The MADMAX experiment: First dark matter constraints and the road ahead

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On behalf of the MADMAX Collaboration, August 26th, 2025

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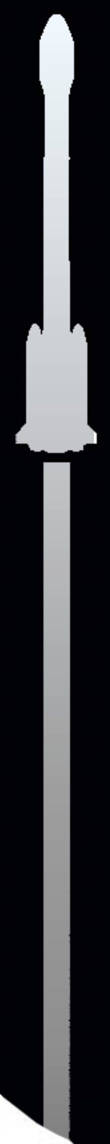
Motivation and need for MADMAX

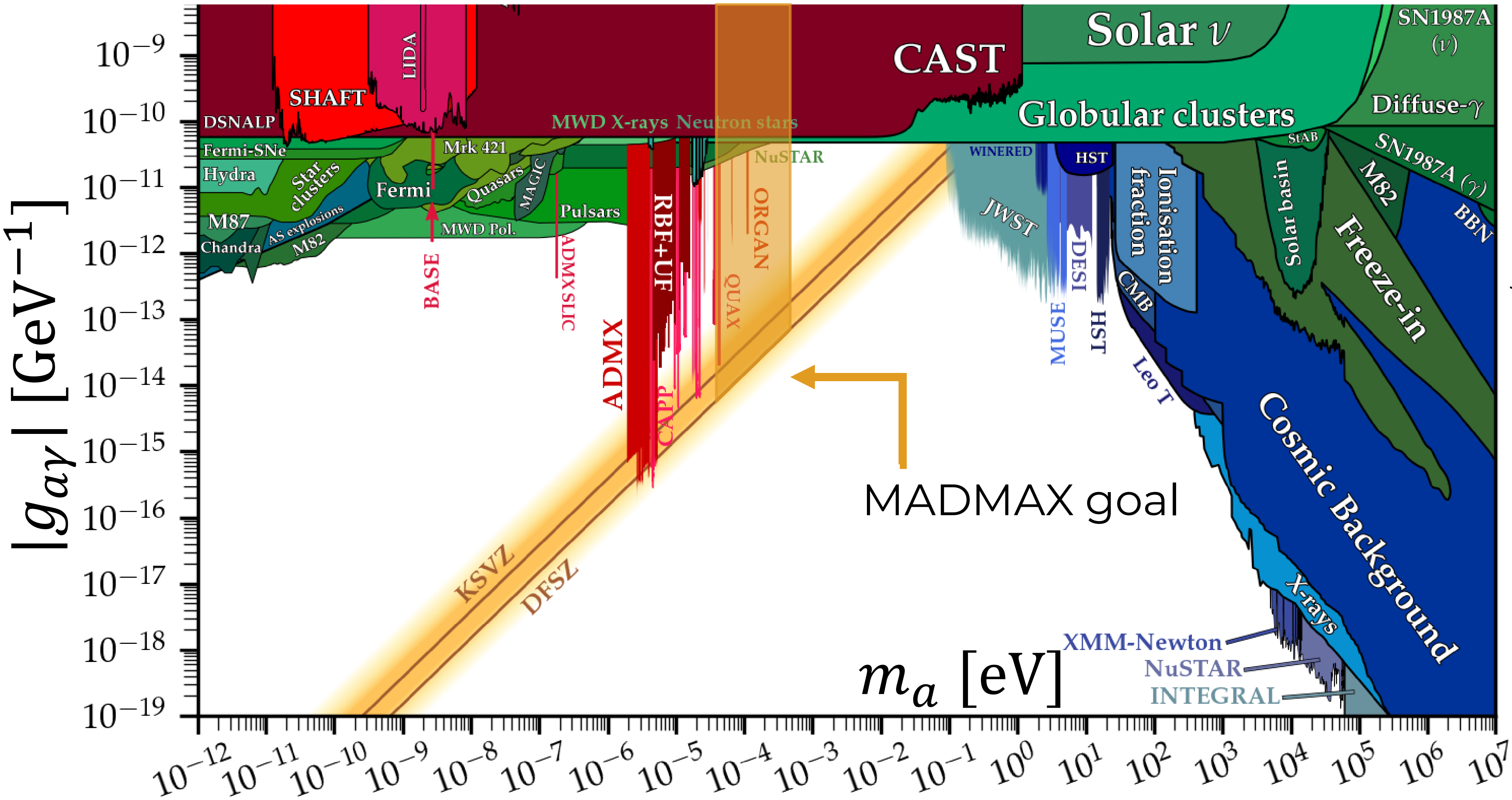
The 40-400 μeV axion region

From particles to waves

Dielectric haloscope approach

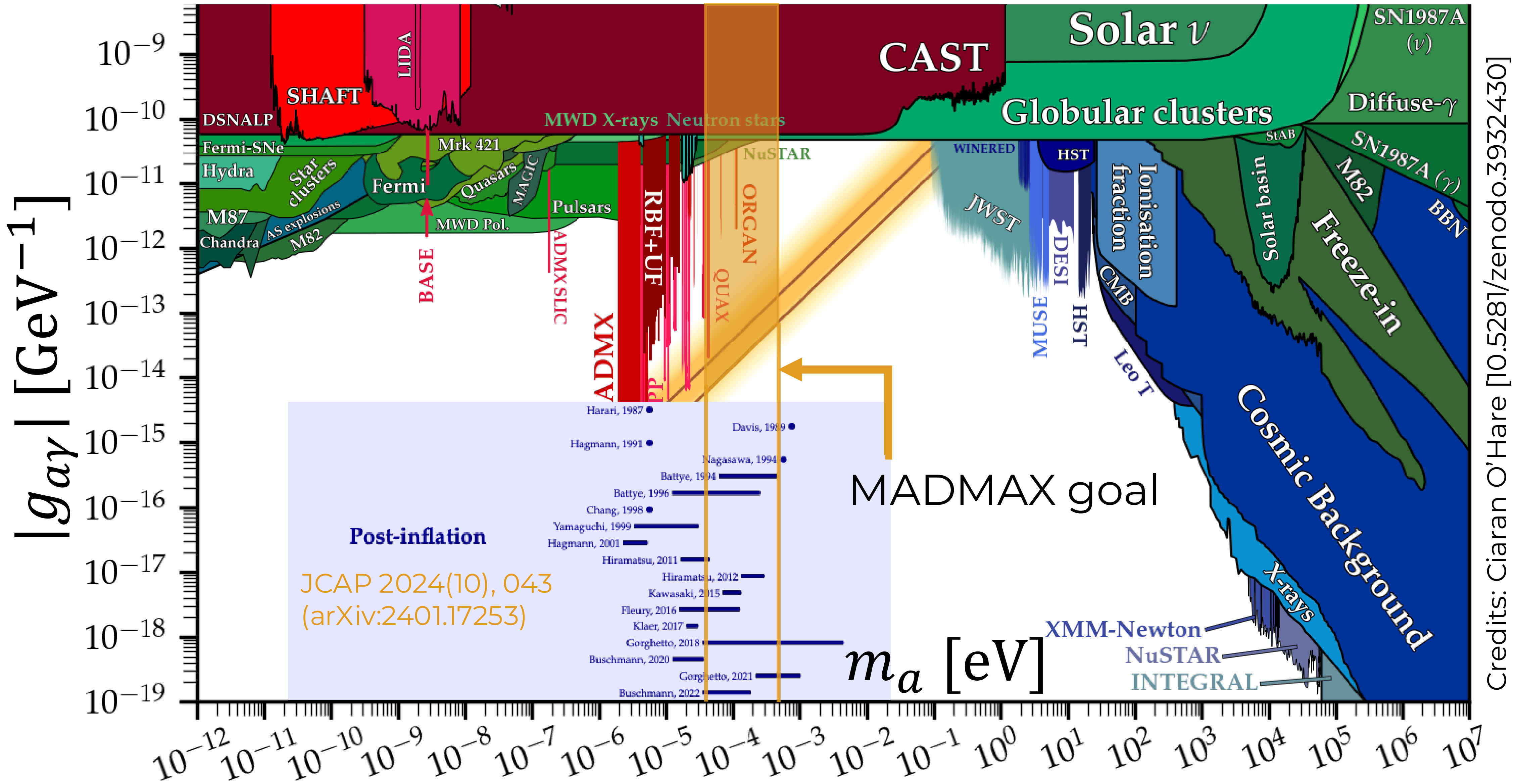


Importance of the 40-400 μeV region



Credits: Ciaran O'Hare [10.5281/zenodo.3932430]

Importance of the 40-400 μeV region

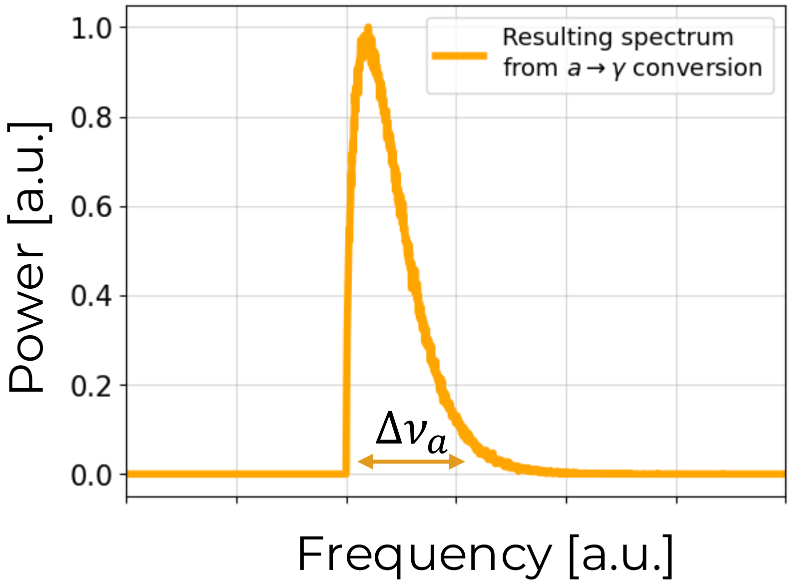


From particles to waves

Note that due to energy conservation

$$m_a c^2 + \frac{1}{2} m_a v^2 = h\nu_a$$

$$\nu_a = \frac{m_a c^2}{h}\left(1 + \frac{1}{2}\left(\frac{v}{c}\right)^2\right)$$



Given that the DM velocity in our halo is $v \sim 10^{-3}c$ with a dispersion velocity $\Delta v \sim v$, the spread of axion-induced photon frequencies is

$$\frac{\Delta\nu_a}{\nu_a} \approx \frac{1}{2}\left(\frac{v}{c}\right)^2 \approx 10^{-6}$$

The coherence time of the axion-induced photon emission is $\tau_c \approx \frac{1}{\Delta\nu_a}$.

