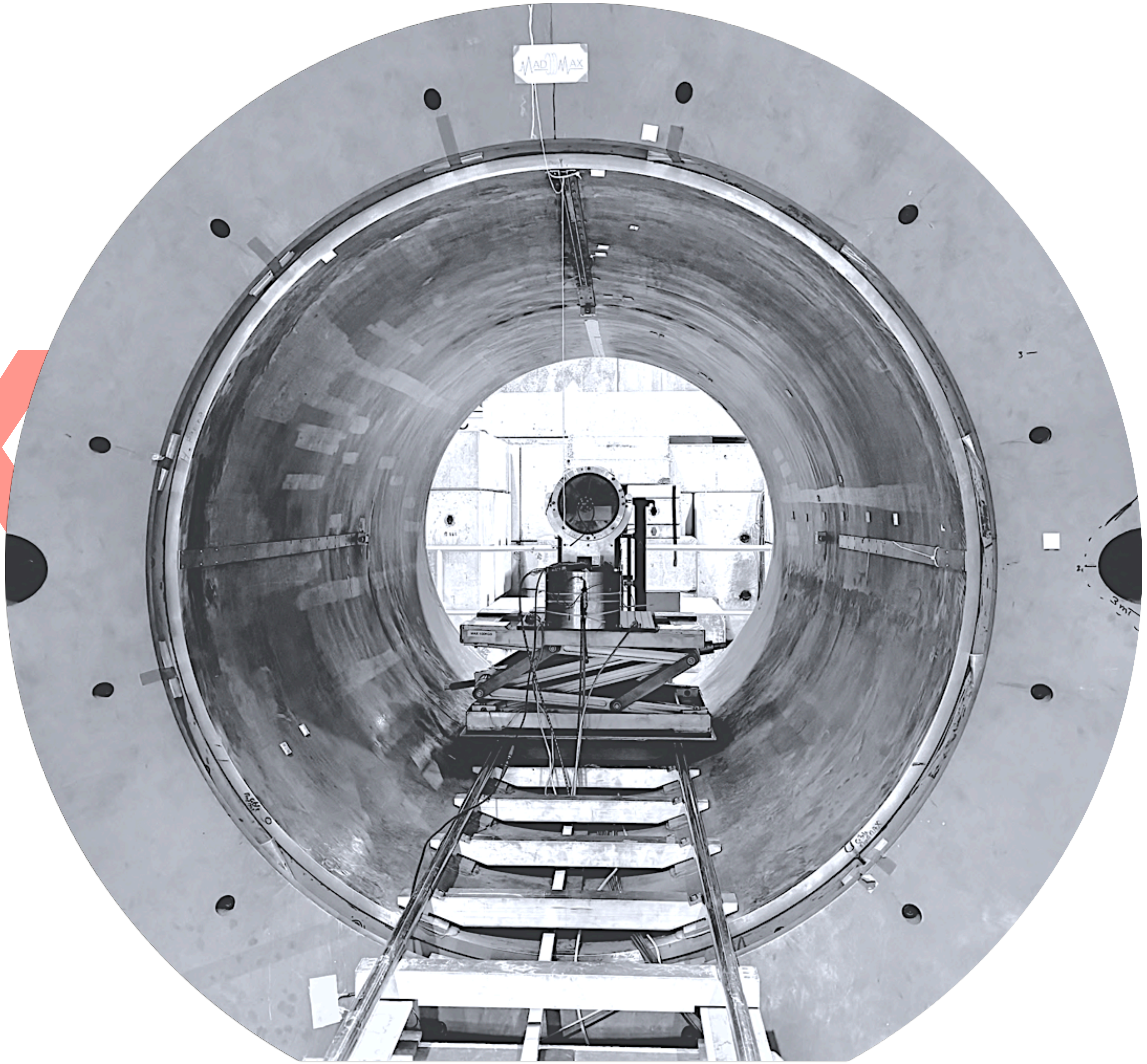
COST Action COSMIC WISPers (CA21106) | Sep 9 - 12, 2025 | Sofia, Bulgaria

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COSMIC WISPERS CA21106

Recent developments in axion detection with MADMAX



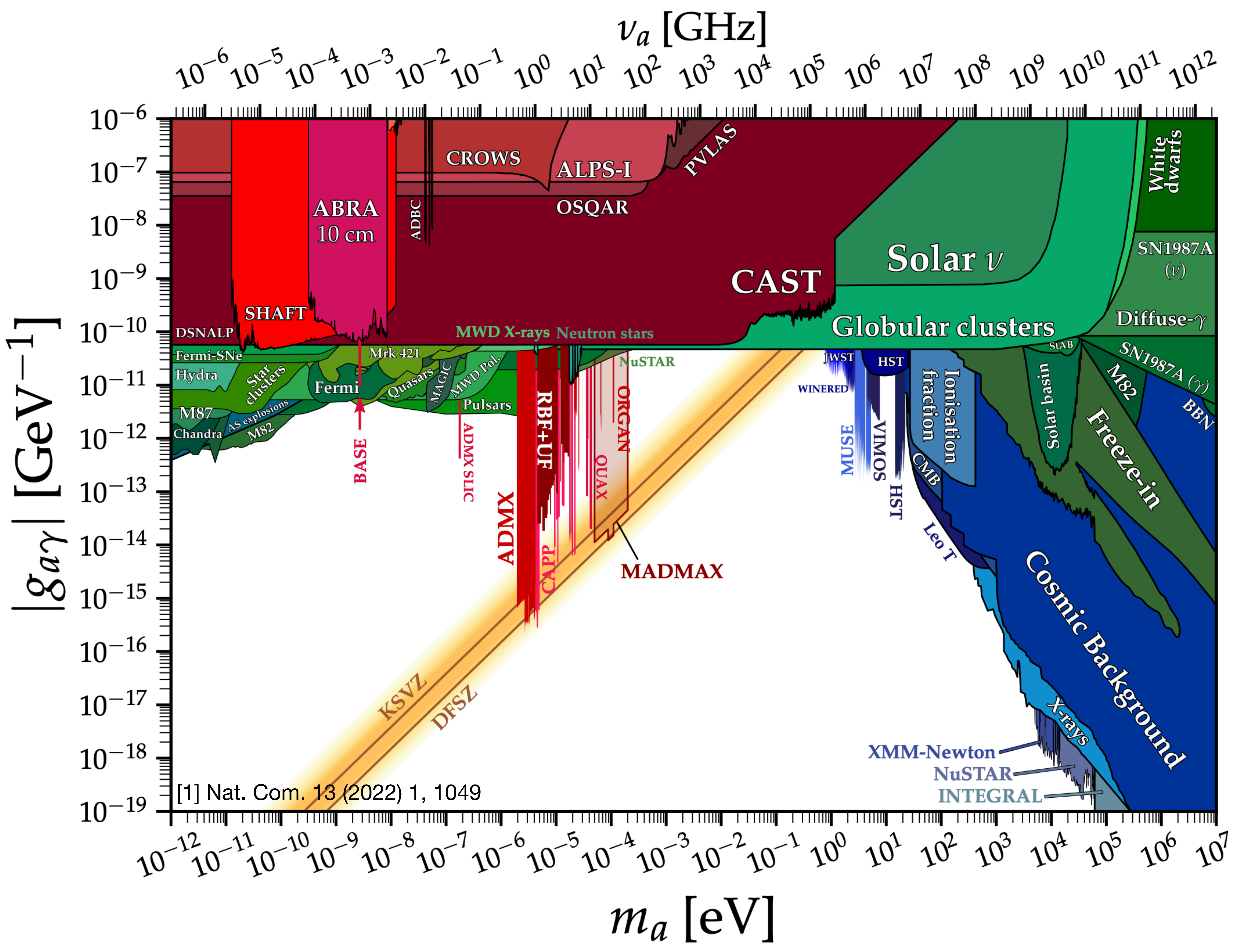
Anton Ivanov
on behalf of MADMAX collaboration

MAX-PLANCK-INSTITUT FÜR PHYSIK

MADMAX COLLABORATION

MAgnetized Disc and Mirror Axion eXperiment

- → MADMAX searches for the dark matter axion
  - ✦ Strongly motivated: QCD and Post-inflationary[1] range
  - ✦ Full-size MADMAX aimed at the 40-400 μeV or 10-100 GHz
  - ✦ Parameter space beyond reach of other experiments
- → MADMAX founded in 2017 with currently O(40) members from 11 institutes



[1] Nat. Com. 13 (2022) 1, 1049

Benchmark models for QCD-axion @ 40-400 μeV:

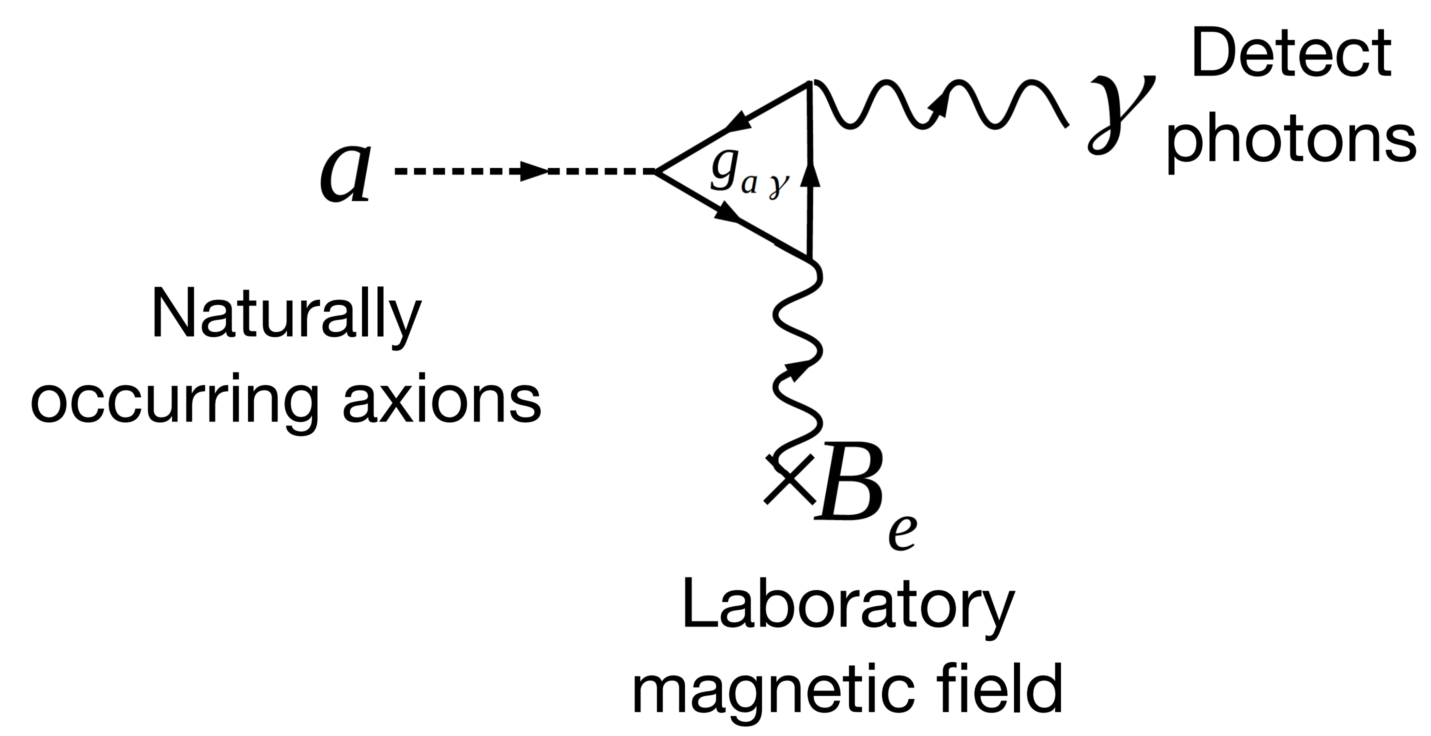
$$g_{a\gamma}^{\rm KSVZ} \approx (1.6 \times 10^{-14} - 1.6 \times 10^{-13})\ {\rm GeV}^{-1}$$

$$g_{a\gamma\gamma}^{\rm DFSZ} \approx (6.1 \times 10^{-15} - 6.1 \times 10^{-14})\ {\rm GeV}^{-1}$$

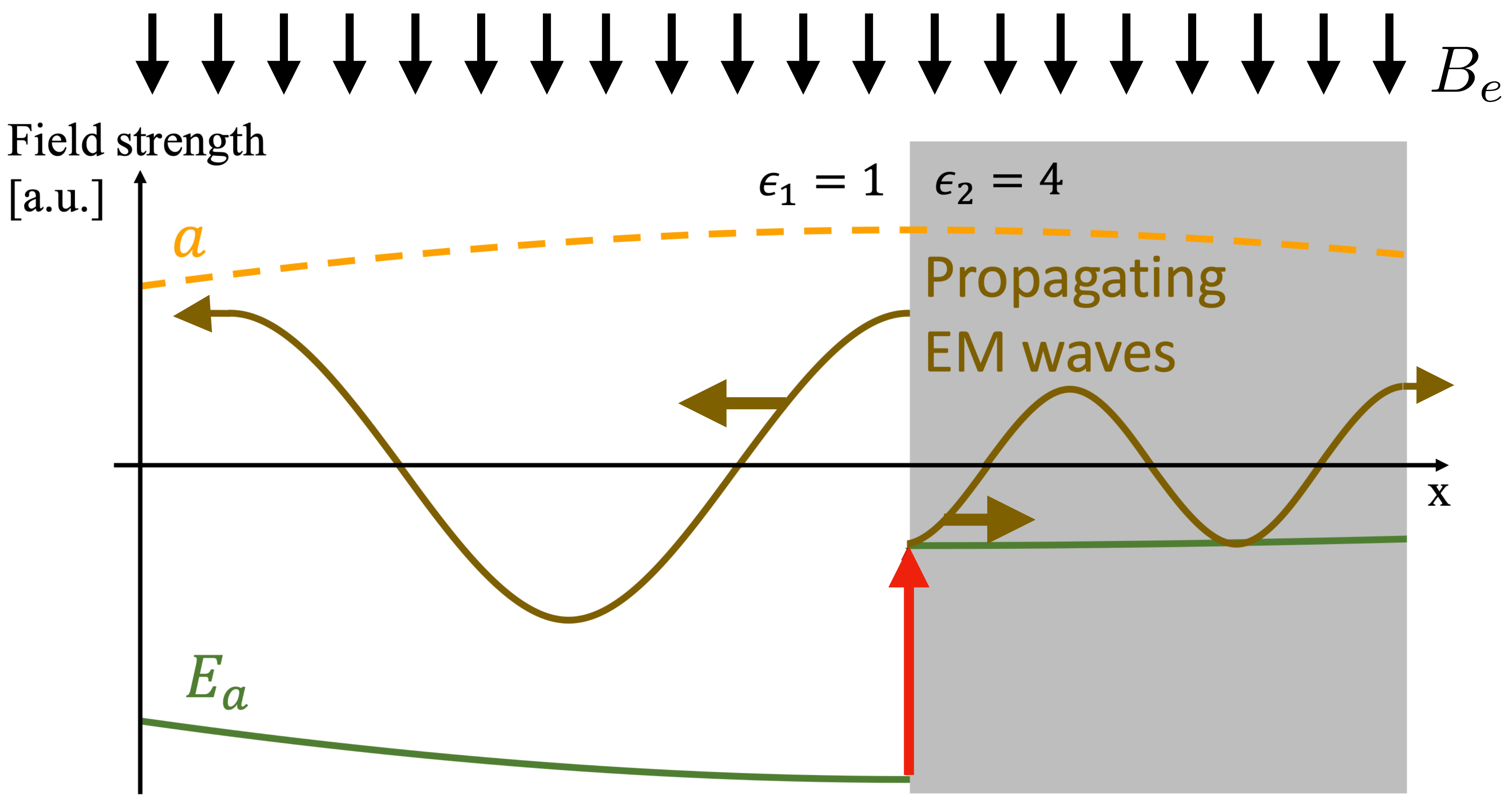
MAX-PLANCK-INSTITUT FÜR PHYSIK · Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG · RWTH AACHEN UNIVERSITY · CERN · DESY · Max-Planck-Institut für Radioastronomie · EBERHARD KARLS UNIVERSITÄT TÜBINGEN · Universidad de Zaragoza · CPPM · IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis · NÉEL institut · Fermilab

Detection principle

→ Axion-to-photon coupling by inverse Primakoff effect



→ Wave emission at a discontinuity



✦ Axion behaves as scalar classical field:

$$a(t) = a_0 \cos(m_a t)$$

Conversion volume much smaller than:

$$\lambda_{\text{deBroglie}} = \frac{h}{p} \approx \frac{h}{m_a \langle v_{DM} \rangle} \approx 75\,\mathrm{m} \cdot \left(\frac{\mu\mathrm{eV}/c^2}{m_a} \right)$$

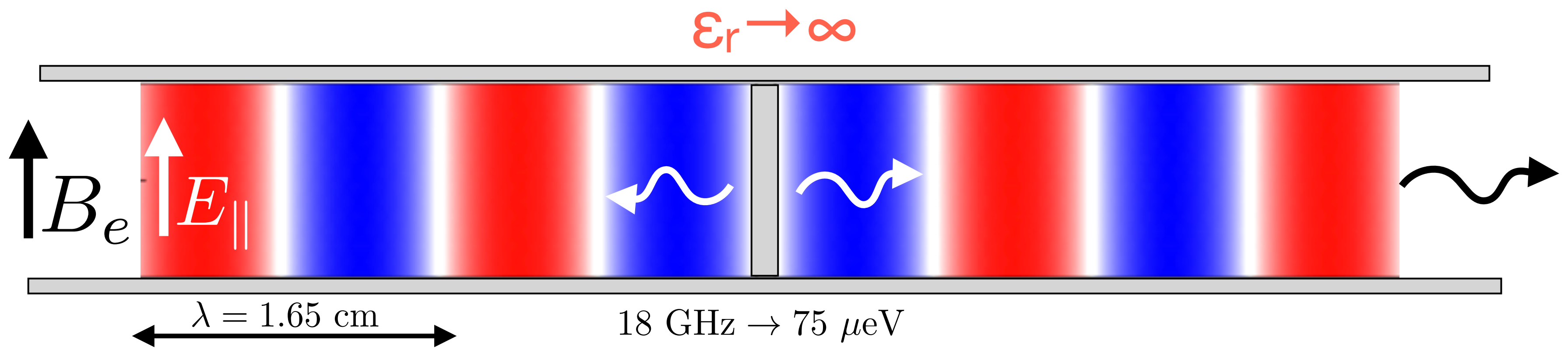
✦ Modified Maxwell's equations:

E-field term: $\vec{E}_a = -\frac{g_{\alpha\gamma}\vec{B}_e}{\epsilon} a_0 \cos(m_a t)$

Source term: $\vec{J}_a = g_{\alpha\gamma}\vec{B}_e \frac{\mathrm{d}a}{\mathrm{d}t}$

