First axion and dark photon dark matter searches with MADMAX

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

1. Scientific context
2. MADMAX, a dielectric haloscope
3. Dark matter searches with MADMAX prototypes
4. Towards final MADMAX
5. Conclusions

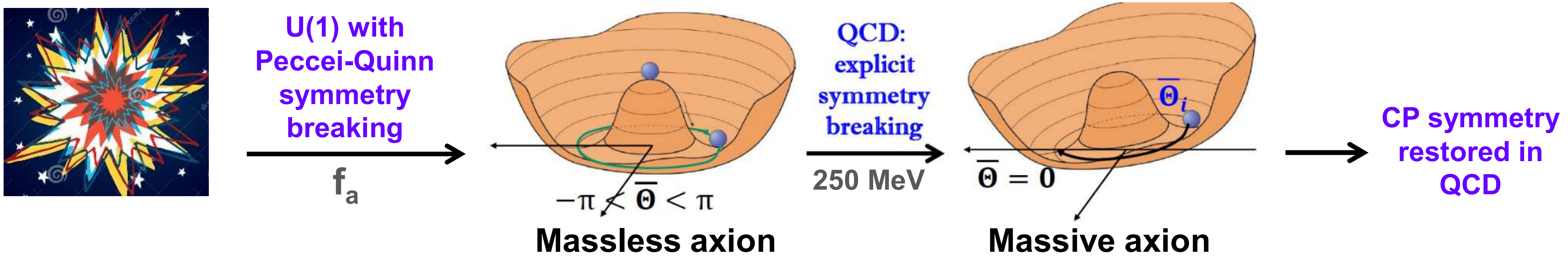
Cosmic Whisper Seminar, January 29 2025

Axion Motivation

☐ Preferred solution to the strong CP problem

- **Problem** : Why no CP violation observed in the strong interaction ?
  - ○ A CP violating parameter (Θ) exists in the QCD Lagrangian …
  - ○ … but is constrained, using neutron electric dipole moment measurement, to be $|\Theta|$ **< 10^{-10}**
  - ➔ **Why is $|\Theta|$ so small ?**

- **Solution**: new global U(1) symmetry *(Peccei-Quinn, 77)* spont. broken at scale f_a [$f_a \gg f_{EWSB}$] O(10^{11}) eV
  - ○ Can occur before or after inflation
  - ○ Axion is the pseudo-goldstone boson of this U(1) symmetry *(Weinberg-Wilczek, 78)*
  - ○ Non-thermal massive axion production at $T \sim \Lambda_{QCD}$



U(1) with Peccei-Quinn symmetry breaking

f_a

$-\pi < \bar{\Theta} < \pi$

Massless axion

QCD: explicit symmetry breaking

250 MeV

$\bar{\Theta}_i$

$\bar{\Theta} = 0$

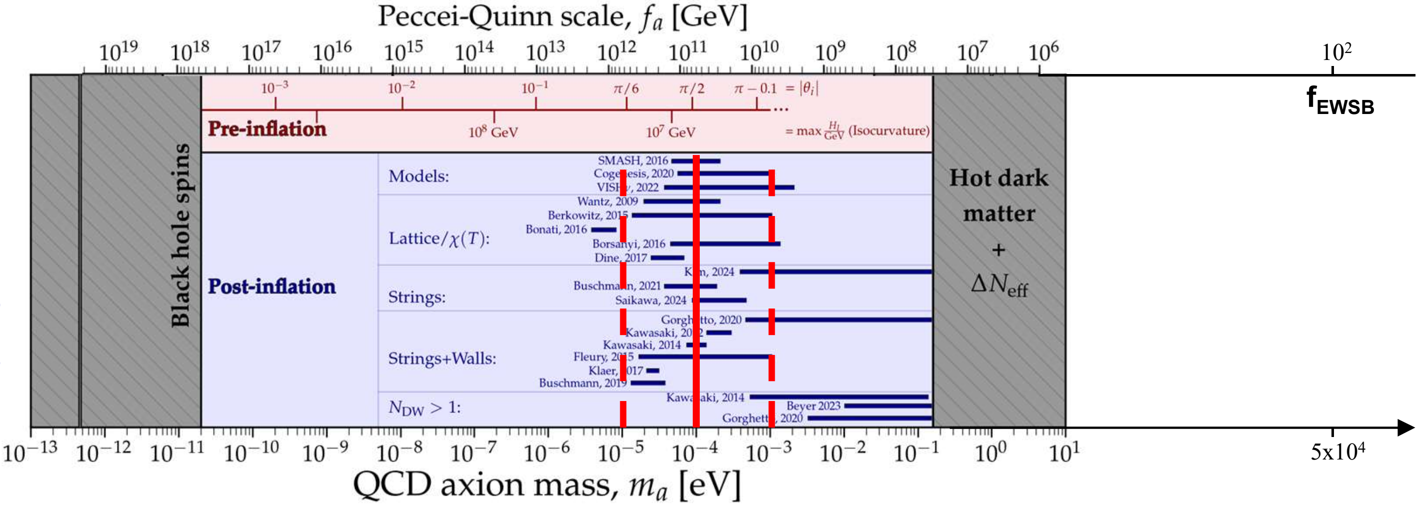
Massive axion

CP symmetry restored in QCD

Axion Dark Matter

❑ Main characteristics

- Axion properties depends only on f_a
  - ○ Tiny mass: $m_a \approx m_\pi f_\pi / f_a <$ eV
  - ○ Weakly interacting: $g_a \propto 1 / f_a$
  - ○ Long-lived: $\tau_{axion} \approx t_{Universe} (20 \text{ eV}/m_a)^5$
- Dark matter candidate *(Preskill et al, 83)*
  - ○ m_a can be computed in post-inflationary scenario



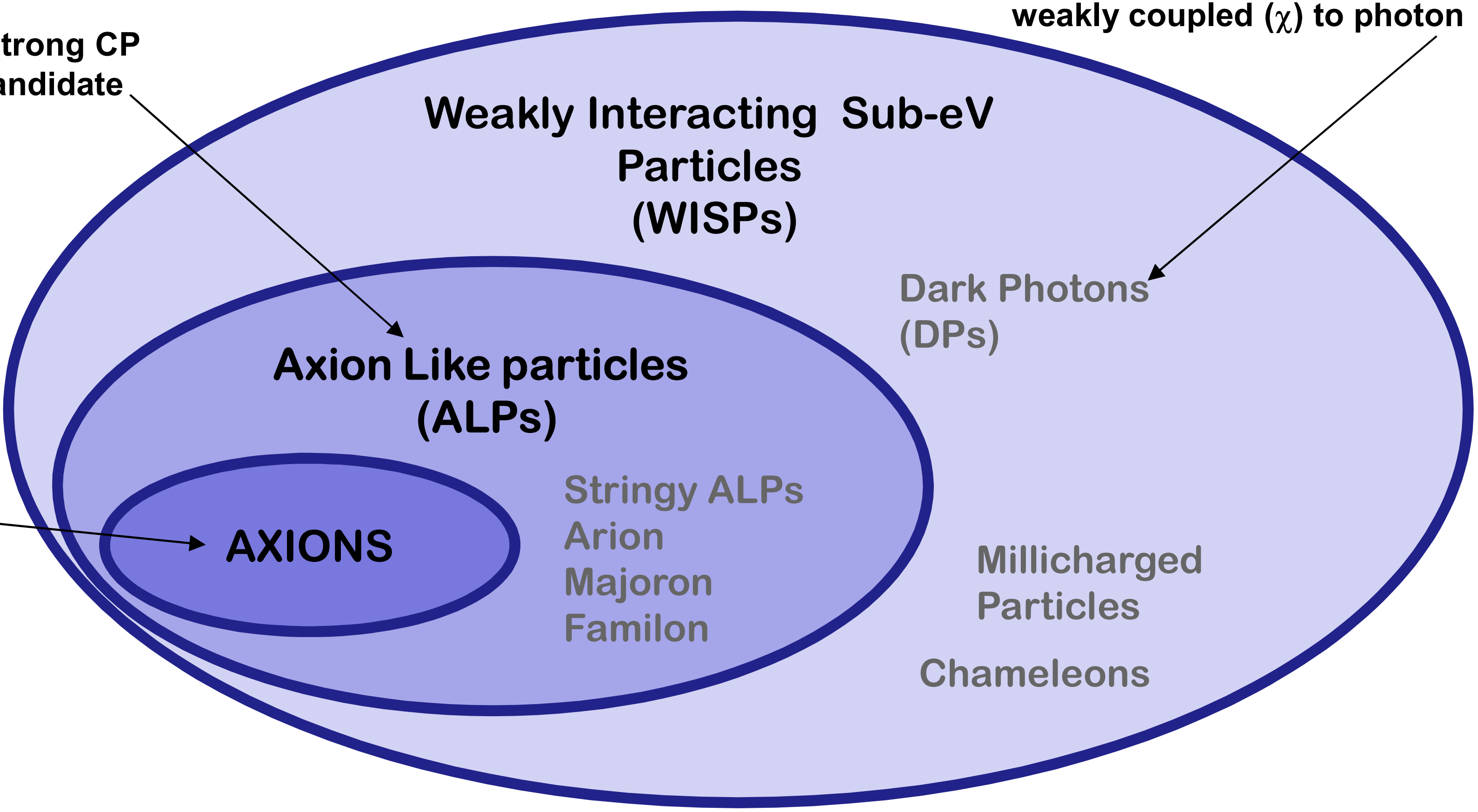
https://cajohare.github.io/AxionLimits/docs/am.html

Axion very well motivated dark matter candidate for $m_a \approx O(100)$ μeV

Wave-like Dark Matter

☐ Other related very light dark matter candidates

- Inspired by axion dark matter "success"



Massive boson m_χ of a new broken $U(1)_\chi$ gauge symmetry, weakly coupled (χ) to photon

pseudo-scalar not solving strong CP problem but potential DM candidate
[relaxing m_a - f_a constraint]

QCD axion

Weakly Interacting Sub-eV Particles (WISPs)

Dark Photons (DPs)

Axion Like particles (ALPs)

AXIONS

Stringy ALPs
Arion
Majoron
Familon

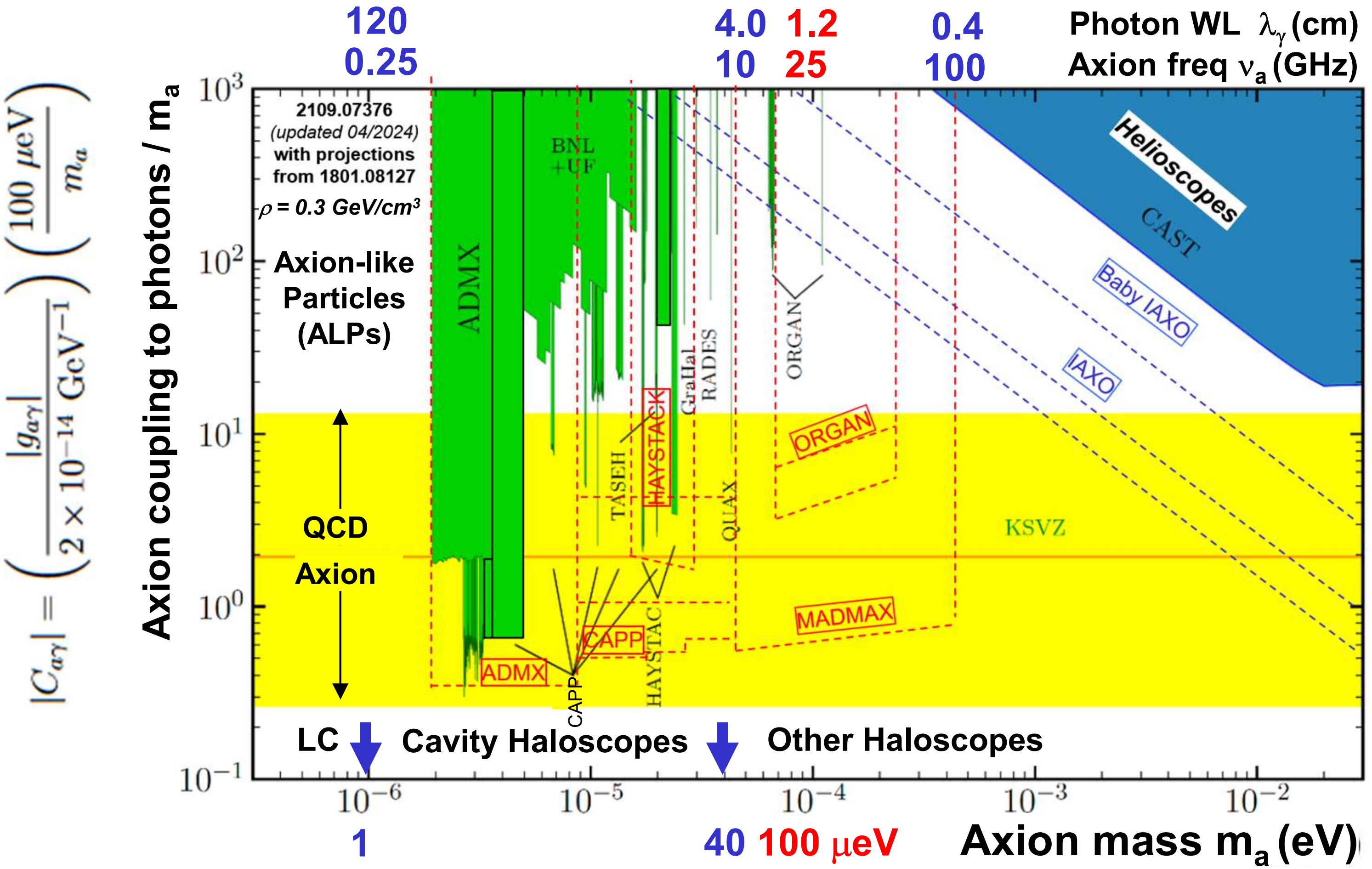
Millicharged Particles

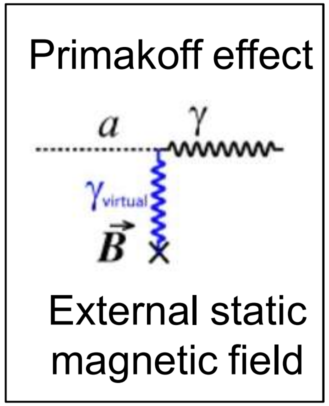
Chameleons

Courtesy of I. Irastorza (ISSAP2024)

Direct detection of DM axions

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





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

MADMAX

JCAP 01 (2017) 061

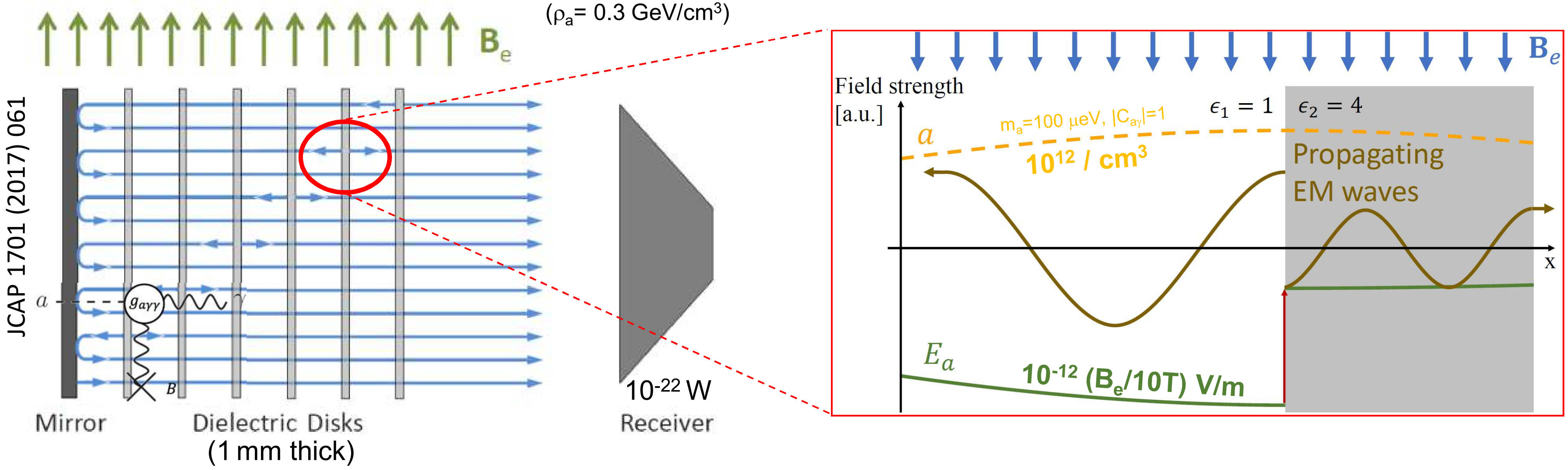
❑ Principles of dielectric haloscope

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

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

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

(ρ_a= 0.3 GeV/cm^3)



MADMAX

EPJC 79 (2019) 186

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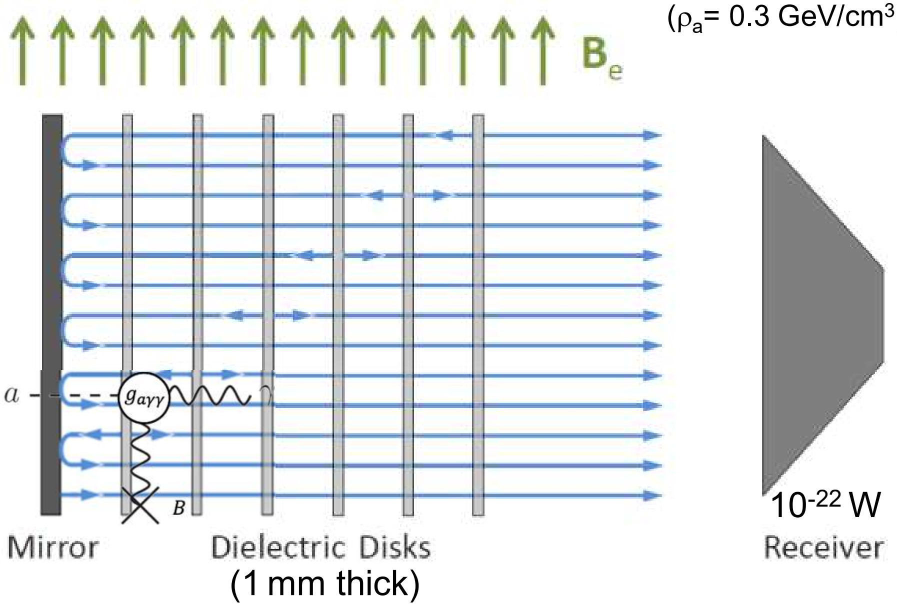
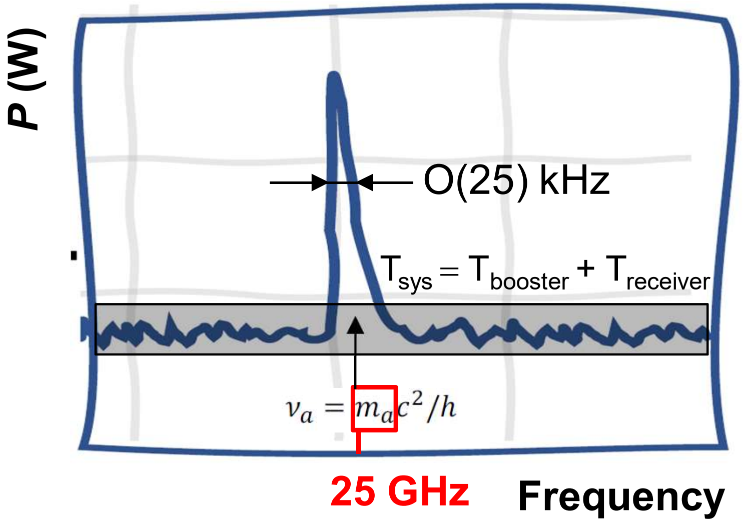


