Haloscopes and the Search for Axion Dark Matter

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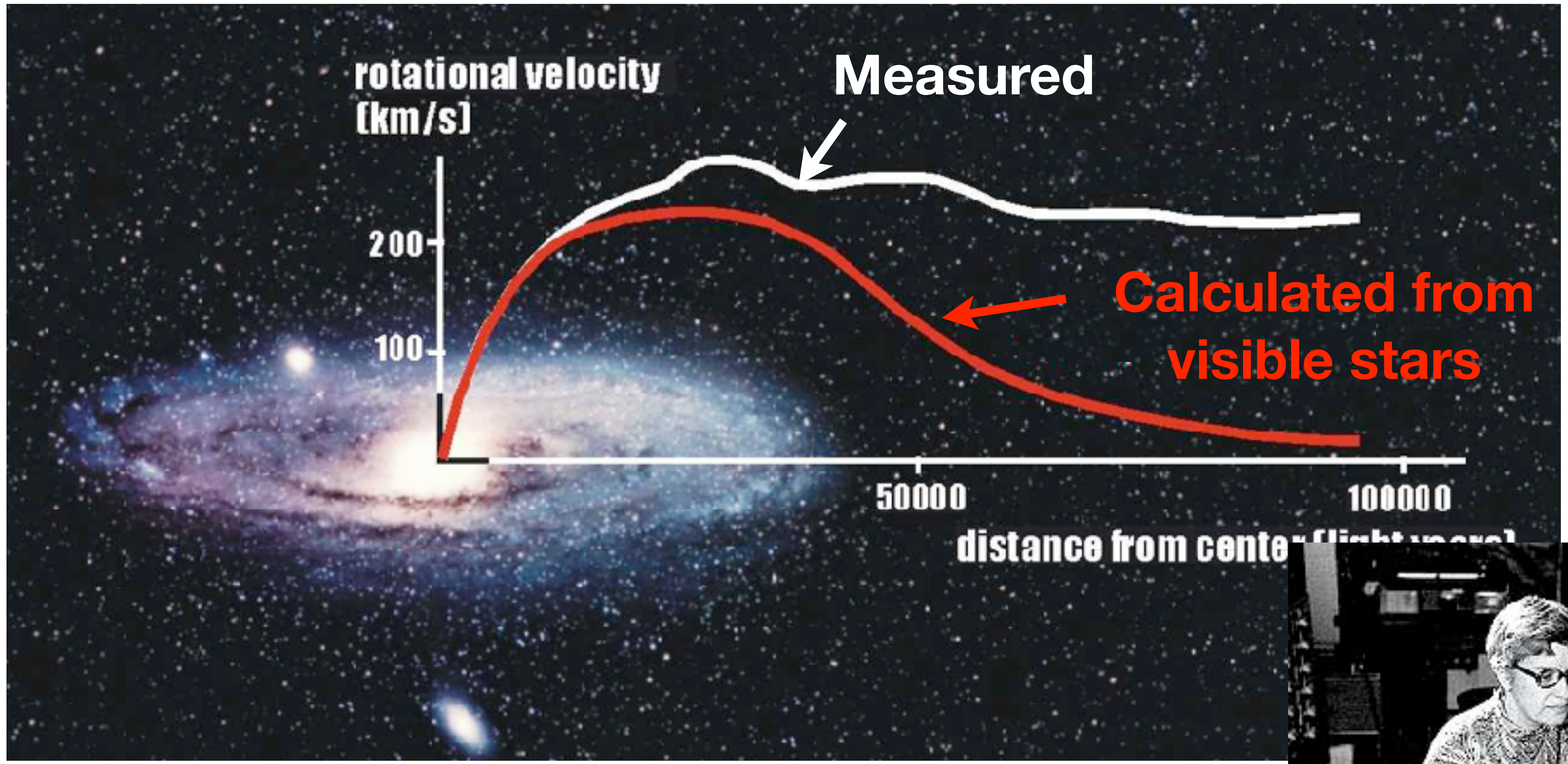
Yale University

Axions in Stockholm 2025
June 23 - July 11, 2025

Amazing Images from Vera Rubin Observatory!

1970‘s: Vera Rubin and co. found that rotation curves are flat, indicating presence of dark matter

Rotation Curve of Galaxies



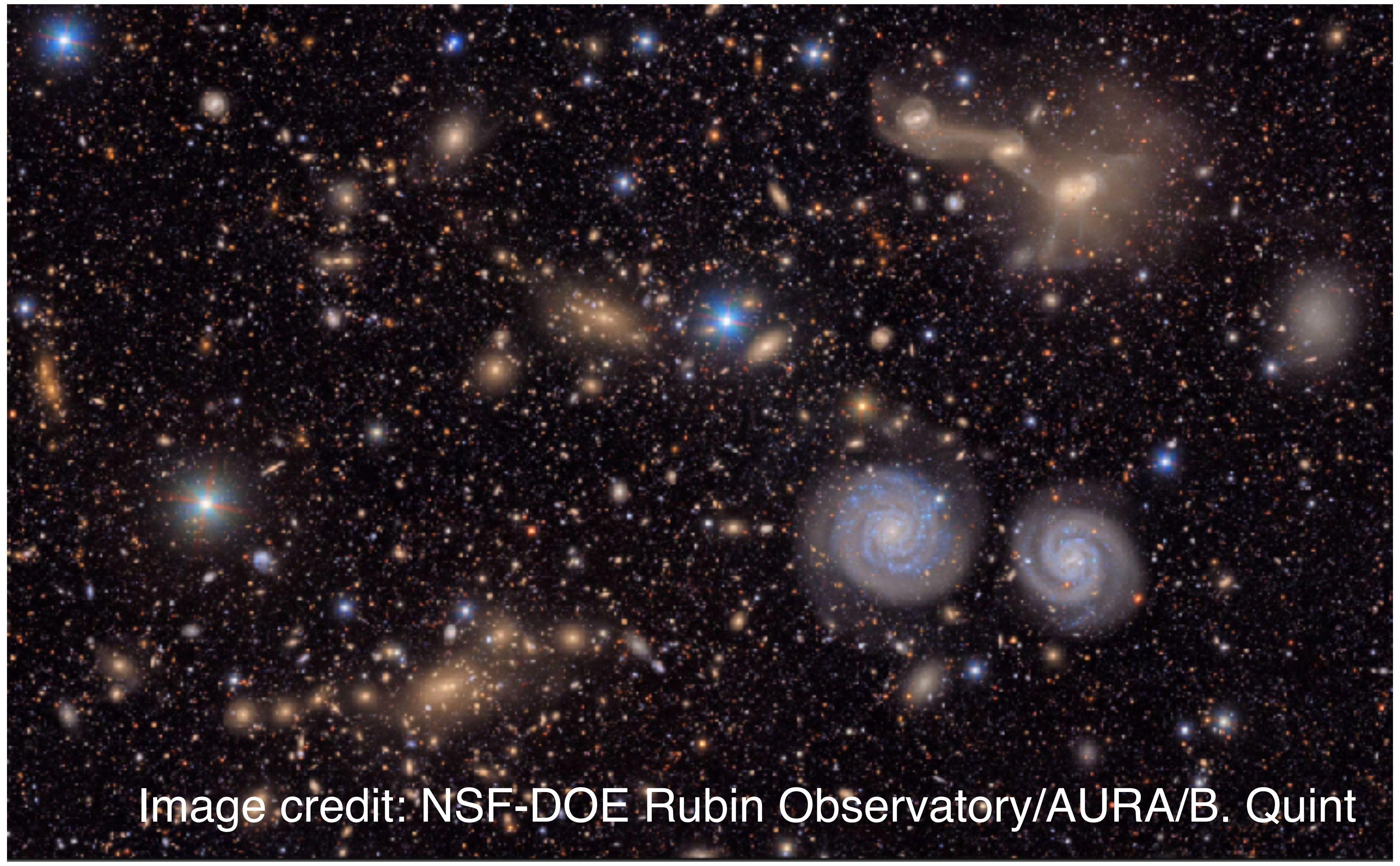
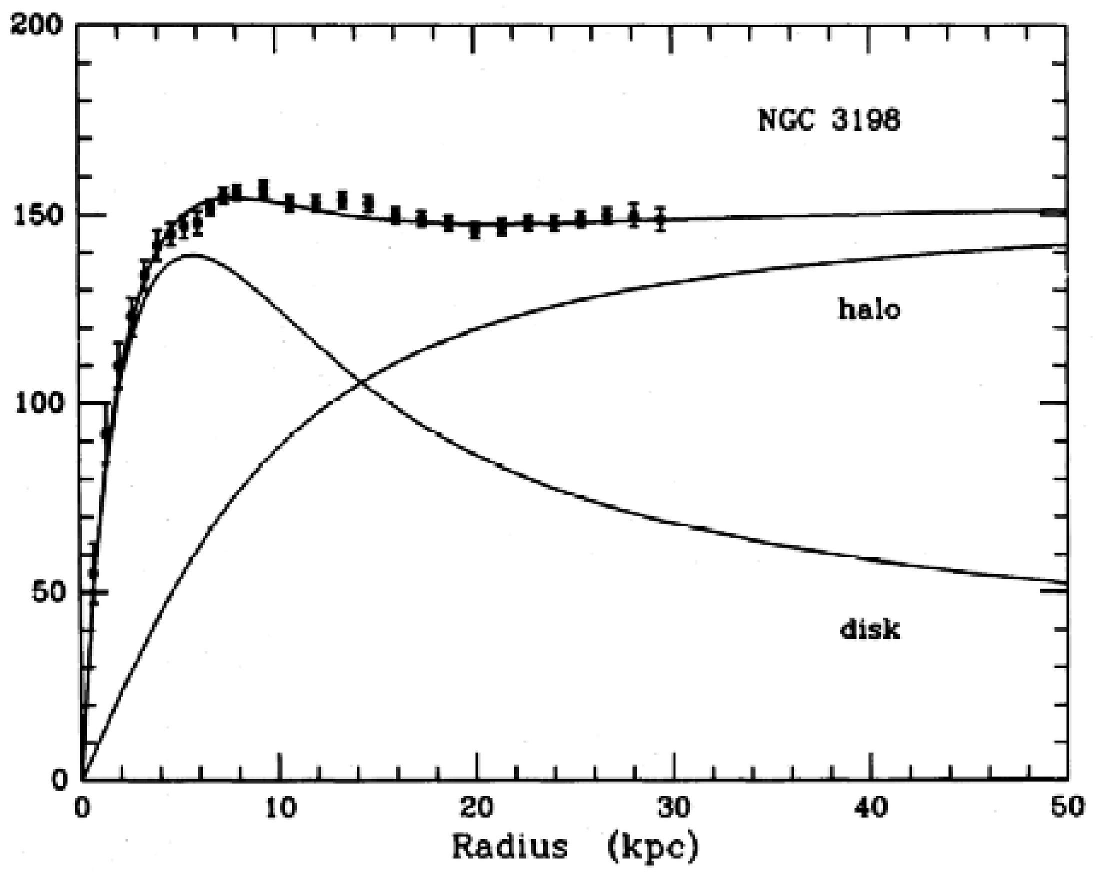


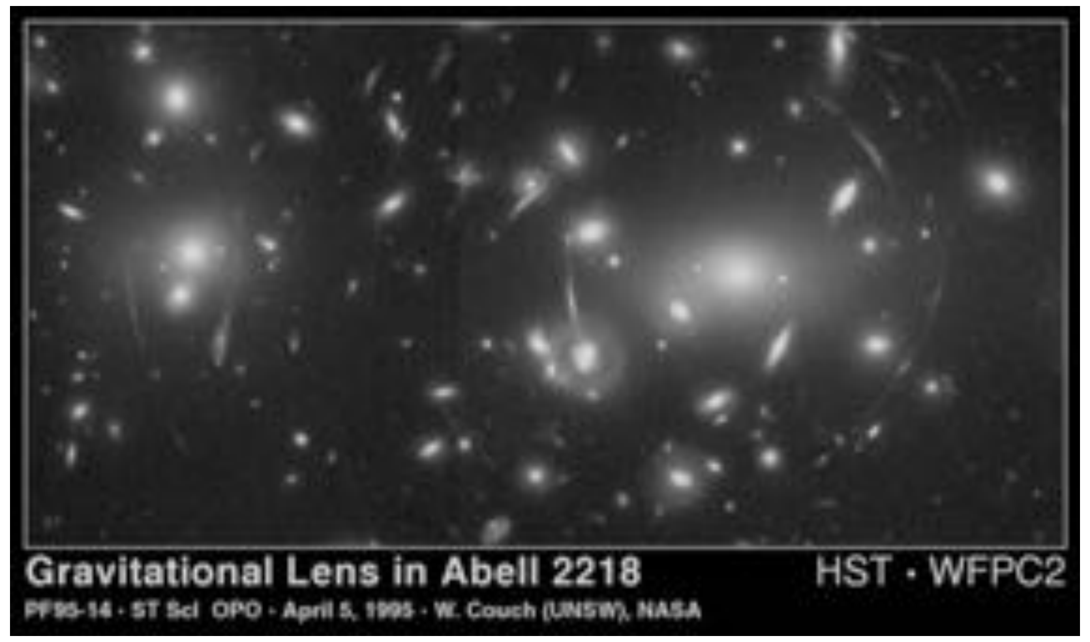
Image credit: NSF-DOE Rubin Observatory/AURA/B. Quint

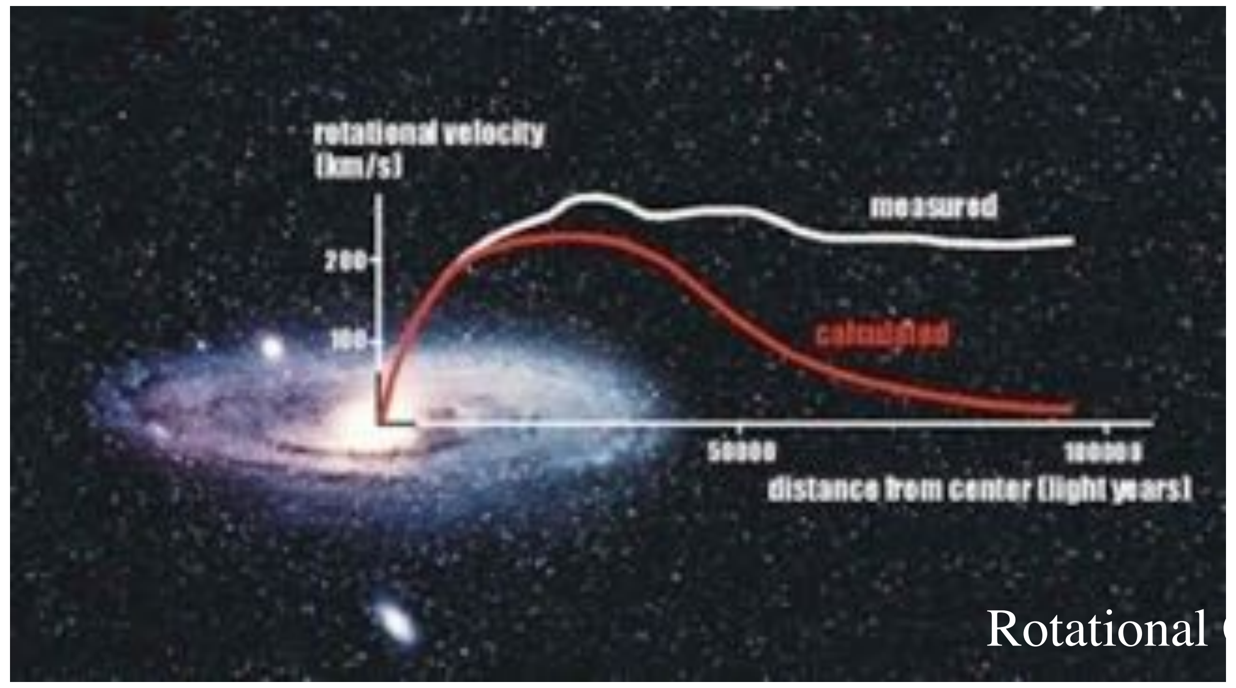
“What you see in a spiral galaxy ...
is not what you get.”

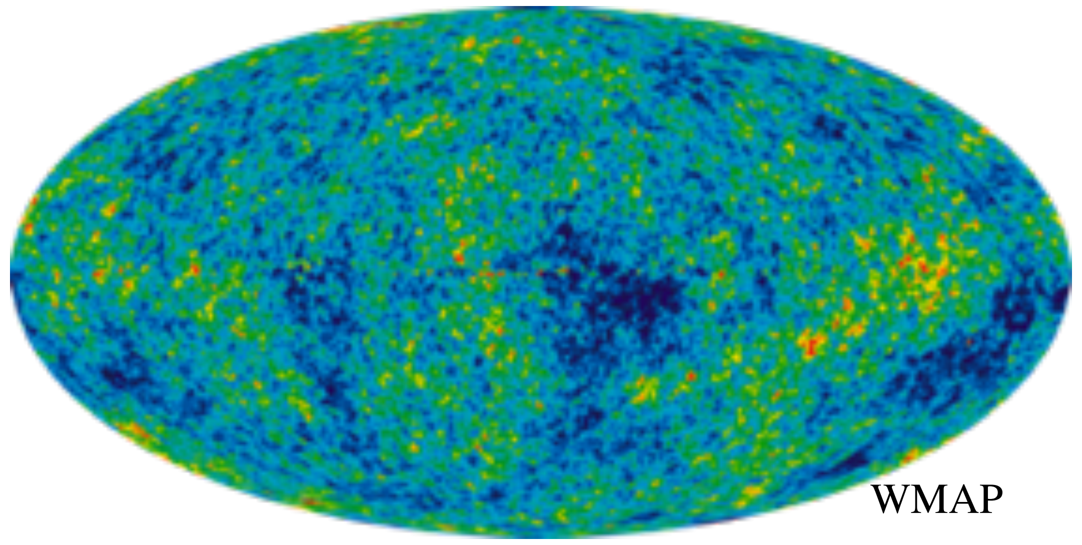
DISTRIBUTION OF DARK MATTER IN NGC 3198

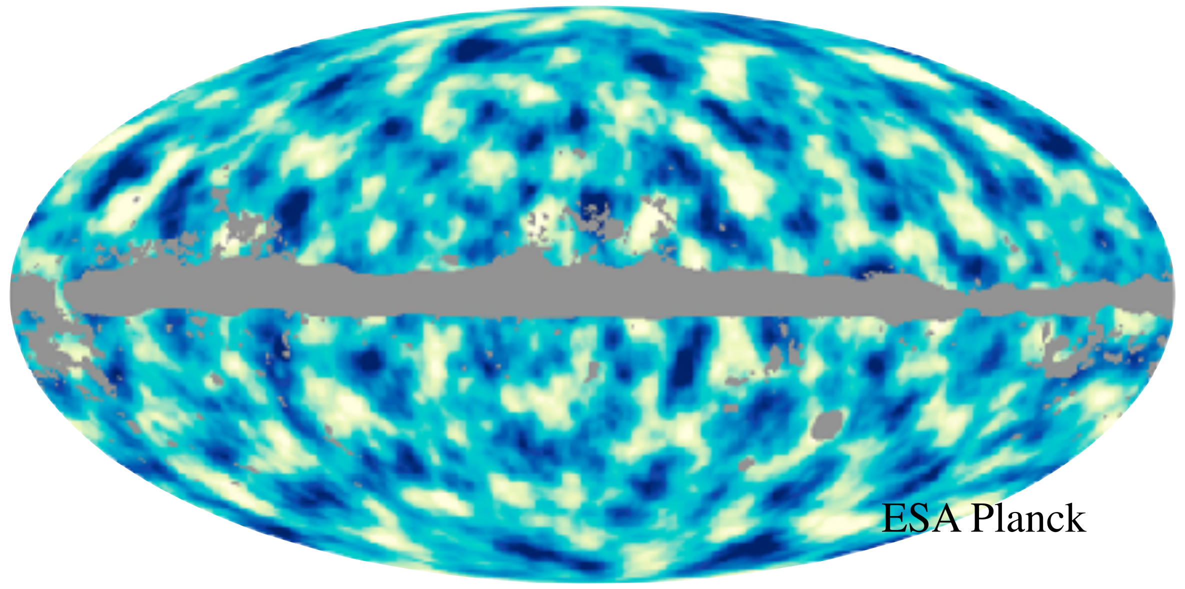


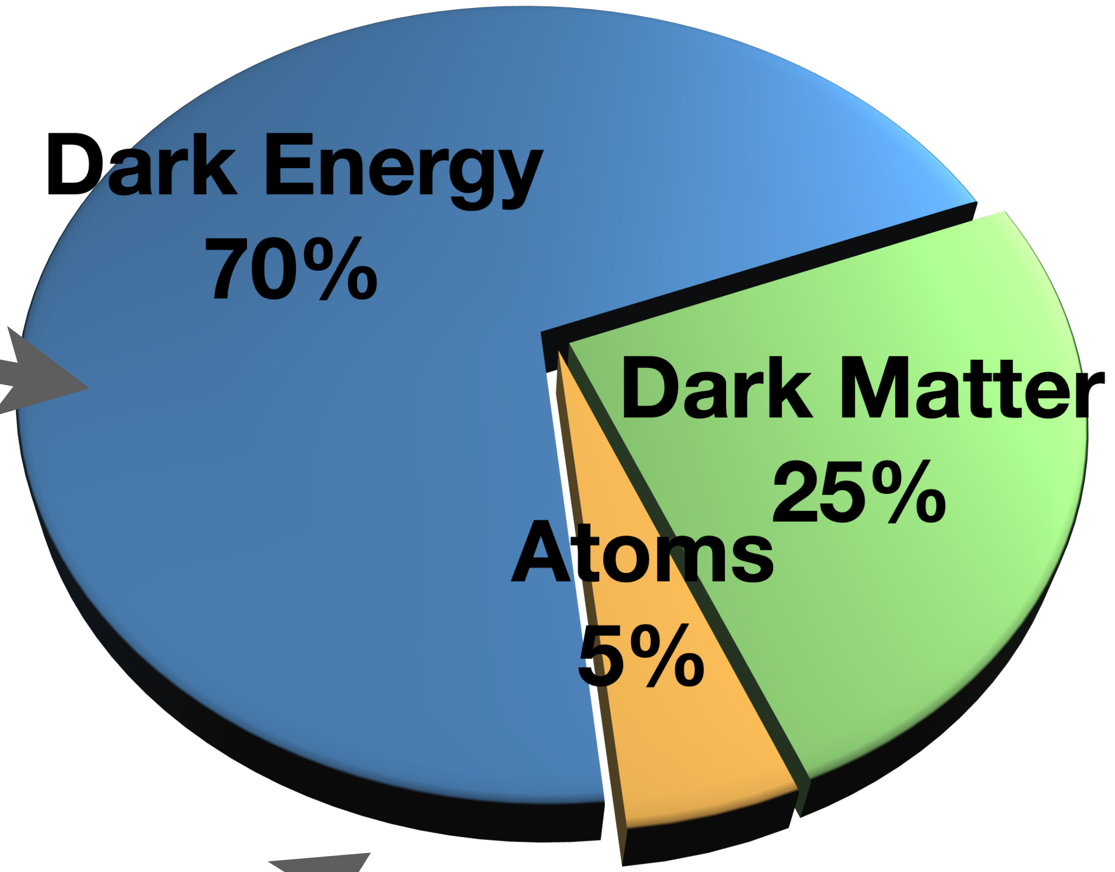
Evidence for Dark Matter











All consistent with ~25% dark matter

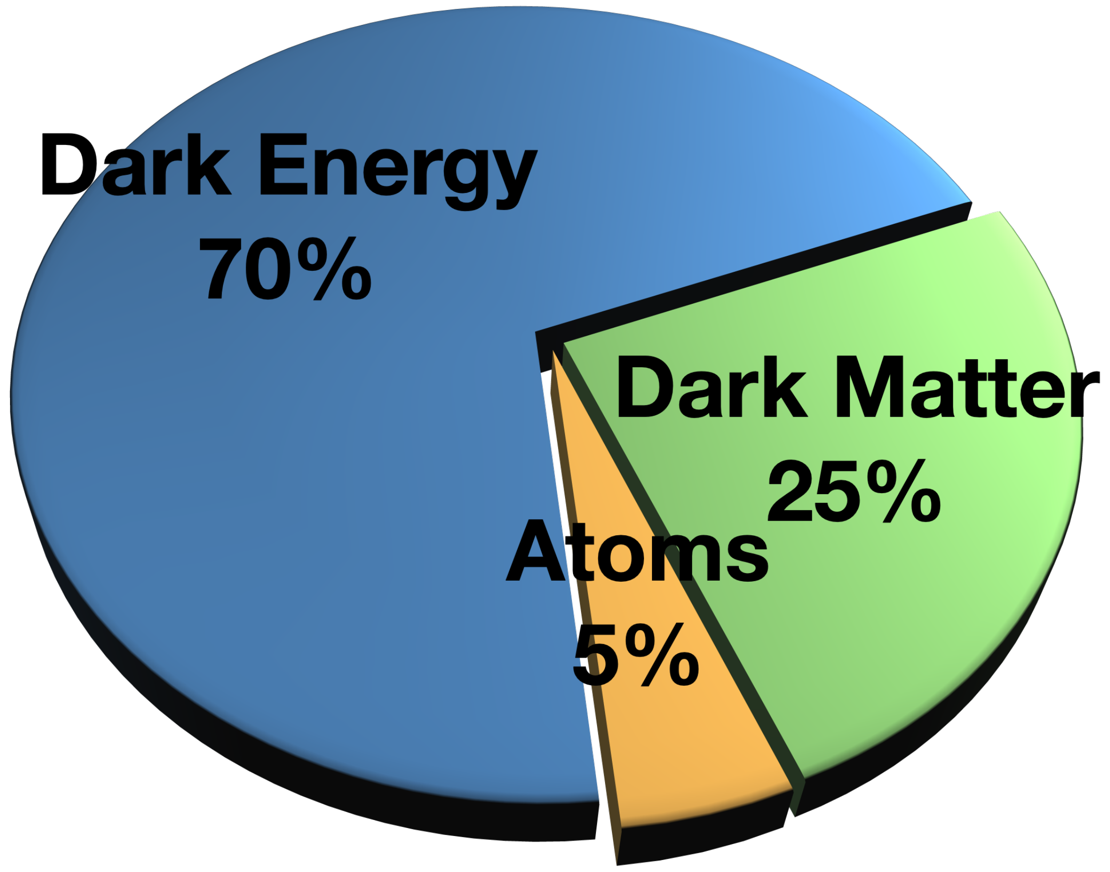
Characteristics of dark matter

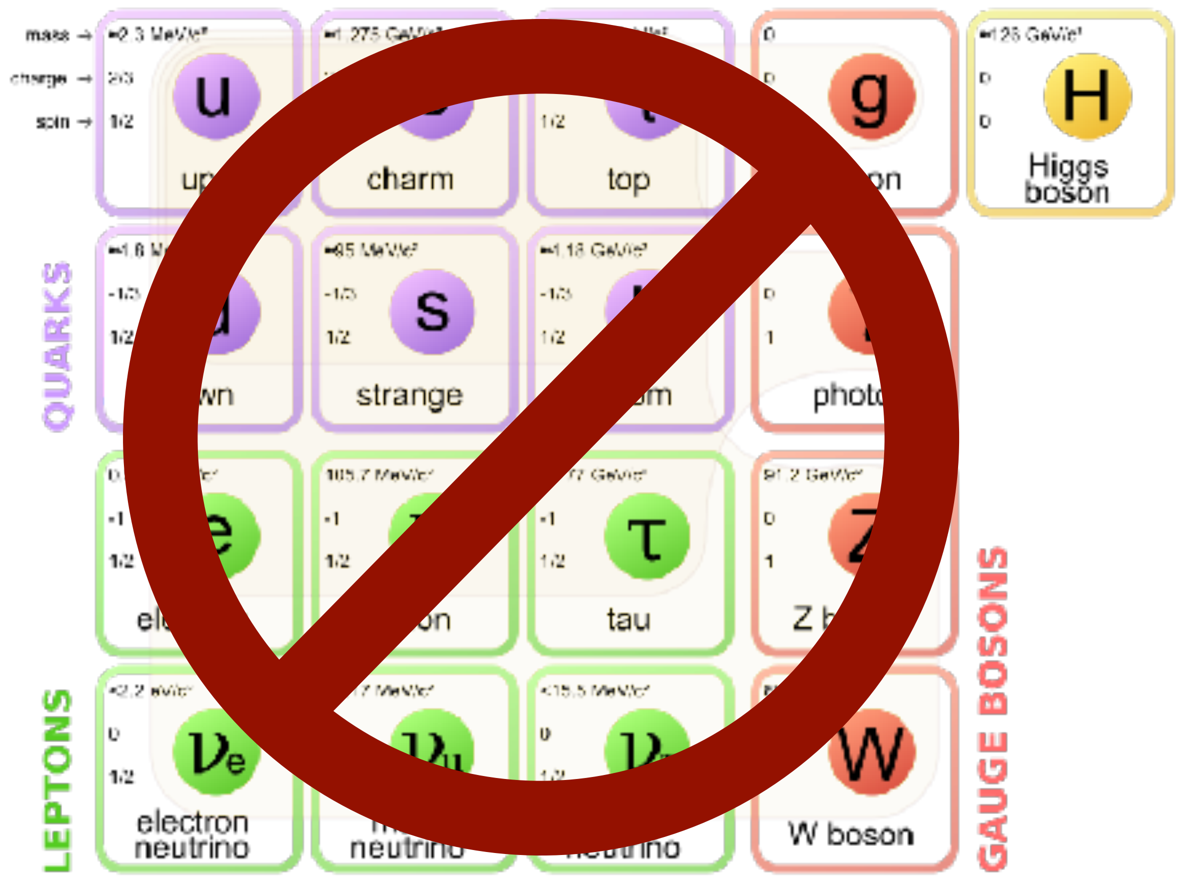
Naturally give right cosmic density

- *thermal production in hot primordial plasma.*

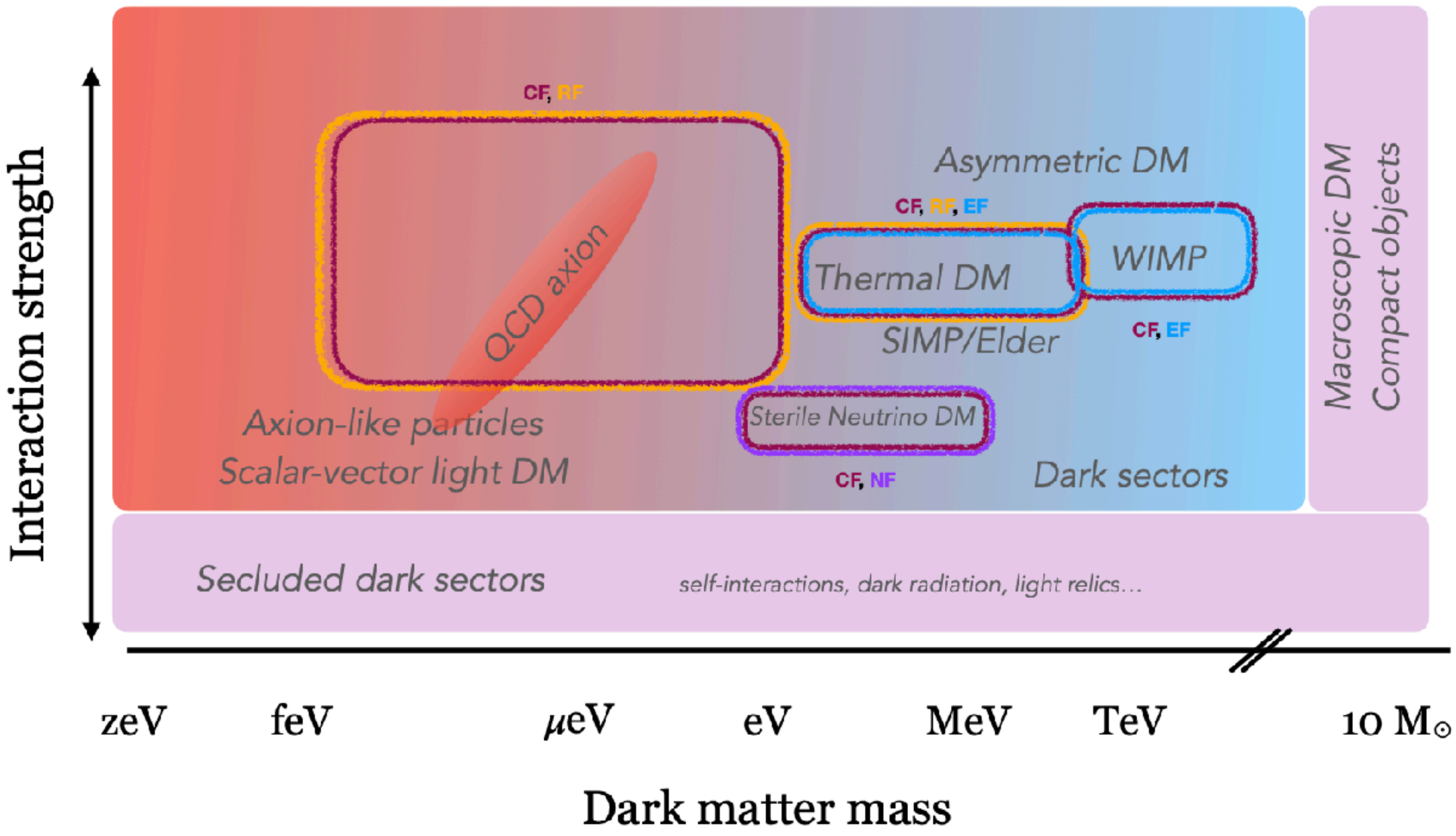
Matches requirements from DM evidence

- *Non-baryonic*
- *non-relativistic and exerts gravity*
- *Interact little with ordinary matter*
- *Stable and long-lived*
- *local density: ρ = 0.4 GeV/cm3*





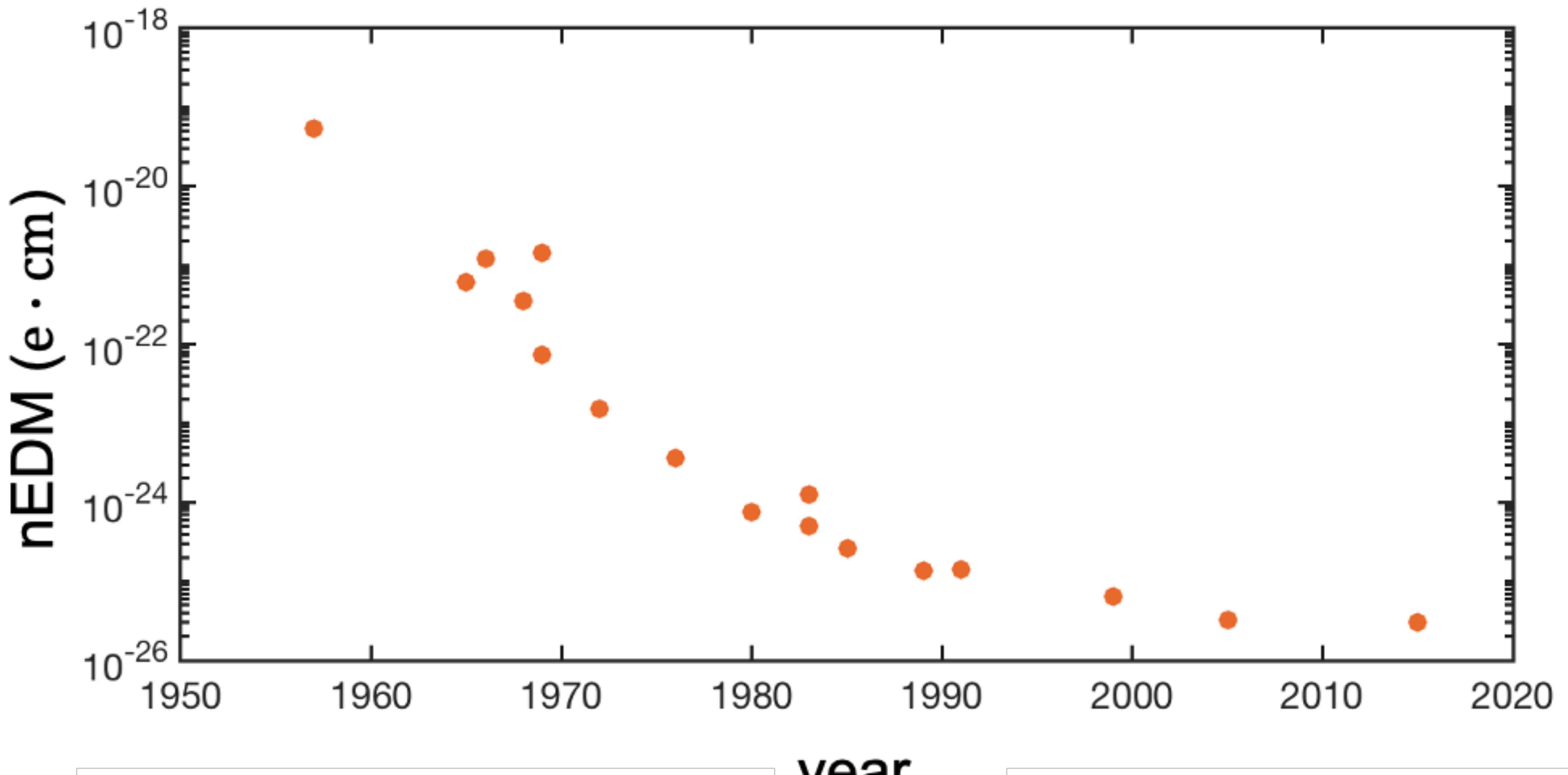
Dark Matter Candidates: Cartoon Version

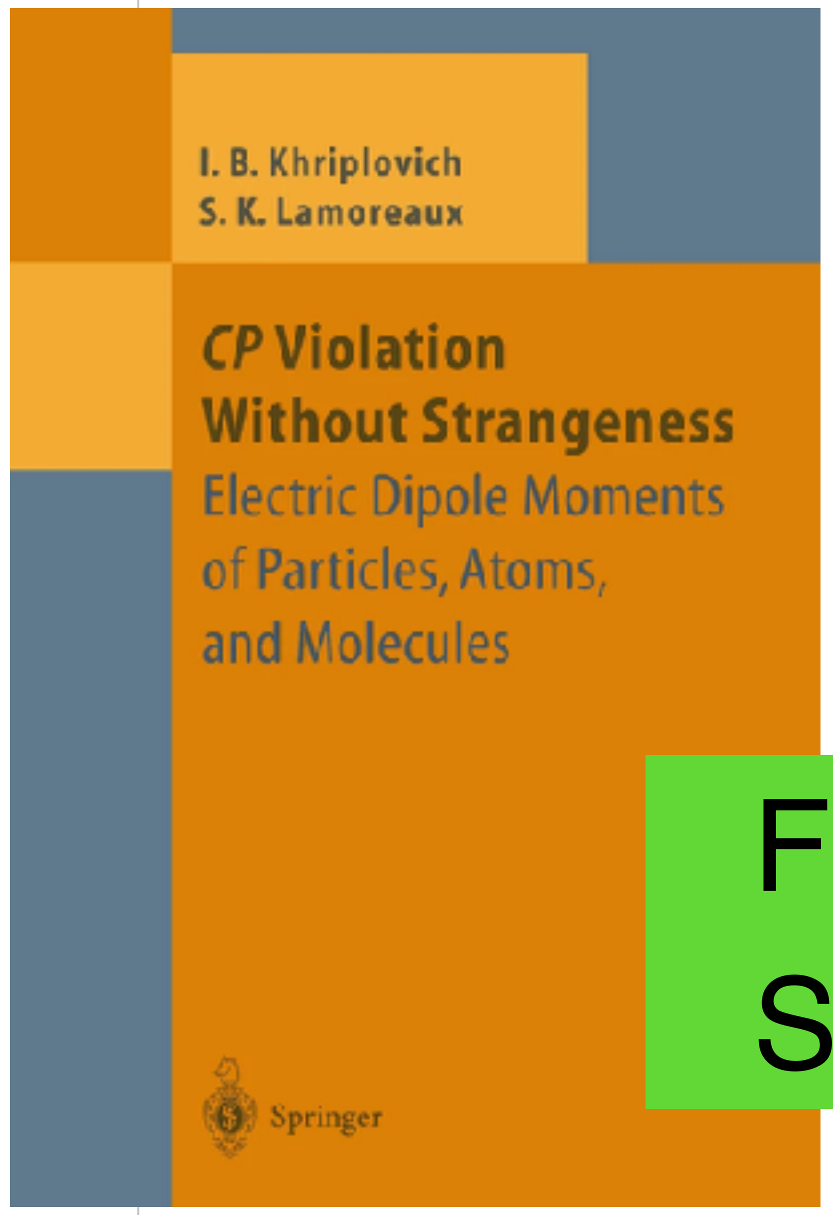


Snowmass 2021 Cross Frontier Report on Dark Matter Complementarity

Strong Charge-Parity (CP) Problem

- CP symmetry violated in the weak force but not in the strong force
  - Weak force: CP violation in neutral kaon decays
  - Strong force: would lead to a neutron EDM $d_N = (5.2 \times 10^{-16}\mathrm{e} \cdot \mathrm{cm})\ \bar{\theta}$
  - Current experimental limits: $d_N < 10^{-26}\mathrm{e} \cdot \mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$



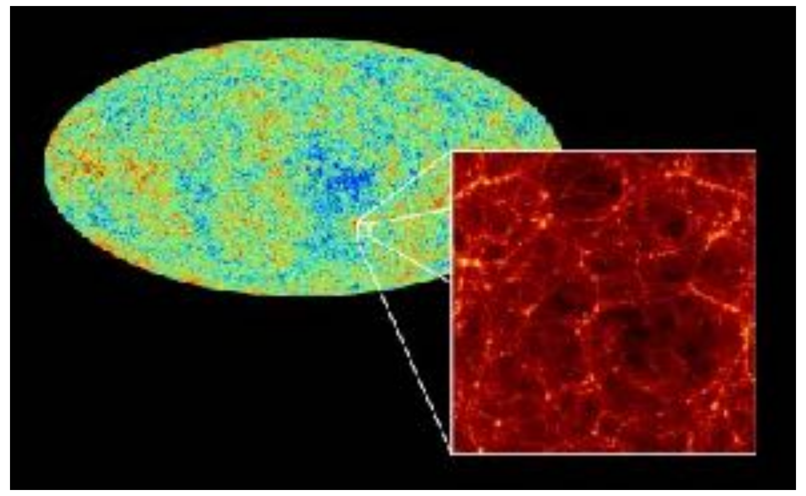


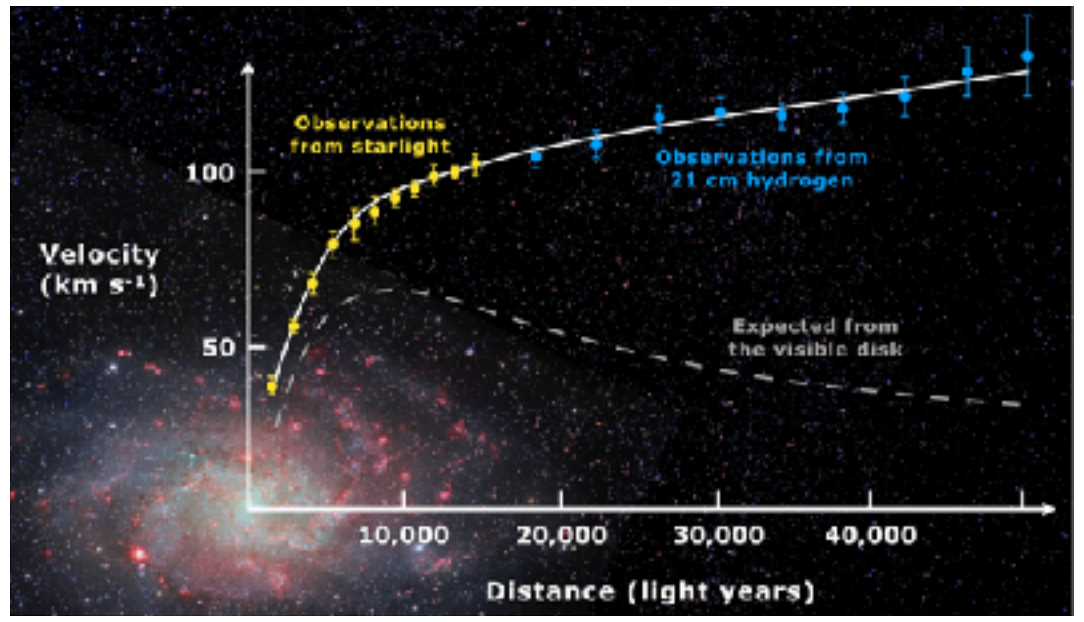
Fine-tuning =
Strong CP problem

Solution: the Axion

Dark Matter

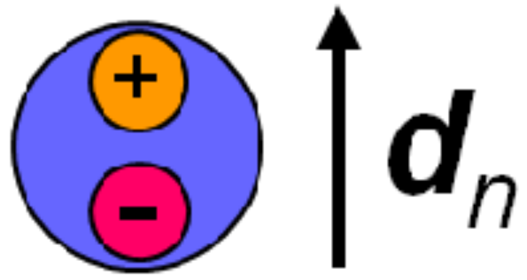
Astrophysical measurements of gravitational interaction

