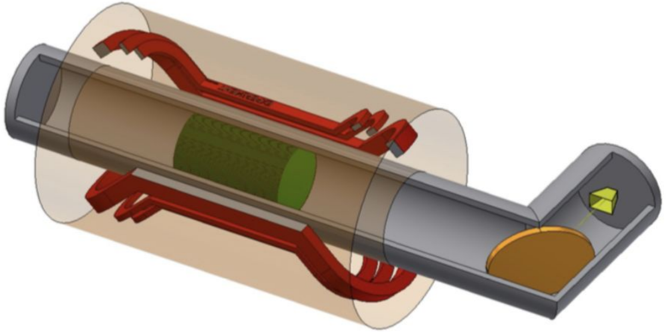
MADMAX:

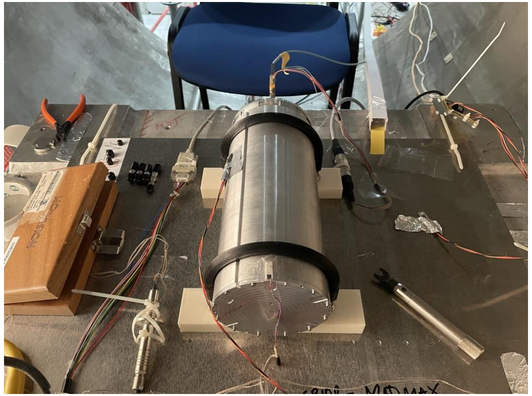
Searching for Axion Dark Matter with a Dielectric Haloscope

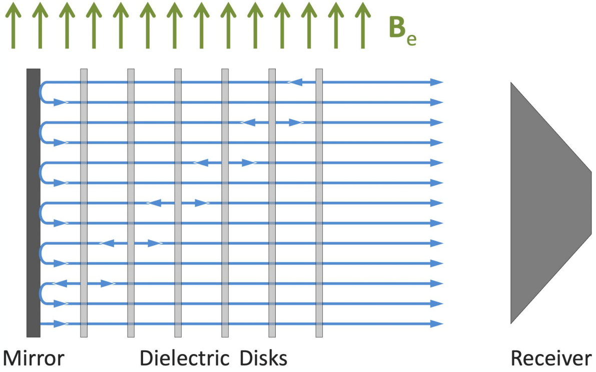
Bernardo Ary dos Santos
“Axions across Boundaries”
GGI 2023

Overview:



- Motivation
- Dielectric Haloscopes
- MADMAX
- Prototype: CB100 at CERN



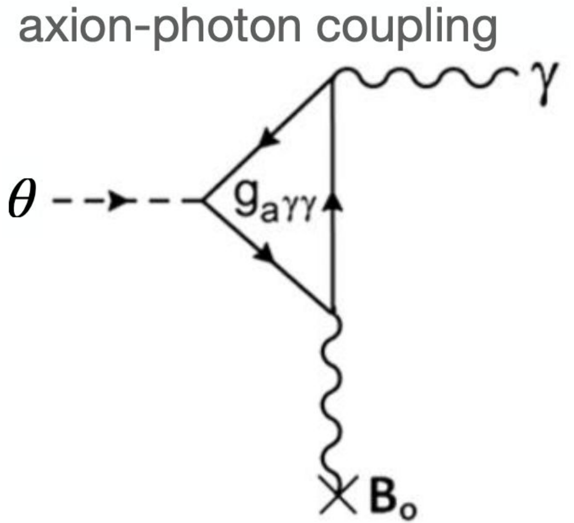


Motivation

- Axion Dark matter could solve Strong CP problem + Dark Matter
- Post Inflationary Scenarios favor axion masses $m_a \sim \mathcal{O}(\mu eV)$
- Large unexplored part of the Parameter Space

Working Principle

Axion to photon conversion in an external Magnetic field
(Primakoff effect)



Modified Maxwell equations

Effective Lagrangian:

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \frac{g_{a\gamma\gamma}}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$

New set of Axion-Maxwell equations:

$$\begin{aligned}
&\vec{\nabla} \cdot \vec{E} = \rho - g_{a\gamma}\vec{B} \cdot \vec{\nabla}a \\
&\vec{\nabla} \times \vec{B} - \dot{\vec{E}} = \vec{J} + g_{a\gamma}(\vec{B}\dot{a} - \vec{E} \times \vec{\nabla}a) \\
&\vec{\nabla} \cdot \vec{B} = 0 \\
&\vec{\nabla} \times \vec{E} + \dot{\vec{B}} = 0 \\
&\ddot{a} - \vec{\nabla}^2 a + m_a^2 a = g_{a\gamma}(\vec{E} \cdot \vec{B})
\end{aligned}$$

Axion Dark Matter

De Broglie wavelength of Axions:

$$\lambda_{dB} = 12{,}4\,\mathrm{m}\left(\frac{100\,\mu eV}{m_a}\right)\left(\frac{10^{-3}}{v_a}\right)$$

$\Longrightarrow$ For small regions $\boldsymbol{k}_a = 0$

From the Modified Maxwell equations:

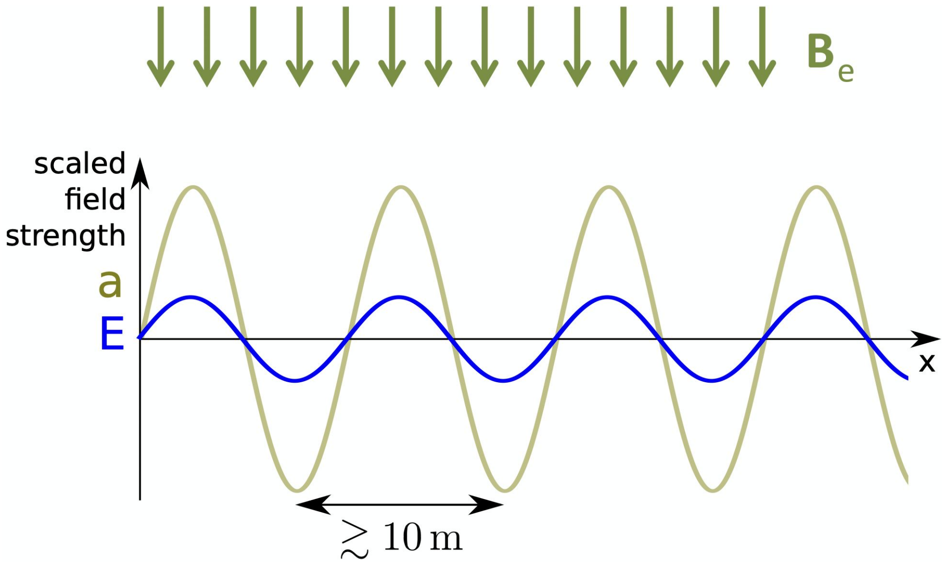
$$\omega = m_a$$

$$\hat{\boldsymbol{E}}_a(t) = -\epsilon^{-1} g_{a\gamma\gamma} \boldsymbol{B}_e \hat{a}(t) = -\frac{\boldsymbol{E}_0}{\epsilon} e^{-i m_a t}$$

Radiation from an Interface

Axion induced Electric field:

$$\hat{\boldsymbol{E}}_a(t) = -\epsilon^{-1} g_{a\gamma} \boldsymbol{B}_e \hat{a}(t)$$



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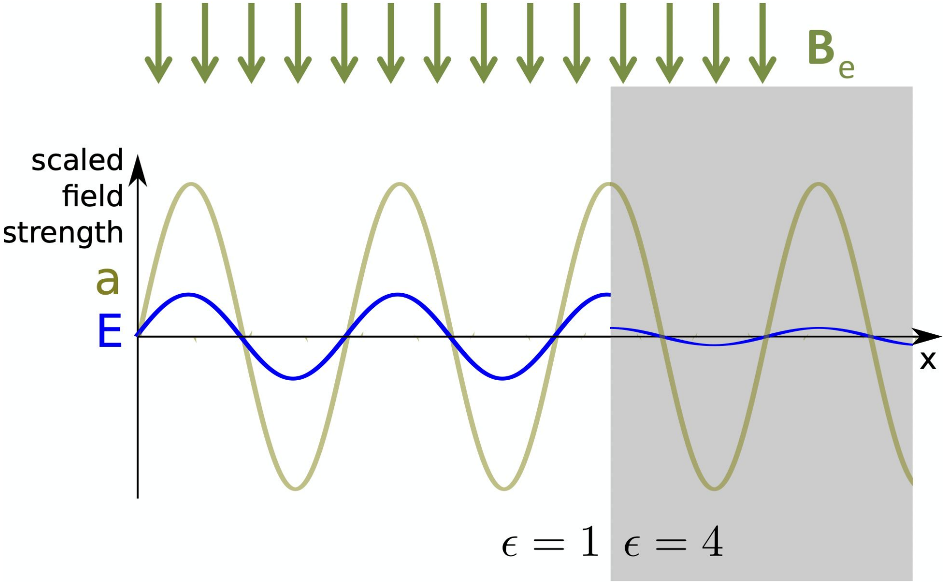

Radiation from an Interface

Axion induced Electric field:

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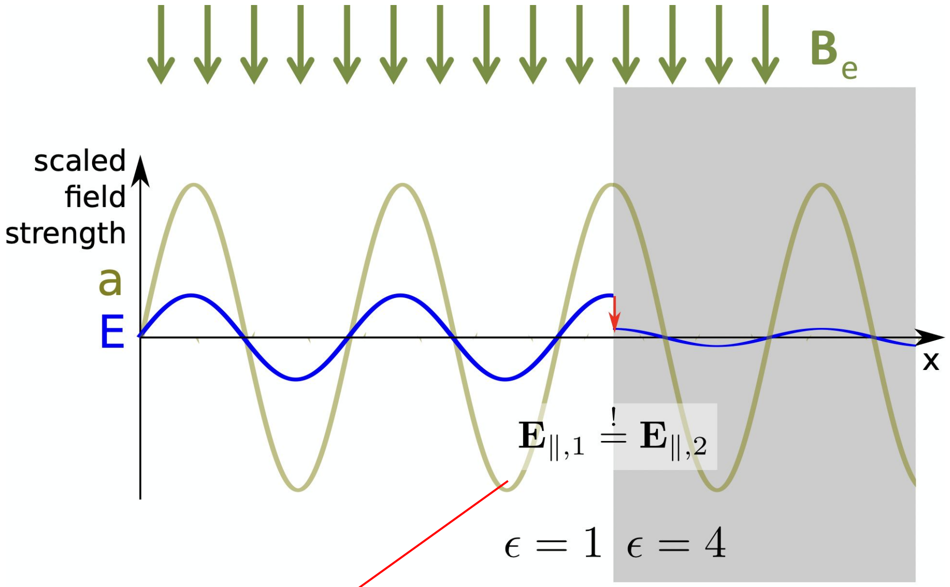


