

Review of Experimental Axion Searches
IDM XVI – 30th Anniversary
Zaragoza

Karl van Bibber
UC Berkeley
3 June 2026

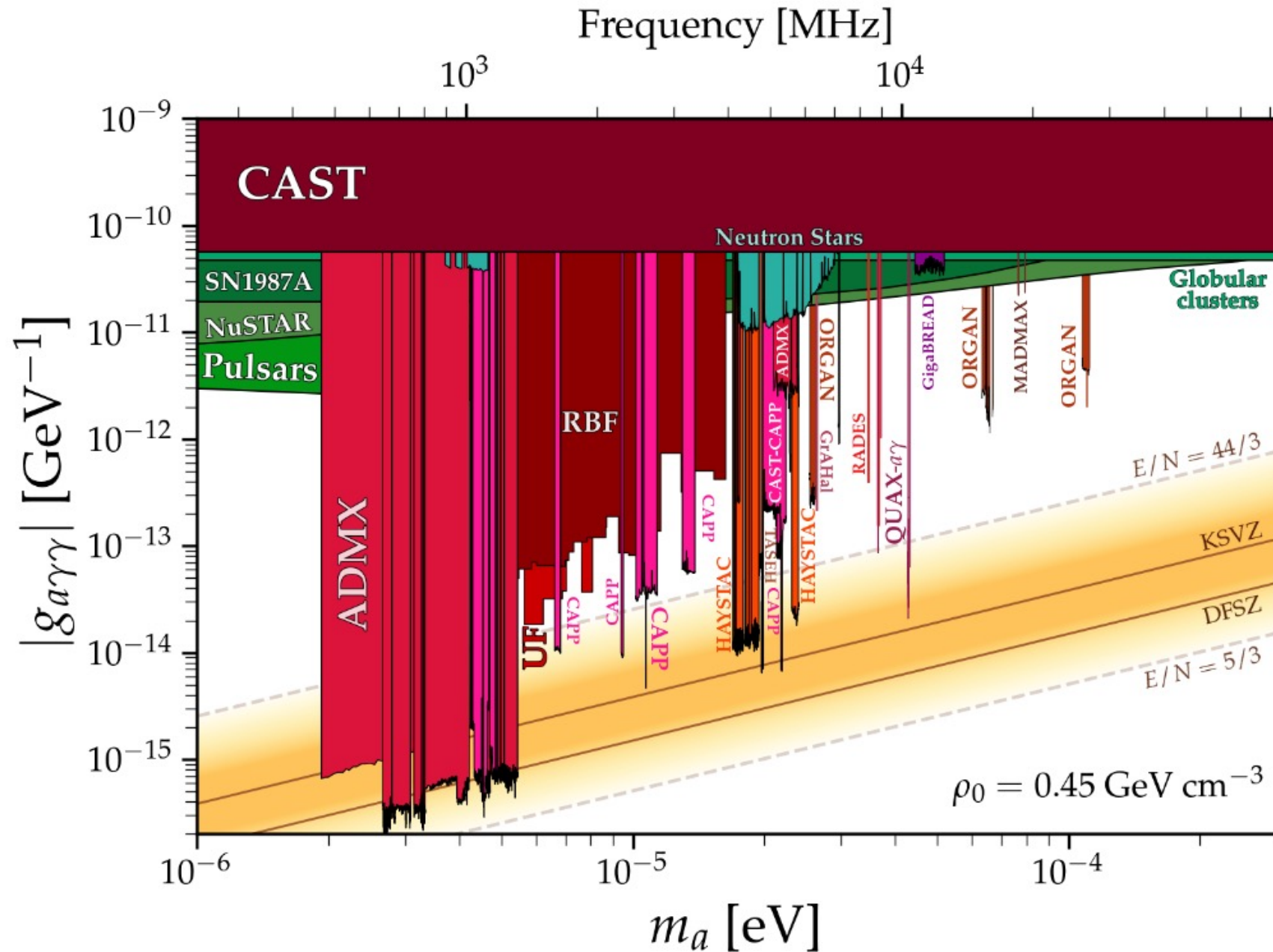
Outline

- Axion landscape
- Dark Matter searches
- Astrophysical searches
- Laboratory experiments
- And when the axion is found
- Summary thoughts

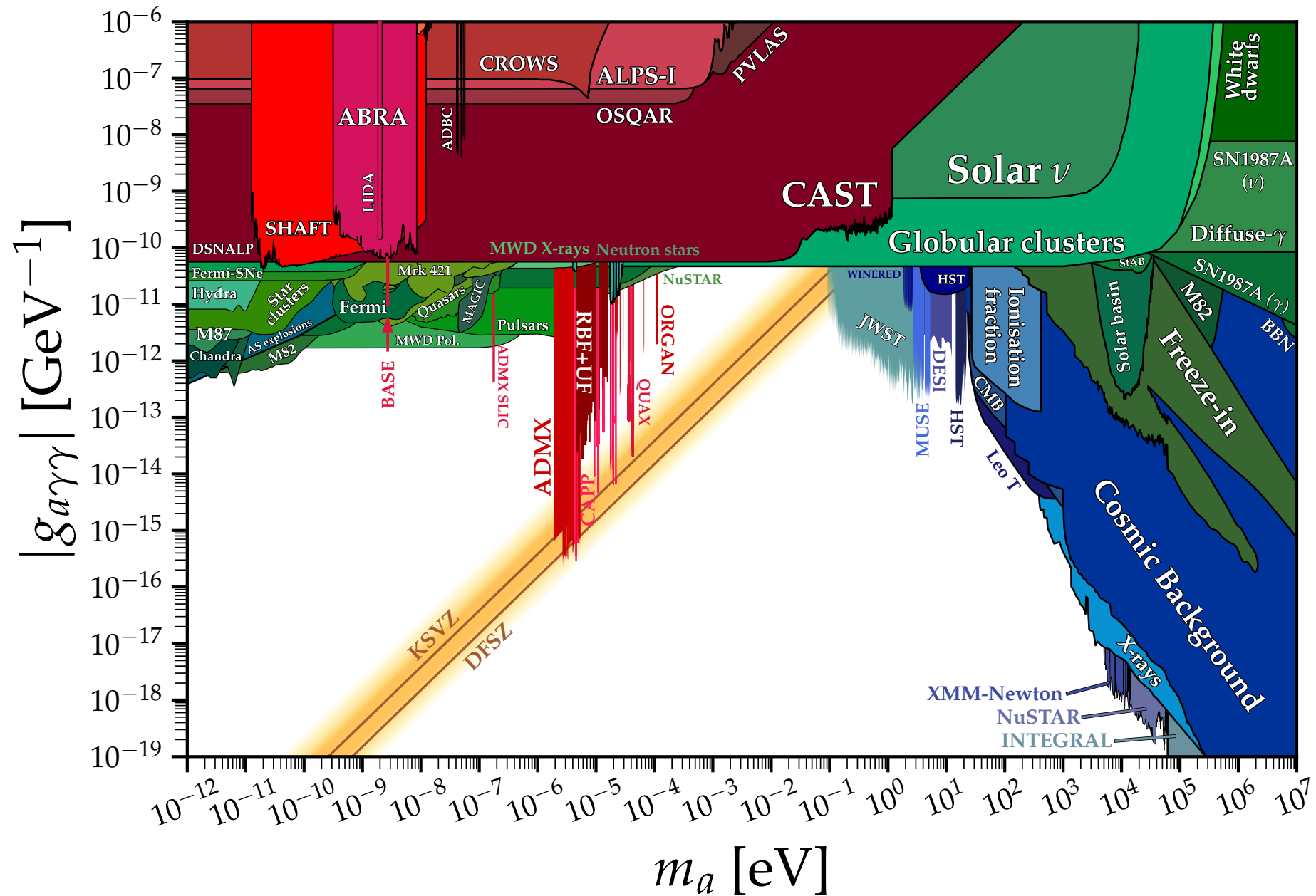
Apologies in advance! The brief time allocated required great selectivity in topics.

Much has been done!

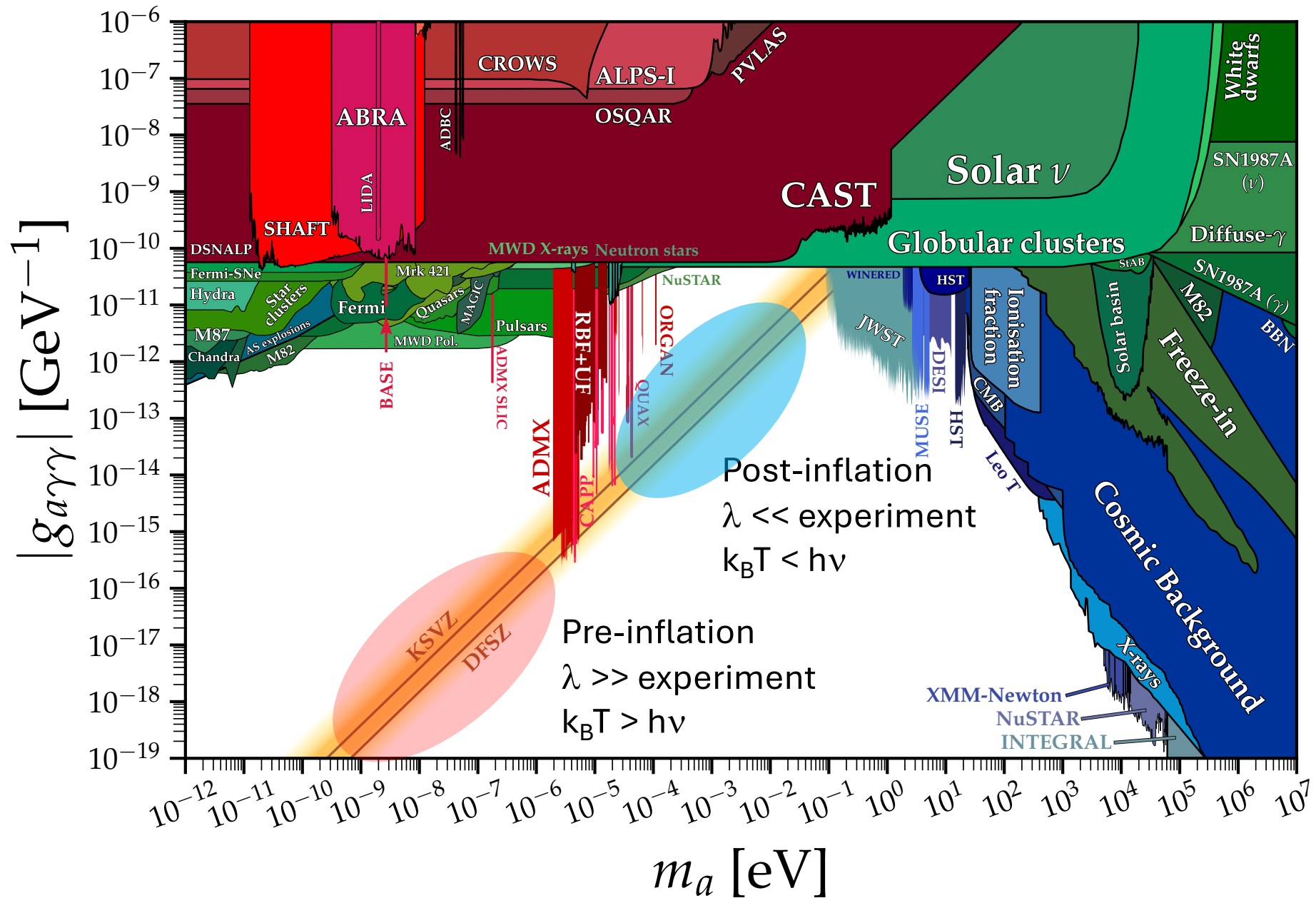
From Ciaran O'Hare, Axion Limits, <https://github.com/cajohare>



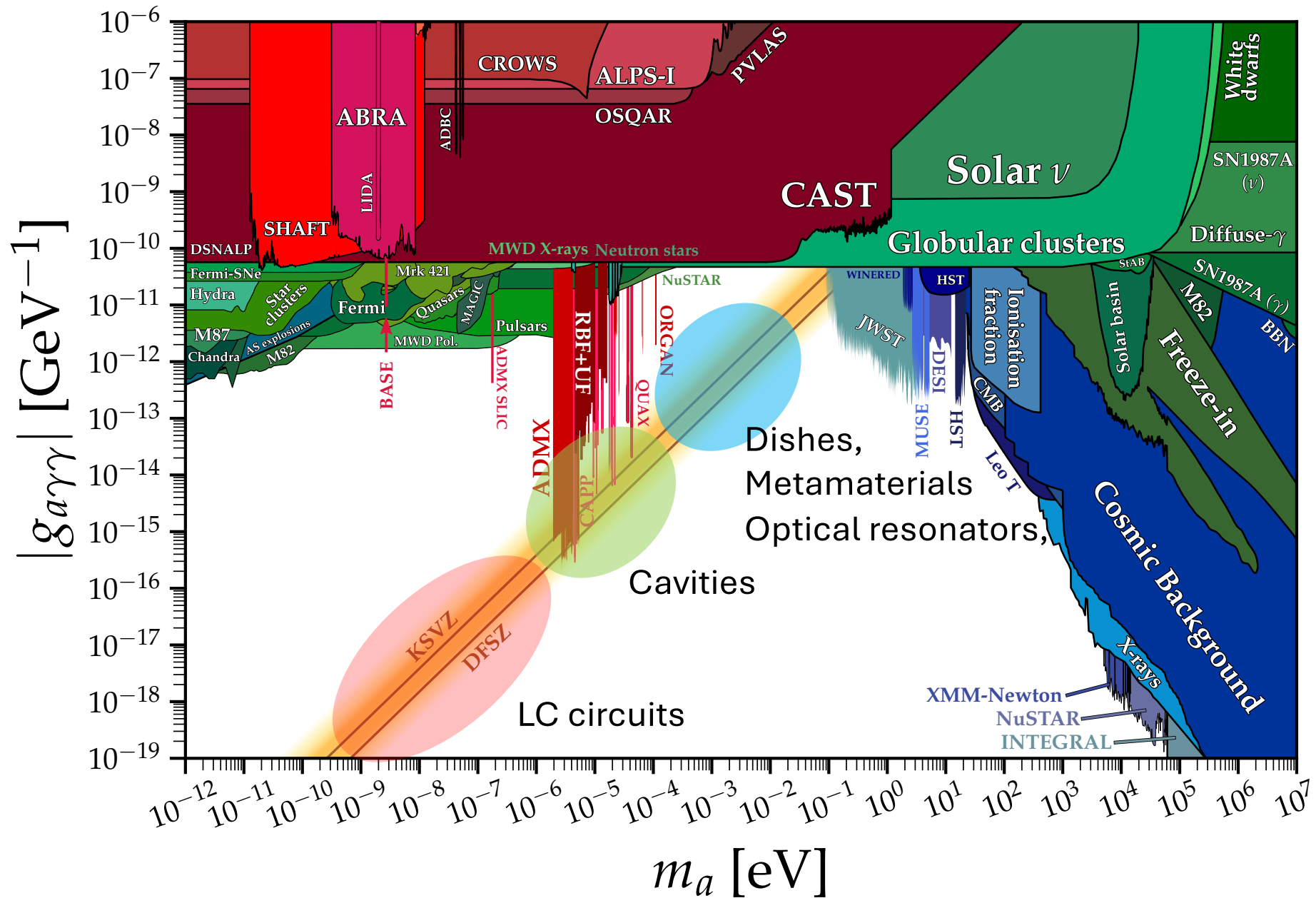
But after 40 years of experiments, we've hardly begun ...



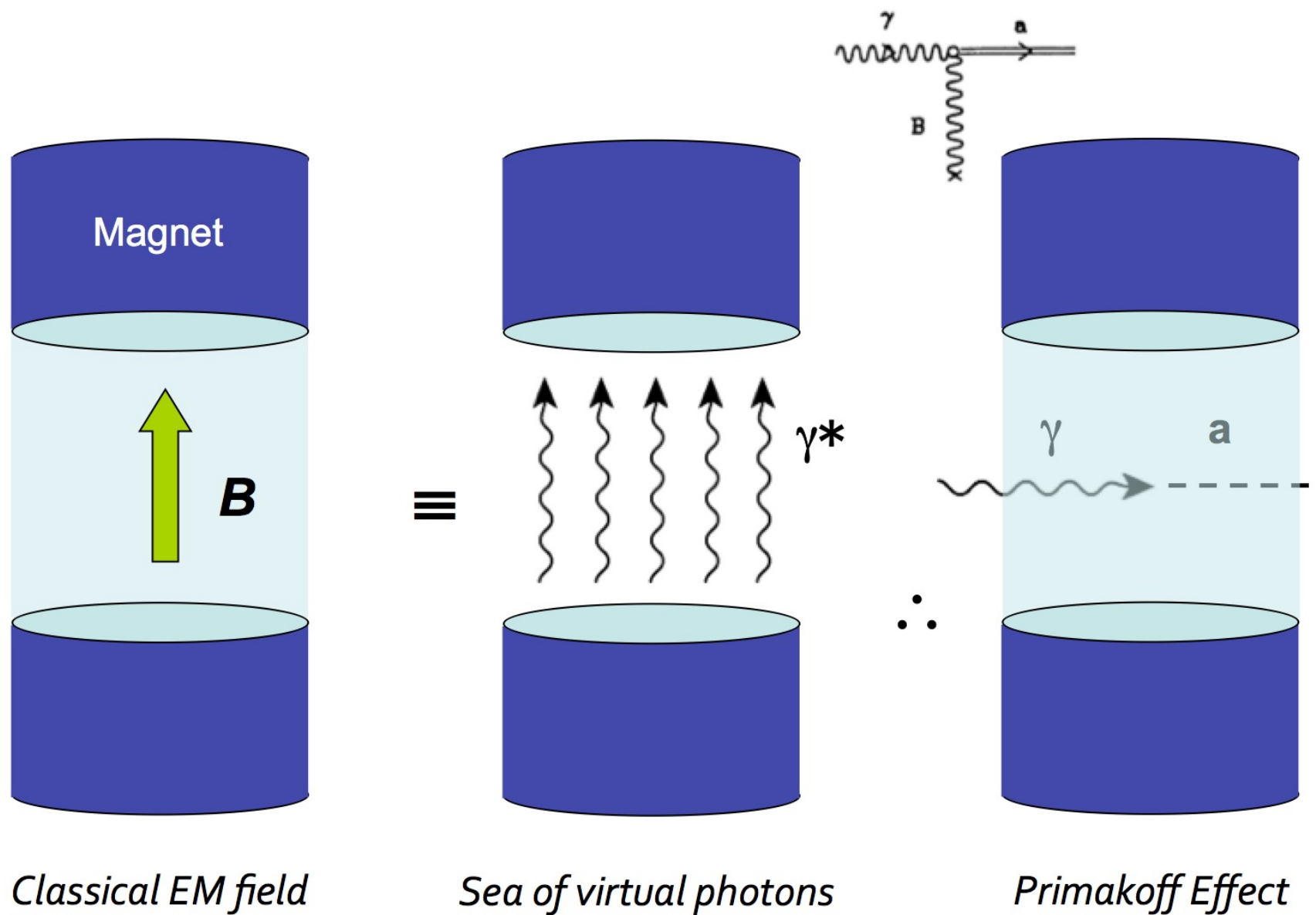
The QCD axion bifurcates cosmologically with implications for instrumentation



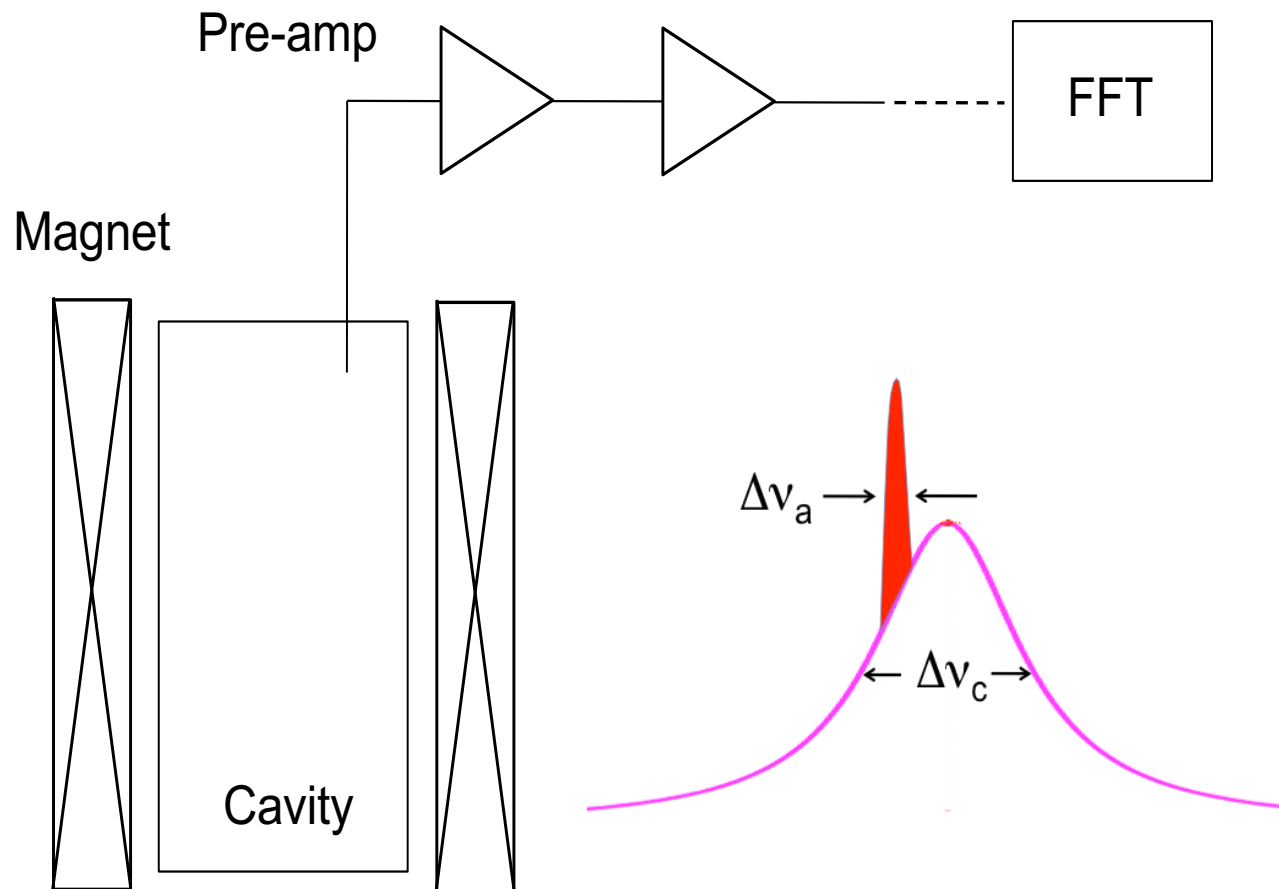
In particular, new resonator paradigms required



