Searching for axion and dark photon dark matter with MADMAX

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PhD thesis defense

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OUTLINE

Introduction to Axion dark matter

The MADMAX Experiment

R&D towards a tunable haloscope

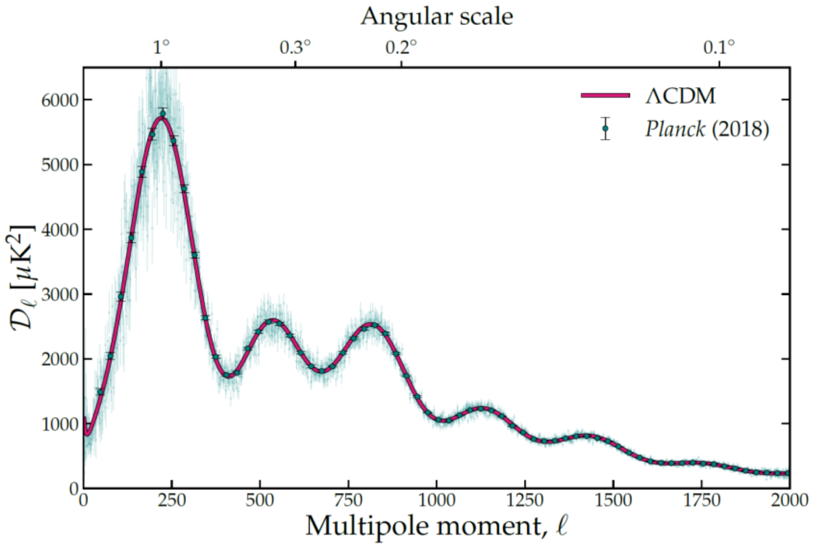
Booster simulations

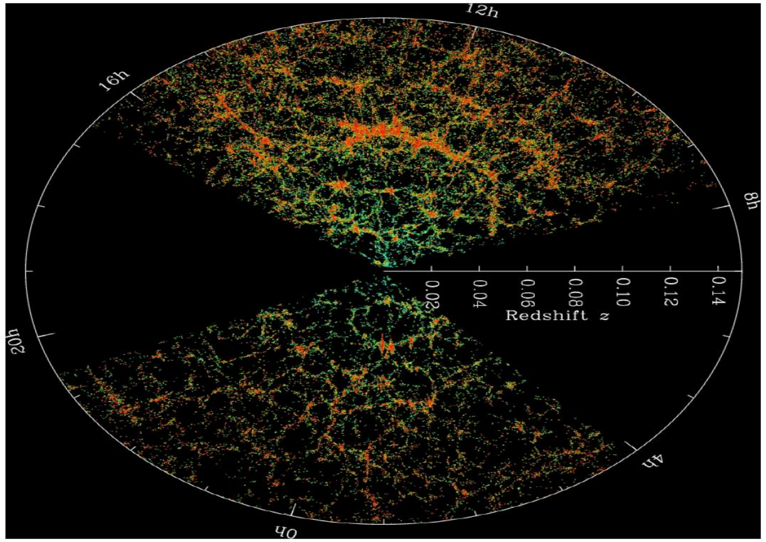
First dark matter searches

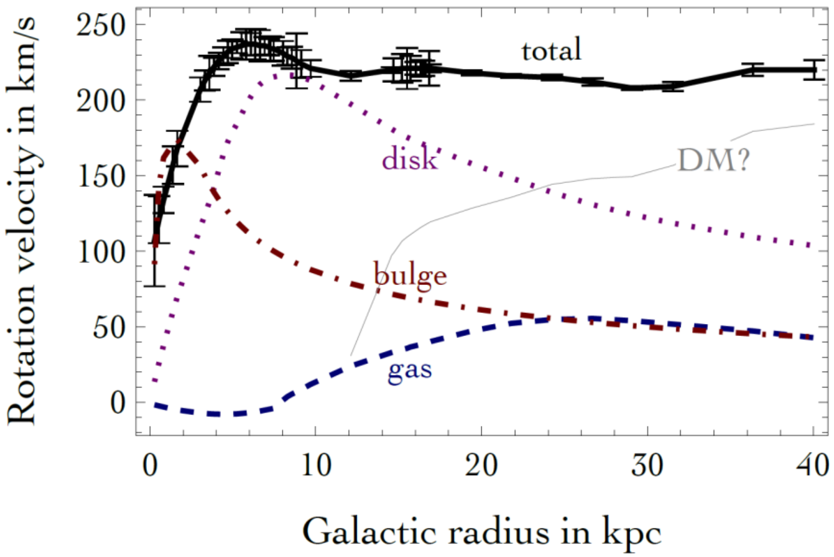
Conclusions and perspectives

Dark matter (DM) in the Universe

- **Observations at different scales since 90 years**
  - Cosmic Microwave Background: cold dark matter needed to fit the data (85% of total matter)
  - Large-scale structure: dark matter needed for galaxy formation
  - Galaxy rotation curves: dark matter halo to explain rotational velocity at large radius
  - Many other observations exist (bullet cluster, gravitational lensing, etc)



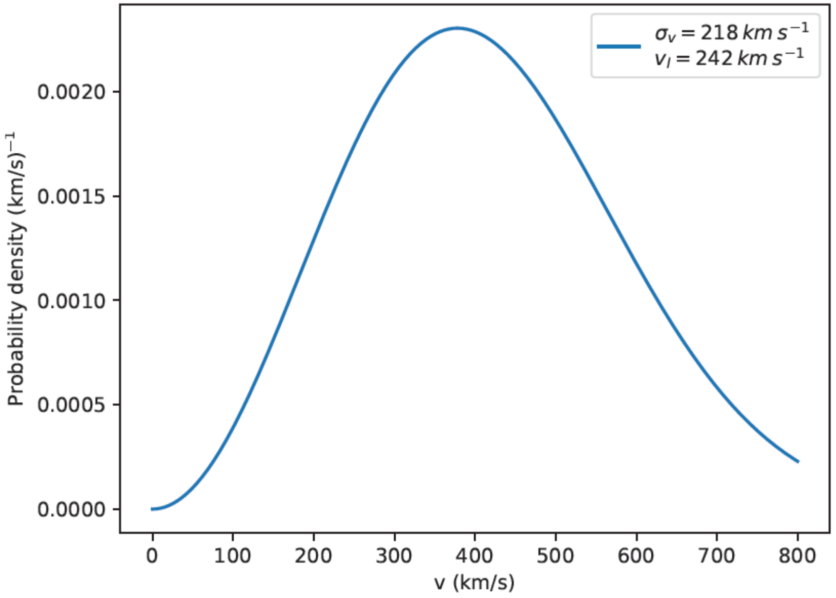




Astrophysical and cosmological observations ➔ Non-luminous substance called dark matter

Dark matter in our galaxy

- **Spherical halo – generic model, with large uncertainties**
  - Density of 0.2 – 0.6 GeV/cm^3 (0.3 chosen in this work)
  - Maxwell-Boltzmann distribution with a virial velocity of 218 ± 6 km/s
  - Contains ~10 times more dark matter than luminous matter



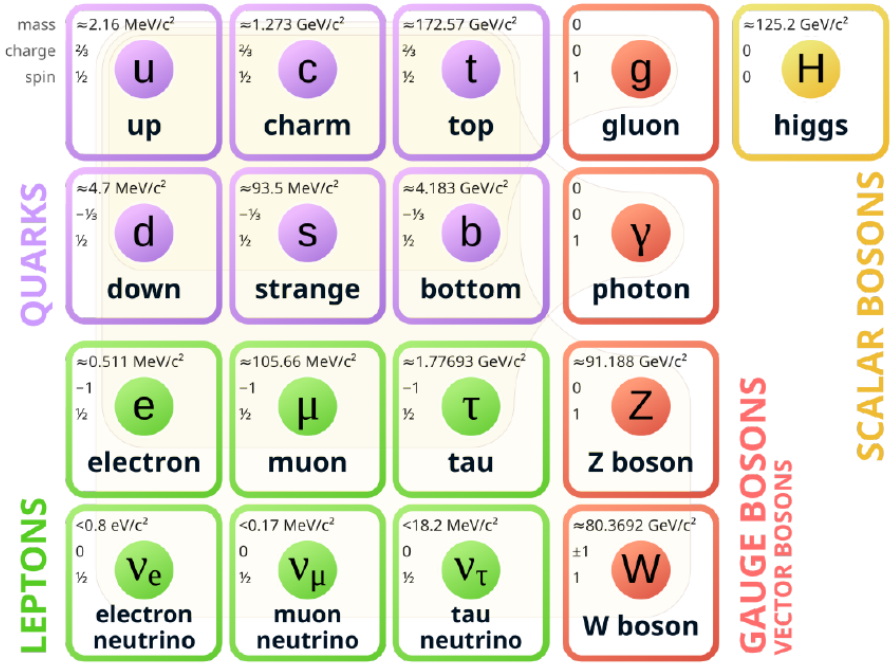
Earth frame

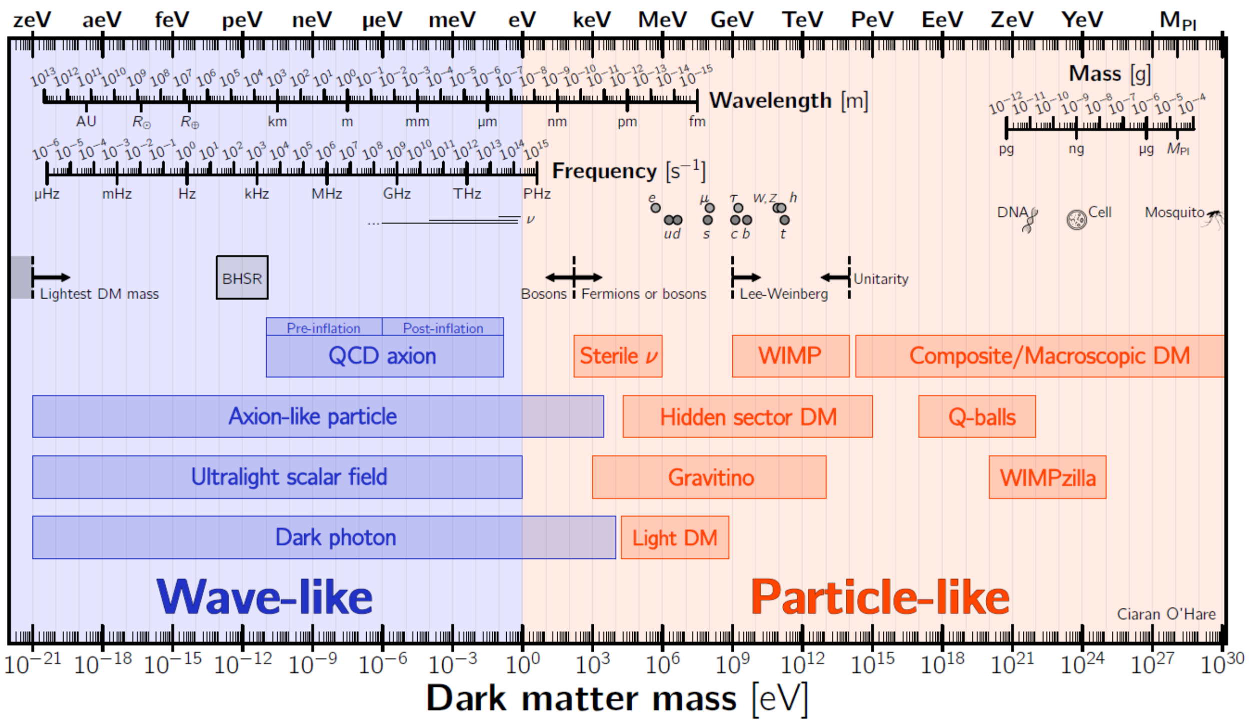
$$\sqrt{\frac{2}{\pi}}\frac{v}{\sigma_v v_l}\exp\left(-\frac{v^2+v_l^2}{2\sigma_v^2}\right)\sinh\left(\frac{v v_l}{\sigma_v^2}\right)$$

Source of dark matter for earth based direct detection experiments

Nature of dark matter

➢ **Dark matter particle candidates:**
- Properties: massive, non-relativistic, neutral, very weakly interacting, stable/long-lived
- No candidate available from the standard model of particles
- Candidates available in beyond standard model theories

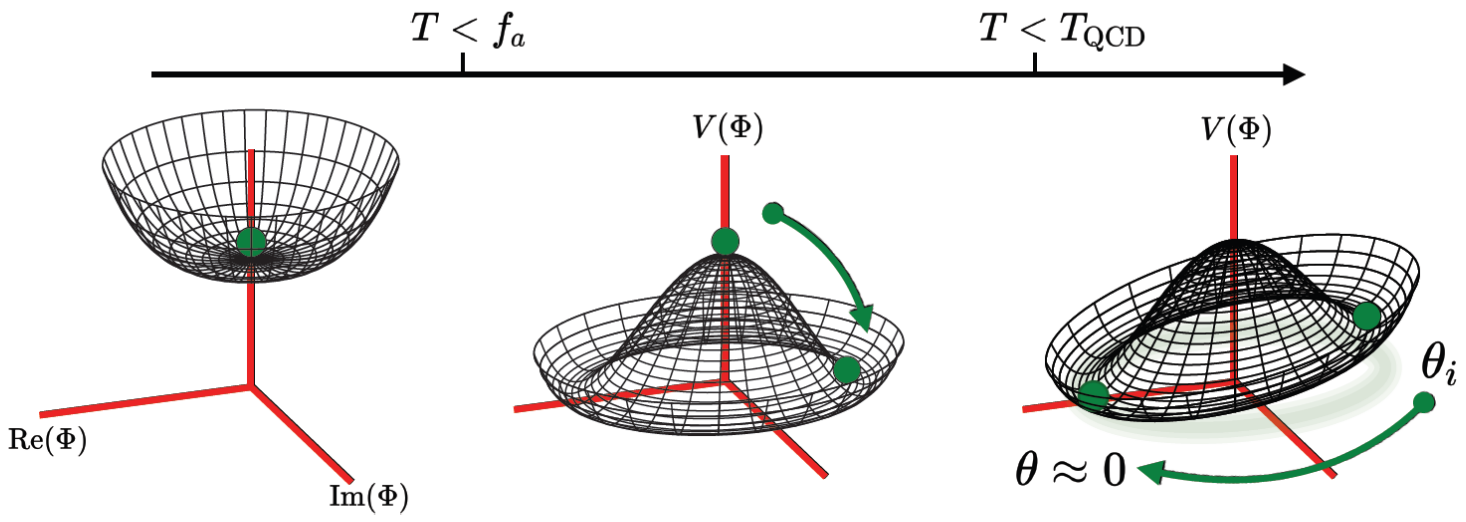




Nature of dark matter: one of the biggest unsolved puzzles in modern physics

Dark matter axion

- **Strong CP problem of standard model**
  - QCD Lagrangian has a CP violating term controlled by $-\pi < \theta < \pi$
  - Leads to a neutron electric dipole moment $d_n = (2.4 \pm 1.0)\,\theta \times 10^{-3}\,\mathrm{e\,fm}$
  - Experimental constraints: $|\theta| < 0.8 \times 10^{-10}$ ➔ why θ so small ?
- **Solution:**
  - Pseudo goldstone boson of a new U(1) symmetry spontaneously broken at scale f_a

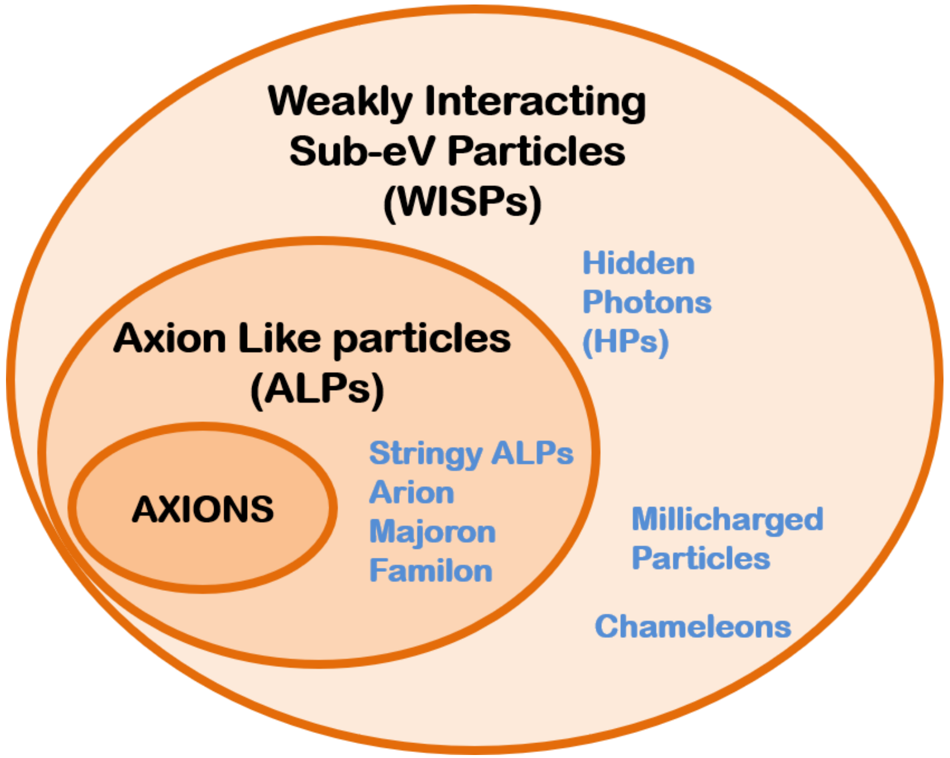


Dark matter axions

- **QCD axion: cold dark matter candidate**
  - f_a ($O(10^{10})$ GeV) >> f_{EW} ($O(10^2)$ GeV)
  - Tiny mass [$\mathbf{m_a} \approx m_p f_p / \mathbf{f_a}$ << eV],
  - Very weakly interacting [suppressed by f_a]
  - $\tau_{axion} > t_{Universe}$

- **Axion production**
  - Non-thermal axions can be produced in the early universe
  - PQ symmetry can be broken before or after inflation

- **Other candidates inspired by QCD axions**
  - Axion like particles (ALPS) = $m_a \times f_a$ not constant
  - Dark photons (Hidden photons)



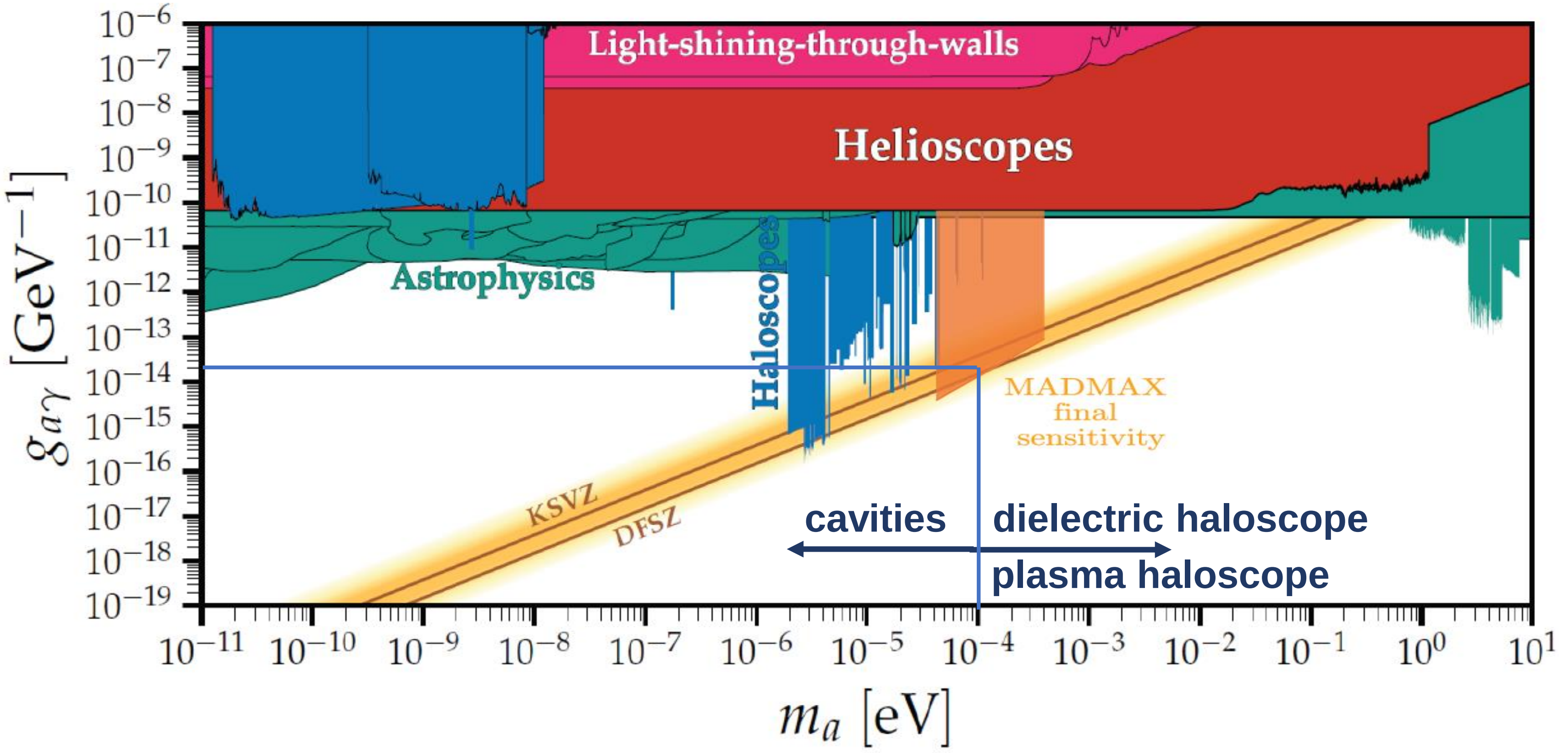
QCD axion : A strongly motivated dark matter candidate

Axion direct searches

Lab experiments	Helioscopes	**Haloscopes**
Lab produced	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**

Axion direct searches

- **Post inflationary scenario predicts mass m_a > 25 μeV in general (>6 GHz)** *Nat. Commun.* **13,** 1049 (2022)
- **Standard cavity experiments have reduced sensitivity > 25 μeV**



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

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

- $g_{a\gamma} \sim 2 \times 10^{-14}$ GeV^{-1} at 100 μeV
- $C_{a\gamma} \sim 1$

New concepts are required to probe the uncovered m_a > 25 μeV range ➔ MADMAX

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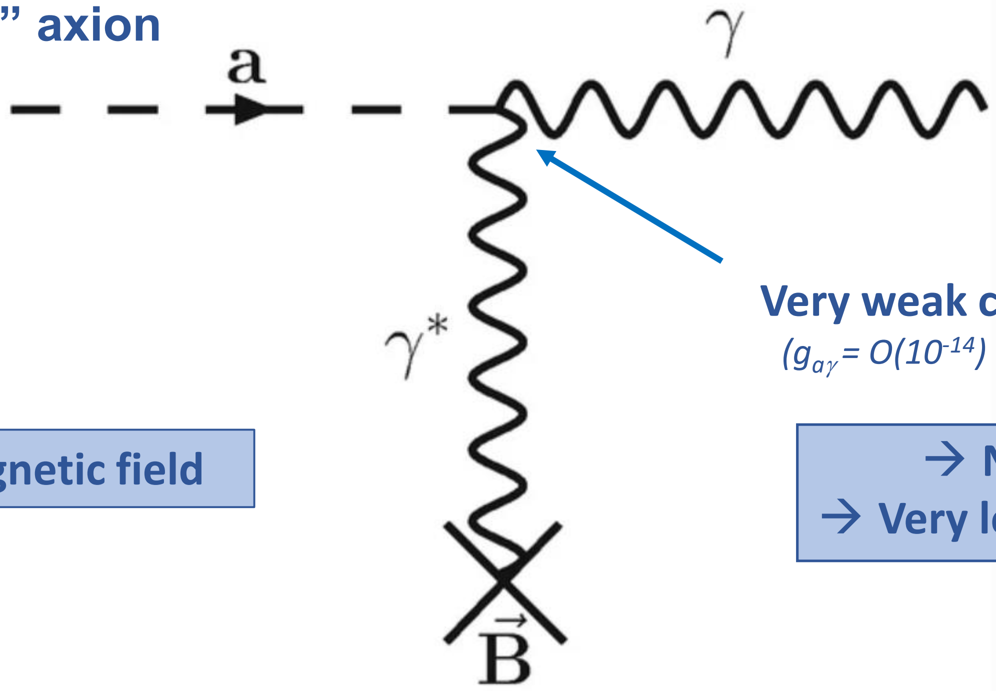
General principles

- **Preferred detection method: Convert it to a photon in the presence of magnetic field**
  - In QCD axions have non-zero coupling to photons
  - Coherent effects can be utilized to increase the strength of the photonic signal

μeV "Invisible" axion
(gas)



GHz Photon
(EM field)

≈ RF, micro-wave

f = 25 GHz, λ = 1.2 cm

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

High Magnetic field

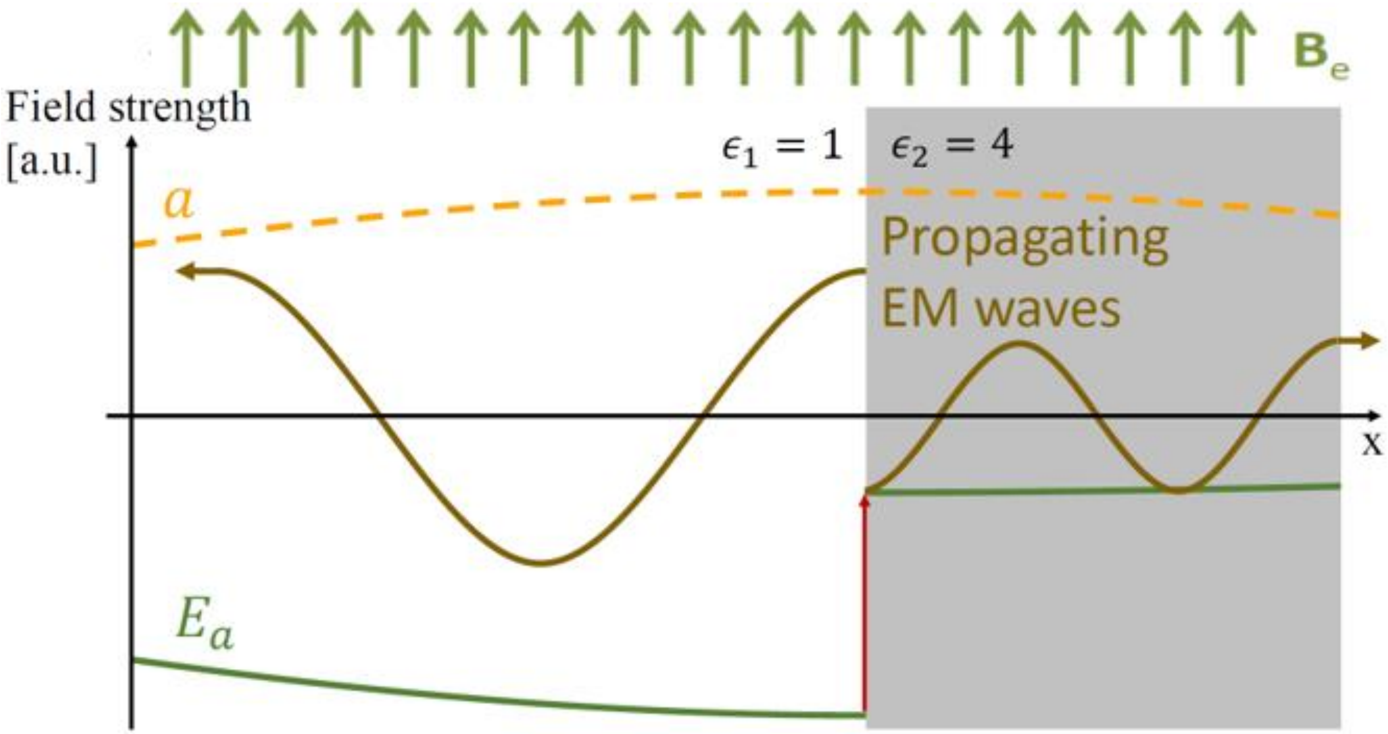
→ Need boost
→ Very low temperature

Axion search very rich in experimental challenges

Dielectric haloscope: principles

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

$$a(t) = a_0\, cos(m_a t) \;\Rightarrow\; E_a \cdot \epsilon \sim 10^{-12}\ {}^{\mathrm{V}}/_{\mathrm{m}} \text{ for } B_e = 10\ \mathrm{T}$$



At the surface, $E_{\parallel}$ must be continuous ➔ Emission of EM waves perpendicular to disk surface

