First axion and dark photon dark matter searches with MADMAX

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

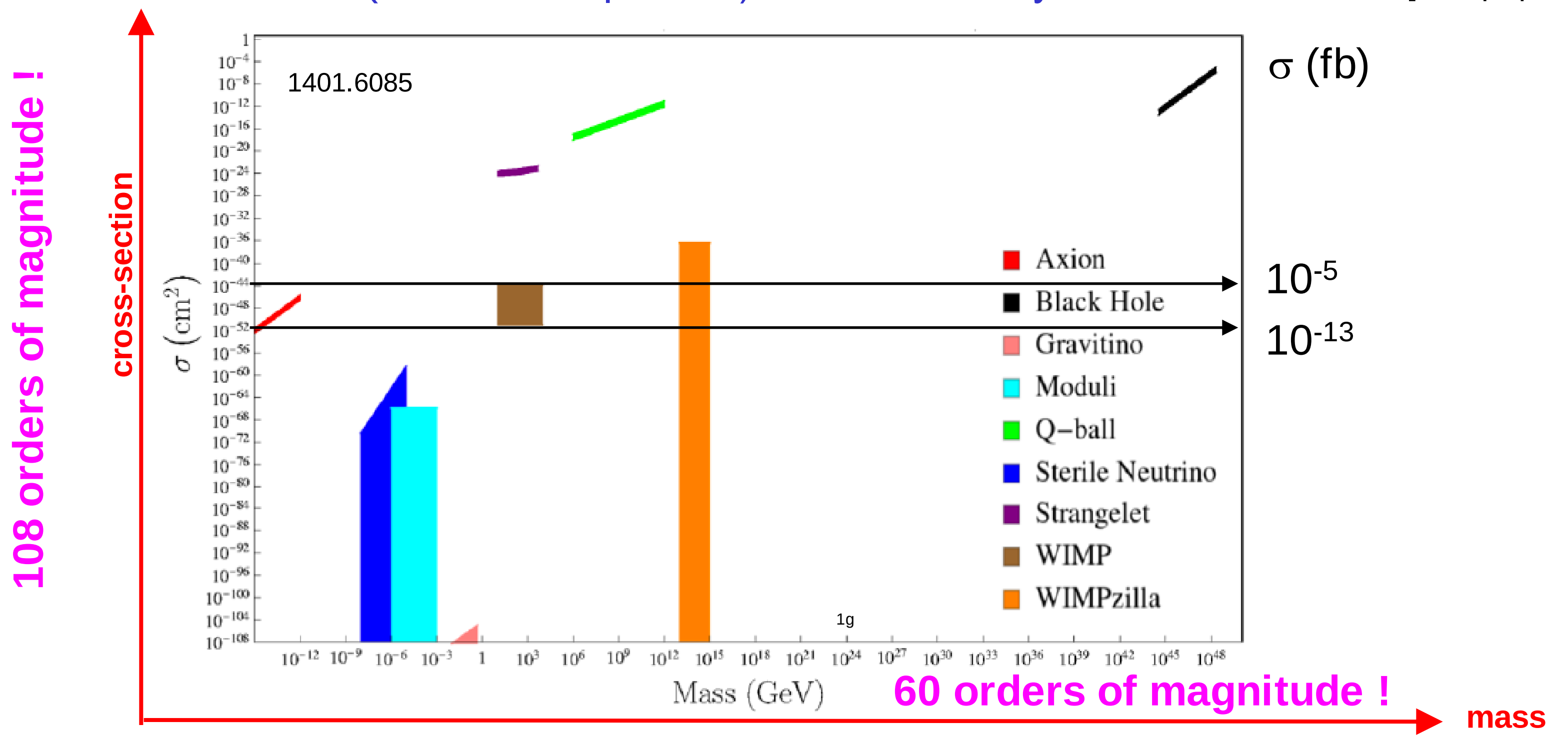
1. Scientific context
2. MADMAX, a dielectric haloscope
3. Dark matter searches with MADMAX prototypes
4. Conclusions and outlook

CPPM, December 16 2024

Introduction

❑ Many dark matter candidates in a gigantic phase space

- No known particle within the SM of particle physics has the required properties to be cold DM
  → all candidates (new **stable** particle) come from Beyond SM theories…[except primordial black holes]



- …but only a few of them are **also strongly motivated by particle physics**, i.e. solving current theoretical SM problems → **WIMP** *(hierarchy pb)*, **Axion** *(~no CP violation in strong interaction)*

[lightest sterile N (neutrino masses and mixing), but only indirect search through X-ray emission line $N \to \nu\gamma$, $E_\gamma = m_N/2$]

(Very short) Theoretical motivations

- **CP violation in strong interaction**? (observed since 1964 in weak interactions)
  - CP-violating term in QCD Lagrangian (controlled by **Θ**) is allowed and **should exist**
  - … but **|Θ|< 10^{-10}** is measured from neutron electric dipole moment

➔ Strong CP Problem = naturalness problem. Why is |Θ| so small ?

(Very short) Theoretical motivations

- **CP violation in strong interaction**? (observed since 1964 in weak interactions)
  - CP-violating term in QCD Lagrangian (controlled by Θ) is allowed and **should exist**
  - … but **$|\Theta| < 10^{-10}$** is measured from neutron electric dipole moment

➔ Strong CP Problem = naturalness problem. Why is $|\Theta|$ so small ?

- **Solution to Strong CP problem** **➔ Axion**
  - Mechanism: new global U(1) symmetry *(Peccei-Quinn, 1977)* spont. broken at scale f_a
    - ➔ Can occur before or after inflation → cosmological implications
  - Consequence: pseudo-Goldstone boson of the theory = **axion** *(Weinberg-Wilczek, 1978)*
    - ➔ Properties are all known given the scale of symmetry breaking f_a [$f_a \gg f_{EW}$]
    - ➔ Tiny mass [$m_a \approx m_\pi f_\pi / f_a \ll$ eV], very weakly interacting [suppressed by f_a] and $\tau_{axion} > t_{Universe}$
  - Cold dark matter: non-thermal massive axion at $T \sim \Lambda_{QCD}$

➔ Axion = DM candidate motivated by particle physics since 40 years

Remark: ALP (Axion Like Particle) = pseudo-scalar not solving strong CP problem but potential DM candidate

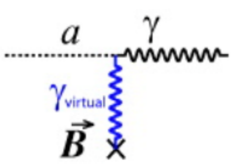
Axion direct searches

Lab experiments	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. (Baby)IAXO**	**e.g. MADMAX**

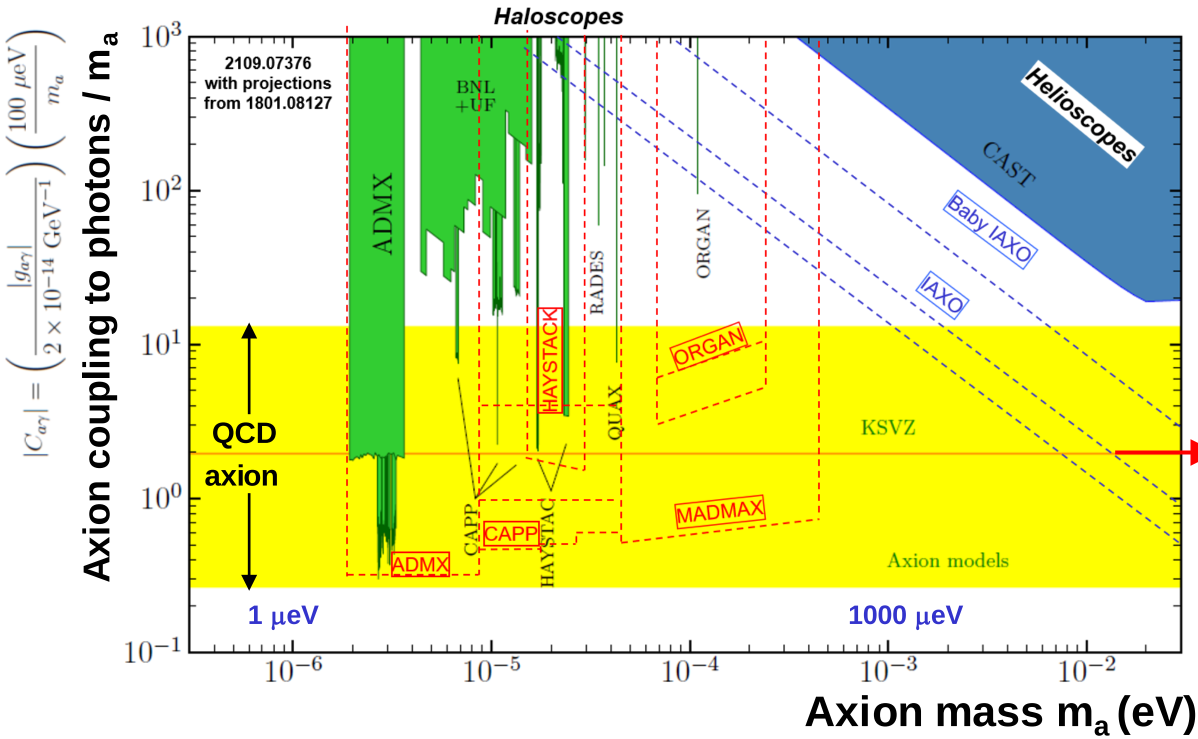
➔ Complementarity of 3 experimental approaches (e.g. DESY axion hub)

DM axion search: status / prospects

❑ Haloscopes = main way to search for Dark Matter axion



Primakoff effect aγ*→γ



Haloscopes

Published

Prospects

Yellow band: benchmark models for **QCD-axion**

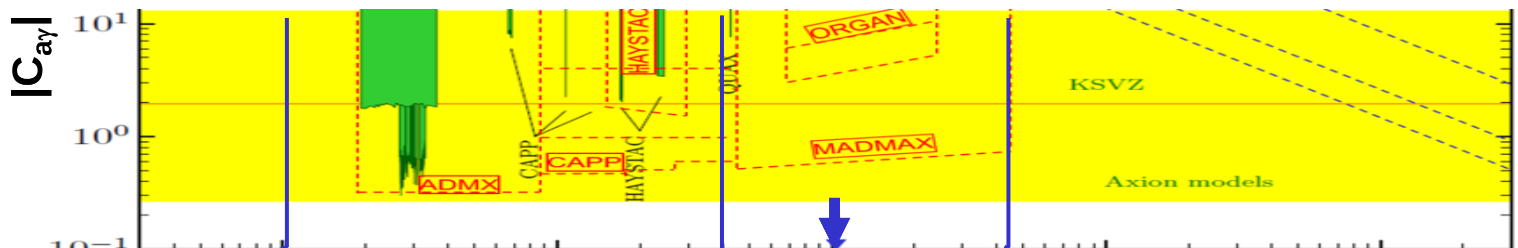
- Only very few experiments currently probe a (very small) part of the QCD axion phase space
- Vast R&D program to improve signal sensitivity and expand range of axion mass search

➔ Rising interest (techno improvements + LHC/WIMP results) : next decade promising

DM axion search: how?

❑ Experimental challenges for haloscopes

- Convert axions into photons *[E field of O($10^{-12}\cdot\frac{B}{10\,T}$) V/m]* ➔ **high B_{field}** *[B >> 1T]*
- Boost E_{field} *[up to detectable P~10^{-22} W]* ➔ **resonant** set-up or **large** area
- Scan over range of axion mass ➔ **tunable** set-up *[precision mechanics]*



100 μeV

m_a (eV)

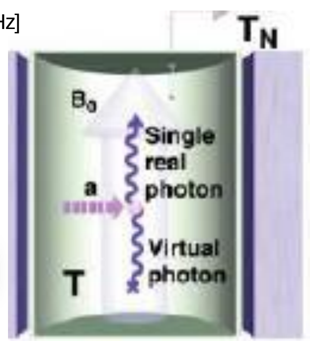
1 μeV [0.25 GHz] **40 μeV** [10 GHz] **400 μeV** [100 GHz] [$\nu_a = \nu_\gamma$]

→ RF / Microwave regime

Cavities

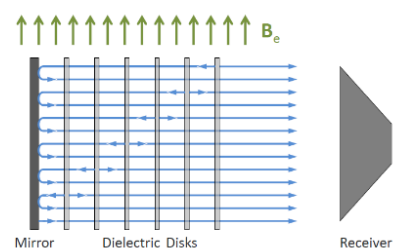
[baseline concept **1983**]

PRL51 (1983) 1415



- ➢ **Very high B**
- ➢ **Quantum noise limit**
- ➢ **Higher Q**
- ➢ **Multi-cavities**

Cavity too small + high noise



MADMAX

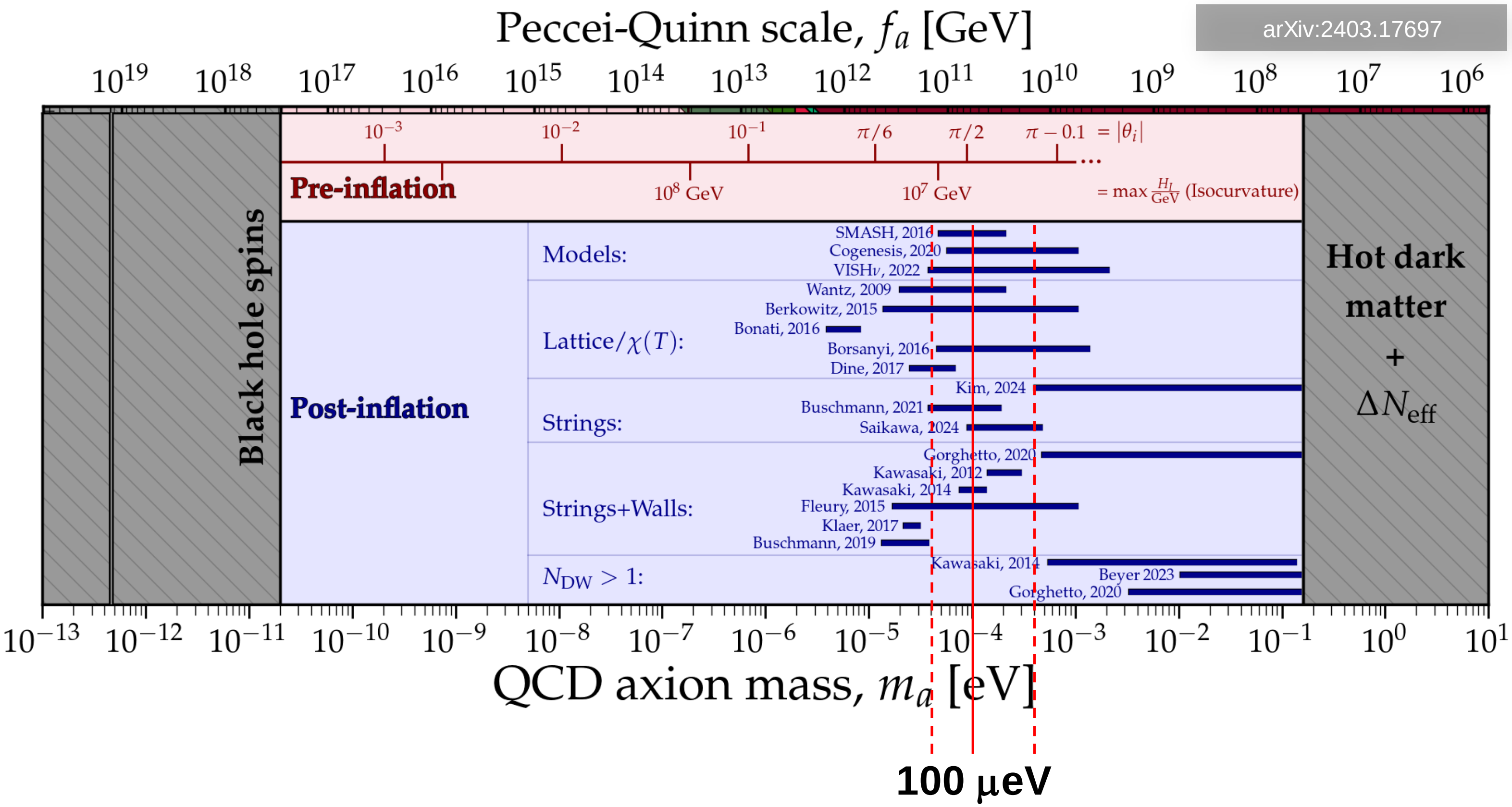
e.g. Dielectric haloscopes

[novel concept **2013**]

PRD88 (2013) 115002

DM axion search: where?

