



MADMAX: status update

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on behalf of the [MADMAX collaboration](#)

QCD axion

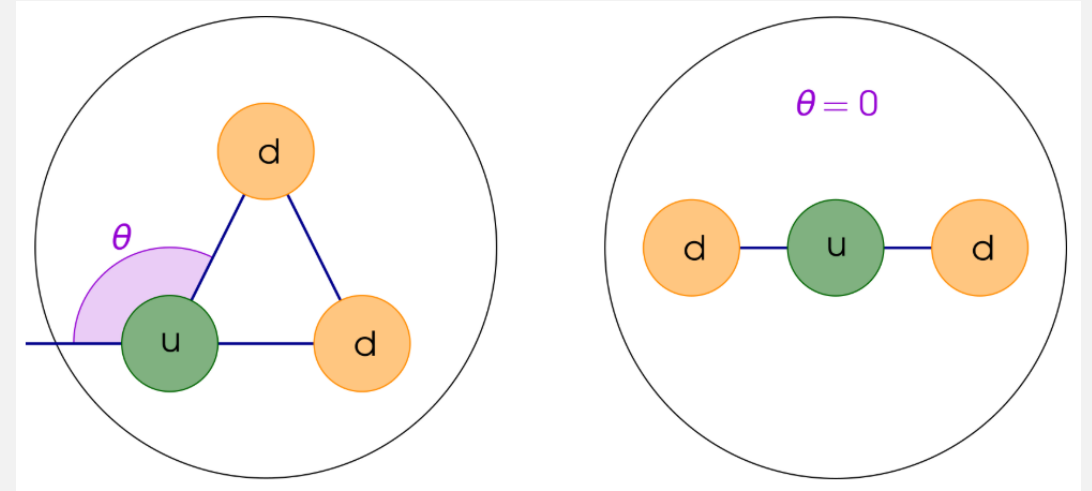
- **The strong CP problem**

- CP violation in QCD is controlled by θ
- Experimental bound: $|\theta| < 10^{-10}$
- There is no reason that CP violation in strong interactions should not occur

- **Peccei-Quinn mechanism**

- Introduces a new symmetry whose spontaneous breaking produces the axion
- This dynamic scalar field effectively replaces θ : $\theta \rightarrow \theta(t, x)$
- The potential of the axion field has a minimum at $\theta = 0$

- This makes the QCD axion a **well-motivated** cold dark matter candidate



QCD axion

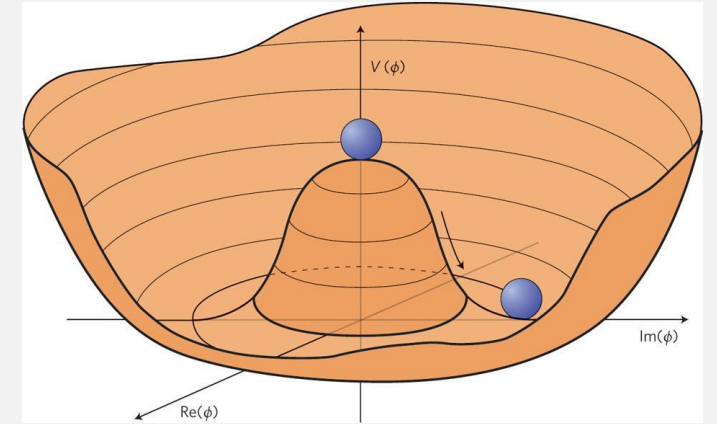
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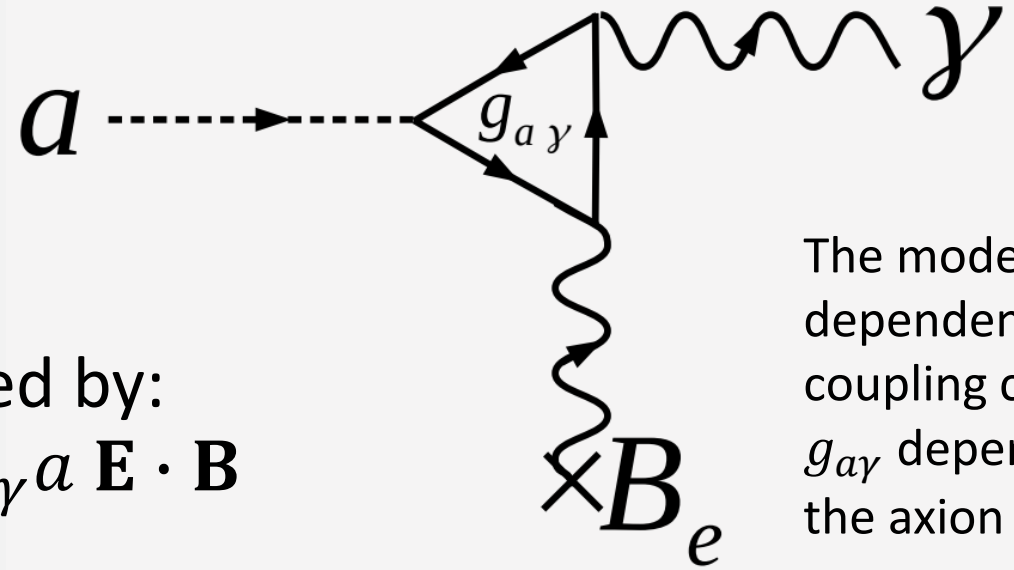
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QCD axion

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Searching for axions



- Axions couple to photons, as described by:

$$\mathcal{L}_{a\gamma} = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$

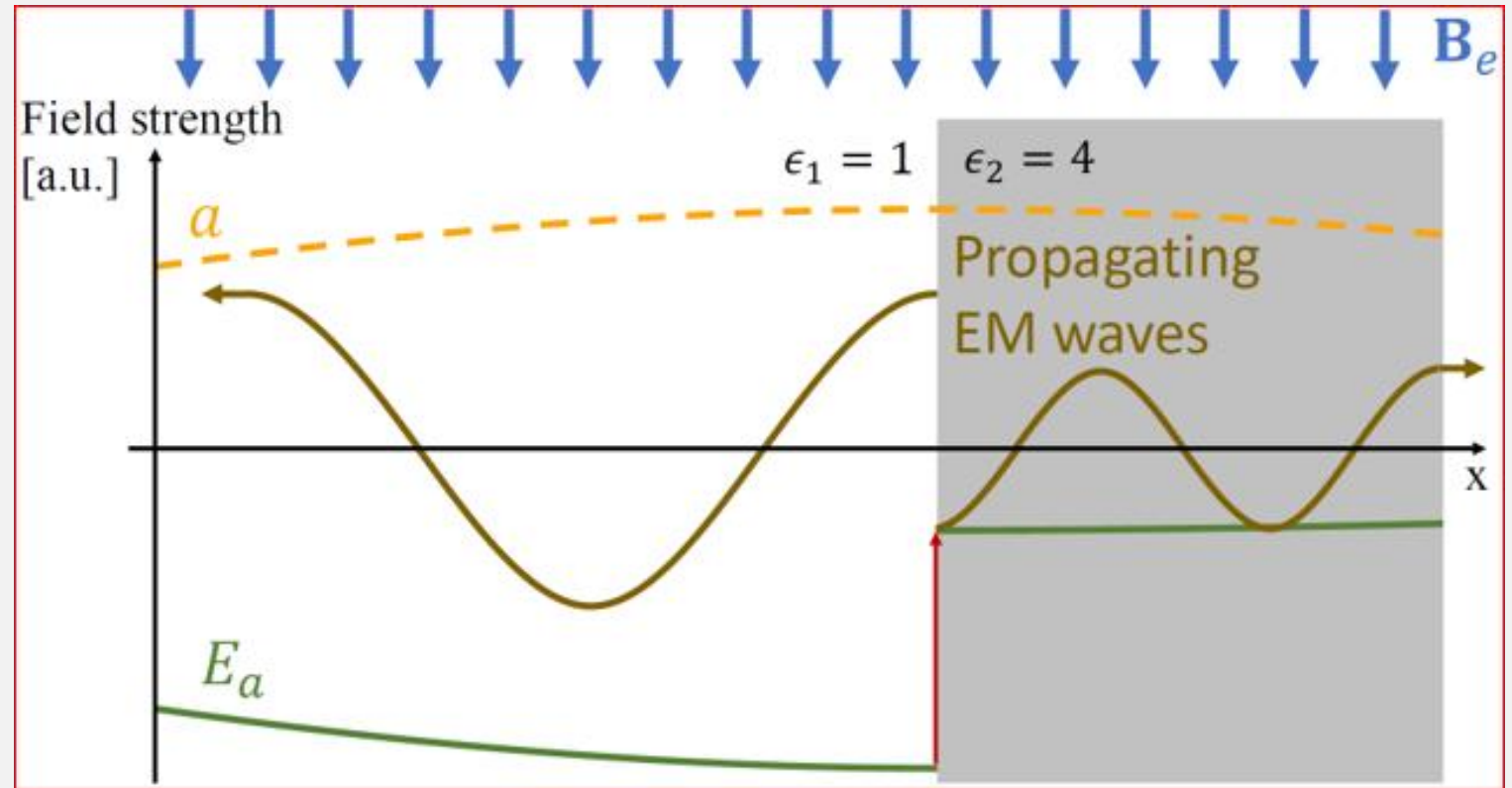
- Haloscope experiments search for axions in the galactic dark matter halo through the detection of the axion-induced electric field

$$\mathbf{E}_a = -\frac{g_{a\gamma}}{\varepsilon} \mathbf{B}_e a(t)$$

- Post-inflationary scenario predicts higher axion masses ($m_a > 40 \mu\text{eV}$) which require **new techniques** to explore

Dielectric haloscope

$$\mathbf{E}_a = -\frac{g_{a\gamma}}{\varepsilon} \mathbf{B}_e a(t)$$



The axion-induced electric field $\mathbf{E}_a$ depends on the dielectric constant of the medium ε



A discontinuity forms at the boundary of media with different ε

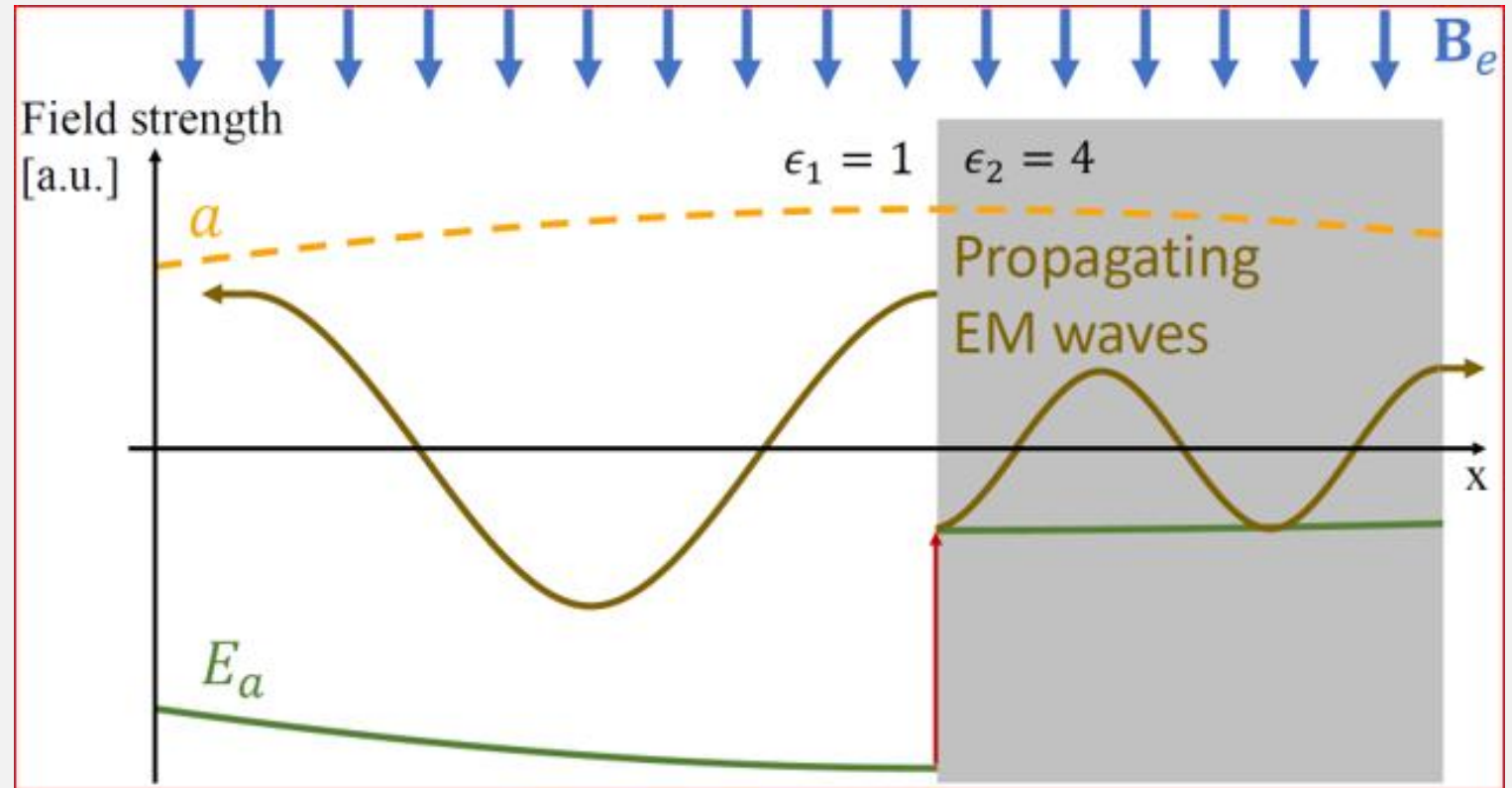


This is satisfied through the emission of EM waves at the interface with frequency