Dielectric haloscope principle

→ Emission from a mirror



✦ Even for strong B-field and large mirror power remains tiny:

$$P_{\text{mirror}} \approx \mathcal{O}(10^{-27})\ \text{W} \left(\frac{A}{1\text{m}^2}\right) \left(\frac{B_{\text{e}}}{10\text{T}}\right)^2 \left(\frac{\text{g}_{a\gamma}}{\text{m}_{\text{a}}}\right)^2$$

$$P_{\text{noise}} @\ 3\ \text{K} \approx \mathcal{O}(10^{-23})\ \text{W/Hz}$$

Dielectric haloscope principle

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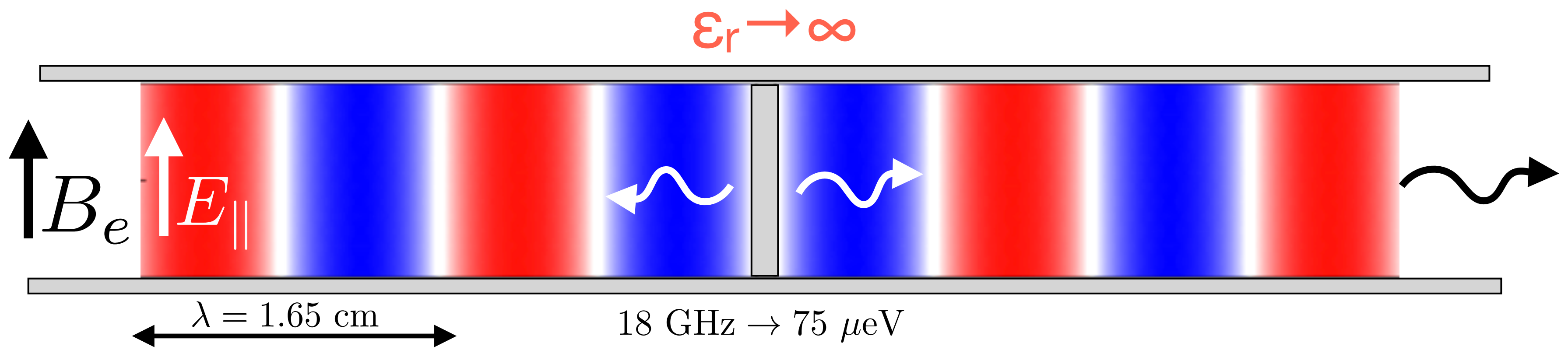
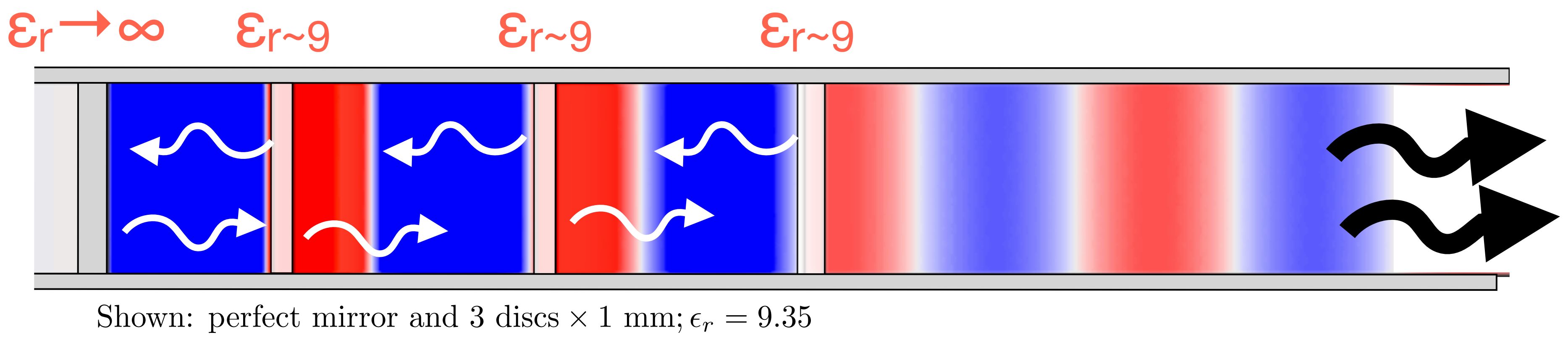


→ Emission from a booster



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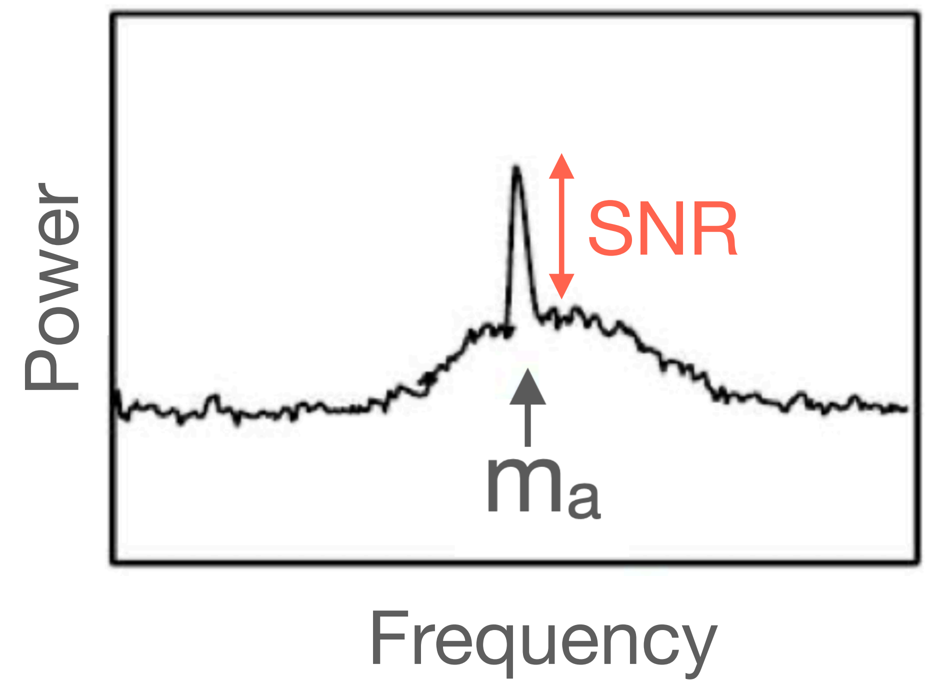
$$P_{\rm mirror} \approx \mathcal{O}(10^{-27})\ \mathrm{W} \left(\frac{A}{1\mathrm{m}^2}\right) \left(\frac{B_{\rm e}}{10\mathrm{T}}\right)^2 \left(\frac{g_{a\gamma}}{\mathrm{m_a}}\right)^2$$

$$P_{\rm noise} @\ 3\ \mathrm{K} \approx \mathcal{O}(10^{-23})\ \mathrm{W/Hz}$$

✦ Output power **boosted:**

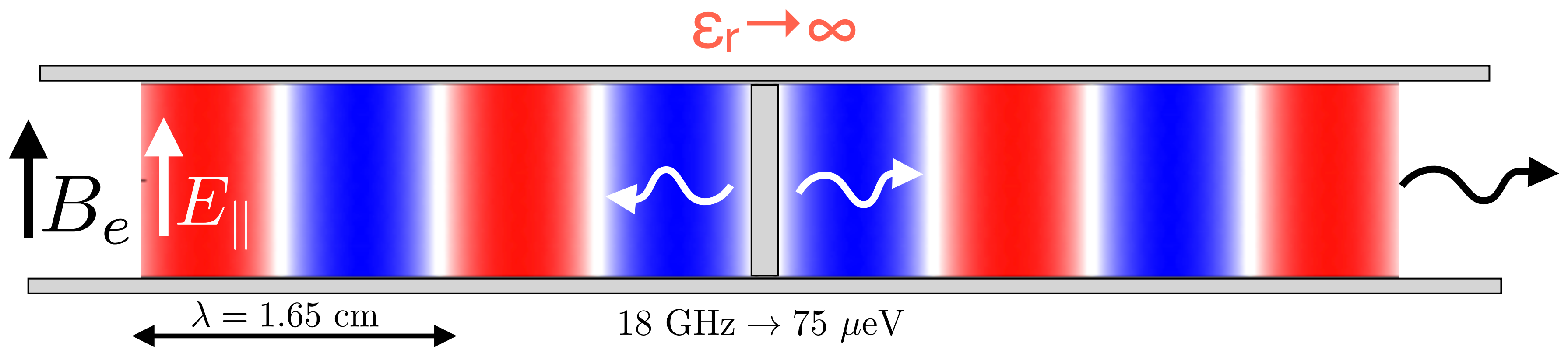
$$P_{\rm boost} = \beta^2 P_{\rm mirror}$$

boost factor

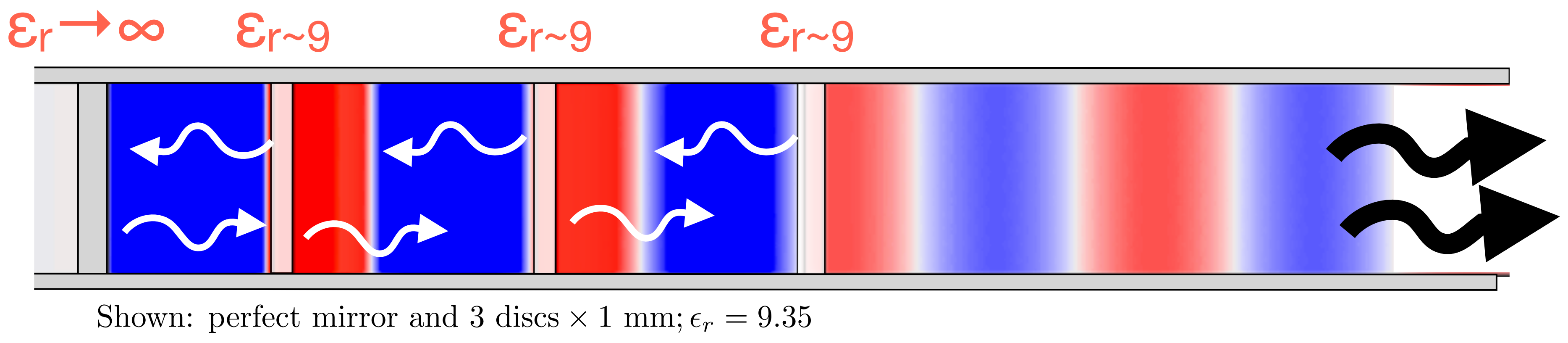


Dielectric haloscope principle

→ Emission from a mirror



→ Emission from a booster



→ Difference to cavity experiments

- **Broad mass range** & high boost possible: $\beta^2 \propto N$
- Booster volume decoupled from axion mass = **large conversion volume** but many higher order modes

- Even for strong B-field and large mirror power remains tiny:

$$P_{\rm mirror} \approx \mathcal{O}(10^{-27})\ \mathrm{W} \left(\frac{A}{1\mathrm{m}^2}\right)\left(\frac{B_{\rm e}}{10\mathrm{T}}\right)^2\left(\frac{\mathrm{g}_{a\gamma}}{\mathrm{m_a}}\right)^2$$

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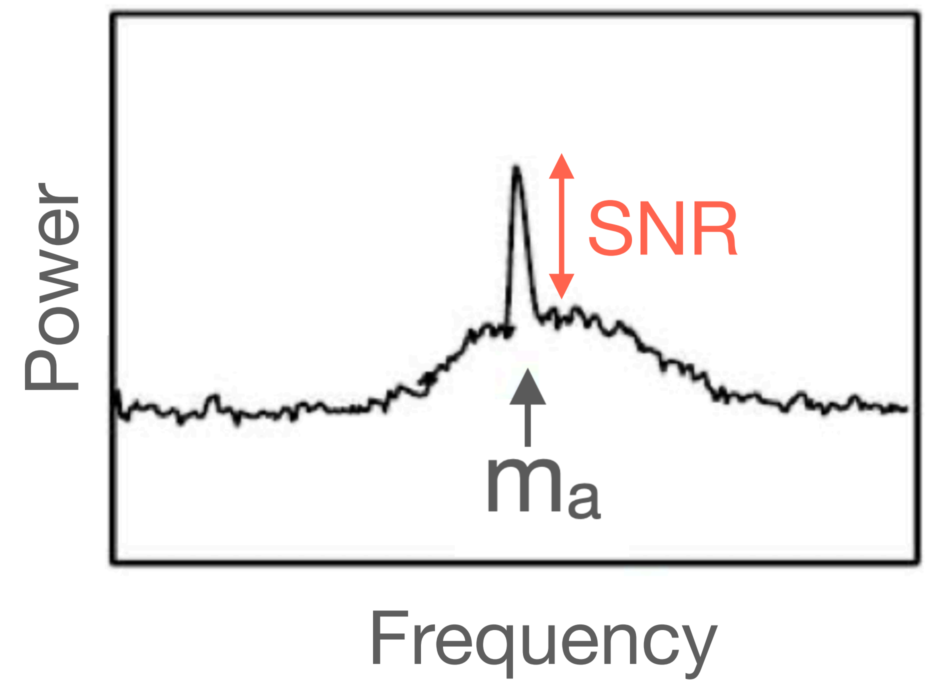
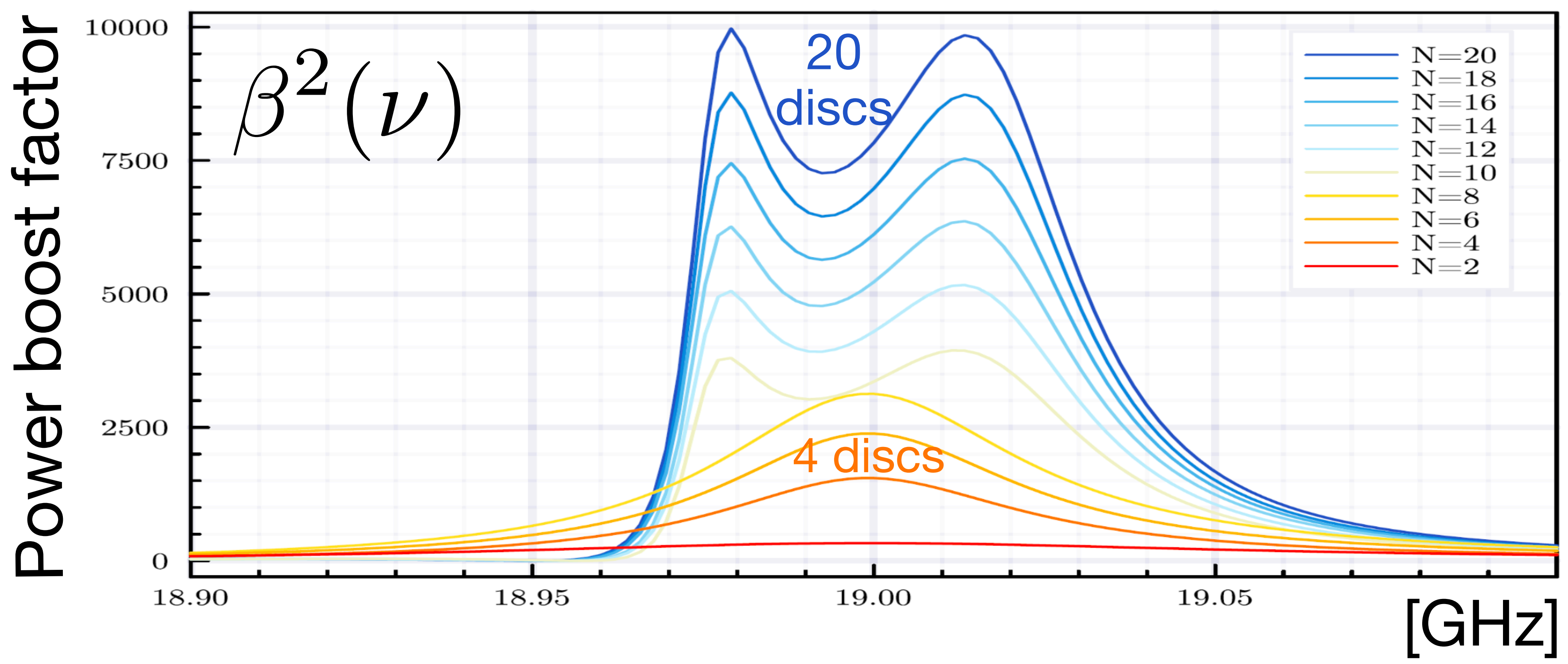
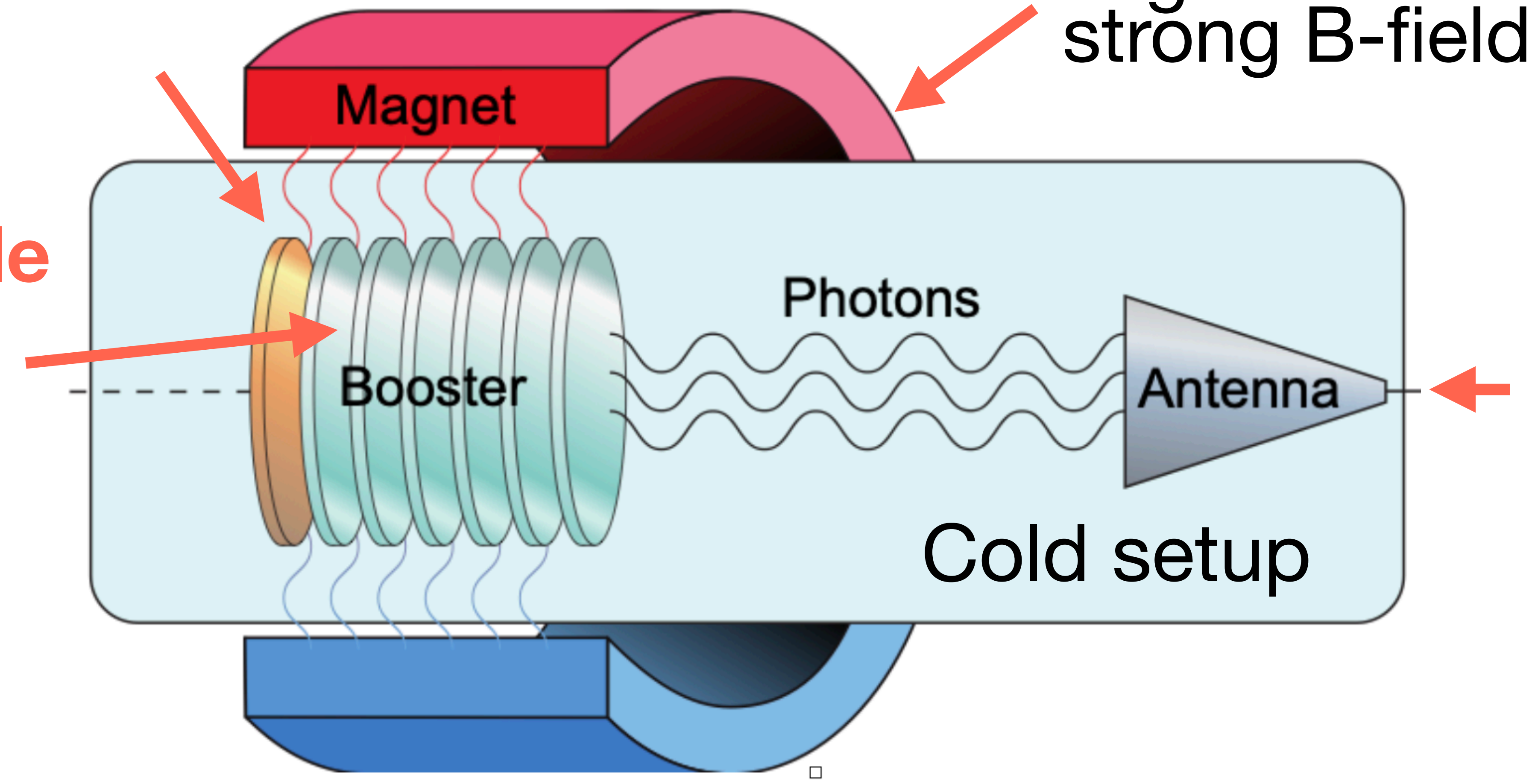