JCAP 1701 (2017) 061

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



MADMAX

EPJC 79 (2019) 186

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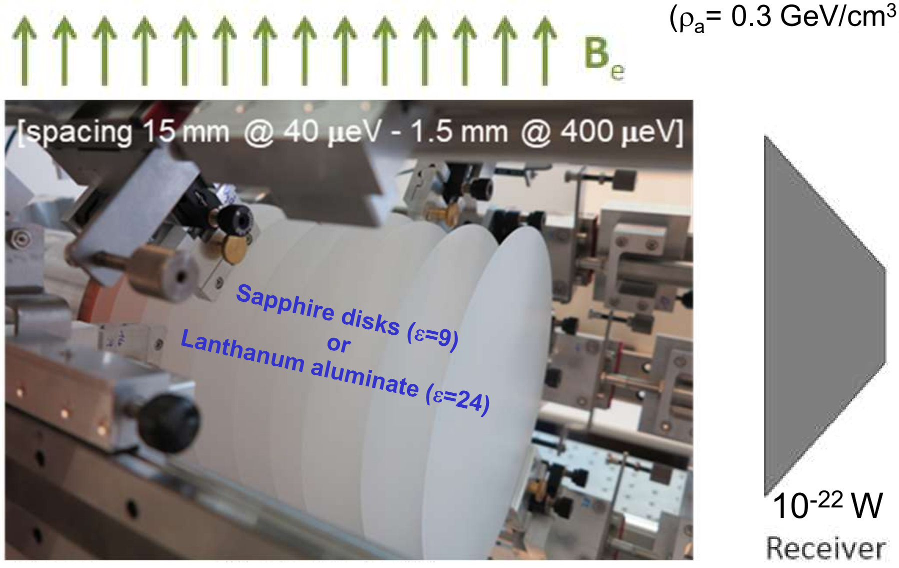
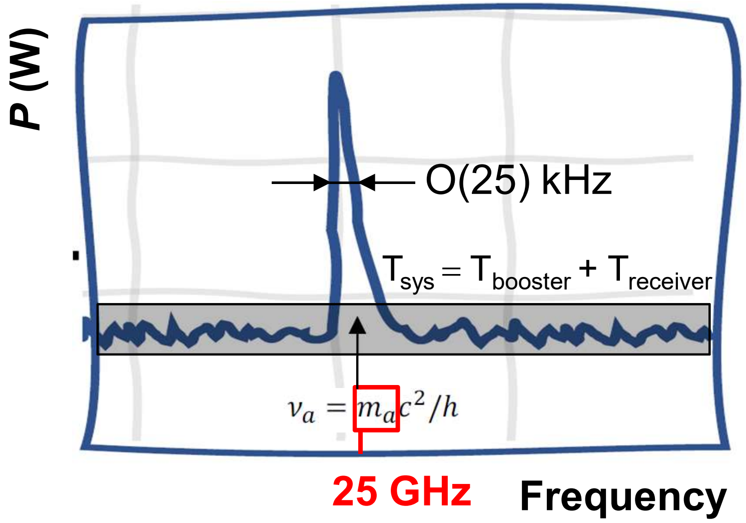




- Axion mass **scan**: by **moving discs** with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

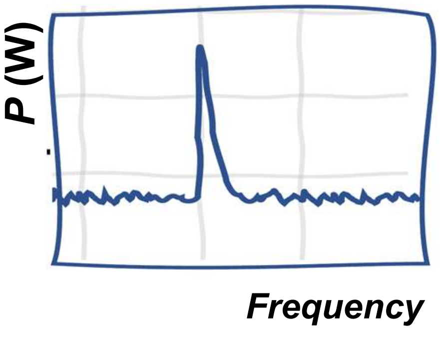
MADMAX exploits a new concept to cover an uncharted phase space

MADMAX

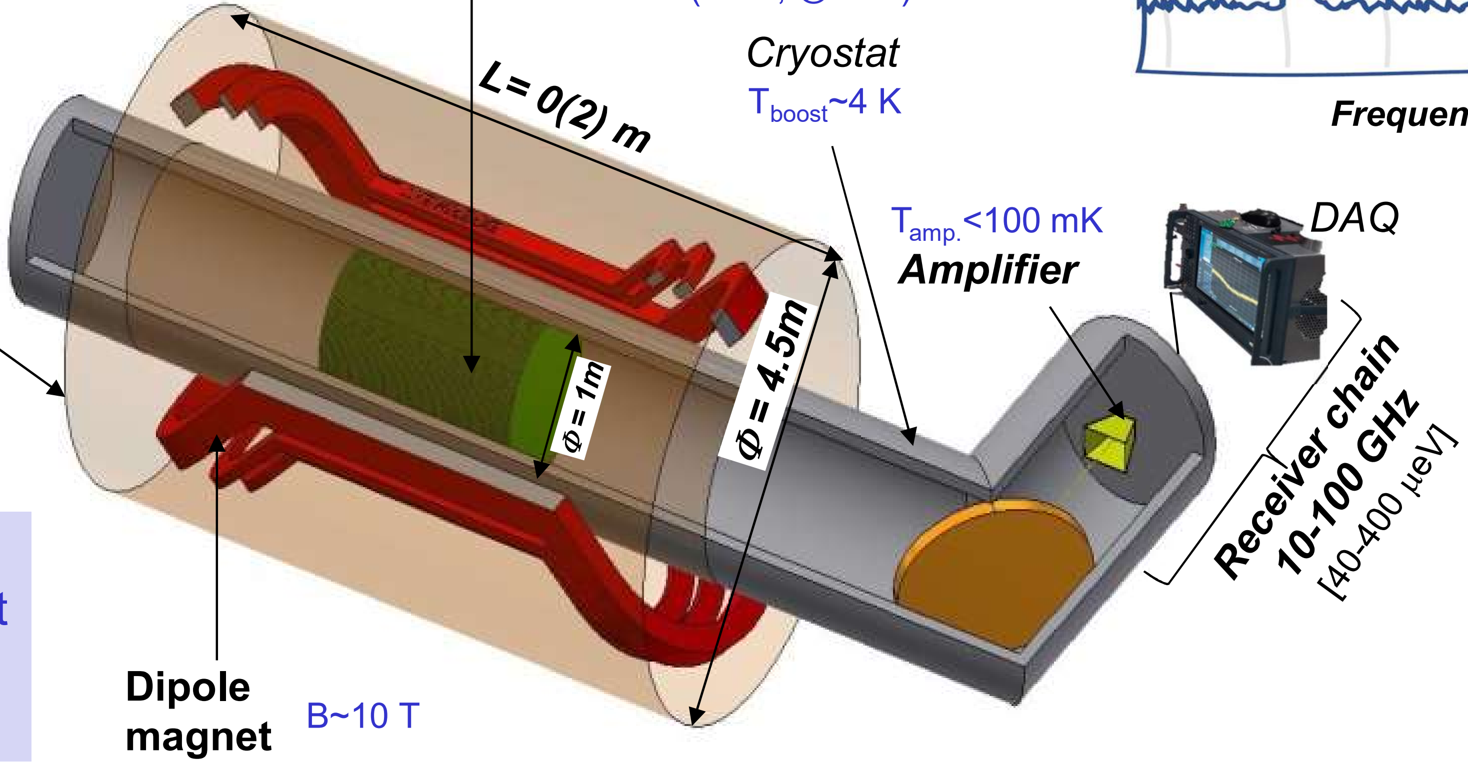
Formed in 2017. 11 institutes, ~50 people

EPJC 79 (2019) 186

Experiment location: HERA in former H1 iron yoke



Booster →80 moveable dielectric discs (ε=24, $\varnothing$=1m)


Cryostat

T_{boost}~4 K

L= 0(2) m

Φ = 1m

Φ = 4.5m

$T_{amp.}$<100 mK

Amplifier

DAQ

Receiver chain

10-100 GHz

[40-400 μeV]

Dipole magnet

B~10 T

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

- Disks *(sapphire $\varepsilon = 9$)*: good planarity *(<10 µm)*, controlled thickness *(1000±10 µm)*, moveable *(piezo motors)*
- 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***

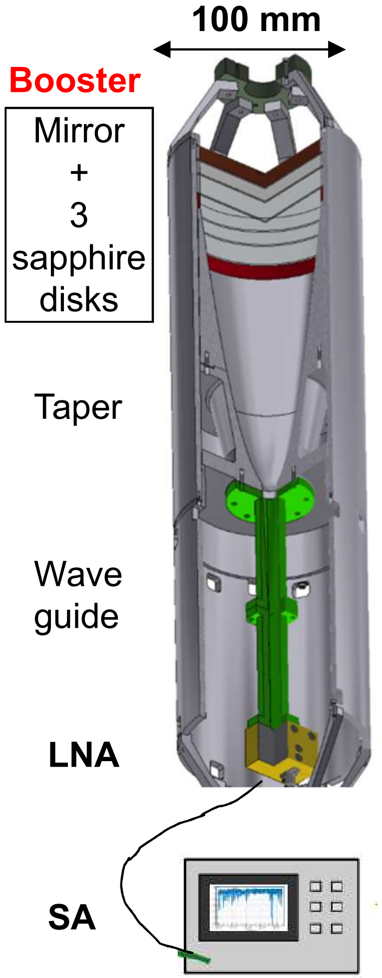
*Dark Photon

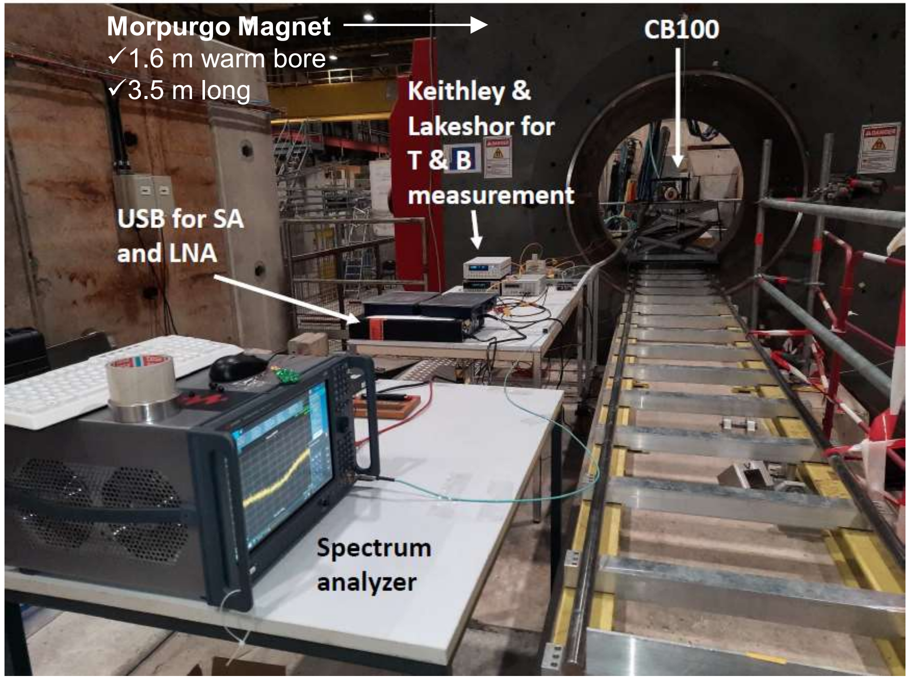
Room Temp.
Cold (10 K)
Bfield
Prospects

- Set-up: prototype cryostats *(G10, stainless-steel)* + CERN Morpurgo dipole magnet *(1.6 T)*

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 (RFI) 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: $P \propto T_{sys} = f(\Gamma_{RC}, G, \nu)$

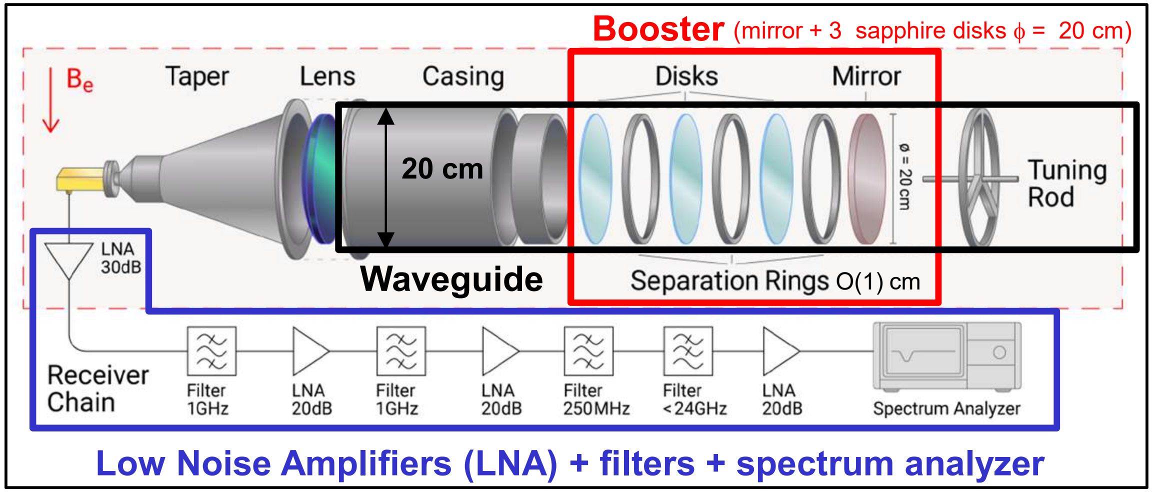
➔ Validated that CERN environment suited for prototype tests

Physics set-up (1/3)

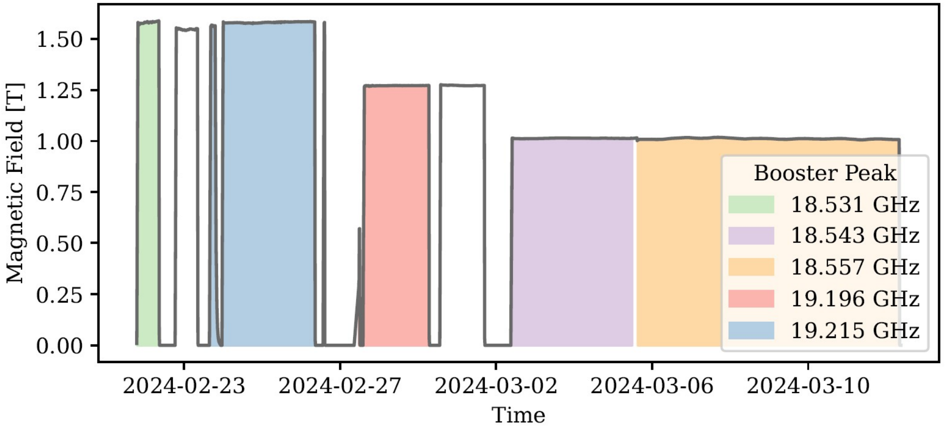
Name	Booster	Disks	Test @CERN
CB200	Closed	3, **fixed** ϕ = 200 mm	2024

- 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)*

Booster



B field



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

Physics set-up (2/3)

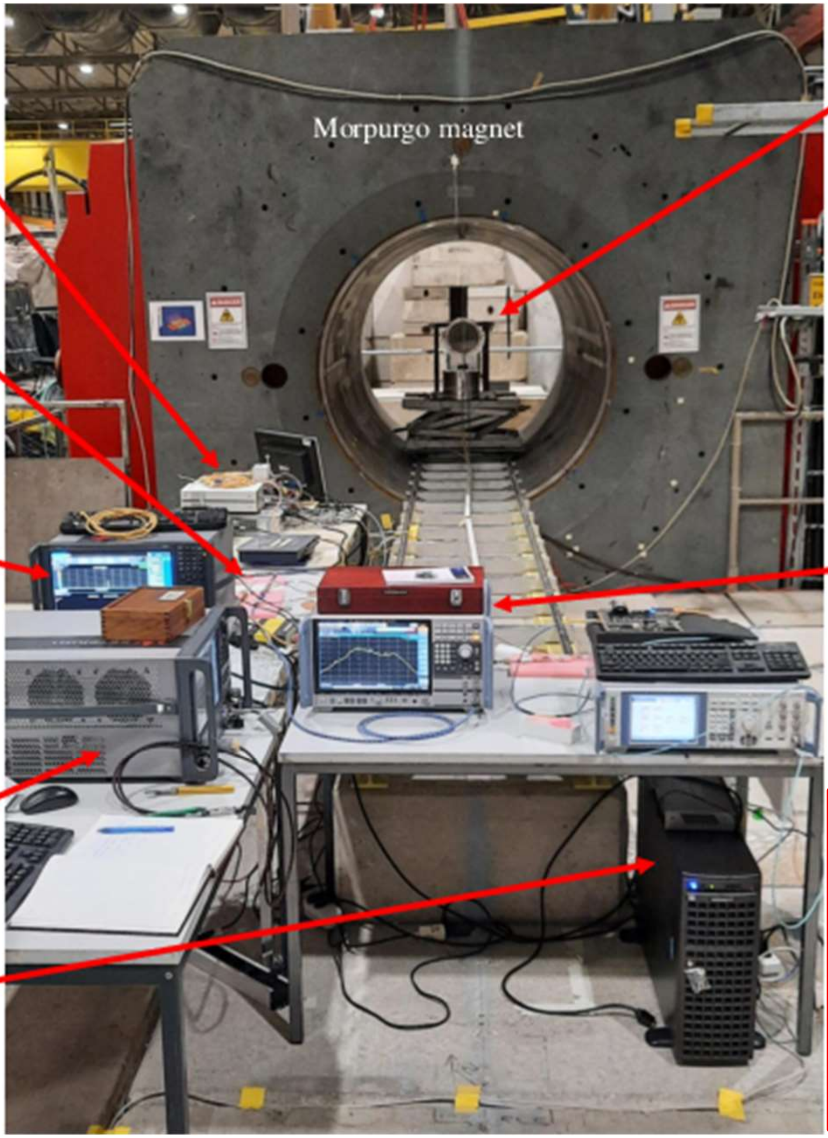
B-field & T - monitors

Receiver chain outside the B-field

Spectrum analyzer for RFI measurement

VNA for S11 calibration measurements

Computer with GPU

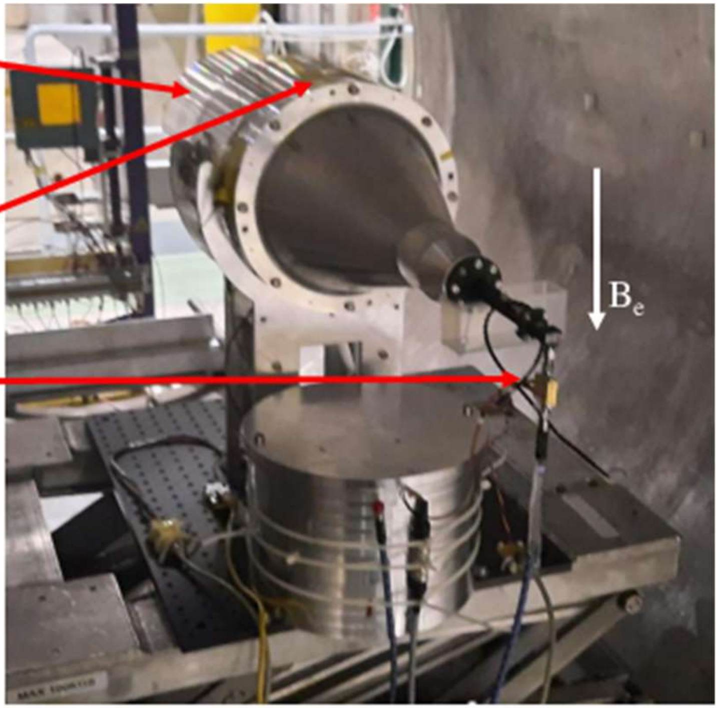


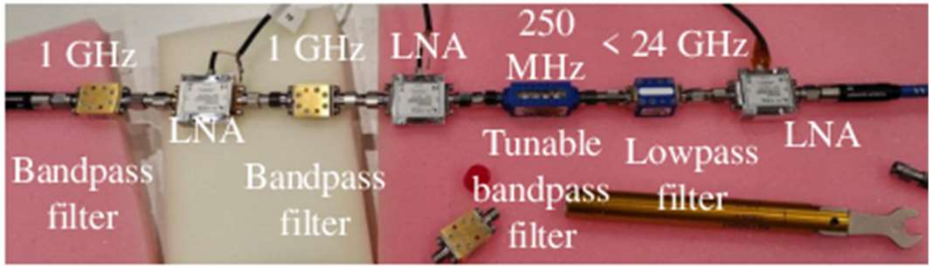
CB200

B-field probe

First LNA with T-sensor attached

R&S spectrum analyzer FSW43



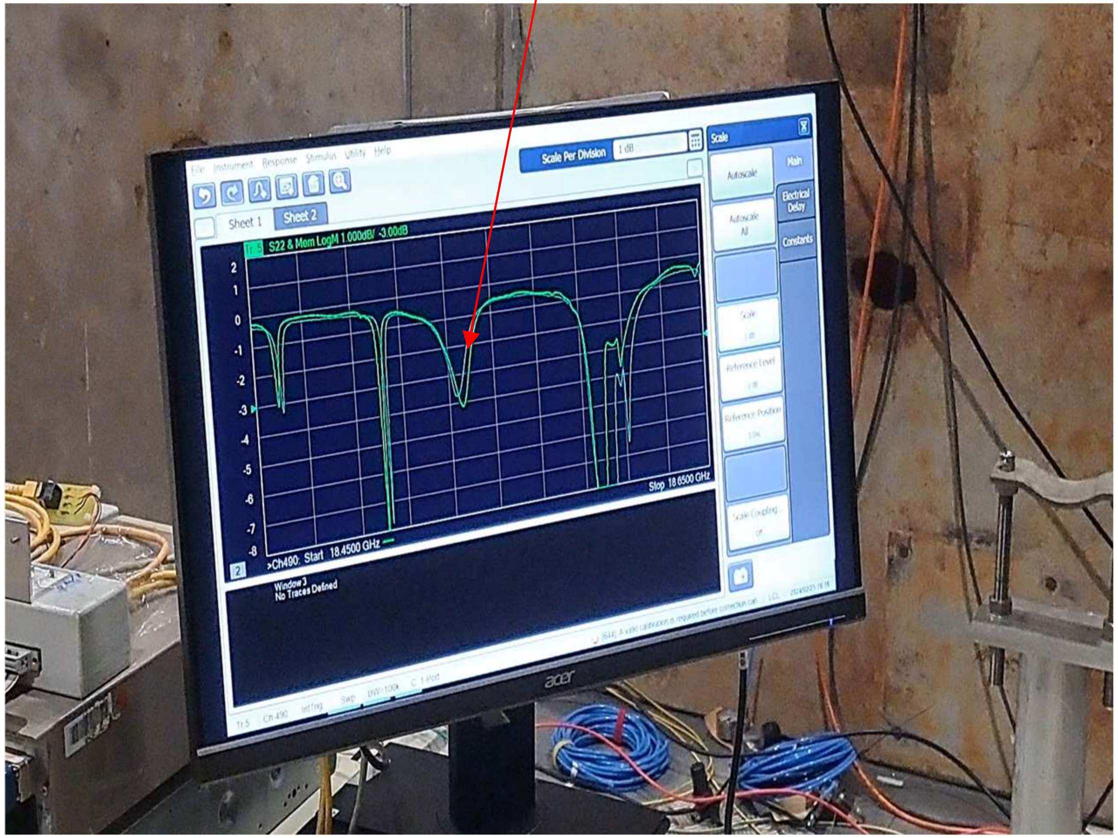


Receiver chain outside the B-field

Physics set-up (3/3)

