The Superconducting Heterodyne Approach to Axion Detection

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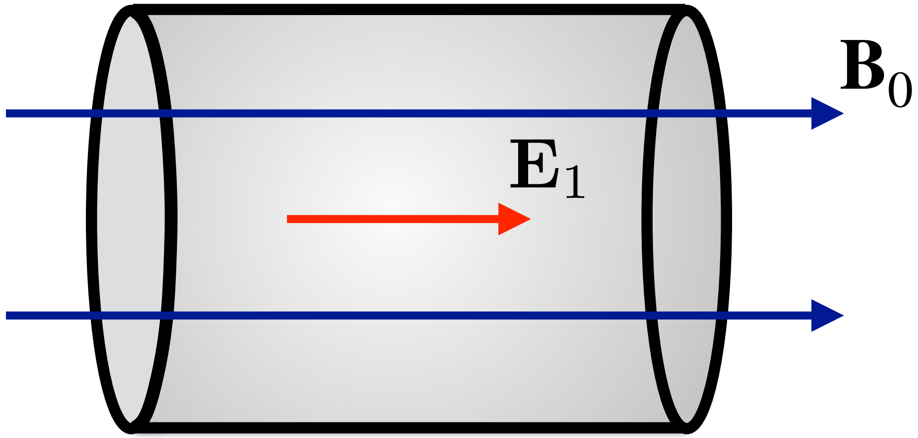
Berkeley Axion Workshop — May 9, 2025

Driving Cavity Modes

A current $\mathbf{J}$ drives the amplitude of a cavity mode with profile $\mathbf{E}_1$ by $\int_V \mathbf{J} \cdot \mathbf{E}_1$

Axion dark matter effectively yields $\mathbf{J} = g_{a\gamma}\, \dot{a}\, \mathbf{B}_0$

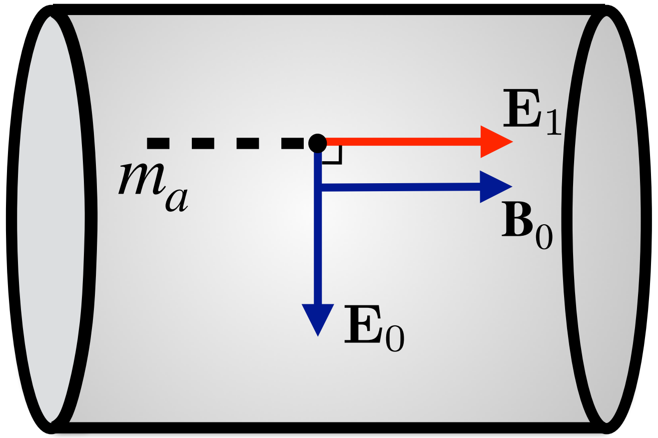


traditional cavity haloscope

place cavity into largest possible static $\mathbf{B}_0$

excites mode at $\omega_1 = m_a$

probes $m_a \sim 1/L \sim \mathrm{GHz}$



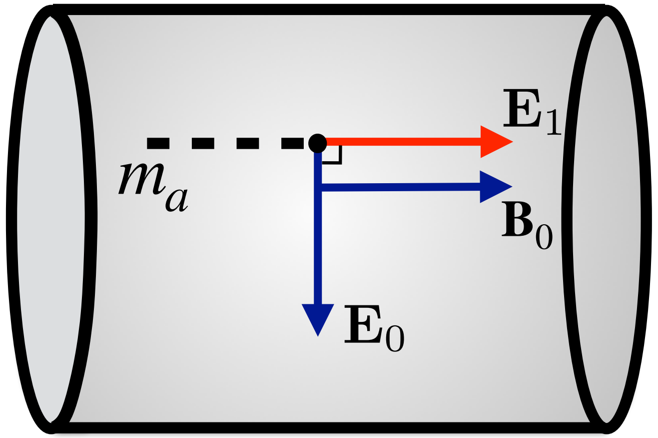
heterodyne approach

excite a cavity mode at $\omega_0 \sim \mathrm{GHz}$

axion transfers energy to mode at $\omega_1 = \omega_0 + m_a$

small difference probes $m_a \ll \mathrm{GHz}$

The Superconducting Heterodyne Approach



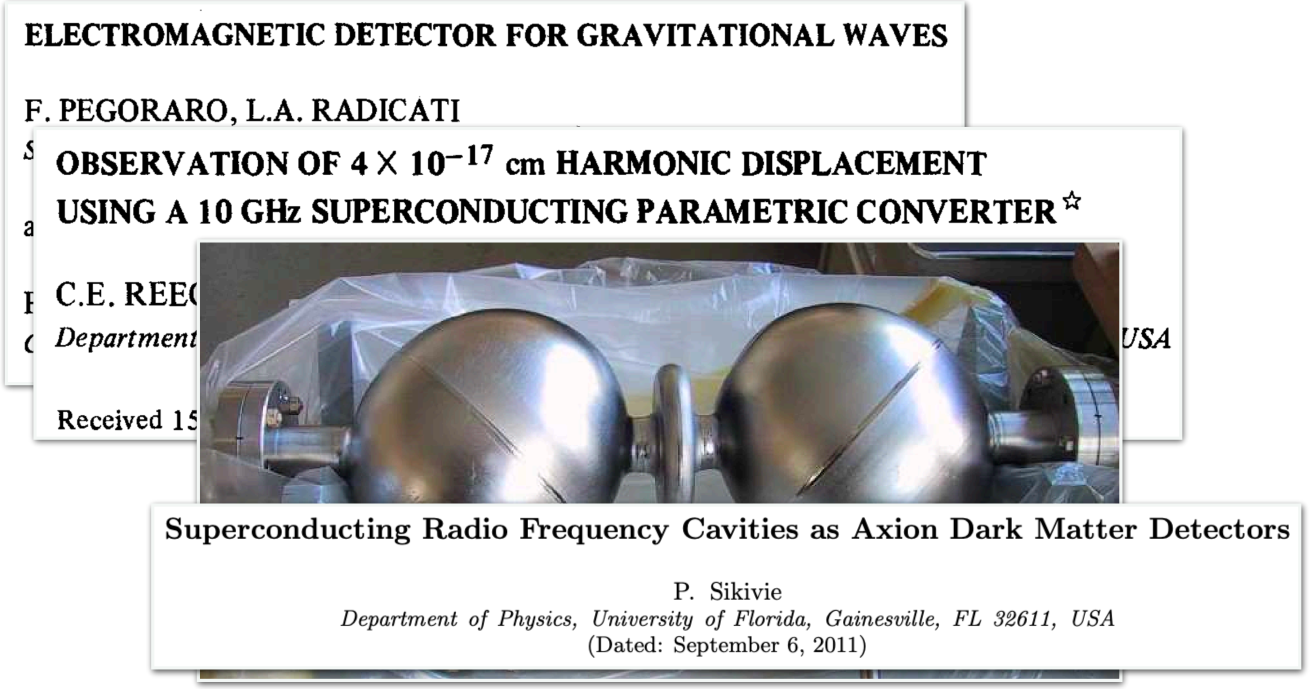
driving $g_{a\gamma}\, \dot{a} \int_V \mathbf{B}_0 \cdot \mathbf{E}_1$ $\qquad P_{\mathrm{sig}} \sim (g_{a\gamma}\, \dot{a}\, B_0)^2\, V \min(t_r\,, t_a)$

