

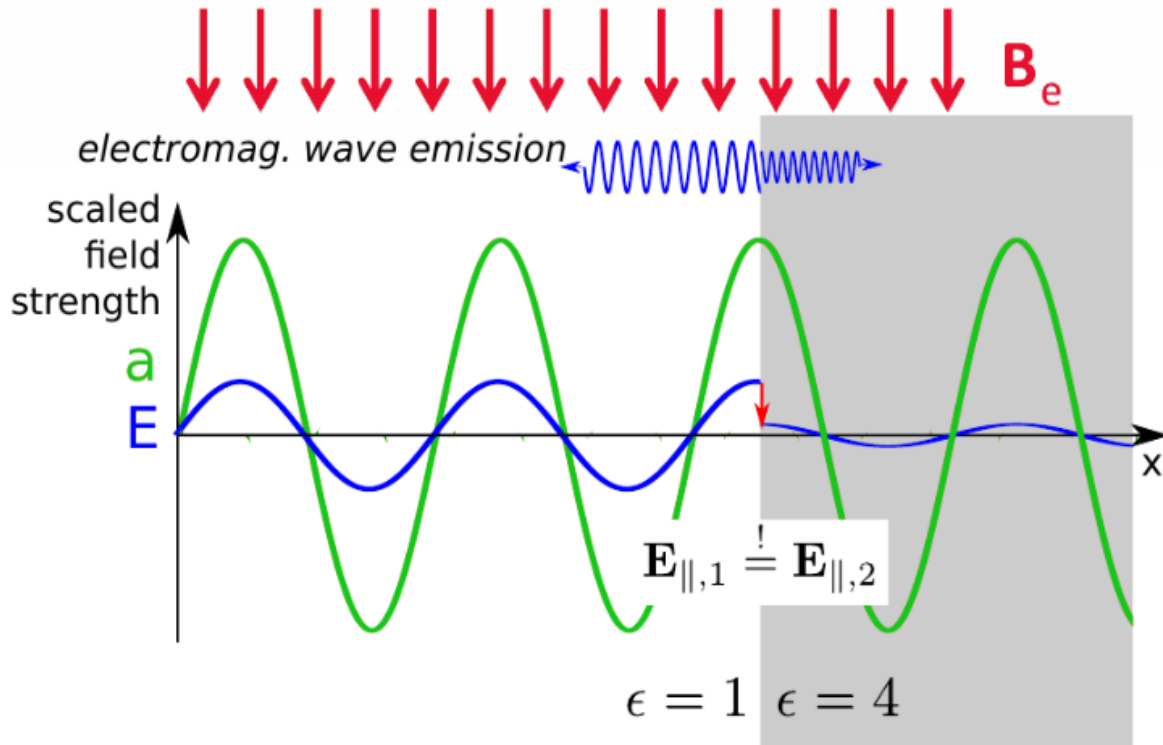
Advances in searching for galactic axions with a Dielectric Haloscope (**MADMAX**)

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On behalf of the MADMAX Collaboration

11th August 2022
17th Patras Workshop on Axions, WIMPs and WISPs
Mainz

The cosmological axion field $a(t)$ inside an external magnetic field B_e sources a tiny axion induced electric field E_α



$$E_\alpha \sim 10^{-12} \text{ V/m for } 10 \text{ T in vacuum}$$

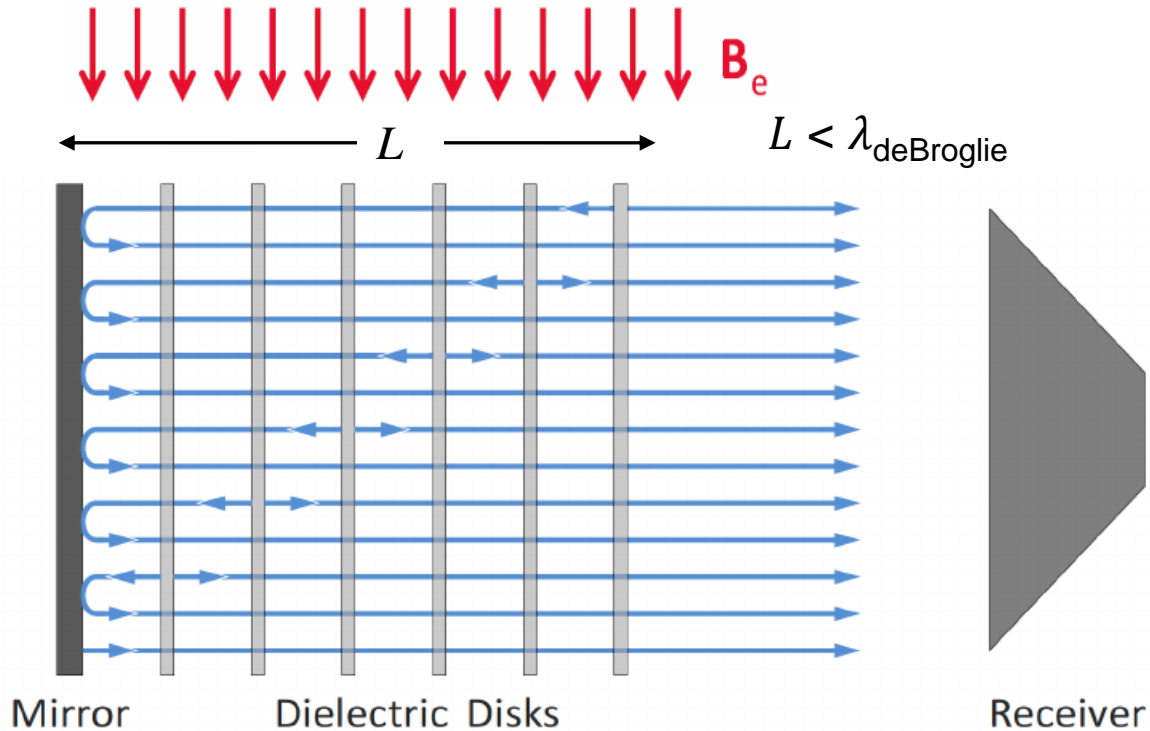
E_α is different in materials with different ϵ

E_{\parallel} must be continuous at the **boundaries**

$$E_\alpha = -\frac{g_{\alpha\gamma} B_e}{\epsilon} \alpha \quad \alpha = \alpha_0 \cos(m_\alpha t)$$

Power emitted from a single surface:

$$P_{sig} = 2.2 \cdot 10^{-27} \text{ W} \left(\frac{A}{1m^2} \right) \left(\frac{B_e}{10T} \right)^2$$



- EM radiation escapes at open end
- Detect Traveling wave instead of standing wave modes

Boosted emitted power :

- coherent emission from multiple interfaces by controlling the discs separations and
- constructive interference

$$P_{sig} = 2.2 \cdot 10^{-27} W \left(\frac{A}{1m^2} \right) \left(\frac{B_e}{10T} \right)^2 \cdot \beta^2$$

power "Boost factor" β^2

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

Simulations indicate:

$|\beta^2| > 10^4$ achievable with 80 disks

with dielectric constant $\epsilon \sim 24$ (LaAlO₃)

β^2 is affected by BC's inaccuracies of the discs: disc mis-positioning, tilting, thickness variations

