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 Axion

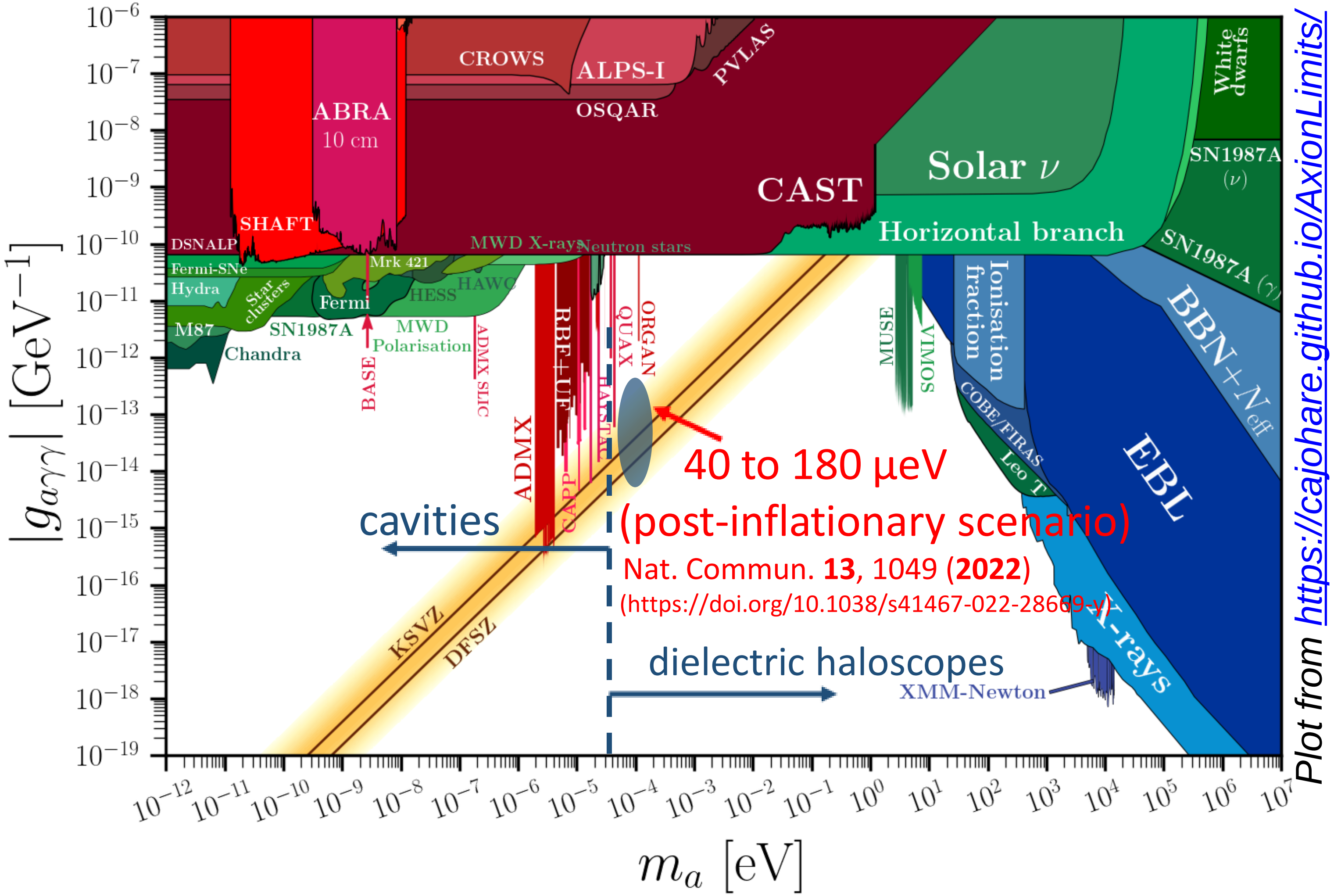
The Axion:

- Pseudo Nambu-Goldstone boson
- Small mass and weak couplings
- Elegant solution of the strong CP problem
- Primakoff/Sikivie effect:

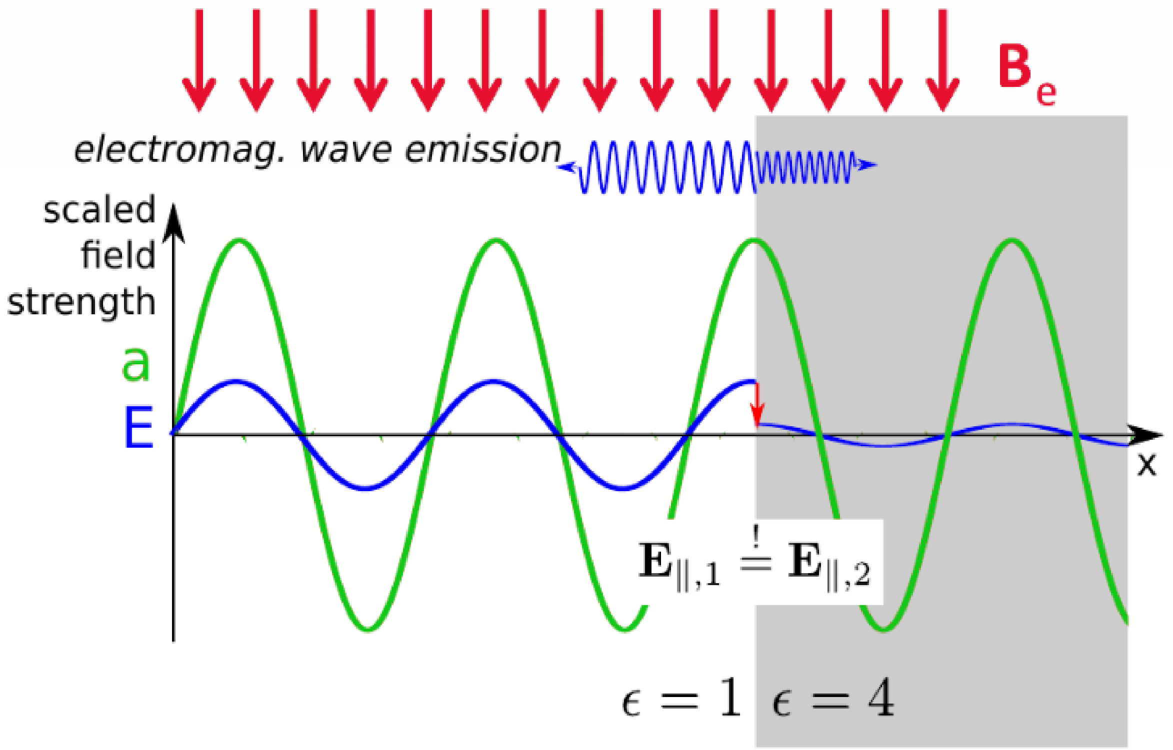
  Photon-Axion conversion in strong EM fields
- Axion can explain the observed DM density

Axion-Maxwell equation under external B-field:

$$\nabla \times H - \dot{D} = J_f + g_{a\gamma} B_0 \dot{a}$$



Dielectric Haloscope



The cosmological axion field **a(t)** inside an external magnetic field $\mathbf{B_e}$ sources a tiny axion induced electric field $\boldsymbol{E_\alpha}$

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

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

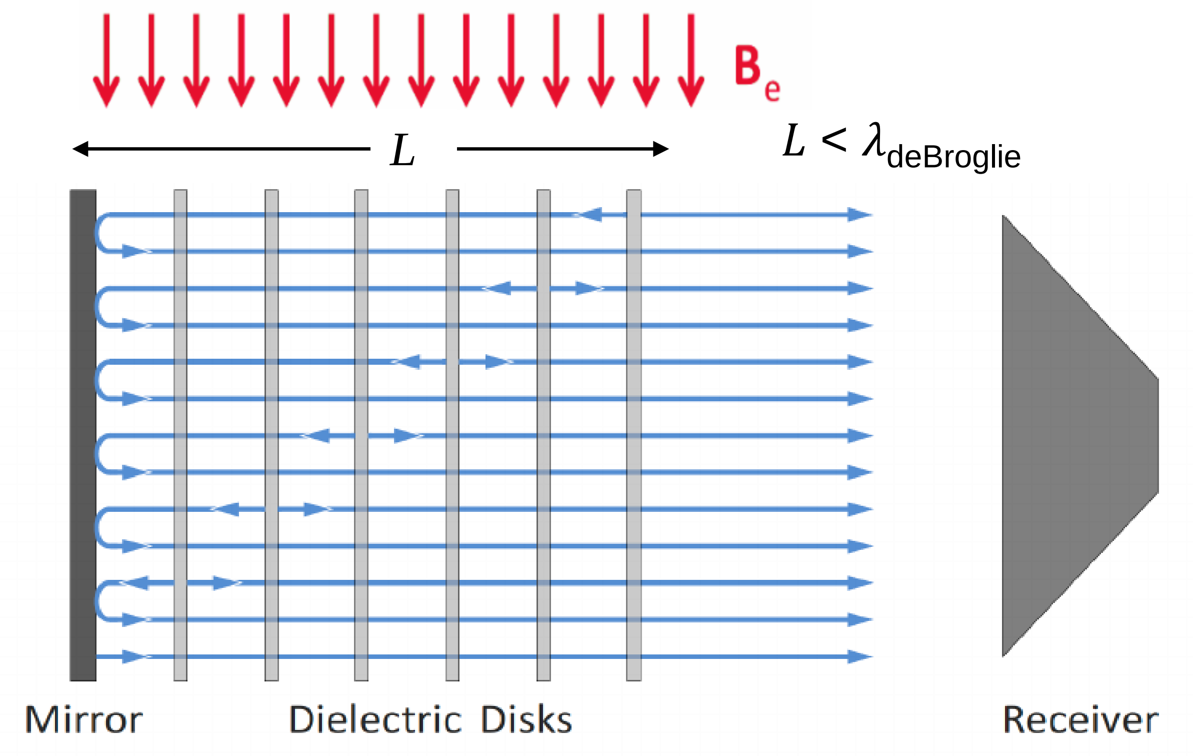
$\mathbf{E}_{||}$ must be continuous at the **boundaries**

$$E_\alpha = -\frac{g_{\alpha\gamma}\mathrm{B}_e}{\varepsilon}\alpha \qquad \alpha = \alpha_0 \cos(m_\alpha t)$$

