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MADMAX

Towards a Dielectric Axion Haloscope

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Universität Hamburg

On behalf of the MADMAX Collaboration

12th December 2022

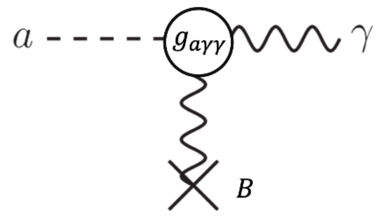
2nd DMLab Meeting

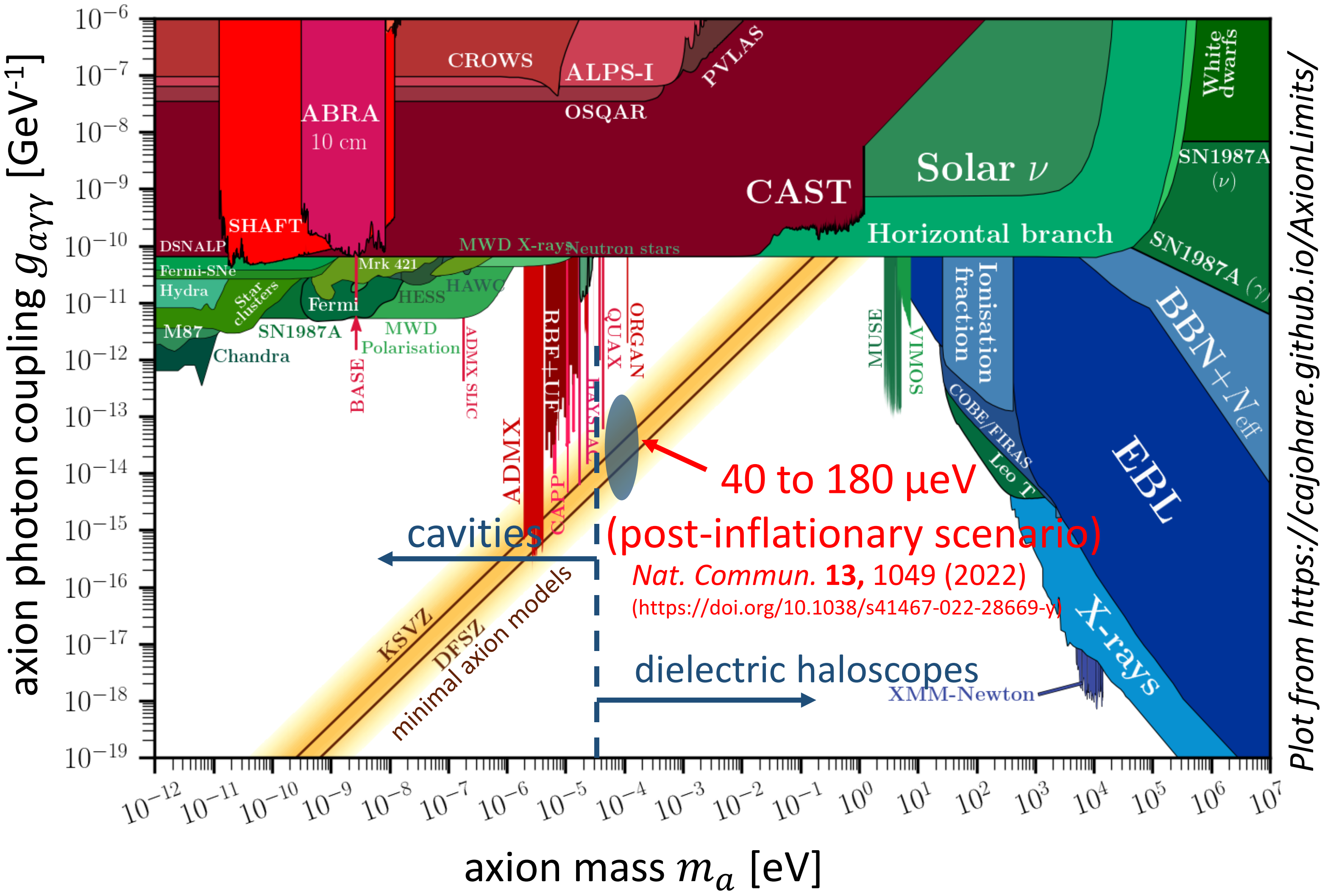
DESY Hamburg

Axion Parameter Space

The Axion:

- Pseudo Nambu-Goldstone boson
- Small mass and small couplings
- Connected to solution of the strong CP problem
- Primakoff/Sikivie effect: Photon-Axion conversion in strong EM fields
- **Axion** can explain (part of) **Cold Dark Matter**





Less minimal axion models can feature larger photon coupling and also be dark matter

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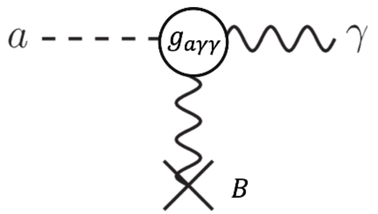
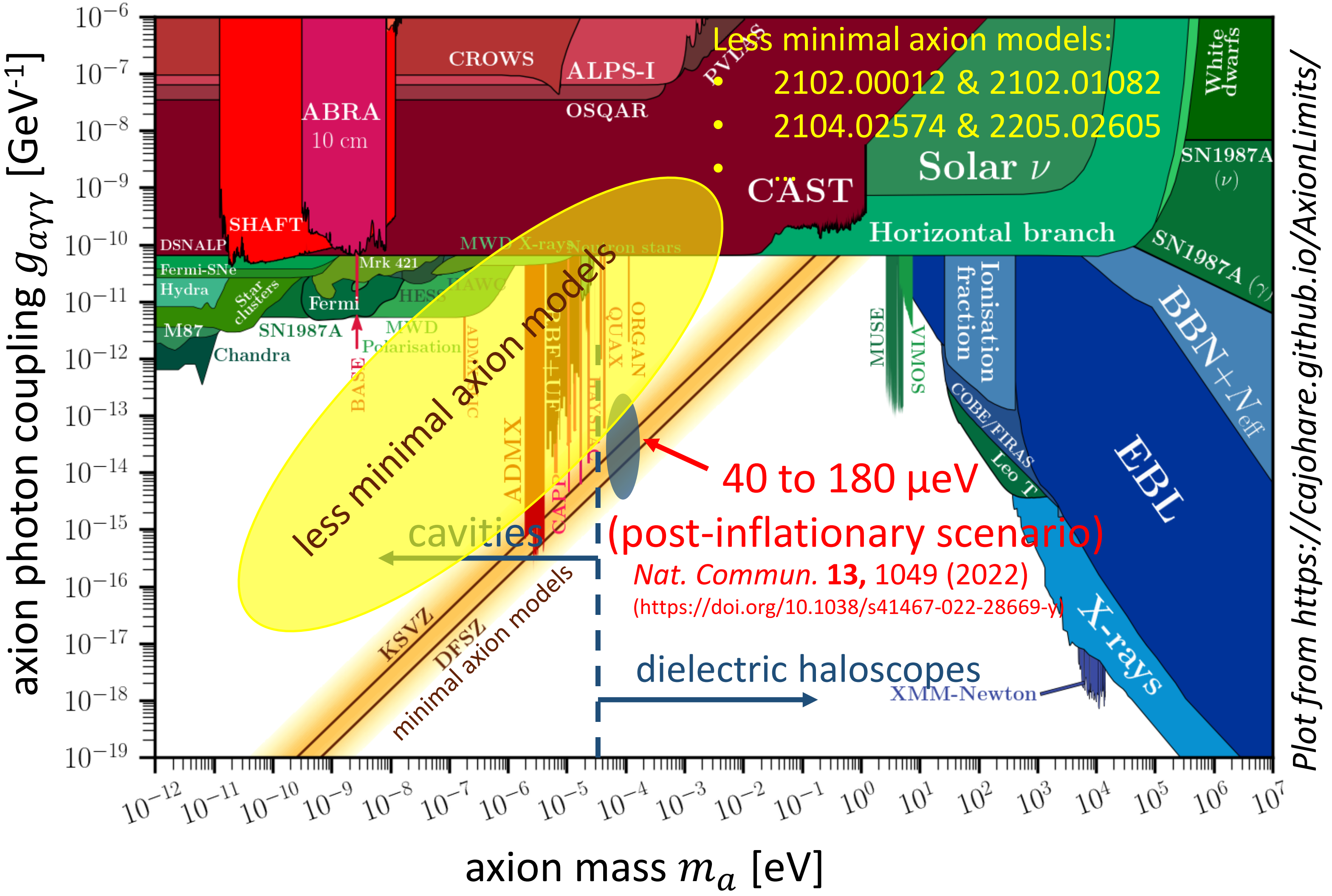
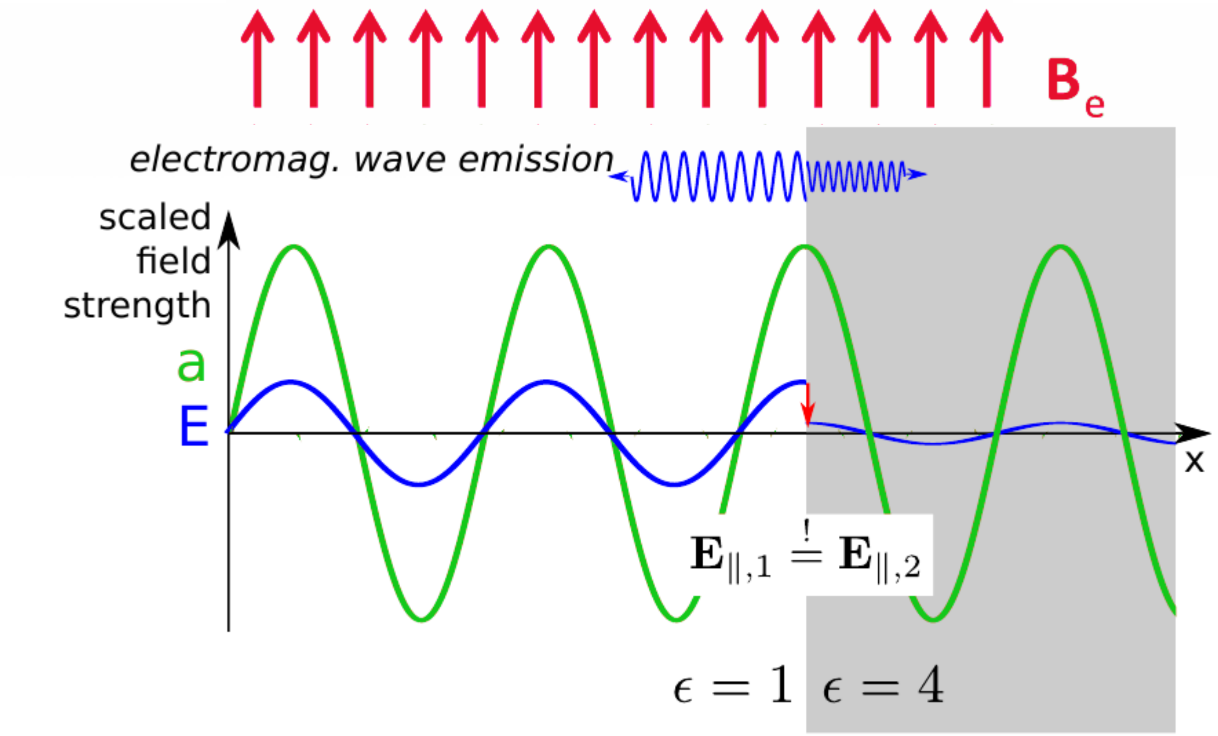