- m_a can be computed in post-inflationary scenario



➔ MADMAX can probe the favored post-inflationary range m_a ~ O(100) μeV

MADMAX (1/2)

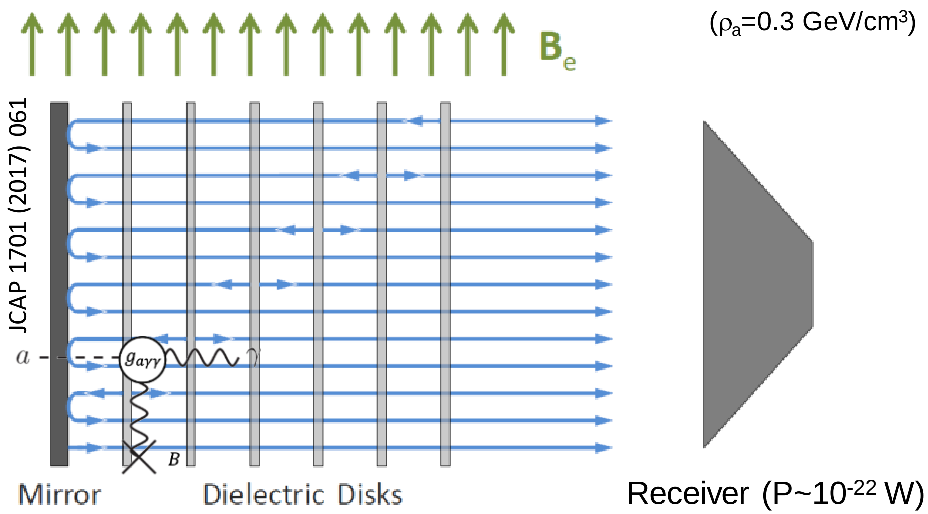
White Paper [EPJC 79 (2019) 186, 1901.07401]

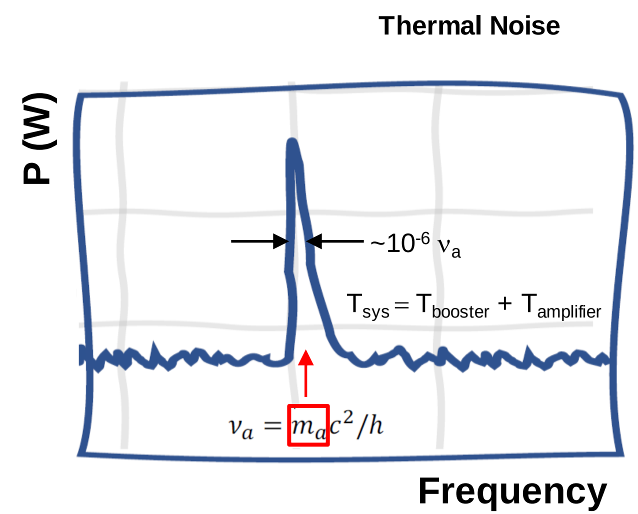
❑ A novel experimental concept: dielectric haloscope

- **Constructive interference** of coherent EM waves emitted at dielectric layer surfaces + **resonant** enhancement (~leaky resonant cavities) : boost (β^2) signal wrt mirror only

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

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





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

➔ MADMAX exploits a novel exp. approach to cover an uncharted phase space

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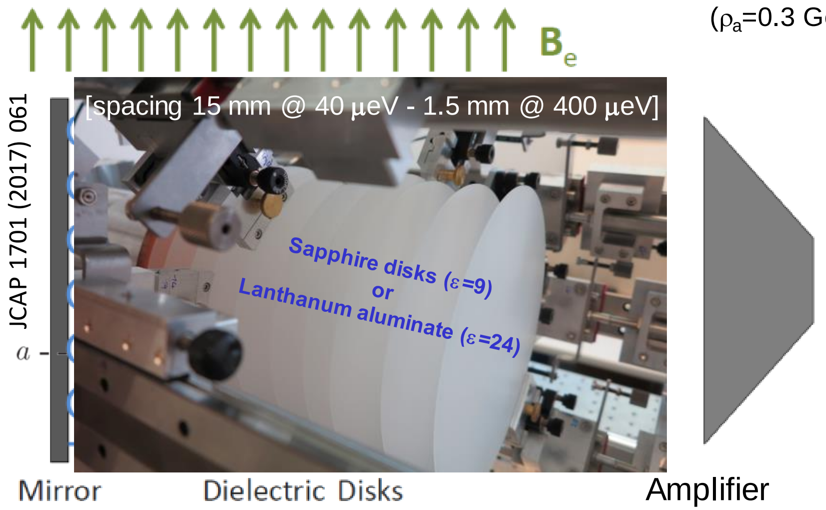
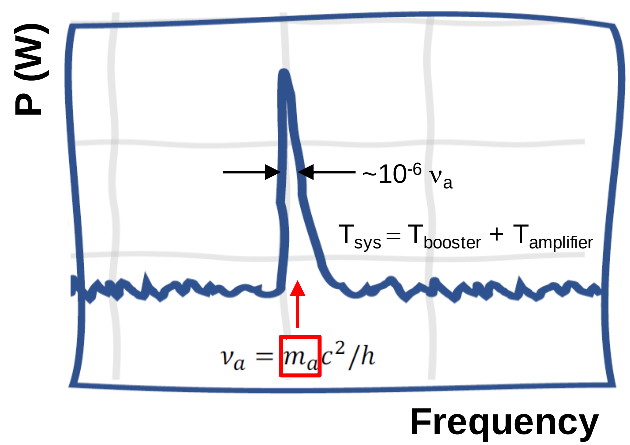
(ρ_a=0.3 GeV/cm^3)



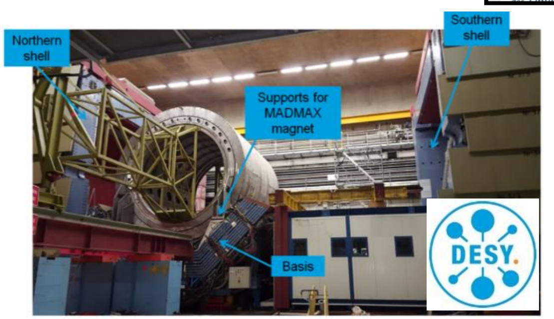


- **Axion mass scan** : move discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

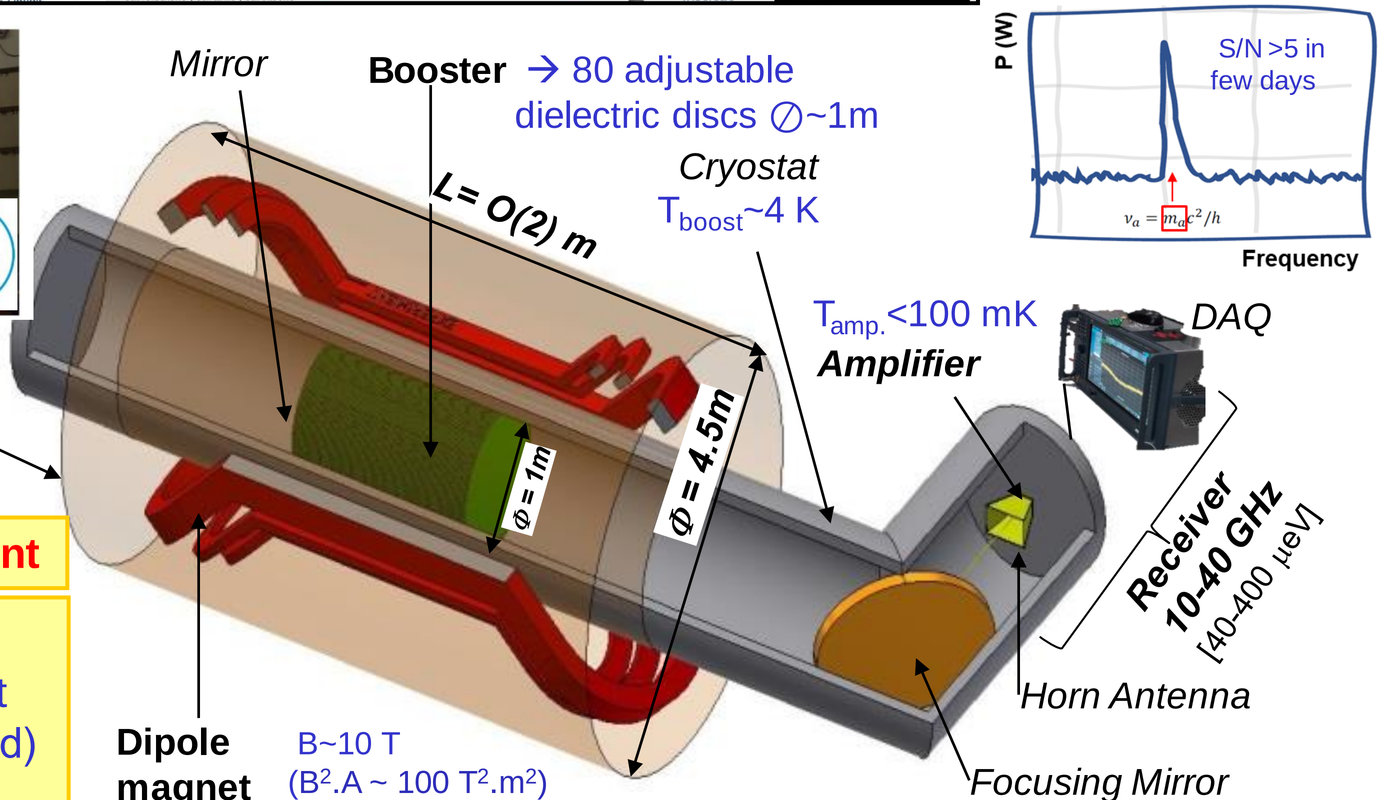
➔ MADMAX exploits a novel exp. approach to cover an uncharted phase space

MADMAX (2/2)

Formed in 2017. 11 institutes: French (3), German (6), Spanish (1) and US (1) → ~50 people



Experiment location: HERA in former H1 iron yoke



1^{st} generation experiment

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

→ Start with prototyping phase to validate concept: cutting-edge R&D

Prototyping phase strategy

- **Address the two main challenges to develop booster concept**
  - Calibrate Radio Frequency (RF) response in O(10) GHz regime
  - Move the disks at μm level precision at cold and under high B-field

Name	Goal	Booster	Disks (1 mm thick)	Test
CB100	RF studies + First axion 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 axion @ 80 μeV*	*Open*	*3-20,* ***moveable*** *ϕ = 300 mm*	***26-28***

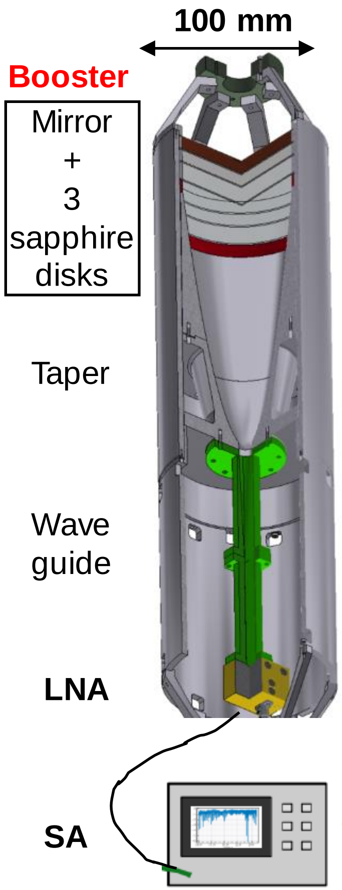
*Dark Photon

Room Temp.
Cold (10 K)
Bfield
Prospects

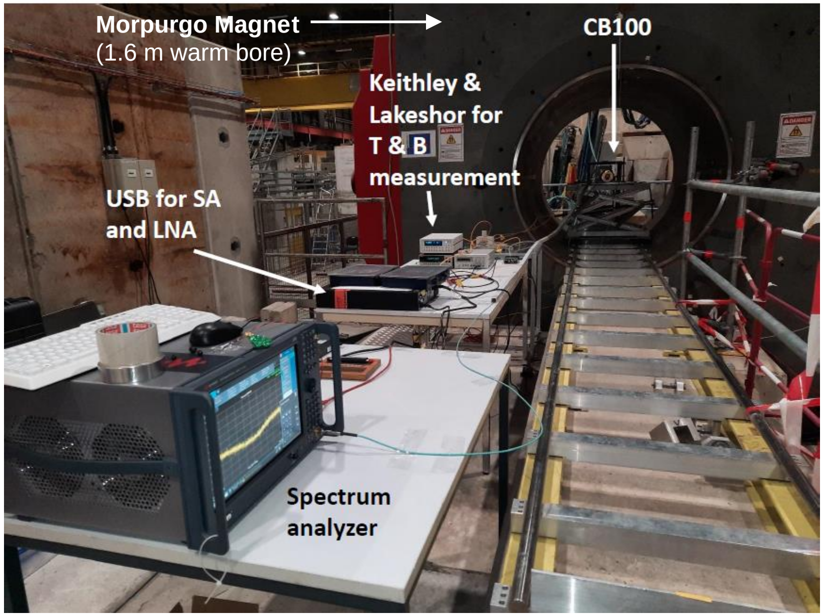
➔ **Gradually build the final booster design + do physics**

Preparatory work

Room Temp.
Cold (10 K)
Bfield
Prospects



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

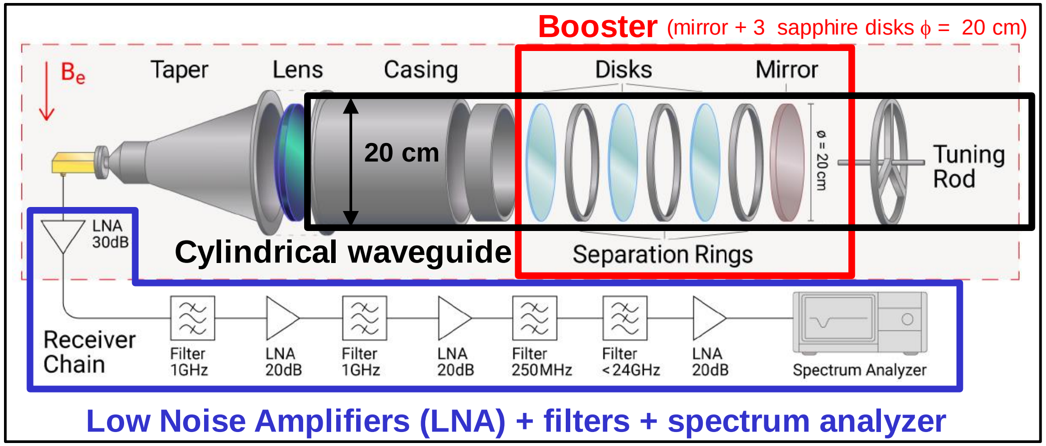


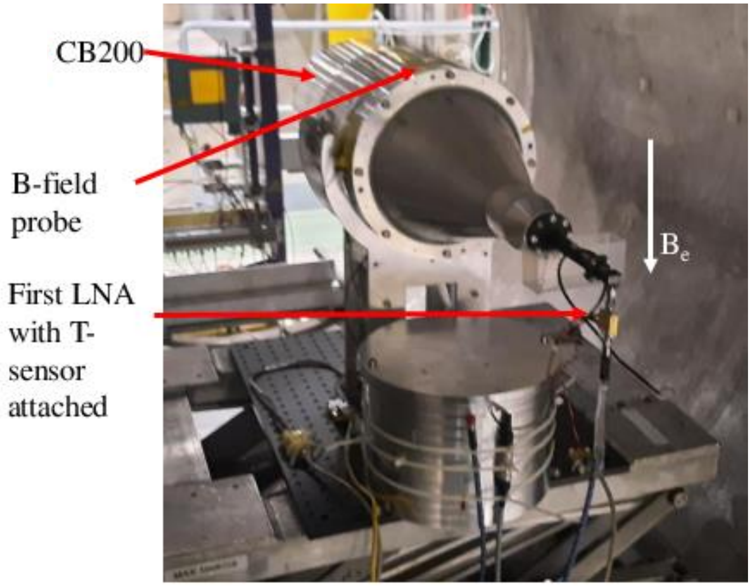
- CERN refurbished the area and the magnet for MADMAX
- Checked that no RF interference with CERN environment
- Checked stability of data taking @19 GHz, 1.6 T: $t_{Live} \propto 1/\sigma_{Noise}^2$
- Calibrated @10% receiver chain power: $P \propto T_{sys} = f(\Gamma_{RC}, G, \nu)$

