Direct detection of Axion dark matter with MADMAX

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JRJC 2023
Journées de Rencontre des Jeunes Chercheurs

OUTLINE

- INTRODUCTION
- MADMAX
- PROTOTYPES
- CONCLUSION

Strong CP problem

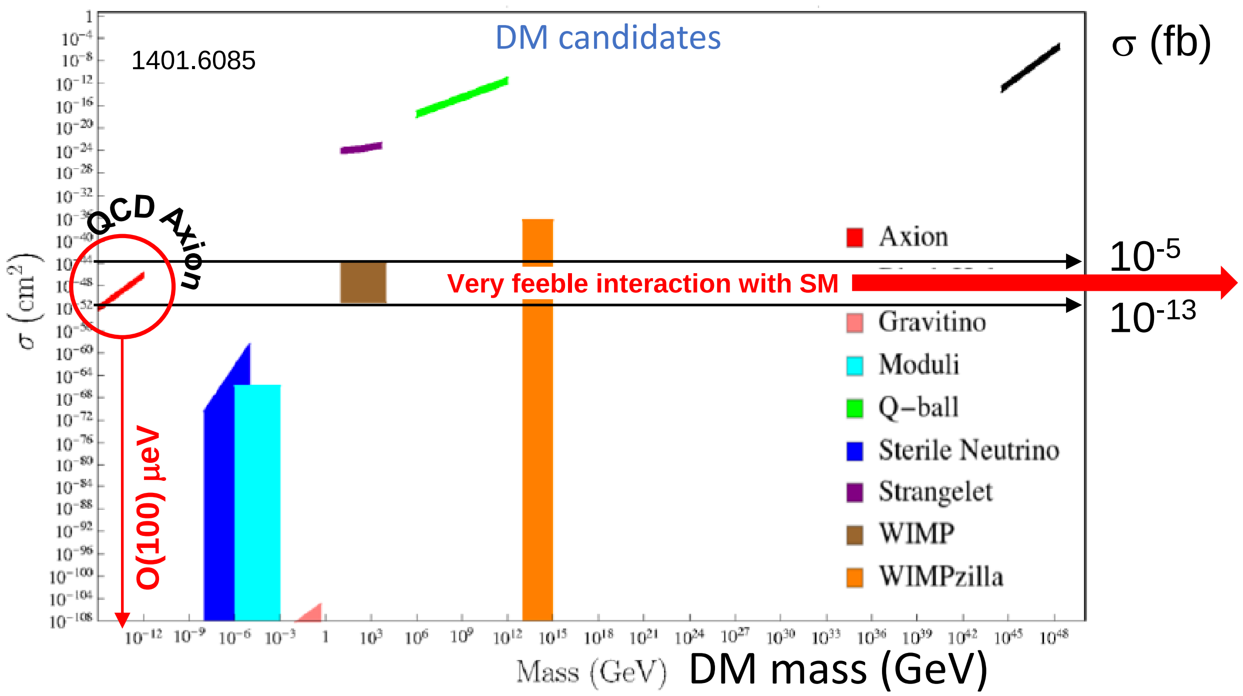
- QCD Lagrangian has a CP violating term that is controlled by θ parameter
- It leads to a neutron electric dipole moment
- Current experiments give upper bound of dN < 10^{-26} e · cm · θ leading to $|\theta|$ < 10^{-10}
- Strong CP problem: The standard model has no explanation for such a small value of θ
- Peccei – Quinn mechanism: introduction of a new symmetry which is broken at some energy scale to generate a goldstone boson called **'Axion'** to suppress the CP violation

DARK MATTER

- Various cosmological observations of gravitational lensing, galactic rotation curves, CMBR, etc point toward the existence of invisible ‘dark matter’ that interact very weakly with standard baryonic matter
- The dark matter is five times more abundant than baryonic matter
- The self interaction of dark matter particles is weak -> cold dark matter
- Dark matter density in our galactic halo: O(0.1) GeV/cm3
- Should be made of extremely stable particles that do not decay into standard model particles
- Many candidates for the particle dark matter: WIMPs, **Axions**, etc.

Visible matter in X-ray in pink and matter distribution calculated from lensing in blue. Credits: NASA

AXION PHASE SPACE

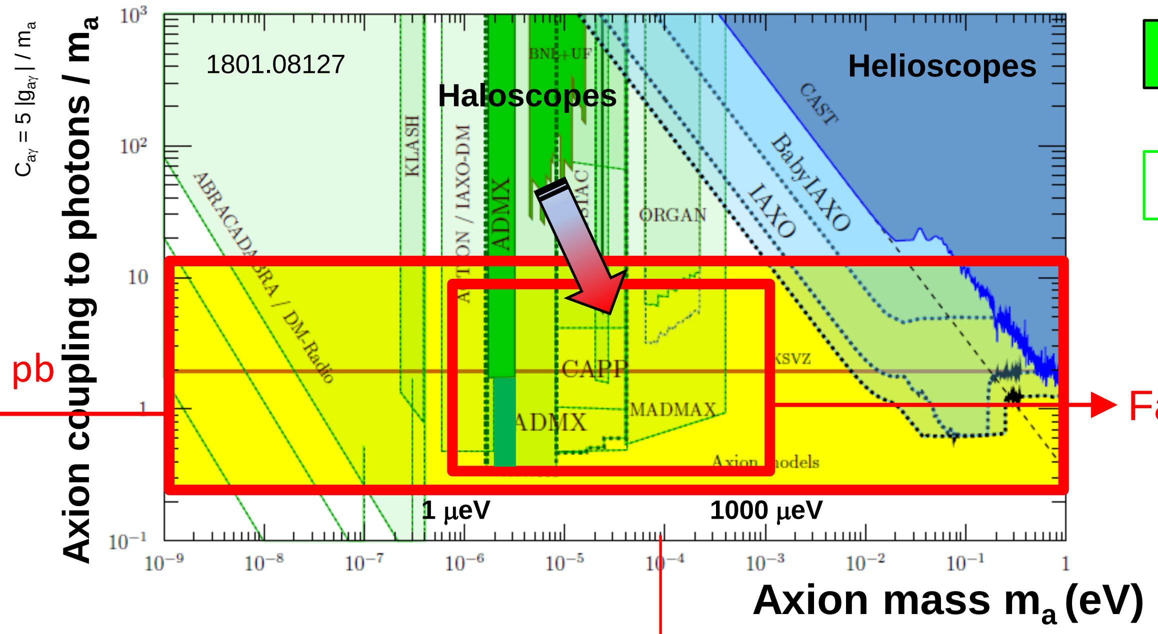


For a haloscope, this is balanced by a huge flux from our galaxy halo → O(0.1) GeV/cm^3 moving at v=10^{-3}c wrt earth

AXION MASS RANGE

[post-inflationary scenario suggests m_a ~ 100 μeV]

QCD-axion, i.e.
solving strong CP pb



2020

2030

Favored axion DM
phase space

- Tiny mass & interaction → Very feeble signal

Challenge: Boost the signal

Traditional cavities unable to probe higher mass ranges > 10 μeV

New technologies are needed to access the mass range > 10 μeV

OUTLINE

INTRODUCTION

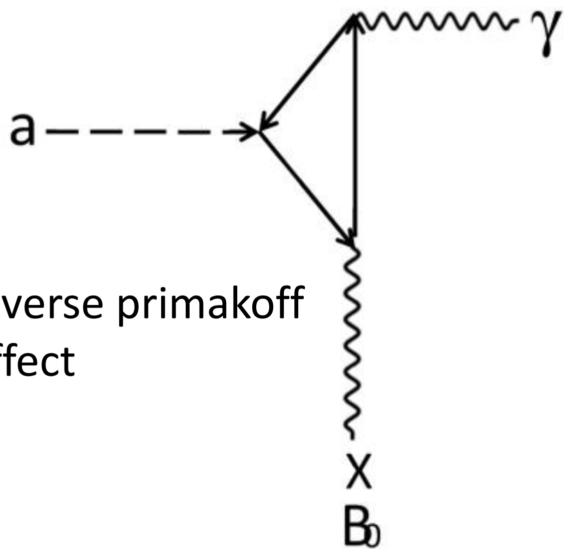
MADMAX

PROTOTYPES

CONCLUSION

❑ MADMAX : a dielectric haloscope

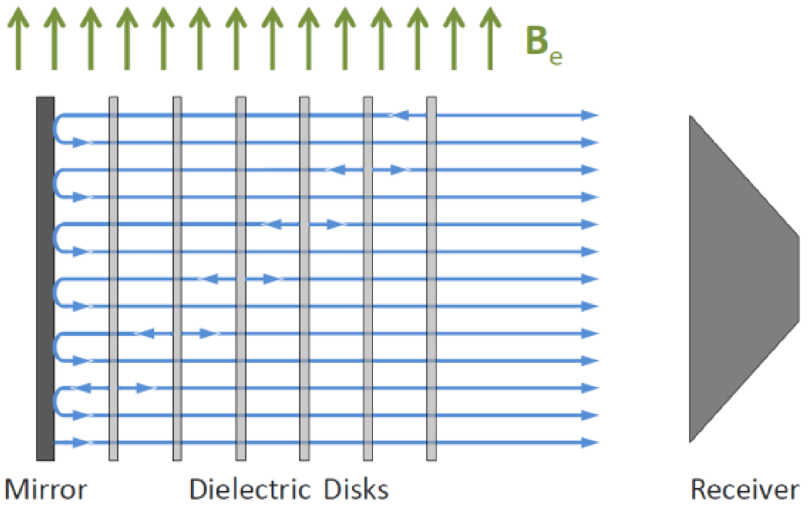
- **Constructive interference** (and resonance) of coherent photon emission at dielectric layers surface (~leaky resonators cavities)



Inverse primakoff effect

$C_{a\gamma} = 5\text{ GeV } |g_{a\gamma}| / (m_a / 1\text{ GeV})$

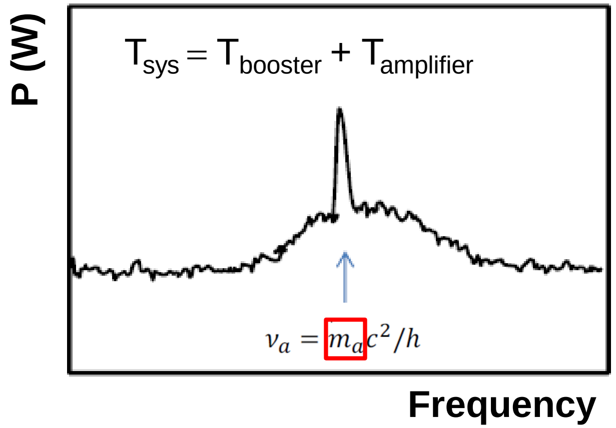
$$P_{sig} = 10^{-22}\text{ W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\text{ T}}\right)^2 \times \left(\frac{A}{1\text{ m}^2}\right) \times C_{a\gamma}^2$$



Booster

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

Thermal Noise



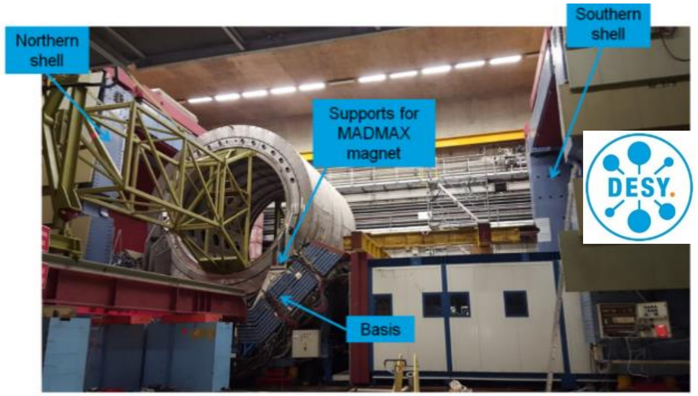
- **Axion mass scan** : by moving discs with μm precision piezo motors at 4K under 10 T *(50 MHz step)*
- ***The new concept of Dielectric Haloscope needs to be validated***

The MADMAX Collaboration

Formed in 2017. 10 institutes: French (2), German (6), Spanish (1) and US (1) → ~50 people

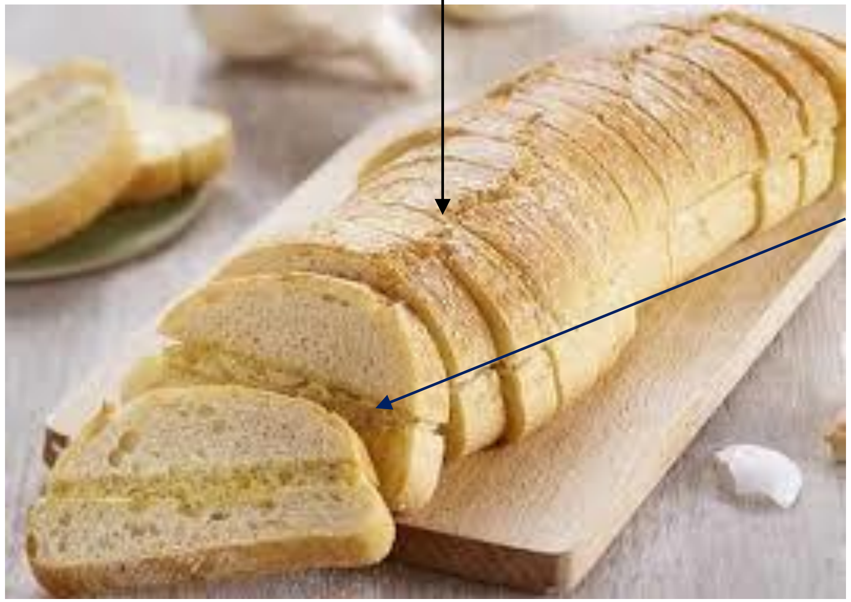
The MADMAX Collaboration

Photon **RE**sonator **F**or axi**O**n in **U**niverse **(Prefou)** Haloscope



Experiment location: HERA H1 iron yoke in DESY, Hamburg

25 layers of fresh Préfou



A layer of butter and garlic that will entice the axions to interact

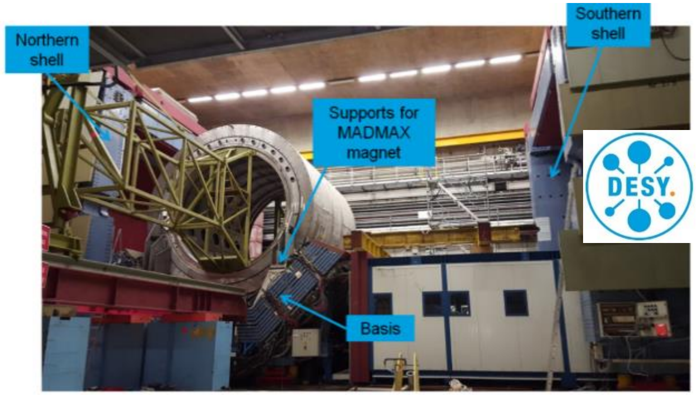
Novel concept

Cutting edge research

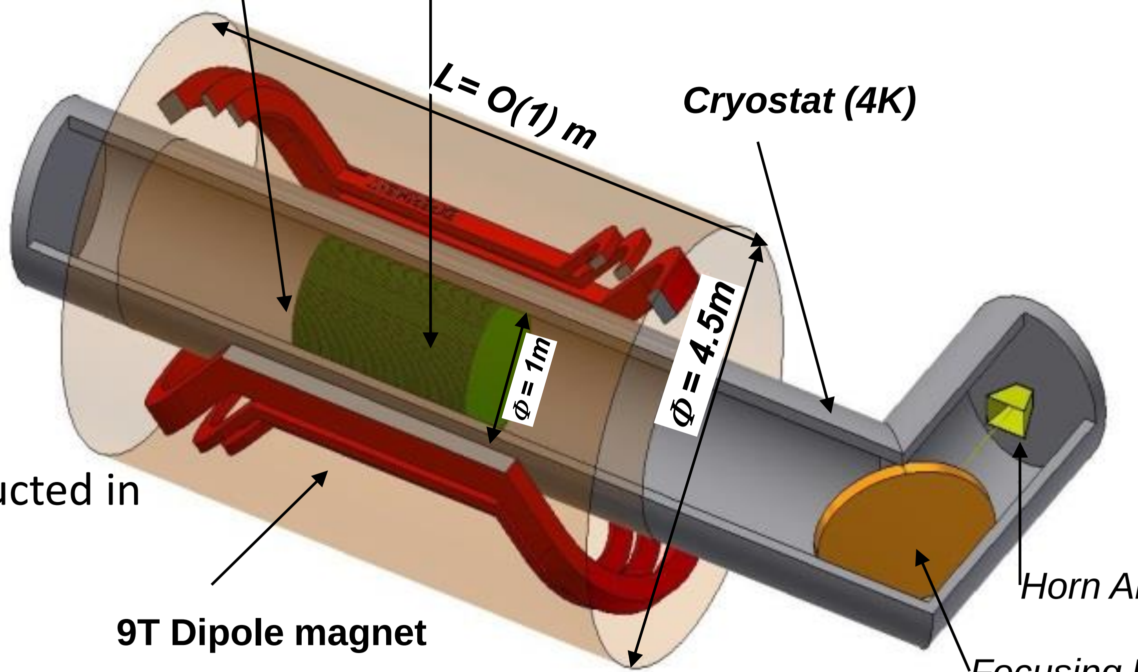
Final experiment design

The MADMAX Collaboration

Formed in 2017. 10 institutes: French (2), German (6), Spanish (1) and US (1) → ~50 people



