Searching for dark matter with MADMAX

Astroparticle symposium 2025

David Leppla-Weber (DESY, Germany)
on behalf of the MADMAX collaboration (https://madmax.mpp.mpg.de)

Orsay, 06.11.2025

The MADMAX collaboration:

Universität Hamburg – DER FORSCHUNG | DER LEHRE | DER BILDUNG; DESY.; MAX-PLANCK-INSTITUT FÜR PHYSIK; MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE; HARVARD UNIVERSITY; IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis; RWTH AACHEN UNIVERSITY; EBERHARD KARLS UNIVERSITÄT TÜBINGEN; Universidad Zaragoza; CPPM; NÉEL institut; Fermilab; Northeastern University

Sponsored by:

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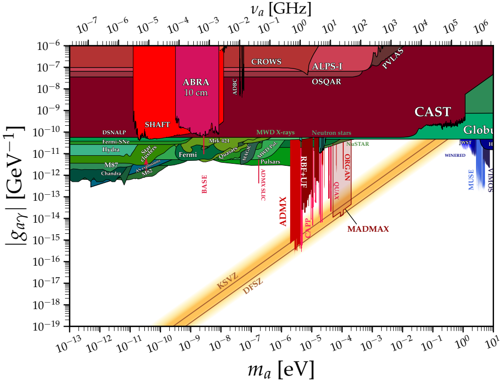
MAgnetized Disk and Mirror Axion eXperiment

Searching for dark matter

- MADMAX motivated by cosmological predictions
- PQ symmetry breaking before or after inflation
- Pre-inflationary:
  - Production only from misalignment
  - Angle θ completely random
- Post-inflationary:
  - Causally disconnected θ patches
  - ”Effective” angle from average
  - Additional production from topological defects
  - $m_a \gtrsim$ 30 µeV
    (in principle fully predictable)



Axion landscape with MADMAX projection

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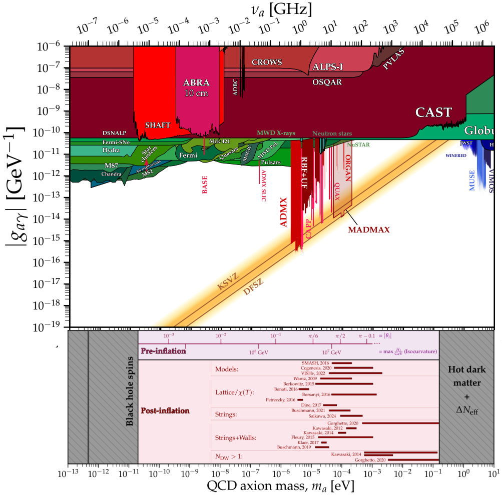
  - $m_a \gtrsim 30\,\mu\text{eV}$ (in principle fully predictable)
- Fullsize MADMAX designed to be sensitive down to QCD band at 40 µeV to 400 µeV

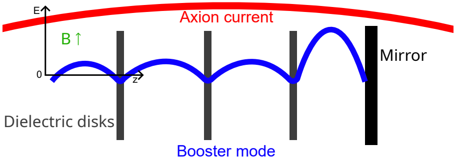


Axion landscape with MADMAX projection
Bottom: Cosmological predictions (from arXiv:2403.17697)

Content

Working principle

Dielectric haloscope

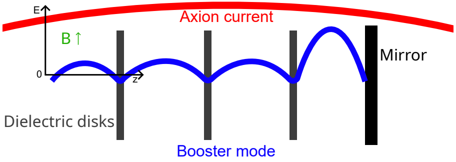


Schematic of E-field and axion current

- Axion within B-field gives effective current $\mathbf{J}_a$
- Booster mode **E** coupled to detector
- Extracted signal power $P_{sig} \propto \int dV \mathbf{E} \cdot \mathbf{J}_a$
- Dielectric disks allow shaping of **E**
  $\rightarrow$ Increase amplitude by resonance
  $\rightarrow$ Decrease negative regions

Working principle

Dielectric haloscope



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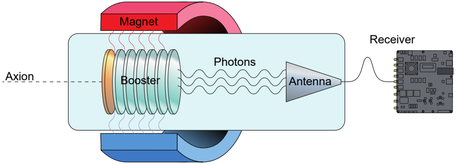

Schematic MADMAX setup

- Axion within B-field gives effective current $\mathbf{J}_a$
- Booster mode **E** coupled to detector
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- MADMAX plans a dielectric haloscope:
  - Stack of up to 80 dielectric disks
  - Placed in $\sim$10 T magnetic field
  - Scanning possible by disk movement
  - Amplification quantified by the boost factor where P_0 = signal power using only a mirror: $\beta^2 = P_{sig}/P_0$ (*central for sensitivity calculation!*)