cavity decay time $t_r \sim Q_1/\omega_1 \sim (1\,\mathrm{ns})\, Q_1$

axion coherence time $t_a \sim (1\,\mathrm{sec})(\mathrm{MHz}/m_a)$

Requires high B_0 and t_r, both enabled by high $Q \sim 10^{11}$ in superconducting cavities

Fabrication, calibration, loading, measurement enabled by decades of accelerator R&D



suggested for gravitational waves in 1970s

prototyped in 1980s

first serious effort (MAGO) in early 2000s

proposed by Sikivie for axions in 2010

revived for light axions in 2019

Unique Features of the Heterodyne Approach

The heterodyne approach upends all conventional wisdom about axion experiments

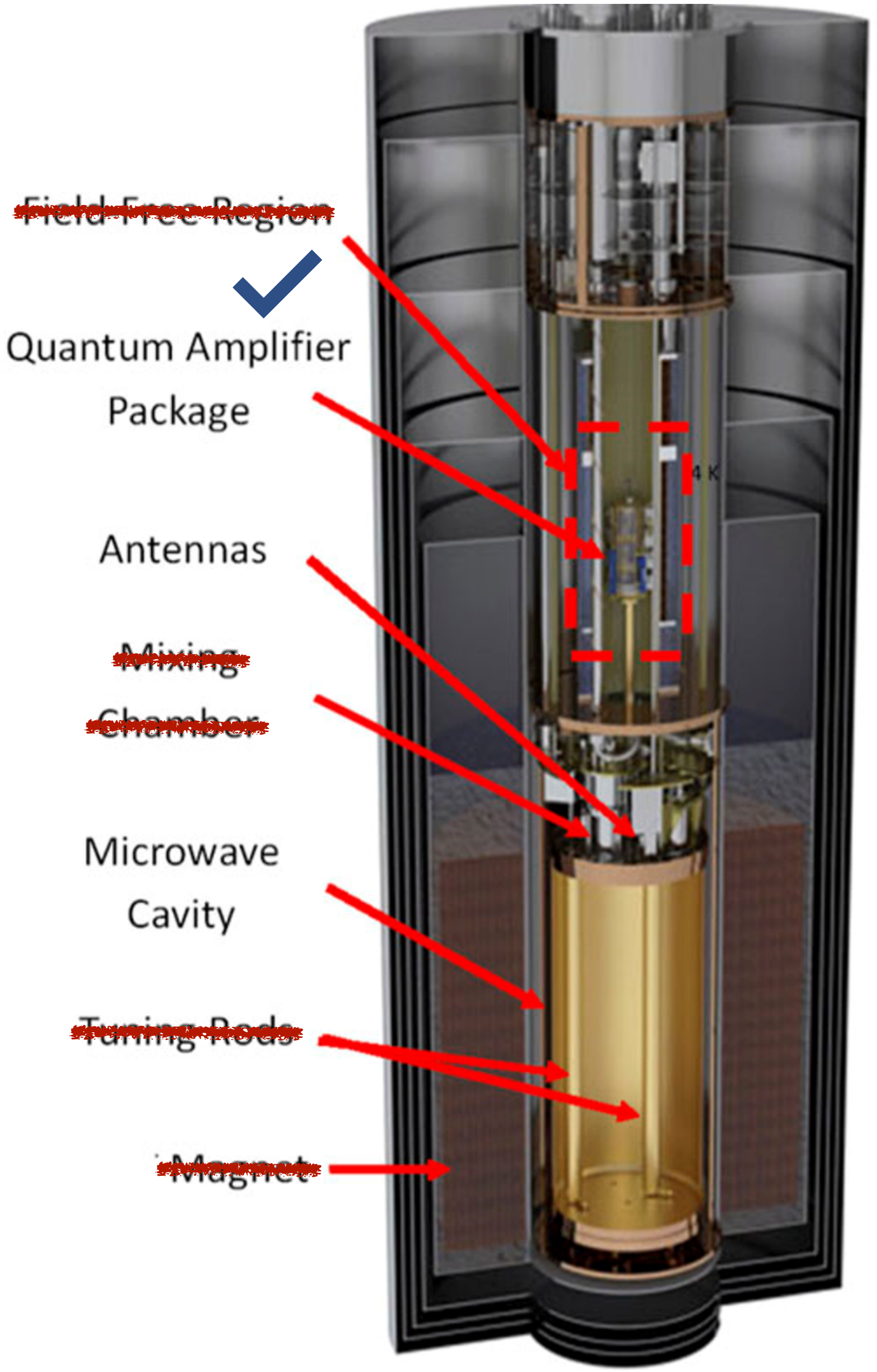
No large magnet: field excited in cavity ($B_0 \sim 0.2\,\mathrm{T}$)

No dilution fridge: use helium cryostat ($T \sim 2\,\mathrm{K}$)

(typical operating points for these cavities)

Same output frequency as ADMX, so use same amplifiers; **no new "quantum tricks"**

Linear tuning: a small shift $\Delta\omega_i/\omega_i \sim 10^{-3}$ in one cavity covers **all** m_a from zero to MHz



Parametric Advantage at Low Axion Mass

At low m_a, using a static $\mathbf{B}_0$ would excite a "magnetoquasistatic" mode

cavity mode: $E_1 \sim B_1$

magnetoquasistatic: $E_1 \sim (m_a L)\, B_1$

$$\frac{P_{\text{sig}}^{(\text{het.})}}{P_{\text{sig}}^{(\text{static})}} \propto \frac{1}{(m_a L)^2} \sim 10^6 \left(\frac{\text{MHz}}{m_a} \right)^2$$

