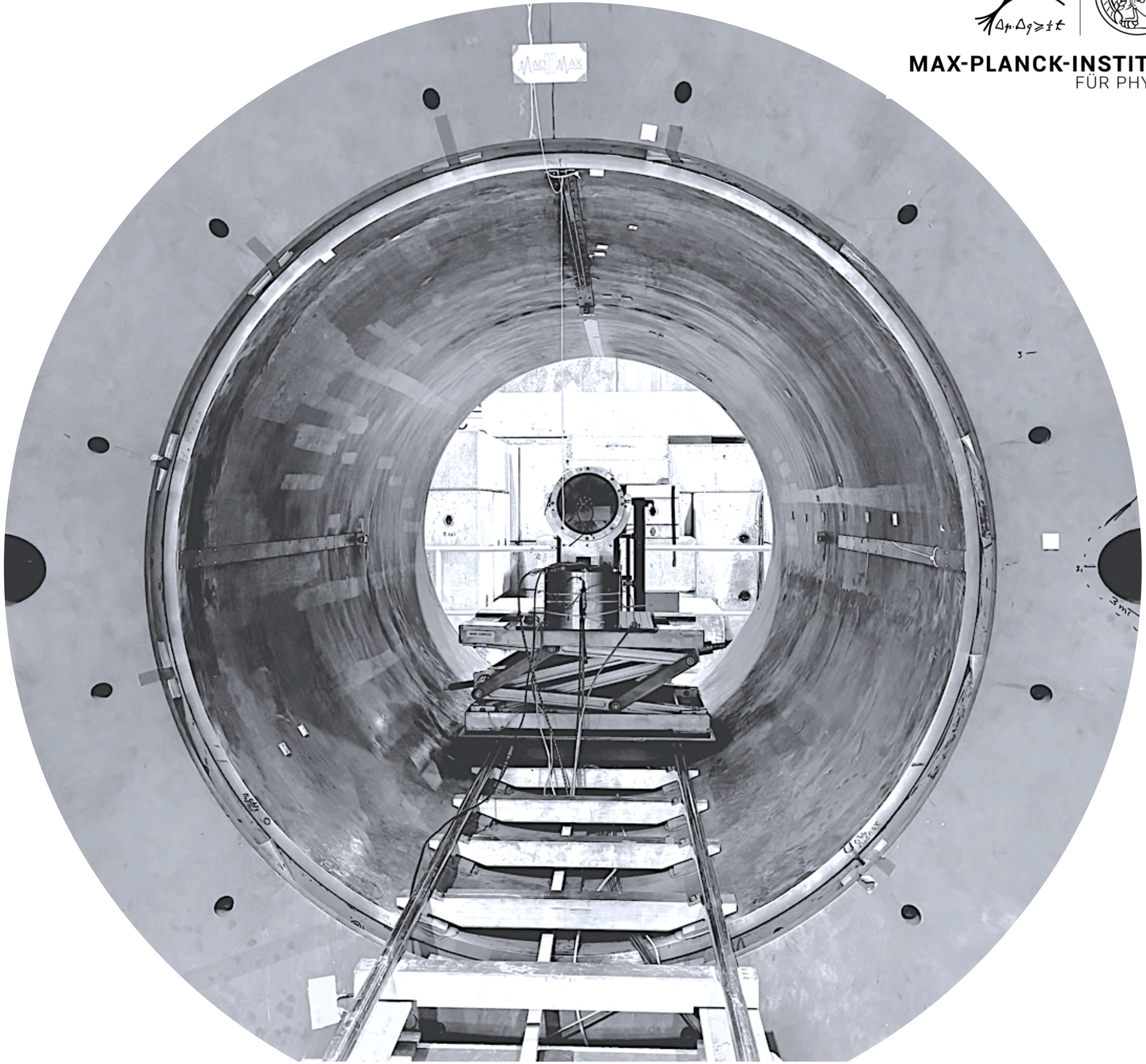
Anton Ivanov for MADMAX
https://madmax.mpp.mpg.de

MAX-PLANCK-INSTITUT FÜR PHYSIK

MADMAX

Dielectric Haloscope Experiment

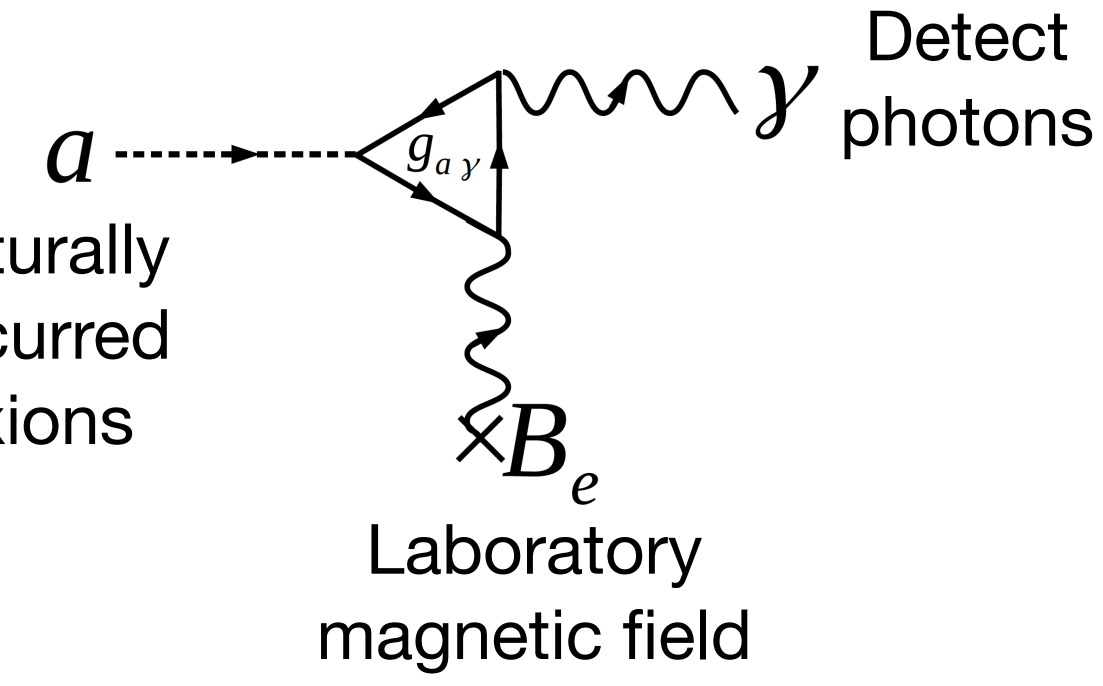
- Principle
- Prototype preparation
- Physics runs
- News

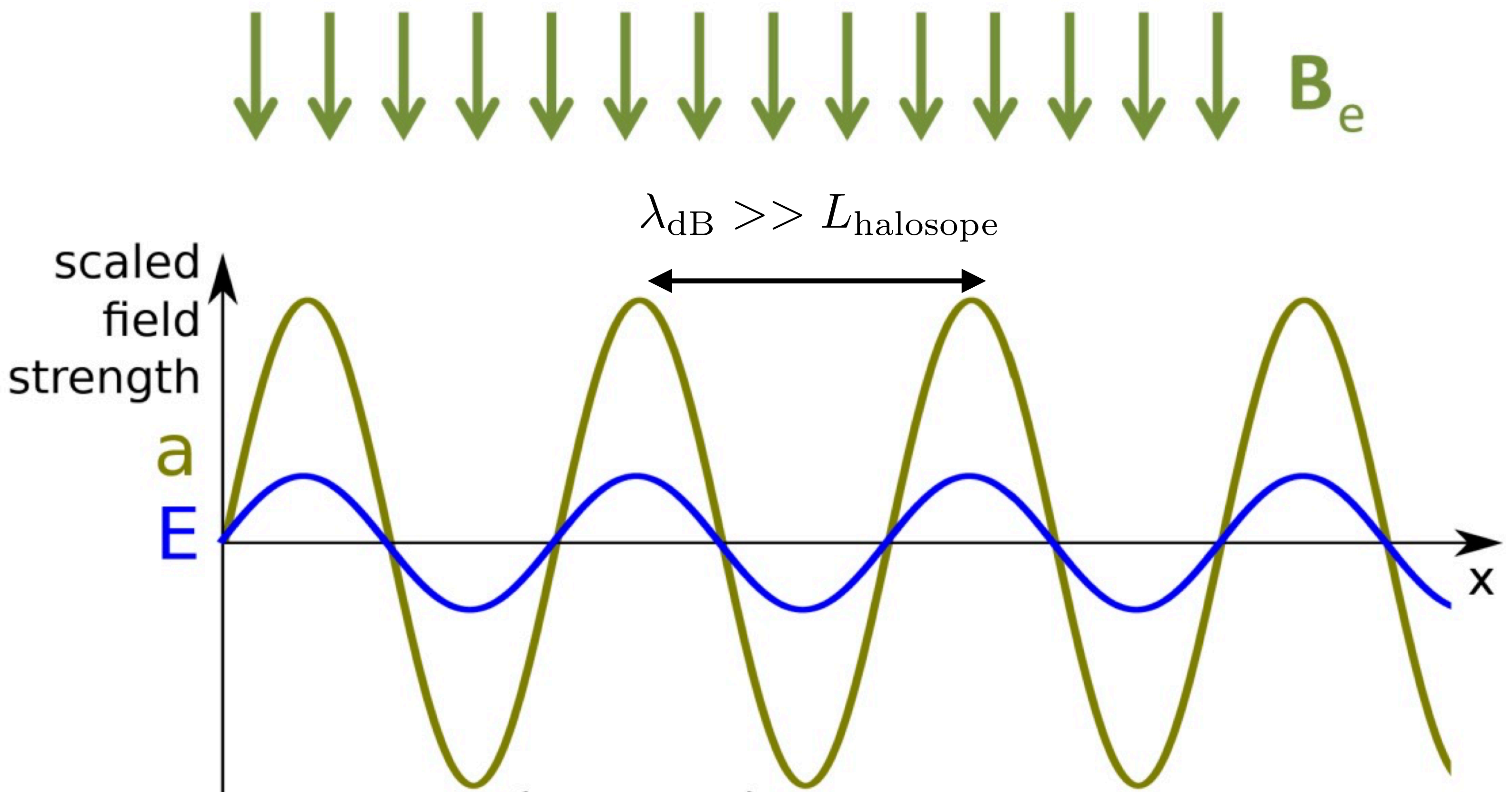


20th Rencontres du Vietnam | August 4 - 10, 2024 | ICISE | Quy Nhon, Vietnam

QCD axion detection principle

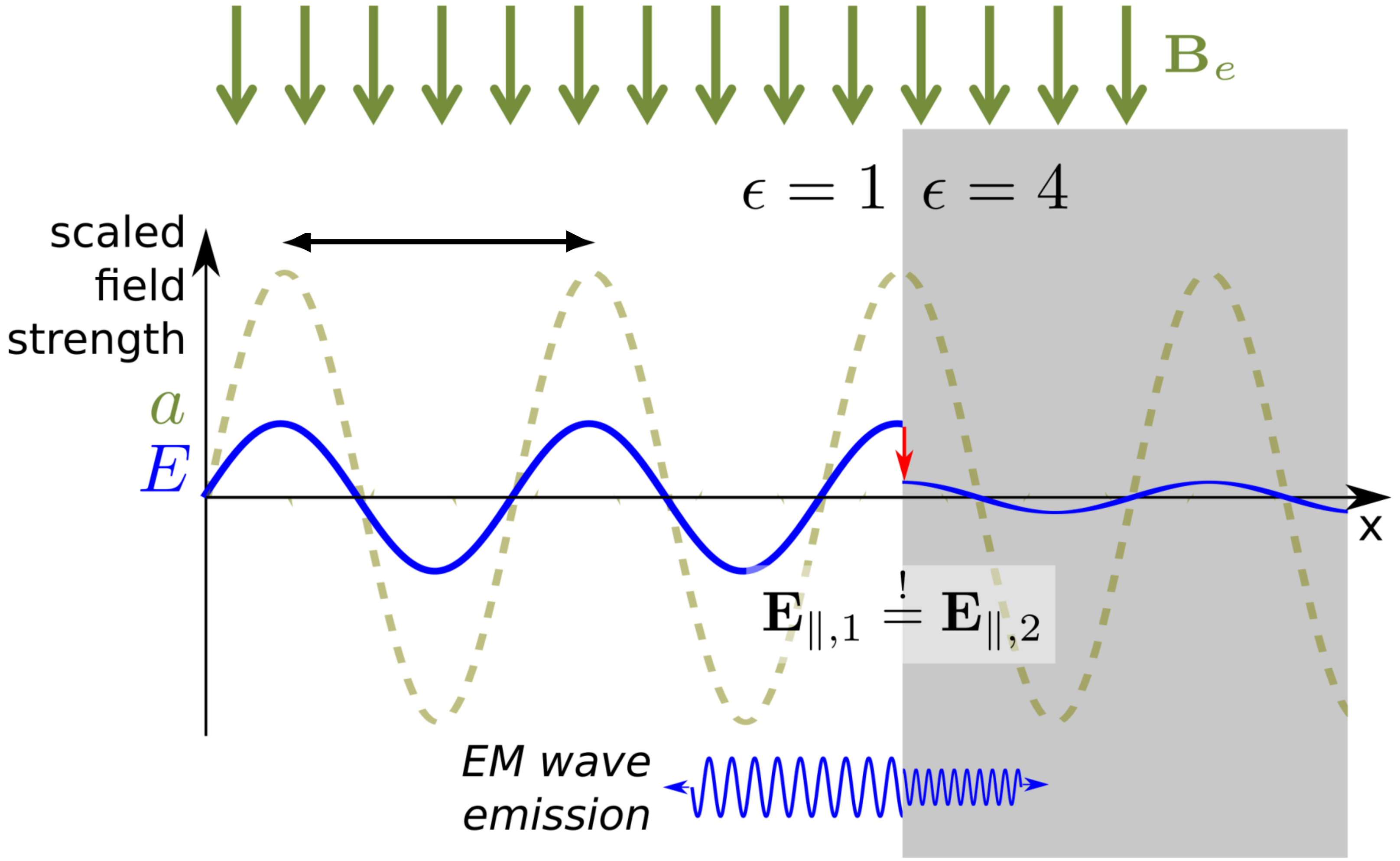
Axion to photon conversion
by **Primakoff effect**





Axions as a scalar classical field: $a(x,t)$

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

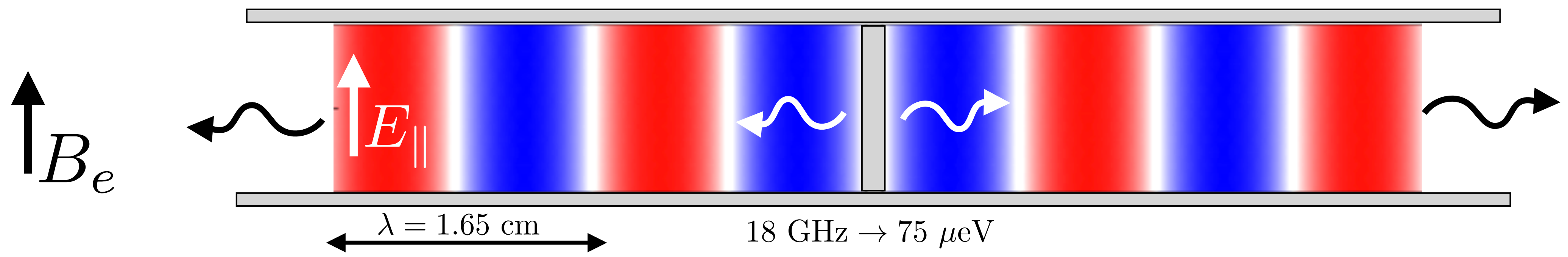


Emission of EM waves at the discontinuity

Dielectric haloscope principle

The 2D toy haloscope

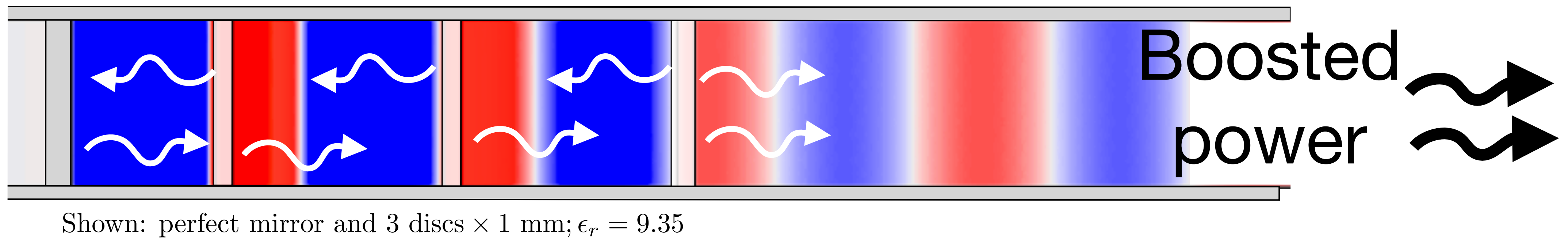
Emission from a perfect mirror



Tiny output power even for a high B-field and a large mirror:

$$P_{sig} = 2.2 \cdot 10^{-27} W \left(\frac{A}{1m^2}\right)\left(\frac{B_e}{10T}\right)^2 \left(\frac{g_{a\gamma}}{m_a}\right)^2$$

Emission from a booster



Output power boosted relative to the mirror emission:

$$P_{sig} = 2.2 \cdot 10^{-27} W \left(\frac{A}{1m^2}\right)\left(\frac{B_e}{10T}\right)^2 \left(\frac{g_{a\gamma}}{m_a}\right)^2 \beta^2$$