$$\nu_a \propto m_a$$

Dielectric haloscope

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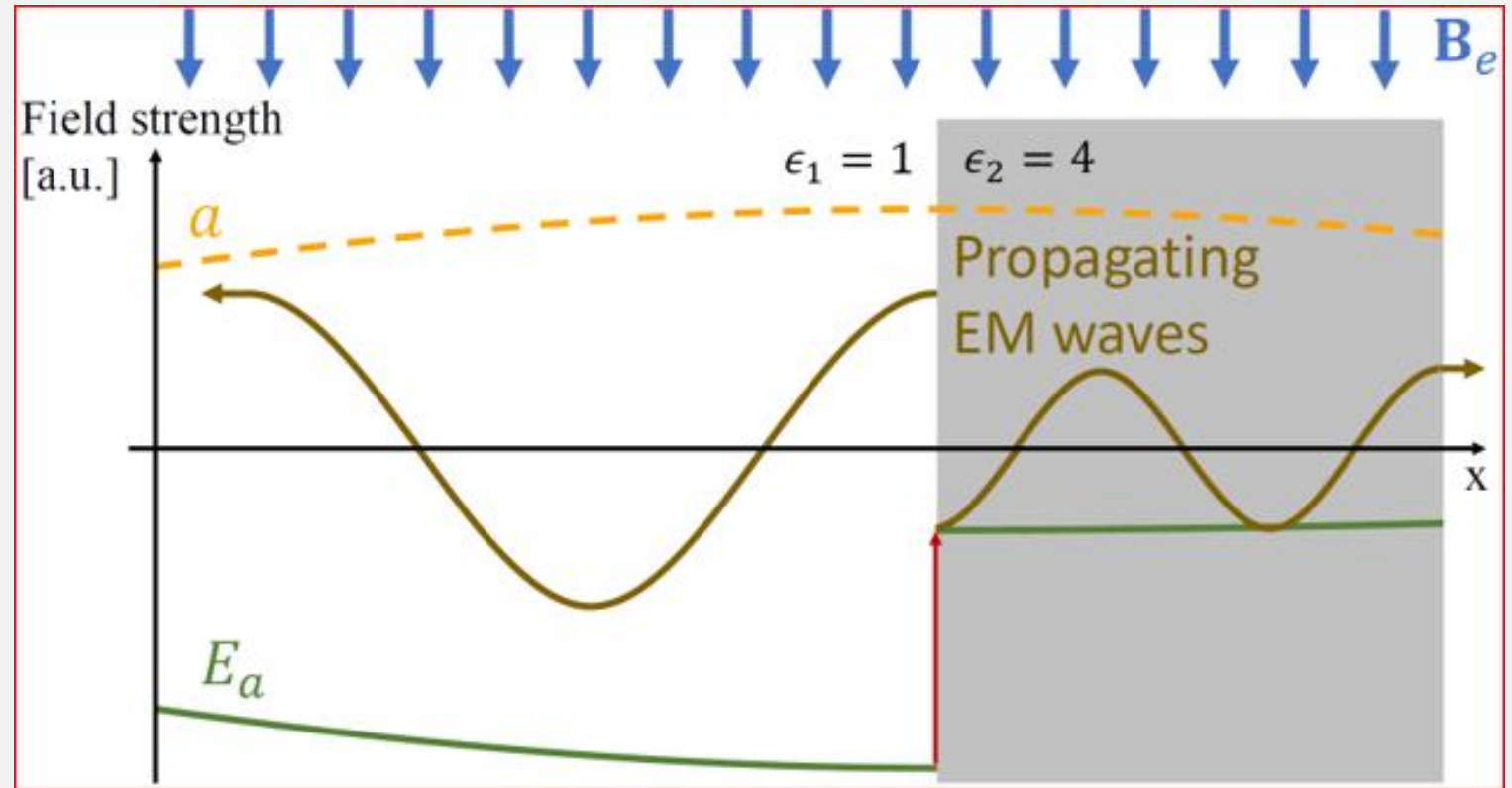
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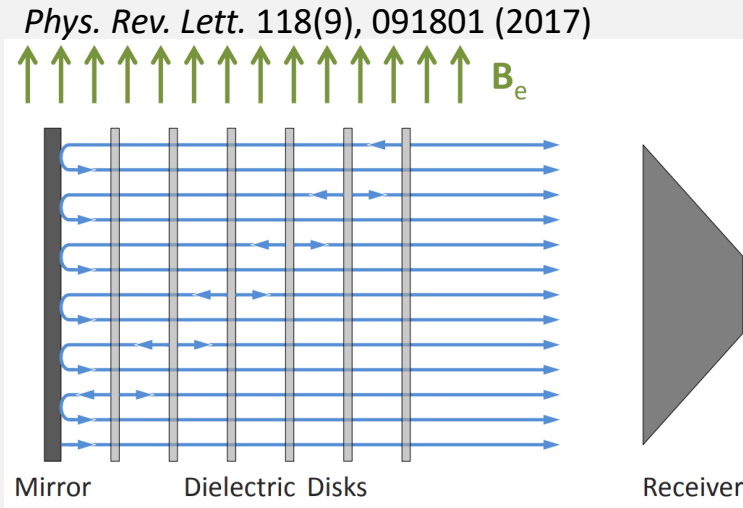
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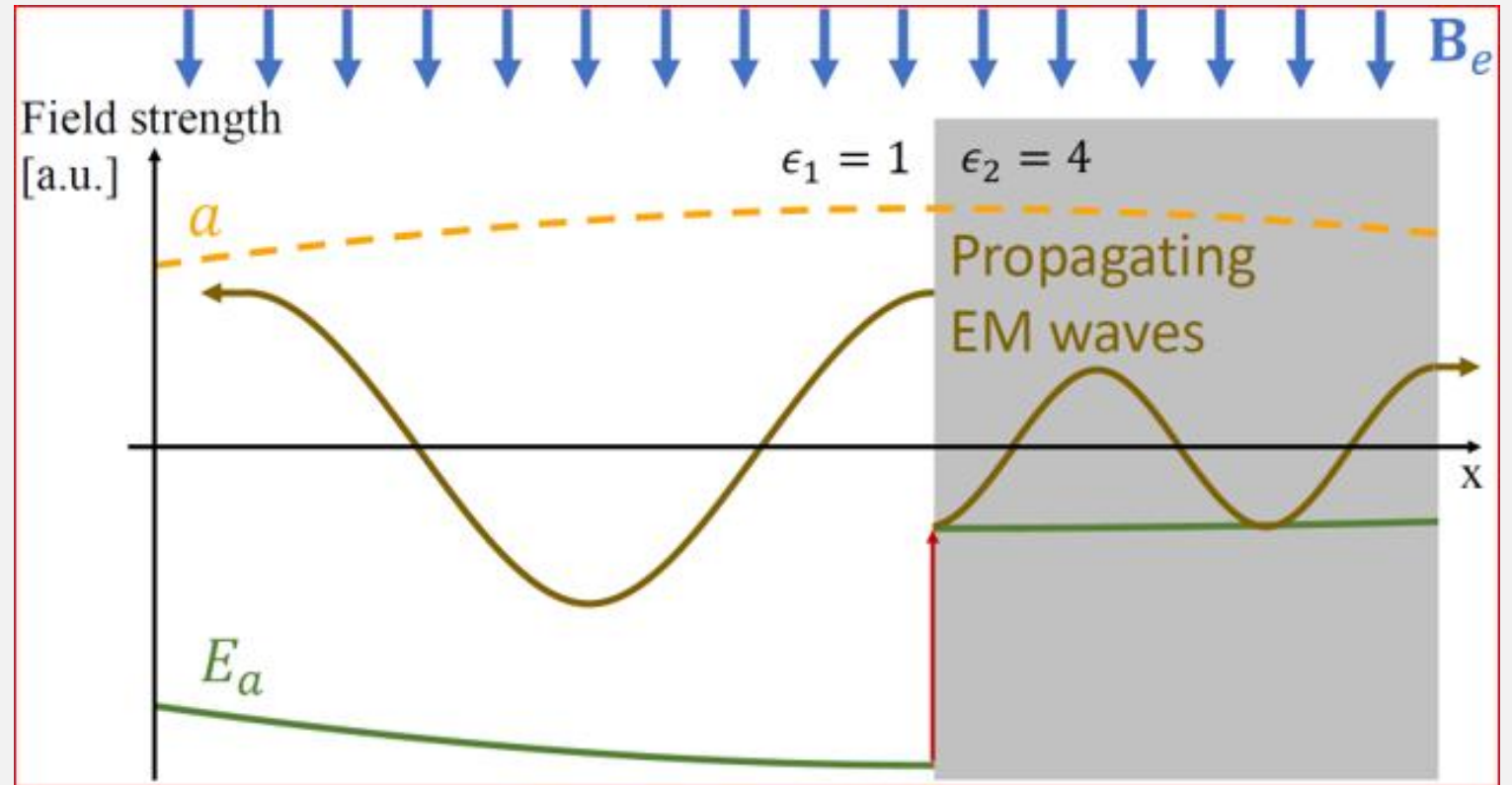
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$$\nu_a \propto m_a$$

Dielectric haloscope



A stack of dielectric **disks + mirror** (booster) can lead to constructive interference → **signal enhancement**



This is a novel approach to experimentally search for axions → **prototyping phase is required**

Dielectric haloscope: signal power

- For an 80 disk + mirror booster, MADMAX is expected to have a signal power of

$$P_{sig} \simeq 10^{-22} \text{ W} \cdot \left(\frac{|g_{a\gamma}|}{2 \times 10^{-14} \text{ GeV}^{-1}} \cdot \frac{100 \text{ } \mu\text{eV}}{m_a} \right)^2 \cdot \left(\frac{\rho_a}{0.3 \text{ GeVcm}^{-3}} \right) \cdot \left(\frac{\beta^2}{5 \times 10^4} \cdot \frac{B_e}{10 \text{ T}} \cdot \frac{A}{1 \text{ m}^2} \right)$$

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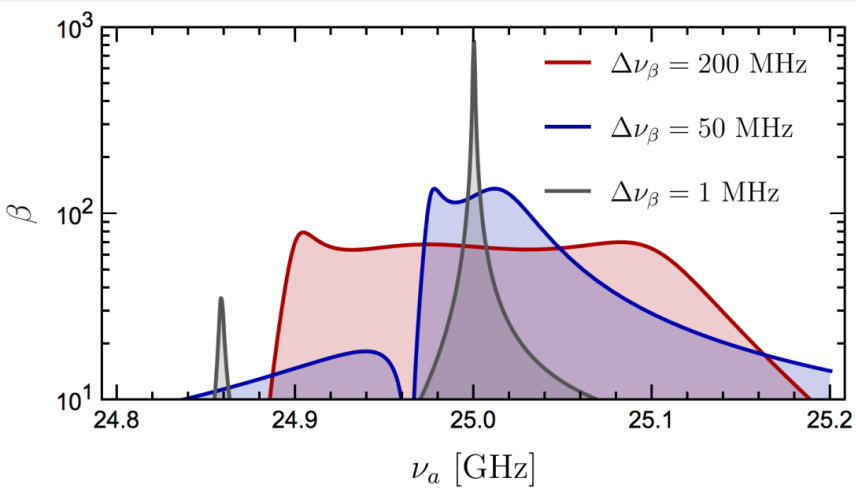
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Design dependent

