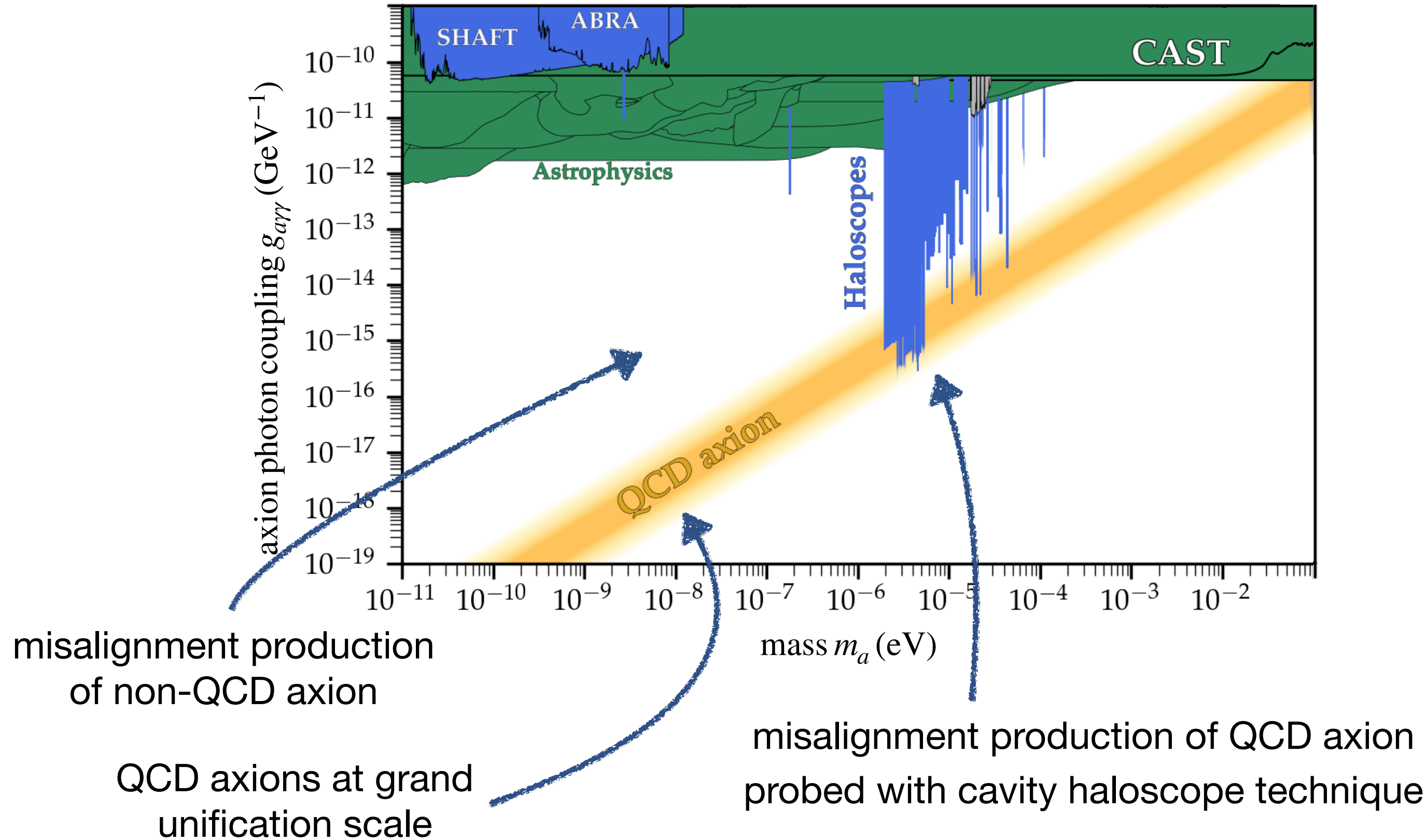


Heterodyne Detection of Axion Dark Matter

Kevin Zhou



TDLI Workshop on Cavities for Fundamental Physics — April 29, 2026



Probing kHz-MHz Axions

Axion effective current $\mathbf{J} = g_{a\gamma\gamma}\dot{a}\mathbf{B}_0$ deposits $P_{\text{sig}} \sim (g_{a\gamma\gamma}^2 \rho_{\text{DM}}) (B_0^2 V) \tau$

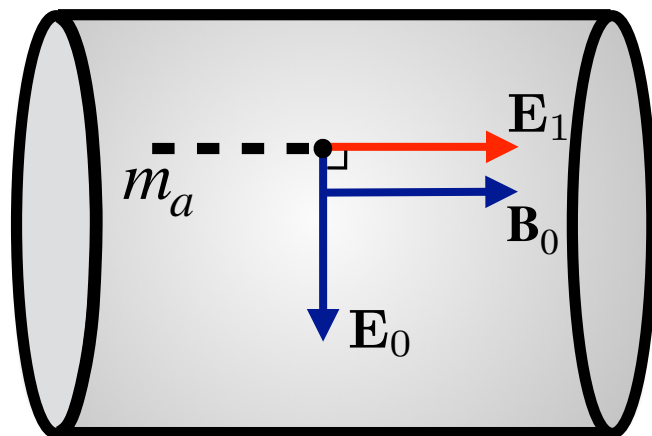
Three routes to probe axions below GHz

Static field, LC circuit: benefits from large $B_0^2 V$, but “magnetoquasistatic” penalty worse at low mass $P_{\text{sig}} \propto (m_a L)^2 \sim 10^{-6} \left(\frac{m_a}{\text{MHz}}\right)^2$

Penalty avoided in setups with radiation fields

Optical field, interferometry: like LIGO, well-developed, but realistic $B_0^2 V$ very low

Microwave field, heterodyne: axion induces transitions in microwave cavity



Drive $\omega_0 \sim \text{GHz}$ mode, read out signal mode at $\omega_1 = \omega_0 \pm m_a$

Technical requirements shared with particle accelerators!

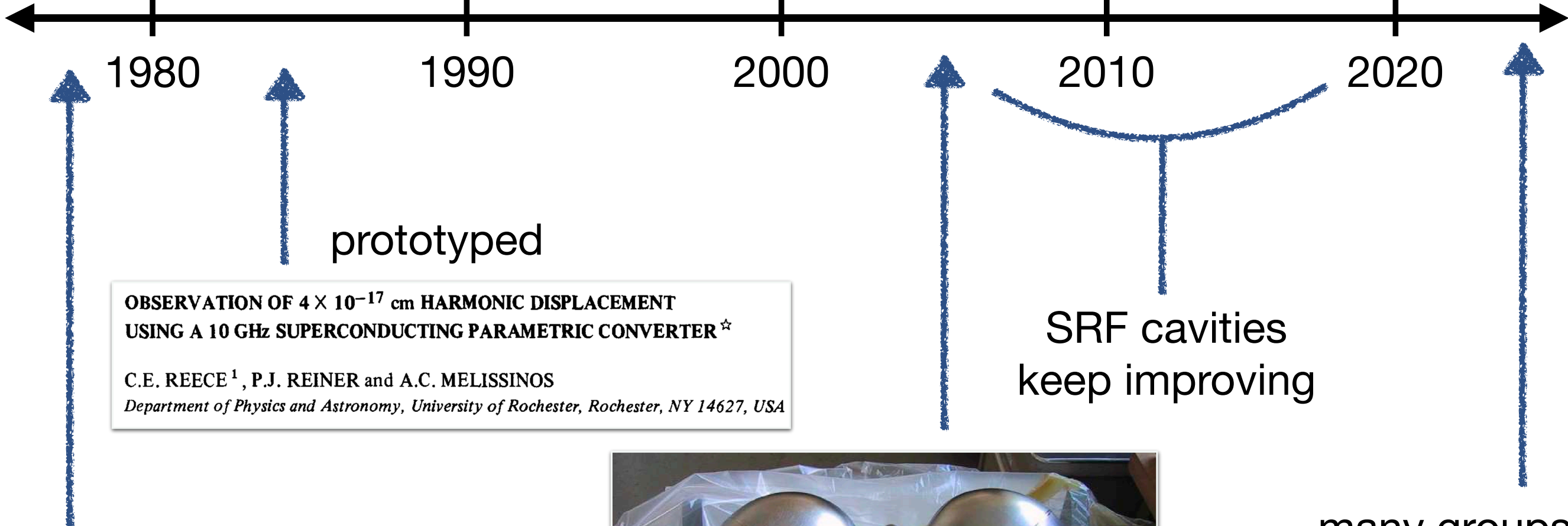
Berlin, D’Agnolo, Ellis, Nantista, Neilson, Schuster, Tantawi, Toro, KZ, JHEP (2020)

broadband: Berlin, D’Agnolo, Ellis, KZ, PRD (2021)

frequency technique: Thomson, McAllister, Goryachev, Ivanov, Tobar, PRL (2021)

downconversion: Sikivie (2010), Liu, Ahmad, Houston, PRR (2026)

