First axion and dark photon dark matter searches 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- MADMAX, a dielectric haloscope
3- Dark matter searches with MADMAX prototypes
4- Conclusions

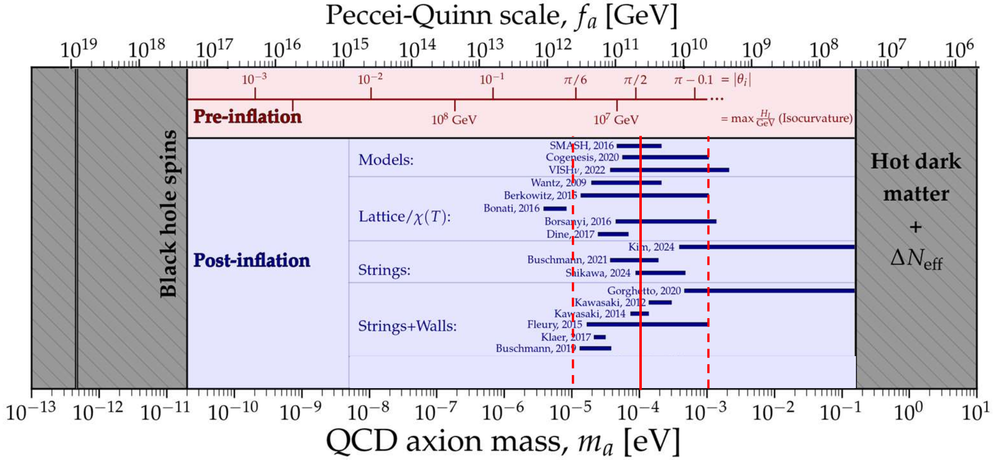
GDR DUPhy– 11 October 2024

Motivation

- ☐ **No CP violation observed in the strong interaction** [Weak CP violation discovered in 64]
  - Even if a CP violating parameter (Θ) exists in the Lagrangian …
  - … $|\Theta|$ **$< 10^{-10}$** is measured from neutron electric dipole moment

Motivation

- ❑ **No CP violation observed in the strong interaction** [Weak CP violation discovered in 64]
  - Even if a CP violating parameter (Θ) exists in the Lagrangian …
  - … $|\Theta|$ **< 10^{-10}** is measured from neutron electric dipole moment
- ❑ **Axion preferred solution to the strong CP problem**
  - Mechanism: new global U(1) symmetry *(Peccei-Quinn, 77)* spont. broken at scale f_a **[$f_a \gg f_{ElectroWeak}$]**
    - Can occur before or after inflation
    - Non-thermal massive axion production at $T \sim \Lambda_{QCD}$
  - Consequence: pseudo-Goldstone boson of the theory = **axion** *(Weinberg-Wilczek, 78)*
    - Tiny mass **[$m_a \approx m_\pi f_\pi / f_a <$ eV]**, weakly interacting **[g_a suppressed by f_a]**, long-lived **[$\tau_{axion} > t_{Universe}$]**
  - Dark matter candidate *(Preskill et al, 83)* **[relaxing m_a constraint → axion-like particles (ALPs)]**
    - m_a can be computed in post-inflationary scenario

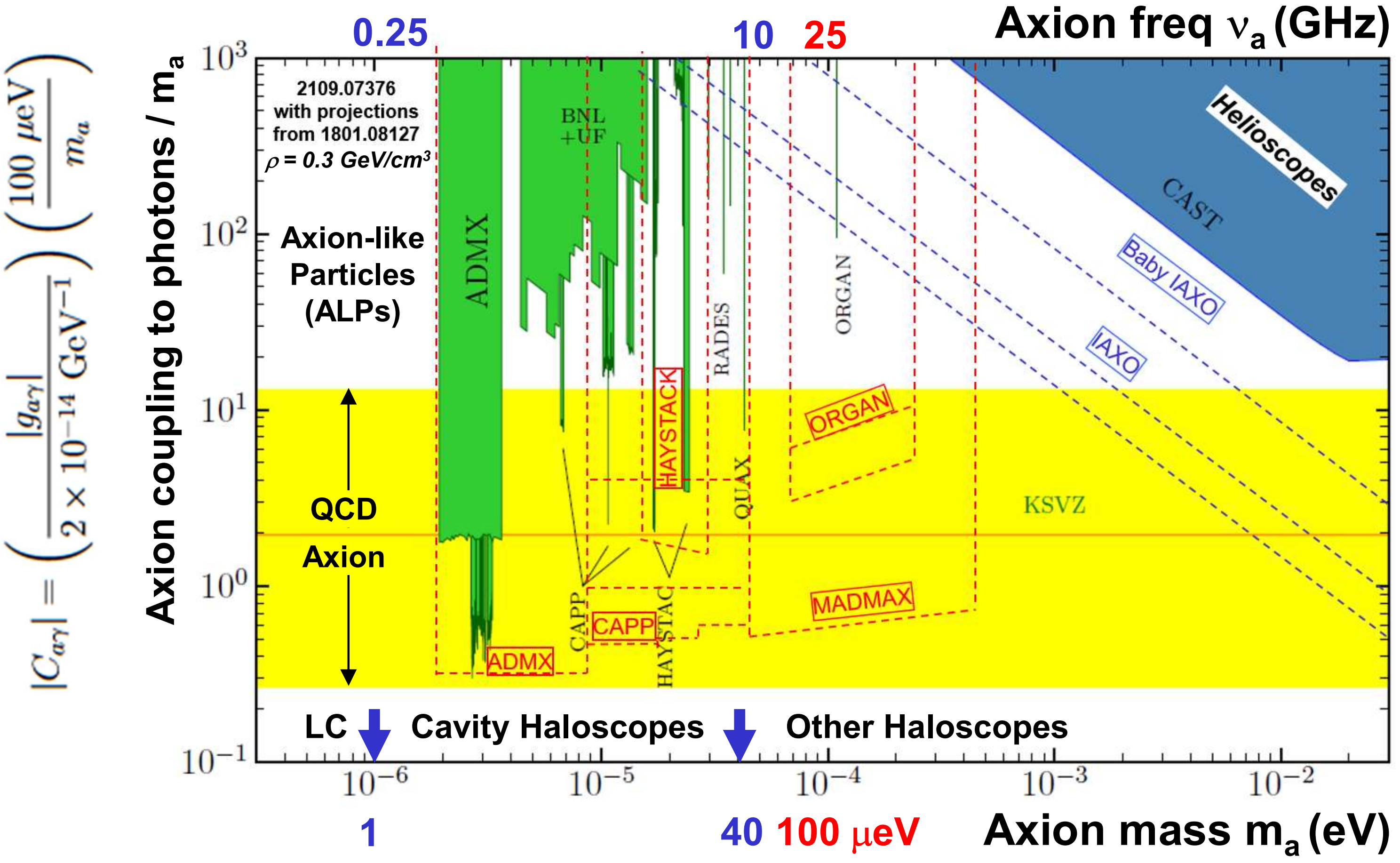


https://cajohare.github.io/AxionLimits/docs/am.html

Post-inflationary scenario predicts $m_a \approx O(100)$ μeV

Axion searches

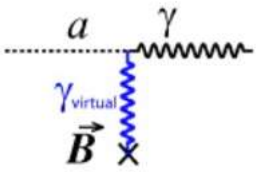
- **Haloscope** *(using a-γ coupling)* **main way to search for dark matter axion**



Haloscopes

🟩 Published

⬚ Prospects



External static magnetic field

MADMAX one of the few exp. sensitive to m_a = O(100) μeV

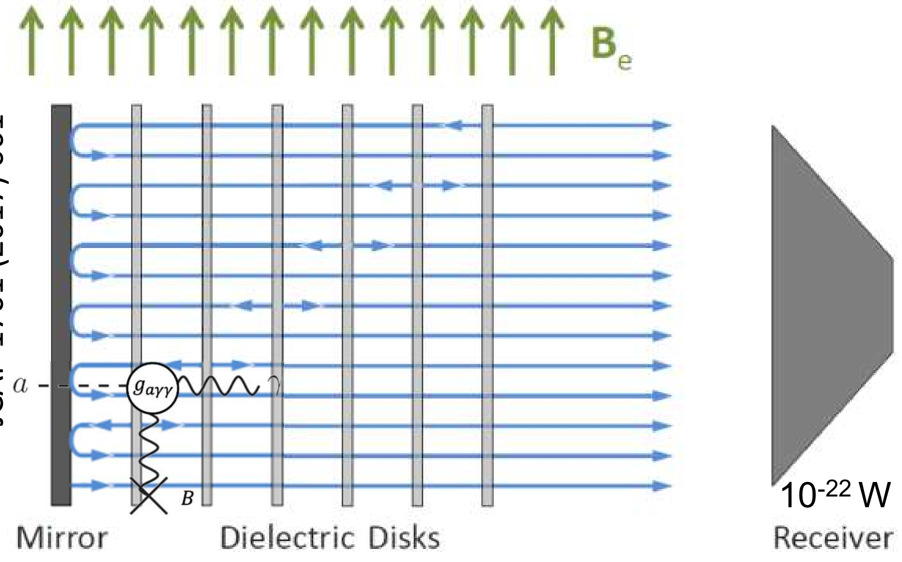
MADMAX

EPJC 79 (2019) 186

Principles of dielectric haloscope

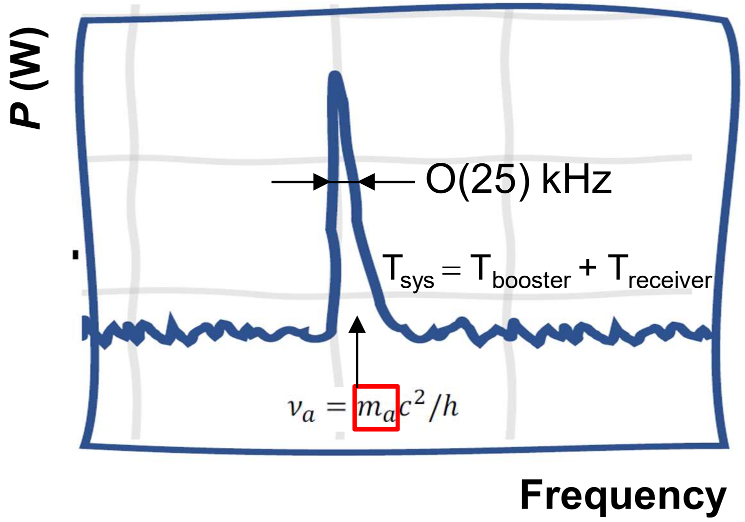
- Constructive interference of coherent photons emitted at the disk surface + resonant enhancement *(~leaky resonator cavities)*: **boost factor β^2** *($\propto \varepsilon$, N_{disk})* wrt mirror only

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



JCAP 1701 (2017) 061

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



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

MADMAX

EPJC 79 (2019) 186

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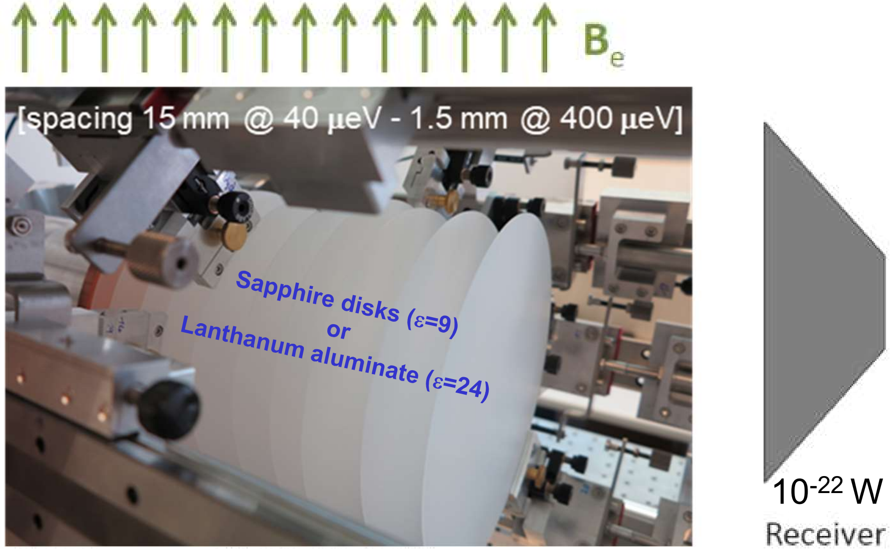
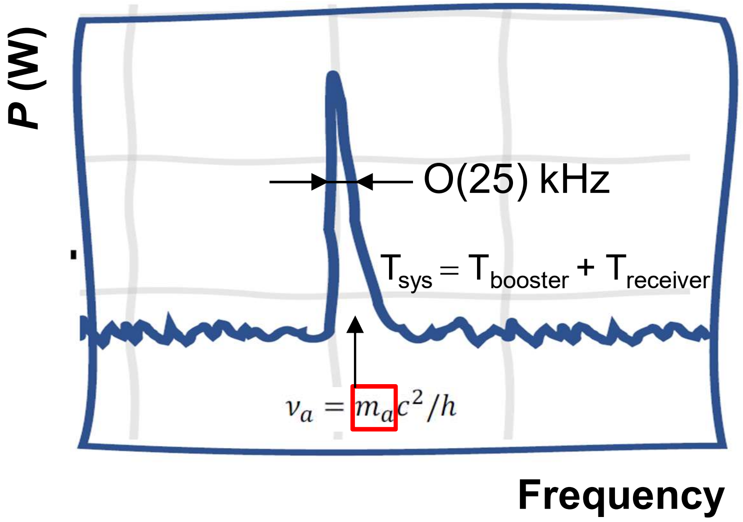




- Axion mass **scan**: by **moving discs** with piezo motors (µm prec.) at 4K under 10 T *(50 MHz step)*

MADMAX exploits a new concept to cover an uncharted phase space

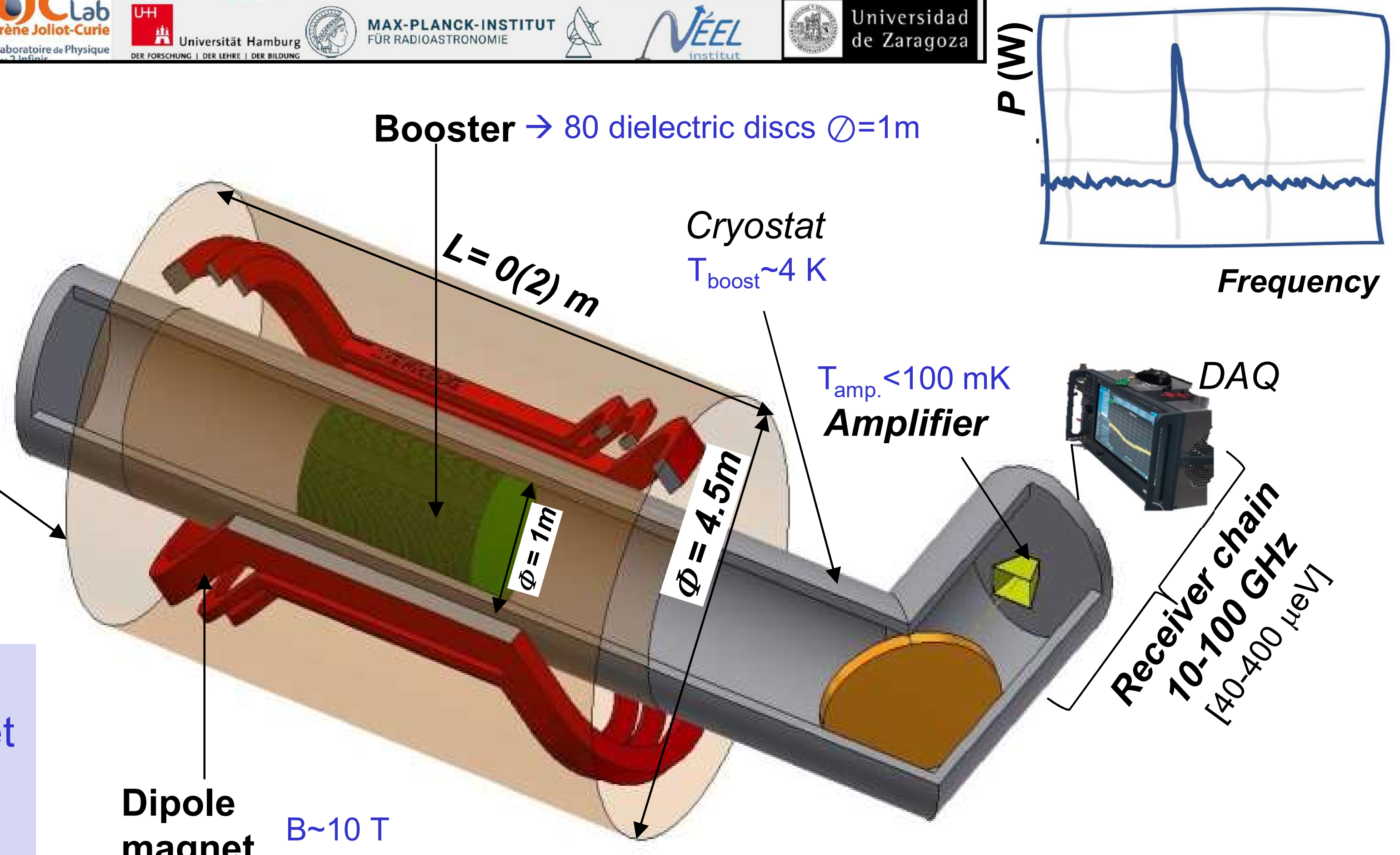
MADMAX

Formed in 2017. 11 institutes, ~50 people

Fermilab
DESY.
CPPM
MAX-PLANCK-INSTITUT FÜR PHYSIK
RWTH AACHEN UNIVERSITY
EBERHARD KARLS UNIVERSITÄT TÜBINGEN
IJCLab Irène Joliot-Curie
Universität Hamburg
MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE
NÉEL institut
Universidad de Zaragoza