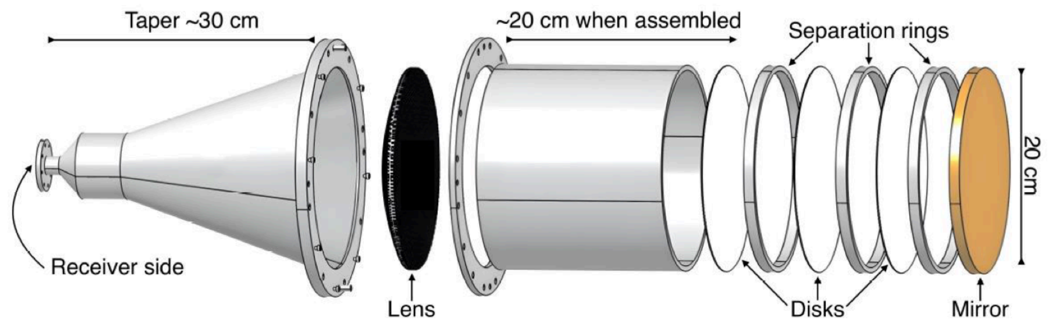


On the path to full-scale MADMAX



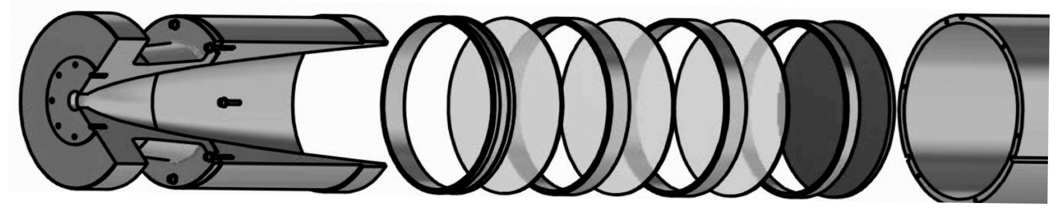
→ Prototyping phase since 2020 with physics runs @CERN (MORPURGO 1.6 T magnet)

ø200 mm closed prototype



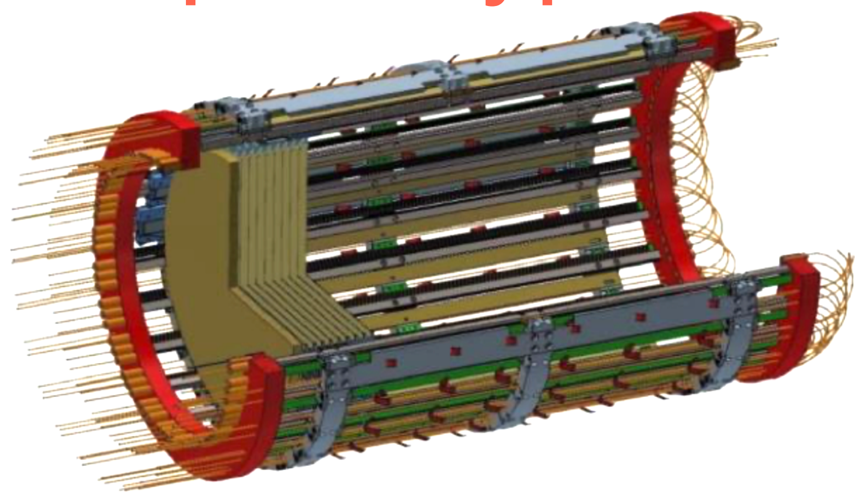
17-day run @18.5, 19.2 GHz with peak $|g_{a\gamma}| \approx O(3\times10^{-11})$ GeV^{-1}

ø100 mm closed prototype



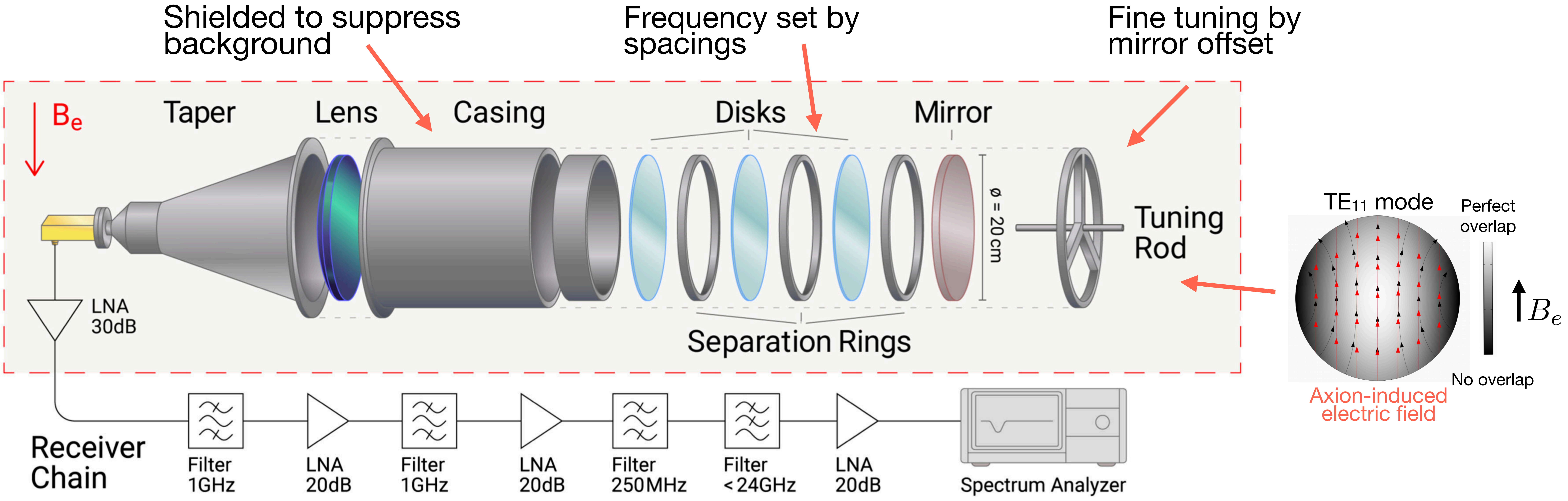
20-hour cold run @ ≈19 GHz and T < 10 K under B field (Analysis ongoing)

ø300 mm open prototype



(2026) 3 discs $|g_{a\gamma}| \approx O(10^{-12})$ GeV^{-1}
(2027-2029) 20 discs $|g_{a\gamma}| \approx O(10^{-13})$ GeV^{-1}

Closed ⌀200 mm prototype booster



$$|g_{a\gamma}| = 3.5 \times 10^{-11}\,\mathrm{GeV}^{-1} \left(\frac{T_{\mathrm{sys}}}{300\,\mathrm{K}}\right)^{\frac{1}{2}} \left(\frac{2.2\,\mathrm{days}}{\tau}\right)^{\frac{1}{4}} \left(\frac{m_a}{80\,\mu\mathrm{eV}}\right)^{\frac{5}{4}} \left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_a}\right)^{\frac{1}{2}} \left(\frac{2000}{\beta^2}\right)^{\frac{1}{2}} \left(\frac{0.1\,\mathrm{m}}{r}\right) \left(\frac{1\,\mathrm{T}}{B_e}\right) \left(\frac{\mathrm{SNR}}{5}\right)^{\frac{1}{2}}$$

Cylindrical TE_{11} wave
~84% power extracted

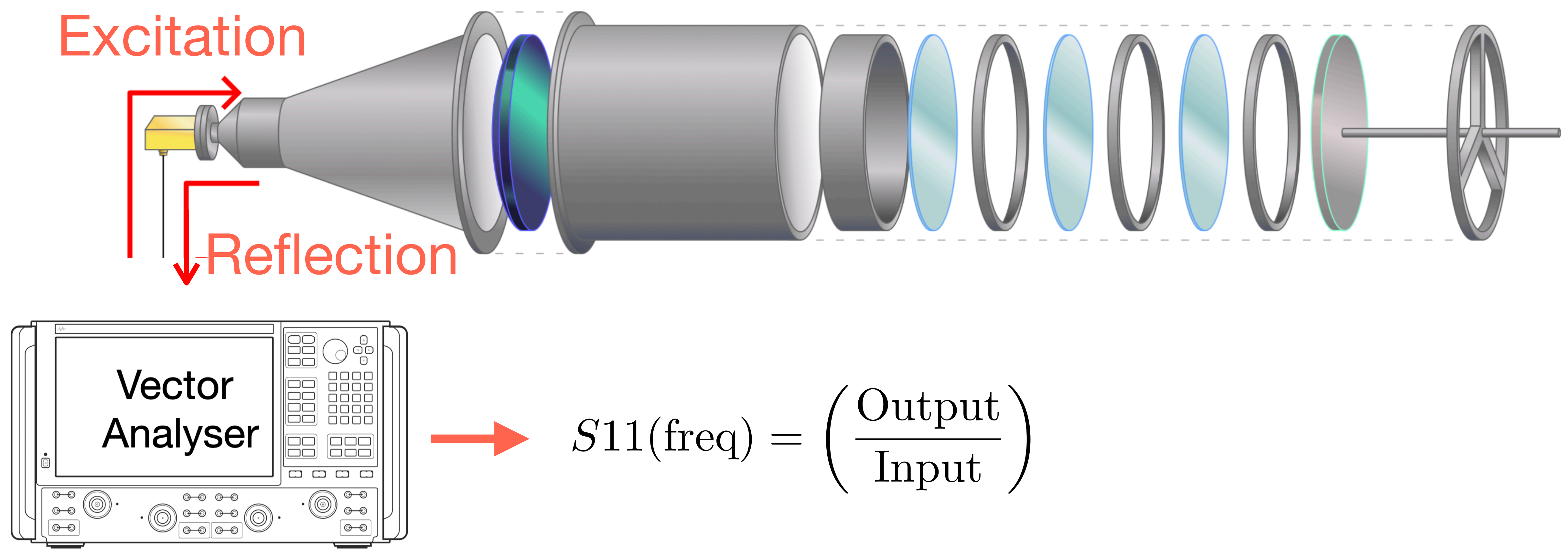
Calibration

→ **Challenge:** Boost factor β^2 cannot be measured directly

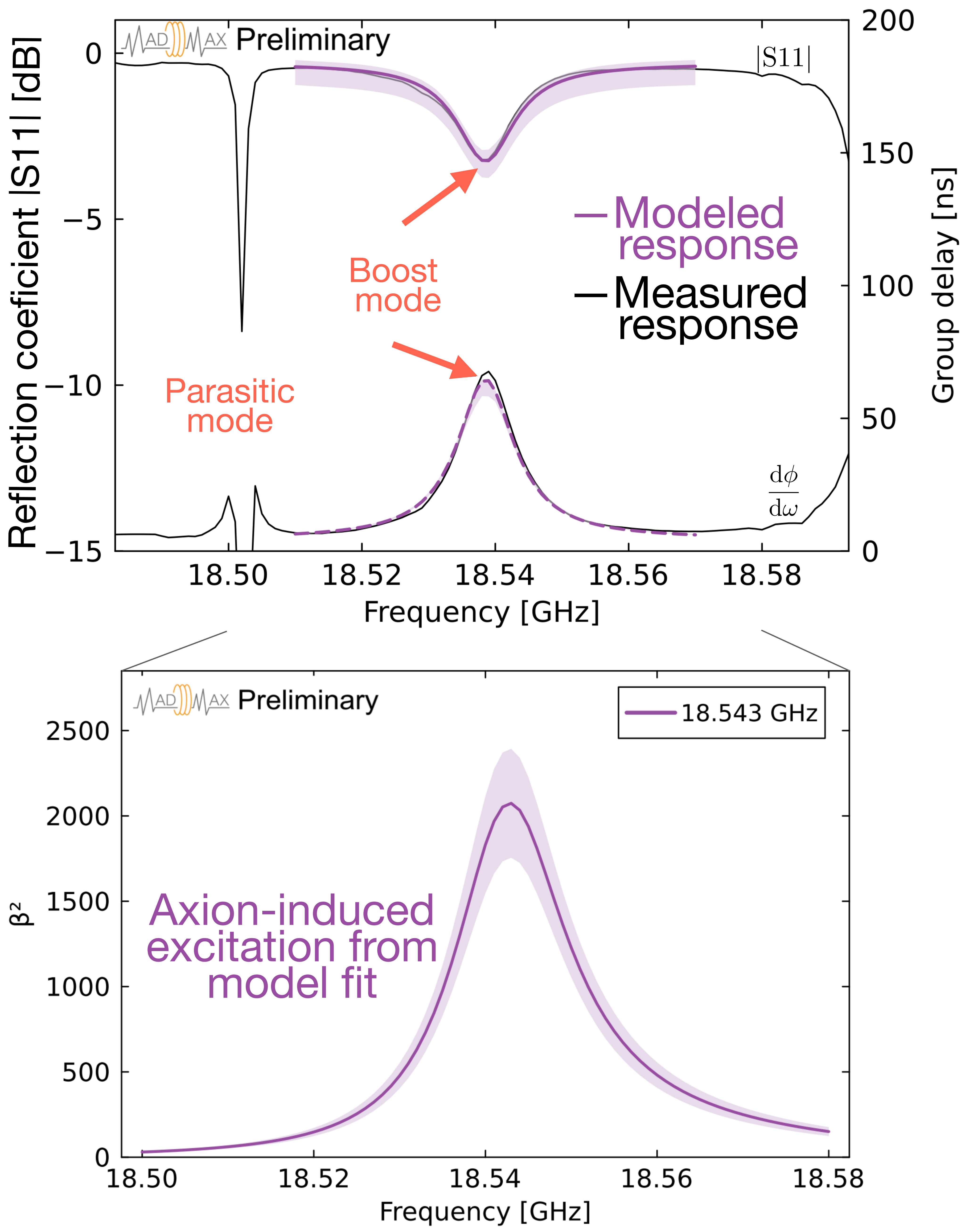
→ **Principle:** β^2 & frequency response depend on the same quantities

✦ 1D **wave-propagation model** from few first-principle parameters predicts: complex S11, noise, β^2

