First searches for axion and dark photon dark matter with MADMAX

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On behalf of the MADMAX collaboration

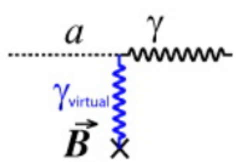
https://madmax.mpp.mpg.de/

EPS-HEP conference, July 07-11 2025

Dark matter (DM) QCD axion search

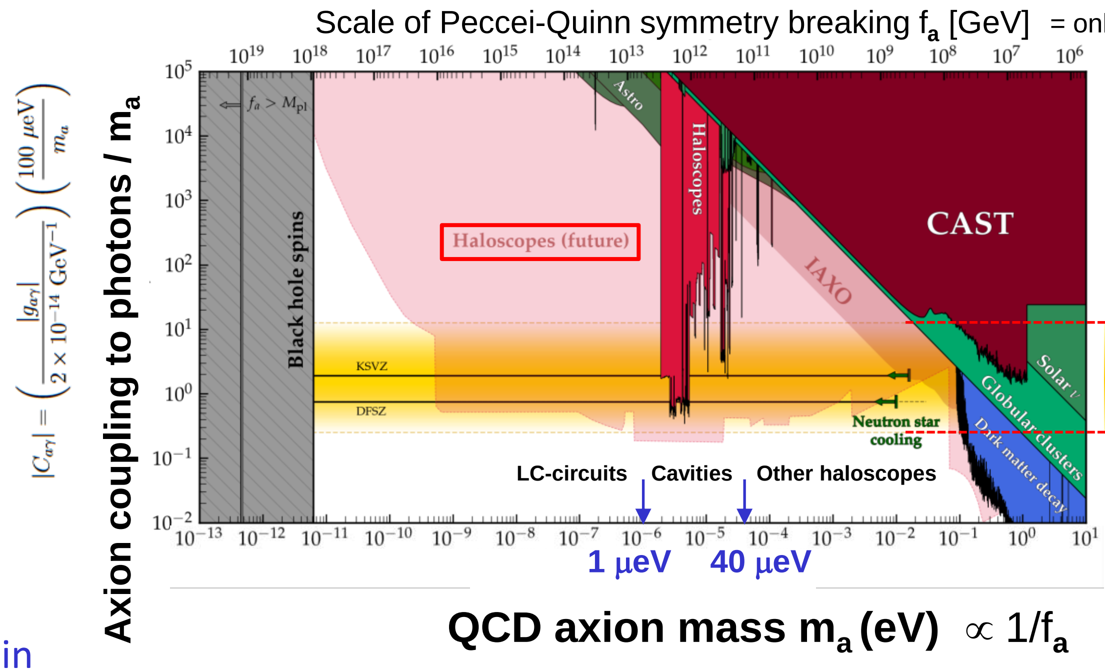
❑ QCD axion = cold DM candidate motivated by particle physics

Inverse-Primakoff effect



(external static magnetic field)

Haloscopes (using a-γ coupling) = main way to search for DM QCD axion



= only free parameter of the theory

arXiv:2403.17697

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

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

$g_{a\gamma} \propto 1/f_a \propto m_a$

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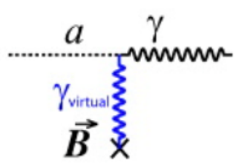

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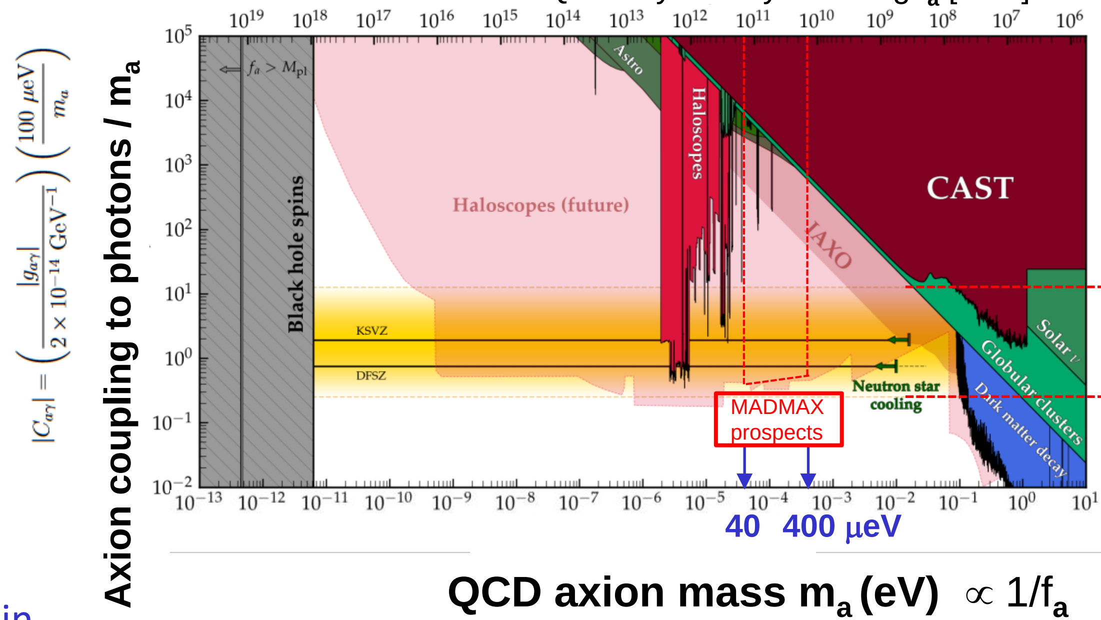
Scale of Peccei-Quinn symmetry breaking f_a [GeV] = only free parameter of the theory



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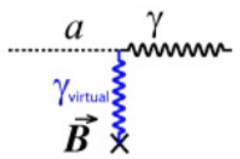

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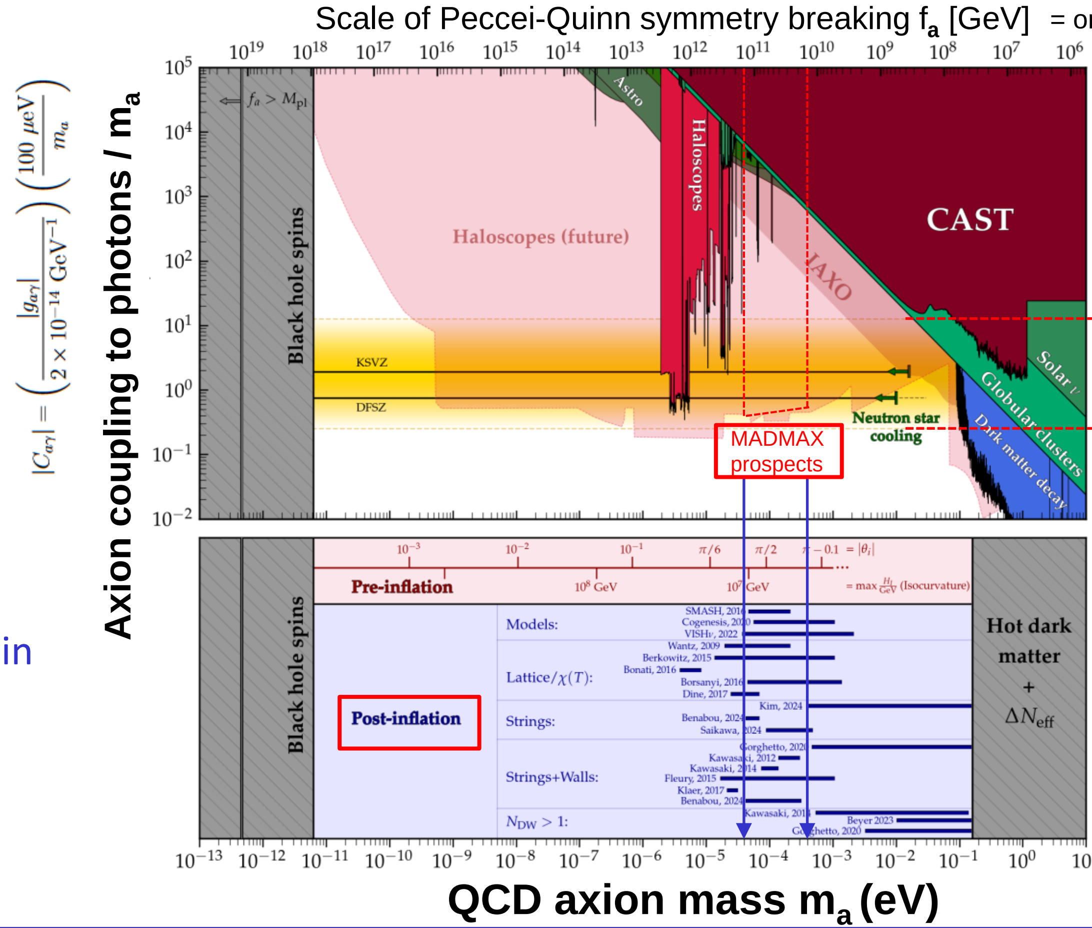

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Yellow band: benchmark models for **QCD-axion**

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

MADMAX (1/2)

JCAP 01 (2017) 061

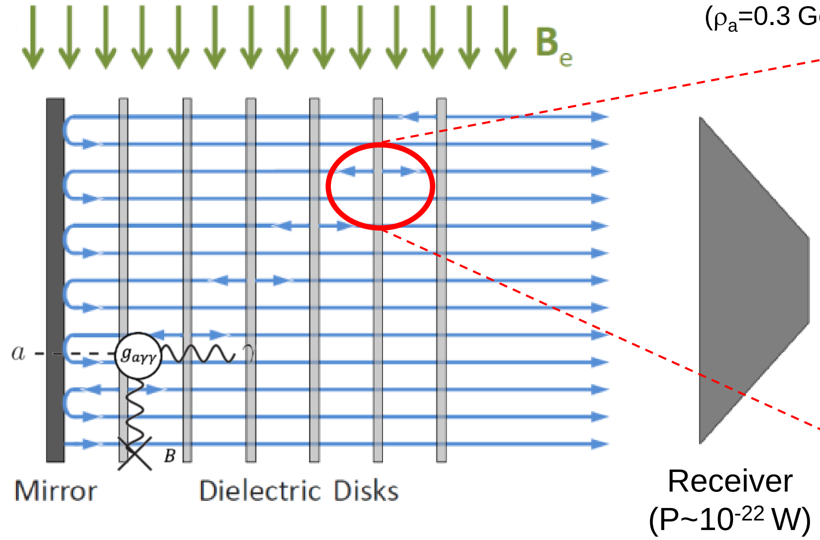
❑ A novel experimental concept: dielectric haloscope

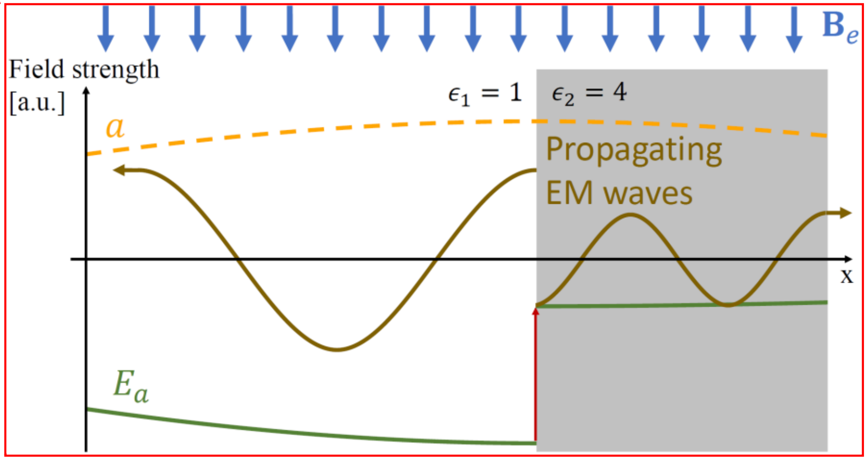
- **Constructive interference** of coherent EM waves emitted at dielectric layer surfaces + **resonant** enhancement (~leaky resonant cavities): boost (β^2) signal wrt mirror only

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

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

(ρ_a=0.3 GeV/cm^3)





➔ **MADMAX** (MAgnetized Disk and Mirror Axion eXperiment)

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JCAP 01 (2017) 061

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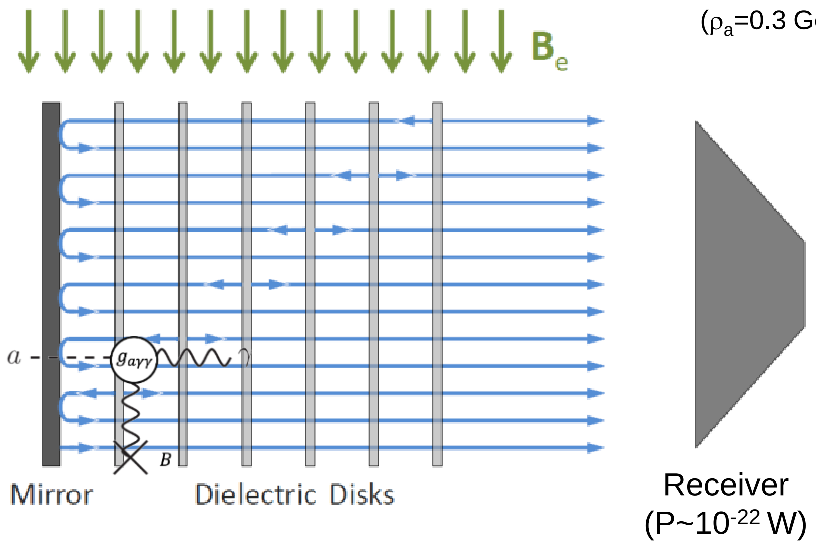

