Advances in searching for axions with MADMAX

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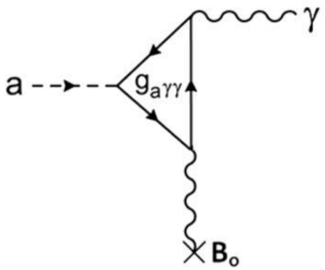
on behalf of the MADMAX collaboration

Dark Matter: From the Smallest to the Largest Scales
June 6th 2025

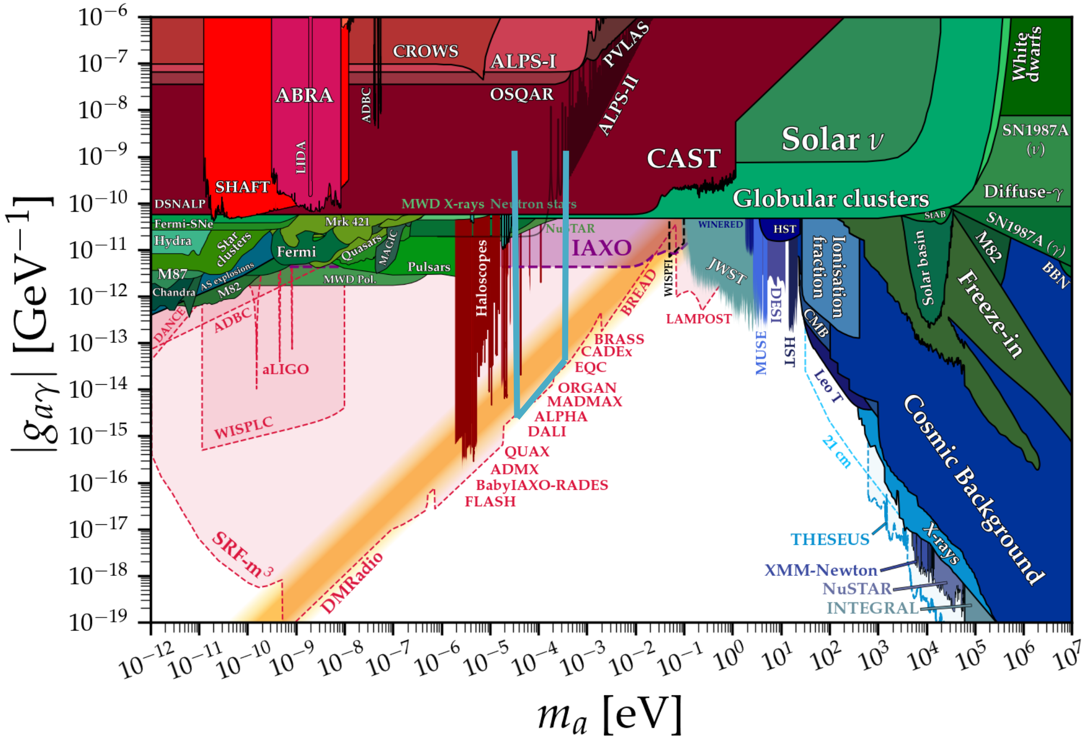
www.madmax.mpp.mpg.de

MADMAX
Looking for the Axion

- Axion is a hypothetical particle introduced to solve the strong CP problem.
- Axions → very low mass, very weak interaction with all SM particles. Behave like waves. Excellent candidate for cold DM.
- Inverse Primakoff effect: axions couple to photons in the presence of a strong magnetic field.



- The MADMAX experiment → search for axion dark matter in the 100 μeV range.



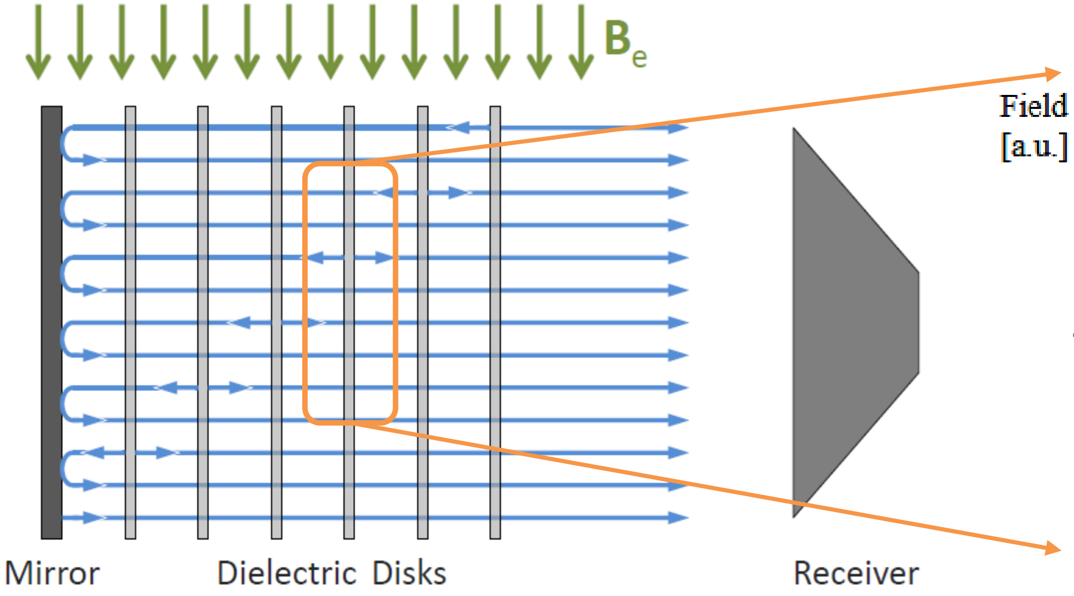
https://cajohare.github.io/AxionLimits/docs/ap.html

MADMAX: A dielectric haloscope

In an external magnetic field $\boldsymbol{B_e}$ the axion field oscillation $a(t)$ sources an oscillating electric field $\boldsymbol{E_a}$

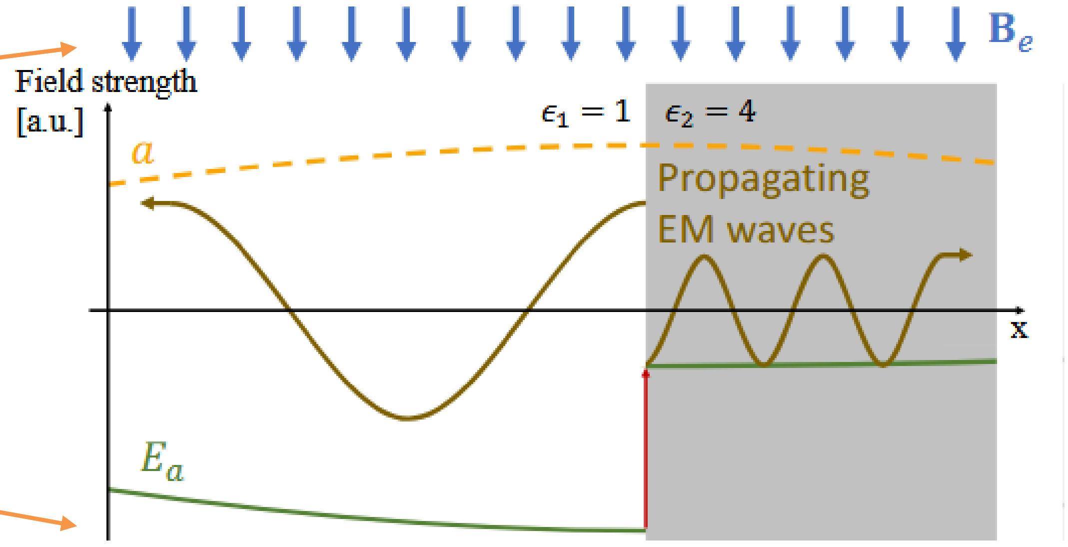
$\boldsymbol{E_a} \cdot \boldsymbol{\epsilon} \sim 10^{-12}\ {}^{\mathrm{V}}/_{\mathrm{m}}$ for $B_e = 10\ \mathrm{T}$

