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

Recontres de Moriond EW 2025

David Leppla-Weber (DESY, Germany)

on behalf of the MADMAX collaboration (https://madmax.mpp.mpg.de)

La Thuile (AO), 28.03.2025

The MADMAX collaboration:

Universität Hamburg — DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

MAX-PLANCK-INSTITUT FÜR PHYSIK

MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE

IJCLab — Irène Joliot-Curie — Laboratoire de Physique des 2 Infinis

RWTH AACHEN UNIVERSITY

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Universidad Zaragoza — 1542

CPPM — CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE

NÉEL institut

Fermilab

Sponsored by:

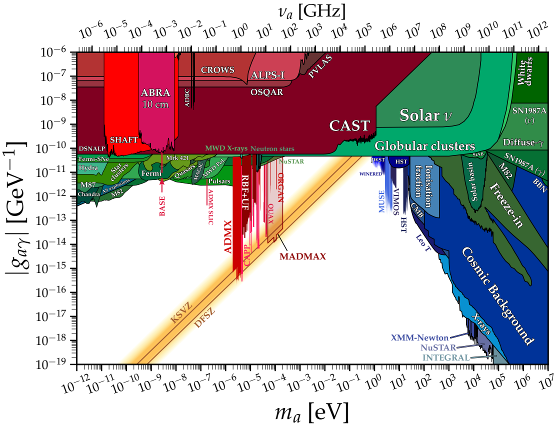
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

HELMHOLTZ

MAgnetized Disk and Mirror Axion eXperiment

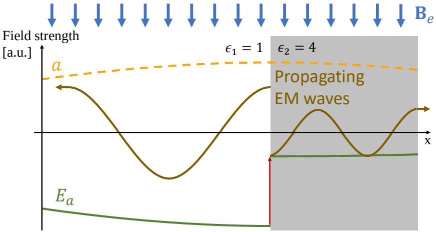
Searching for dark matter

- MADMAX searches for the dark matter axion
- Axion motivated by solution to strong CP problem
- Abundant production by vacuum realignment and topological defects
- Popular dark matter candidate
- Axions within a magnetic field induce an effective current: $\mathbf{J}_a = g_{a\gamma}\mathbf{B}\dot{a}$ (modified Maxwell)
- Fullsize MADMAX designed to be sensitive down to QCD band at 40 µeV to 400 µeV
- Parameter space out-of-reach for current dark matter searches and laboratory experiments



Axion landscape with MADMAX projection
Yellow band: benchmark QCD axion models

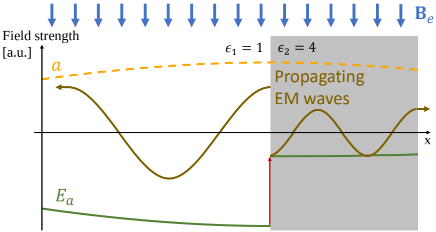
Working principle



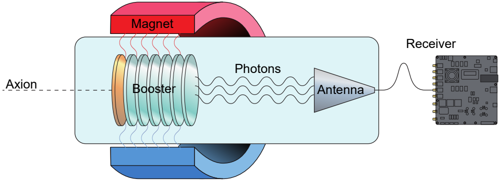
Electric fields at a dielectric interface

- Photon emission at dielectric interfaces:
  - Electric field from axion $\leftrightarrow$ B-field coupling
  - Discontinuity at interface solved by γ emission
  - Interface to a mirror: $\epsilon_2 \to \infty$
    $\to$ Called a dish antenna, signal power $\equiv P_0$

Working principle



Electric fields at a dielectric interface

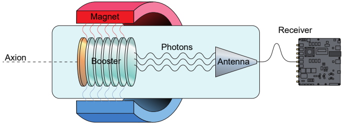


Schematic MADMAX setup

- Photon emission at dielectric interfaces:
  - Electric field from axion $\leftrightarrow$ B-field coupling
  - Discontinuity at interface solved by γ emission
  - Interface to a mirror: $\epsilon_2 \to \infty$
    $\to$ Called a dish antenna, signal power $\equiv P_0$

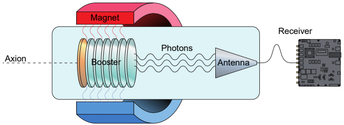
- MADMAX booster is a dielectric haloscope:
  - Stack of dielectric disks in front of a mirror
  - Photons emitted at dielectric interfaces ($\omega = m_a$)
  - Signal amplified by resonances and interference
  - Scanning possible by disk movement
  - Amplification quantified by the boost factor
    $\beta^2 = P_{sig}/P_0$
    (*central for sensitivity calculation!*)