For $m_a = 10\ \mu\text{eV}, \tau_c = 1\ \text{ms}$

From particles to waves

If the experiment is smaller than $\sim \lambda^3_{\text{deBroglie}}$:

$$\lambda_{\text{deBroglie}} = \frac{h}{p} \sim \frac{h}{m_a \langle v_{DM} \rangle} \sim 75m \cdot \left(\frac{\mu eV/c^2}{m_a} \right)$$

and data is taken for a time $\tau < \tau_c \approx \frac{1}{\Delta \nu_a}$,

the axion-photon conversion can be thought as a source of coherent microwave radiation:

$$\boldsymbol{E_a}(\boldsymbol{t}) = -\frac{g_{a\gamma}\overrightarrow{\boldsymbol{B_0}}}{\epsilon}\boldsymbol{a}(\boldsymbol{t}), \text{ with } a(t) = a_0 \cos(m_a t)$$

$a_0 \propto \sqrt{\rho_{DM}}$

Dielectric haloscope

[arXiv:1611.05865 (PRL 118, 091801 (2017))]

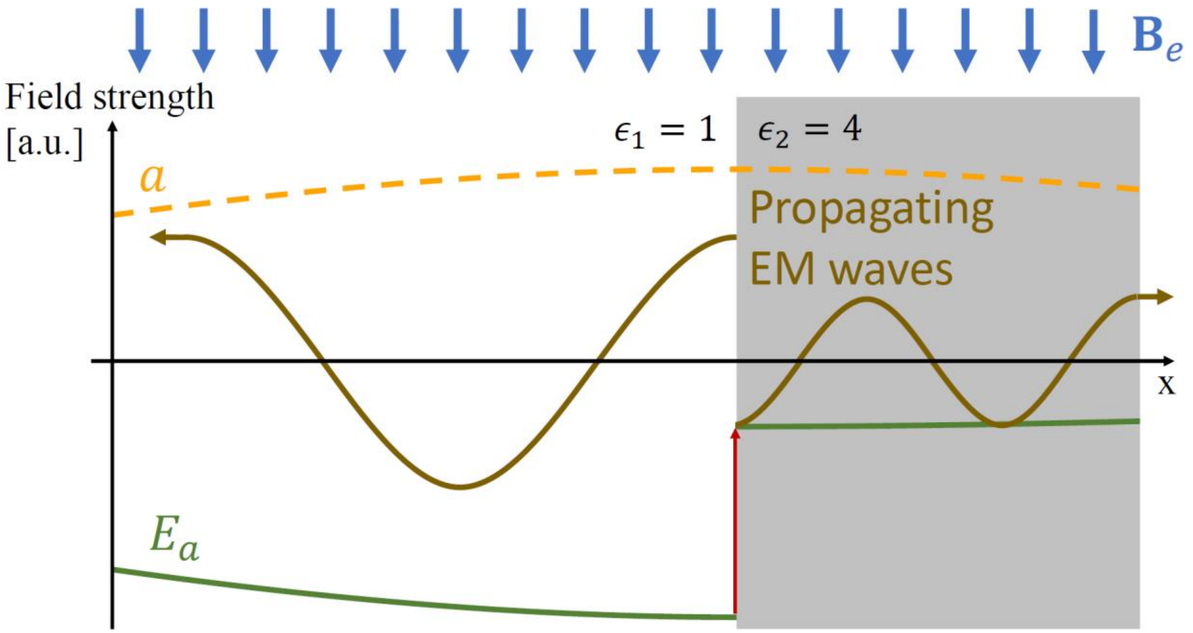
1) Induce inverse Primakoff effect in a strong external B field

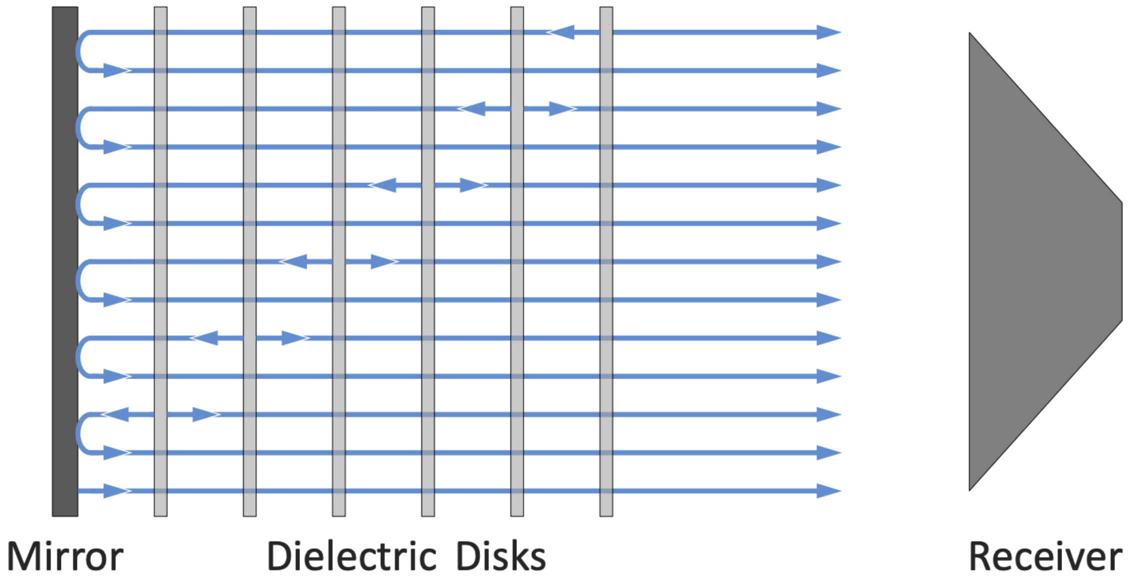
$$\overrightarrow{E_a} = -\frac{g_{a\gamma}\overrightarrow{B_e}}{\epsilon} a_0 \cos(m_a t)$$

2) Boost the signal using dielectric discontinuities: Constructive interference and resonance effects

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

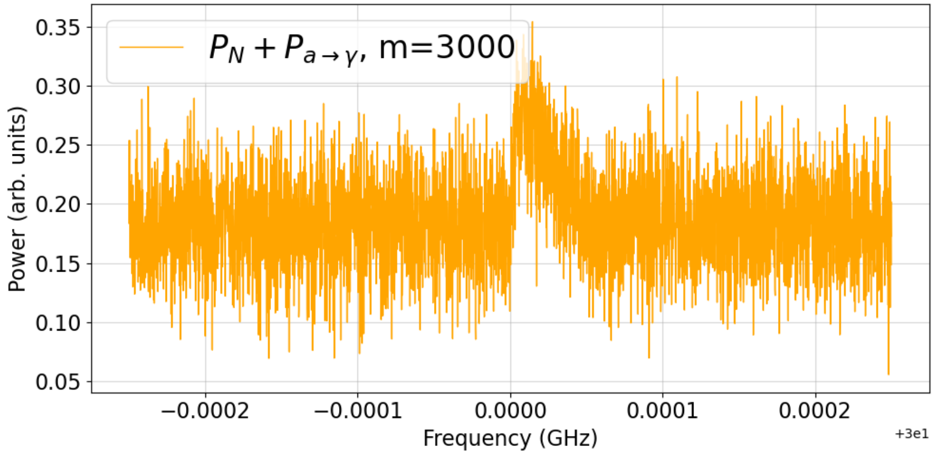
3) Maximize signal, minimize noise





Dielectric haloscope

[arXiv:1611.05865 (PRL 118, 091801 (2017))]



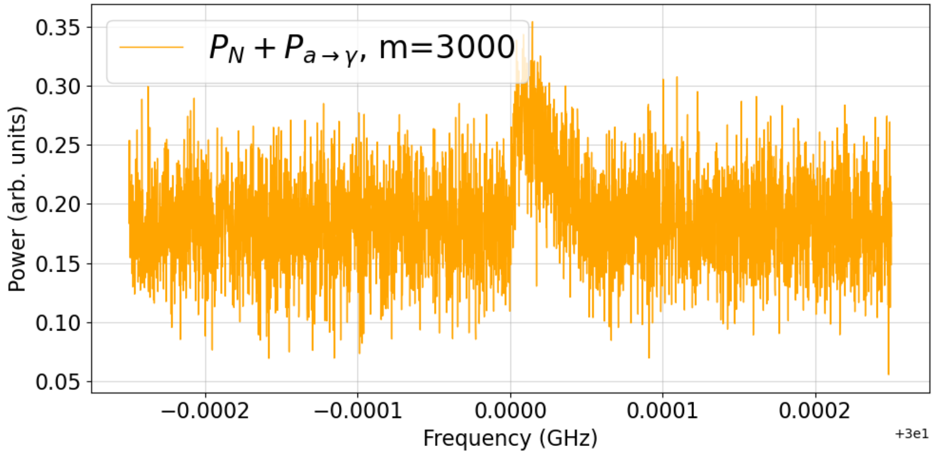
$$\mathrm{SNR} = \frac{P_{a\to\gamma}}{\sigma(P_N)}$$

$$P_{a\to\gamma} \propto \beta^2 \int \langle\vec{S}\rangle \cdot d\vec{A} \propto A\left\langle\overrightarrow{E_a^2}\right\rangle \propto \beta^2 g_{a\gamma}^2 B_e^2 \rho_{DM} A$$

Disc area $A = \pi r^2$

Dielectric haloscope

[arXiv:1611.05865 (PRL 118, 091801 (2017))]



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Disc area $A = \pi r^2$

Frequency resolution $\sim \Delta\nu_a \propto 10^{-6} m_a$

$$\sigma(P_N) = \frac{P_N}{\sqrt{m}} = \frac{kBT_N}{\sqrt{m}} = \sqrt{\frac{\Delta\nu}{\tau}}\, kT_N$$

Total integration time

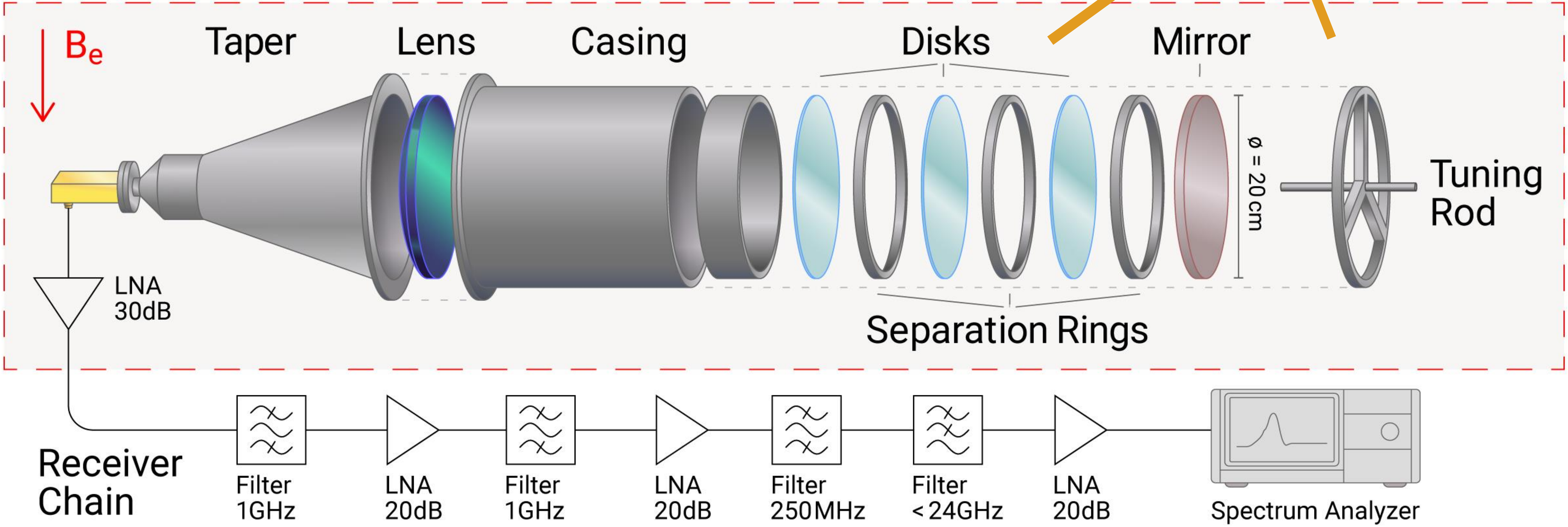
Noise power in terms of an effective black-body temperature.

What is the lowest $g_{a\gamma}$ we can probe ($\mathrm{SNR} \sim 5$) given a setup?