Constructive interference of coherent photon emission at several interfaces



MADMAX PRL118 (2017) 091801

$\boldsymbol{E_a}$ is different in materials with different ε



At the surface, $E_{\parallel}$ must be continuous

→ Coherent emission of electromagnetic waves

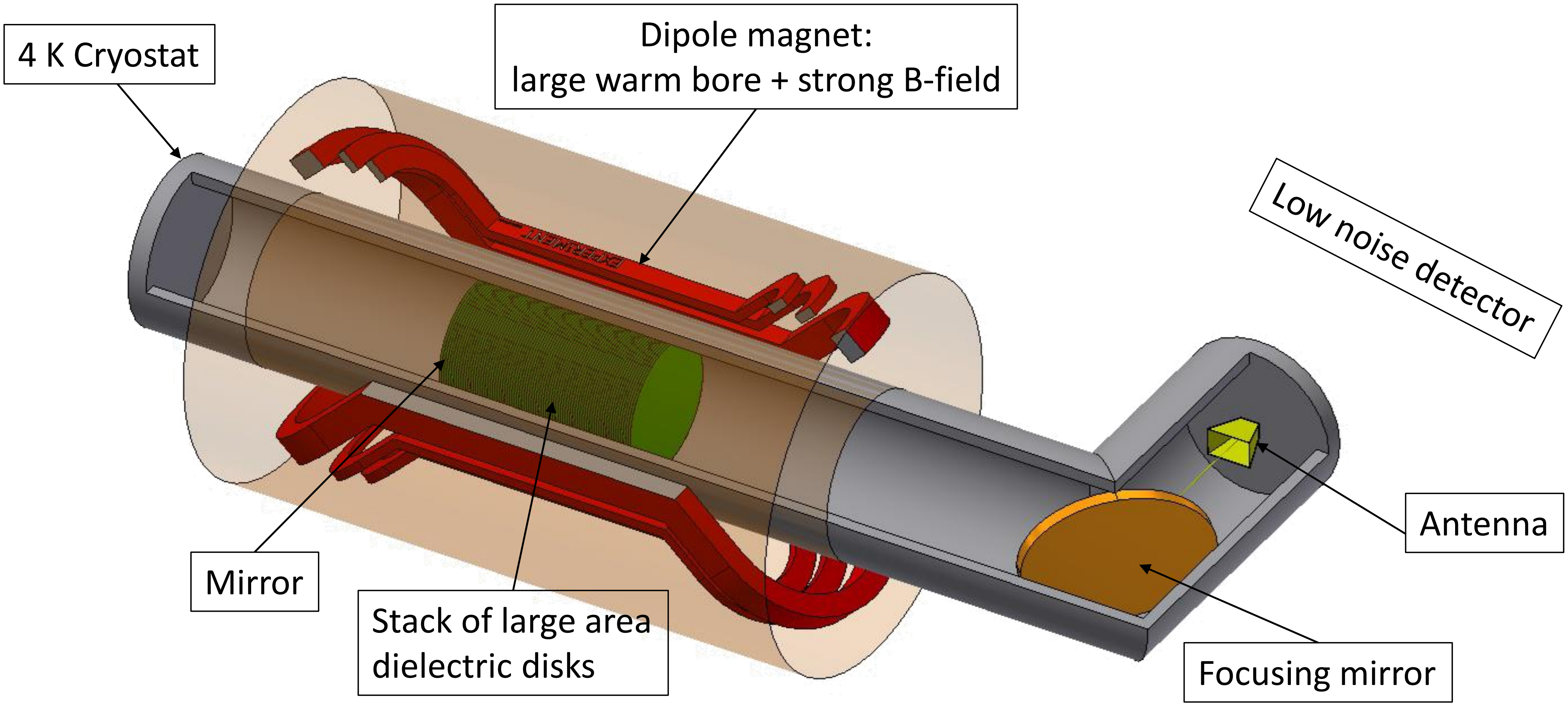
Output power P of the dielectric haloscope per unit area A is:

$$\left(\frac{\boldsymbol{P}}{\boldsymbol{A}}\right)_{\boldsymbol{booster}} \sim \mathbf{2} \cdot \mathbf{10^{-27}} \frac{\mathbf{W}}{\mathbf{m^2}} \left(\frac{\boldsymbol{B_{||}}}{\mathbf{10}\ \boldsymbol{T}}\right)^{\mathbf{2}} \left(\boldsymbol{g_{a\gamma\gamma}}/\boldsymbol{m_a}\right)^{\mathbf{2}} \boldsymbol{\beta^2}$$

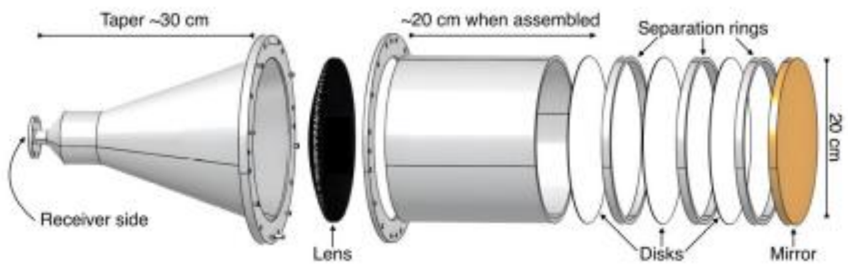
The boost factor

$$\boldsymbol{\beta^2} = \frac{\boldsymbol{P_{booster}}}{\boldsymbol{P_{mirror}}}$$

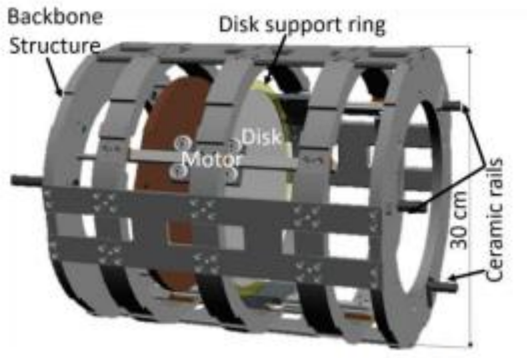
MADMAX: baseline design



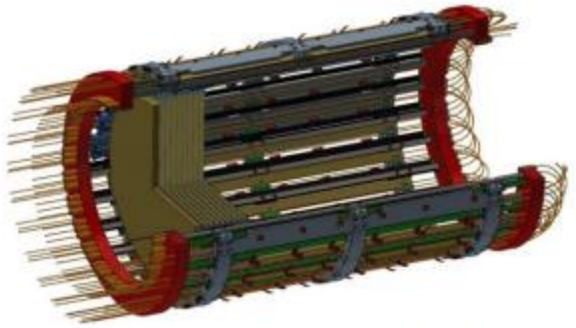
MADMAX prototypes



Closed booster with 200 mm disks (CB200)



