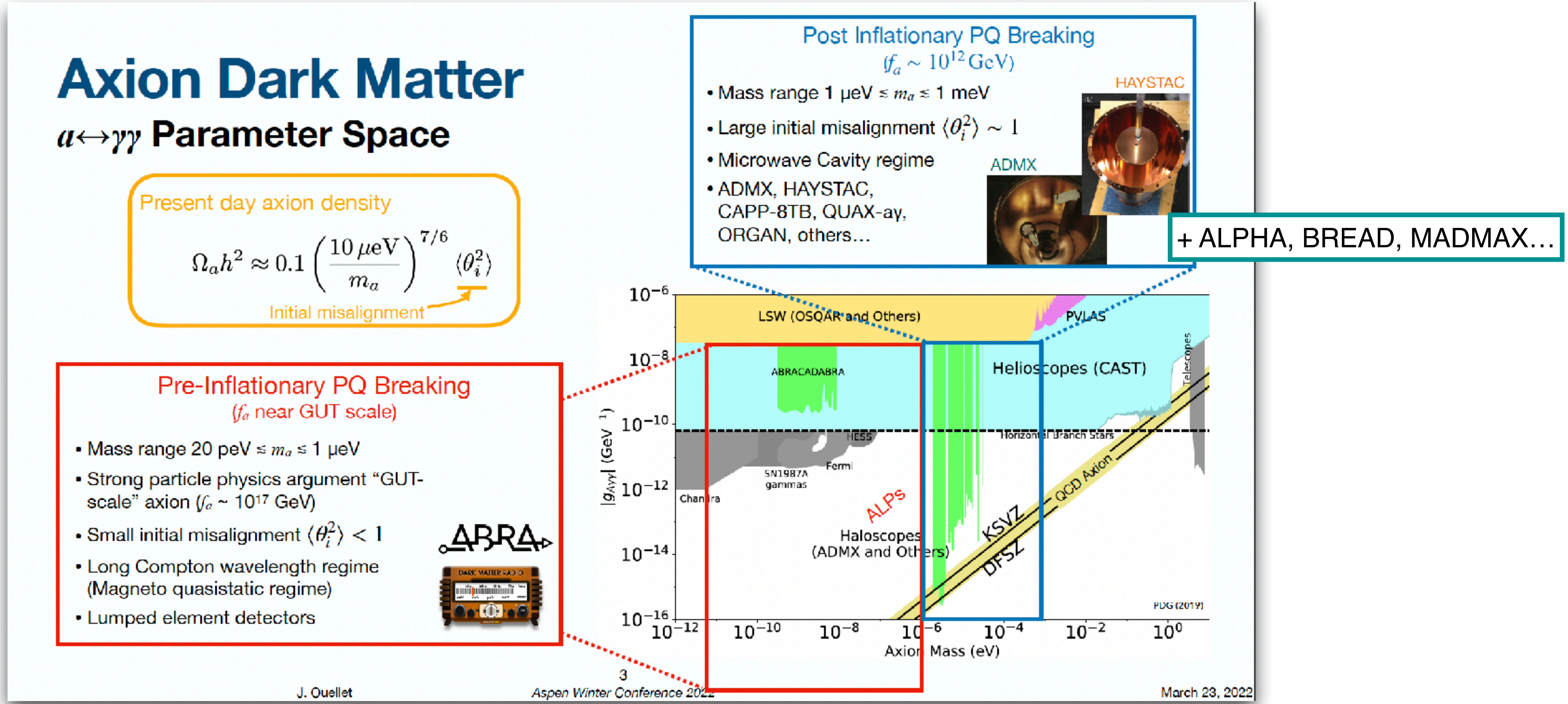
Snowmass 2022

“Snowmass 2022”: U.S. Dark Matter Program



Snowmass 2022

Axions are well motivated



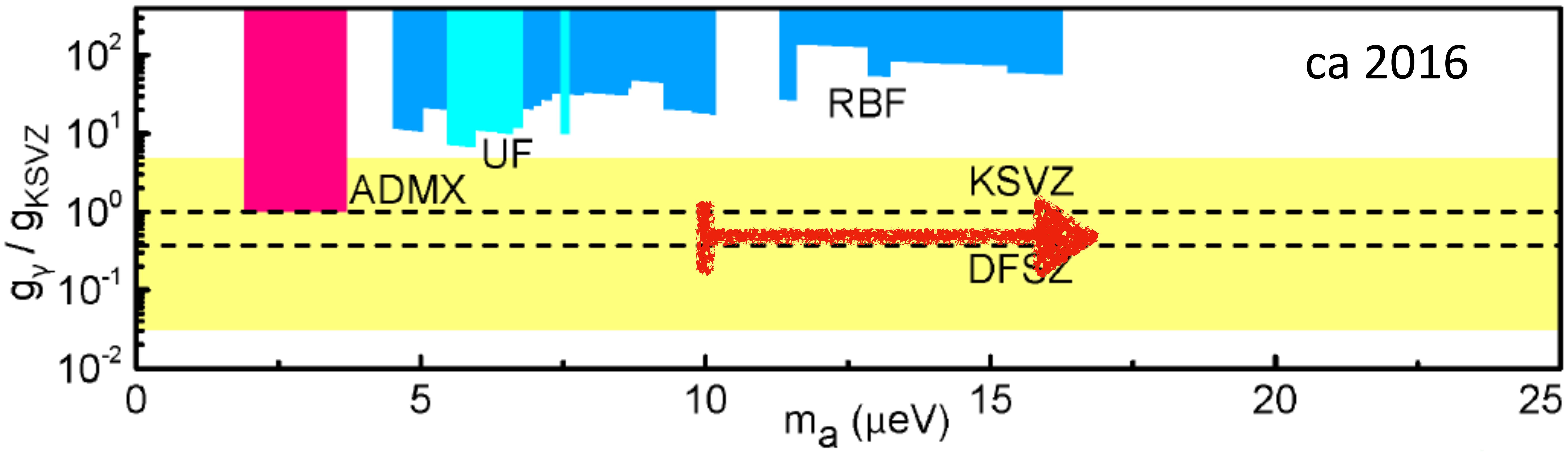
J. Ouellet, Aspen 2022

HAYSTAC's Aim: Going high

- Innovation testbed for axion searches in QCD band > 10 μeV (~2.5 GHz)
- Challenges:
  - Photon detection, noise
  - Scan rate: $V \propto \nu^{-2}$, $\frac{d\nu}{dt} \propto V^2$, $\frac{d\nu}{dt} \propto \nu^{-4}$

Borsanyi et al (2016) PQ symmetry broken after inflation: m_a > 10 μeV

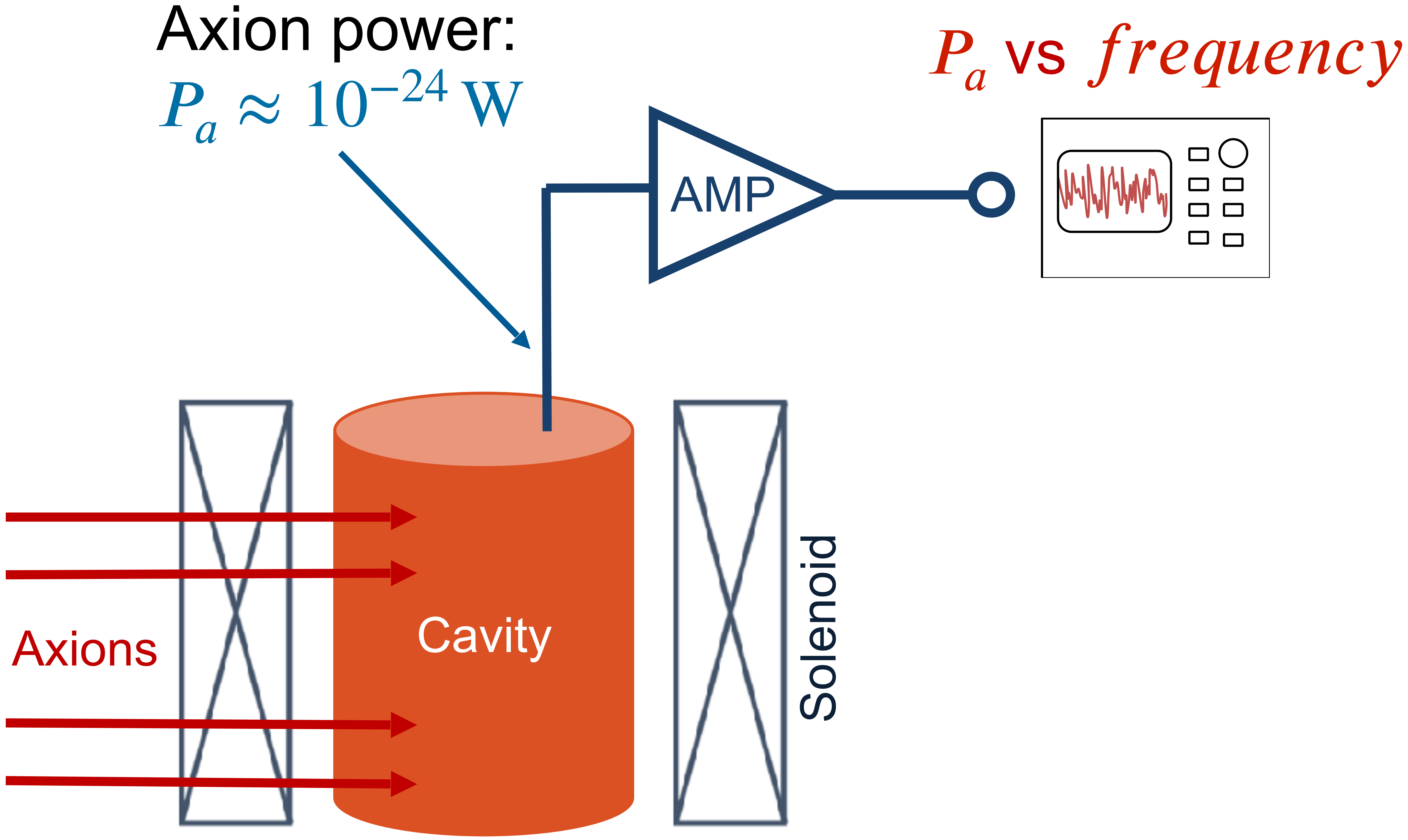
Klaer & Moore (2017); 26.2 ± 3.4 μeV



Buschmann, et al. (2022): 40 μeV [65 ± 6 μeV, q=1; scale invariant spectrum]

* In $\Omega_A \sim f_A^{\alpha}$, the best fit α = 1.24 ± 0.04
Rather than analytical 1.187

Detecting Axions: Sikivie's Haloscope



Interaction of interest: $\mathcal{L} \supset g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$

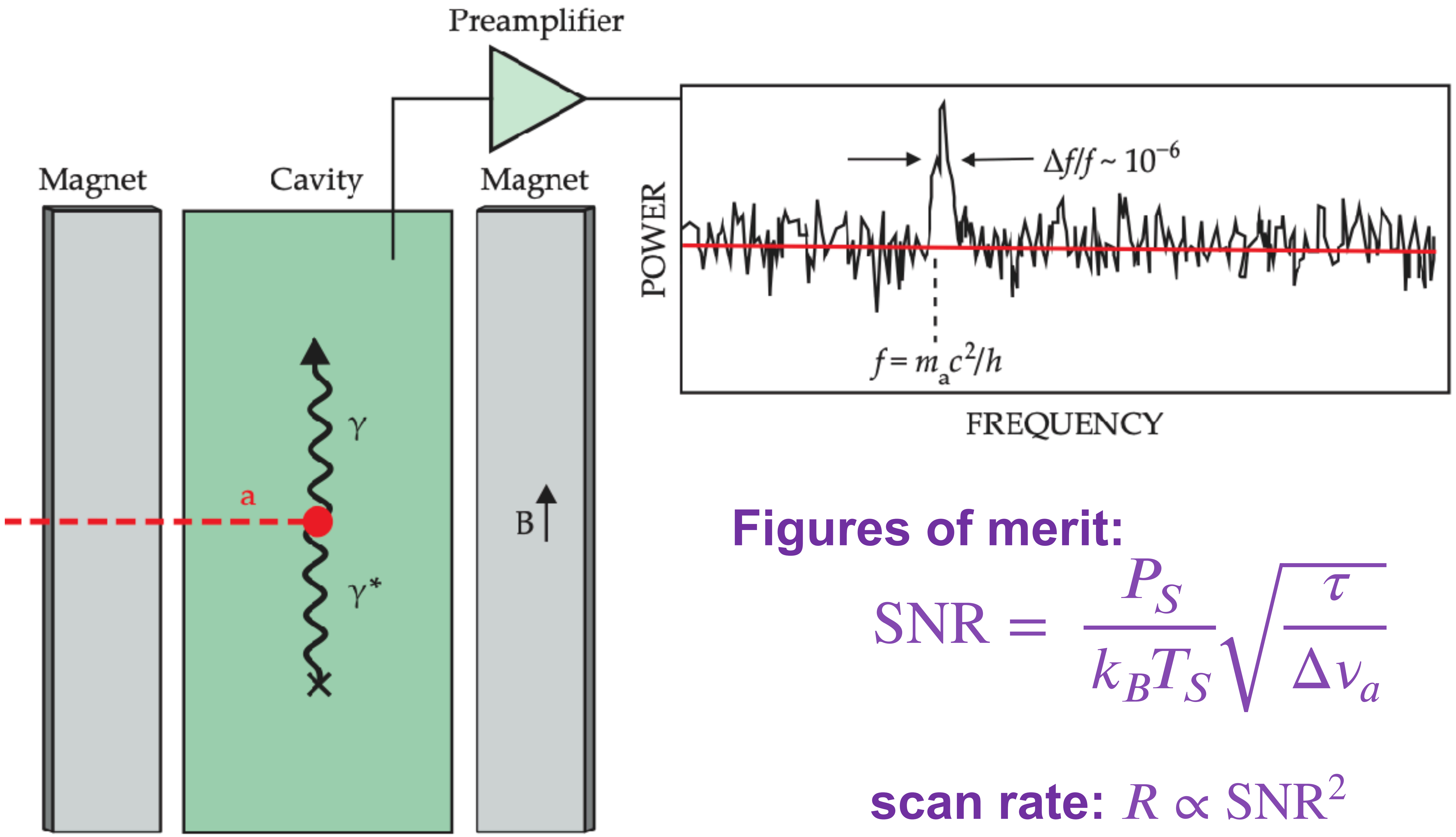
ADMX

HAYSTAC

Haloscope principle: P. Sikivie, *Phys. Rev. Lett.*, **51**, 1415 (1983)

HAYSTAC detector: Nucl. Instrum. Methods A 854, 11 (2017)

Detecting Axions: the Haloscope Principle



Figures of merit:

$$\mathrm{SNR} = \frac{P_S}{k_B T_S}\sqrt{\frac{\tau}{\Delta \nu_a}}$$

scan rate: $R \propto \mathrm{SNR}^2$

Scaling:

Signal power:

$$P = \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B_e^2$$

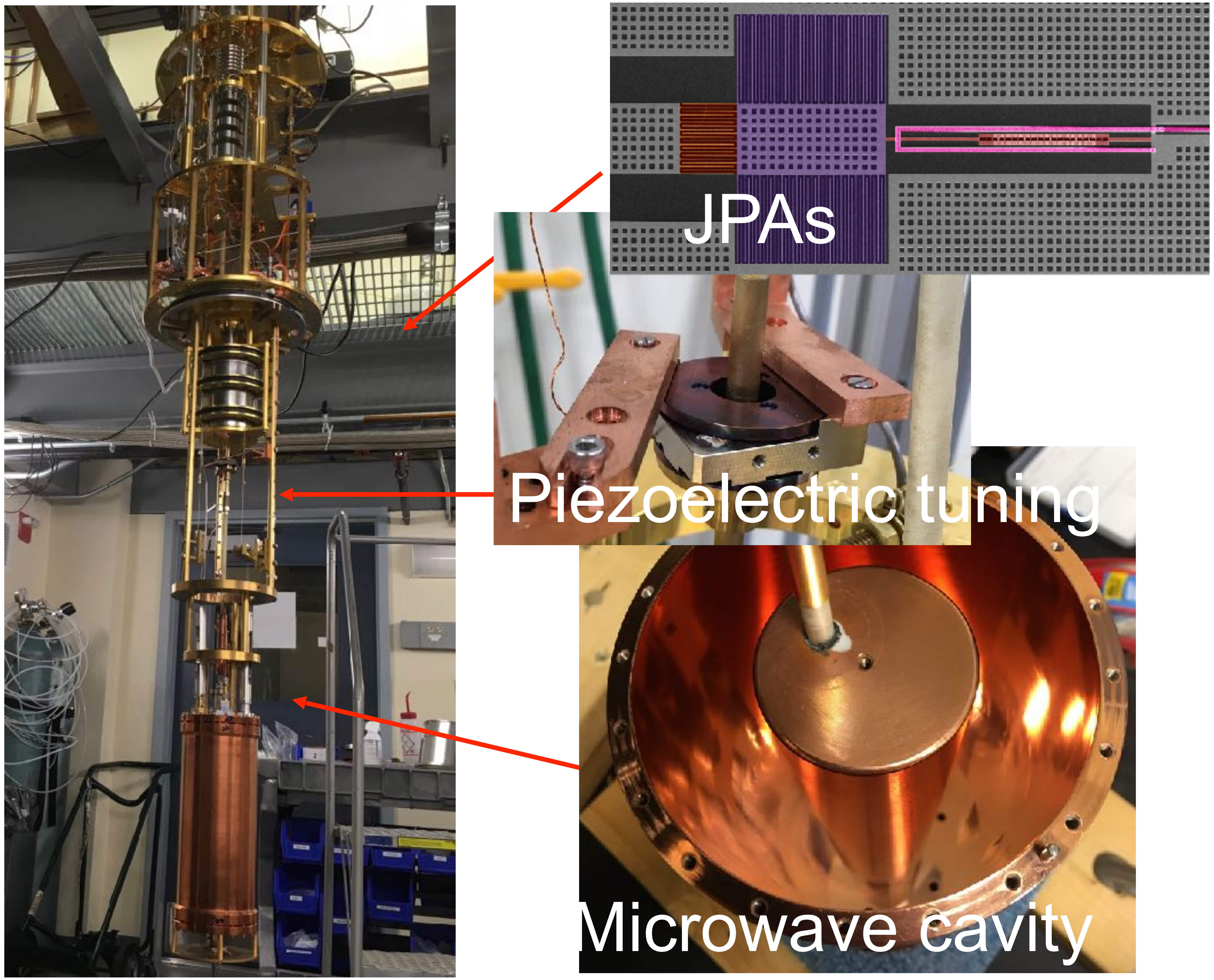
m_a = (4.1 μeV) ⨉ (f / GHz)

$$(f)_{TM_{010}} = \frac{2.405}{2\pi a\sqrt{\mu_0\epsilon_0}} = \frac{0.115}{a}\ \mathrm{GHz}$$

For f = 10 GHz, cavity of ~1.15 cm

Physics Today 72, 6, 48 (2019)

