Direct searches for dark matter axion with MADMAX

Pascal Pralavorio
pralavor@cppm.in2p3.fr
Aix-Marseille Université, CNRS/IN2P3, CPPM (Marseille, France)
on behalf of the MADMAX collaboration

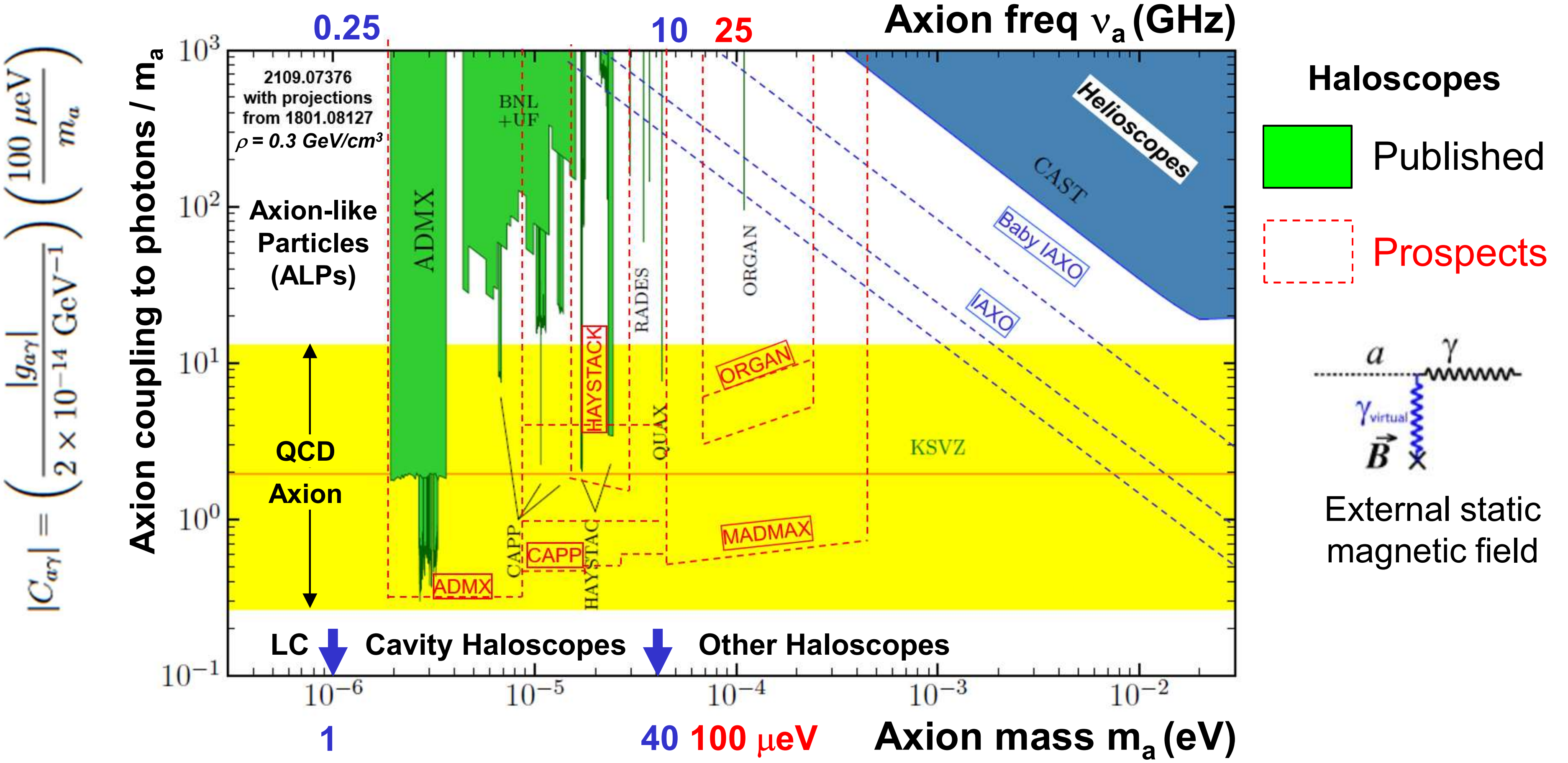
https://madmax.mpp.mpg.de/

1- Scientific context
2- Dielectric haloscope concept
3- Towards the final booster design
4- First dark matter searches with prototypes
5- Conclusions

ICHEP 2024 Conference – 18 July 2024

Scientific context

❑ **Haloscope** *(using a-γ coupling)* **main way to search for dark matter axion**



MADMAX can probe the favored post-inflationary range m_a = O(100) μeV*

*Nat. Com. 13 (2022) 1, 1049: 40 < m_a [μeV] <180

MADMAX

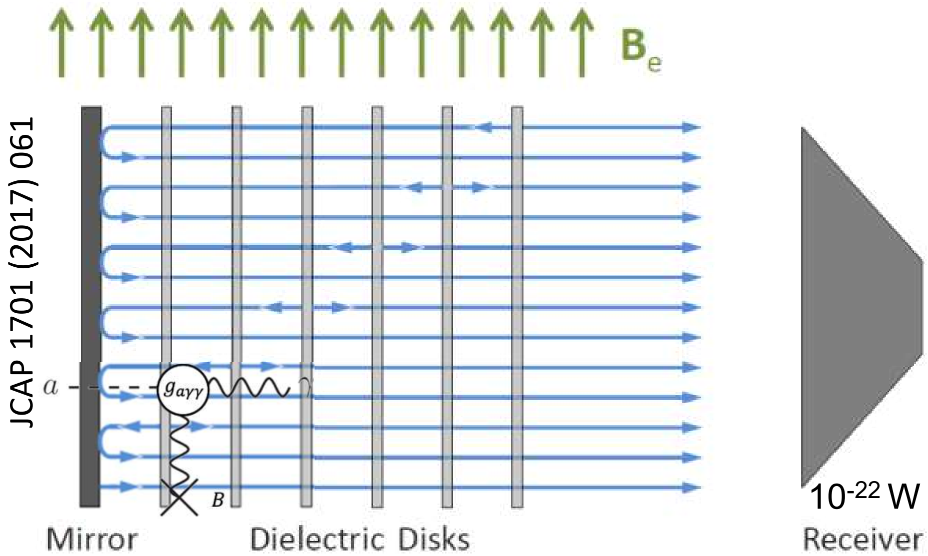
EPJC 79 (2019) 186

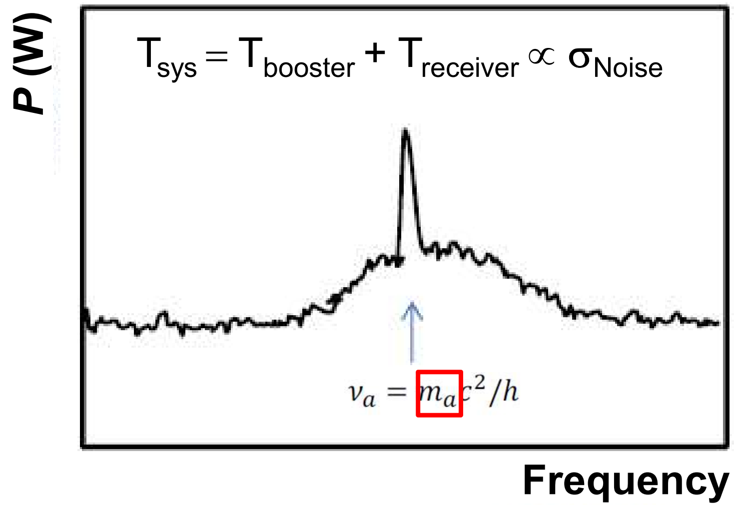
❑ Principles of dielectric haloscope

- Constructive interference of coherent photons emitted at the disk surface + resonant enhancement *(~leaky resonator cavities)*: **boost factor** β^2 *($\propto \varepsilon$, N_{disk})* wrt mirror only

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

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





- Axion mass **scan**: by moving discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

MADMAX

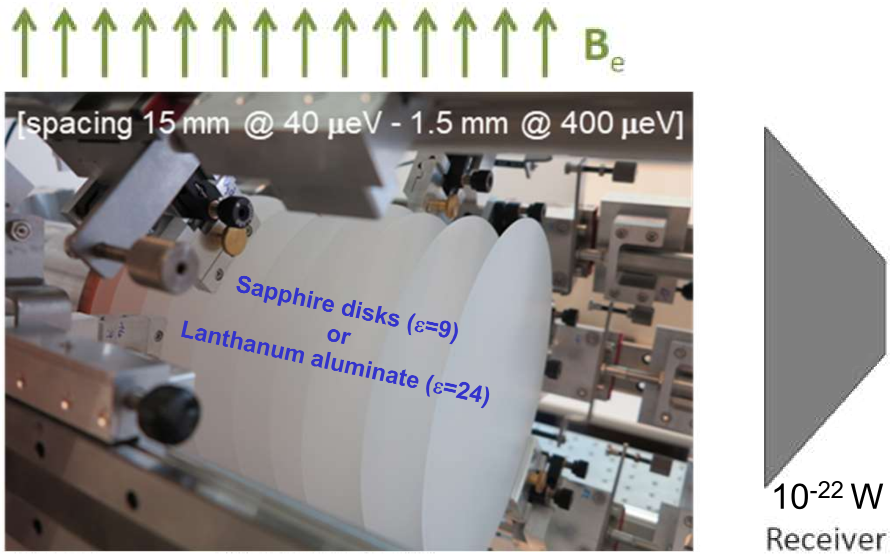
❑ Principles of dielectric haloscope

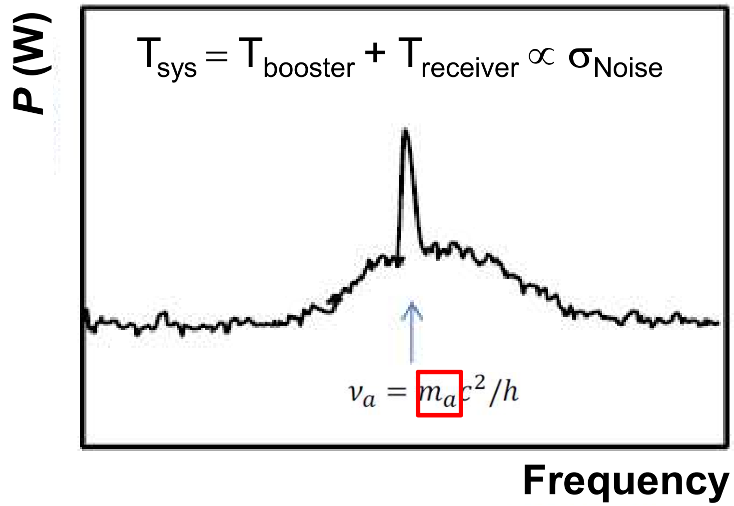
EPJC 79 (2019) 186

- Constructive interference of coherent photons emitted at the disk surface + resonant enhancement *(~leaky resonator cavities)*: **boost factor β^2** *($\propto \varepsilon$, N_{disk})* wrt mirror only

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

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





- Axion mass **scan**: by moving discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

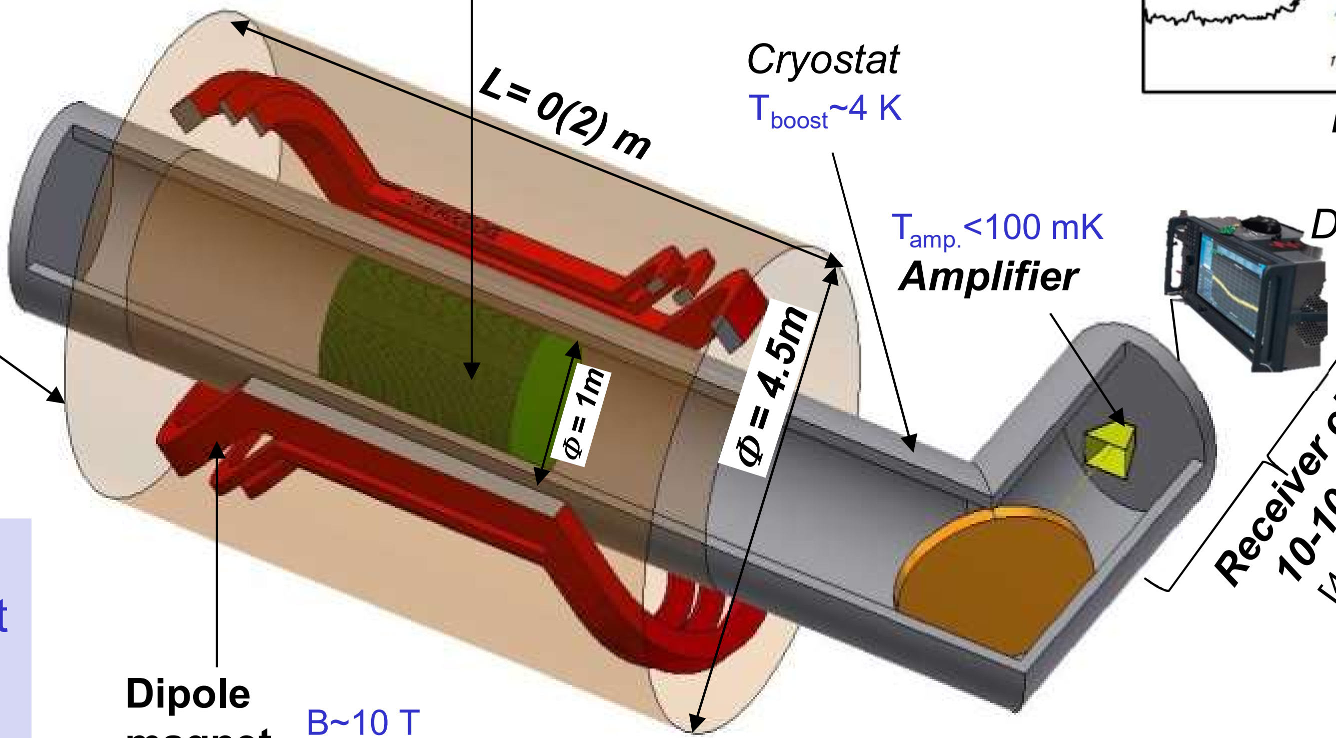
MADMAX exploits a new concept to cover an uncharted phase space