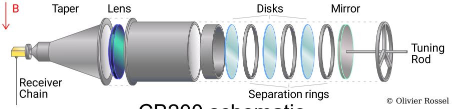
Booster prototypes

Closed booster:

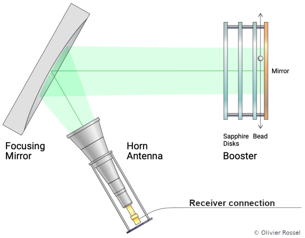
- CB200: 3 $\varnothing$200 mm sapphire disks
- Easier simulation due to fixed boundary conditions

Open booster:

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



CB200 schematic

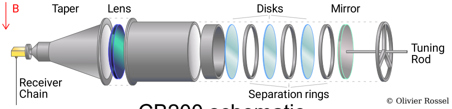


OB300 schematic

Booster prototypes

Closed booster:

- CB200: 3 ⌀200 mm sapphire disks
- Easier simulation due to fixed boundary conditions

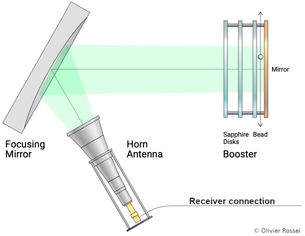


CB200 schematic

Open booster:

- OB300: 3 ⌀300 mm sapphire disks
- Easier tunability due to free movement of components

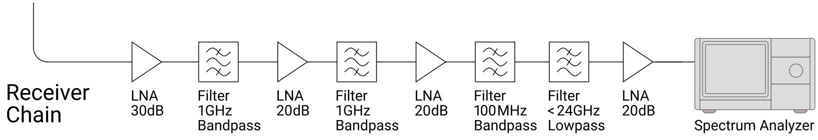
→ First results with CB200 and OB300 shown later



OB300 schematic

Common parts

Receiver chain



Receiver chain

- Expected signal below the typical noise floor of a spectrum analyser
  $\rightarrow$ Multiple amplifier stages required
- Additional filters prevent amplifier saturation
- First stage amplifier dominates noise of the chain
  $\rightarrow$ Low Noise Amplifier (LNA) required
- Power calibration using known noise source
- Note: system temperature = temperature at which a black body would emit the same power
  $\rightarrow$ For microwaves: $P = k_B B T_{sys}$

Receiver chain

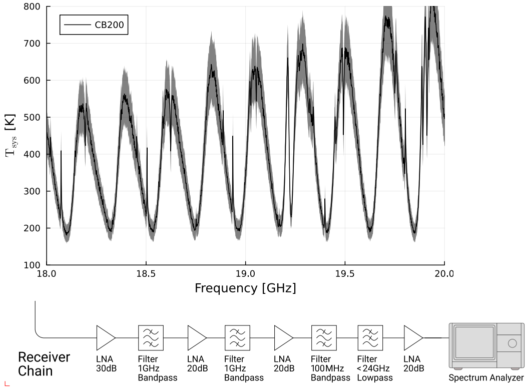
Boost factor modification

- Receiver chain reflects parts of signal
- Modifies boost factor by:

$$\beta_{RC}^2 = \frac{1 - |\Gamma_{RC}|^2}{|1 - \Gamma e^{i\delta}\Gamma_{RC}|^2}\beta^2$$

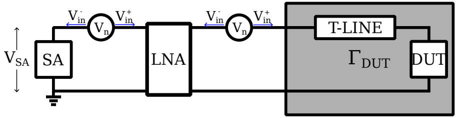
(Γ: Booster reflectivity, Γ_{RC}: receiver chain reflectivity, δ: phase difference)

- Causes oscillation in T_{sys} due to resonance between booster and receiver
- δ related to oscillation length!



CB200 system temperature measurement (top) performed with receiver chain (bottom)

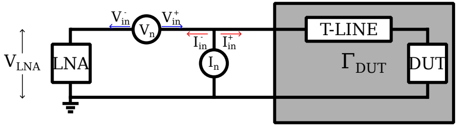
Amplifier noise



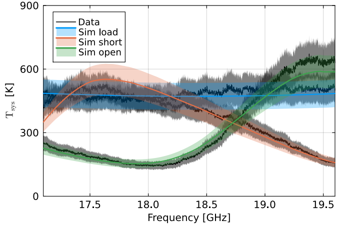
LNA schematic

- Amplifier noise modelled by correlated voltage sources
- Parameters extracted from fits to measurements of RF standards
- Combined with booster model: adjusting δ fits booster system temperature!

