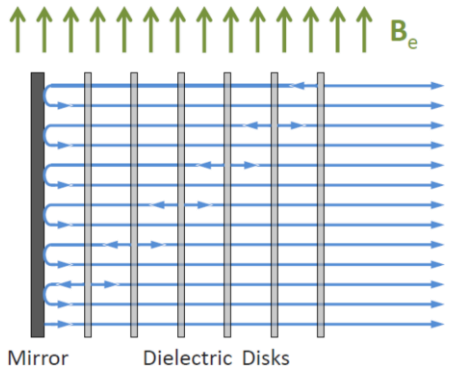


Béla Majorovits
on behalf of the collaboration
MAX-PLANCK-INSTITUT FÜR PHYSIK

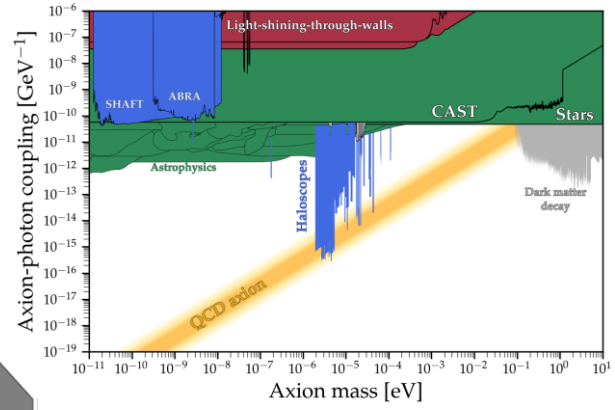
First MADMAX searches for axion and dark photon dark matter

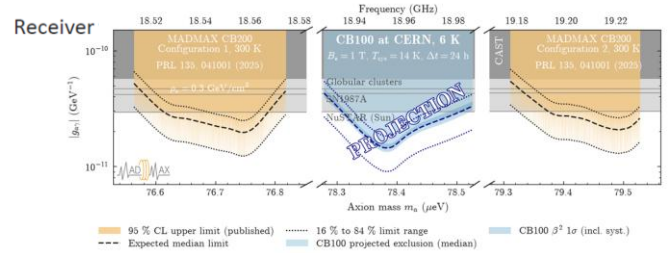
A G E N D A

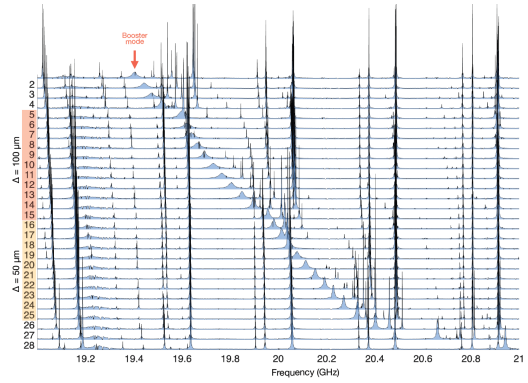
- MADMAX axion mass range
- The dielectric haloscope concept
- Boost factor determination
- First MADMAX axion and dark photon dark matter limits
- MADMAX @ CERN
- Further plans: scaling up







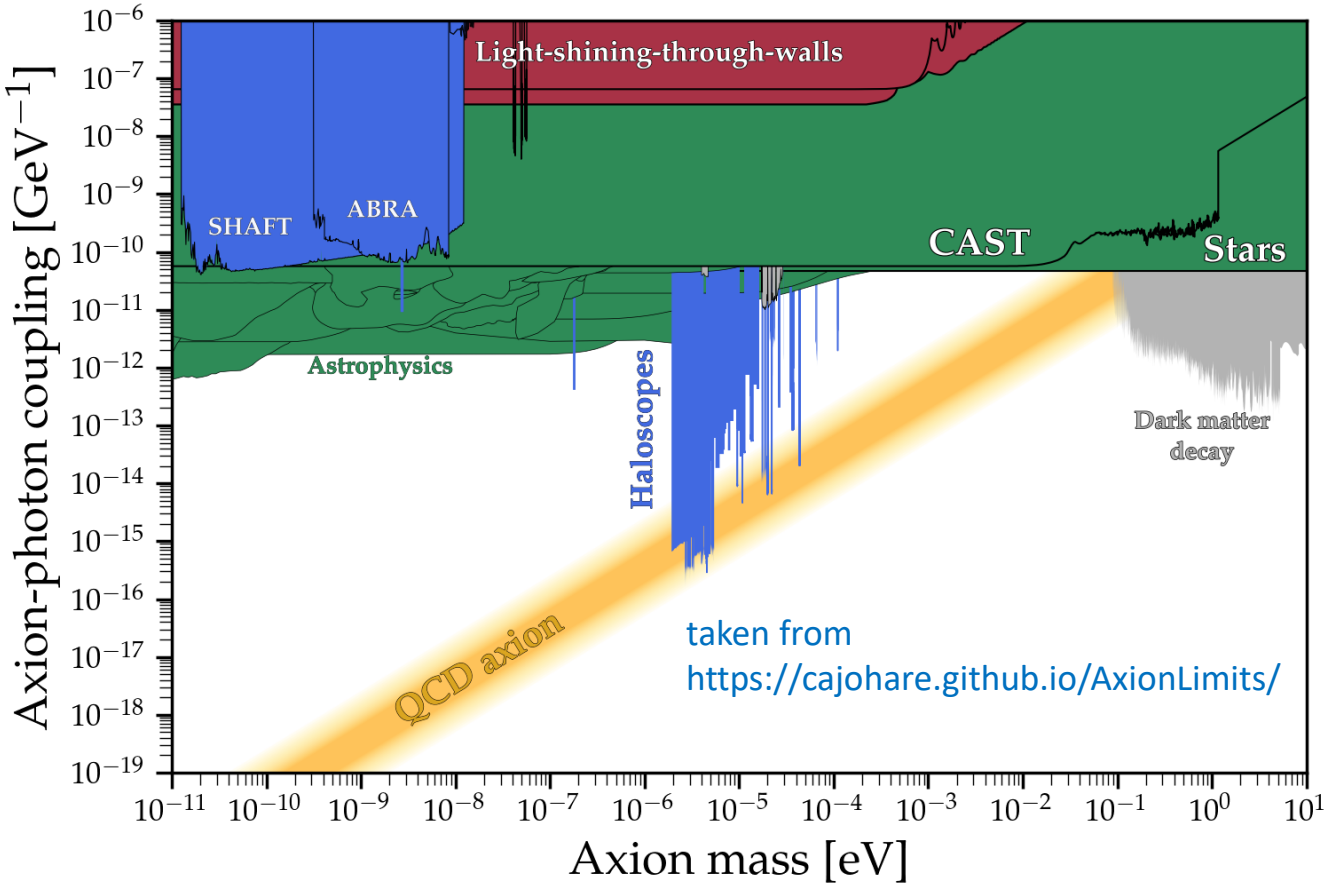




Axion mass range

- **QCD axion solves strong CP problem**
- **Can explain cold dark matter**
- **„Highly degenerate Bose Einstein Condensate“:**
  → wave like with $\lambda_{deBroglie} > L_{exp}$
- **For Peccei Quinn symmetry breaking after inflation ~ 25µeV < m_a < 0.1 eV**

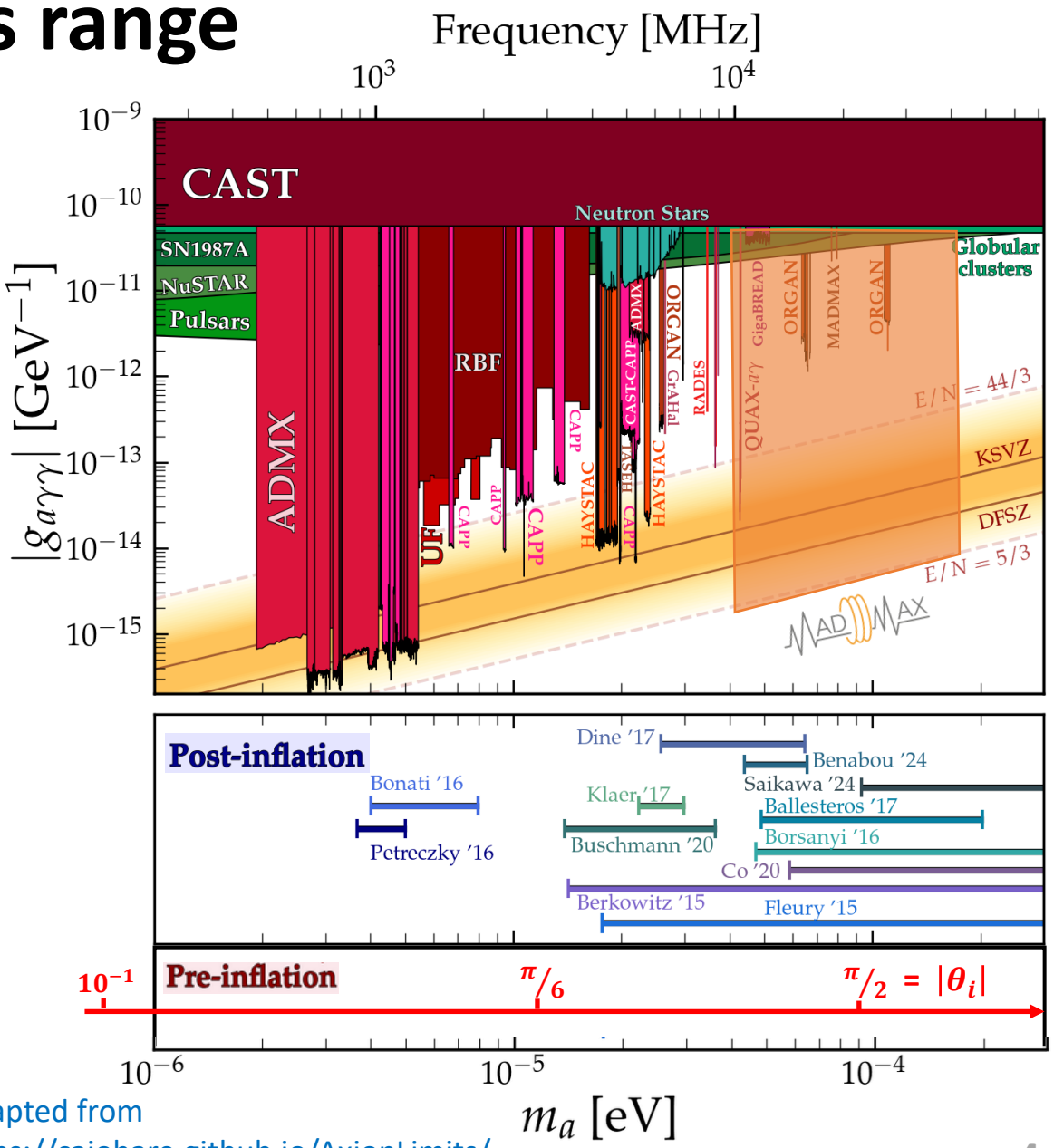
→ MADMAX **covers mass range ~ 100 µeV**



Axion mass range

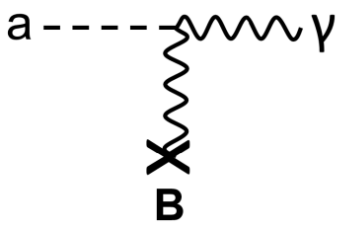
- QCD axion solves strong CP problem
- Can explain cold dark matter
- „Highly degenerate Bose Einstein Condensate“:
  → wave like with $\lambda_{deBroglie} > L_{exp}$
- For Peccei Quinn symmetry breaking after inflation ~ 25µeV < m_a < 0.1 eV

→ MADMAX covers mass range ~ 100 µeV

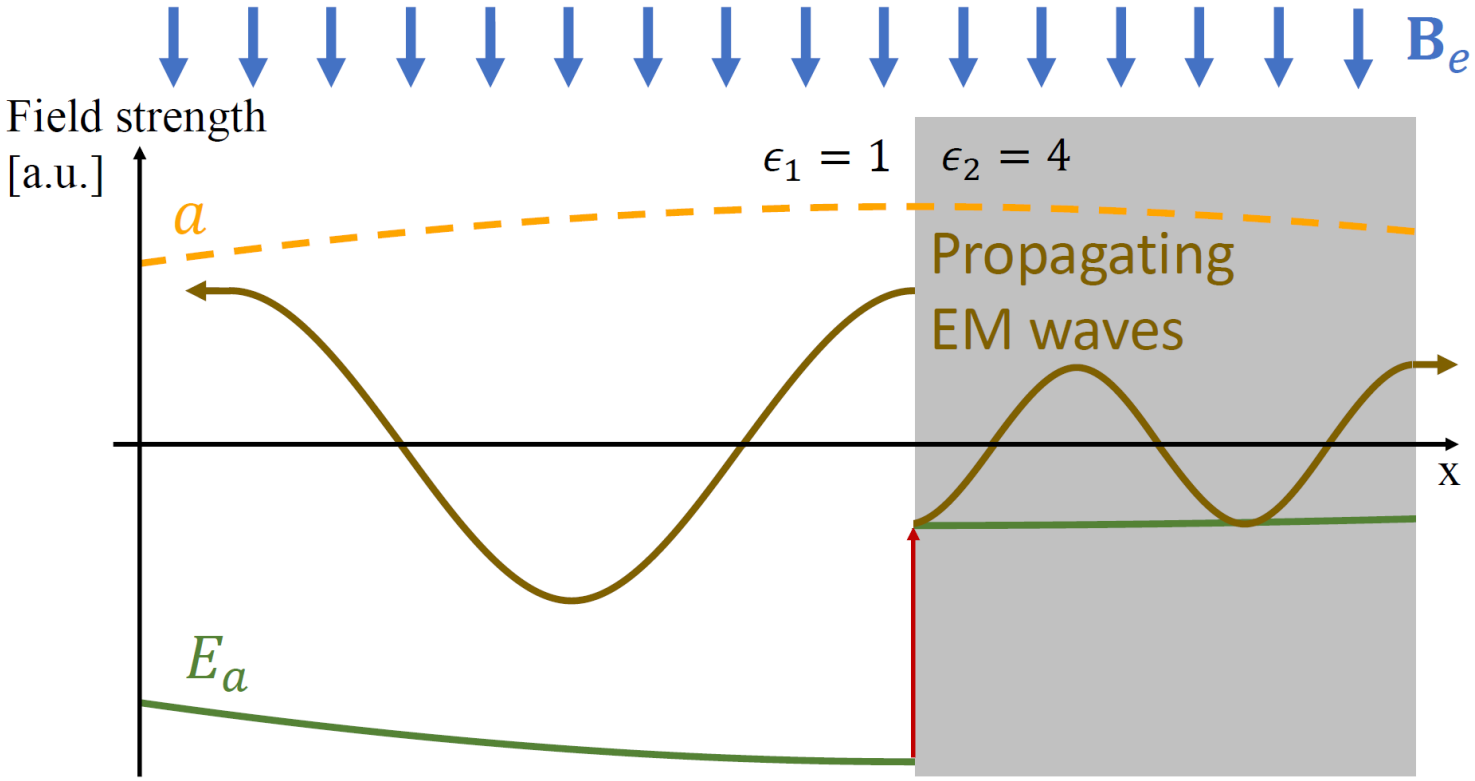


Adapted from
https://cajohare.github.io/AxionLimits/

The MADMAX dielectric haloscope



Axion field oscillation in B-field
→ Induce E-field oscillation



Dielectric discontinuity at boundary

→ Emission of EM wave with

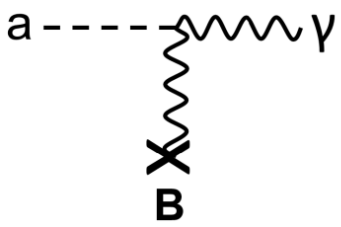
$$E = m_a c^2 = h\nu_a$$

→ Dish antenna approach

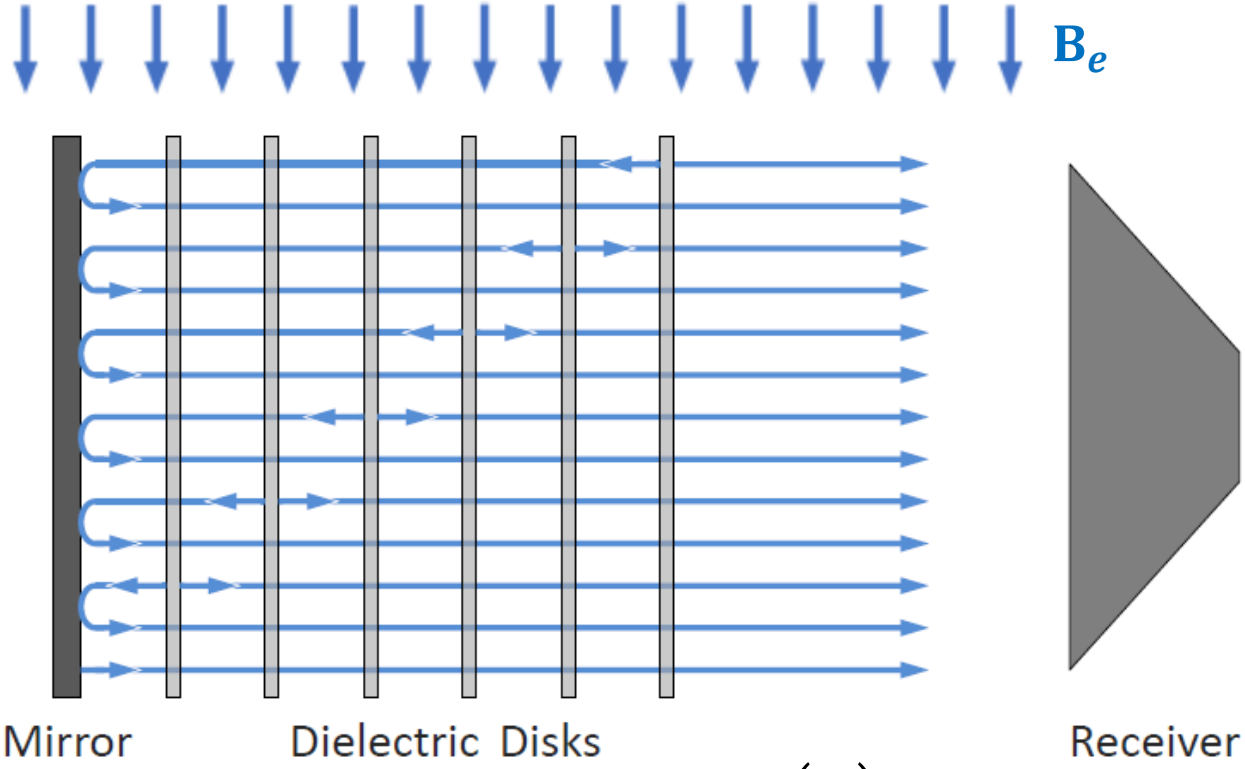
Horns et al JCAP04(2013)016

$$\left(\frac{P}{A}\right)_{mirror} \approx 2 \cdot 10^{-27} \left(\frac{B_e}{10\ T}\right)^2 \frac{W}{m^2}$$