Experiment location: HERA H1 iron yoke in DESY, Hamburg

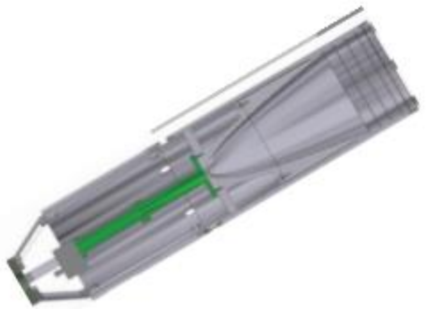


To be constructed in 2028

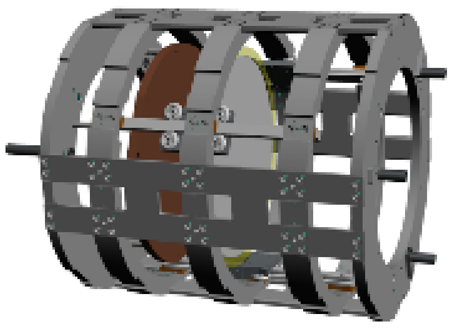
[Eur. Phys. J. C **79** (2019) 186]

Experimental Challenges :
- **High B-field**
- **Low Temp. (4 K)**
- **μm precision for mechanics**

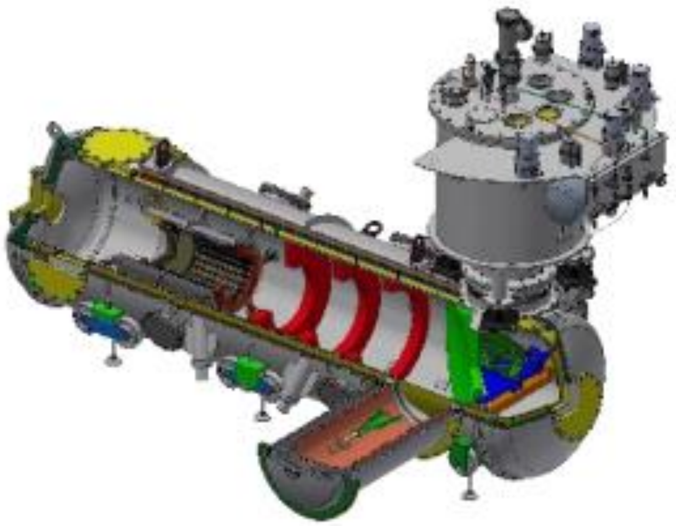
Construct several **prototypes** to validate the key technologies :



CB100



P200

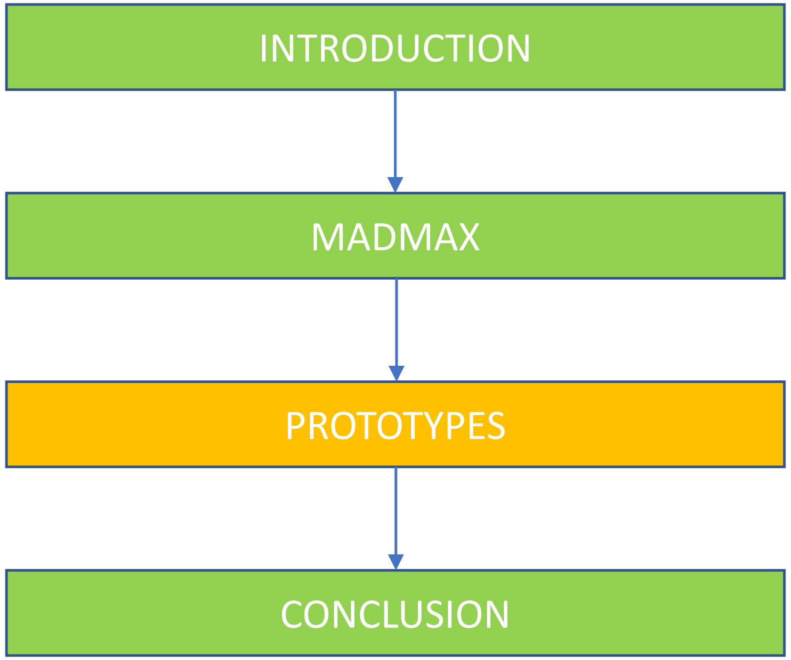


OB300

Name	Setup	Goal	Available
CB100	3 fixed disks, ϕ = 100mm	RF studies + First physics	2021
P200	1 moveable disk, ϕ = 200 mm	Piezo-motor + mechanics	2021
OB300	3 moveable disks, ϕ = 300 mm	Scan ALP around 100 μeV	2024

Prototypes to probe the region:: ma ~ 80 μeV, f ~ 20 GHz

OUTLINE

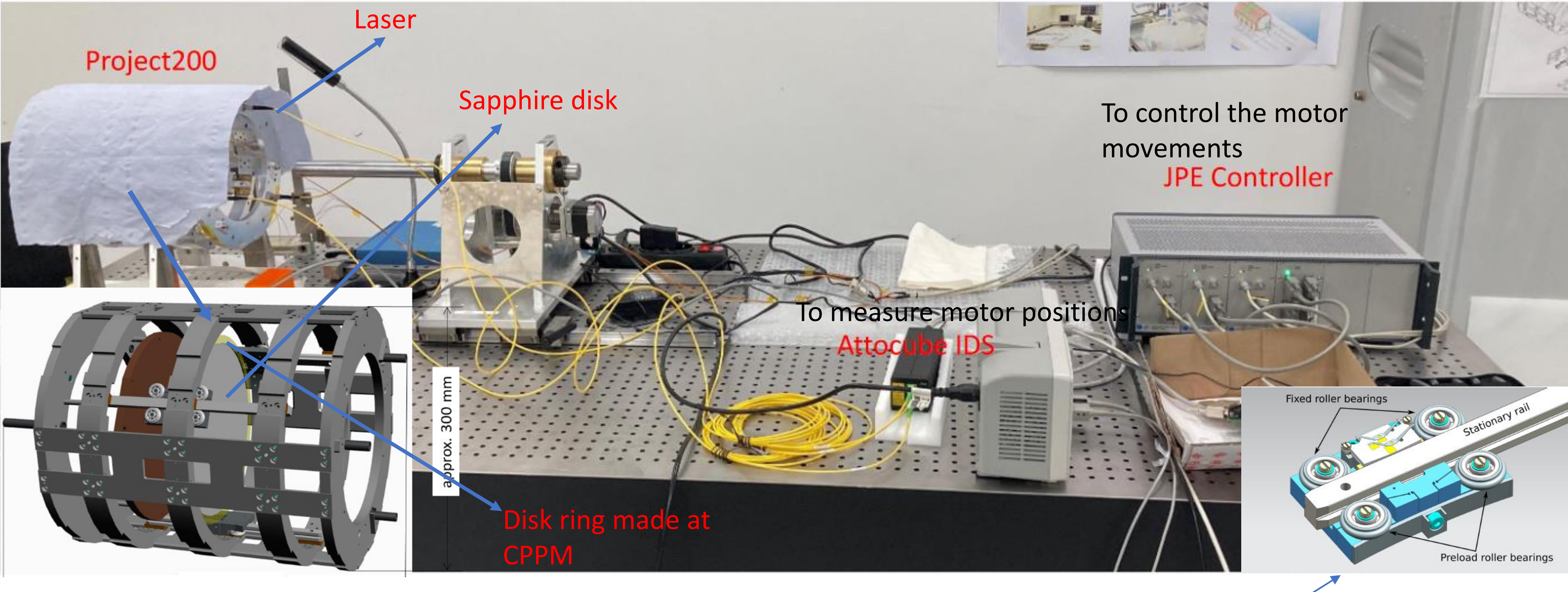


P200: data analysis and summary plots

CB100: preliminary data analysis of the physics run at CERN

OB300: Simulations to optimize the boost factor

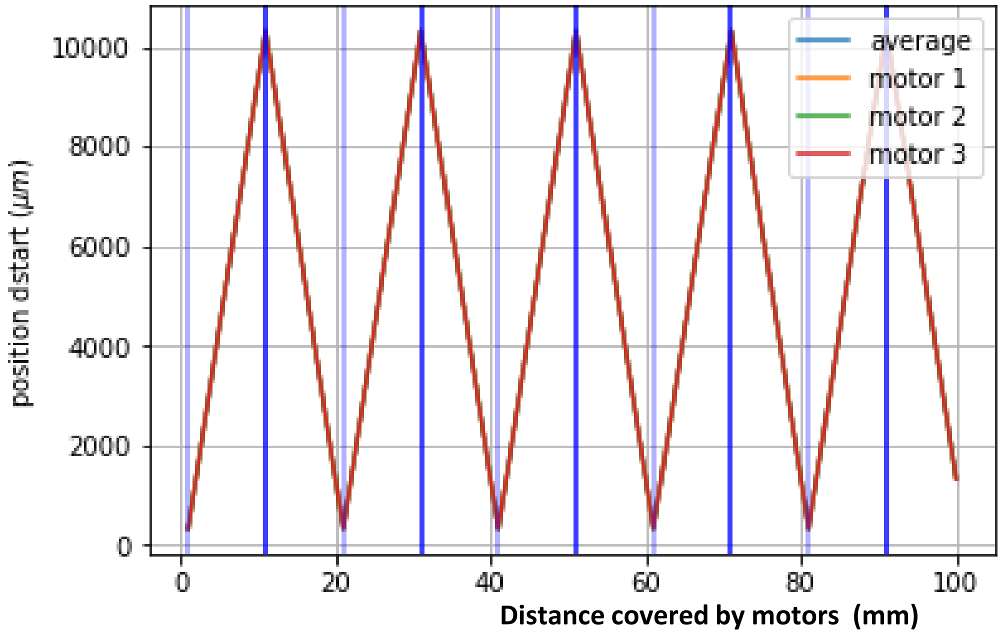
P200 : testing the piezo motors

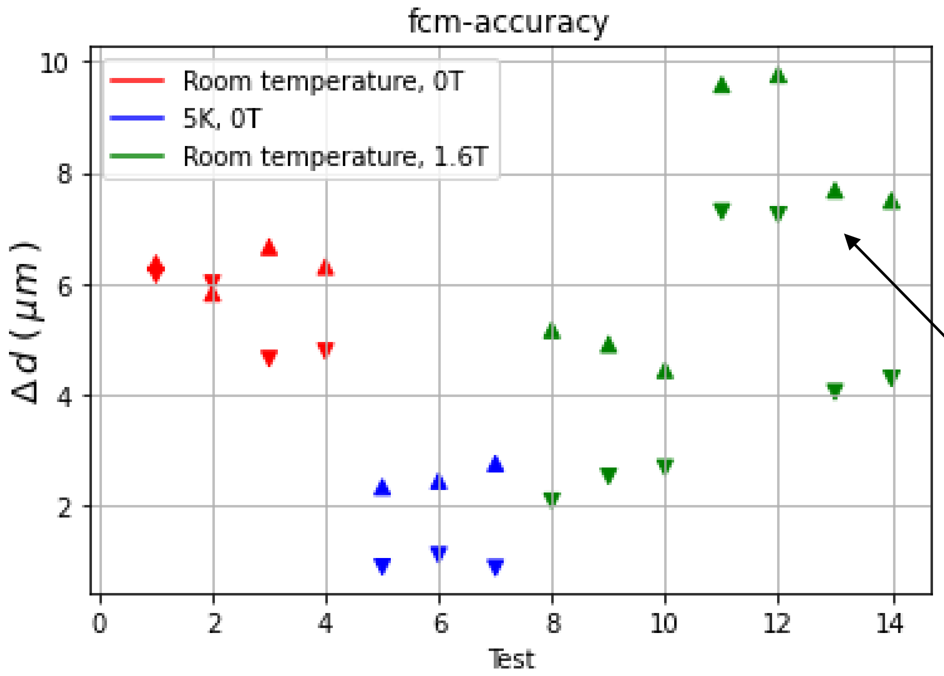


- Principle of the measurement: precise control of 200 mm diameter sapphire disk position with three piezo motors
  - Move the motors using a controller
  - Motor positions measured using laser interferometers and tiny mirrors on the disk with precision better than 100 nm
  - Position error Δd = target position (provided to the controller) – actual position (measured by the interferometer)

P200 : measurement results

- The motors were tested in 2022 at room temperature (DESY), at cryogenic temperatures (CERN), and in magnetic field (CERN MORPURGO)
- I performed some data analysis to produce summary-benchmark plots of the tests



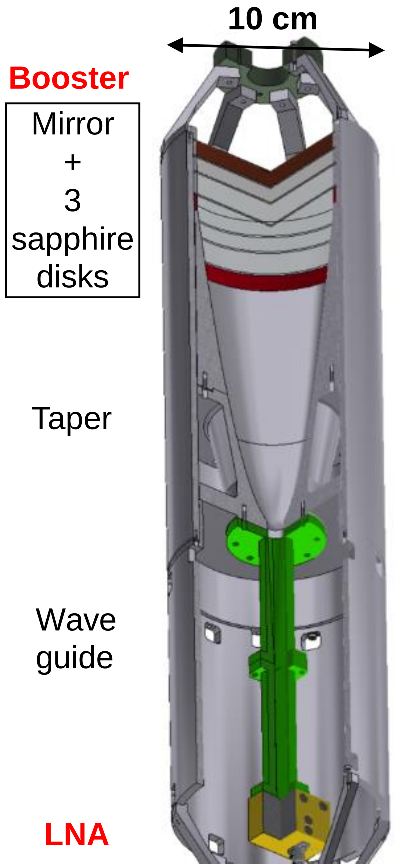


The triangles show the measured position error during forward and backward motion