Amplifier noise

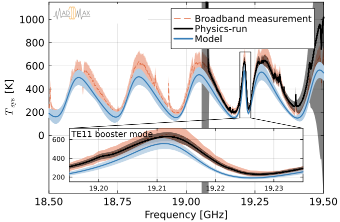


LNA schematic



Standards measurements

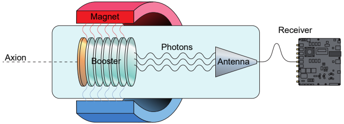
- Amplifier noise modelled by correlated voltage and current source
- Parameters extracted from fits to measurements of RF standards
- Combined with booster model: adjusting δ fits booster system temperature!



Resulting booster noise fit

Statistical analysis

Short summary



Experiment

Statistical analysis

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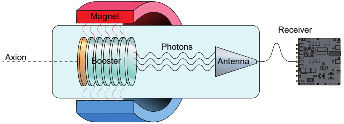

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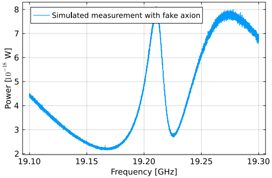

Simulated measurement
(with software-injected axion)

- Baseline shape subtracted using savitzky golay filter

Statistical analysis

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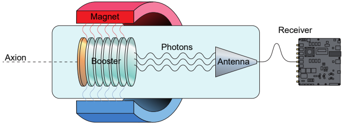

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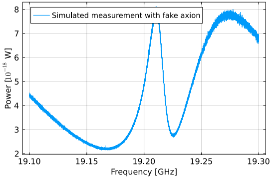

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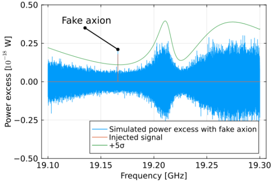


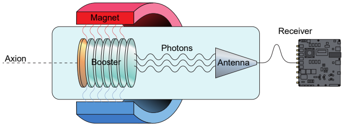
Residual power
(with software-injected axion)

- Baseline shape subtracted using savitzky golay filter
- Expected noise fluctuation $\sigma \propto \frac{P}{\sqrt{t_{int}}}$ known

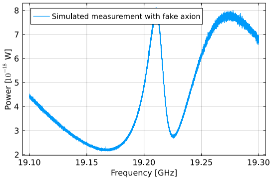
  $\rightarrow$ Power excess can be translated to units of σ (with some extra steps)

Statistical analysis

Short summary



Experiment



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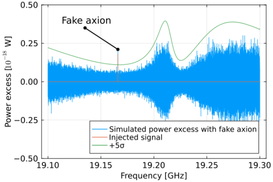

Residual power
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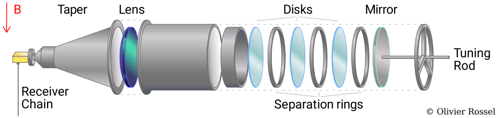
- Baseline shape subtracted using savitzky golay filter
- Expected noise fluctuation $\sigma \propto \frac{P}{\sqrt{t_{int}}}$ known
  $\rightarrow$ Power excess can be translated to units of σ (with some extra steps)
- Potential outcomes:

  1. $\geq 5\sigma$ excess found:
     $\rightarrow$ potential discovery, perform rescan
  2. No $\geq 5\sigma$ excess found, set bin-by-bin limit:
     $\rightarrow g_{a\gamma}$ that is ruled out by measurement with 95 % confidence (requires boost factor!)

Recent results

Axion run

CERN



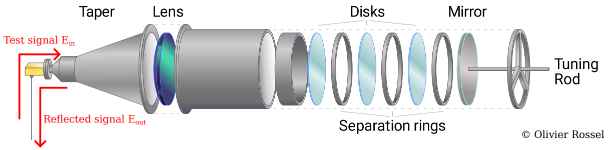
Setup schematic

- 3 $\varnothing$200 mm sapphire ($\epsilon \simeq 9.36$) disks
- Tuning rod enables frequency fine-tuning
- Closed design allows for easy simulation
- 1.6 T Morpurgo dipole magnet
- Run performed from February to March 2024

Setup in Morpurgo magnet

Boost factor determination

Model based



- Boost factor is not directly measureable
- Reflectivity is: $S_{11} = \Gamma = \frac{E_{\text{out}}}{E_{\text{in}}} = |\Gamma| e^{-i\phi}$
- S_{11} depends on the same quantities as β^2
  $\rightarrow$ Model parameters extracted from S_{11} fit