❑ Setting-up the configuration at CERN

- Reproducing the configuration prepared in advance using the VNA



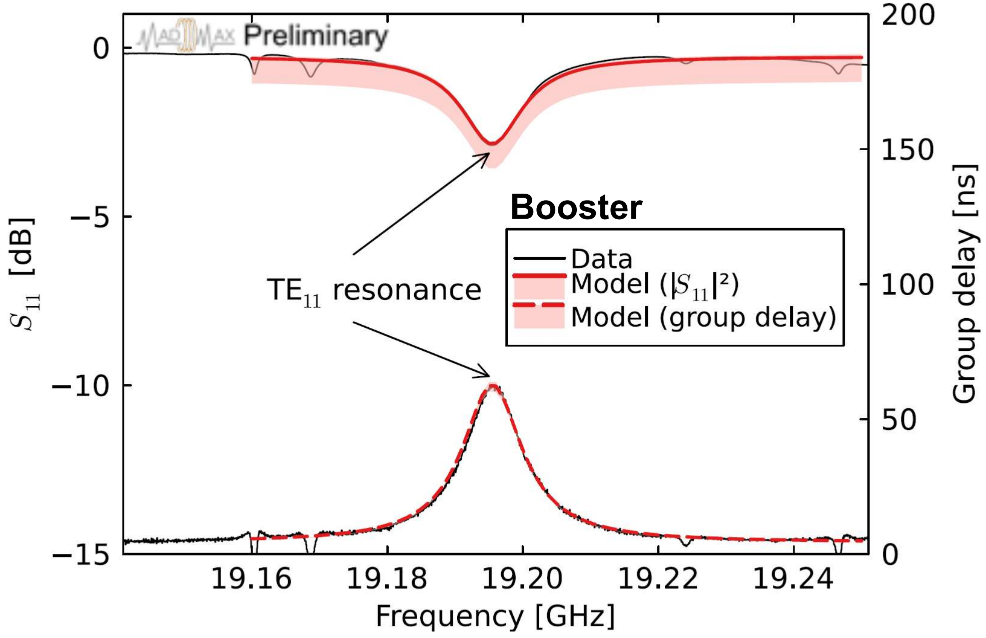
Boost factor (1/2)

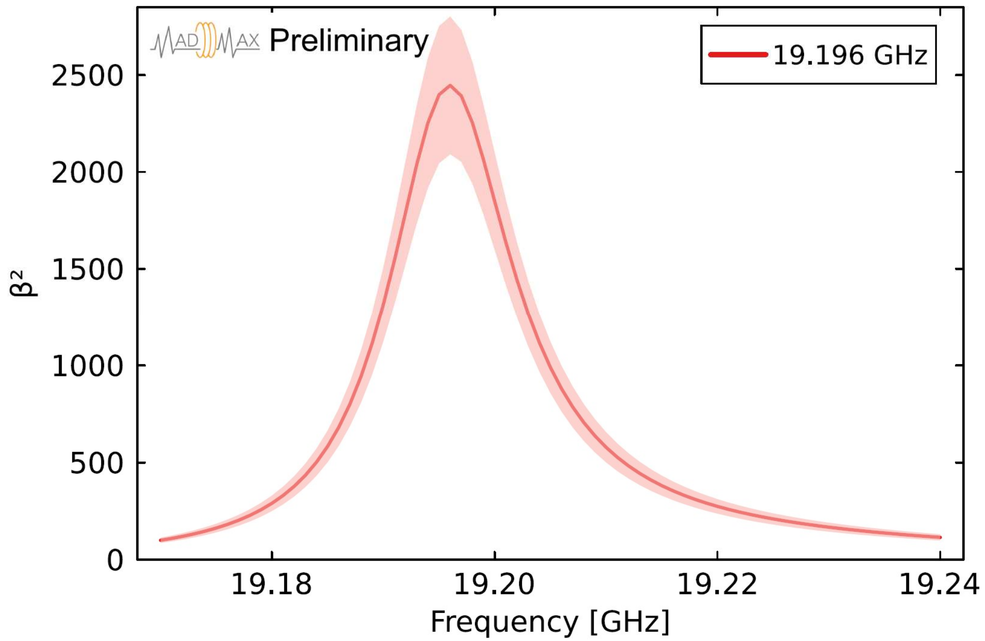
❑ Modelling the boost factor

- **Booster 1D model** obtained by fitting VNA reflectivity measurements
  - ✓ 3D effects taken into account and corrected for

noise diode

- **Receiver model** obtained by fitting standard calibration measurements (short, open, load)
- **Booster + receiver model** obtained by fitting system noise measurements in [18, 20] GHz
- This procedure allows to determine systematics uncertainties from fit parameters



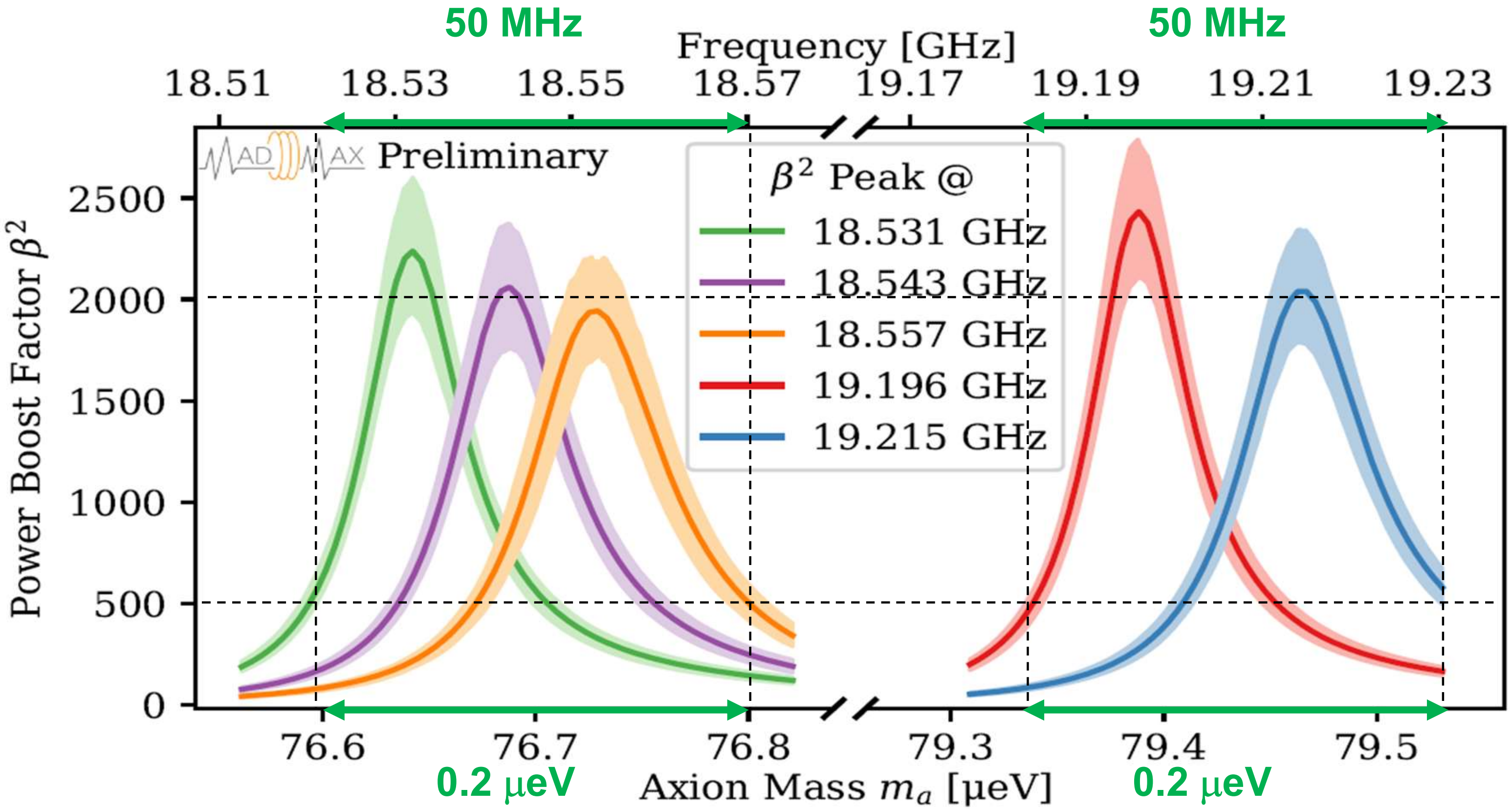


Boost factor curves determined at 15%

Boost factor (2/2)

❑ Computing the boost factor for all configurations

- $\beta^2_{peak} \approx 0(2000)$ and scan 100 MHz with $\beta^2 > 500$



Demonstrating the scanning capacity of MADMAX booster

Data analysis (1/2)

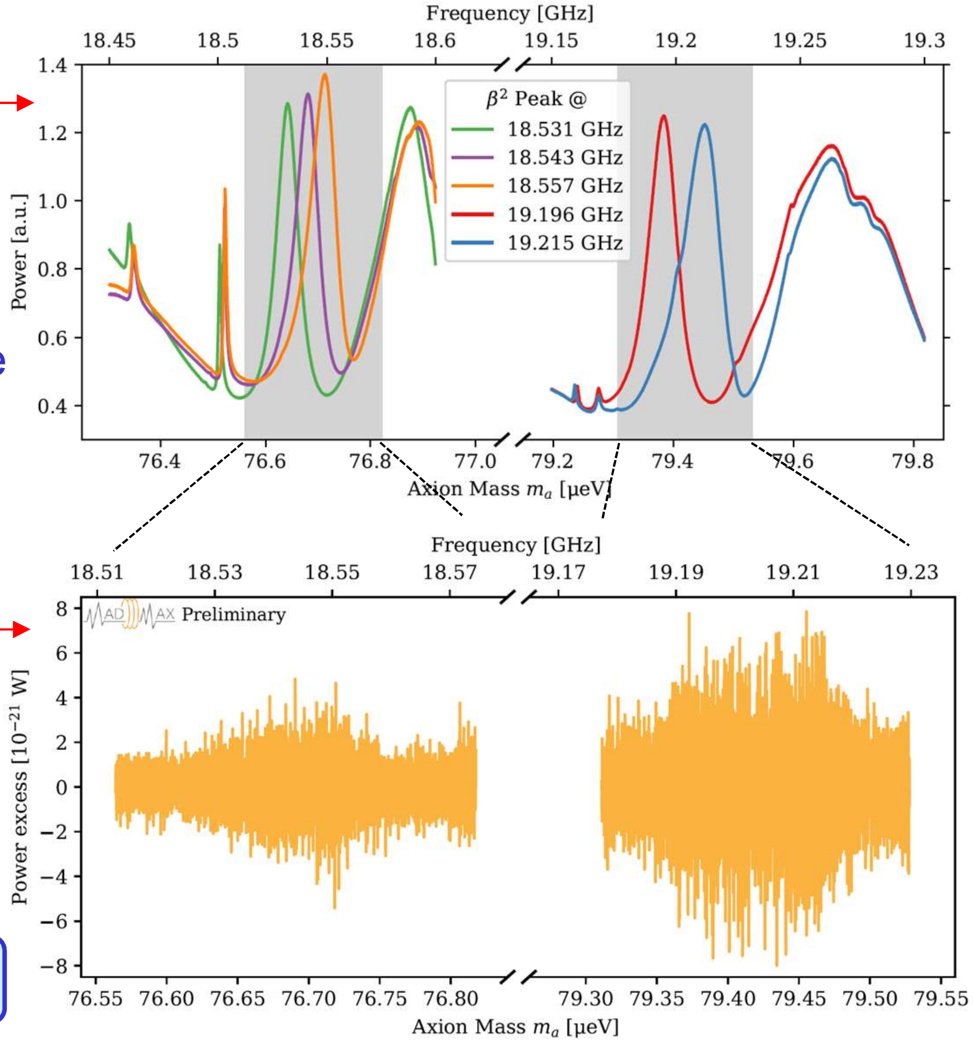
Power spectra data analysis *(based on HAYSTACK procedure, PRD 96 (2017) 123008)*

- Acquire raw power spectra (vs frequency) →
  (one 15' physics run for each configuration → ~1400 runs with bins of 0.9 kHz)

- Filter power spectra (Savitsky-Golay filter) to remove system noise (booster+receiver) "baseline" → residuals

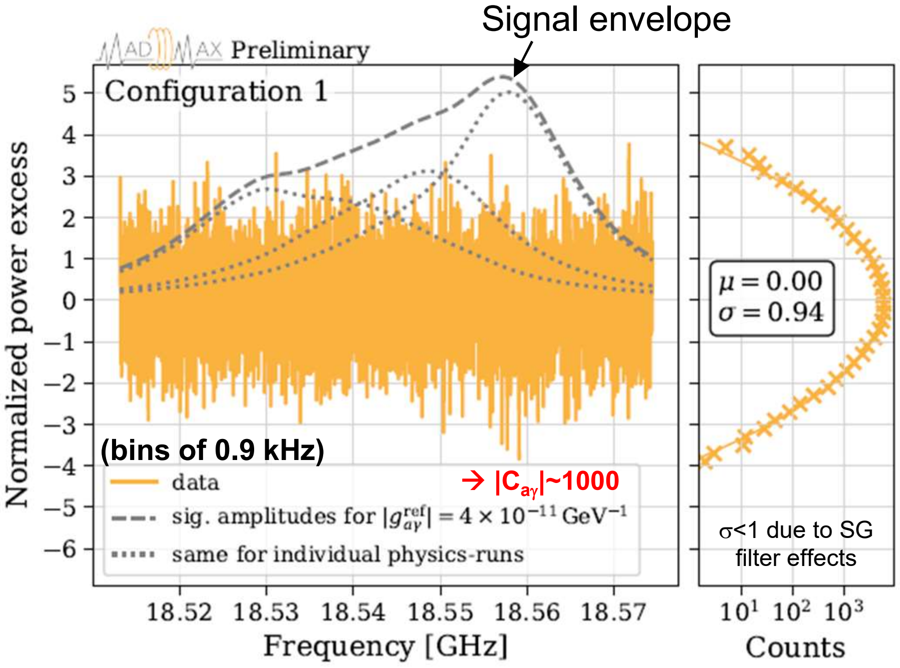
- Combine residual spectra optimizing SNR / bin →
  (using power calibration to W) & cross-correlating with axion line shape (signal is present in ~ 50 neighboring bins)

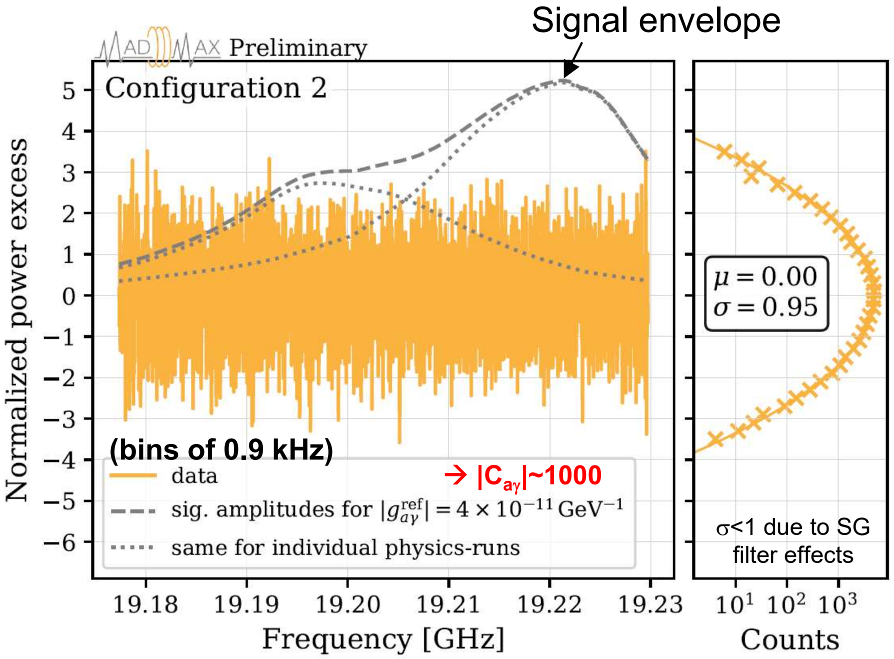
Sensitive to signal power of O(10^{-21} W)



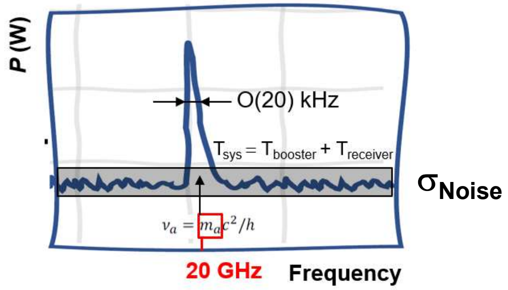
Data analysis (2/2)

- Normalize by thermal noise σ_{Noise} ($\propto T_{sys}$) → normalized power excess vs frequency





- No excess over Gaussian white noise ➔ limits on axion-photon coupling $|g_{a\gamma}|$ for each frequency bin
- Impact of systematics on limit 5-10% (dominated by boost factor)

