20th Patras Workshop on Axions, WIMPs and WISPs

25.09.2025

DARK PHOTONS & AXION LIKE PARTICLES INTERFEROMETER

DALI: A Novel Magnetized Phased Array Haloscope for Axion Dark Matter Searches

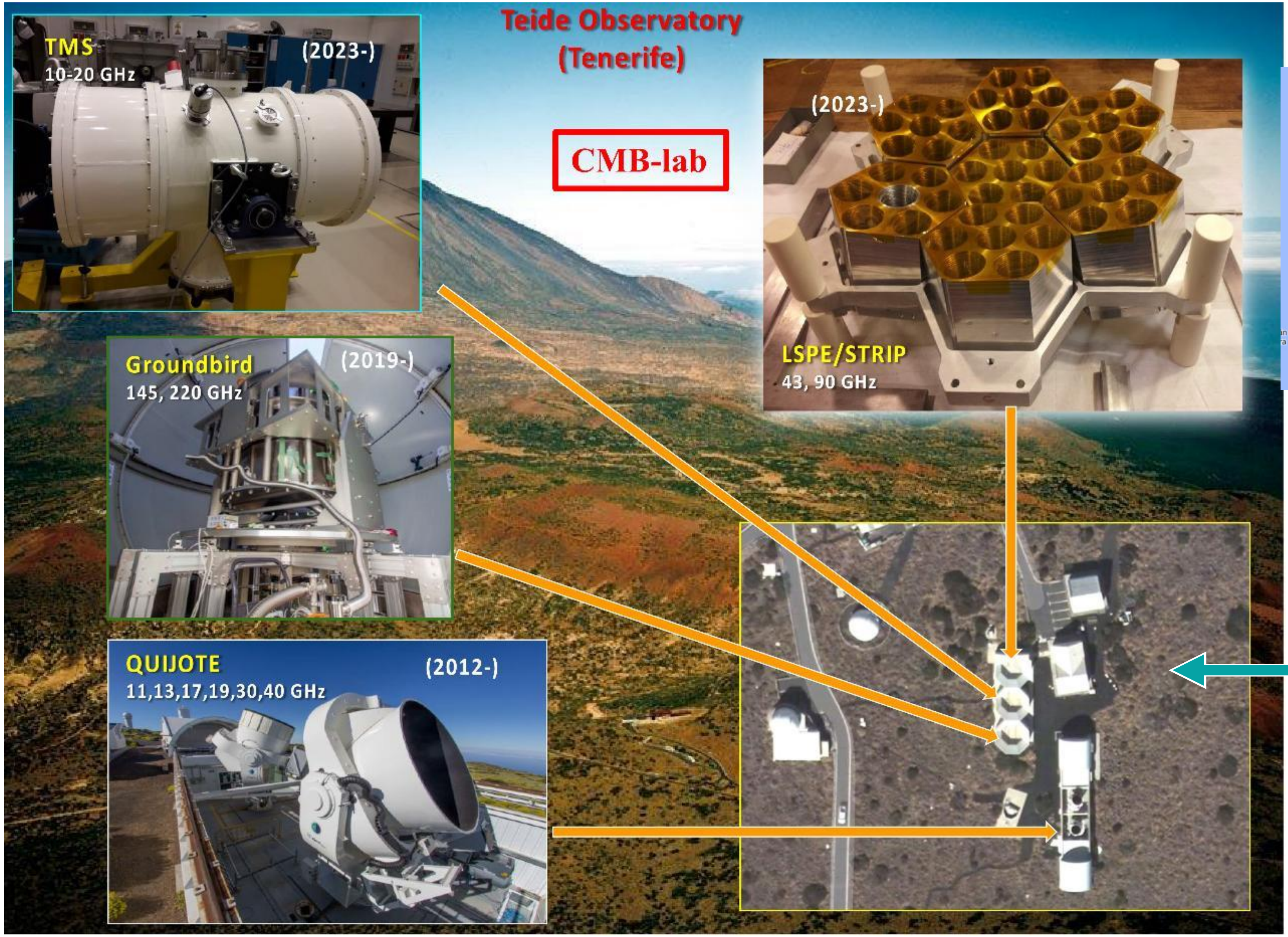
Dr. Antonios Gardikiotis
(on behalf of DALI Collaboration)

Teide Observatory

- Astrophysics in the Canaries began here at this Observatory
- 2390 meters above sea level
- The first telescope on the site was set up by the University of Bordeaux in 1964
- Teide Observatory became the birthplace of helioseismology
- Telescopes & CMB

--First-ever detection of a brown dwarf
--exoplanet transits
--confirmation of the presence of microwave background anisotropies ('cosmosomas')

Teide Observatory hosts multiple CMB/microwave instruments



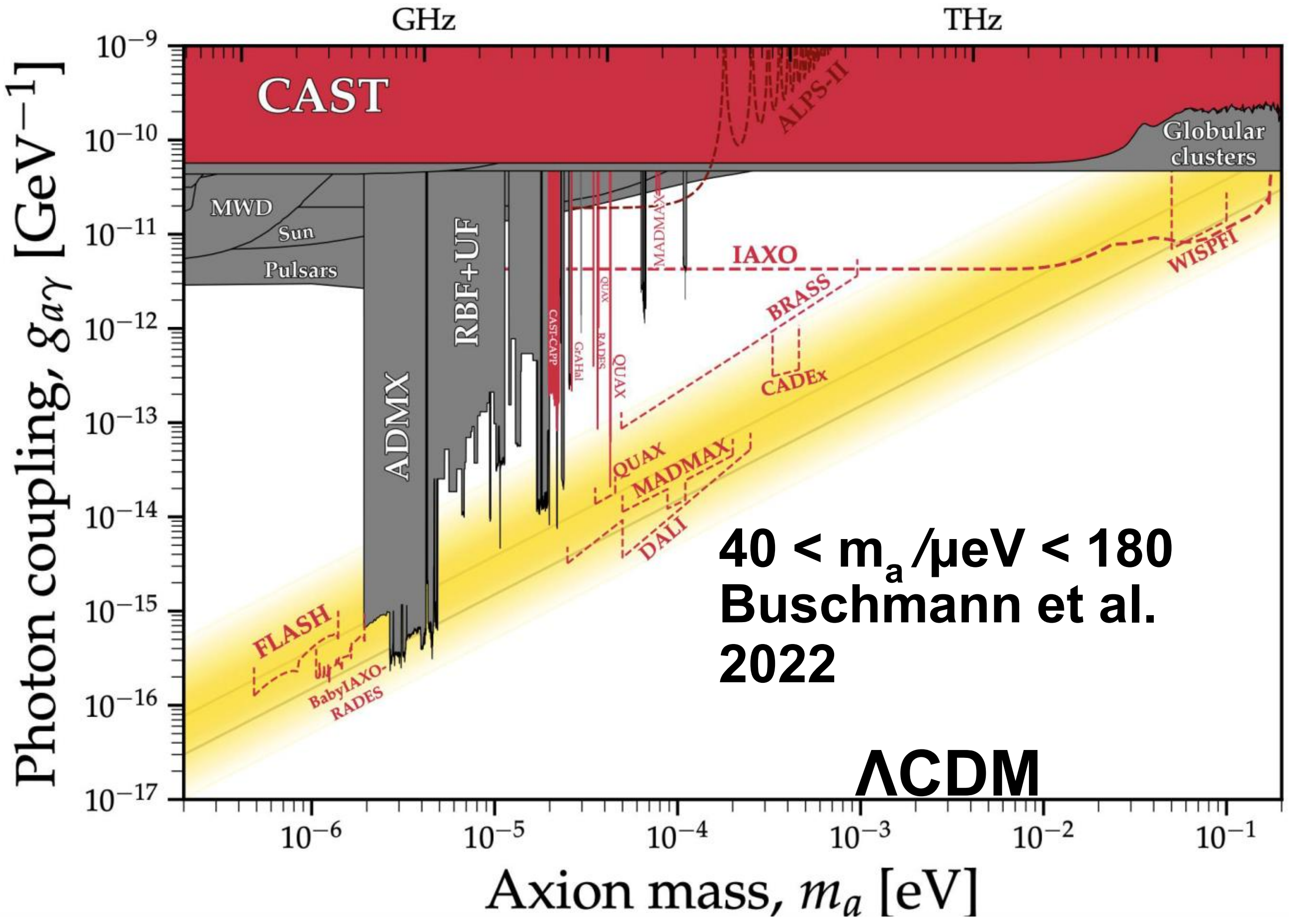
DARK PHOTONS & AXION LIKE PARTICLES INTERFEROMETER

DALI

Motivation

WE ARE HERE

$\rho_{DM} \sim ½\ \mathrm{GeV/cm^3}$



Axions solve the strong CP problem / prominent dark matter candidate

Why DALI? *Above a few GHz, $V \propto \lambda^3$ kills cavity power.*

*DALI uses a **Fabry–Pérot dielectric resonator** and **phased-array readout** to keep effective aperture while maintaining **Q** and bandwidth.*

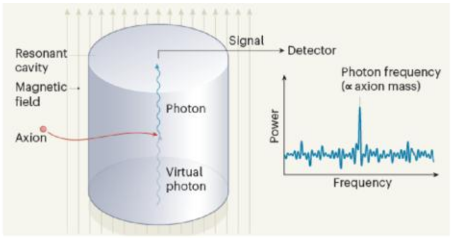
Experimental efforts at high frequencies

- Experimental direct search for Galactic DM proposed by Sikivie in the 1980s, the axion haloscope
- Ambient axions are converted into microwaves in a magnetized resonant cavity via the inverse Primakoff effect
- Cavity haloscope presents some technical hurdles for masses of several dozen μeV and beyond
- Evolved from the dish-antenna setup to Fabry-Pérot interferometer

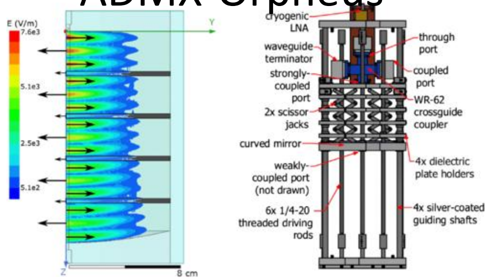
Dielectric Haloscopes:
ADMX-Orpheus, DBAS, LAMPOST, MADMAX , and MuDHI