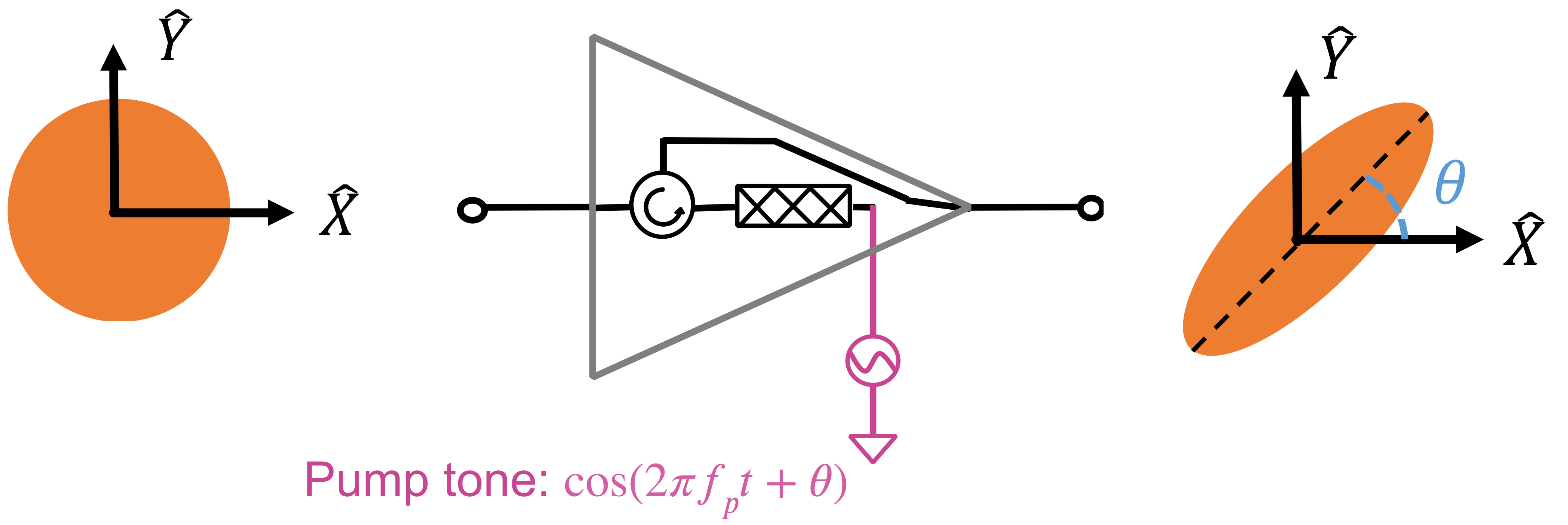
HAYSTAC Experiment

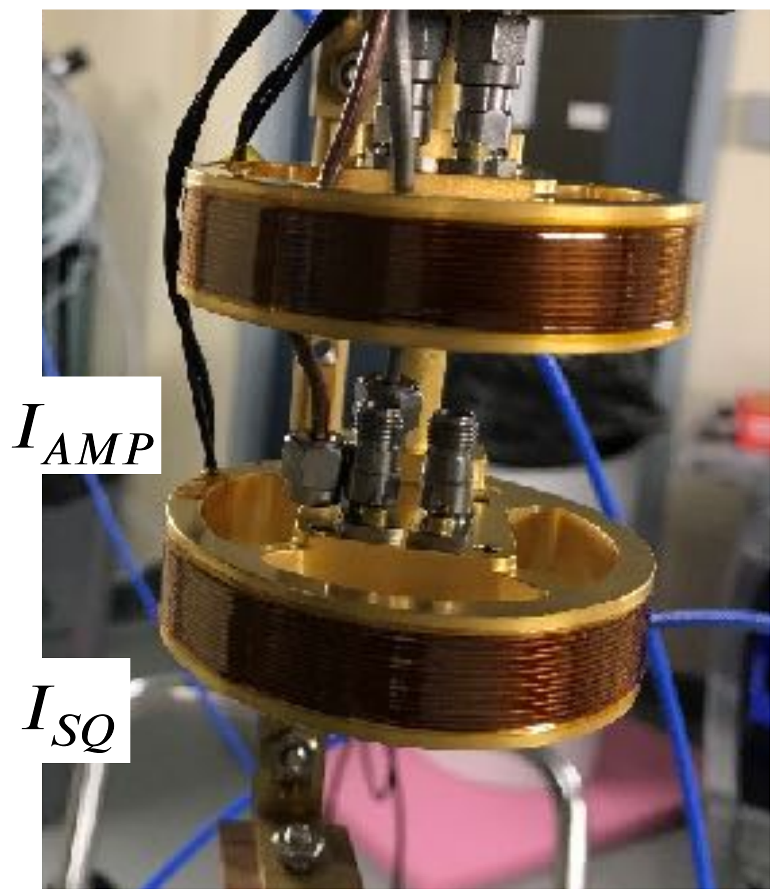


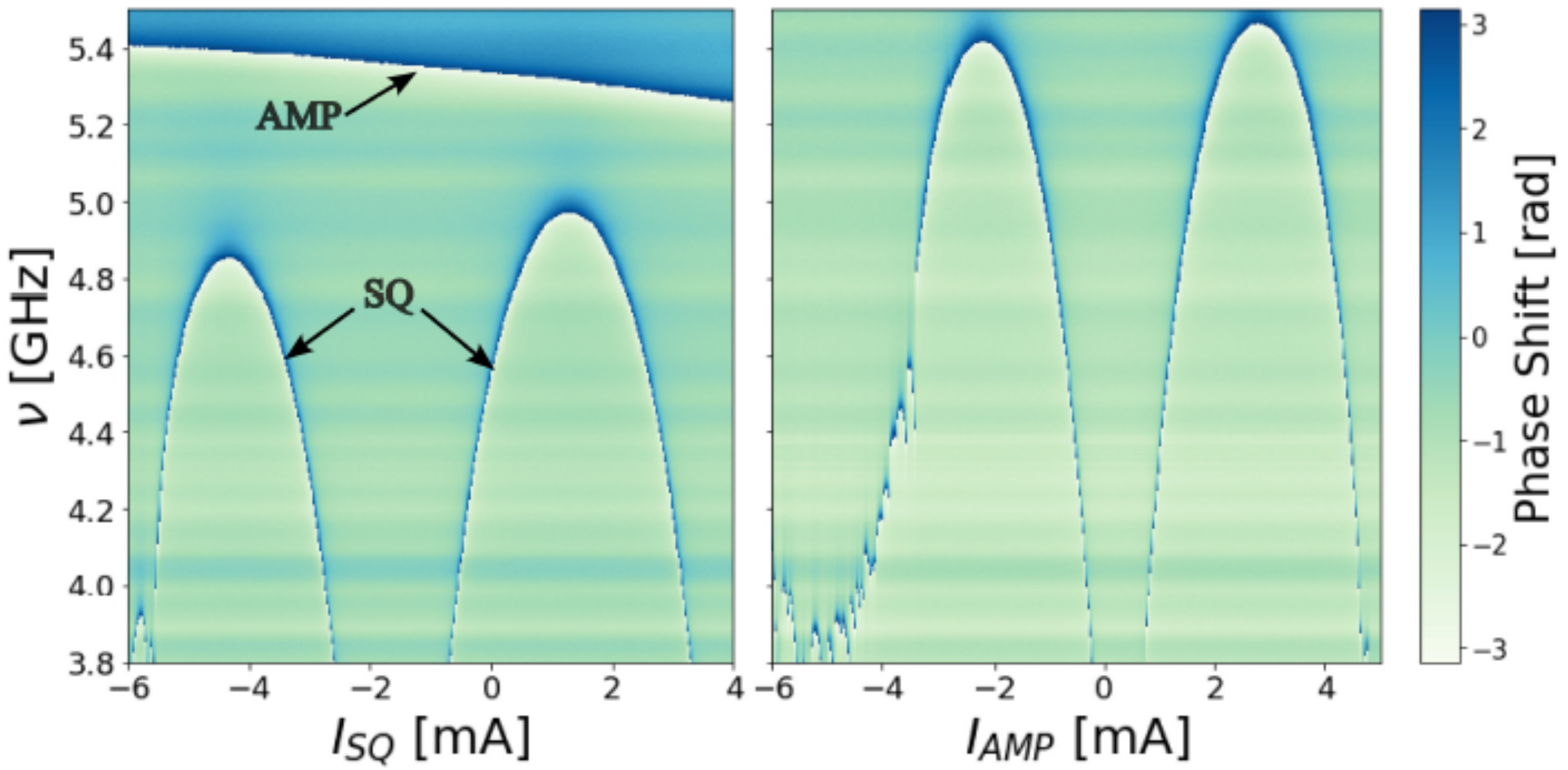
Brubaker et al., PRL 118 061302 (2017)

HAYSTAC's Innovations: Phase 1

- Use JPAs to lower the system noise
- Tunable LC resonators
- Near Quantum Limited Noise
- Can Operate in Phase Sensitive mode



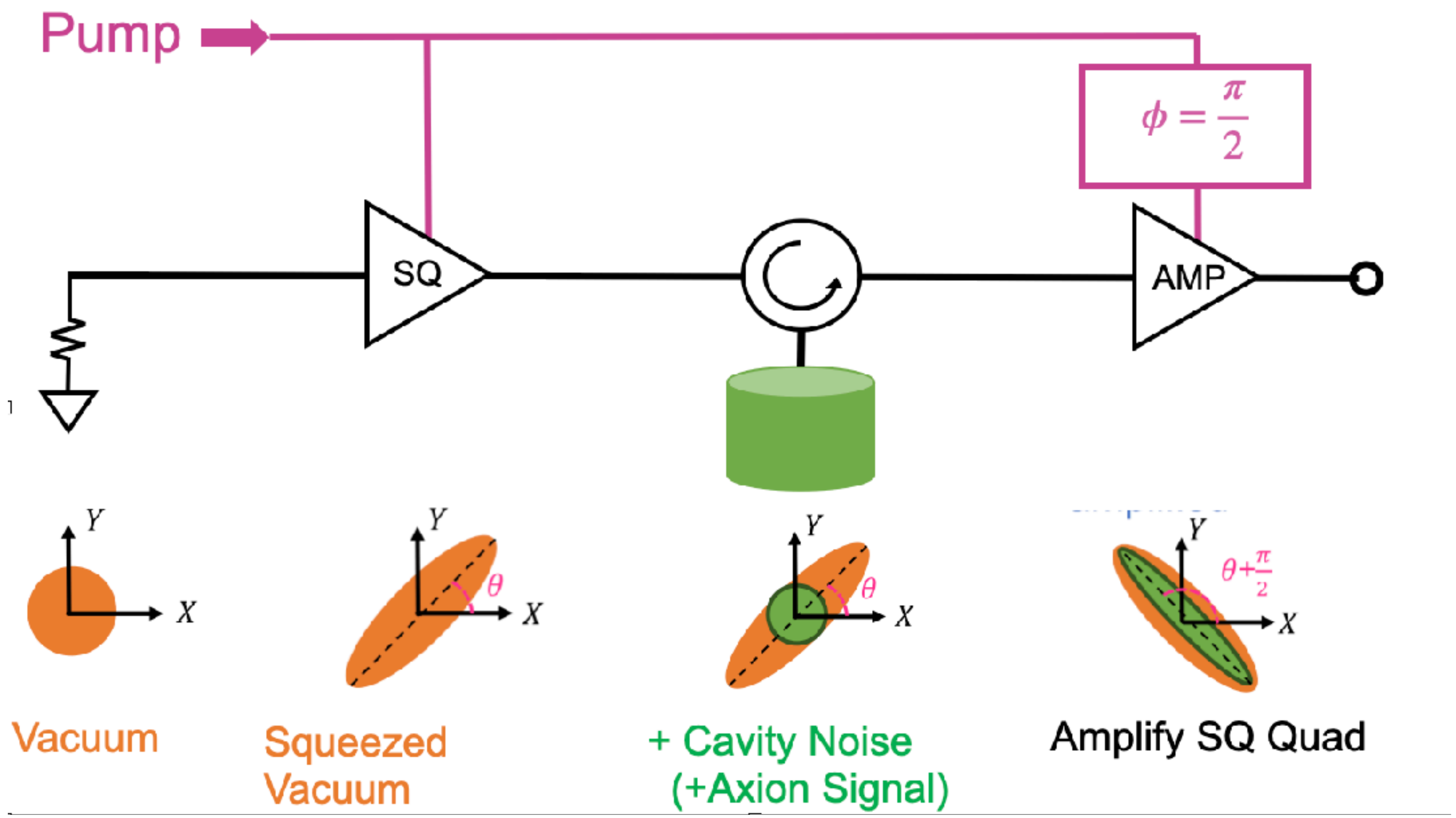




Malnou et al., Phys. Rev. X 9, 021023 (2019)

HAYSTAC Innovation Phase 2: Squeezing

- 2 JPAs in tandem can even beat the Quantum Limit
- Squeezed State Receiver



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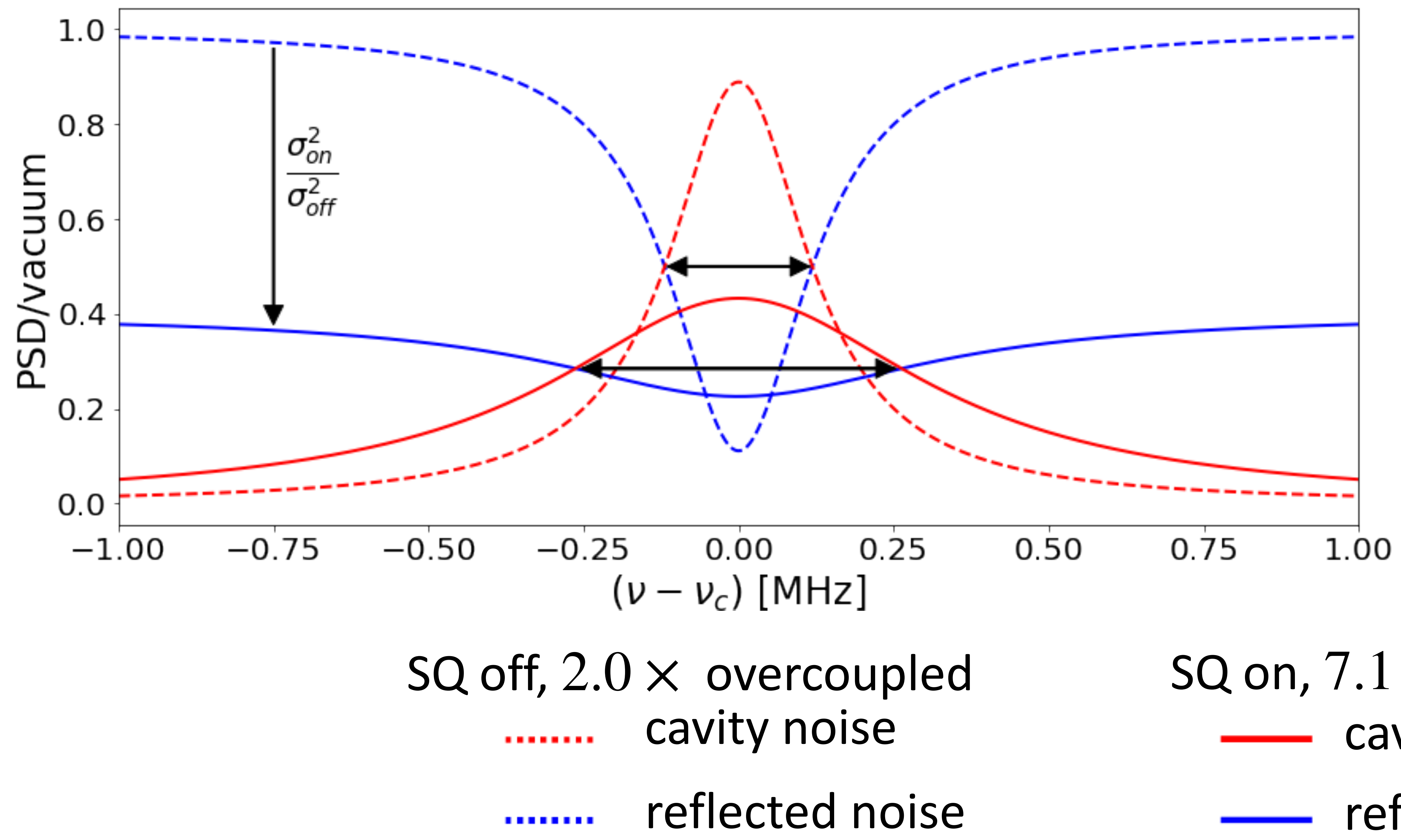
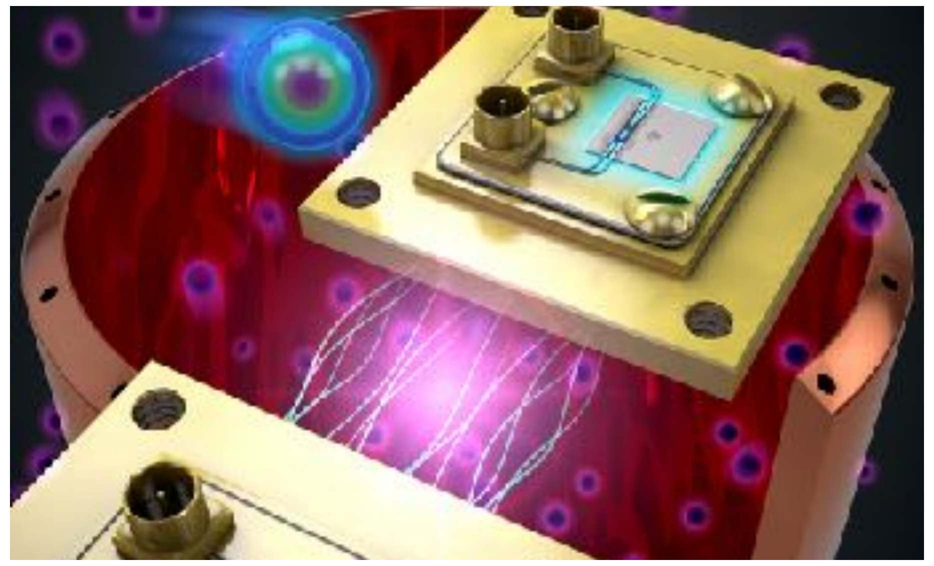


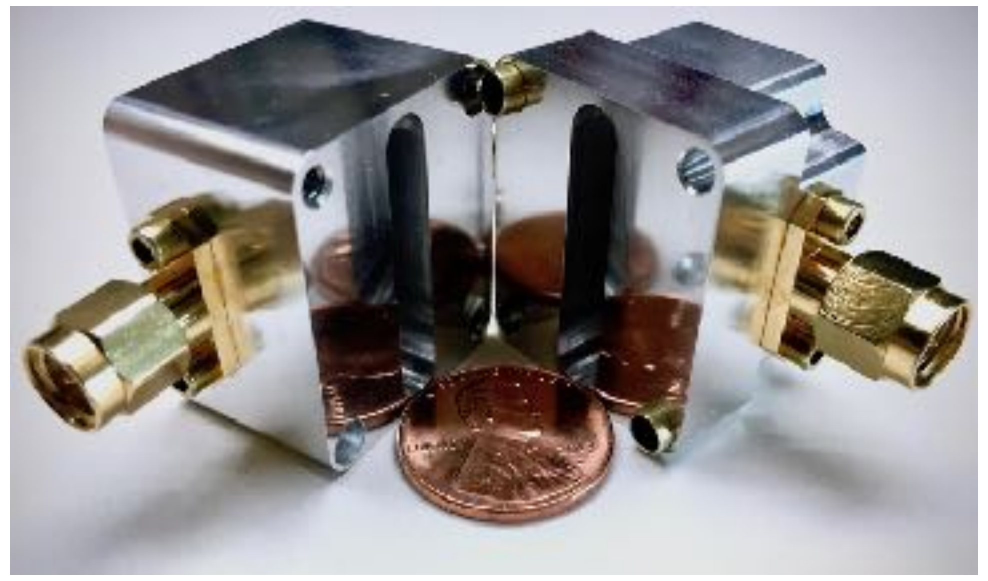
S = $\frac{\sigma^2_{on}}{\sigma^2_{off}} = 4.0dB$

~2x Speed

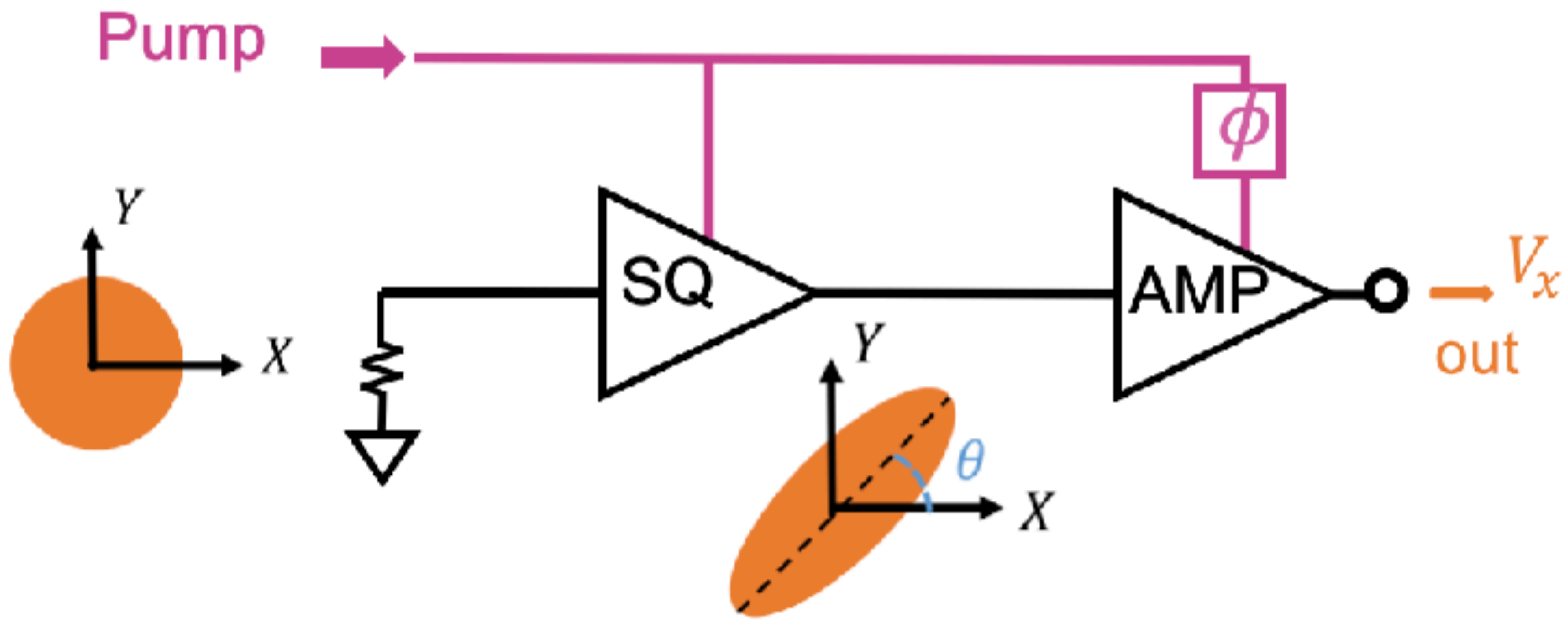
Backes et al., Nature, **590**, 238 (2021)