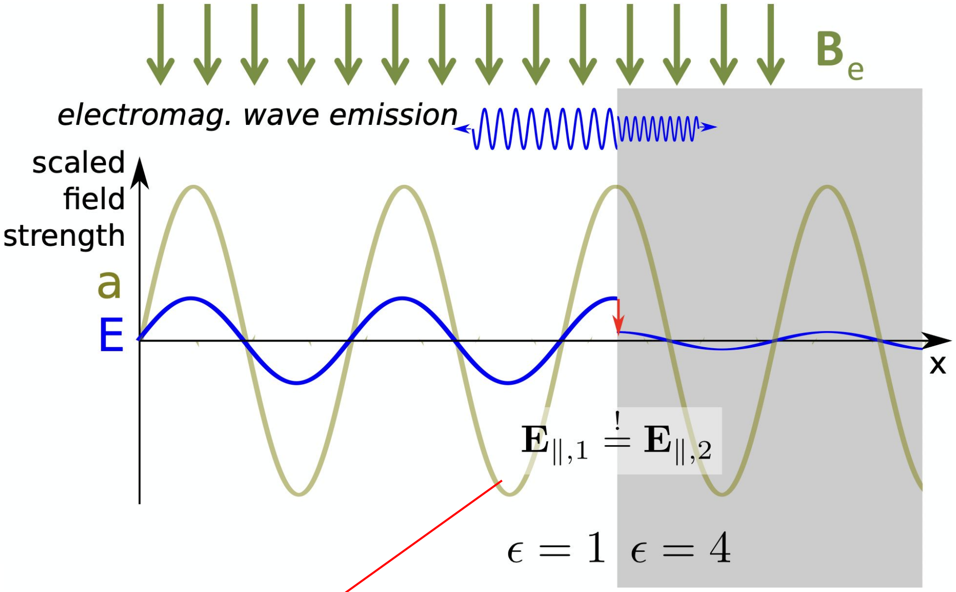
Boundary conditions from Maxwell equations

Radiation from an Interface

Axion induced Electric field:

$$\hat{\boldsymbol{E}}_a(t) = -\epsilon^{-1} g_{a\gamma} \boldsymbol{B}_e \hat{a}(t)$$

Emission at the interface from dielectric constant discontinuity



Boundary conditions from Maxwell equations

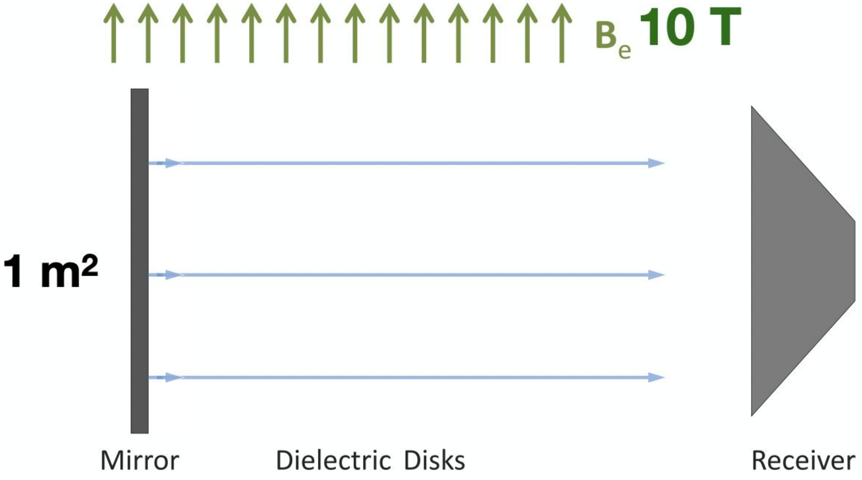
Radiation from Single Mirror

- Single Mirror in 10 T Magnetic Field:

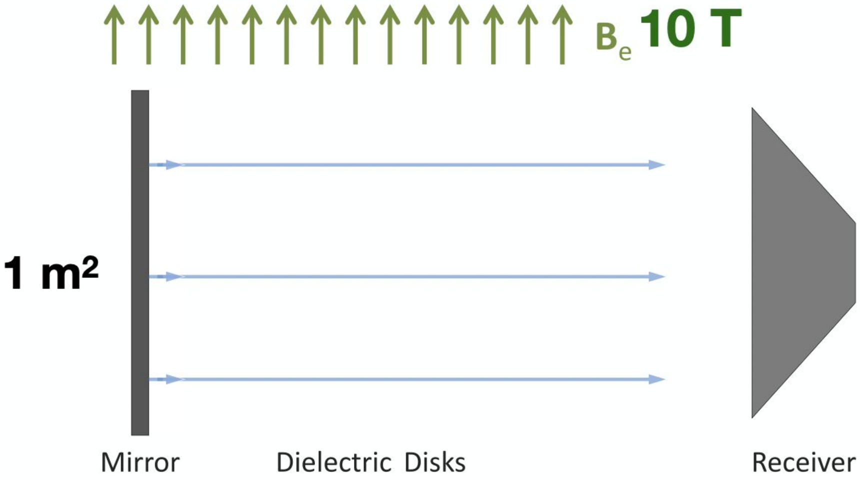
$$\frac{P_\gamma}{A} = 2.2 \times 10^{-27} \frac{W}{m^2} \left(\frac{B_e}{10T}\right)^2 C_{a\gamma}^2 f_{DM}$$

- Signal to Noise Ratio:

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_\gamma}{T_{\mathrm{sys}}}\sqrt{\frac{\Delta t}{\Delta \nu_a}} = 1.0 \times 10^{-4} \left(\frac{A}{1\,\mathrm{m}^2}\right) \sqrt{\frac{100\,\mu\mathrm{eV}}{m_a}} \sqrt{\frac{\Delta t}{\mathrm{week}}} \left(\frac{8\,\mathrm{K}}{T_{\mathrm{sys}}}\right) \left(\frac{B_{\mathrm{e}}}{10\,\mathrm{T}}\right)^2 C_{a\gamma}^2 f_{\mathrm{DM}}$$



Radiation from Single Mirror



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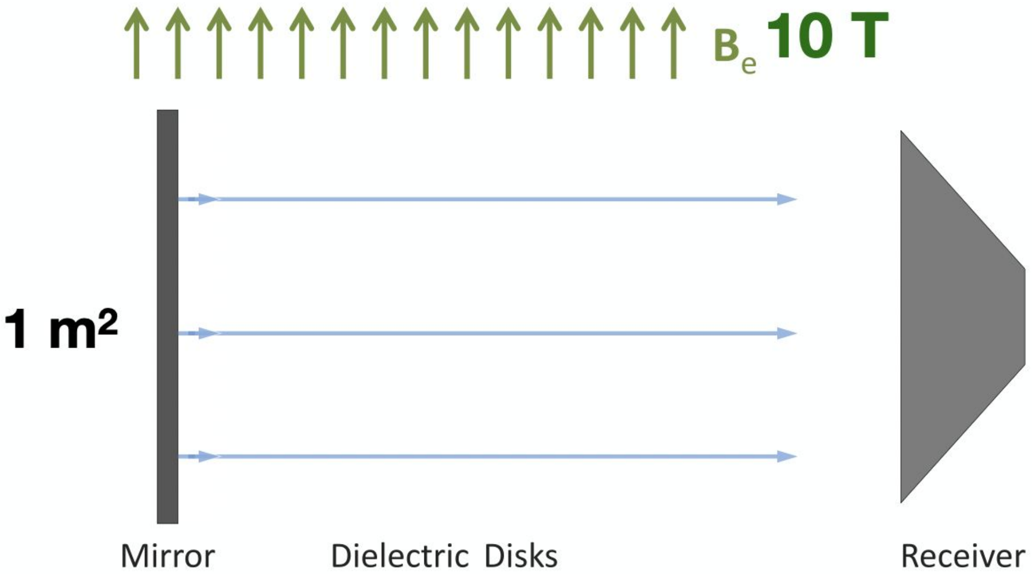
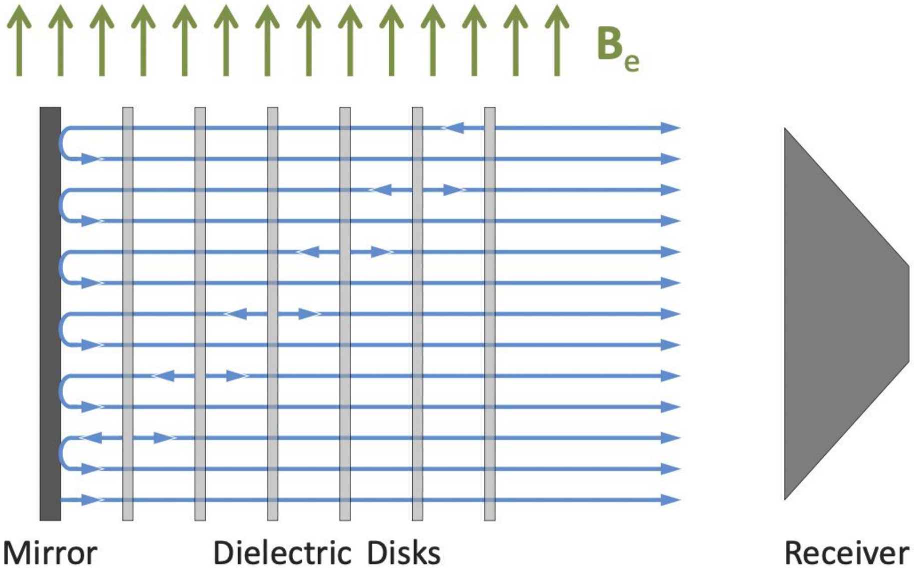
Too Small!