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

Prototype boosters

❑ Gradually building the final ‘open’ booster

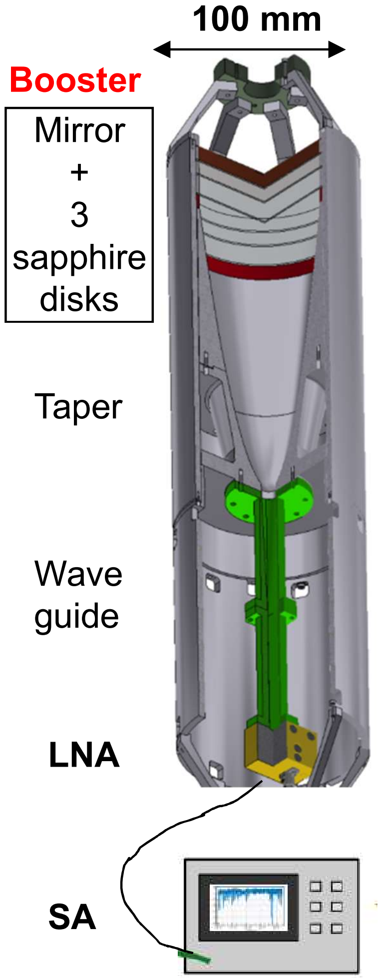
- Set-up: CERN Morpurgo magnet *(1.6 T)* + prototype cryostats *(G10, stainless-steel)*
- Disks *(sapphire)*: moveable *(piezo motors)*, good planarity *(<10 µm)*, controlled thickness *(1000±10 µm)*
- Receiver chain: low noise amplifier *(HEMT)* + Spectrum Analyser or custom-made board

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***

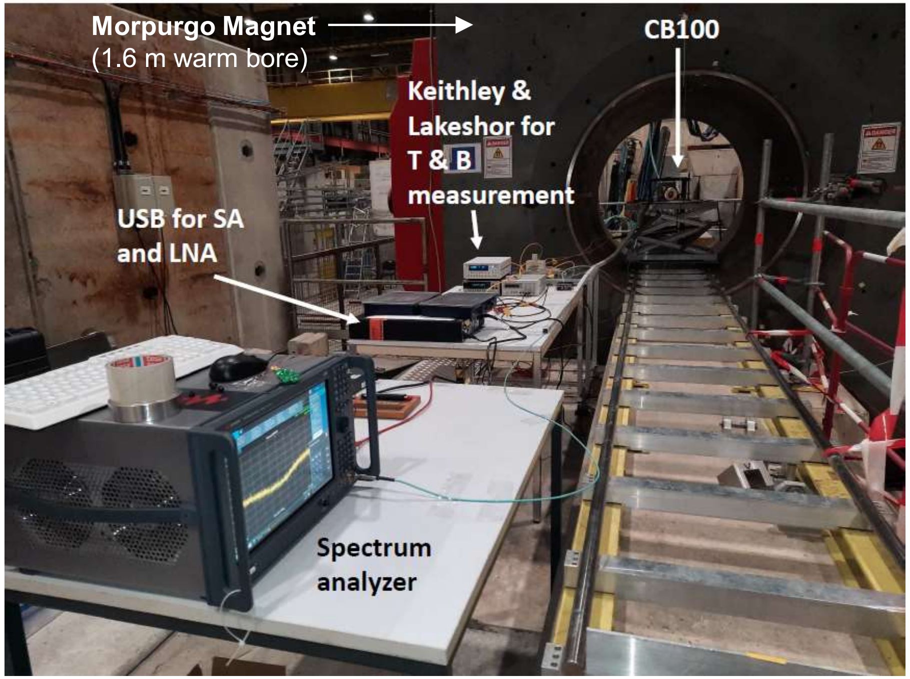
*Dark Photon

Room Temp.
Cold (10 K)
Bfield
Prospects

Preparatory work



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



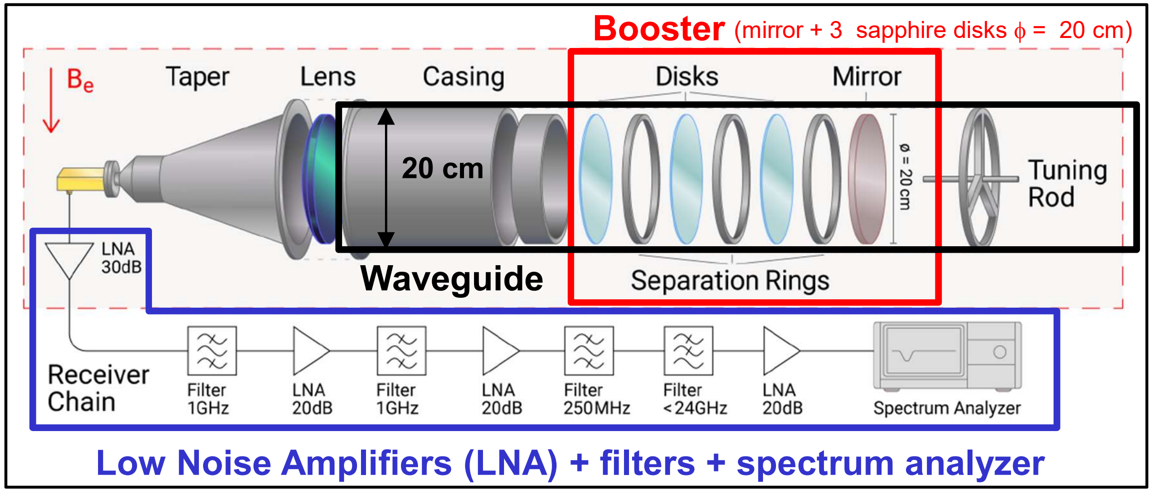
- CERN refurbished the area and the magnet for MADMAX
- Checked that no RF interference with CERN environment
- Checked stability of data taking @19 GHz, 1.6 T: $t_{Live} \propto 1/\sigma_{Noise}^2$
- Calibrated @10% receiver chain power: $P \propto T_{sys} = f(\Gamma_{RC}, G, \nu)$

Validated that CERN environment suited for prototype tests

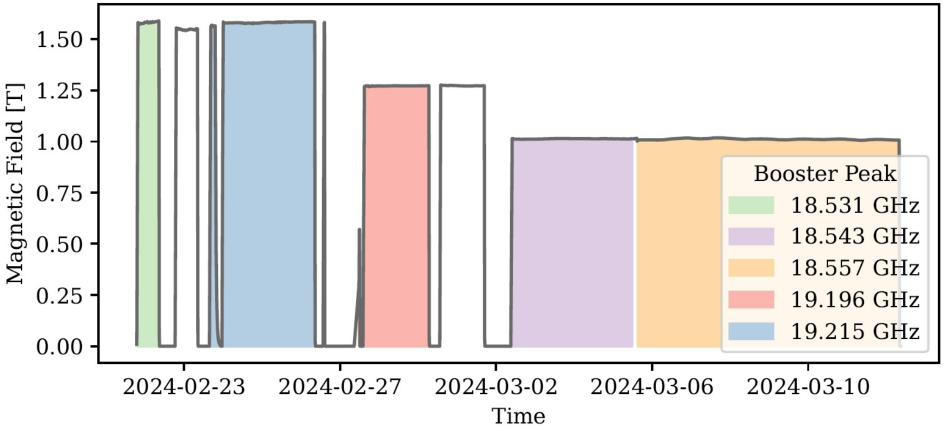
Axion search (1/5)

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

- Before going to CERN, prepared **5 disk configurations** with different β_{peak}^2 frequency
- Configurations obtained by changing manually the disk distances *(separation rings, tuning rod)*



Low Noise Amplifiers (LNA) + filters + spectrum analyzer

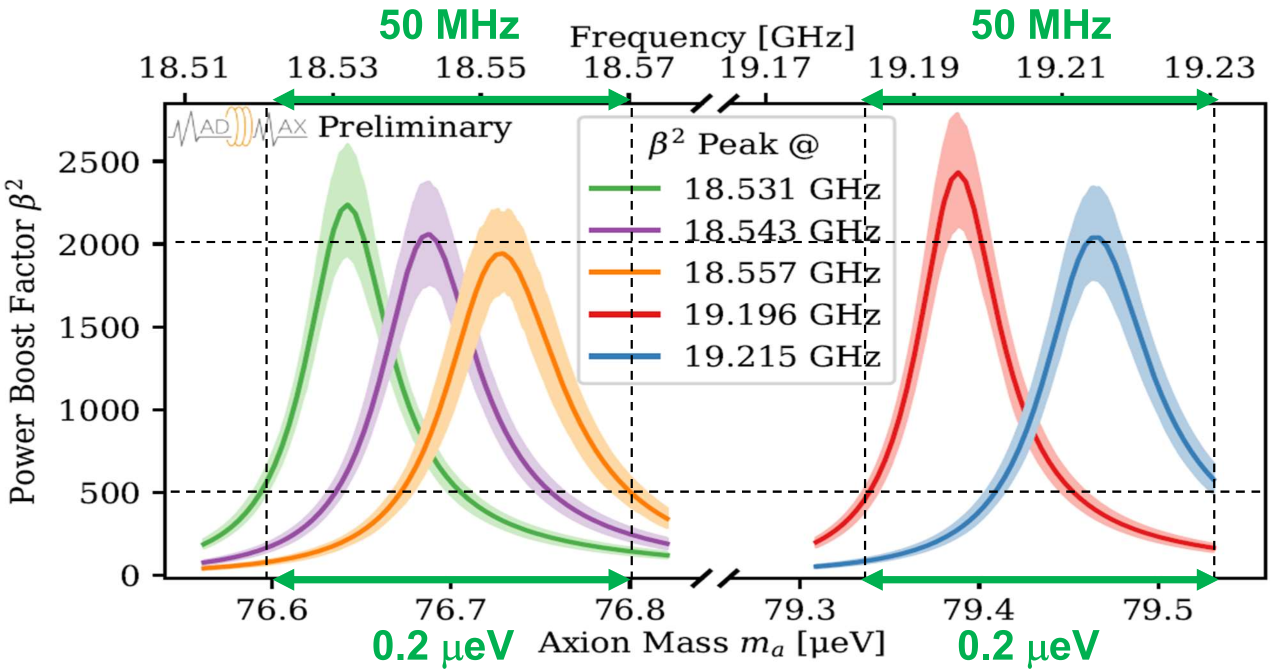


14.5-day physics run @18.5, 19.2 GHz and under B = 1 - 1.6 T

Axion search (2/5)

❑ Computing the boost factor

- Booster & receiver noise model through fits of reflectivity and noise measurements
- Boost factor curves $\beta^2(\nu)$ determined with ~15% systematics
  - ✓ $\beta^2_{peak} \approx 0(2000)$ and scan 100 MHz with $\beta^2 > 500$



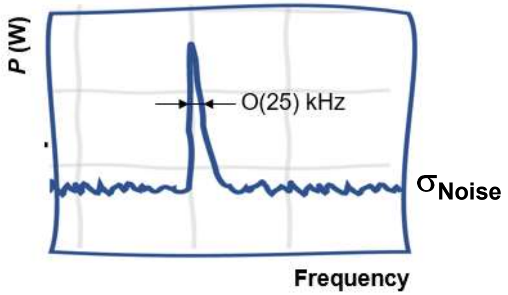
Demonstrating the scanning capacity of MADMAX booster

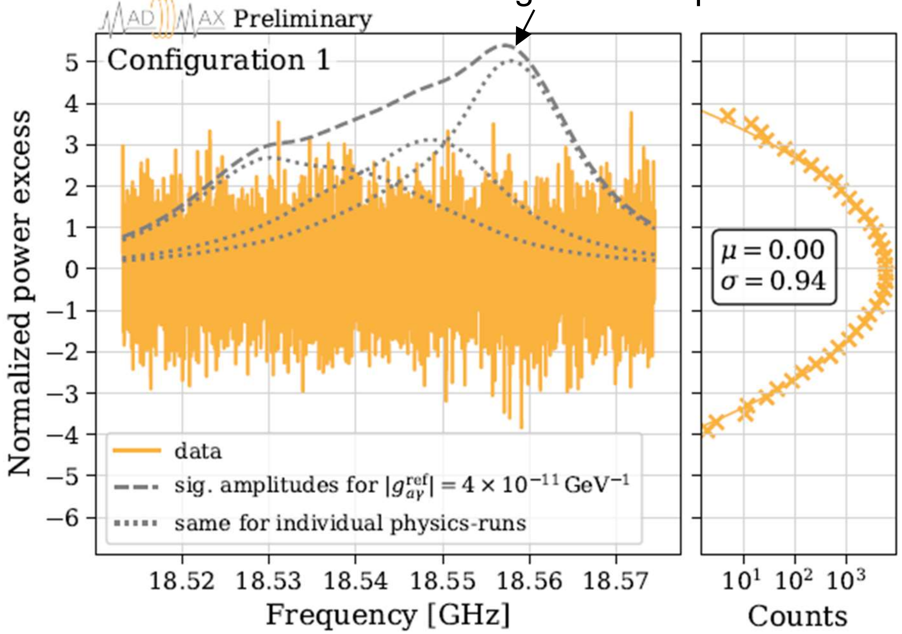
(1 paper in prep.)