The Primakoff Effect redux *P. Sikivie, Phys. Rev. Lett. 51 (1983) 1415*



Rudiments of axion haloscopes



Dicke radiometer equation:

$$SNR = \frac{P}{k_B T_{SYS}} \sqrt{\frac{t}{\Delta\nu_a}}$$

$$P(a \rightarrow \gamma) \propto (B^2 V Q C) \left(g_\gamma^2 \frac{\rho_a}{m_a} \right)$$

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

T Physical temperature

T_A Amplifier noise temperature

t Integration time

The Standard Quantum Limit
for Linear Amplifiers

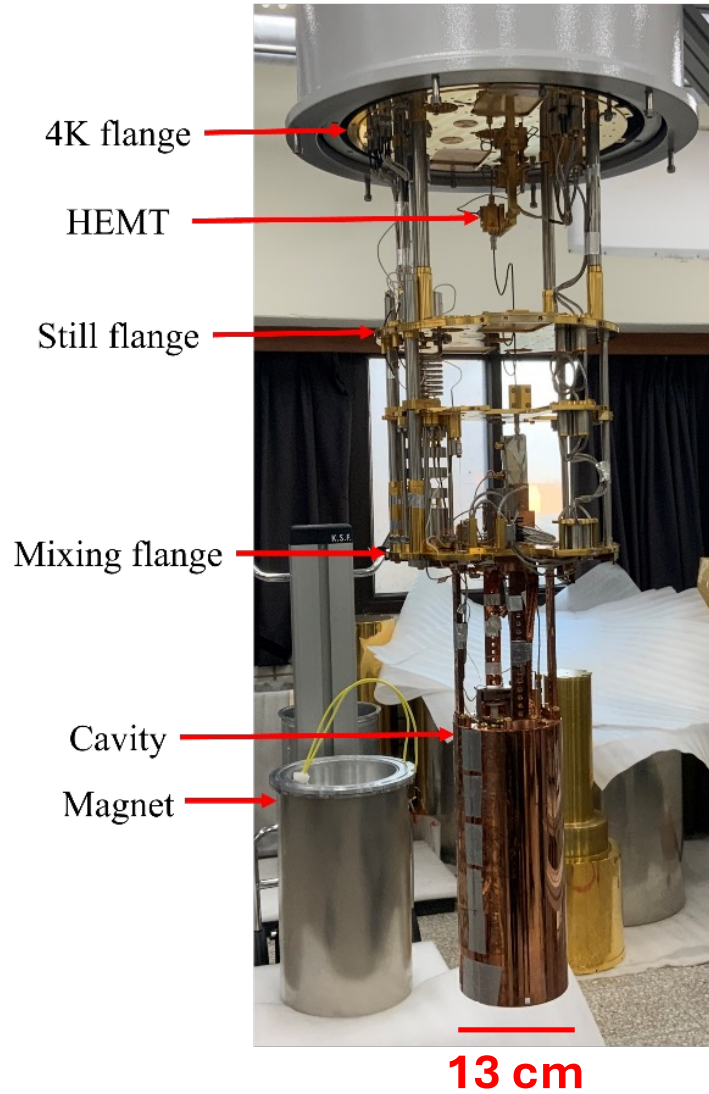
$$T_A > T_{SQL}$$

where

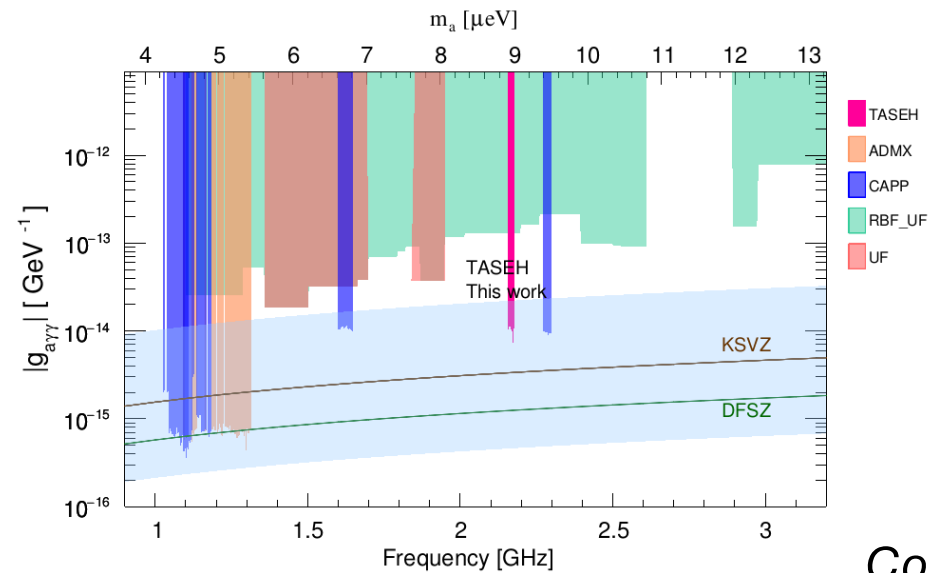
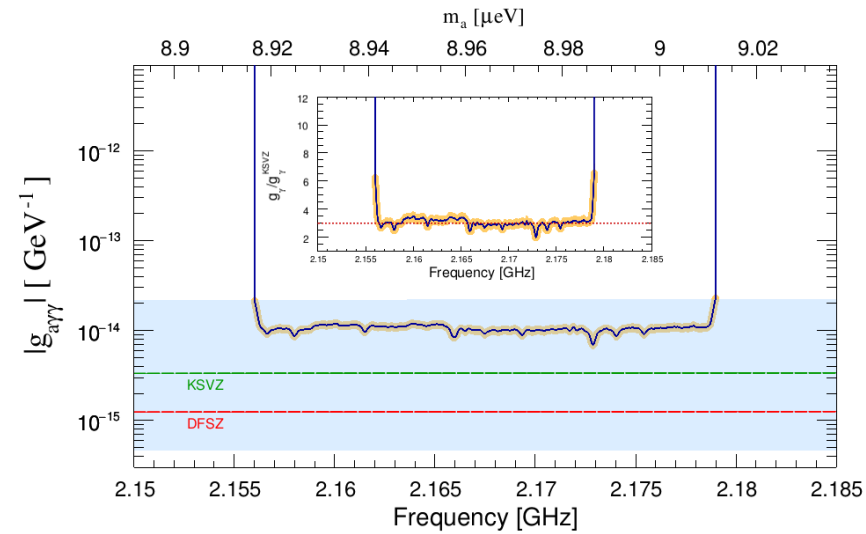
$$k_B T_{SQL} = h\nu$$

$$FOM \propto \frac{B^4 V^2 C^2 Q}{T_{SYS}}$$

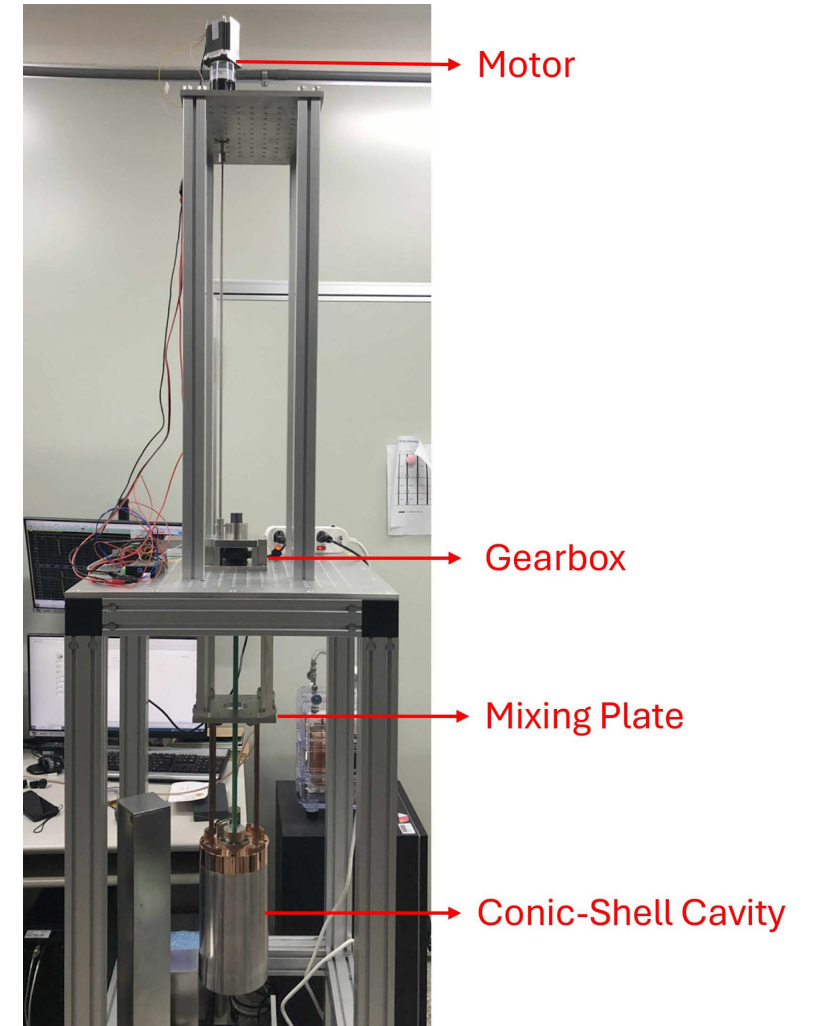
Welcome TASEH – Taiwanese Axion Search Haloscope



12/25 run: 6 T, 4 L cavity, JPA

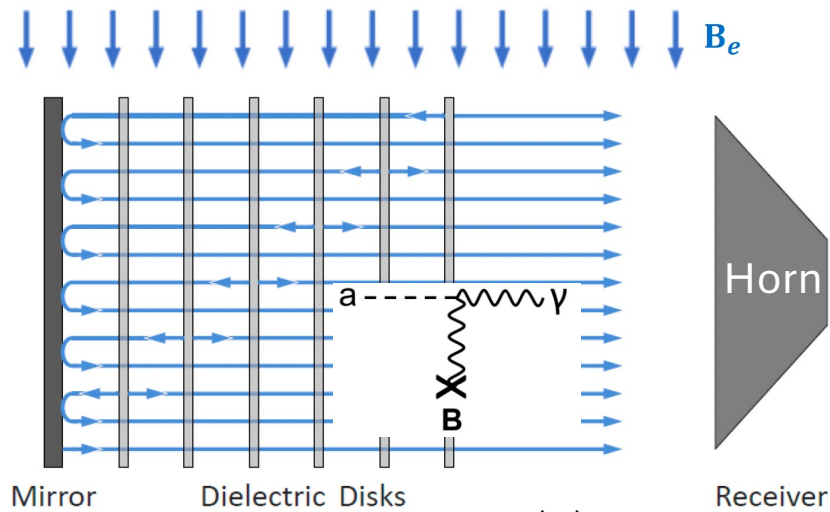


~ x3 KSVZ

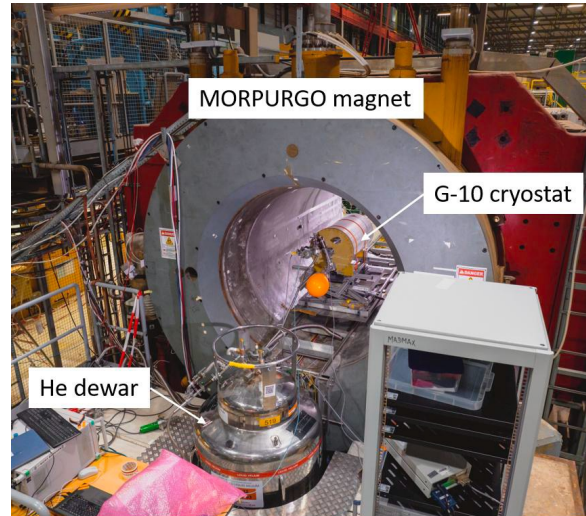


Coming soon: Conical shell cavity & multiple cavities

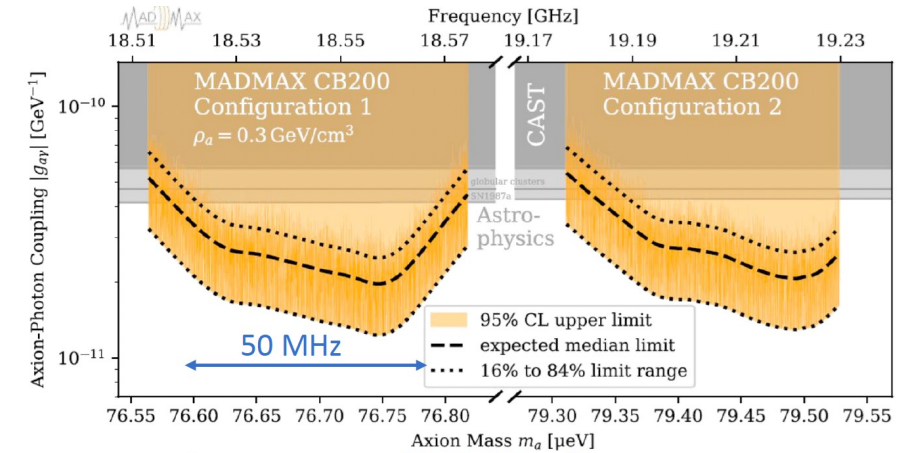
MADMAX (MAGnetized Disc and Mirror Axion eXperiment) see *talk of Bela Majorovits*



- Discontinuity radiation
- β^2 is the boost factor
- $\Delta v/v \sim 10^{-2}$ “Goldilocks”



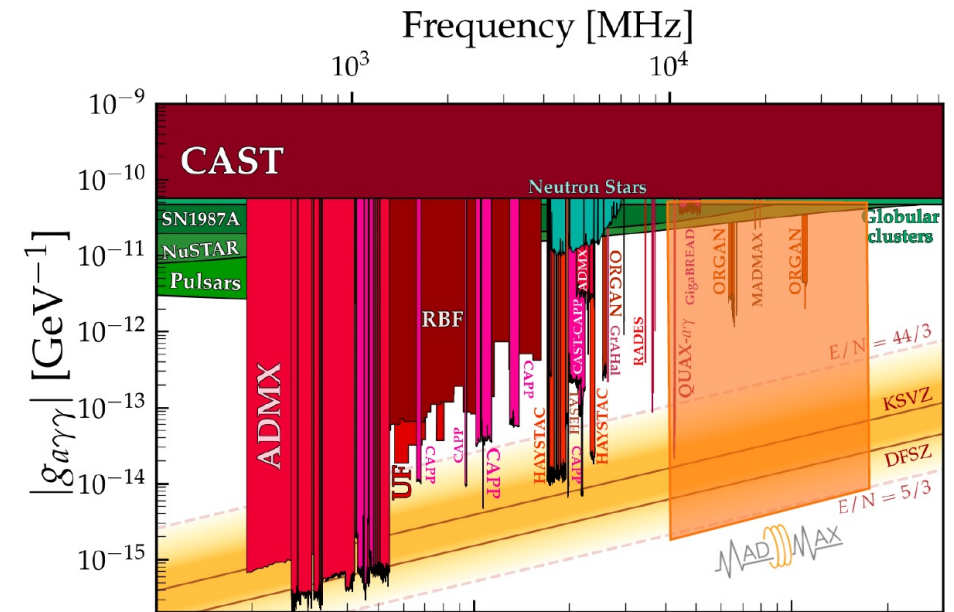
$$\left(\frac{P}{A}\right)_{\text{booster}} \approx 2 \cdot 10^{-27} \left(\frac{B_e}{10 \text{ T}}\right)^2 \beta^2 \frac{W}{m^2}$$



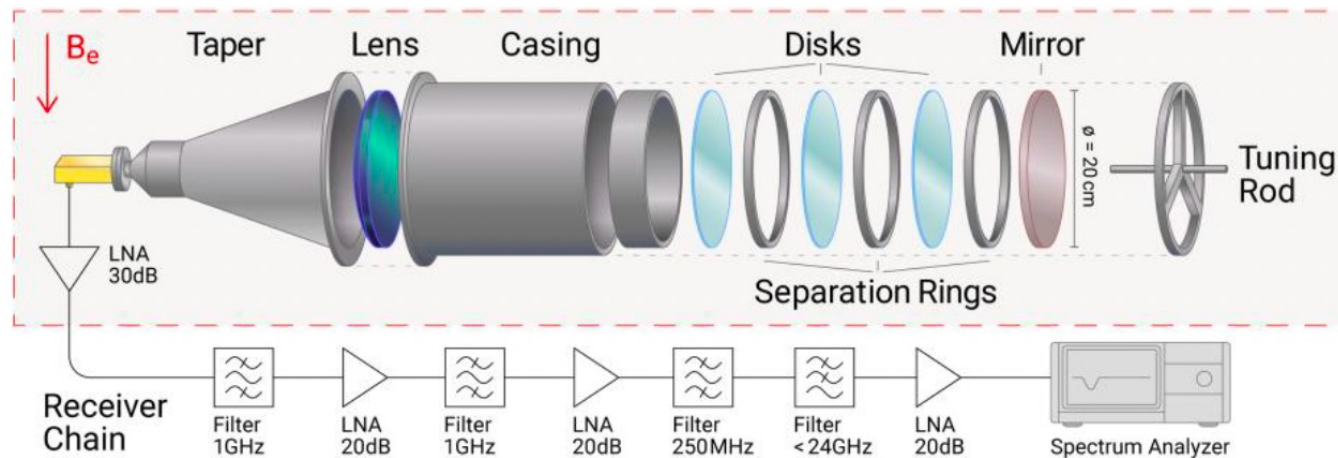
Assume $\rho_{DM} = 0.3 \text{ GeV}/\text{cm}^3$

B. Ary dos Santos Garcia et al., PRL (2025) 135 041001

J. Egge et al., PRL 134 (2024) 151004



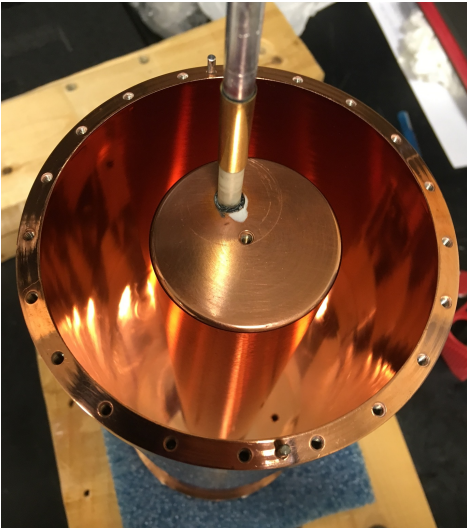
Projected with 4T, cryo, quantum (2031)



ALPHA – Axion Longitudinal Plasma Haloscope

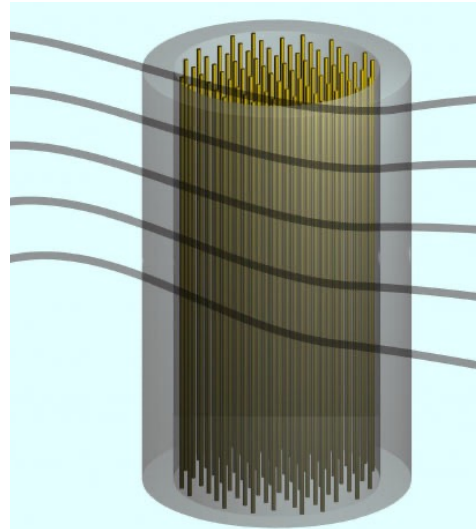
Concept: M. Lawson et al., PRL 123 (2019) 141802

Microwave Cavity

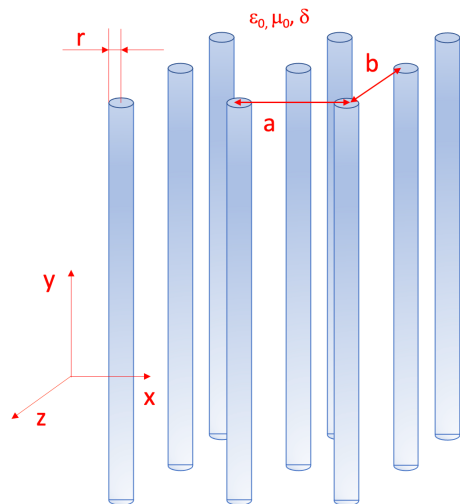


Frequency determined by boundary conditions (size)

Metamaterial Resonator



Frequency determined by bulk property (unit cell)