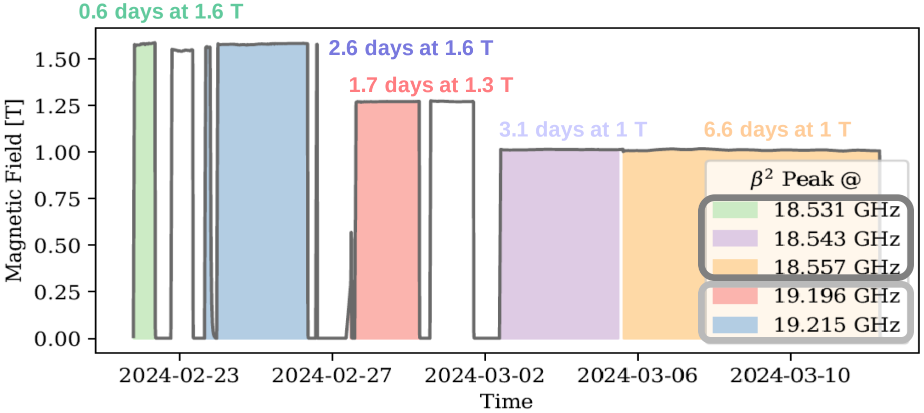
➔ Validated that CERN environment suited for prototype tests

MADMAX search for axion (1/5)

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

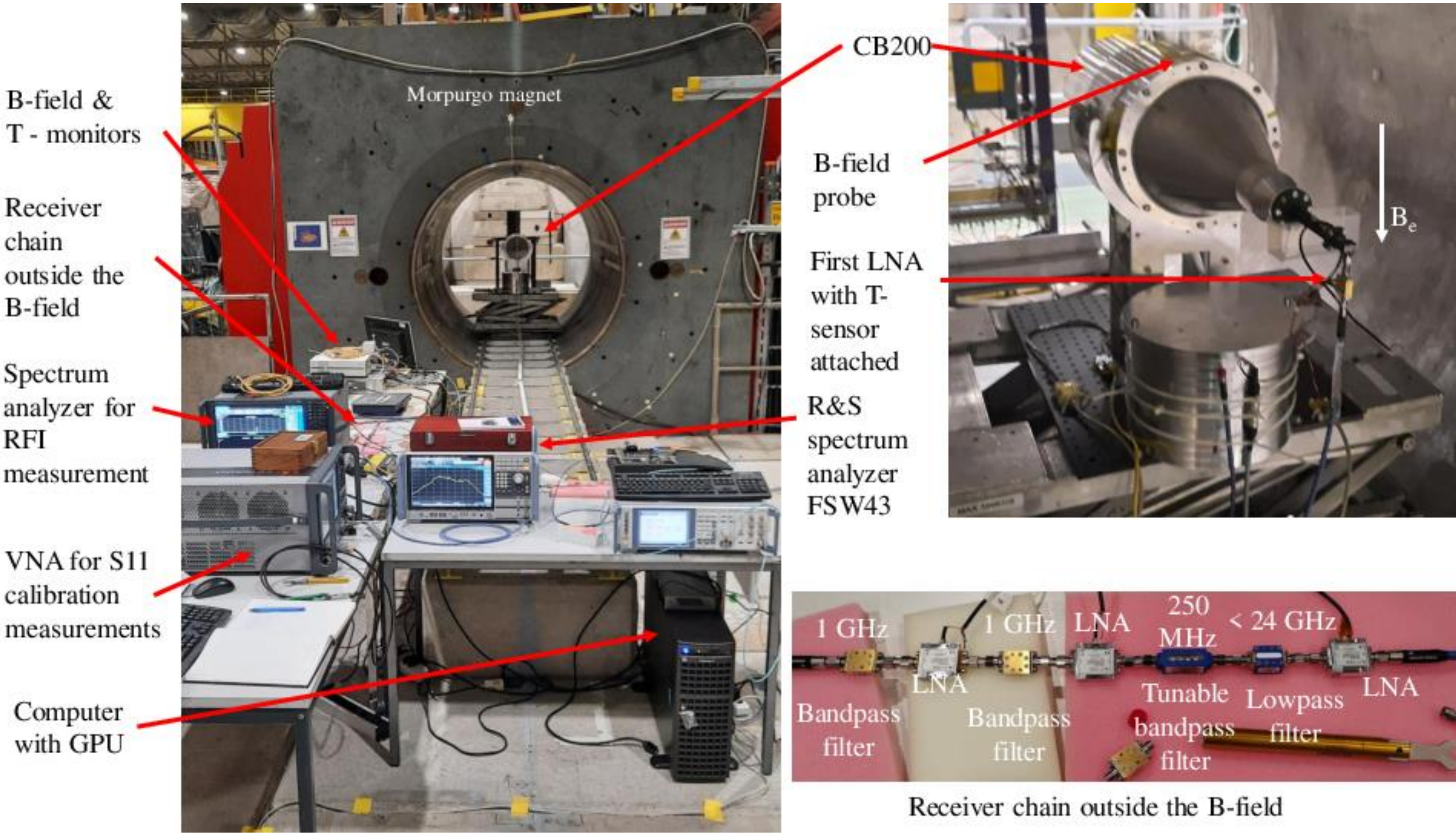






- Booster peak tuned at 2 frequencies ~18.5 and 19.2 GHz [manual change of disk distances by ~0.5 mm with separation rings]
- O(10 MHz) variations around them [O(10 μm) mirror move through tuning rod]
- 14.5 days of data at B=1 to 1.6 T

MADMAX search for axion (1'/5)



Receiver chain outside the B-field

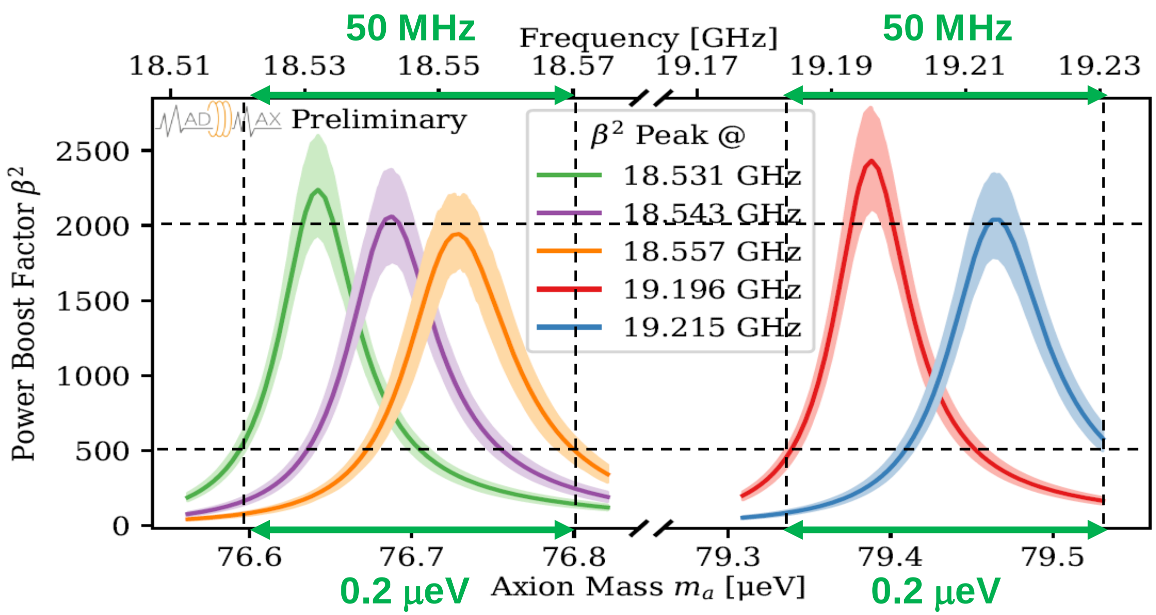
MADMAX search for axion (1’’/5)

MADMAX search for axion (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% systematic uncertainties

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



Demonstrating the scanning capacity of MADMAX booster

MADMAX search for axion (3/5)

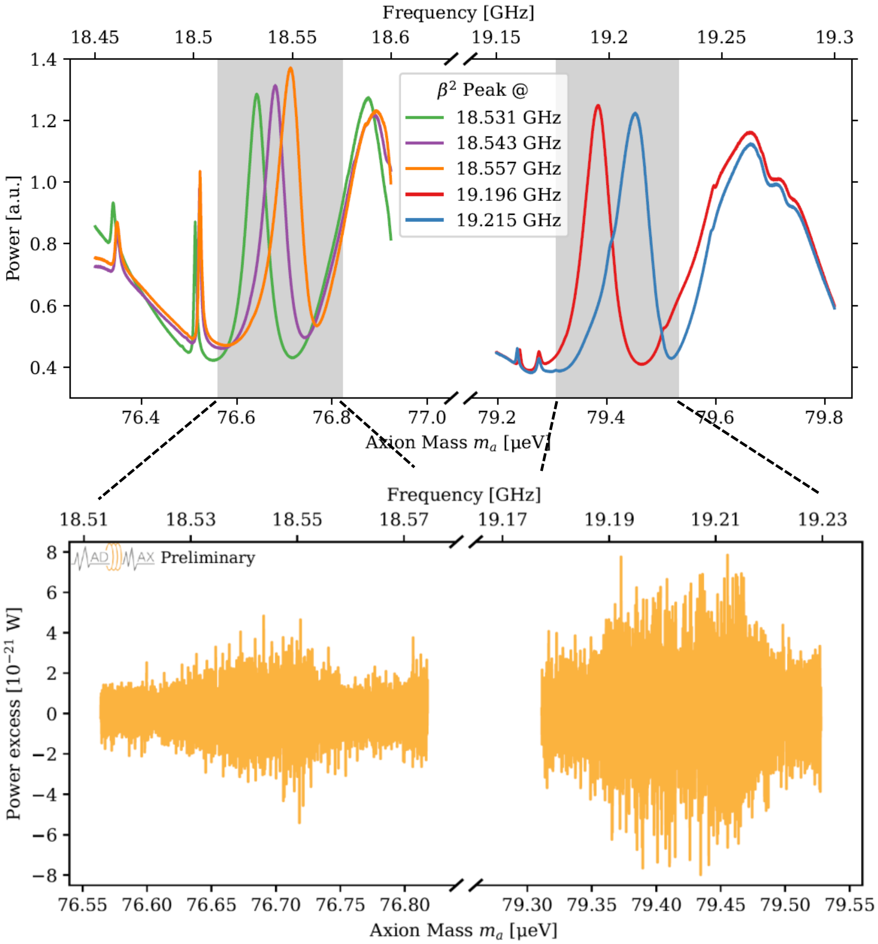
❑ Power spectra data analysis *(based on HAYSTACK procedure, PRD 96 (2017) 123008)*

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

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

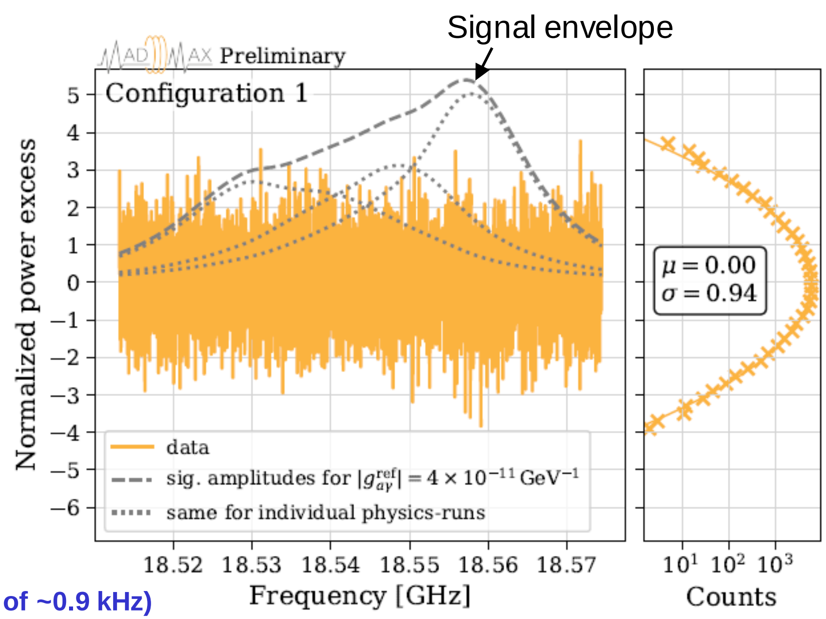
- Combine residual spectra (thermal noise) → optimising SNR (using power calibration to W) & cross-correlating with axion lineshape

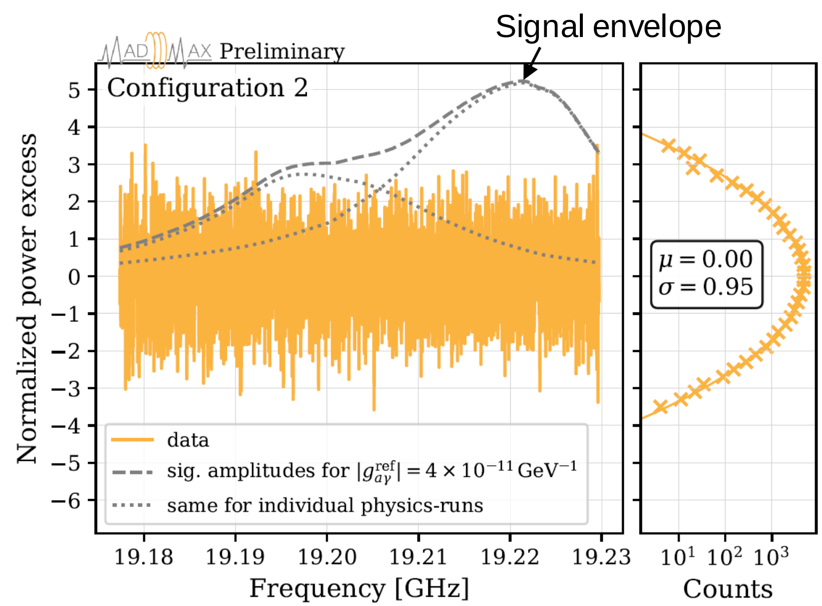
➔ Sensitive to axion signal power of O(10^{-21} W)



MADMAX search for axion (4/5)

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

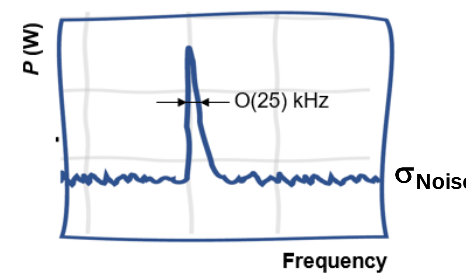




(bins of ~0.9 kHz)

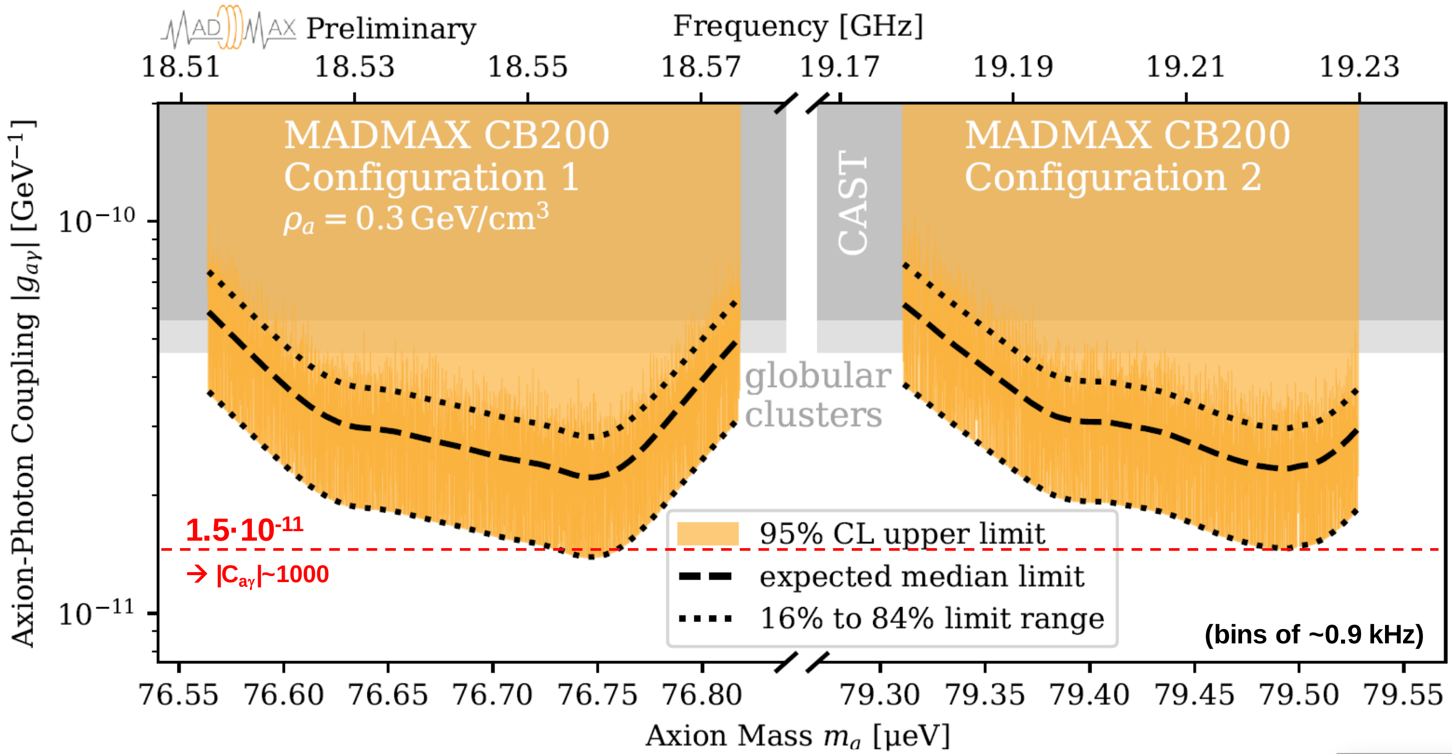
σ<1 due to SG filter effects

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



MADMAX search for axion (5/5)