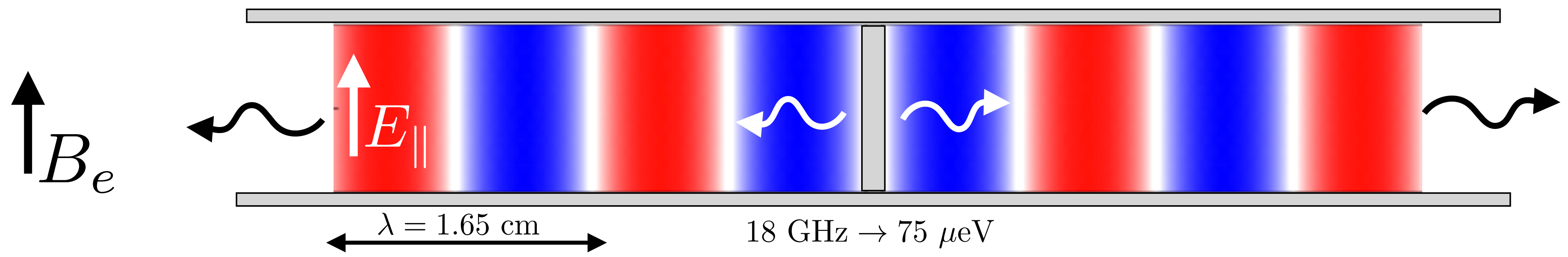
Power “Boost factor” β^2

$$\beta^2 = \frac{P_{booster}}{P_{mirror\ only}}$$

Dielectric haloscope principle

The 2D toy haloscope

Emission from a perfect mirror



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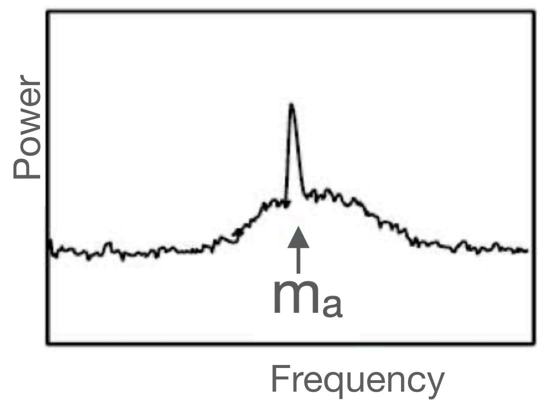
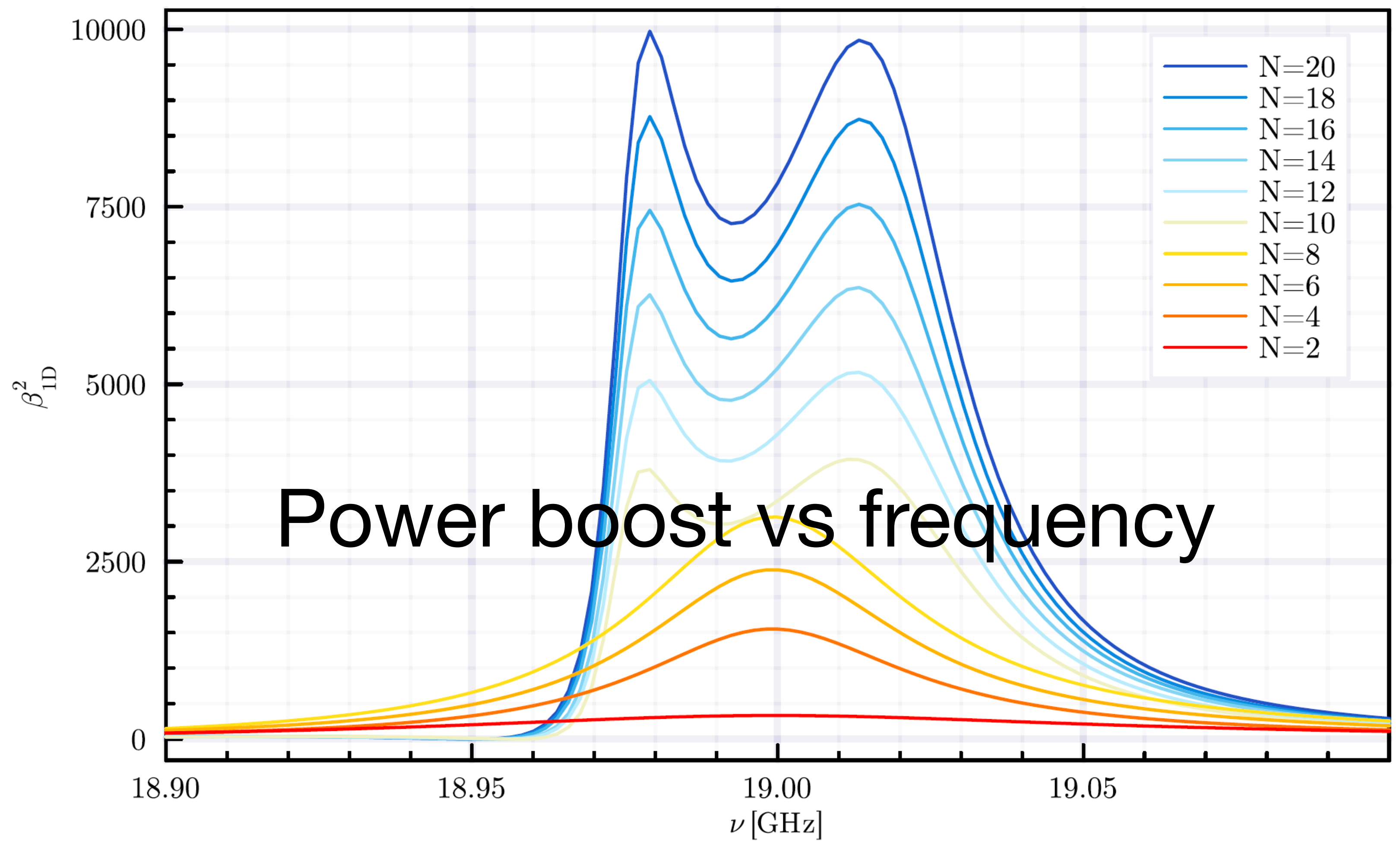
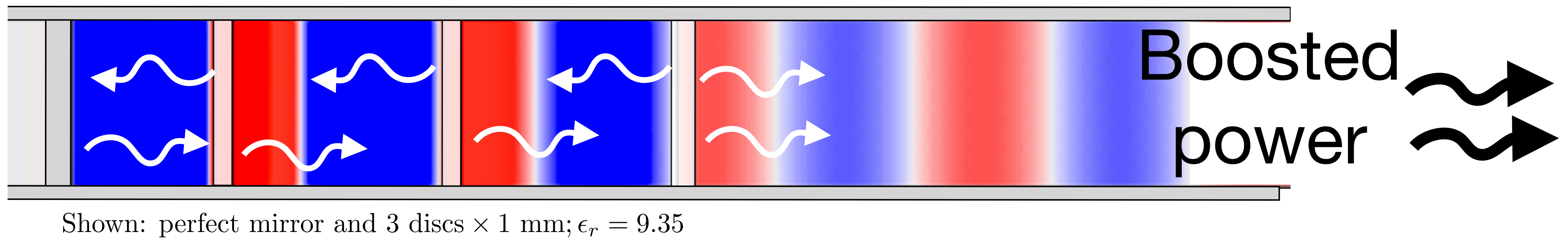




Emission from a booster



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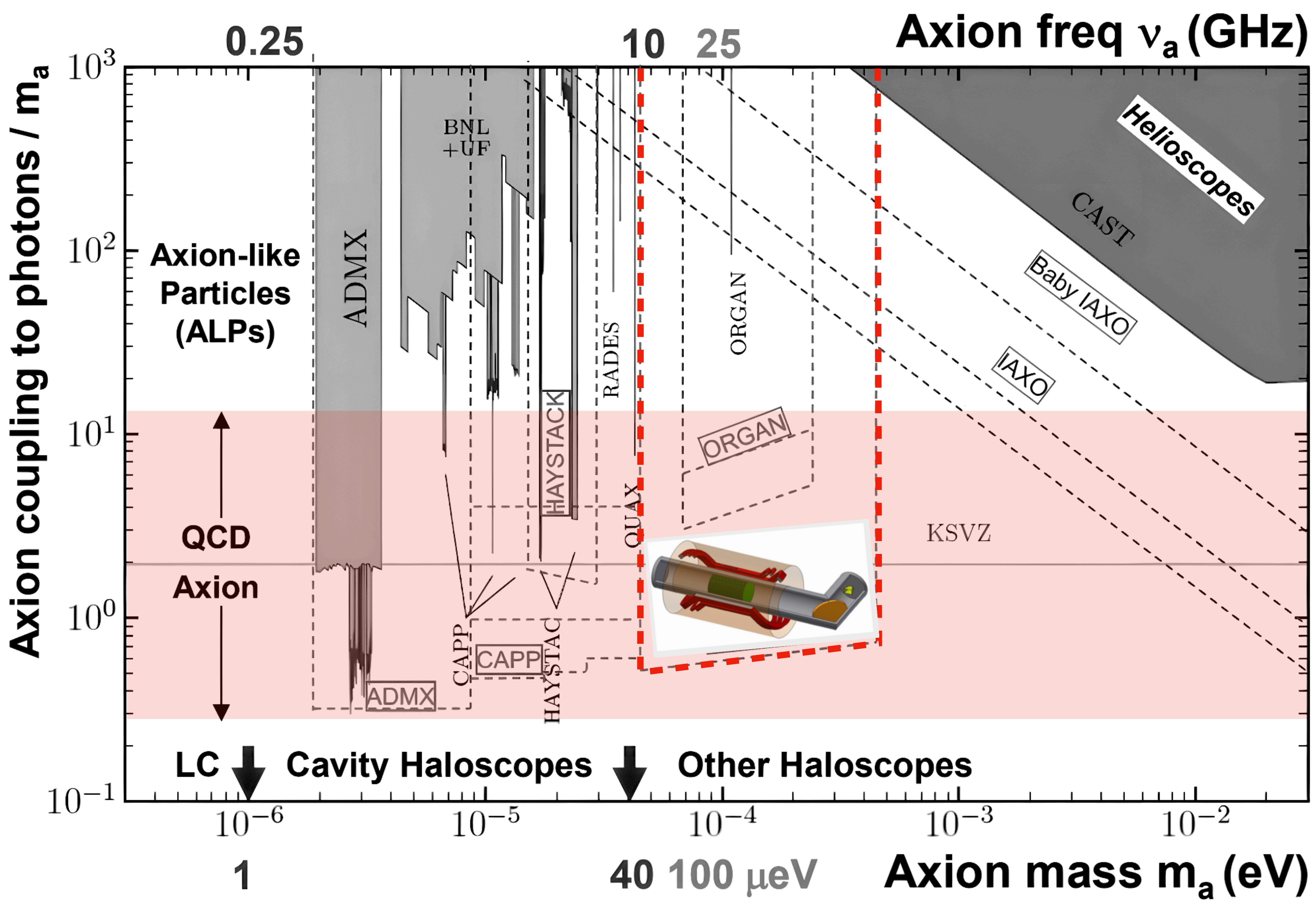
Power "Boost factor" β^2

$$\beta^2 = \frac{P_{booster}}{P_{mirror\ only}}$$

- Broad mass range and high boost possible
- Conversion volume and axion mass **decoupled**

Magnetized Disc and Mirror Axion experiment

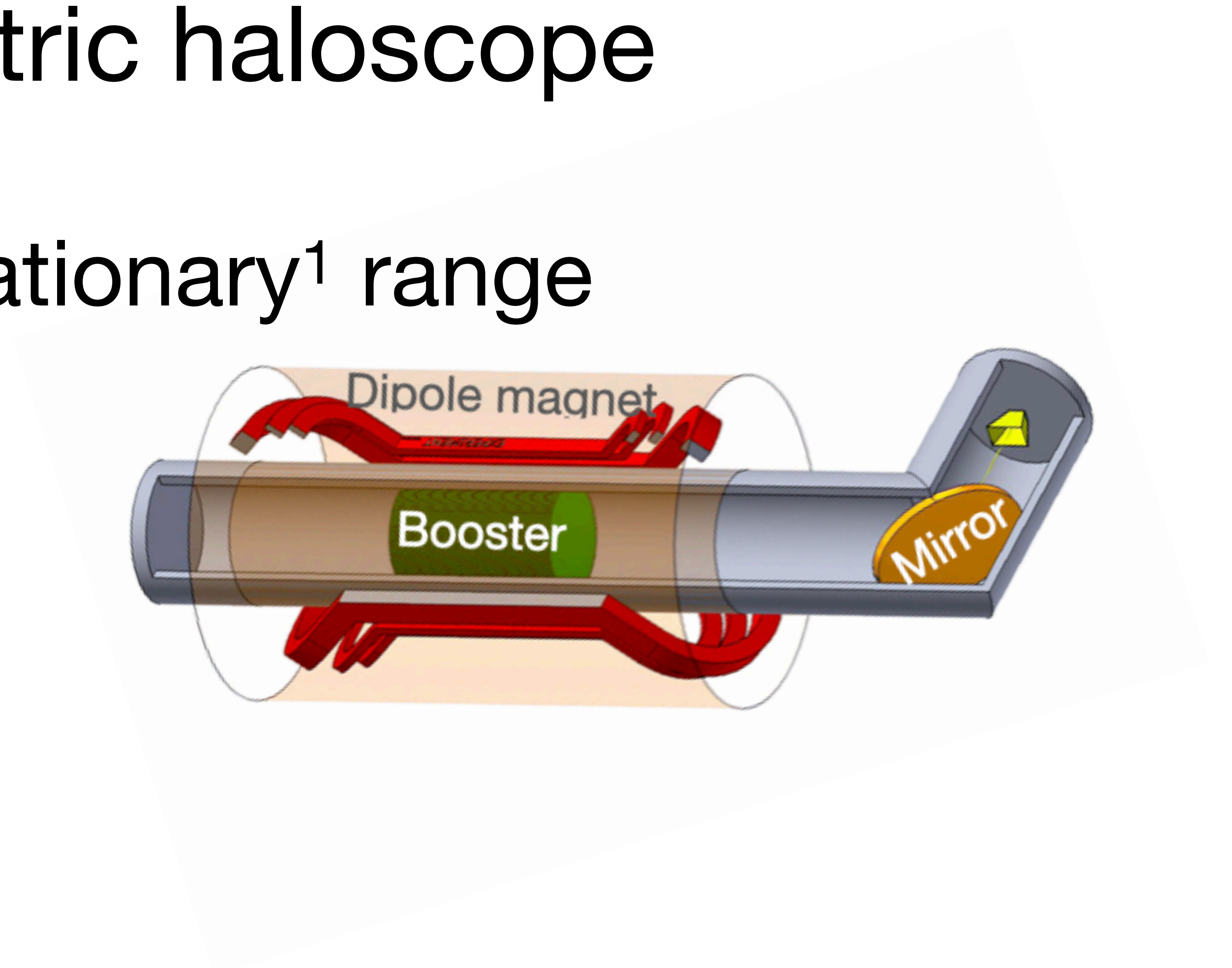
Goal and exciting developments of MADMAX



$$g_{a\gamma} \approx 2\cdot 10^{-14}\,\mathrm{GeV}^{-1} \left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_a}\right)^{1/2} \left(\frac{10^5}{\beta^2}\right)^{1/2} \left(\frac{1\,\mathrm{m}^2}{A}\right)^{1/2} \left(\frac{T_{sys}}{8\,\mathrm{K}}\right)^{1/2} \left(\frac{10\,\mathrm{T}}{B_e}\right) \left(\frac{1.3\,\mathrm{d}}{\tau}\right)^{1/4} \left(\frac{SNR}{5}\right)^{1/2} \left(\frac{m_a}{100\,\mu\mathrm{eV}}\right)^{5/4}$$

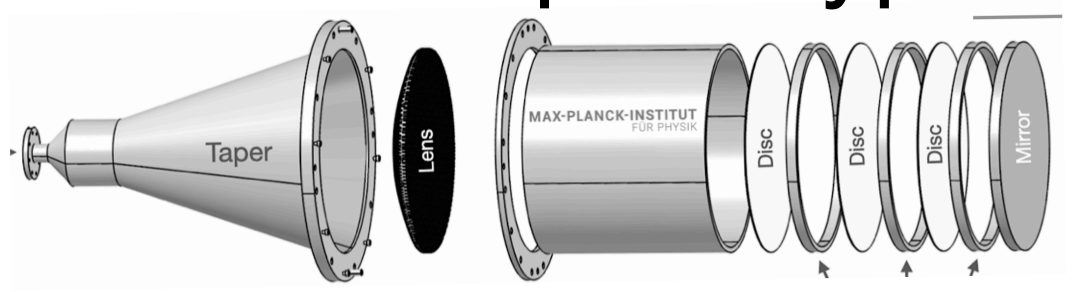
Goal: Tunable dielectric haloscope

- Aimed at QCD and Post-inflationary[1] range
- 40-400 μeV or 10-100 GHz
- Many discs of 1 m^2
- T_{sys} = 8 K and B_e = 9 T

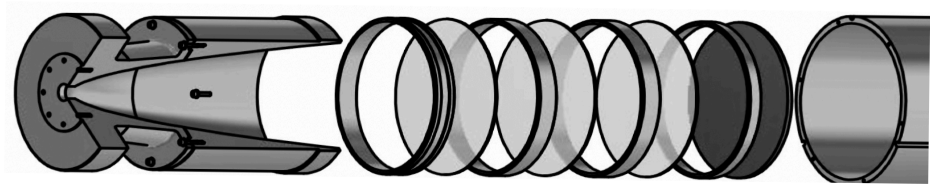


First axion search at CERN 2024

200 mm prototype



100 mm prototype



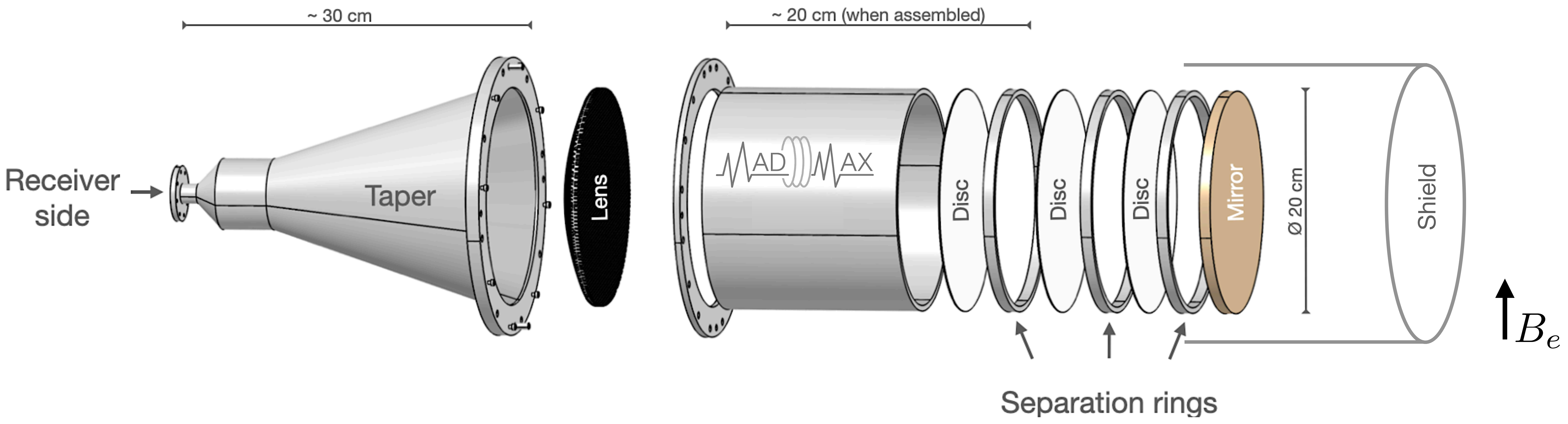
- Demonstrate tuning
- Control unwanted modes
- Receiver in noisy environment
- Physics with expected sensitivity beyond CAST
- Cold operation