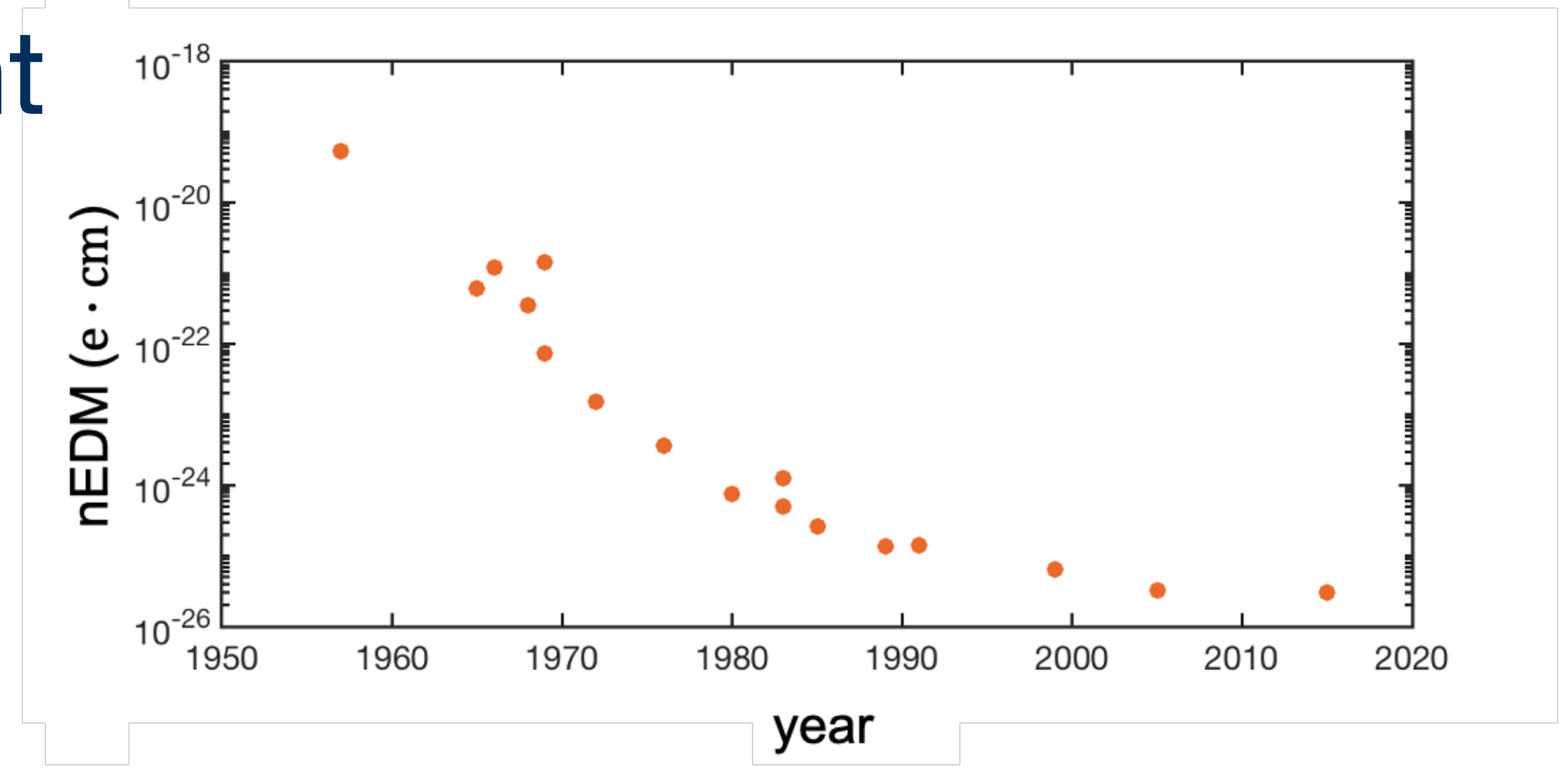


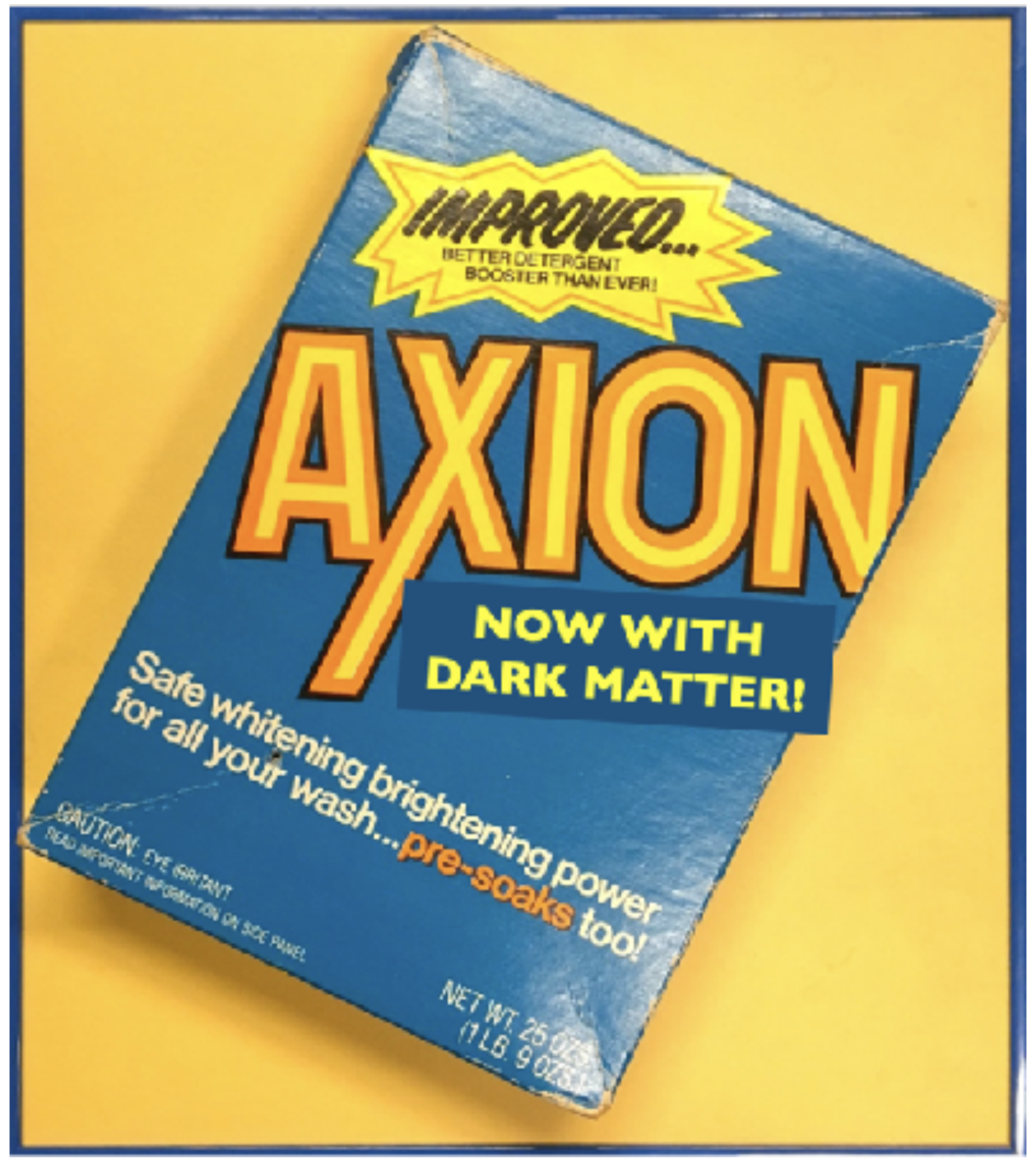


Strong CP Problem

No neutron electric dipole moment





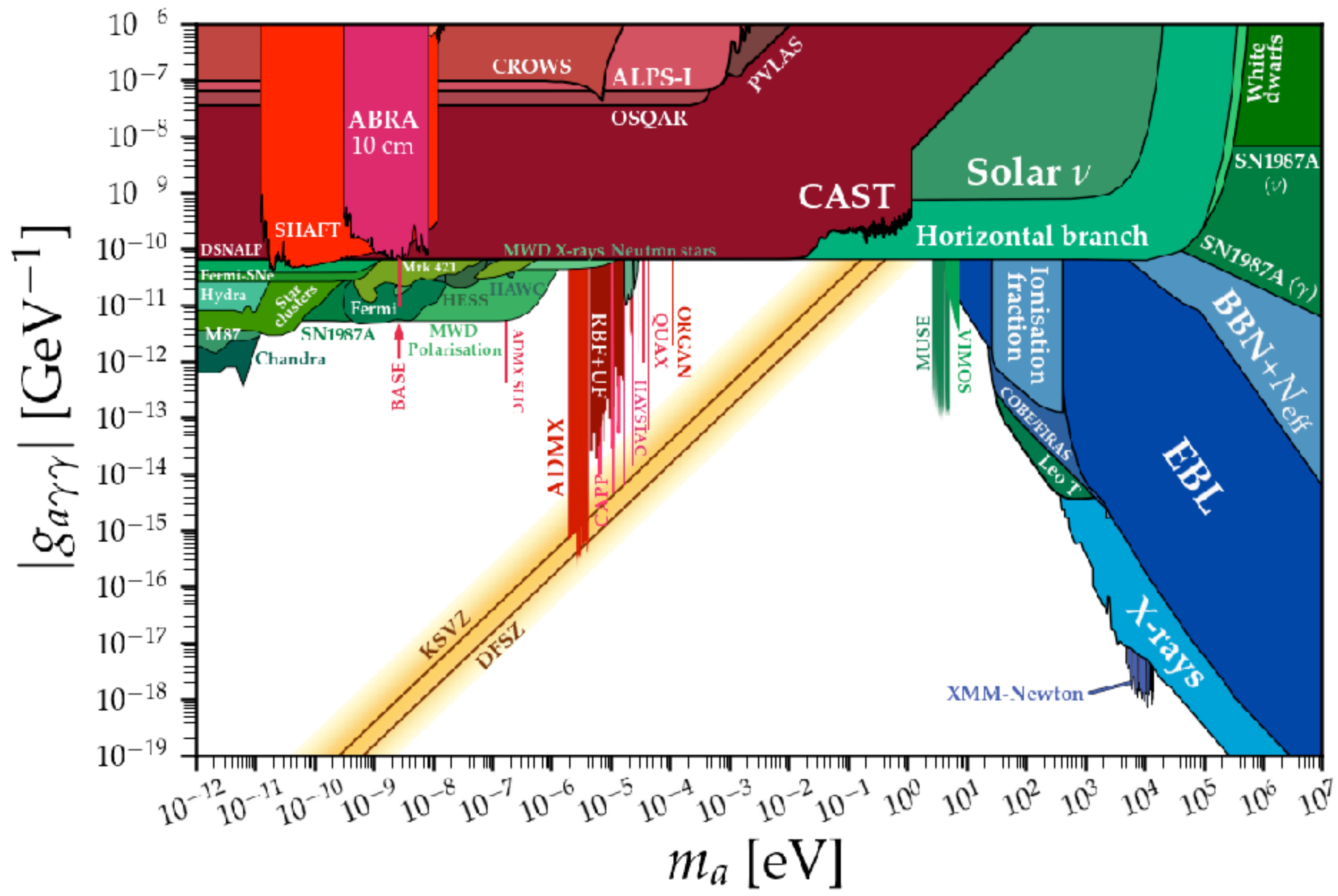


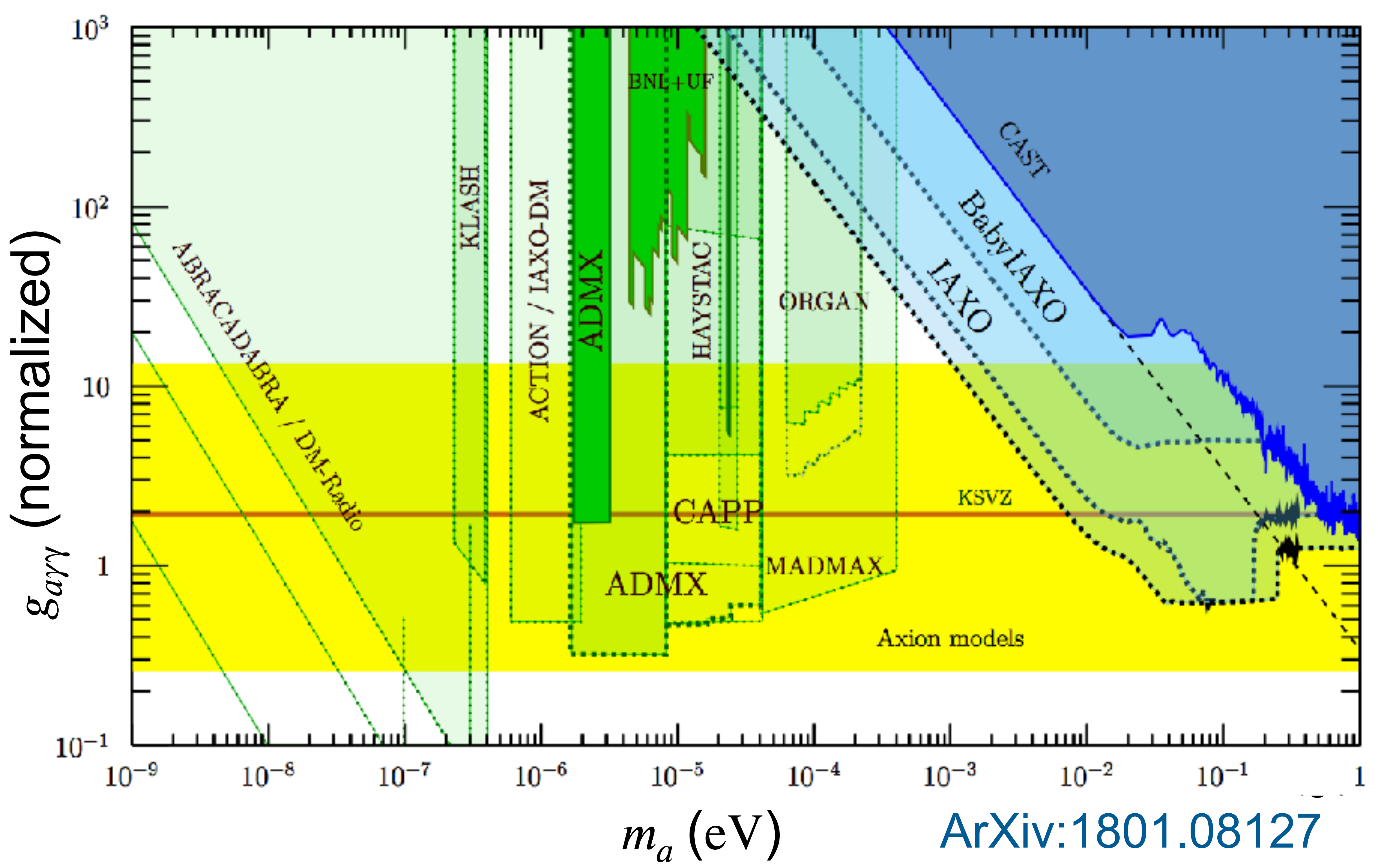
Solution to “clean up” both problems

Adapted from M. Silva-Feaver

Axion coupling and bounds

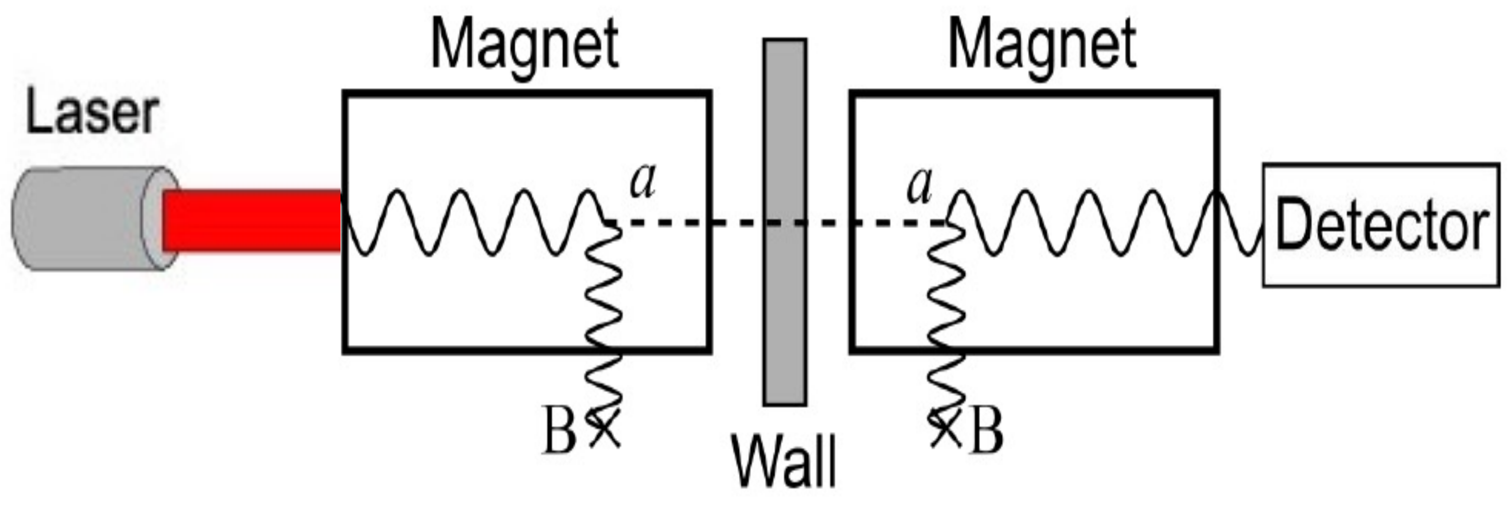
- An upper bound on m_a from supernova SN1987a
- Lower bound from universe overclosure





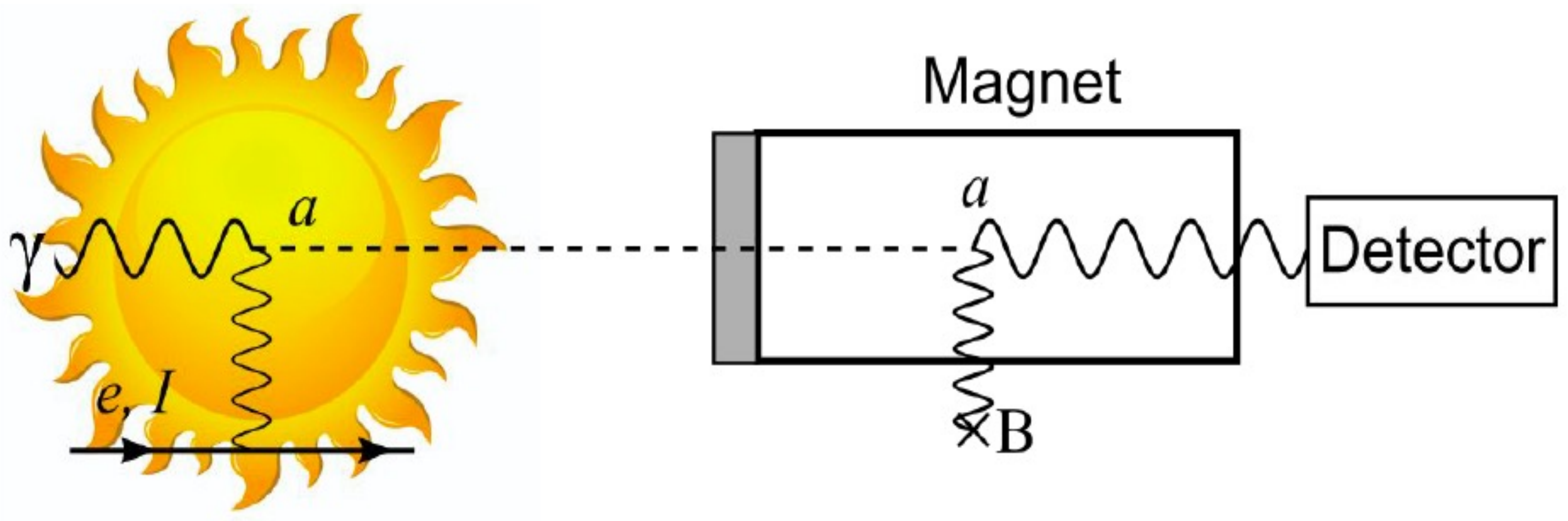
ArXiv:1801.08127

Ways to look for Axions



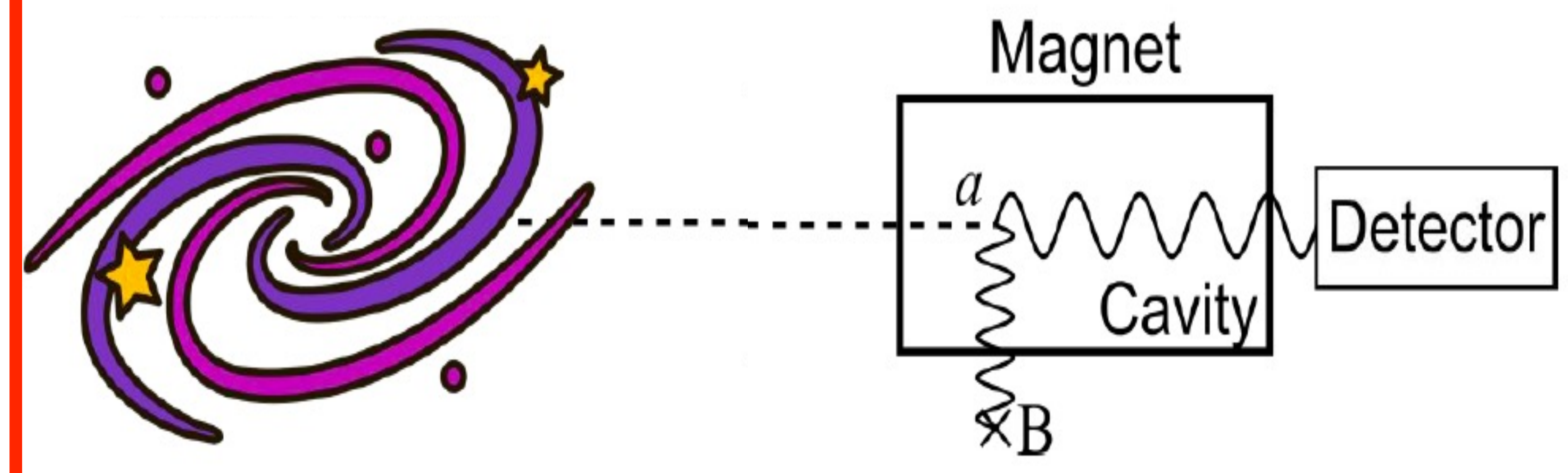
Light-Shining-Through-Wall Experiment

Laboratory-based experiments producing and detecting axions



Helioscope

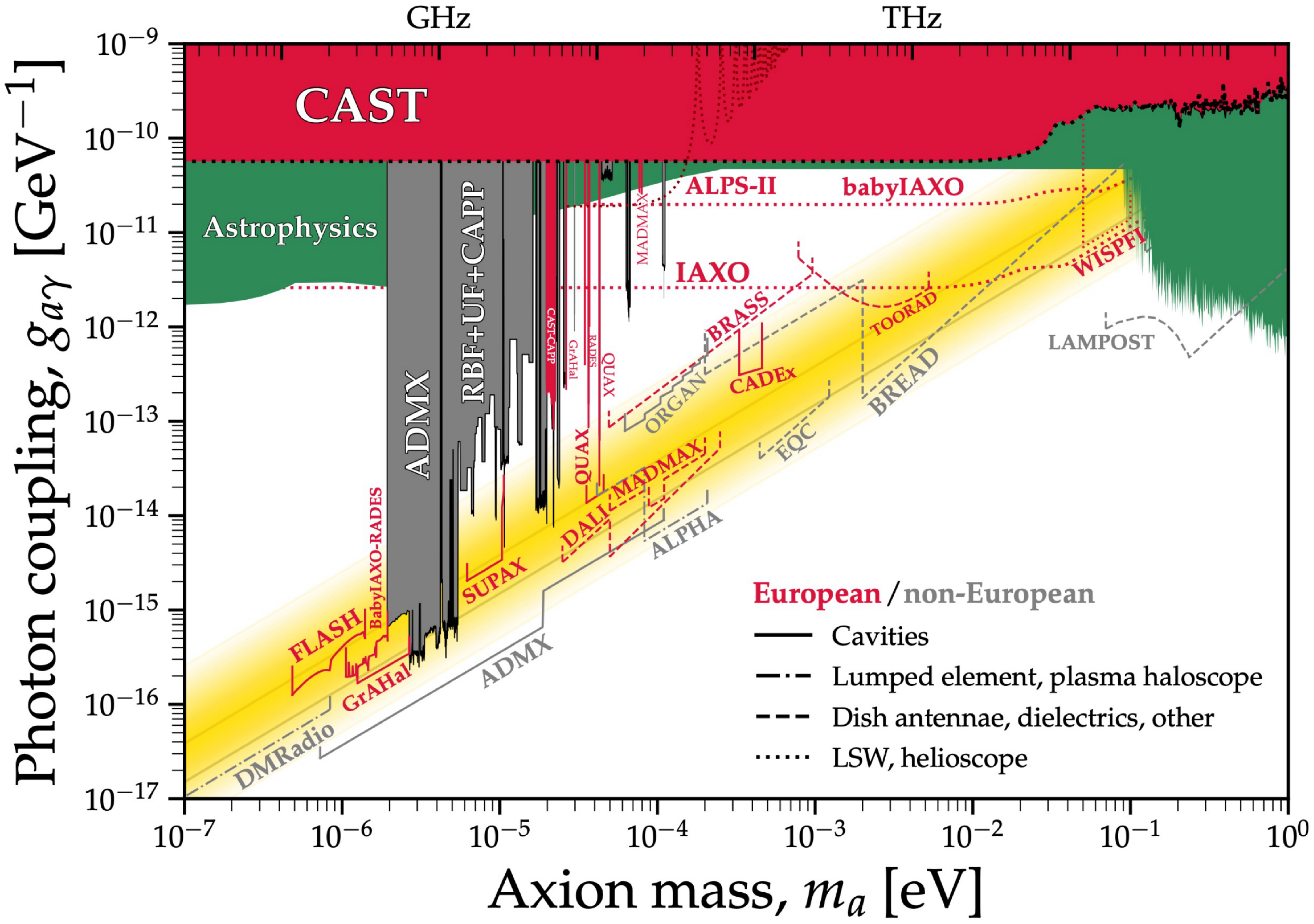
Scientific instrument designed to detect axions or axion-like particles (ALPs) coming from the Sun



Haloscope

Scientific instrument designed to detect axions in the Milky Way halo

Axion Searches: Current Status and Reach

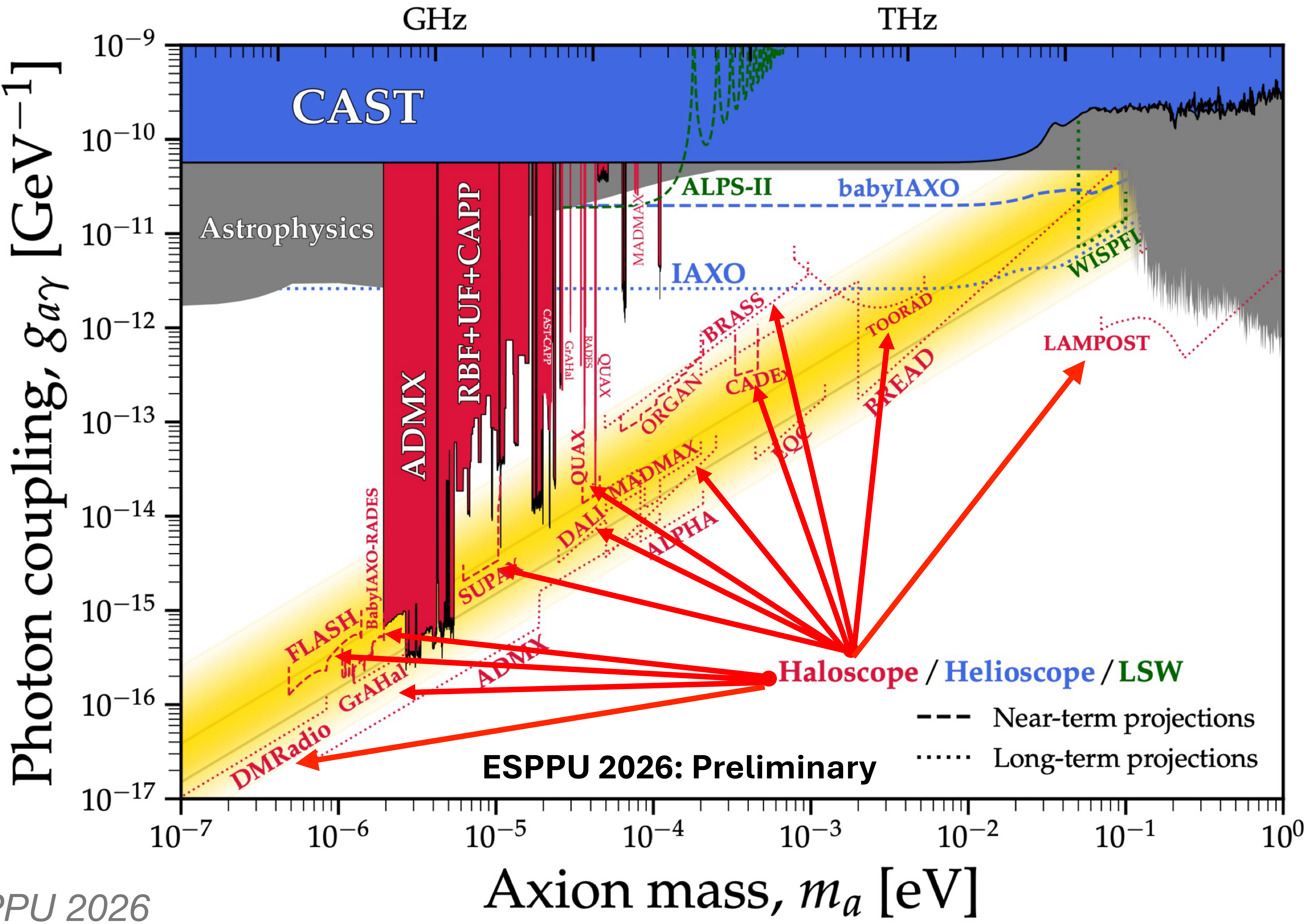


Explore the axion + ALP parameter space with:

- Haloscopes
- Light-shining-through-wall experiments
- Helioscopes

Adapted from Julia Vogel, ESPPU 2026

Haloscope Dark Matter Searches

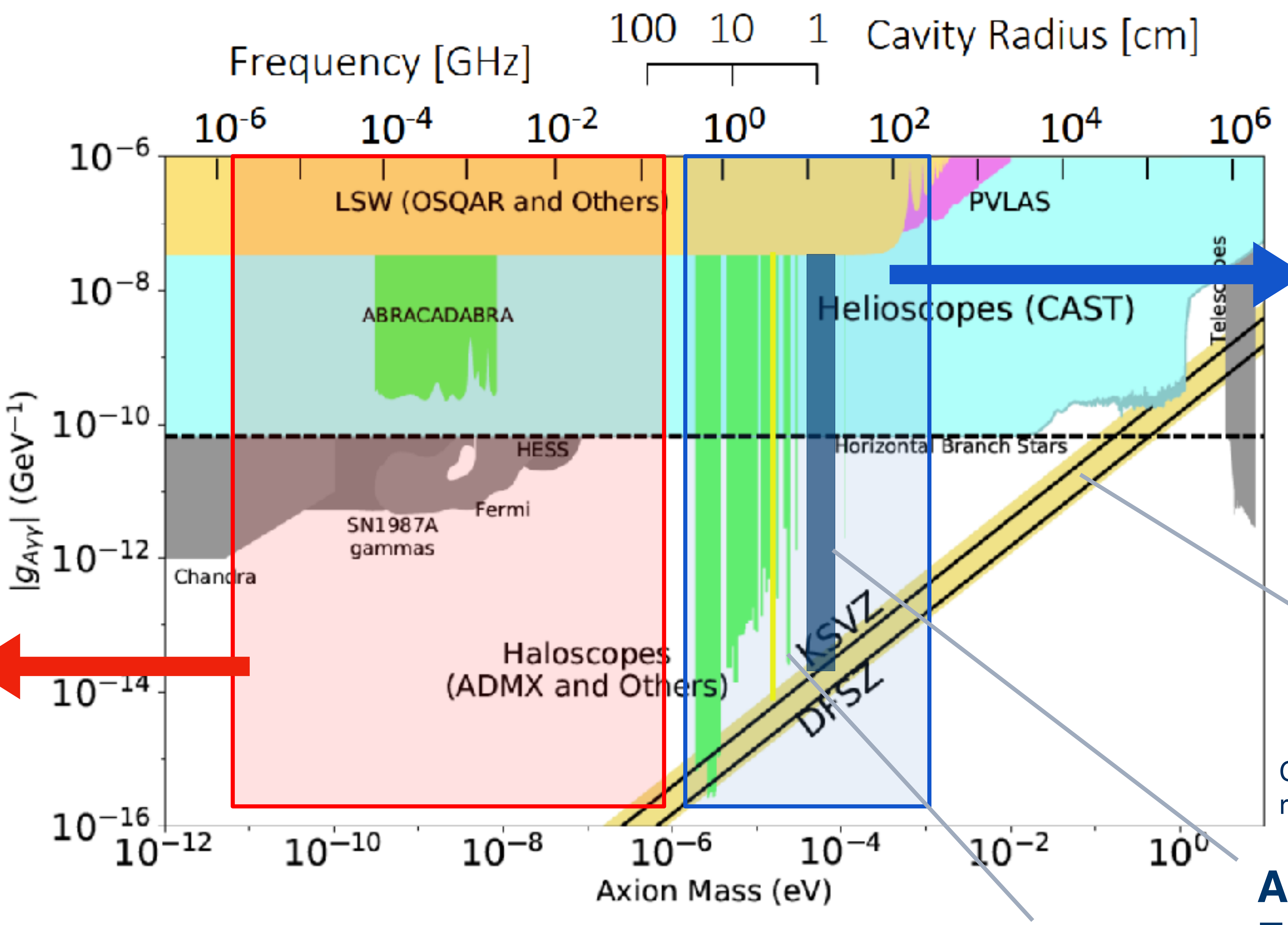


Julia Vogel, ESPPU 2026

Axions' Pre- vs. Post-Inflation Production

Pre-inflation axion –
wide range of viable masses.
"GUT-scale" axion.

Mass: below 1 μeV
Typical Measurement:
Lumped element detectors



Post-inflation axion –
theoretically calculable from string production mechanisms.

Mass: above 1 μeV
Typical Measurement:
Cavity haloscopes

Coupling for QCD Axion

Credit: Particle Data Group 2020 review of axion particle physics

ALPHA Phase 1 Forecast

HAYSTAC

Adapted from Max Silva-Feaver

Detecting Axion Dark Matter

The Axion Haloscope

- Axions modify Maxwell's equation and produce an **effective AC current**, which couples Axions to EM.
- **High Q-factor** cavity to capture photons produced through axion-photon conversion
- Measuring our local dark matter halo = "haloscope"

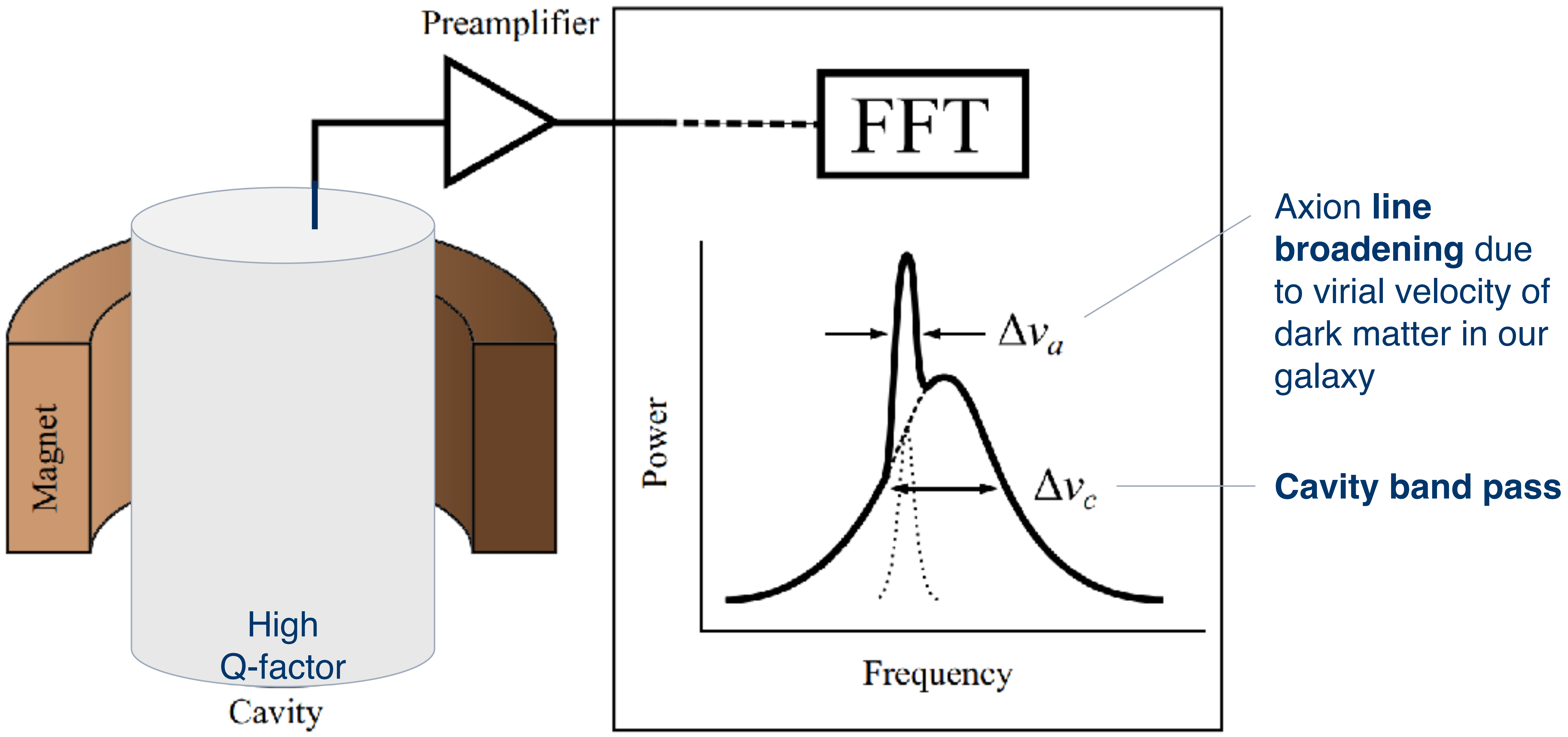


Figure: Kowitt, Balafendiev et al. (2023) *Tunable wire metamaterials for an axion haloscope*

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

Detecting Axions

Signal Power:

$$P \propto B^2 CVQ \simeq 10^{-24}\mathrm{W}$$

B = External field

V = Cavity Volume

Q = Quality Factor

C = Overlap of cavity mode & magnetic field

System Noise:

$$k_b T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_b T} - 1} + \frac{1}{2} \right) + k_b T_A$$

T_{sys} = System temp.

T = Cavity temperature

T_A = Amp. noise temp.

Requirements: Low T and custom amplification

Figure of Merit:

(FOM)

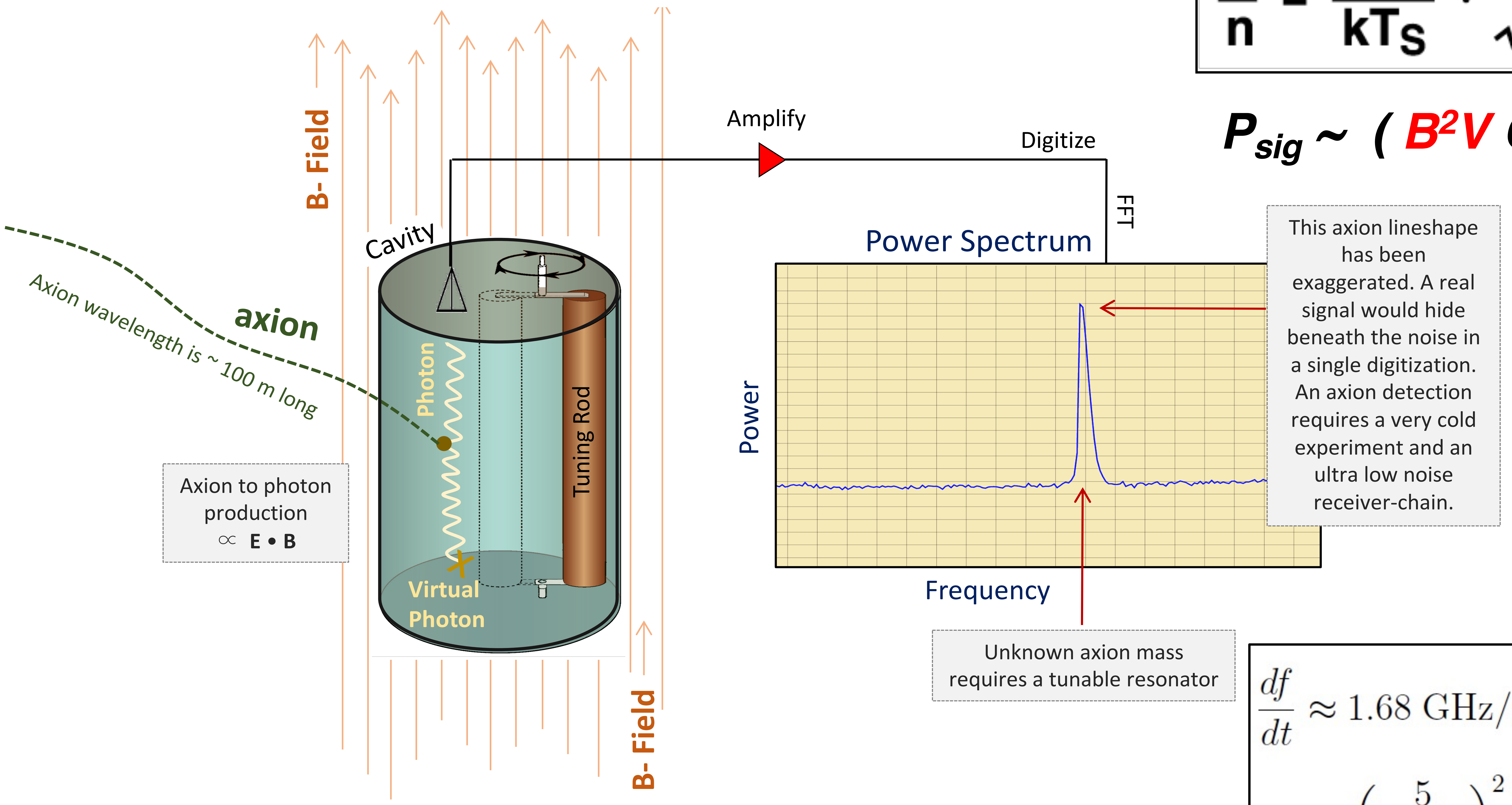
$$\frac{d\nu}{dt} \propto \frac{V^2 B^4 C^2 Q}{T_{sys}^2}$$

Challenge: Do experiments in human timescales!

ADMX

Principles of ADMX

Gold standard



$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

$$P_{sig} \sim \left(B^2 V\, Q_{cav} C_{010} \right)\left(g^2\, m_a\, \rho_a \right) \sim 10^{-24}\ W$$

System noise temp.