Dielectric Haloscope and the Boost Factor



$$\frac{P_\gamma}{A} = \frac{E_0^2}{2}$$

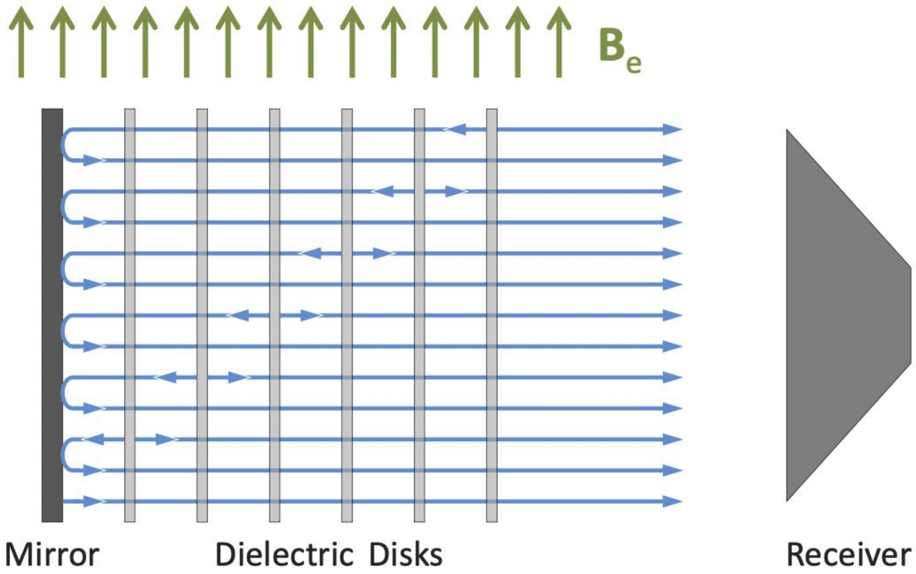
Dielectric Haloscope and the Boost Factor



- Dielectric interfaces in front of mirror
- More coherent sources
- Constructive interference

$$\frac{P_\gamma}{A} = \frac{E_0^2}{2} \rightarrow \frac{P_\gamma}{A} = \frac{\beta^2(\nu)E_0^2}{2}$$

Dielectric Haloscope and the Boost Factor



- Dielectric interfaces in front of mirror
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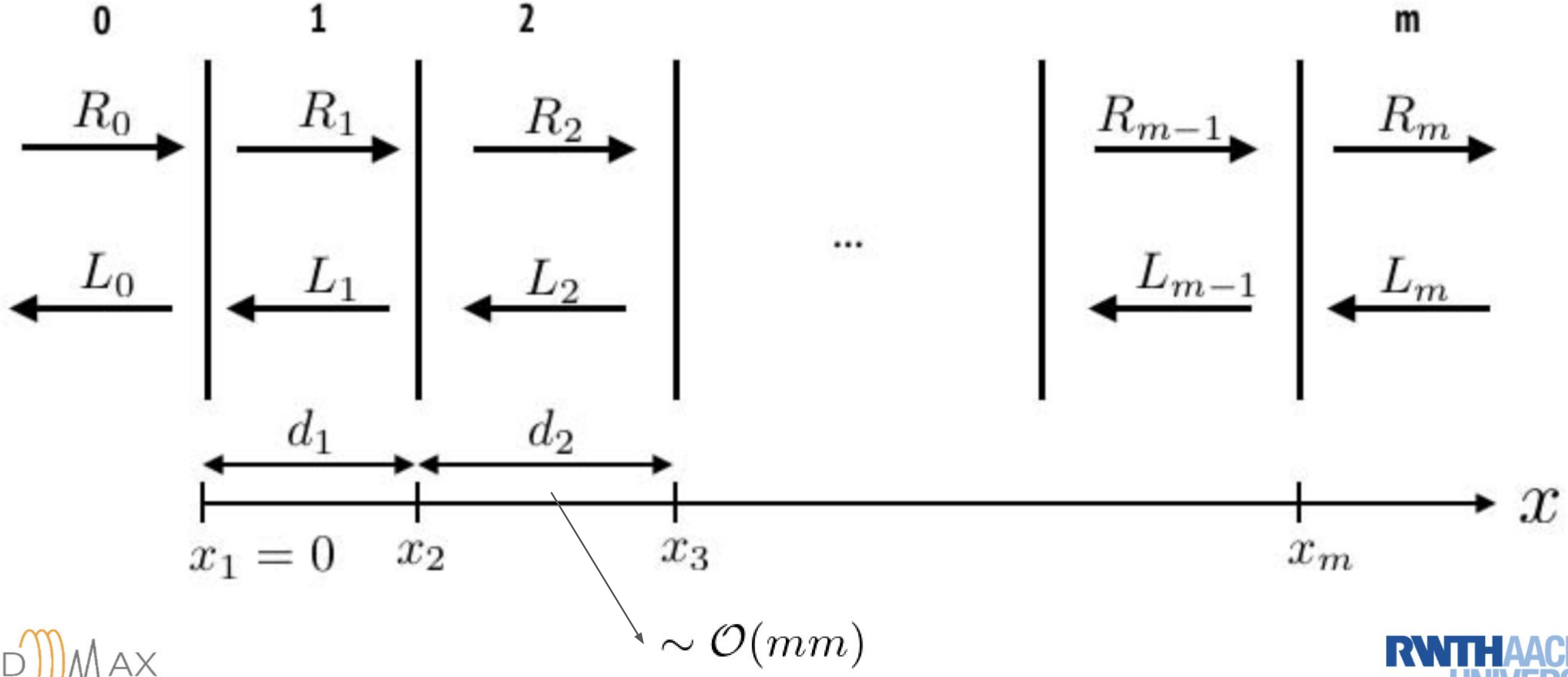
$$\frac{P_\gamma}{A} = \frac{E_0^2}{2} \rightarrow \frac{P_\gamma}{A} = \frac{\beta^2(\nu) E_0^2}{2}$$

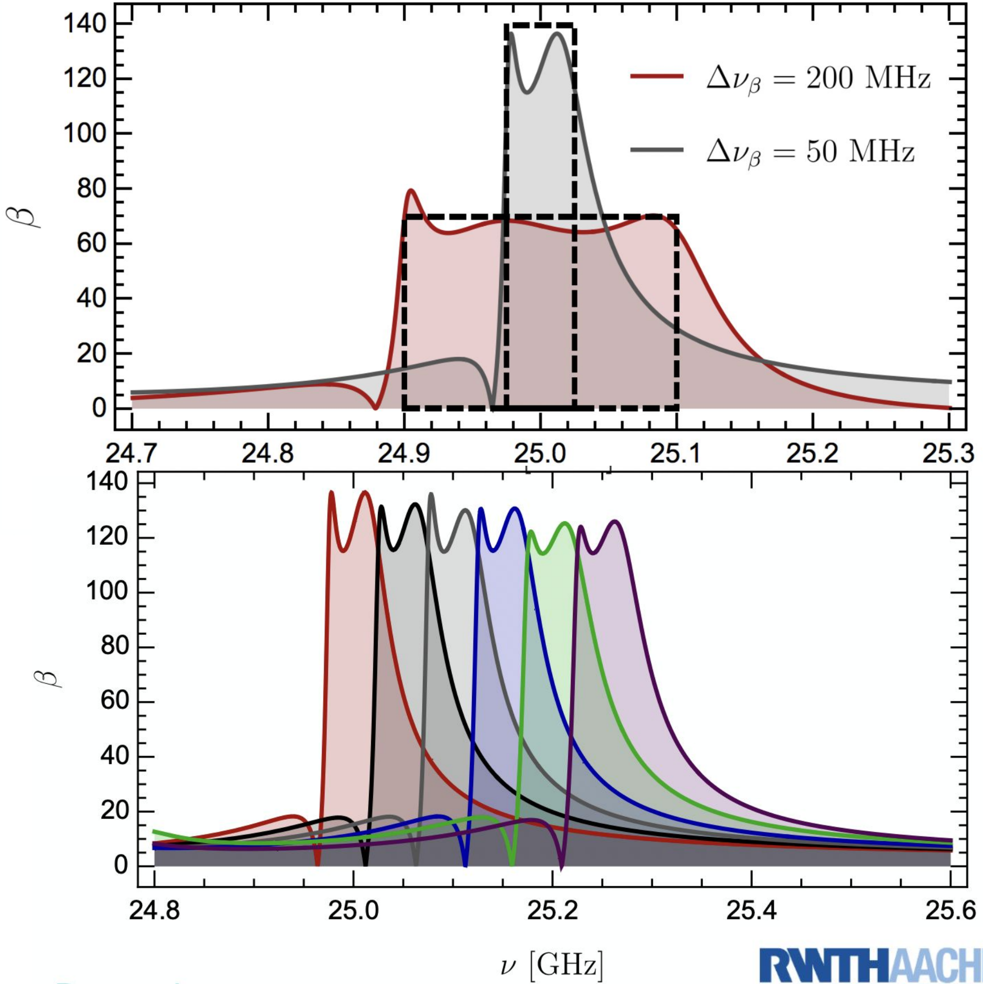
Boost Factor for fixed disc positions depends on: dielectric constant (ε), frequency (ν)

Coherent Superposition Inside Dielectric Haloscope

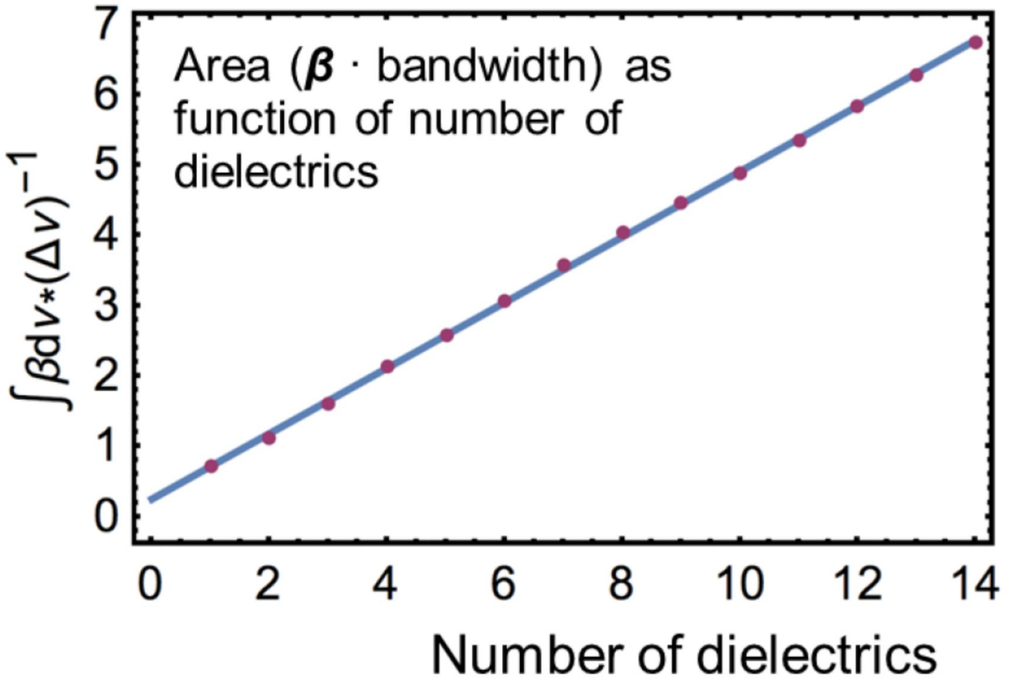


Boost Factor

- Disk Positioning changes boost factor
- Area under curve always the same (Area Law)
- Higher boost factor = Lower Bandwidth
- Lower Boost Factor = Higher Bandwidth