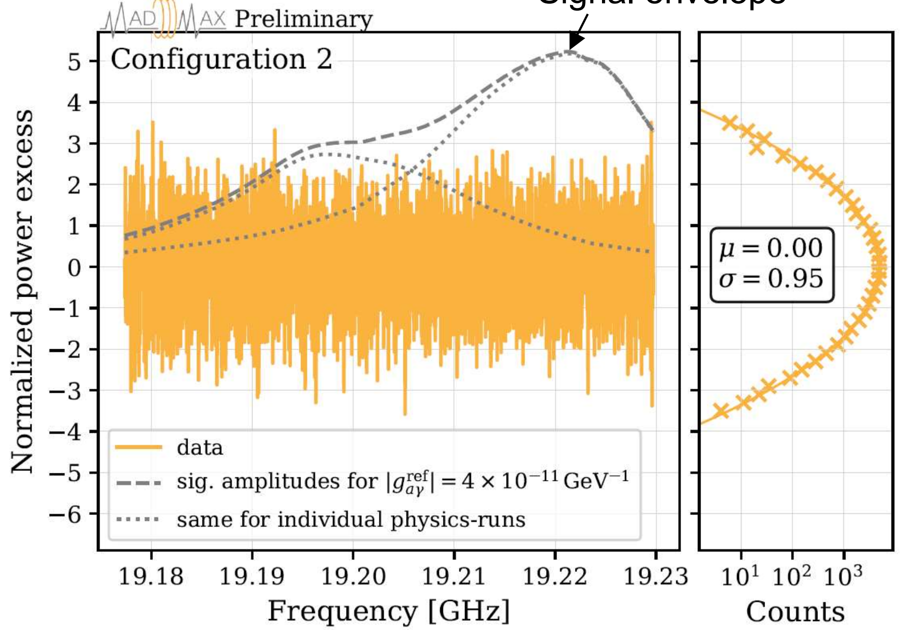
Axion search (3/5)

❑ Full power spectrum data analysis

- Build the normalized power excess spectrum *(HAYSTACK procedure, PRD 96 (2017) 123008)*:
  - ✓ (Savitsky-Golay -- SG) filter of the calibrated power spectra
  - ✓ Residuals divided by σ_{Noise} ($\propto T_{sys}$) → Normalized power excess vs frequency
  - ✓ Combine spectra by weighting with the expected SNR in each 0.9 kHz bin
- See no excesses → set limit at 95% CL on $|g_{a\gamma}|$ for each bin




Signal envelope

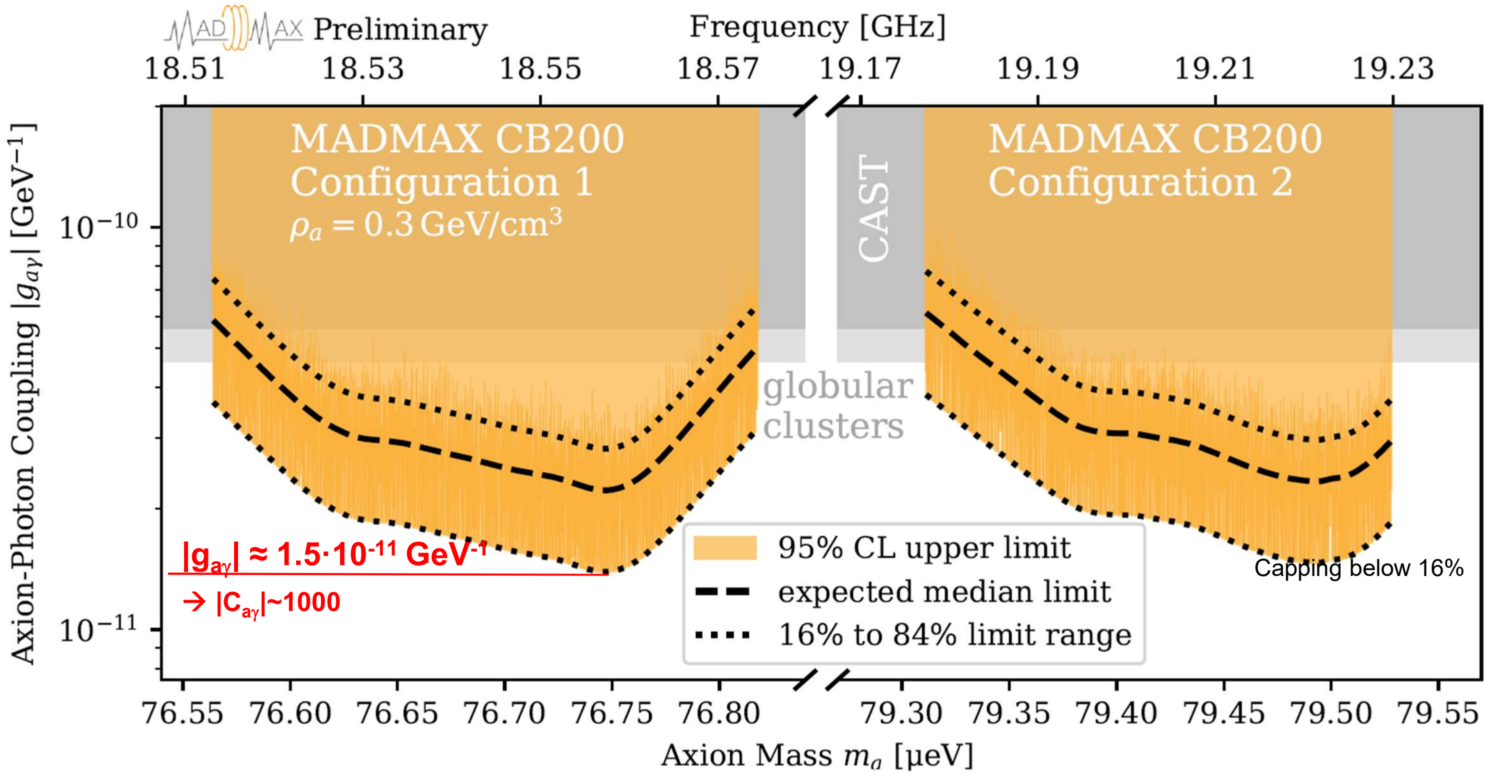

Signal envelope

Axion search (4/5)

2409. 11777

❑ Setting limit in the $|g_{a\gamma}|$ – m_a plane

- Limits below (new) CAST and globular clusters, down to **$|g_{a\gamma}|$ ~ O(1.5x10^{-11}) GeV^{-1}**
- Validate the dielectric haloscope concept with a small prototype set-up



$|g_{a\gamma}| \approx 1.5 \cdot 10^{-11}$ GeV^{-1}

→ $|C_{a\gamma}|$~1000

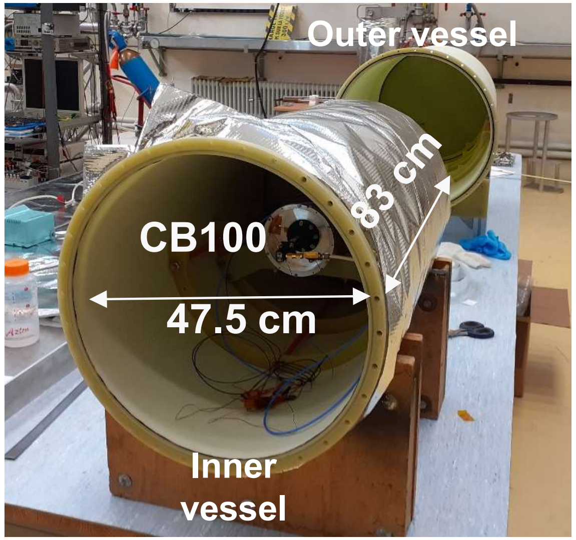
Capping below 16%

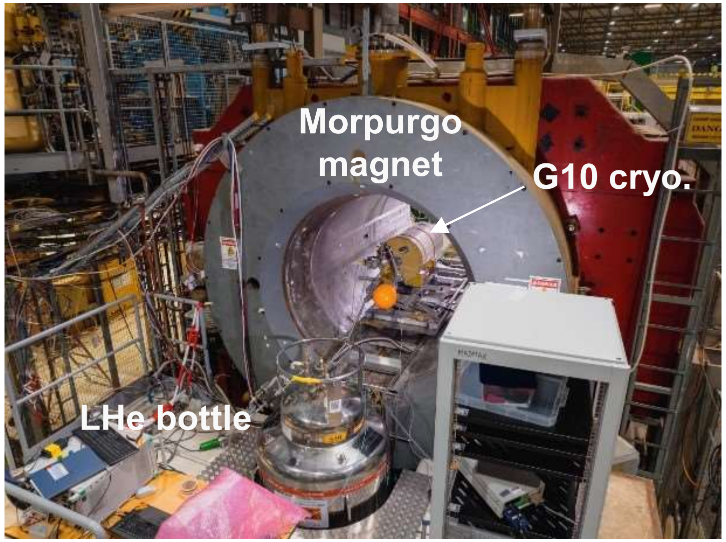
First dark matter axion search with a dielectric haloscope

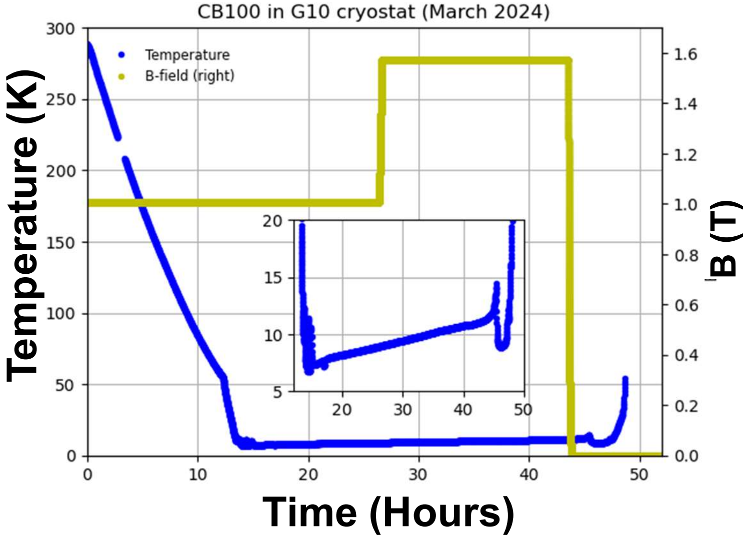
Axion search (5/5)

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)*







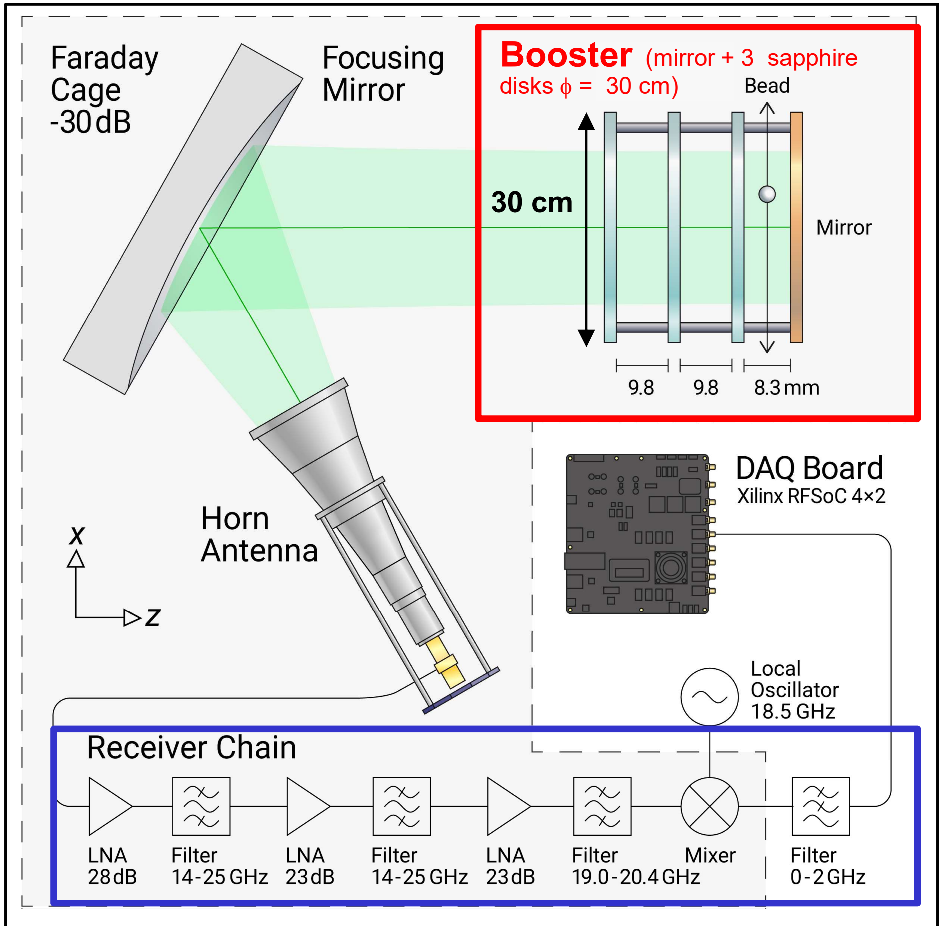
First operation of a dielectric haloscope at cold under B field

(data analysis ongoing → 3 papers in prep.)

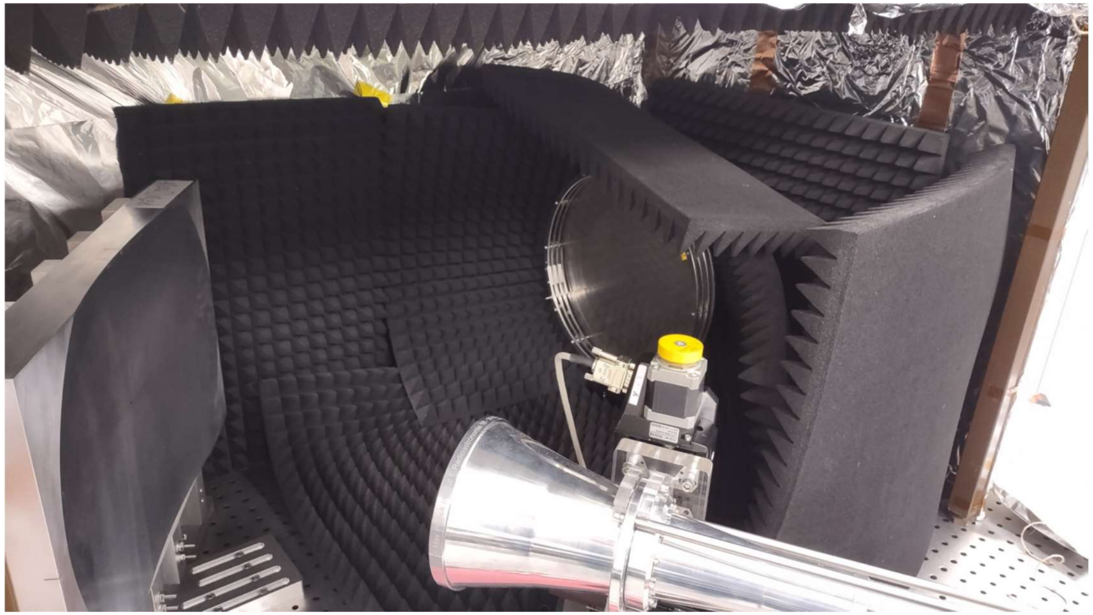
Dark photon search (1/3)

Room Temp.
Cold (10 K)
Bfield
Prospects

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



Low Noise Amplifiers (LNA) + filters + mixer



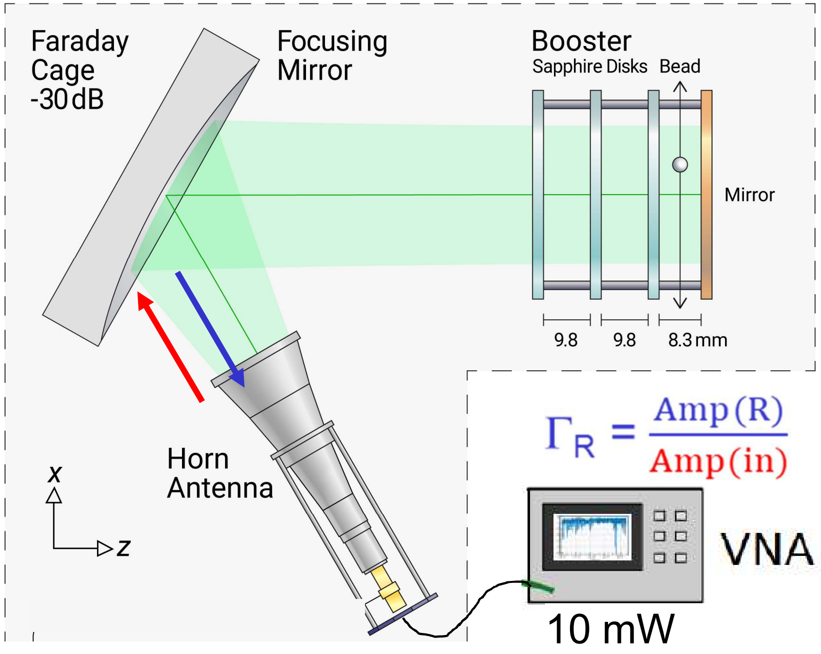
12-day physics run @19.0-20.3 GHz with open booster *(no waveguide)* **and without Bfield**