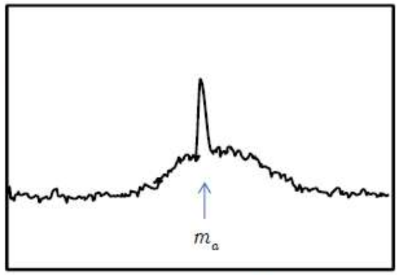
MADMAX

Formed in 2017,11 institutes, ~50 people

EPJC 79 (2019) 186

Experiment location: HERA in former H1 iron yoke





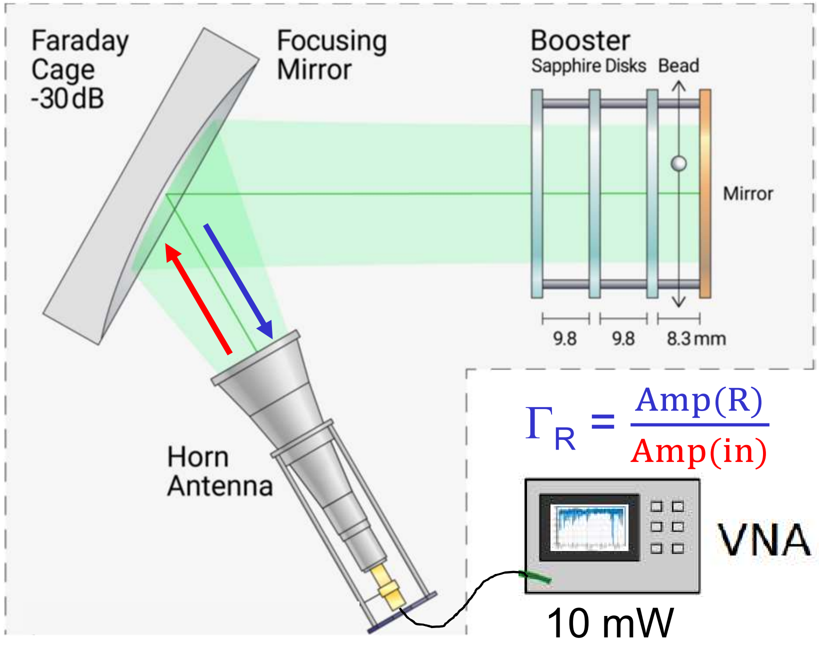
3 main challenges :
- High field dipole magnet
- Receiver (10's GHz)
- Booster (cold, B field)

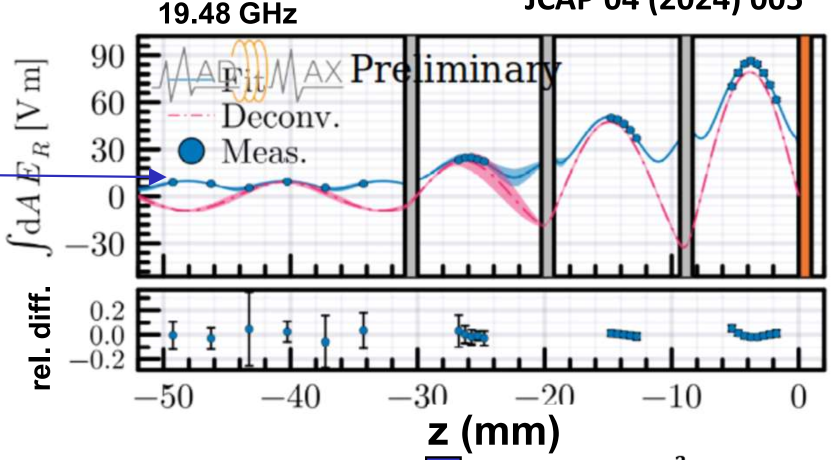
Prototyping phase since 2020 to validate the concept

Boost factor determination

- **Developed method to measure β^2 *in-situ***
  - Put 1.5 mm radius **bead** in booster volume → 3D scan
  - **VNA** to send signal and measure reflected amplitude for each bead position → $\Delta\Gamma_R \propto E_R^2$
  - **Deconvolute** bead's response → $E_R(z,\nu)$
  - **Integrate** E_R over volume → measure $\beta^2(\nu)$

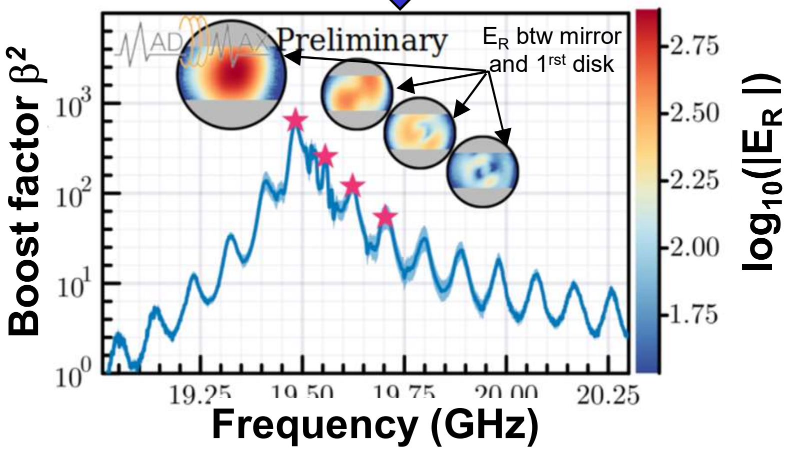
JCAP 04 (2023) 064
JCAP 04 (2024) 005





Reciprocity approach

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



EM characterization of open booster with bead-pull meas.

Prototype boosters

❑ Gradually building the final 'open' booster

- Set-up: CERN Morpurgo magnet *(1.6 T)* + prototype cryostats *(G10, stainless-steel)*
- Disks *(sapphire)*: moveable *(piezo motors)*, good planarity *(<10 μm)*, controlled thickness *(1000±10 μm)*
- Receiver chain: low noise amplifier *(HEMT)* + Spectrum Analyser or custom-made board

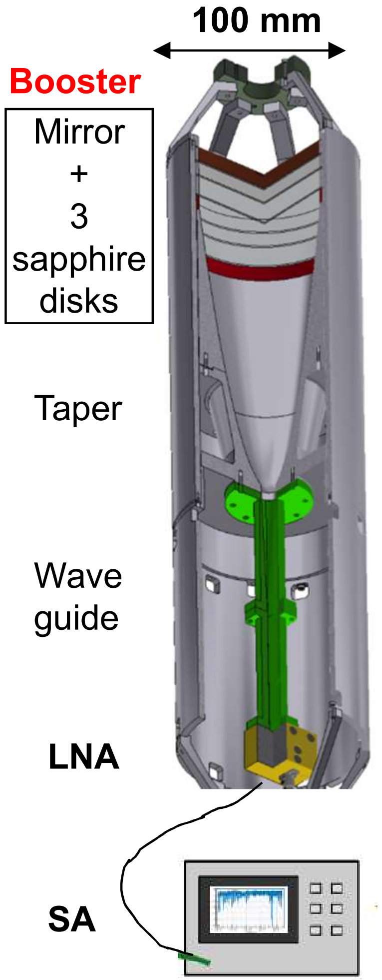
Name	Goal	Booster	Disks	Test
CB100	RF studies + First ALP searches	Closed	3, **fixed** ϕ = 100 mm	2022, 23, **24**
CB200		Closed	3, **fixed** ϕ = 200 mm	24
OB300v1	Scan DP* @ 80 μeV	Open	3, **fixed** ϕ = 300 mm	23-24
OB200	Piezo-motor + mechanics	Open	1, **moveable** ϕ = 200 mm	2022, **22**
OB300v2 (in prep.)	*Scan ALP @ 80 μeV*	*Open*	*3-20, **moveable*** *ϕ = 300 mm*	***26-28***

*Dark Photon

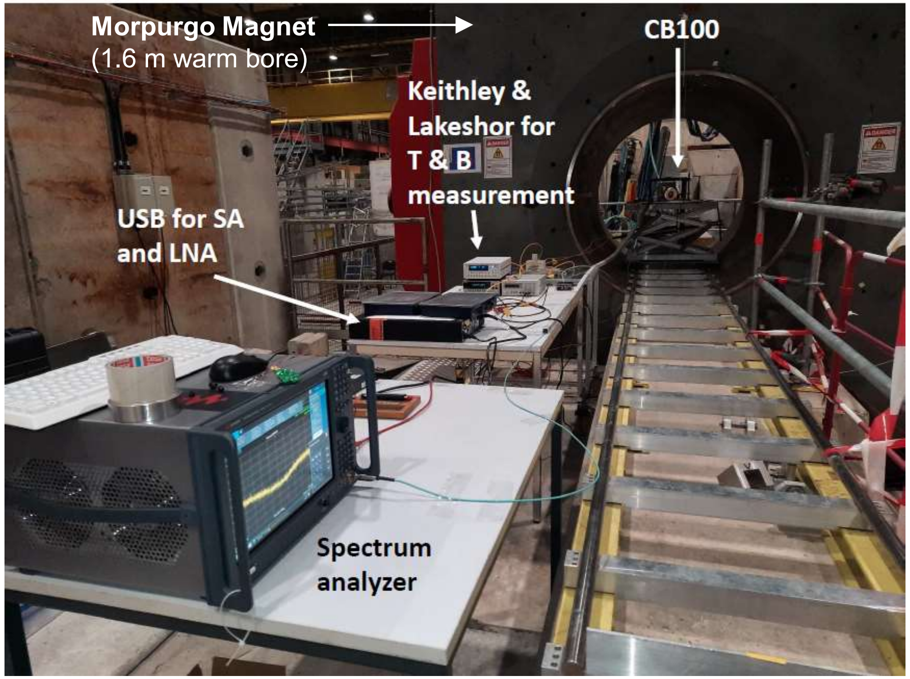
Room Temp.
Cold (10 K)
Bfield
Prospects

Preparatory work

Room Temp.
Cold (10 K)
Bfield
Prospects



Name	Booster	Disks	Test @CERN
CB100	Closed	3, **fixed** ϕ = 100 mm	2022, 23



- CERN refurbished the area and the magnet for MADMAX
- Checked that no RF interference with CERN environment
- Checked stability of data taking @19 GHz, 1.6 T: $t_{Live} \propto 1/\sigma_{Noise}^2$
- Calibrated @10% receiver chain power: $P \propto T_{sys} = f(\Gamma_{RC}, G, \nu)$

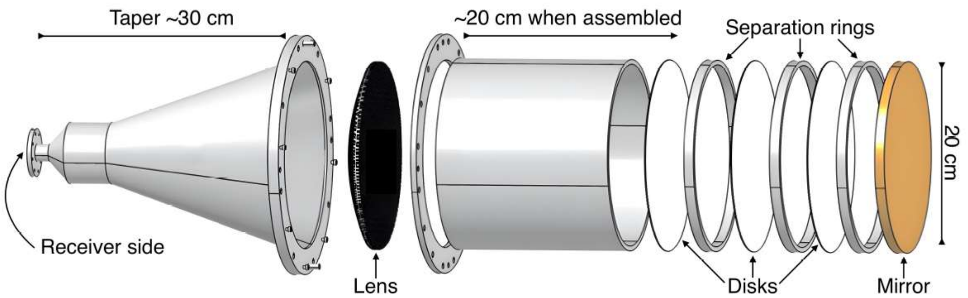
Validated that CERN environment suited for prototype tests