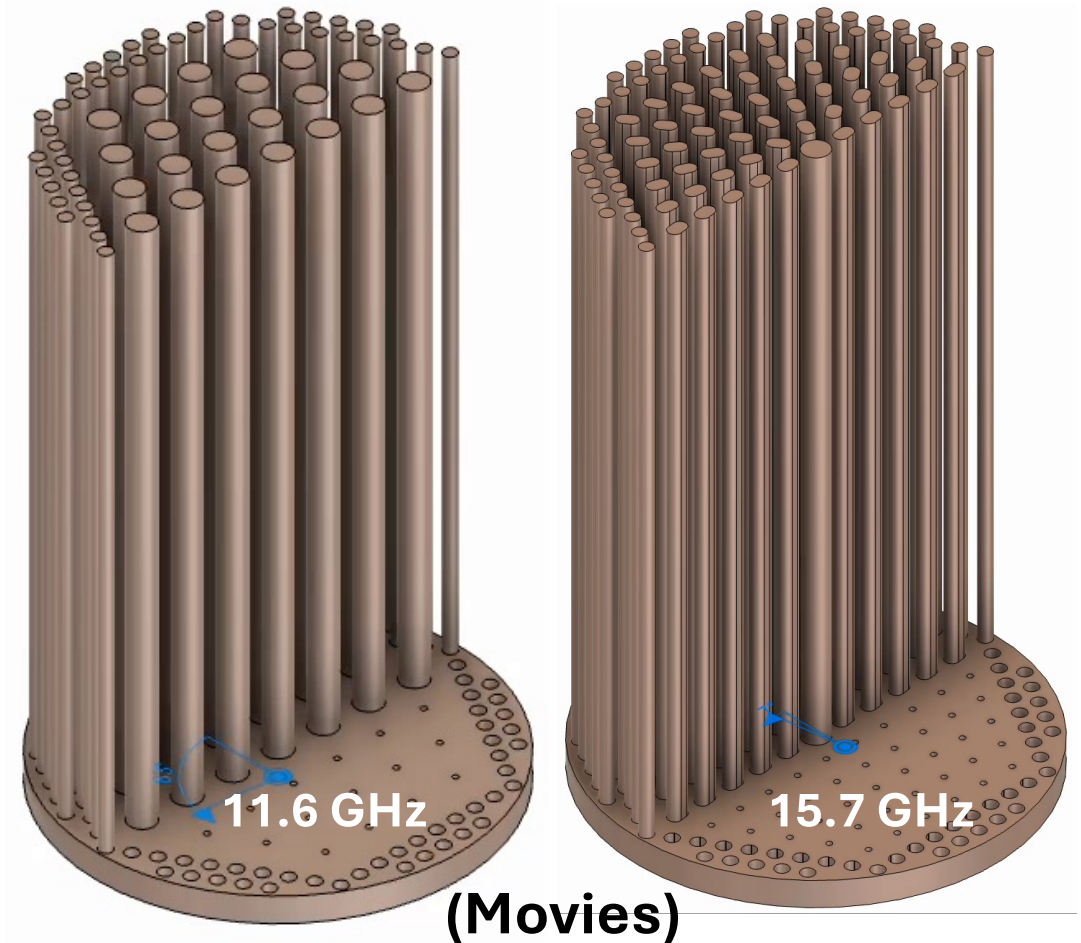
For square lattice of wires, radius r , spacing a :

$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{a^2 \log(a/r)}$$

$$r = 25 \mu\text{m}, a = 5 \text{ mm} \rightarrow \nu_{pl} = 10 \text{ GHz}$$

J.B. Pendry et al., J. Phys.:
Cond. Matt. 10 (1998) 4785

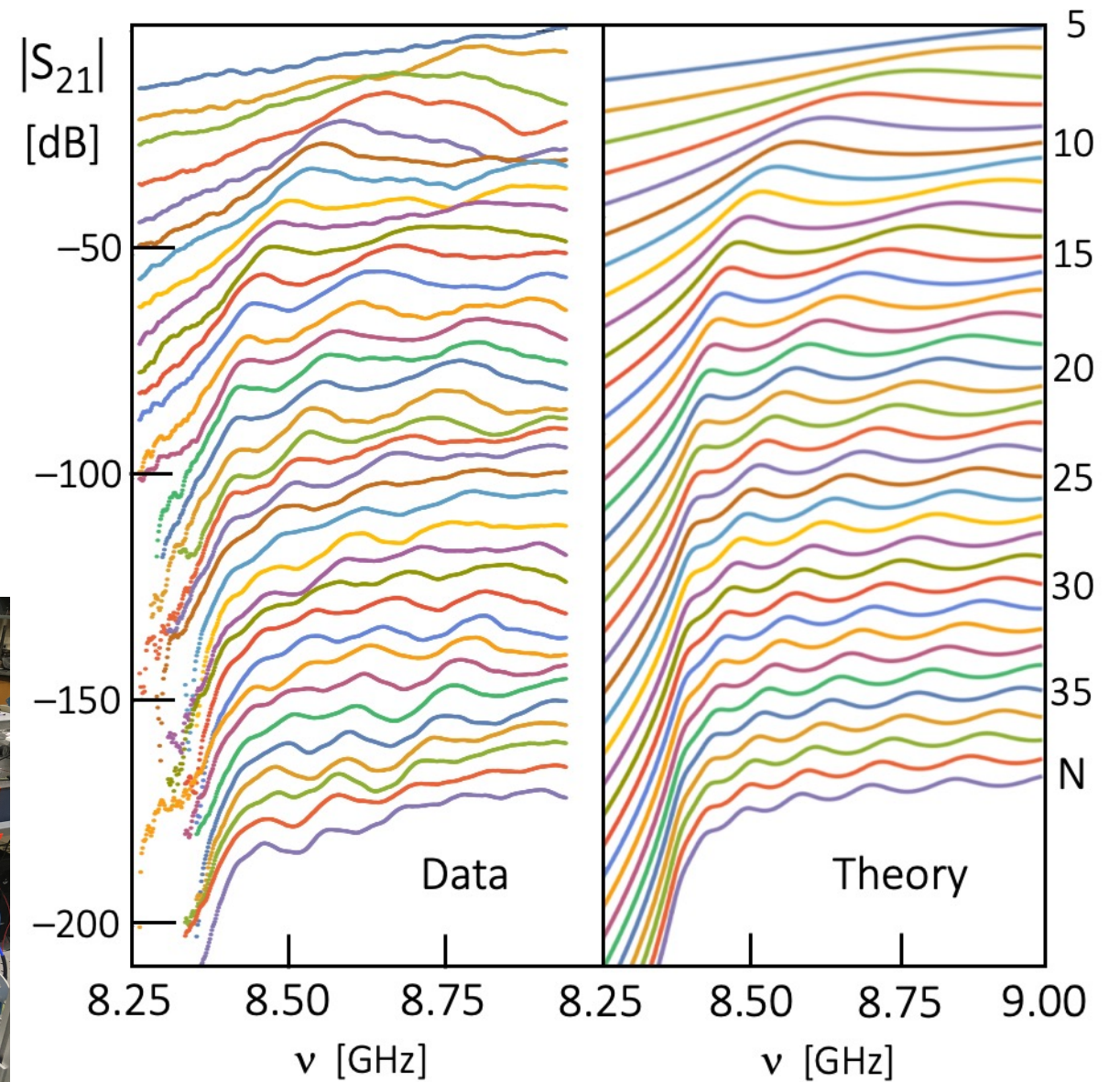
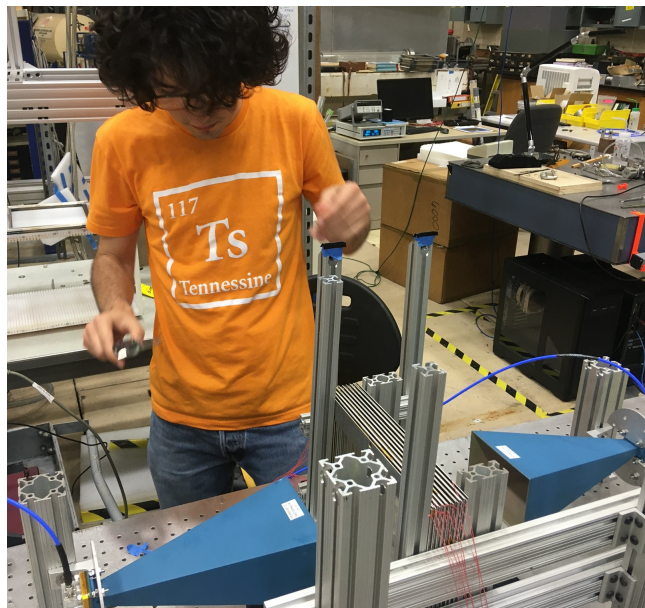
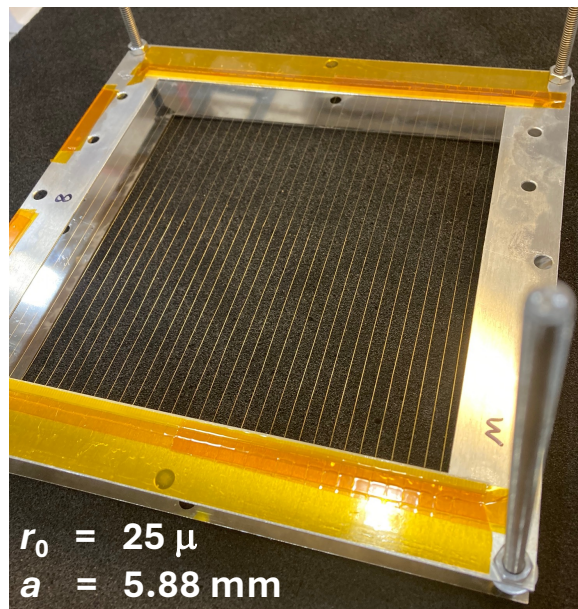
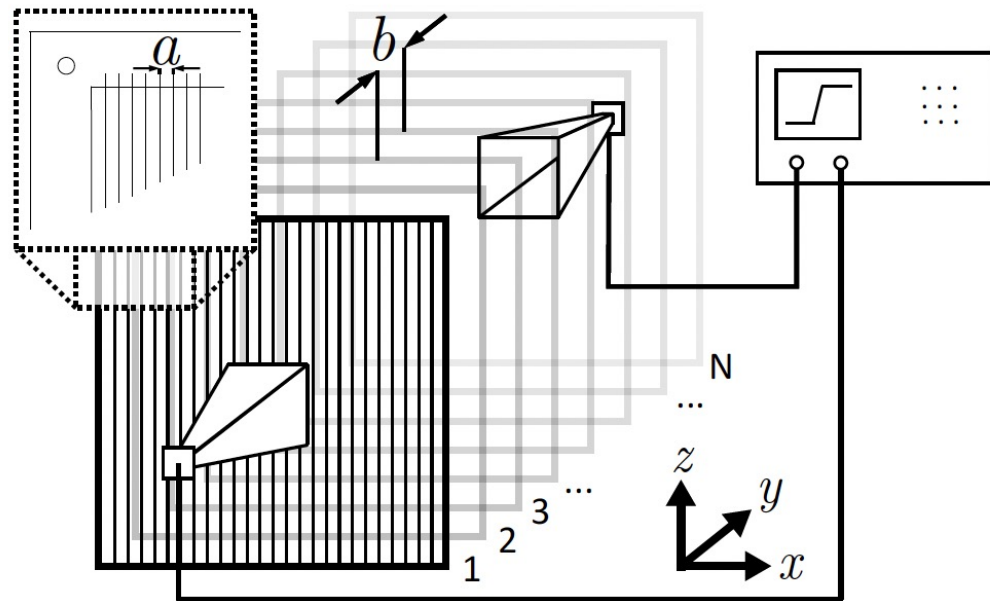
see talks by Samantha Lewis, Jianyang Qi



(Movies)

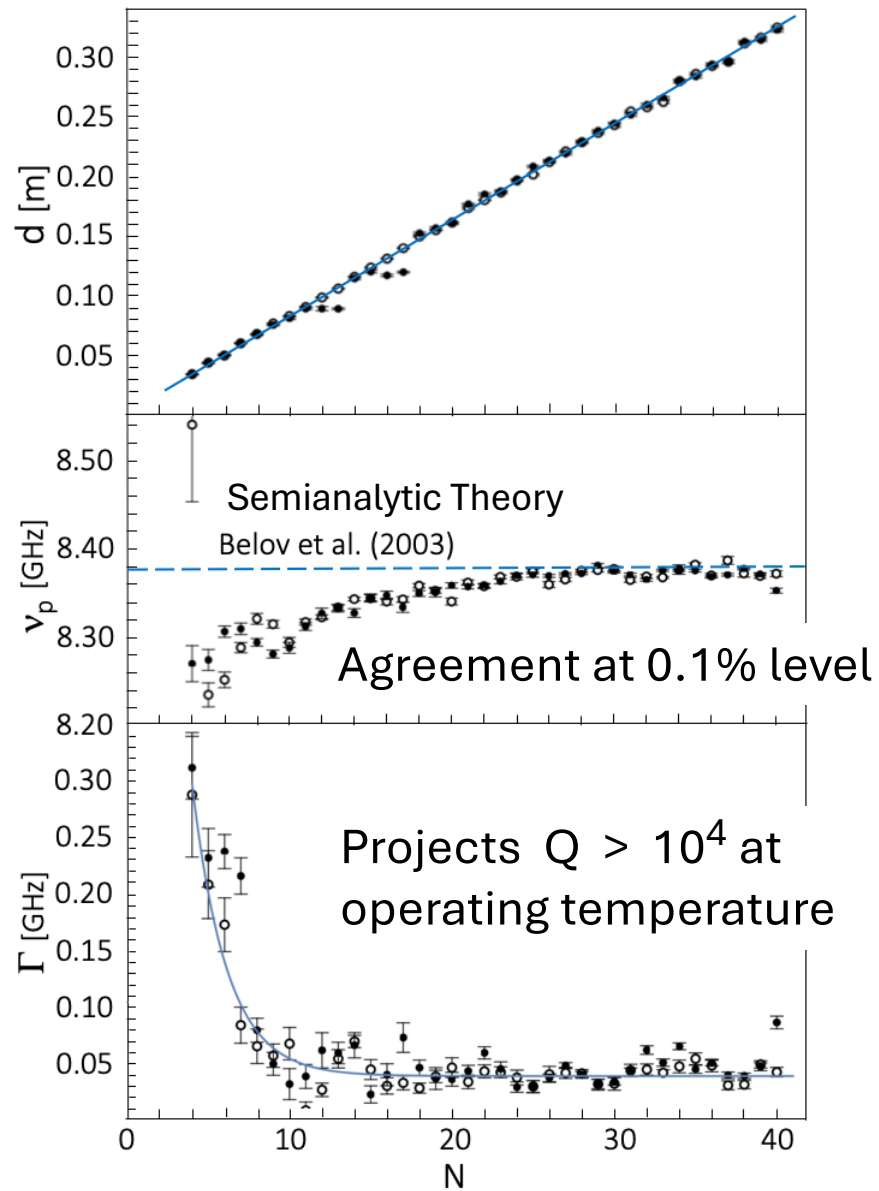
Under construction at Yale, 11 institutions
Phase I: 10-20 GHz, Phase II: 20-50 GHz
Commissioning 2027, Operation 2027-28

S_{21} measurements of wire array metamaterials



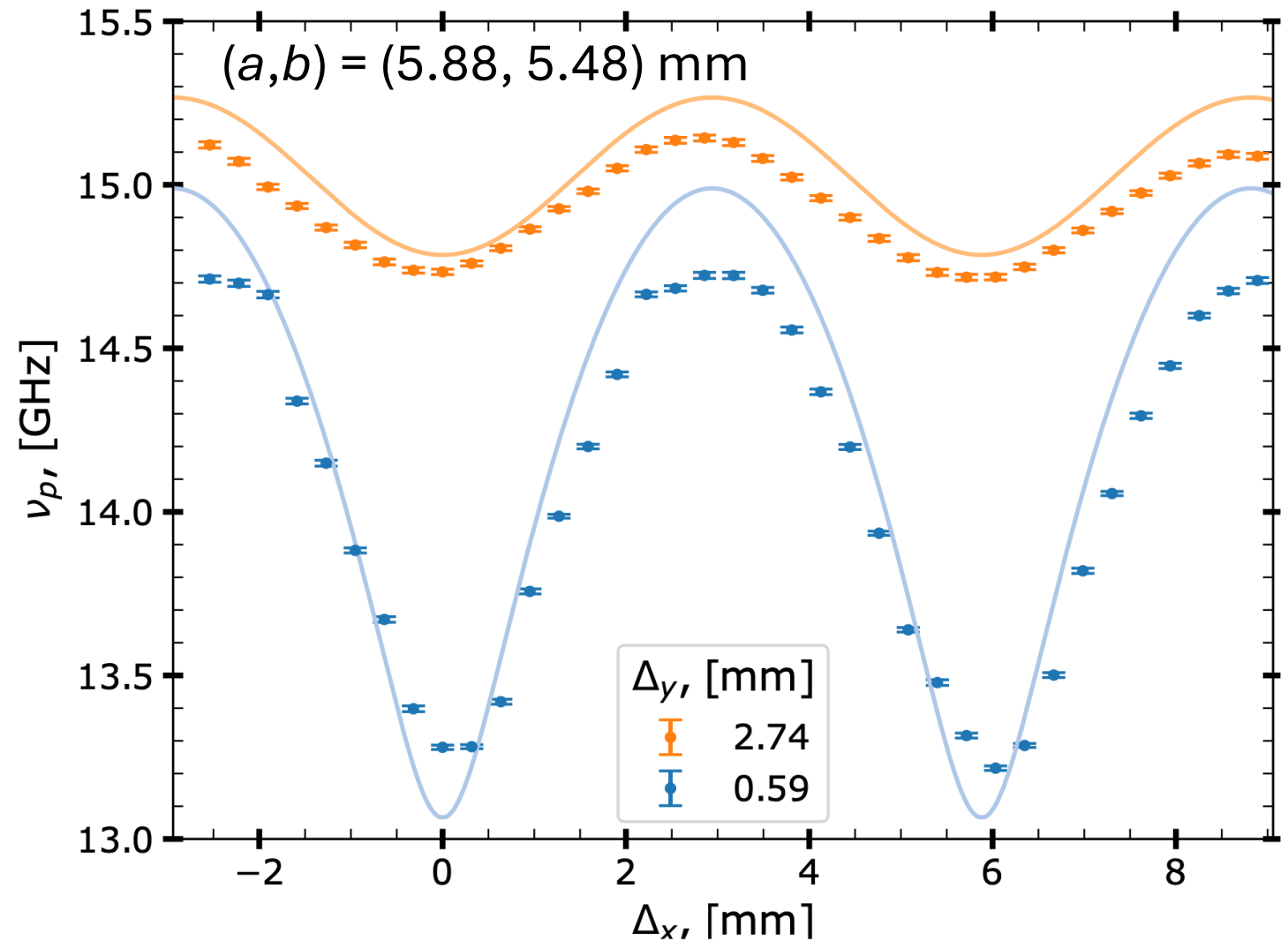
M. Wooten et al., Ann. Phys. (2023) 2200479

Metamaterial properties



M. Wooten et al., Ann. Phys. (2023)

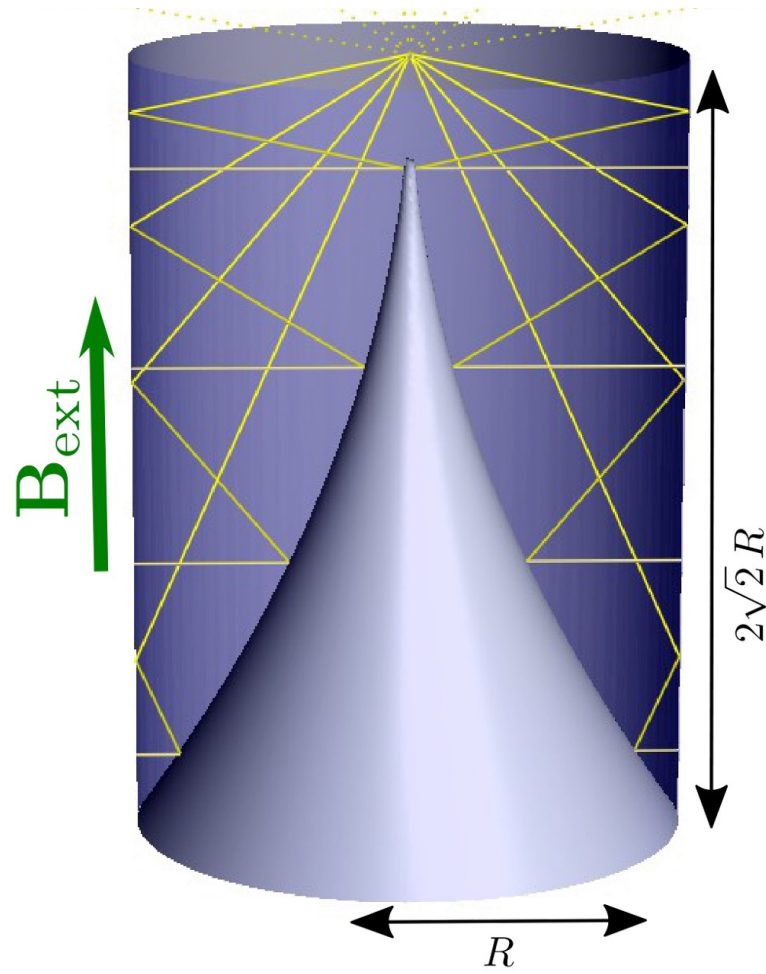
Plasma frequency dependence on unit cell



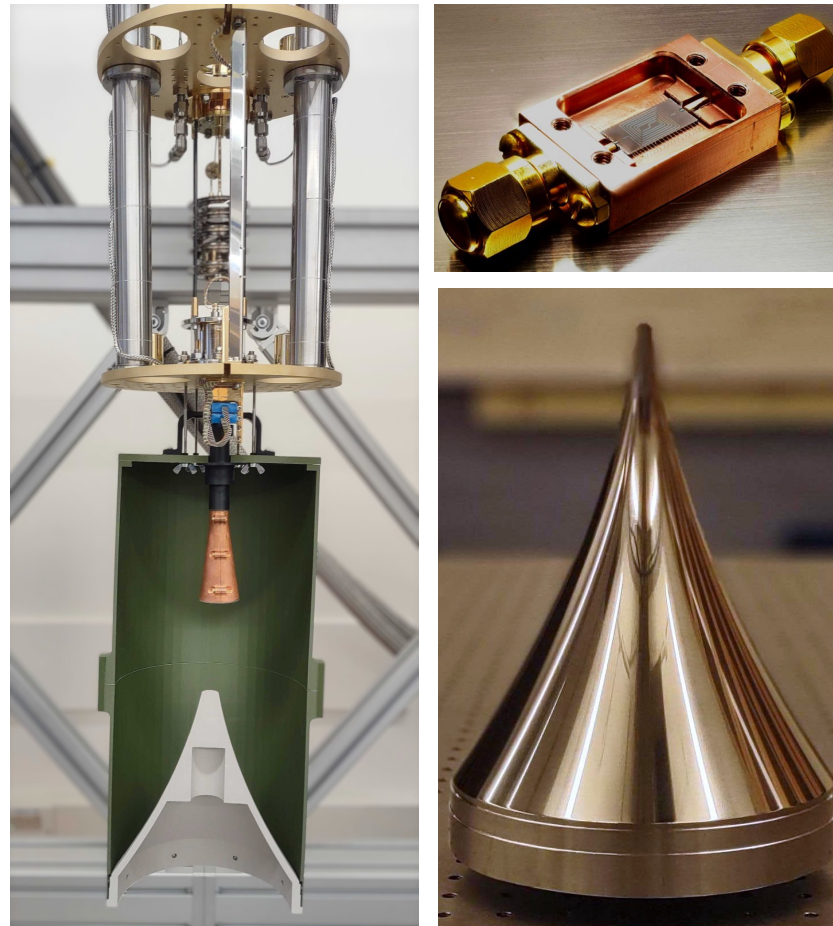
N. Kowitt et al., Phys. Rev. Appl. 20 (2023) 044051

BREAD: Broadband Reflector Experimental Axion Detector

- Highly flexible concept, adaptable to a wide array of configurations
- Will be a franchise of many experiments of different frequencies
- GigaBREAD, TeraBREAD, InfraBREAD, QualityBREAD ...