Boost factor determination

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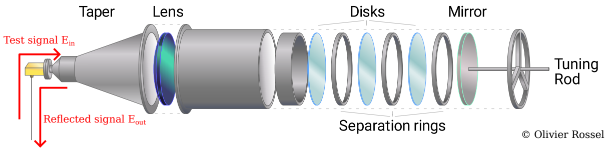

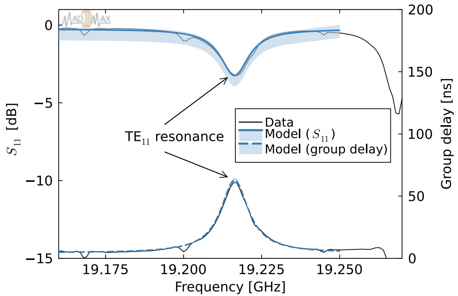

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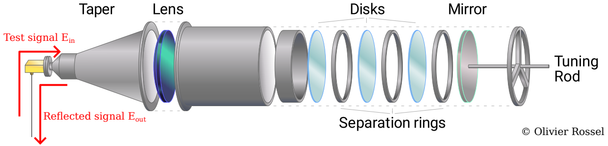

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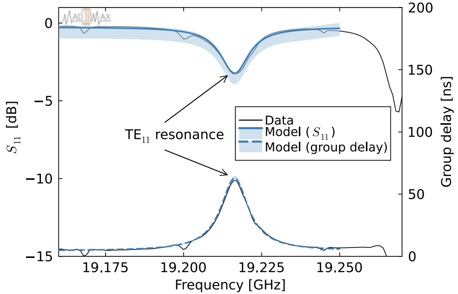
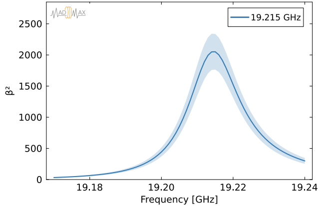
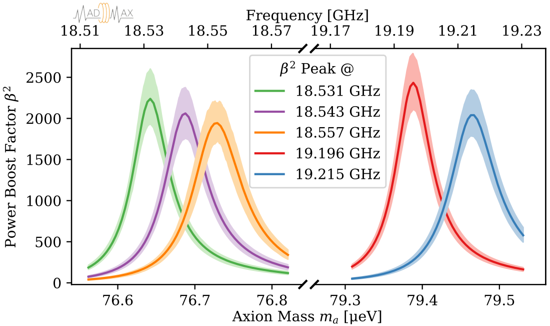
- S_{11} depends on the same quantities as β^2
  $\rightarrow$ Model parameters extracted from S_{11} fit
- Group delay: $\tau_{gd} = -\frac{\partial\phi}{\partial\omega}$
- β^2 uncertainties from goodness of fit, 3D correction and time stability



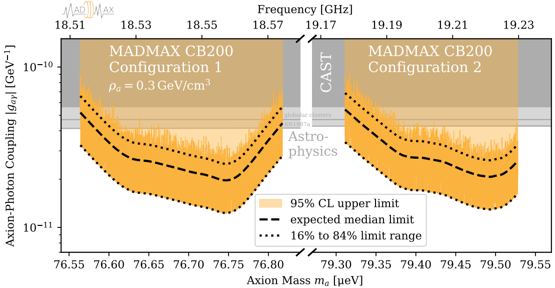


Reflectivity fit and resulting boost factor

Axion run



Boost factors of all datasets



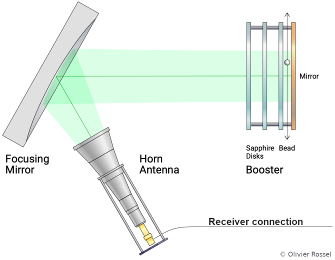
Combined limit

- 5 different booster configurations used
  $\rightarrow$ Demonstrates tuning capability

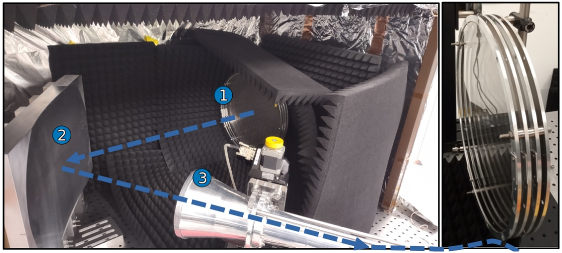
- First axion search with a dielectric haloscope
- Published in PRL (10.1103/c749-419q)

Dark photon run

Universität Hamburg (UHH)