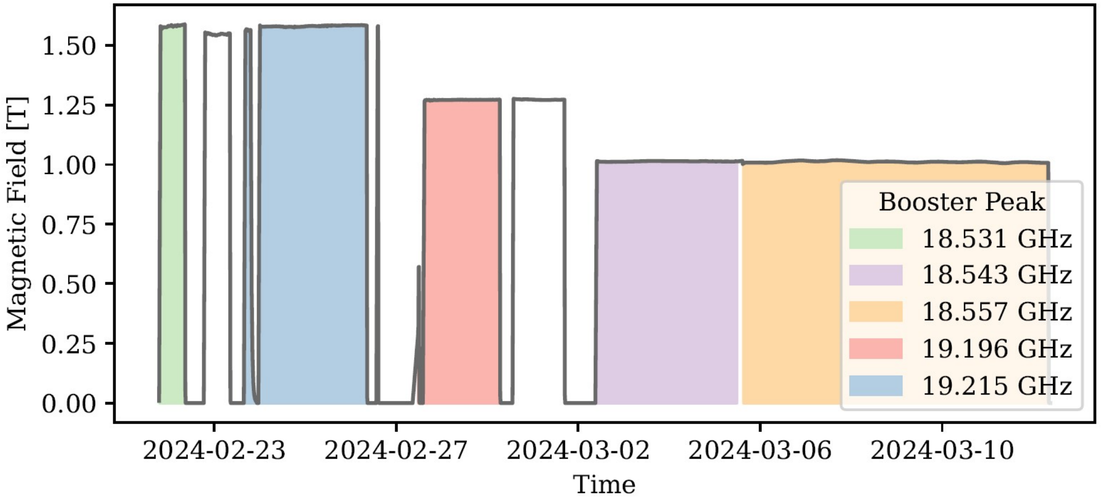
ALP search (1/2)

Room Temp.
Cold (10 K)
Bfield
Prospects

Name	Booster	Disks	Test @CERN
CB200	Closed	3, **fixed** ϕ = 200 mm	2024

- Before CERN, prepared 5 disk configurations with different β_{peak}^2 freq. *(checked with bead-pull)*
- Configurations obtained by changing manually the disk distances *(separation rings)*



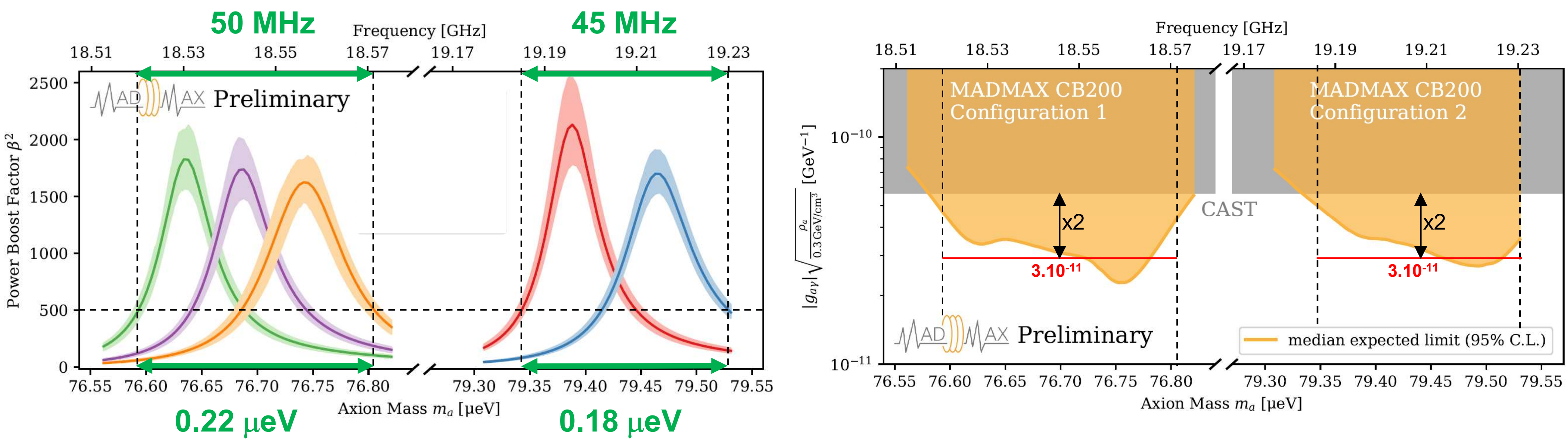


17-day physics run @18.5, 19.2 GHz and under B field

ALP search (1'/2)

❑ Finalizing data analysis

- Computed boost factors for the 5 configurations including systematics *(± 15%)*
  - ✓ Scan 100 MHz with β^2 >500 → **expected** sensitivity below (new) CAST limit
  - ✓ β_{peak}^2 >1500 → **expected** sensitivity down to **$|g_{a\gamma}|$ ~ O(3x10^{-11}) GeV^{-1}**



Demonstrating the scanning capacity of MADMAX booster

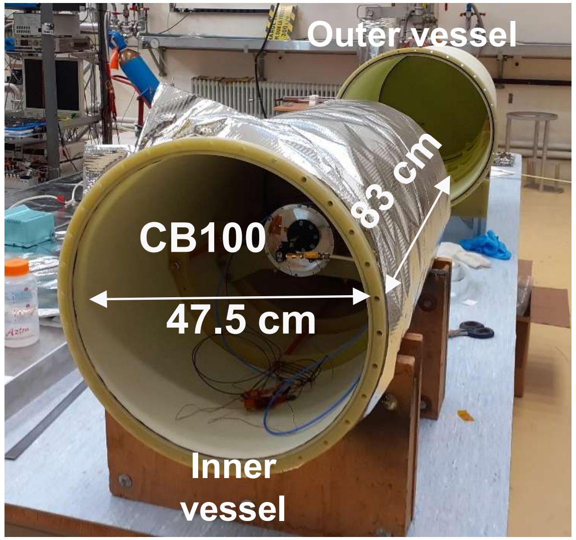
(preliminary sensitivity, data analysis ongoing)

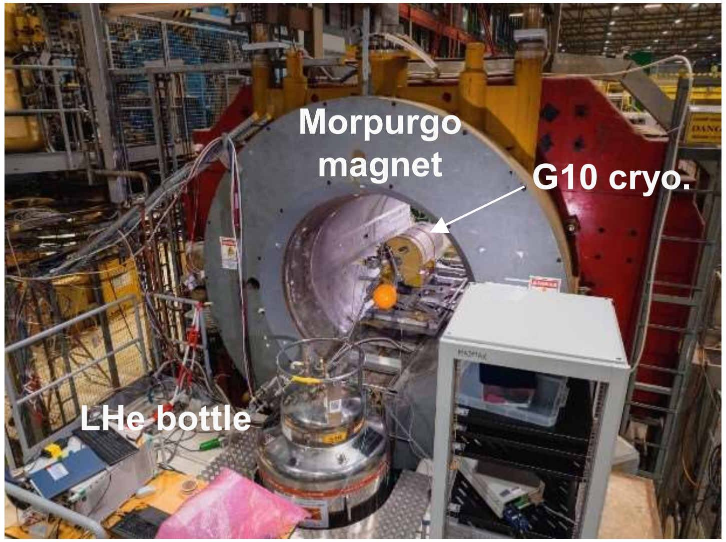
ALP search (2/2)

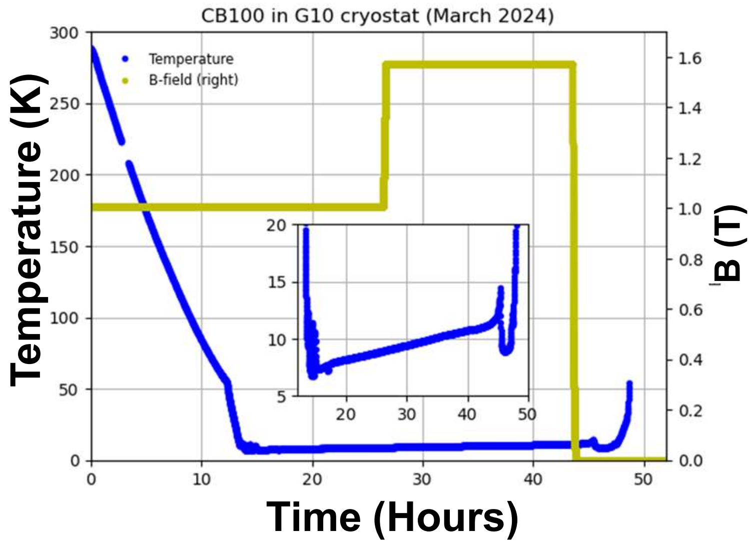
Room Temp.
Cold (10 K)
Bfield
Prospects

Name	Booster	Disks	Test @CERN
CB100	Closed	3, **fixed** ϕ = 100 mm	**2024**

- Developed low-cost cryostat in G10 with CERN cryolab: O(20) hours below 10 K
- Established receiver chain calibration procedure at cold *(validated at the CERN cryolab)*





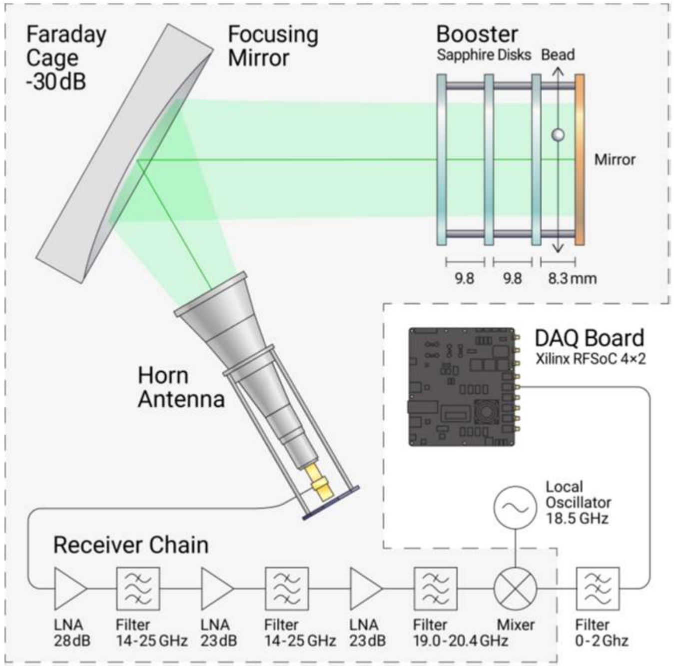


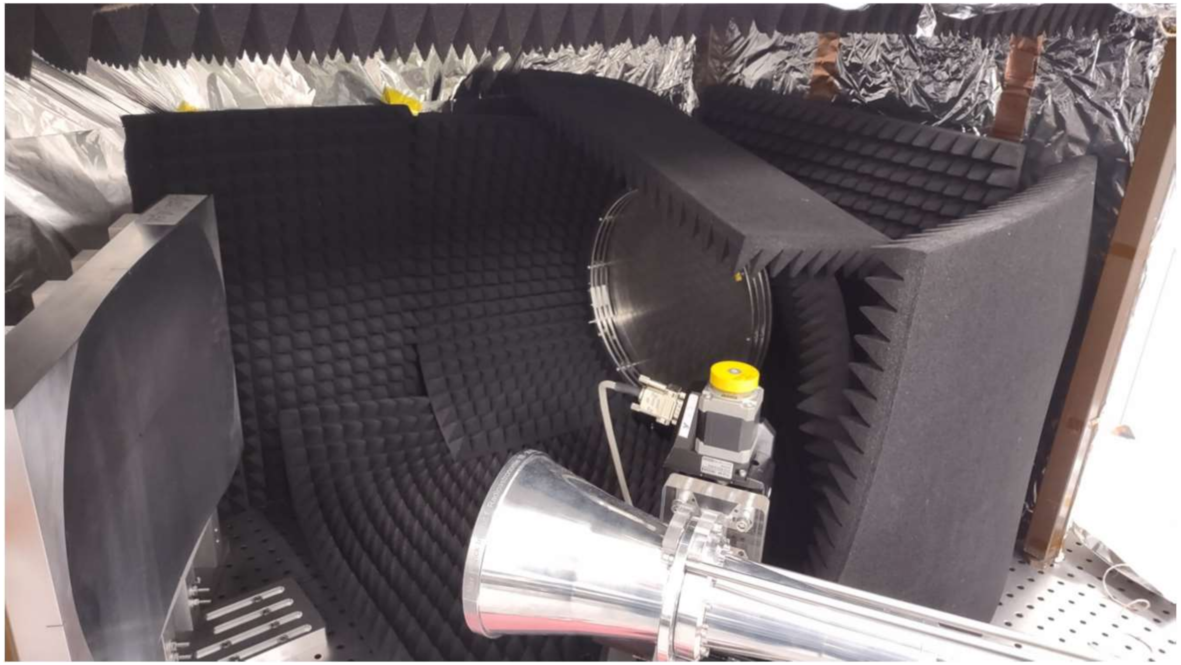
20-hour physics run @19 GHz, < 10 K and under B field