Simulated measurements

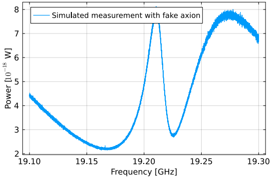


Experiment

Simulated measurements



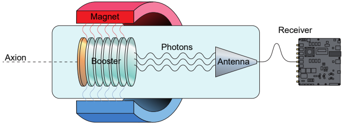
Experiment



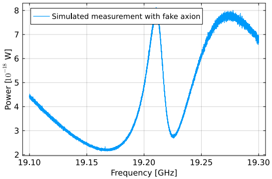
Simulated measurement
(with software-injected axion)

> Baseline shape subtracted using savitzky golay filter

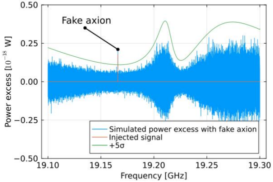
Simulated measurements



Experiment



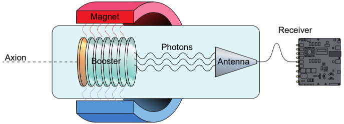
Simulated measurement
(with software-injected axion)



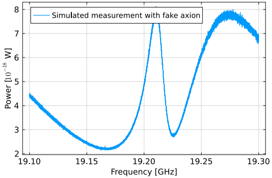
Residual power
(with software-injected axion)

- 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)

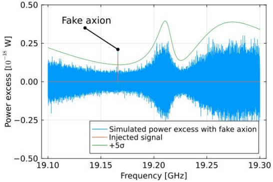
Simulated measurements



Experiment



Simulated measurement
(with software-injected axion)

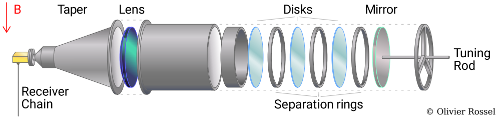


Residual power
(with software-injected axion)

- 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)
- 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!)

Axion run
CERN



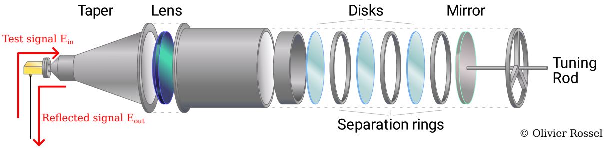
Setup schematic

- 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

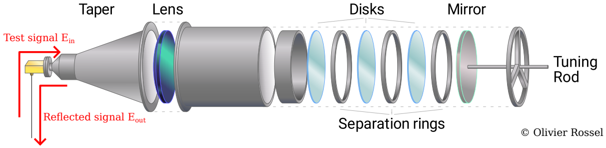
Model based

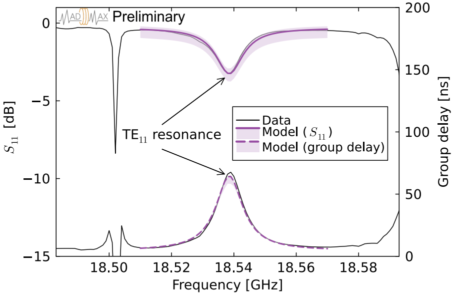


- Boost factor is not directly measureable
- Reflectivity is: $S_{11} = \Gamma = \frac{E_{\text{out}}}{E_{\text{in}}} = |\Gamma| e^{-i\phi}$
- S_{11} depends on the same quantities as β^2
  $\rightarrow$ Model parameters extracted from S_{11} fit

Boost factor determination

Model based

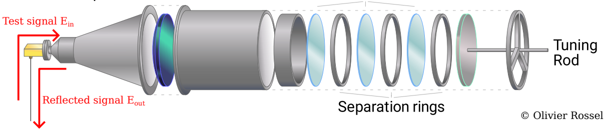




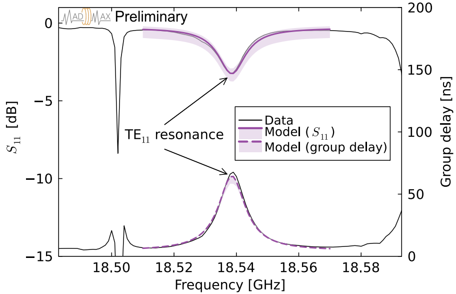
- Boost factor is not directly measureable
- Reflectivity is: $S_{11} = \Gamma = \frac{E_{\text{out}}}{E_{\text{in}}} = |\Gamma| e^{-i\phi}$
- S_{11} depends on the same quantities as β^2
  $\rightarrow$ Model parameters extracted from S_{11} fit
- Convention: $S_{11}[dB]$ shows $|\Gamma|^2$ in logarithmic scale
- Group delay: $\tau_{gd} = -\frac{\partial \phi}{\partial \omega}$