DALI : magnetized phased array *(MPA) with a* Fabry–Pérot

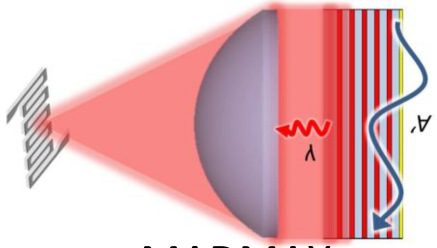
axion Haloscope



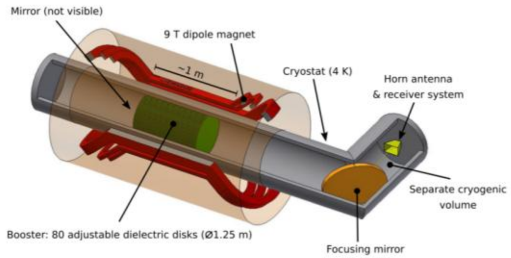
ADMX-Orpheus



LAMPOST

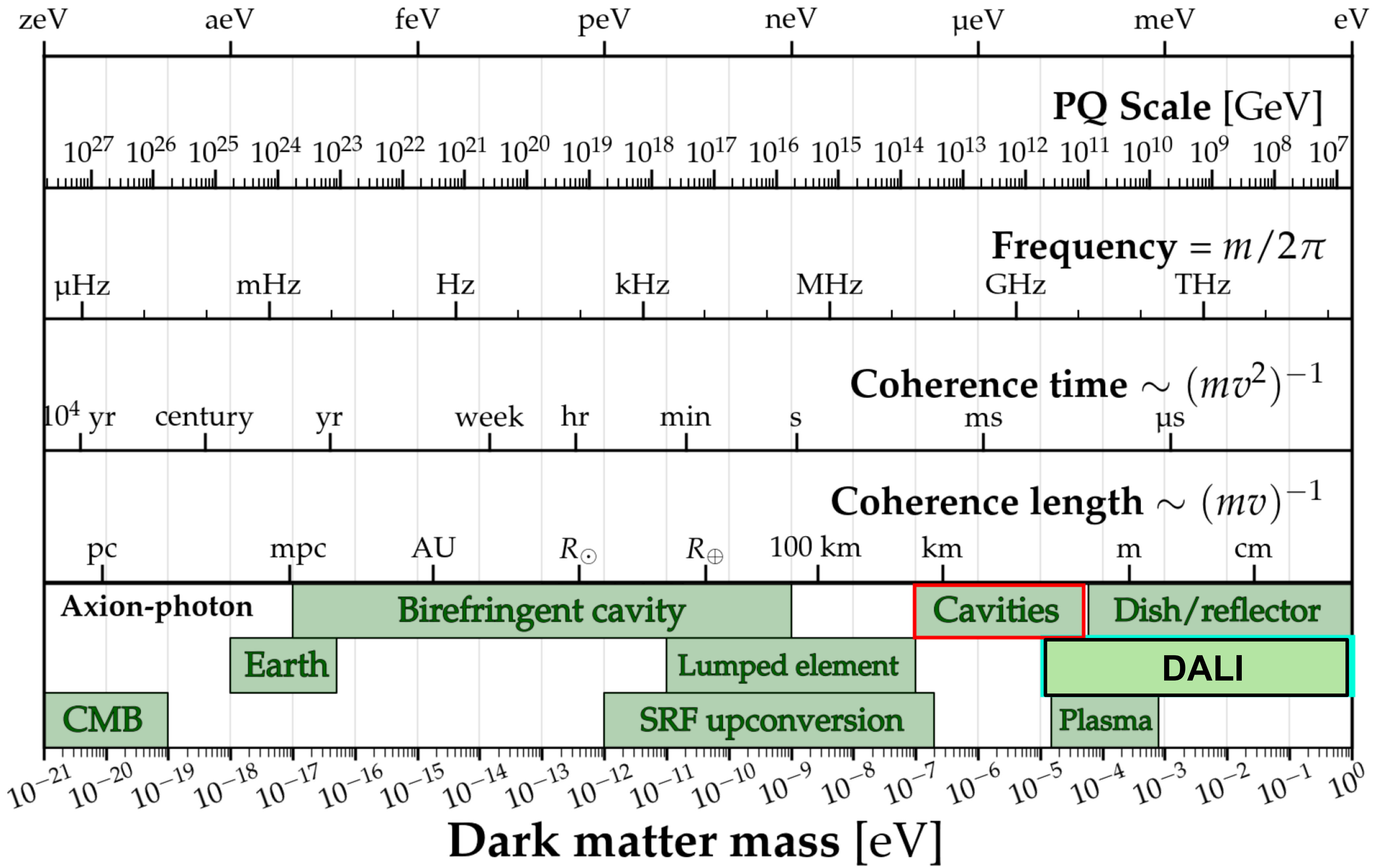


MADMAX



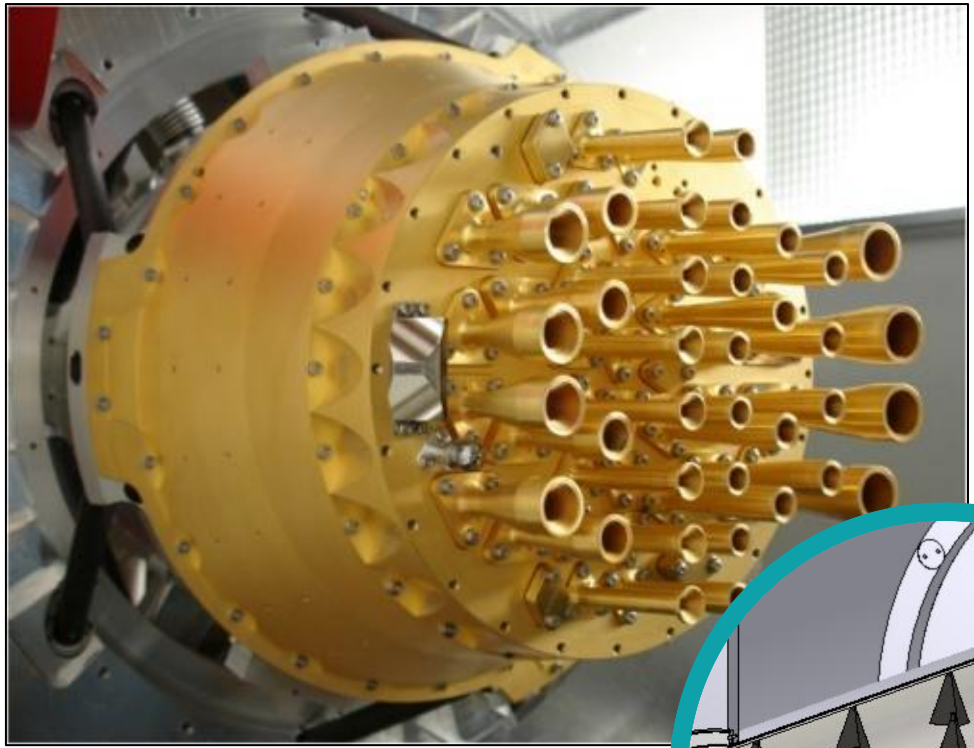
Dark matter mass

Credits C. O'Hare



DARK PHOTONS & AXION LIKE PARTICLES INTERFEROMETER DALI

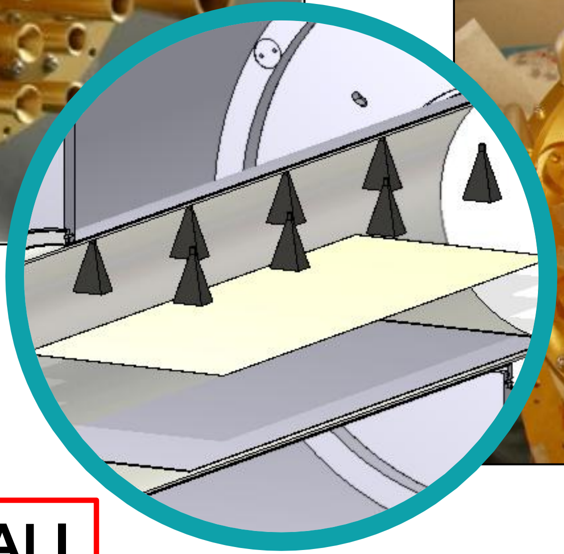
Phased arrays for CMB - DALI



Planck

BICEP

QUaD



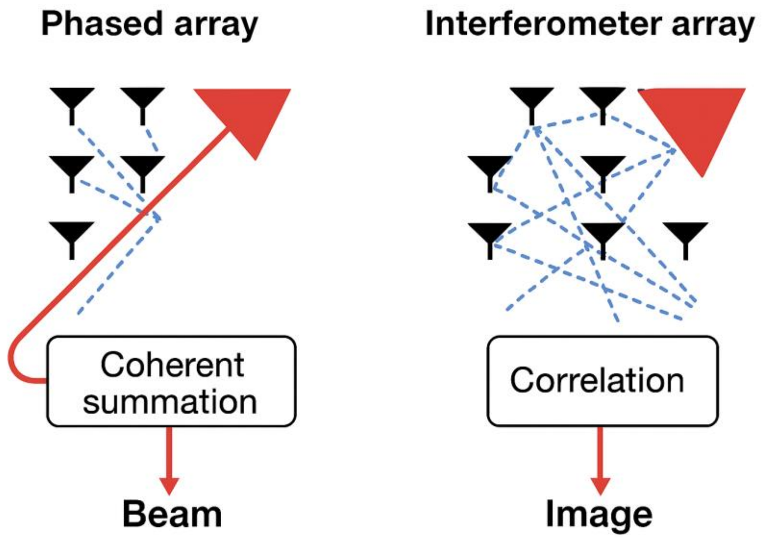
DALI

DARK PHOTONS & AXION LIKE PARTICLES INTERFEROMETER DALI

CMB (free-space)

"PHASED ARRAY"

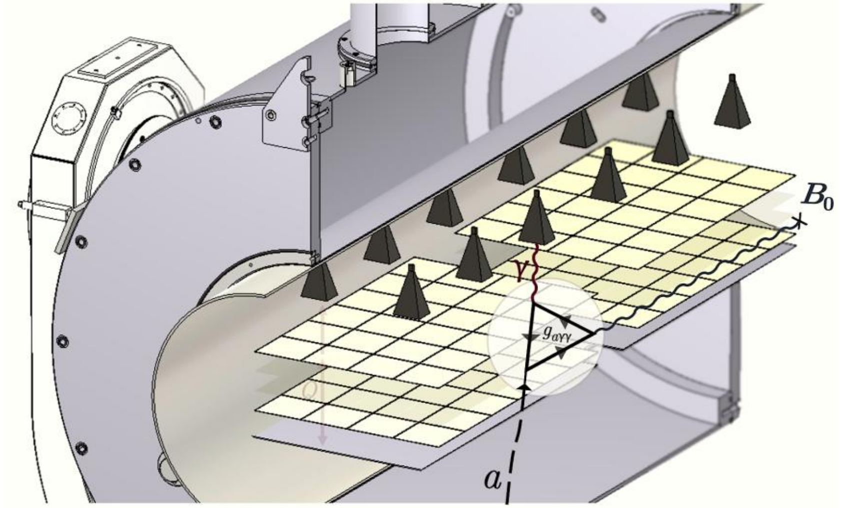
TELESCOPES



Dark Matter (uniform B_0)

"MAGNETIZED PHASED ARRAY"

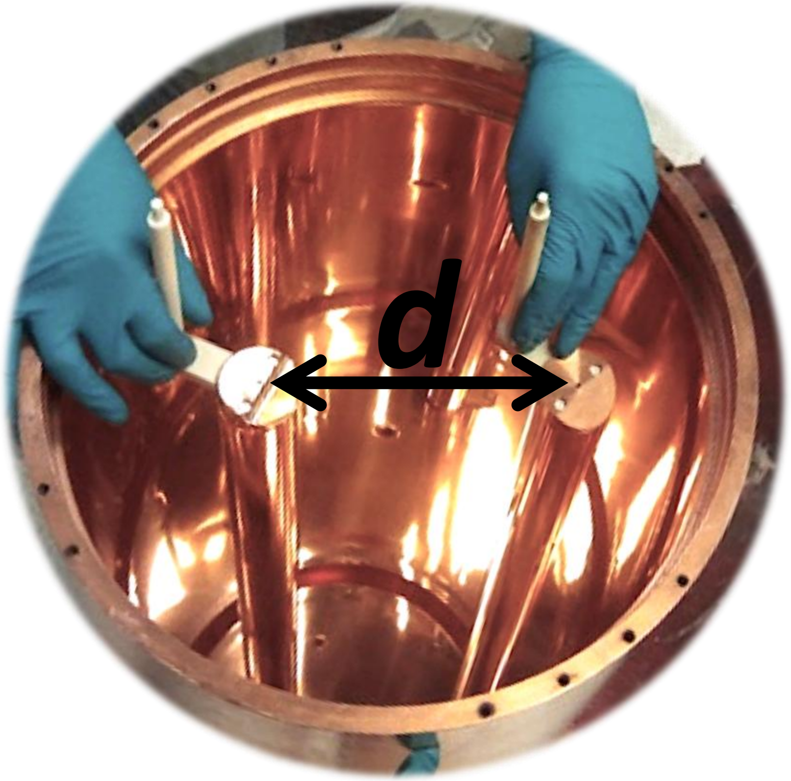
HALOSCOPE



CMB arrays beamform **sky brightness**;

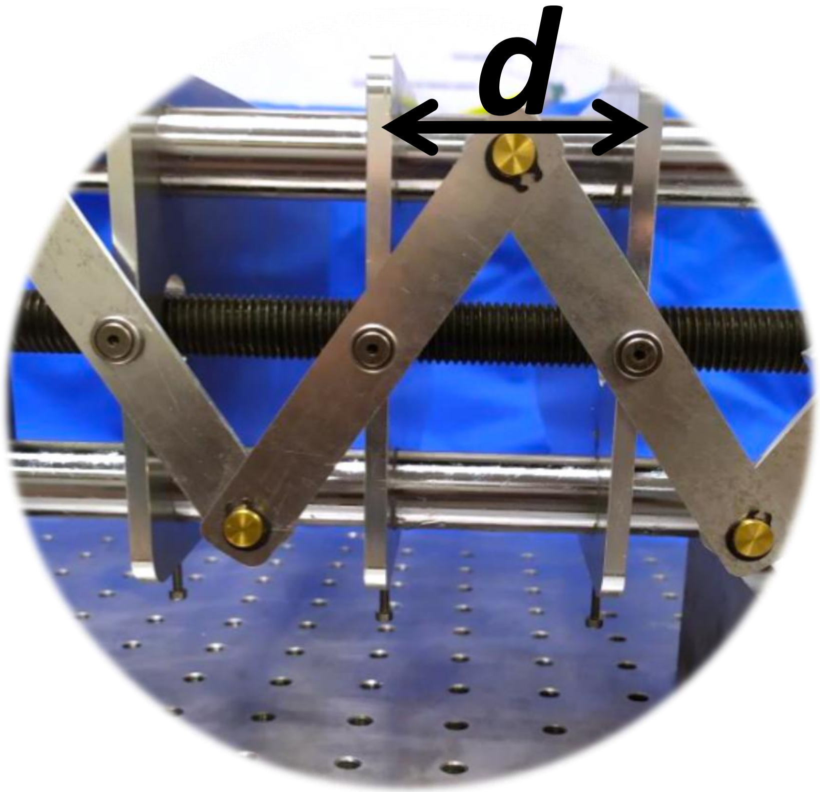
DALI beamforms **axion-induced E-fields** inside B_0.

Resonant cavity haloscope



Cavity: $P \propto V Q_L$ but $V \downarrow$ rapidly with ν.

Fabry-Pérot haloscope (DALI)

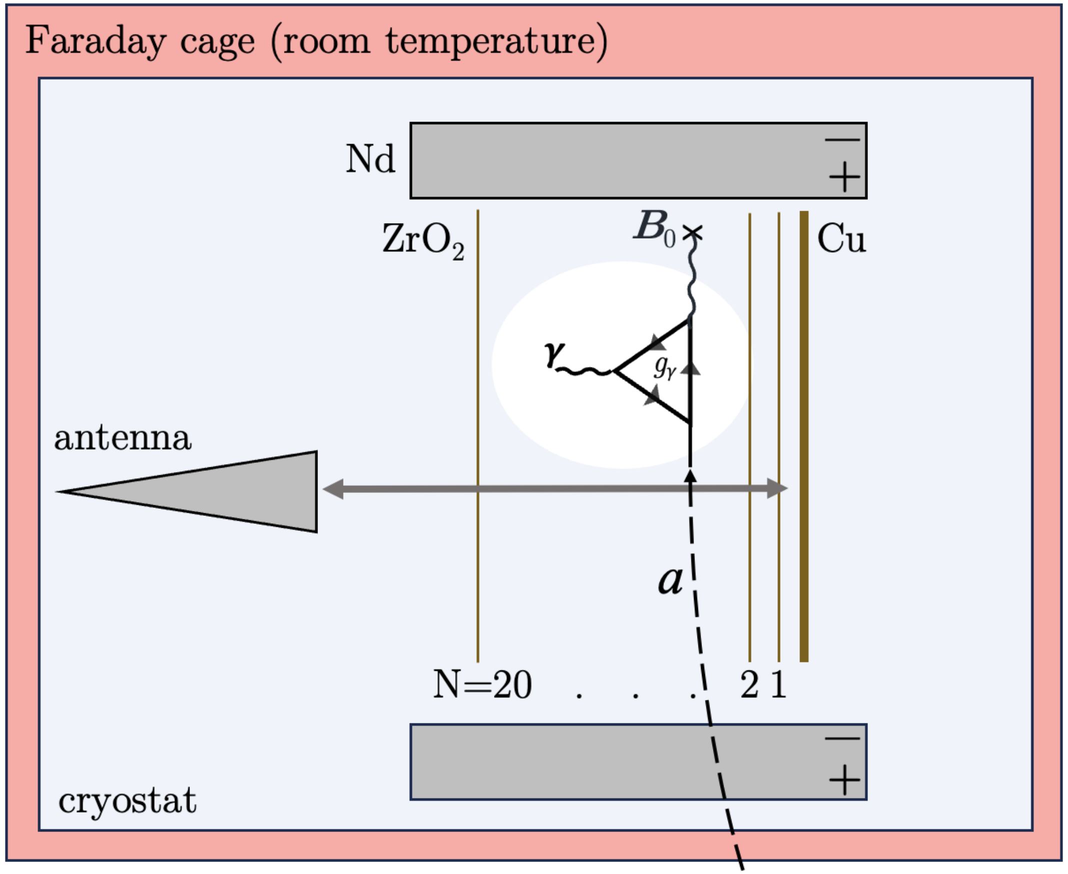


DALI: keeps **effective aperture** A large with a **phased FP stack**,
retains $\boldsymbol{Q}$ and offers **multi-resonance** coverage
→ **broad, step-tuned scans** at high mass

Conceptual Design

- Magnetized Phased Array (MPA) principle
- Combination with Fabry–Perot haloscope
- Novel broadband tunable axion search

Dielectric stack enhances axion–photon conversion via constructive interference of emitted fields.
Instantaneous bandwidth ≈ 100 MHz; step-tuning across 6–60 GHz (design).



