Direct detection of axion dark matter with MADMAX

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Outline

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

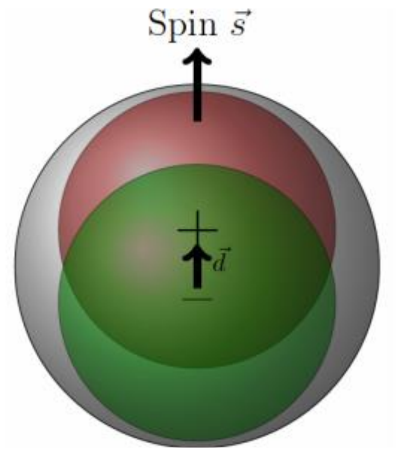
CPPM PHD scientific forum 2024

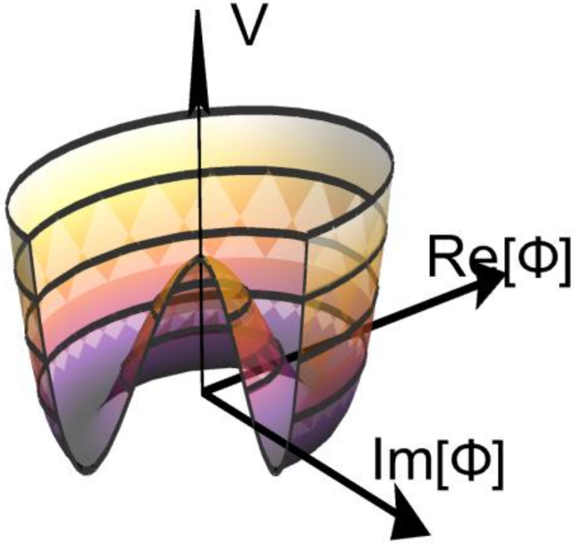
Dark matter axion

- 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 = fine tuning problem: Why is a free parameter θ so small?
- Solution: Introduce a new U(1) symmetry spontaneously broken -> **'QCD Axion'**
  - A strongly motivated dark matter candidate
- Axion like particles (ALPs) solve the dark matter problem but not the strong CP problem





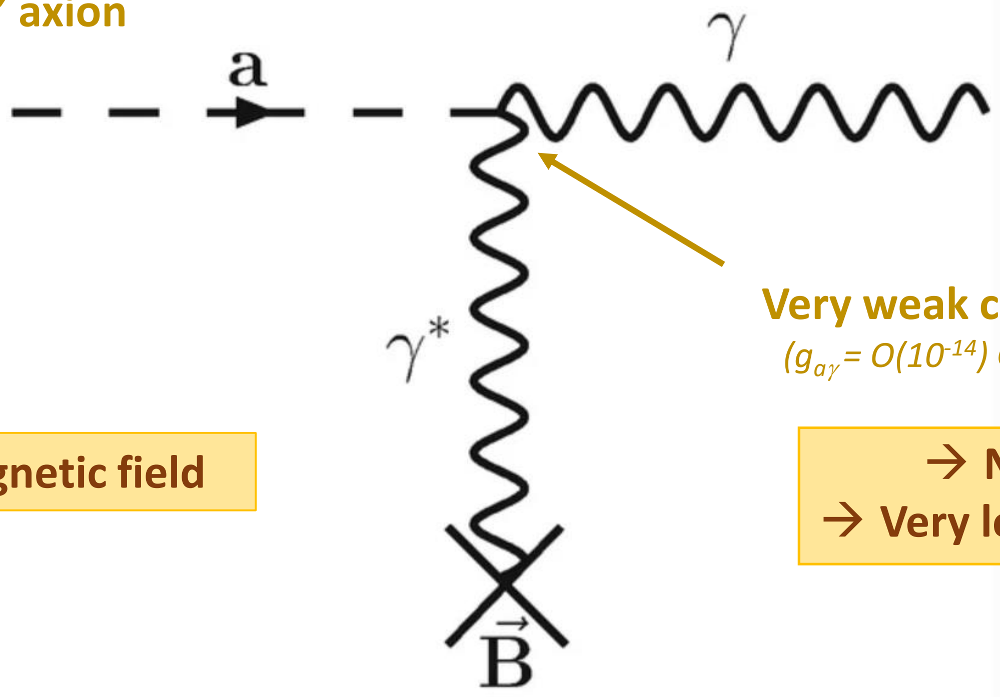
How to see the dark matter axions ?

- ❑ 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

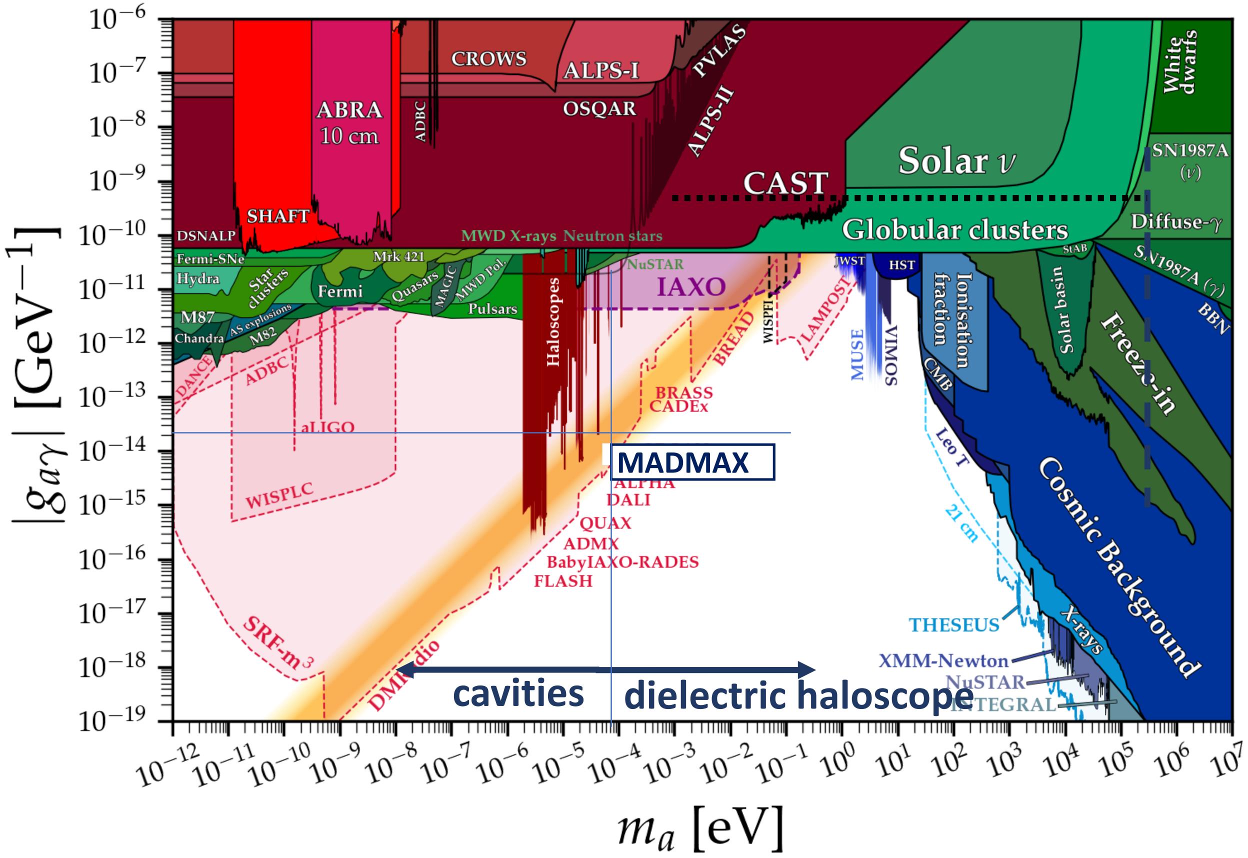
→ Need boost
→ Very low temperature

Axions can be detected as radio waves in presence of high magnetic field

Dark matter axion mass range

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

- ❑ 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



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

Dielectric haloscope: principles

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

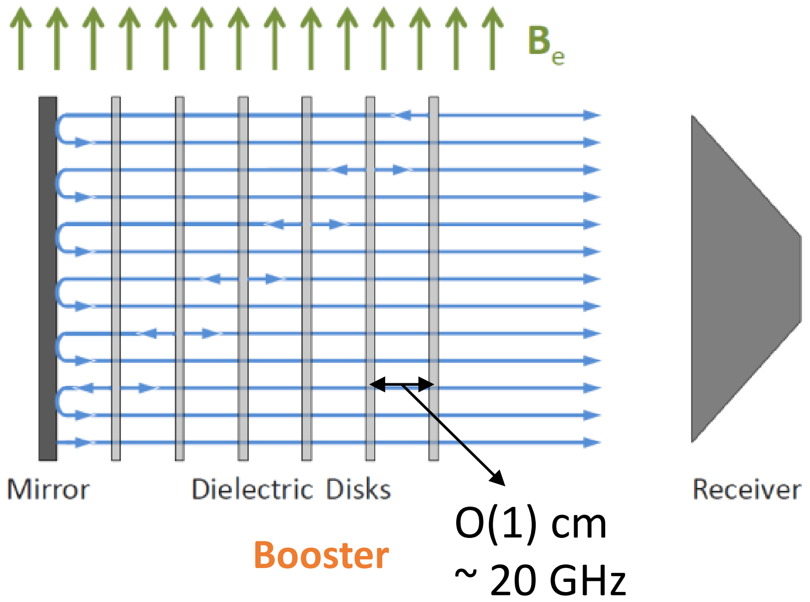
$$|C_{a\gamma}| = \left(\frac{|g_{a\gamma}|}{2\times 10^{-14}\ \mathrm{GeV}^{-1}}\right)\left(\frac{100\ \mu\mathrm{eV}}{m_a}\right)$$

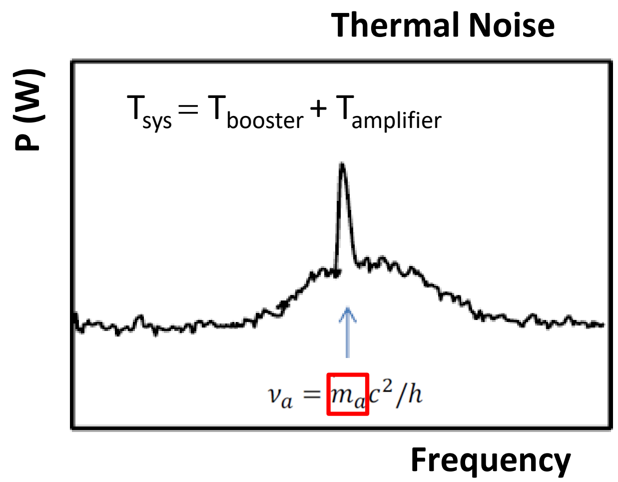
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

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

Power boost factor:

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

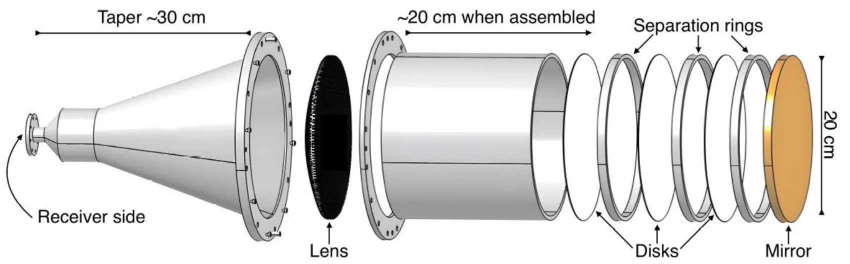




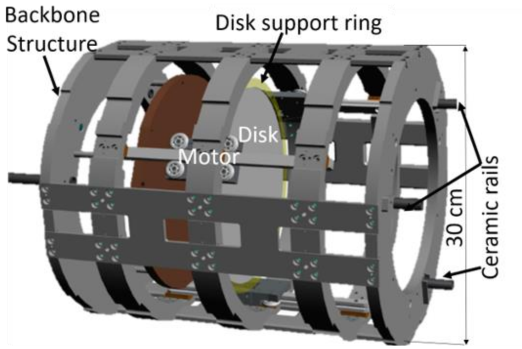
- ❑ **Axion mass scan** : by positioning discs with µm precision at 4K under 10 T *(50 MHz step)*

MADMAX prototypes

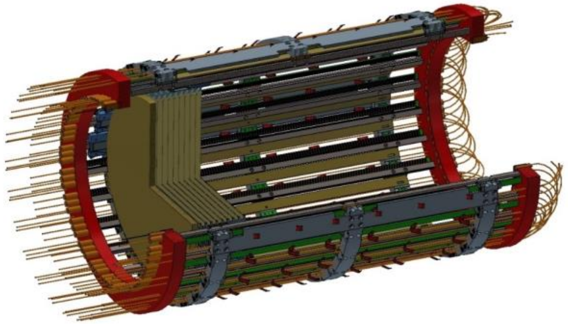
- Validate the new concept of dielectric haloscope using several prototypes



Closed booster with 200 mm disks (CB200)