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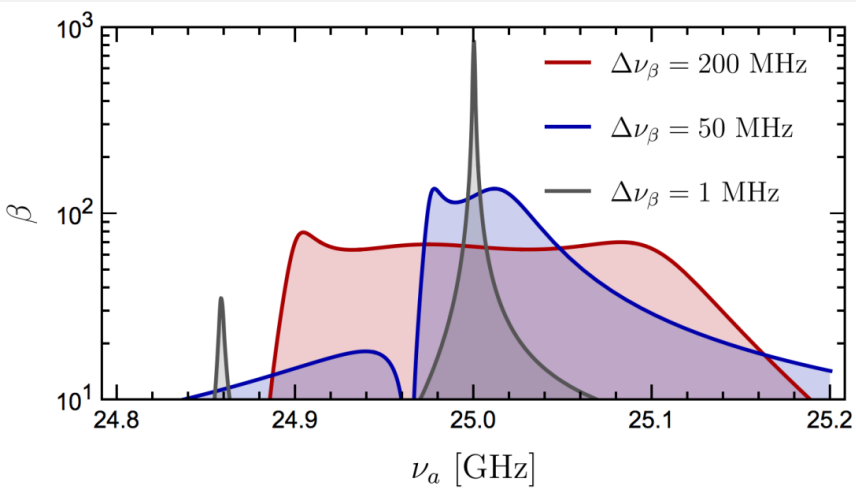
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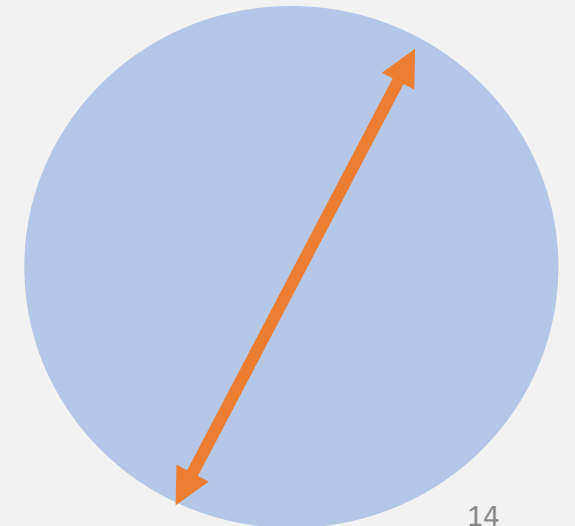
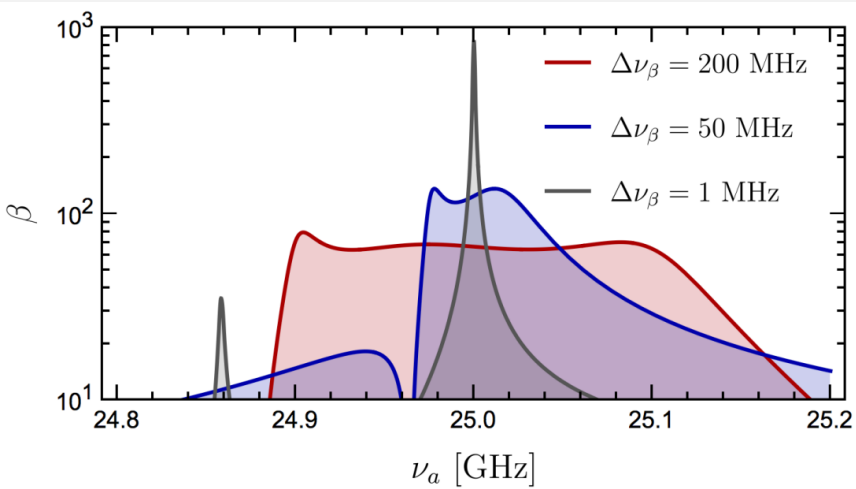
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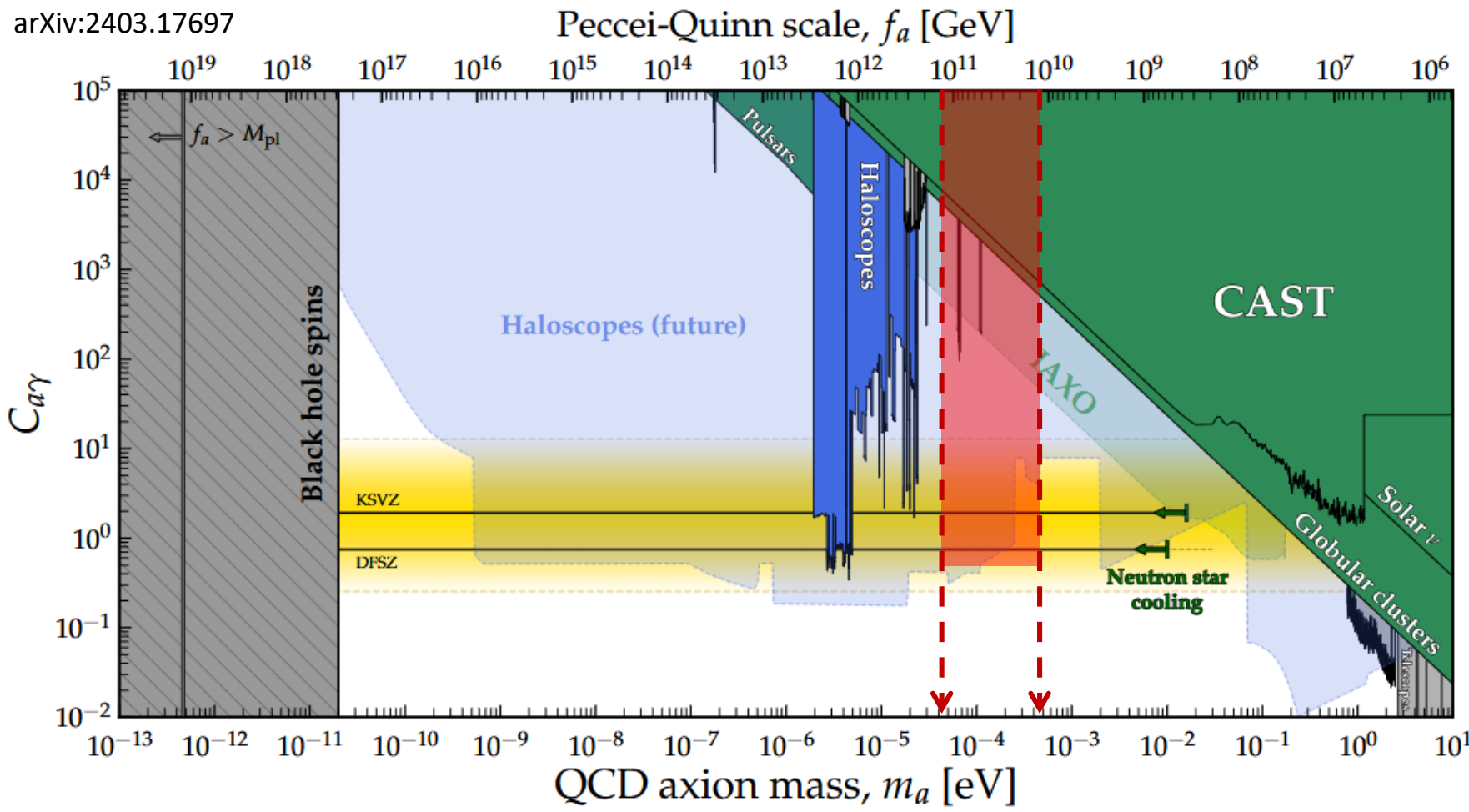
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MADMAX: overview

$$|C_{a\gamma}| = \left(\frac{|g_{a\gamma}|}{2 \times 10^{-14} \text{ GeV}^{-1}} \right) \left(\frac{100 \mu\text{eV}}{m_a} \right)$$

The **MA**gnetized **D**isk and **M**irror **A**xion **eX**periment will use a dielectric haloscope within a magnetic field to search for axions



Formed in 2017
with ~50
members across
13 institutes



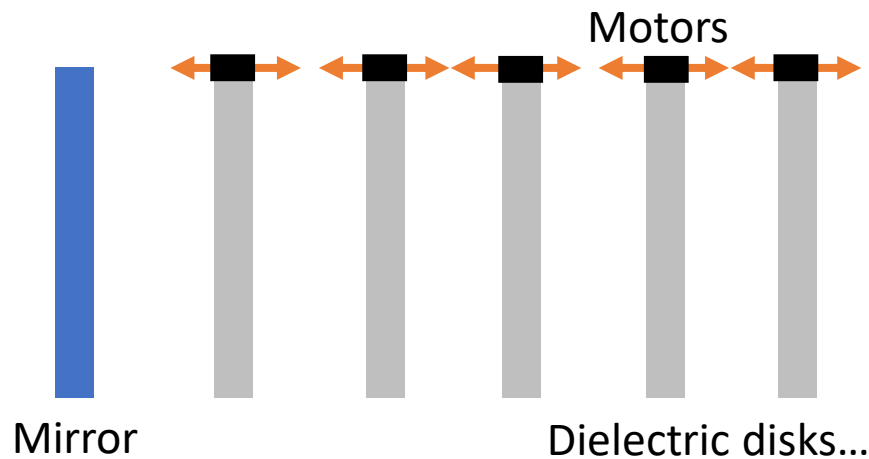
Location: DESY,
Hamburg

Goal: scan an axion mass range of **40-400 μeV** (post-inflationary)

MADMAX: design

Booster:

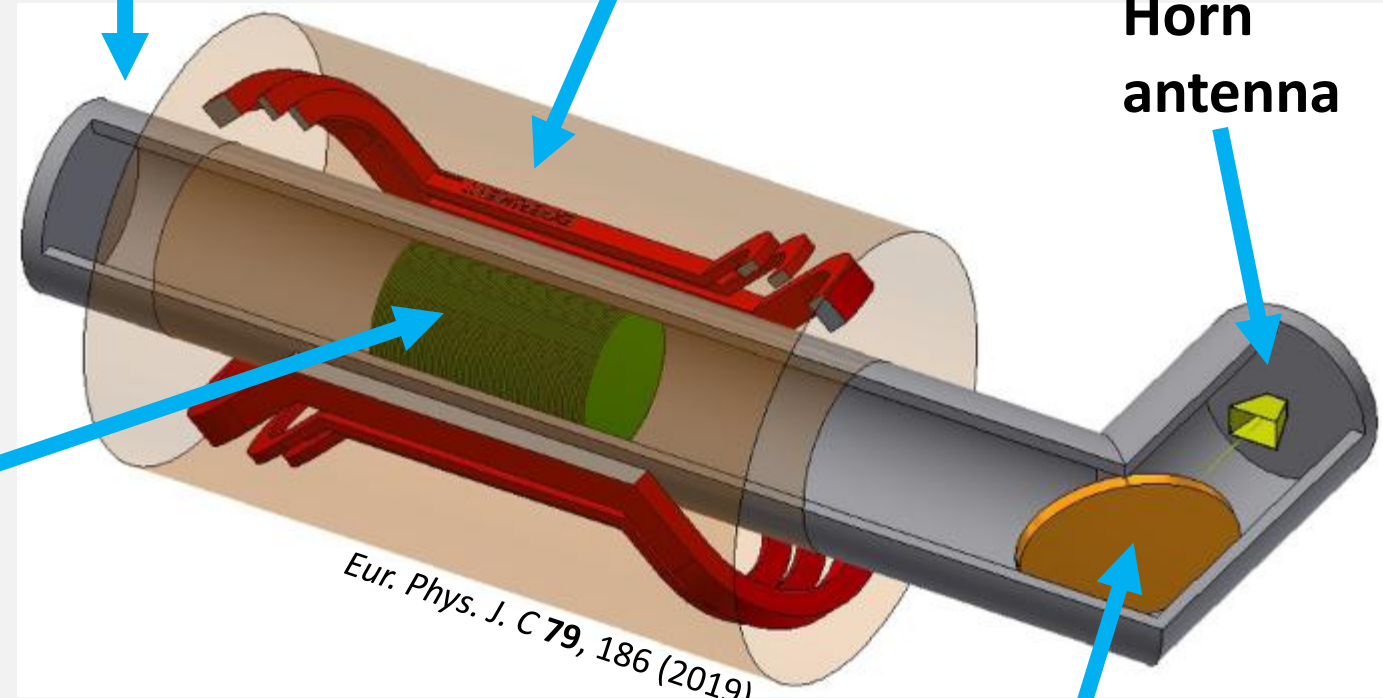
- Amplifies the signal and allows us to scan a range of frequencies
- Consists of 80 movable disks and a mirror
- Disks will have $\epsilon \gtrsim 10$