(data analysis ongoing)

Dark photon (DP) search

Name	Booster	Disks	Test @DESY
OB300v1	Open	3, **fixed** ϕ = 300 mm	2023-24



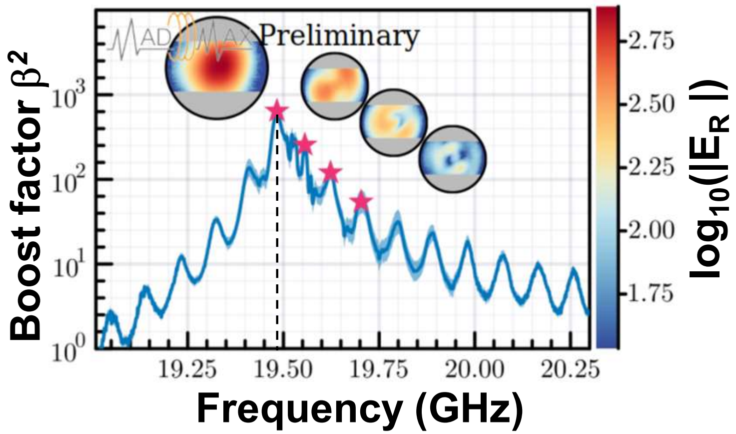


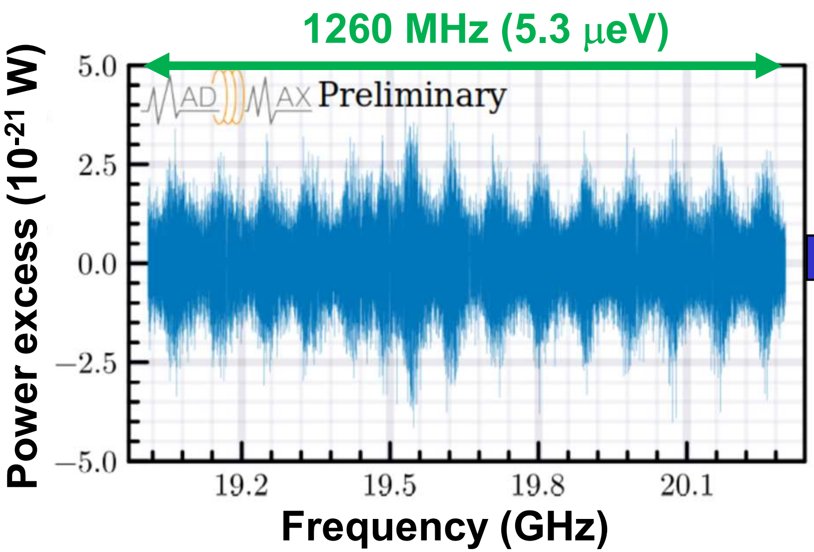
12-day physics run @19.0-20.3 GHz with an open booster

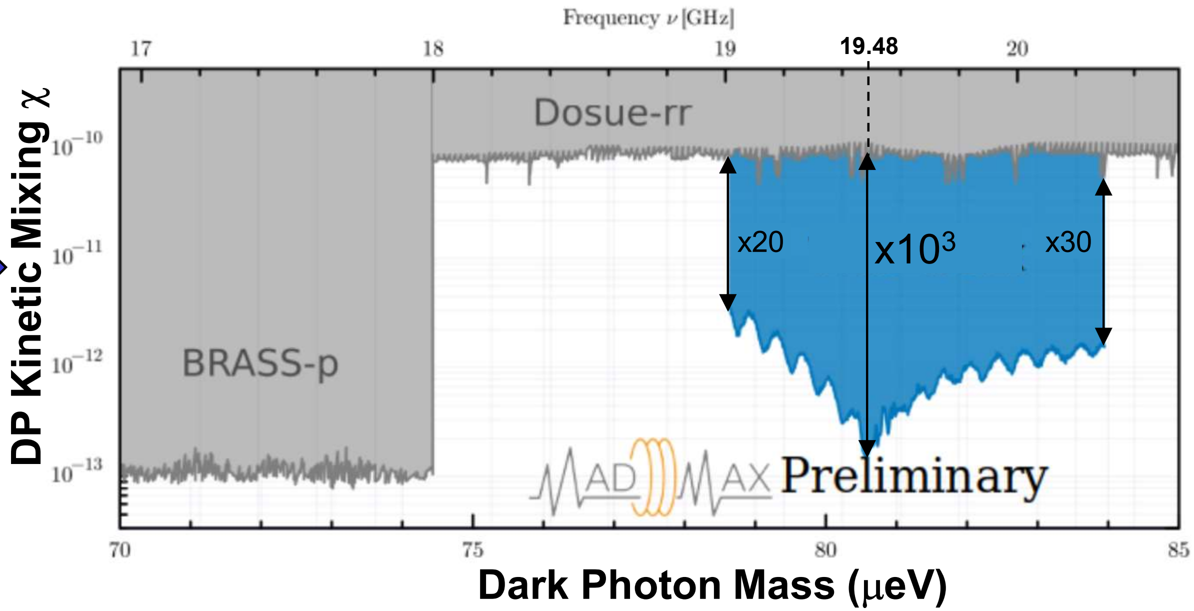
Dark photon (DP) search

❑ Completed data analysis

- β^2 measurement using bead-pull method (β_{peak}^2=600) →
- No signals of unknown origin detected
- 95% CL **observed limit** on DP kinetic mixing χ
  - ✓ world best limits in m_χ [78-6, 83.9] μeV
  - ✓ **1-3 order of magnitude** below previous limits







Demonstrated the broadband capacity of MADMAX booster

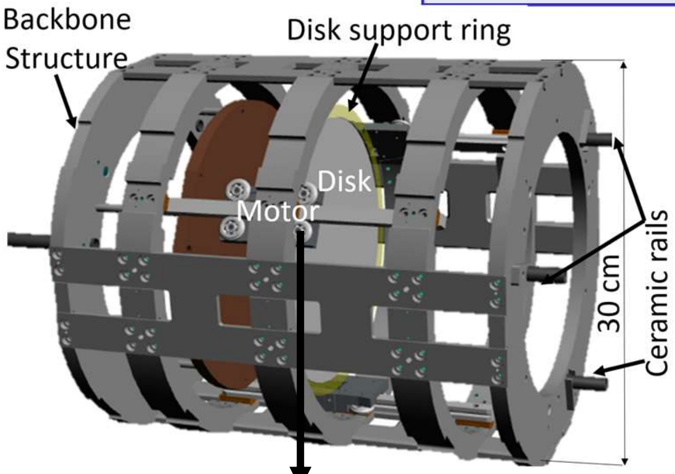
(preliminary results)

Open booster mechanics

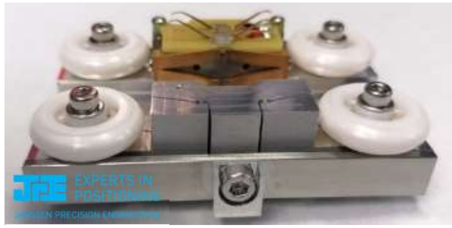
Room Temp.
Cold (10 K)
Bfield
Prospects

JINST 18 (2023) P08011
arXiv:2407.10716

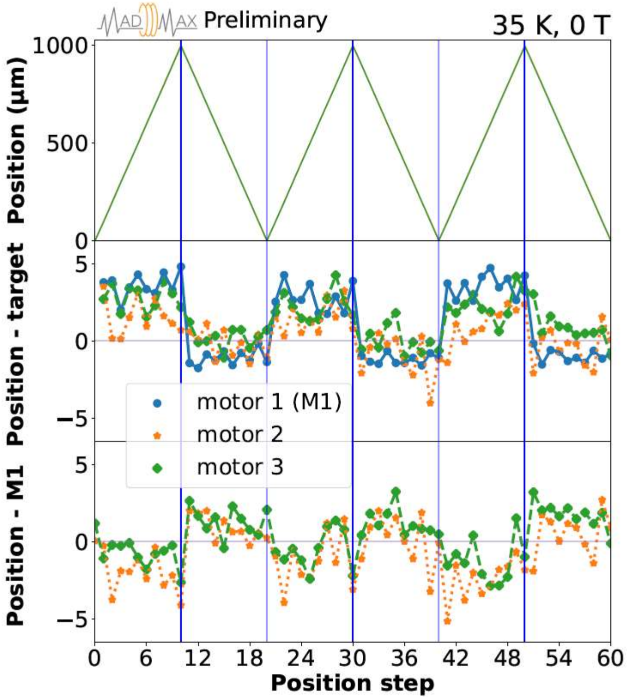
Name	Booster	Disks	Test @CERN
OB200	Open	1, **moveable** ϕ = 200 mm	2022, **22**



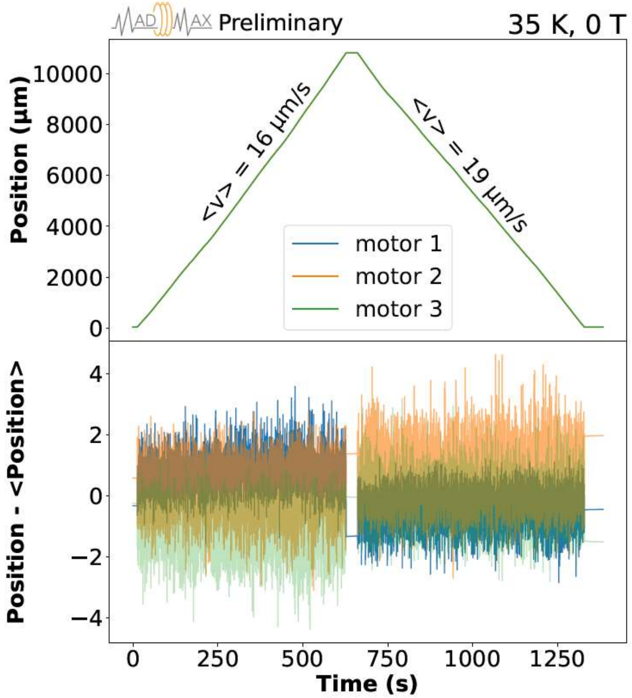
Successful test of JPE piezo motor at 5 K and 5.3 T *(ALP magnet @DESY)*



Motors positioned at 5 µm



v > 15 µm / s



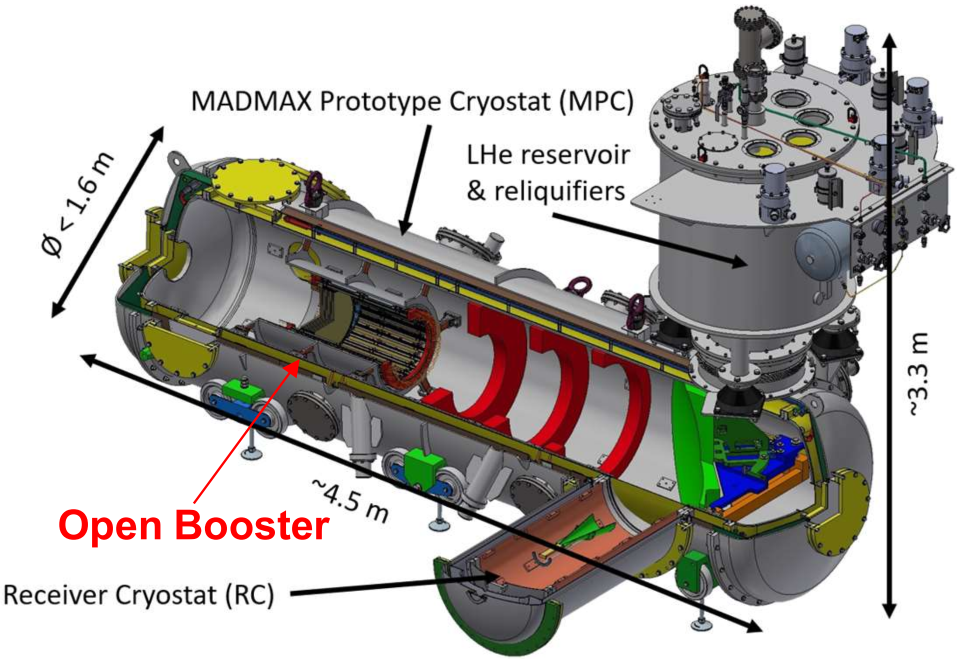
Validated piezo motors and mechanics for open booster

