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QUANTUM UNIVERSE

MADMAX

Towards a Dielectric Axion Haloscope

Christoph Krieger
Universität Hamburg

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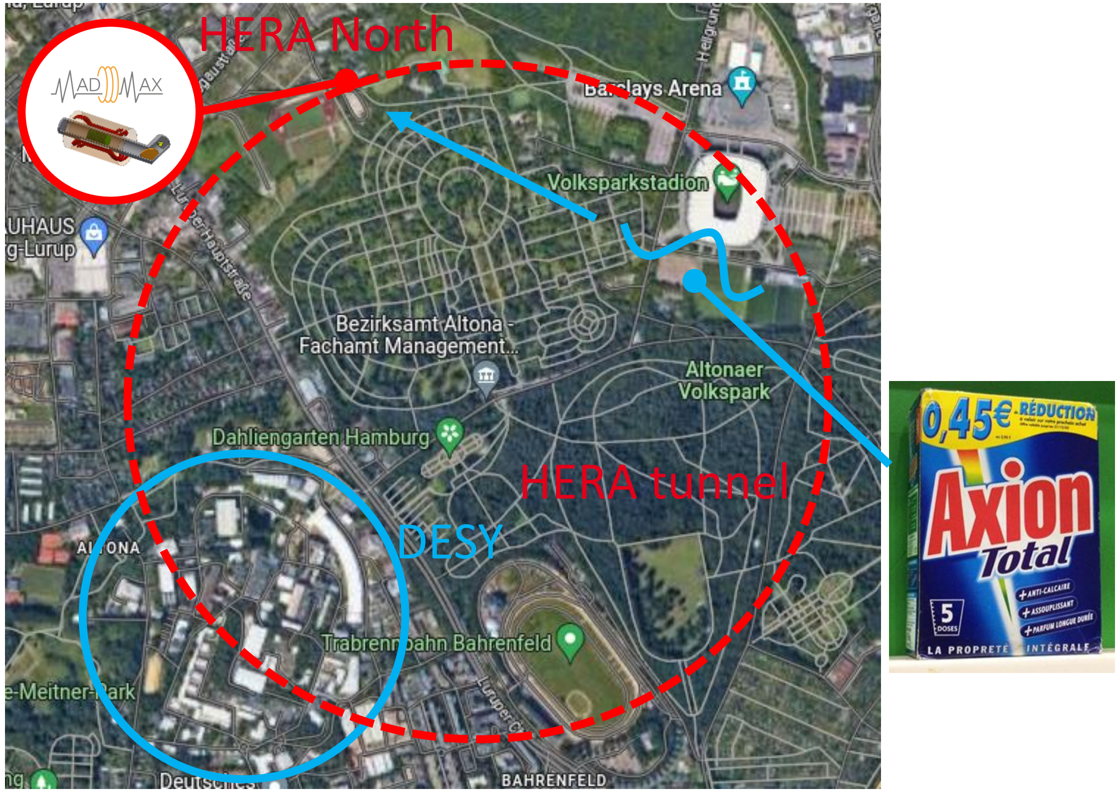
Hamburg

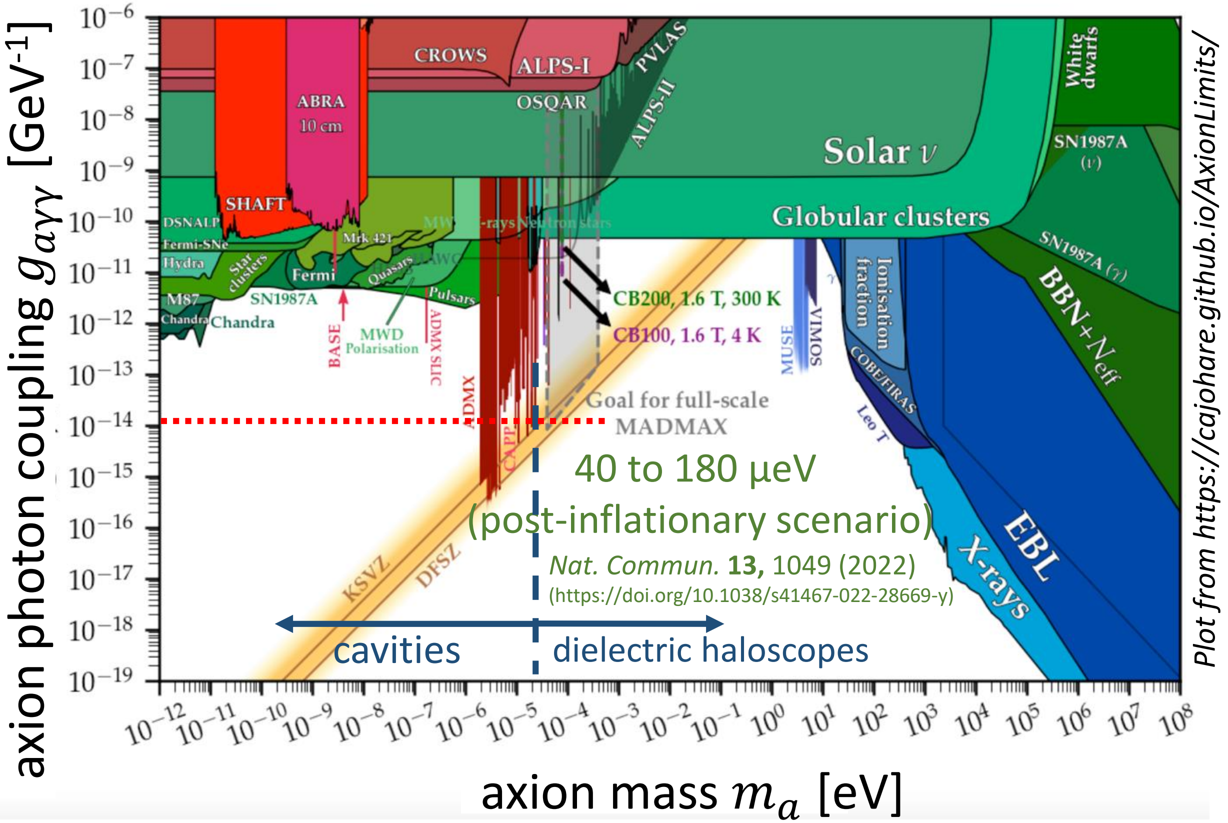
On behalf of the MADMAX Collaboration

DESY. CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM · MAX-PLANCK-INSTITUT FÜR PHYSIK · RWTH AACHEN UNIVERSITY · EBERHARD KARLS UNIVERSITÄT TÜBINGEN · Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG · MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE · NÉEL institut · Universidad de Zaragoza

Searching Dark Matter Axions

- Solution to Strong CP problem via PQ mechanism → Breaking of PQ symmetry → Axion
- Axion to photon conversion in strong EM fields via Primakoff/Sikivie effect
- Axion can be (cold) dark matter → Axion field with huge de-Broglie wavelength

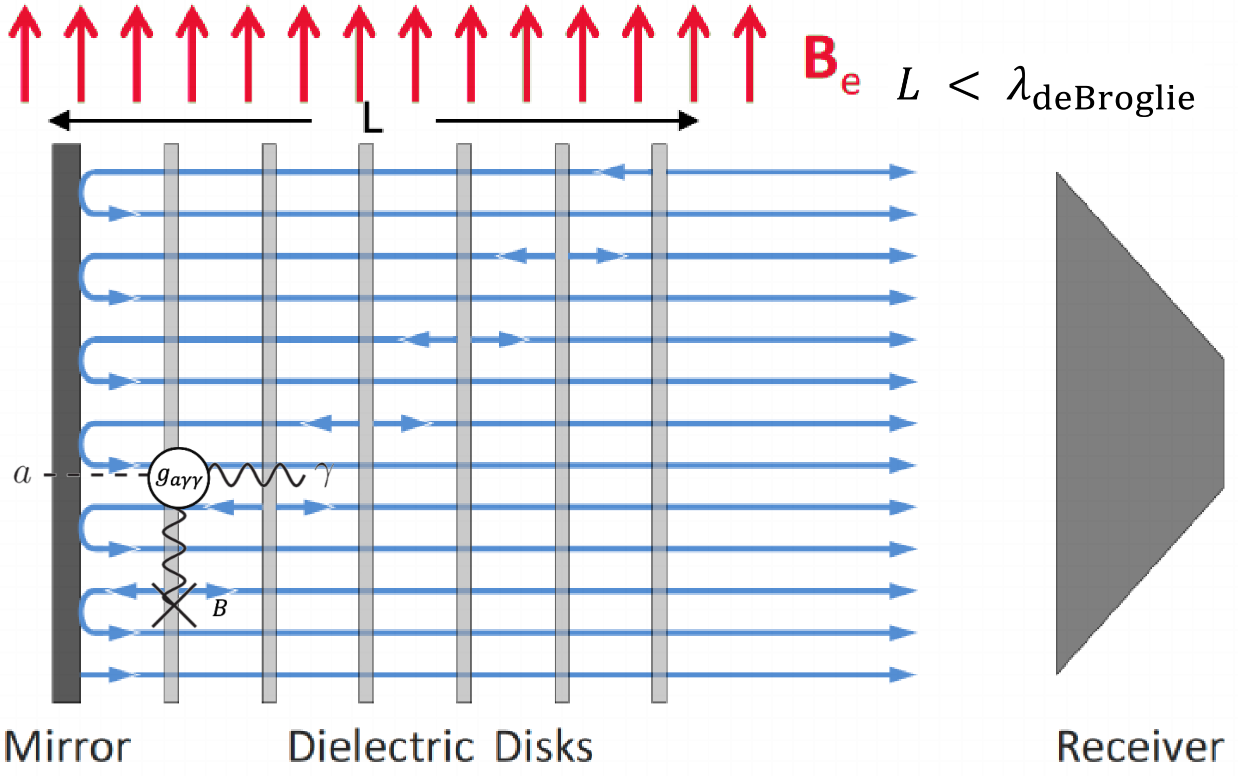




Open Dielectric Haloscope

MADMAX:
- Tunable in frequency coverage:
  ~10-100 GHz (40-400 μeV axion mass)
- Boost emitted power through:
  - coherent emission from multiple interfaces
  - constructive interference effects
- Coupling to $g_{a\gamma\gamma}$ scales with:
  - external field, $\propto B$
  - conversion surface, $\propto A^{0.5}$

Power boost factor: $\beta^2 = \frac{P_{\text{total}}}{P_{\text{mirror}}}$



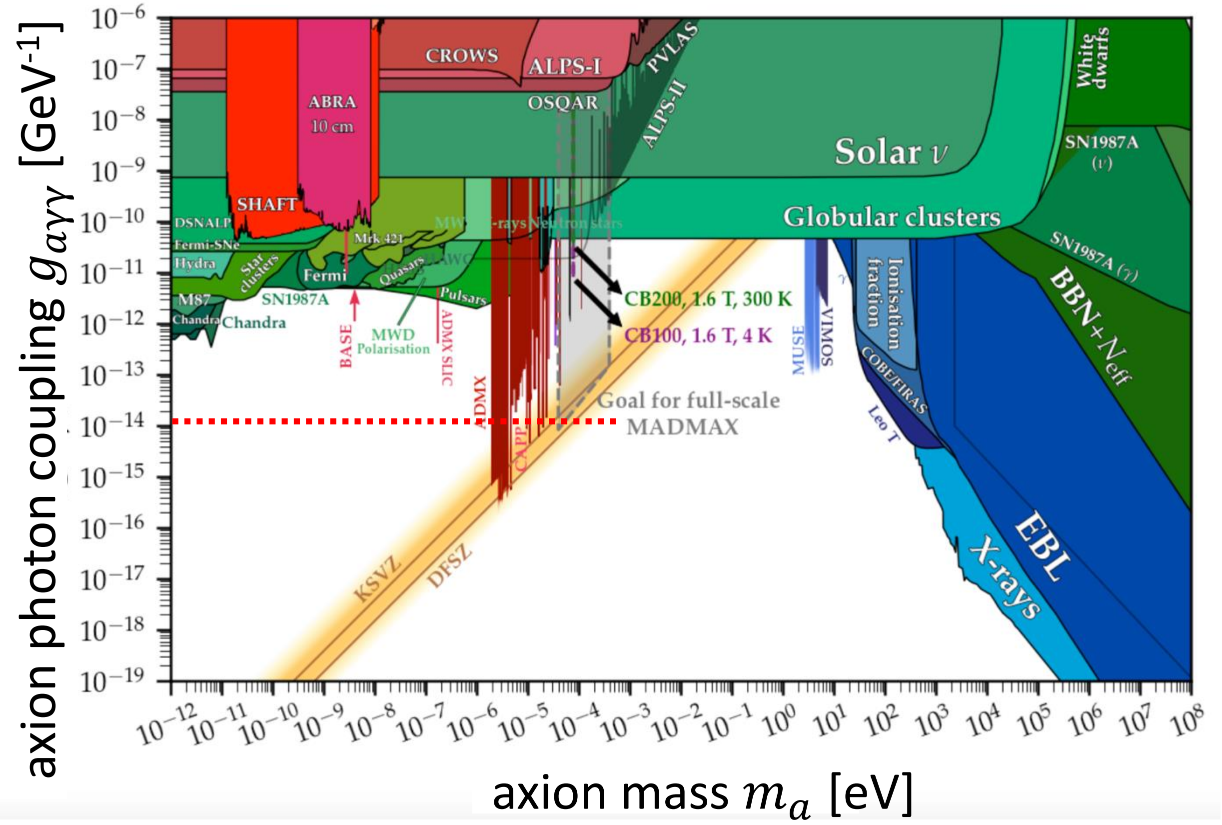
$$g_{a\gamma} = 2.04(3) \times 10^{-14}\ \text{GeV}^{-1} \sqrt{\frac{\text{SNR}}{5}}\ \frac{400}{\sqrt{\beta^2}} \sqrt{\frac{1\text{m}^2}{\text{A}}} \sqrt{\frac{\text{T}_{\text{sys}}}{8\text{K}}}\ \frac{10\ \text{T}}{\text{B}_\text{e}} \sqrt{\frac{0.8}{\eta}} \left(\frac{1.3\ \text{days}}{\Delta\text{t}}\right)^{1/4} \sqrt{\frac{300\ \text{MeV}^2}{\rho_0}} \left(\frac{\text{m}_\text{a}}{100\ \mu\text{eV}}\right)^{5/4}$$