Cryostat: 4K

Magnet: 9T

Horn antenna



Focusing mirror

MADMAX: design

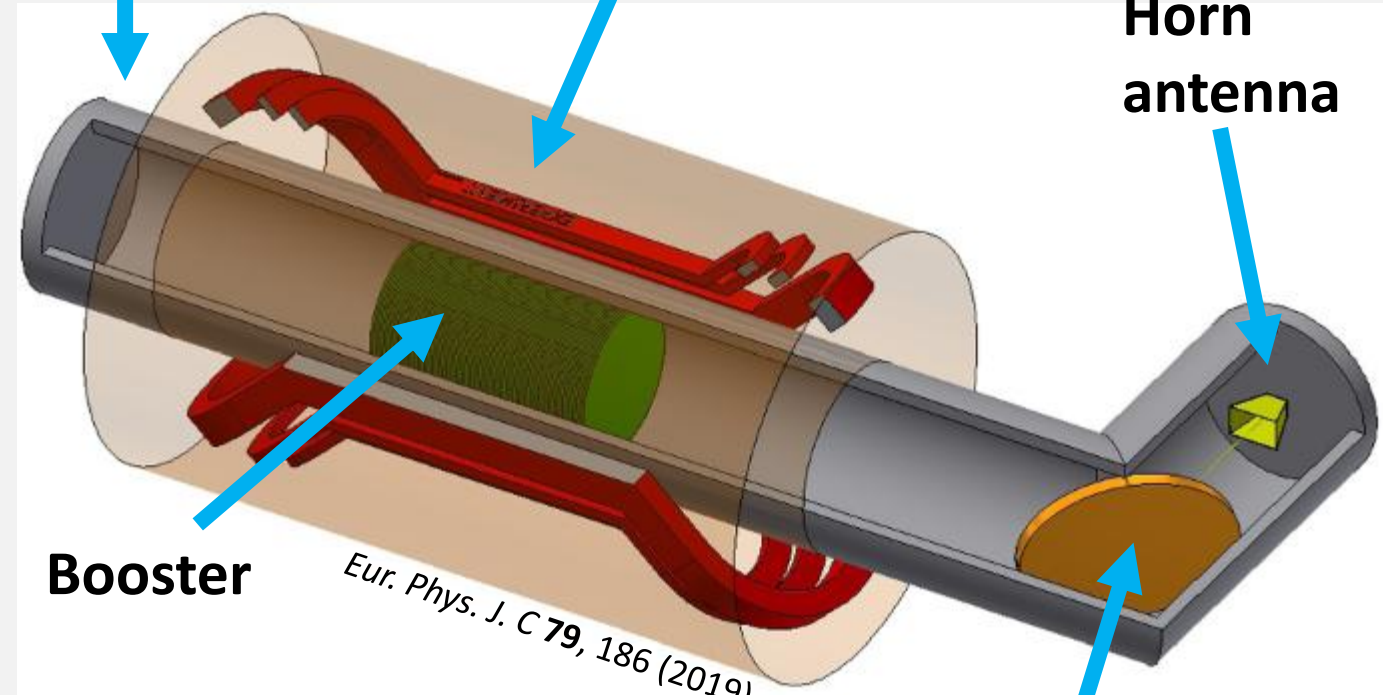
Technical challenges:

1. Develop and build a large dipole magnet
2. Calibrate RF response for frequencies > 10 GHz
3. Design moveable disks at μm level precision

Cryostat: 4K

Magnet: 9T

Horn antenna

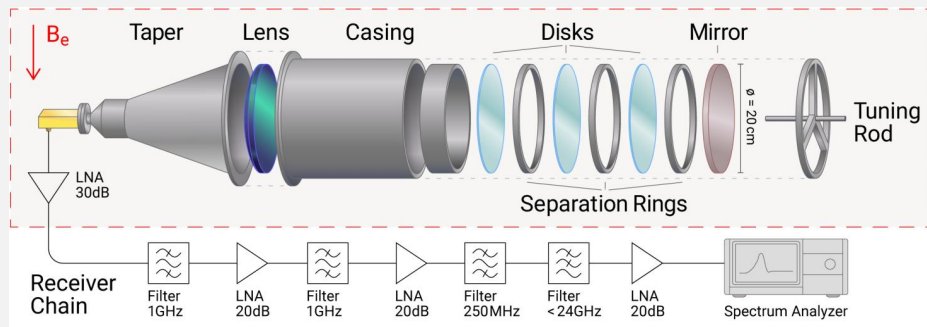


Booster

Eur. Phys. J. C 79, 186 (2019)

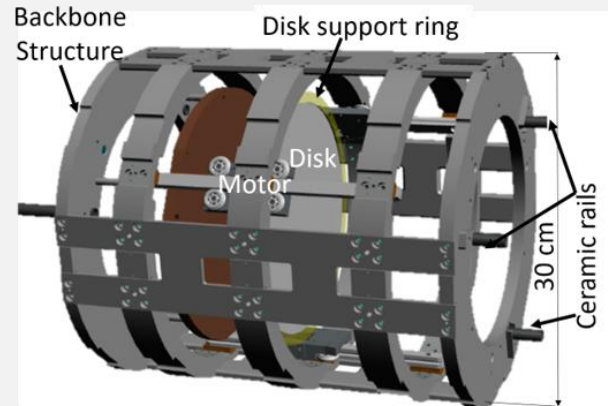
Focusing mirror

MADMAX: prototypes



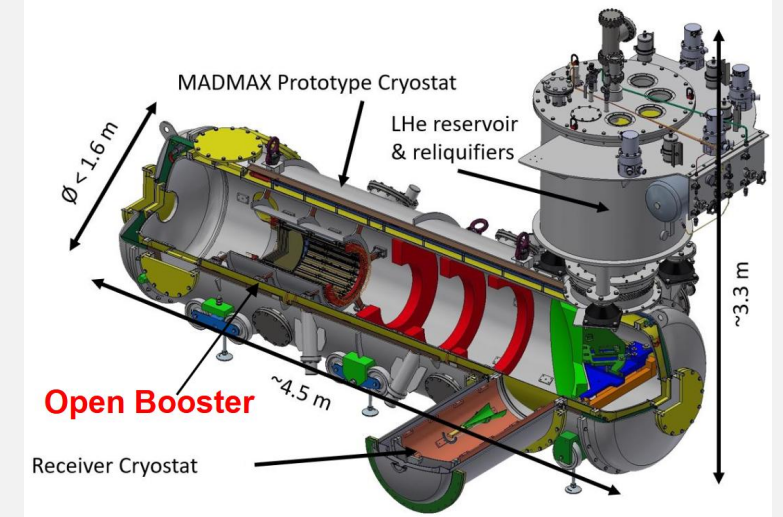
CB200

First axion dark matter search using a dielectric haloscope



OB200

First demonstration of tunability



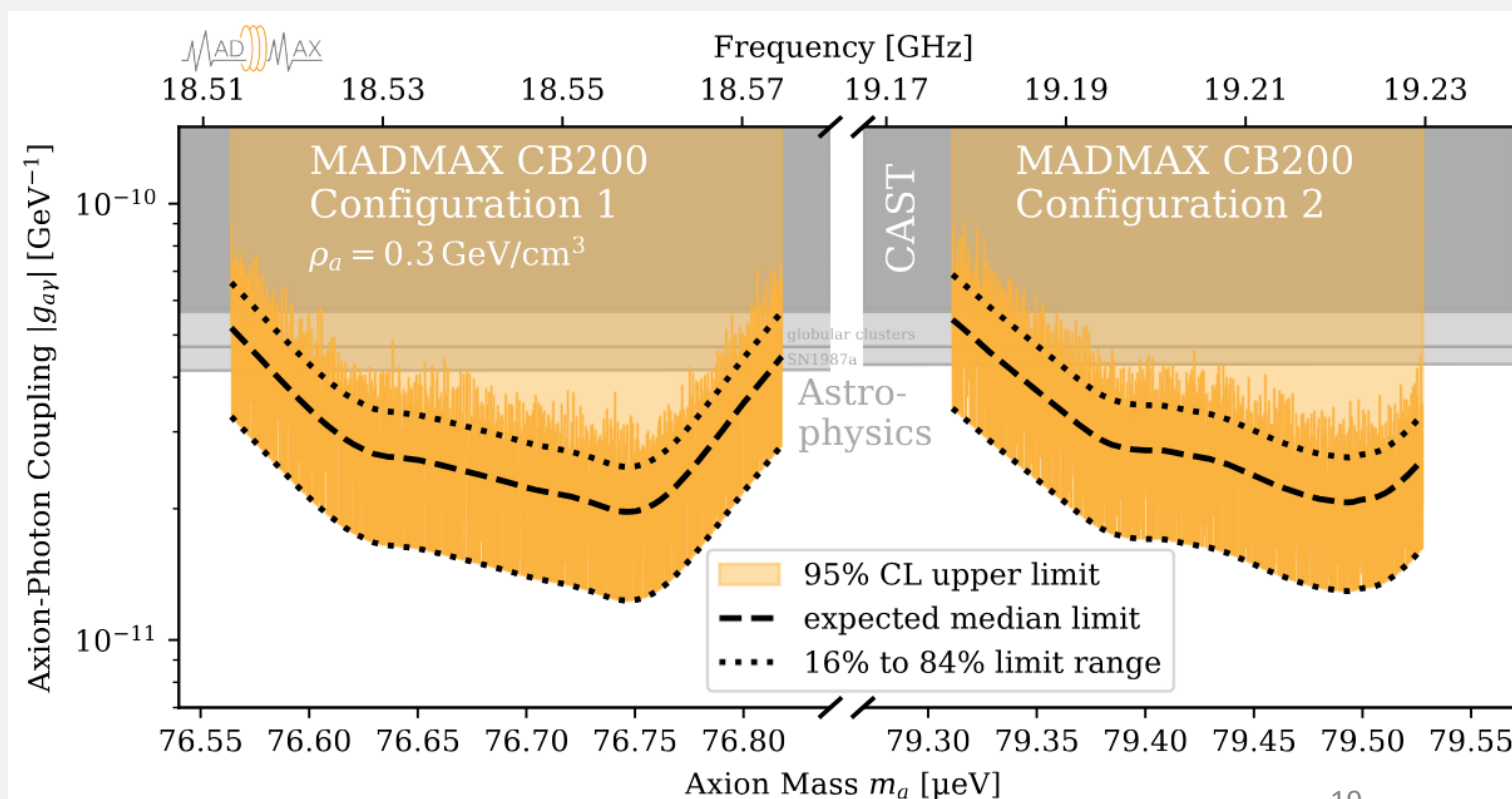
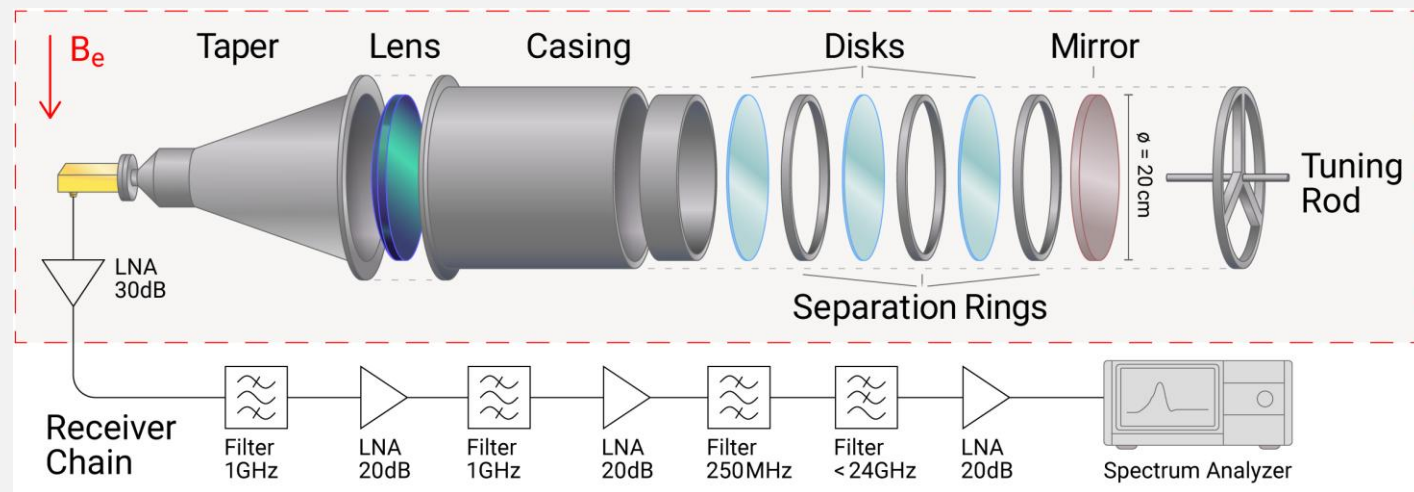
OB300

The final prototype

CB200

- First DM axion search using a dielectric haloscope
- Performed inside the 1.6 T Morpurgo magnet at CERN
- Over 14.5 days of data collection, no axion signal was detected
- World's best limit at $\sim 80 \mu\text{eV}$