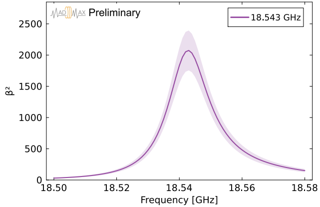
Boost factor determination

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
- Convention: $S_{11}[dB]$ shows $|\Gamma|^2$ in logarithmic scale
- Group delay: $\tau_{gd} = -\frac{\partial \phi}{\partial \omega}$
- β^2 uncertainties from goodness of fit, 3D correction and time stability

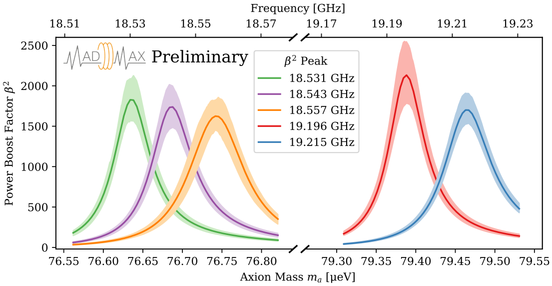




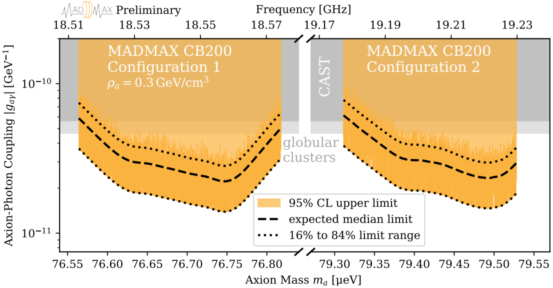
Reflectivity fit and resulting boost factor

Axion run

Results



Boost factors of all datasets



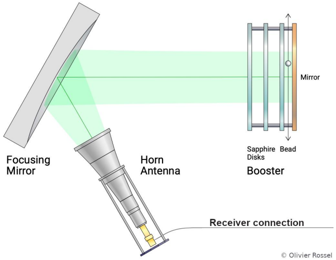
Combined limit

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

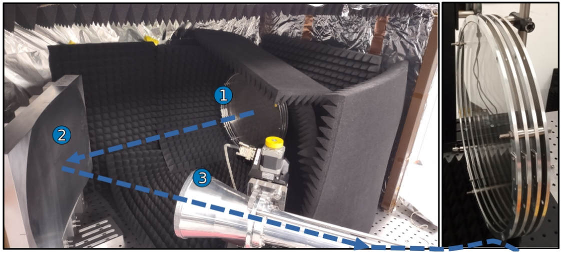
- First axion search with a dielectric haloscope
- Submitted to PRL, [arXiv:2409.11777]

Dark photon run

Universität Hamburg (UHH)