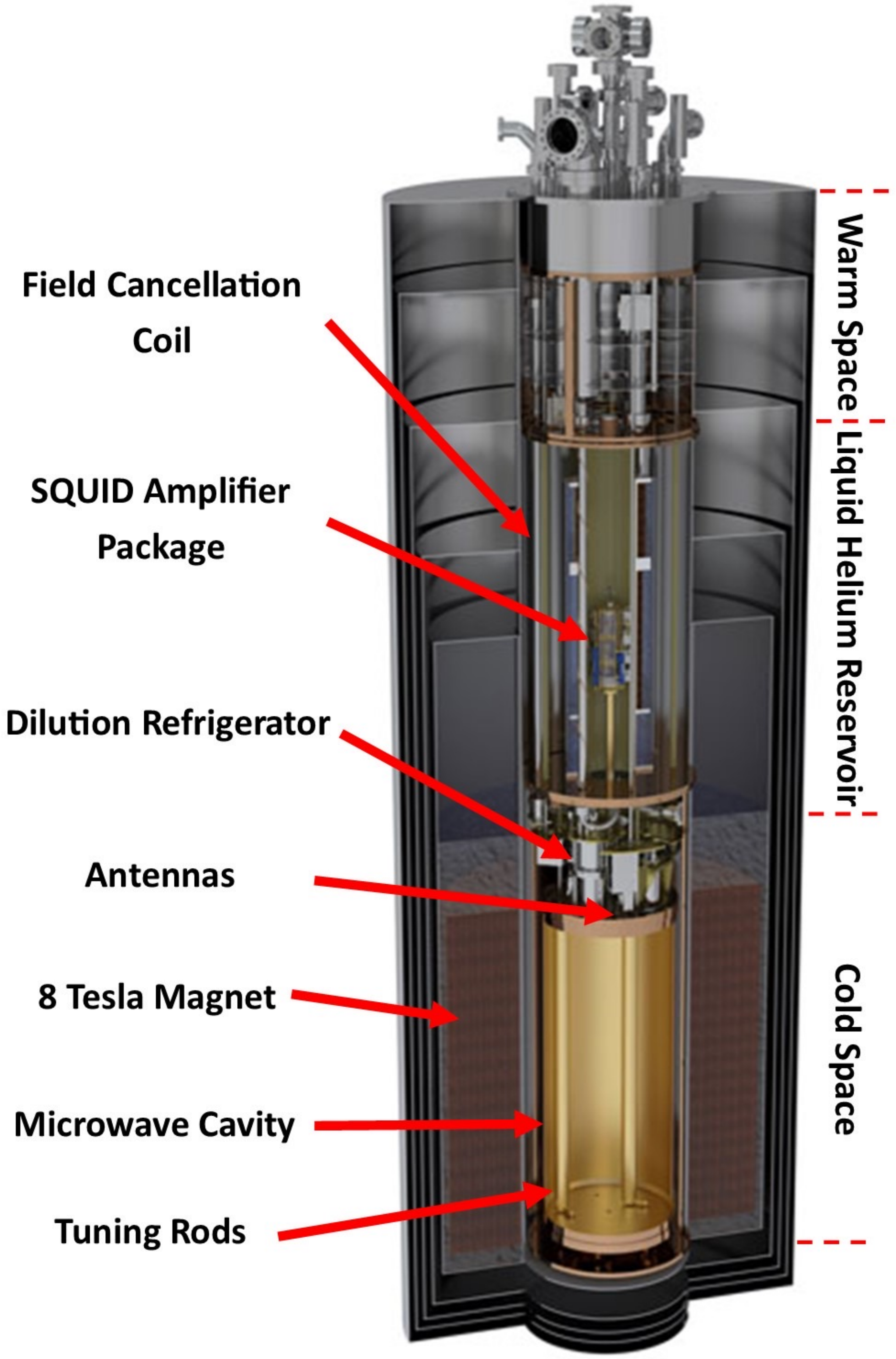
$$T_S = T_{phys} + T_N$$

$$T_{Quant} \sim 48\ mK\ @\ 1\ GHz$$

t = Integration time limited to ~ 100 sec

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

ADMX Experimental Layout

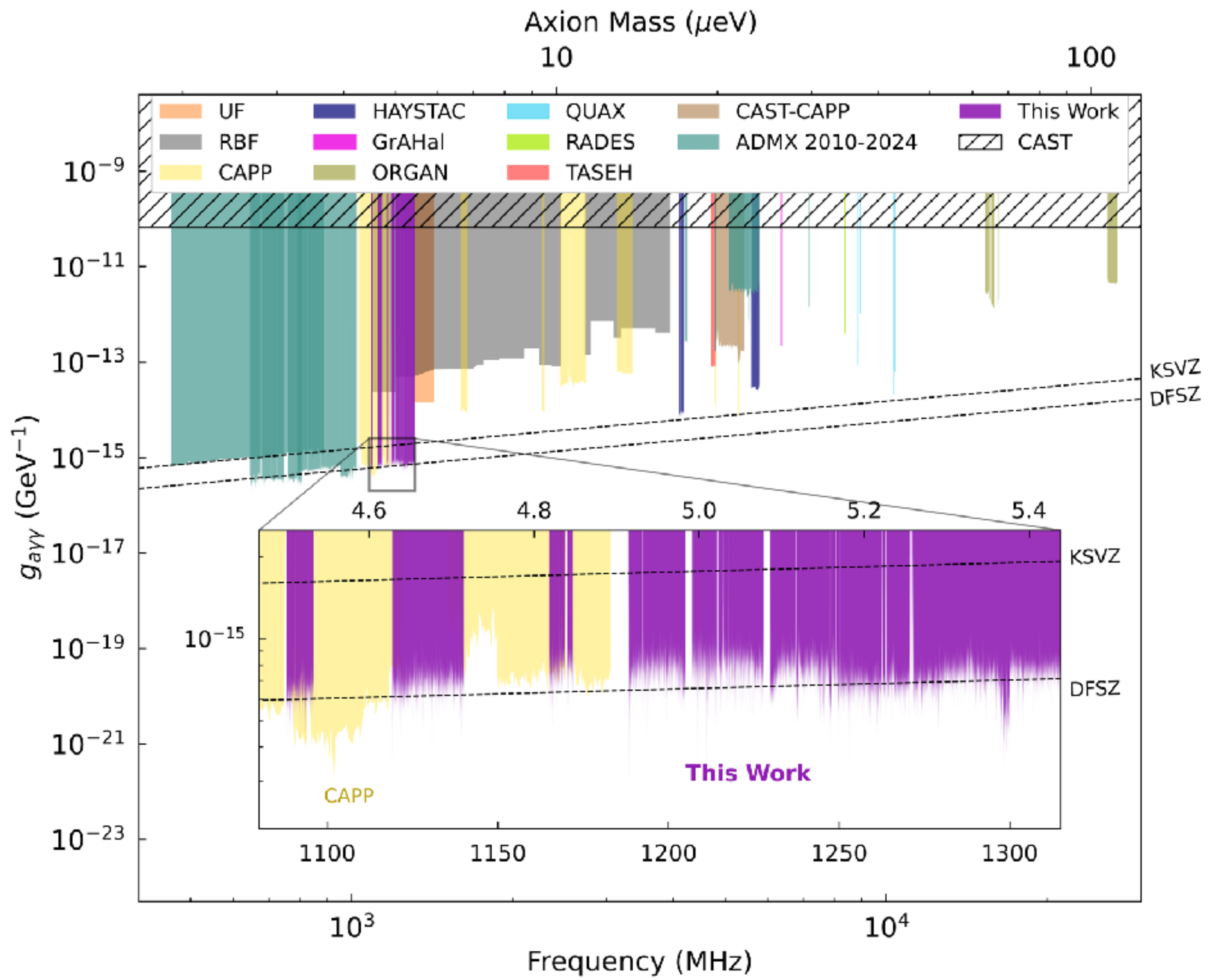


Carosi, Axions Beyond Boundaries Workshop – 2023

ADMX 2024 Results

Over the range explored:

- KSVZ Axion Model at nominal dark matter density excluded at 90% confidence between 1 GHz and 1.3 GHz
- DFSZ Axion Model at slightly higher densities excluded

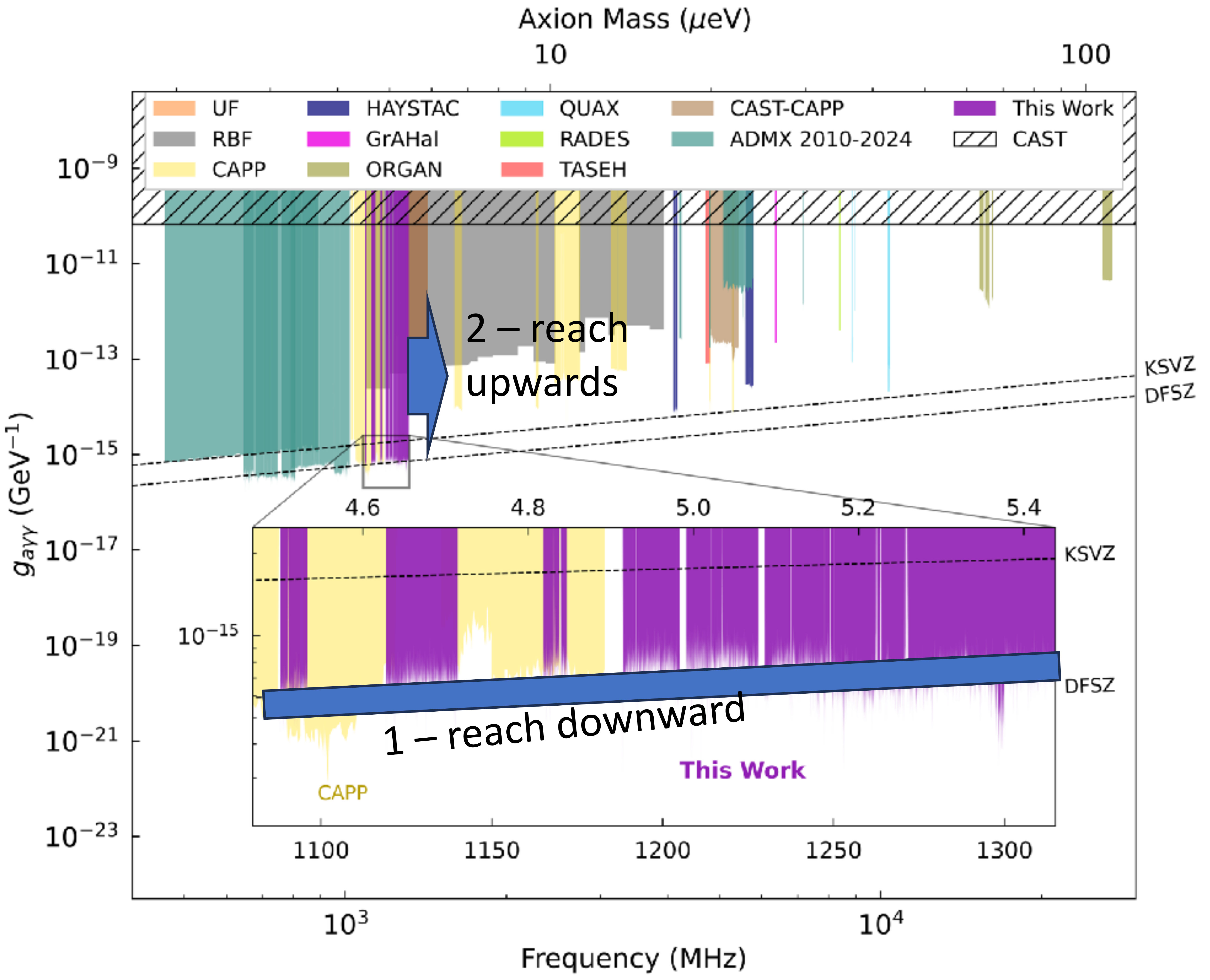


https://arxiv.org/abs/2504.07279

ADMX Near Future

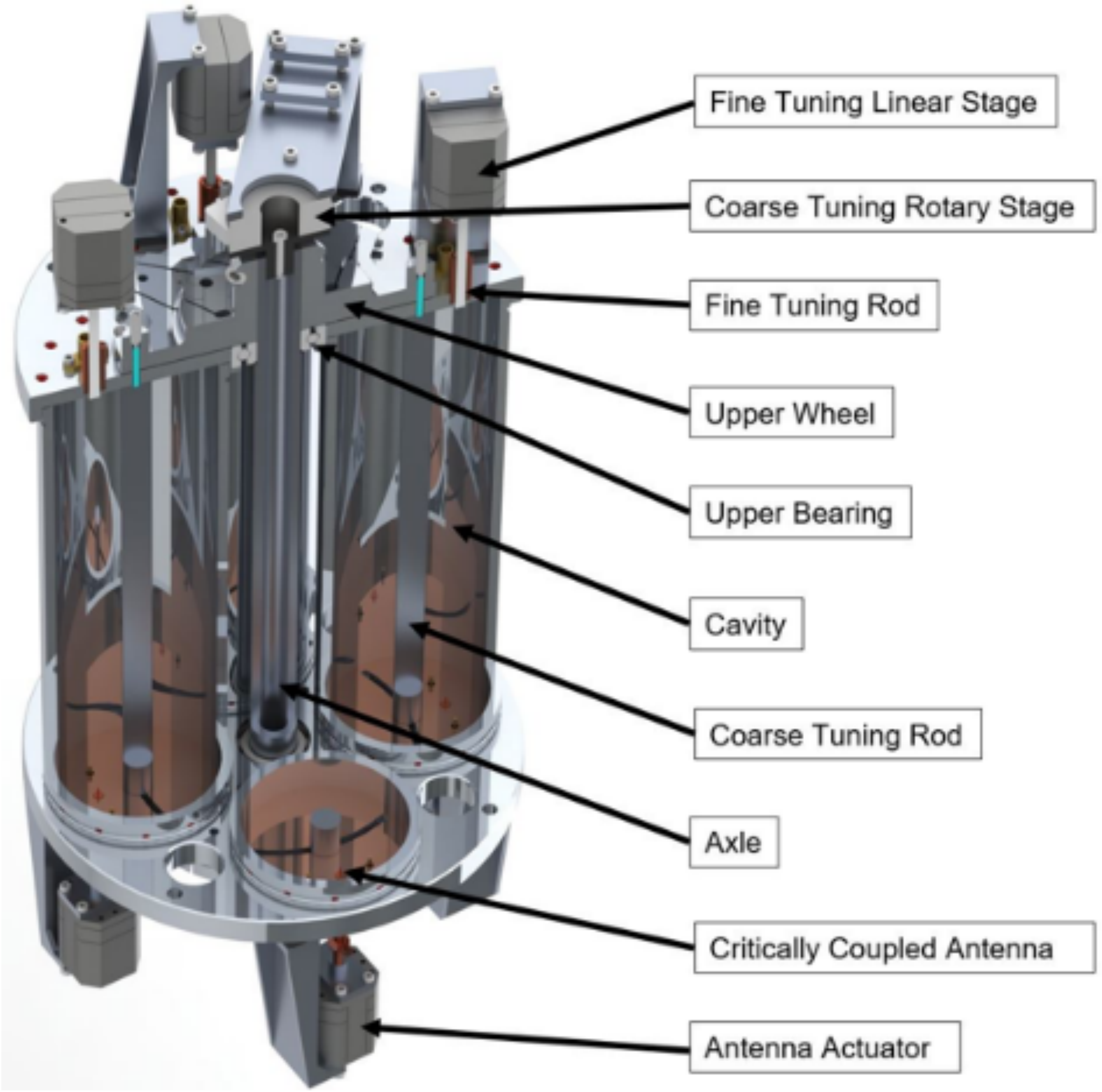
Work in the next few years:

1. Extend reach down to DFSZ at below-nominal dark matter density
2. Extend sensitivity to higher masses using a multicavity system

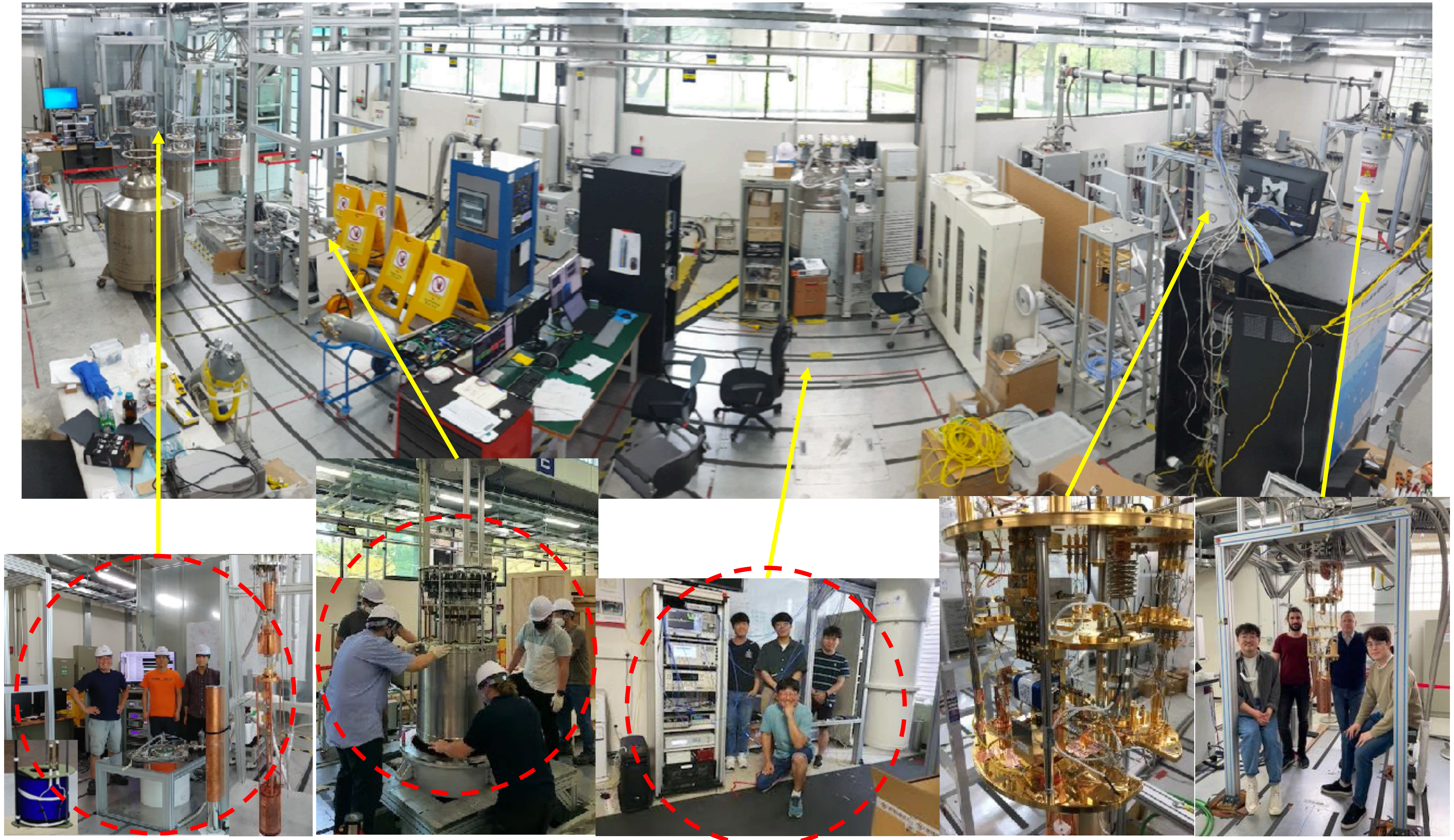


Next Year – 4 cavity system

- Power from 4 cavities are combined coherently to maintain detector volume at higher frequencies



IBS-CAPP (2013~2024)



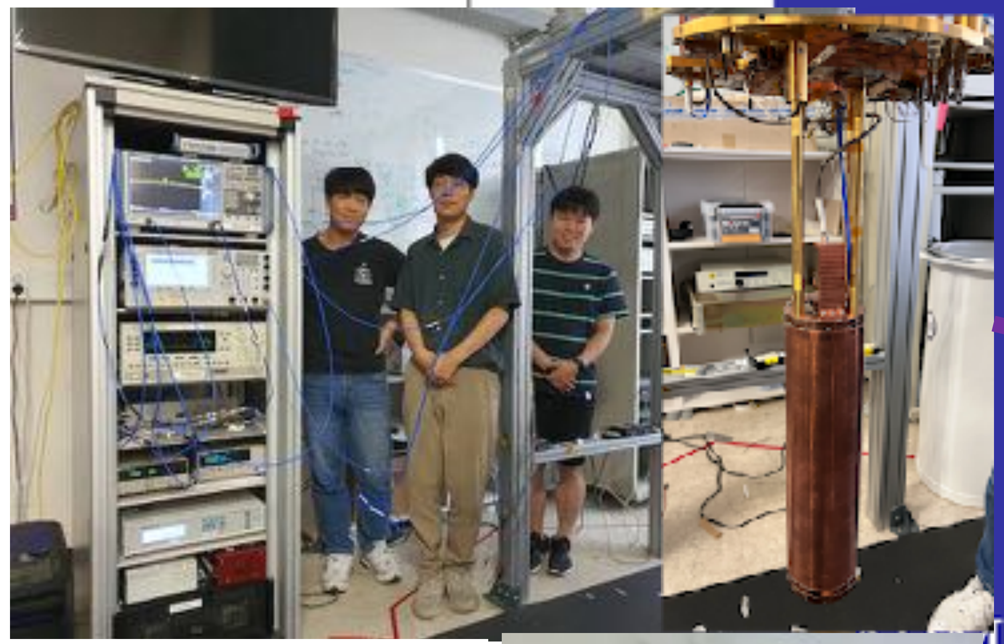
CAPP-9T CAPP-12TB CAPP-12T CAPP-8T CAPP-8TB

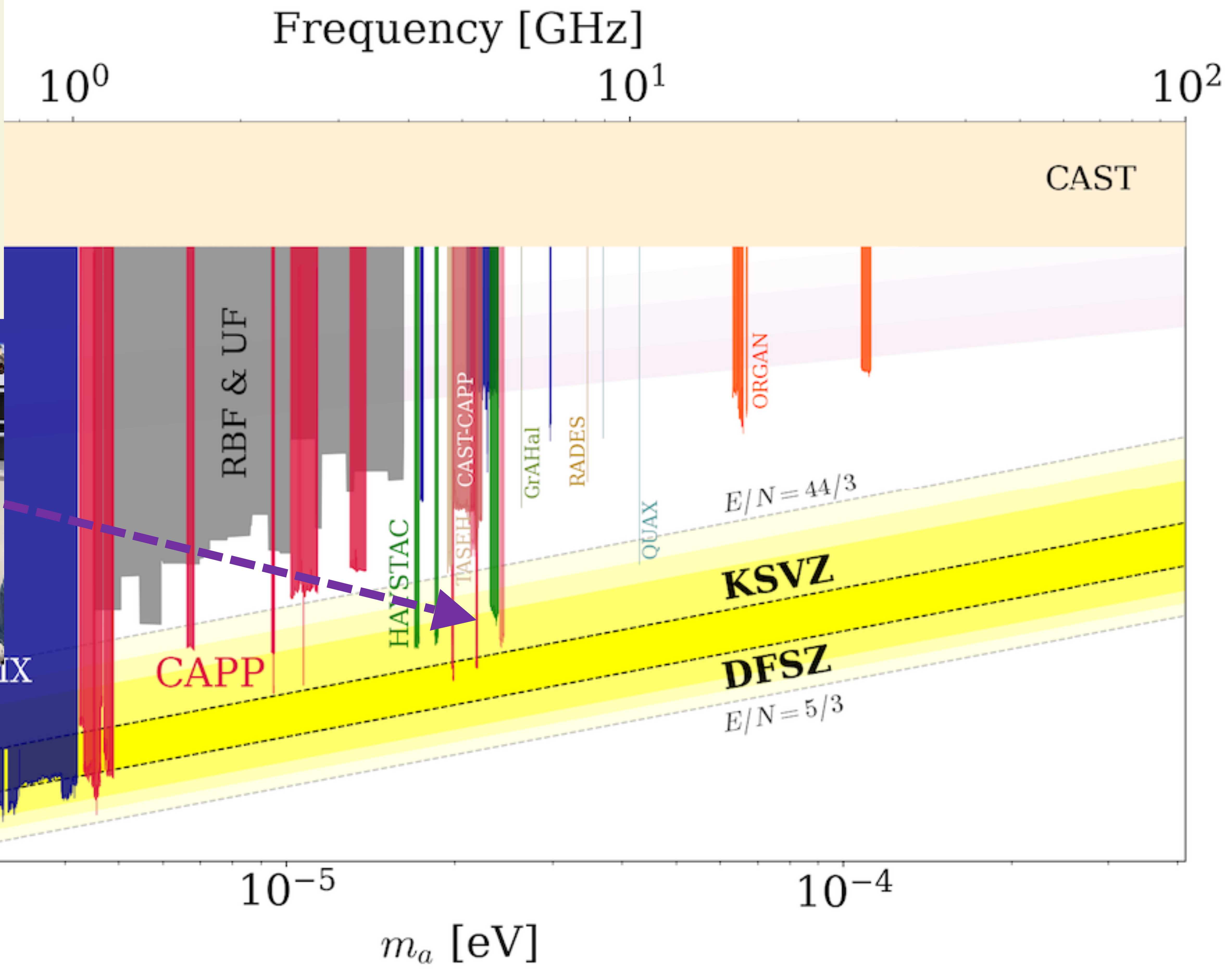
SungWoo Youn

Search highlight (I)

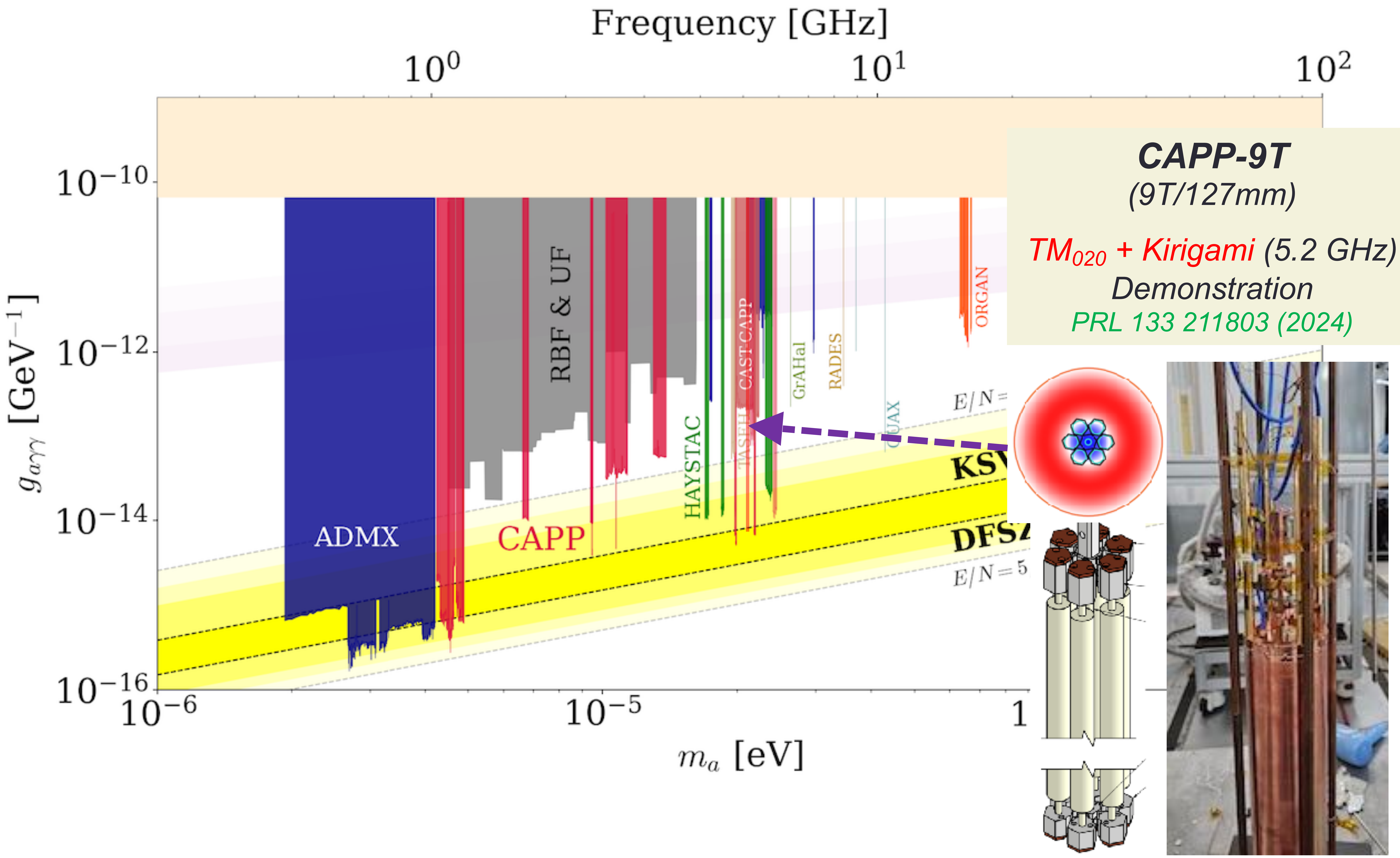
CAPP-12T
(12T/96m)

3-cell + JPA
(5.3 GHz, 400 mK)
KSVZ sensitivity
NM algorithm
PRL **133** 051802 (2024)





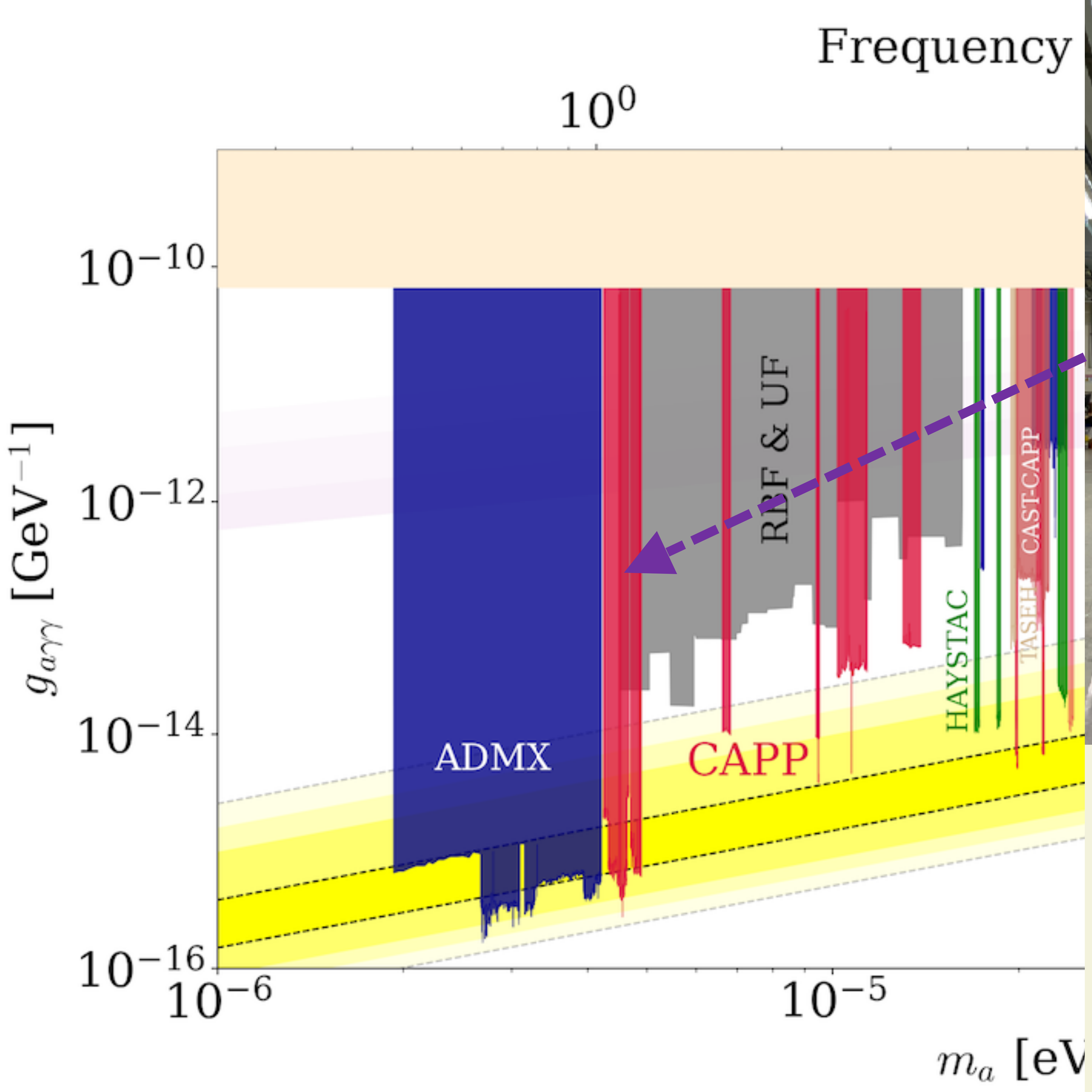
Search highlight (II)

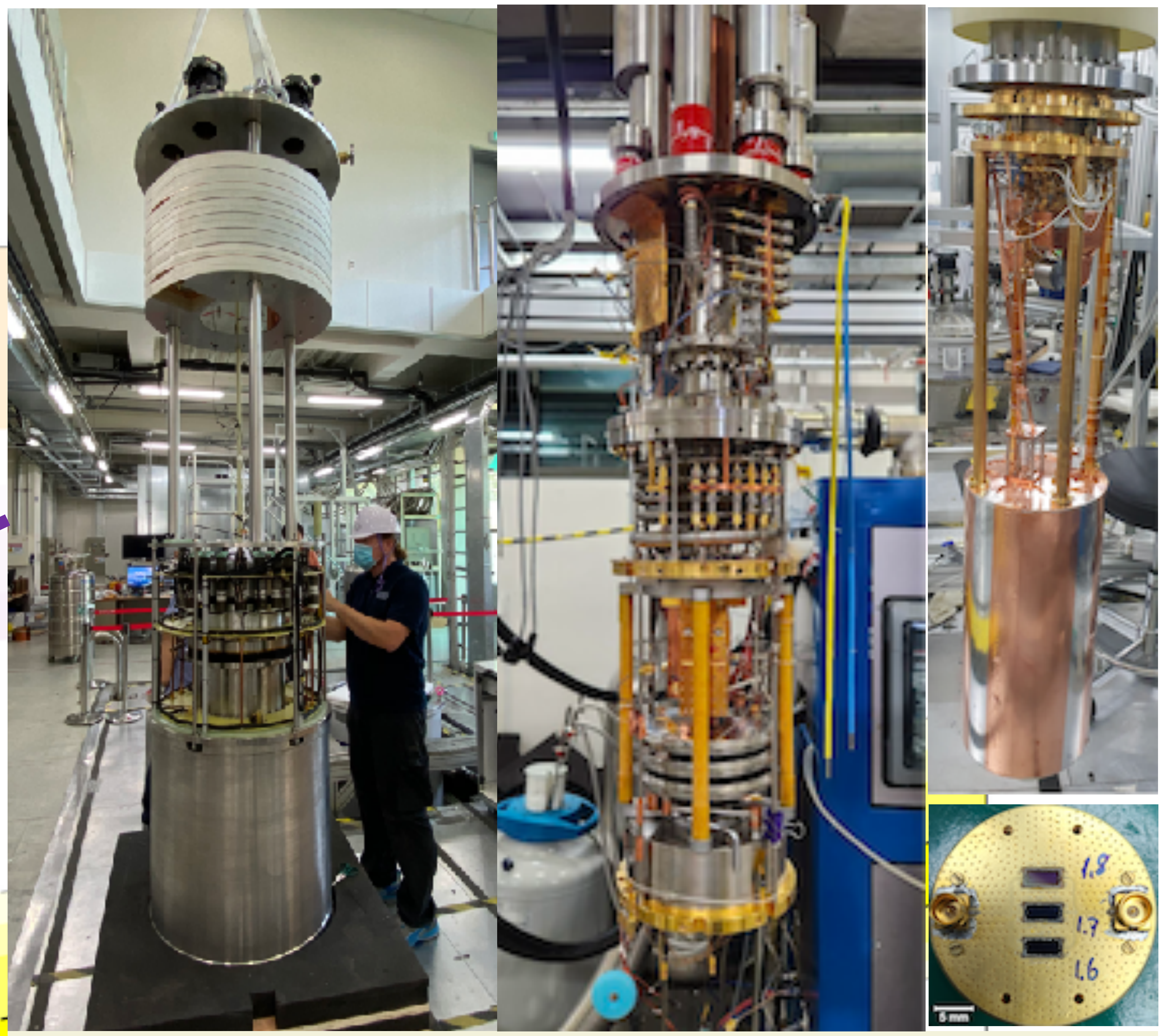


CAPP-9T
(9T/127mm)

TM_{020} + Kirigami (5.2 GHz)
Demonstration
PRL 133 211803 (2024)

Search highlight (III)





CAPP-12TB

(12T/320mm)

f > 1 GHz, V = 37 L, T_{sys} < 250 mK

df/dt ~ 2 MHz/day @ DFSZ

PRL ***130*** *071002 (2023)*

Extended scan (Δf~120 MHz)

PRX ***14*** *031023 (2024)*

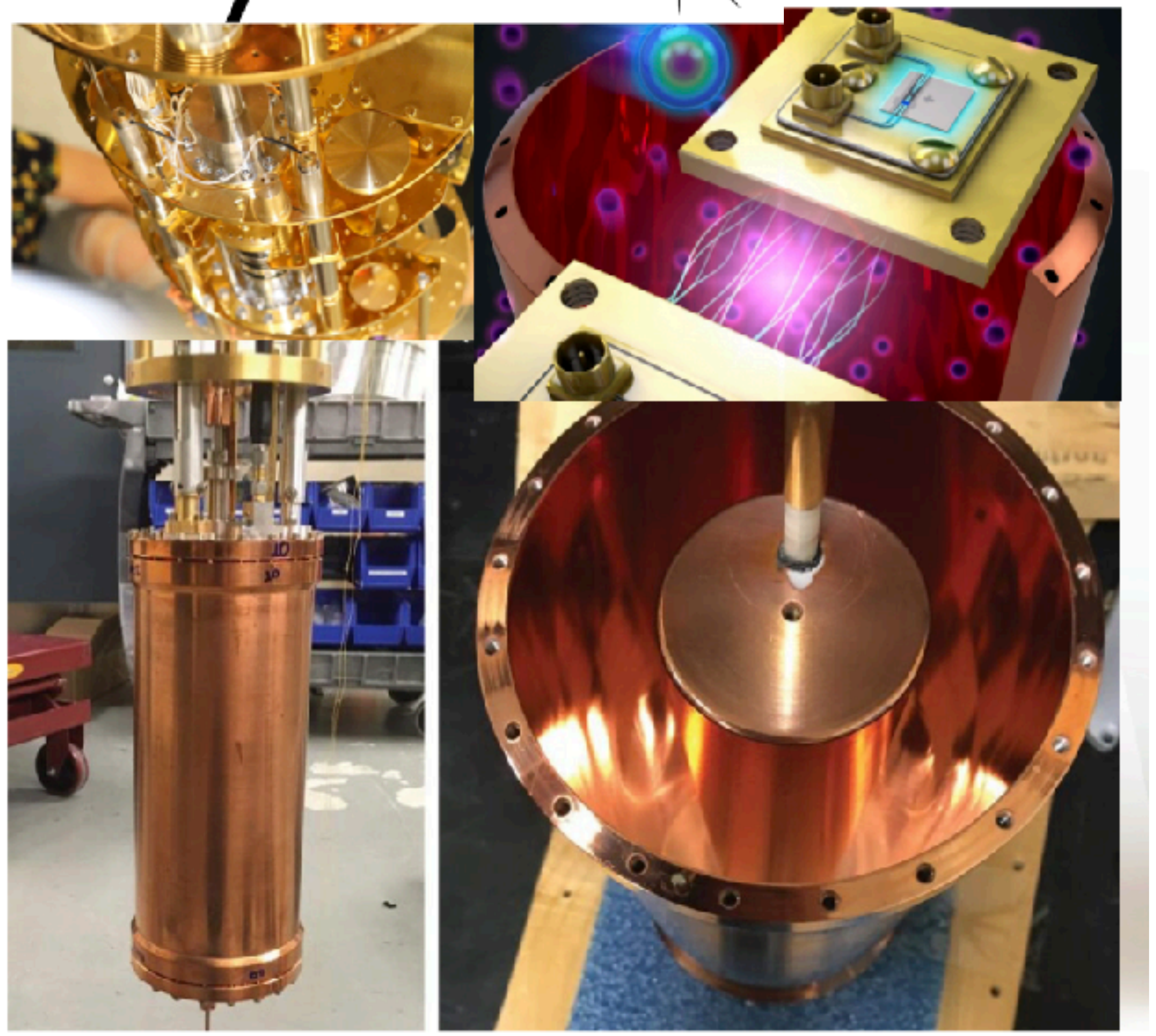
Ready for 300-MHz run w/ SC cavity

Summary

- *CAPP has established a world-class facility for axion search*
- *Novel R&D efforts and productive scientific results*
- *Substantial contributions to exploring the parameter space*
- *The effort was taken over in 2025 by a smaller group, DMAG (Dark Matter Axion Group), the successor to CAPP.*

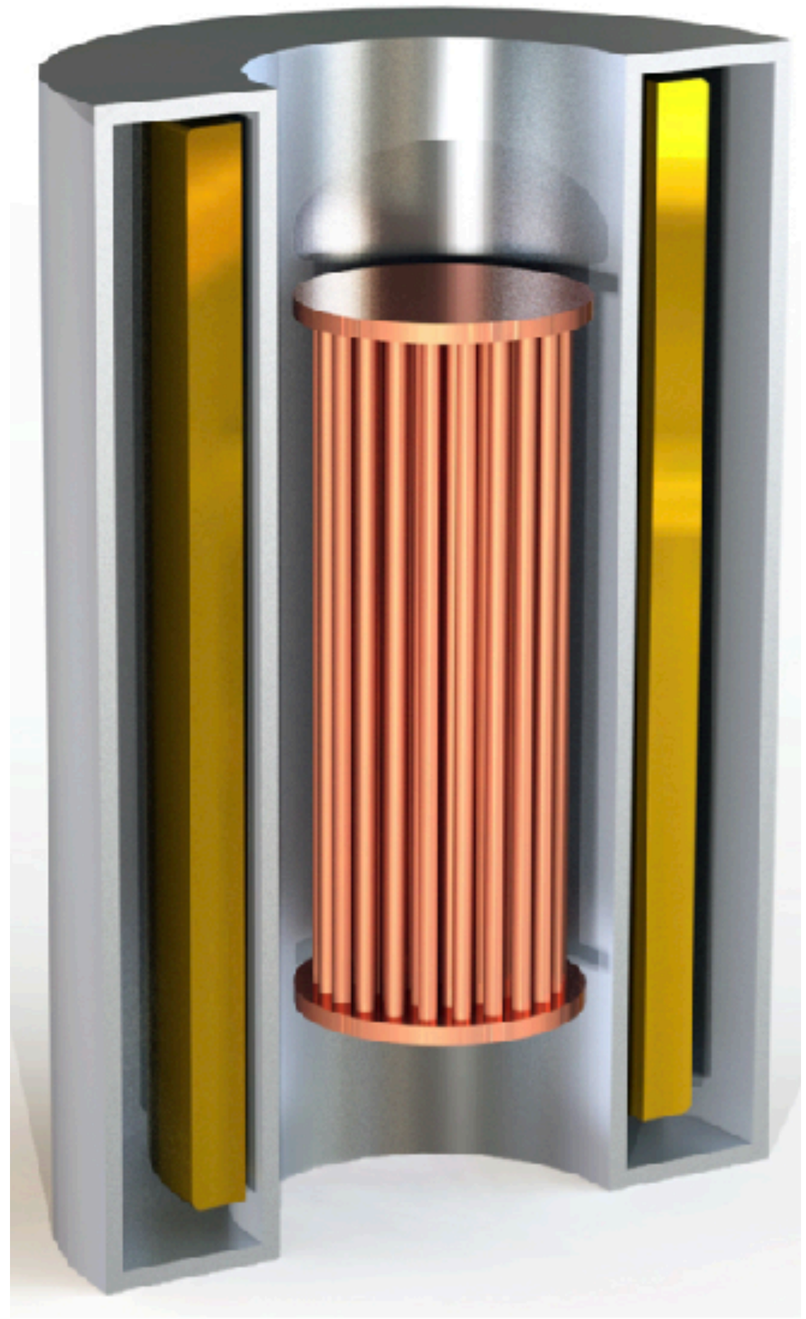
Axion Searches at Yale

Haystac



Nature **590**, 238–242 (2021)
PRD **107** 072007 (2023)
PRL **134**, 151006 (2025) *Editors' Suggestion*

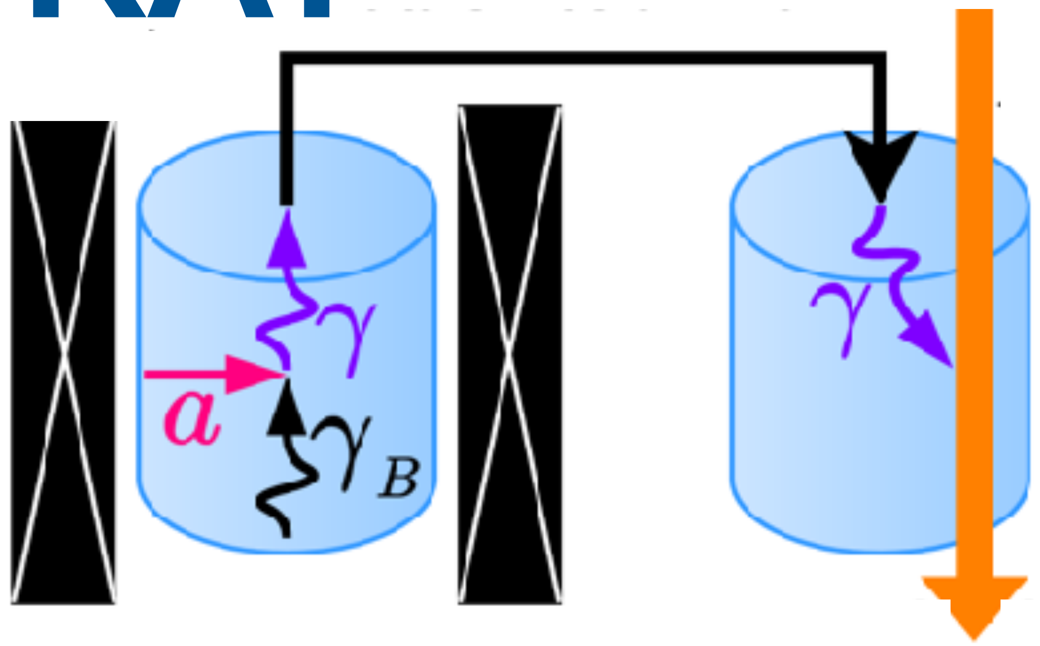
alpha
Phase1

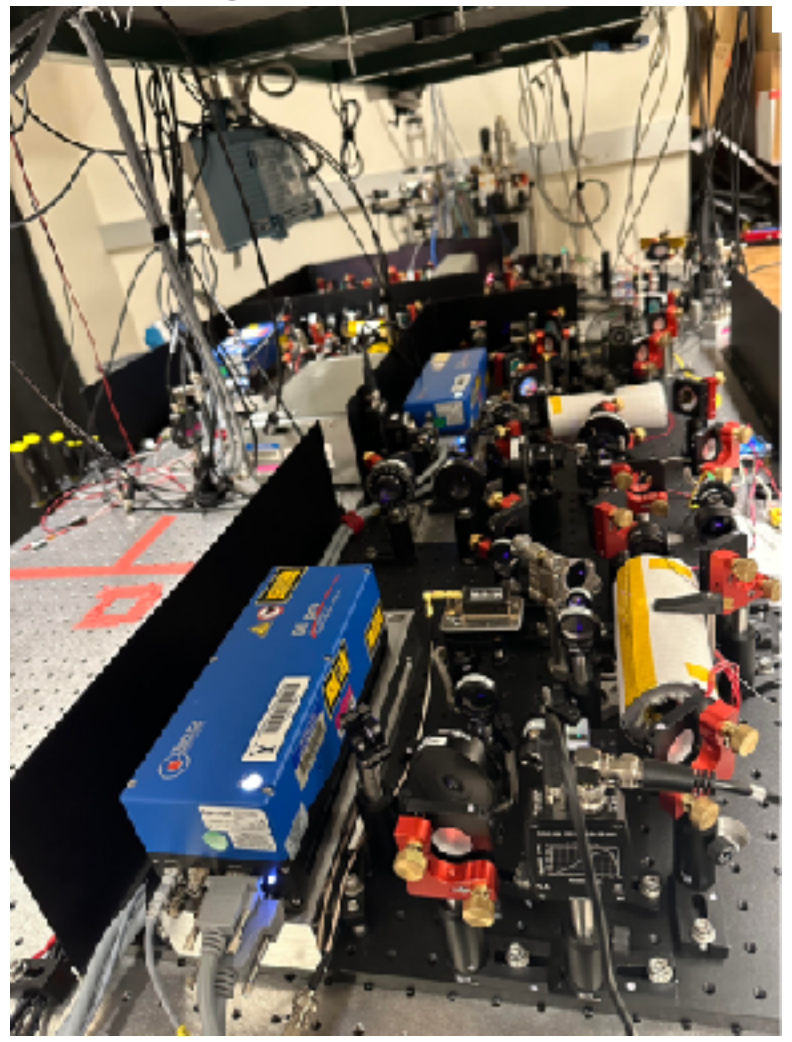


PRL **123**, 141802 (2019)
PRD **107**, 055013 (2023)

RAY

Single photon detection
with Rydberg atoms

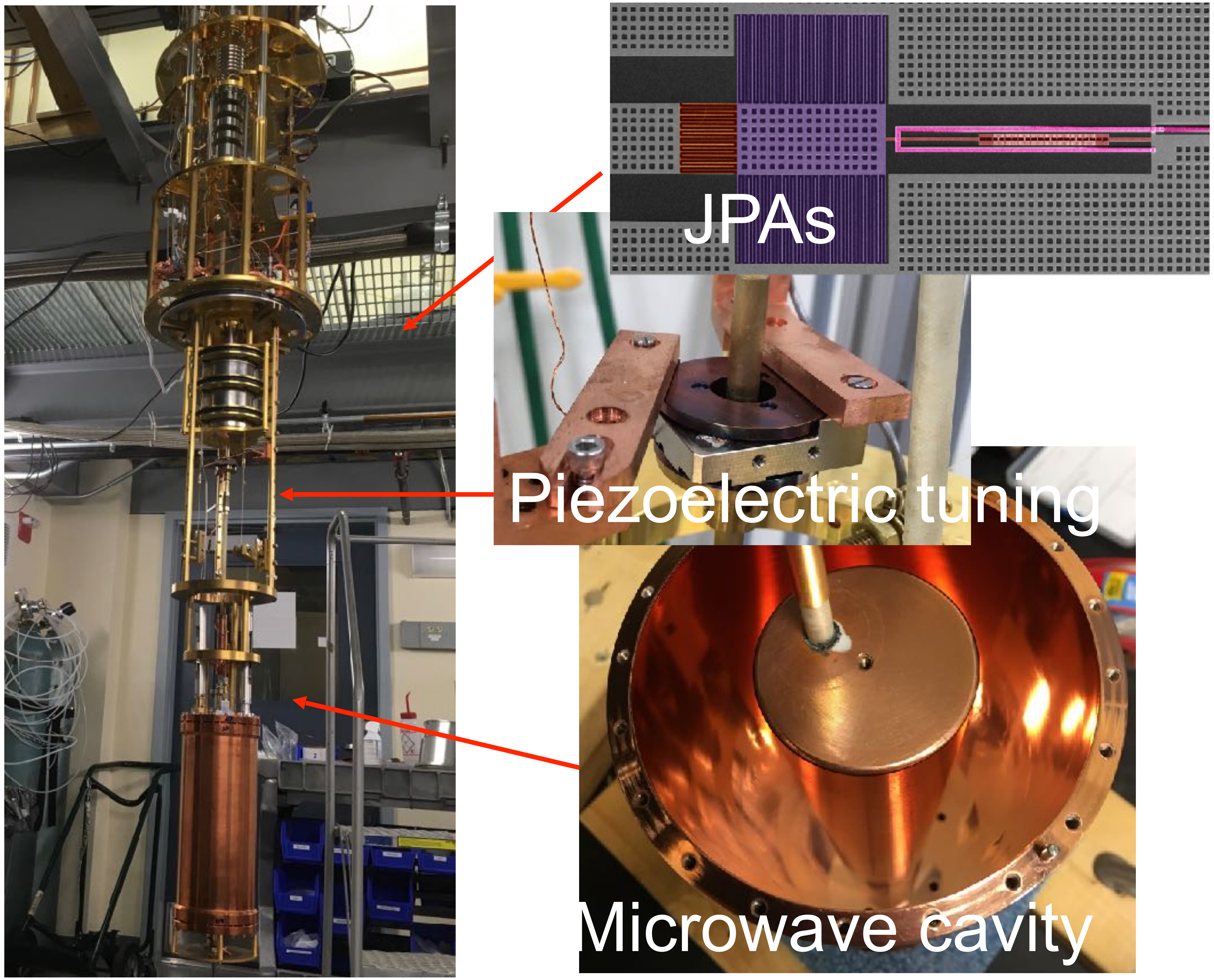




Phys. Rev. D **109**, 032009 (2024)

