MADMAX status and first dark matter searches

Vijay Dabhi

Aix-Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

Theory meeting experiment 2025

10 January 2025

On behalf of the MADMAX collaboration

Outline

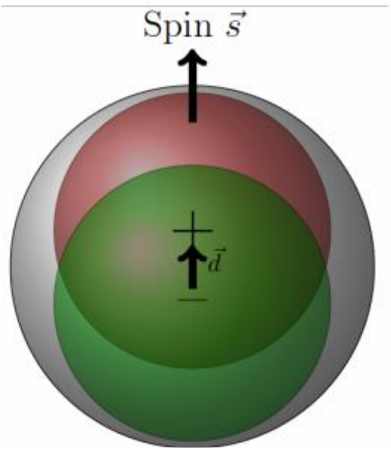
- Introduction to Axions
- Dielectric haloscope concept
- First dark matter searches with MADMAX prototypes
- Plans for final prototype
- Conclusions

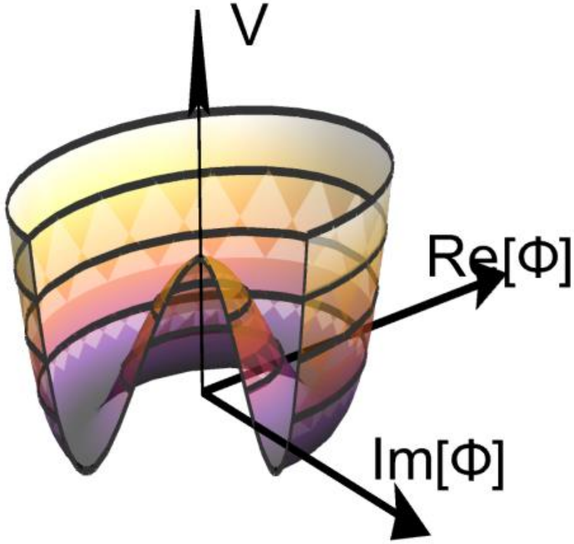
Strong CP Problem

- CP violation in strong sector
  - QCD Lagrangian has a CP violating term that is controlled by θ parameter ($-\pi < \theta < \pi$)
  - This term leads to a neutron electric dipole moment

$$d_n = (2.4 \pm 1.0)\,\theta \times 10^{-3}\,\mathrm{e\,fm}$$

  - Current experiments give upper bound of $|d_n| < 1.8 \times 10^{-13}\,\mathrm{e\,fm}$ leading to $|\theta| < 0.8 \times 10^{-10}$
- Strong CP problem : Why is a free parameter θ so small?
- Solution: Peccei – Quinn mechanism provides a dynamic reason for the small value of θ by introducing a new U(1) symmetry that is spontaneously broken at a high energy scale f_a ; generating a new- light neutral pseudo scalar boson that is called **'Axion'**





Axion properties

- Whatever the cosmological scenario, mechanisms exist to produce non-thermal axions in the early universe
  - Natural candidate for Cold Dark Matter
- All properties of axions controlled by just one parameter: f_a
  - Models with $f_a \sim f_{EW}$ excluded a long time ago, new models (KSVZ and DFSZ) have f_a ($O(10^{10})$ GeV) >> f_{EW}
  - Tiny mass [$\mathbf{m_a} \approx m_p f_p / \mathbf{f_a} \ll$ eV],
  - Very weakly interacting [suppressed by $f_\mathbf{a}$]
  - $\tau_{axion} > t_{Universe}$
- Axion like particles (ALPS) = $m_a \times f_a$ not constant

QCD Axion = DM candidate motivated by particle physics since 40 years

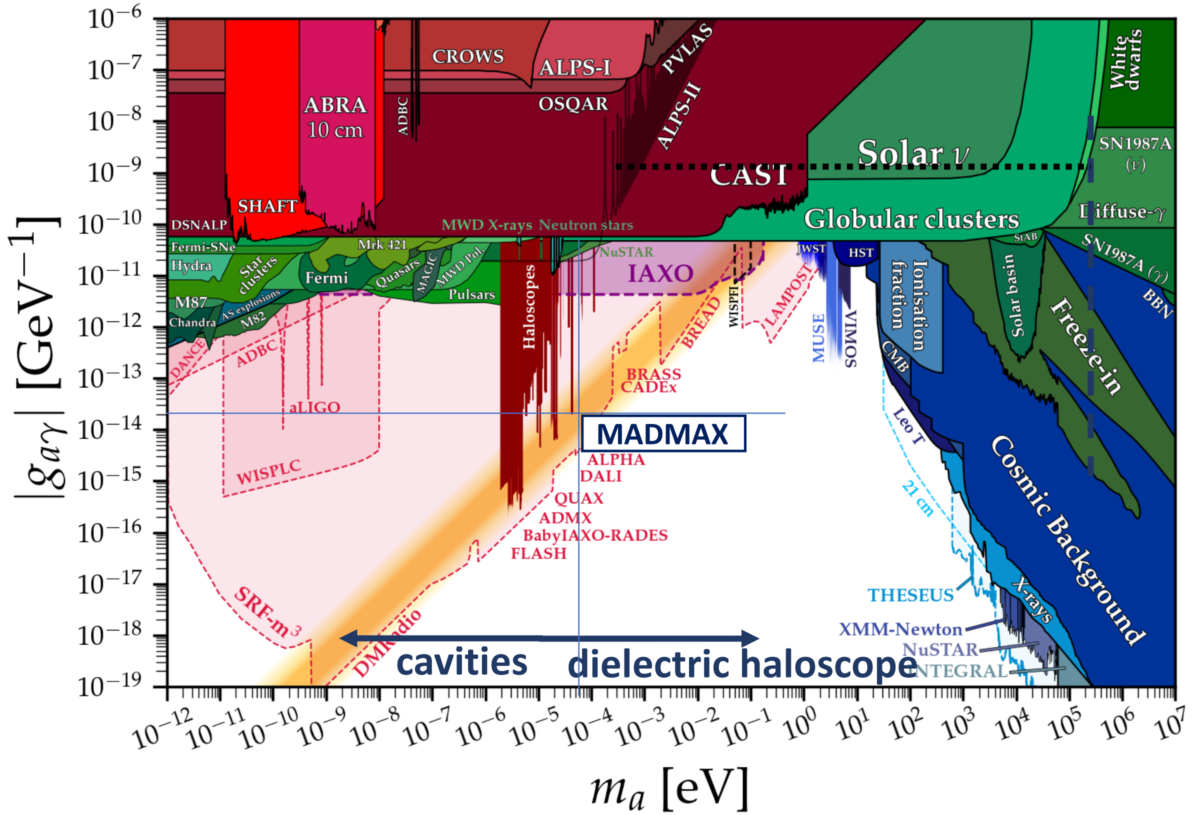
Axion/ALP direct searches

Lab experiments	Helioscopes	**Haloscopes**
Lab produced fully controlled setup	Solar axions	Relic DM axions
Low axion flux	Medium axion flux	High axion flux
Model independent	Mildly model dependent	Model dependent
ALP	QCD axion / ALP	QCD axion DM [1-1000 μeV]
e.g. ALPS II	**e.g. (Baby)IAXO**	**e.g. MADMAX**

Dark matter axion mass range

- Post inflationary scenario predicts >25 μeV in general (>6 GHz)
- Standard cavity experiments have reduced sensitivity > 25 μeV
- New concepts are required to probe this range → MADMAX

Nat. Commun. **13,** 1049 (2022)

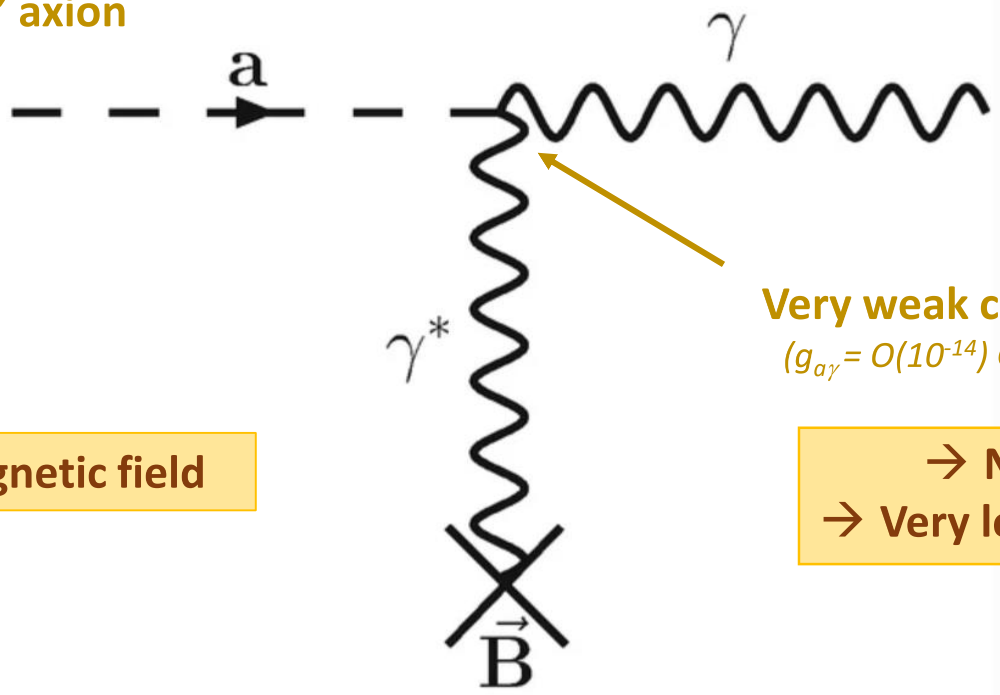


Plot from https://cajohare.github.io/AxionLimits/

How to see the dark matter axions ?