Dielectric Haloscope



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

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

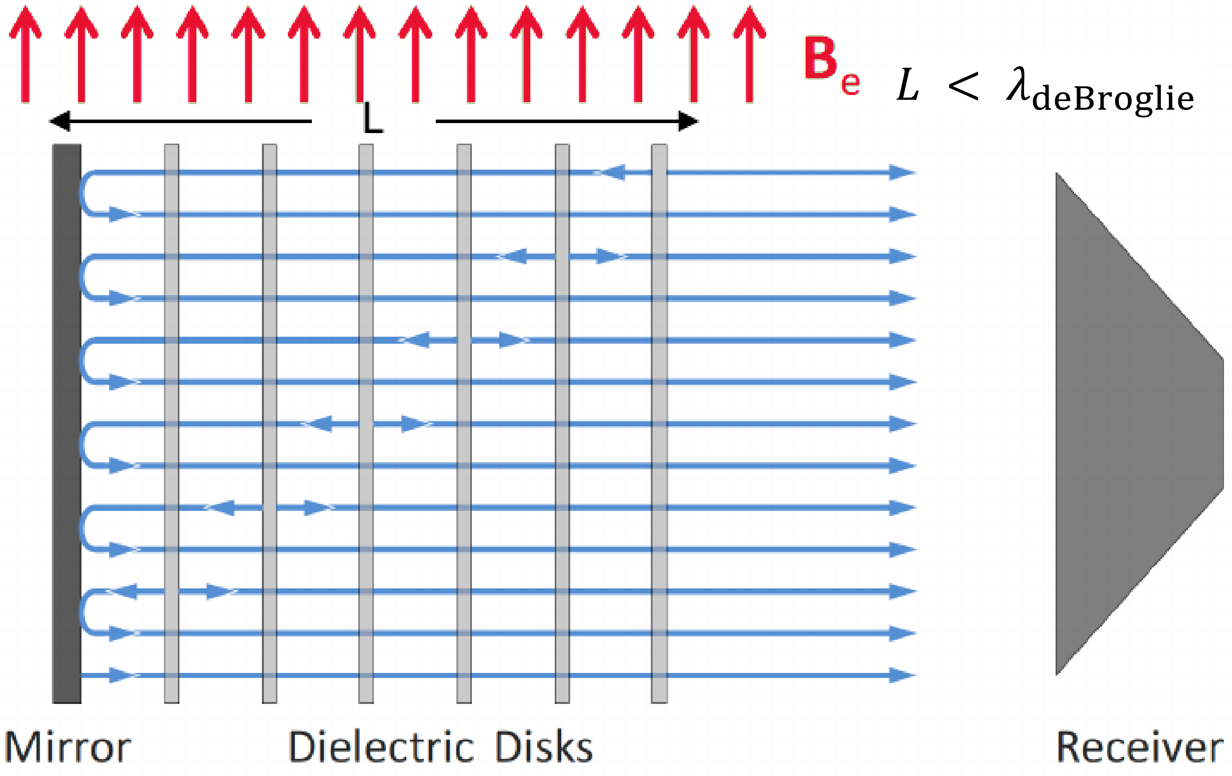
$\boldsymbol{E_a}$ is different in materials with different ε

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



$L < \lambda_{\text{deBroglie}}$

Boost emitted power through:

- coherent emission from multiple interfaces
- constructive interference effects

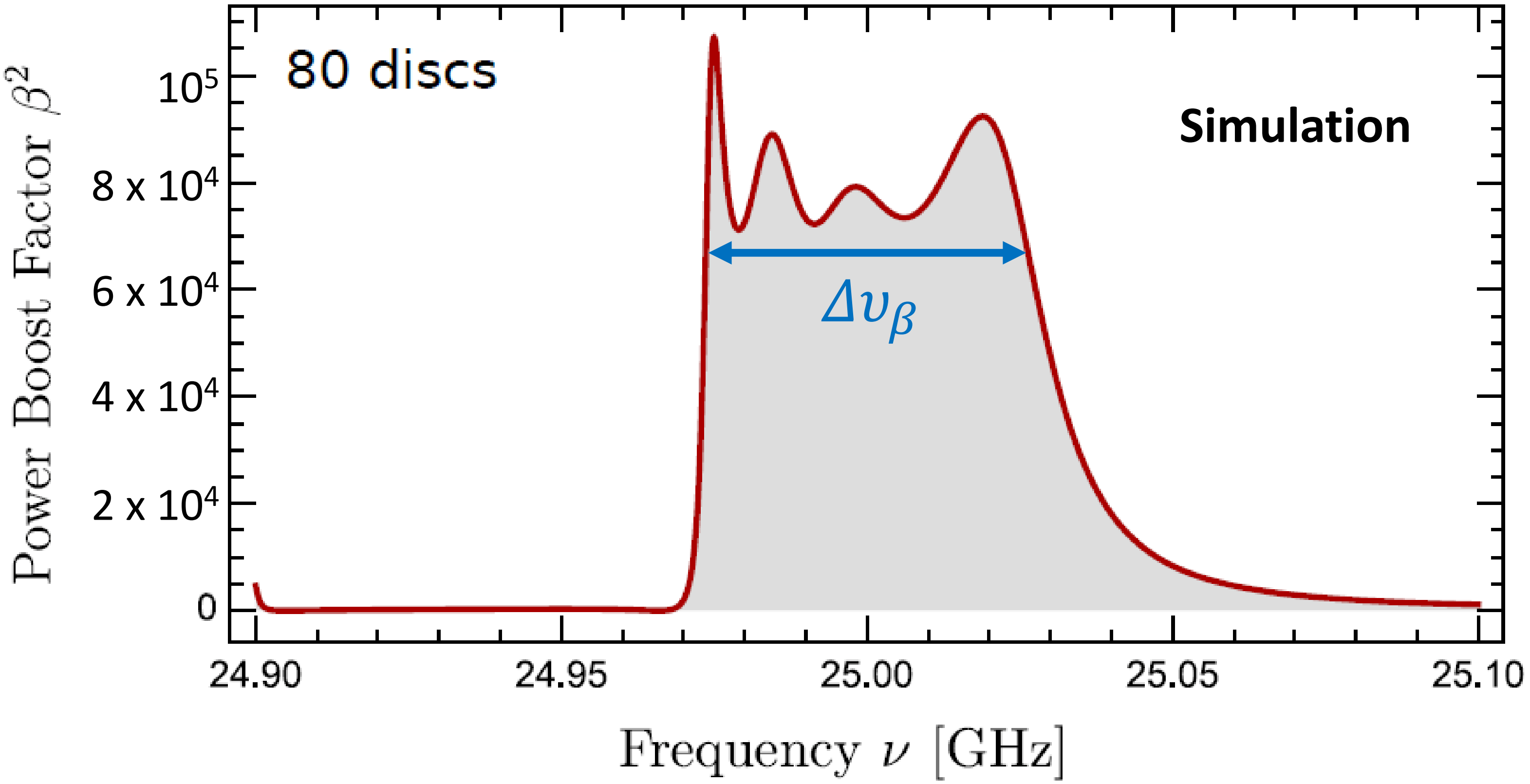
Power boost factor:

$$\beta^2 = {}^{P_{\text{total}}}/_{P_{\text{mirror}}}$$

Power emitted from all interfaces: $${}^{P}/_{A} = 2.2 \cdot 10^{-27} \frac{\text{W}}{\text{m}^2} C_{a\gamma} \left(\frac{B}{10\ \text{T}}\right)^2 |\beta^2|$$