Setup schematic

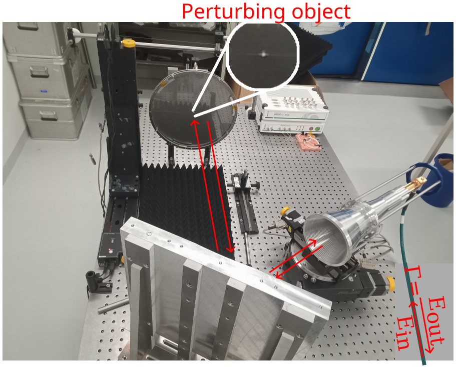


Setup with added absorbers
1: Booster, 2: Focusing mirror, 3: Antenna

- 3 $\varnothing$300 mm sapphire ($\epsilon \simeq 9.36$) disks
- No magnet: perform dark photon search (massive photon mixing with SM photon)
- Open prototype for full-scale MADMAX
- Run performed over Christmas 2023

Boost factor determination

Measurement based



- Boost factor $\beta^2 \propto \int_V dV \, \mathbf{E} \cdot \mathbf{J}$
  (**E**: Antenna induced field, **J**: axion/dark photon current)
- Difference perturbed - unperturbed reflectivity: $\Delta\Gamma \propto \mathbf{E}^2$

Boost factor determination

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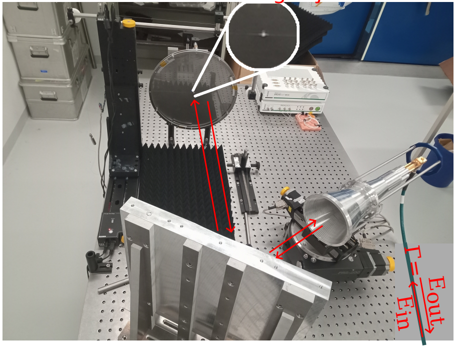

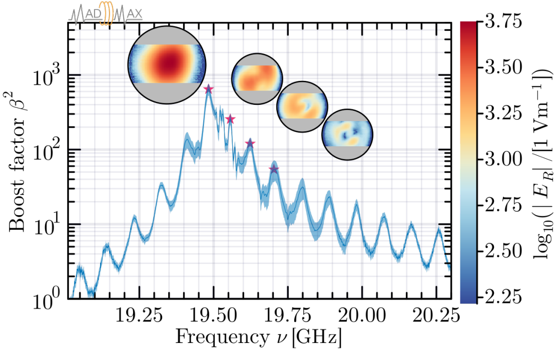

Boost factor dark photon run

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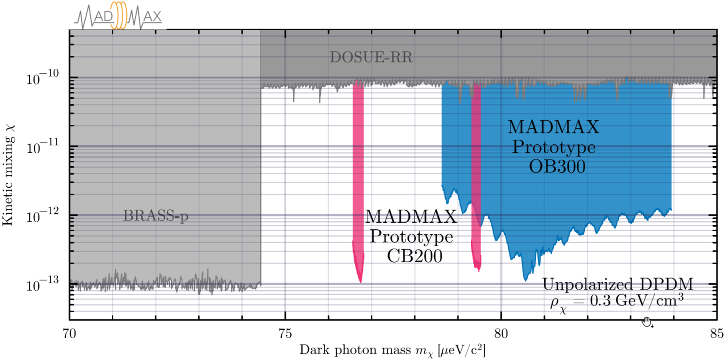
  (**E**: Antenna induced field, **J**: axion/dark photon current)
- Difference perturbed - unperturbed reflectivity: $\Delta\Gamma \propto \mathbf{E}^2$

- Described in detail in `[JCAP04(2024)005]` (J. Egge et al) and `[JCAP04(2023)064]` (J. Egge)

Dark photon run

Results



Results of OB300 dark photon search, including reinterpreted axion limits

- Sensitivity to the kinetic mixing χ
- Published in PRL (10.1103/PhysRevLett.134.151004)
- Leading dark photon limits over a $\sim$ 1.2 GHz = 5 μeV range

The Future

How to improve

Estimated sensitivity gains

- Going cold, reduce noise: $g_{a\gamma} \propto \sqrt{T_{sys}}$
  $\rightarrow$ factor $\sim 10 - 100$ improvement

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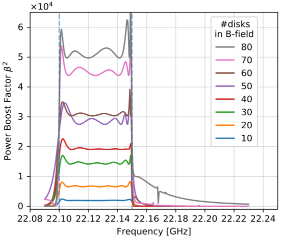
- More disks: $g_{a\gamma} \propto 1/\sqrt{\beta^2}$
  $\rightarrow$ factor $\sim 5 - 10$ improvement