Power emitted from a single surface:

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

Dielectric Haloscope



- 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

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

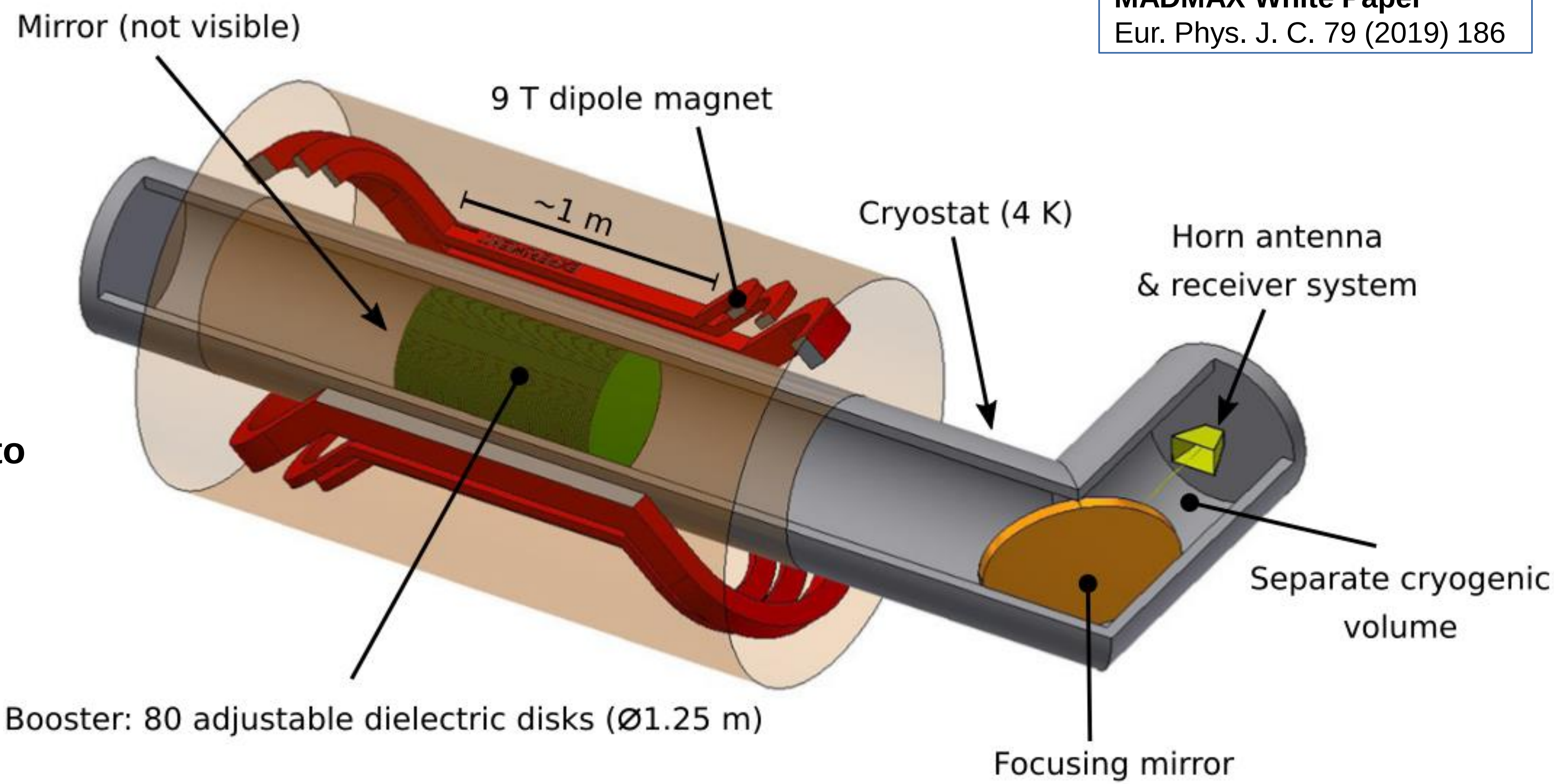
Simulations indicate:
$|\beta^2| > 10^4$ achievable with 80 disks
with dielectric constant ε~ 24 ($LaAlO_3$)
β^2 is affected by BC's inaccuracies of the discs: disc mis-positioning, tilting, thickness variations

The MADMAX Experiment

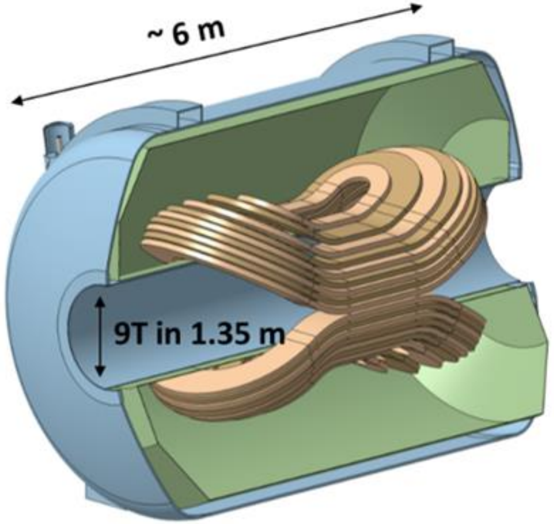
MADMAX White Paper
Eur. Phys. J. C. 79 (2019) 186

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

Start with prototypes to validate concepts



MADMAX Magnet Update



Development in innovation partnership

BILFINGER NOELL GMBH

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

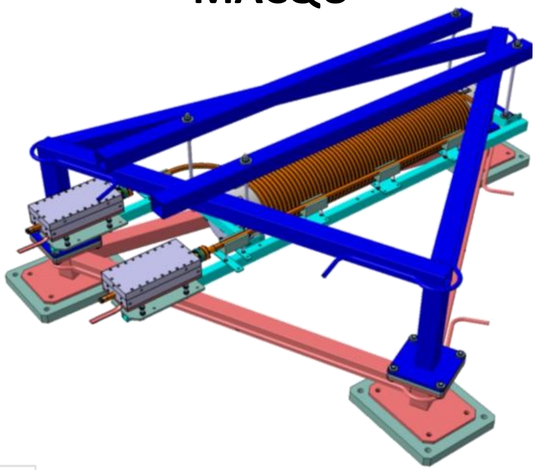
→ Main Challenges :

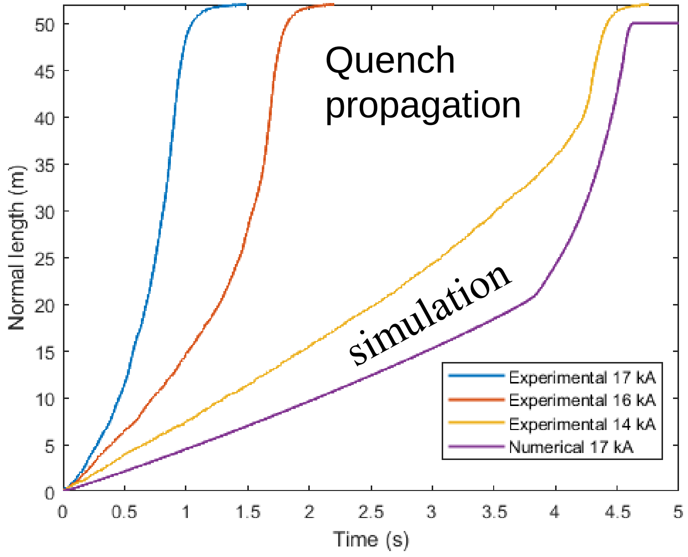
- Reliable quench protection
- **Feasibility of conductor production (CICC)**
- Quench propagation velocity were measured in a dedicated setup: **MA**dmax **C**oil for **Q**uench **U**nderstanding →

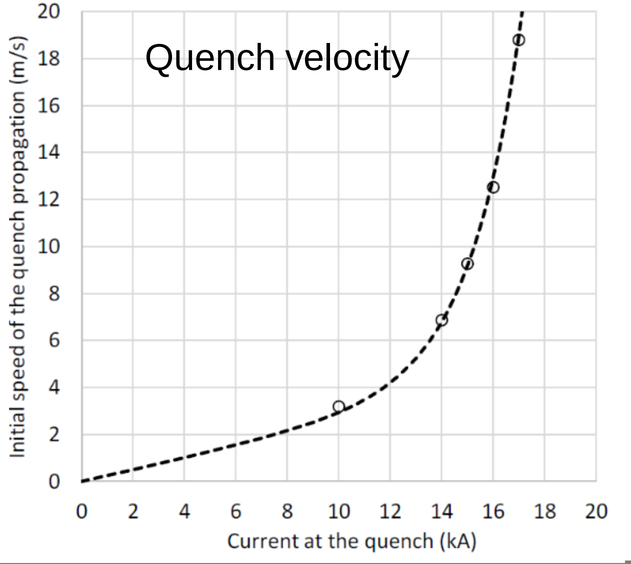
→ Main project risk mitigated:

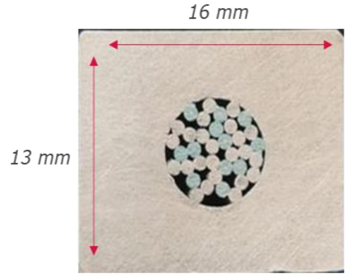
Quench propagation according to requirements for safe operation