The MADMAX dielectric haloscope



Axion field oscillation in B-field
→ Induce E-field oscillation



MADMAX interest group, PRL 118, 091801 (2017)

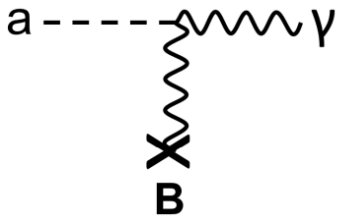
Booster: dielectric mirror & disks

→ Emission of EM waves @ all surfaces
→ Coherent superposition of waves
→ Constructive (or destructive) interference
→ Boost as fct. of frequency
→ Boost depends on # of disks
→ Frequency depends on disk spacings
→ Broad-band vs. resonant

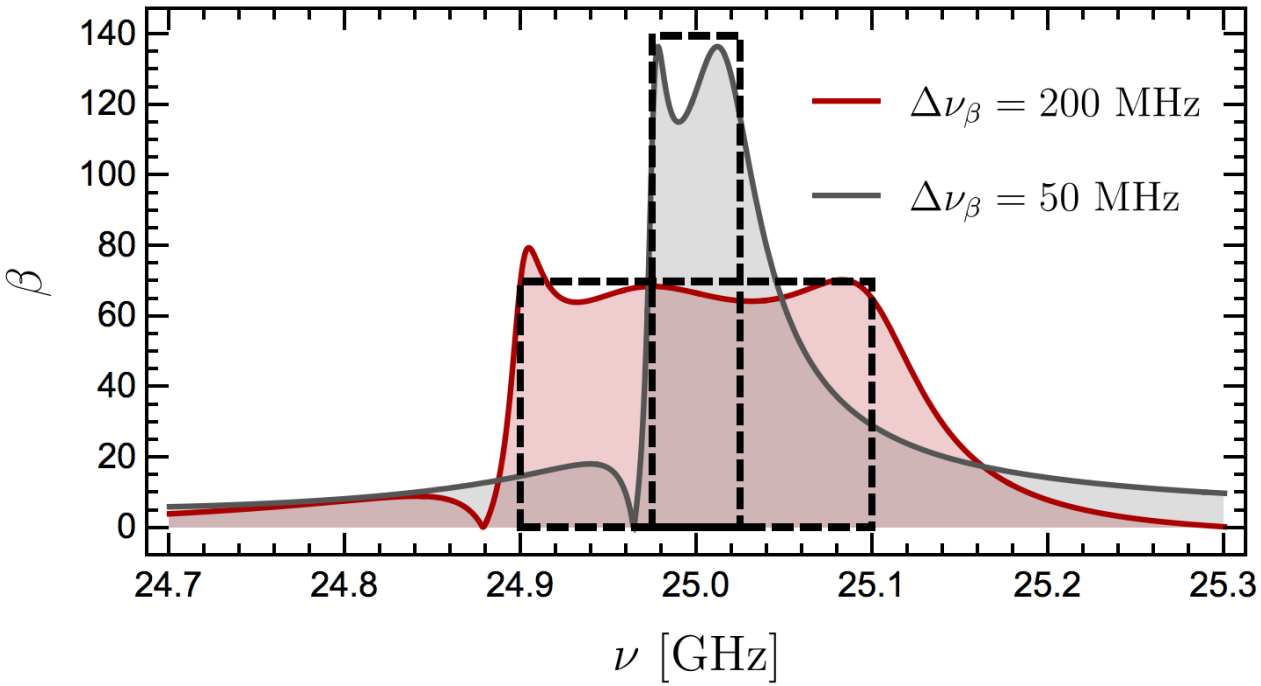
Jaeckel & Redondo, Phys. Rev. D 88, 115002 (2013)

$$\left(\frac{P}{A}\right)_{booster} \approx 2 \cdot 10^{-27} \left(\frac{B_e}{10\ T}\right)^2 \beta^2 \frac{W}{m^2}$$

The MADMAX dielectric haloscope



Axion field oscillation in B-field
→ Induce E-field oscillation



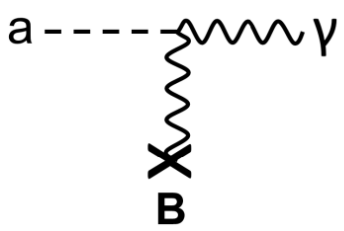
Millar et al., JCAP01(2017)061

Booster: dielectric mirror & disks

- → Emission of EM waves @ all surfaces
- → Coherent superposition of waves
- → Constructive (or destructive) interference
- → Boost as fct. of frequency
- → Boost depends on # of disks
- → Frequency depends on disk spacings
- → Broad-band vs. resonant

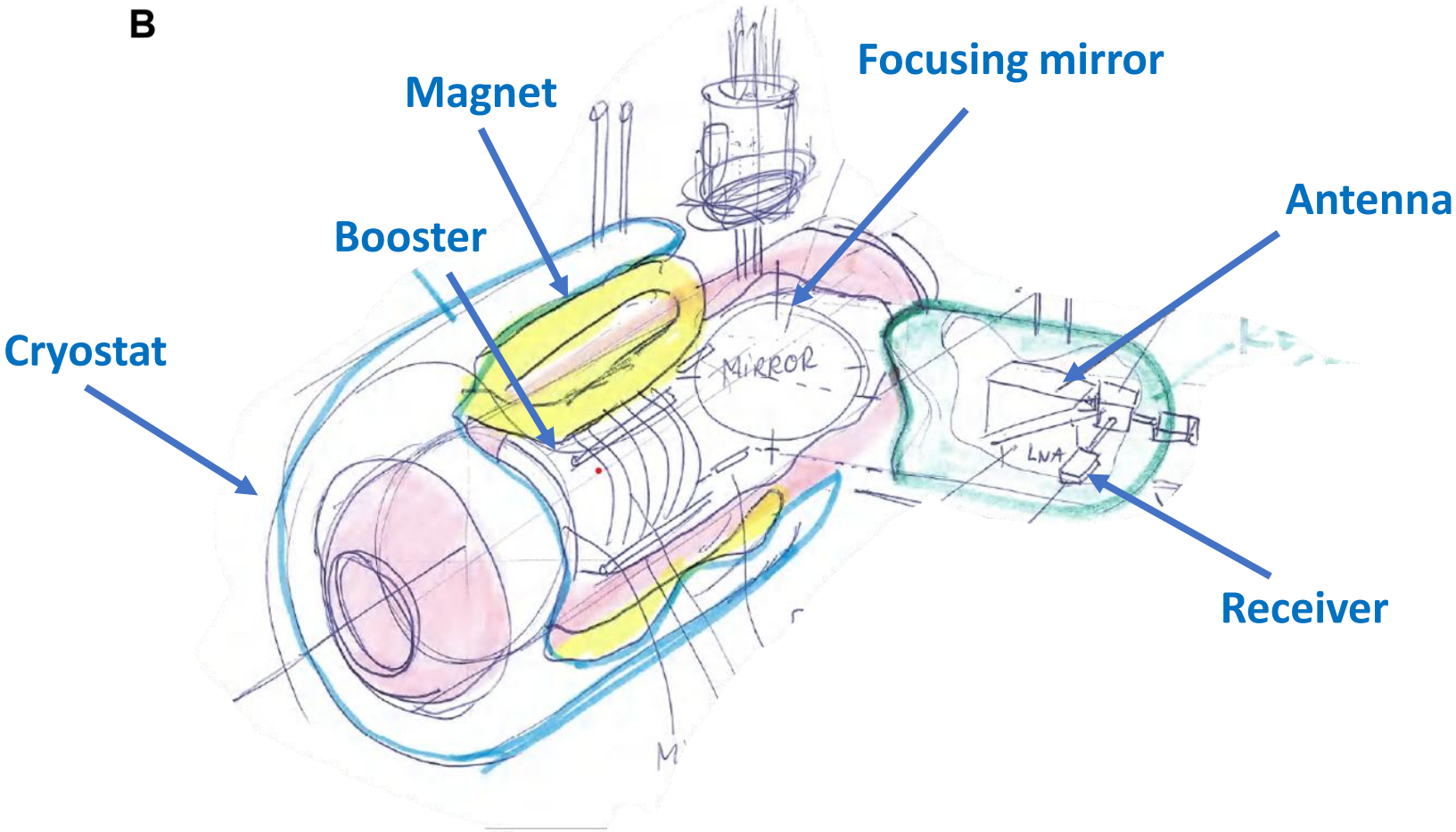
$$\left(\frac{P}{A}\right)_{booster} \approx 2 \cdot 10^{-27} \left(\frac{B_e}{10\ T}\right)^2 \beta^2 \frac{W}{m^2}$$

The MADMAX dielectric haloscope



„booster“amplifies axion- to E- field conversion

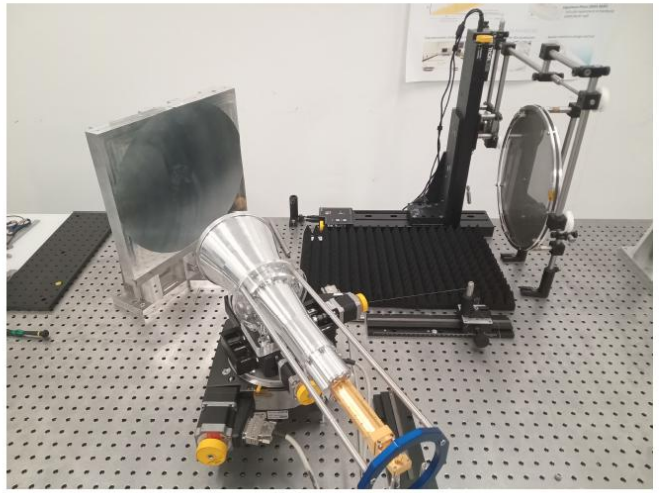
→ **Tune frequency by adjusting disk positions**

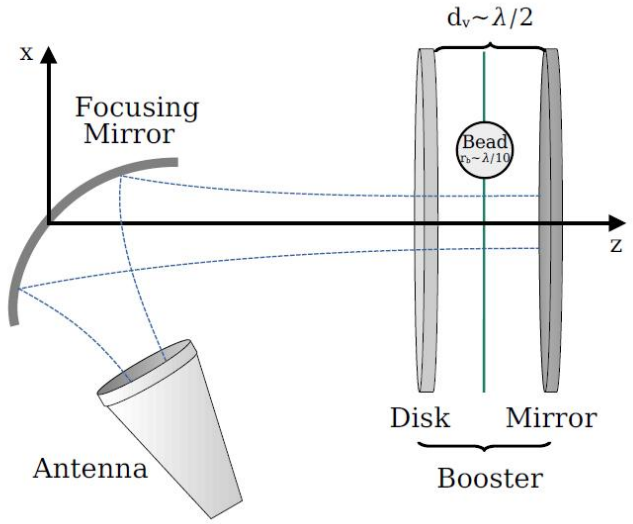


Boost factor determination

„open booster“ OB300

Reciprocity & bead pull method

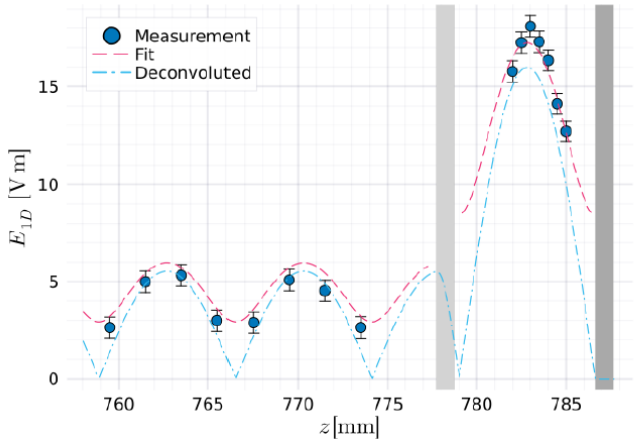


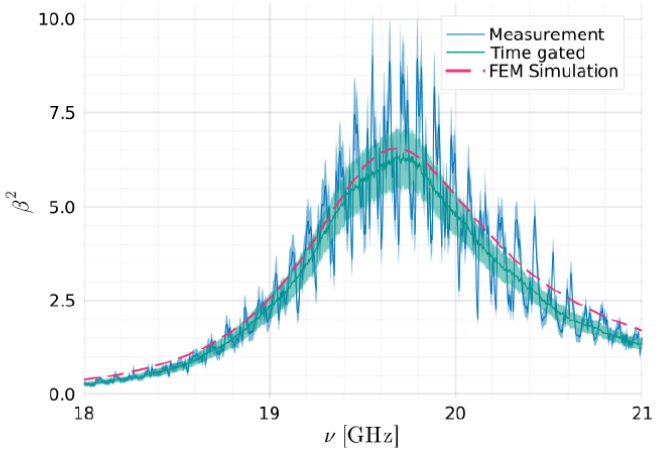


Determination of boost factor by reciprocity:

$$\beta^2 = \frac{P_{\mathrm{sig}}}{P_0} = \frac{4\pi^2 \epsilon_0 \nu^2 F_{\mathrm{RC}}}{8 c P_{\mathrm{in}} A} \left| \int \mathrm{d}V \, E_R \right|^2$$

Boost factor: integrate over E-field inside booster



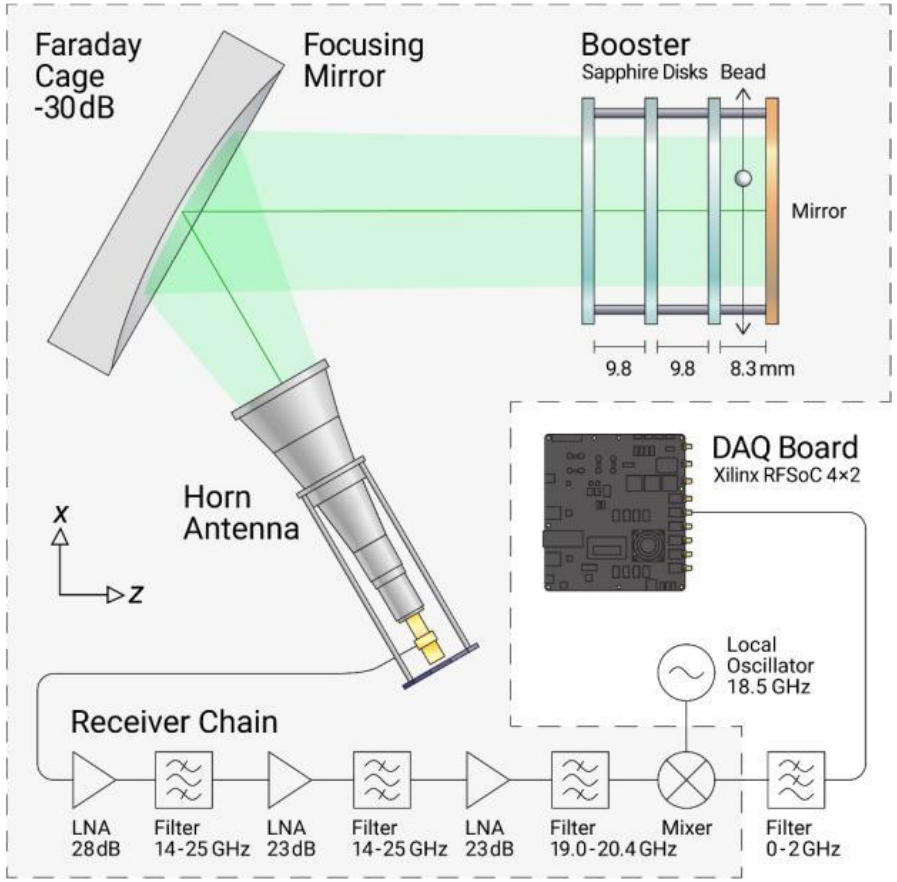


$$\Delta\Gamma = \frac{\epsilon_0 \delta_e \alpha_0 \omega}{4 P_{\mathrm{in}}} \boldsymbol{E}^2$$

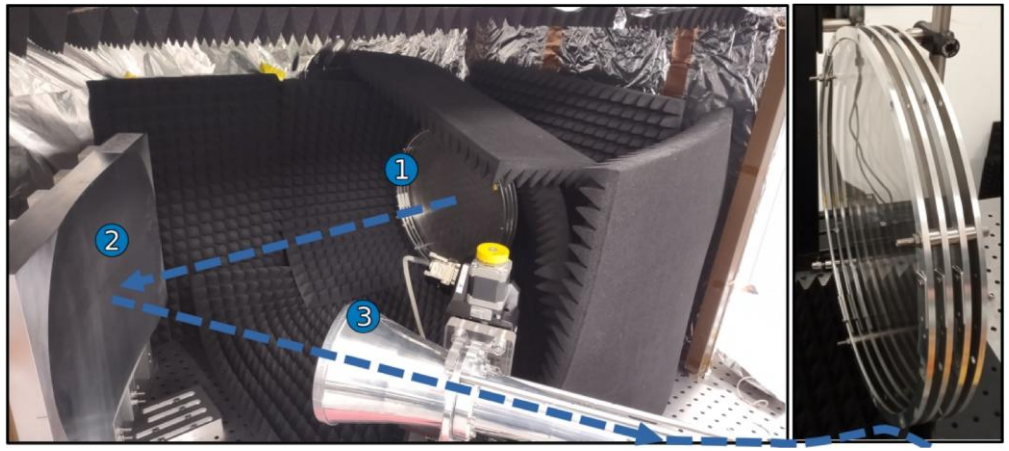
Determination of E-field using bead-pull method in „open“ booster