Number of Dielectric Discs

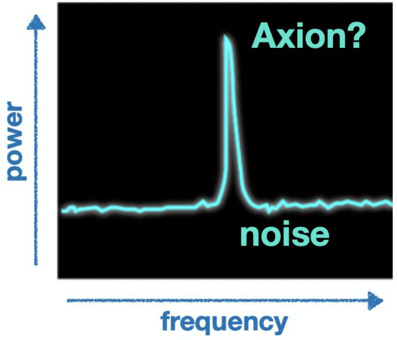


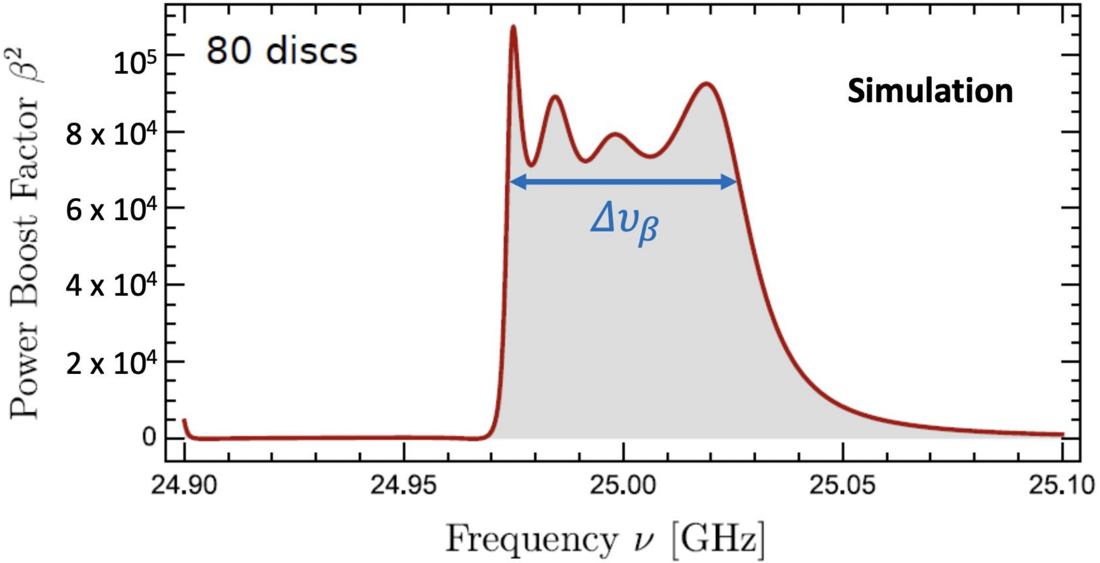
- Area under Boost factor curve increases with number of discs

➔ More Discs ➪ Higher Boost Factor

Boost Factor 1D Simulations

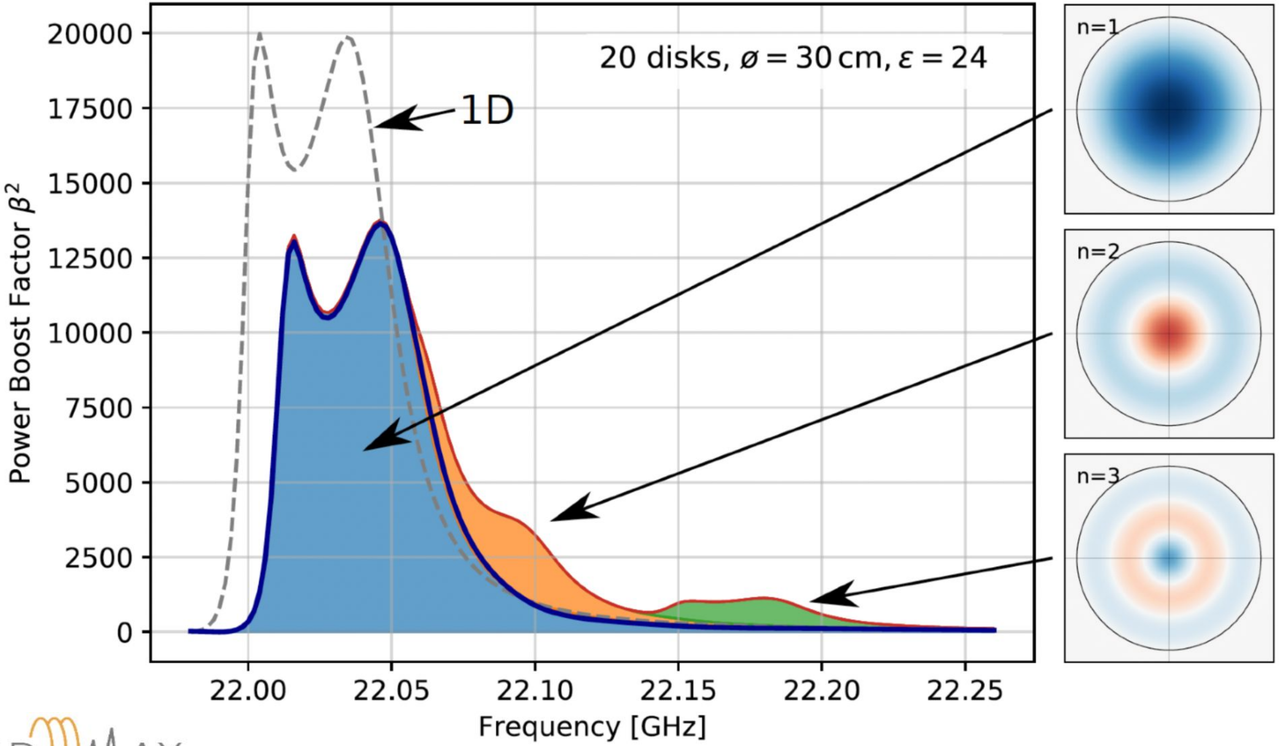
- 1D simulations for $\varepsilon = 24$ with 80 discs allow us to obtain $|\beta^2| > 10^4$



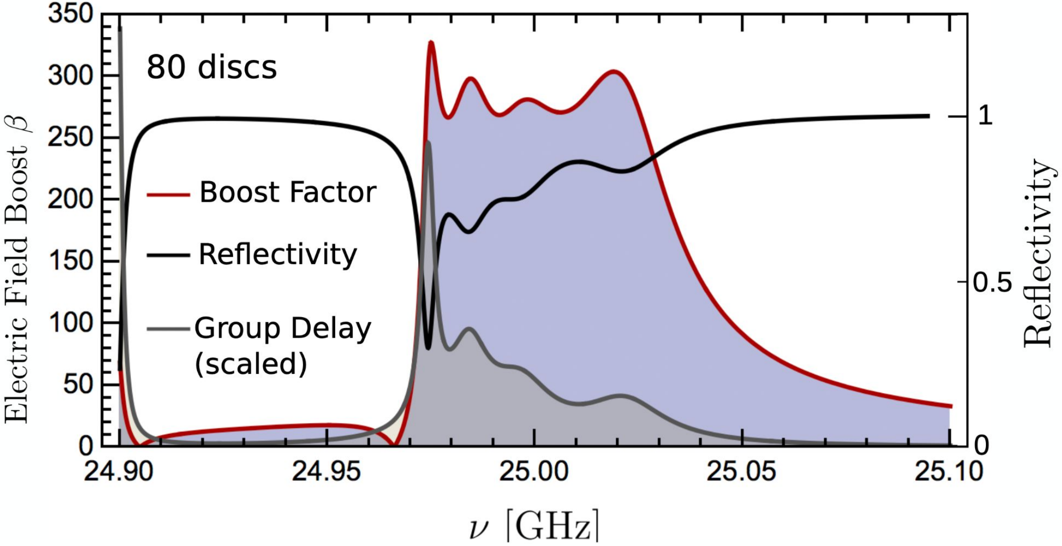


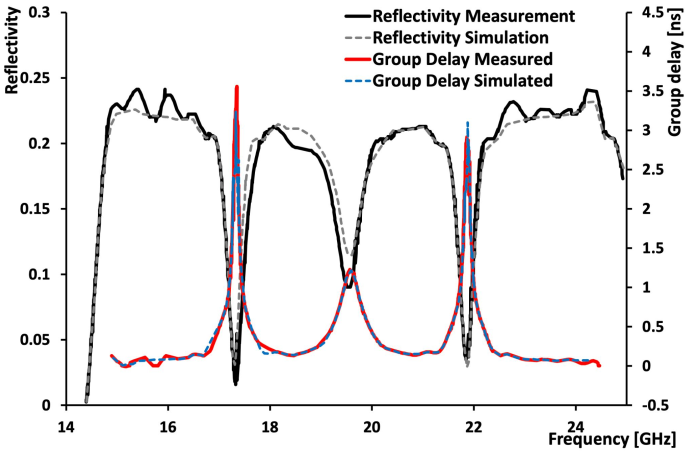
$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_\gamma}{T_{\mathrm{sys}}}\sqrt{\frac{\Delta t}{\Delta \nu_a}} = 1.0 \times 10^{-4} \left(\frac{A}{1\,\mathrm{m}^2}\right) \sqrt{\frac{100\,\mu\mathrm{eV}}{m_a}} \sqrt{\frac{\Delta t}{\mathrm{week}}} \left(\frac{8\,\mathrm{K}}{T_{\mathrm{sys}}}\right) \left(\frac{B_{\mathrm{e}}}{10\,\mathrm{T}}\right)^2 C_{a\gamma}^2 f_{\mathrm{DM}}\ \beta^2 \sim \mathcal{O}(1)$$

Boost Factor 3D Simulations



Measuring the Boost factor





- Boost factor cannot be experimentally measured

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

➔ Inferred from <u>reflectivity</u> and <u>group delay</u>

MADMAX

MAgnetized **D**isc and **A**xion e**X**periment

DESY.