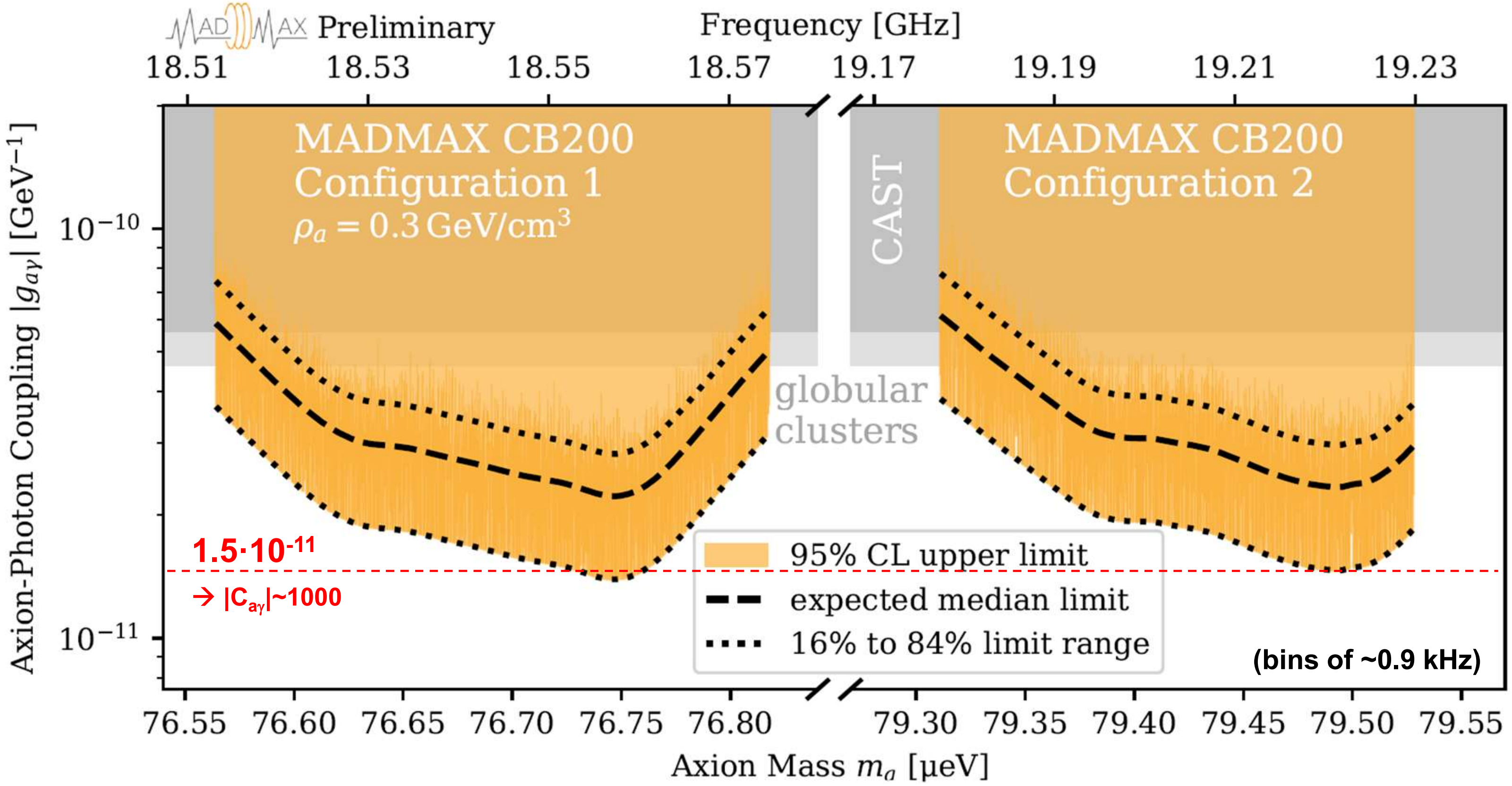


Axion search

arXiv:2409.11777
(submitted to PRL)

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

- Limits on $|g_{a\gamma}|$ better than existing constraints by up to factor 3
- Modest set-up with only 2 weeks data ➔ confirm **substantial potential** of MADMAX scan



$1.5{\cdot}10^{-11}$

→ $|C_{a\gamma}|$~1000

(bins of ~0.9 kHz)

CAST: direct search with helioscope

Globular clusters: indirect astrophysical constraint from stellar evolution

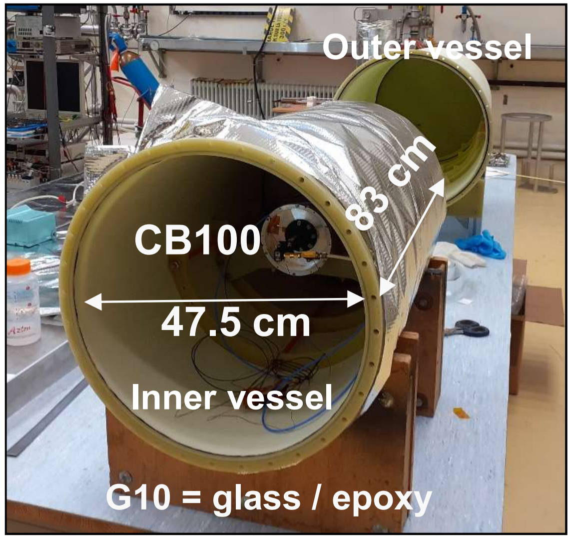
First dark matter axion search with dielectric haloscope

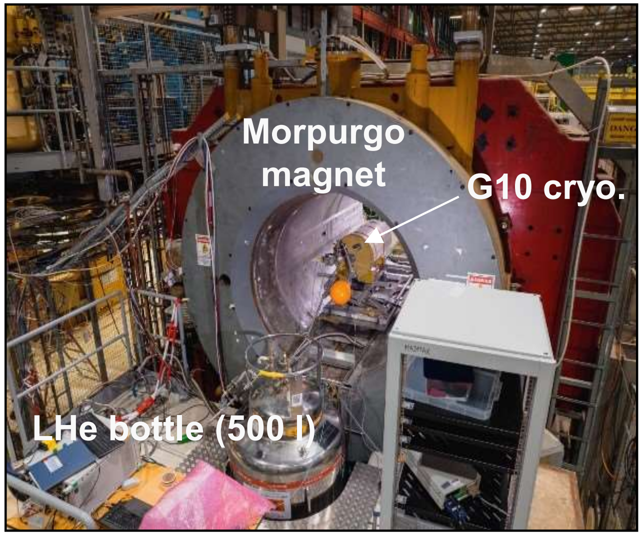
Axion search (at cold !)

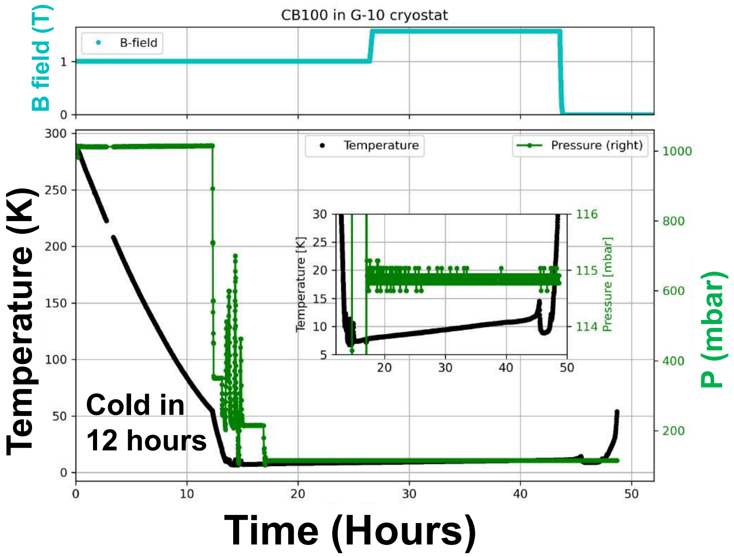
Name	Booster	Disks	Test @CERN
CB100	Closed	3, **fixed** ϕ = 100 mm	2024

arXiv:2412.12818 (accepted by JINST)

- Developed low-cost cryostat in G10 with CERN cryolab: 25 hours below 10 K
- Established and validated receiver chain calibration procedure at cold







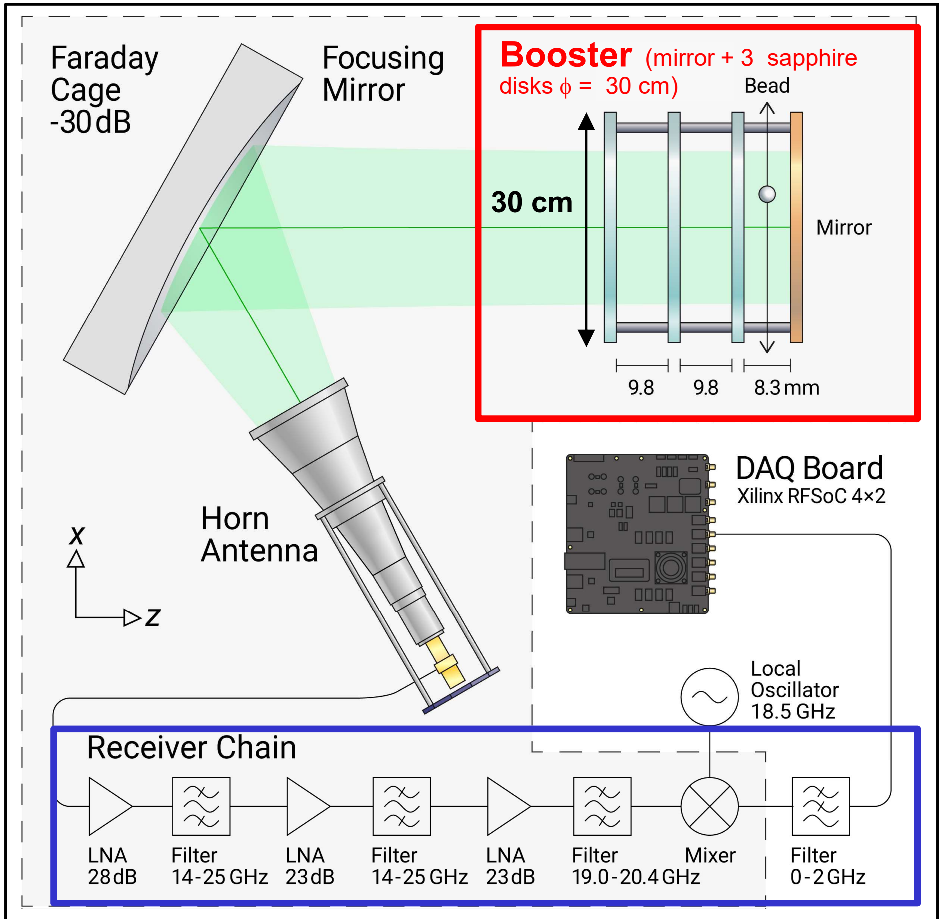
First operation of a dielectric haloscope at cold under B field

[2 analysis papers in preparation]

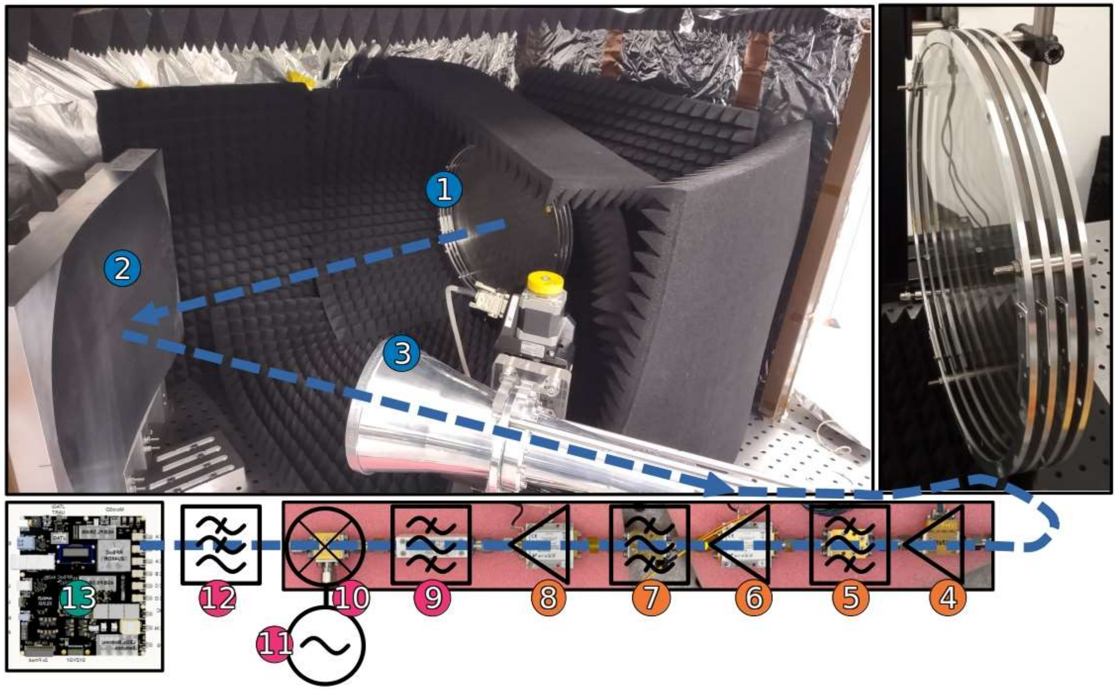
Dark Photon search

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

Boost Factor (1/2)

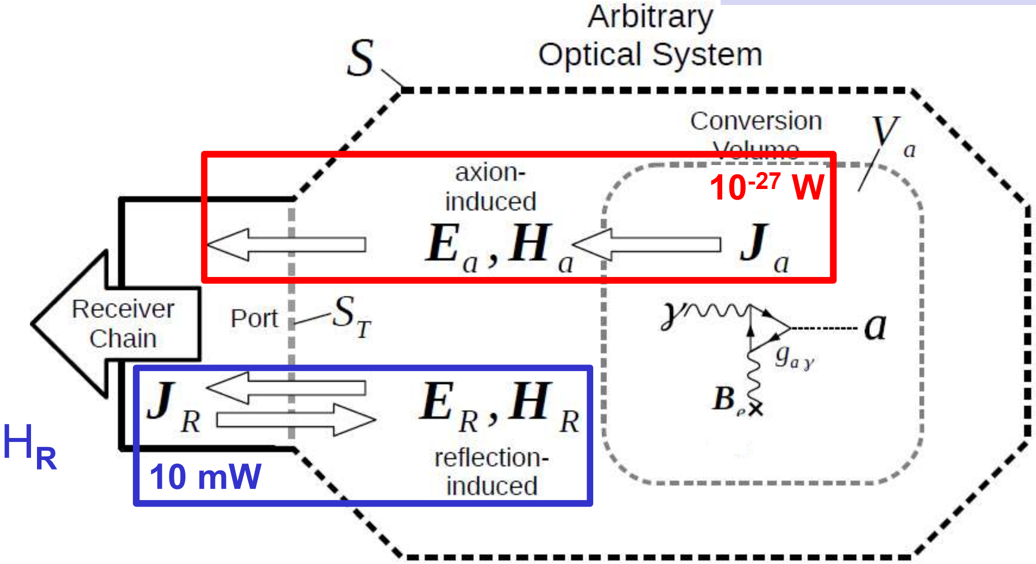
JCAP 04 (2023) 064

❑ Reciprocity approach

- Lorentz reciprocity theorem relates EM fields

J_a = effective current density from axion 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



- System response to **reflection measurement** gives direct access to β^2

$$P_{\text{sig}} = \frac{g_{a\gamma}^2}{16 P_{\text{in}}} \left| \int_{V_a} \mathrm{d}V \, \boldsymbol{E}_R \cdot \dot{a} \boldsymbol{B}_e \right|^2 \propto \beta^2 \xrightarrow{\text{Vertical } B_e} P_{sig} = \frac{\omega_a^2 \overbrace{g_{a\gamma}^2 a_0^2 B_e^2}^{(\varepsilon_0 E_a)^2}}{16 P_{in}} \left| \int \mathrm{d}V \, E_R \right|^2$$

Dark Photon (DP) **mixing** with the photon (χ) and **unpolarized.**
DP fraction with polarisation aligned with the receiver system (α)

$$\longrightarrow P_{sig} = \frac{\omega_\chi^2 (\chi \alpha \epsilon_0 E_\chi)^2}{16 P_{in}} \left| \int \mathrm{d}V \, E_R \right|^2$$

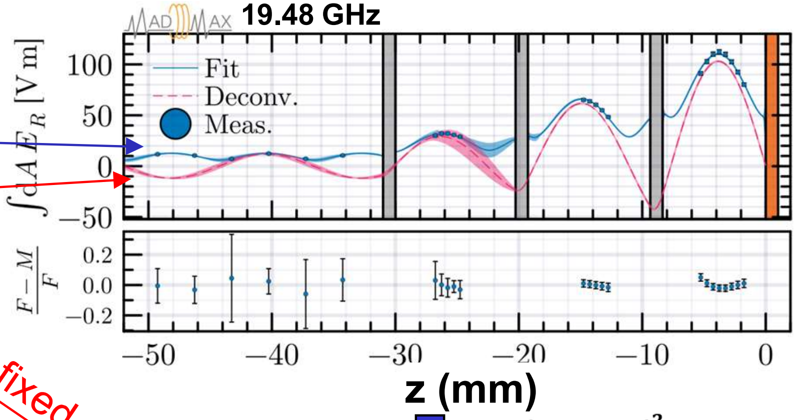
E_R 3D map in the booster needed to measure in-situ β^2

Boost Factor (2/2)

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

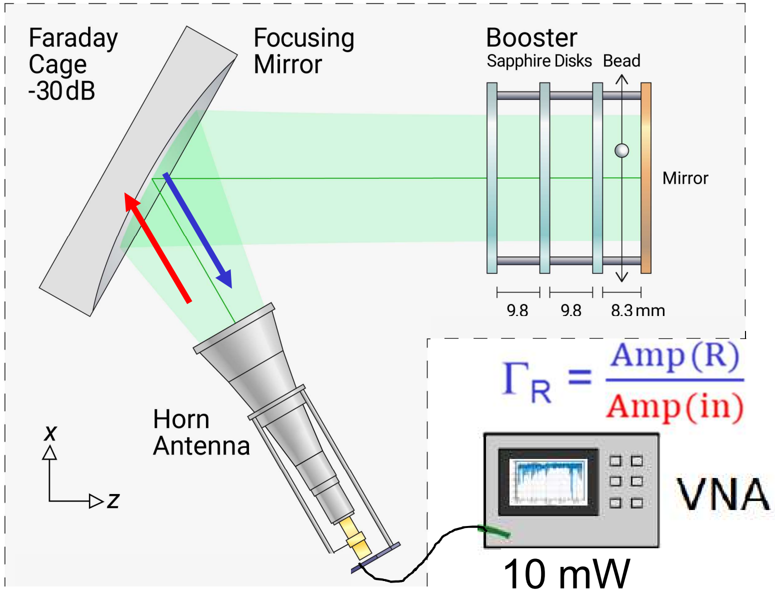
❑ Developed a bead-pull method to measure E_R

- Put 1.5 mm radius **bead** in booster volume → 3D scan
  $<< \lambda_a$
- **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 → $E_R(z, \nu)$
- **Correct** for receiver chain mismatch and finite domain measurement → $\beta^2(\nu)$



vs z

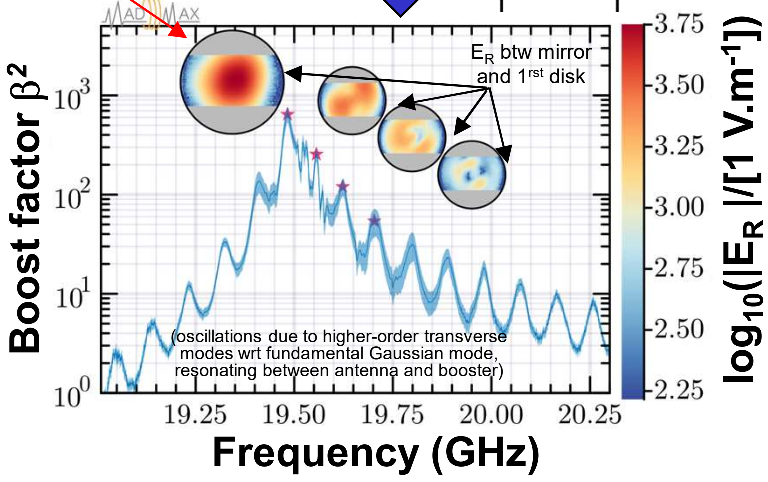
2D map at fixed ν



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

Reciprocity approach

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



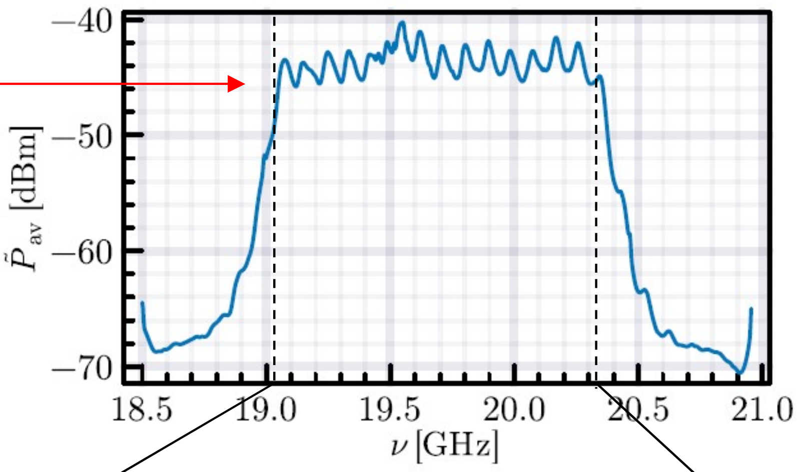
(oscillations due to higher-order transverse modes wrt fundamental Gaussian mode, resonating between antenna and booster)