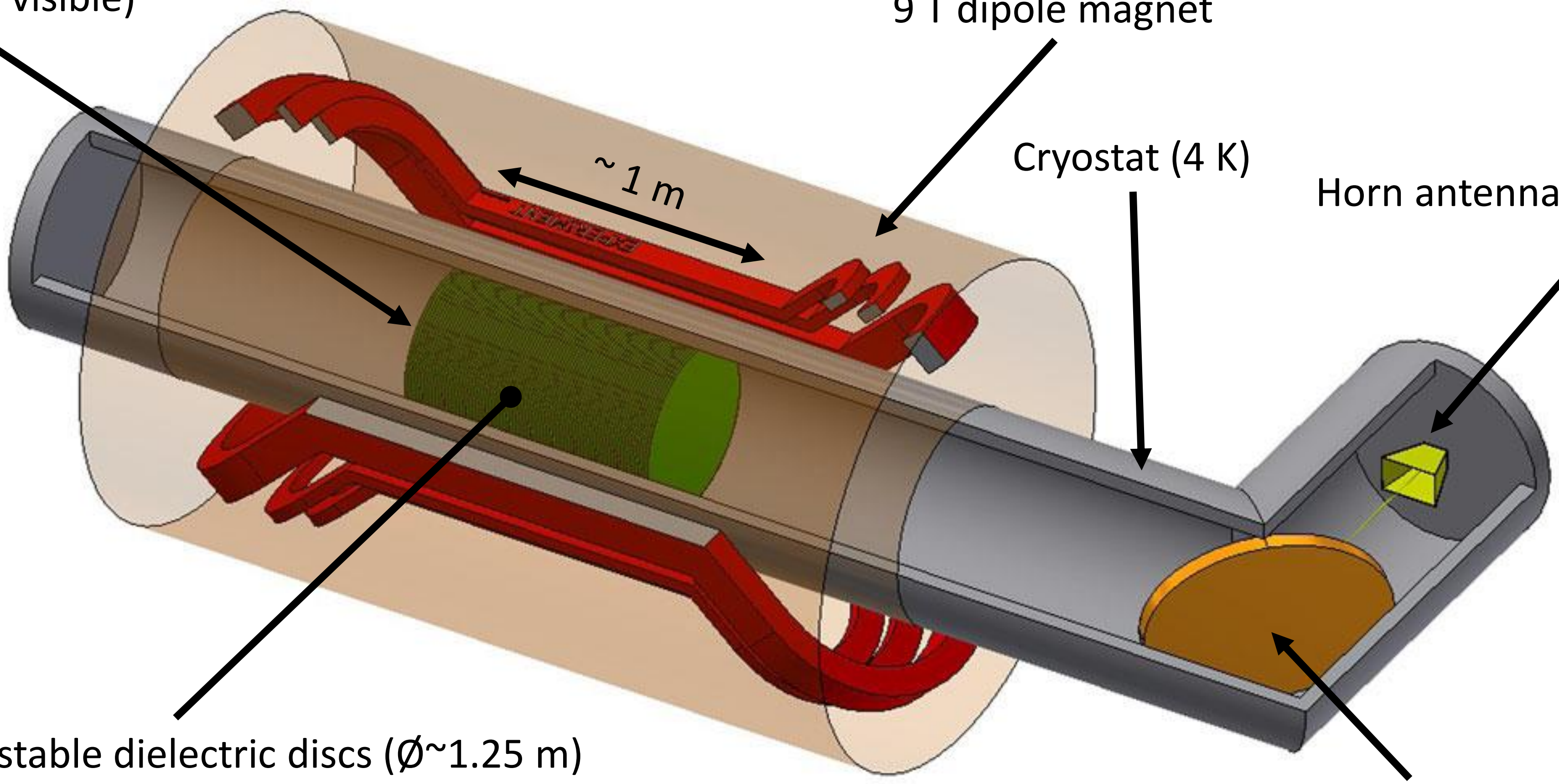
Dielectric Haloscope

- In perfect world (1D simulation): $|\beta^2| > 10^4$ achievable with 80 discs and $\varepsilon = 24$
- Non-uniform disk spacing of $\sim \lambda/_2$ can achieve broadband response
- Tuning of sensitive frequency range by adjusting disc spacing
- Area law: $\beta^2 \Delta\upsilon_\beta$ ~ const.