MACQU







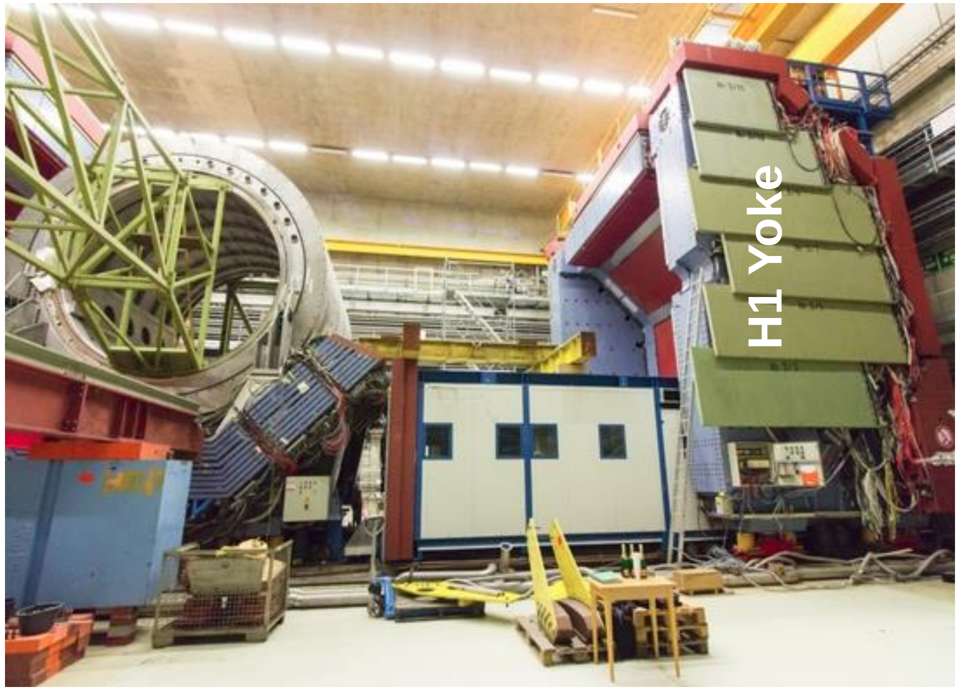


MACQU profile with cable inside

Novel conductor:
Cable **I**n **C**opper **C**onduit

Designated Experimental Site @ DESY

- 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

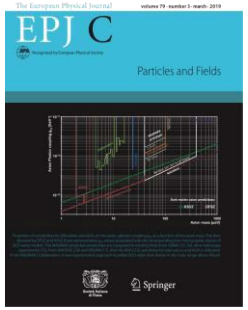
2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | >= 2028

Design Phase

Prototyping Phase

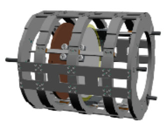
Construction Phase

Foundation of MADMAX Collaboration

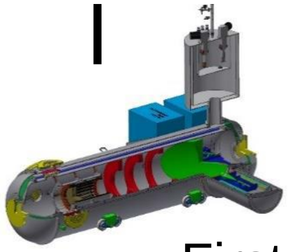


First endorsement by DESY PRC

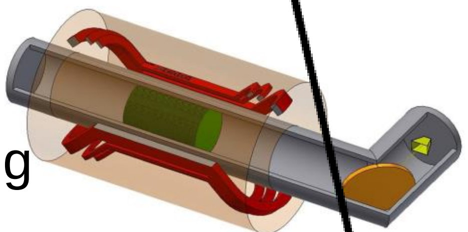
First ALP measure-ment at CERN



Prototype commissioning to start in 2023



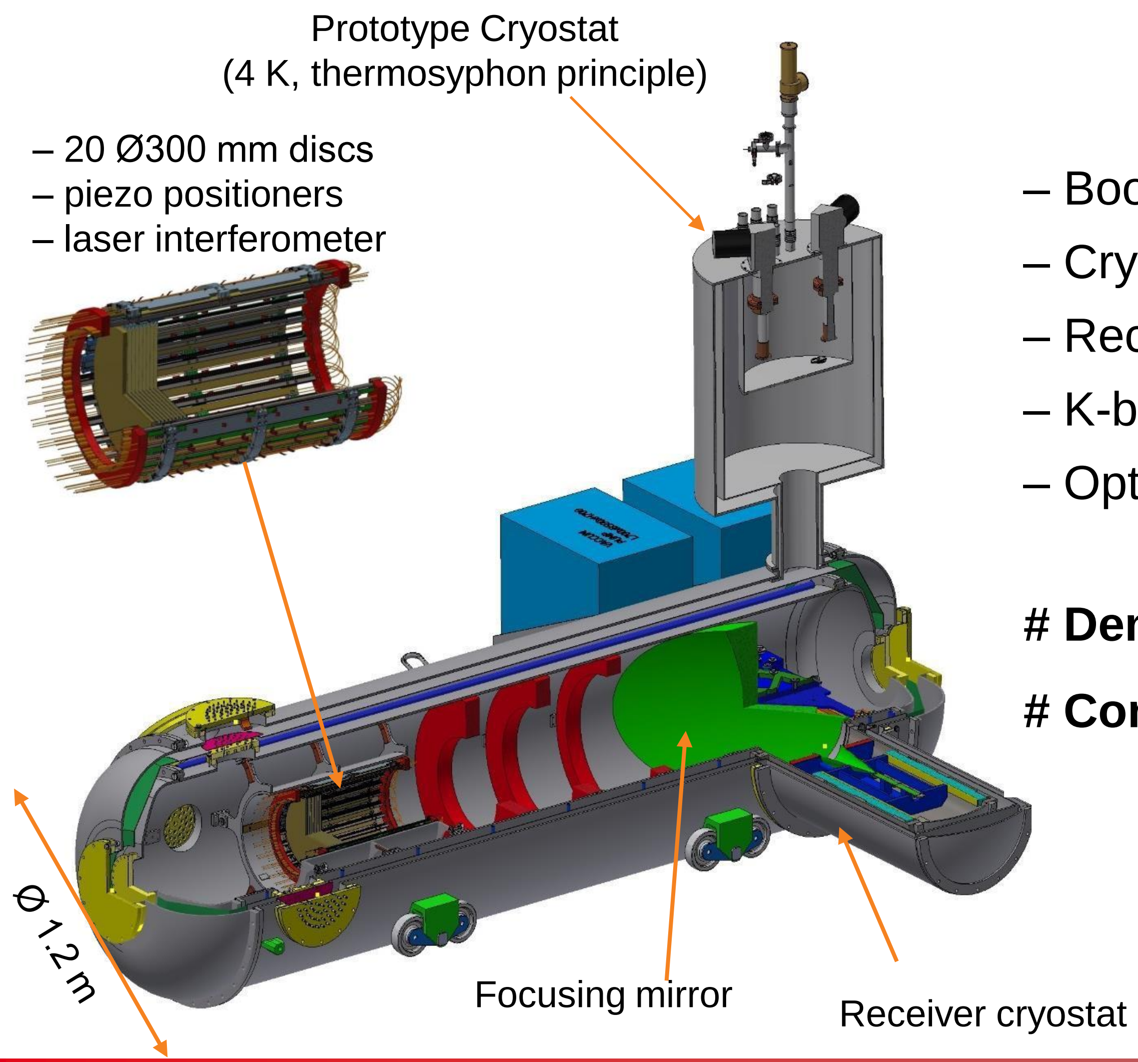
First physics data taking at cold @ CERN



Full-size MADMAX magnet commissioning

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

The MADMAX Prototype



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

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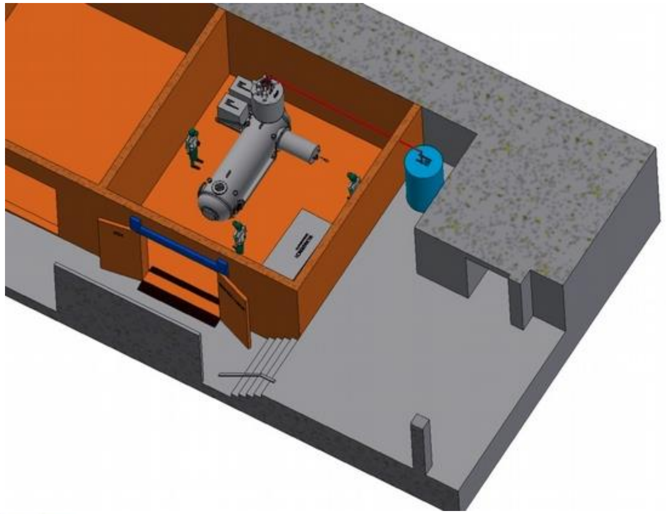
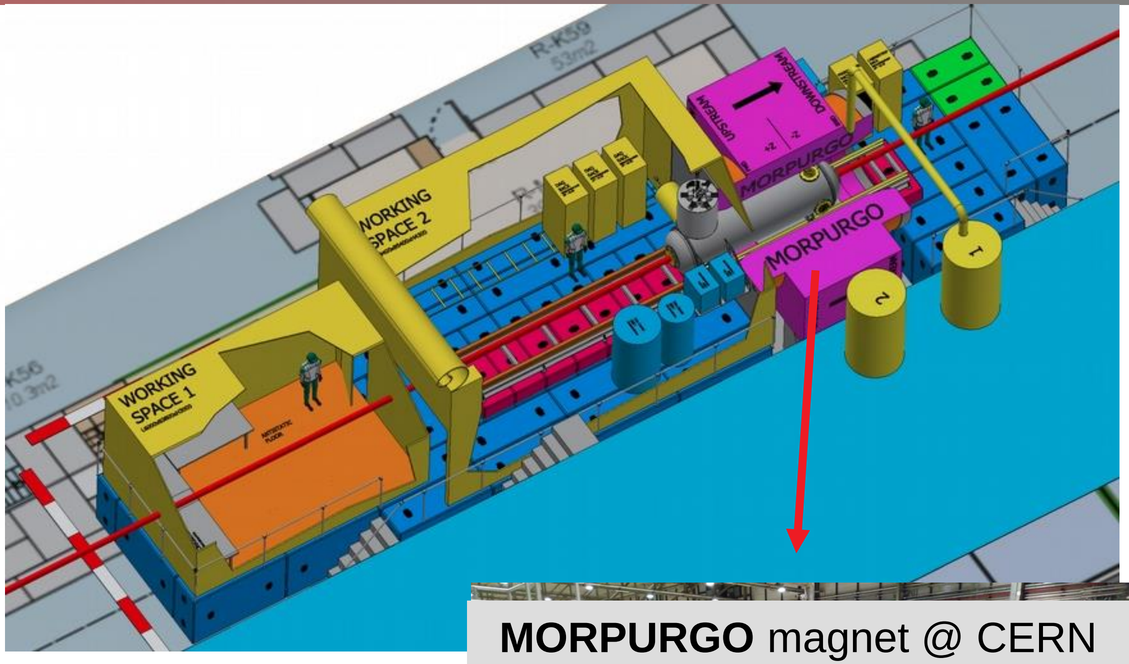
The MADMAX Prototype