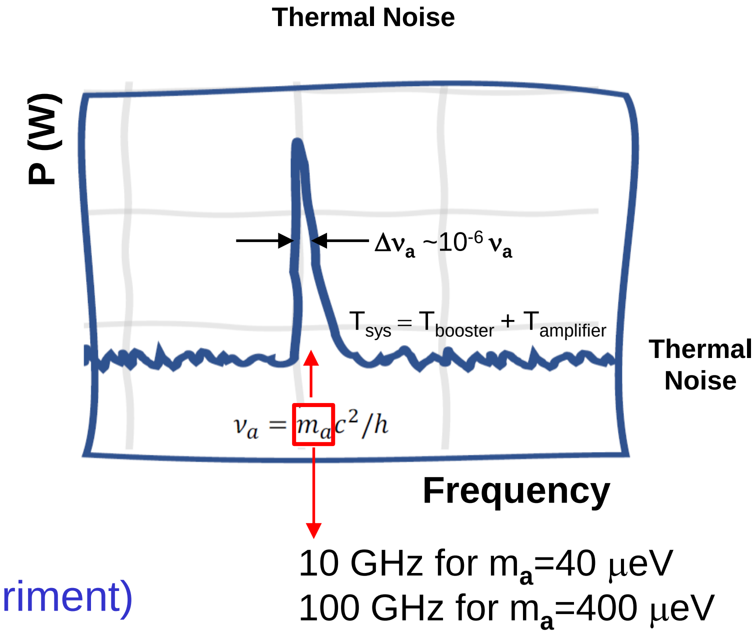

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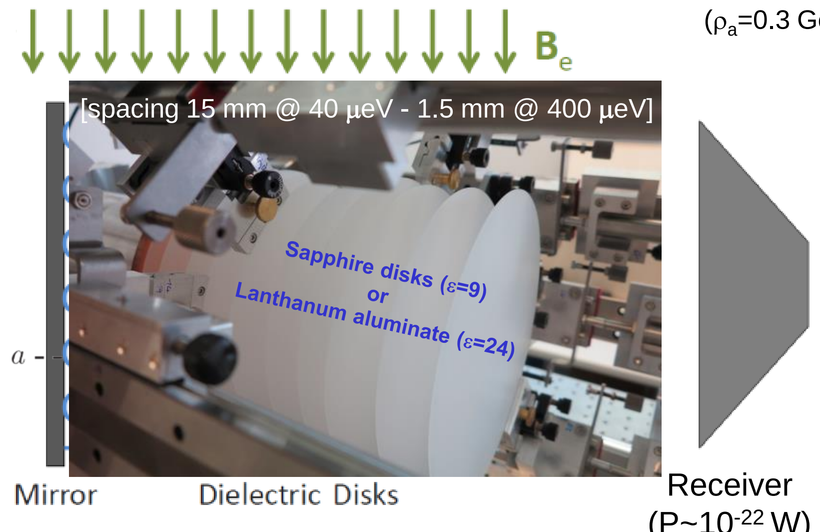
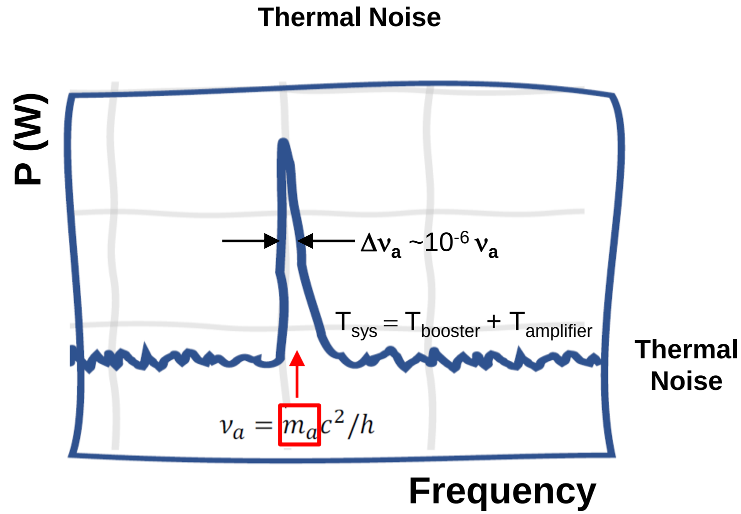




- **Axion mass scan**: move discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz steps)*

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

MADMAX (2/2)

❑ A novel experimental concept: dielectric haloscope

EPJC 79 (2019) 186

- Collaboration formed in 2017 ➔ O(50) physicists and engineers from 11 institutes

Fermilab · DESY · CPPM · Max-Planck-Institut für Physik · RWTH Aachen University · Eberhard Karls Universität Tübingen · IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis · Universität Hamburg · Max-Planck-Institut für Radioastronomie · Néel institut · Universidad de Zaragoza

- First generation experiment with **3 main challenges**:

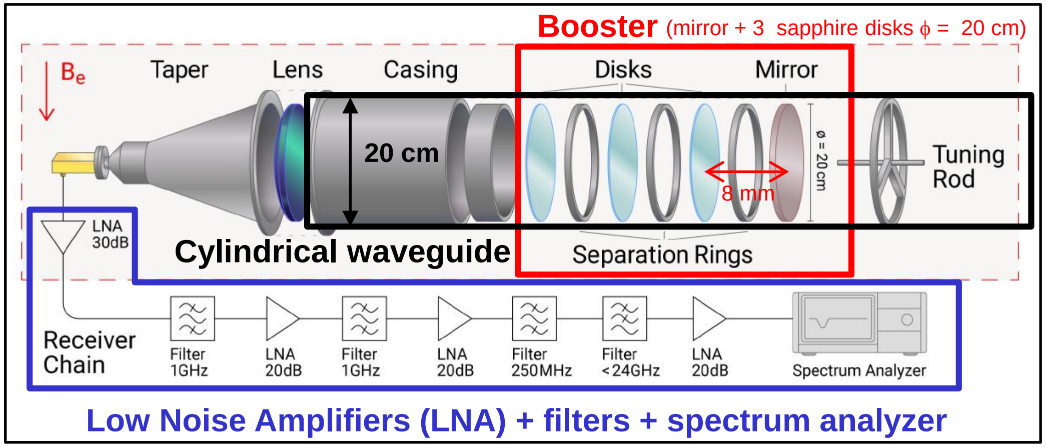
1. Develop and build a large dipole magnet providing a O(10 T) B-field
2. Calibrate RF response of receiver at cold in O(10) GHz regime
3. Move disks (tunable booster) at μm level precision at cold and under high B-field

➔ Prototyping phase since 2020 to validate the concept

➔ Gradually build the final booster design + perform 1st searches

MADMAX search for axion (1/3)

Name	Booster	Disks	Test @CERN
CB200	Closed	3, **fixed** ϕ = 200 mm	2024 (room temp., B-field)

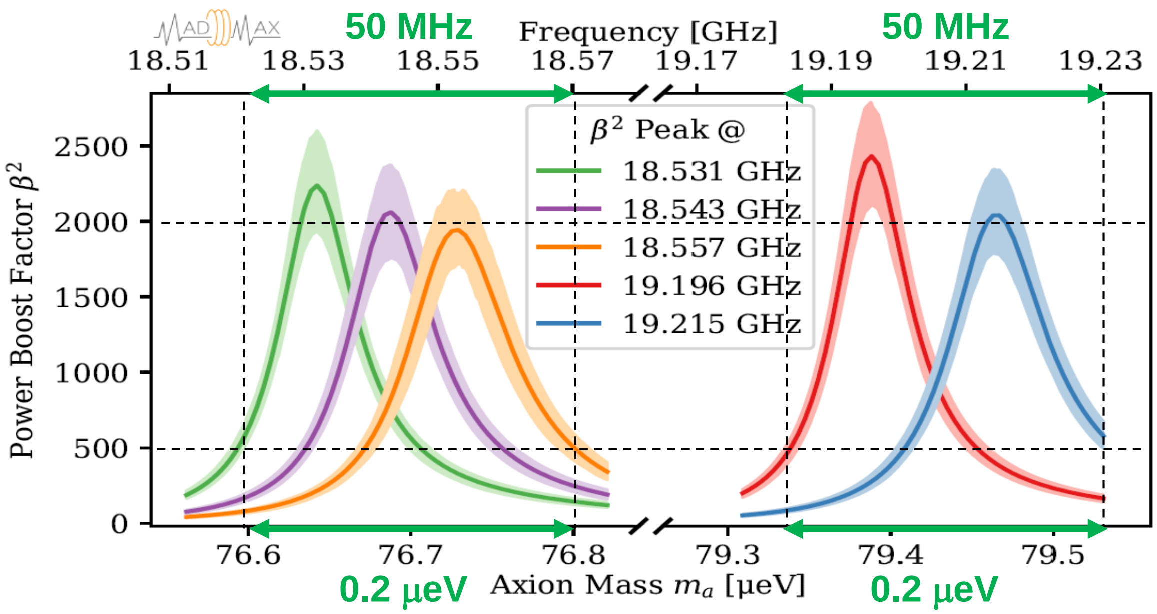


- Booster peak tuned at 2 frequencies ~18.5 and 19.2 GHz
  [manual change of disk distances by ~0.3 mm with separation rings]
- O(10 MHz) variations around these frequencies
  [manual change of mirror-disk distance by O(10 μm) with tuning rod]
- 15 days of data in Morpurgo magnet at CERN providing B=1 to 1.6 T

MADMAX search for axion (2/3)

❑ Determination of the boost factor

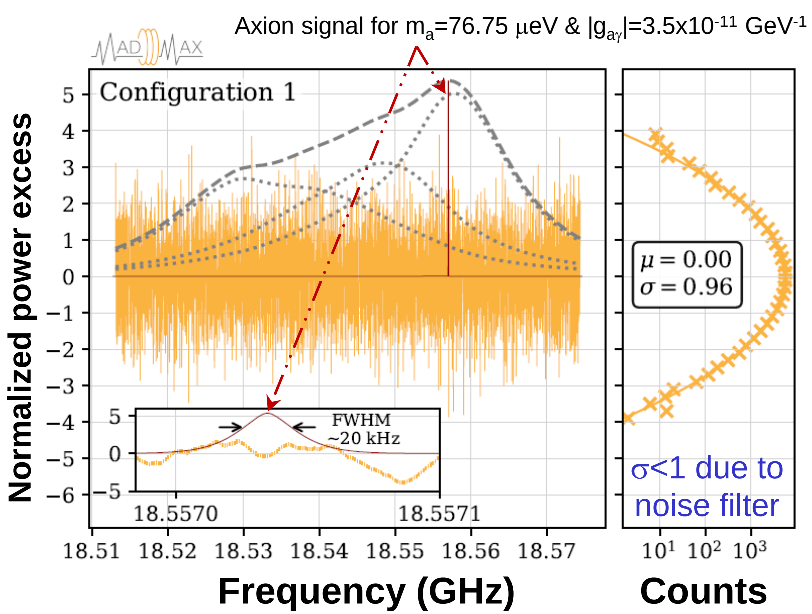
- Booster & receiver noise model through fits of reflectivity and noise measurements
- Boost factor curves $\beta^2(\nu)$ determined with ~15% systematic uncertainties
  - ➔ $\beta^2_{peak} \approx O(2000)$; $\beta^2 > 500$ over 2x50 MHz bandwidths [=2x0.2 μeV axion mass scan]

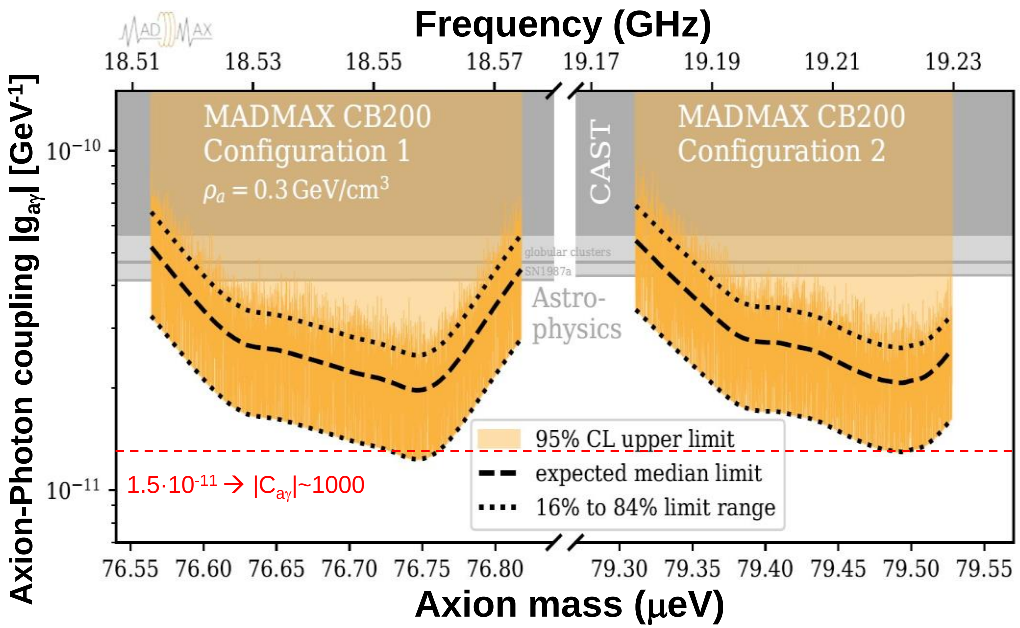


➔ Demonstrate the scanning capacity of MADMAX booster

MADMAX search for axion (3/3)

- No excess observed in acquired power spectra [HAYSTACK procedure PRD96 (2017) 1523008]
  - ➔ limits on axion-photon coupling $|g_{a\gamma}|$ [for each 0.9 kHz bin]
- Limits better than existing ones by up to x3 with modest system [few small disks, reduced B field]
  - ➔ confirm **substantial potential** of MADMAX concept





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

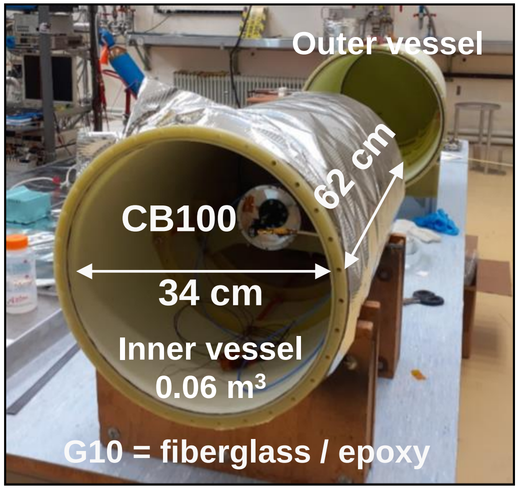
arXiv:2409.11777 (accepted by PRL)

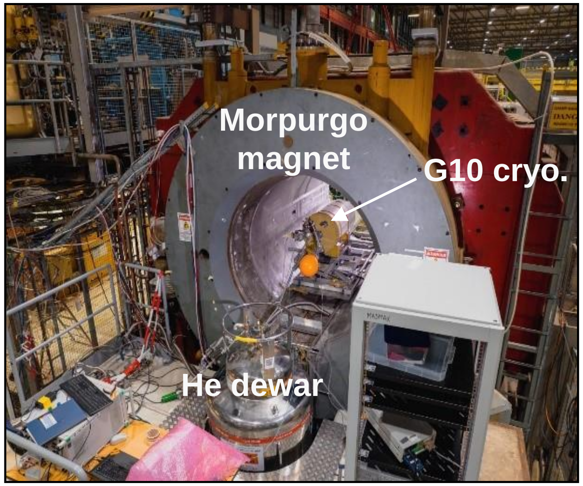
MADMAX search for axion (at cold)