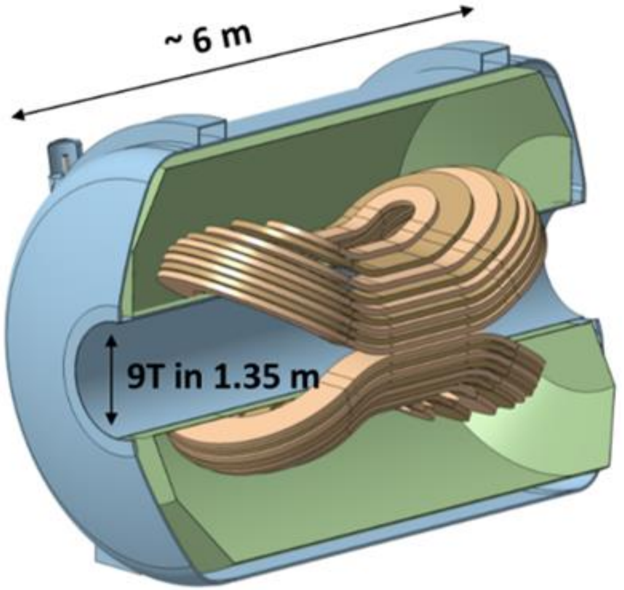
The MADMAX Experiment

MAgnetized **D**isc and **M**irror **A**xion e**X**periment



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

MADMAX Magnet Update

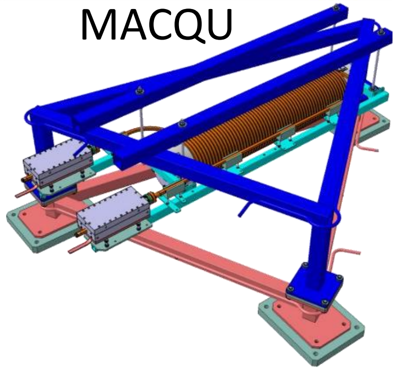


Development in innovation partnership

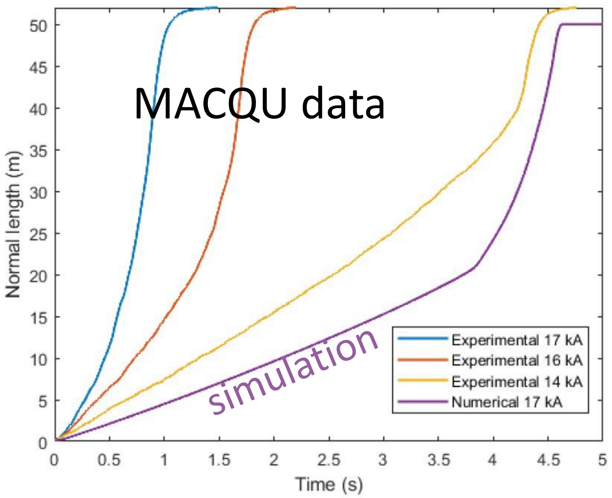
BILFINGER NOELL GMBH

- 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**

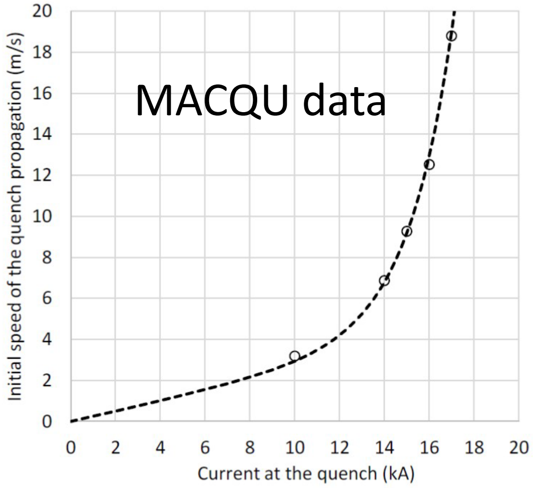
MACQU

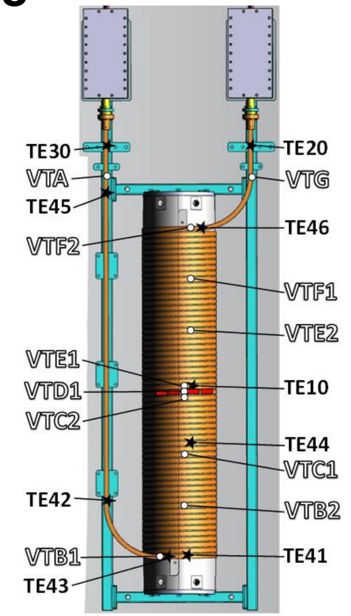


Quench propagation



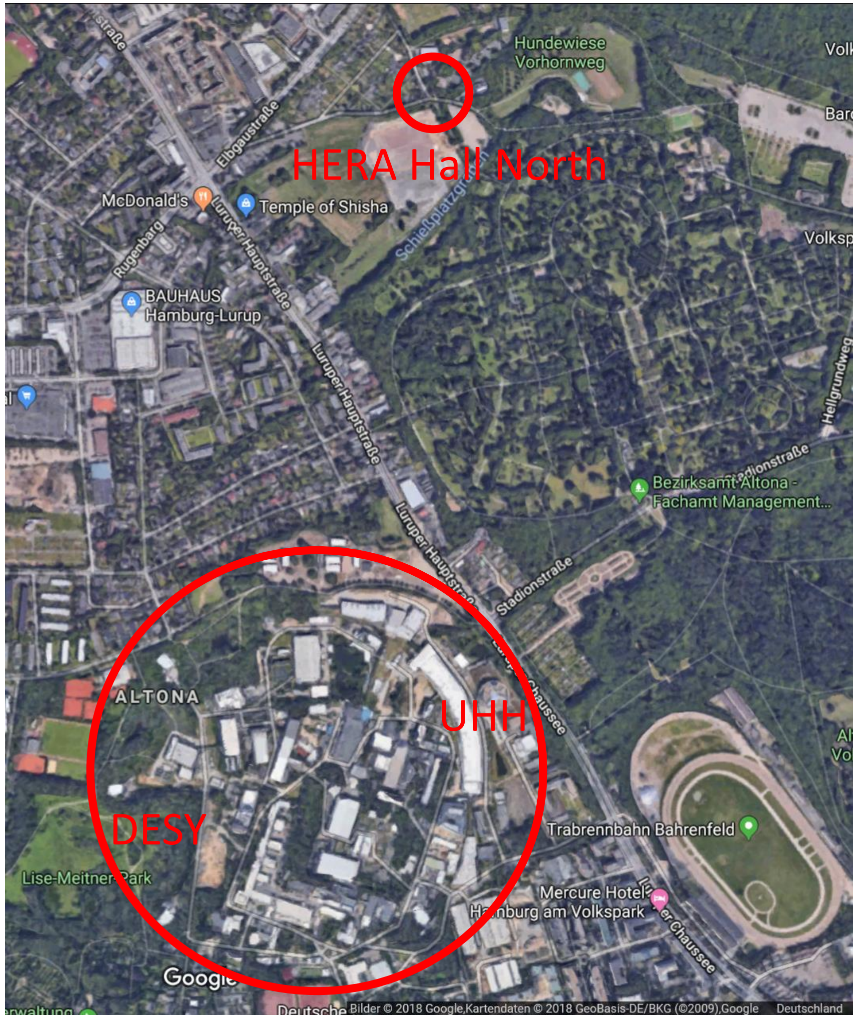
Quench velocity

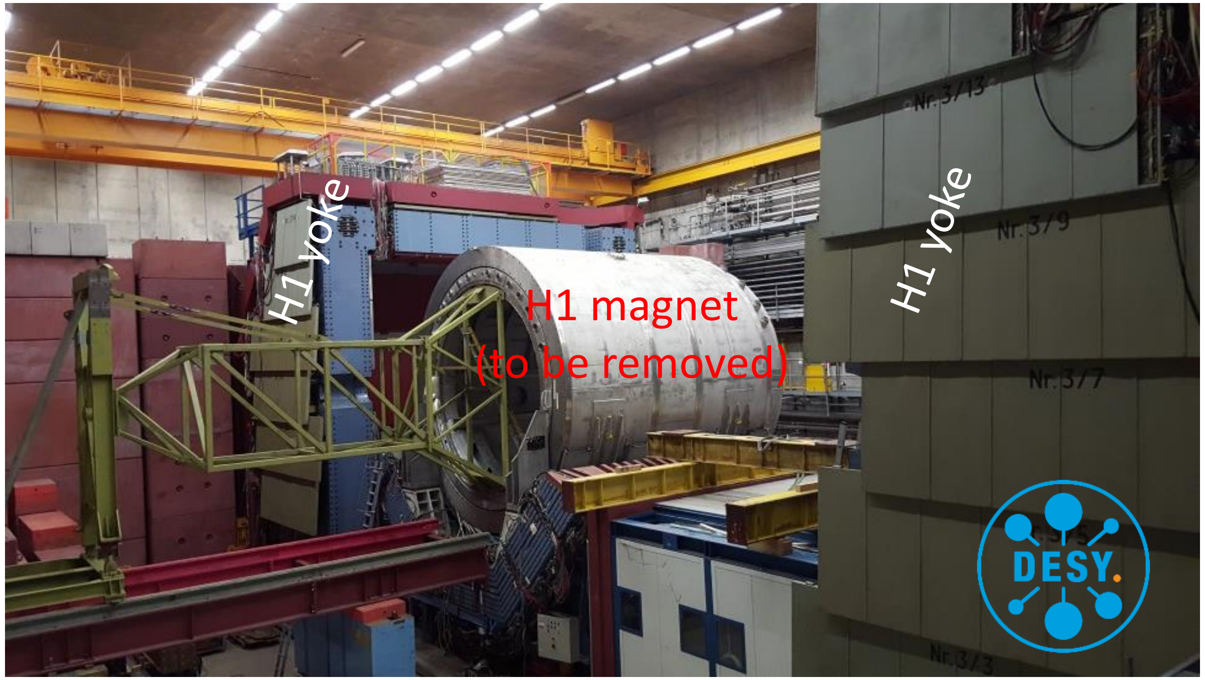




Designated Experimental Site

- 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





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Time Scale

MADMAX

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

Design Phase

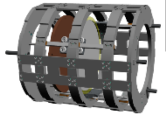
Prototyping Phase

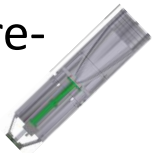
Construction Phase

Foundation of MADMAX Collaboration

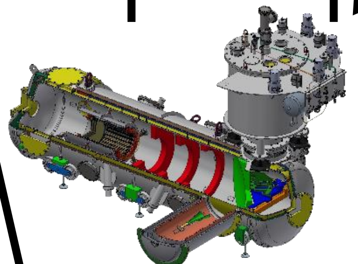
First endorsement by DESY PRC

First ALP measurement at CERN

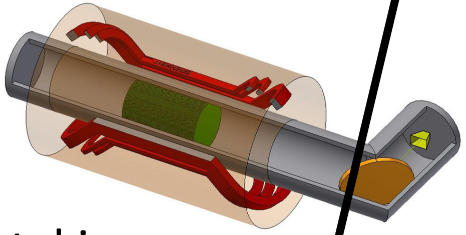




Prototype commissioning to start in 2023



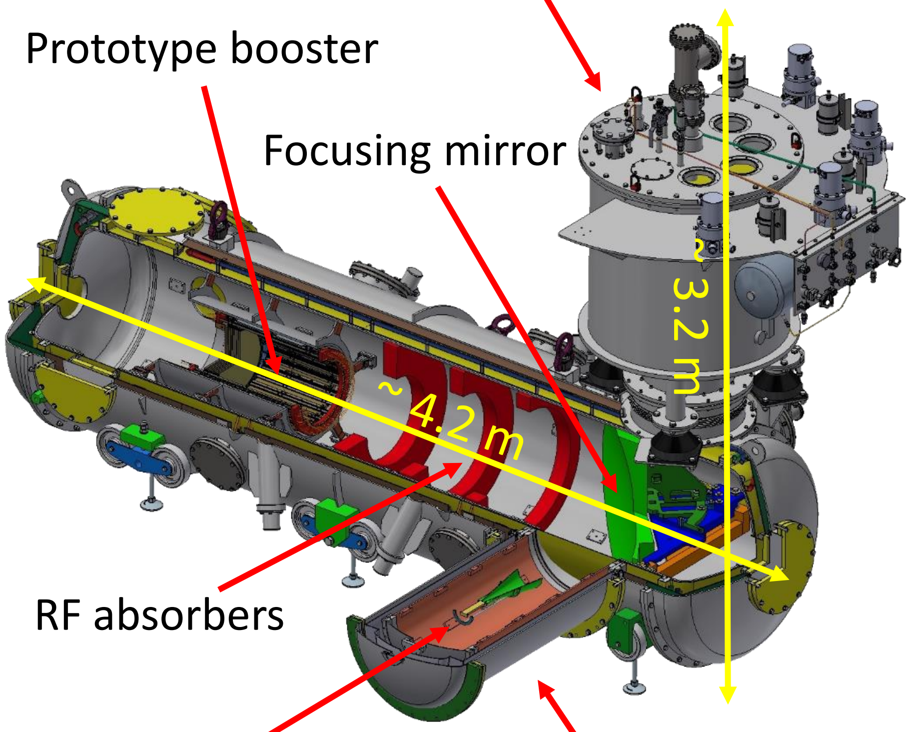
First physics data taking at cold @ CERN