Dielectric haloscope: principles

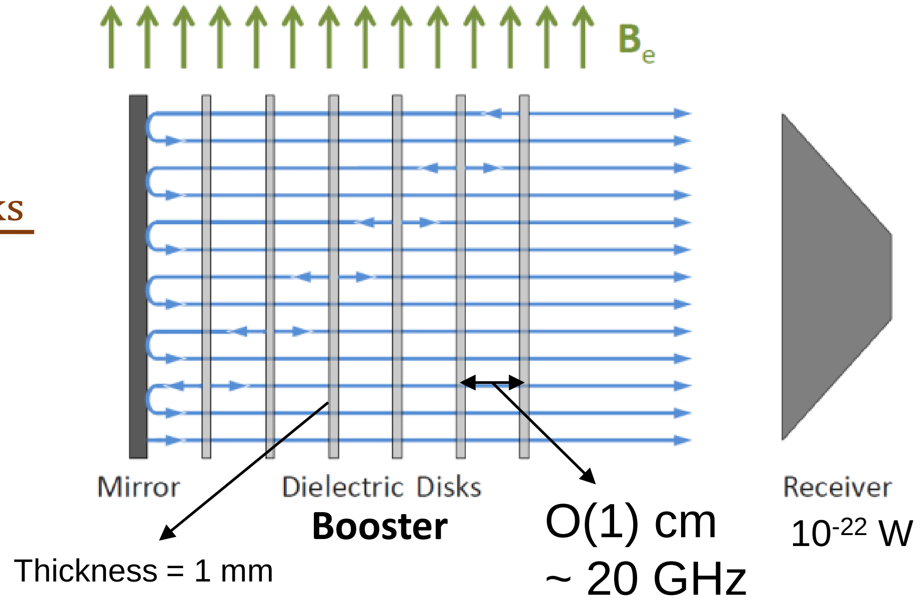
- **Constructive interference (and resonance) of coherent EM waves emitted at dielectric surfaces**

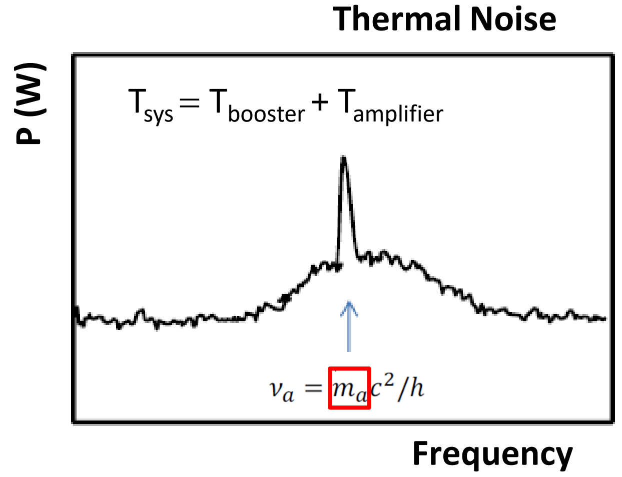
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

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

Power boost factor:

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



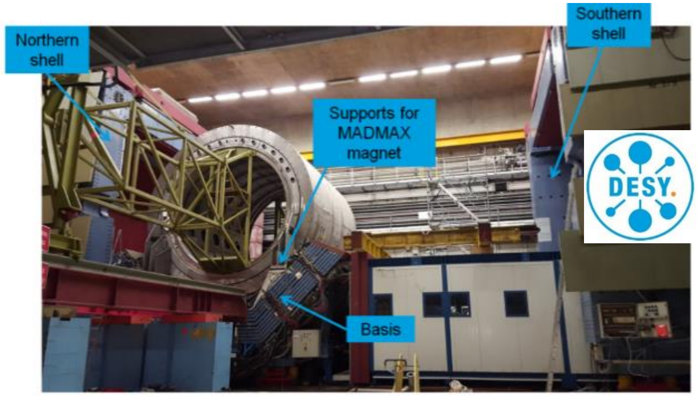


- **Axion mass scan** : by positioning disks with μm precision at 4K under 10 T *(50 MHz step)*

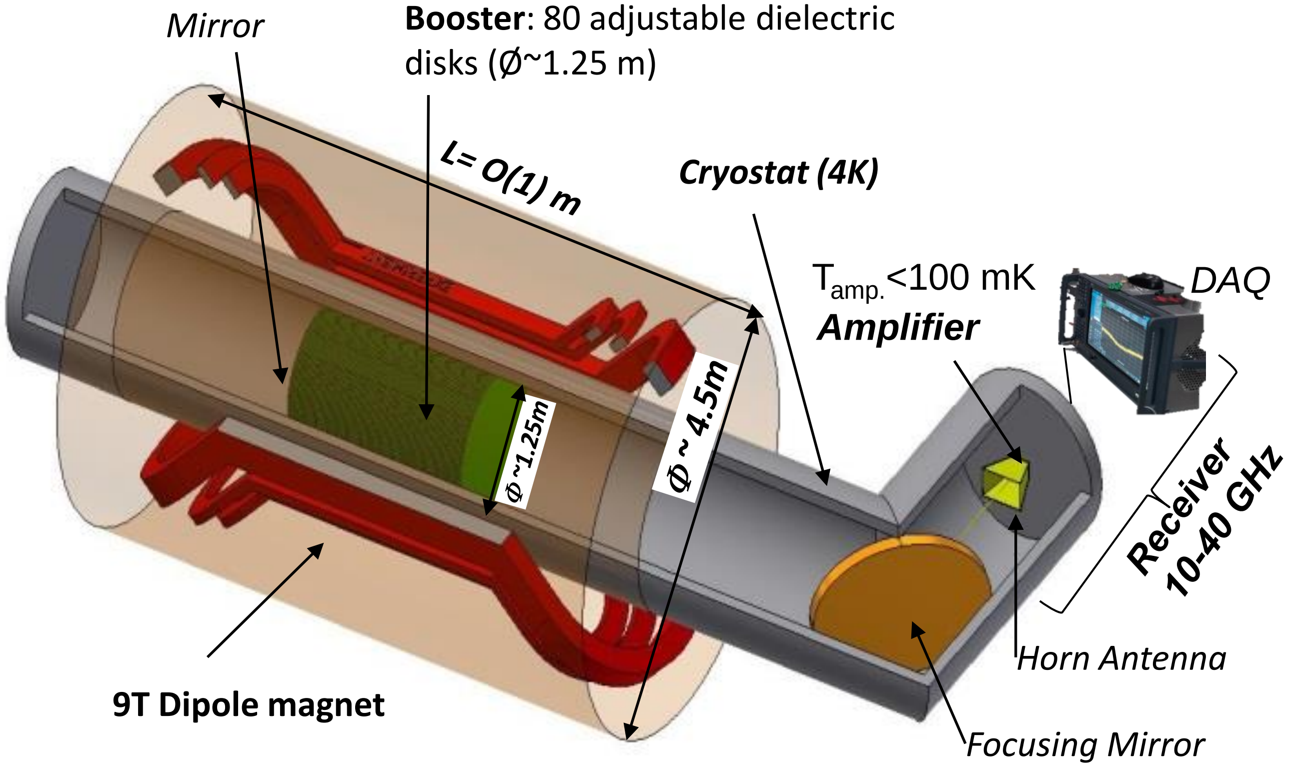
Dielectric haloscope: very promising technology to search for QCD axions

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



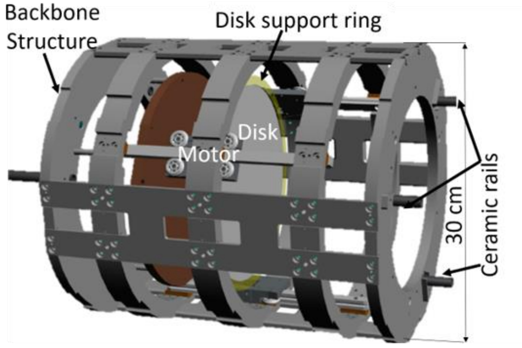
[Eur. Phys. J. C **79** (2019) 186]

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

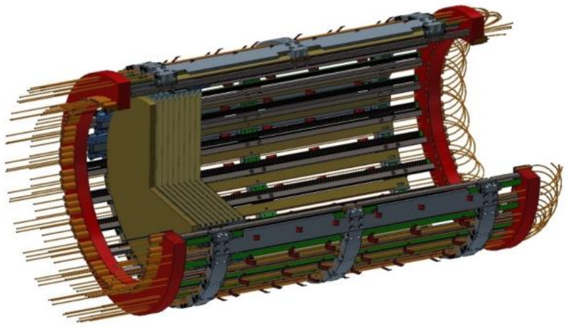
MADMAX prototypes

★ Indicates my contributions

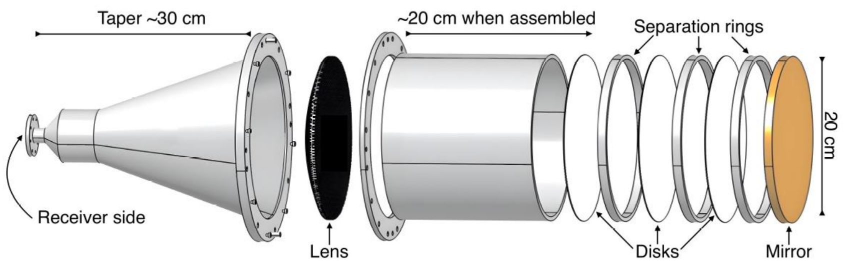
- **Goal: validate the new concept of dielectric haloscope**



Open booster OB200



Open booster OB300



Closed booster with 200 mm disks (CB200)

Name	Setup	Temperature	B T	Site	My work
OB200	1 moveable disk	Warm	0, 1.6	CERN	Mechanical feasibility of disk movement
OB300v1	3 fixed disks	Warm	0	DESY	3D Booster simulation
CB200	3 fixed disks	Warm	1.6	CERN	Data analysis, first dark photon search

Worked on main challenges: Disk movement (tuning), booster simulations (β^2), and statistical analysis

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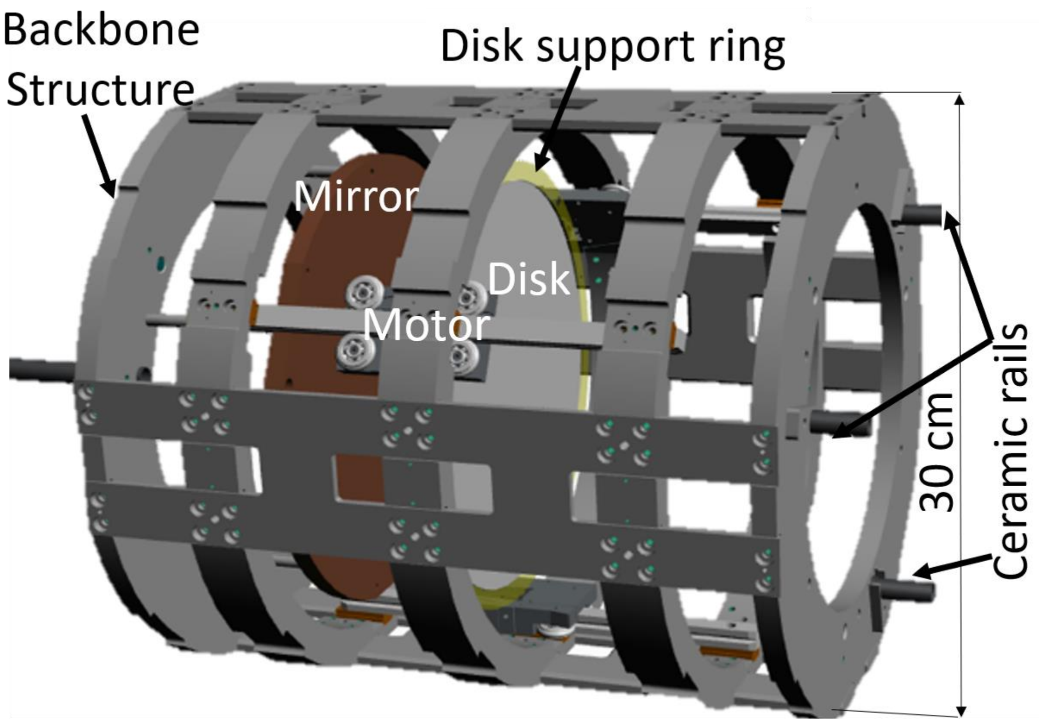
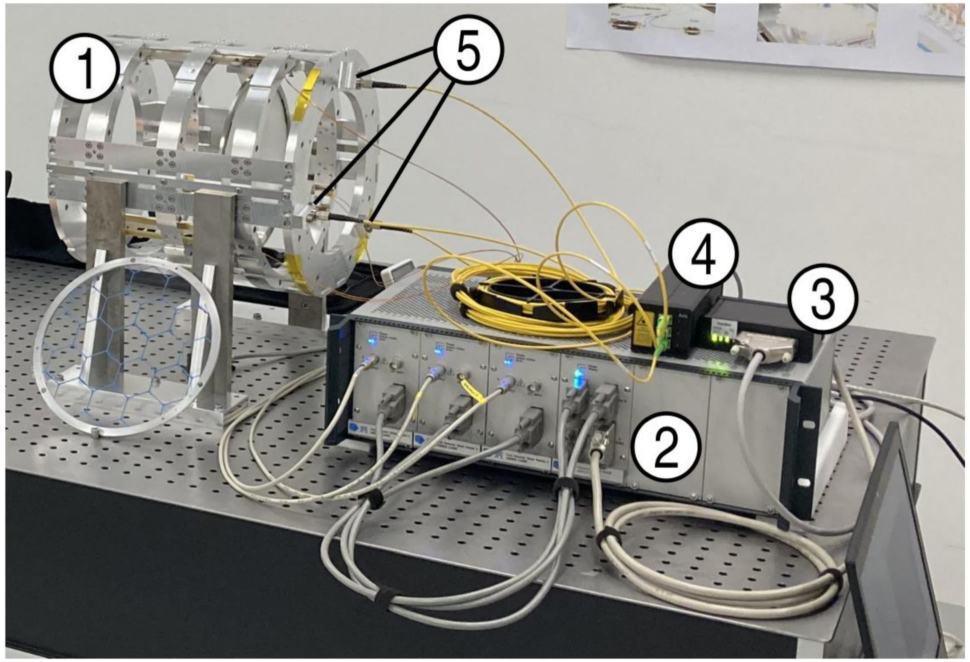
Tuning a haloscope

- **MADMAX requirement for the disk positioning system**
  - Disk positioning accuracy better than **10 µm** (to preserve the boost factor at ~30% level)
  - Motor speed needs to be above **10 µm/s** (to change the disk configuration in O(2) hours)
  - Operation at **cryogenic temperatures** and under **strong magnetic field**

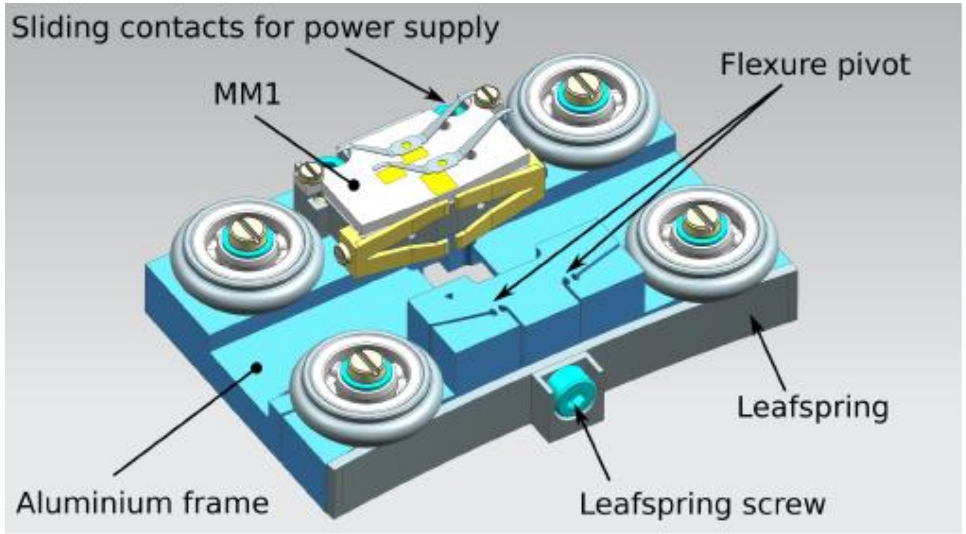


Disk positioning system

➢ **Test setup for the disk positioning system**



JINST, 18(08):P08011, 2023



1. OB200 prototype
2. motor controllers
3. FPGA board
4. Laser interferometer
5. Optical sensor heads

- 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

- Testing under 1.6 T magnetic field at CERN

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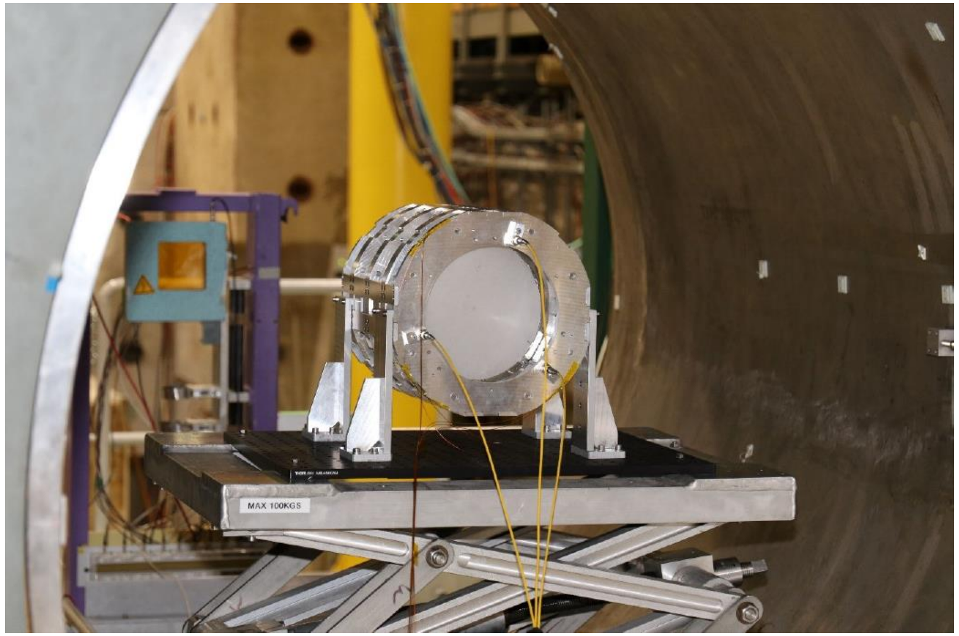

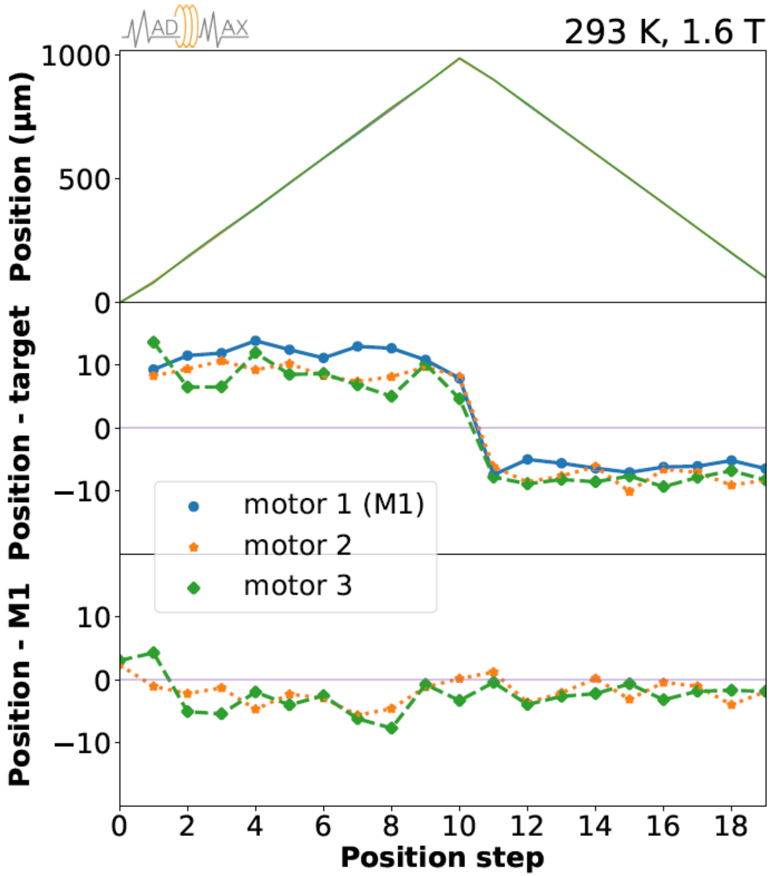

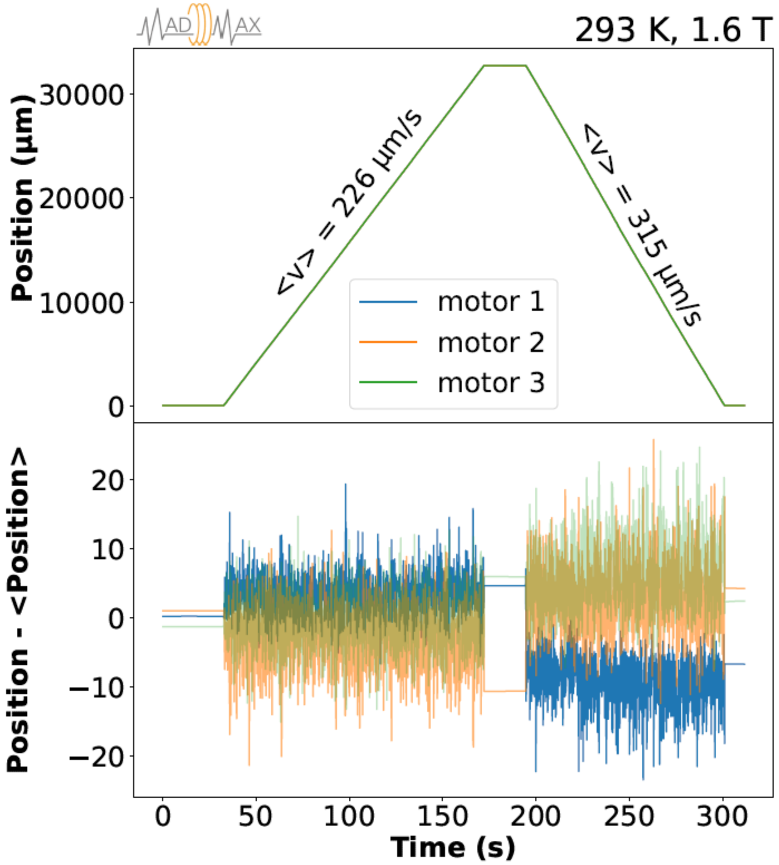

Positioning accuracy < 10 µm and speed 200 > µm/s

Disk positioning system: Tests

- Testing at cryogenic temperatures at CERN

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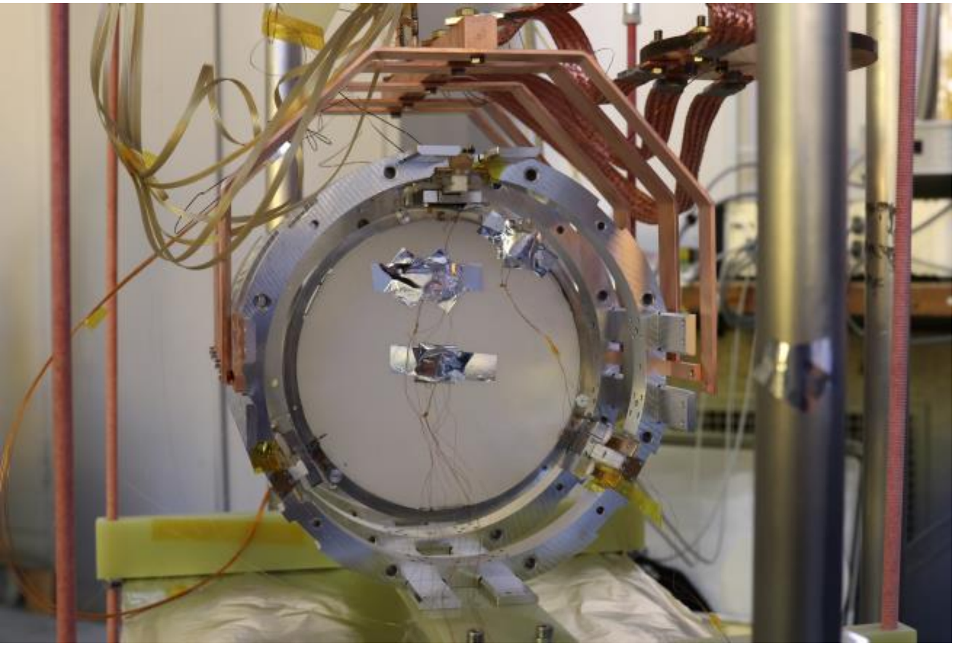

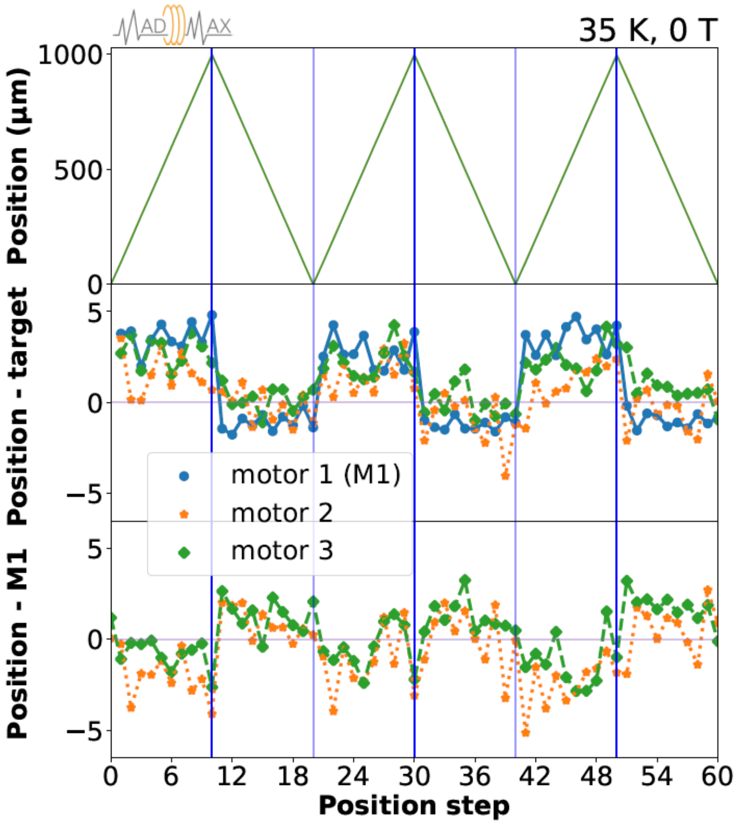

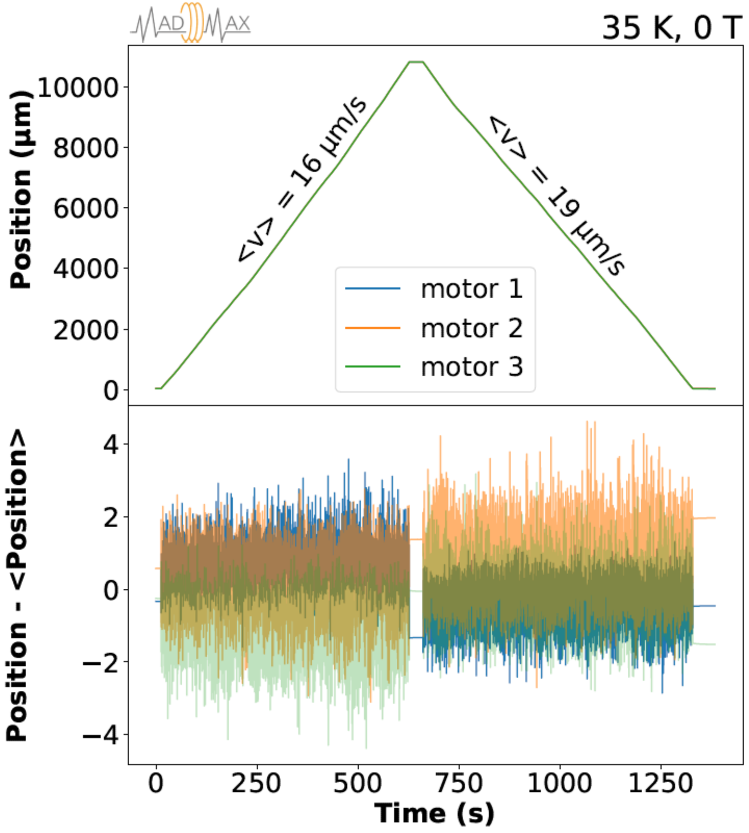

Positioning accuracy < 5 μm and speed > 15 μm/s

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- **Booster simulations**
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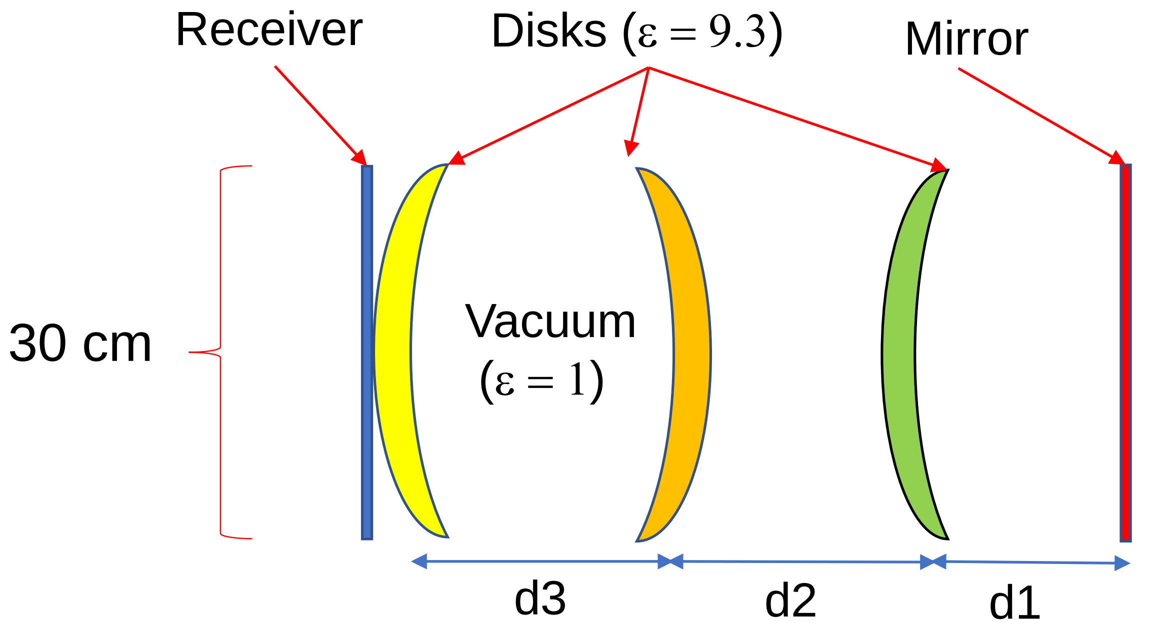
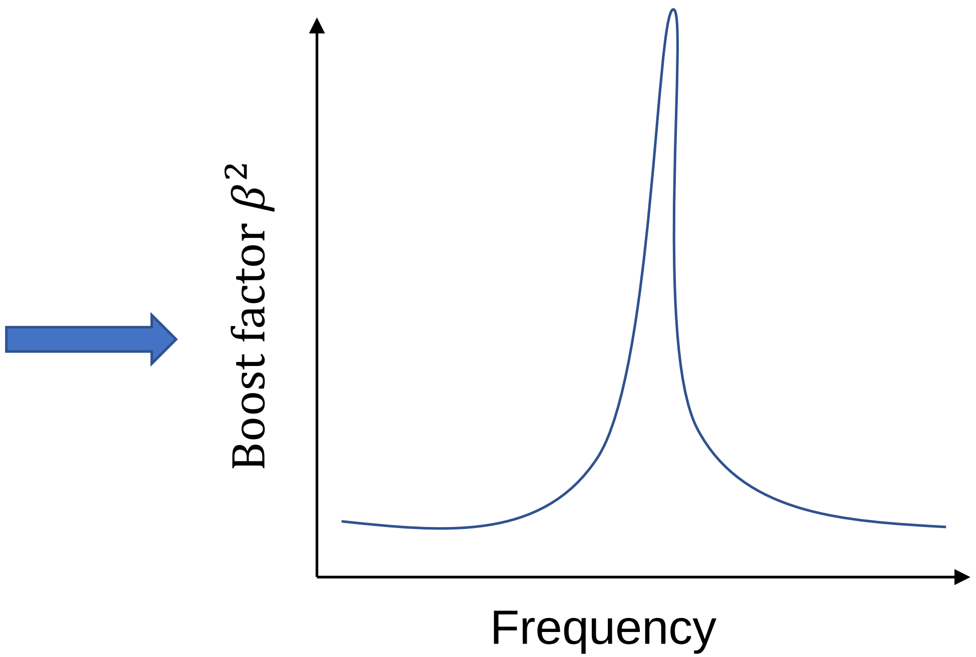
3D Simulation