History of the Heterodyne Approach



1980

1990

2000

2010

2020

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

SRF cavities
keep improving

suggested for gravitational waves



MAGO experiment

many groups
developing prototypes

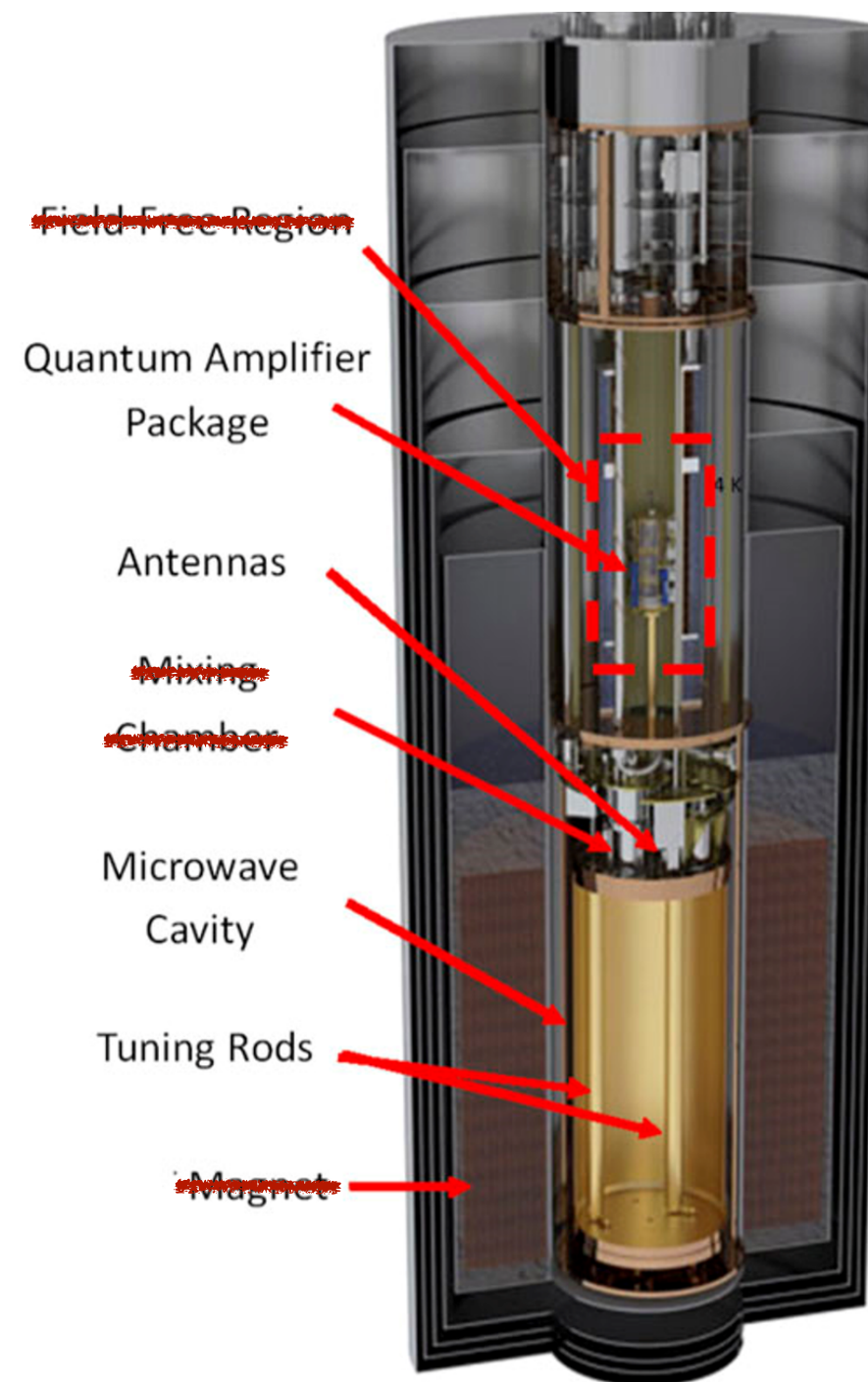


ELECTROMAGNETIC DETECTOR FOR GRAVITATIONAL WAVES
 F. PEGORARO, L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy
 and
 Ph. BERNARD and E. PICASSO
CERN, Geneva, Switzerland

Heterodyne Experiments vs. Cavity Haloscopes

No large magnet: field excited in cavity ($B_0 \sim 0.1$ T)

No dilution fridge: use helium cryostat ($T \sim 2$ K)
(typical operating points for accelerator cavities)



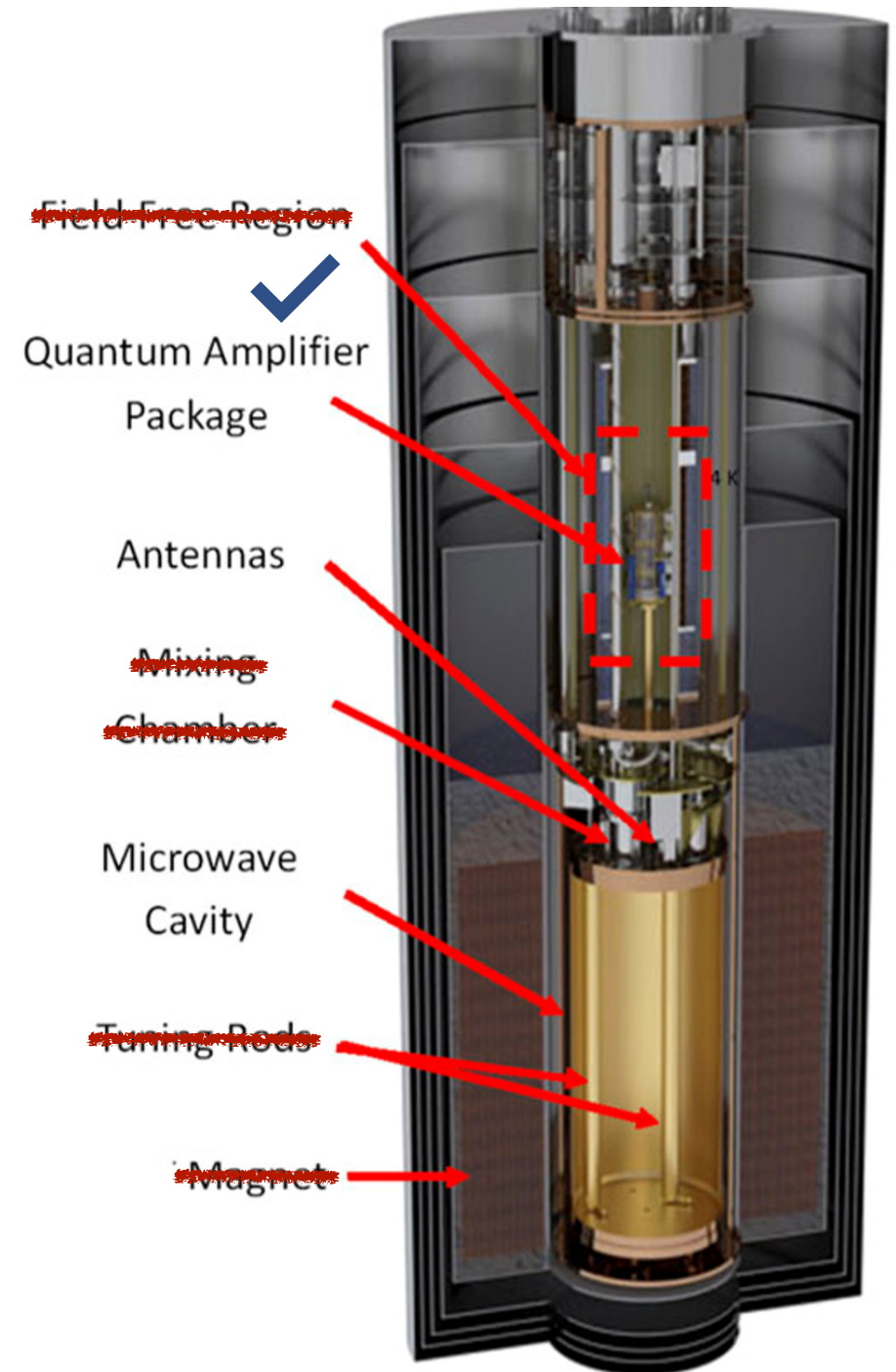
Heterodyne Experiments vs. Cavity Haloscopes

No large magnet: field excited in cavity ($B_0 \sim 0.1$ T)

No dilution fridge: use helium cryostat ($T \sim 2$ K)
(typical operating points for accelerator cavities)

GHz output frequency, so similar readout system

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



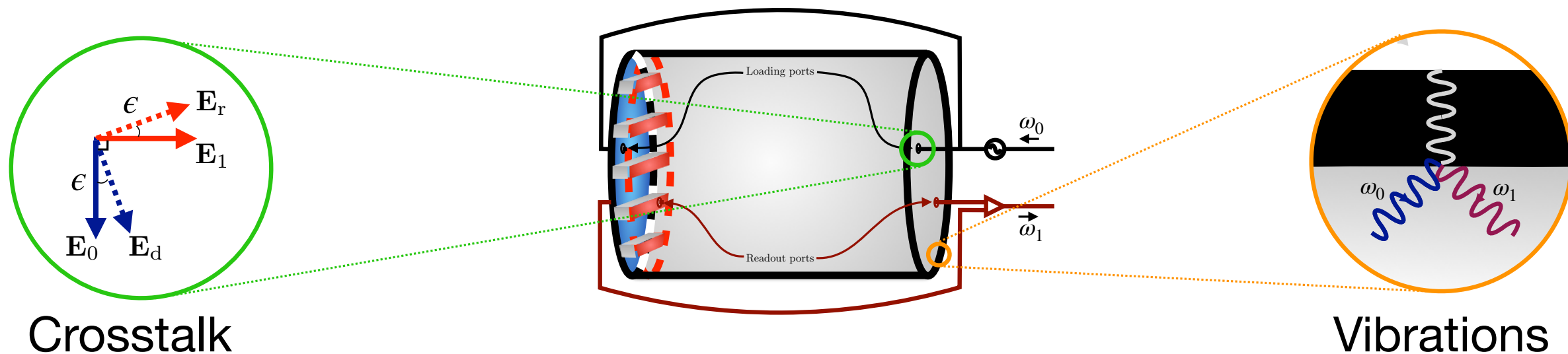
Leakage Noise

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

Suppressed by geometric factors, and frequency separation of modes

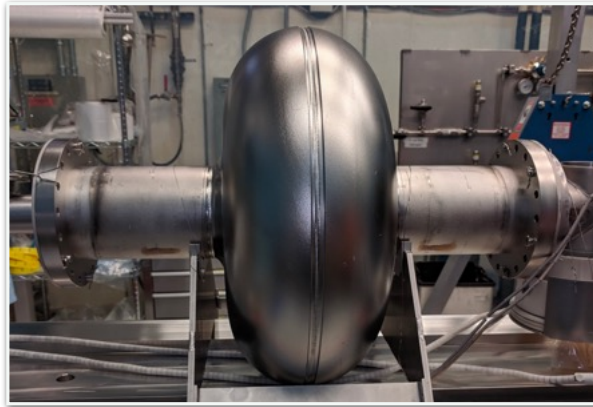
$$S_{\text{leak}}(m_a) \propto P_{\text{in}} \times \begin{cases} \epsilon^2 S_{\varphi}(m_a) & \text{oscillator phase noise} \\ \epsilon^2 S_{\delta}(m_a) & \text{mode frequency jitter} \\ \eta^2 S_{\delta}(m_a) & \text{mechanical mode mixing} \end{cases}$$