Full-size MADMAX magnet commissioning

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

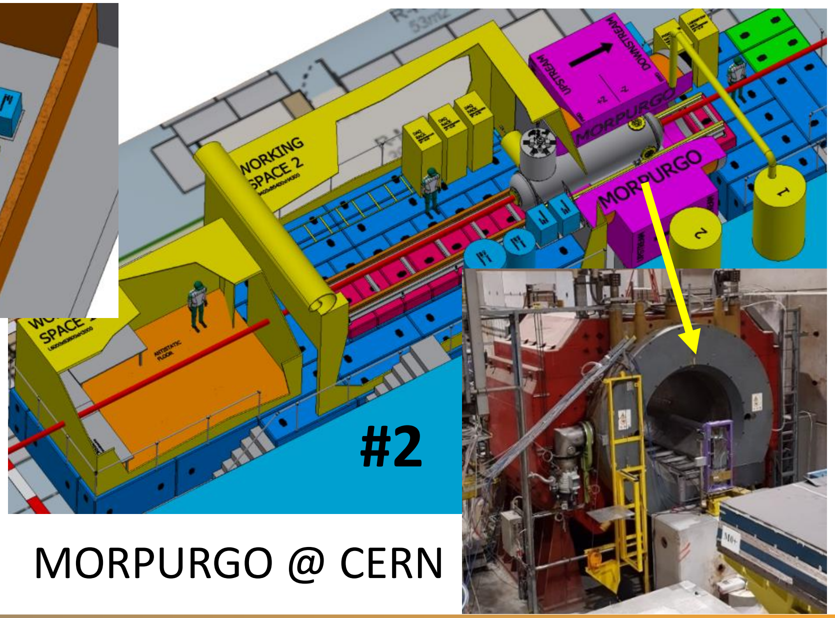
The MADMAX Prototype



- Scaled-down version of MADMAX:
  - Reduced number of discs
  - 1/16 disc area
  - 1/5 magnetic field
- **Main goal #1**: Demonstrating and prototyping key technologies
- **Main goal #2**: Competetive ALP search with a dielectric haloscope

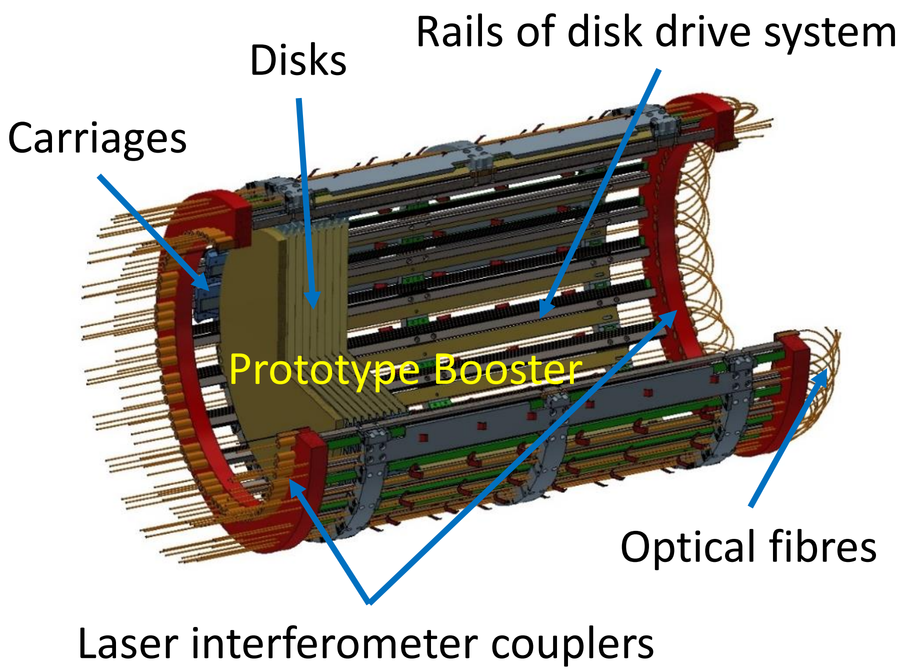
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

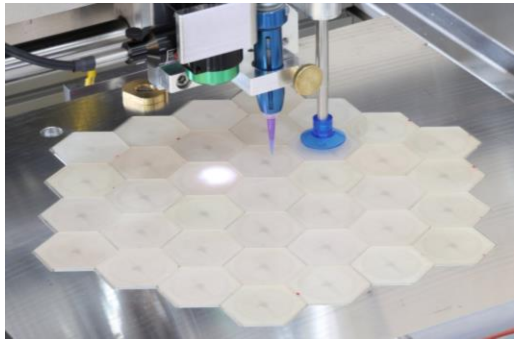
SHELL @Hamburg

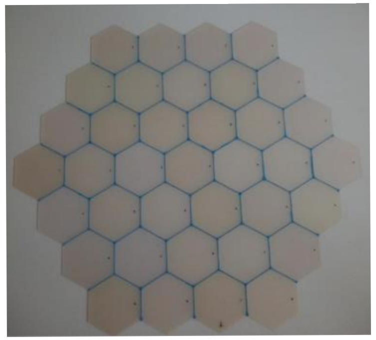


MORPURGO @ CERN

Prototyping the Booster



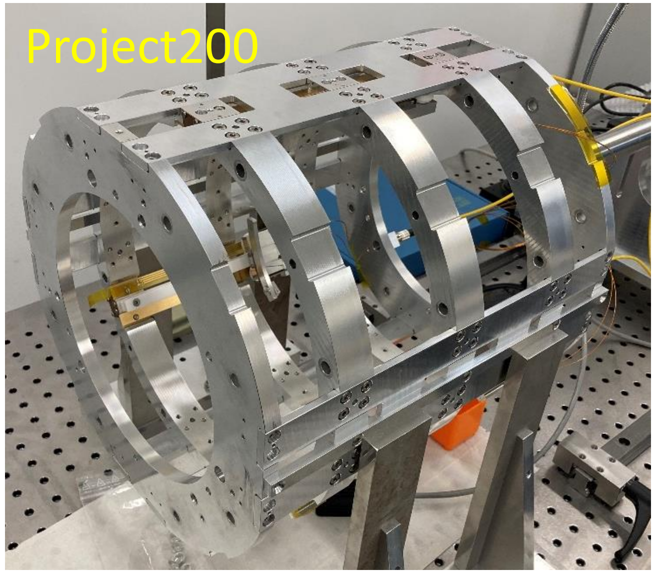


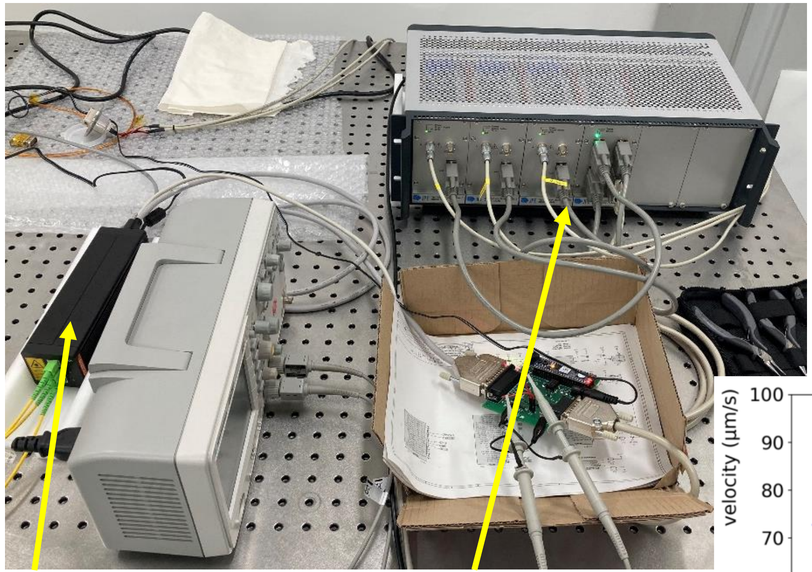


- Booster is the heart of MADMAX
- Need to manipulate many large area discs with precision < 10 µm
- Operating conditions:
  - Cryogenic temperatures: 4 K
  - High magnetic field: up to ~10 T
  - Vacuum or cold gHe exchange gas
- Long travel range
- Disk weight: 600 g for Ø300 mm
- ➢ **Piezo-driven actuator system with feedback from laser interferometer with absolute precision**

- Candidate disk materials:
  - **$LaAlO_3$ ($\varepsilon \approx 24$, tan$\delta \approx$ a few 10^{-5})**
  - Sapphire ($\varepsilon \approx 9$, tan$\delta \approx 10^{-5}$)
- $LaAlO_3$ available as 3″ wafers at maximum
- ➢ **Tiling necessary → Semi-automatic gluing machine**

Testing the Disk Drive





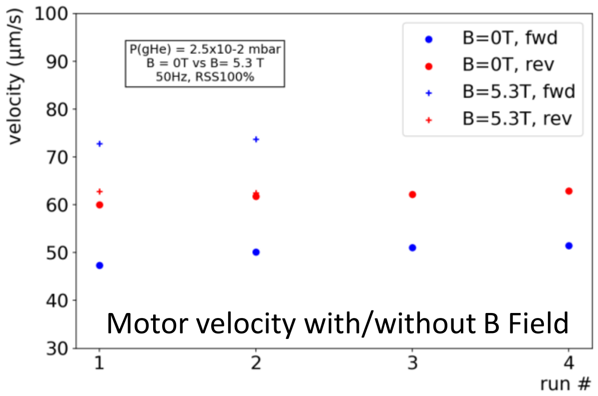
Laser interferometer Piezo controllers

- Project200 built as **mechanical demonstrator**
- Three JPE piezo actuators on self-built carriages
- **Piezo controller system for driving a disc with three motors**
- Attocube laser interferometer for displacement measurement
- Single 200 mm sapphire disk in titanium disc ring can be mounted