Open booster OB200



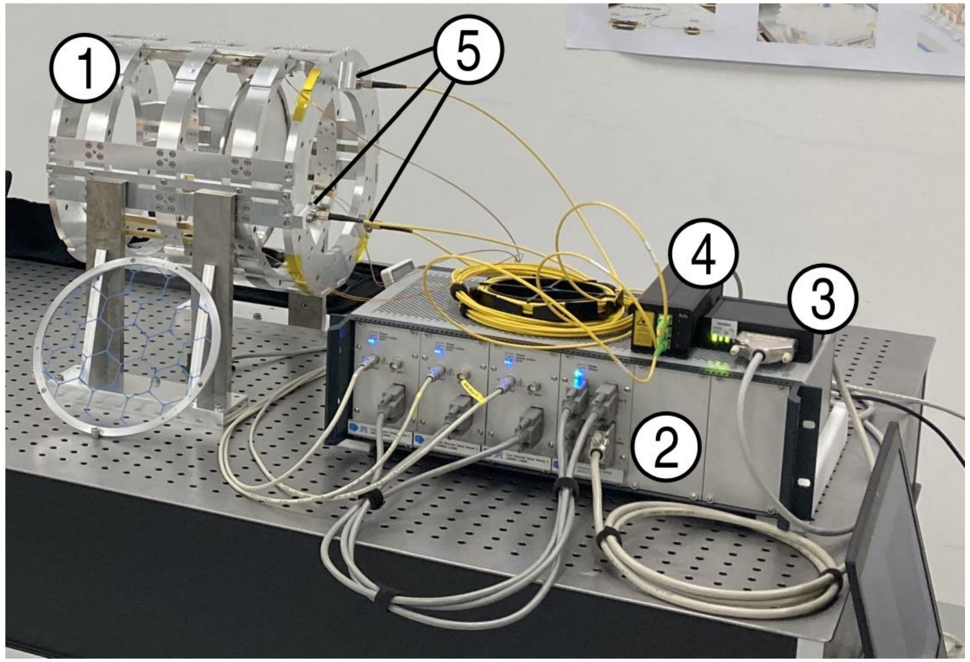
Open booster OB300

Name	Setup	Temperature	Goal
OB200	1 moveable disk	Warm	Moving the disks
OB300v1	3 fixed disks	Warm	First Open booster
CB200	3 fixed disks	Warm	First ALPs search
OB300v2	>= 3 moveable disks	Cold	Final prototype

I participated to OB200 data analysis, OB300 simulations, and CB200 data taking/analysis

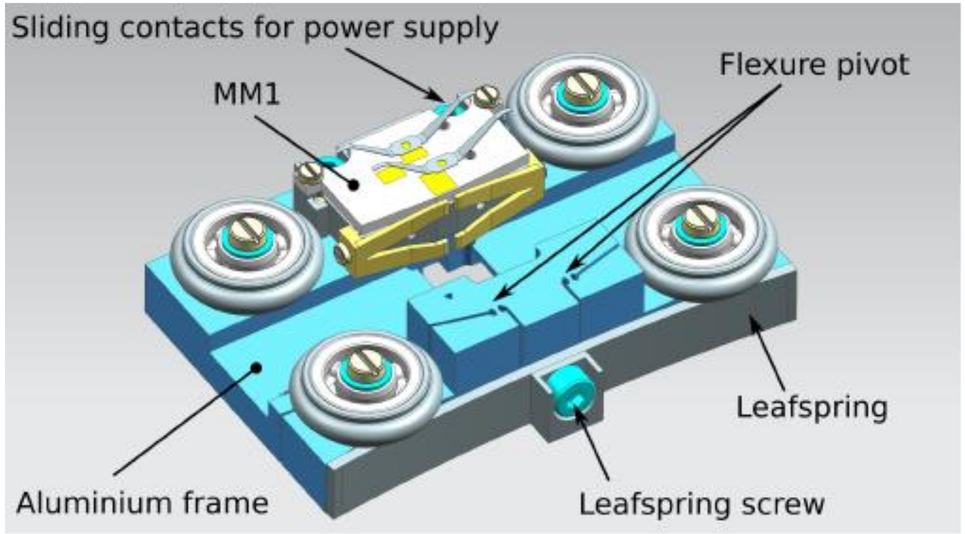
Disk positioning system

- ❑ Mechanical prototype OB200



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

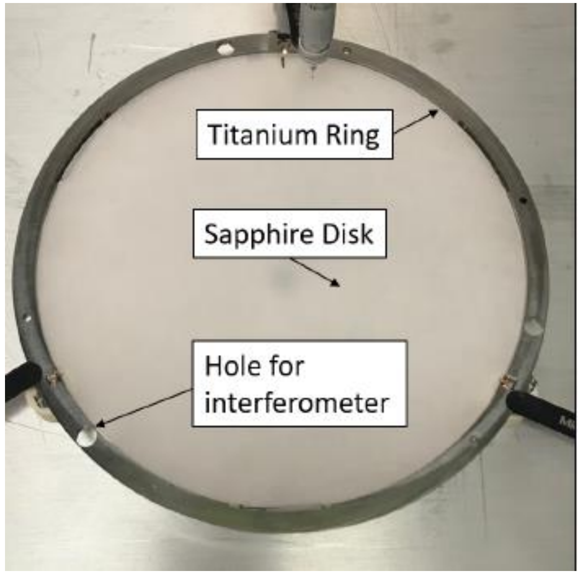
JINST, 18(08):P08011, 2023

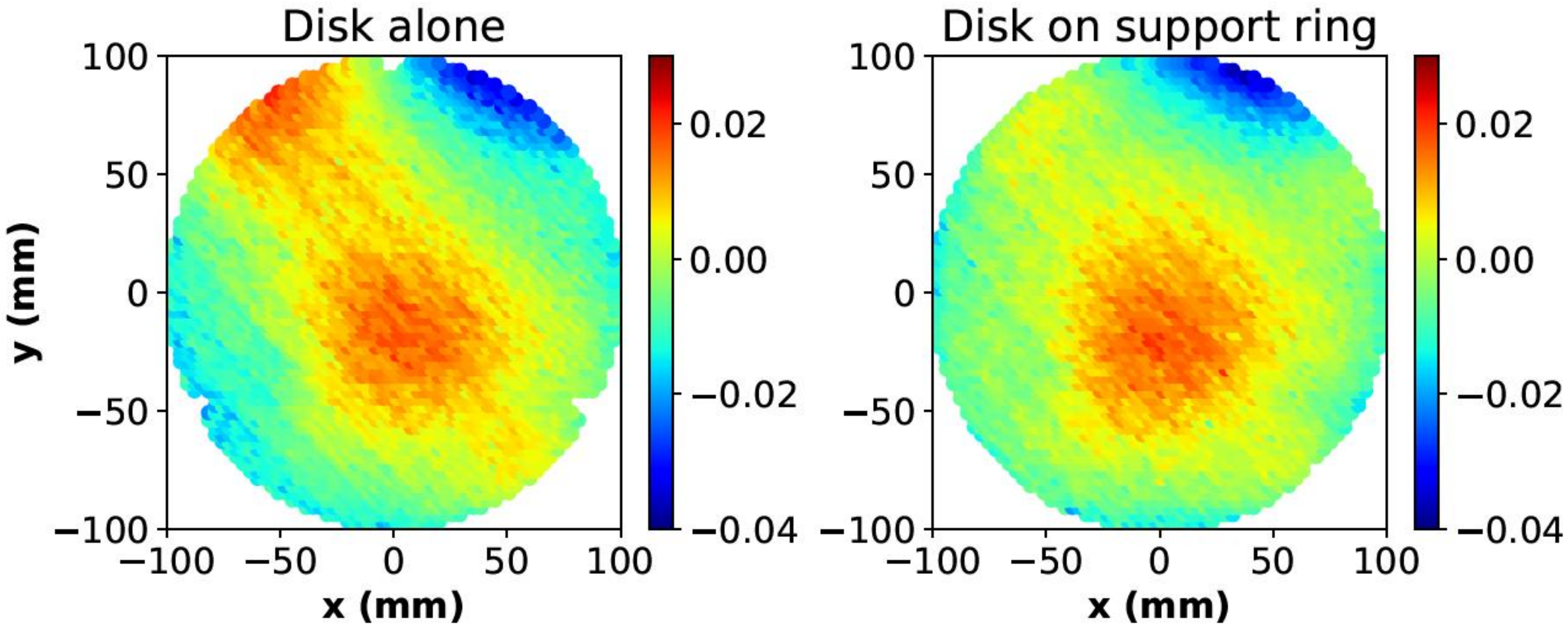


- ❑ Piezo motors for precision movement in cryogenic temperatures up to 4 K and high magnetic field up to 9 T
- ❑ 3 of them required to move one disk

Disk ring

- The ring to hold the disk inside the booster was manufactured at CPPM (Fabrice Gallo)
    - The disk shape was measured at CPPM to insure no deformation

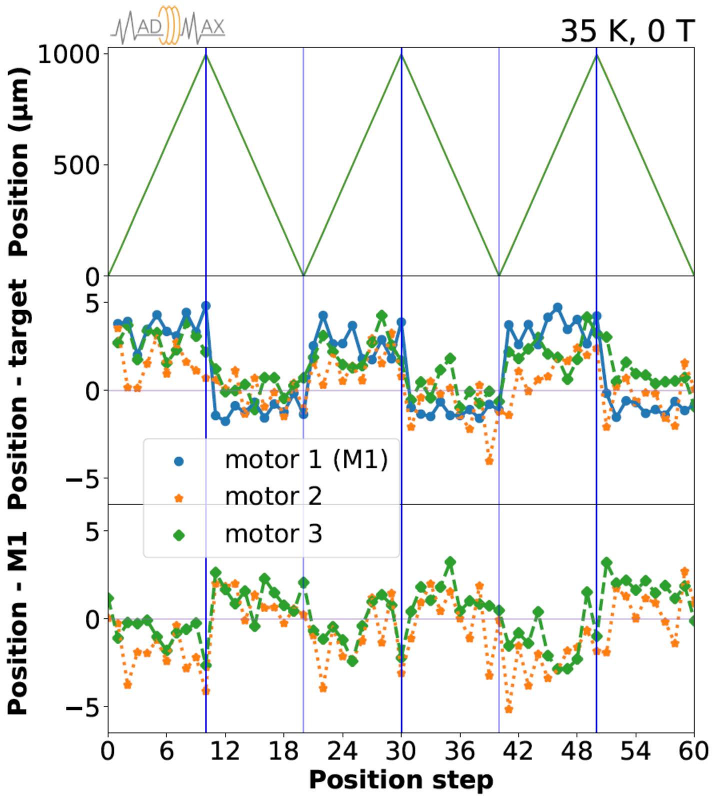


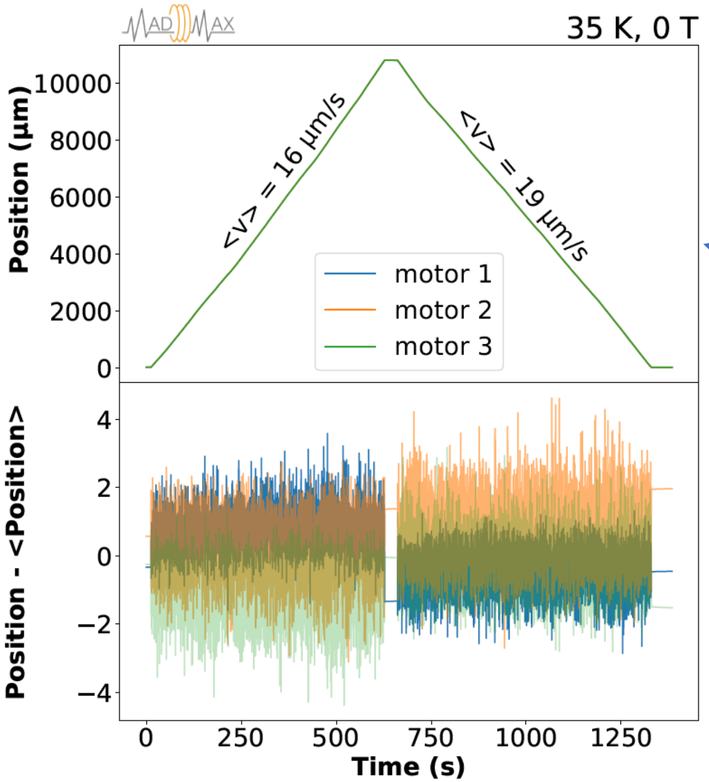


Disk ring shows minimal deformation of the sapphire disk

Disk positioning system: Test results

- Motors 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 to test the precision, speed, operability, drift, step size of the motors, etc.





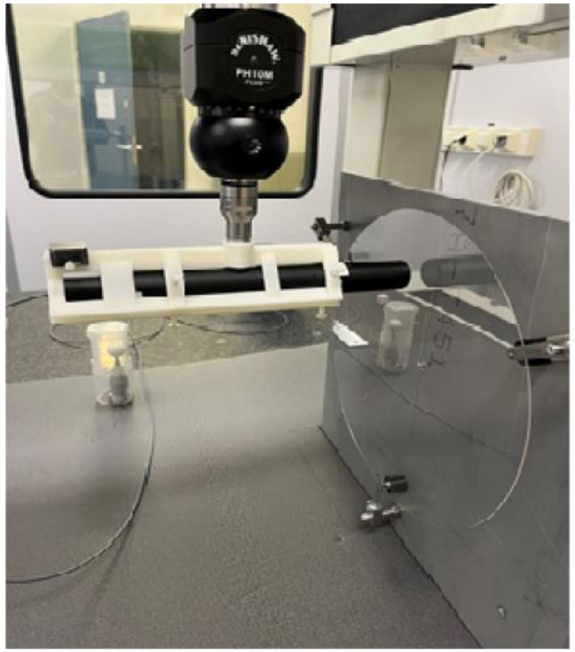
An example figure (from the paper) of a test performed at cryogenic temperatures

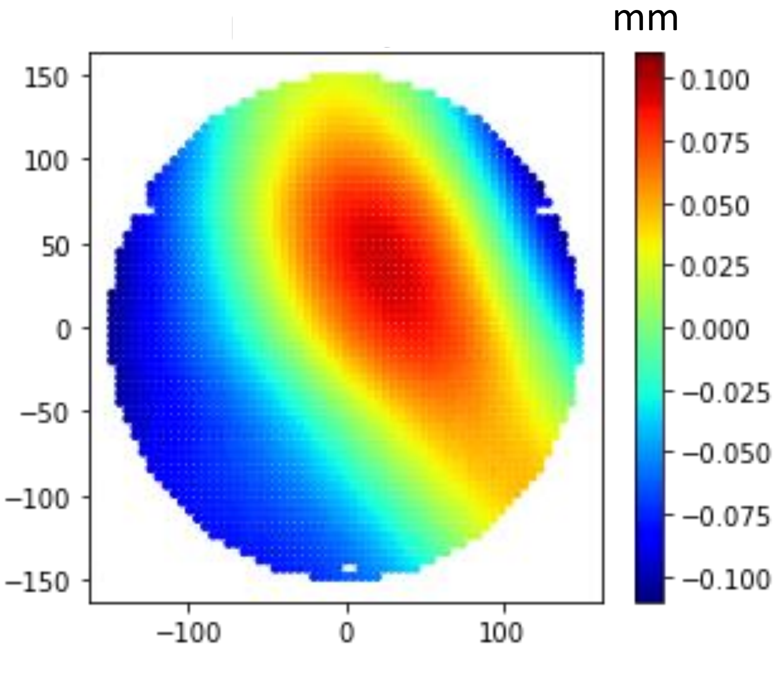
arXiv:2407.10716v2
Accepted by JINST

The positioning system shown to work according to requirements

Disk planarity measurement

- ❑The final prototype in MADMAX
  - OB300v1 with fixed disks, OB300v2 with movable disks
- ❑ Planarity of sapphire disks of 300 mm diameter and 1 mm thickness measured at CPPM Marseille with O(1) μm precision