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

MADMAX

Universidad
de Zaragoza

RWTH AACHEN
UNIVERSITY

UHH
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

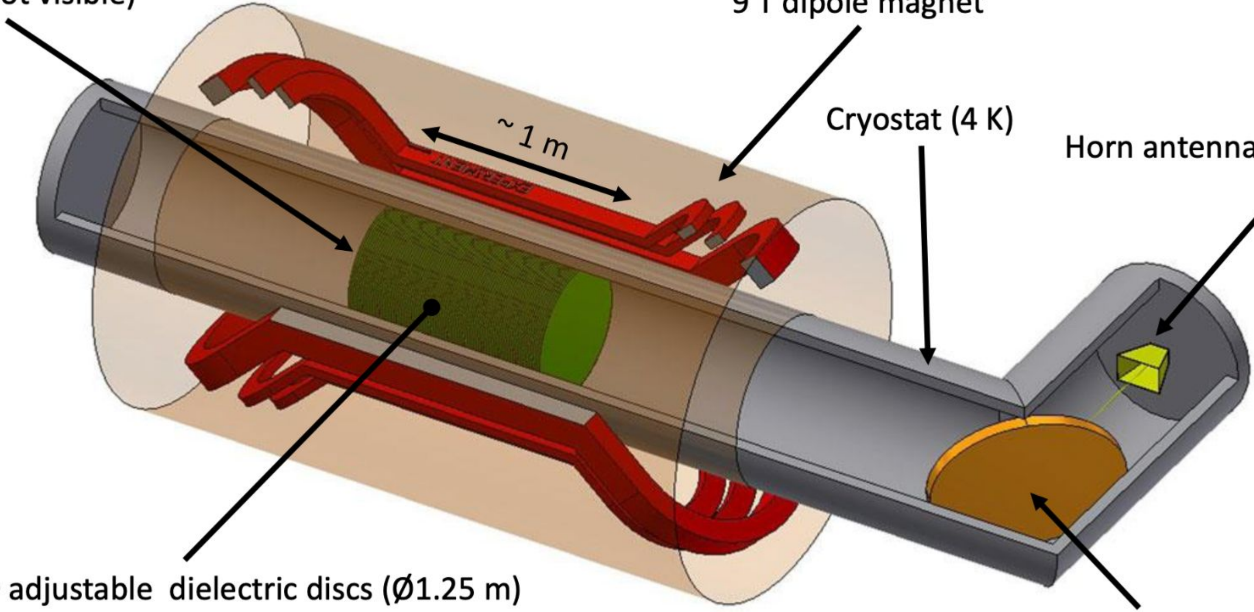
MAX-PLANCK-INSTITUT
FÜR PHYSIK

Max-Planck-Institut
für Radioastronomie

CENTRE DE PHYSIQUE DES
PARTICULES DE MARSEILLE
CPPM

NÉEL
institut

Full Size MADMAX



Mirror (not visible)

9 T dipole magnet

Cryostat (4 K)

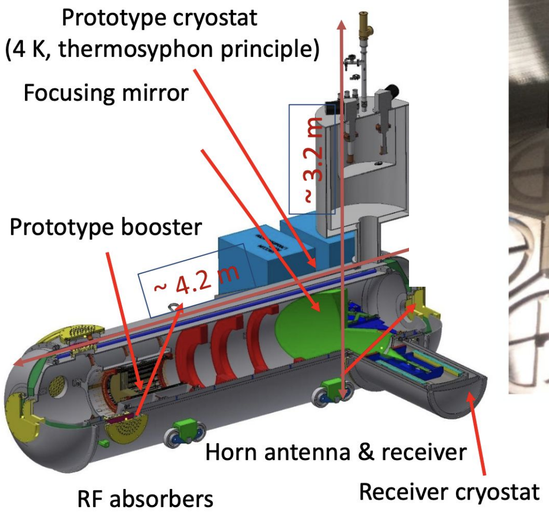
Horn antenna & receiver system

Booster: 80 adjustable dielectric discs (Ø1.25 m)

Focusing mirror

[Eur. Phys. J. C **79** (2019) 186]

Technological Challenges



Prototype cryostat
(4 K, thermosyphon principle)

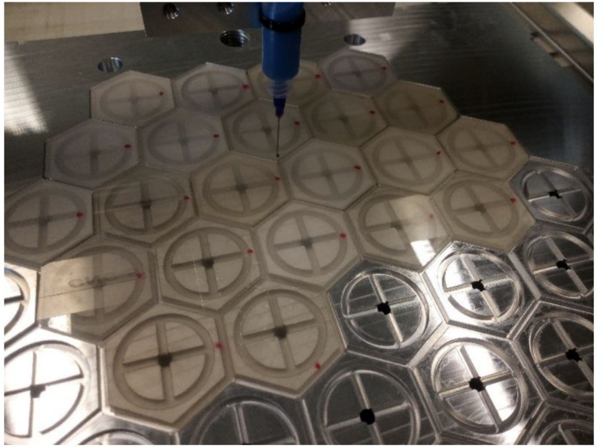
Focusing mirror

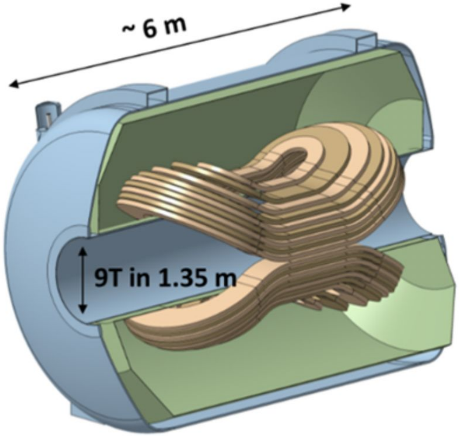
Prototype booster

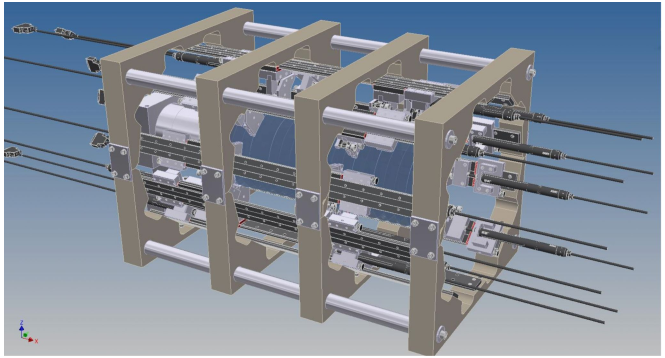
Horn antenna & receiver

RF absorbers

Receiver cryostat







Disc Properties

$$\hat{\boldsymbol{E}}_a(t) = -\epsilon^{-1} g_{a\gamma} \boldsymbol{B}_e \hat{a}(t)$$

- High dielectric constant (ε) → higher axion to photon conversion
- Low loss (tan δ) → reduced photon loss

Sapphire (Al_2O_3):

$$tan\delta \sim 10^{-5}$$

$$\epsilon \approx 9.4$$

Lanthanum Aluminate ($LaAlO_3$):

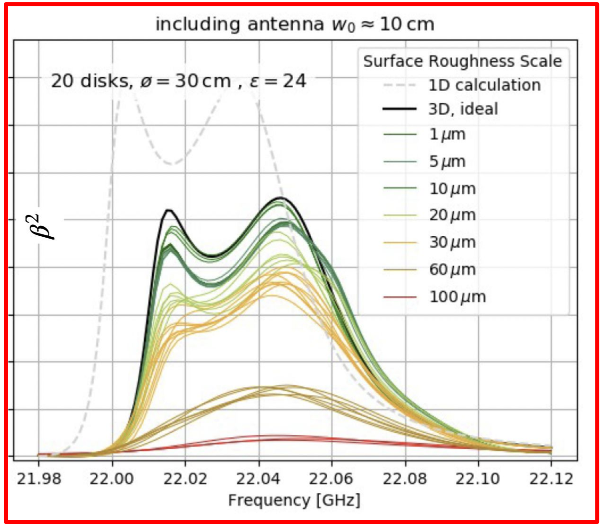
$$tan\delta \sim 10^{-5}$$

$$\epsilon \approx 24$$

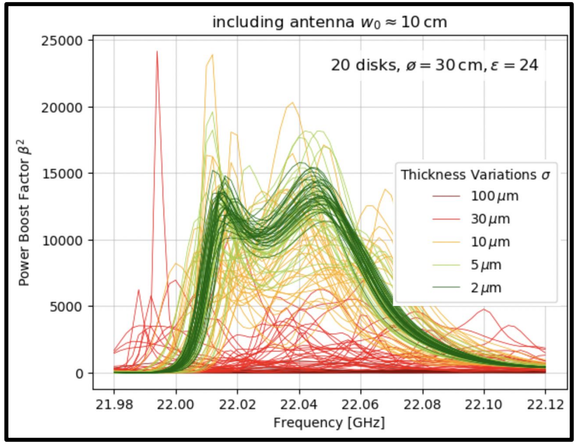
Precision Challenges

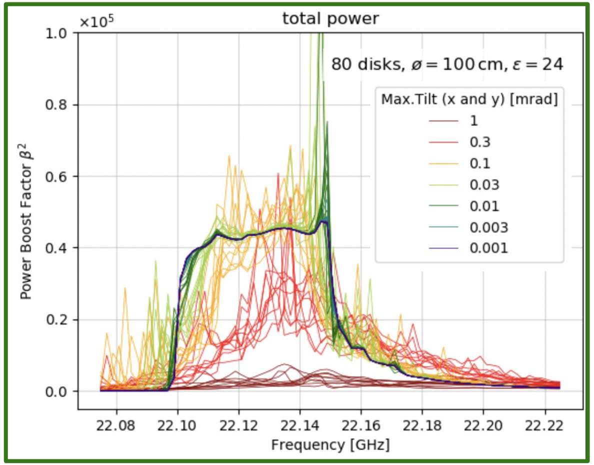
Non ideal discs → Loss of Boost factor:

$$\beta^2(\nu)$$

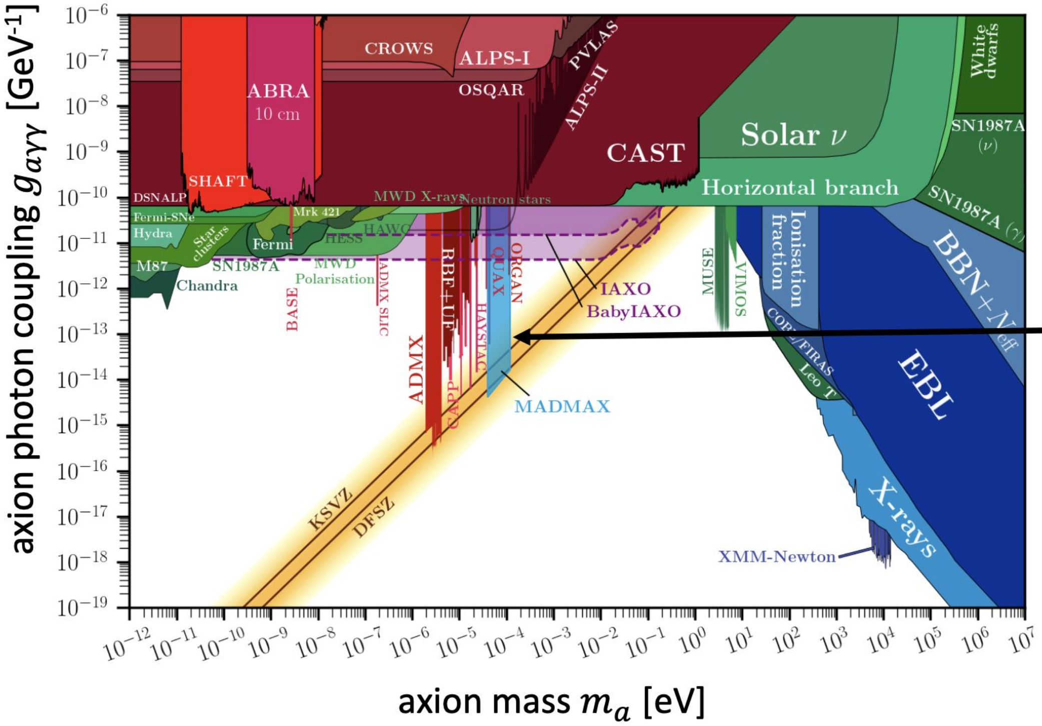


- Thickness variation
- Surface roughness
- Disc Tilting



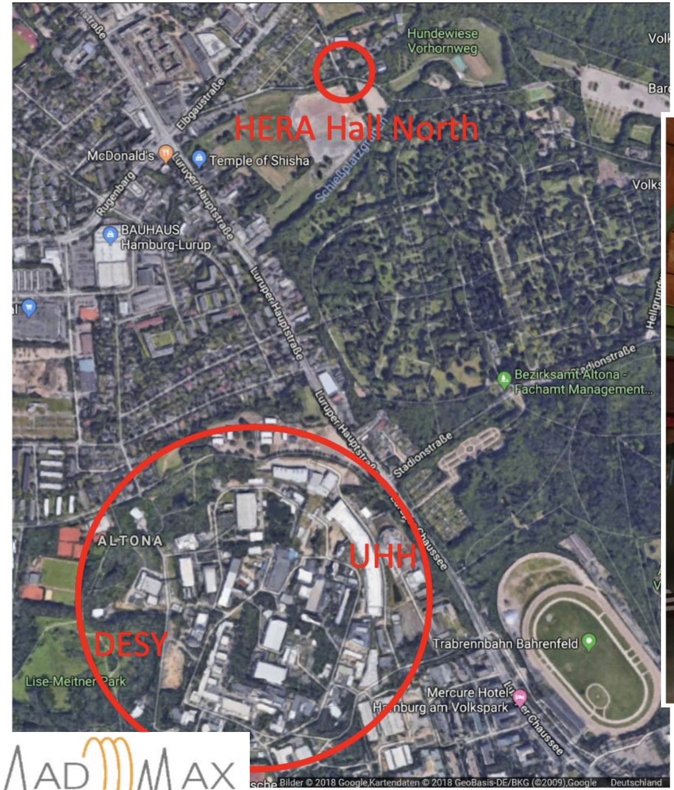


Parameter Space



- 80 Dielectric discs
- 1m² Area
- 9 T Magnetic field
- 8K System Temperature

Experimental Site at DESY



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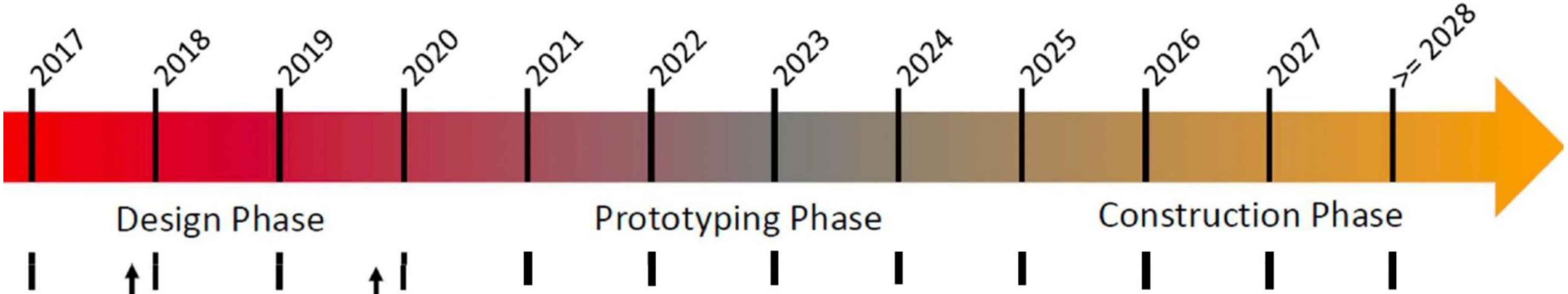
- MADMAX expected to be at HERA Hall North (DESY)