- **Software from MADMAX collaboration based on axion electrodynamics (*JCAP* 08 (2019) 026)**
- **Prepare for a 3 disk system (OB300v1)**



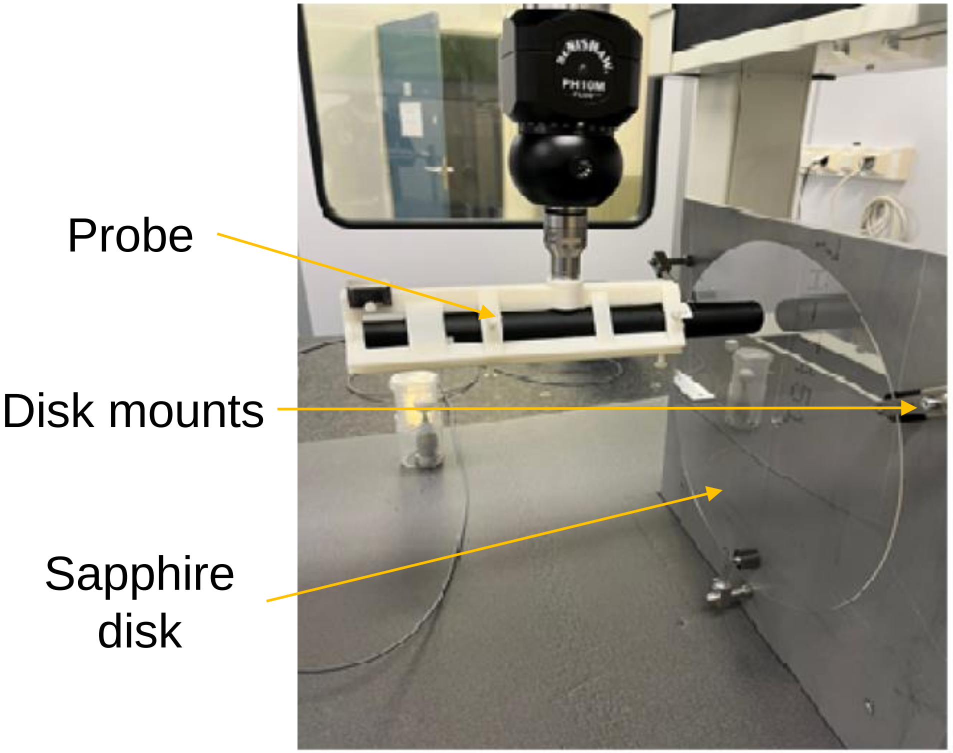
Booster geometry

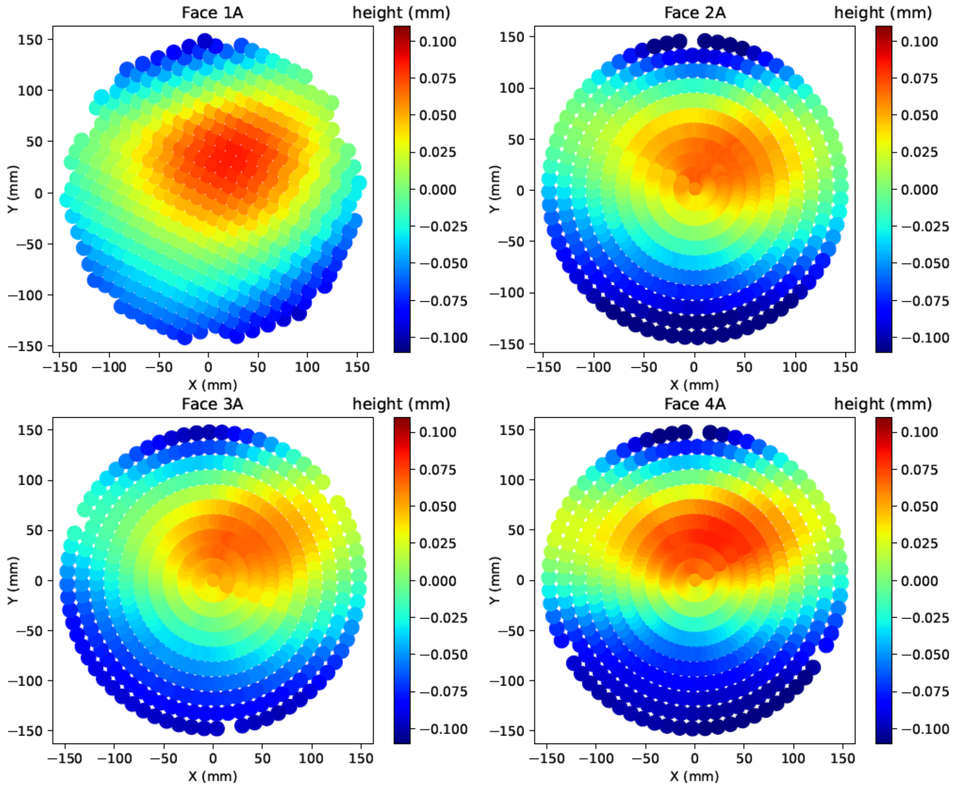


My work: 1) include disk planarity in 3D simulation and 2) compare with data

Disk planarity measurements (1/3)

- **Four disks measured at CPPM**
  - 30 cm diameter and 1 mm thickness
  - Disks manufactured from slicing single sapphire crystals

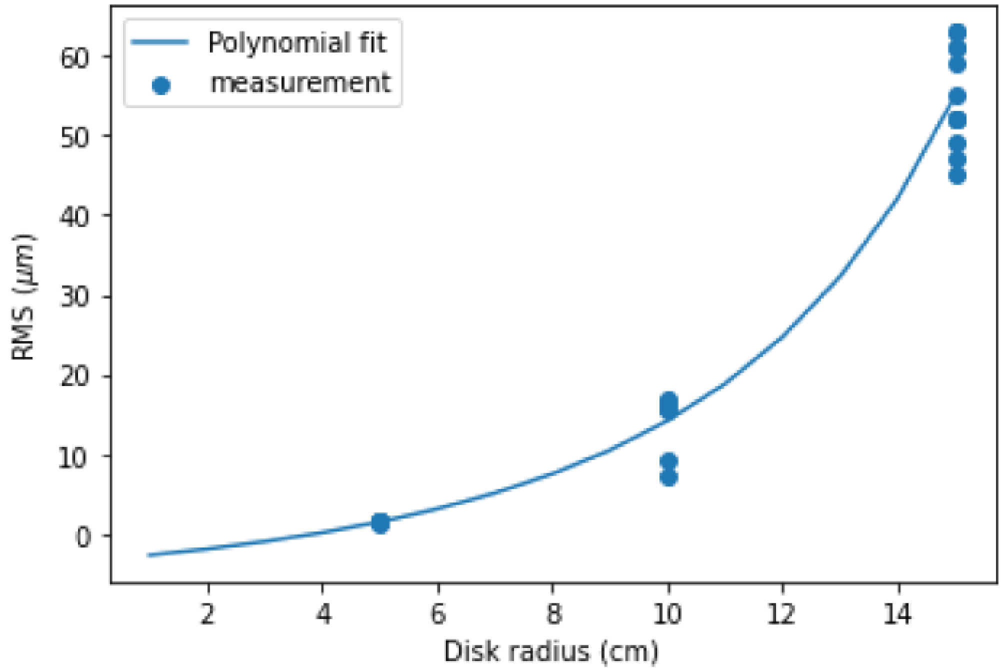


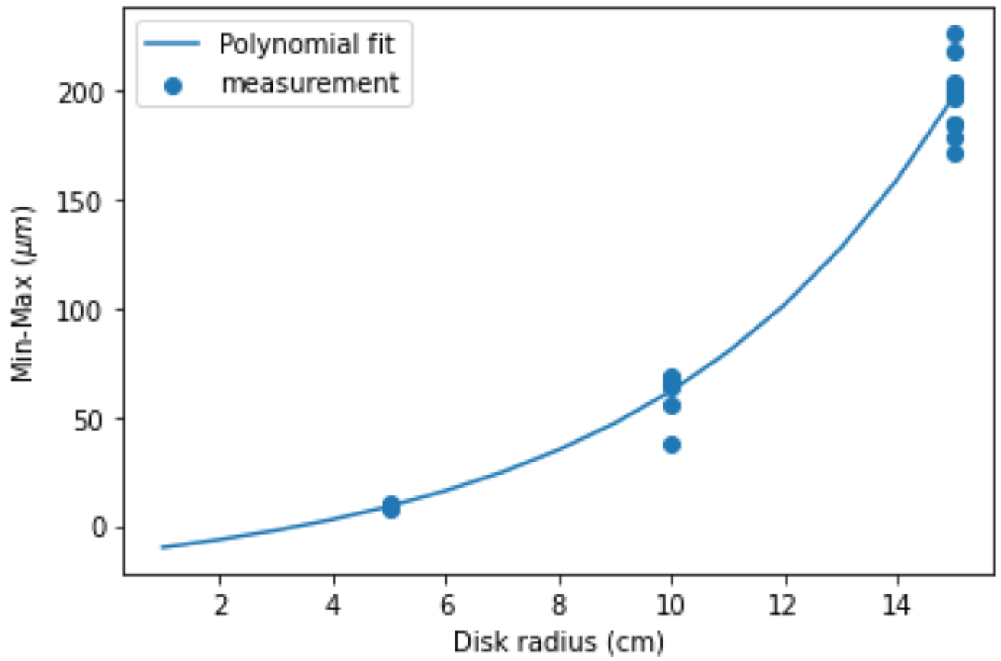


All the 30 cm disks have a bowl shape with ~ 50 μm RMS planarity deviation

Disk planarity measurements (2/3)

- Total 26 disk faces measurements: 10, 20, and 30 cm diameter disks
- Non-planarity increases significantly with disk radius

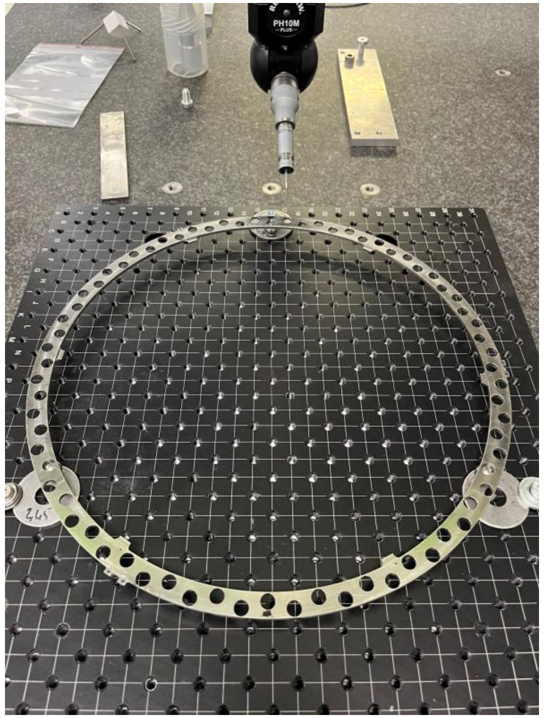


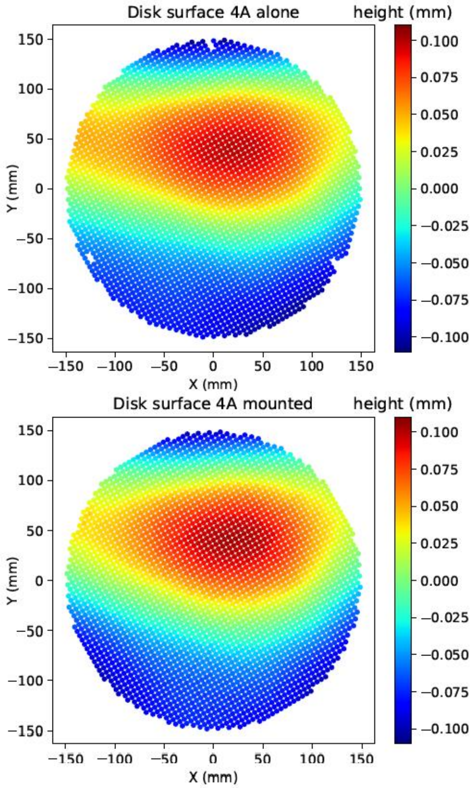


Need to find new solutions for bigger disks

Disk planarity measurements (3/3)

➢ **4 disk rings manufactured at CPPM**
- Check the impact of the ring on disk planarity





30 cm disks

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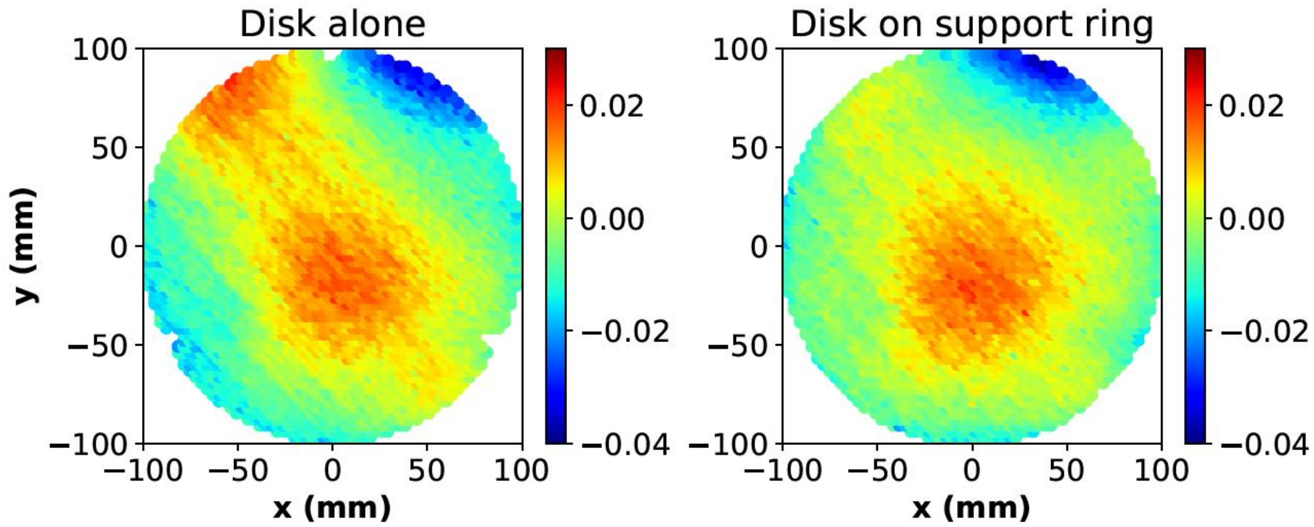
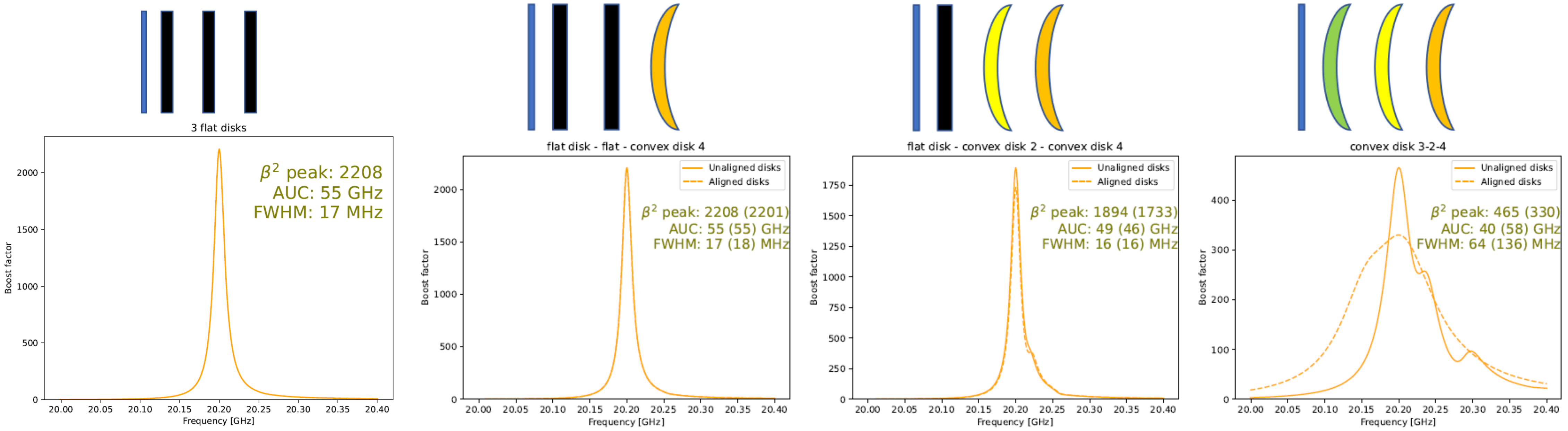


20 cm disks

The disk rings have low impact on the disk shape and the disk planarity

Boost factor simulation (1/4)

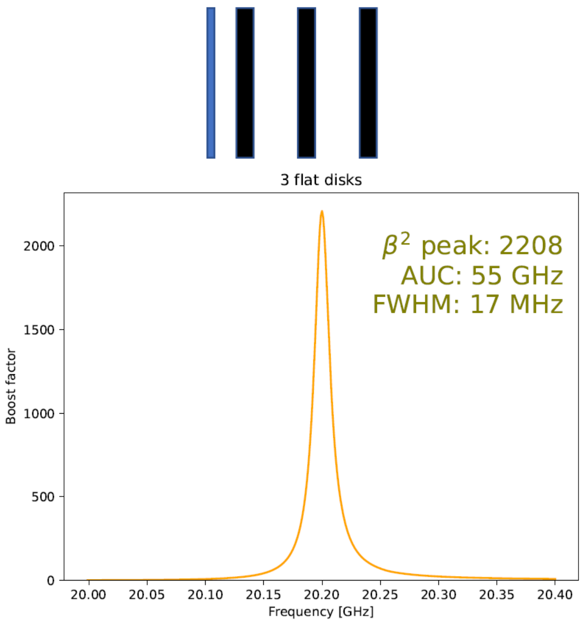
- **Simulation of a resonant narrow band configuration at 20 GHz**
  - Simulations with disks shapes aligned vs unaligned
  - Performance criteria: β^2 peak, area under curve (AUC), and full width at half maximum (FWHM)

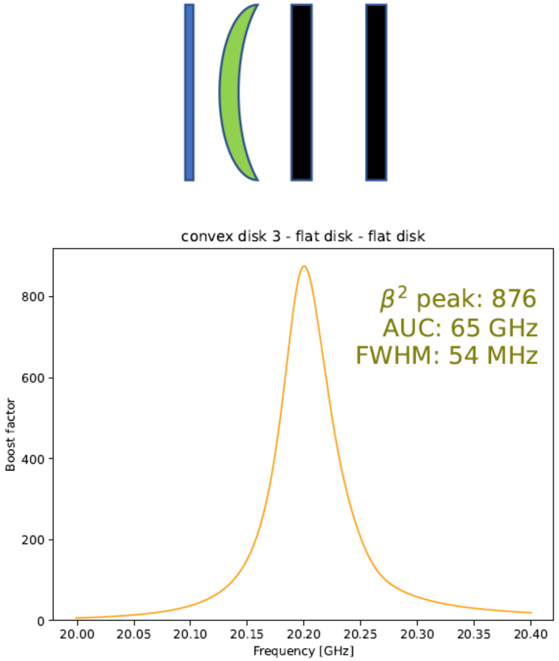


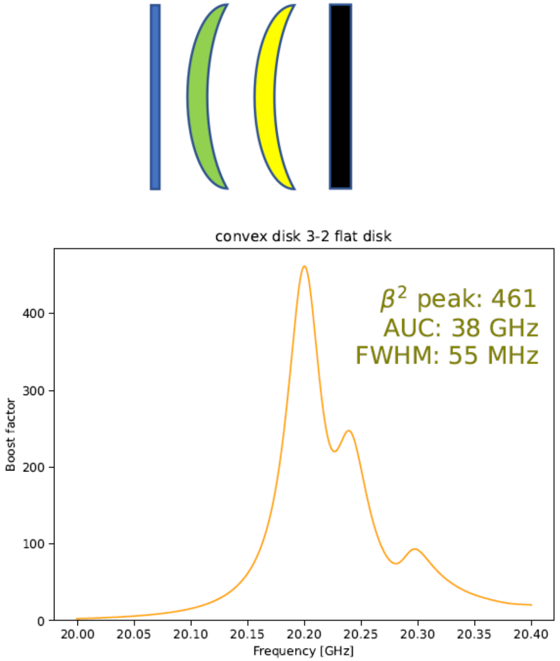
Disks with bowl shape degrade the boost factor by up to ~80%

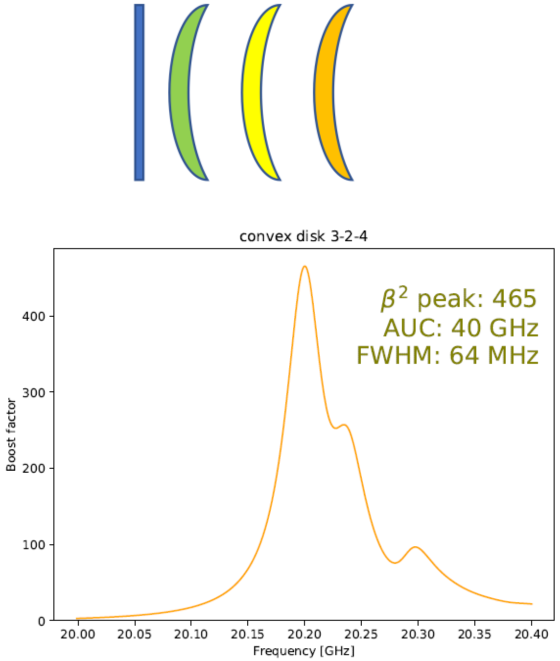
Boost factor simulation (2/4)

- **Simulation of a resonant configuration at 20 GHz**
  - Gradually adding non-planar disks in the booster





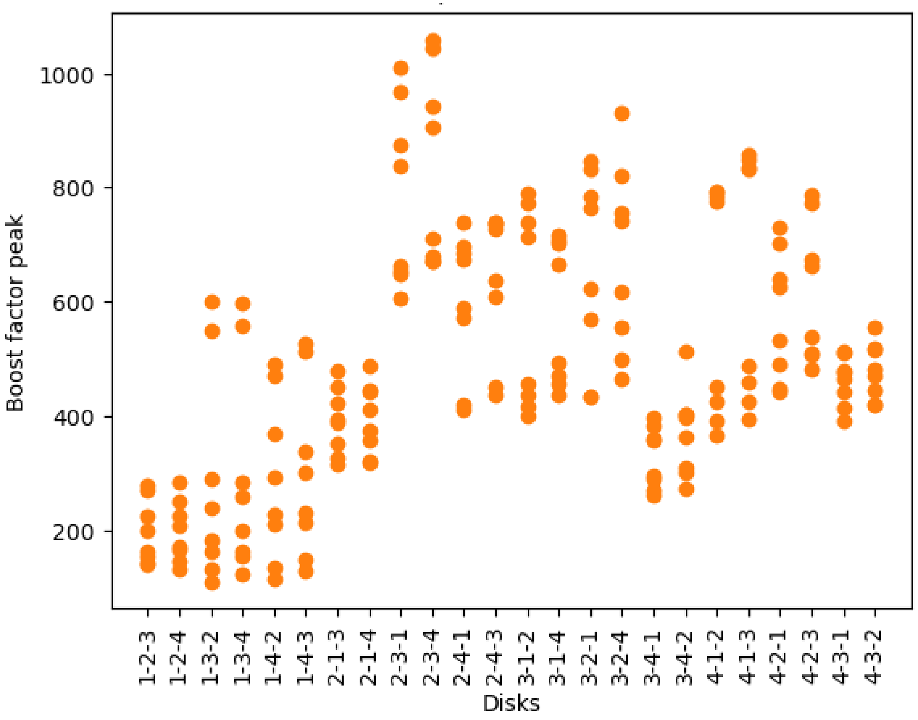


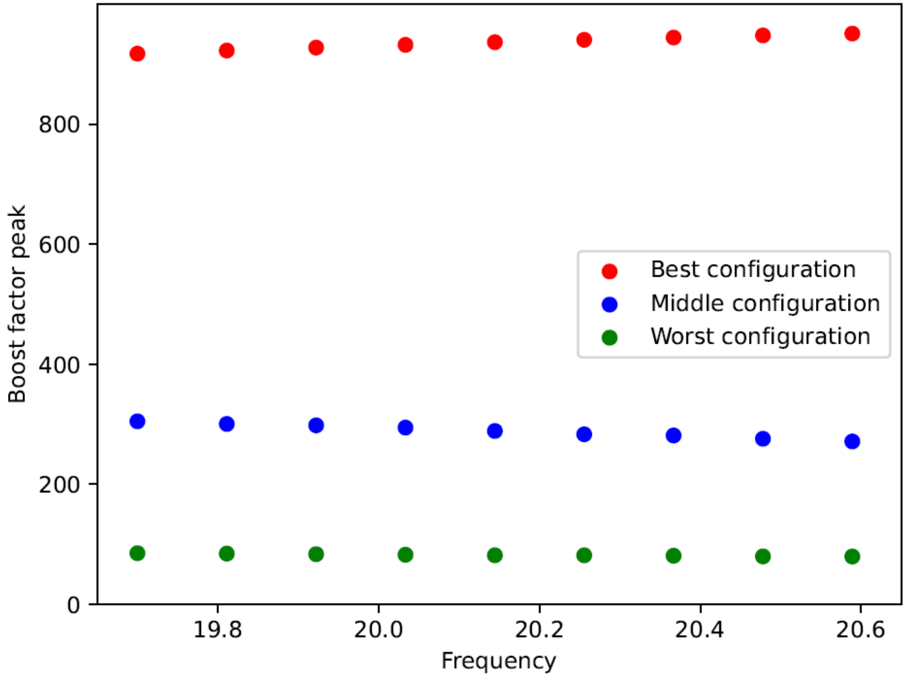


Disks closer to the mirror have more impact on the booster performance

Boost factor simulation (3/4)

