The Superconducting Heterodyne Approach to Axion Detection

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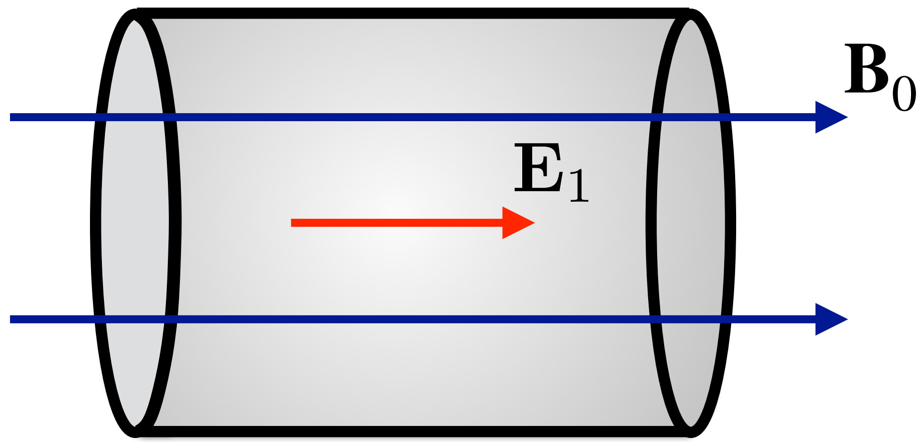
BERKELEY LAB

Axions in Stockholm — July 3, 2025

Driving Cavity Modes

In background $\mathbf{B}_0$, axion drives cavity mode with profile $\mathbf{E}_1$ by $g_{a\gamma\gamma}\,\dot{a}\int_V \mathbf{B}_0 \cdot \mathbf{E}_1$



traditional cavity haloscope

use large static $\mathbf{B}_0$, excites mode at $\omega_1 = m_a$

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

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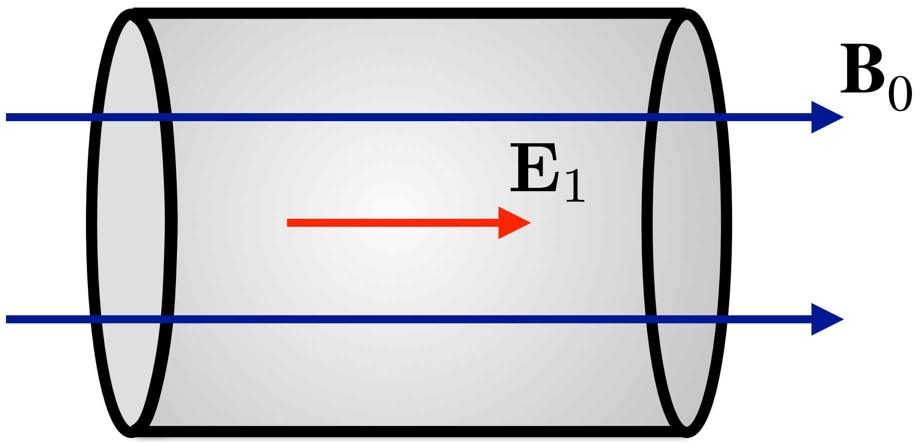

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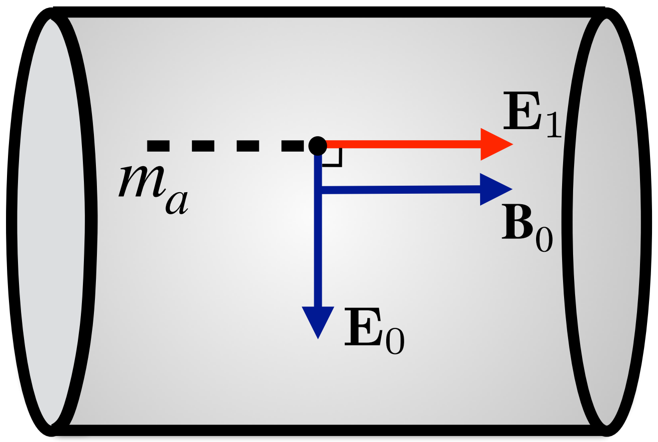

heterodyne approach

drive cavity mode, $\mathbf{B}_0$ oscillates at $\omega_0 \sim \mathrm{GHz}$

excites signal mode at $\omega_1 = \omega_0 \pm m_a$

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

Heterodyne Signal Power

$$P_{\rm sig} \sim (g_{a\gamma\gamma}^2 \rho_{\rm DM})\,(B_0^2 V)\,(Q_1/\omega_1)$$

energy stored in driven mode

decay time of signal mode

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Strong potential sensitivity in superconducting cavities, where $Q \sim 10^{11}$

Fabrication, calibration, loading, measurement
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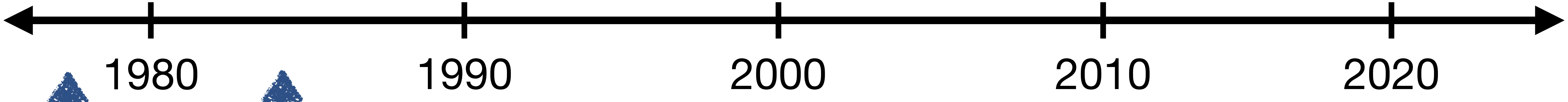
Why is this competitive with using a much larger static field?

avoids the magnetoquasistatic penalty factor: $(m_a L)^2 \sim 10^{-6} \left(\frac{m_a}{\text{MHz}}\right)^2$

History of the Heterodyne Approach



prototyped

OBSERVATION OF 4 × 10^{-17} cm HARMONIC DISPLACEMENT USING A 10 GHz SUPERCONDUCTING PARAMETRIC CONVERTER ☆

C.E. REECE [1], P.J. REINER and A.C. MELISSINOS
Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

suggested for gravitational waves

ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES

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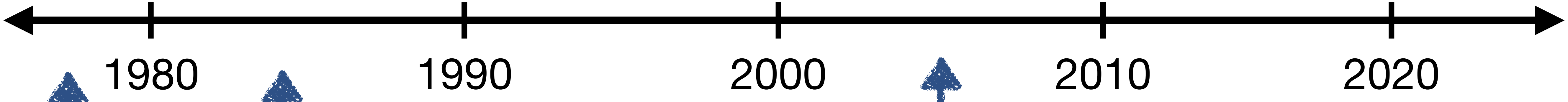