✦ Measure frequency response S11 for a **known excitation** to compare to model

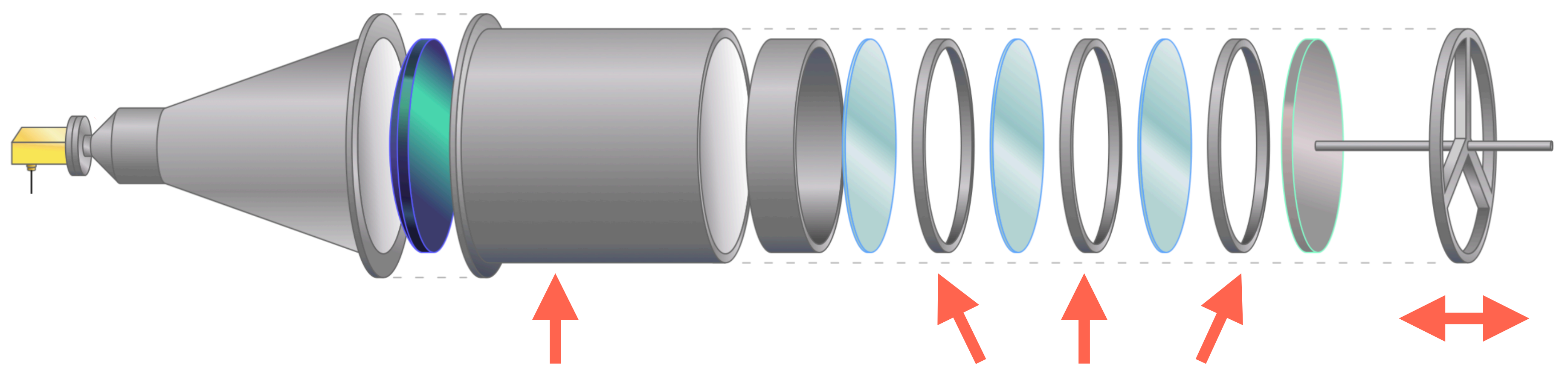


$$S11(\text{freq}) = \left(\frac{\text{Output}}{\text{Input}}\right)$$



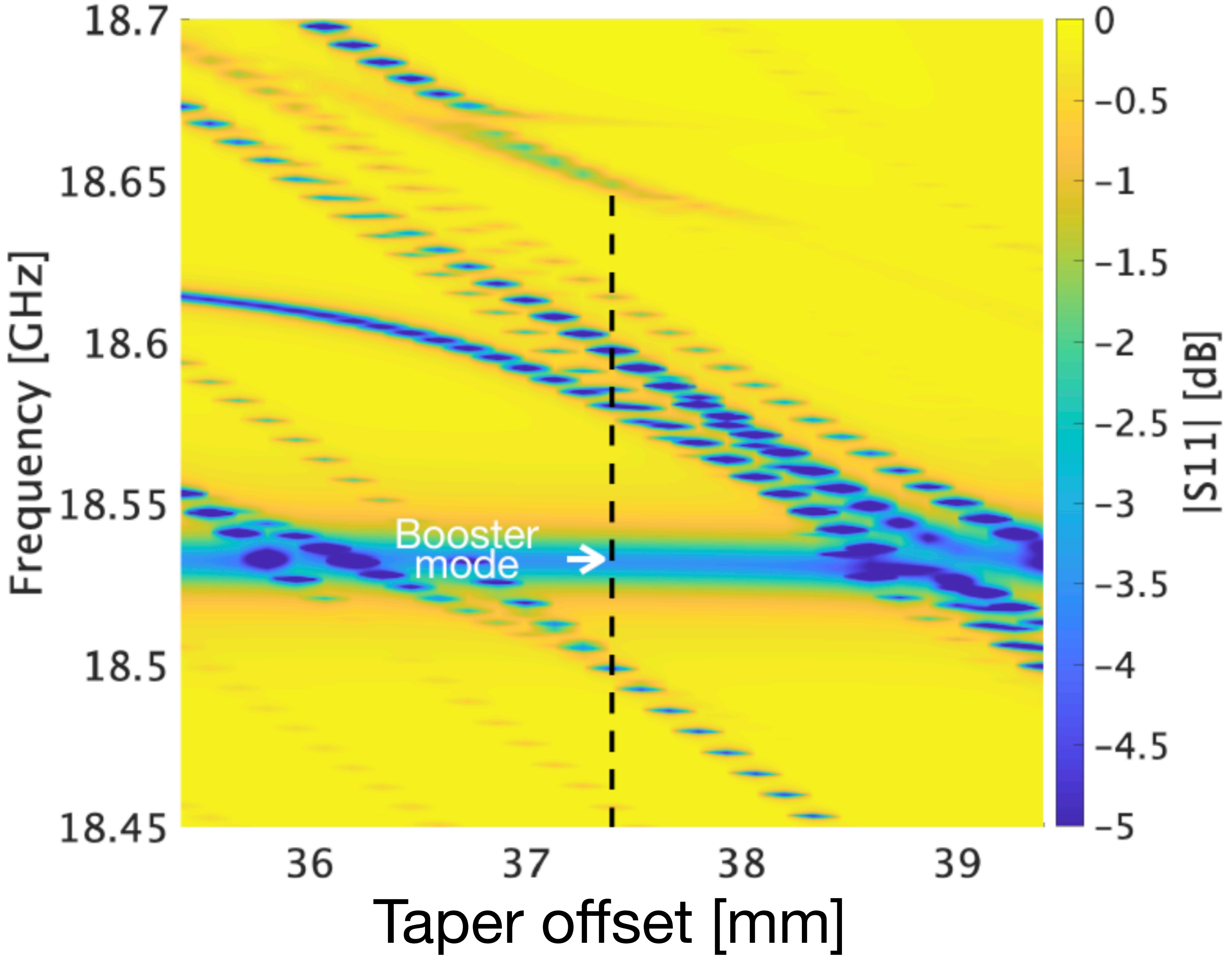
Higher order modes & tuning

→ **Challenge:** Large conversion volume = highly over-moded spectrum

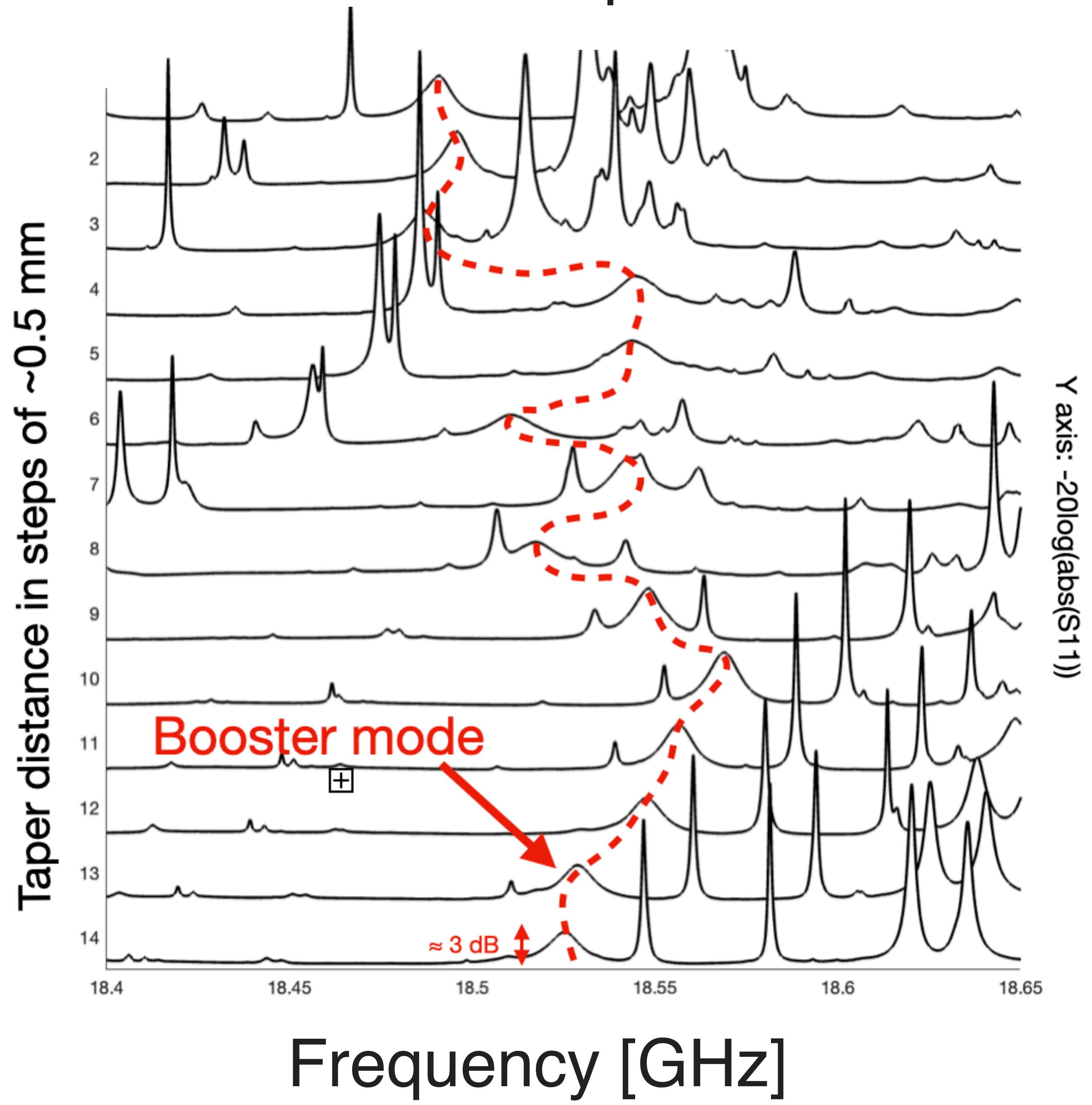


- Parasitic modes can decouple from booster mode
- Range set by the taper (18-21 GHz)
- Mass set by the spacer rings
- Fine-tuning by mirror displacement O(50 MHz)

Simulated spectra

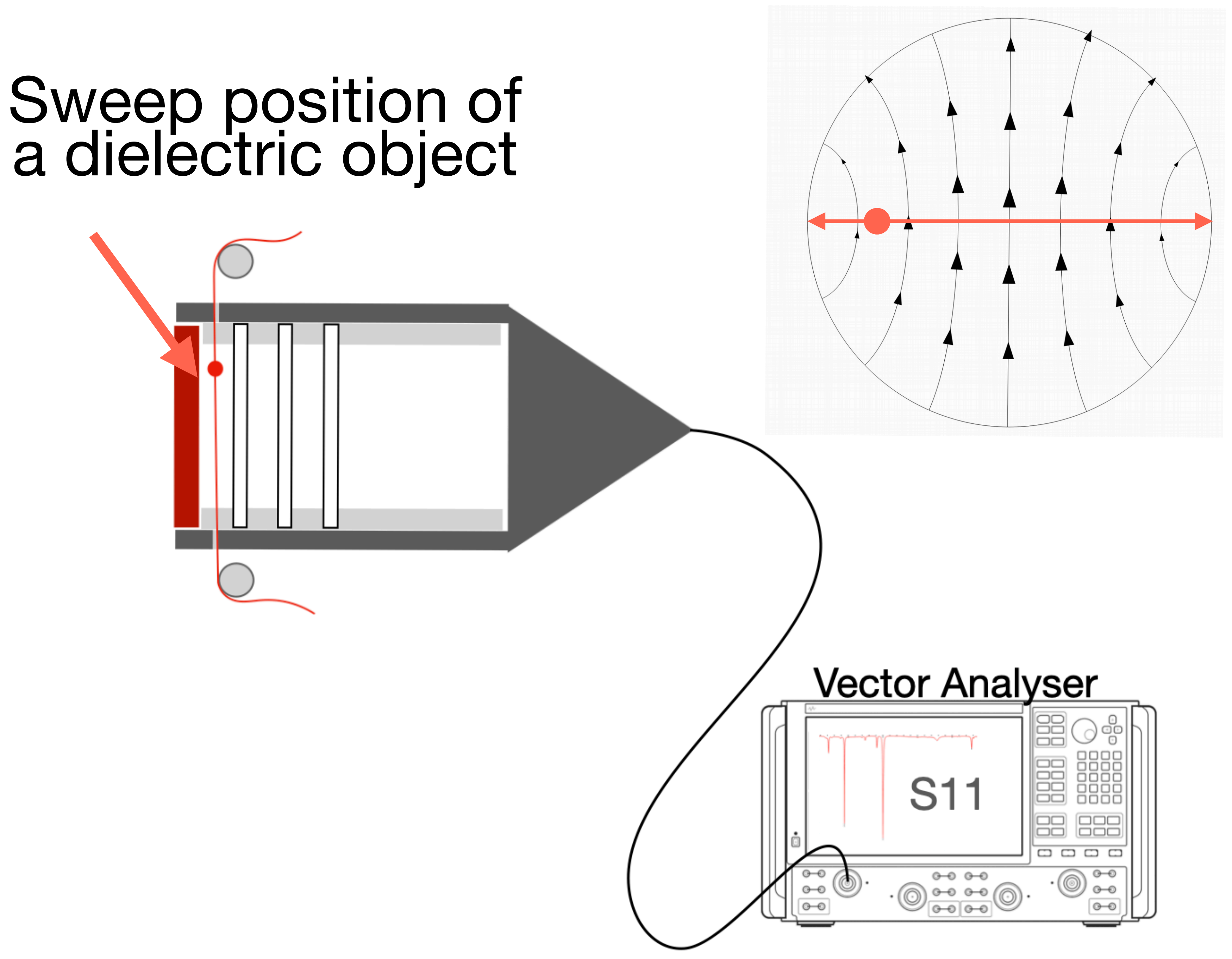


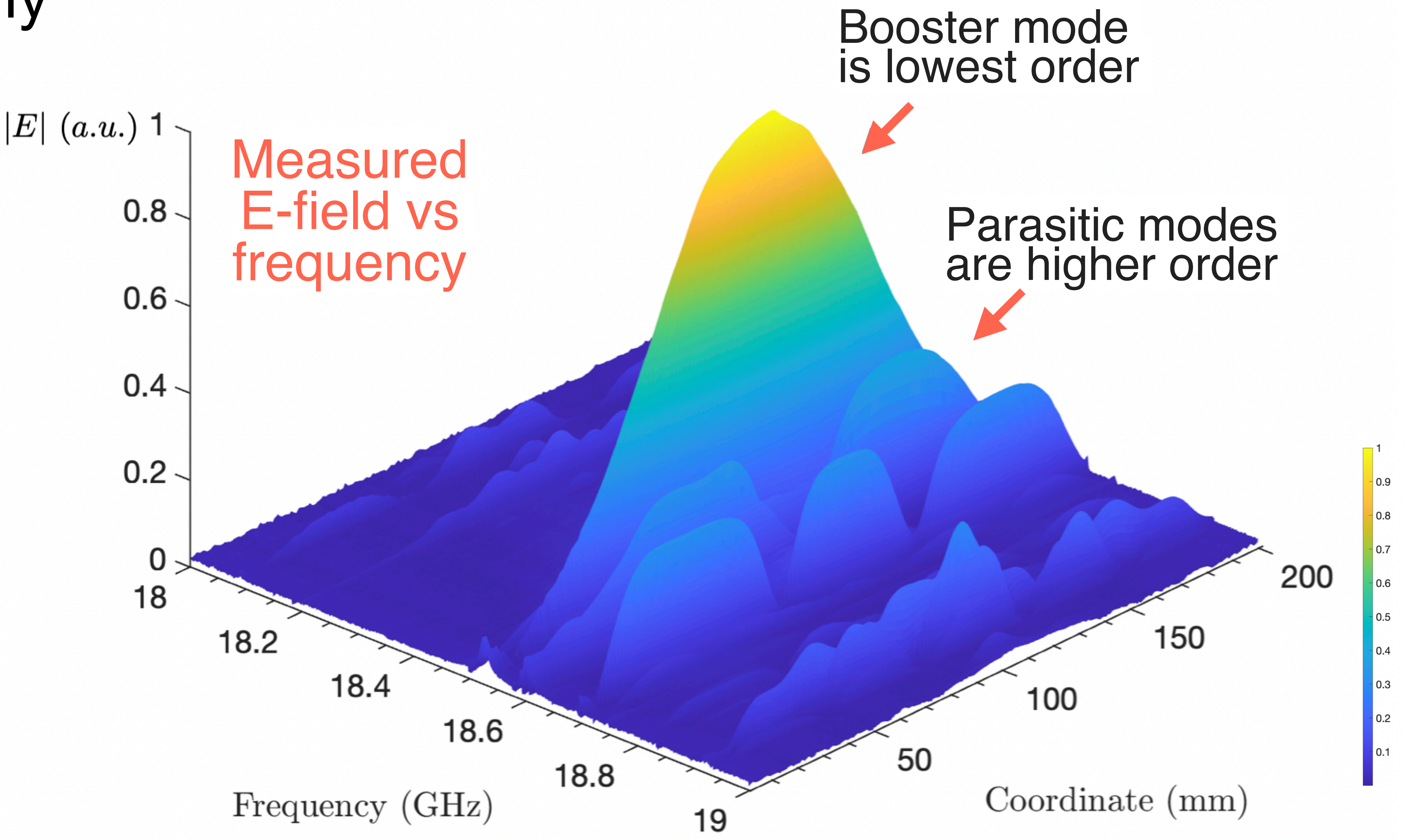
Measured spectra



Field measurement

→ **Challenge:** Field distribution inside booster can be complicated (many modes unlike cavities)



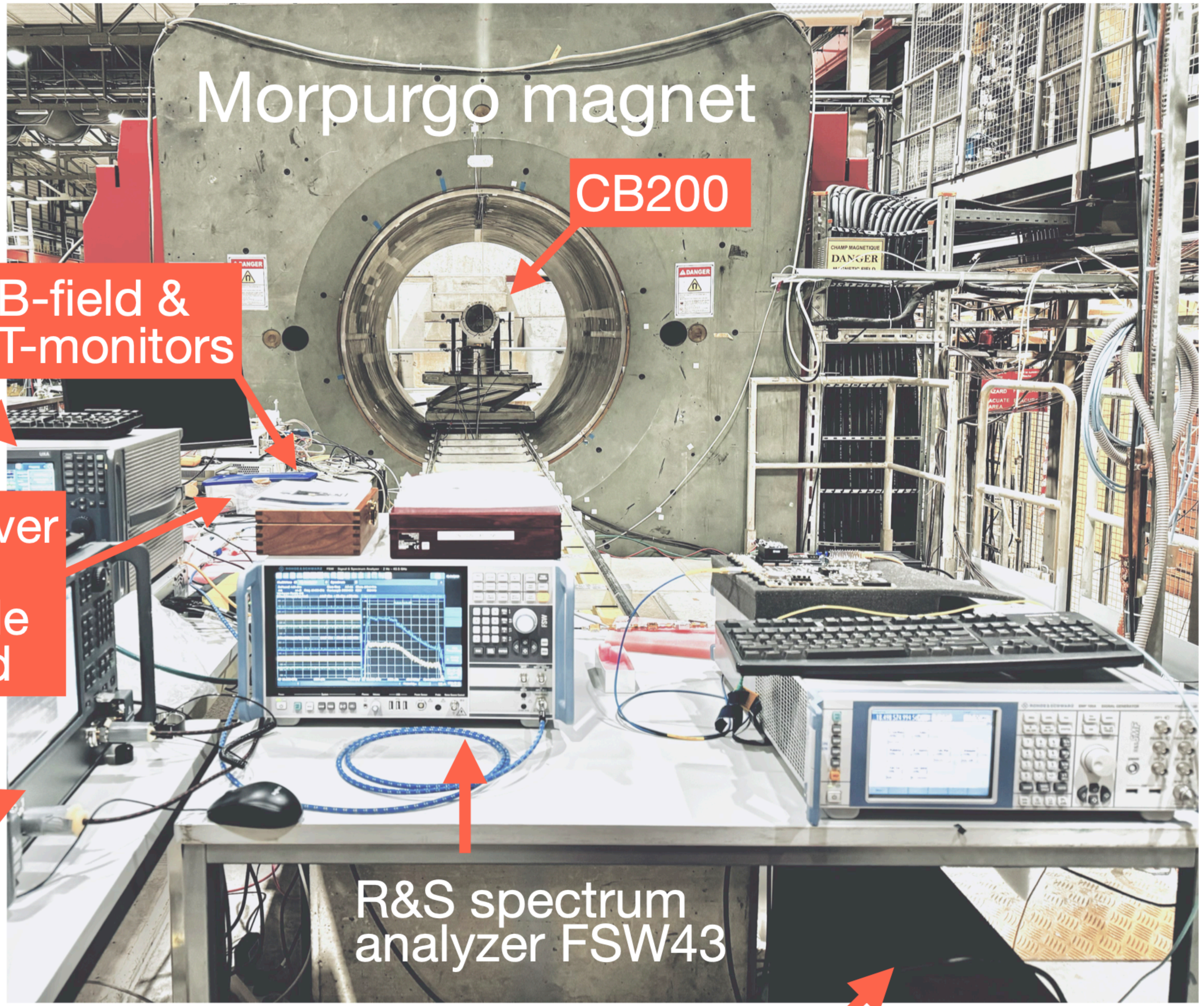


- Perturbative measurement resolves |E| profile across diameter
- Booster & parasitic modes **identified directly** from measured E-field

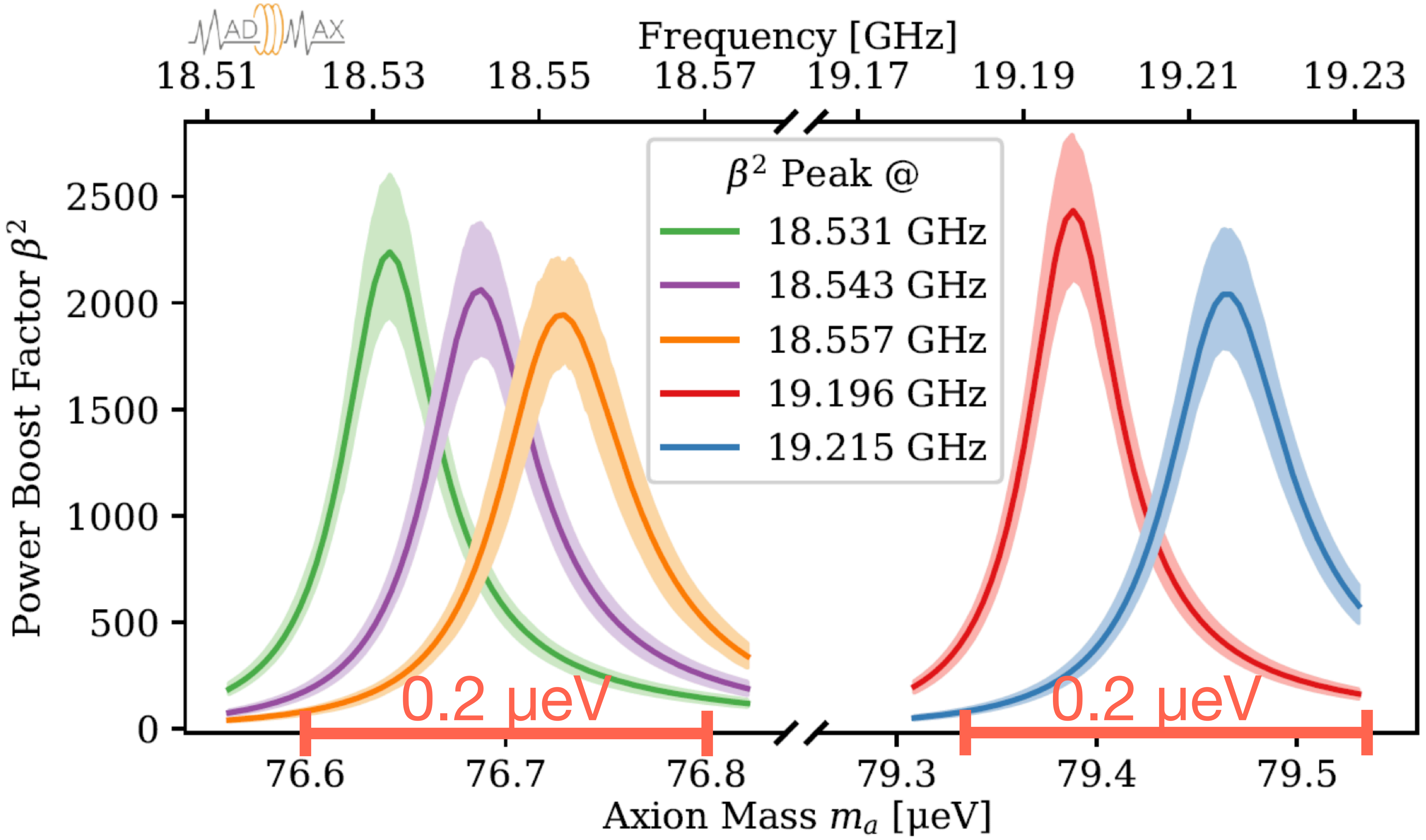
First axion search with MADMAX (1)