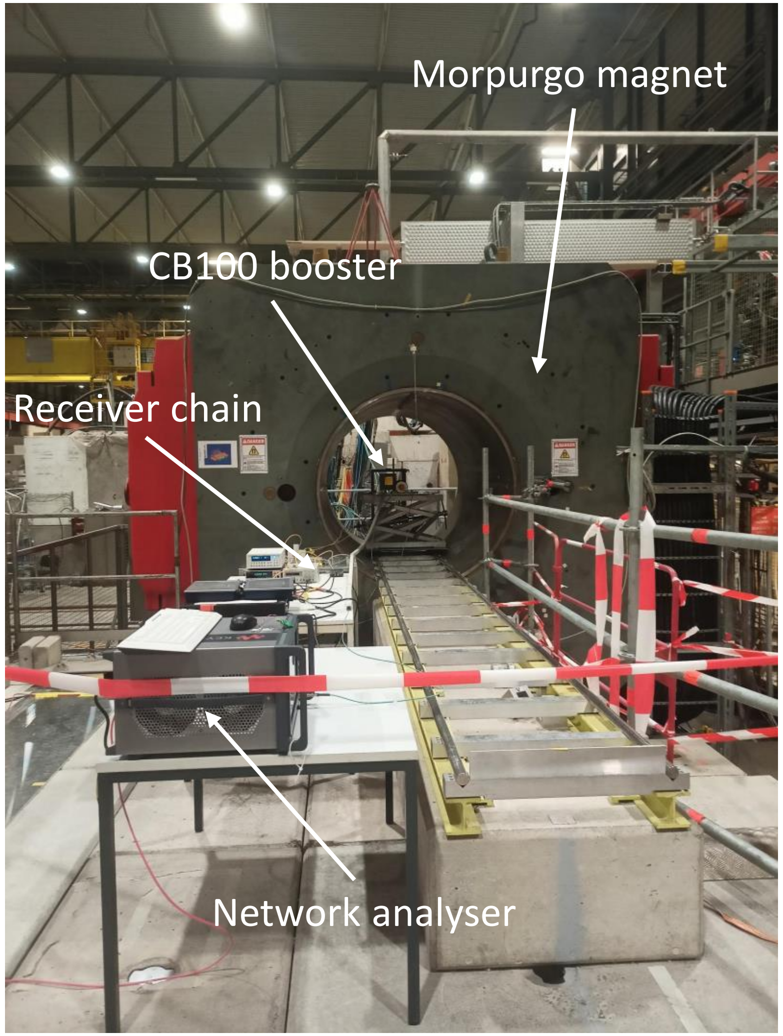
➔ Motors/mechanics work at cold temperature (5K) and high magnetic field (1.6 T)
➔ The accuracy of piezo motor positioning better than 10 µm
➔ Paper in preparation

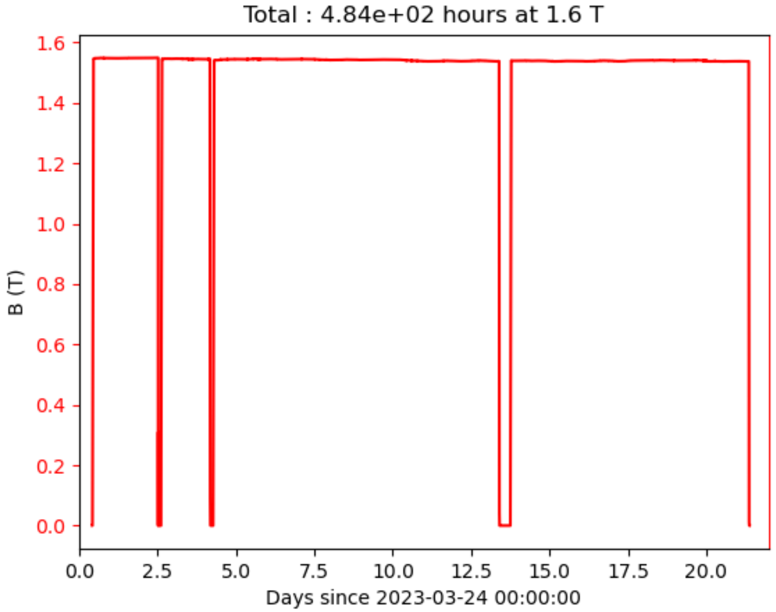
CB100 experimental run at CERN

Goal: To understand the RF response of the system and perform an ALP search



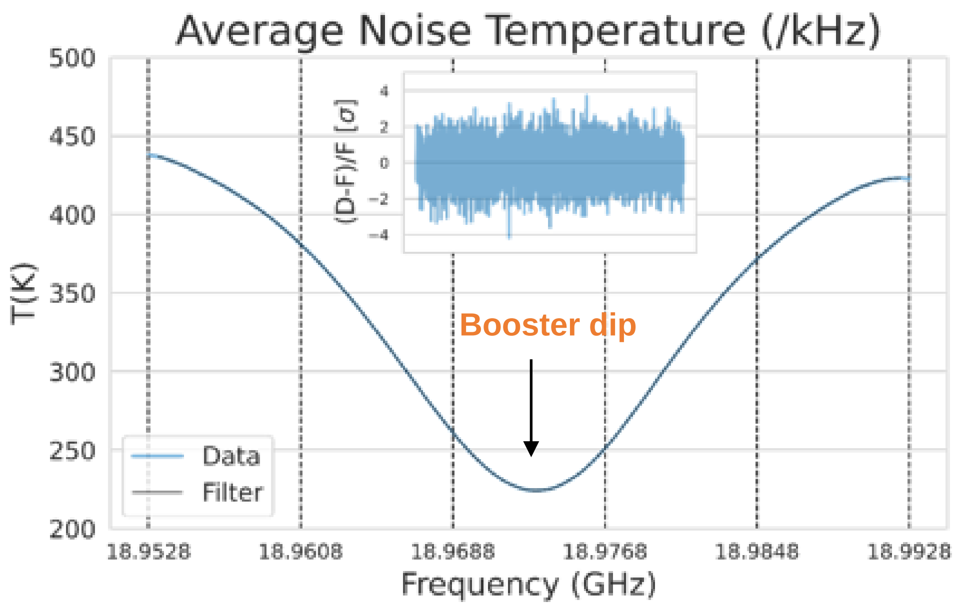
CB100 booster prototype



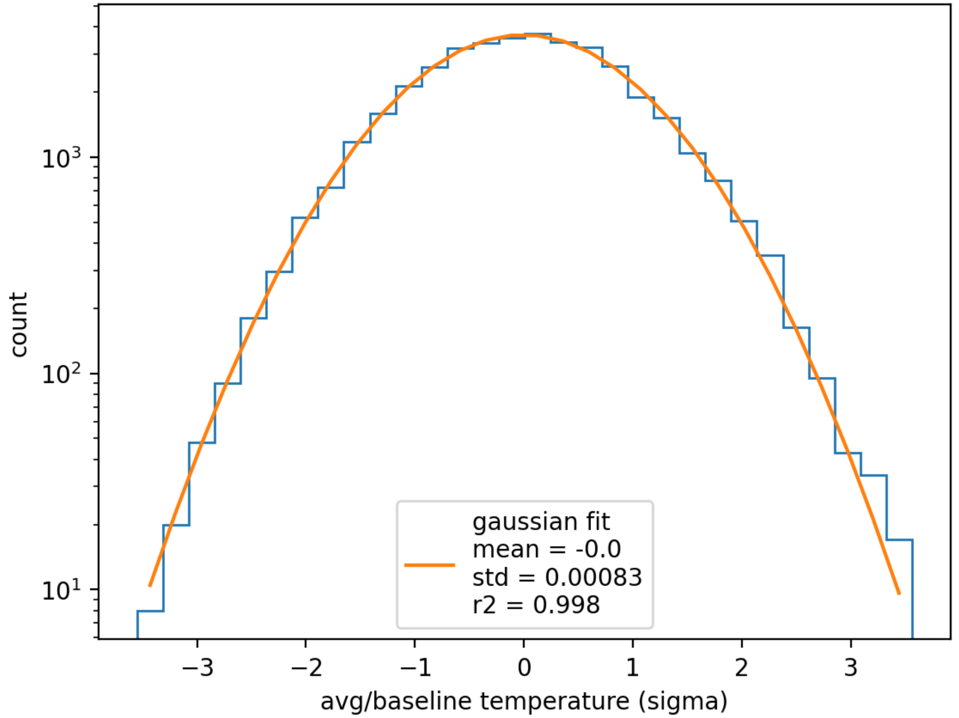


Magnetic field availability was very stable - 95% availability during 21 days of data taking

CB100 experimental run at CERN 2023



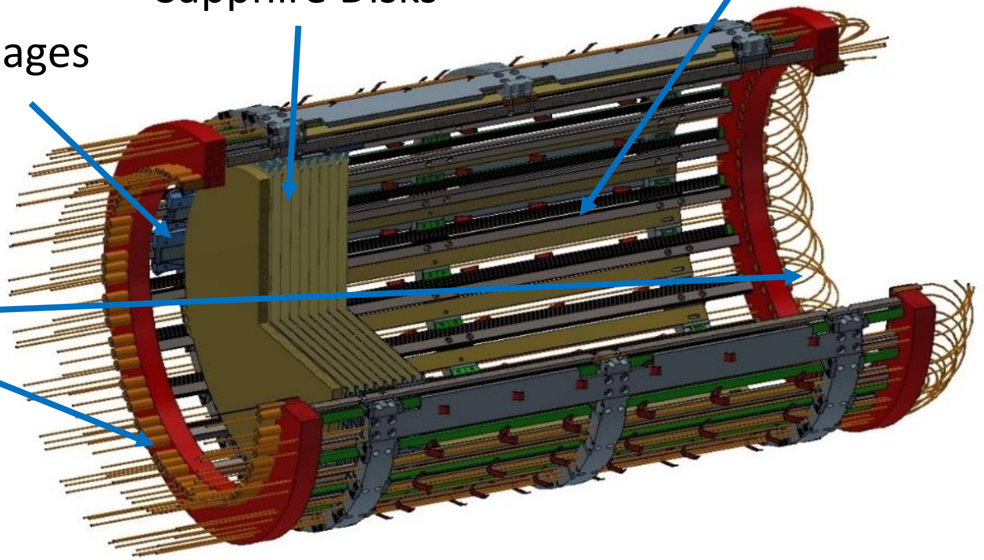
The averaged signal observed at the spectrum analyser (blue curve). A Savitzky-Golay filter is applied to the data (purple curve) which is almost superimposed on the blue curve. The top subplot shows the residuals in the data due to noise.



The gaussian function fits very well to the residual. This shows that there is no anomalies/axion signal in the data.

➔ Analysis on going … Paper in preparation

OB300 Booster

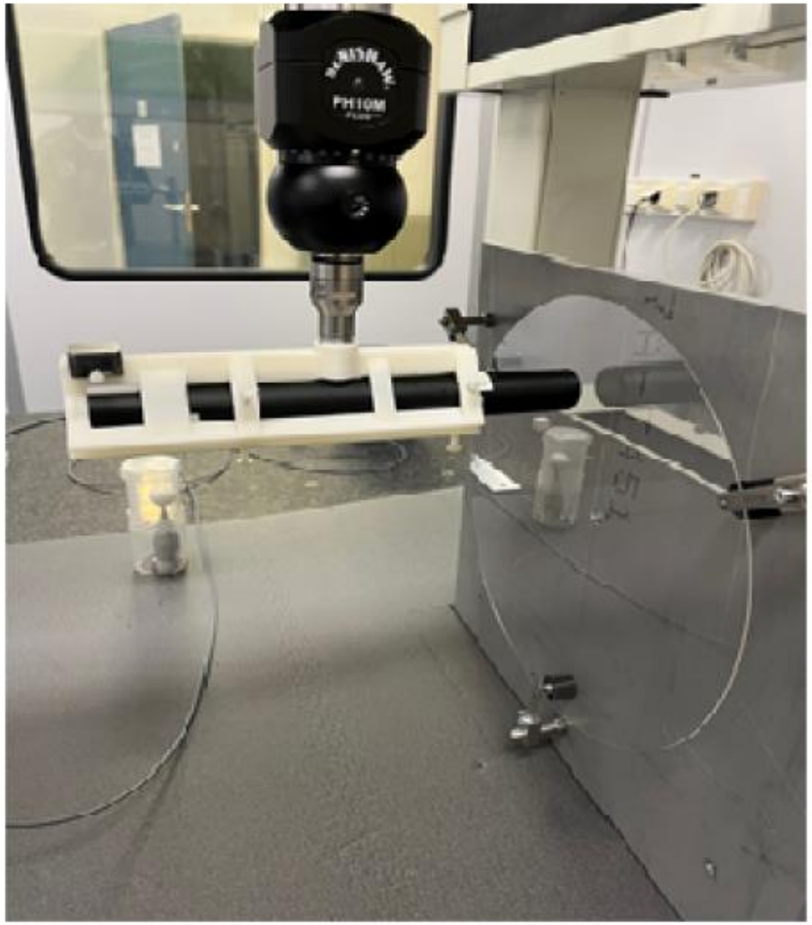


To be assembled in Hamburg
December 2023

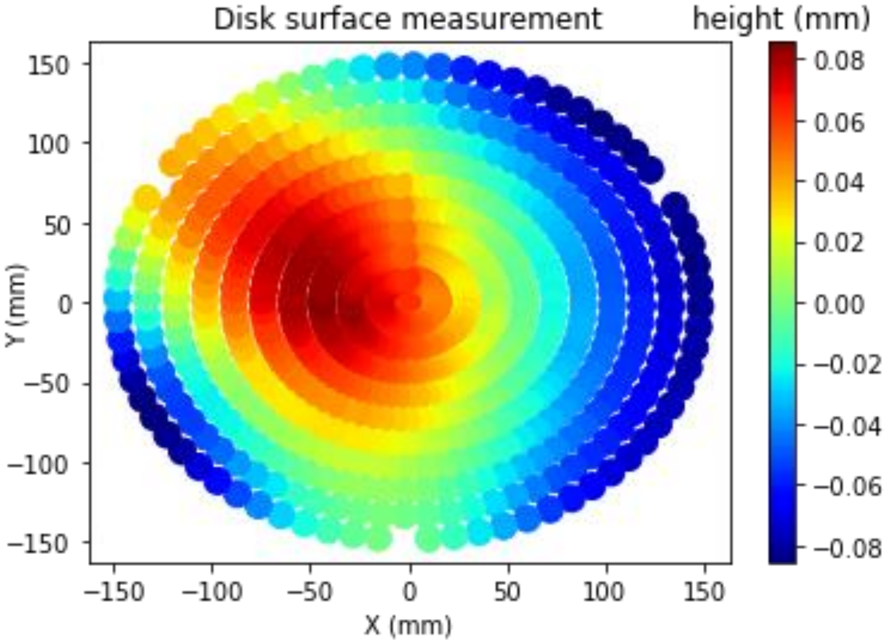
The goals of the study:

1) Measure the disk planarity,
2) Perform simulations to decide on the order and position of the disks to obtain the best boost factor,
3) Predict electric field and compare it with measurements.