The MADMAX Experiment

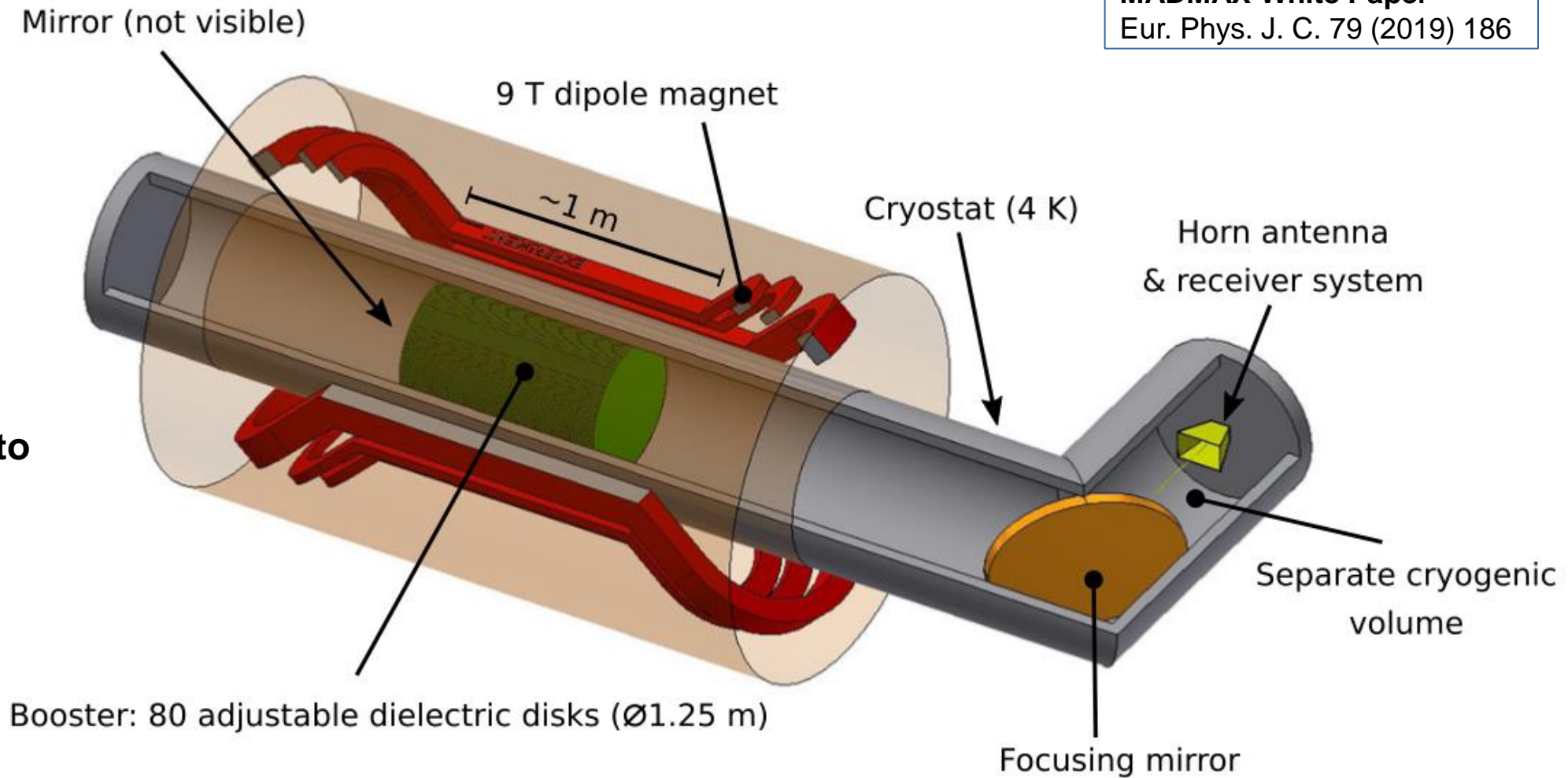


MADMAX White Paper
Eur. Phys. J. C. 79 (2019) 186

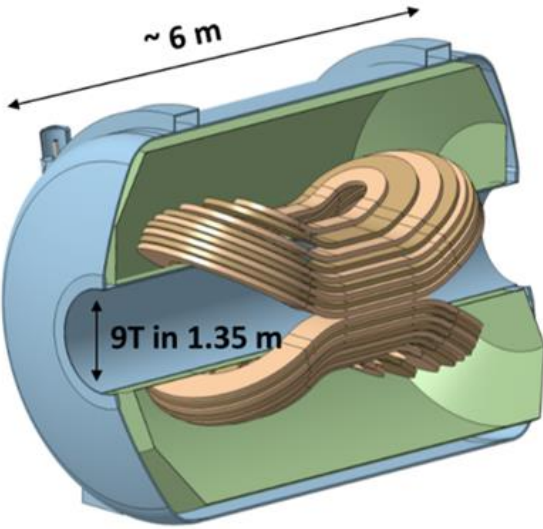
Main challenges

- Booster mechanics
- Magnet
- Receiver at cold, B-field environment

Start with prototypes to validate concepts



MADMAX Magnet Update

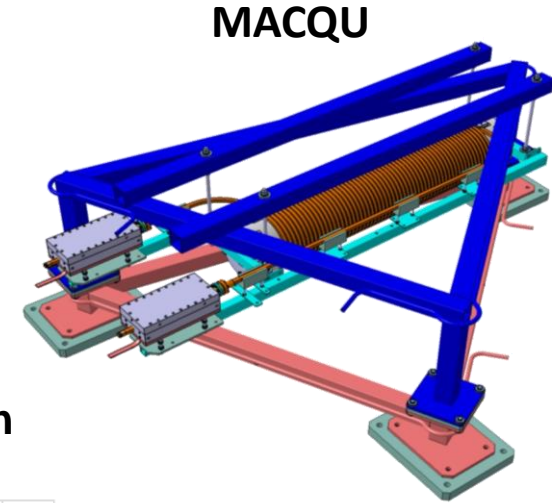


→ Main Challenges :

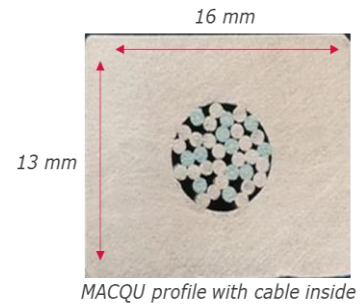
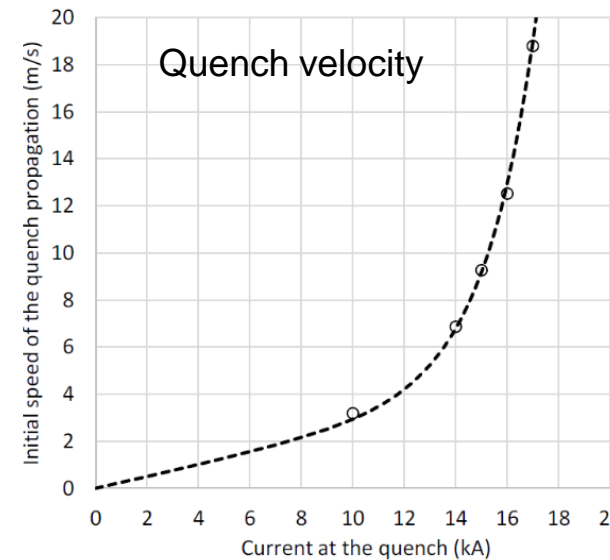
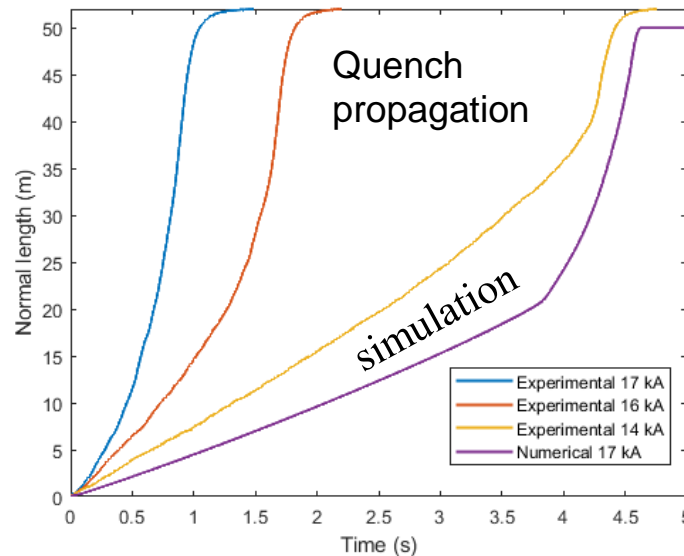
- Reliable quench protection
- **Feasibility of conductor production (CICC)**
- Quench propagation velocity were measured in a dedicated setup: **MAdmax Coil for Quench Understanding** →

→ Main project risk mitigated:

Quench propagation according to requirements for safe operation

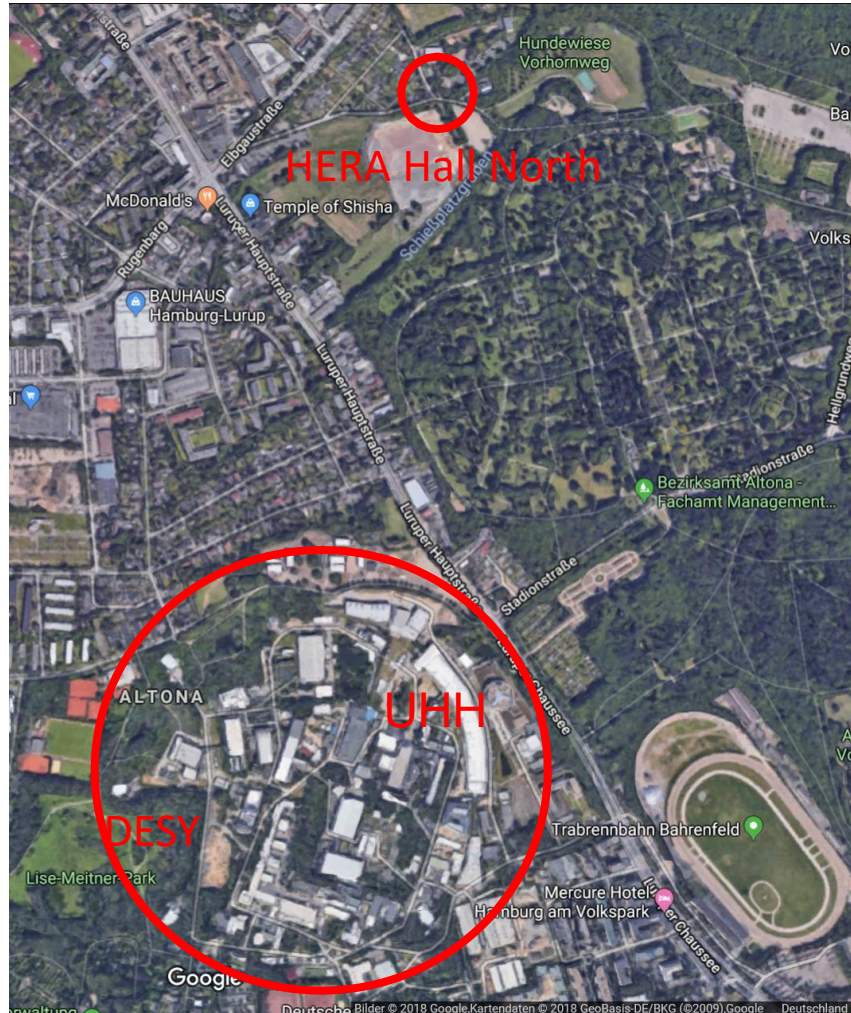


Development in innovation partnership

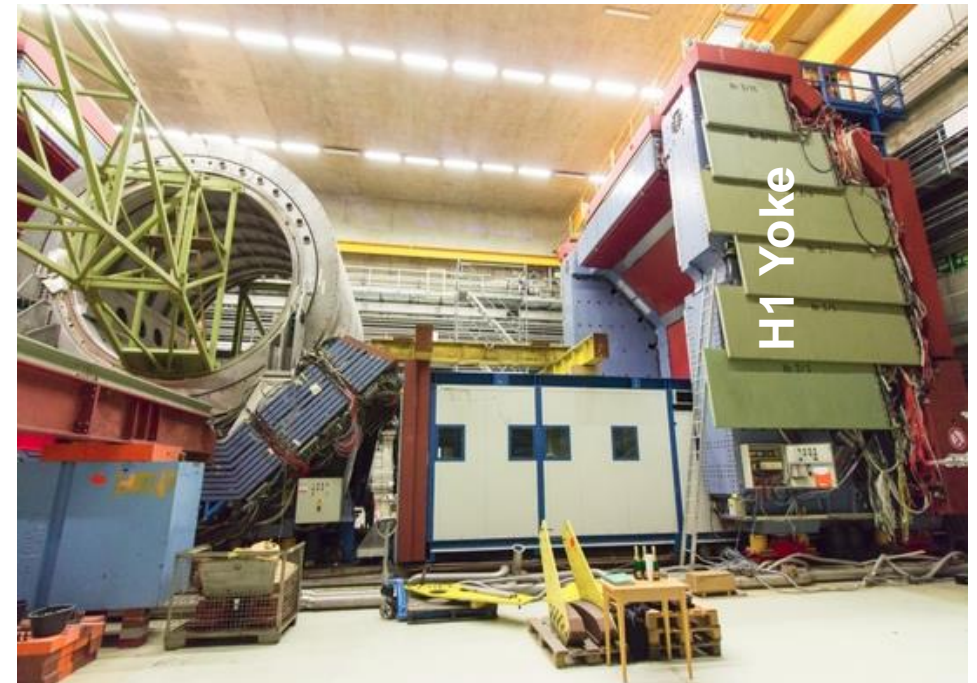


**Novel conductor:
Cable In Copper Conduit**

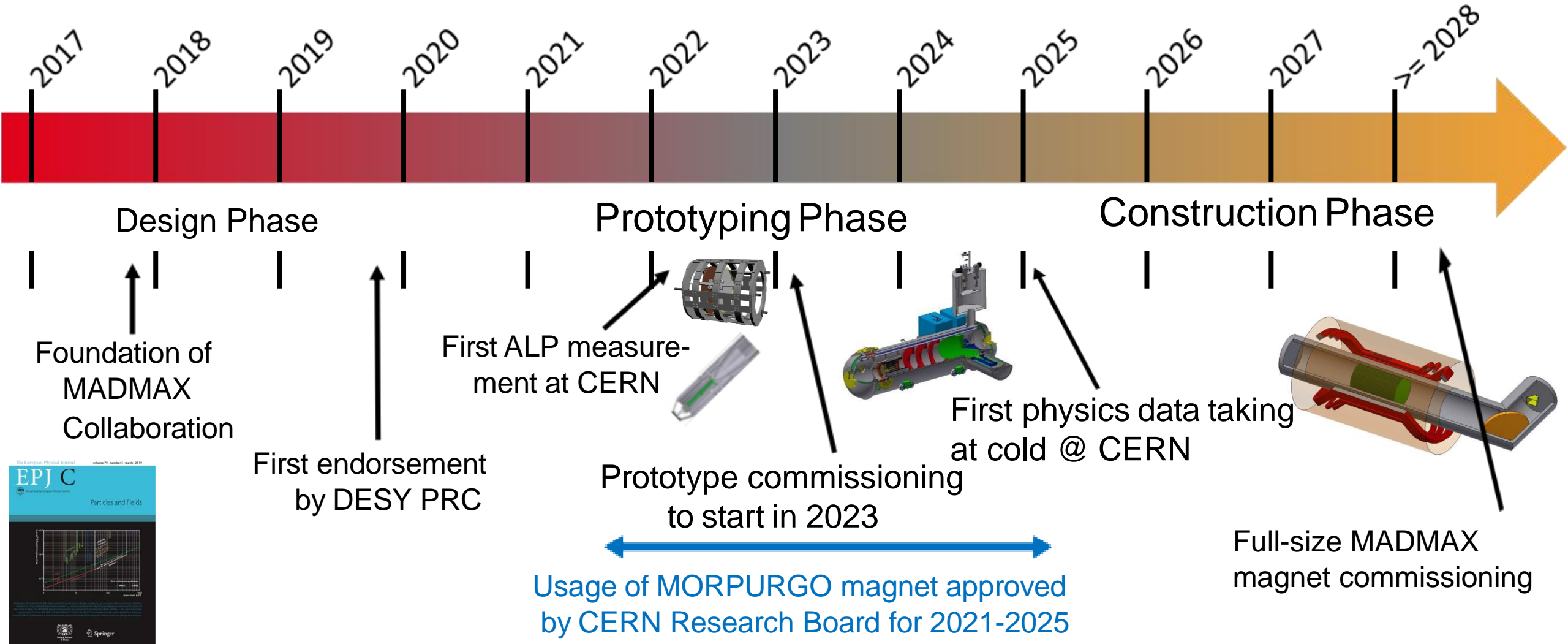




- MADMAX to be built at HERA Hall North
- Make use of DESY infrastructure
- Benefit: re-use H1 yoke as magnetic shielding to reduce fringe field



Time Scale

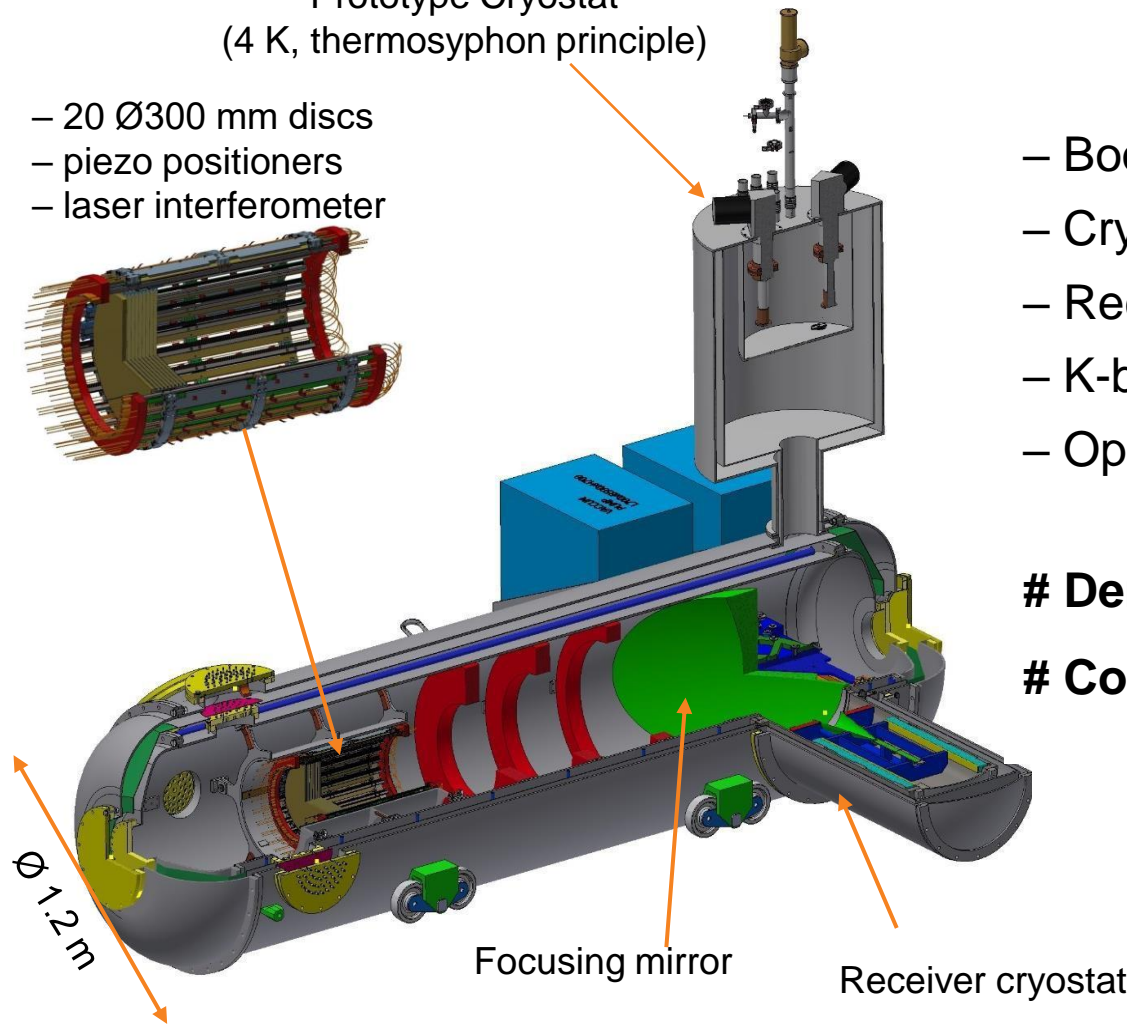


The MADMAX Prototype



Prototype Cryostat
(4 K, thermosyphon principle)

- 20 Ø300 mm discs
- piezo positioners
- laser interferometer



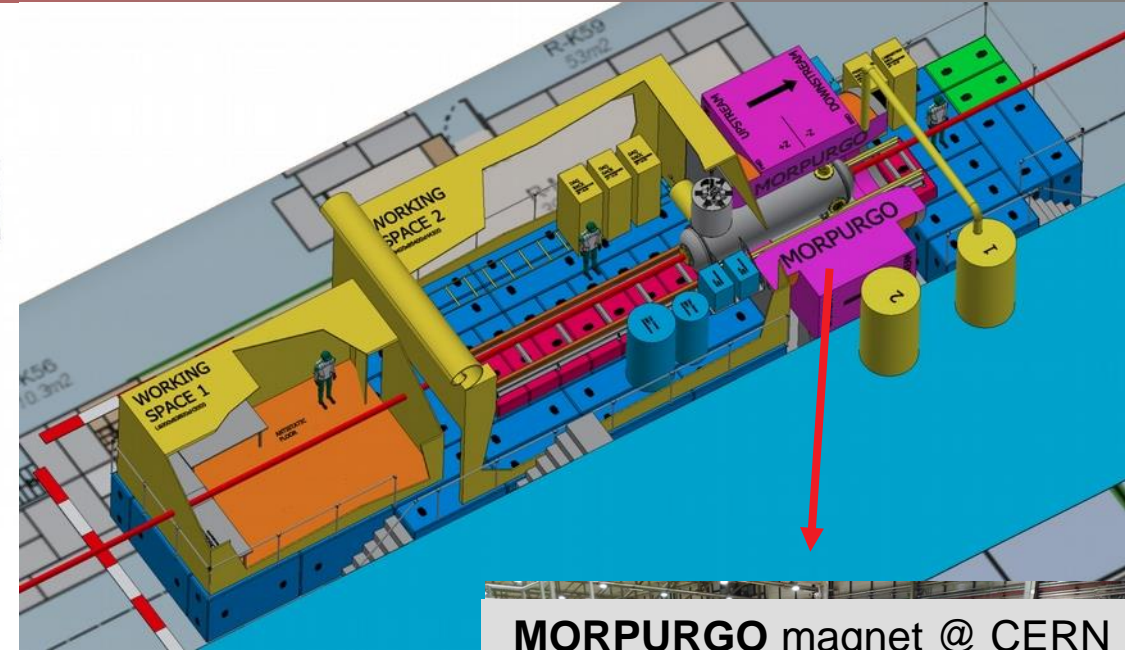
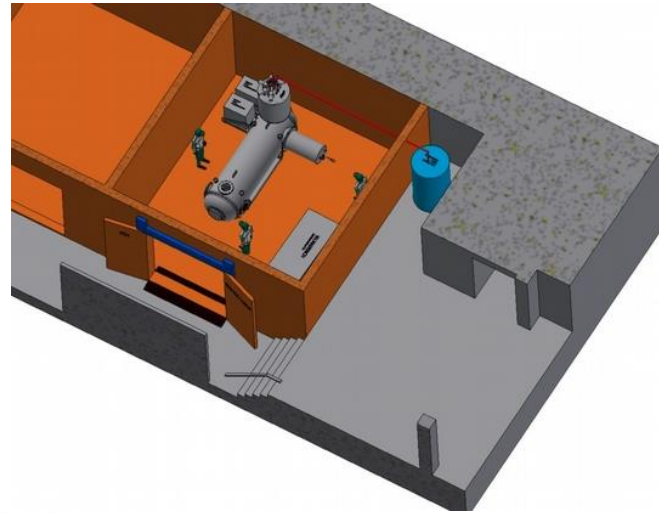
Scaled down prototype of MADMAX