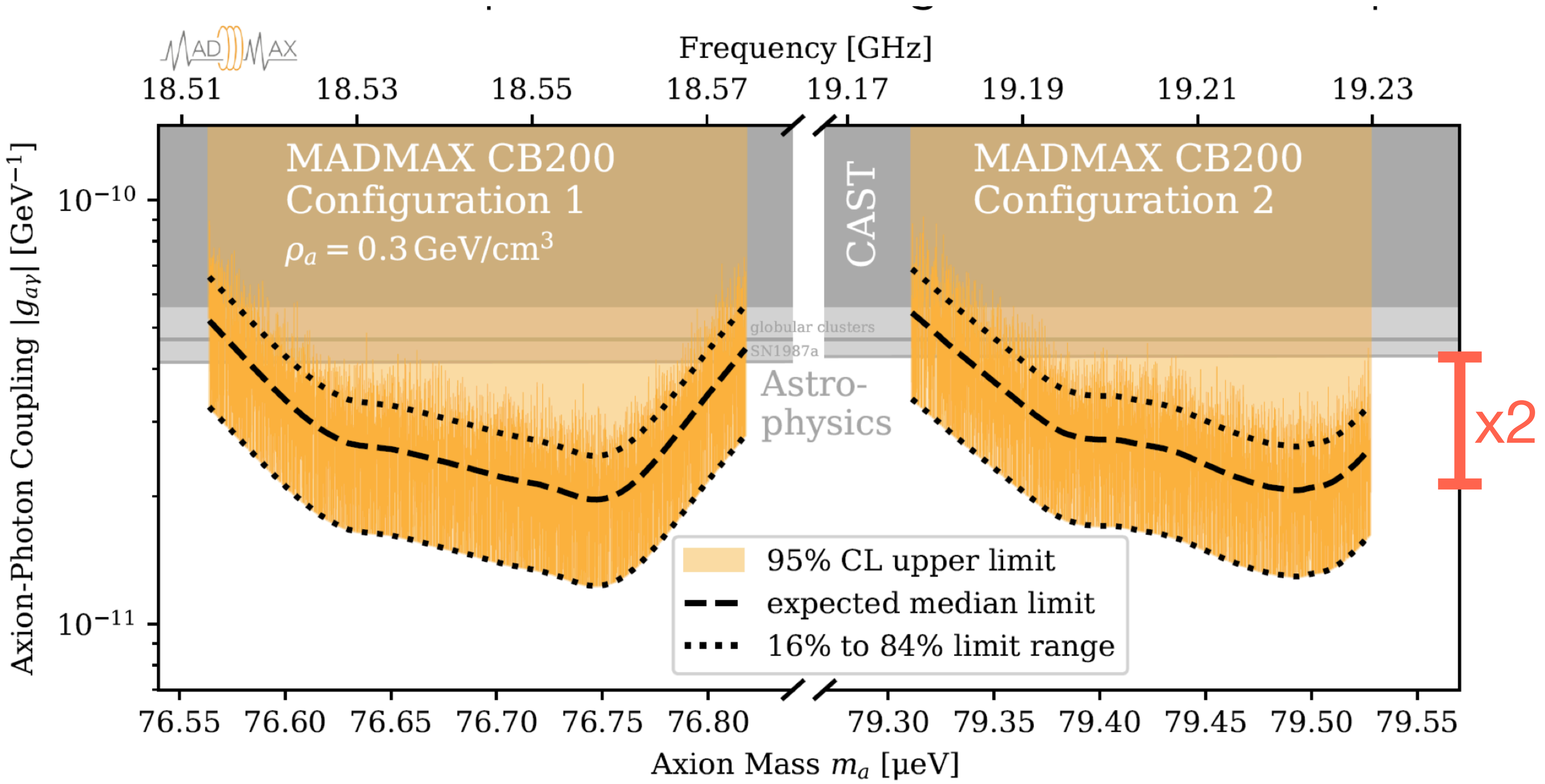
→ 2024 at CERN's 1.6 T MORPURGO magnet

- ✦ 5 booster configurations tuned manually
- ✦ ≈ 15 day run @ ≈ 1 T and room temperature



First axion search with MADMAX (2)





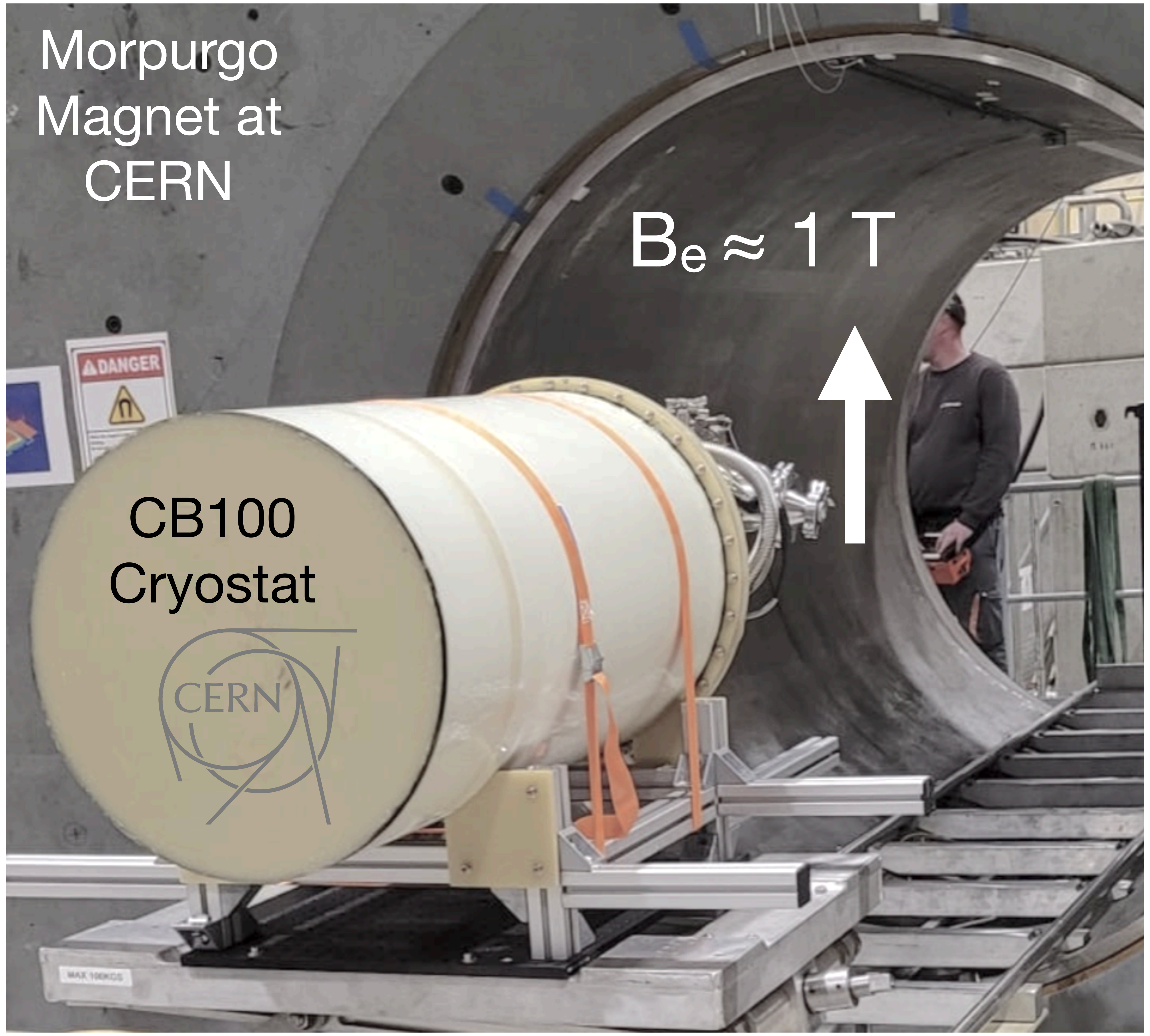
- Successfully reconfigured boost: 5 configurations with systematics (≈ 15%)
- Peak $\beta^2 \approx O(2000)$
  $\beta^2 > 500$ over 2x50 MHz bandwidths

- No excess observed: ≈ 2× better than current CAST limits with a modest system

[PRL 135 (2025): 041001]

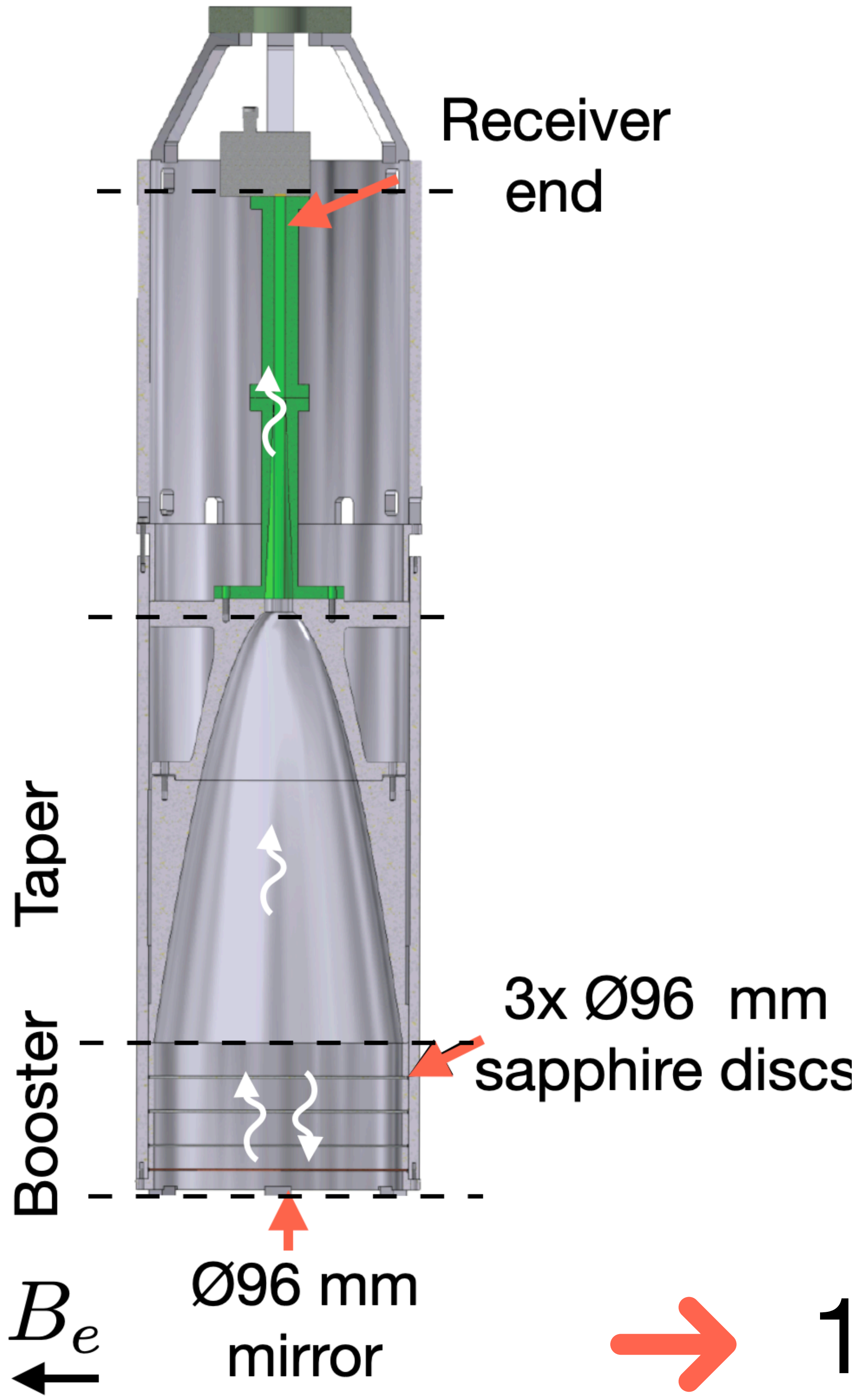
Cold setup & cold axion search at CERN

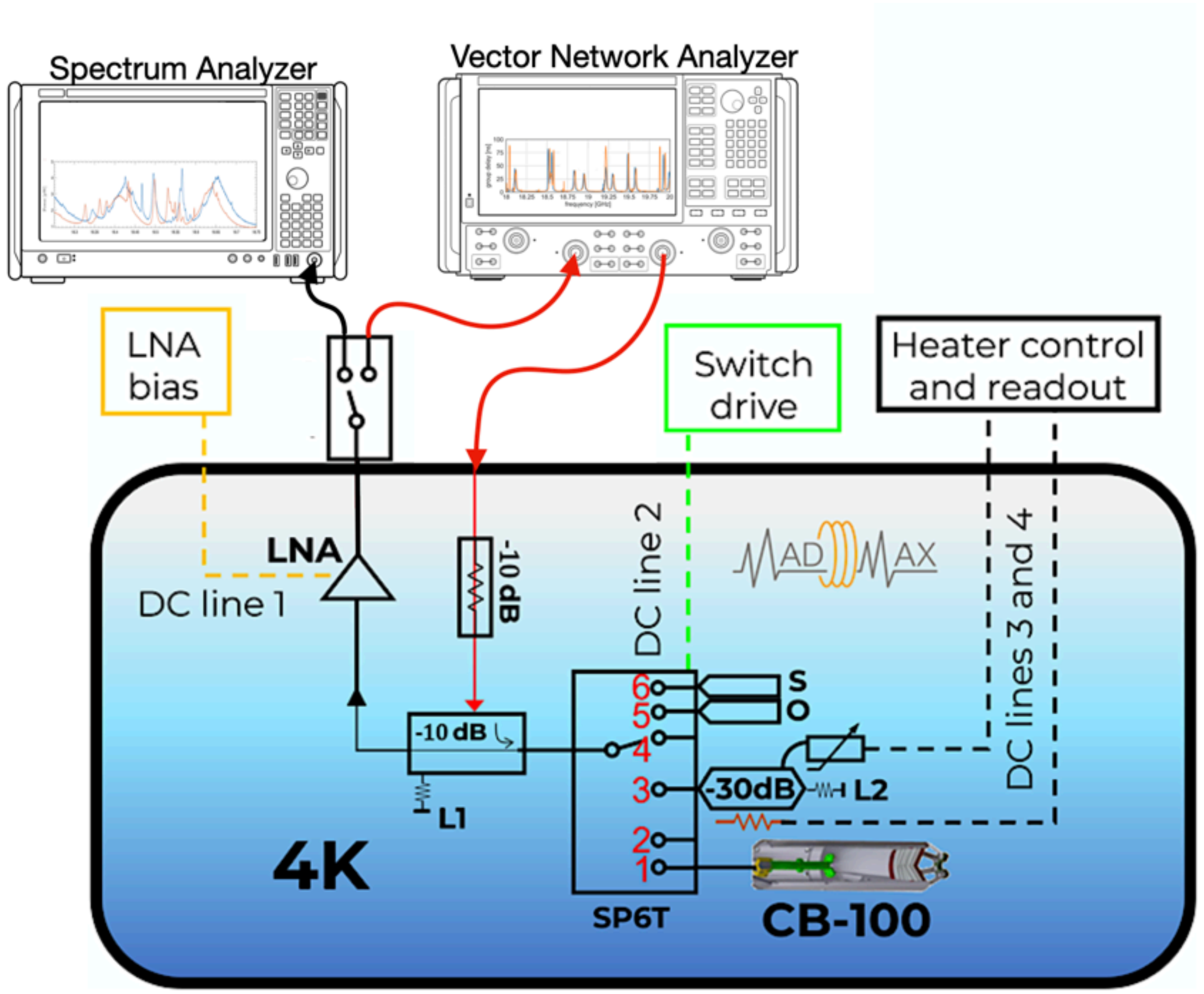
→ Horizontal non-magnetic cryostat developed with CERN (Cryolab)



[JINST 20 T02005 (2025)]

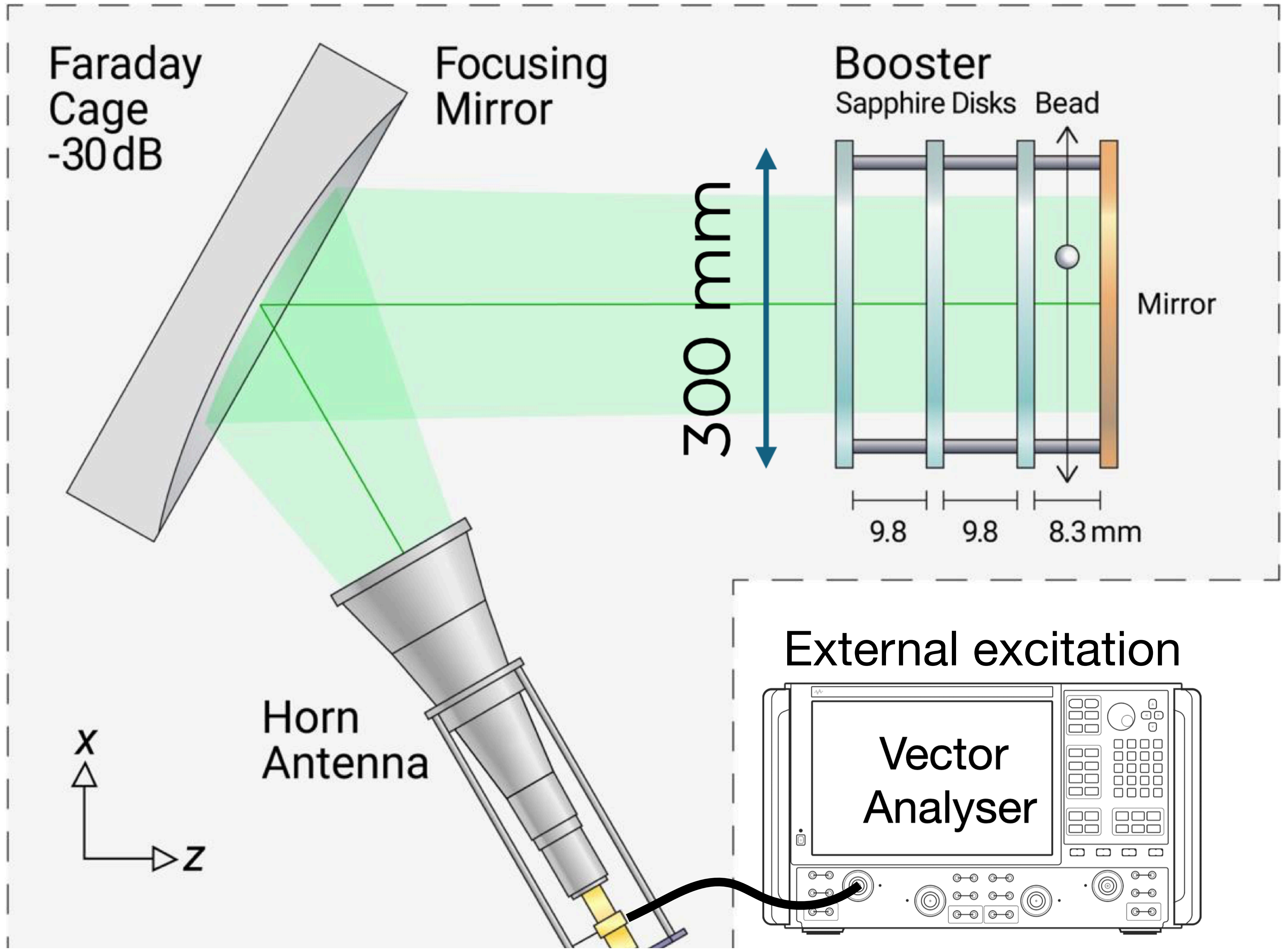
→ Dedicated ⌀100 mm closed prototype & cold calibration setup





→ 1 day axion search:
≈ 19 GHz @ ≈ 1.6 T @
$T_{sys} \approx 14$ K (analysis ongoing)