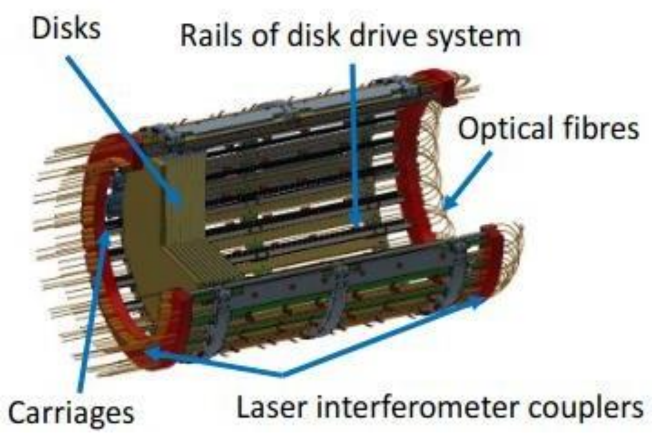
Shielded RF lab in Hamburg

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

MORPURGO magnet @ CERN

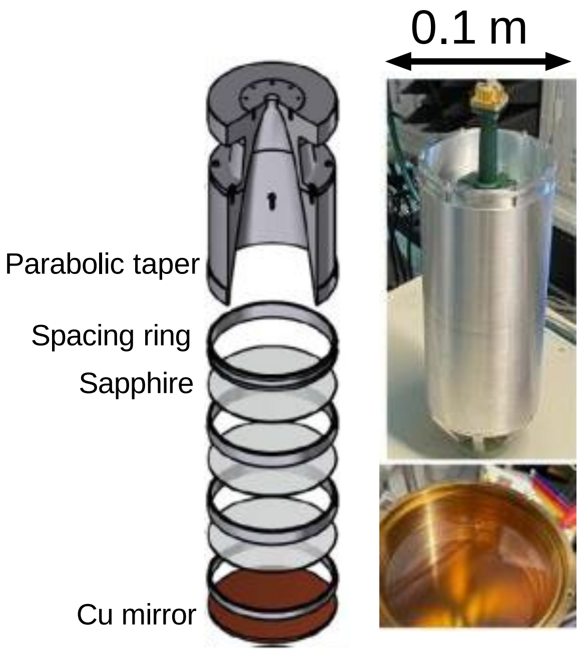

Prototyping strategy: MADMAX test setups



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 $LaAlO_3$ 3'' wafers

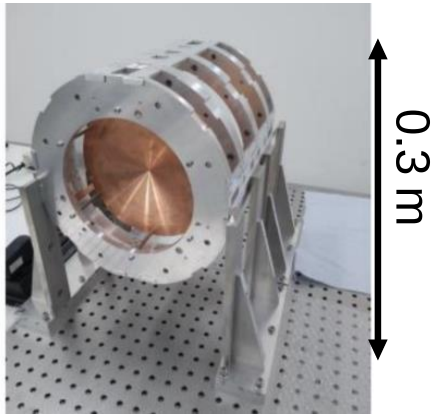


CB100

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

CB200

Closed booster
Cu mirror
≥3 Ø200 mm discs

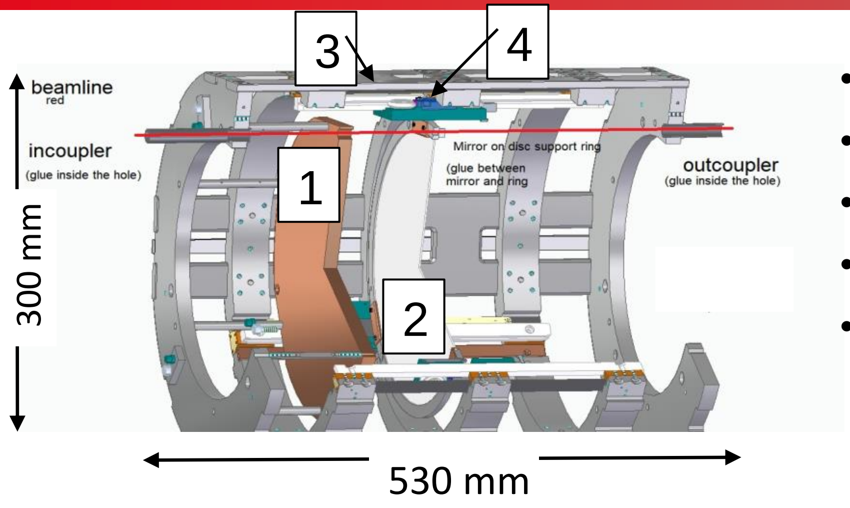


P200

Open booster
Cu mirror
1 Ø200 mm disc

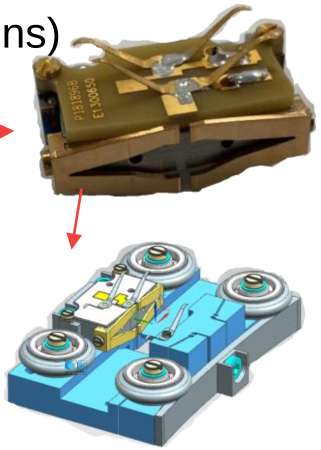
Test setups to assess the RF response to small changes (or inaccuracies) in the hardware potentially effecting the boost factor

Mechanics Prototype: Project 200

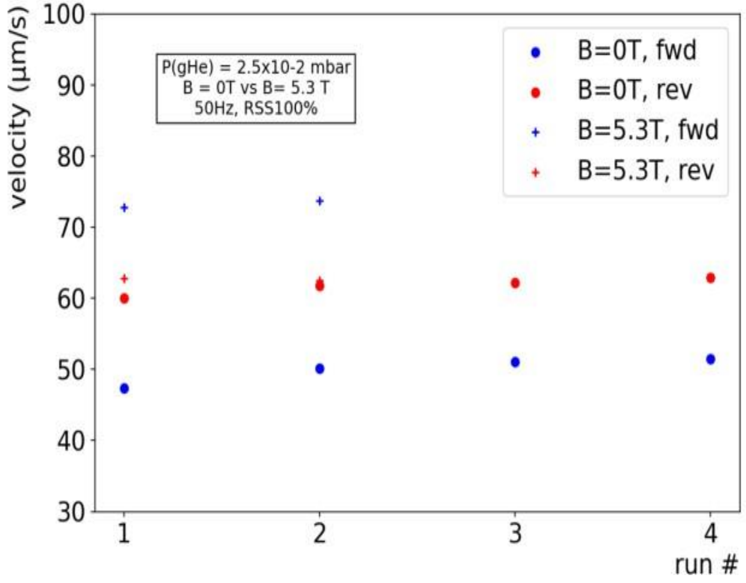


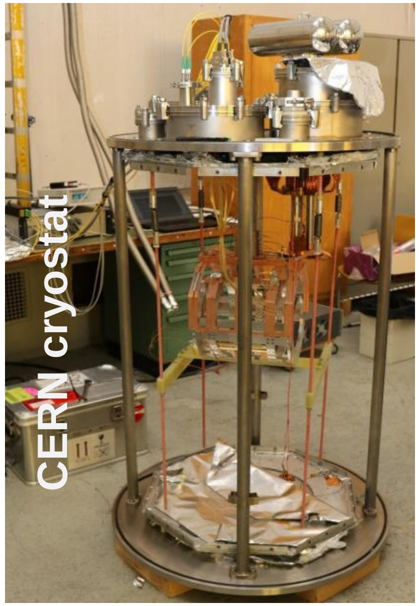
- **Piezo-motor operated inside the 5.3 T ALPS II magnet @ 5 K**
- Project200 **successfully tested at CERN's cryolab and in 1.6 T Morpurgo magnet**
- Attocube laser interferometer works at cryogenic temperatures
- P200 backbone structure **keeps optics alignment during cool-down**
- A disk can be moved 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 μm/s in cold
– position accuracy < 2 μm in cold