Dark photon search (2/3)

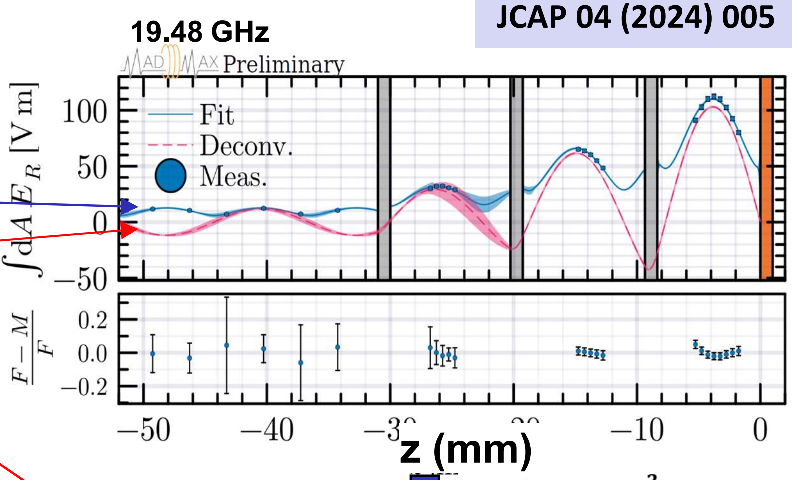
JCAP 04 (2023) 064
JCAP 04 (2024) 005

❑ Developed a new method to measure β^2

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

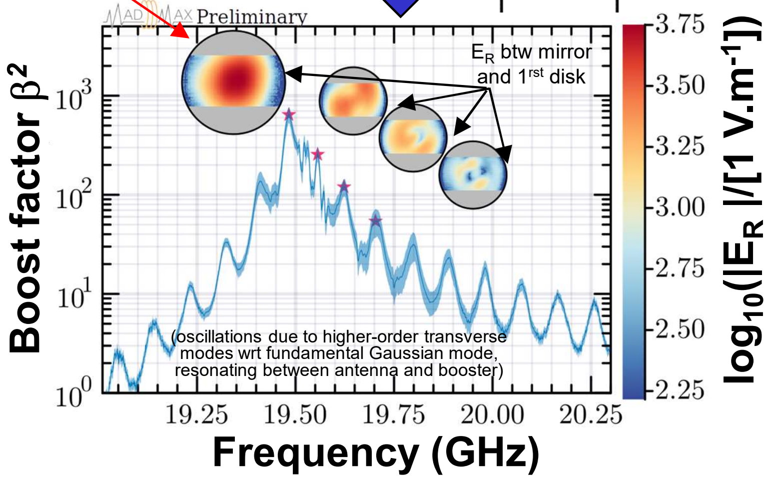


$$\Gamma_R = \frac{\text{Amp(R)}}{\text{Amp(in)}}$$



Reciprocity approach

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



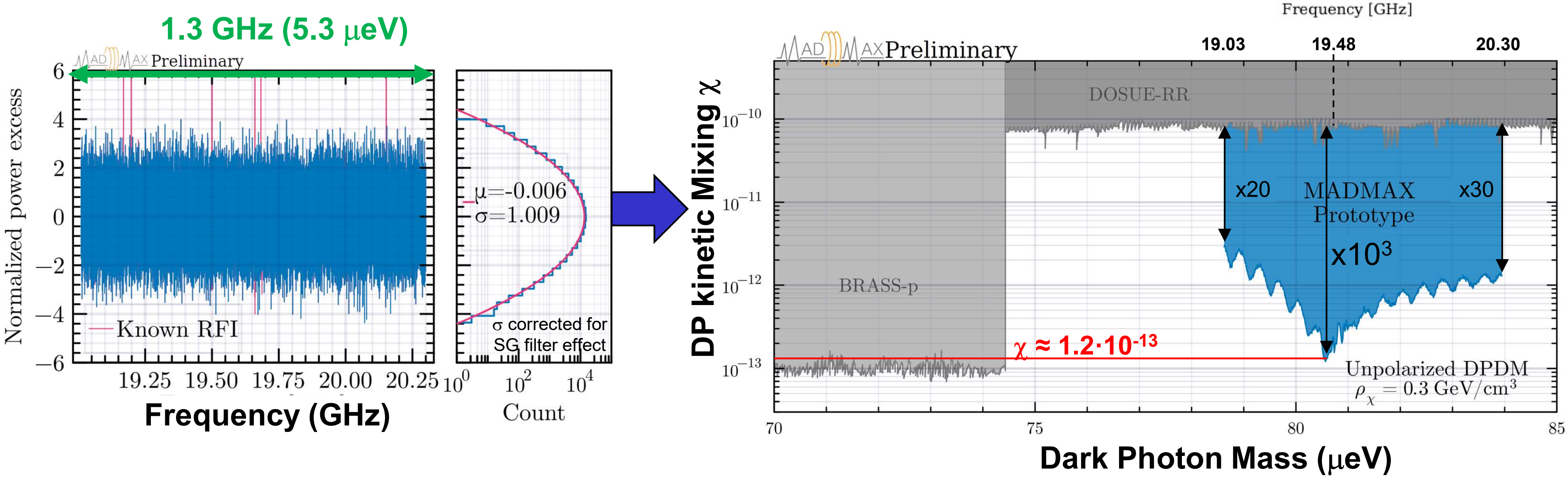
In-situ measurement of β^2 and its uncertainties with bead-pull method

Dark photon search (3/3)

arXiv:2408.02368
(submitted to PRL)

❑ Setting limits in the χ – m_χ plane

- β_{peak}^2=600 extending on 1.3 GHz
- No signals of unknown origin detected → Set 95% CL **limit** on Dark Photon kinetic mixing χ
  - ✓ World best limits in m_χ [78-6, 83.9] μeV
  - ✓ **1-3 order of magnitude** below previous limits



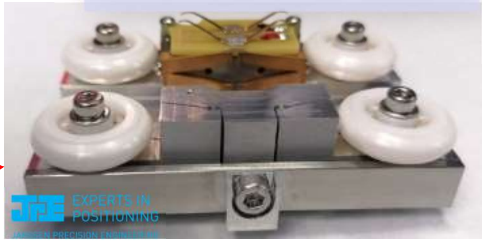
Demonstrated the broadband capacity of MADMAX booster

Tunable open booster (1/2)

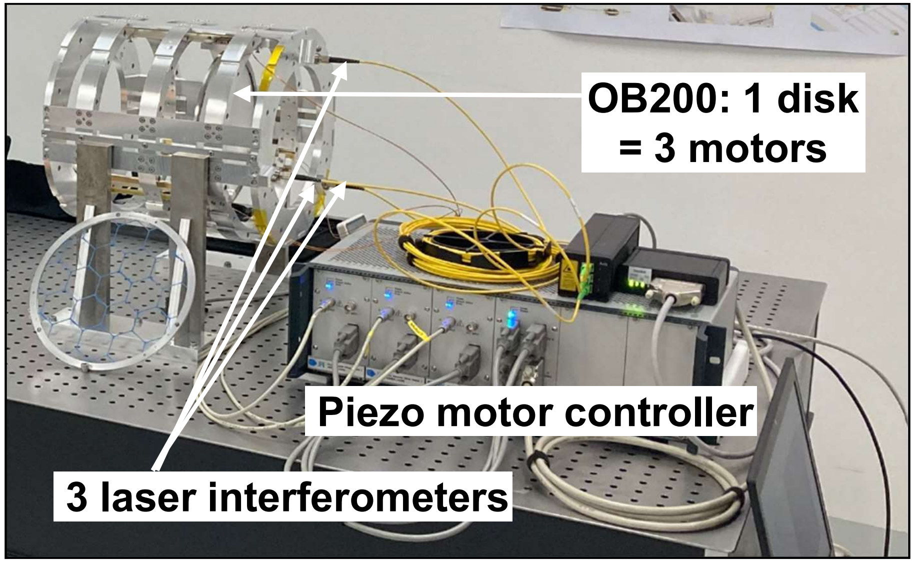
Room Temp.
Cold (10 K)
Bfield
Prospects

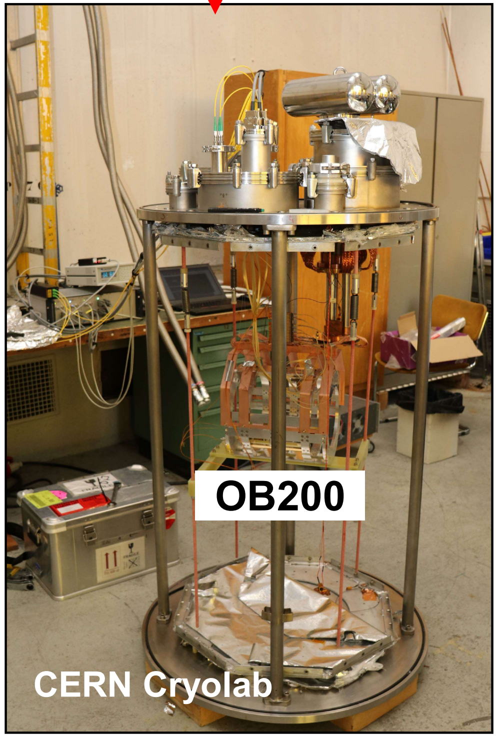
Name	Booster	Disks	Test @CERN
OB200	Open	1, **moveable** $\phi =$ 200 mm	2022, **22**

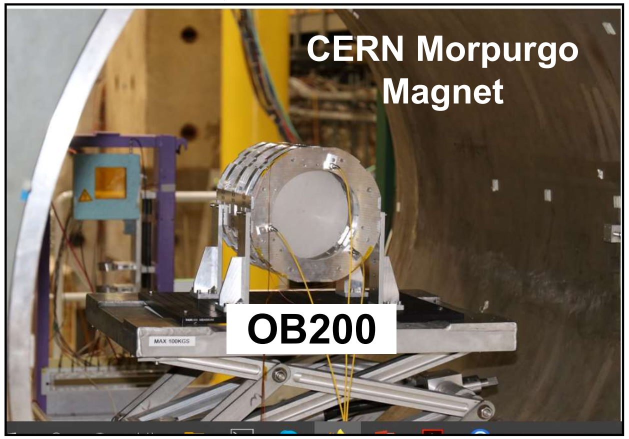
JINST 18 (2023) P08011



- 2021: Successful test of 1 piezo motor at 5 K and 5.3 T (ALP magnet in DESY)
- 2022: OB200 proto tested in the lab, in a CERN cryostat (35 K) … and in 1.6 T at CERN







Tunable open booster (2/2)

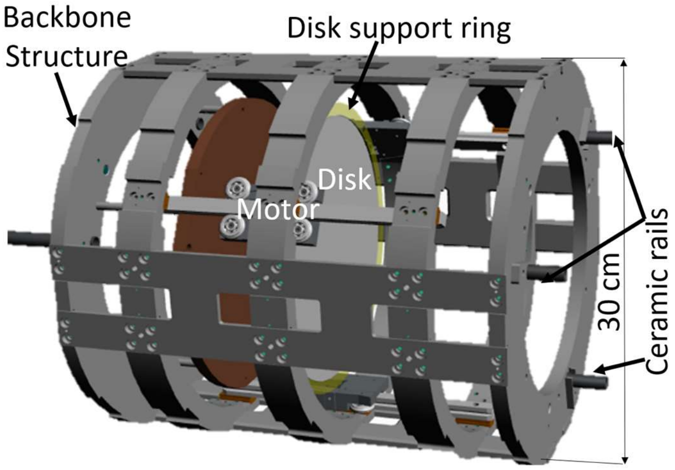
Room Temp.
Cold (10 K)
Bfield
Prospects

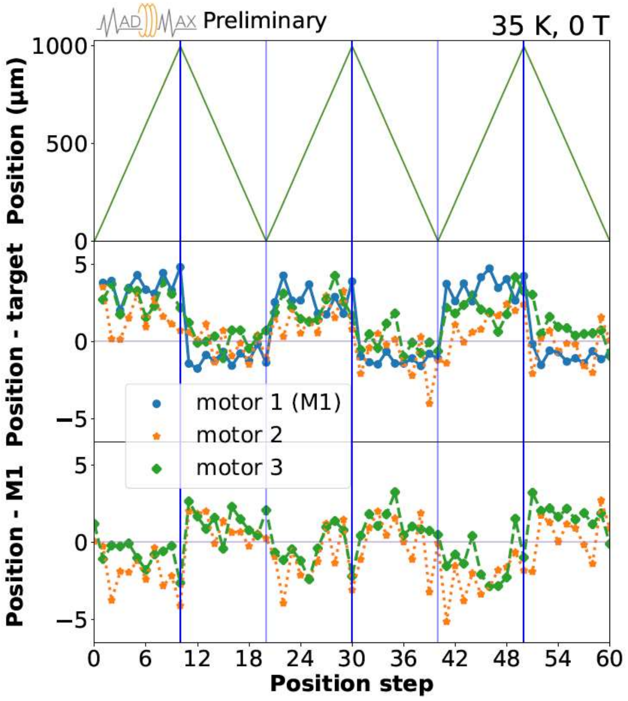
arXiv:2407.10716 (accepted by JINST)

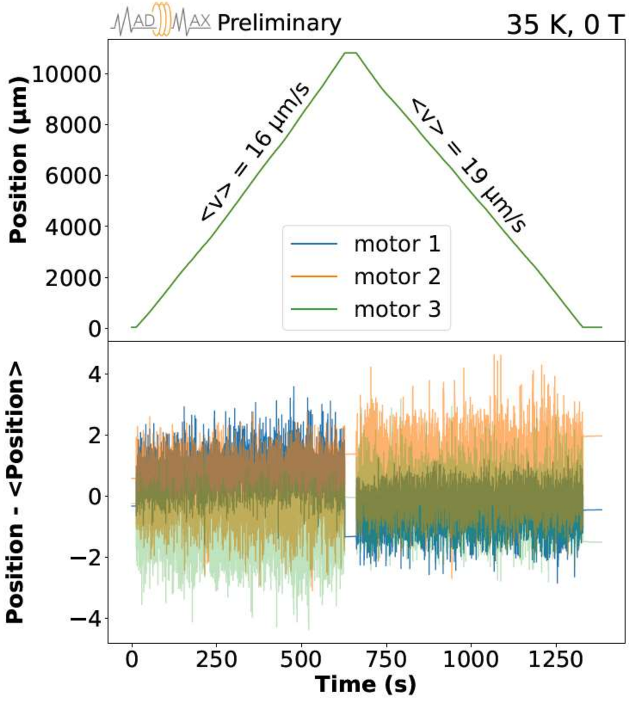
Name	Booster	Disks	Test @CERN
OB200	Open	1, **moveable** ϕ = 200 mm	2022, **22**