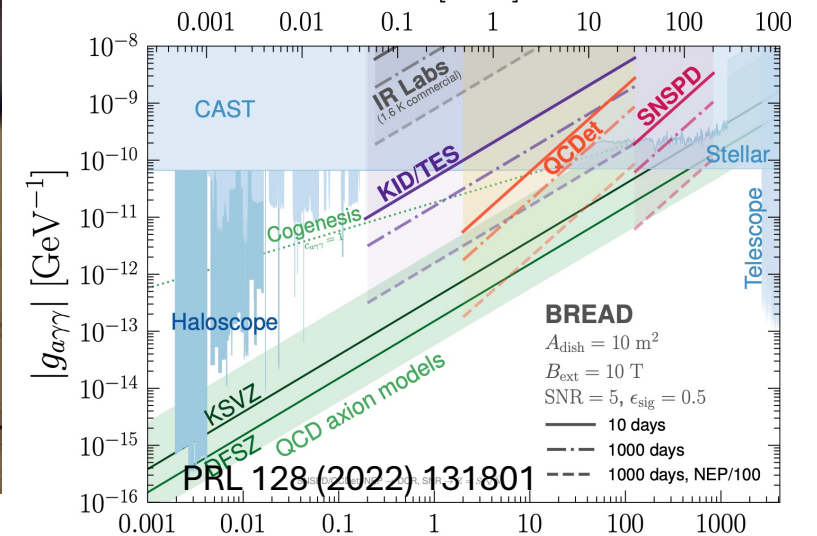
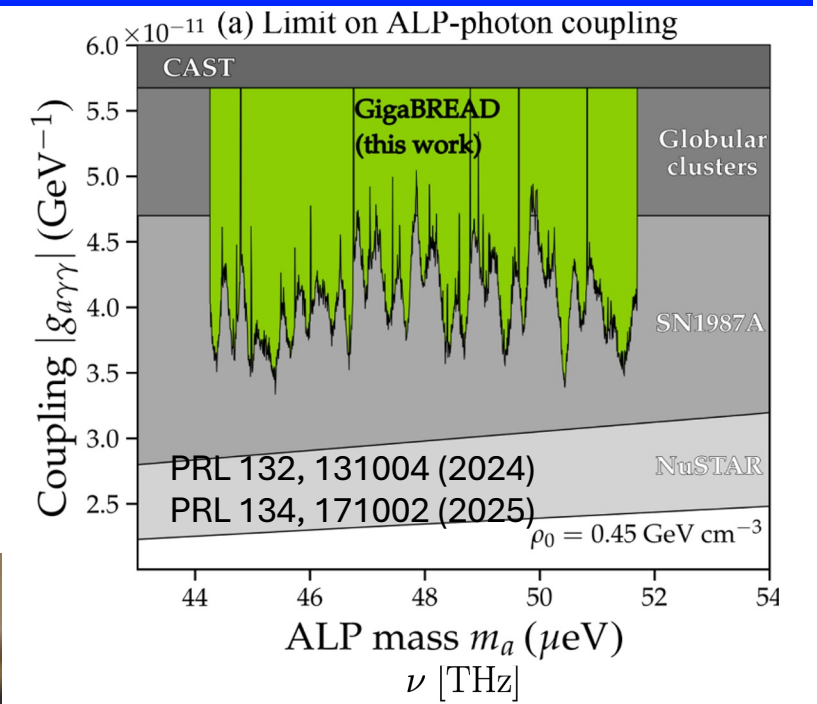


Concept – achromatic reflector



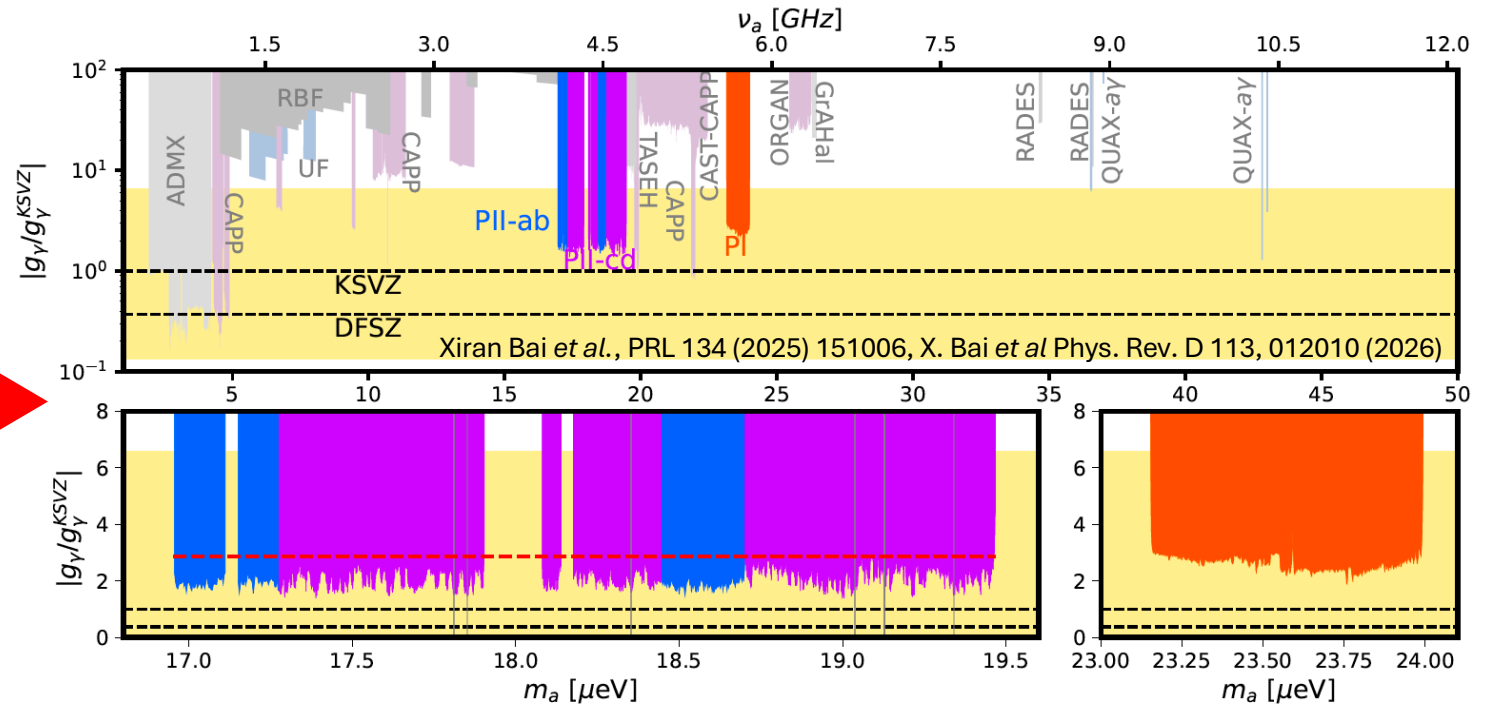
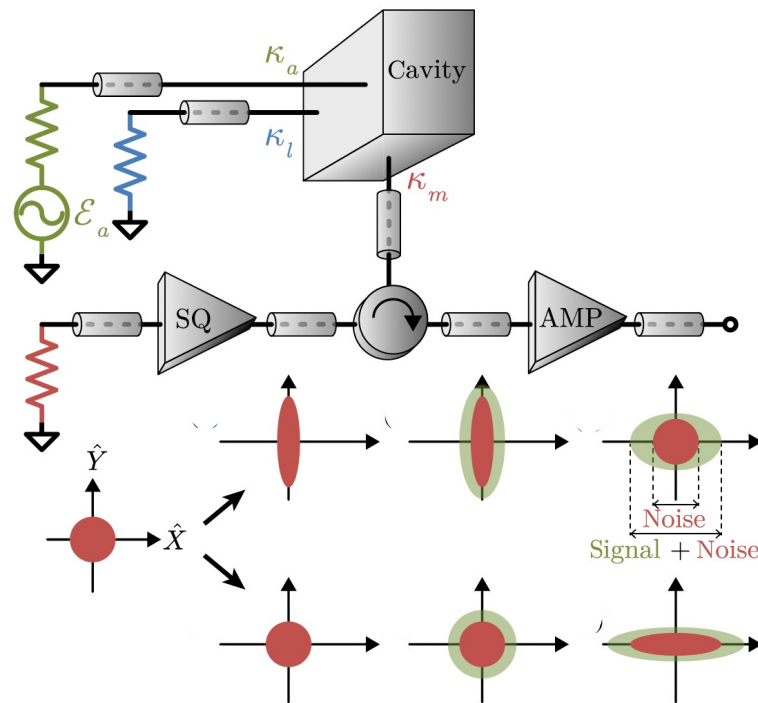
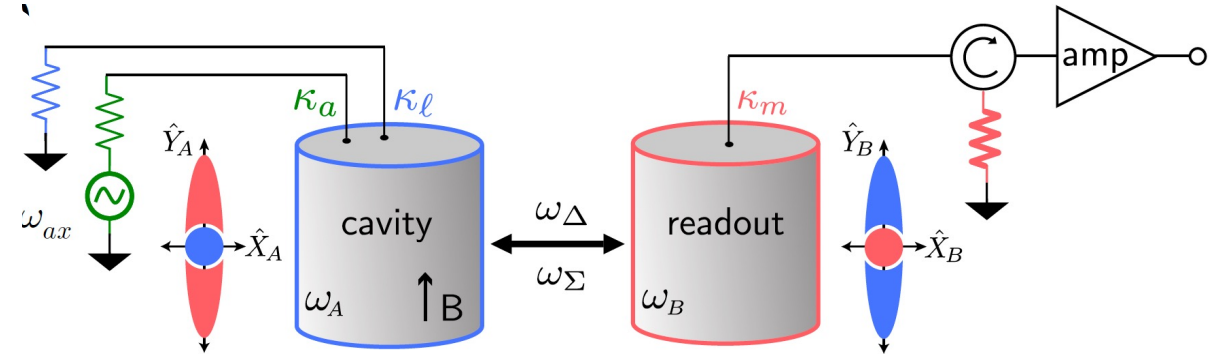
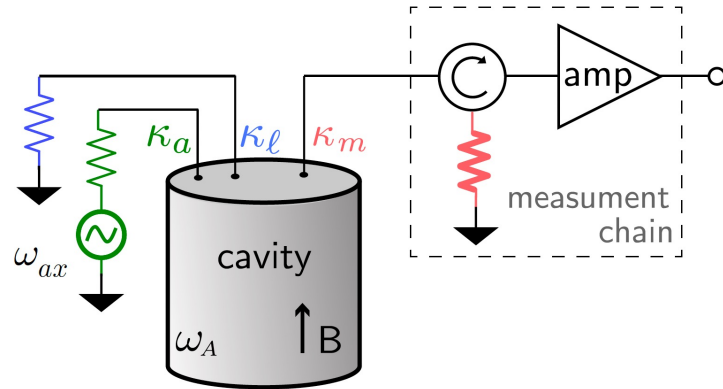
GigaBREAD components @ Harvard

courtesy Stefan Knirck



First limits (top) m_a [meV] & projections

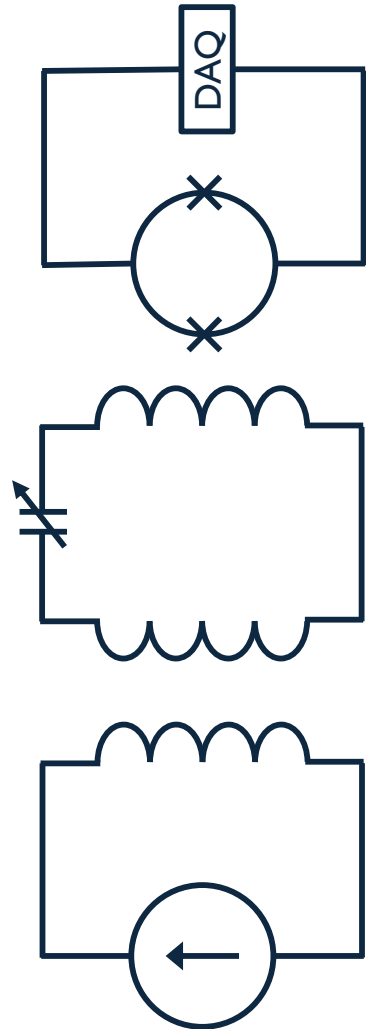
HAYSTAC: Quantum & sub-quantum receivers



Phase II (2019 -) Squeezing: $\sim \frac{1}{4} h\nu$

Squeezed State Receiver in routine operation for 5 years

The path to GUT-scale axions: Lumped element haloscopes see Victoria Ankel 2/6



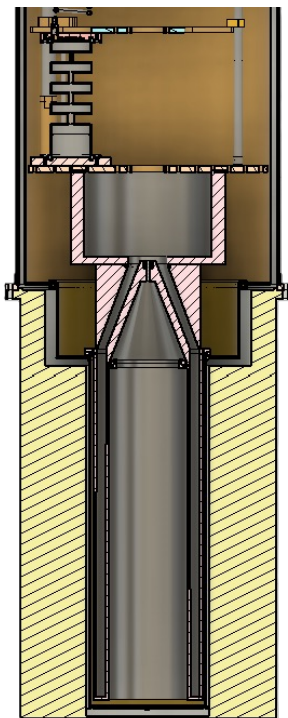
*Concept: Separate LC
from conversion volume*



ADMX-SLIC: PRL 124 (2020) 241101
ABRACADABRA: PRL 127 (2021) 081801

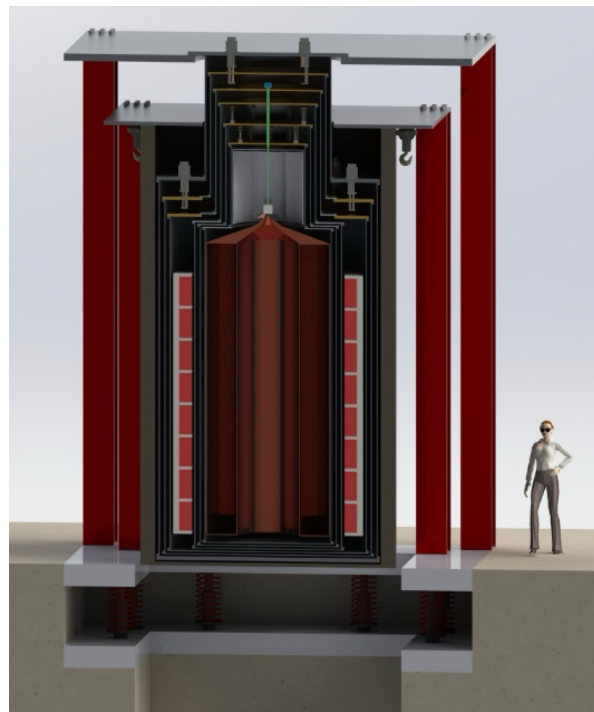


Laying the groundwork for GUT-scale axions



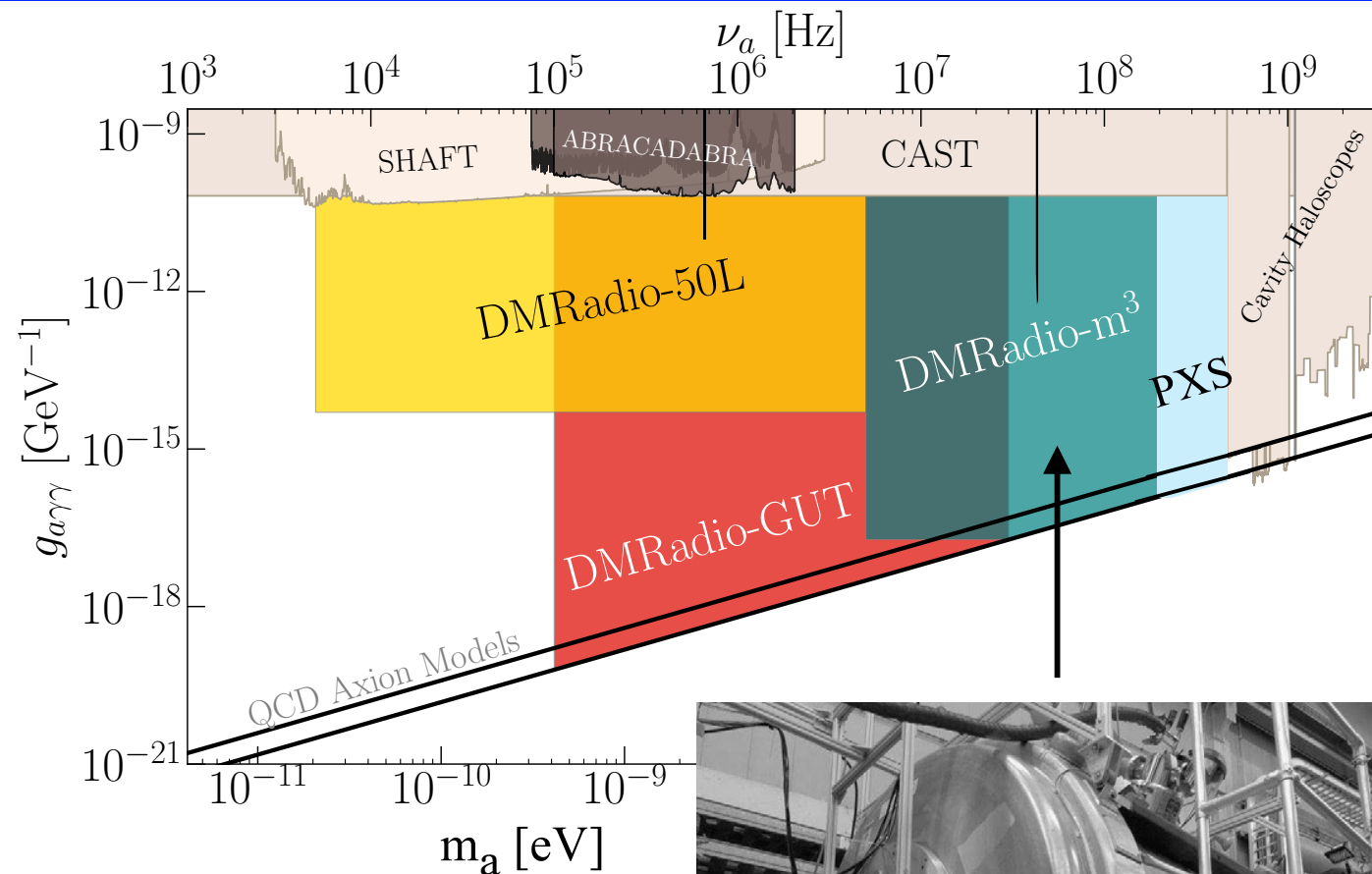
CAL-Pathfinder

Magnet 10L 9T
Coaxial pickup
Better SQUIDs
Data run 2027



DMRadio-GUT

~ 10 T, 10 m³
Competing geometries under study; magnet requires R&D
\$100M experiment, 2030's



DMRadio-m³

DOE DMNI program terminated
Intermediate scale experiment
being designed around existing
magnet & fridge; 2-year build

