# First searches for axion and dark photon dark matter using MADMAX prototypes

Matter and Universe days 2024

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on behalf of the MADMAX collaboration

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The MADMAX collaboration:

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MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE
IJCLab Irène Joliot-Curie – Laboratoire de Physique des 2 Infinis
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Universidad Zaragoza
CPPM – Centre de Physique des Particules de Marseille
NÉEL institut
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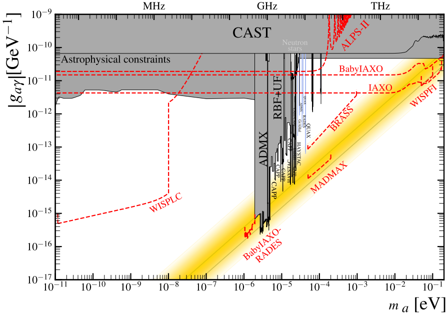
# MAgnetized Disk and Mirror Axion eXperiment

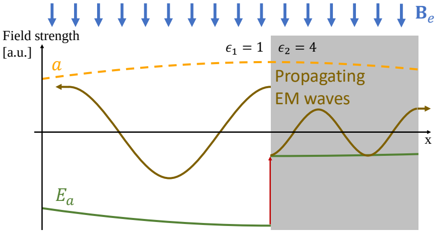
## Searching for dark matter

- MADMAX searches for the dark matter axion
- Axion motivated by solution to strong CP problem
- Popular dark matter candidate
- Axions within a magnetic field induce an effective current: $\mathbf{J}_a = g_{a\gamma}\mathbf{B}\dot{a}$
- Fullsize MADMAX designed to be sensitive down to QCD band at $40$ µeV to $400$ µeV
- Mass too low for accelerators and too high for conventional cavities




Axion landscape with projections of DESY experiments. Yellow band: DFSZ & KSVZ QCD axion models. Outside of yellow band: Axion like particles (ALPs)

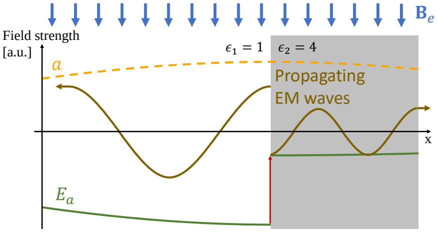
# Working principle




Fields at a dielectric interface

- Photon emission at dielectric interfaces:
  - Electric field from axion $\leftrightarrow$ B-field coupling
  - Discontinuity at interface solved by $\gamma$ emission
  - Interface to a mirror: $\epsilon_2 \to \infty$
    $\to$ Called a dish antenna

# Working principle

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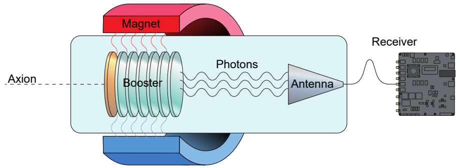



Schematic MADMAX setup

> MADMAX booster is a dielectric haloscope:
- Stack of dielectric disks in front of a mirror
- Photons emitted at dielectric interfaces ($\omega = m_a$)
- Signal amplified by resonances and interference
- Amplification w.r.t. dish antenna quantified by the boost factor $\beta^2$ (*central for sensitivity calculation!*)

# Booster prototypes

## Closed booster:

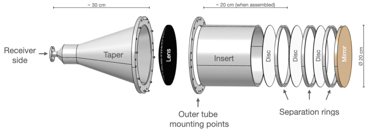
- CB100: 3 $\varnothing 100$ mm sapphire ($\epsilon \simeq 9.36$) disks
- CB200: 3 $\varnothing 200$ mm sapphire disks
- Easier simulation due to fixed boundary conditions
- Axion couples to TE11 mode

## Open booster:

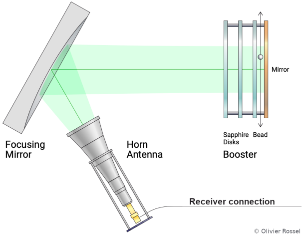
- OB300: 3 $\varnothing 300$ mm sapphire disks
- Easier tunability due to free movement of components
- Axion couples to gaussian beam

$$g_{a\gamma} = 2.04(3) \times 10^{-14}\ \mathrm{GeV}^{-1} \sqrt{\frac{\mathrm{SNR}}{5}} \sqrt{\frac{400^2}{\beta^2}} \sqrt{\frac{1\mathrm{m}^2}{\mathrm{A}}} \sqrt{\frac{\mathrm{T_{sys}}}{8\mathrm{K}}} \frac{10\ \mathrm{T}}{\mathrm{B_e}} \sqrt{\frac{0.8}{\eta}} \left(\frac{1.3\ \mathrm{days}}{\Delta \mathrm{t}}\right)^{1/4} \sqrt{\frac{300\ \mathrm{MeV}^2}{\rho_0}} \left(\frac{\mathrm{m_a}}{100\ \mu\mathrm{eV}}\right)^{5/4}$$