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

The CB 200 booster prototype

200 mm closed dielectric haloscope booster

- Works at 290 K
- 74 to 87 μeV depending on the disc separation
- $\beta^2 \sim 2000$
- Shielded from RFI



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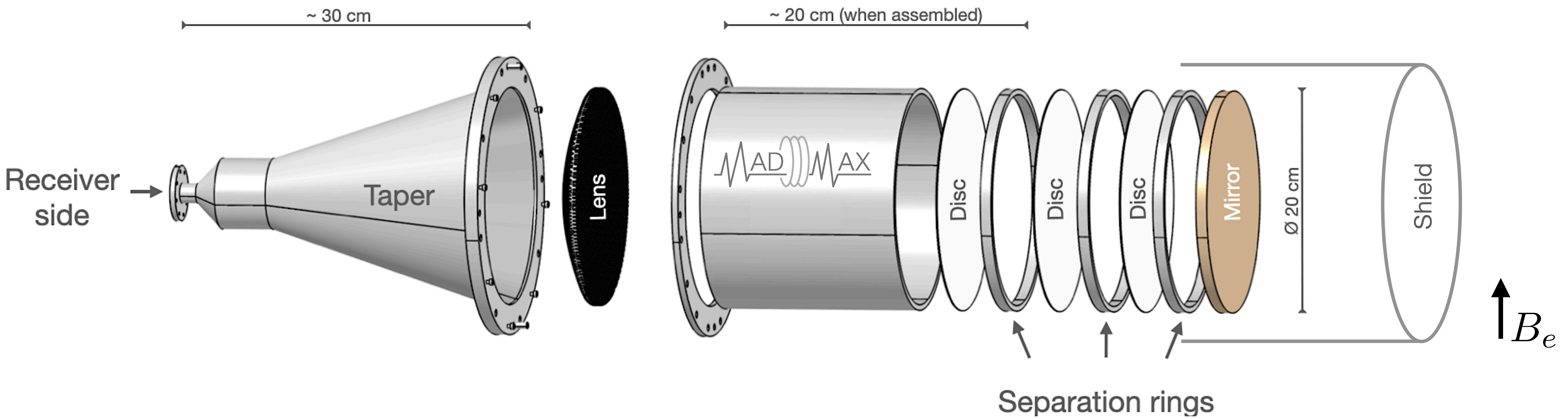
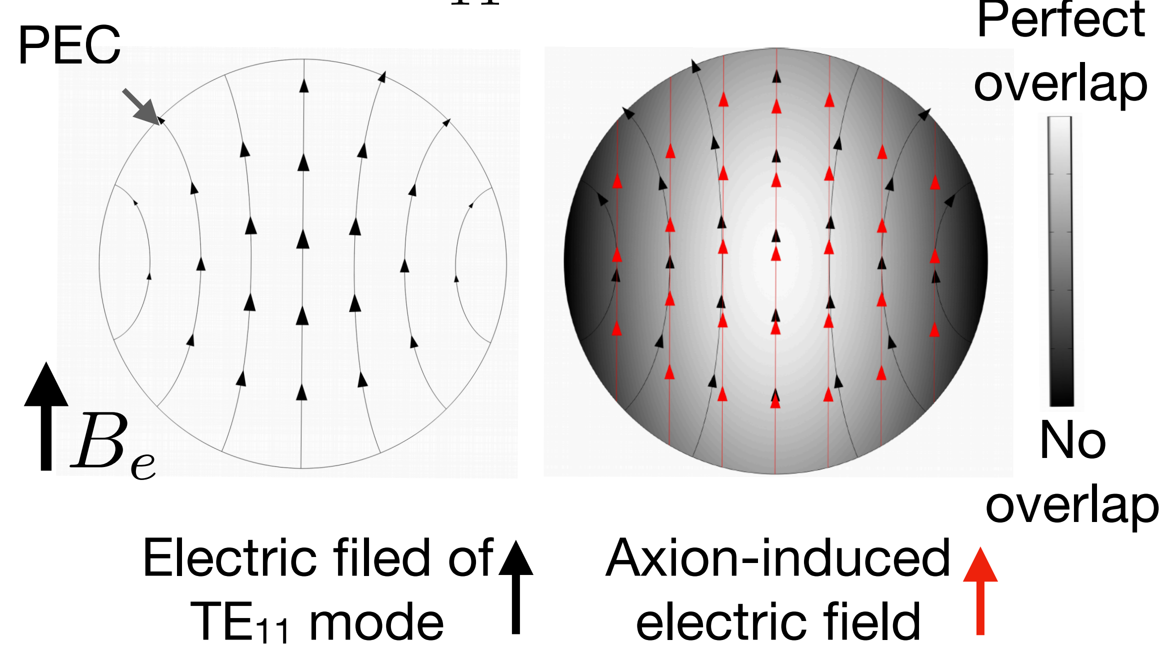
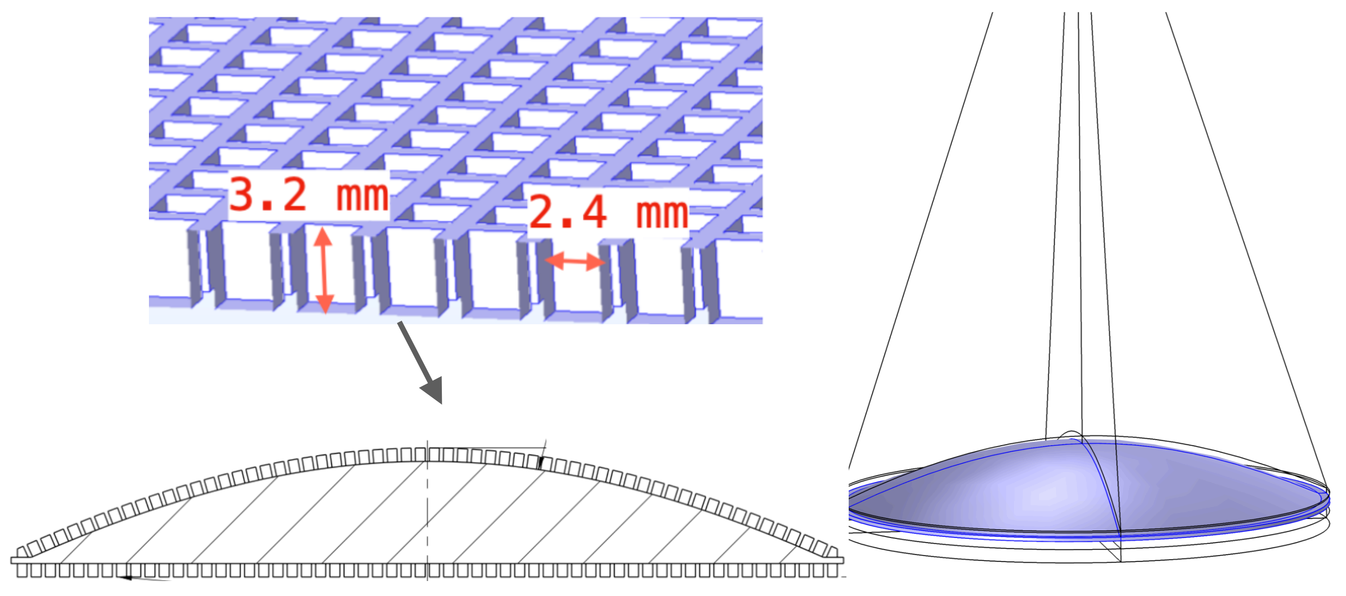


Cylindrical wave emitted
~84% power extracted

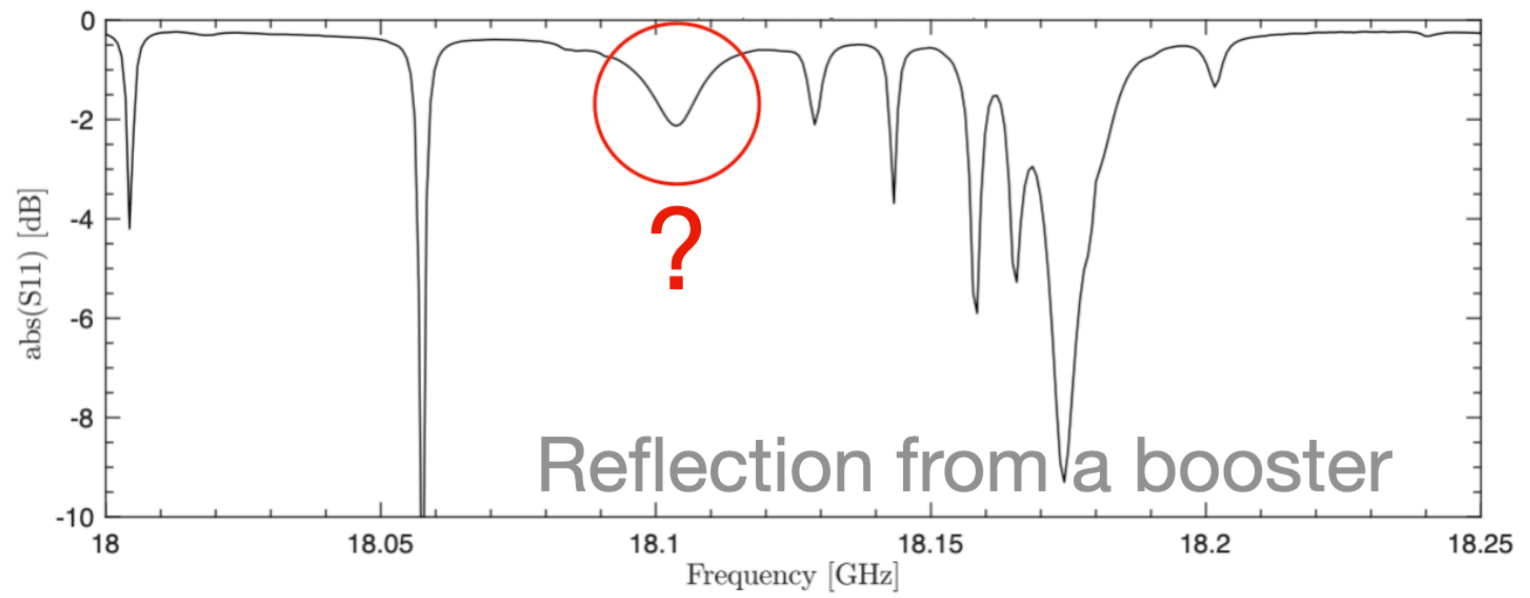
$$\beta^2_{TE_{11}} = 0.84\beta^2_{1D}$$



Optimised coupling
compact taper with **dielectric lens**

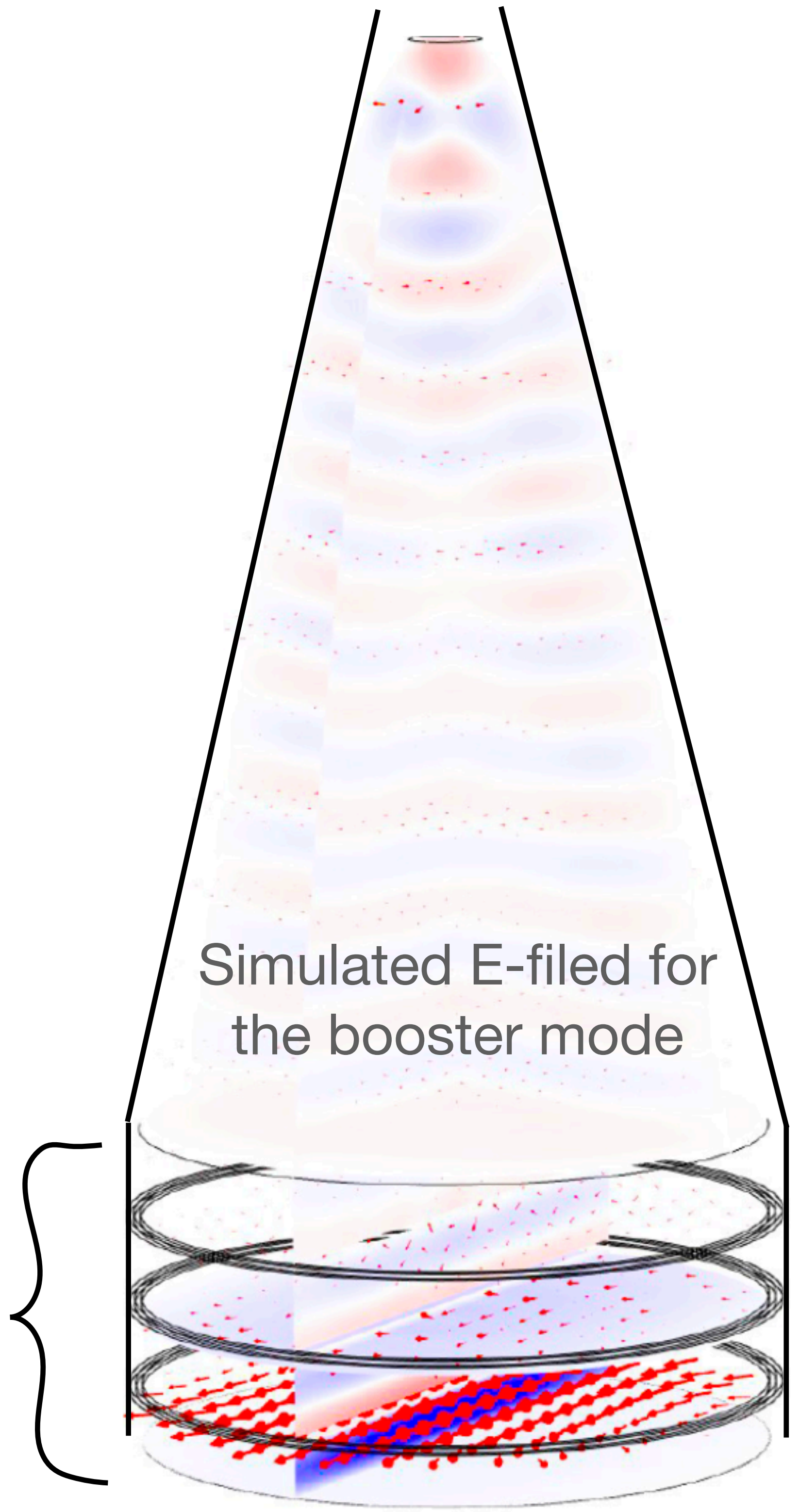


Challenge:
Over-moded spectrum



Tuning into the axion radio

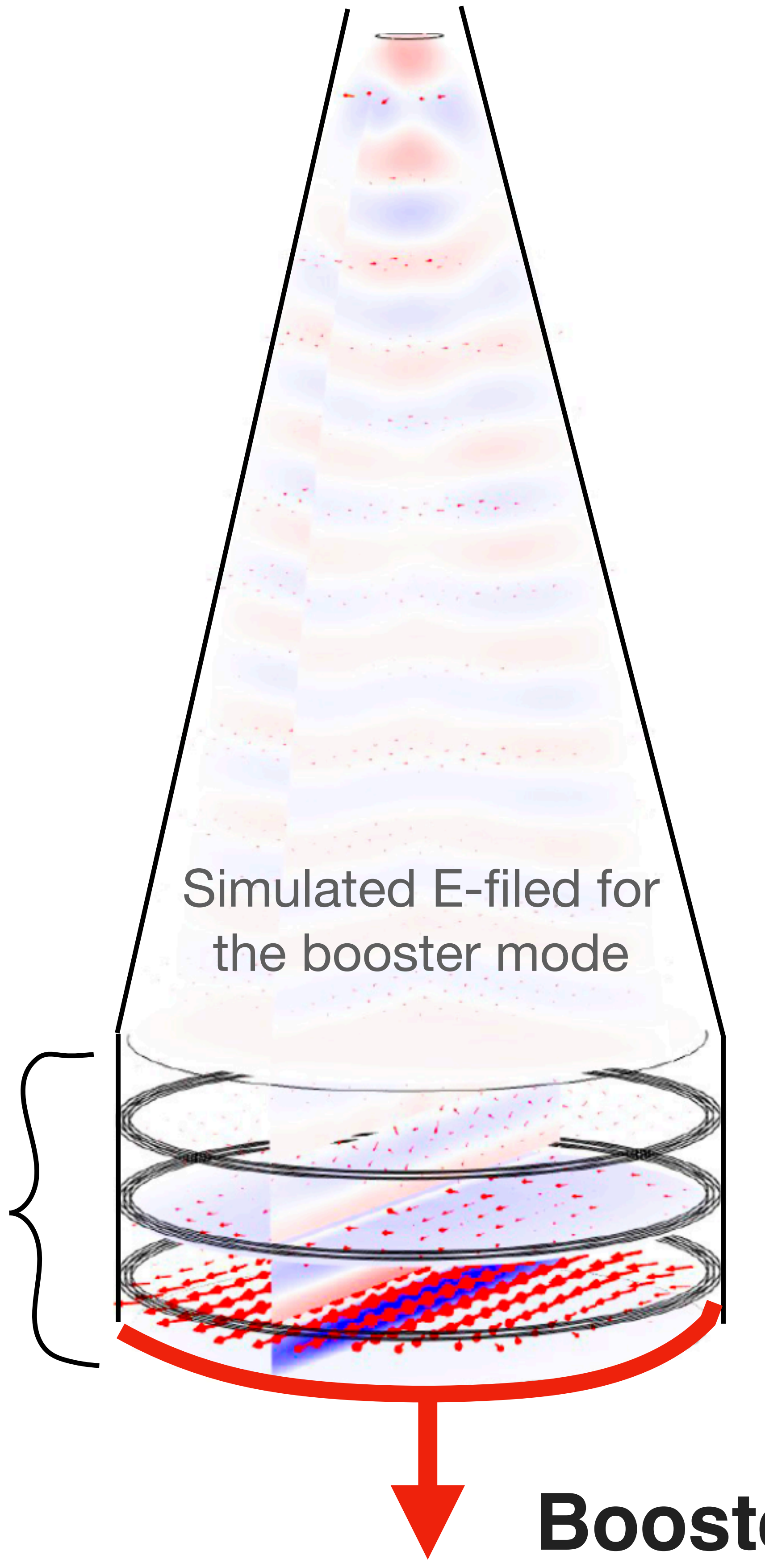
How to tune the booster frequency?