Final prototype

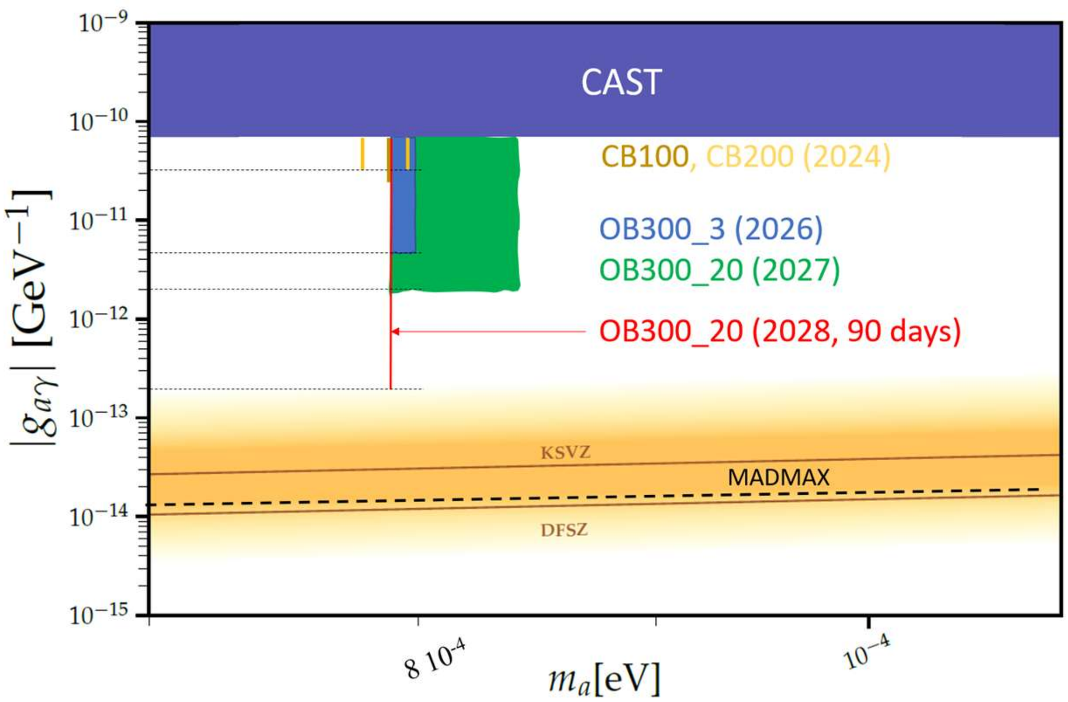
Room Temp.
Cold (10 K)
Bfield
Prospects

Name	Booster	Disks	Test @CERN
OB300v2 (in prep.)	*Open*	*3-20, **moveable*** *ϕ = 300 mm*	***2026-28***

- Booster inserted in a stainless steel cryostat



- Tentative physics program *(under discussion)*



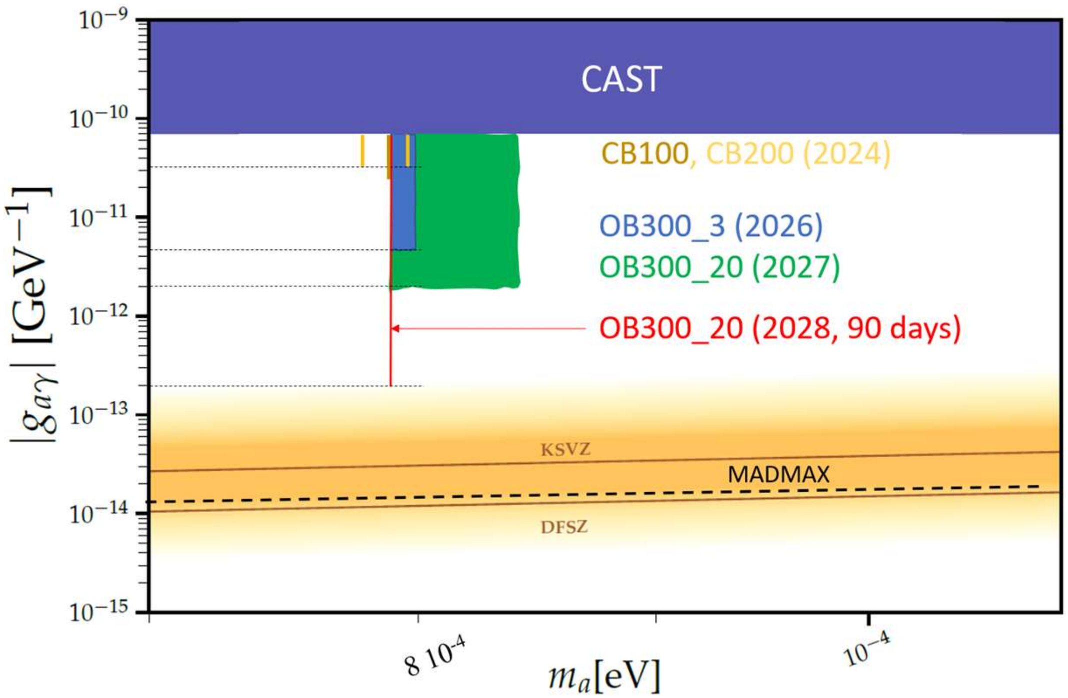
Final prototype

Room Temp.
Cold (10 K)
Bfield
Prospects

Name	Booster	Disks	Test @CERN
OB300v2 (in prep.)	*Open*	*3-20, **moveable*** *ϕ = 300 mm*	***2026-28***

- Booster inserted in a stainless steel cryostat *(in construction to be delivered @DESY in Sep 2024)*

- Tentative physics program *(under discussion)*



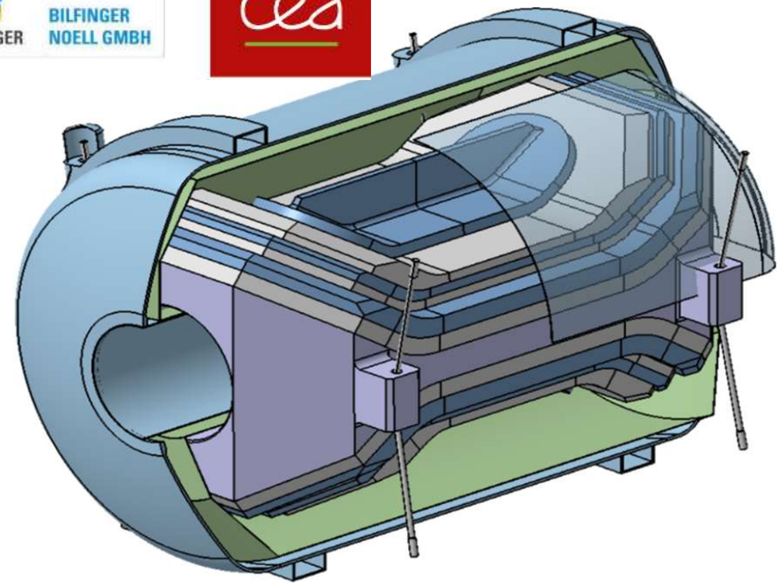
Prospects: 3 mths / yr @ 8 K to scan ALPs →Final MADMAX

Towards final MADMAX

❑ Magnet

- Design completed: 2x9 skateboard coils with novel copper CICC conductor

[NbTi with Cu jacket @ 1.8K]



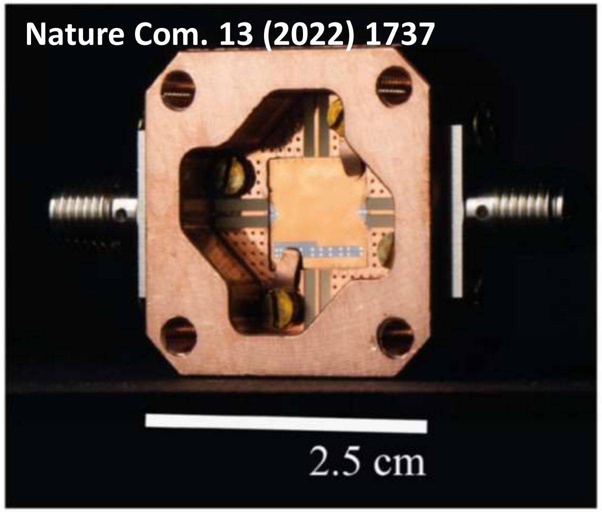
- Demonstrated that coils will be safe in terms of quench protection **IEEETAS 33 (2023) 1**
- Budget secured for a demonstrator coil
  → Expected in 2027

❑ Receiver Chain

- For now use classic low noise amplifier

HEMT (G=33 dB, 4K added noise) below 40 GHz

- Josephson Junction being developed to further minimize noise *(quantum limit)*



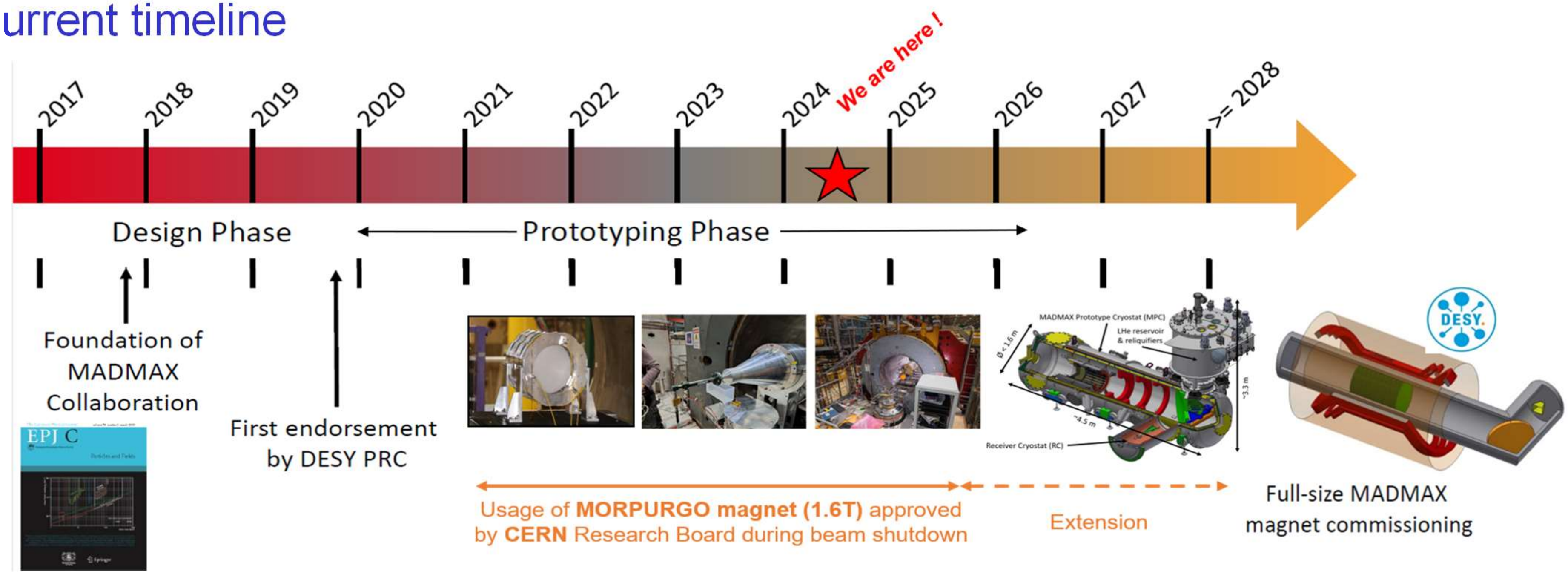
TWPA prototype with G>20 dB and 1K added noise at 10 GHz

- **Next**: >40 GHz technology to be developed

Conclusions

❑ MADMAX: dielectric haloscope for dark matter axion search ~100 μeV

- Recent achievements with booster prototypes
  - ✓ Validated mechanics at cold, under B_{Field} — **JINST 18 (2023) P08011, arXiv:2407.10716**
  - ✓ Established method to measure in situ β^2 — **JCAP 04 (2023) 064, JCAP 04 (2024) 005**
  - ✓ Performed dark matter searches **@18-20 GHz**
    - ○ Dark Photon (β_{peak}**^{2}~600**): world best limits in m_χ [78-6, 83.9] μeV — **Preliminary results**
    - ○ ALP (β_{peak}**^{2}~1700**): expected sensitivity below CAST down to **$|g_{a\gamma}|$ ~ 3×10^{-11} GeV^{-1}** — **Analysis ongoing**
- Current timeline