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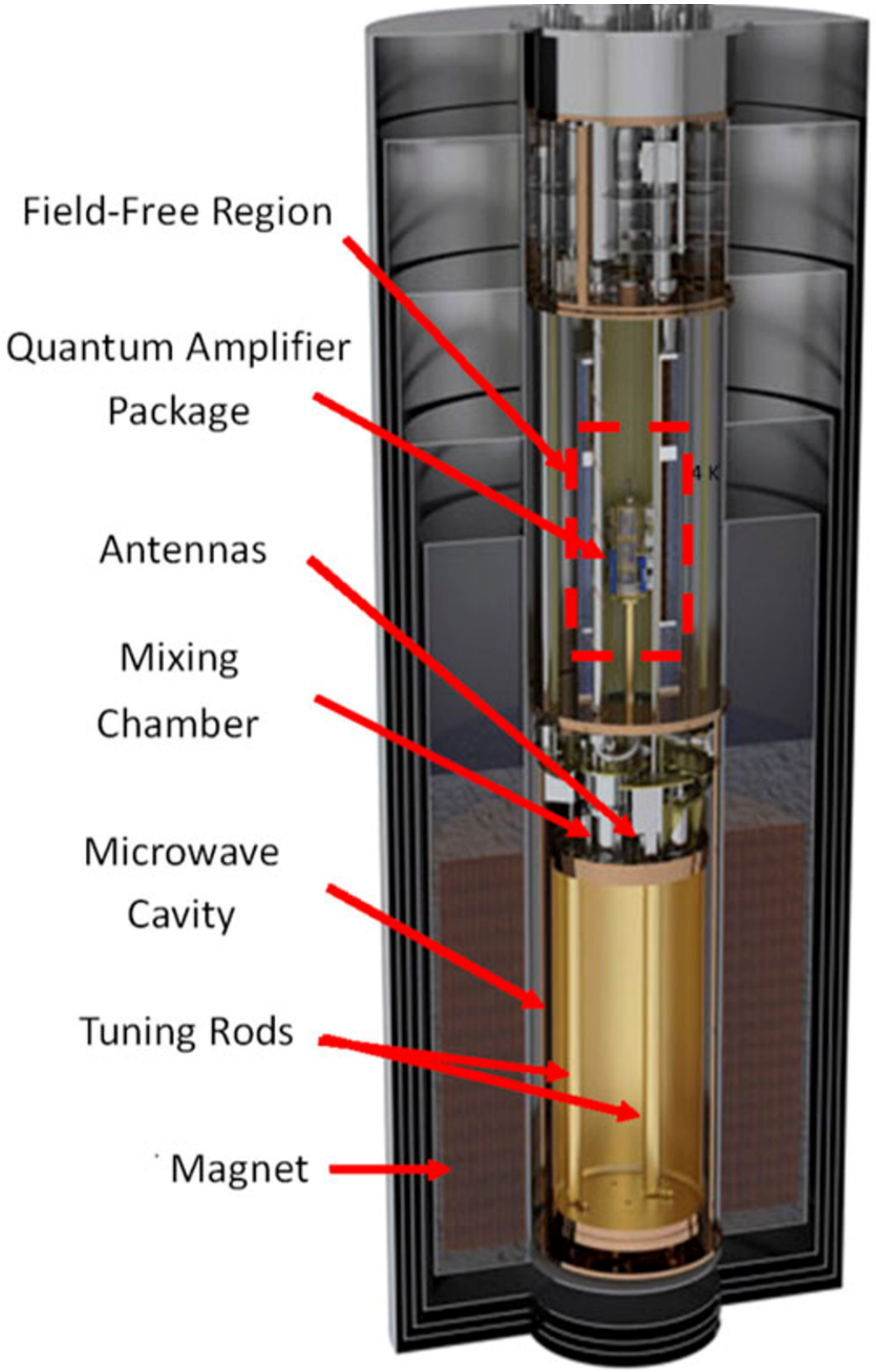
~5 groups developing prototypes

Heterodyne Experiments Look Different



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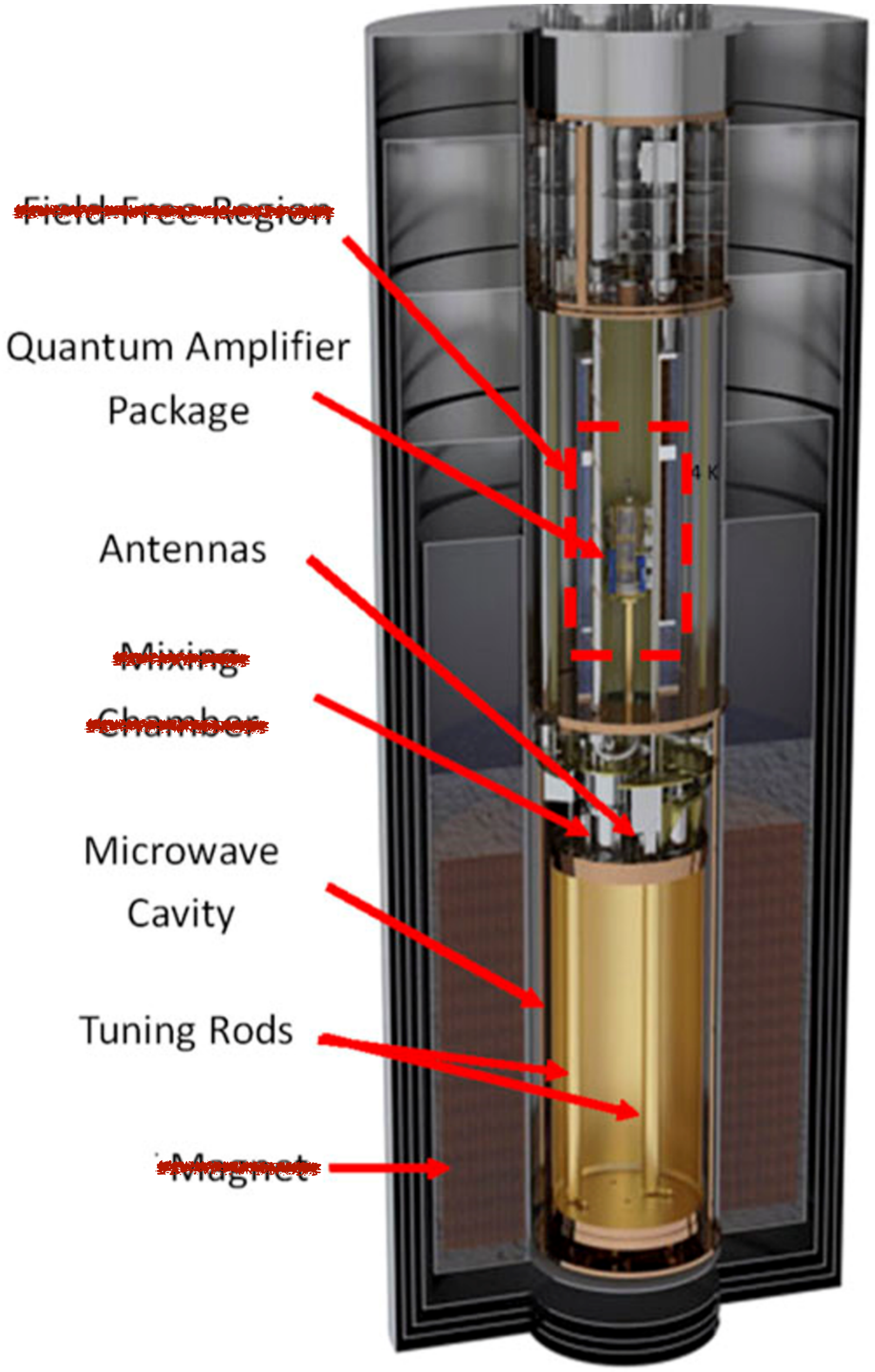
No large magnet: field excited in cavity ($B_0 \sim 0.2\,\mathrm{T}$)

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

(typical operating points for these cavities)



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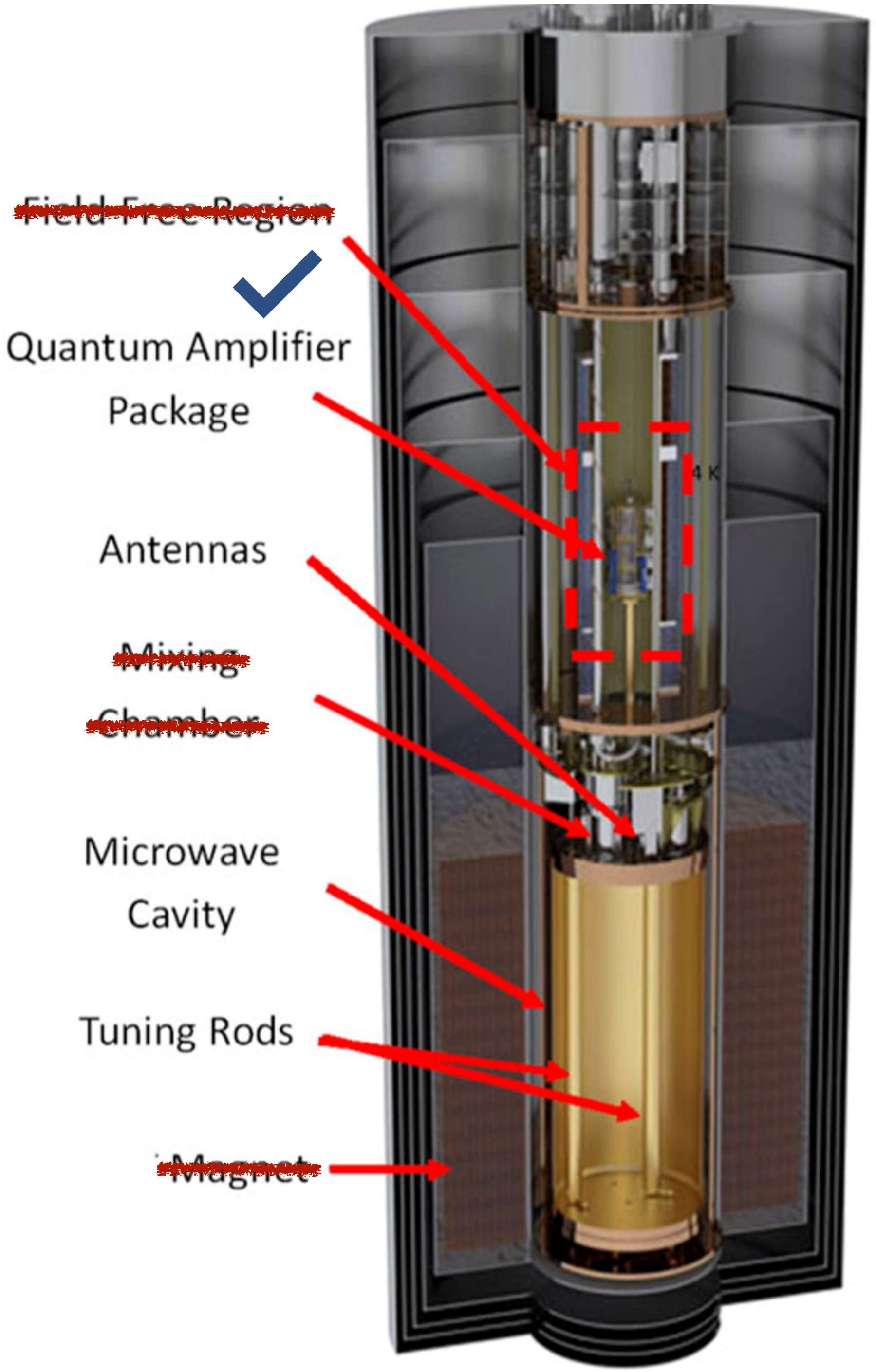