Dominates at kHz, but subdominant at MHz if $\epsilon, \eta \ll 1$, requiring good cavity design (last issue most important, also exists for setups with large static background fields)



Design of a Heterodyne Experiment

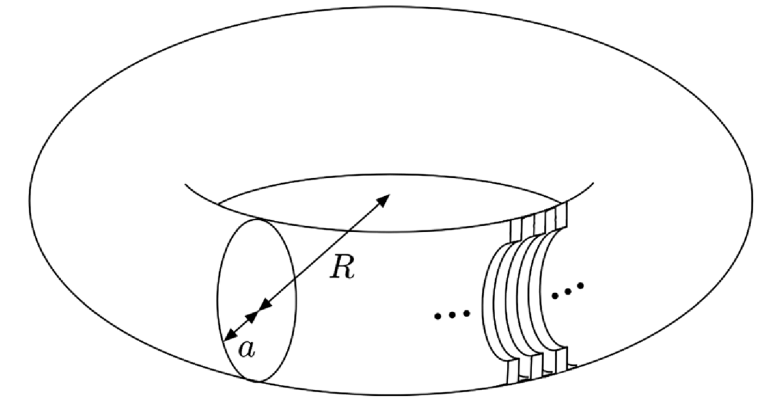
Cool cavity in a helium cryostat, drive one mode, read out the other
Need good overlap of \mathbf{B}_0 and \mathbf{E}_1 , tunability, noise suppression



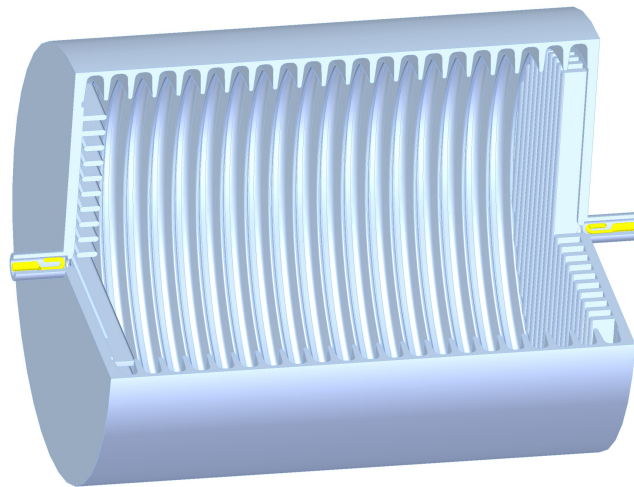
typical accelerator cavity



two-sphere cavity
MAGO collaboration (2000s)

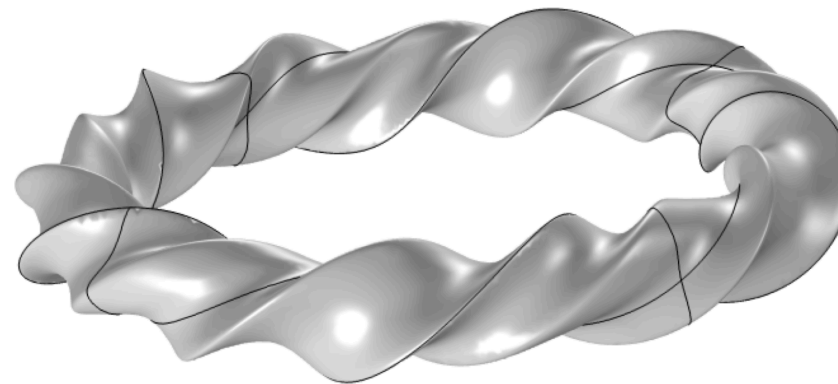


corrugated toroid
Lasenby, PRD (2020)



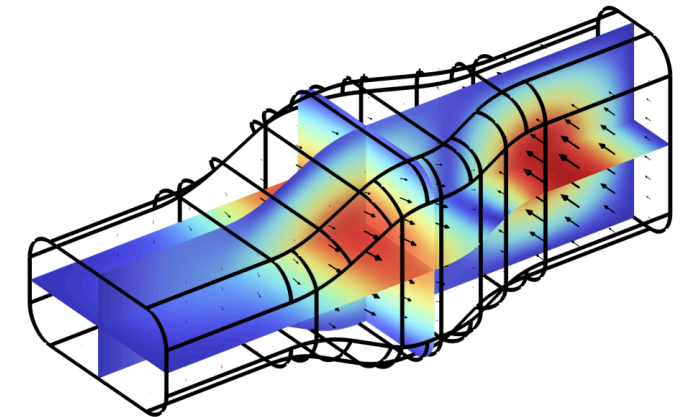
corrugated cylinder

Berlin, D'Agnolo, Ellis, Nantista, Neilson, Schuster, Tantawi, Toro, KZ, JHEP (2020)



twisted toroid

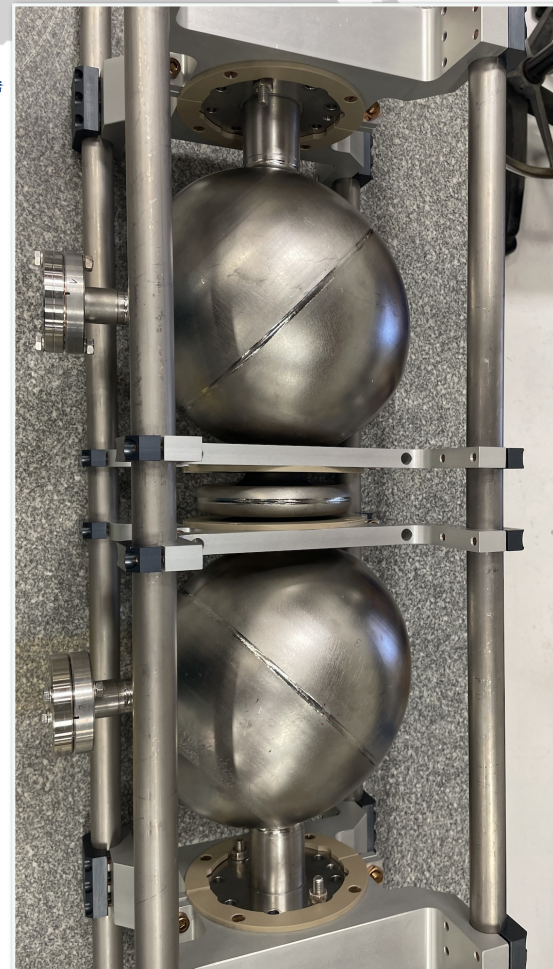
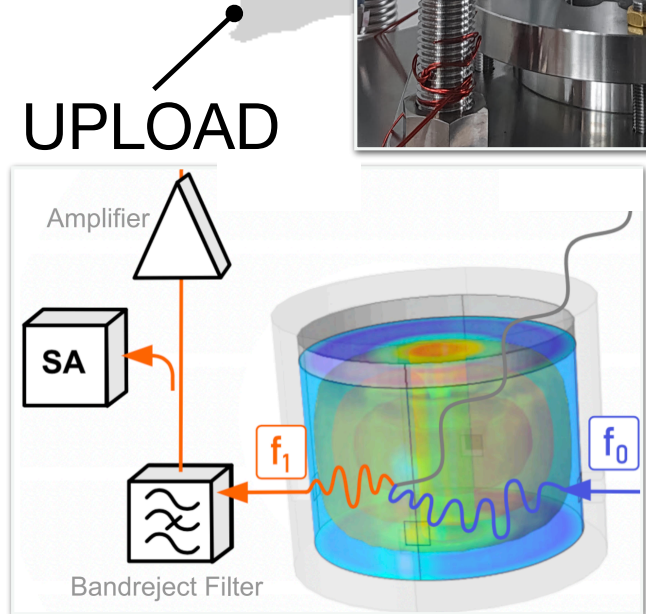
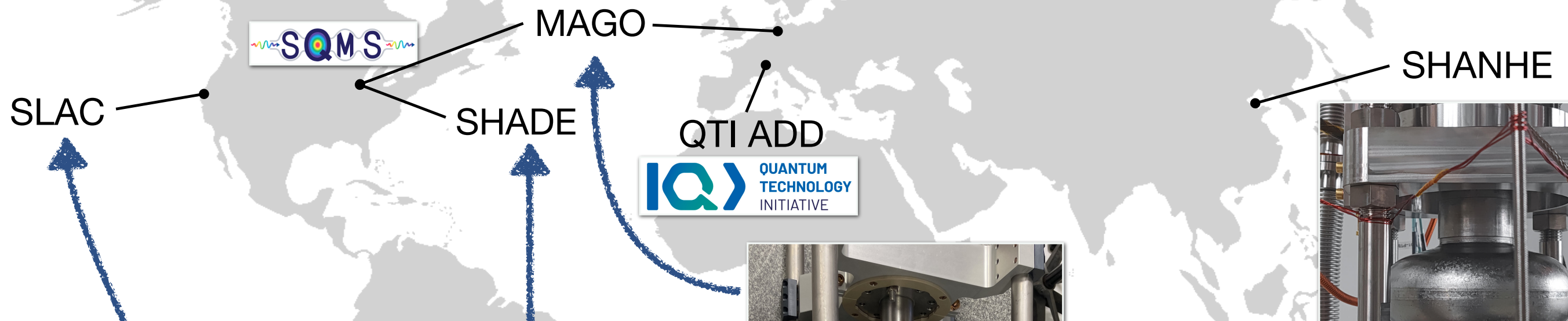
Bourhill, Paterson, Goryachev, Tobar, PRD (2023)