Open Dielectric Haloscope

MADMAX
baseline design

Feasibility studies
on prototype systems

$N_{\text{disc}} = 80$
$A_{\text{disc}} = 1.2\ \text{m}^2$ } Disk tiling, flatness alignment, …
$B_{\parallel} = 9\ \text{T}$ → Checked with MACQU
$T_{\text{sys}} = 8\ \text{K}$ → Require prototype tests in a cryostat



$$g_{a\gamma} = 2.04(3)\times 10^{-14}\ \text{GeV}^{-1}\sqrt{\frac{\text{SNR}}{5}}\,\frac{400}{\sqrt{\beta^2}}\sqrt{\frac{1\text{m}^2}{A}}\sqrt{\frac{T_{\text{sys}}}{8\text{K}}}\,\frac{10\ \text{T}}{B_e}\sqrt{\frac{0.8}{\eta}}\left(\frac{1.3\ \text{days}}{\Delta t}\right)^{1/4}\sqrt{\frac{300\ \text{MeV}^2}{\rho_0}}\left(\frac{m_a}{100\ \mu\text{eV}}\right)^{5/4}$$

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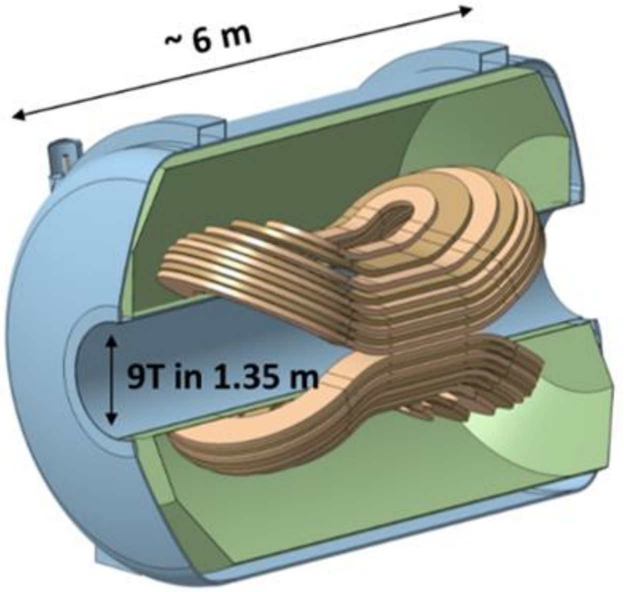
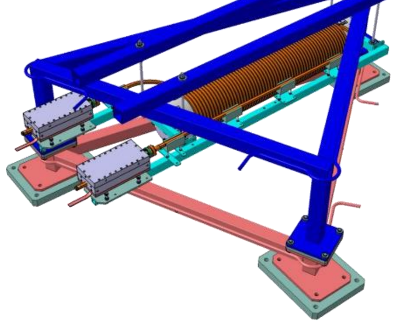
MADMAX Magnet Update



- Dipole Magnet most critical item for full-size MADMAX
- Design for 9 T large bore conceptually very well advanced
- **Novel conductor: cable in copper conduit**
  ➔ Production is feasible
- Quench propagation velocity was measured in dedicated setup: **MA**dmax **C**oil for **Q**uench **U**nderstanding
  ➔ Main project risk mitigated: **Quench propagation according to requirements for safe operation**

MACQU



Development in innovation partnership

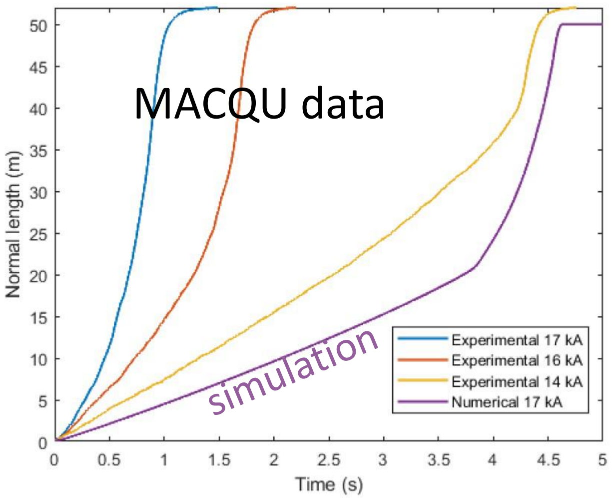
BILFINGER

BILFINGER NOELL GMBH

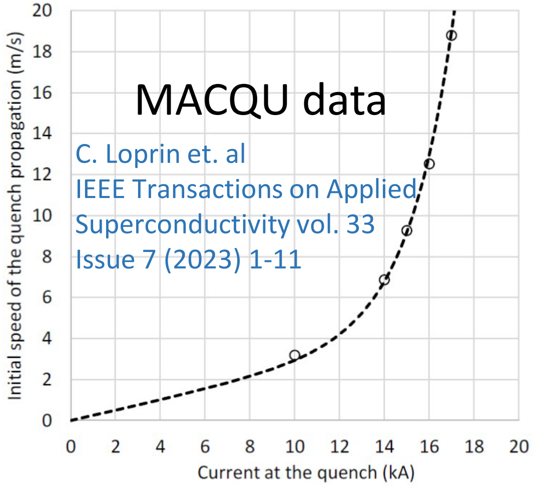
cea

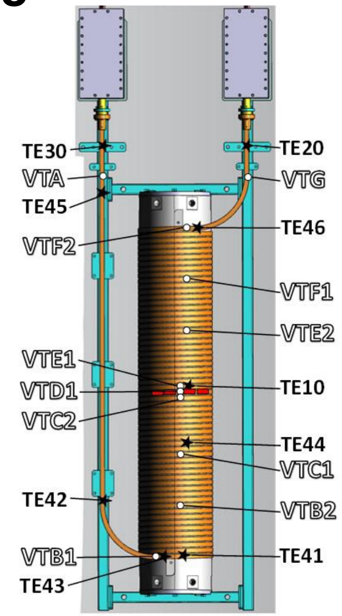
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Quench propagation

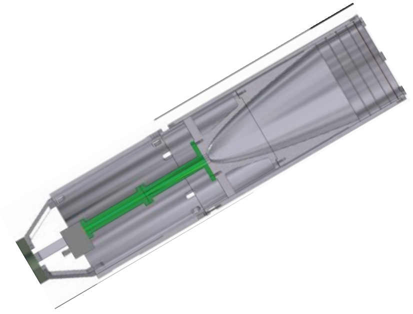


Quench velocity





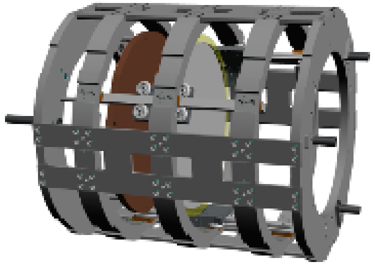
Staged Prototype Program



Closed Boosters (CB):

∅ = 100 mm (**CB100**), 3 Al_2O_3 disks

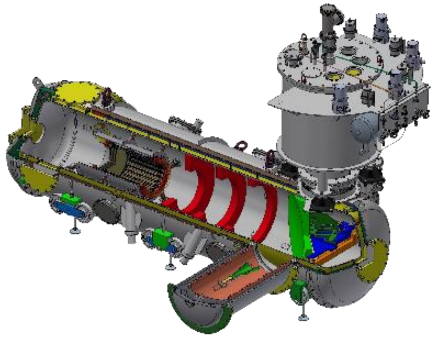
∅ = 200 mm (**CB200**), 3 Al_2O_3 disks



Open Boosters (OB):

∅ = 200 mm (**OB200**), 2 Al_2O_3 disks

∅ = 300 mm (**OB300**), 3 disks (Al_2O_3 & $LaAlO_3$)



Large bore (∅ = 760 mm) cryostat allows operation of all prototypes

Fits into the 1600 mm warm bore of MORPURGO magnet at CERN

Aim:

First ALP run at ~19 GHz with system "easy to simulate"

Increase ALP sensitivity & understand scaling issues

➔ Understanding readout chain and RF behaviour

Technical test of components (motors, interferometer, ..)

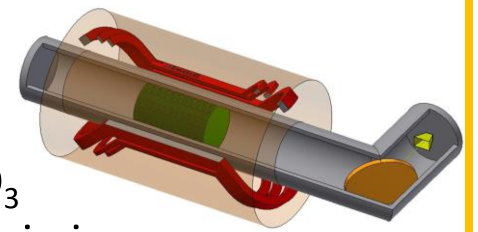
Proof-of-concept for MADMAX

➔ Establish boost factor calibration in an OB

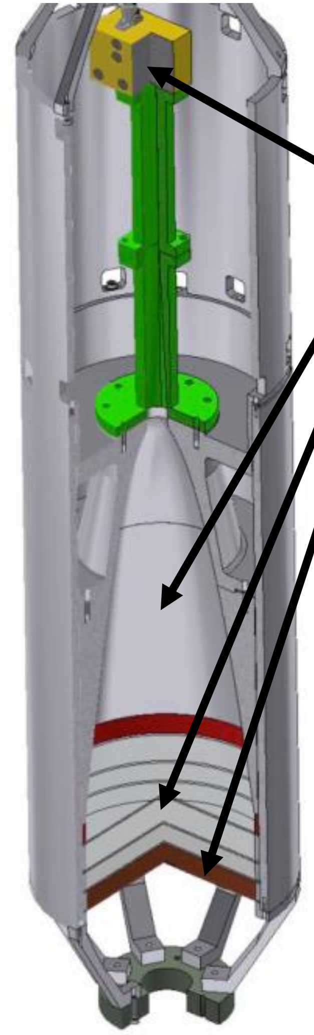
GOAL

MADMAX

- Many disks with large ∅ ➔ **tiled** $LaAlO_3$
- Boost dish antenna emission

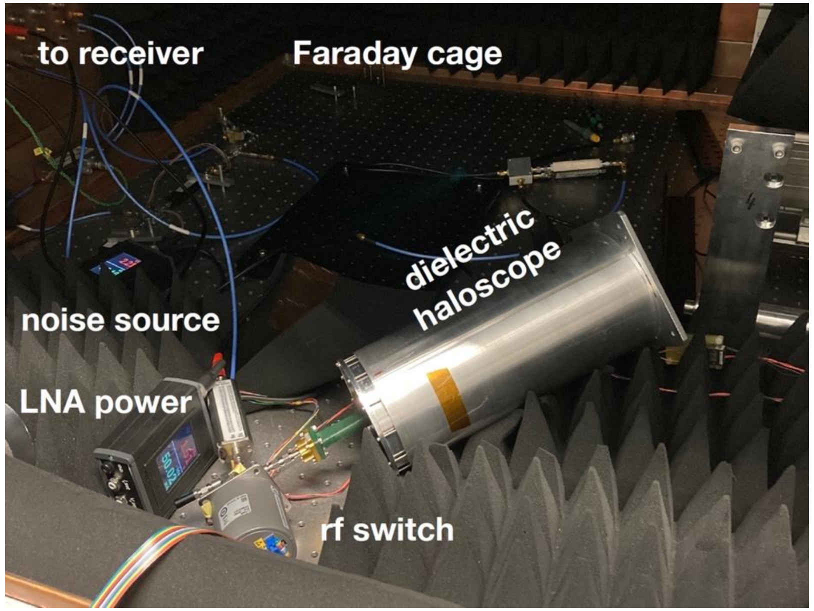


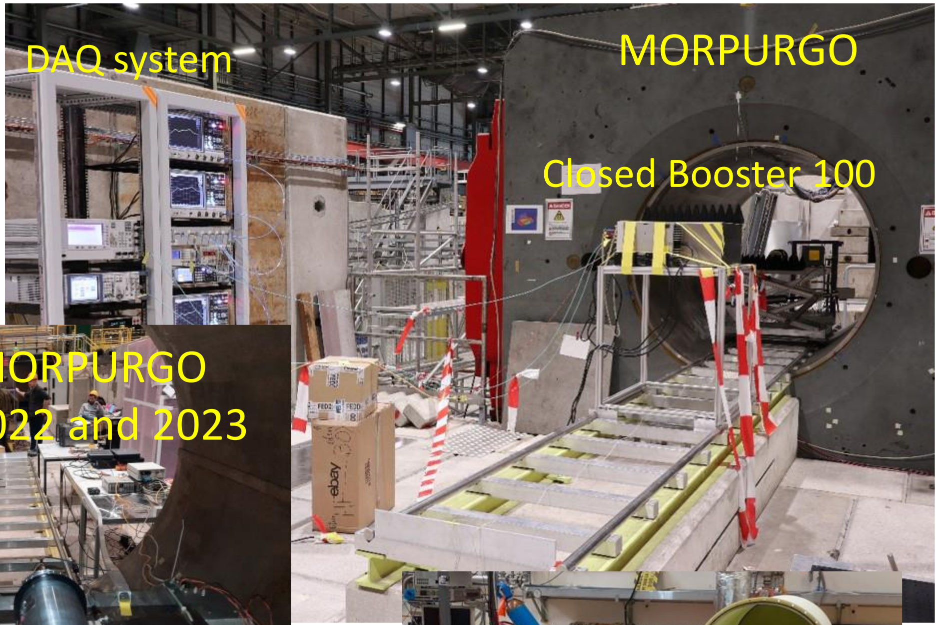
CB100: First ALP Search



Simple closed system to understand RF behaviour

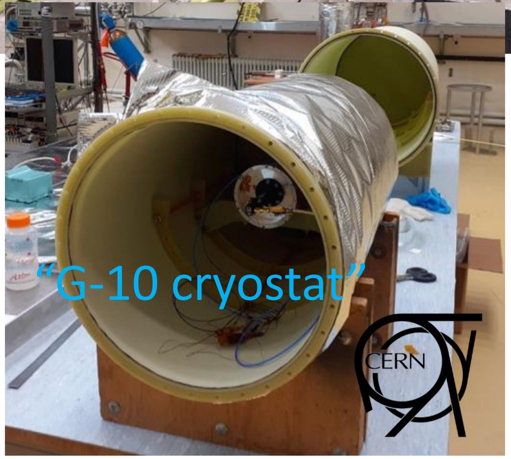
- Receiver
- Parabolic taper
- 3x Ø100 mm disks (fixed distances)
- Copper mirror