- **Narrow band optimization of all possible disk configurations at 20 GHz**
  - 196 possibilities of disk ordering (24) and disk orientations (8)

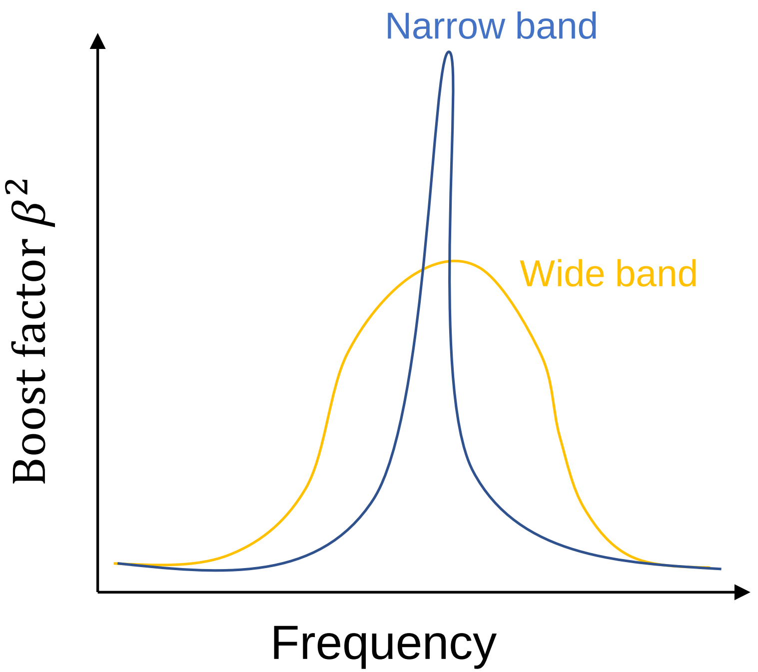


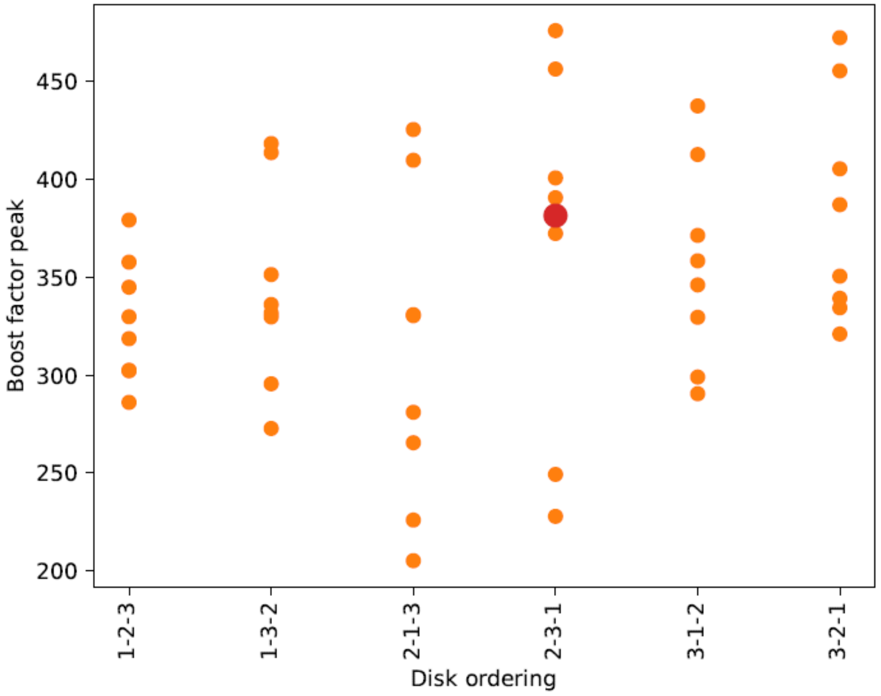


Optimizing and evaluating all possible booster configurations using simulations

Boost factor simulation (4/4)

- **Wide band optimization for dark photon search**
  - 48 possibilities of disk ordering (6) and disk orientations (8)
  - 2-3-1 Concave-Concave-Concave disk configuration (shown in red) used for the DPDM search

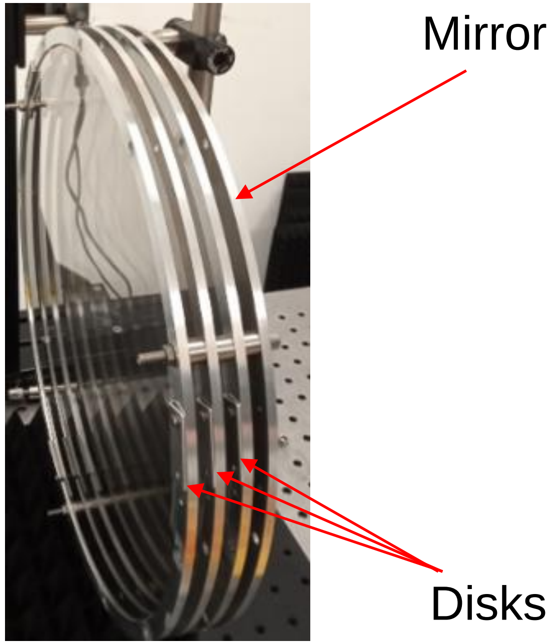




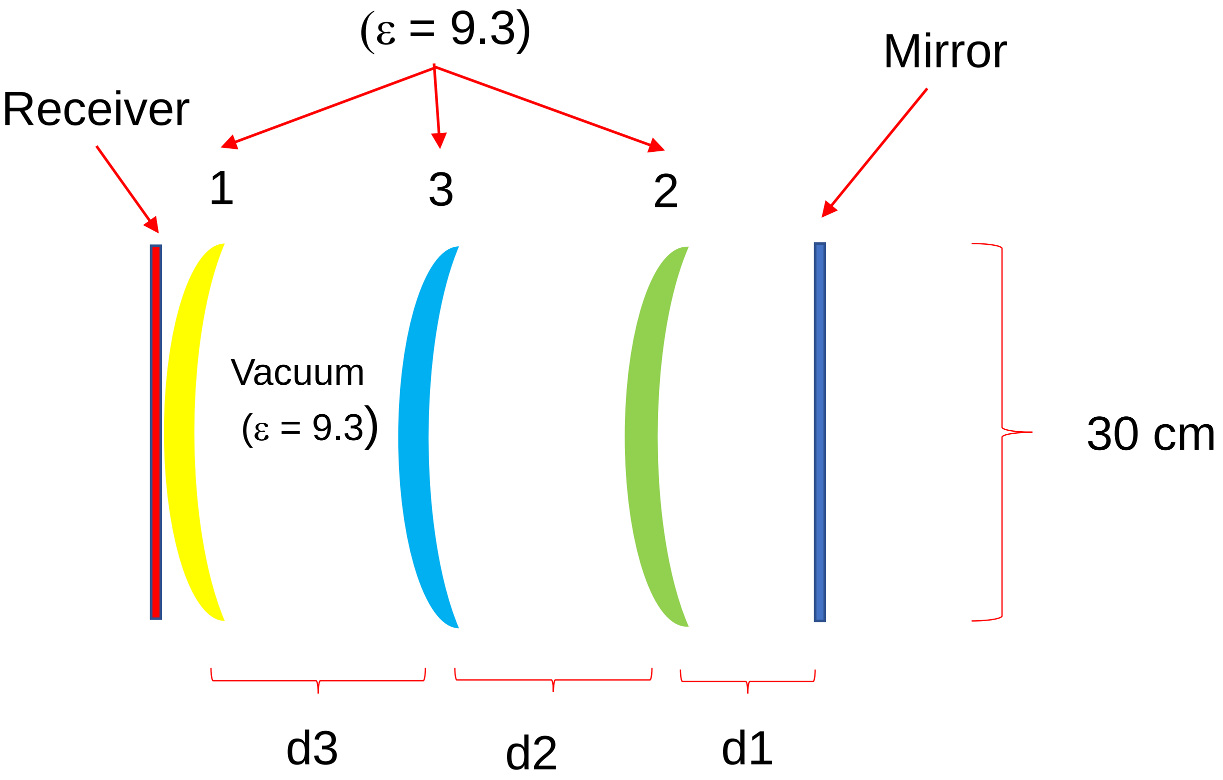
Choosing the booster configuration facilitated by simulations

Boost factor simulation vs data (1/2)

- **Simulating a laboratory setup**
  - A booster with fixed 3 disks of 30 cm diameter
  - Disks 2-3-1 in concave-concave-concave configuration
  - Distances chosen for a wide band search of dark matter

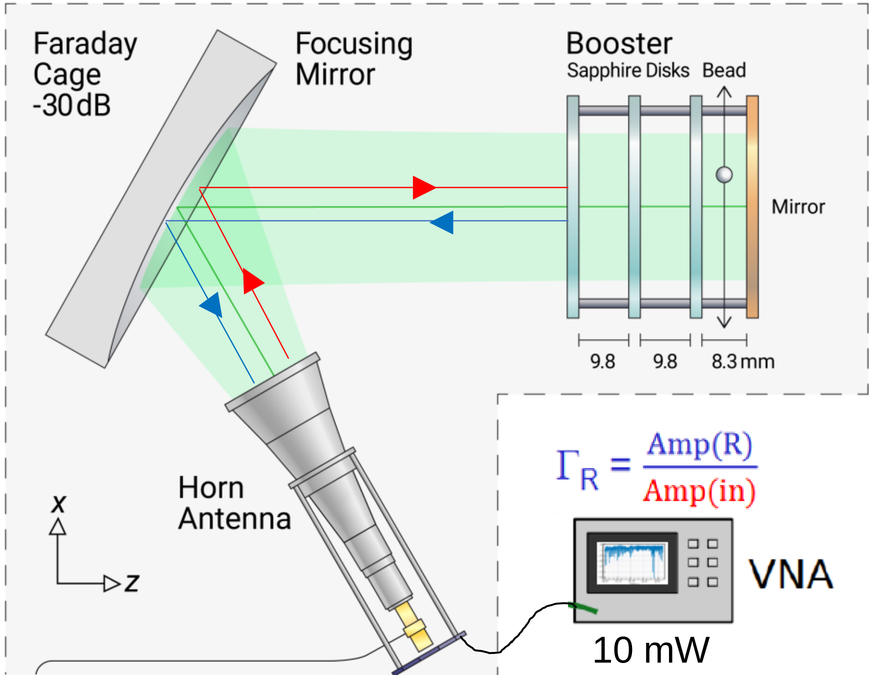


Booster



Boost factor measurement (1/2)

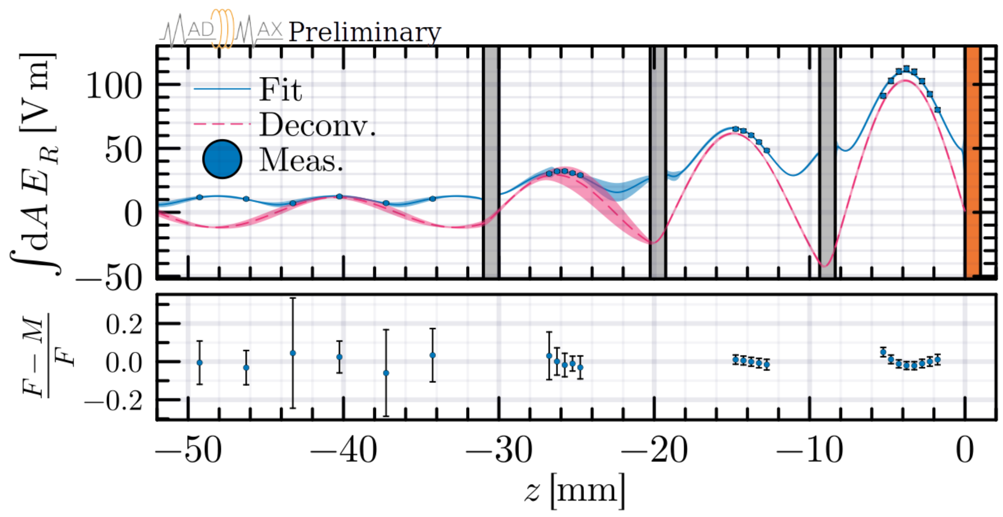
- **Bead pull measurement method**
  1. Reflectivity (Γ_R) measurements with and without a small dielectric bead placed at different positions to make a 3D scan inside the booster
  2. Calculate the electric field $E_R \propto \sqrt{\Delta\Gamma_R}$



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

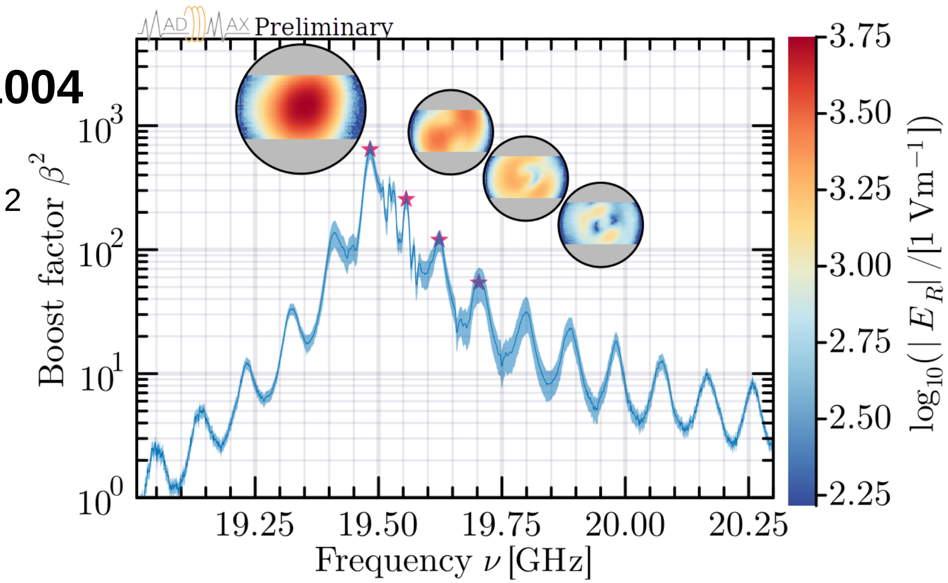
Boost factor measurement (2/2)

- **Bead pull measurement method**
  3. Fit the electric field measurements to a 1D booster model ➔ extract effective booster parameters
  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 (reciprocity theorem)



PRL 134, 151004

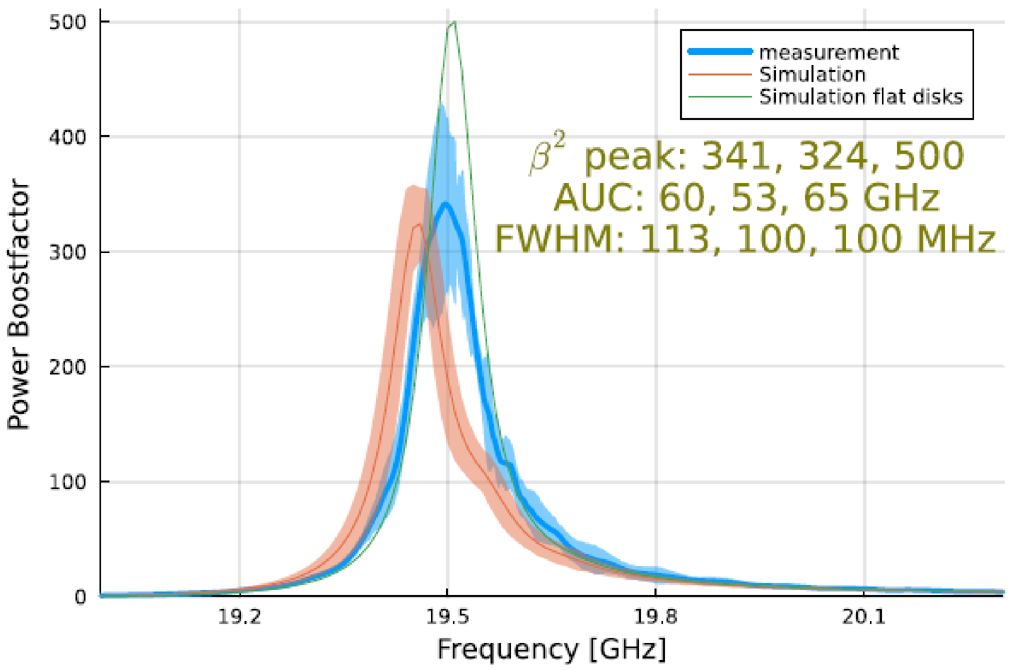
$\beta^2 \propto |\int dV\, E_R|^2$

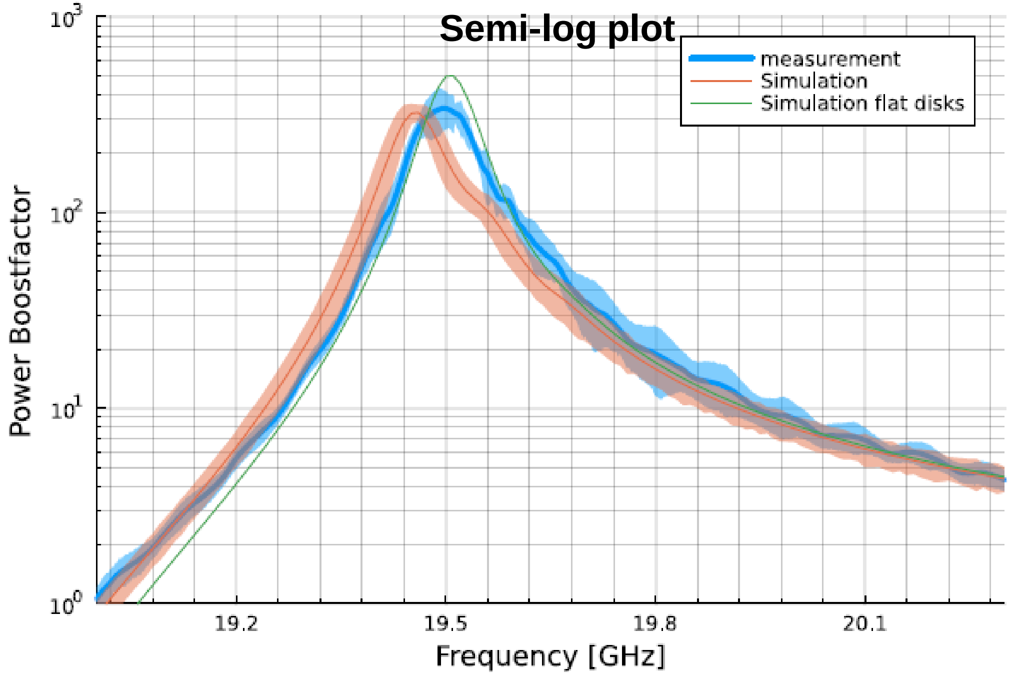


First direct in-situ measurement of boost factor

Boost factor simulation vs data (2/2)

- **First 3D simulation of open booster to take into account the disk planarity**
  - Simulation uncertainty obtained by varying all booster parameters
  - The measurement is smoothened using Savitzky Golay filter to remove antenna – booster resonances



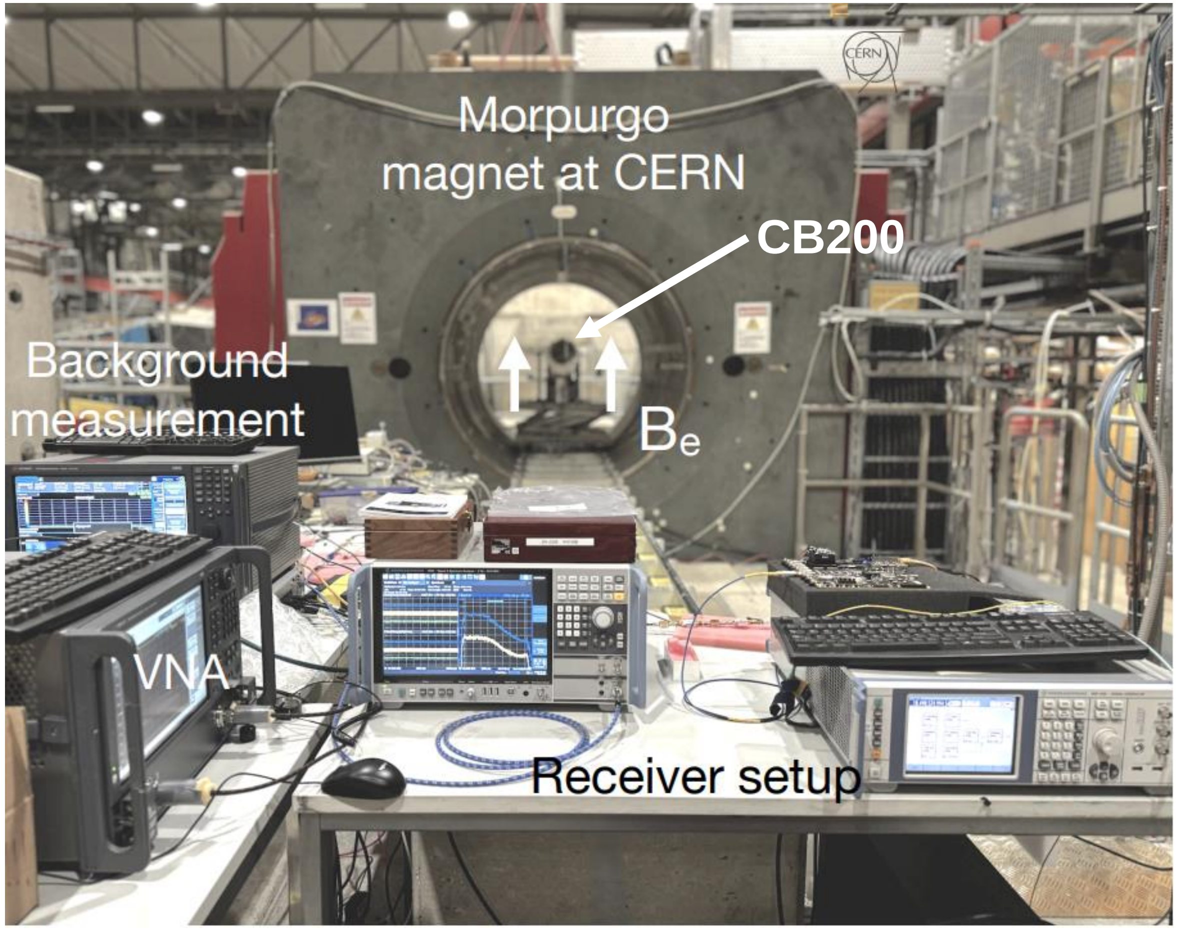


First data-simulation comparison of boost factor at MADMAX

OUTLINE

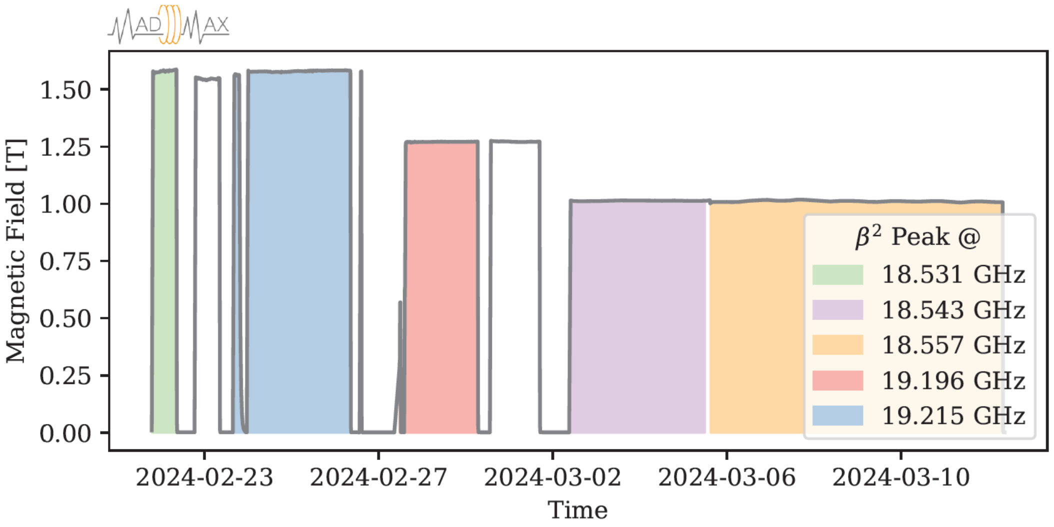
- Introduction to Axion dark matter
- The MADMAX Experiment
- R&D towards a tunable haloscope
- Booster simulations
- **First dark matter searches**
- Conclusions and perspectives

First ALPs search with MADMAX



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

PRL 135, 041001

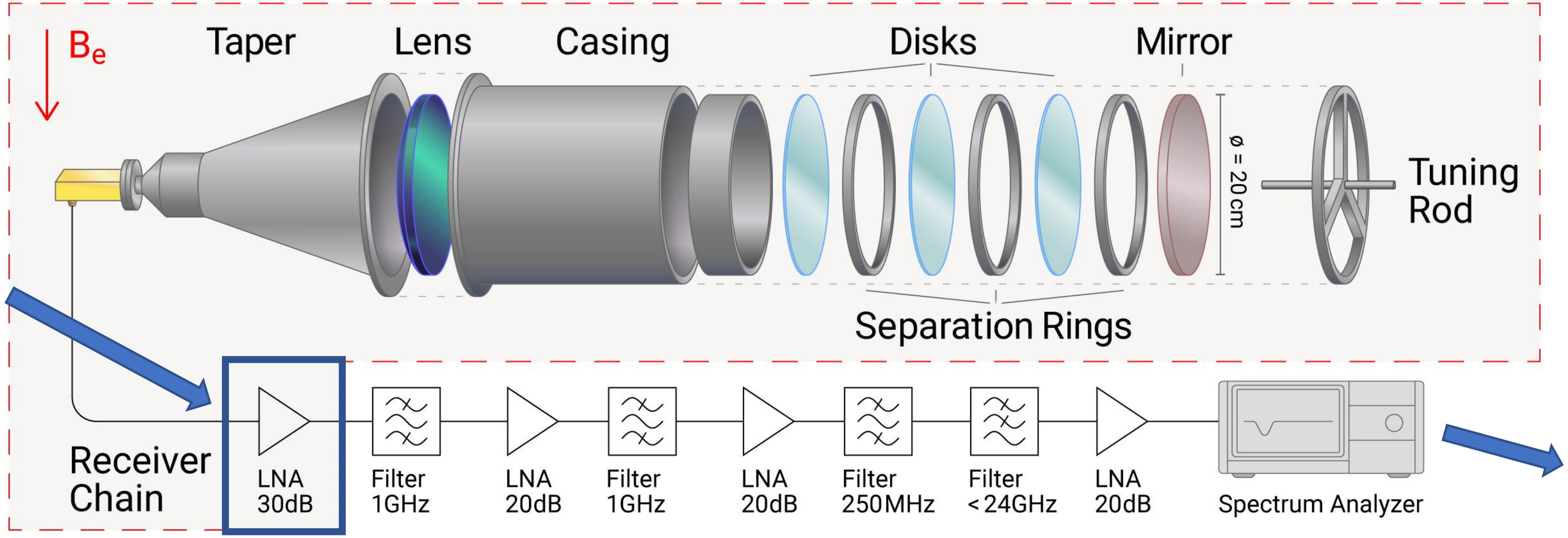


14.5 days of physics data at CERN with CB200 prototype

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 and 79 μeV axion search
  - Tuning rod can push the mirror ➔ O(10) μm push to change booster frequency by O(10) MHz