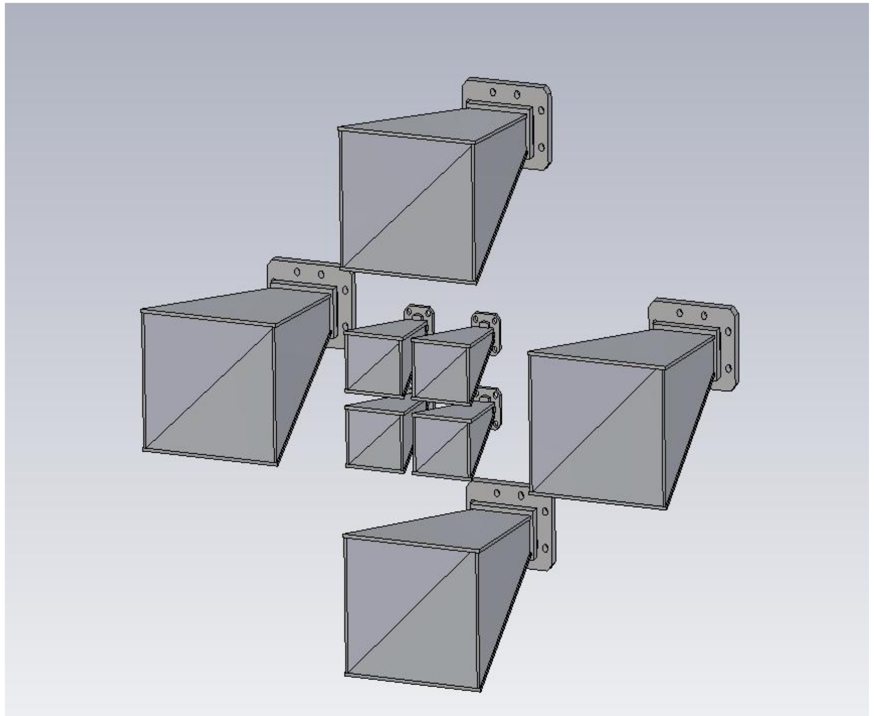
The resonant frequency is tuned by setting a plate distance of a fraction of the scanning wavelength, typically ~**λ/2** with a plate thickness of ~**λ/(2√εr)** in a half-wavelength stack

$$P \approx 10^{-23}\,\mathrm{W} \times \frac{A}{\mathrm{m}^2} \times \left(\frac{B_0}{10\,\mathrm{T}}\right)^2 \times Q \times \left(\frac{g_{a\gamma}}{10^{-14}\mathrm{GeV}^{-1}}\right)^2 \times \left(\frac{\mu\mathrm{eV}}{m_a}\right)^2 \frac{\rho_a}{0.3\,\mathrm{GeV cm}^{-3}}$$

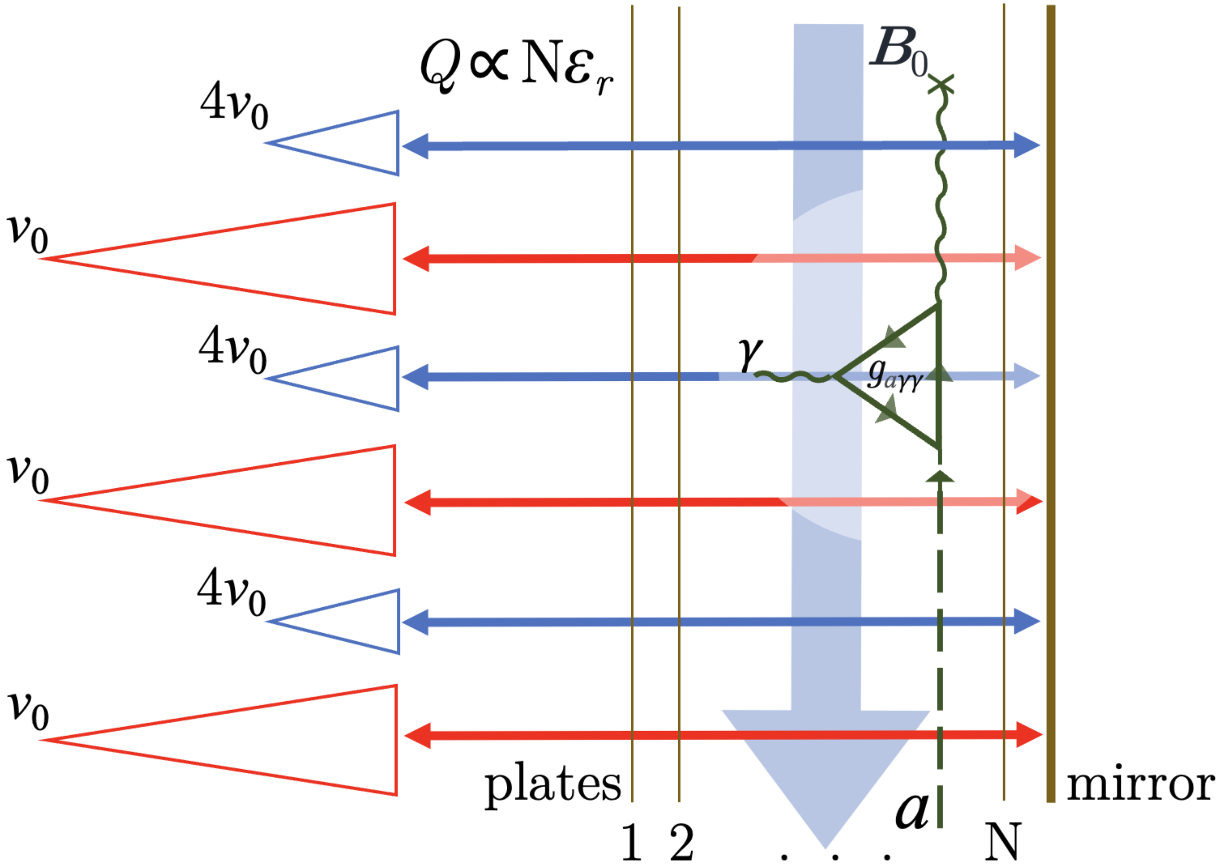
D. Horns et al J. Cosmol. Astropart. Phys. 04 (2013) 016.

Magnetized phased array (MPA) haloscope

CST Time Domain Simulation

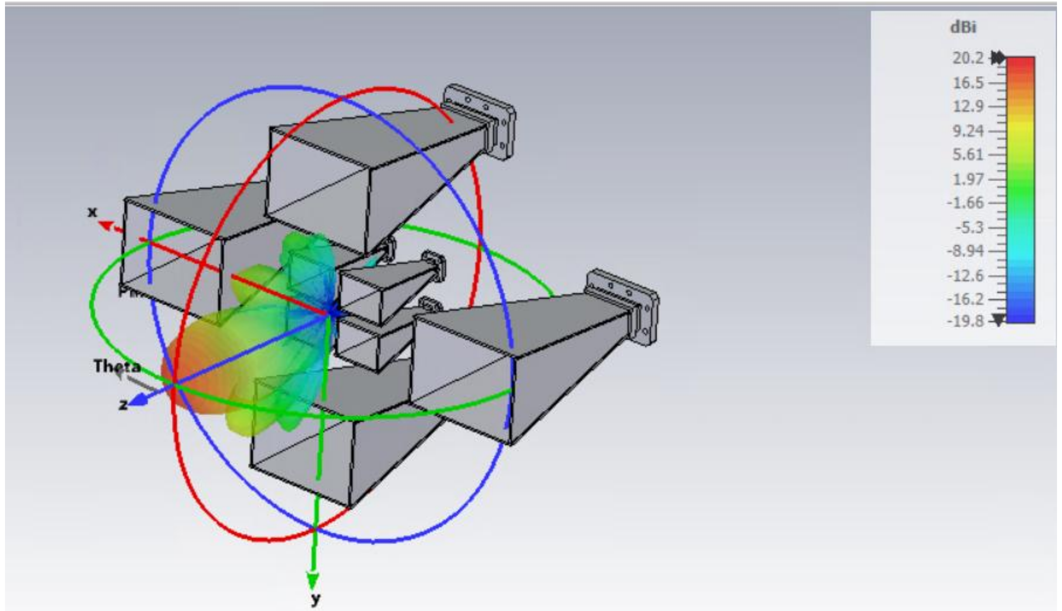


Element spacing $d \lesssim \lambda/2$
to avoid grating lobes;

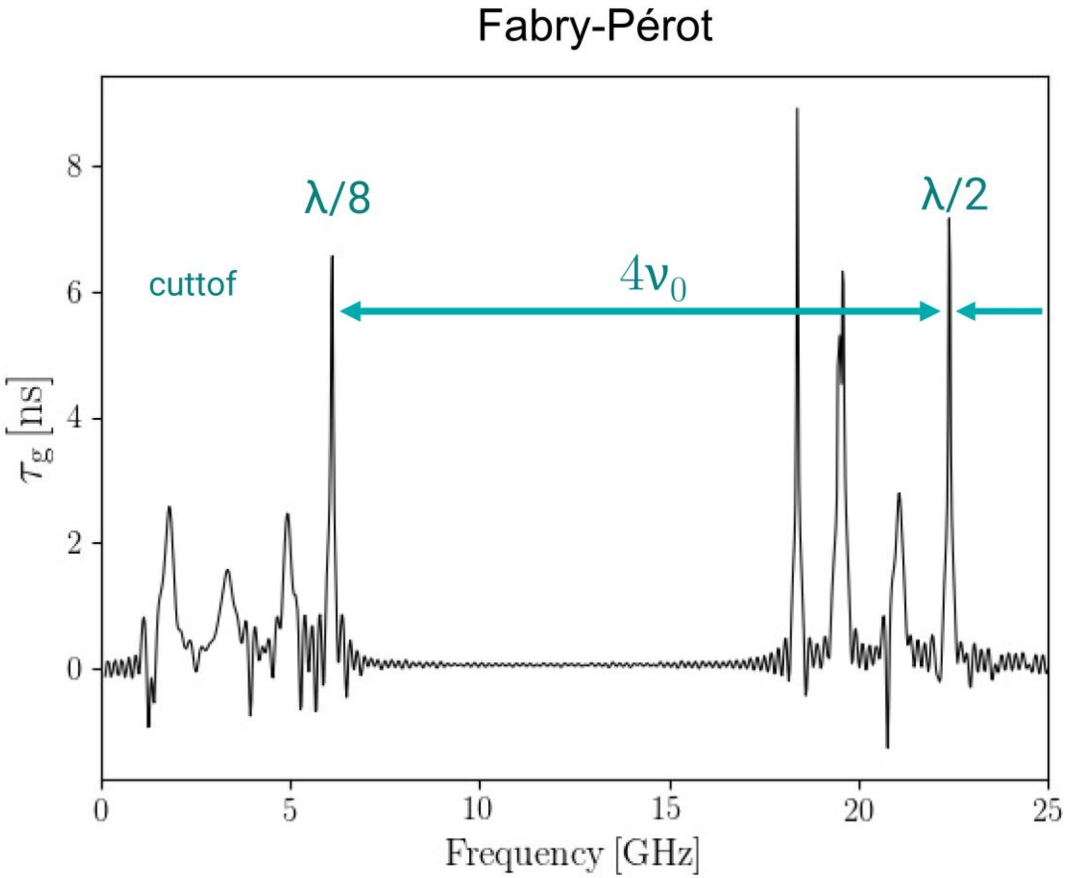


capacity to probe two different resonance frequencies simultaneously

Magnetized phased array (MPA) haloscope



CST simulations of the farfield directivity at 33 GHz (without dielectrics)



group delay τ_g of our Fabry–Pérot stack the height is proportional to the **dwell time** of the field, so $Q = \omega_0 \tau_g$

--By choosing plate spacings we get a **multi-resonance response**: several high-Q modes across roughly **four free-spectral-ranges** (marked $\sim 4\nu_0$)

DARK PHOTONS & AXION LIKE PARTICLES INTERFEROMETER DALI

DALI (Dark-photons & Axion-Like particles Interferometer)

- **Multilayer Fabry–Pérot resonator.** DALI uses a **dielectric FP stack** to coherently sum emissions at each interface (axion) or to resonantly enhance a dark-photon field.