Open ⌀300 mm 3-disc prototype booster



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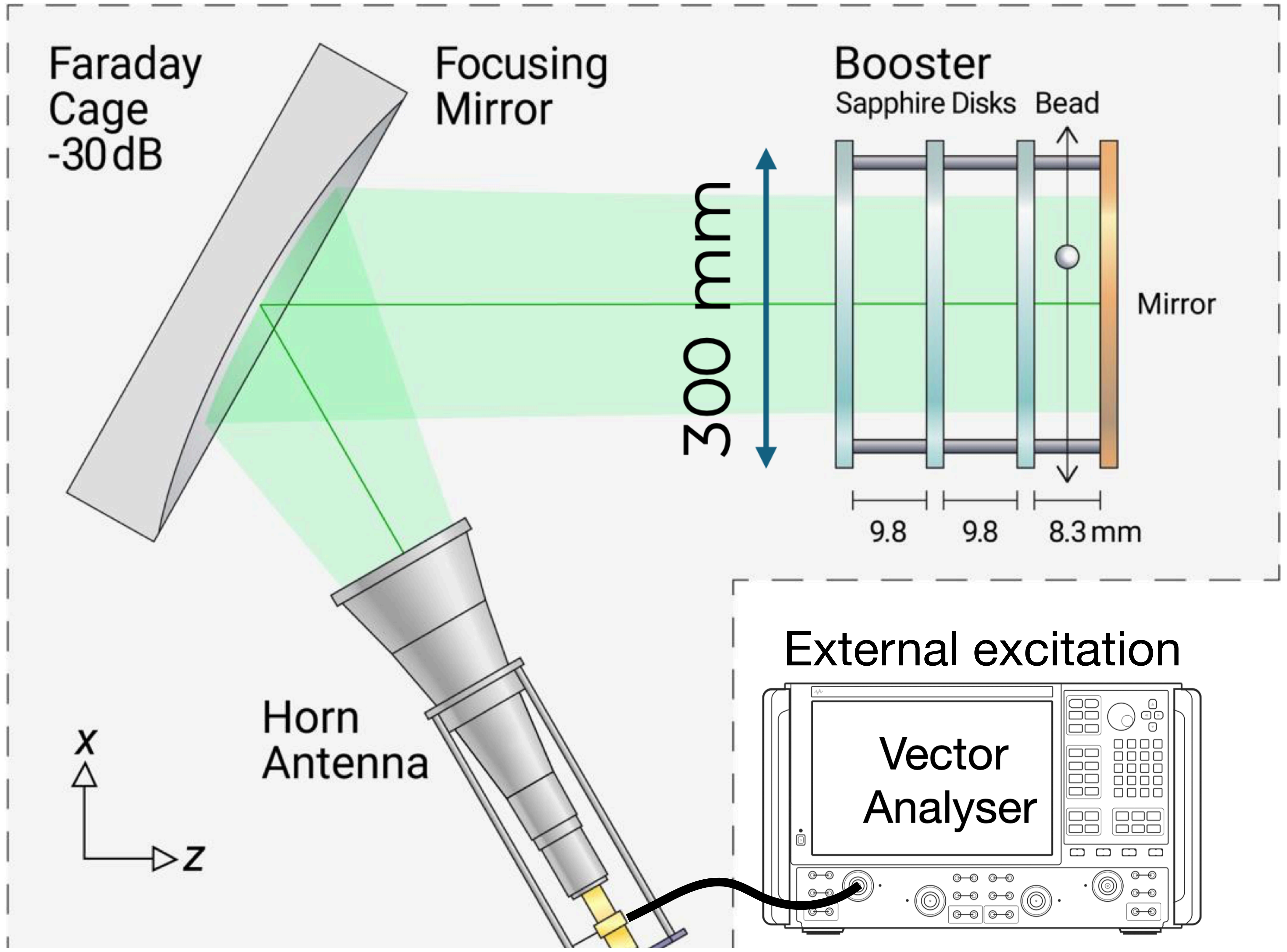
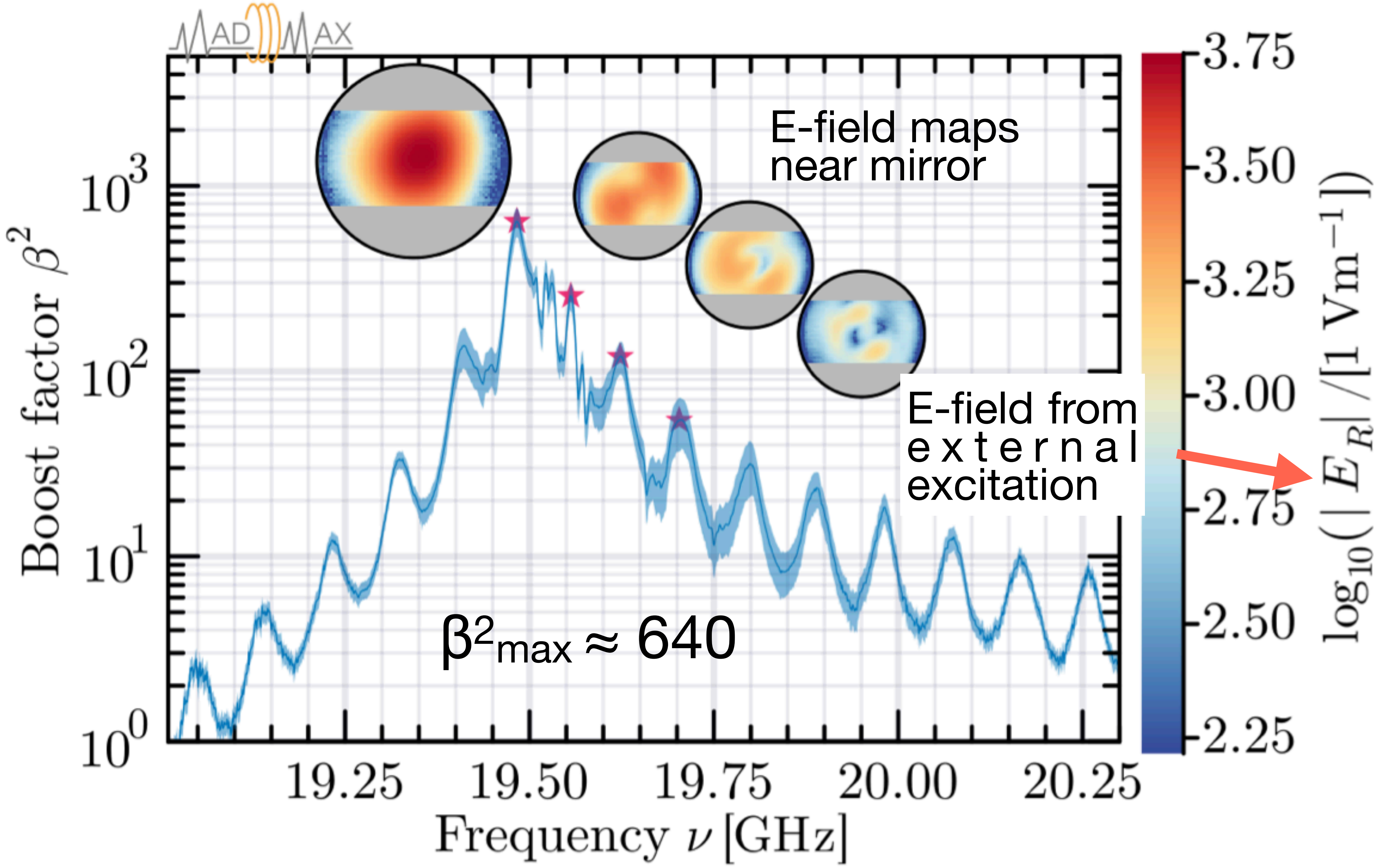


→ **Challenge:** Spectrum affected by reflections in the environment



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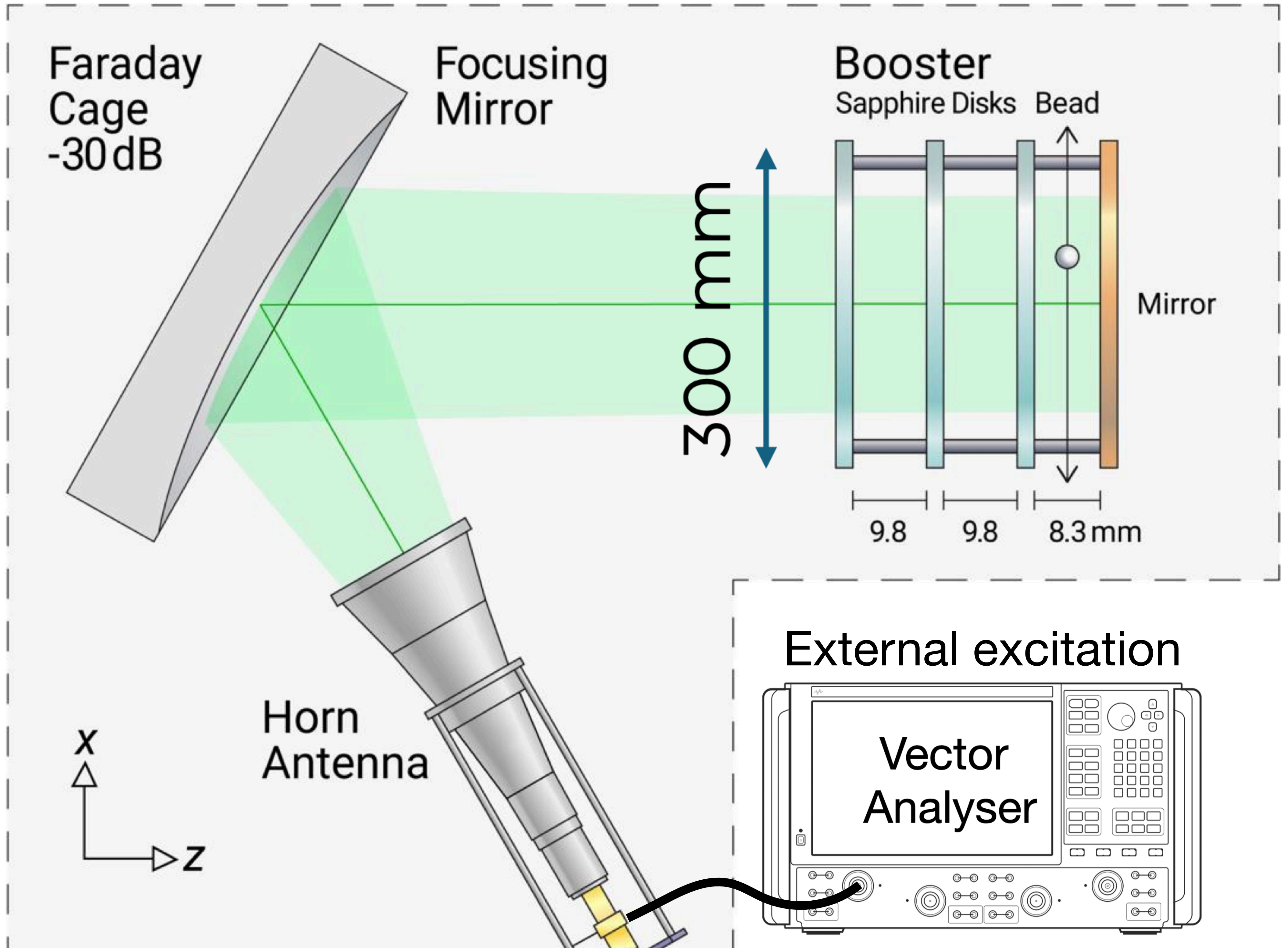
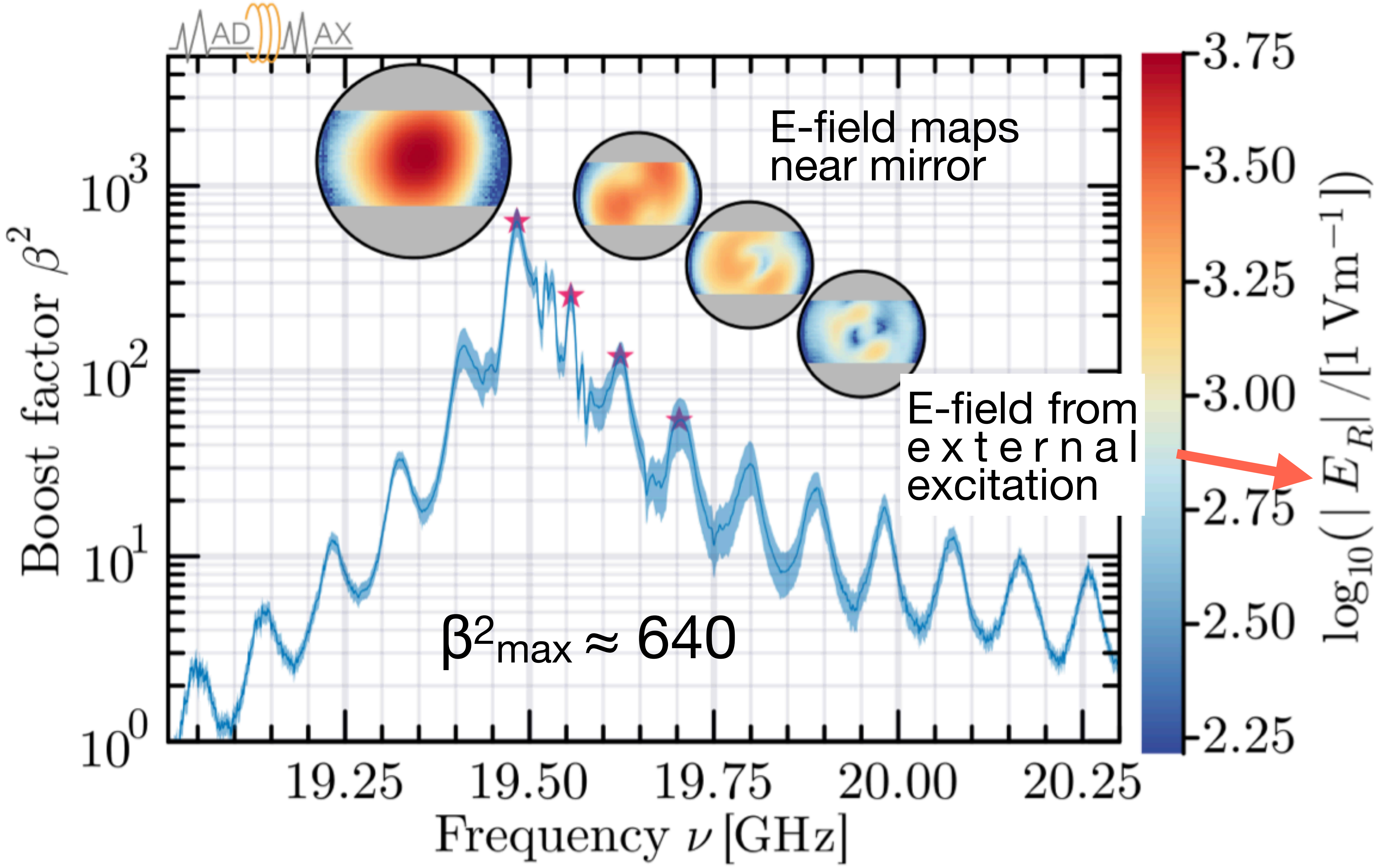




→ In situ booster calibration by reciprocity between external/axion-induced waves:

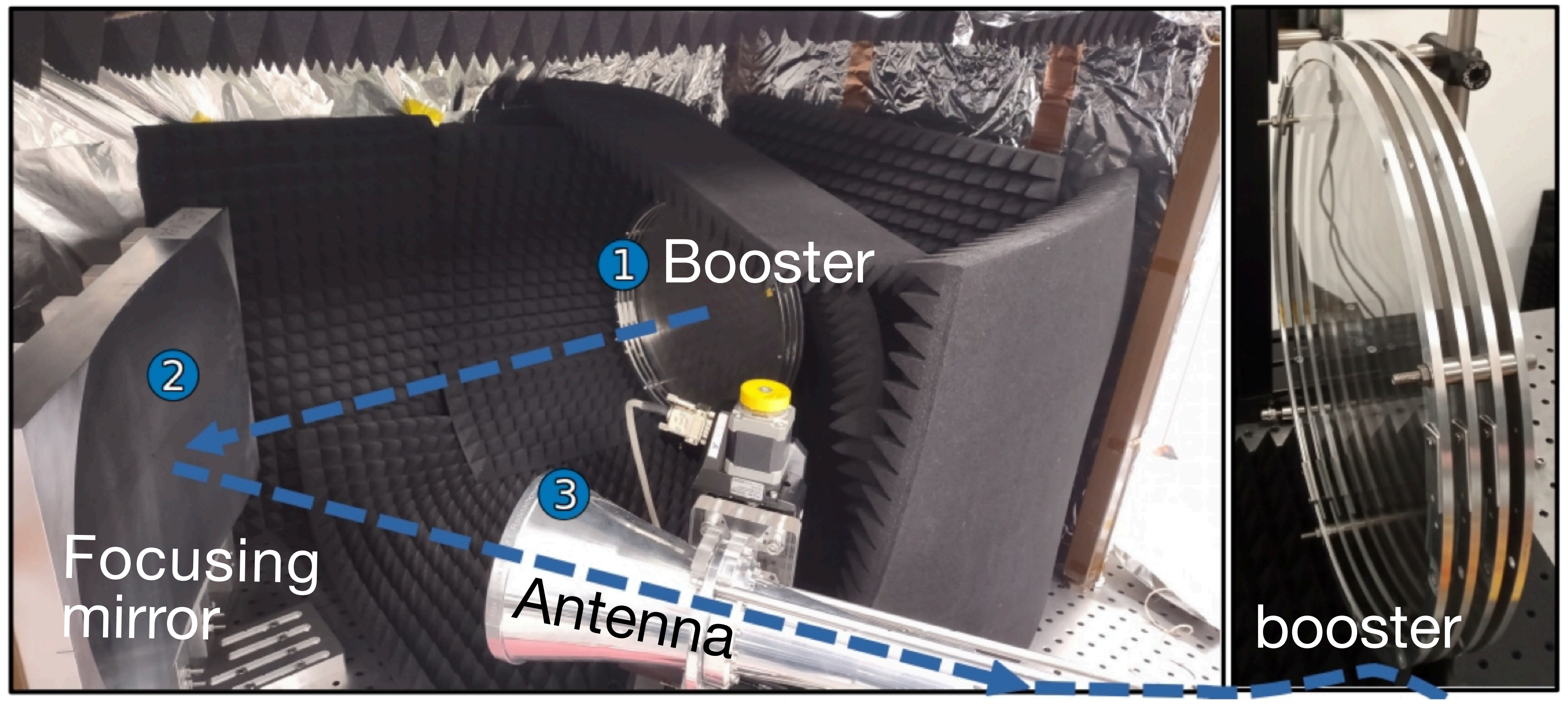
Booster externally excited with VNA → |E-field(x,y,z,v)| measured between the discs → β² & uncertainties obtained from measured E-field:

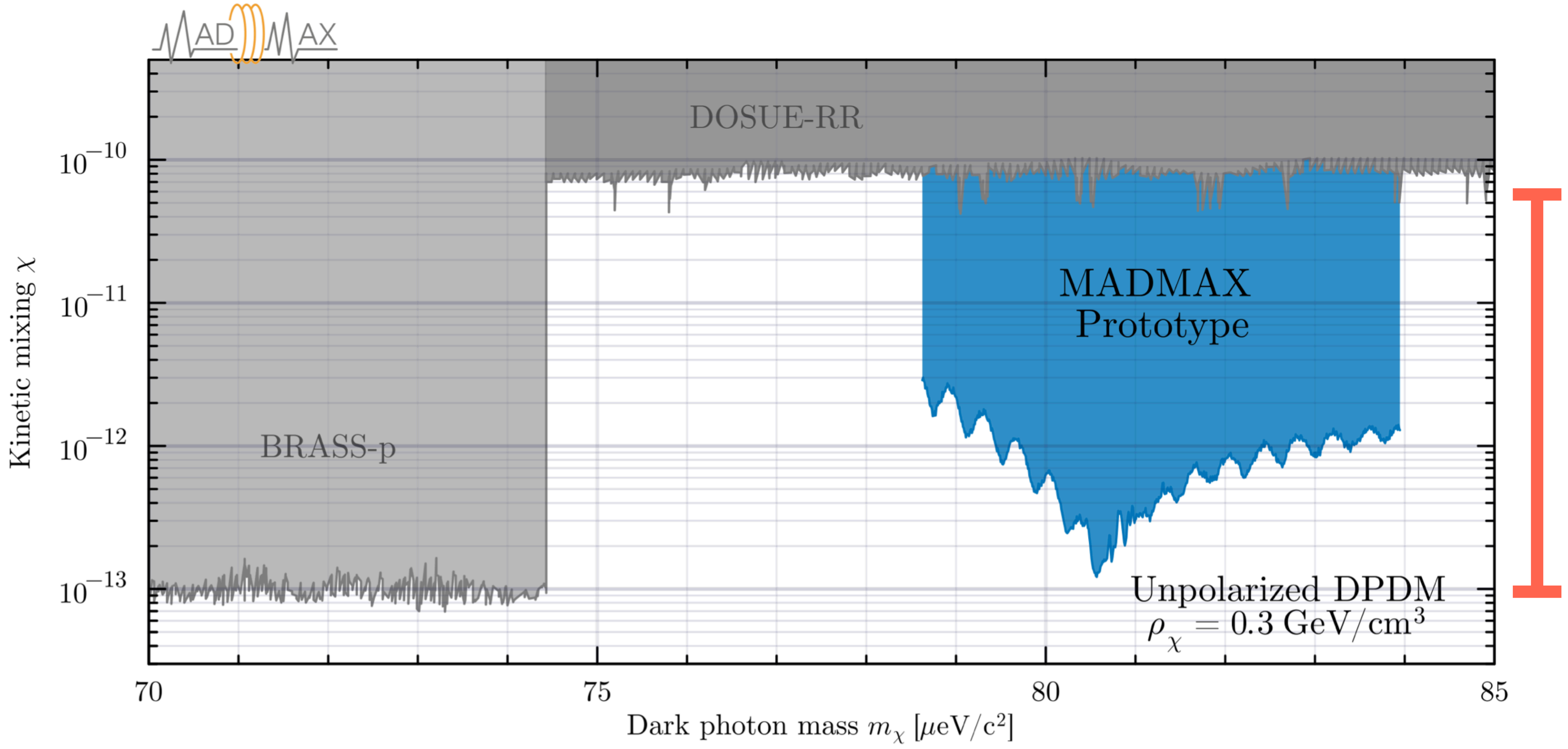
Conversion volume

$$\beta^2 \propto \left| \int dV\, E_R \right|^2$$

[JCAP04(2024)005]
[JCAP04(2023)064]