Motors positioned at 5 μm

v > 15 μm / s





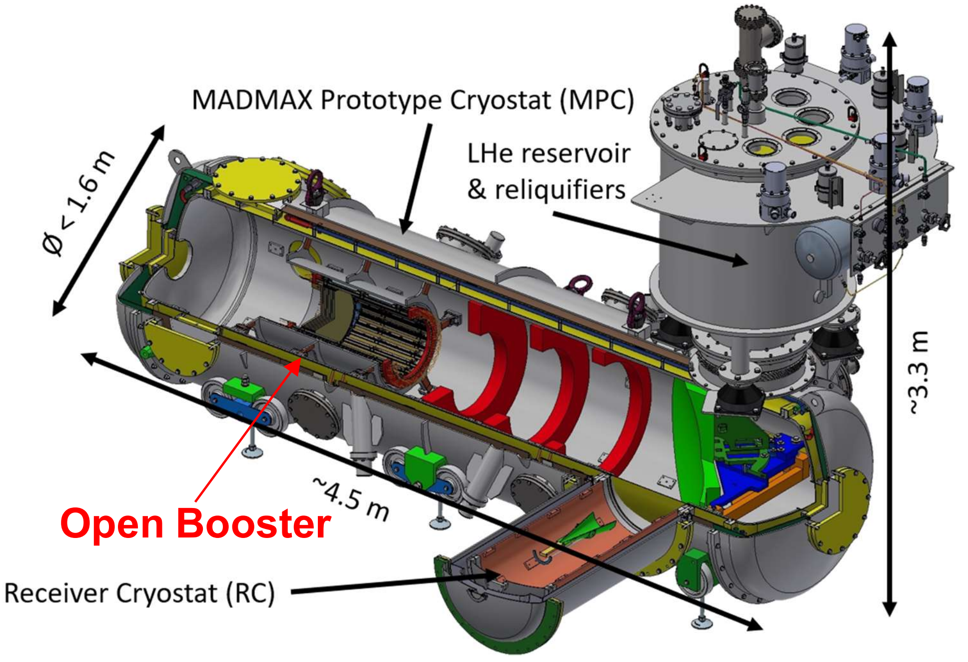


Validated piezo motors and mechanics for open booster

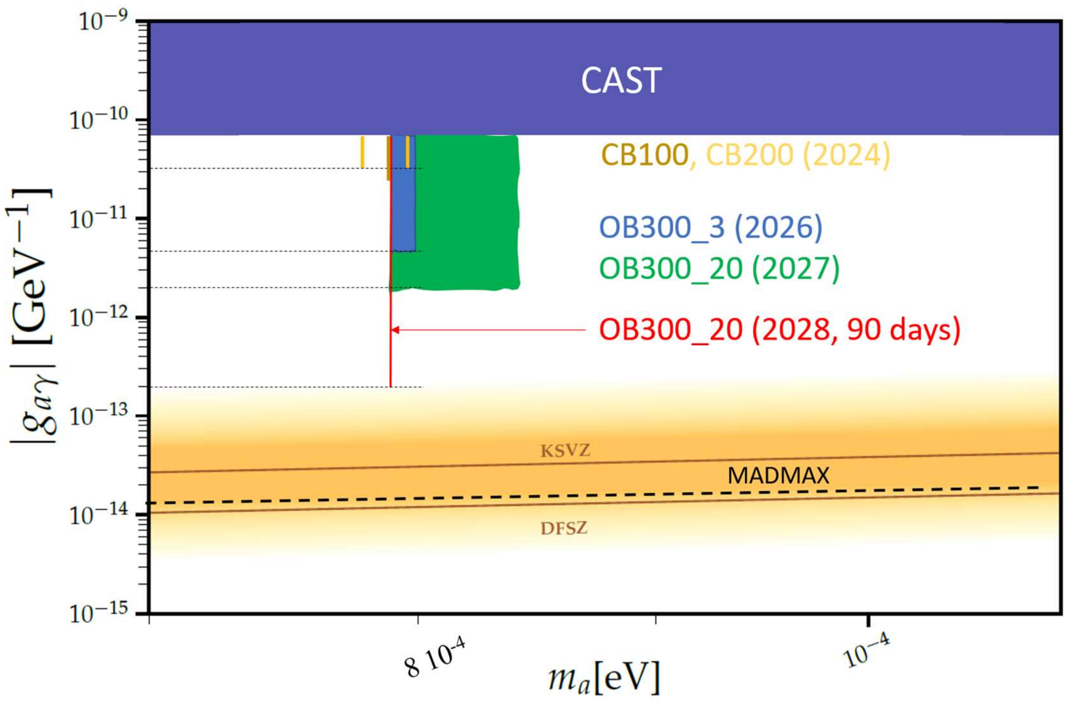
Final prototype

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

- Booster inserted in a stainless steel cryostat



- Physics program during LHC shutdown

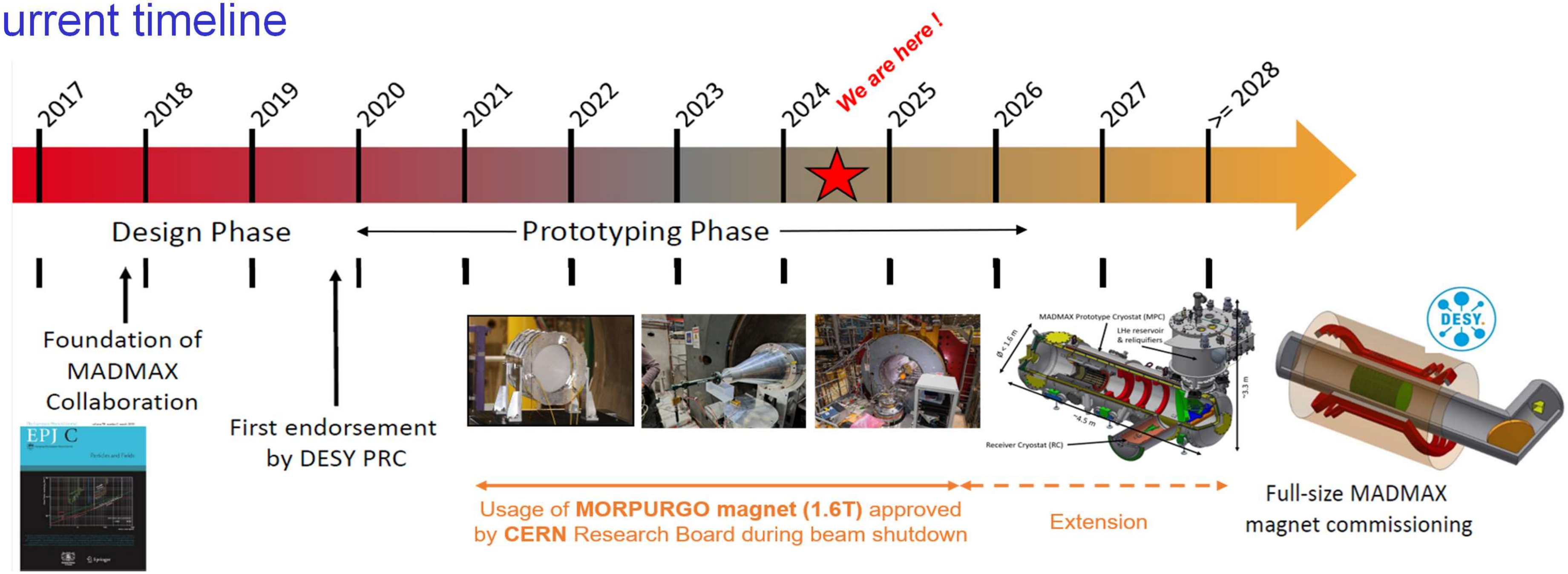


Plan 3 months of axion search / year at CERN in 2026-28 → Final MADMAX

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 β^2 in situ **JCAP 04 (2023) 064, JCAP 04 (2024) 005**
  - ✓ Performed first dark matter searches **@18-20 GHz**
    - ○ Axion (β_{peak}^2 **~ 2000**): world best limits down to **$|g_{a\gamma}|$ ~ 1.5x10^{-11} GeV^{-1}** **arXiv:2408. 02368**
    - ○ Dark Photon (β_{peak}^2 **~ 600**): world best limits in m_χ [78-6, 83.9] μeV **arXiv:2409.11777**
- Current timeline



Design Phase

Prototyping Phase

Foundation of MADMAX Collaboration

First endorsement by DESY PRC

Usage of **MORPURGO magnet (1.6T)** approved by **CERN** Research Board during beam shutdown

Extension

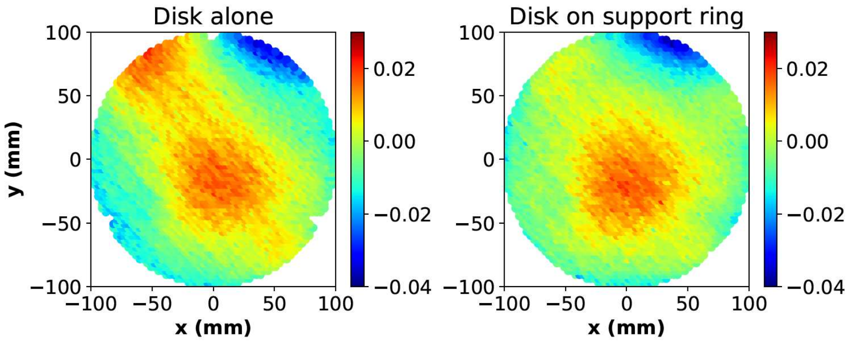
Full-size MADMAX magnet commissioning

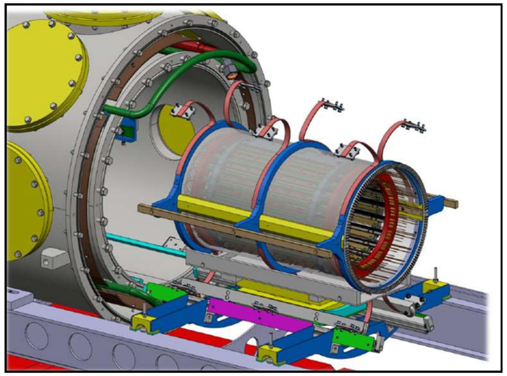
MADMAX in France

- **CEA-IRFU** innovation partner for the magnet, **Institut Néel** (INP) involved in LNA (TWPA)
- **IN2P3: CPPM** MADMAX member (>2019), **IJCLab** associate MADMAX member since (>2023)
+ **CNRS IRL “*DMLab*” @ DESY (with Helmholtz** centers**)** → MADMAX is a central project

☐ Main IN2P3 contributions to MADMAX

- Mechanics:
  - ✓ Disk planarity measurements
  - ✓ Precision mechanics for the prototype boosters
  - ✓ Design of RF absorbers
  - ✓ Equipment for tests at CERN
- Coordination of prototype tests at CERN
- Simulation / data analysis





Pioneering experimental work at IN2P3 on DM axion search

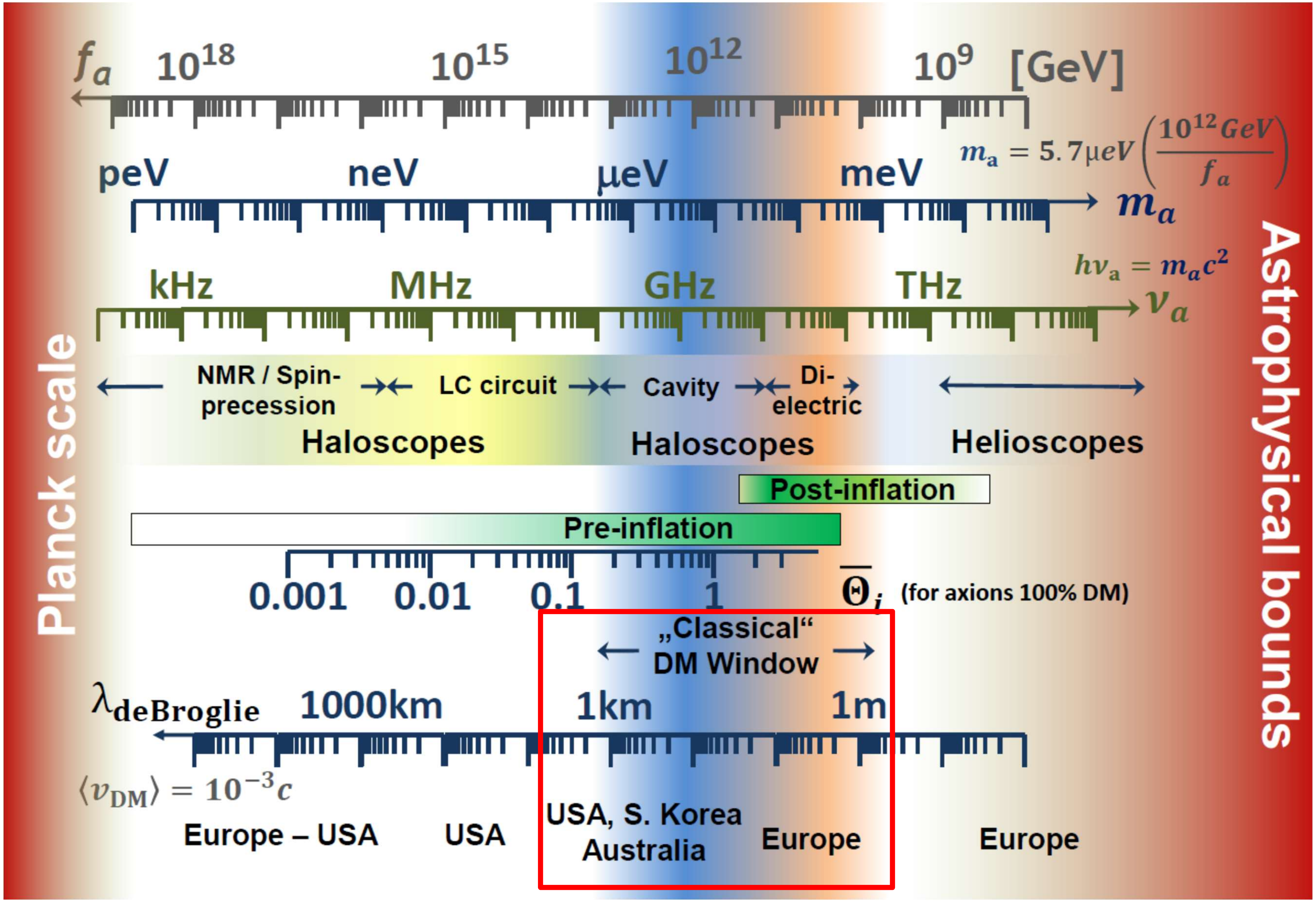

CERN March 2024
MADMAX

BACKUP

Axion scales

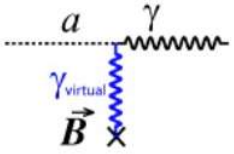
APPEC Committee Report

Rept. Prog. Phys., 85(5):056201, 2022, 2104.07634



Axion search strategy

Main access through axion conversion to photon in a B-field



Light Shining through walls (LSW)	**Helioscopes**	**Haloscopes**
Lab produced → fully controlled setup	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. CAST, (Baby)IAXO**	**e.g. MADMAX**

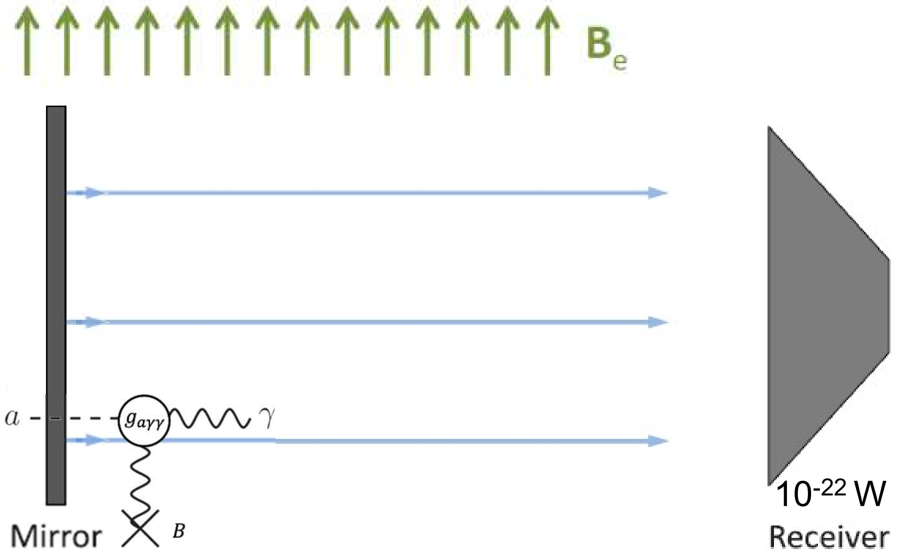
Complementarity of 3 experimental approaches