In-situ measurement of β^2 at 15% level → β_{peak}^2 = 600 over 1.3 GHz

Data analysis

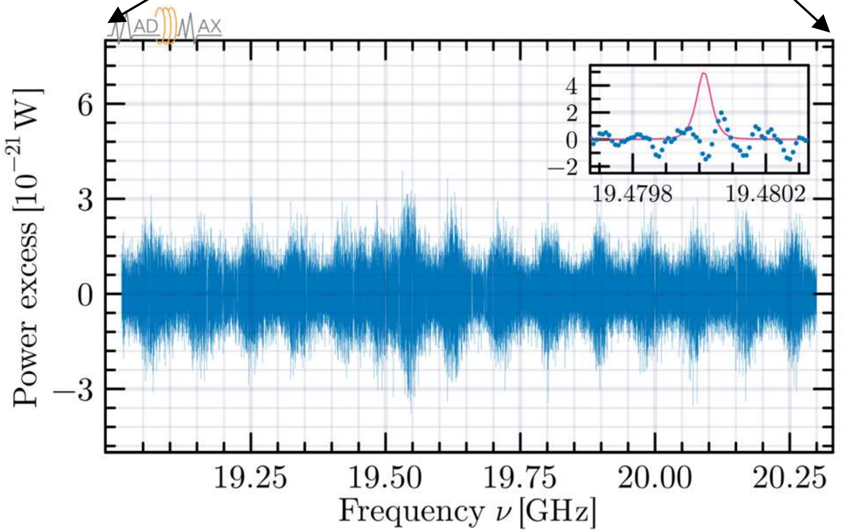
❑ Power spectra data analysis *(based on HAYSTACK procedure. PRD 96 (2017) 123008)*

- Acquire raw power spectra (vs frequency) →
  (one 10’ physics run for each configuration → ~2400 runs with bins of 9 kHz)



- Filter power spectra (Savitsky-Golay filter) to remove system noise (booster+receiver) “baseline” → residuals

- Combine residual spectra optimizing SNR / bin →
  (using power calibration to W) & cross-correlating with axion line shape (signal is present in ~ 5 neighboring bins)



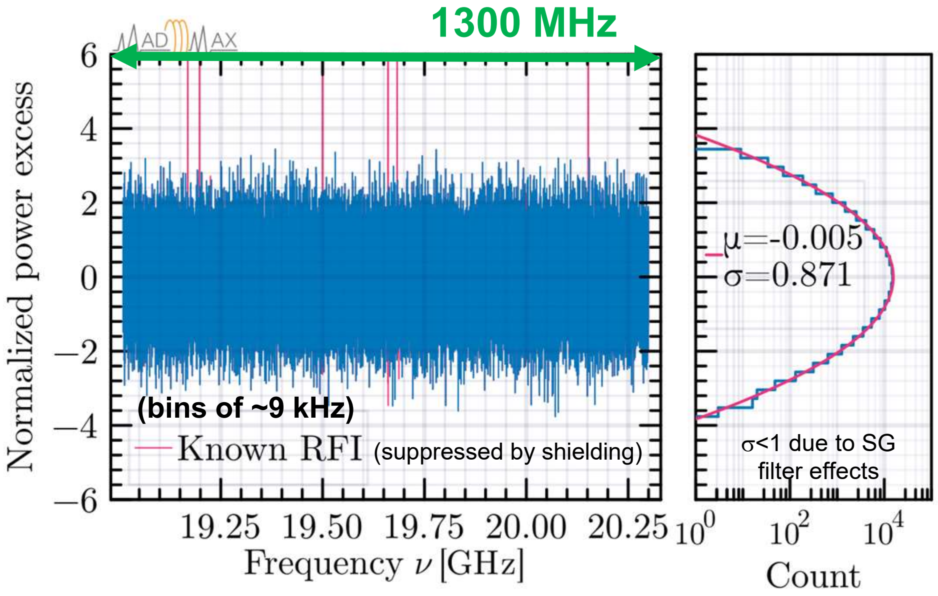
Sensitive to signal power of O(10^{-21} W)

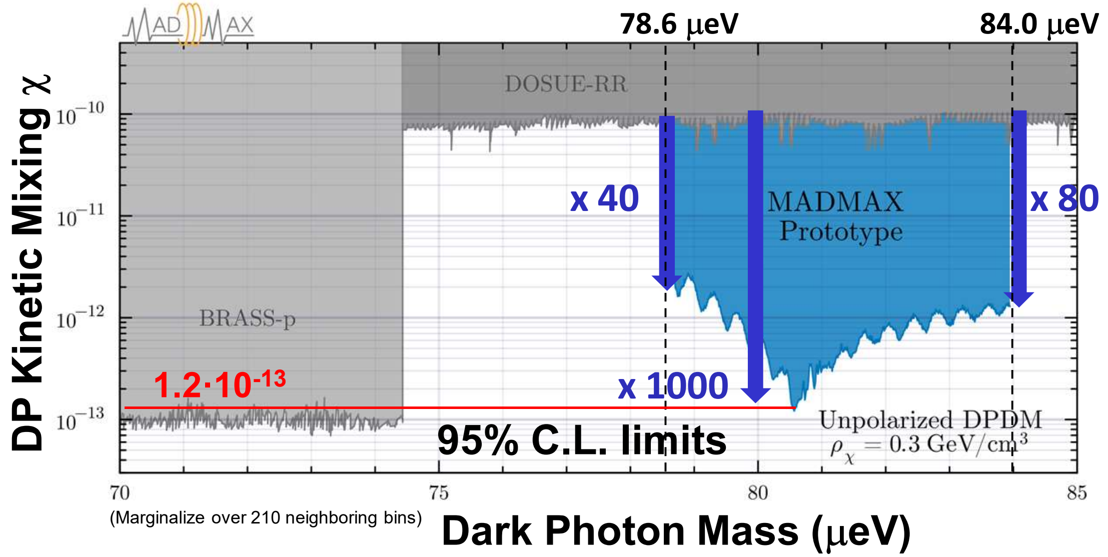
Dark Photon search

arXiv:2408.02368
(submitted to PRL)

❑ Setting limits in the χ – m_χ plane

- No signals of unknown origin detected
  - ✓ Set 95% CL **limit** on unpolarized Dark Photon (α=1/3)
  - ✓ World best limits in 5 μeV interval, **1-3 order of magnitude** below previous limits
- Modest system confirm **substantial potential** of MADMAX concept (broadband)



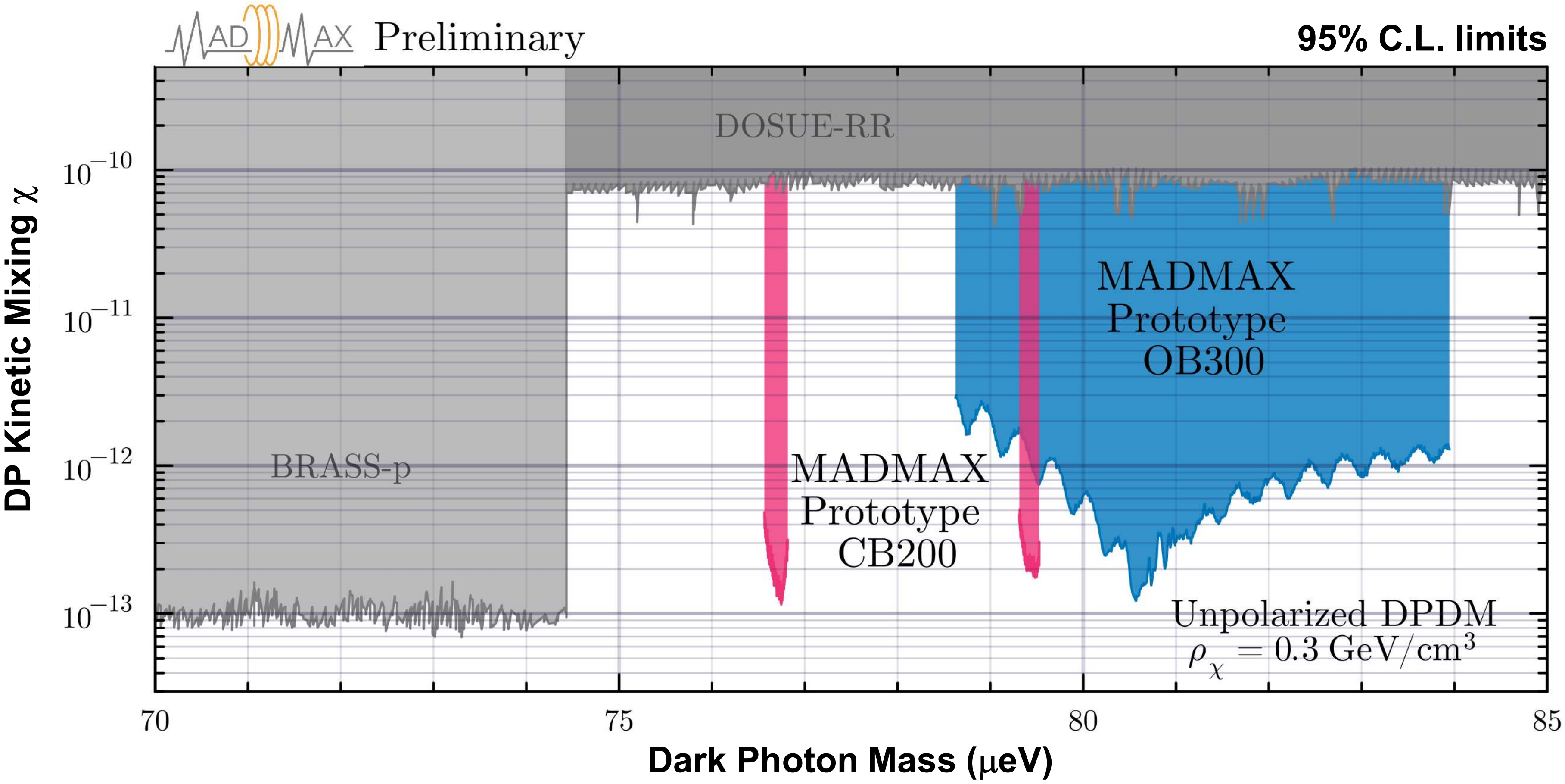


➔ **First dark matter DP search with MADMAX prototype**

Overall Dark Photon search

❑ Setting limits in the χ – m_χ plane

- Reinterpreting the axion search as dark photon search extends the excluded region



Tuneable booster (1/3)

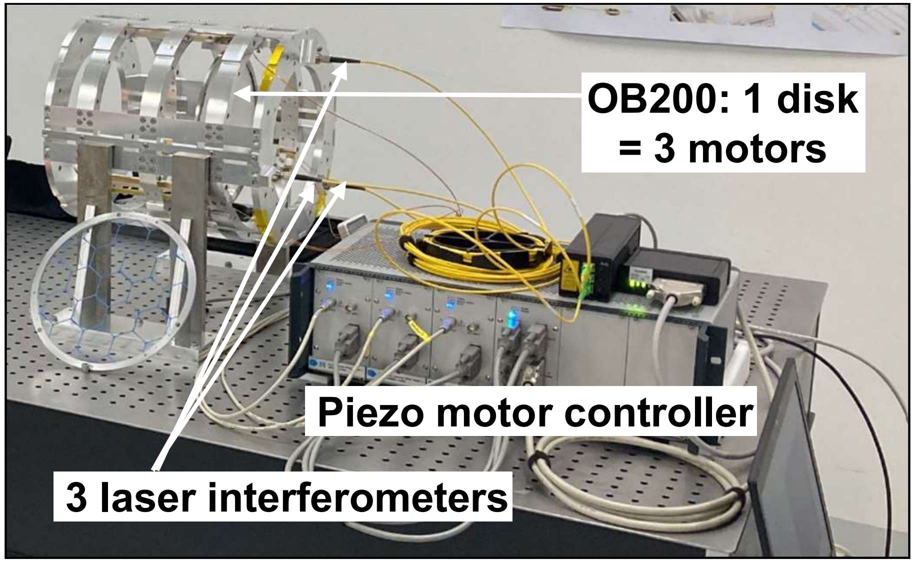
Room Temp.
Cold (10 K)
Bfield
Prospects

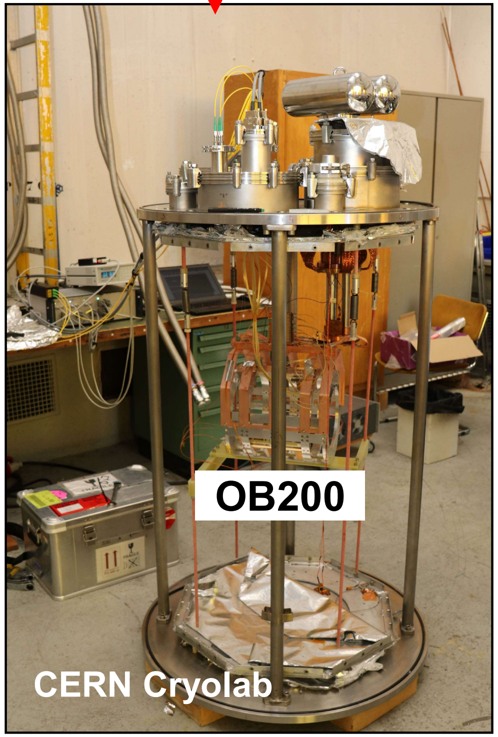
Name	Booster	Disks	Test @CERN
OB200	Open	1, **moveable** ϕ = 200 mm	2022, **22**

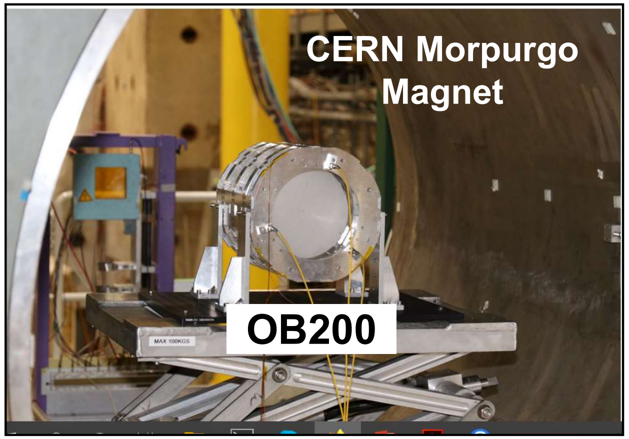
- 2021: Successful test of 1 piezo motor at 5 K and 5.3 T (ALP magnet in DESY)

JINST 18 (2023) P08011

- 2022: OB200 proto tested in the lab, in a CERN cryostat (4 K) … and in 1.6 T at CERN







Tuneable booster (2/3)

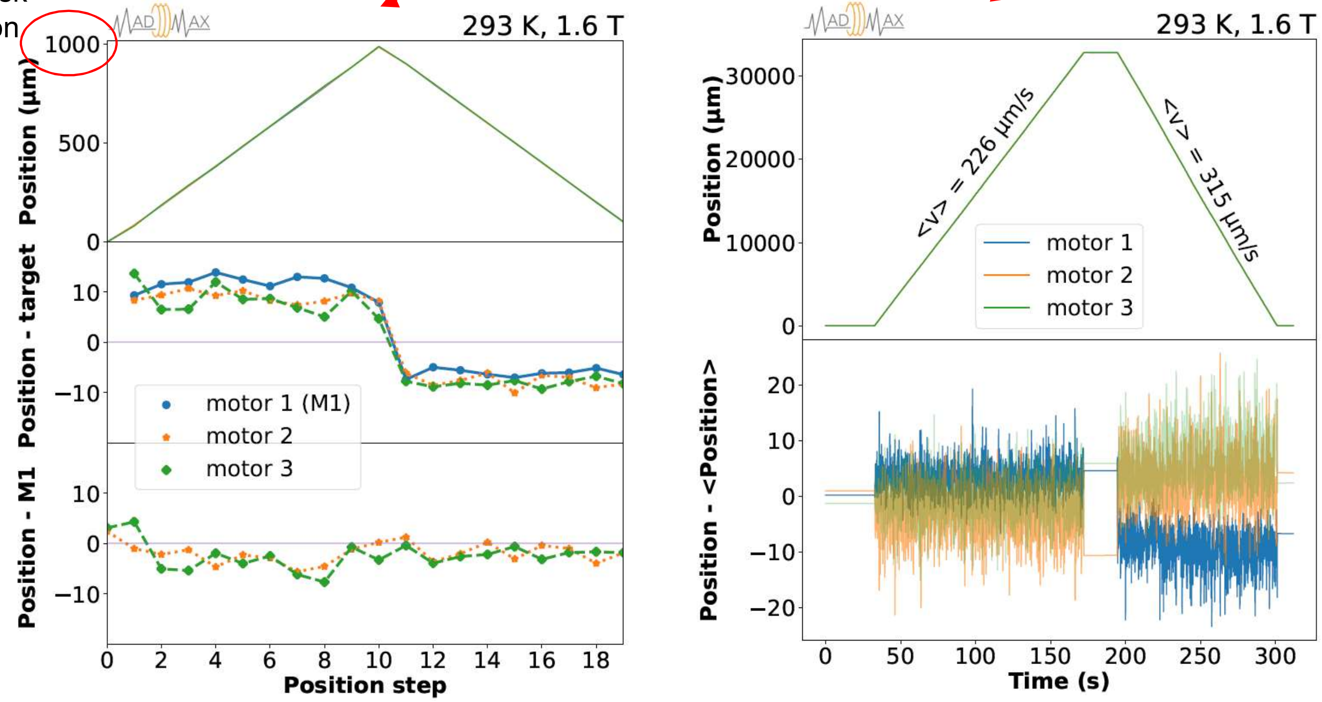
Room Temp.
Cold (10 K)
Bfield
Prospects

JINST 19 (2024) T11002

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

Typical move for the 80th disk when changing configuration in final MADMAX

Motors positioned at 10 μm



Disk speed >225 μm/s

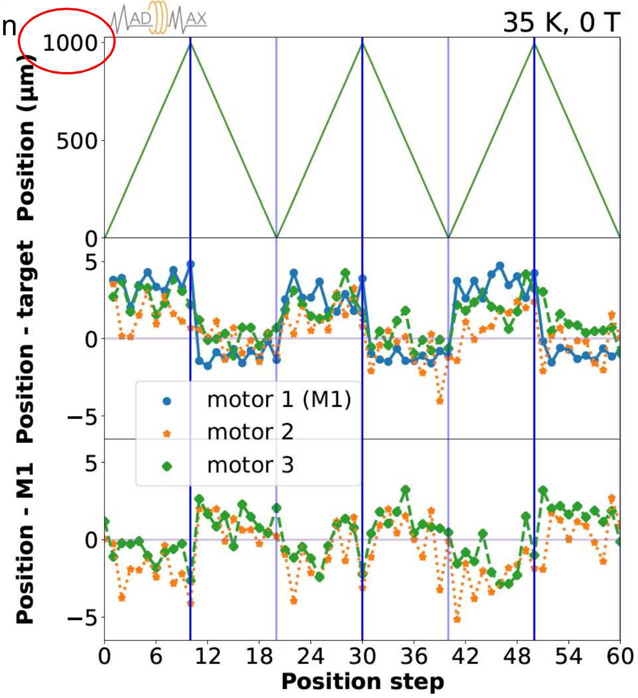
Very similar to the results obtained without Bfield

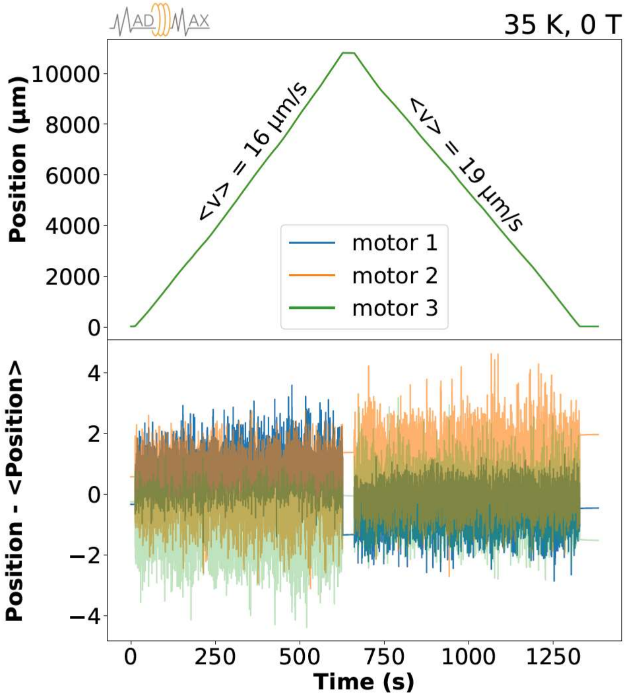
Tuneable booster (3/3)