First MADMAX dark photon search

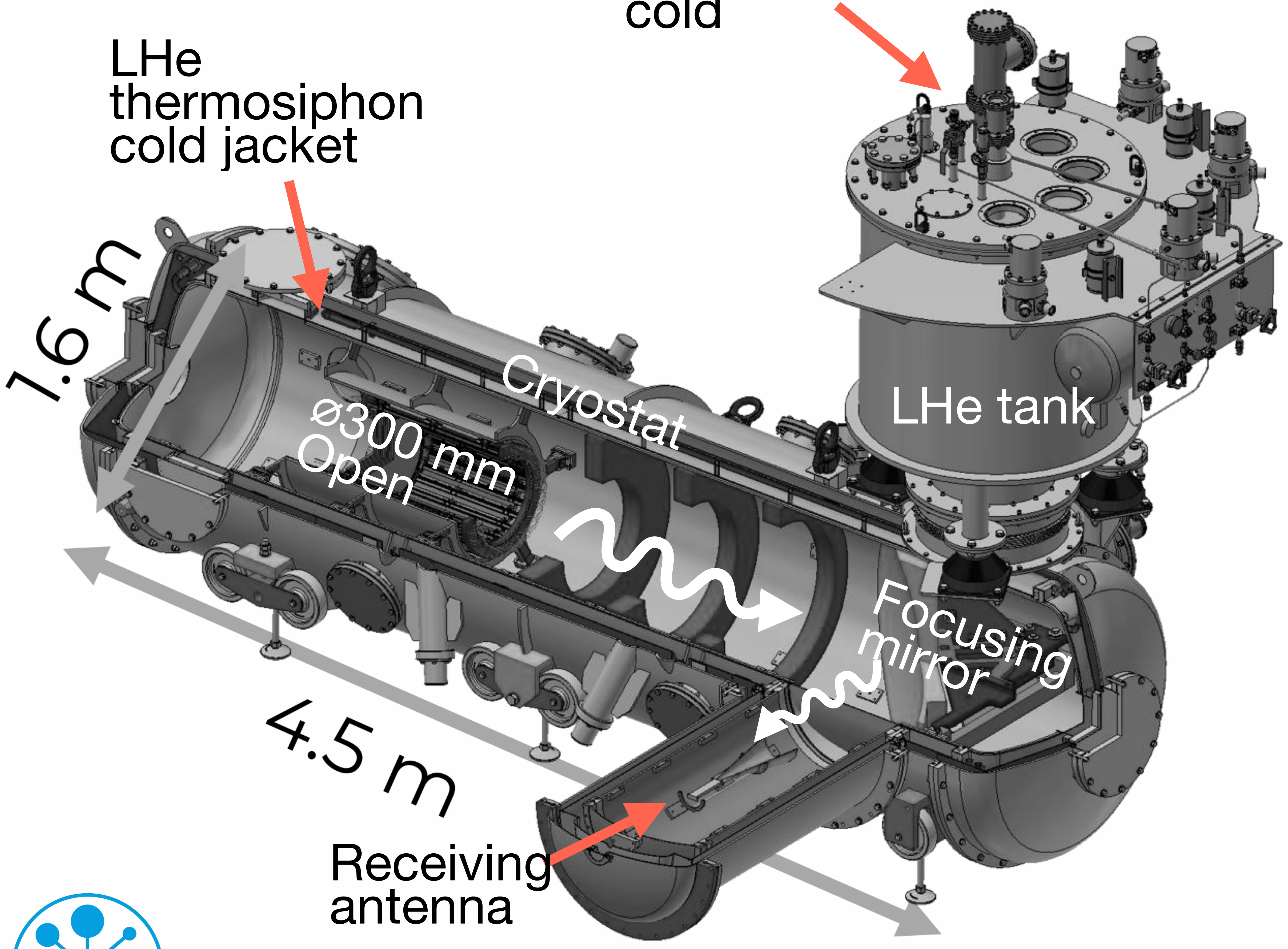




- No B-field: Dark photons can mix into standard model photons via kinetic mixing
- ⌀300 mm 3 fixed disc booster
- Open setup in a Faraday cage to mitigate background
- 15 days data taking at fixed β^2
- $\beta^2_{max} \approx 640$ with $\approx$ 15% error obtained in situ by reciprocity method
- No excess found: $\approx$ 3 order improved existing limits over $\approx$ 1.2 GHz = 5 μeV range

[PRL 134.15 (2025): 151004]

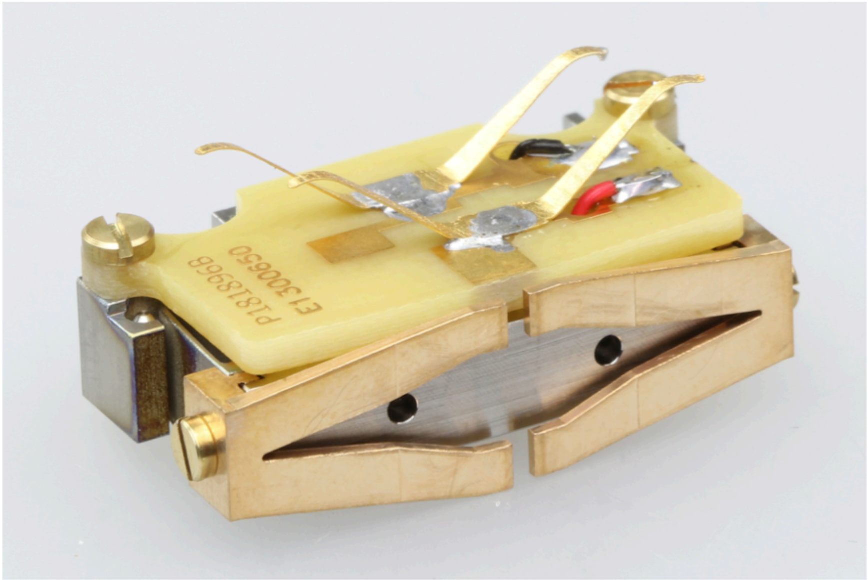
Next: cold setup with ⌀300 mm open booster (1)

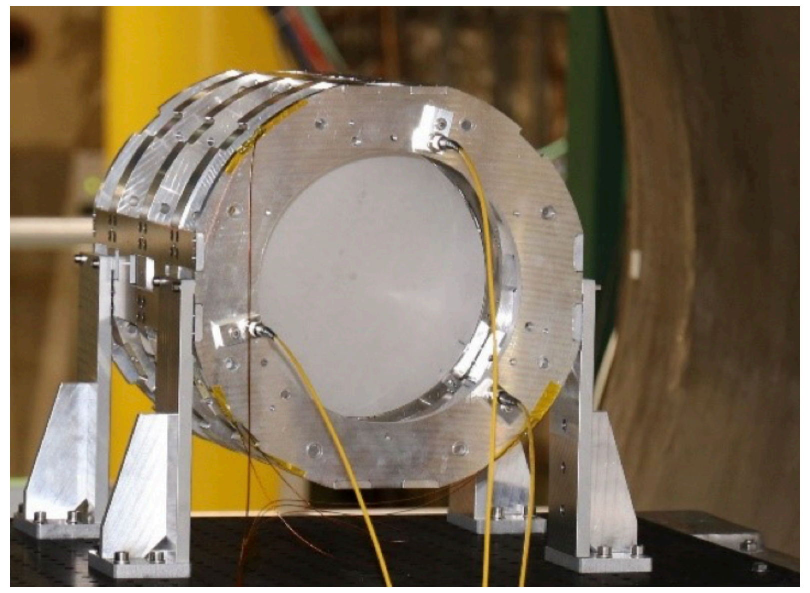


→ **Goal 1:** Cryogenic setup that fits in the MORPURGO magnet at CERN

- Cold run @ ≈ 4-5 K
- Cryostat fits ⌀300 mm open booster setup

→ **Goal 2:** Control disc spacing to scan masses at cold



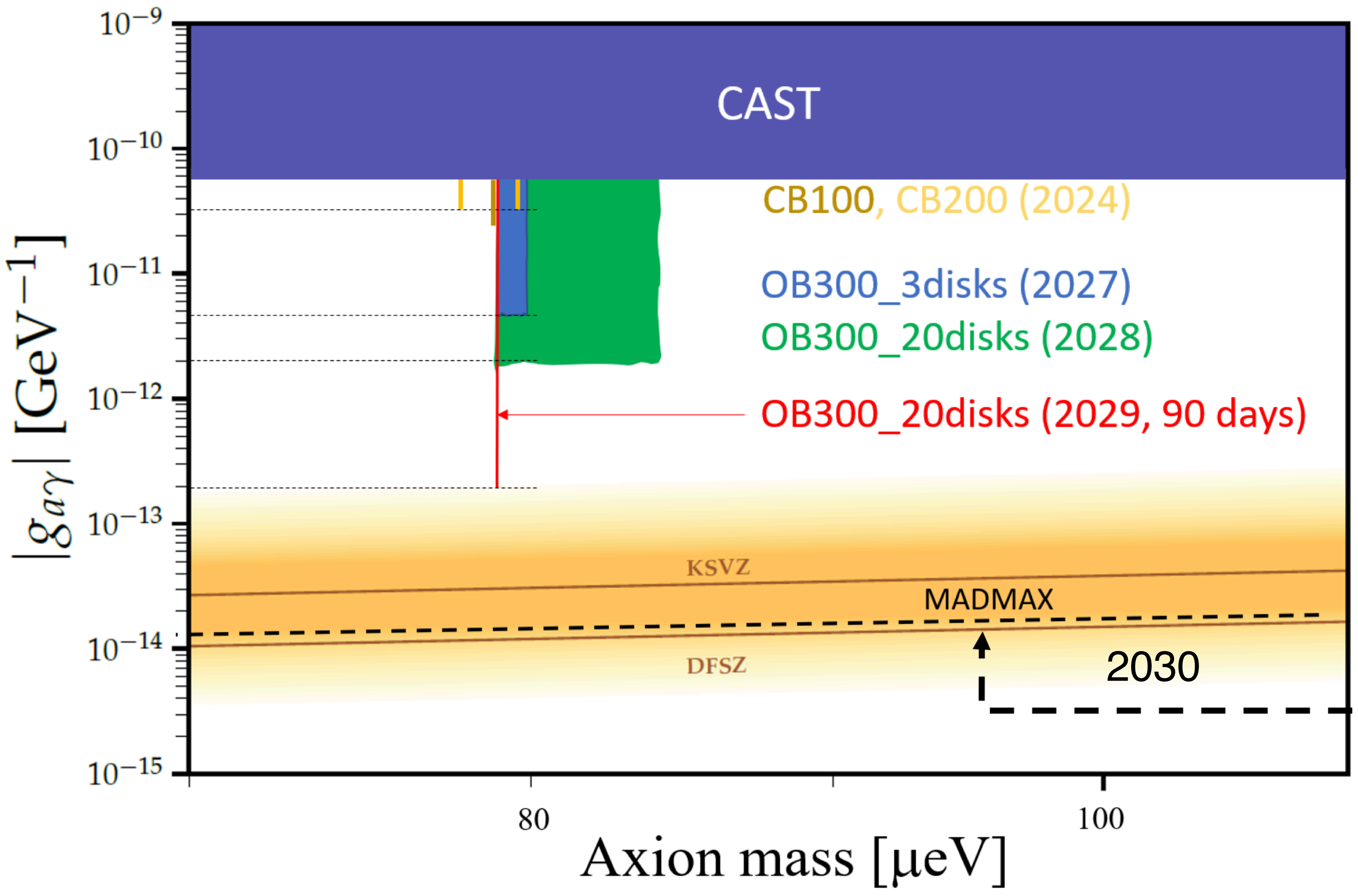


- Cryogenic piezo actuators allow for ≈1 μm at 1.6 T & 35 K

[JINST 18 P08011 (2023)] [JINST 19 T11002 (2024)]

Next: cold setup with ⌀300 mm open booster (2)

→ Physics reach forecast at CERN's MORPURGO magnet

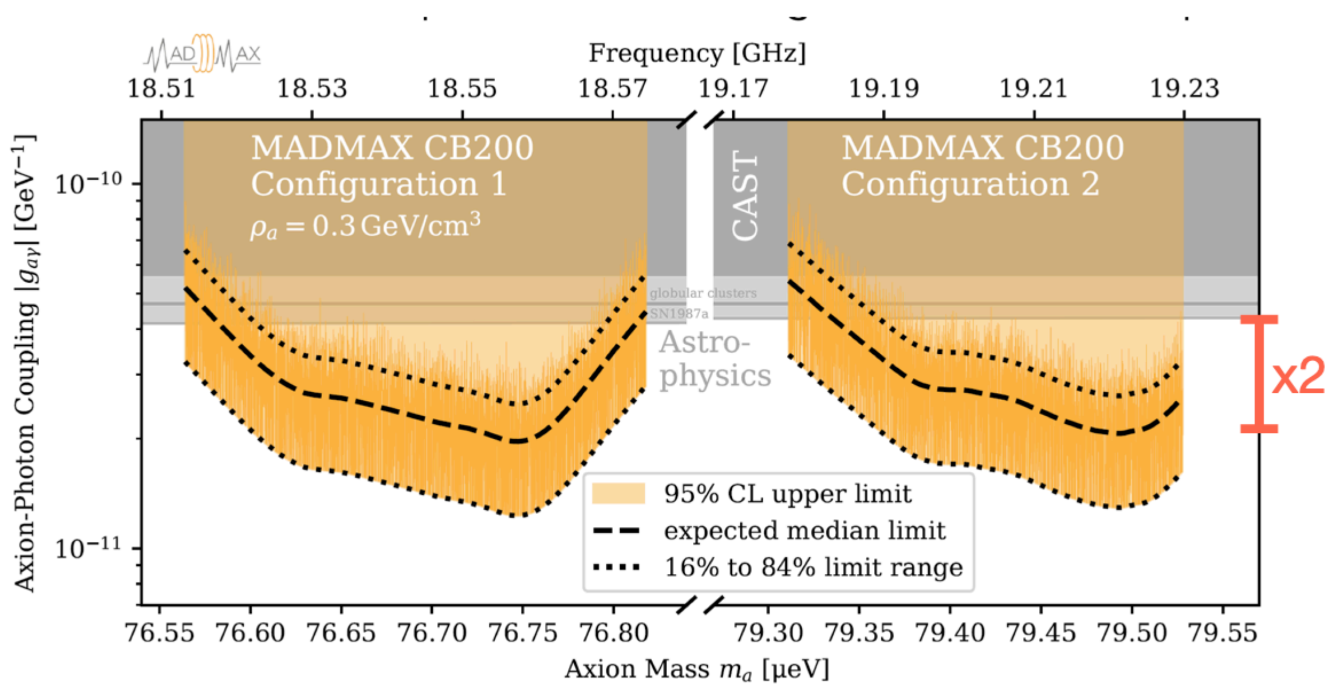


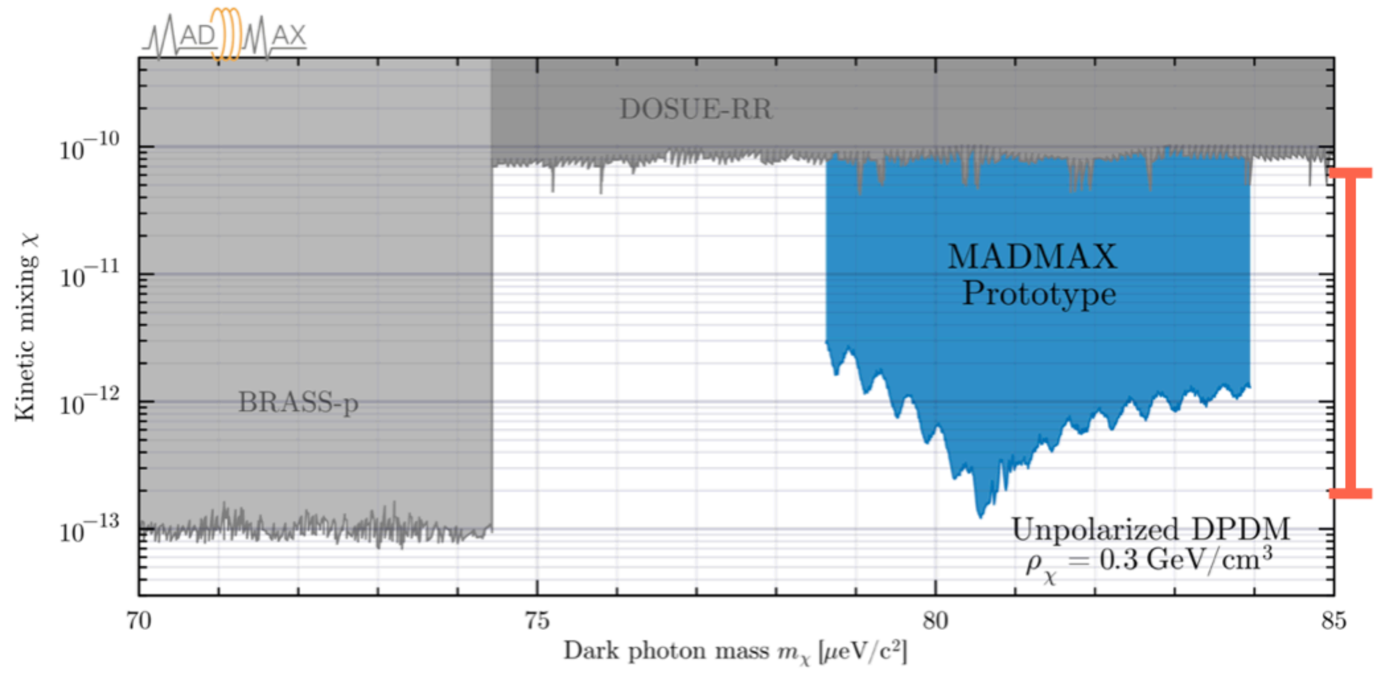
- Long run planned during the long LHC shutdown (2027-2029)
- Cryostat delivered in 2025 & first successful cooldown achieved