Prototype: Closed Booster (CB200)

[PRL 135 (2025): 041001. (arXiv:2409.11777)]

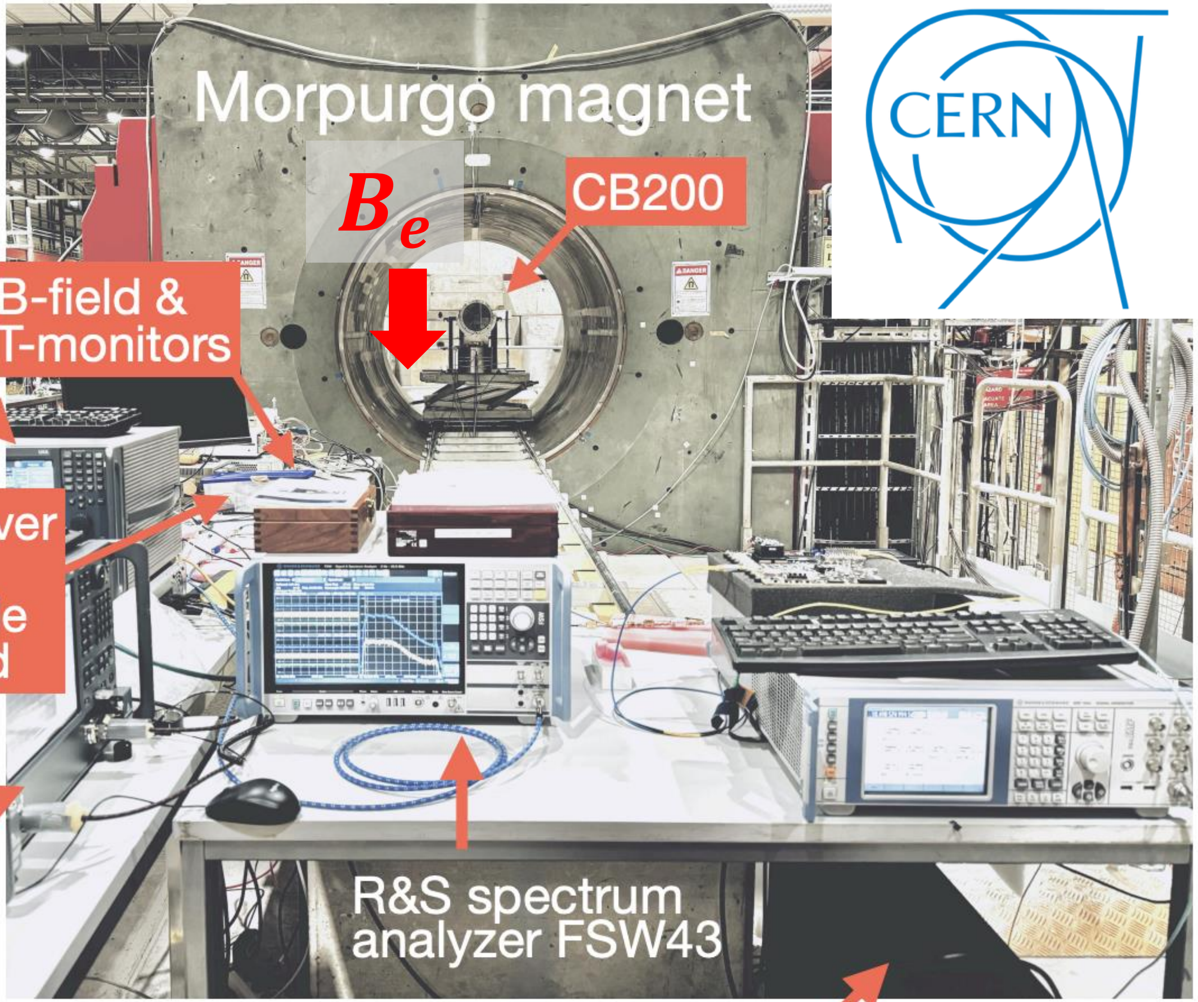
Manual tunability by rod and spacer thickness



$$|g_{a\gamma}| = 3.5\times10^{-11}\,\mathrm{GeV}^{-1}\left(\frac{T_{\mathrm{N}}}{300\ \mathrm{K}}\right)^{\frac{1}{2}}\left(\frac{2.2\ \mathrm{days}}{\tau}\right)^{\frac{1}{4}}\left(\frac{m_a}{80\ \mu\mathrm{eV}}\right)^{\frac{5}{4}}\left(\frac{0.3\ \mathrm{GeV/cm^3}}{\rho_a}\right)^{\frac{1}{2}}\left(\frac{2000}{\beta^2}\right)^{\frac{1}{2}}\left(\frac{0.1\ \mathrm{m}}{r}\right)\left(\frac{1\ \mathrm{T}}{B_e}\right)\left(\frac{\mathrm{SNR}}{5}\right)^{\frac{1}{2}}$$

Local DM density

Prototype closed booster for axion search



Spectrum analyzer for RFI measurement

VNA for S11 calibration measurements

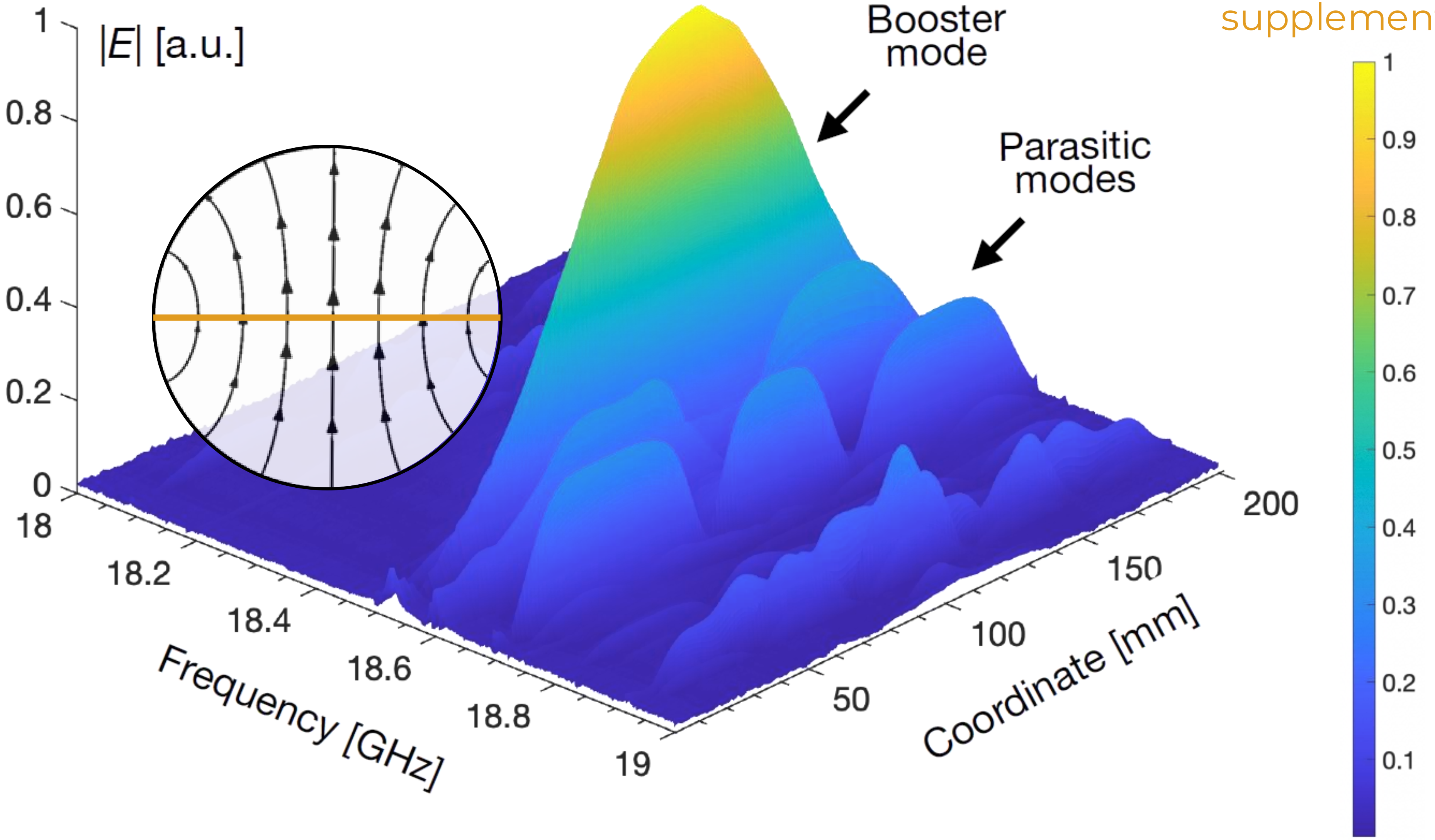
Computer with GPU

Many thanks to

Calibration and analysis procedure

Booster mode identification
Boost factor determination
Axion search exclusion limit

Identification of booster mode



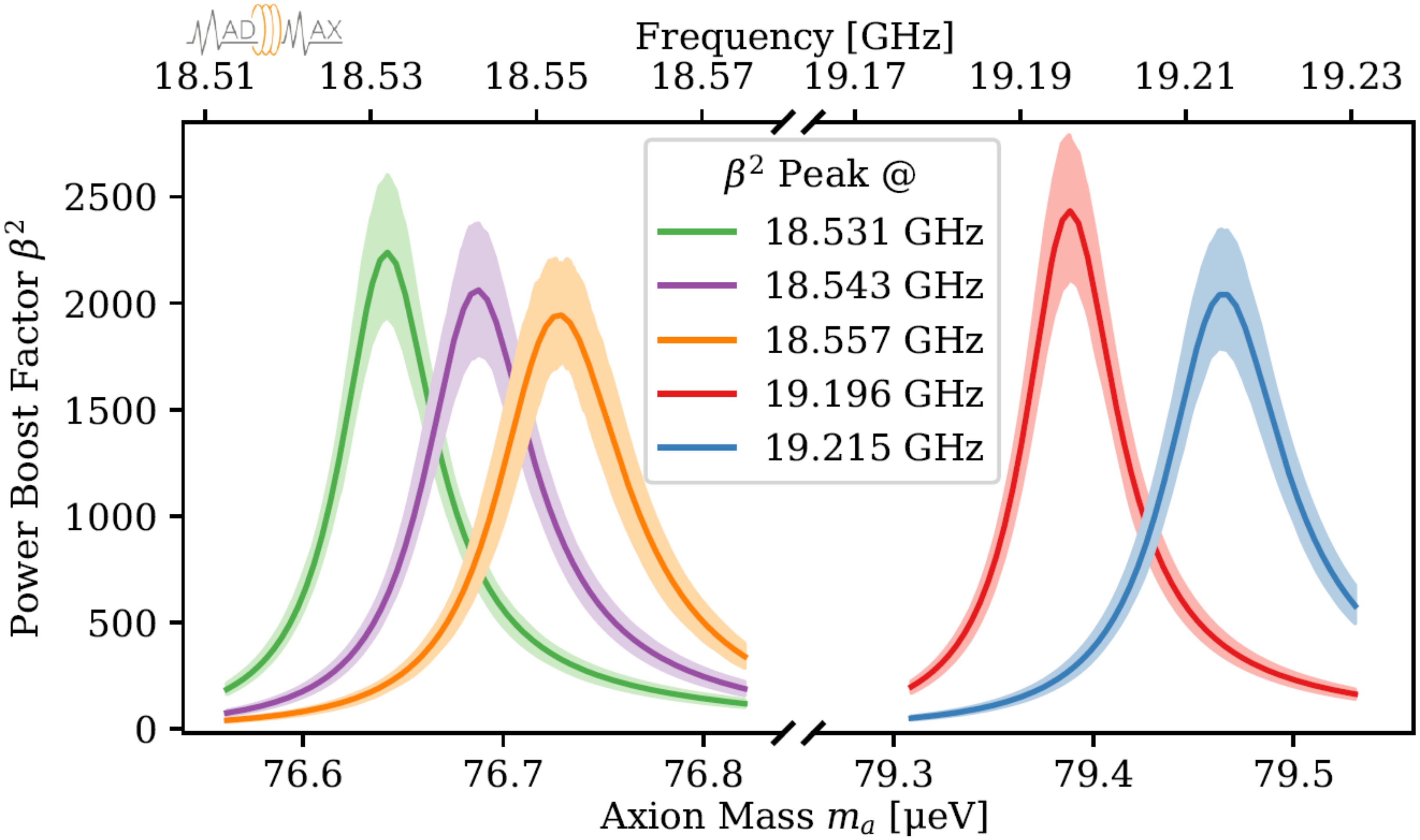
PRL. 135, 4, 041001 (2025) supplemental material

Experimental identification of the booster mode.