JINST 19 (2024) T11002

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

Typical move for the 80th disk when changing configuration in final MADMAX





Motors positioned at 5 µm

Disk speed >15 µm/s

~1min for the 80th disk
→ ~1 hour to change disk configuration

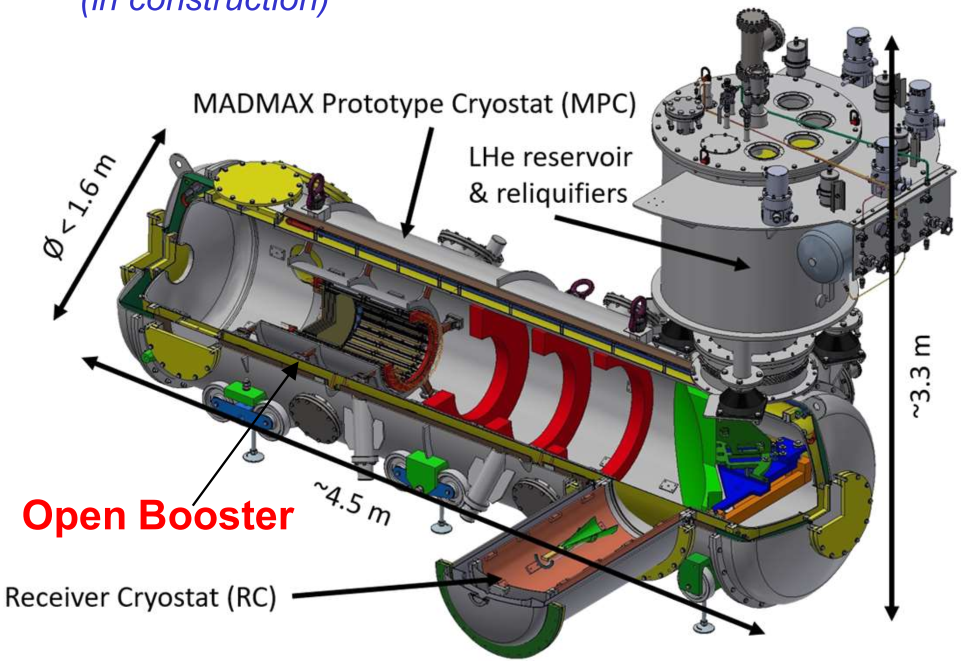
→ Precisely move the disk at cold and in B-field

→ Validate booster mechanics

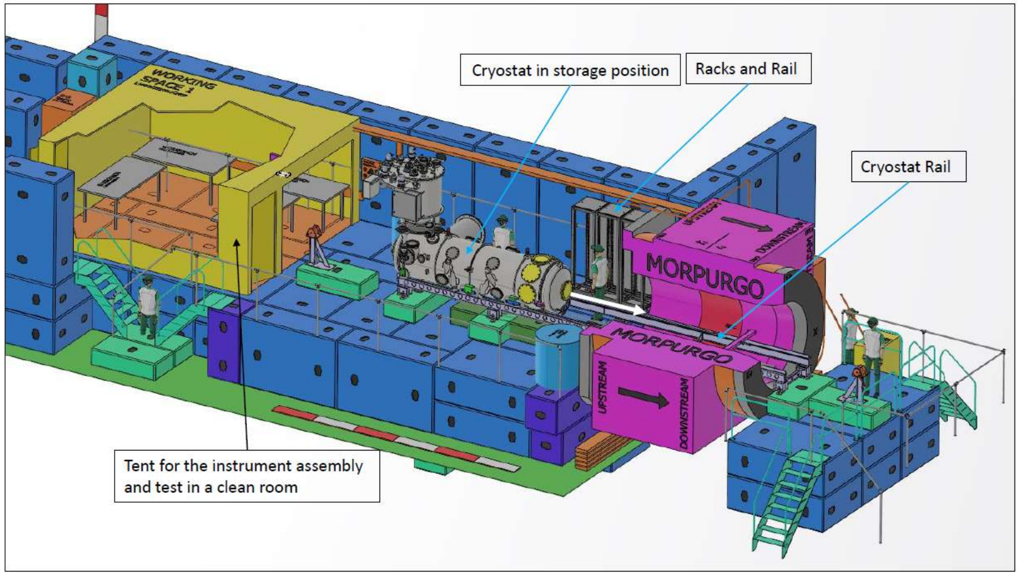
Final prototype (1/2)

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

- ☐ Booster inserted in stainless steel cryostat *(in construction)*



- ☐ Test area at CERN *(ready)*

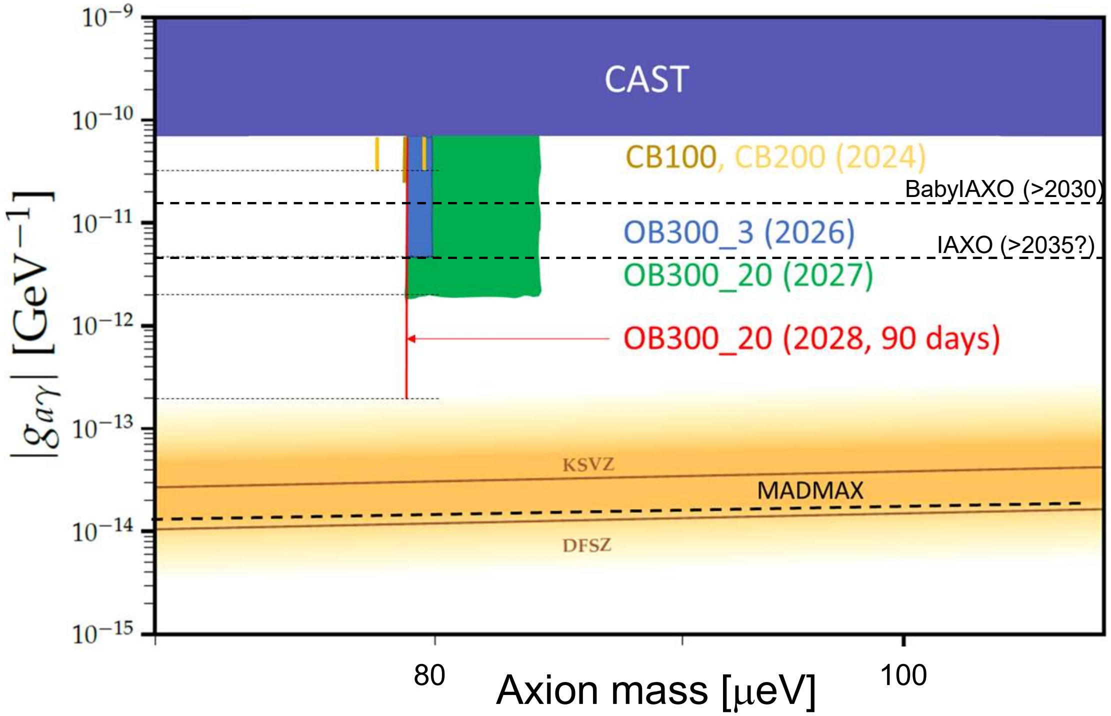


Final prototype (2/2)

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

- ☐ Booster inserted in stainless steel cryostat
  (in construction)

- ☐ Physics program during LHC shutdown



Long runs at cold with moving disks in 2026-28
→ scan axion masses

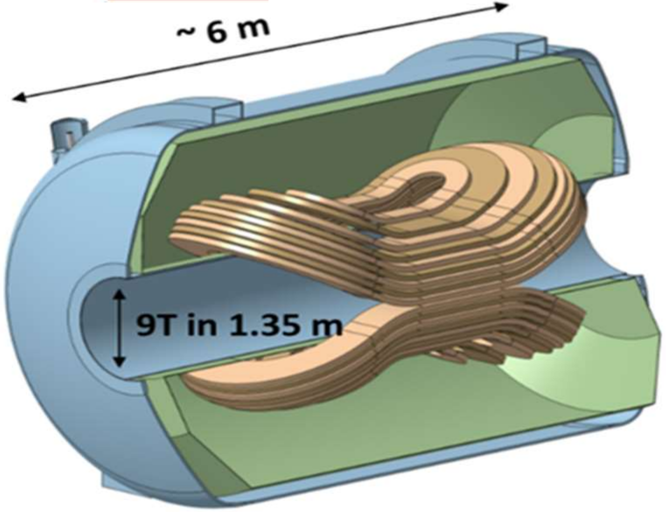
ANR obtained (HALOX)
1 postdoc position will be
open at CPPM in Sep. 2025

Towards final MADMAX

❑ Dipole Magnet

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

[NbTi with Cu jacket @ 1.8K]



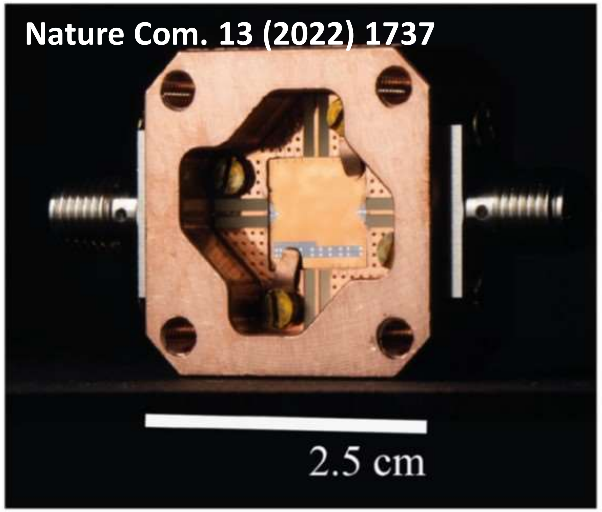
- Demonstrated that coils will be safe in terms of quench protection **IEEETAS 33 (2023) 1**
- Budget secured for a demonstrator coil → expected in 2027

❑ 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)*



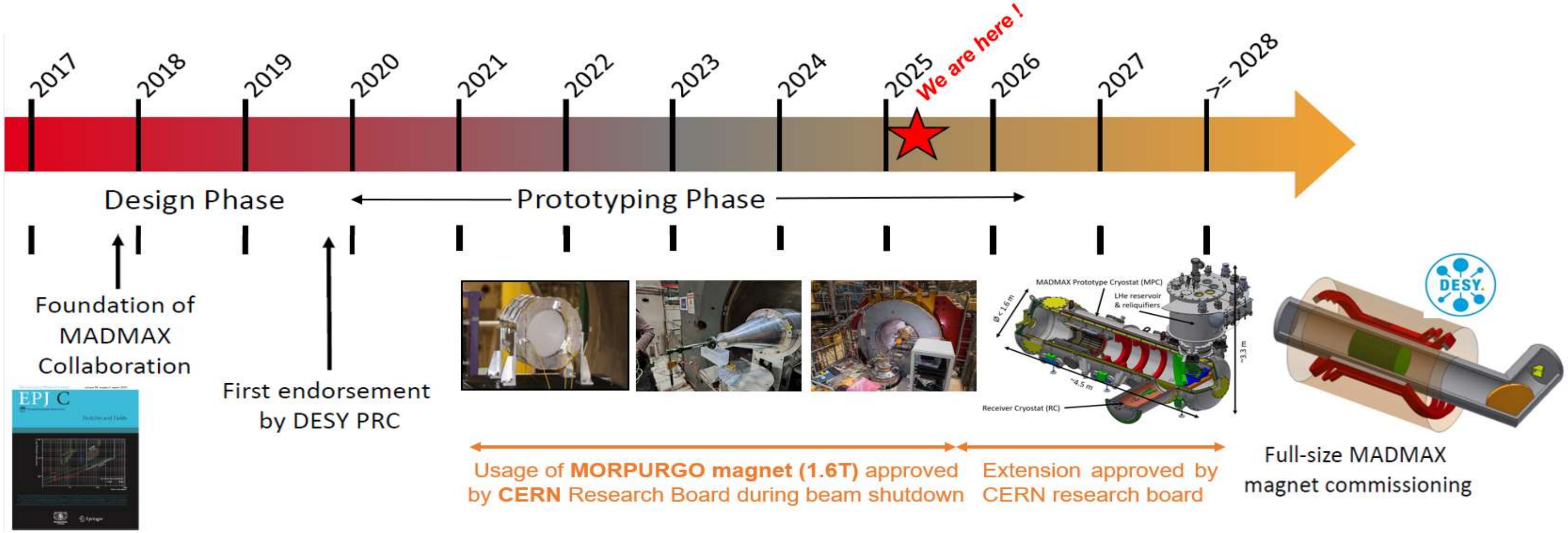
TWPA prototype with G>20 dB and 1K added noise at 10 GHz

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

Conclusions

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

- Prototyping phase in 2020-2028 to validate the concept
  - ✓ Validated mechanics at cold, under B_{Field} → **JINST 18 (2023) P08011** **JINST 19 (2024) T11002**
  - ✓ Established method to measure in situ boost factor → **JCAP 04 (2023) 064** **JCAP 04 (2024) 005**
  - ✓ Performed first DM searches → axion and dark photon world best limits for mass ~ 80 μeV → **arXiv:2408.02368 (submitted to PRL)** **arXiv:2409.11777 (submitted to PRL)**
  - ✓ First booster tests at cold and under B-field → **arXiv:2412.12818 (accepted by JINST)** **2 papers at work**
  - ➢ Final prototype tests during LHC Long Shutdown 3 at CERN

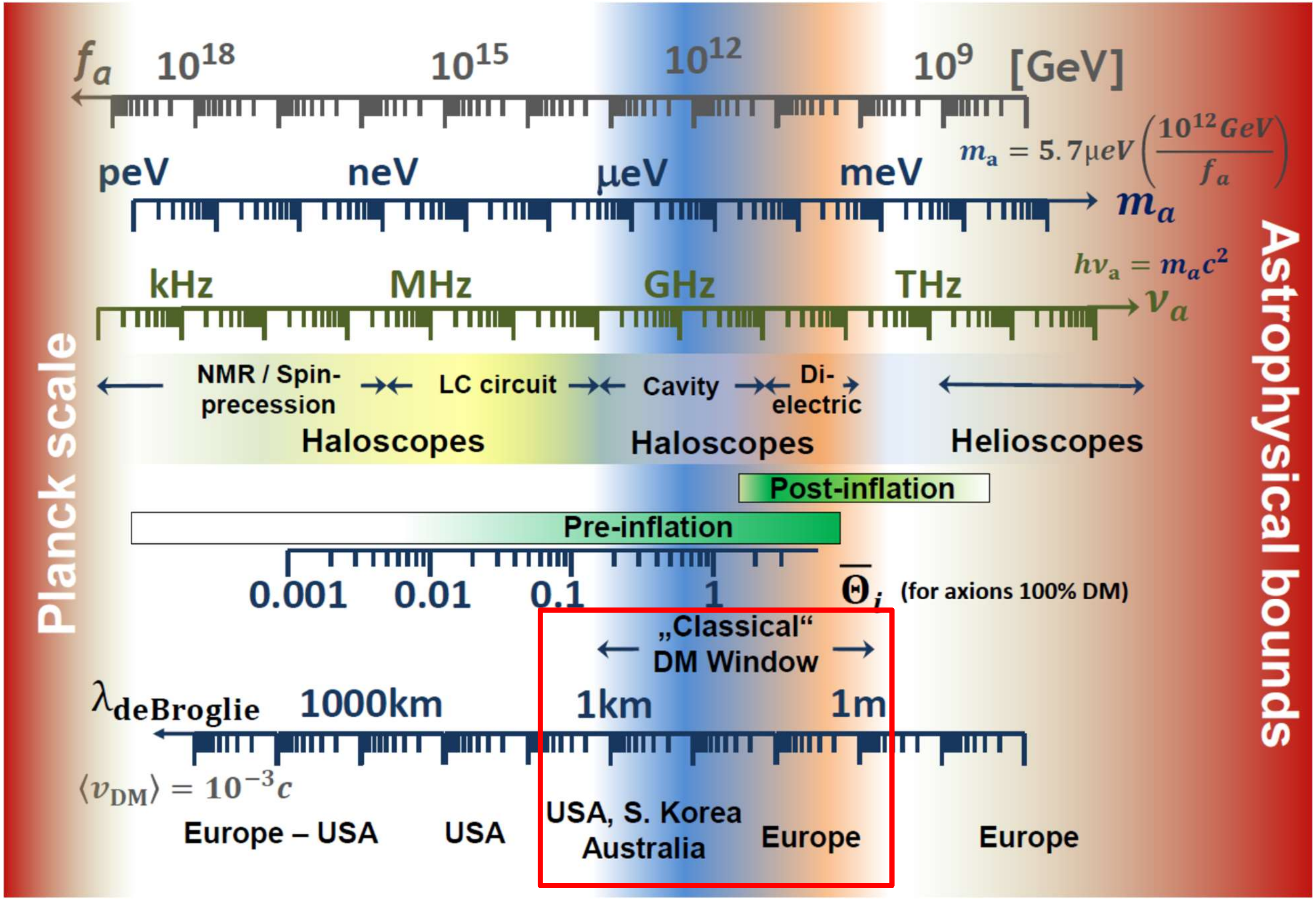


BACKUP

Axion scales

APPEC Committee Report

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



Vaccuum Realignment

Vaccuum realignment (VR)

$$\frac{\Omega_{A,\mathrm{VR}}}{\Omega_{\mathrm{DM}}} \approx \theta_i^2 F \left(\frac{f_A}{9\times 10^{11}\mathrm{GeV}}\right)^{7/6}$$

$$\approx \theta_i^2 F \left(\frac{6\ \mu\mathrm{eV}}{m_A}\right)^{7/6}$$

Ratio of VR axion density over total DM density

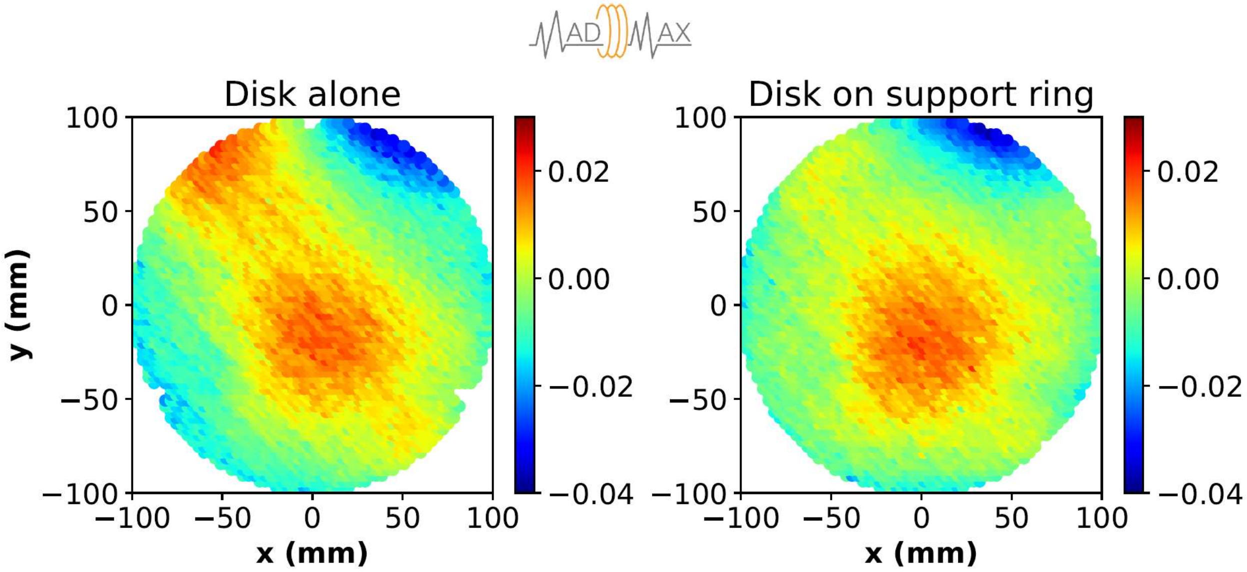
O(1) factor accounting for anharmonicities in the axion potential (calculable in principle – QCD effects)

For $\theta_i \sim 1$ a $\sim 6\ \mu\mathrm{eV}$ axion would fill the needed DM axion via VR mechanism

Note the approx. inversely proportional relation between $\Omega \sim 1/m_A$. Contrary to thermal relics.