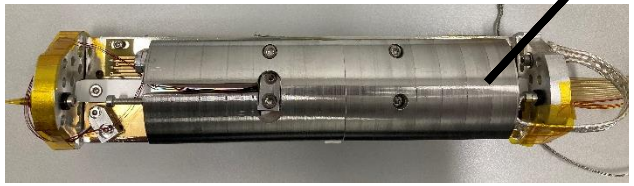
Single motor tests

- Motor developed by company JPE
- Motor successfully tested at RT and 4 K
- Begin of 2022 test in ALPS II magnet

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



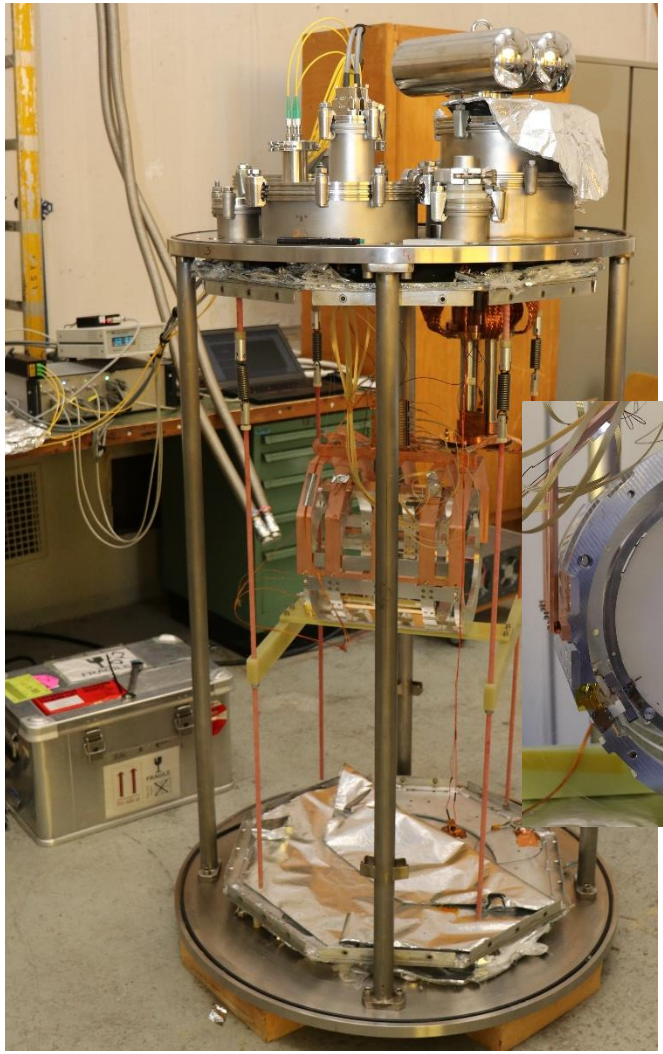
Single motor test rig

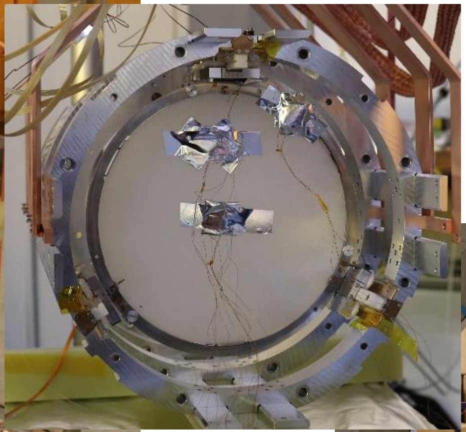


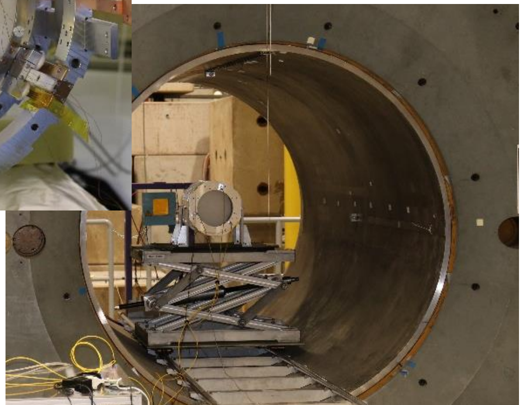
ALPS II magnet test stand

Testing the Disk Drive

- 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 **disc can be moved with three motors** using the laser interferometer feedback