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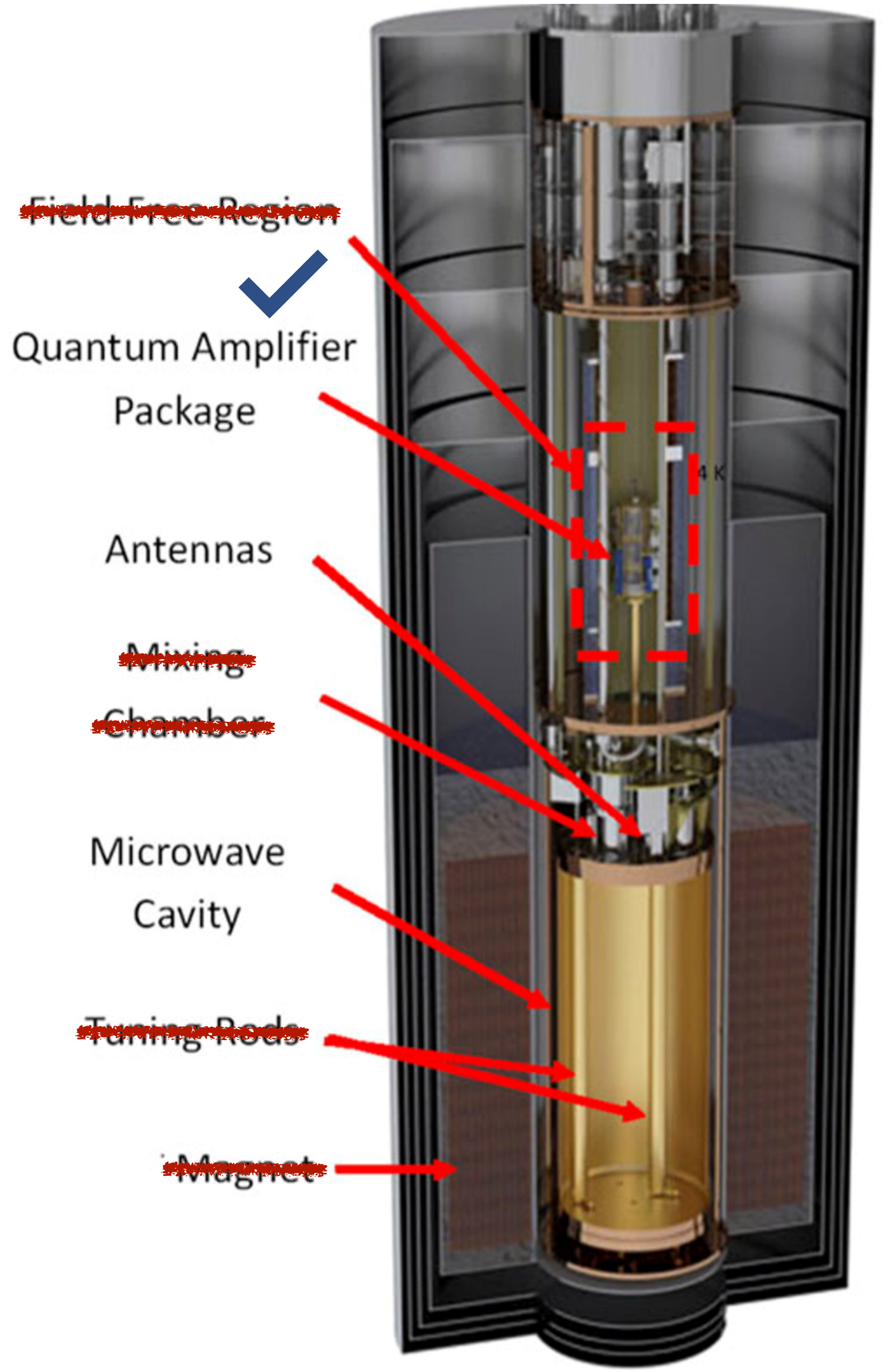
Linear tuning: a small shift $\Delta f/f \sim 10^{-3}$ of one cavity mode covers **all** m_a from zero to MHz

naturally allows one to "rip across frequencies"



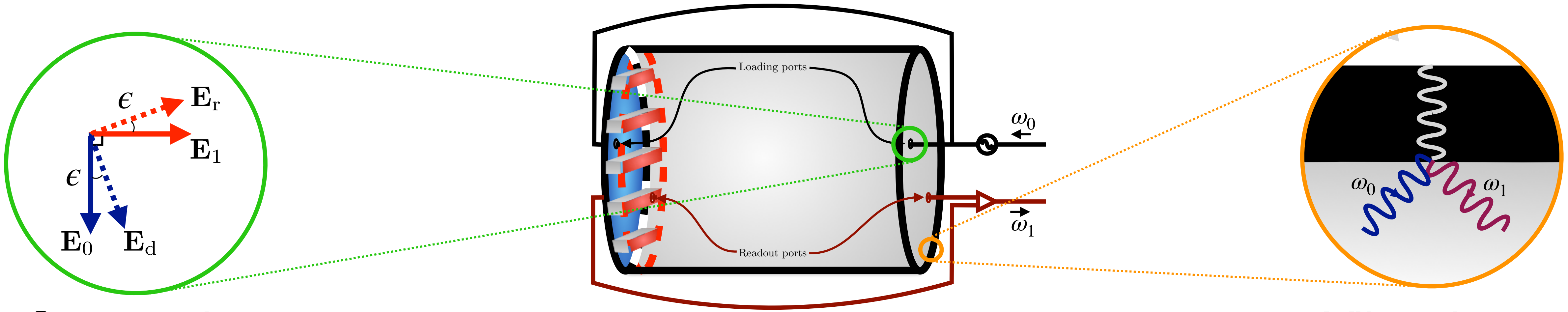
Leakage Noise

Key technical issue: input power can “leak” to signal

Suppressed by geometric factors, and frequency separation of modes

$$S_{\text{leak}}(m_a) \propto P_{\text{in}} \times \begin{cases} \epsilon^2\, S_\varphi(m_a) & \text{oscillator phase noise} \\ \epsilon^2\, S_\delta(m_a) & \text{mode frequency jitter} \\ \eta^2\, S_\delta(m_a) & \text{mechanical mode mixing} \end{cases}$$

Dominates at kHz, but subdominant at MHz if $\epsilon, \eta \ll 1$, requiring good cavity design