- ❑ If axions comprise all of dark matter -> 0.3 GeV/cm^3 in the galactic halo
- ❑ Preferred detection: Convert it to a photon in the presence of magnetic field

μeV "Invisible" axion
(gas)



GHz Photon
(EM field)

≈ RF, micro-wave

Very weak coupling: tiny signal
($g_{a\gamma}$ = O(10^{-14}) GeV^{-1} for m_a = 100 μeV)

High Magnetic field

→ Need boost
→ Very low temperature

Axion search very rich in experimental challenges

Dielectric haloscope: principles

- **Constructive interference** (and resonance) of coherent photon emission at dielectric layers surface (leaky resonators cavities)

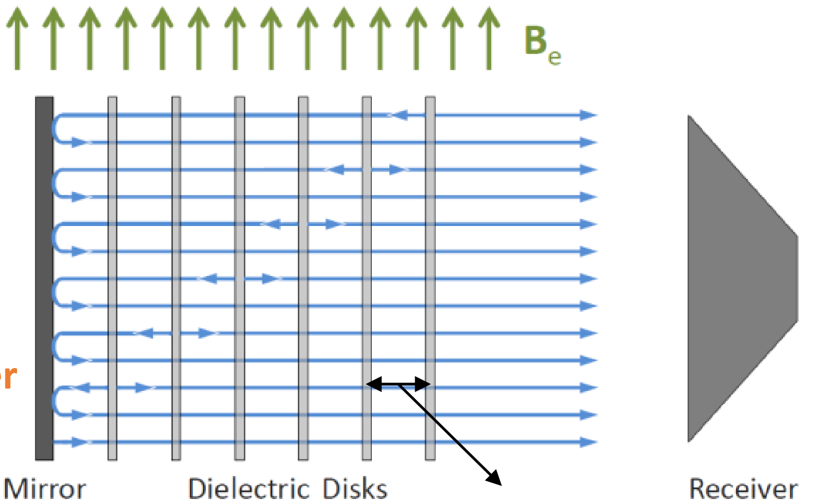
$$|C_{a\gamma}| = \left(\frac{|g_{a\gamma}|}{2\times 10^{-14}\ \mathrm{GeV}^{-1}}\right)\left(\frac{100\ \mu\mathrm{eV}}{m_a}\right)$$

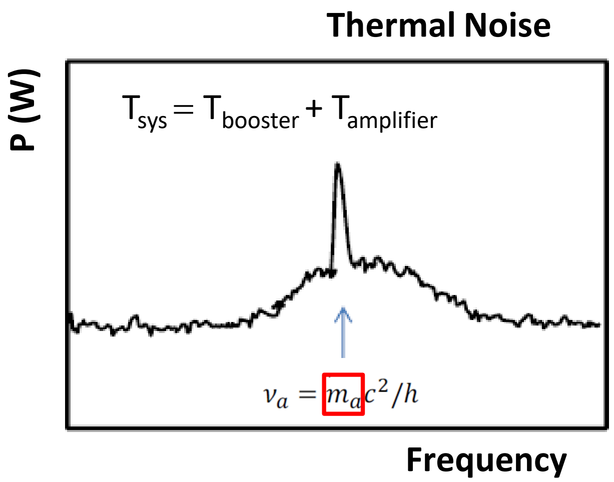
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

$$P_{sig} = 10^{-22}\mathrm{W} \times \left(\frac{SNR}{5}\right) \times \left(\frac{T_{sys}}{4\ \mathrm{K}}\right) \times \left(\frac{4\ \mathrm{days}}{t}\right)^{1/2}$$

Power boost factor:

$$\beta^2 = \frac{P_{\mathrm{mirror+disks}}}{P_{\mathrm{mirror}}}$$

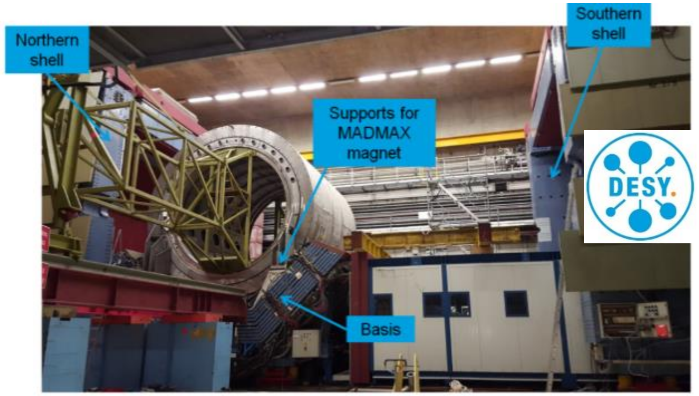




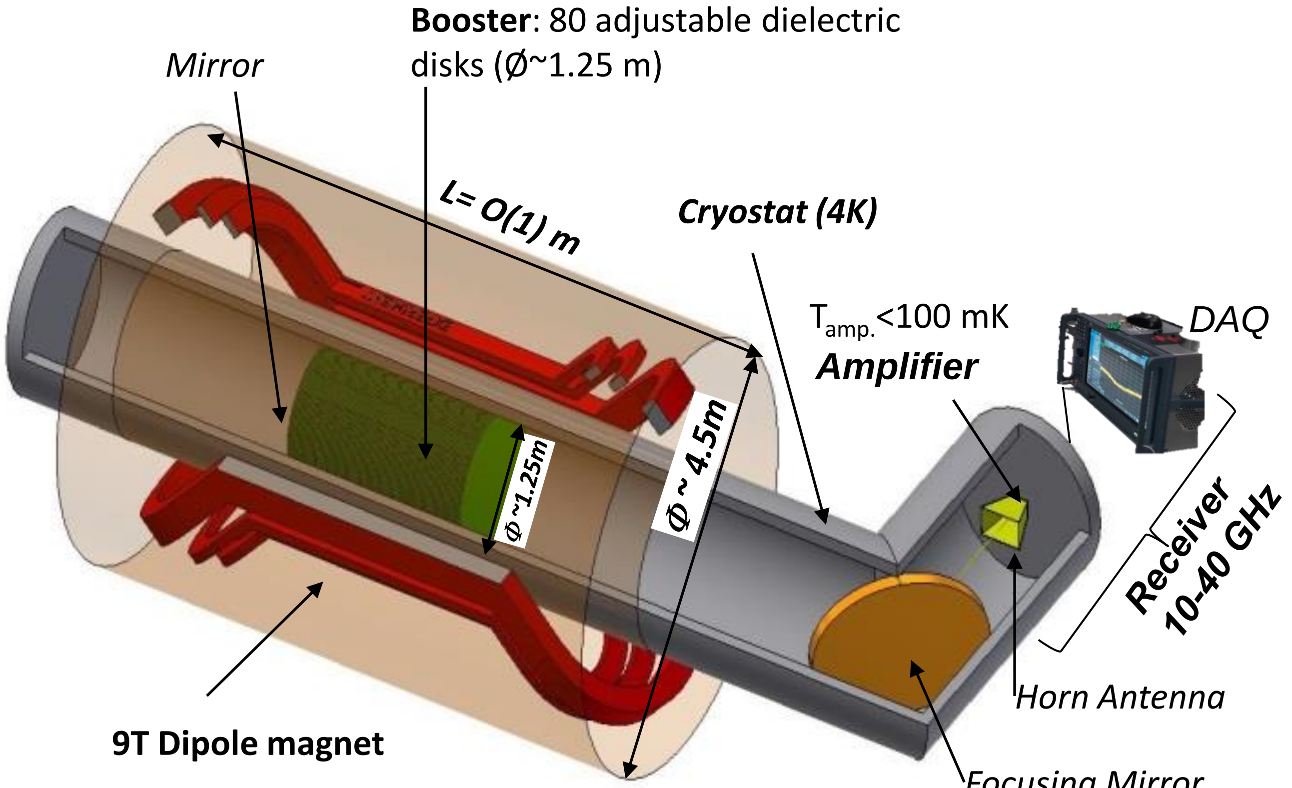
- **Axion mass scan** : by positioning discs with µm precision at 4K under 10 T *(50 MHz step)*

The MADMAX collaboration

- ❑ Formed in 2017, 11 institutes: French (3), German (6), Spanish (1) and US (1) → ~50 people



Experiment location: HERA H1 iron yoke in DESY, Hamburg

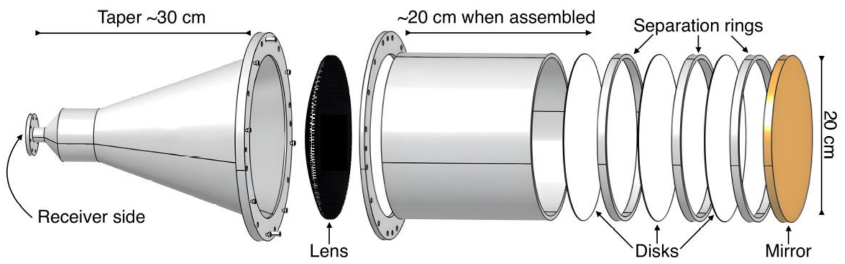


[Eur. Phys. J. C **79** (2019) 186]

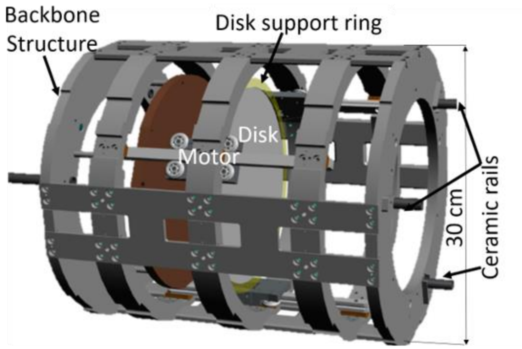
Experimental Challenges :
- High B-field
- Low Temp. (4 K)
- O(10) GHz regime
- μm precision for mechanics

MADMAX prototypes

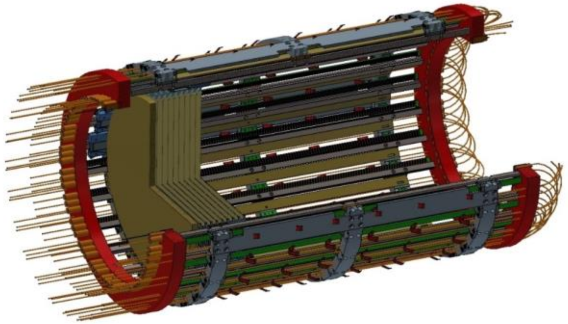
- Validate the new concept of dielectric haloscope using several prototypes