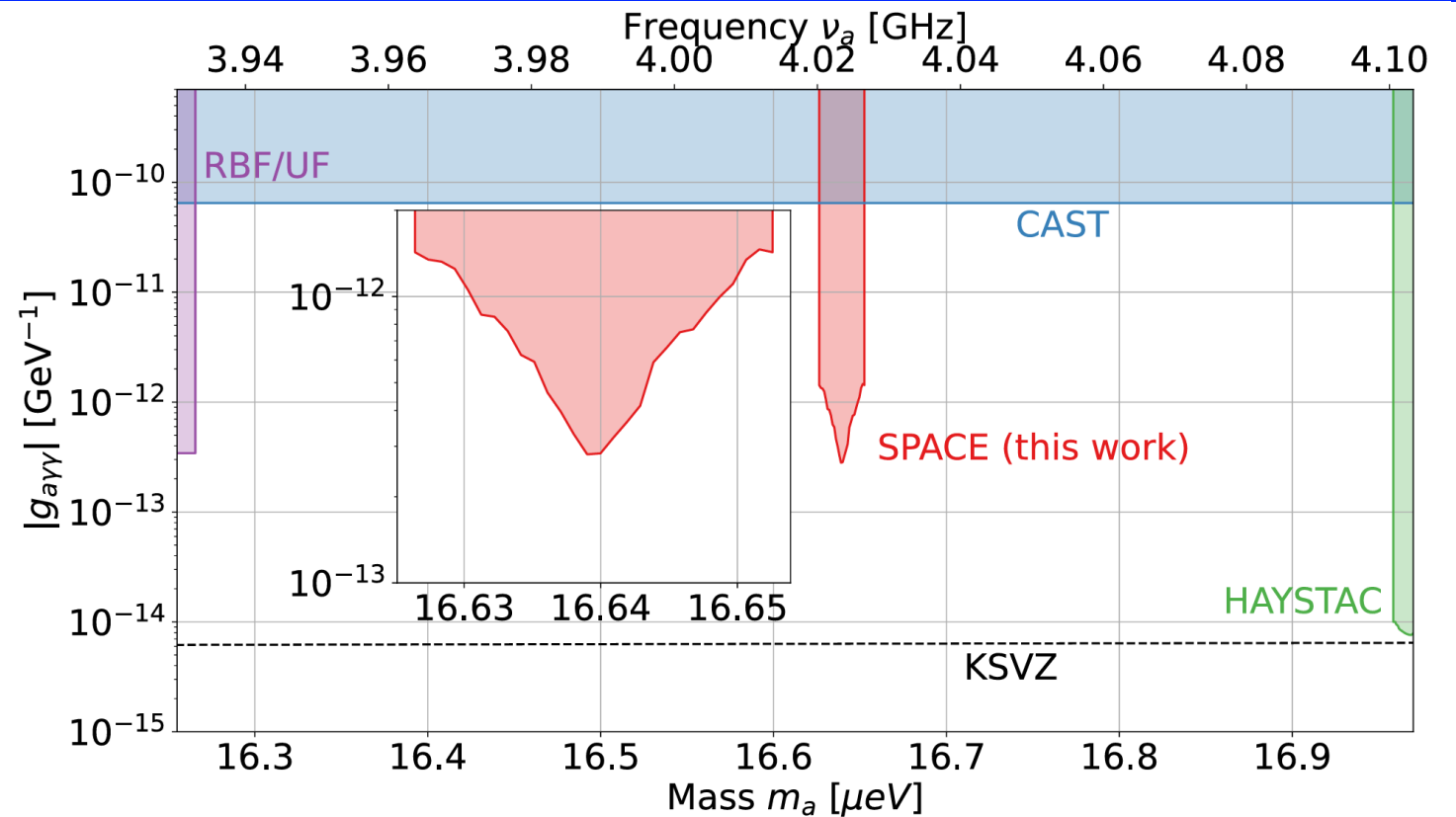


e.g. 3T repurposed MRI

SPACE (Student Project for an Axion Cavity Experiment): *Axions to the People!*

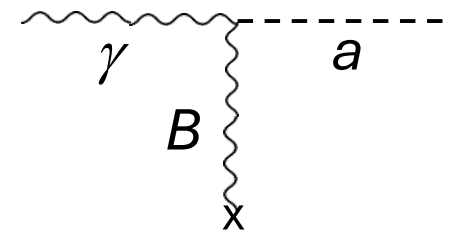
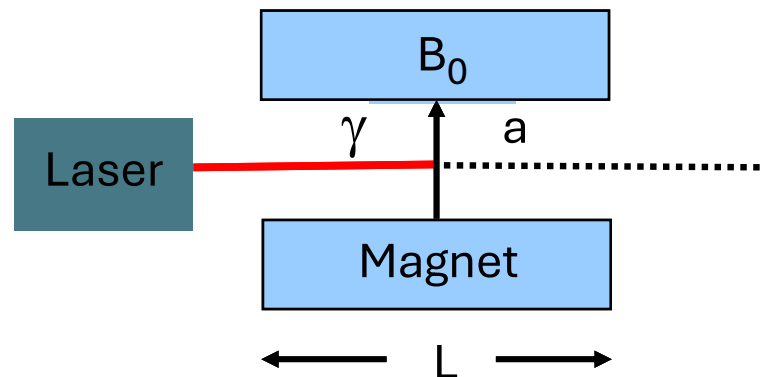


- Undergraduates at Univ. of Hamburg build an axion haloscope on their own
- Warm experiment, HEMT-only receiver
- Set limits 10^2 better than CAST
- JCAP 04 (2026) 054



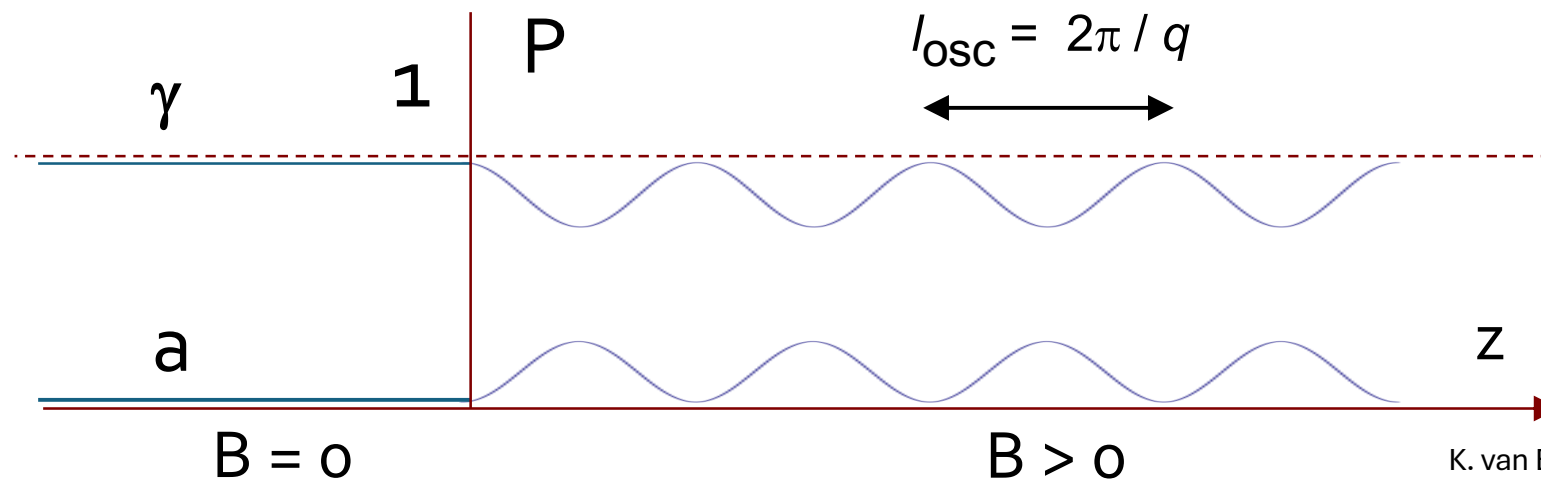
We had often said that when the axion experiment was discovered, it would become an undergraduate teaching lab the same week. This team didn't wait!

Axion-photon mixing in a transverse magnetic field

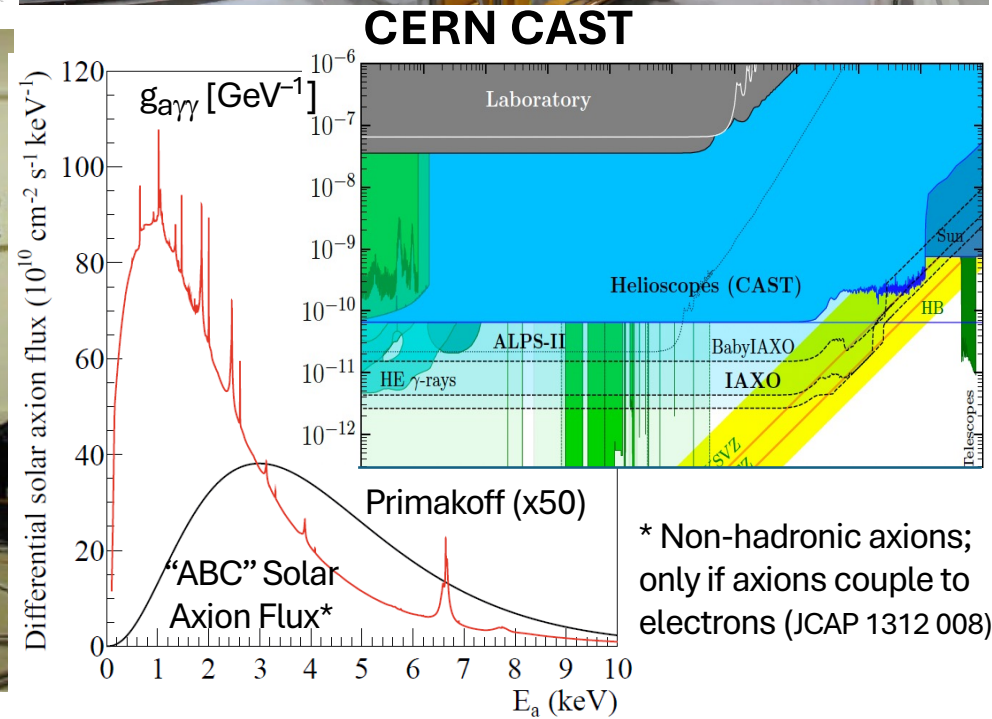
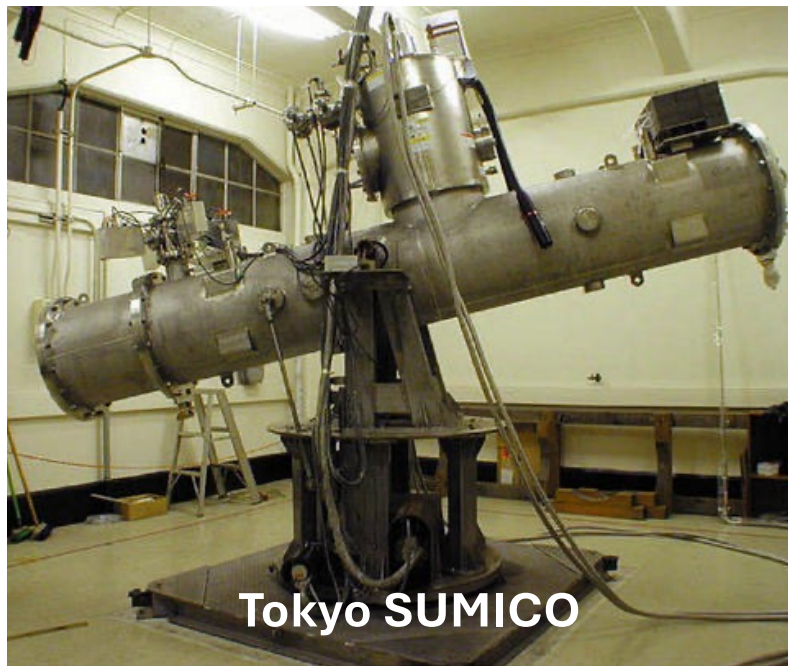
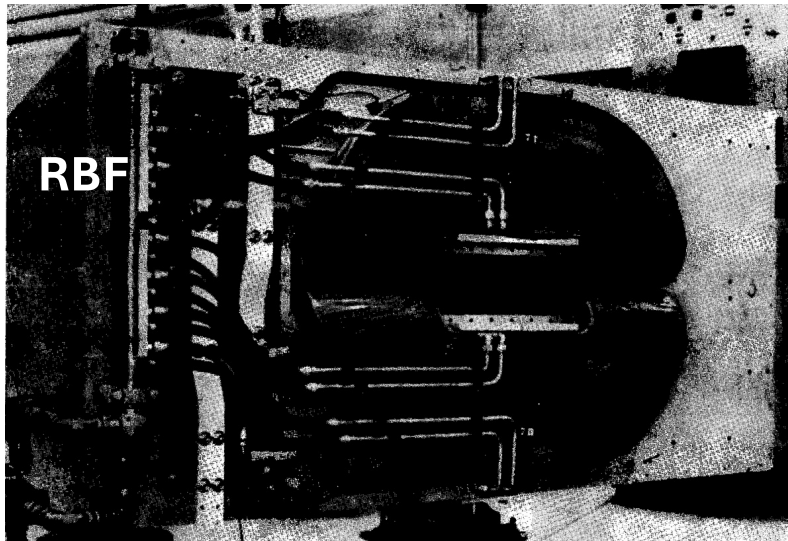


$$P(\gamma \rightarrow a) = \Pi = \frac{1}{4} (g B_0 L)^2 |F(q)|^2$$

$$F(q) = \frac{\sin(qL/2)}{(qL/2)}, \quad F(0) = 1 \quad \text{where} \quad q = k_\gamma - k_a \approx m_a^2 / 2\omega$$



A history of helioscopes



BabylAXO description and status

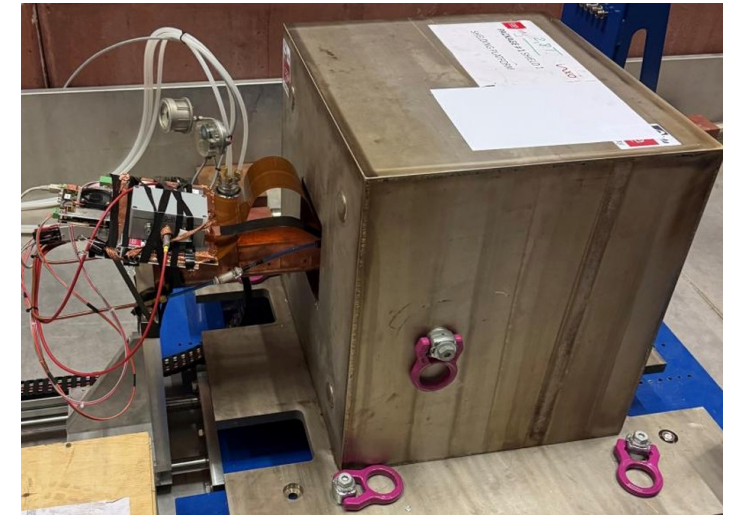
see Ana Quintana Garcia's talk 2/6

IAXO prototype (2 of 8 bores), SNR x100 CAST
Cutting-edge technologies in large magnets,
x-ray optics, detectors, etc.

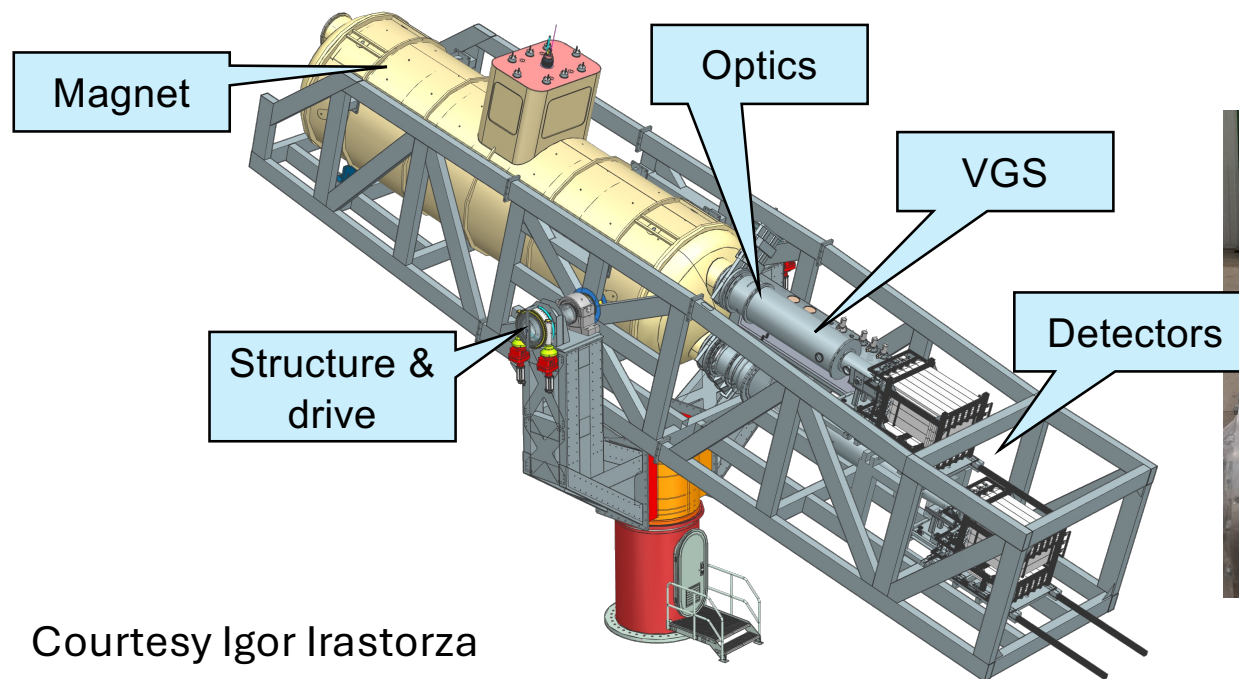
Non-magnet components being assembled
Rich ALPs, GW etc. program, 150 collaborators
2028: Dark photon run; 2030+: Axion running



First km of Rutherford
design cable delivered



First Micromegas x-ray detector
with shielding taking data at DESY



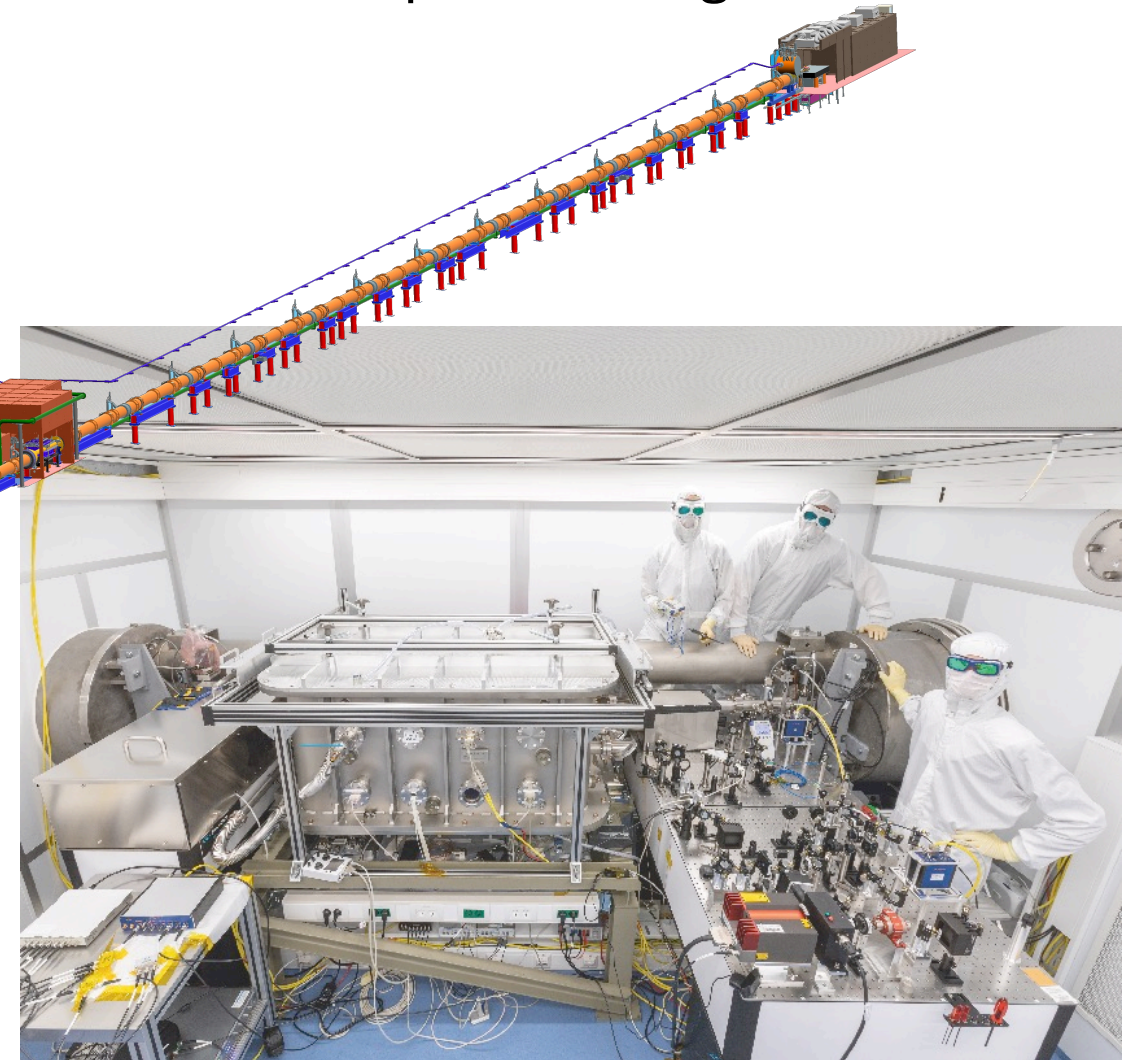
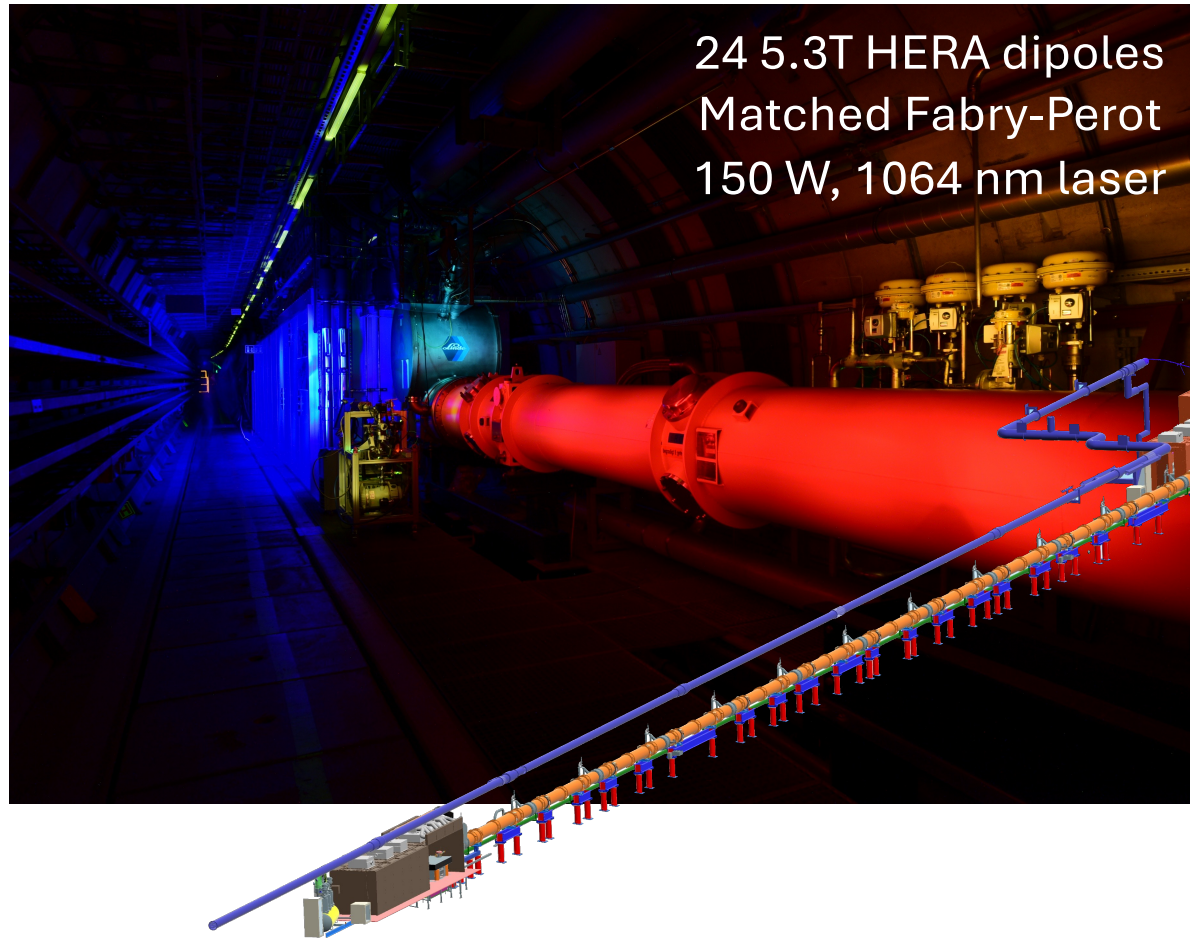
Courtesy Igor Irastorza