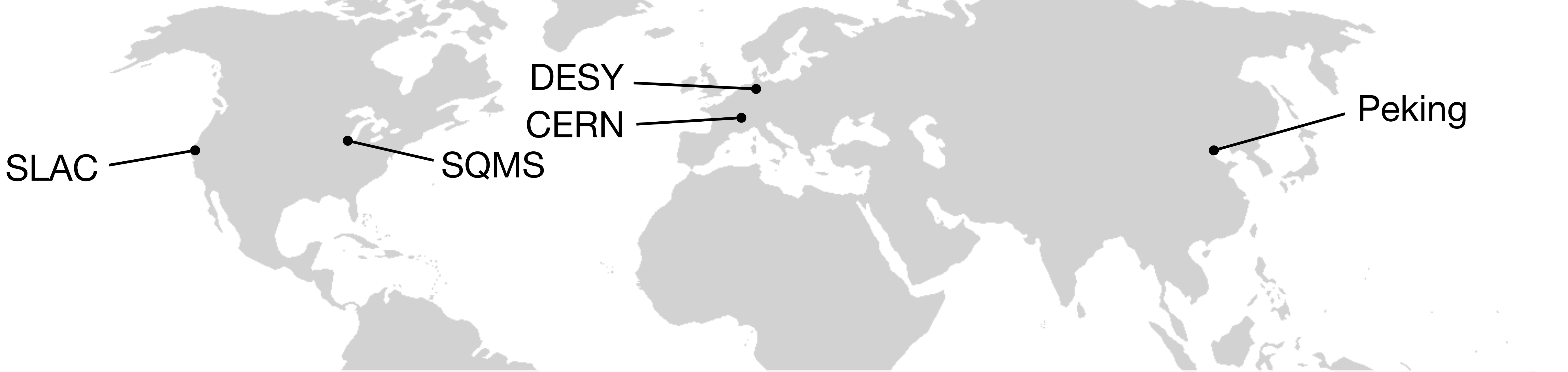


Crosstalk

Vibrations

1912.11048, 1912.11056, 2007.15656

Global Status Update



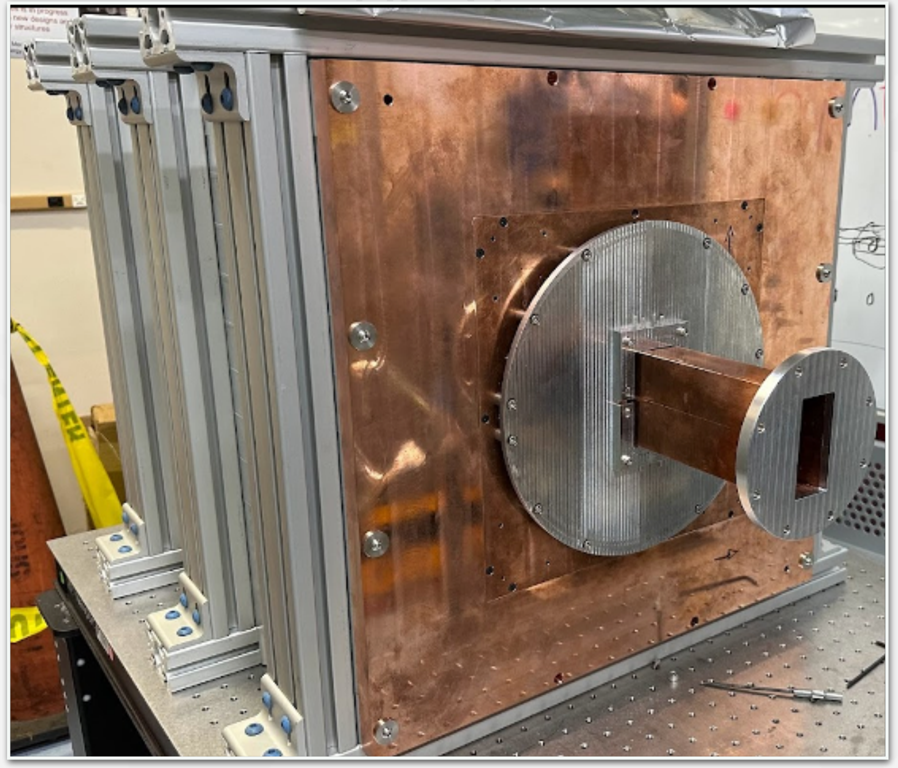
Several groups, at labs with expertise in superconducting cavities, are currently designing prototypes and taking measurements

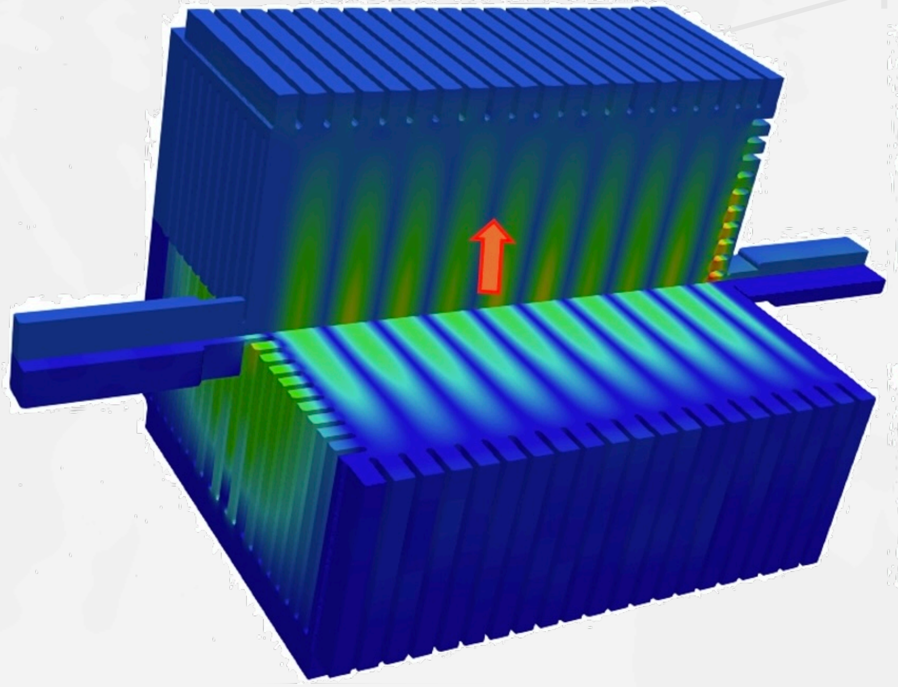
Current level of funding is sufficient to demonstrate proof of principle and probe far beyond astrophysical bounds

Scaling to QCD axion sensitivity requires qualitative increase in funding

SLAC

LDRD effort at SLAC (2022-2024)





corrugated cavity has hybrid modes with $\mathbf{B}_0$ aligned to $\mathbf{E}_1$

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

mode profiles enable $\eta \ll 1$ and $\epsilon \lesssim 10^{-4}$

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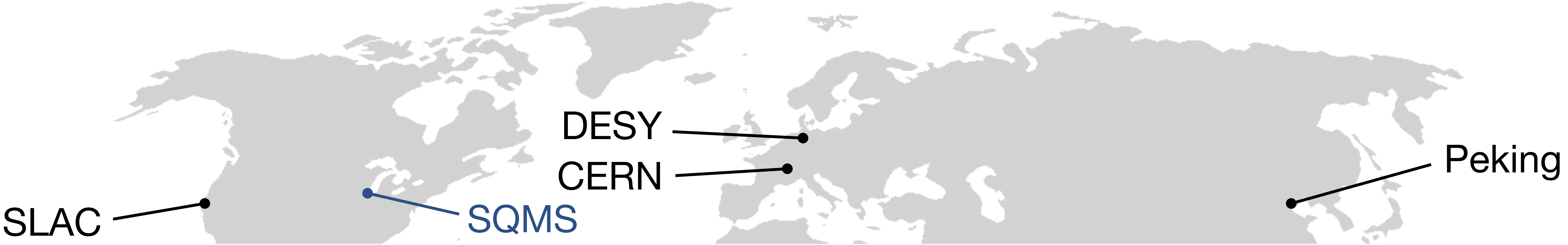