Clear distinction of TE_{11} with respect to parasitic/higher order modes

Modeled boost factor distributions

[arXiv:2409.11777 (PRL 135 (2025): 041001)]



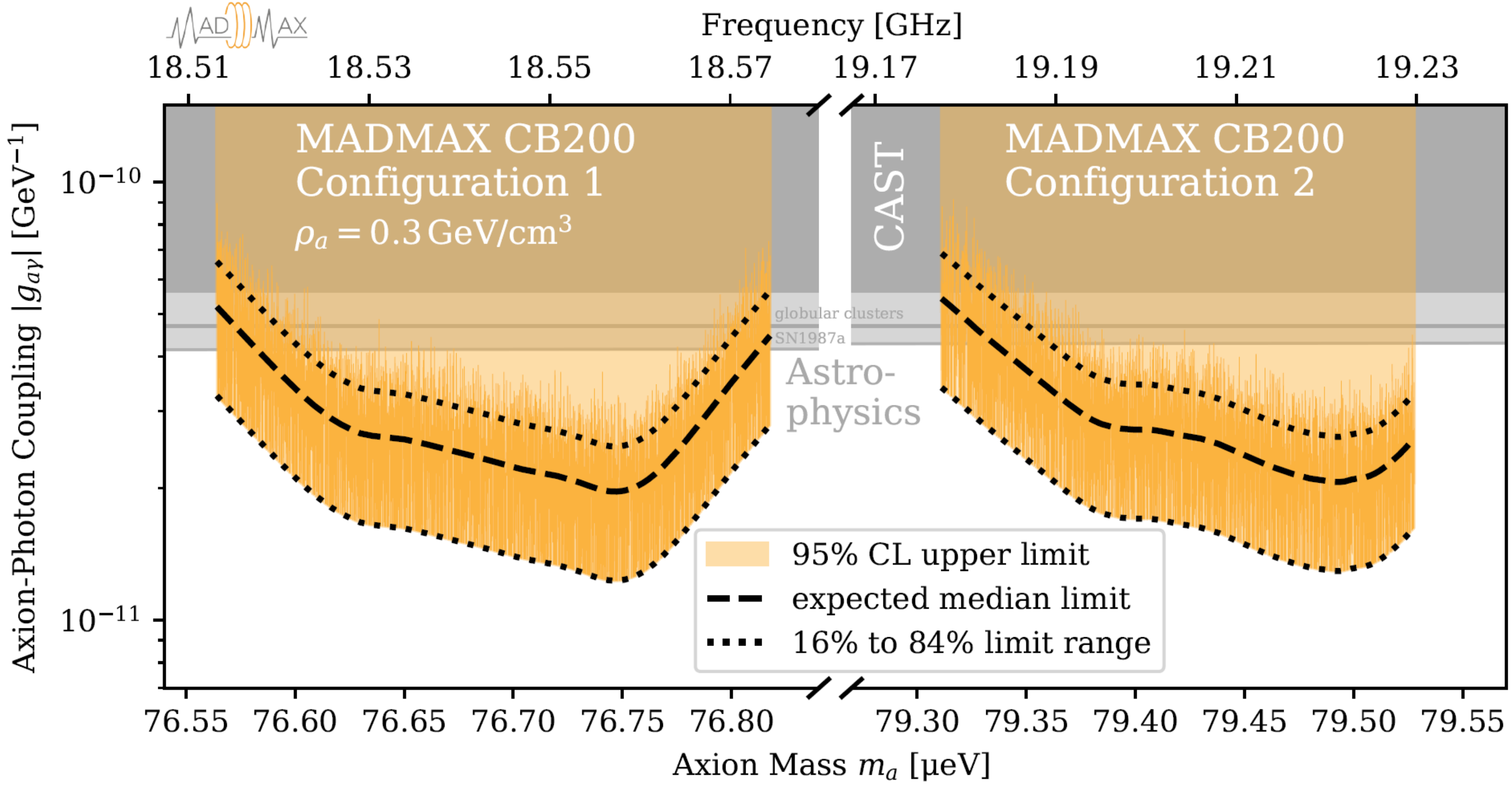
β^2 around 2000 with only 3 disks + mirror.

Uncertainties of ~15%.

First dielectric haloscope ALP limit

[PRL 135 (2025): 041001. (arXiv:2409.11777)]

World's best limit on this frequency region and first axion-like particle search using a dielectric haloscope



~ 2 times more sensitive than CAST and globular clusters limits

Limit set in two regions around 76 µeV and 79 µeV covering ~ 100 MHz

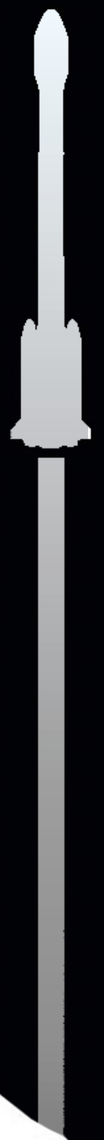
Opening the system

The open booster setup

Experimental determination of β^2

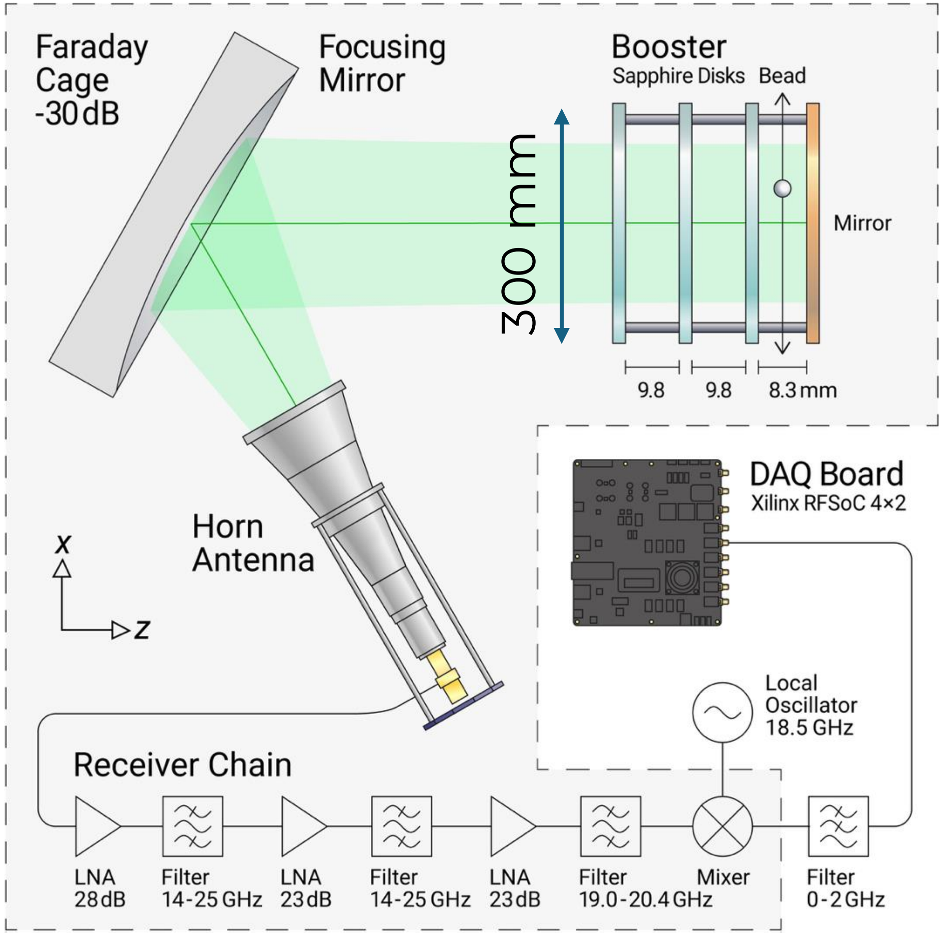
Dark photon run

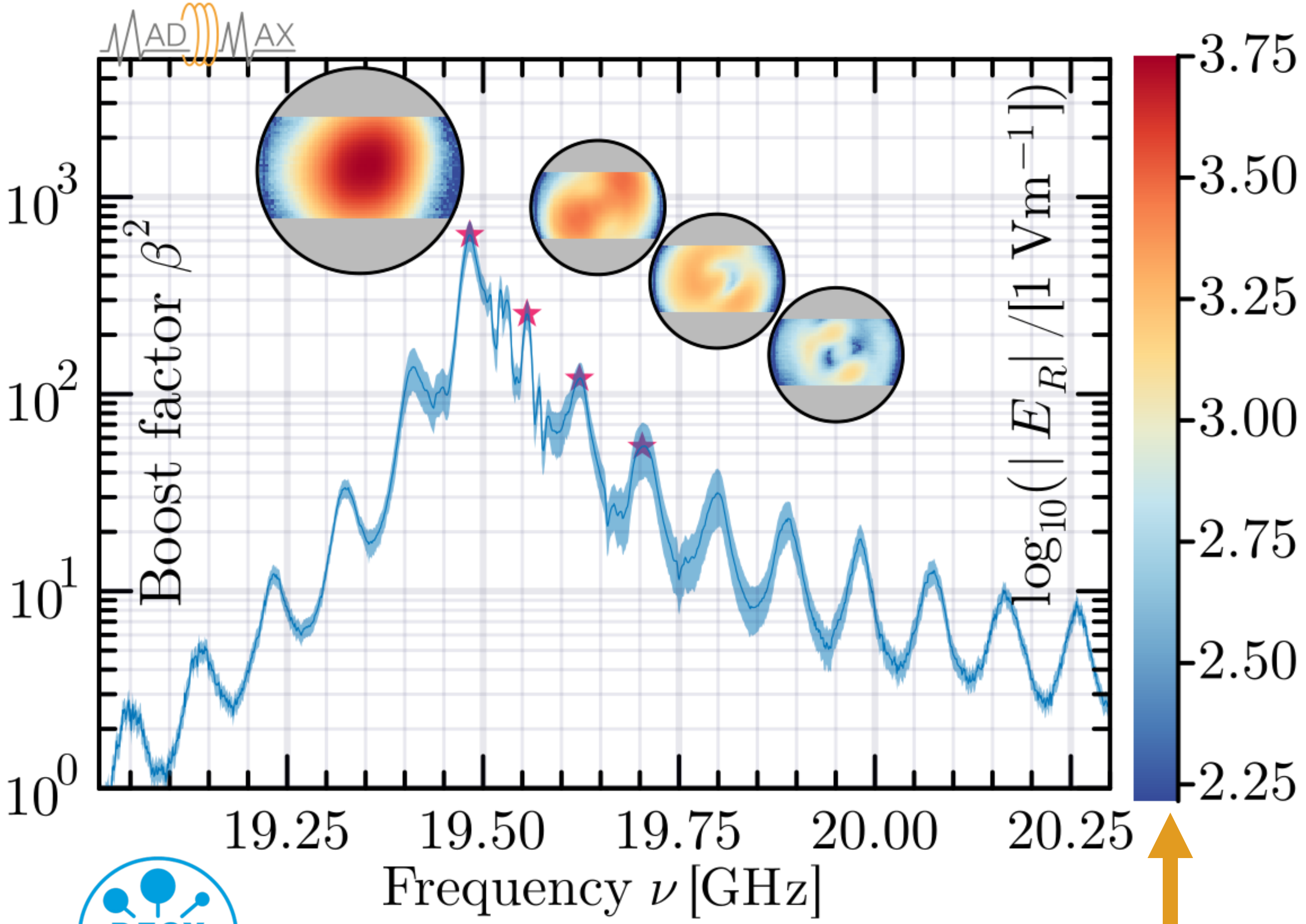
Towards a tunable booster



Open booster, 300 mm disc diameter (OB300)

[PRL 134.15 (2025): 151004. (arXiv:2408.02368)]