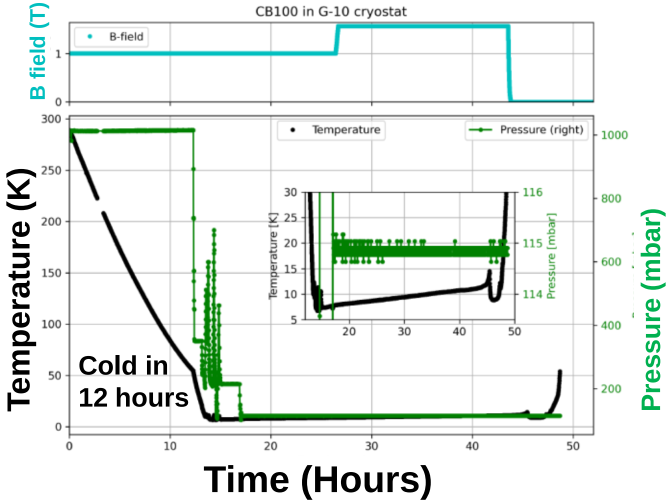
Name	Booster	Disks	Test @CERN
CB100	Closed	3, **fixed** ϕ = 100 mm	2024 (cryo temp., B-field)

- Developed low-cost cryostat in G10 with CERN cryolab: >24 hours below 10 K
- Developed receiver chain calibration procedure at cold

JINST 20 (2025) T02005







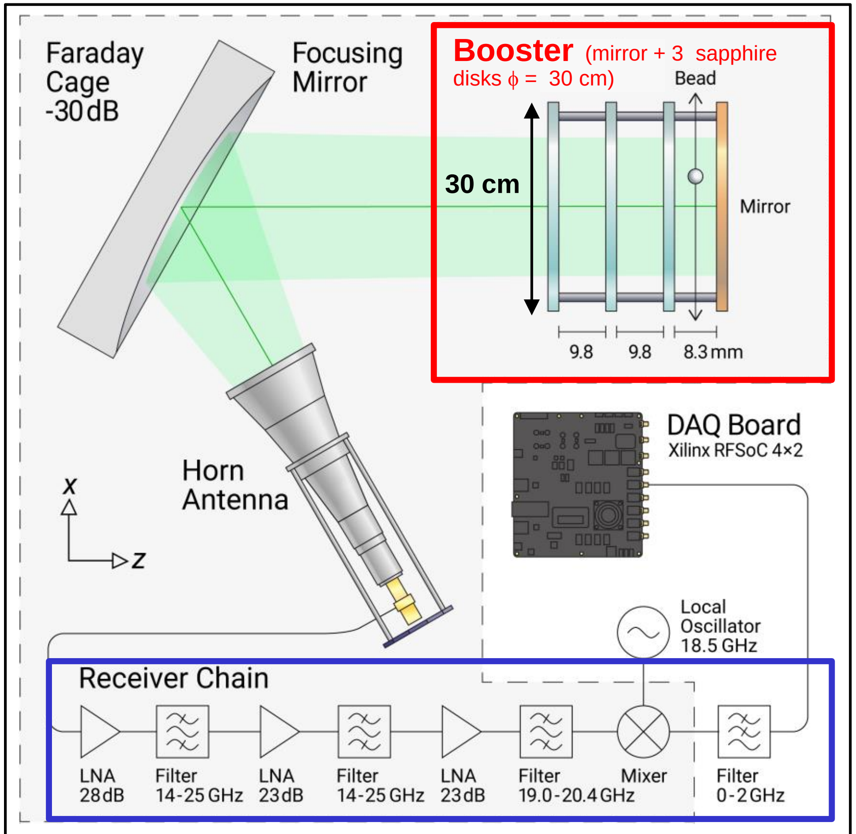
➔ **First operation of a dielectric haloscope at cold under B field**

2 analysis papers in preparation

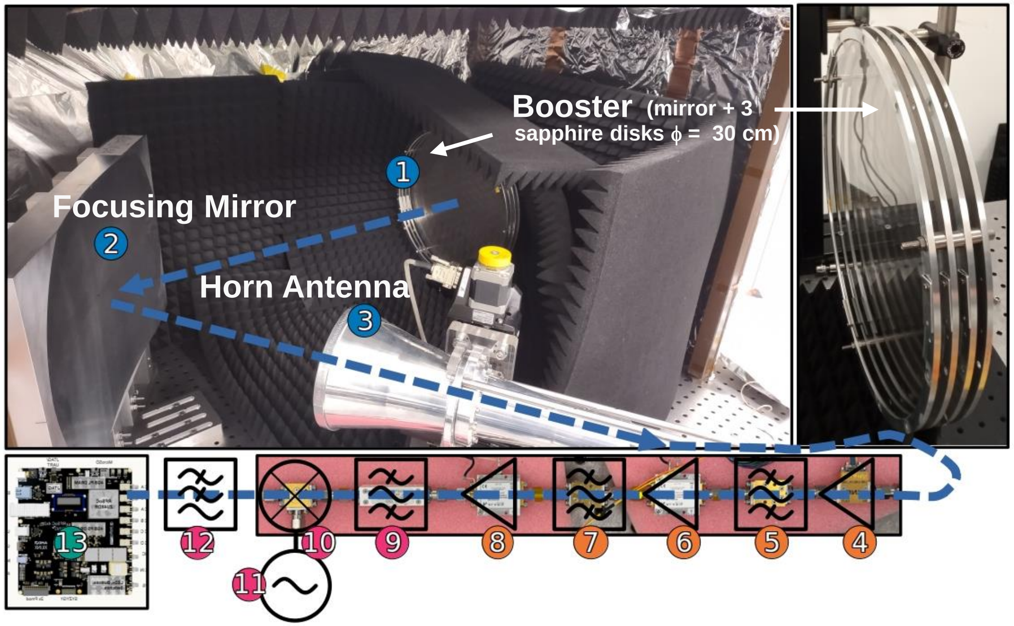
MADMAX search for Dark Photon

Name	Booster	Disks	Test @DESY
OB300v1	Open	3, **fixed** ϕ = 300 mm	2023-24 (room temp.)

- 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



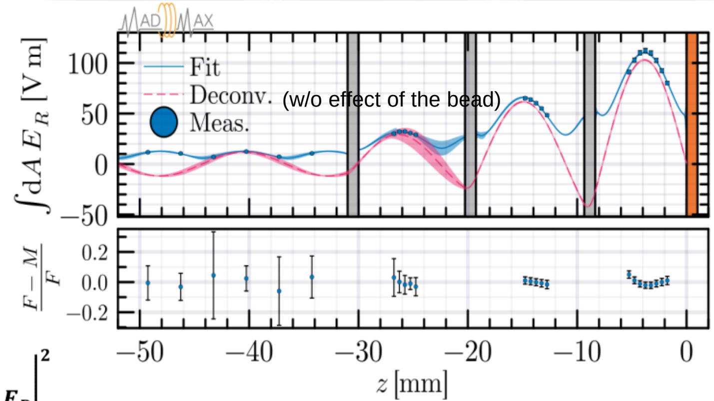
Low Noise Amplifiers (LNA) + filters + mixer



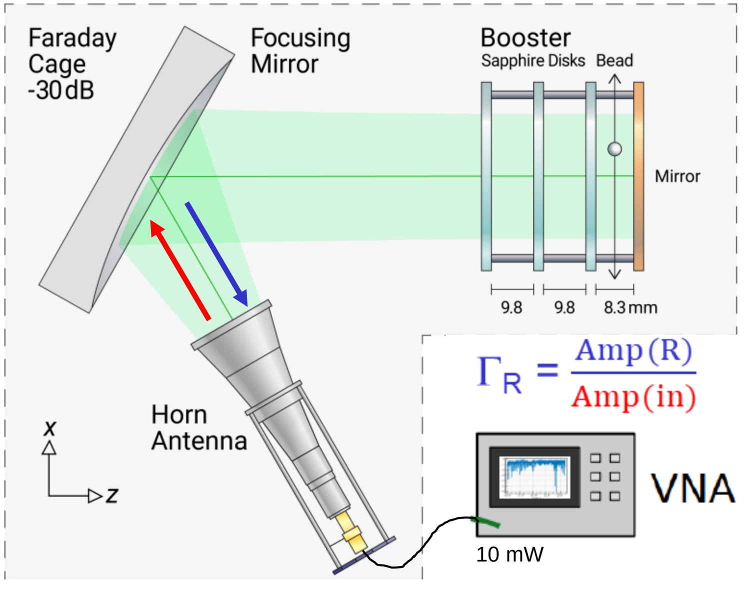
In situ determination of boost factor

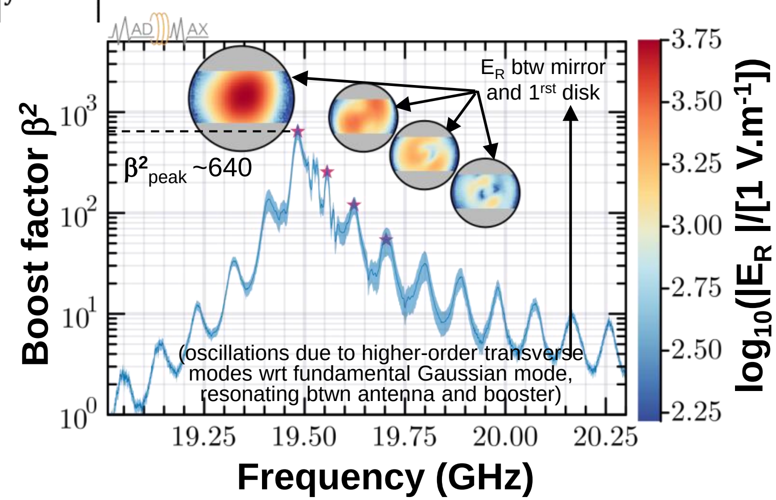
- Measure change in booster reflection coefficient $\Delta\Gamma_R$ caused by small perturbing dielectric object (bead)
- Deduce reflection-induced electric field at bead position (3D scan) → $E_R(\nu,x,y,z) \propto \sqrt{\Delta\Gamma_R(\nu,x,y,z)}$
- Deduce boost factor $\beta^2(\nu)$ through Lorentz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

JCAP 04 (2023) 064 | JCAP 04 (2024) 005 | PRL134 (2025) 151004



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



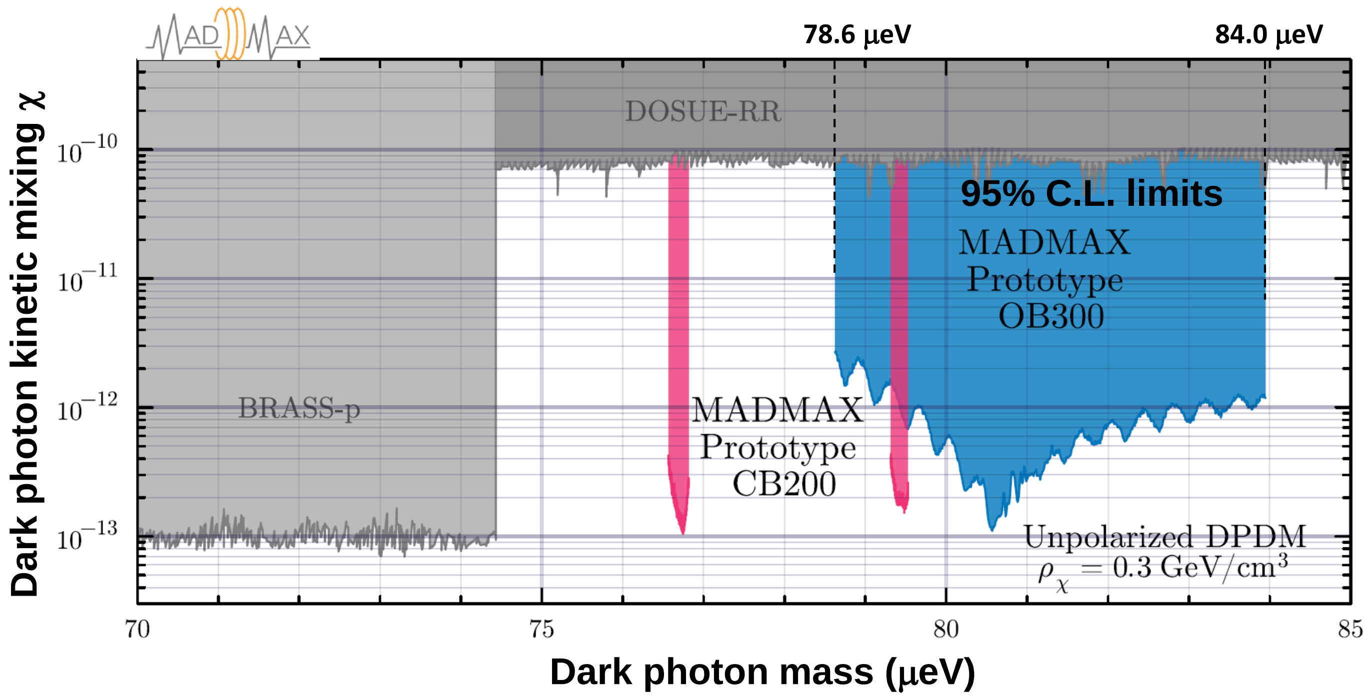


→ Developed bead-pull method to measure β^2 and its uncertainties

MADMAX search for Dark Photon

- Boost factor $\beta^2(\nu)$ measured with ~15% errors ➔ β^2_{peak} ~640 ; β^2 >1 over 1.3 GHz [=5.4 μeV]
- No excess ➔ limits on kinetic mixing χ between photon and DP for m_{DP} [78.6, 84.0] μeV
- Limits better than existing ones by up to x1000 with modest system [few small disks]

➔ confirm **substantial potential** of MADMAX concept [resonant and broadband]