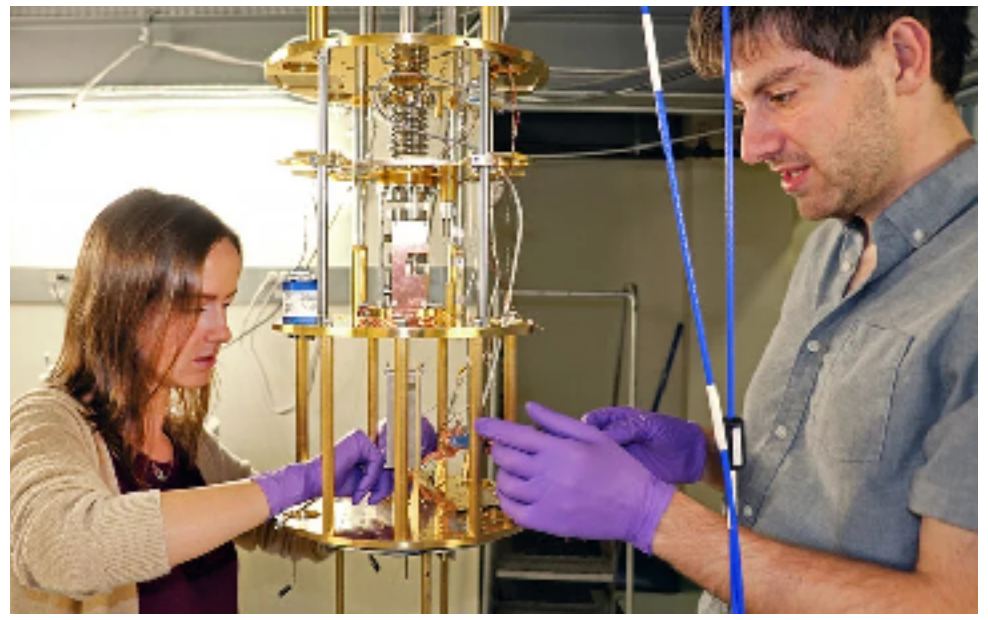
HAYSTAC: Phase 2

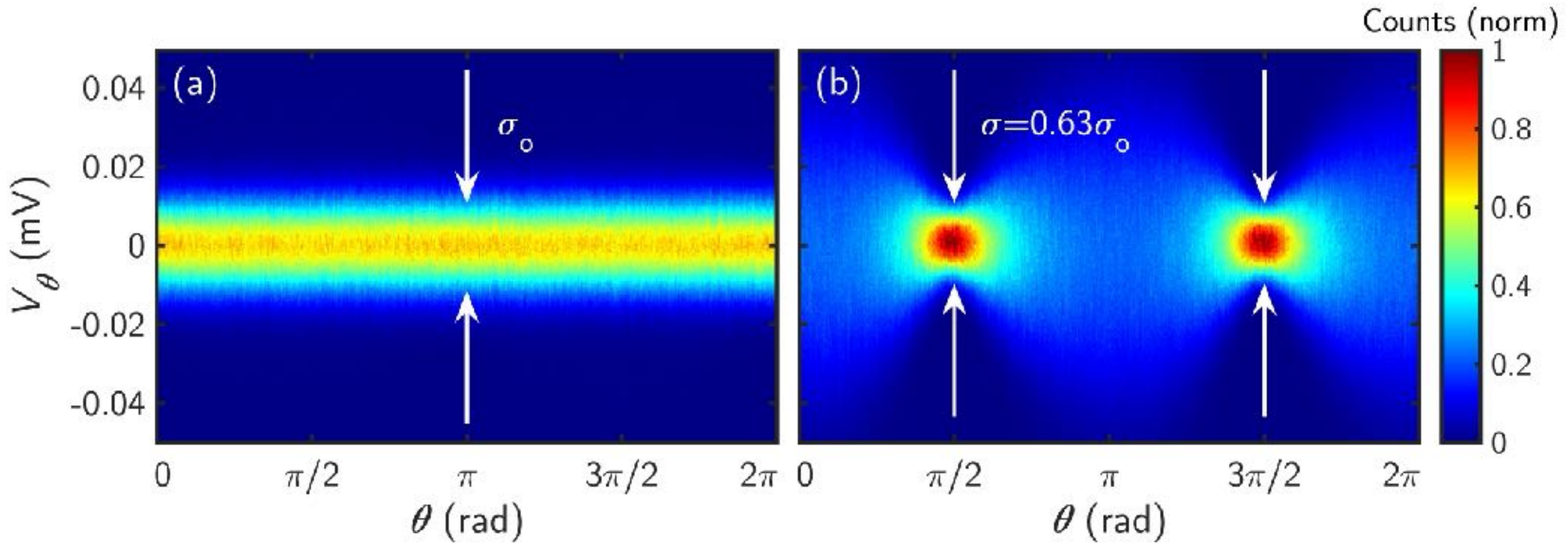




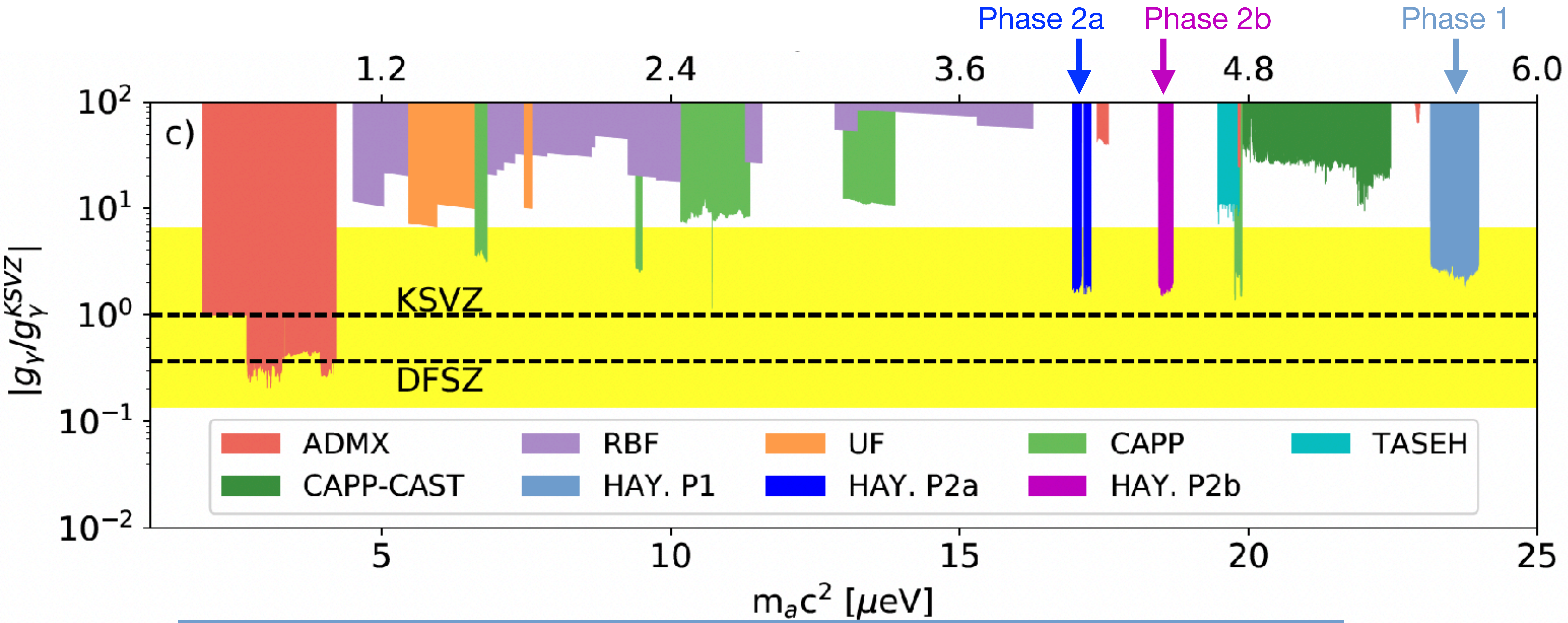
- Dark matter search enhanced by quantum squeezing
- Josephson Parametric Amplifier source squeezed states
- Squeezed state receiver operation
- -4dB noise reduction
- x2 speedup







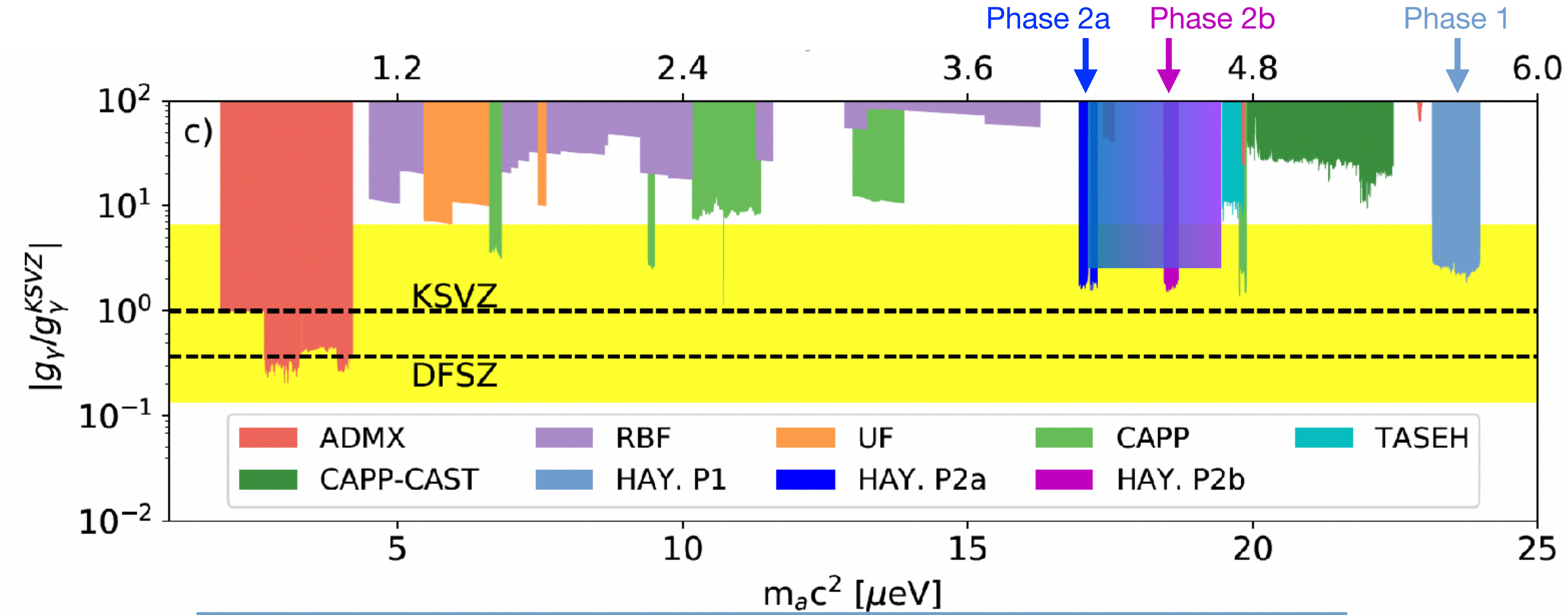
HAYSTAC: Results so far



~330MHz of parameter space in the QCD band between 4.1-5.8 GHz

- Brubaker et al., PRL 118 061302 (2017), Axion search with Quantum limited Noise
- Zhong et al., PRD 97, 092001 (2018)
- Backes et al., Nature, 590, 238–242 (2021), reach below the SQL
- Jewell et al., PRD, 107, 072007 (2023)

HAYSTAC: Phase 2 Projected



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HAYSTAC & ALPHA: Going higher

- Axion searches in QCD band > 10 μeV -> (~2.5 GHz)
- Challenges:
    - Photon detection, noise
    - Scan rate: $V \propto \nu^{-2}$, $\frac{d\nu}{dt} \propto V^2$, $\frac{d\nu}{dt} \propto \nu^{-4}$

Borsanyi et al (2016) PQ symmetry broken after inflation: m_a > 10 μeV

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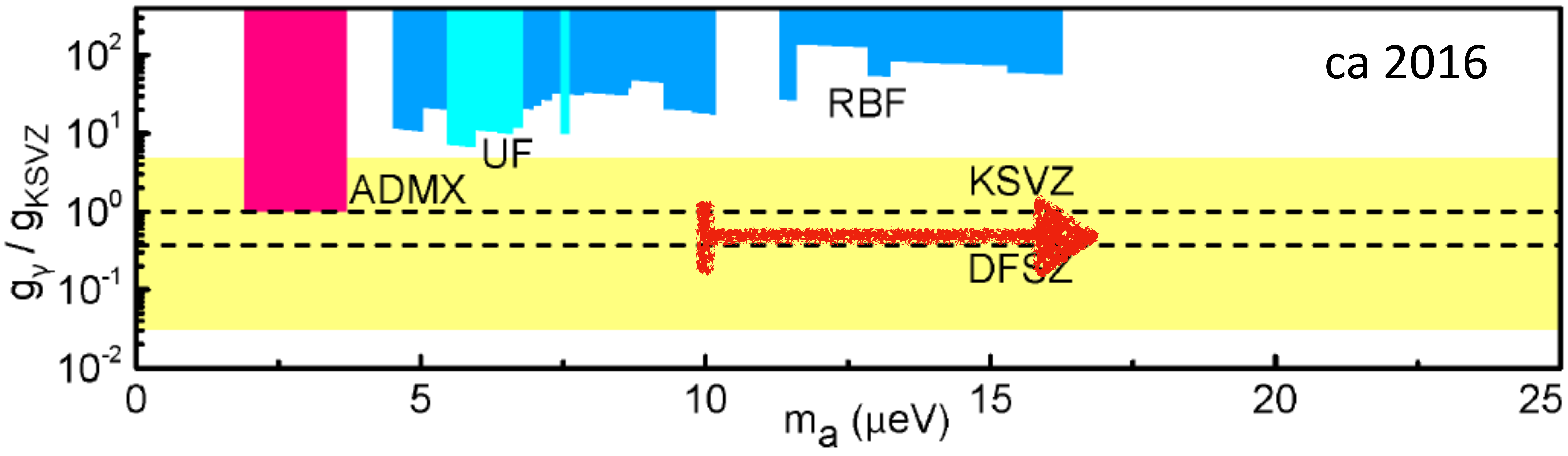

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* In $\Omega_A \sim f_A^\alpha$, the best fit α = 1.24 ± 0.04
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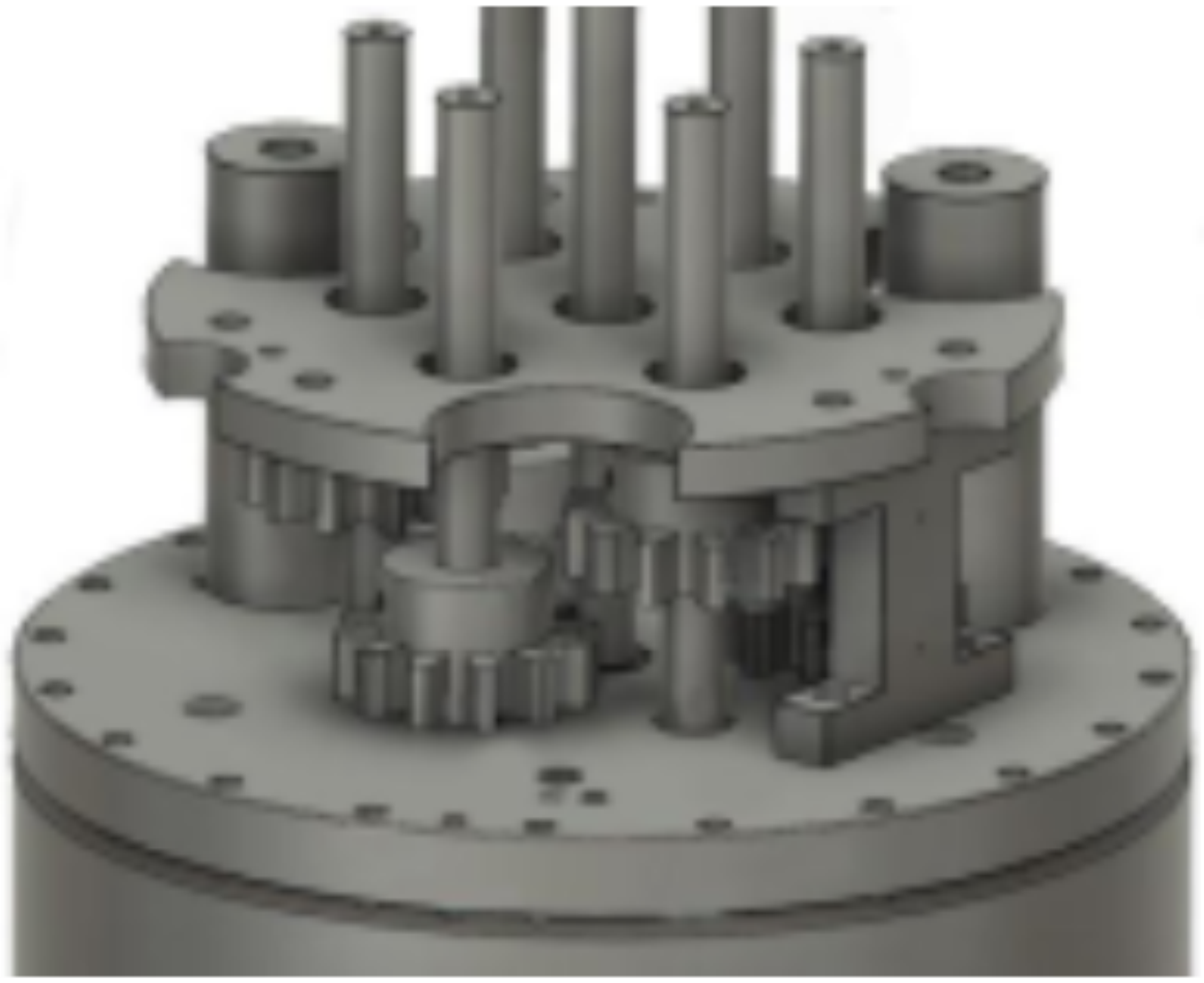
Next set of innovations