Setup schematic

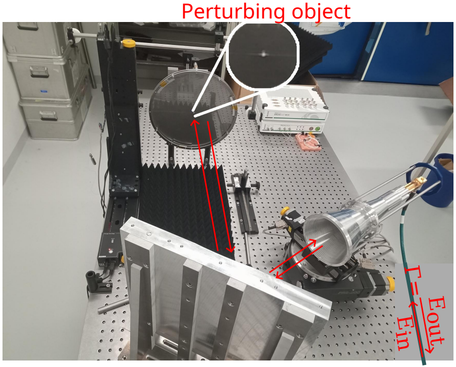


Setup with added absorbers
1: Booster, 2: Focusing mirror, 3: Antenna

- 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

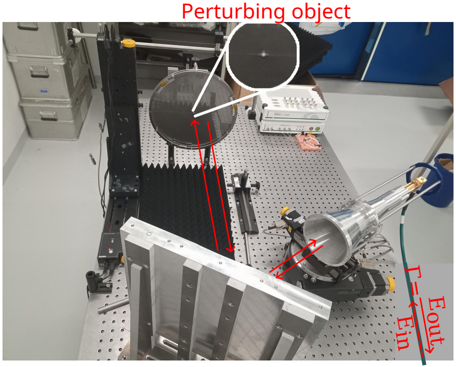
Measurement based

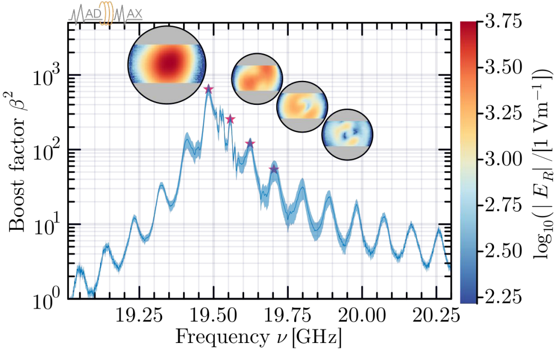


- Boost factor $\beta^2 \propto \int_V dV\, \mathbf{E} \cdot \mathbf{J}$
  (**E**: Antenna induced field, **J**: axion/dark photon current)
- Difference perturbed - unperturbed reflectivity: $\Delta\Gamma \propto \mathbf{E}^2$

Boost factor determination

Measurement based





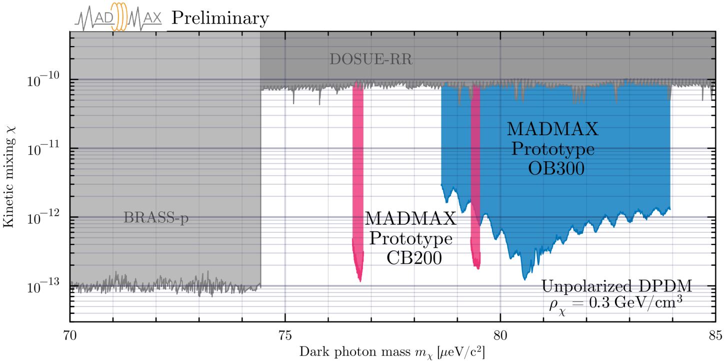
Boost factor dark photon run

- 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: $\Delta\Gamma \propto \mathbf{E}^2$

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

Dark photon run

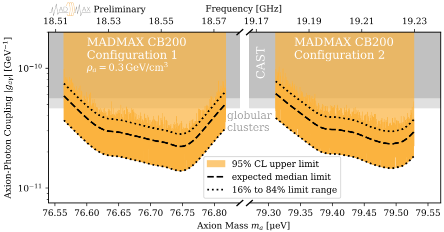
Results

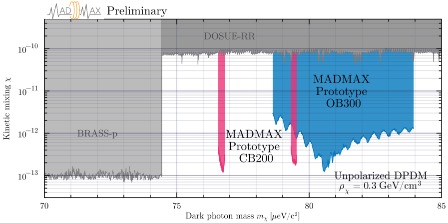


First MADMAX physics results, including reinterpreted axion limits

- Sensitivity to the kinetic mixing χ
- Accepted by PRL, `[arXiv:2408.02368]`
- Leading dark photon limits over a $\sim 1.2\,\mathrm{GHz} = 5\,\mu\mathrm{eV}$ range

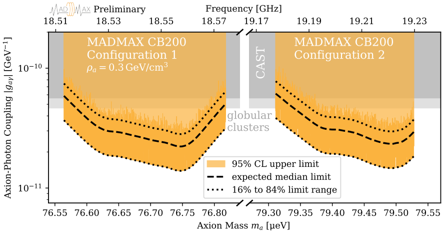
Summary & Outlook

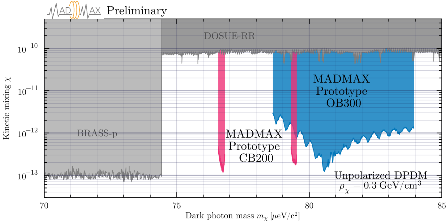




- MADMAX is a dielectric haloscope looking for axion dark matter around 100 µeV
- Two full calibration schemes have been developed
- Axion and dark photon search successfully performed with prototypes
- Prototype limits already world-leading at their mass range

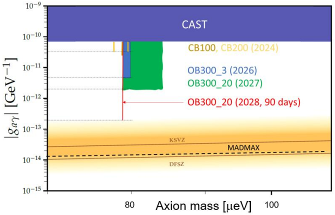
Summary & Outlook





- MADMAX is a dielectric haloscope looking for axion dark matter around 100 μeV
- Two full calibration schemes have been developed
- Axion and dark photon search successfully performed with prototypes
- Prototype limits already world-leading at their mass range

- **Outlook**:
  - Cold data from CERN currently being analysed
  - Custom MADMAX cryostat expected next month
  - Increase number of disks from 3 to 20
  - Movable disks with piezo motors
  - Full-scale setup installed at DESY cryoplatform $\gtrsim$ 2030



Thank you!