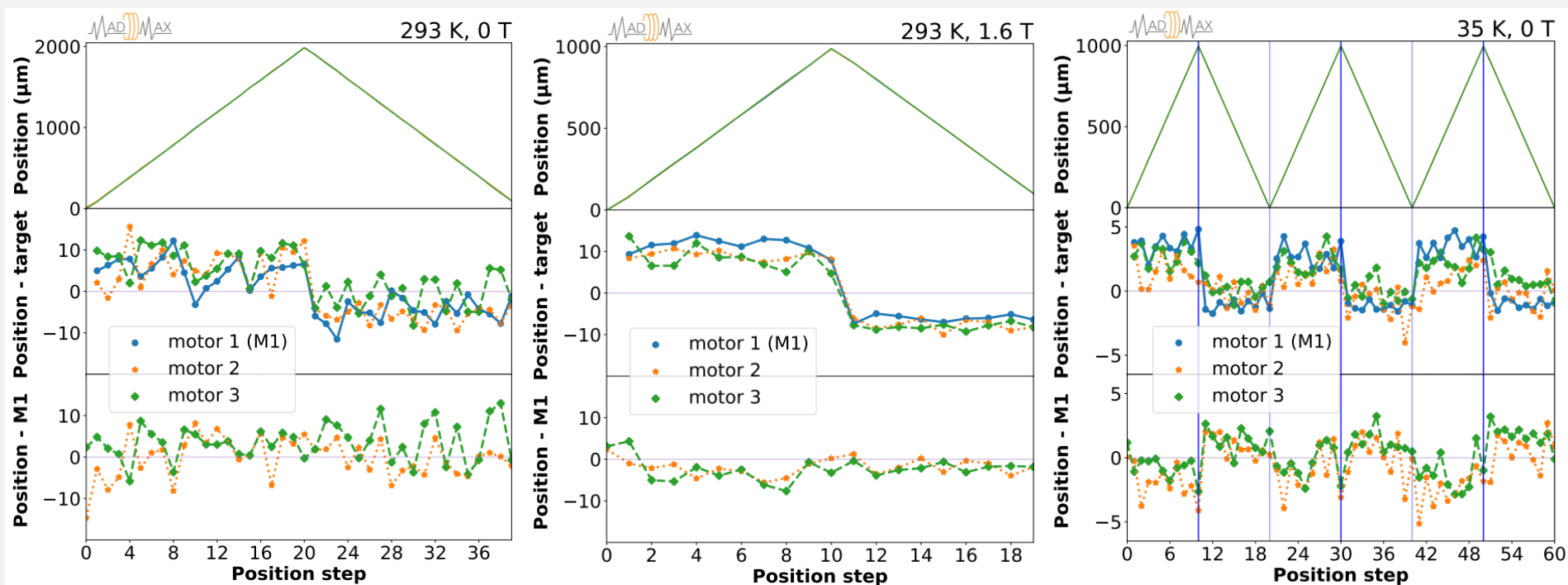
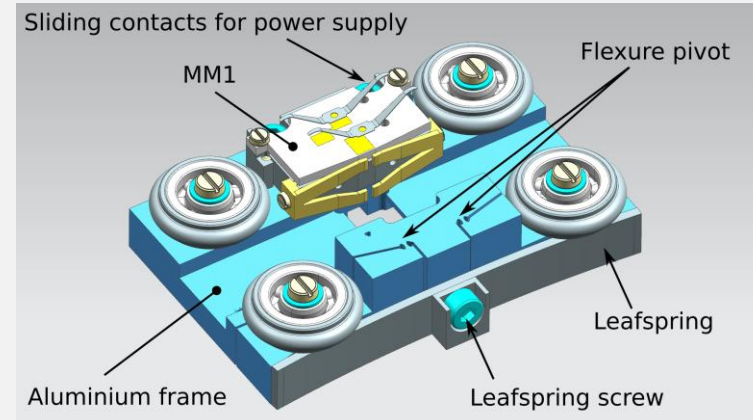
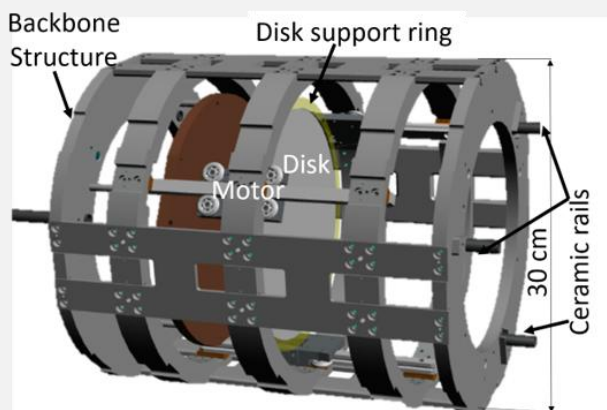
95% CL exclusion limit down to
 $|g_{a\gamma}| \sim 2 \times 10^{-11} \text{ GeV}^{-1}$



OB200

Inter-motor distance $< 20 \mu\text{m}$

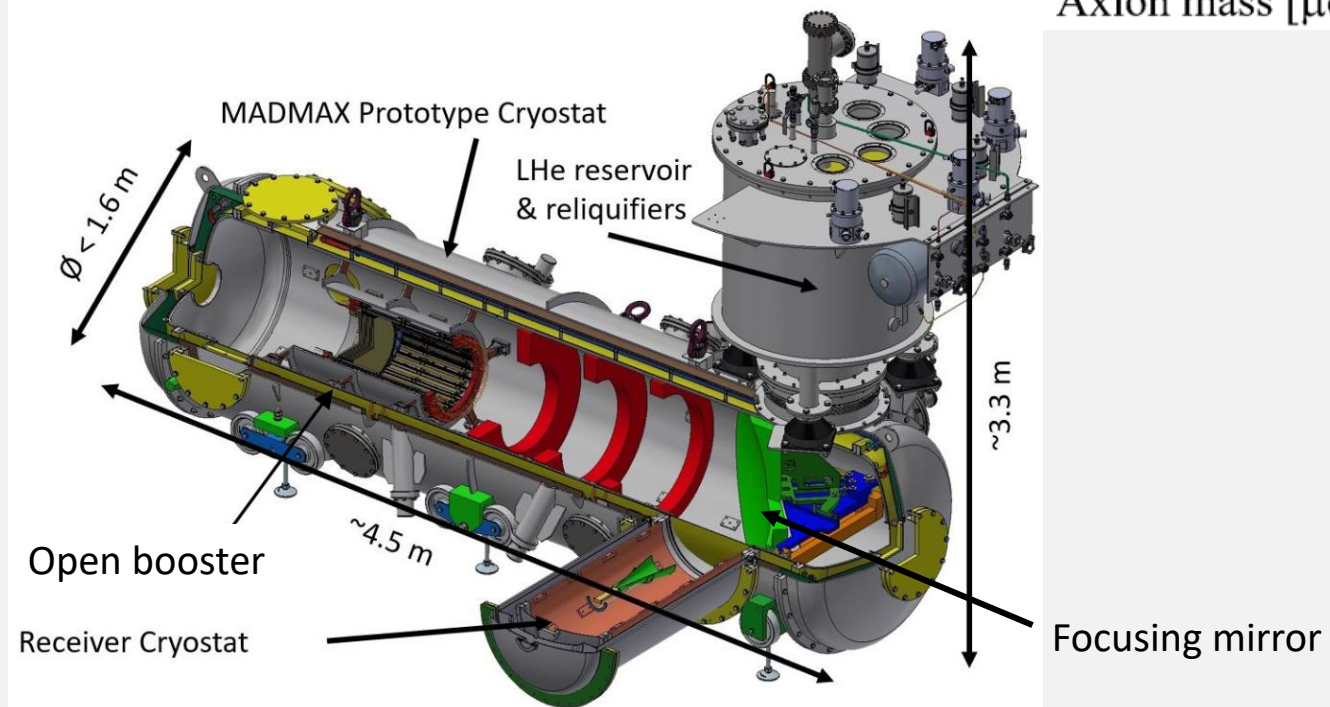
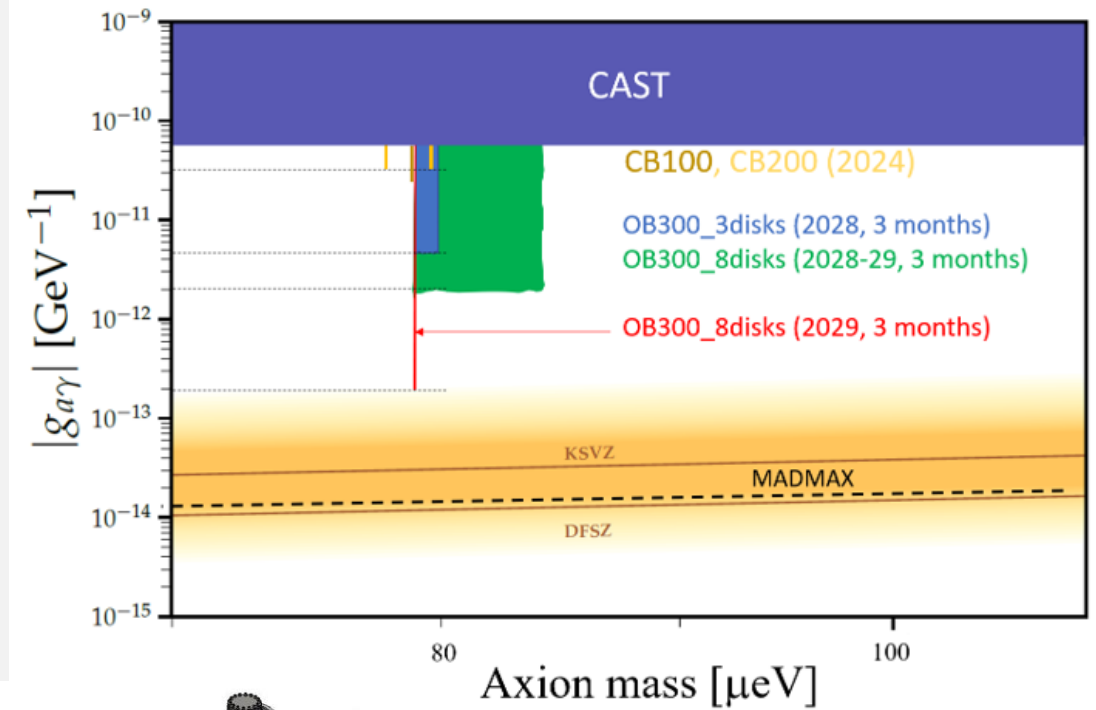
Stability $< 1 \mu\text{m}$



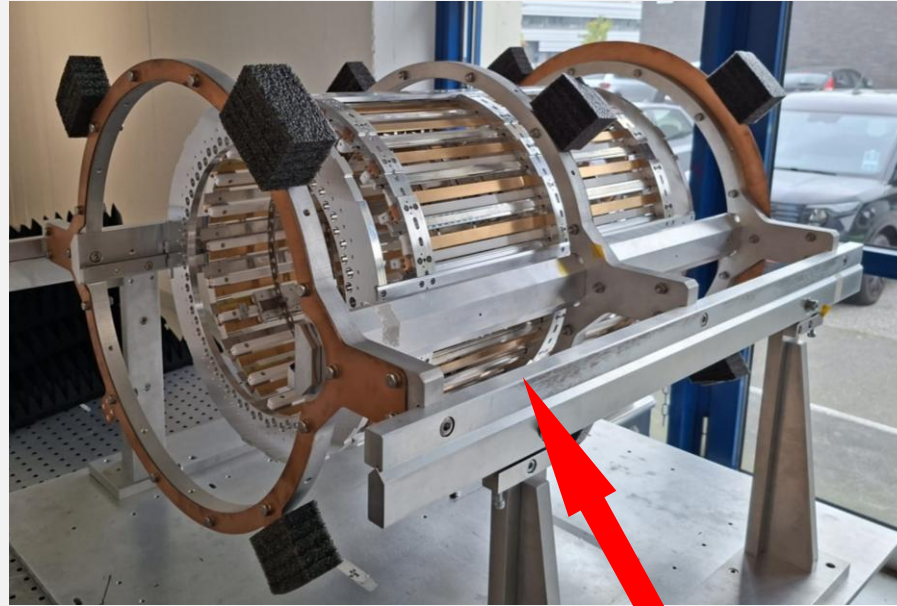
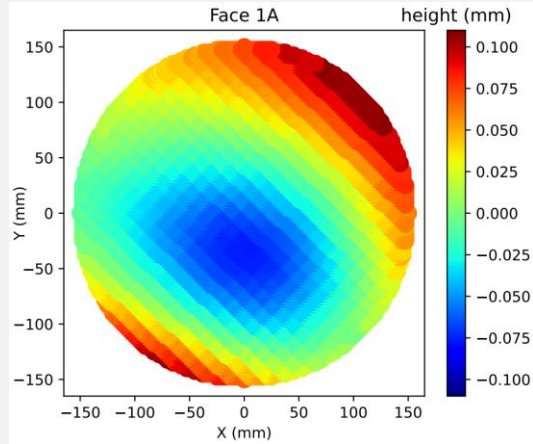
Disks can be precisely moved in the cold state, demonstrating the **feasibility of a tunable booster**

OB300

- Final prototype
- 3-20 moveable disks with a 300 mm diameter
- The booster will be mounted within a cryostat
- Cryostat will be placed inside the Morpurgo magnet