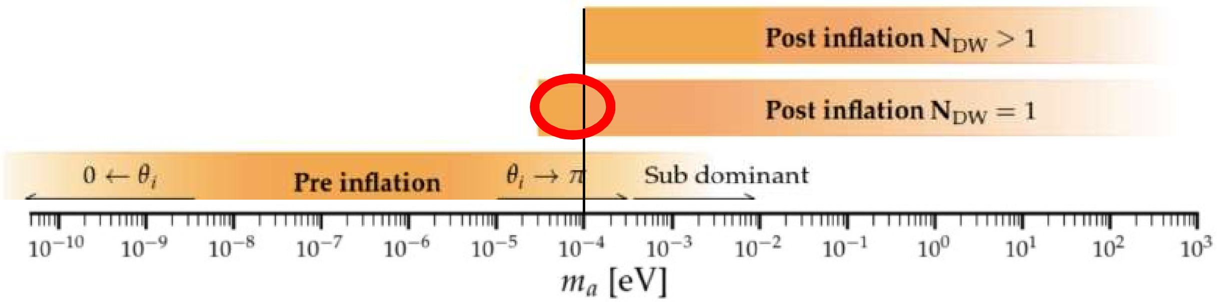

CERN March 2024
MADMAX

BACKUP

Axion

- **Axion: preferred solution to the strong CP problem**
  - Mechanism: new global U(1) symmetry *(Peccei-Quinn, 1977)* spont. broken at scale f_a
    - Can occur before or after inflation
  - Consequence: pseudo-Goldstone boson of the theory = **axion** *(Weinberg-Wilczek, 1978)*
    - Properties given by the symmetry breaking scale f_a [$f_a >> f_{ElectroWeak}$]
    - Tiny mass [$m_a \approx m_\pi f_\pi / f_a << eV$], weakly interacting [suppressed by f_a], long-lived [$\tau_{axion} > t_{Universe}$]
- **Axion: natural dark matter candidate** *(Preskill et al, 1983)*
  - Non-thermal massive axion at $T \sim \Lambda_{QCD}$ → cold dark matter
  - If relax constraint on m_a → axion like particles (ALPs)
- **m_a can be computed in post-inflationary scenario**

100 μeV *[24 GHz]*



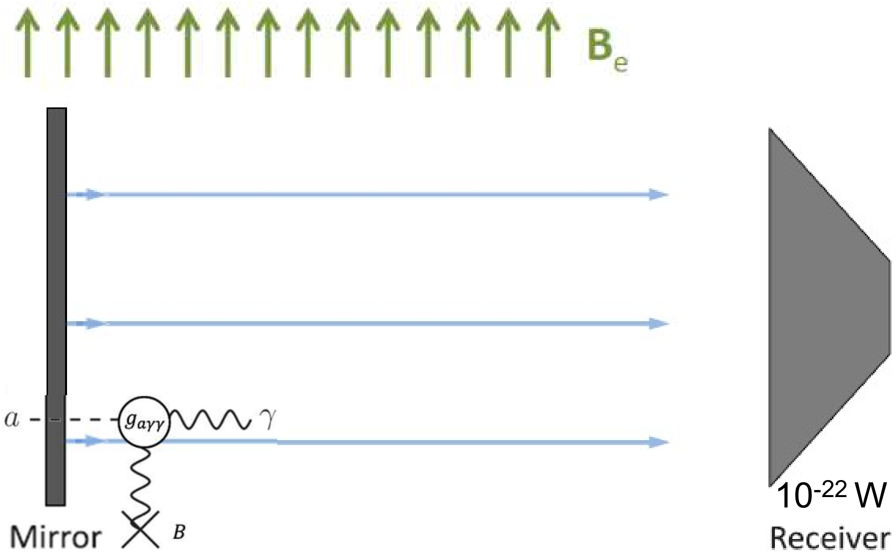
Nat. Com. 13 (2022) 1049
40 < m_a [μeV] <180

Dielectric haloscope

- Constructive interference of coherent photons emitted at dielectric layer surface + resonant enhancement *(~leaky resonator cavities)*: **boost factor** β^2 *($\propto \varepsilon$, N_{disk})* wrt mirror only

Mirror only

$$P_{sig} = 2 \times 10^{-27}\ \mathrm{W} \times \left(\frac{\beta^2}{1}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

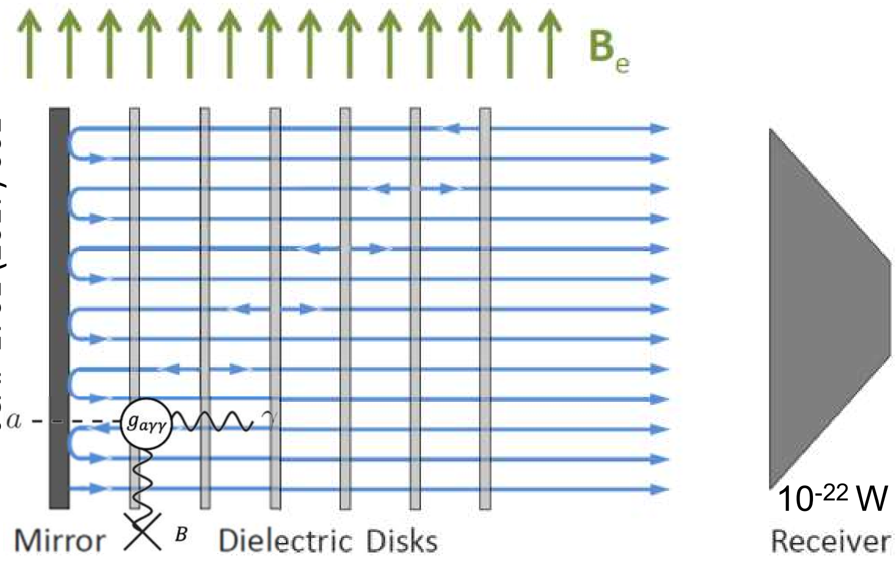


~12 photon / day (@ 25 GHz)

Dielectric haloscope

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

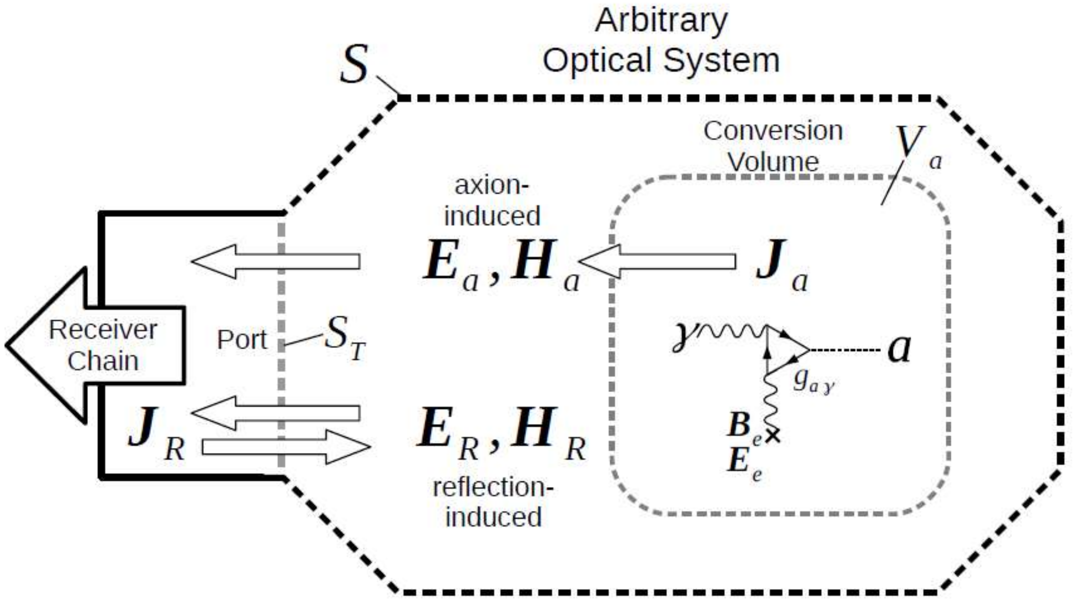
JCAP 1701 (2017) 061

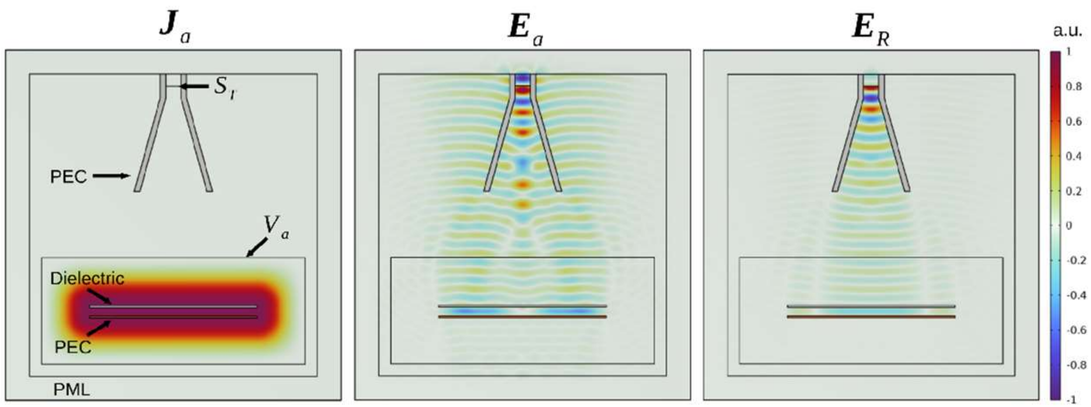


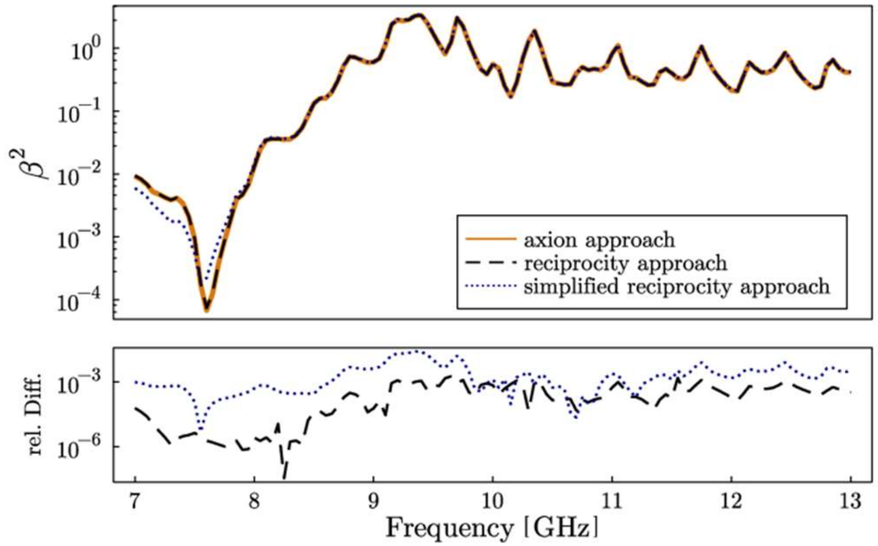
7 photons / second (@ 25 GHz)