Contact

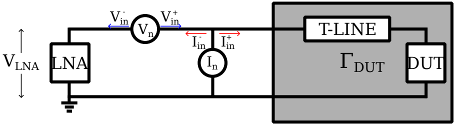
Deutsches Elektronen-
Synchrotron DESY

www.desy.de

David Leppla-Weber
ALPS
david.leppla.weber@desy.de

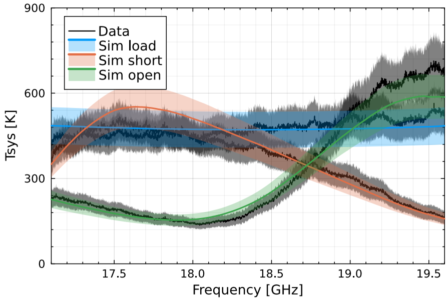
Backup

LNA noise model



Noise model schematic

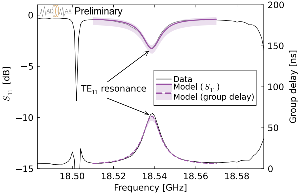
- Noiseless two-port device with voltage and current source connected in parallel
- Two-port device impedance from deembedding of LNA internal length
- Parameters:
  - Voltage noise amplitude V_n
  - Current noise amplitude I_n
  - Voltage/current noise correlation c



LNA standard fits

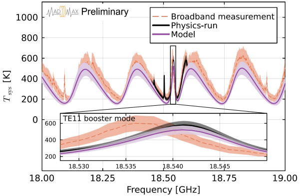
Booster noise model

Closed booster



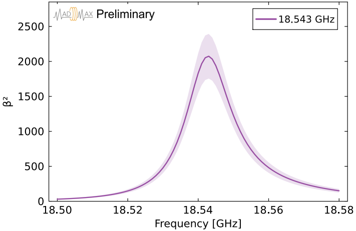
Reflectivity fit

+



Noise signal fit

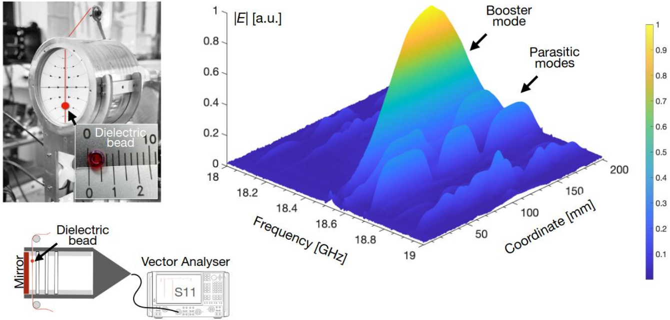
⇒



Resulting boost factor

- Receiver chain modifies boost factor by reflecting parts of the signal
- Noise model of booster with receiver chain
- Electrical distance between receiver and booster varied
  → Good fit confirms understanding of full experimental setup