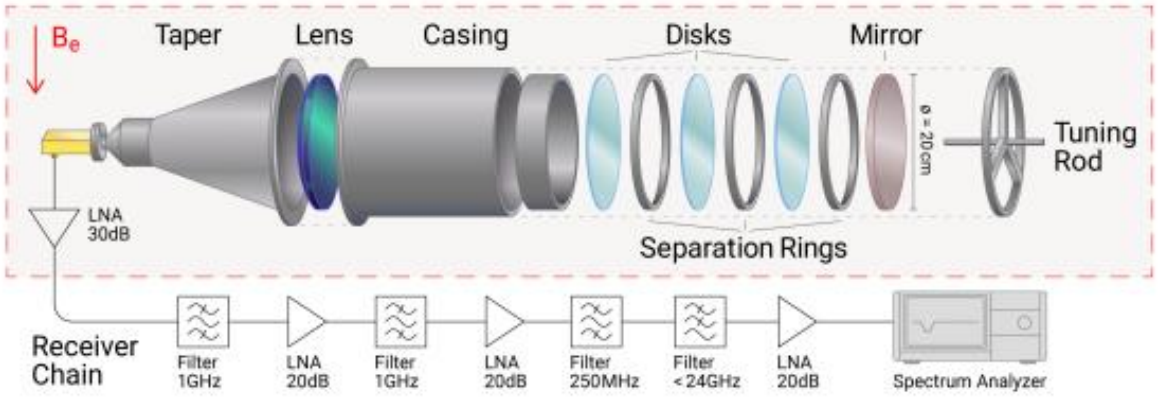
Open booster OB200

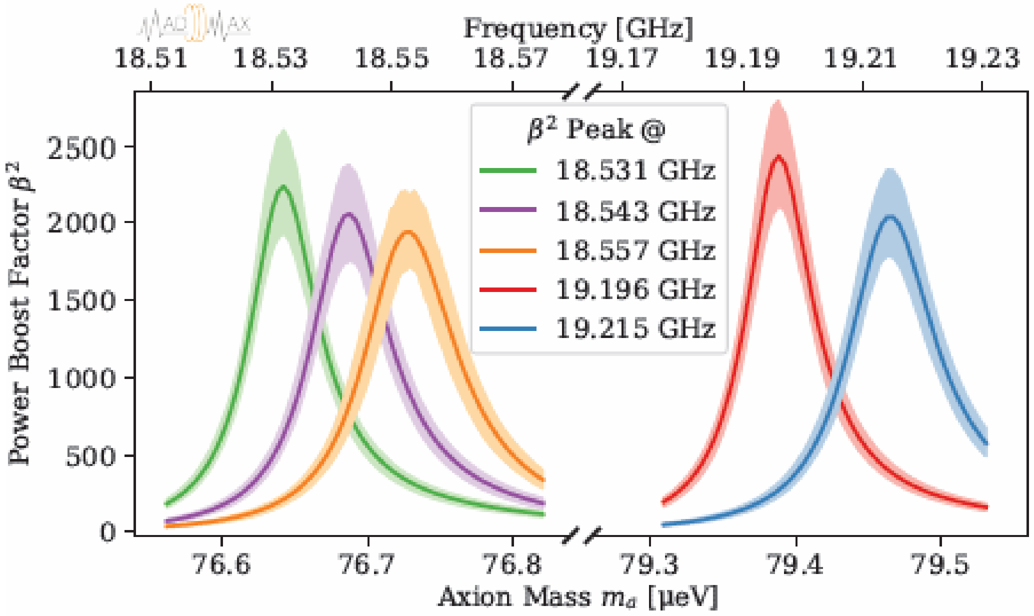


Open booster OB300

Name	Setup	Temperature	Goal
CB200	3 fixed disks	Warm	First ALPs search, booster modelling
CB200v2	< 10 moveable disks	Warm	Prove broad band tunability with many disks
OB300v1	3 fixed disks	Warm	First open booster, booster modelling
OB200	1 moveable disk	Cold	Mechanical feasibility of disk movement
CB100	3 fixed disks	Cold	Cryogenic calibration, first ALPs search at cryo T
OB300v2	>= 3 moveable disks	Cold	Scan mass range in B-field and cryogenic

First Axion search with CB200



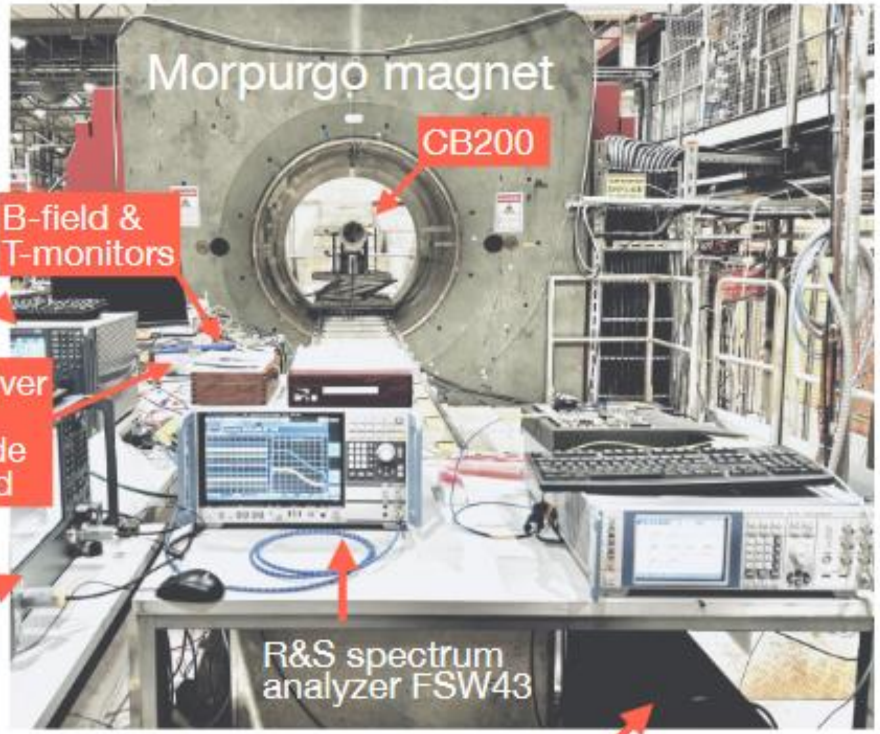


- CB200 – 1 mirror + 3 sapphire disks of 200 mm diameter
- Disks separated by (2 sets of) spacer rings → distance optimised for desired frequency range (76-80 μeV)
- Tuning rod slightly modifies the distance between mirror and 1st disk → tuning of sensitivity range
- Setup at room temperature; B-field ~ 1 T at CERN
- 14.5 days of total measurement time for 5 configurations

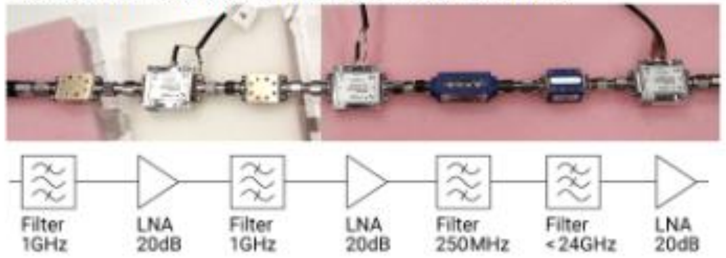
- Determination of boost factor:
  - using reflectivity (S11)
  - Simulation of booster + receiver
- Peak of boost factor → approx. 2000 +/- 15%
- Frequency range covered with $\beta^2 > 500$ → 100 MHz

arXiv:2409.11777
Accepted for publication in PRL

First Axion search with CB200



Receiver chain outside the B-field



arXiv:2409.11777
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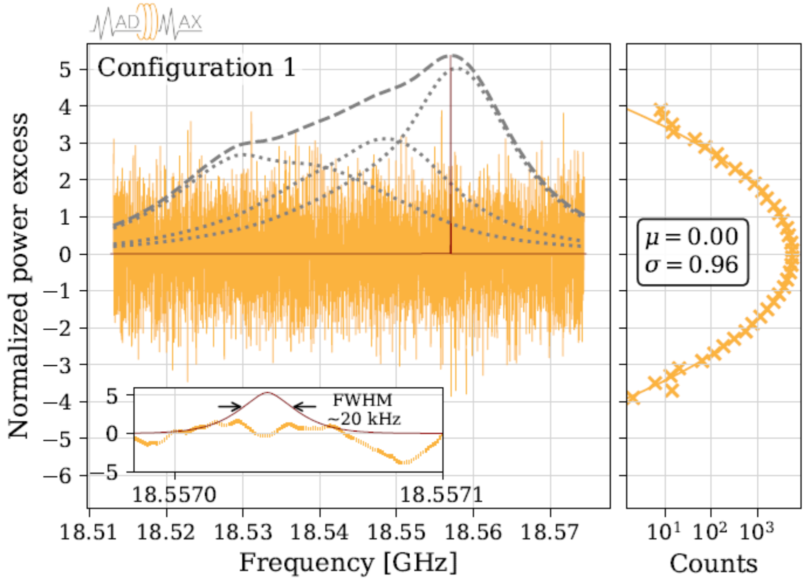
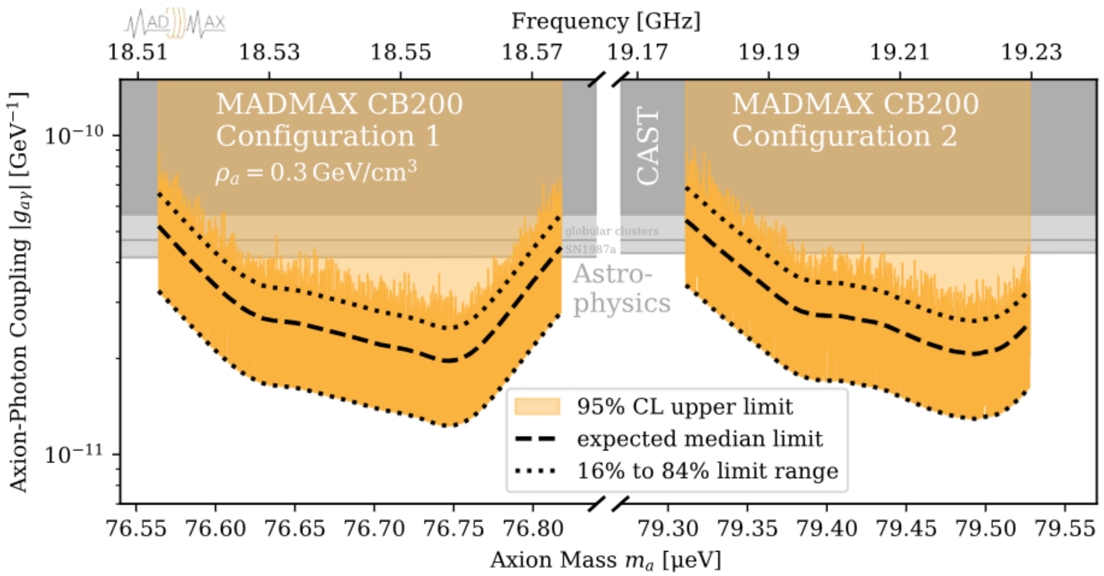
First Axion search with CB200