Reciprocity approach

JCAP 04 (2023) 064



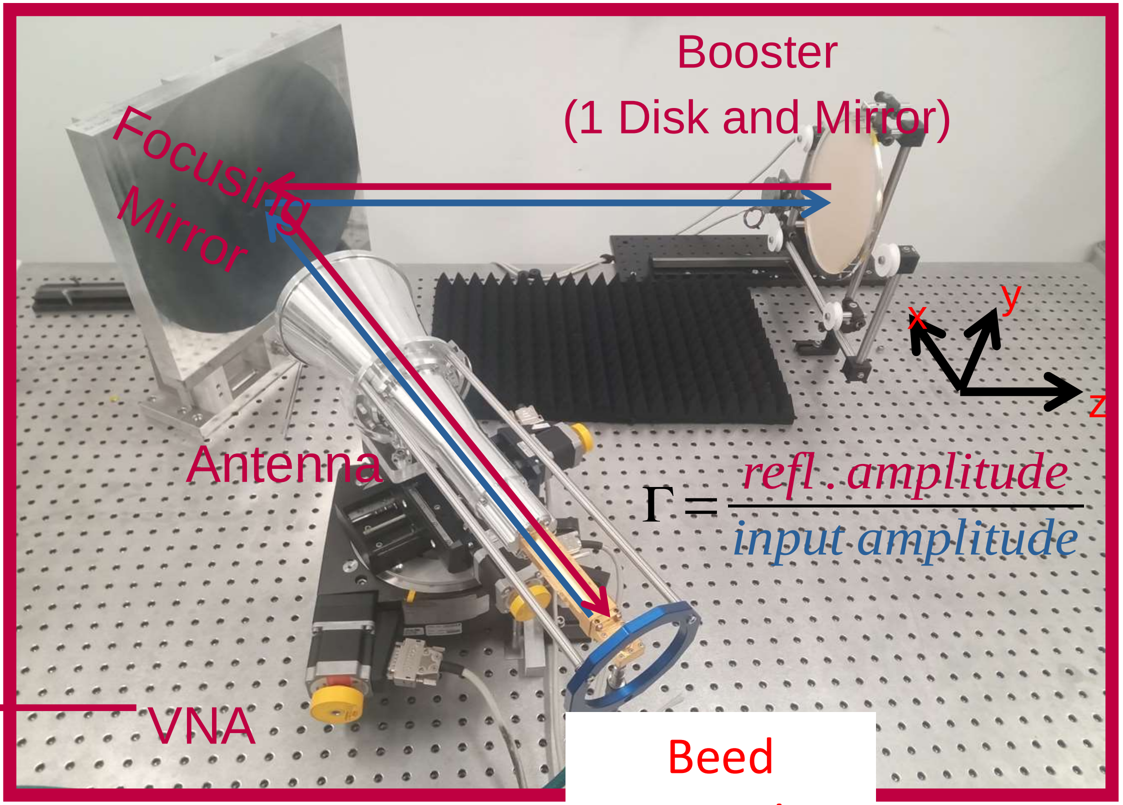


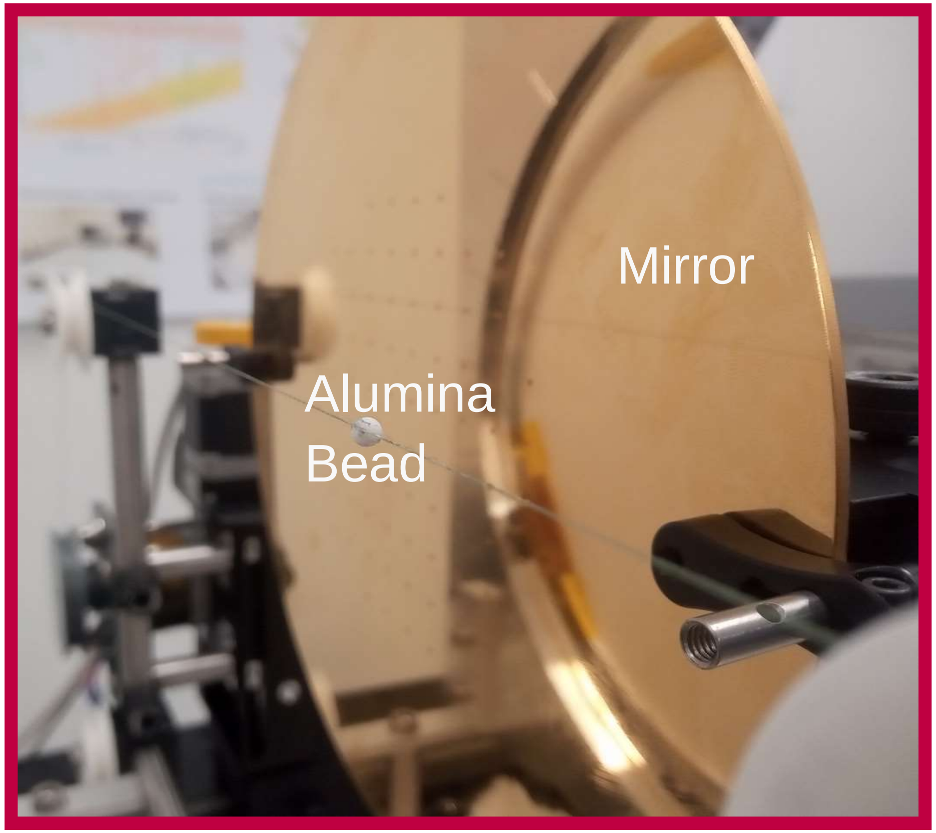


Bead-pull method (1/2)

JCAP 04 (2023) 064

Boost factor determined using Bead-pull Method (non-resonant perturbation theory) + reciprocity theorem





Beed properties

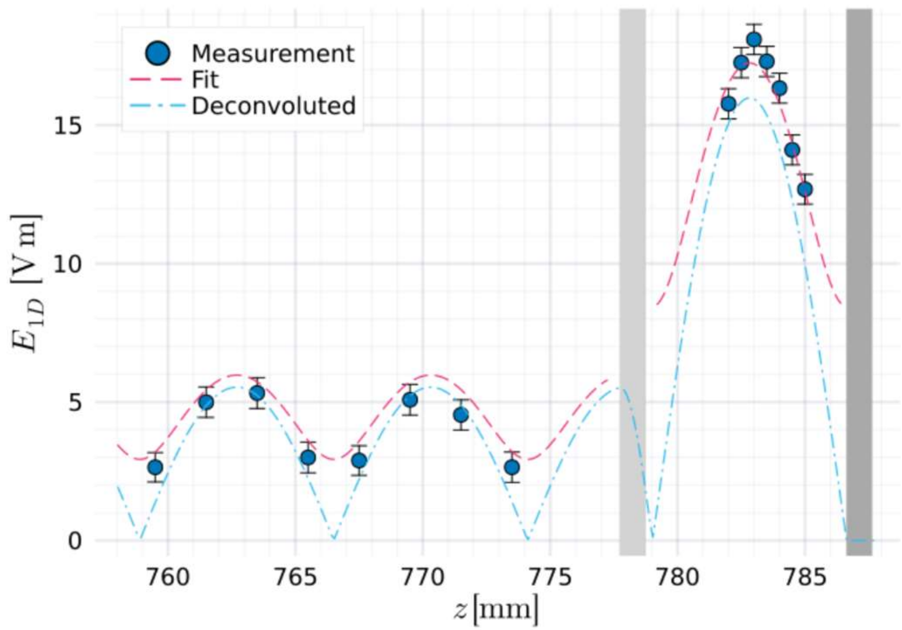
Change in reflection coefficient → $$\Delta\Gamma = \frac{\alpha_e \omega}{4P_{\text{in}}} \boldsymbol{E}_R^2$$ → E field

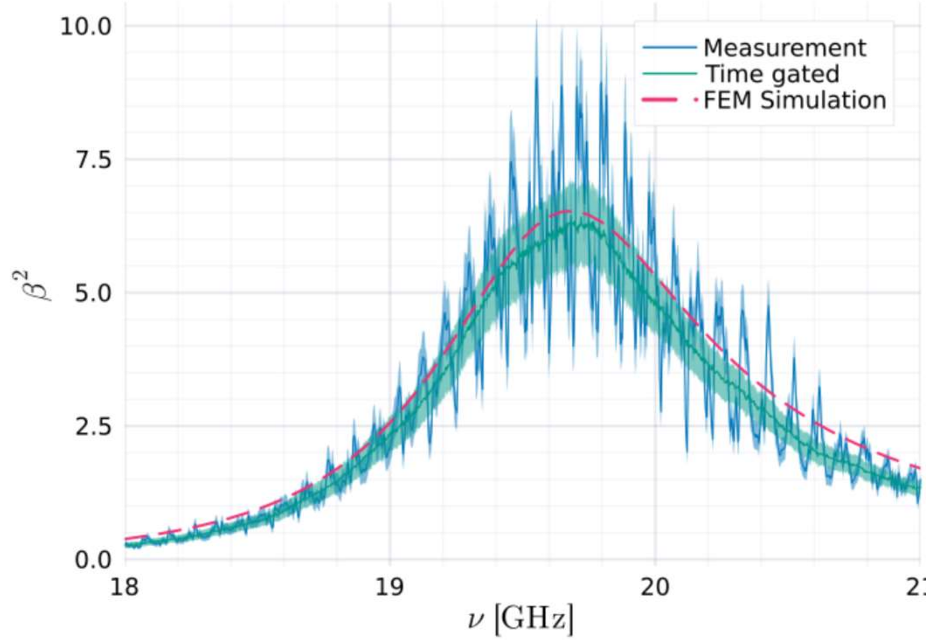
$$P_{\text{sig}} = \frac{g_{a\gamma}^2}{16P_{\text{in}}} \left| \int_{V_a} \mathrm{d}V\, \boldsymbol{E}_R \cdot \dot{a} \boldsymbol{B}_e \right|^2 \Rightarrow \beta^2 = \frac{P_{\text{sig}}}{P_0}$$

Bead-pull method (2/2)

JCAP 04 (2024) 005

Test with a single disk (low boost factor)

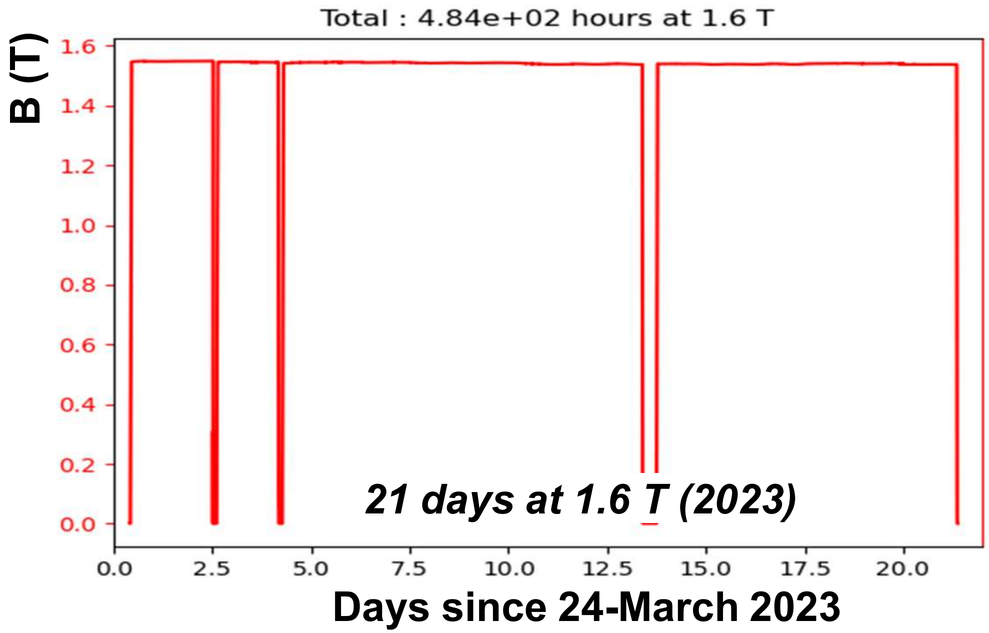


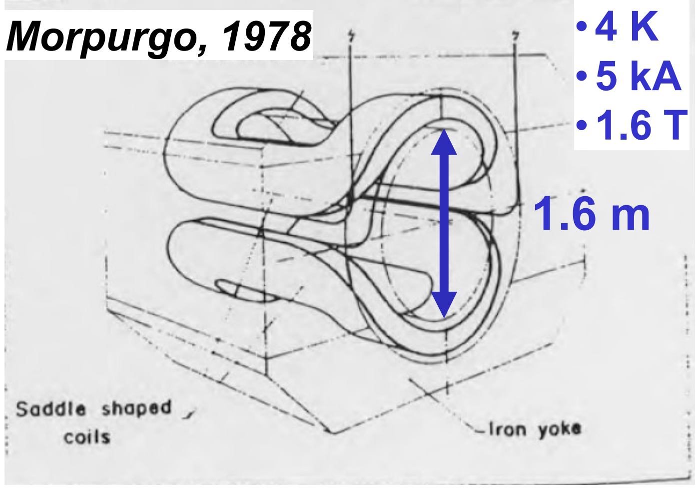


Magnet for prototype test

❑ CERN lends us the world largest warm bore dipole magnet

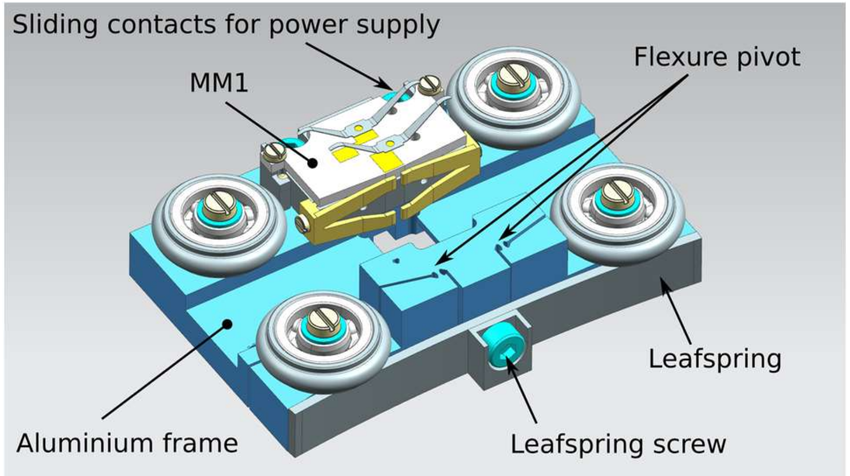
- **Jun 1978:** Installation in the North Area at CERN
- **Sep 2020:** CERN RB approves usage by MADMAX
- **Mar 2021:** full refurbishing around magnet area
- **Mar 2022:** installation of new power converters
- **Apr 2022**: magnet recommissioning
- **≥Mar 2023:** MADMAX full user of the magnet