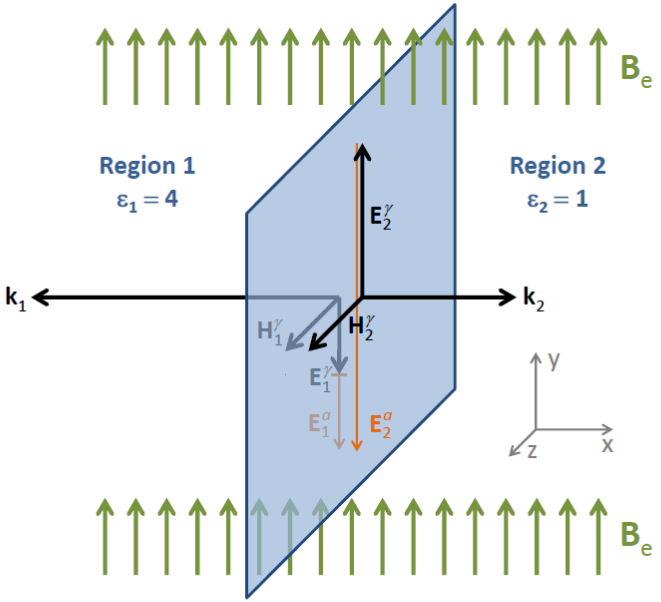




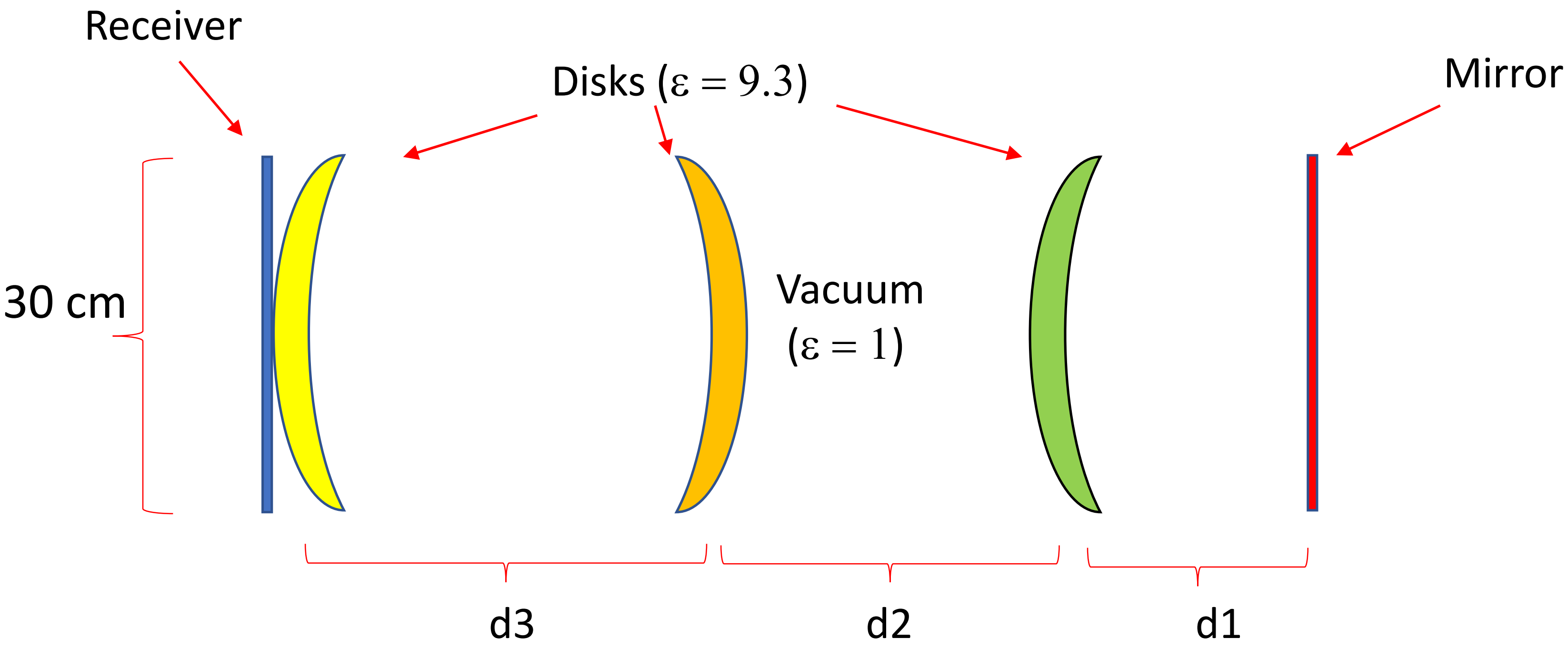
Surface planarity deviation RMS : 50 μm, and min-max : 200 μm

3D Simulation

- ❑ Software from MADMAX collaboration based on axion electrodynamics (1906.02677)
- ❑ Based on recursive Fourier propagation of EM waves in the booster geometry



Emission of radiation
(Axion electrodynamics)

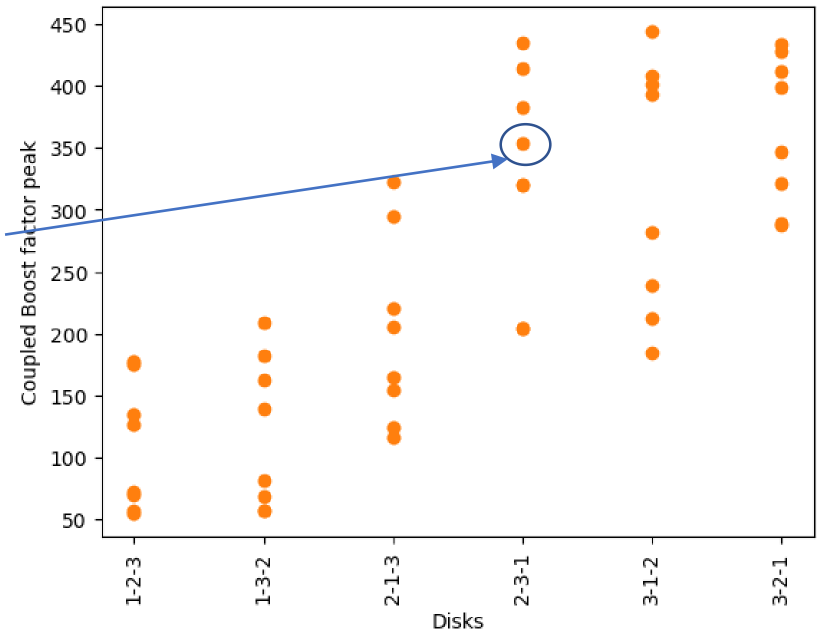


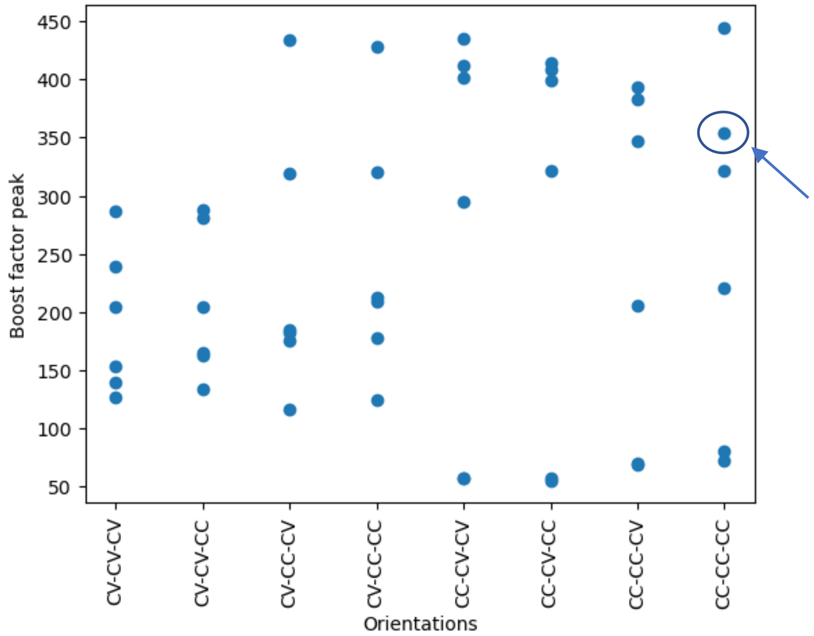
Booster geometry

How to map possible configurations

- 48 possible configurations of disk ordering and orientations
  - Need to evaluate these choices using some metrics e.g. the boost factor peak

Final chosen configuration



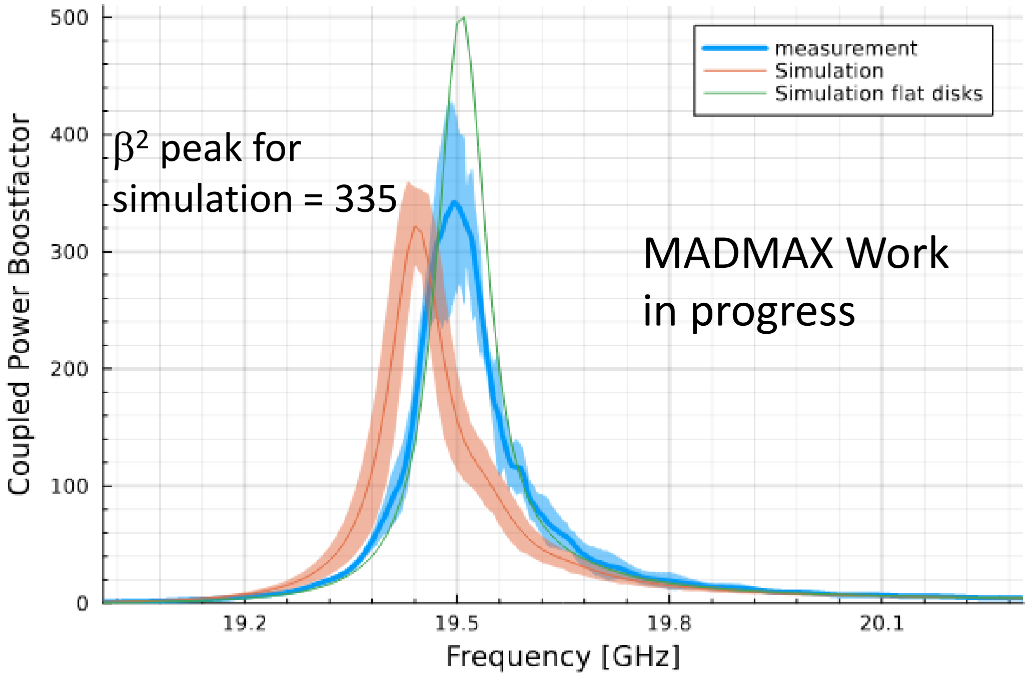


Final chosen configuration

Final configuration for OB300v1 chosen with input from simulations

3D Simulation: broadband configuration

- First 3D simulation of open booster to take into account the disk planarity
  - Smoothened measurement to filter the boost-antenna resonances
  - Simulation uncertainty obtained by varying all booster parameters



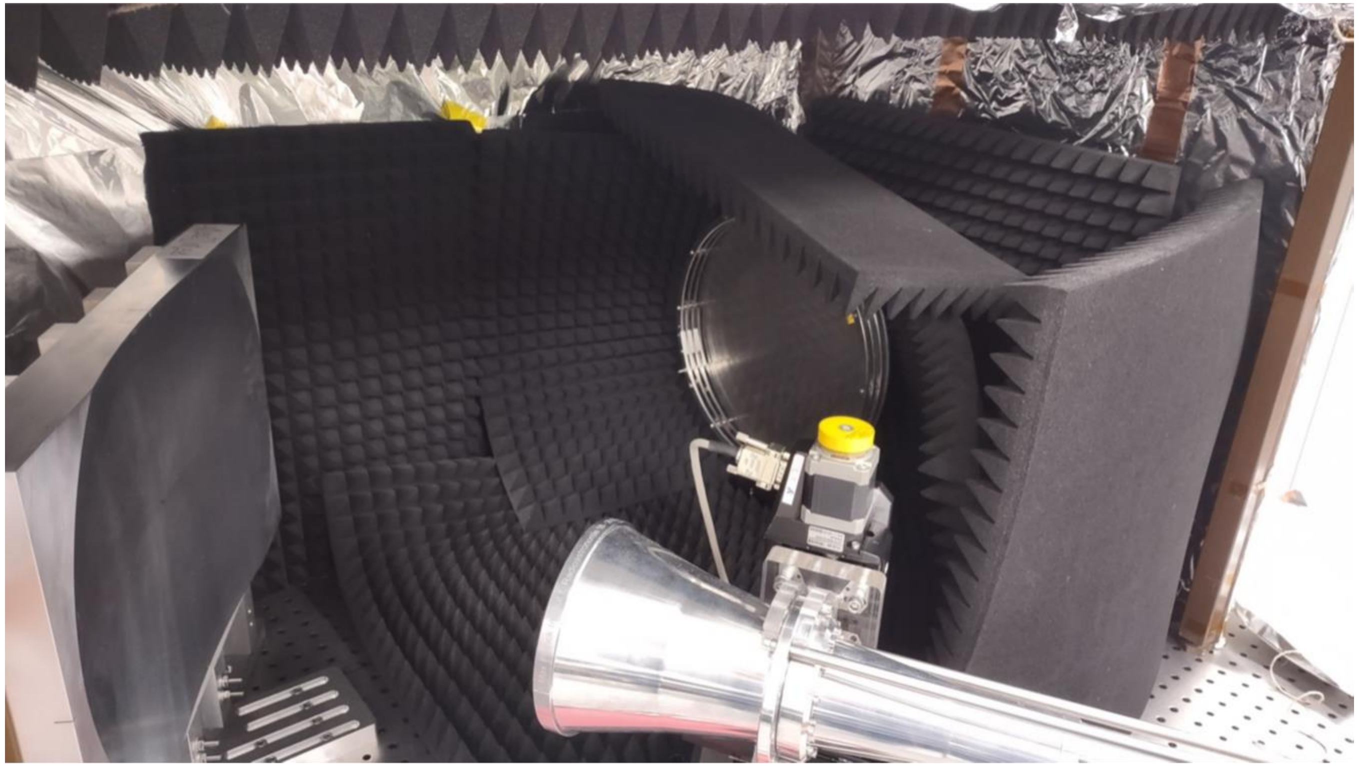
Effect of parameters on the boost factor