OB300 : Disk measurement

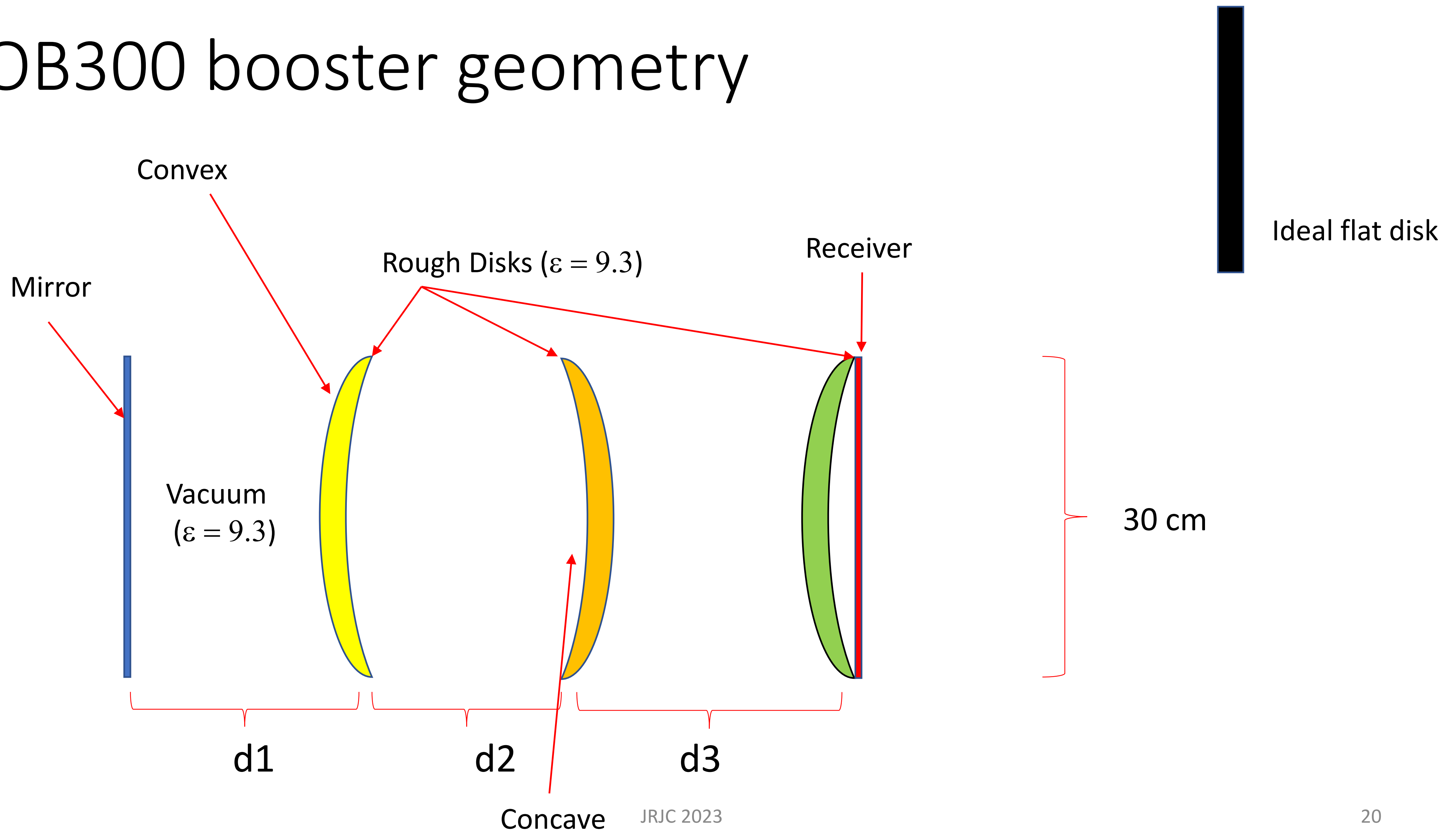


Planarity of 4 sapphire disks of 300 mm diameter and 1 mm thickness were measured at CPPM with O(1) μm precision



The planarity scatter plot with ~500 points of measurement. The colors show the variation in the height of the sapphire disk surface. The min-max variation of surface height is ~200 μm with 52 μm RMS deviation. All the disks appear to be in a somewhat bowl shape.

OB300 booster geometry

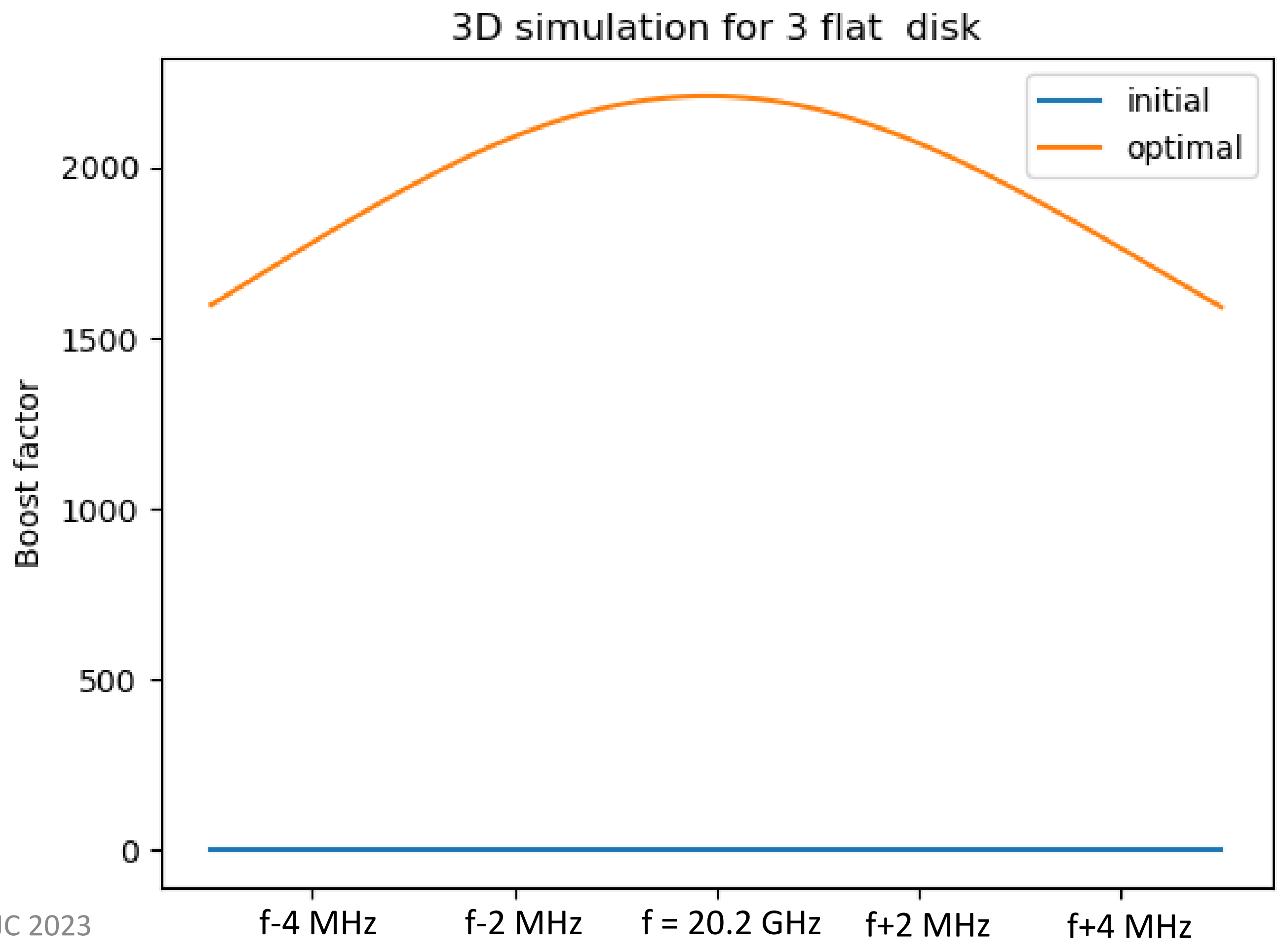


OB300 : boost factor simulation

```
Initial distance: [7.42, 11.13, 11.13] mm
Optimized distance: [7.72, 10.78, 11.13] mm
Boost factor peak: 2209
```

Simulation using a software package developed by the MADMAX collaboration based on the theoretical paper: arXiv:1906.02677

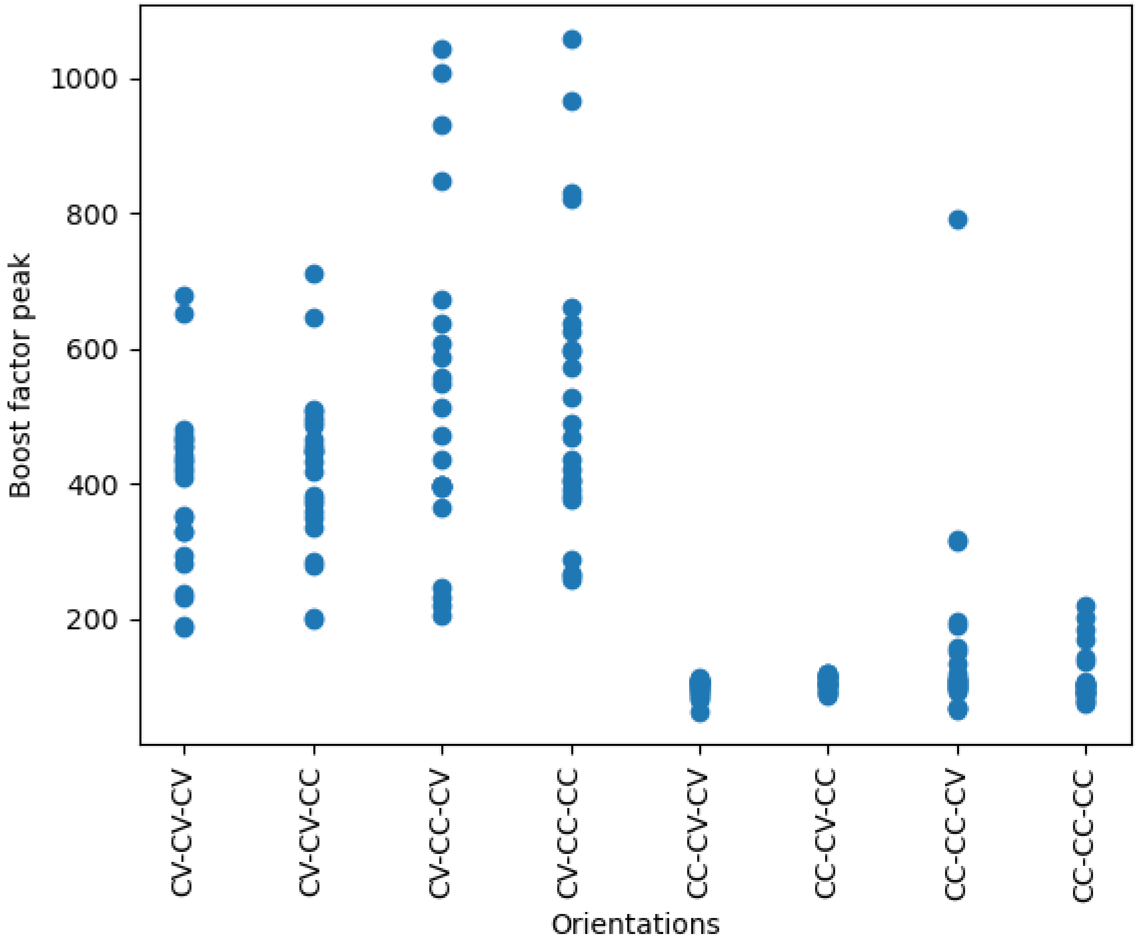
- Calculate 'Boost Factor' (power from the booster setup compared to the power from just a mirror) by Fourier propagation of EM fields in a given booster geometry
- Starting from an initial distance, the optimizer tries to maximize the boost factor by varying the distances
- First result obtained using ideal flat disks to serve as a benchmark