- Limits on axion-photon coupling $|g_{a\gamma}|$ better than existing constraints by up to factor 3
- Modest system (few small disks in reduced magnetic field) with only 2 weeks data
  ➔ confirm **substantial potential** of MADMAX concept



CAST: direct search with helioscope

Globular clusters: indirect astrophysical constraint from stellar evolution

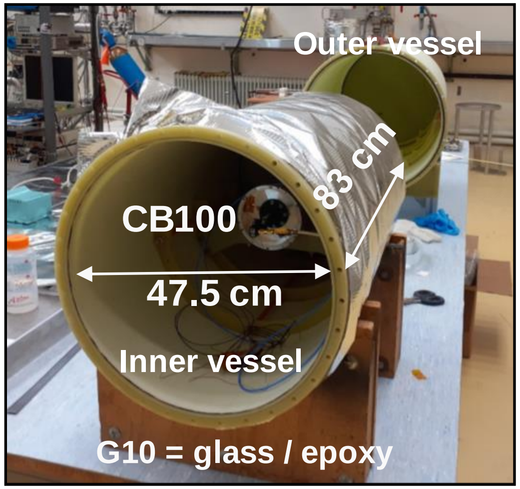
➔ **First dark matter axion search with dielectric haloscope**

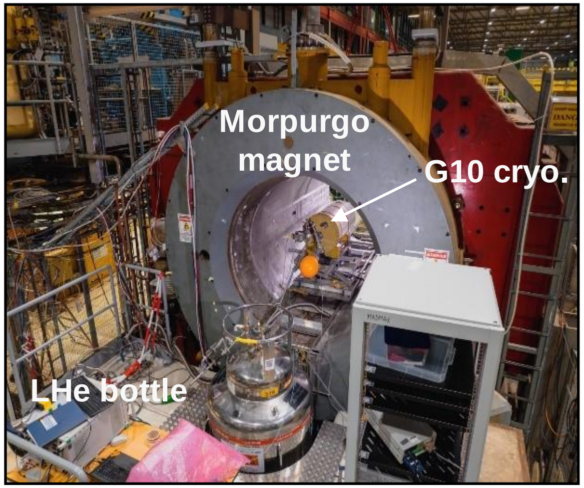
arXiv:2409.11777 (submitted to PRL)

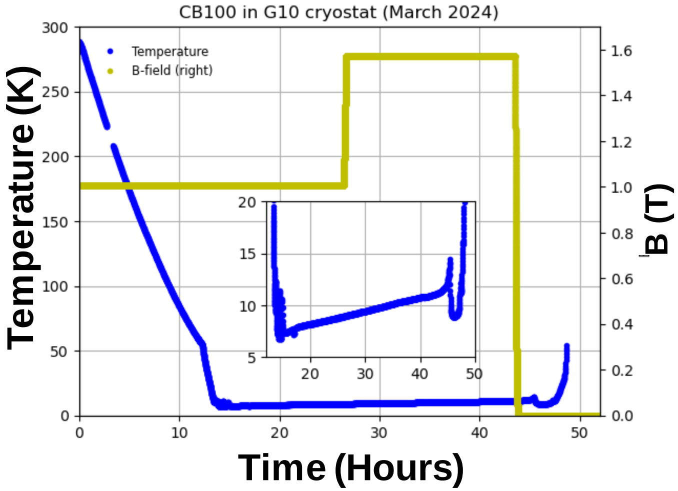
MADMAX search for axion (at cold)

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 and validated receiver chain calibration procedure at cold





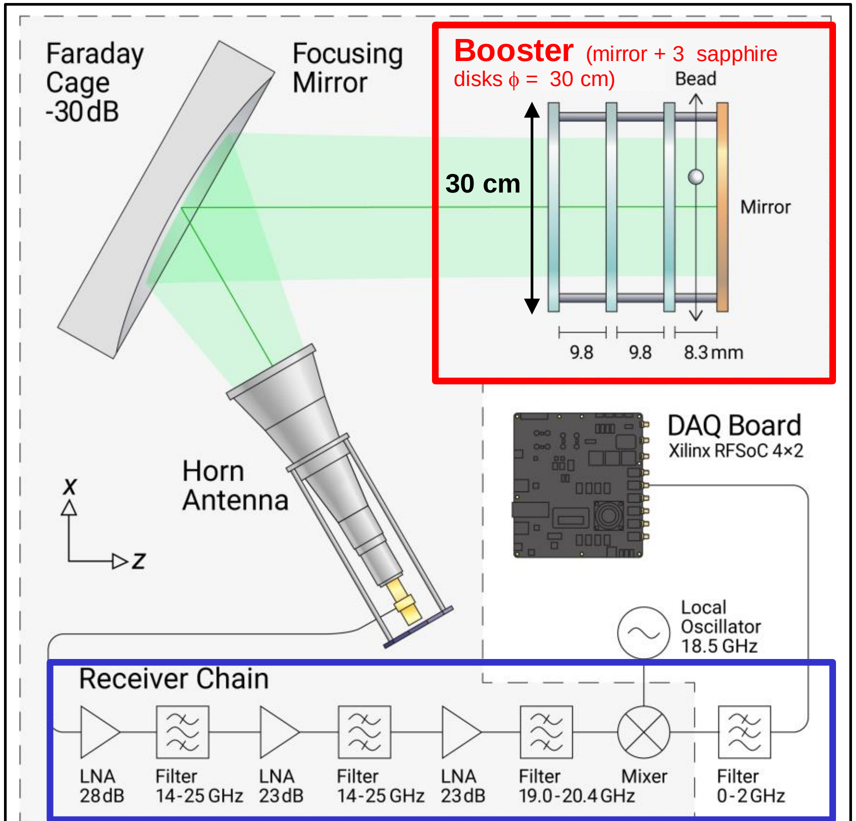


➔ First operation of a dielectric haloscope at cold under B field [3 papers in preparation]

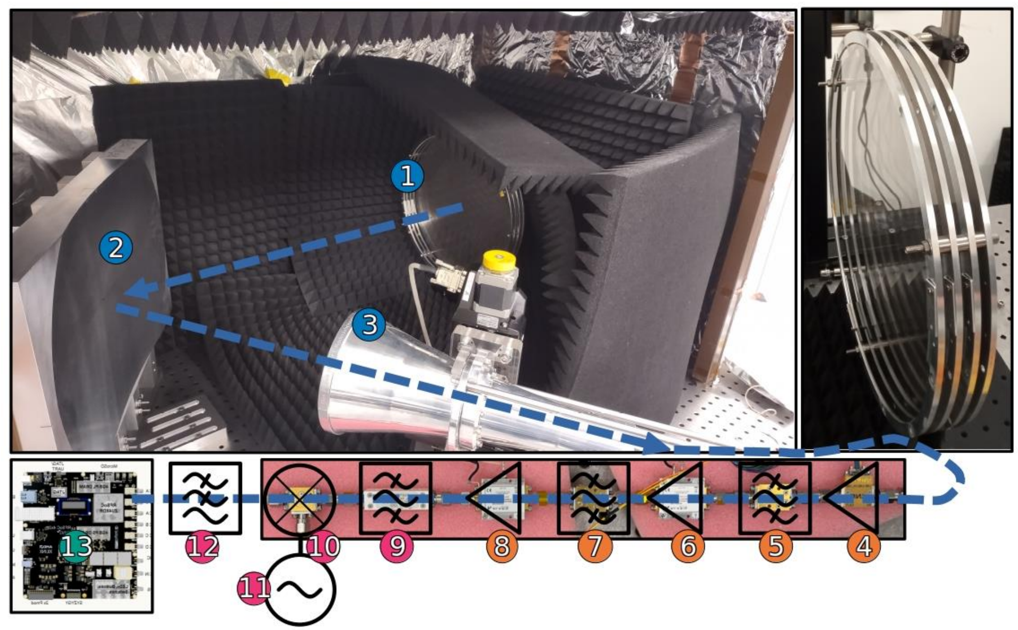
MADMAX search for Dark Photon

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

- No magnetic field ➔ Dark Photon (DP) search, with 12 days of data
- Booster peak tuned at 19.5 GHz [fixed disk spacing] ➔ m_{DP}~80 μeV



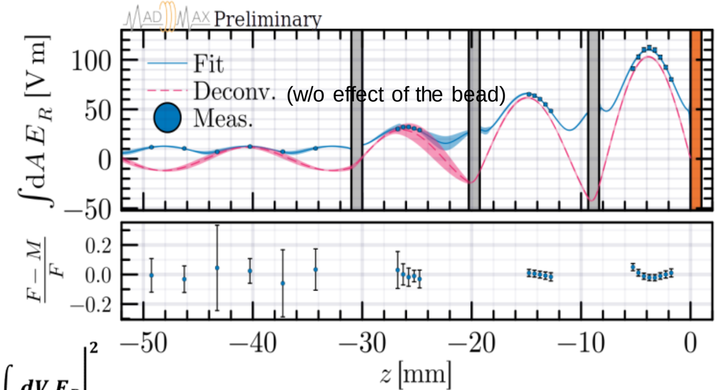
Low Noise Amplifiers (LNA) + filters + mixer

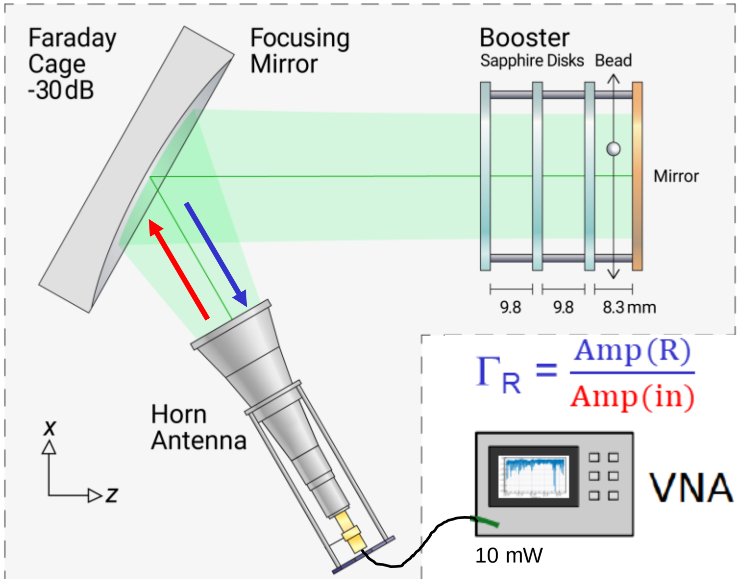


In situ determination of boost factor

- Measure change in booster reflection coefficient $\Delta\Gamma_R$ caused by small dielectric bead (non-resonant perturbation)
- Deduce reflection-induced electric field at bead position (3D scan) → $E_R(\nu,x,y,z) \propto \sqrt{\Delta\Gamma_R(\nu,x,y,z)}$
- Deduce boost factor $\beta^2(\nu)$ through Lorentz reciprocity approach, relating EM fields of 2 different sources

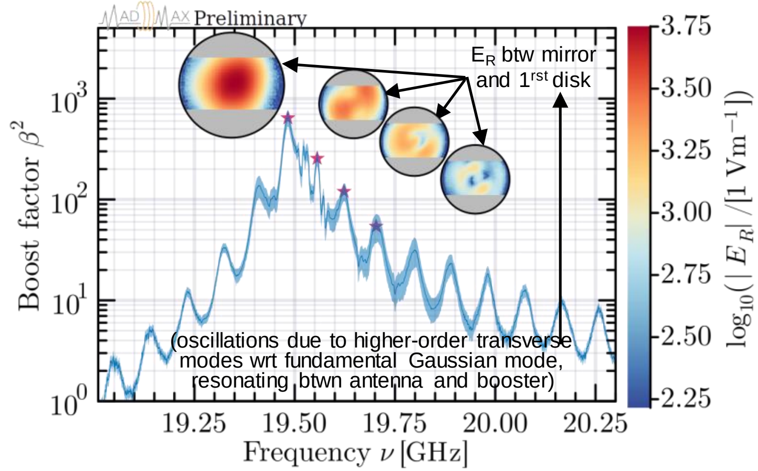
JCAP 04 (2023) 064 | JCAP 04 (2024) 005 | arXiv:2408.02368 (submitted to PRL)





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

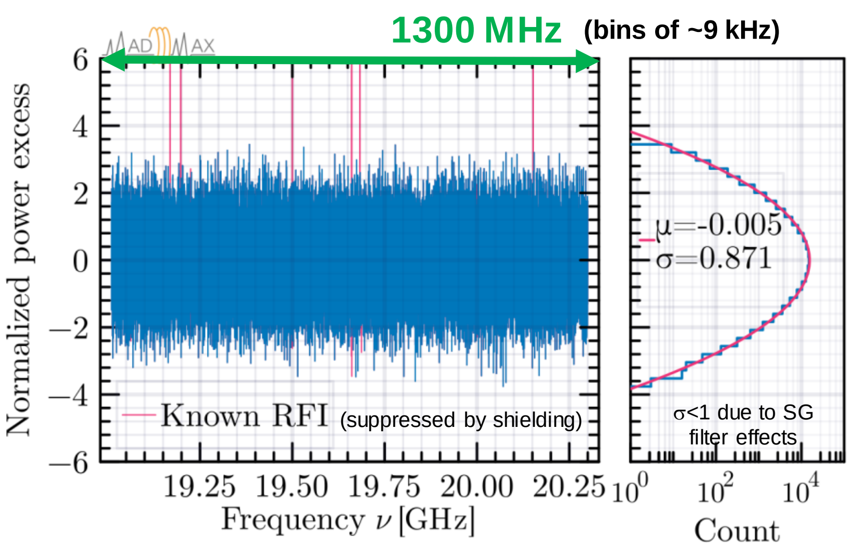
$$\beta^2 \propto \left| \int dV\, E_R \right|^2$$

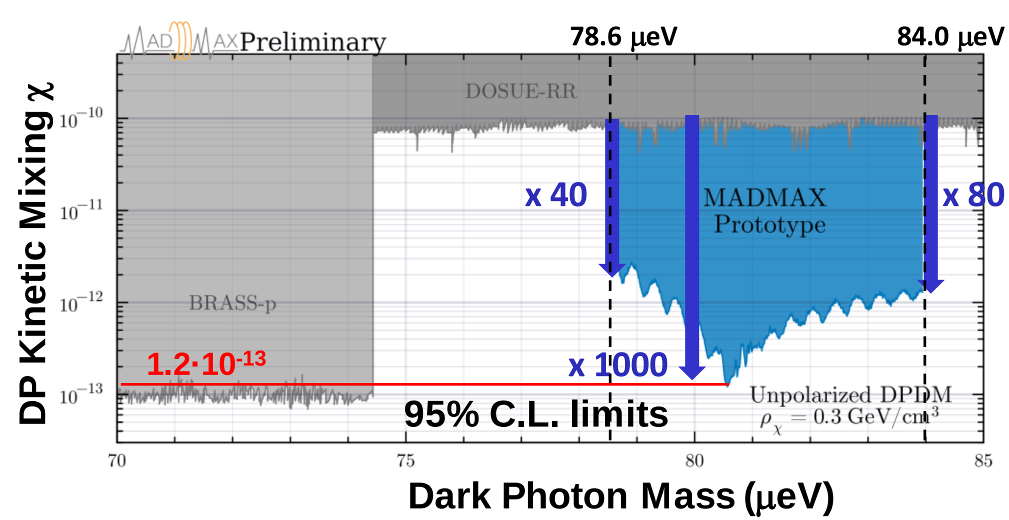


→ Developed bead-pull method to measure β^2 and its uncertainties

MADMAX search for Dark Photon

- Boost factor $\beta^2(\nu)$ measured with ~15% errors ➔ β^2_{peak}~640 extending on 1.3 GHz
- No signal of unknown origin ➔ limits on kinetic mixing **κ** between photon and DP
- Limits better than existing limits in m_{DP} [78.6, 84.0] μeV by up to factor 1000
- Modest system (few small disks) with only 12 days of data
  ➔ confirm **substantial potential** of MADMAX concept (resonant and broadband)