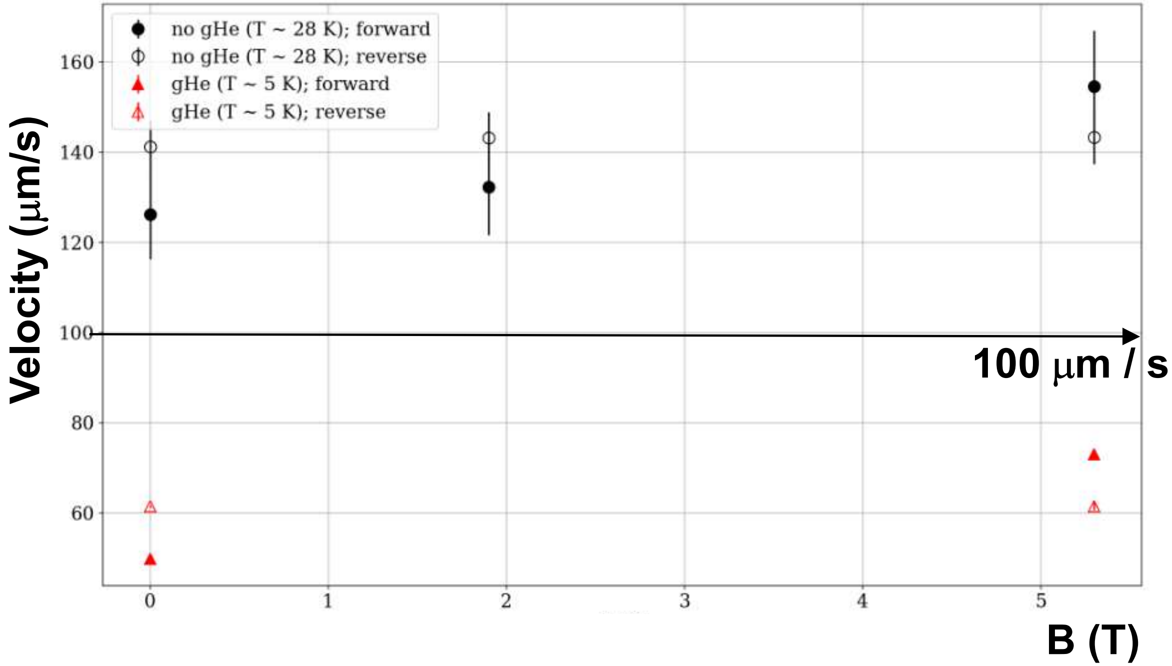




Piezo Motor

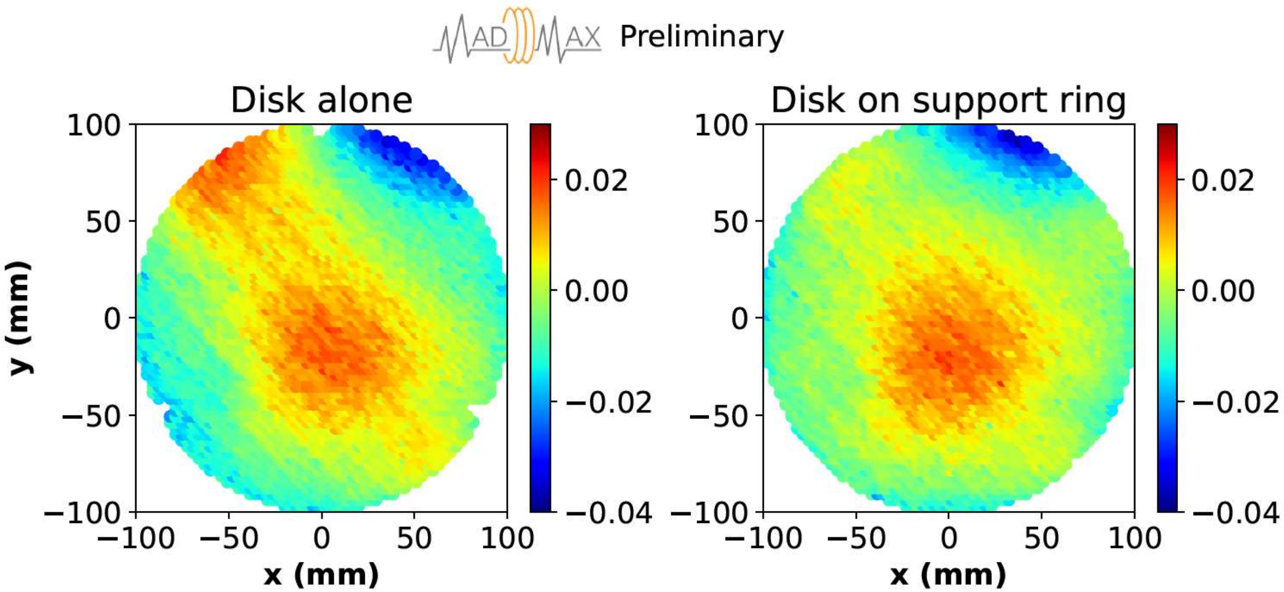
JINST 18 (2023) P08011





Disk Planarity

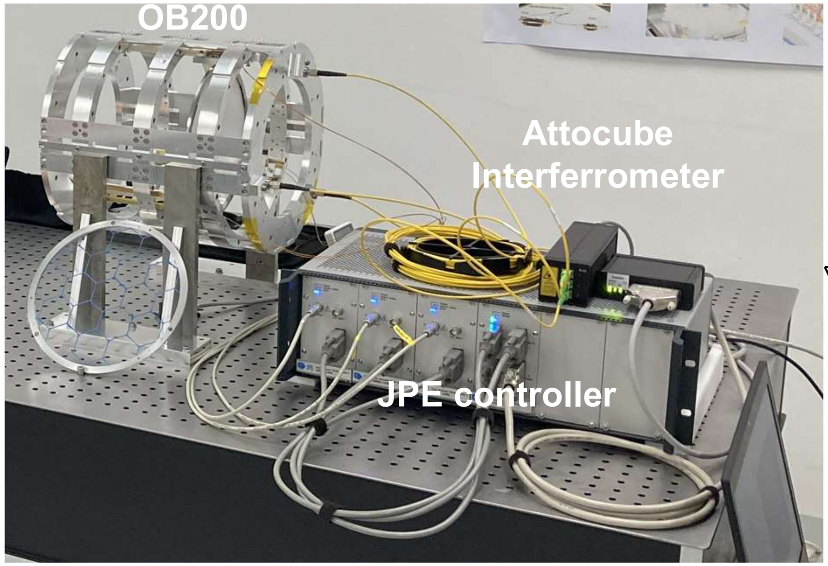
arXiv:2407.10716



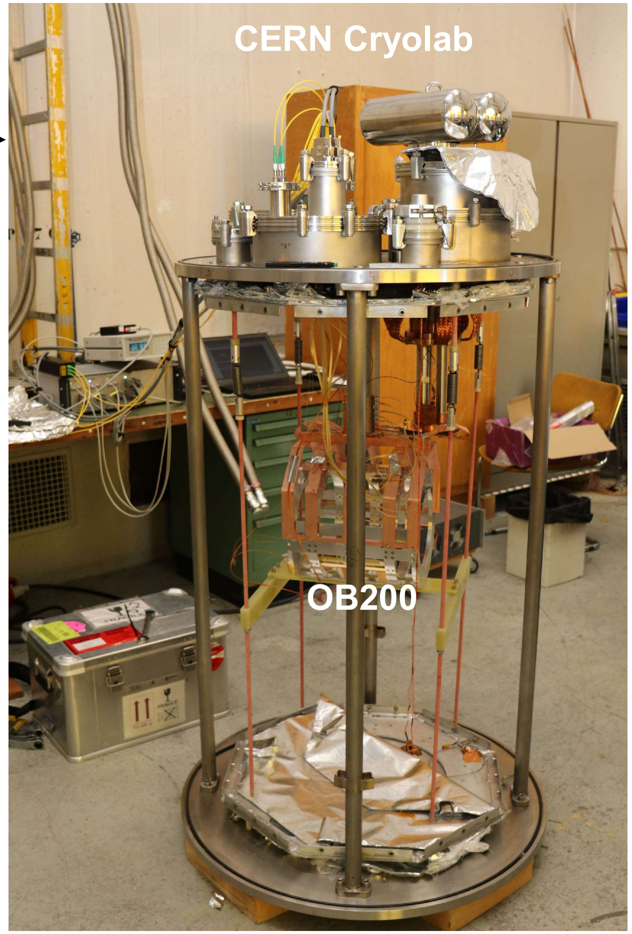
RMS < 10 μm

OB200 tests

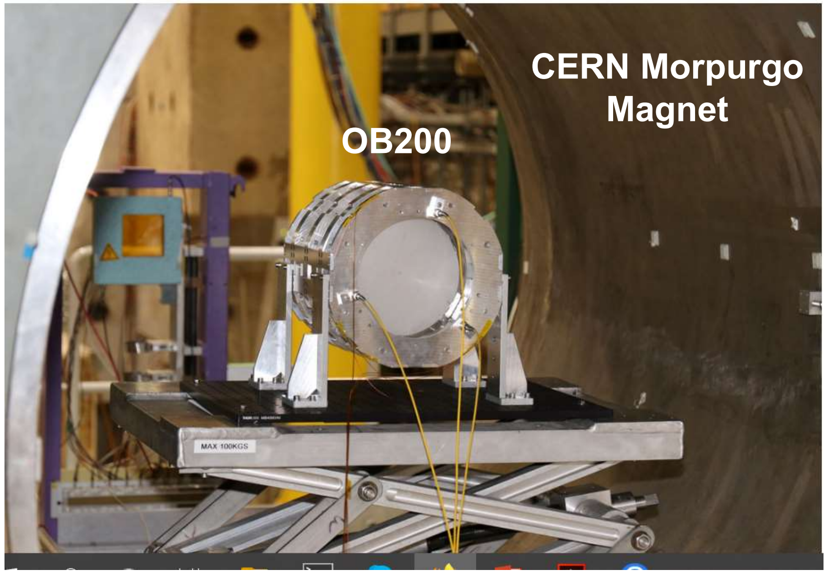
arXiv:2407.10716



March, April and
October 2022



Apr 2022



Dark Matter Searches

- **Dark Photon kinetic mixing angle with photon, χ** *(broadband β^2)*
  - Assuming unpolarized Dark Photon:

$$\chi = 1.43 \times 10^{-13} \left(\frac{400}{\beta^2}\right)^{1/2} \left(\frac{707\,\mathrm{cm}^2}{A}\right)^{1/2} \left(\frac{T_{sys}}{290\,\mathrm{K}}\right)^{1/2} \left(\frac{11.7\,\mathrm{d}}{\Delta t}\right)^{1/4} \left(\frac{SNR}{5}\right)^{1/2} \left(\frac{0.3\,\mathrm{GeV}/\mathrm{cm}^3}{\rho_{\mathrm{DM}}}\right)^{1/2}$$

- **ALP-photon coupling, $g_{a\gamma}$** *(optimised β^2)*

$$g_{a\gamma} \approx 2 \times 10^{-14}\,\mathrm{GeV}^{-1} \left(\frac{0.3\,\mathrm{GeV}/\mathrm{cm}^3}{\rho_a}\right)^{1/2} \left(\frac{10^5}{\beta^2}\right)^{1/2} \left(\frac{1\,\mathrm{m}^2}{A}\right)^{1/2} \left(\frac{T_{\mathrm{sys}}}{8\,\mathrm{K}}\right)^{1/2} \left(\frac{10\,\mathrm{T}}{B_e}\right) \left(\frac{1.3\,\mathrm{d}}{\tau}\right)^{1/4} \left(\frac{SNR}{5}\right)^{1/2} \left(\frac{m_a}{100\,\mu\mathrm{eV}}\right)^{5/4}.$$

QCD Axion

Include signal width

$$\left(\frac{\Delta\nu}{20\ \mathrm{kHz}}\right)^{1/4} = 1.049 \left(\frac{m_a}{100\ \mu\mathrm{eV}}\right)^{1/4}$$