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

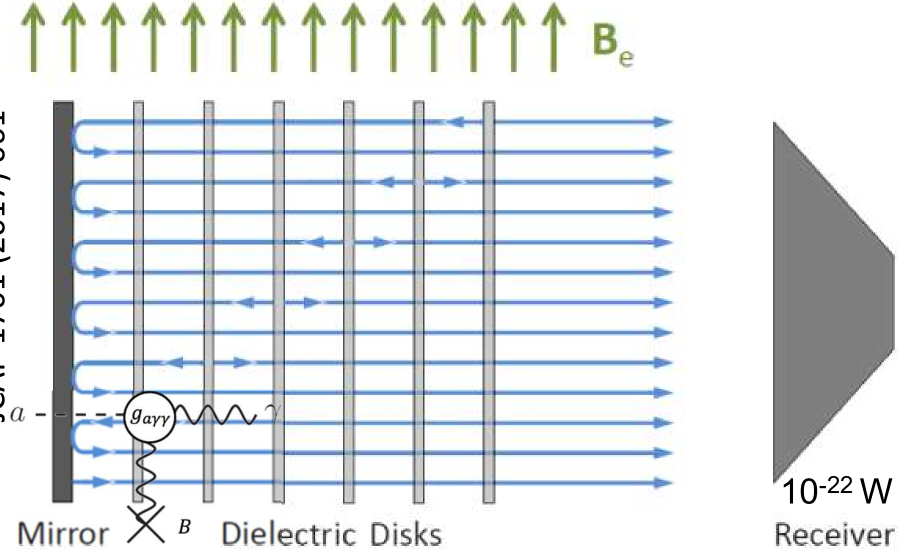
$$P_{sig} = 2 \times 10^{-27}\ \mathrm{W} \times \left(\frac{\beta^2}{1}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$



~12 photon / day (@ 25 GHz)

Dielectric haloscope

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

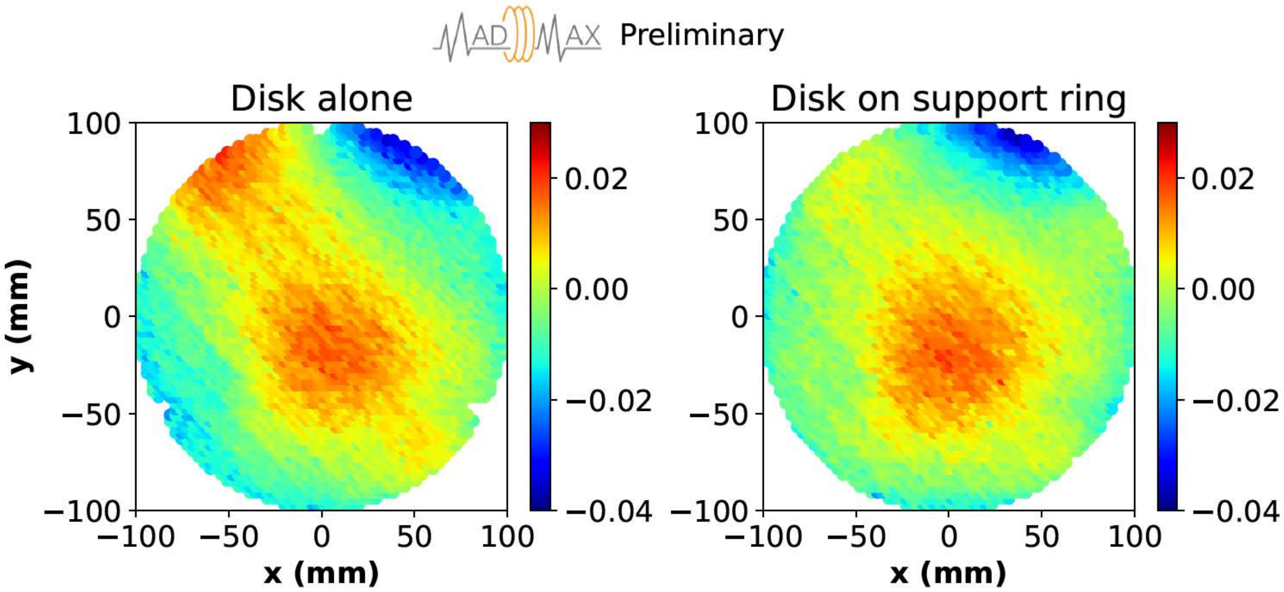


JCAP 1701 (2017) 061

7 photons / second (@ 25 GHz)

Disk planarity

arXiv:2407.10716
(accepted by JINST)

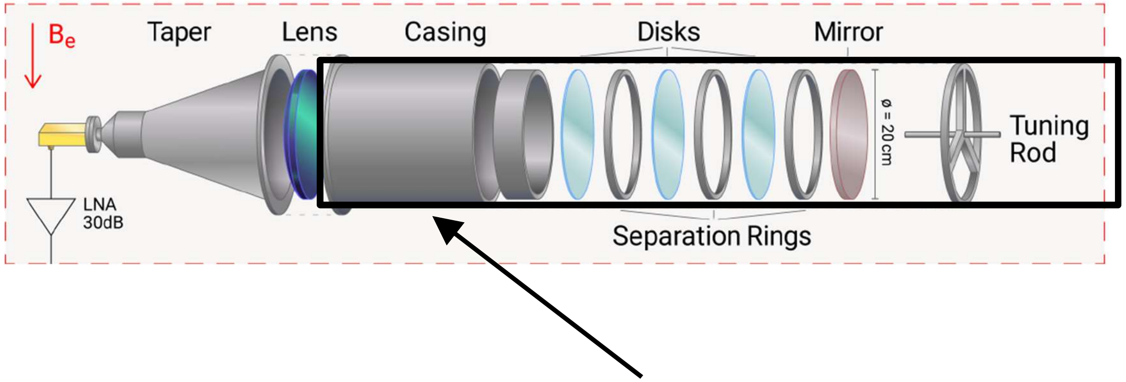


RMS < 10 μm

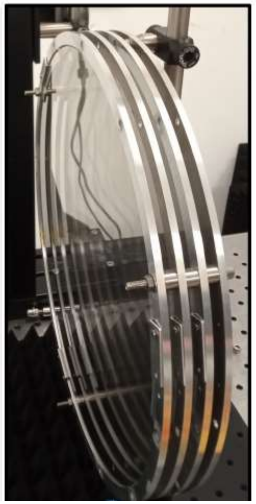
Closed vs open booster

Closed booster

Open booster



- Booster enclosed in cylindrical waveguide, ensuring fixed boundary conditions
- Fundamental mode (cylindrical TE11 mode) dominant and coupled to receiver (lens) → simplifies RF response modelling
- 1D model enough to extract boost factor, with 1D→3D correction (field overlap with axion field)
- Difficult to insert bead for boost factor measurement with bead-pull method



- Free space outside disks
- Higher-order transverse modes wrt fundamental Gaussian mode can propagate and resonate
- Easy to insert bead for boost factor measurement with bead-pull method

Tuneable setup

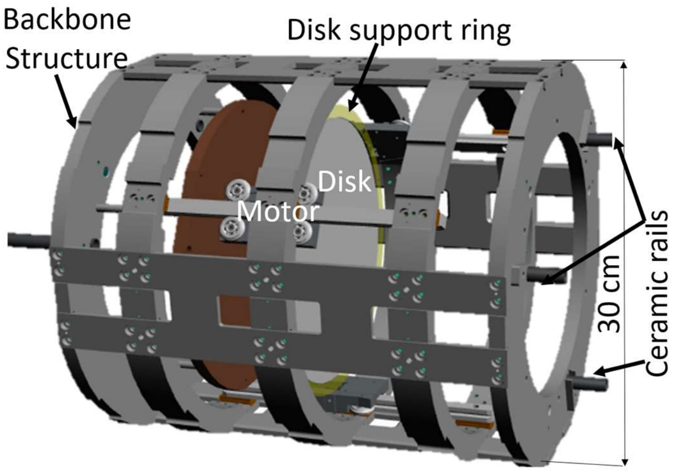
Room Temp.
Cold (10 K)
Bfield
Prospects

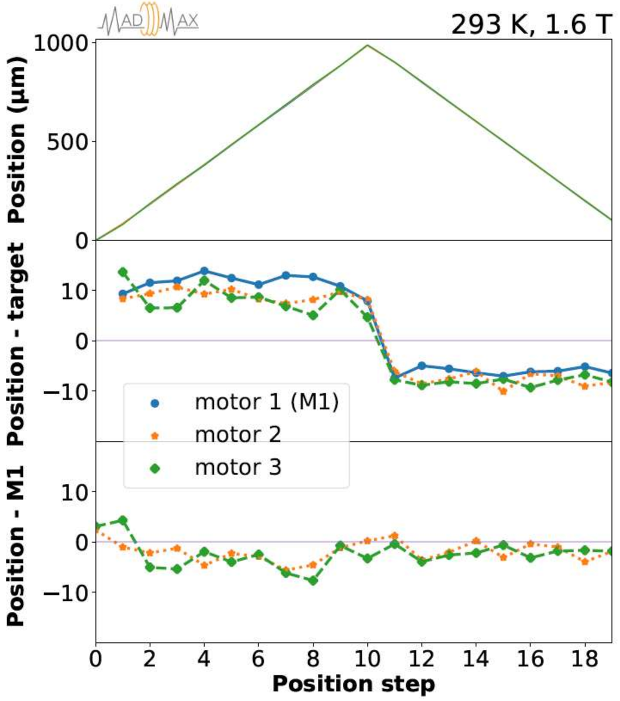
arXiv:2407.10716
(accepted by JINST)

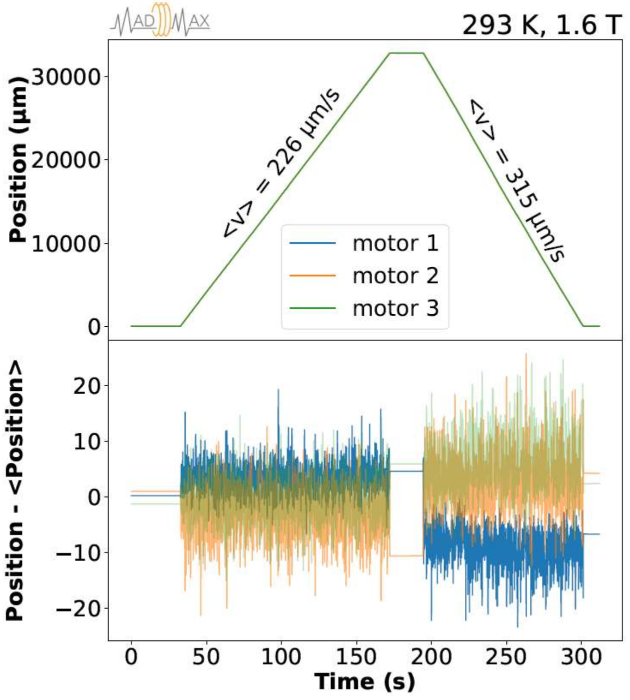
Name	Booster	Disks	Test @CERN
OB200	Open	1, **moveable** ϕ = 200 mm	2022, **22**

Motors positioned at 10 μm

v > 200 μm / s



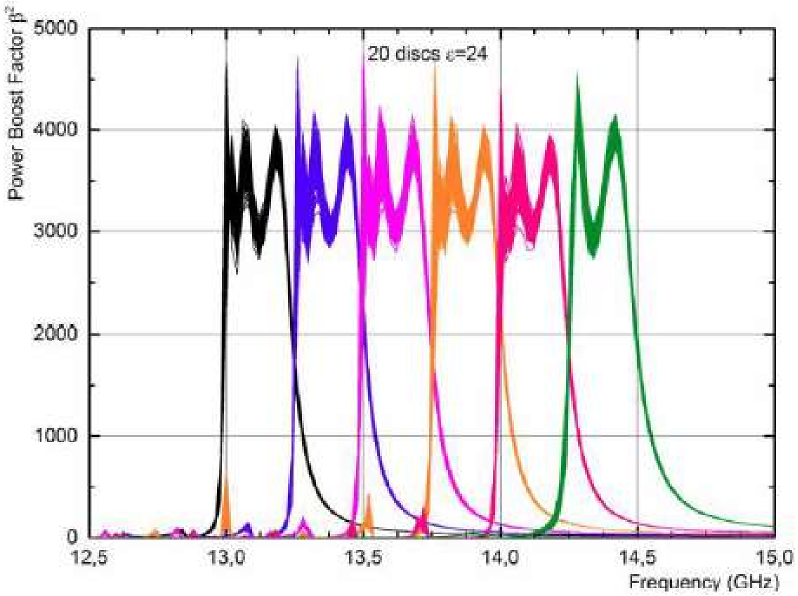




Boost factor

❑ MADMAX Versatility

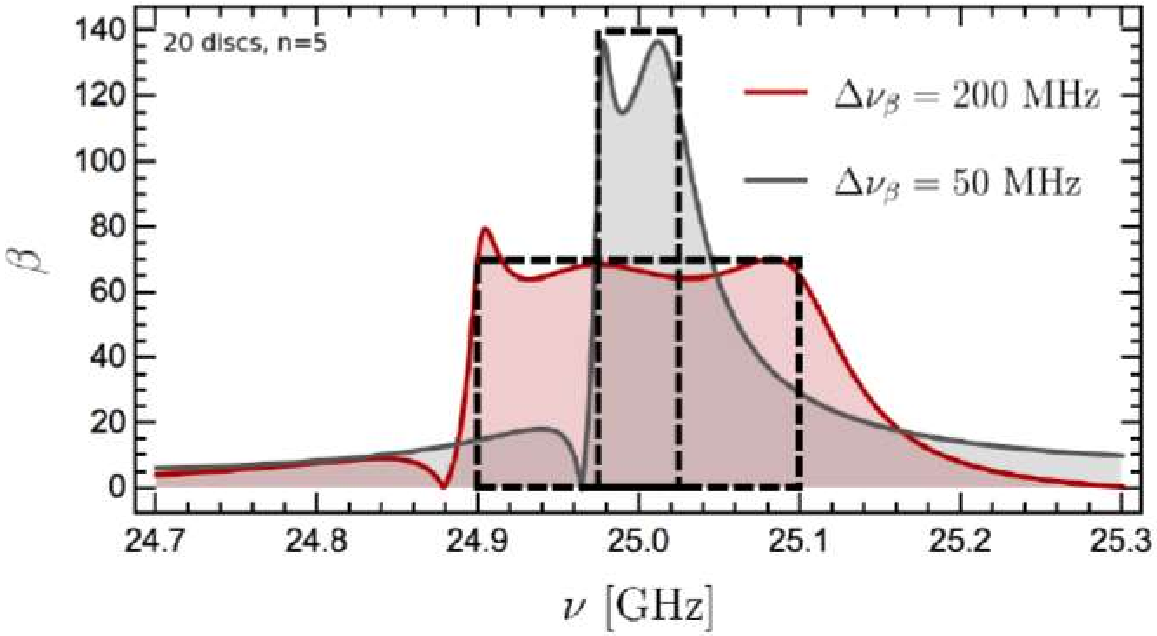
Tuning of sensitive frequency range by adjusting disc spacing



Area law: $\beta^2 \Delta\upsilon_\beta$ ~ const.