MADMAX sensitivity




CB200 schematic



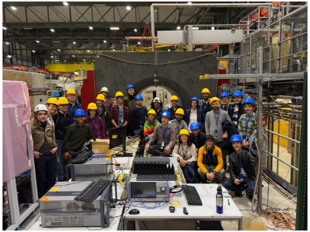

OB300 schematic

# Data takings

## OB300 at UHH

- Data taking at SHELL over Christmas 2023
- No magnet $\rightarrow$ Dark photon search
- Goal:
  - Demonstrate feasability of open booster

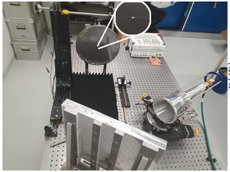
## CB100 & CB200 at CERN

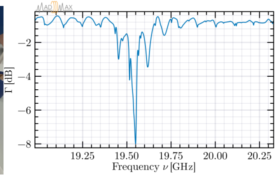


- CERN visit at $1.6\,$T Morpurgo magnet in February & March 2024
- Goals:
  - Demonstrate ability to set ALPs limits
  - Demonstrate tuning ability

# Boost factor determination

## Beadpull method



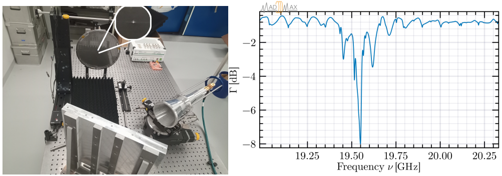



Beadpull setup & reflectivity measurement

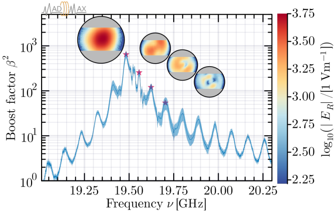
- Reflectivity measurement with and without bead: $\Delta\Gamma = \frac{\epsilon_0 \delta_e \alpha_0 \omega}{4 P_{\text{in}}} \mathbf{E}^2$
- Bead pulled through the setup
  $\rightarrow$ Full field within the booster measured
- Described in detail in [JCAP04(2024)005] (J. Egge et al)

# Boost factor determination

## Beadpull method




Beadpull setup & reflectivity measurement




OB300 measured boost factor

- Reflectivity measurement with and without bead: $\Delta\Gamma = \frac{\epsilon_0 \delta_e \alpha_0 \omega}{4 P_{\text{in}}} \mathbf{E}^2$
- Bead pulled through the setup
  $\rightarrow$ Full field within the booster measured
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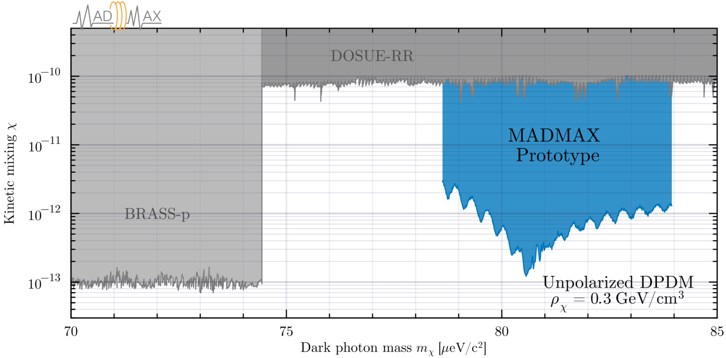
- Field **E** related to boost factor

$$\beta^2 = \frac{g_{a\gamma}^2}{16 P_{\text{in}} P_0} \left| \int_{V_a} dV \, \mathbf{E} \cdot \dot{a} \mathbf{B} \right|^2$$

- Described in detail in `[JCAP04(2023)064]` (J. Egge)

# OB300 @ SHELL/UHH

## Dark photon search

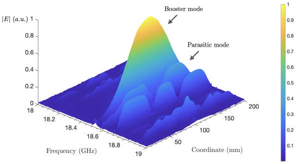



Limit of OB300 christmas run

- Competitive dark photon limits over a $\sim 1.2$ GHz $= 5$ µeV range
- Demonstrates open booster feasability
- Submitted to PRL, [arXiv:2408.02368]

# Boost factor determination

## Model fit

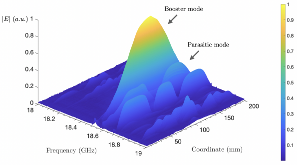



CB200 field shape

- Verification of TE11 mode resonance using 1D beadpull
- Field shape matches TE11 mode
  $\rightarrow$ Booster modelled by single mode simulation