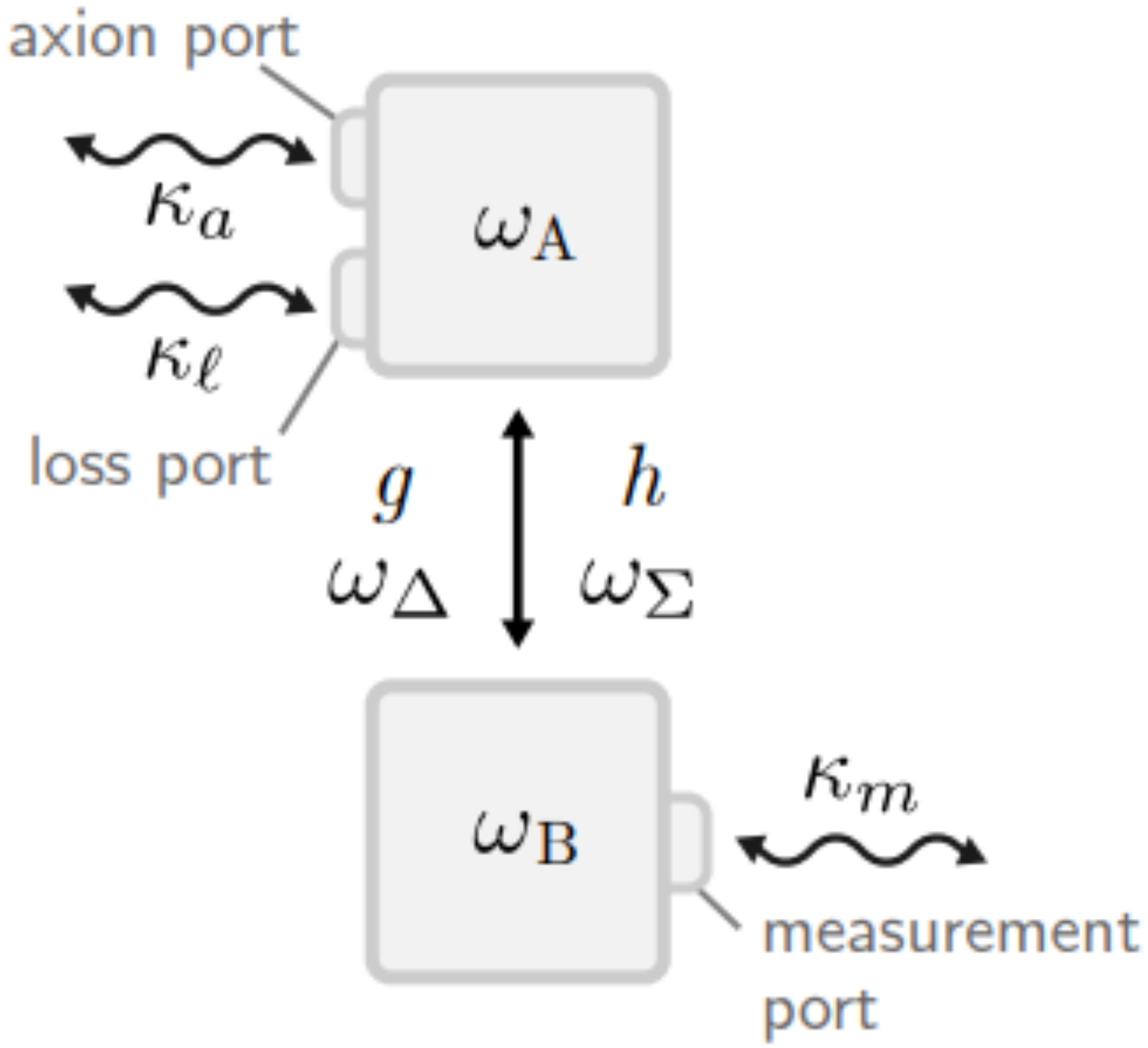
Multi-Rod Cavity

Same Radius but extend >6GHz



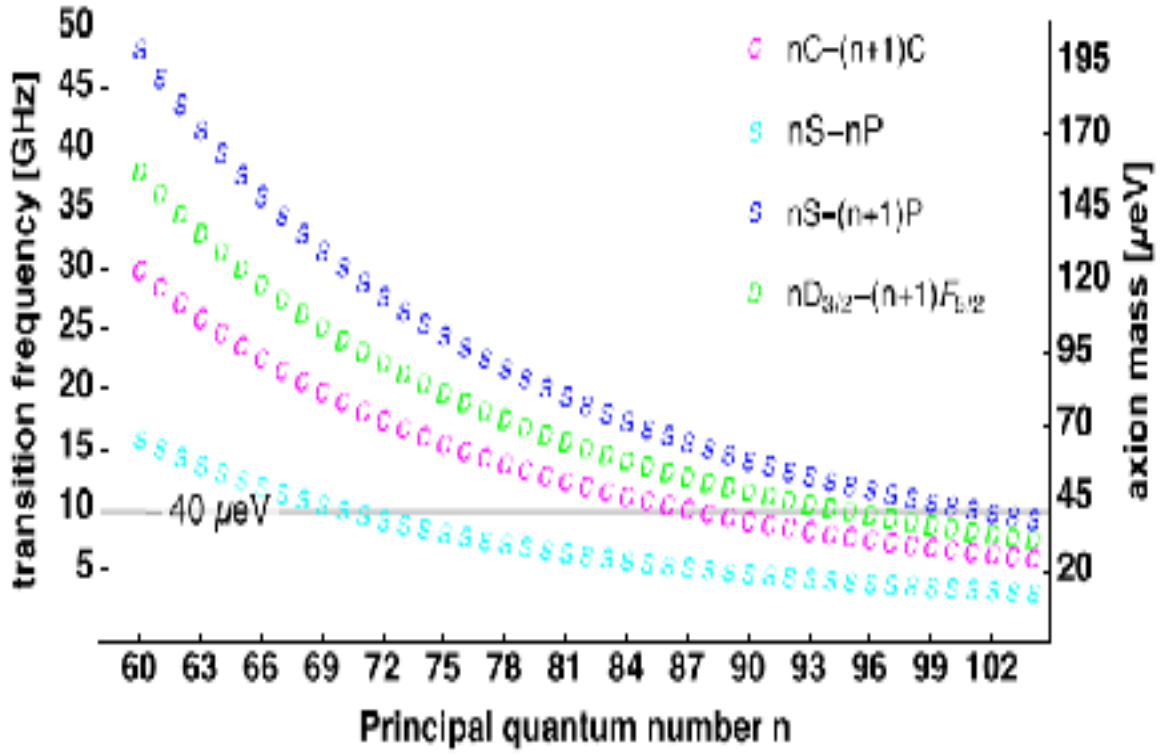
CEASEFIRE

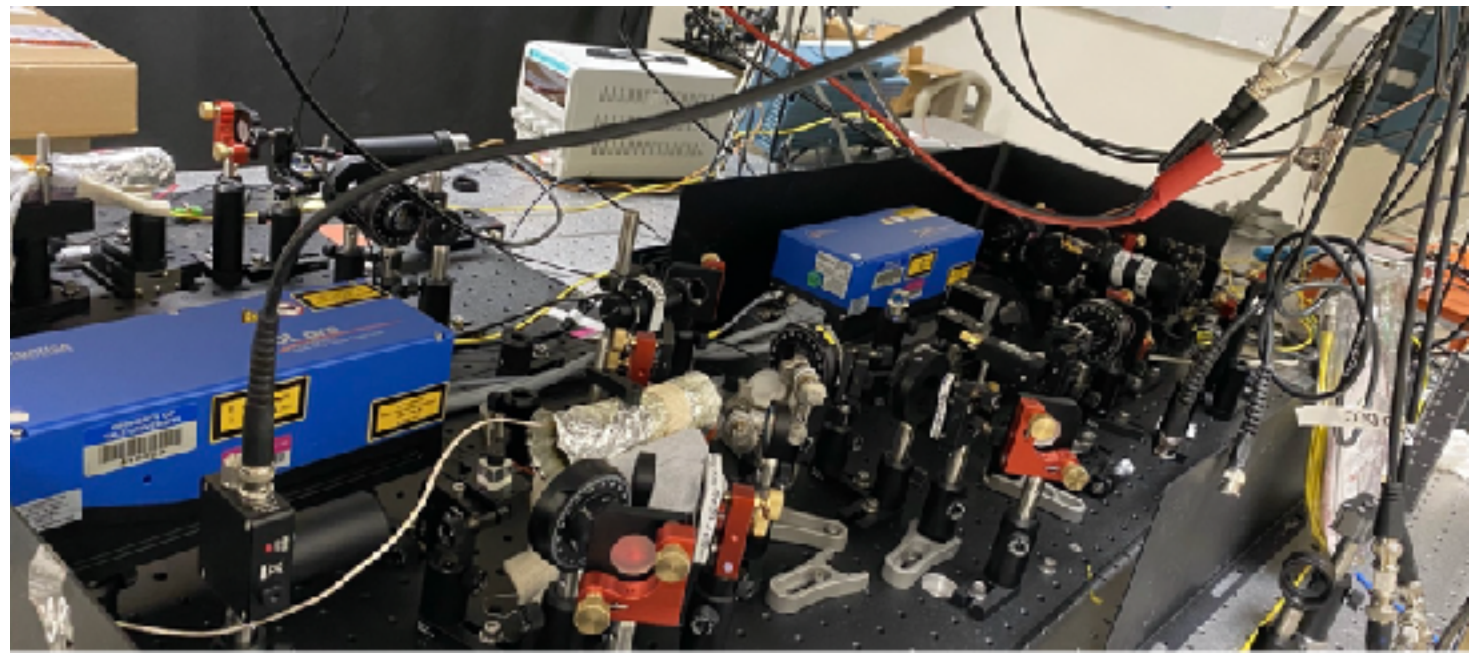
Improve the level of squeezing we achieve



RAY

Use Rydberg atoms as single photon counters for > 10GHz

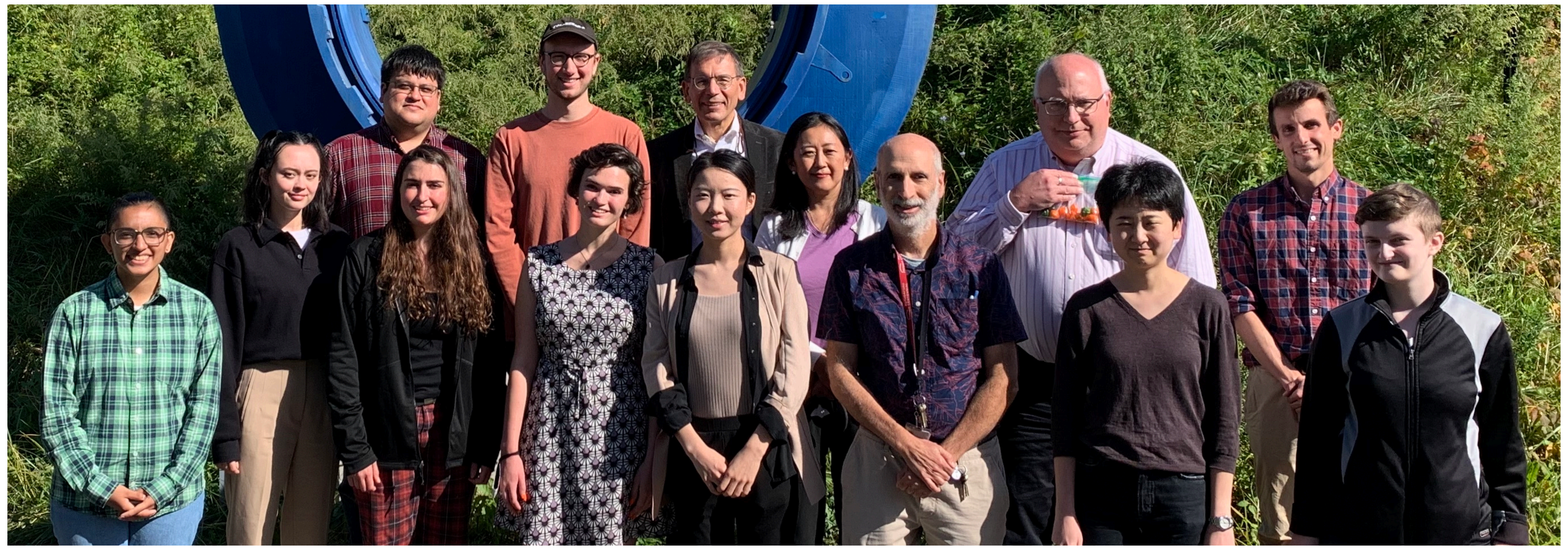




Credit: M. Jewell

https://axion-dm.yale.edu/

Haystac



YALE (HOST), UC BERKELEY, CU-BOULDER, & JOHNS HOPKINS

U.S. DEPARTMENT OF ENERGY | Office of Science
QuantiSED
NSF

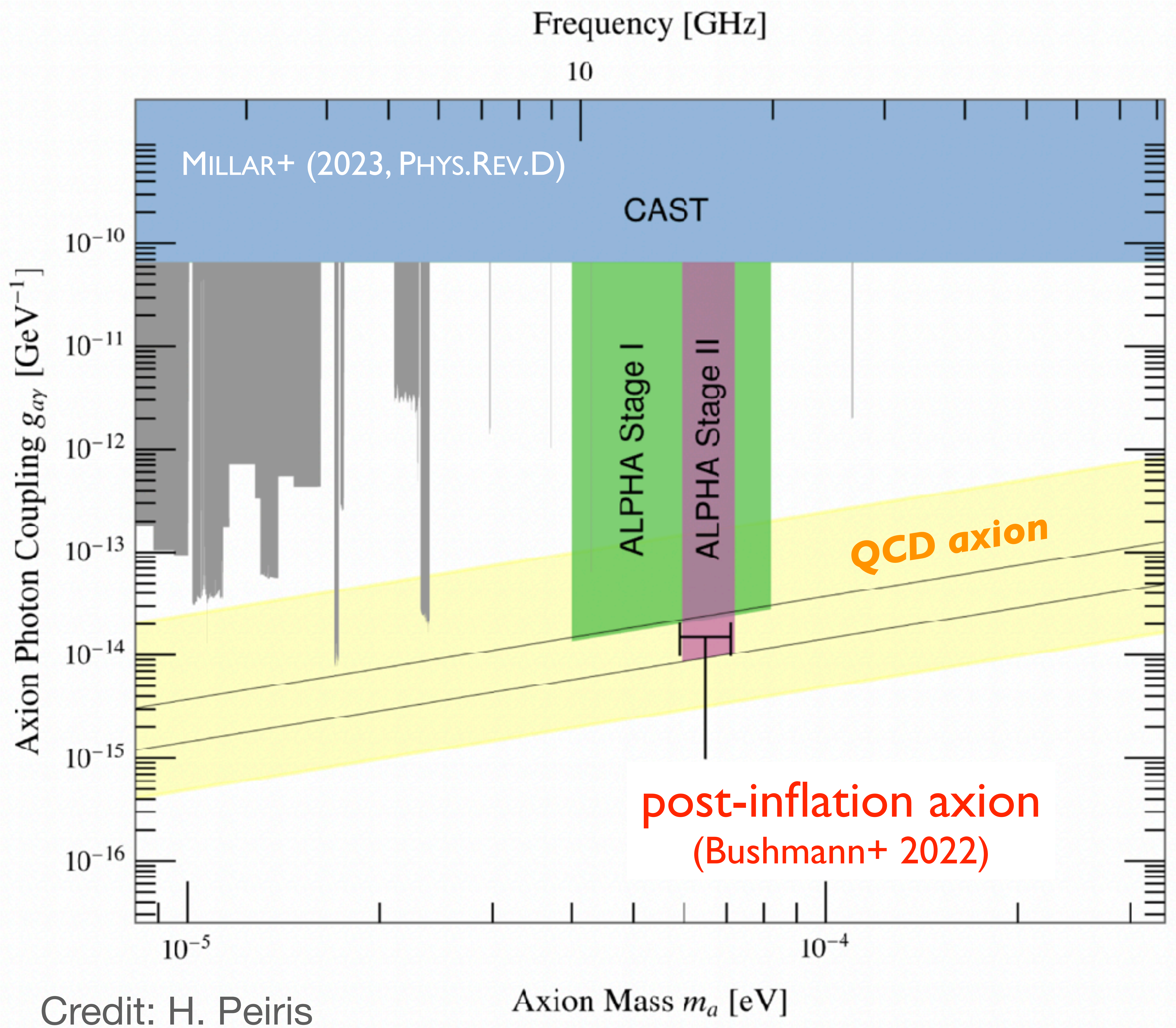
Wright Laboratory
Yale

ALPHA

YALE (HOST), ASU, UC BERKELEY, CAMBRIDGE, COLORADO (BOULDER), ICELAND, ITMO, JHU, MIT, ORNL, STOCKHOLM, AND WELLESLEY.

SIMONS FOUNDATION
John Templeton Foundation — Inspiring Awe & Wonder
Knut and Alice Wallenberg Foundation
Swedish Research Council
Rymdstyrelsen — Swedish National Space Agency
Funded by the European Union
erc — European Research Council

ALPHA

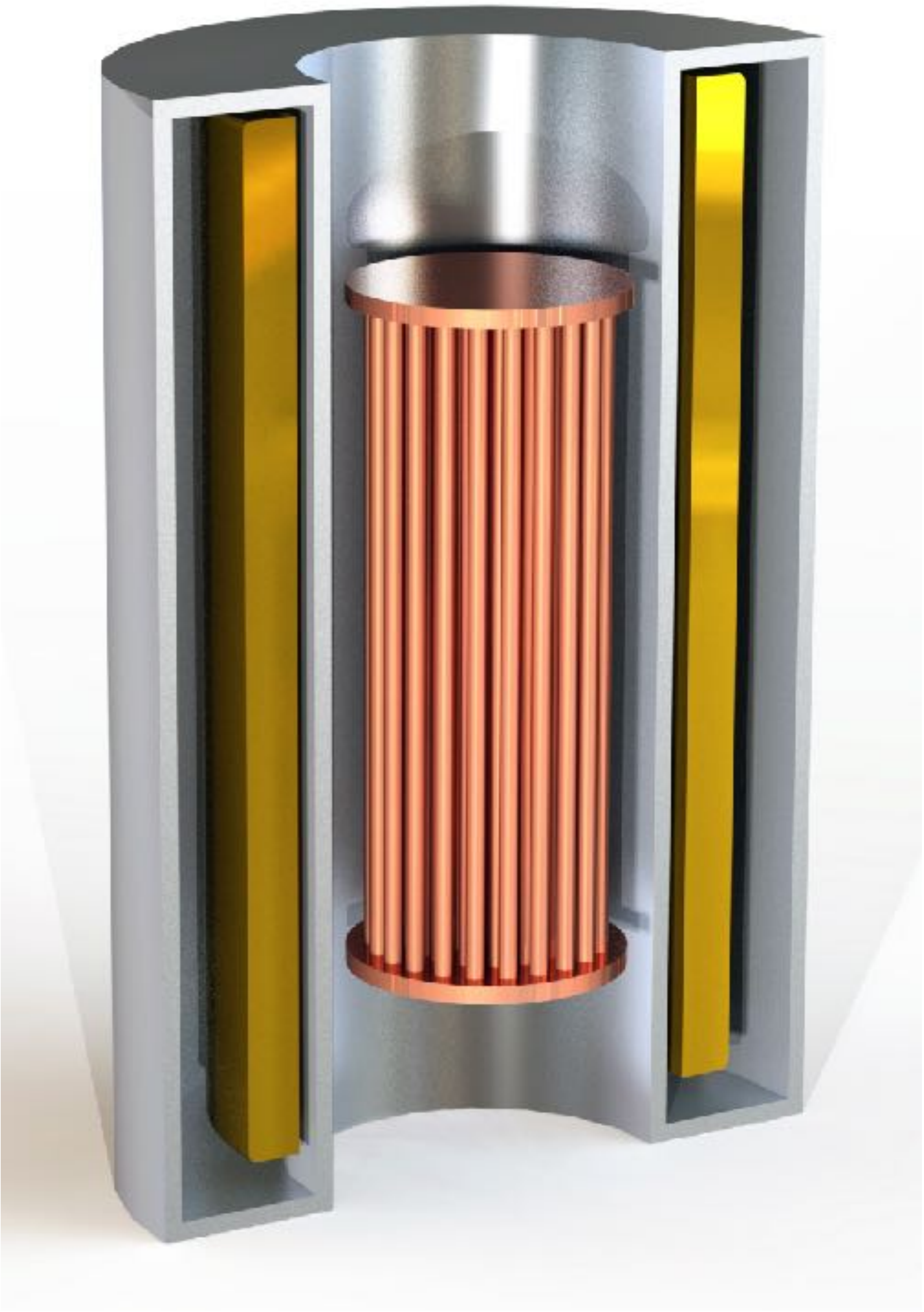


Credit: H. Peiris

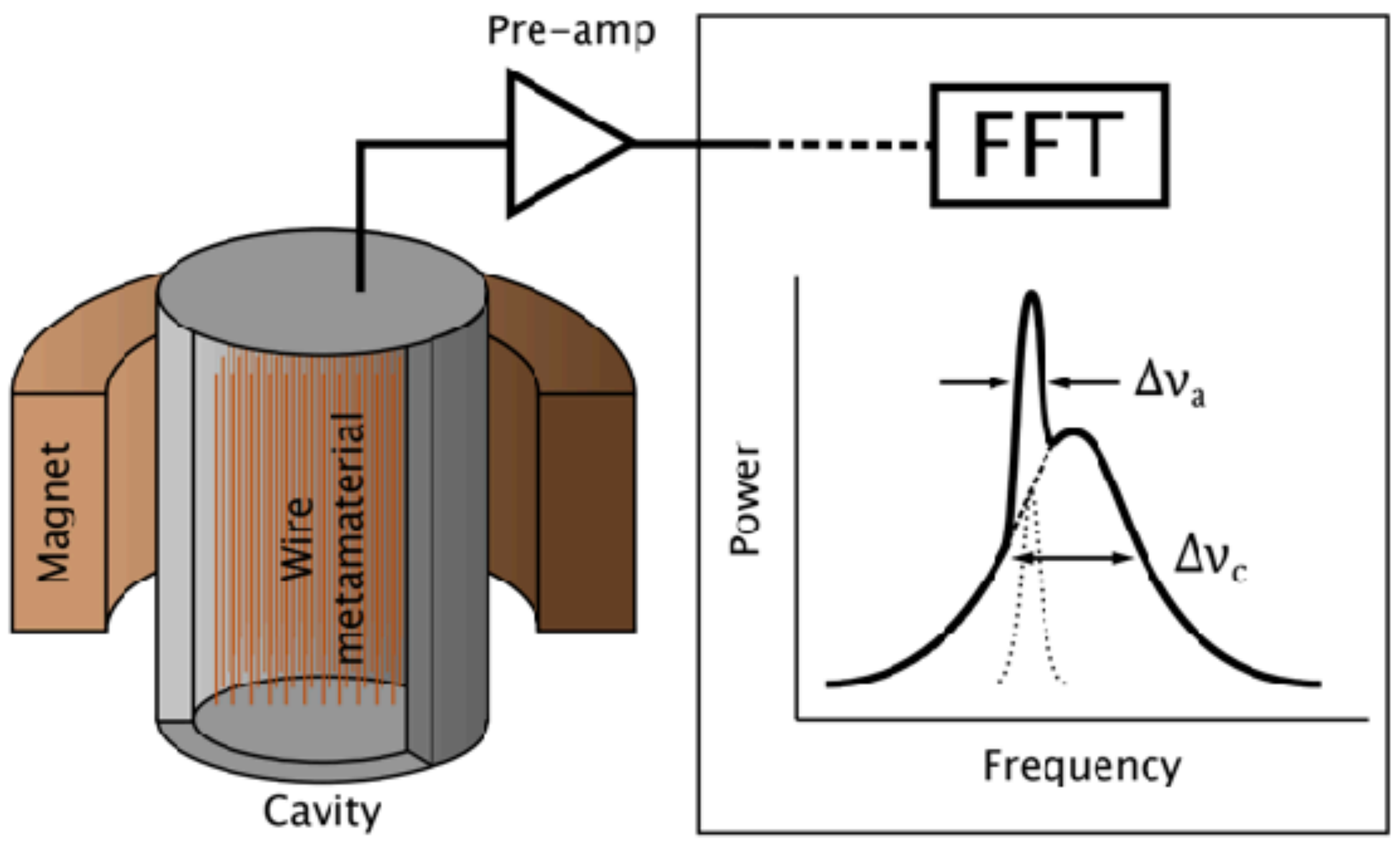
- Post-inflation axion: one of two well-motivated mass ranges.
- Mass is uniquely determined, limited only by computation.
- Recent calculations: ~15 GHz, 65 µeV (Buschmann+ 2022)
- Out of reach of conventional cavities but accessible to plasma haloscope
- Construction of ALPHA underway, experiment hosted at Yale

YALE (HOST); ASU; UC BERKELEY; CAMBRIDGE; COLORADO (BOULDER); ICELAND; ITMO; JHU; MIT; ORNL; STOCKHOLM, WELLESLEY.