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

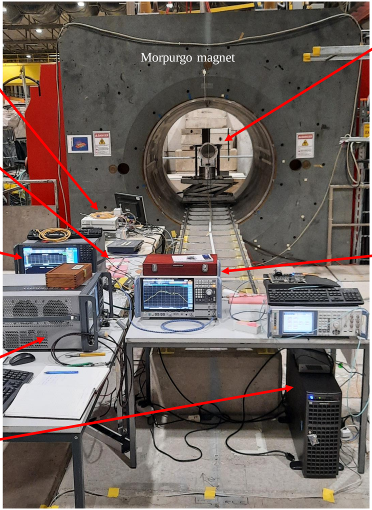
B-field & T - monitors

Receiver chain outside the B-field

Spectrum analyzer for RFI measurement

VNA for S11 calibration measurements

Computer with GPU

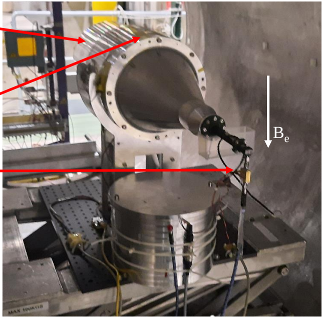


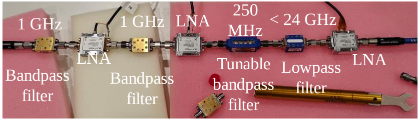
CB200

B-field probe

First LNA with T-sensor attached

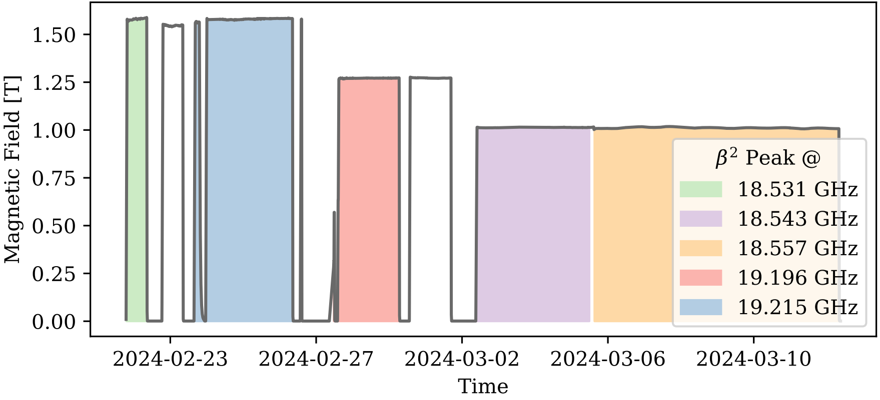
R&S spectrum analyzer FSW43



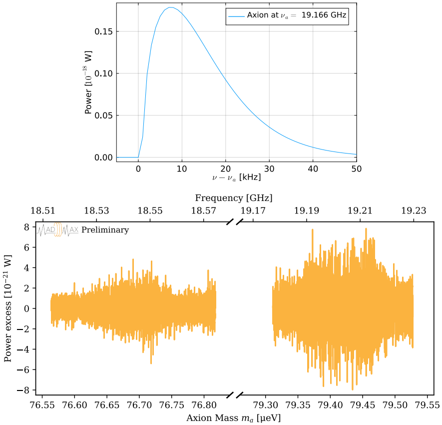


Receiver chain outside the B-field

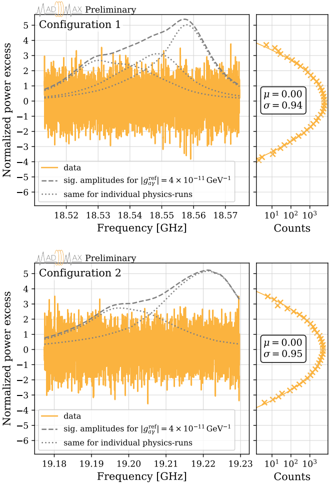
CB200 B field overview



CB200 statistical analysis



Axion lineshape and cross-correlated power excess



Cross-correlated normalized power excess

Uncertainties

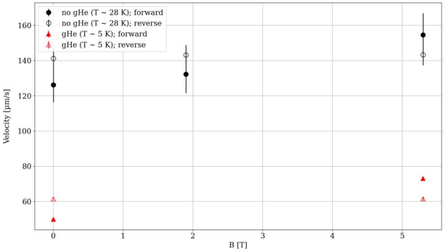
Effect	Uncertainty in $|g_{a\gamma}|$
Y-factor power calibration	3 % to 5 %
Receiver chain power stability	$\leq$ 2 %
Axion field – TE_{11} overlap	6 %
Boost factor determination	< 5 %
Frequency stability of TE_{11} mode	< 2 %
Total	5 % to 10 %

Axion run uncertainties

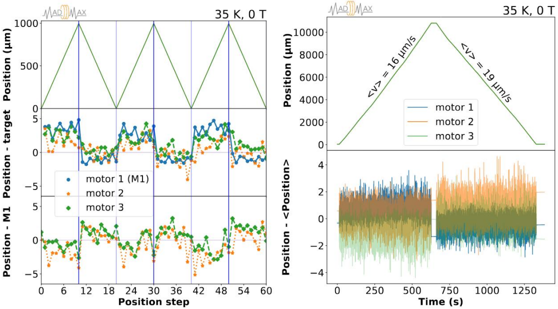
Effect	Uncertainty on χ
Bead-pull measurements	2 to 17%
Bead pull finite domain correction	5%
Receiver chain impedance mismatch	<1%
Y-factor calibration	4%
Power stability	3%
Frequency stability	2%
Line shape discretization	4%
Total	9 to 19%

Dark photon run uncertainties

Open booster 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]