The most critical component In the receiver chain

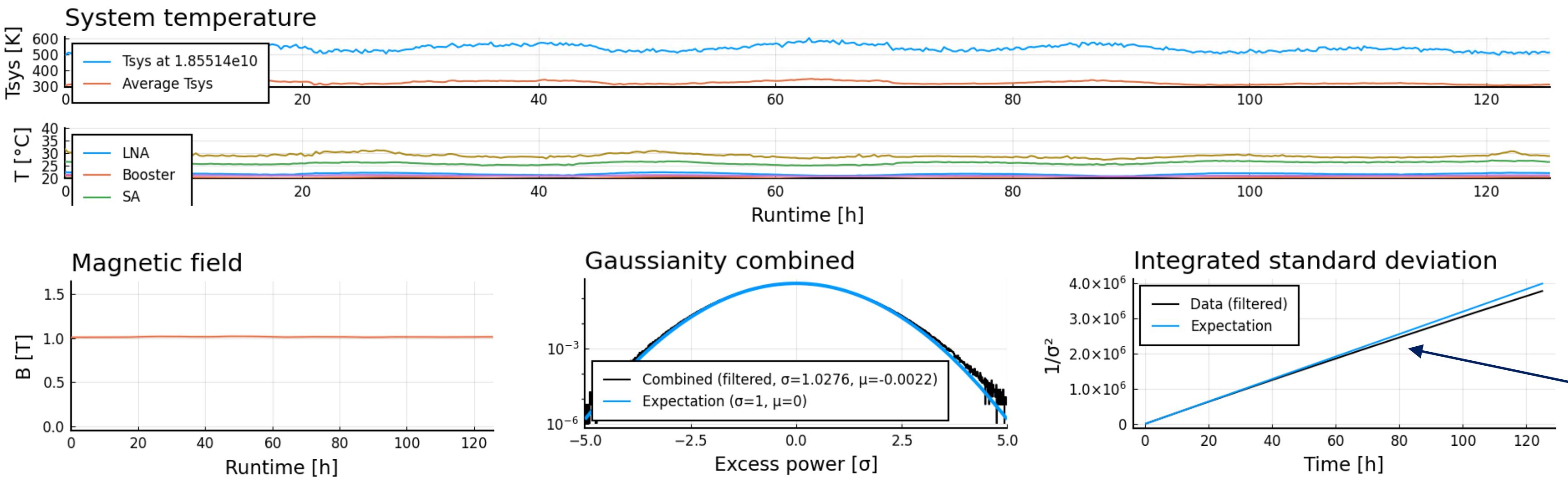


Data transformed through FFT ➔ produce a power spectrum

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

Data monitoring

- **Check online power spectrum and the noise behavior**
  - Performed shifts during the data taking period



Slow control data (Physical temperatures)

$$\tau = \frac{1}{B\sigma^2}$$

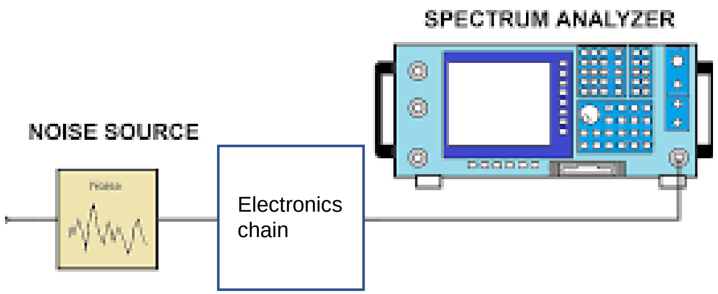
B = bandwidth (~1 kHz)

14.5 days worth of good quality data taken in Feb-March 2024 at CERN

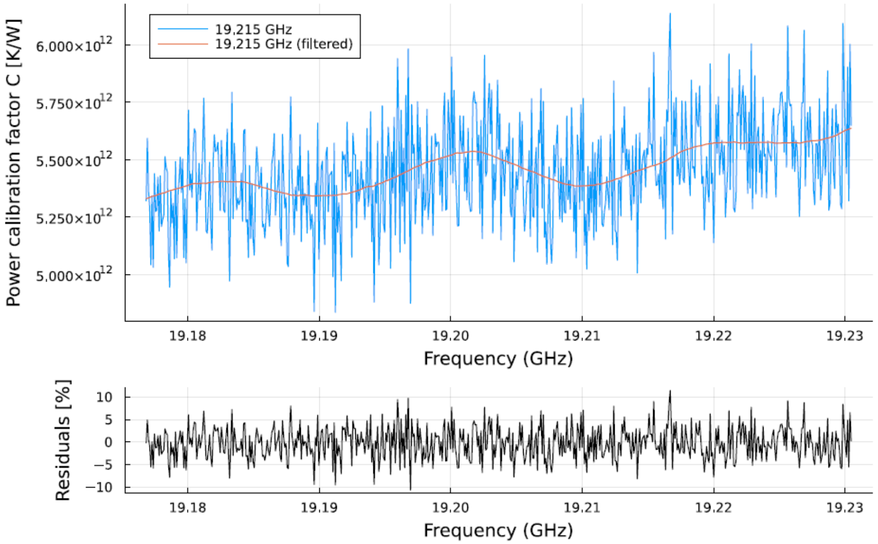
Power calibration

- **Raw power spectrum ➔ system temperature: $T_{sys} = P_{raw}\,C$**
  - C determined using well defined noise diodes (Y-factor method) ➔ $C = \Delta T/\Delta N\,(1-|\Gamma|^2)$
  - Filter noise component using Savitzky Golay filter

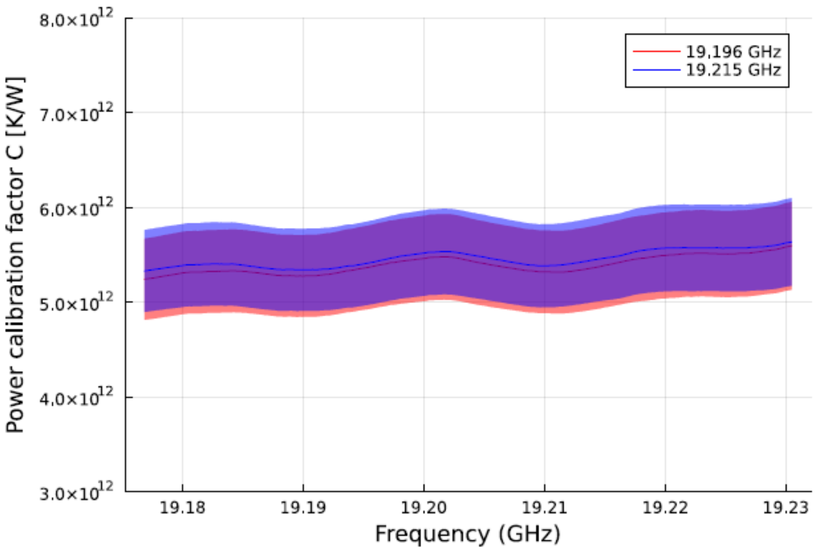
Calibrating with a noise source



Unfiltered calibration factor



Filtered calibration factor



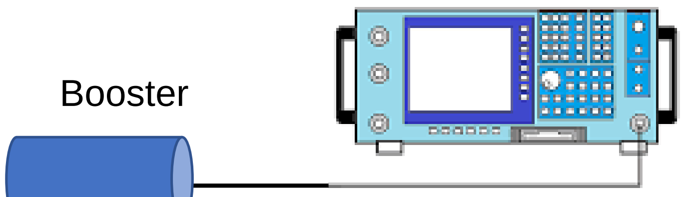
Calibration factors calculated at 10% uncertainty

Booster modelling

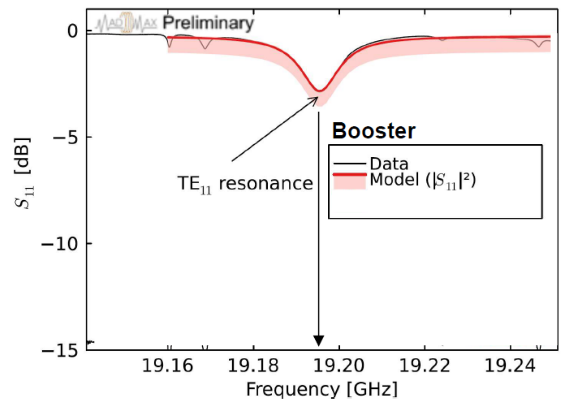
- **Based on reflection measurements using a Vector Network Analyzer (VNA)**
  - Effective 1D ADS model with 10 parameters fitted to Booster only, LNA only and Booster+LNA data

VNA

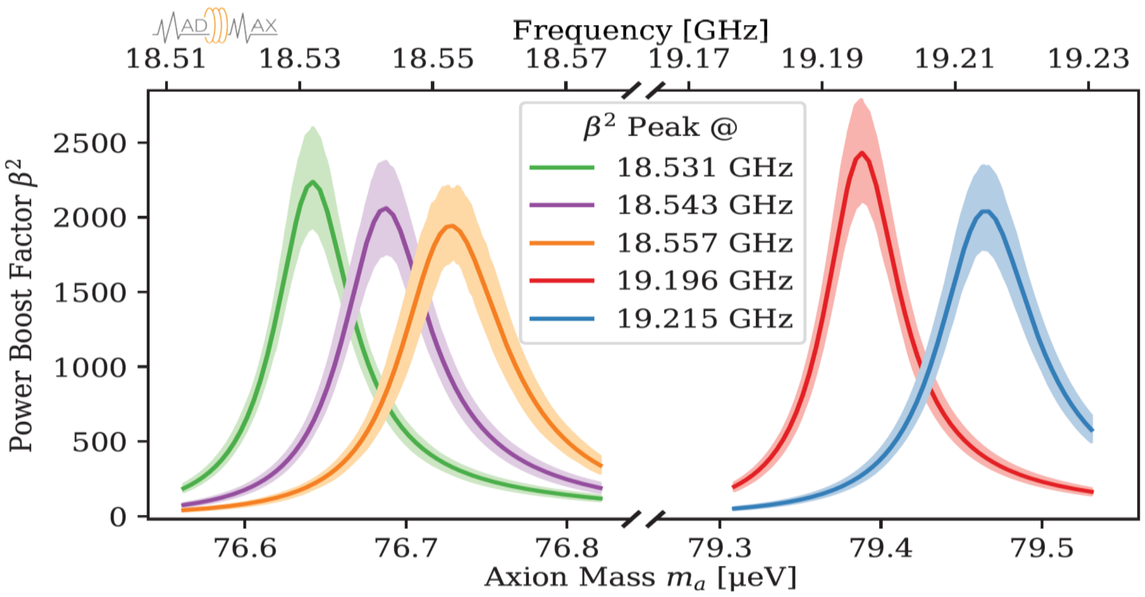
Booster



Fitting booster parameters to the measurement



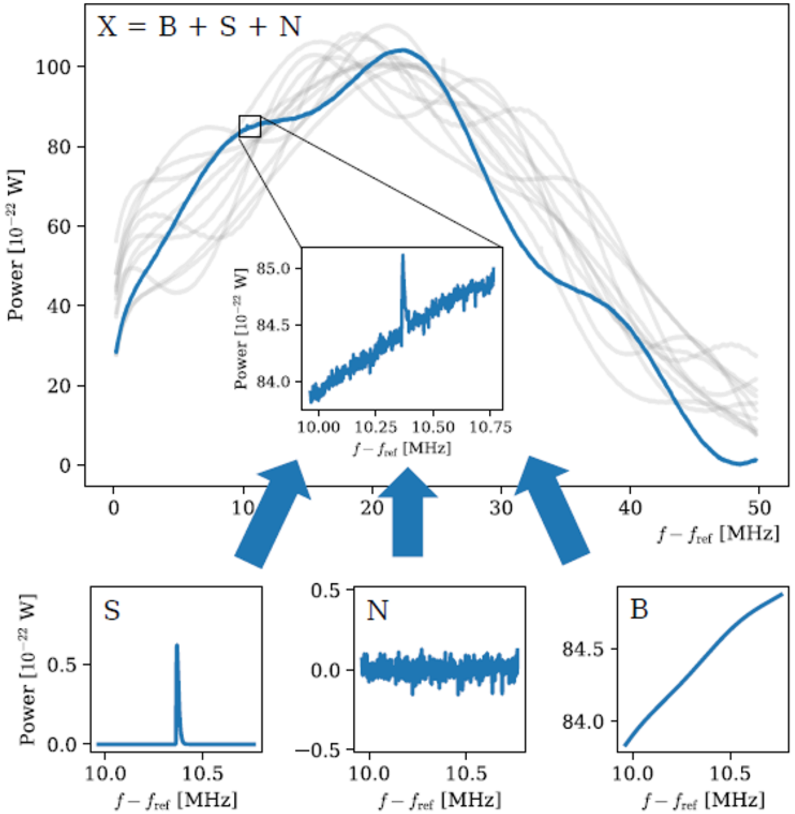
Using the booster parameters to simulate boost factor



β^2 calculated for all 5 data runs with ~ 15% uncertainty

Statistical analysis strategy

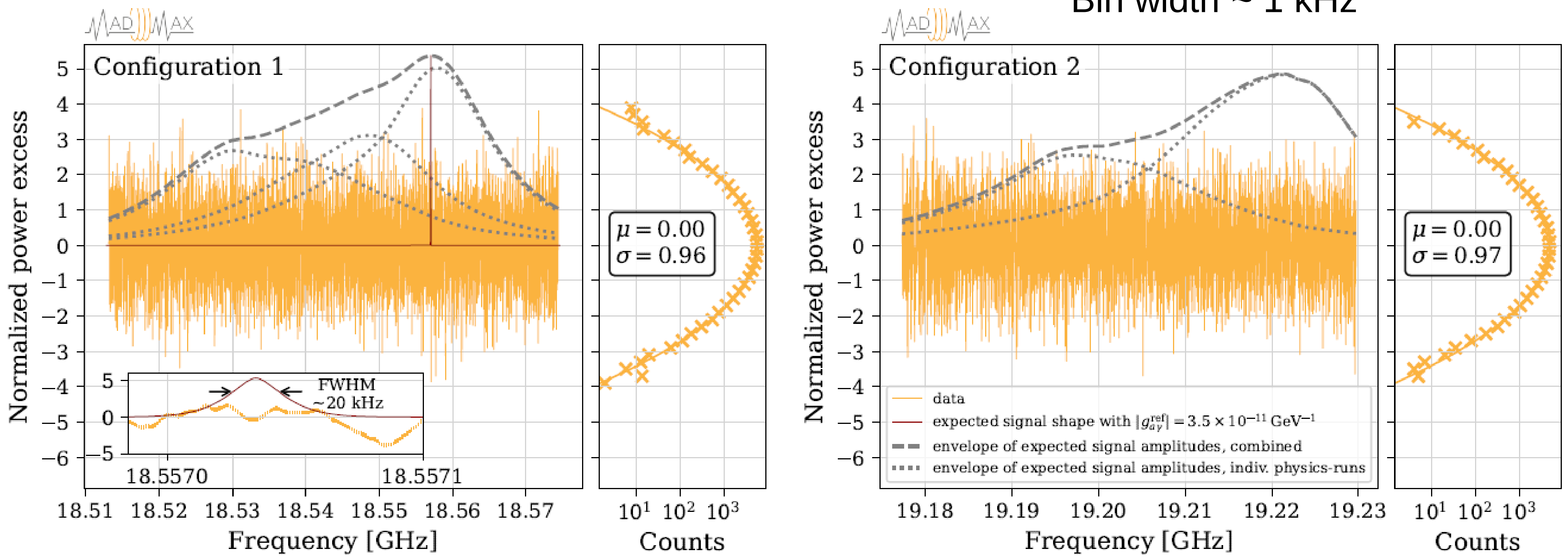
- **Search for axion signal in the data**
  1. Filter the baseline (**B**) using Savitzky Golay ➔ Residuals (hypothetical axion signal (**S**) + noise (**N**))
  2. Combine the individual raw spectra (different Bfield, time, β^2) to maximize the signal to noise ratio (SNR)
  3. Further gain by correlating adjacent bins according to axion line shape ➔ Grand Spectrum



Statistical analysis

- **Grand spectrum for two configurations**
  - Axion lineshape assumes standard halo model
  - Gaussian distribution of the normalized power excess
  - Analysis procedure applied to 130 000 bins

Bin width ~ 1 kHz

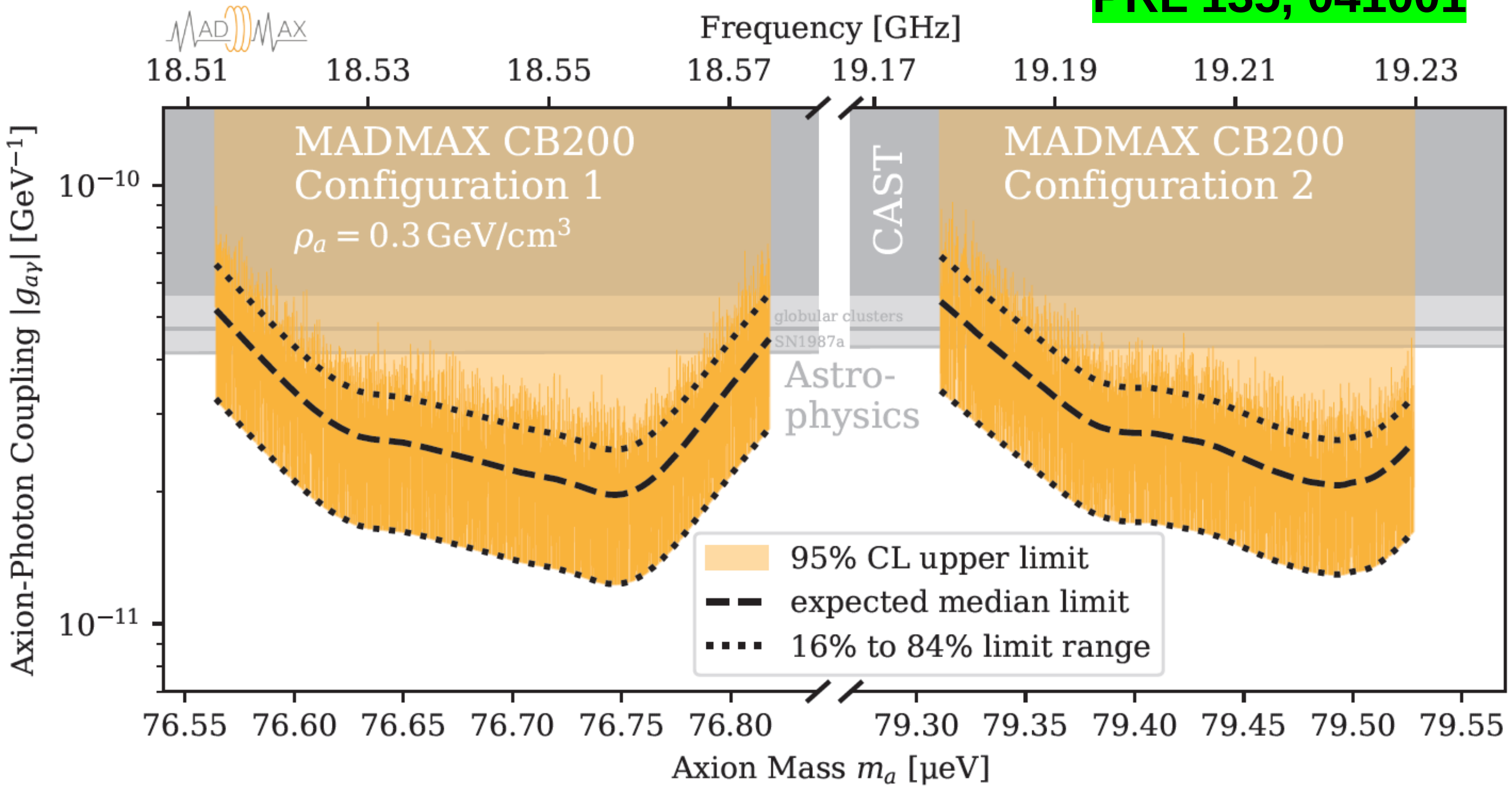


Max power excess at 4 σ → p value of 0.08 given 130 000 bins

Axion search

- **First axion dark matter exclusion limit in the world using dielectric haloscope**
  - Systematics at 5-10% level
  - 95% confidence level upper limit

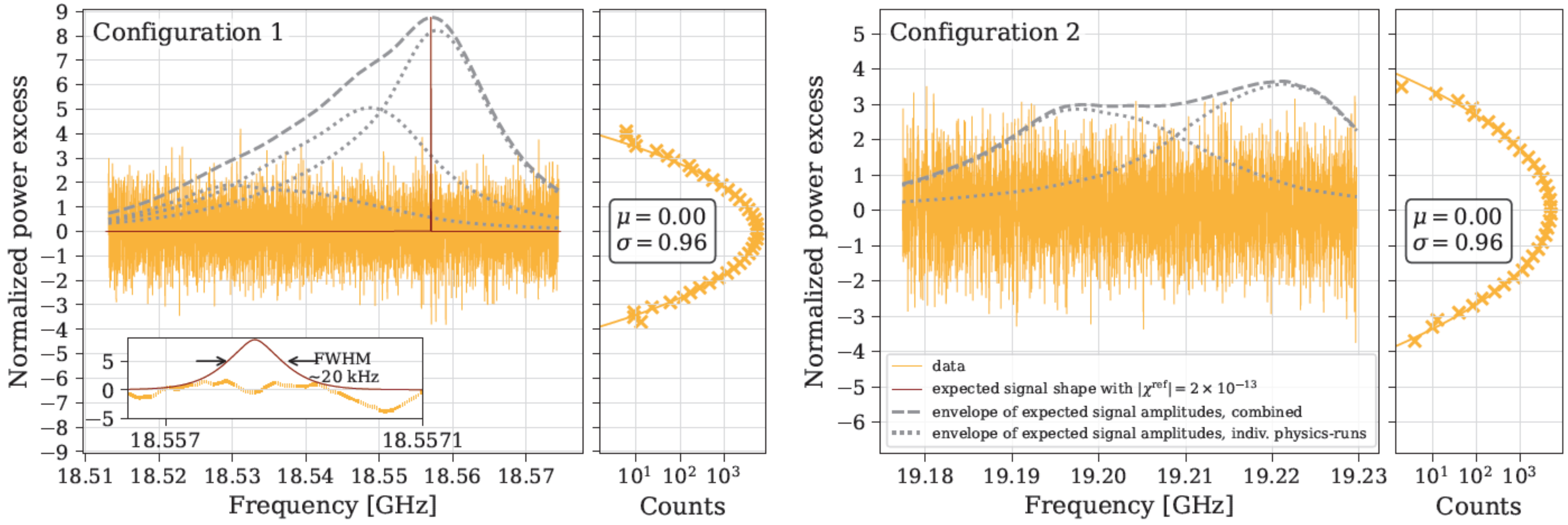
PRL 135, 041001



World best median limit down to 2×10^{-11} GeV^{-1} around 76 and 79 μeV

Dark Photon search (1/2)

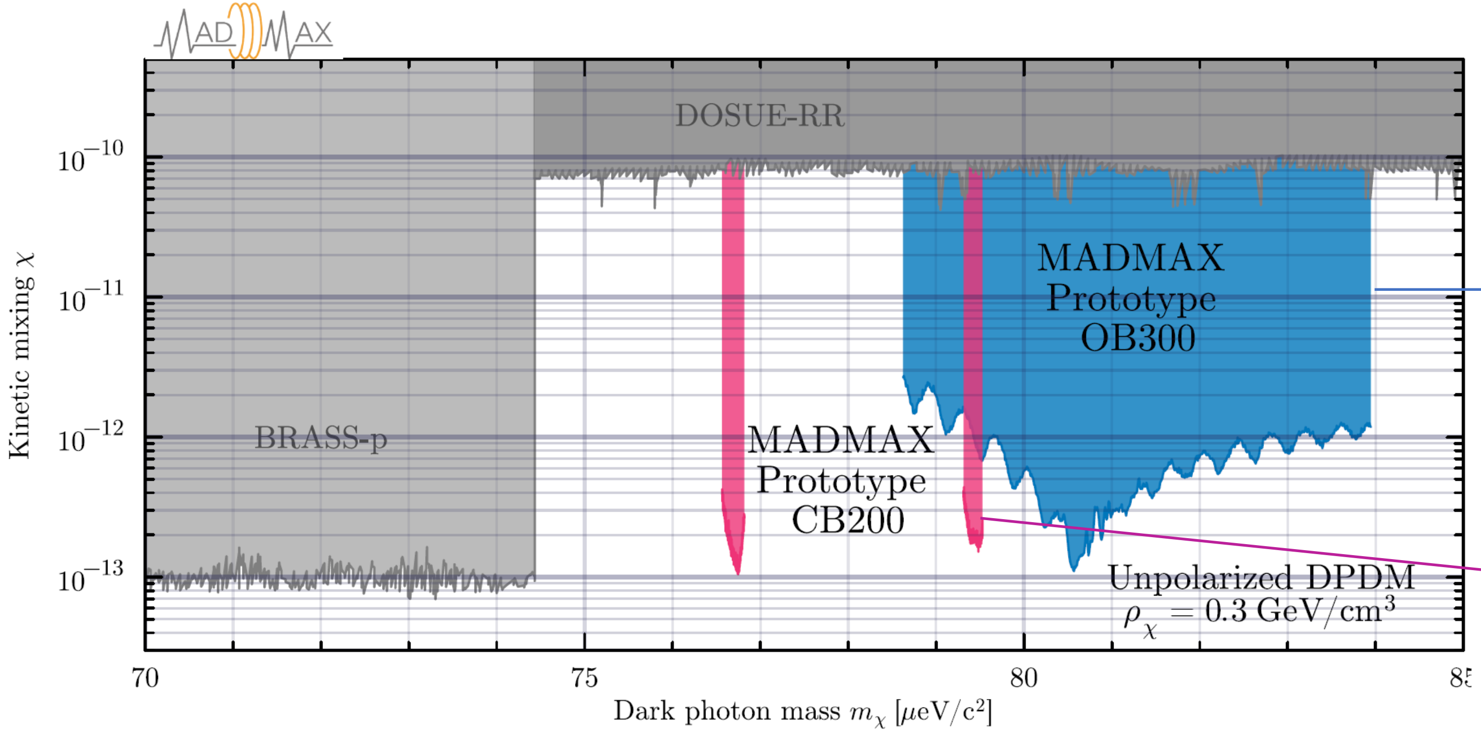
- **Dielectric haloscopes also allow to search for dark photons**
  - Interact with photons through kinetic mixing χ
  - The sensitivity is different compared to axions as the magnetic field has no impact on kinetic mixing
  - Random polarization of dark photons is considered ➔ statistical average computed for analysis



Dark photon search performed with the same data used for axion search

Dark Photon search (2/2)

- **First dark photon dark matter searches**
  - Presented first at Vietnam 2025 conference



First dark photon search at MADMAX

My work

- World best 95% CL limit on DP kinetic mixing χ in m_χ (76.56 to 76.82, 79.31 to 79.53) µeV
- Improving upon previous limits by almost 3 orders of magnitude

OUTLINE

Introduction to Axion dark matter

The MADMAX Experiment

R&D towards a tunable haloscope

Booster simulations

First dark matter searches

Conclusions and perspectives

Conclusions

- Axions are motivated dark matter candidates that also solve the strong CP problem of the standard model

- Post-inflationary models predict axion mass > 25 μeV
  - MADMAX: novel dielectric haloscope experiment for dark matter search

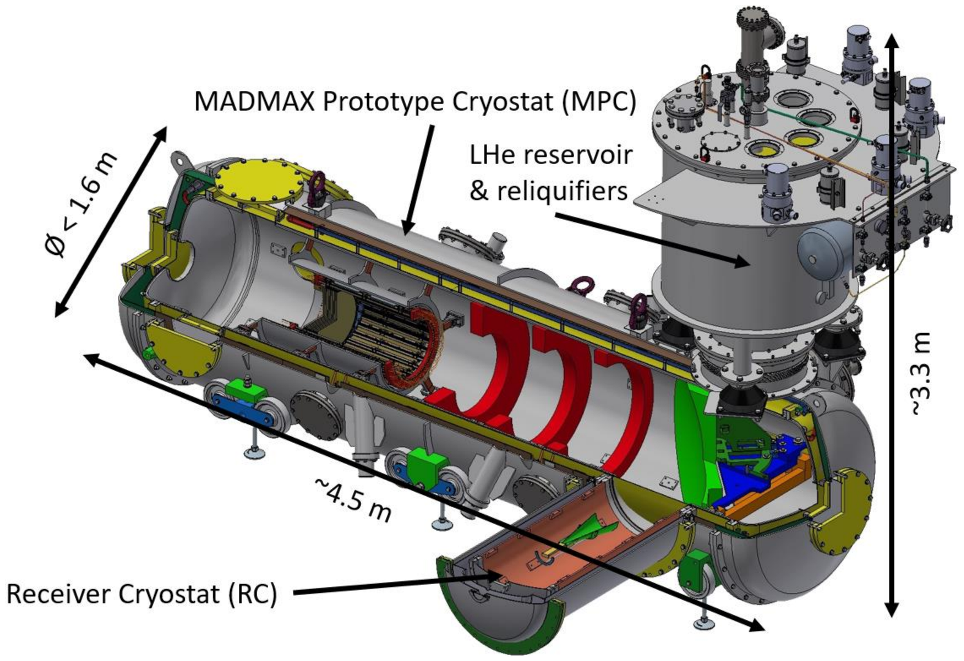
- Worked on three main challenges of this new concept
  - Feasibility of the disk positioning system at cryogenic temperatures and under high magnetic field
    - Motor positioning accuracy < 10 μm and speed > 10 μm/s achieved in all conditions

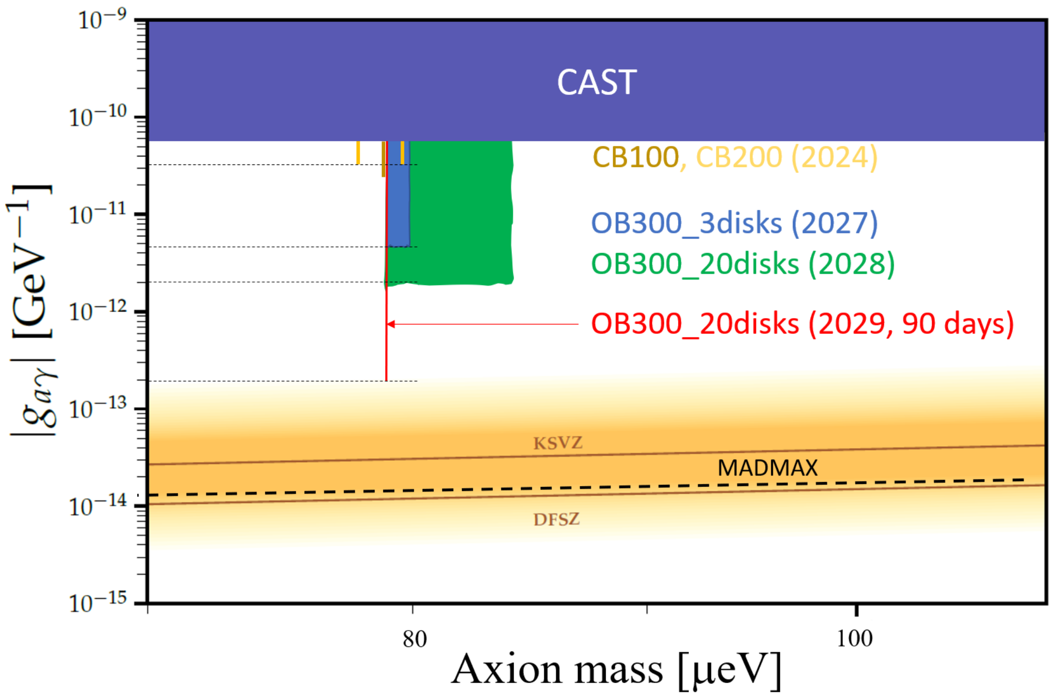
  - Realistic booster simulation Including disk planarity measurement performed at CPPM
    - First comparison of measurement of β^2 with simulation

  - Axion and dark photon dark matter searches
    - World-leading limits in both dark photon and axion searches around 80 μeV (20 GHz)

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 2027-2029 at CERN





Thank you!