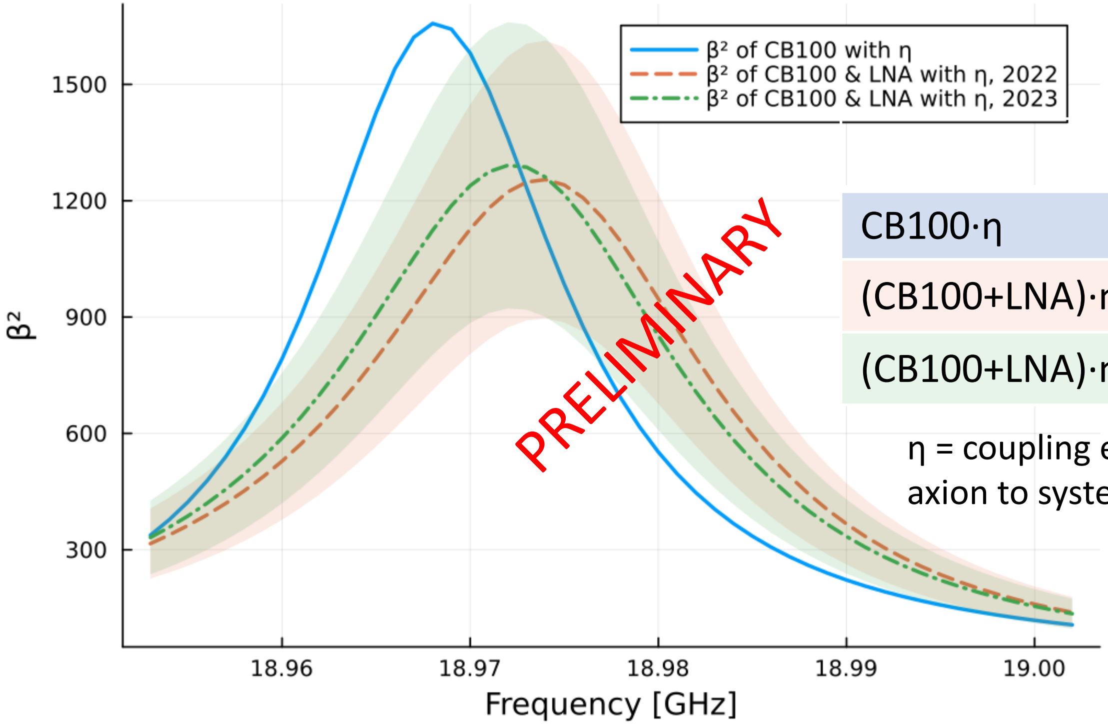
Outlook for 2024:

- G-10 cryostat for CB100 @ 10 K
- CB200 @ RT (larger area)



CB100: First ALP Search

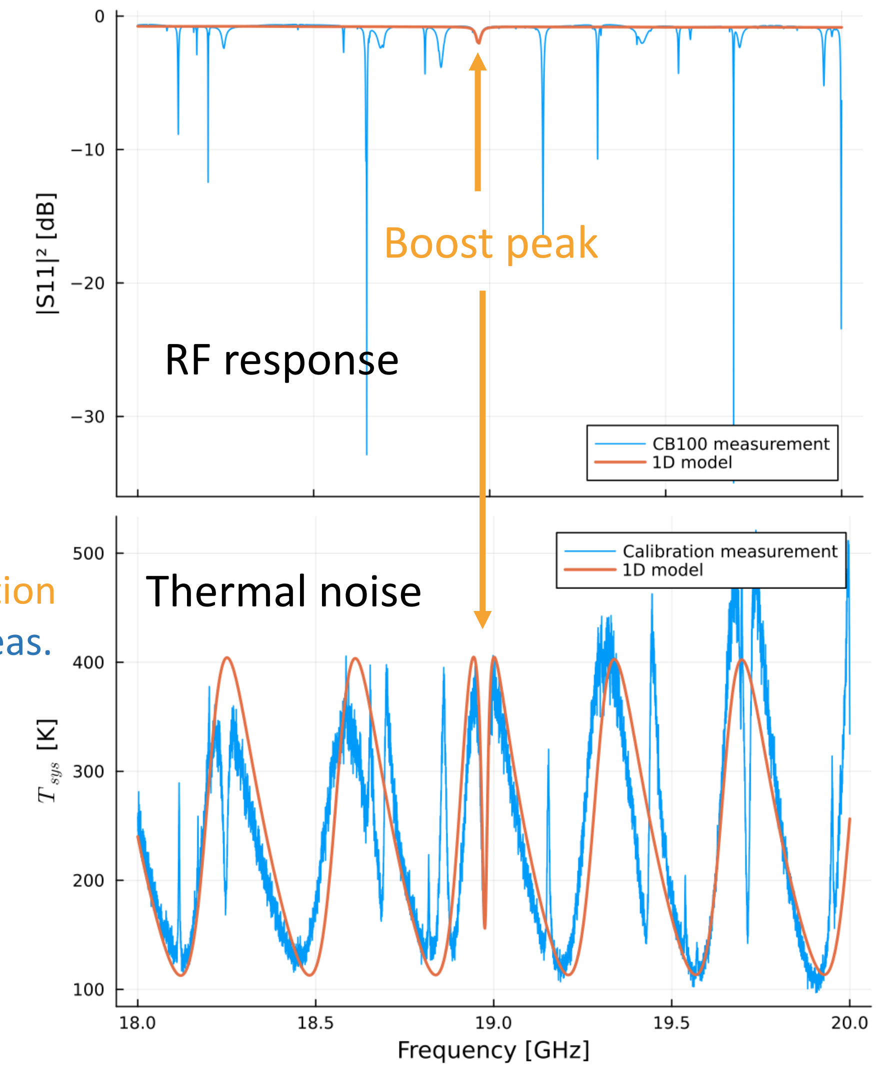
Boost factor extracted from model tuned to data ➔



	Q
CB100·η	1185
(CB100+LNA)·η	862
(CB100+LNA)·η	903

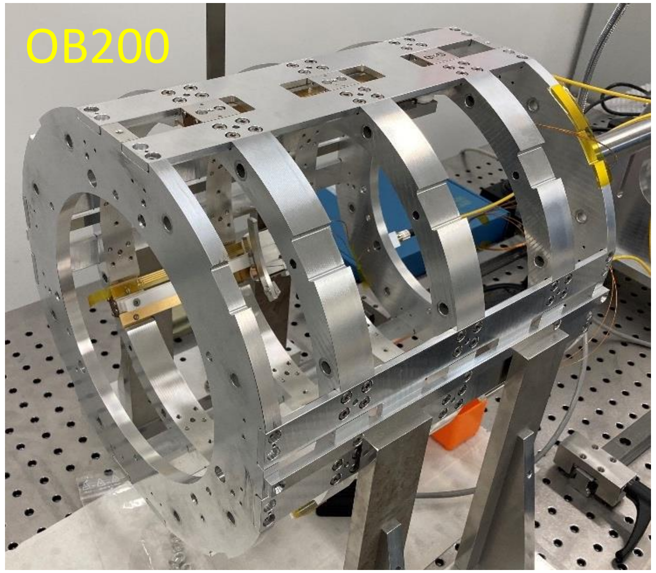
η = coupling efficiency of axion to system

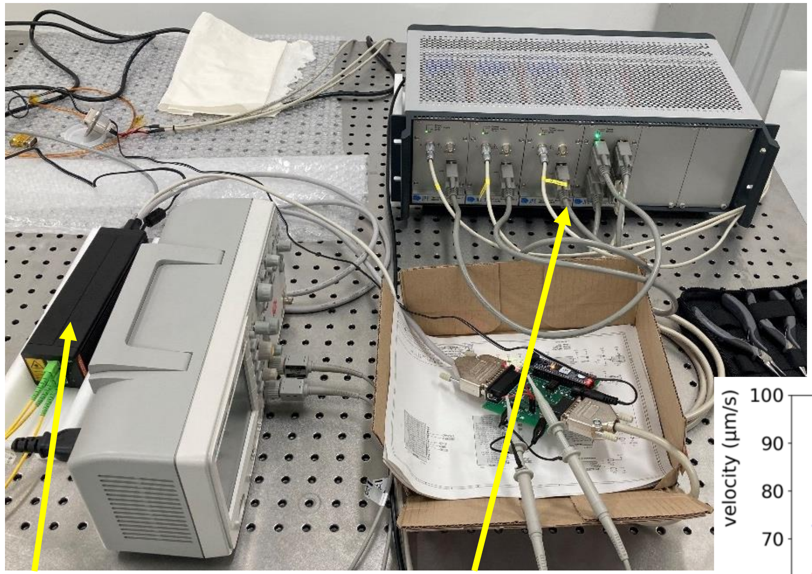
ADS simulation
2GHz SA meas.



Consistent Boost factor in 2022 and 2023
Different LNA matching impedance: 25 Ohm (2022), 30 Ohm (2023)
➔ Data analysis ongoing

OB200: Technical Feasibility



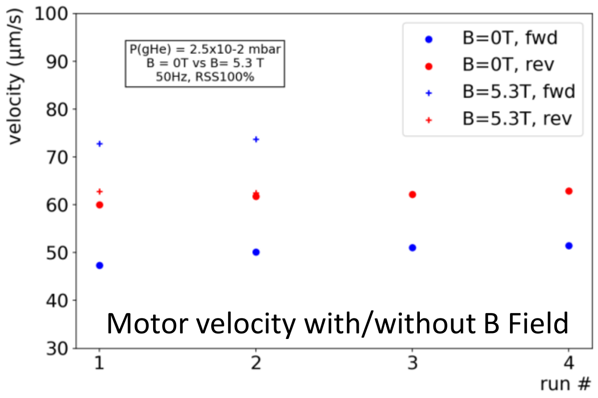


Laser interferometer   Piezo controllers

Successful piezo motor tests
in cryogenics & inside ALPS II magnet

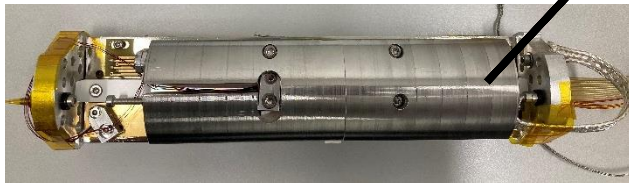
→ **Motor works in 5.3 T field and at 5 K**

E. Garutti *et al* 2023 *JINST* **18** P08011
(arxiv:2305.12808)



ALPS II magnet test stand

Single motor test rig



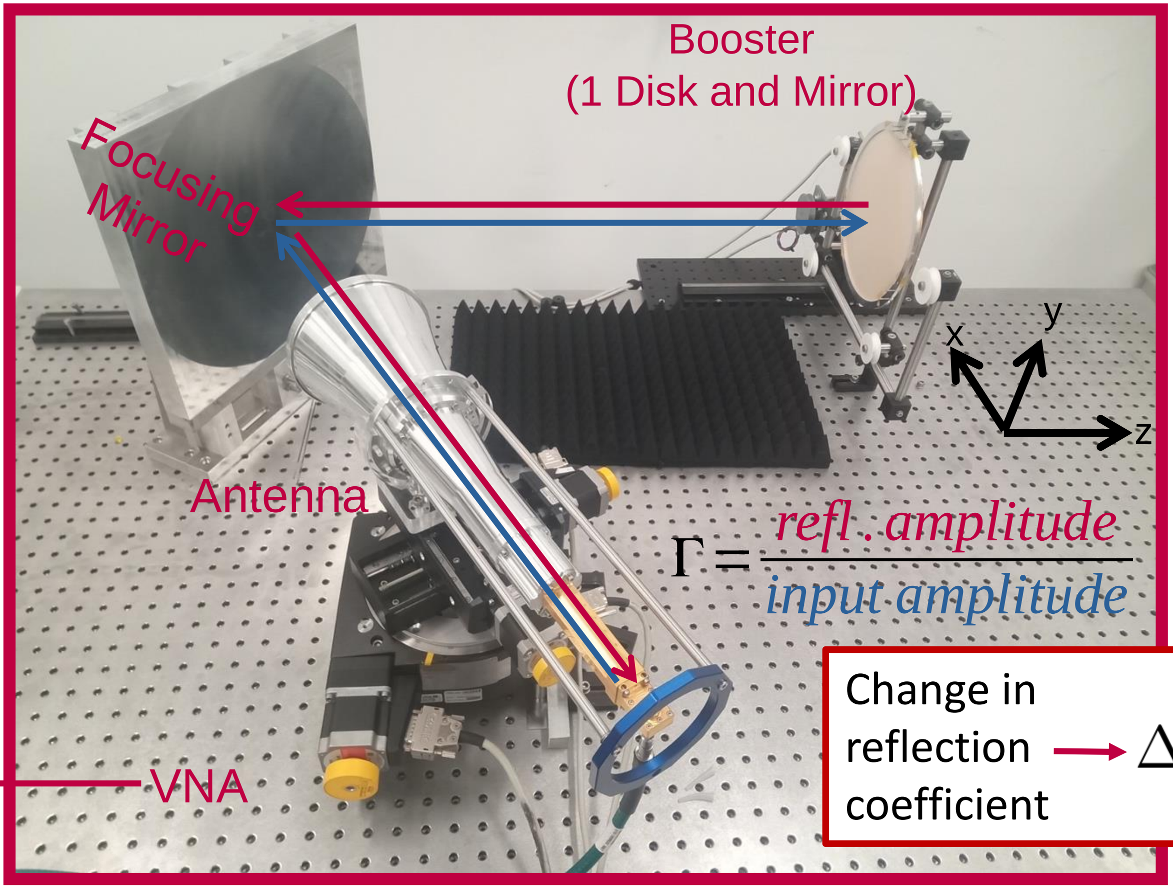
Mechanical demonstrator with:

- One 200 mm sapphire disk in titanium ring + mirror
- Three JPE piezo motors on self-built carriages
- Piezo controller system for driving a disk with three motors
- attocube WITTENSTEIN Group interferometer for displacement measurement

➔ **Successfully tested at CERN Cryolab and at MORPURGO**

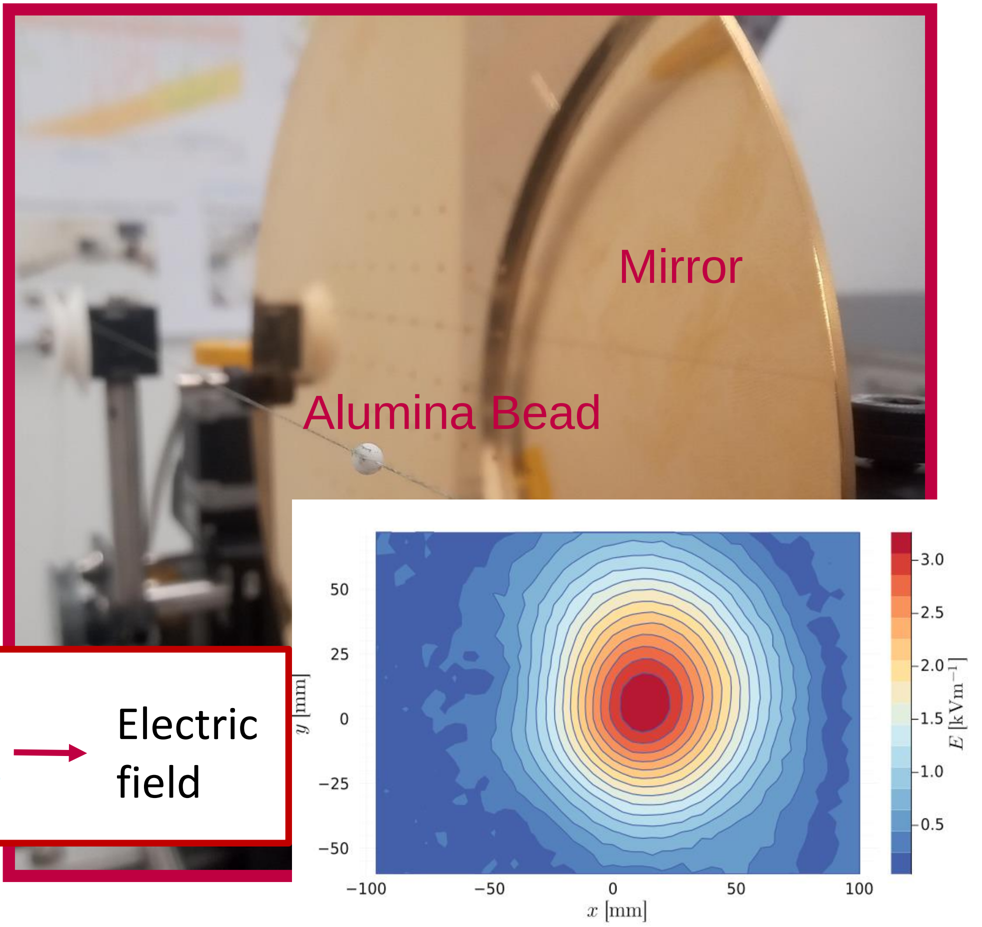
Open Booster Calibration

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



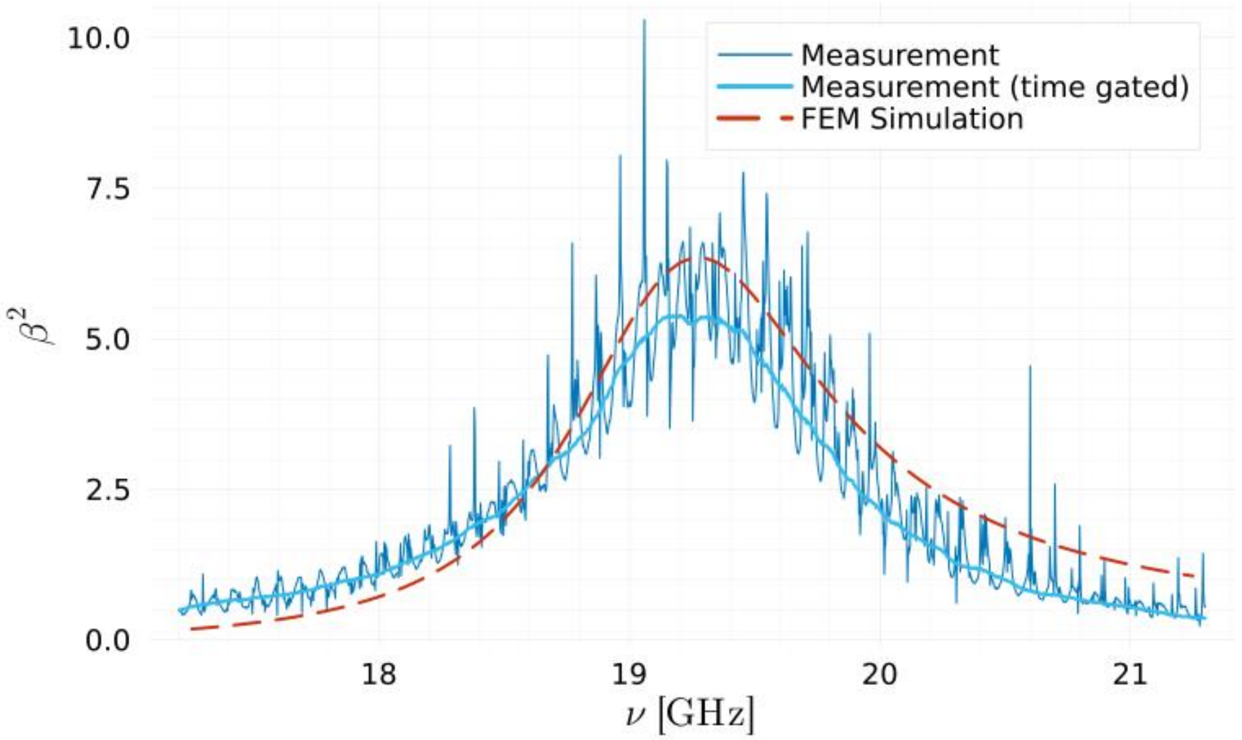
Bead properties

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



Signal Power

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



Single disk "low" boost factor

- Measure max. E-field between disk and mirror
- Calculate signal power
- Includes effects currently not simulated:
  - Antenna coupling
  - Transverse field perturbations

Jacob Egge JCAP04(2023)064 (arXiv:2211.11503)

MADMAX Staged Program

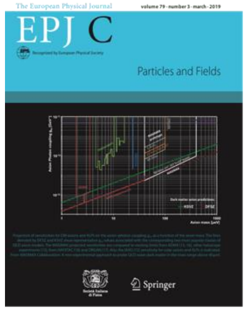
2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | >= 2028