- Booster with up to 20 dielectric discs 300 mm in diameter
- Cryostat will be delivered at DESY @ 2022-2023
- Receiver cryostat designed and flexible in use
- K-band Antenna received
- Optical system components under construction

Demonstrating the feasibility of key technologies for MADMAX

Competitive ALP search with a dielectric haloscope

The MADMAX Prototype



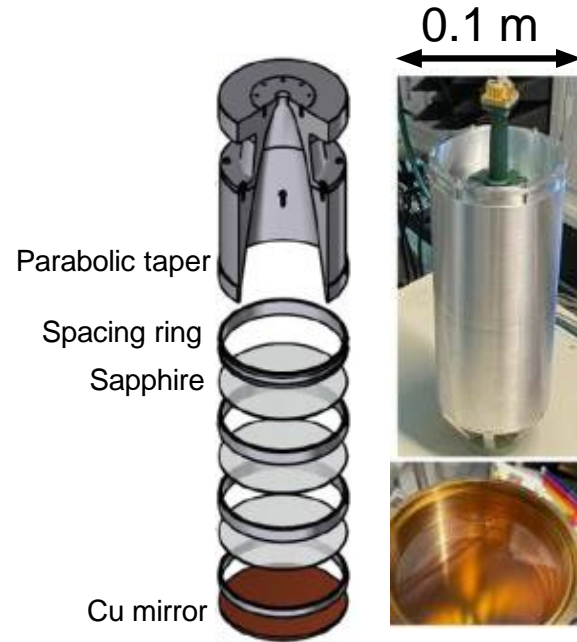
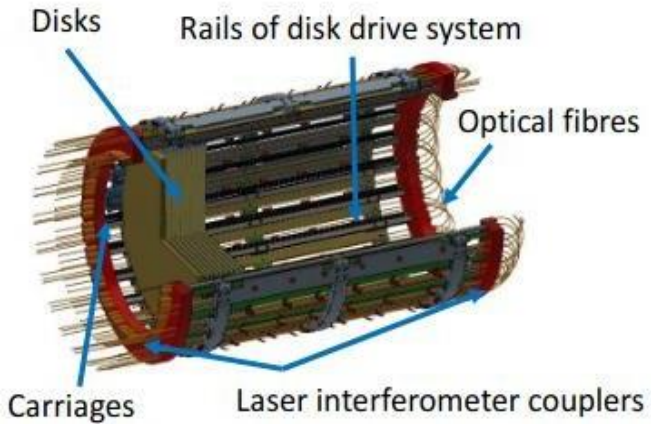
MORPURGO magnet @ CERN



Shielded RF lab in Hamburg

MADMAX Prototype to be installed in the Shielded Experimental HaLL (SHELL) @ DESY
• Commissioning begin of 2023

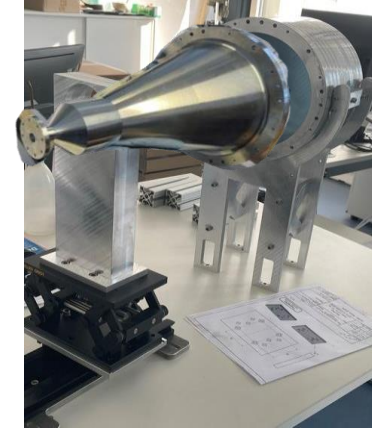
First axion physics measurements in **MORPURGO magnet @ CERN**
• Physics runs at CERN in 2024 & 2025



CB100

Closed booster

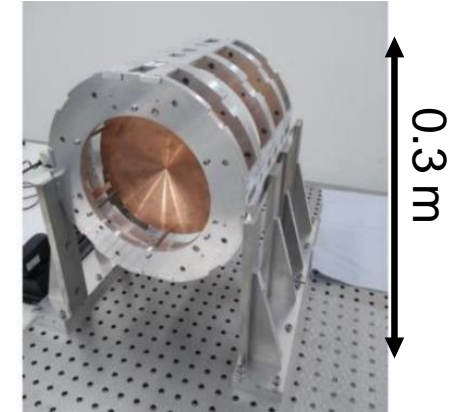
Cu mirror
 3 Ø100 mm discs
 fixed disc spacing
 Optimized @ ~19 GHz



CB200

Closed booster

Cu mirror
 ≥3 Ø200 mm discs



P200

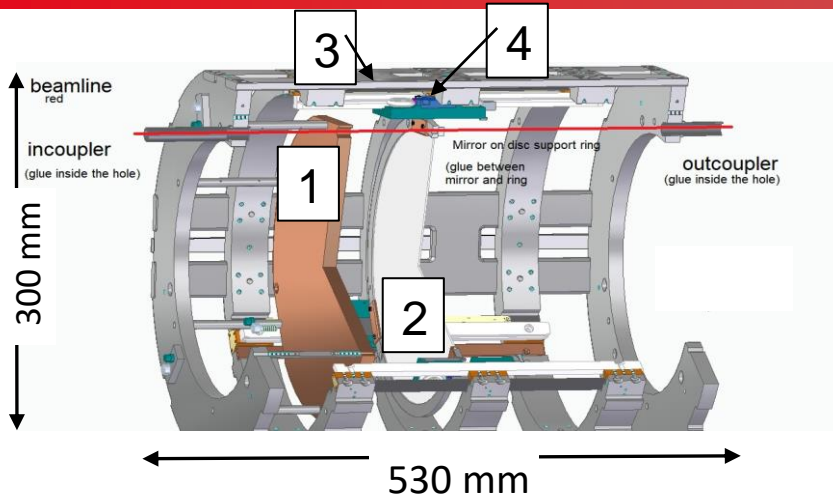
Open booster

Cu mirror
 1 Ø200 mm disc

Test setups to assess the RF response to small changes (or inaccuracies) in the hardware potentially effecting the boost factor

Prototype booster
 Operating conditions:
 - Cryogenic temperatures: 4 K
 - High magnetic field: up to ~10 T
 - Vacuum or cold He exchange gas

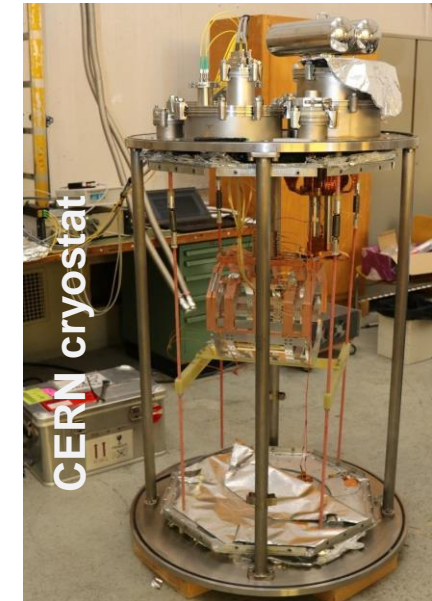
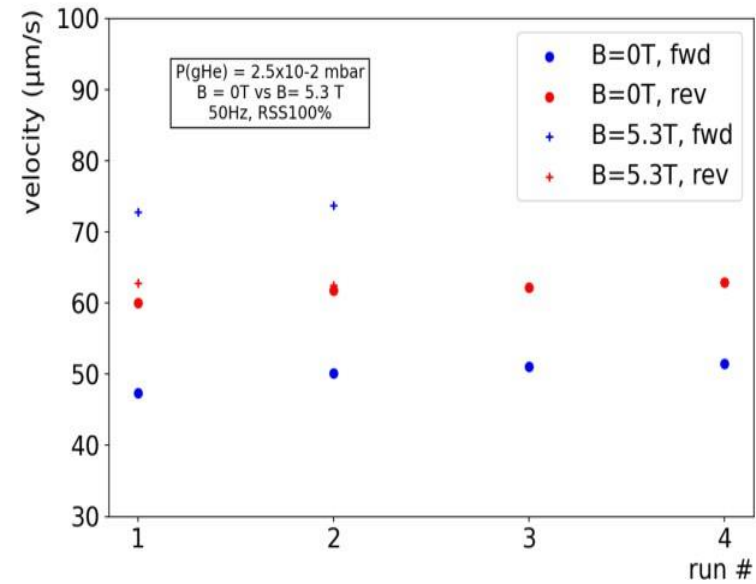
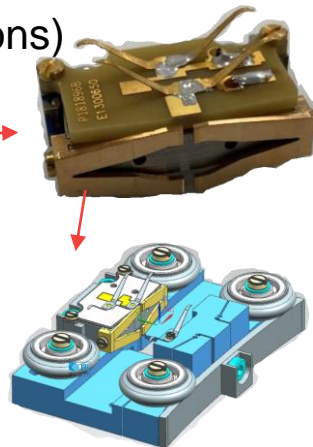
Single Sapphire Ø300 mm discs
 or
Tiled discs made of LaAlO₃ 3" wafers