OUTLINE

Introduction to Axion dark matter

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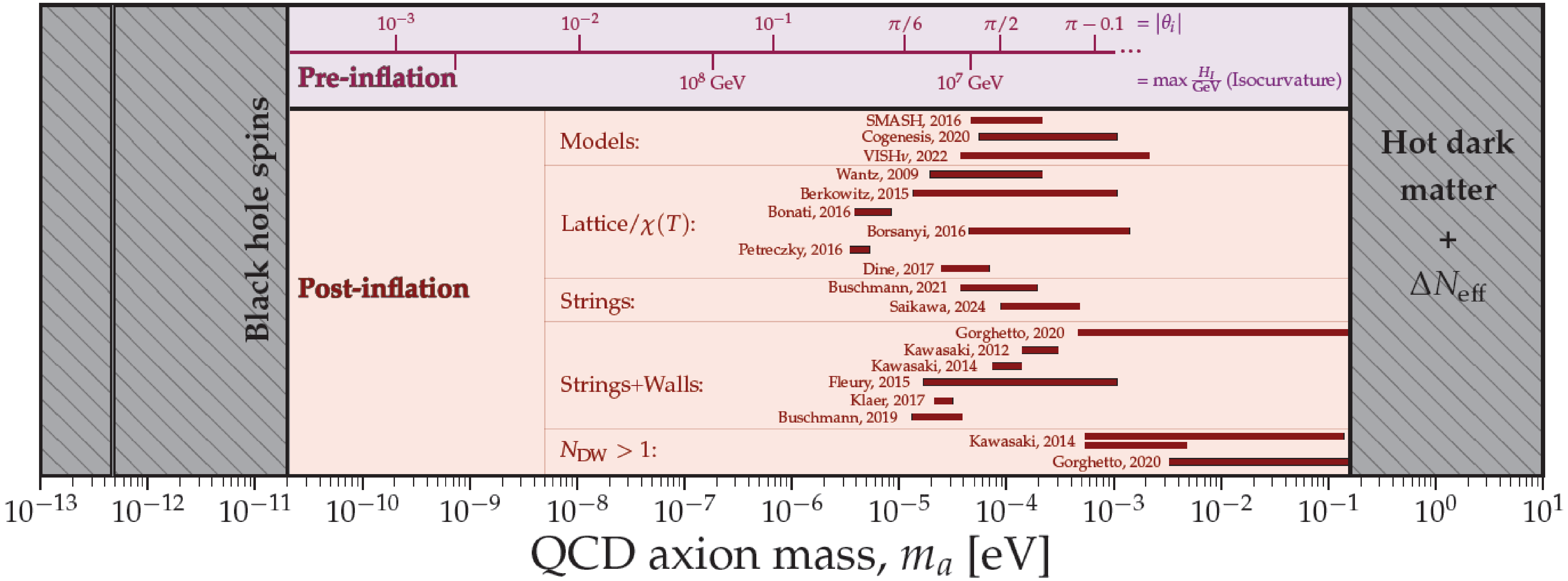
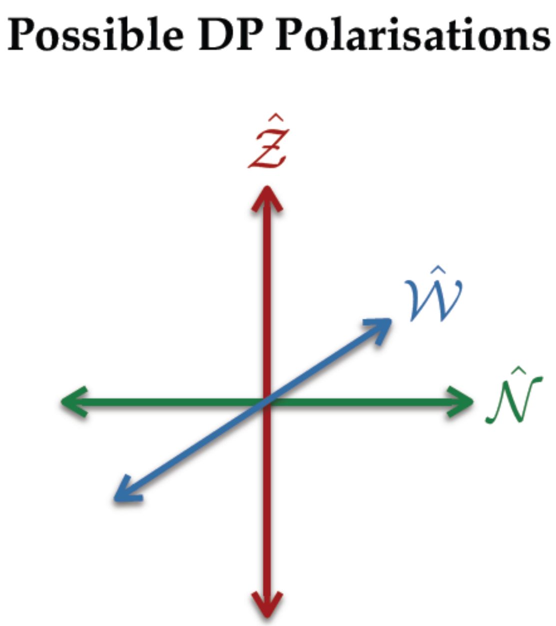
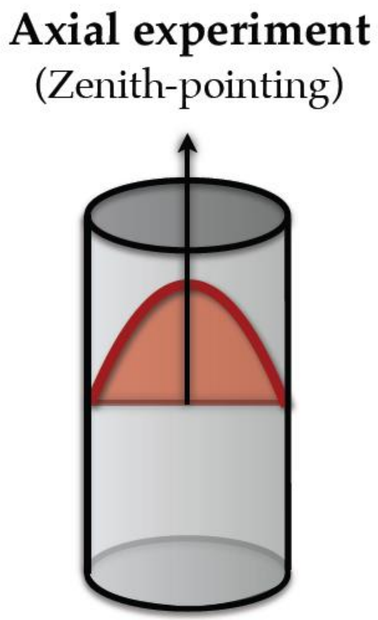
Axion mass predictions



Dark photons

- **A new dark U(1) symmetry added to the standard model**
  - Does not interact with standard model particles, other than kinetic mixing with photons
  - Many production mechanisms exist, among them the misalignment mechanism
  - The production mechanisms can result in fixed polarization or mixed random polarization
  - Most axion experiments are also sensitive to dark photons ➔ does not require magnetic field
  - In this work, random polarization is assumed → Conversion to photons is reduced by a factor $\langle \cos^2\theta \rangle = 1/3$





OUTLINE

- Introduction to Axion dark matter
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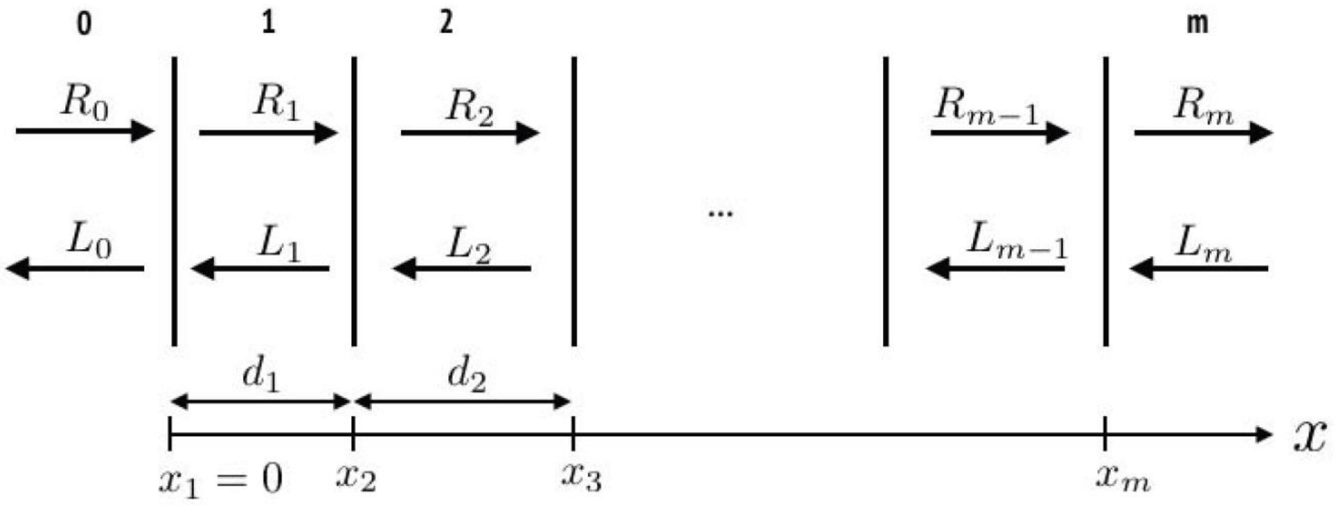
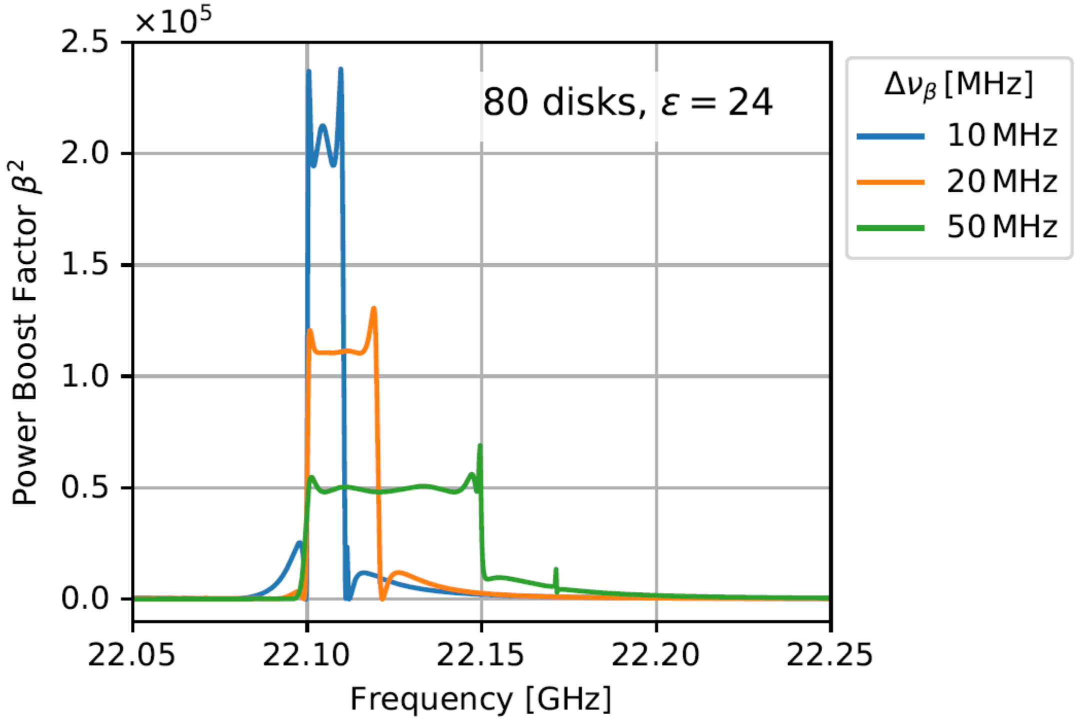
Simulating dielectric haloscopes

- **Booster simulation strategy**
  - The booster is divided into regions with differing thickness and dielectric constant
  - At the interface, the dielectric constant determines the reflection and transmission coefficients
  - The fields propagate inside each regions according to the boundary conditions (i.e. open vs closed booster)
  - In each region, the amplitudes of the left moving and right moving fields are calculated by superposition of axion induced field, reflected field, and transmitted field
  - 3D effects are modeled by making the field amplitudes dependent on transverse coordinates and tracking their evolution



Area law for dielectric haloscopes

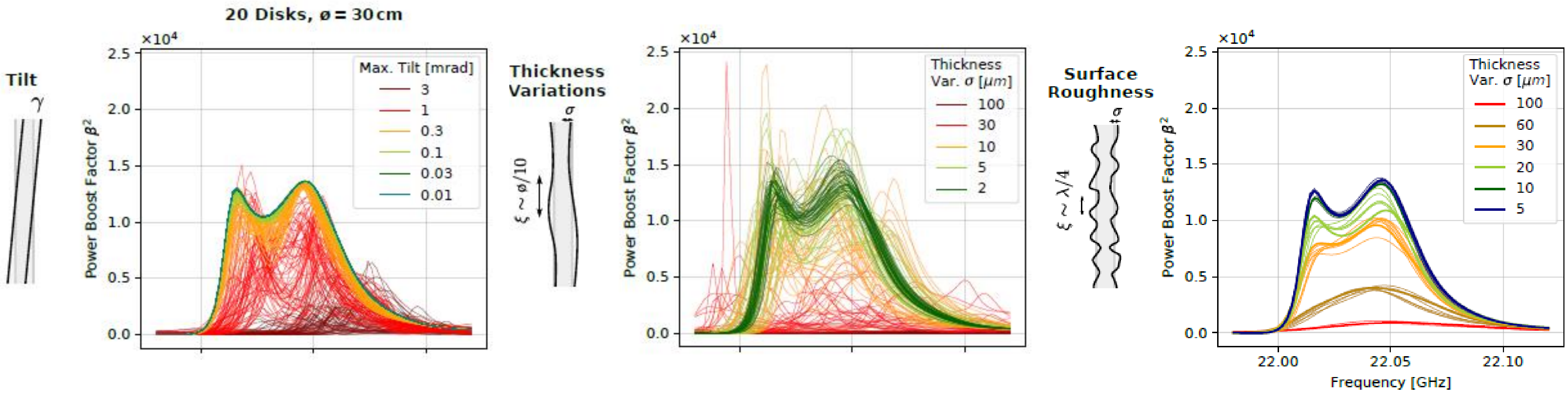
- **The area $\int \beta^2 df$ stays constant for all configurations of a 1D booster with given number of disks**
  - The narrow high boost factor comes from resonant configurations that maximize the reflectance of the disks for a given frequency
  - The wider boost factor results from a constructive interference of the emitted waves coming from the transpaprent configuration of the disks



There is a tradeoff between a narrow and high boost factor or wider but lower boost factor

Constraints on the booster geometry

- **Adding uncertainties on disk parameters worsens the boost factor**
  - The resonant configuration is the most affected by small changes in the booster geometry



To maintain boost factor within 10 %, the RMS surface roughness of the dielectric disks ideally needs to be less than 10 μm, disk thickness RMS variation less than 2 μm and the disk tilt less than 0.1mrad.

MADMAX prototypes testing timeline

Name	Goal	Booster	Disks	Test year
CB100	RF studies + first ALPs searches	Closed	3 fixed, $\phi = 100$ mm	2022, 2023, 2024
CB200	RF studies + first ALPs searches	Closed	3 fixed, $\phi = 200$ mm	2024
OB200	Mechanical studies	Open	1 movable, $\phi = 100$ mm	2022, 22
OB300v1	First dark photon search	Open	3 fixed, $\phi = 300$ mm	2023-24
OB300v2	ALPs search with more sensitivity	Open	3-20 movable, $\phi = 300$ mm	2027-29

OUTLINE

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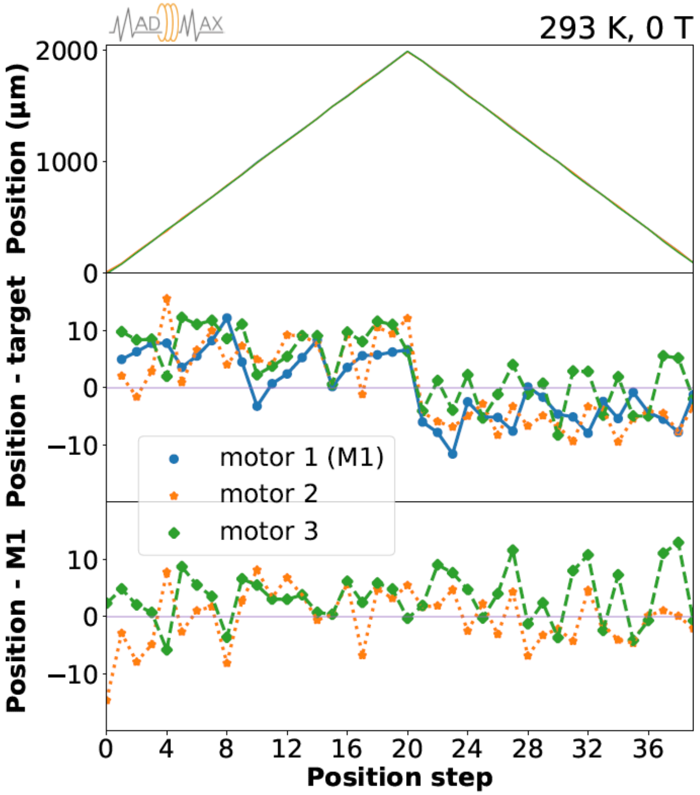
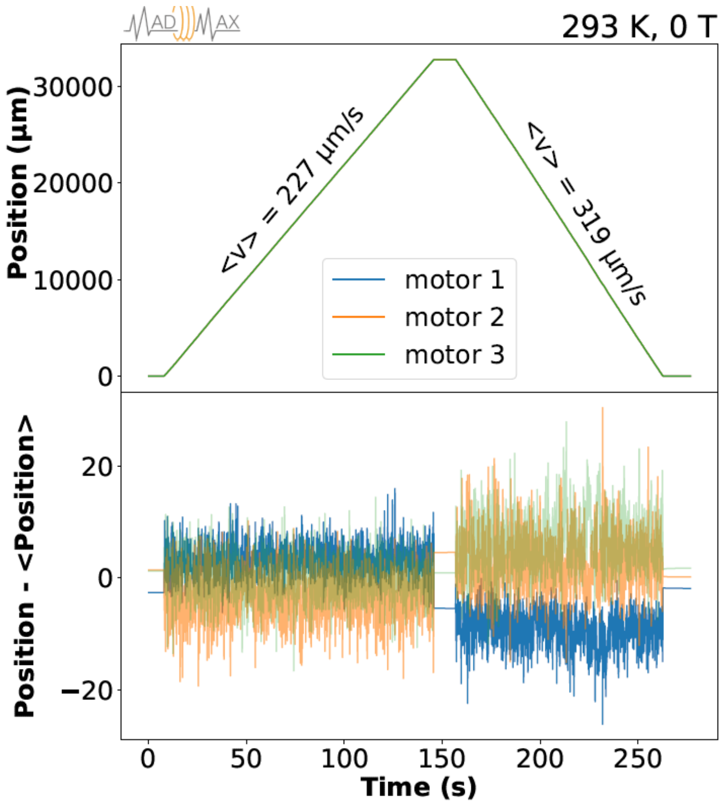
Disk positioning system: Test results

- **Testing at room temperature**

JINST **19 (2024) T11002**



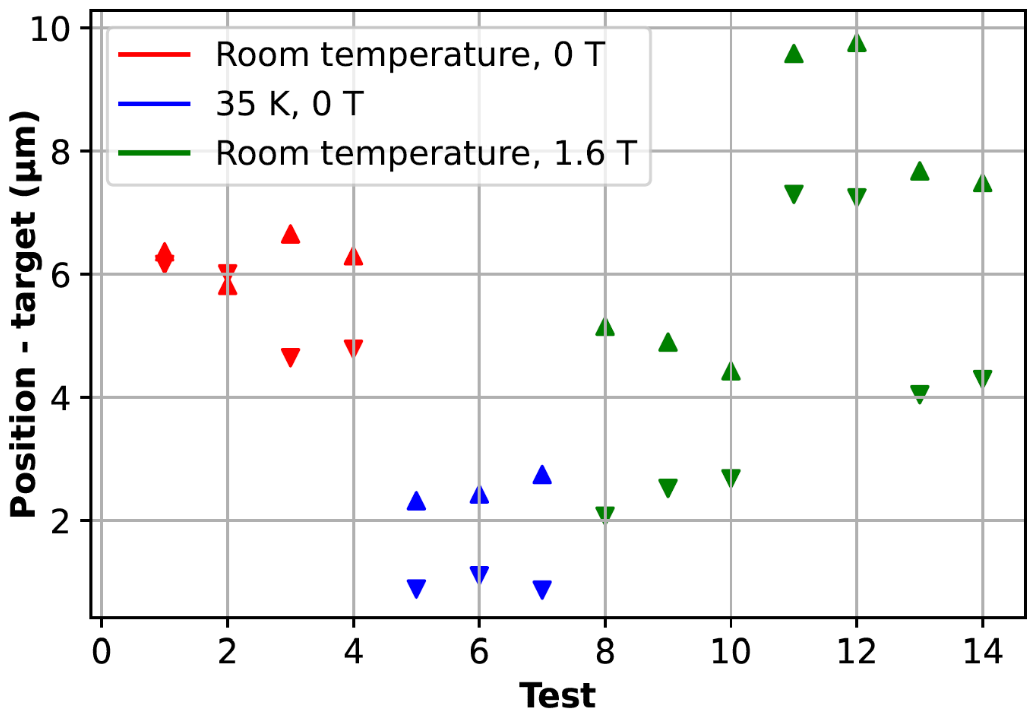


The positioning system shown to work at room temperature

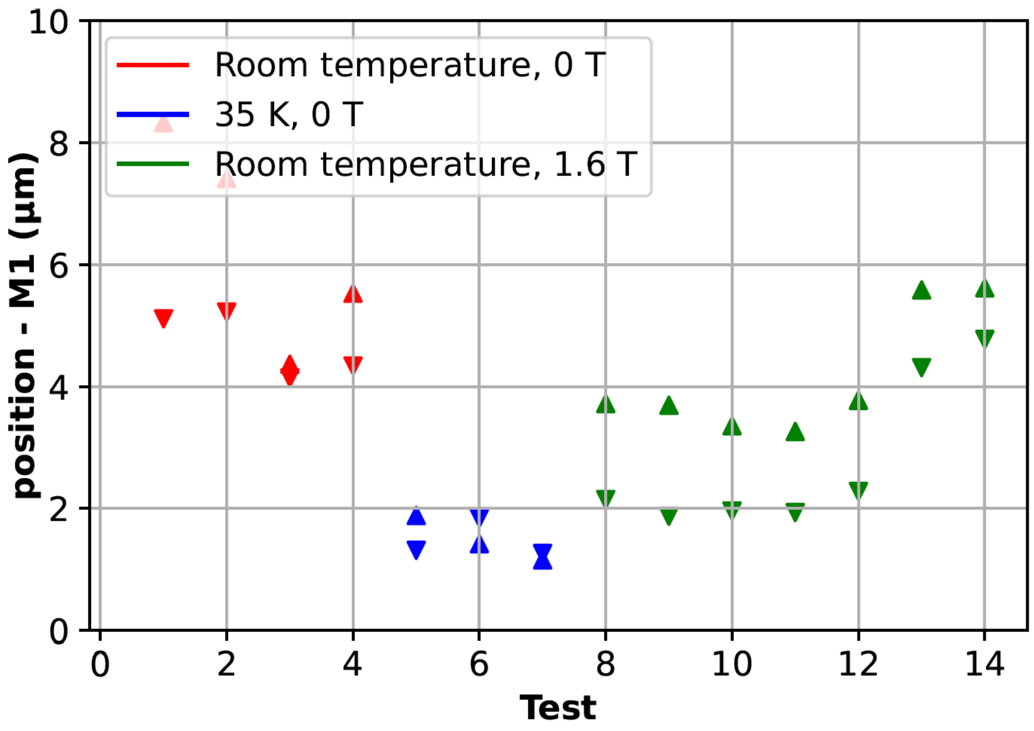
Disk positioning system: Test results

➢ **Summary of all measurements**

Position precision: < 10 μm



Inter motor distance: < 10 μm



The positioning system shown to work according to requirements across repeated measurements

OUTLINE

- Introduction to Axion dark matter
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- **Booster simulations**
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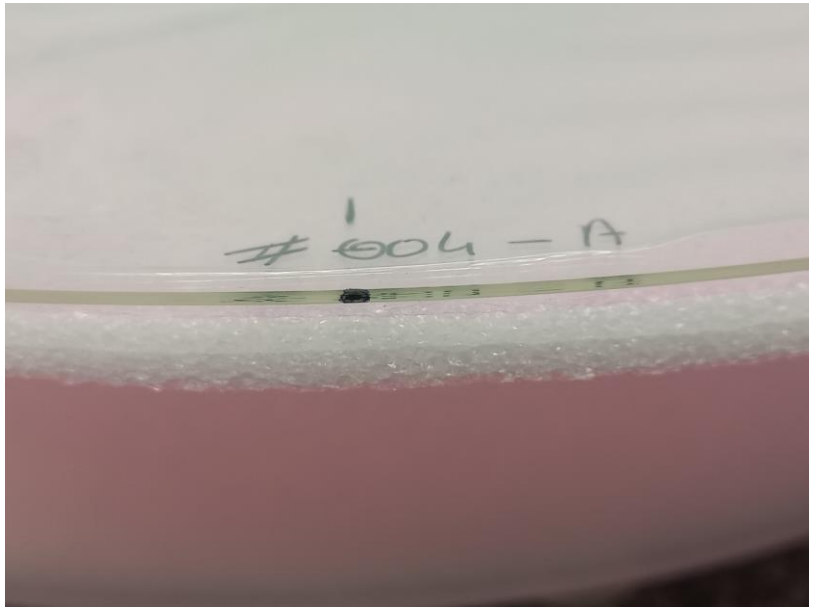
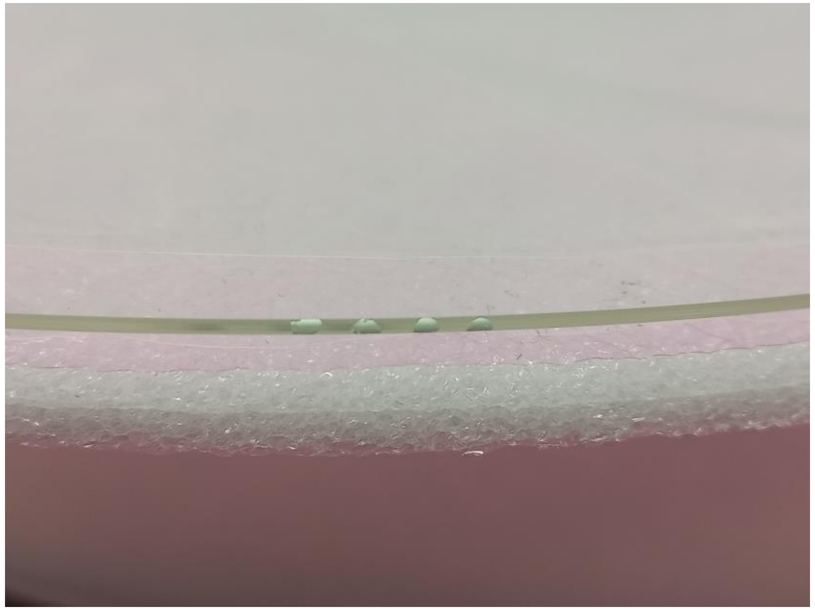
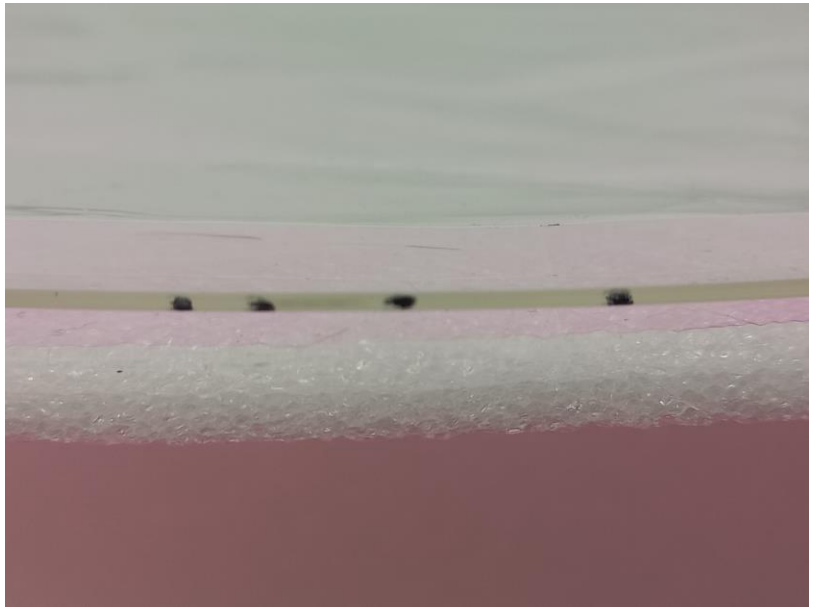
Disk identification marks