- Five data runs in two configurations ~ 18.5 GHz and 19.2 GHz (in total 100 MHz frequency range covered)
- World best limits for axion masses 76.5-76-8 μeV and 79.5-79.7 μeV
- First axion dark matter limit using dielectric haloscope

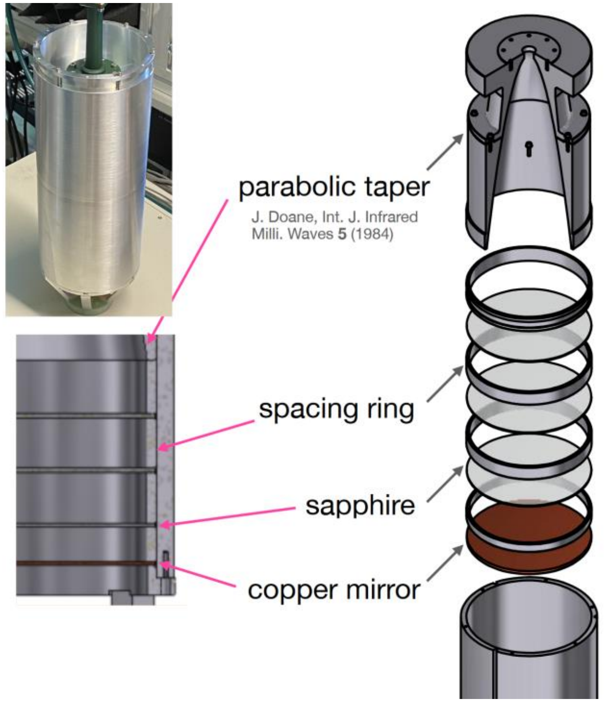


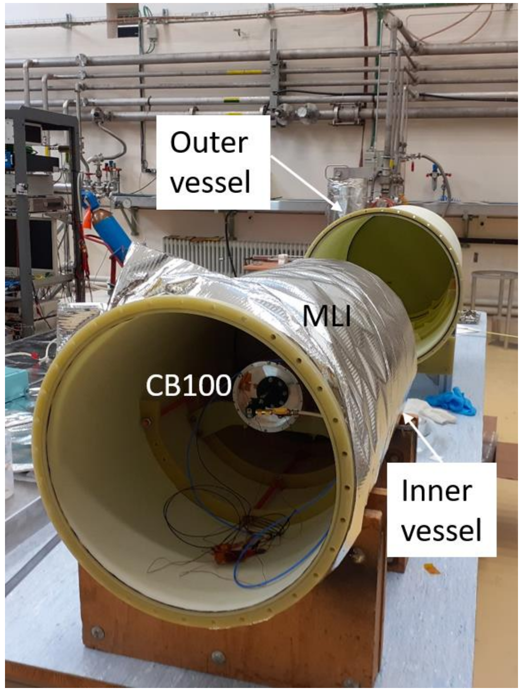


arXiv:2409.11777
Accepted for publication in PRL

First ALPs search in the cold

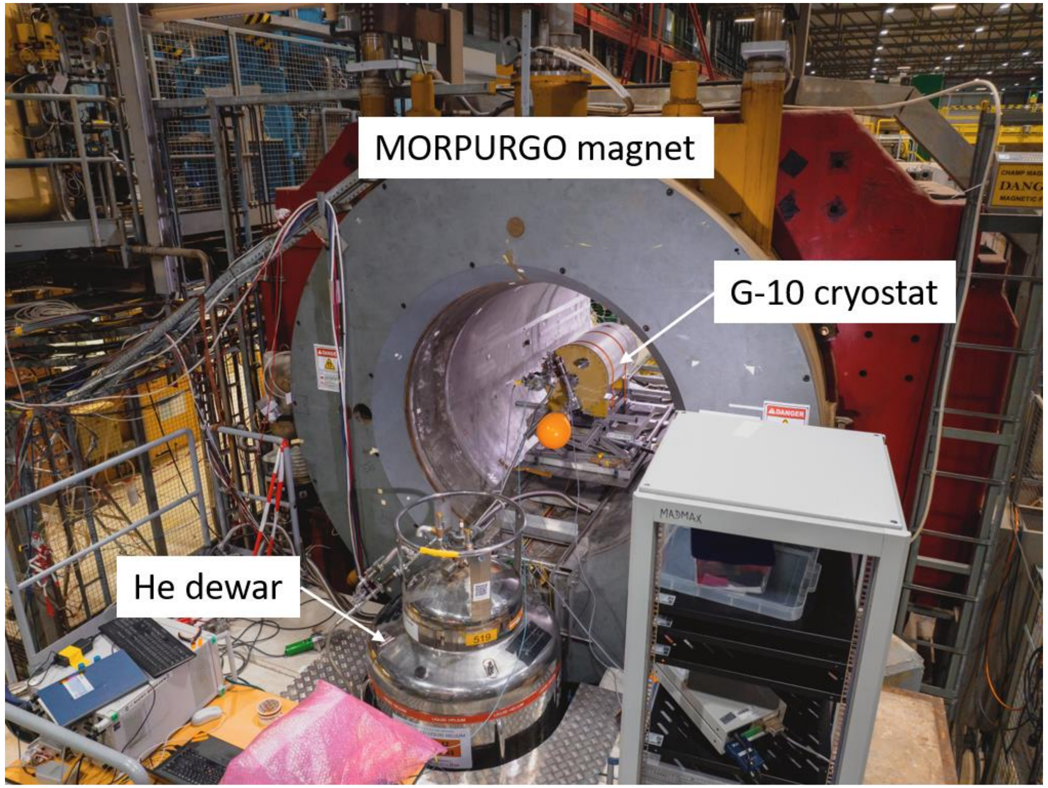
- Low-cost non-magnetic glass-fiber cryostat
- Continuous circulation flow of He gas
- Setup : CB100 (100 mm diameter disk)
- End temperature approx. 7 K for >24 hours
- Test calibration procedure at cold temperatures and…
- First MADMAX ALPs search in the cold at 1.6 T at CERN