Timeline



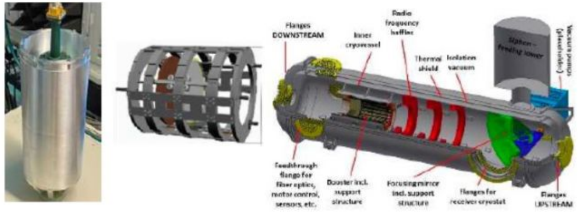
Design Phase

Prototyping Phase

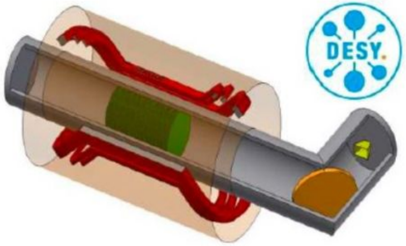
Construction Phase

Foundation of MADMAX Collaboration

First endorsement by DESY PRC

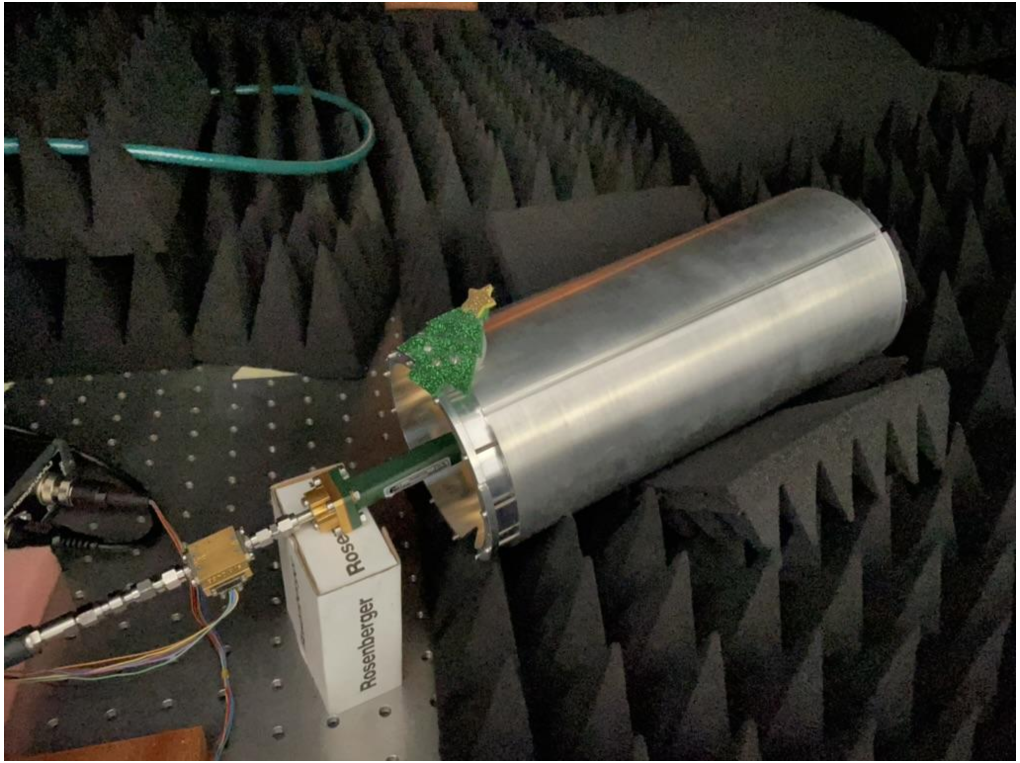


Usage of MORPURGO magnet approved by CERN Research Board for 2021-2024

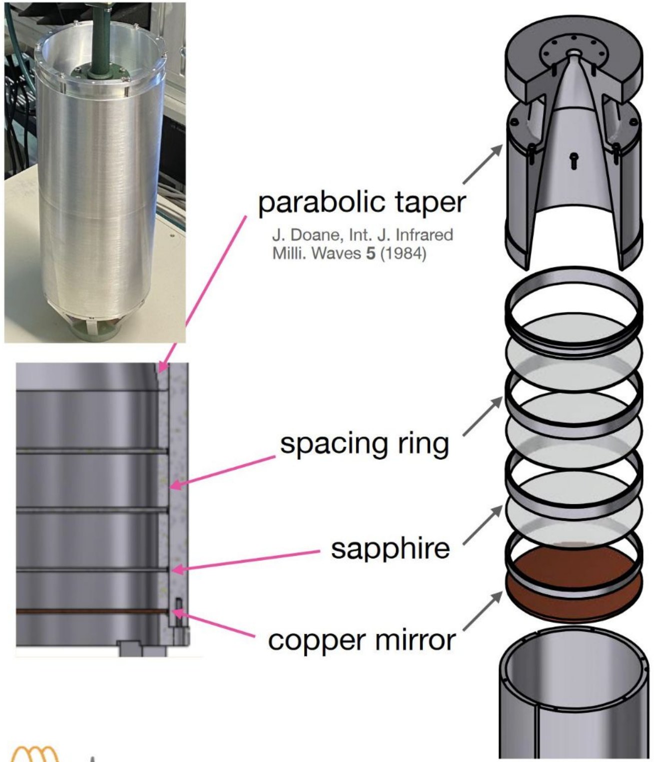


Full-size MADMAX magnet commissioning

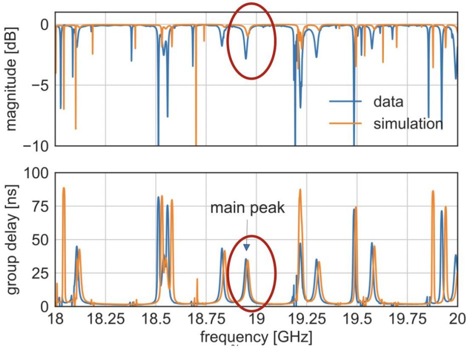
Prototype: CB100 at CERN

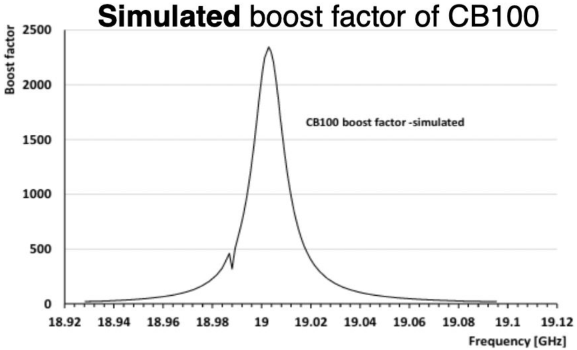


Prototype: CB100



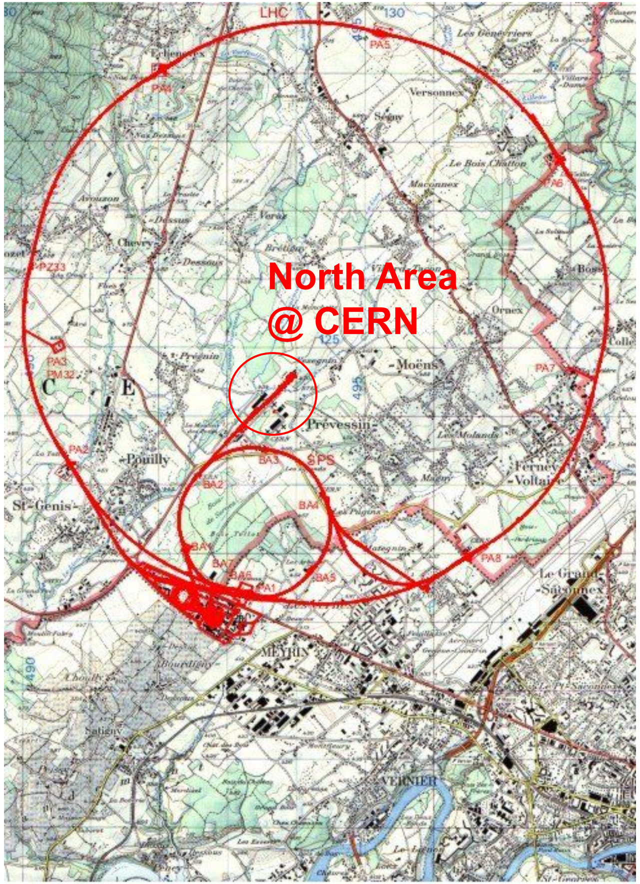
- Closed Booster
- 100 mm Sapphire Discs ($\varepsilon = 9.4$)
- Discs in fixed Position
- Optimized for Boost factor $\beta^2 \sim 2000$
- 50 MHz bandwidth