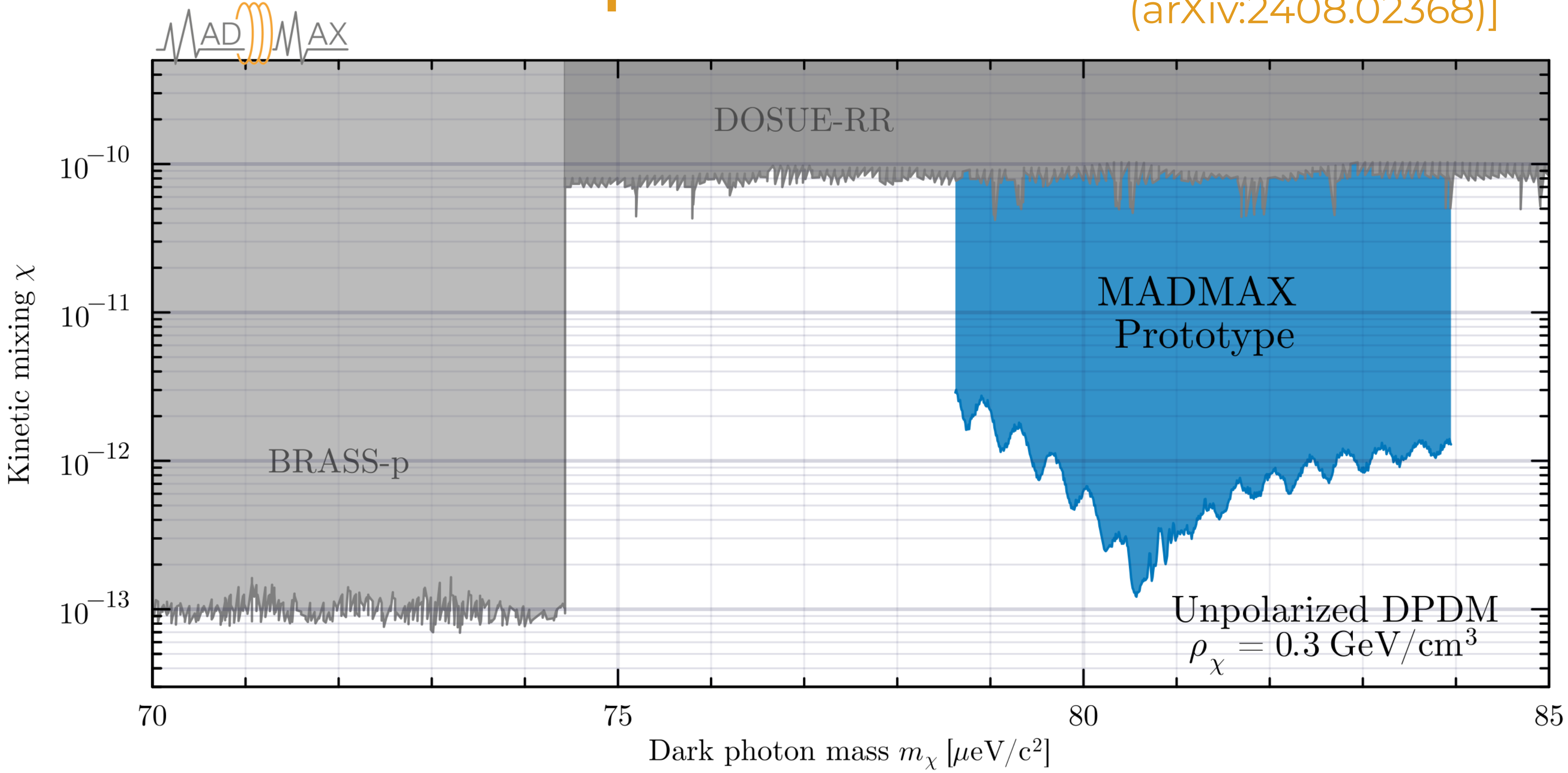


Open booster with 3 sapphire discs
Room Temp. Without magnetic field
Inside an EMC room at SHELL

E_R: reflection-induced electric field, excited by the VNA

First MADMAX dark photon limit

[PRL 134.15 (2025): 151004. (arXiv:2408.02368)]



15 days data-taking at room temperature with 3 disks in a fixed position

Improved existing limits by ~ 3 orders of magnitude

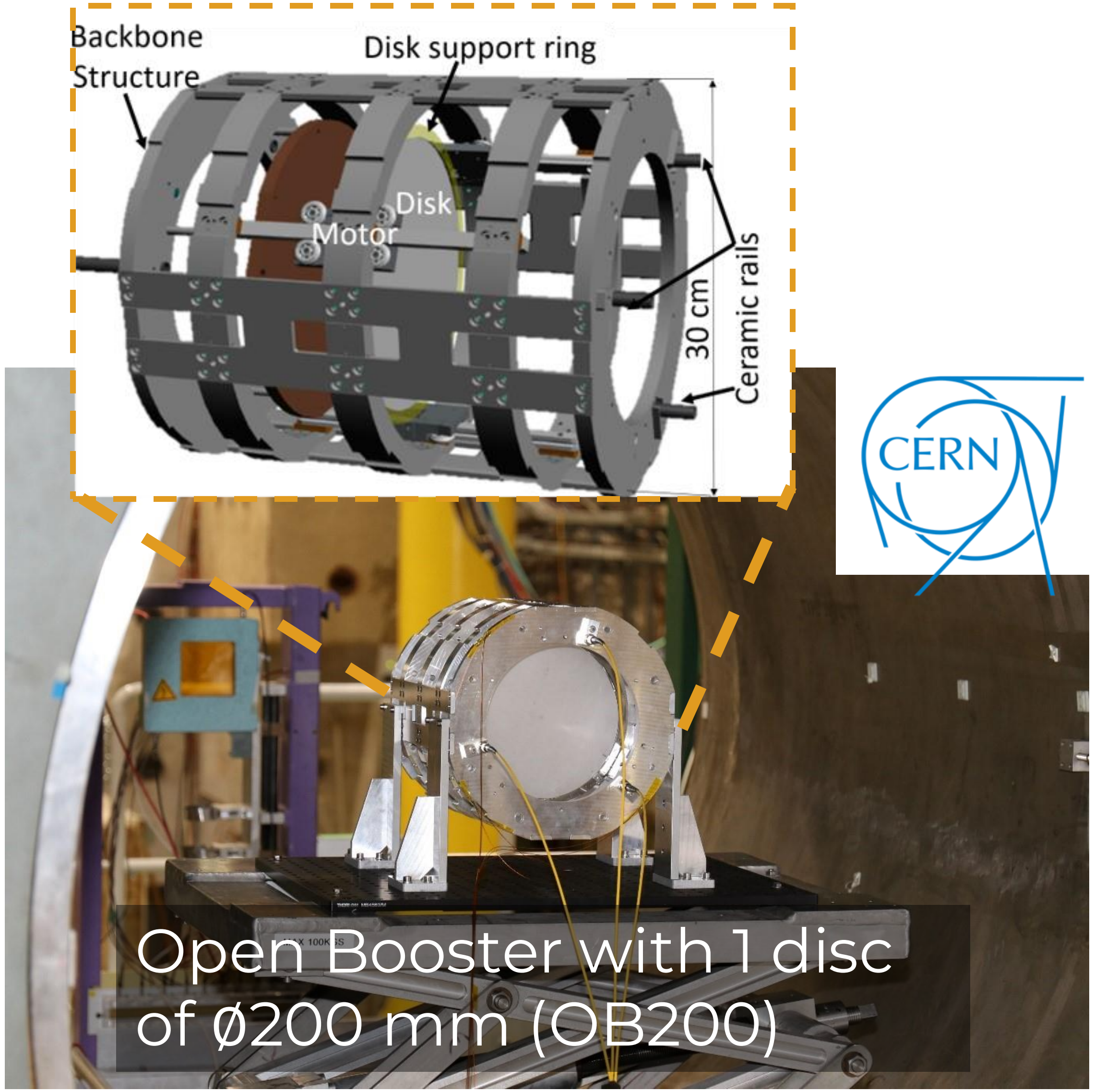
Towards a tunable booster

Goal: Scan different mass ranges by changing the relative positions of the discs

Setup: OB200 + 3 motors on disc + interferometer.

- RT test at 1.6 T
- Cryogenic test (35 K)

Outcome:
Successful manipulation down to $1\ \mu\text{m}$ stability at a speed of $16\frac{\mu\text{m}}{\text{s}}$

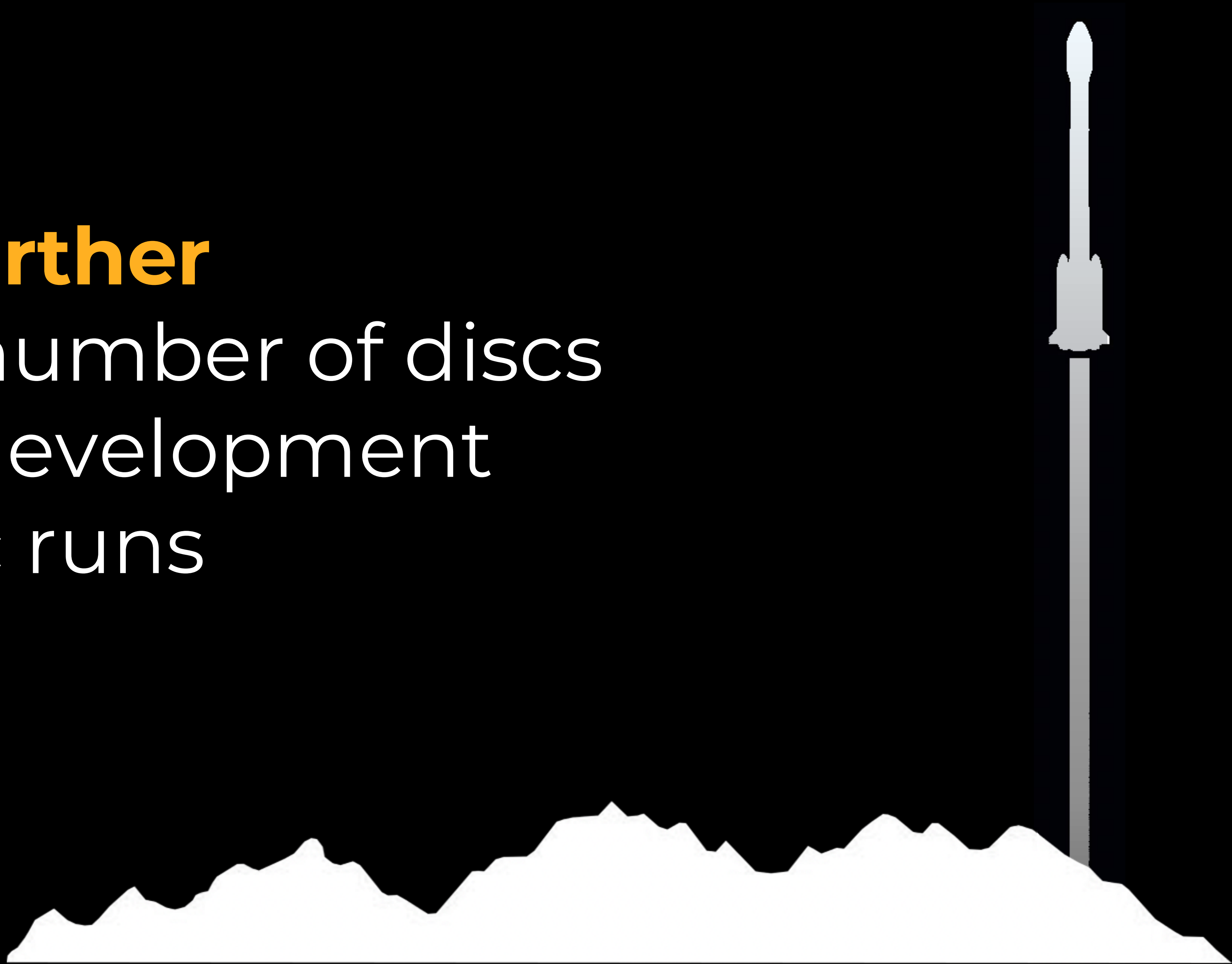


Open Booster with 1 disc of ø200 mm (OB200)