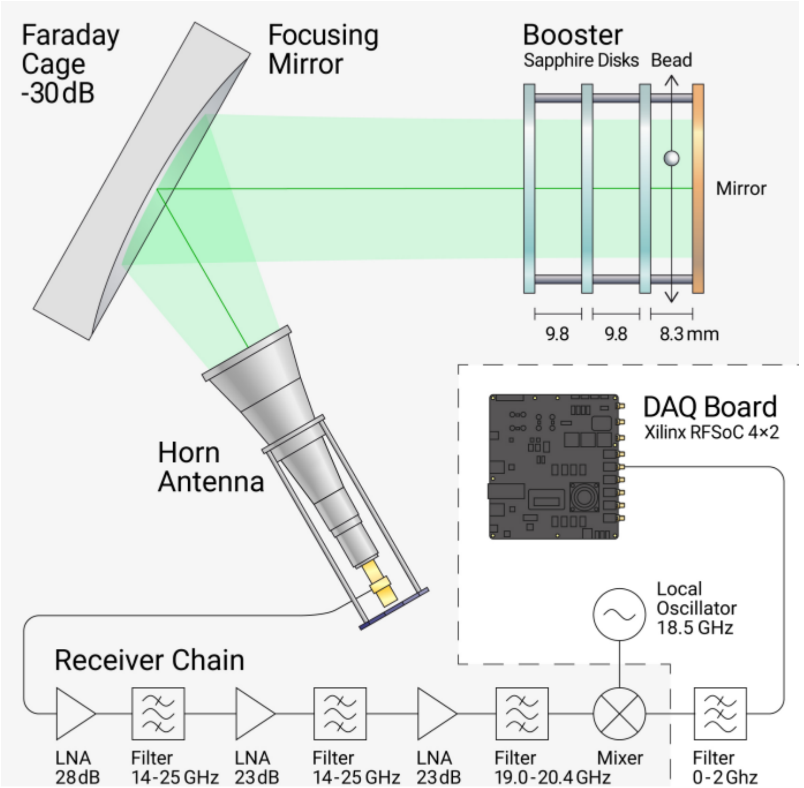
Parameter	Value	Impact on amplitude	Impact on peak frequency	Impact on AUC
Gaussian beam waist variation	+- 10 mm	7%	0 MHz	17%
Thickness variation	+- 30 μm	17%	80 MHz	2%
Distance variation	+- 10 μm	1%	100 MHz	0.2%
Tilt variation	+- 0.1 mrad	28%	30 MHz	11%

Good agreement between measurement and simulation apart from a peak frequency offset ~ 50 MHz

First Dark photon search with MADMAX

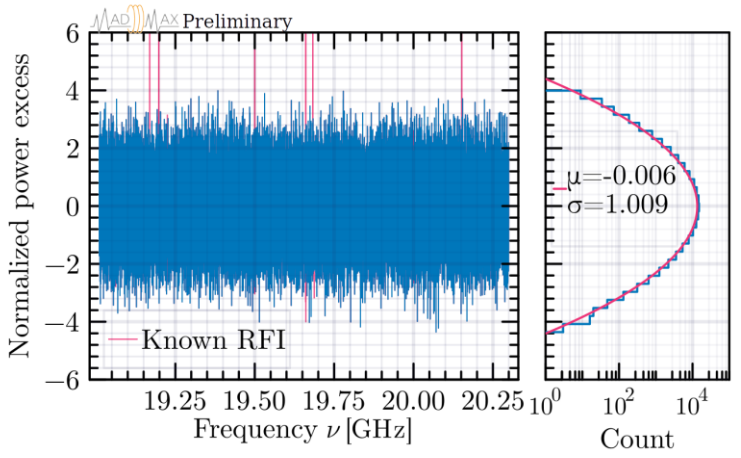
- OB300v1 booster for dark photon (DP) search with 12 days of data taking (no B field)
  - Setup at room temperature, surrounded by RFI shielding walls





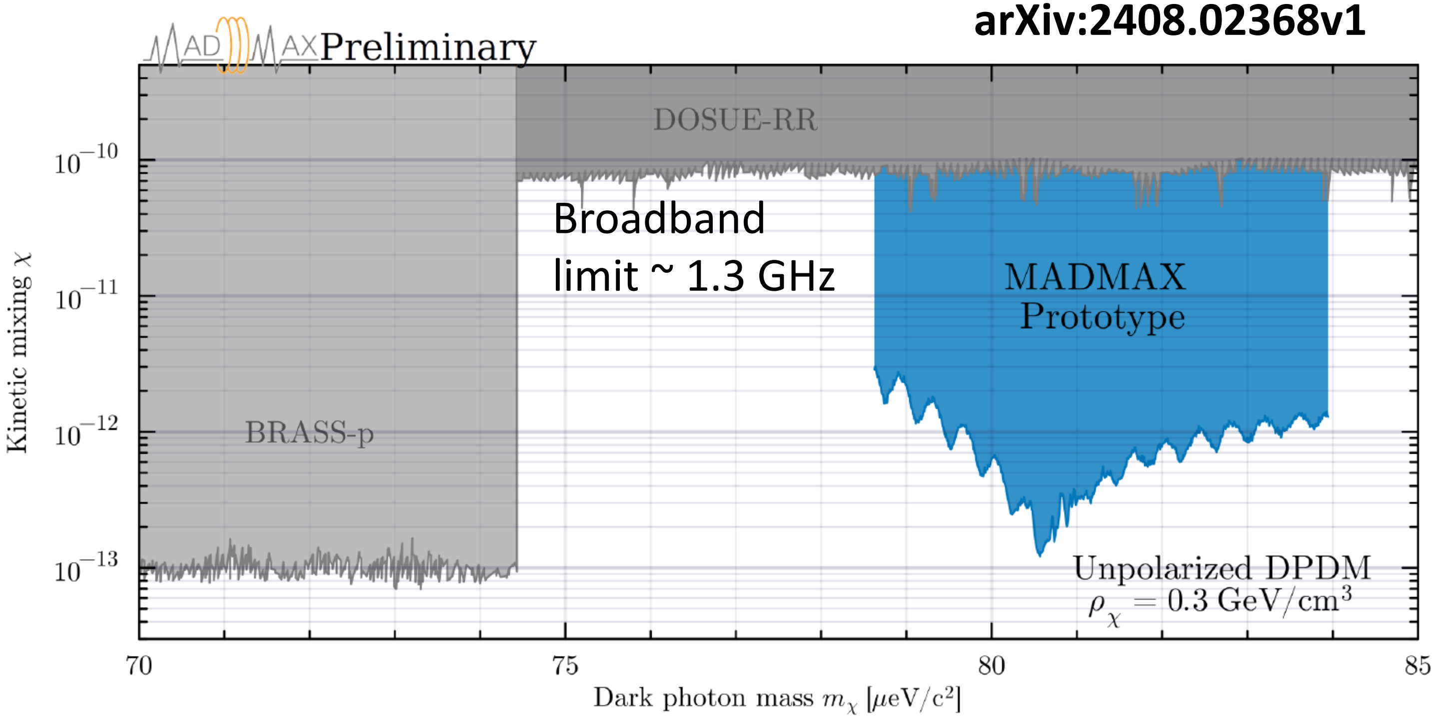
First Dark Photon limit with MADMAX

- Combining all raw spectra measurements to get one "grand spectrum"
  - Based on HAYSTAC analysis procedure (PRD 96 (2017) 123008)
  - Boost factor measured in-situ with bead-pull method



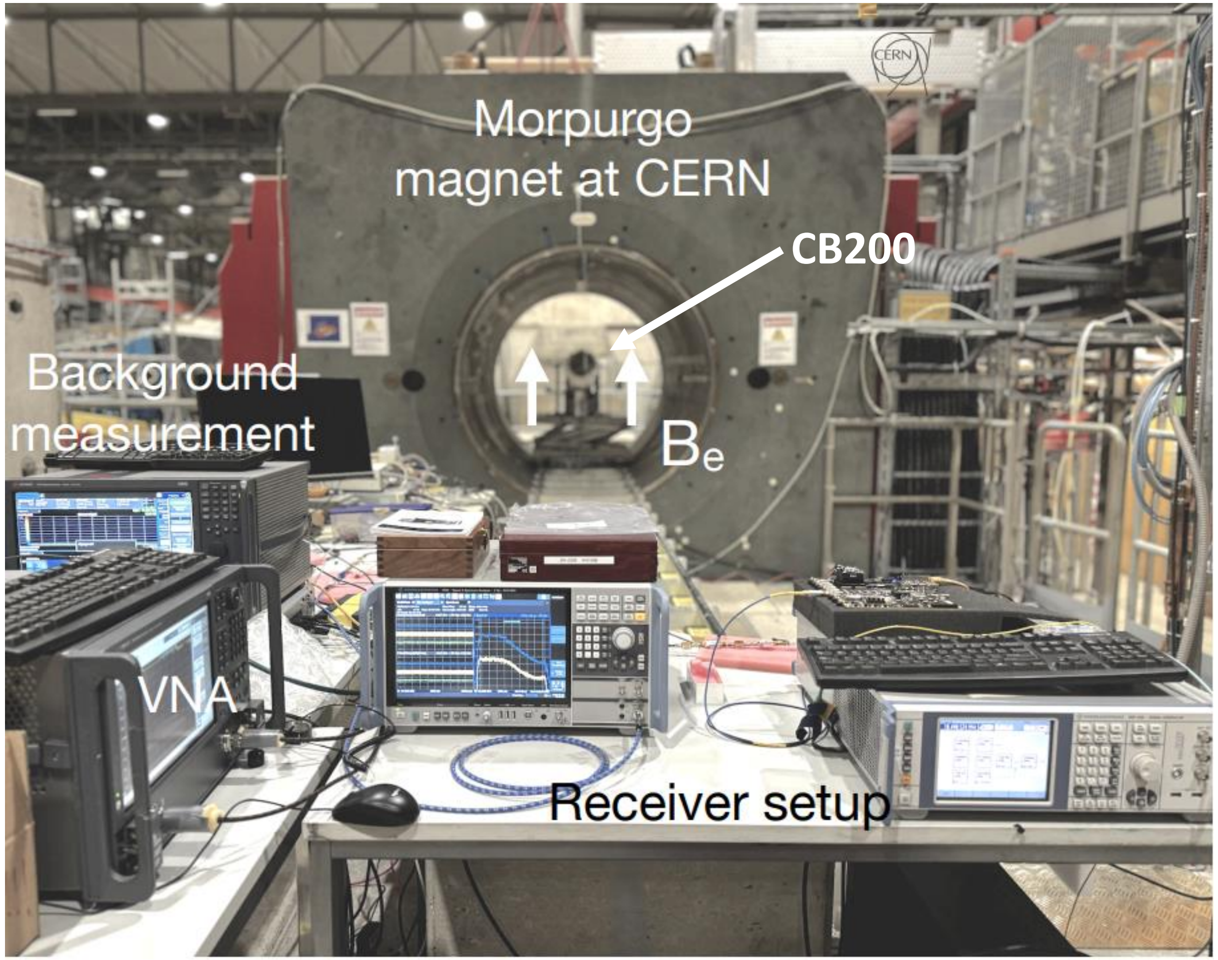
No peaks of unknown origin is observed

arXiv:2408.02368v1

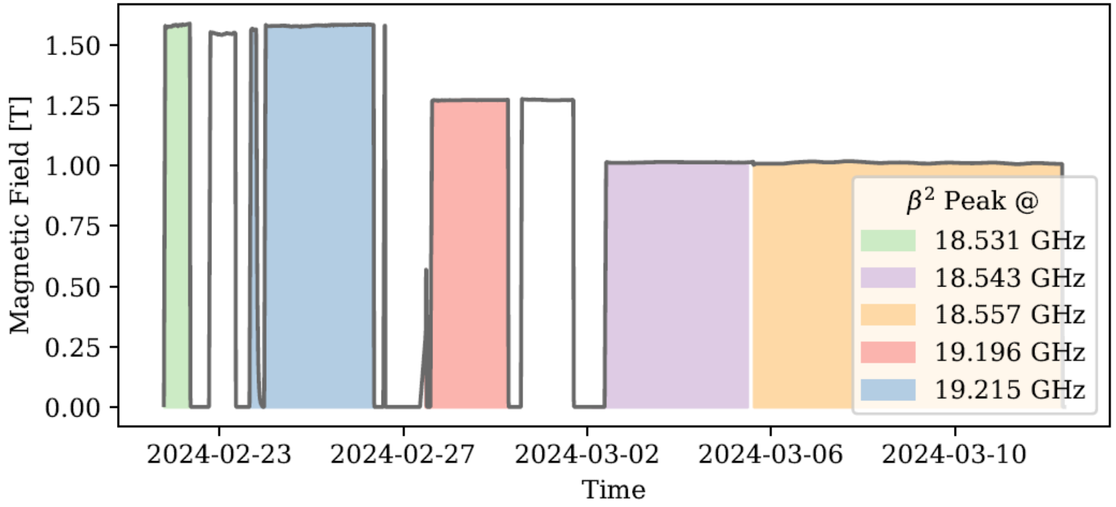


- World best 95% CL limit on DP kinetic mixing χ in m_χ [78.6, 83.9] μeV using OB300v1
  - 1-3 order of magnitude below previous limits