Set of rings defines the **booster frequency:** 18 to 21 GHz

Tuning into the axion radio

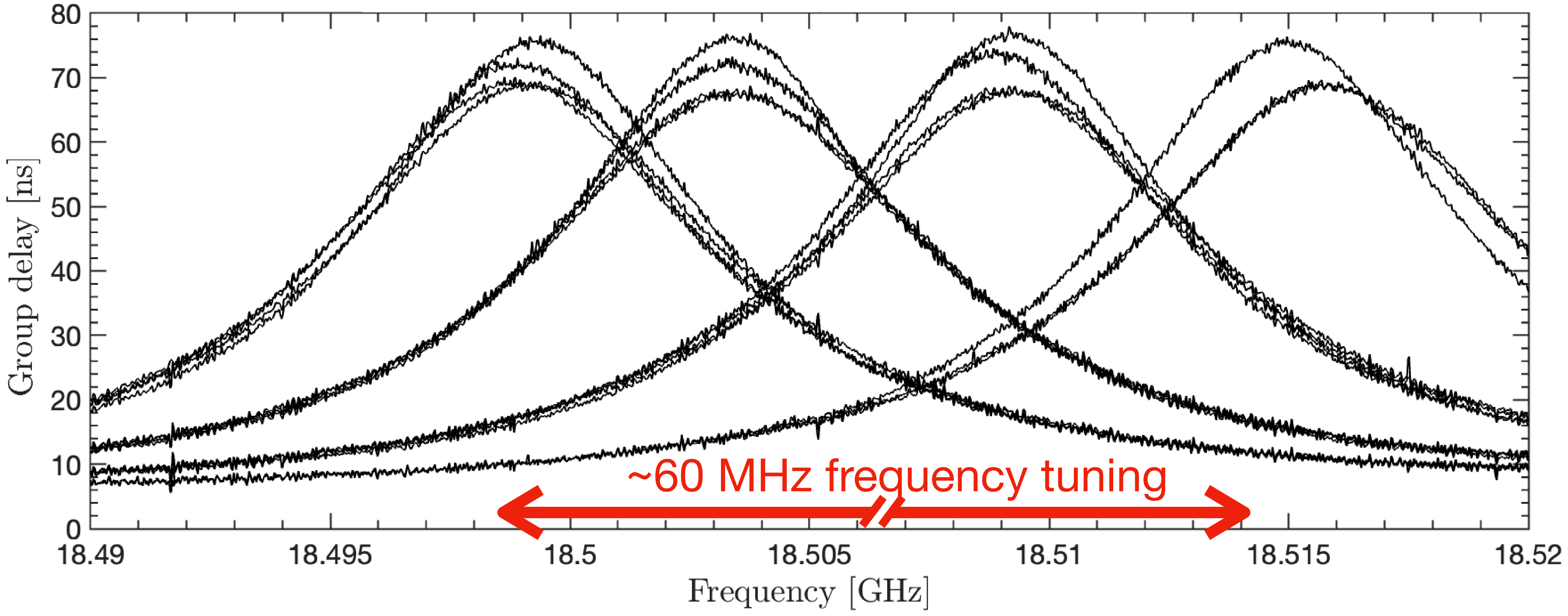
How to tune the booster frequency?



Set of rings defines the **booster frequency:** 18 to 21 GHz

Booster mode sensitive to mirror offset

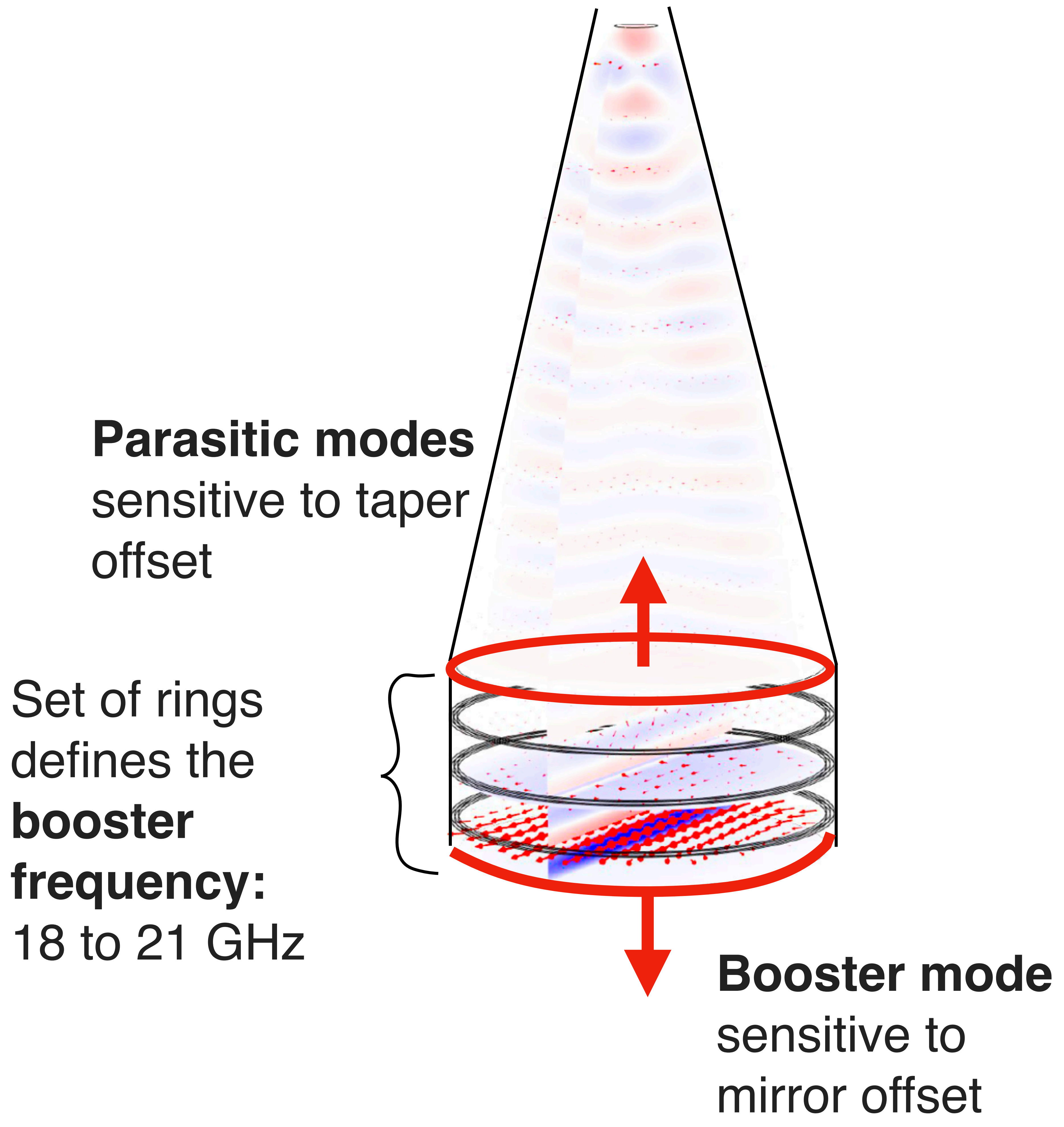
Measured Group delay vs mirror offset



Fine frequency **tuning possible** for booster configurations: 18 to 21 GHz

Tuning into the axion radio

How to avoid mode-crossing?

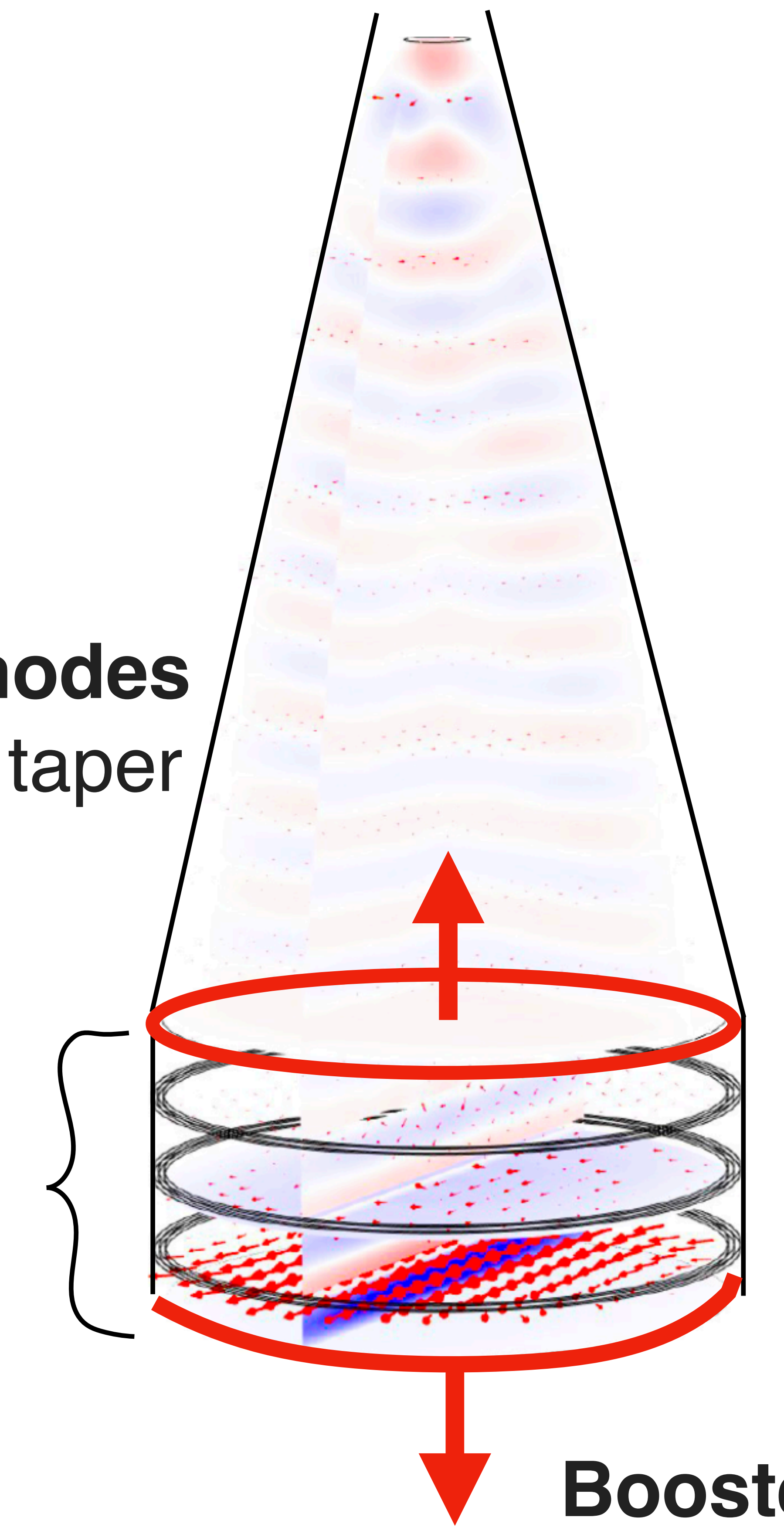


Tuning into the axion radio

How to avoid mode-crossing?

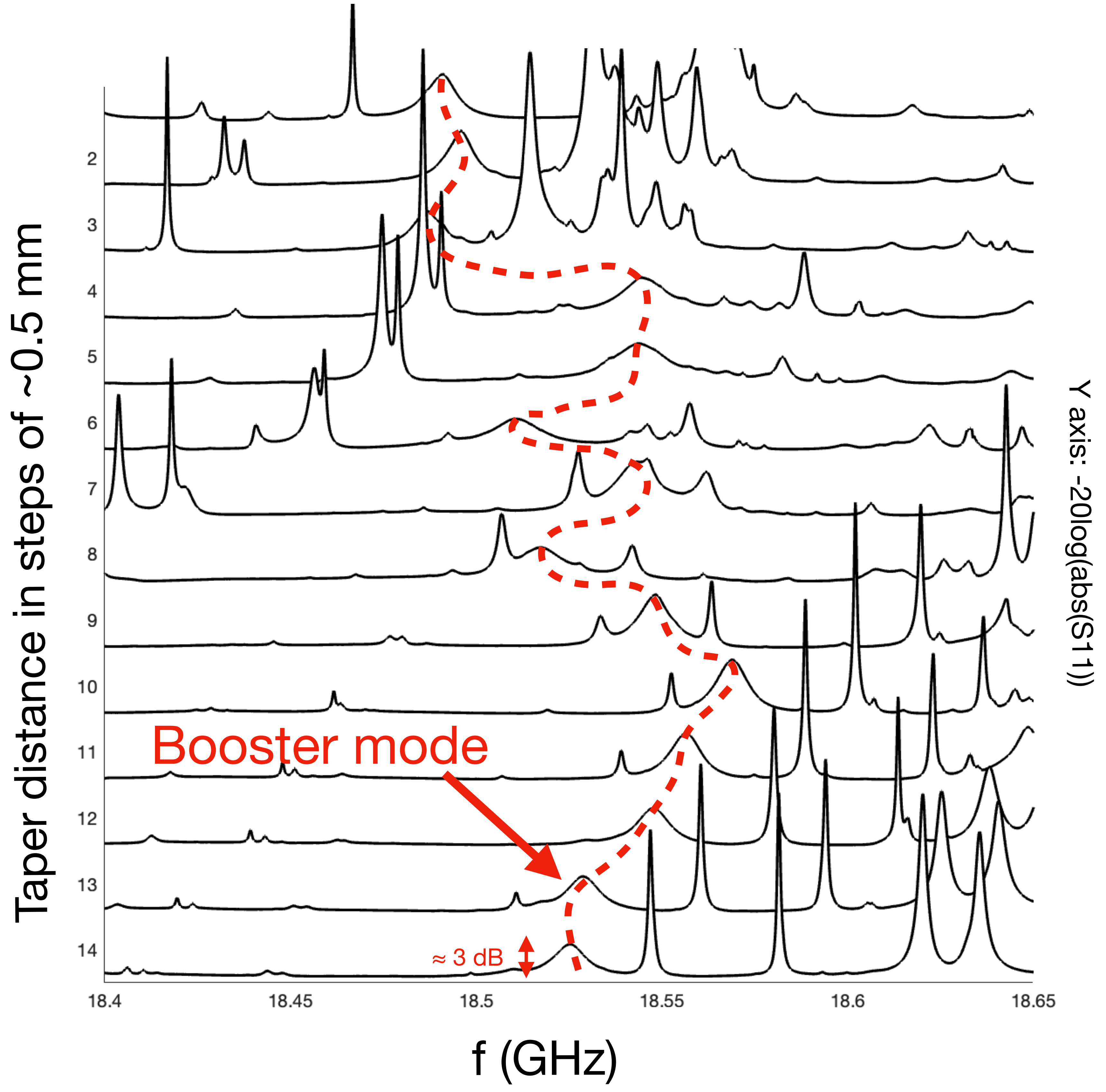
Parasitic modes sensitive to taper offset

Set of rings defines the **booster frequency:** 18 to 21 GHz



Booster mode sensitive to mirror offset

Measured reflectivity spectra



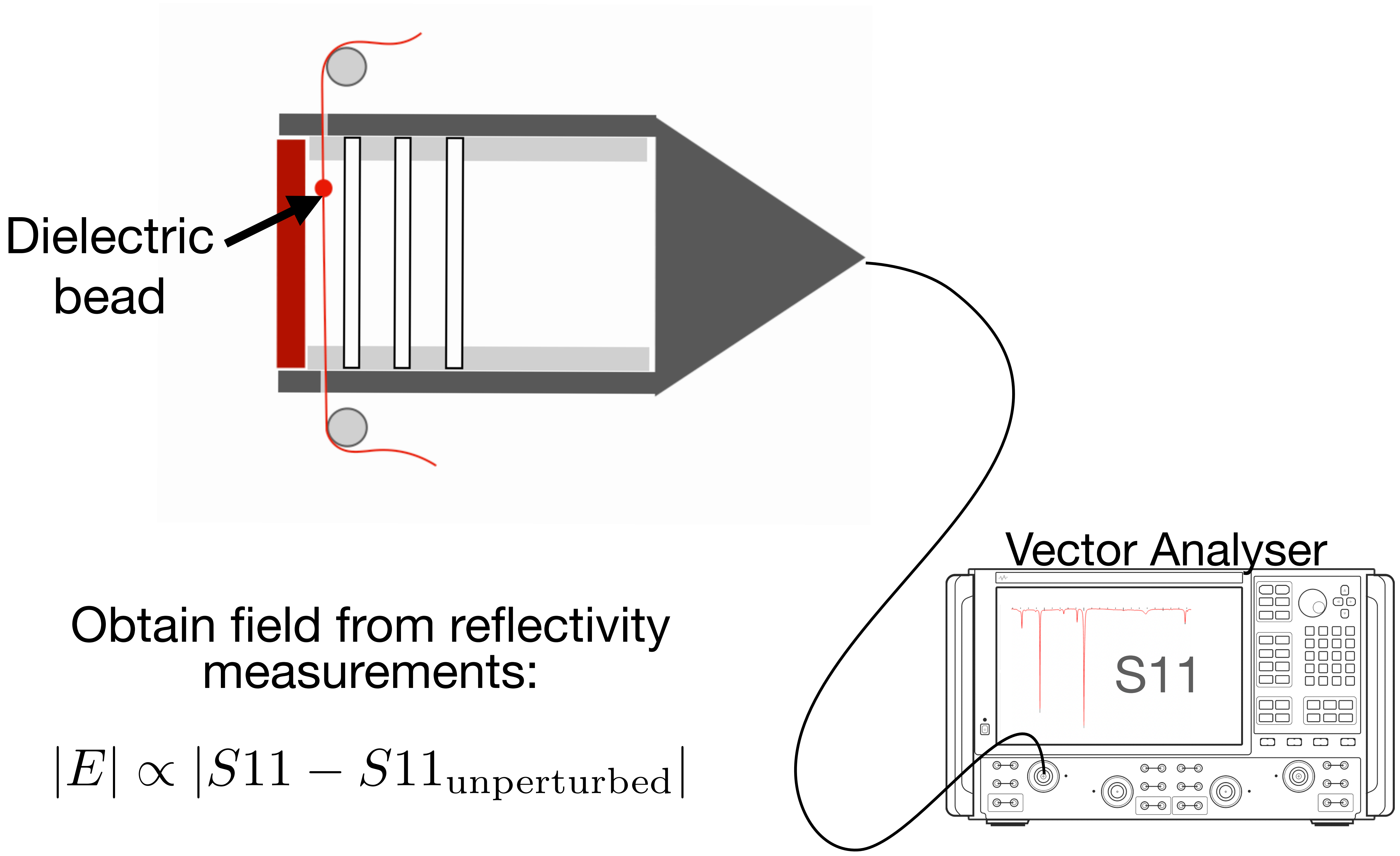
Tuning knobs:

- **Booster mode** controlled by mirror offset
- **Parasitic modes** (most) controlled by taper offset