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

HAYSTAC Experiment



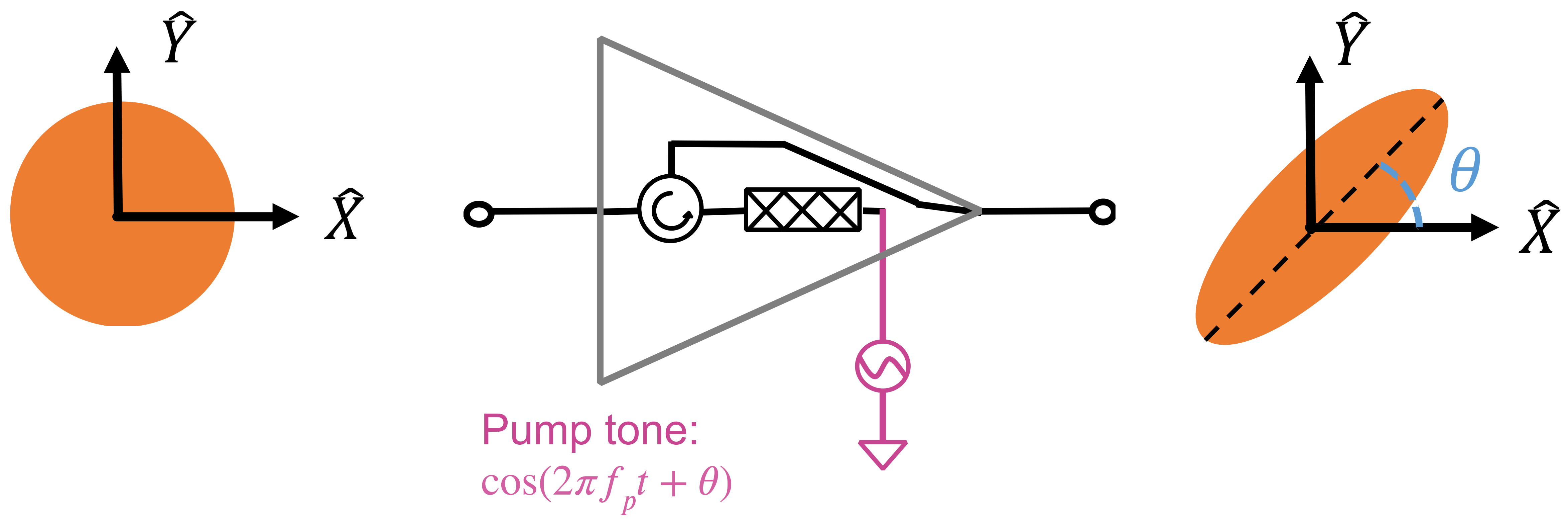
Brubaker et al., PRL 118 061302 (2017)

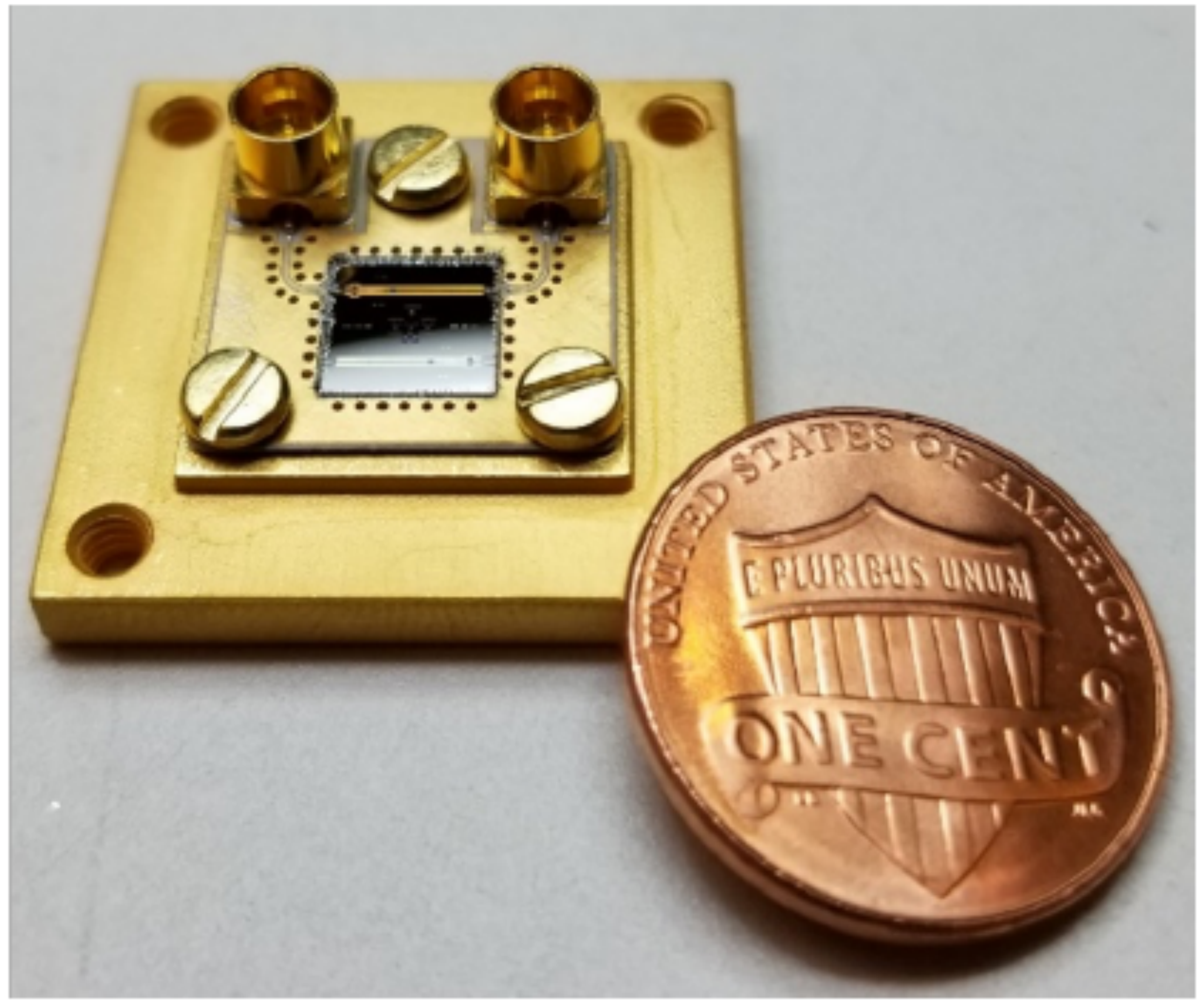
HAYSTAC Innovations: Phase 1

Ben Brubaker

Josephson Parametric Amplifier (JPA)

- Near quantum-limited noise
- Tunable LC resonators
- Phase-sensitive amplifier

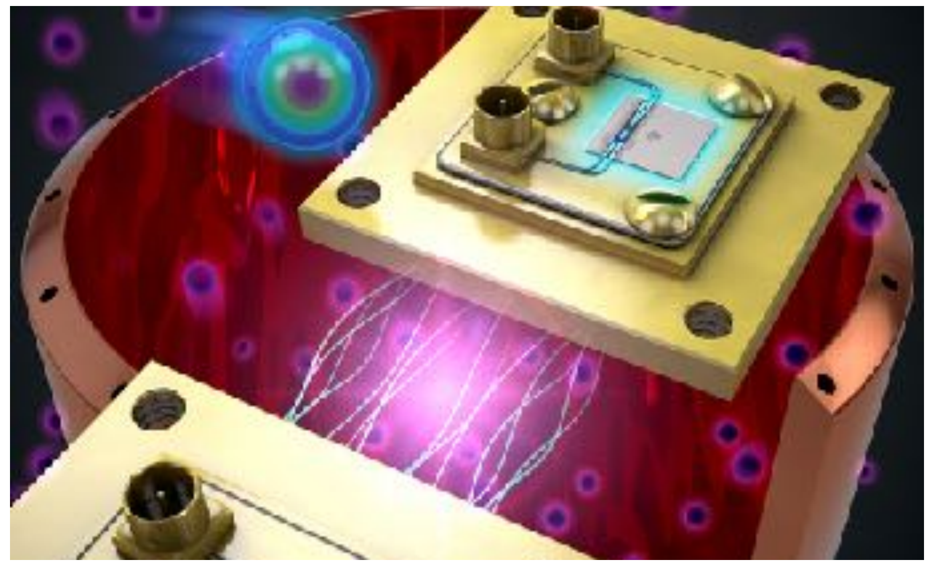


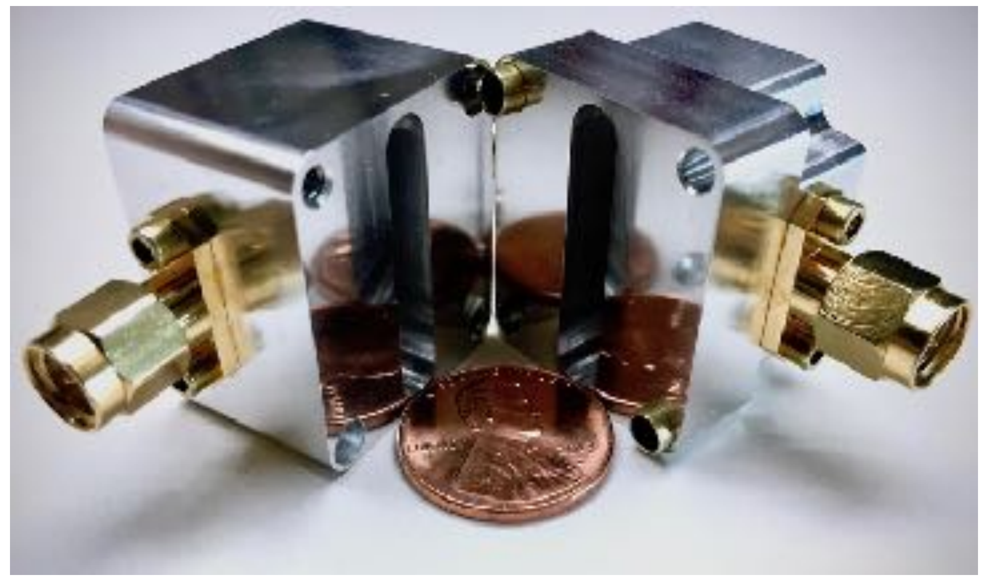


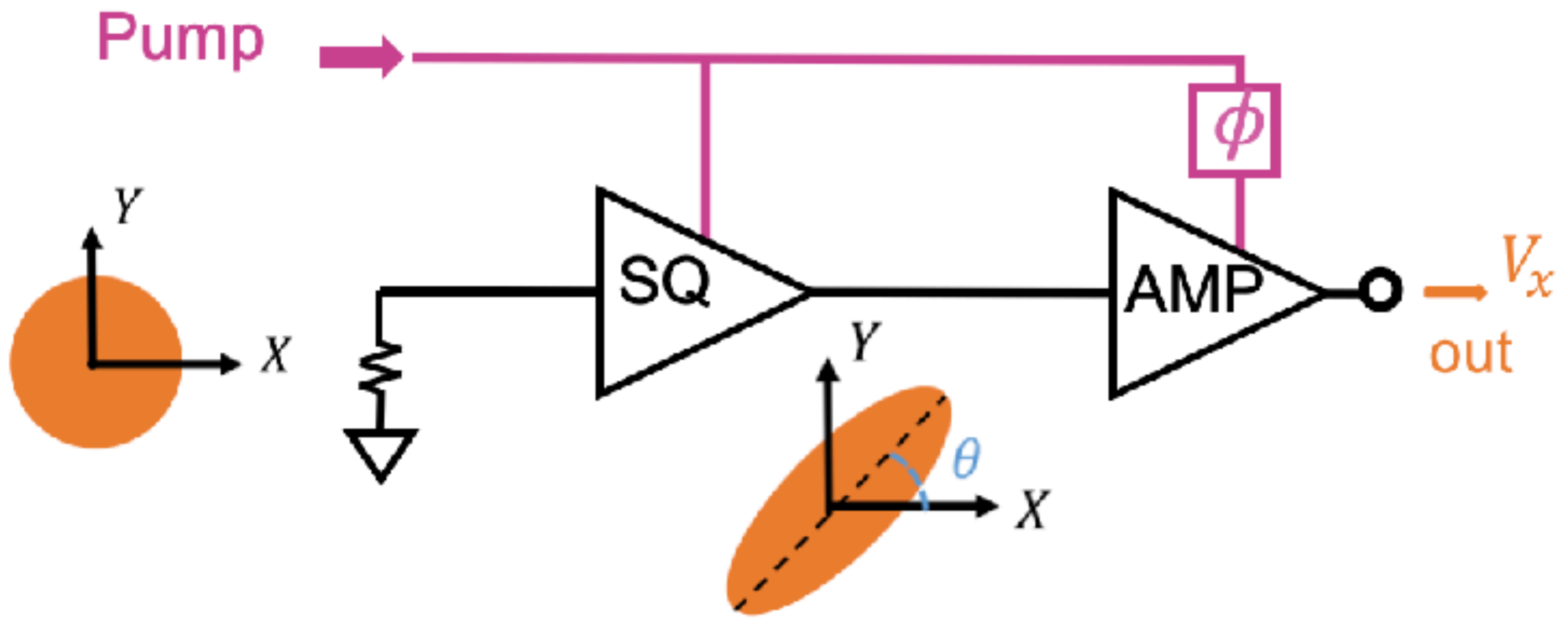
[Malnou et al., Phys. Rev. X 9, 021023 (2019)]
[Backes et al., Nature, **590,** 238 (2021)]

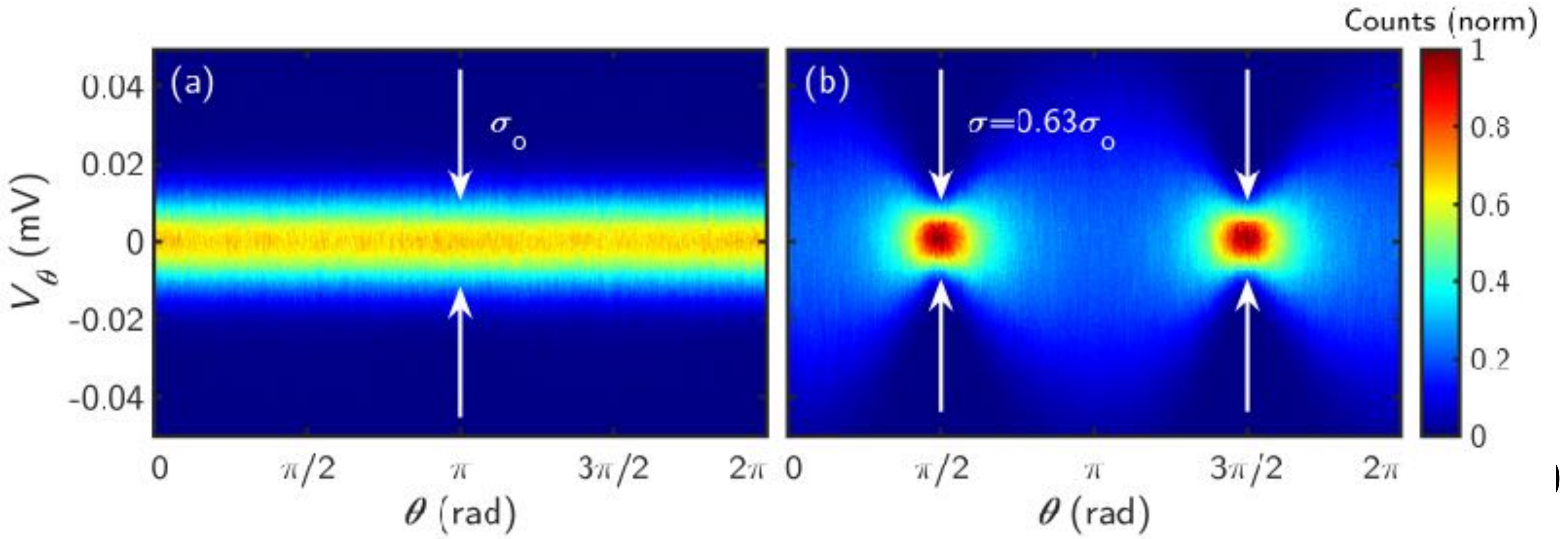
HAYSTAC: Phase 2

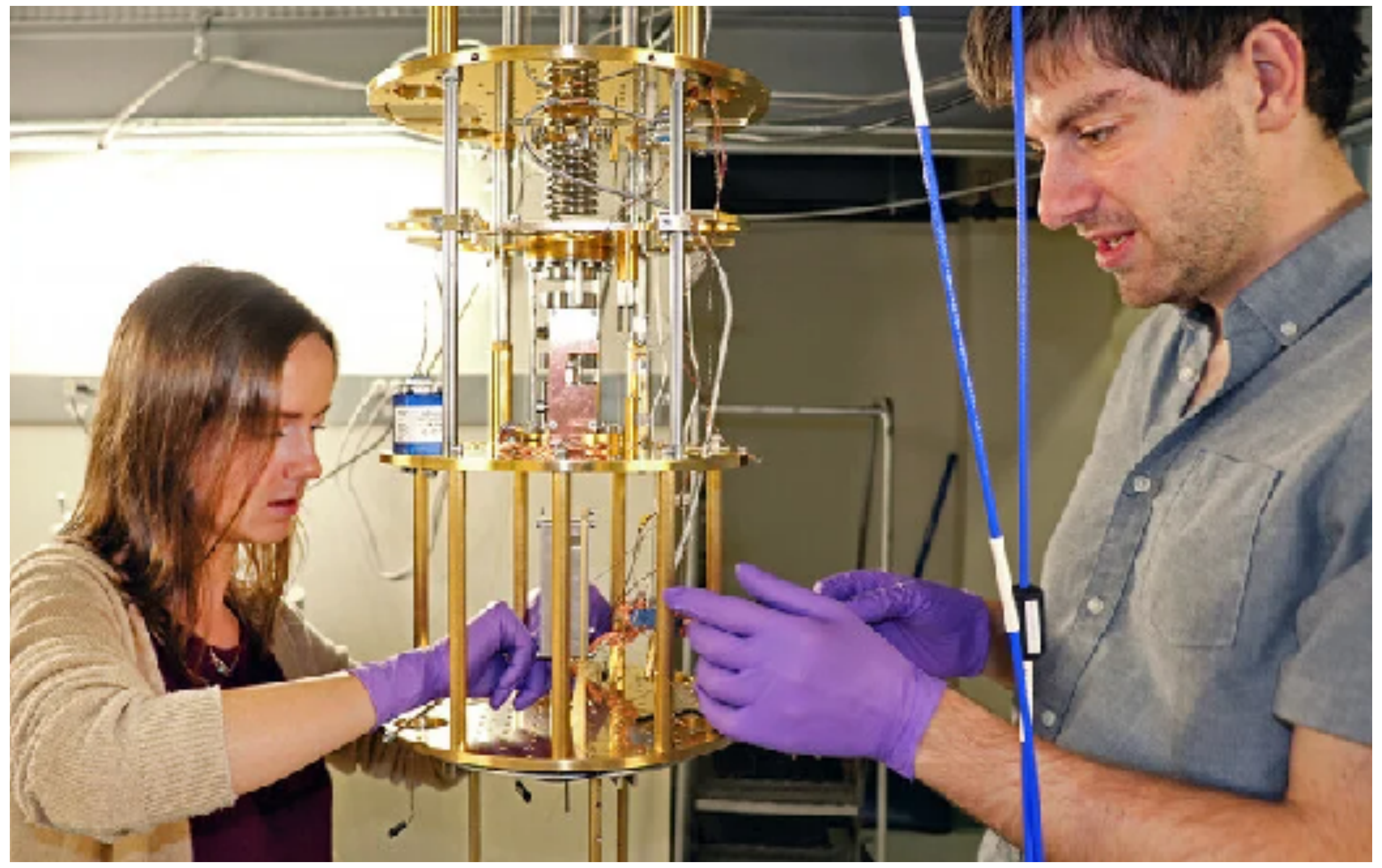
- Dark matter search enhanced by quantum squeezing
  - LIGO - the other experiment that uses squeezing to enhance signal
- -4dB noise reduction
- x2 speedup







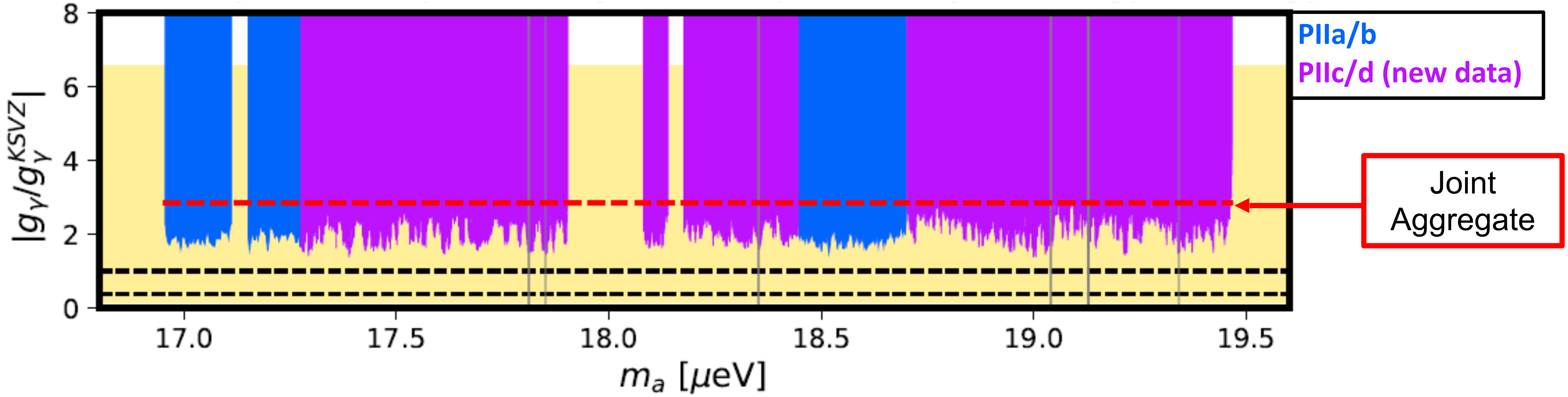




Kelly Backes, Dan Palken

Results from Phase II

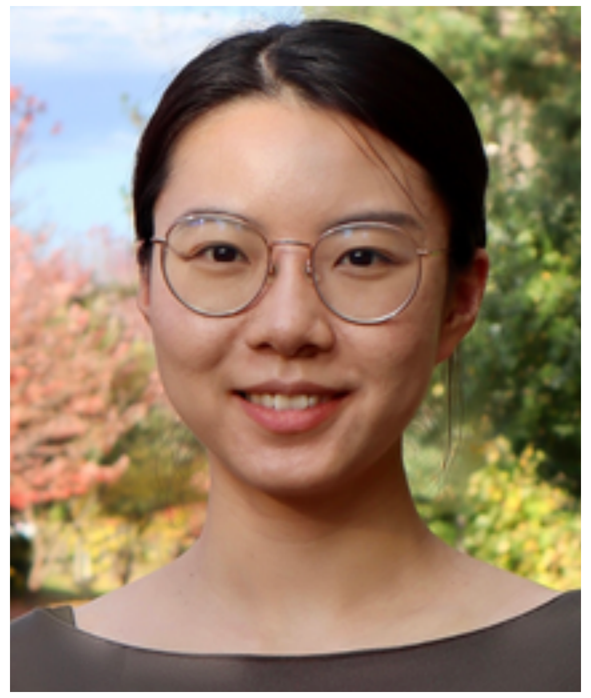
- Phase II covered 550MHz of unexplored parameter space
  - With 413MHz covered in new data
  - Remaining gaps are inaccessible due to mode crossings
- **<u>No evidence of an axion signal</u>**
- 90% Aggregate exclusion $|g_\gamma| > 2.86\,|g_\gamma^{KSVZ}|$ over all Phase II



PRL **134**, 151006 (2025)

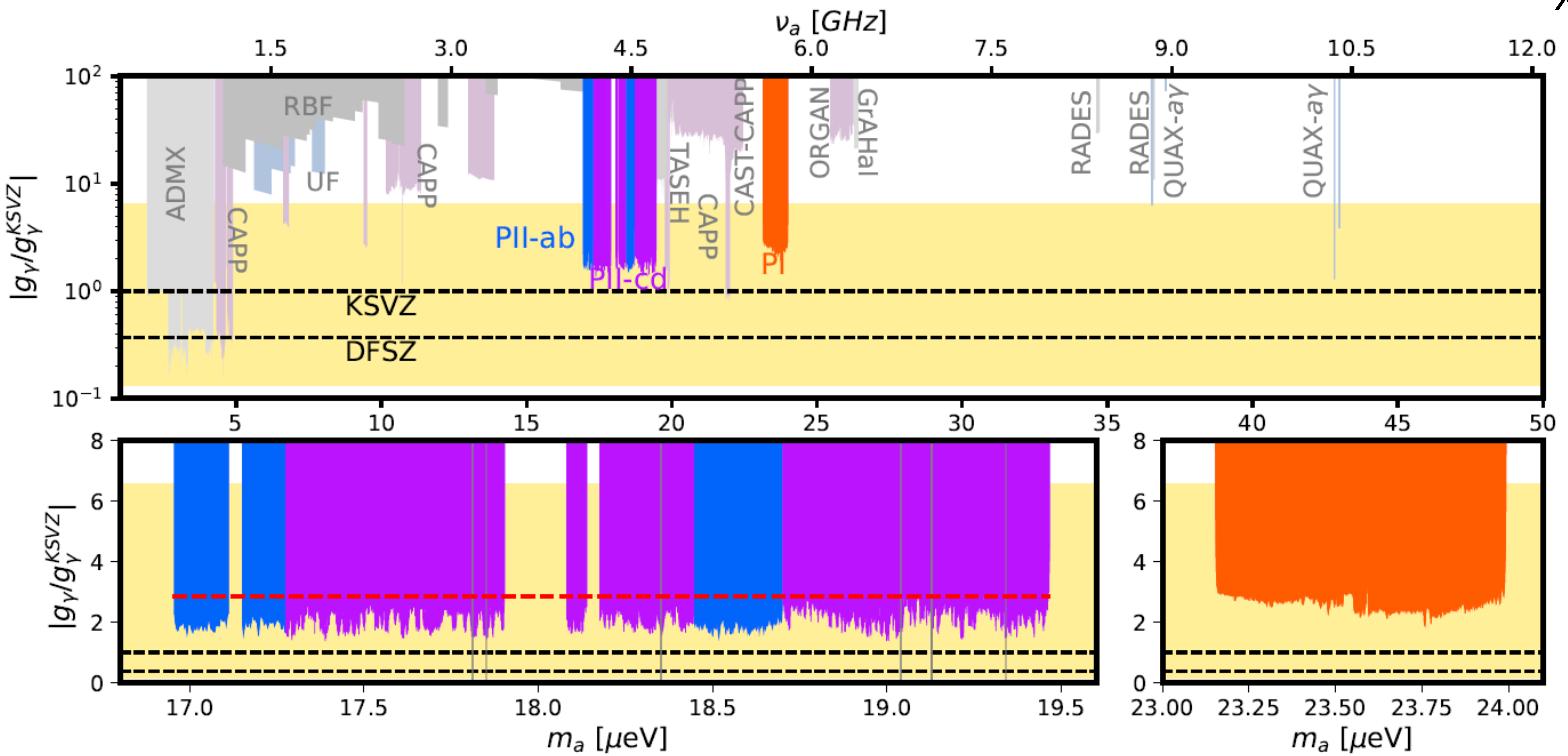
Final Exclusion

- Combined with Phase I we have covered ~750 MHz @ 4 – 6GHz



Xiran Bai

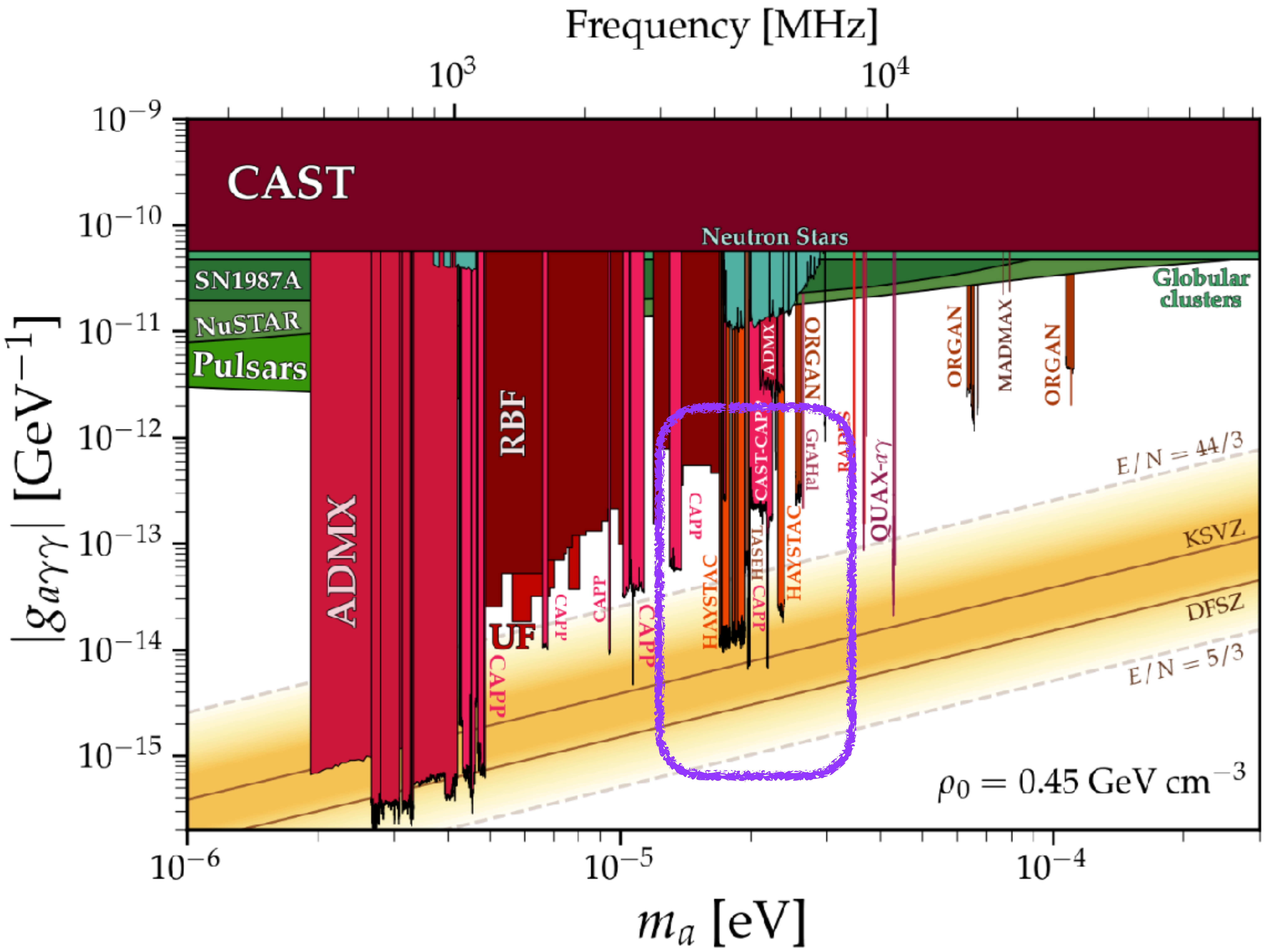
Mike Jewell



See talk on Friday
Karl van Bibber

Bai, Jewell, *et al.*, PRL **134**, 151006 (2025)

HAYSTAC in 2025

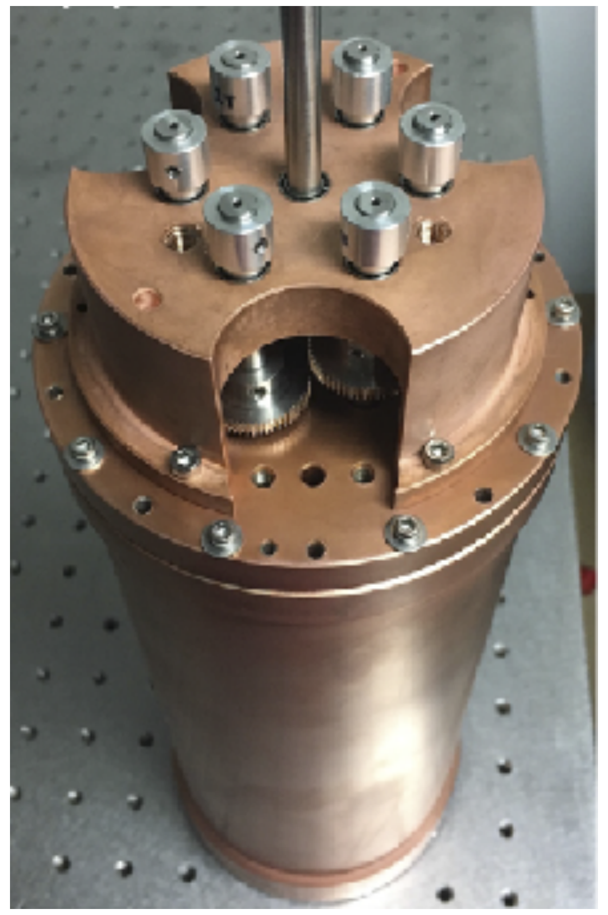


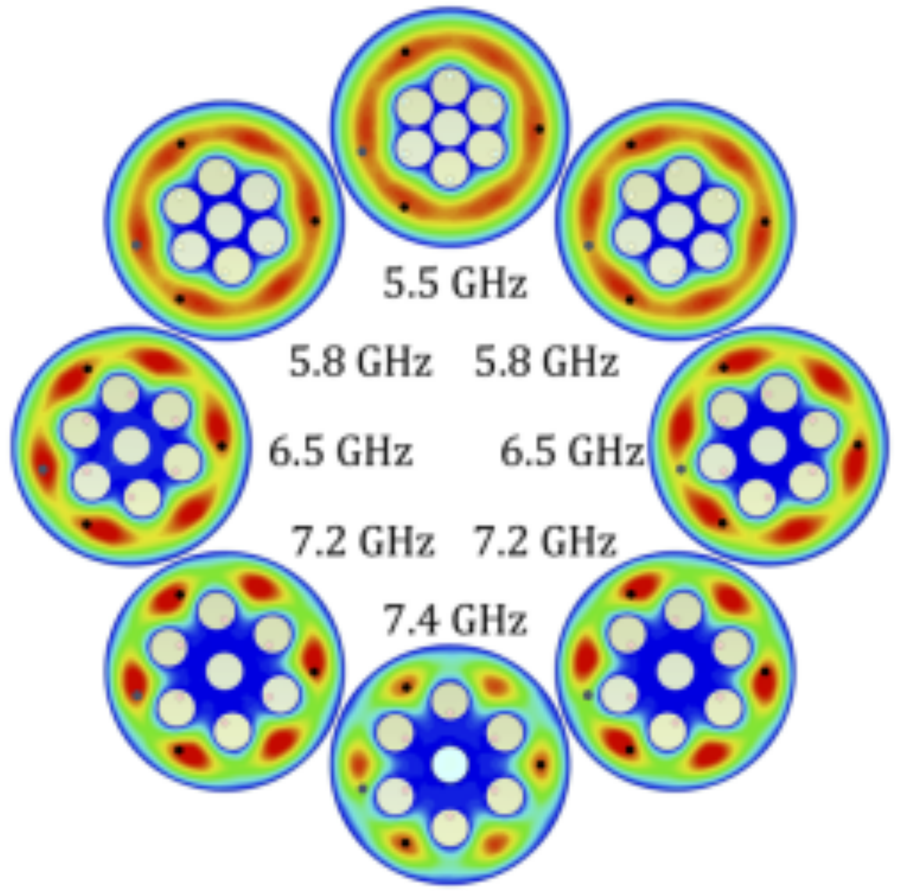
Visible on log-log scale!

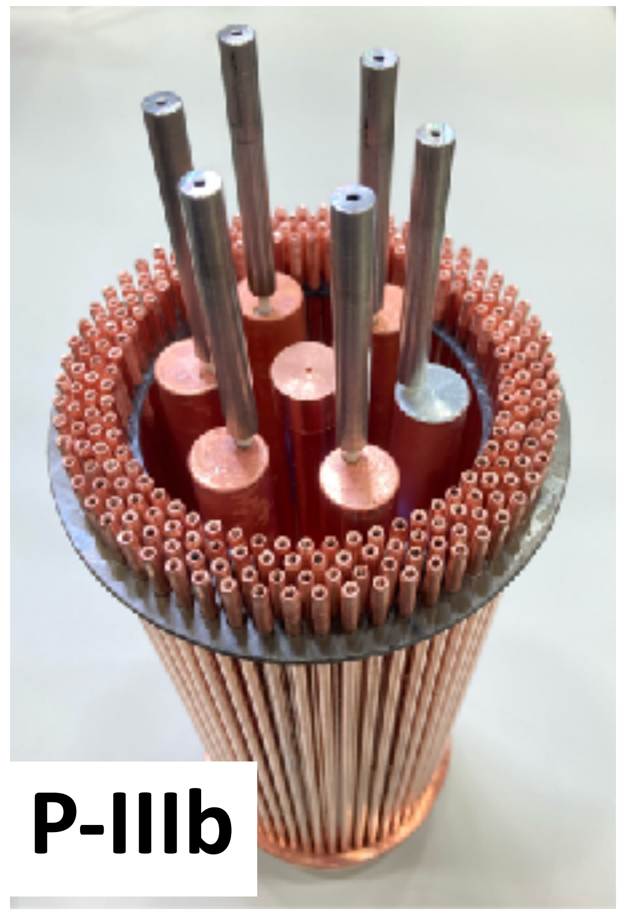
Pushing the Frontiers: New Techniques

HAYSTAC: Beyond Phase II

P-IIIa

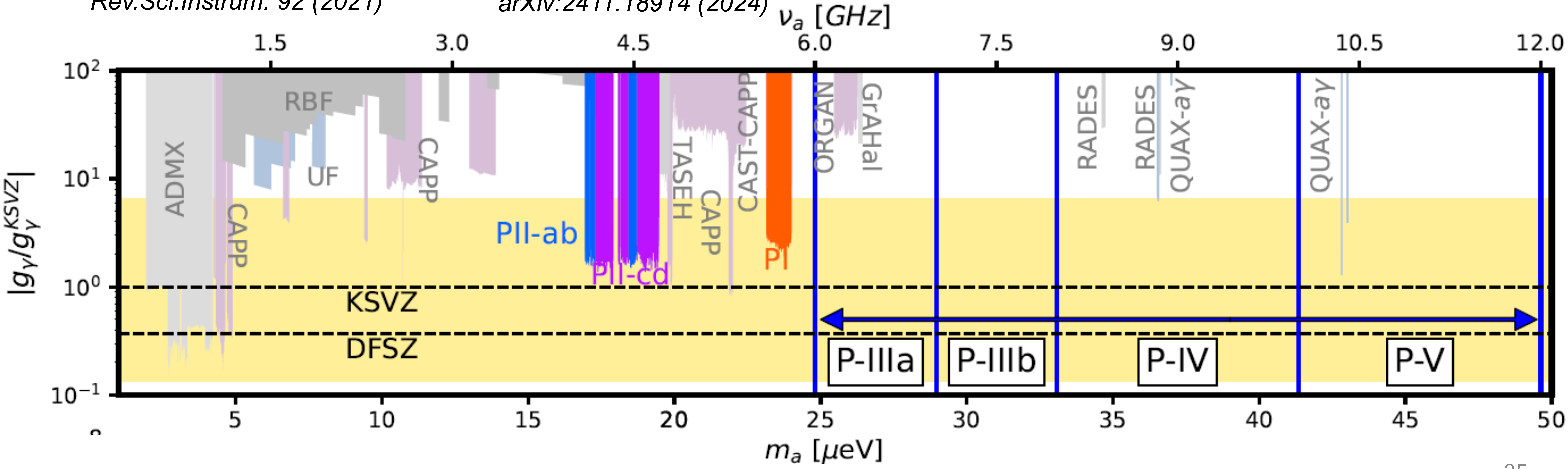






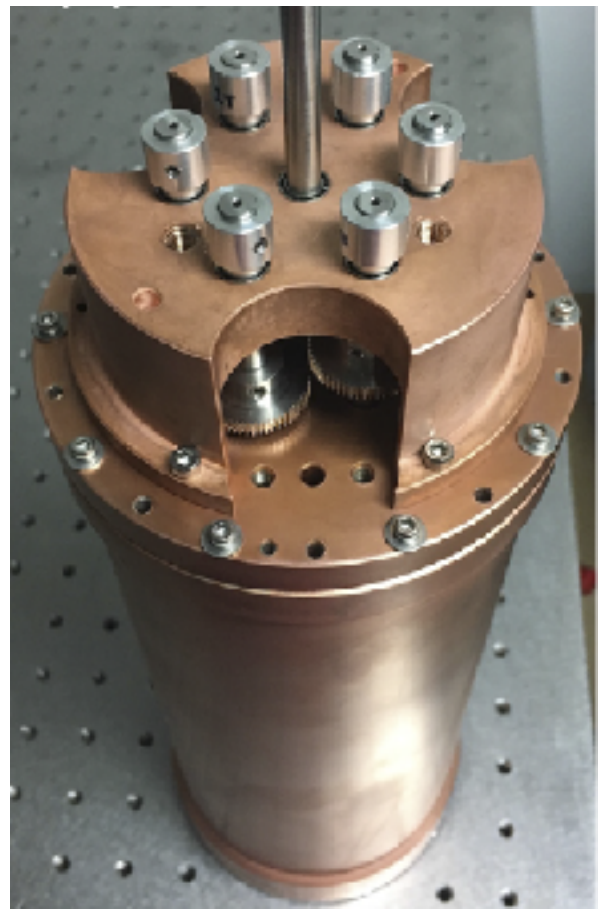
Rev.Sci.Instrum. 92 (2021)

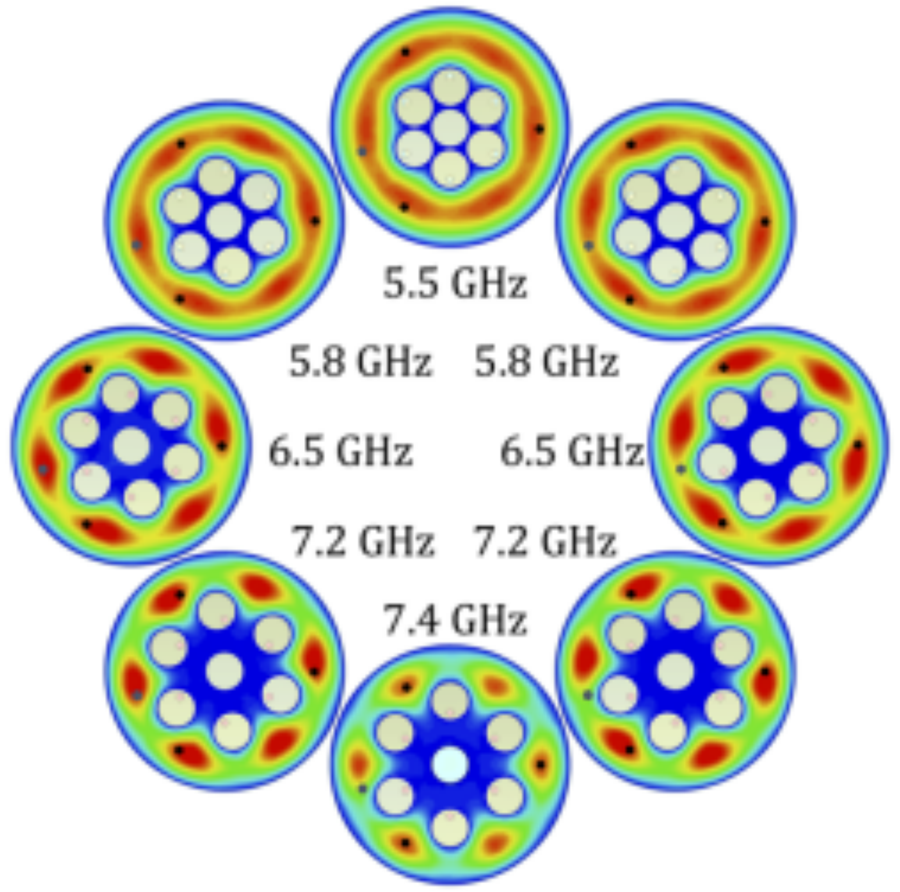
arXiv:2411.18914 (2024)



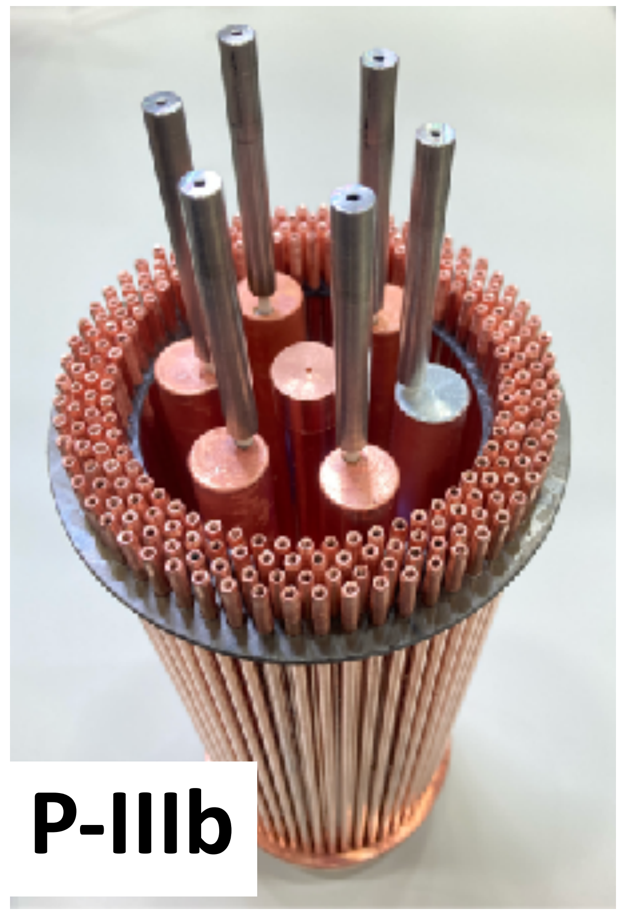
HAYSTAC: Beyond Phase II

P-IIIa





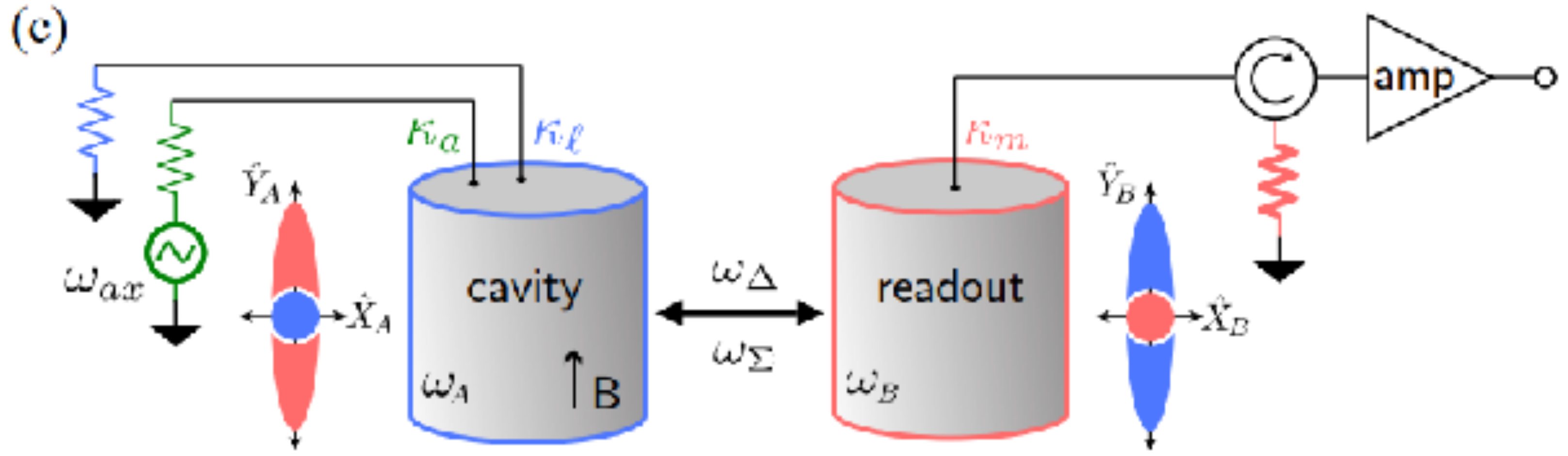
Rev.Sci.Instrum. 92 (2021)