Design Phase

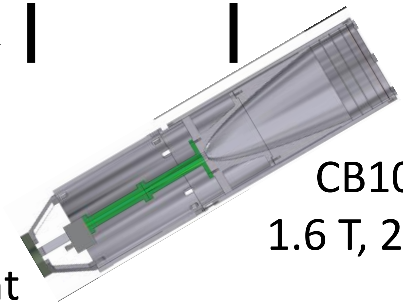
Prototyping Phase

Construction Phase

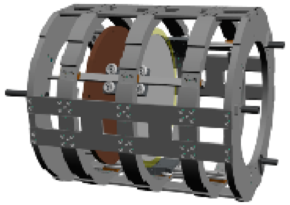
Foundation of MADMAX Collaboration



DESY PRC endorsement



CB100
1.6 T, 295 K

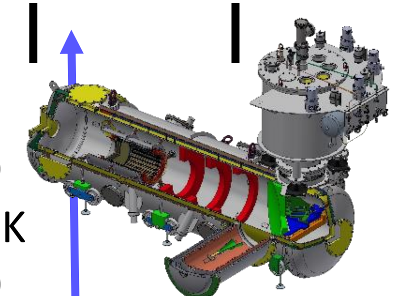


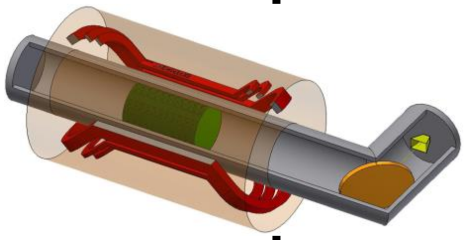
CB100
1.6 T, 4 K
CB200
1.6 T, 295 K

OB300
295 K

OB300
4 K

OB300
1.6T, 4 K



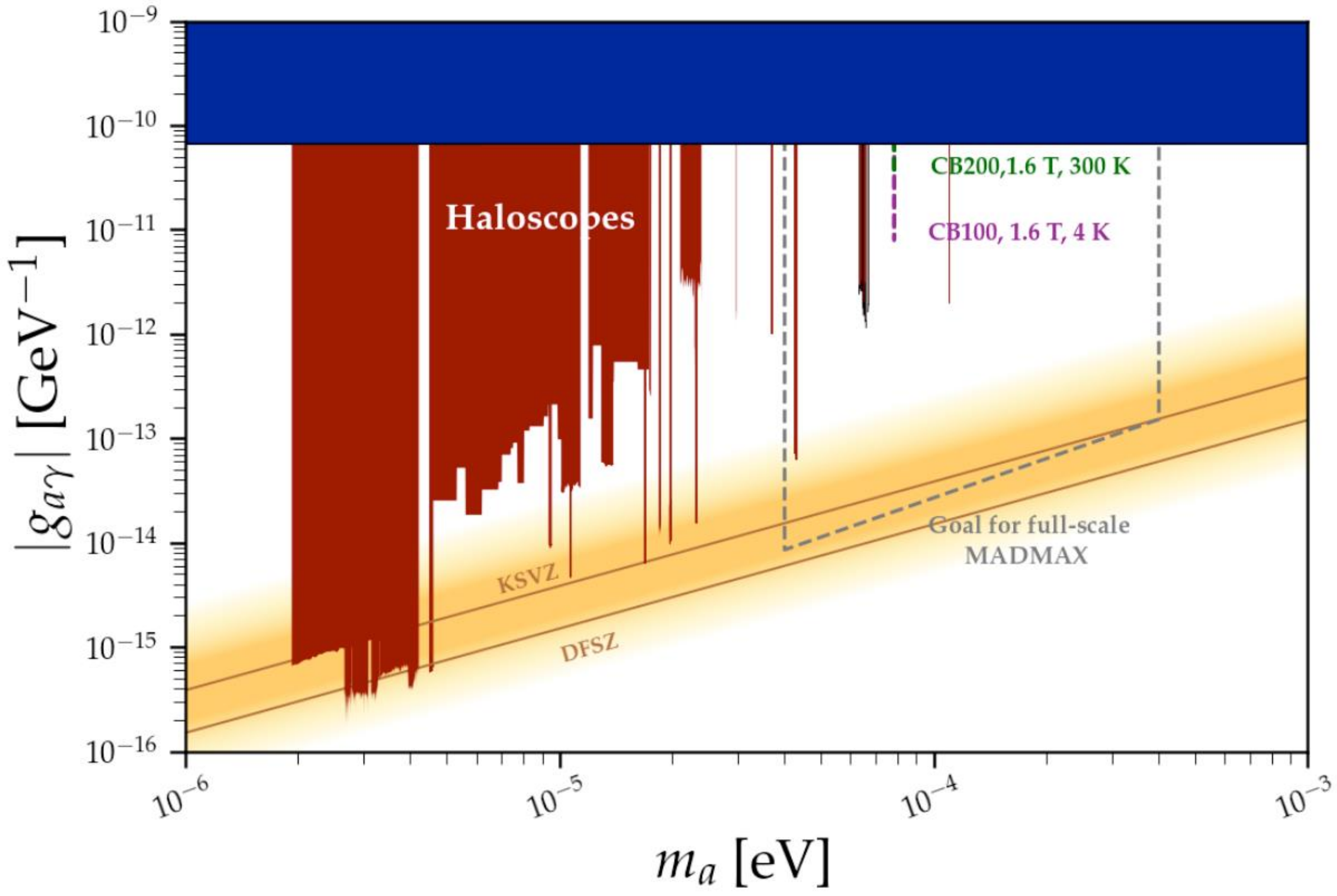


Full-size MADMAX commissioning

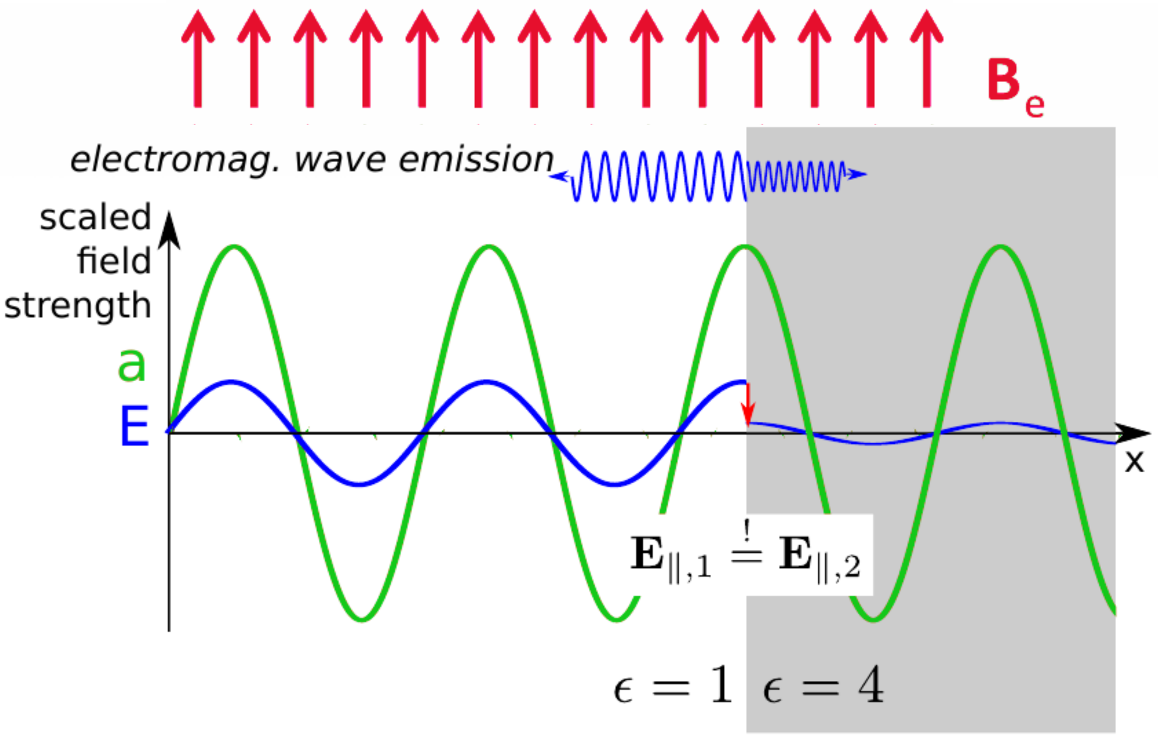
Usage of MORPURGO magnet approved by CERN Research Board for 2021-2025

BACKUP

Coverage


Haloscopes
CB200,1.6 T, 300 K
CB100, 1.6 T, 4 K
KSVZ
DFSZ
Goal for full-scale MADMAX
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

Dielectric Haloscope



In an external magnetic field $\boldsymbol{B_e}$ the axion field $a(t)$ sources an oscillating electric field $\boldsymbol{E_a}$

$$\boldsymbol{E_a} \cdot \boldsymbol{\epsilon} \sim 10^{-12}\ ^{\mathrm{V}}/_{\mathrm{m}} \text{ for } B_e = 10\ \mathrm{T}$$

$\boldsymbol{E_a}$ is different in materials with different ε

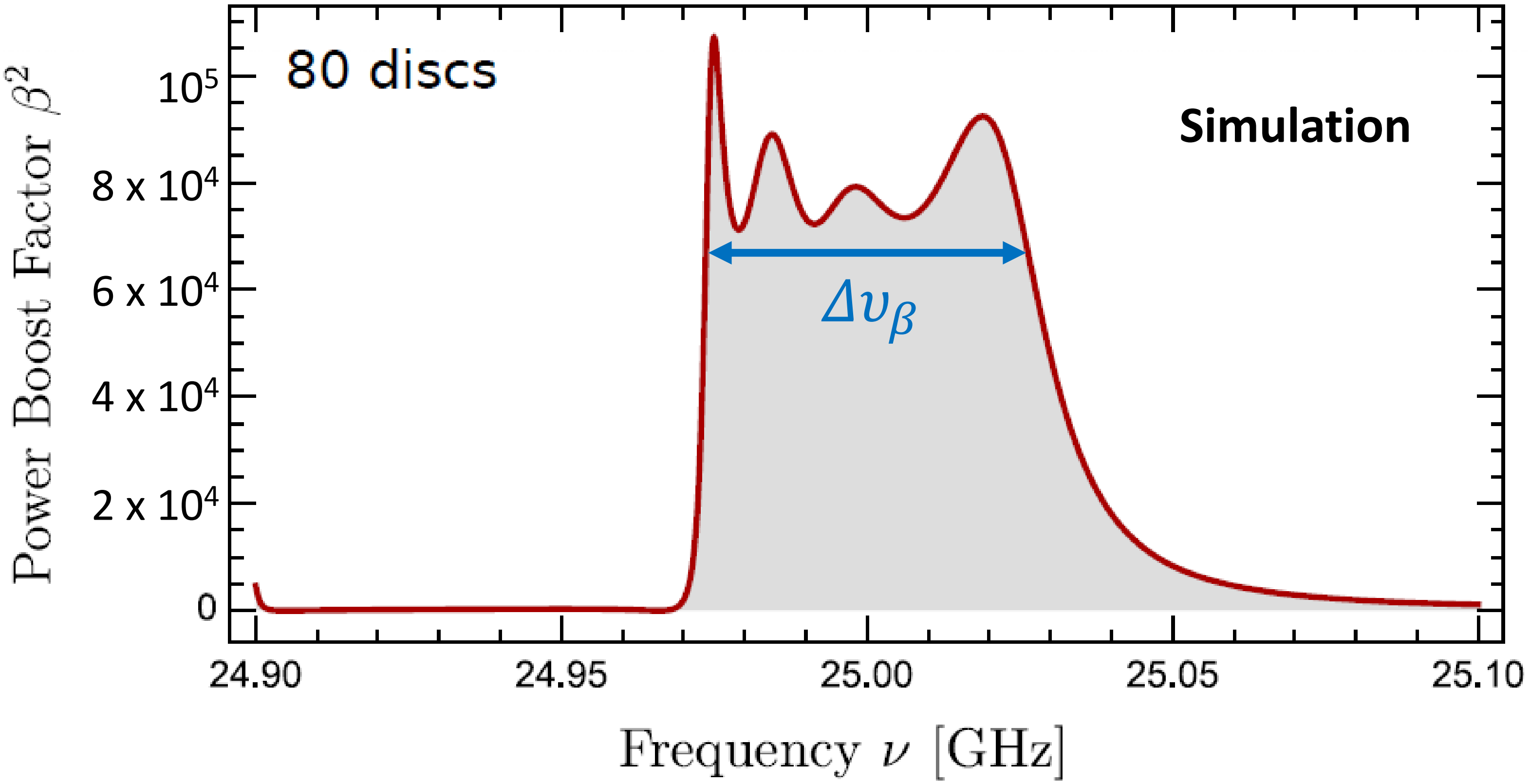
At the surface, $E_\parallel$ must be continuous
→ Emission of electromagnetic waves

$\mathcal{O}(C_{a\gamma}) = 1$

Power emitted from a single surface: $^{P}/_{A} = 2.2 \cdot 10^{-27}\,\frac{\mathrm{W}}{\mathrm{m}^2}\, C_{a\gamma} \left(\frac{B}{10\ \mathrm{T}}\right)^2$

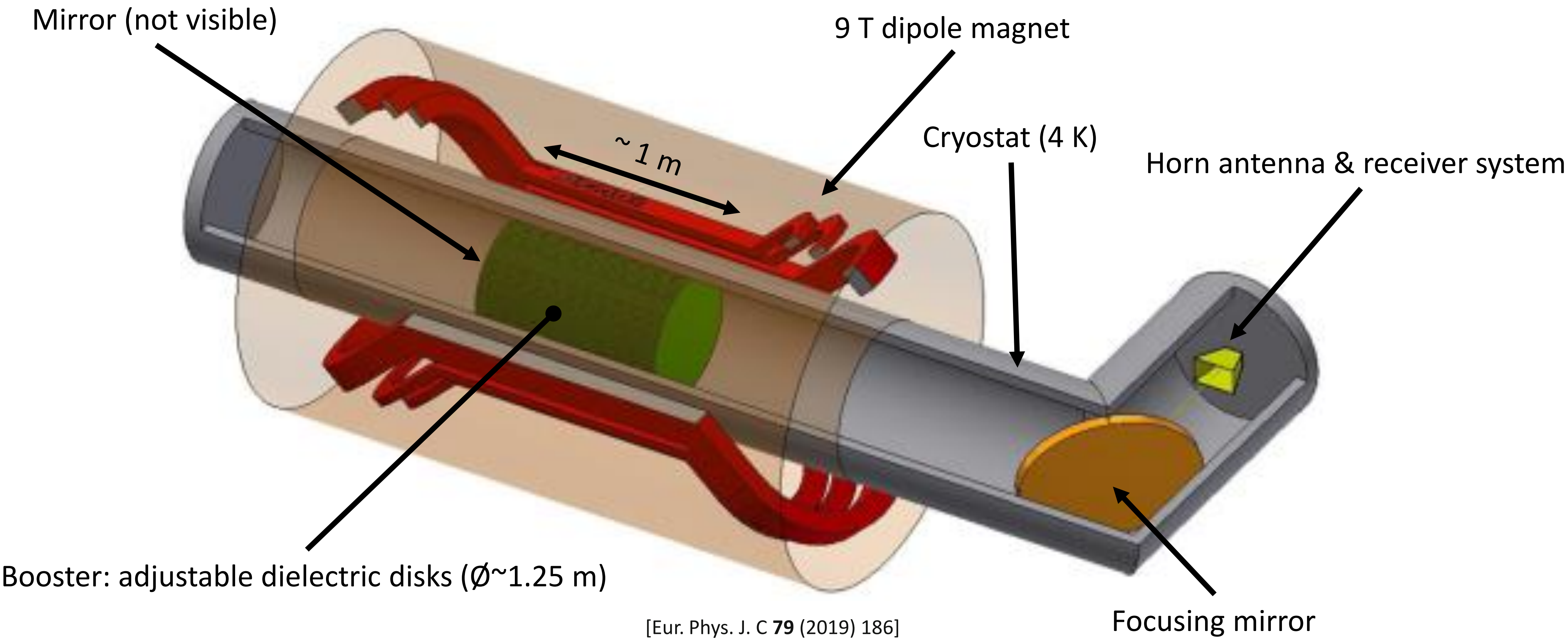
Dielectric Haloscope

- In perfect world (1D simulation): $|\beta^2| > 10^4$ achievable with 80 disks and $\varepsilon = 24$
- Non-uniform disk spacing of $\sim \lambda/2$ can achieve broadband response
- Tuning of sensitive frequency range by adjusting disk spacing
- Area law: $\beta^2 \Delta\upsilon_\beta$ ~ const.