Assuming thermal + standard quantum limited amplifier noise:

$$\frac{\text{SNR}^{(\text{het})}}{\text{SNR}^{(\text{static})}} \sim \frac{\omega_1}{m_a} \left(\frac{Q}{Q_{\text{static}}} \right)^{1/2} \left(\frac{T_{\text{static}}}{T} \right)^{1/2} \left(\frac{B}{B_{\text{static}}} \right)^2$$

$\sim 10^3$ enhancement at MHz
(more if static doesn't reach SQL)

$\sim 10^2$ enhancement

$\sim 1/10$ penalty

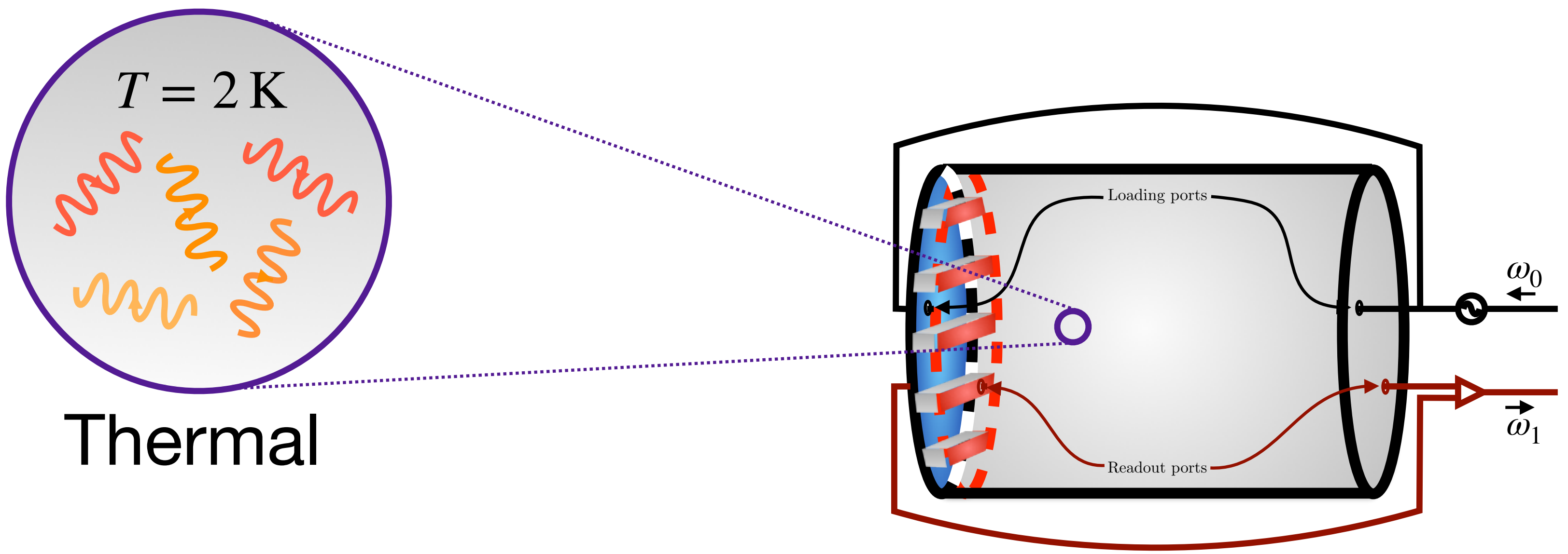
$\sim 1/10^3$ penalty

Estimating Noise: Thermal

$$S(m_a) \sim T \sim 10^{-4}\,\mathrm{eV}$$

Higher temperature than other axion experiments,
signal mode has ~ 100 thermal photons

But compensated by much higher signal power



1912.11048, 1912.11056, 2007.15656

Estimating Noise: Crosstalk

$P_{\text{in}} \sim (1\,\text{kW})\,(10^{11}/Q) \sim 10^{20}\,P_{\text{sig}}$, isolated by geometric and frequency separation

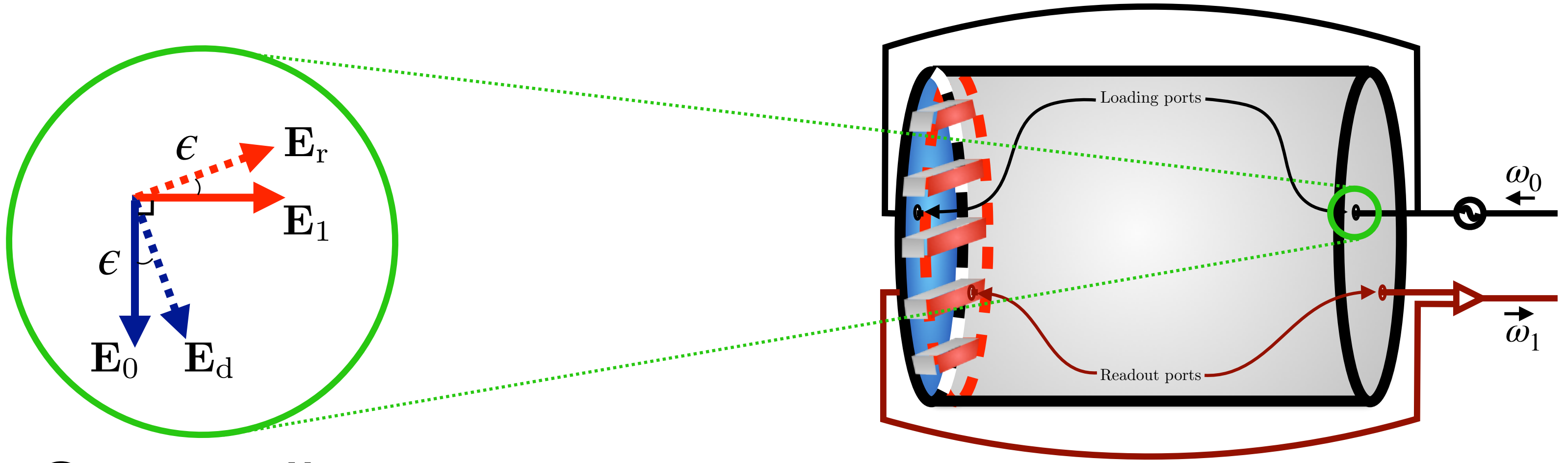
$$S(m_a) \sim P_{\text{in}}\,\epsilon^2 \times \begin{cases} S_\varphi(m_a) & \text{oscillator phase noise} \\ S_\delta(m_a) & \text{fractional wall deformation} \end{cases}$$

cross-coupling factor,
$\epsilon = 10^{-7}$ achieved by MAGO

for commercial oscillators: $S_\varphi(\text{kHz}) \sim 10^{-12}/\text{Hz}$

DarkSRF measurement: $S_\delta(100\,\text{Hz}) \sim (10^{-9})^2/(100\,\text{Hz})$