- Piezo-motor operated inside the 5.3 T ALPS II magnet @ 5 K
- Project200 successfully tested at CERN's cryolab and in 1.6 T Morpurgo magnet
- Attocube laser interferometer works at cryogenic temperatures
- P200 backbone structure **keeps optics alignment during cool-down**
- A disk can be moved with three motors using the laser interferometer feedback

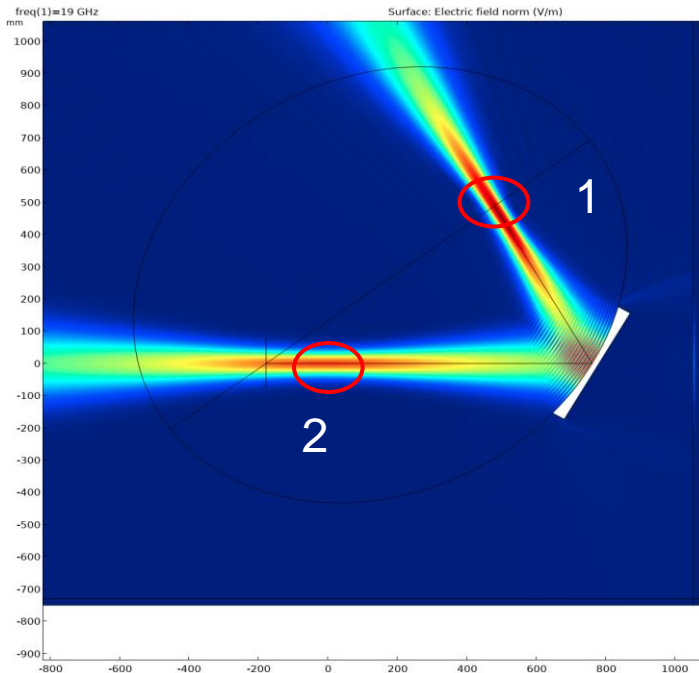
- 1 - Cu mirror (fixed position)
- 2 - Sapphire disc (adjustable positions)
- 3 - P200 support structure
- 4 - (3x) JPE piezo motors

- speed of > 100 $\mu\text{m/s}$ in cold
- position accuracy < 2 μm in cold

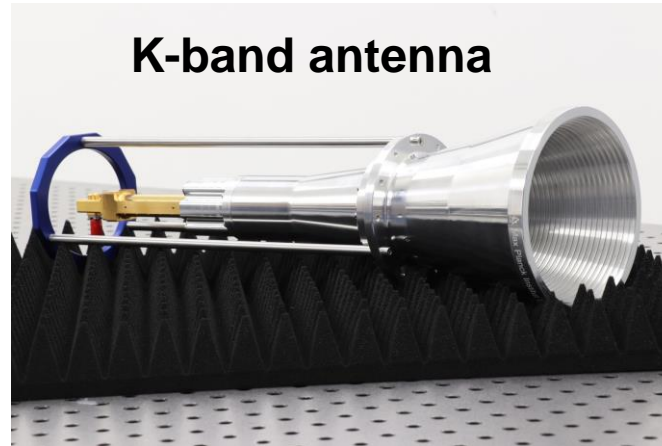


Mechanical feasibility R&D Milestones achieved

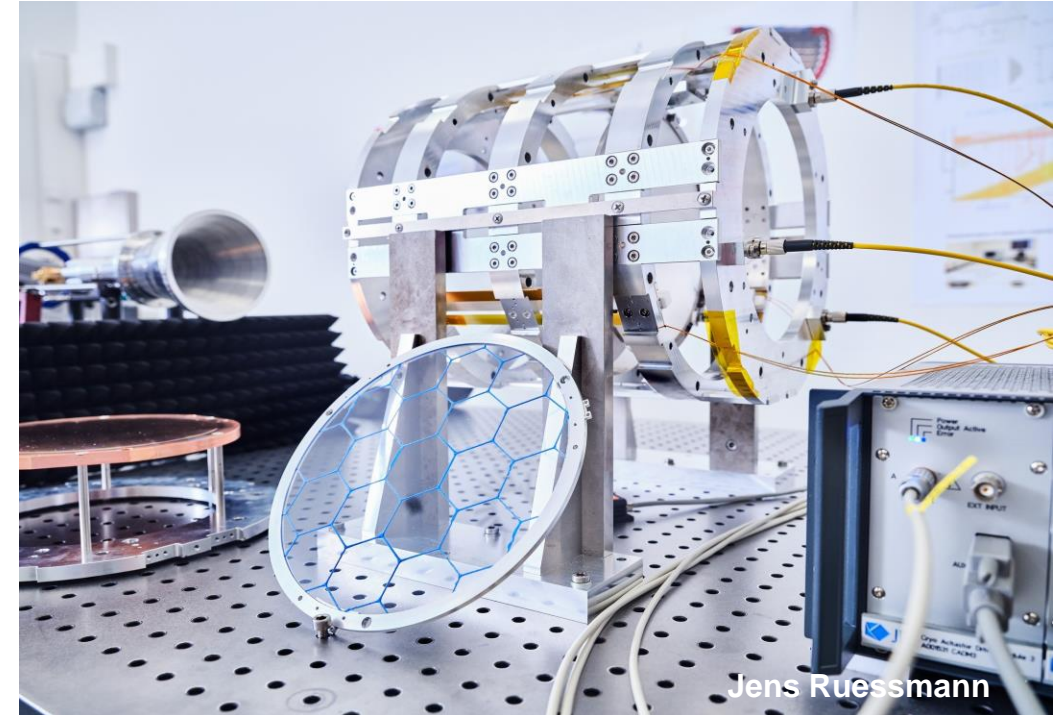
COMSOL 2D simulation



Simulated Gaussian beam from:
1. Phase center of the K-band antenna
to
2. Booster's nominal phase center



K-band antenna



Jens Ruessmann

- Test Prototype antenna
- Reflectivity measurements of the (P200 – ellipsoid mirror- antenna) system for losses estimation
- 3D CST MWS and COMSOL simulations
- Measurements and simulations of tiled discs

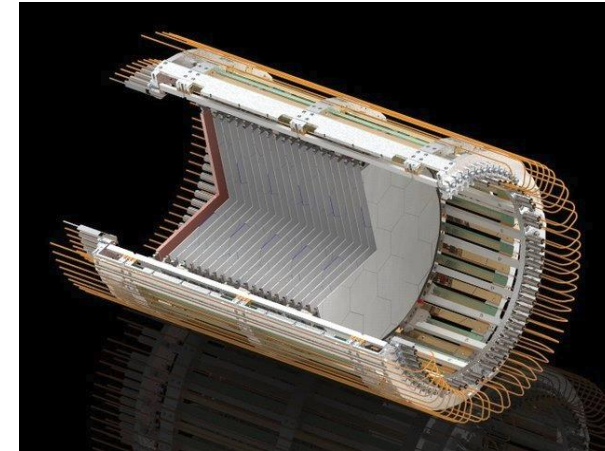
CB100



P200



R / P - booster

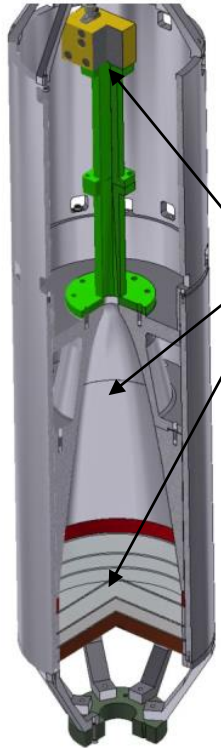


2022 - 2023

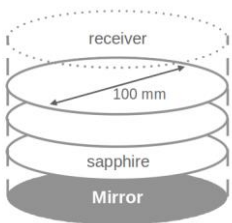
Gradually study effects of open boundary conditions

- Reflectivity and noise power measurements in CB100
- T_{sys} gives valuable information on the system response and the boost factor
- A promising approach under investigation:
reciprocity* between axion-induced and reflectivity-induced electromagnetic fields

* See Poster “Axion Haloscope Calibration from Reciprocity” by J. Egge



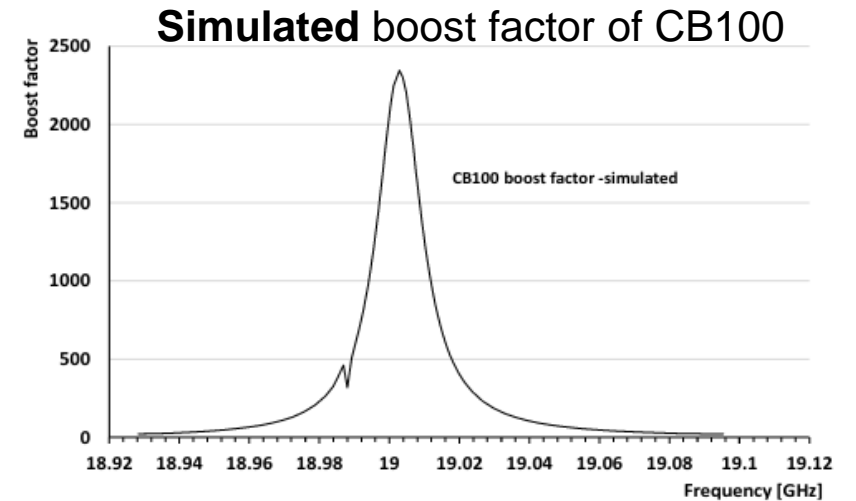
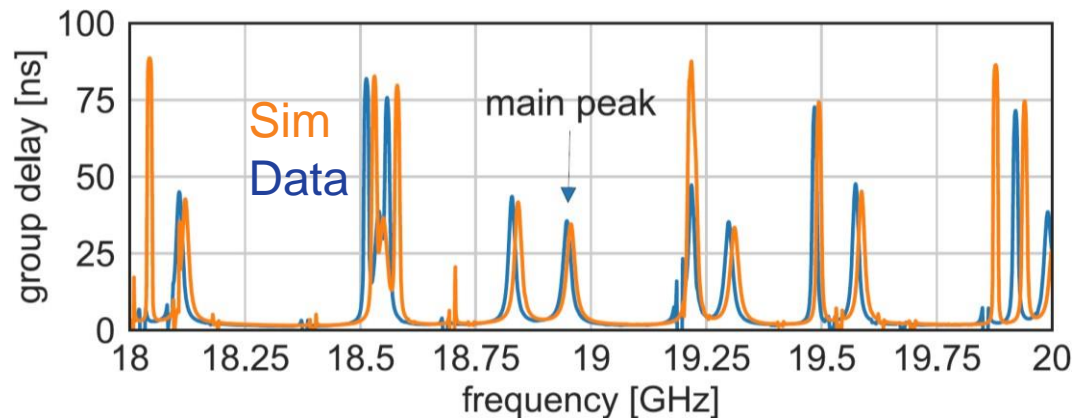
→ Receiver
 → Parabolic taper
 → 3x Ø100 mm sapphire disks