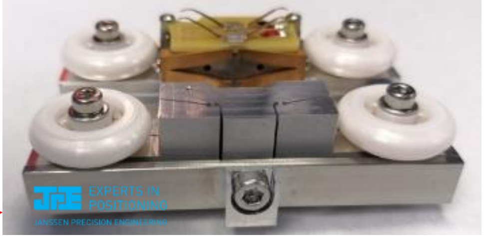


➔ First dark matter dark photon search with MADMAX protos

PRL134 (2025) 151004 (arXiv:2408.02368)

Tunable setup: move the disk

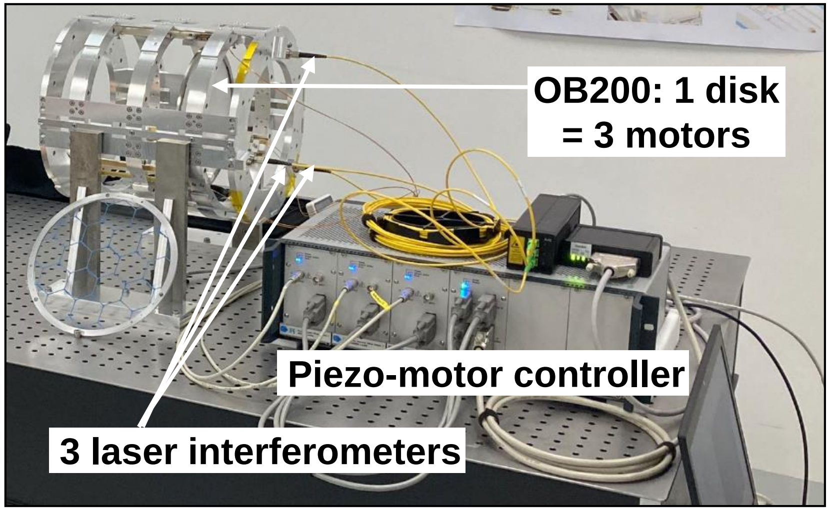
Name	Booster	Disks	Test @CERN
OB200	Open	1, **movable** ϕ = 200 mm	2022 (cryo temp. or B-field)

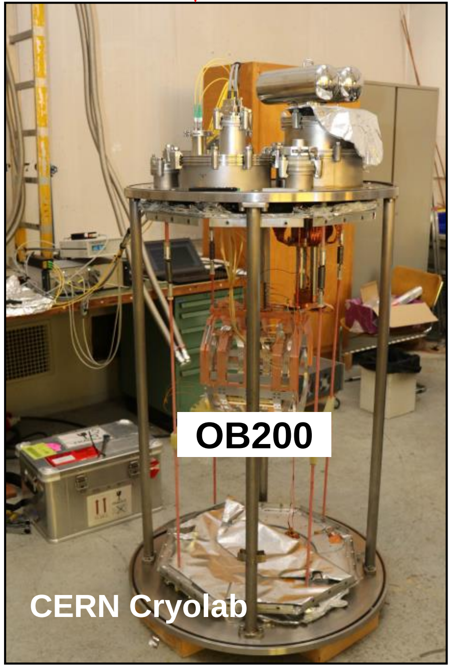


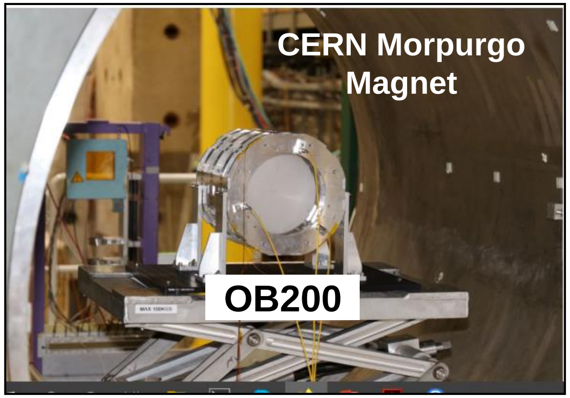
- 2021: Successful test of 1 piezo-motor at 5 K and 5.3 T (ALP magnet in DESY)

JINST 18 (2023) P08011

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







Tunable setup: move the disk

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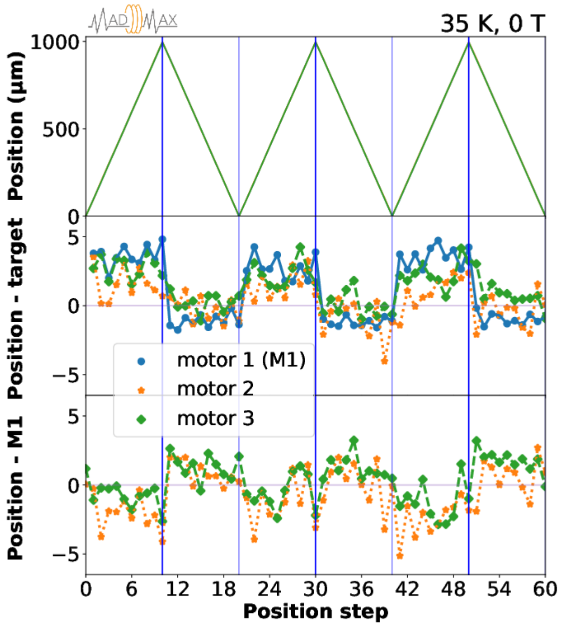
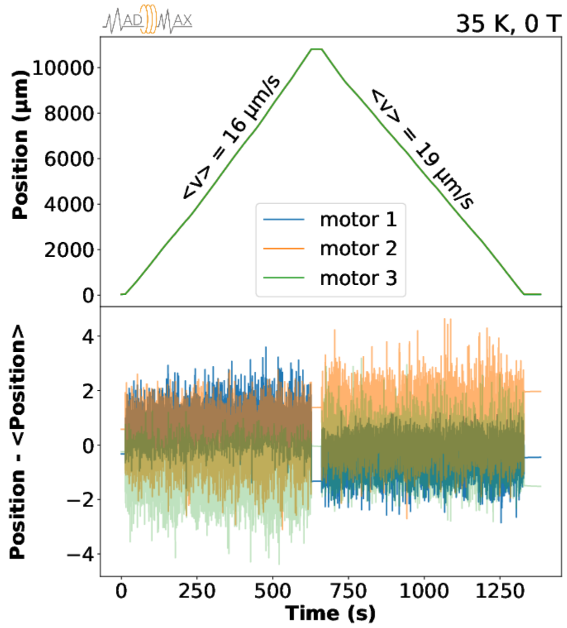
Motors positioned at <5 μm





Disk speed >15 μm/s

➔ **Precisely move the disk at cold and in B-field**

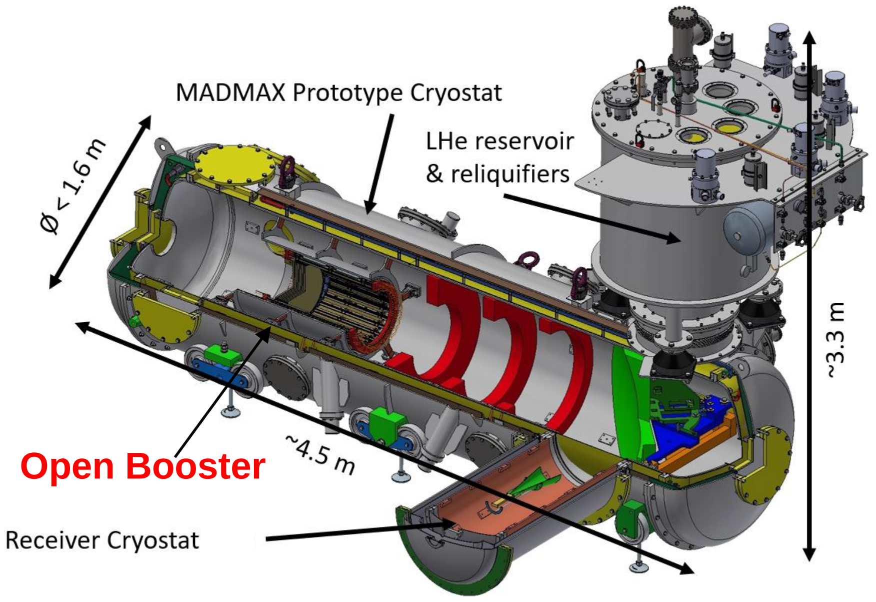
➔ **Validate booster mechanics**

JINST 19 (2024) T11002
(arXiv:2407.10716)

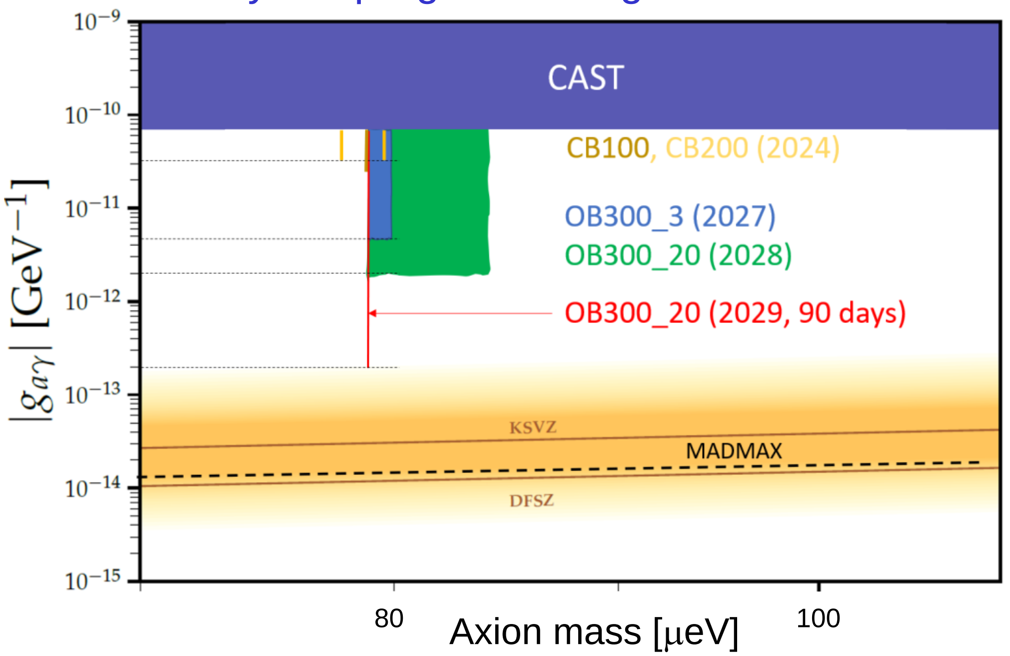
Final prototype

Name	Booster	Disks	Test @CERN
OB300v2 *(in prep.)*	Open	3-20, **movable** ϕ = 300 mm	2027-29 (cryo temp., B-field)

- Booster inserted in stainless steel cryostat



- Physics program during LHC shutdown



Long runs at cold with moving disks in 2027-29 → scan axion masses

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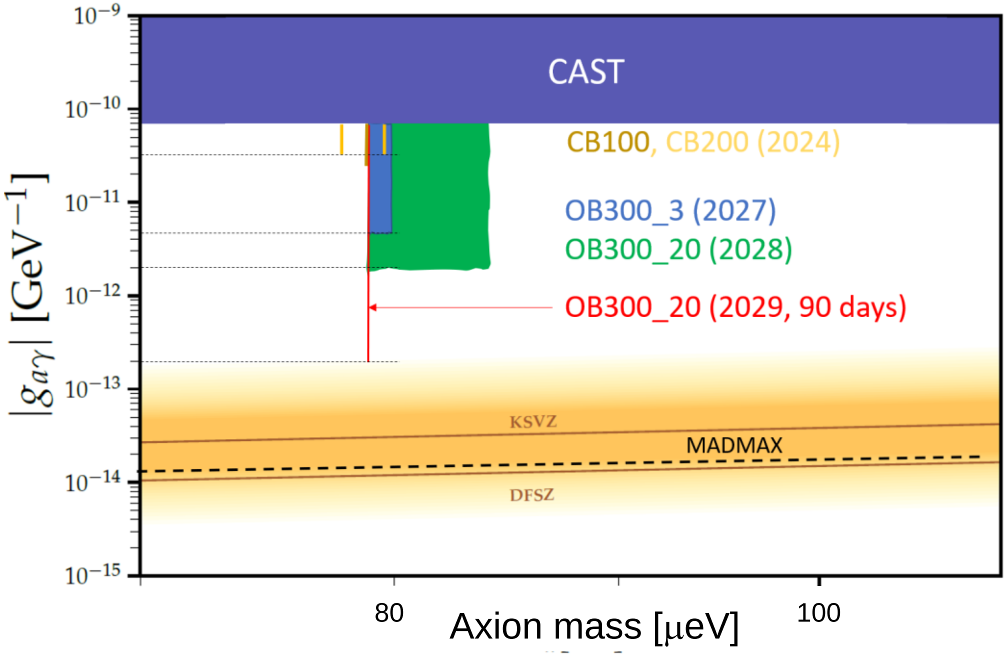
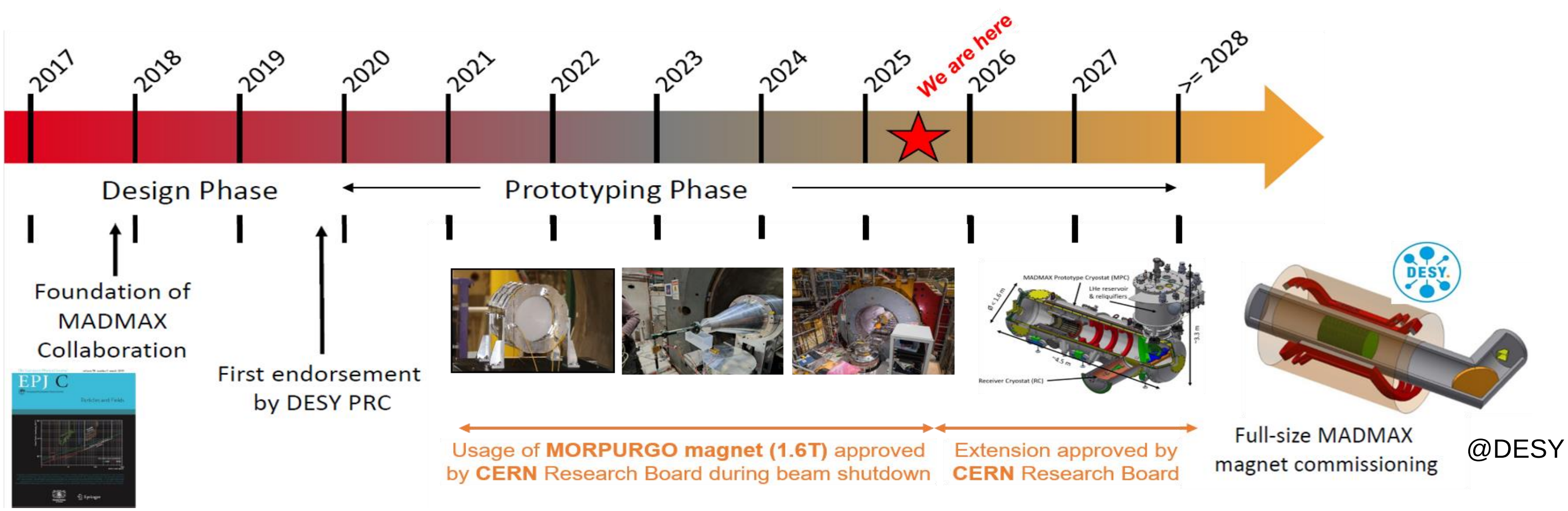


Long runs at cold with moving disks in 2027-29 → scan axion masses

Conclusions

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

- Prototyping phase since 2020 to validate the concept
  - ✓ Validated mechanics at cold and 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:2409.11777 (accepted by PRL) | PRL134 (2025) 151004
  - ✓ First booster tests at cold and under B-field → JINST 20 (2025) T02005 | 2 papers at work
  - ➢ Final prototype tests during LHC Long Shutdown 3 at CERN



BACKUP

(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 ?