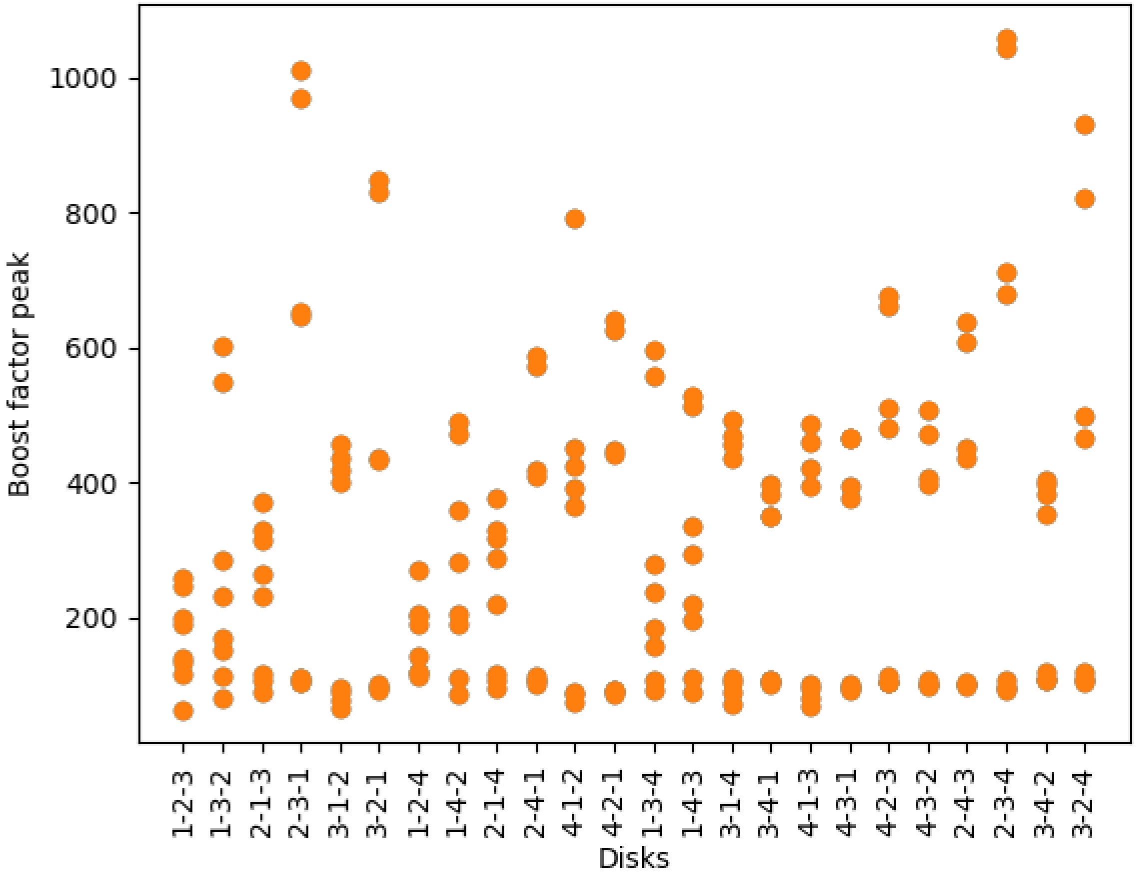


Optimizing the boost factor for 192 combinations of disks and their orientations

CC = concave, CV = convex

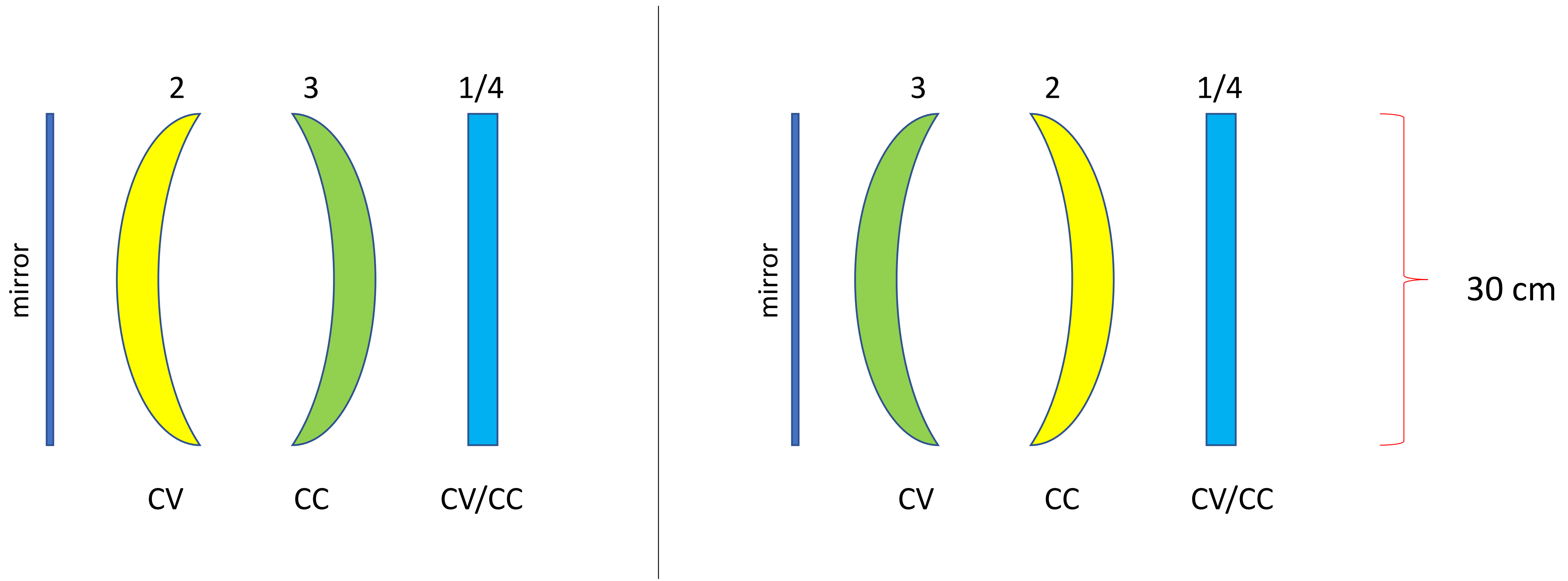
Work in progress





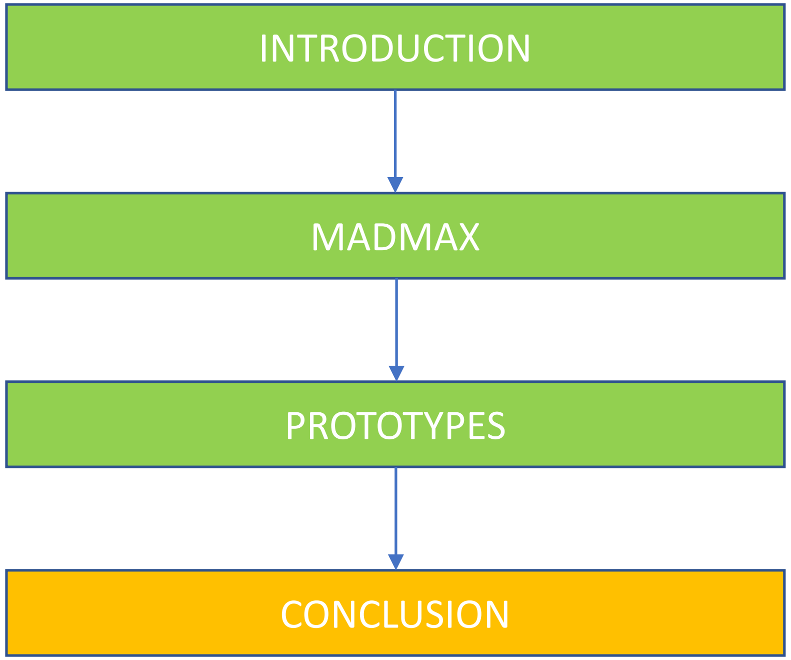
Top 8 configurations

Work in progress



Typical distances around 8-11 mm

OUTLINE

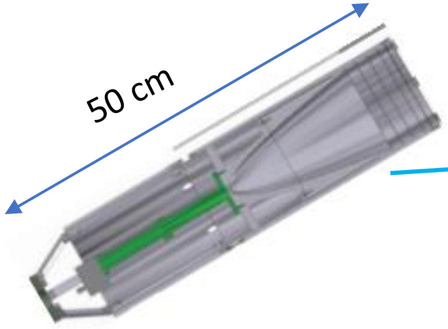


Plan for the coming years

Name	setup	Task
P200	1 moveable disk ϕ 200 mm	Analysis ongoing, a paper in making
CB100	3 fixed disks ϕ = 100mm	Analysing 2023 data, possible experimental run at cold and in magnetic field at CERN 2024
CB200	4 fixed disks ϕ = 200 mm	Possible experimental run at cold and in magnetic field at CERN 2024
OB300	3 moveable disks ϕ = 300 mm	Plan to analyse the calibration data and visit DESY again in December 2023.

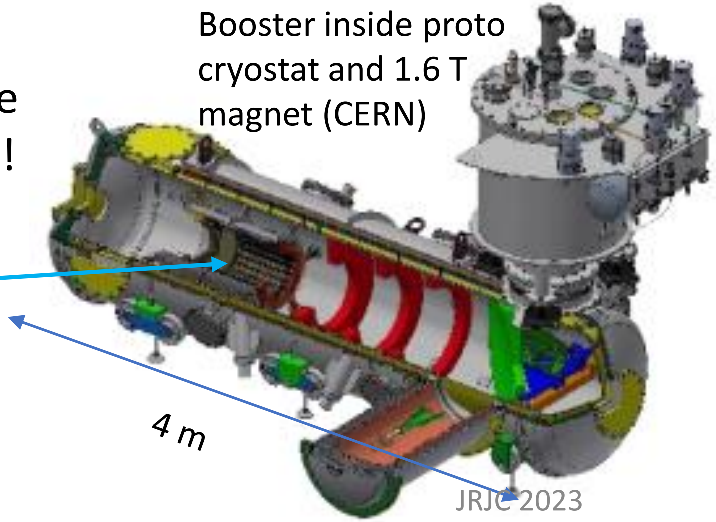
2021 → 2025 → 2028

Proto booster
CB 100

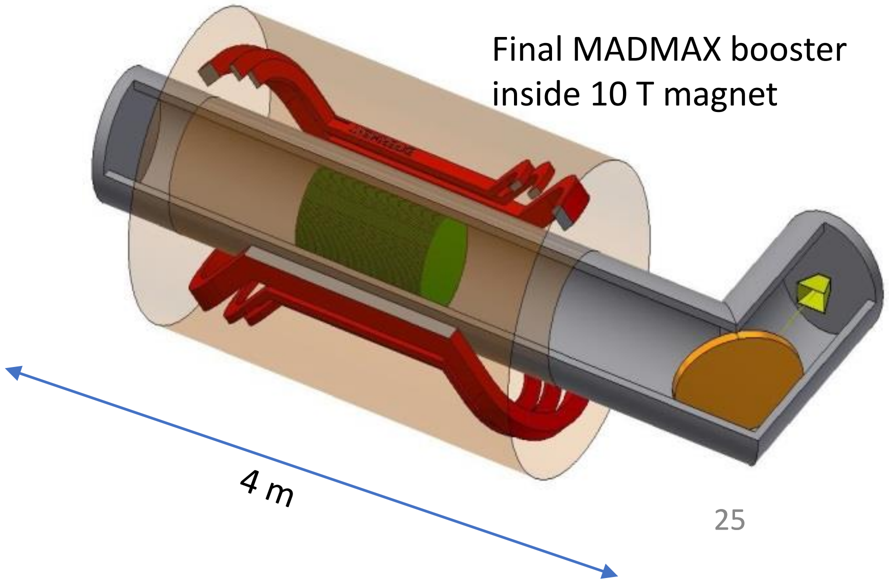


We are here!!!

Booster inside proto cryostat and 1.6 T magnet (CERN)