Egge , JCAP04(2023)064 & Egge et al, JCAP04(2024)005

Dark photon dark matter search using a MADMAX open booster – OB300

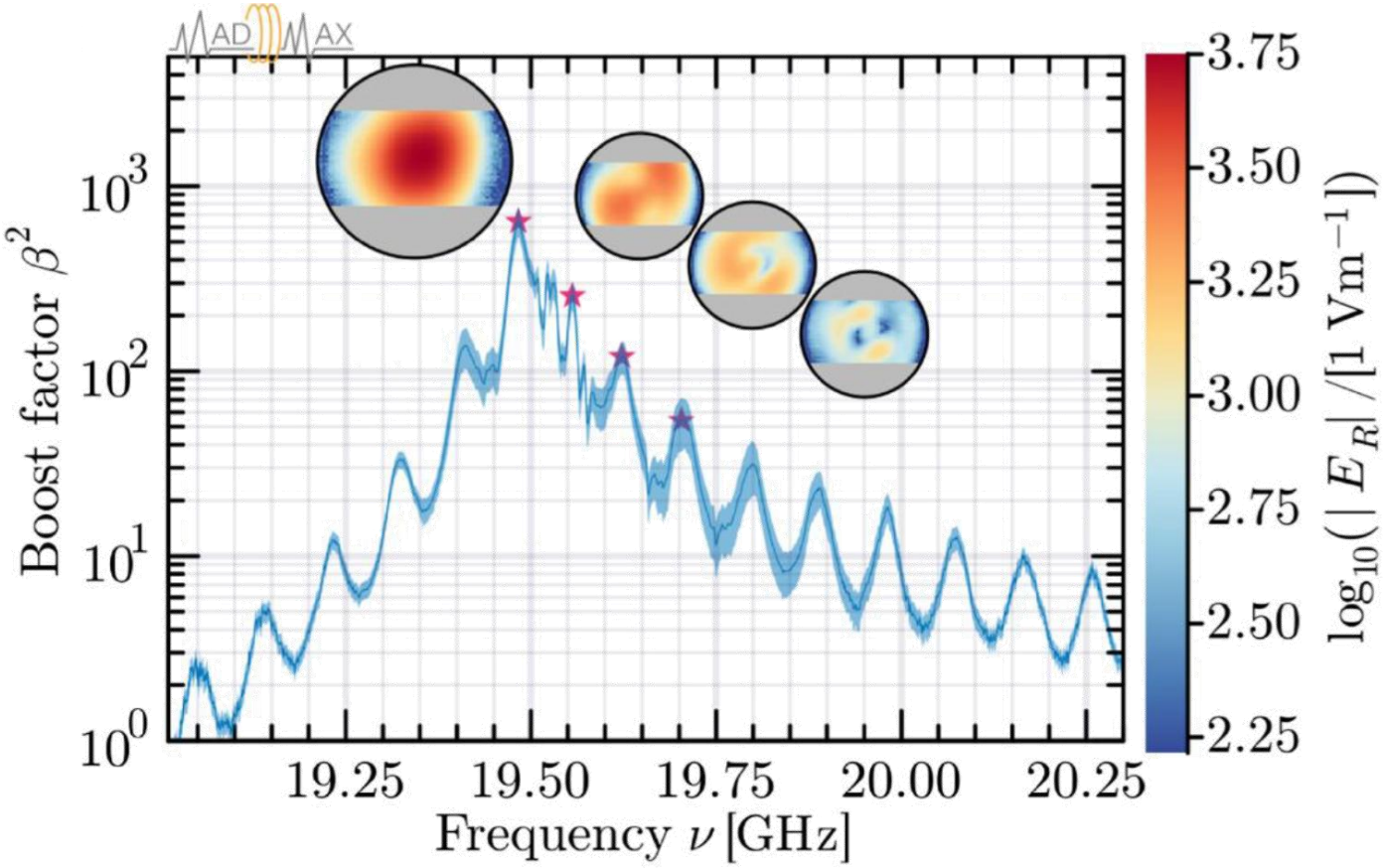


MADMAX collaboration, PRL 134, 15, 151004 (2025)

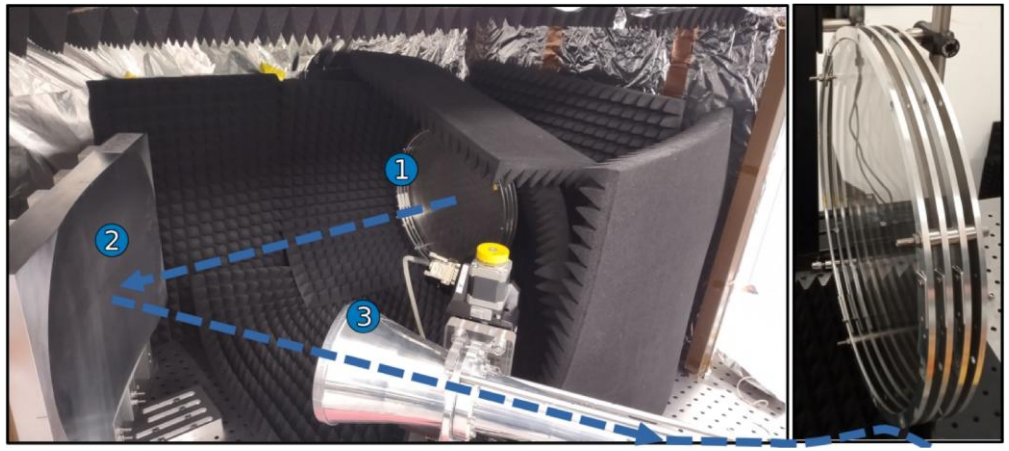


- **Boost factor peak ~ 600**
- **Broad band configuration:**
  $\beta^2 > 100$ **over 100 MHz**
  $\beta^2 > 10$ **over 400 MHz**
- **Limits on dark photon dark matter improved by up to factor 500**

Dark photon dark matter search using a MADMAX open booster – OB300

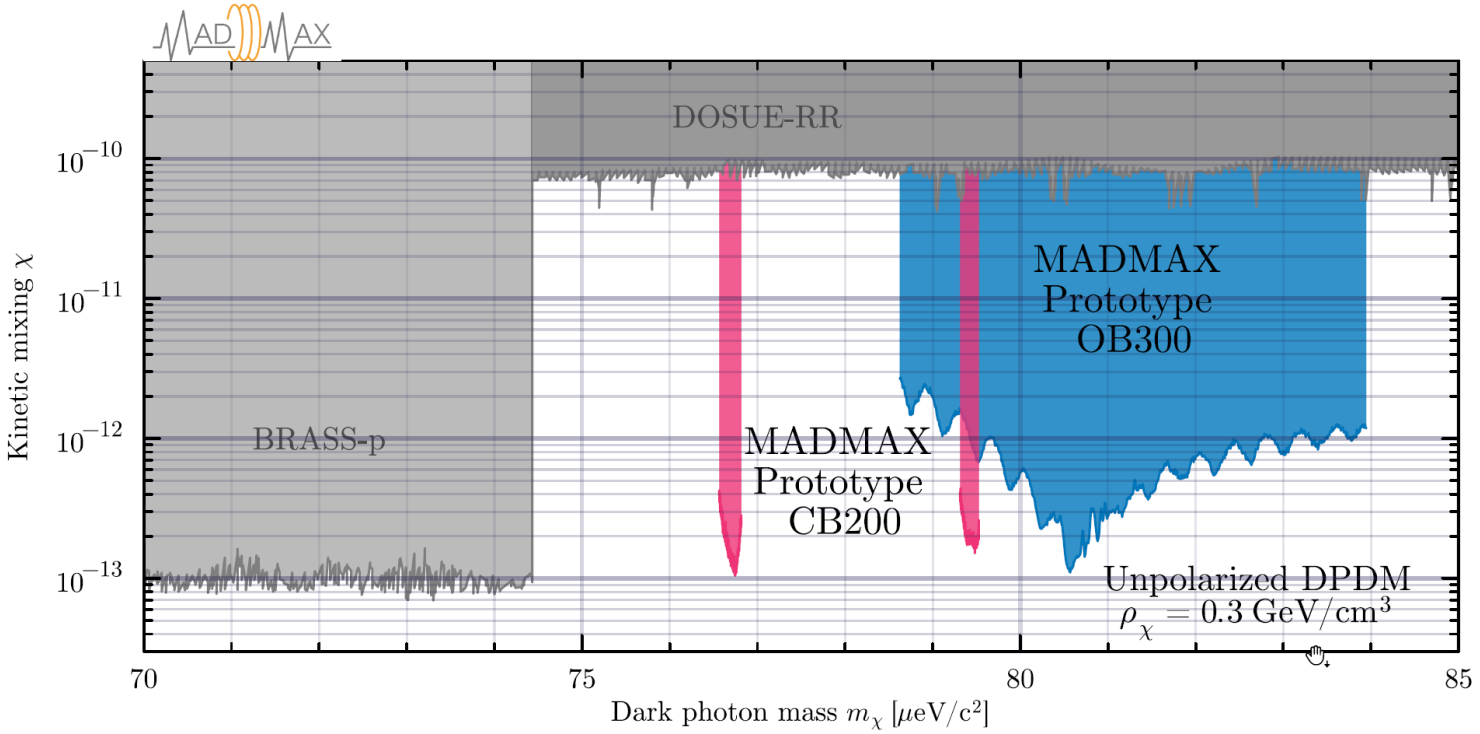


MADMAX collaboration, PRL 134, 15, 151004 (2025)

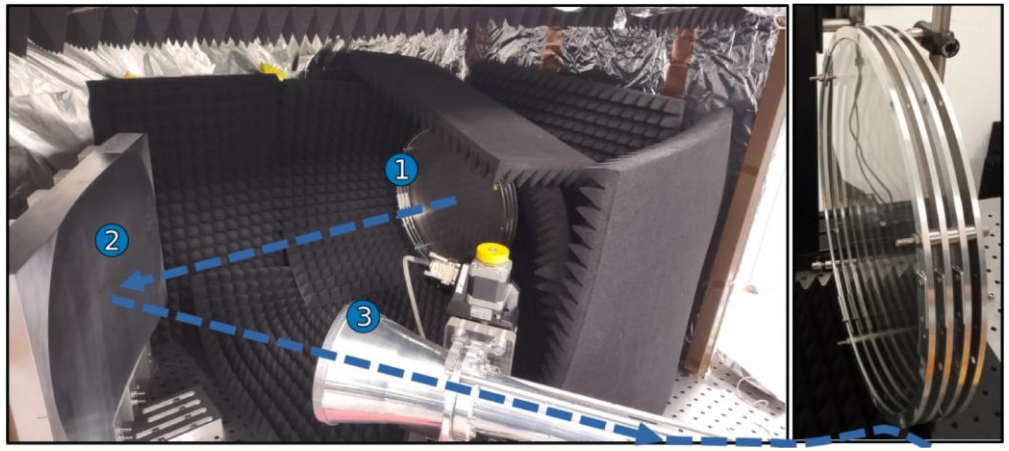


- **Boost factor peak ~ 600**
- **Broad band configuration:**
  $\beta^2 > 100$ over 100 MHz
  $\beta^2 > 10$ over 400 MHz
- **Limits on dark photon dark matter improved by up to factor 500**

Dark photon dark matter search using a MADMAX open booster – OB300



CB200 & OB300 Dark photon dark matter limits complementary
http://vietnam.in2p3.fr/2025/tmex/transparencies/5_friday/morning/DM4/04_Dabhi.pdf

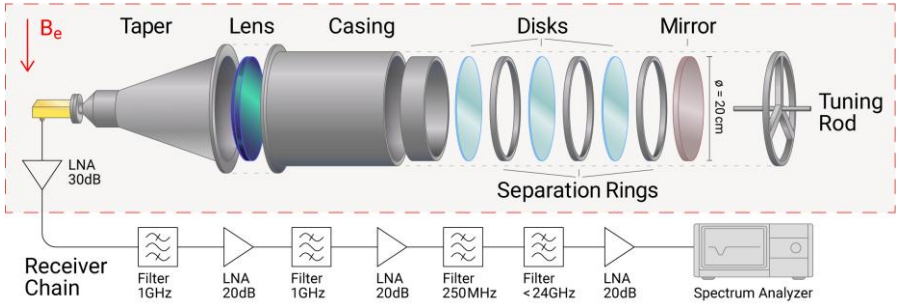


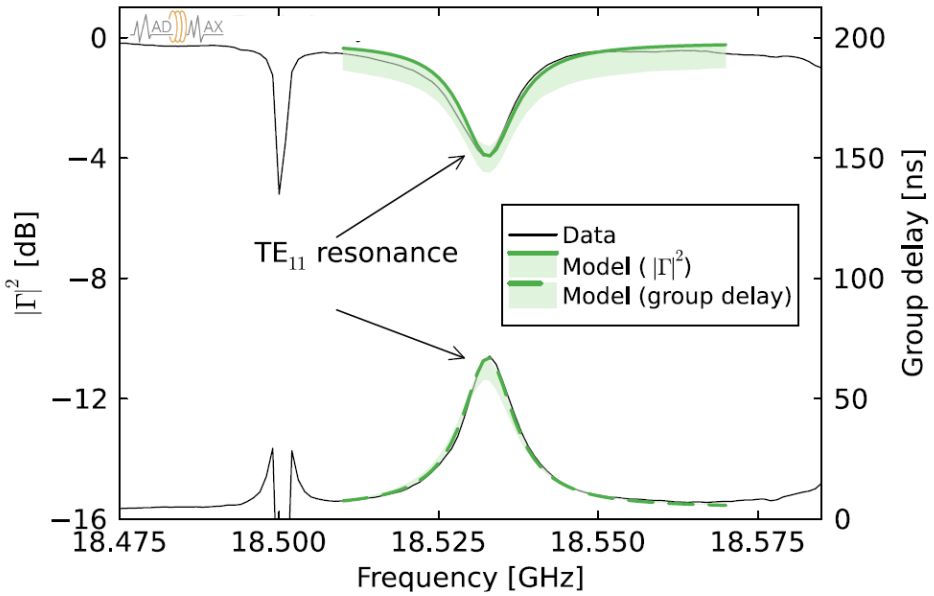
- **Boost factor peak ~ 600**
- **Broad band configuration:**
  $\beta^2 > 100$ over 100 MHz
  $\beta^2 > 10$ over 400 MHz
- **Limits on dark photon dark matter improved by up to factor 500**

Boost factor determination

„closed booster“ CB200

Reflectivity, power spectrum & modelling





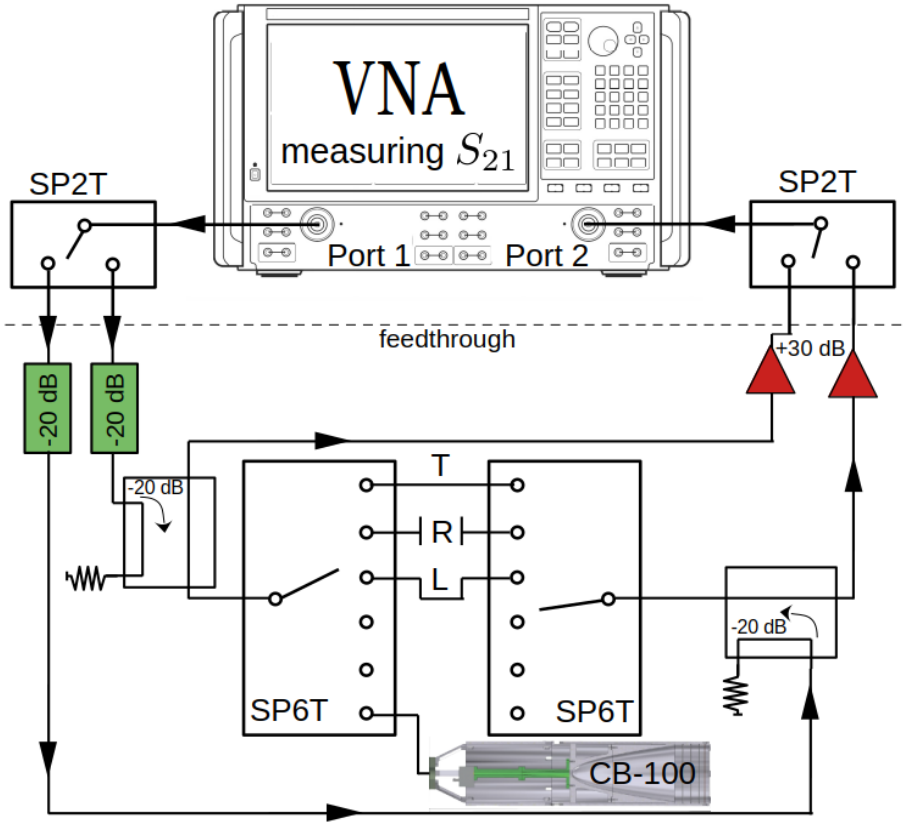
Boost factor of CB200

- Avoid overlap with parasitic modes: Field shape measured using „bead pull“ method
- Extraction of model parameters using reflectivity and power spectra
- Boost factor & uncertainties from modelling using experimentally verified parameters

MADMAX collaboration, JCAP06(2026)046 , arXiv:2603.05006

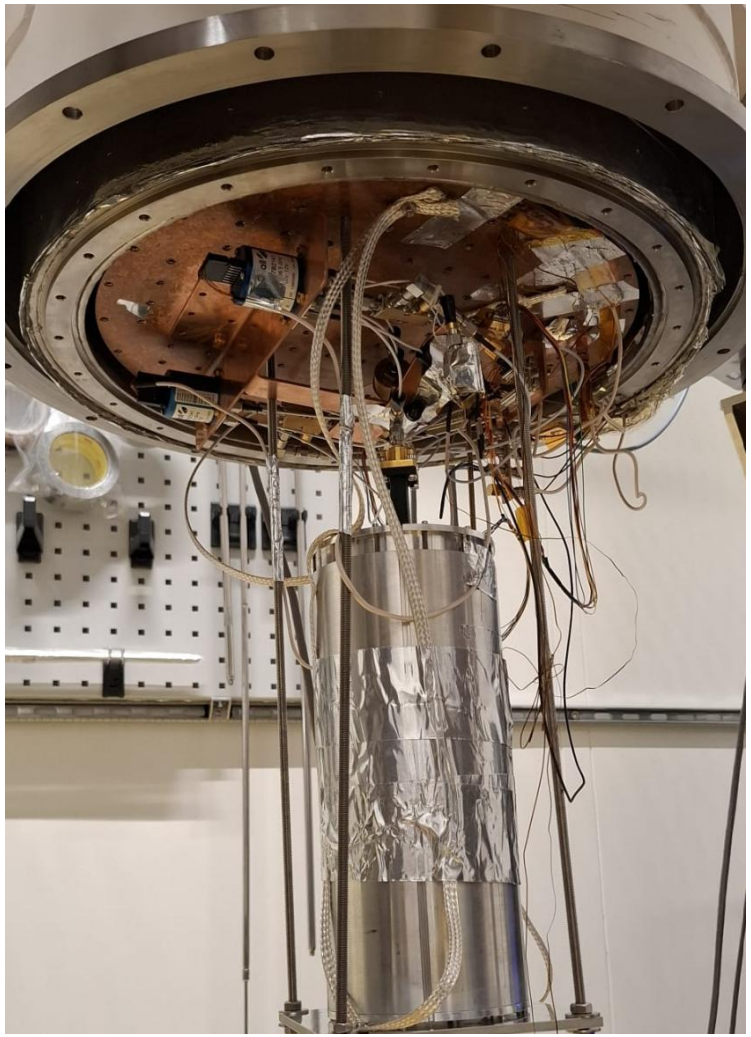
Boost factor determination

„closed booster“ CB100 – cold calibration



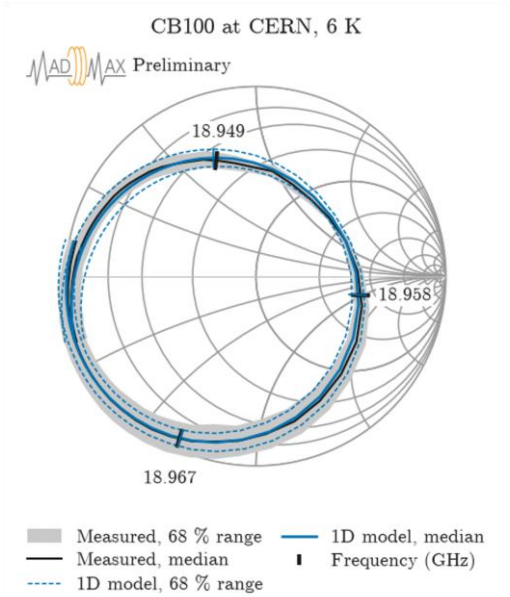
Cryogenic environment:

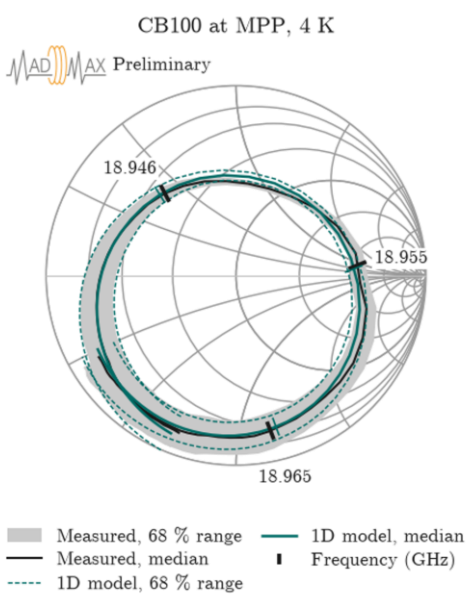
- Switching btw. Spectrum analyzer and VNA
  → need for extra components
- Reflectivity at cold needed for all components

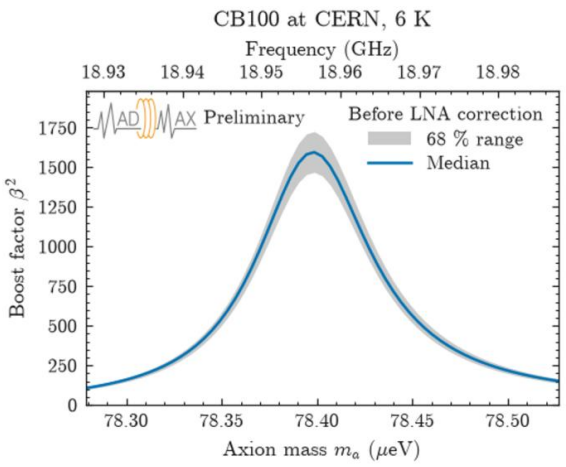


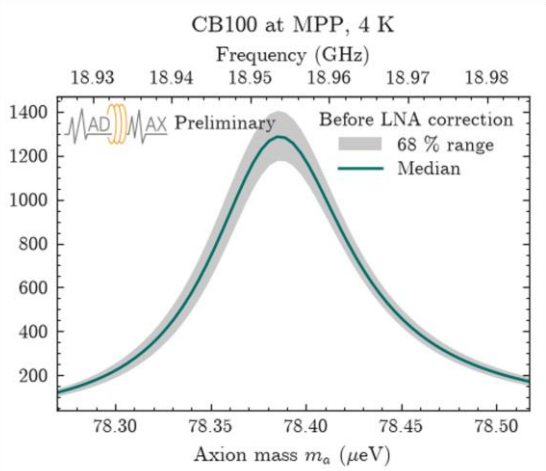
Boost factor determination

„closed booster“ CB100 – cold calibration





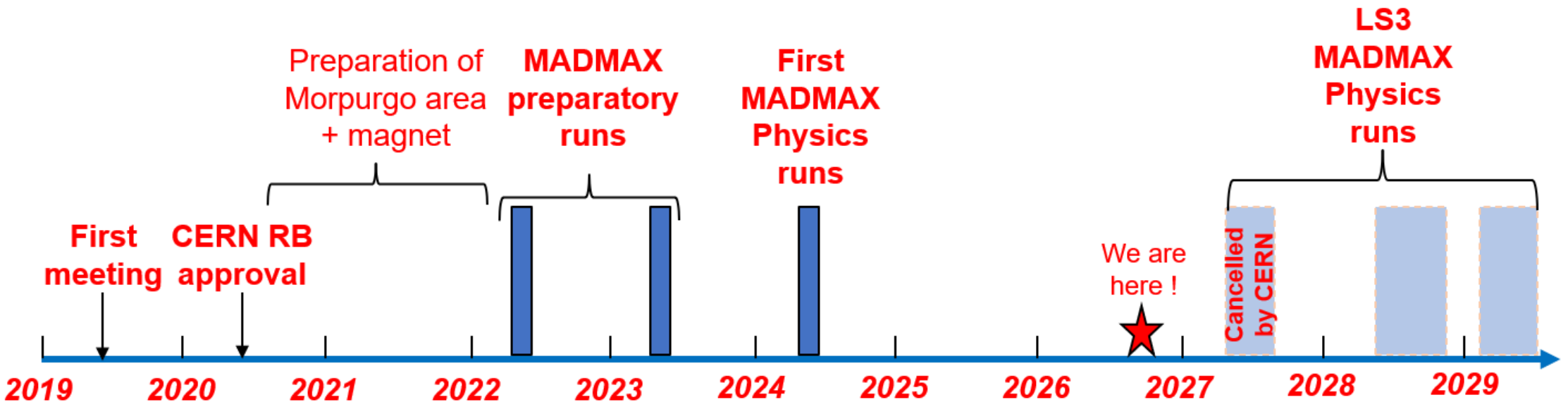




Cryogenic environment:

- Switching btw. Spectrum analyzer and VNA → need for extra components
- Reflectivity at cold needed for all components
- Developmed cryogenic reflectivity calibration
- Power calibration using heater on cryogenic match

Usage of MORPURGO magnet at CERN



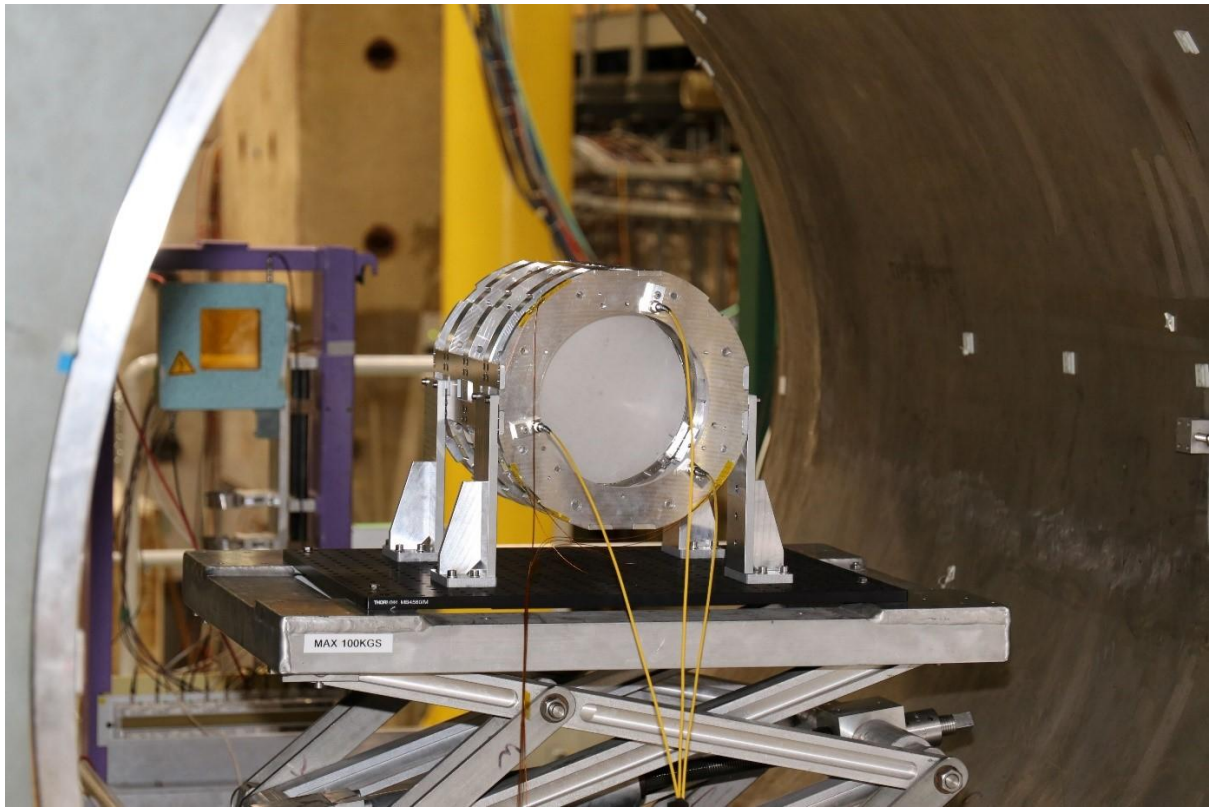
- Morpurgo magnet in SPS H8 beam line
- "Test bed" for MADMAX during beam shut down until own magnet procured
- 1.6T dipole magnet with 1.6m warm bore – biggest of its kind world wide
- CERN support: magnet consolidation & supply infrastructure
- During LS3: extended time slot for longer measurements in 2028 & 2029

Usage of MORPURGO magnet at CERN

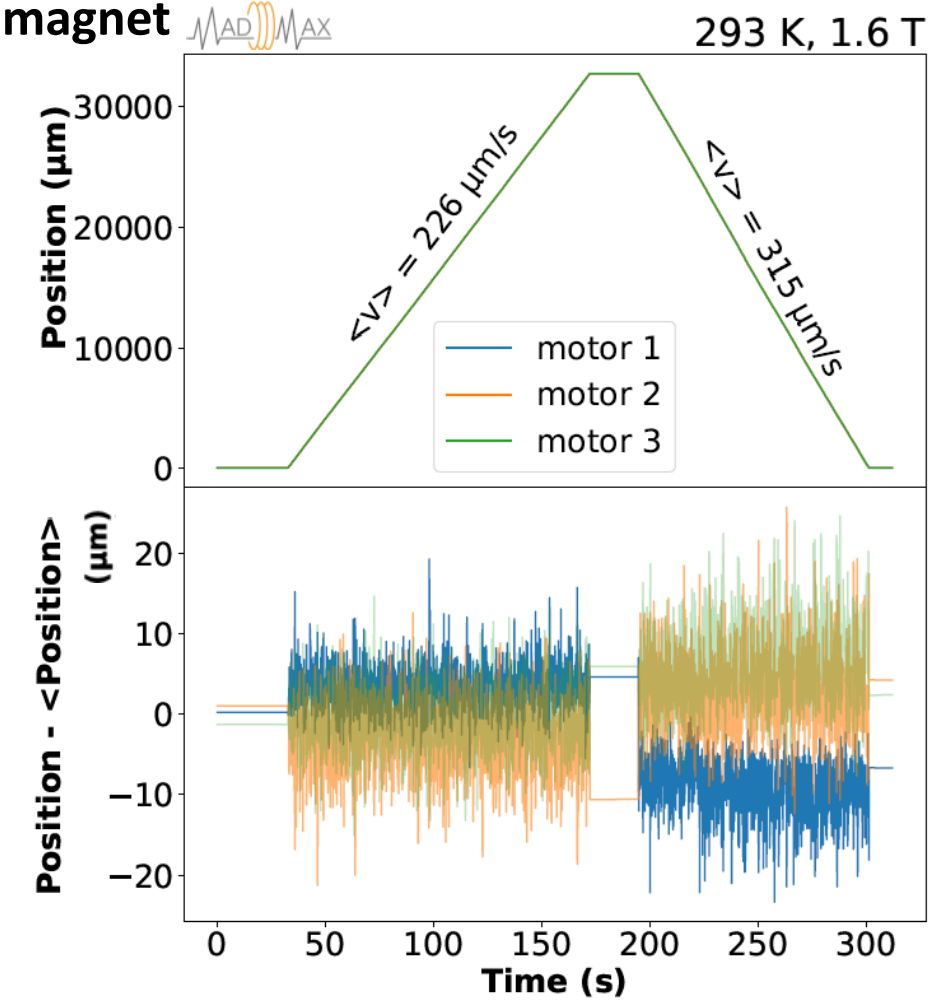
Technology: Actuation of disks for frequency tuning

Tunable booster with 1 disk:

in 1.6 T B-field @ CERN MORPURGO magnet



Motor movement

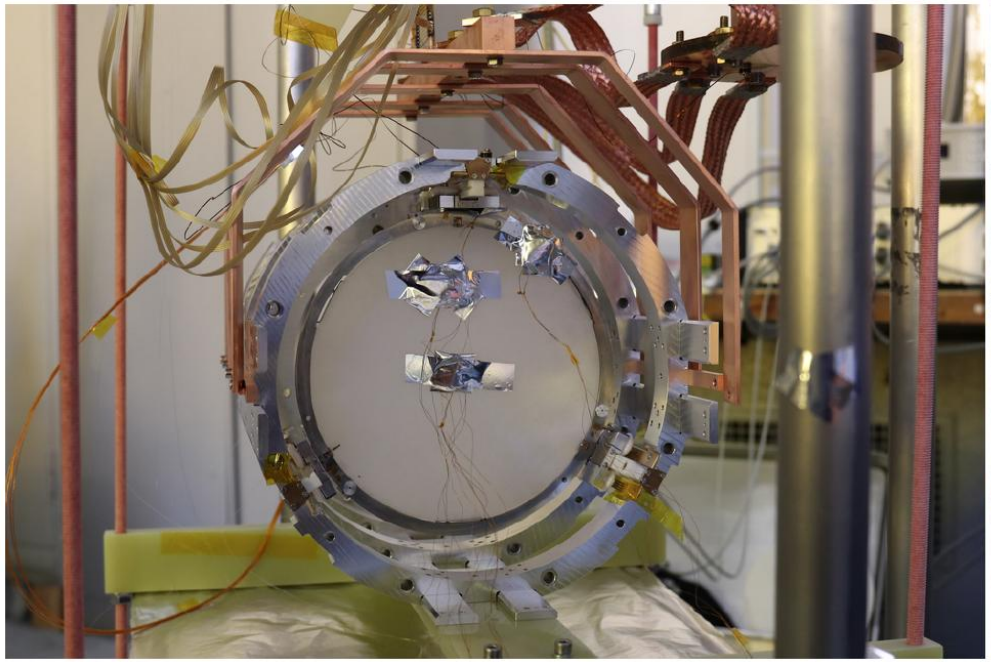


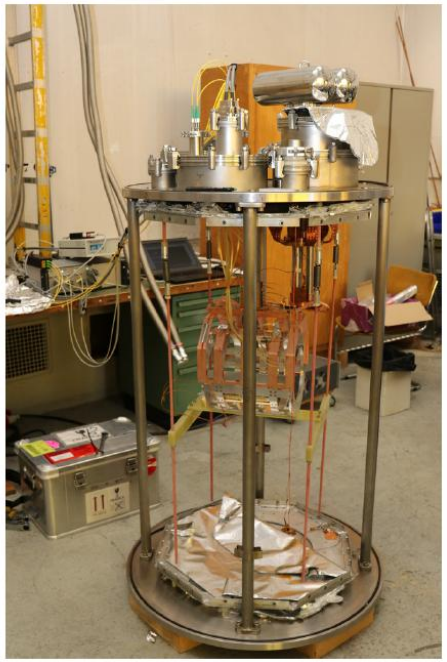
MADMAX collaboration, 2024 JINST 19 T11002

Usage of infrastructure at CERN

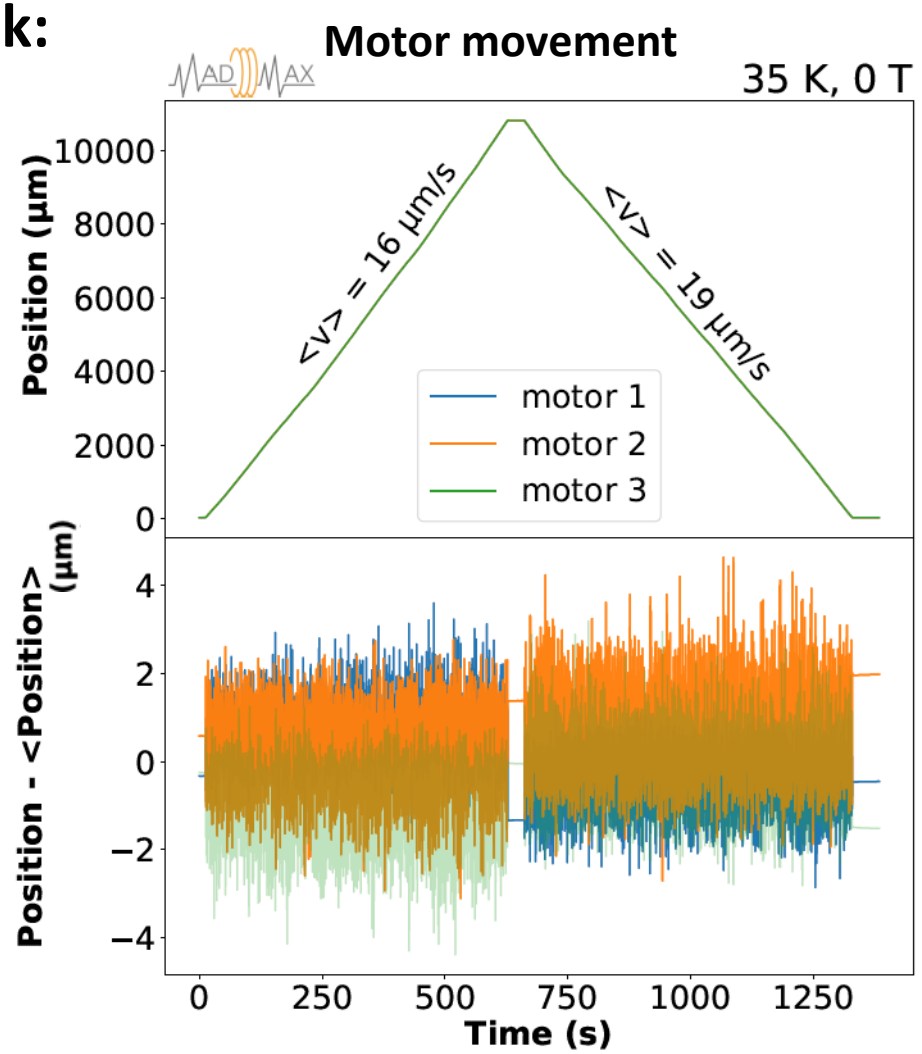
Technology: Actuation of disks for frequency tuning