First ALPs search with MADMAX



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

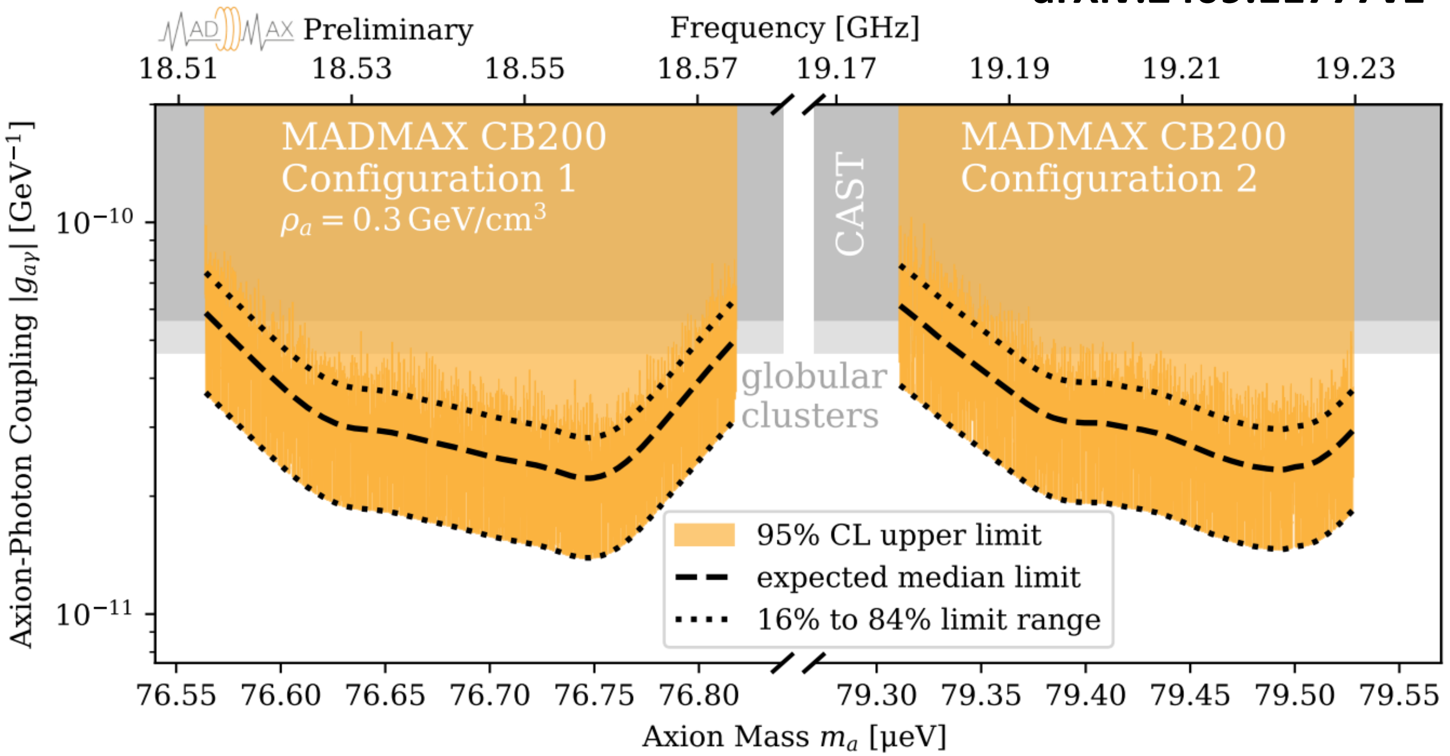


14.5 days of physics data at CERN with CB200 prototype

First ALPs limit with MADMAX

- First axion dark matter search using dielectric haloscope

arXiv:2409.11777v1

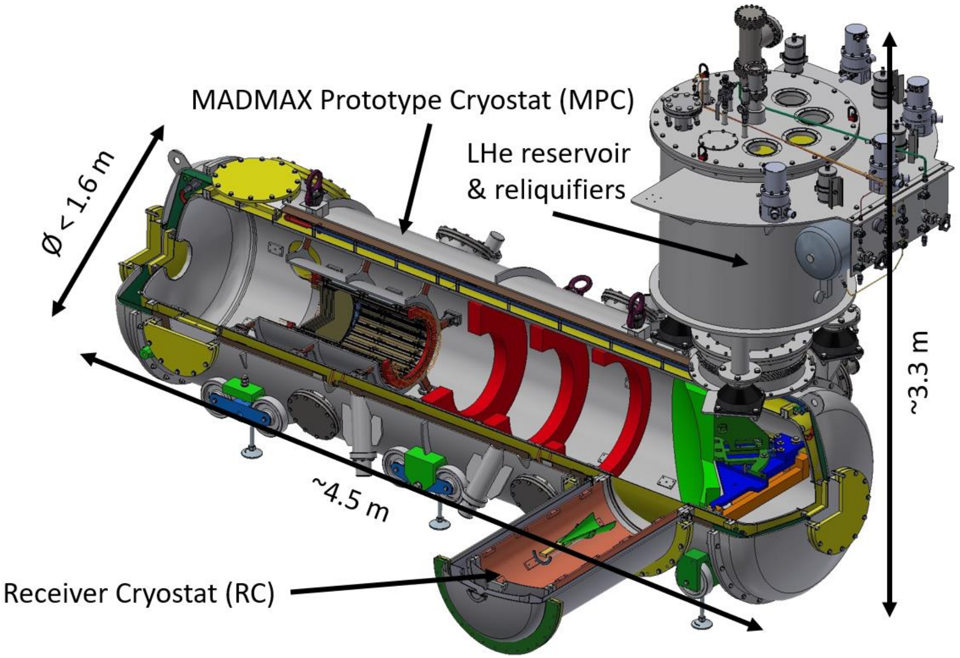


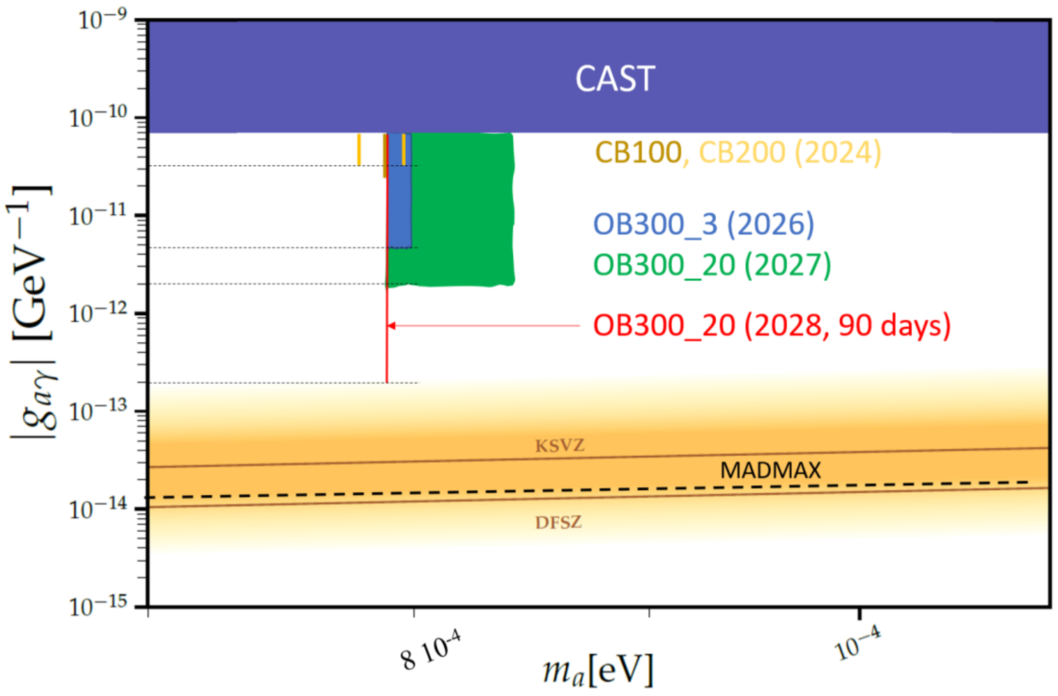
95% confidence exclusion limit
bin width = 0.9 kHz

- World best median limit down to 2×10^{-11} GeV^{-1} around 78 μeV
- I am currently working on producing a dark photon exclusion limit using the same data

Final prototype: Future plan

- OB300v2 prototype with 3 to 20 movable disks
- Under 1.6 T magnetic field and 4 K temperature
- 3 physics runs with different search ranges during the long shutdown period 2026-2028 at CERN





Articles

- First search for dark photon dark matter with a MADMAX prototype (MADMAX collaboration, submitted for publication in August 2024)
  - Took part in the simulation of the setup and choosing the disk configuration
- First mechanical realization of a tunable dielectric haloscope for the MADMAX axion search experiment (MADMAX collaboration, accepted for publication in JINST)
  - Took part in the data analysis
- First search for axion dark matter with a MADMAX prototype (MADMAX collaboration, submitted for publication in September 2024)
  - Took part in the data taking and the statistical analysis
- One internal note on disk measurements and simulations of OB300 prototype
  - Preparation for the longer experimental runs at CERN in 2026-2028

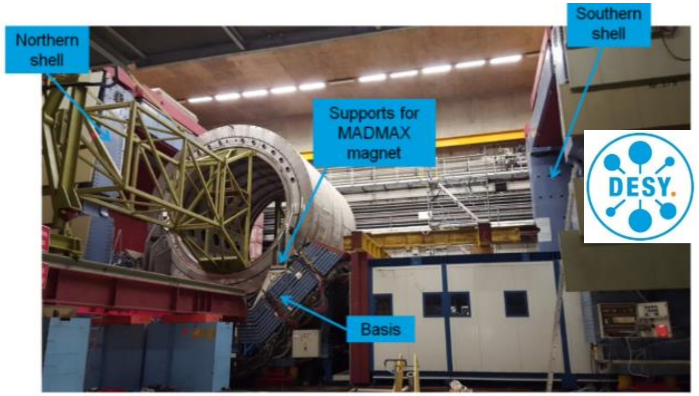
Workshop/Conferences

- Journées de Rencontres Jeunes Chercheurs - Oct 2023
- DMLab Annual meetings in 2023 and 2024
- IRN Terascale - Nov 2024
- TMEX Vietnam - Jan 2025