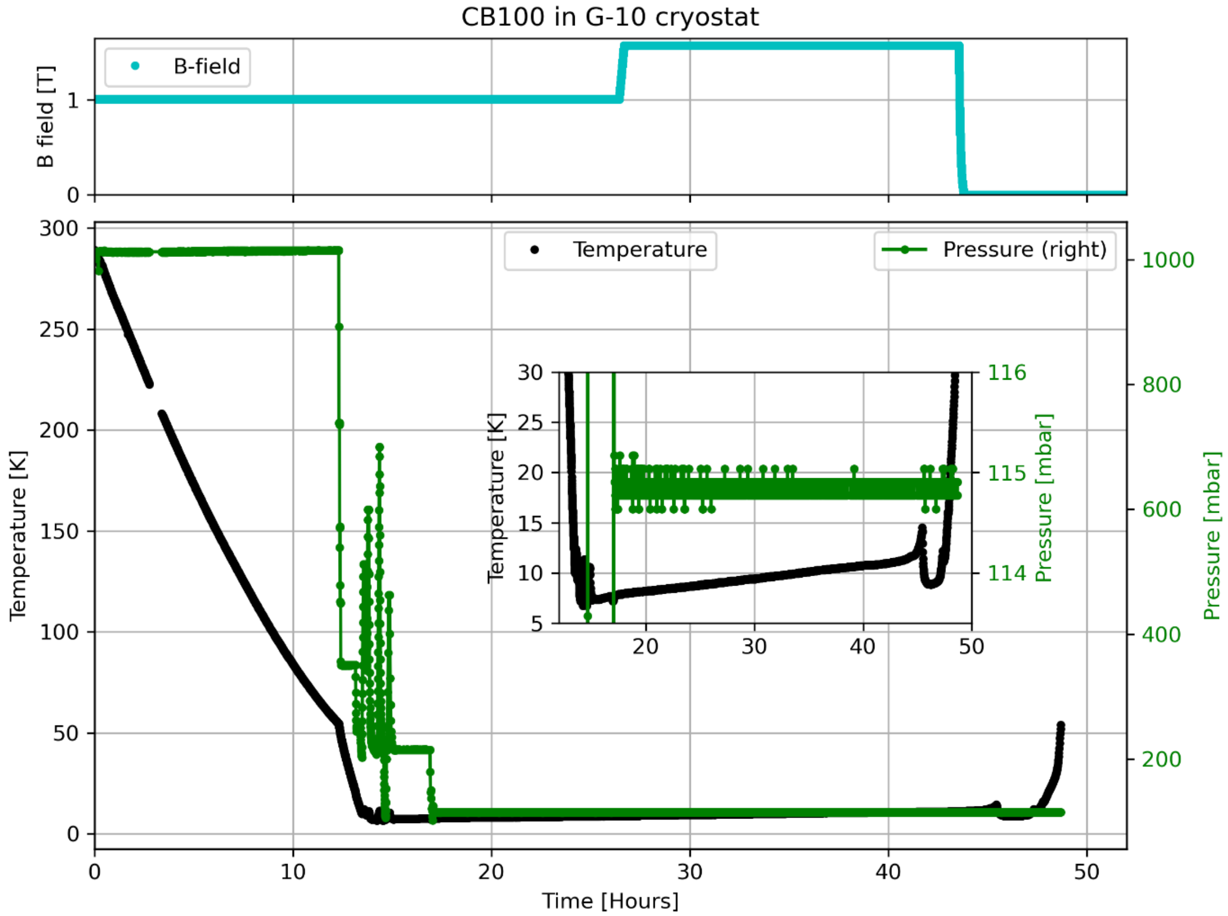




JINST, Volume 20, Issue 02, T02005 (2025)
arXiv:2412.12818

First ALPs search in the cold



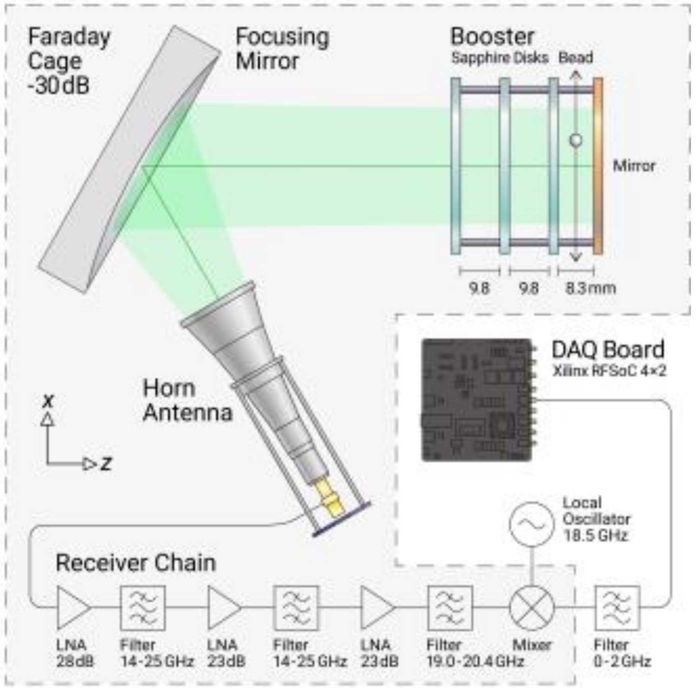


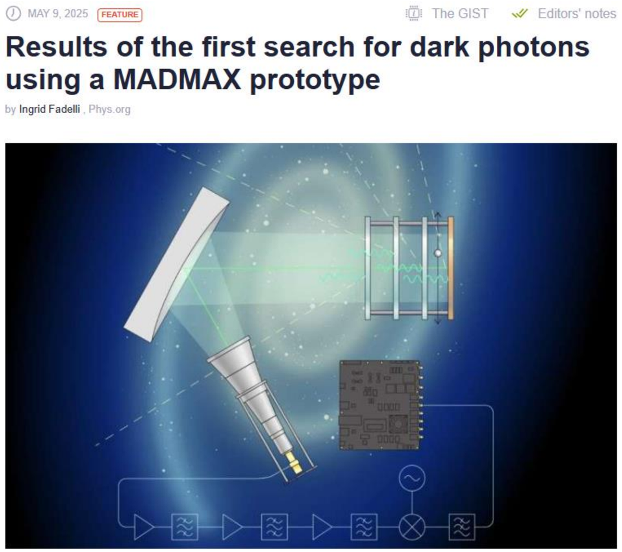
Stay tuned for upcoming results!

[JINST, Volume 20, Issue 02, T02005 (2025)](#)
[arXiv:2412.12818](#)

Dark photon dark matter

- Dark photon dark matter search with OB300 (no magnetic field)
  - OB300 with 3 fixed disks + a Cu mirror
  - Custom-made receiver system
  - Setup at room temperature
  - 12 days of data-taking
- Boost factor determination
  - using in-situ bead-pull method (JCAP 04 (2023) 064 , JCAP 04 (2024) 005)
  - β^2 peak ~ 600
  - Broadband config.: frequency covered 1.2 GHz
- No signal excess being observed
- First DPDM exclusion limit with MADMAX





MADMAX featured at physics.org: Results of the first search for dark photons using a MADMAX prototype

Phys. Rev. Lett. 134, 15, 151004 (2025)
arXiv:2408.02368

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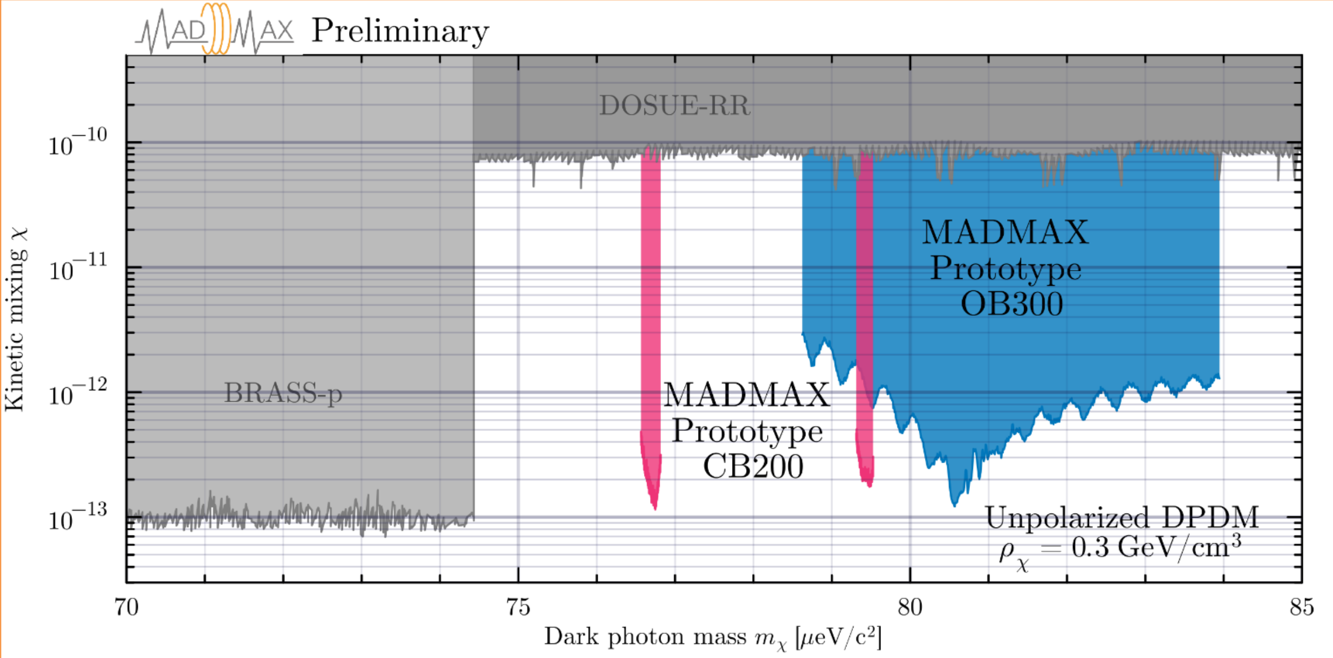
World-best exclusion limit (95% CL)
→ 1-3 order of magnitude below previous limits