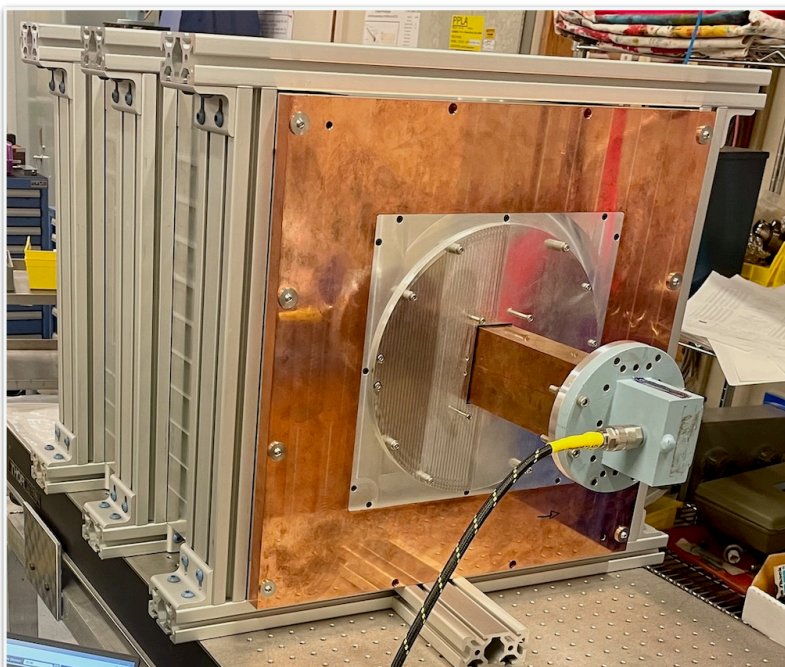
orthogonal waveguides

QTI ADD collaboration (2026)

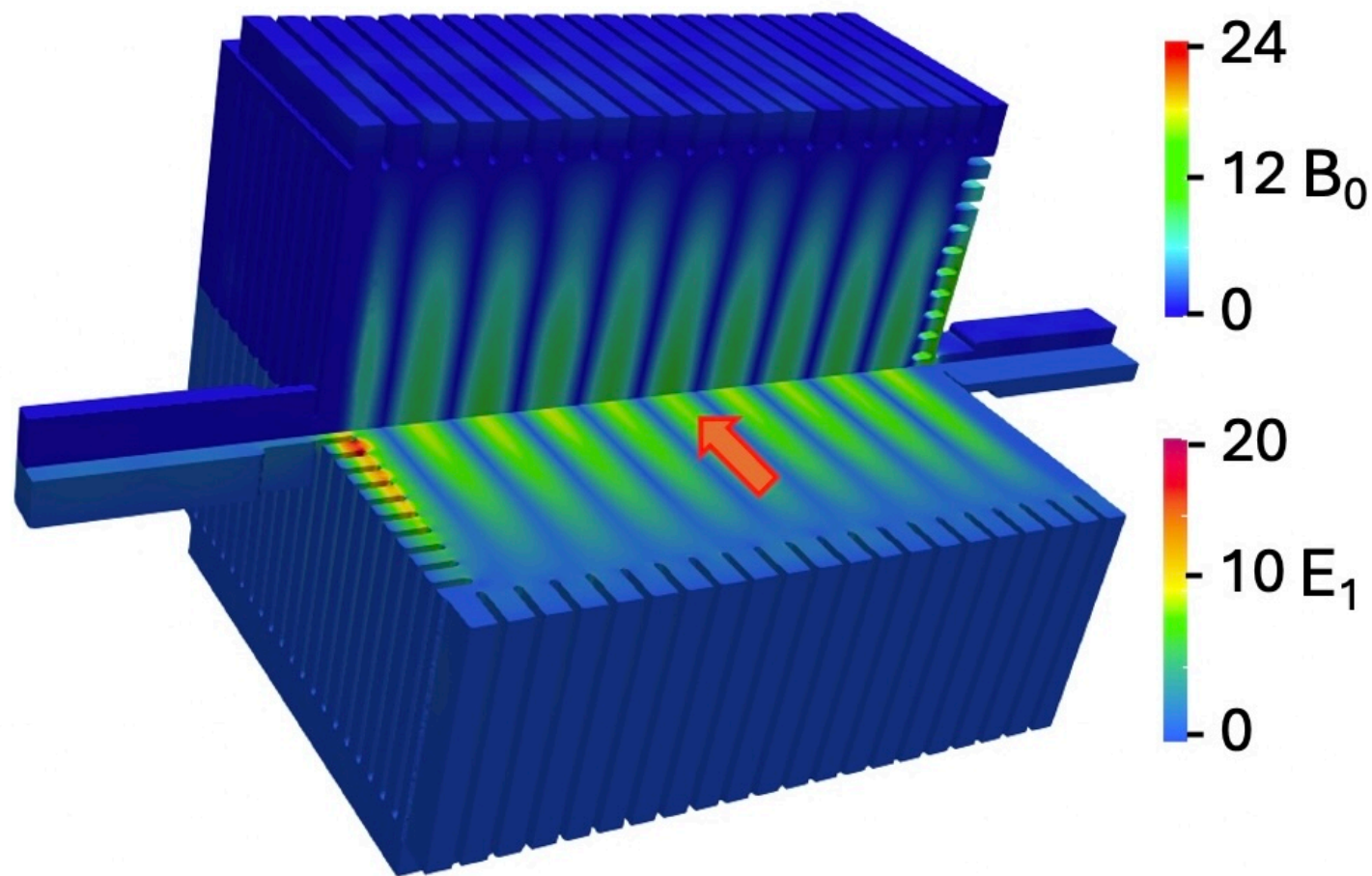
Global Status of the Heterodyne Approach



Li, KZ, Oriunno, et al., NIMA (2026)



SLAC Prototype: Modes



Corrugated side walls yield “hybrid” HE_{11} modes, which are perfectly linearly polarized