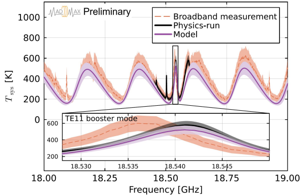
# Boost factor determination

## Model fit




CB200 field shape

+

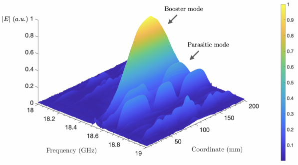



CB200 noise signal fit

- Noise model of booster with receiver chain
- Important checks (simplified):
  - Match of broadband oscillation length → receiver model correct
  - Match of TE11 resonance position → booster model correct

# Boost factor determination

## Model fit

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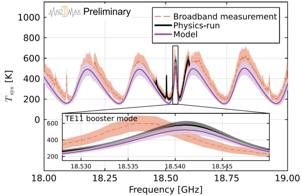


CB200 noise signal fit

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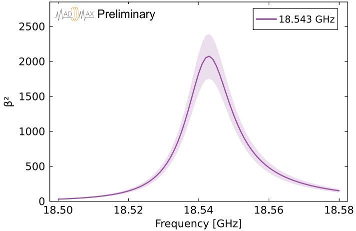
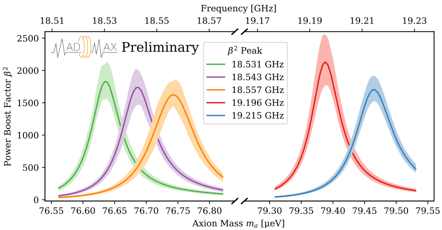



CB200 resulting boost factor

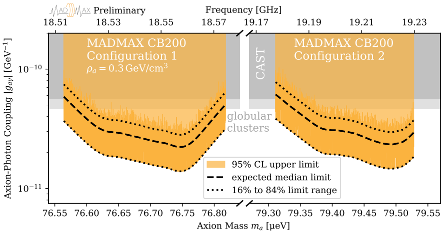
- Boost factor simulated by this model
- Uncertainties from fit procedure, 3D correction and time stability

# CB200 @ CERN

## Results



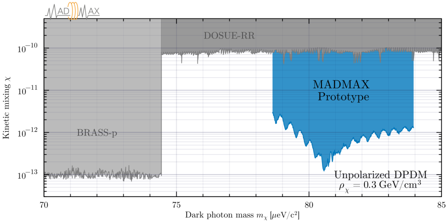

Boost factors of all datasets

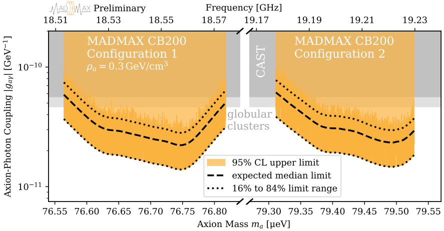



Combined limit

- 5 different booster configurations used
- Limits already competitive
- Paper on arXiv `[arXiv:2409.11777]`
- Submitted to PRL

# Summary & Outlook




- MADMAX is a dielectric haloscope looking for axion dark matter around $100$ μeV
- Axion and dark photon search successfully performed with prototypes
- Prototype limits already competitive with existing limits

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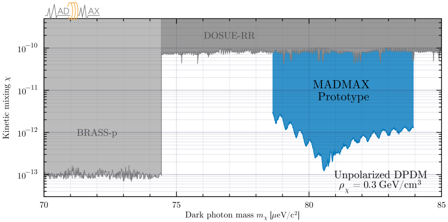


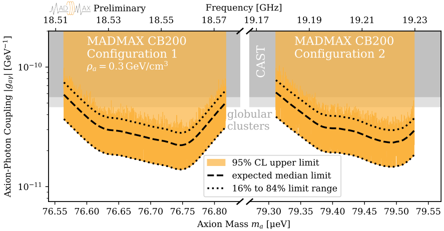


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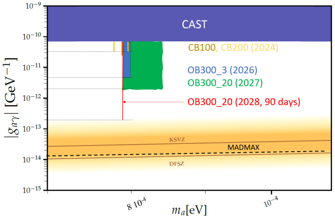
- Outlook:
  - Cold data from CERN currently being analysed
  - Prototype cryostat expected next year
  - Stronger magnetic fields (e.g. at DarkWave lab)



# Thank you!

**Contact**

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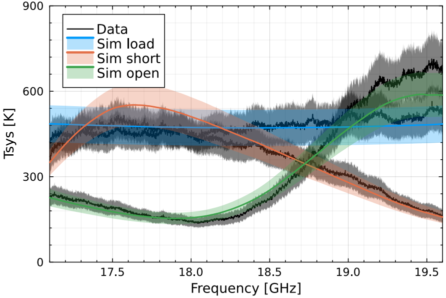
# Backup

# LNA noise model

- Noiseless two-port device with voltage and current source connected in parallel
- Two-port device impedance from deembedding of LNA internal length
- Parameters:
  - Voltage noise amplitude $V_n$
  - Current noise amplitude $I_n$
  - Voltage/current noise correlation $c$




LNA standard fits