Tunable booster with 1 disk:
at cryogenic temperature



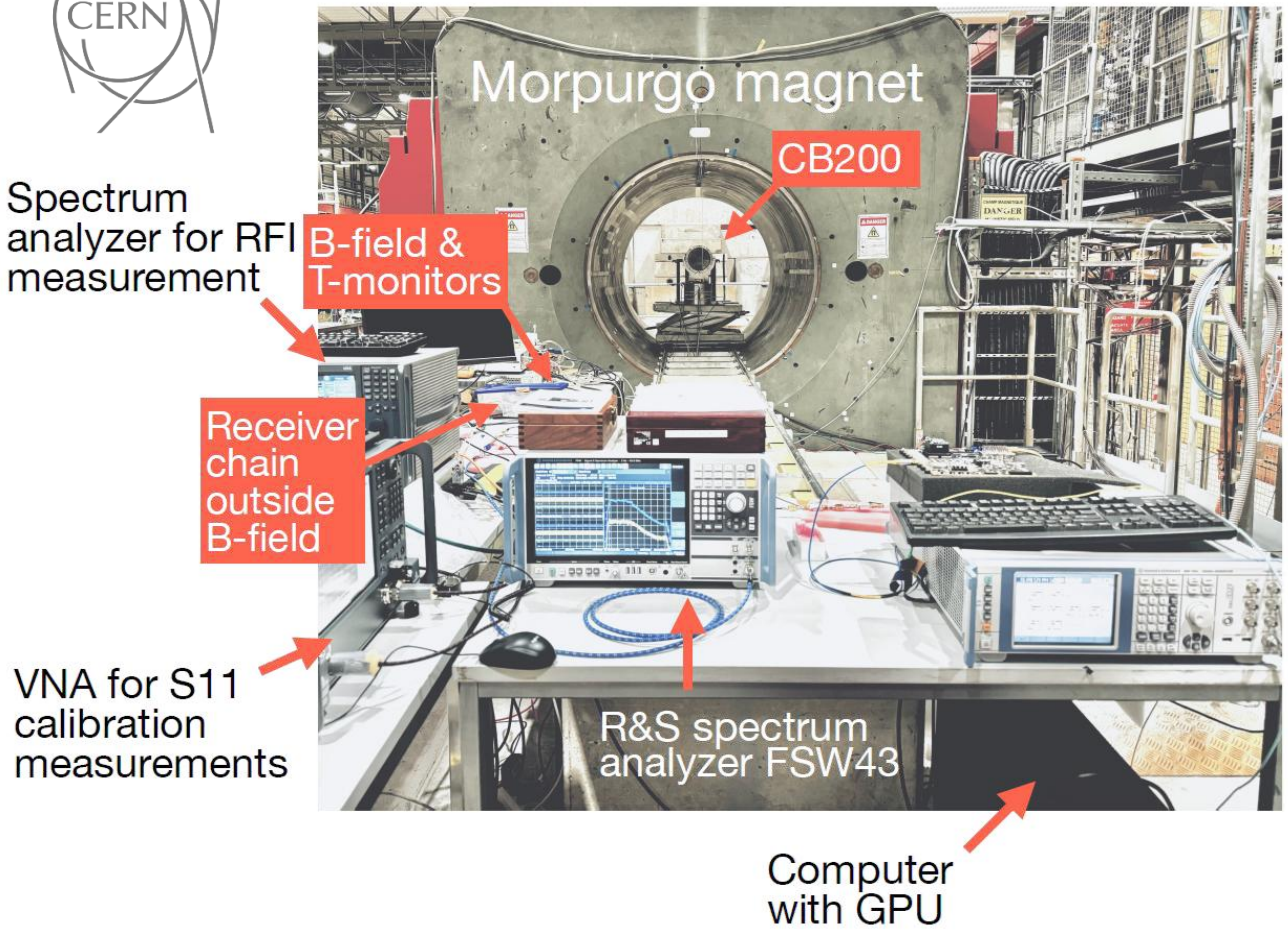


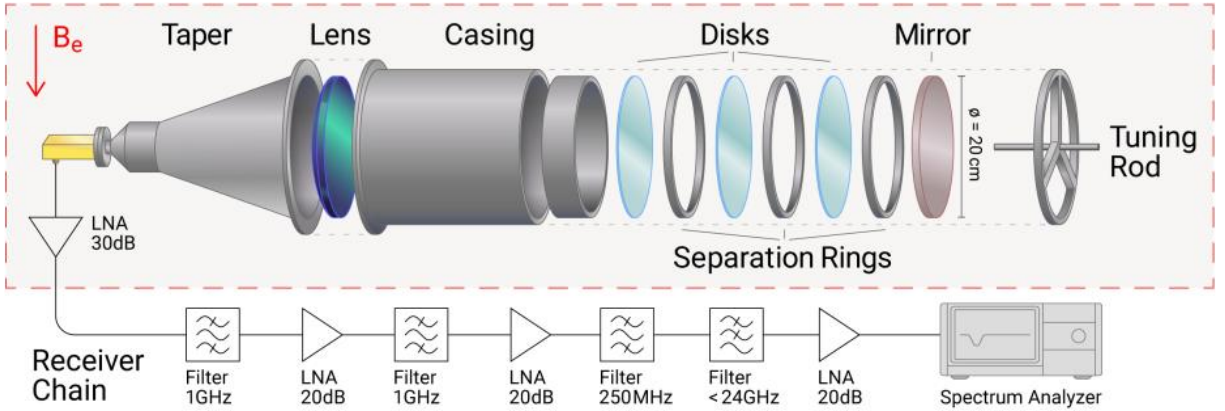
Cryostat from CERN cryolab



MADMAX collaboration, 2024 JINST 19 T11002

The 1st MADMAX ALP dark matter search with dielectric haloscope

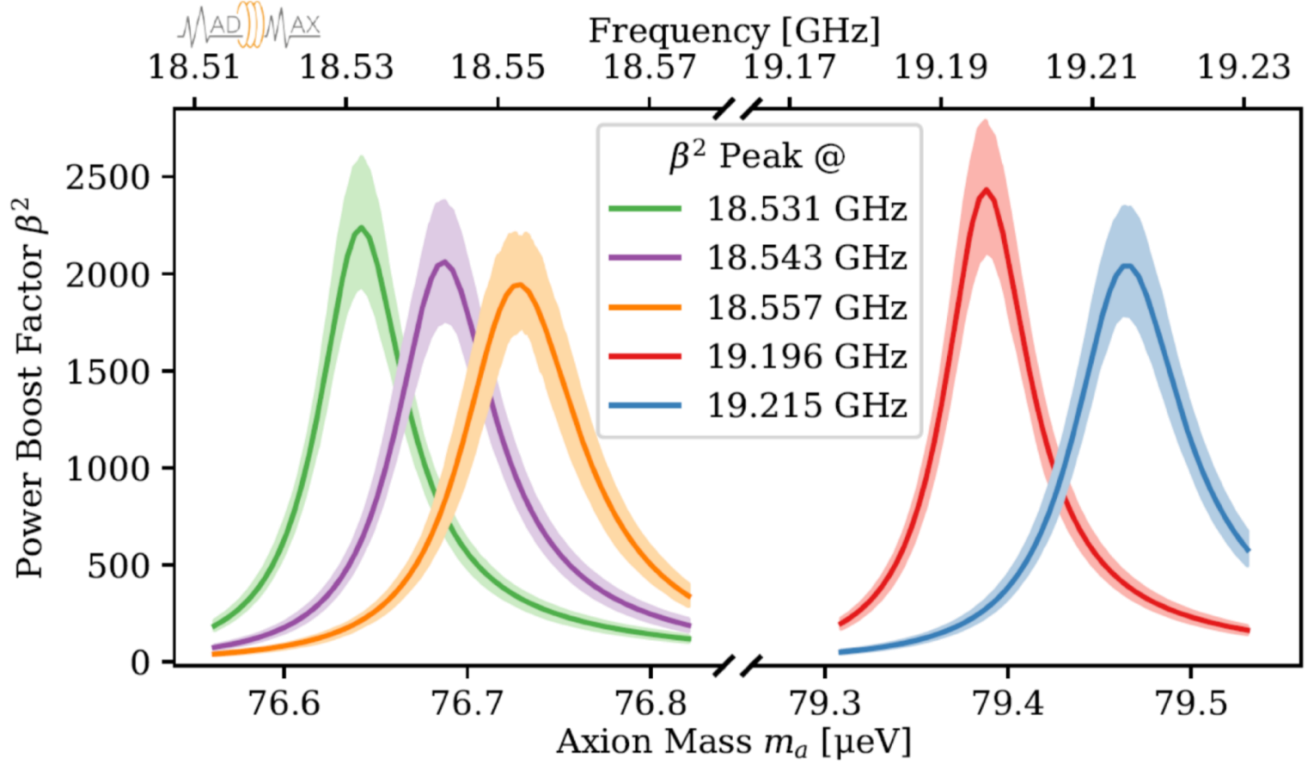


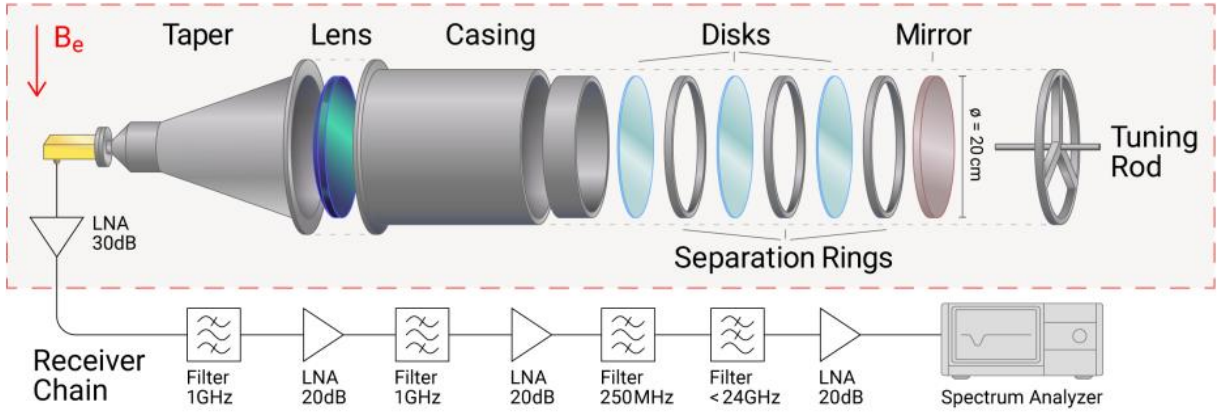


- **Measurements taken 2024 at CERN inside MORPURGO magnet**
- **CB200 at Room temperature**
- **17 days of measurements in different configurations**
- **1.0 T < B < 1.6 T**

MADMAX collaboration, PRL 135, 041001 (2025)

The 1st MADMAX ALP dark matter search with dielectric haloscope



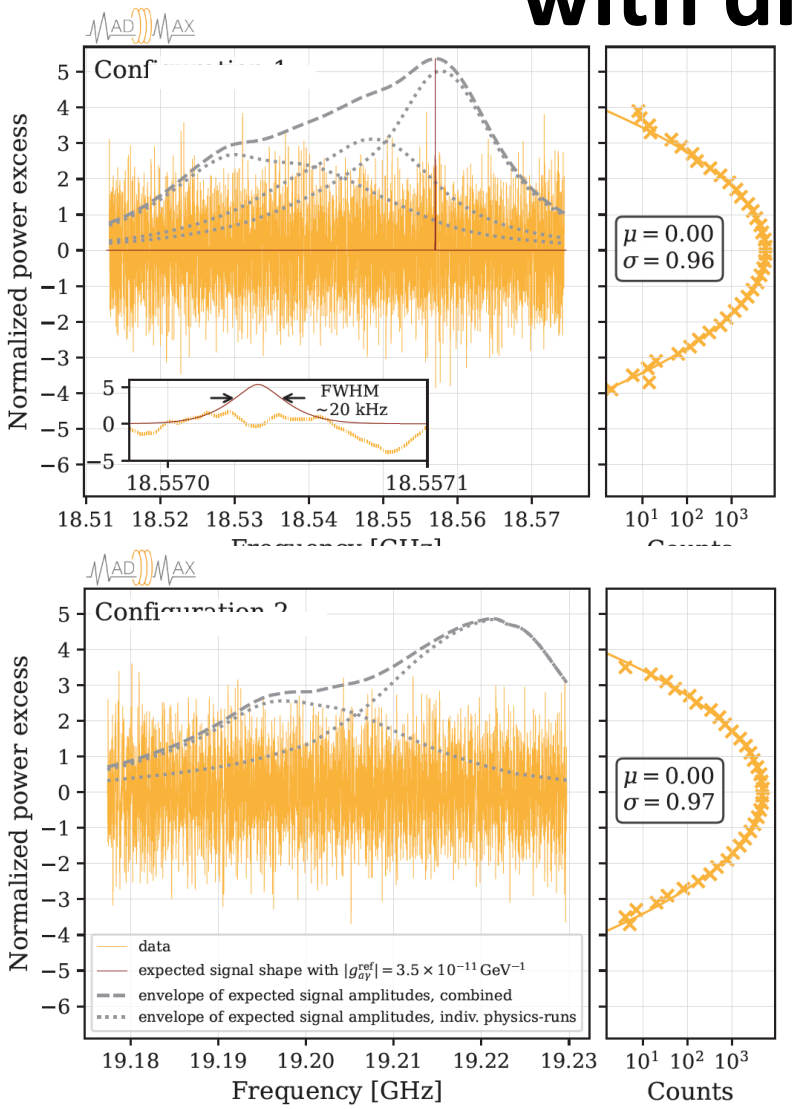


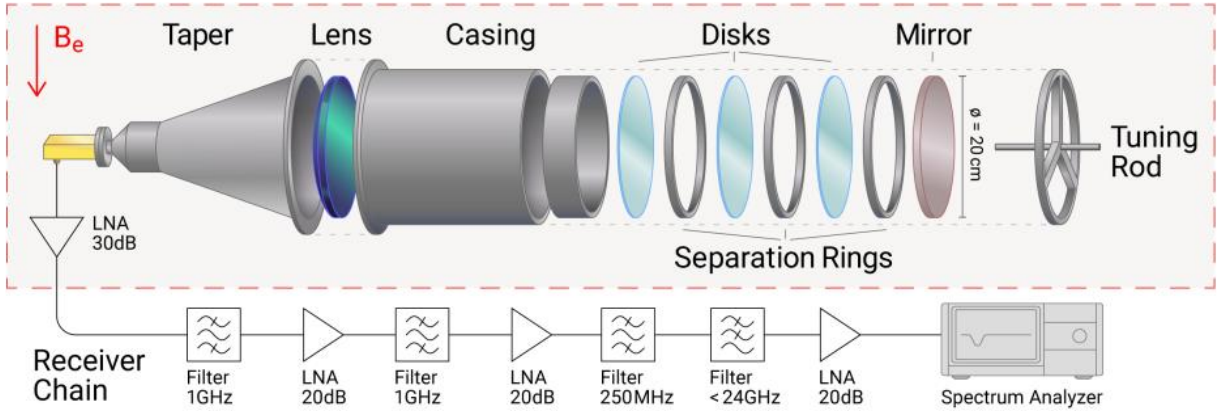
- Scanned 5 different ~20MHz frequency ranges
- Boost factor peak @ ~ 2000
- No excess observed
- Limits on ALP Dark Matter exceed ALPS limits from CAST and astrophysics

MADMAX collaboration, PRL 135, 041001 (2025)

The 1st MADMAX ALP dark matter search with dielectric haloscope

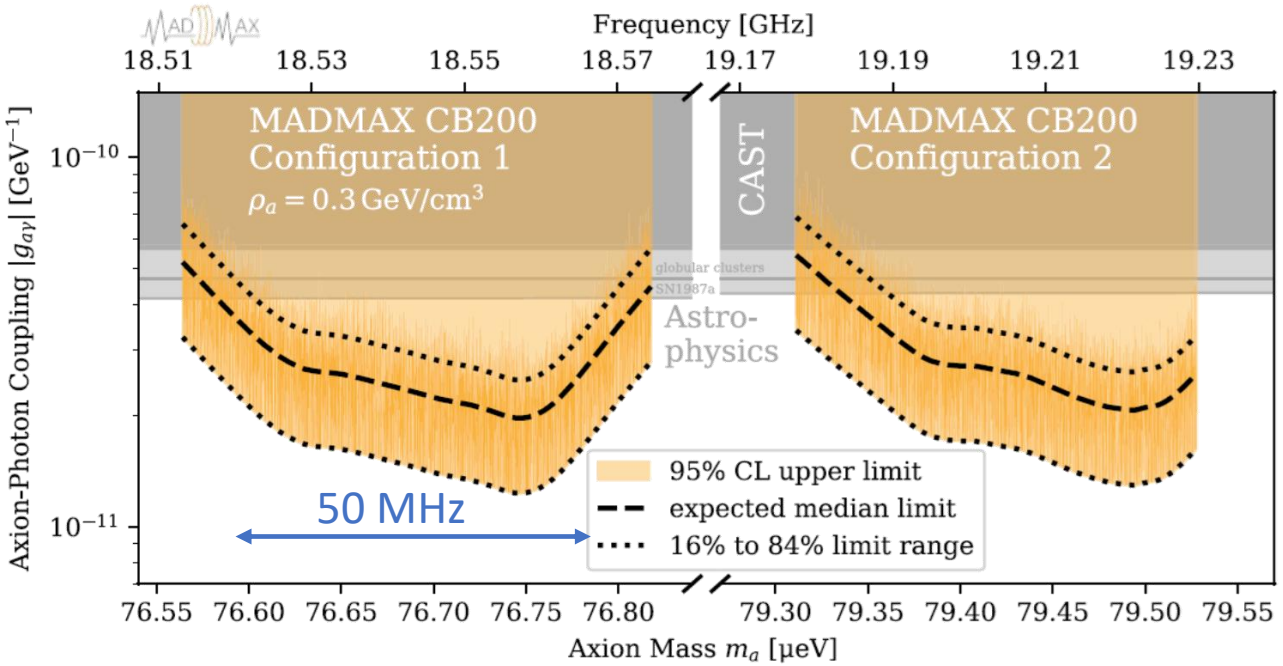
MADMAX collaboration, PRL 135, 041001 (2025)