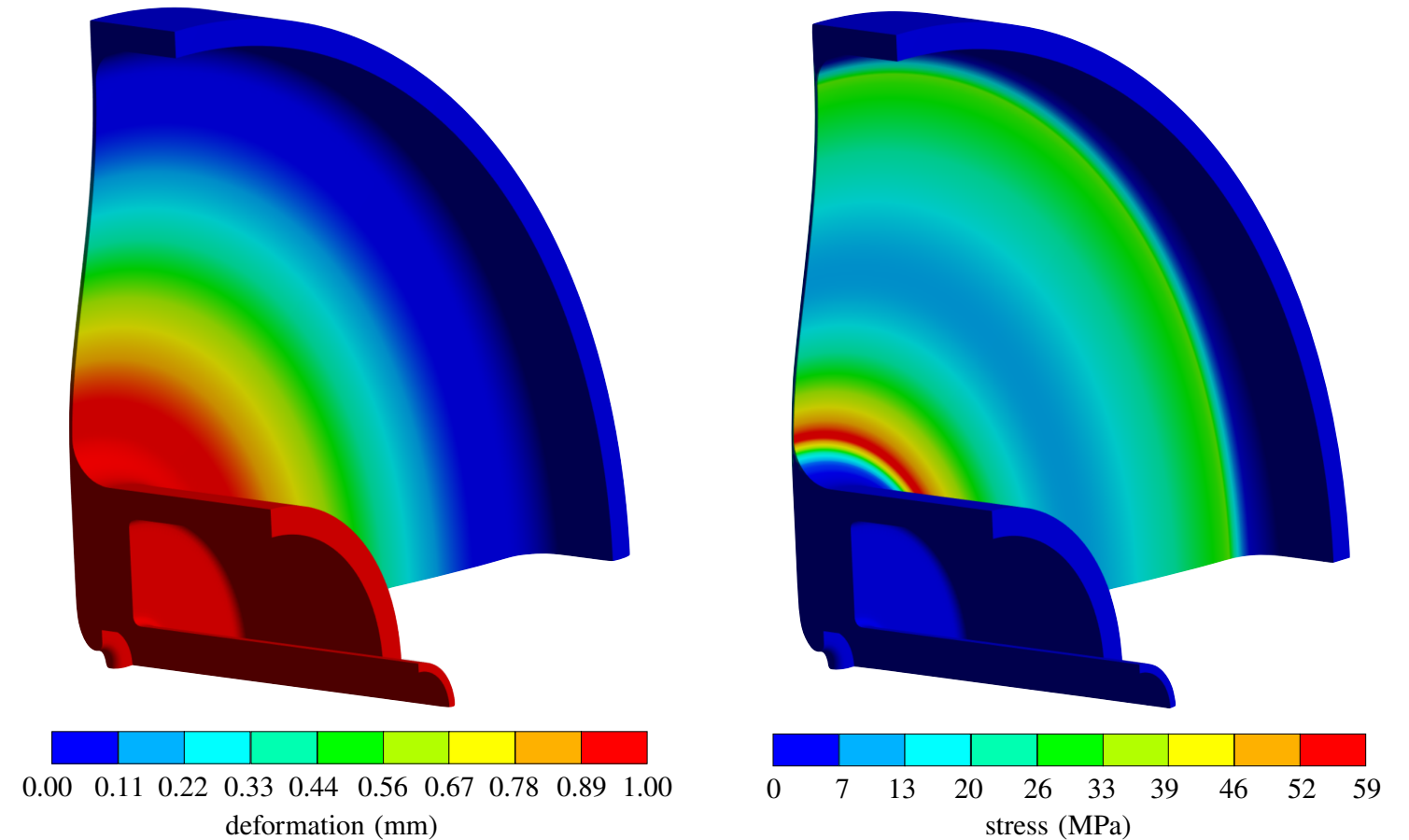
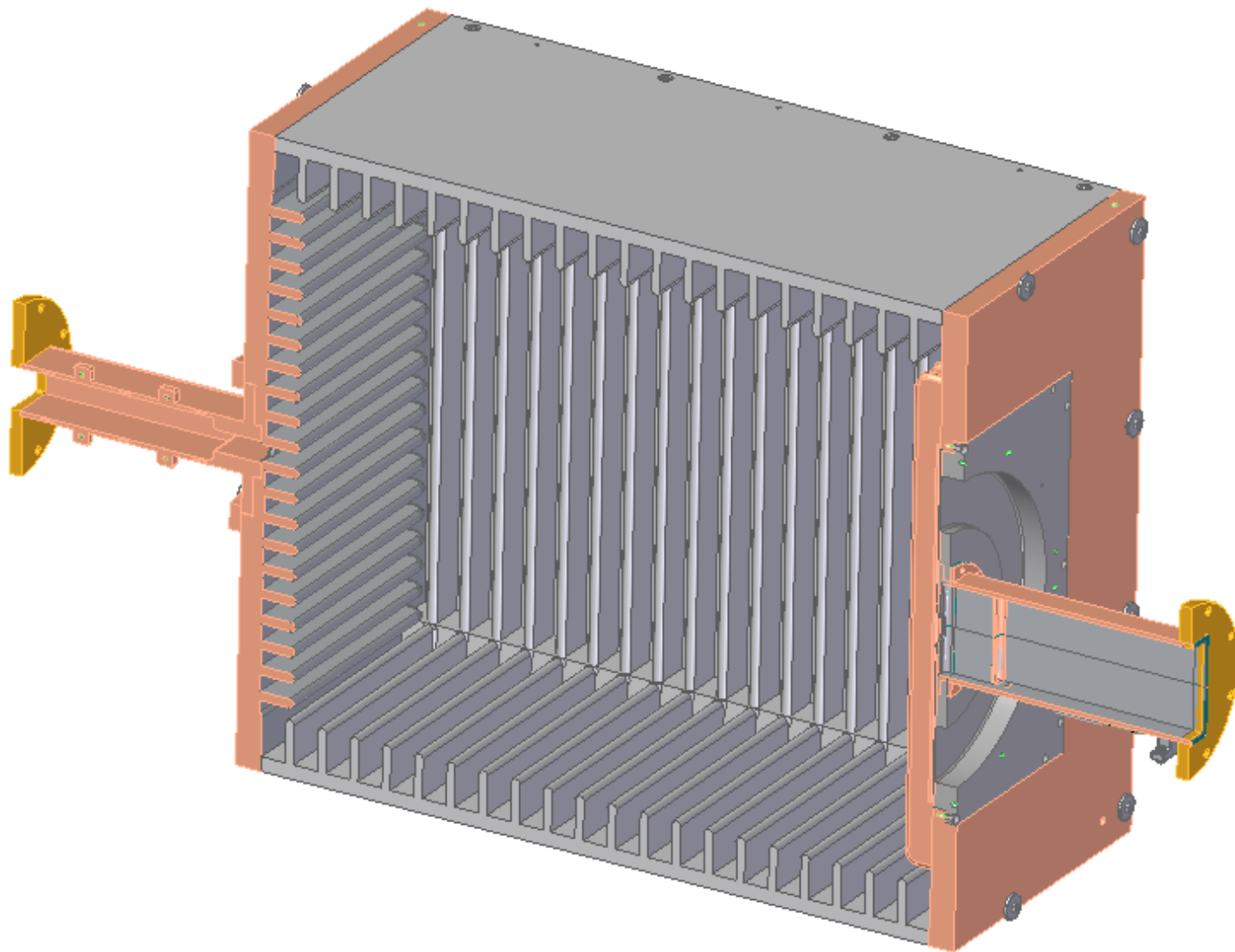
Then \mathbf{B}_0 and \mathbf{E}_1 are aligned, but out of phase along axis

Put horizontal corrugations on one endplate, vertical corrugations on the other

Each endplate reflects one mode, shifting mode profiles and suppressing cross-coupling

$$P_{\text{sig}} \propto C_{\text{sig}}^2 \quad C_{\text{sig}} = \int_V \tilde{\mathbf{B}}_0 \cdot \tilde{\mathbf{E}}_1 \simeq \begin{cases} m_a L \ll 1 & \text{LC circuit} \\ 0.2 & \text{cylinder} \\ 0.3 & \text{typical SRF cavity} \\ 0.9 & \text{this cavity} \end{cases}$$

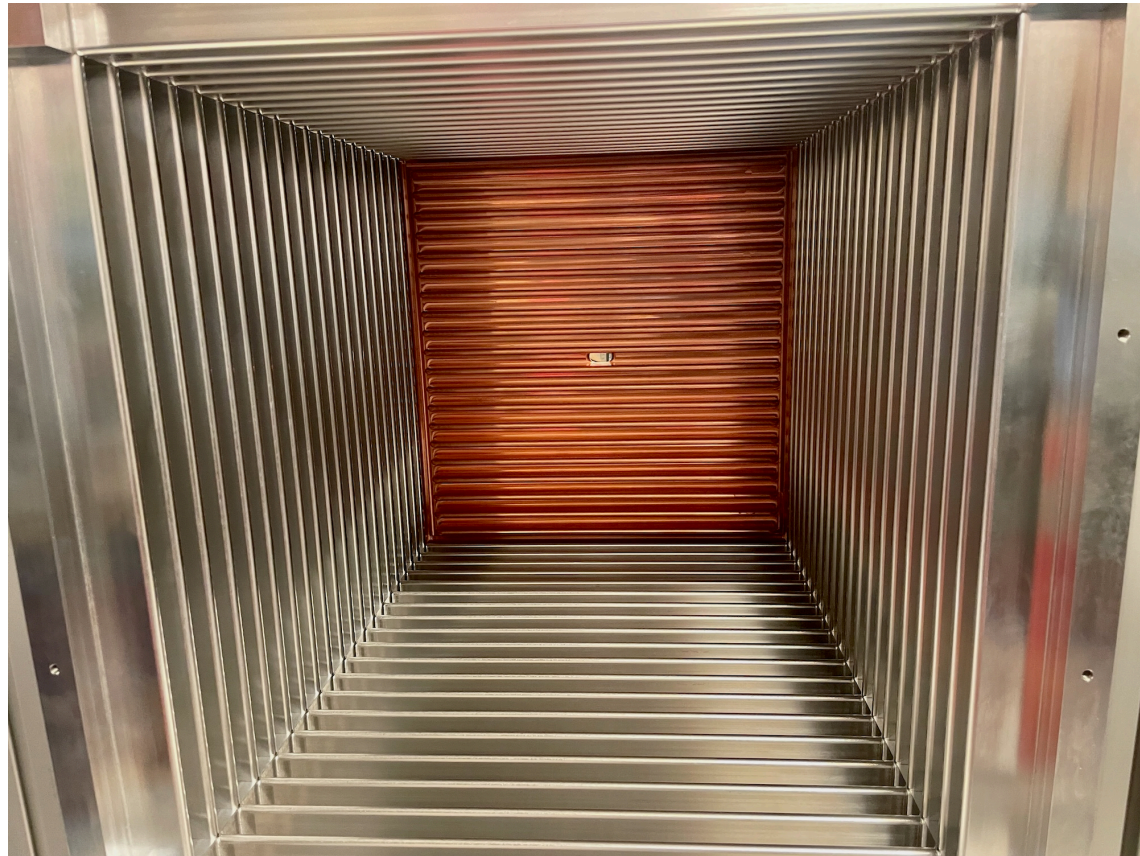
SLAC Prototype: Mechanical Design



Waveguides attached to each endplate,
couple preferentially to one mode

“Tunable” endplate open at back,
capped with thin membrane
deformable by ~ 1 mm for tuning