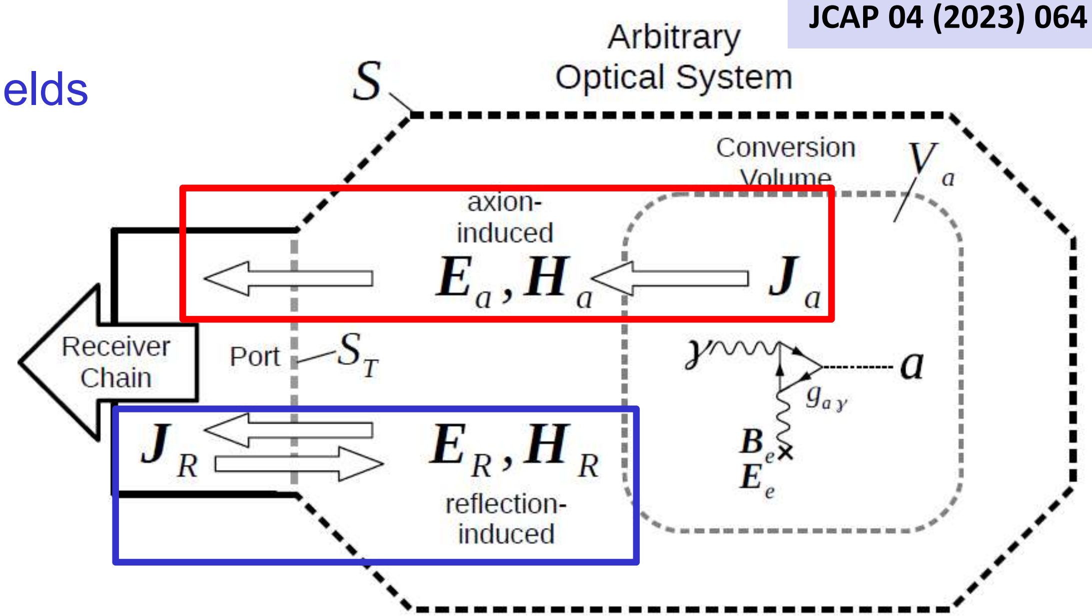
→ broad-band scan for search

→ narrow-band to confirm possible signals



Reciprocity approach

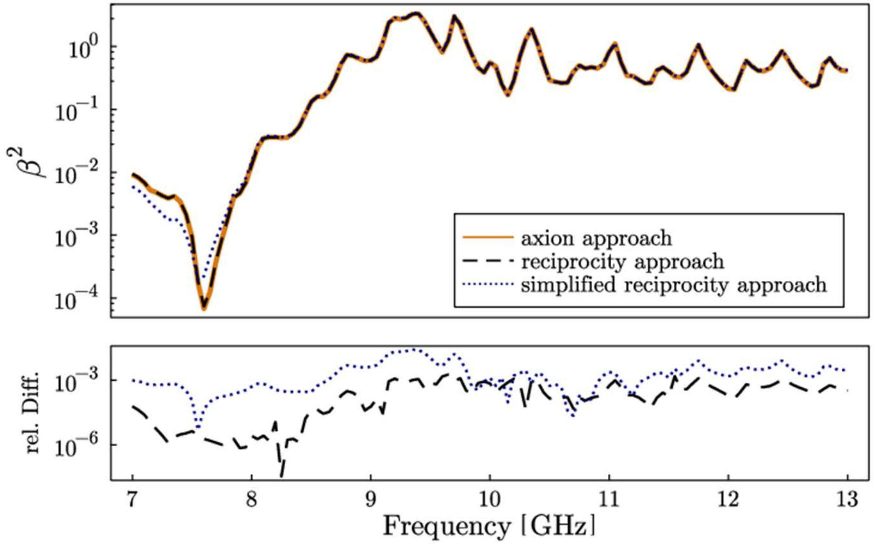
JCAP 04 (2023) 064



- Lorentz reciprocity theorem relates EM fields of 2 different sources
  - J_a = axion effective current density in B-field, sourcing axion-induced fields E_a, H_a
  - J_R = current density from external injected signal, sourcing reflection-induced fields E_R, H_R

- Allows to express haloscope sensitivity to axions from its response to reflection measurement

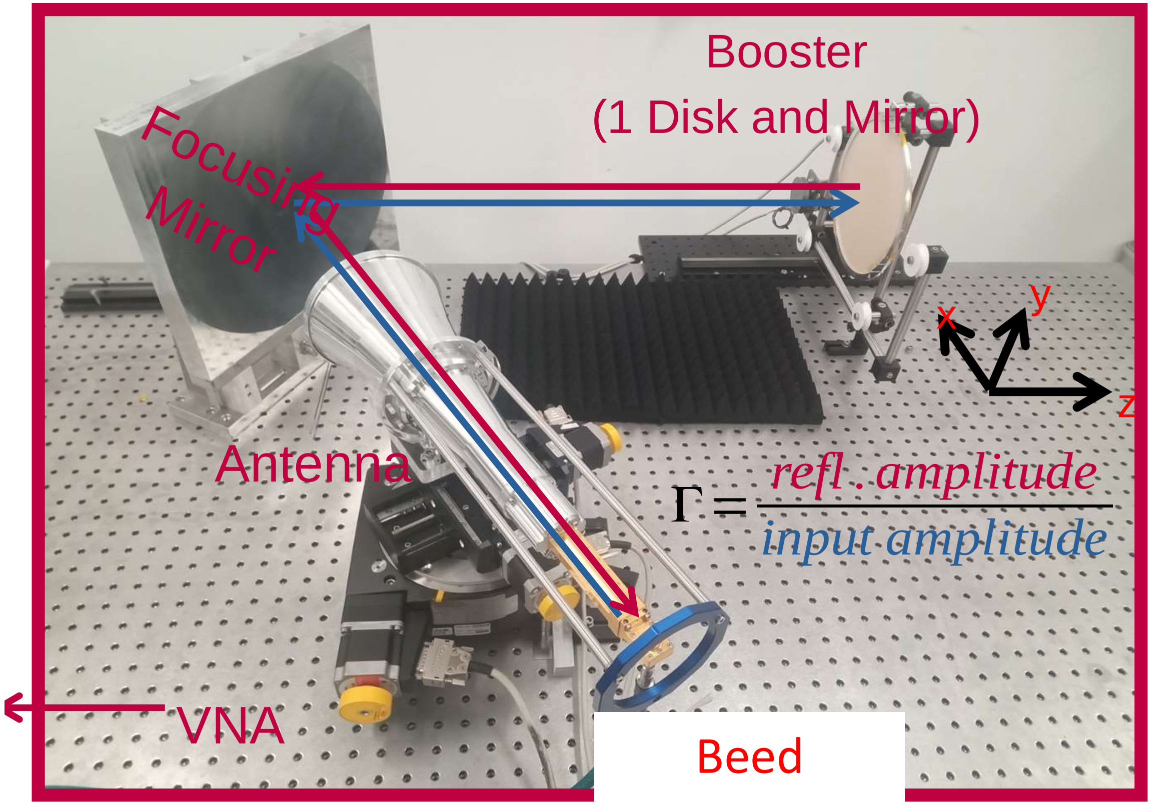
$$P_{\text{sig}} = \frac{g_{a\gamma}^2}{16 P_{\text{in}}} \left| \int_{V_a} \mathrm{d}V \, \boxed{\boldsymbol{E}_R} \cdot \dot{a} \boldsymbol{B}_e \right|^2 \qquad \propto \beta^2$$



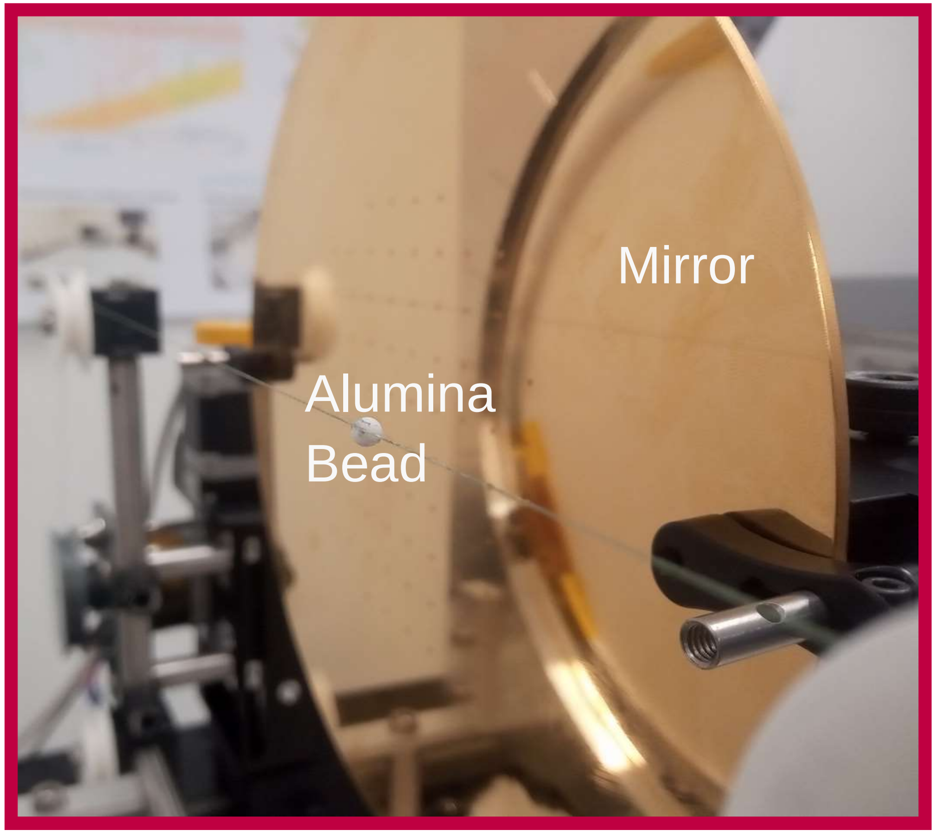
Bead-pull method

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

Boost factor determined using bead-pull method (non-resonant perturbation theory) + reciprocity theorem



$$\Gamma = \frac{refl.\ amplitude}{input\ amplitude}$$



Beed properties

Change in reflection coefficient →

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

→ E field

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

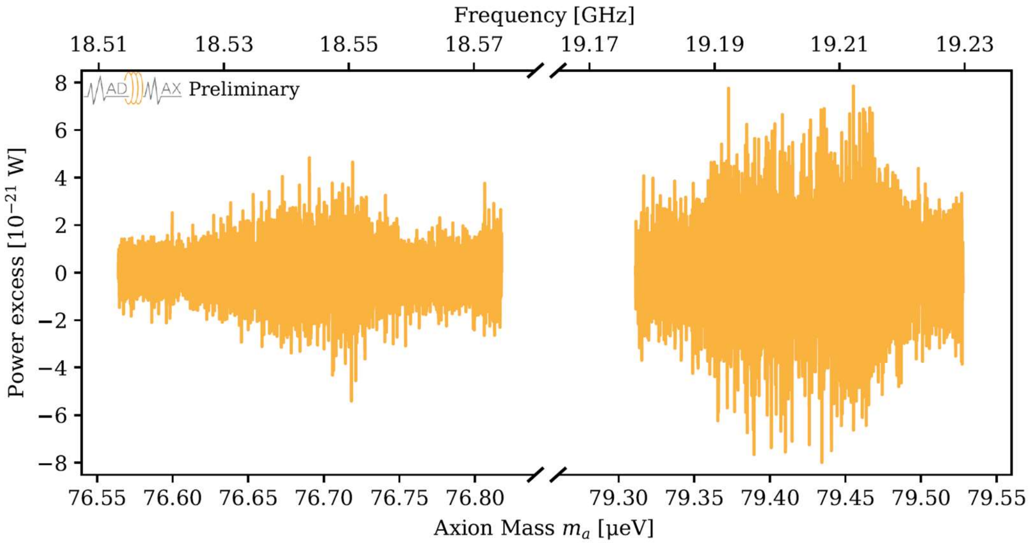
Axion search

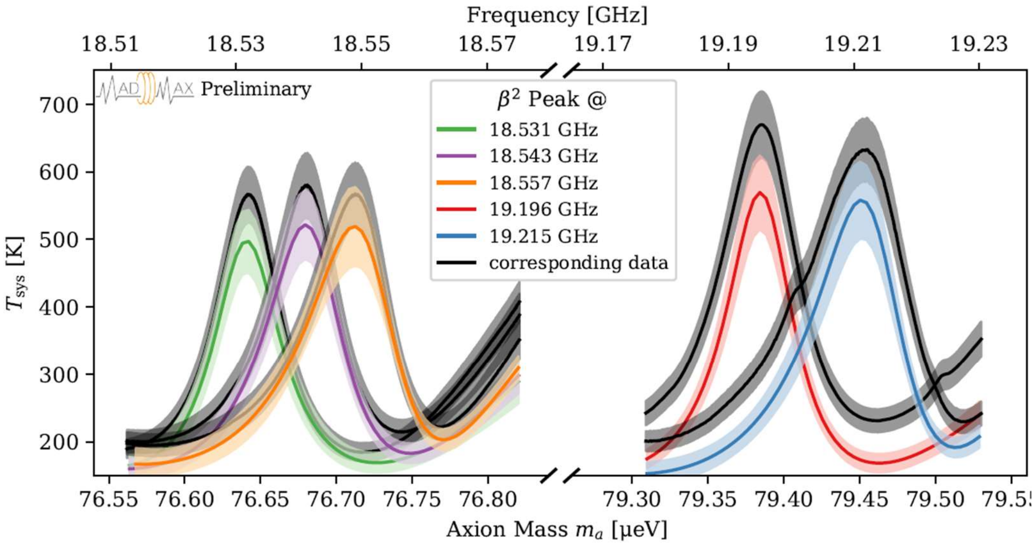
Fluctuations of power from thermal radiations → standard deviation = $k_B \cdot T_{sys} \cdot \mathrm{sqrt}(\Delta\nu/t)$

$P = k_B \cdot T_{sys} \cdot \Delta\nu$

T_{sys} = system noise temperature

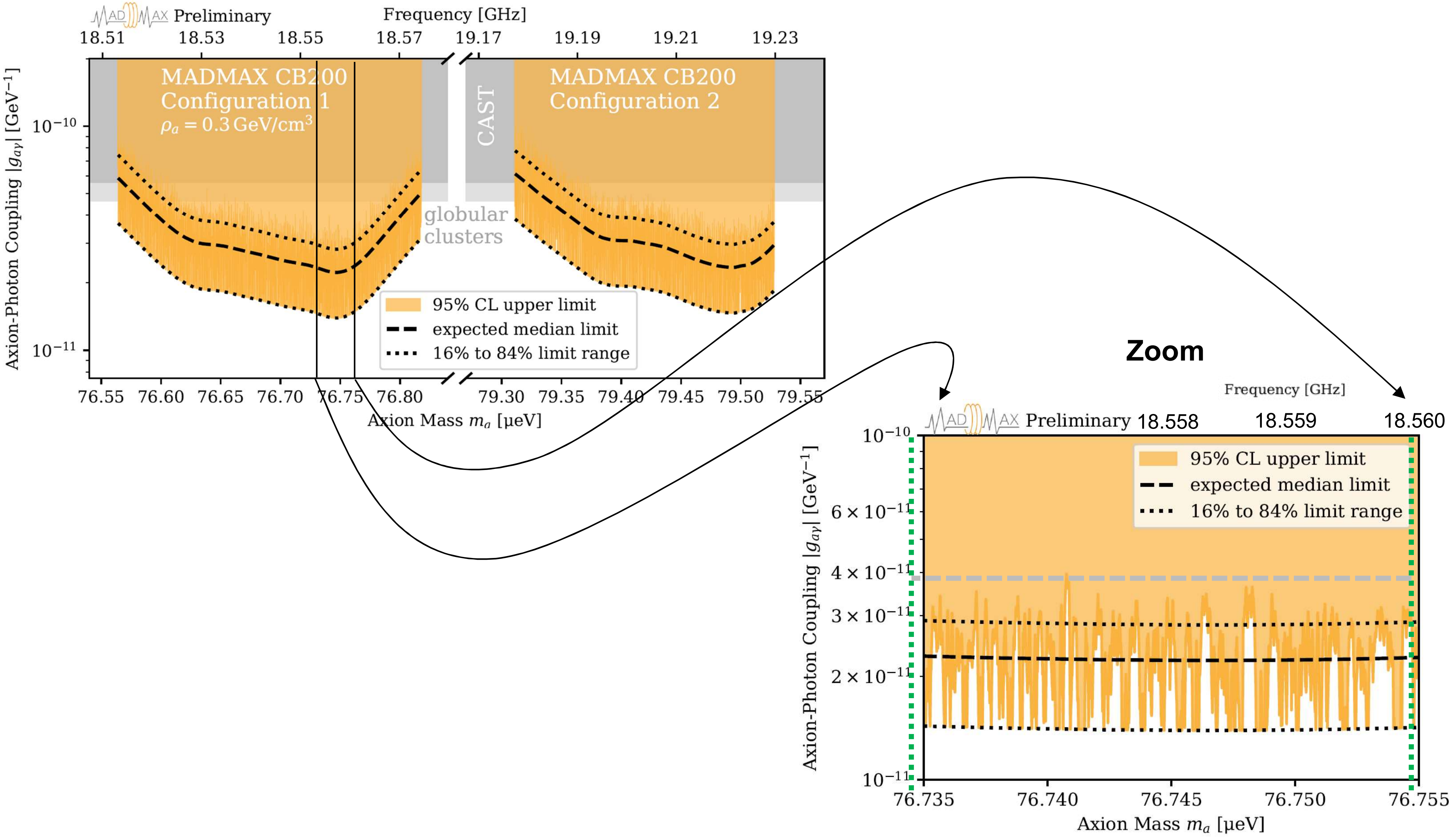
$k_B = 1.4 \cdot 10^{-23}$ J/K
$\Delta\nu$ = frequency bin size
t = measurement time