Verifying the field distribution

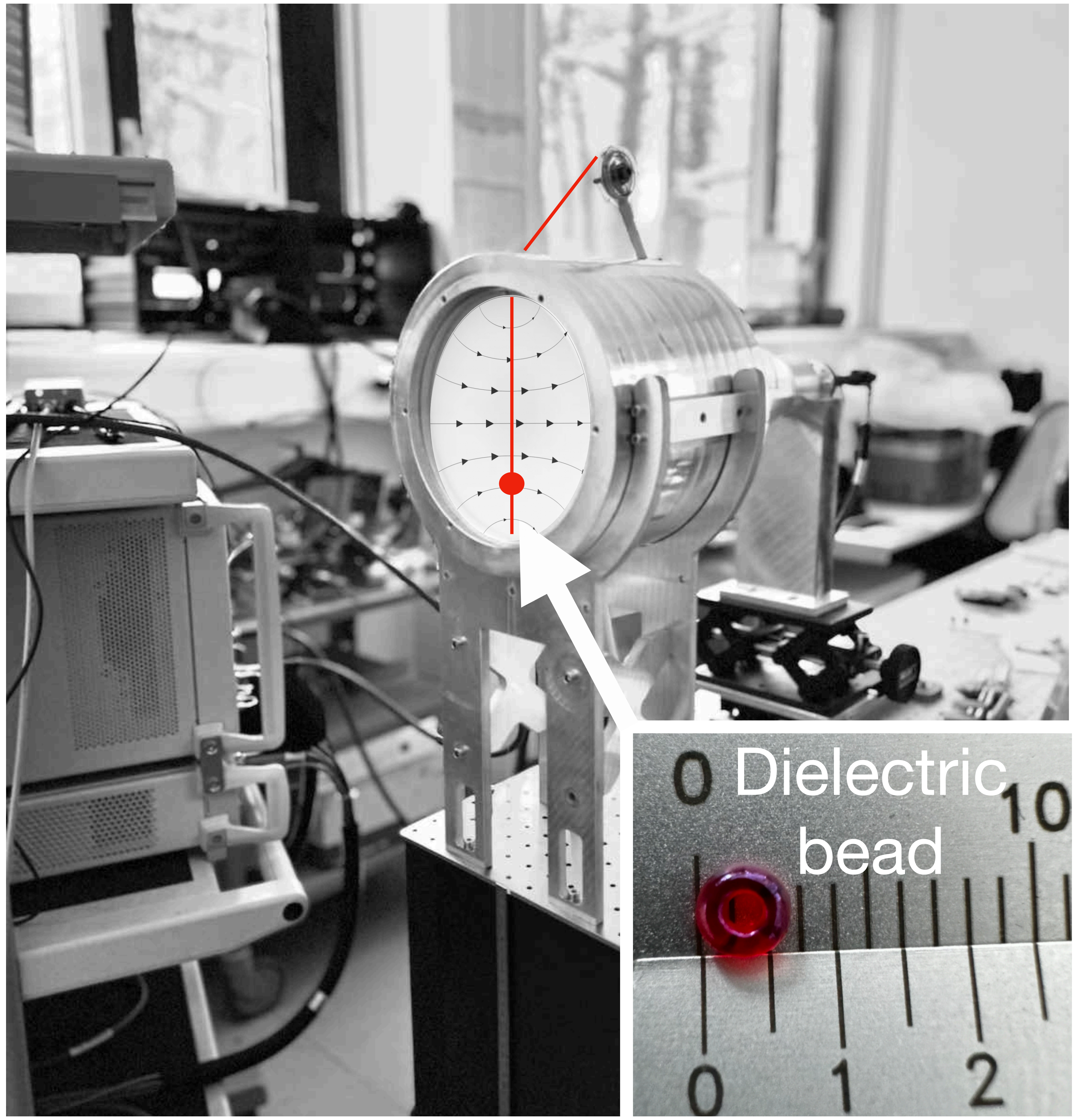
Field measurement setup

Perturbation-based (bead-pull) field measurement setup



Obtain field from reflectivity measurements:

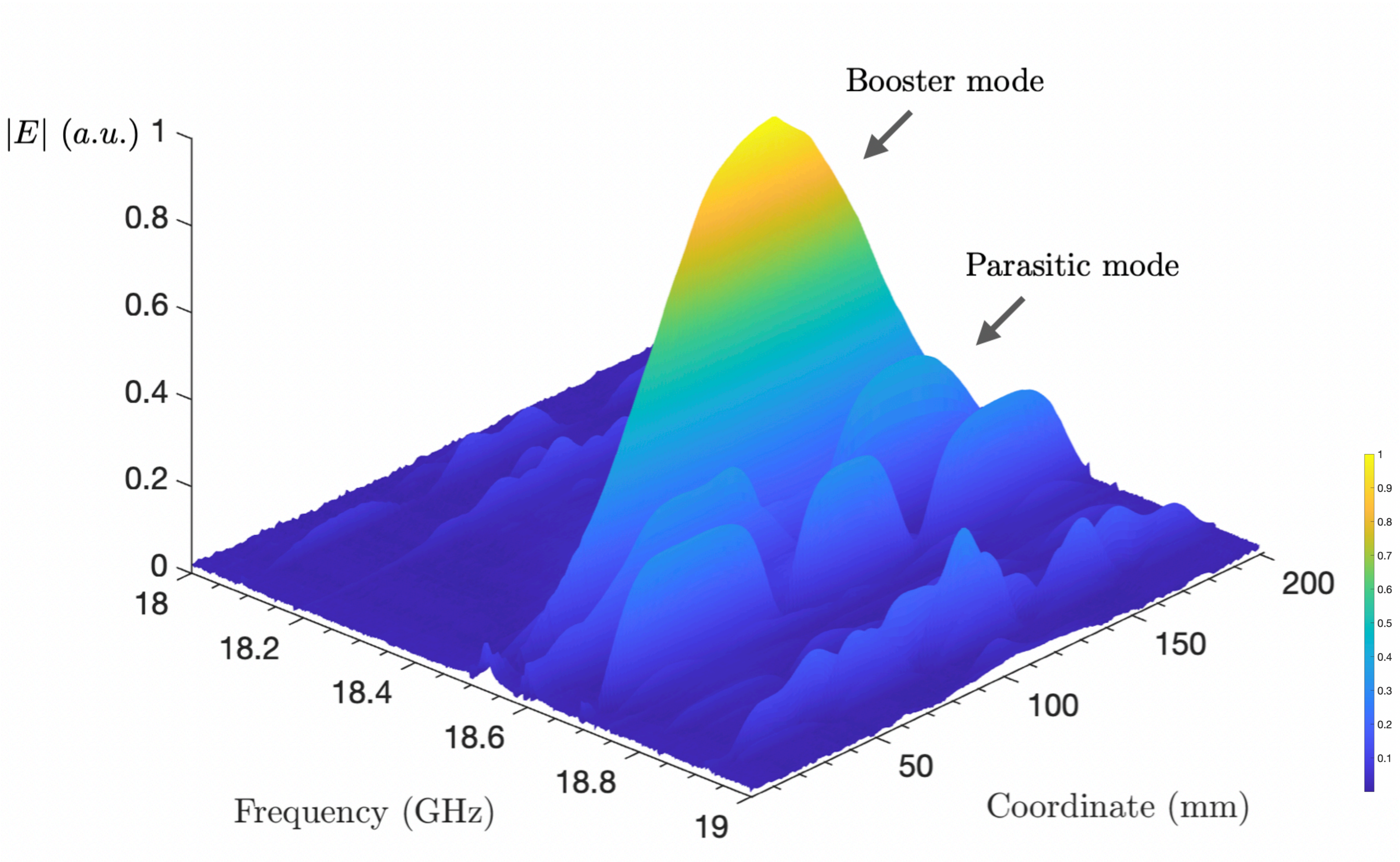
$$|E| \propto |S11 - S11_{\text{unperturbed}}|$$



Verifying the field distribution

Field distribution inside the closed booster

Measured electric field vs frequency

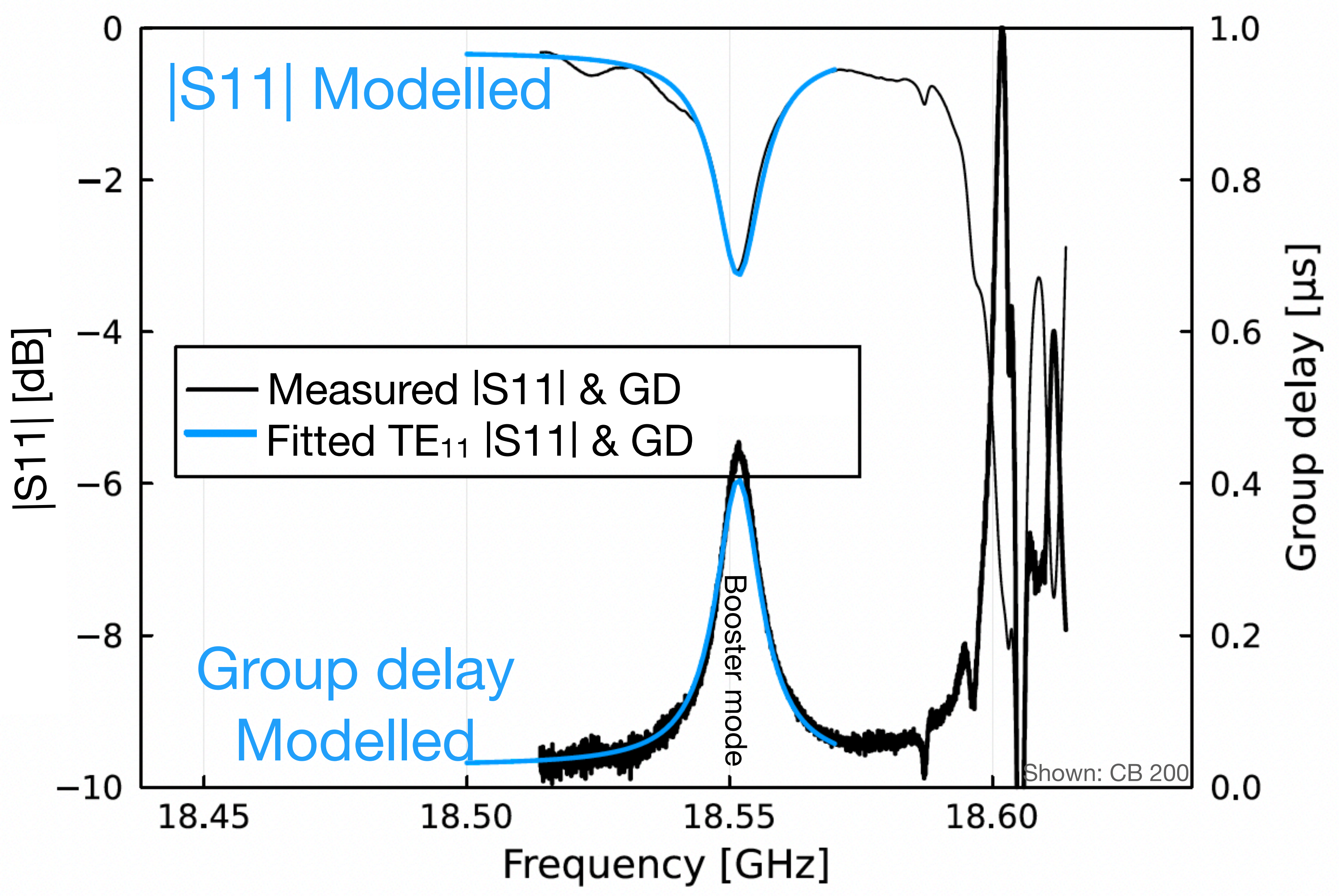


- Booster mode verified
- Parasitic modes easy to identify
- Confirmed for configurations in the range: ~ 18 to 21 GHz

Boost factor determination

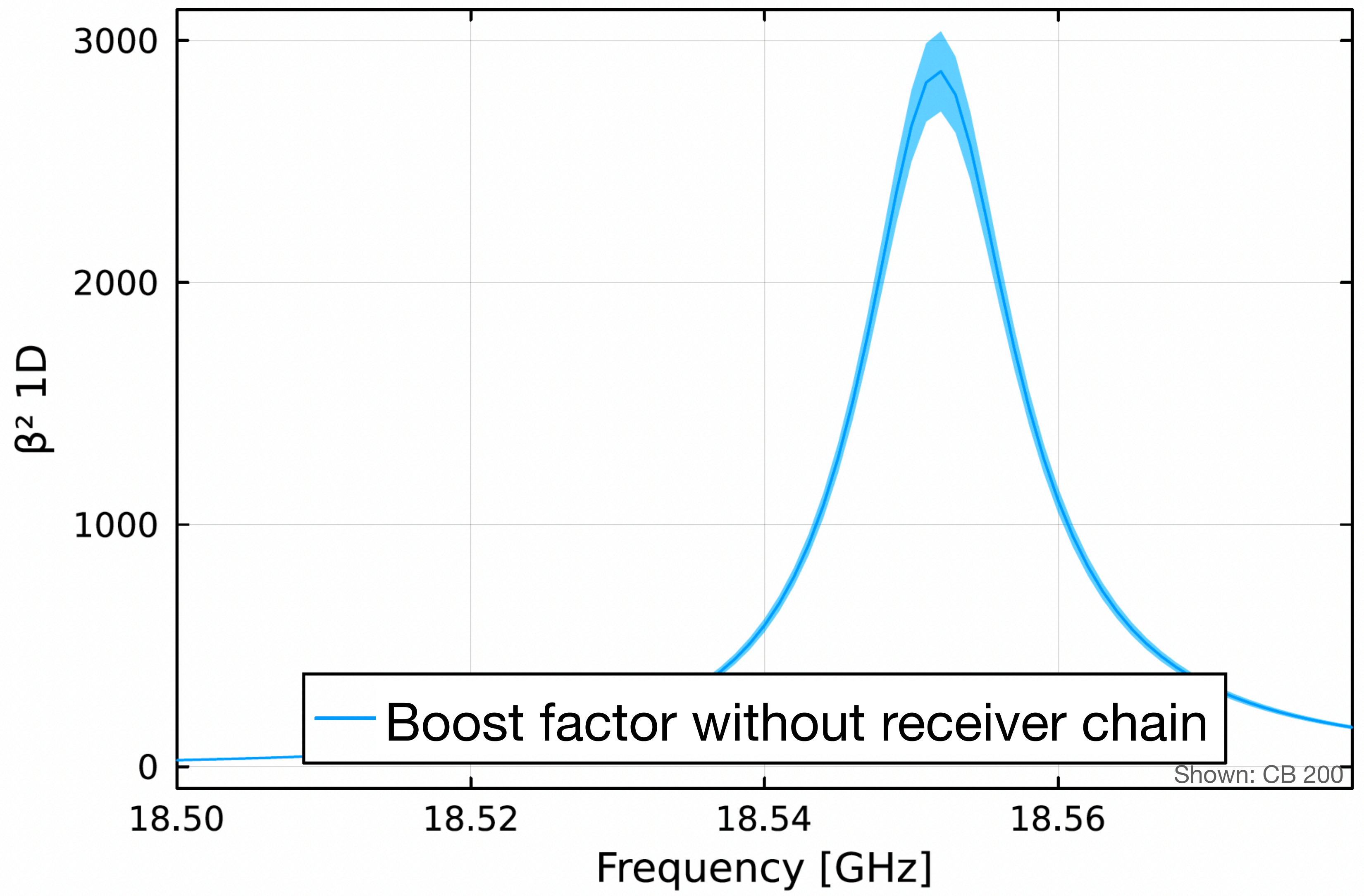
Using reflectivity and noise to obtain the boost factor of closed boosters

1. Fitting the reflectivity measurement with a 1D wave-propagation model



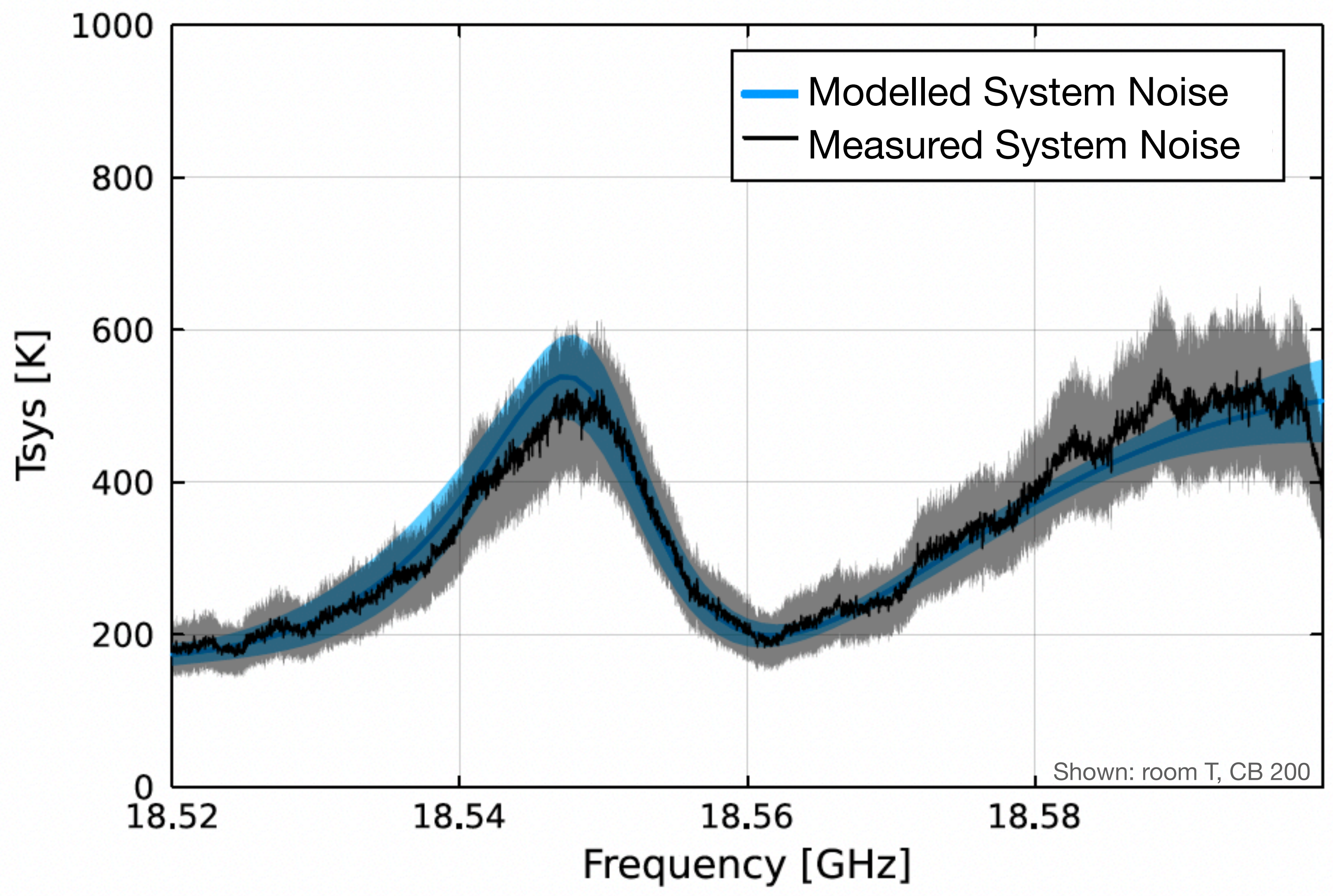
- Requires geometry and material constants; VNA response
- Can confirm in simulations

2. Obtaining boost factor from the fitted 1D wave propagation model



- External excitation predicts the axion induced excitation (at the port of the booster)