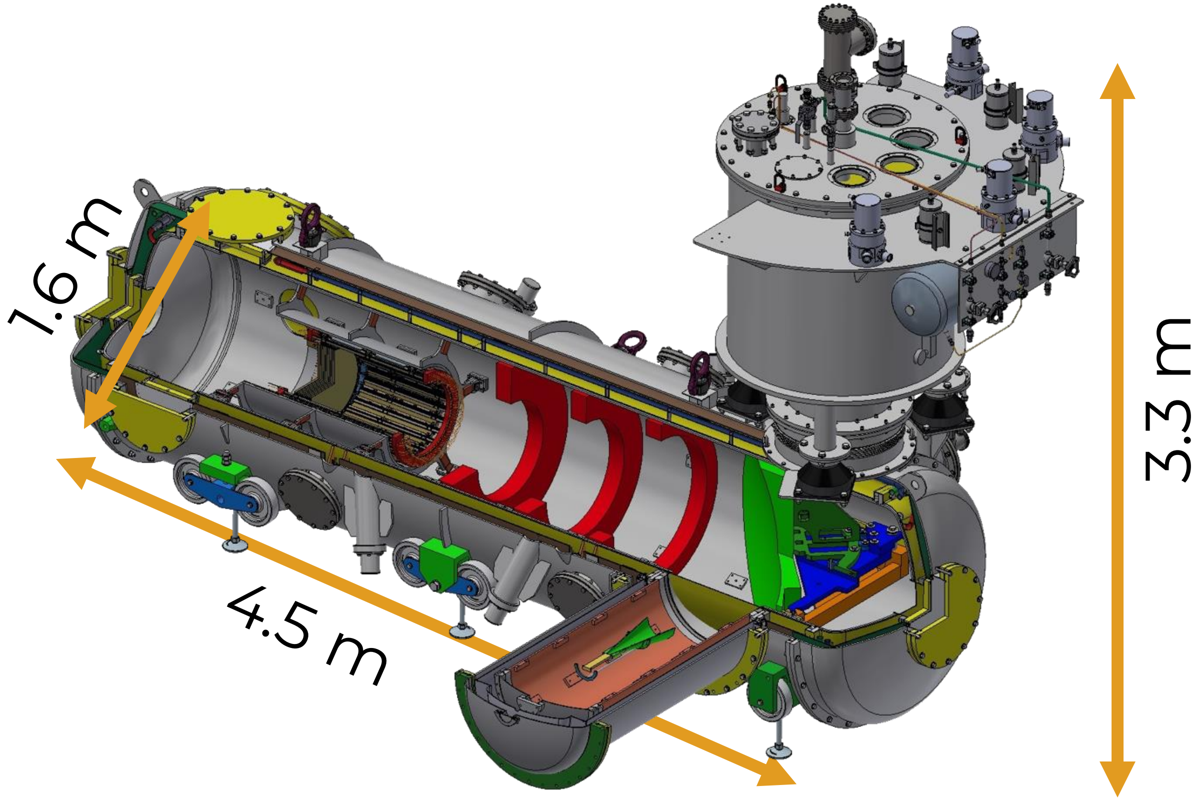
[JINST 18 P08011 (2023) (arXiv:2305.12808)]
[JINST 19 T11002 (2024) (arXiv:2407.10716)]

Scaling up further

Increase number of discs
Cryostat development
Cryogenic runs



New (Main) Cryostat

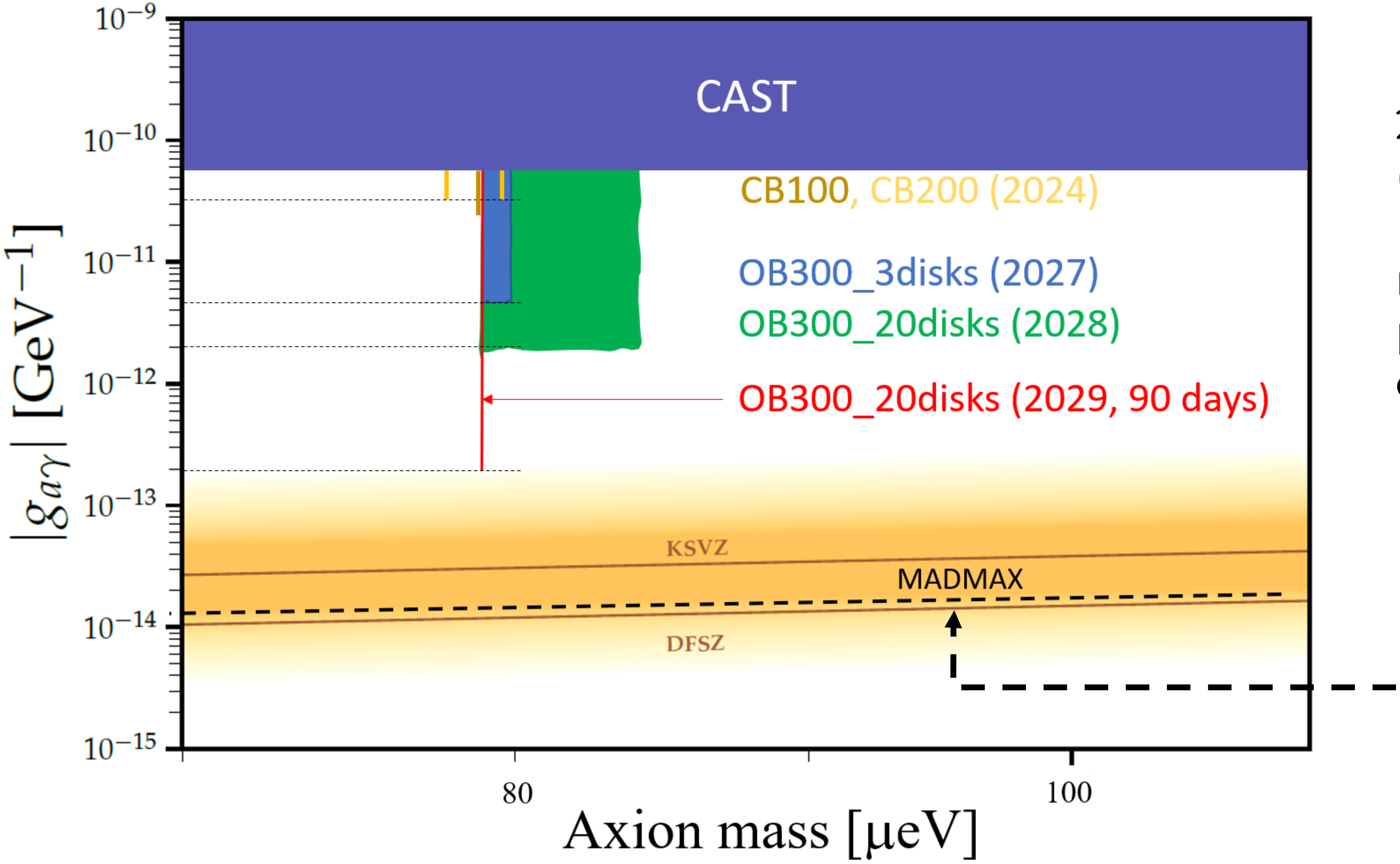


New cryostat delivered in 2025 to Hamburg site

Axion search at CERN: 2027-2029

Goal: cryogenic axion search using the Morpurgo 1.6 T B field

Physics reach forecast



Plans for 2027-2029 at CERN (long shutdown LHC) Morpurgo magnet + prototype cryostat

Aspirational MADMAX sensitivity (after 2030)

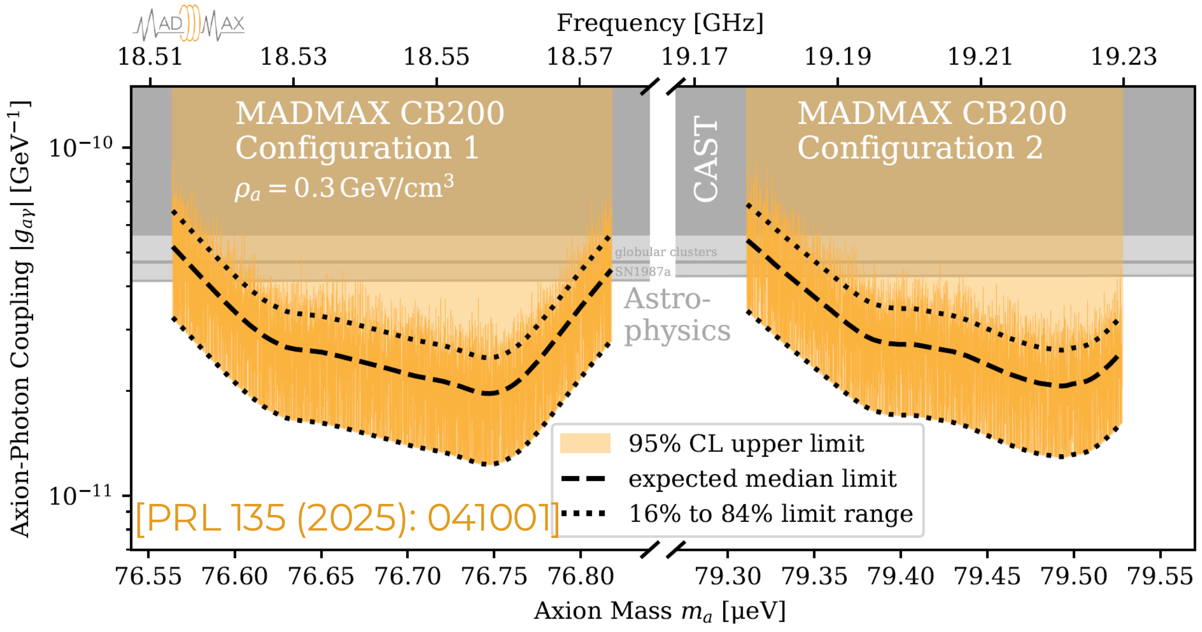
Take home message

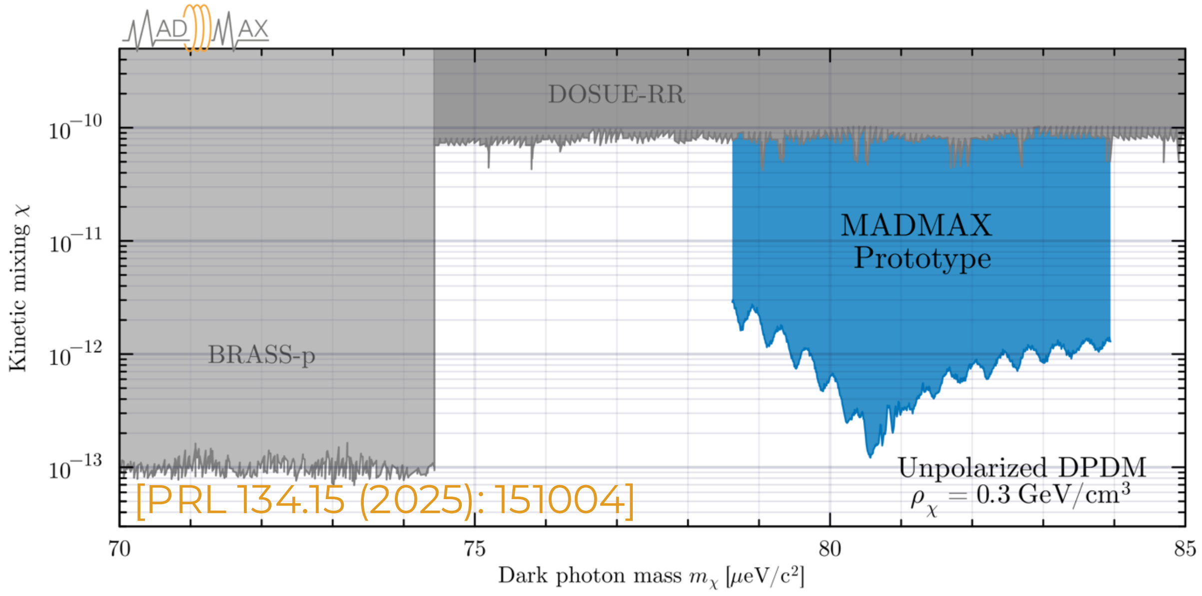
First time a dielectric haloscope sets axion limits

World-leading limits in both dark photon and axion searches around $80\ \mu eV$

Booster quickly tuned and recalibrated, larger-range frequency scans possible

Ongoing R&D regarding B field, cryogenics, booster size, and more...