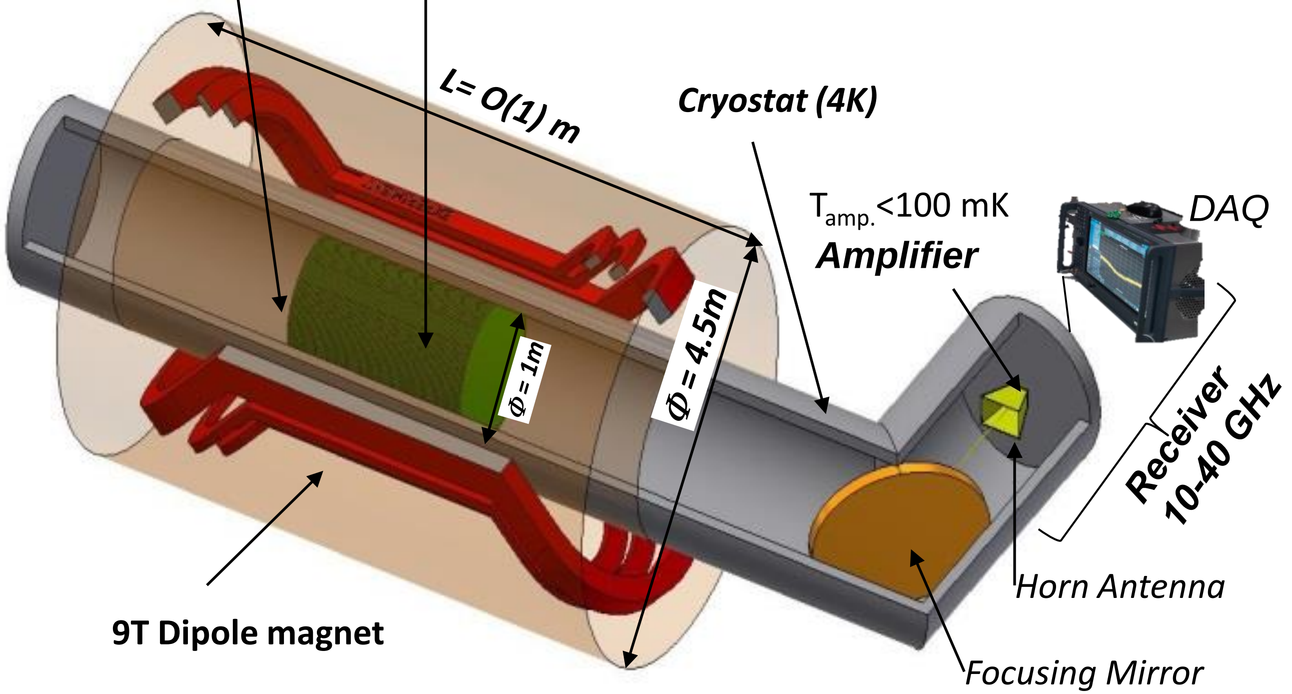
Thank you

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

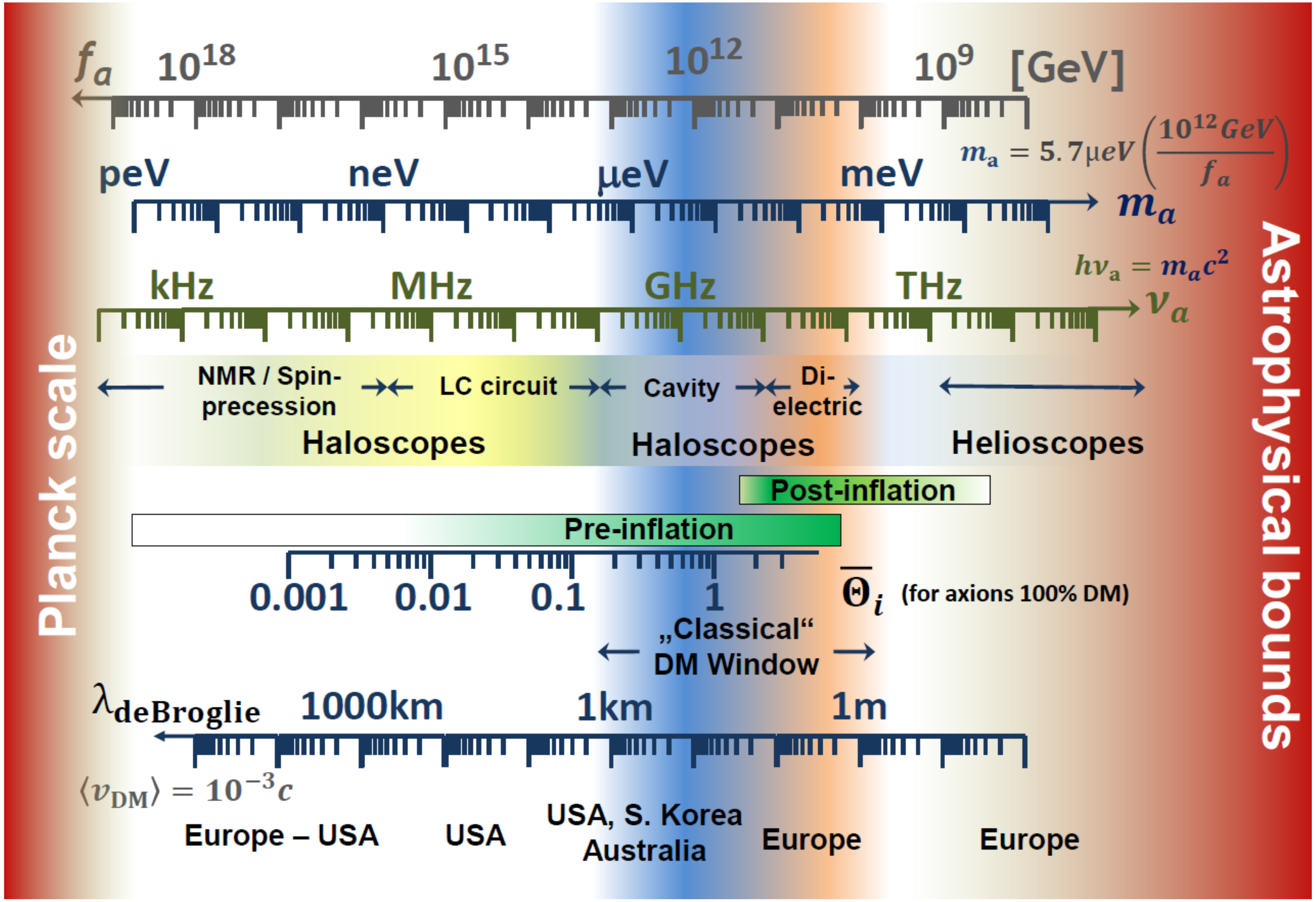


Experimental Challenges :

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

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

Axion scales



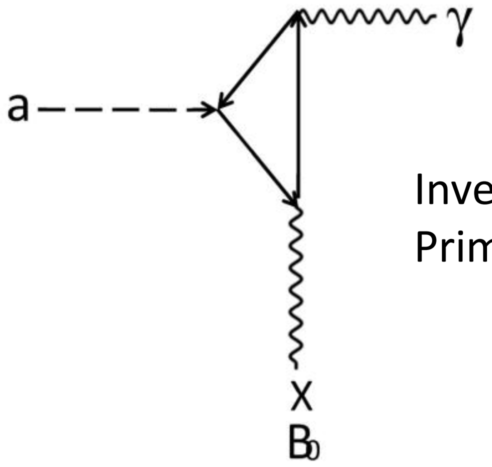
Dielectric haloscope: principles

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

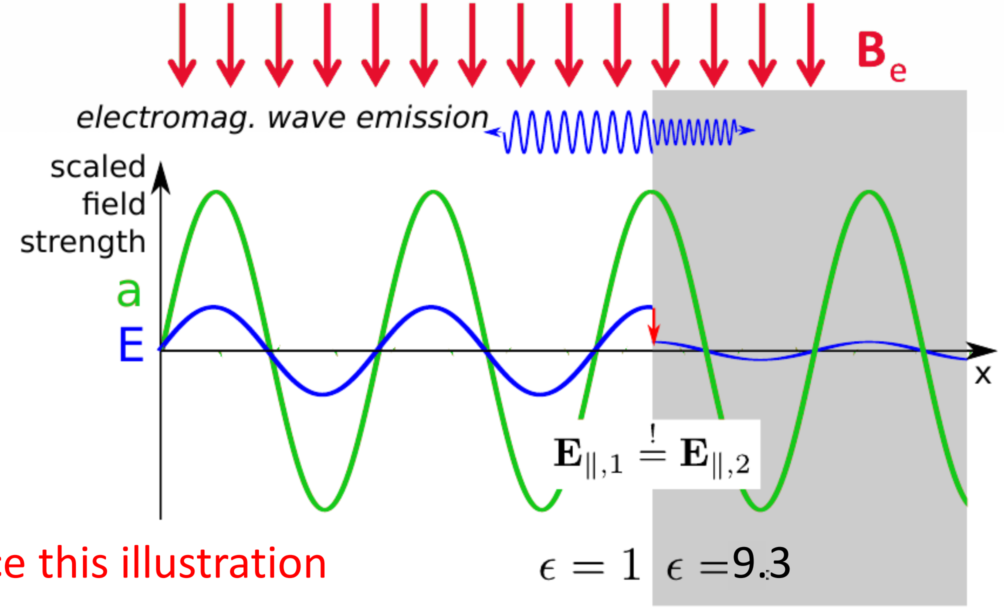
$$\boldsymbol{E_a} \cdot \boldsymbol{\epsilon} \sim 10^{-12}\ {}^{\mathrm{V}}\!/_{\mathrm{m}} \text{ for } B_e = 10\ \mathrm{T}$$

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

At the surface, $E_{\parallel}$ must be continuous
→ **Emission of electromagnetic waves**