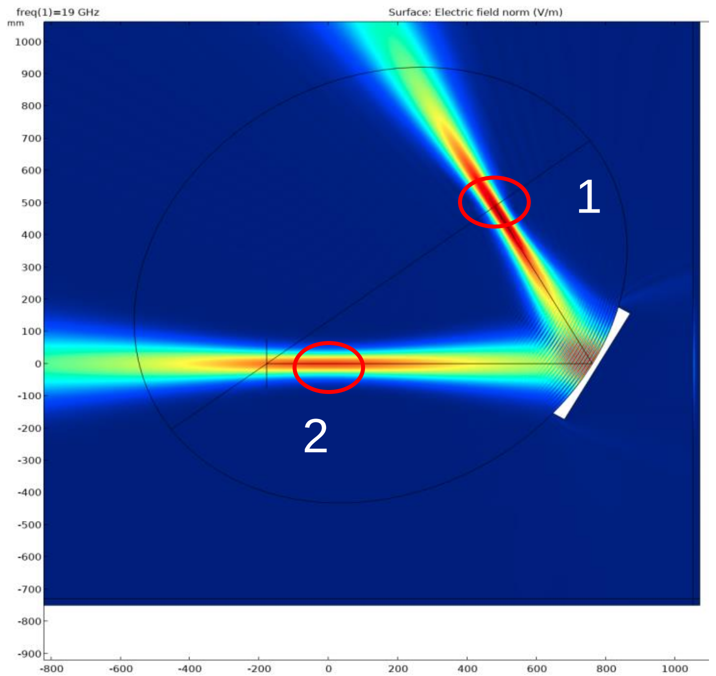




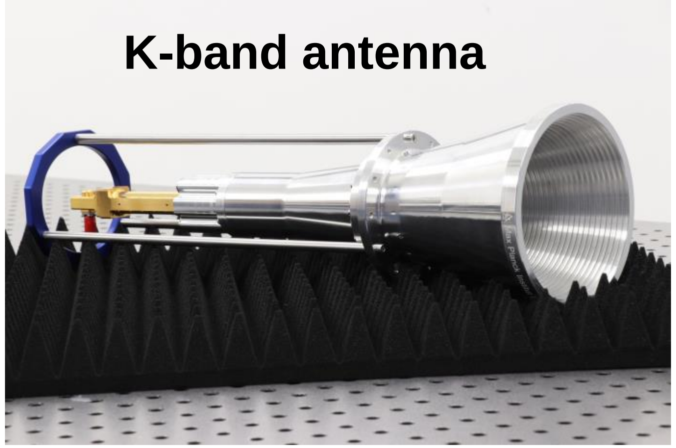
Mechanical feasibility R&D Milestones achieved

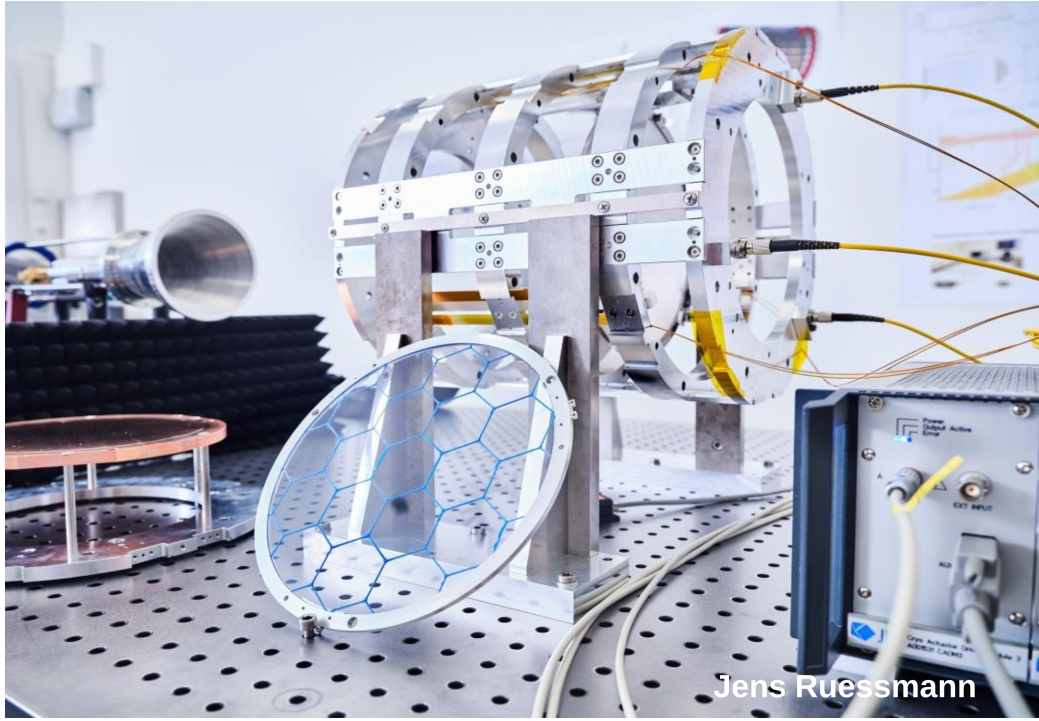
Project200 RF studies @ SHELL

COMSOL 2D simulation



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





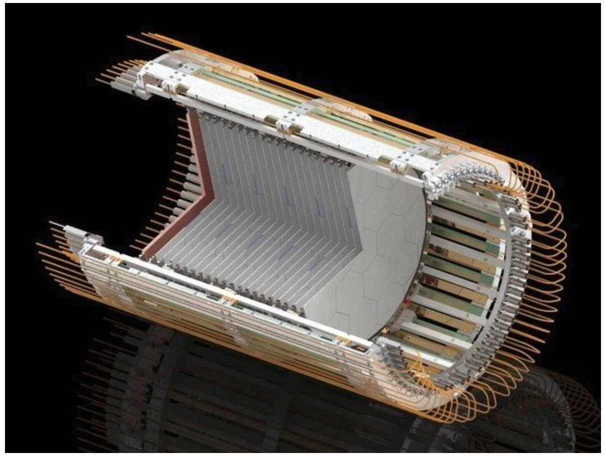
- Test Prototype antenna
- Reflectivity measurements of the (P200 – ellipsoid mirror- antenna) system for losses estimation
- 3D CST MWS and COMSOL simulations
- Measurements and simulations of tiled discs

Understanding the RF behavior of boosters

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

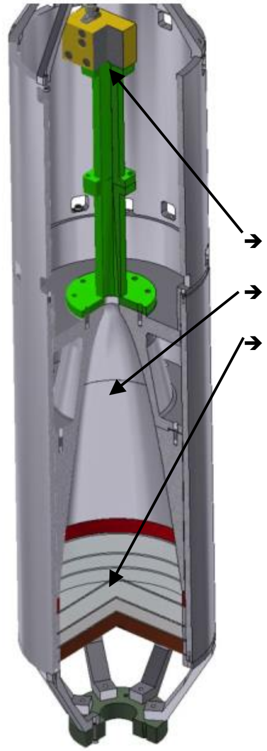
* See Poster "Axion Haloscope Calibration from Reciprocity" by J. Egge

Closed Booster simulations & measurements

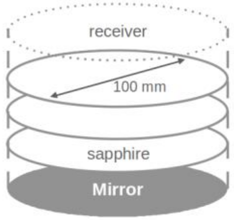
- A small & simple dielectric haloscope
- “Closed”: conducting boundary
  (understand and mitigate transverse losses)
- Can be operated at cryogenic temperatures
- **Good qualitative match between simulation & measurement**

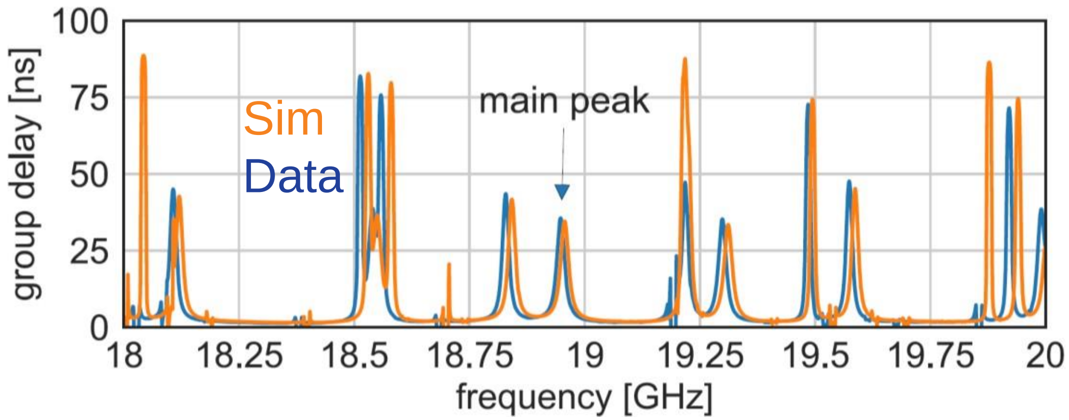
 # First Hidden Photon search @ MPP

 # First ALP search in MORPURGO magnet @ CERN

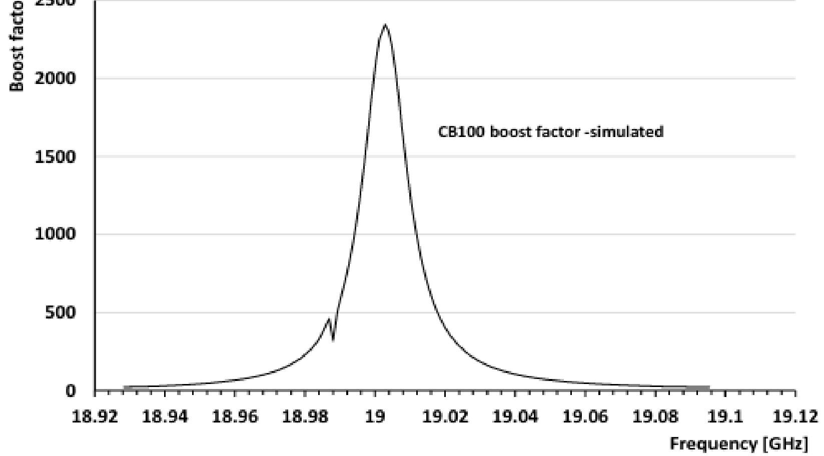


Receiver
Parabolic taper
3x Ø100 mm sapphire disks





Simulated boost factor of CB100



CB100 temperature/Reflectivity measurements

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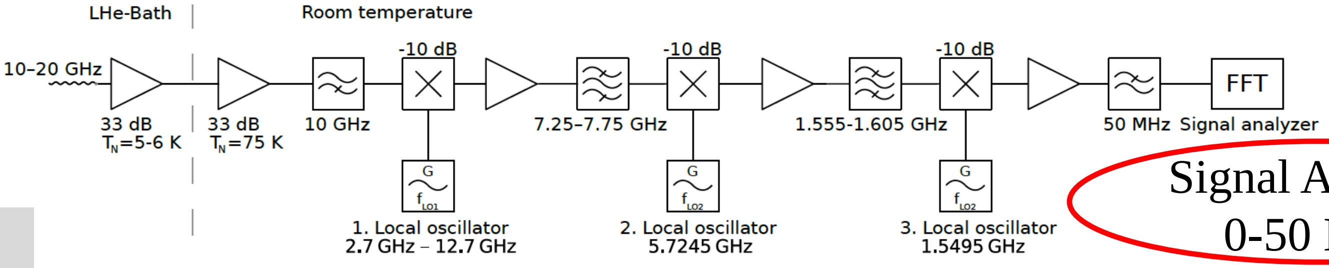
Pre-Amplifier
10-20 GHz