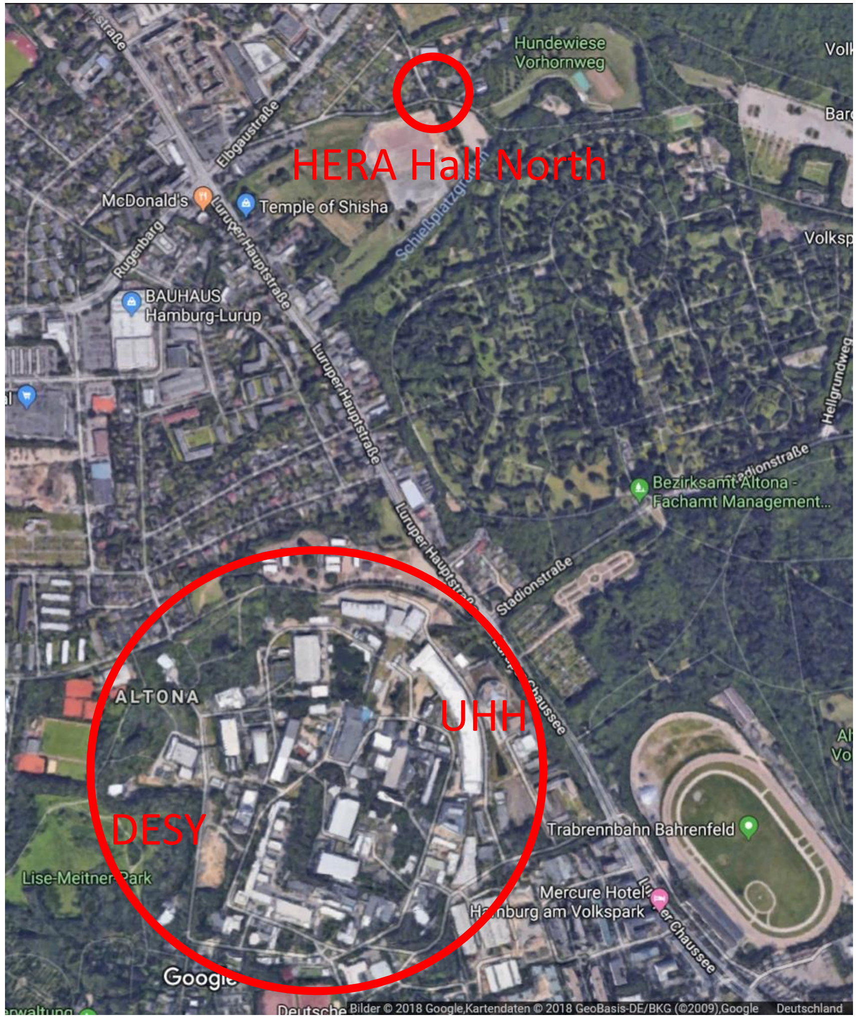
The MADMAX Experiment

MAgnetized Disk and Mirror Axion eXperiment

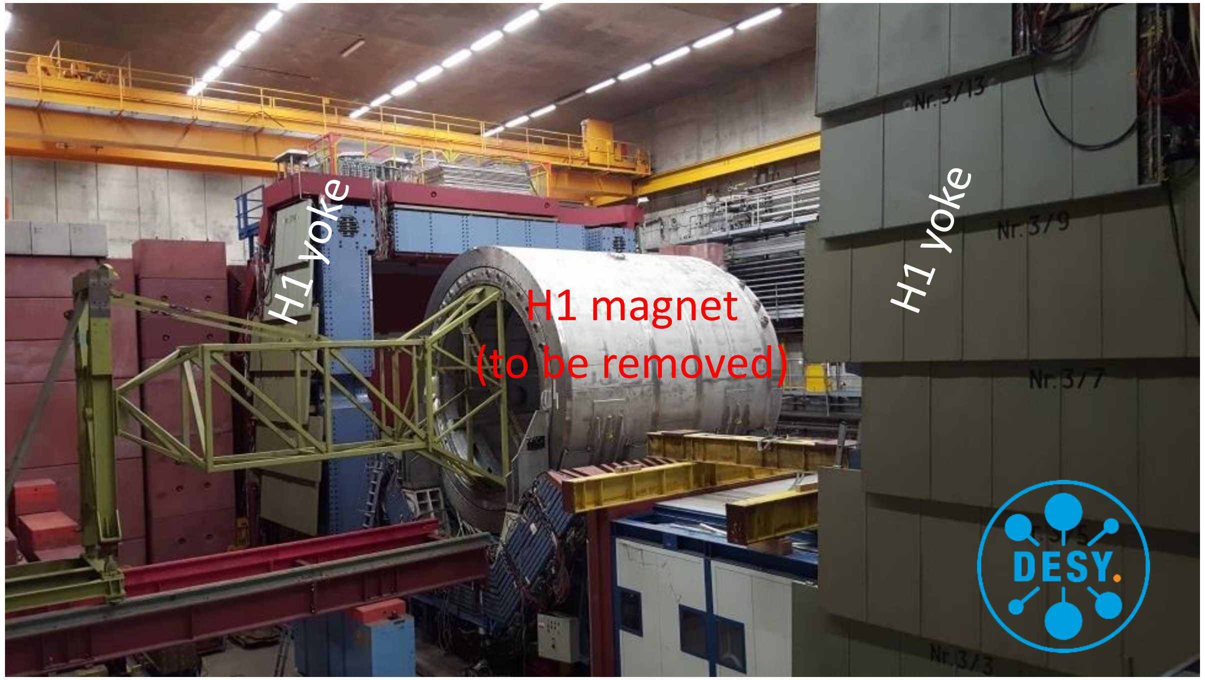


[Eur. Phys. J. C **79** (2019) 186]

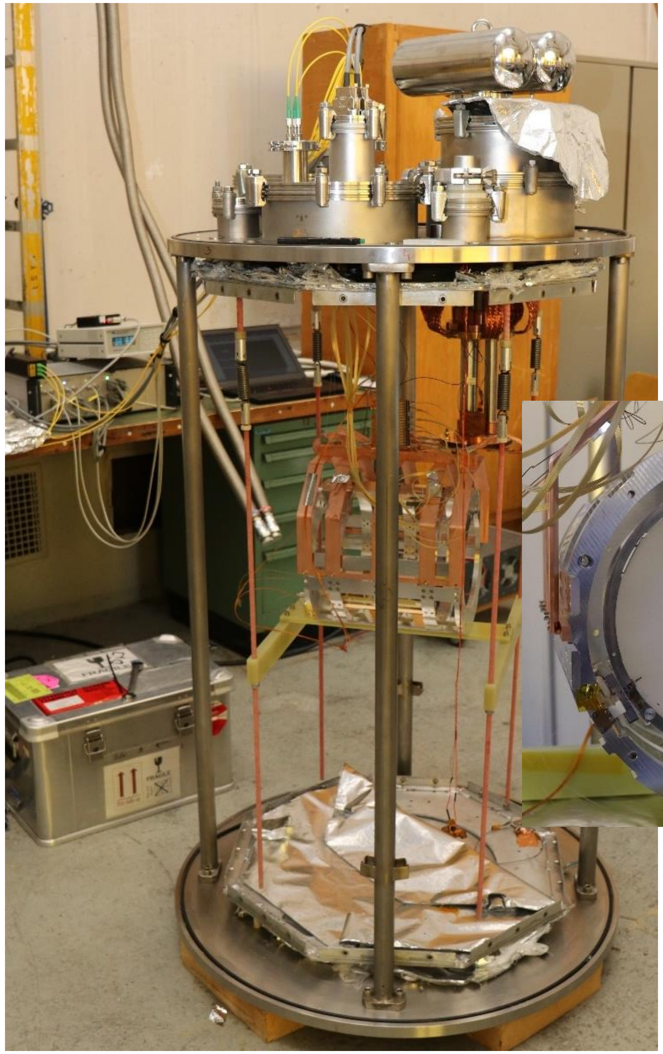
Designated Experimental Site

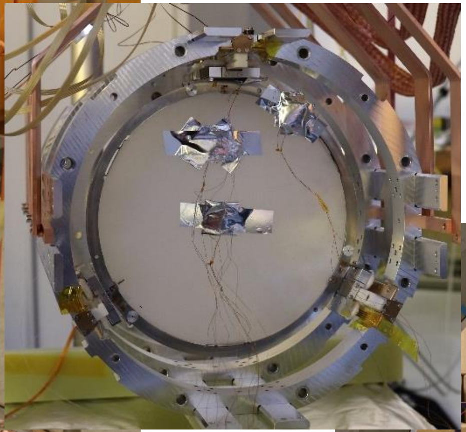


- MADMAX to be operated at HERA Hall North
- Make use of DESY infrastructure
  → Cryoplatform to be operational in 2025
- Benefit: re-use H1 yoke as magnetic shielding



Testing the Disk Drive

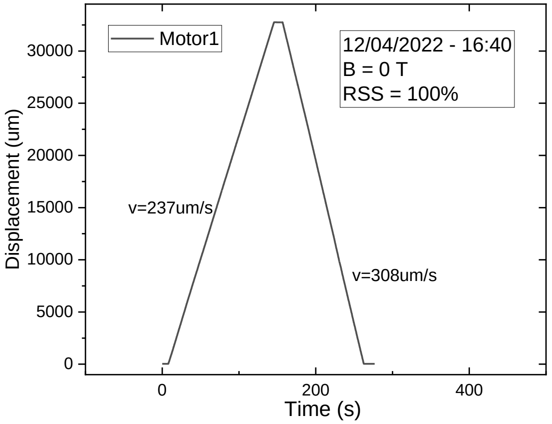


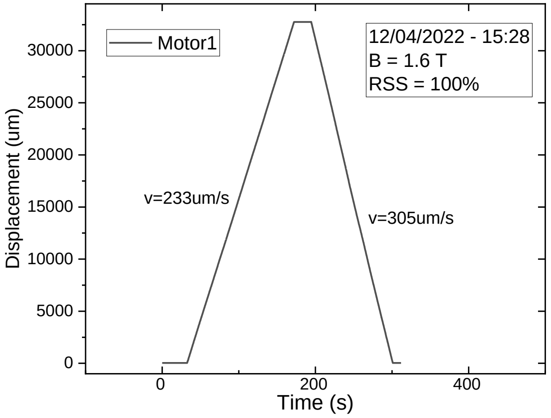


Project200 inside Morpurgo

- Project200 **successfully tested at CERN Cryolab and in CERN's Morpurgo magnet**
- All three **piezo motors work at cryogenic temperatures and in 1.6 T field** (at RT)
- Attocube laser interferometer works at cryogenic temperatures
- Project200 backbone structure **keeps optics alignment during cool-down**
- A **disk can be moved with three motors** using the laser interferometer feedback

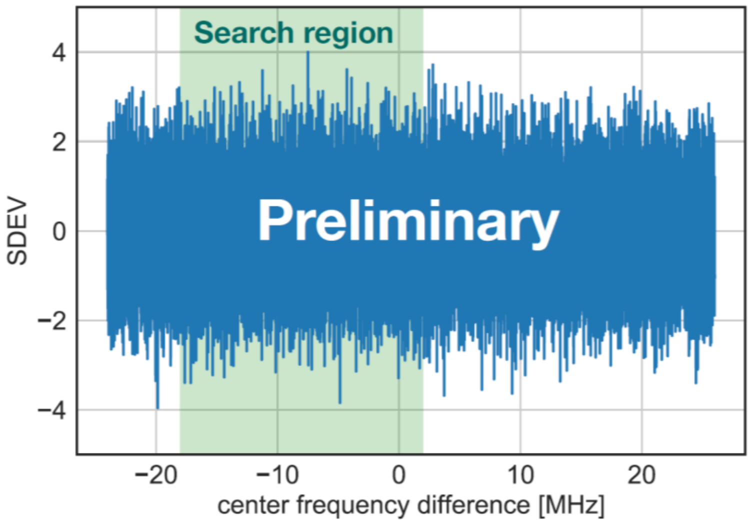
No difference in disk velocity with/without B field