Disk number, face, and the bottom point of the disk (at the time of measurements)

Disk number (again)

Disk face indication (increasing distance on the right means the face above is face A

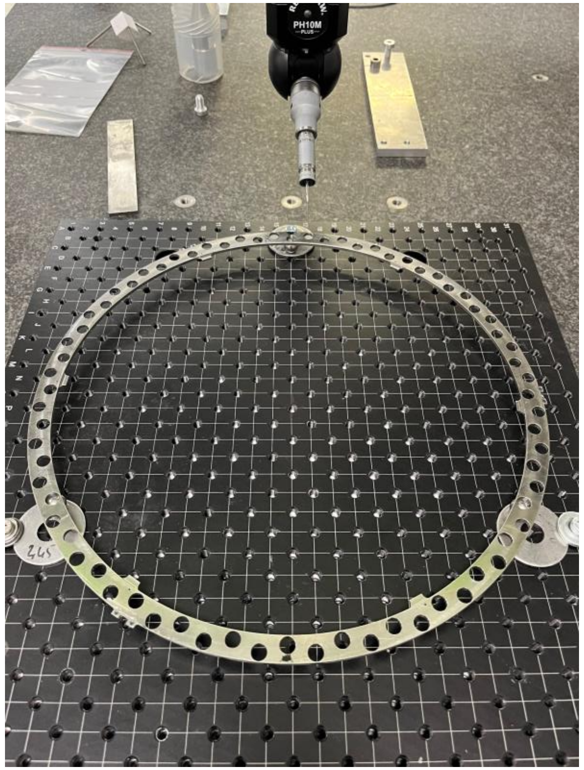
Disk planarity measurements

Disk face	Number of points	Raw RMS (μm)	Interpolated RMS (μm)
1A’	491	45	43
1B’	491	46	45
2A’	492	50	49
2B’	492	52	52
2A	720	52	54
2B	720	55	56
3A	715	46	47
3B	715	48	48
4A	718	56	58
4B	718	60	62
4A"	2884	55	55
4B"	2791	63	62

Min-max ~ 200 μm

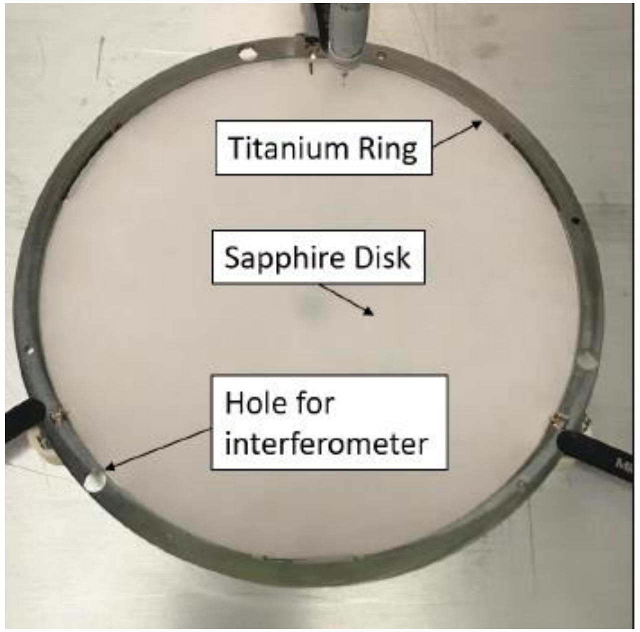
Disk ring manufacturing

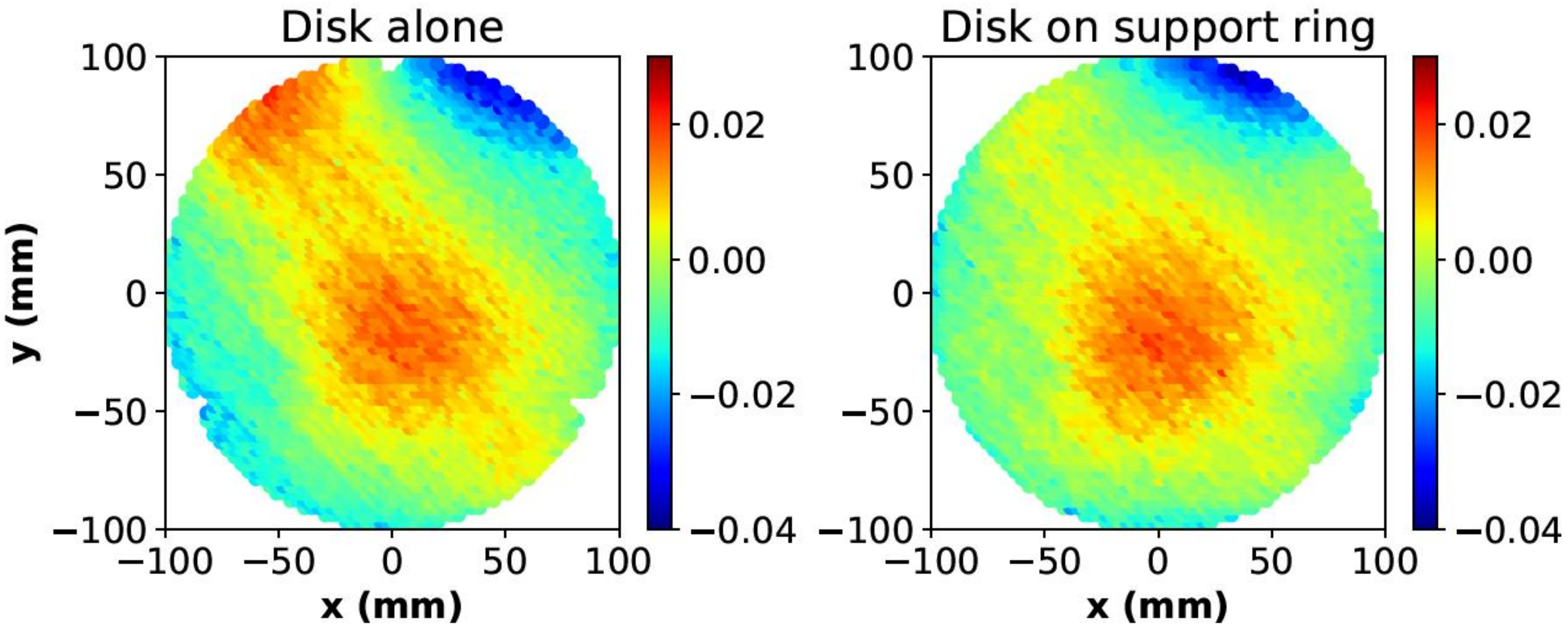
- **Very challenging to manufacture thin ring with correct planarity (performed at CPPM)**
  - Titanium ring in rough shape received from manufacturer
  - The shape is refined in the lab, holes are made for interferometers
  - The ring shape is corrected using a weight machine



20 cm Disk ring

- **Disk ring utilized for testing of disk positioning system**
  - Holds a disk with 20 cm diameter

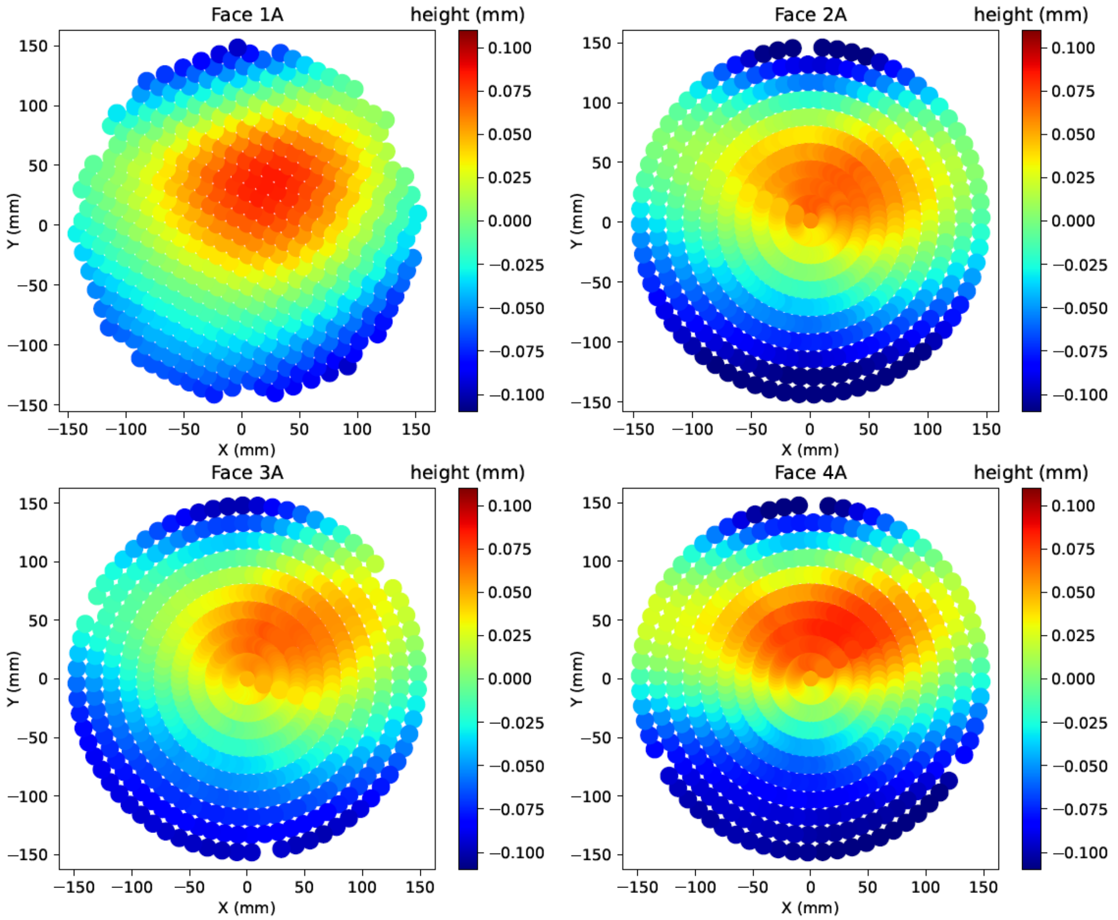




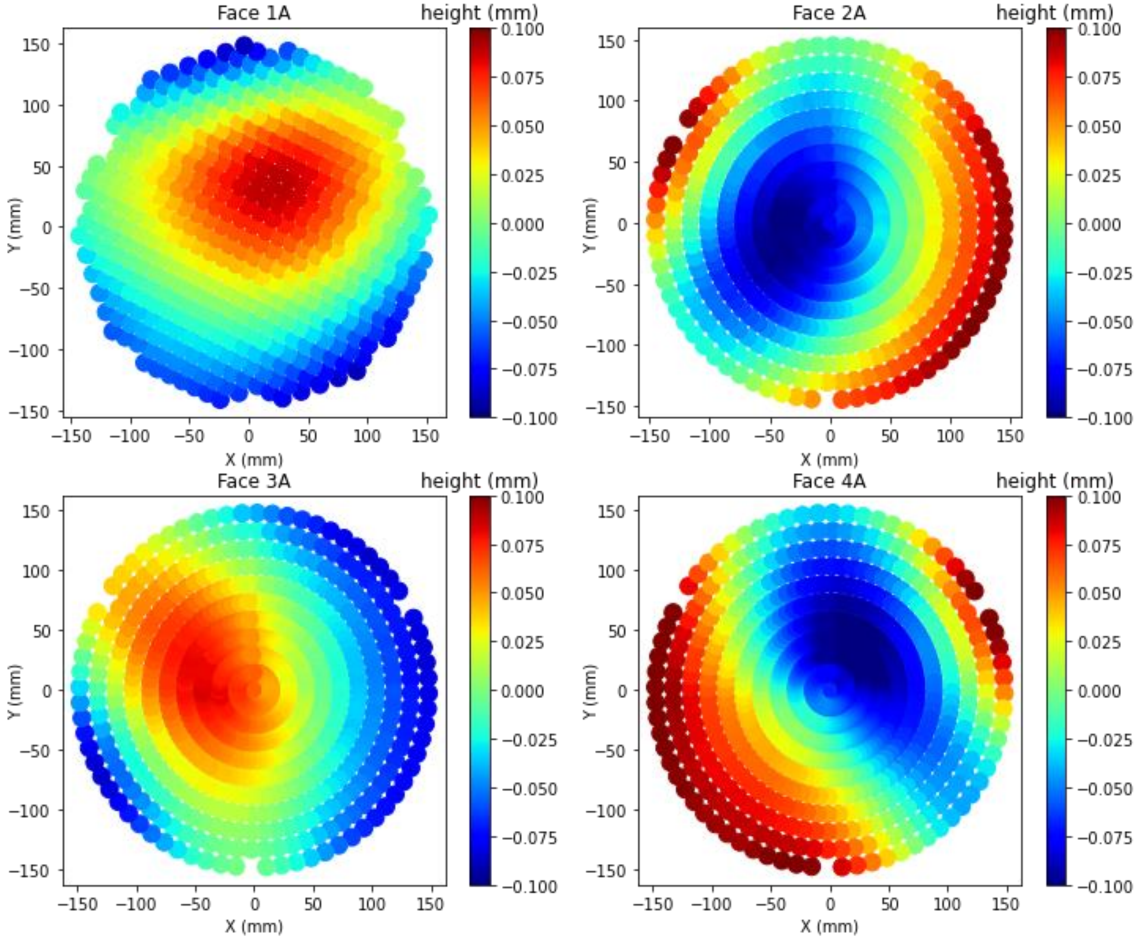
Disk ring shows minimal deformation of the sapphire disk

Aligned vs non-aligned disks

Aligned

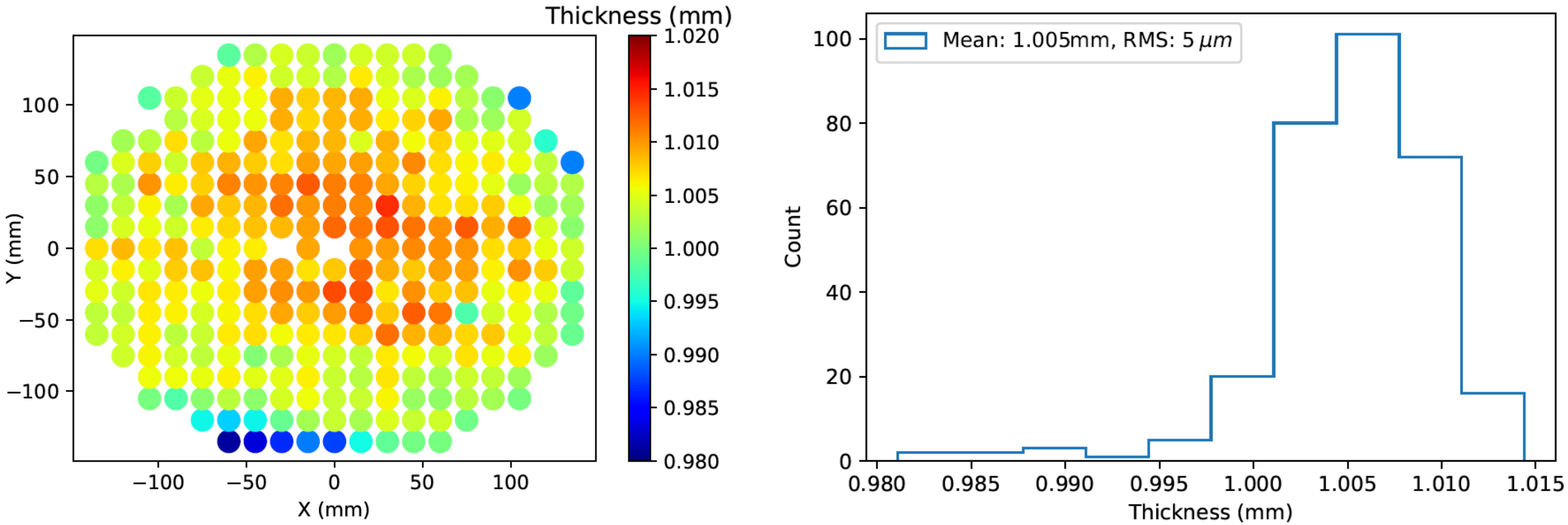


Non aligned



Disk measurement

➢ **Thickness measurement: two faces measured simultaneously and subtracted from each other**



Disk rings

➢ **Measurements with disk mounted on ring (and disk alone)**

Disk4 with rings	Side	Raw RMS	Raw min-max	Interpolated RMS	Interpolated min-max
1	A	49(63)	194(226)	48(62)	194(226)
1	B	57(55)	208(204)	56(55)	206(204)
2	A	57(63)	206(226)	56(62)	204(226)
2	B	55(55)	200(204)	55(55)	199(204)
3	A	58(63)	204(226)	57(62)	203(226)
3	B	58(55)	198(204)	57(55)	197(204)
4	A	49(63)	191(226)	48(62)	187(226)
4	B	57(55)	223(204)	56(55)	222(204)

Summary of uncertainty effects

Parameter	Variation	effect on amplitude	effect on peak freq
Tilt	$\pm$ 0.1 mrad	up to 20%	up to 20 MHz
Thickness	$\pm$ 10 μm	up to 5%	up to 50 MHz
Distance	$\pm$ 10 μm	Negligible	up to 50 MHz

OB300 simulation parameters

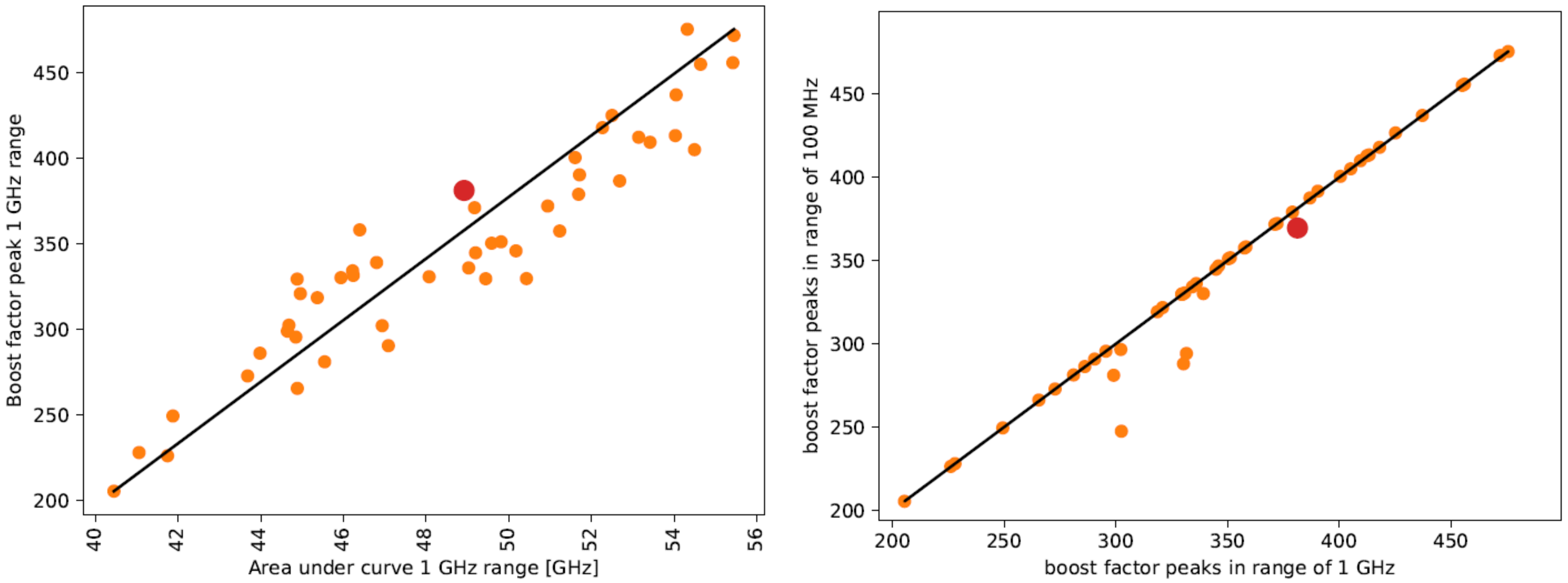
➢ **All parameters for OB300v1 booster setup (narrow and wide band configurations)**

Setup parameters	
Disk diameter	30 cm
Disk thickness	1 mm
Disk dielectric constant	9.3
Mirror dielectric constant	Nan
Mirror thickness	0
Initial distances array	[7.42, 11.13, 11.13] mm
Receiver distance from last interface	0
Coupling to a Gaussian antenna	No
Input parameters	
Julia version	1.6.7
Frequency	20.2 GHz
Disk grid size	0.4 m × 0.4 m
Disk grid length	2.5 mm
3D algorithm	Mode matching
Mode indices M_{max}, L_{max}	3, 3
Optimization parameters	
Optimization grid intervals	50 µm
Optimization grid size	2500 µm
Frequency width for optimization	10 MHz
Optimization points in frequency range	4

Setup parameters	
Disk diameter	30 cm
Disk thickness	1 mm
Disk dielectric constant	9.3
Mirror dielectric constant	Nan
Mirror thickness	0
Distances array	[8.265, 9.813, 9.813] mm
Receiver distance from last interface	0
Coupling to a Gaussian antenna	Yes
Gaussian beam width	85 mm
Input parameters	
Julia version	1.6.7
Frequency	19.2-20.2 GHz
Disk grid size	0.4 m × 0.4 m
Disk grid length	2.5 mm
3D algorithm	Mode matching
Mode indices L_{max}, M_{max}	3, 3

Peak Frequency

➢ **Comparing the peak frequency and AUC inside 100 MHz and 1 GHz range around 19.7 GHz**



All boost factor curves lie between 19.65 to 19.75 GHz

OB300 simulation fit parameters

- **Parameter values different from the original specification values**
  - Calculated from the best fit to the laboratory measurements
  - Contains mean value and uncertainty

Parameter	**Original**	**Measured**
mirror conductivity [S/m]	inf	$(5 \pm 1) \times 10^7$
Disk1 distance [mm]	8.265	8.3664 ± 0.0017
Disk2 distance [mm]	9.813	9.9606 ± 0.0032
Disk3 distance [mm]	9.813	9.7314 ± 0.0036
Disk thickness [mm] (3 parameters)	1	1 ± 0.005
Disk ϵ (3 parameters)	9.3	9.3 ± 0.1
Disk loss parameter $\tan\delta$ (3 parameters)	0	$(1 \pm 0.1) \times 10^{-5}$

OUTLINE

- Introduction to Axion dark matter
- The MADMAX Experiment
- R&D towards a tunable haloscope
- Booster simulations
- **First dark matter searches**
- Conclusions and perspectives

MADMAX dark matter searches

Type	acronym	ϕ disc [mm]	Nb of discs	Available	Test at CERN Temp. [K]	Test at CERN 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.

Frequency scales involved in axion search

Quantity	Width	Description
Axion signal width	20 kHz	Determined by the velocity dispersion of the dark matter halo in the galaxy at 20 GHz
Frequency resolution of data	9 Hz	The maximum resolution of the spectrum analyzer Rohde & Schwarz FSW43
Frequency resolution of analysis data	0.9 kHz	The frequency resolution was reduced to conserve computation time for the analysis. It is still much lower than the width of the axion signal.
Boost factor bandwidth	10 MHz	Determined by the spacing between the disks and the mirror. It was optimized for boost factor amplitude, resulting in narrow bandwidth.
Receiver bandwidth physics data	250 MHz	determined by the band pass filter in the receiver chain
Receiver bandwidth calibration data	1 GHz	Should be wide enough to encompass the oscillation pattern induced by the LNA noise creating standing waves between the LNA and the booster.