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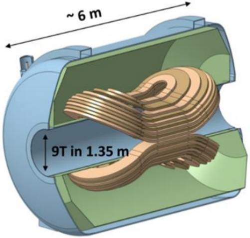
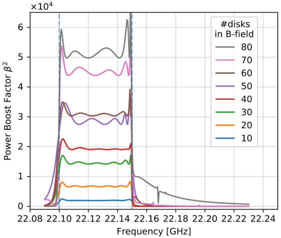
- Stronger magnetic fields: $g_{a\gamma} \propto 1/B$
  $\rightarrow$ factor ~ 5 improvement





Development in innovation partnership

BILFINGER NOELL GMBH

How to improve

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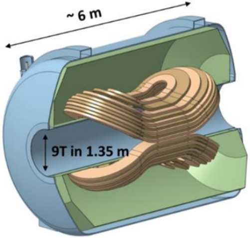
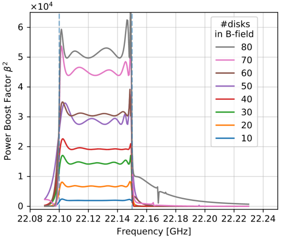
  $\rightarrow$ factor $\sim 5 - 10$ improvement
- Stronger magnetic fields: $g_{a\gamma} \propto 1/B$
  $\rightarrow$ factor ~ 5 improvement
- Bigger disks, different materials, longer integration time, …

$\rightarrow$ Improvement from $g_{a\gamma} \simeq 10^{-10}$ (CB200 result) to $g_{a\gamma} \simeq 10^{-13}$ (QCD band)!





Development in innovation partnership

BILFINGER
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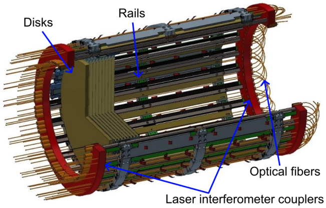
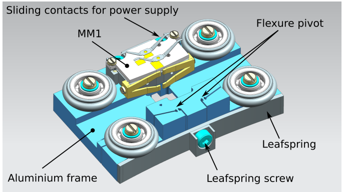
cea
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Next setup



Booster structure with movable disks

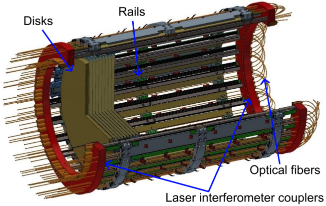


Piezo motor

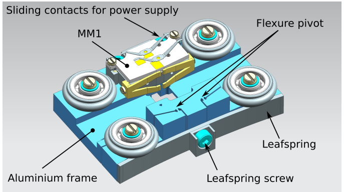
MADMAX cryostat

- Work on fully tunable open booster ongoing
- Up to 20 disks, movable using piezo motors
- Commissioning of custom cryostat in Hamburg

Next setup



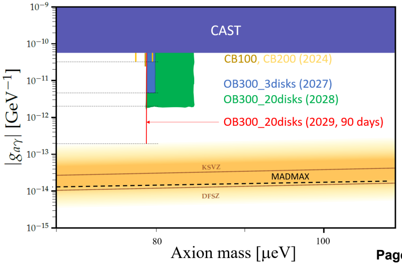
Booster structure with movable disks



Piezo motor

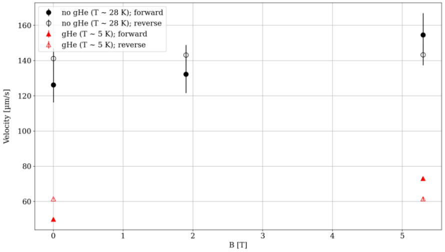
MADMAX cryostat

- Work on fully tunable open booster ongoing
- Up to 20 disks, movable using piezo motors
- Commissioning of custom cryostat in Hamburg
- Placed in 1.6 T Morpurgo magnet at CERN in 2027
- Tender process for intermediate ∼4 T magnet started

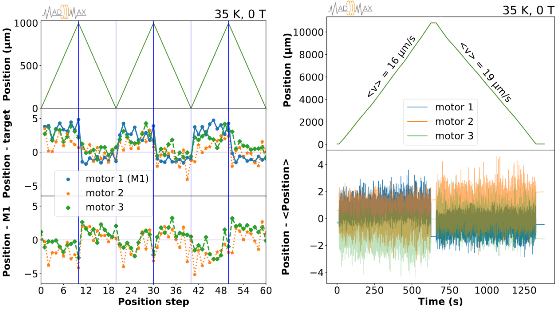


Next setup

Mechanics



Loaded motor movement at cryogenic temperatures in a magnetic field



Disk movement at cryogenic temperature in a magnetic field

Qualification of piezo-electric actuators for the MADMAX booster system at cryogenic temperatures and high magnetic fields
[JINST 18 P08011]

First mechanical realization of a tunable dielectric haloscope for the MADMAX axion search experiment
[JINST 19 T11002]

General news

MADMAX is growing - from 11 to 13 partner institutes!