Closed booster with 200 mm disks (CB200)



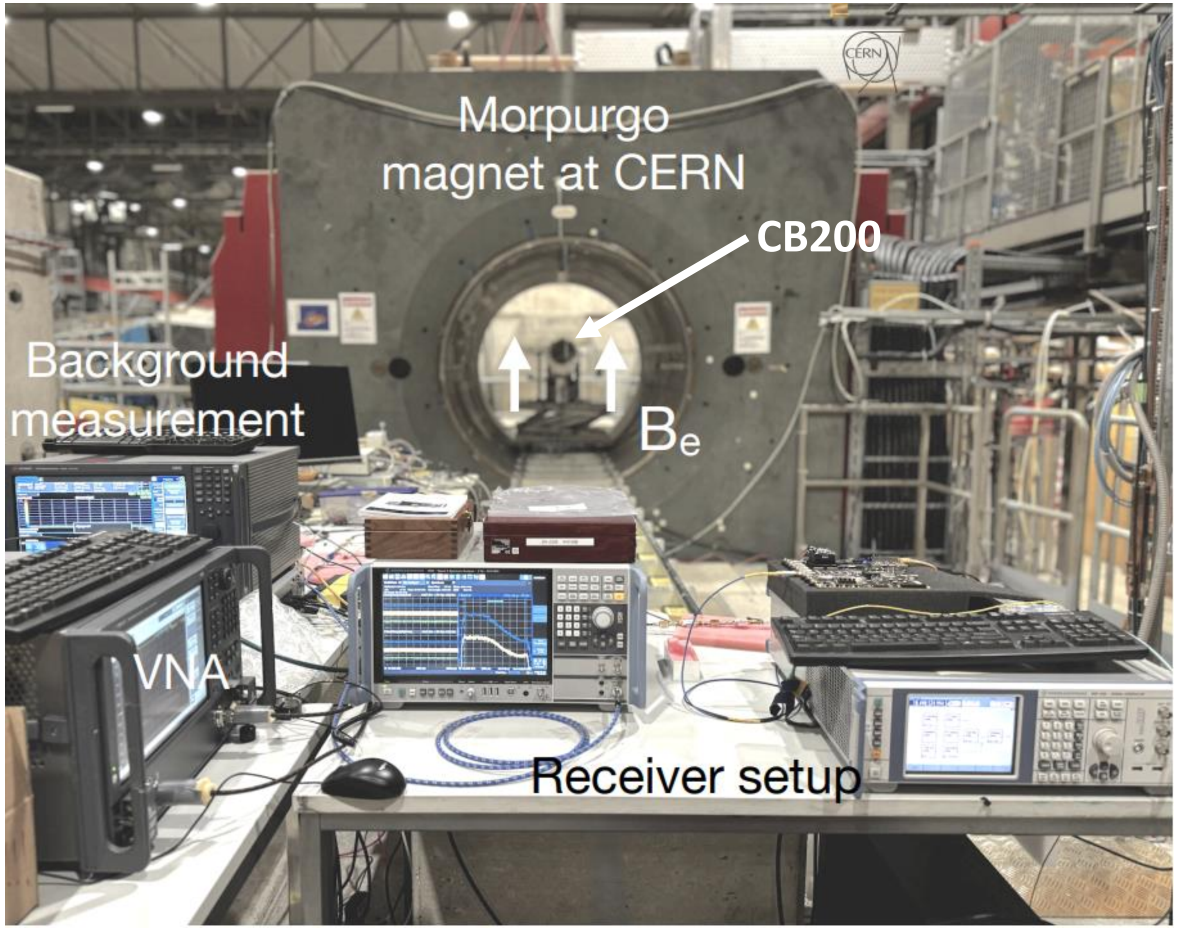
Open booster OB200



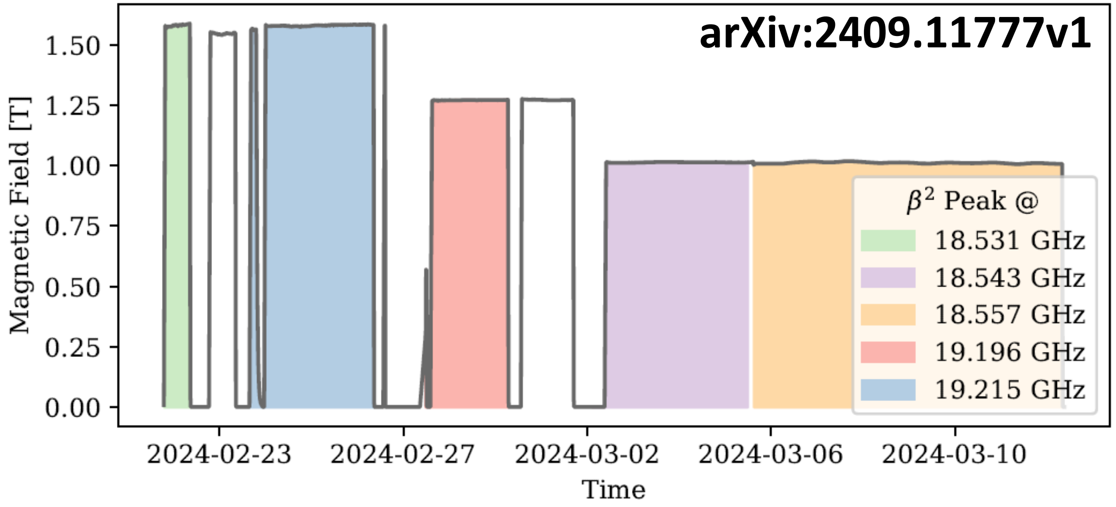
Open booster OB300

Name	Setup	Temperature	Goal
CB200	3 fixed disks	Warm	First ALPs search, booster modelling
OB300v1	3 fixed disks	Warm	First Open booster, booster modelling
OB200	1 moveable disk	Warm	Mechanical feasibility of disk movement
CB100	3 fixed disks	Cold	Cryogenic calibration
OB300v2	>= 3 moveable disks	Cold	Scan mass range in B-field and cryogenic

First ALPs search with MADMAX



- Room temperature
- 1 - 1.6 T magnetic field inside the Morpurgo magnet

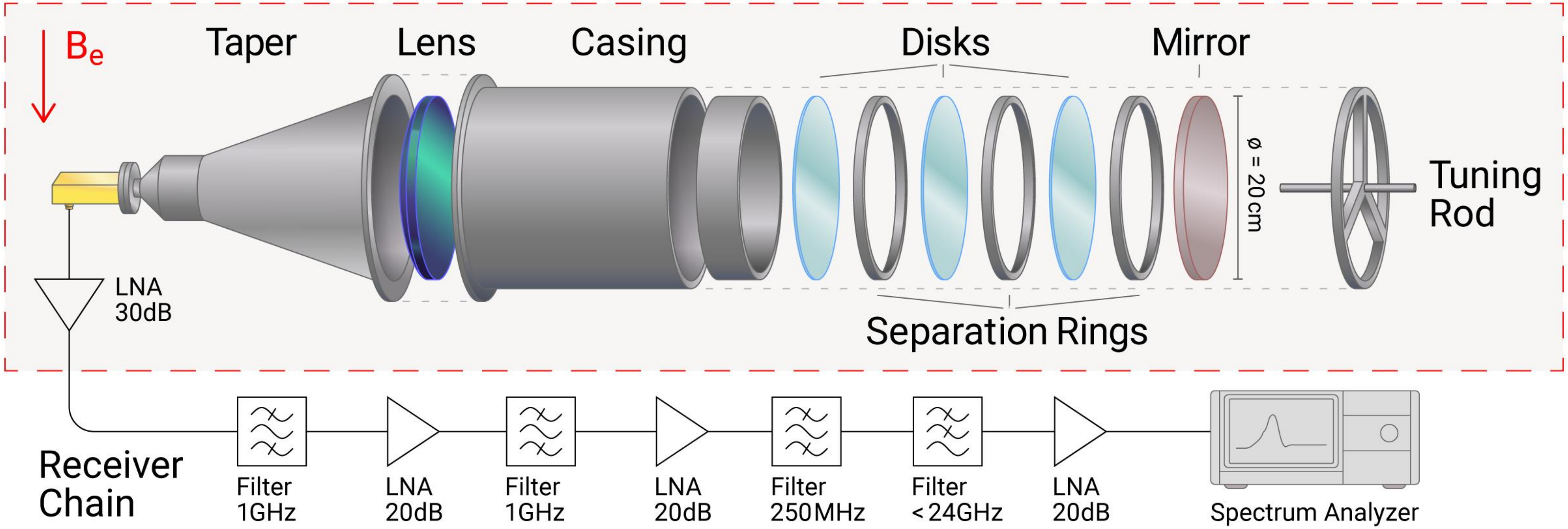


14.5 days of physics data at CERN with CB200 prototype

First ALPs search with MADMAX

- ❑ A prototype with 1 mirror and three sapphire disks of 200 mm diameter
- ❑ Distance between the disks is determined by separation rings, optimized for 76-80 μeV axion search
- ❑ Tuning rod can push the mirror to change the desired search range