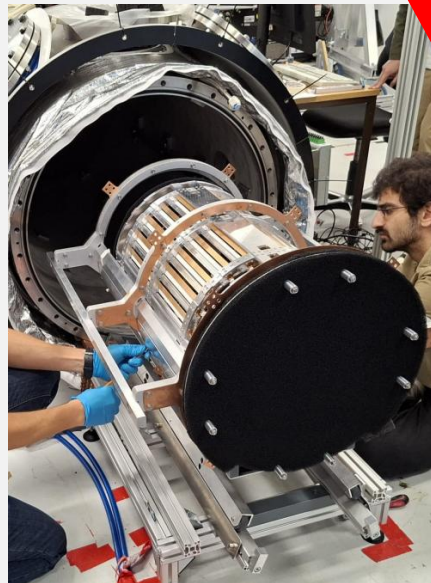


The booster

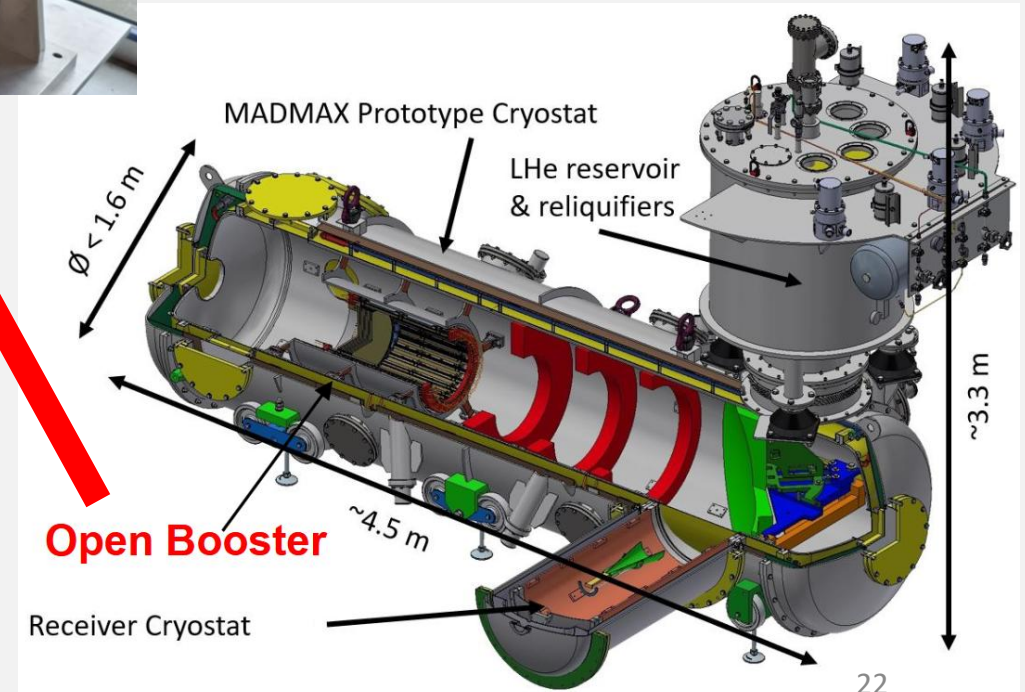


The sapphire disks are held in a titanium support ring

The booster is placed into the cryostat using a specially designed insertion tool



- Each disk will have three motors
- The motors slides along the rails
- The maximum number of disks the booster can hold depends on the number of rails

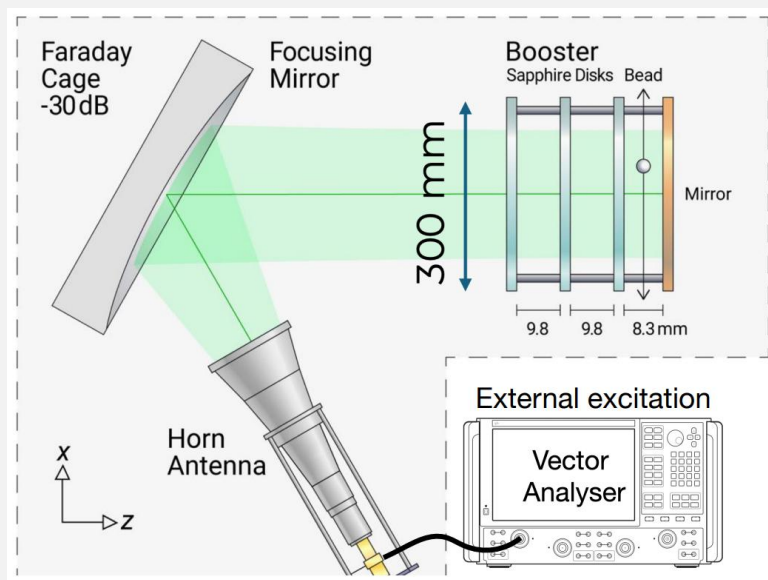


In-situ boost factor determination

- **Reciprocity:** introduce a reflection-induced electric field to determine the boost factor

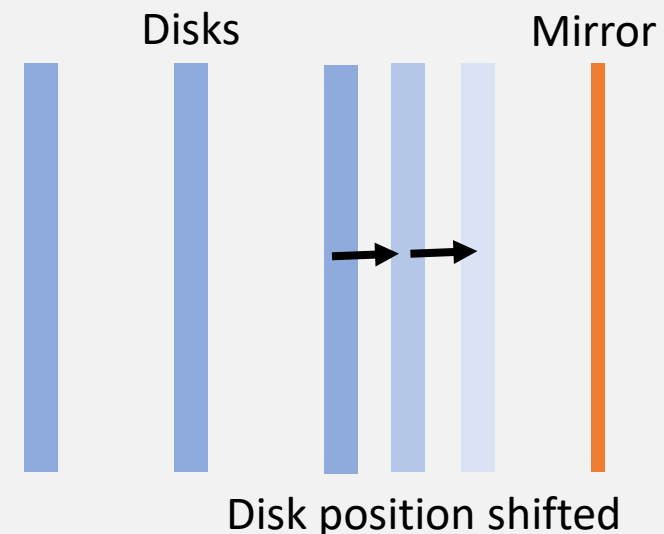
Bead-pull

- **Bead used to perturb the field** and change in reflection coefficient is determined



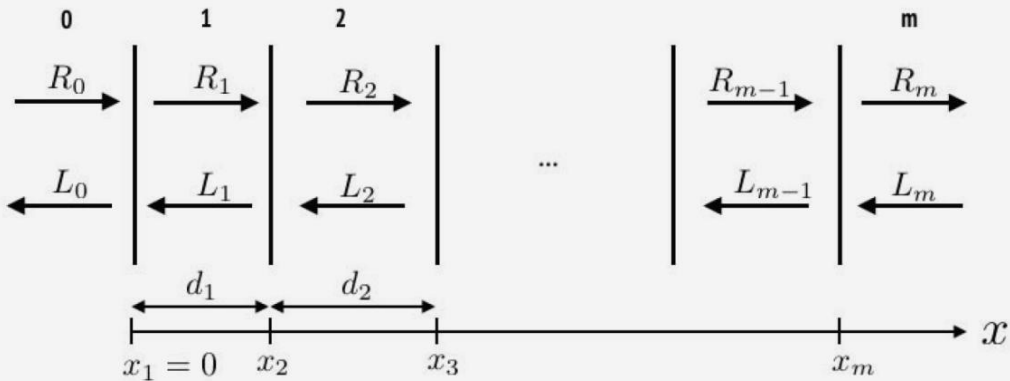
Gradient method

- **Field is perturbed by tiny movements of the disks** themselves and change in reflection coefficient is determined



Boost factor simulations

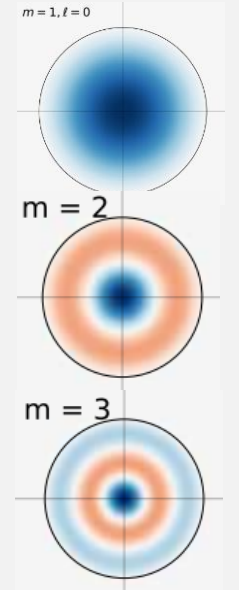
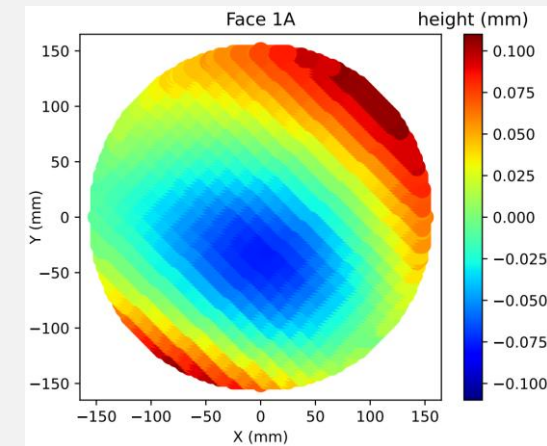
Transfer matrices



$$\begin{pmatrix} R_m \\ L_m \end{pmatrix} = T \begin{pmatrix} R_0 \\ L_0 \end{pmatrix} + M \begin{pmatrix} E_0 \\ E_0 \end{pmatrix}$$

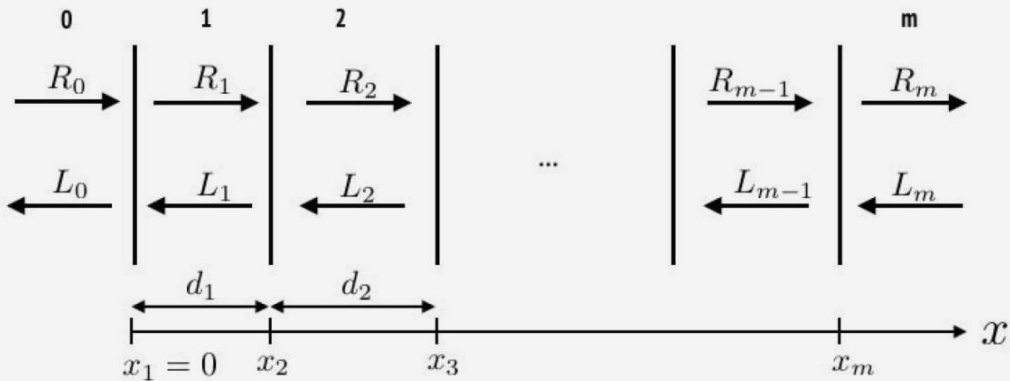
3D simulations

- Breaks the total electric field into radial and azimuthal modes
- Imperfections in the disks cause these to mix as they propagate through the system



Boost factor simulations

Transfer matrices

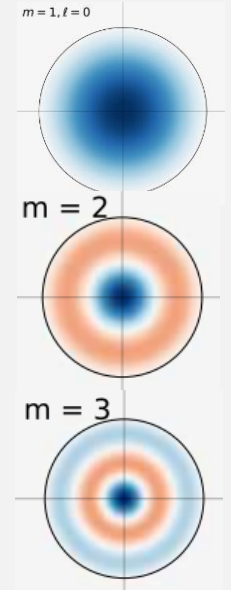
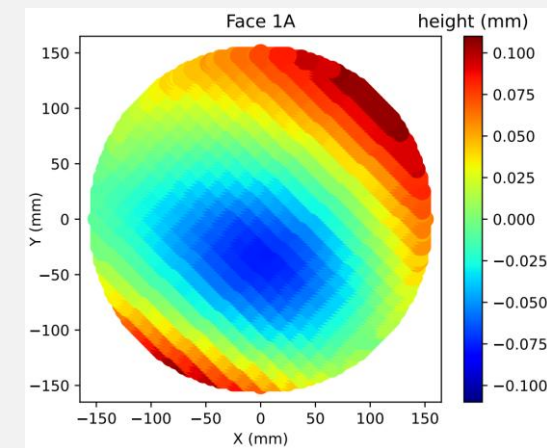


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Describes how the EM waves propagate, reflect and transmit through each layer of the booster