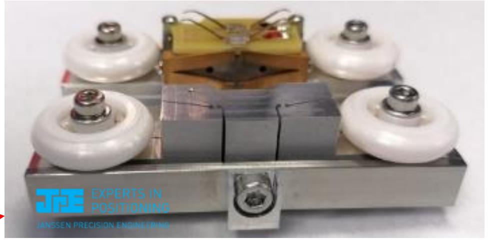


➔ First dark matter DP search with MADMAX prototype

arXiv:2408.02368
(submitted to PRL)

Tuneable setup: move the disk

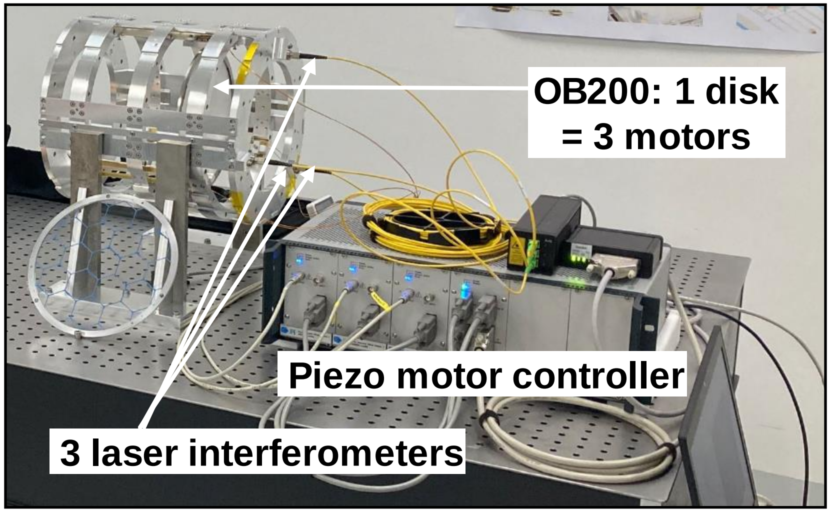
Name	Booster	Disks	Test @CERN
OB200	Open	1, **moveable** ϕ = 200 mm	2022, **22**

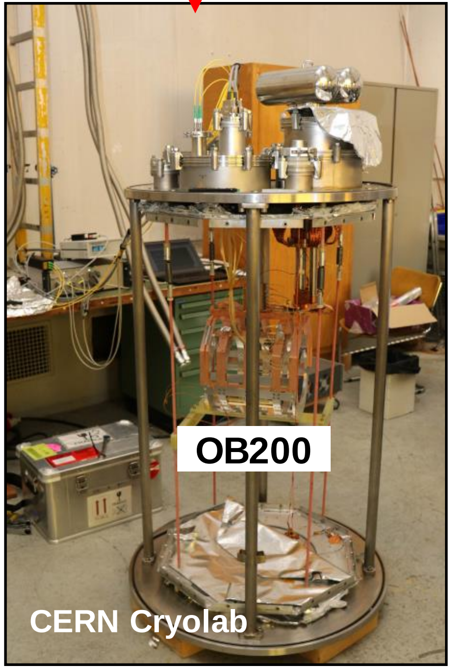


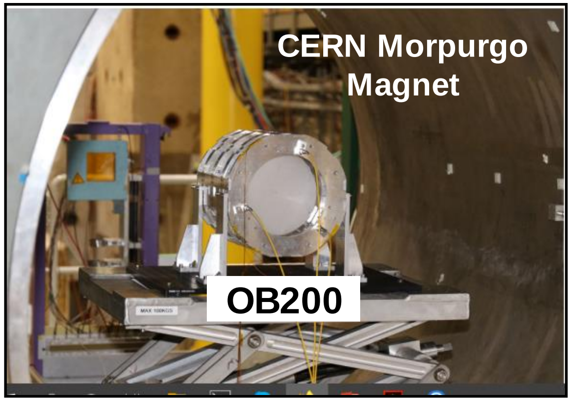
- 2021: Successful test of 1 piezo motor at 5 K and 5.3 T (ALP magnet in DESY)

JINST 18 (2023) P08011

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





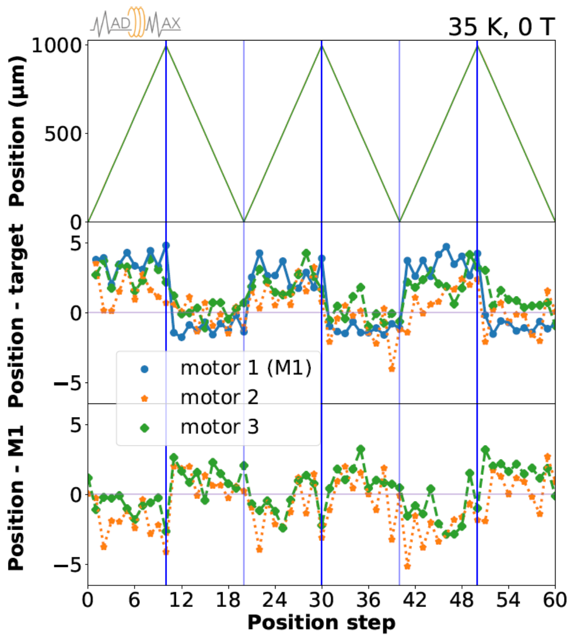


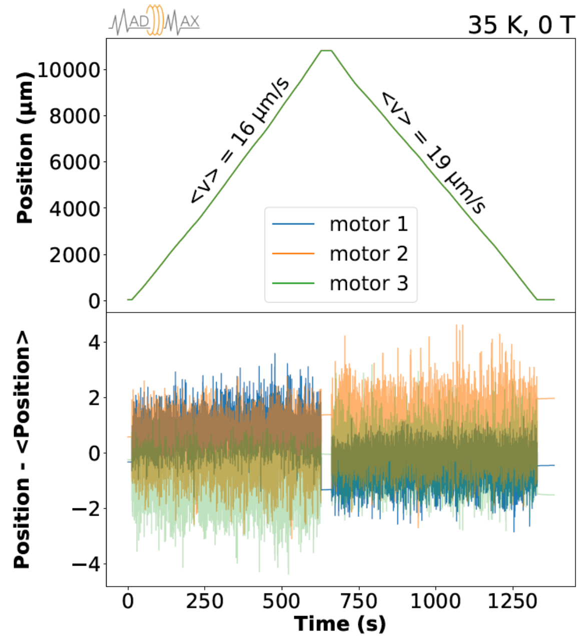
Tuneable setup: move the disk

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

Room Temp.
Cold (10 K)
Bfield

Motors positioned at 5 μm





Disk speed >15 μm/s

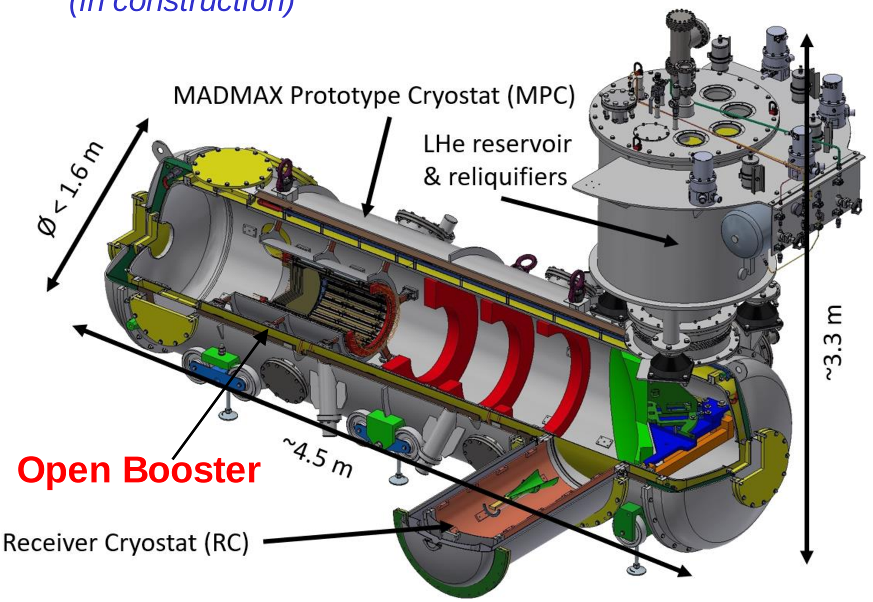
➔ Precisely move the disk at cold and in B-field
➔ Validate booster mechanics

JINST 19 (2024) T11002
(arXiv:2407.10716)

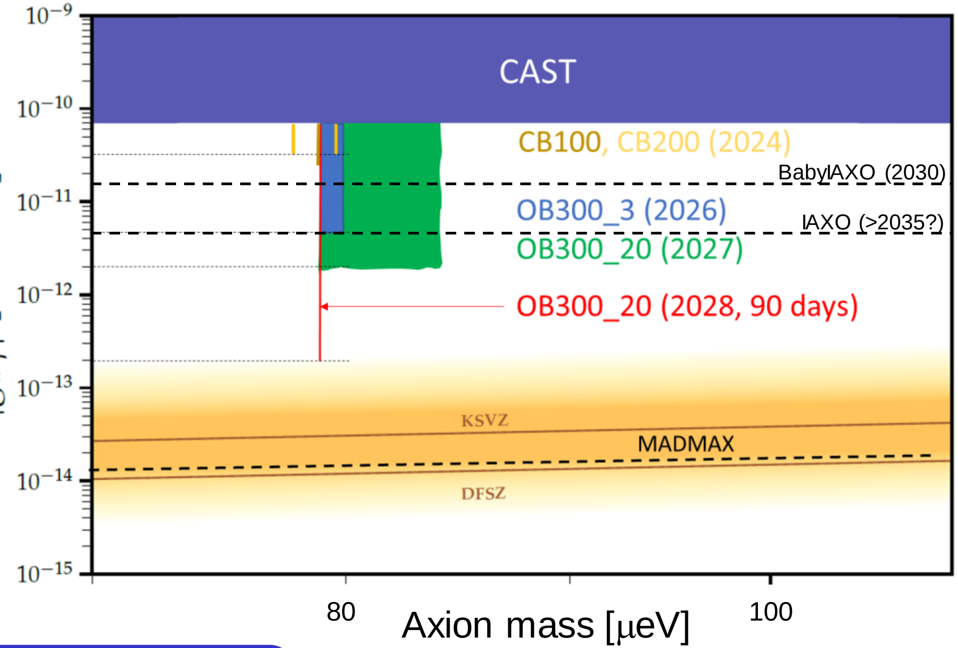
Final prototype

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)



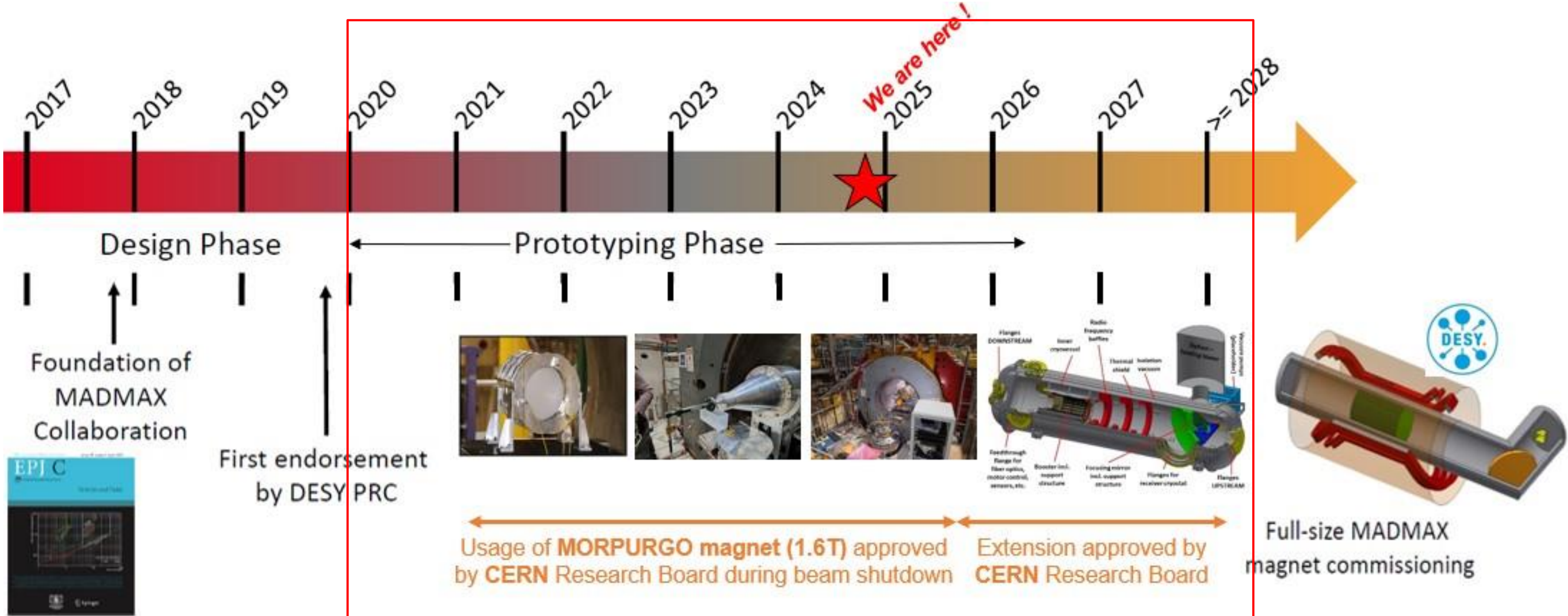
❑ Physics program during LHC shutdown



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

ANR obtained (HALOX)
→ will hire postdoc in 2025

MADMAX timescale



1000-10000   10 – 300   1.6   0.01-0.1

$$g_{a\gamma} \propto \left(\frac{50000}{\beta^2}\right)^{1/2} \times \left(\frac{T_{sys}}{4\ \mathrm{K}}\right)^{1/2} \times \left(\frac{10\ \mathrm{T}}{B_e}\right) \times \left(\frac{1\ \mathrm{m}^2}{A}\right)^{1/2} \times \left(\frac{2\ \mathrm{days}}{t}\right)^{1/4} \times \left(\frac{\mathrm{SNR}}{5}\right)^{1/2}$$

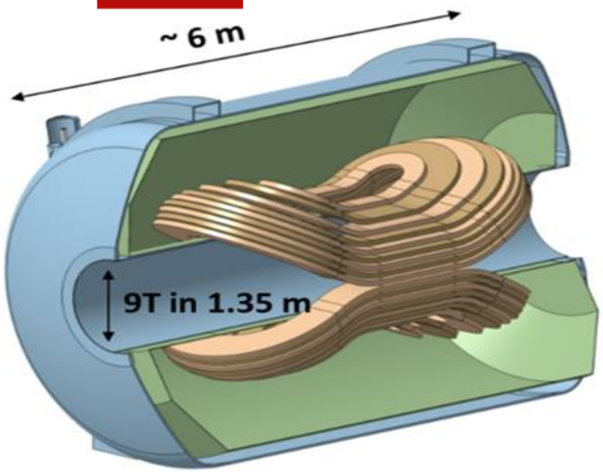
[$\beta^2 = f(N, \varepsilon)$]

Towards final MADMAX

❑ Magnet

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

[NbTi with Cu jacket @ 1.8K]



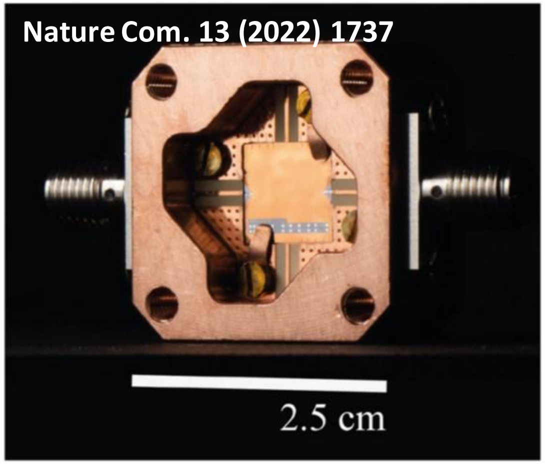
- Demonstrated that coils will be safe in terms of quench protection **IEEETAS 33 (2023) 1**
- Budget secured for a demonstrator coil → expected in 2027