Large vacuum beampipes just finished

ALPS II @ DESY: generate and detect dark matter candidates

Two football pitches long!

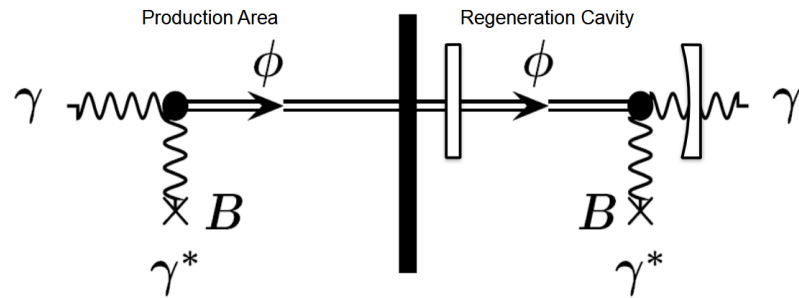


F. Hoogeveen, T. Ziegenhagen, *Nucl. Phys. B* 358 (1991) 3
P. Sikivie, D.B. Tanner, K. van Bibber, *Phys. Rev. Lett.* 98 (2007) 172002
G. Mueller, P. Sikivie, D.B. Tanner, K. van Bibber, *Phys. Rev. D* 80 (2009) 072004

Courtesy Axel Lindner

ALPS II @ DESY: First results

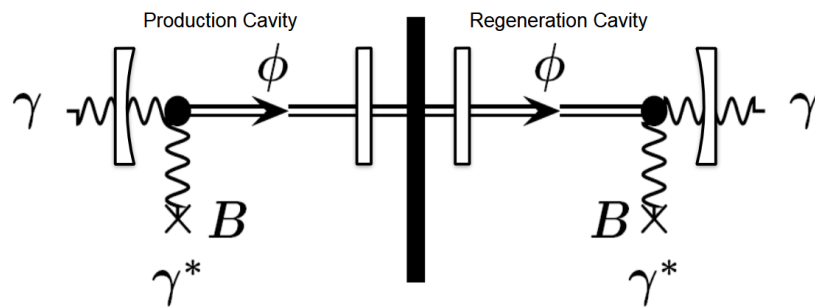
Results of first axion search science campaign just published



$$N_i \sim 10^{26} \text{ photons } (10^6 \text{ seconds})$$

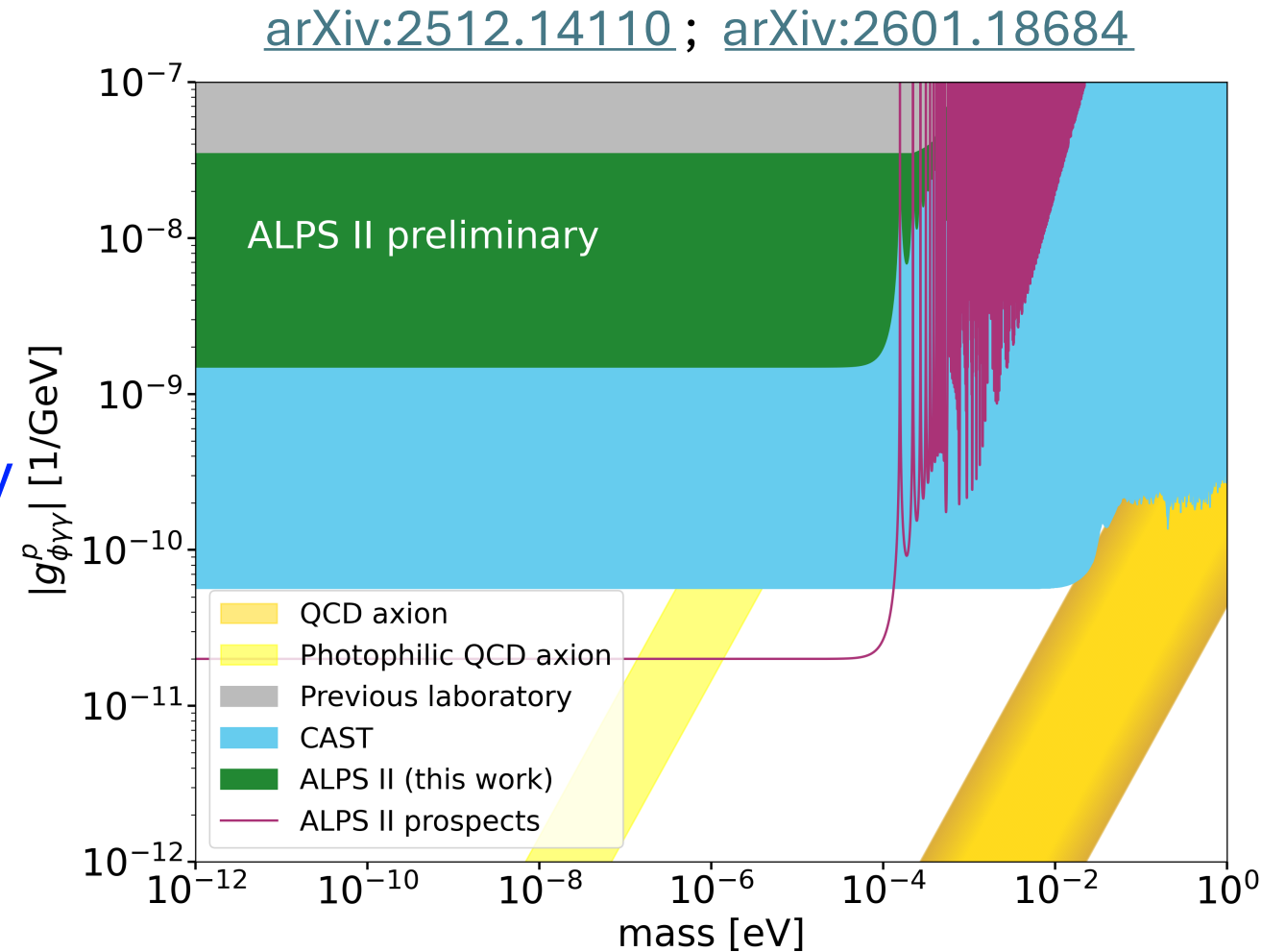
$$N_b \sim 200 \text{ photons } (10^6 \text{ seconds})$$

Optics upgrade for axions underway

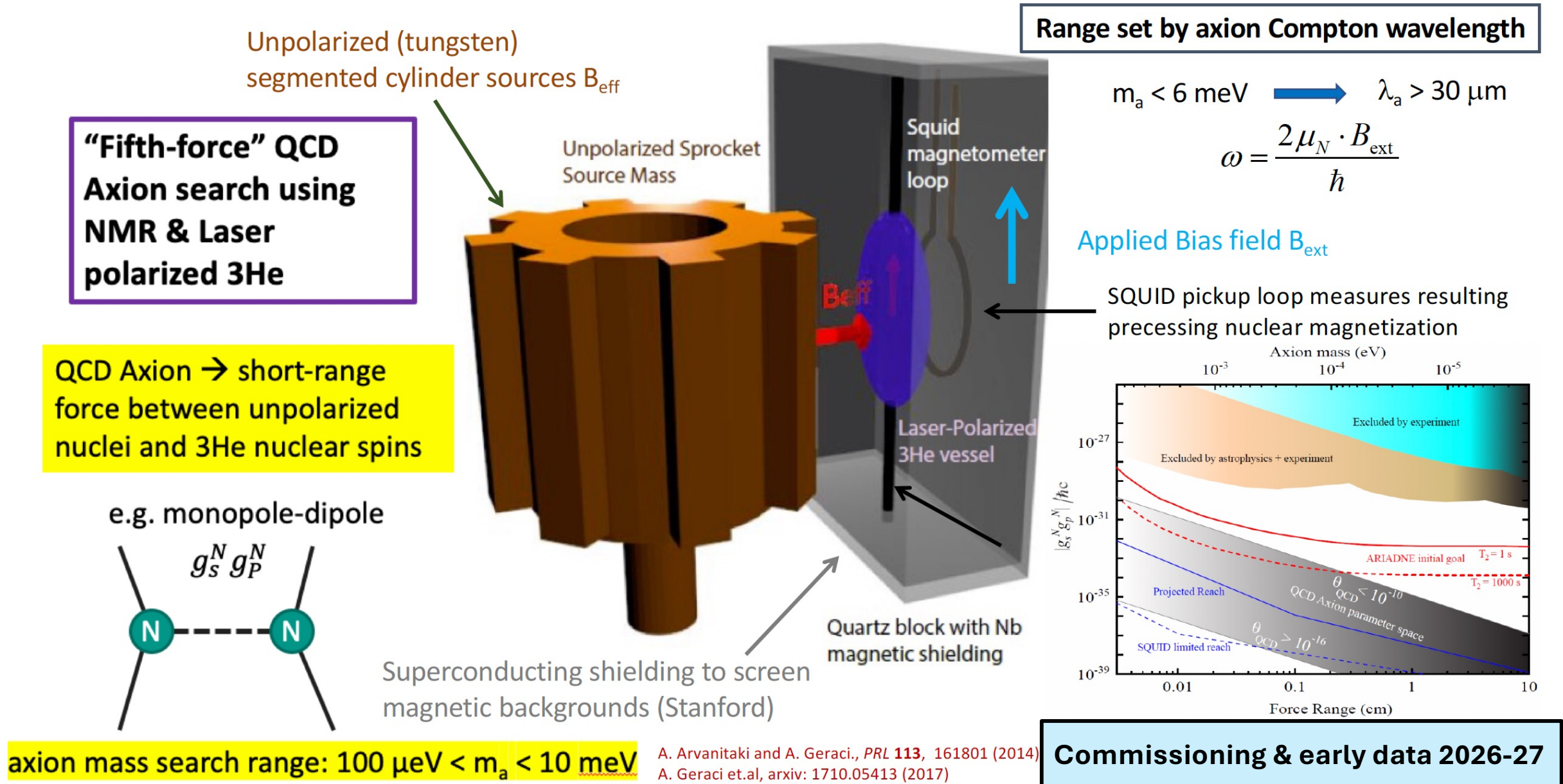


$$N_i \sim 10^{30} \text{ photons } (10^6 \text{ seconds})$$

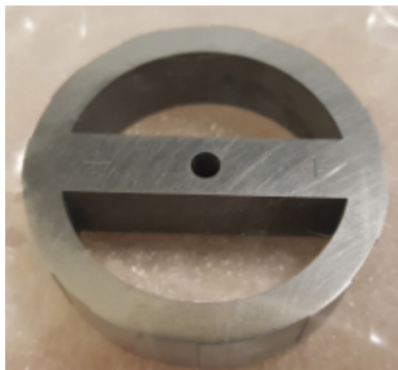
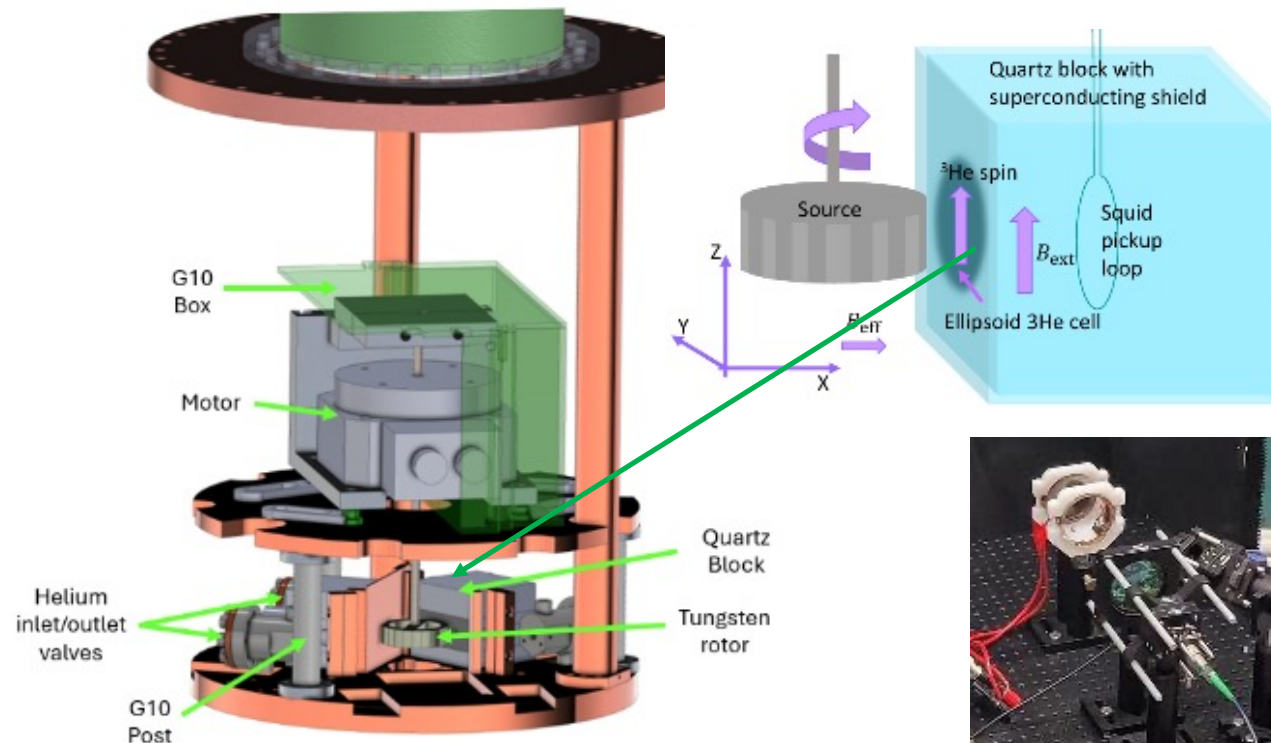
$$N_b \sim 1 \text{ photon } (10^6 \text{ seconds})$$



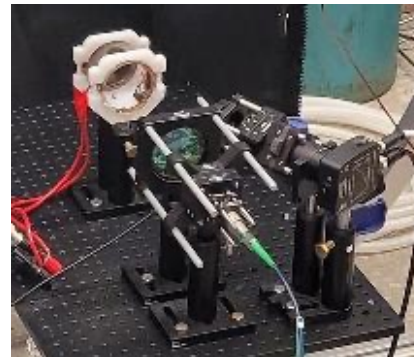
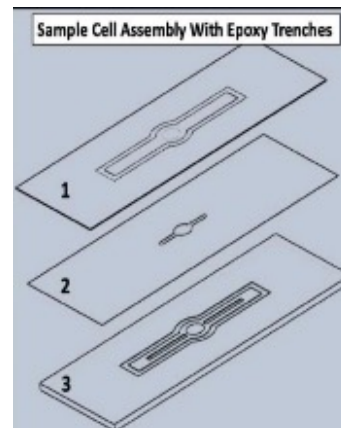
ARIADNE (Axion Resonant InterAction Detection Experiment) *courtesy A. Geraci, A. Hipp*



ARIADNE setup – passing all tests so far



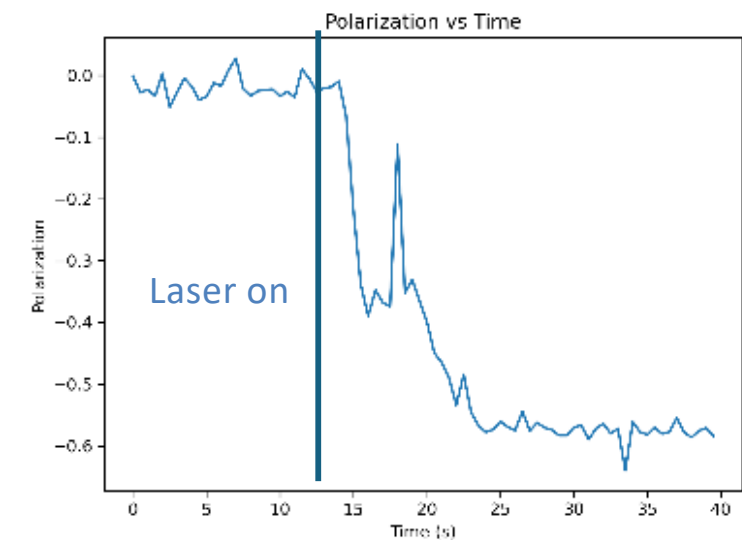
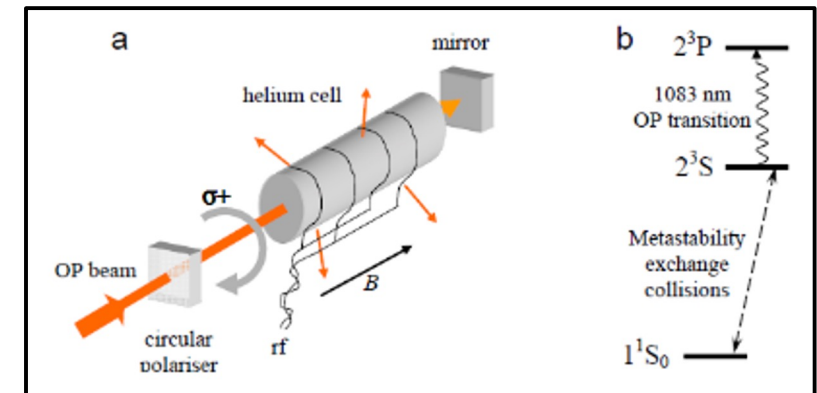
Tungsten source mass rotor
11 segments
3.8 cm diameter
1 cm height



Spheroid Volume
100 Hz nuclear spin precession frequency
 $2 \times 10^{21} / \text{cc}$ ^3He density
3 mm x 3 mm x 150 μm volume
Separation $\sim 200 \mu\text{m}$