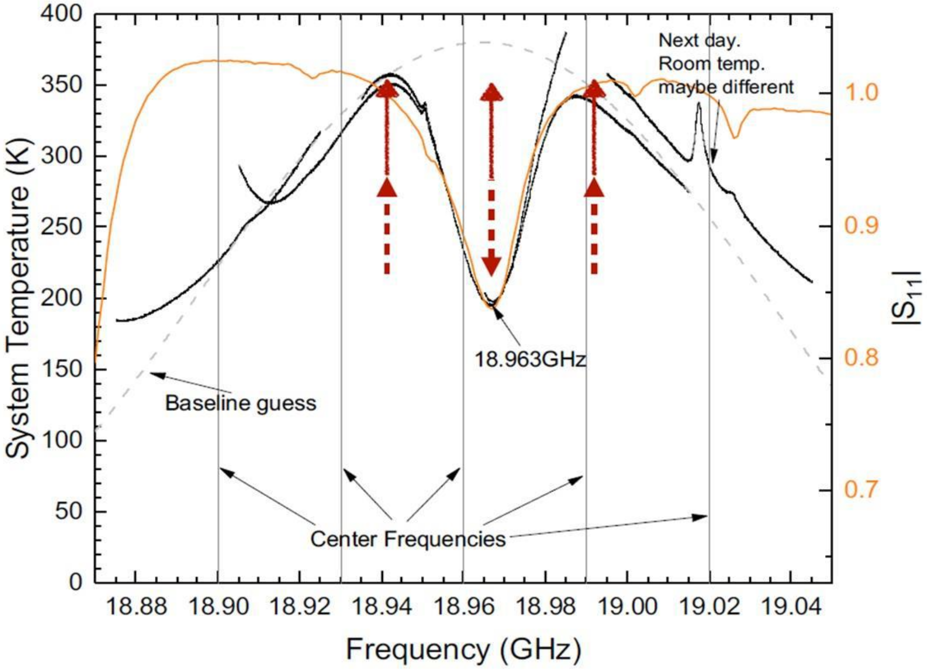
Detection system



Signal Analyzer
0-50 MHz

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

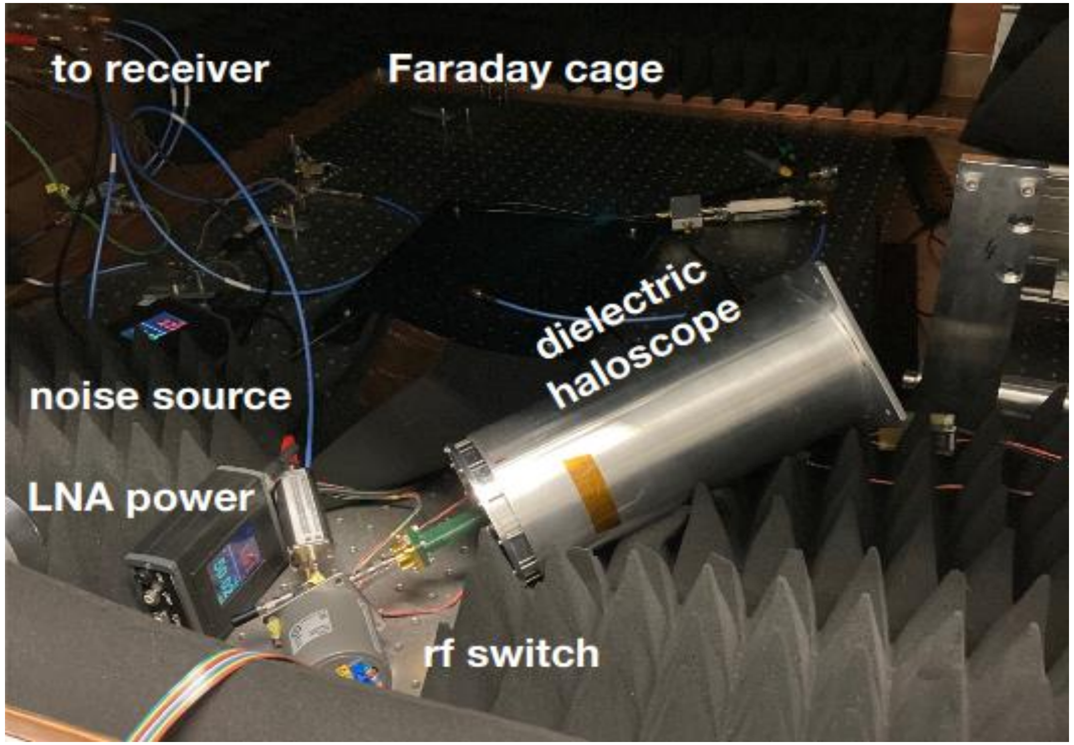
- T_{sys} behavior at 5 RT measurements
- T_{sys} calibration with a noise source
- Dip in T_{sys} corresponds to the dip of the Reflectivity measurement
- Infer **boost factor** using model with parameters inferred from thermal and RF measurements