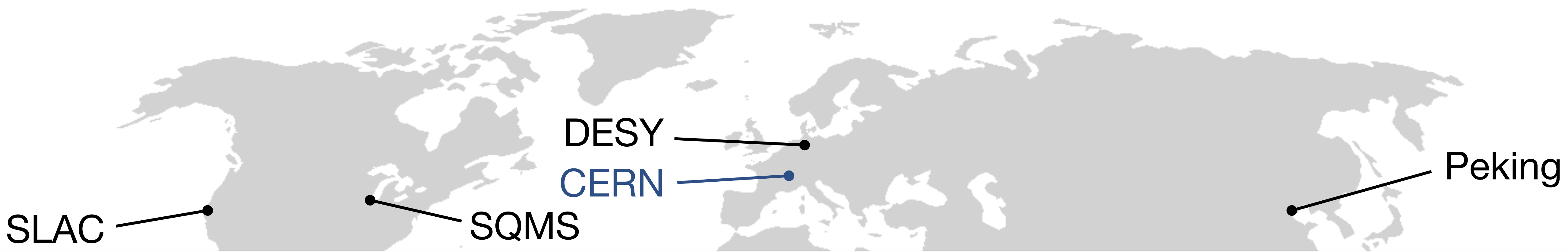
SHADE collaboration at SQMS (started 2021)

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

2024: new cavities with small η instrumented

2025: cold measurement, tuning test

2207.11346



New effort at CERN (started 2025)

Funded by QTI in affiliation with PBC

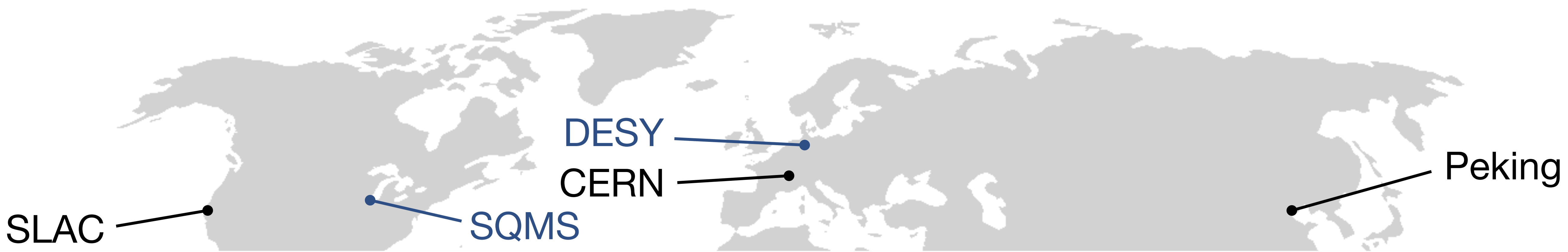
Aims to develop and run superconducting prototype in next 2-3 years

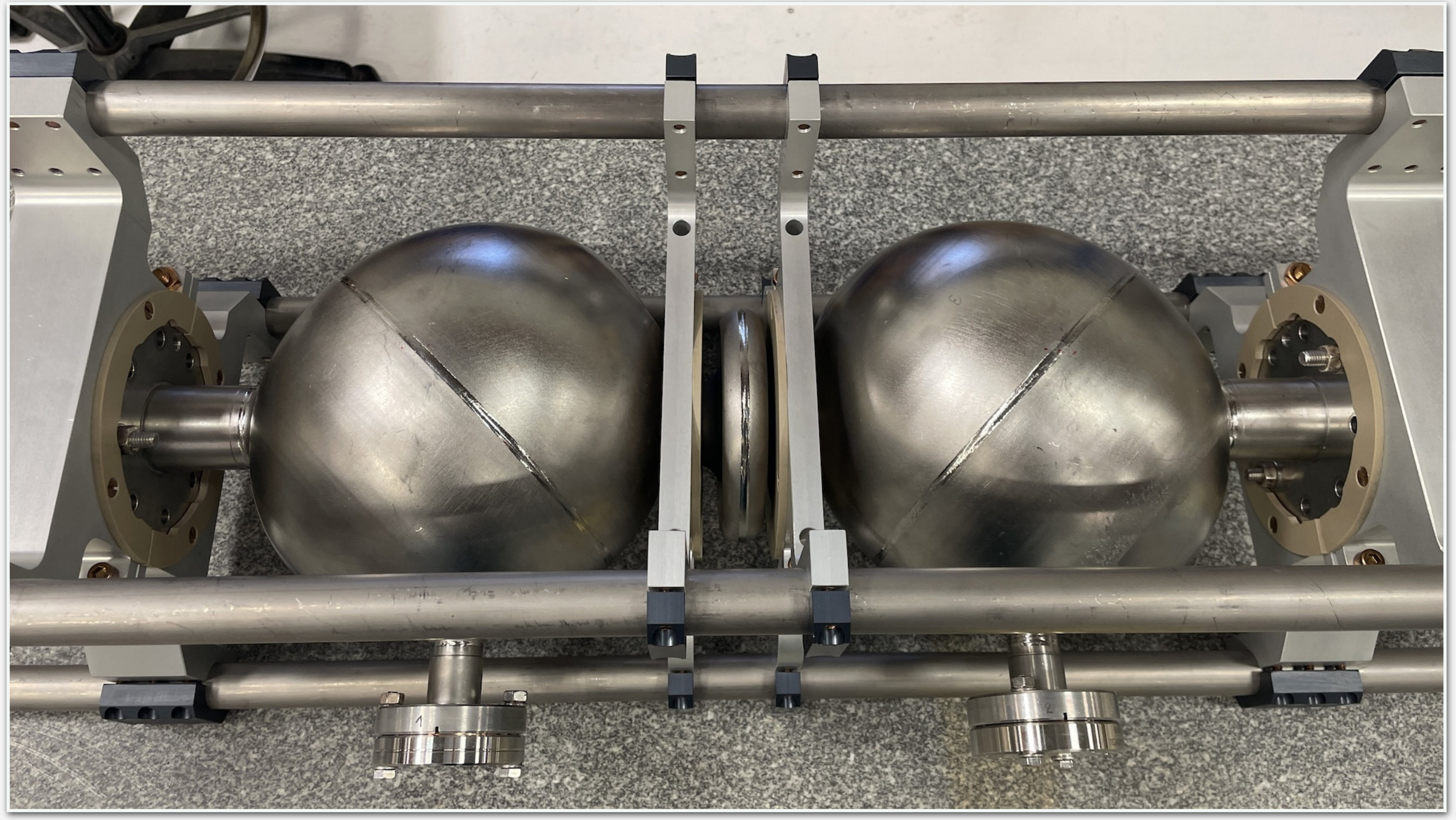
Developing optimizations for heterodyne detection:

non-mechanical tuning,
to operate cryogenically

new cavity designs to
reduce ϵ and η

2505.00947





Revival of MAGO (started 2024)