BACKUP

Overlap and why it matters

Remember $\overrightarrow{E_a} = -\frac{g_{a\gamma}\overrightarrow{B_e}}{\epsilon} a_0 \cos(m_a t)$.

We induce the radiation inside a circular waveguide:

$$\overrightarrow{E_a} = E_a\,\hat{y} = E_a \left(\sum_{i=0}^{\infty} \vec{E}_{nm}(\phi) c_{nm} \right)$$

$$c_{nm} = \frac{\int \vec{y} \cdot \vec{E}_{nm}\, dS}{\int |\hat{y}|^2 dS \int E_{nm}^2 dS}$$

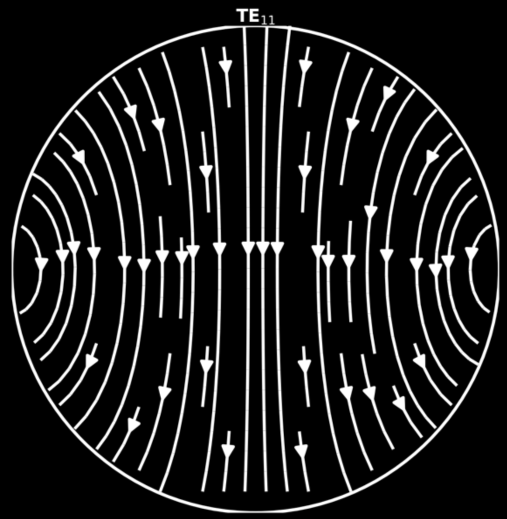
$$\sum_{n,m} c_{n,m} = 1$$

TE_{11} (c^2=0.84)

TE_{01} ($c \ll 1$)

$\overrightarrow{B_e}$

=



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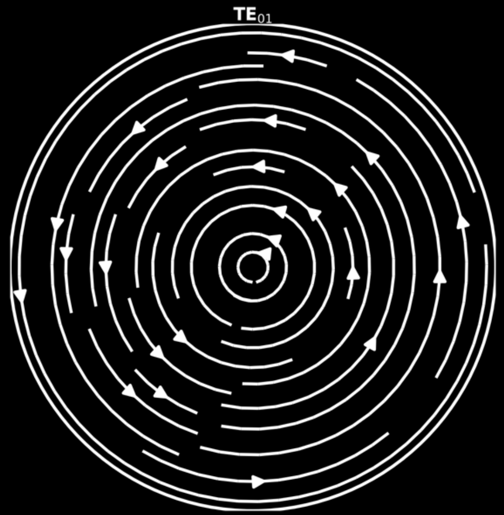
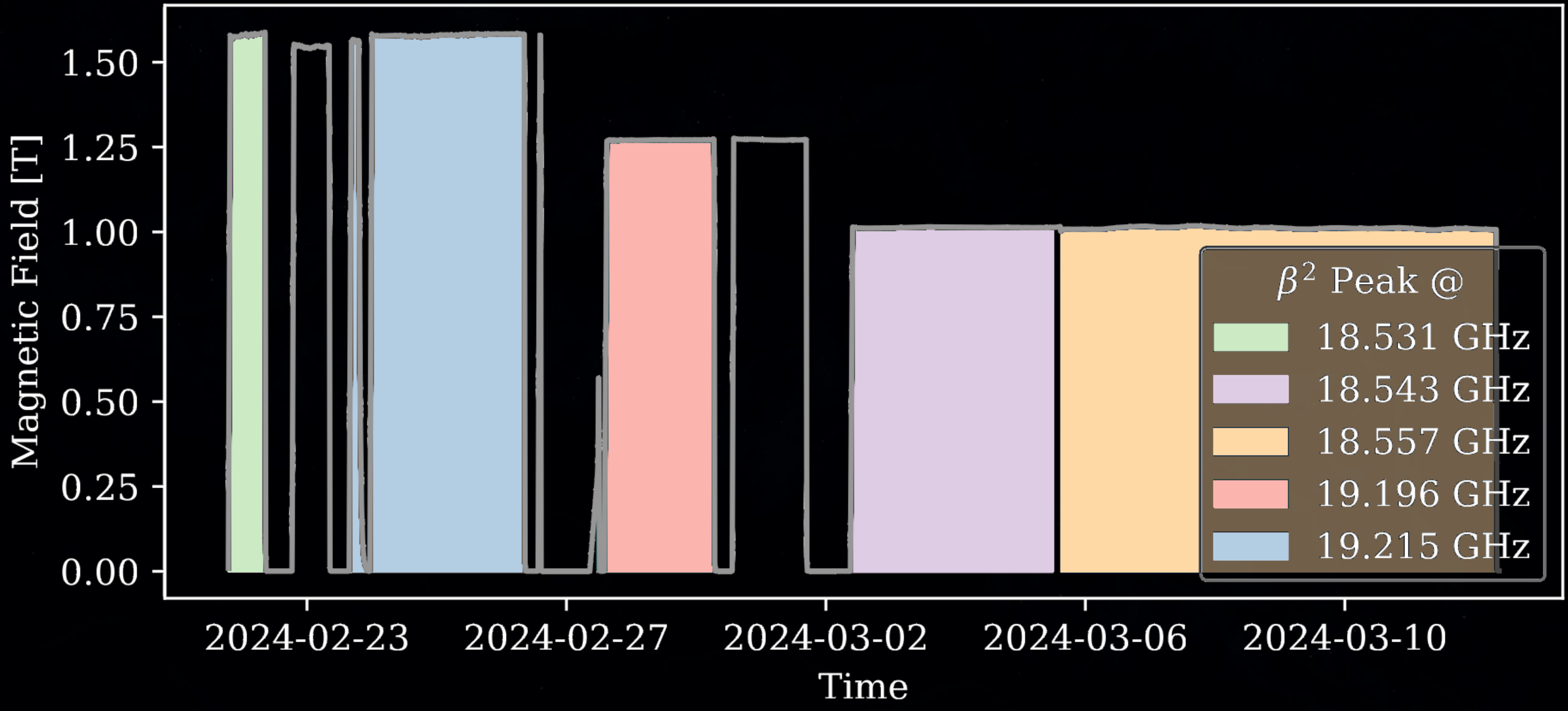


+ …

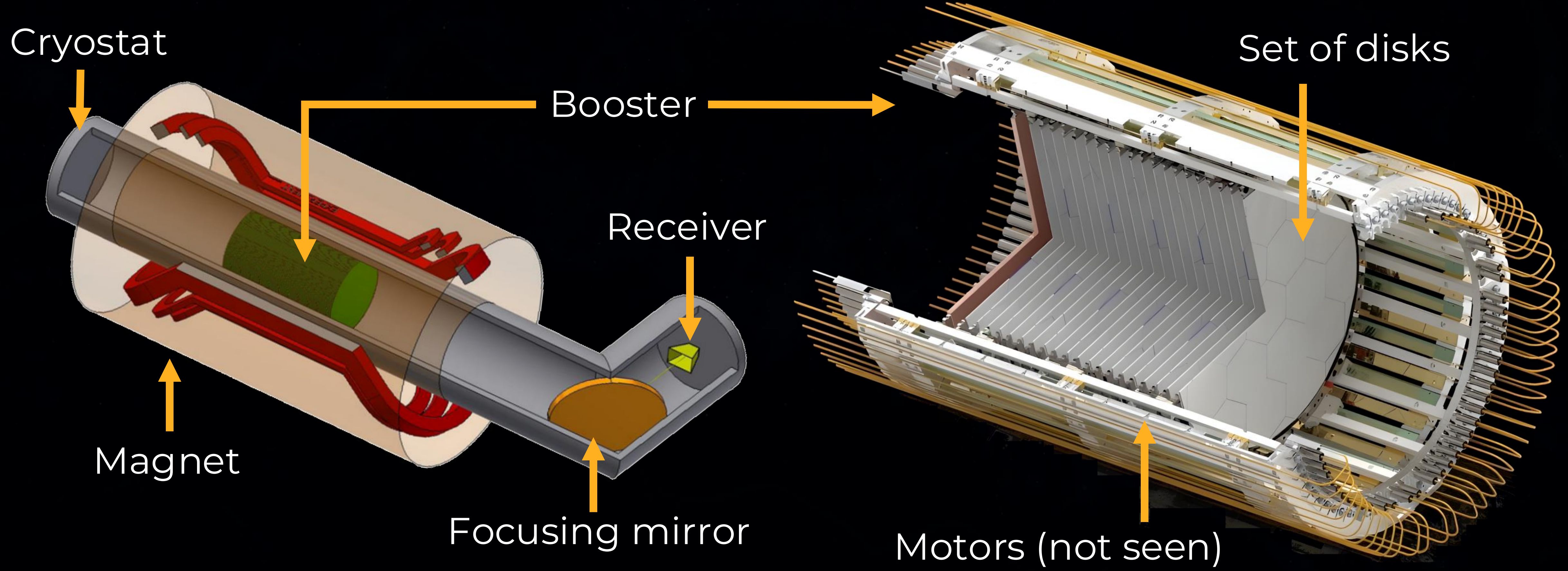
84% of the signal power couples to TE_{11}.
We need to make sure we are at the right mode

Magnetic field during run



Aspirational setup

$$|g_{a\gamma}| \propto \sqrt{P_{\text{signal}}} \propto \sqrt{10^{-22}\ \text{W}} \left(\frac{10\ \text{T}}{B}\right) \left(\frac{1\ \text{m}^2}{A}\right)^{\frac{1}{2}} \left(\frac{50000}{\beta^2}\right)^{\frac{1}{2}} \left(\frac{T_{\text{sys}}}{4\ \text{K}}\right)^{\frac{1}{2}} \left(\frac{1.8\ \text{days}}{\tau}\right)^{\frac{1}{4}}$$



Uncertainty in exclusion limit

[PRL 135 (2025): 041001.]