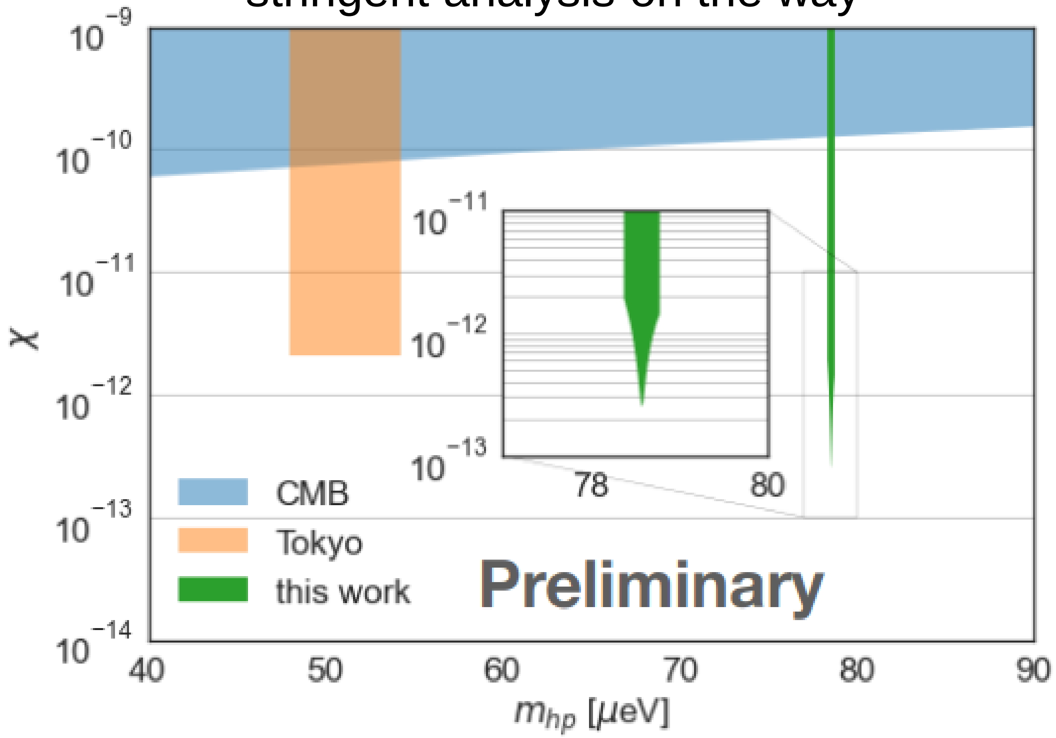
Hidden photon search

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

- 32 days of data taking
- Noise temperature ~ 200K
- No excess power observed

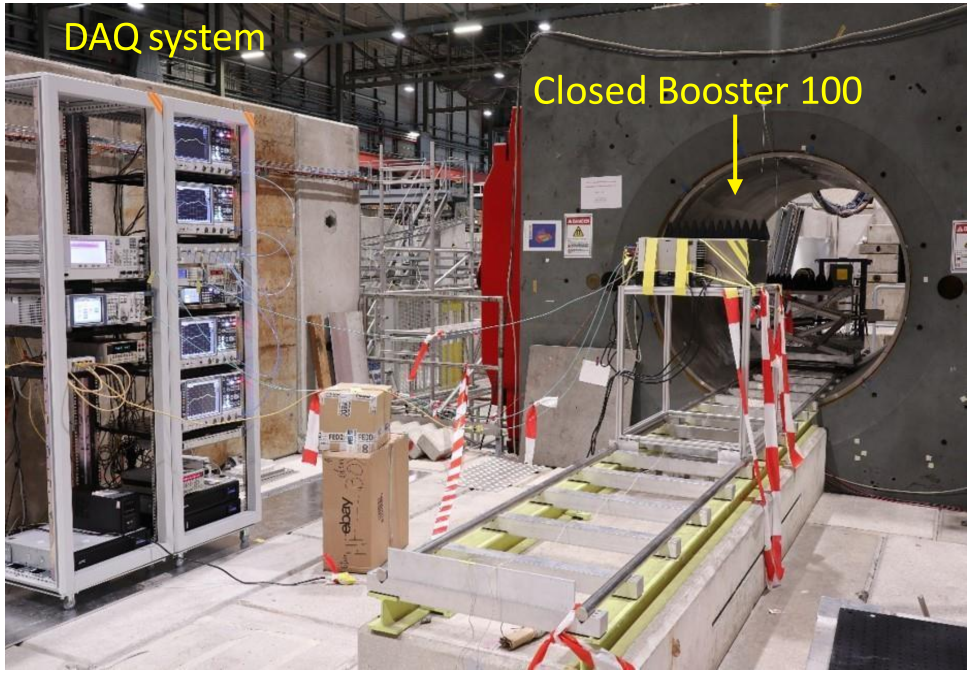


SENSITIVITY:
stringent analysis on the way



First ALP search

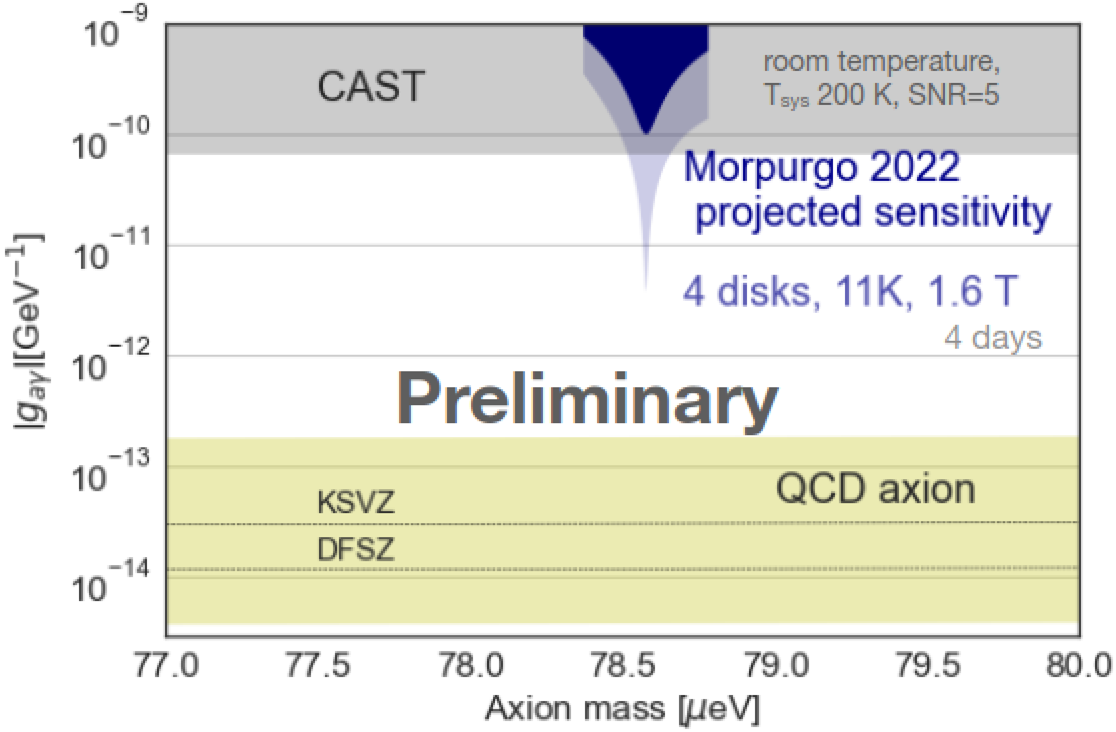
ALP search in CERN 's Morpurgo magnet (1.6 T) in Mar/Apr 2022



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

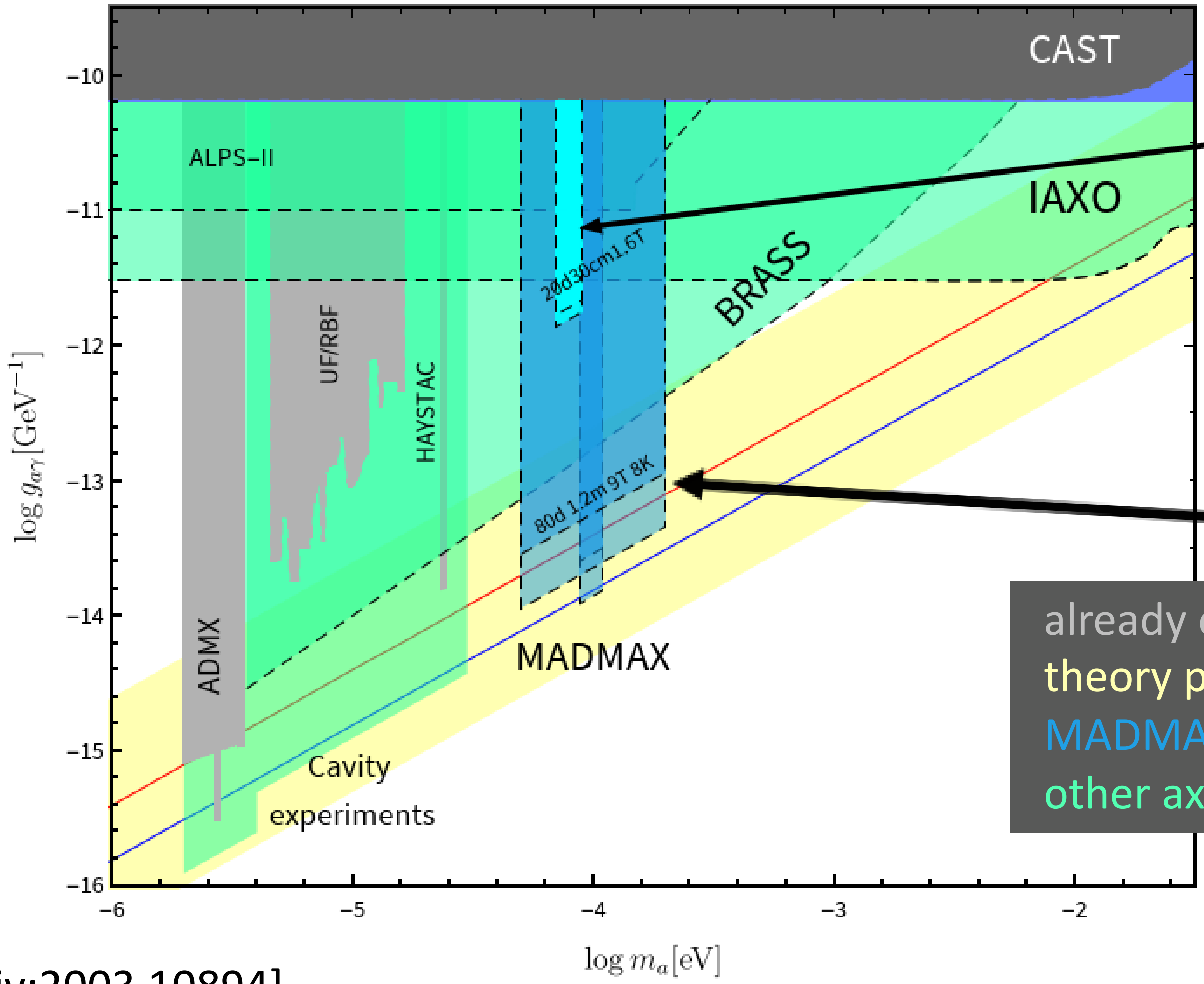
Planning upgrade with a T < 10 K system

SENSITIVITY:
stringent analysis on the way



MADMAX Sensitivity

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



MADMAX Prototype:
$N_{disk} = 20$
$A_{disk} = 0.07\ \mathrm{m}^2$
$B_{\parallel} = 1.6\ \mathrm{T}$
$T_{sys} = 8\ \mathrm{K}$

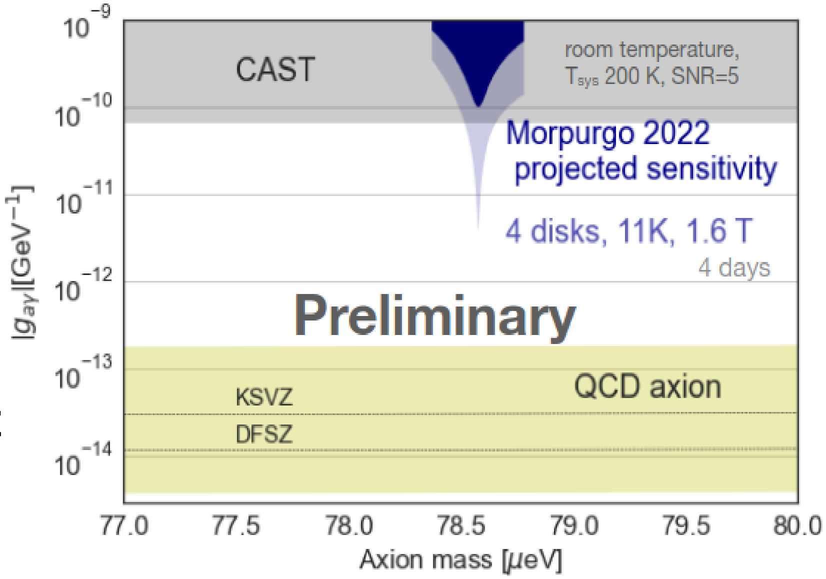
MADMAX:
$N_{disk} = 80$
$A_{disk} = 1.2\ \mathrm{m}^2$
$B_{\parallel} = 9\ \mathrm{T}$
$T_{sys} = 8\ \mathrm{K}$