Phys. Rev. Lett. 134, 15, 151004 (2025)
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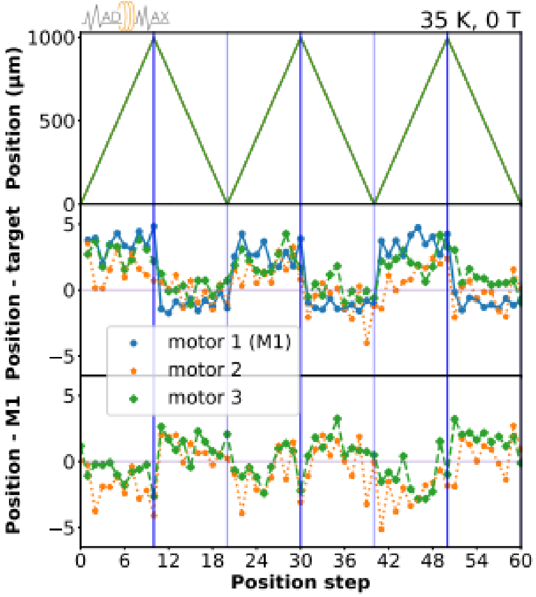
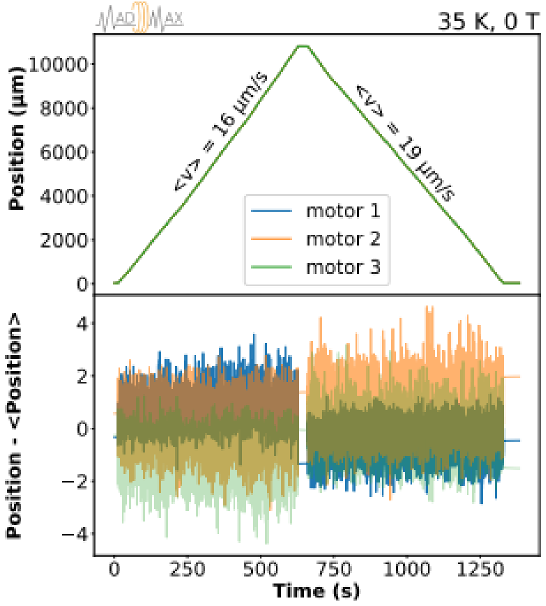
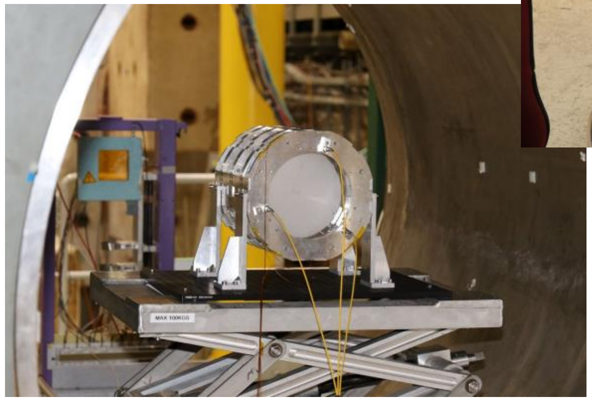
Tunability of disks: OB200 in B-field & in the cold

- OB200 contains one 200 mm sapphire disk + one Cu mirror
- Three piezo-motors (to move one disk) + laser interferometer
- OB200 tested at cryogenic temperatures (~35 K) (CERN Cryolab) and at 1.5 T B-field at room temperature (Morpurgo/CERN)
- Disk movement successfully tested: precision, speed, stepsize & drift within requirements







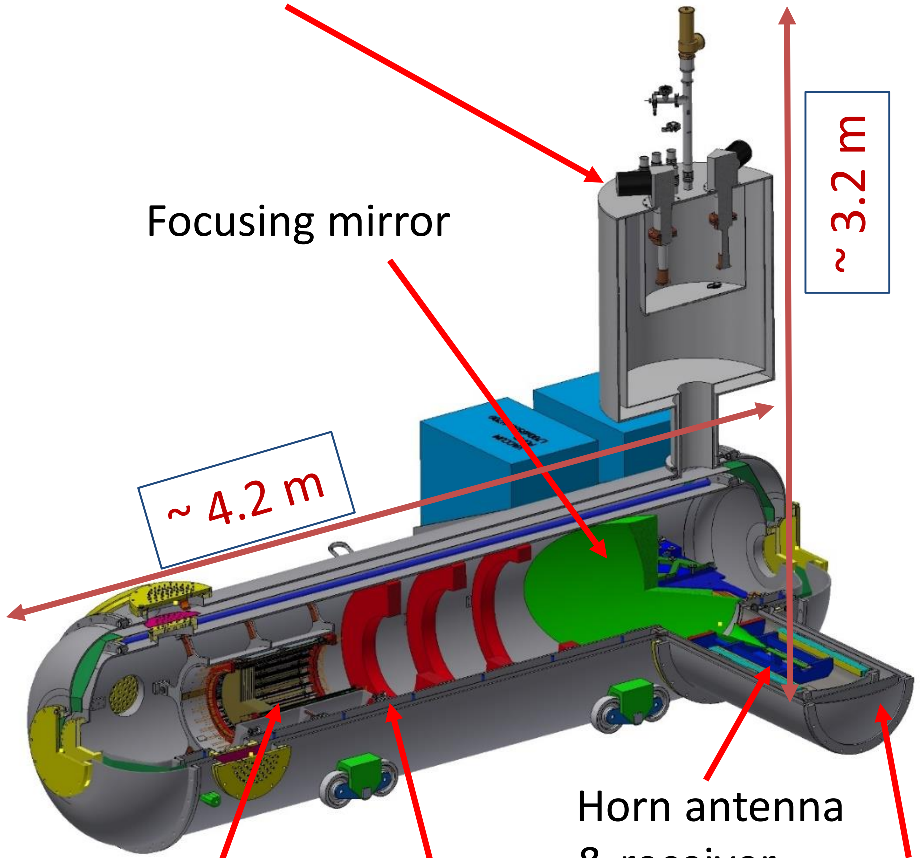
OB200: [JINST, Volume 19, Issue 11, T11002 (2024)](); [arXiv:2407.10716]()

Single piezo-motor: [JINST, Volume 18, Issue 08, P08011 (2023)]()

The MADMAX cryostat for OB300

MADMAX cryostat
(4 K, thermosyphon principle)