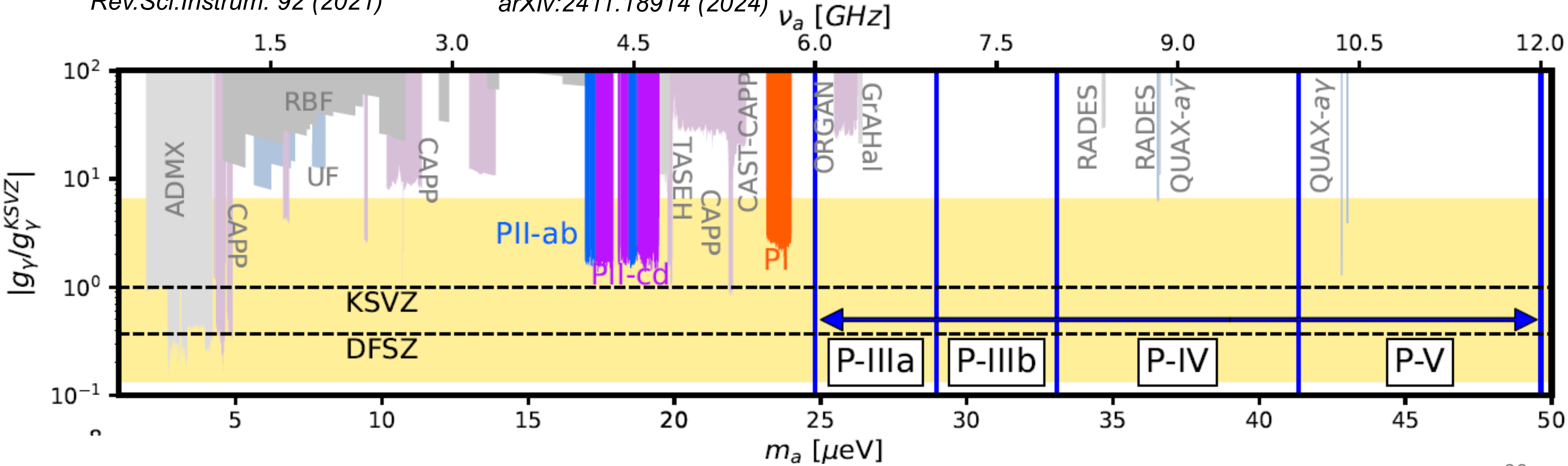
P-IIIb

arXiv:2411.18914 (2024)

Lehnert Group:
Y. Jiang et al., PRX Quantum 4 (2024)



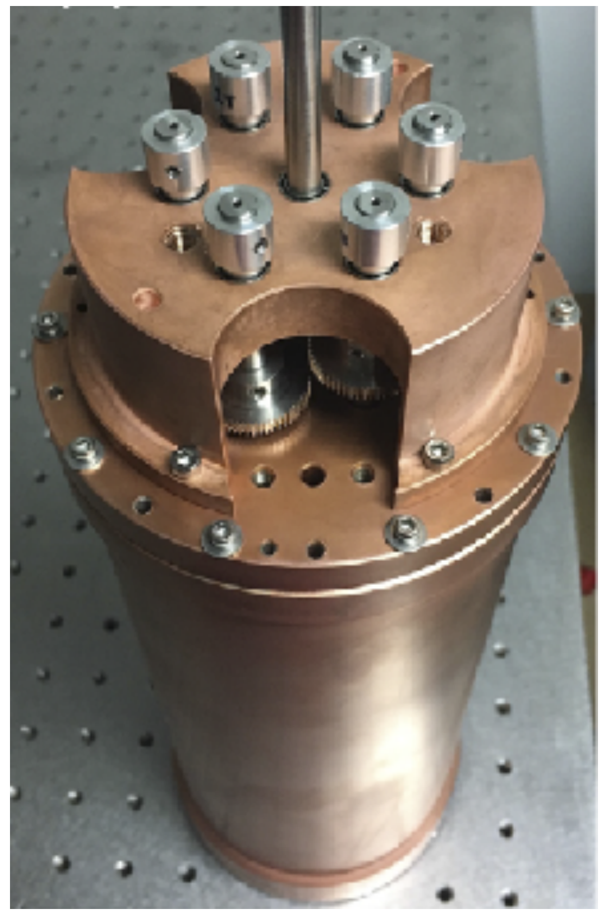
P-IV

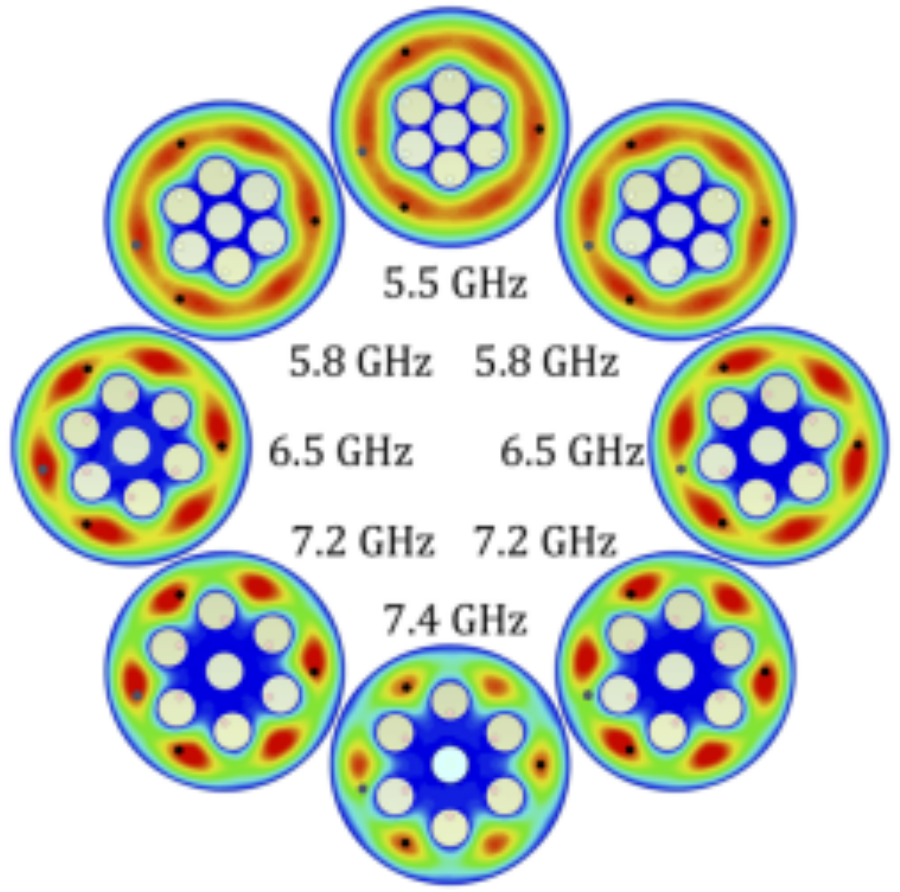


HAYSTAC: Beyond Phase II

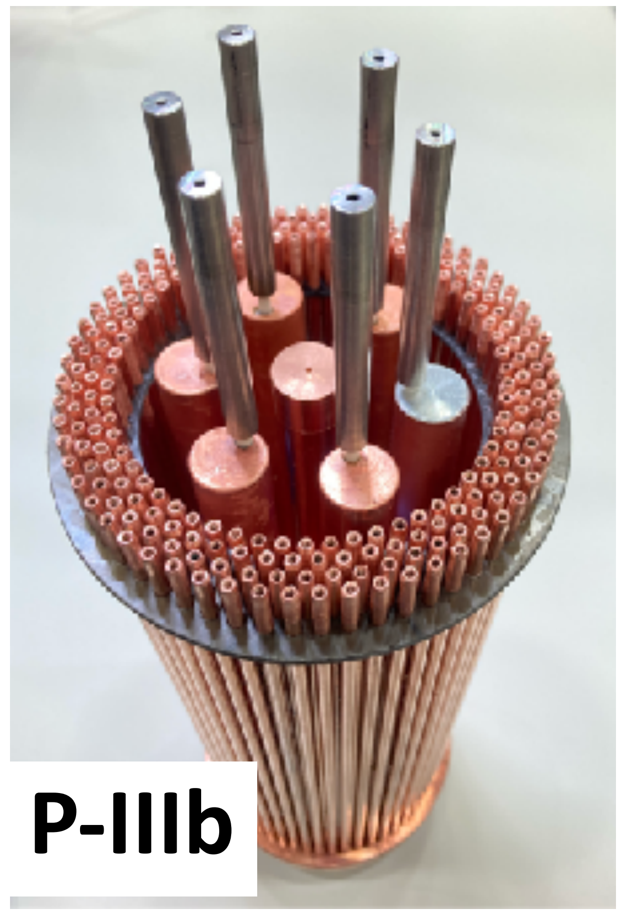
van Bibber Group

P-IIIa



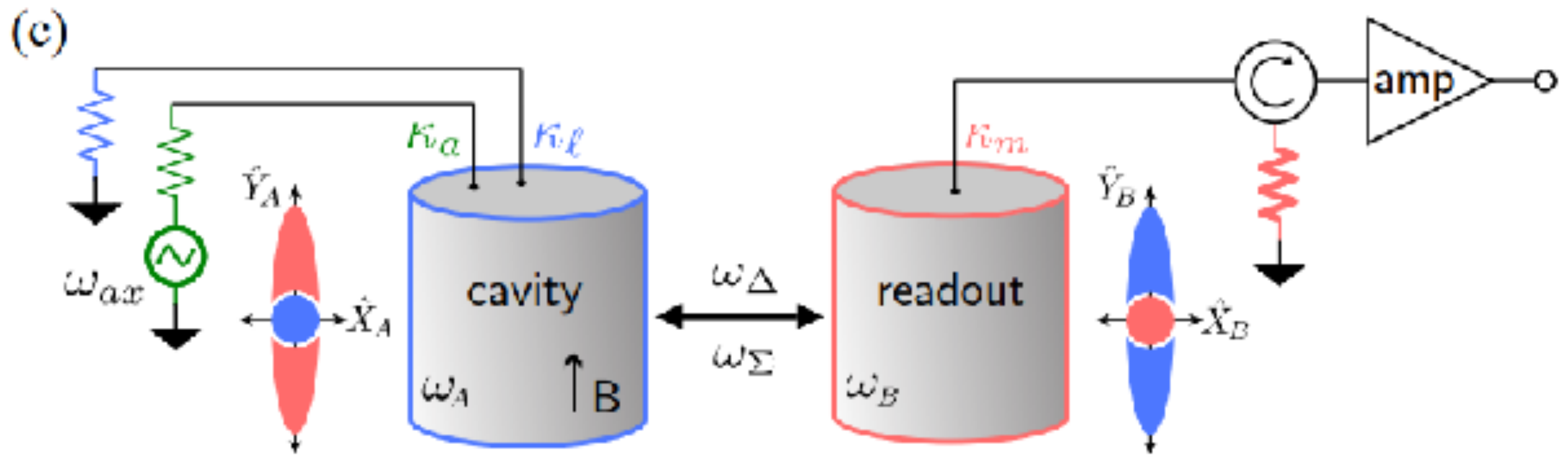


Rev.Sci.Instrum. 92 (2021)

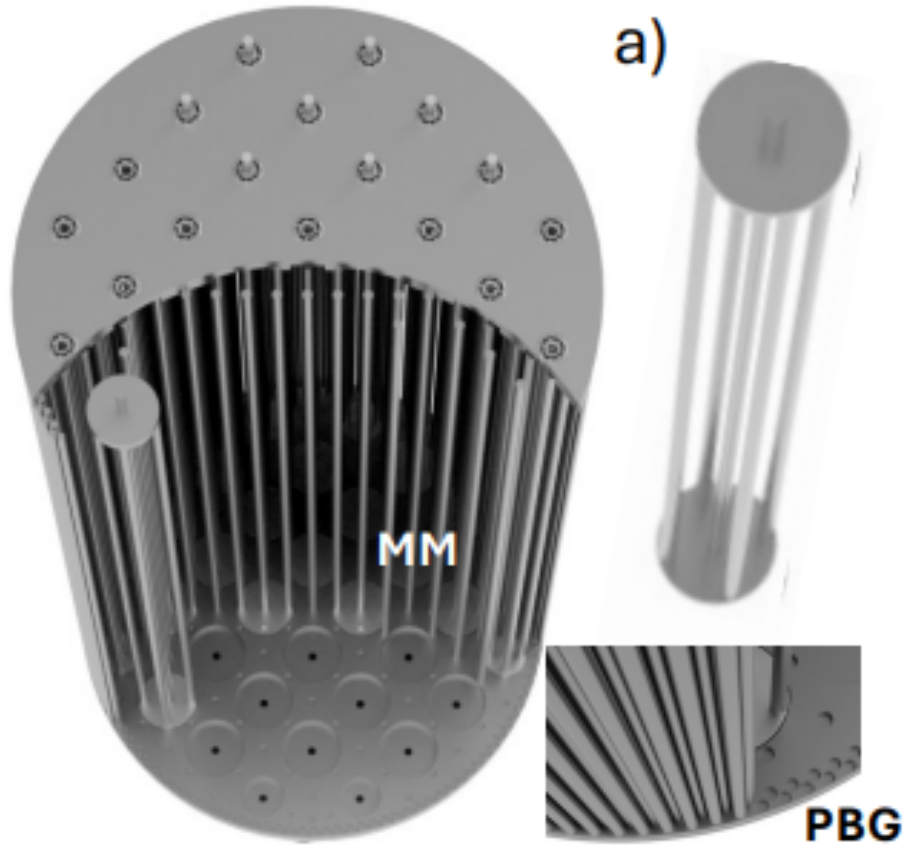


arXiv:2411.18914 (2024)

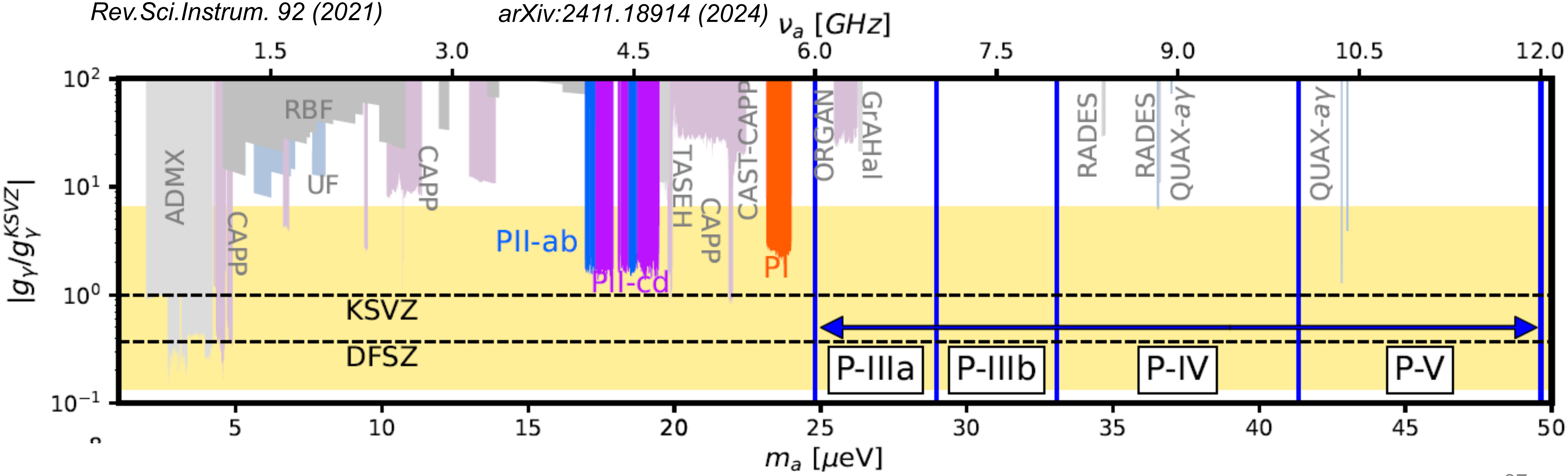
Lehnert Group:
Y. Jiang et al., PRX Quantum 4 (2024)



P-IV



P-V



Resonant cavities get smaller at higher frequencies

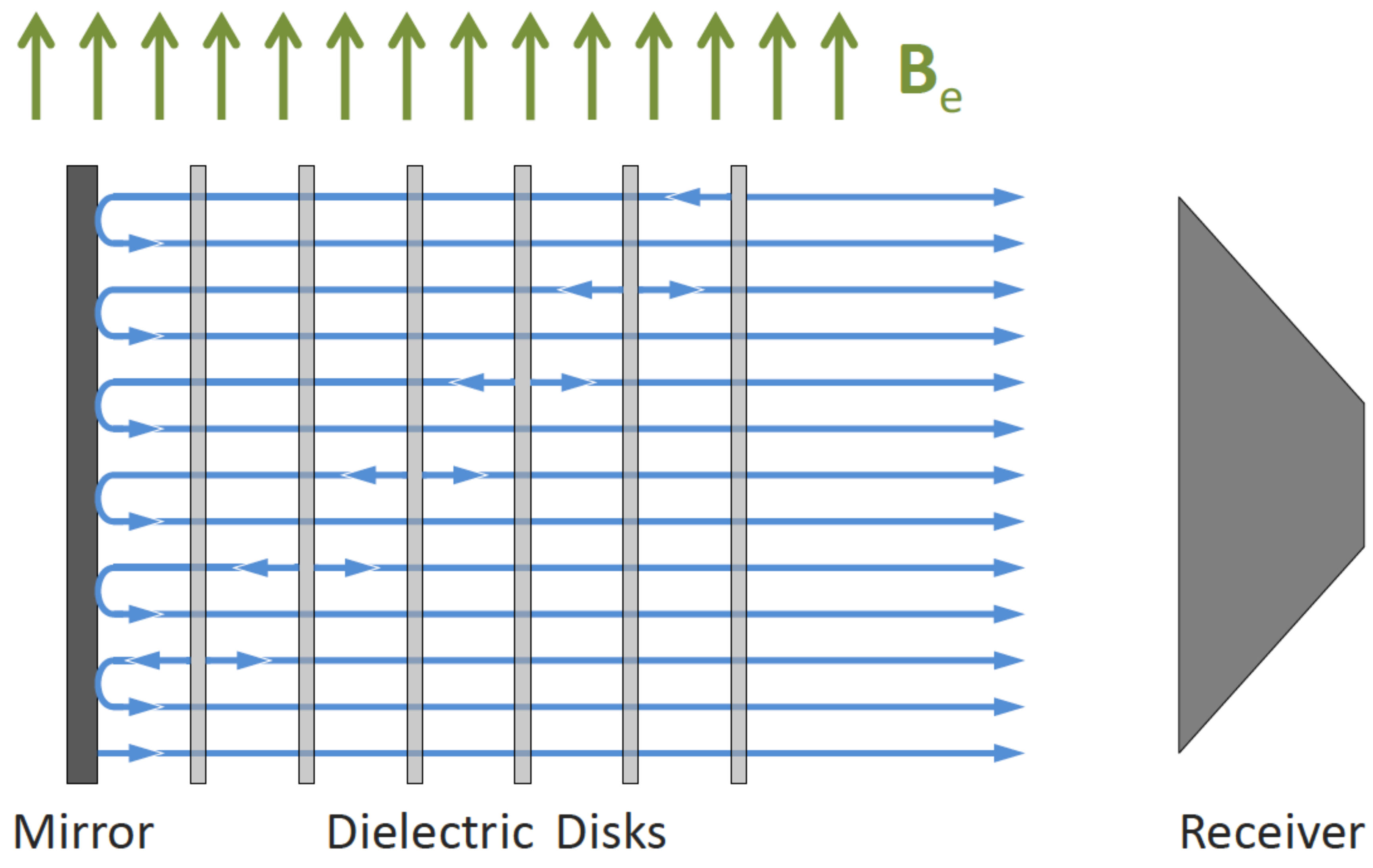
ADMX

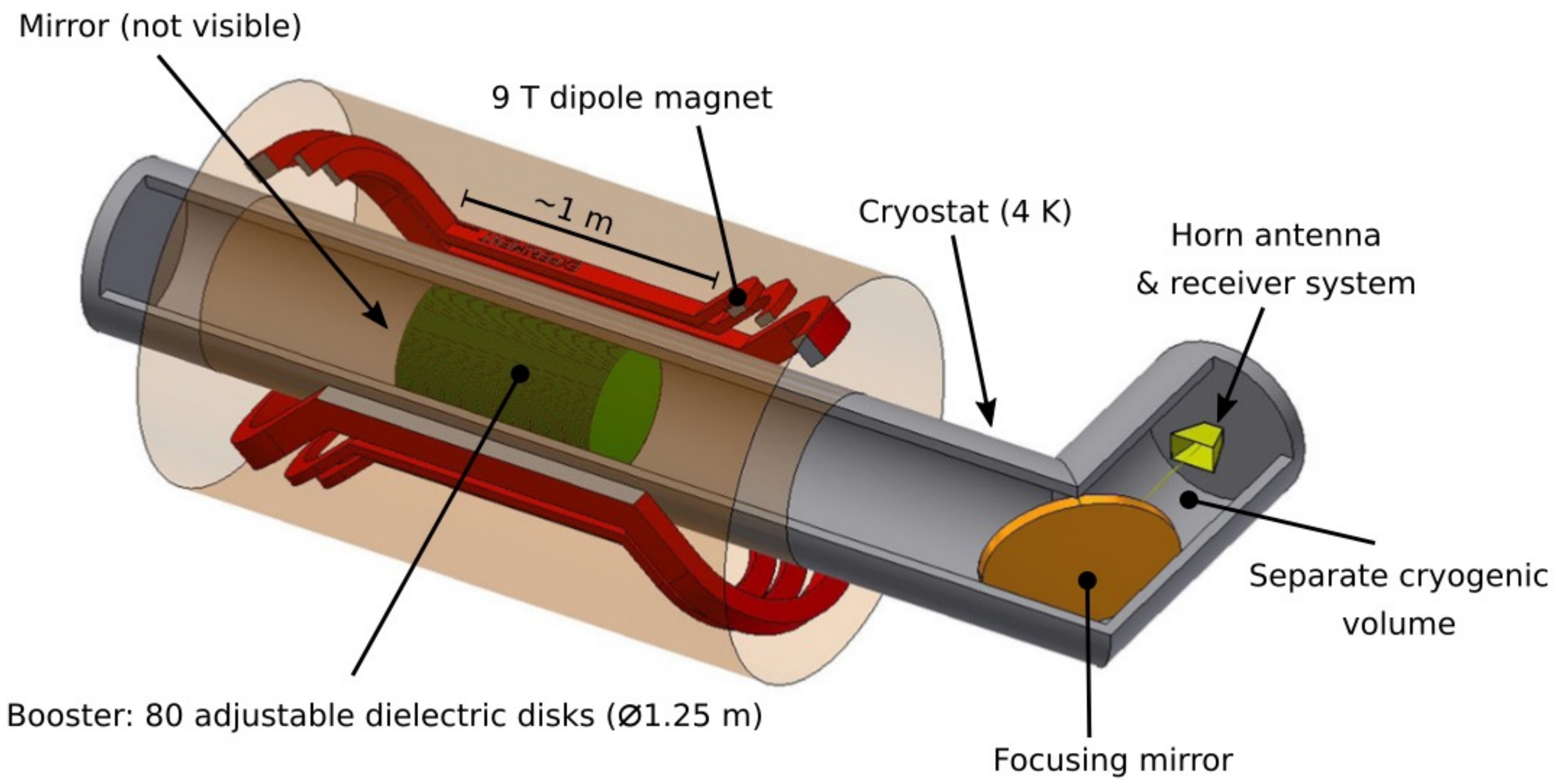
HAYSTAC

Solution: decouple cavity size from mass

MADMAX: Magnetized Disc and Mirror Axion experiment

- Weak signal power at single interface boosted
- using a tunable stack of dielectric plates
- Aims to probe 40-400 μeV range (10-100 GHz)
- 10 T field & ~80 disks
- Currently in prototype phase with CERN dipole magnet





MADMAX PRL118 (2017) 091801

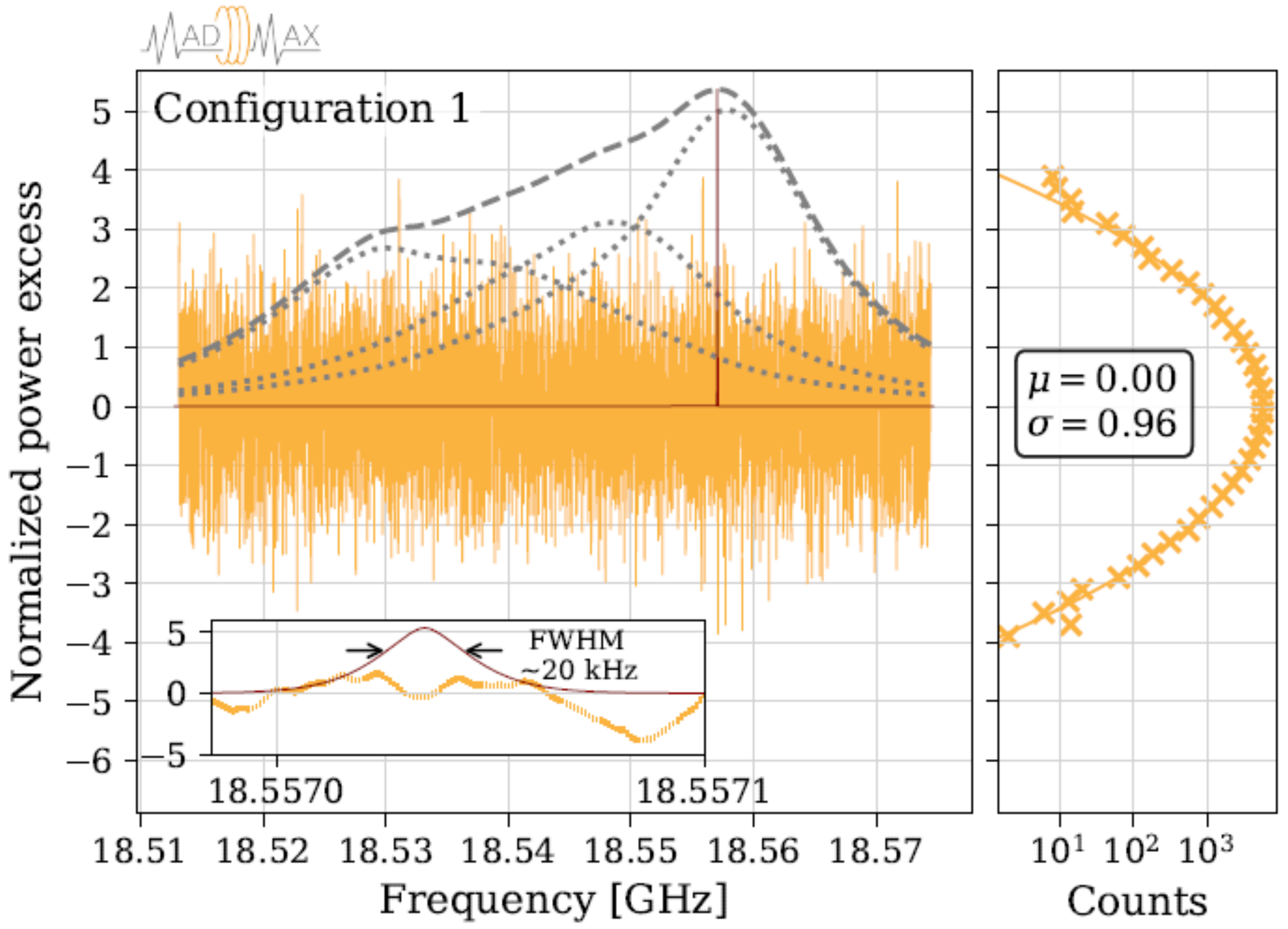
Output power P of the dielectric haloscope per unit area A is:

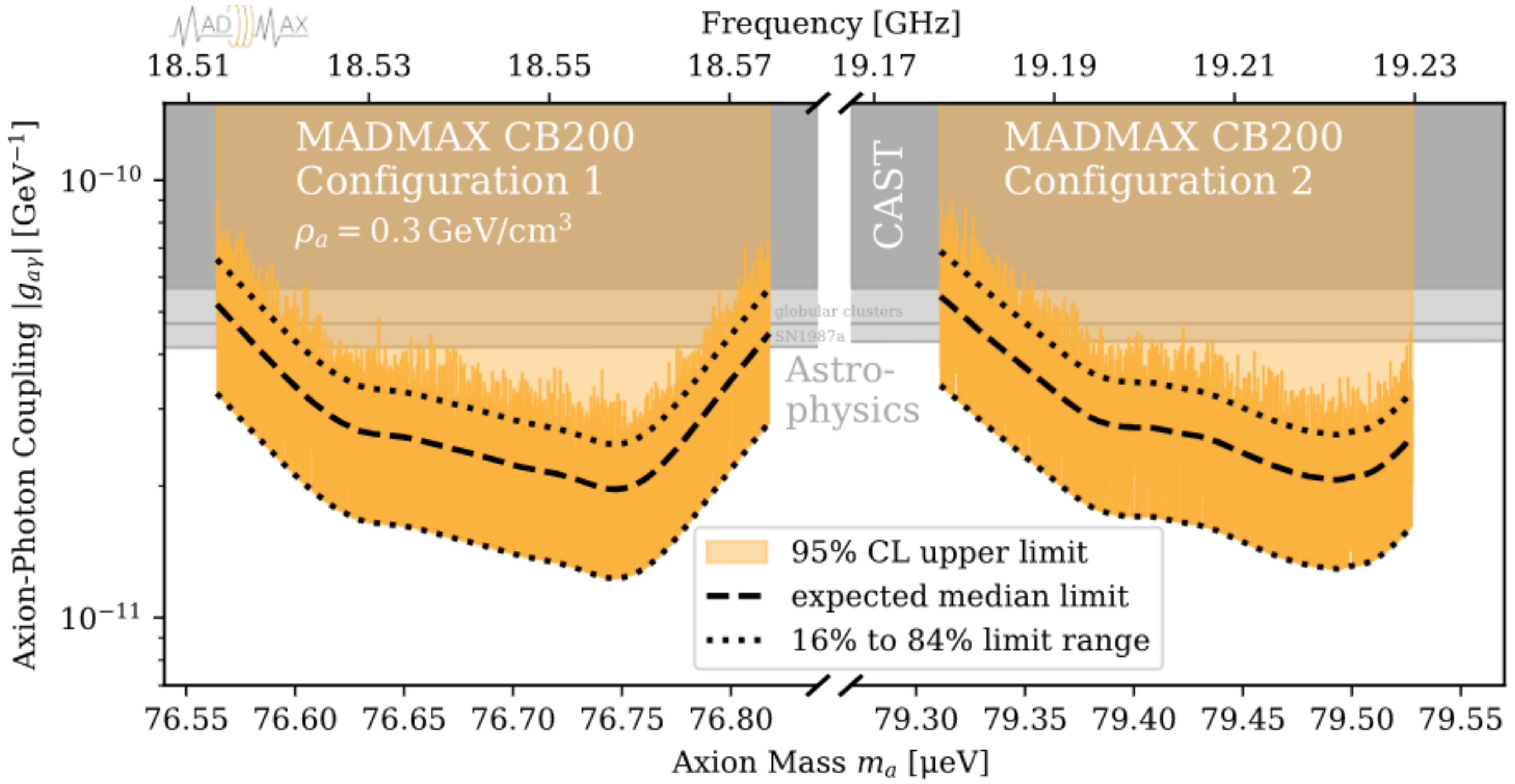
$$\left(\frac{P}{A}\right)_{booster} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{||}}{10\,T}\right)^2 \left(g_{a\gamma\gamma}/m_a\right)^2 \beta^2$$

$$\beta^2 = \frac{P_{booster}}{P_{mirror}}$$

MADMAX: First Axion Search with CB200

- Five data runs in two configurations ~ 18.5 GHz and 19.2 GHz (in total 100 MHz frequency range covered)
- World best limits for axion masses 76.5-76-8 μeV and 79.5-79.7 μeV
- First axion dark matter limit using dielectric haloscope



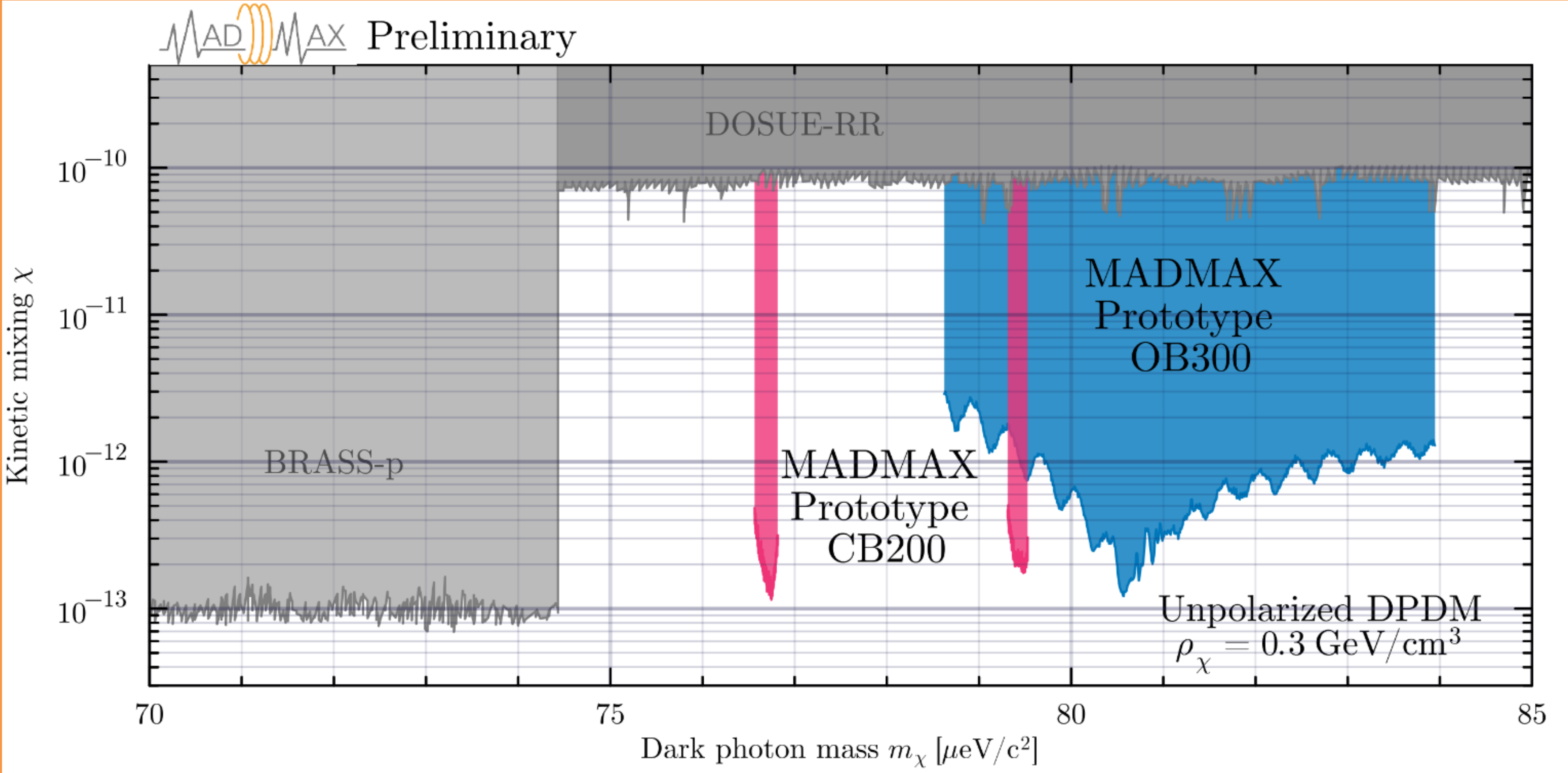


[arXiv:2409.11777](https://arxiv.org/abs/2409.11777)
Accepted for publication in PRL

MADMAX: Dark Photon Search

- Dark photon dark matter search with OB300 (no magnetic field)
  - OB300 with 3 fixed disks + a Cu mirror
  - Custom-made receiver system
  - Setup at room temperature
  - 12 days of data-taking
- Boost factor determination
  - using in-situ bead-pull method (JCAP 04 (2023) 064 , JCAP 04 (2024) 005)
  - β^2 peak ~ 600
  - Broadband config.: frequency covered 1.2 GHz
- No signal excess being observed
- First DPDM exclusion limit with MADMAX

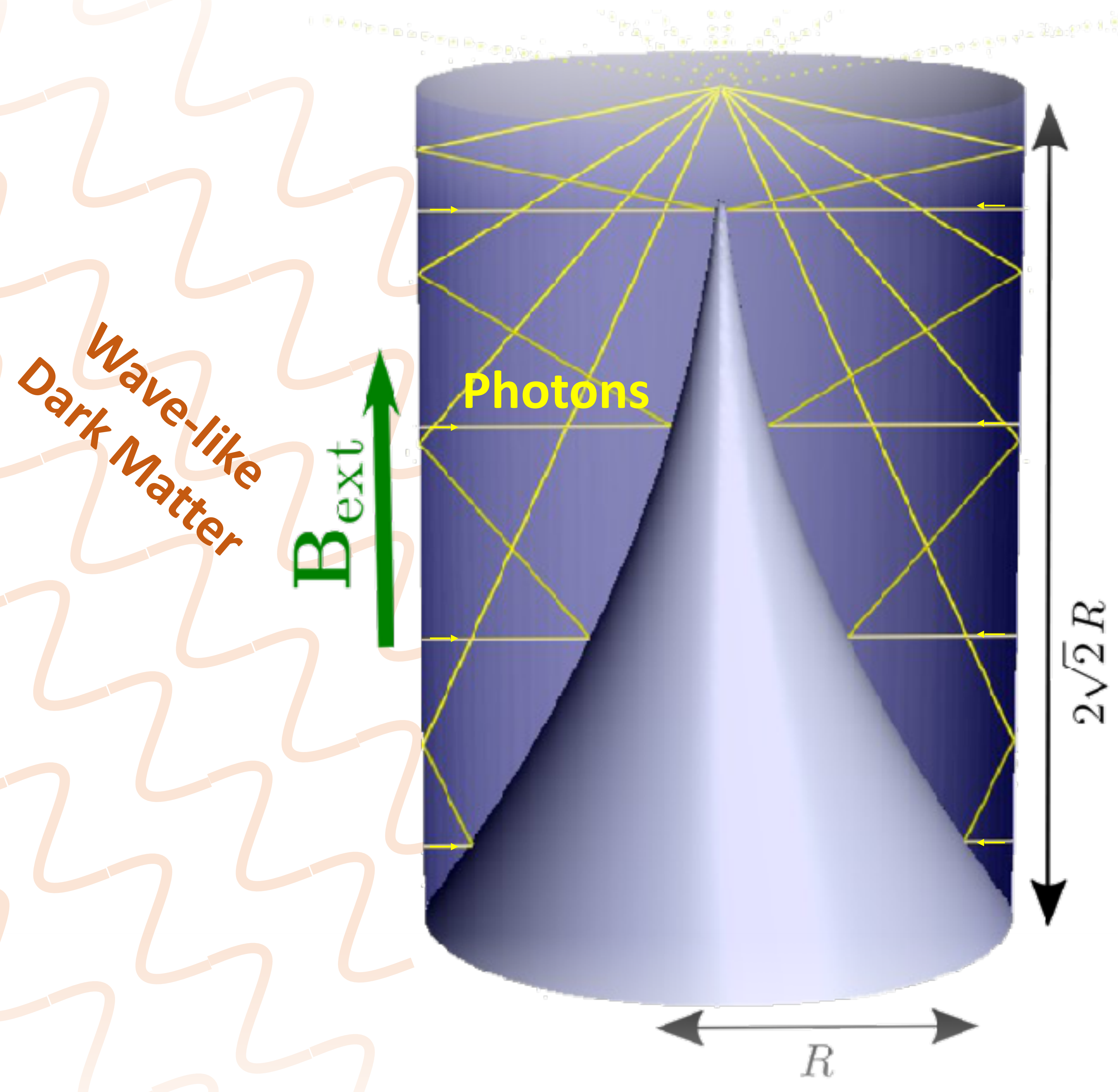
World-best exclusion limit (95% CL)
→ 1-3 order of magnitude below previous limits

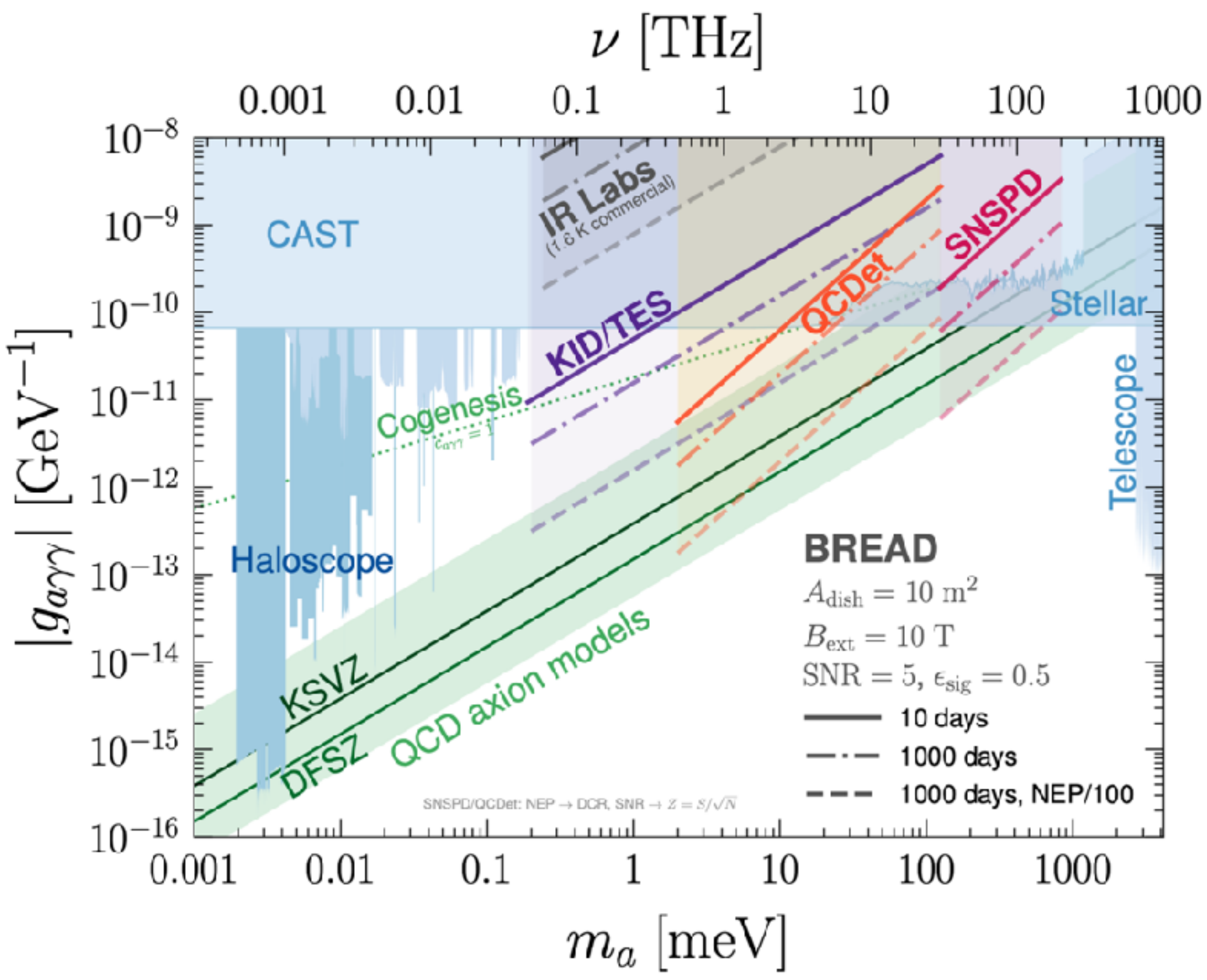


Phys. Rev. Lett. 134, 15, 151004 (2025)
arXiv:2408.02368

BREAD in a Nutshell

(Broadband Reflector Experiment for Axion Detection)



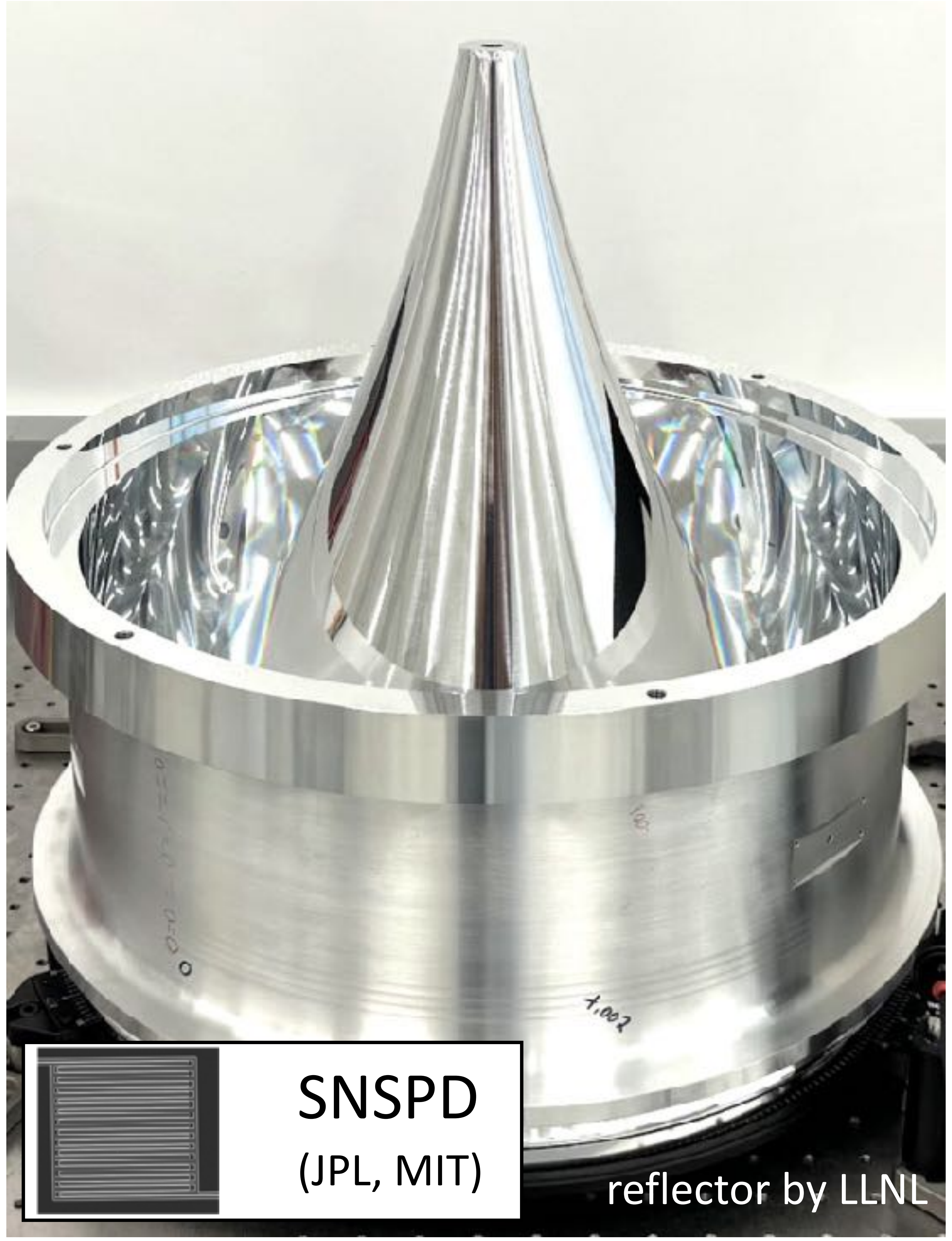


[PRL 128 (2022) 131801]

broadband axion detector from μeV (GHz) to eV (Infrared)