- A small & simple dielectric haloscope
- “Closed”: conducting boundary (understand and mitigate transverse losses)
- Can be operated at cryogenic temperatures
- **Good qualitative match between simulation & measurement**

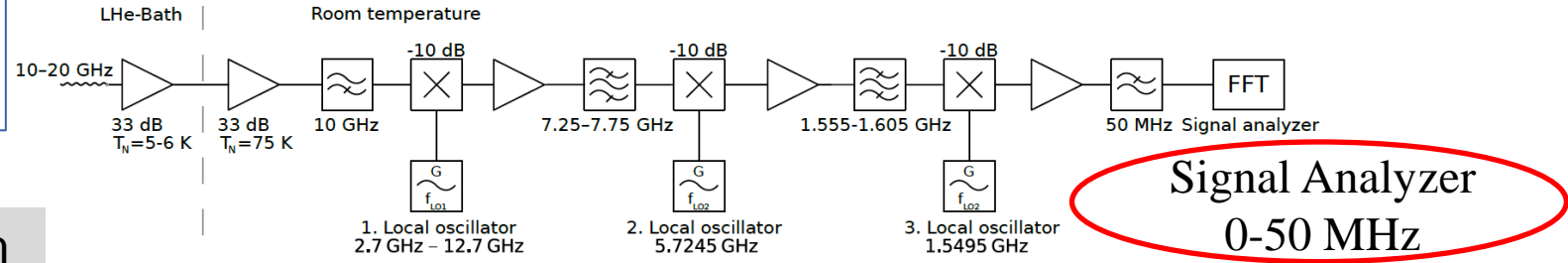
First Hidden Photon search @ MPP

First ALP search in MORPURGO magnet @ CERN

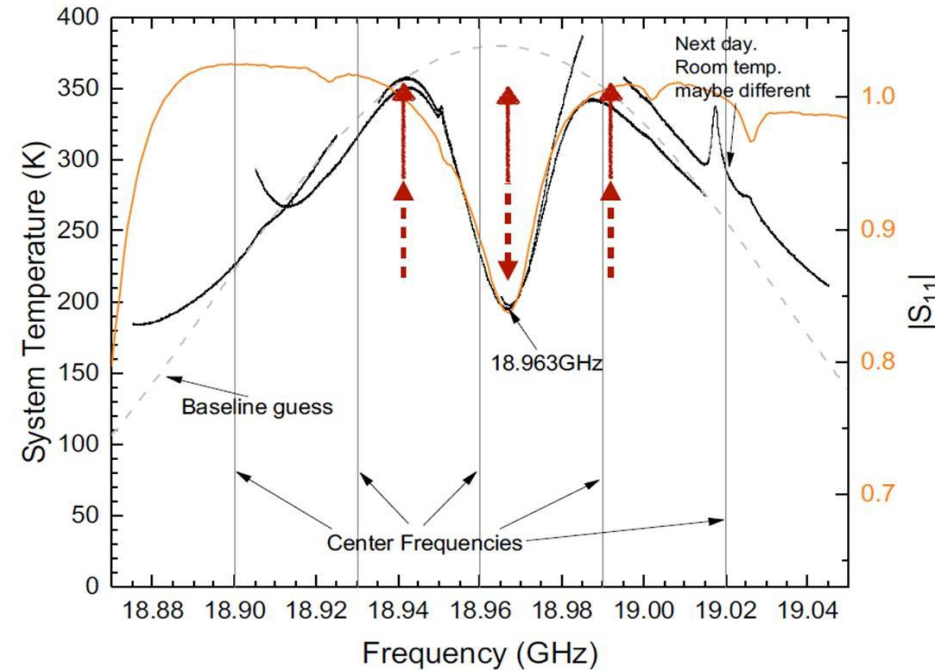


Pre-Amplifier
10-20 GHz

Detection system



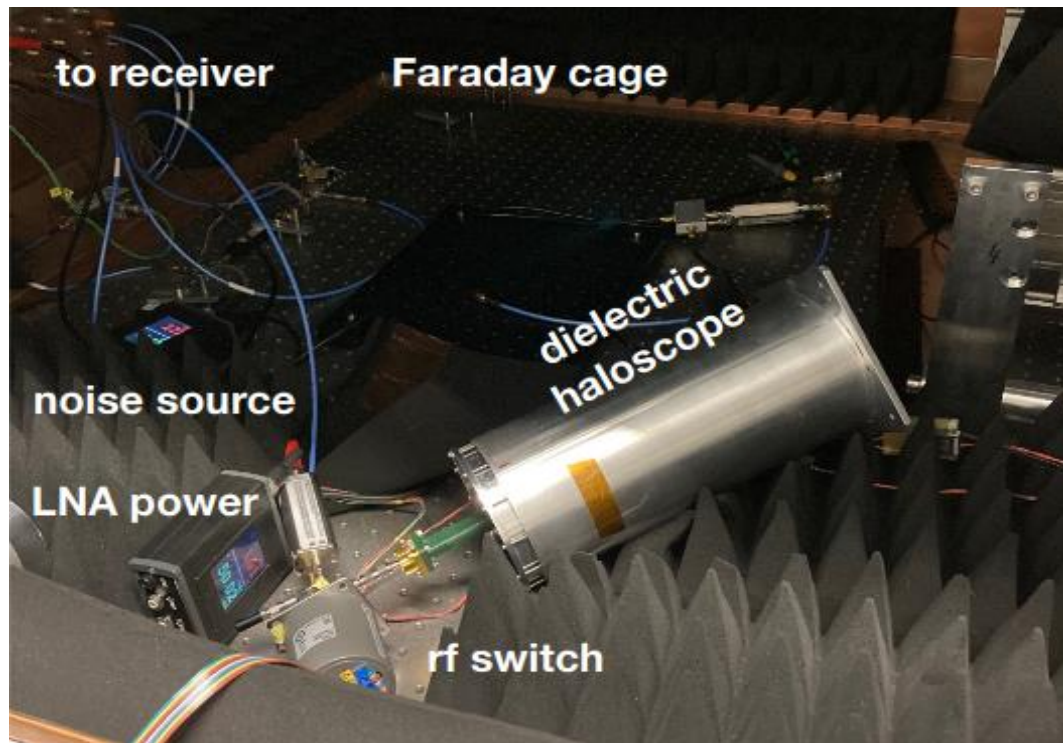
- T_{sys} behavior at 5 RT measurements
- T_{sys} calibration with a noise source
- Dip in T_{sys} corresponds to the dip of the Reflectivity measurement
- Infer **boost factor** using model with parameters inferred from thermal and RF measurements



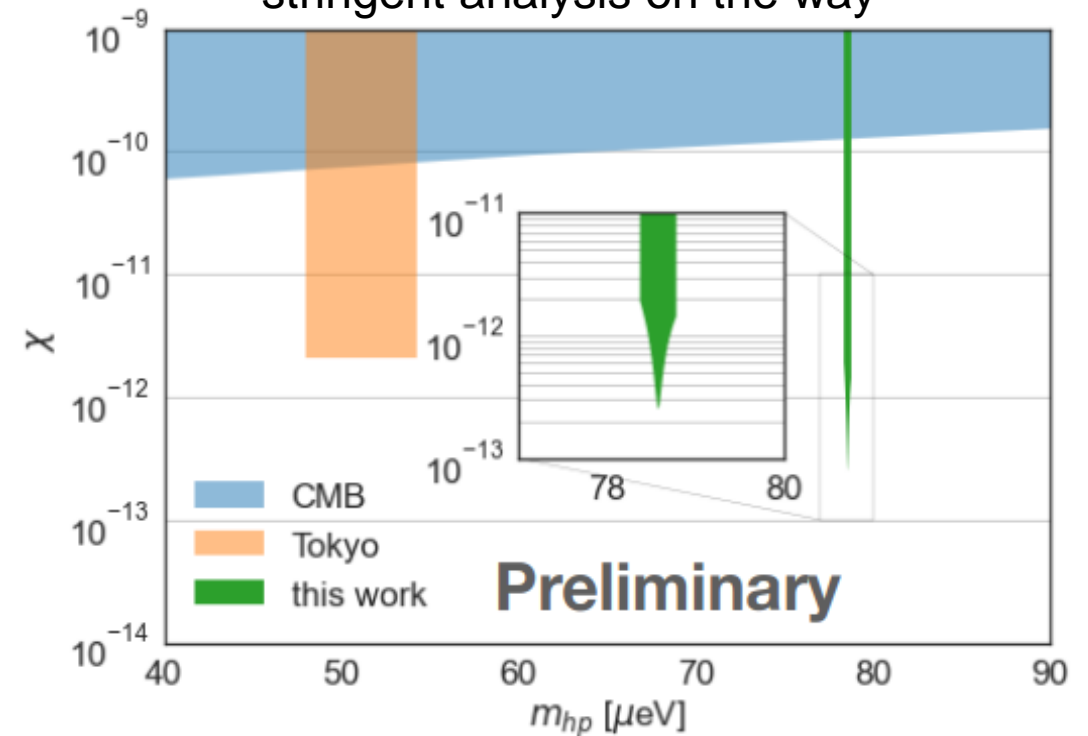
Test setup with 4 samplers and fake axion injection:
Detection of 1.2×10^{-22} W signal within few days