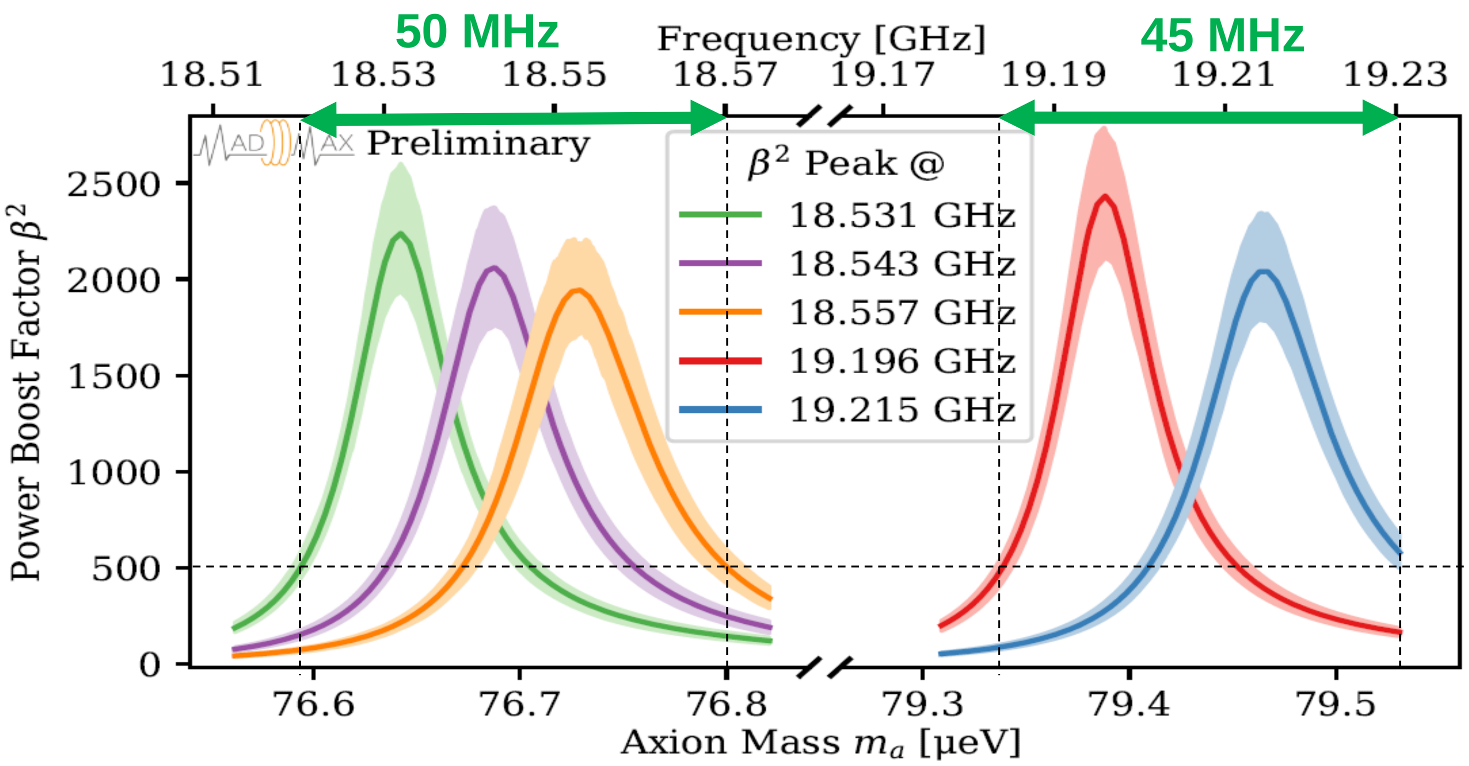
arXiv:2409.11777v1



Five data runs in two configurations (two sets of separation rings) ~ 18.5 GHz and 19.2 GHz

Booster modelling

- β² extracted from booster measurements and 1D modelling using ADS software



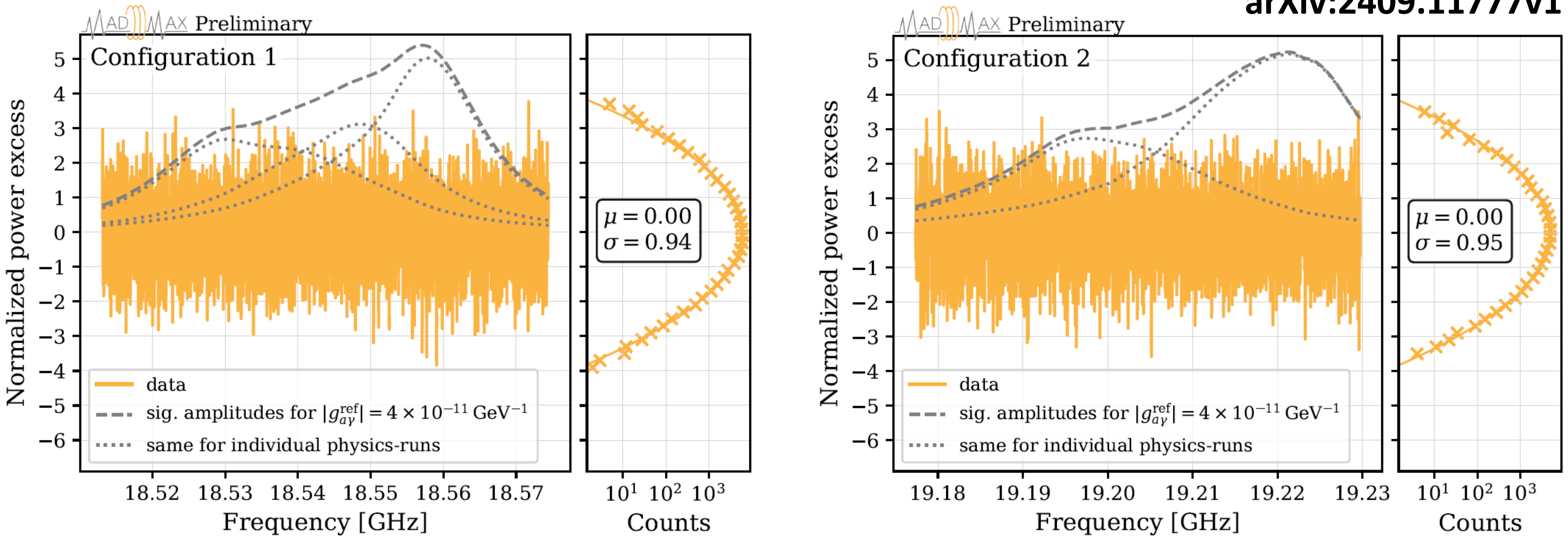
arXiv:2409.11777v1

- β² > 500 in 100 MHz bandwidth
- β² peaks around 2000 for all 5 data runs with ~ 15% uncertainty

Statistical analysis

- Combining all raw spectra measurements to get one "grand spectrum"
  - Optimize the SNR in the process
  - Based on HAYSTAC analysis procedure (PRD 96 (2017) 123008)