MADMAX sensitivity

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

$$\chi = 1.0 \times 10^{-13} \left(\frac{640}{\beta^2}\right)^{1/2} \left(\frac{707\,\mathrm{cm}^2}{A}\right)^{1/2} \times \left(\frac{T_{\mathrm{sys}}}{240\,\mathrm{K}}\right)^{1/2} \left(\frac{11.7\,\mathrm{d}}{\Delta t}\right)^{1/4} \left(\frac{\mathrm{SNR}}{5}\right)^{1/2} \times \left(\frac{0.3\,\mathrm{GeV/cm^3}}{\rho_\chi}\right)^{1/2} \left(\frac{\Delta\nu_\chi}{20\,\mathrm{kHz}}\right)^{1/4}$$

Overview of data runs for axion search

Start date	f(max β^2) [GHz]	measurement time [h]	Median B field [T]
21 February	18.531	13.5	1.58
29 February	18.543	73.75	1.01
5 March	18.557	159.0	1.01
27 February	19.196	40.75	1.27
23 February	19.215	61.25	1.58

Power calibration

➢ **Receiver chain calibration based on ‘hot’ and ‘cold’ noise measurements**

$T_{sys} = N_L C$ ⟶ C = Calibration factor

$$\frac{\Delta T}{\Delta N} = \frac{1}{KGB\,(1 - |\Gamma|^2)} = \frac{C}{(1 - |\Gamma|^2)}$$

$$C = \frac{\Delta T}{\Delta N}(1 - |\Gamma|^2)$$

$$N_{hot} - N_{cold} = KGB\,(T_{hot}(1 - |\Gamma|^2) + \not{T_e} - T_{cold}(1 - |\Gamma|^2) - \not{T_e})$$

$$= KGB\,(T_{hot} - T_{cold})(1 - |\Gamma|^2)$$

DATA (diode on/ diode off)

Deembeded reflectivity

Values from Diode:

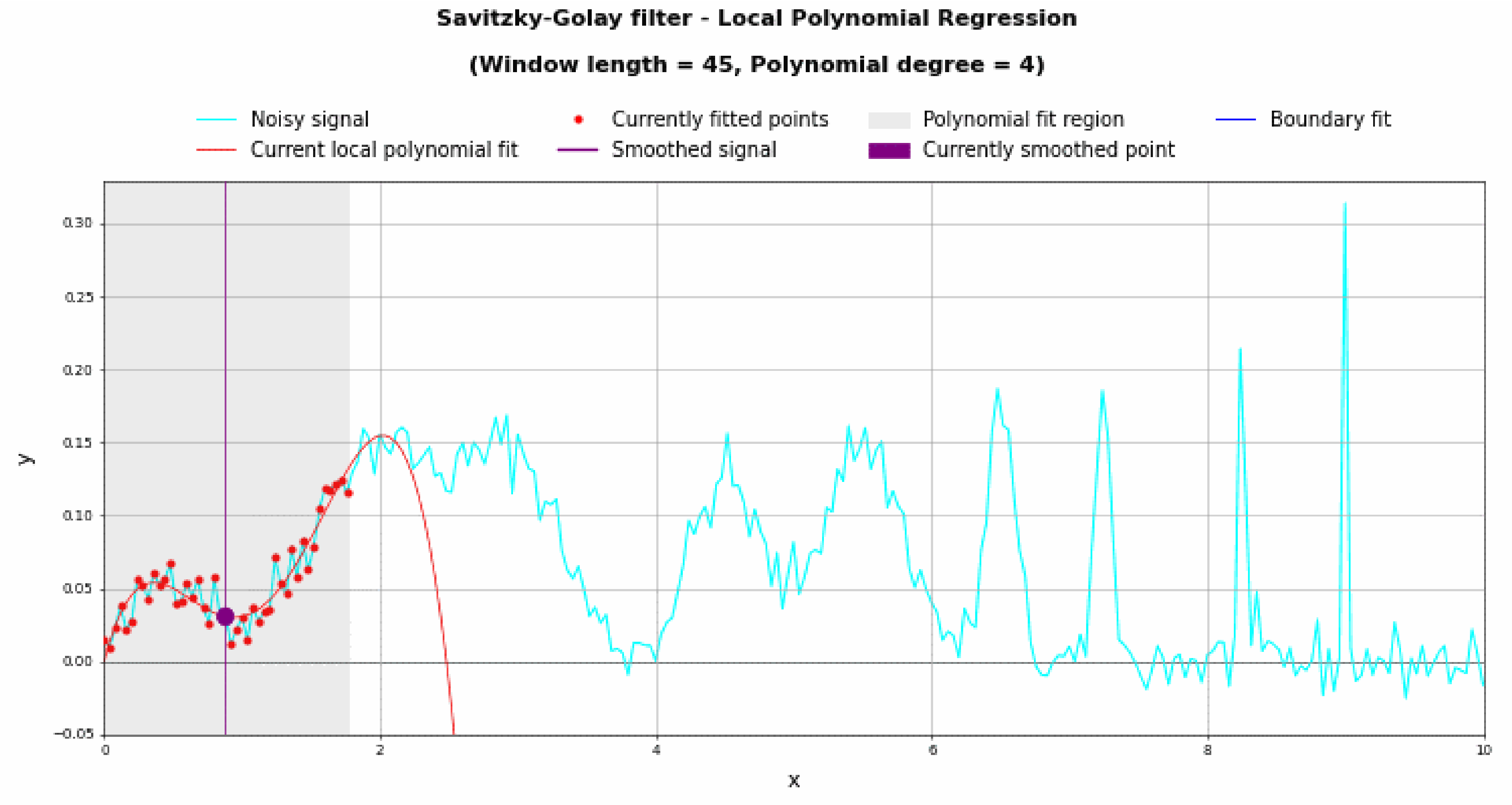
T_{hot} = 348.25 K
T_{cold} = 297 K

- Calibration factor converts the noise power to system temperature
- Can be calculated using ΔT (noise diode values), ΔN (noise diode on and noise diode off measurements), and Γ (reflectivity of LNA)

- N = noise power measurements
- K = Boltzmann’s constant
- G = gain of LNA
- B = bandwidth of the measurements
- T = hot and cold temperature values of the noise diode
- Γ = reflectivity of LNA

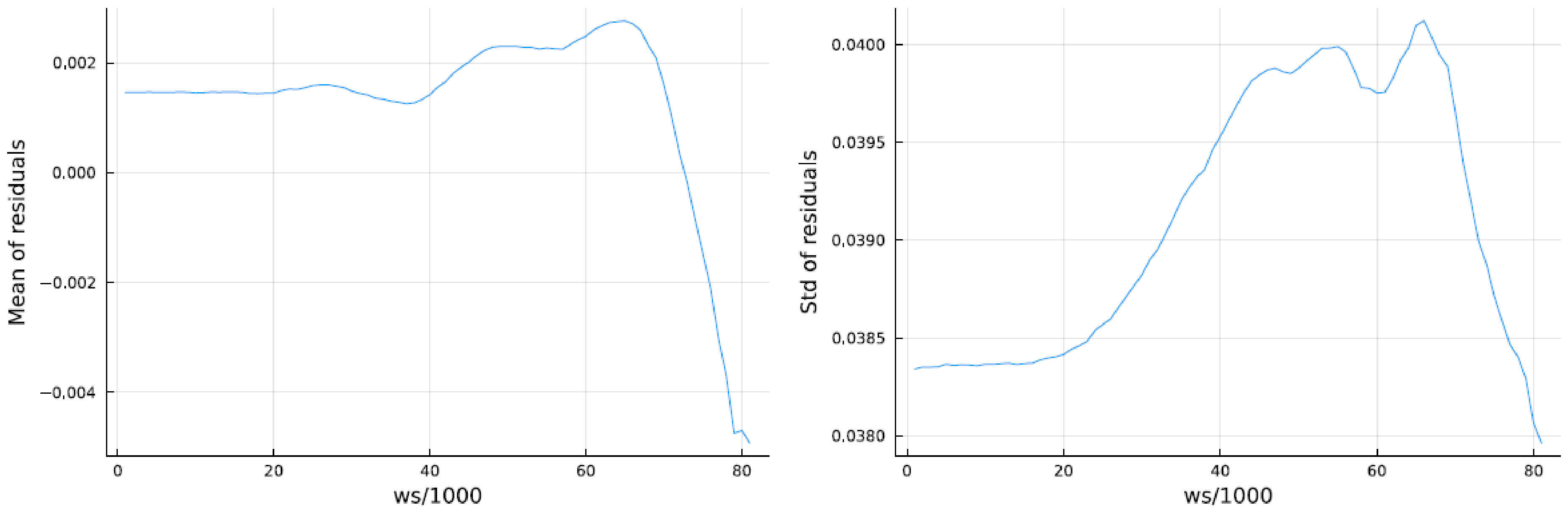
Savitzky Golay filter

- **Calculates a best fit to a polynomial inside an interval of discrete data points**
  - Characterized by two parameters: Window size (ws) and polynomial order (o)



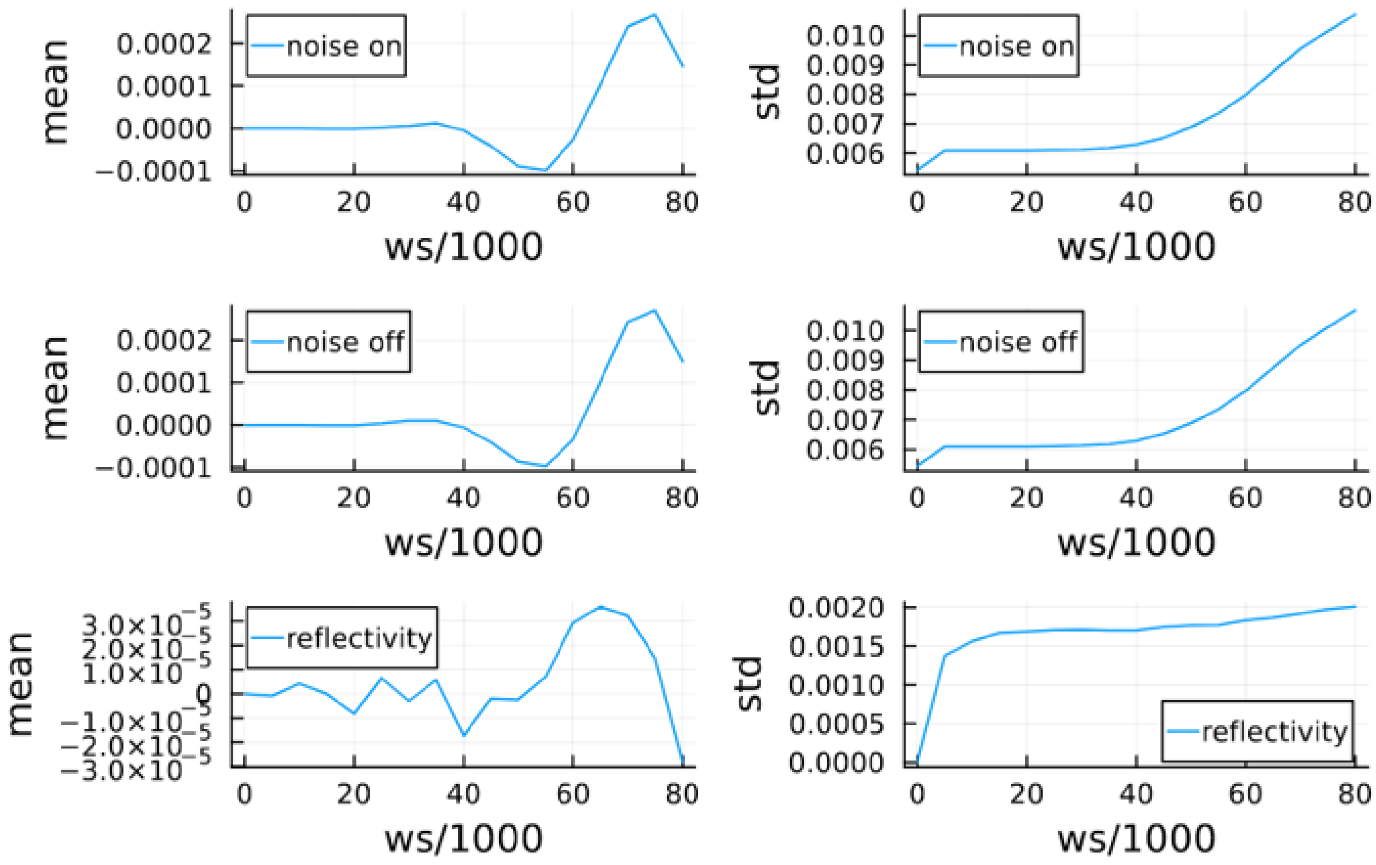
Filtering the power calibration factor

- **SG filter applied to the power calibration factor to calculate the baseline and the residuals**
  - The goal is to make the mean and std of residuals smallest as possible to ensure correct estimation of the baseline
  - The window size of 8001 is chosen because of low mean and std of residuals



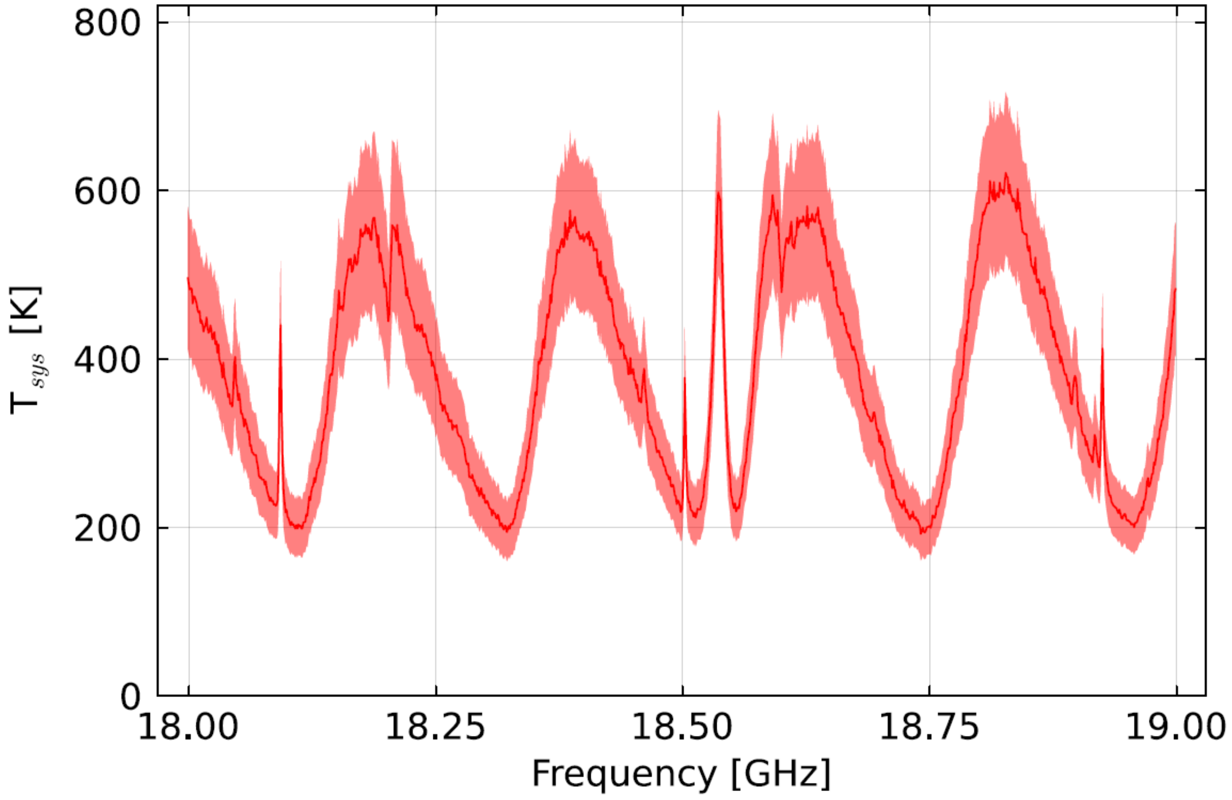
Filtering the power calibration factor

- **Calculating the residuals for individual components of the power calibration**
  - All of them show similar behavior, and a stable zone of performance for SG filter parameters



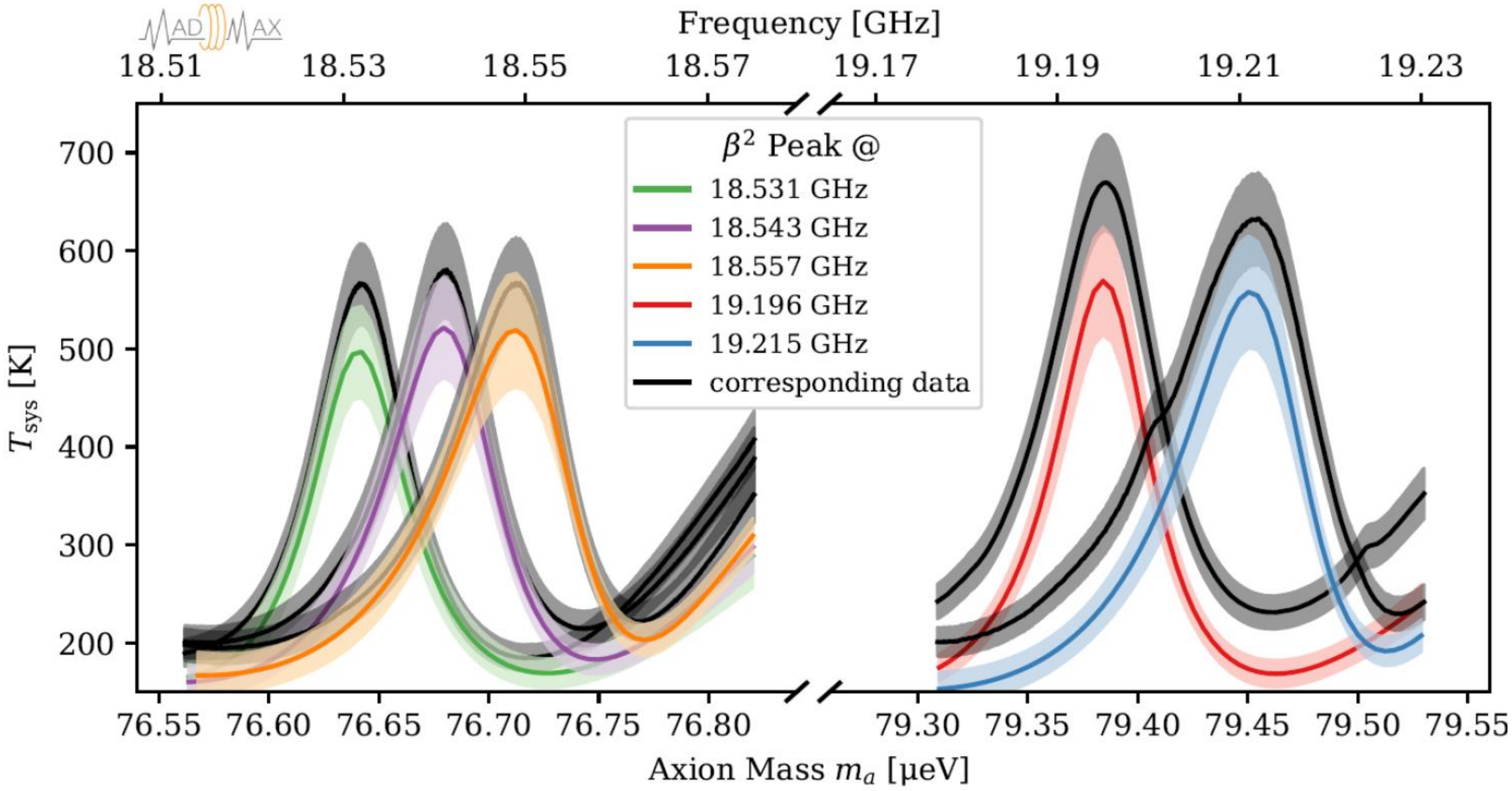
Calibrated booster system temperature

- **Converted from raw spectra using the calibration factor**
  - $T_{sys} = N_I C$



Booster model validation

➢ **Comparing the system temperature coming from data and booster model**
- The frequency behavior is the not relevant, and it is very well reproduced
- The amplitude is underfitted, but not important for calculating the boost factor



Systematics for MADMAX DM searches

Axion search

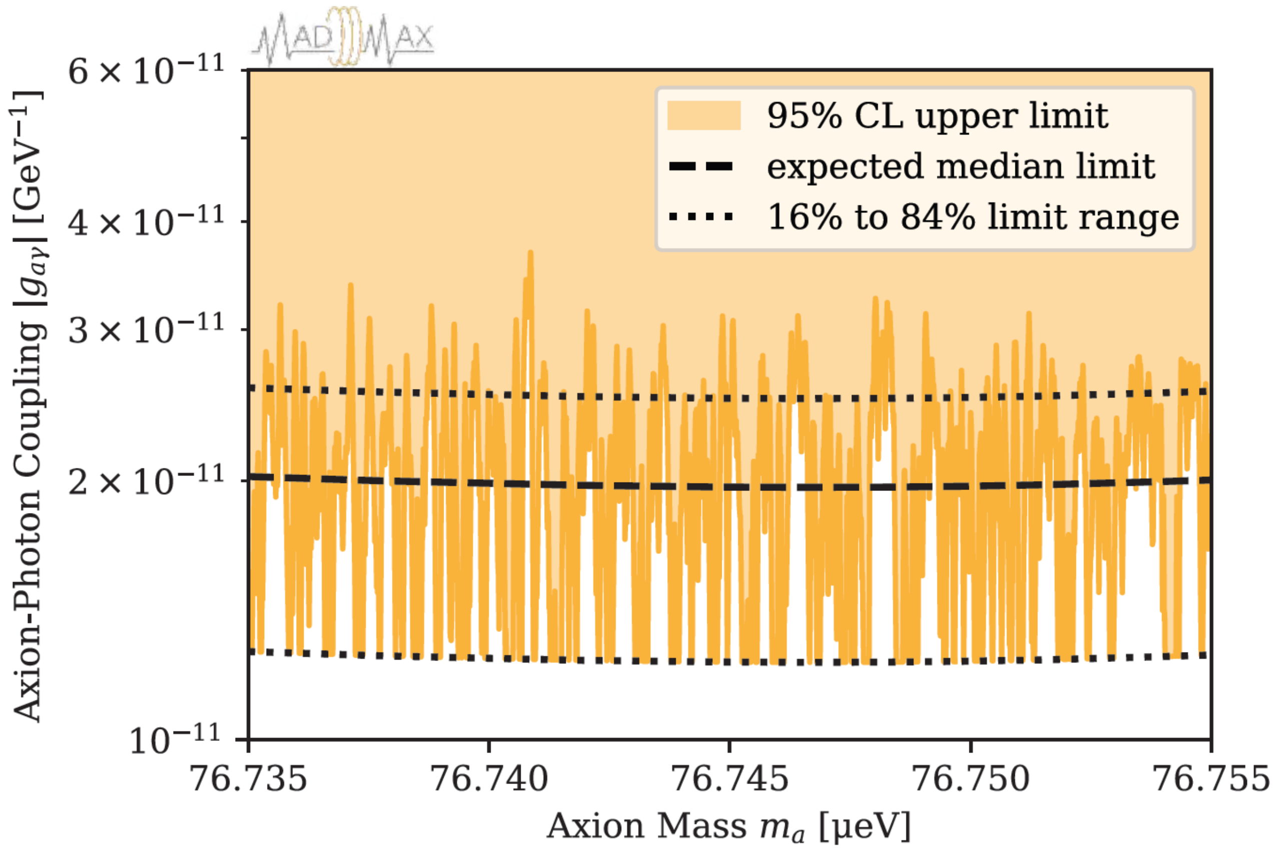
Effect	Uncertainty in $\|g_{a\gamma}\|$
Y-factor power calibration	3 % to 5 %
Receiver chain power stability	$\leq$ 2 %
Axion field – TE_{11} overlap	6 %
Boost factor determination	< 5 %
Frequency stability of TE_{11} mode	< 2 %
Total	5 % to 10 %

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%

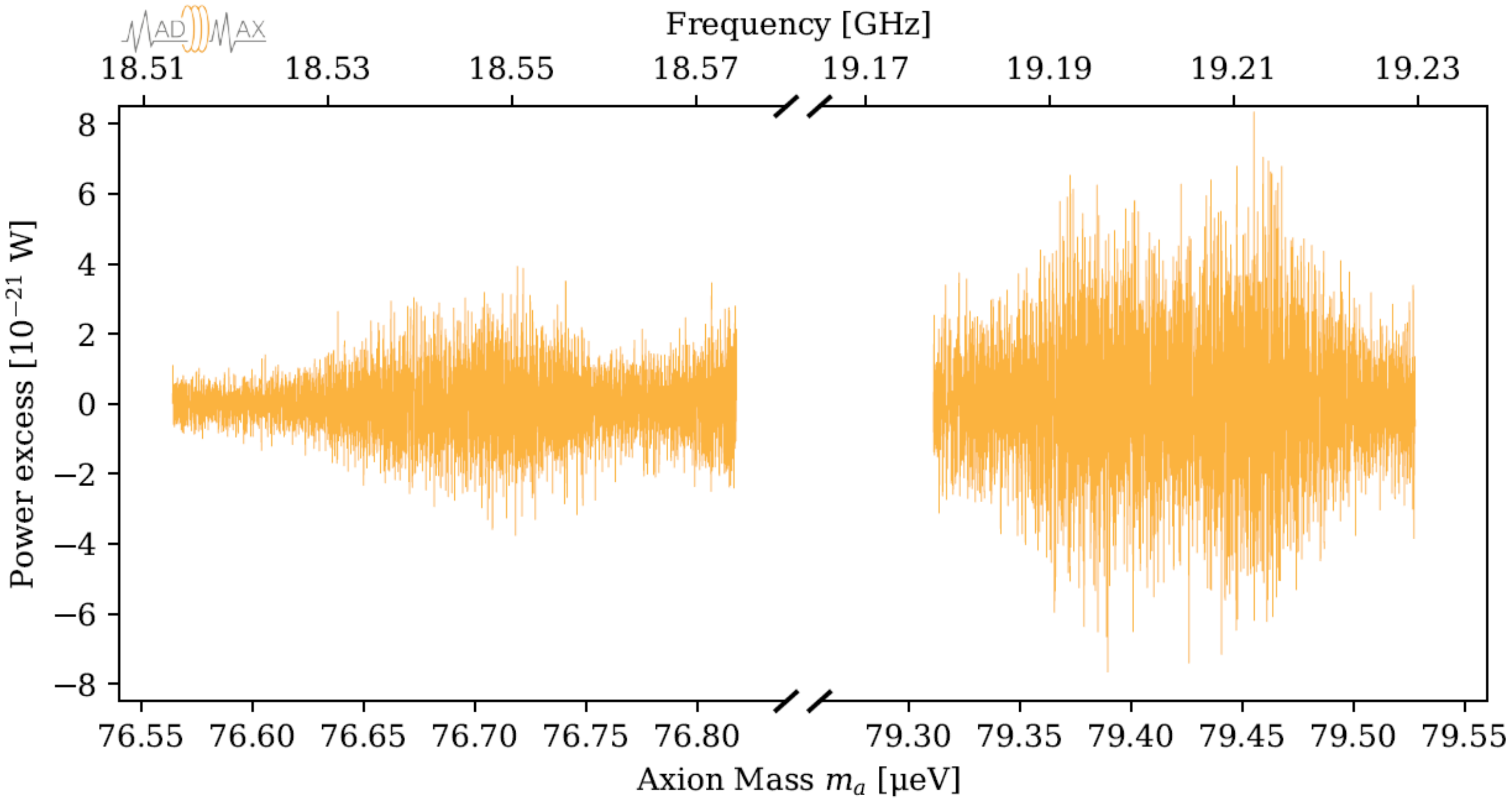
MADMAX ALPs limit zoom

- **Observed exclusion limit for mass 76.735 – 76.755** μeV
  - The correlations in the limit are the result of the cross-correlation with the axion signal shape



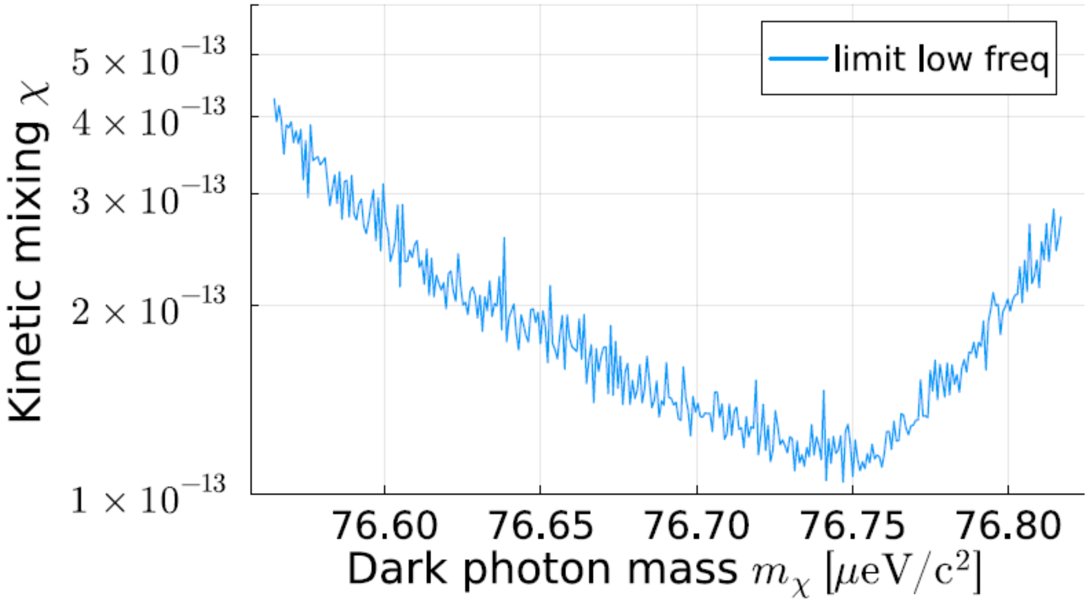
Cross- correlated power excess

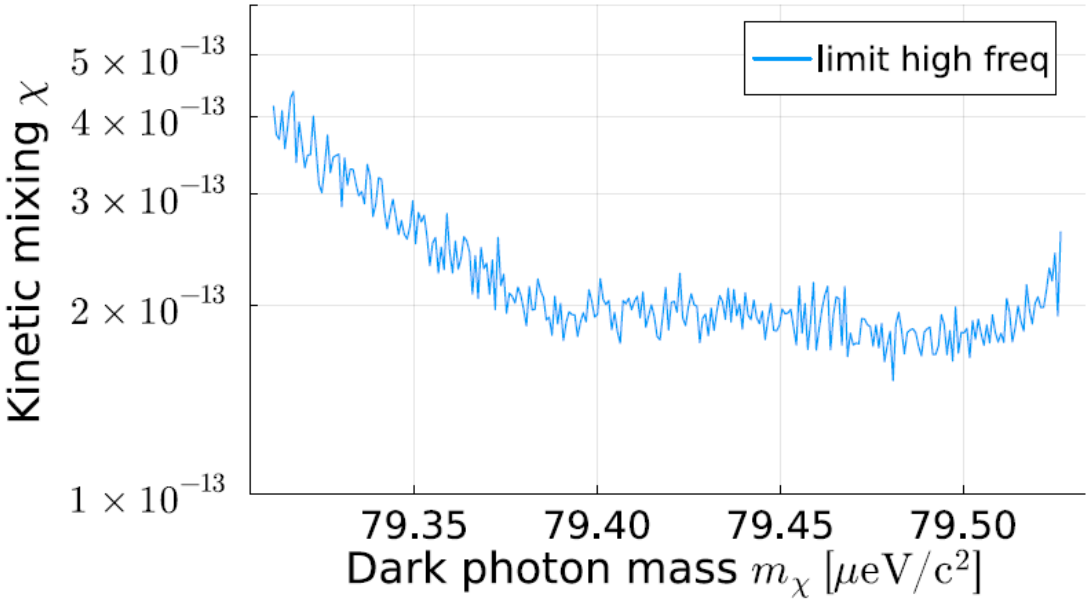
➢ **Calculated by correlating adjacent bins of combined spectrum with expected axion signal shape**



2^{nd} Dark Photon limit with MADMAX

- **Using the same systematics as axion search procedure**
  - Cosmic No significant peaks are observed in the grand spectra
  - Exclusion limits (rebinned) are set in the mass region around 76 μeV and 79 μeV





Final prototype: Future plan

Booster	Cryostat	β^2	T_{sys} [K]	Sensitivity $\lvert g_{a\gamma}\rvert$[GeV^{-1}]	Freq. Range [MHz]	Duration [Months]	Year
OB300v2	MPC	1000	10	$\approx 5 \times 10^{-12}$	200 (scan)	3	2027
$OB300_F$	MPC	7000	10	$\approx 2 \times 10^{-12}$	1000 (scan)	3	2028
		50000	7	$\approx 2 \times 10^{-13}$	1	3	2029