Hidden photon to microwave conversion w/o B field @ RT

- 32 days of data taking
- Noise temperature $\sim 200\text{K}$
- No excess power observed



SENSITIVITY:
stringent analysis on the way



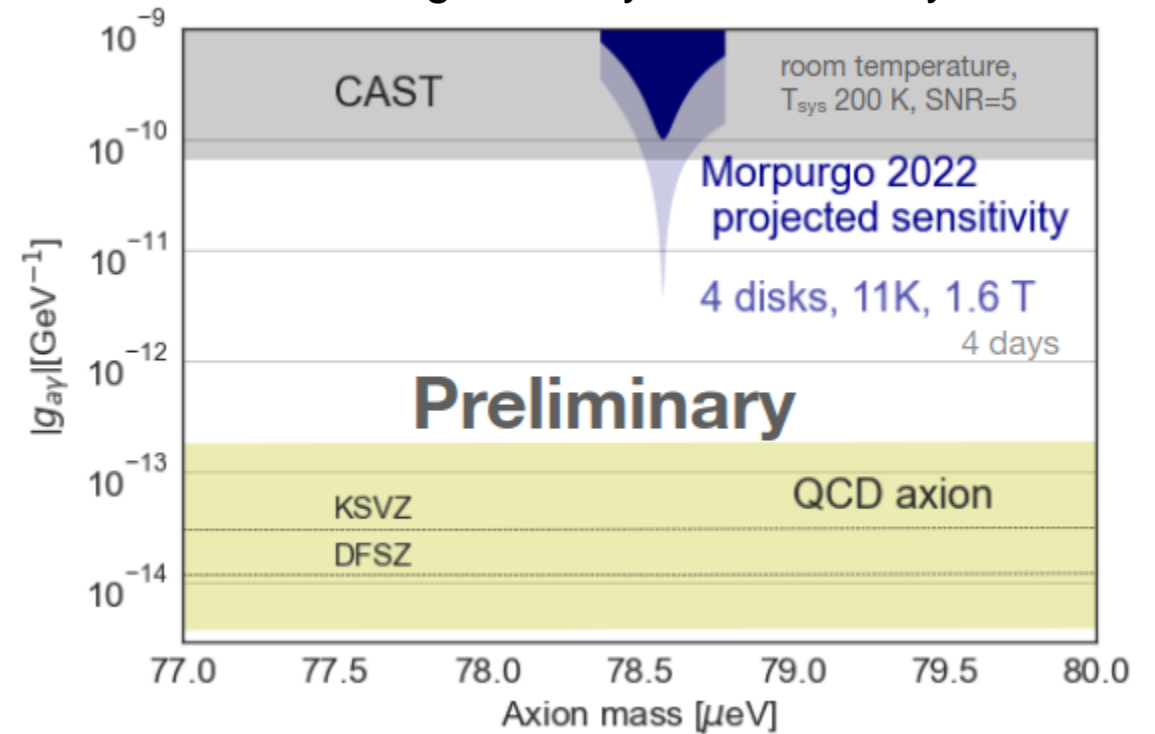
ALP search in CERN's Morpurgo magnet (1.6 T) in Mar/Apr 2022



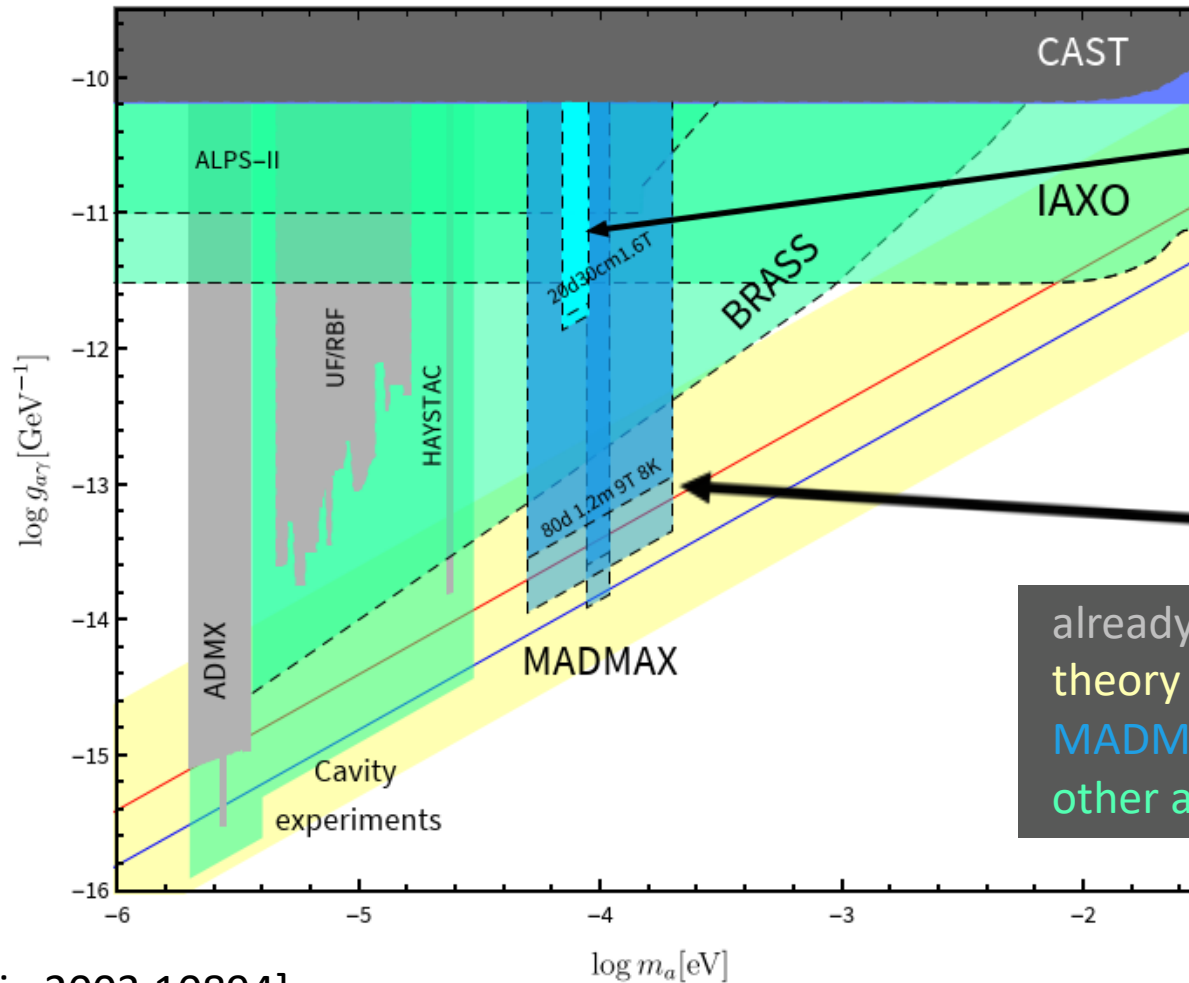
- 10 hrs @ 1.6T, with ~200 K noise temperature
- No excess power found.

Planning upgrade with a $T < 10$ K system

SENSITIVITY:
stringent analysis on the way



5σ above system noise temperature
 50 % of the theoretically obtainable maximum power



MADMAX Prototype:

$$\begin{aligned}
 N_{\text{disk}} &= 20 \\
 A_{\text{disk}} &= 0.07 \text{ m}^2 \\
 B_{\parallel} &= 1.6 \text{ T} \\
 T_{\text{sys}} &= 8 \text{ K}
 \end{aligned}$$

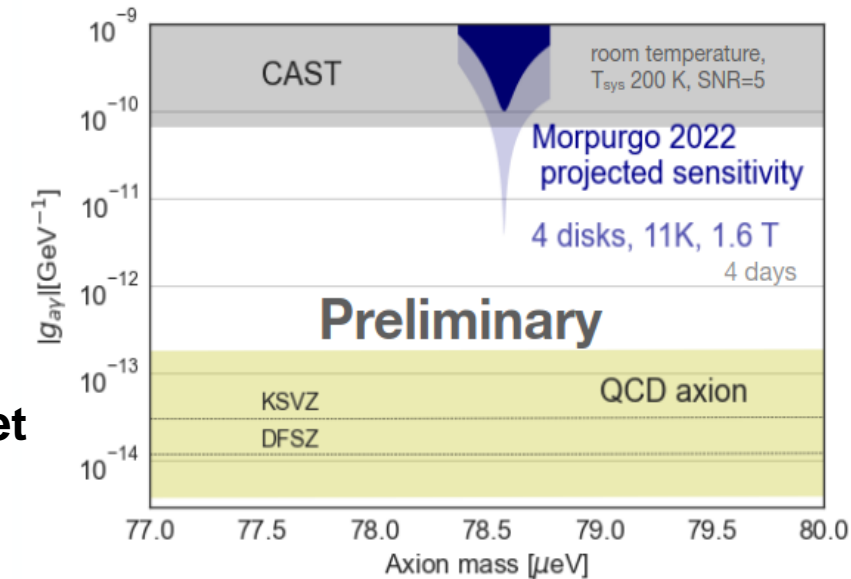
MADMAX:

$$\begin{aligned}
 N_{\text{disk}} &= 80 \\
 A_{\text{disk}} &= 1.2 \text{ m}^2 \\
 B_{\parallel} &= 9 \text{ T} \\
 T_{\text{sys}} &= 8 \text{ K}
 \end{aligned}$$

already explored/excluded
 theory prediction
 MADMAX (Prototype)
 other axion experiments

[arXiv:2003.10894]

- MADMAX prototype **cryostat** to be delivered 2023 at UHH
- Major R&D **milestones** reached
- Feasibility of **piezo** actuators at 5 K & 5.3 T
- Mechanical concept of **MADMAX** baseline design verified → P200
- Highest technological risk for magnet eliminated → **MACQU**
- **Booster** understanding well under way
- First physics measurements with CB100 in CERN MORPURGO magnet