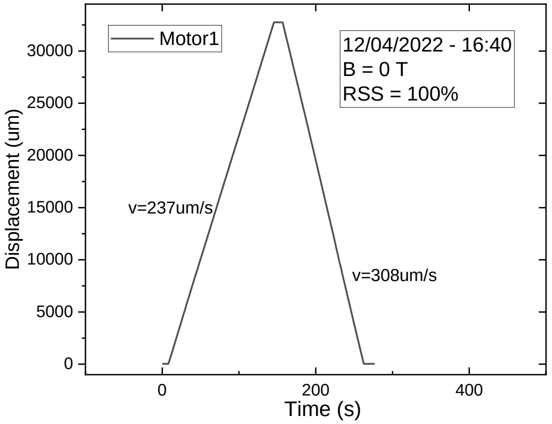


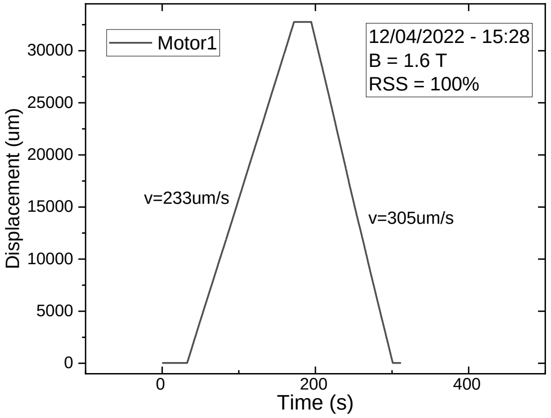




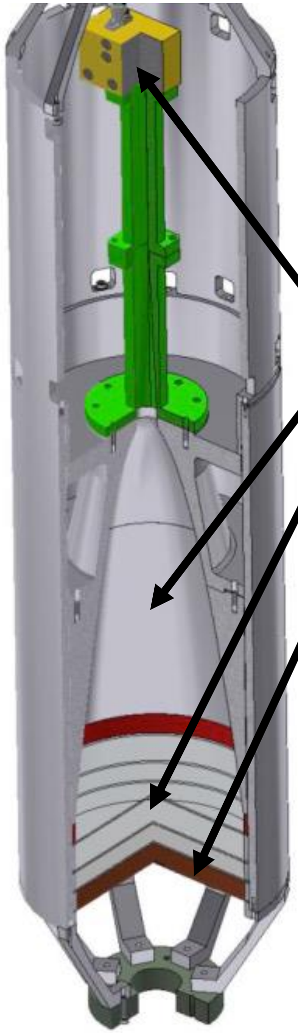
Project200 inside Morpurgo

No difference in disk velocity with/without B field



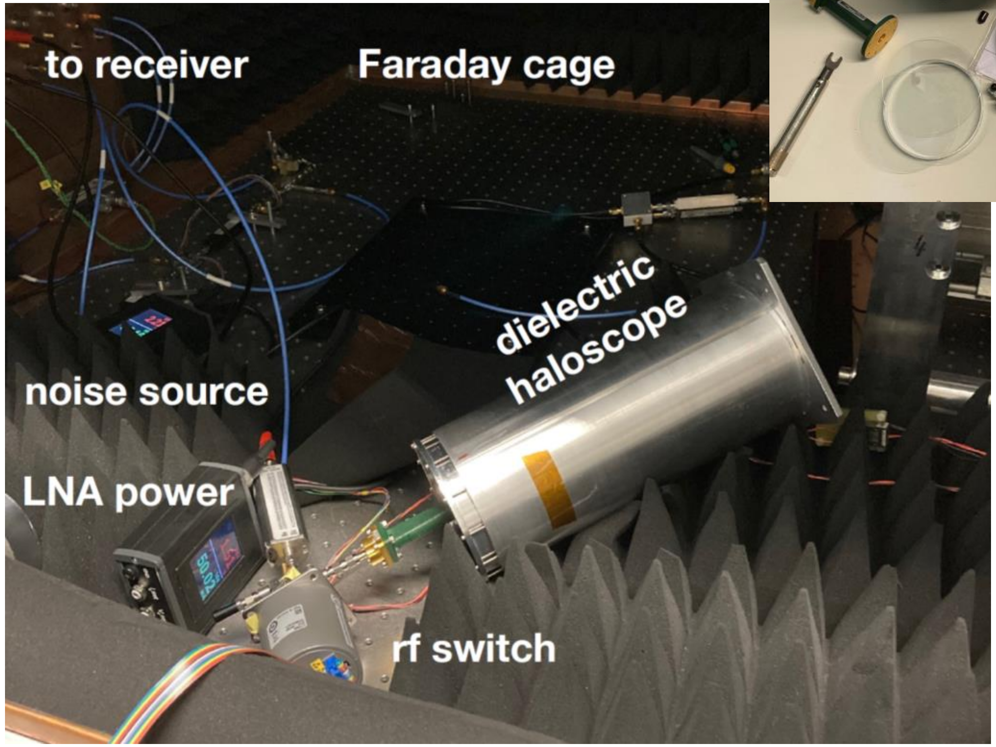


Closed Booster System



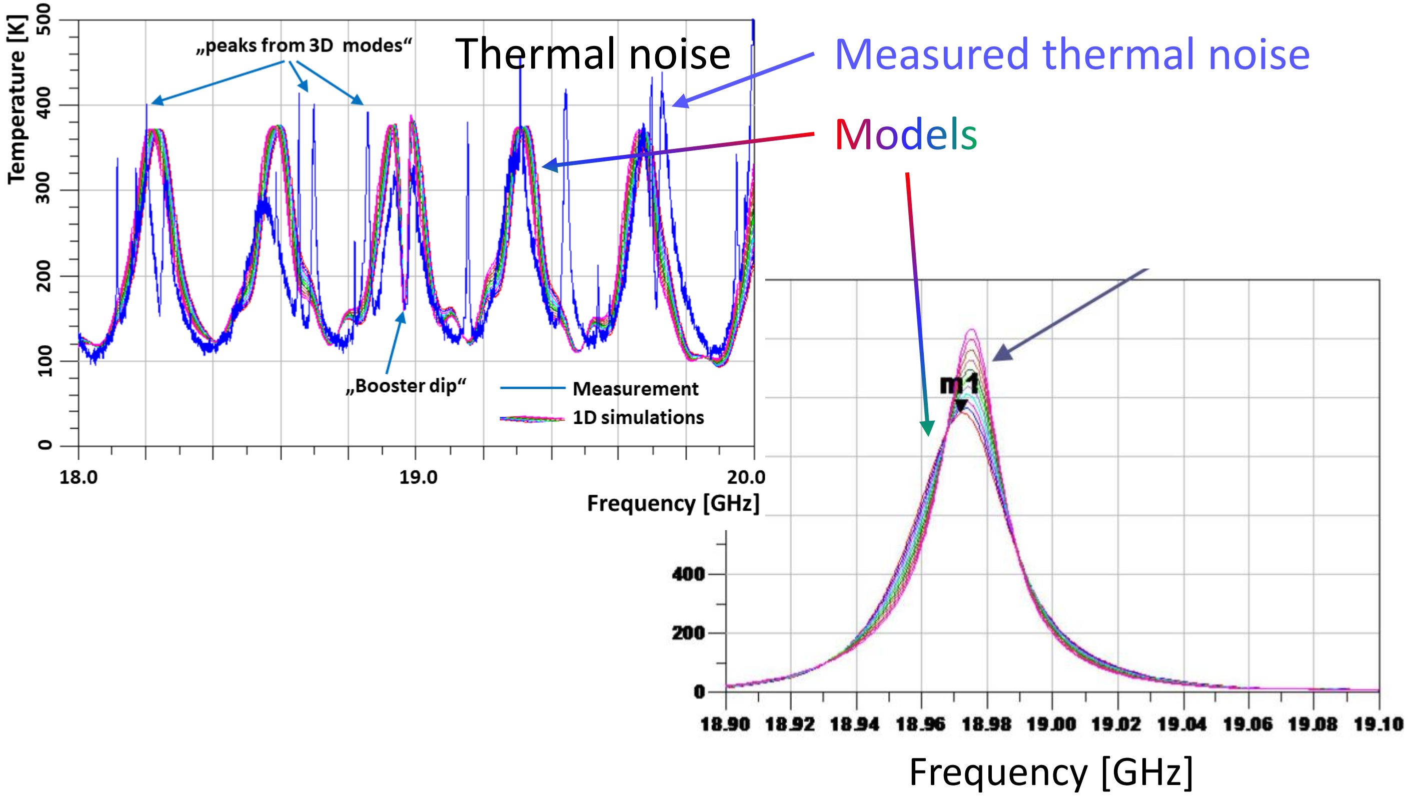
- Simple closed system to understand behaviour
- Can be operated at cryogenic temperatures
- Hidden Photon search and ALP search with Closed Booster 100

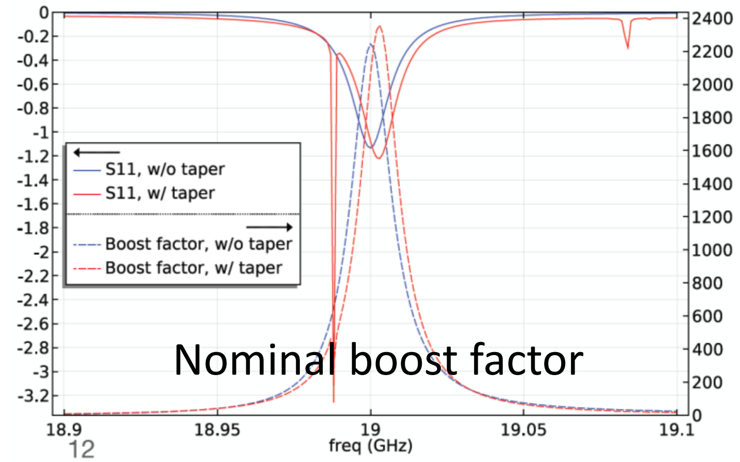
➢ Receiver
➢ Parabolic taper
➢ 3x Ø100 mm sapphire disks (fixed distances)
➢ Copper mirror



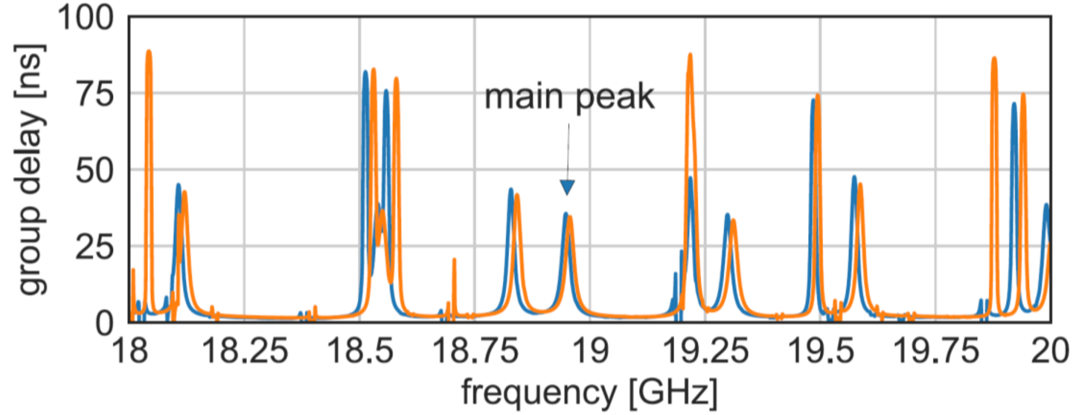
Boost Factor Calibration

- Measurement of thermal noise & RF response (reflectivity and/or group delay)
- Match model to reproduce measured quantities
- Extract boost factor from model