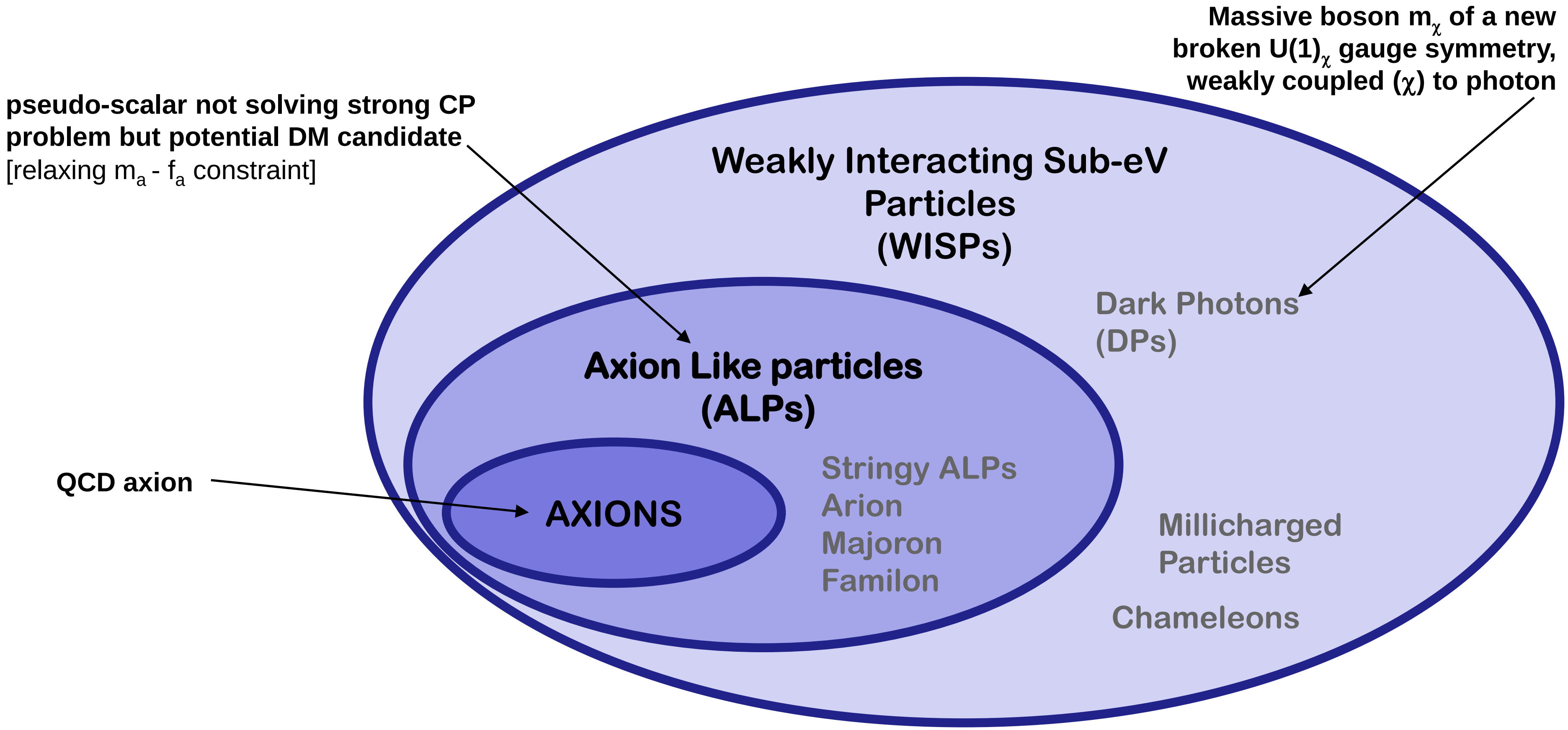
- **Solution to Strong CP problem** **➔ Axion**
  - Mechanism: new global U(1) symmetry *(Peccei-Quinn, 1977)* spont. broken at scale f_a
    - ➔ Can occur before or after inflation → cosmological implications
  - Consequence: pseudo-Goldstone boson of the theory = **axion** *(Weinberg-Wilczek, 1978)*
    - ➔ Properties are all known given the scale of symmetry breaking f_a [$f_a >> f_{EW}$]
    - ➔ Tiny mass [$m_a \approx m_\pi f_\pi / f_a$ << 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 = cold 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

Wave-like Dark Matter

❑ Other related very light dark matter candidates

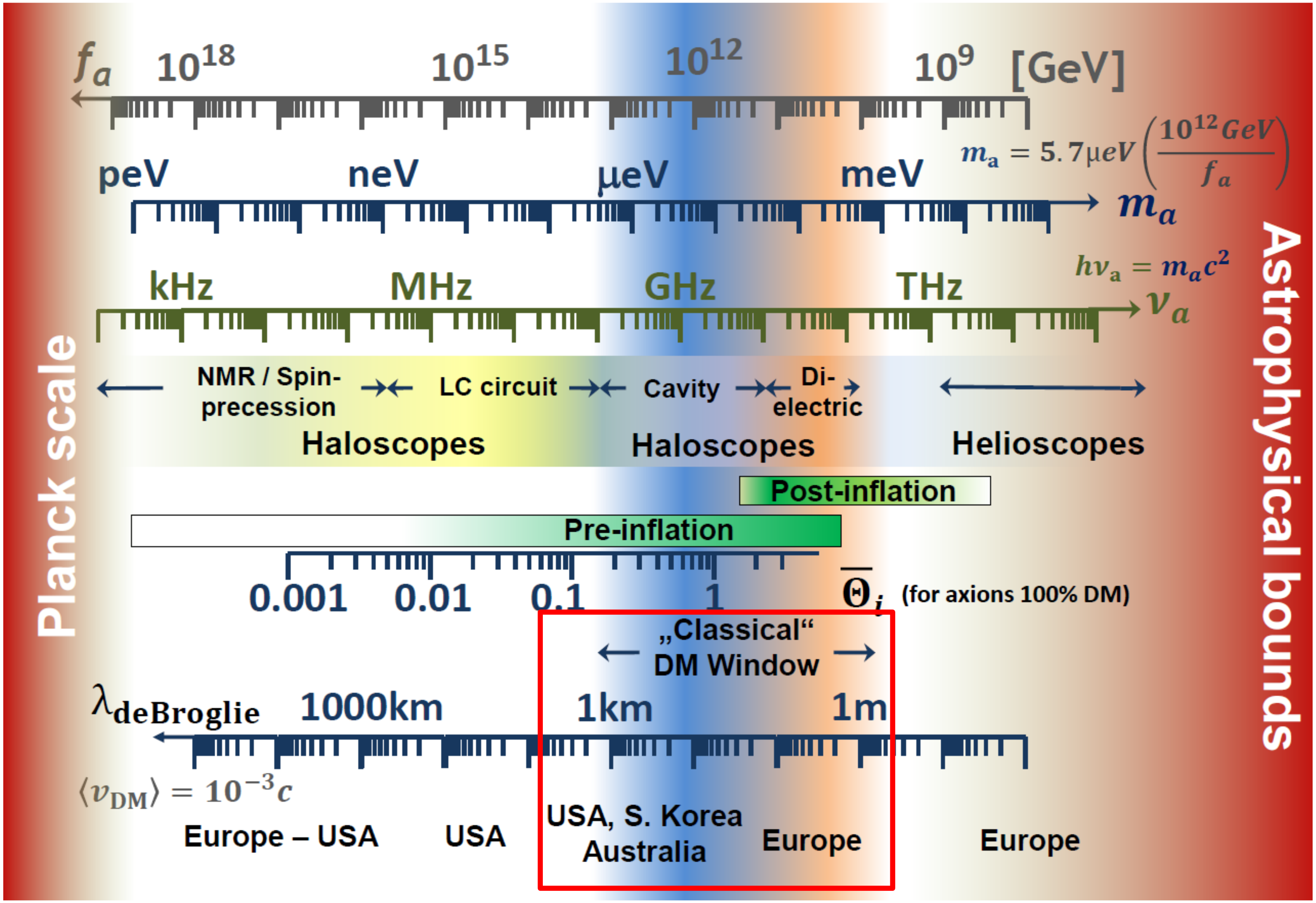


Courtesy of I. Irastorza (ISSAP2024)

Axion scales

APPEC Committee Report

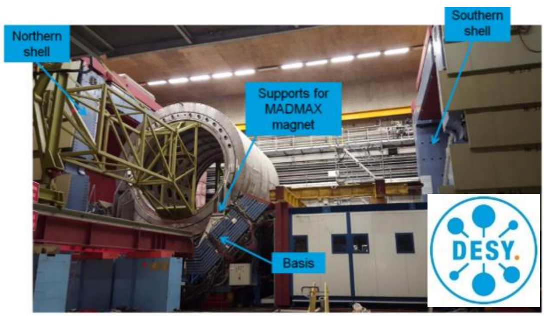
Rept. Prog. Phys., 85(5):056201, 2022, 2104.07634



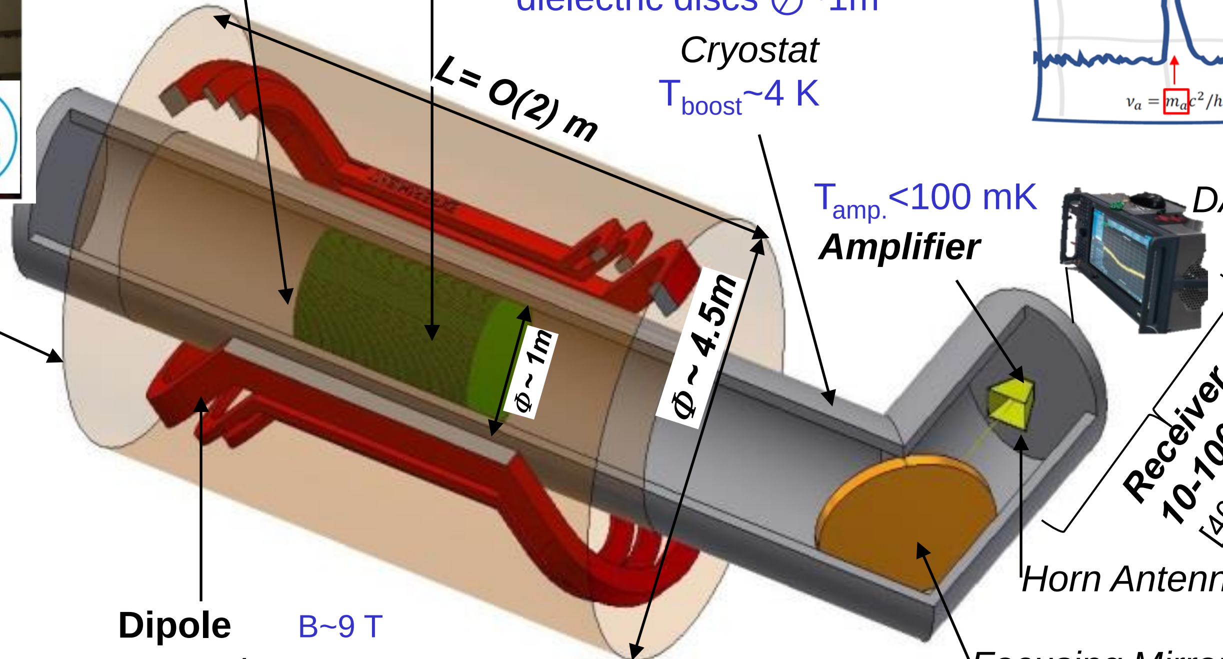
MADMAX

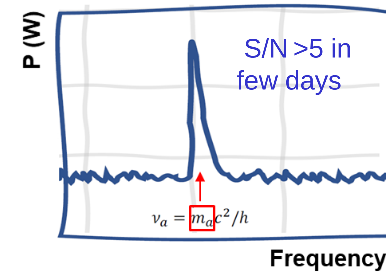
MAgnetized Disk and Mirror Axion eXperiment

EPJC 79 (2019) 186



Experiment location: HERA in former H1 iron yoke





MADMAX sensitivity

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

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

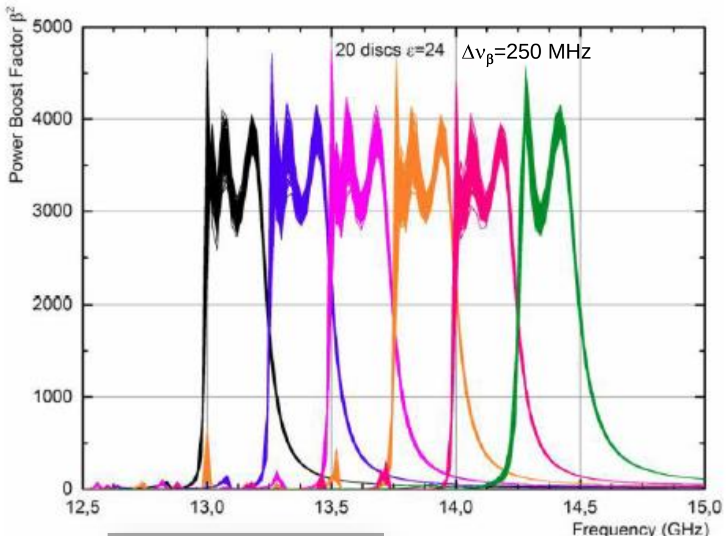
❑ Dark Photon kinetic mixing angle with photon, χ