Welcome to our new associate members:

HARVARD UNIVERSITY

Stefan Knirck

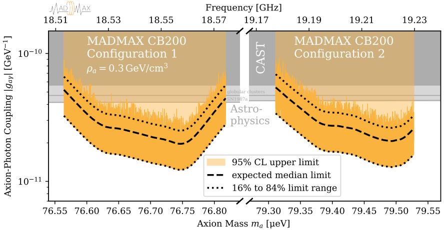
Working on the DAQ, cryogenic receiver and single photon detection

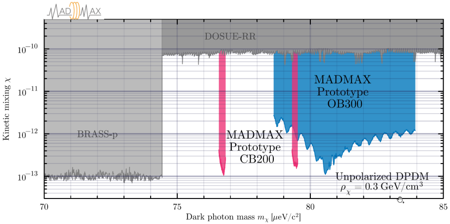
Northeastern University

KC Fong

Working on graphene based single-photon detection and the characterization of components

Summary



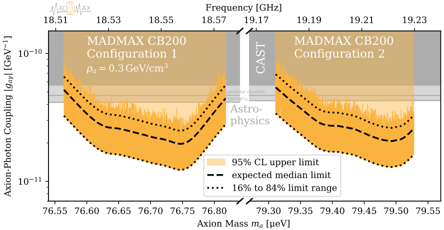


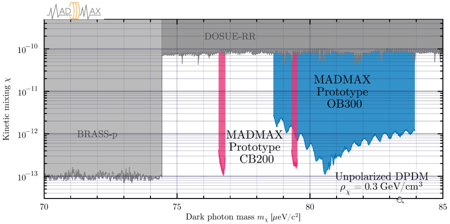
> MADMAX is a dielectric haloscope looking for axion dark matter around 100 μeV
> Axion and dark photon search successfully performed with prototypes
> Scanning capacity demonstrated
> Limits already world-leading at their mass range

Future plans:

> New tunable open booster is being build
> Custom cryostat is in commissioning
> New Axion data taken at CERN in 2027

Summary





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Publications:

- Design:
  10.1103/PhysRevLett.118.091801 (PRL, 2017)
  10.1088/1475-7516/2017/01/061 (JCAP, 2017)
- Mechanics: 10.1088/1748-0221/19/11/T11002 (JINST, 2019)
- Magnet development: 10.1109/TASC.2023.3273734 (IEEE, 2023)
- Calibration:
  10.1088/1475-7516/2023/04/064 (JCAP, 2023)
  10.1088/1475-7516/2024/04/005 (JCAP, 2024)
- Results:
  10.1103/c749-419q (PRL, 2025)
  10.1103/PhysRevLett.134.151004 (PRL, 2025)

Thank you!

Contact

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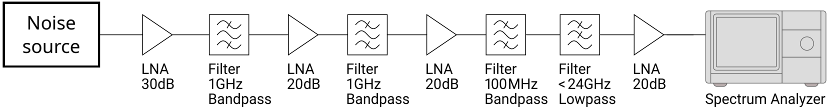
Backup

Receiver chain

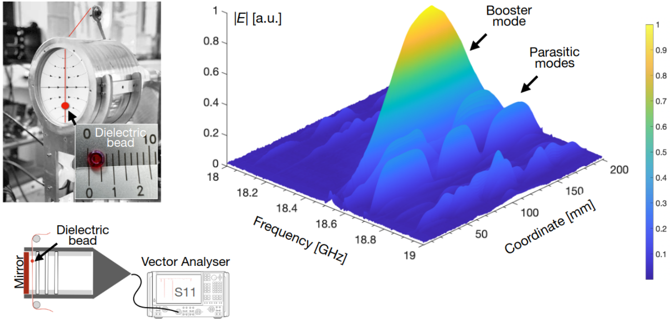
Power calibration



Receiver chain with noise source

- Connect known noise source to chain
- Two unknowns: receiver gain and its added noise
  $\rightarrow$ Two well-known measurements needed
  - Noise source on: power given by datasheet
  - Noise source off: power given by thermal radiation
- Note: system temperature = temperature at which a black body would emit the same power
  $\rightarrow$ For microwaves: $P = k_B B T_{sys}$

CB200 bead pull



Measured E field within closed booster

- Frequency of TE_{11} mode resonance confirmed by bead pull measurement
- Parasitic modes well separated