BREAD Reflector Prototypes

GigaBREAD (10-12GHz, 300K, 4T)
first physics results

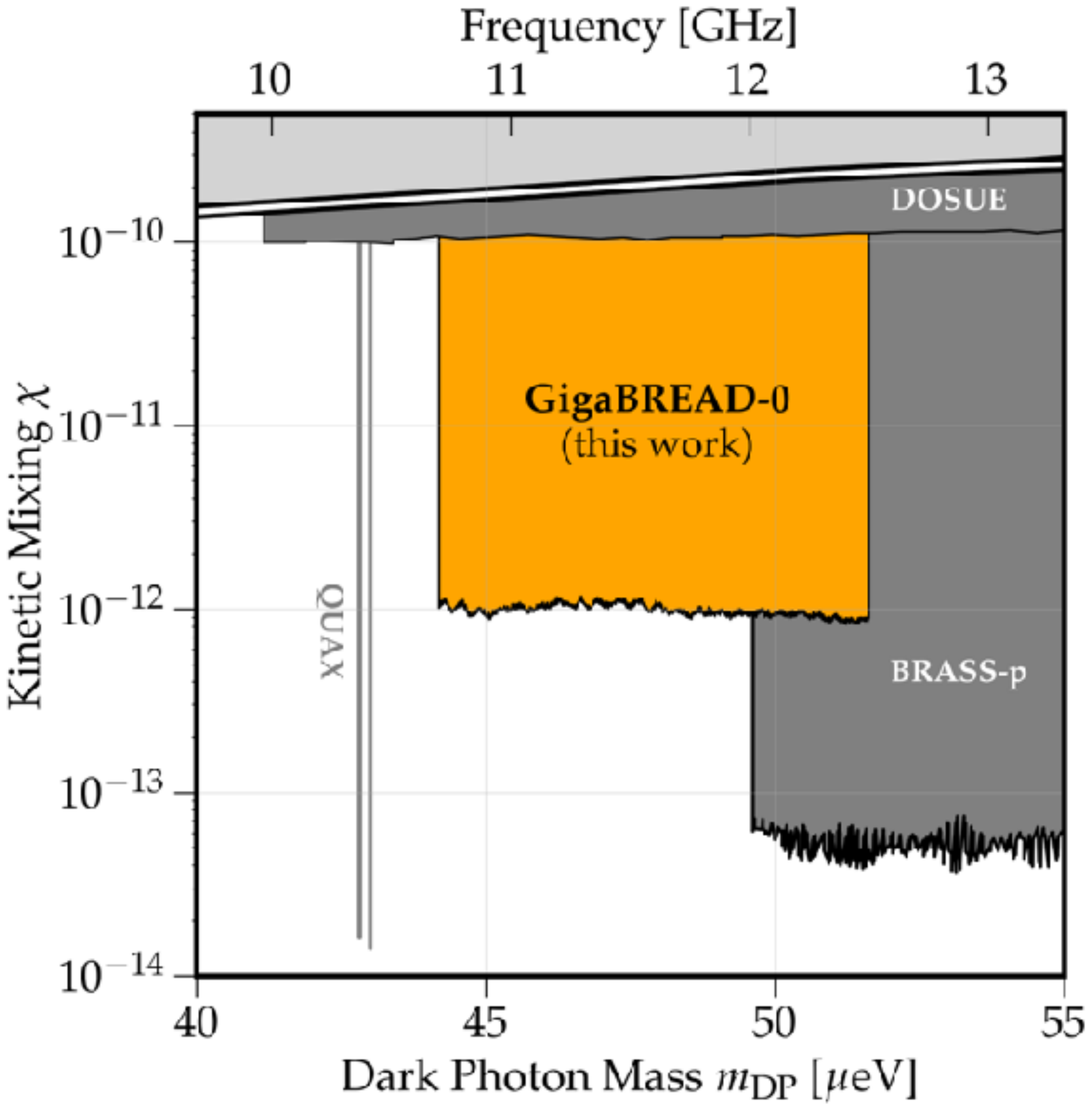


InfraBREAD (infrared, cryo)
construction & testing

8T cryogenic (GHz, THz)
in preparation

GigaBREAD: First Science Results

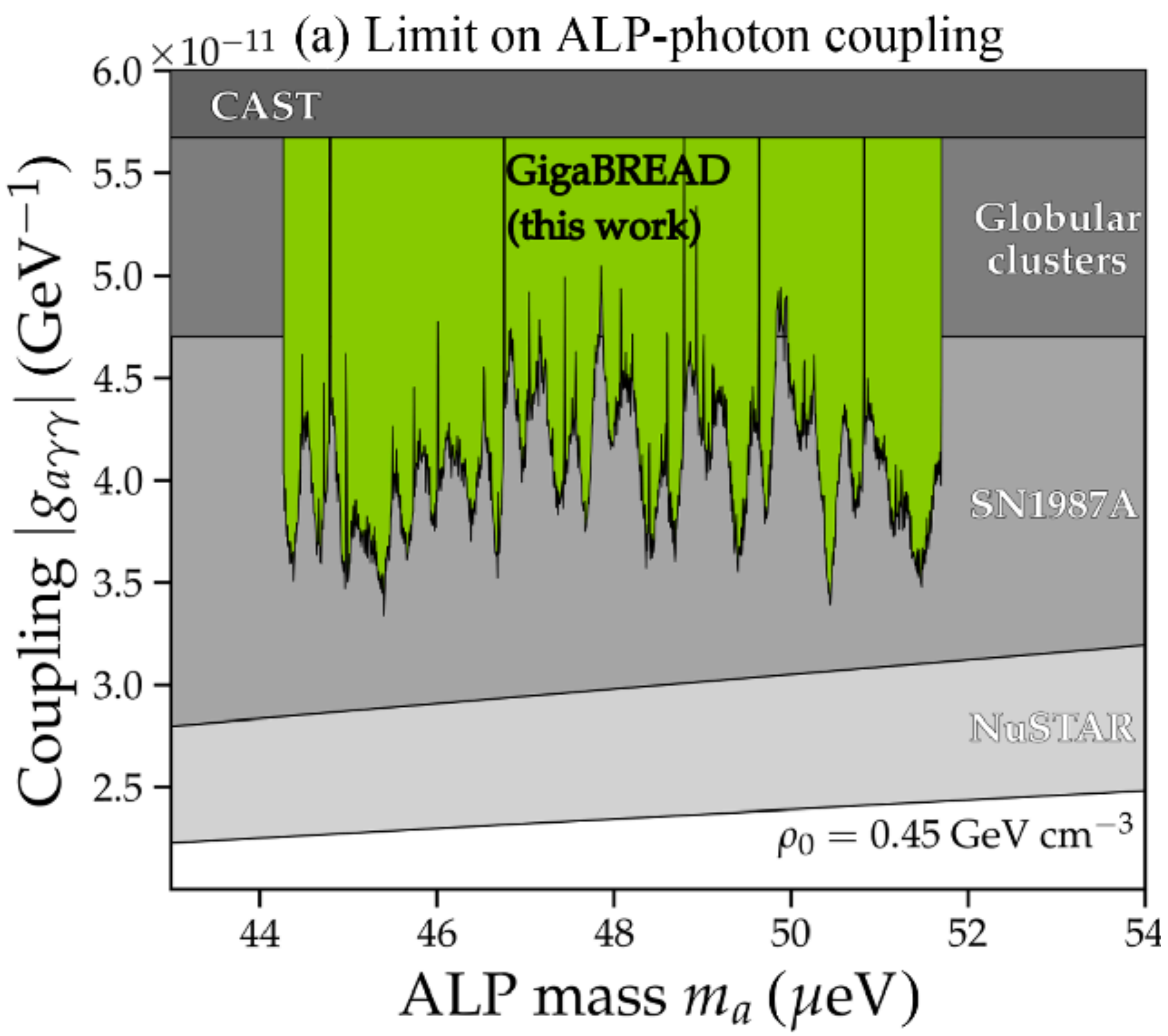
Dark Photon Run (2023)



[S. Knirck *et al. (GigaBREAD)*, **PRL 132, 131004 (2024)**]

first BREAD science data

Axion-Like-Particle Run (2024)

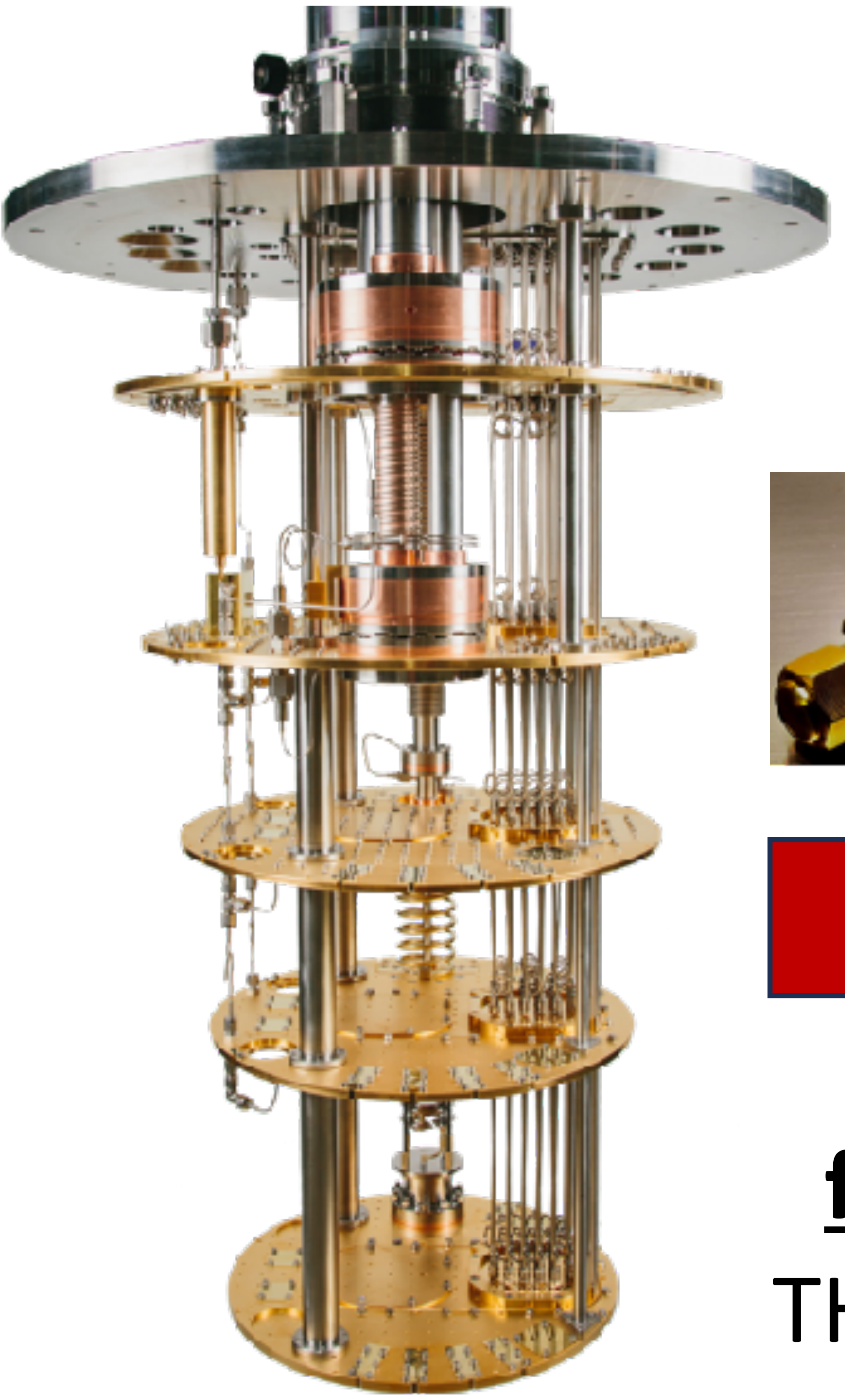


[G. Hoshino, *et al.* (GigaBREAD), **PRL 134, 171002 (2025)**]

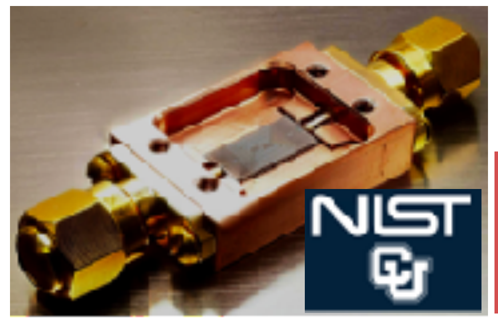
world's first dish antenna ALP result!

BREAD: Next Steps

✅ ***Lower Noise:*** *Quantum Sensing*



GigaBREAD
+ TWPA
+ 8T Magnet @ HARVARD UNIVERSITY



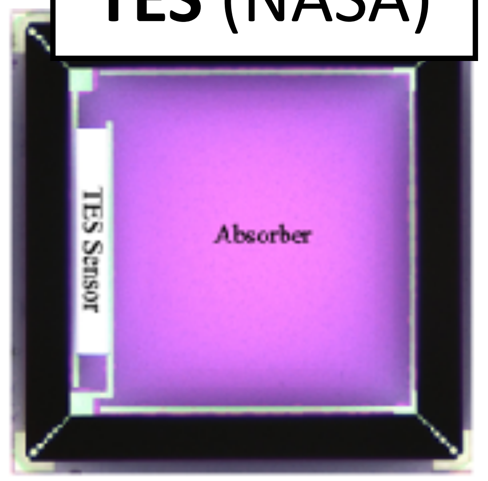
~ 10-30 GHz

in preparation

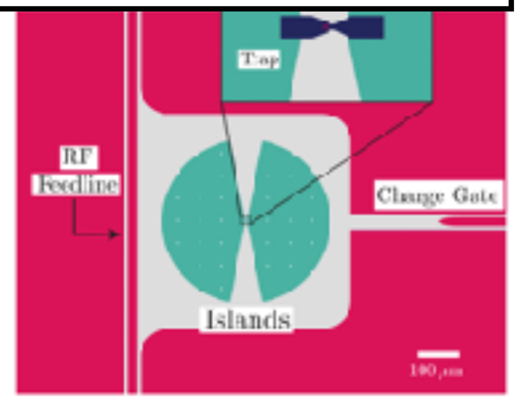
future: TeraBREAD
THz quantum sensing

e.g.,

TES (NASA)



SQUAT (SLAC)

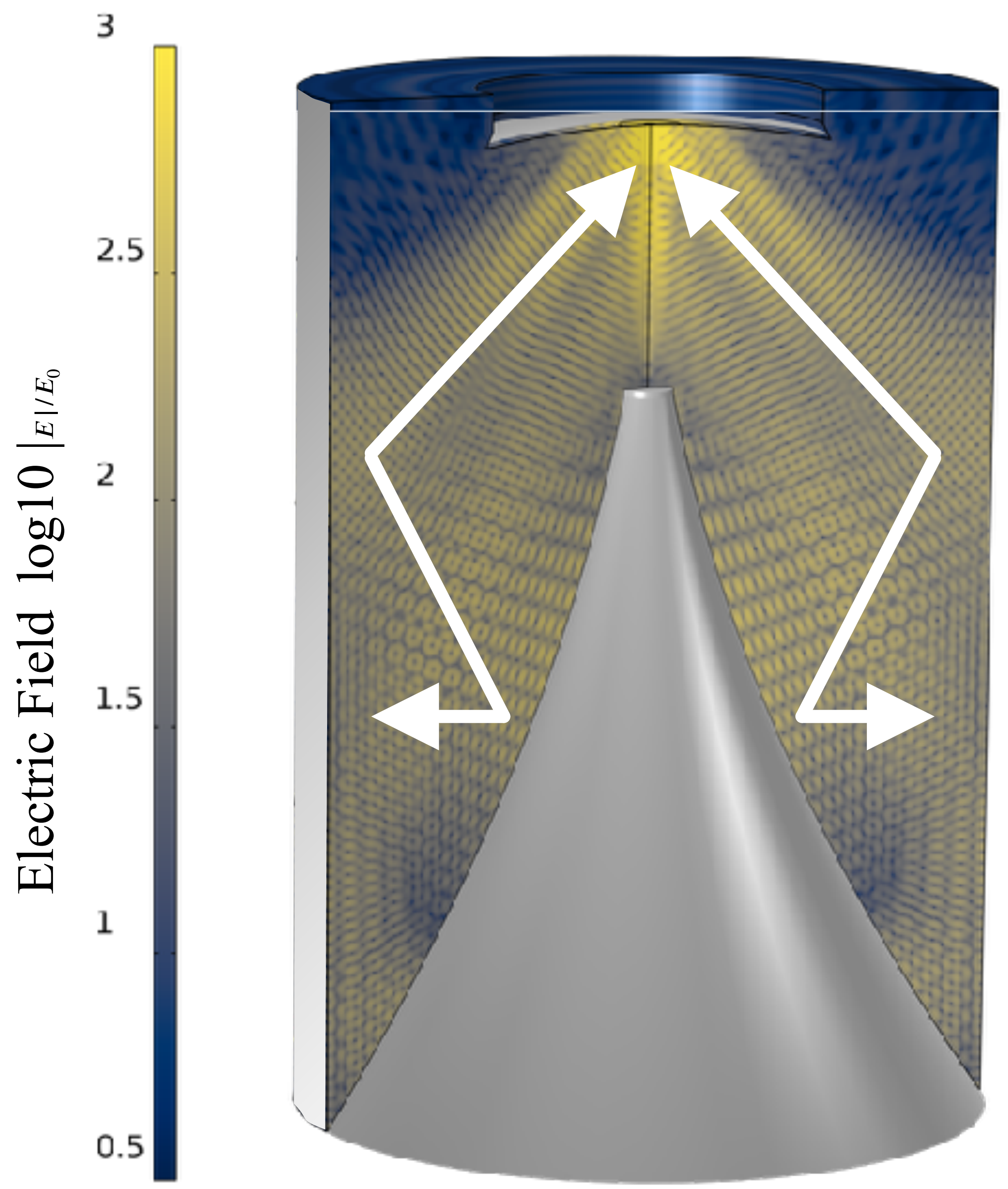


. . .

THz

✅ ***Higher Signal:*** *Large-Volume Resonators*

Fabry–Pérot Resonator BREAD

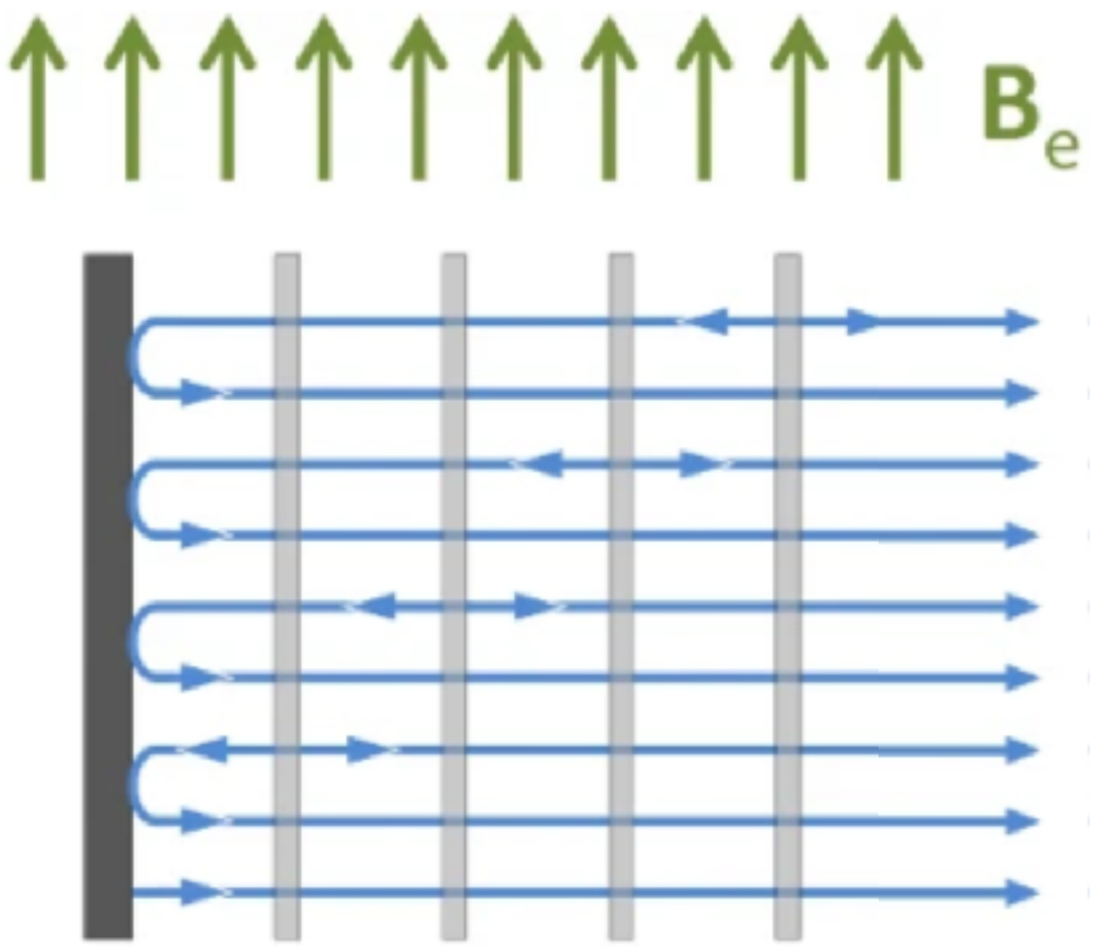


FNAL/Chicago/Harvard

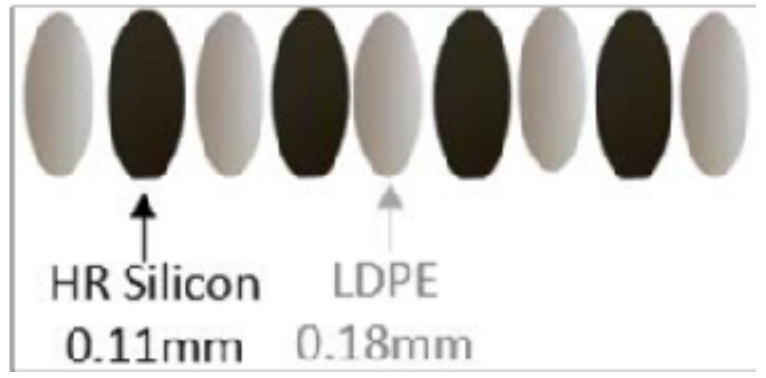
being constructed

~ 100 GHz

Multilayer Haloscope



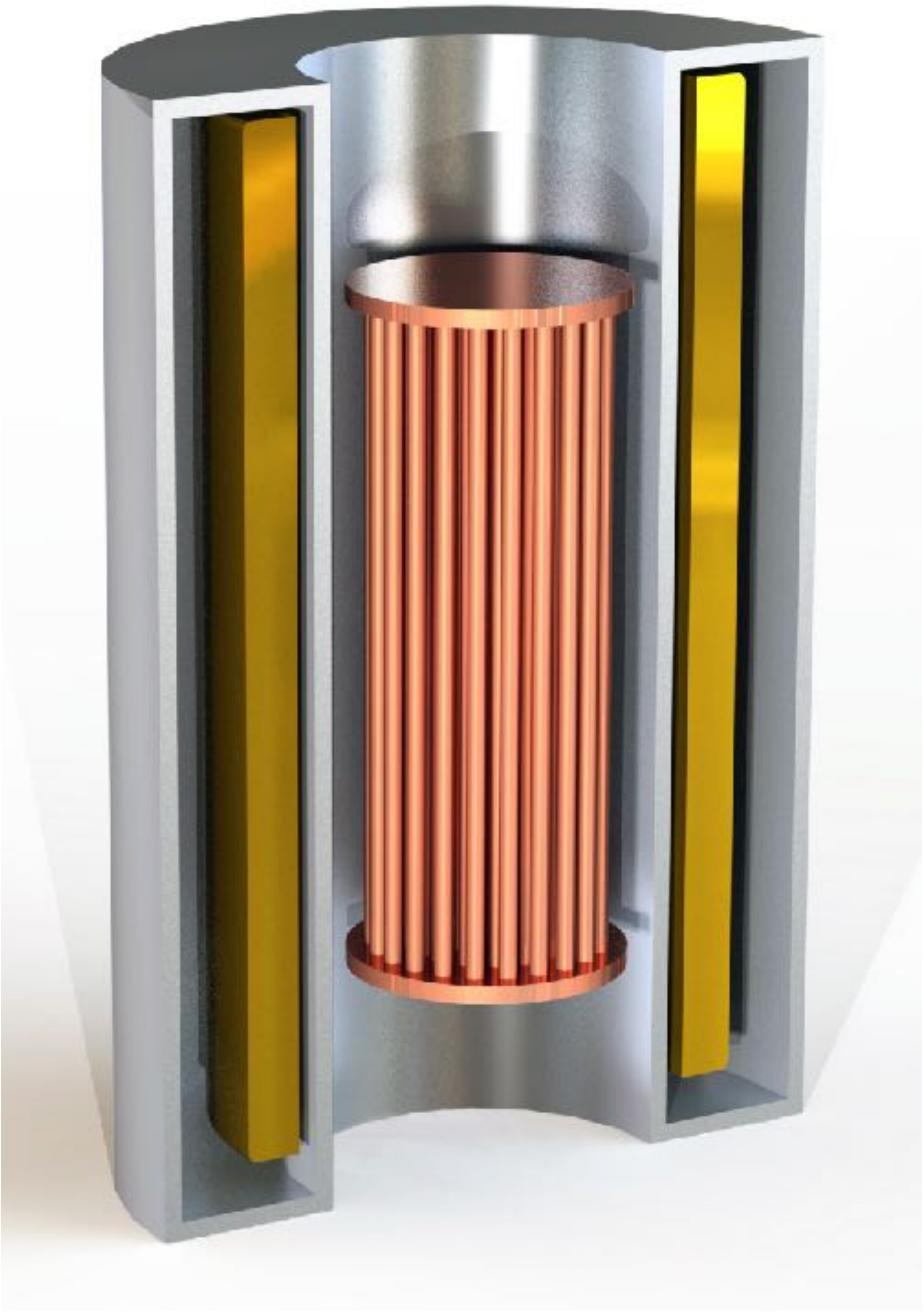
Existing Diel. Stacks at Harvard:



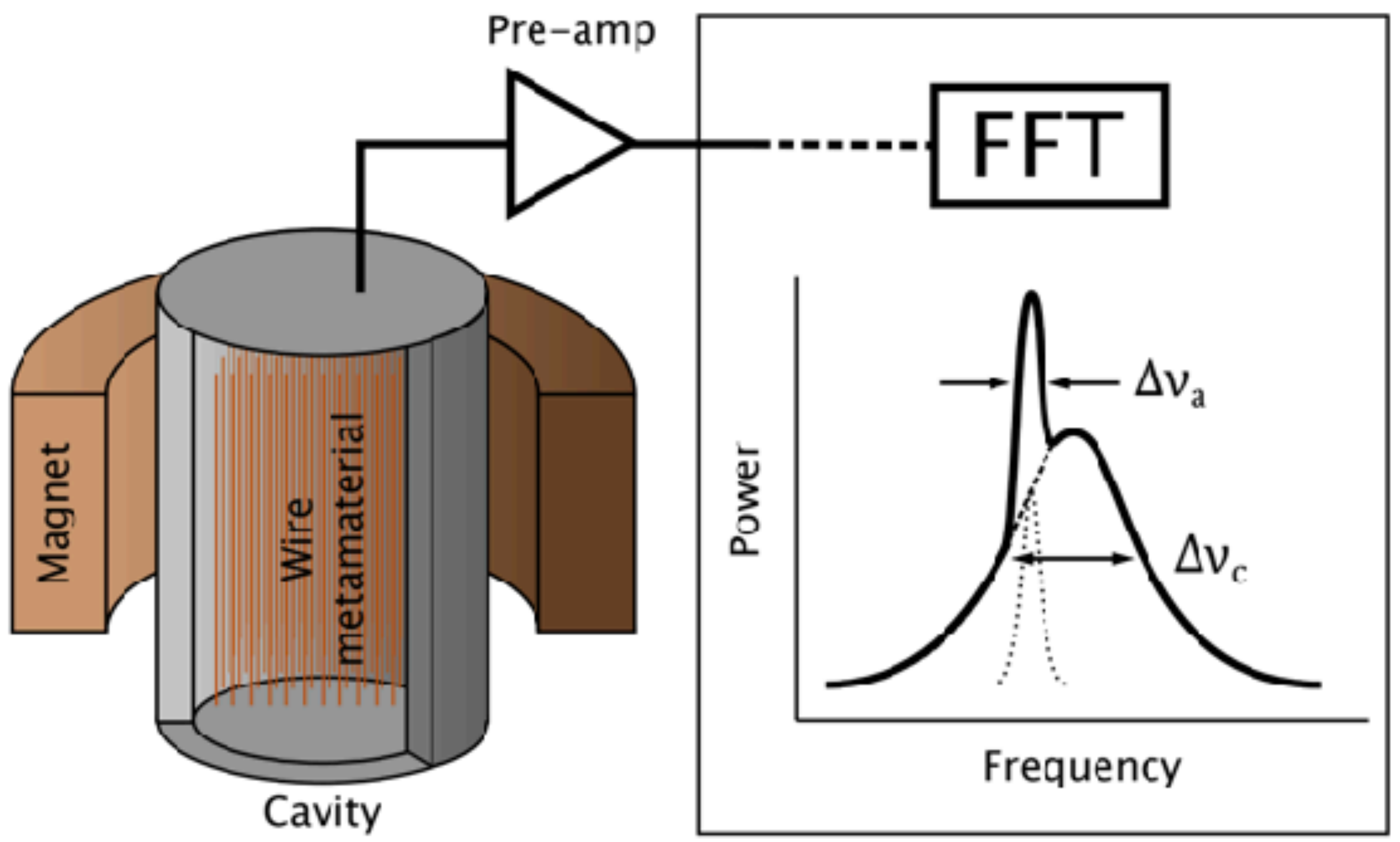
CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN
Edward Tong

> 100 GHz

ALPHA: Tunable Axion Plasma Haloscopes

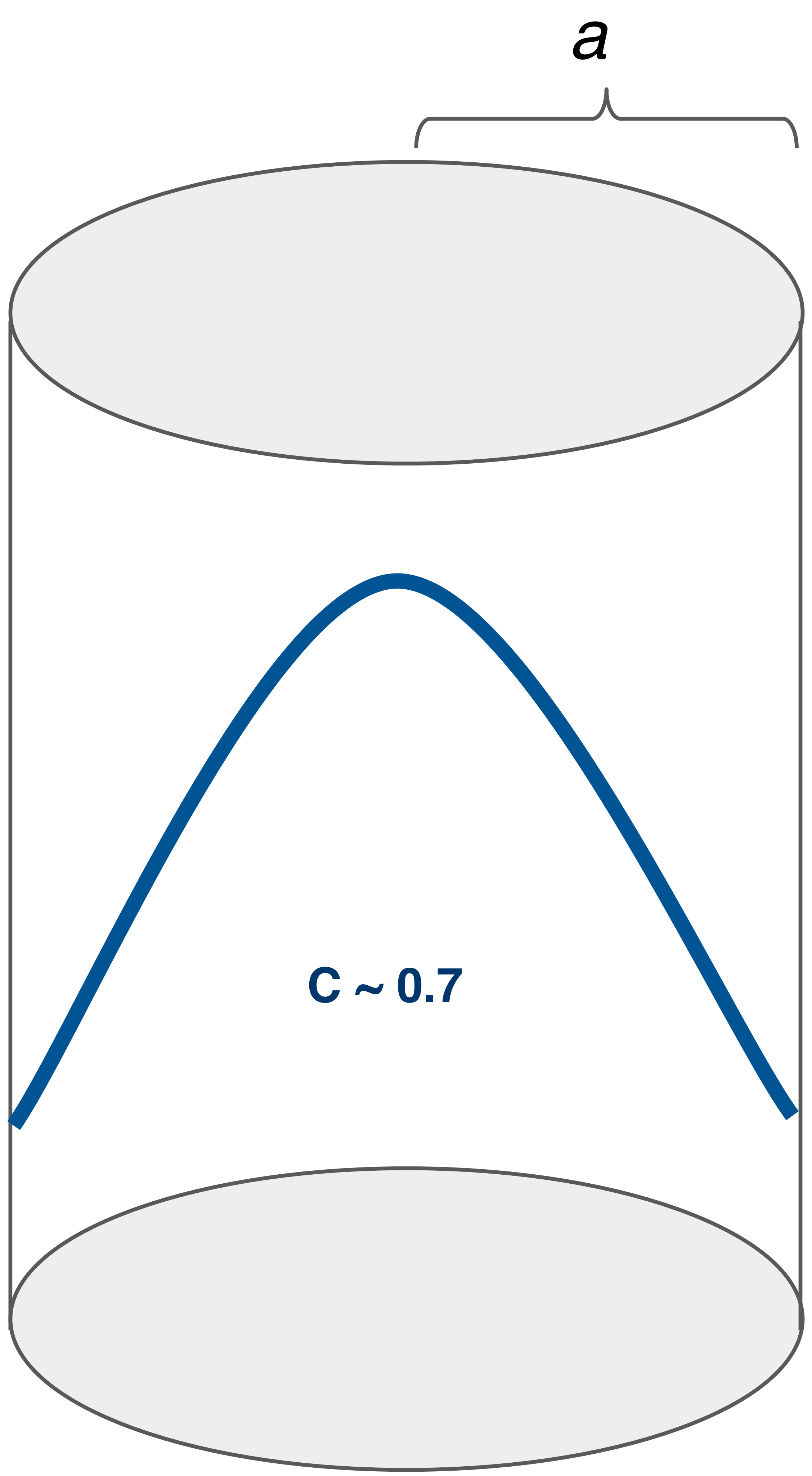


- Idea in Lawson, Millar, Pancaldi, Vitagliano & Wilczek, Phys. Rev. Lett. 123 (2019)
- Allows for larger volumes/higher power for high frequencies than traditional approaches
- + HAYSTAC-like quantum detectors for readout

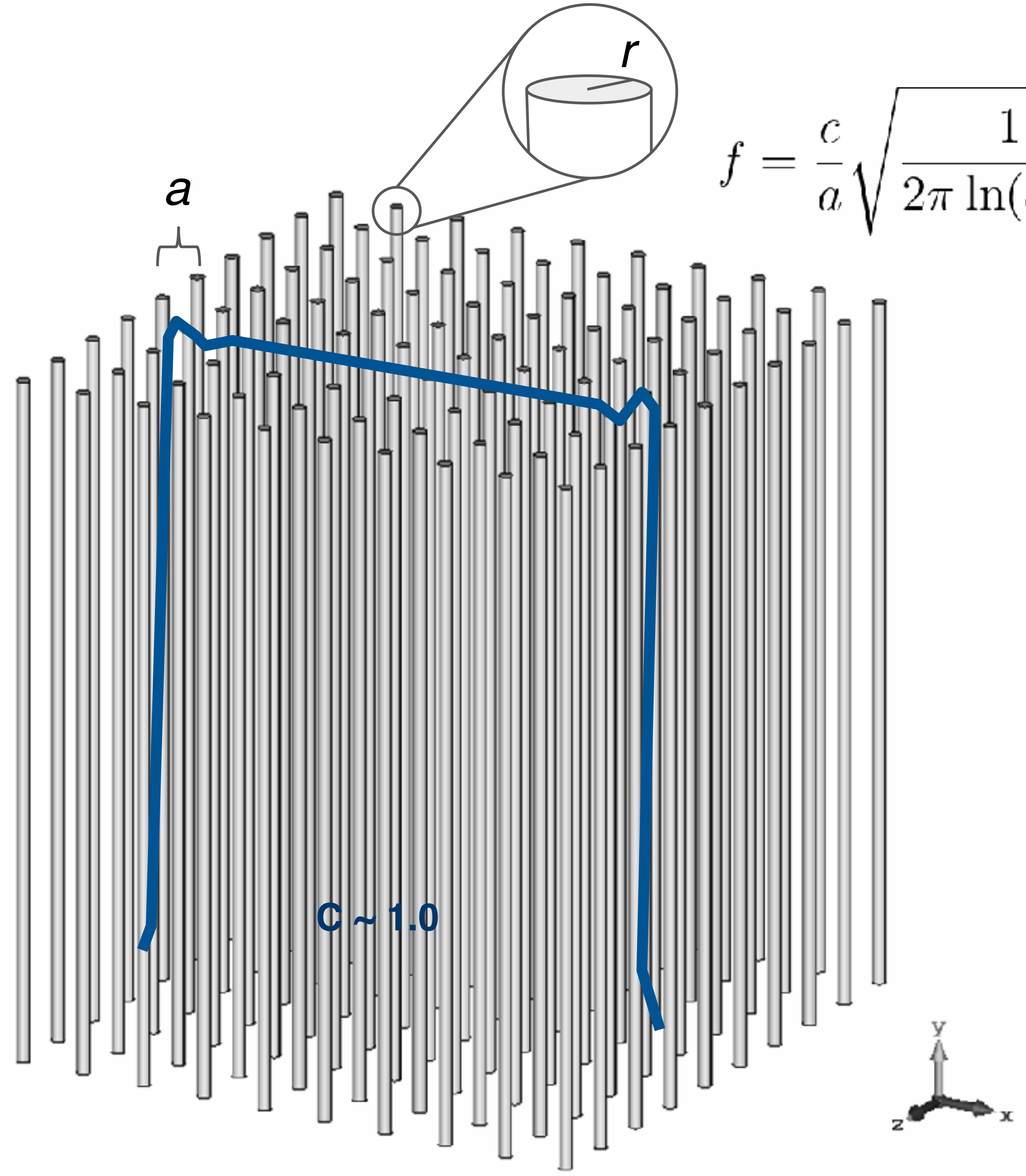


Kowit et al, *Phys.Rev.Applied* 20 (2023)

Solution: plasmonic resonance



$$f = \frac{1.202}{\pi}\frac{c}{a}$$



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

- Wires mutually induct, changing the plasma frequency
- Resonant frequency is decoupled from the size of the system
- A wire-spacing of 1 cm gives a plasma frequency of ~10 GHz

Theory of wire metamaterial: Pendry (1998) and Belov, et al. (2003)