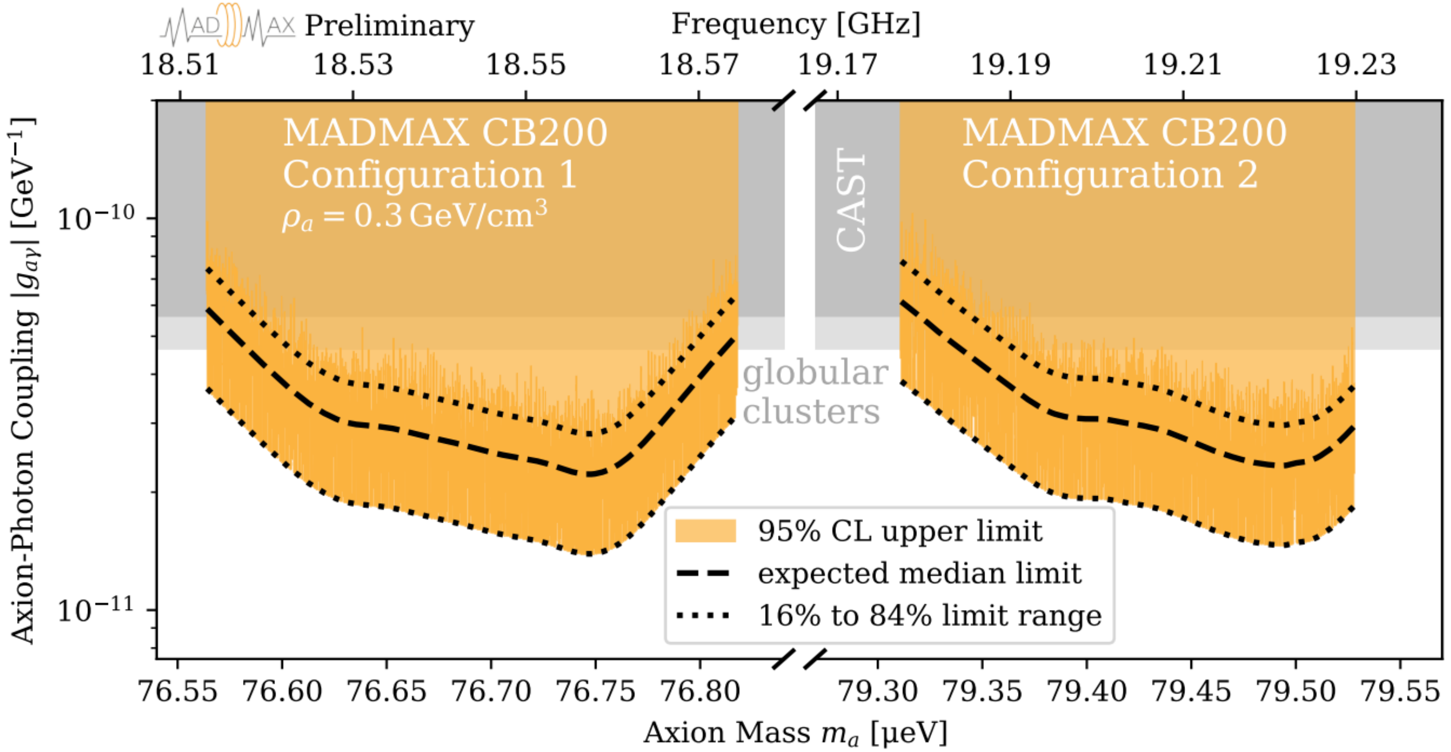
arXiv:2409.11777v1



Grand spectrum for two different configurations @ 18.5 GHz and 19.2 GHz

First ALPs limit with MADMAX

- First axion dark matter limit using dielectric haloscope



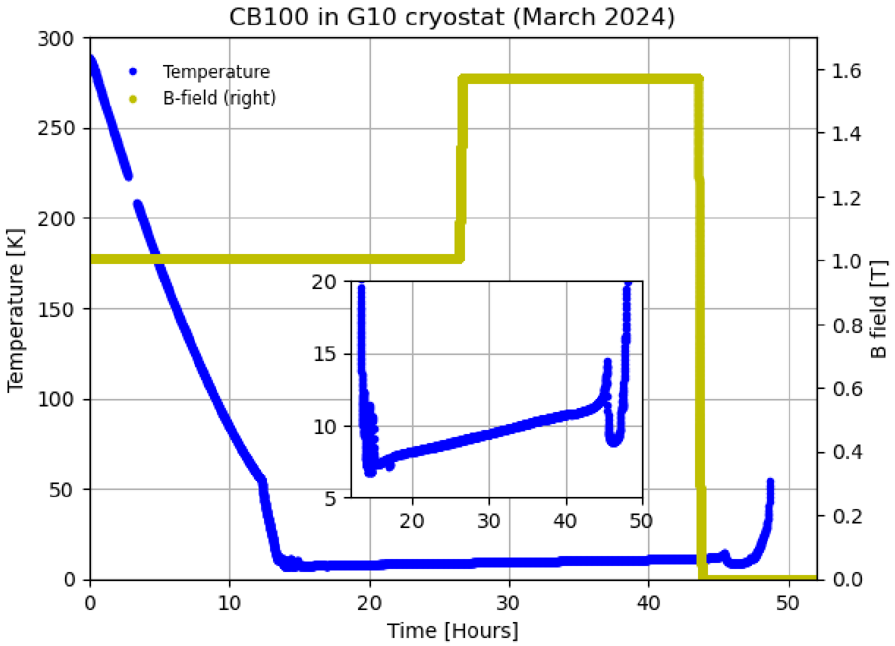
arXiv:2409.11777v1 (submitted to PRL)

95% confidence exclusion limit
bin width = 0.9 kHz

- World best median limit down to 2×10^{-11} GeV^{-1} around 78 μeV

First ALPs search at cold

- ❑ Developed low cost cryostat with CERN cryolab using G10 material
  - O(20) hours below 10 K
- ❑ Developed receiver chain calibration procedure at cold

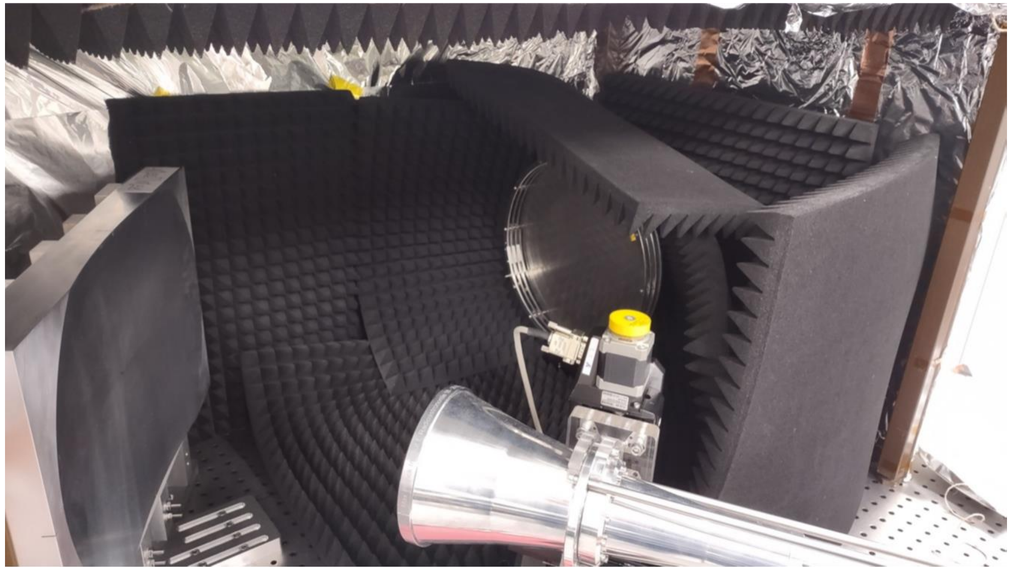


Analysis ongoing!

arXiv:2412.12818

First Dark photon search with MADMAX

- ❑ Moving from closed booster towards bigger and open booster
  - OB300v1 with fixed disks
  - OB300v2 with movable disks
- ❑ OB300v1 booster for dark photon dark matter (DPDM) search (no B field)
  - Setup at room temperature, surrounded by RFI shielding walls
  - Assuming unpolarized DPDM



In-situ β^2 determination

1. Reflectivity (Γ_R) measurements with and without a small bead to make a 3D scan inside the booster (not possible with closed booster)
2. Calculate the electric field $E_R \propto \sqrt{\Delta\Gamma_R}$

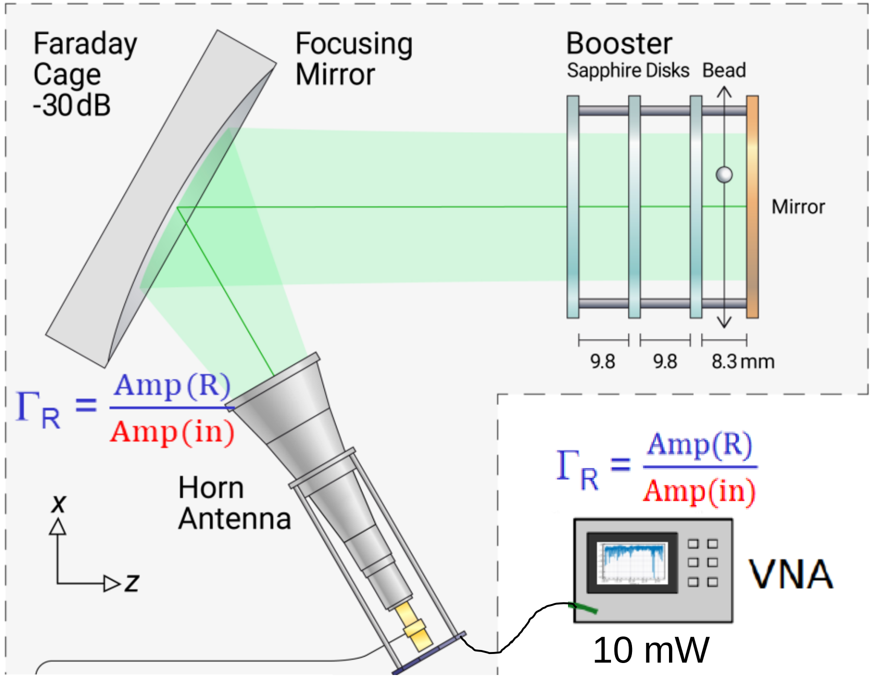
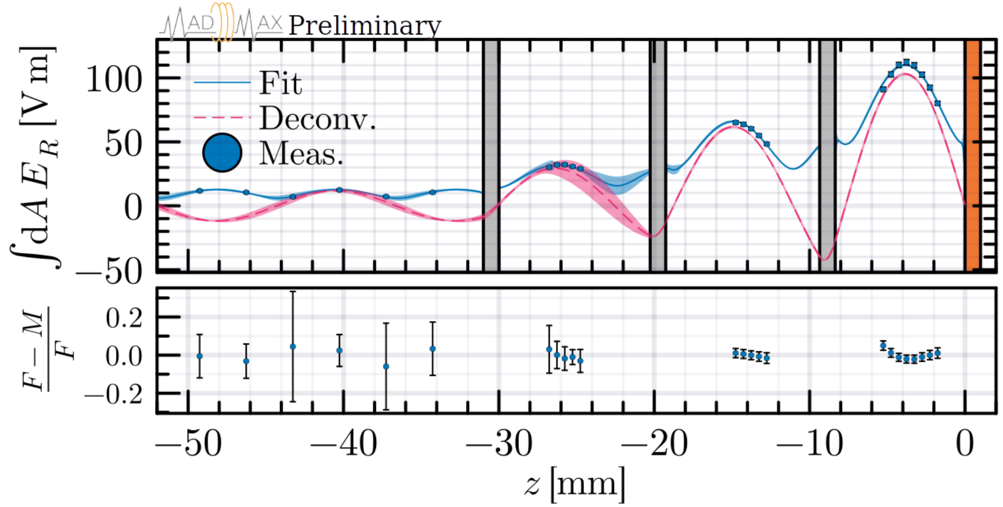


Figure from arXiv:2408.02368v1

JCAP 04 (2023) 064
JCAP 04 (2024) 005

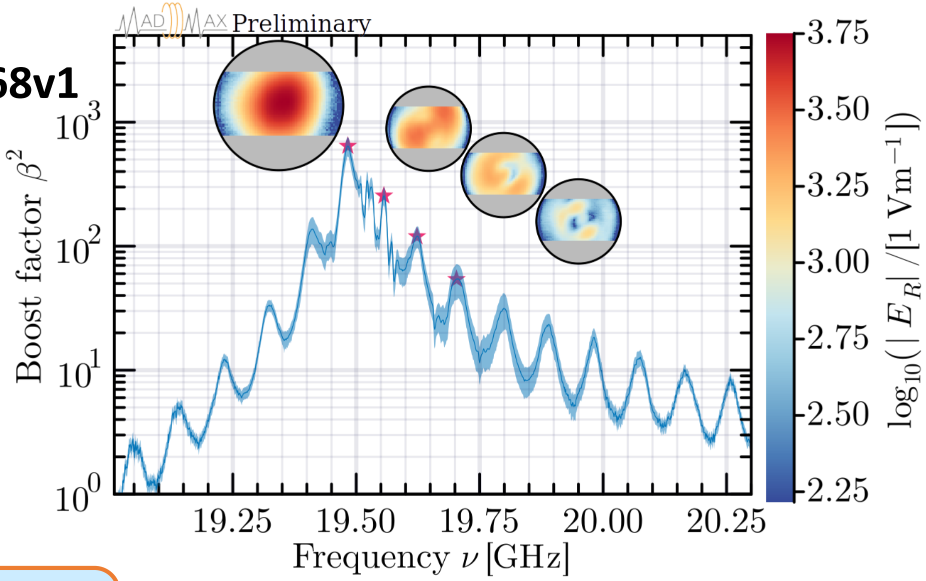
In-situ β^2 determination

3. Fit the electric field measurements to a 1D booster model
4. Deconvolute the bead response to get reflection induced electric field
5. Integrate the electric field over the booster volume to calculate the boost factor