Focusing mirror



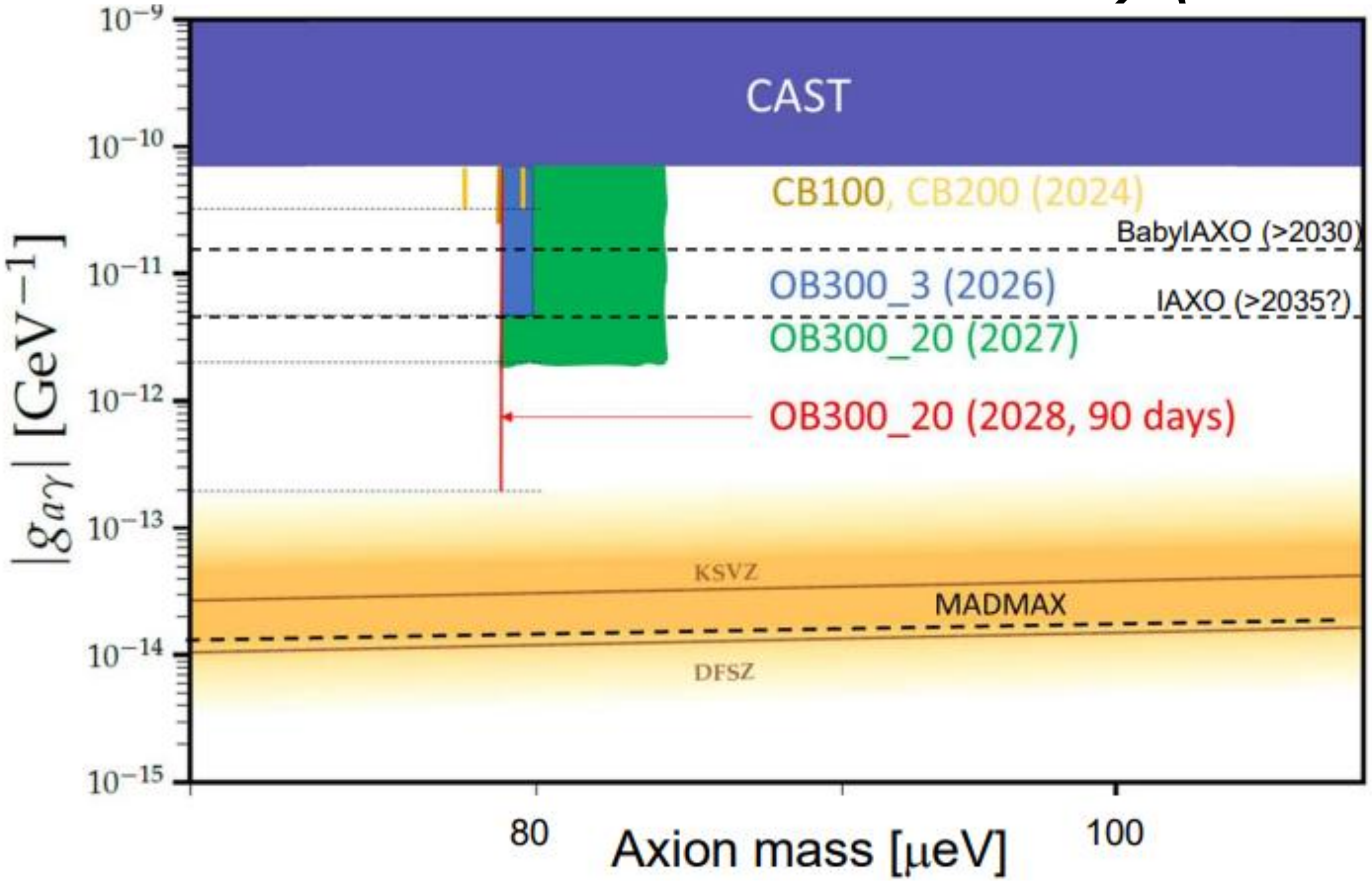
Horn antenna
& receiver

Receiver
cryostat

Prototype
booster

RF absorbers

Projected sensitivity – measurements at CERN



MADMAX

MAgnetized Disk and Mirror Axion eXperiment

NEXT steps:

- Commissioning of OB300 at cryogenic temperatures
- Axion search data taking at CERN/Morpurgo magnet during LHC long shutdown period 2027-2029
- Scale up area and number of disks
- Develop more sensitive detection techniques
- Stay tuned for upcoming results at cryogenic temperatures!

MADMAX

MAgnetized Disk and Mirror Axion eXperiment

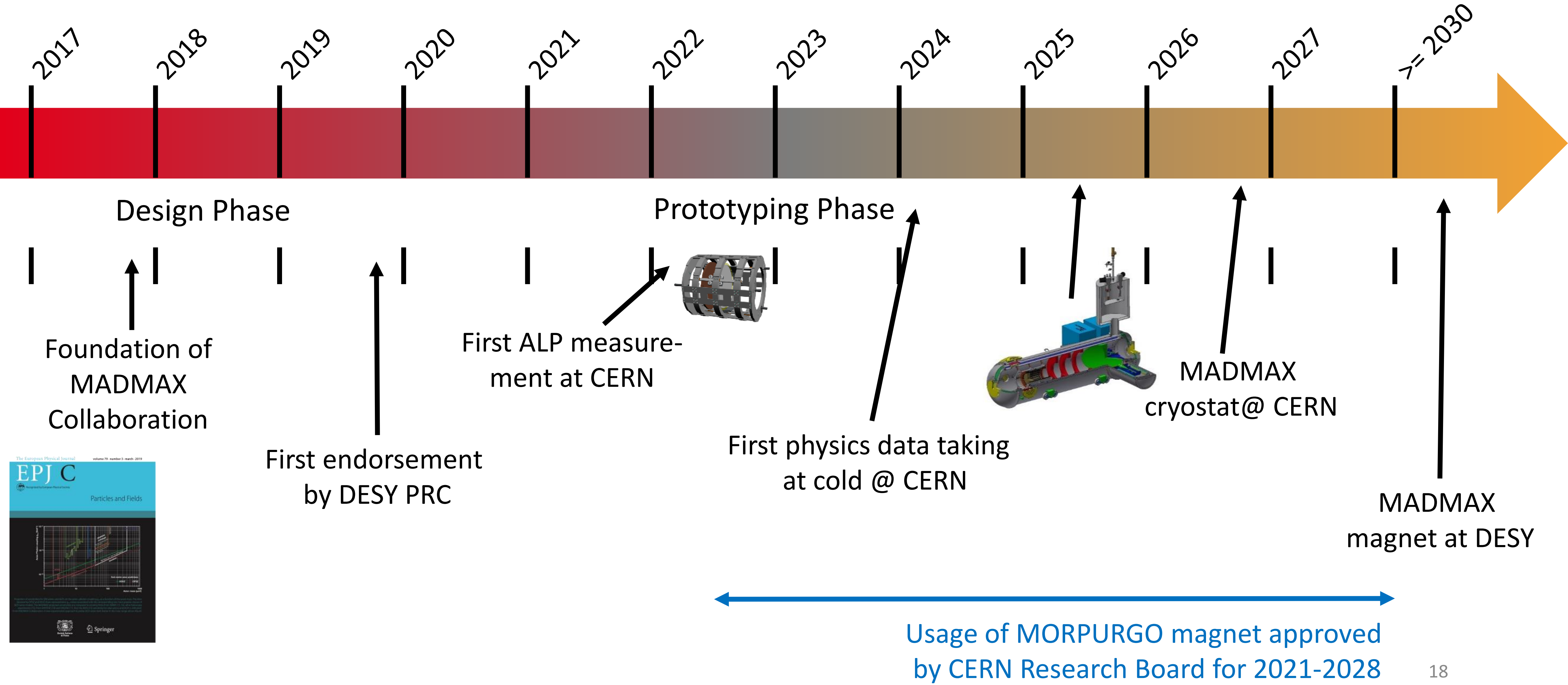
Conclusions:

- MADMAX is a dielectric haloscope experiment for axion dark matter search around 100 μeV
- Validation of disk movement at cold, under B-field → *JINST 18 (2023) P08011; JINST 19 (2024) T11002*
- Established method to measure in-situ boost factor → *JCAP 04 (2023) 064; JCAP 04 (2024) 005*
- First dielectric haloscope to search for ALPs → world-leading limits in both dark photon (*PRL 134 15 (2025) 151004)* and axion searches (*arXiv:2409.11777 – accepted at PRL)* around 80 meV (20 GHz)
- First booster tests at cold under B-field → *JINST (2025) 20 T02005*

Thank you for your attention!

Backup slides

Timeline


2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
>= 2030
Design Phase
Prototyping Phase
Foundation of MADMAX Collaboration
First endorsement by DESY PRC
First ALP measure-ment at CERN
First physics data taking at cold @ CERN
MADMAX cryostat@ CERN
MADMAX magnet at DESY
Usage of MORPURGO magnet approved by CERN Research Board for 2021-2028
EPJ C
Particles and Fields
Springer

MADMAX collaboration

MAgnetized Disk and Mirror Axion eXperiment

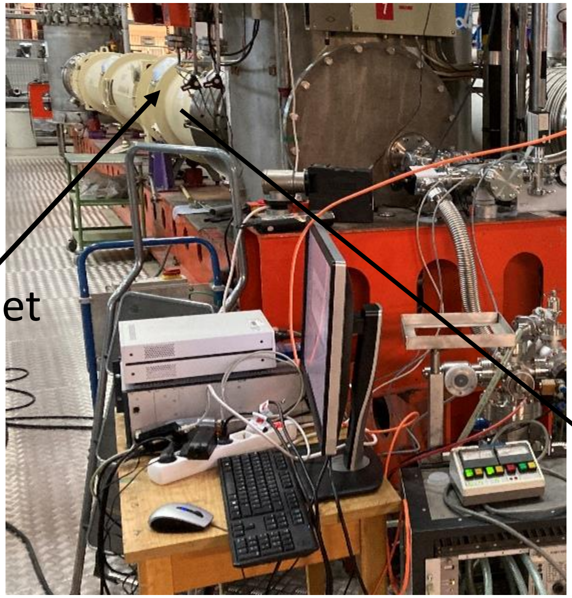
approximately 50 scientists from 11 institutes in 4 countries

www.madmax.mpp.mpg.de

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

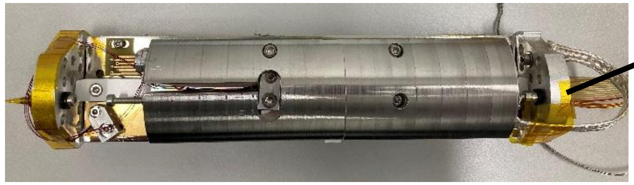
Piezo motor tests

First tests → no laser interferometer
Use end switches → measure time
→calculate motor speed