Concept: Tunable Axion Plasma Haloscopes

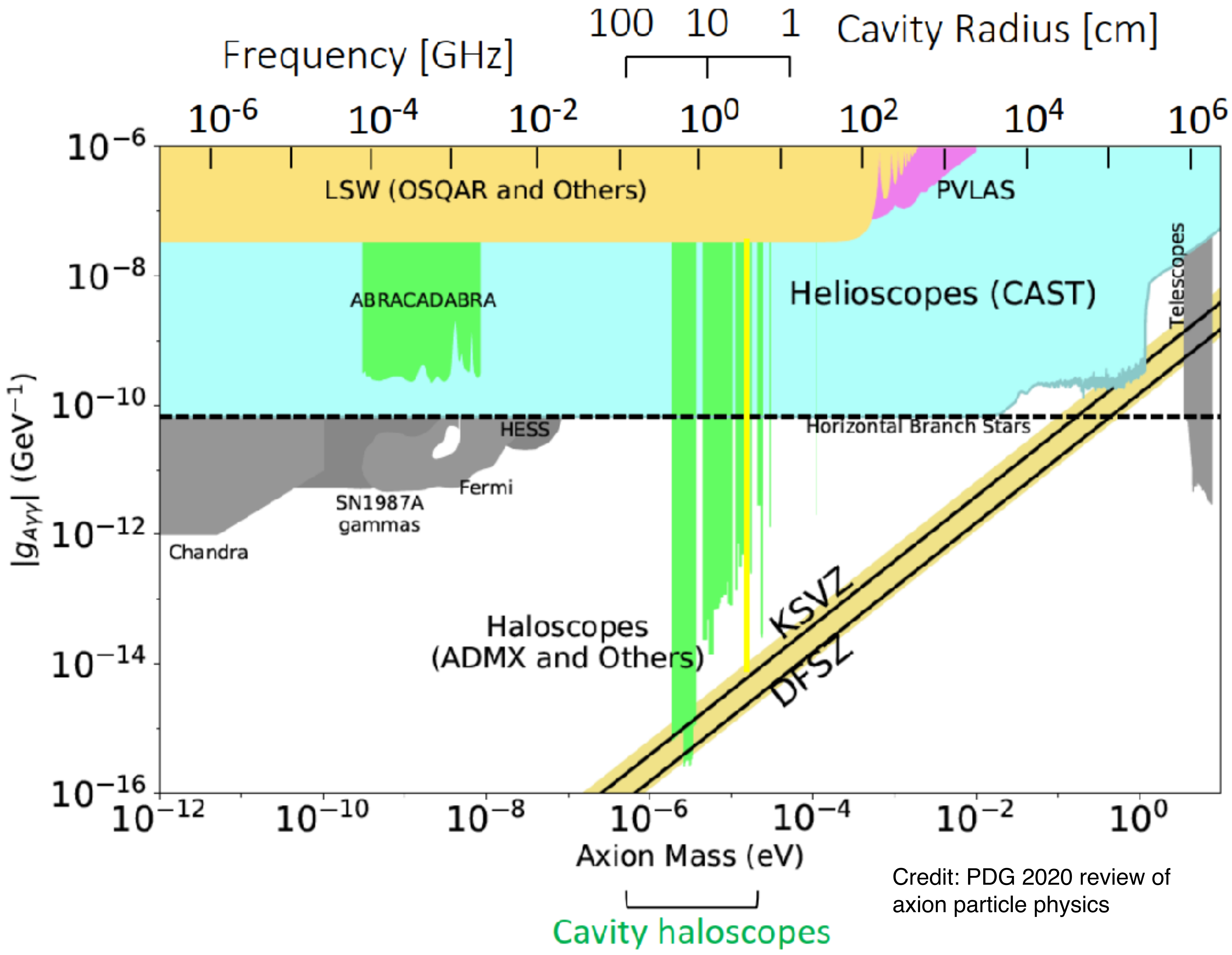


- Idea in Lawson, Millar, Pancaldi, Vitagliano & Wilczek, Phys. Rev. Lett. 123 (2019)
- Allows for larger volumes/higher power for high frequencies than traditional approaches
- + HAYSTAC-like quantum detectors for readout



Kowit et al, *Phys.Rev.Applied* 20 (2023)

Large mass → small volume

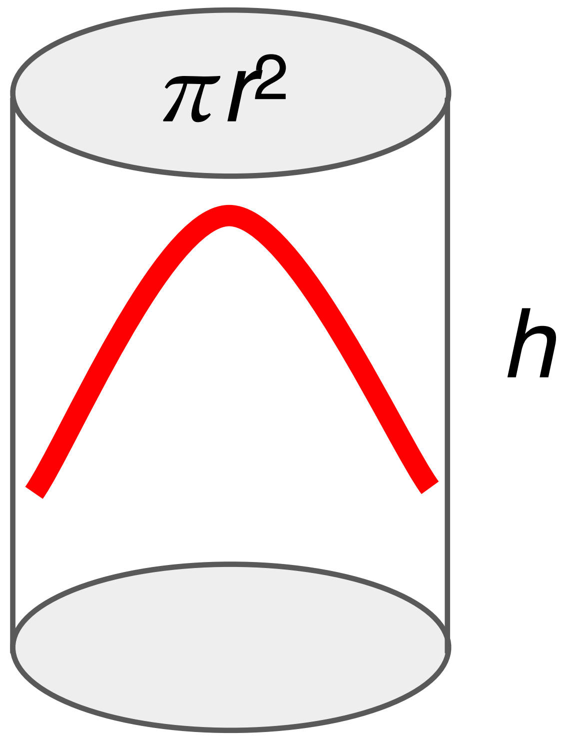


Credit: PDG 2020 review of axion particle physics

The power produced in a haloscope:

$$P = \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B_e^2$$

Volume = $h \pi r^2$



m_a = (4.1 μeV) × (f / GHz)

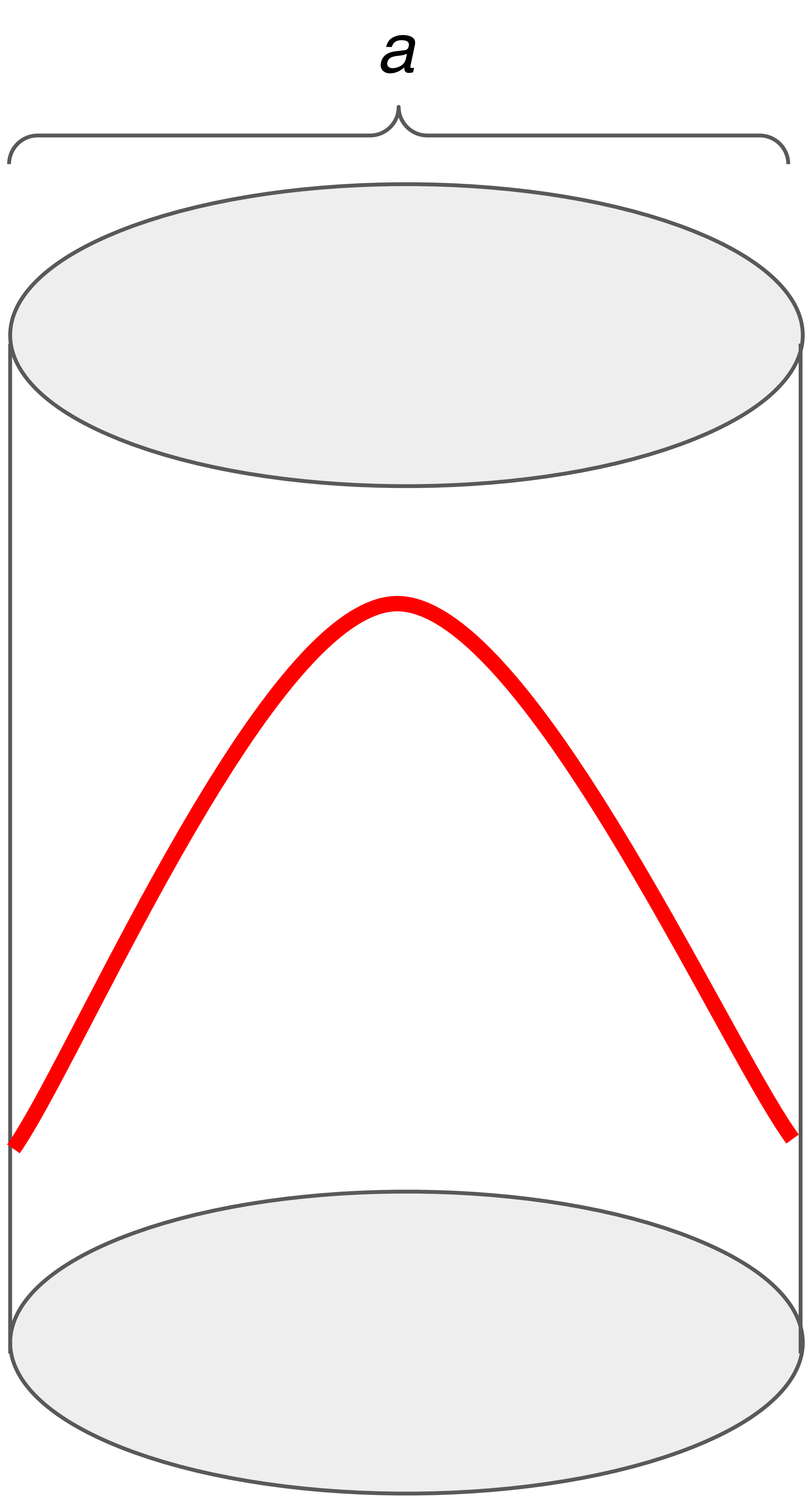
$$(f)_{TM_{010}} = \frac{2.405}{2\pi a \sqrt{\mu_0 \epsilon_0}} = \frac{0.115}{a}\ \mathrm{GHz}$$