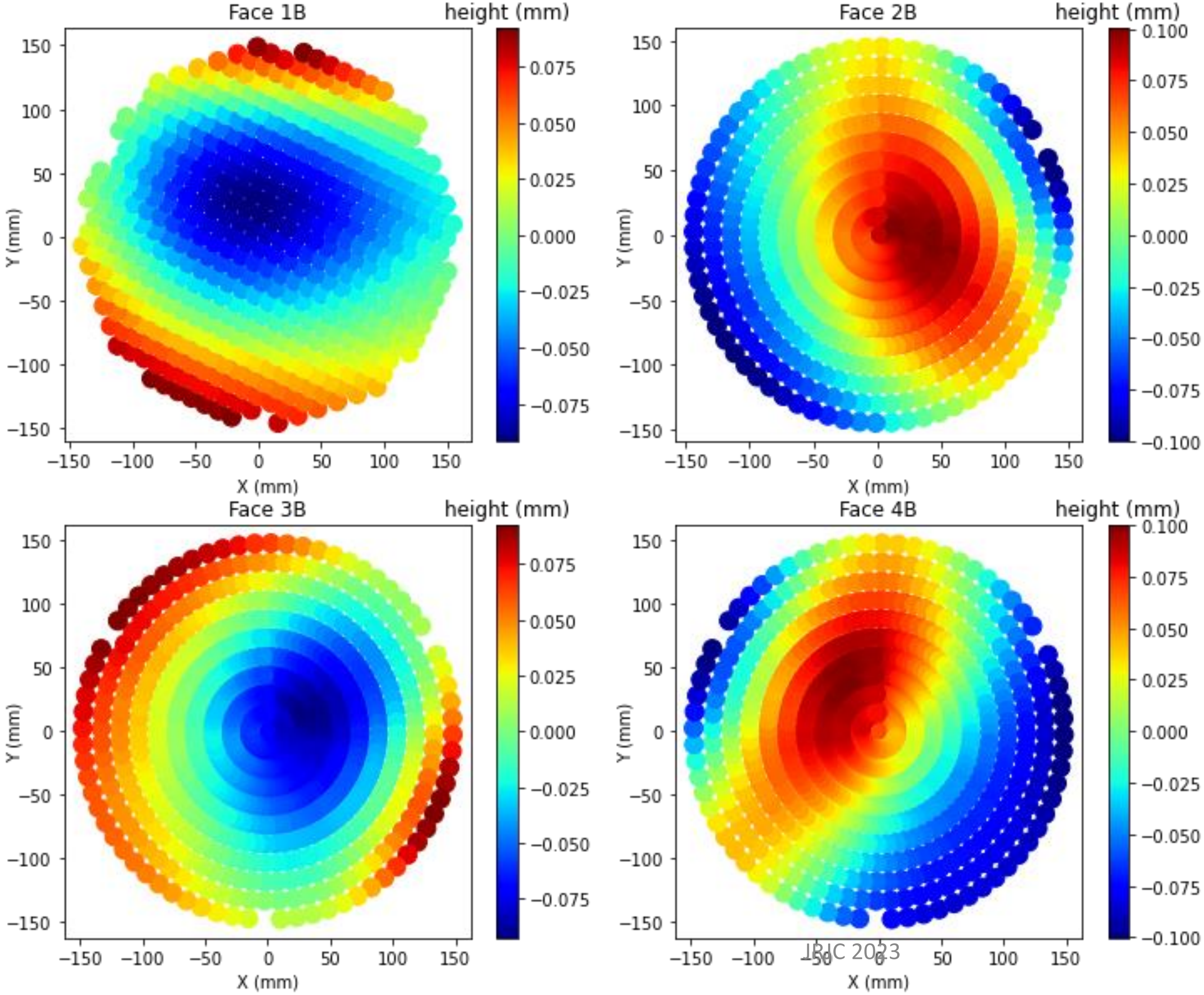
Final MADMAX booster inside 10 T magnet

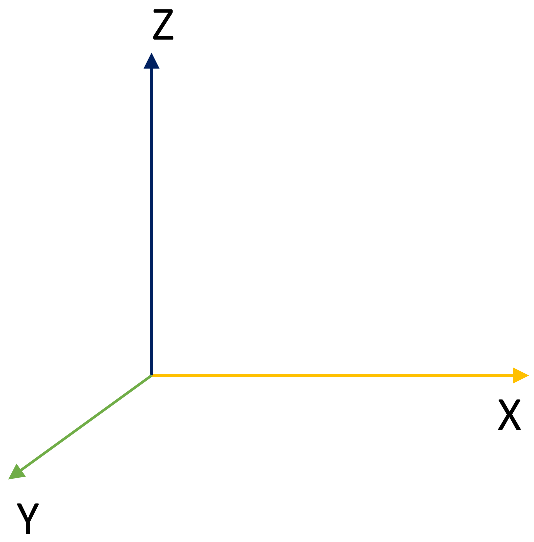


Thank you

Backup slides

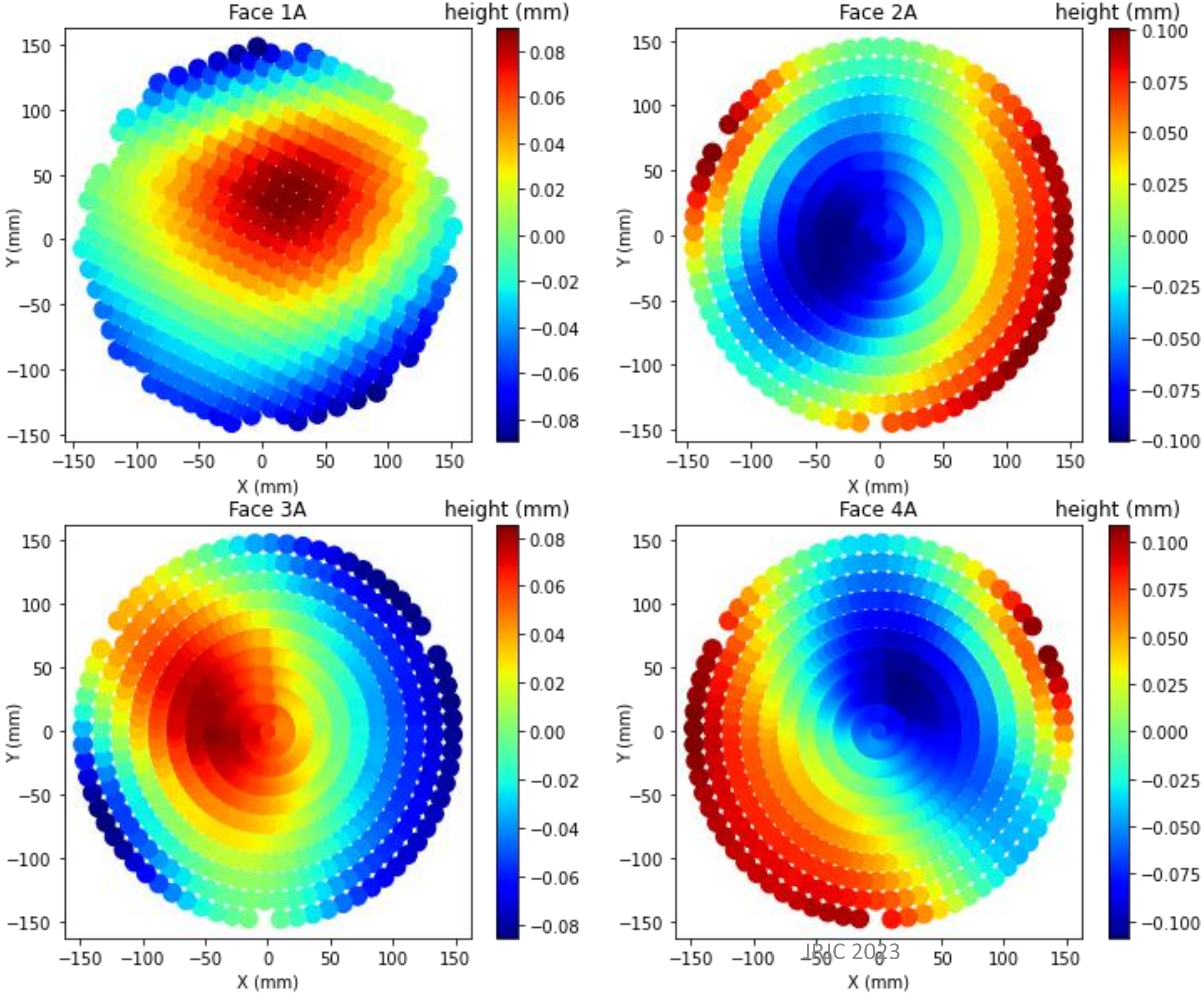
Disk raw measurements

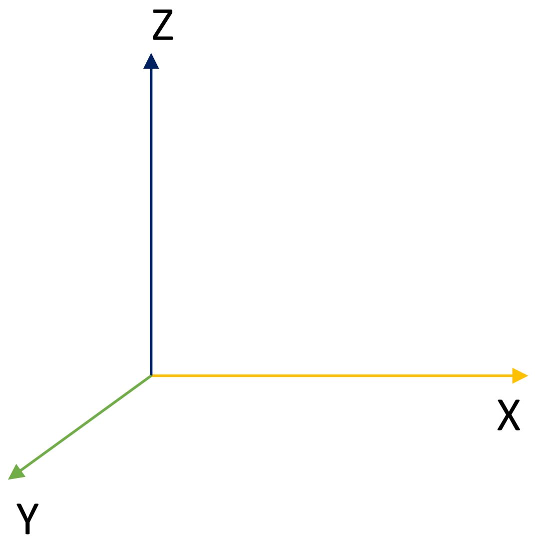




All the disk faces similar to each other

Disk raw measurements





Déformation 3D grossit x500

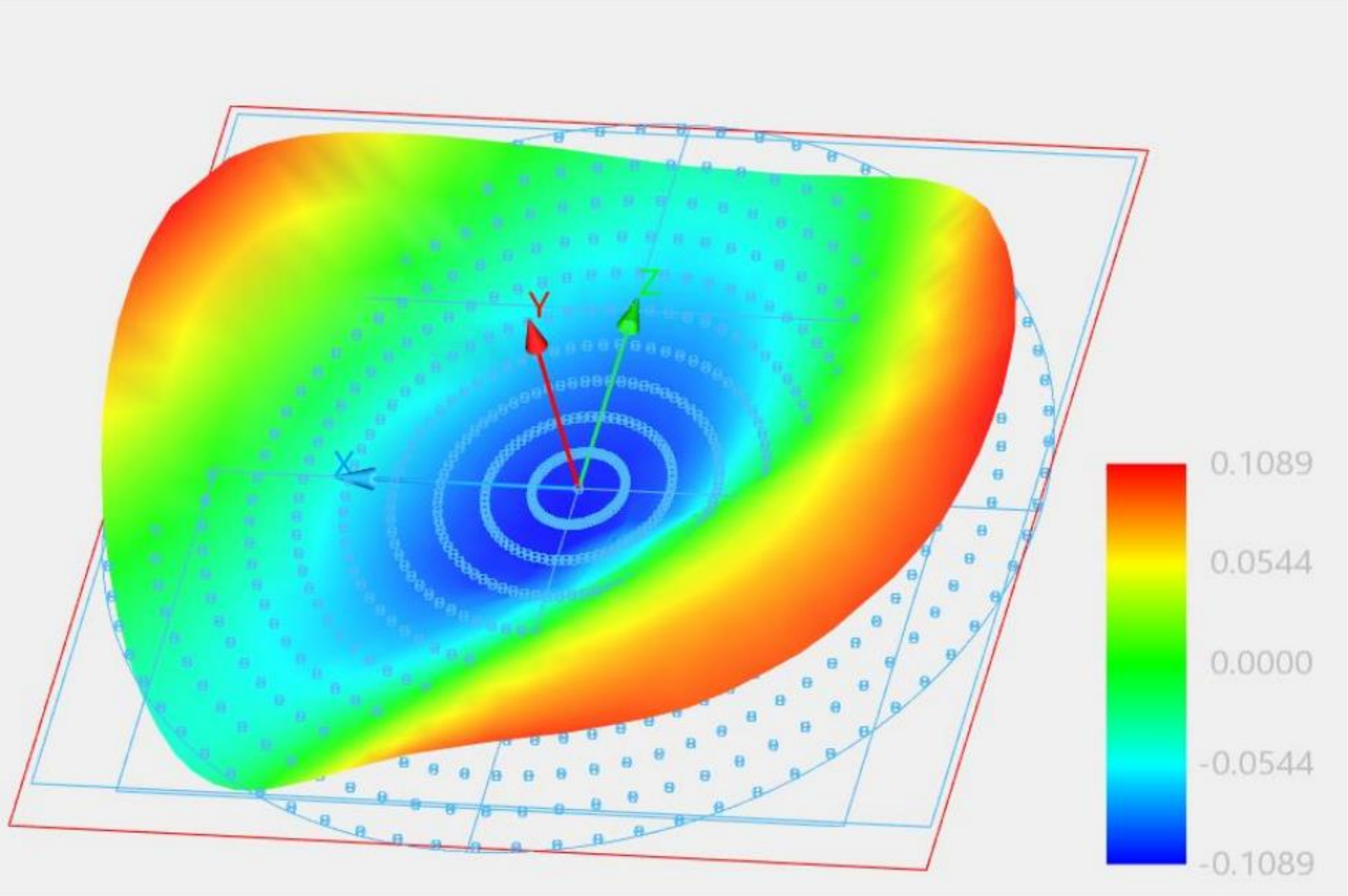
ID	PLN_3
Type	Plan, Tchebychev, Construction ı
Description	Plan Total Face A

Géométrie Détails Points

Date / Heure	21.03.2023	16:14:54
Points	718	
Ecart-type	0.0605	
Point / Min.	-0.1089	64
Point / Max.	0.1089	140
Etendue	0.2178	
Longueur	295.9551	
Largeur	295.6166	
Epaisseur matériau		

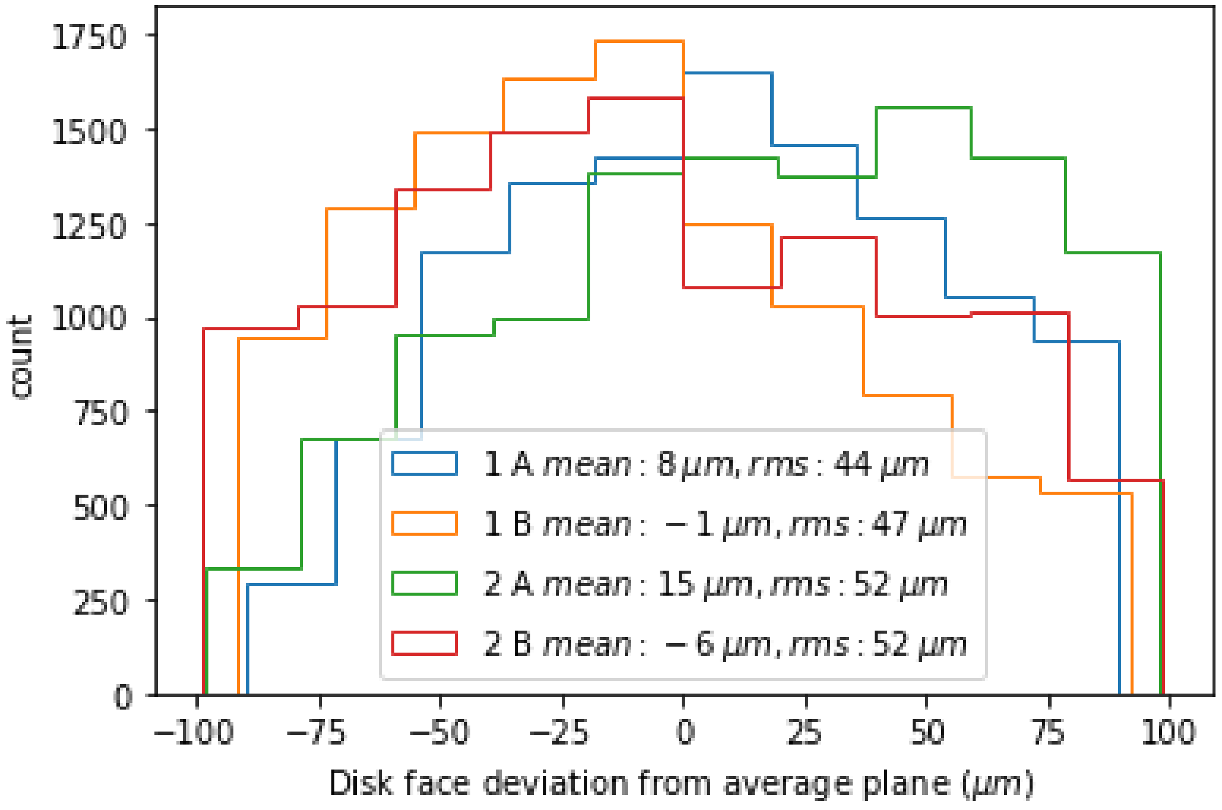
Tolérances et déviations

	Tol sup	Tol inf	Ecart	Graphiqu
x			0.0000	
y			0.0000	
z			0.0000	
R			0.2178	



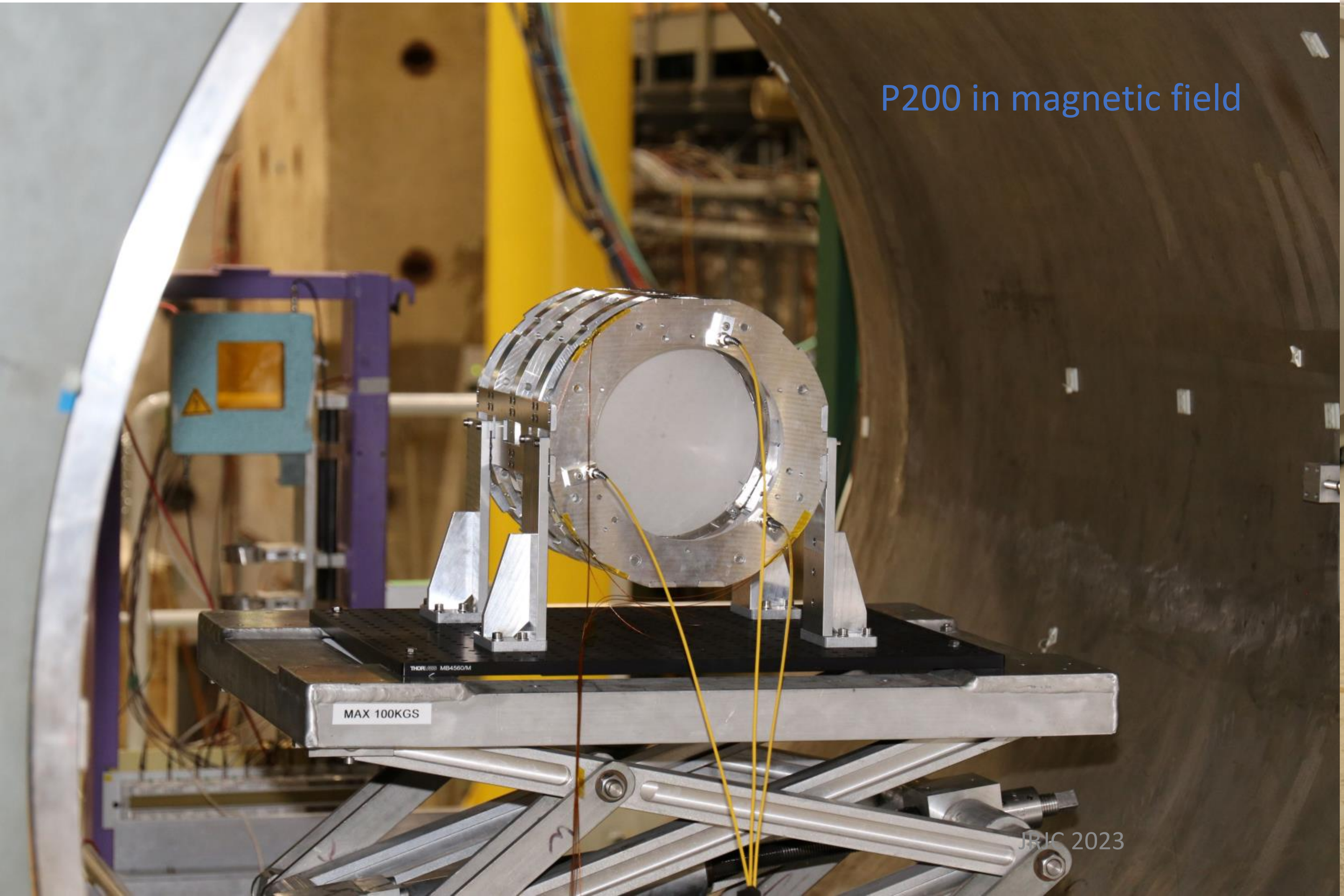
Disk 4 face A shape visualized by multiplying the surface height by 500

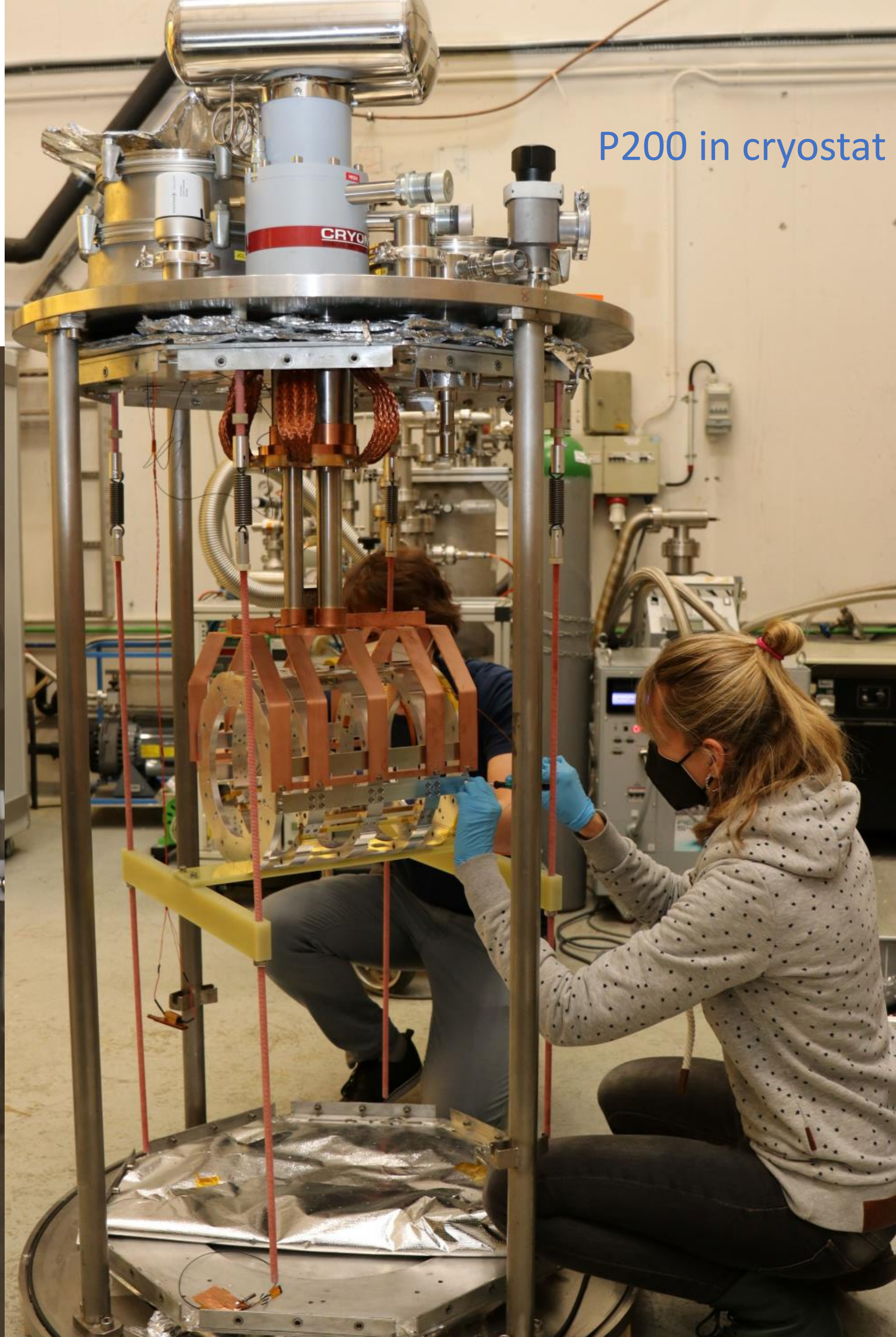
Using disk measurement interpolation 2.5 mm * 2.5 mm



Disk 1 faces has less deviations in the surface measurement (lower rms values) than disk 2