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

[arXiv:2003.10894]

Summary & Conclusion

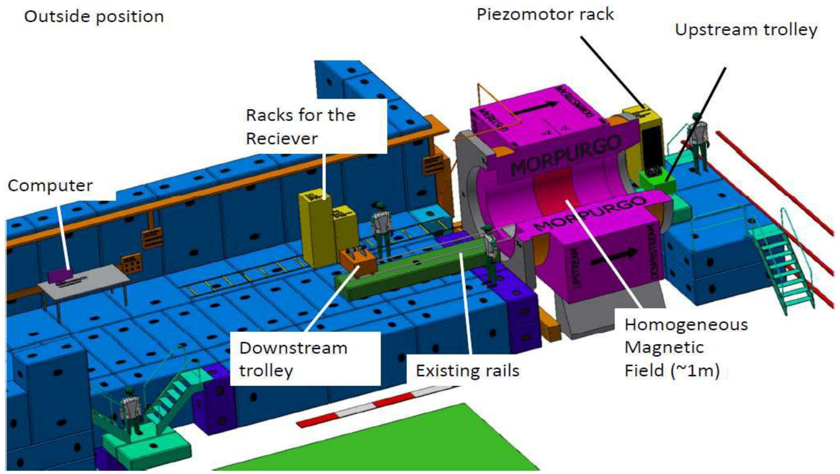
- **MADMAX prototype cryostat to be delivered 2023 at UHH**
- **Major R&D milestones reached**
- **Feasibility of piezo actuators at 5 K & 5.3 T**
- **Mechanical concept of MADMAX baseline design verified→ P200**
- **Highest technological risk for magnet eliminated → MACQU**
- **Booster understanding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



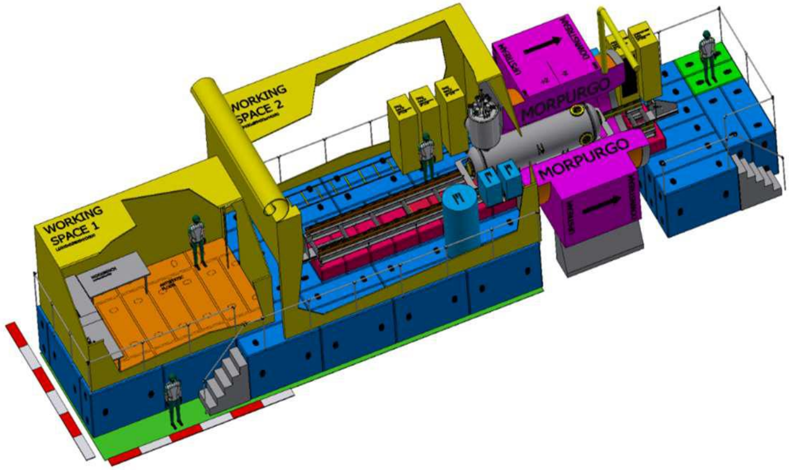
Backup

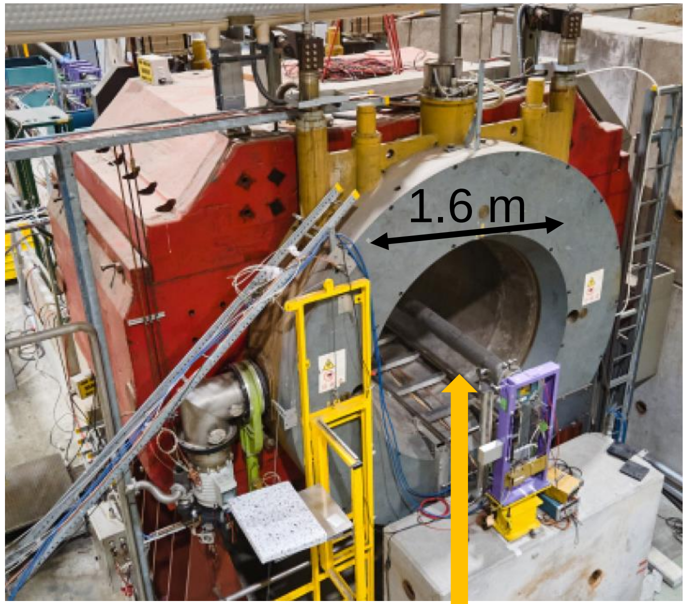
Morpurgo Magnet at CERN

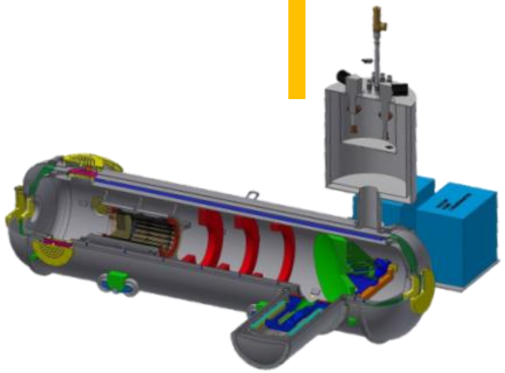
2022+2023 warm tests



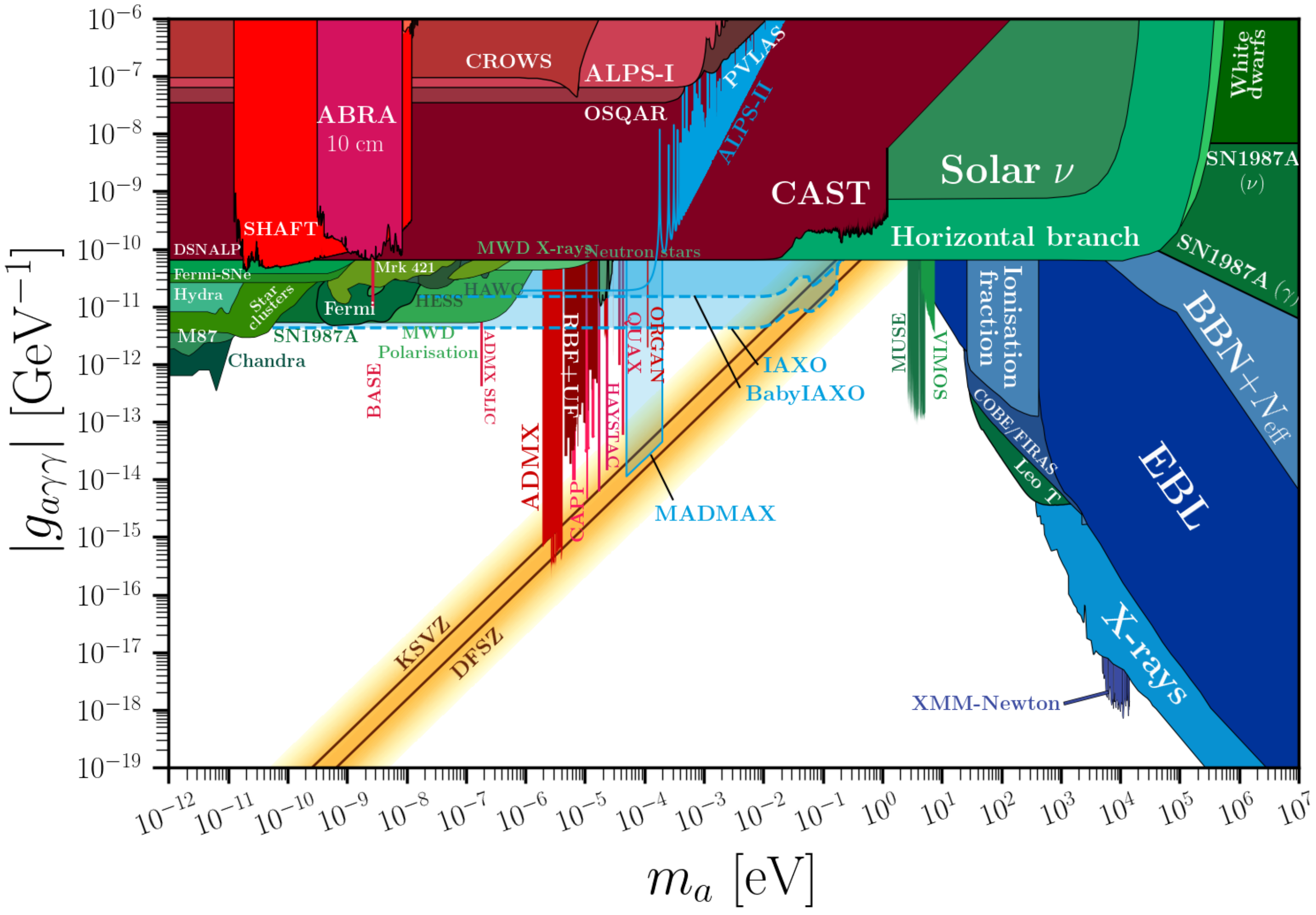
2023/24+2024/25 cold tests







Time slots for MADMAX at MORPURGO


$|g_{a\gamma\gamma}|$ [GeV−1]
m_a [eV]
CROWS
ALPS-I
PVLAS
ALPS-II
OSQAR
ABRA
10 cm
SHAFT
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
DSNALP
MWD X-rays
Neutron stars
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
HAWC
M87
SN1987A
MWD Polarisation
Chandra
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
IAXO
BabyIAXO
MADMAX
MUSE
VIMOS
Ionisation fraction
COBE/FIRAS
Leo T
BBN+N_{eff}
EBL
X-rays
XMM-Newton
KSVZ
DFSZ

Prototyping strategy: MADMAX test setups

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**