For a = 1.15 cm, we get f = 10 GHz

Credit: J. Gudmundsson

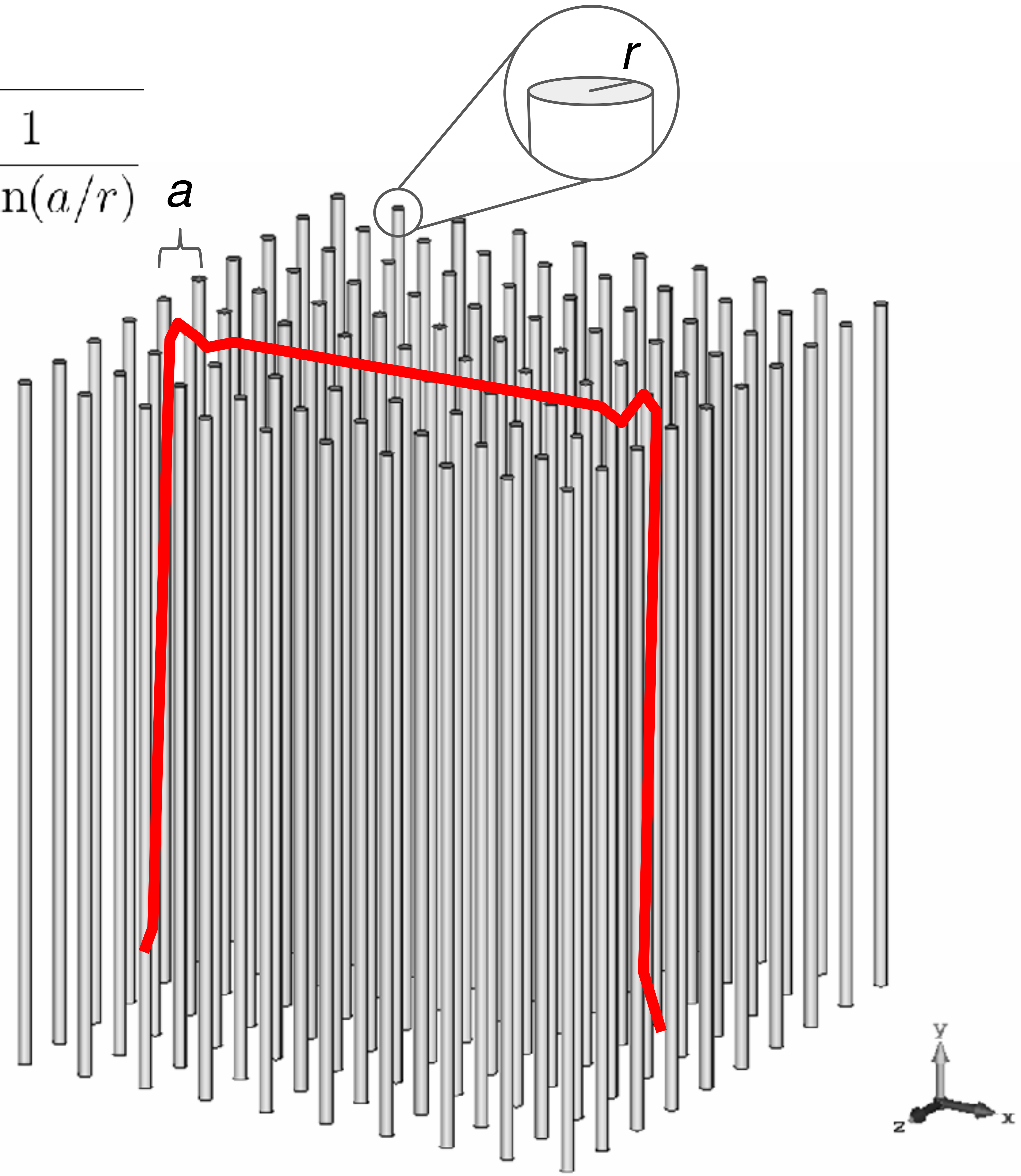
Solution: plasmonic resonance

$$f = \frac{2.405}{2\pi a\sqrt{\mu_0 \epsilon_0}}$$



Sikivie (1983), PRL

$$f = \frac{c}{a}\sqrt{\frac{1}{2\pi \ln(a/r)}}$$



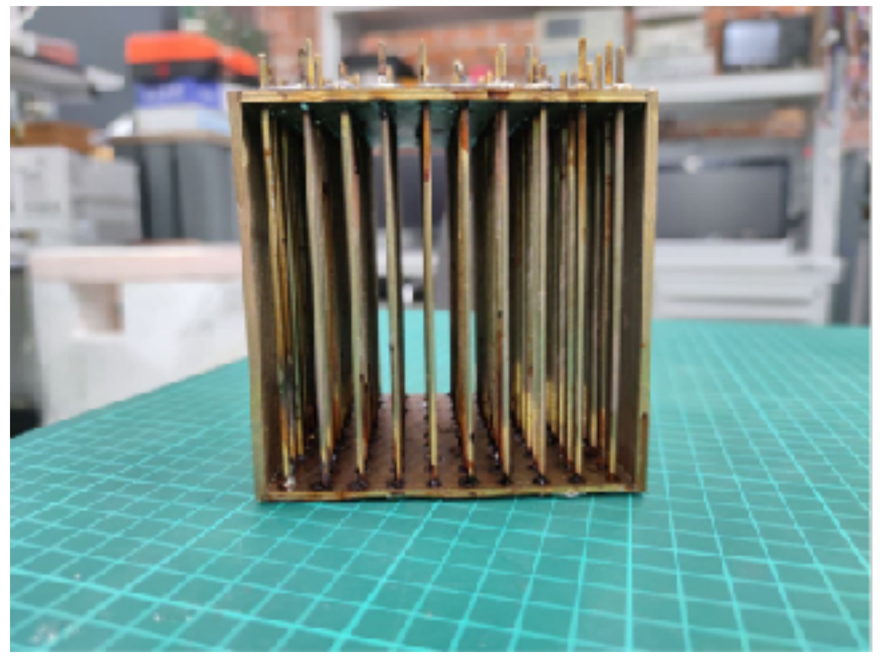
Lawson et al. (2019), PRL

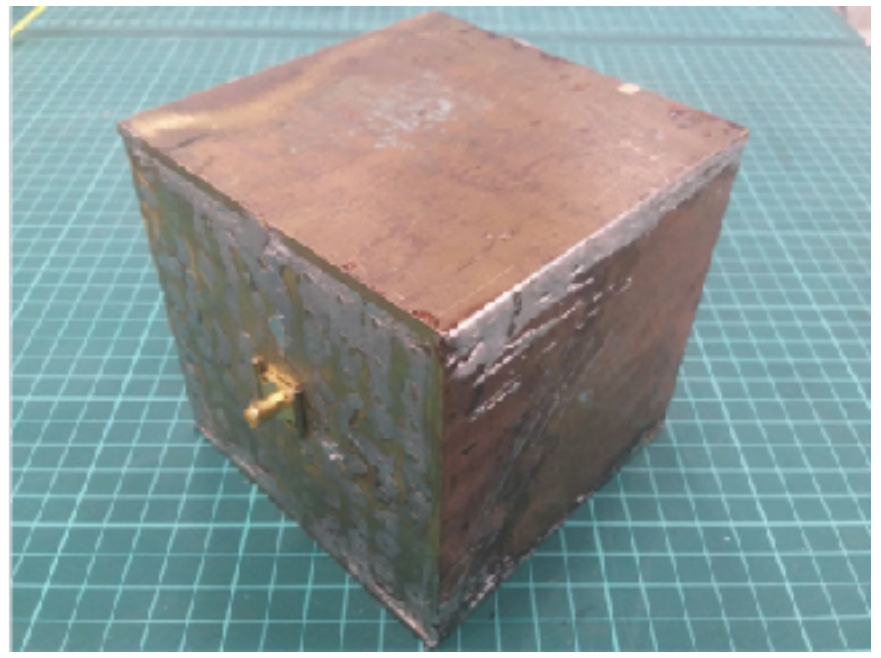
Credit: J. Gudmundsson

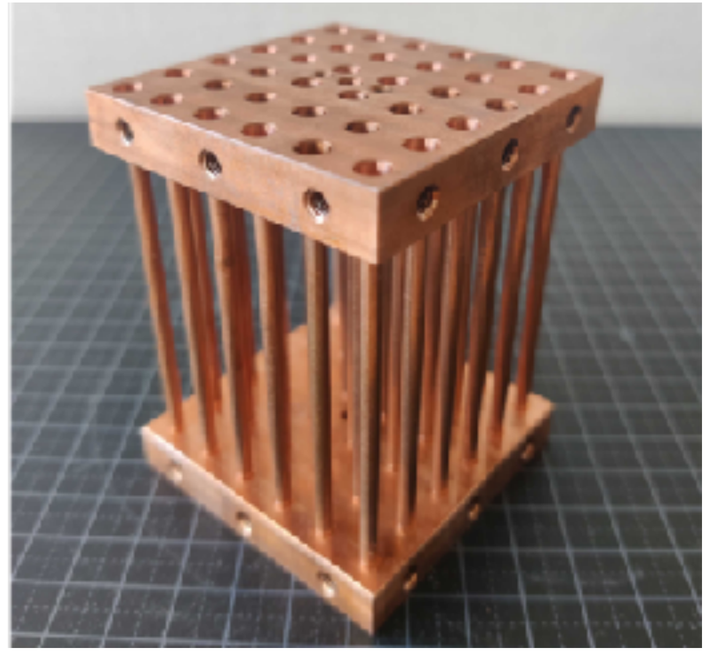
Berkeley resonator prototype

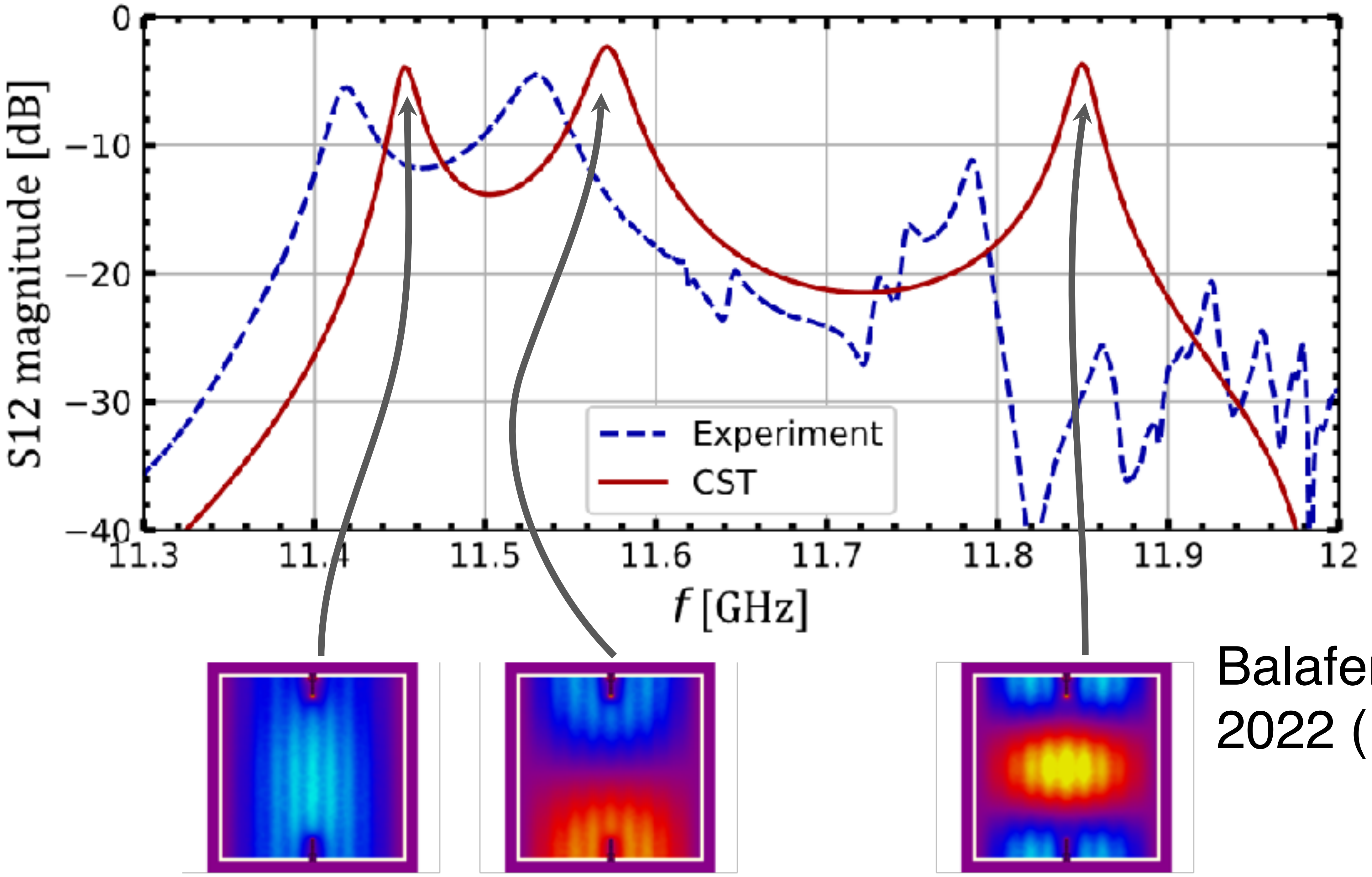
Stockholm resonator prototype

Cavity Development: Stockholm

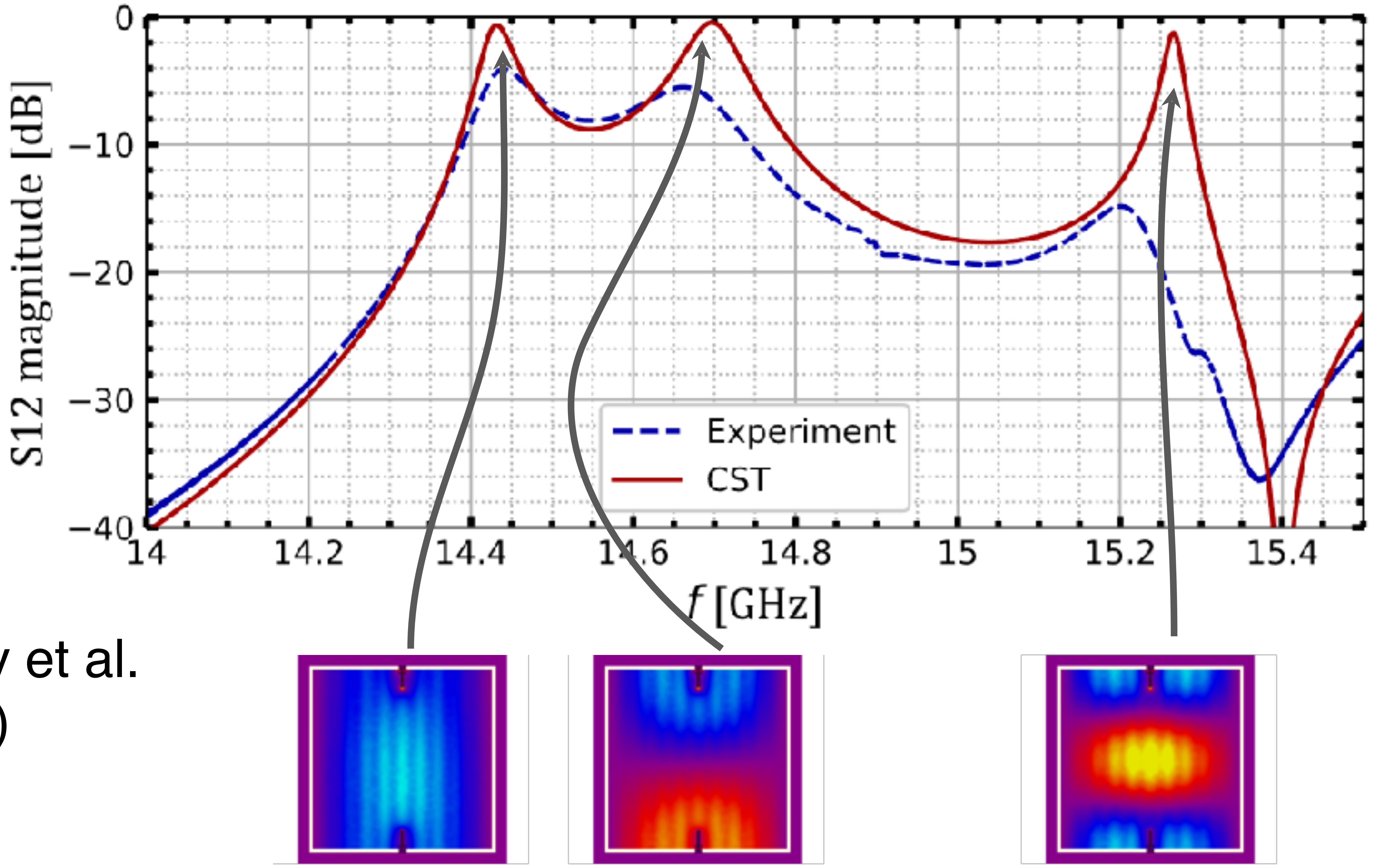








Balafendiev et al.
2022 (PRB)



Credit: J. Gudmundsson

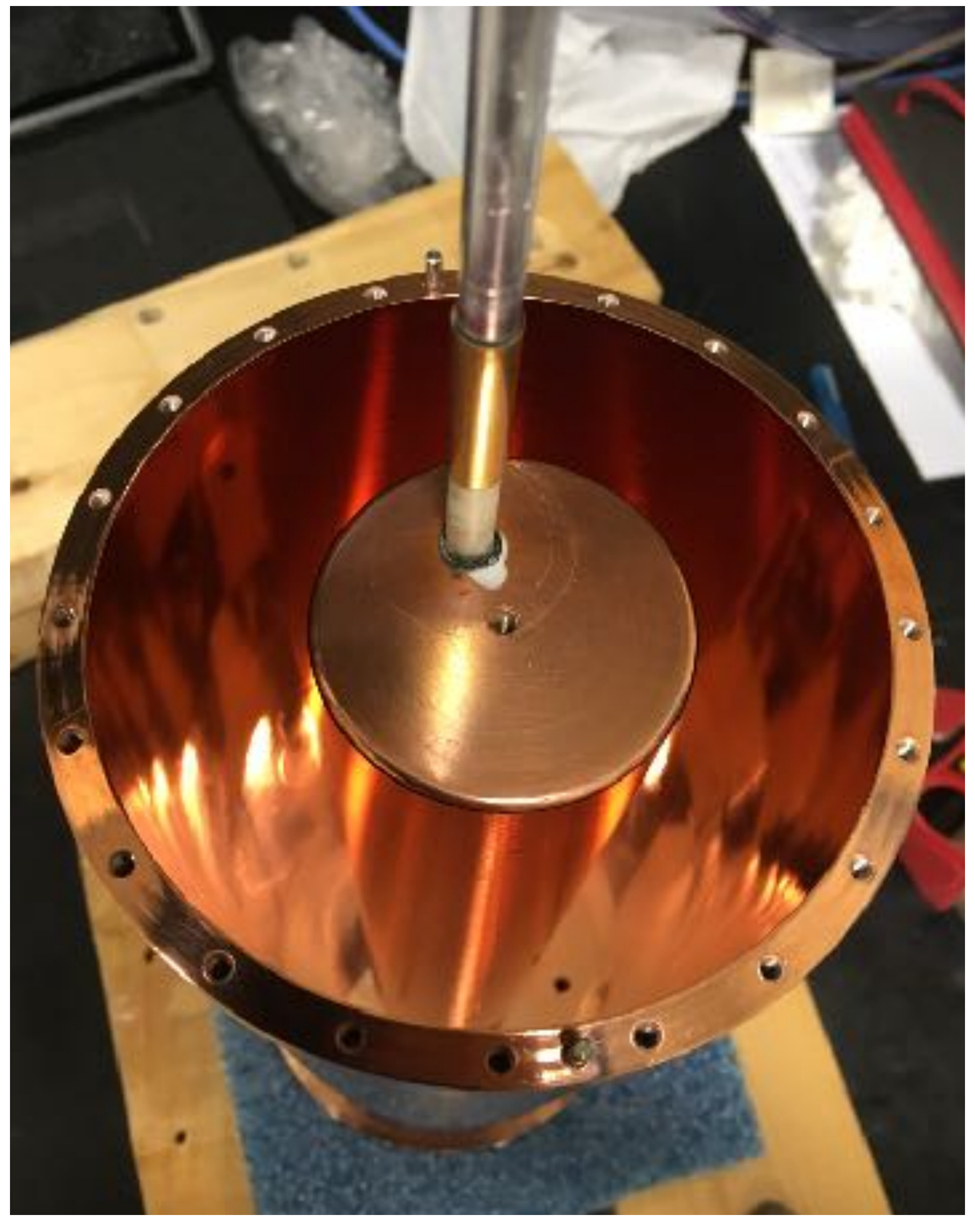
Resonator development for the post-inflation axion: Berkeley

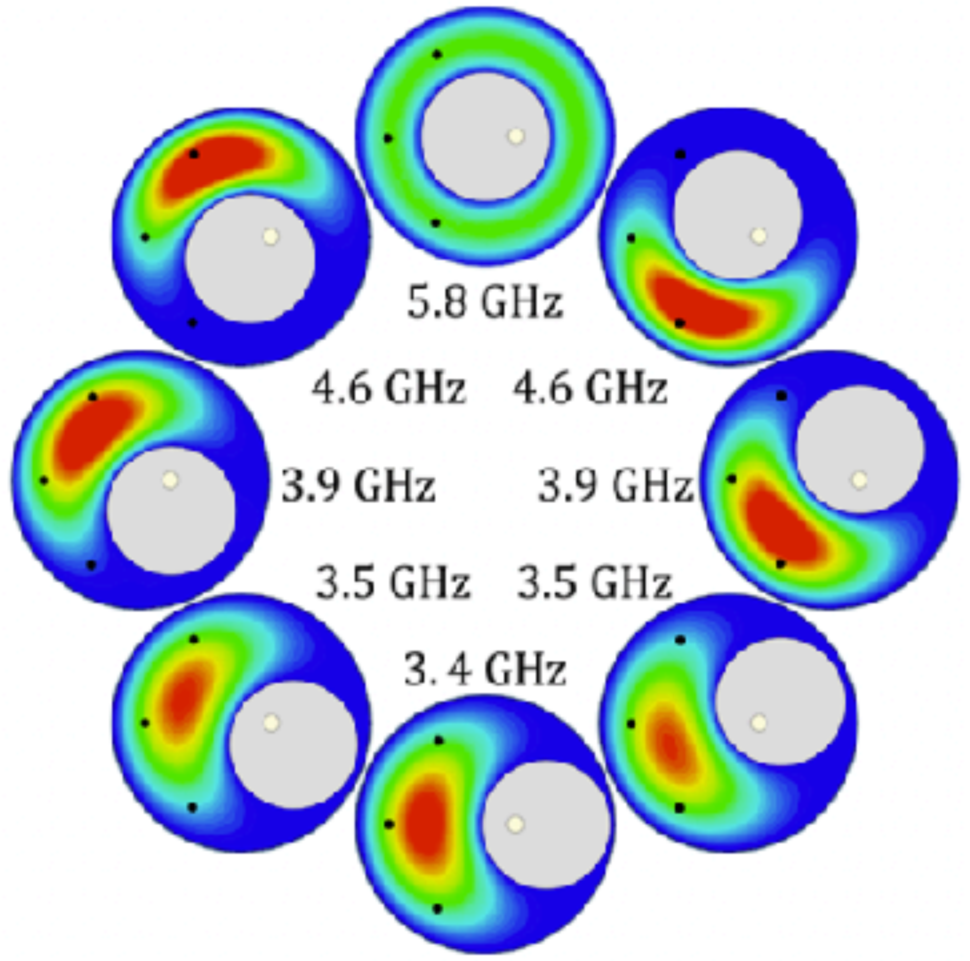
Microwave resonators at very high frequencies must satisfy multiple demanding (and often conflicting) requirements

- Large Volume
- High quality factor *Q*
- High form factor *C*
- Tunable over a wide dynamic range
- Minimal crossings and hybridization of the TM_{010} mode of interest with the forest of TE modes

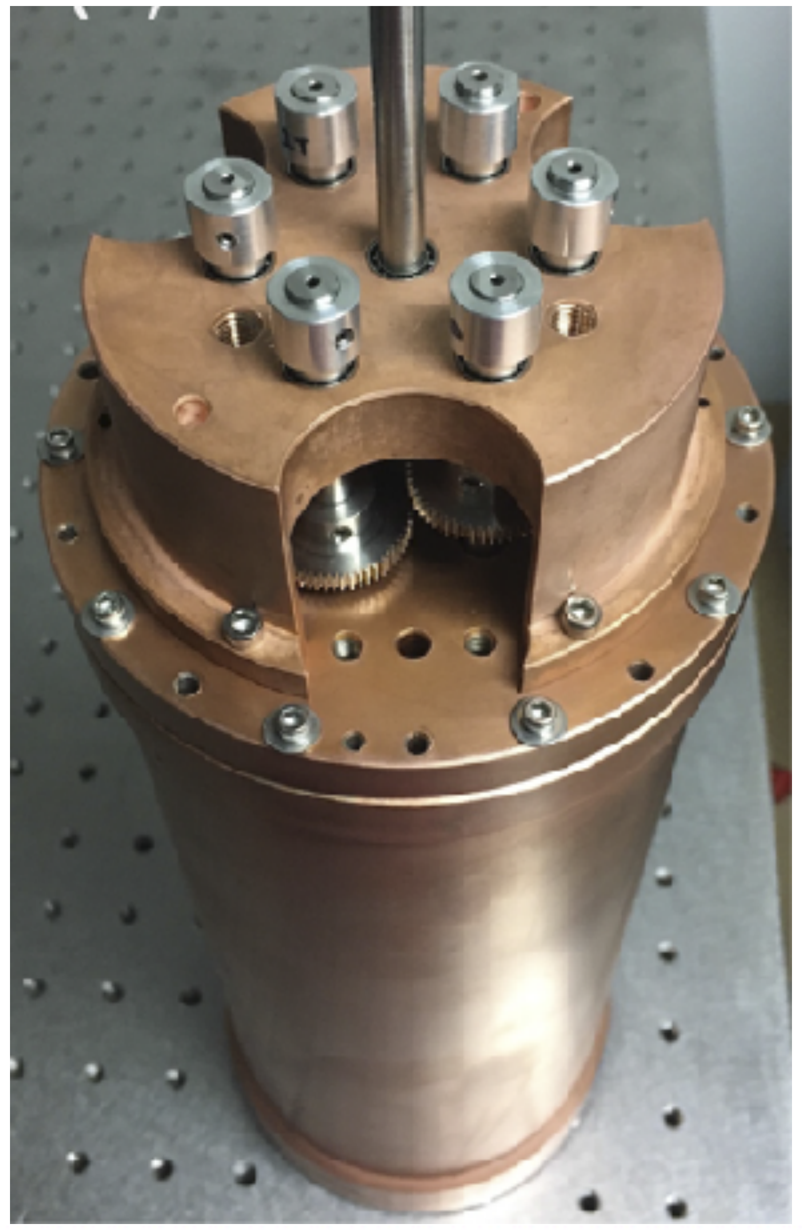
Credit: K. van Bibber

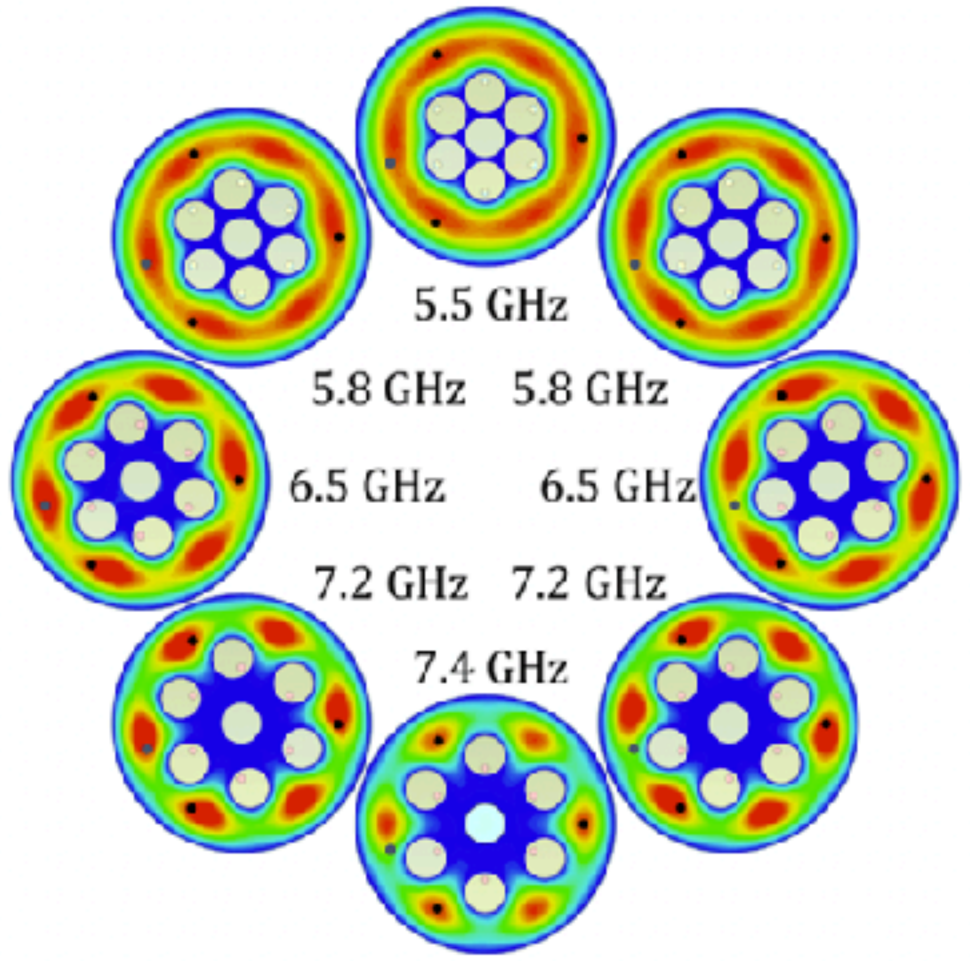
HAYSTAC Runs I+II





HAYSTAC Run III





HAYSTAC Runs I+II employed an annular cavity to cover 4-6 GHz
S. Al Kenany et al., NIM A 854 (2017) 11