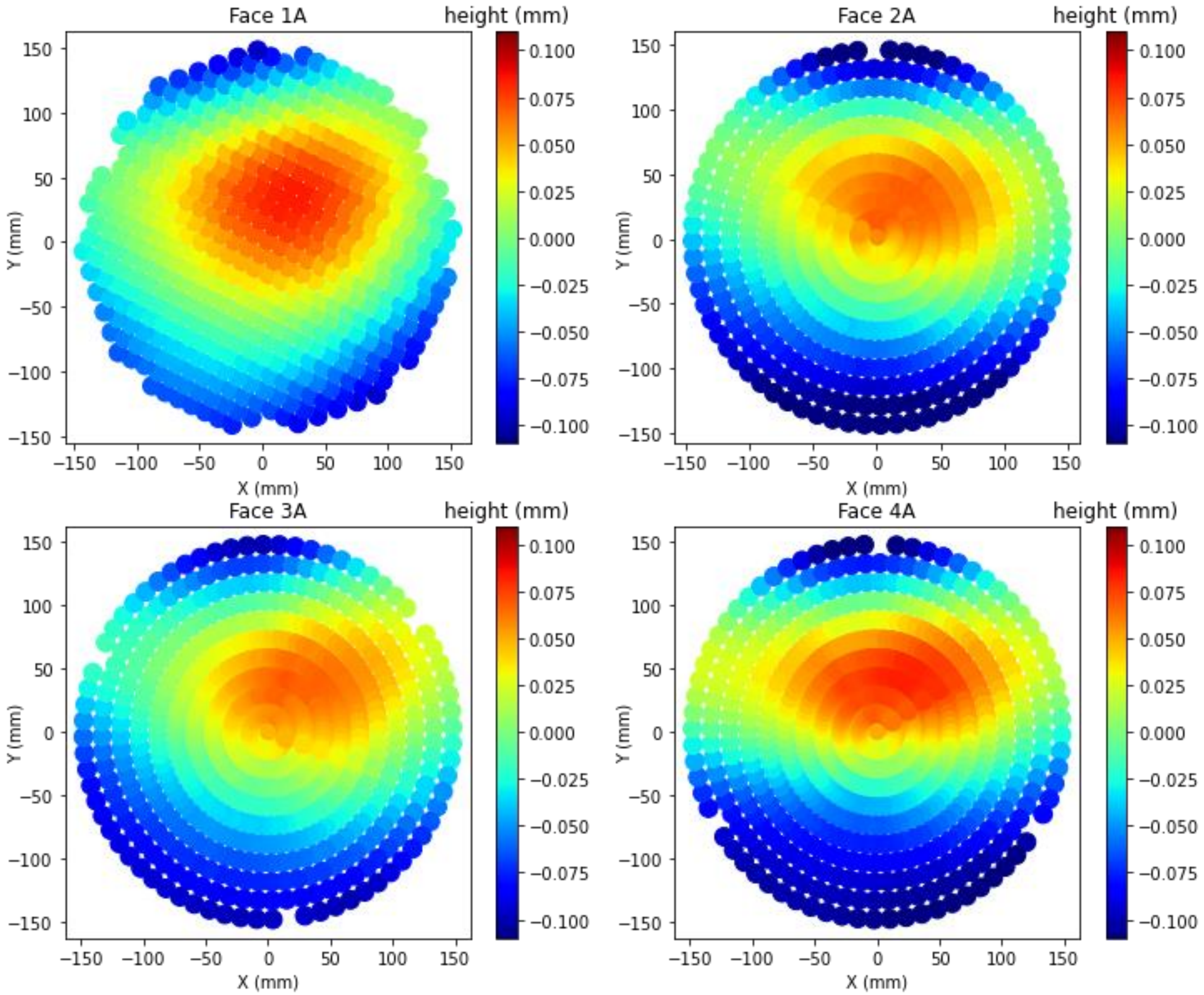


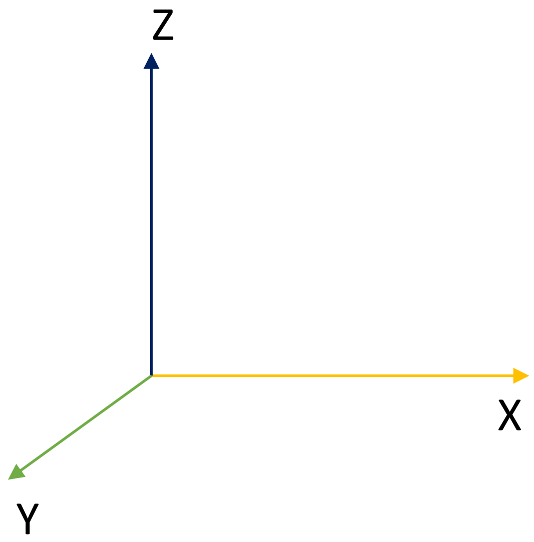
Inverse Primakoff effect



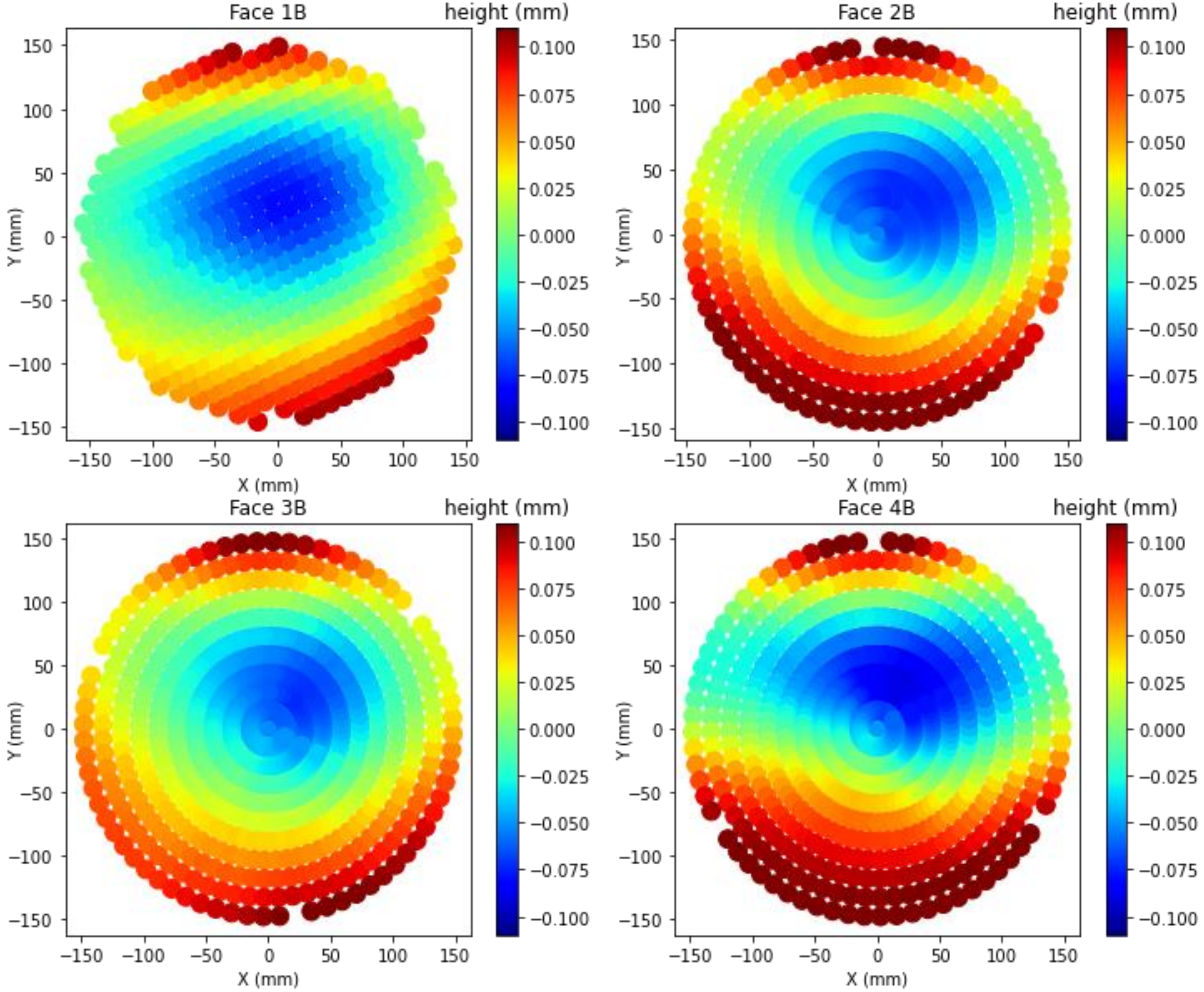
Replace this illustration

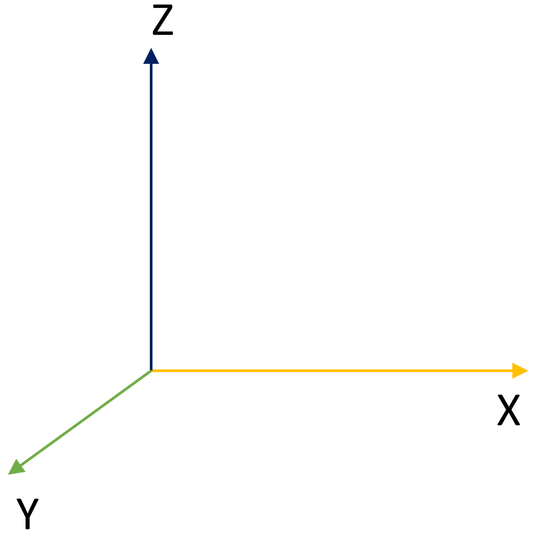
Disk raw measurements





Disk raw measurements





All the disk faces similar to each other

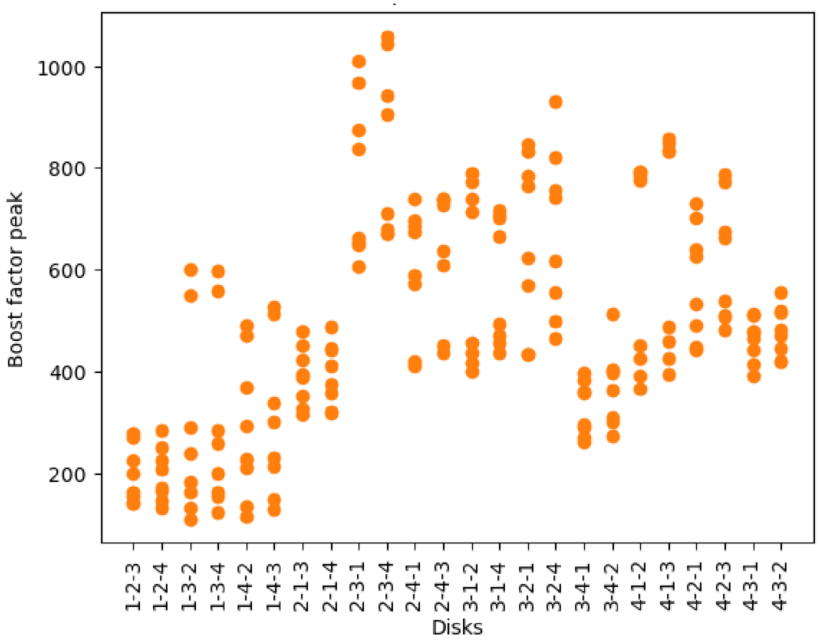
OB300v1 3D simulations: uncertainty

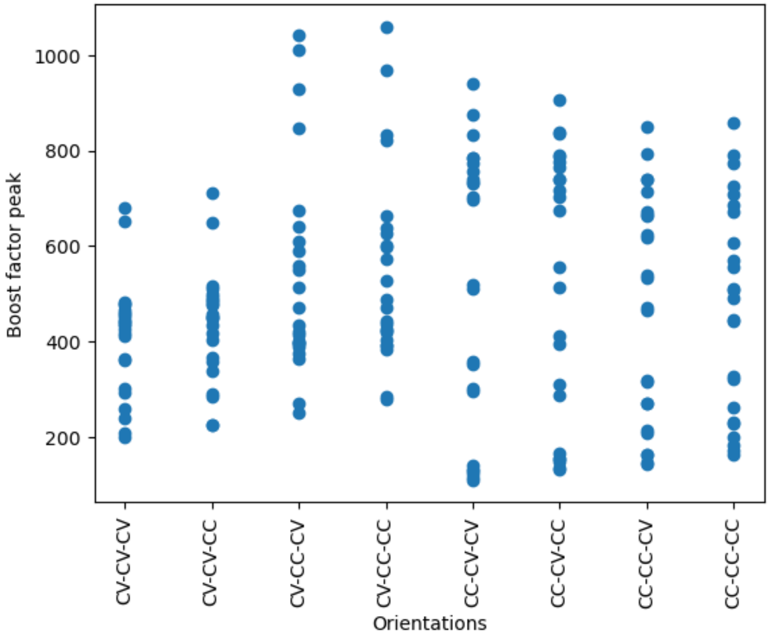
- The booster parameters and their uncertainty calculated from measurements
  - mirror conductivity [S/m]: 5e7 ± 1e7
  - Disk1 distance [m]: 0.0083664 ± 1.7e-6
  - Disk2 distance [m]: 0.0099606 ± 3.2e-6
  - Disk3 distance[m]: 0.0097314 ± 3.6e-6
  - Disk thickness[m] (3 parameters): 0.001 ± 5e-6
  - Disk epsilon (3 parameters) :   9.3 ± 0.1
  - Disk loss tangent (3 parameters) :   1e-5 ± 1e-6

- Simulation uncertainty corresponds to std of 100 boost factor simulations
  - Each simulation picks a parameter value randomly from a gaussian distribution of mean and std as shown above

Narrow band searches for future

- Future MADMAX booster prototype will have movable disks
  - Boost factor can be increased for narrower frequency band
  - Need to find best configuration at each frequency

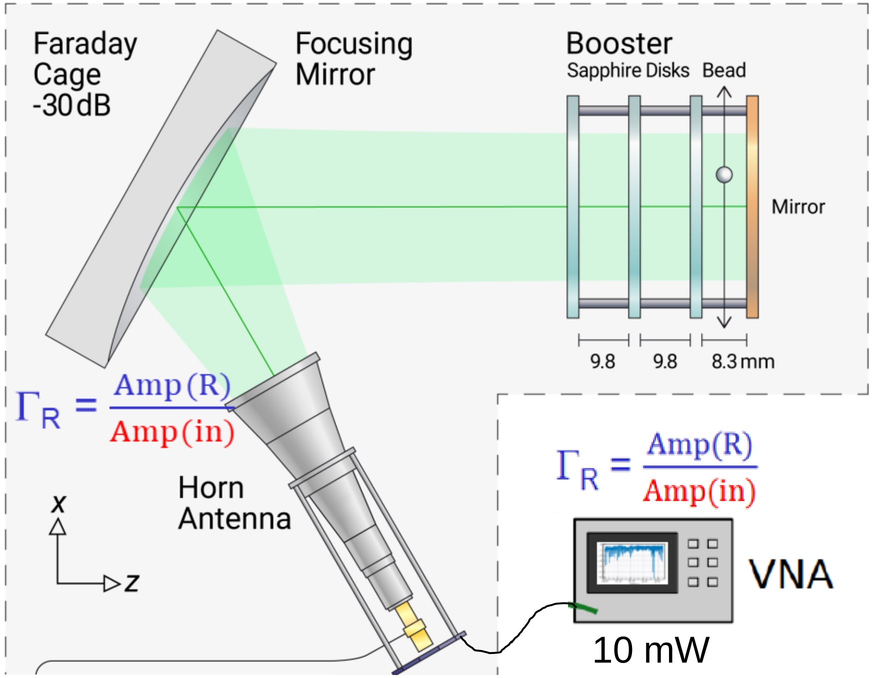




Large variance in the boost factor between different configurations at each frequency

OB300v1: In-situ β^2 determination

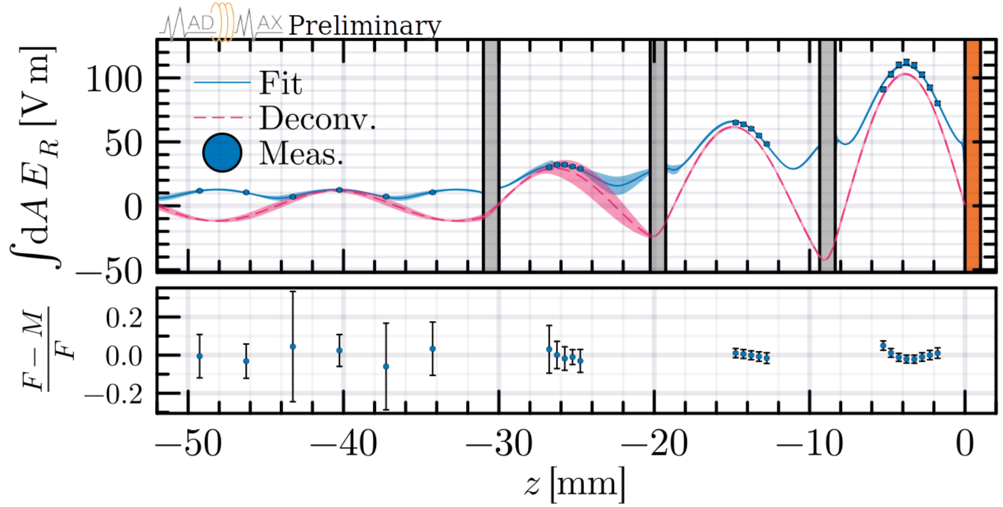
1. Reflectivity (Γ_R) measurements with and without a small bead to make a 3D scan inside the booster (not possible with closed booster)
2. Calculate the electric field $E_R \propto \sqrt{\Delta\Gamma_R}$