Joint effort of DESY and SQMS

Original cavity tested, tuned

Electromagnetic, mechanical modes simulated

Optimized for gravitational waves, but shares noise sources

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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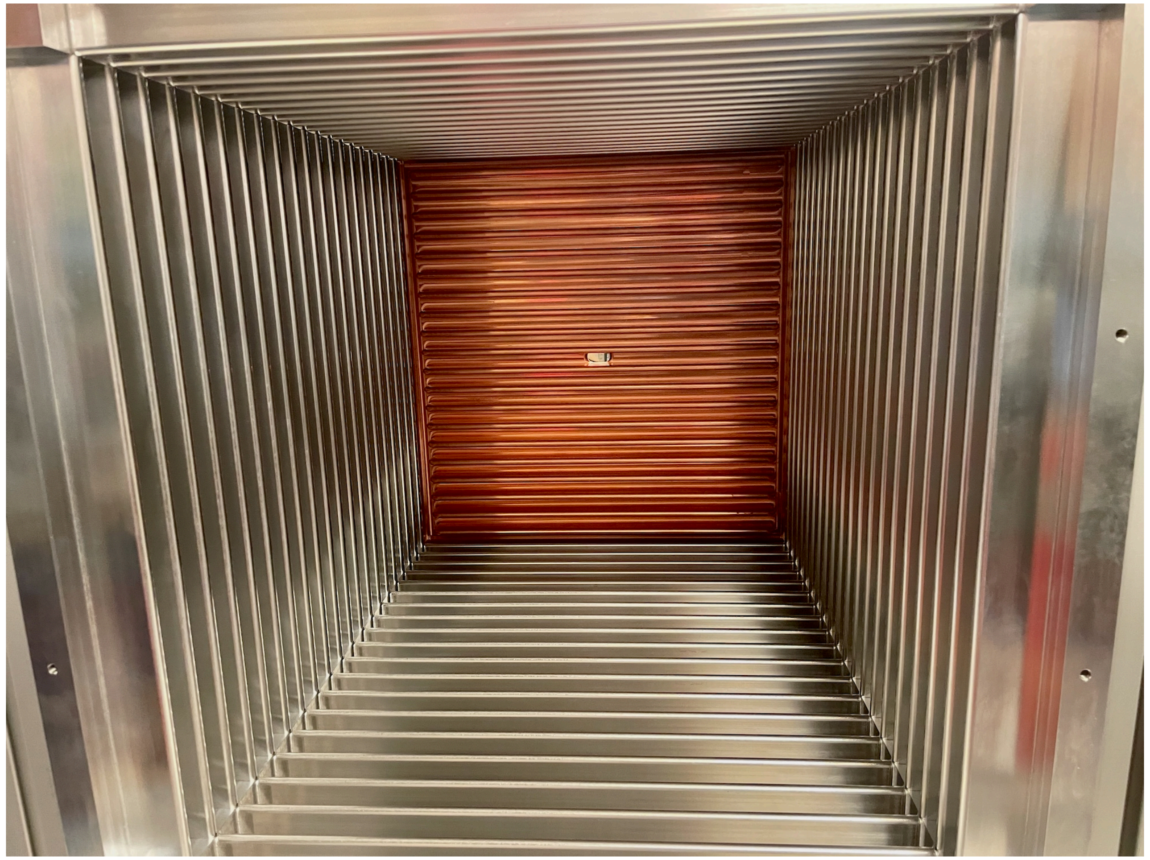
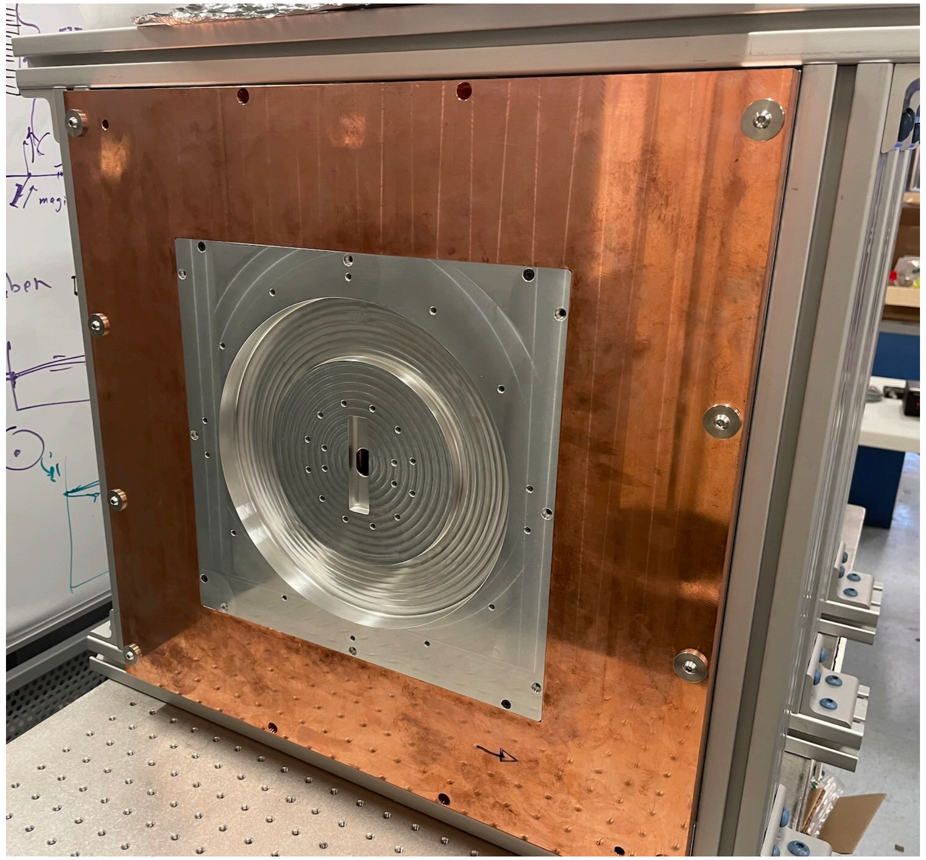
More About SLAC Prototype: Fabrication