Disk planarity

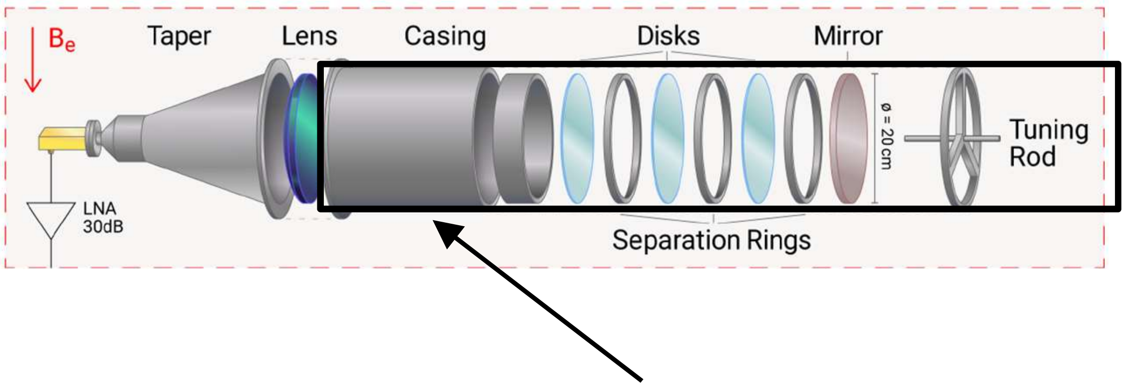
JINST 19 (2024) T11002
(arXiv:2407.10716)



RMS < 10 mm

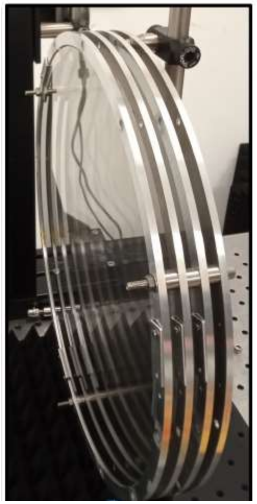
Closed vs open booster

Closed 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

Open booster

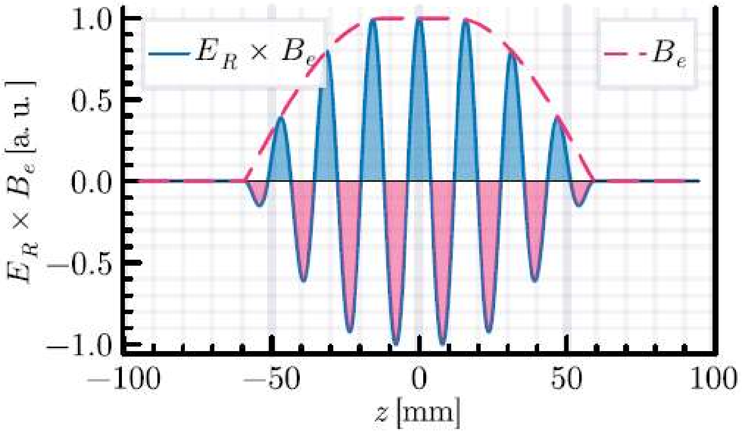


- Free space outside disks
- Higher-order transverse modes wrt fundamental Gaussian mode can propagate and resonate
- Easy to insert bead for boost factor measurement with bead-pull method

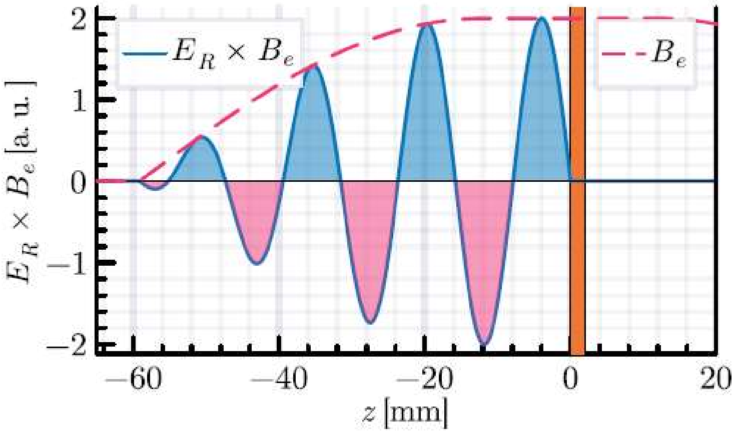
Boost factor

Thesis J. Egge

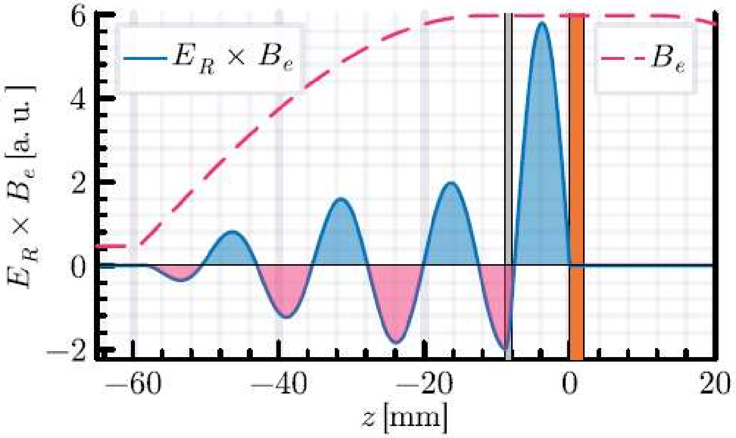
Travelling wave



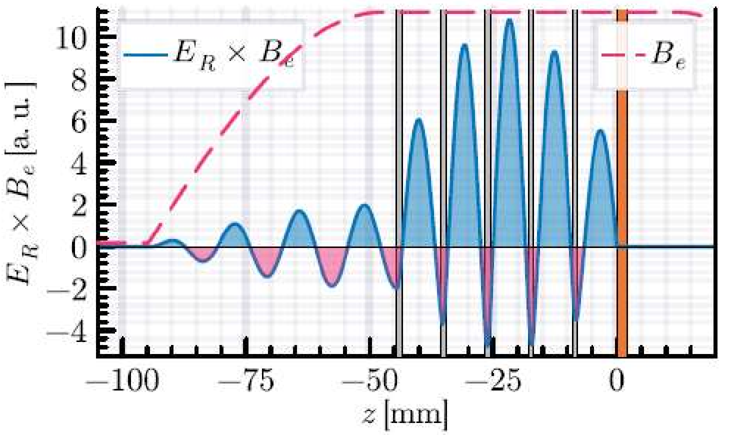
One mirror → standing wave



One mirror + one disk

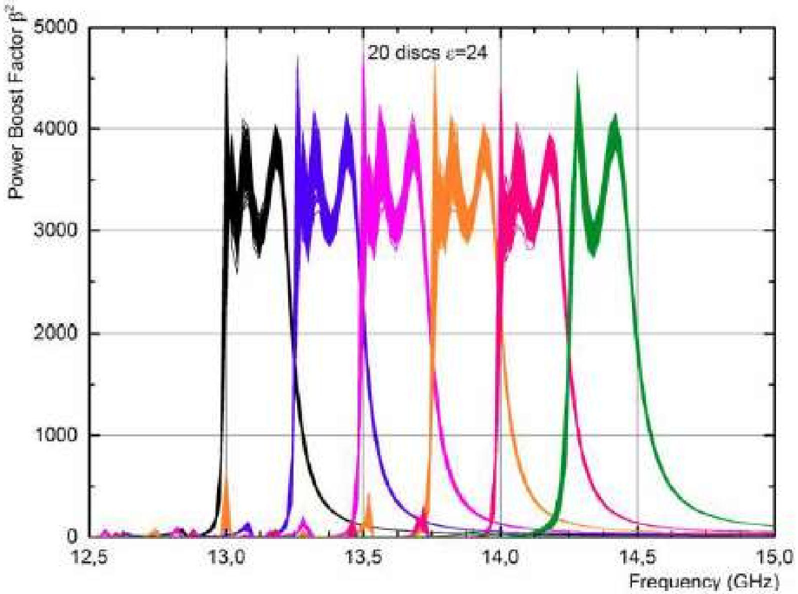


One mirror + disks ≅ MADMAX



Boost factor

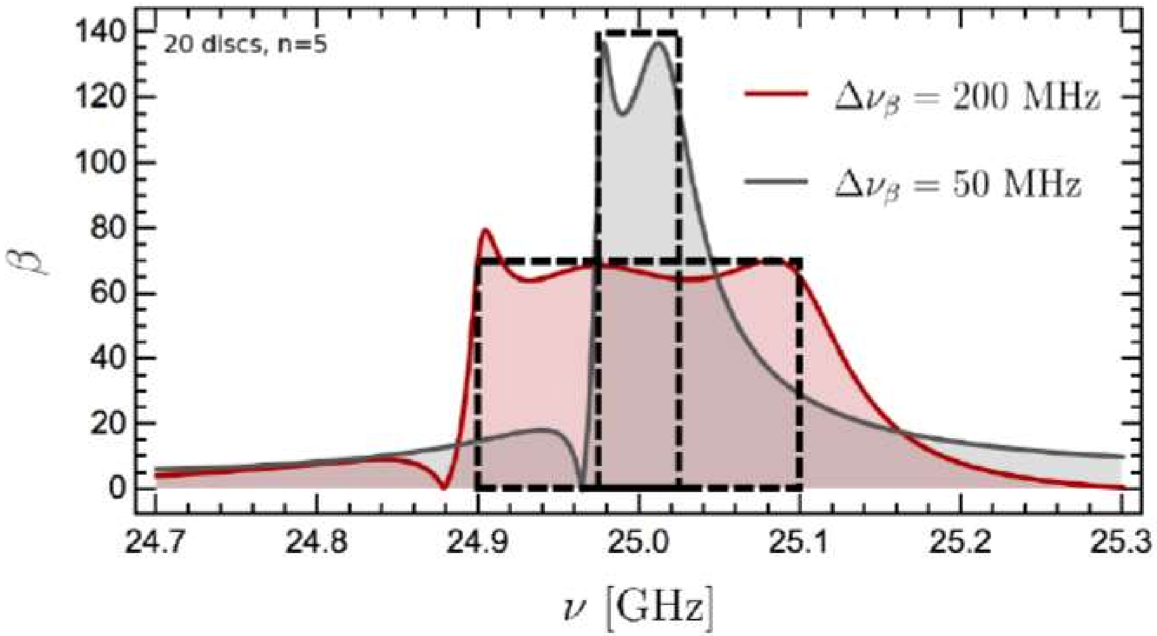
Tuning of sensitive frequency range by adjusting disc spacing



Area law: $\beta^2 \Delta\nu_\beta \sim$ const.

→ broad-band scan for search

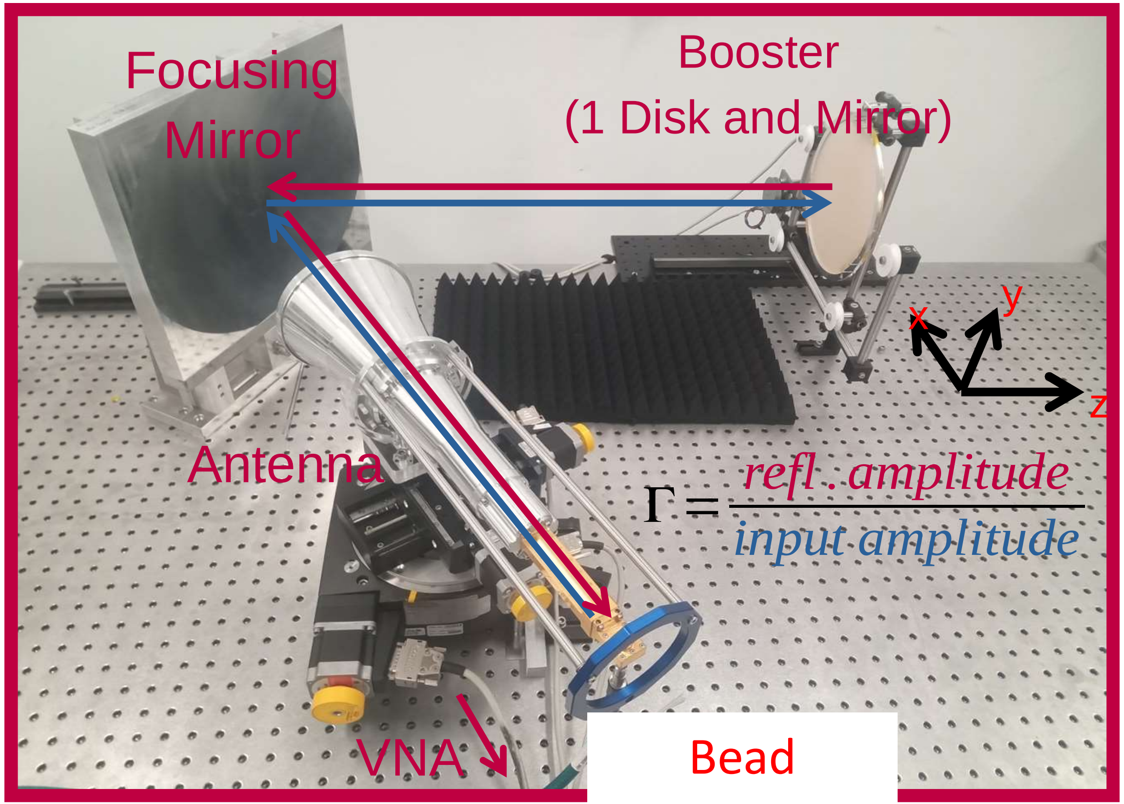
→ narrow-band to confirm possible signals



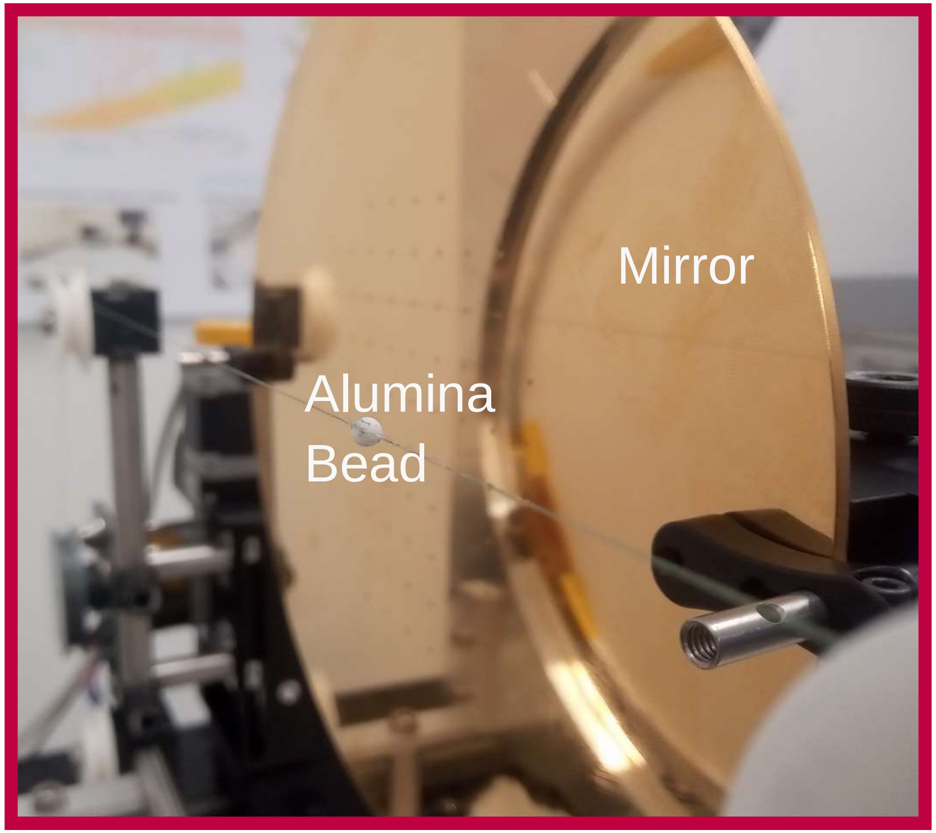
→ MADMAX versatility

Bead-pull method (1/2)

Boost factor determined using Bead Pull Method (non-resonant perturbation theory)
+ Lorentz reciprocity theorem **JCAP 04 (2023) 064**



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



Bead properties

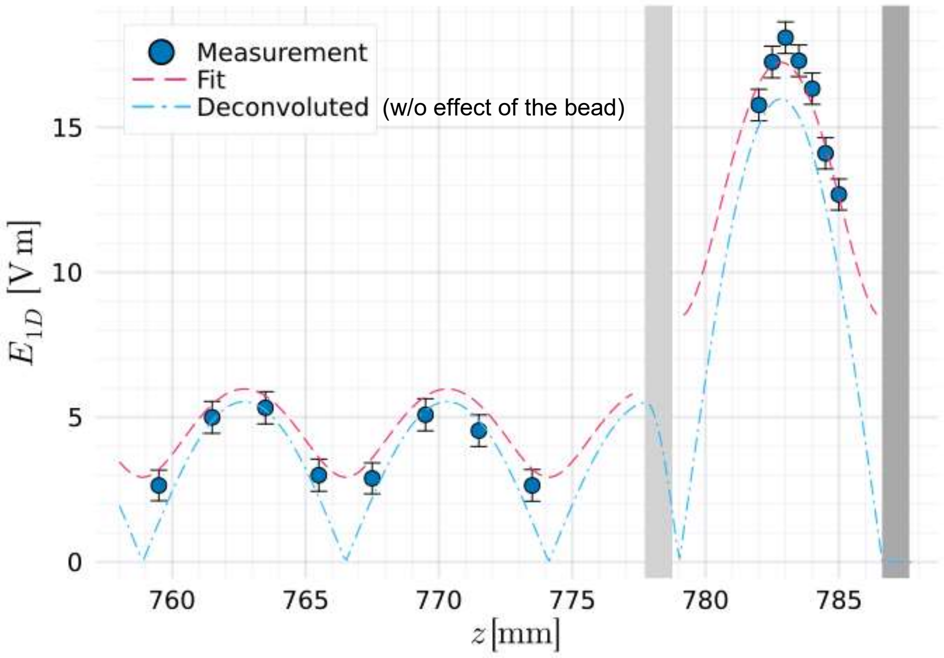
Change in reflection coefficient → $\Delta\Gamma = \frac{\alpha_e \omega}{4P_{\text{in}}} \boldsymbol{E}_R^2$ → E field

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

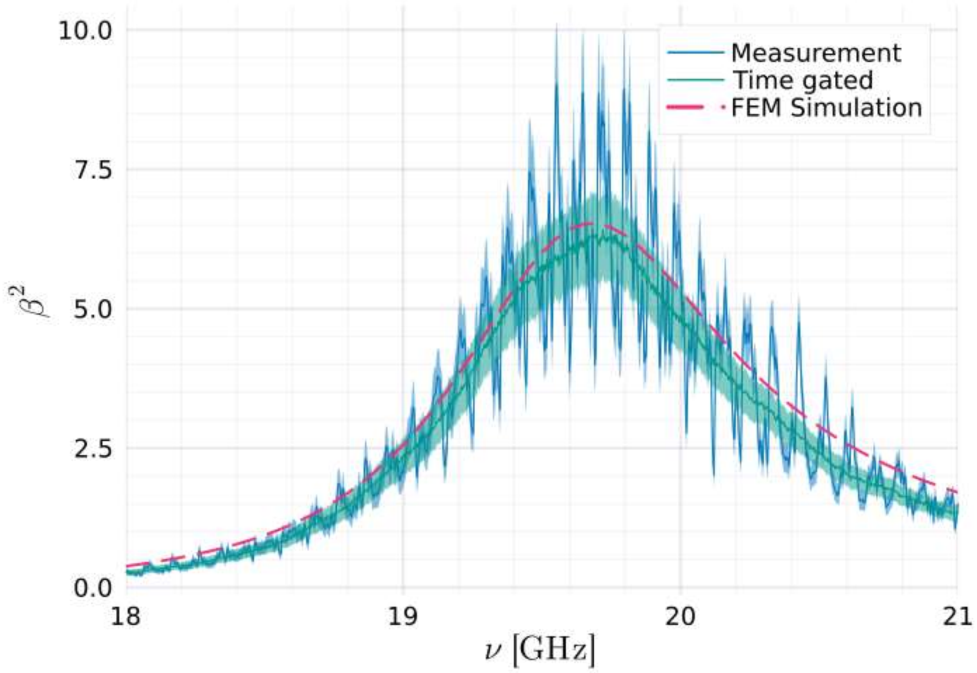
Bead-pull method (2/2)