SLAC Prototype: Fabrication

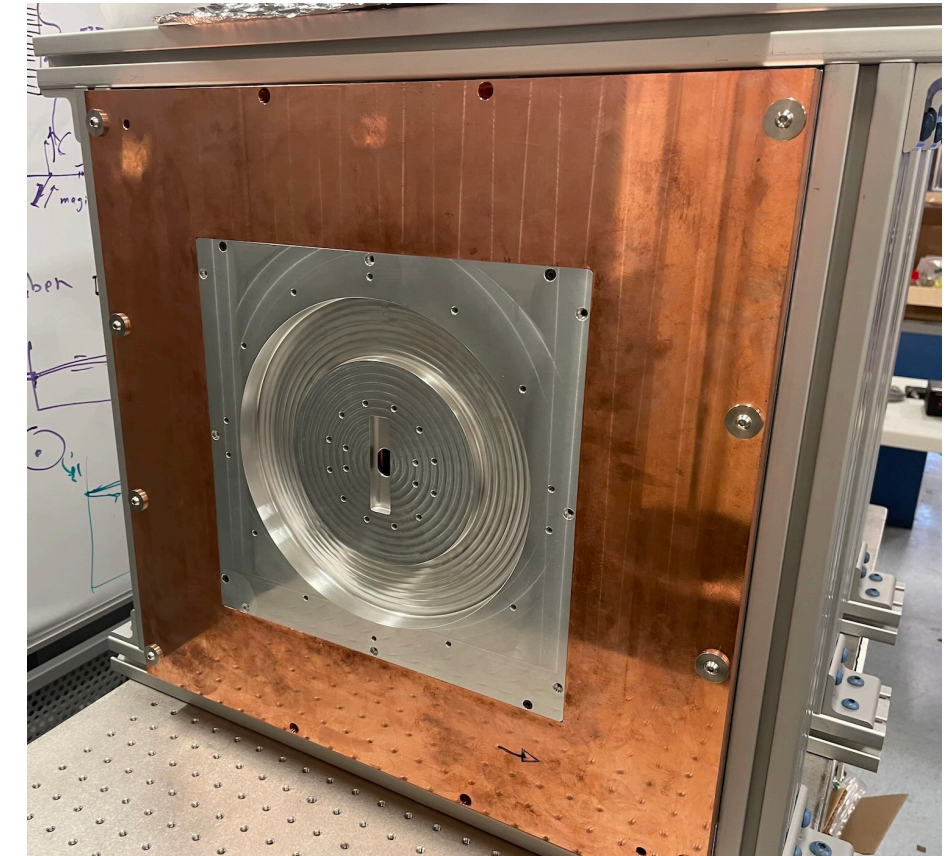


Six corrugated aluminum/copper plates, side length 0.5 m

Much thicker than typical SRF cavity

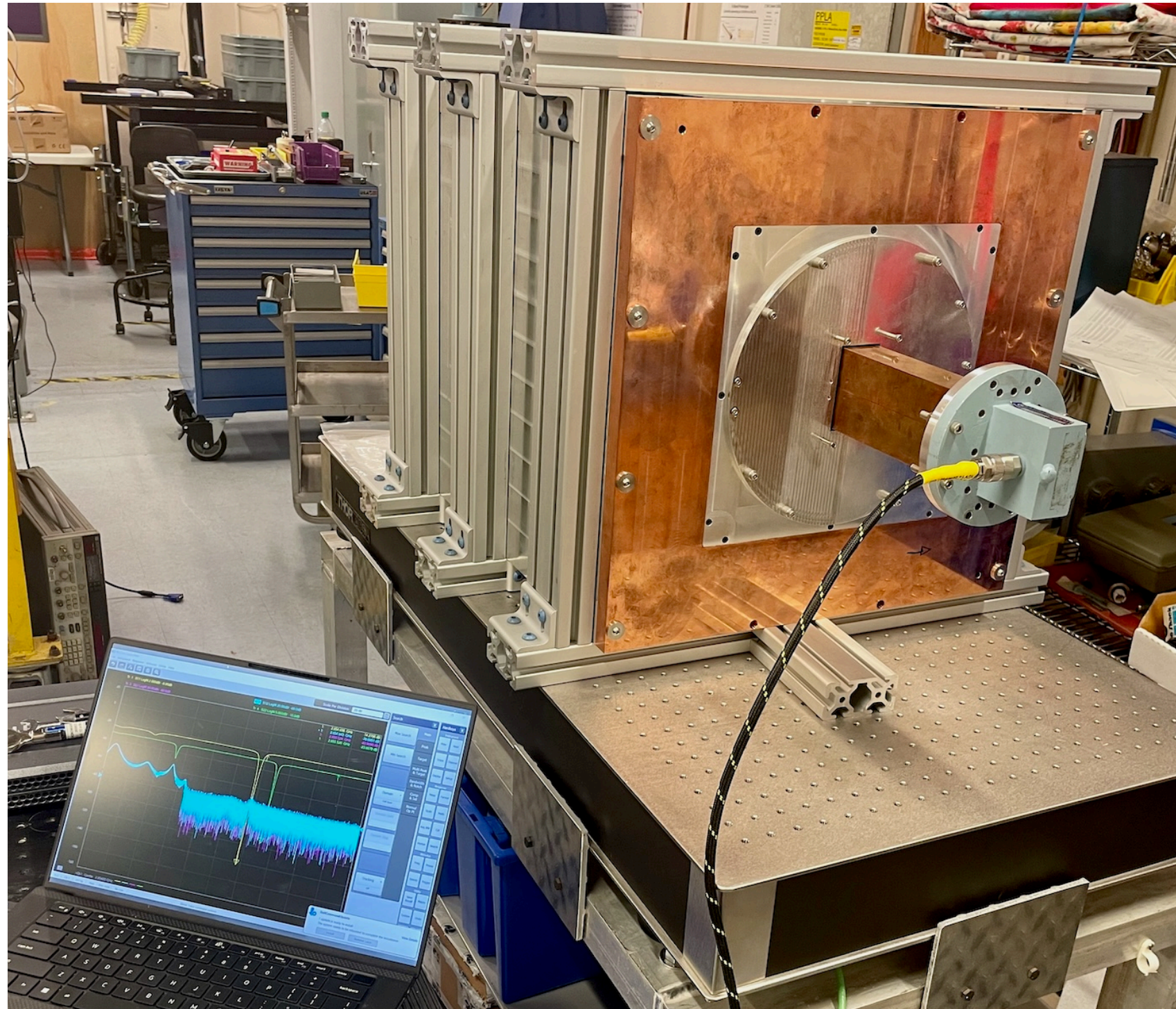


Fixed and tunable endplates



Tunable endplates with thin tuning membrane

SLAC Prototype: Measurements

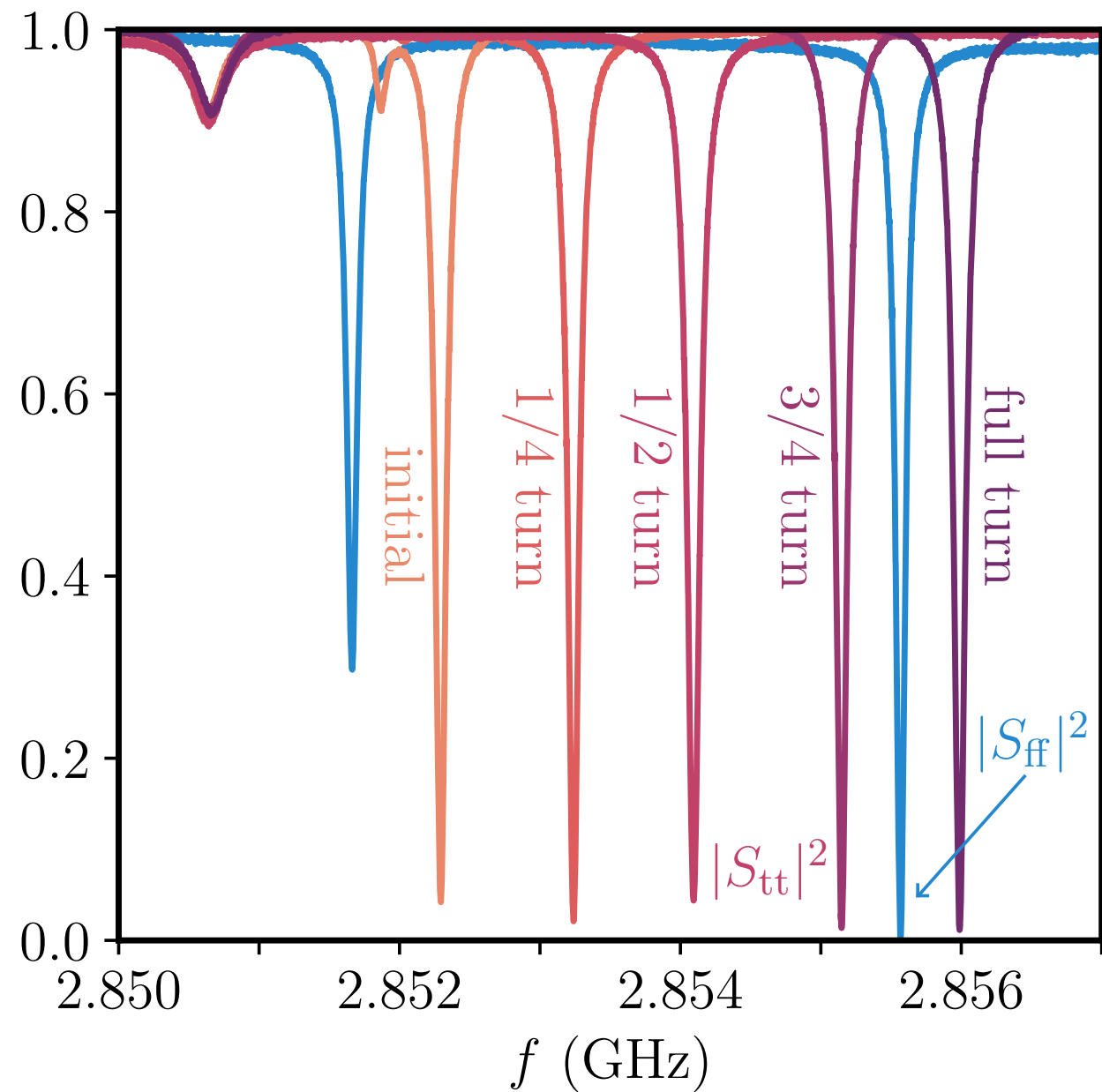


Bench measurements with waveguides and spectrum analyzer

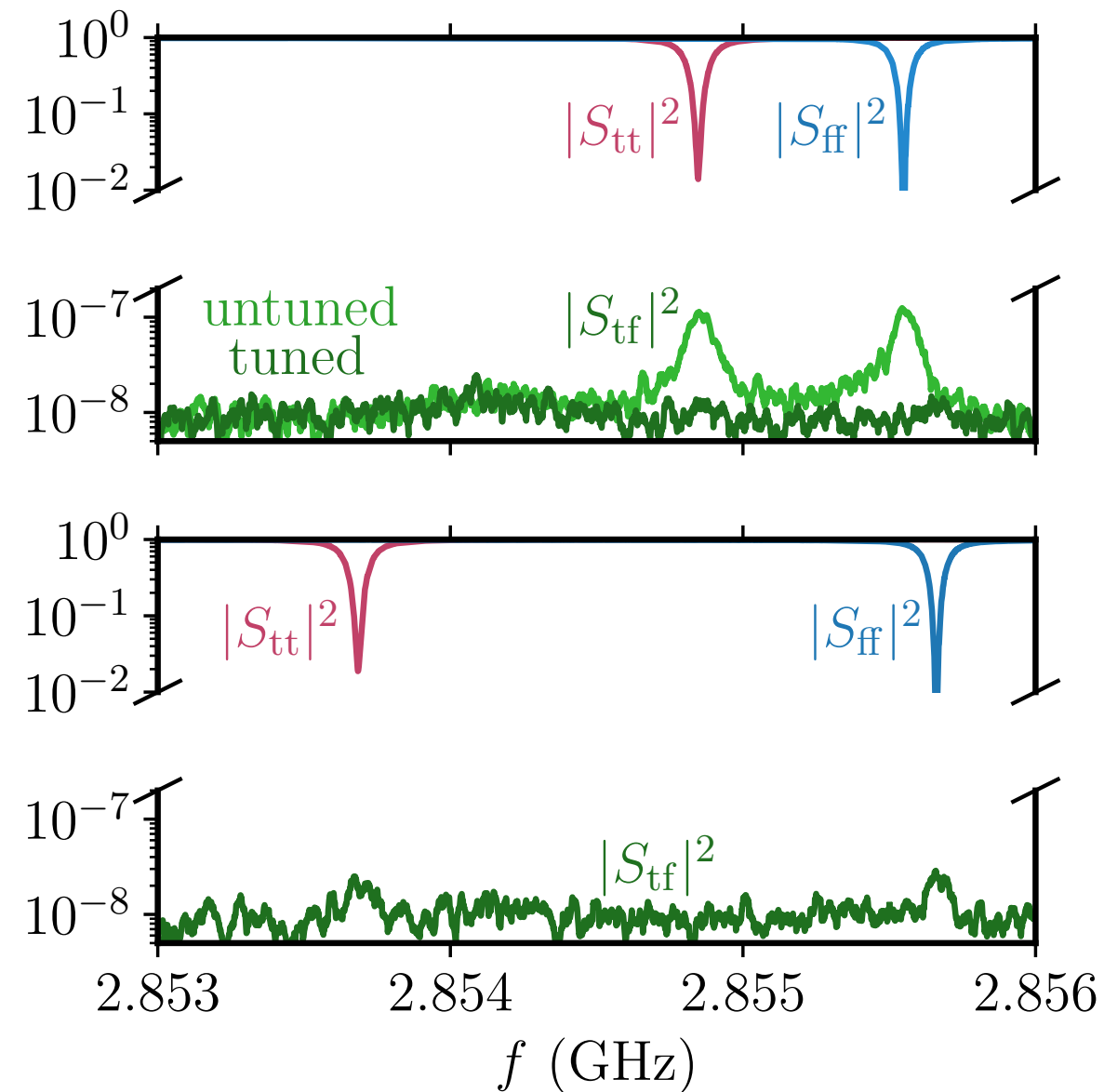