made from six corrugated aluminum/copper plates, side length $0.5\,\mathrm{m}$

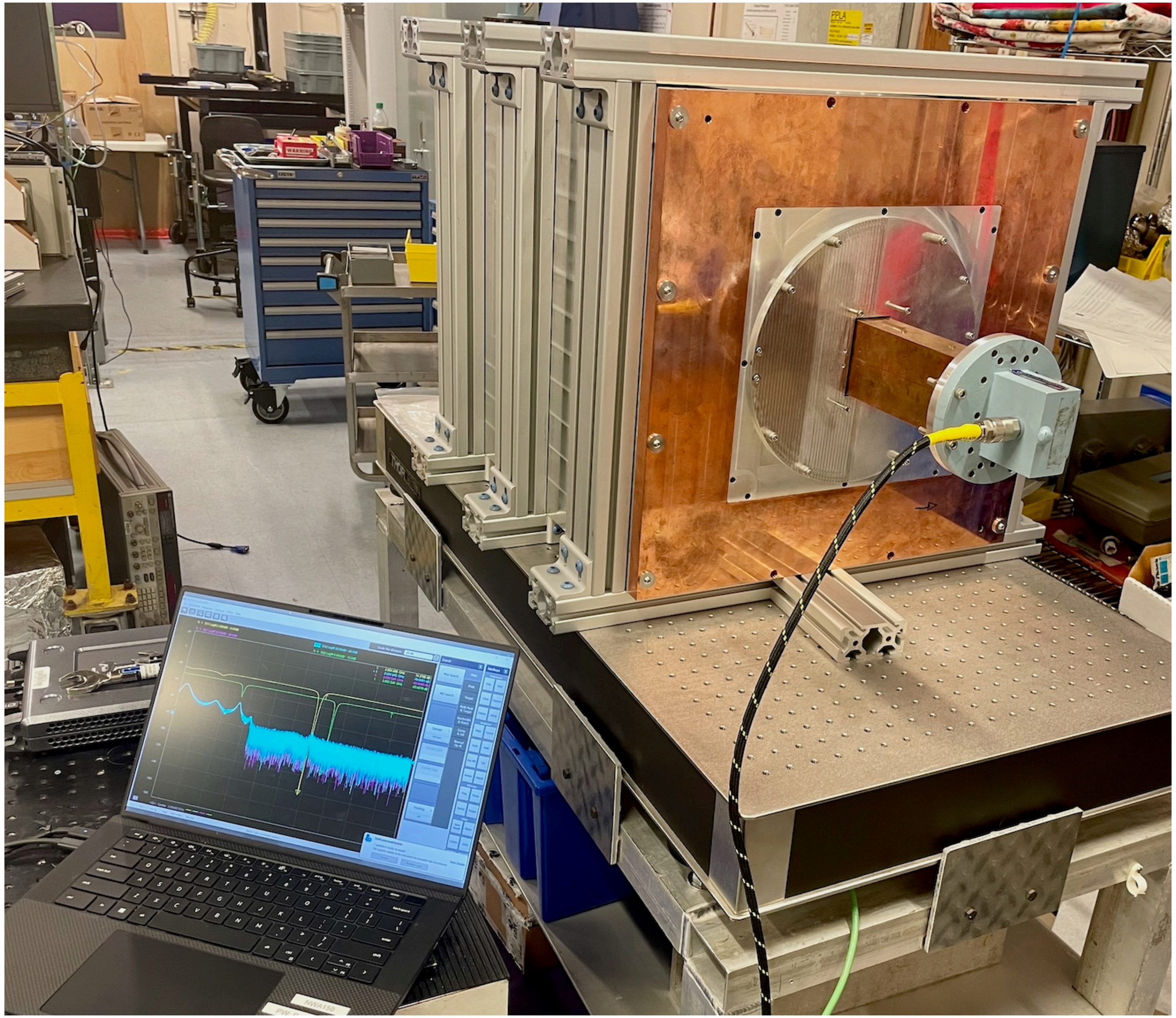
$\sim 100\,\mathrm{kg}$ of material

“tunable” endplate open on back



tuning membrane deformable by $1\,\mathrm{mm}$

More About SLAC Prototype: Measurements

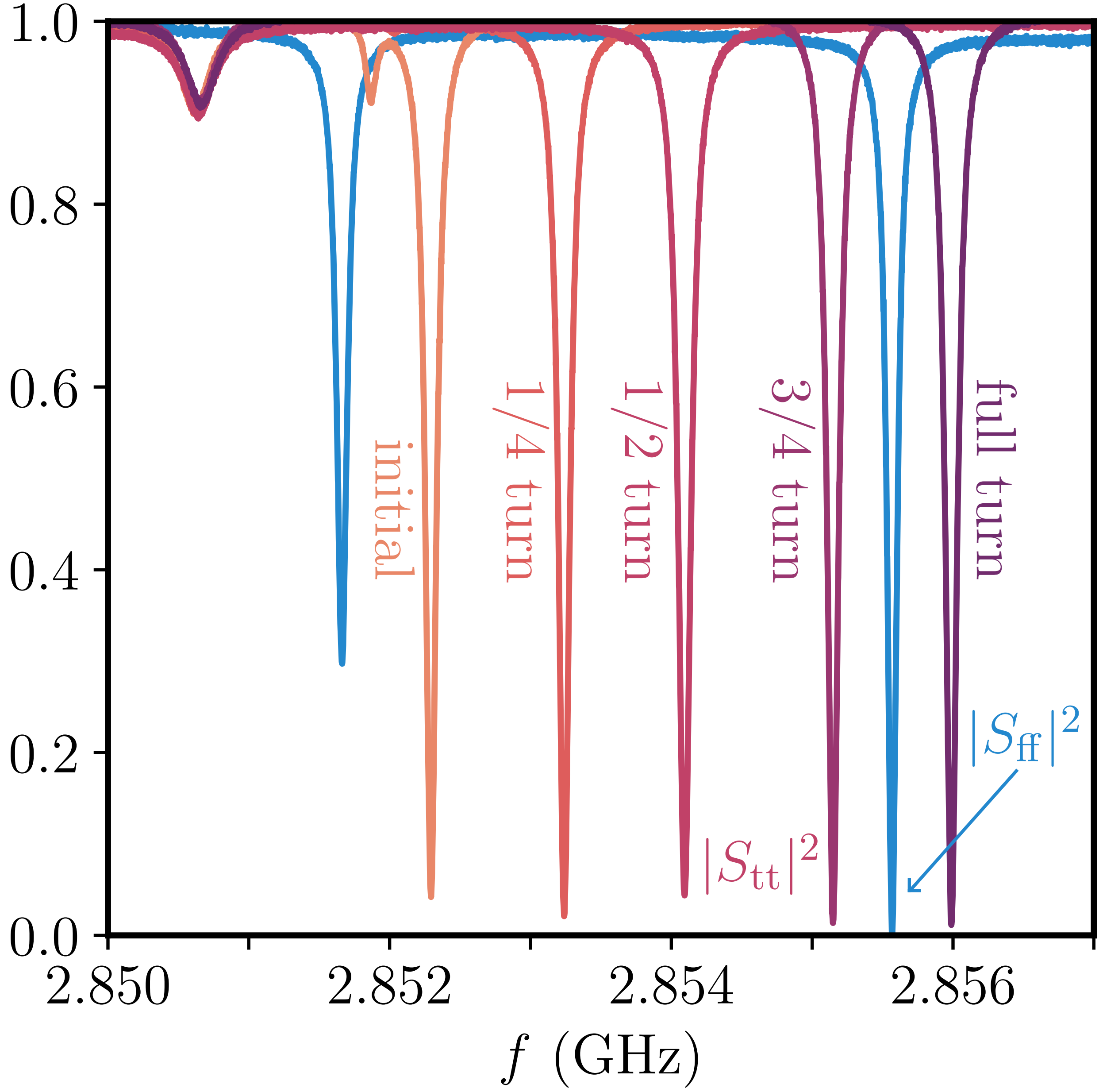


setup for bench measurements, waveguides coupled to each mode

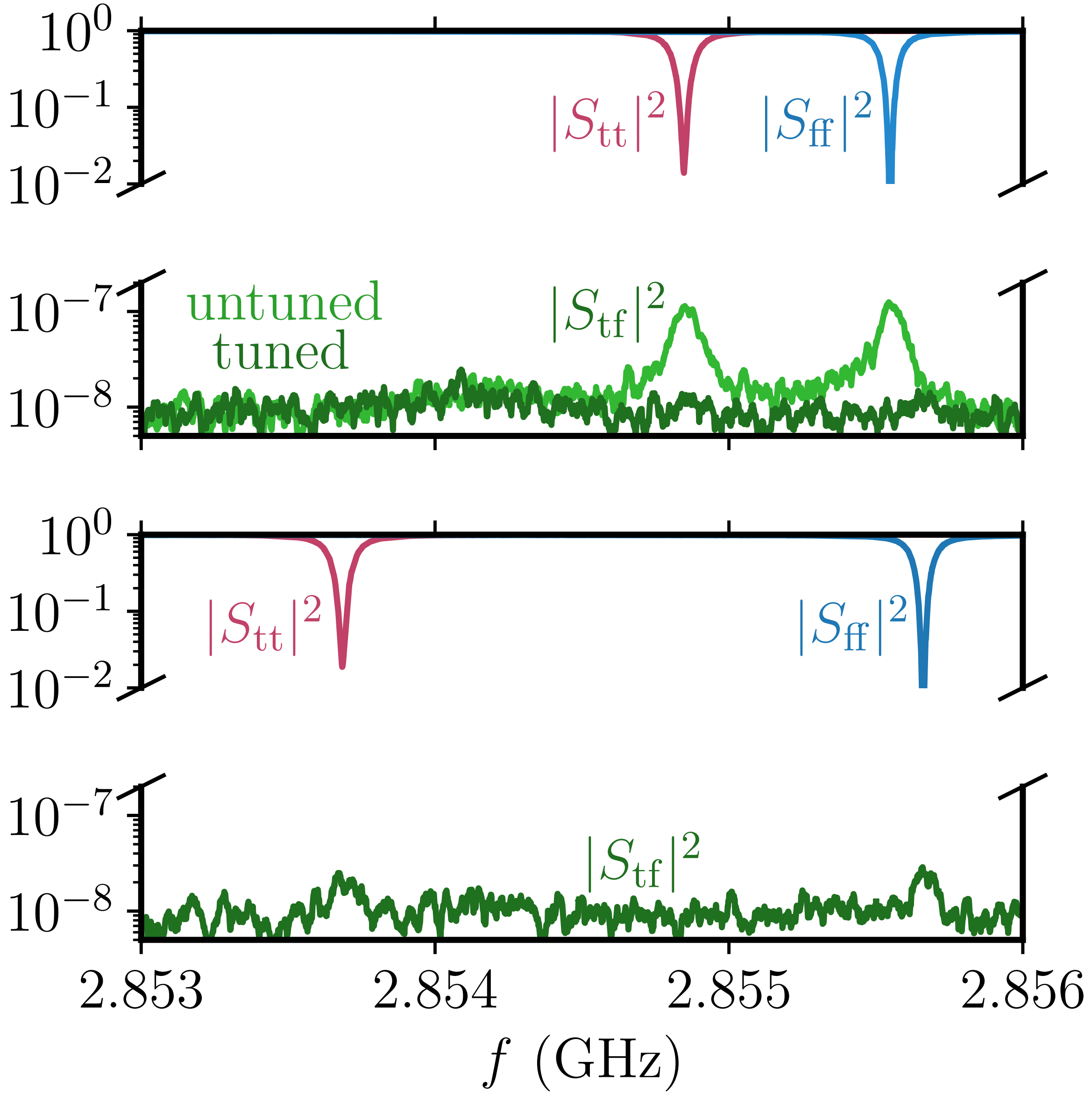
endplate can be rotated with jack screws