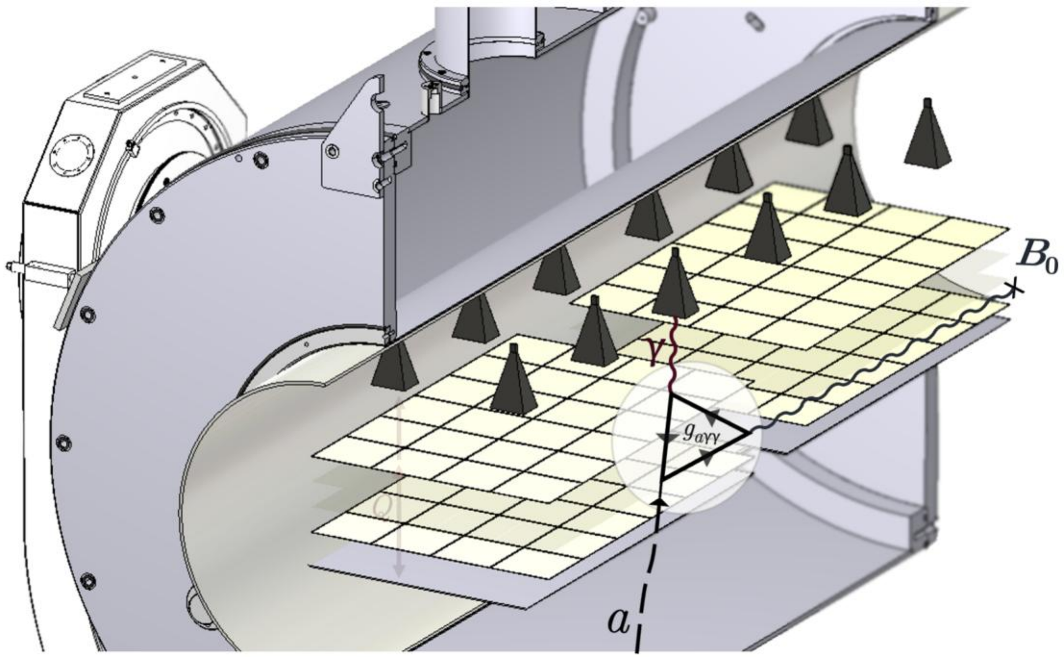
- **Multi-frequency operation.** Resonances repeat at intervals ≃the **free spectral range** (FSR);

  plate gaps tune the passbands → **multi-resonance scan**.

- **Conversion channel.** Axion: $a + \mathbf{B}_0 \to \gamma$

  Primakoff, $\mathbf{E} \parallel \mathbf{B}_0$.(Dark photon: kinetic mixing χ without $\mathbf{B}_0$.

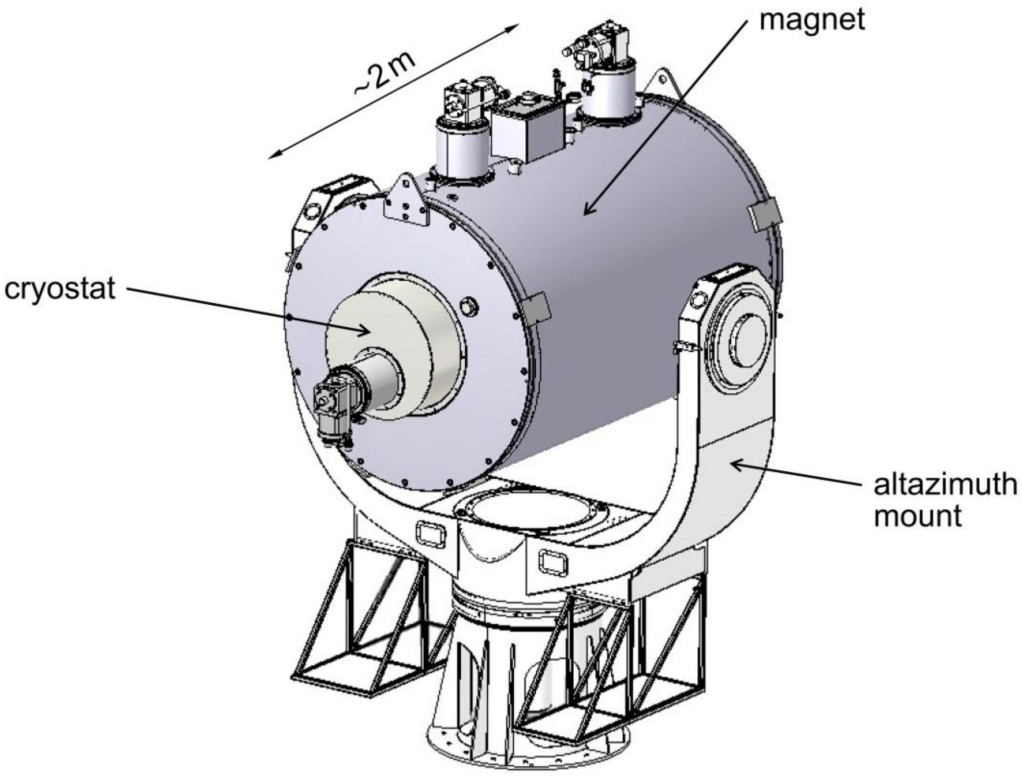
- **Scaling in DALI.** Effective signal scales with Q_L ,B_0^2 , effective aperture A, and $g_{a\gamma\gamma}$ or χ for dark photons.



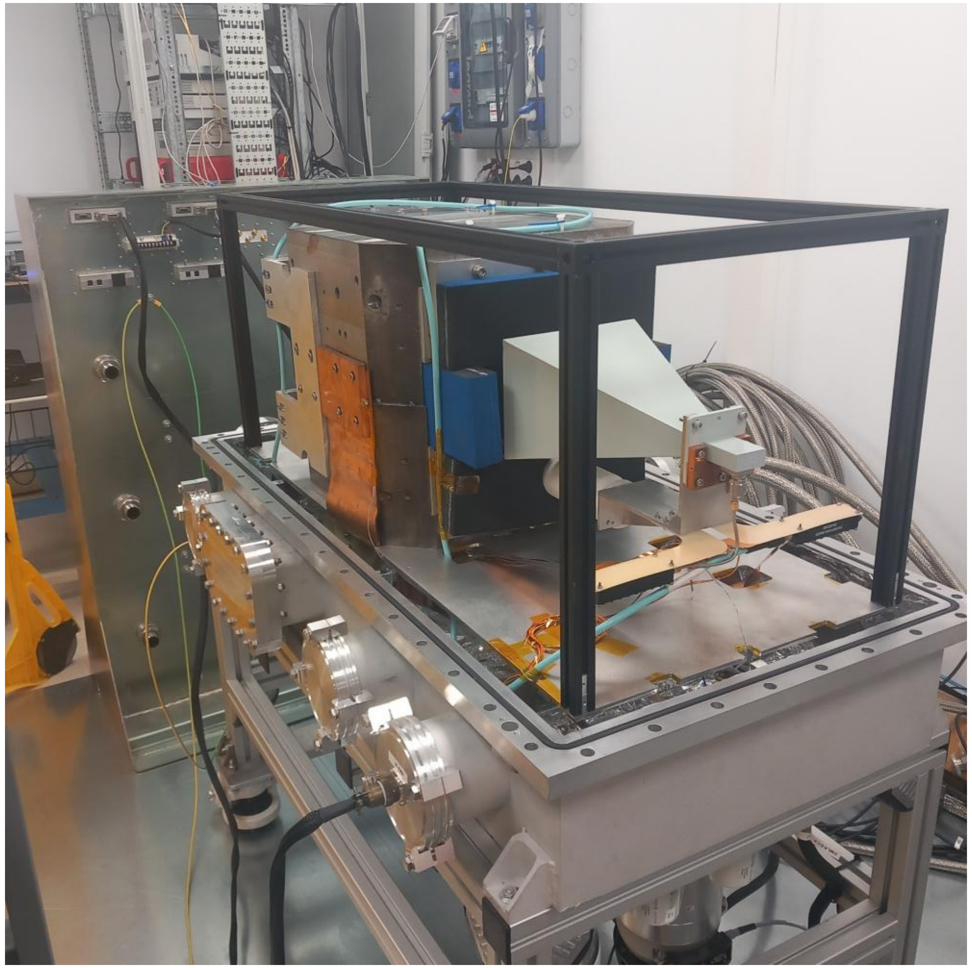
$$P_{\text{cav}} \propto g_{a\gamma\gamma}^2 B_0^2 V C Q_L \frac{\rho_a}{m_a},$$
$$P_{\text{DALI}} \propto g_{a\gamma\gamma}^2 B_0^2 A\, Q \frac{\rho_a}{m_a^2}.$$

Instrument overview" (magnet + cryostat)

- **Instrument concept.** Cryogenic **Fabry–Pérot interferometer** inside a vacuum shield; housed in a **multicoil superconducting magnet** providing uniform $\mathbf{B}_0$.
- **Envelope (approx.).** Magnet: $\sim 1.5\,m \times \emptyset 1\,m$; experiment cryostat: $\sim 2\,m \times \emptyset 0.5\,m$.
- **Mount. Alt-azimuth** mount for pointing/tracking and fast rotation (for systematics & daily-modulation studies).
- **Cold stages (typical).** LNA $\sim 1\,K$; antenna $\sim 0.1\,K$;
- **Integration notes.** Radiation shield, G10 isolators to yoke, copper thermal links to cold head.

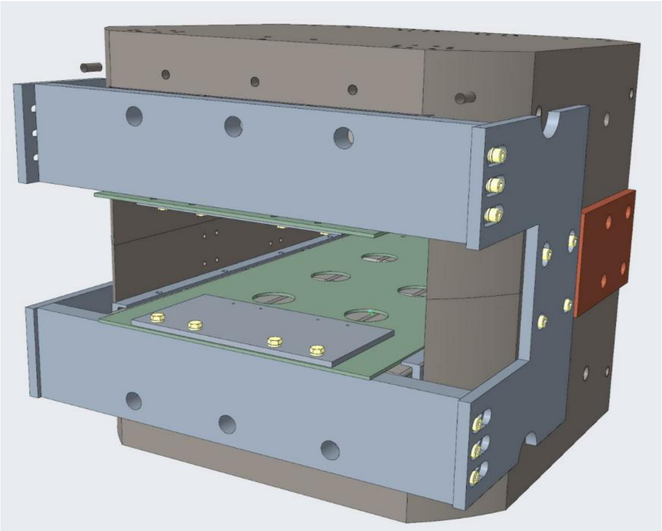


Proof-of-Principle Prototype



Magnet Array — As-Built Summary

- Ultimately magnet array assembly completed
- **Magnetic Field Goal Achieved**
  (0.59±0.01 T within the volume set for the 20-layer resonator)
- Original fully compacted 12×3 triplet design
  proved unstable due to strong triplet-triplet repulsion
- As-built solution: mechanically constrained compacting
  with **lateral retainers**, **top lids**, and local **reinforcement plate**
- Safety incident revealed potential for triplet 'jump/flip'
  → acrylic test lid replaced by 3-mm AL6061 lids



INITIAL DESIGN

AS-BUILT

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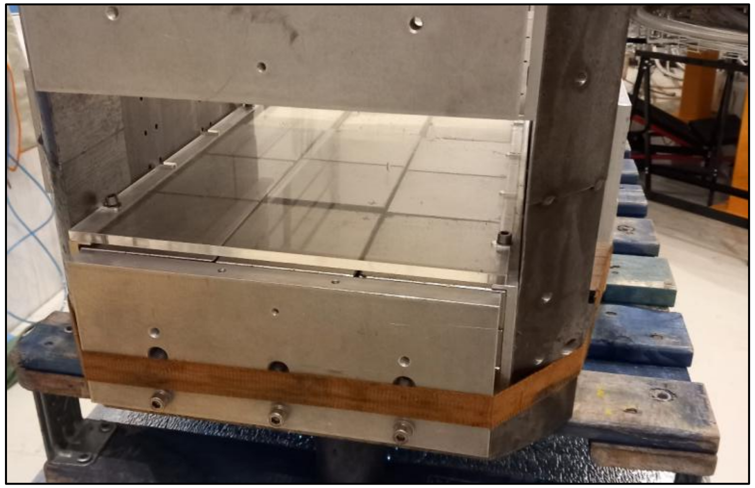
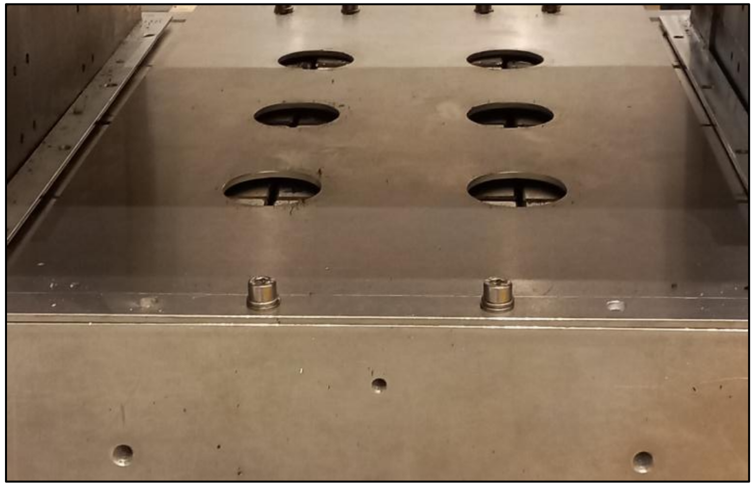
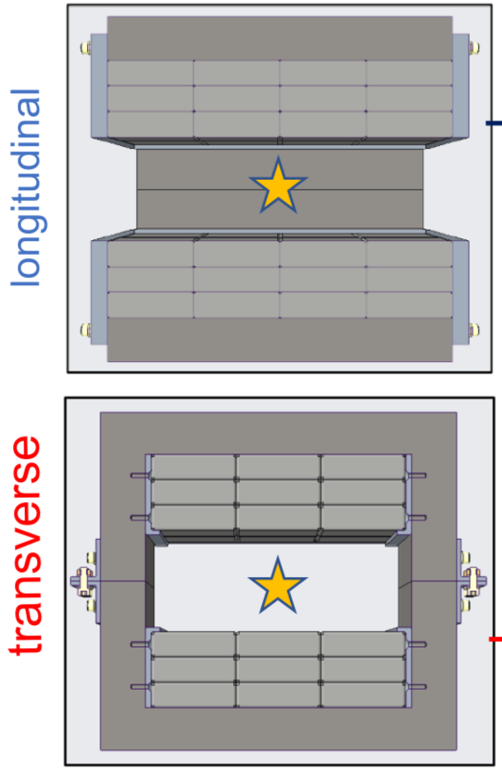