Laser-polarized ^3He sensor

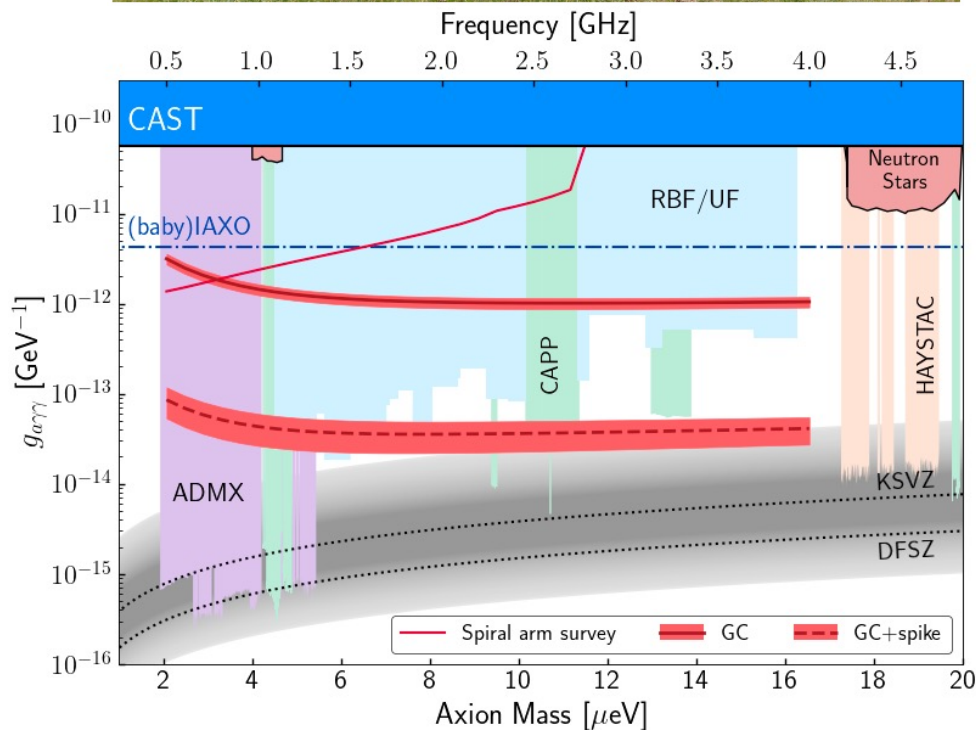
- Metastability exchange optical pumping



ASTRA – A dedicated radio telescope for axion searches



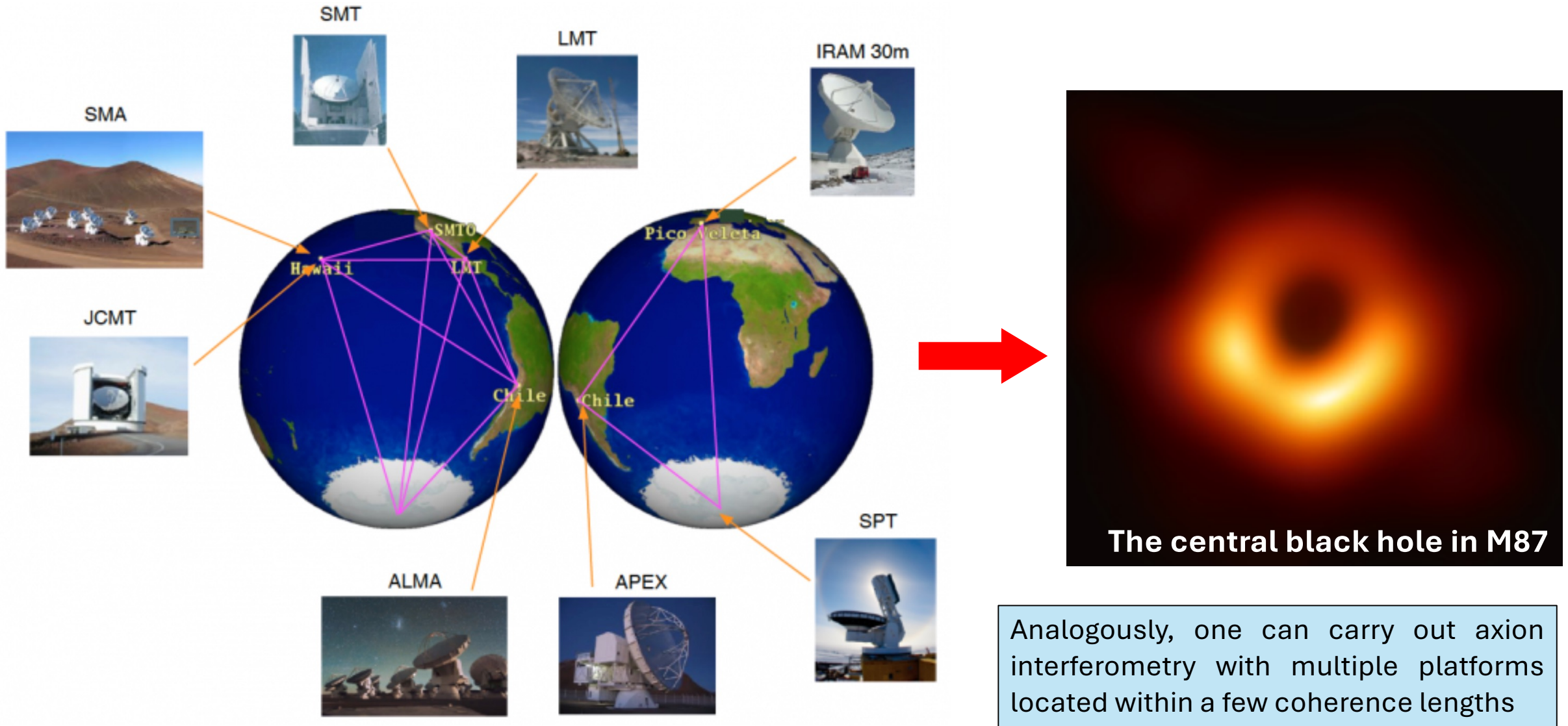
- 5-meter dish installed on Mt. Fan, part of the NRAO radio quiet zone
- L-band initially, later S- and C-band
- Will tile the sky 24/7/365 particularly focusing on discrete and unresolved young pulsars
- Sees the galactic center 4 hours/day
- Can see axions in new parameter space for axion miniclusters traversing NS
- Cost: \$250K for initial configuration



Axion interferometry!

J. Foster et al., Phys. Rev. D 103 (2021) 076018

A recent spectacular example from radio astronomy (2019): The Event Horizon Telescope (EHT)



Example from Foster paper

Coherence length & coherence time:

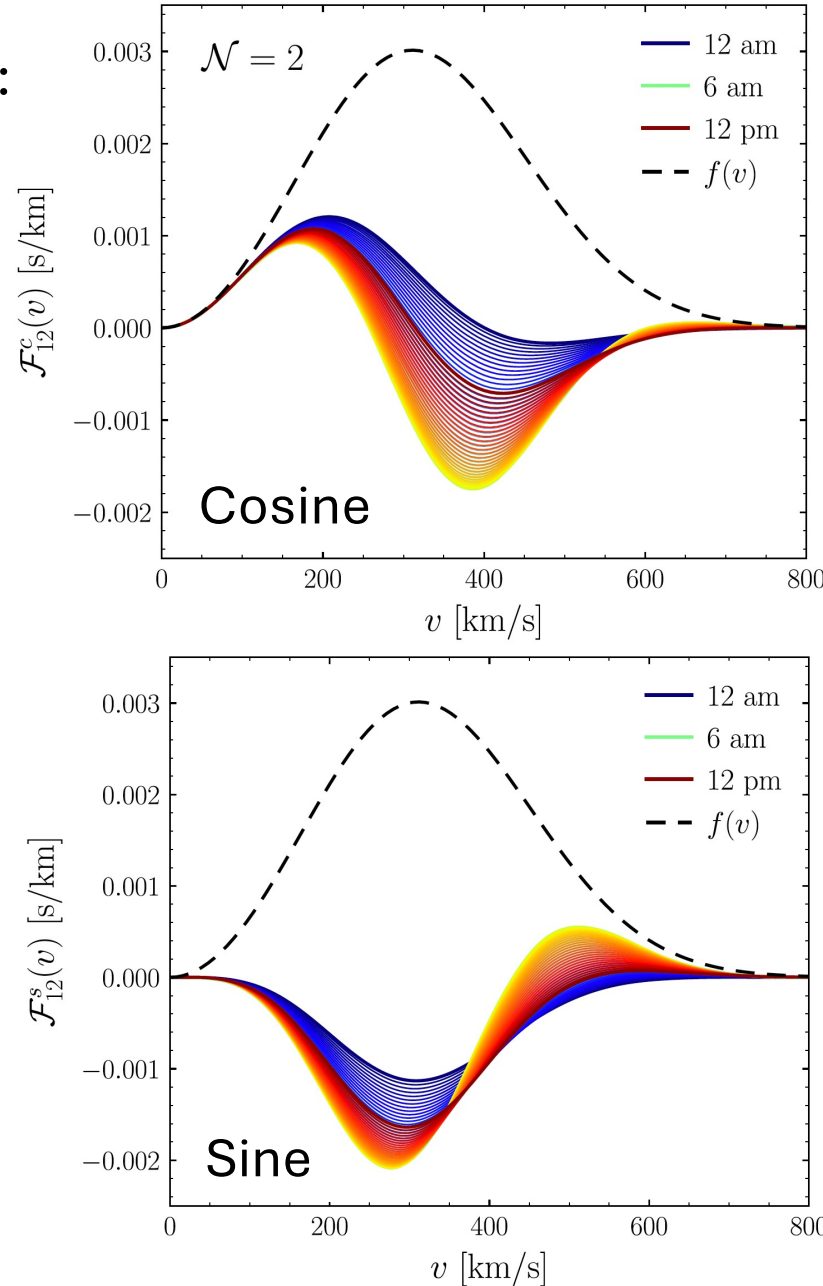
$$\lambda_c \sim \frac{1}{m_{DM} v_0}, \quad \tau \sim \frac{1}{m_{DM} \bar{v} v_0}$$

m_{DM} = dark matter mass
 v_0 = velocity dispersion
 $\bar{v}$ = mean velocity
 $\mathbf{x}_{12}$ = detector separation

Cosine & Sine components of the interference term:

$$\mathcal{F}_{12}^c(v) = \int d^3\mathbf{v} f(\mathbf{v}) \cos(m_{DM} \mathbf{v} \cdot \mathbf{x}_{12}) \delta[|\mathbf{v}| - v]$$

$$\mathcal{F}_{12}^s(v) = \int d^3\mathbf{v} f(\mathbf{v}) \sin(m_{DM} \mathbf{v} \cdot \mathbf{x}_{12}) \delta[|\mathbf{v}| - v]$$



The axion mass in this example is $m_{DM} = 25.2 \mu\text{eV}$

The lab located at $(41^\circ \text{N}, 73^\circ \text{W})$

The second detector lies north of the first detector by $2\lambda_c \sim 20 \text{ m}$

The curves are every 10 minutes beginning midnight Jan. 1, 2020

Two detectors constitute an interferometer, three are an observatory!

As well as confirming the motion of the solar system through the galactic halo. Individual tidal streams could be located within 1° in a matter of hours

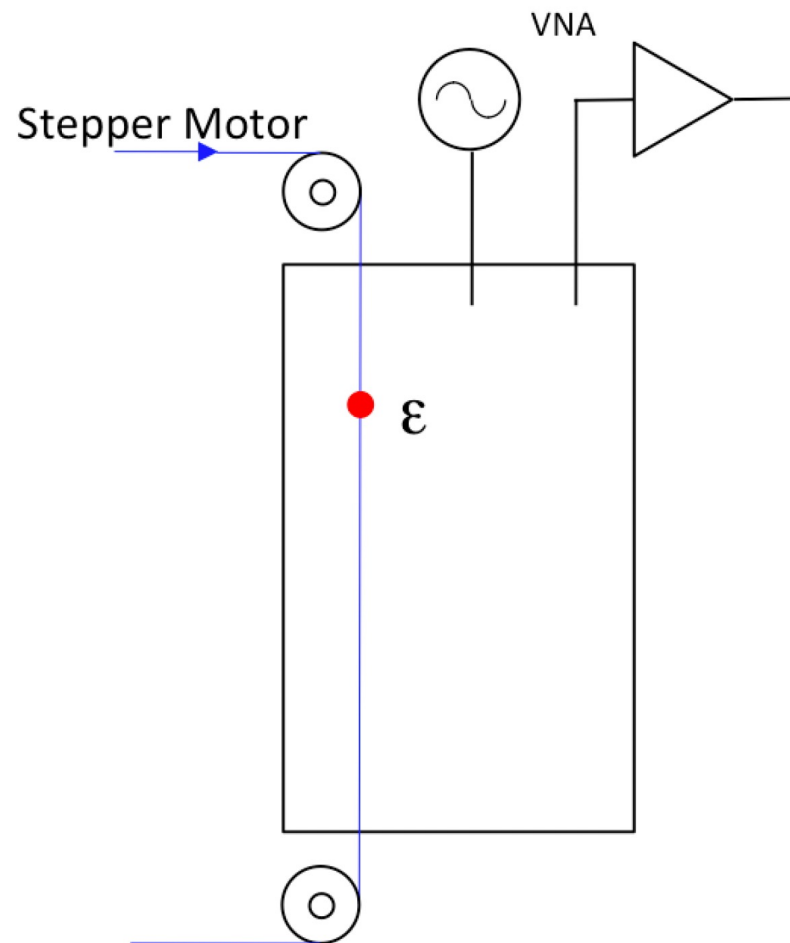
Summary and some personal observations

- The breadth and progress of the technical and scientific work in the Axion/ALPs domain is breathtaking – my congratulations to all of you!
- That being said, we are not yet progressing fast enough. Because these searches are overwhelmingly resonant tuning experiments, there is an undercurrent of tension in the field between going deep and going wide.
- Technology development is wonderful, but don't forget why we are here.
- We are not smarter than nature, and discovery could lurk anywhere in the white space. Thus, we need a few experiments willing to cover decades of mass very quickly, with studious disregard to theoretical models.
- **IDM 2028 will be the 50th anniversary of the axion. Let's make sure it shows up for the party!**

Additional slides as time permits

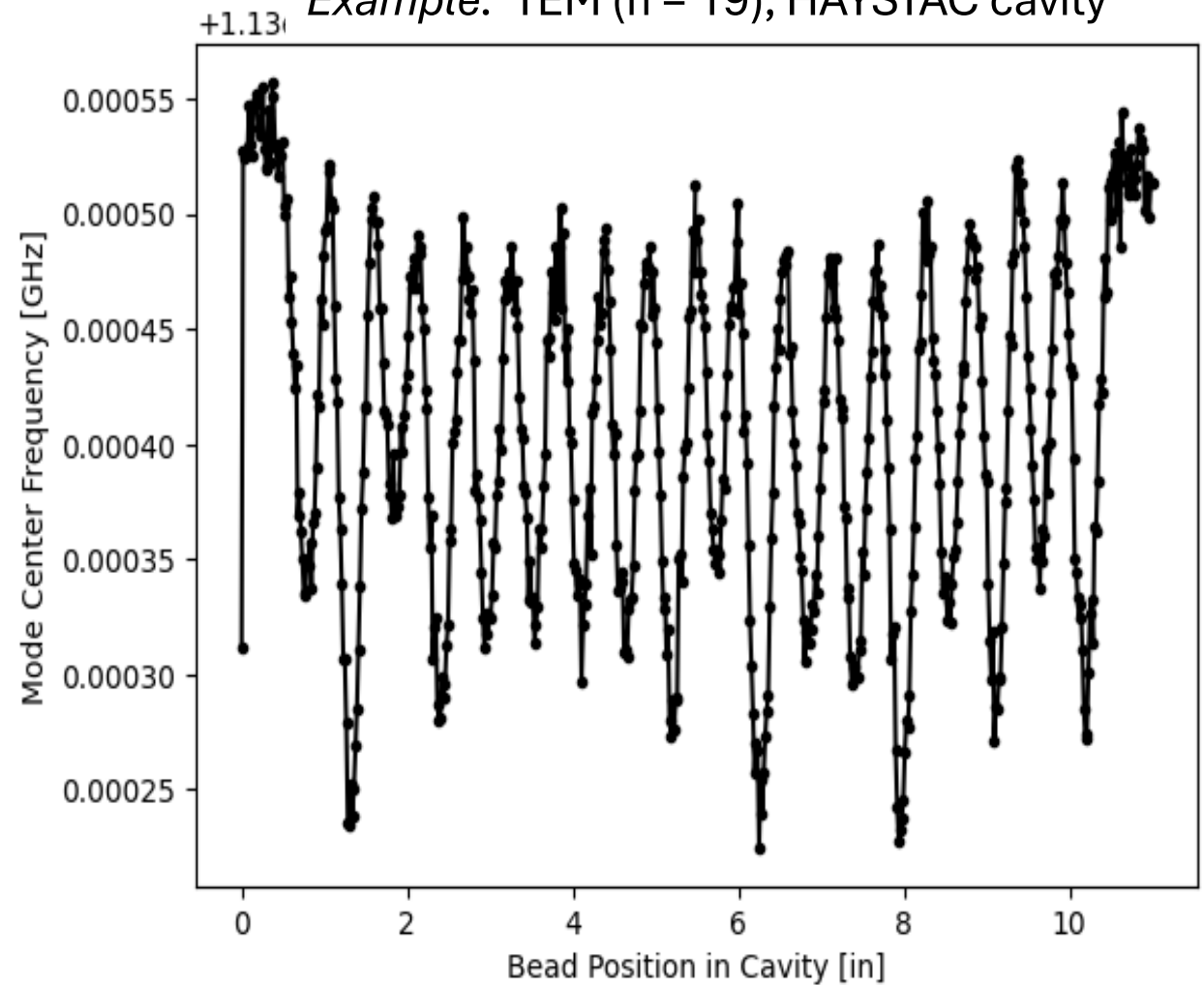
Field Mapping – Bead Perturbation method

$$\frac{\Delta\omega}{\omega} = \frac{-(\epsilon - 1)}{2} \frac{V_{\text{bead}}}{V_{\text{cav}}} \frac{E(r)^2}{\langle E(r)^2 \rangle_{\text{cav}}}$$

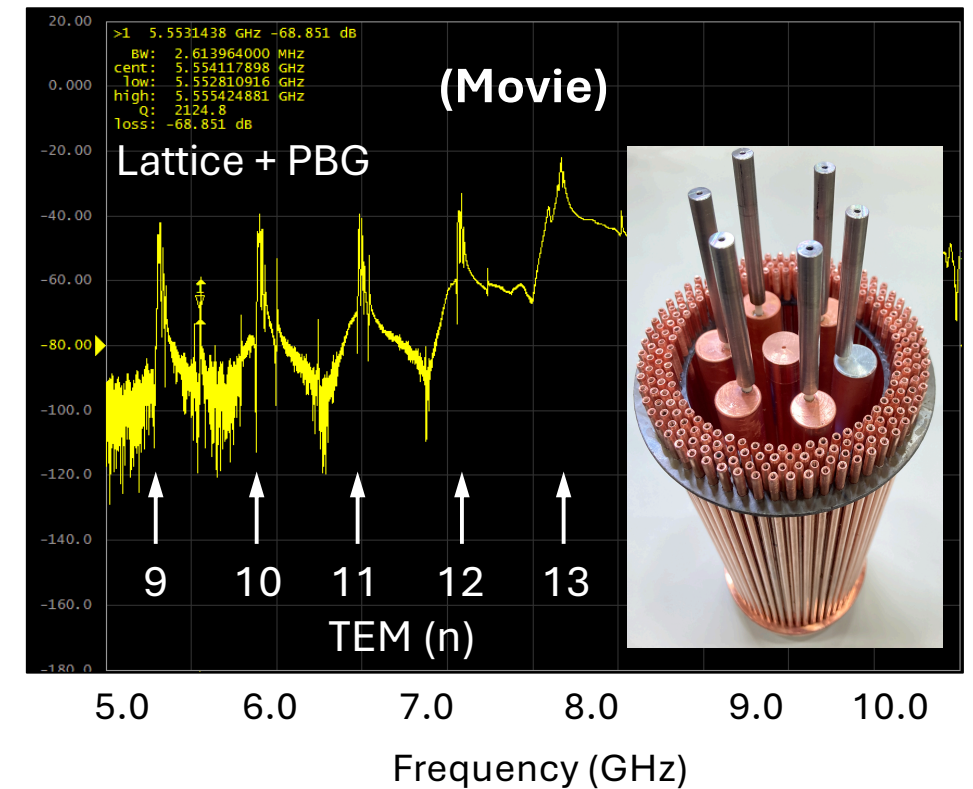
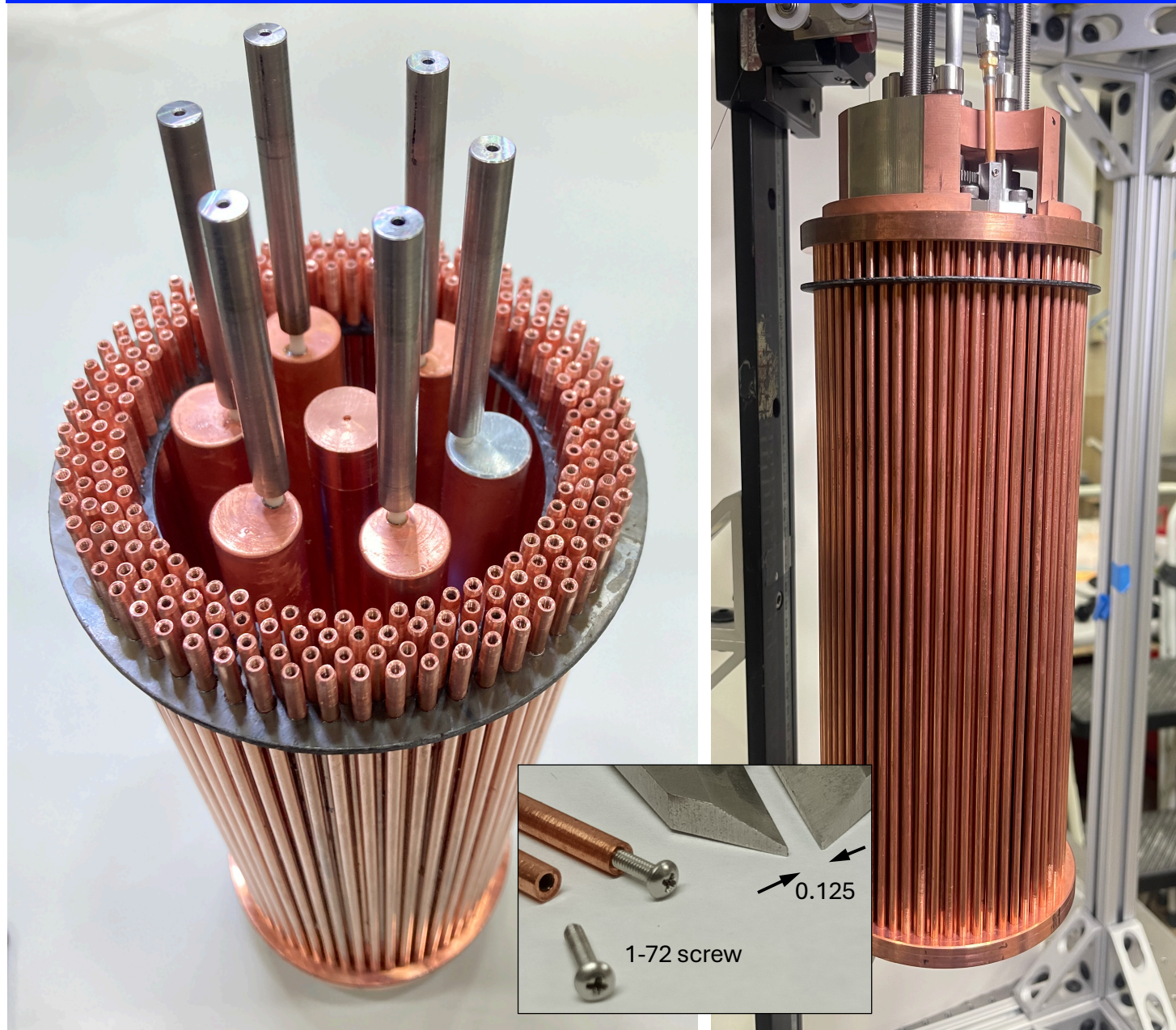