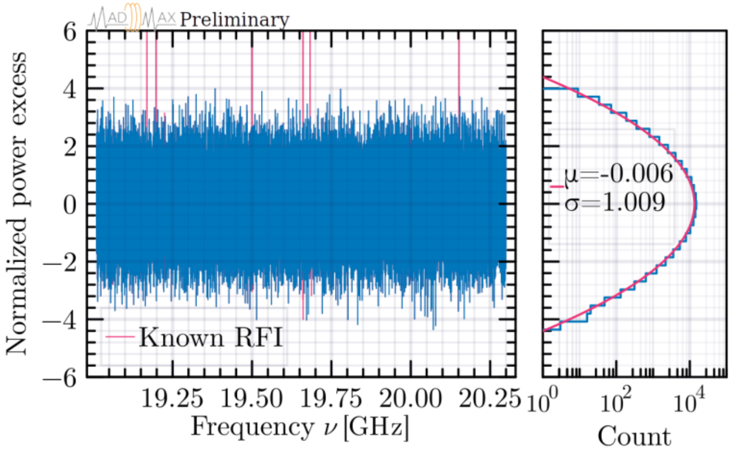
arXiv:2408.02368v1

$\beta^2 \propto |\int dV\, E_R|^2$



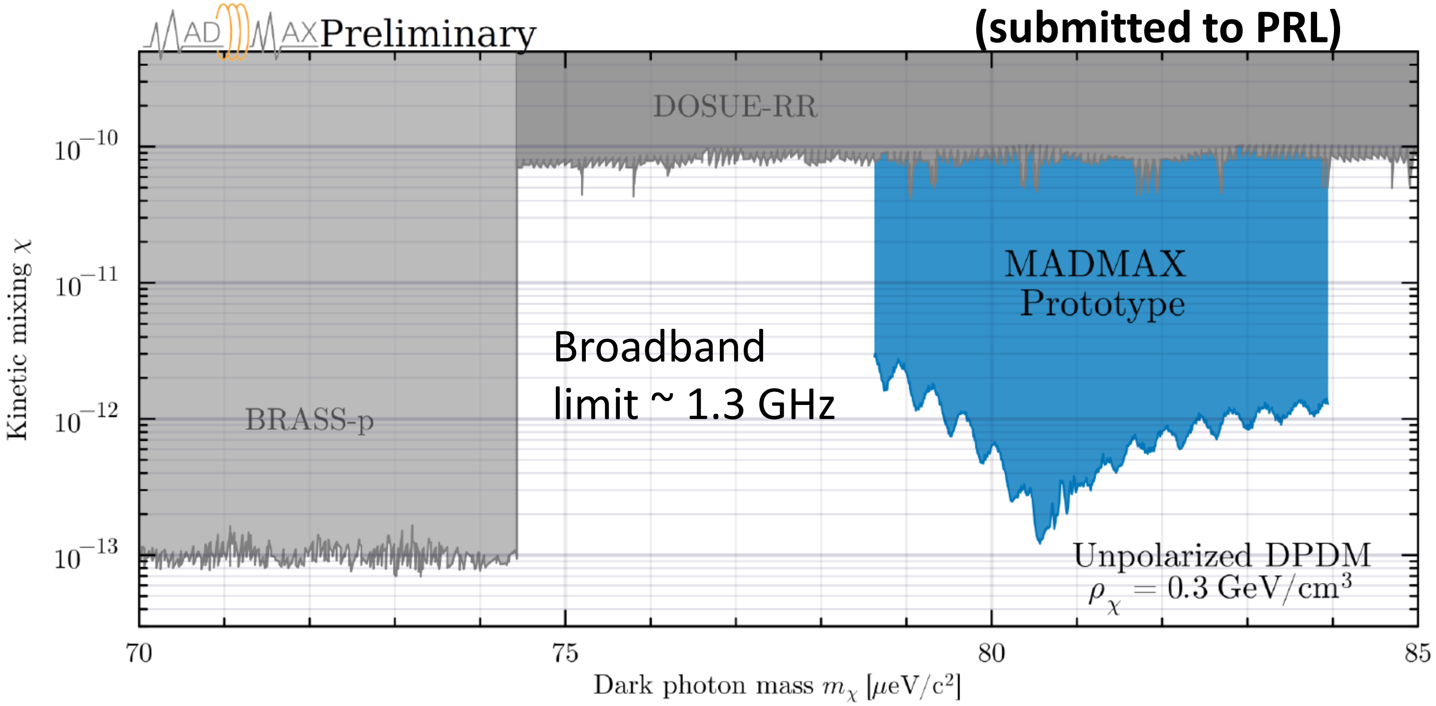
- β^2 > 1 in 1.3 GHz bandwidth
- β^2 peak around 600 with ~ 15% uncertainty

1^{st} Dark Photon limit with MADMAX



No peaks of unknown origin are observed

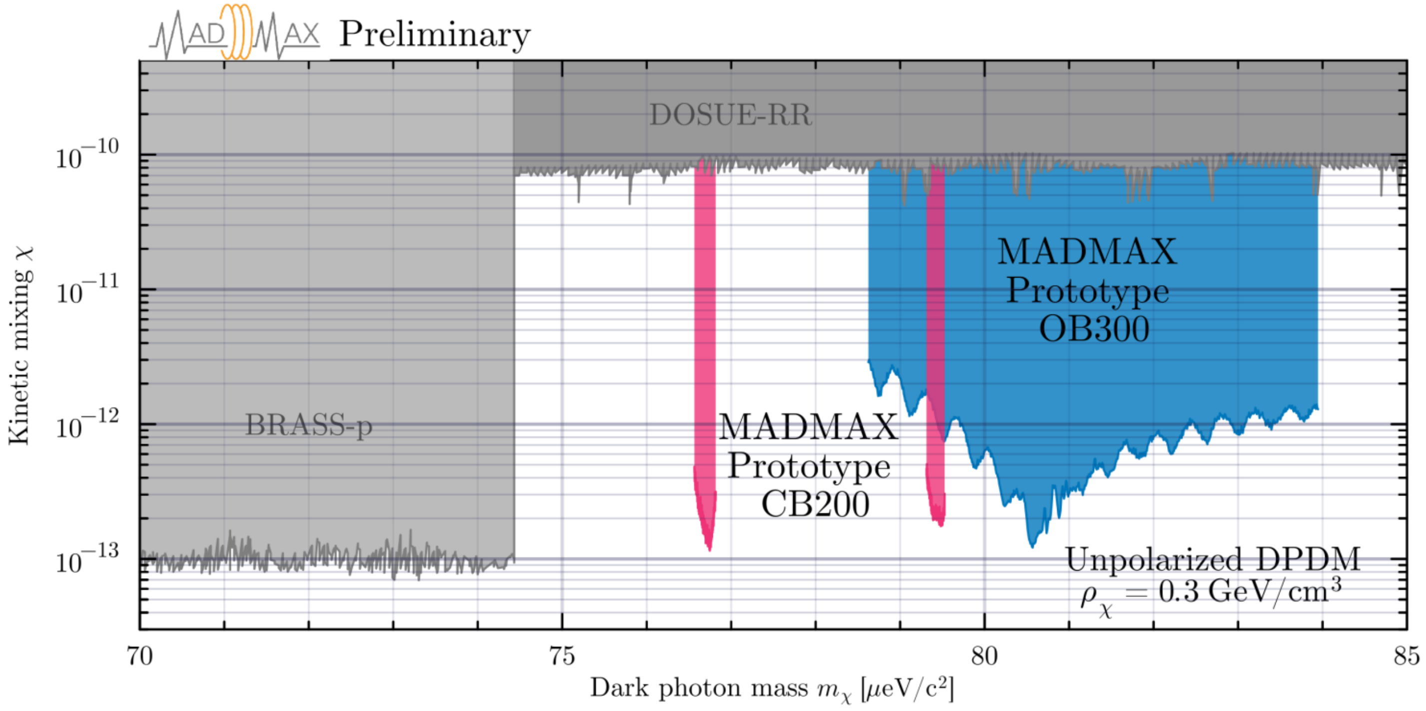
arXiv:2408.02368v1 (submitted to PRL)



- World best 95% CL limit on DP kinetic mixing χ in m_χ [78.6, 83.9] μeV using OB300v1
  - 1-3 order of magnitude below previous limits

2nd Dark Photon limit with MADMAX

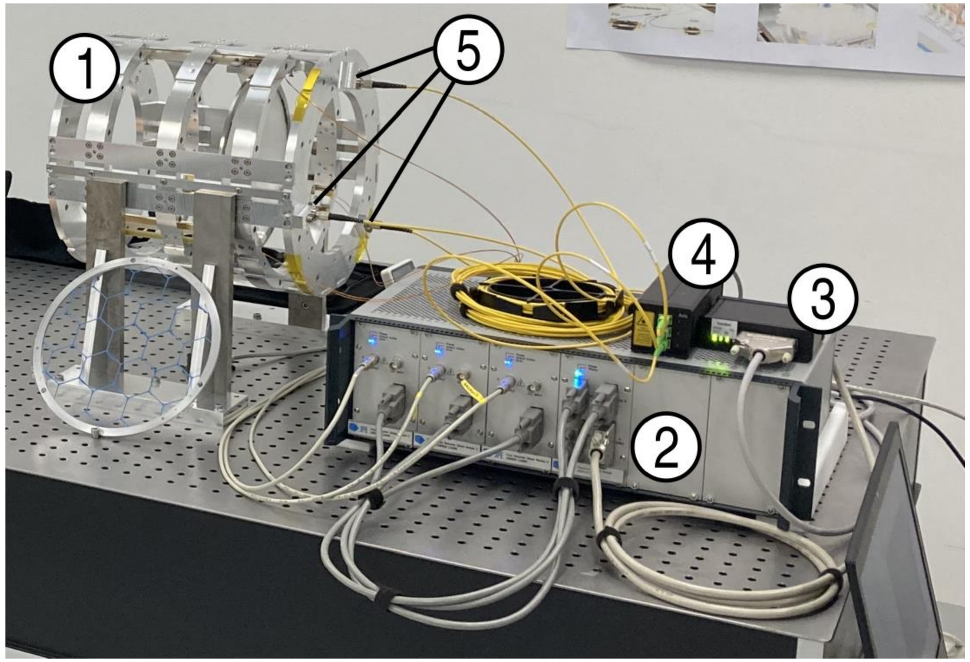
- Reinterpret the ALP search null result as Dark photon limit
- Assuming unpolarized DPDM