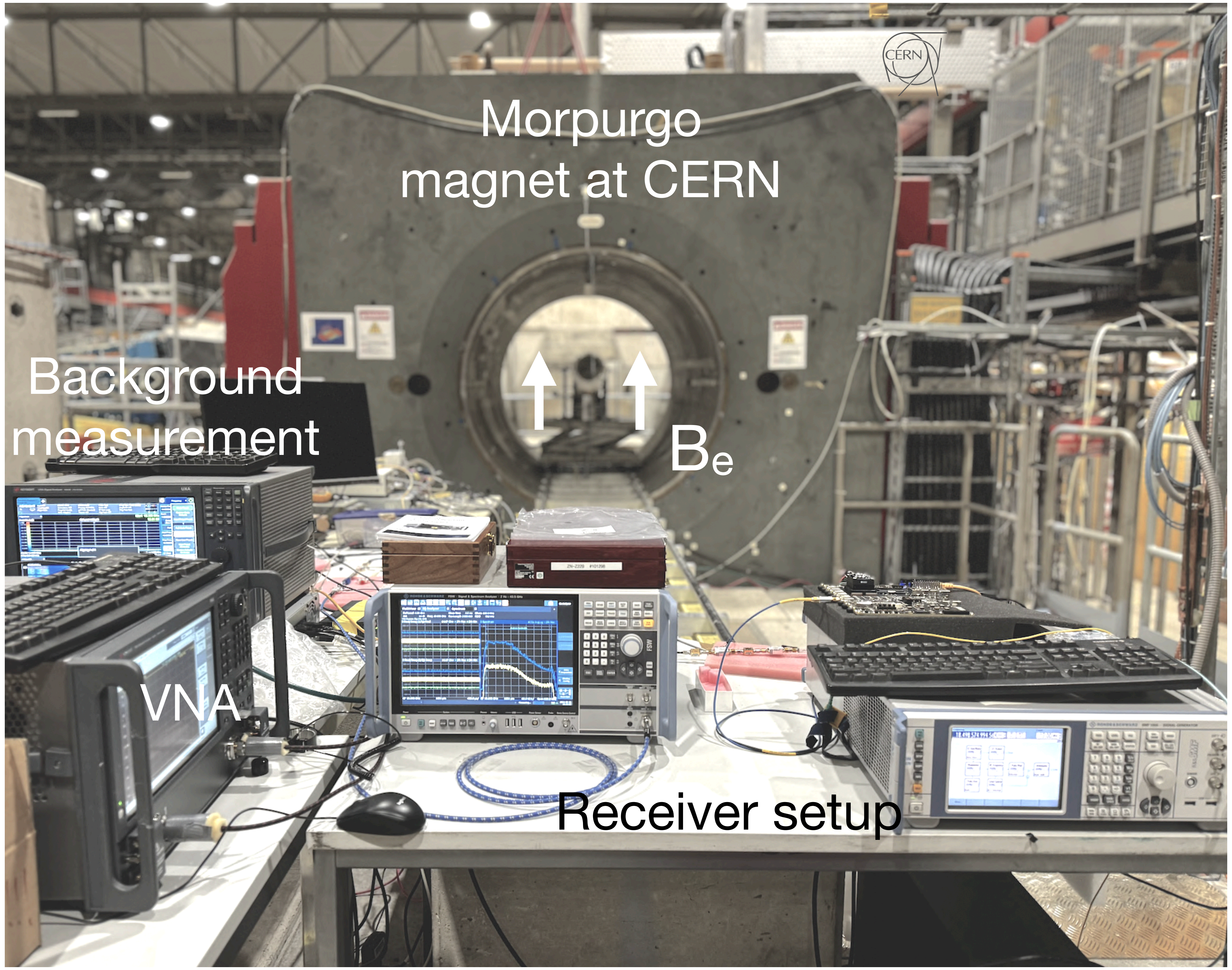
3 Including receiver chain systematics by fitting a Noise Model



- 1D model combined to NM
- LNA Added: NM; impedance, length and power calibration
- System Noise T useful metric during long runs

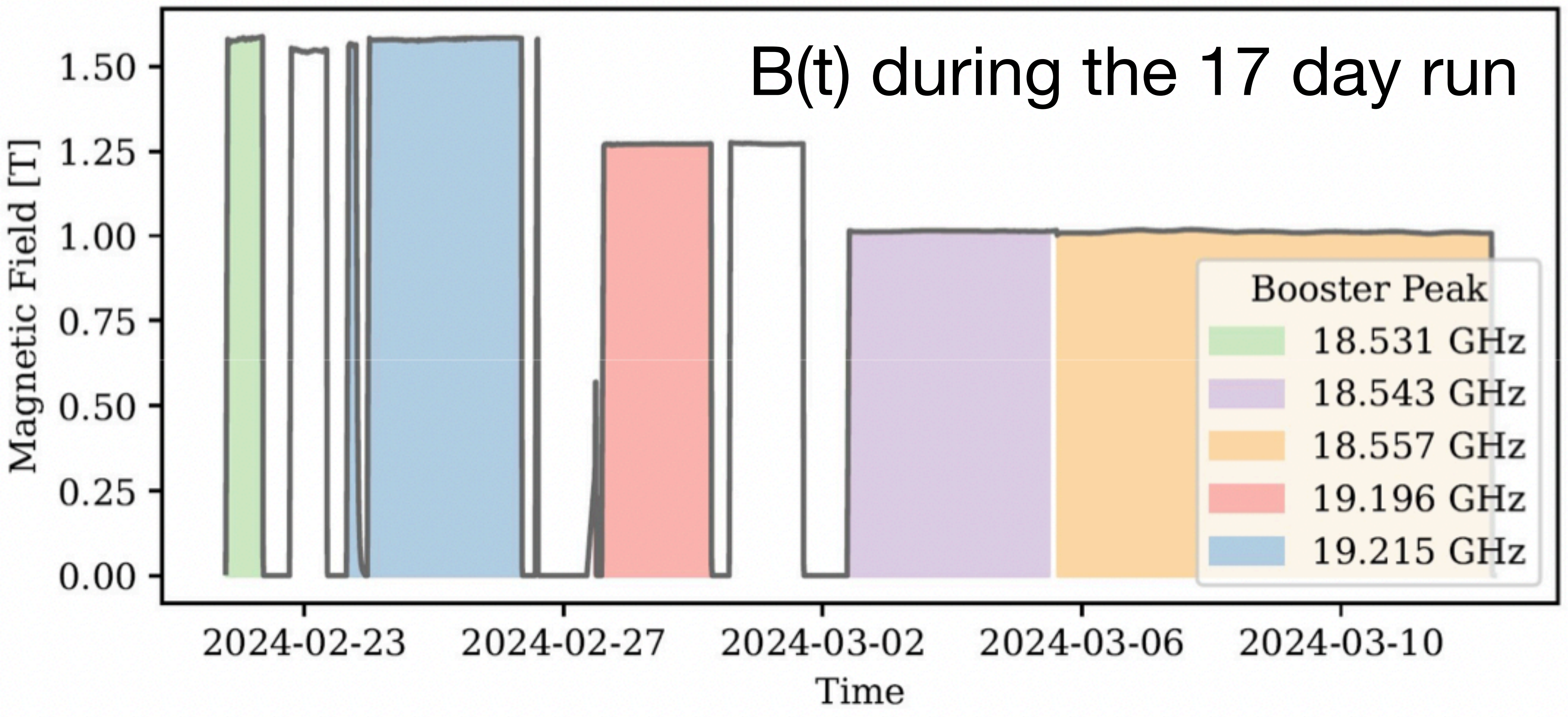
Physics with CB 200

Room temperature axion search using CERN's MORPURGO magnet



17-day physics run at MORPURGO:

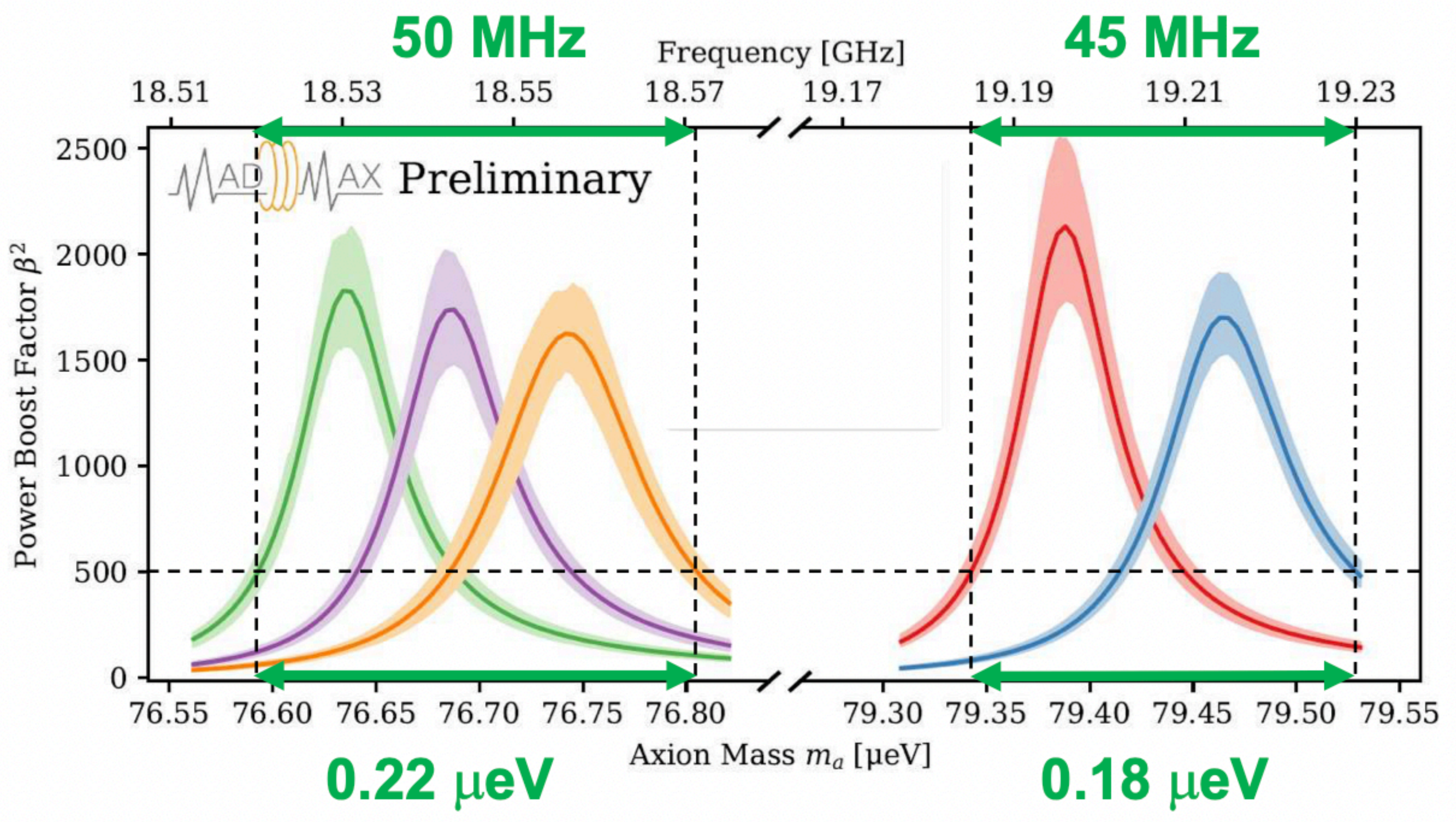
- 5 booster configurations
- ≈18.5 and ≈19.2 GHz under B-field
- Tuned manually
- Operation at room T



Physics with CB 200

Finalising data analysis

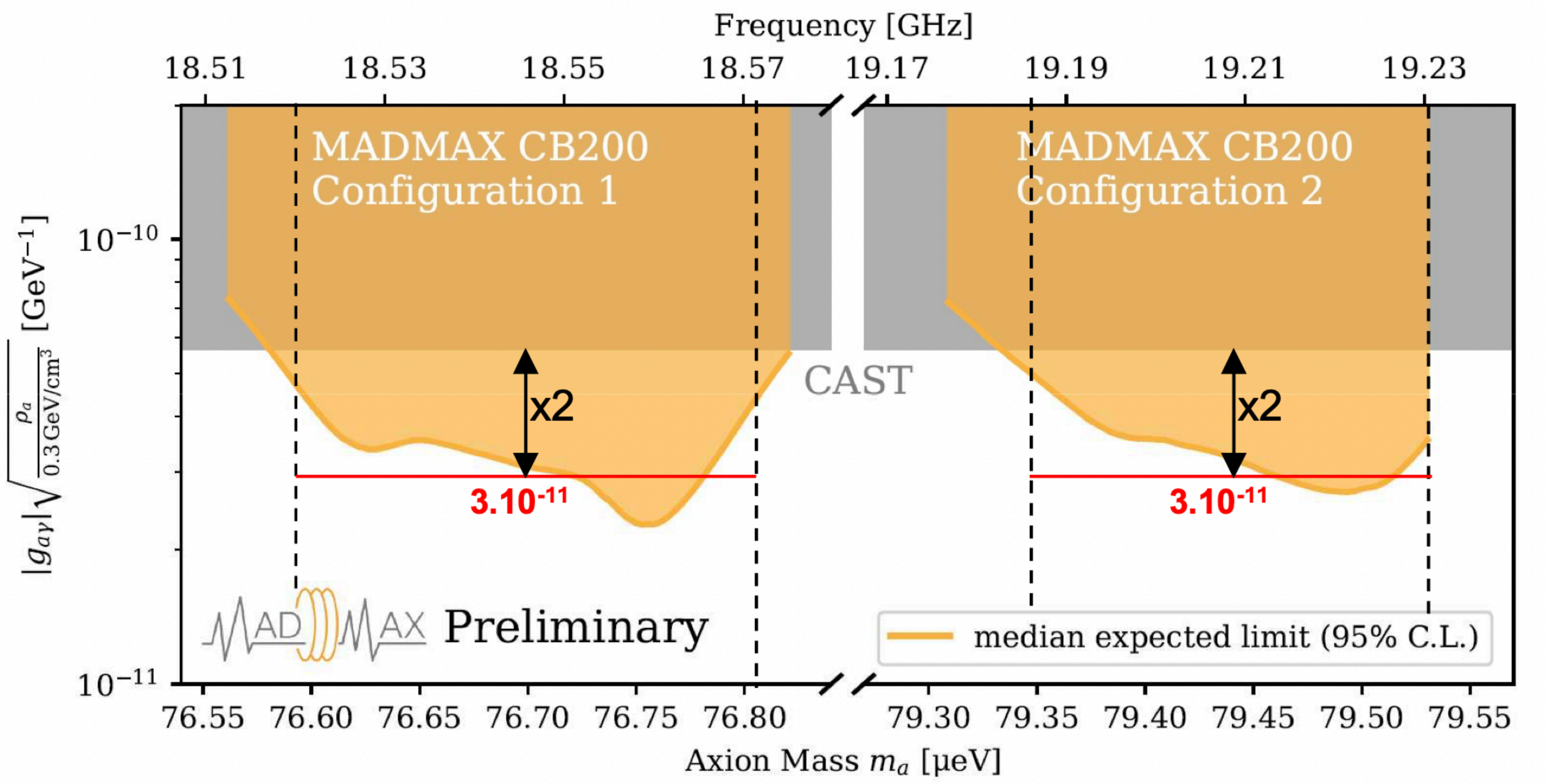
Obtained boost factors for 5 configurations including systematics (± 15%)



$\beta^2 > 500$ —> expected sensitivity: below CAST limit for scan of ≈ 100 MHz

Preliminary sensitivity

data analysis ongoing

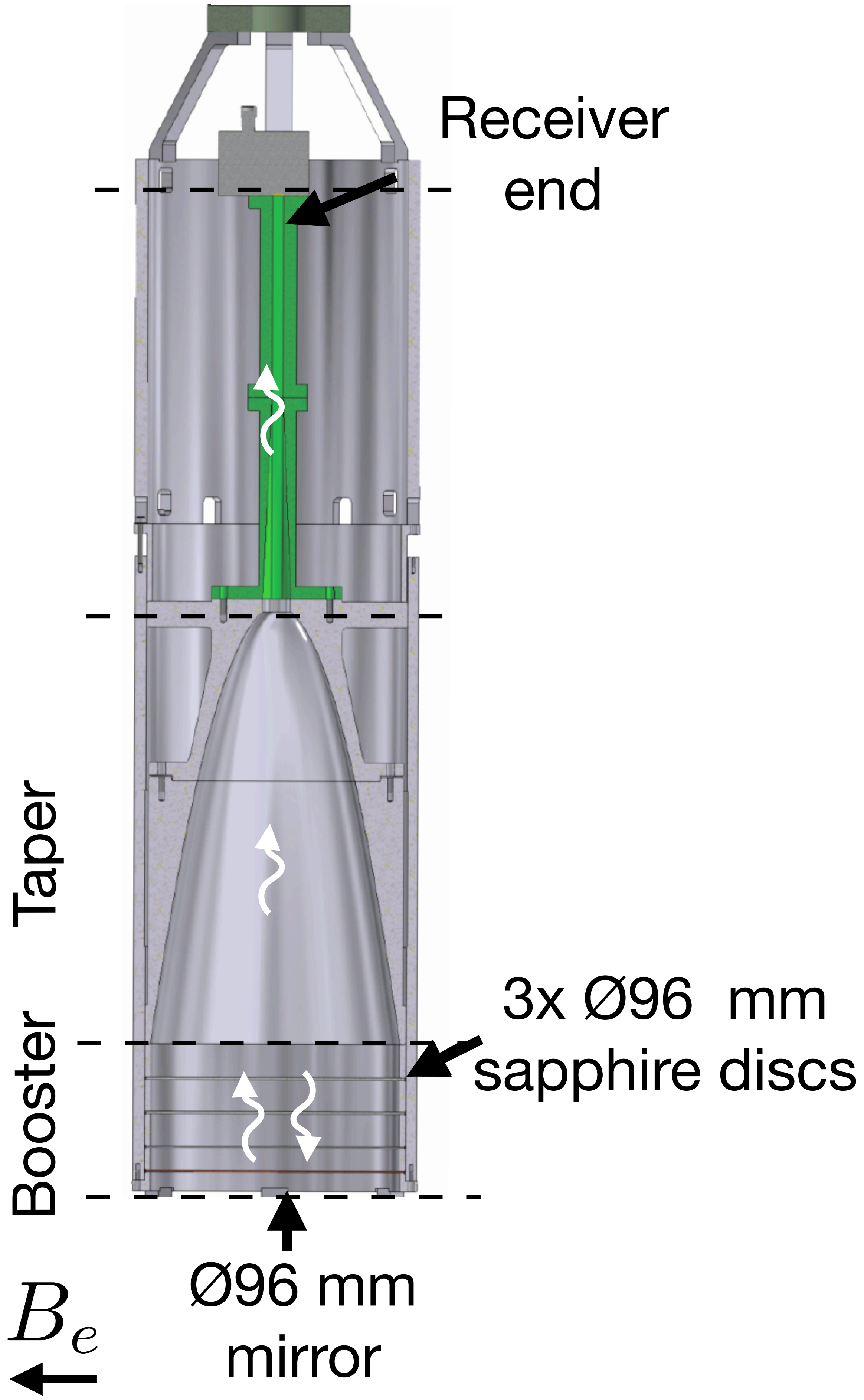


$\beta^2 > 1500$ —> expected sensitivity: $|g_{a\gamma}| \approx O(3\times10^{-11})$ GeV^{-1}