both rapidly fall off for higher frequency



Crosstalk

Thermal noise larger above:

kHz: $\epsilon = 10^{-7}$

MHz: $\epsilon = 10^{-4}$

1912.11048, 1912.11056, 2007.15656

Estimating Noise: Vibrations

As usual for axion experiments, vibrational noise greatly dominates at kHz

$$S(m_a) \sim P_{\mathrm{in}}\, \eta^2\, Q_1^2\, S_\delta(m_a)$$

mode mixing form factor

$$\eta = \int_S (\mathbf{u} \cdot d\mathbf{S})\,(\mathbf{B}_0 \cdot \mathbf{B}_1 - \mathbf{E}_0 \cdot \mathbf{E}_1)$$

ideally zero for certain cavity geometries

often set by $\sim 10^{-4}$ precision of manufacture

falls off for higher mech. modes, $\eta \propto \omega_{\mathrm{min}}/m_a$

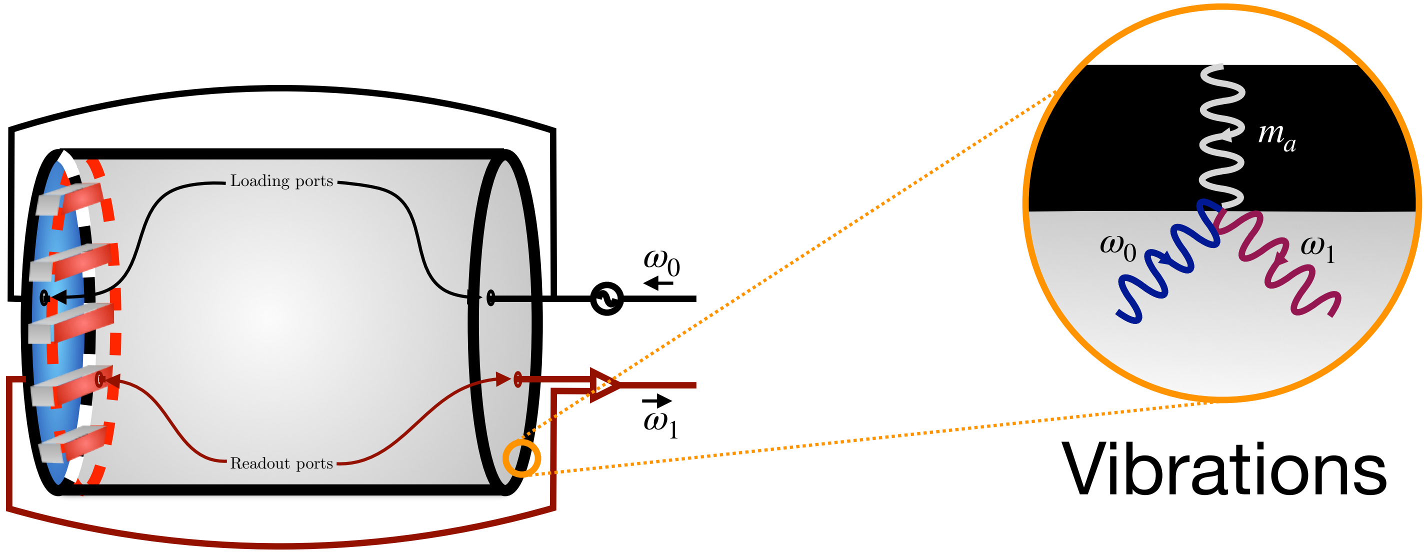
(reducible by stiffening walls)