tuning membrane can be pushed inward by outer tuning plate

More About SLAC Prototype: Data

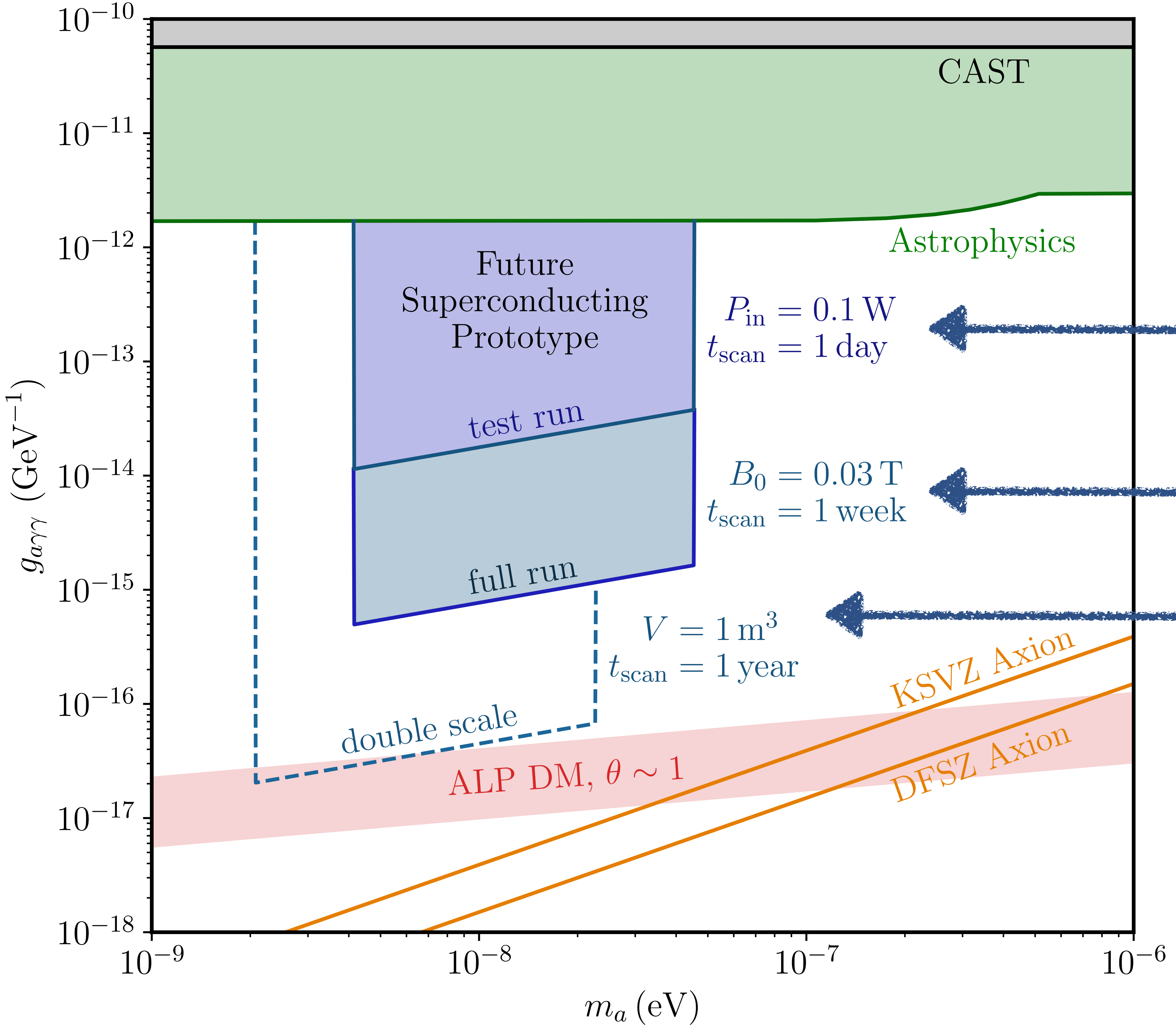


mode tunes across 4 MHz range as expected



cross-coupling suppressed by 80 dB by rotating endplate

More About SLAC Prototype: Projections



Superconducting cavity with same geometry as prototype, same surface treatment as LCLS-II

driven by microwave oscillator

driven like standard SRF cavity

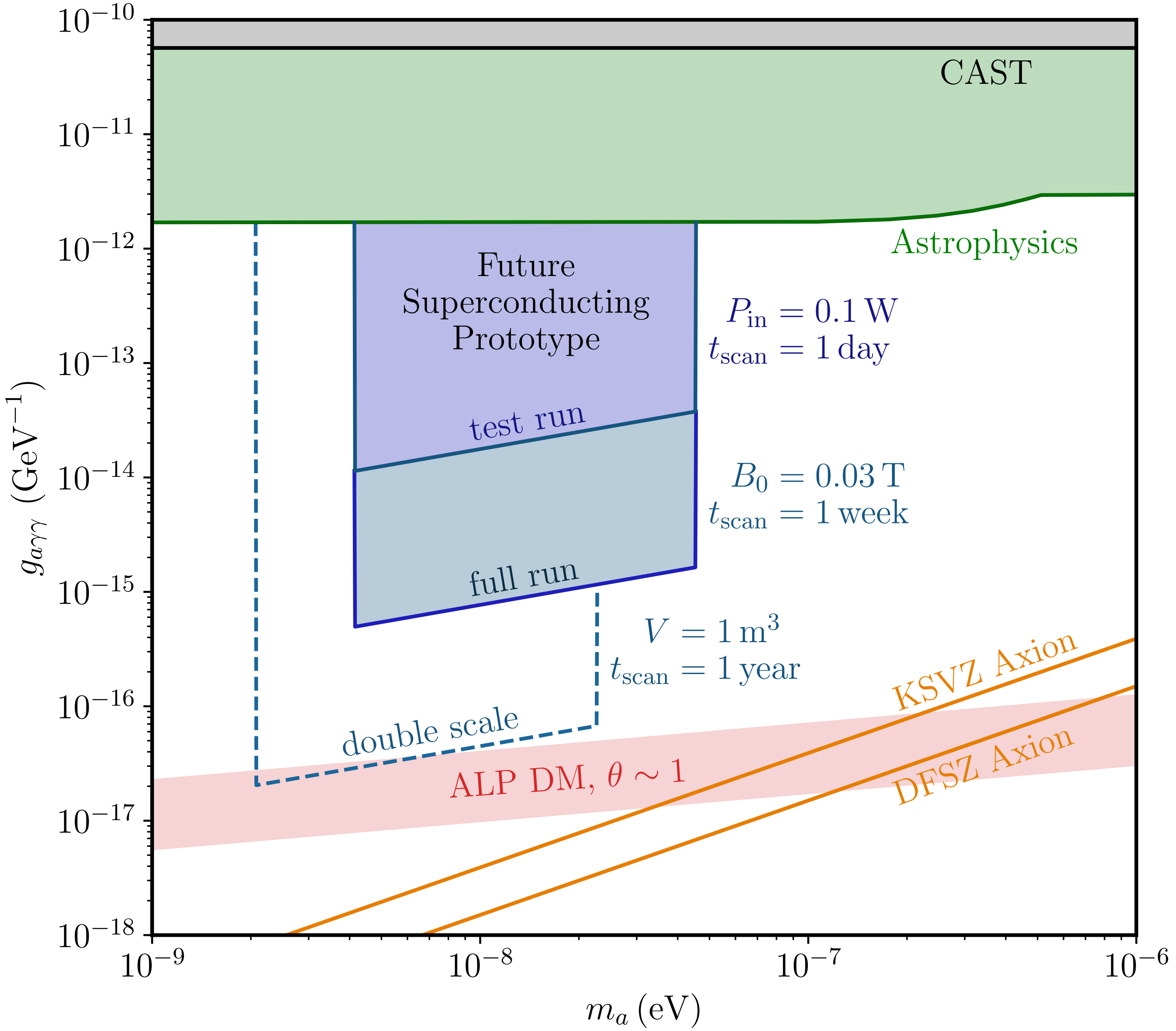
just double all dimensions

Reaching QCD axion requires combination of higher B_0 and volume, better surface treatment

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