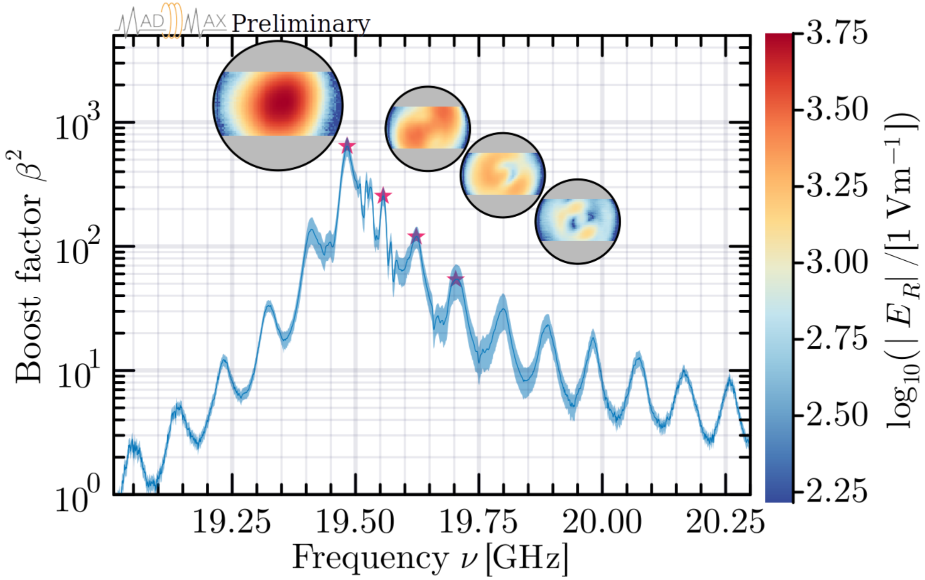
JCAP 04 (2023) 064
JCAP 04 (2024) 005

OB300v1: In-situ β^2 determination

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



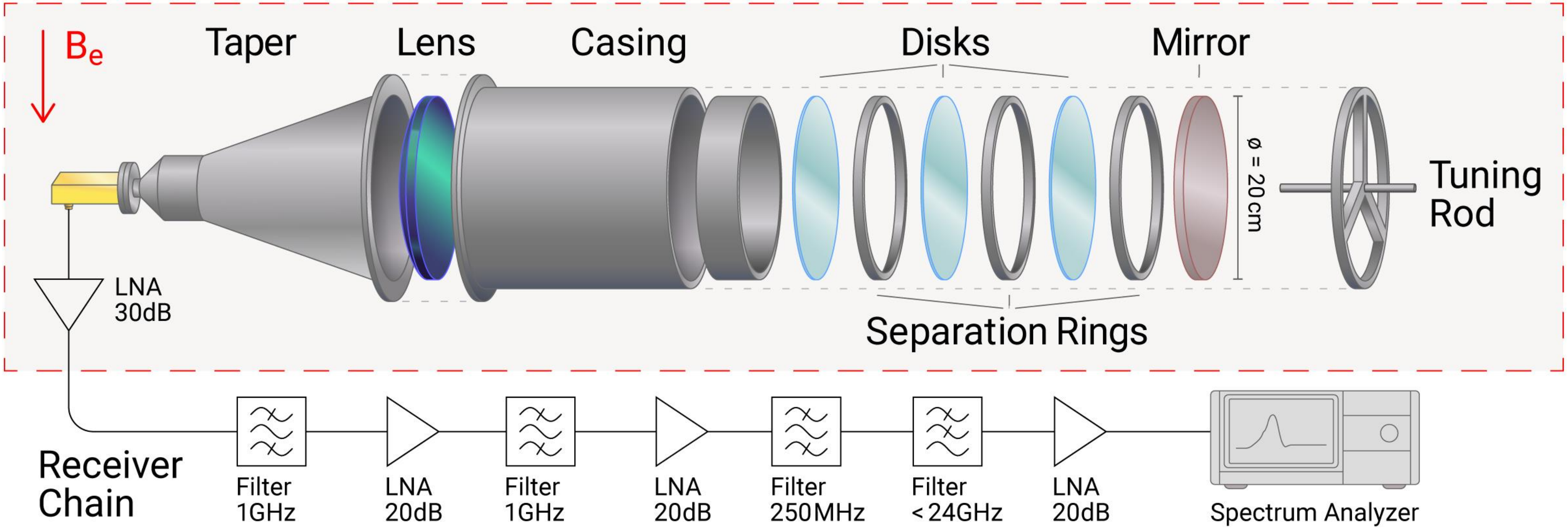
$\beta^2 \propto |\int dV\, E_R|^2$



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

First ALPs search with MADMAX

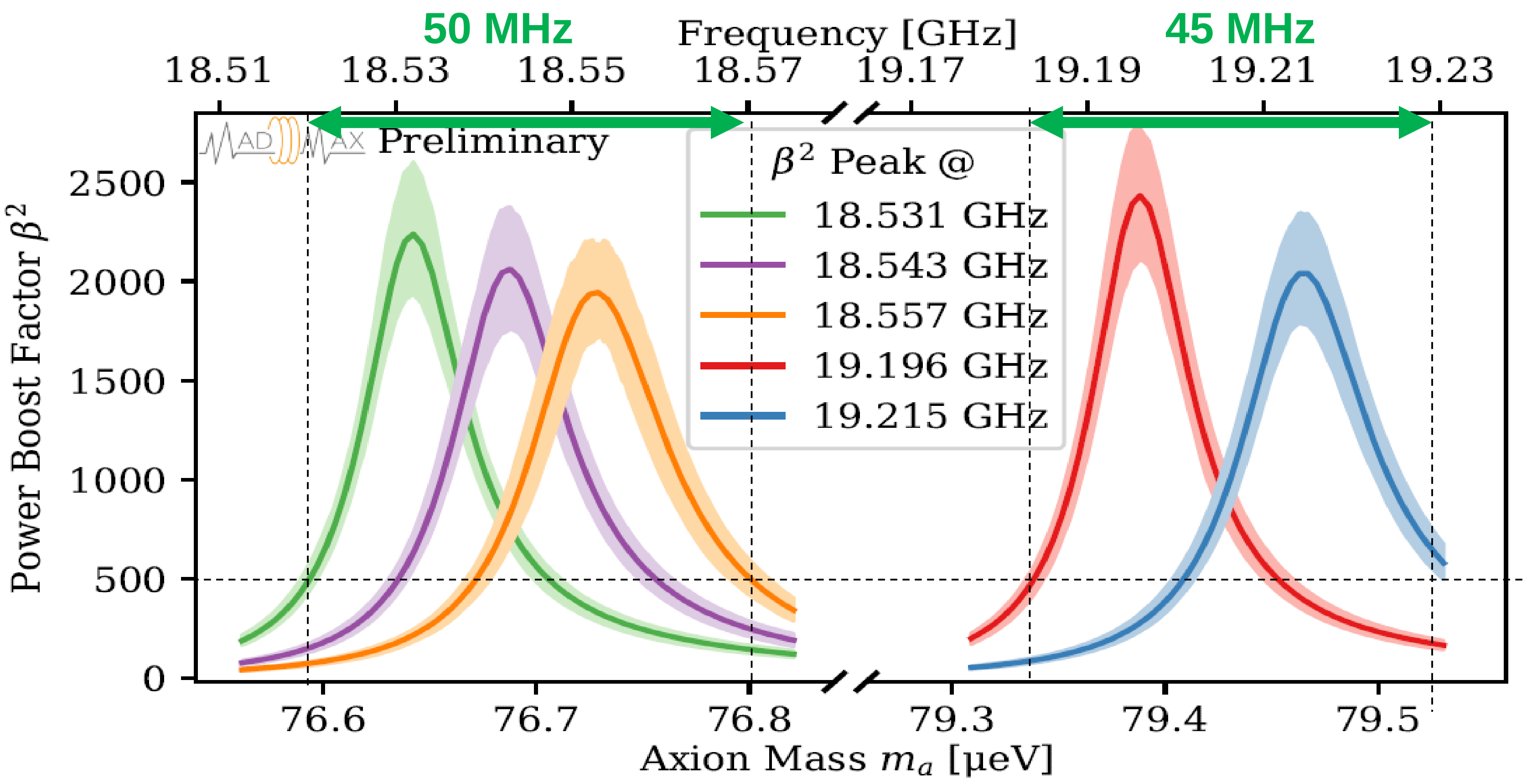
- A prototype with 1 mirror and three sapphire disks of 200 mm diameter
- Distance between the disks is determined by separation rings, optimized for 76-80 μeV axion search
- Tuning rod can push the mirror to change the desired search range



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

CB200: Booster modelling

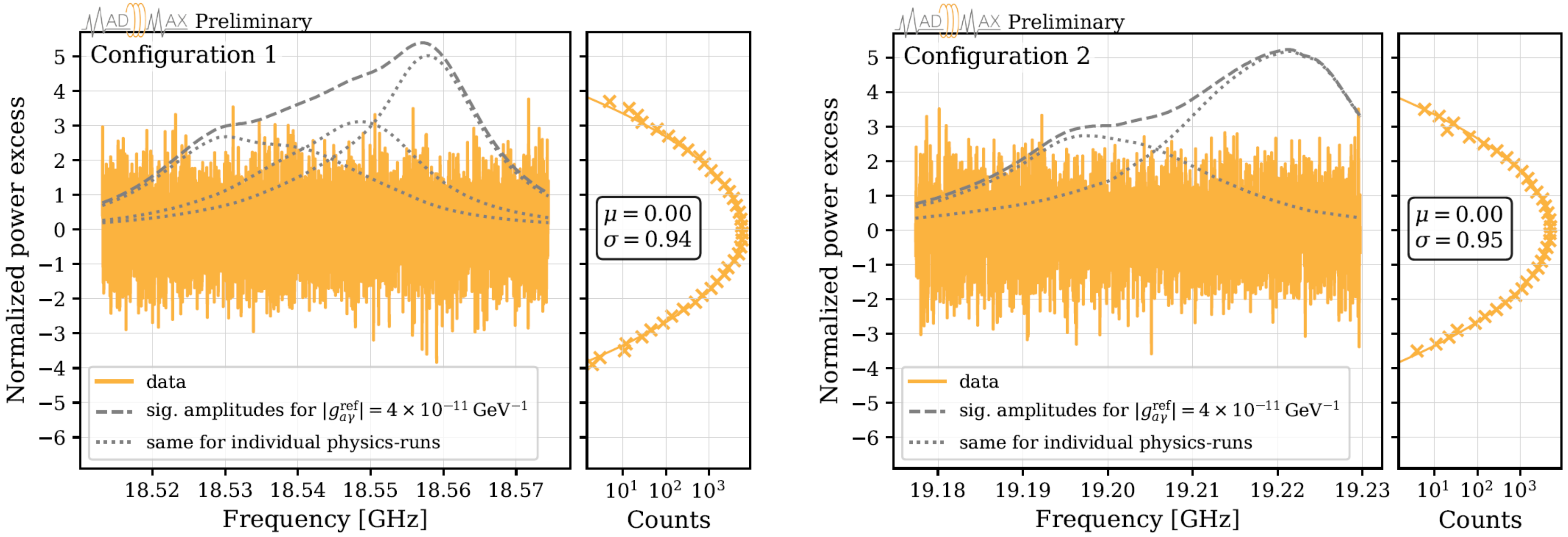
- ❑ β^2 extracted from booster measurements and 1D modelling using ADS software



- β^2 > 500 in 100 MHz bandwidth
- β^2 peaks around 2000 for all 5 data runs with ~ 15% uncertainty

CB200: 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)

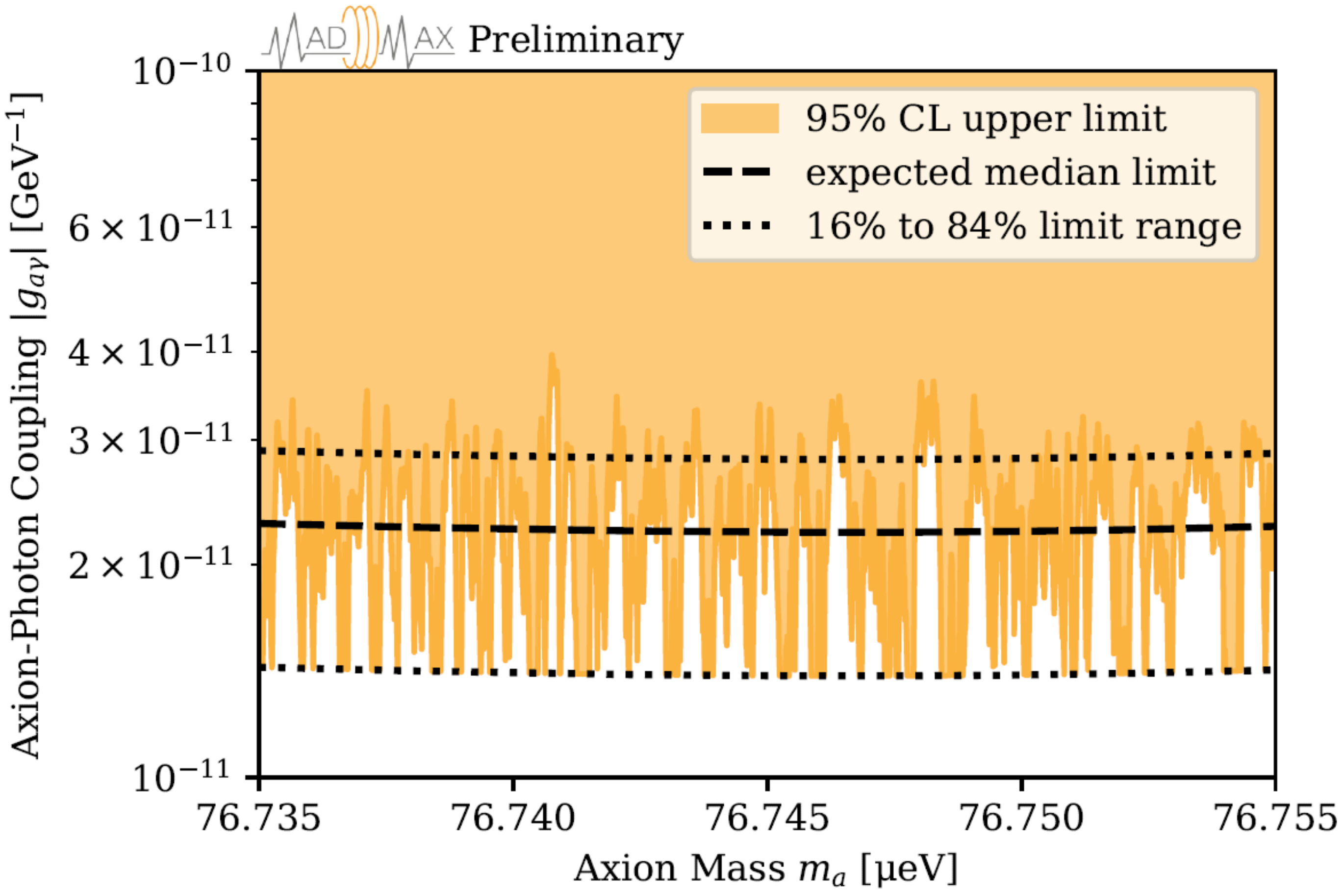


Grand spectrum for two different configurations @ 18.5 GHz and 19.2 GHz

MADMAX sensitivity

$$|g_{a\gamma}| = 4 \times 10^{-11}\,\mathrm{GeV}^{-1} \sqrt{\frac{2\times 10^3}{\beta^2}} \sqrt{\frac{T_{\rm sys}}{300\,\mathrm{K}}} \times \left(\frac{0.1\,\mathrm{m}}{r}\right) \left(\frac{1\,\mathrm{T}}{B_e}\right) \left(\frac{1.3\,\mathrm{days}}{\Delta t}\right)^{1/4} \sqrt{\frac{\mathrm{SNR}}{5}} \times \left(\frac{m_a}{80\,\mu\mathrm{eV}}\right)^{5/4} \sqrt{\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_a}},$$

MADMAX ALPs limit



Systematics

Axion search

Effect	Uncertainty in $\lvert g_{a\gamma} \rvert$
Y-factor power calibration	3% to 5%
Receiver chain power stability	$\leq$ 2%
Axion field – TE_{11} overlap	6%
Booster model parameters	3% to 6%
LNA impedance mismatch	$\leq$ 7%
Frequency stability of TE_{11} mode	$<$ 1%
Total	5% to 10%

Dark photon search

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%

MADMAX future plan

Type	acronym	ϕ disc [mm]	Nb of discs	Available	Test at CERN Temp. [K]	Year
Open Booster 200	OB200	200	1	2021	290	2022
Closed Booster 100	CB100	100	3	2021	290	2022, 2023
					10	2024
Closed Booster 200	CB200	200	3	2022	290	2024
			10	*2025*	*290*	*2025*
Open Booster 300	*OB300*	*300*	*3*	*2024*	*10*	*2026*
Prototype Open Booster	*OB300_F*	*300*	*20*	*2026*	*10, 7*	*2027, 2028*

Table 1: MADMAX tests performed (plain) and planned (italic) in the Morpurgo magnet.

Booster	Cryostat	β^2	T_{sys} [K]	Sensitivity [GeV^{-1}]	freq. range [MHz]	Duration [Months]	Year
CB200	–	2000	600	$\approx 35 \times 10^{-12}$	50	0.1	2024
CB100	G10	1000	20	$\approx 20 \times 10^{-12}$	10	0.03	2024
CB200	–	*7000*	*600*	$\approx 10 \times 10^{-12}$	*10*	*0.2*	*2025*
OB300	*MPC*	*1000*	*10*	$\approx 5 \times 10^{-12}$	*200 (scan)*	*3*	*2026*
OB300_F	*MPC*	*7000*	*10*	$\approx 2 \times 10^{-12}$	*1000 (scan)*	*3*	*2027*
		50000	*7*	$\approx 0.2 \times 10^{-12}$	*1*	*3*	*2028*

Table 2: Physics reach of various booster setups tested in the Morpurgo magnet. For the 2024 measurements, values from the most sensitivity run are taken. while for the planned measurements, shown in italic, 1 day measurement is assumed for scanning runs with SNR = 5, a DAQ efficiency of 85 % and an ALP mass around 80 μeV. At this ALP mass, the corresponding CAST limit is 66×10^{-12} GeV^{-1} [6]. For the last line, no scan is performed instead a 10 times higher boost factor is obtained by reducing the frequency width to 1 MHz.