(assuming unpolarized Dark Photon)

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

Boost factor

Tuning of sensitive frequency range by adjusting disc spacing



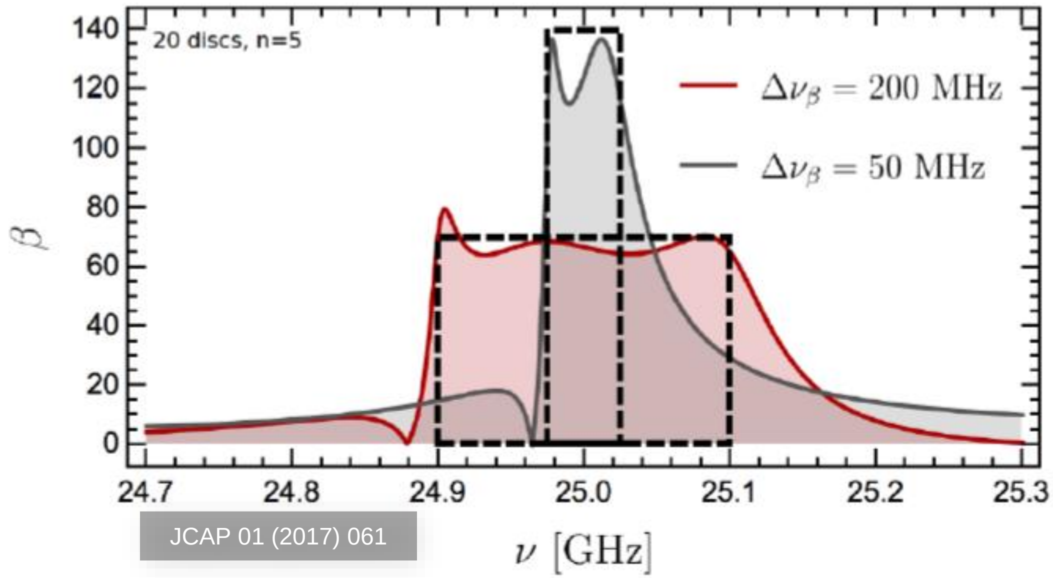
EPJC 79 (2019) 186

At each step, distance between disks changed by O(200 μm)

Area law: $\beta^2 \Delta\upsilon_\beta$ ~ const. $\propto N_{disks}$

→ broad-band scan for search

→ narrow-band to confirm possible signals



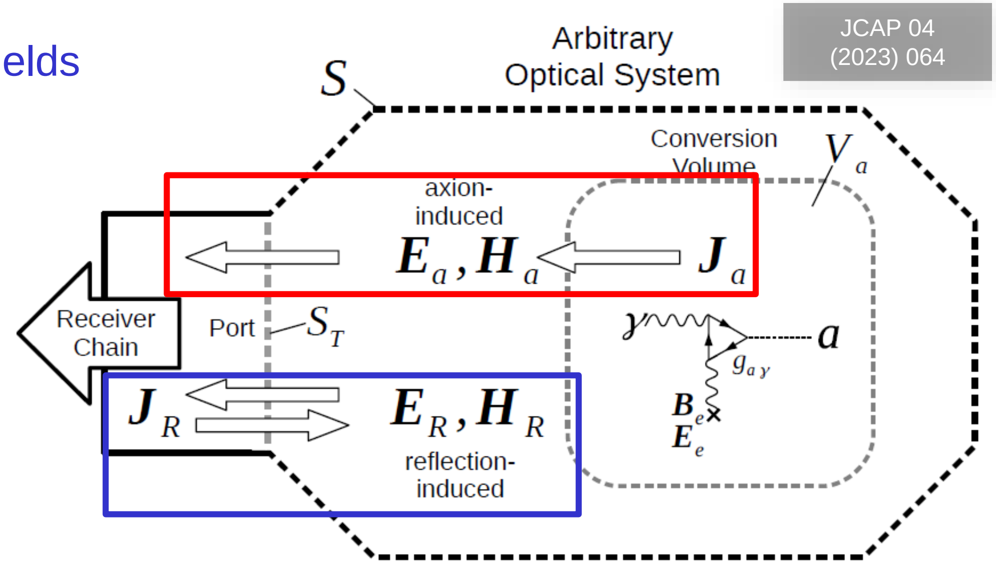
JCAP 01 (2017) 061

➔ **MADMAX versatility**

In situ determination of boost factor

- 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 (VNA), sourcing reflection-induced fields E_R, H_R

JCAP 04 (2023) 064



- Allows to express haloscope sensitivity to axions/DP from measurement of reflection-induced field

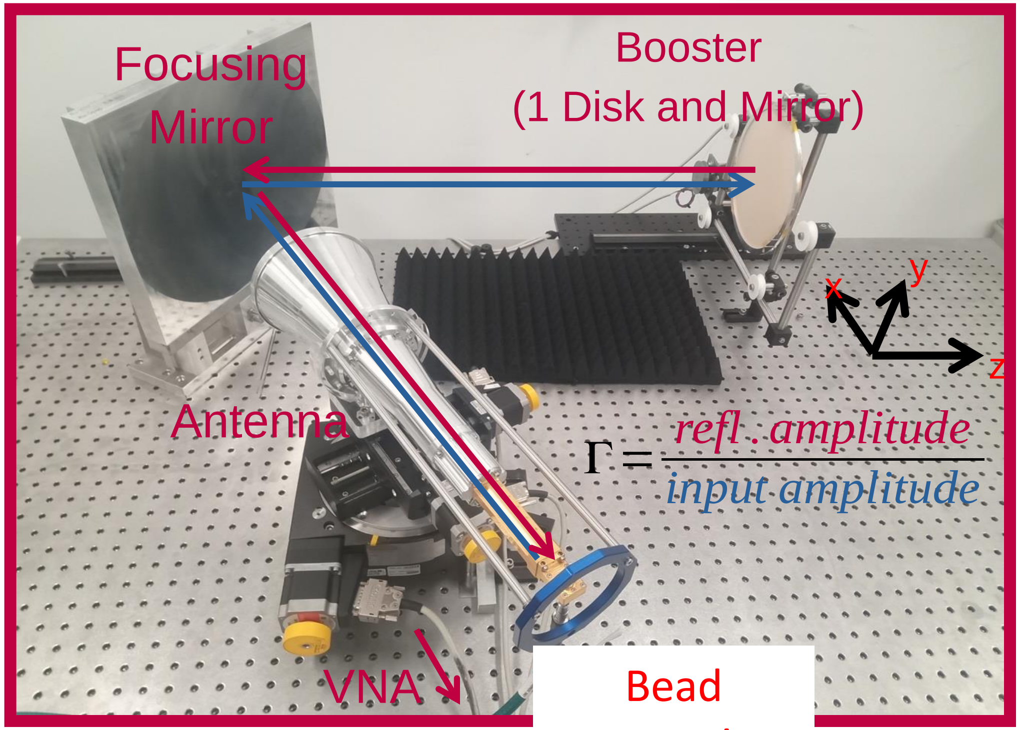
$$\beta^2 \propto \left| \int dV \, E_R \right|^2$$

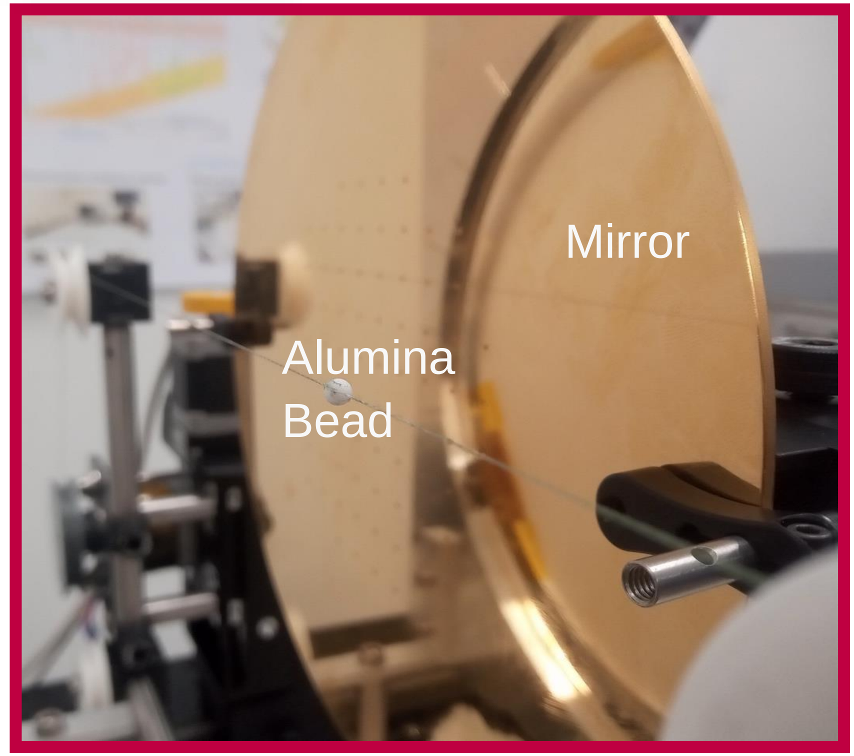
→ measured from non-resonant bead-pull method (next slide)