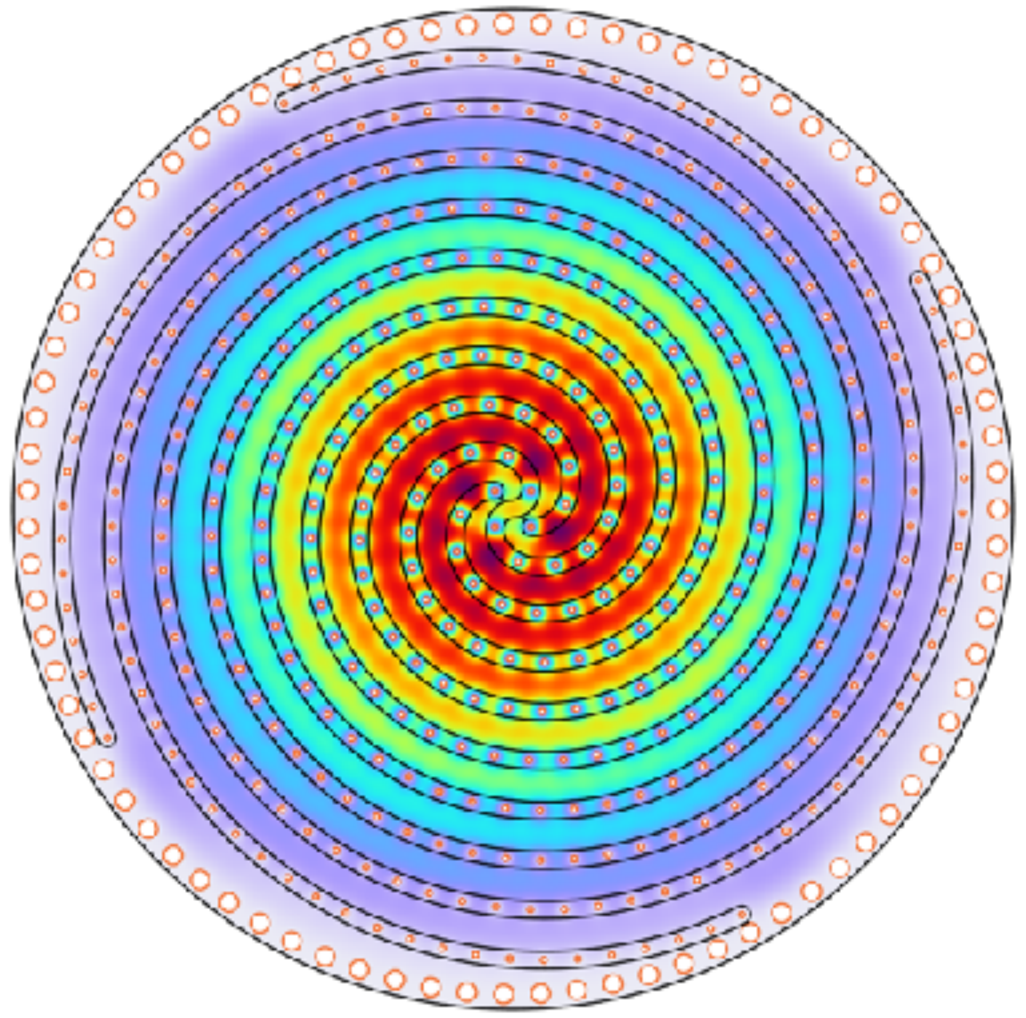
Lawson et al. (2019), PRL

Credit: J. Gudmundsson Sikivie (1983), PRL

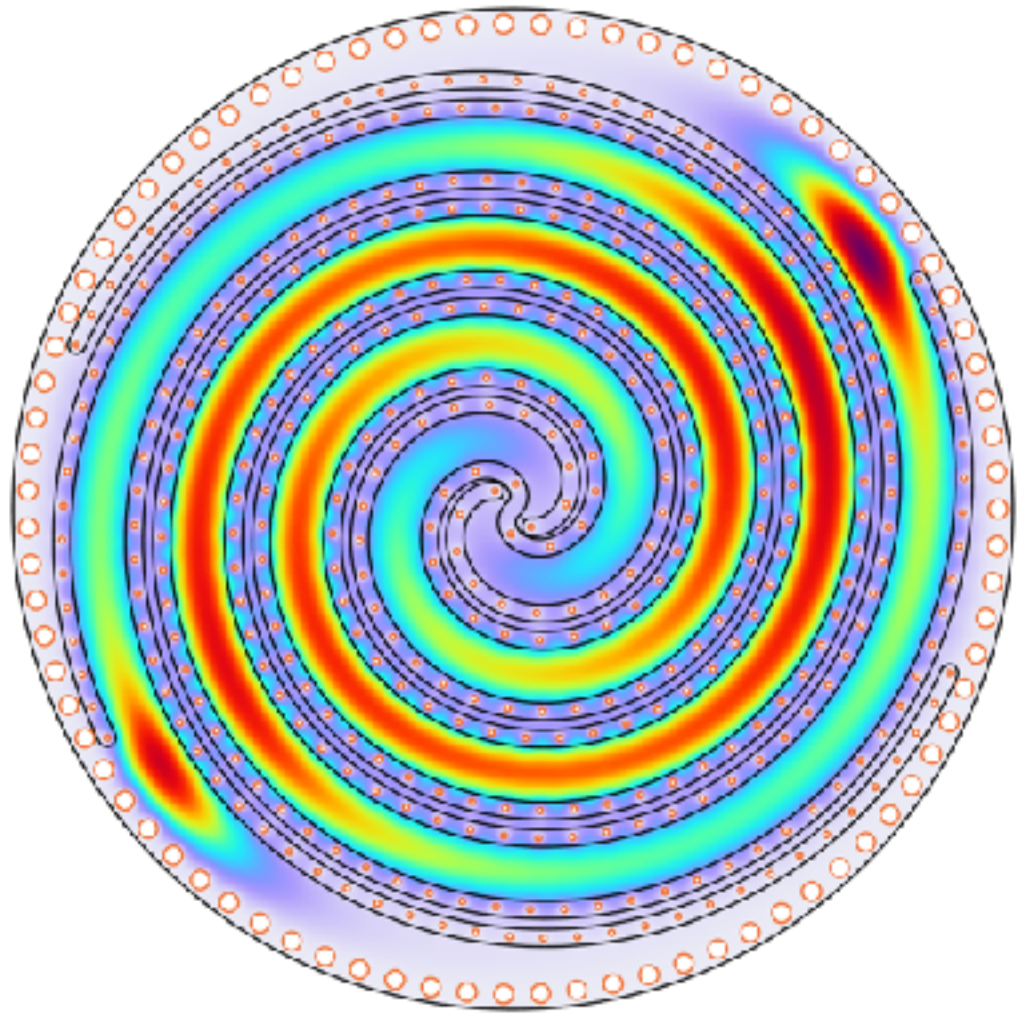
ALPHA Phase I Resonators

Spiral Tuning Mechanism

Junu Jeong, Stockholm Group



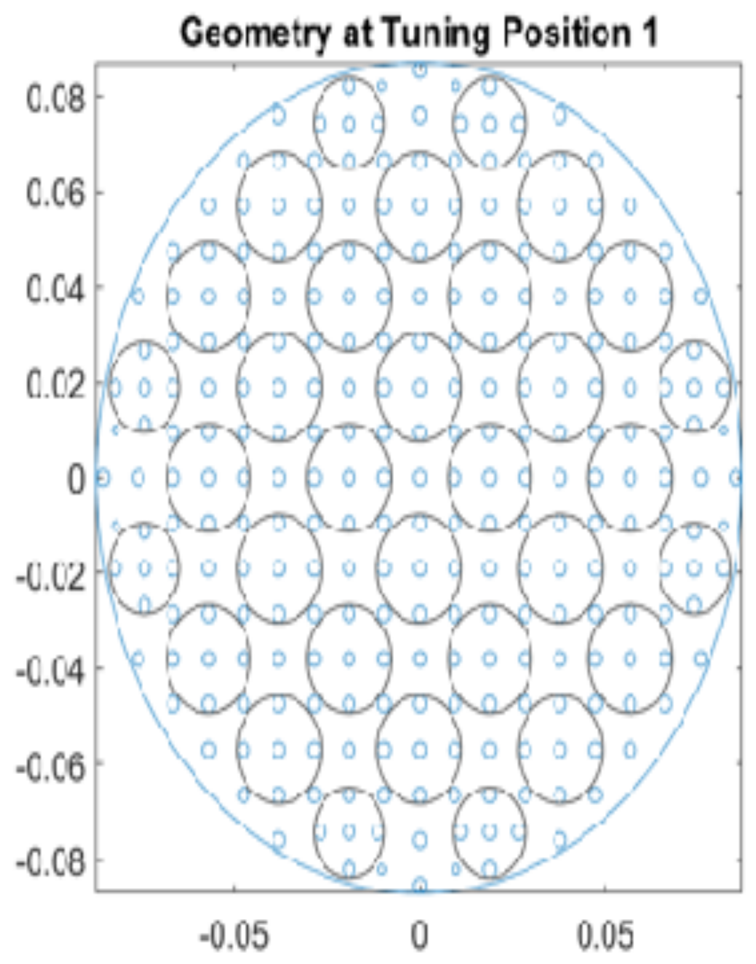
12.483 GHz

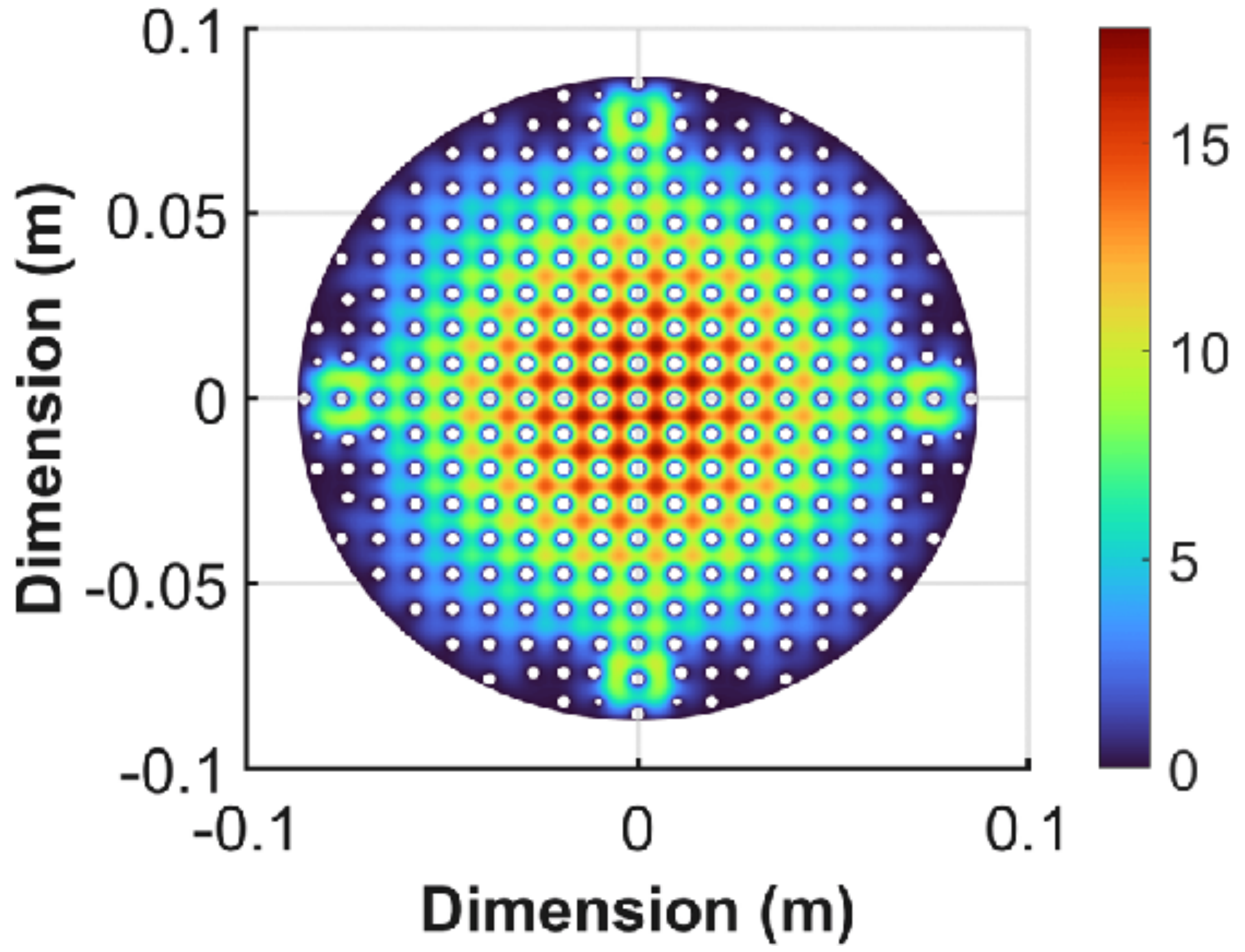


10.678 GHz

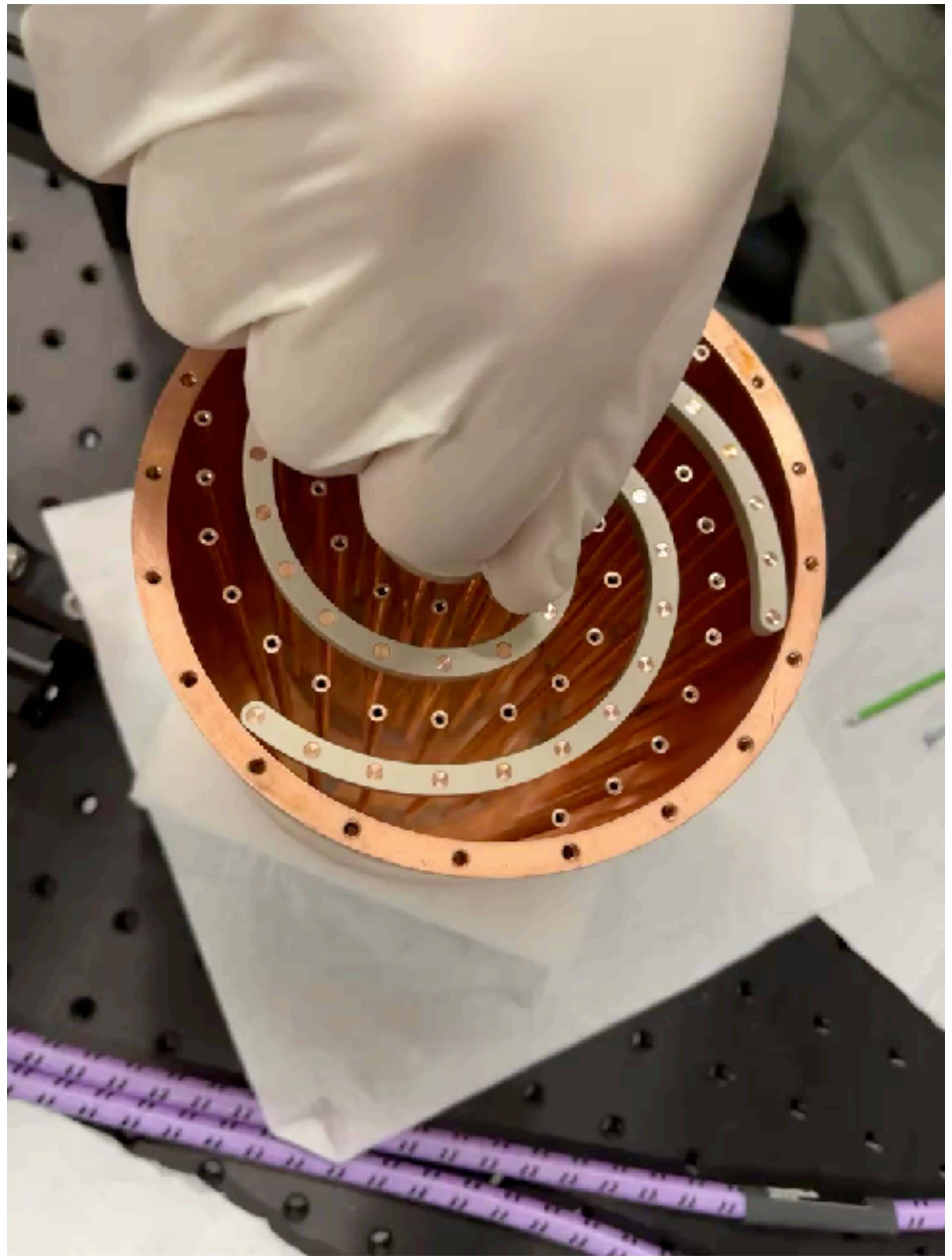
Quadropode Spinor Mechanism

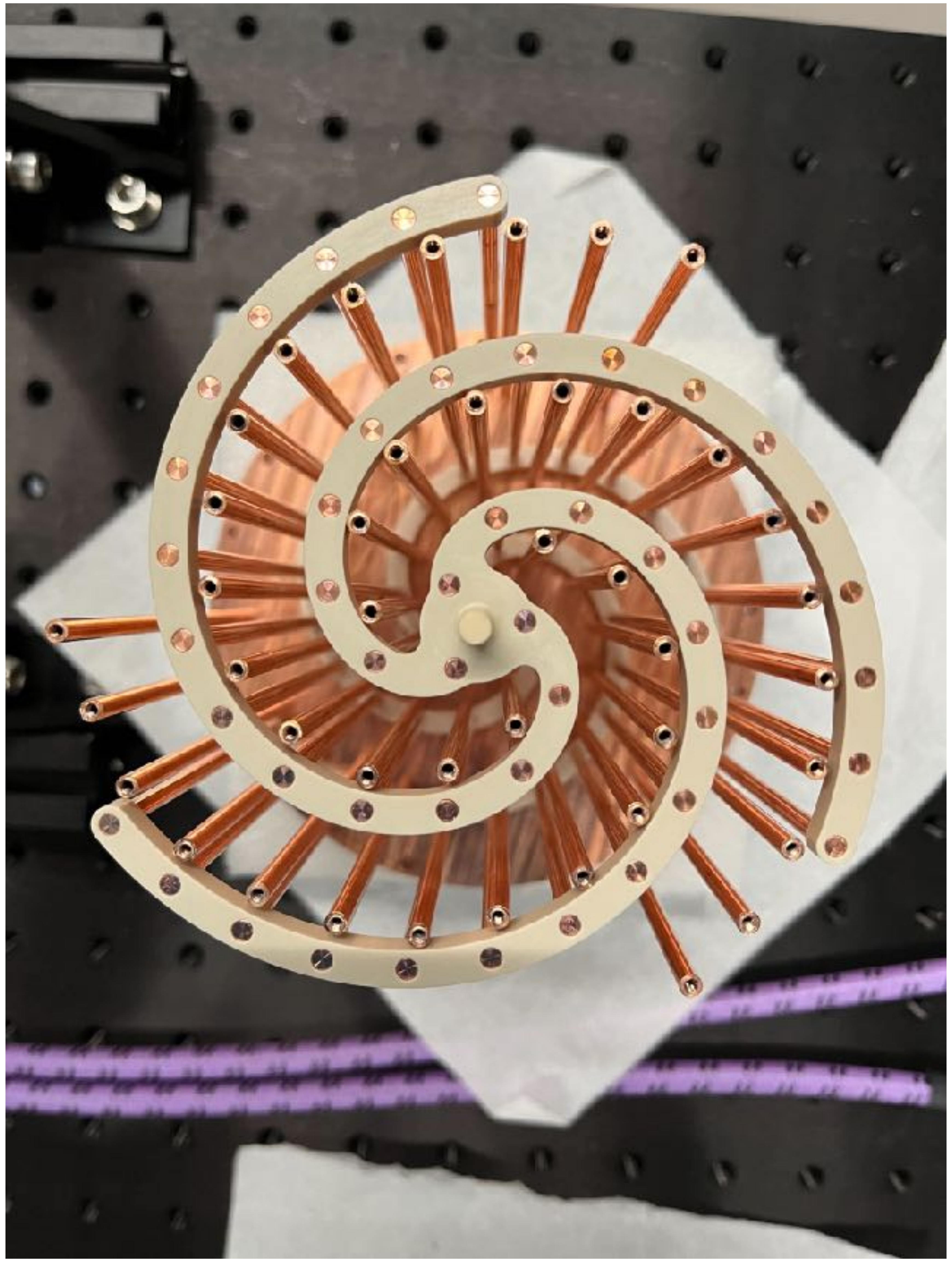
Shriram Sadashivajois, K van Bibber, UCB Group

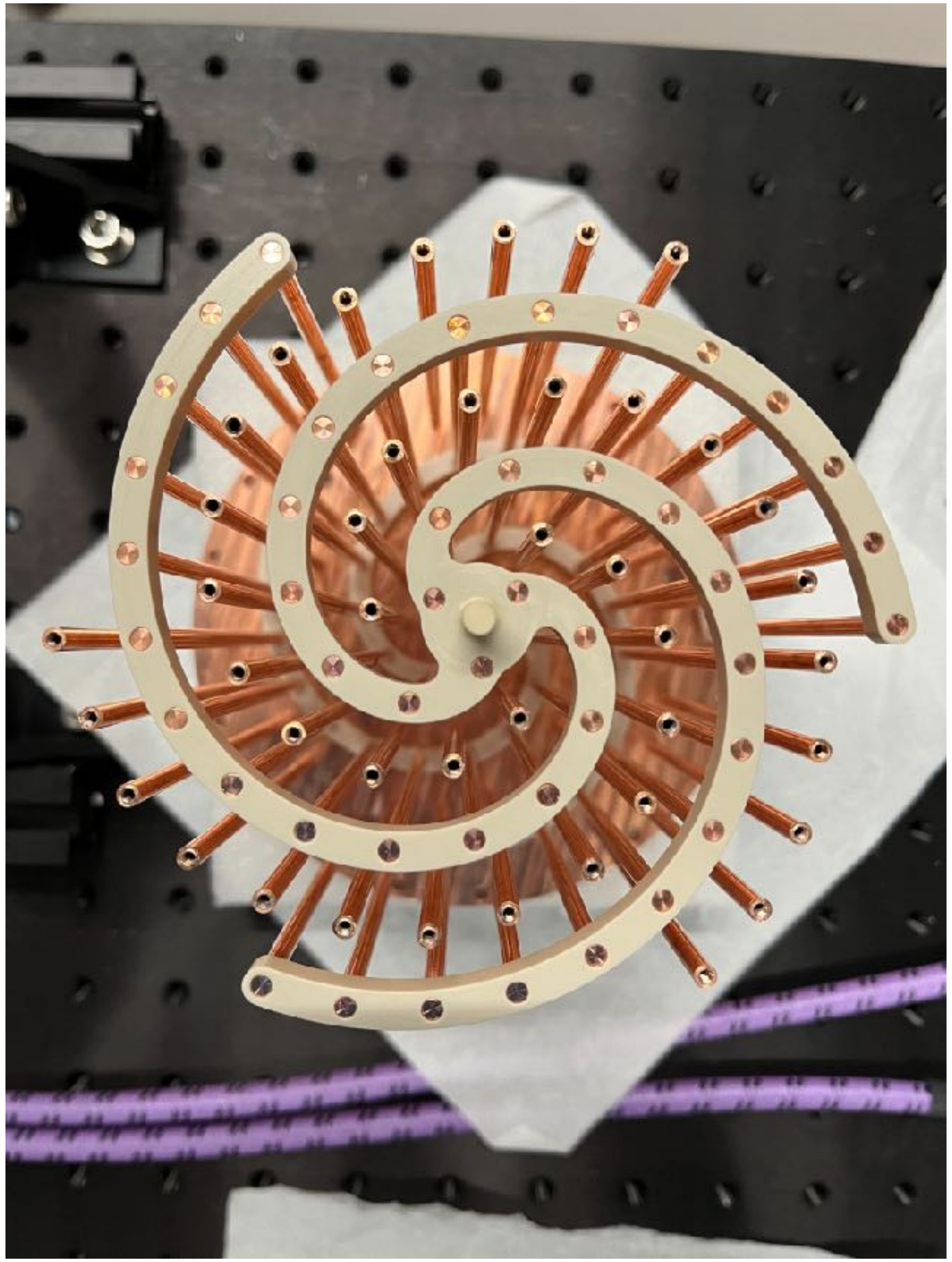




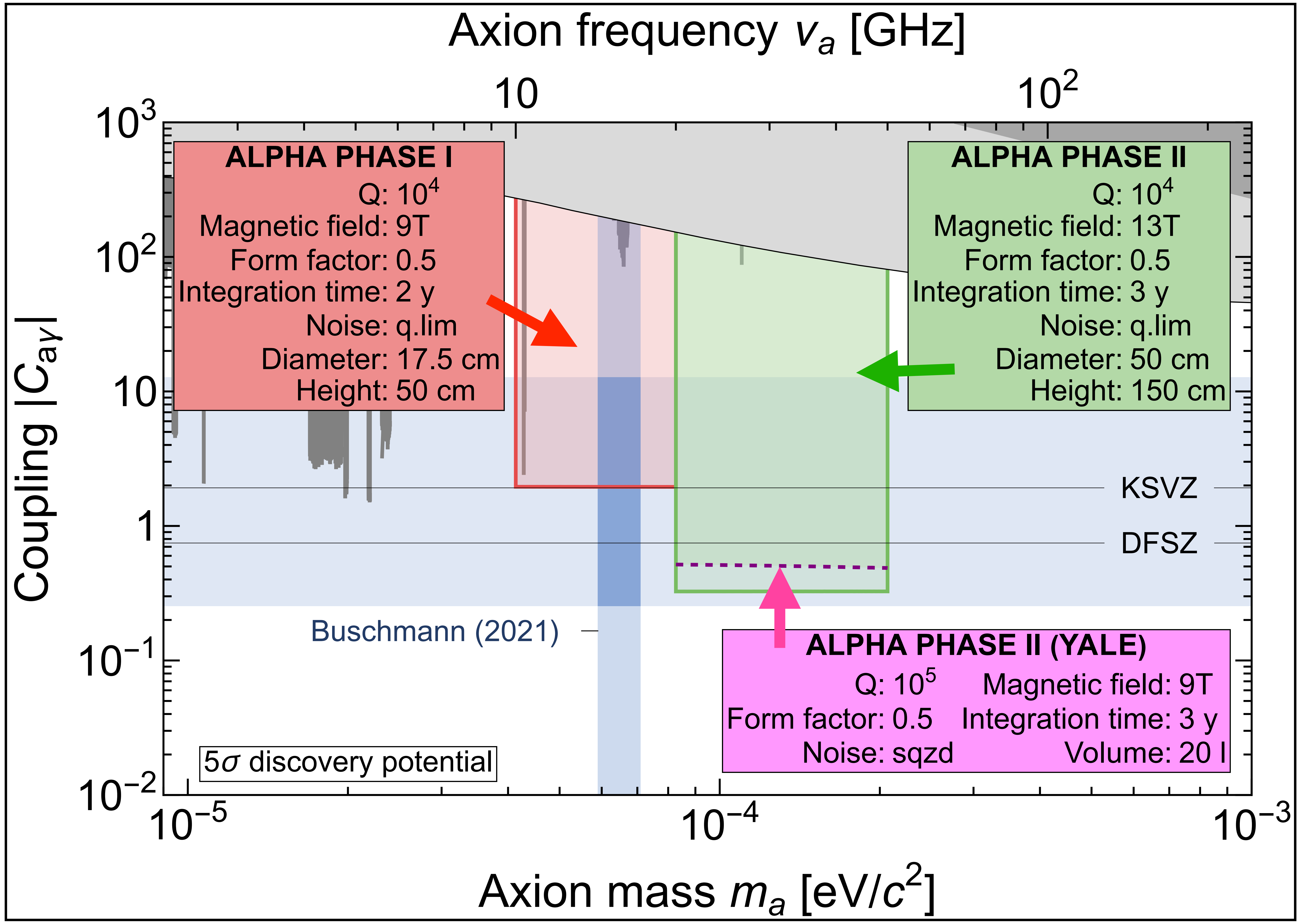
6-arm Protoype cavity





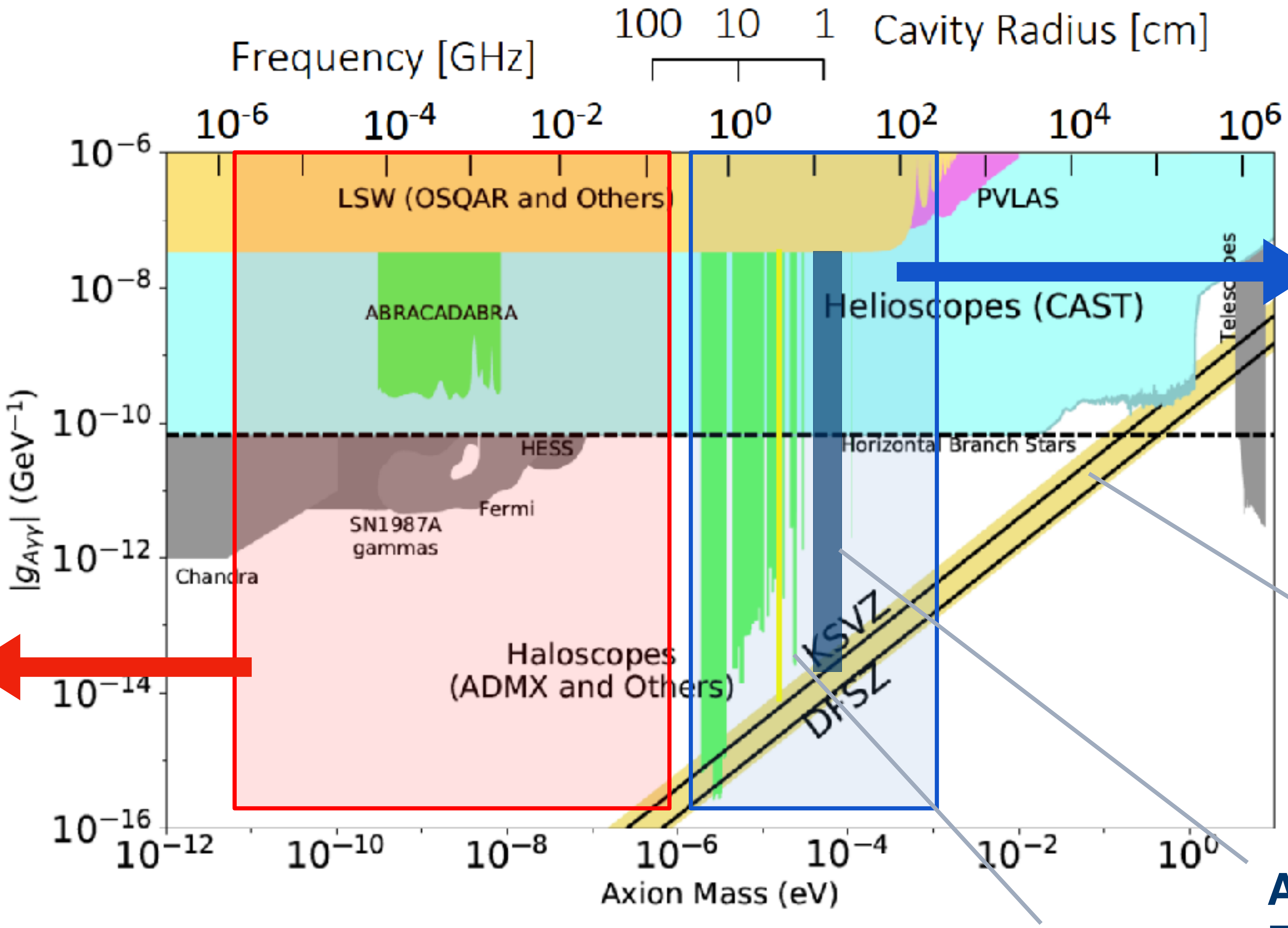


ALPHA: Projected Sensitivity



More on Friday
Karl van Bibber

Axions’ Pre- vs. Post-Inflation Production



Pre-inflation axion –
wide range of viable masses.
“GUT-scale” axion.

Mass: below 1 μeV
Typical Measurement:
Lumped element detectors

Post-inflation axion –
theoretically calculable from string production mechanisms.

Mass: above 1 μeV
Typical Measurement:
Cavity haloscopes

Coupling for QCD Axion

Credit: Particle Data Group 2020 review of axion particle physics

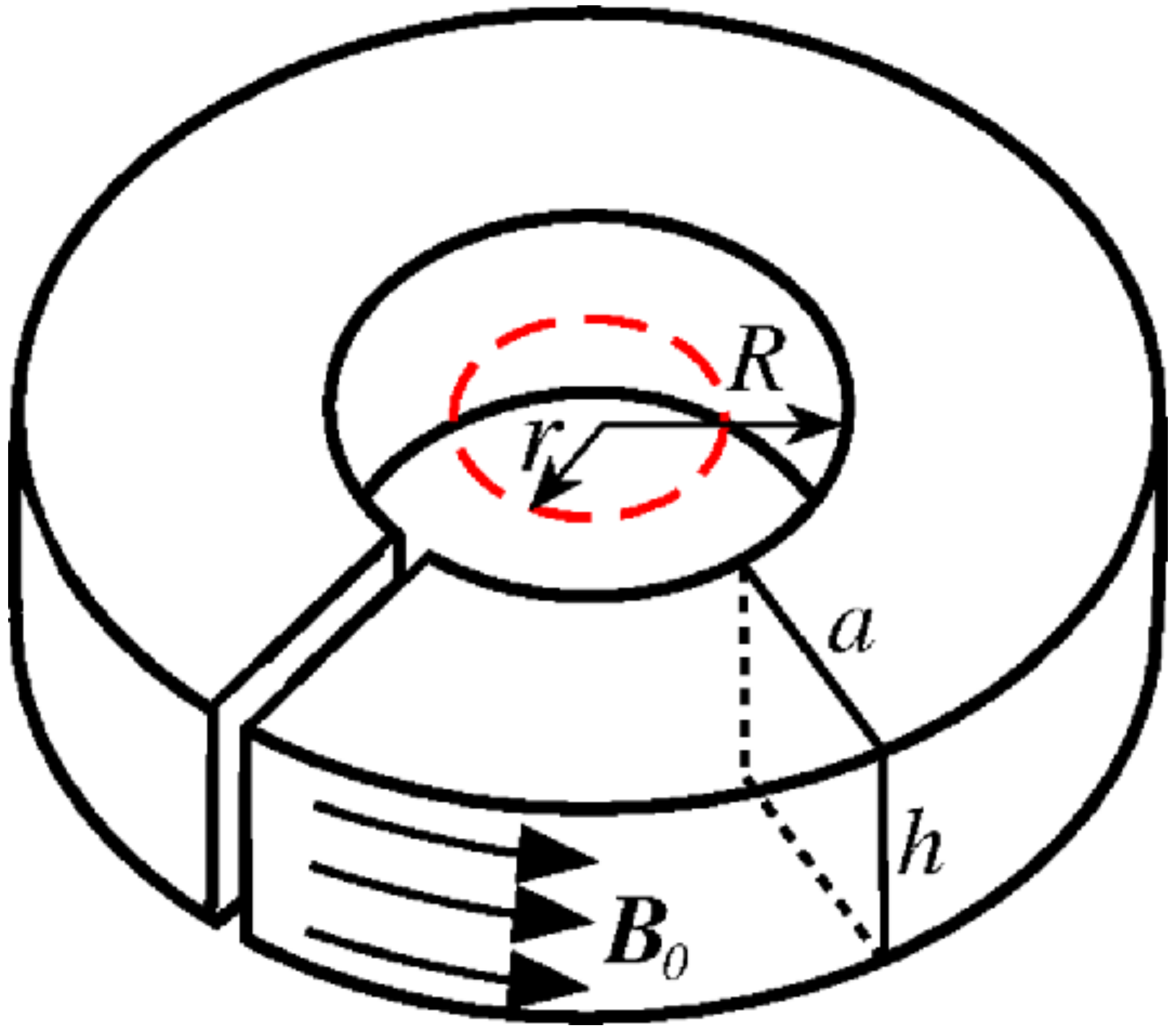
ALPHA Phase 1 Forecast

HAYSTAC

Adapted from Max Silva-Feaver

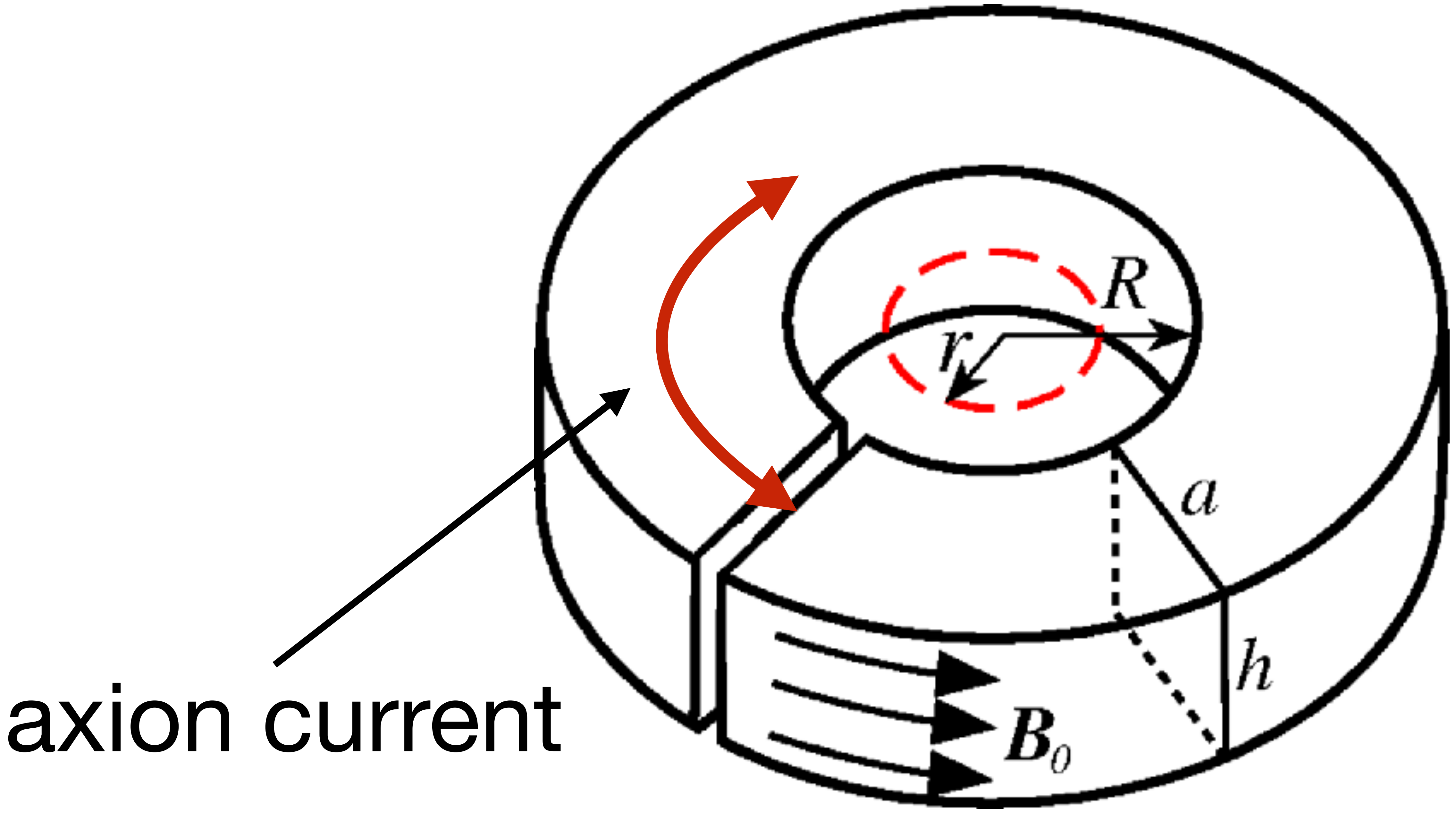
A **B**roadband / **R**esonant **A**pproach to **C**osmic **A**xion **D**etection with an **A**mplifying **B**-field **R**ing **A**pparatus

The cartoon experiment

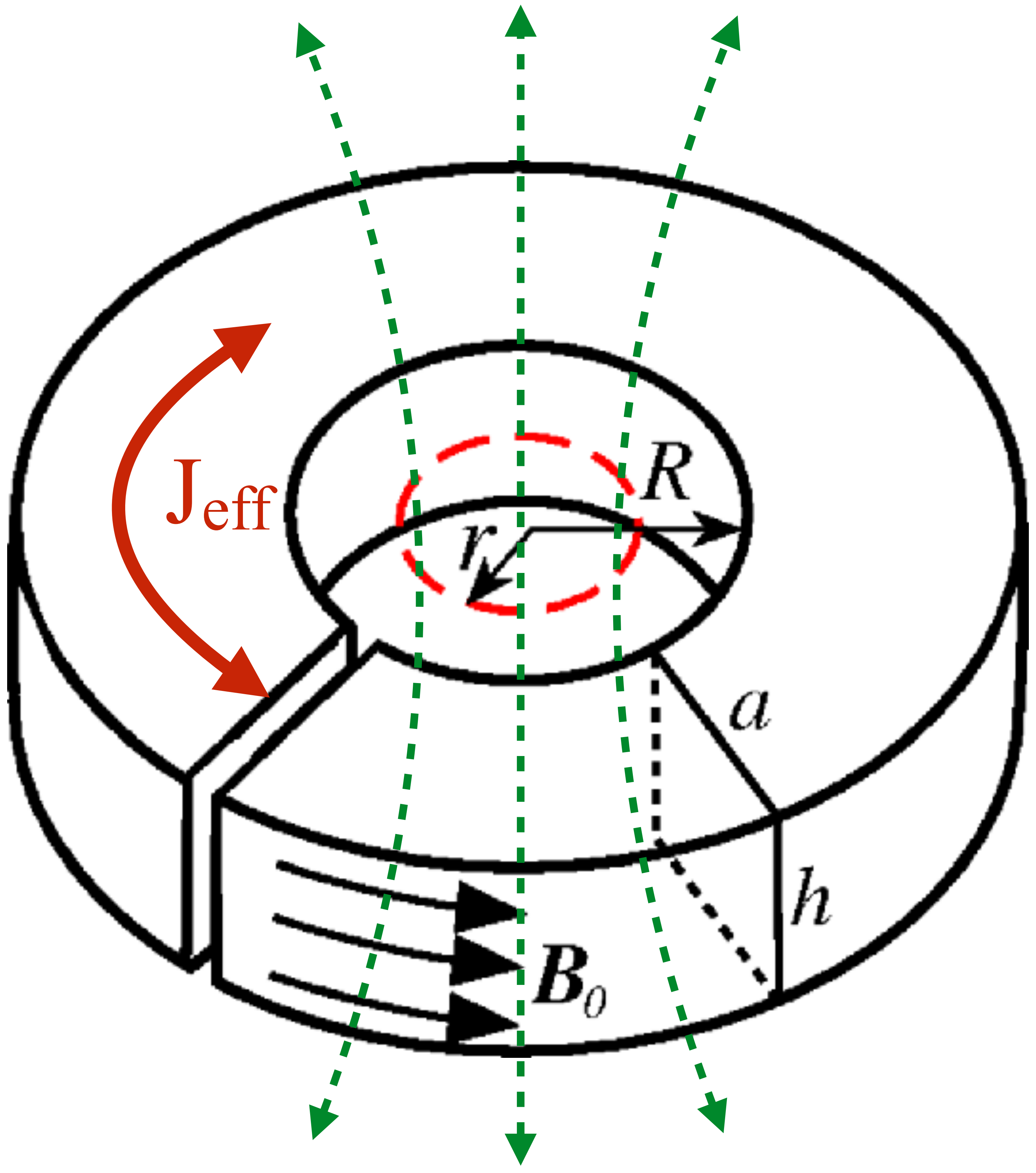


Based on Kahn, Safdi and Thaler, Phys.Rev.Lett. 117 (2016) no.14, 141801

The cartoon experiment

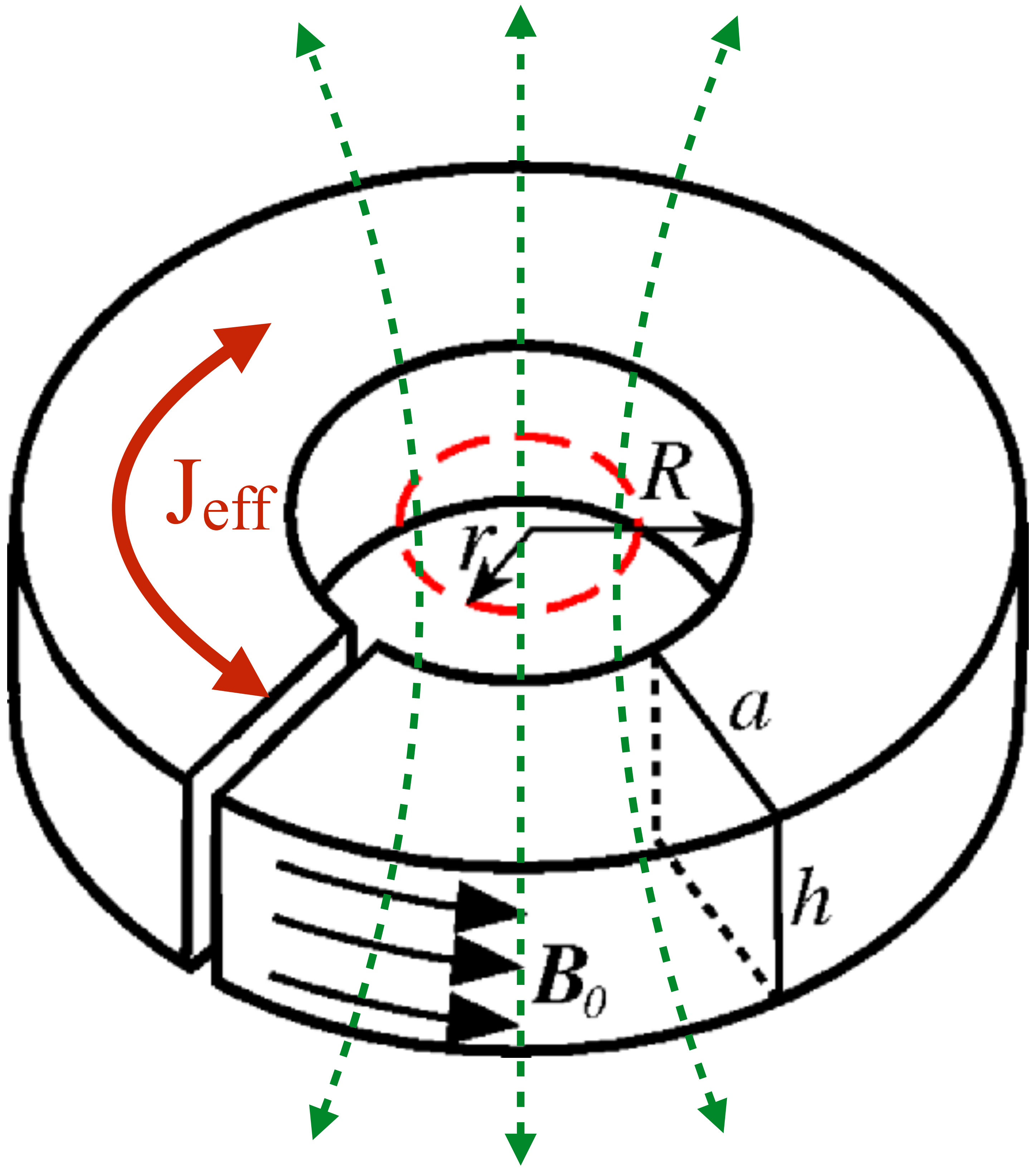


The cartoon experiment



Real Magnetic Field!

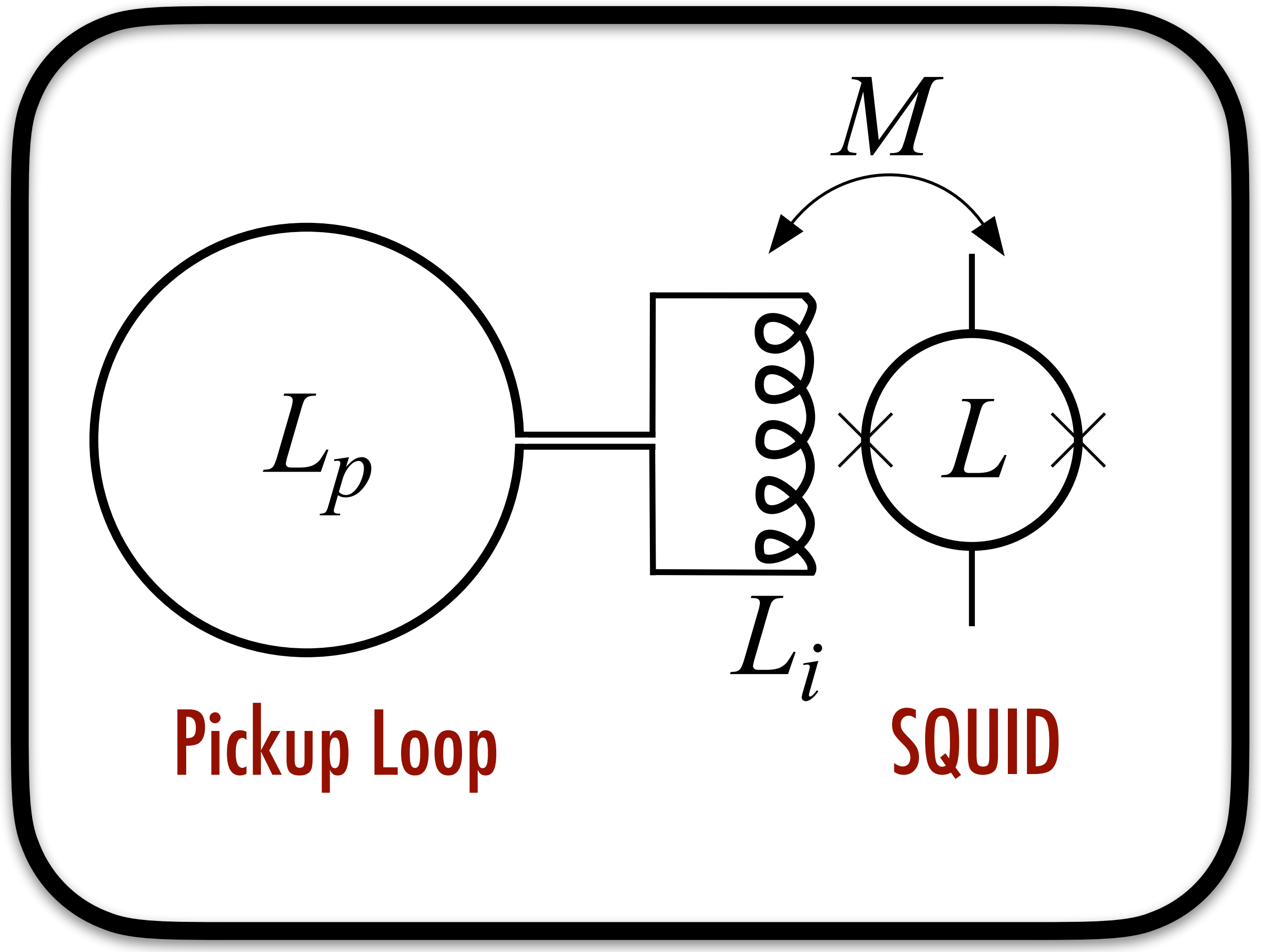
The cartoon experiment



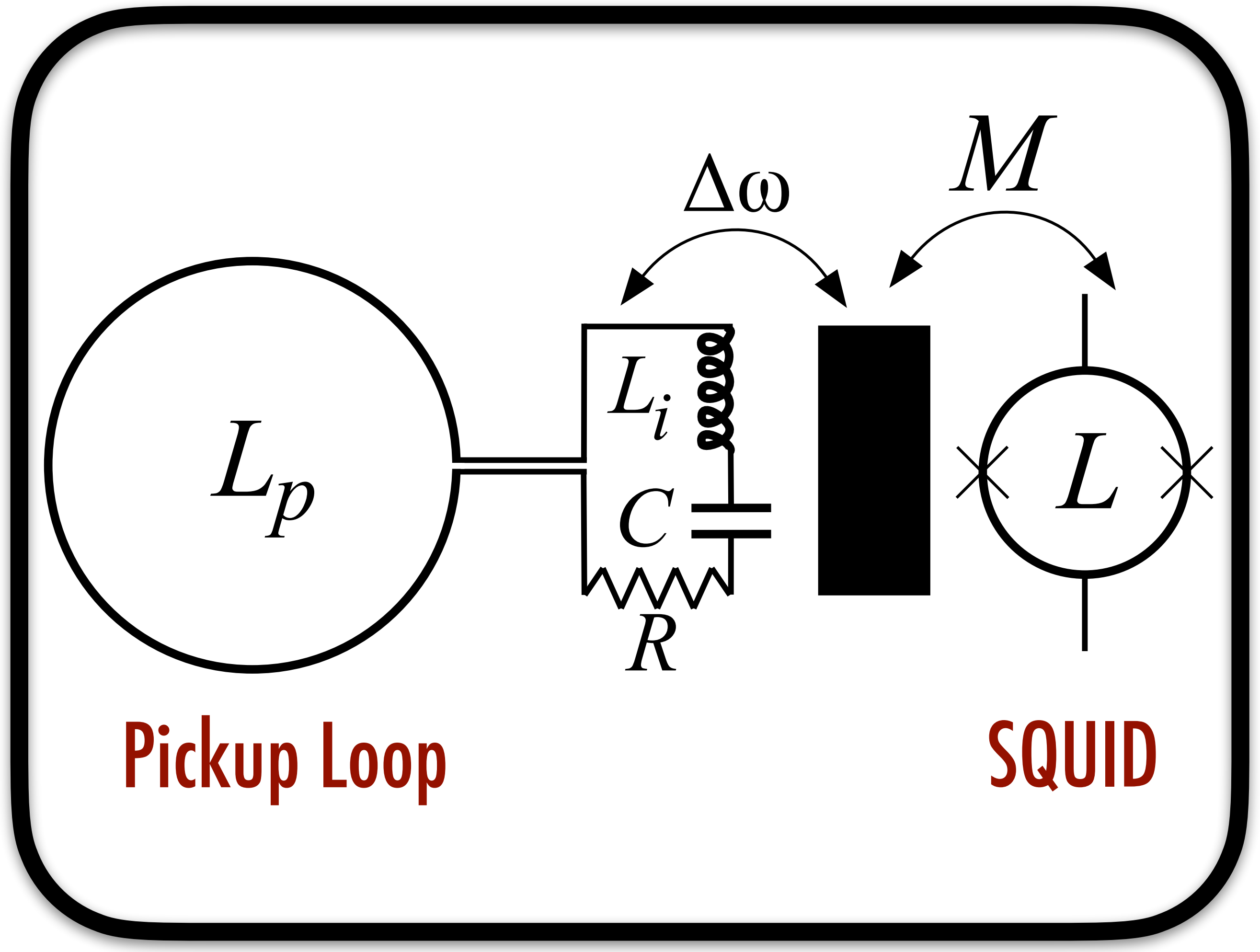
A real magnetic field induced in a zero field region.