largely due to cooling system

pessimistic assumption: $S_F(m_a) \propto 1/m_a$

at high frequency, $S_\delta(m_a) \propto S_F(m_a)/m_a^4$

subdominant at MHz if η reasonably small

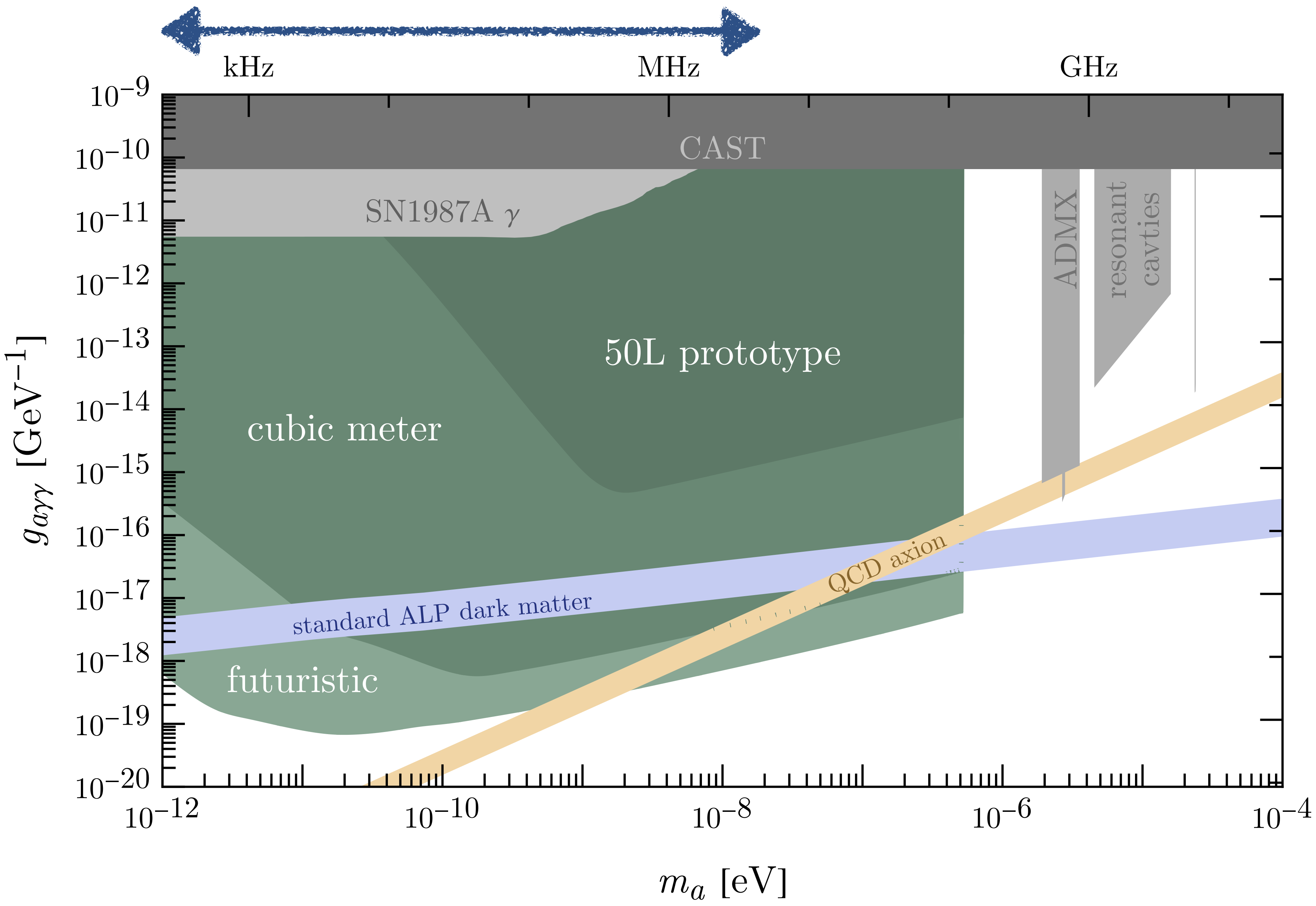


Vibrations

1912.11048, 1912.11056, 2007.15656

Potential Sensitivity

tuning range of a single cavity



High mass: thermal limited

$$B_0 = 0.2\,\mathrm{T}, T = 2\,\mathrm{K}$$

$$Q = \begin{cases} 10^{10} & \text{prototype} \\ 10^{12} & \text{cubic meter} \end{cases}$$

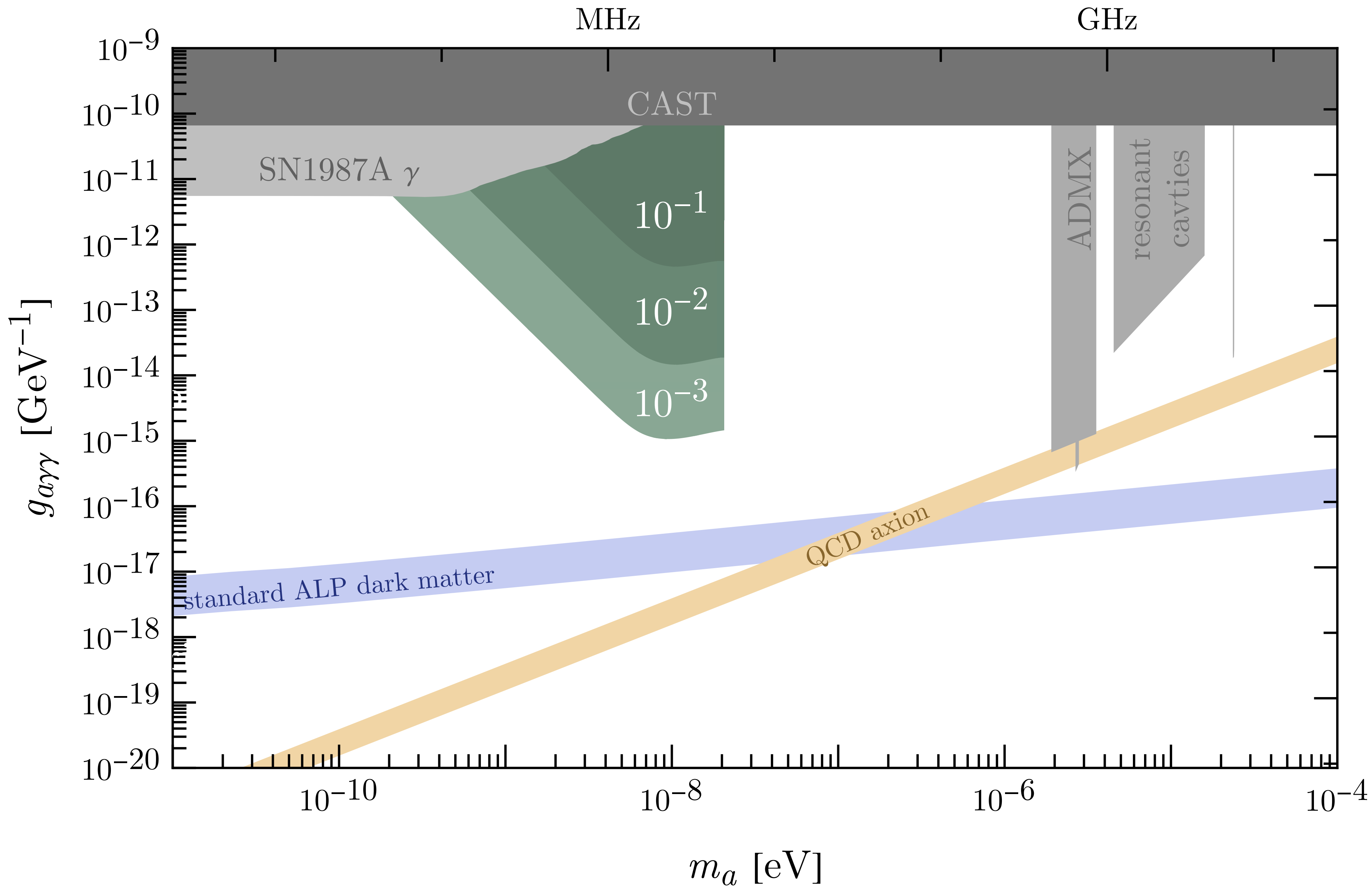
Lower mass: crosstalk/vibration

$$\epsilon = \begin{cases} 10^{-3} & \text{prototype} \\ 10^{-7} & \text{cubic meter} \end{cases}$$

$$\eta = \begin{cases} 10^{-4} & \text{prototype} \\ 10^{-5} & \text{cubic meter} \end{cases}$$