CB200, axion search

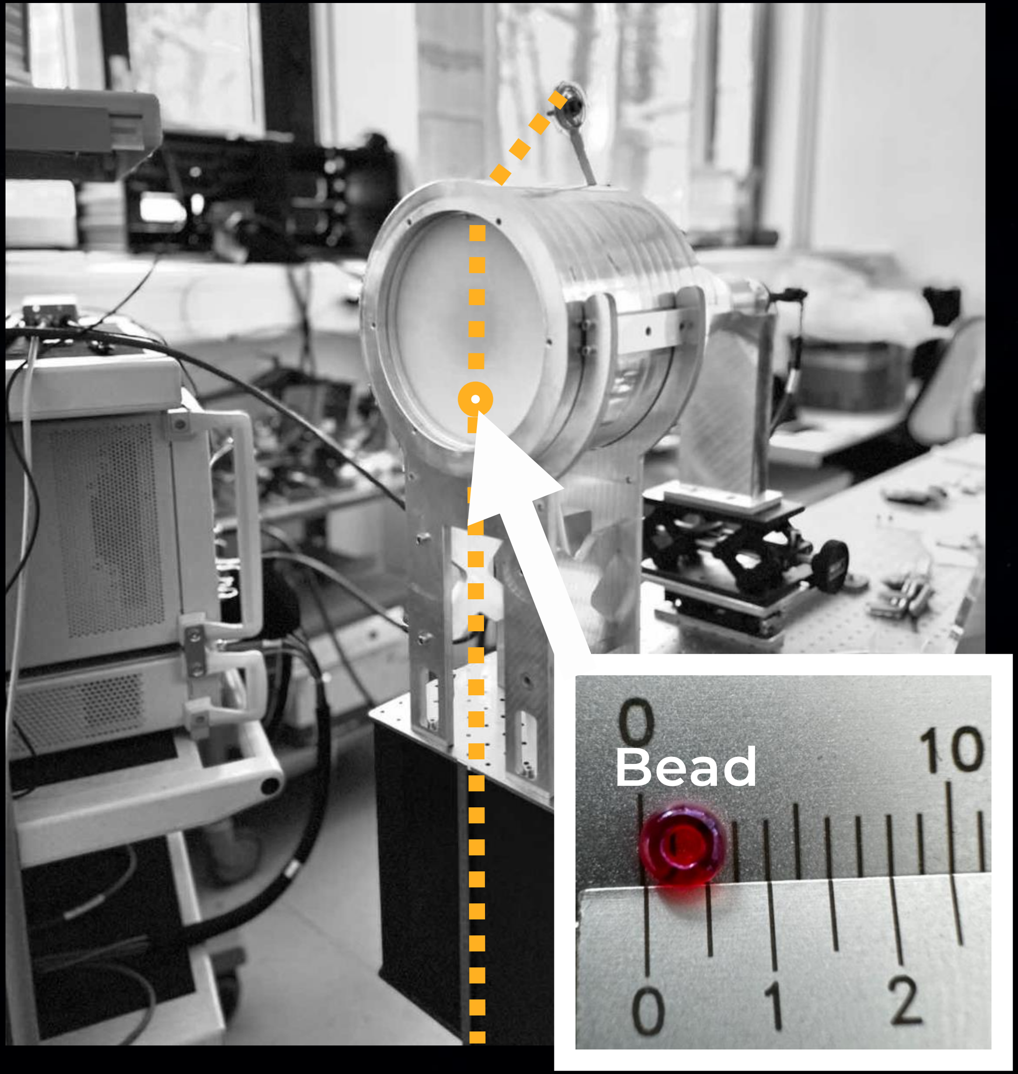
Effect	Uncertainty in $\lvert g_{a\gamma} \rvert$
Y-factor power calibration	3 to 5%
Receiver chain power stability	≤2%
Axion field—TE_{11} overlap	6%
Boost factor determination (excluding overlap)	<5%
Frequency stability of TE_{11} mode	<2%
Total	5 to 10%

OB300, Dark photon search

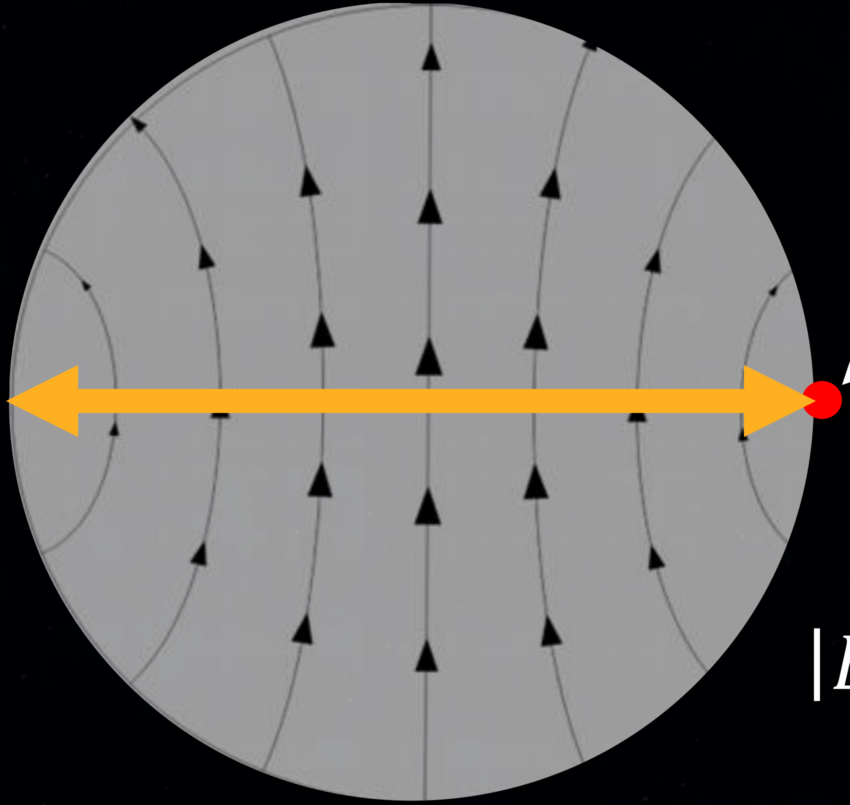
[PRL 134.15 (2025): 151004]

Effect	Uncertainty on χ
Boost factor determination	
Bead-pull measurements	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%

Field measurement setup



TE_{11} (84% overlap)



E ~ 0 here

75 bead positions

Reflection coefficient

$$|E|^2 \propto |S_{11} - S_{11}^0|$$

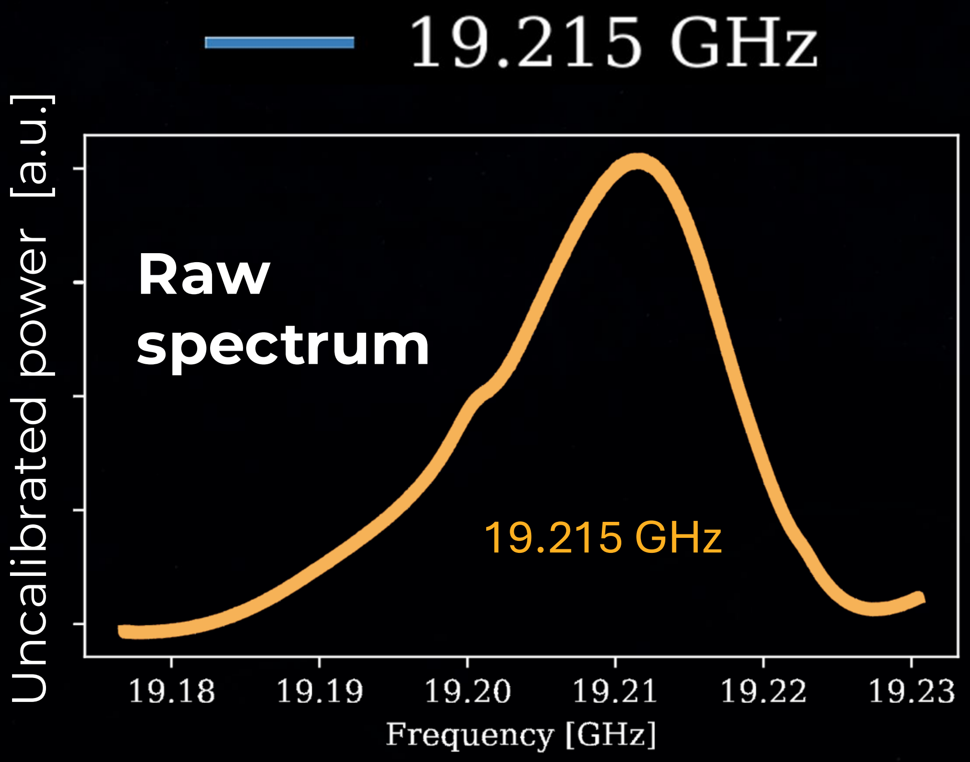
Bead at $E \sim 0$ (unperturbed)

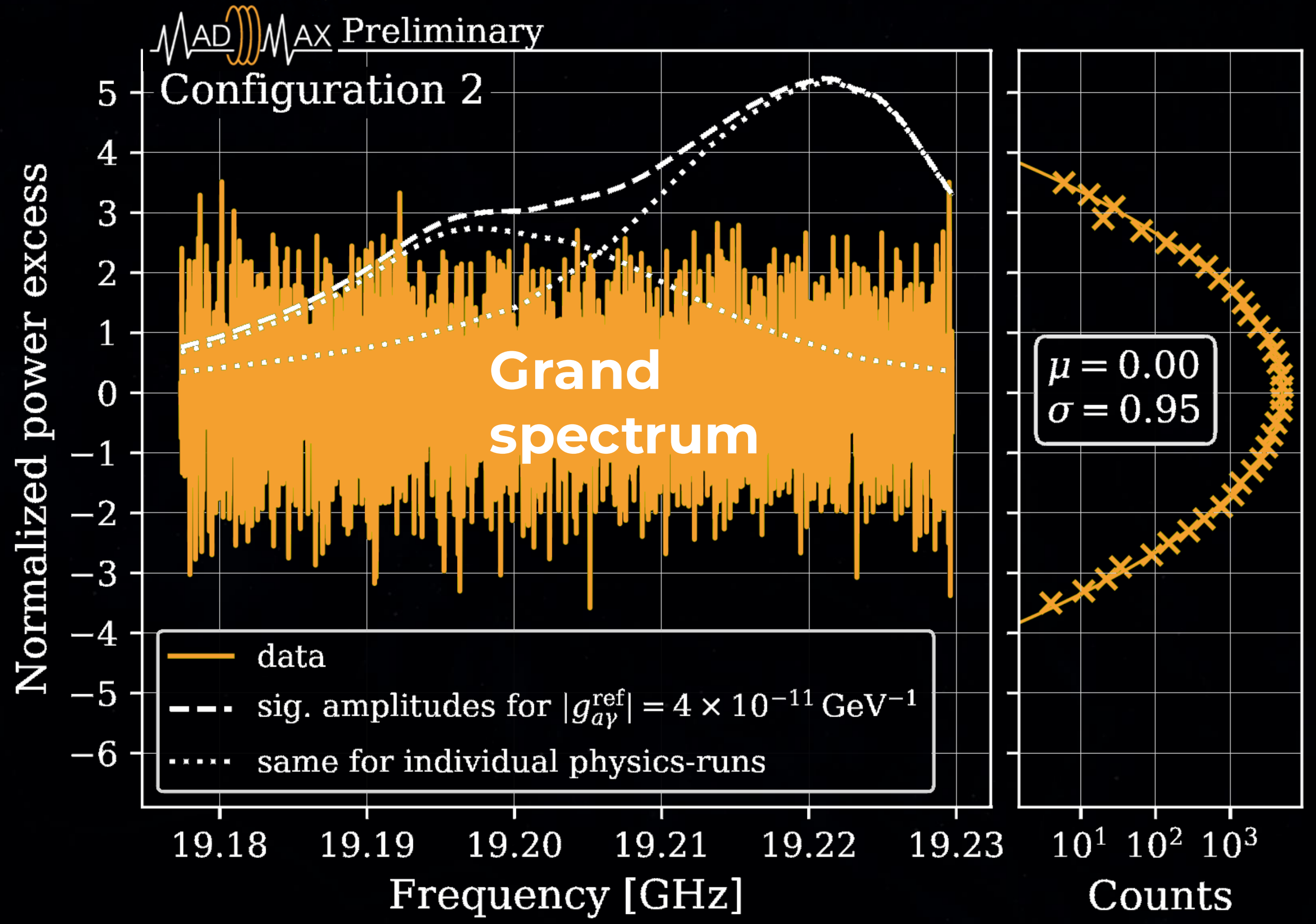
Analysis chain

Based on HAYSTAC: arxXiv:1706.08388 [PRD 96.12(2017)]

Raw spectrum → **Processed spectrum** → **Combined spectrum** → **Rescaled spectrum** → **Grand spectrum** → **Exclusion Limit**

Example from





Cold axion / dark photon searches

Single thermal cycle
semi-automatic
calibration

Horizontal non-magnetic
cryostat developed with
CERN Cryolab
[JINST 20 T02005 (2025) (arXiv:2412.12818)]

1 day long axion search at
19 GHz at CERN in a 1.6 T
field at 14 K system
temperature

Stay tuned!