CB200 full setup

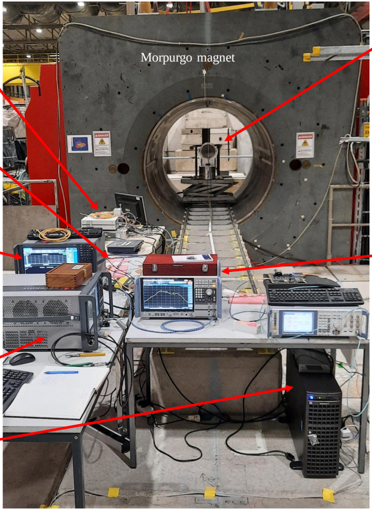
B-field &
T - monitors

Receiver
chain
outside the
B-field

Spectrum
analyzer for
RFI
measurement

VNA for S11
calibration
measurements

Computer
with GPU

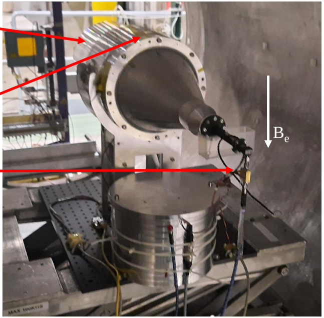


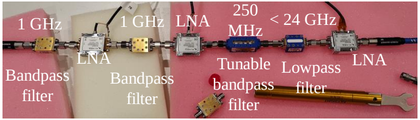
CB200

B-field
probe

First LNA
with T-
sensor
attached

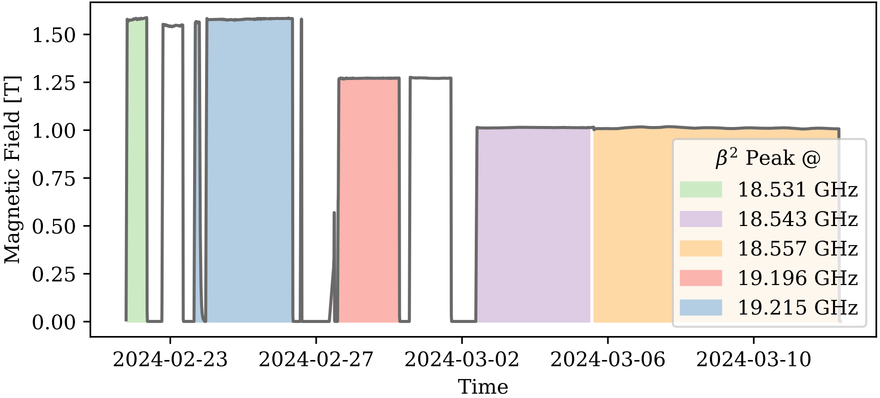
R&S
spectrum
analyzer
FSW43



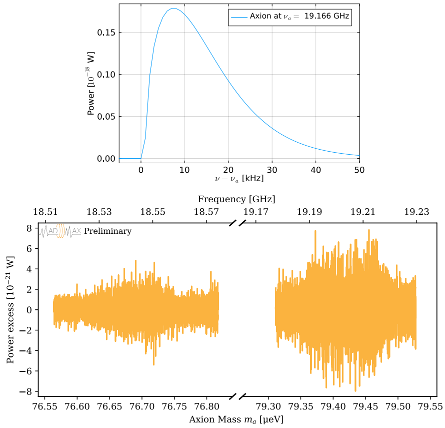


Receiver chain outside the B-field

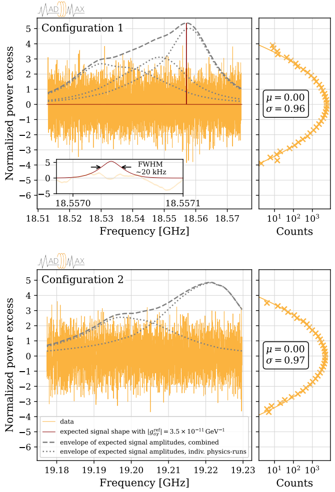
CB200 B field overview



CB200 statistical analysis



Axion lineshape and cross-correlated power excess



Cross-correlated normalized power excess

Uncertainties

Effect	Uncertainty in $|g_{a\gamma}|$
Y-factor power calibration	3 % to 5 %
Receiver chain power stability	$\leq$ 2 %
Axion field – TE_{11} overlap	6 %
Boost factor determination	< 5 %
Frequency stability of TE_{11} mode	< 2 %
Total	5 % to 10 %

Axion run uncertainties

Effect	Uncertainty on χ
Bead-pull measurements	2 to 17%
Bead pull finite domain correction	5%
Receiver chain impedance mismatch	<1%
Y-factor calibration	4%
Power stability	3%
Frequency stability	2%
Line shape discretization	4%
Total	9 to 19%

Dark photon run uncertainties