❑ 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)*



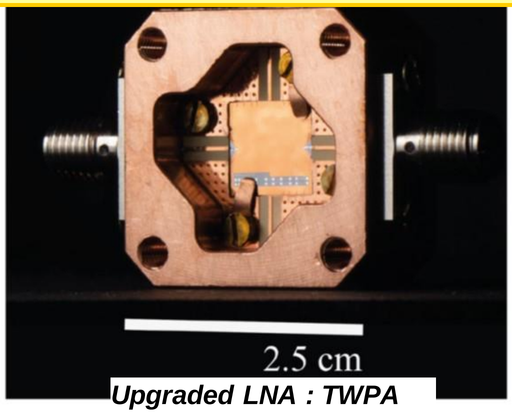
TWPA prototype with G>20 dB and 1K added noise at 10 GHz

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

MADMAX & France

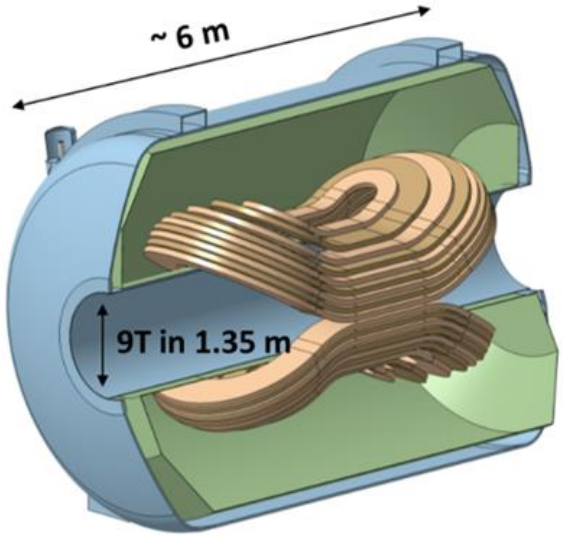
- **Outside IN2P3:** Institut Néel (INP, in MADMAX) & CEA-IRFU (innovation partner)

Final ultra-low noise amplifier



Upgraded LNA : TWPA

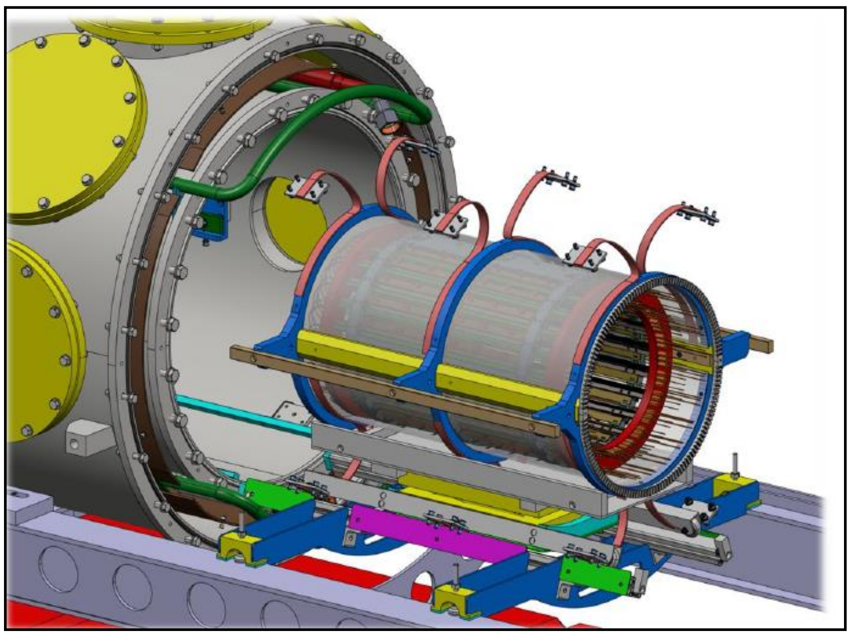
Final magnet design

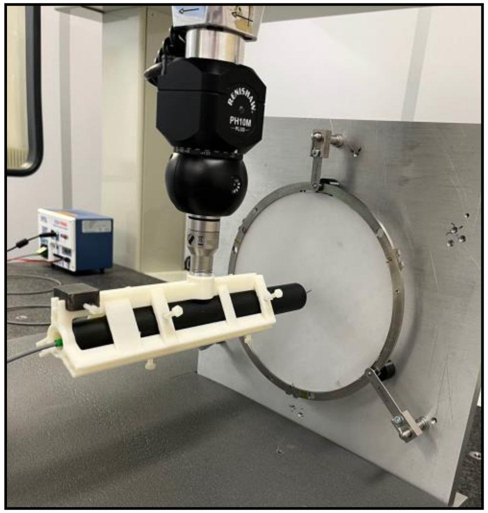


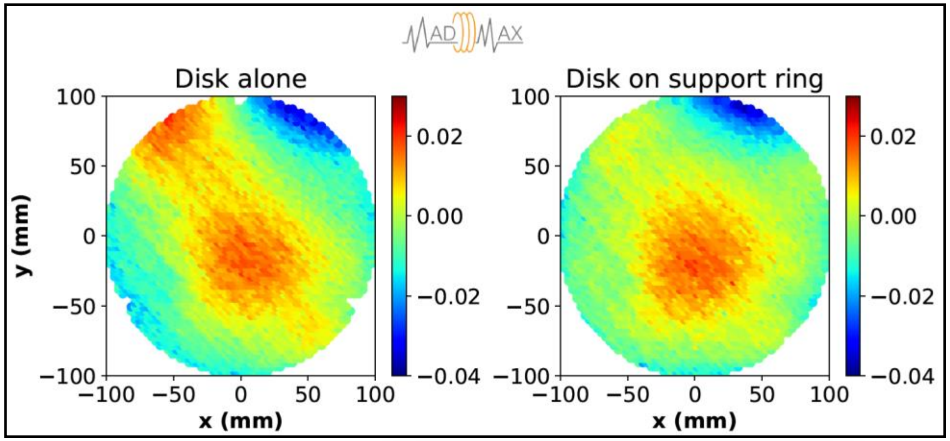
- **At IN2P3:**
  - **CPPM** joined MADMAX in 2020 (recommendations from CPPM scientific council)
  - **IJCLab**: joined MADMAX end 2023 as associate member.
  - Remark: **CNRS IRL “*DMLab*” (with Helmholtz** centers**)** → MADMAX is a central project

MADMAX & IN2P3

- Precision mechanics for the prototype boosters
- Design and tests of RF absorbers
- Coordination of prototype tests at CERN in Morpurgo magnet
- Simulation / data analysis







RMS < 10 μm

JINST 19 (2024) T11002
(arXiv:2407.10716)

Conclusions

❑ DM axion direct search: rising interest, next decade promising

- Axion = DM candidate motivated by particle physics since 40 years
- Resonant cavity sensitivity starts to scratch the QCD axion phase space (~1-10 μeV)
- Will be extended to most of the interesting mass range (10-1000 μeV) with novel experiments

❑ MADMAX = novel exp. approach to cover theory-favored phase space

- MADMAX can probe the favored post-inflationary range $m_a \sim O(100)\ \mu$eV
- Prototyping phase at CERN 2021-2028 to validate the dielectric haloscope concept
  - ➢ Validated mechanics at cold, under $B_{\mathbf{Field}}$ — 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 DP world best limits for mass ~ 80 μeV

arXiv:2409.11777 (submitted to PRL) — arXiv:2408.02368 (submitted to PRL)

➔ Pioneering experimental work at IN2P3 on DM axion search

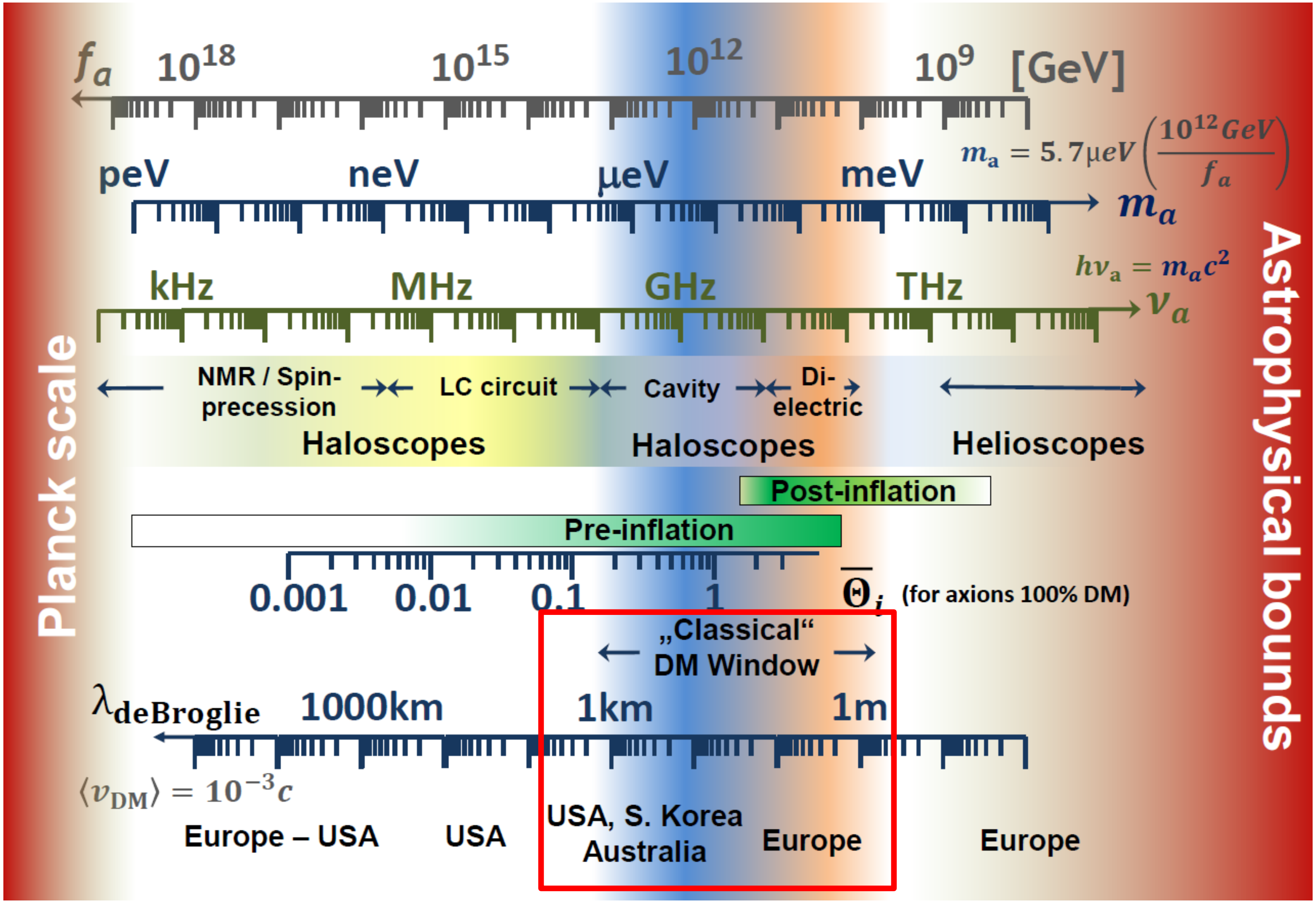
BACKUP (MADMAX)


Collab Week at CPPM (Apr 2023)

Axion scales

APPEC Committee Report

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



Axions

Axion phenomenology

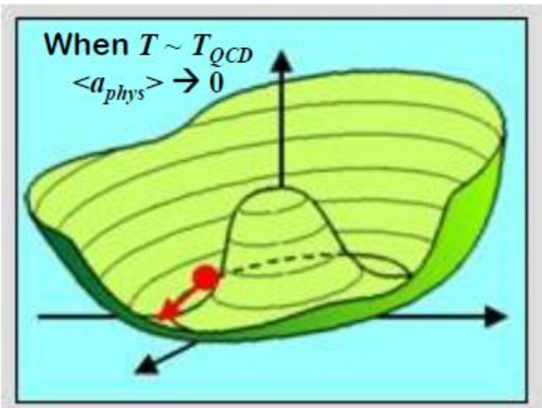
- Some phenomenology depends on the **"axion model"**, e.g.
  - KSVZ axions are "hadronic axions" (no coupling with leptons at tree level)
  - DFSZ axions couple to electrons

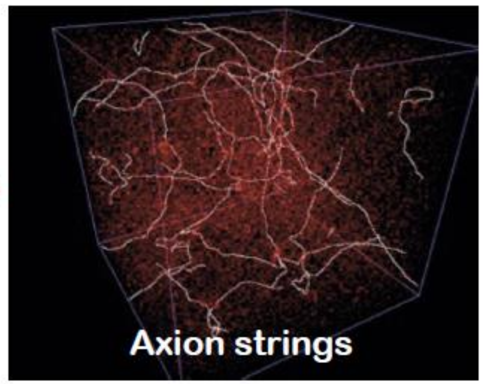
Gluon coupling	Mass	Photon coupling	Fermion couplings
$\frac{\alpha_s}{8\pi f_a} aG\tilde{G}$	$m_A = 5.70(7)\mu\text{eV} \times \left(\frac{10^{12}\text{GeV}}{f_A}\right)$	$g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$ $g_{a\gamma\gamma} = \frac{\alpha_s}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	Electron coupling Nucleon coupling ...
generic	*generic*	*generic but value model dependent*	*Model dependent*

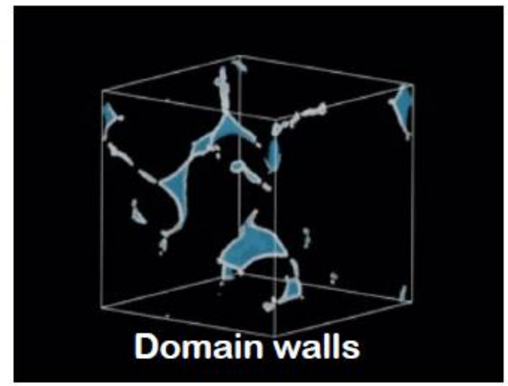
ESSP Granada, 14-May-2019 Igor G. Irastorza 27

Axions

Cosmological axions







Axion realignment

(initial misalignment angle?)