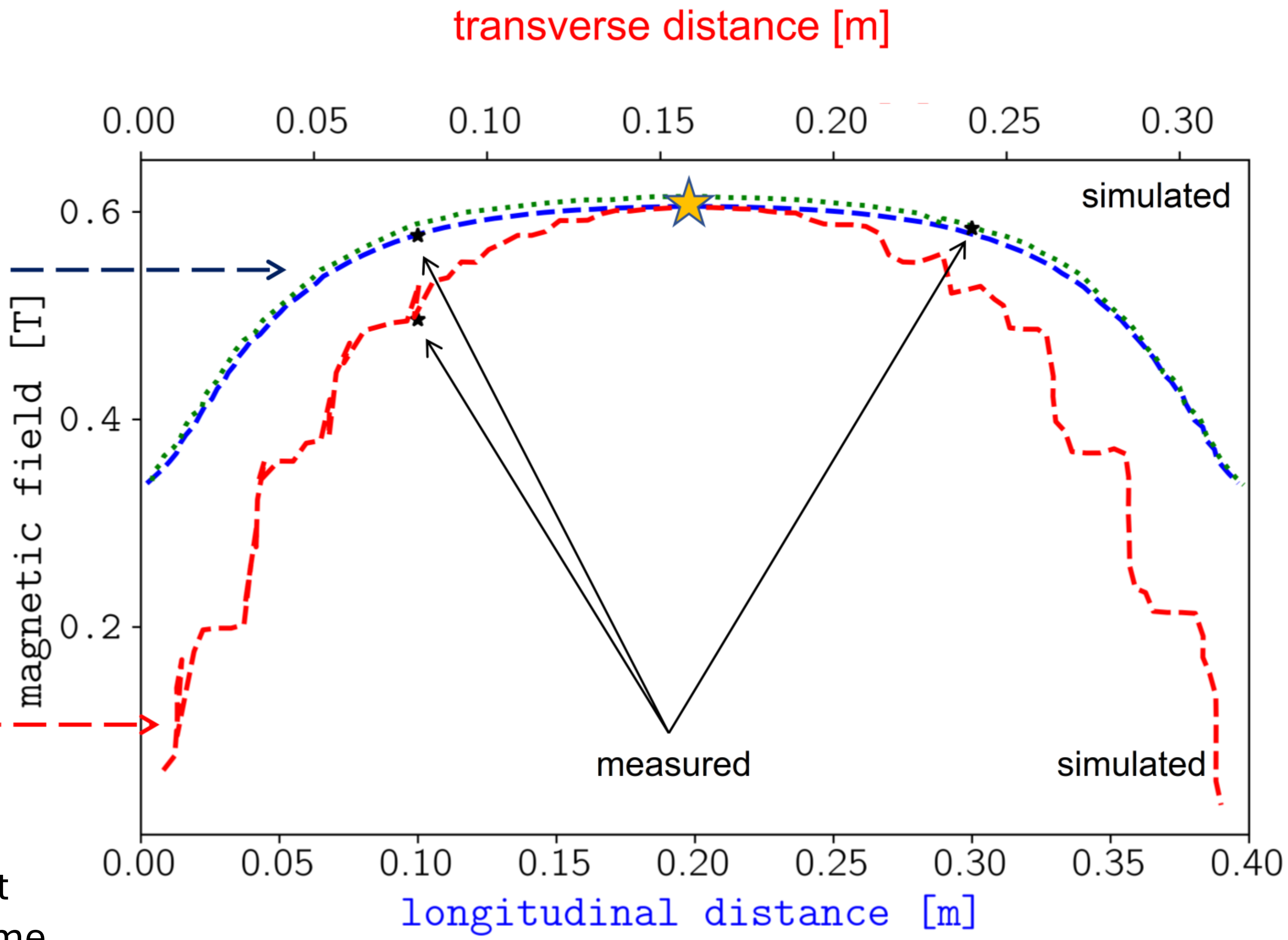
INITIAL DESIGN



AS-BUILT

Field map vs. model

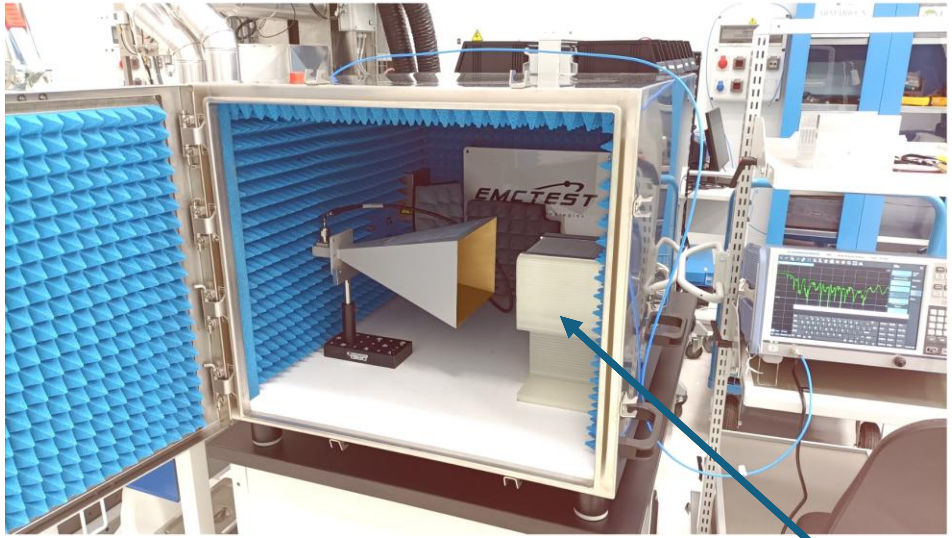


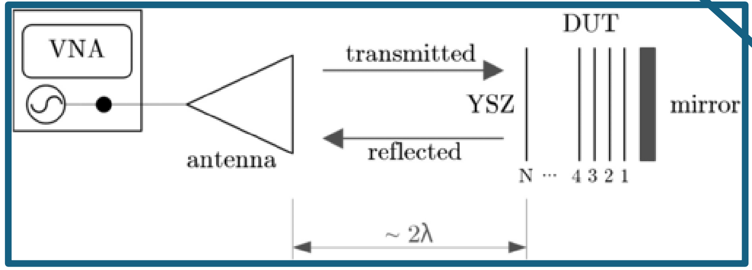


Center field ≈ 0.59 T; agreement within <X% over resonator volume

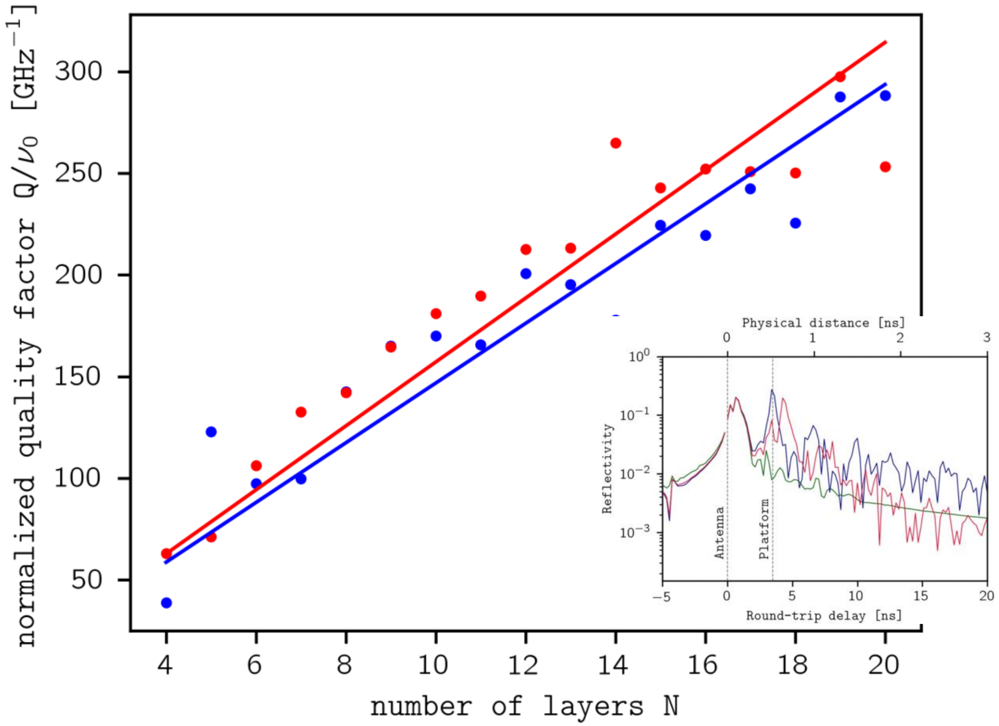
DARK PHOTONS & AXION LIKE PARTICLES INTERFEROMETER

Anechoic measurement of the Quality factor





20-plate



- Q-factor measurements with 1–20 ZrO_2 layers (100×100)±0.5mm & thickness of 1± 0.03 mm
- Scaling: Q ~200–250 per layer → Q ~4×10^3
- Measured vs FEM simulations

DUT1 (6.04 mm spacing) 7.01 GHz and
DUT2 (6.21 mm spacing) 6.90 GHz
Q ~ 2*10^3 for N=20

Phys. Rev. D **110**, 072013 – **Published 21 October, 2024**
DOI: https://doi.org/10.1103/PhysRevD.110.072013

Tuner Mechanism

Tekniker | 09/09/2025

- Fabry–Perot tuner: ‘scissor’ system
- As-built modifications: reduced clearance
- Frame adjustments, motor support redesign

The ‘scissor’ concept is used to allow adjacent plates to move simultaneously while maintaining the same spacing

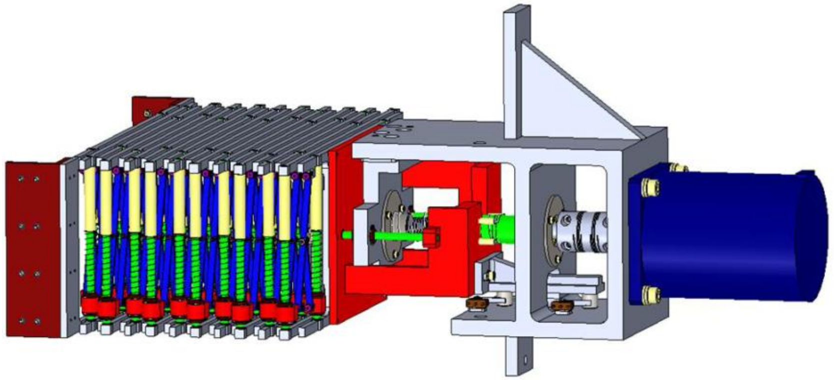
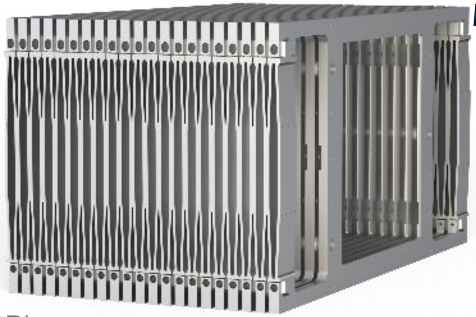
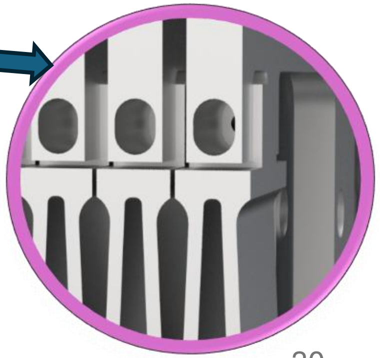


Figure 1: Tune Mechanism Illustration (Original Design)