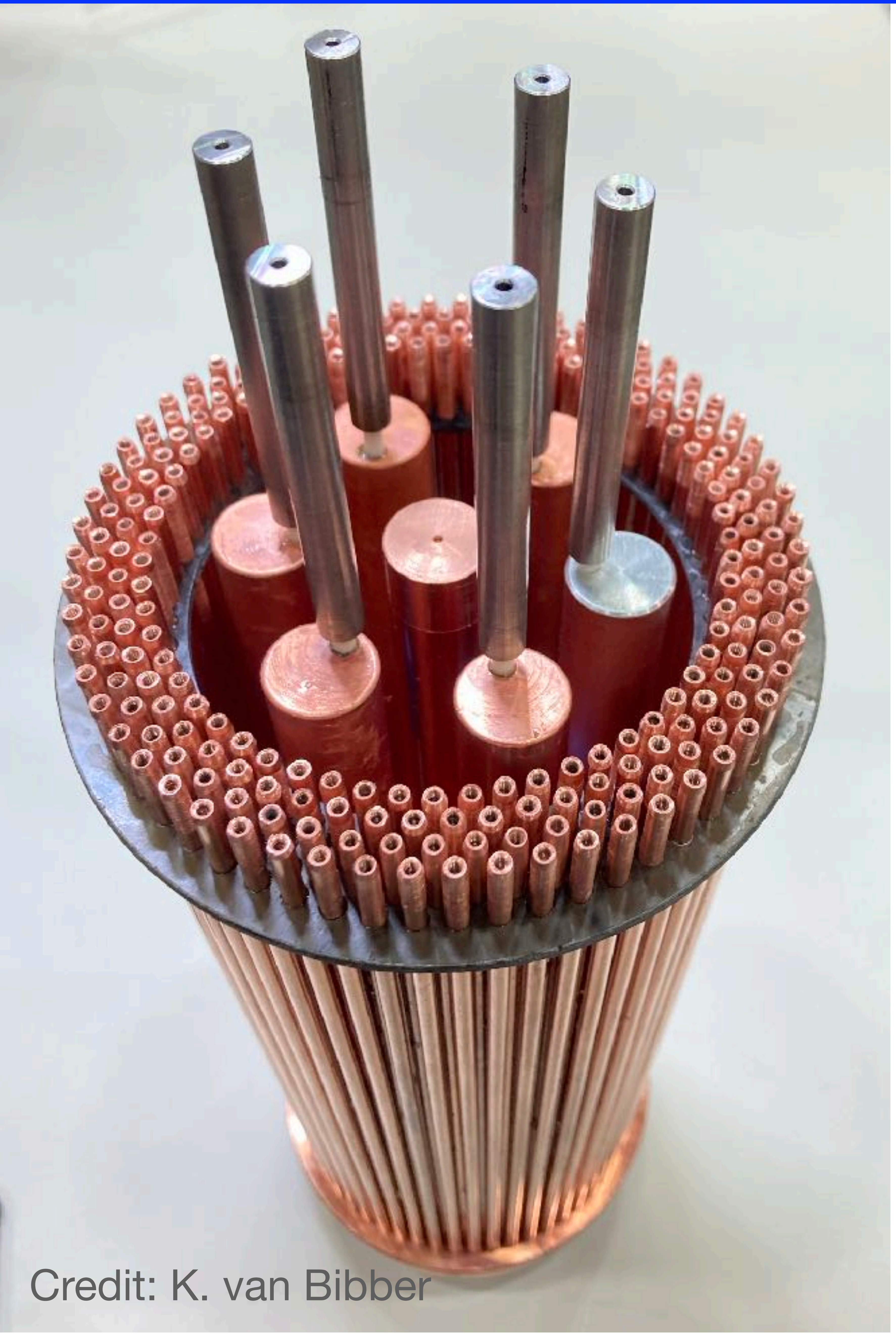
Run III (5/2024) will deploy a tunable symmetric multirod cavity to cover 6-10 GHz
M. Simanovskaia et al., RSI 92 (2021) 033305

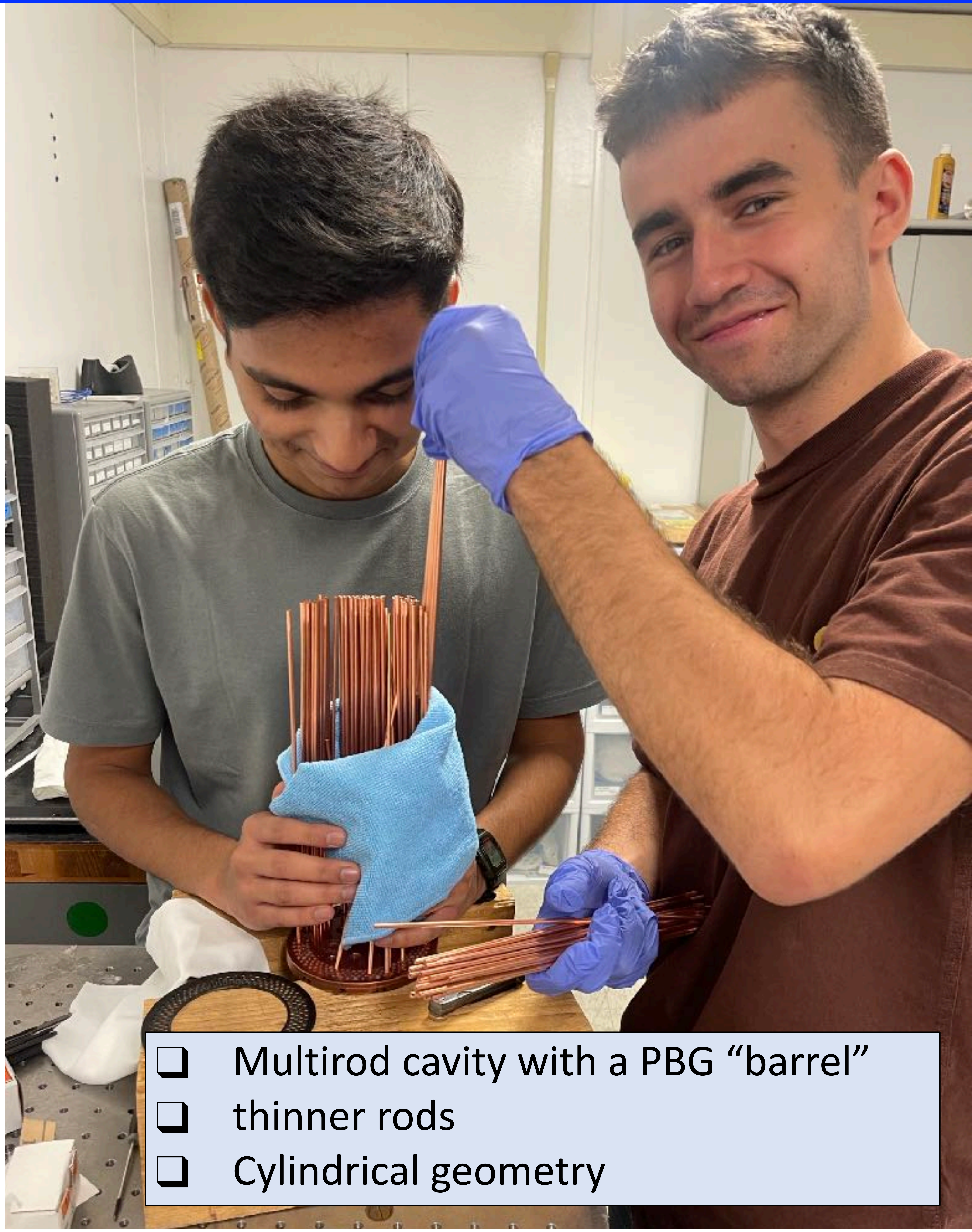
The multirod program confirmed the importance of preserving symmetry to achieve a uniformly high figure of merit (FOM) as a function of frequency:

$$FOM \propto C^2 V^2 Q$$

At frequencies < 10 GHz, the impact of mode mixing between the TM_{010} and TE modes on the frequency range to be scanned is tolerable, not requiring Photonic Band Gap Structures

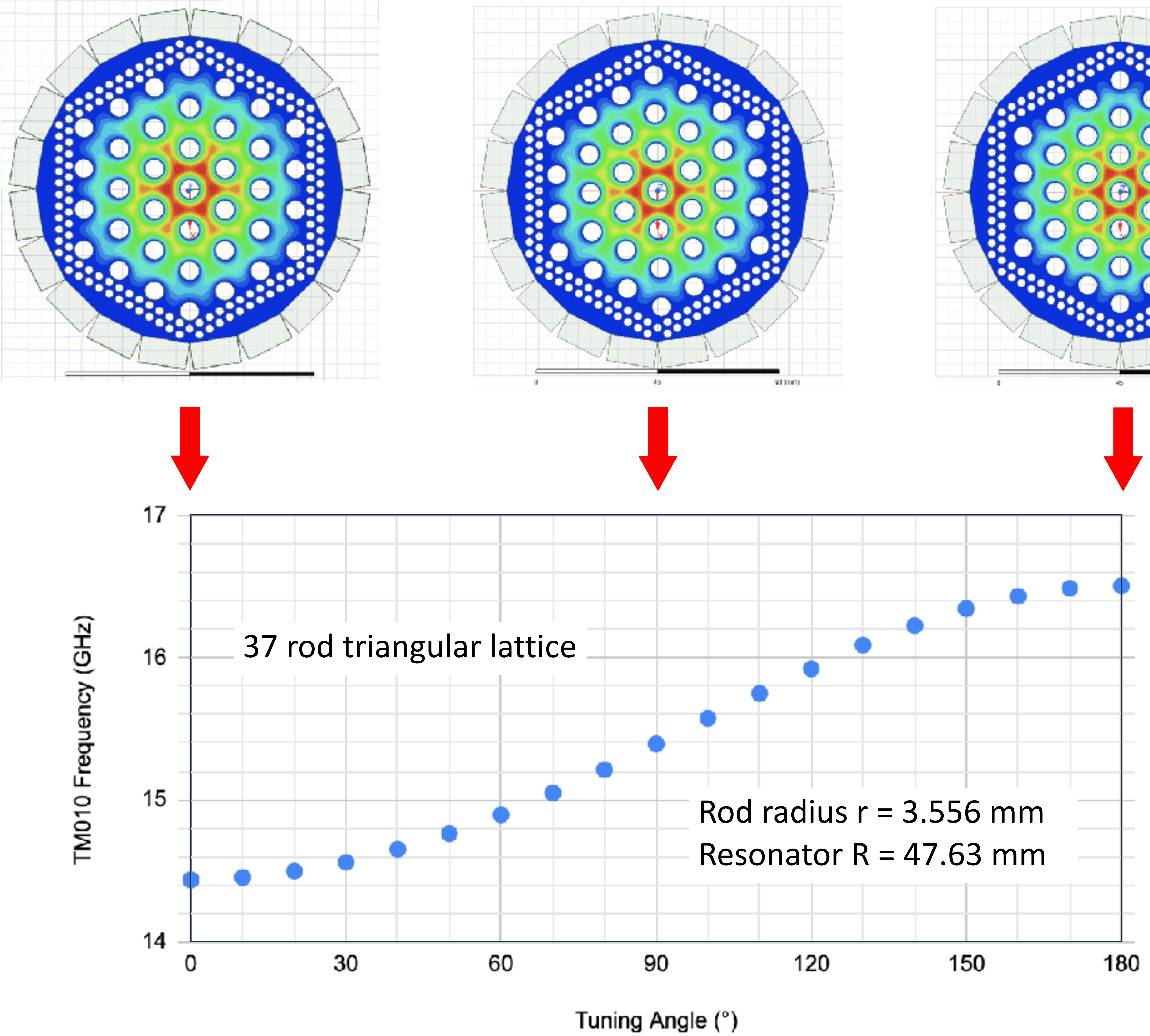
ALPHA resonators will require incorporating Photonic Band Gap structues

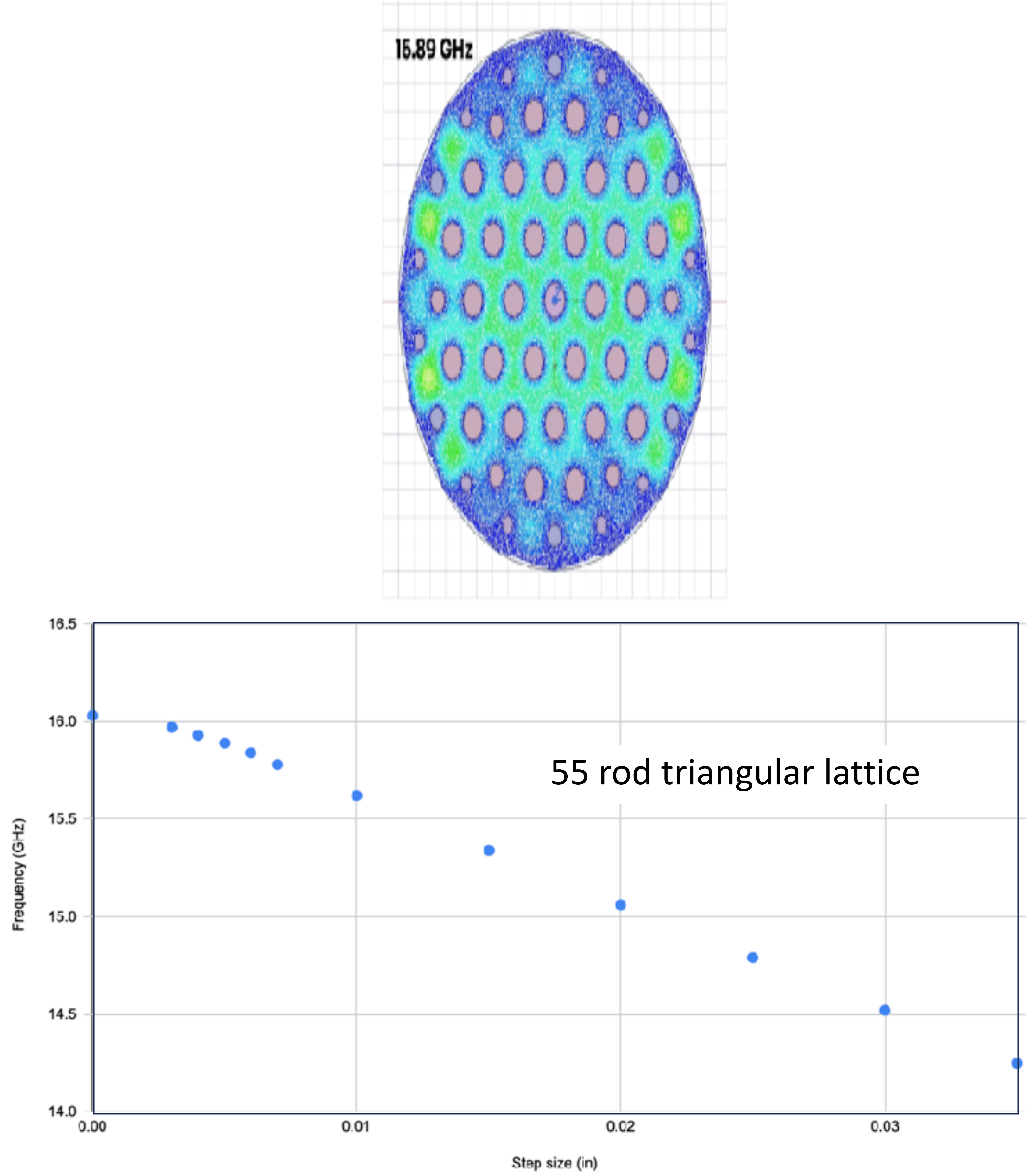




- ❑ Multirod cavity with a PBG "barrel"
- ❑ thinner rods
- ❑ Cylindrical geometry

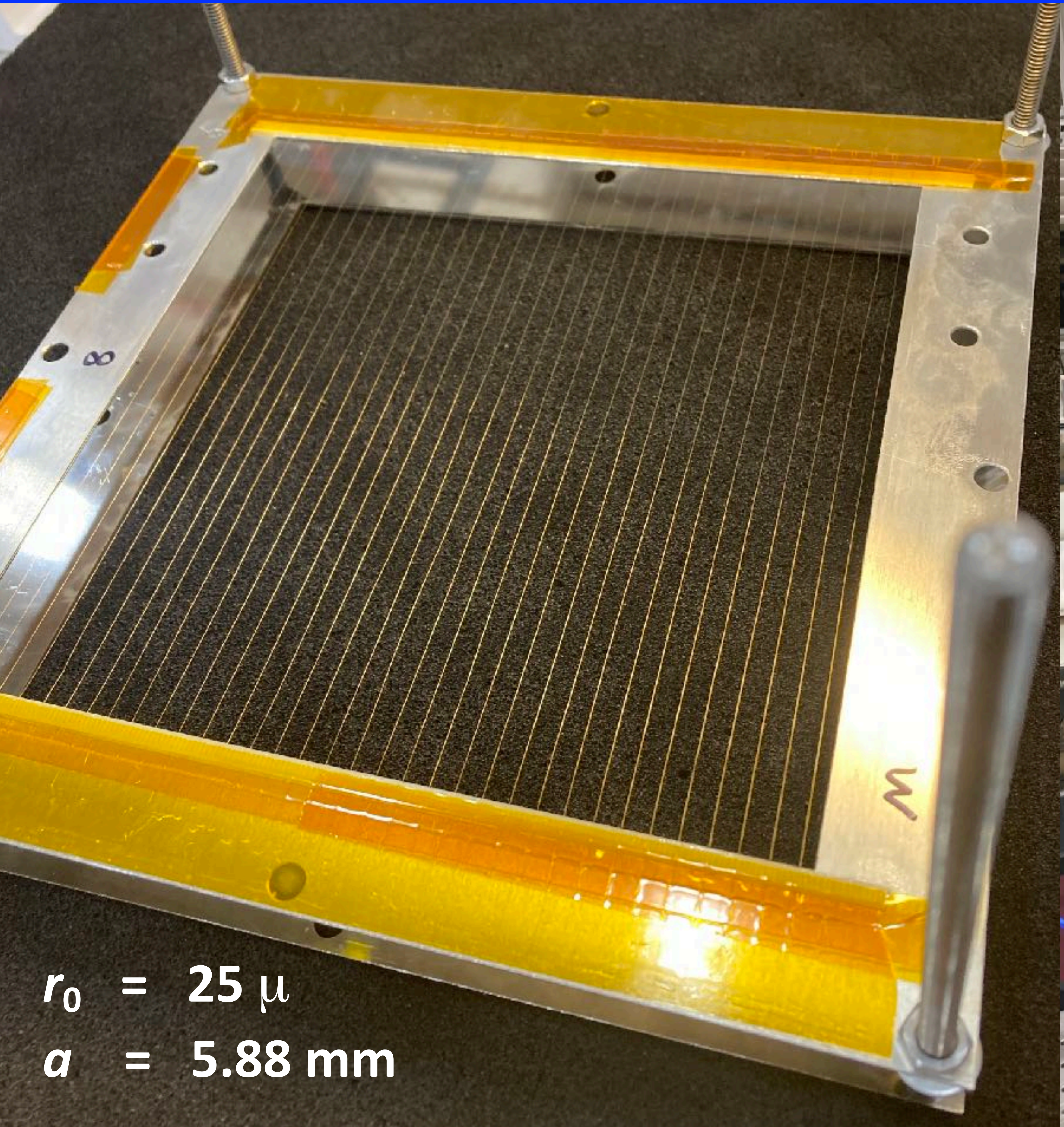
Simulations are underway for the 10-20 GHz range, with an optimized prototype to be fabricated in late 2024