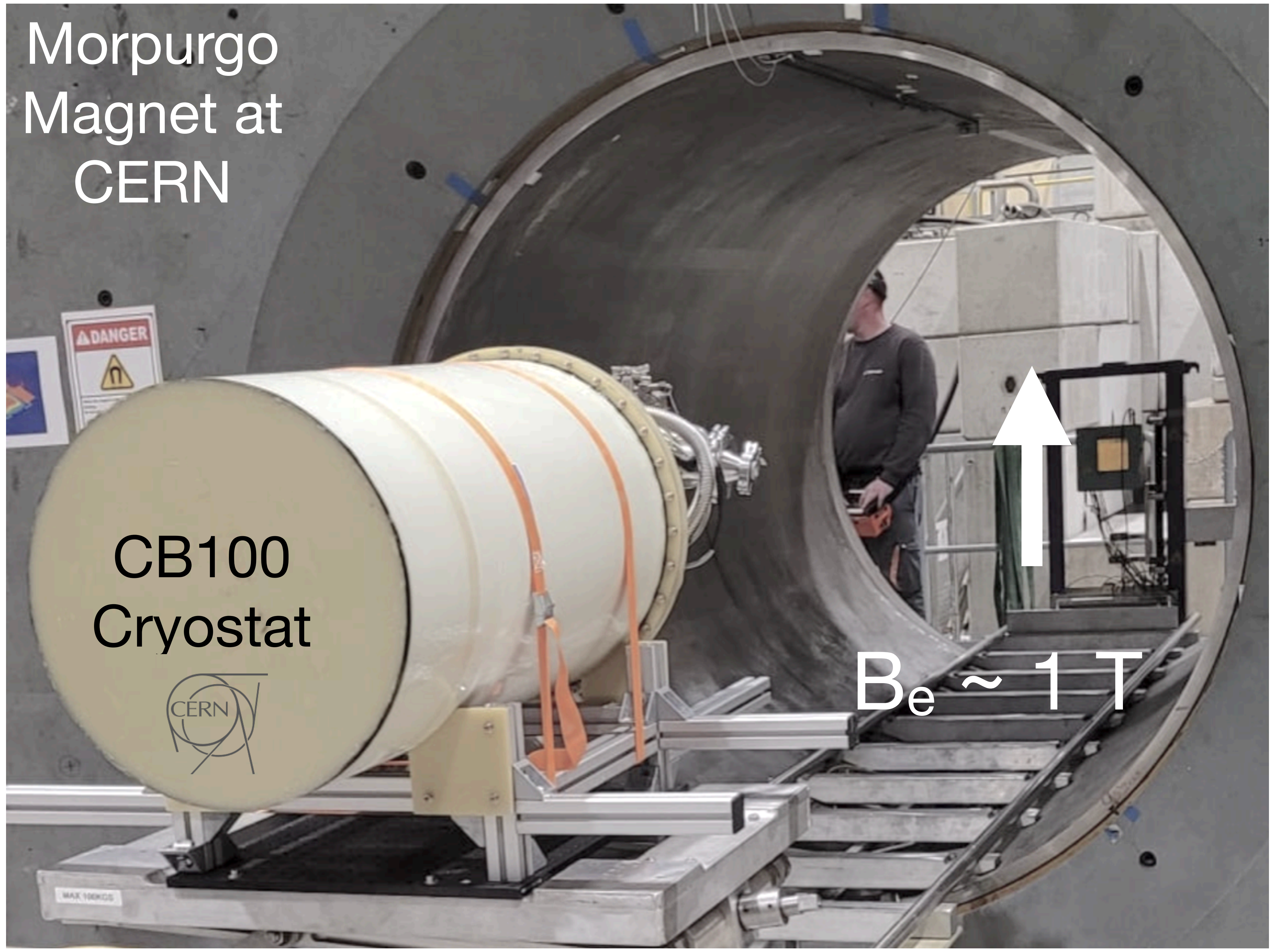
Scanning ability of the booster validated

Physics with CB 100 at cold

Cold run using CERN’s MORPURGO magnet and 100 mm closed booster



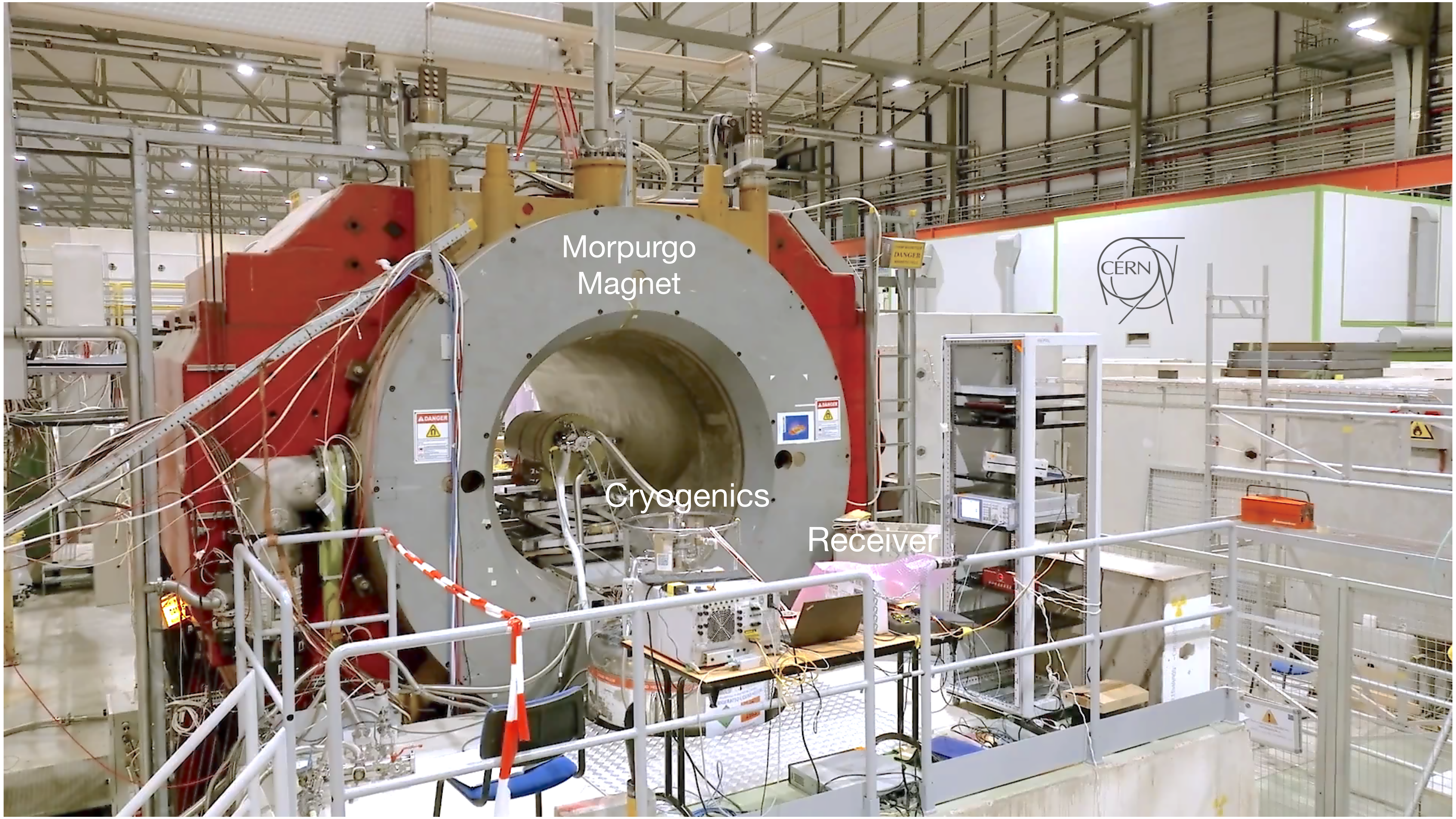
- Single fixed configuration ≈19 GHz



- Cryostat: Glass-fabric/epoxy laminate (G11)
- Reaches 4 K
- Cooled by He vapor
- Custom-made at CERN

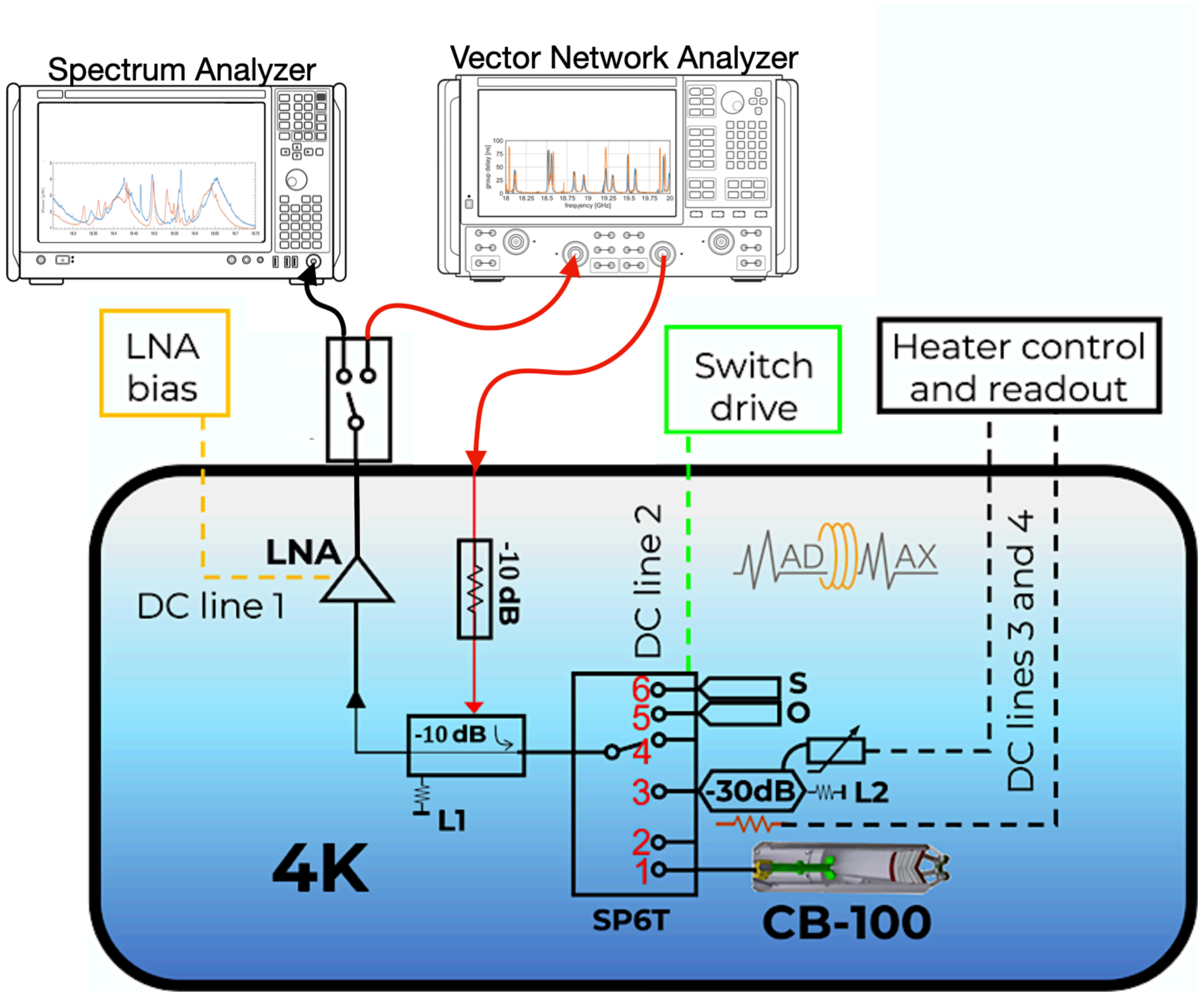
Physics with CB 100 at cold

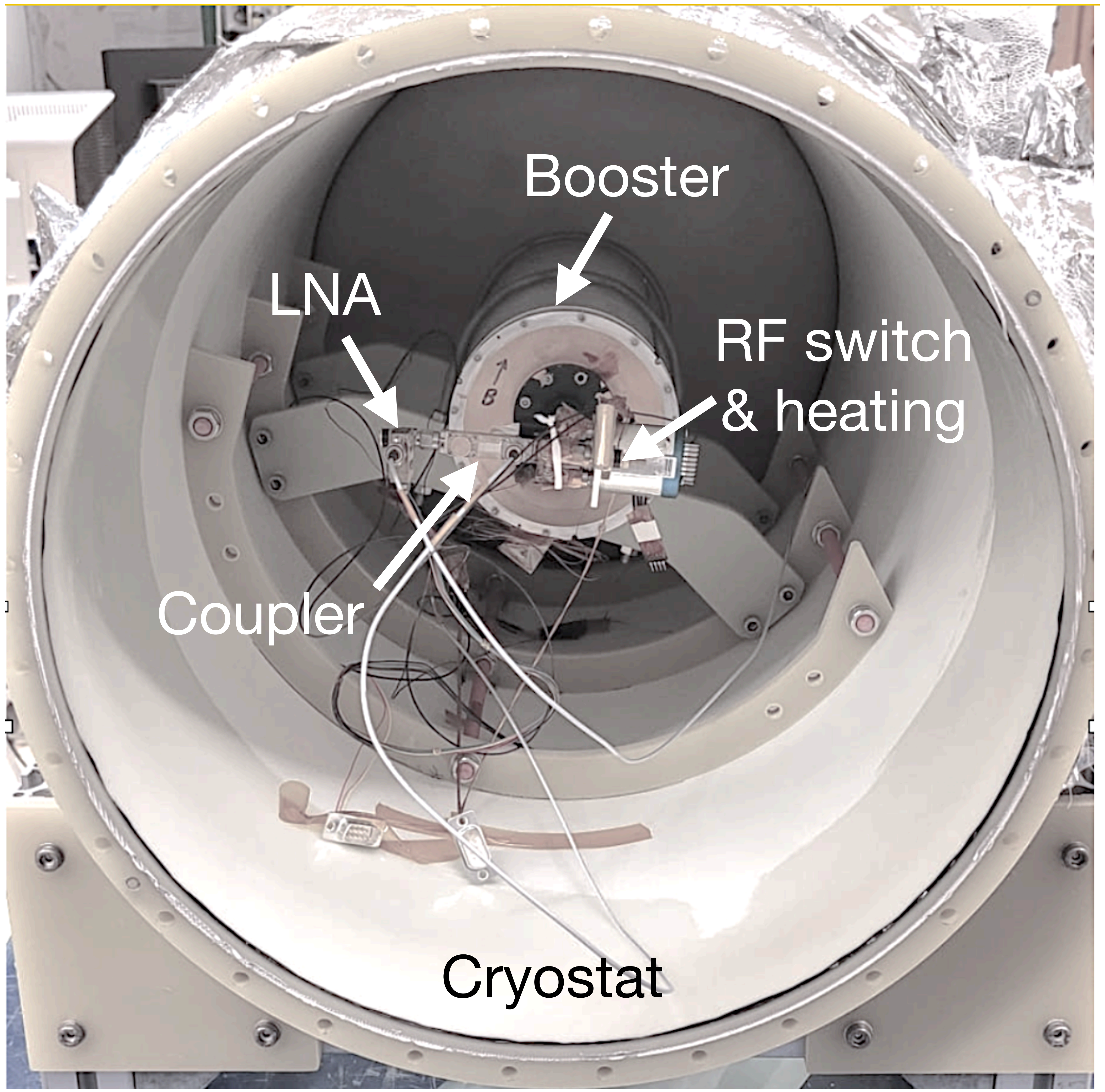
The cold setup at CERN's North Area



Cold operation and calibration

How to run the cold experiment?