In situ determination of boost factor

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

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





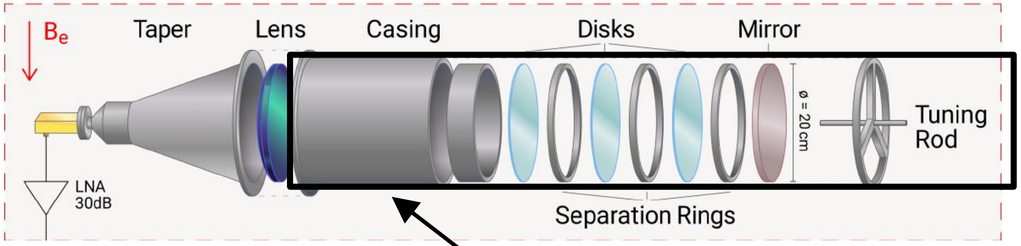
Bead properties

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

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

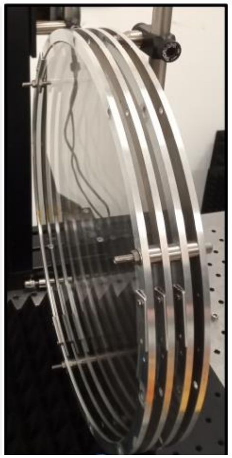
Closed vs open booster

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

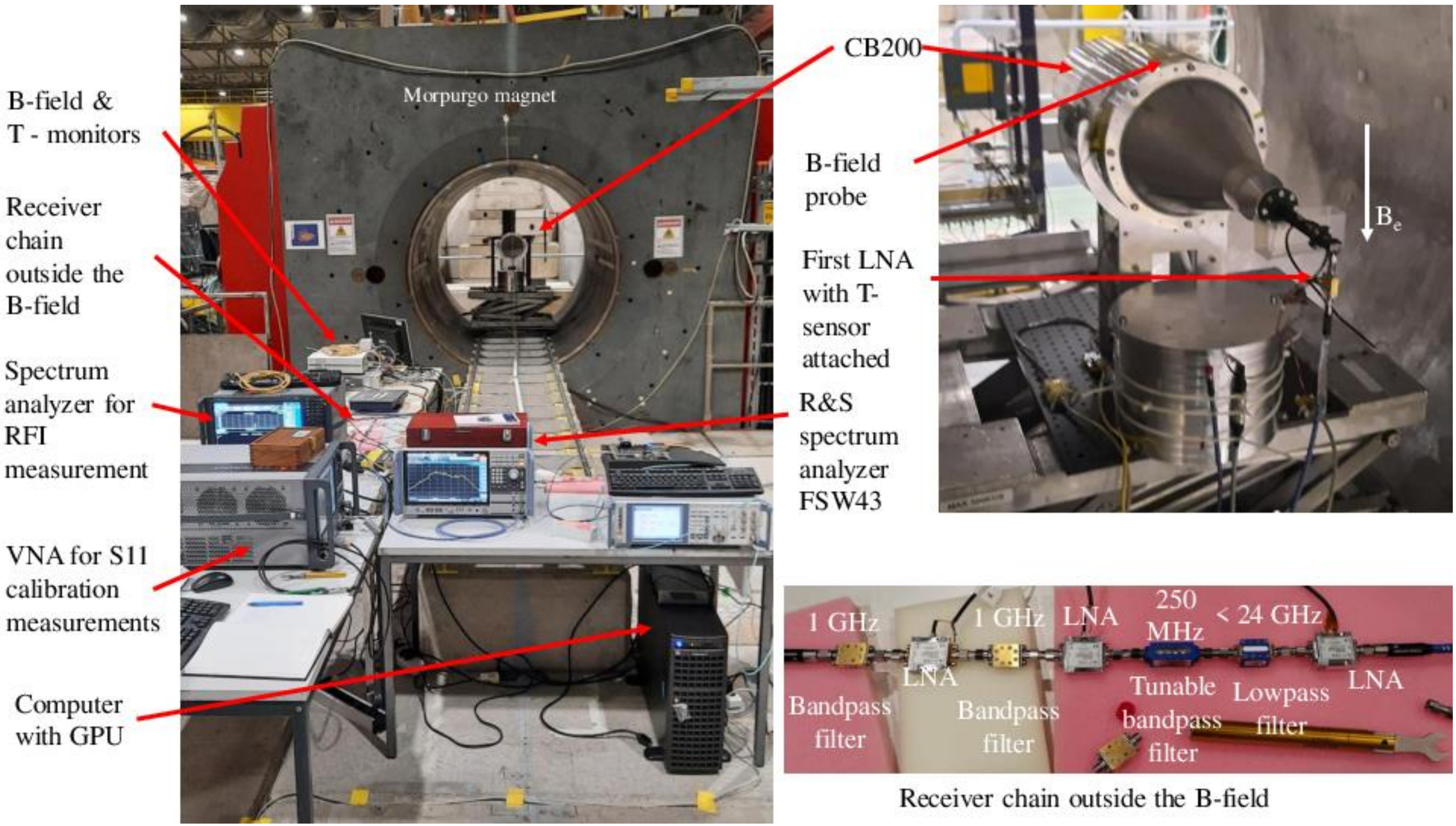
Open booster



- 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

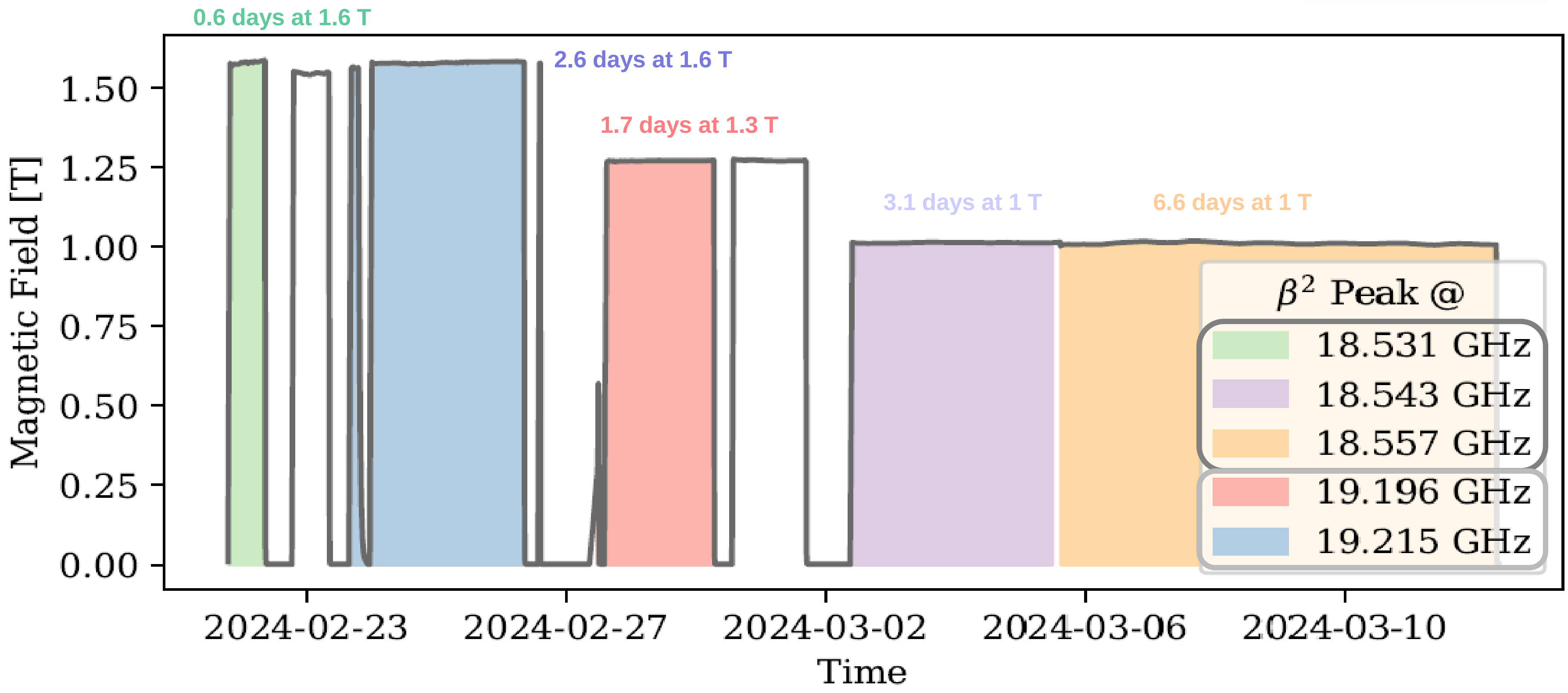
MADMAX search for axion

arXiv:2409.11777
(accepted by PRL)



MADMAX search for axion

arXiv:2409.11777
(accepted by PRL)



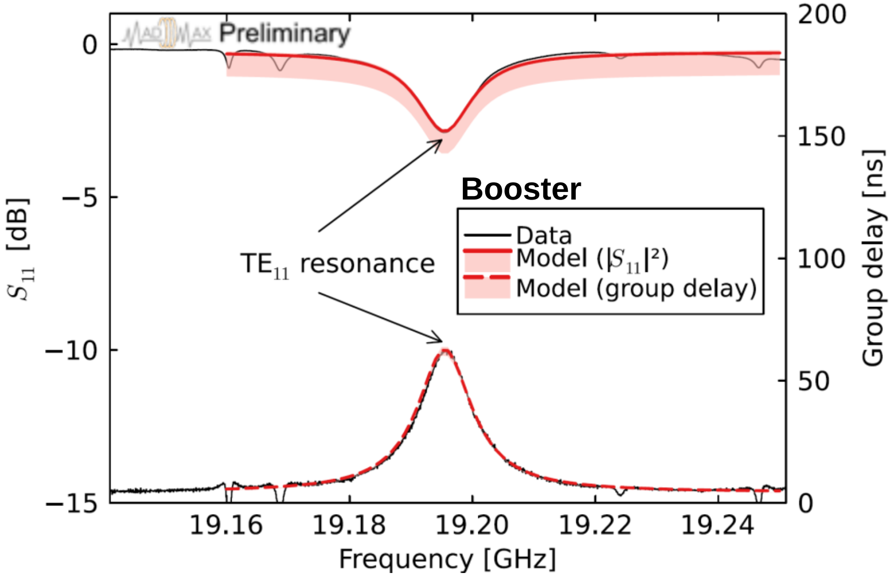
MADMAX search for axion

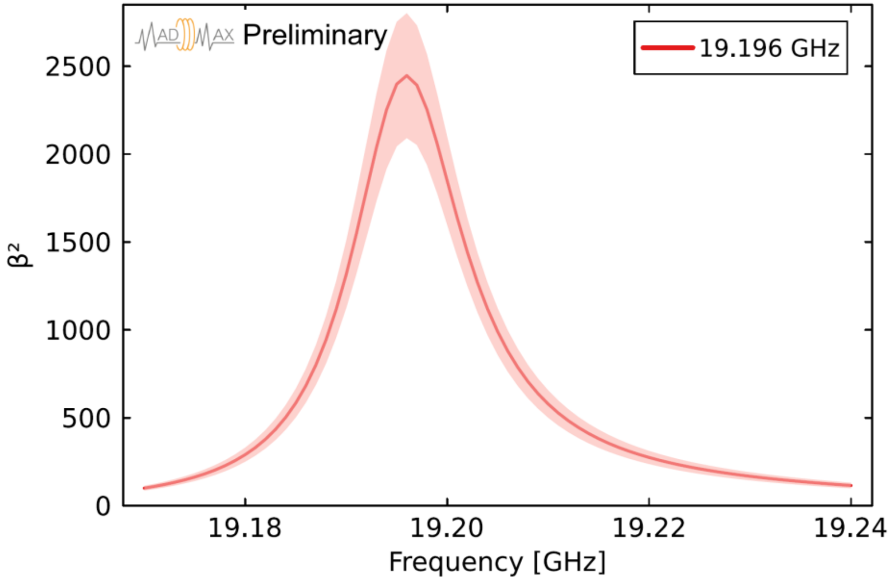
❑ Modelling the boost factor

paper in preparation

- **Booster 1D model** obtained by fitting VNA reflectivity measurements
  - ✓ 3D effects taken into account and corrected for
- **Receiver model** obtained by fitting standard calibration measurements (short, open, load) noise diode
- **Booster + receiver model** obtained by fitting system noise measurements in [18, 20] GHz

➔ allows to determine systematic uncertainties from fit parameters





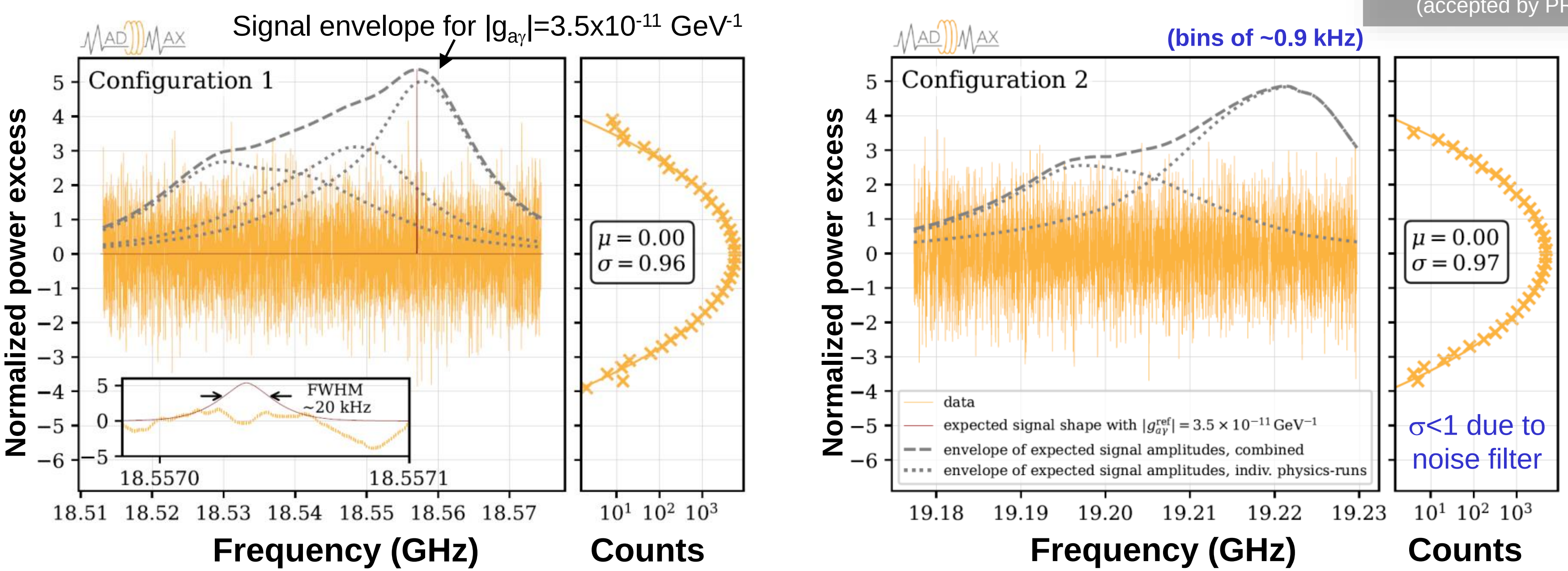
➔ Boost factor curves determined at 15%

MADMAX search for axion

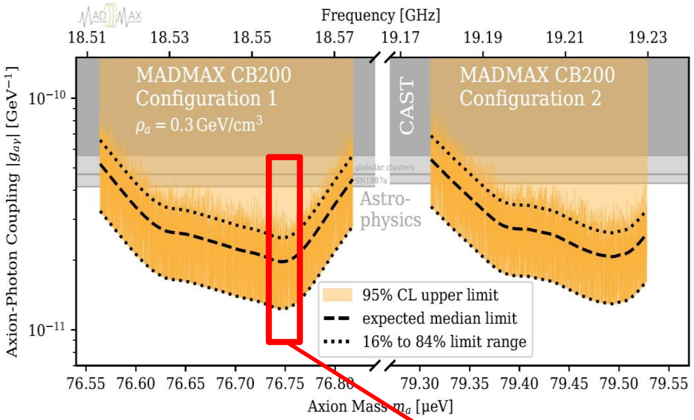
❑ Full power spectrum data analysis [HAYSTACK procedure PRD96 (2017) 1523008]

- 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 ~25 neighboring bins)
- Normalize by thermal noise σ_{Noise} ($\propto T_{sys}$) → Normalized power excess vs frequency

arXiv:2409.11777 (accepted by PRL)



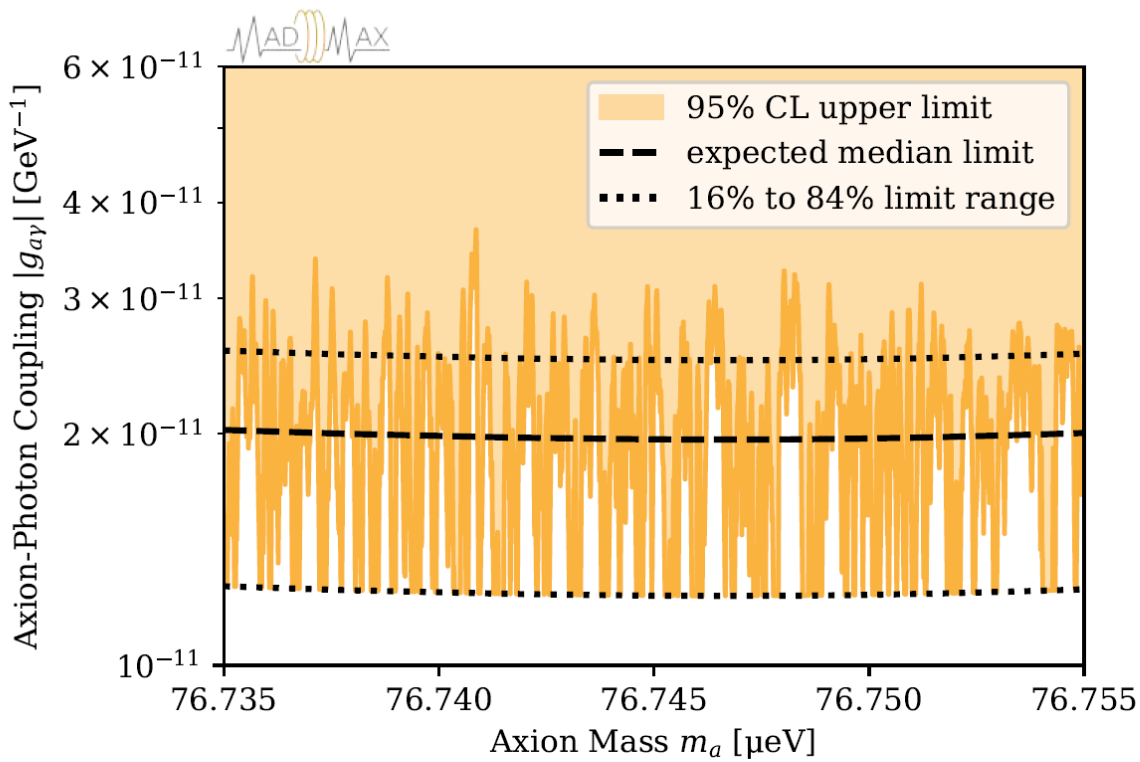
MADMAX search for axion



Zoom

(bins of ~0.9 kHz)

arXiv:2409.11777 (accepted by PRL)