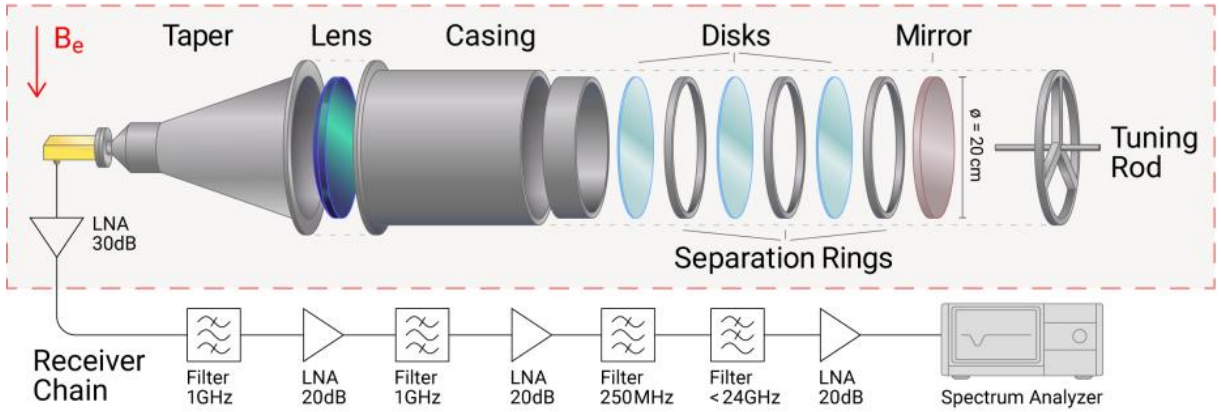


- Scanned 5 different ~20MHz frequency ranges
- Boost factor peak @ ~ 2000
- No excess observed
- Limits on ALP Dark Matter exceed ALPS limits from CAST and astrophysics

The 1st MADMAX ALP dark matter search with dielectric haloscope



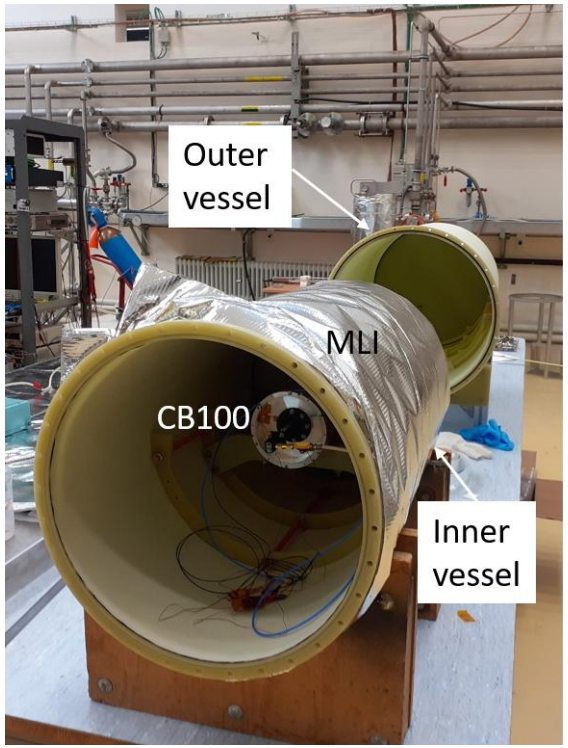
Assume $\rho_{DM} = 0.3\ GeV/cm^3$

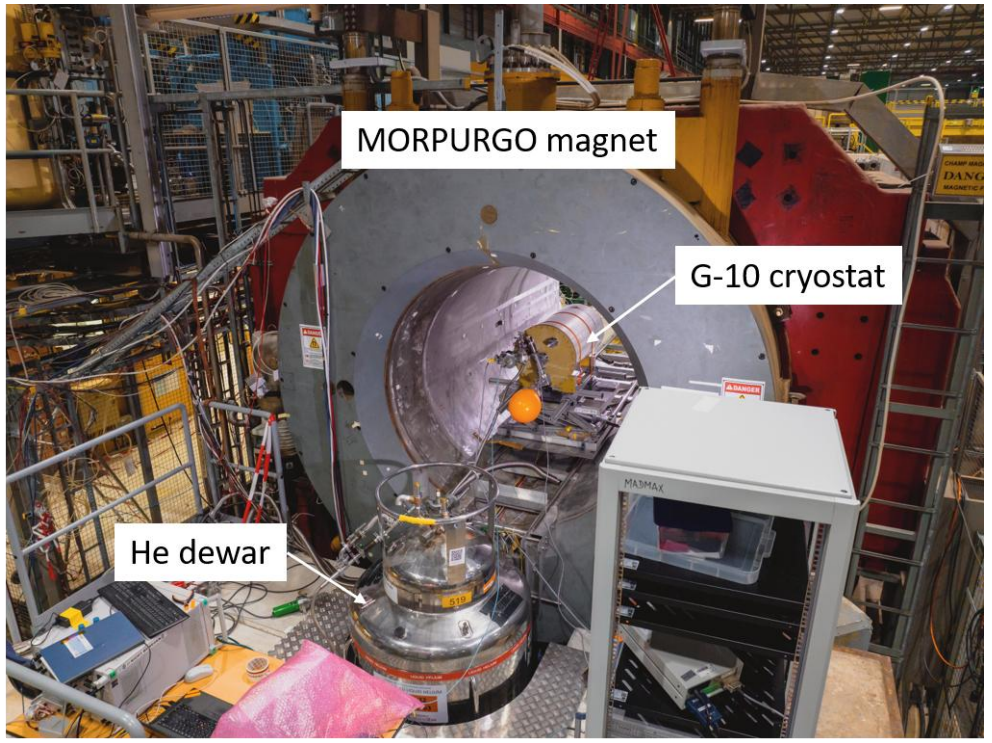


- **Scanned 5 different ~20MHz frequency ranges**
- **Boost factor peak @ ~ 2000**
- **No excess observed**
- **Limits on ALP Dark Matter exceed ALPS limits from CAST and astrophysics**

MADMAX collaboration, PRL 135, 041001 (2025)

The 1st MADMAX ALP dark matter search with cryogenic dielectric haloscope



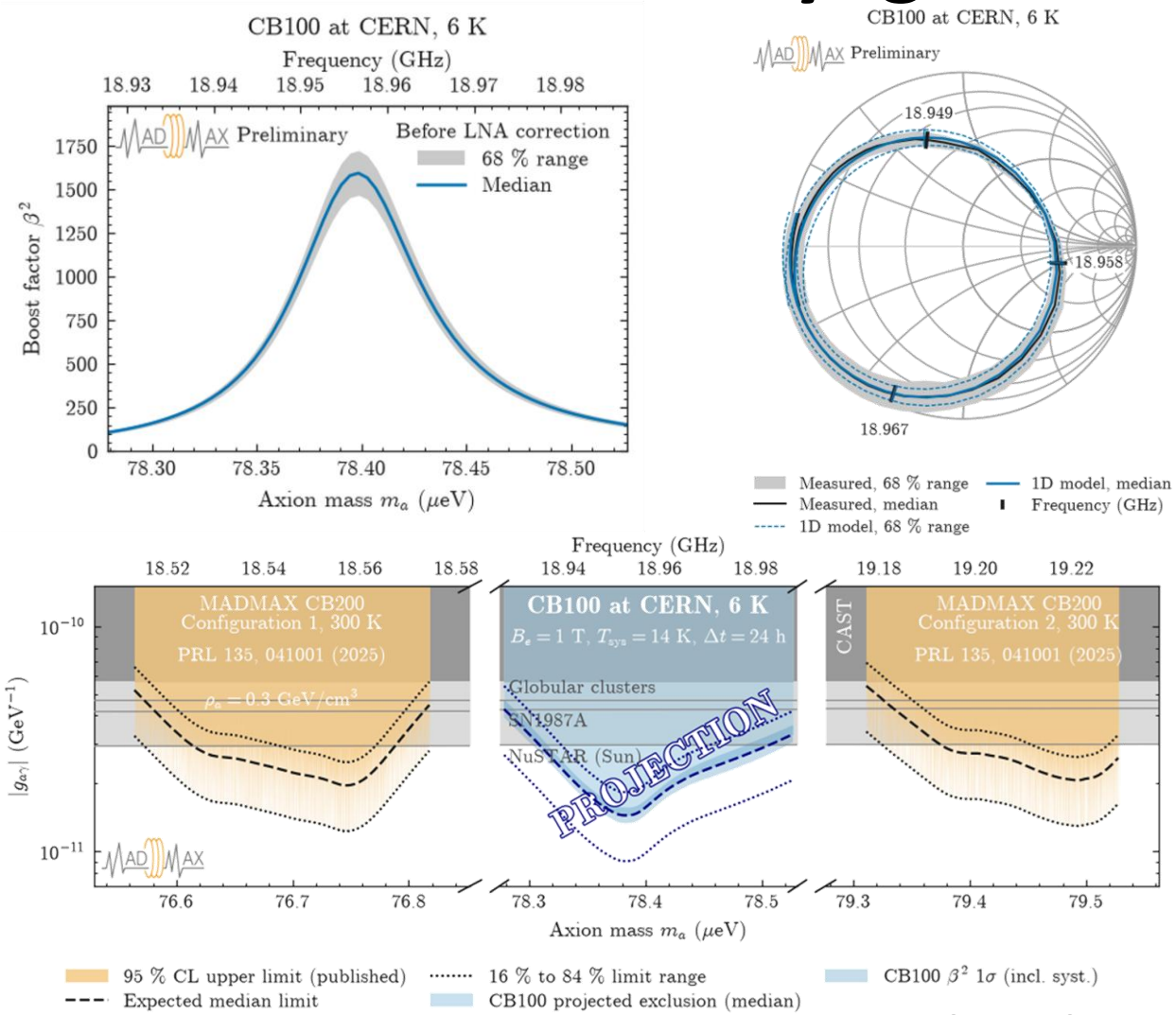


First cryogenic measurements with dielectric haloscope:

- **Used closed booster CB100 inside G10 cryostat for fast cool down**
- **Measurements in 2024 inside MORPURGO magnet @ CERN**

Kreikemeyer et al., JINST 20 T02005 (2025)

The 1st MADMAX ALP dark matter search with cryogenic dielectric haloscope

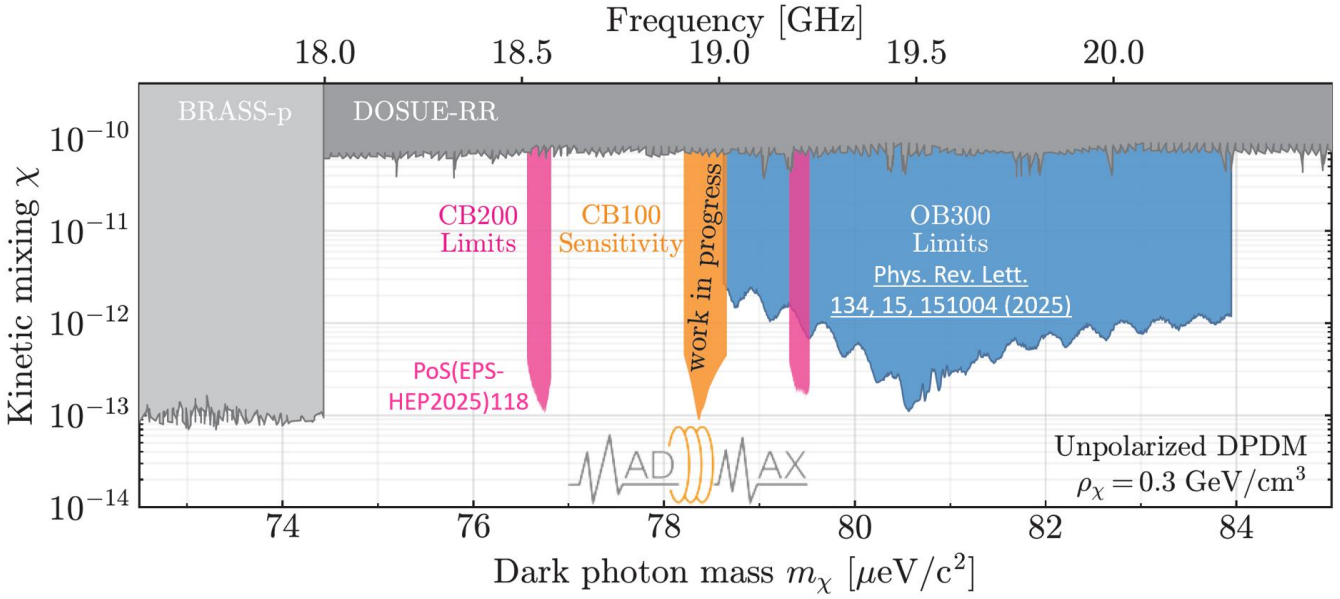


First axion dark matter limits from dielectric haloscope:

- Cryogenic calibration of reflectivity now available
- Boost factors including uncertainties derived, still under scrutiny
- Limit setting sensitivity competitive with earlier limits
- Statistical analysis ongoing

The 1st MADMAX dark photon dark matter search with cryogenic dielectric haloscope

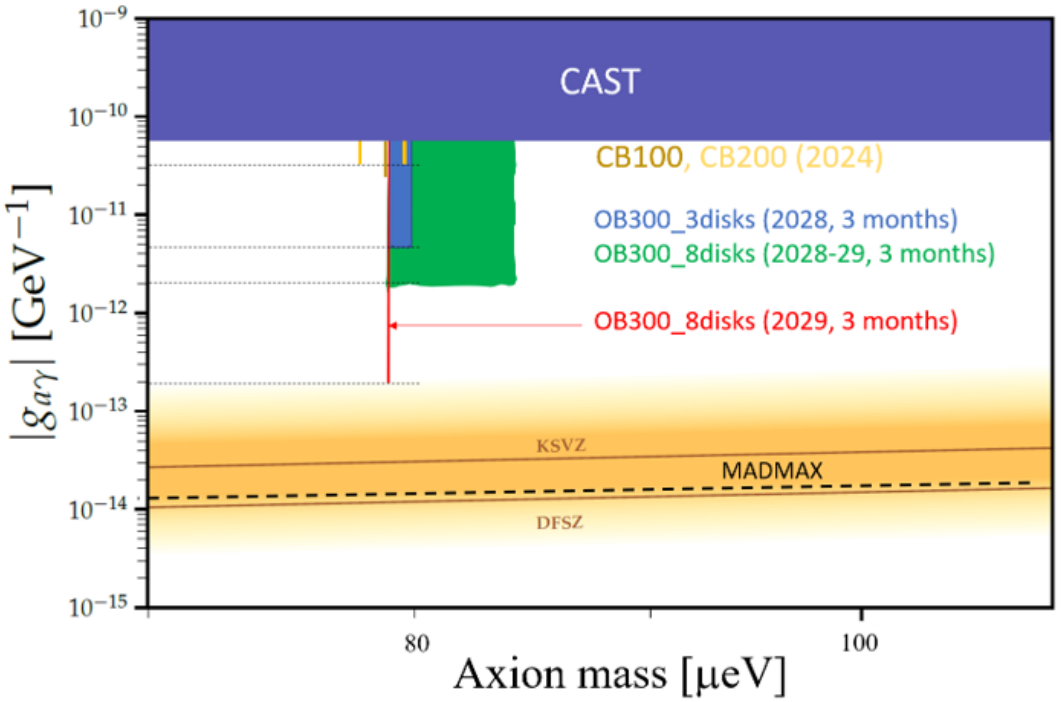


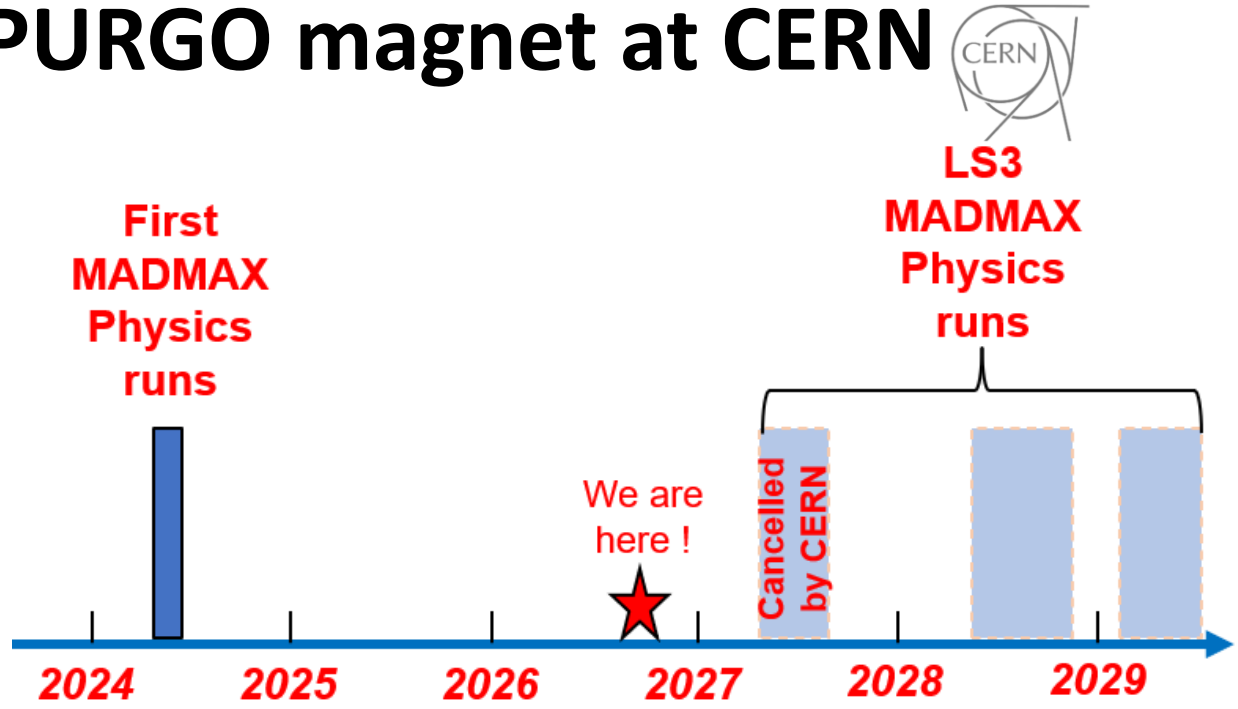


First dark photon dark matter limits from dielectric haloscope:

- **Cryogenic calibration of reflectivity now available**
- **Boost factors including uncertainties derived, still under scrutiny**
- **Limit setting sensitivity competitive with earlier limits**
- **Statistical analysis ongoing**

Usage of MORPURGO magnet at CERN





- Morpurgo magnet in SPS H8 beam line
- "Test bed" for MADMAX during beam shut down until own magnet procured
- 1.6T dipole magnet with 1.6m warm bore – biggest of its kind world wide
- CERN support: magnet consolidation & supply infrastructure
- During LS3: extended time slot for longer measurements in 2028&2029

Preparations for MORPURGO data taking

The cryostat



MADMAX cryostat SAT successful!
Tested additional 3.5 W heat load expected from receiver cryostat + cables
Some margin…

Preparations for MORPURGO data taking

Mounting of OB300 booster



Presently ongoing:

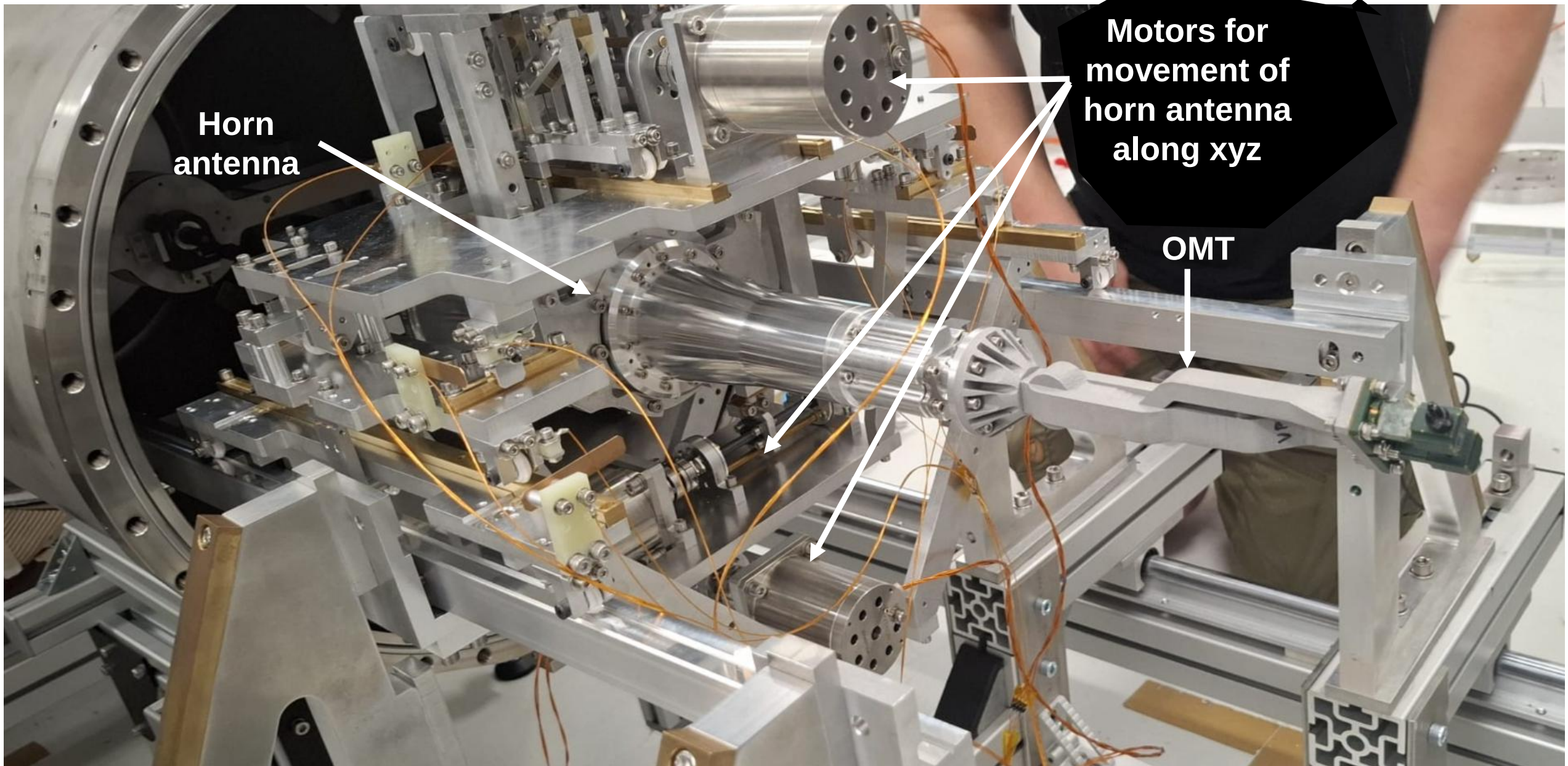
Alignment Booster – focusing mirror – horn antenna
&
Measurement of beam shape

Mounting of receiver cryostat outer vessel

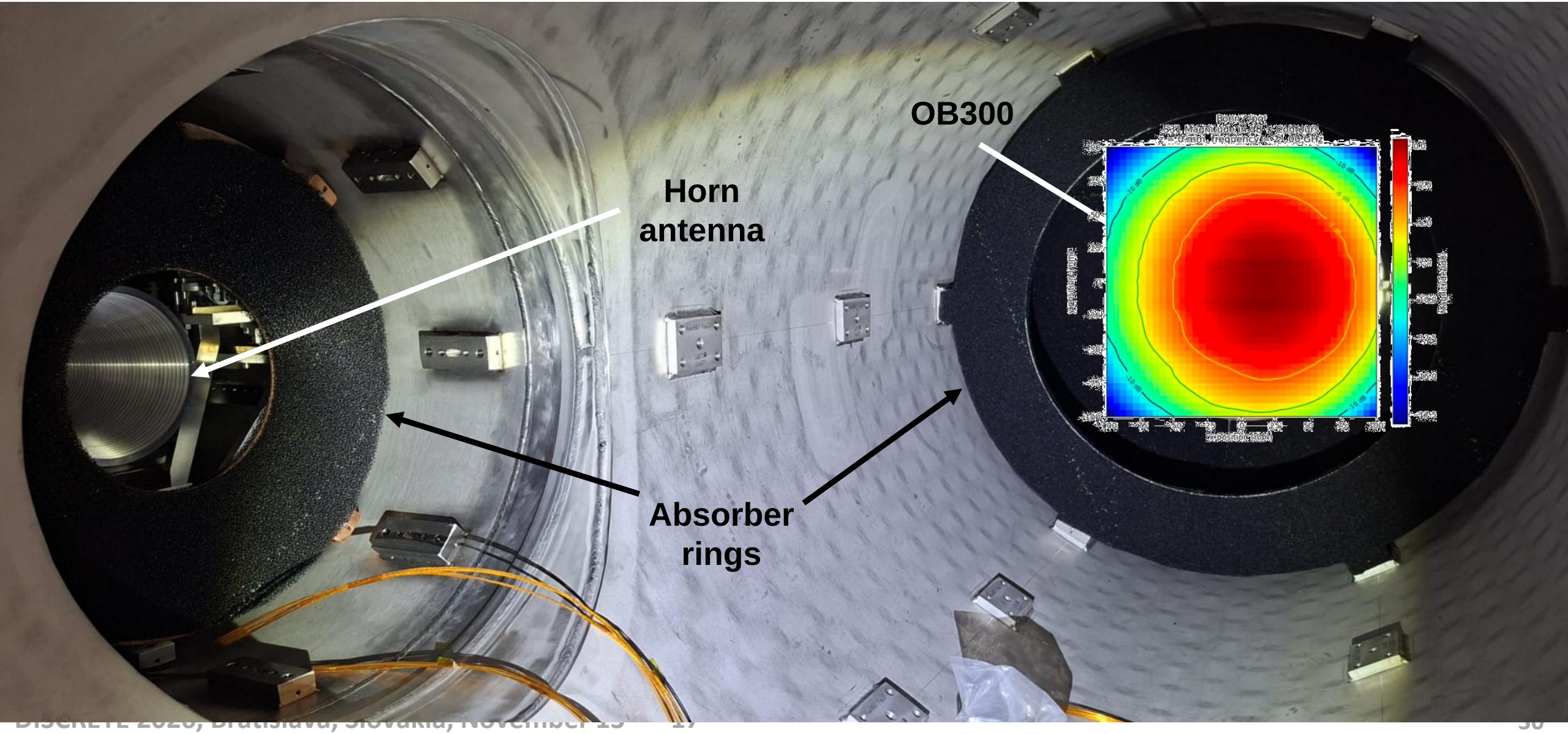
Installation of cables

→ Expect 1st cool down early next year

Preparations for MORPURGO data taking



Preparations for MORPURGO data taking

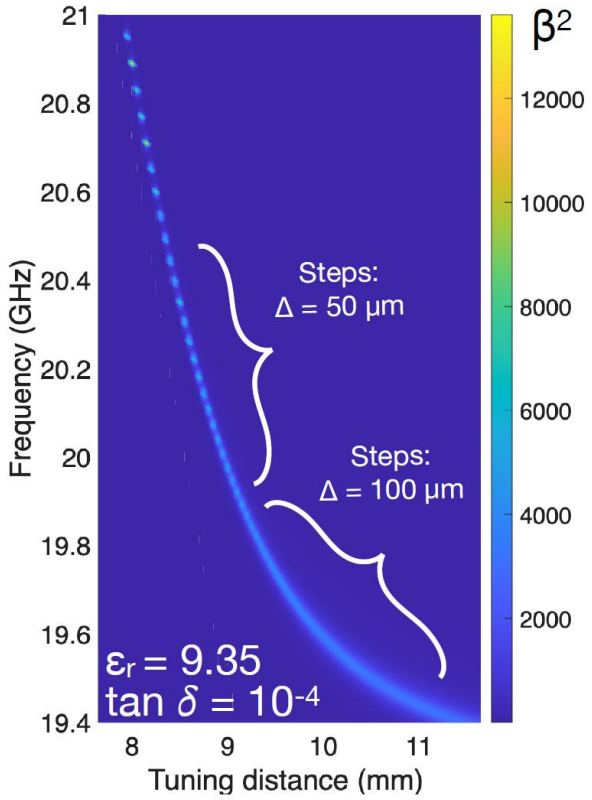


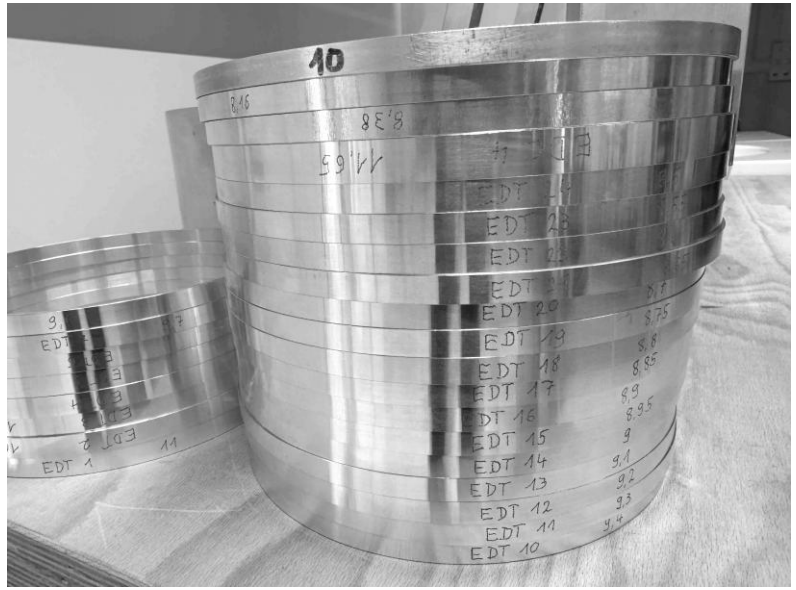
Ongoing R&D: scaling up sensitivity

Increase number of disks: extended CB200

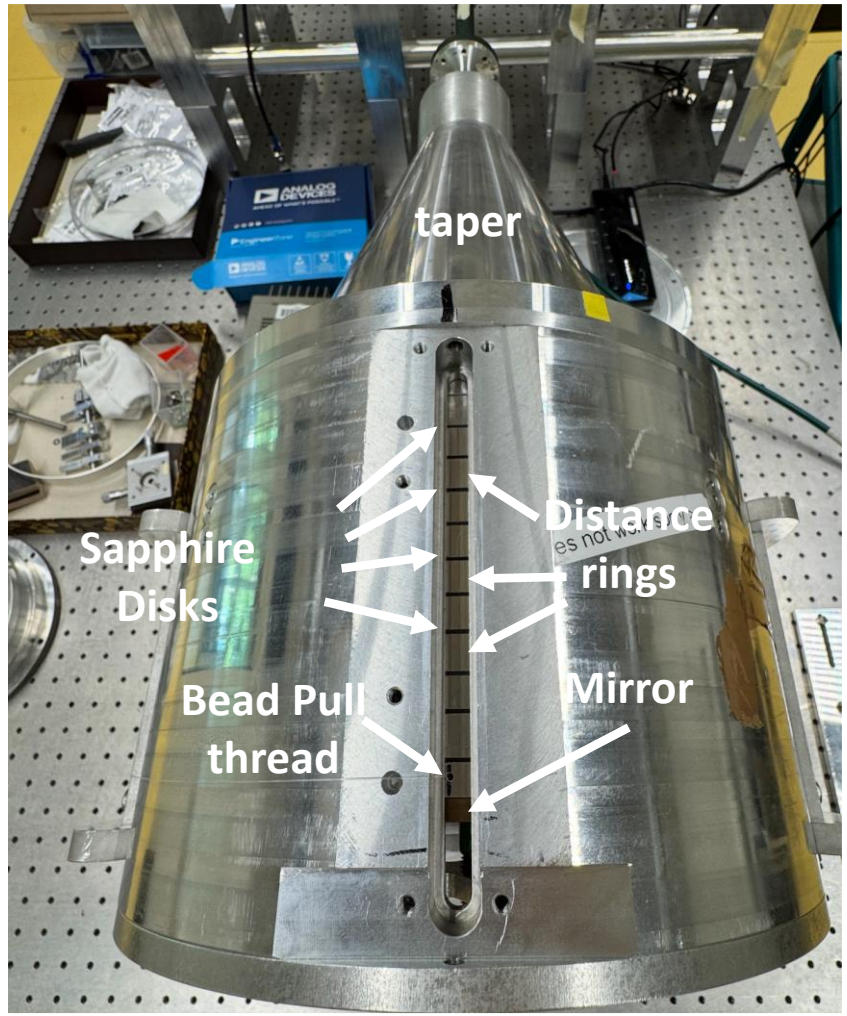
$$|g_{a\gamma}|_{sens} \propto (\beta)^{-1/2} \propto (\#\ \mathbf{of\ disks})^{-1/2}$$