But also… topological defects

(inflation can wipe them out if it happens afterwards)

Note: thermal production of axions (as neutrinos) gives hot DM (upper limit ma~1 eV)

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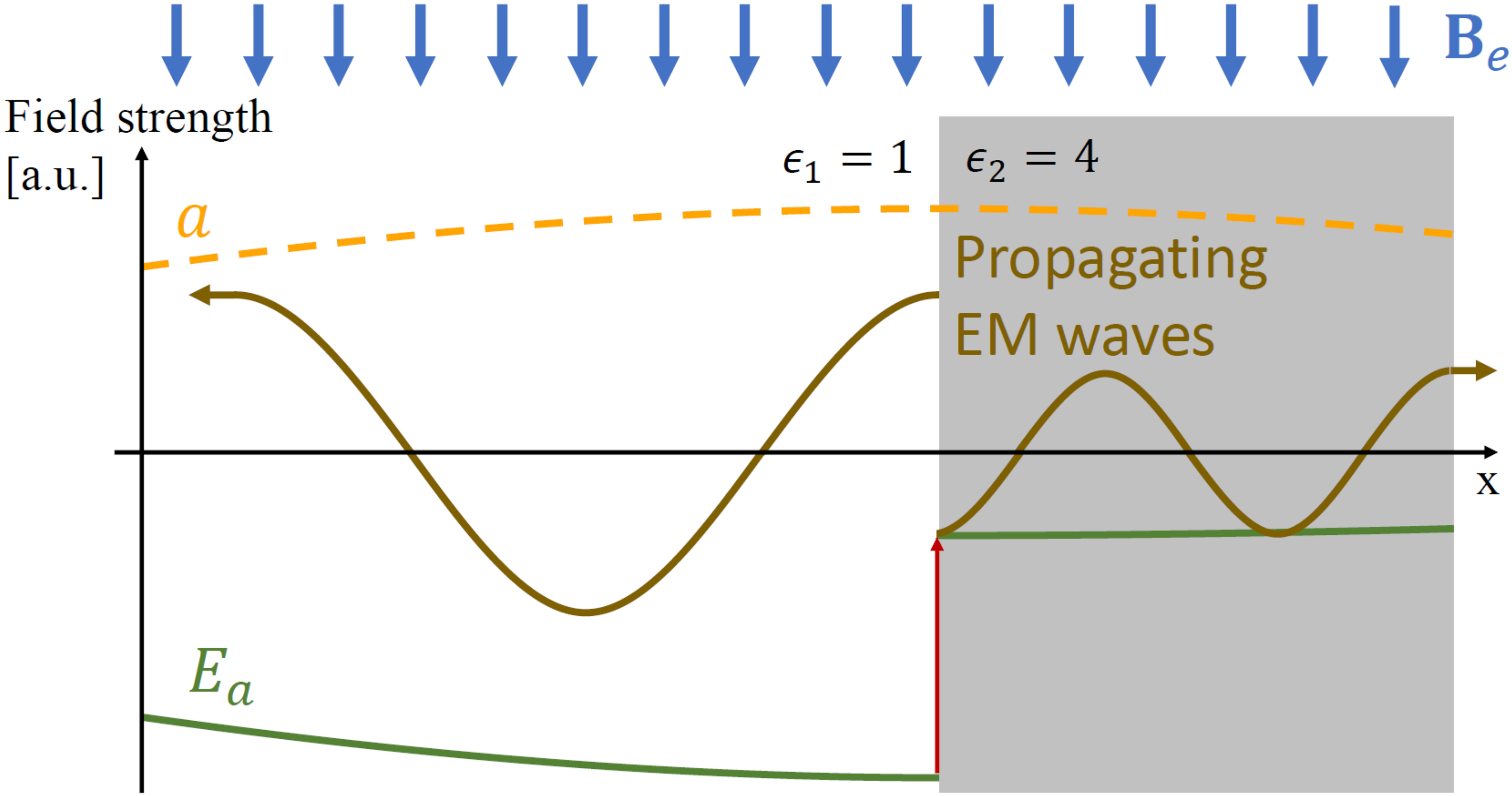
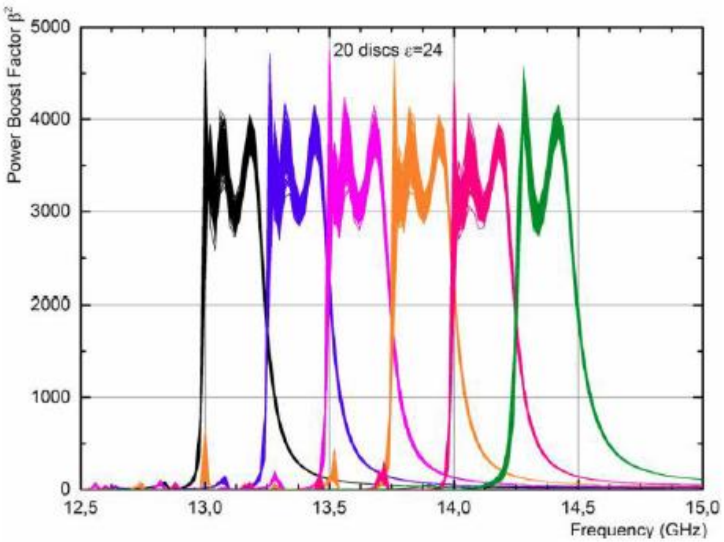
Dielectric interface



Boost factor

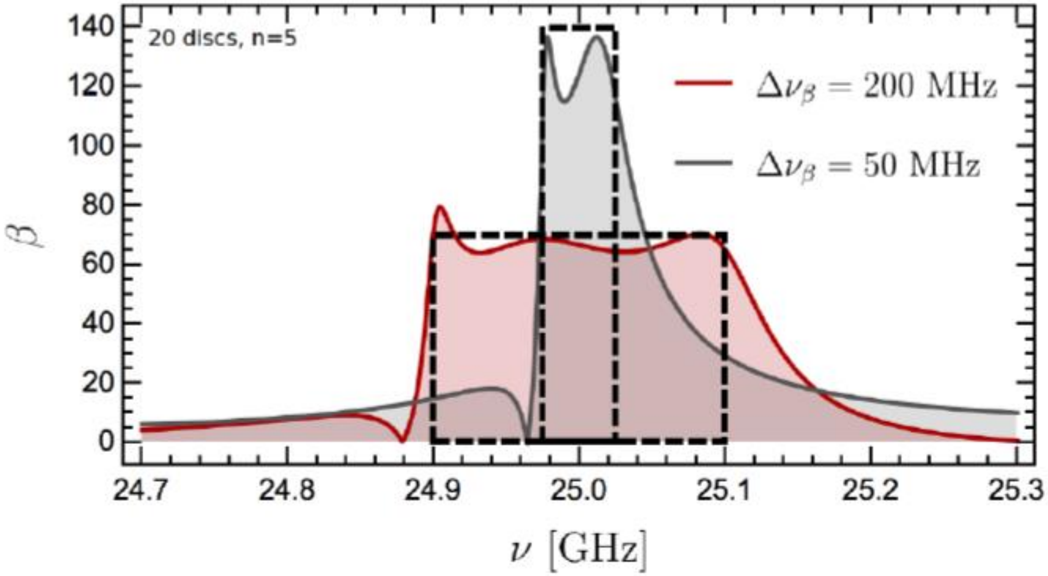
Tuning of sensitive frequency range by adjusting disc spacing



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

→ broad-band scan for search

→ narrow-band to confirm possible signals



➔ **MADMAX versatility**

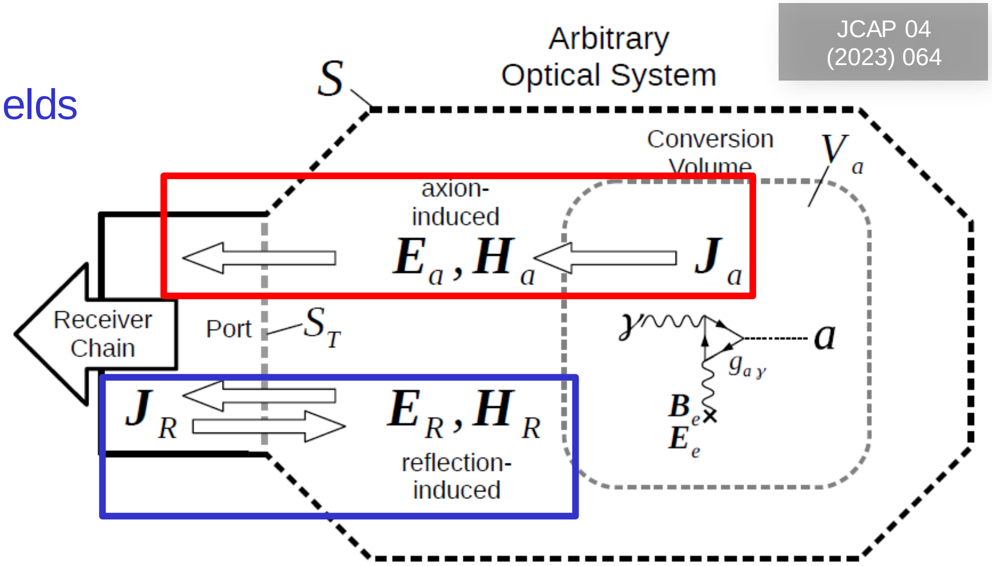
In situ determination of boost factor

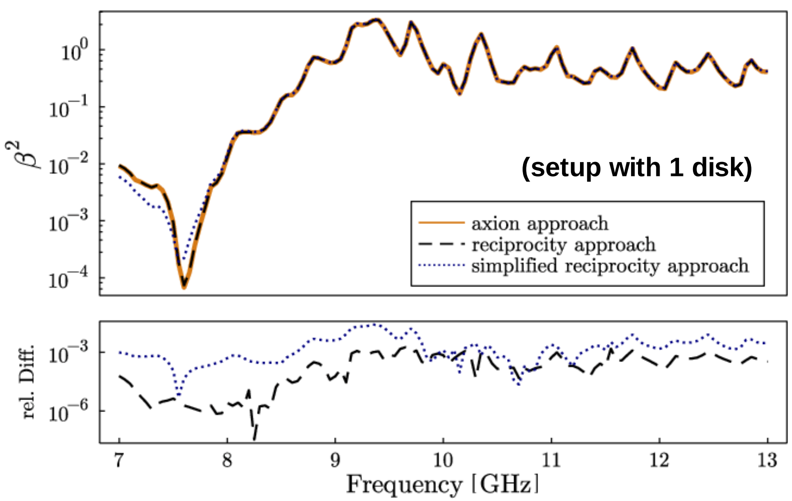
JCAP 04 (2023) 064

- Lorentz reciprocity theorem relates EM fields of 2 different sources
  - J_a = axion/DP effective current density in B-field, sourcing axion/DP-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/DP from its response to reflection measurement

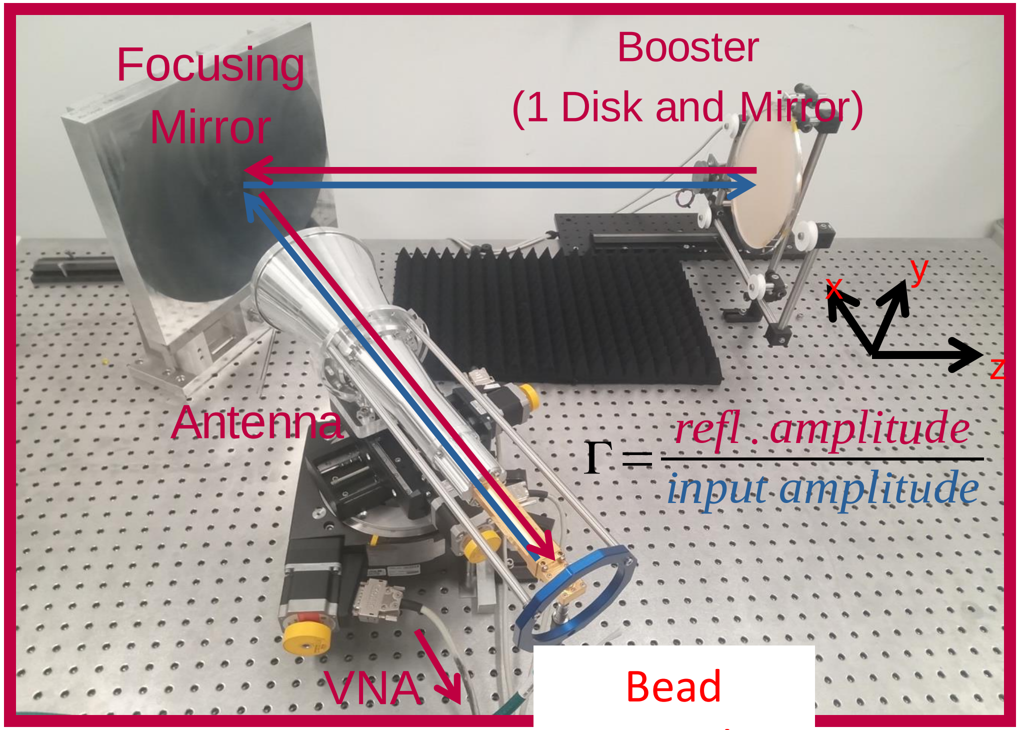
$$\beta^2 \propto \left| \int dV E_R \right|^2$$

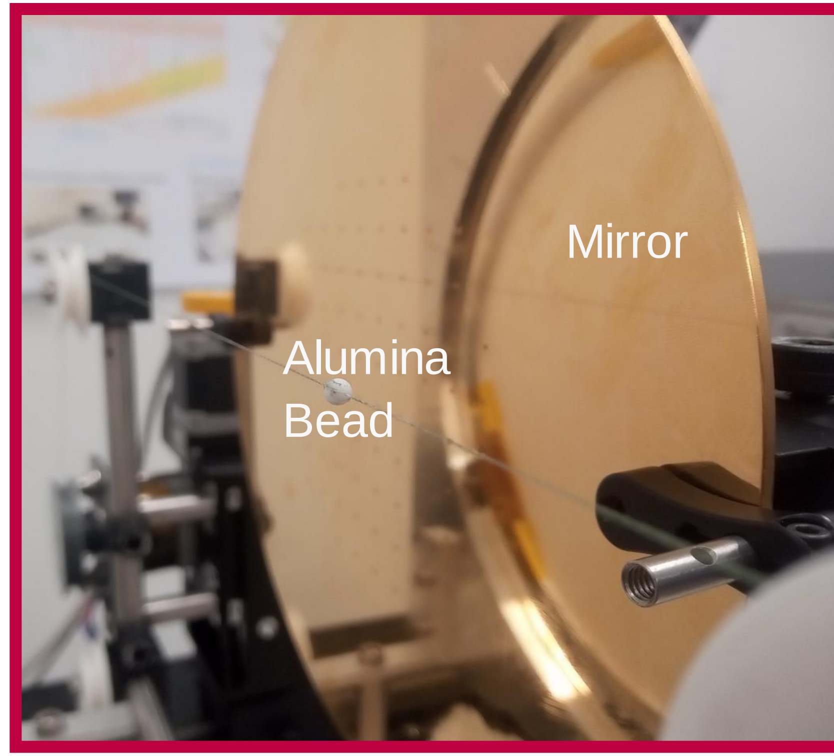




In situ determination of boost factor (1/2)

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





Bead properties

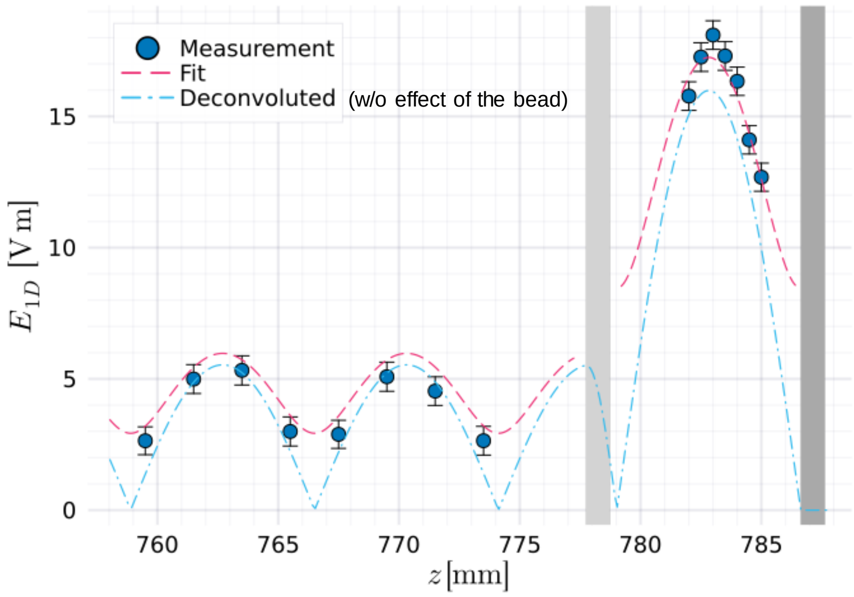
Change in reflection coefficient → $\Delta\Gamma = \frac{\alpha_e \omega}{4P_{\mathrm{in}}} \boldsymbol{E}_R^2$ → E field

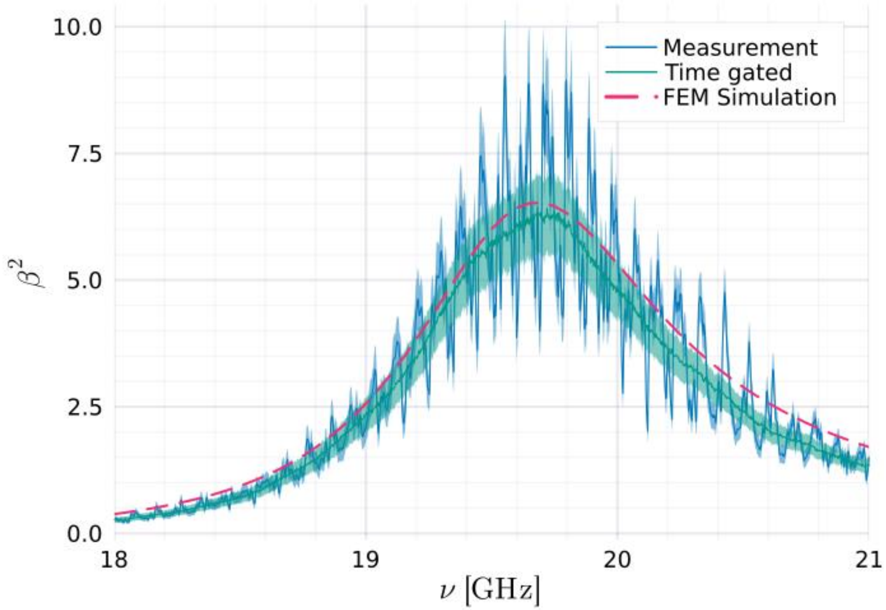
$$P_{\mathrm{sig}} = \frac{g_{a\gamma}^2}{16P_{\mathrm{in}}} \left| \int_{V_a} \mathrm{d}V\, \boldsymbol{E}_R \cdot \dot{a} \boldsymbol{B}_e \right|^2 \Rightarrow \beta^2 = \frac{P_{\mathrm{sig}}}{P_0}$$