- World best 95% CL limit on DP kinetic mixing χ in m_χ (76.56 to 76.82, 79.31 to 79.53) µeV using CB200 prototype

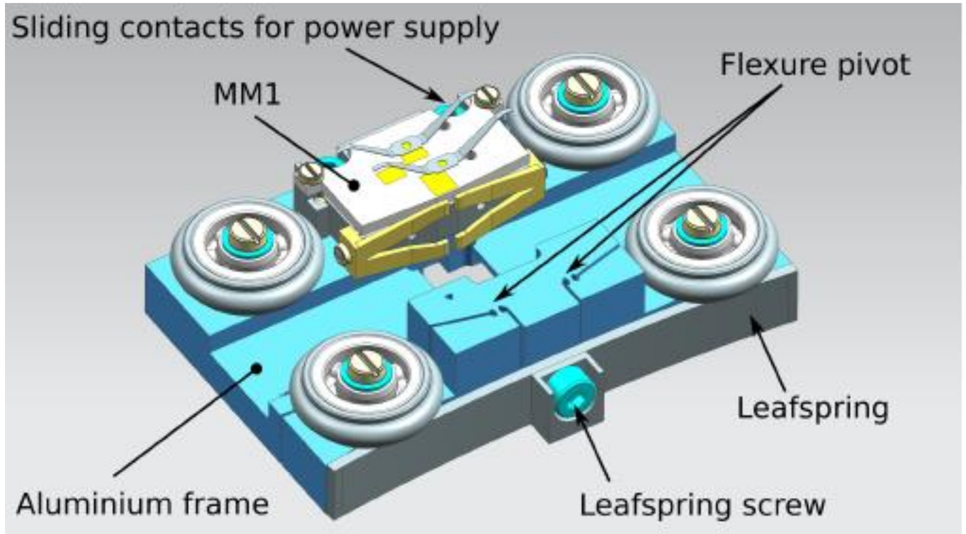
Disk positioning system

- ❑ Moving from fixed disks to movable disks -> dedicated prototype OB200



1. OB200 and motor controllers
2. FPGA board
3. Laser interferometer
4. Optical sensor 5. mounted to the backbone

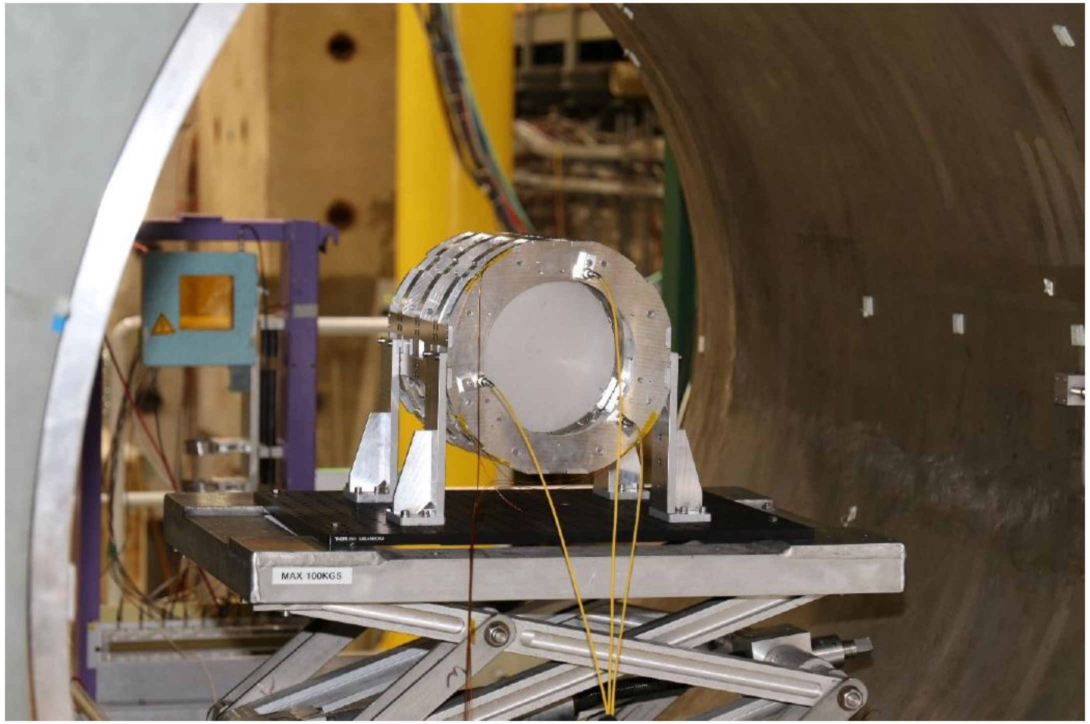
JINST, 18(08):P08011, 2023



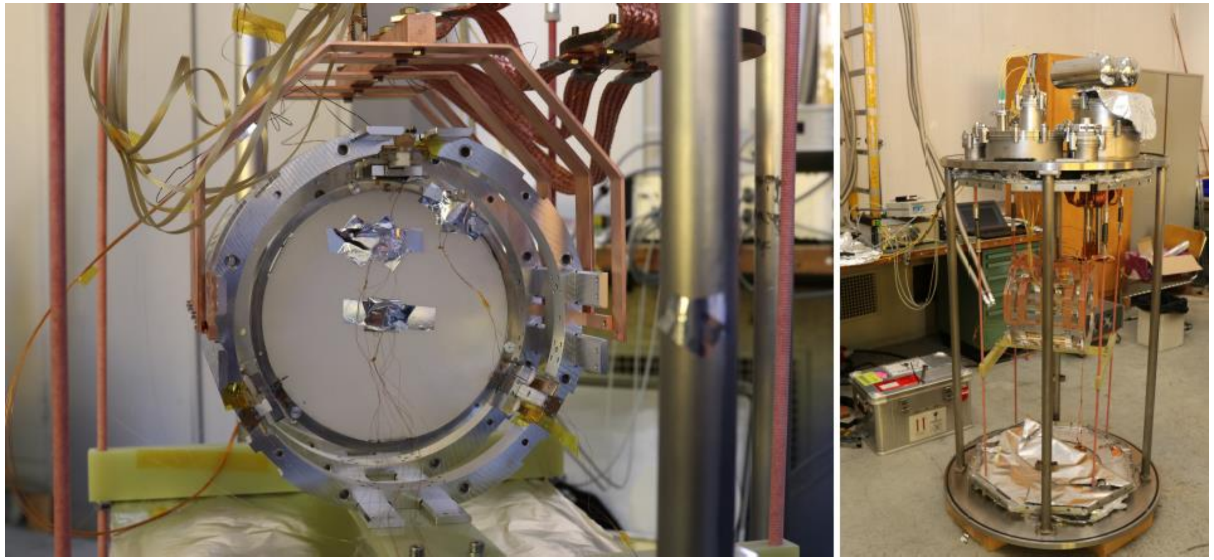
- ❑ Piezo motors for precision movement tested at cryogenic temperatures down to 4.5 K and high magnetic field up to 5.3 T
- ❑ 3 of them required to move one disk

Disk positioning system: Tests

- Disk movement tested in 2022 in B field (CERN) and cryogenic temperatures (CERN cryolab)
  - Precise control of 200 mm diameter sapphire disk position with three piezo motors
  - Many tests were made at cryogenic temperature (35 K) and magnetic field (1.6 T) to test the precision, speed, operability, drift, step size of the motors, etc.