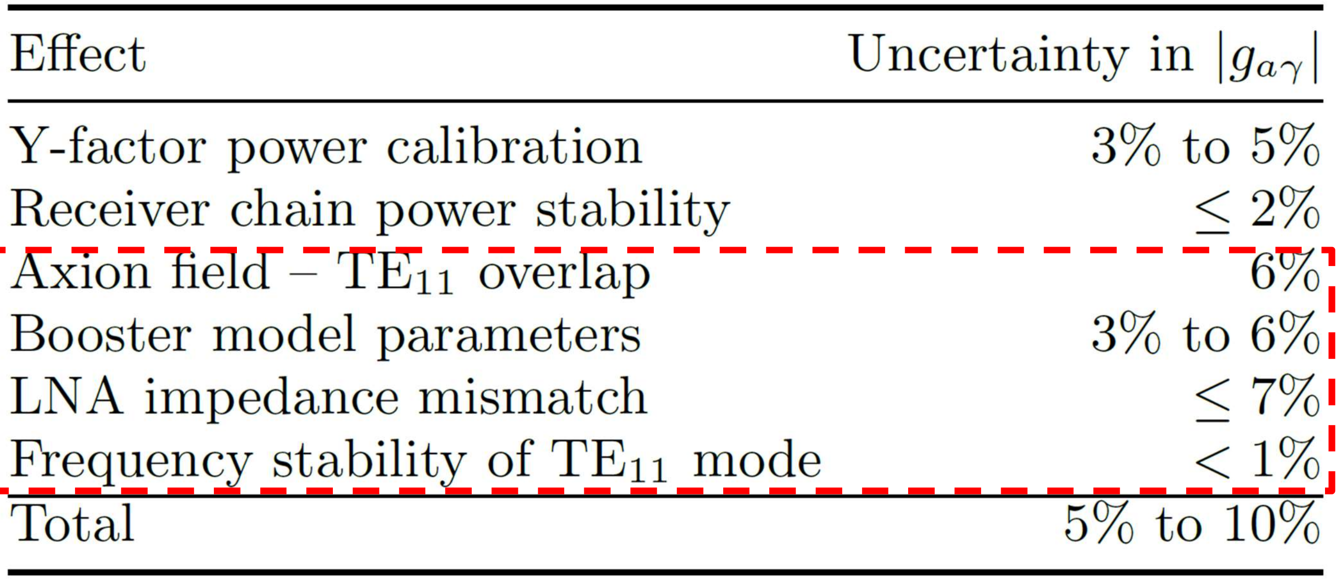
➔ Sensitive to ALP signal power of $O(10^{-21}$ W)

Axion limit


MADMAX Preliminary
Frequency [GHz]
18.51
18.53
18.55
18.57
19.17
19.19
19.21
19.23
MADMAX CB200
Configuration 1
$\rho_a = 0.3\,\mathrm{GeV/cm^3}$
CAST
MADMAX CB200
Configuration 2
globular
clusters
10^{-10}
10^{-11}
Axion-Photon Coupling $|g_{a\gamma}|$ [GeV^{-1}]
95% CL upper limit
expected median limit
16% to 84% limit range
76.55
76.60
76.65
76.70
76.75
76.80
79.30
79.35
79.40
79.45
79.50
79.55
Axion Mass m_a [μeV]
Zoom
Frequency [GHz]
MADMAX Preliminary
18.558
18.559
18.560
10^{-10}
6×10^{-11}
4×10^{-11}
3×10^{-11}
2×10^{-11}
10^{-11}
Axion-Photon Coupling $|g_{a\gamma}|$ [GeV^{-1}]
95% CL upper limit
expected median limit
16% to 84% limit range
76.735
76.740
76.745
76.750
76.755
Axion Mass m_a [μeV]

Axion limit

Systematics on $|g_{a\gamma}|$ (configuration dependent)



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

Systematics from boost factor determination

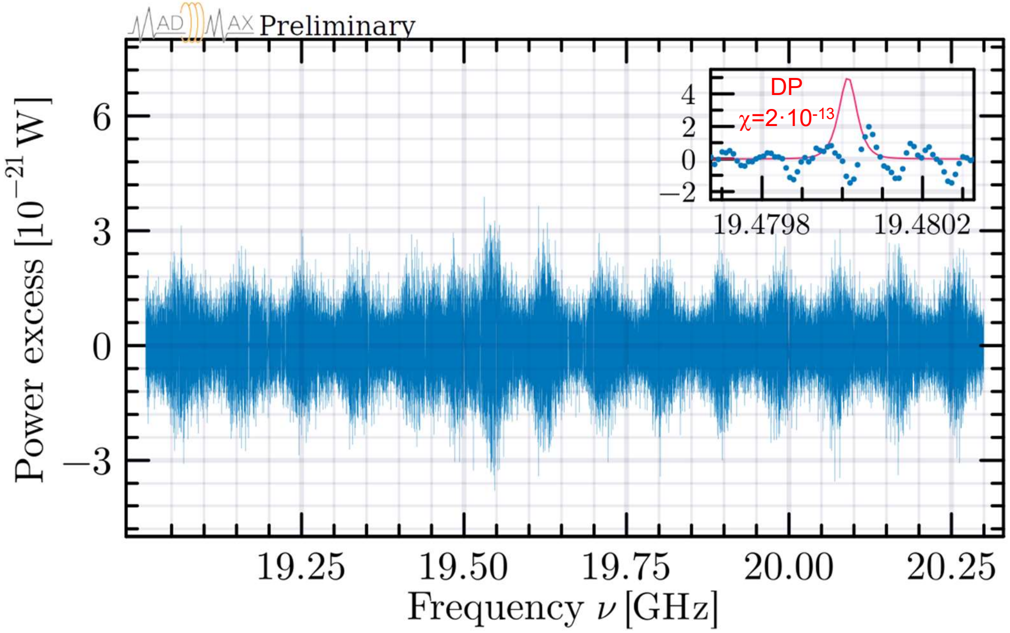
Dark Photon search

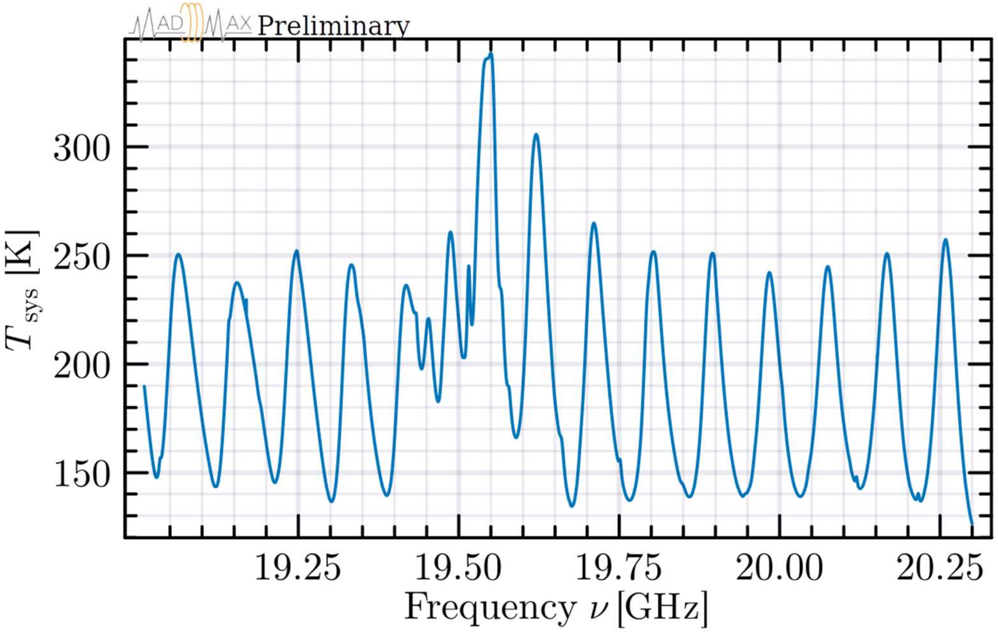
Fluctuations of power from thermal radiations → standard deviation = $k_B \cdot T_{sys} \cdot \mathrm{sqrt}(\Delta\nu/t)$

$P = k_B \cdot T_{sys} \cdot \Delta\nu$

T_{sys} = system noise temperature

$k_B = 1.4 \cdot 10^{-23}$ J/K
$\Delta\nu$ = frequency bin size
t = measurement time





➔ Sensitive to dark photon signal power of $O(10^{-21}$ W)

Dark Photon limit

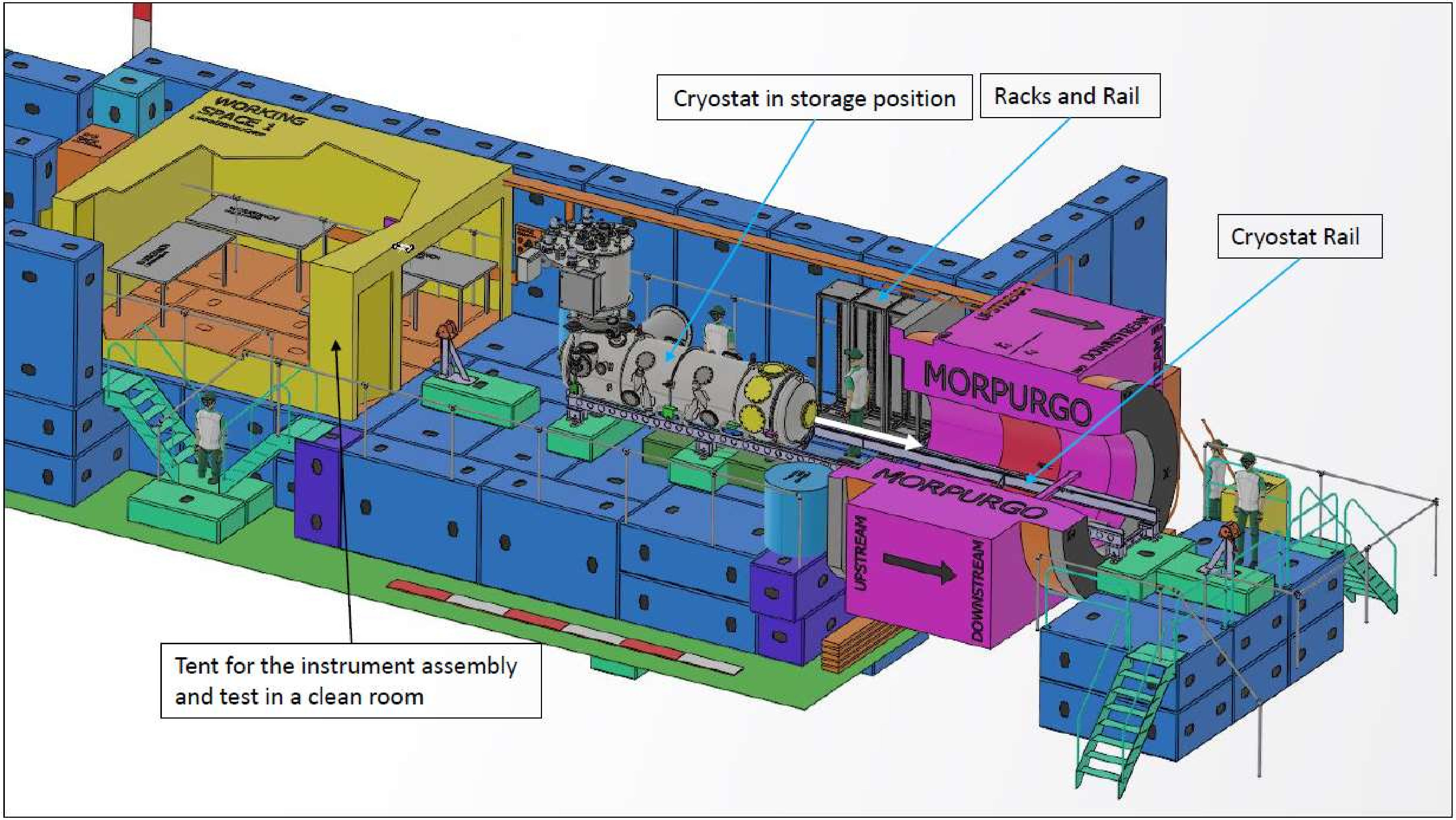
Systematics on χ

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%

(frequency dependent)

Systematics from boost factor measurement

Final prototype test at CERN



Cryostat in storage position

Racks and Rail

Cryostat Rail

Tent for the instrument assembly and test in a clean room

Towards final MADMAX

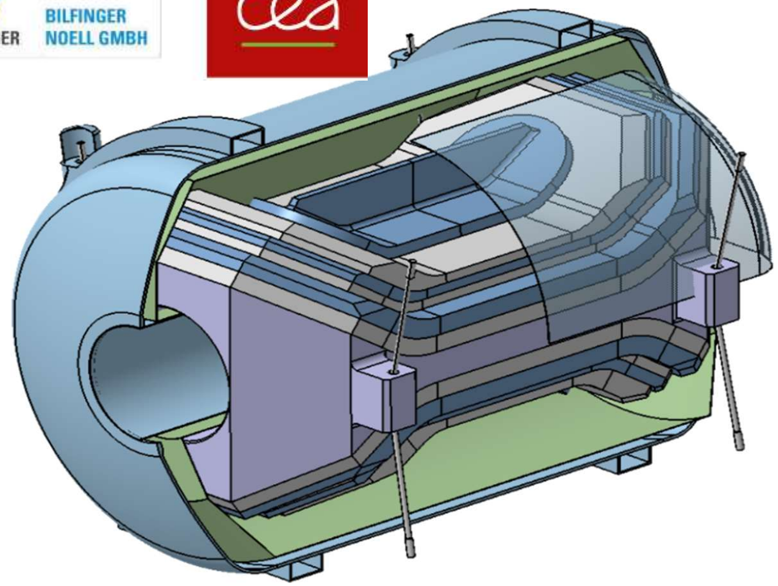
☐ Magnet

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

[NbTi with Cu jacket @ 1.8K]

BILFINGER BILFINGER NOELL GMBH

cea



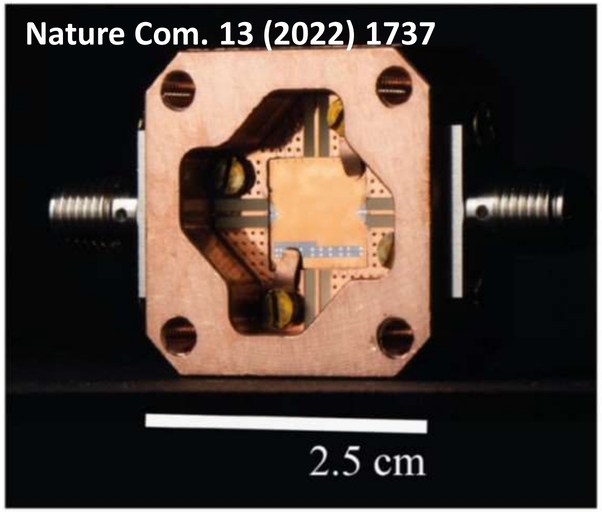
- Demonstrated that coils will be safe in terms of quench protection **IEEETAS 33 (2023) 1**
- Budget secured for a demonstrator coil
  → Expected in 2027

☐ 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)*


Nature Com. 13 (2022) 1737

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

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