ABRA Readout Options:

Option #1 - Broadband Readout
- pickup loop directly coupled to the SQUID
- simultaneous scan of all frequencies
- simple and fast



Option #2 - Resonant Readout
- pickup loop coupled to the SQUID through a resonant circuit
- scan across all frequencies
- signal enhancement by $Q_{value} \sim 10^6$ on resonance but significant enhancement of sidebands as well
- better ultimate sensitivity



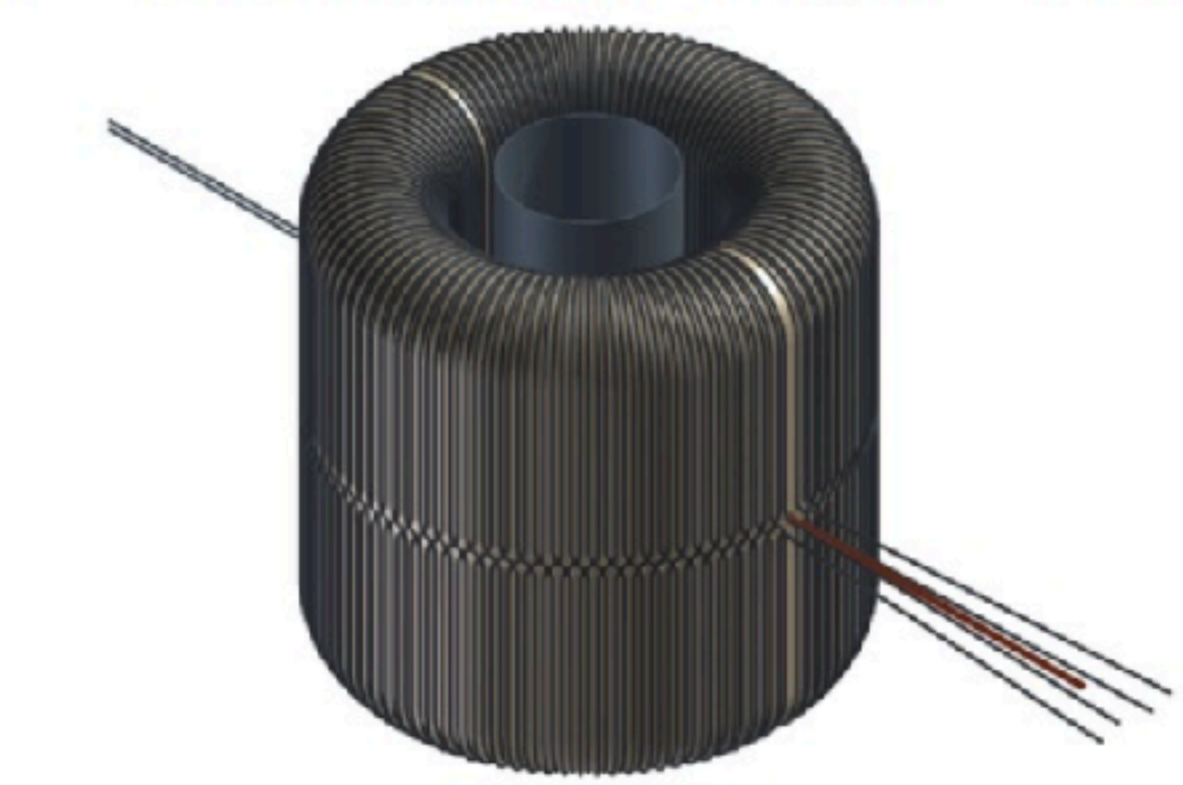
For a review of this issue see Chaudhuri, Irwin et al. arXiv:1803.01627

ABRACADABRA

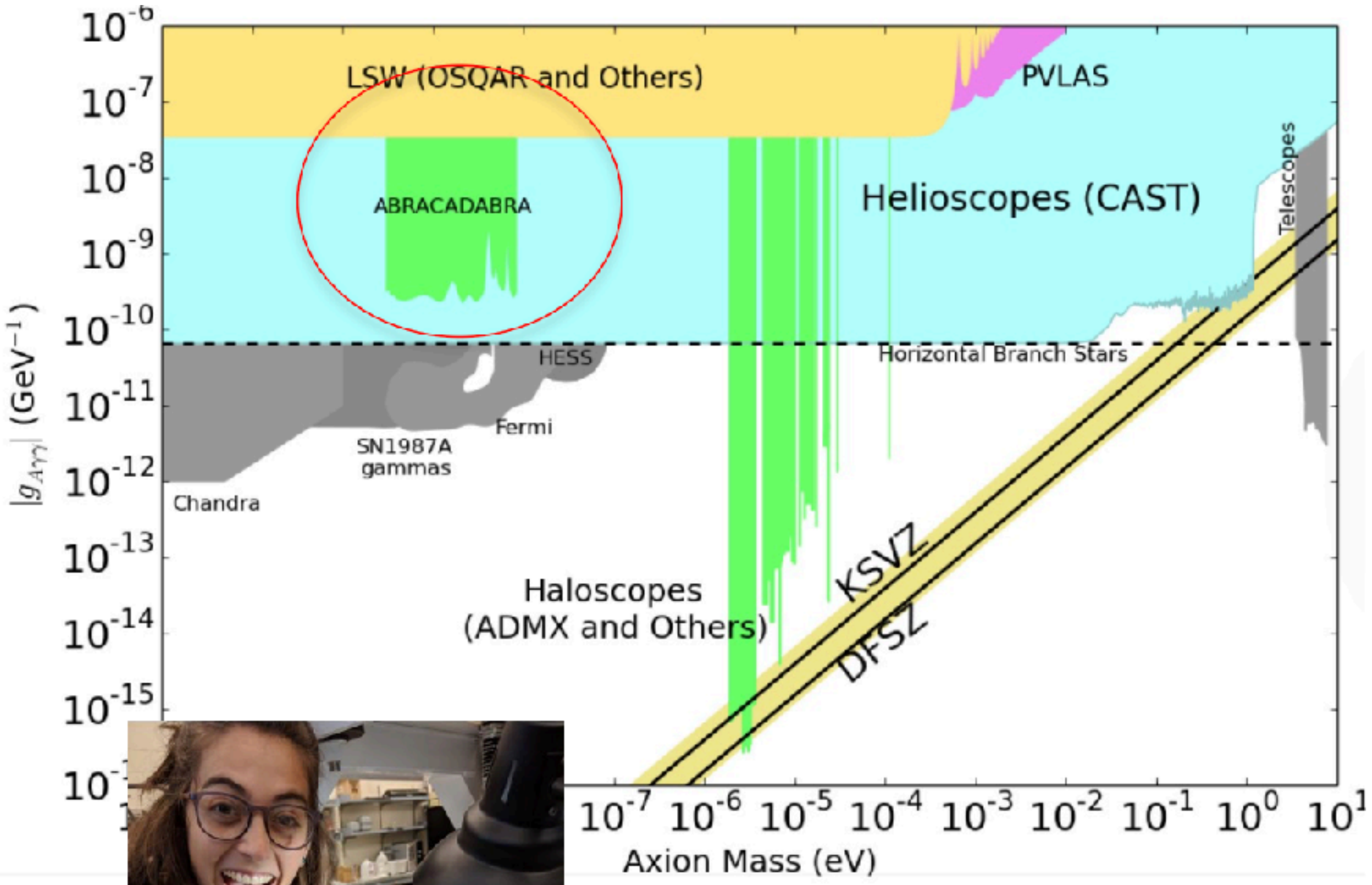
Experiment:

Prototype specs:

$R_{\text{in}} = 3$ cm, $R_{\text{out}} = 6$ cm, $h = 12$ cm,
$V = 680\ \text{cm}^3$, $B_{\text{max}} = 1$ T, $G = 0.085$



ABRA-10cm @ MIT



C. Salemi at MIT

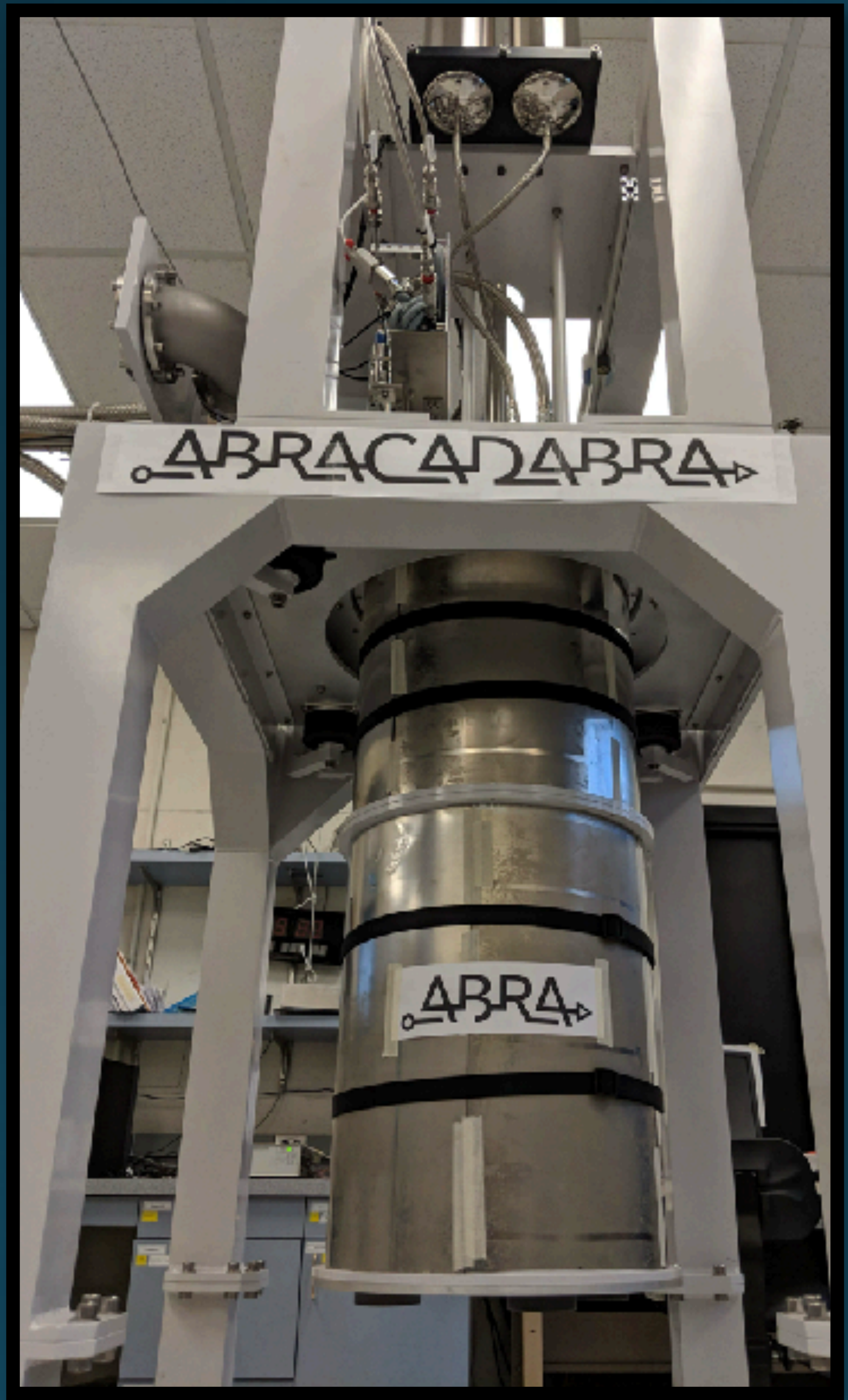
First Results

2019: Phys. Rev. Lett. **122**, 121802

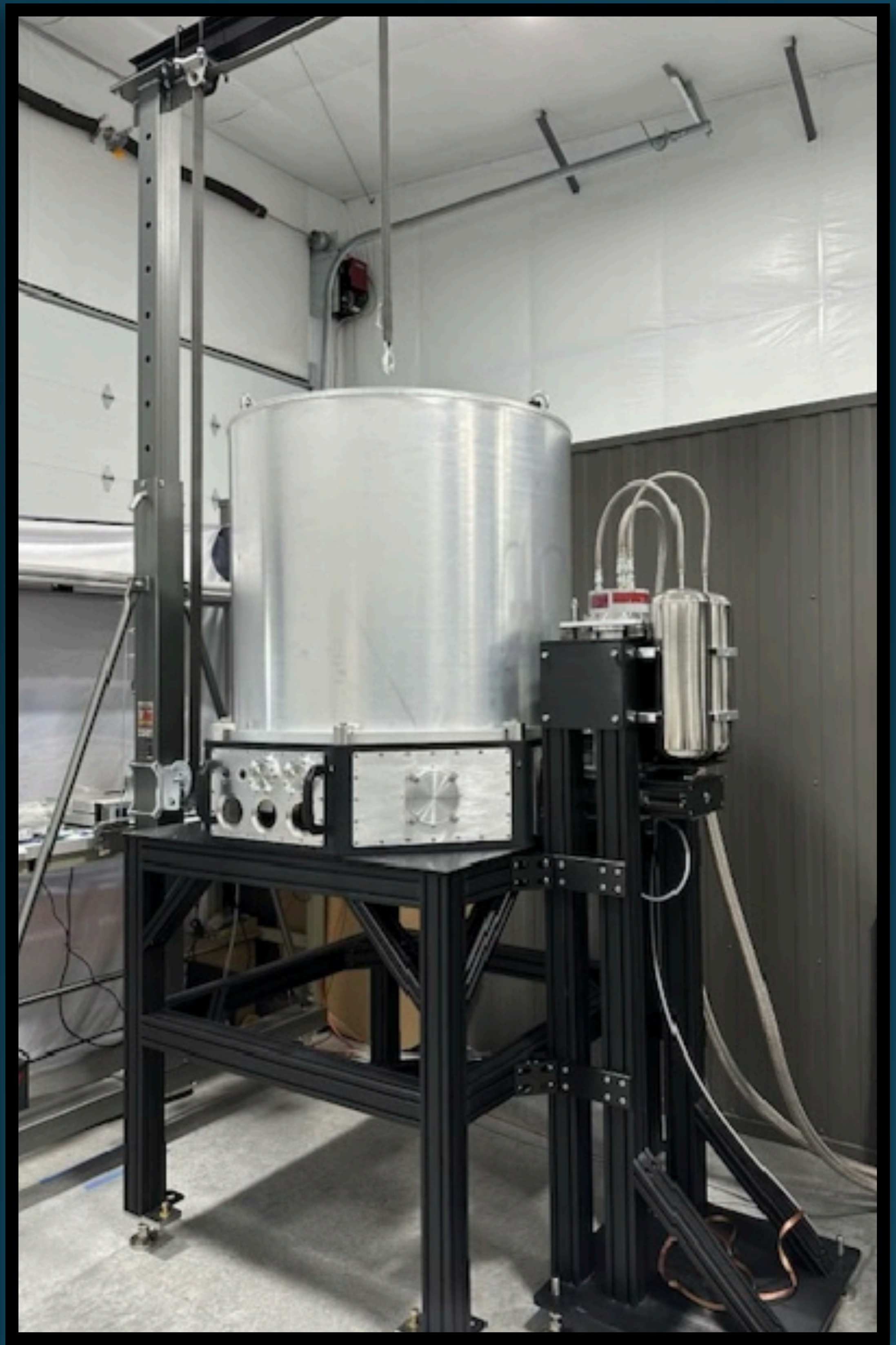
2021: Phys. Rev. Lett. **127**, 081801

DMRadio

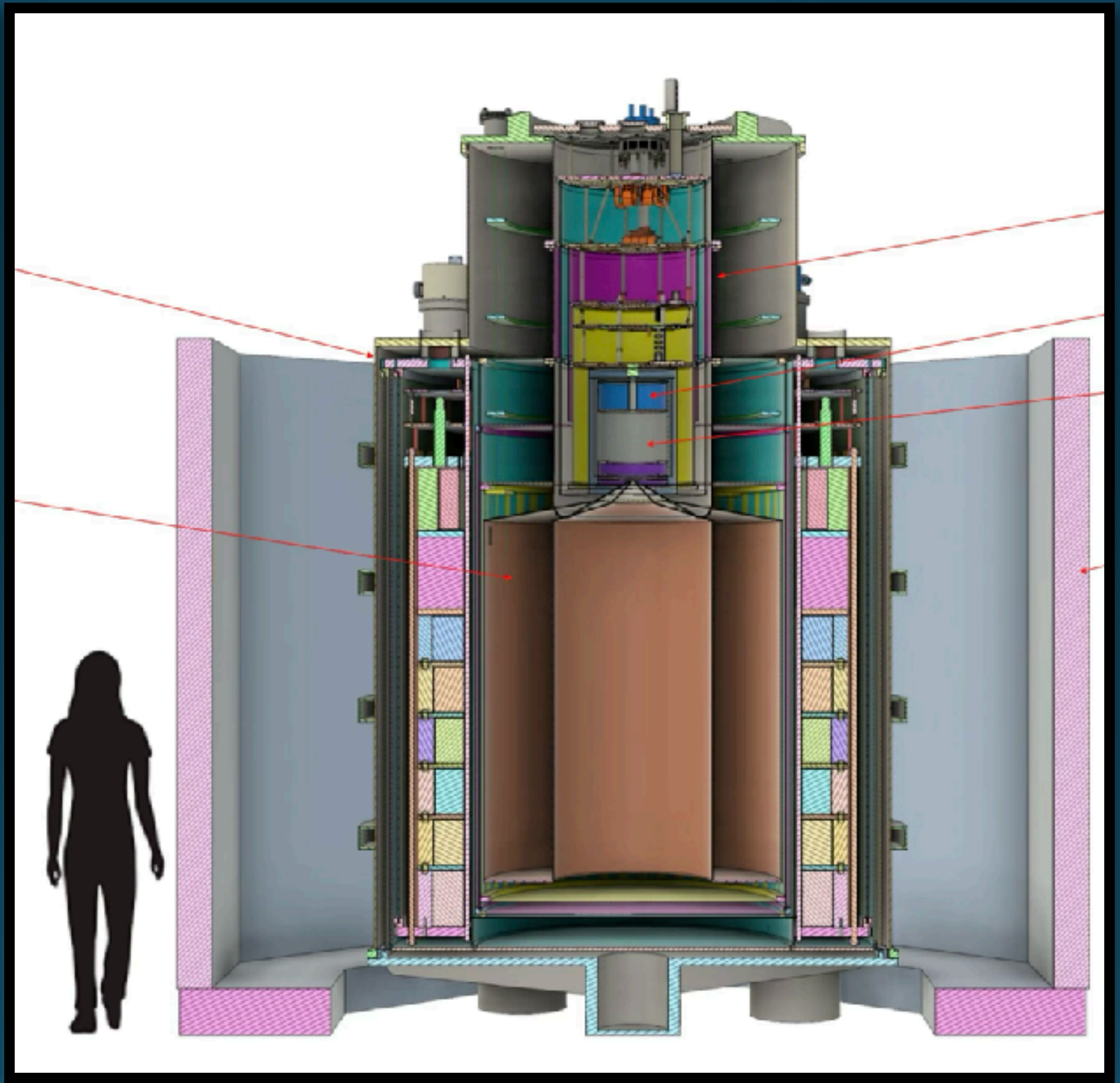
A staged approach to searching for QCD axions at sub-μeV masses



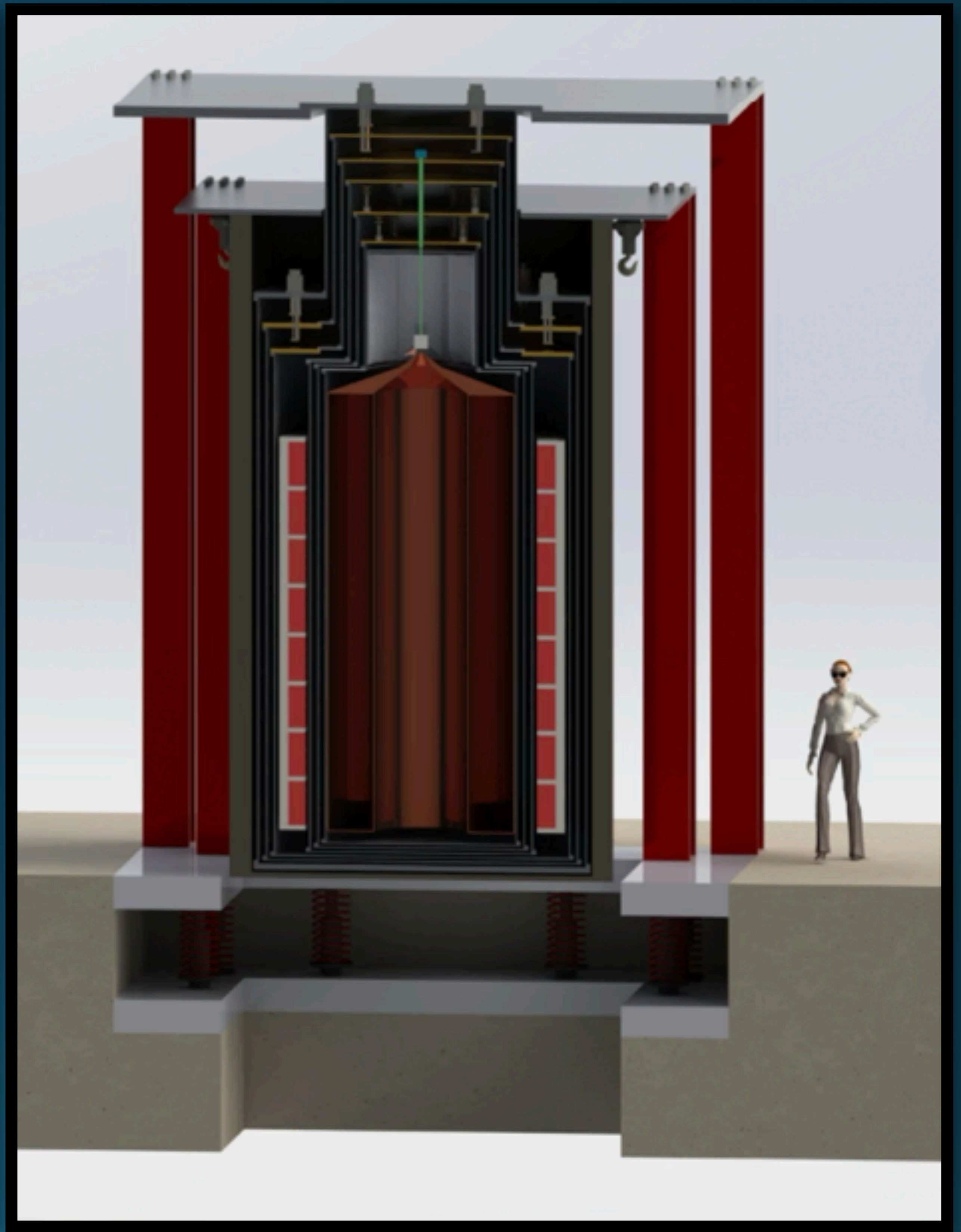
ABRA-10cm



DMRadio-50L



DMRadio-m^3

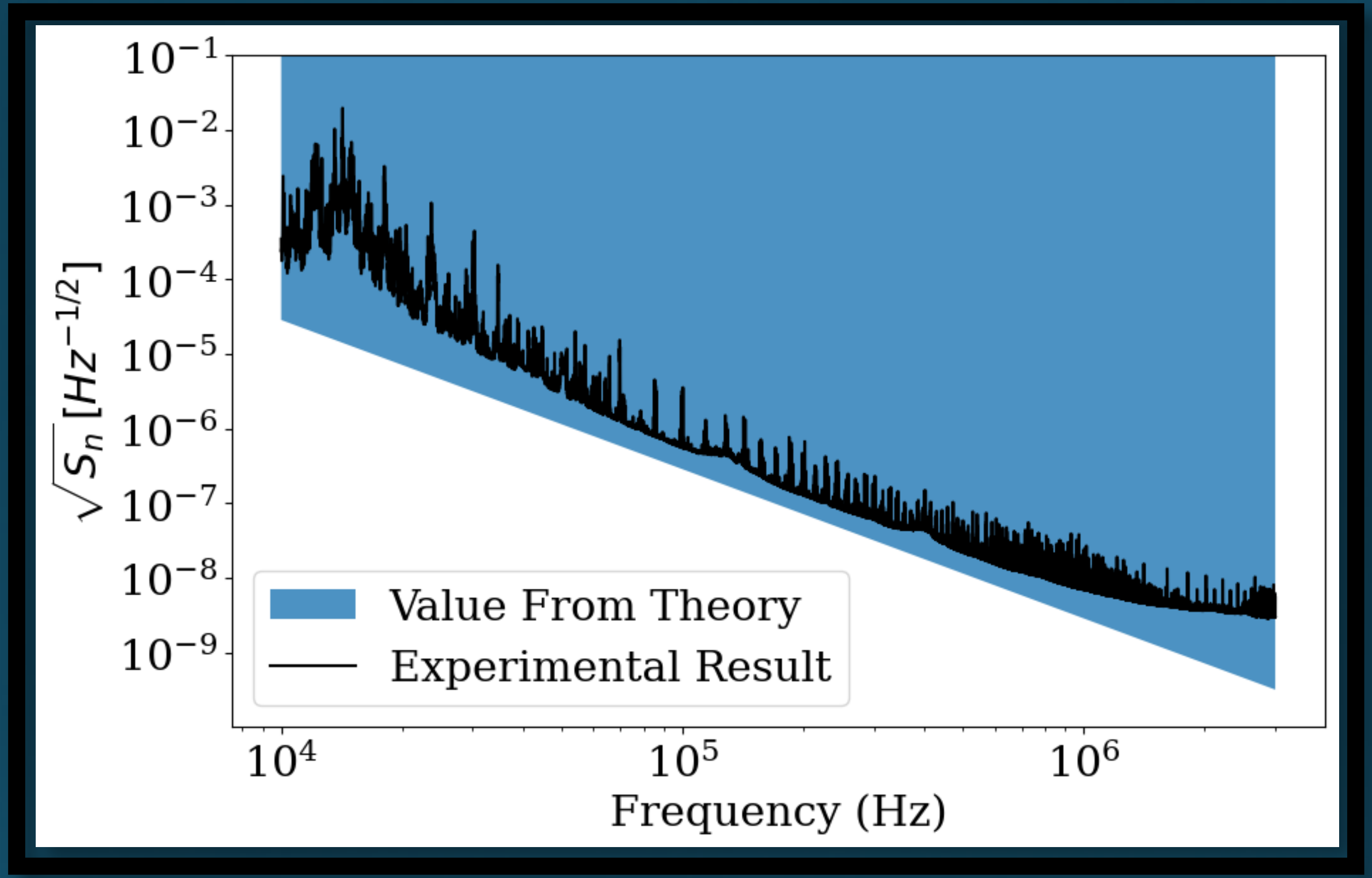


DMRadio-GUT

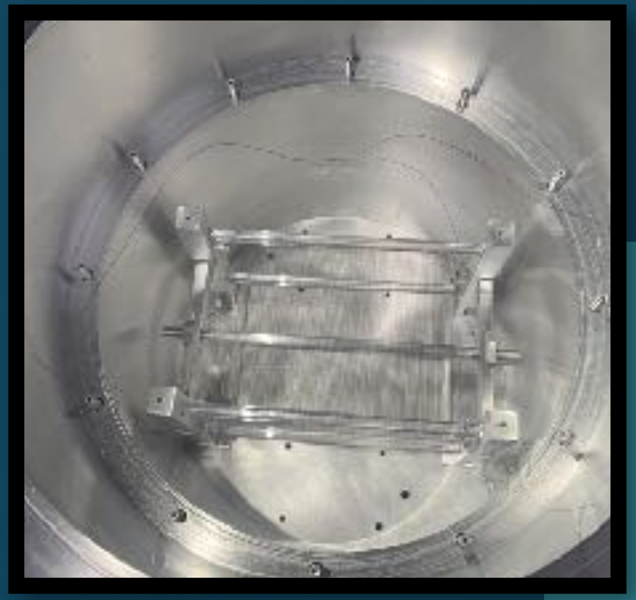
More lumped-element detection

DMRadio-50L
construction underway now

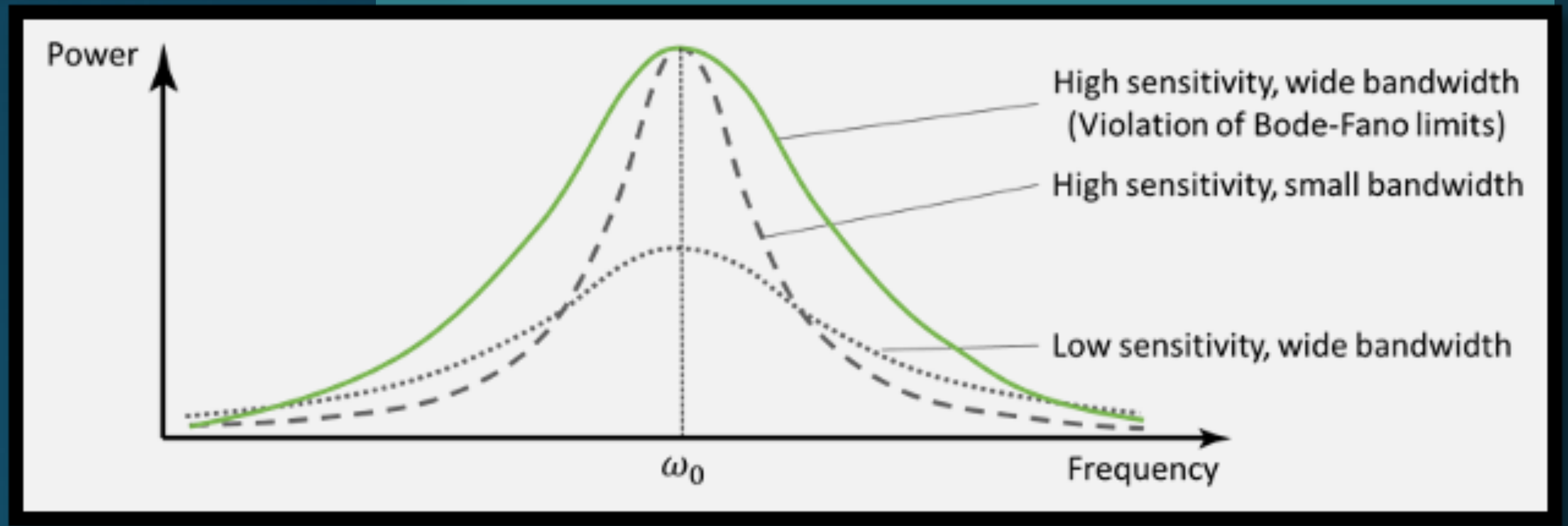
First gravitational wave results
from ABRA-10cm

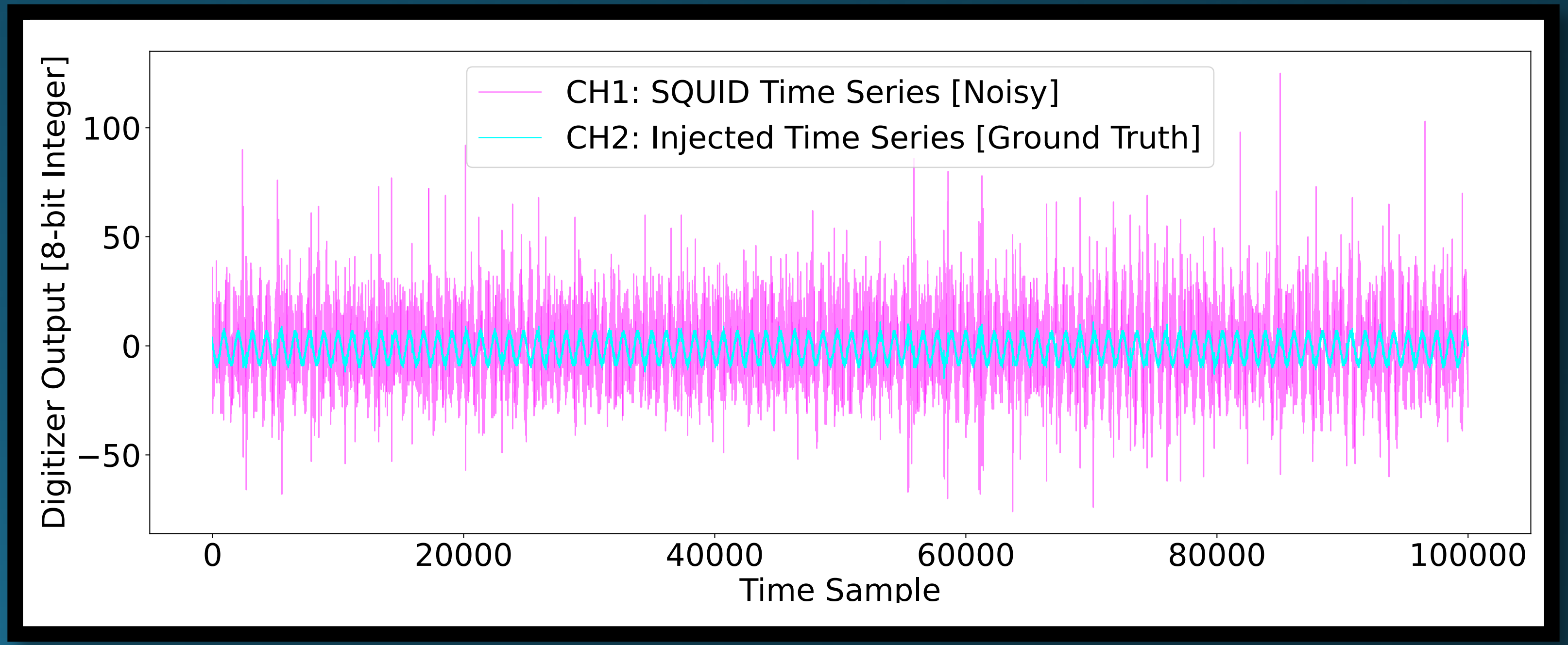


arxiv:2505.0282
1



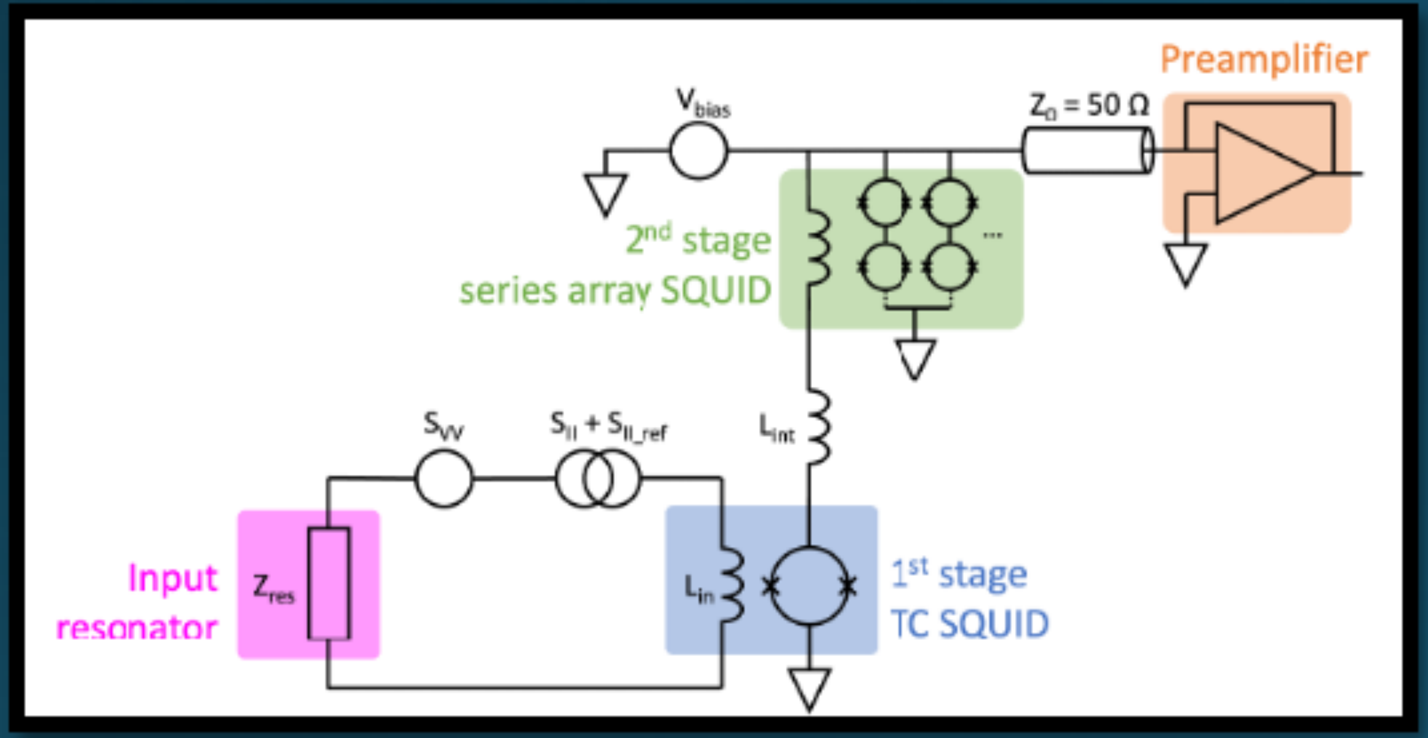
Resonant readout R&D:
- High Q passive resonators
- Beyond Bode-Fano



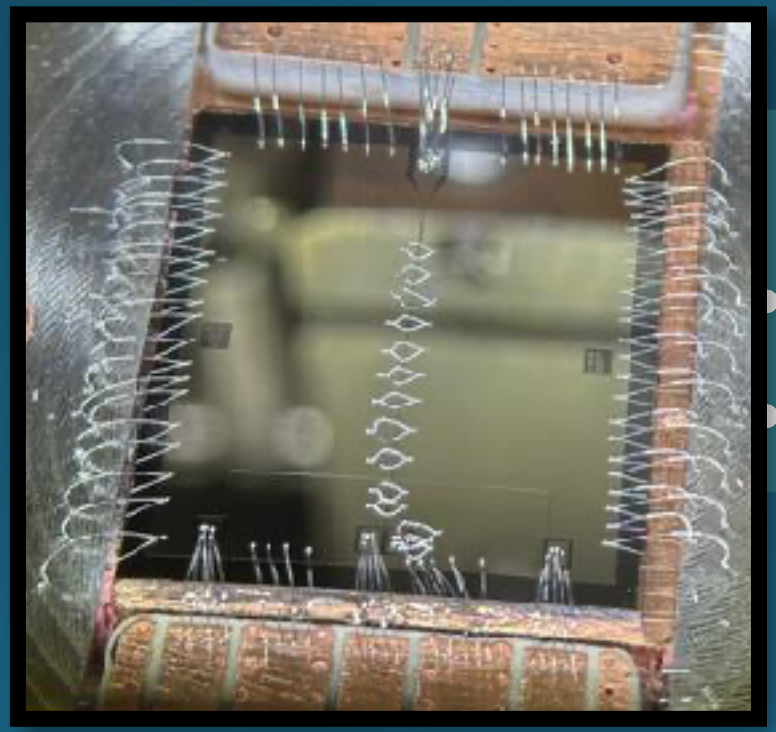


arxiv:2406.04378

ML-based denoising



arxiv:2504.2039
8

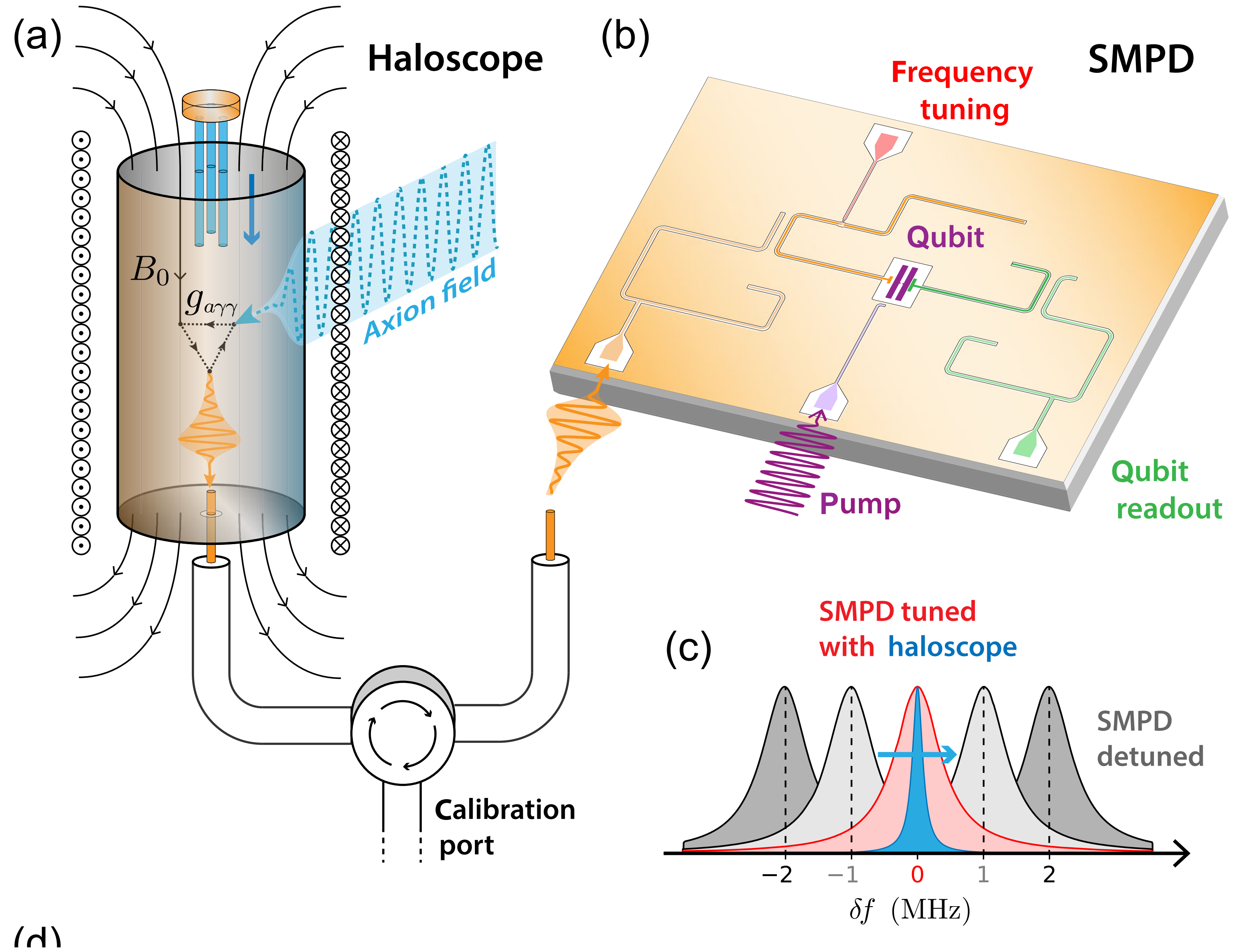


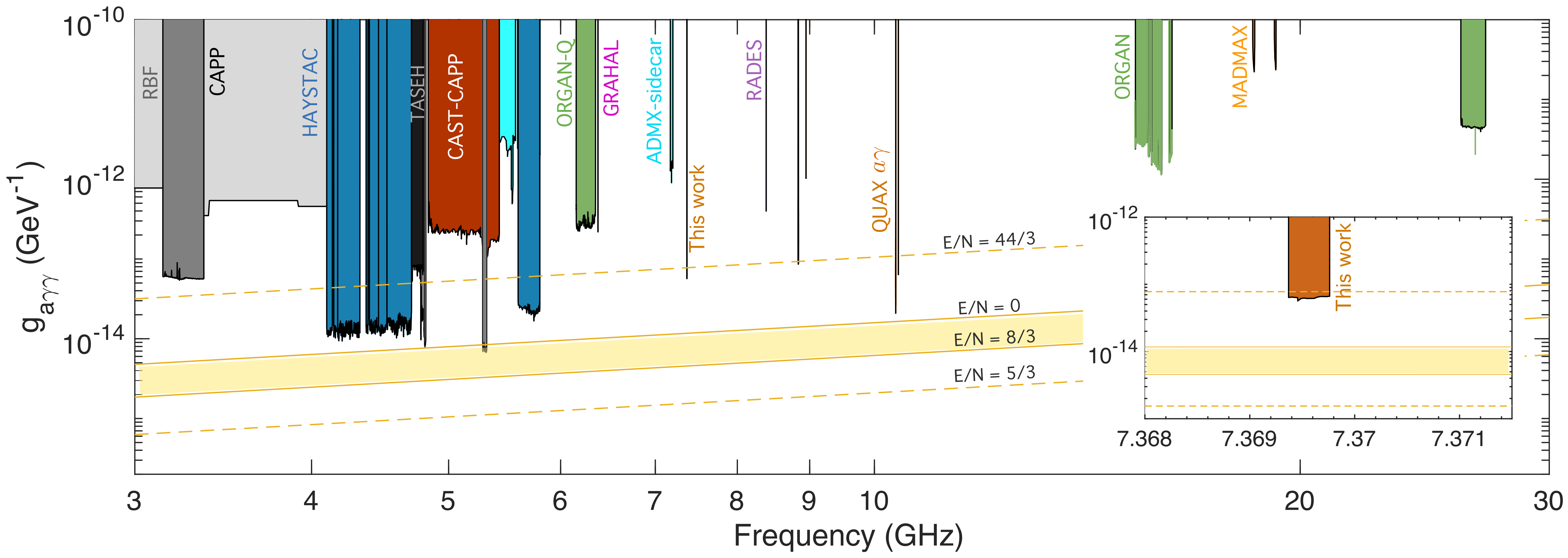
Sensor R&D:
- Optimal SQUID chain
- SQL-beating RQUs

arxiv:2210.0557
6

QUAX Experiment

- **Look for an axion "wind"** which acts as an **effective RF magnetic field on electron spin** via **electron-axion coupling**
- This axion induced RF excites **magnetic transition in a magnetized sample** (Larmor frequency) and produces a detectable signal

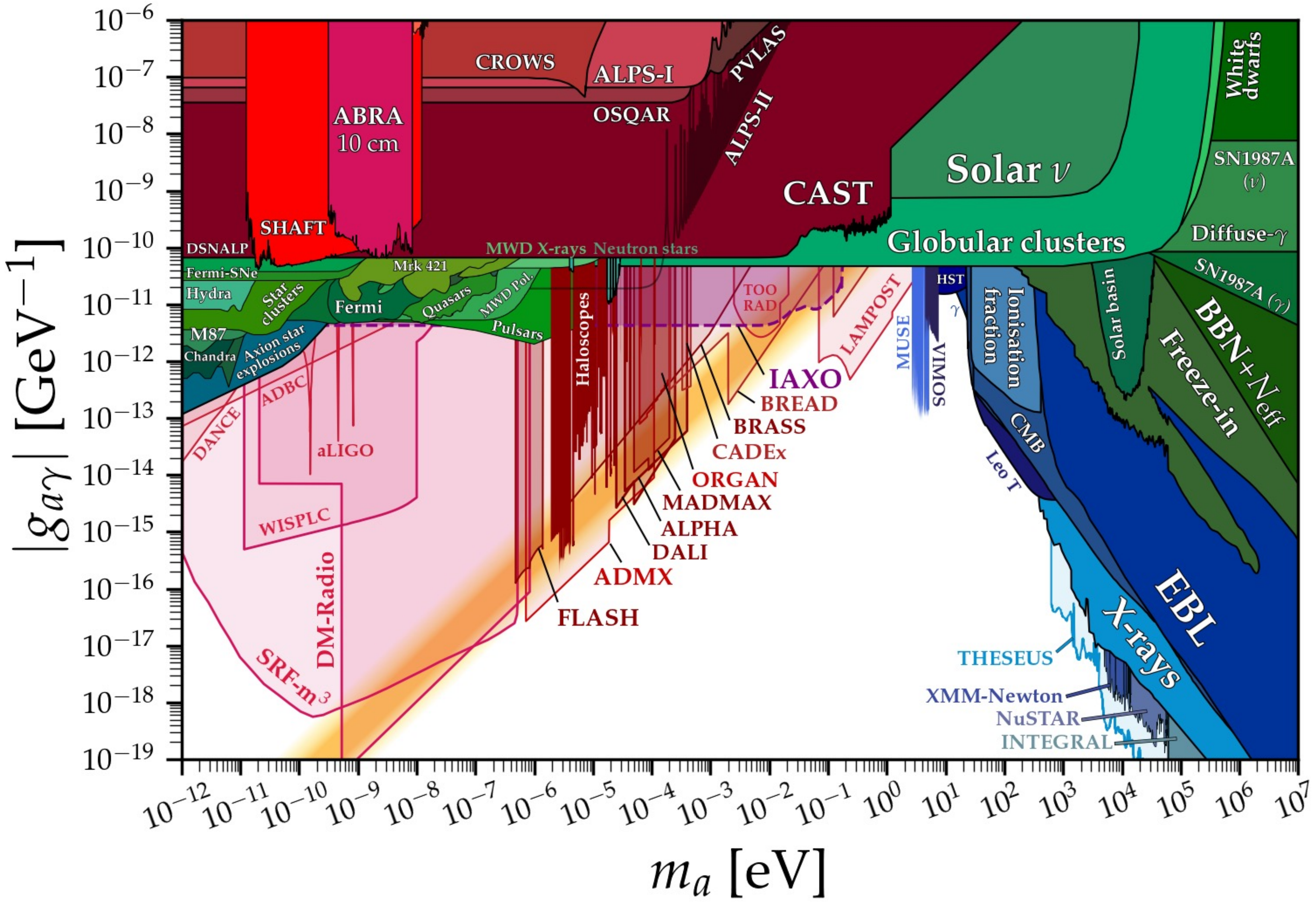




Crescini et al., Phys. Rev. Lett. 124, 171801 (2020)
Braggio et al, Phys. Rev. X 15, 021031 (2025)

Summary & Outlook

- Axions are a great dark matter candidate and solve the strong-CP problem
- Exciting developments - so much I did not cover!
- New experiments, new technologies, new ideas, new people
  - Cavities, quantum sensors, magnets, …
- Potential for discovery in the next decade.
- Discussions this afternoon



Special thanks to everyone who provided slides