→ implemented 8 disk configuration





Distance rings for tuning
$\Delta d_{central}$ 50 and 100 µm

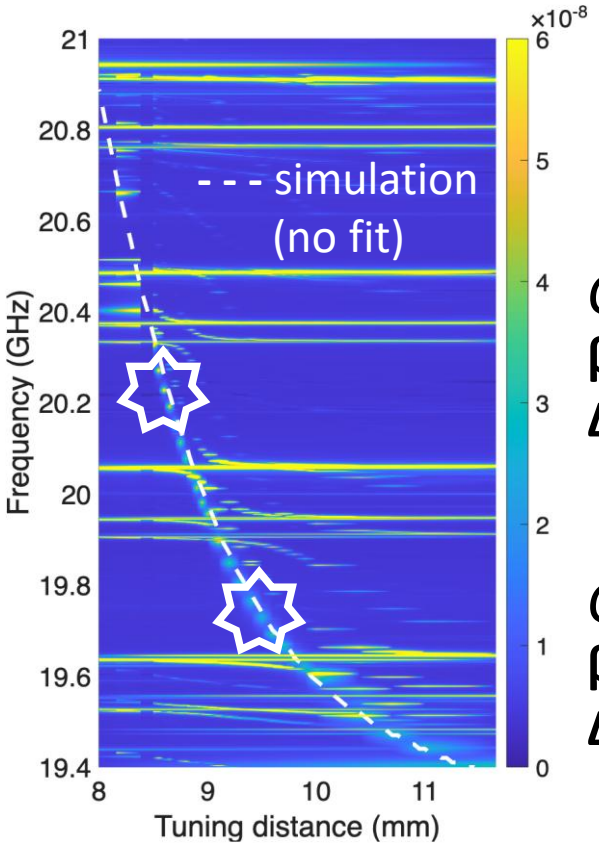


Ongoing R&D: scaling up sensitivity

Increase number of disks: extended CB200

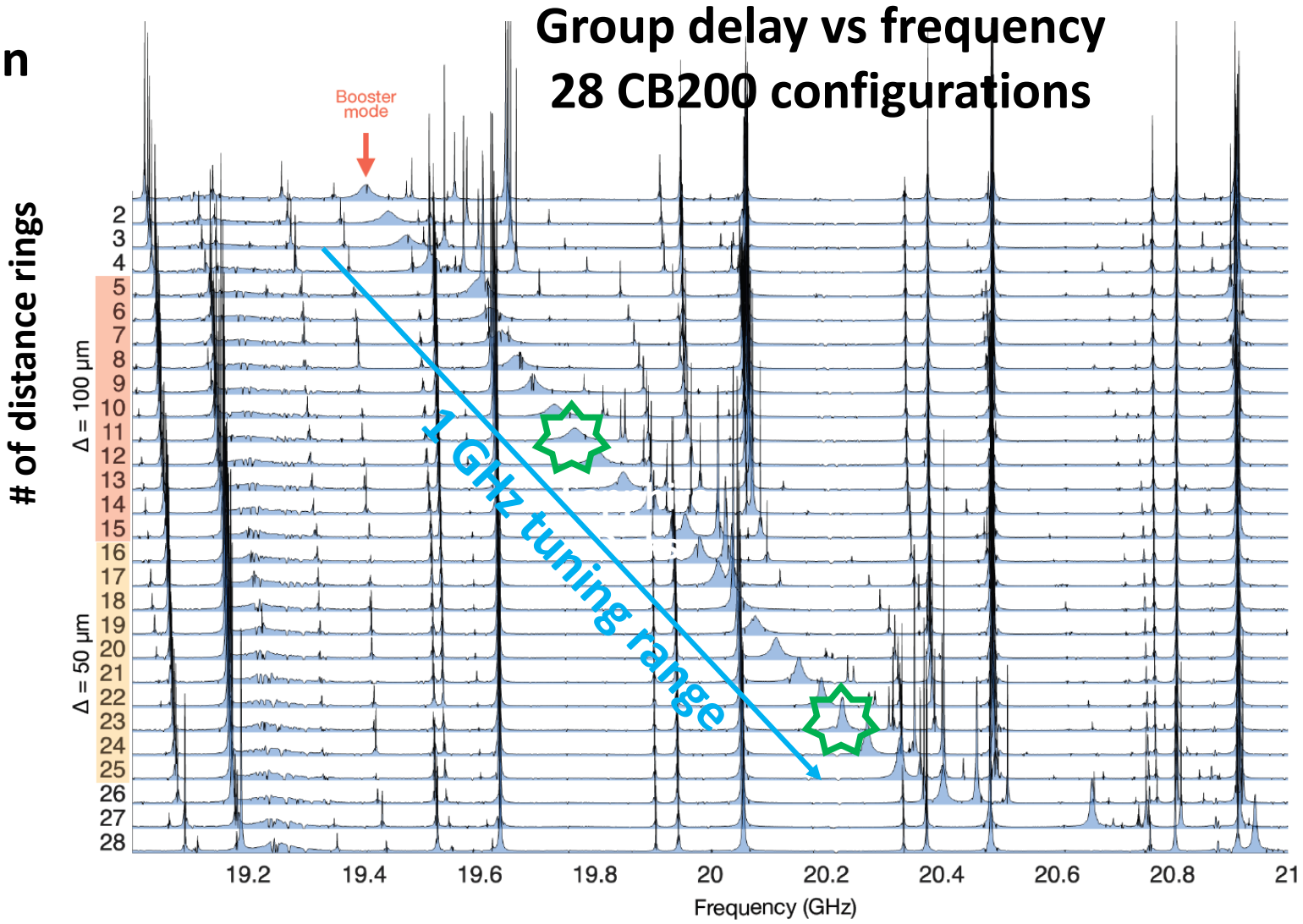
→ implemented 8 disk configuration

→ Dark Photon run ongoing



@20.2 GHz:
β^2 ~ 7500
$\Delta\nu$ ~20MHz

@19.7 GHz:
β^2 ~ 4000
$\Delta\nu$ ~50MHz



Ongoing R&D: going quantum

Overcome SQL: Graphene detector

Development of dark count & background free single photon detector

Based on Graphene calorimeter

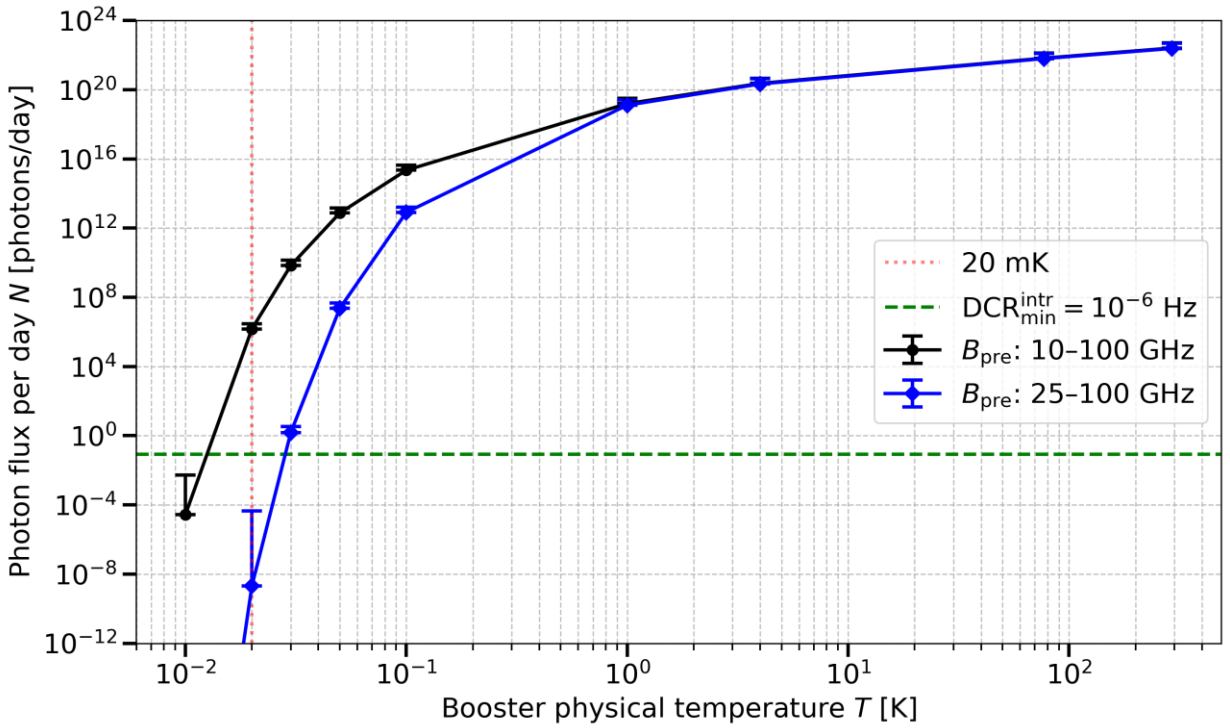
For 20mK: Above 20GHz

No black body radiation!

→ Background free measurement?

Graphene film in high Q-resonator
Tiny heat capacity of Graphen electron system, no coupling to photons!
$\Delta T_{e,\,Graphene} \rightarrow \Delta \nu_{res}$
Measure resonance frequency of resonator using off the shelf JPA

Thermal photons vs booster temperature



Ongoing R&D: going quantum

Overcome SQL: Graphene detector

Development of dark count & background free single photon detector

Based on Graphene calorimeter

For 20mK: Above 20GHz

No black body radiation!

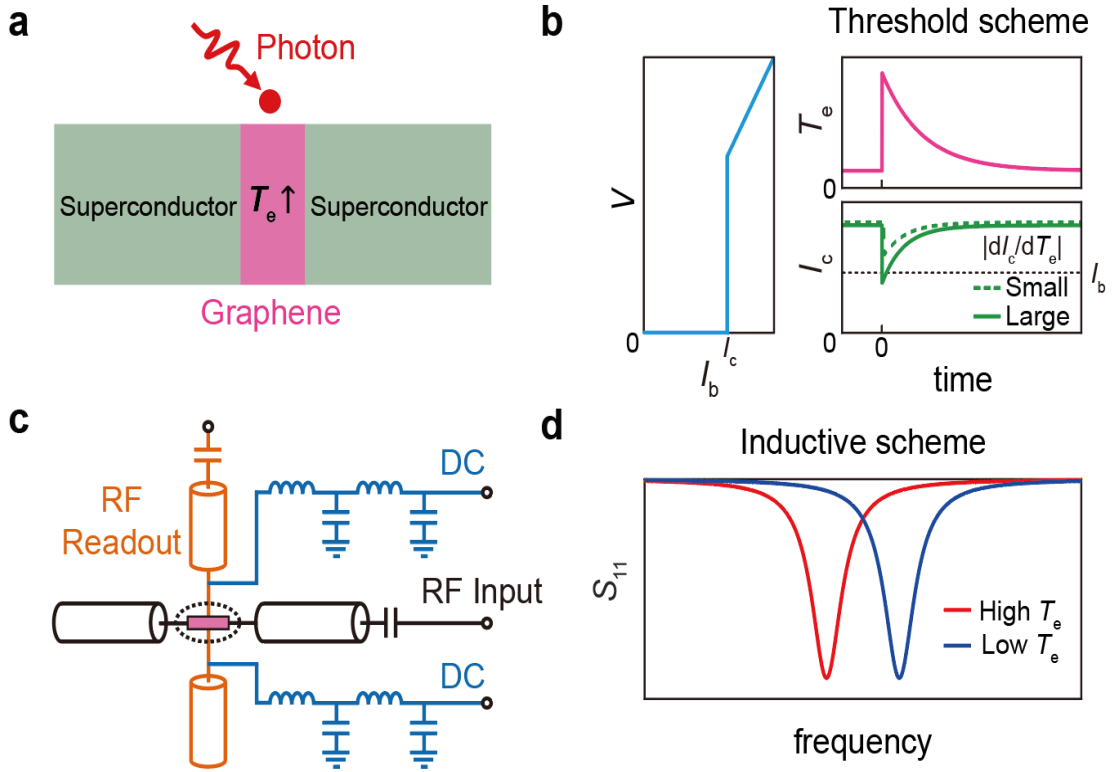
→ Background free measurement?

Graphene film in high Q-resonator

Tiny heat capacity of Graphen electron system, no coupling to photons!

$\Delta T_{e,\,Graphene} \rightarrow \Delta \nu_{res}$

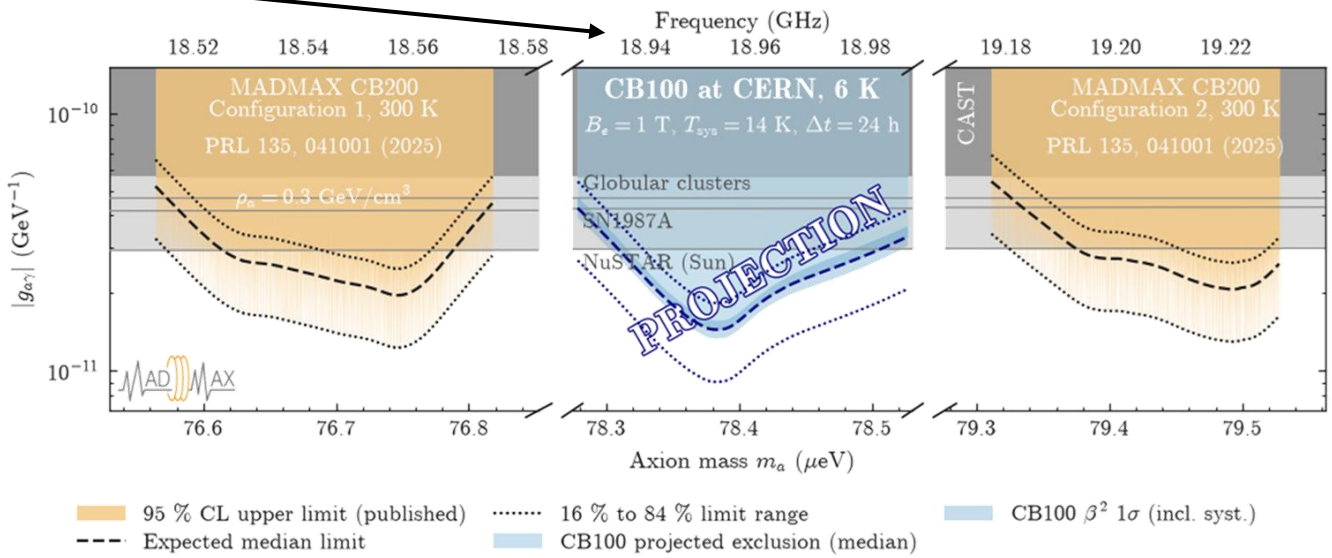
Measure resonance frequency of resonator using off the shelf JPA



Phys. Rev. Applied 8, 024022 (2017), Nature 586, 42 (2020), Science 372, 409 (2021), arxiv.org/abs/2410.22433, arXiv:2503.06850

CONCLUSIONS

- MADMAX designed to be senstive in ~100 µeV mass range → Caldwell et al., PRL 118, 091801 (2017) Millar et al., JCAP01(2017)061
- Technological progress : RF understanding of booster, mechanics, magnet → Egge , JCAP04(2023)064 Egge et al, JCAP04(2024)005 MADMAX, JCAP [2603.05006] MADMAX collaboration, 2024 JINST 19 T11002 Lorin et al., IEEE TAS 33 (2023) 1
- First competitive MADMAX limits published in two PRL articles → MADMAX collaboration, PRL 134, 15, 151004 (2025) MADMAX collaboration, PRL 135, 041001 (2025)
- First limits using cryogenic booster →



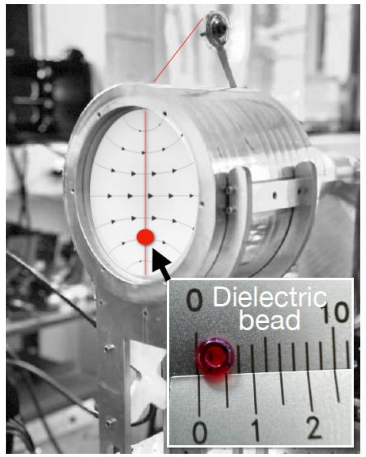
- Next steps:
  - Scale up booster → #of disks & Ø
  - Prototype studies & physics runs@ CERN @ 4K in B-field
  - Acquire MADMAX magnet for DESY.
  - Investigate single photon detector @ 20 mk & 20 GHz

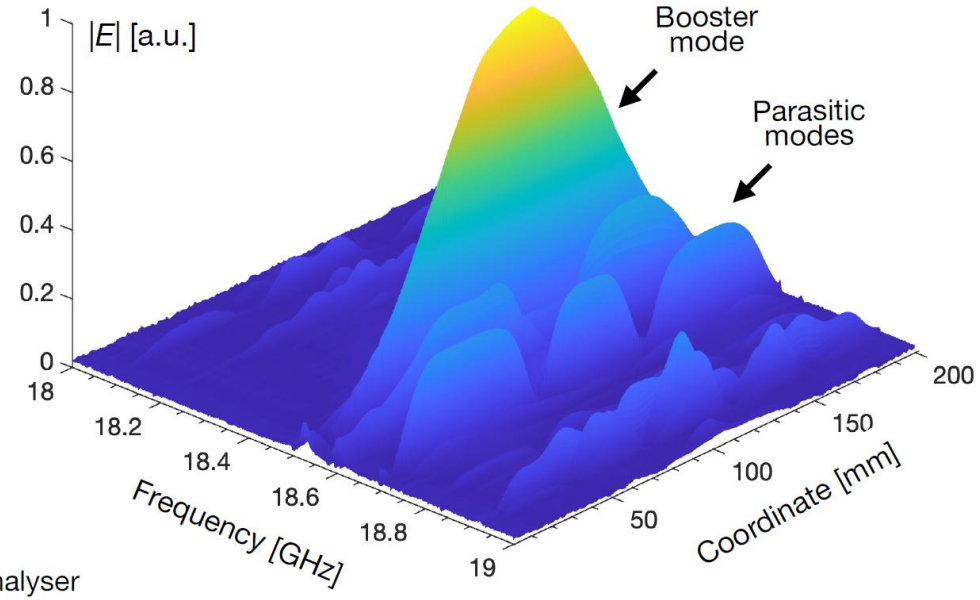
Boost factor determination

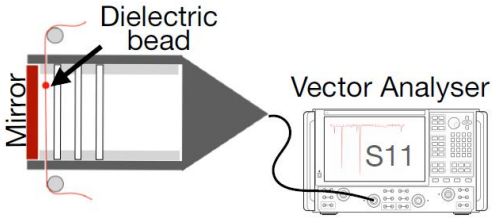
„closed booster“ CB200

Reflectivity, power spectrum & modelling

Boost factor of CB200









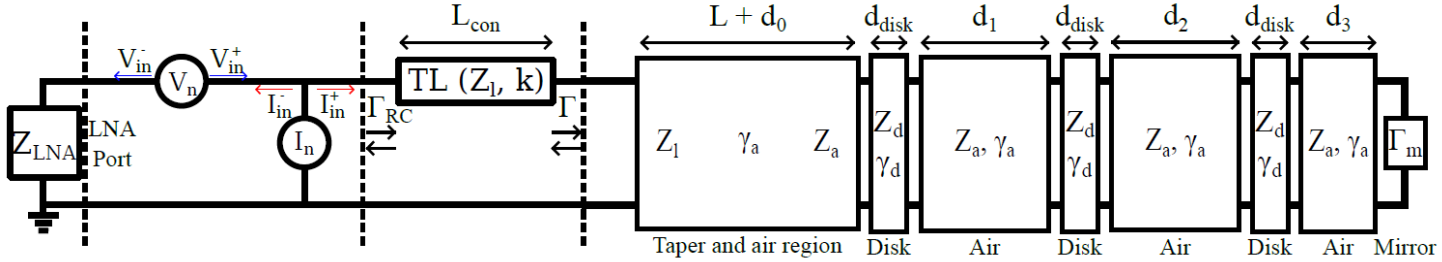
- **Avoid overlap with parasitic modes: Field shape measured using „bead pull“ method**
- **Extraction of model parameters using reflectivity and power spectra**
- **Boost factor & uncertainties from modelling using experimentally verified parameters**

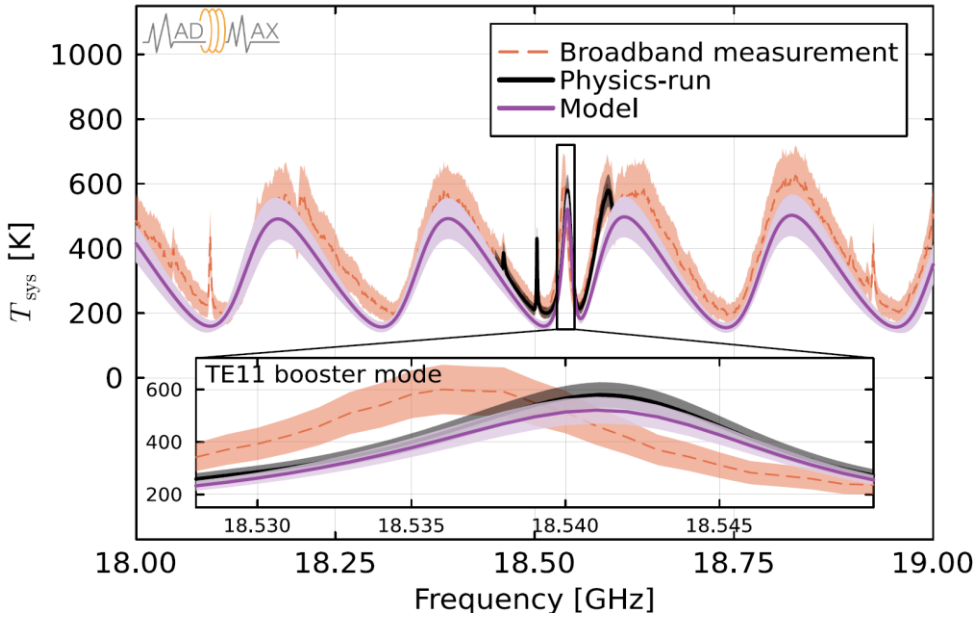
MADMAX collaboration, JCAP06(2026)046 , arXiv:2603.05006

Boost factor determination

„closed booster“ CB200

Reflectivity, power spectrum & modelling





Boost factor of CB200

- Avoid overlap with parasitic modes: Field shape measured using „bead pull“ method
- Extraction of model parameters using reflectivity and power spectra
- Boost factor & uncertainties from modelling using experimentally verified parameters

MADMAX collaboration, JCAP06(2026)046 , arXiv:2603.05006