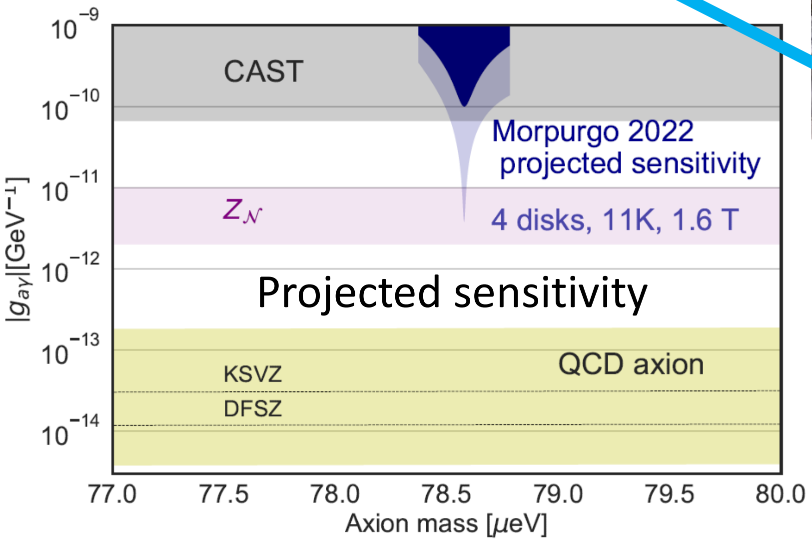


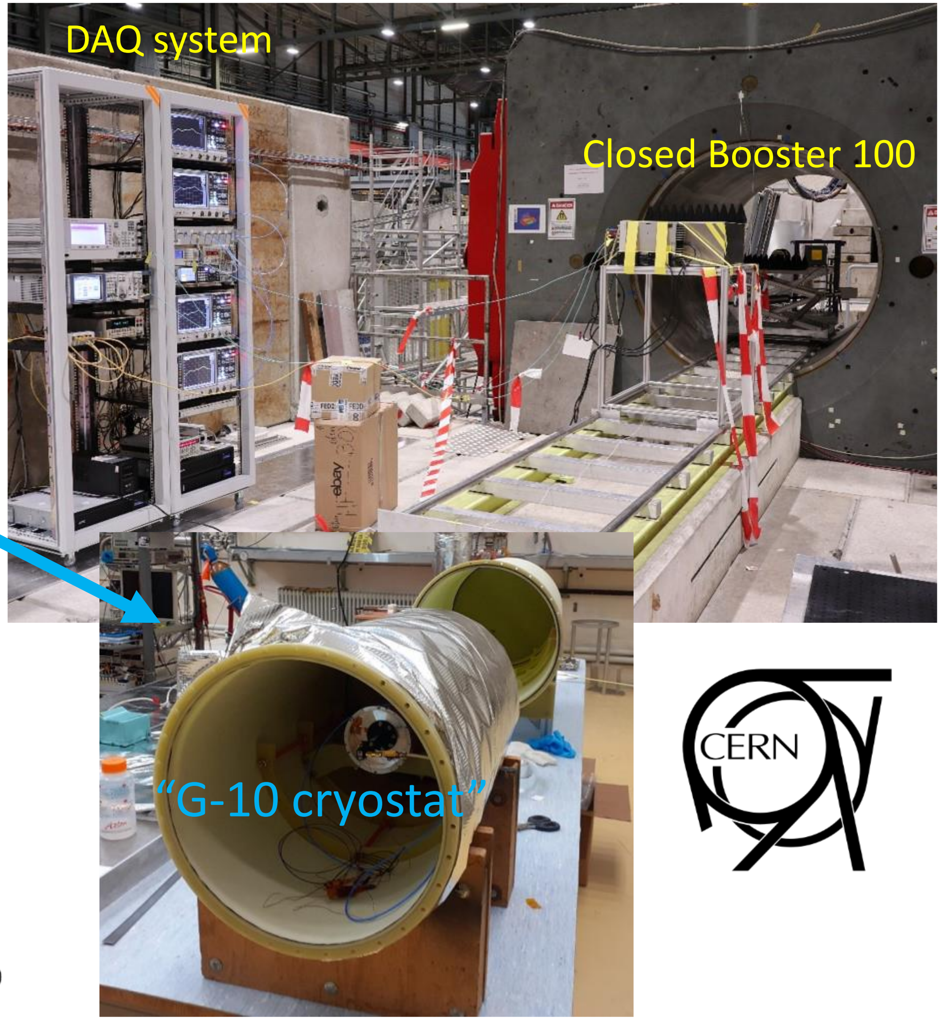


Axion Like Particle Search

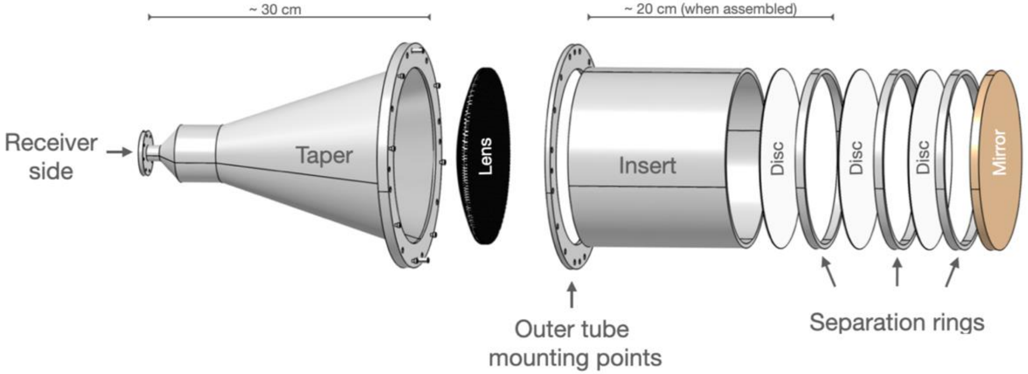
- Opportunity to perform ALP search in CERN's Morpurgo magnet (1.6 T) was used in Mar/Apr 2022
- In total 10 h at 1.6 T with ~ 200 K noise temperature
- Sensitivity not dominated by RFI in CERN North Hall
- Possibilities for an upgrade allowing to cool the setup to < 10 K in Morpurgo currently in preparation





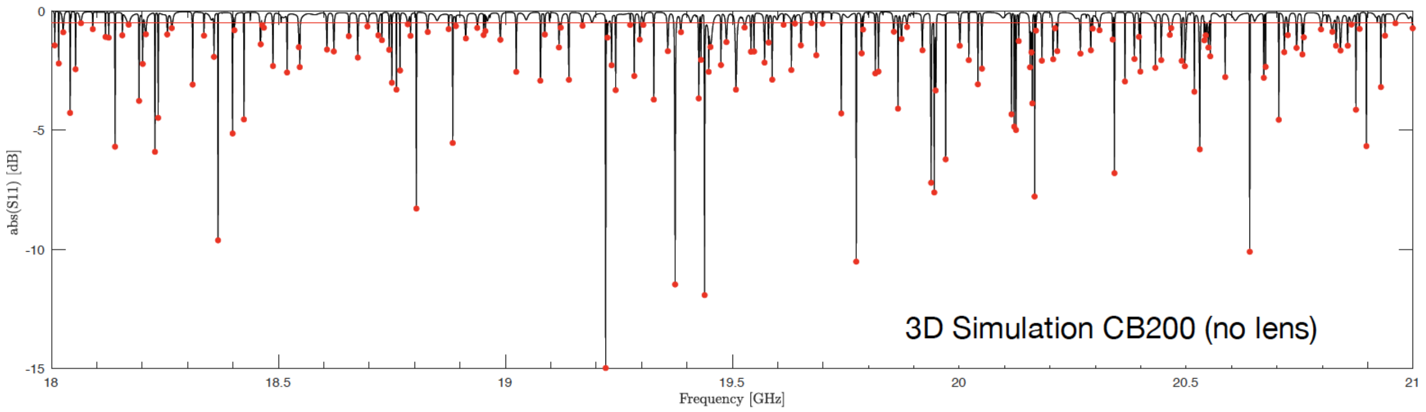


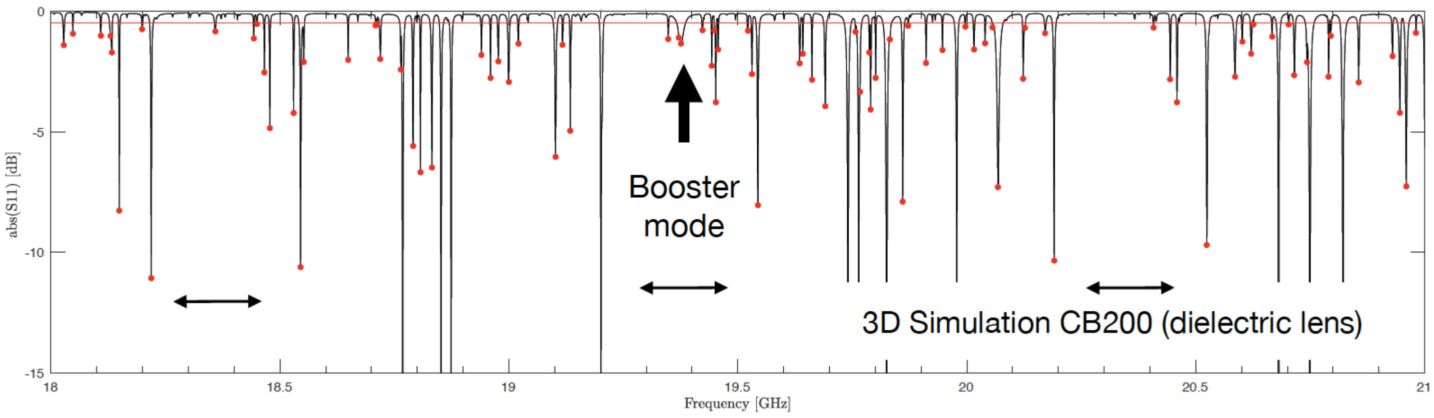
CB200: Understanding Scaling



- Coupling to $g_{a\gamma\gamma}$ scales with:
  - conversion surface, $\propto A^{0.5}$

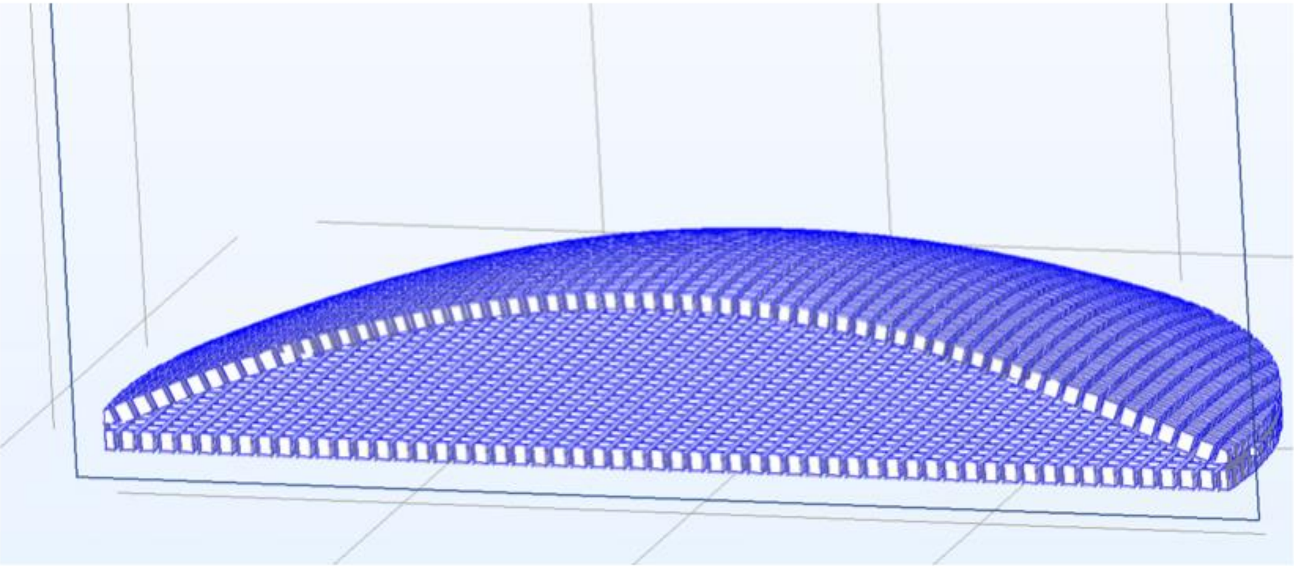
Larger dimensions increase the number of allowed modes
➔ Learn to deal with overmoded systems relevant for OB
➔Using a dielectric lens (Rexolite) decreases coupling of unwanted modes and allows for “quiet" regions in the spectrum

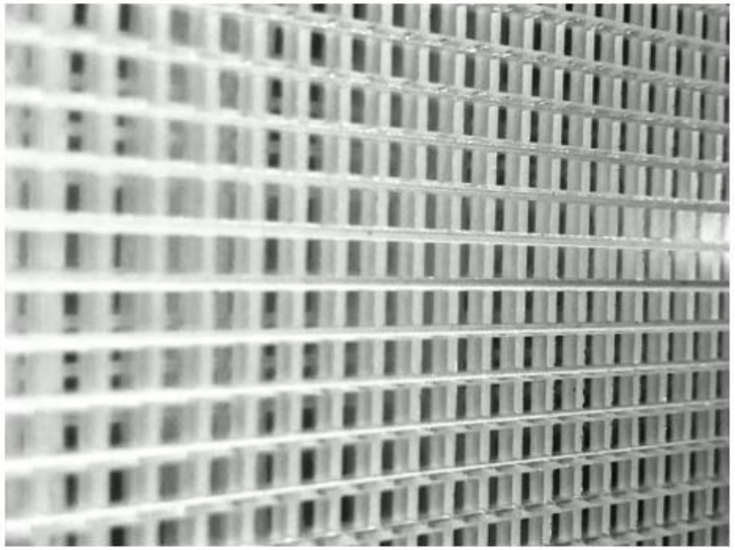




Dielectric Lens

Rexolite: dielectric constant = **2.53** and low loss
3d-printed and designed to mitigate reflection for our range of interest of ~18 to 20 GHz.

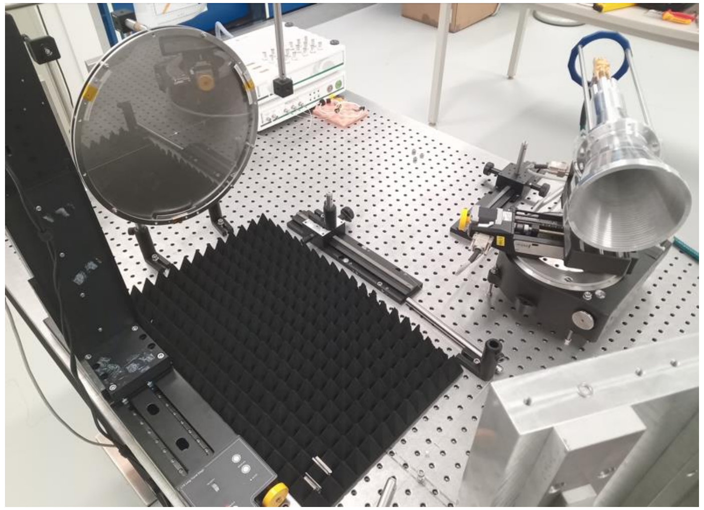




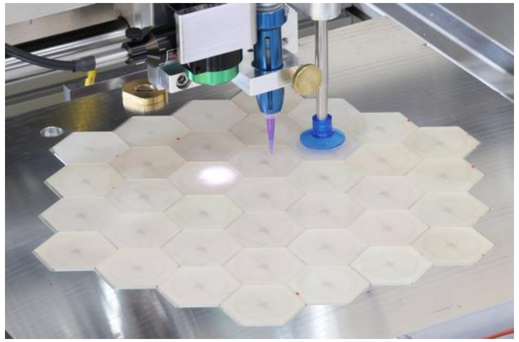
Contact: Anton Ivanov <ivanovan@mpp.mpg.de>