JCAP 04 (2024) 004

Test with a single disk and non-optimized set-up

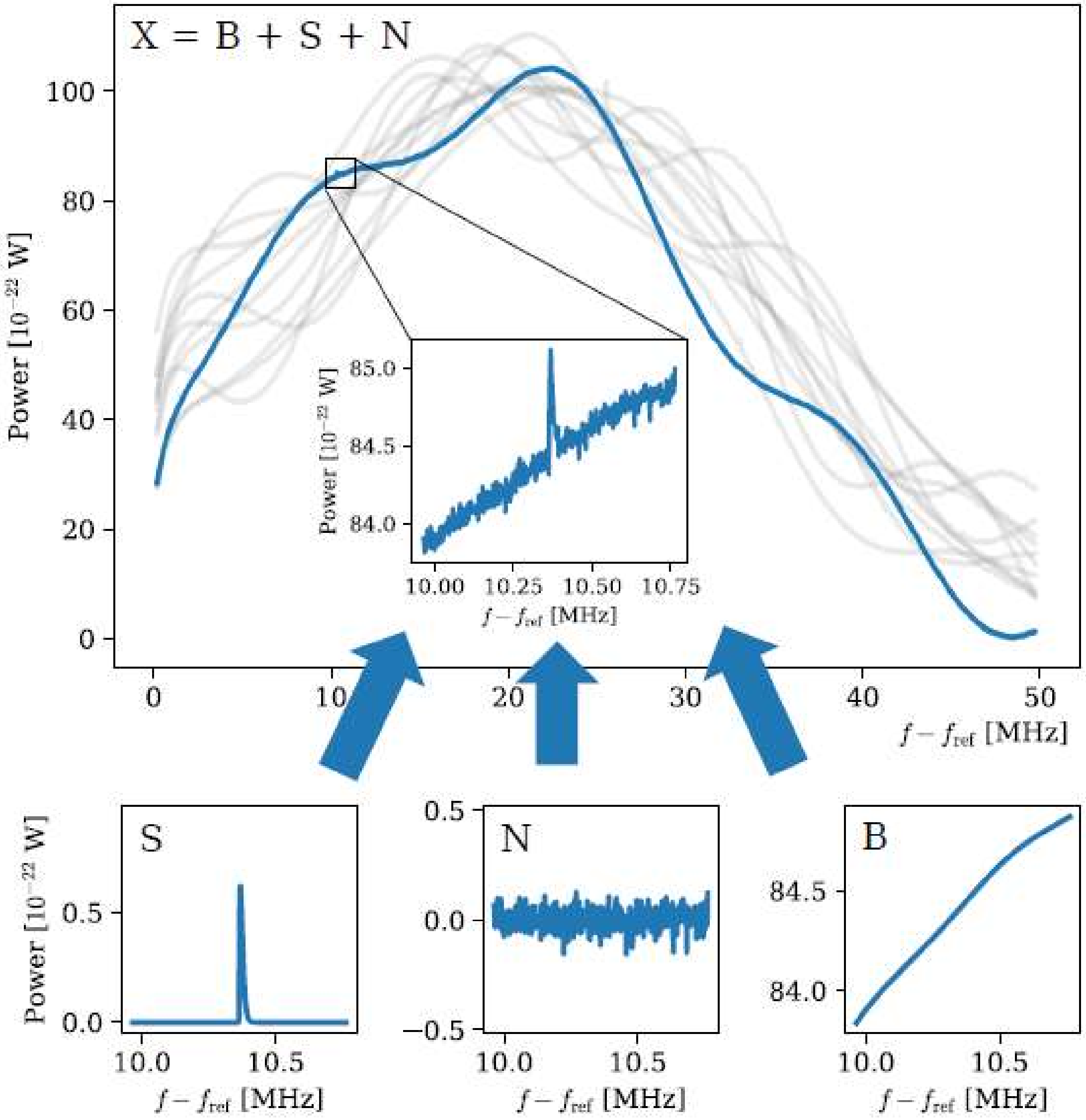


(w/o effect of the bead)

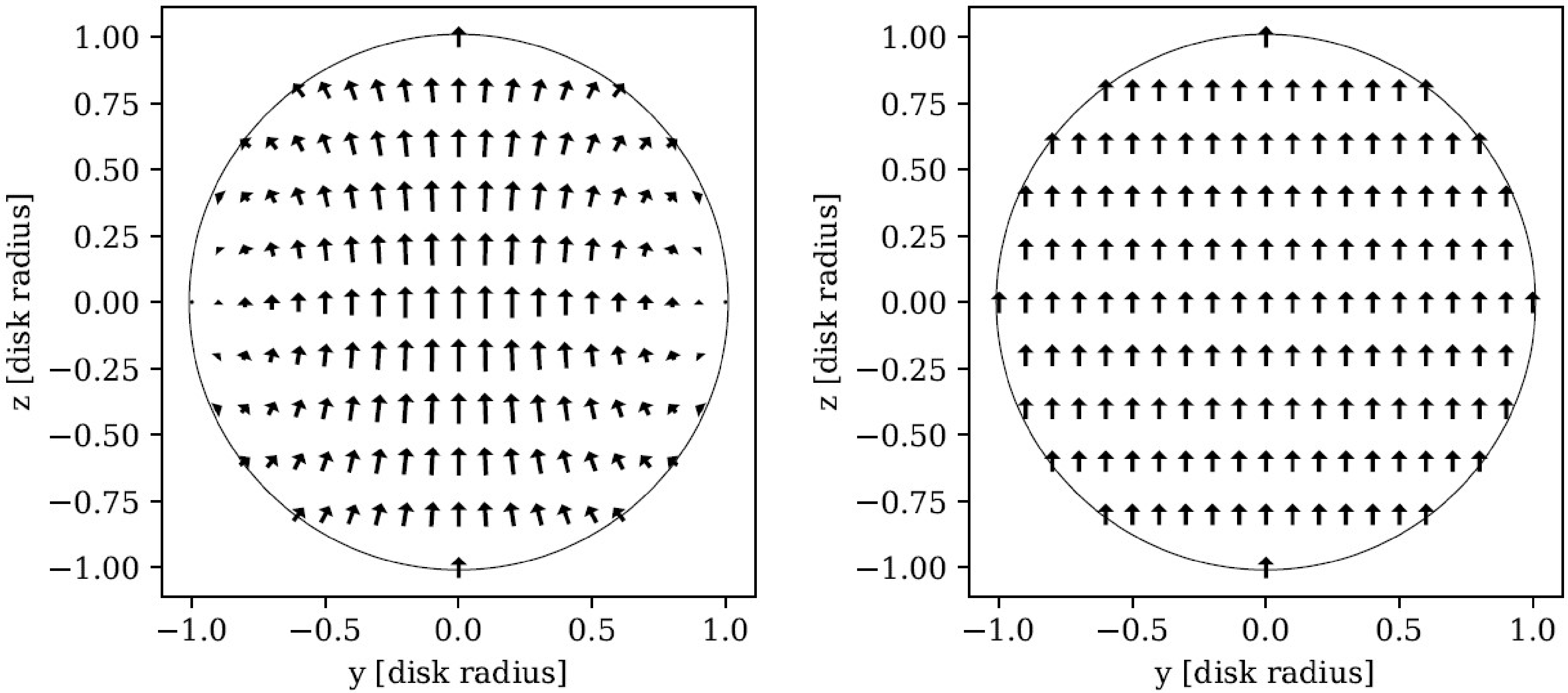


[time gating allows to filter out antenna-booster resonances]

HAYSTACK analysis



TE11 → Axion in CB



Form factor ≅ 84%

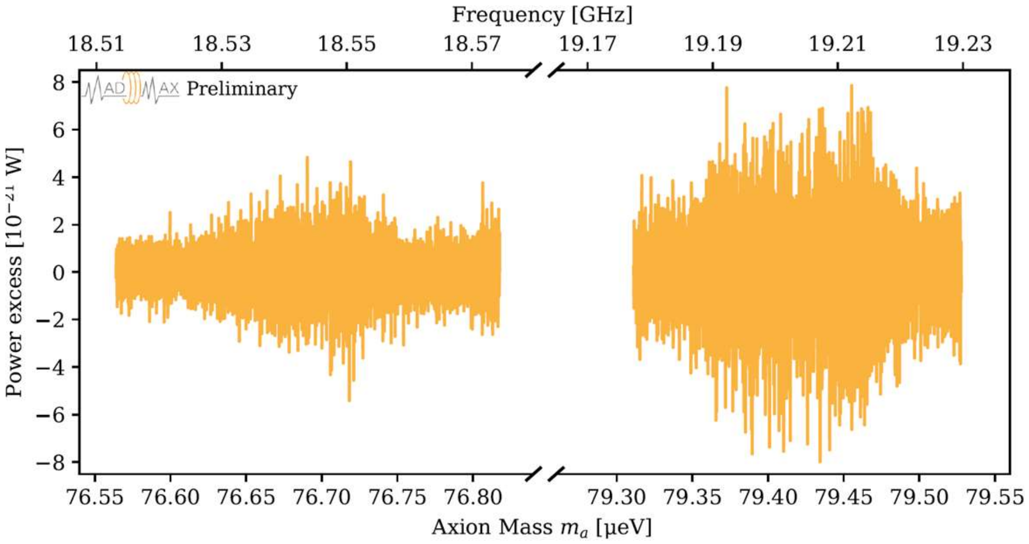
Grand spectrum

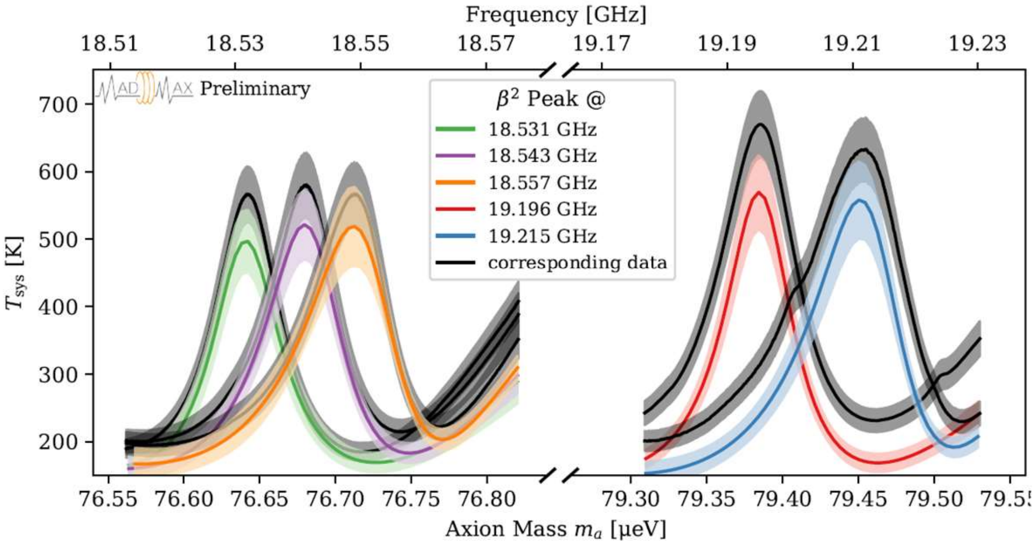
Fluctuations of power from thermal radiations / [standard deviation = $k_B \cdot T_{sys} \cdot \mathrm{sqrt}(\Delta\nu/t)$]

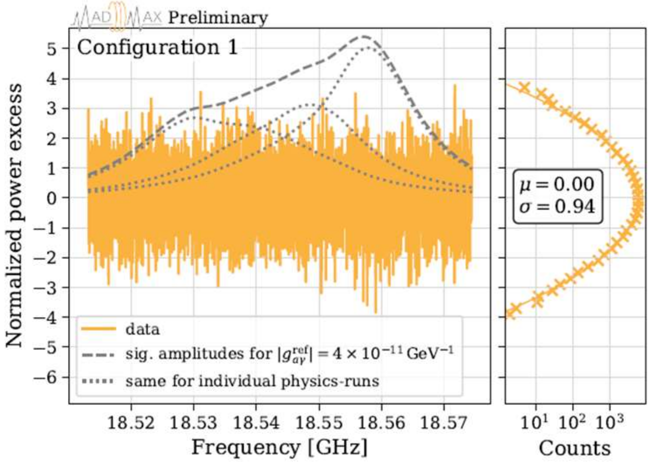
$P = k_B \cdot T_{sys} \cdot \Delta\nu$

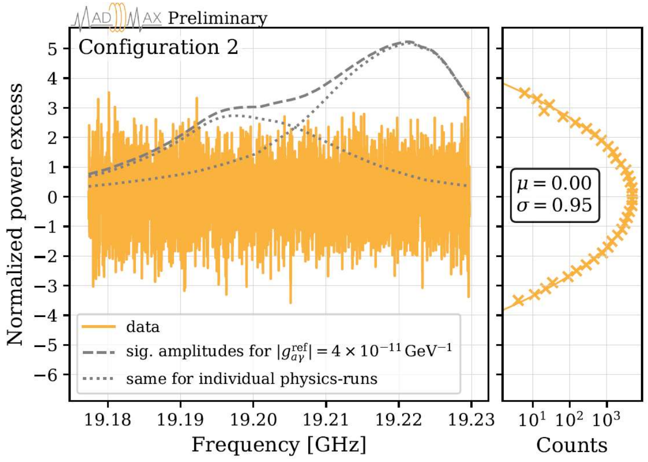
T_{sys} = system noise temperature

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









MADMAX sensitivity

☐ Axion-photon coupling $|g_{a\gamma}|$

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

☐ Dark Photon kinetic mixing angle with photon, χ

- Assuming unpolarized Dark Photon:

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

Systematics impact on $|g_{a\gamma}|$

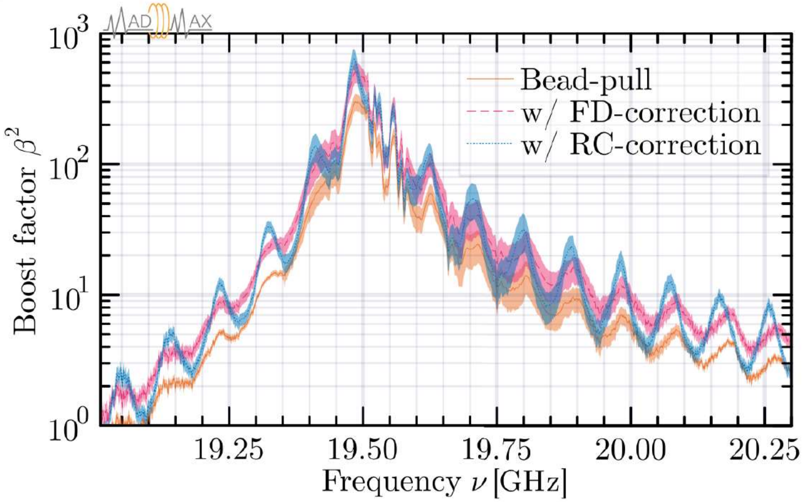
☐ Axion-photon coupling $|g_{a\gamma}|$

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

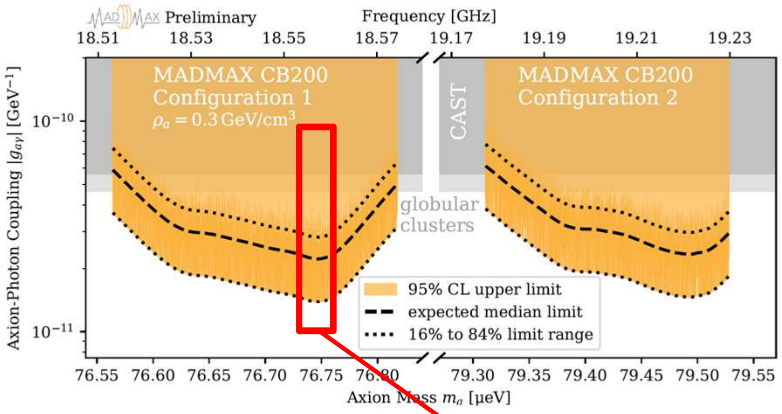
boost factor

☐ Dark Photon kinetic mixing angle with photon, χ

Effect	Uncertainty on χ
Boost factor determination (frequency dependent)	
Bead-pull measurements	2 to 17%
Bead pull finite domain correction (FD)	5%
Receiver chain impedance mismatch (RC)	<1%
Y-factor calibration	4%
Power stability	3%
Frequency stability	2%
Line shape discretization (9 kHz bin)	4%
Total	9 to 19%

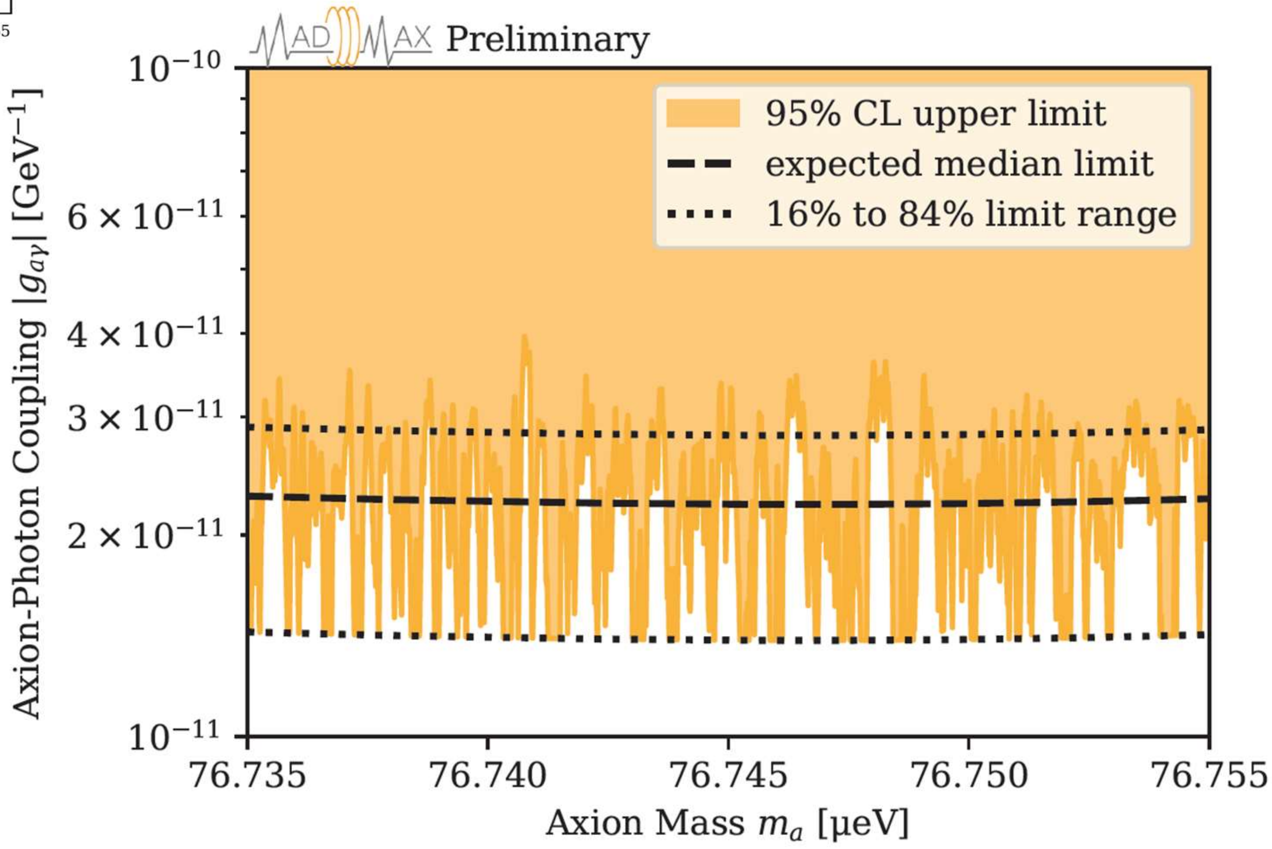


Axion limit



Zoom

(bins of ~0.9 kHz)

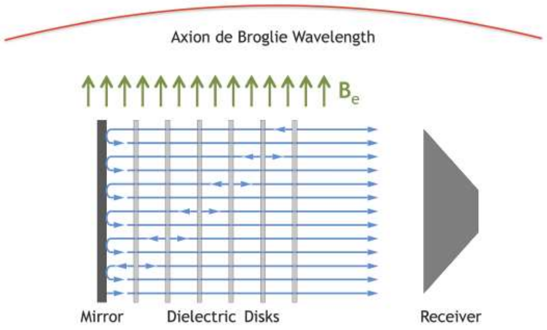


Directionality with MADMAX

1707.04266
1806.05927

- « Search / Discovery » mode = MADMAX with 80 disks

As DM is highly non-relativistic ($v_a \sim 10^{-3}$), the associated De Broglie wavelength is large, i.e. larger than the detector with 80 disks



$$\lambda_{\mathrm{dB}} = \frac{2\pi}{m_a v_a} = 12.4\ \mathrm{m}\left(\frac{100\ \mu\mathrm{eV}}{m_a}\right)\left(\frac{10^{-3}}{v_a}\right)$$

- ➢ Velocity effects only important for haloscopes with a size >~20% of de Broglie wavelength
- ➢ Can be safely neglected for setup with 80 disks → Good (no model dependence of boost factor)
- ➢ Annual modulations could be detected for sufficiently long measurements

- « Axion telescope » mode → directionally sensitive to axion velocity

➔ Effects come from axion velocity in direction perpendicular to the disks (→ change in phase over the haloscope)

➔ need increased length of the device: O(1) effect if haloscope length similar to De Broglie wavelength

- → Use the same disks but increase separation between disks: from $\lambda/2$ → $3\lambda/2$, $5\lambda/2$
- → Increase the number of disks