Probes QCD axion at $\sim 10\,\mathrm{MHz}$

“Off the Shelf” Prototype Sensitivity



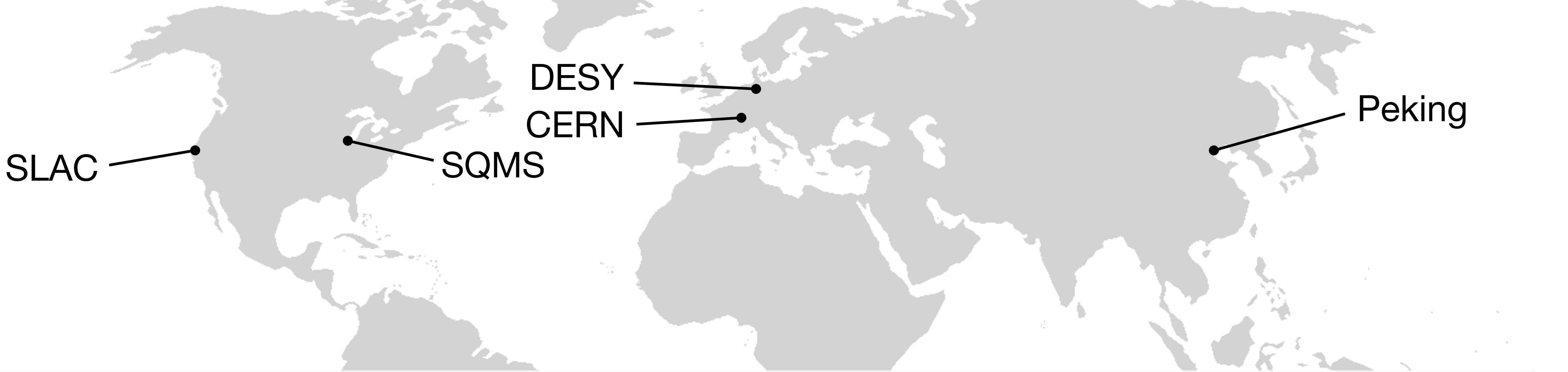
Projection for existing **unoptimized** cavities

High values of ϵ and η

Low signal form factor, multiples power by 0.04

Vibrational force PSD scaled up by $\sim 10^6$

Global Status Update



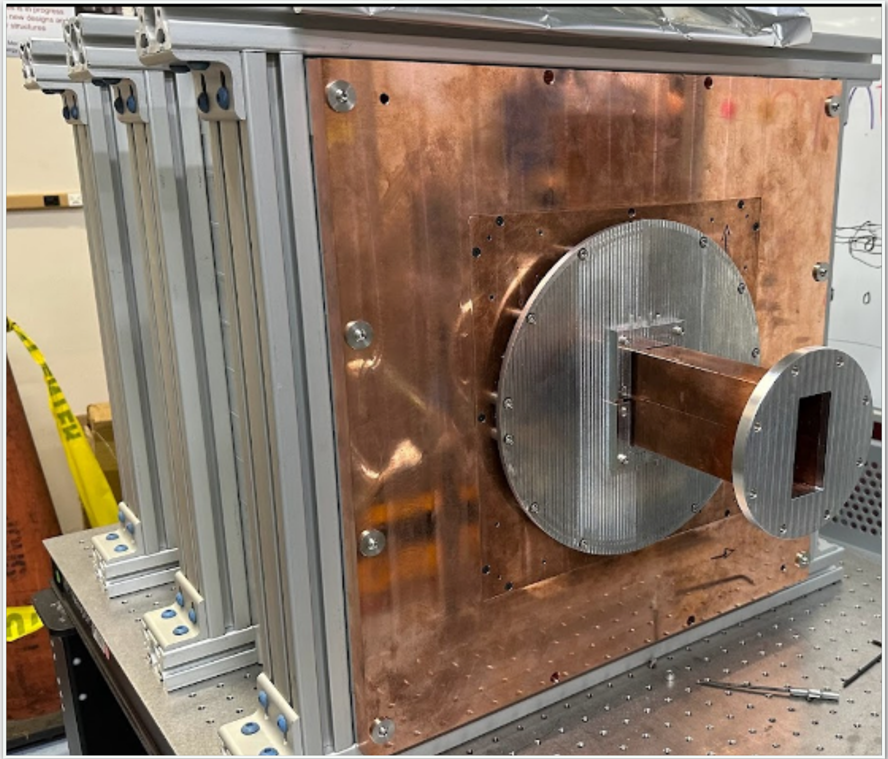
Several groups, at labs with expertise in superconducting cavities, are currently designing prototypes and taking measurements

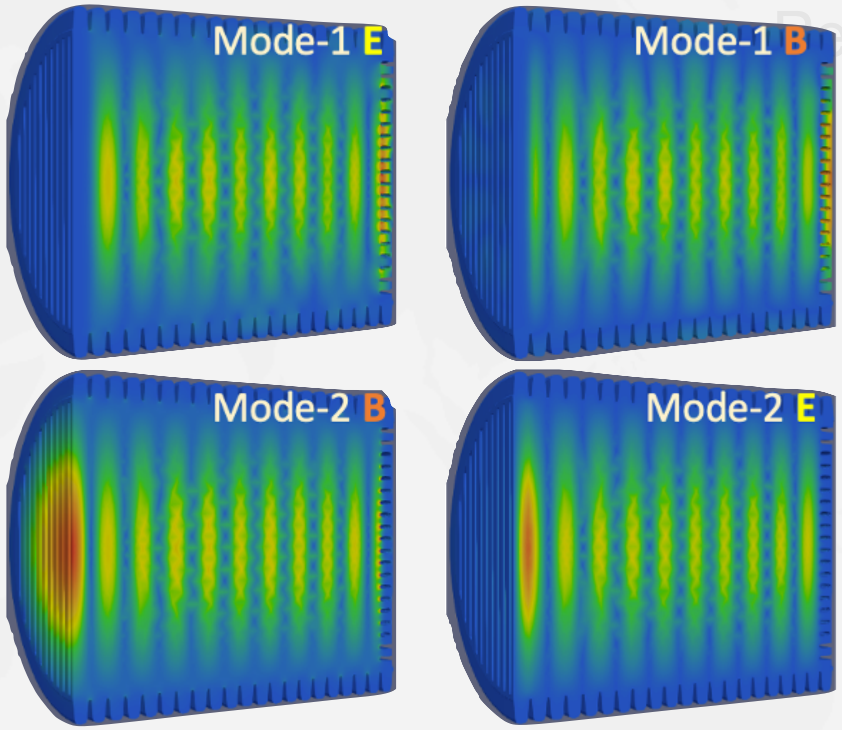
Current level of funding is sufficient to demonstrate proof of principle and probe far beyond astrophysical bounds

Scaling to QCD axion sensitivity requires qualitative increase in funding

SLAC

LDRD effort at SLAC (2022-2024)