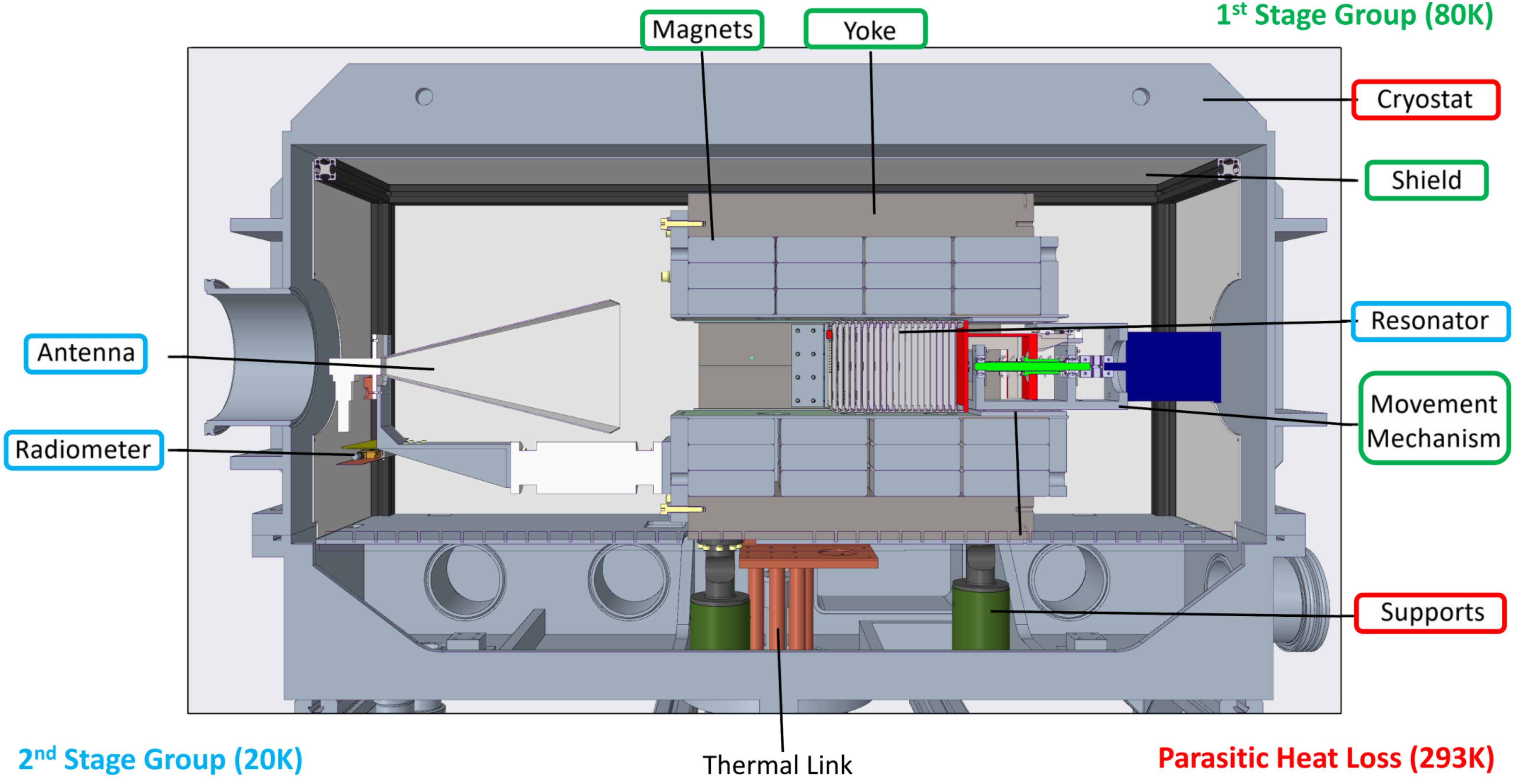
Max deviation: 0.027 mm

finite element method (FEM) simulations establish the mechanical error/uncertainty in the layer positioning
$e \lesssim \lambda/500$





Cryostat (LISA) — Integration & Performance



1st Stage Group (80K)

2nd Stage Group (20K)

Parasitic Heat Loss (293K)

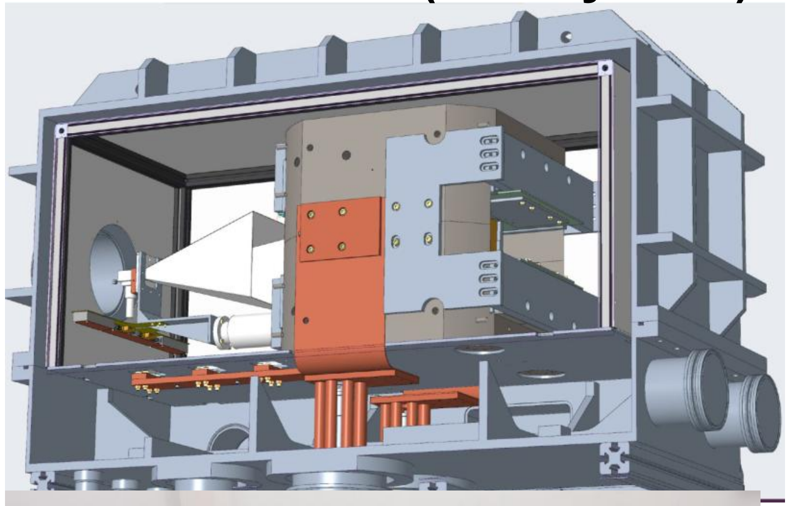
Cryostat (LISA) — Integration & Performance

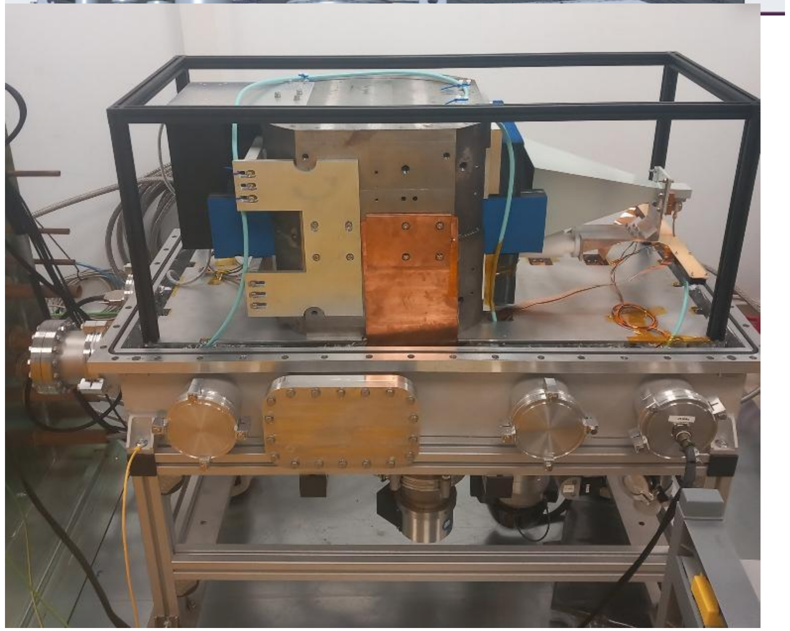
- LISA MWIR **large cryostat**, modified for DALI PoP (new radiation shield; optical bench removed).
- **Mounting & isolation:** yoke base legs integrated; **G10 pads** fix the shield to the yoke (low thermal conductance).
- **Operating conditions: LNA ~9 K, antenna ~14–16 K, yoke ~38–40 K**; vacuum **$\sim 2\times10^{-8}$ mbar** during cooldown.
- **EMC:** operated inside a portable **Faraday** tent with a connector terminal interface.
- **Envelope note:** magnet as-built reduces vertical clearance by **~7 mm (top) / ~5 mm (bottom)** → aim for **≥6 mm** net reduction in mechanism/system

≈60 dB insulation.

Mechanical Update
Dylan Carroll

DALI-LISA PoP (Full System)





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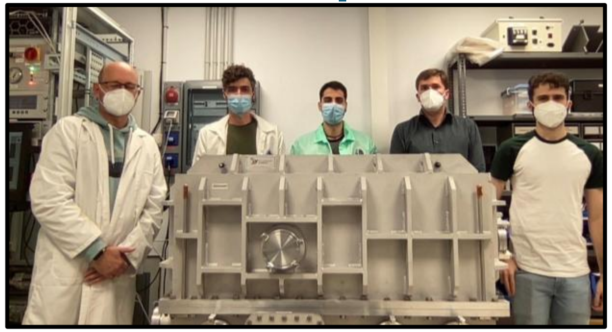
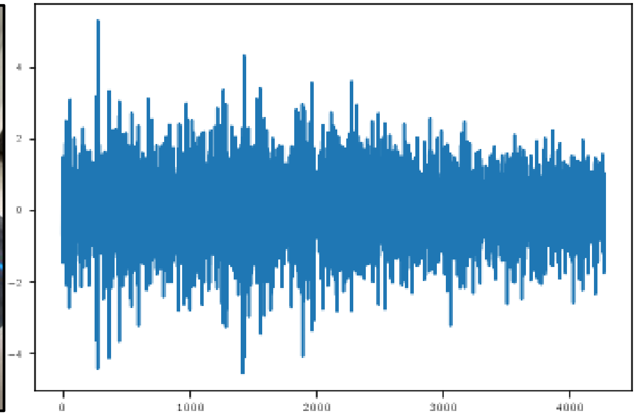
Work in progress : Cryogenics & Data Acquisition





Calibration & Data Acquisition (DALI PoP)

- **Signal chain (overview):** horn → BPF (6.5–8 GHz) → LNA(s) → ZIF down-converter → I/Q **LPFs** → **14-bit ADC** → SSD.

  Observable BW ≈ **80 MHz**; typical sampling **100–125 MS/s**

- **Radiometer calibration (Y-factor):** acquire N spectra on hot/cold loads

$$Y = \frac{\langle P_{hot} \rangle}{\langle P_{cold} \rangle}, T_{sys} = \frac{T_{hot} - Y\,T_{cold}}{Y - 1}$$

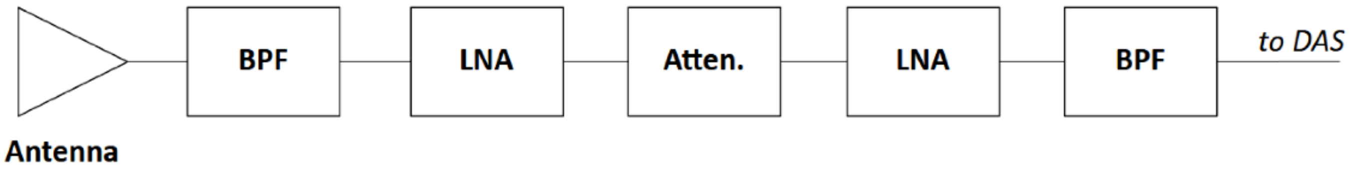
- Two thermal loads (e.g., blackbody at 200 K and 400 K)

  presented at the input.

- Repeat cycles; correlate with stage temperatures and pilot tone; perform inside Faraday tent if possible.

T_{sys}= 20-40 K
Y = 1.8 (~2.3% error in T_{sys})

NF $\approx 0.47\ dB$



DALI prototype	B_0 [T]	Area [m^2]	Range [GHz]	T_{sys} [K]	Q	Sensitivity in $t\sim1$ day g_γ [GeV^{-1}]
Scaled-down	~1	1/100	6-8 31-35	~30 K	~2,000 ~8,000	$\sim10^{-11}$
full-scale Phase I	9.4	1/2	6-60	2-10 K	~50,000	$\sim5\times10^{-15}$
full-scale Phase II	11.7	3/2	~10-100	2-10 K	~70,000	$\sim10^{-15}$

Prototype Status

- **PoP** integration with cryostat **ongoing**
- **Pilot runs**: resonators at 6.9 & 7.01 GHz
- Radiometer chain calibration

$$g_{a\gamma\gamma} \gtrsim 10^{-14}\ \text{GeV}^{-1} \times \left(\frac{\text{SNR}}{Q}\right)^{1/2} \times \left(\frac{\text{m}^2}{A}\right)^{1/2} \times \left(\frac{m_a}{\mu\text{eV}}\right) \times \left(\frac{10\ \text{s}}{t}\right)^{1/4} \times \left(\frac{T_{\text{sys}}}{\text{K}}\right)^{1/2} \times \frac{10\ \text{T}}{B_0} \times \underbrace{\left(\frac{\delta\nu}{\text{Hz}}\right)^{1/4}}_{\text{(i)}} \times \underbrace{f_{\text{DM}}^{-1/2}}_{\text{(ii)}},$$

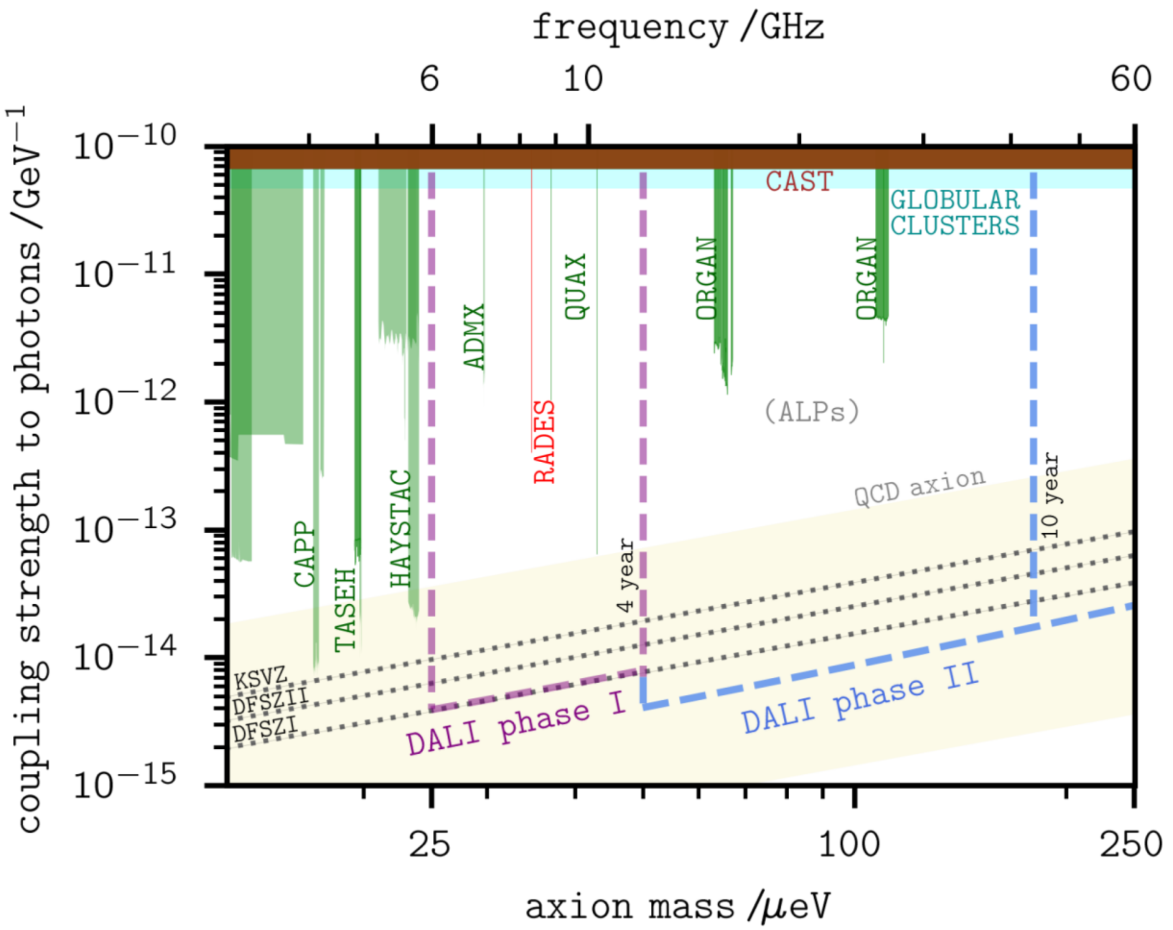
Uncertainties are weighted according to their order in Eq. to estimate the propagated cumulative uncertainty in this run