P200 tests



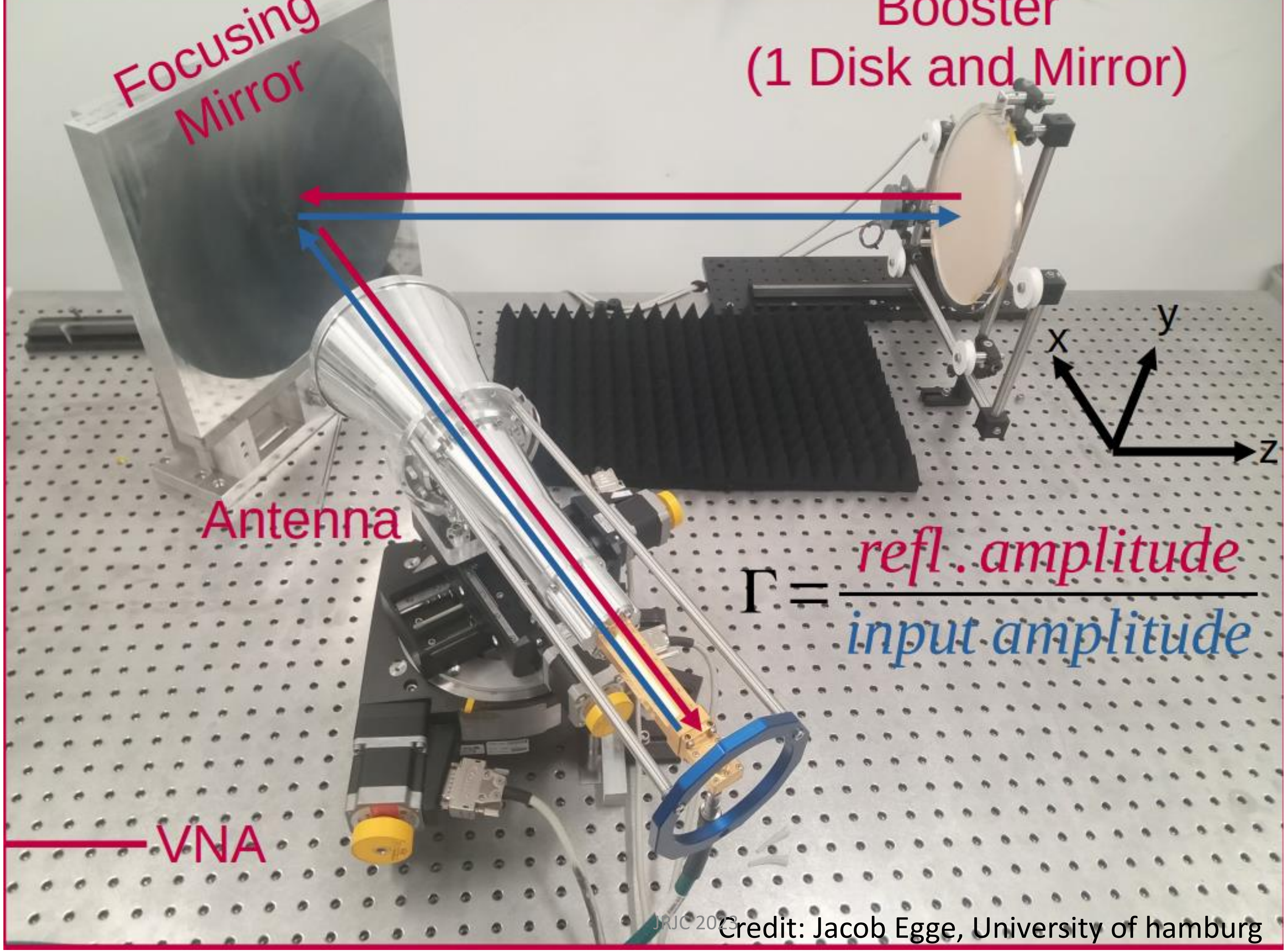


Booster calibration using the bead pull method

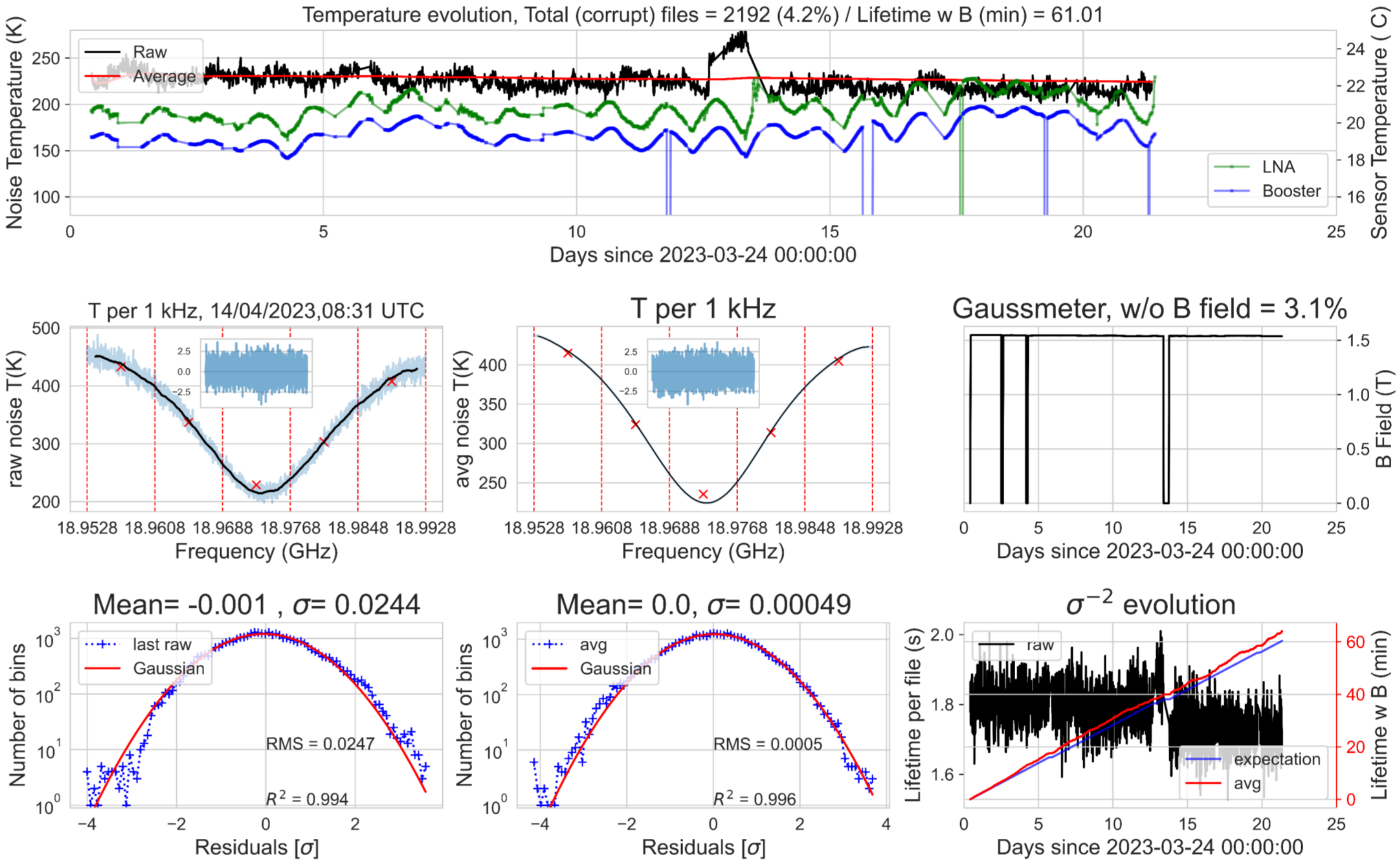
$$P_{sig} = \frac{g_{a\gamma\gamma}^2}{16\, P_{in}} \left| \int_{V_a} dV\, \mathbf{E}_R \cdot \dot{a}\, \mathbf{B}_e \right|^2$$

Electric field excited
by reflection
measurement

$$\mathbf{E}_R^2 = \frac{4\, P_{in}}{\alpha_e\, \omega} \Delta\Gamma$$



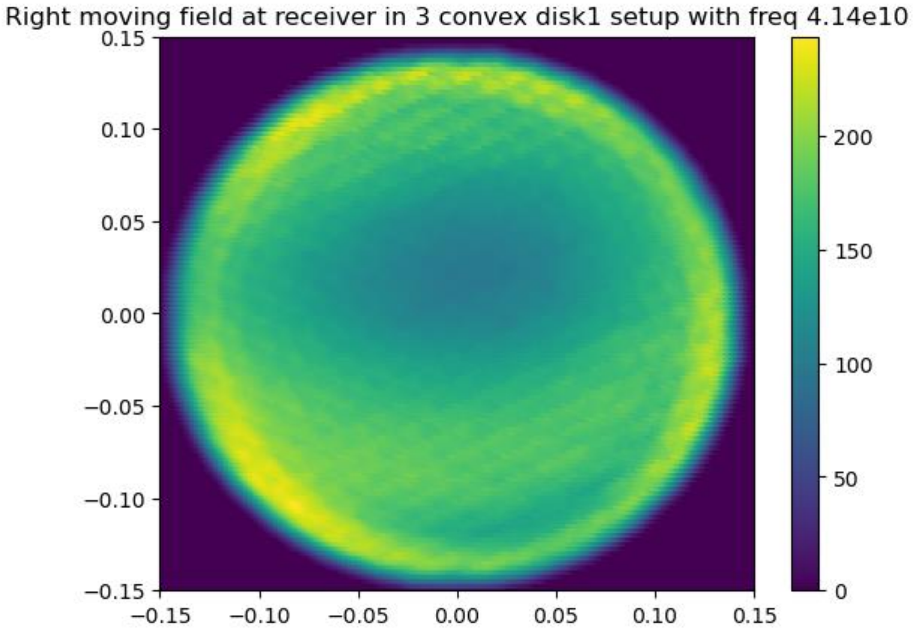
Credit: Jacob Egge, University of hamburg



Credit: Juan Maldonado, MPP Munich

Validation of the simulation method

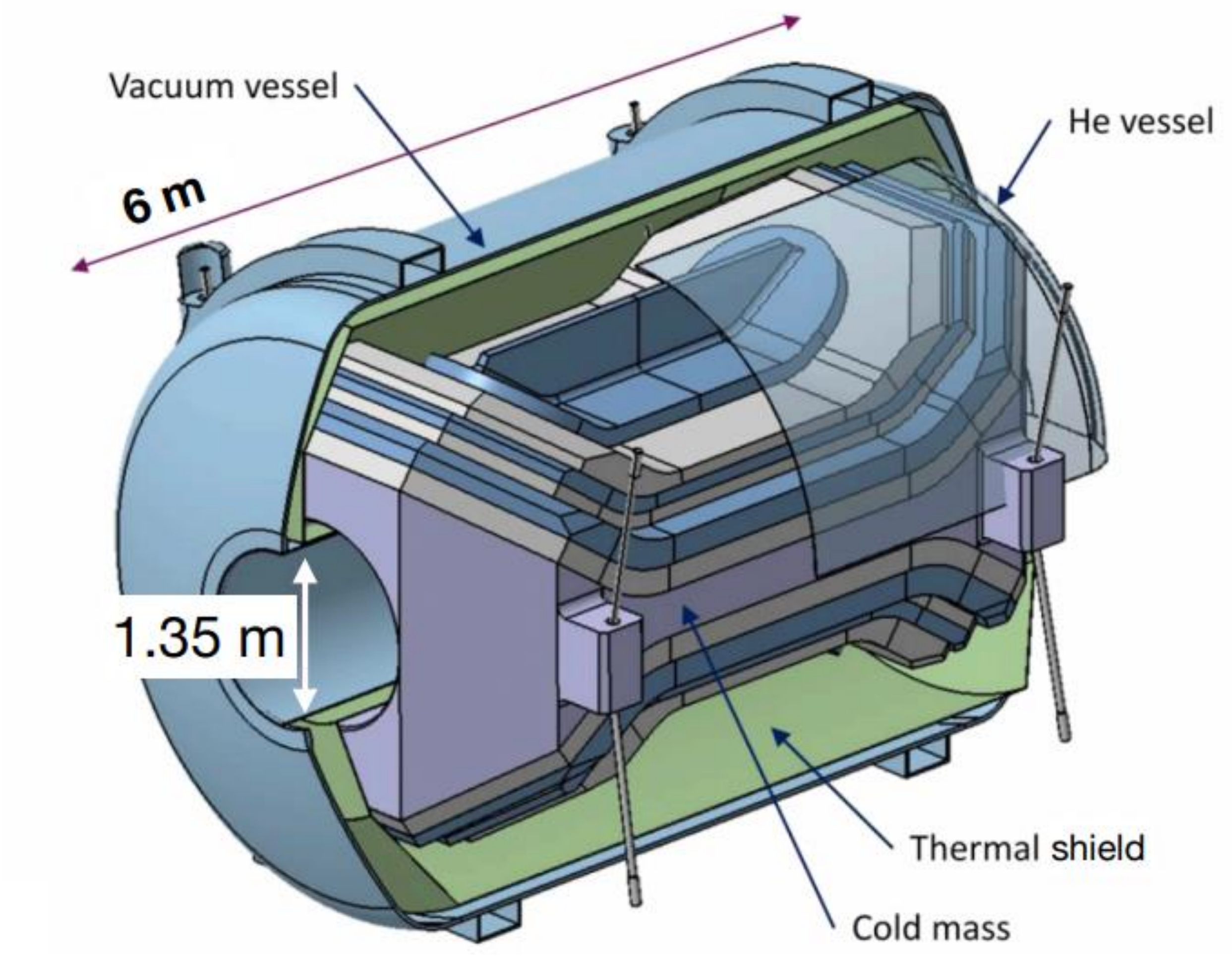
- Compare the measured electric field of the booster with the simulated one

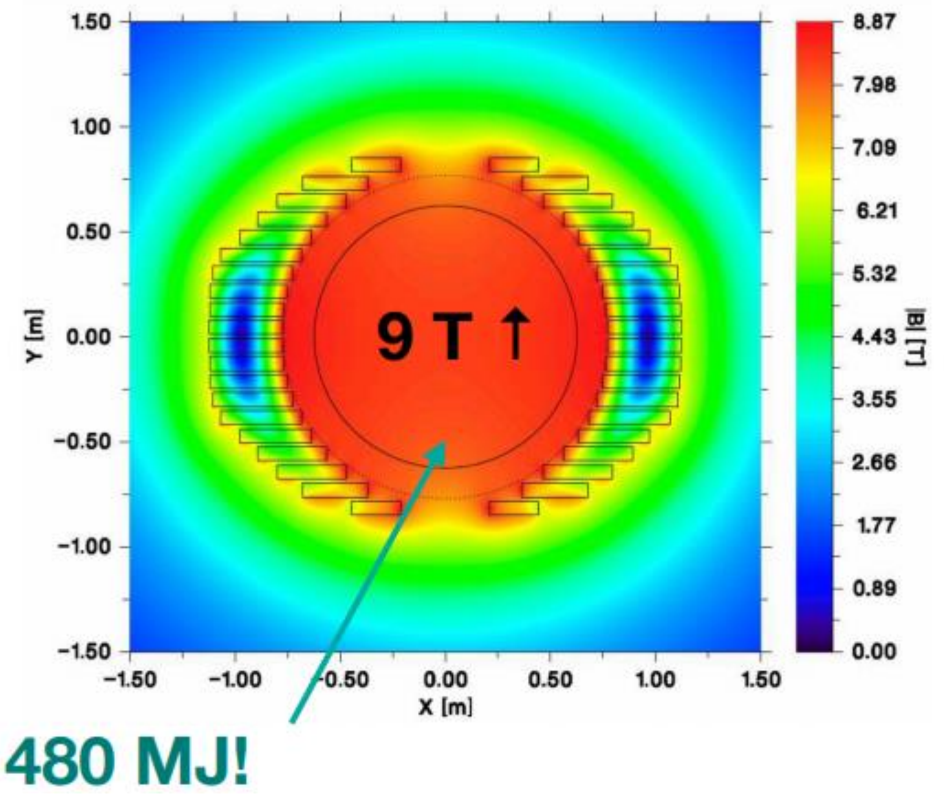


Shape of the electric field on the receiver side in presence of real disks

Magnet

- European Innovation partners: CEA Saclay and Bilfinger Noell
- FoM: B^2A = **100 T^2m^2**