Discontinuities in Waveguides, J. Schwinger & D. Saxon (1968)

Example: TEM ($n = 19$), HAYSTAC cavity

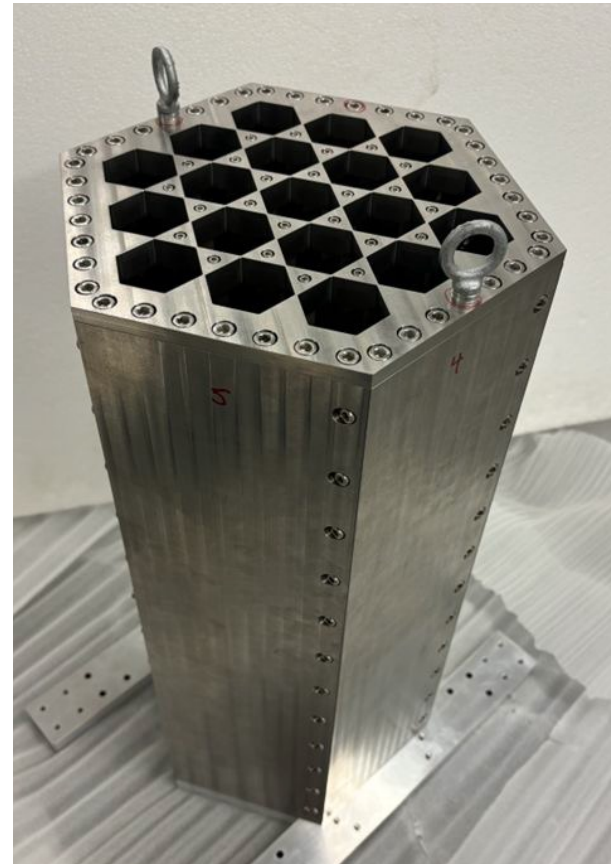
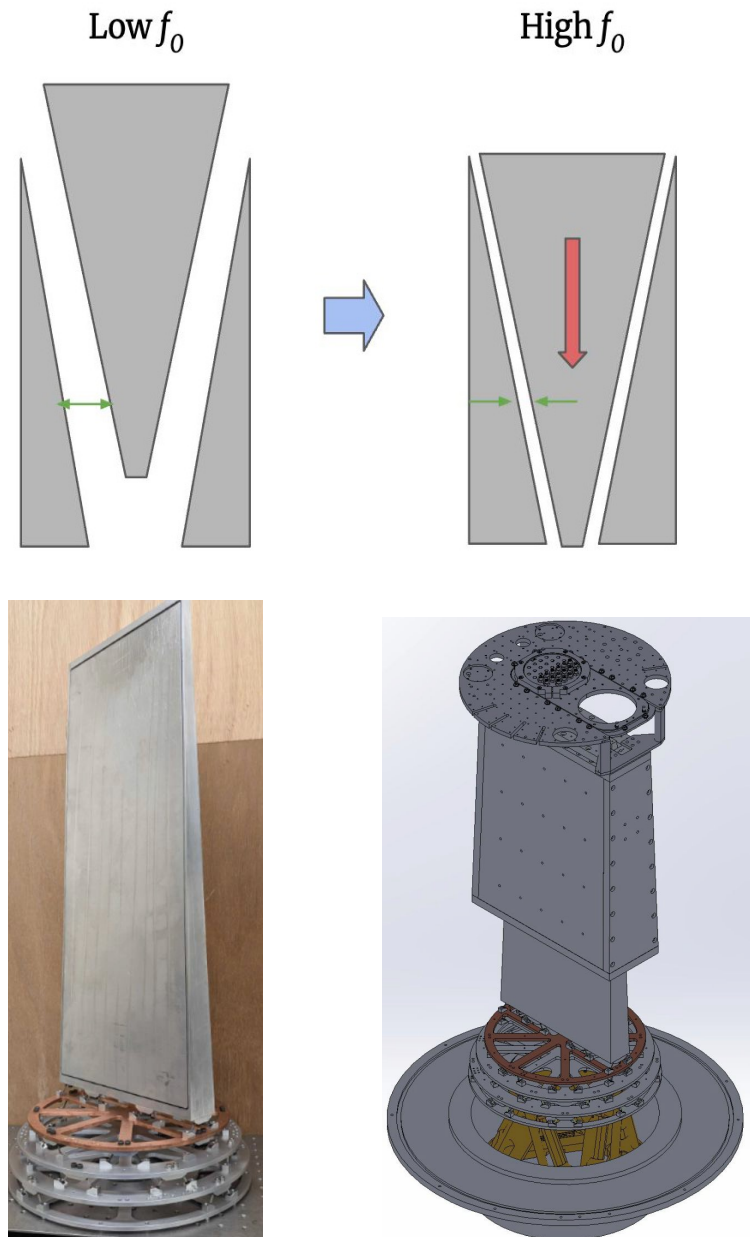


Photonic Band Gap structures to suppress forest of TE modes

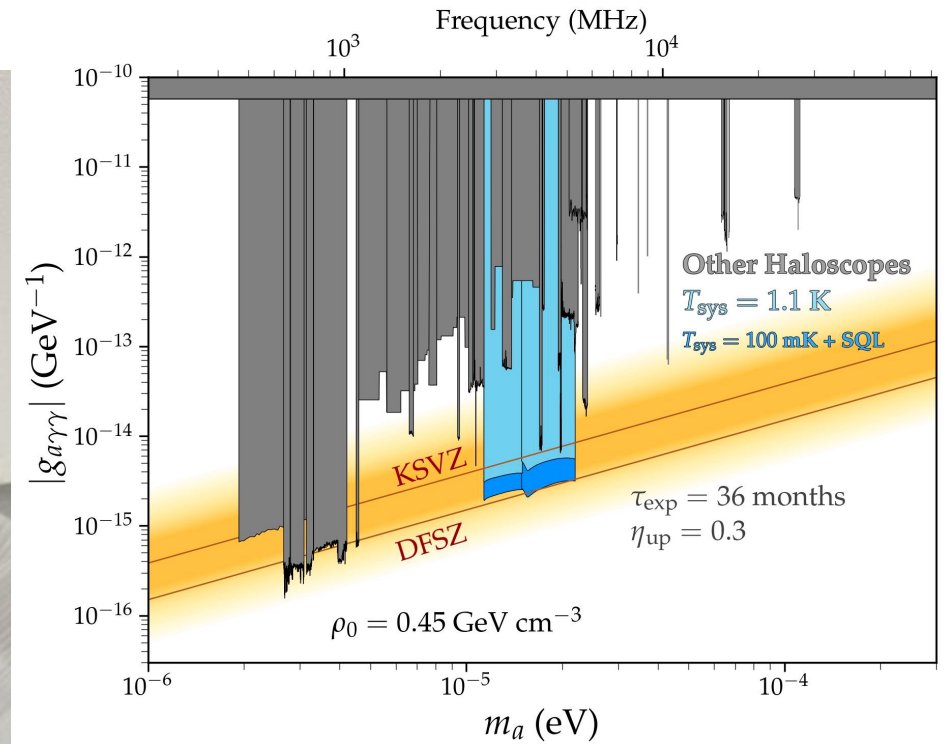


Even a single-row PBG can confine the TM_{010} with losses of only $O(10^{-8})$ while fully suppressing the spectrum of TE modes.

ADMX – VERA: Innovations to increase frequency without loss of volume



3-D multiplexed version “Beehive”
← Single 1D wedge resonator

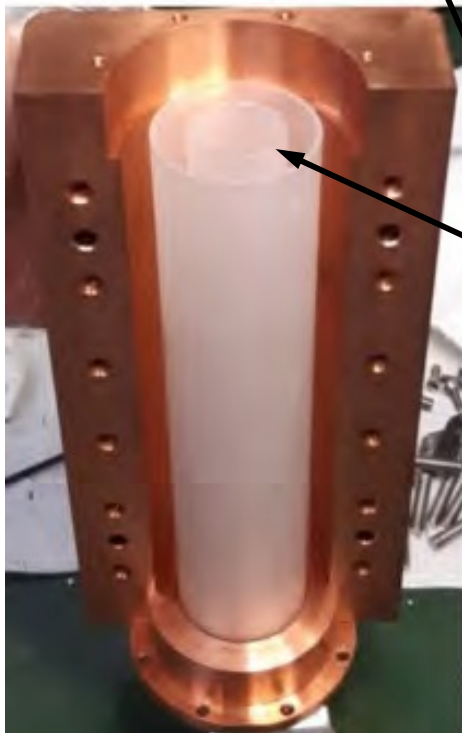
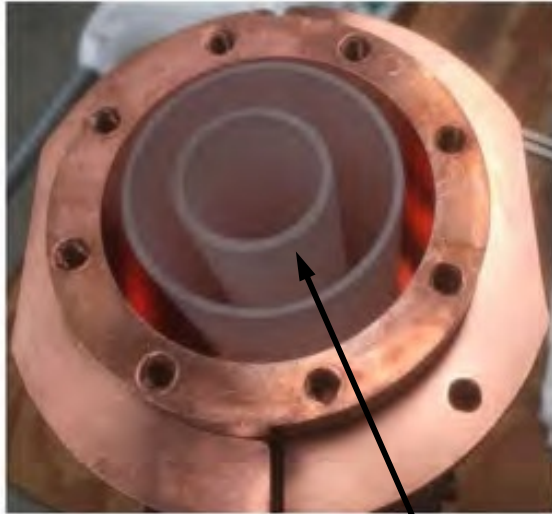


ADMX-VERA proposal: 2.7-5.3 GHz
(Light blue) 3 years run time
(Dark blue) w/ SQL detector

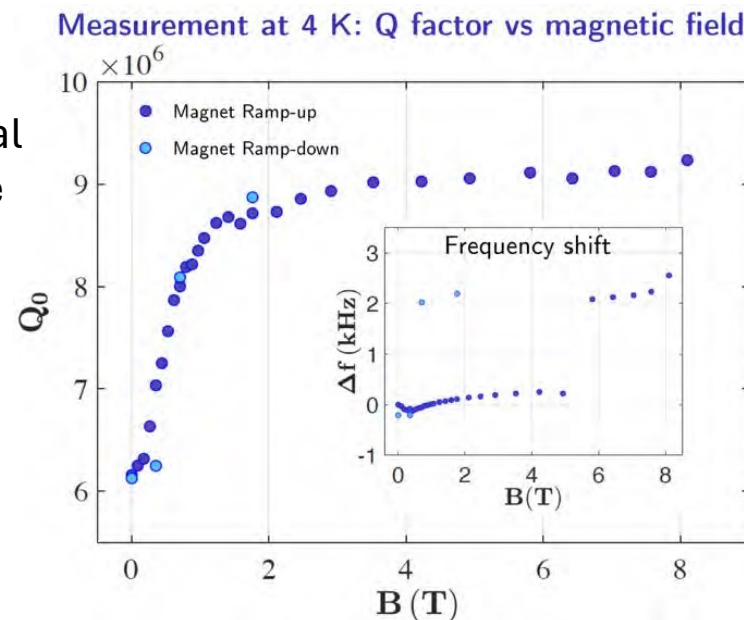
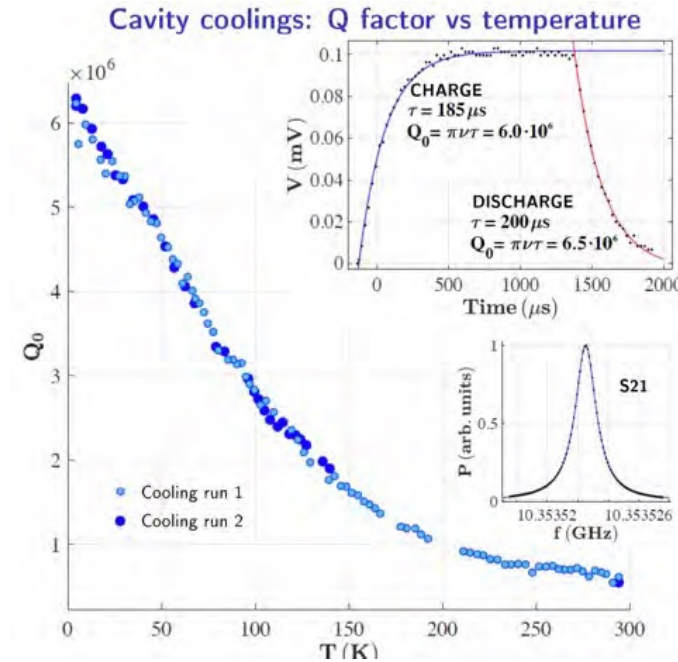
Courtesy Chelsea Bartram (SLAC)

QUAX – Boosting the quality factor Q

R. Di Vora et al., Phys. Rev. Appl. 17, 054013 (2022)



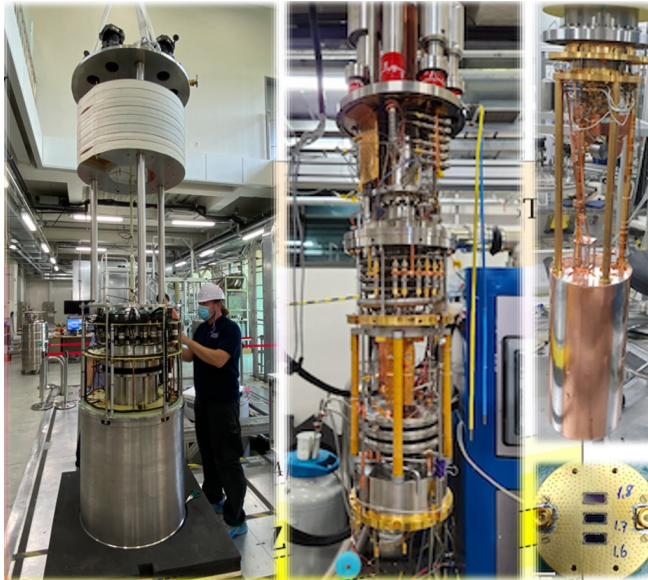
Cylindrical
Sapphire
Shells



- A copper cavity loaded with two concentric sapphire cylindrical shells achieves $Q = 6\text{M}$ @ 4K in the TM_{030} mode
- No superconducting materials!
- Well know that one can use shells to reduce the E-field at the copper surface, and thus resistive loss
- But very surprisingly, Q increases by 50% with magnetic field; $Q = 9\text{M}$ at $B = 8\text{ T}$
- Far exceeds $\sim 2\%$ increase due to magnetoresistive effect in Cu; hypothesis that B-field suppresses losses in Fe, Cr, V impurities

CAPP → DMAG

Many resonator innovations particularly superconductivity



DMAG-12TB (12T/320mm)

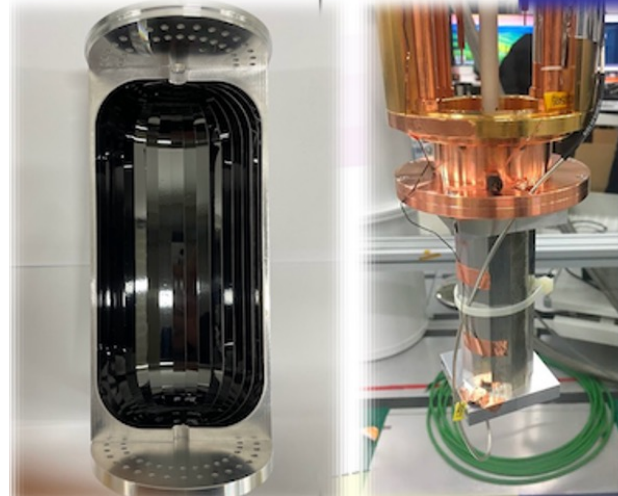
$f > 1$ GHz, $V = 32$ L, $T_{\text{sys}} \sim 200$ mK
 $df/dt \sim 2$ MHz/day @ DFSZ
 PRX 14 031023 (2024)

Hybrid cavity
 (Cu cavity + HTS tuning rod)
 DAQ since Nov. 2025 (1.3–1.5 GHz)

Hybrid cavity with
 HTS tuning rod

CAPP-8T
 (8T/125mm)

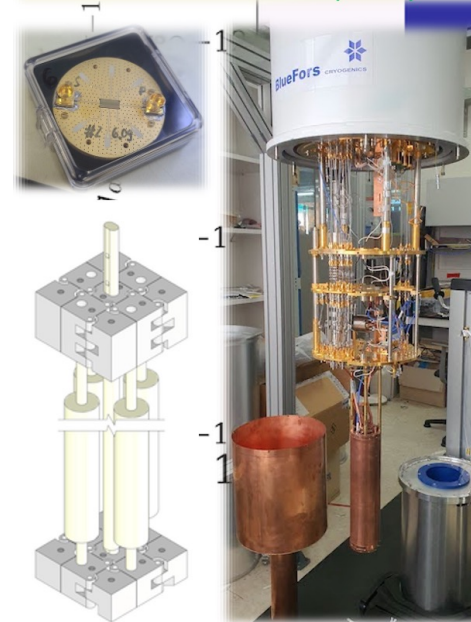
HTS SC cavity + JPA
 (2.3 GHz, $Q \sim 3.5$ M)
 AQN search
 PRD 112, L121305 (2025)



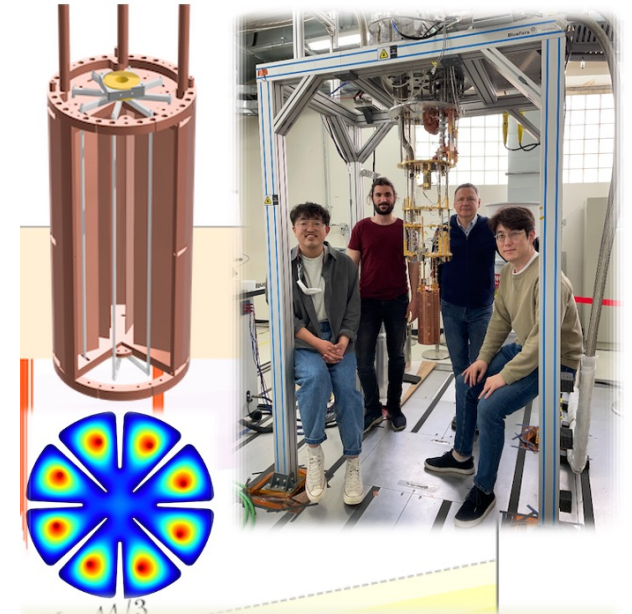
HTS cavity, $Q \sim 3.5$ M

DMAG-12T
 (12T/96m)

TM_{020} + auxetic + JPA
 (5.1 GHz)
 Near KSVZ sensitivity
 PRL 135 091804 (2025)



Auxetic tuning
 mechanism



DMAG-8TB
 (8T/165mm)

8-cell + JPA
 (5.9 GHz, 400 mK)
 KSVZ sensitivity
 PRL 135 211801 (2025)

Coupled multicell
 'pizza' cavity

Photon Regeneration (“Light Shining through Walls”) my debut in axions 1987

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PHYSICAL REVIEW LETTERS

17 AUGUST 1987

Proposed Experiment to Produce and Detect Light Pseudoscalars

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(Received 12 May 1987)

We propose a laboratory experiment to produce and detect a light neutral pseudoscalar particle that couples to two photons. The pseudoscalar would be produced by a (real) photon from a laser beam interacting with a second (virtual) photon from a static magnetic field; it would be detected after it reconverts to a real photon in a duplicate magnetic field. The bounds on the coupling constant that could be obtained from a null result in such an experiment compete favorably with astrophysical limits and would substantially improve those from direct measurements.