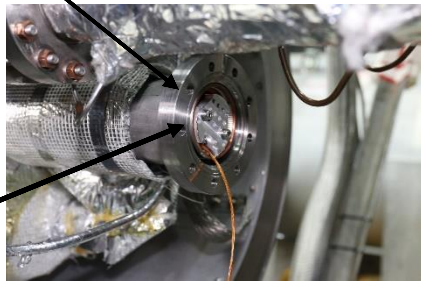


magnet

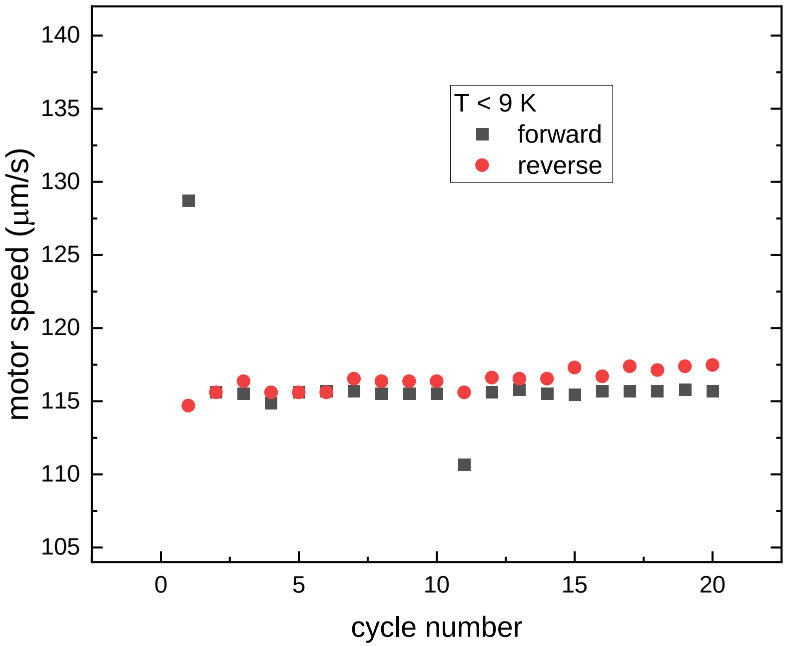
ALPS II test magnet



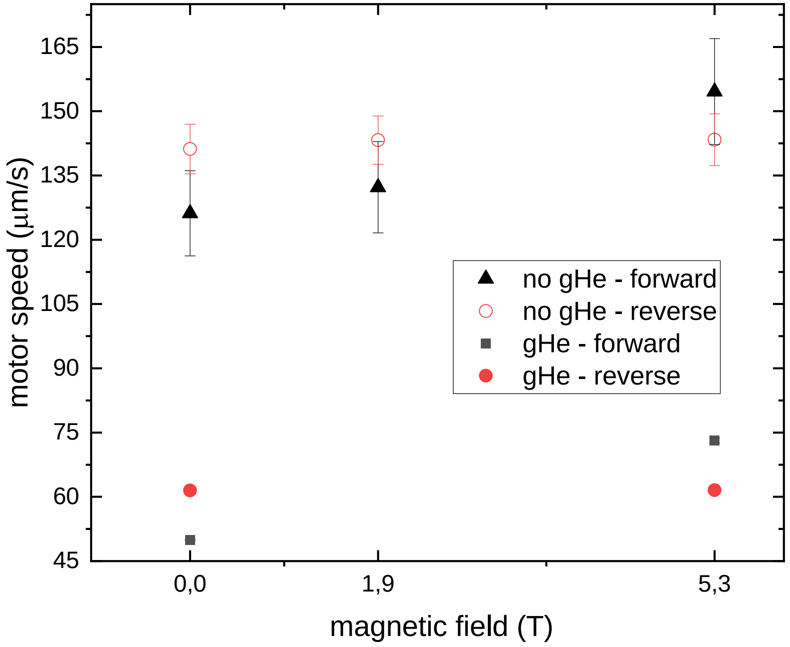
Piezo motor setup



Tests at 4 K – no B-field



Tests in the magnet



- Small hysteresis forward/reverse direction
- Tests in vacuum (no field) within specs v > 100 μm/s
- Tests at 1.9 T and 5.3 T in vacuum (28 K)
- Use of gHe to improve cooling of setup (to 5 K)

JINST, Volume 18, Issue 08, P08011 (2023)

The booster

- Booster is the heart of MADMAX : a mirror and several adjustable dielectric disks

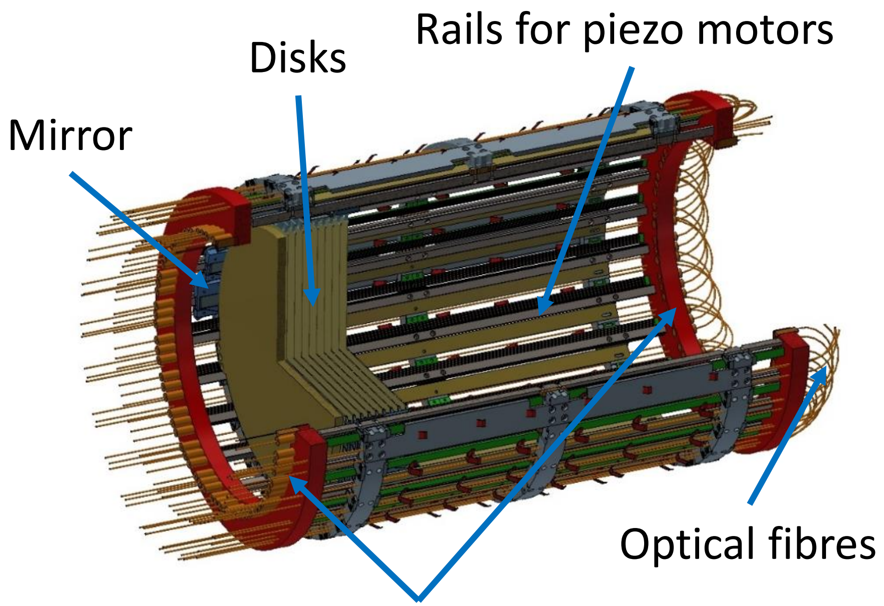
- Operating conditions:
  - Cryogenic temperatures: 4 K
  - High magnetic field: up to ~10 T
  - Vacuum or cold (He) exchange gas

- Disk weight: 600 g for Ø300 mm

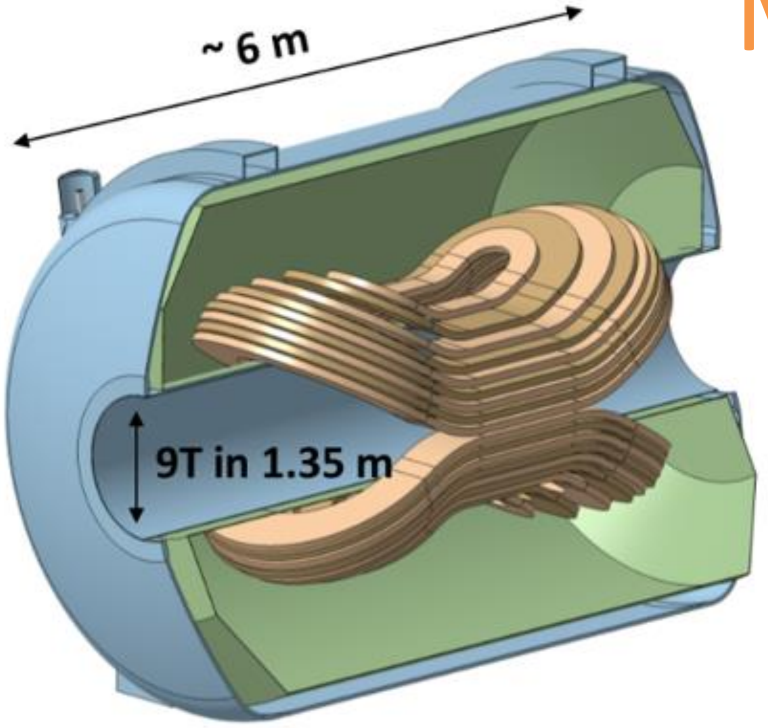
➢ **Piezo-driven actuator system with feedback from laser interferometer with absolute precision**

- Disk material:
  - **Sapphire ($\varepsilon \approx 9$, $\tan\delta \approx 10^{-5}$)**

OB300



MADMAX Magnet



- Dipole magnet with FOM ~ 100 T^2m^2 to reach QCD axion
- Magnetic field must be parallel to disk surfaces → dipole
- Large warm-bore for the cryostat
- Staged-approach
- Novel CICC conductor qualified: quench velocity propagation successfully tested
- → as a result: 7 publications featured in special issue on IEEE Transactions on Applied Superconductivity
- Next steps being prepared

https://ieeexplore.ieee.org/document/10280304