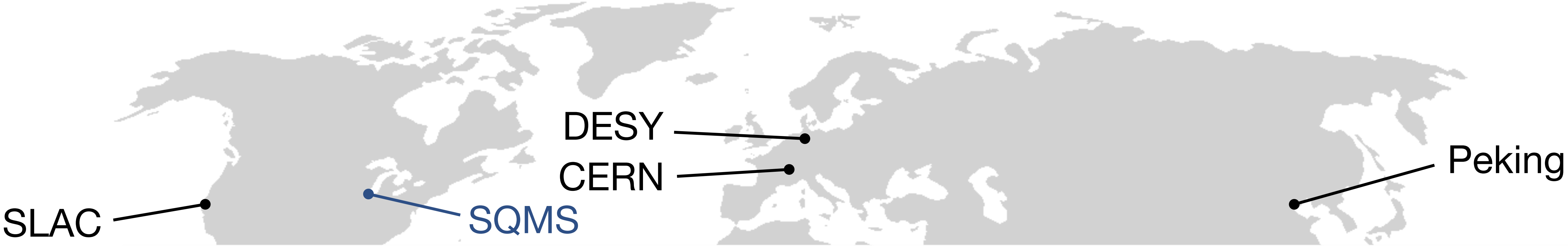


made corrugated copper cavity with two orthogonal modes

moving tuning fins gives range $\Delta f = 4\,\mathrm{MHz}$

mode profiles enable: $\eta < 10^{-3}$ for **any** vibration

$\epsilon \leq 2 \times 10^{-4}$ by just hand tuning



SHADE collaboration at SQMS (started 2021)

longest running and most developed effort

2022: measurement of existing 9-cell cavity at $T = 2\,\mathrm{K}$, no exotic noise observed

2024: new cavities with small η instrumented

2025: planned cold measurement, tuning test

further details in Bianca Giaccone's talk

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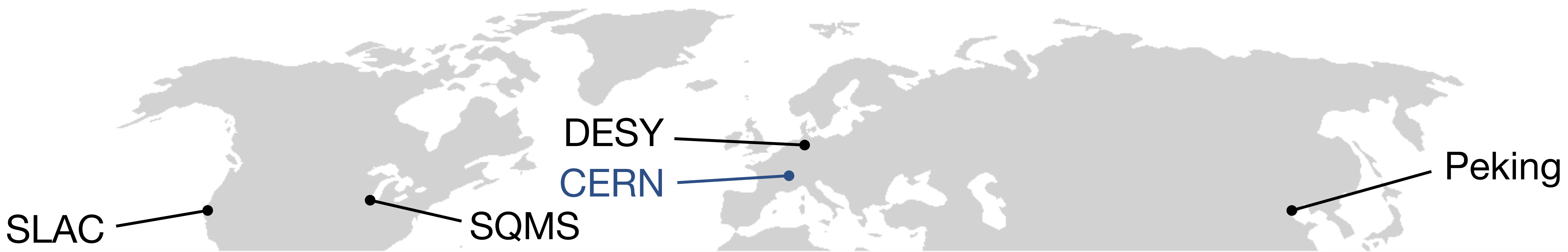

QUANTUM TECHNOLOGY INITIATIVE

New effort at CERN (started 2025)

Funded by QTI in affiliation with PBC

Aims to develop and run superconducting prototype in next 2-3 years

Developing optimizations for heterodyne detection:

non-mechanical tuning,
to operate cryogenically

new cavity designs to
reduce ϵ and η

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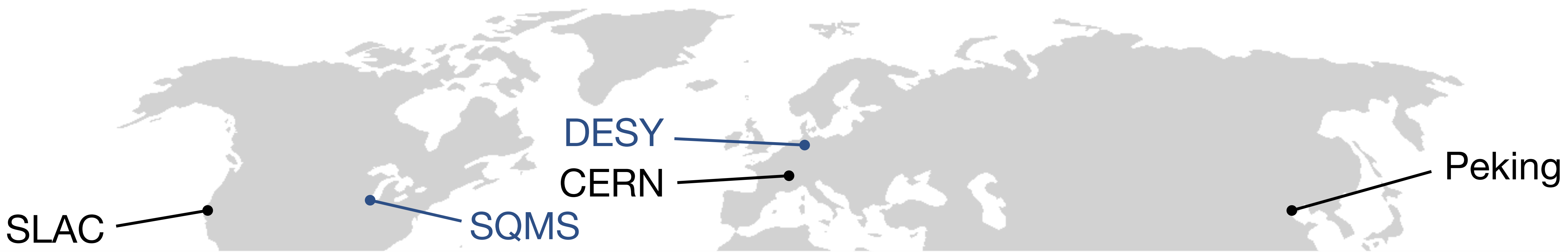