Wrap-up

→ MADMAX prototype stage:
Concept successfully validated

- Axion and dark photon searches reach leading sensitivity
- Calibration schemes for β^2 established
- Mechanical control at cold demonstrated
- First cold run axion search performed (analysis ongoing)
- New cryostat delivered and undergoing testing





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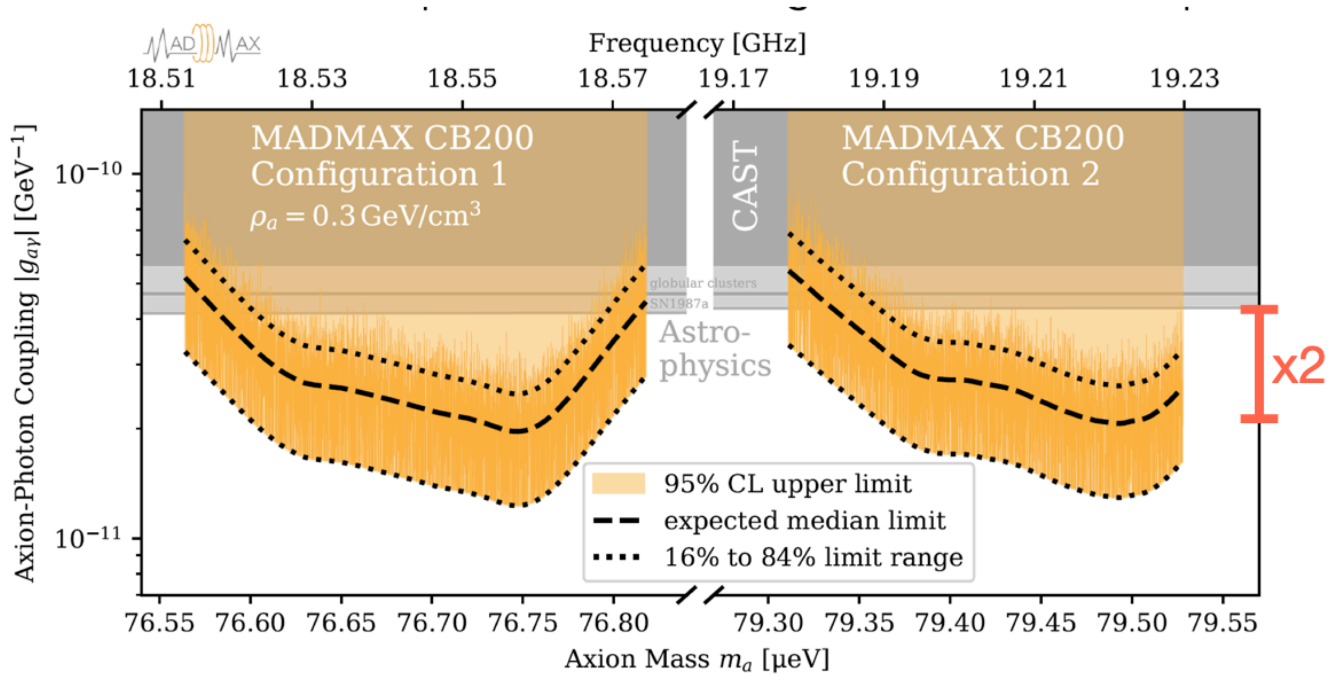
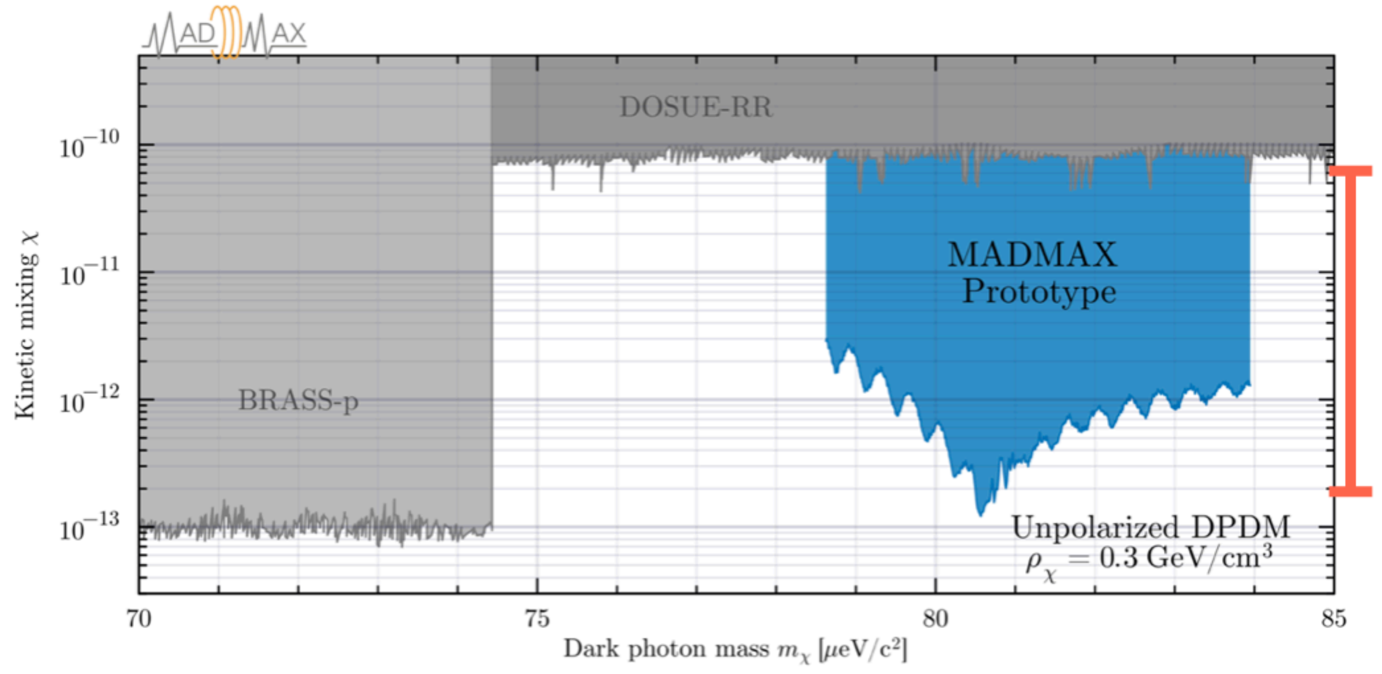
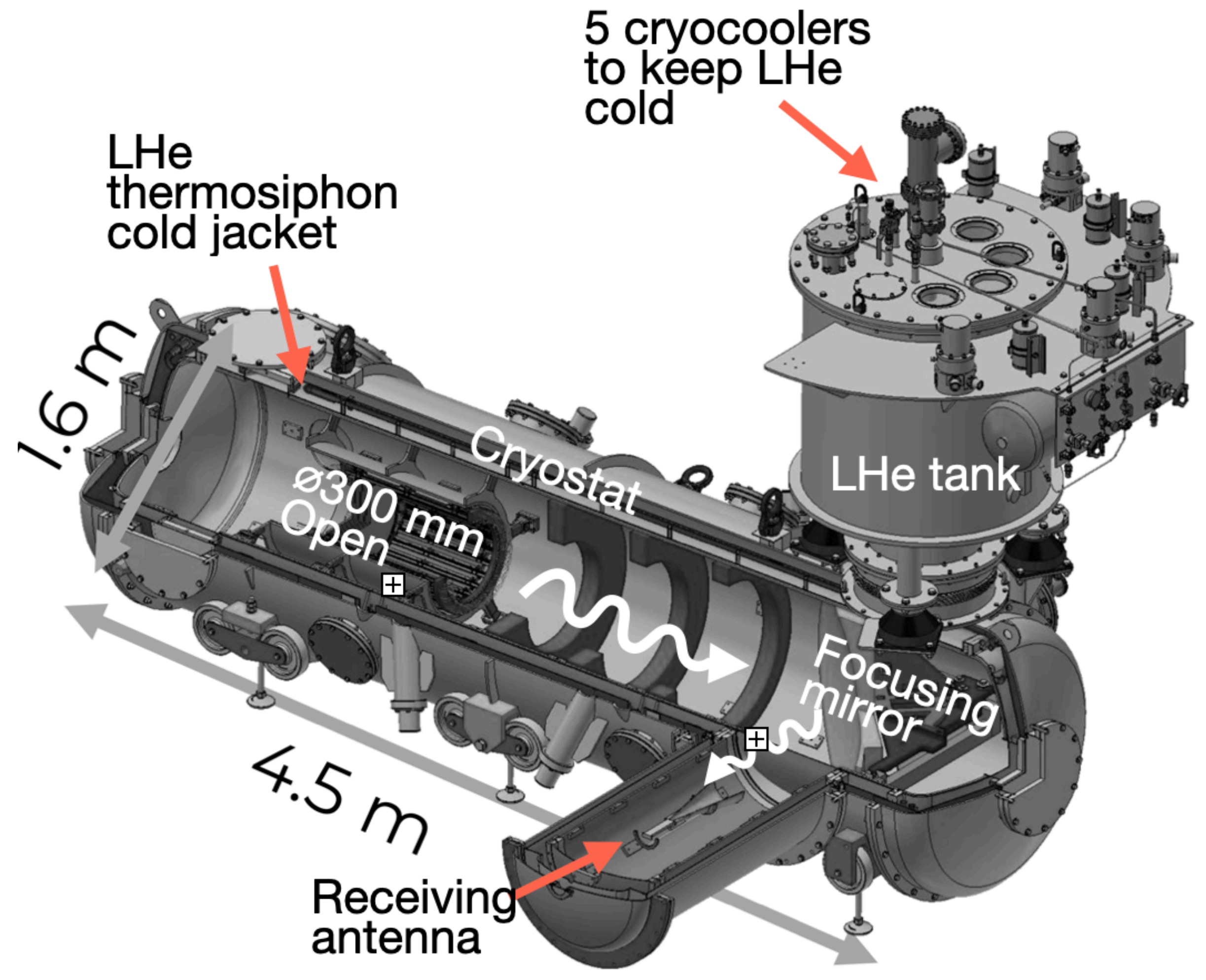




→ **Next goal:** Multi-disc reconfigurable cryo-setup at 1.6 T during LHC long shutdown (2027–2029)



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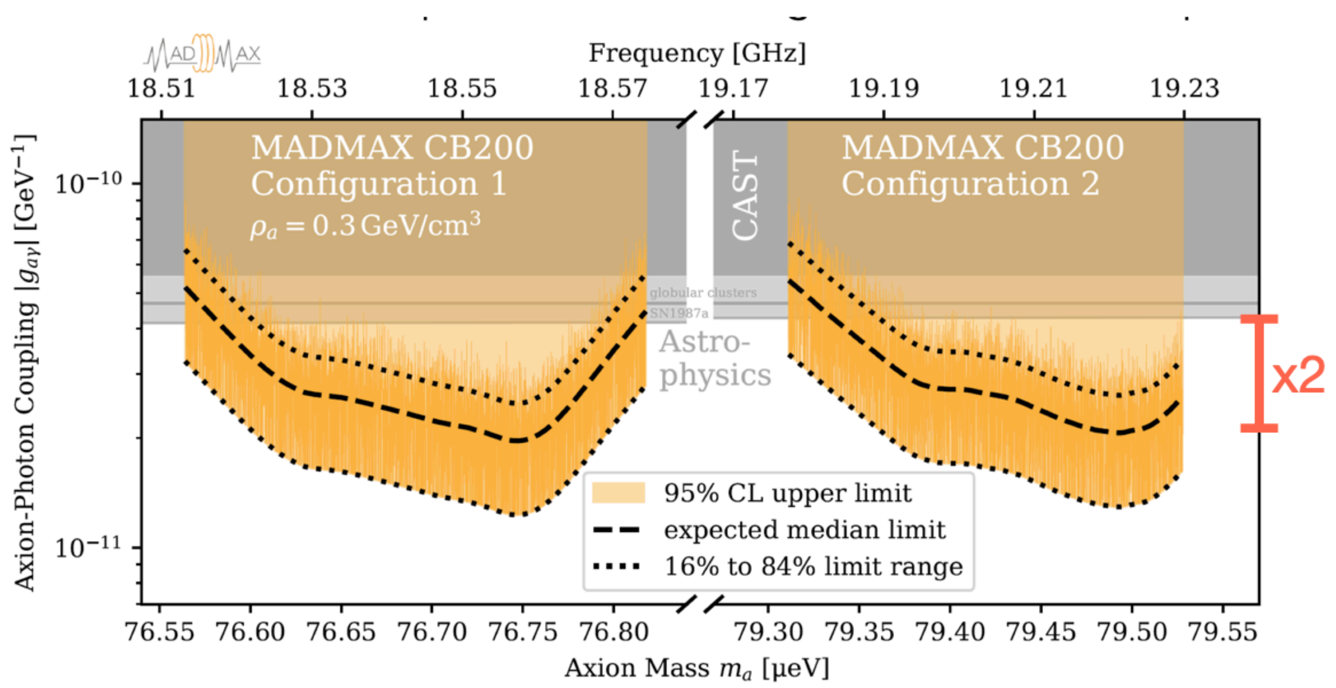

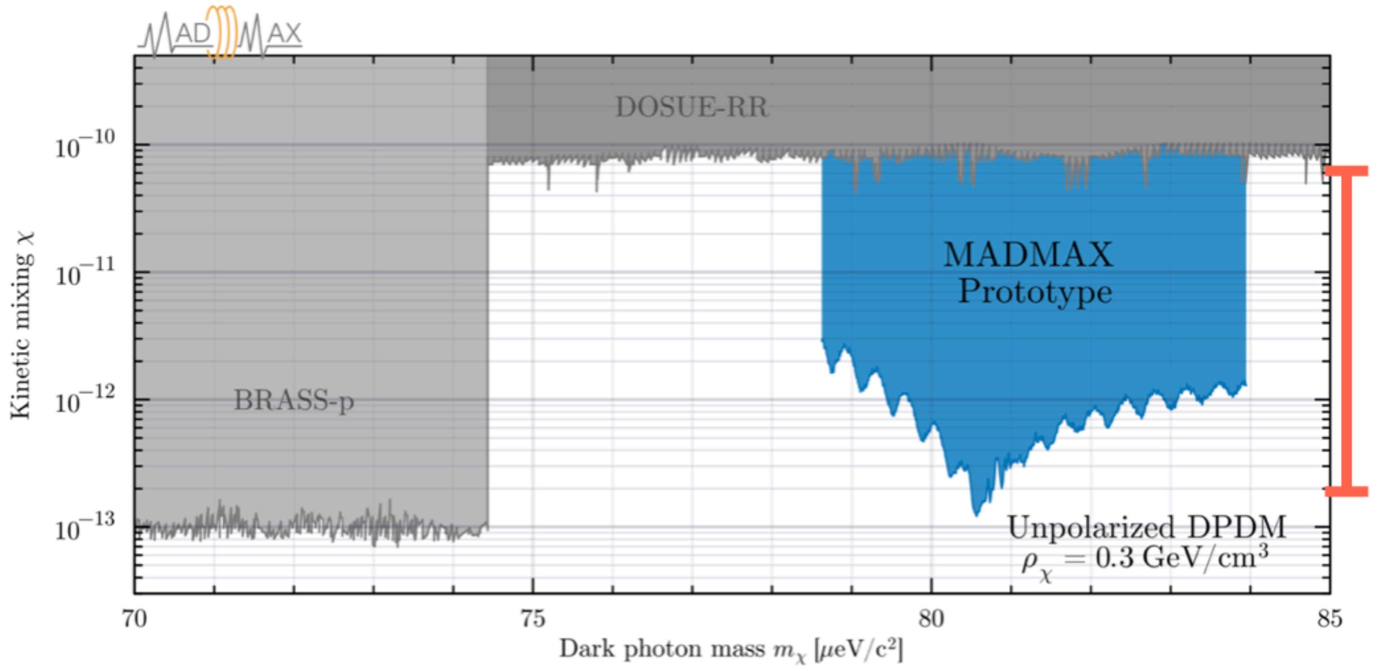

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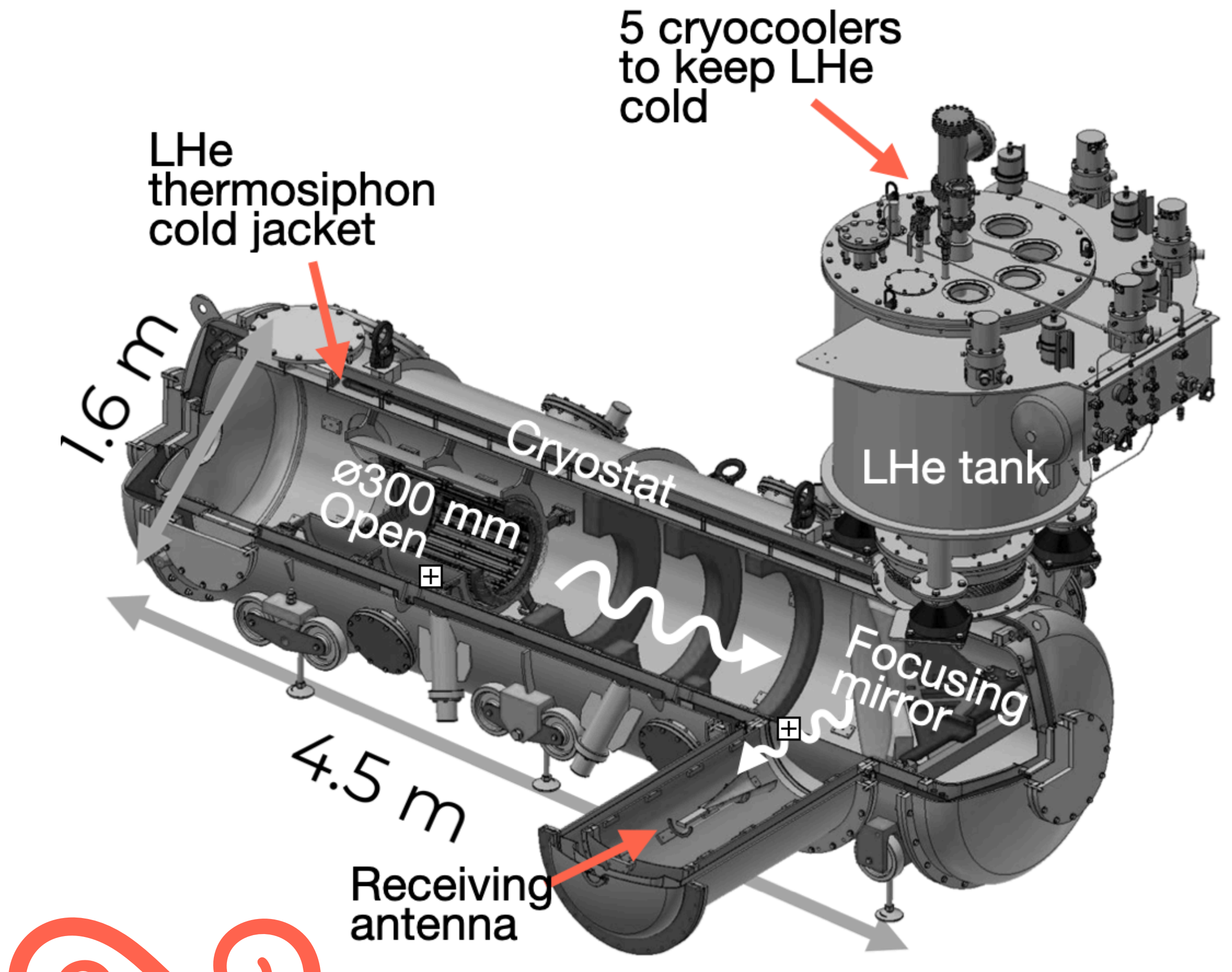

Stay tuned!

https://madmax.mpp.mpg.de/news.html