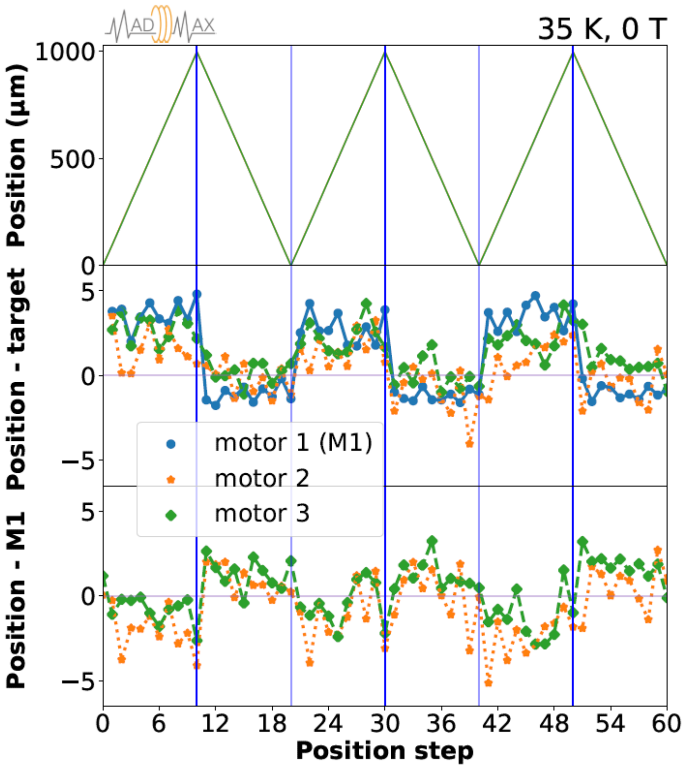
JINST **19** (2024) T11002



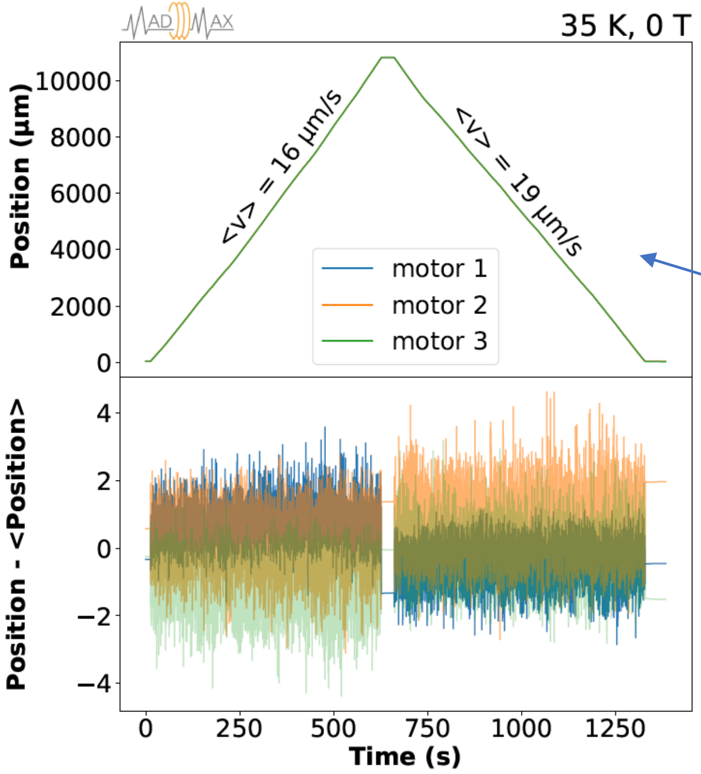
Disk positioning system: Test results

- Representative plots of the tests:

Position precision: <10 μm



Motor speed: >10 μm/s



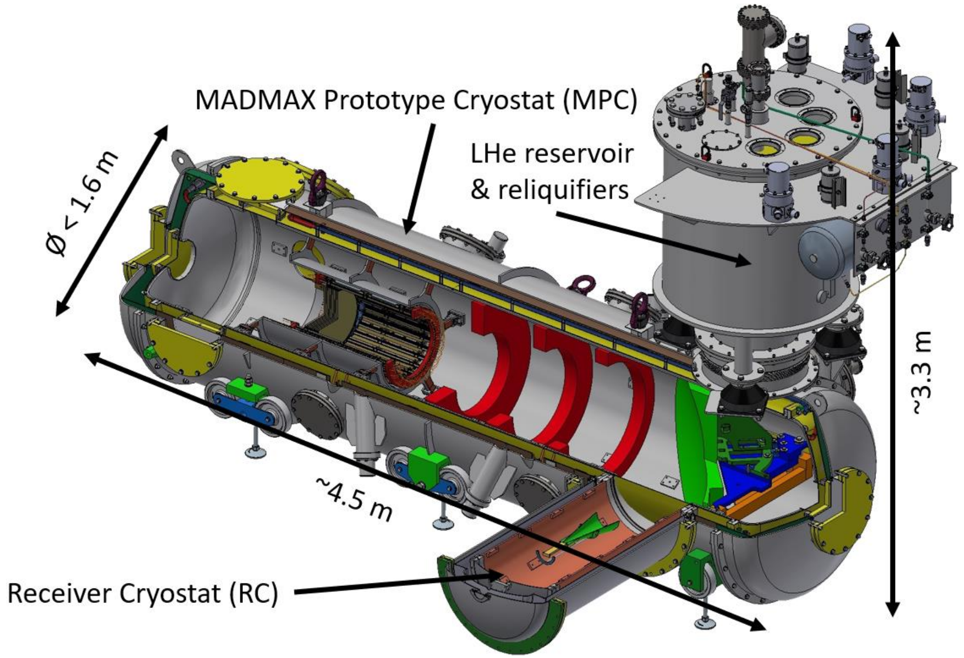
An example figure (from the paper) of a test performed at cryogenic temperatures

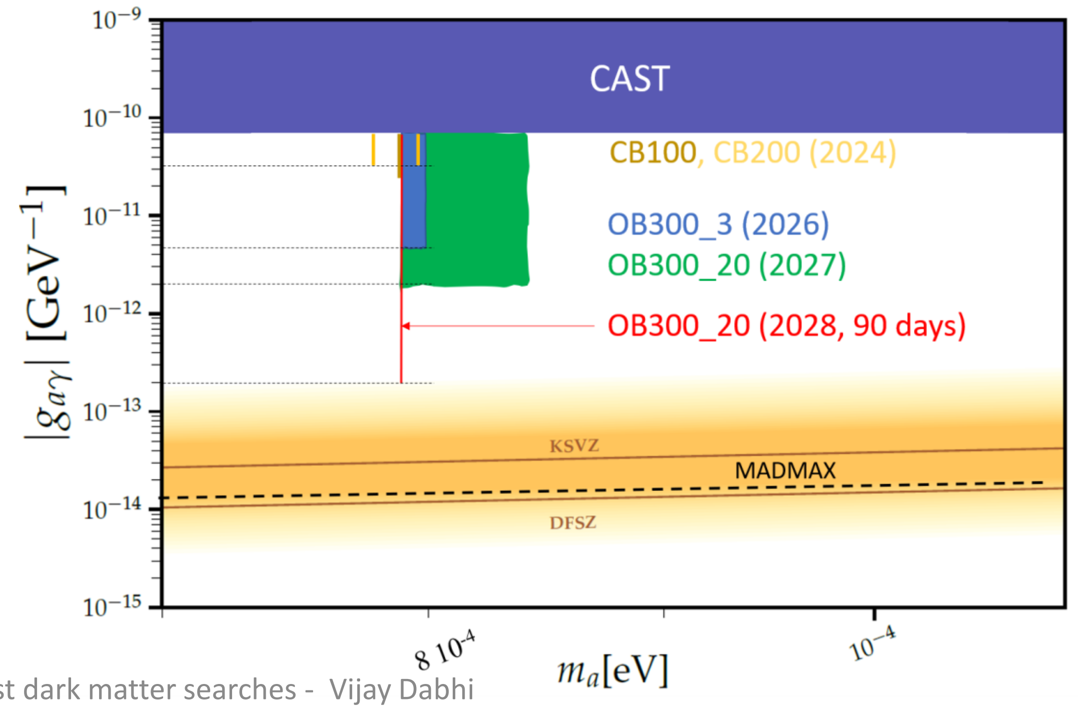
JINST **19** (2024) T11002

The positioning system shown to work according to requirements

Final prototype: Future plan

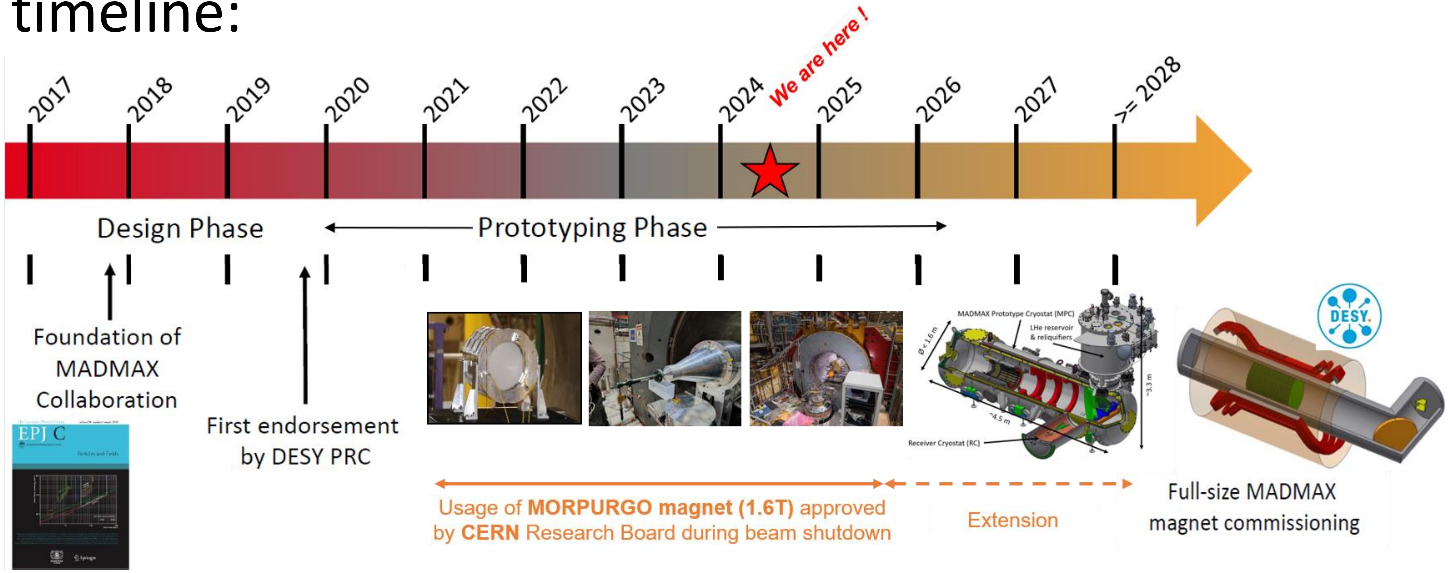
- ❑ OB300v2 prototype with 3 to 20 movable disks (presently being assembled)
- ❑ Under 1.6 T magnetic field and 4 K temperature (proto cryostat arriving in 2025)
- ❑ 3 physics runs planned with different search ranges during the long shutdown period 2026-2028 at CERN





Conclusions

- ❑ MADMAX: dielectric haloscope experiment for axion DM search around 100 μeV
- ❑ First dielectric haloscope to search for ALPs
  - World-leading limits in both dark photon and axion searches around 80 μeV (20 GHz)
- ❑ Novel booster calibration methods developed for closed and open boosters
- ❑ Validated the mechanics at cryogenic temperature and high magnetic field
- ❑ Current timeline:




MADMAX