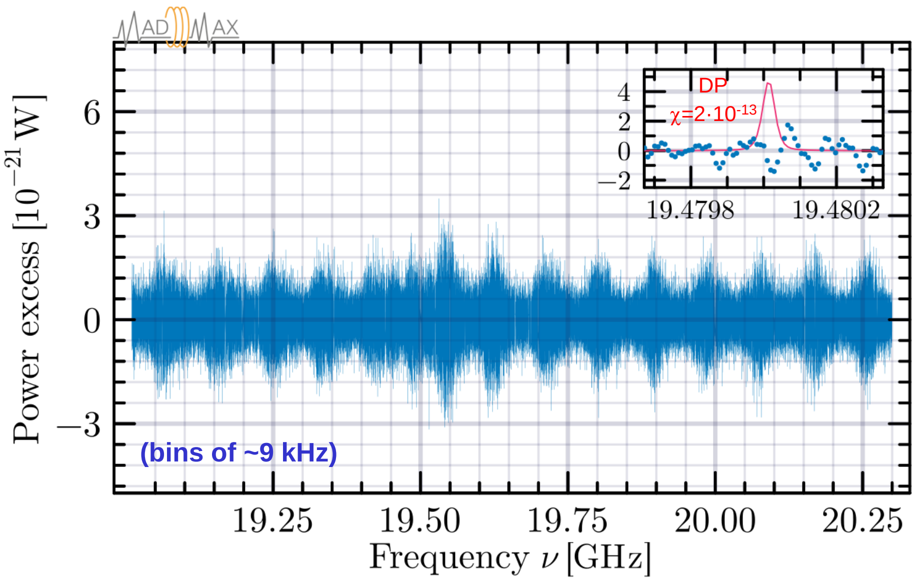
MADMAX search for Dark Photon

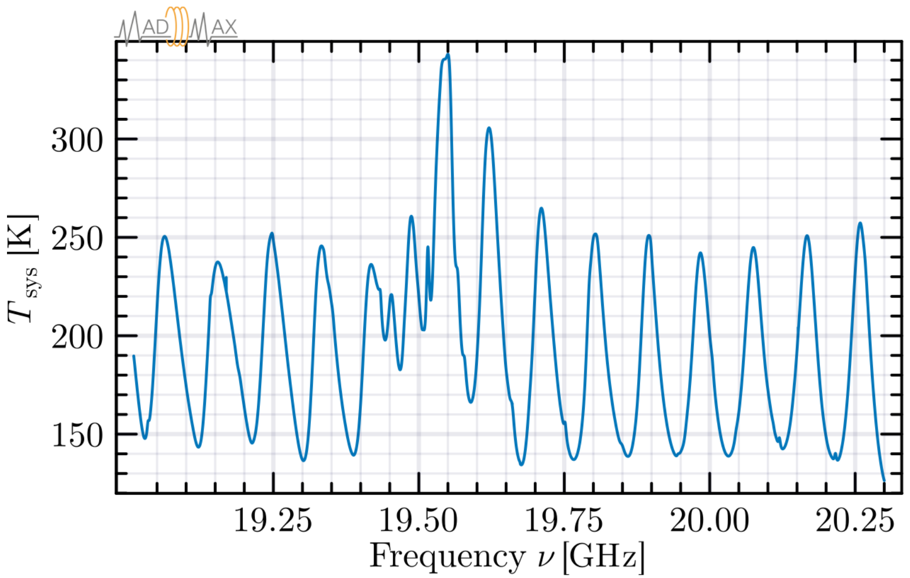
Fluctuations of power from thermal radiations → standard deviation = $k_B \cdot T_{sys} \cdot \mathrm{sqrt}(\Delta\nu/t)$

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

T_{sys} = system noise temperature

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





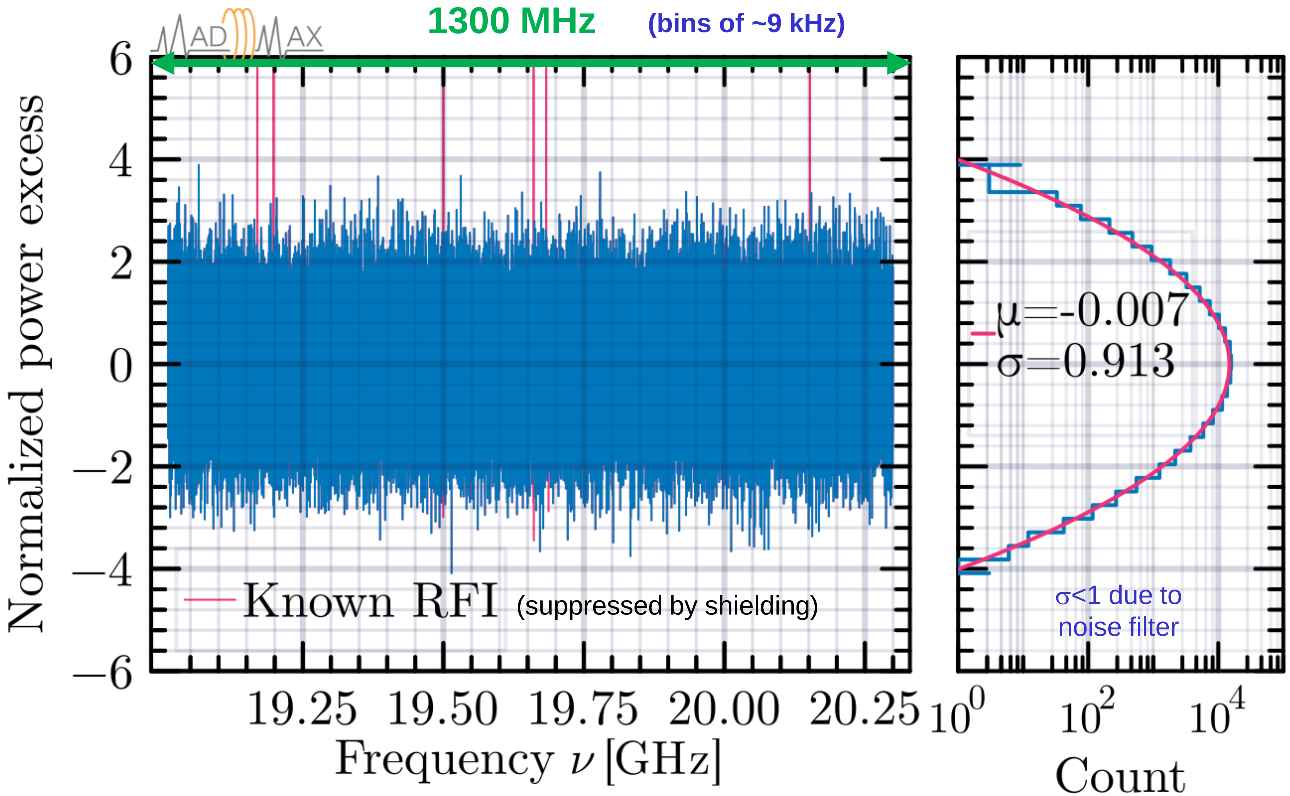
Broadband oscillatory standing wave due to LNA noise interfering with its reflections in the booster

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

PRL134 (2025) 151004

MADMAX search for Dark Photon

PRL134 (2025) 151004



➔ No signal of unknown origin

Systematic uncertainties

Axion search

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

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

boost factor

arXiv:2409.11777
(accepted by PRL)

Dark photon search

Impact of systematics on χ limit

Effect	Uncertainty on χ
Boost factor determination	
Bead-pull measurements (frequency dependent)	2 to 17%
Bead pull finite domain correction	5%
Receiver chain impedance mismatch	<1%
Subtotal	5 to 18%
Y-factor calibration	4%
Power stability	3%
Frequency stability	2%
Line shape discretization	4%
Total	9 to 19%

PRL134 (2025) 151004

➔ Dominated in both cases by uncertainties on boost factor determination

Towards final MADMAX

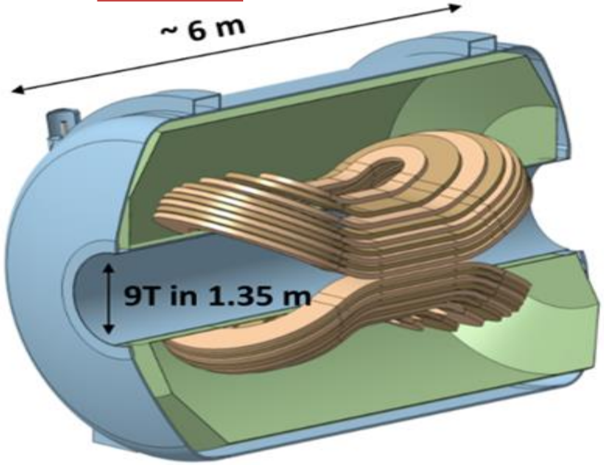
❑ Dipole magnet

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

[NbTi with Cu jacket @ 1.8K]

BILFINGER NOELL GMBH

cea



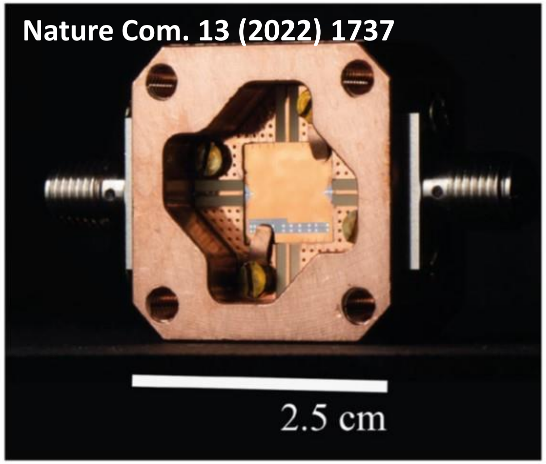
- Demonstrated that coils will be safe in terms of quench protection **IEEE TAS 33 (2023) 1**

❑ Receiver Chain

- For now use classic low noise amplifier

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

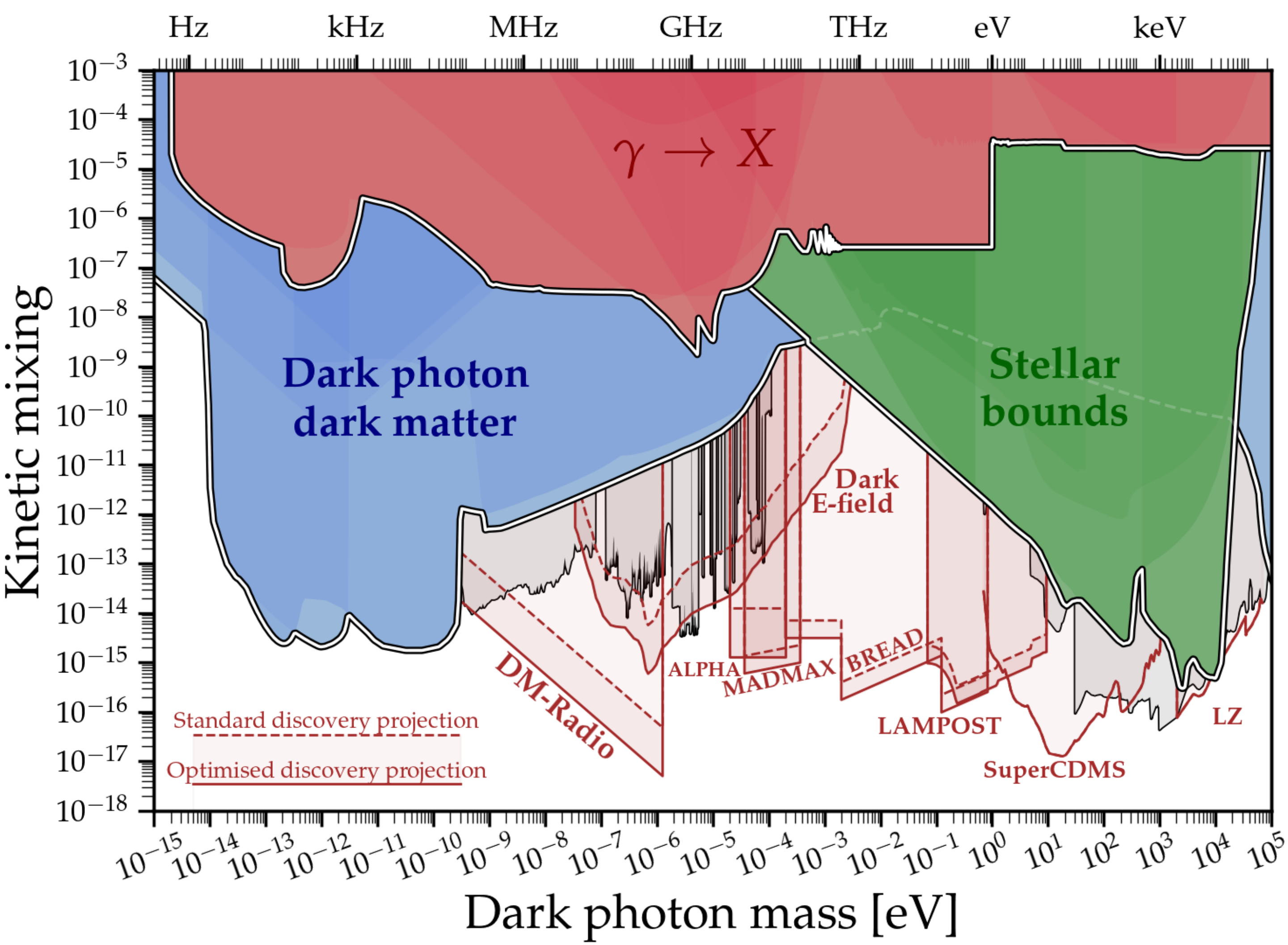
- Josephson Junction being developed to further minimize noise *(quantum limit)*



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

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

Dark Photon: projections



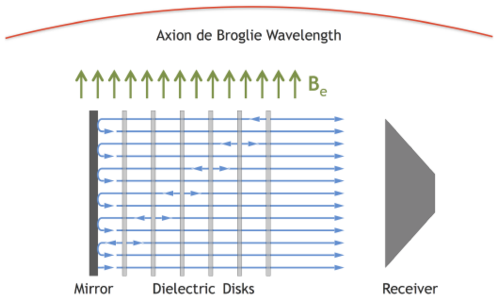
PRD104 (2021) 095029

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

Directionality with MADMAX

JCAP 10 (2017) 006   EPJC 78 (2018) 793

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



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

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

- ➢ 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 λ/2 → 3λ/2, 5λ/2
- → Increase the number of disks