Jack screws used to push tuning membrane inward

Can also rotate an endplate, to further suppress cross-coupling η

SLAC Prototype: Data

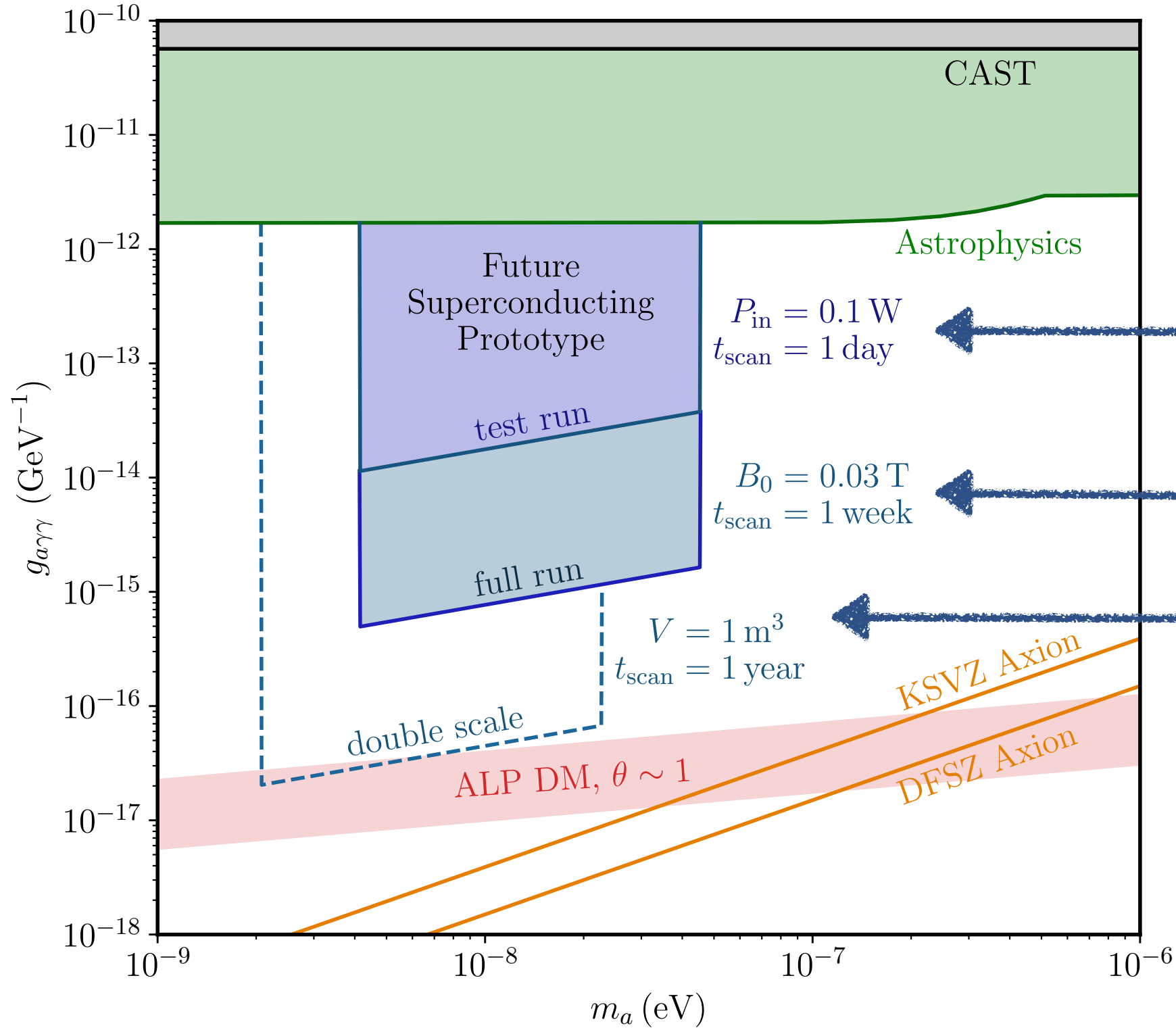


mode tunes across 4 MHz range as expected



rotating endplate suppresses cross-coupling, $\gtrsim 80$ dB rejection

Future of the Heterodyne Approach



Projected reach if one gave this cavity standard superconducting surface treatment