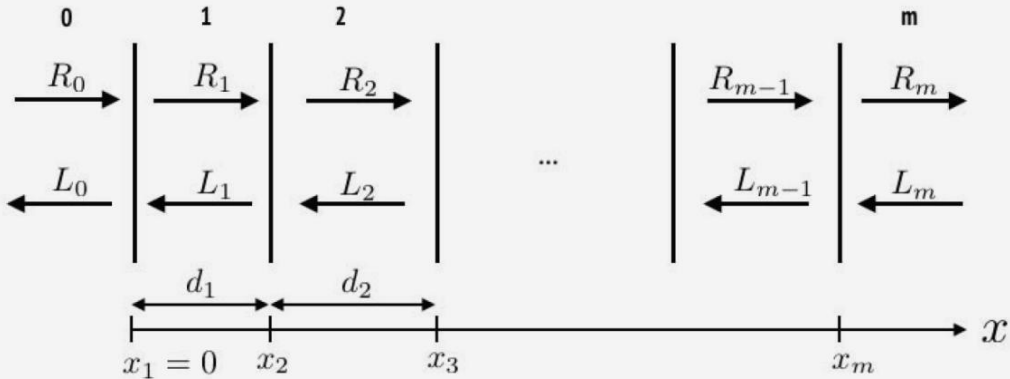
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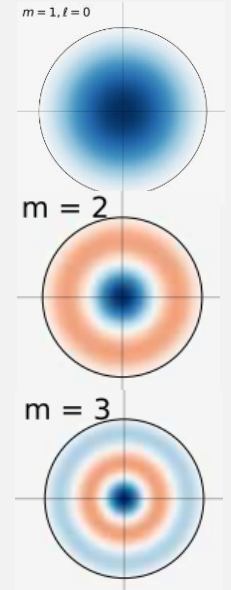
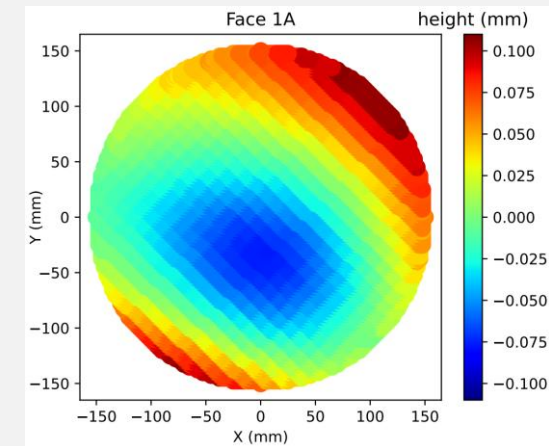


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Describes how the EM waves are generated at each boundary

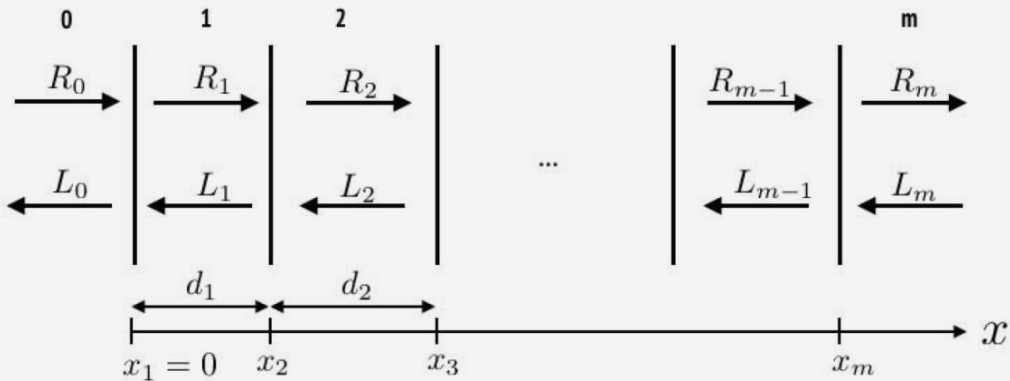
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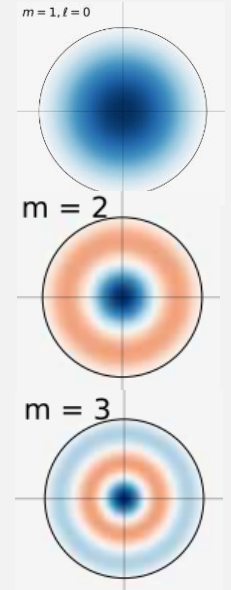
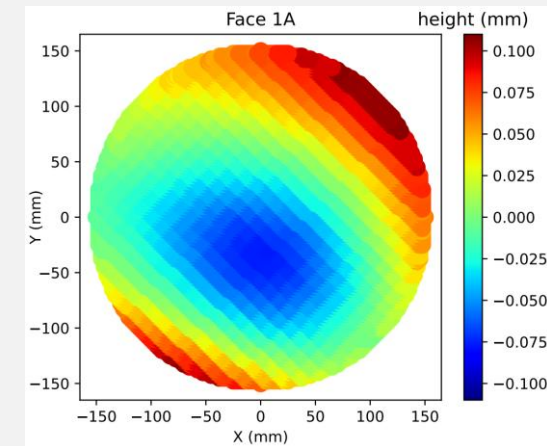


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$$\beta = \frac{L_0}{E_0} = \frac{M[2,1] + M[2,2]}{T[2,2]}$$

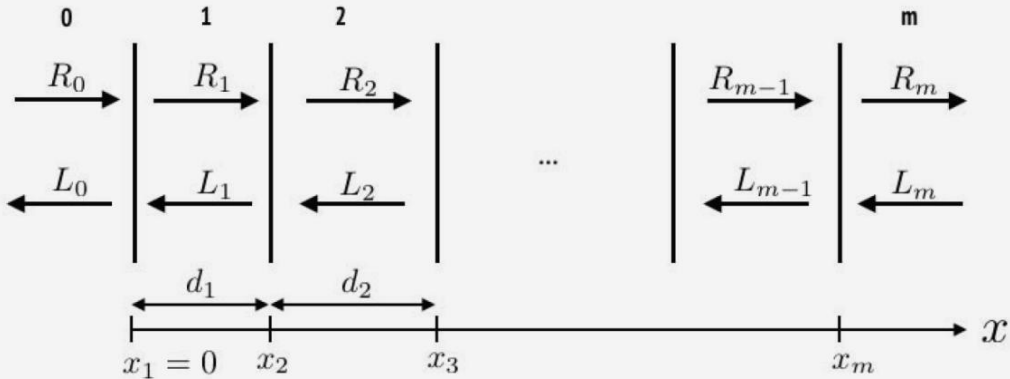
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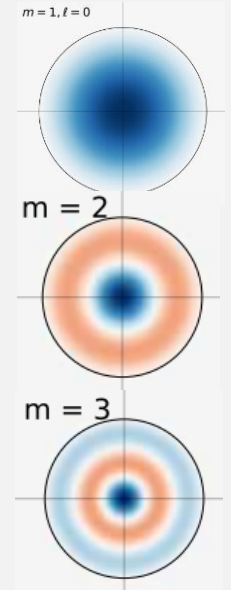
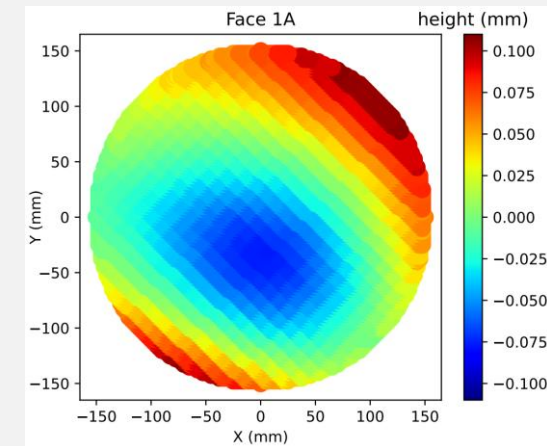


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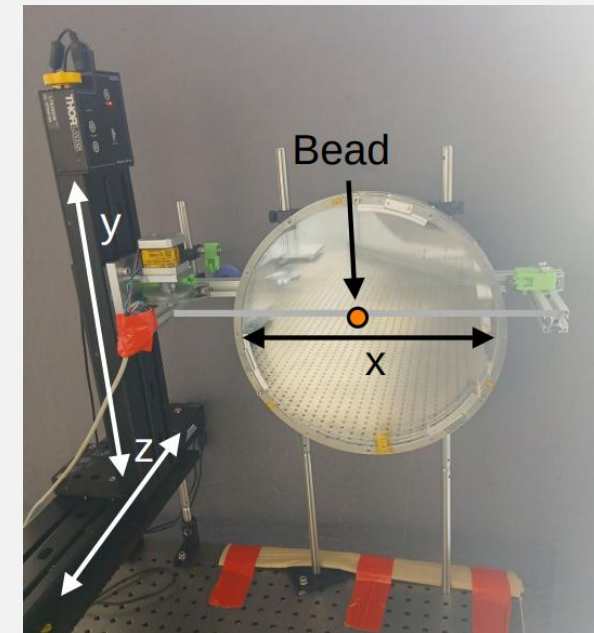
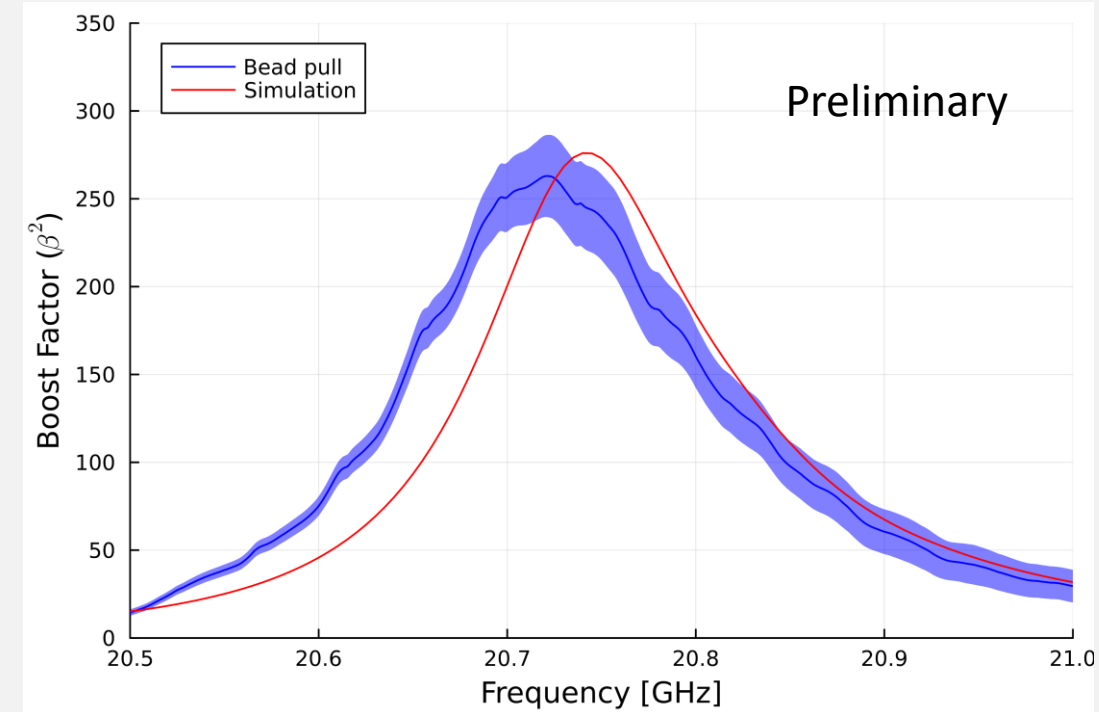
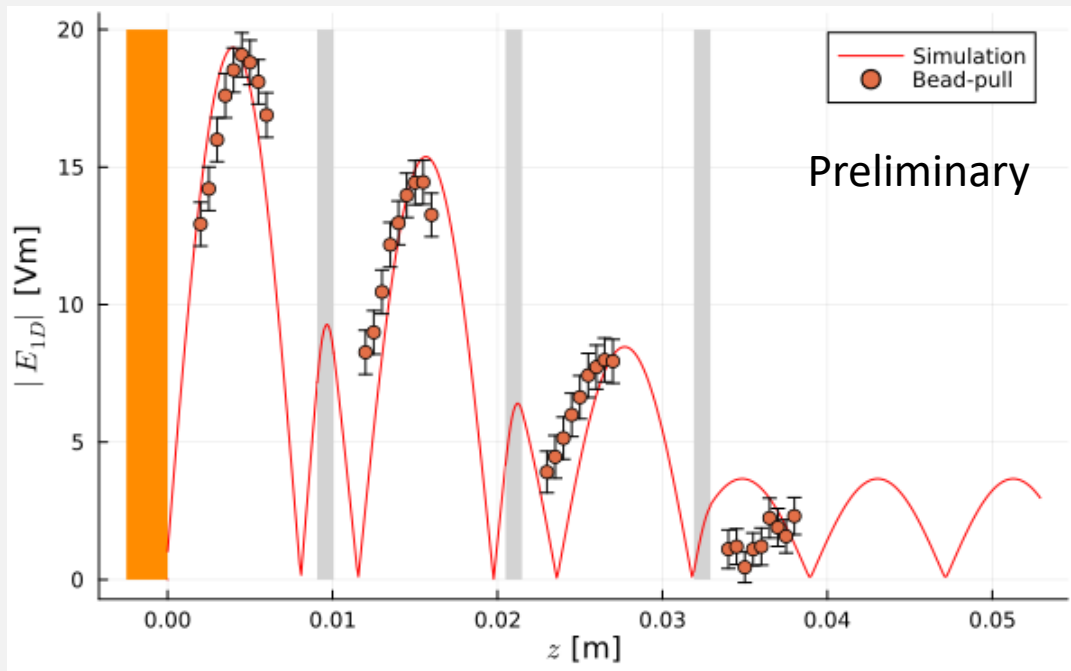
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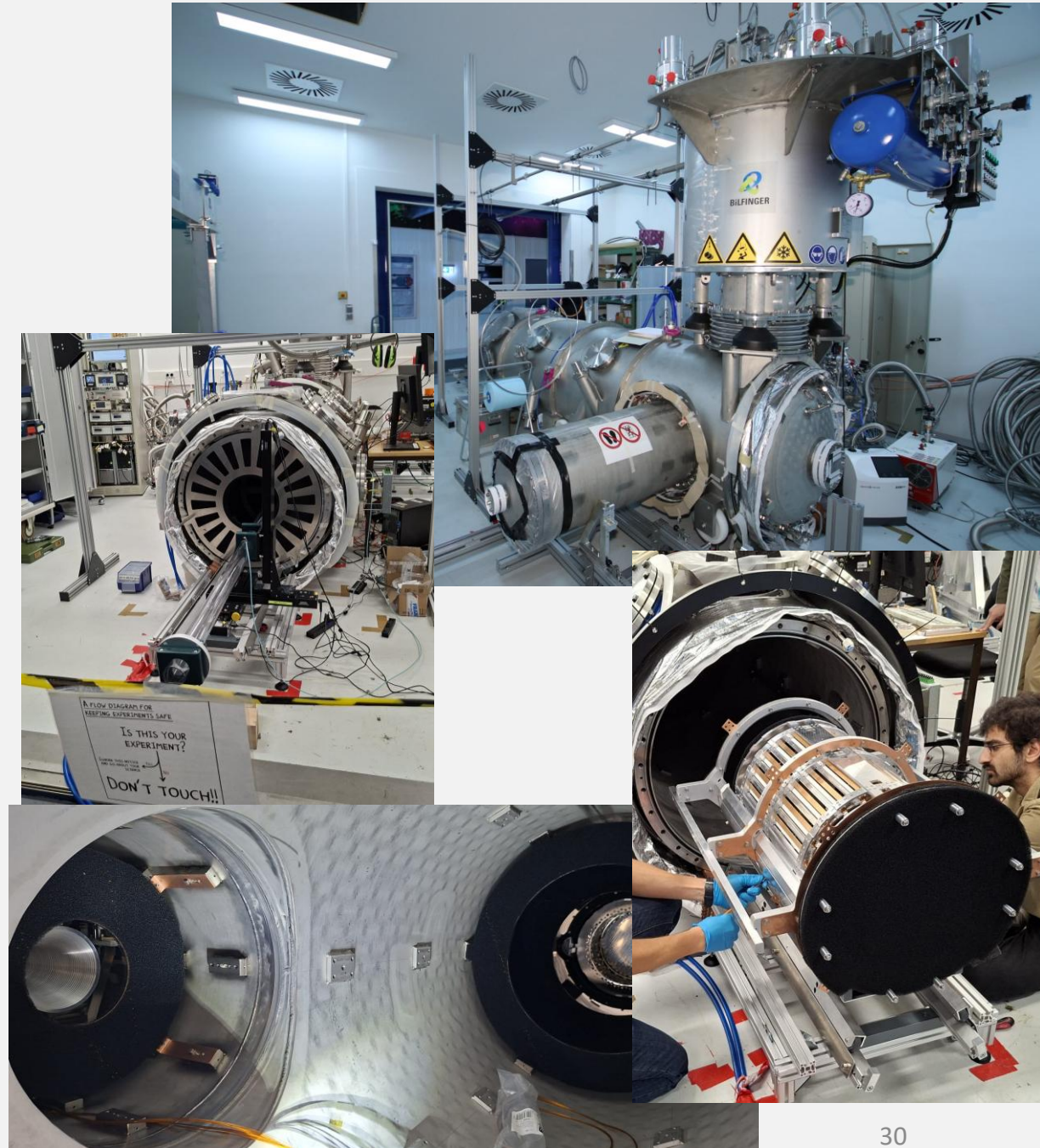
Preliminary bead pull results