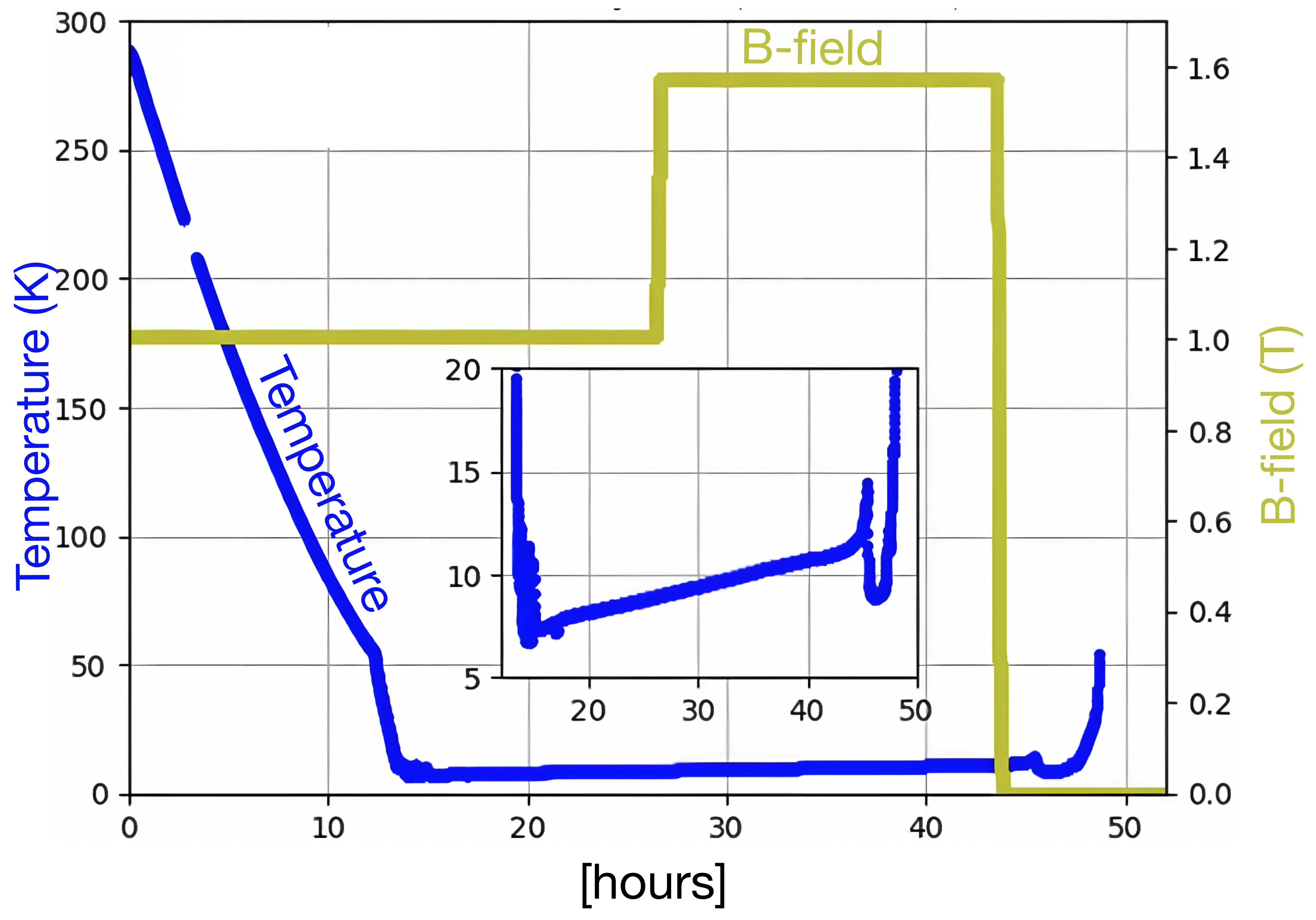


- Power calibration by Y-factor at several T
- VNA measurement to determine the boost factor
- Circulator-free operation

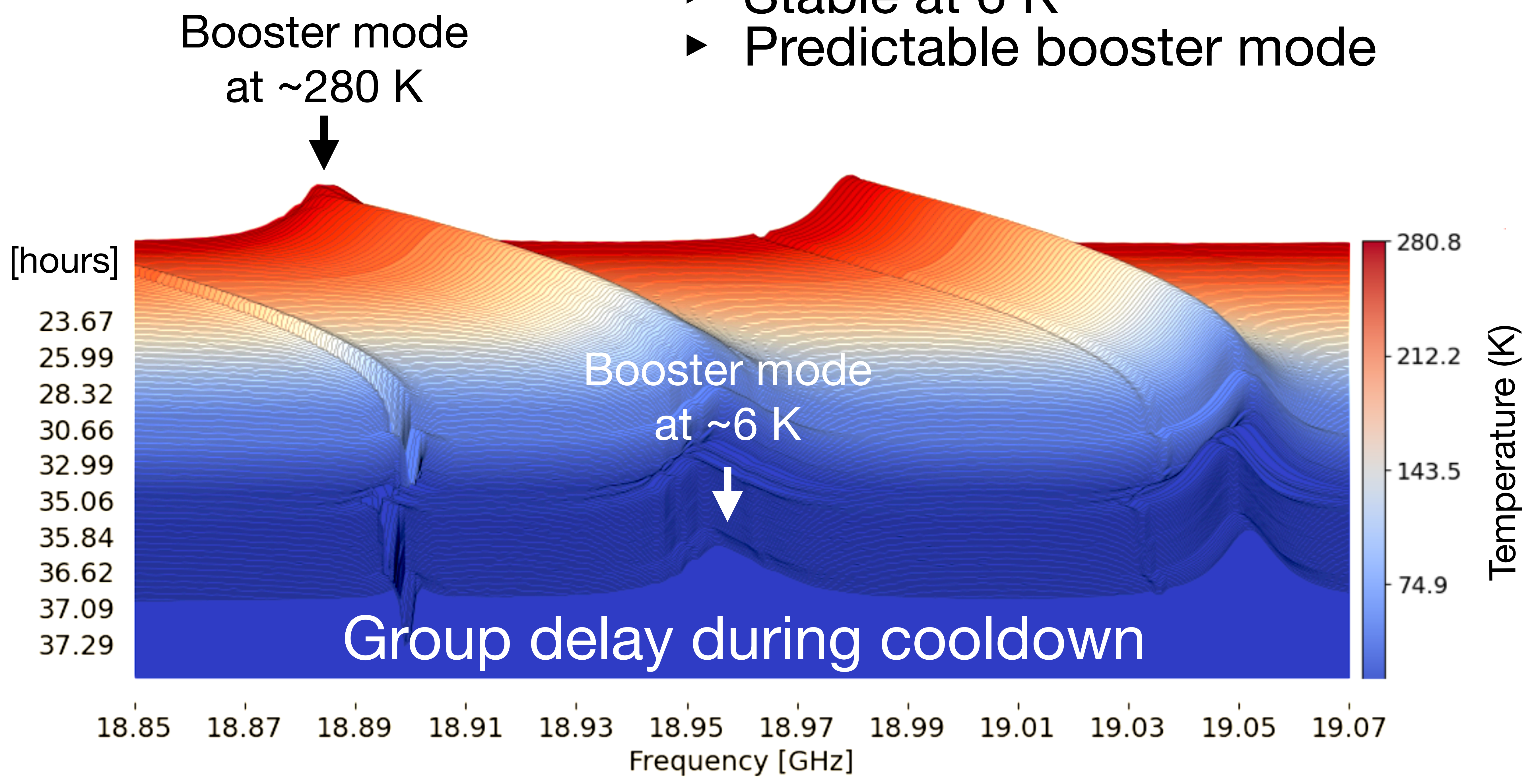
Cold operation and calibration

Can we achieve stable cool-down and operation at cold?

20-hour cold physics run at MORPURGO
≈19 GHz and T < 10 K under B field
(data analysis ongoing)



- Cool-down ~15 h
- Stable at 6 K
- Predictable booster mode



Operation and receiver chain calibration at cold achieved

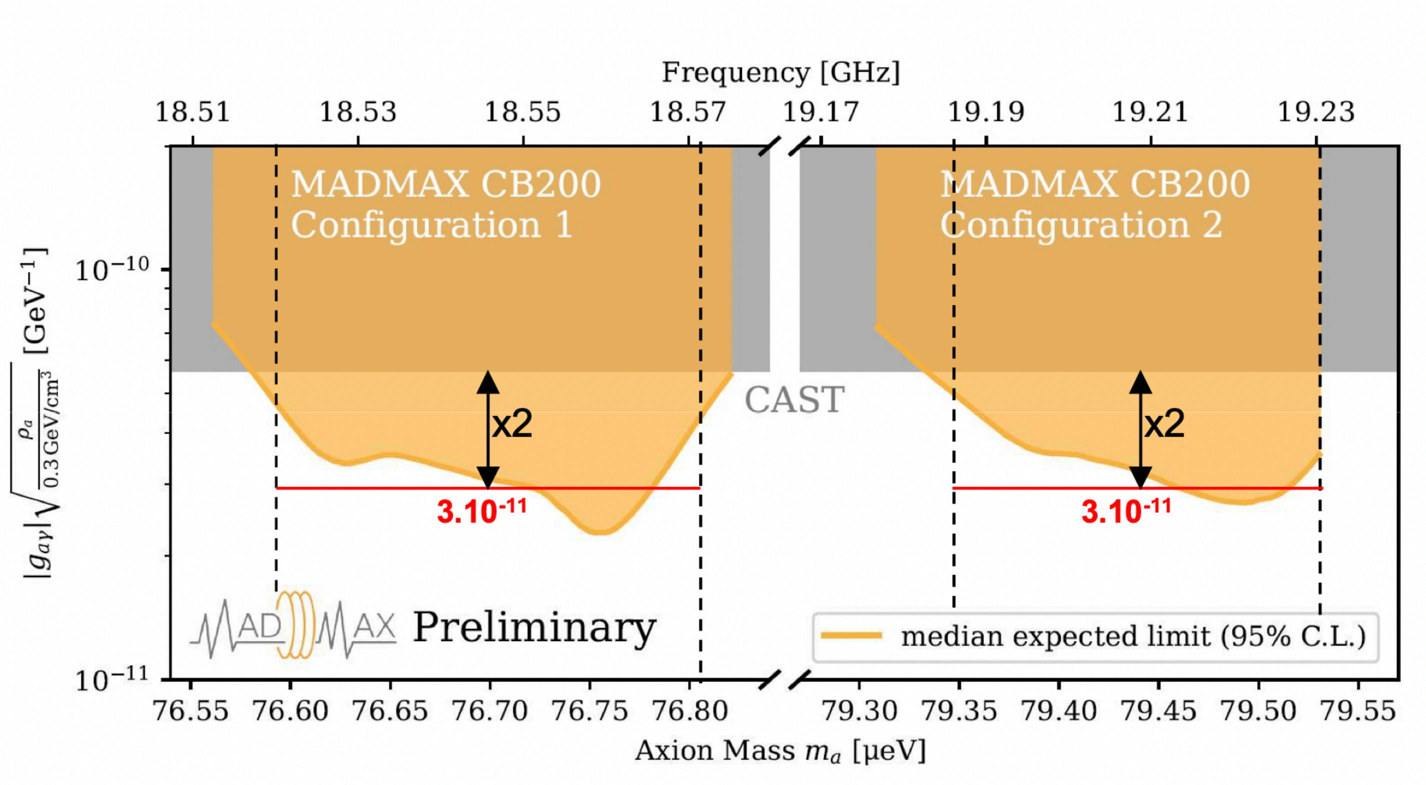
Wrap-up

Booster-related development and proof of concept:

- Frequency tuning
- Control of unwanted modes
- Boost factor determination
- Field distribution measurements
- Noise modelling and receiver chain
- Cold operation and calibration

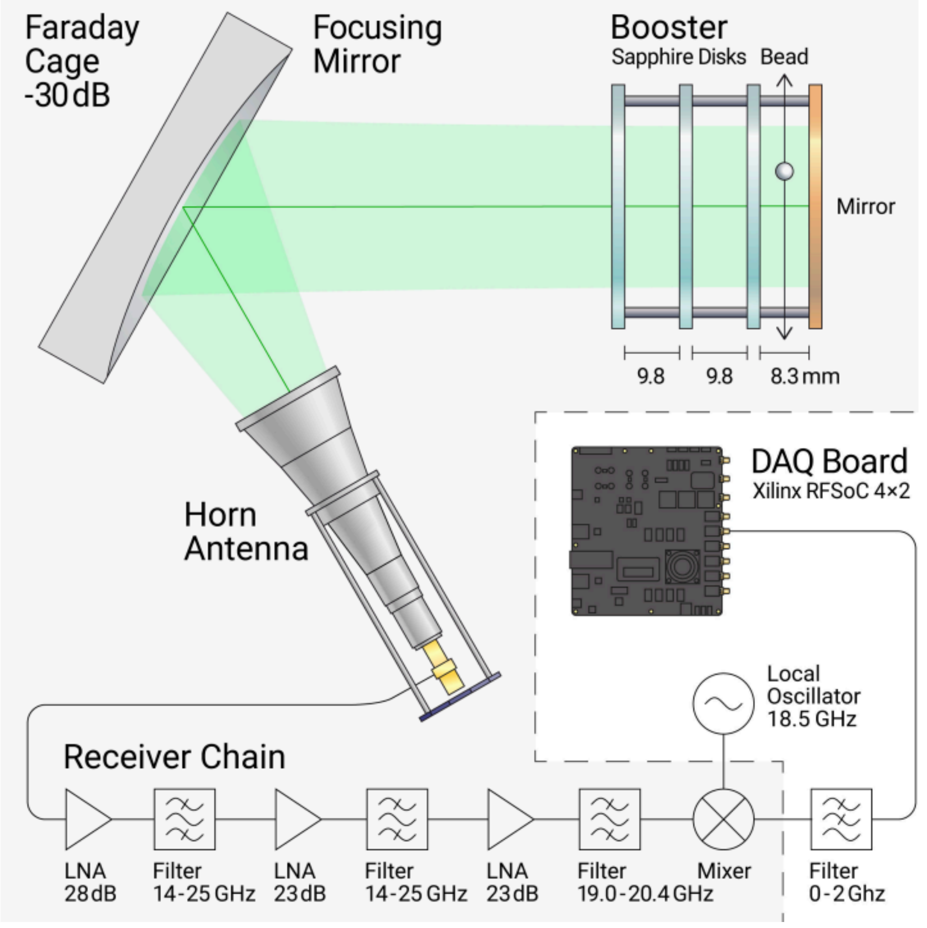
Preliminary results from first axion searches at CERN:

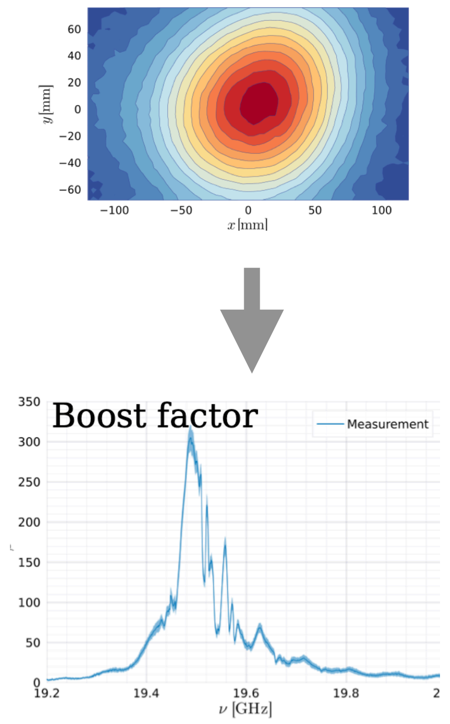
- 17-day run @18.5, 19.2 GHz with expected peak sensitivity: $|g_{a\gamma}| \approx O(3x10^{-11})$ GeV^{-1}
- 20-hour cold run @19 GHz, T < 10 K



Recent news from MADMAX

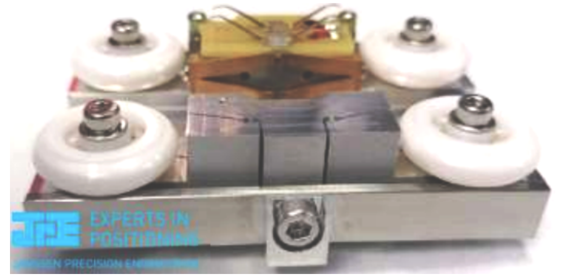
Development of open boosters





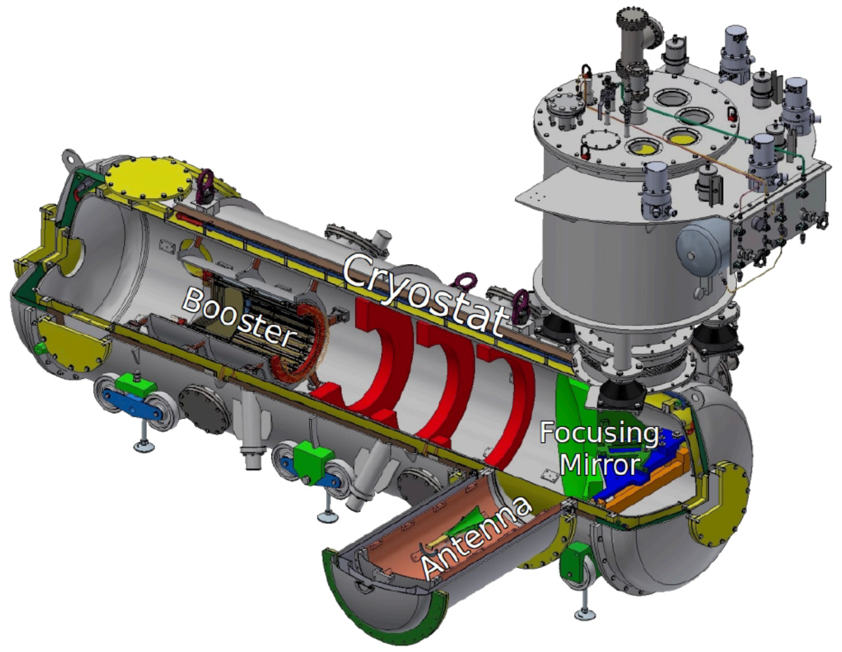
(JCAP 04 (2024) 005)
(JCAP 04 (2023) 064)

- Novel way to determine boost factor directly from field measurement
- 12-day dark photon search @19-20.3 GHz and open booster (preliminary)
- Tested piezo motor: 5 K & 5.3 T and validated booster mechanics



(arXiv:2407.10716)

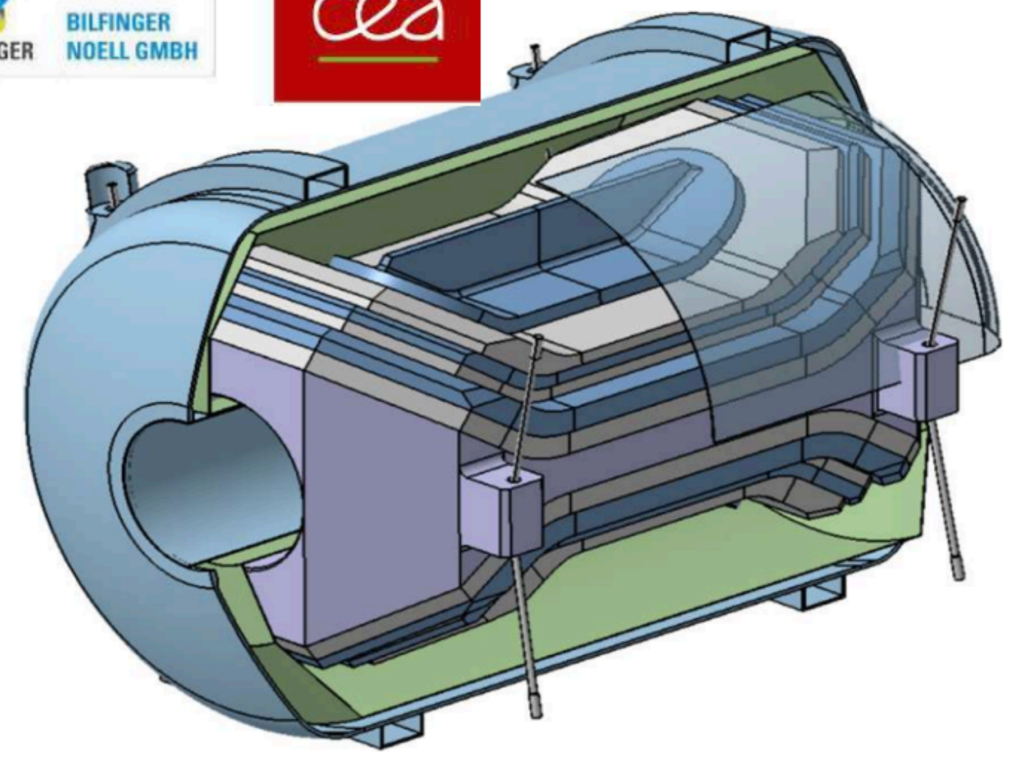
MADMAX Prototype Cryostat



- ⌀ = 760 mm
- Allows all prototypes
- Fits CERN's MORPURGO
- Planned for: 2026-2028 (long LHC shutdown)

R&D of magnet

[NbTi with Cu jacket @ 1.8K]



- Dipole Magnet critical for full-size MADMAX
- Latest news: budget secured for demonstrator coil

Stay tuned!

https://madmax.mpp.mpg.de