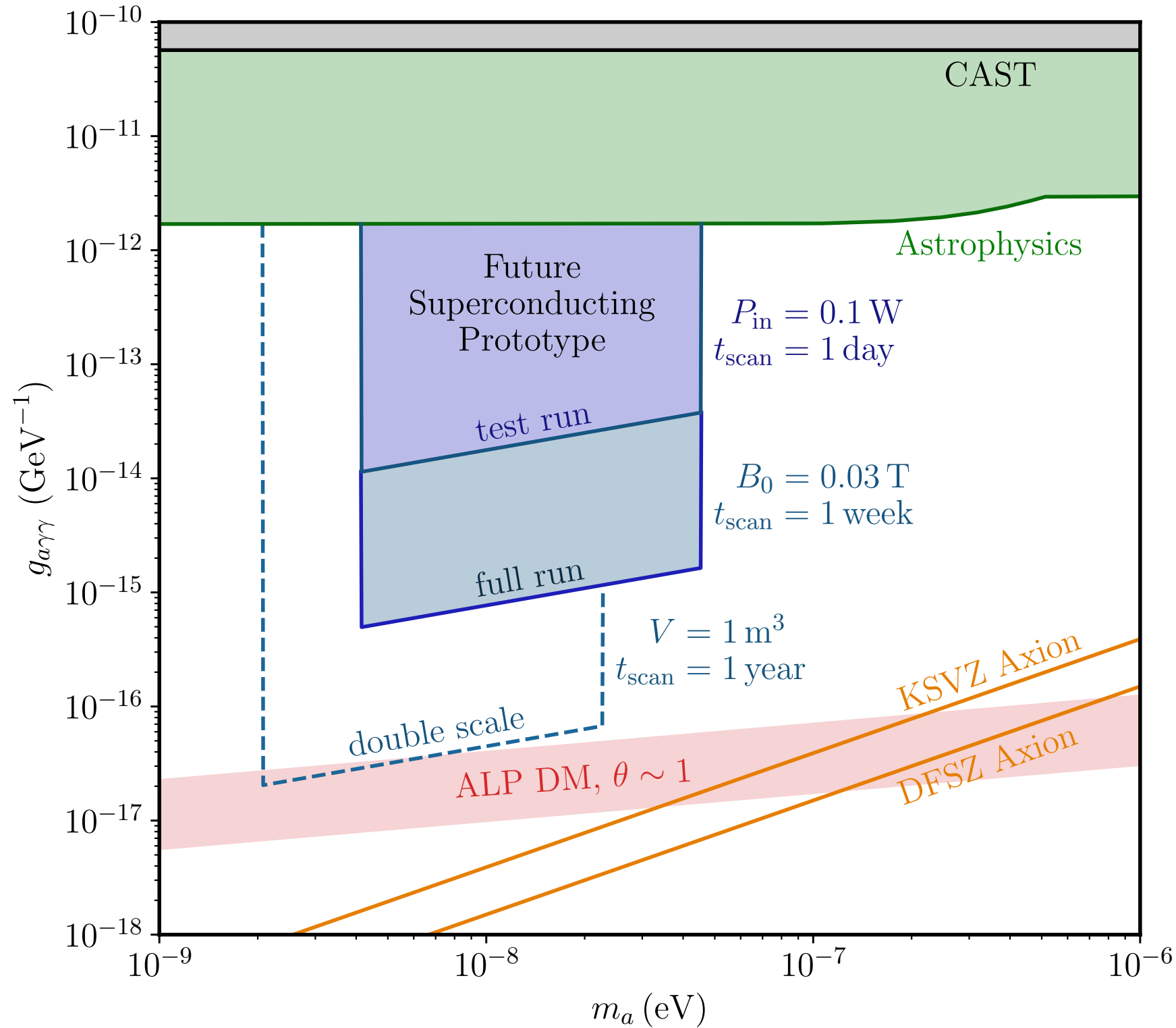
driven by microwave oscillator

driven like standard SRF cavity

just double all dimensions

Direct scaling to $V \sim 10 \text{ m}^3$ would probe QCD axion; no magnet or dilution fridge!

Outlook

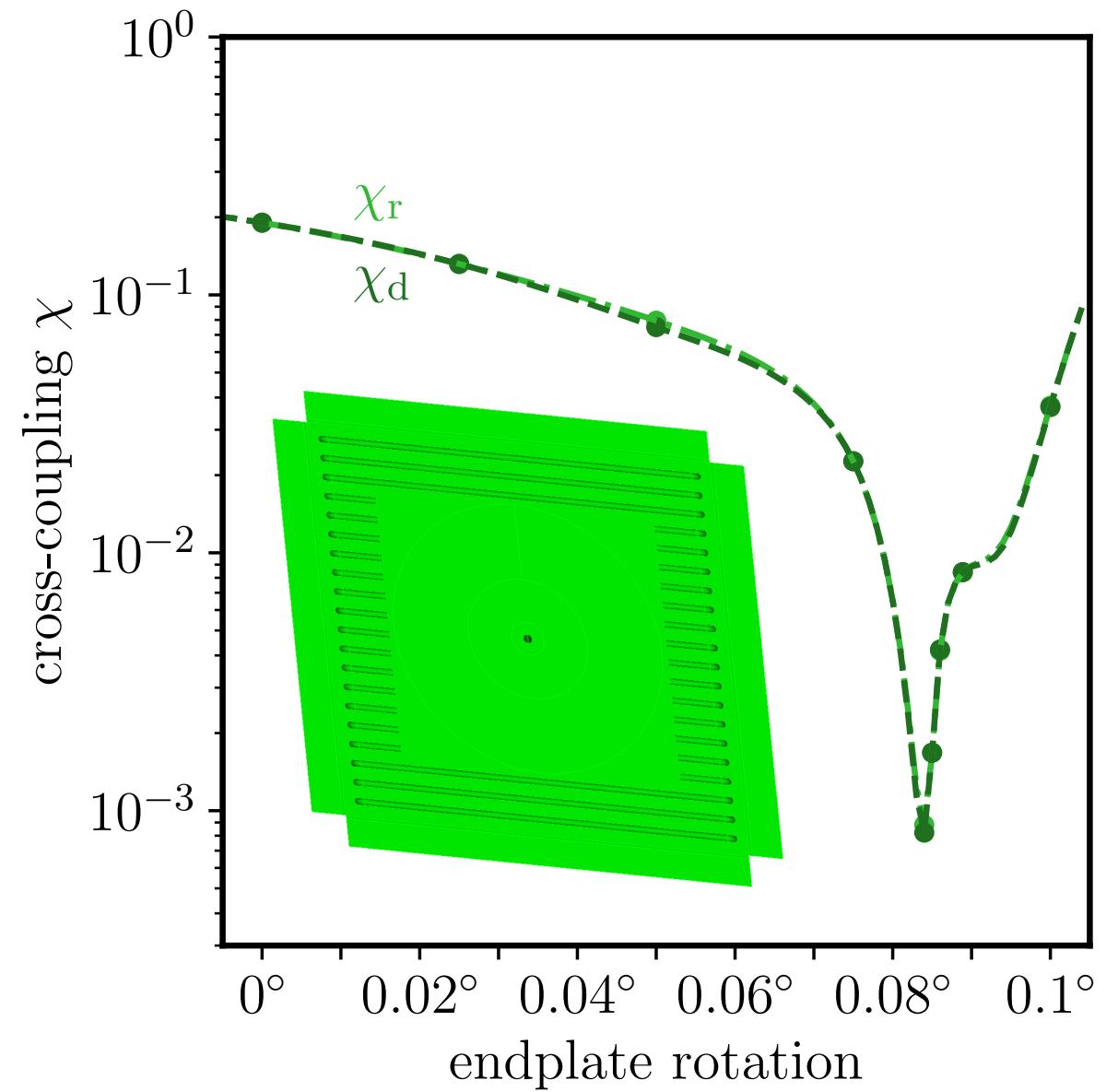
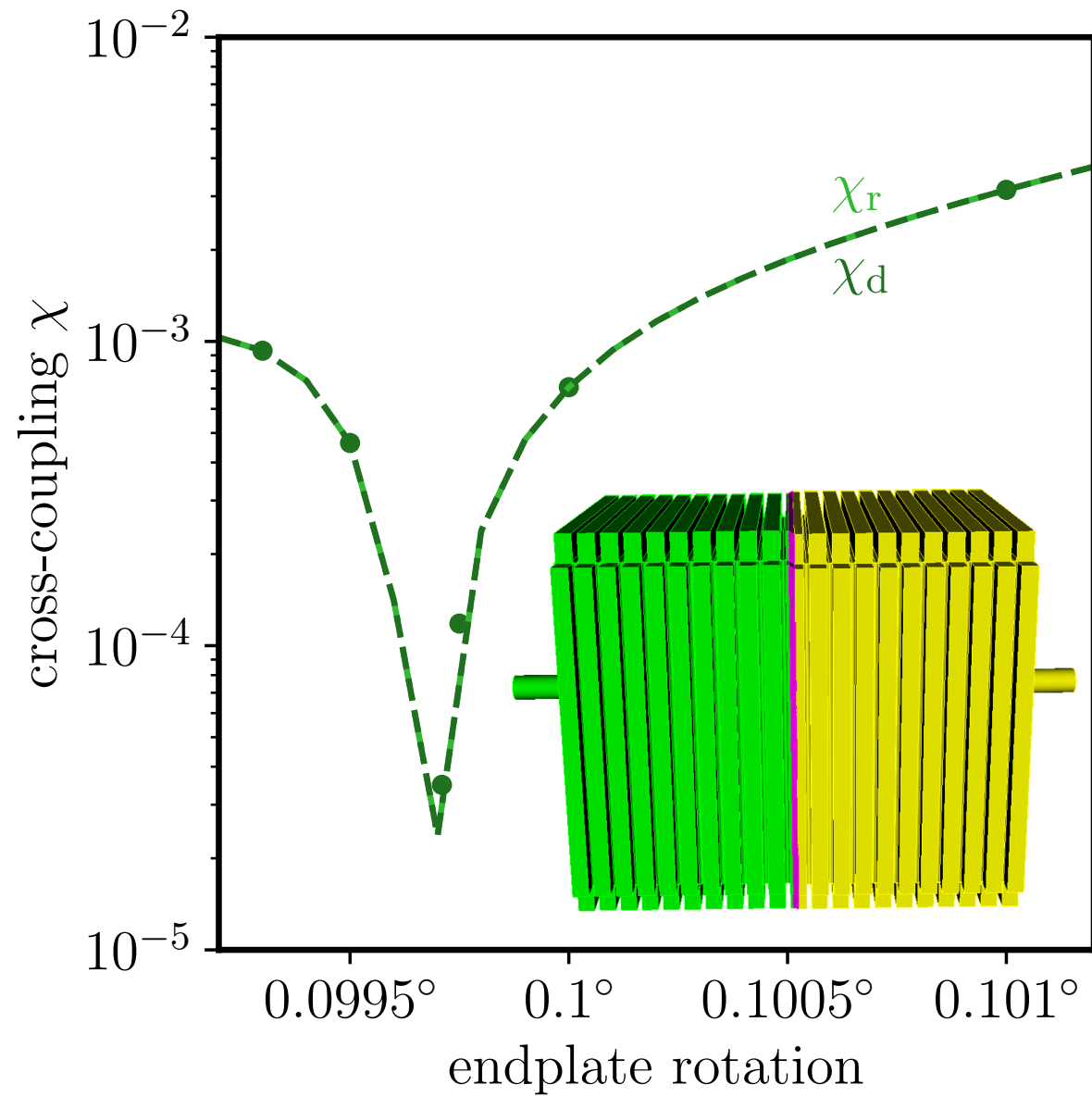


The axion is a well-motivated dark matter candidate, can be decisively probed in near-future experiments

Superconducting cavities are well-developed technology, can yield strong sensitivity to lighter axions

Multiple ongoing efforts will demonstrate feasibility

Backup: Simulated Imperfections



Can compensate for mm-scale rotation or skew by rotating endplate