Parameter	Measured	Uncertainty
Magnetic field (B_0)	.59 T	<3%
System temperature (T_{sys})	33 K	<2%
Quality factor (Q)	≲2198	<8%
Efficiency ($\mathcal{E}$)	<0.3	<5%
Propagation to g_γ sensitivity		≲10%

Projected sensitivity to ALPs coupling to photons

A forecast of the sensitivity of DALI Experiment to Galactic axion dark matter projected onto current exclusion limits

The haloscope is sensitive to axion-like particles with a coupling strength to photons According to the scaling relation :

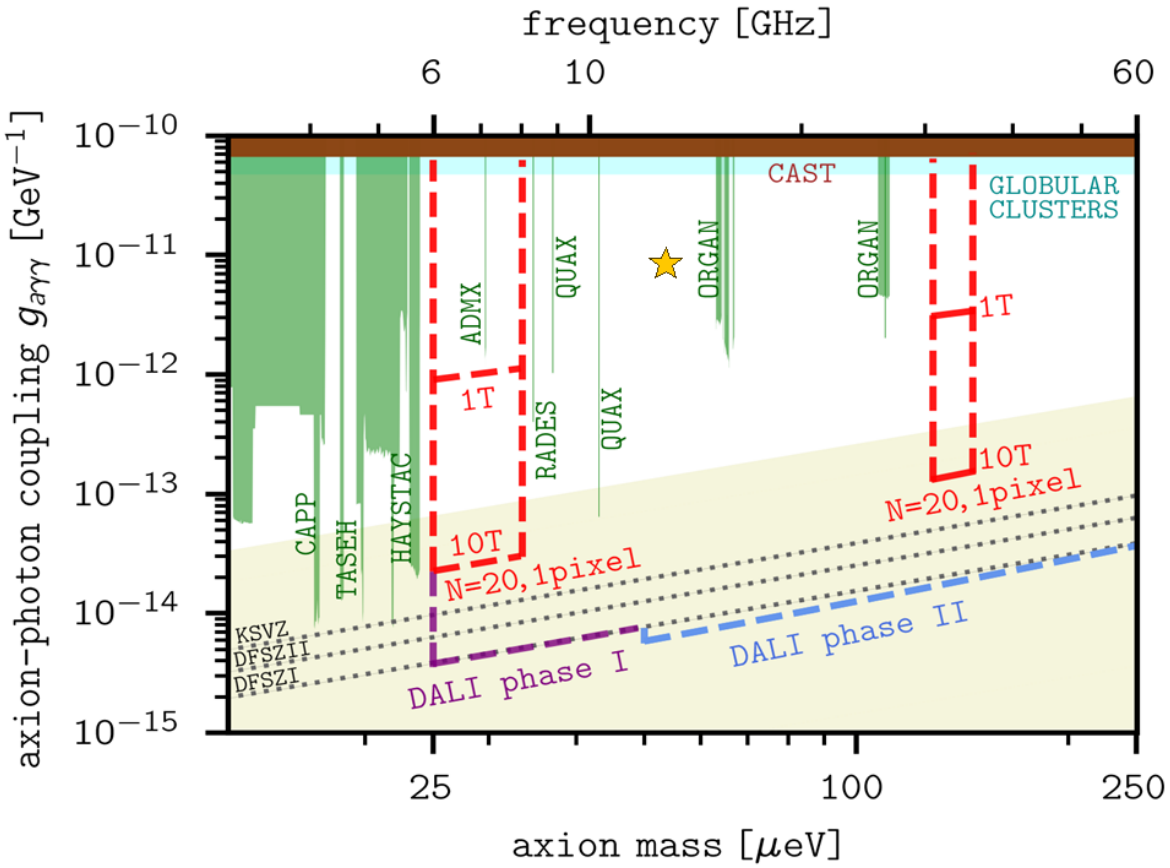


$$g_{a\gamma\gamma} \gtrsim 10^{-14}\ \mathrm{GeV}^{-1} \times \left(\frac{\mathrm{SNR}}{Q}\right)^{1/2} \times \left(\frac{\mathrm{m}^2}{A}\right)^{1/2} \times \left(\frac{m_a}{\mu\mathrm{eV}}\right) \times \left(\frac{10\ \mathrm{s}}{t}\right)^{1/4} \times \left(\frac{T_{\mathrm{sys}}}{\mathrm{K}}\right)^{1/2} \times \frac{10\ \mathrm{T}}{B_0} \times \left(\frac{\delta\nu}{\mathrm{Hz}}\right)^{1/4} \times f_{\mathrm{DM}}^{-1/2},$$

Projected sensitivity to ALPs coupling to photons

- $\nu = 6.9\ \text{GHz} \Rightarrow m_a = \nu/0.241799 \approx \mathbf{28.5\ \mu eV}$
- $B_0 = \mathbf{0.59\ T}$, $Q_L = \mathbf{2.2 \times 10^3}$, $T_{\text{sys}} = \mathbf{33\ K}$
- $\text{SNR} = 5$, $\delta\nu = \nu \times 10^{-6} \approx \mathbf{6.9\ kHz}$, $t = \mathbf{10^6\ s}$, $f_{\text{DM}} = 1$

$$g_{a\gamma\gamma} \approx 6.8 \times 10^{-12}\ GeV^{-1}\ at\, 6.9{\sim}GHz$$



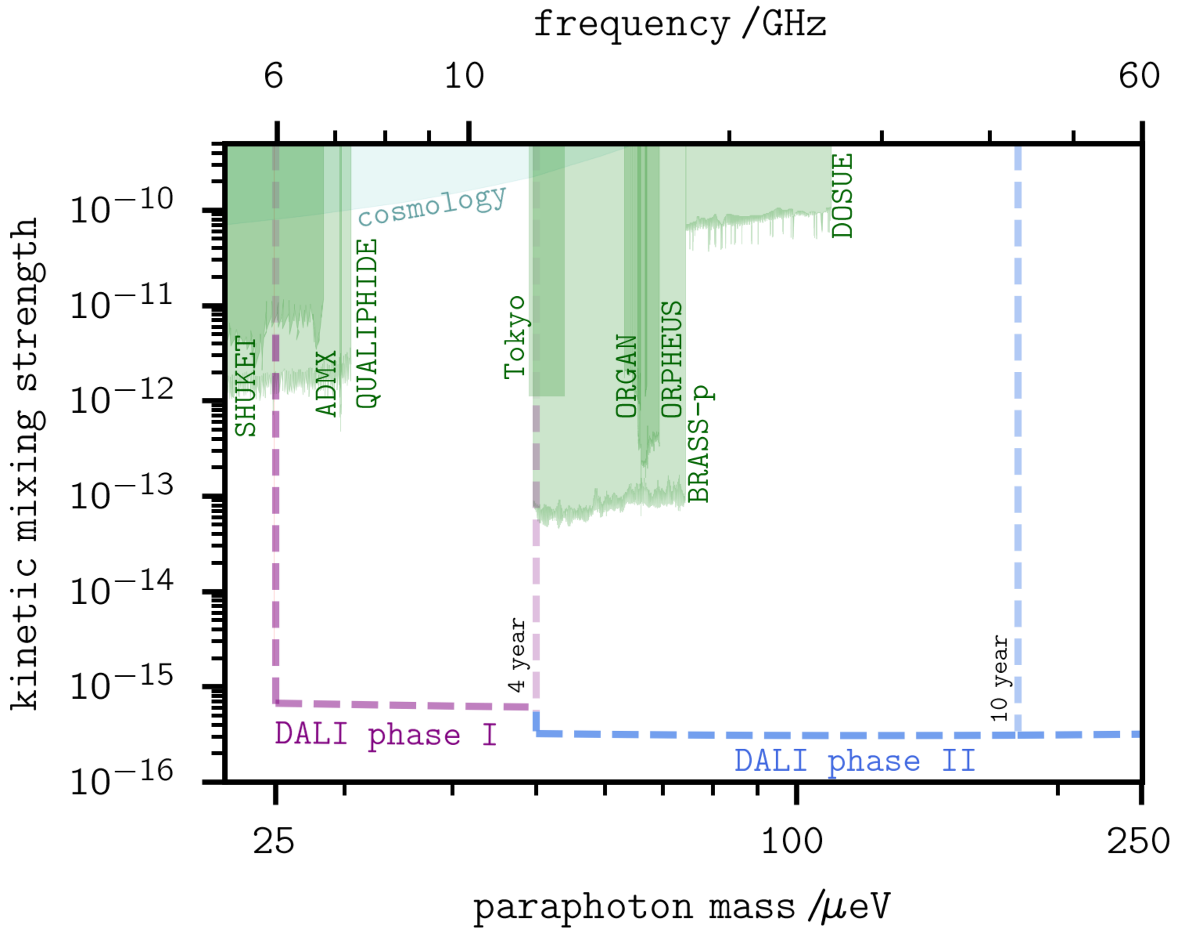
- $g \propto B_0^{-1}$: a **10 T** magnet instead of 0.59 T improves by **×17**.
- $g \propto T_{\text{sys}}^{1/2}$: cooling to **10 K** gives × $\sqrt{33/10}$ ≈ **1.8** better.
- $g \propto Q^{-1/2}$: raising Q_L from 2.2k to 5k gives × $\sqrt{2200/5000}$ ≈ **0.66**.
- $g \propto A^{-1/2}$: doubling A improves by × $\sqrt{2}$.
- $g \propto t^{-1/4}$: ×10 longer dwell improves by **×1.78**.

The star shows just the first measurement

Projected **DALI** sensitivity to **dark-photon DM**

DALI reach: Phase I (purple) and Phase II (blue) probe down to **few × 10^{-16}** over **25–250 μeV**, improving on SHUKET/ADMX/ORGAN-class bounds in this band

Assumptions: Galactic dark-photon DM (local density $\rho_{\gamma'}$ comparable to halo DM), multi-layer FP resonator, sub-K system temperature, multi-year integration



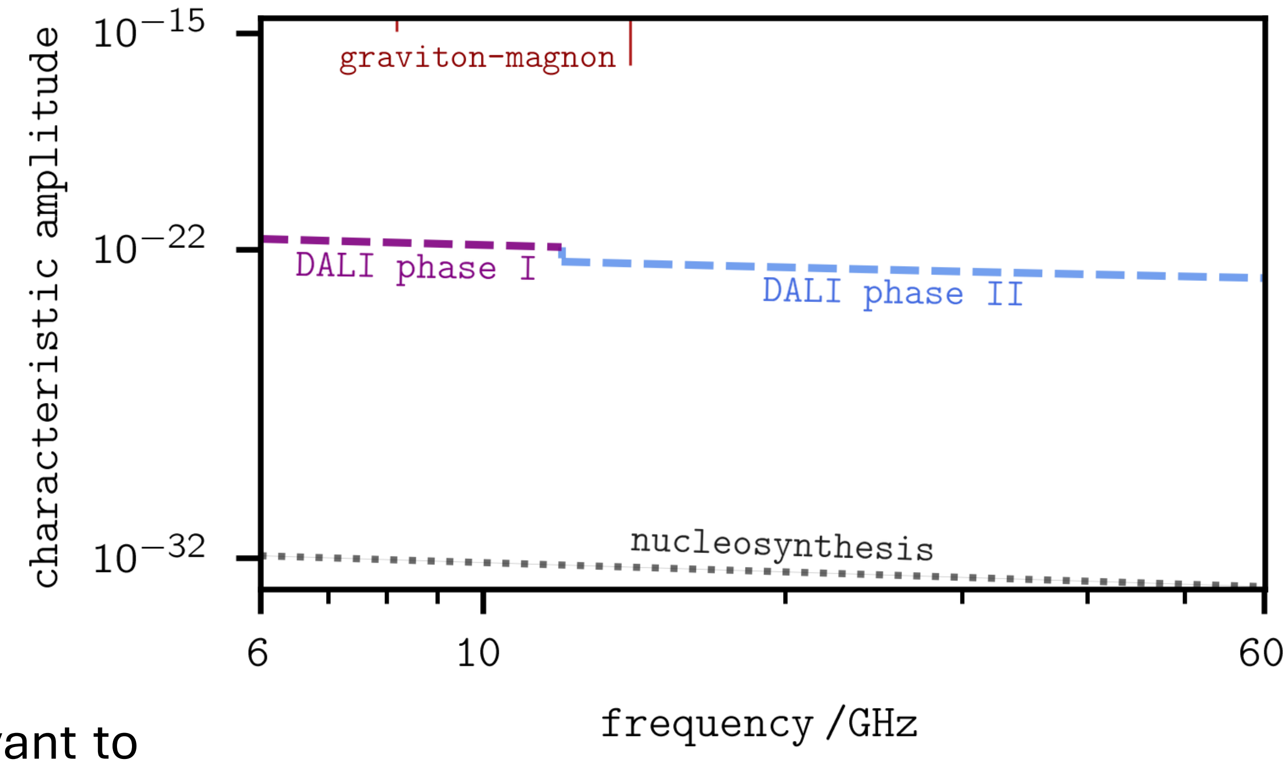
$$\chi \gtrsim 2.9 \times 10^{-14} \left(\frac{SNR}{Q}\right)^{1/2} \left(\frac{m^2}{A}\right)^{1/2} \left(\frac{\Delta\nu}{Hz}\right)^{1/4} \left(\frac{1\,s}{t}\right)^{1/4} \left(\frac{T_{sys}}{K}\right)^{1/2} \left(\frac{\rho_{\gamma'}}{GeV\,cm^{-3}}\right)^{1/2} \times \alpha$$

$$\alpha = \sqrt{2/3}$$

High-Frequency GW Search Window with DALI

DALI reach: the dashed **Phase I** (purple) and **Phase II** (blue) lines show the **minimum** h_c a DALI-style receiver could detect across the band under your assumed integration time, bandwidth, and SNR.