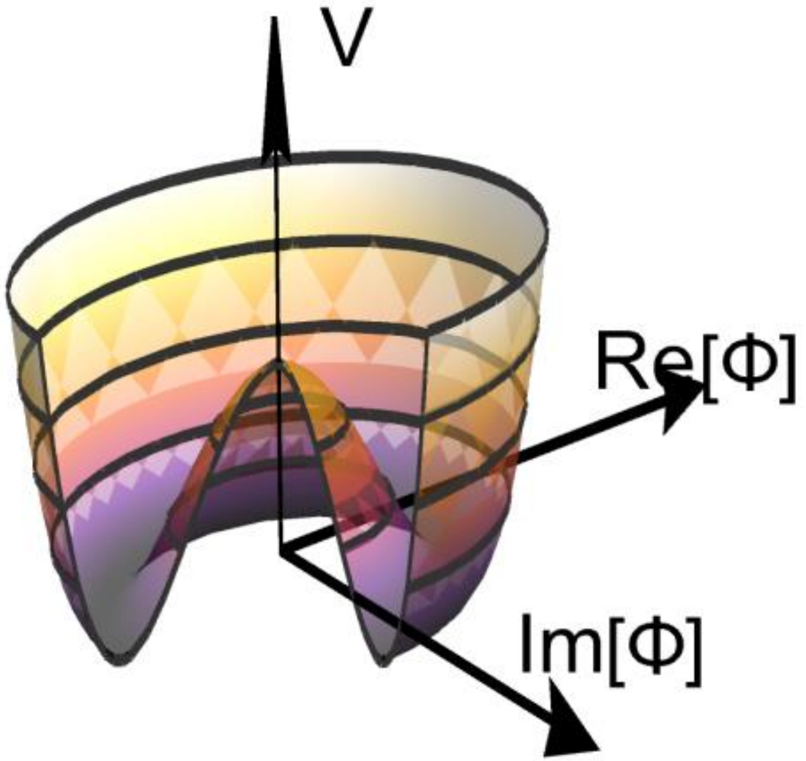


PQ mechanism

New field: $\Phi = R(t, \mathbf{x}) \exp[i\theta(t, \mathbf{x})]$

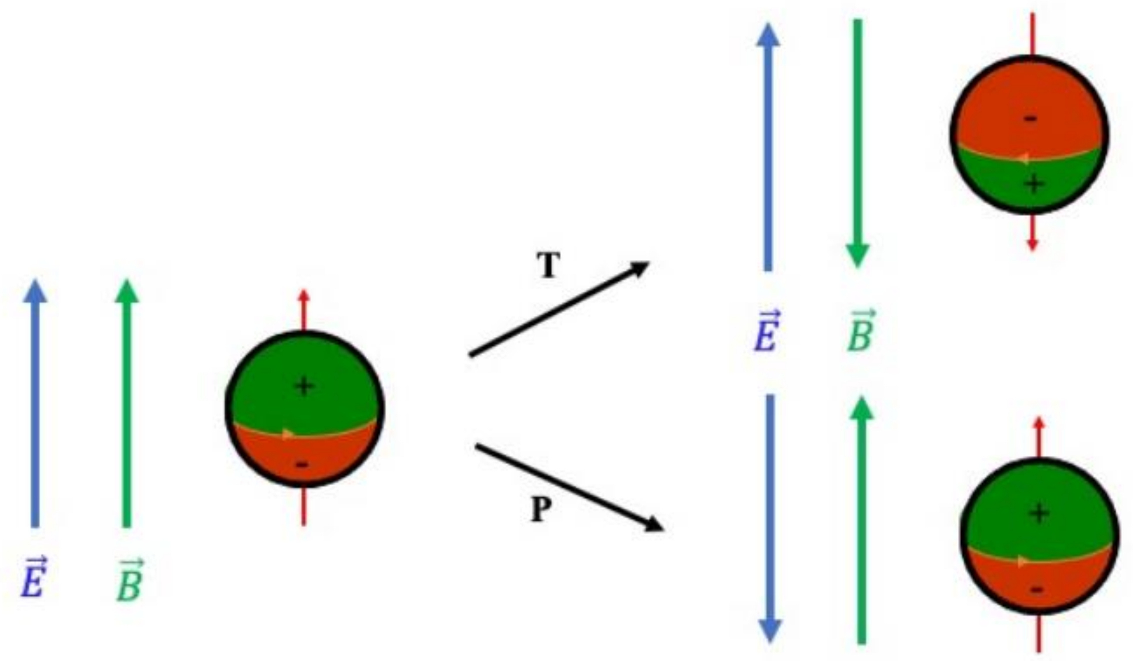
The potential favors θ = 0, thus solving the strong CP problem

Original PQ mechanism already disproved, two modified PQ mechanisms are the object of interest for current experiments



Arxiv: 2308.16003

Neutron Electric dipole moment (nEDM)



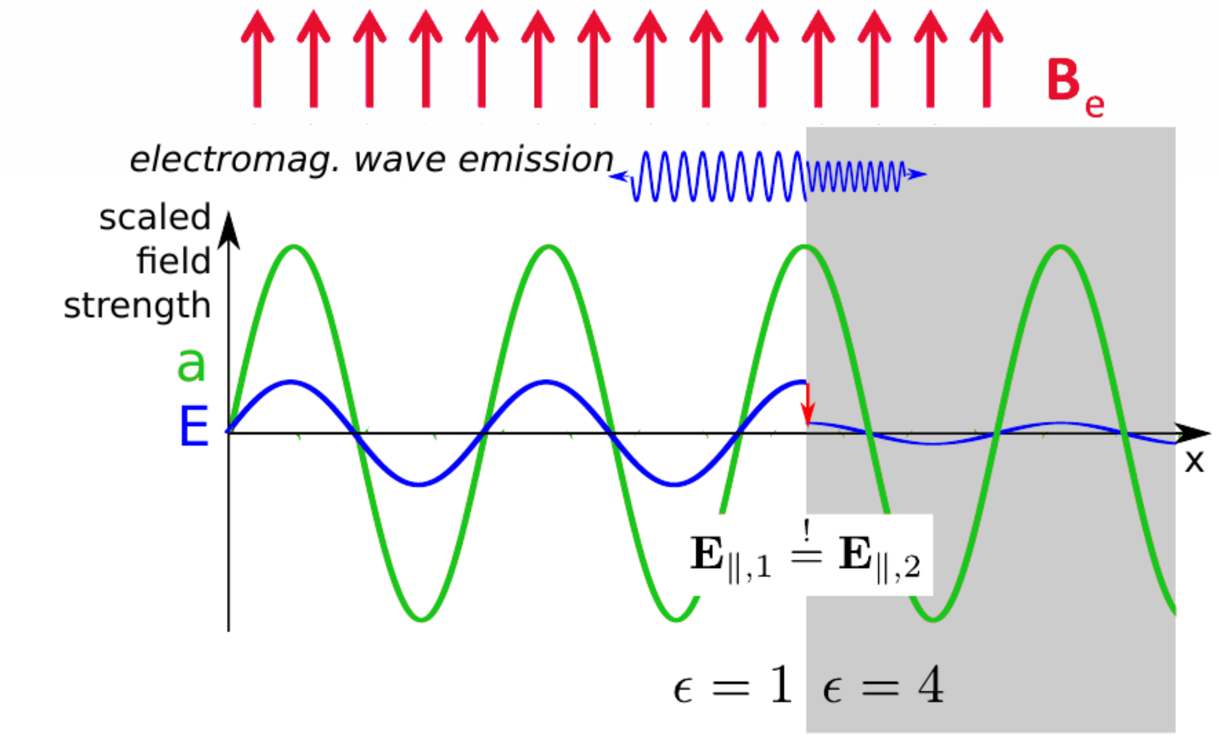
$H = -\mathbf{d} \cdot \mathbf{E}$

$\mathbf{d} = d\boldsymbol{\sigma}$ is the electric dipole moment, E is electric field

d is odd under CP, while E is even

The combined term leads to CP violation

Dielectric Haloscope



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

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

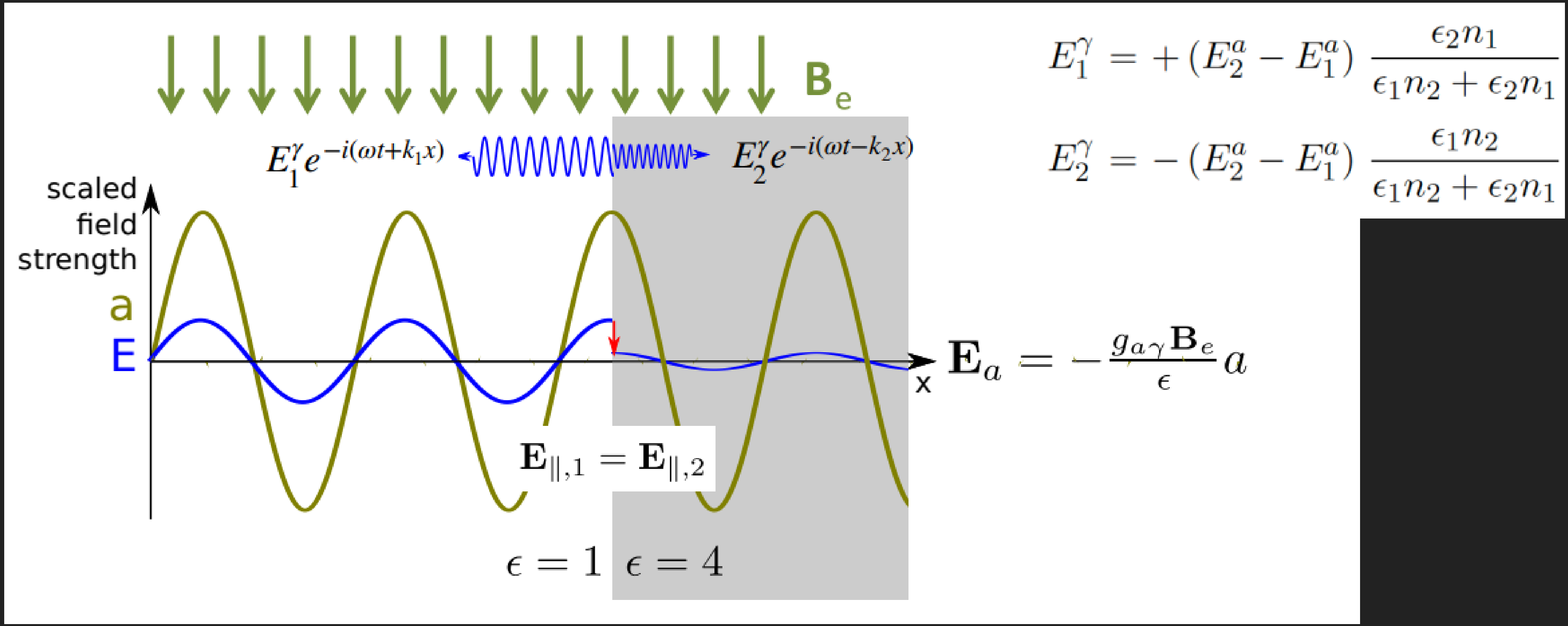
$\boldsymbol{E_a}$ is different in materials with different ε

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

Power emitted from a single surface: $P/_A = 2.2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} C_{a\gamma} \left(\frac{B}{10\ \mathrm{T}}\right)^2$

$\mathcal{O}(C_{a\gamma}) = 1$

DIELECTRIC HALOSCOPE (1)



- Power emitted at a vacuum-to-perfect-conductor interface:

$$\frac{P_{sig}^{\gamma}}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 C_{a\gamma}^2$$

Axion/ALP searches

Haloscopes

Relic DM axions

High axion flux

Model dependent

QCD axion DM

[1-1000 μeV]
[0.25-250 GHz]

e.g. MADMAX

Helioscopes

Solar axions

Medium axion flux

Mildly model dependent

QCD axion / ALP

[higher masses up to keV]

e.g. (Baby)IAXO

Lab experiments

Lab produced
→ fully controlled setup

Low axion flux

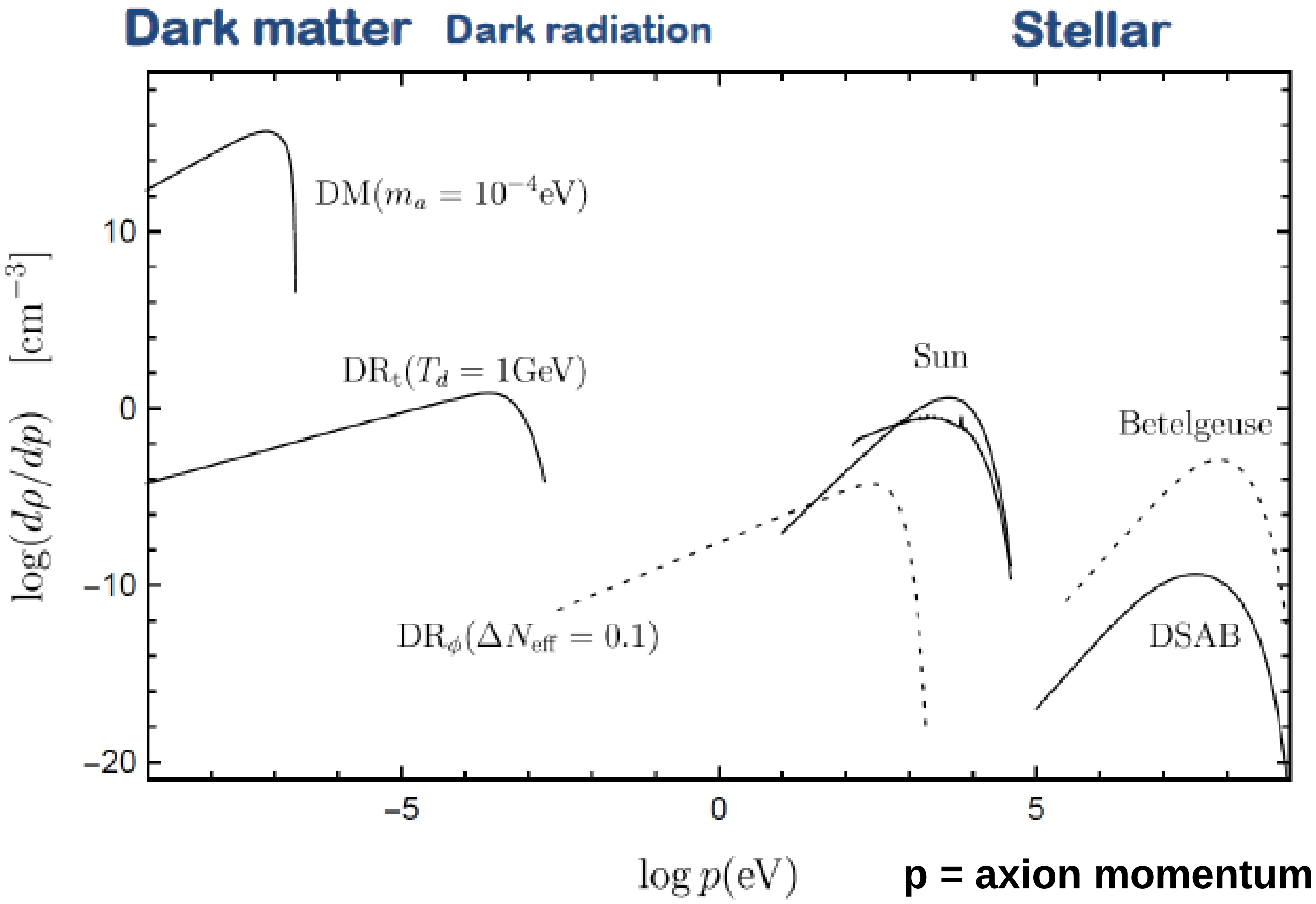
Model independent

ALP

e.g. ALPS II

Complementarity between the 3 approaches at the DESY Hub

Sources of axions



p = axion momentum

Axion scales