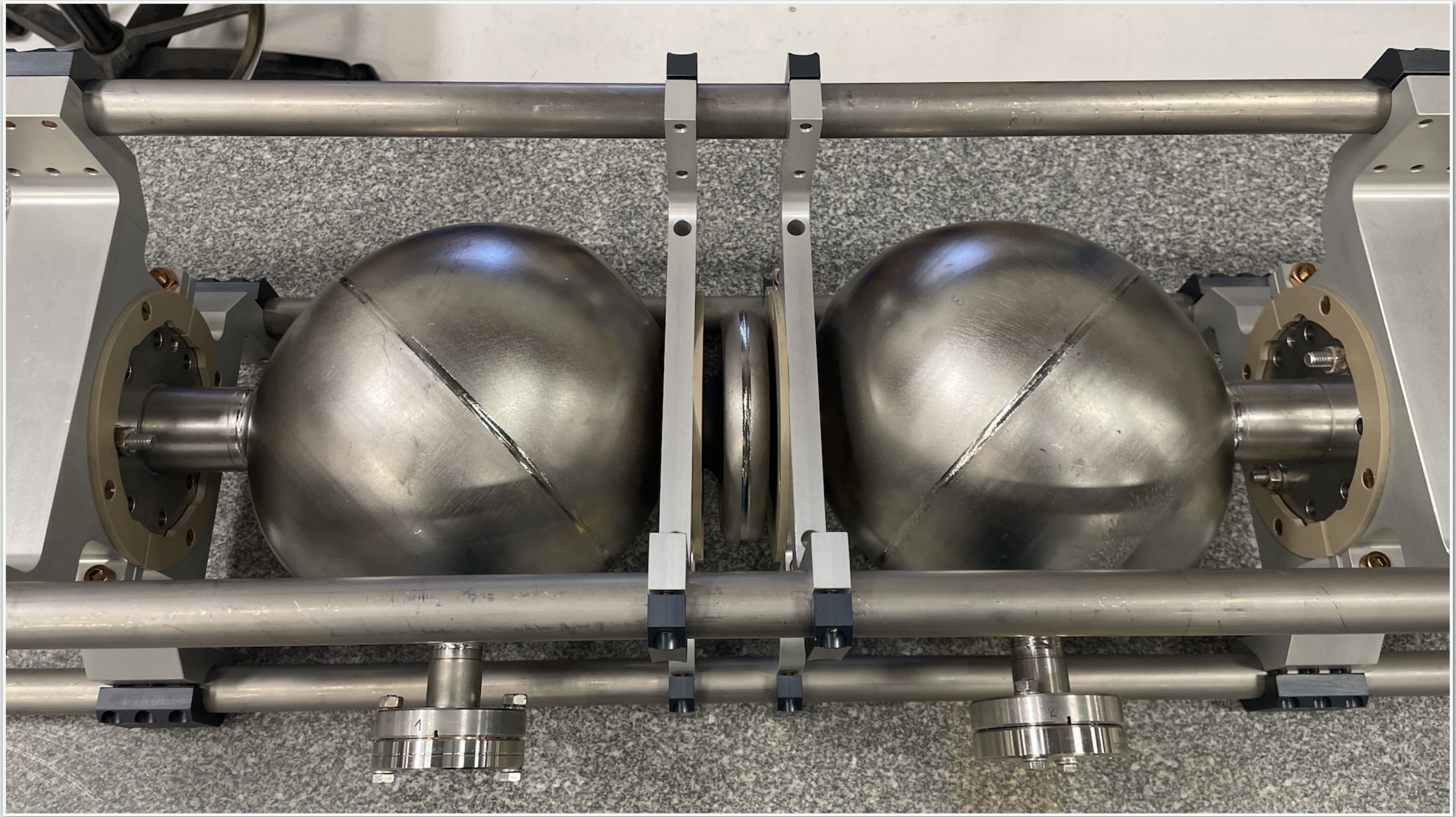

Revival of MAGO (started 2024)

Joint effort of DESY and SQMS

Two-sphere cavity recovered, tuned

Vibrational modes simulated

Optimized for gravitational waves,
but shares noise sources

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SHANHE collaboration at Peking (started 2023)

2023: dark photon search, no driving

early 2025: calibration run at $T = 4\,\mathrm{K}$, only thermal noise seen

mid 2025: data taking run ongoing

2026: planned run with new cavity designed to reduce ϵ and η

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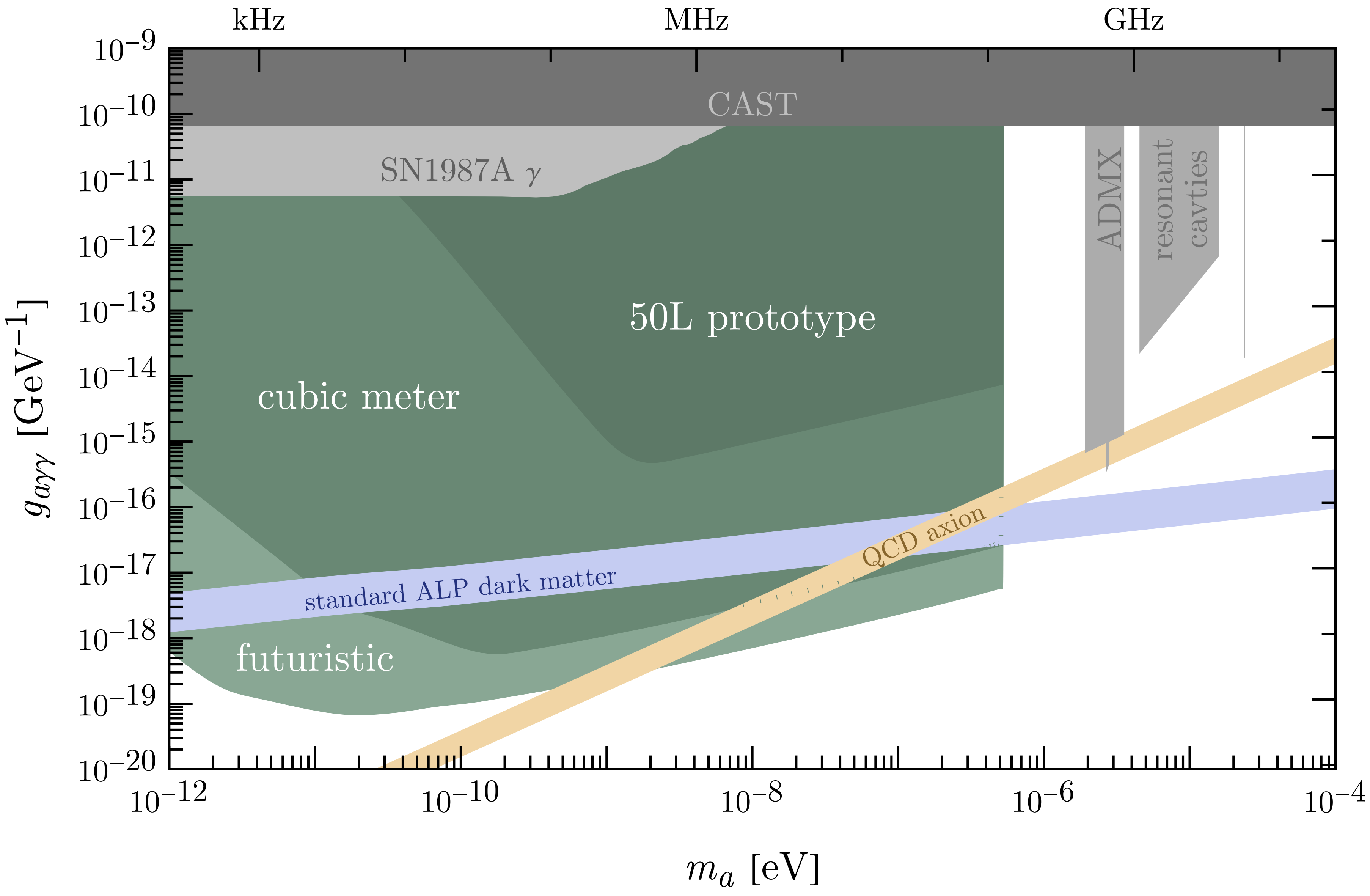
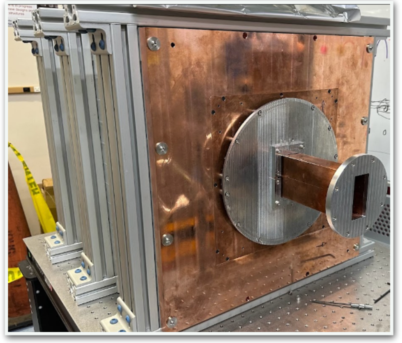
Outlook

Superconducting cavities are **not** science experiments

They are mass-produced, practical technology





But they have the potential to transform the search for light axion dark matter

Multiple ongoing efforts will demonstrate feasibility in next ~2 years