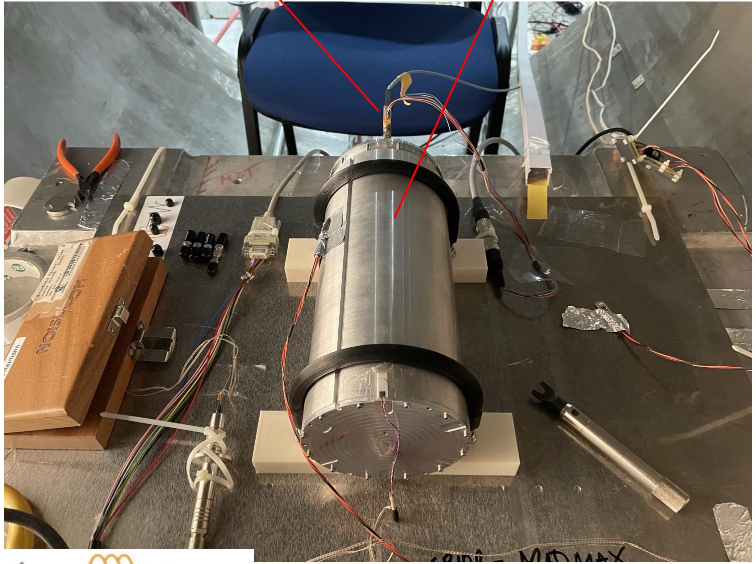


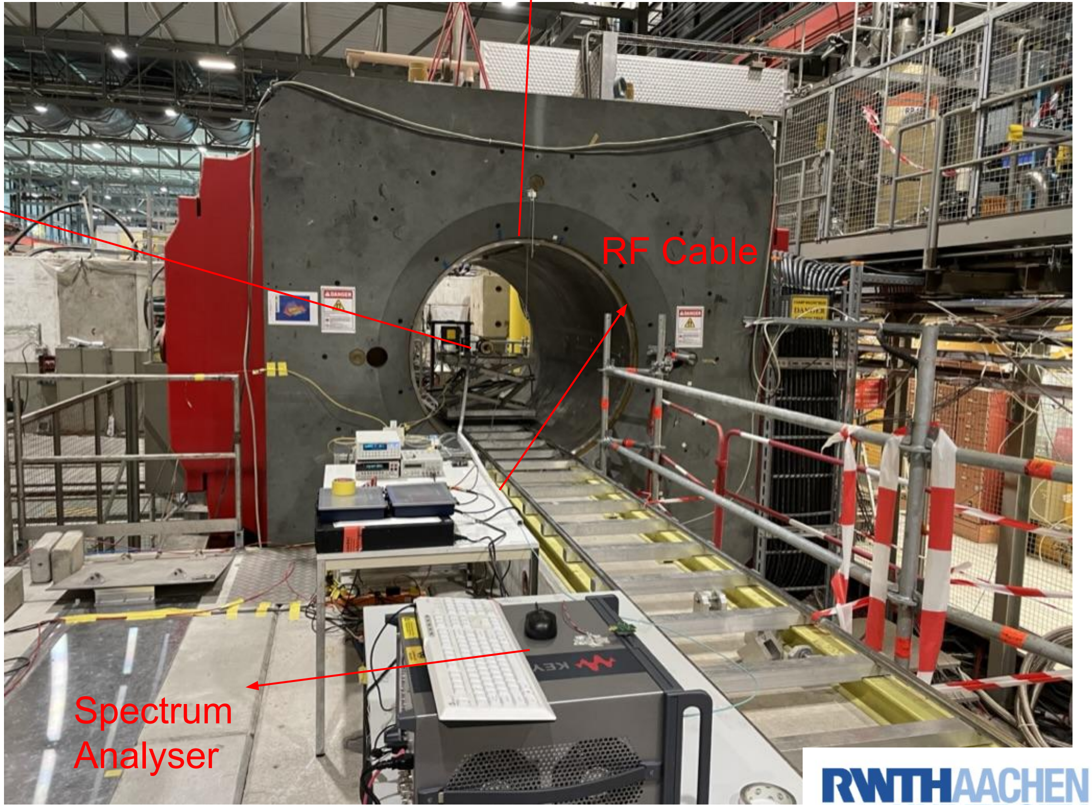
CB100 CERN 2023

Morpurgo Magnet



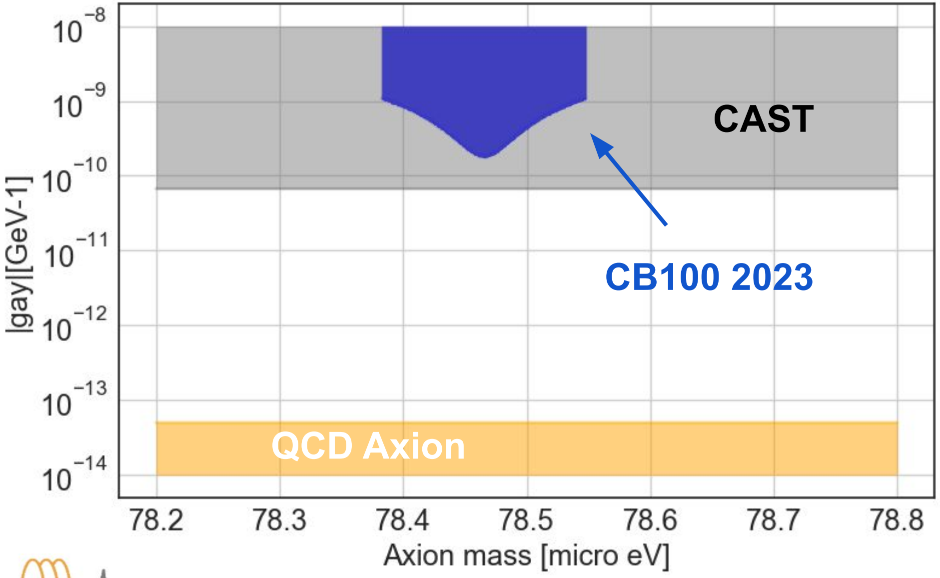
Set-up at Morpurgo

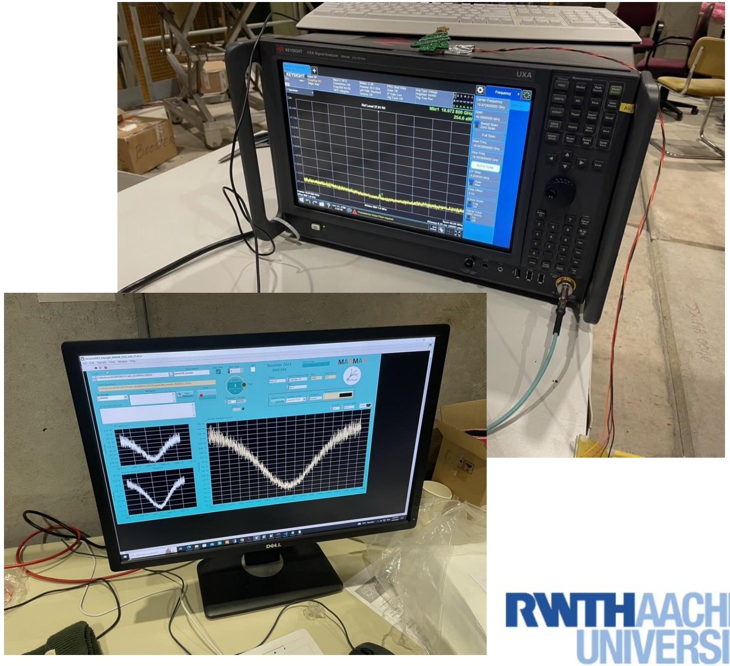




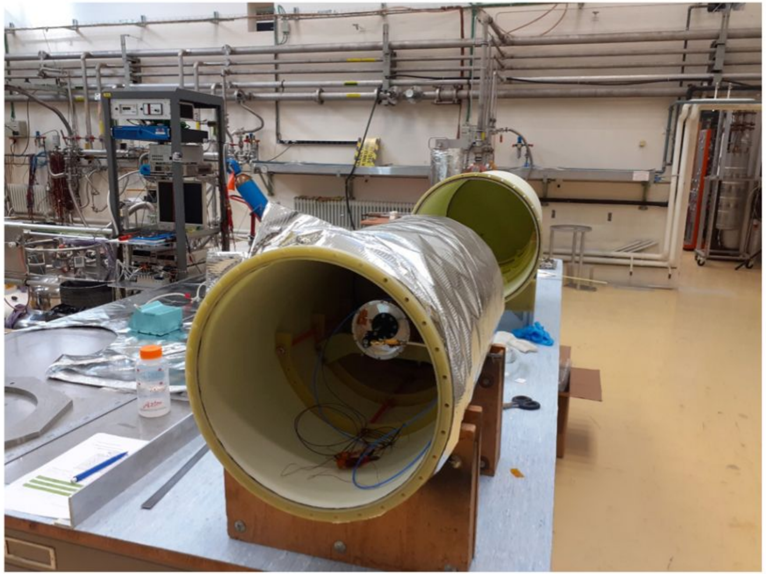
Sensitivity of CB100 2023

$$C_{a\gamma} = 234.3 \left(\frac{1m^2}{A}\right)^{1/2} \left(\frac{1.6T}{B_e}\right) \left(\frac{300MeV}{\rho_a}\right)^{1/2} \left(\frac{2200}{\beta^2}\right)^{1/2} \left(\frac{T_{sys}}{410}\right)^{1/2} \left(\frac{\Delta\nu}{20kHz}\right)^{1/4} \left(\frac{4days}{\Delta t}\right)^{1/4} \left(\frac{SNR}{5}\right)^{1/2}$$

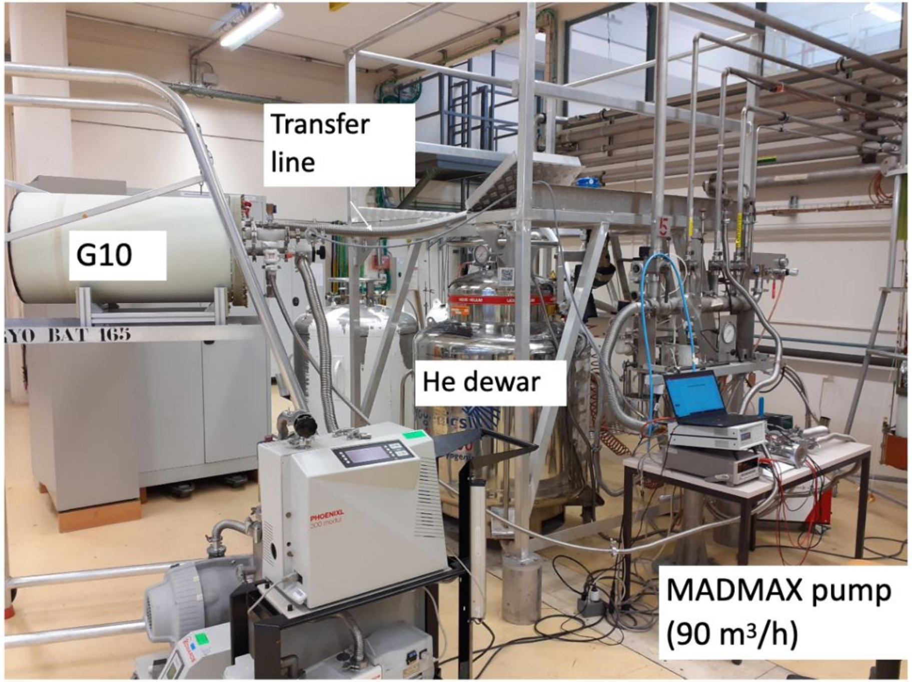




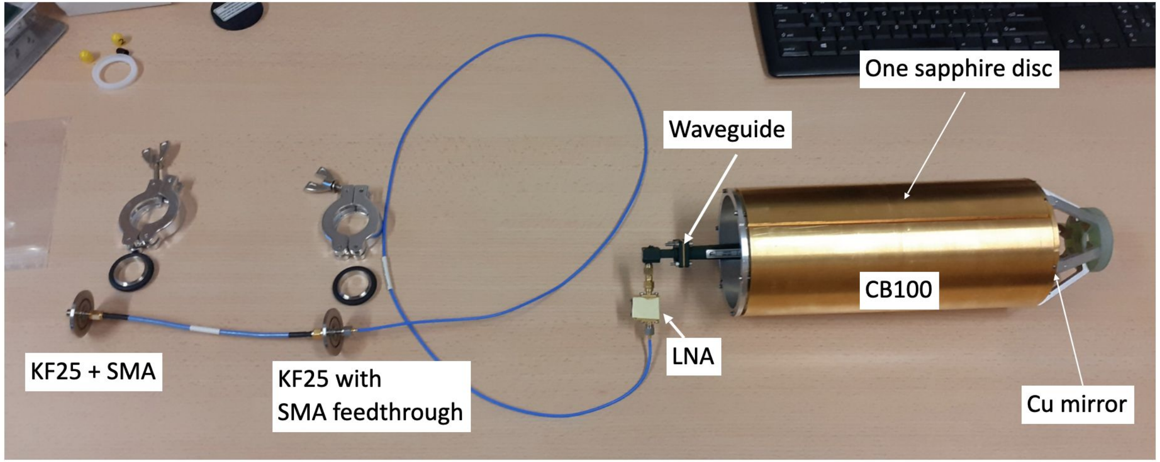
G10 Commissioning at CERN



Dimensions:
Length: 830 mm
Diameter: 475 mm



CB100 Mock-up



Three temperature sensors:

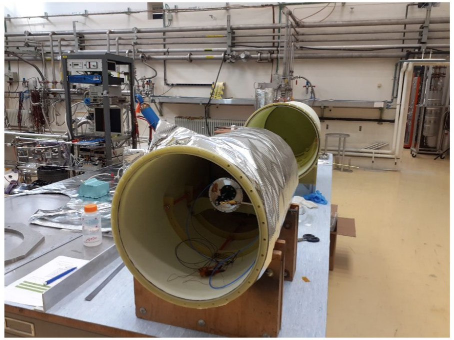
1) on LNA;
2) on sapphire disc;
3) on Cu mirror

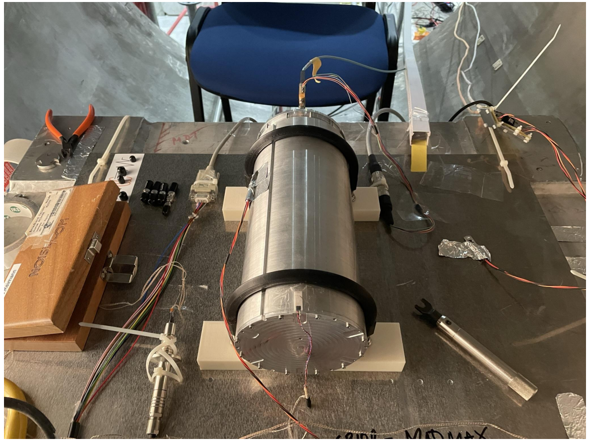
- All three sensors showed similar T(+/- 0.3K)
- approx 7 hours for cooldown (not optimised procedure)
- 23 hours stable conditions (bellow 10K)

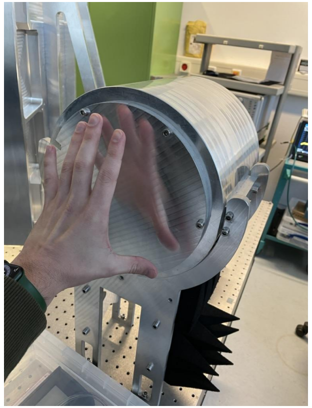
Future Plans 2024 - forward

- Continuation of Morpurgo Activities:

  CB100
  CB200 (200 mm diameter closed Booster)
  G10 Cryogenic chamber (Liquid He bellow 10K)







Conclusions

- Axions could solve strong CP problem + DM at the same time
- Dielectric Haloscopes can probe the existence of axion DM through axion to photon conversion
- MADMAX capable of spanning the unexplored range between 40 - 400 µeV
- First data taking with CB100 in March 2023
- Currently in Protoype stage and starting to take Data