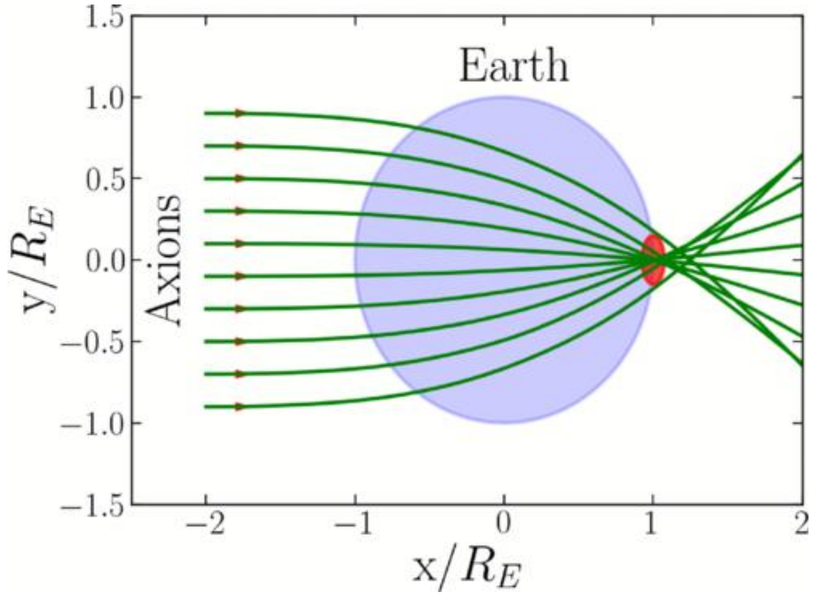
In **Phase I** DALI is sensitive around $h_c \sim 10^{-22}$;

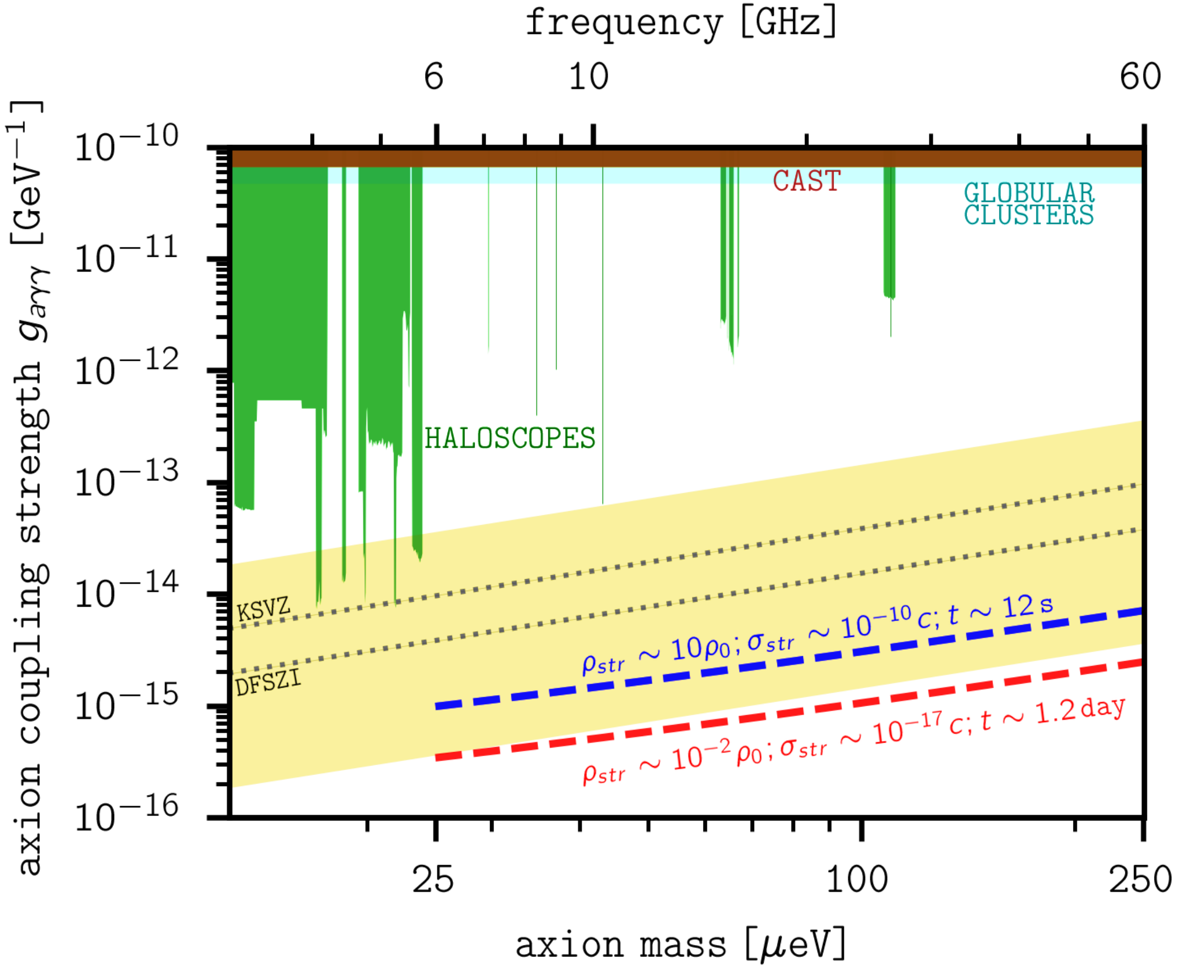


graviton–magnon (top) marks amplitudes relevant to proposals coupling GWs to magnons.
nucleosynthesis (bottom) is a conservative cosmological bound—anything well above this line is not excluded by BBN/energy-density limits.

DALI sensitivity to streaming DM

1. DALI intercepts the DM axion stream just **before** it passes through the Earth (potentially small fraction density of an individual stream)
2. DALI intercepts the DM axion stream just **after** it passes through the Earth (gravitational focusing effects -> increased flux)





arXiv:2404.13970

Outlook & Summary

- Short term: PoP data-taking in 2025 @ 6.9 & 7 GHz (50 MHz BW)
- Medium term: scanning program 6–8 GHz
- Long term: full DALI with broader coverage

MILESTONES REACHED

❑ First magnetized phased-array haloscope

❑ Novel optical design → multi-frequency coverage (λ/8 & λ/2) -> faster scan

❑ Mechanical + cryogenic prototype ready

❑ Calibration and physics Run Data taking on the way

THANK YOU

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❖ Call For Paper: [Symmetry] Special Issue - Demystifying the Dark Sector of the Cosmos in the Lab: Astrophysical Ingredients in Laboratory Searches near the Quantum Limit

- **Website:** https://www.mdpi.com/journal/symmetry/special_issues/625TP738Z1
- **Guest Editor:** Dr. Antonios Gardikiotis
- **Deadline for manuscript submissions:** 31 January 2026

This Special Issue aims to review new methods in laboratory searches for **dark matter (DM) axions** or **ALPs** that are approaching fundamental quantum sensitivity limits. Emphasis will be placed on advanced technologies and innovations intended to broaden the search range or significantly enhance the scan rate.

We invite original research articles and review papers for this Special Issue. Topics of interest include, but are not limited to, **experimental efforts that implement state-of-the-art technologies to explore the parameter space of axions and axion-like particles (ALPs).** Contributions presenting new ideas in **dark photon research** are also welcome. **Detector developments and quantum-enhanced detection schemes** are among the discovery prospects associated with ongoing and future axion research.

Special Issue

Demystifying the Dark Sector of the Cosmos in the Lab: Astrophysical Ingredients in Laboratory Searches near the Quantum Limit

Guest Editor
Dr. Antonios Gardikiotis

Deadline
31 January 2026

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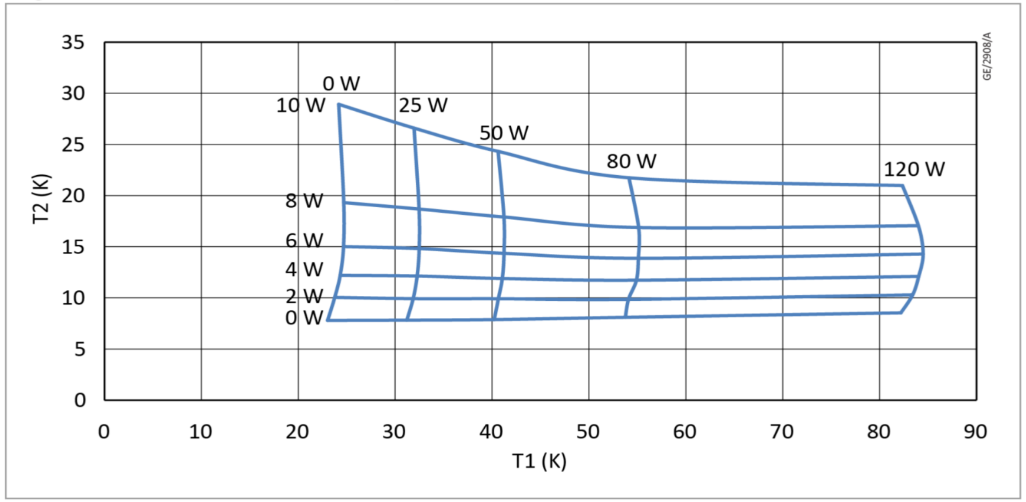
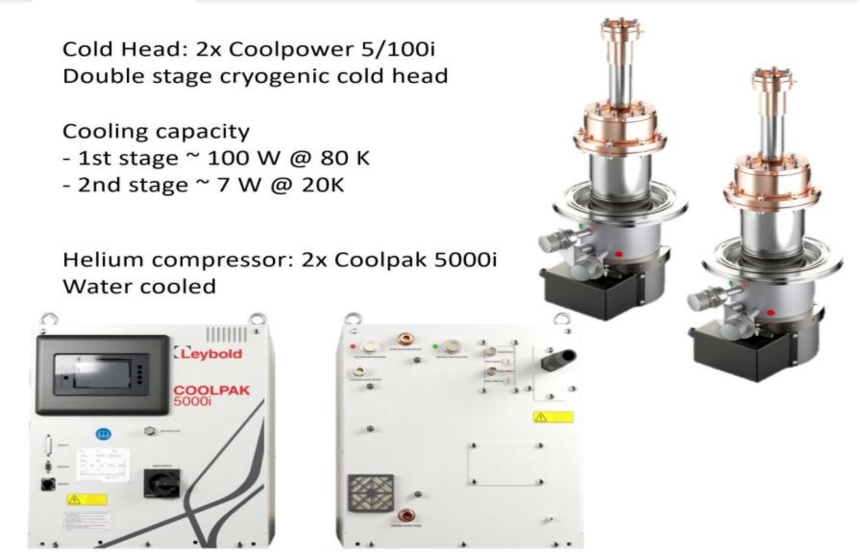
Backup slides

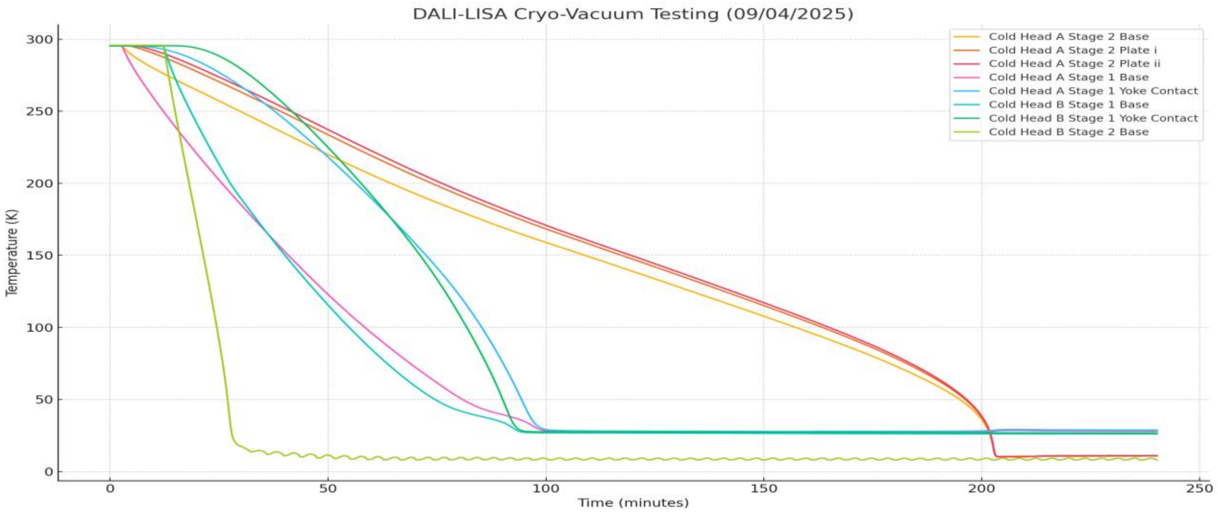
Thermal Architecture & Next Steps

- **Thermal groups: 1st stage ~80 K**, **2nd stage ~20 K**, plus parasitic loads from 293 K; copper **thermal link** to cold head.
- **PoP runs** fixed-resonator pilot (6.9 & 7.01 GHz) for cooldown timing & stability
- **Pending upgrades:** solid copper base + **flexible links**, shield machining for access, resonator size adaptation, fixture supports

Figure 15. Performance map - COOLPOWER 5/100i







A fundamental component to the LISA-DALI system is the yoke structure, consisting of two solid raw steel pieces which combine to form a cube-like shape with a central cavity.

The Yoke structure functions as the base foundation of the system, housing all instrument elements and providing a ferromagnetic body for which to mount the magnetic array.

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