Credit: K. van Bibber

Resonators for >20 GHz will require superconducting wire array metamaterials



r_0 = 25 μ

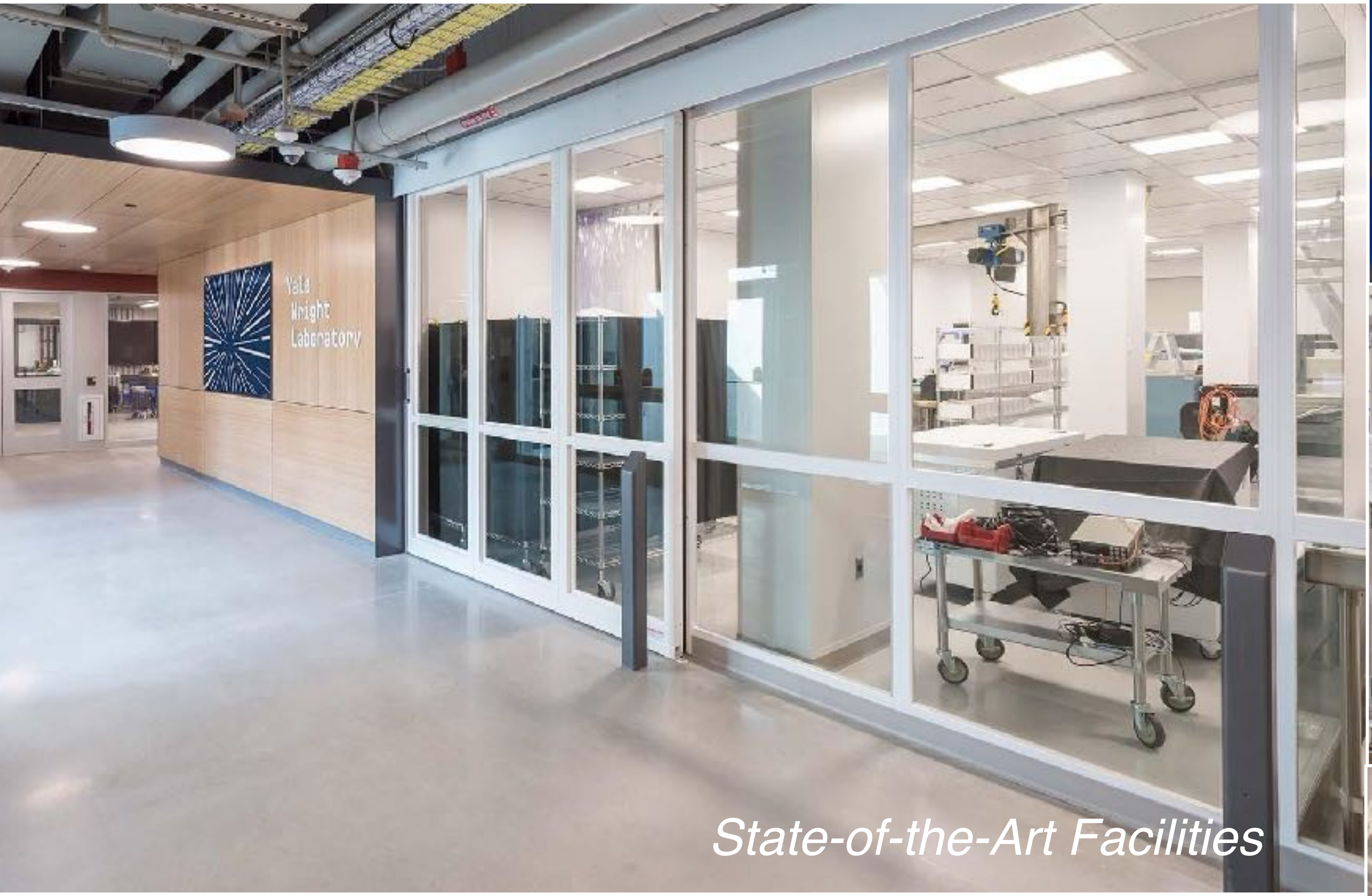
a = 5.88 mm

Credit: K. van Bibber

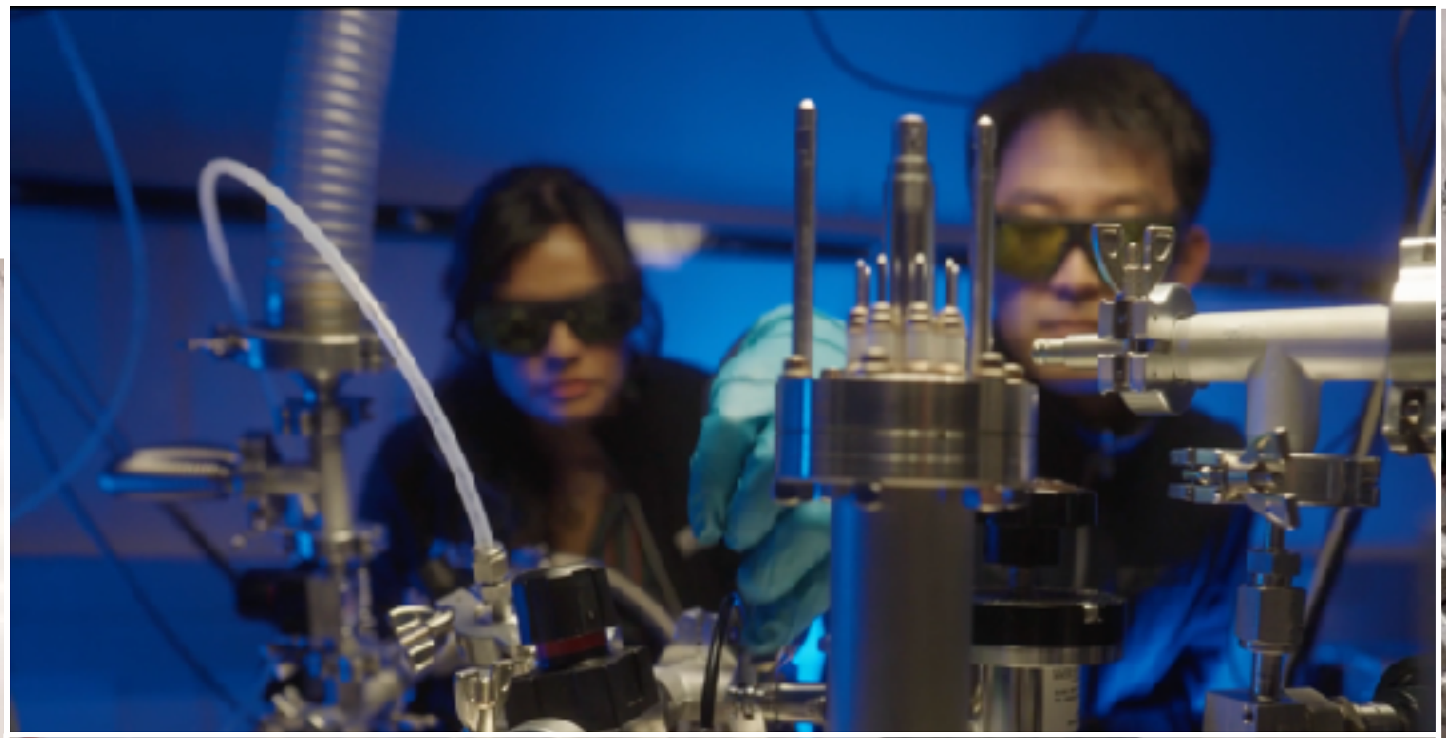
Yale Wright Laboratory

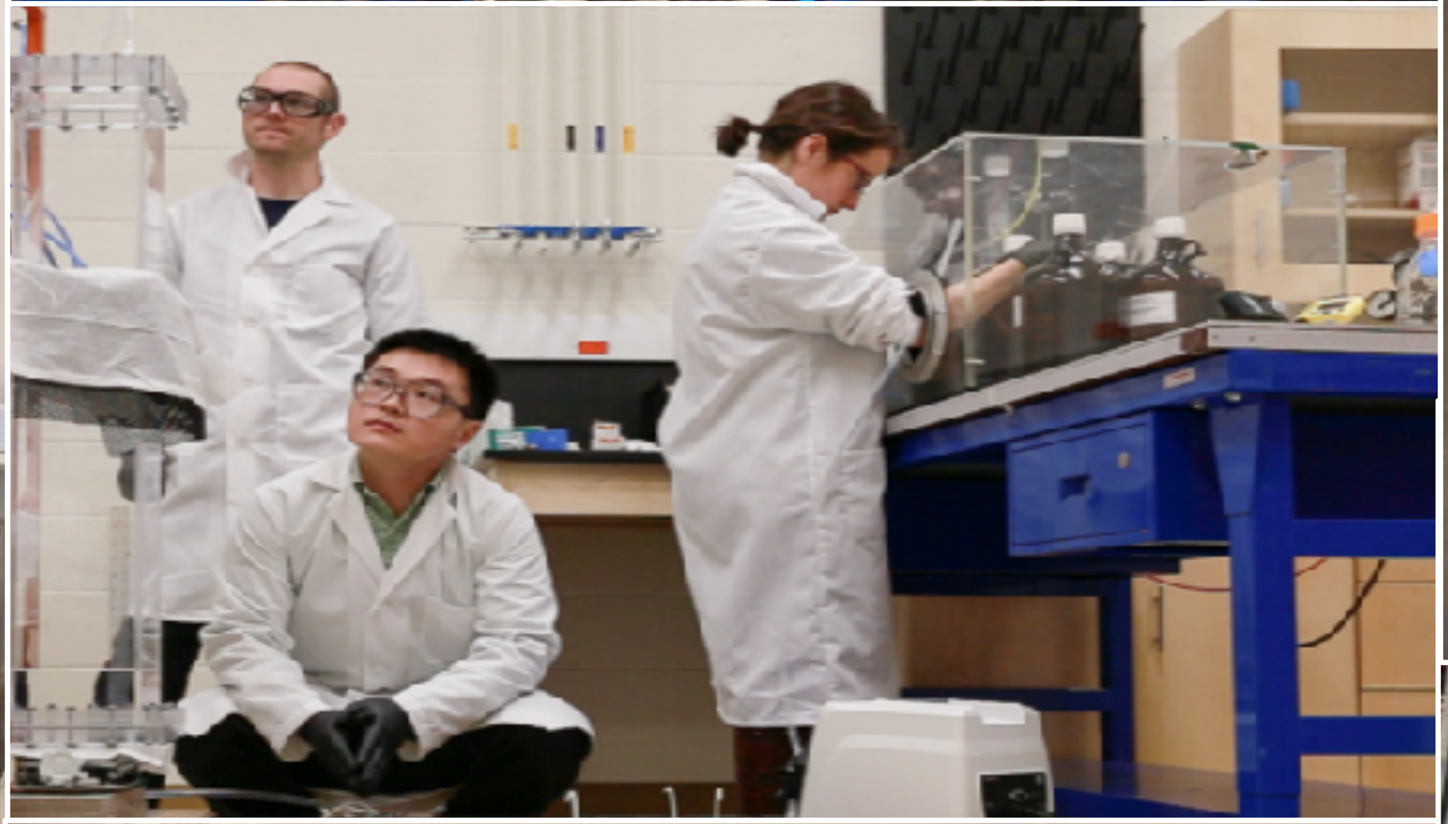
Developing Tools for Discoveries

Exploring the Invisible Universe

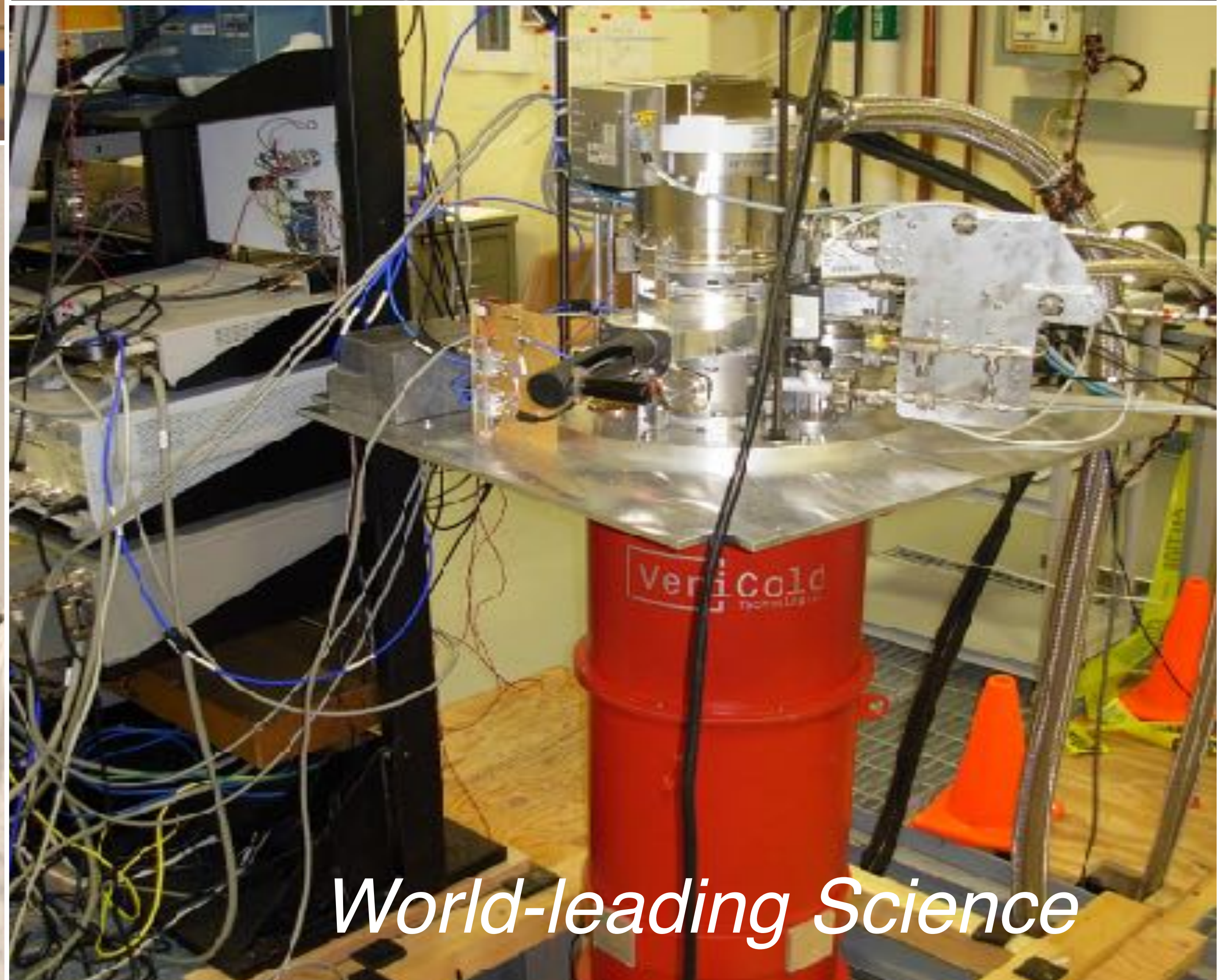


State-of-the-Art Facilities






Training Future Scientists



World-leading Science

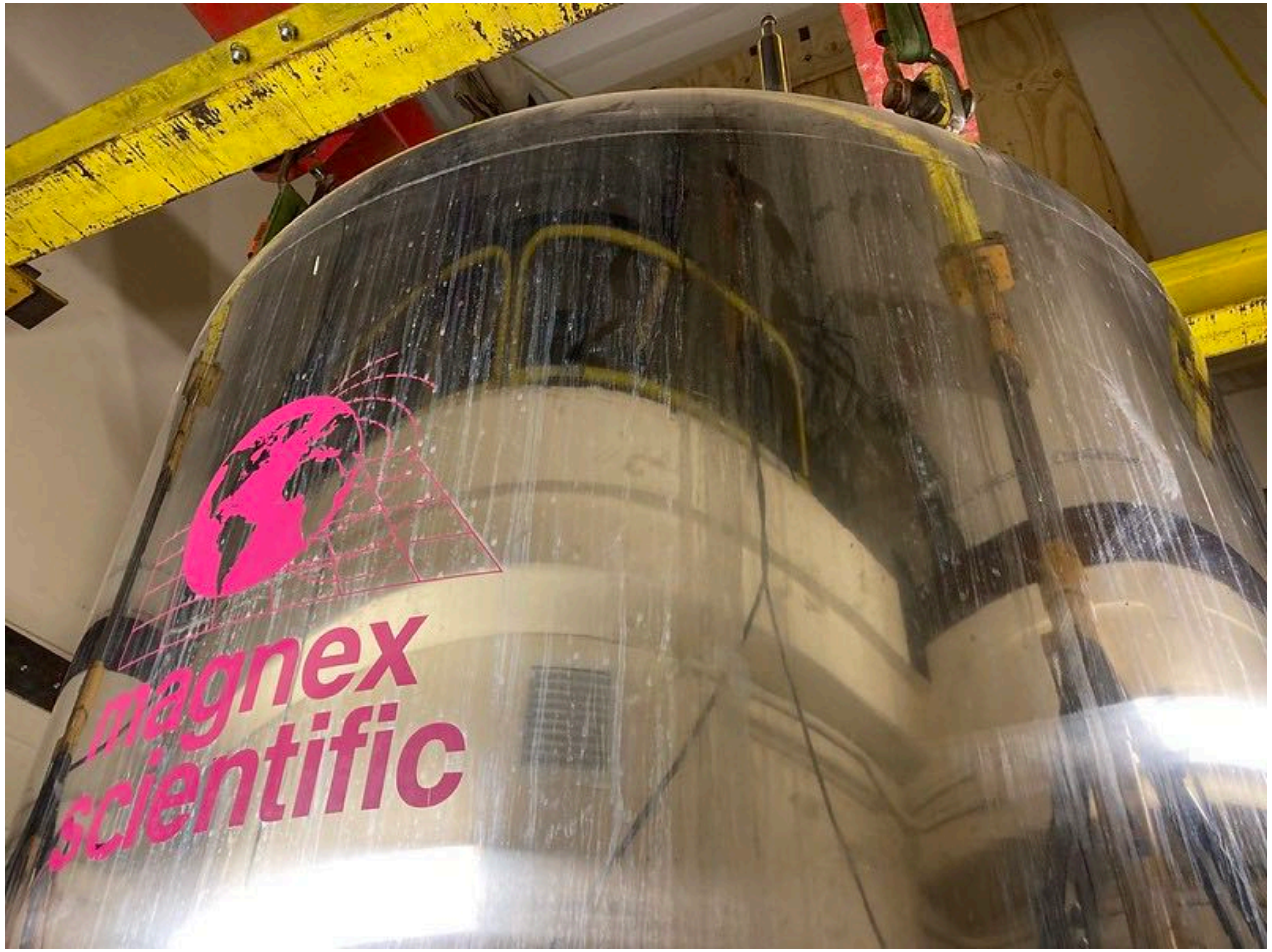
Advancing frontiers of nuclear, particle, and astrophysics including studies of **neutrinos**; searches for **dark matter**; understanding **matter**; exploration of **quantum science** and observations of **the early Universe**.

https://wlab.yale.edu

Site: Wright Lab @ Yale

Yale Wright Laboratory

Magnet



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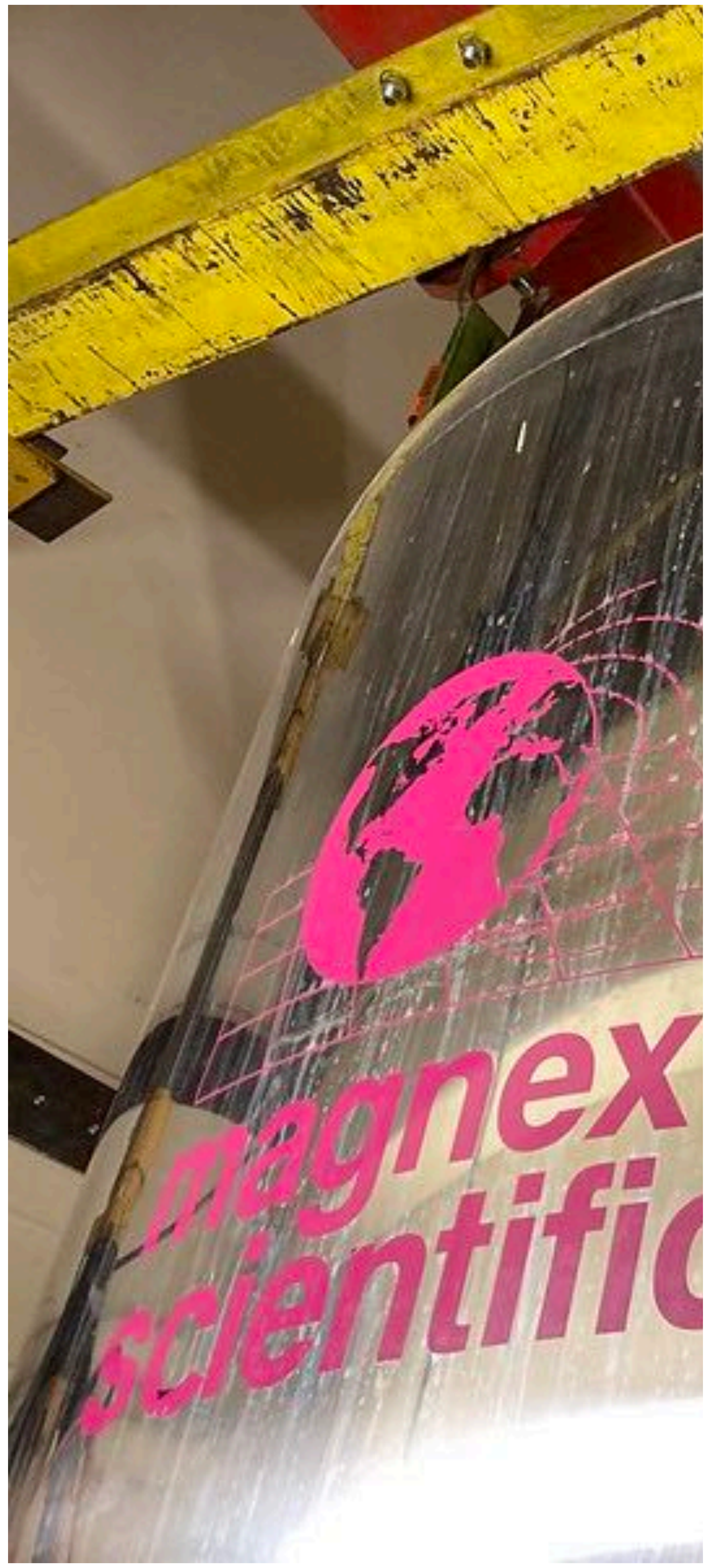
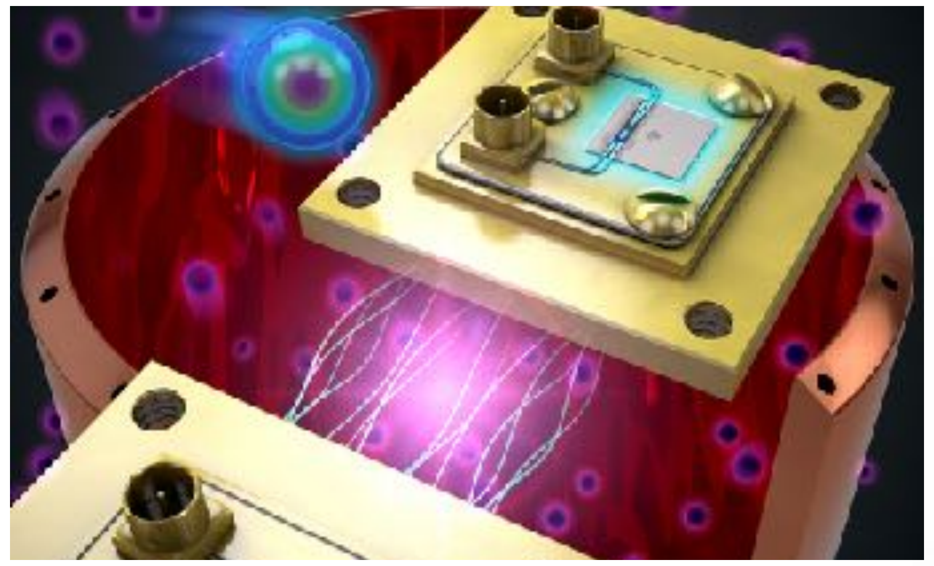


Conclusions



- New results and exciting developments for dark matter searches
- Exciting developments
    - Rapid advances in quantum science
    - Several new experiments proposed and starting to explore new parameter space
    - New ideas, new people, & new ways of working for new discovery
- Compelling case for axions at higher masses
    - HAYSTAC continues to scan 16 – 40 μeV
    - ALPHA extends search reach to 40 – 80 μeV