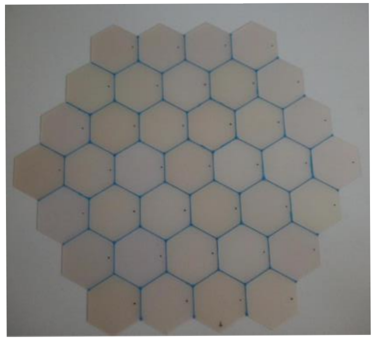
OB300: work in progress

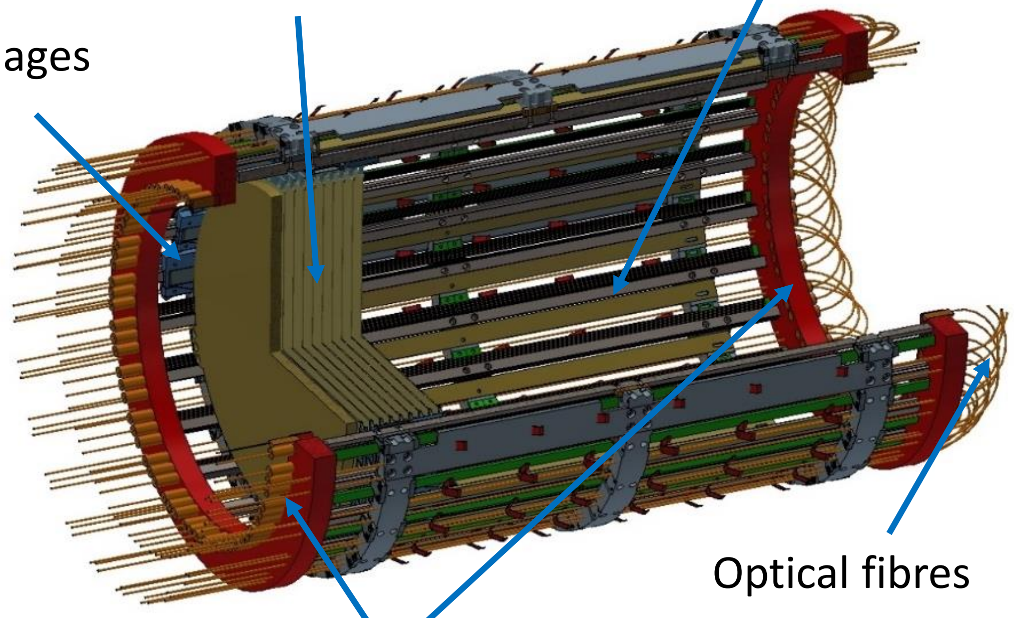
- Calibration of boost factor with 3 x ∅ = 300 mm disks



- Tiling of ∅ = 300 mm $LaAlO_3$ disks

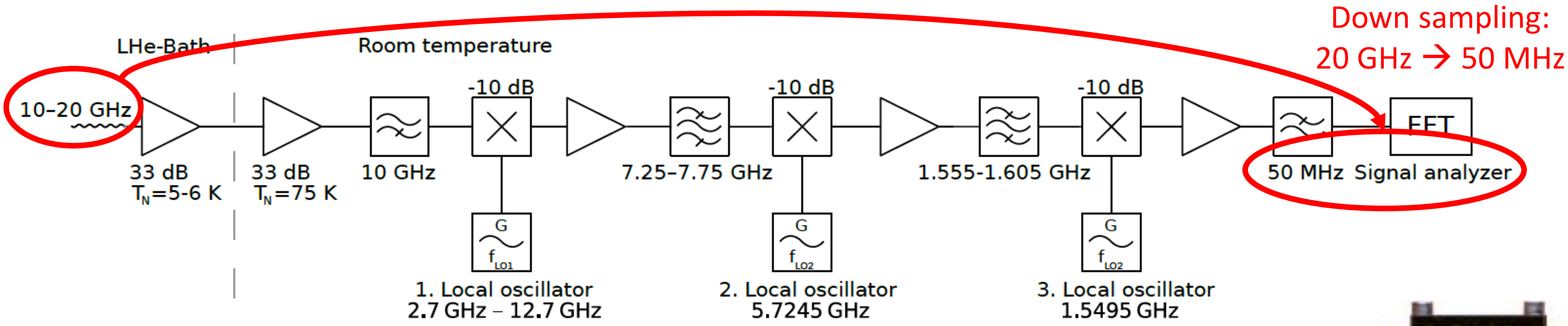


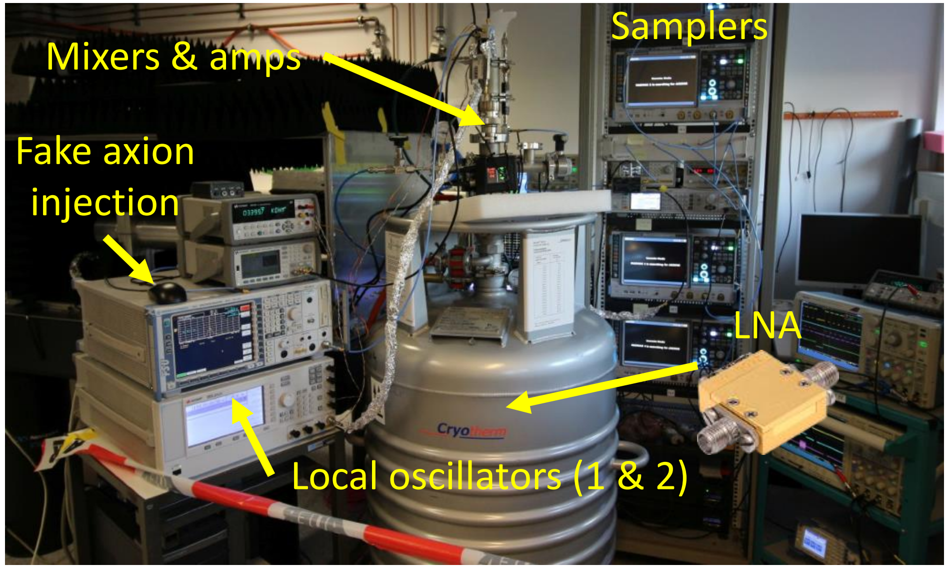




- Building mechanical structure for OB300

Receiver Chain



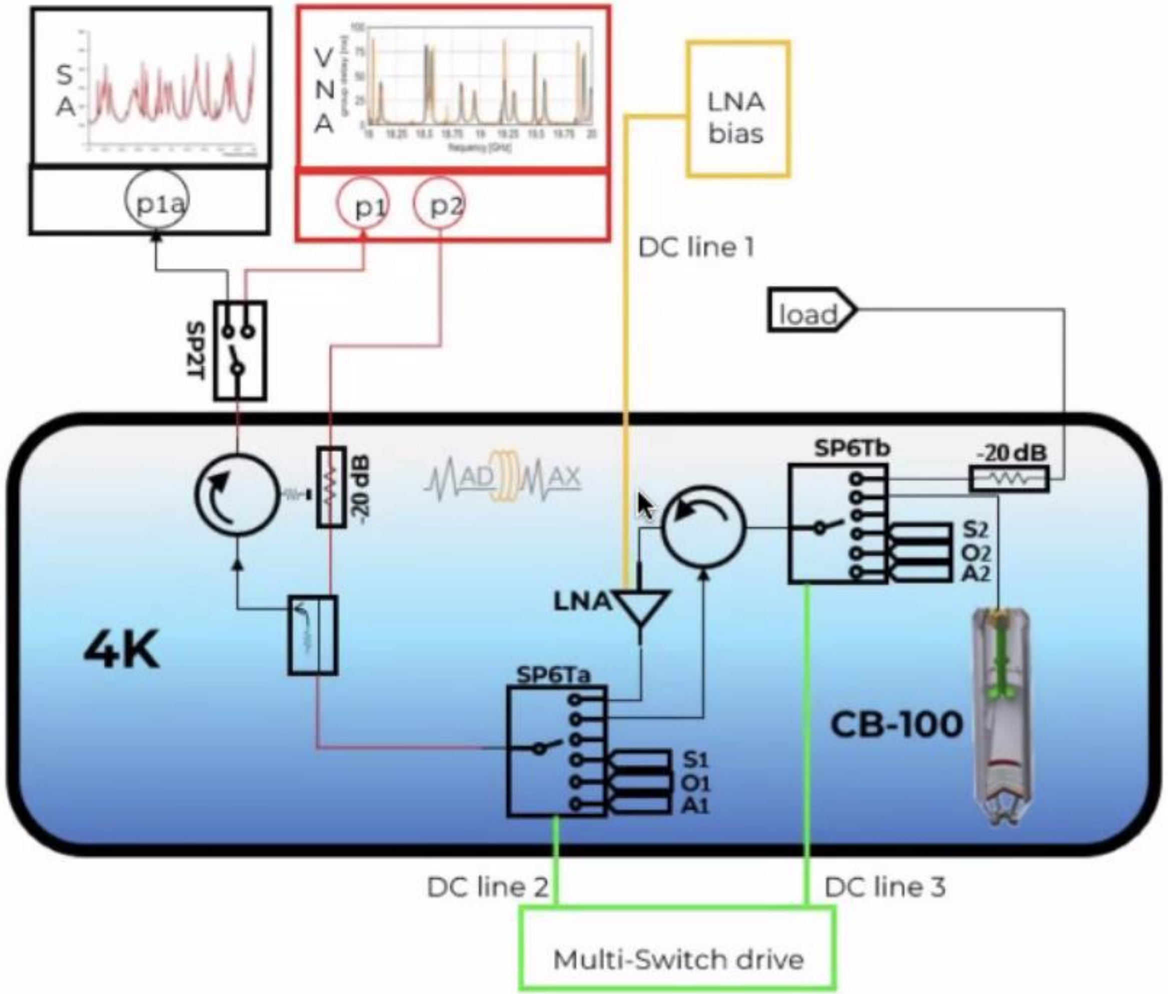


- Receiver chain with low-noise amplifier and three mixing stages
- Amplifiers for high frequencies developed: TWPAs for < 30 GHz

Test setup at MPP with 4 samplers and fake axion injection:
Detection of 1.2×10^{-22} W signal within few days

Low-noise cryogenic amplifier (noise temperature 5 to 6 K)

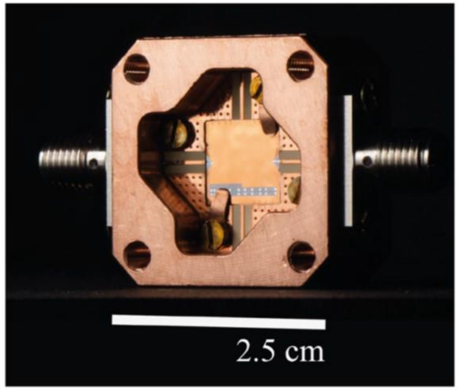
Cold Calibration Idea

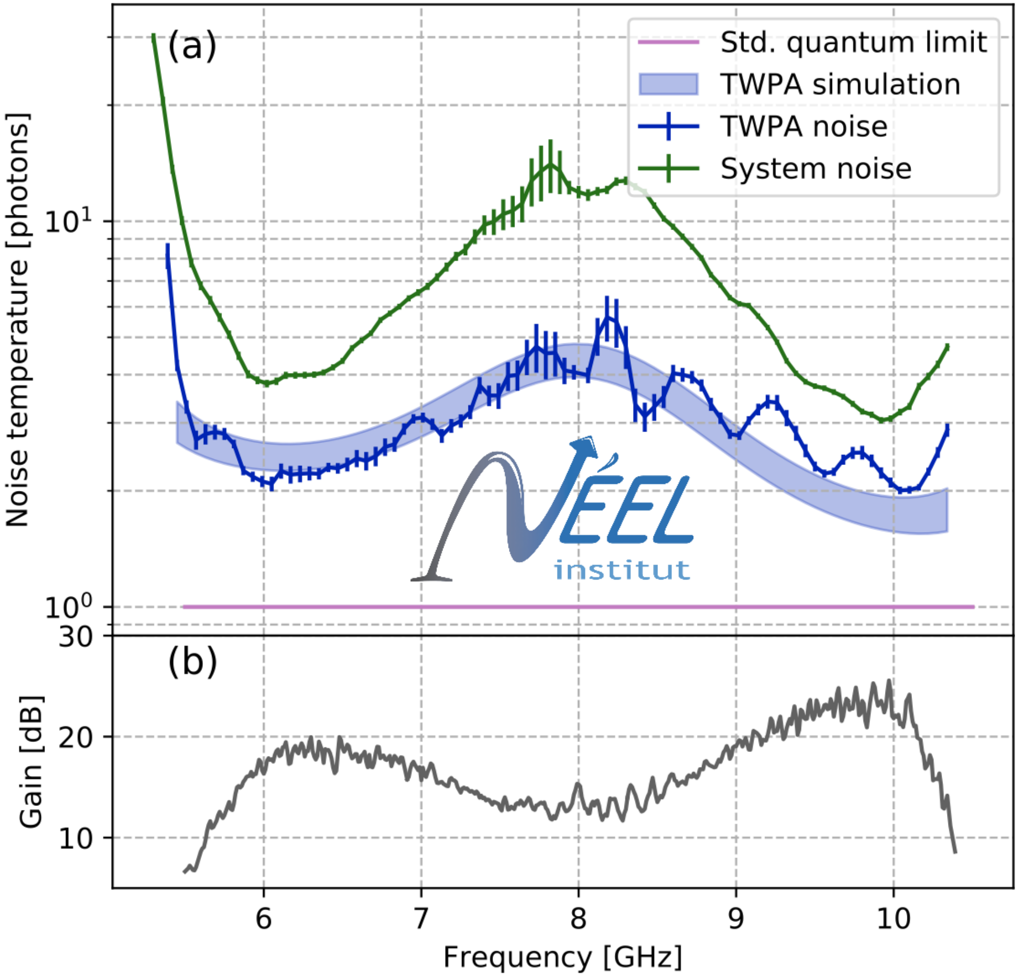


Simulation still missing

Quantum-limited Amplifier

- Traveling wave parametric amplifier (TWPA)
- **First 10 GHz TWPA** produced (PRX 10, 021021)
- Added noise: 1 K above quantum limit
  (20 dB gain @ 10 GHz)
- Future development to 30 GHz





[Reversed Kerr TWPA arXiv:2101.05815]

MADMAX Collaboration Meeting
September 2022 @ Hamburg

MADMAX Collaboration