- Bead pull measurements on a three disk setup outside the booster structure have been performed
- Results show good agreement with simulations

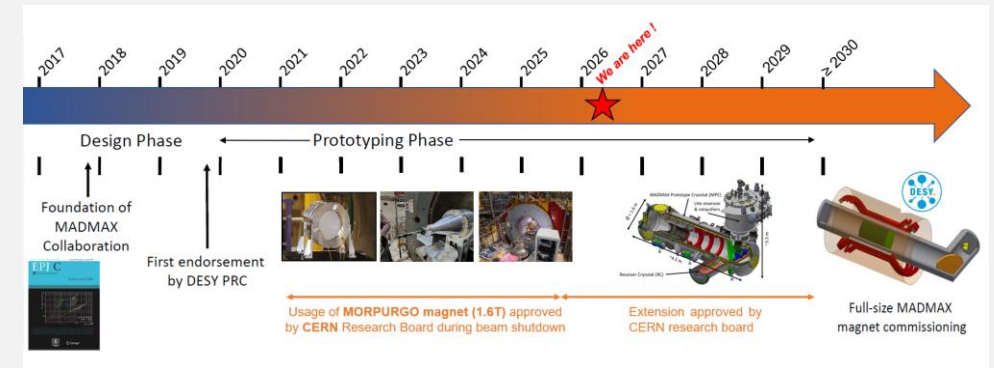


Hardware status

- **Booster** has been assembled and motor system is being tested
- **Cryostat** has been installed, a successful cooldown has been completed and part of the receiver cryostat has been installed
- Insertion methods for **RF system** (booster, focusing mirror, antenna) have been tested
- **RF absorbers** have been installed into the cryostat, and their impact on the RF behaviour inside the cryostat has been checked



Conclusions and outlook



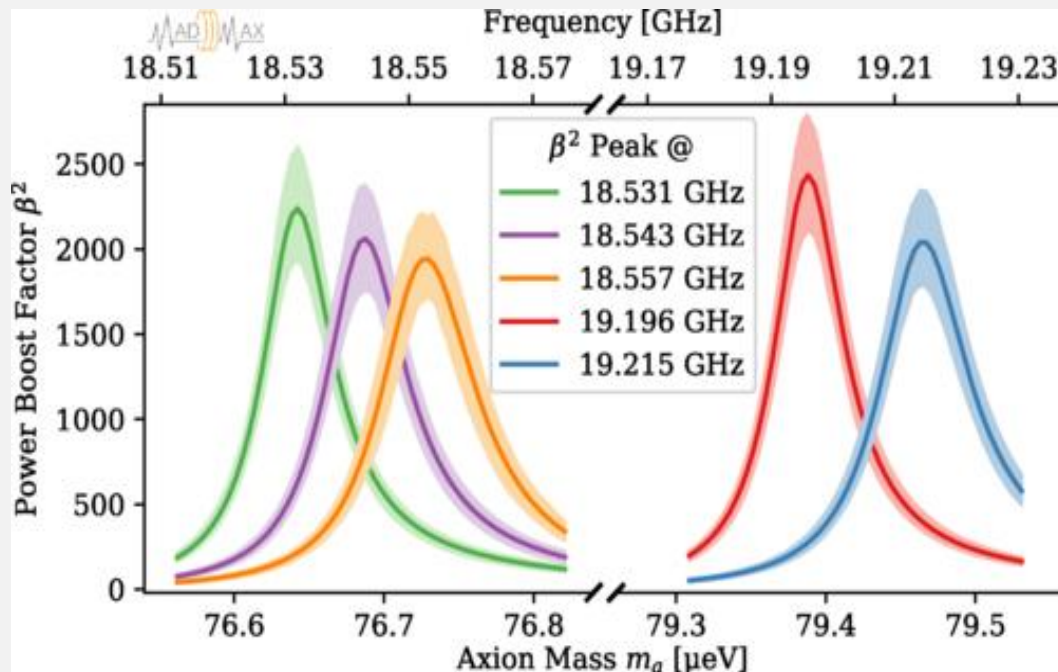
- The QCD axion is a well motivated dark matter candidate
- MADMAX will search for the axion using a dielectric haloscope which allows us to scan around $100 \mu\text{eV}$ mass, as predicted by post-inflationary models
- Validated dielectric haloscope concept and MADMAX versatility (scan and search) to give world's best limit at $80 \mu\text{eV}$
- The 'final' prototype currently being built will be tested at CERN in 2028-29 to perform:
 - i. Long-term runs at LHe temperature
 - ii. Axion search down to theory prediction around $100 \mu\text{eV}$

Thanks for listening!

Backup slides

CB200: boost factor determination

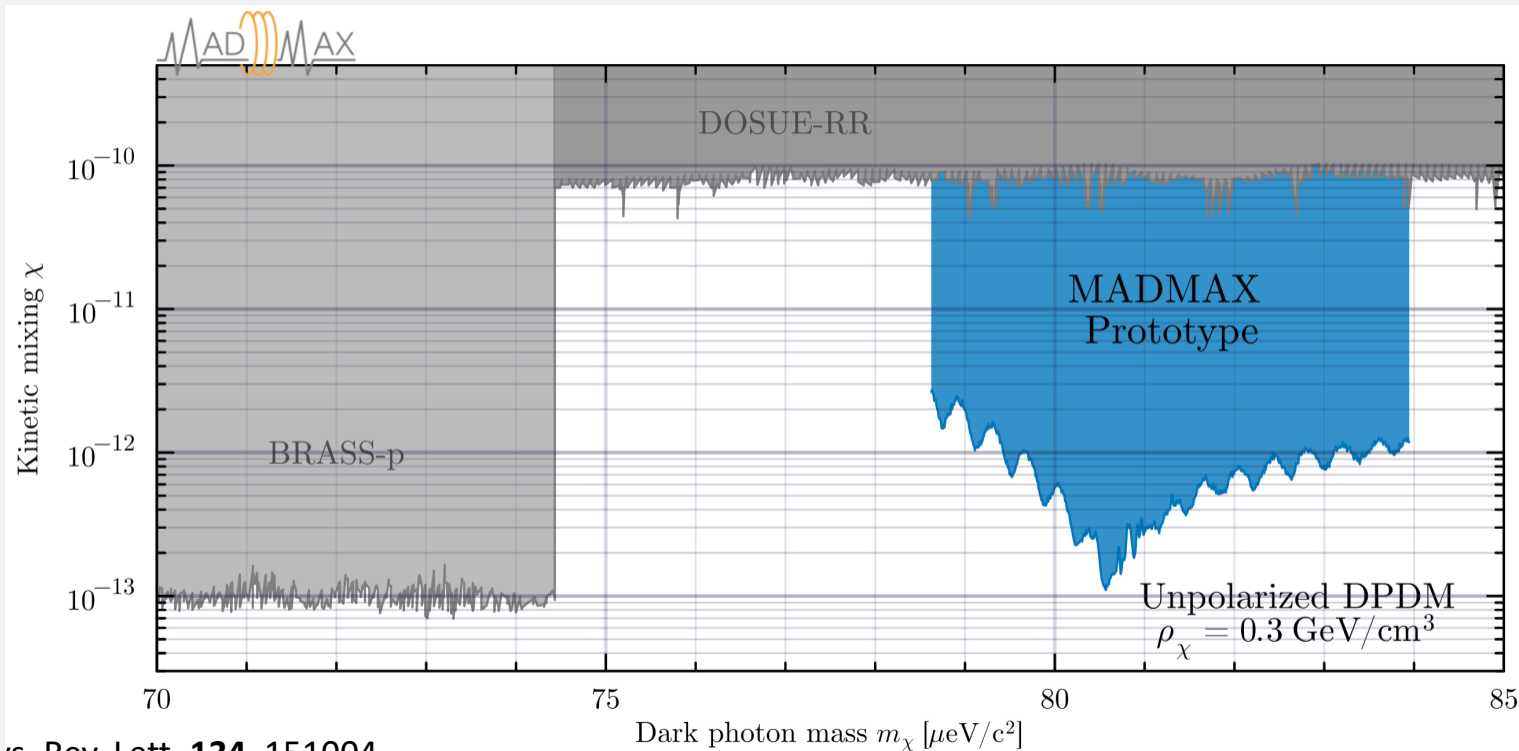
- The disk spacings define the two boost factor configurations: 18.55 GHz (76.72 μeV) and 19.21 GHz (79.45 μeV)
- The boost factor peaks are shifted using the tuning rod



β^2 and its uncertainties are determined using a 1D model fitted to reflectivity measurements

Dark photon search

- MADMAX can also perform dark photon searches, which do not require a magnetic field
- **Setup:** three 300 mm diameter disks + mirror separated using fixed spacers corresponding to a mass range of 78.62 to 83.95 $\mu\text{eV}c^{-2}$



Data: 16.5 days of data taking at room temperature

Results: 95% CL exclusion limit on the dark photon kinetic mixing angle

$$\chi > 2.7 \times 10^{-12}$$