In situ determination of boost factor (2/2)

JCAP 04 (2024) 004

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

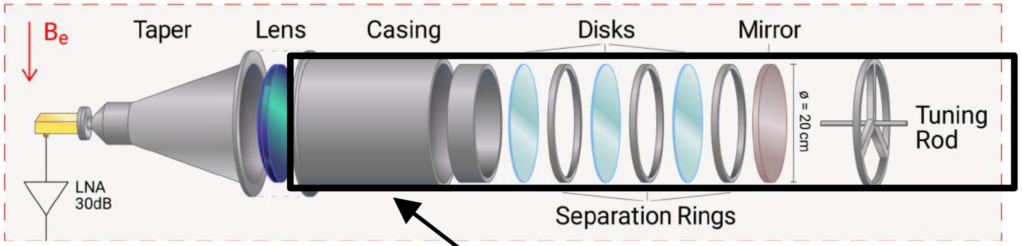




[time gating allows to filter out antenna-booster resonances]

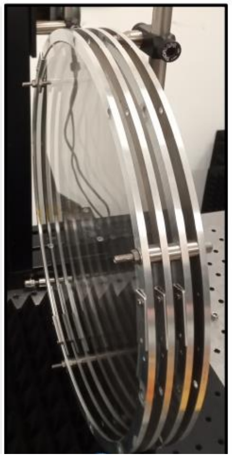
Closed vs open booster

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

MADMAX sensitivity

❑ **Axion-photon coupling, $g_{a\gamma}$**

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

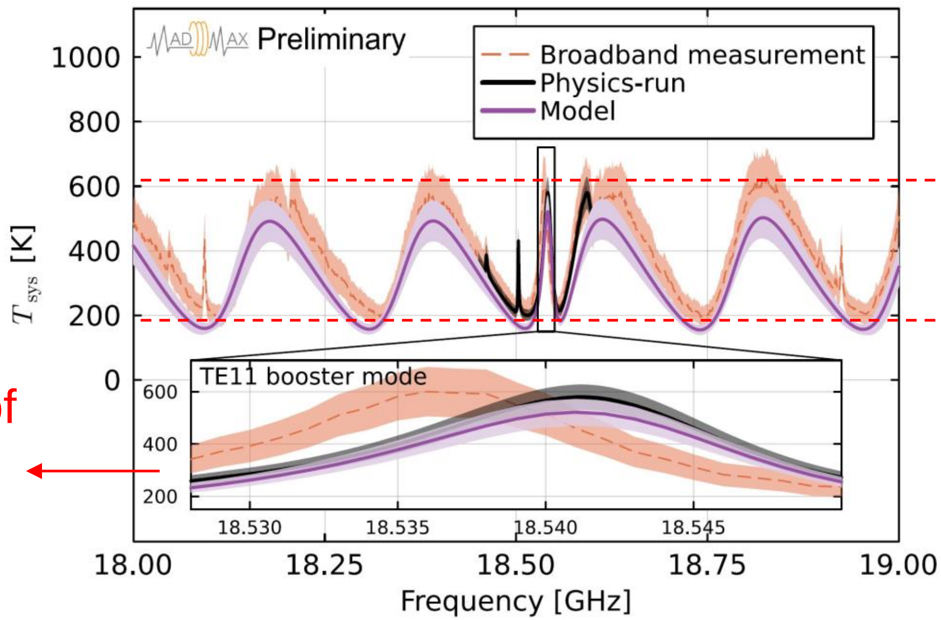
❑ **Dark Photon kinetic mixing angle with photon, χ**

- Assuming unpolarized Dark Photon:

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

MADMAX search for axion

- Booster reflectivity measurements → fit 1D booster model (with uncertainties)
- 3D effects taken into account and corrected for
- Receiver reflectivity + standard calibration measurements → fit receiver model (with unc.)
- System noise (thermal radiations) measurements in 18-20 GHz → fit combined (booster & receiver) model (impedance mismatch between booster and 1st LNA, with unc.)
- Extract the boost factor curve $\beta^2(\nu)$ (with uncertainties)



Good model of frequency behavior of system power spectrum at the booster resonance

Broadband oscillatory standing wave due to LNA noise interfering with its reflections in the booster

Zoom on booster resonance

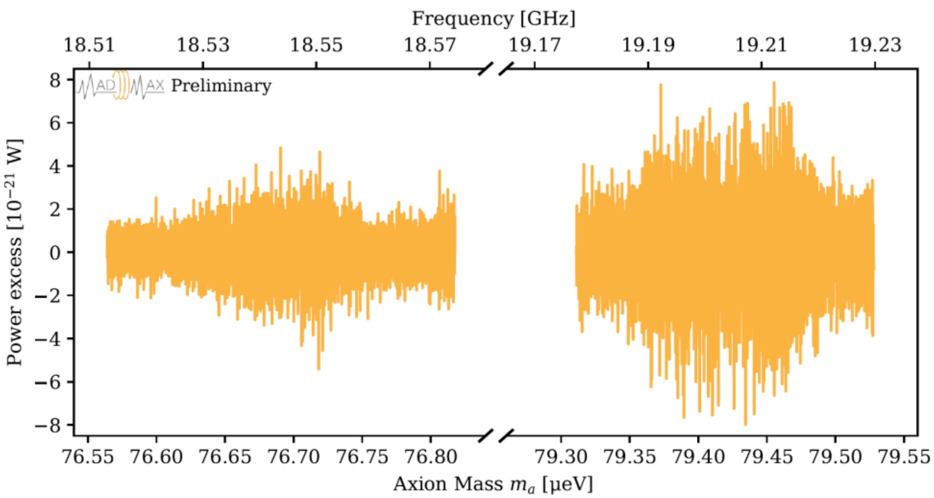
MADMAX search for axion

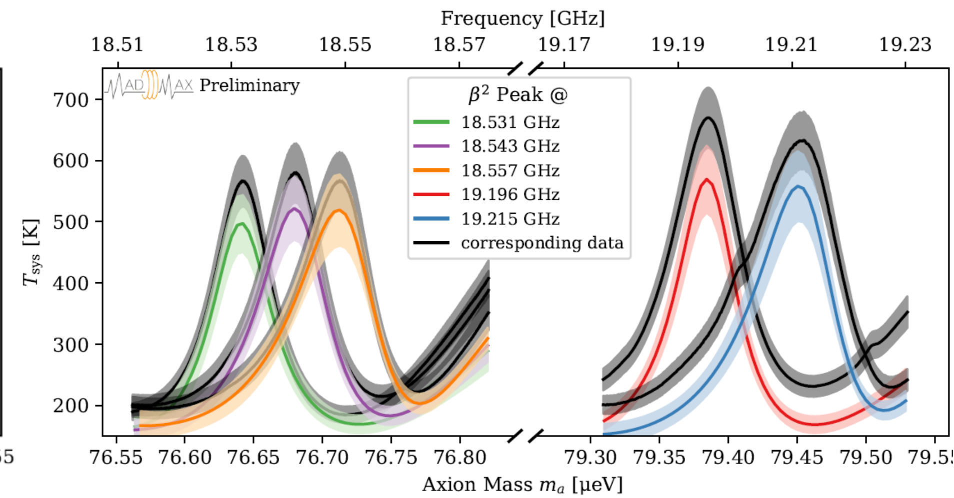
Fluctuations of power from thermal radiations → standard deviation = $k_B \cdot T_{sys} \cdot \mathrm{sqrt}(\Delta\nu/t)$

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

T_{sys} = system noise temperature

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





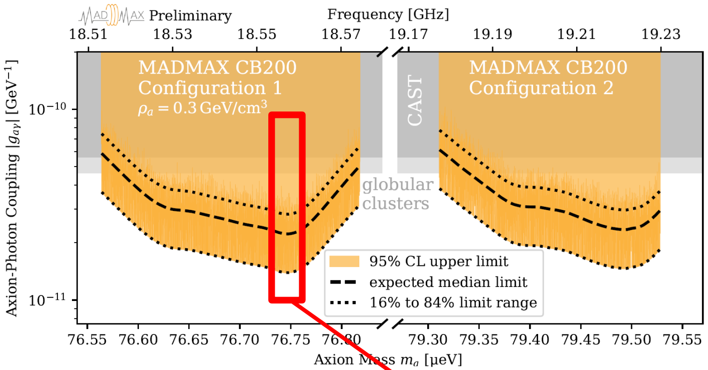
➔ Sensitive to axion signal power of $O(10^{-21}$ W)

MADMAX search for axion

Impact of systematics on $|g_{a\gamma}|$ limit

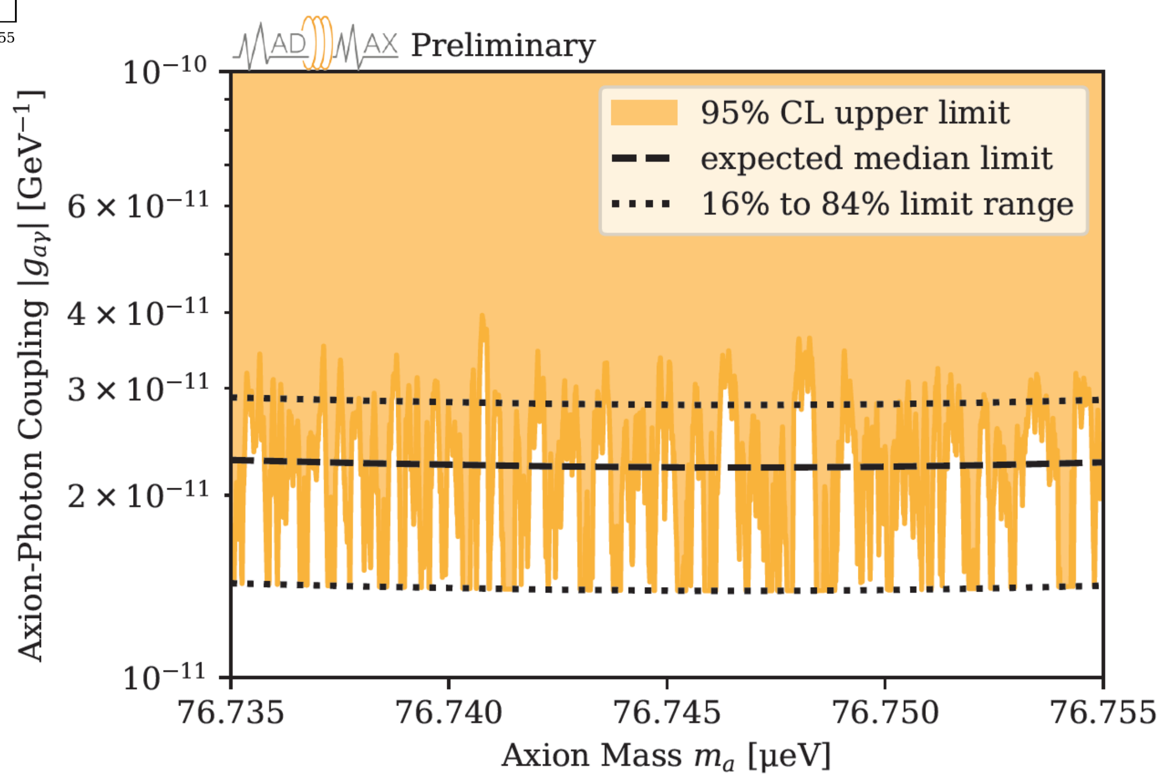
Effect	Uncertainty in $\lvert g_{a\gamma} \rvert$	
Y-factor power calibration	3 % to 5 %	(configuration dependent)
Receiver chain power stability	$\leq$ 2 %	
Axion field – TE_{11} overlap	6 %	boost factor
Boost factor determination	< 5 %	boost factor
Frequency stability of TE_{11} mode	< 2 %	boost factor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

MADMAX search for axion



Zoom

(bins of ~0.9 kHz)



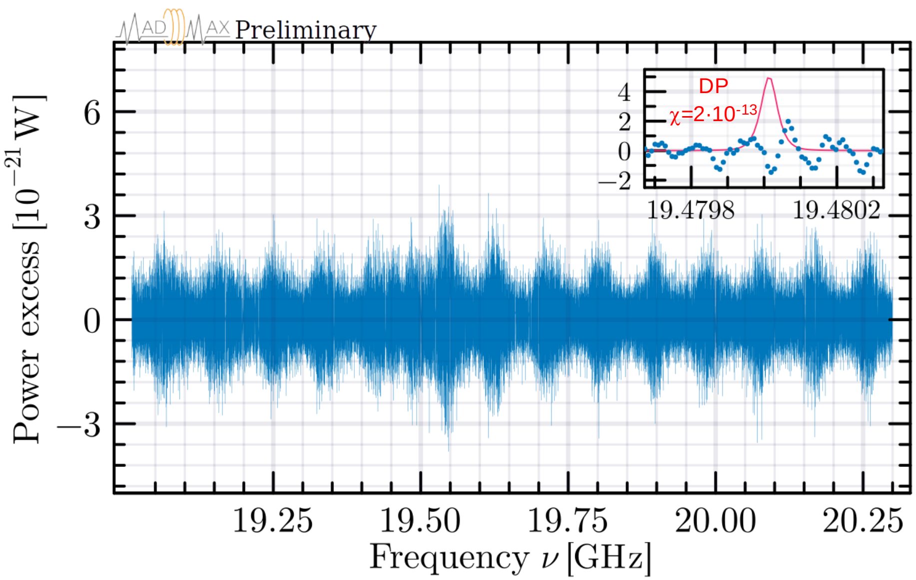
MADMAX search for Dark Photon

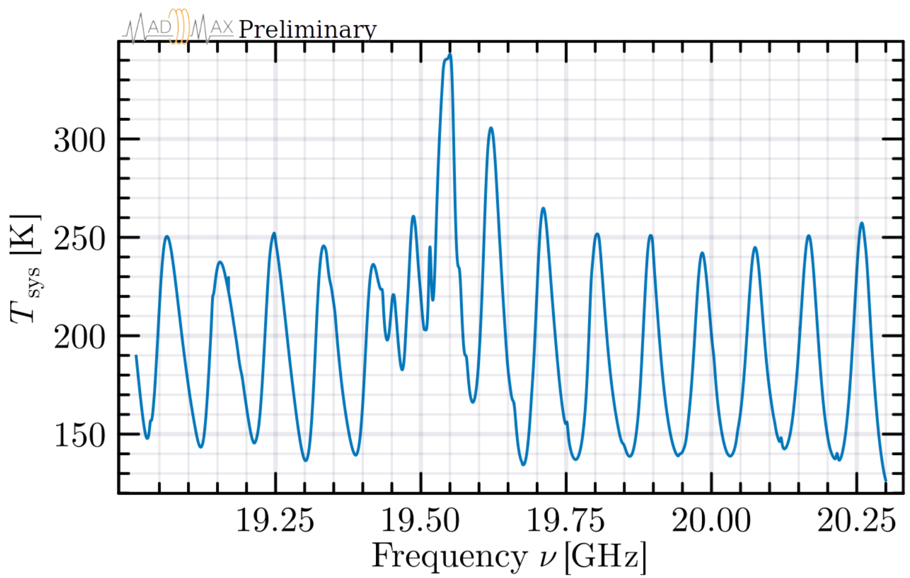
Fluctuations of power from thermal radiations → standard deviation = $k_B \cdot T_{sys} \cdot \mathrm{sqrt}(\Delta\nu/t)$

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

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)

MADMAX search for Dark Photon

Impact of systematics on χ limit

Effect	Uncertainty on χ
Boost factor determination	
Bead-pull measurements	2 to 17% (frequency dependent)
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%

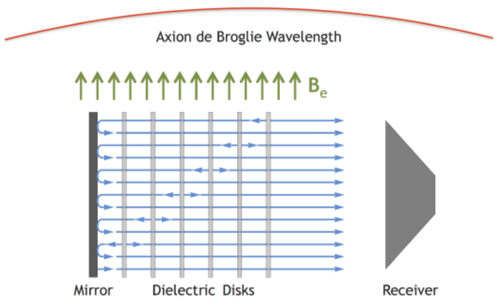
Directionality with MADMAX

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

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



  - 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