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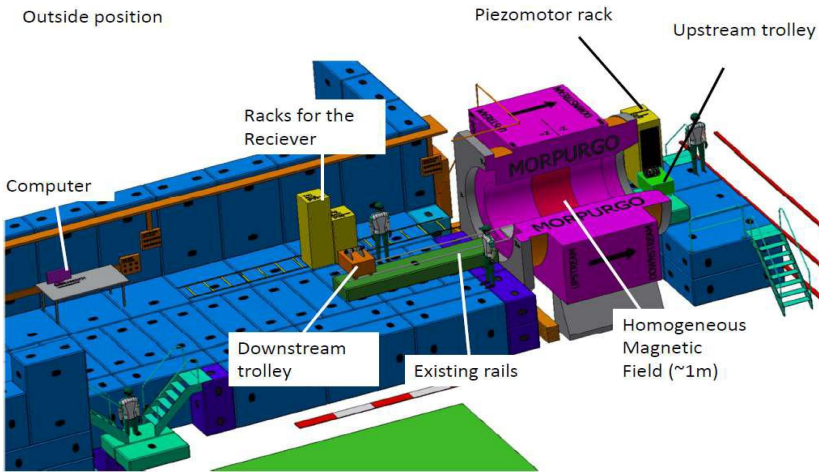
Backup



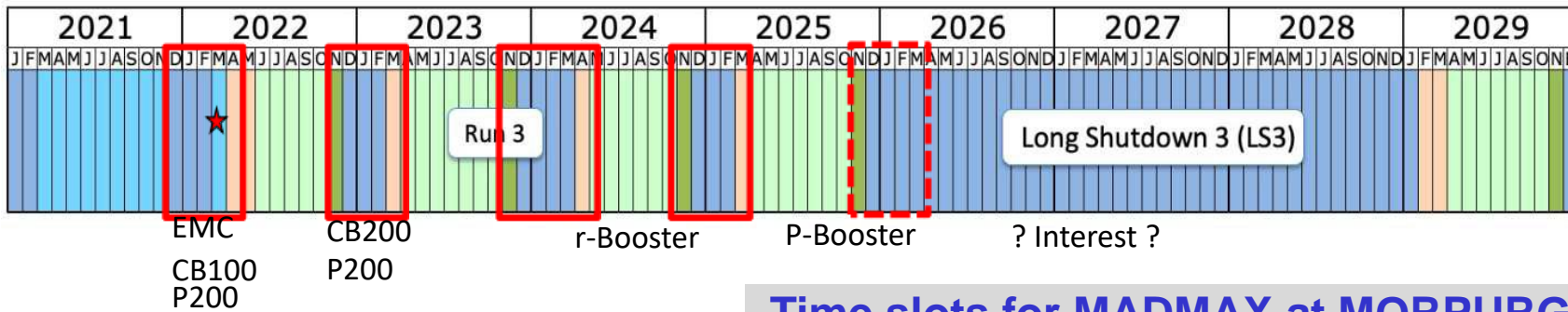
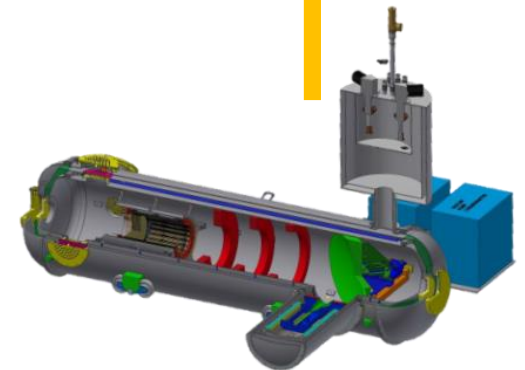
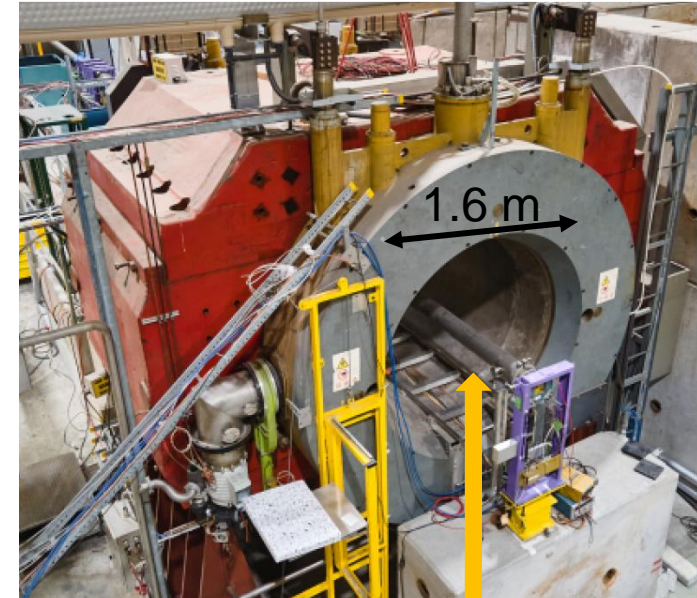
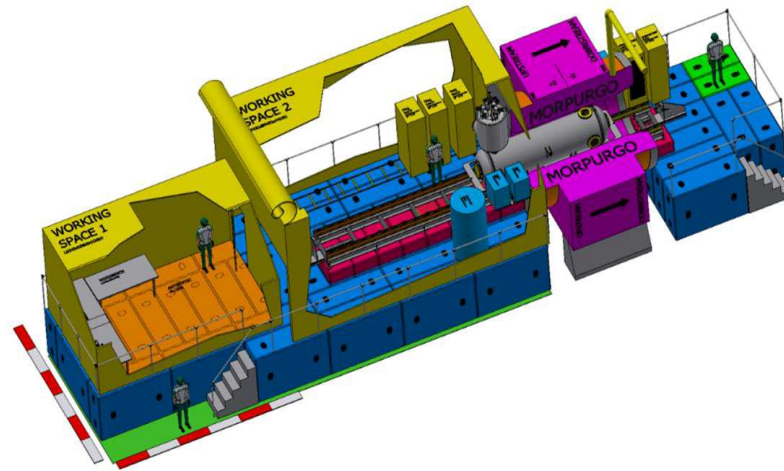
Morpurgo Magnet at CERN



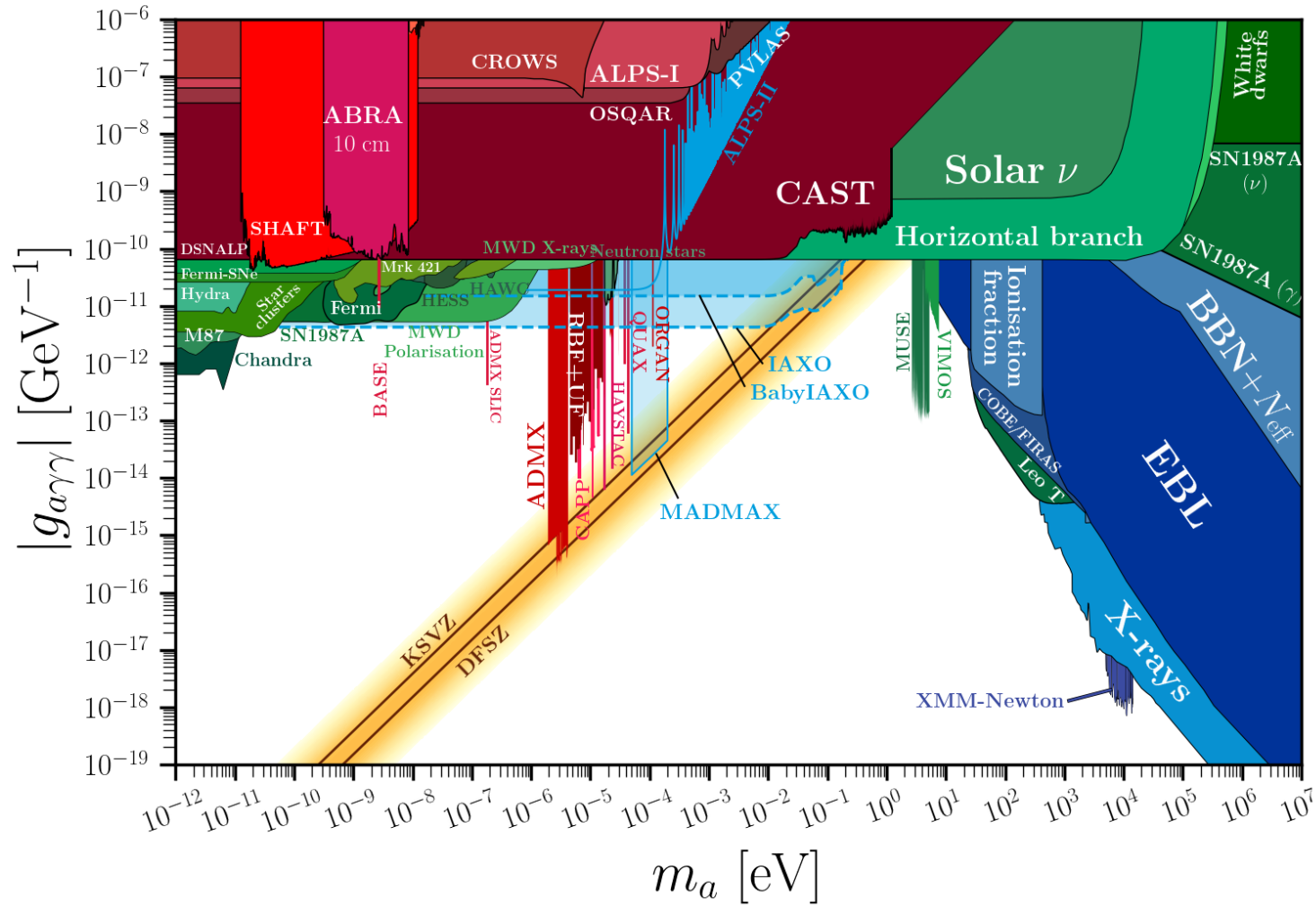
2022+2023 warm tests



2023/24+2024/25 cold tests



Time slots for MADMAX at MORPURGO





Name	acronym	disc diameter [mm]	Nr. of discs	Availability
Closed booster 100	CB100	100	3	2021
Closed booster 200	CB200	200	≥ 3	2022
Project 200	P200	200	1	2021
Reduced booster	R-booster	300	≥ 3	2023
Prototype booster	P-booster	300	20	2024