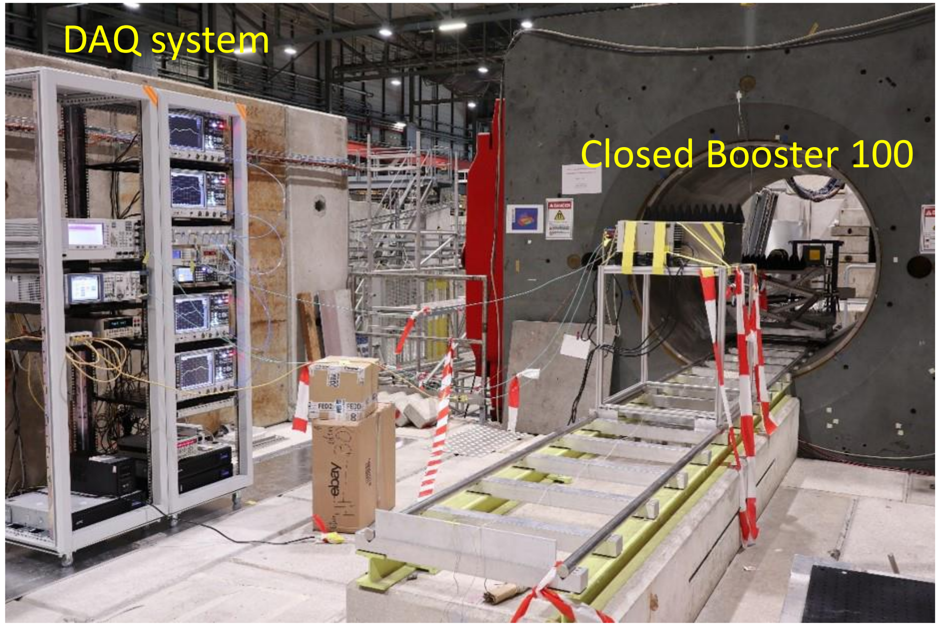


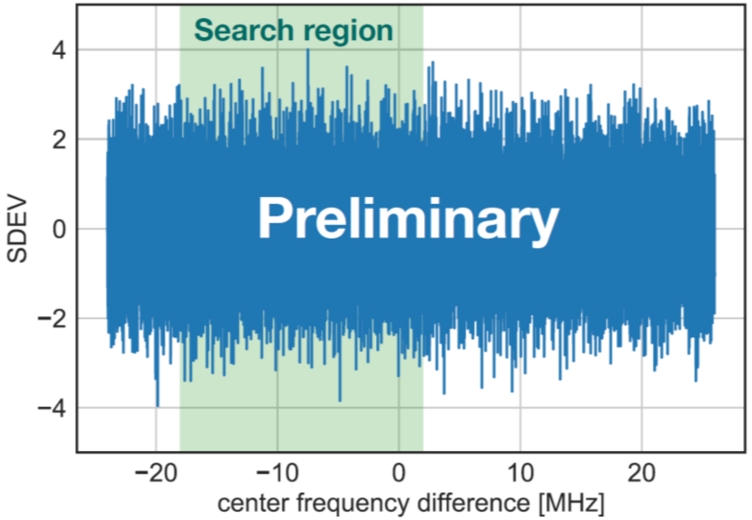
Simulated vs. measured RF response

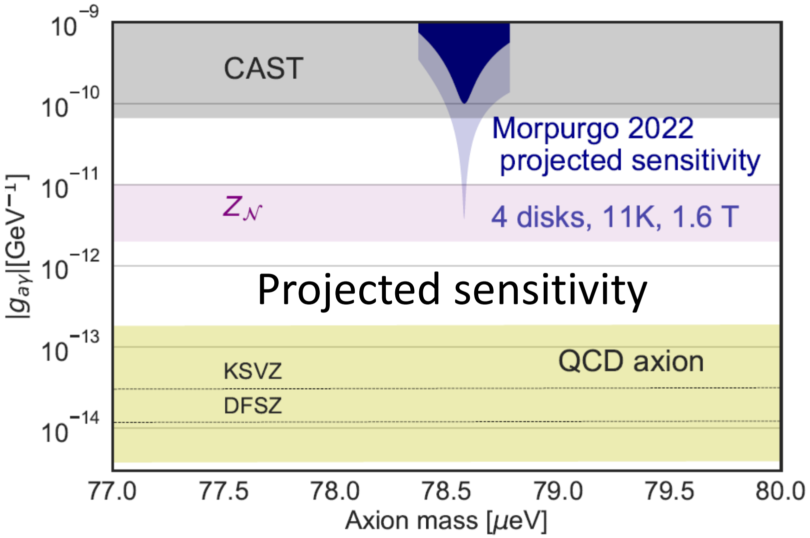


Axion Like Particle Search

- 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







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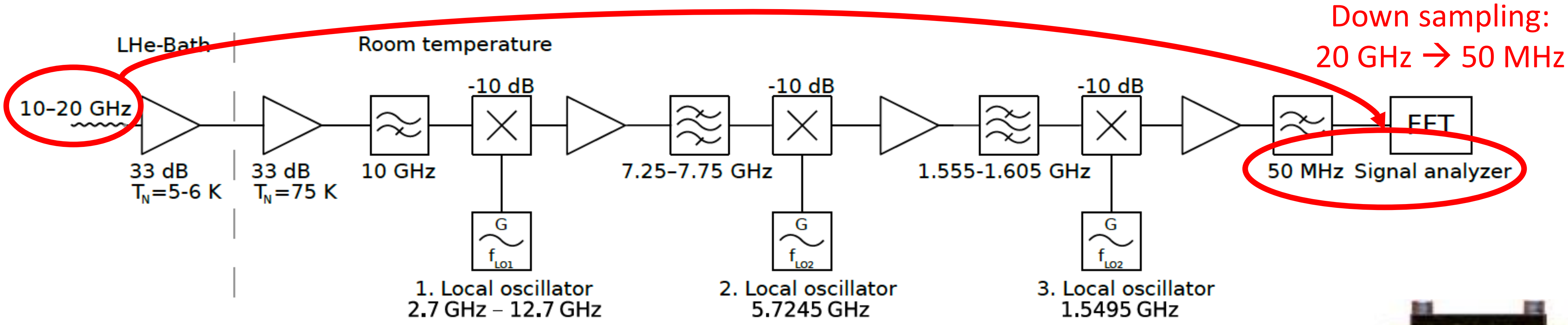
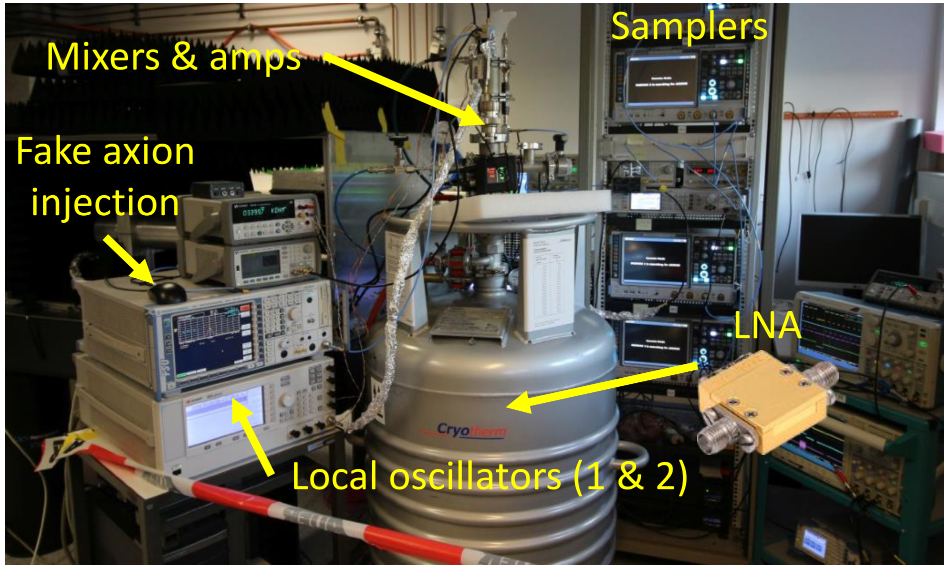
Receiver Chain





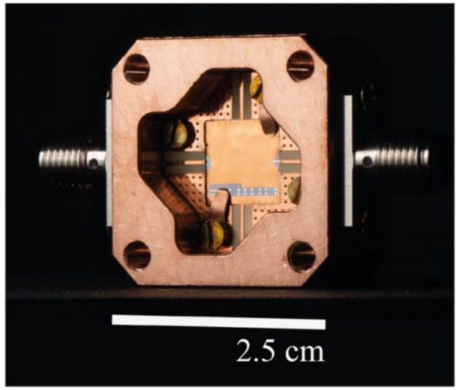
- Receiver chain with low-noise amplifier and three mixing stages
- Amplifiers for high frequencies developed: TWPAs for < 30 GHz

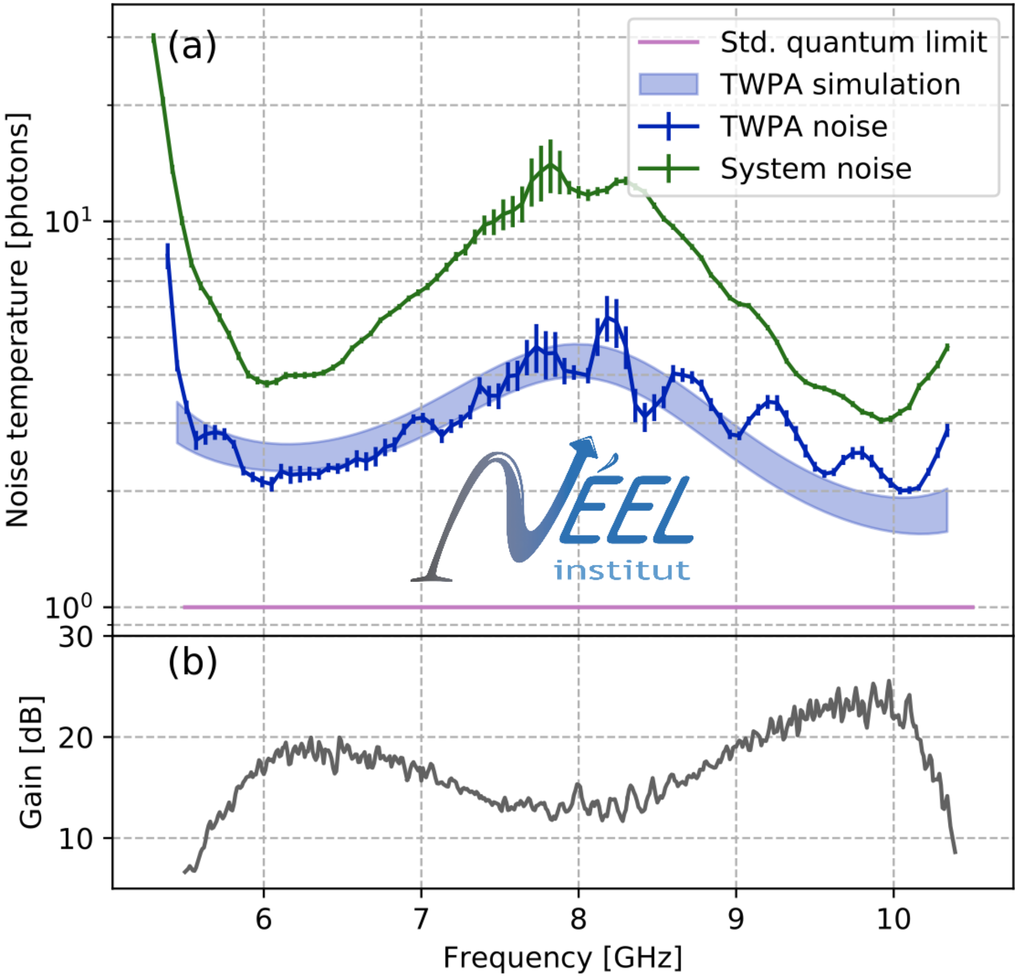
Test setup at MPP with 4 samplers and fake axion injection:
Detection of 1.2 x 10^{-22} W signal within few days

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

Quantum-limited Amplifier

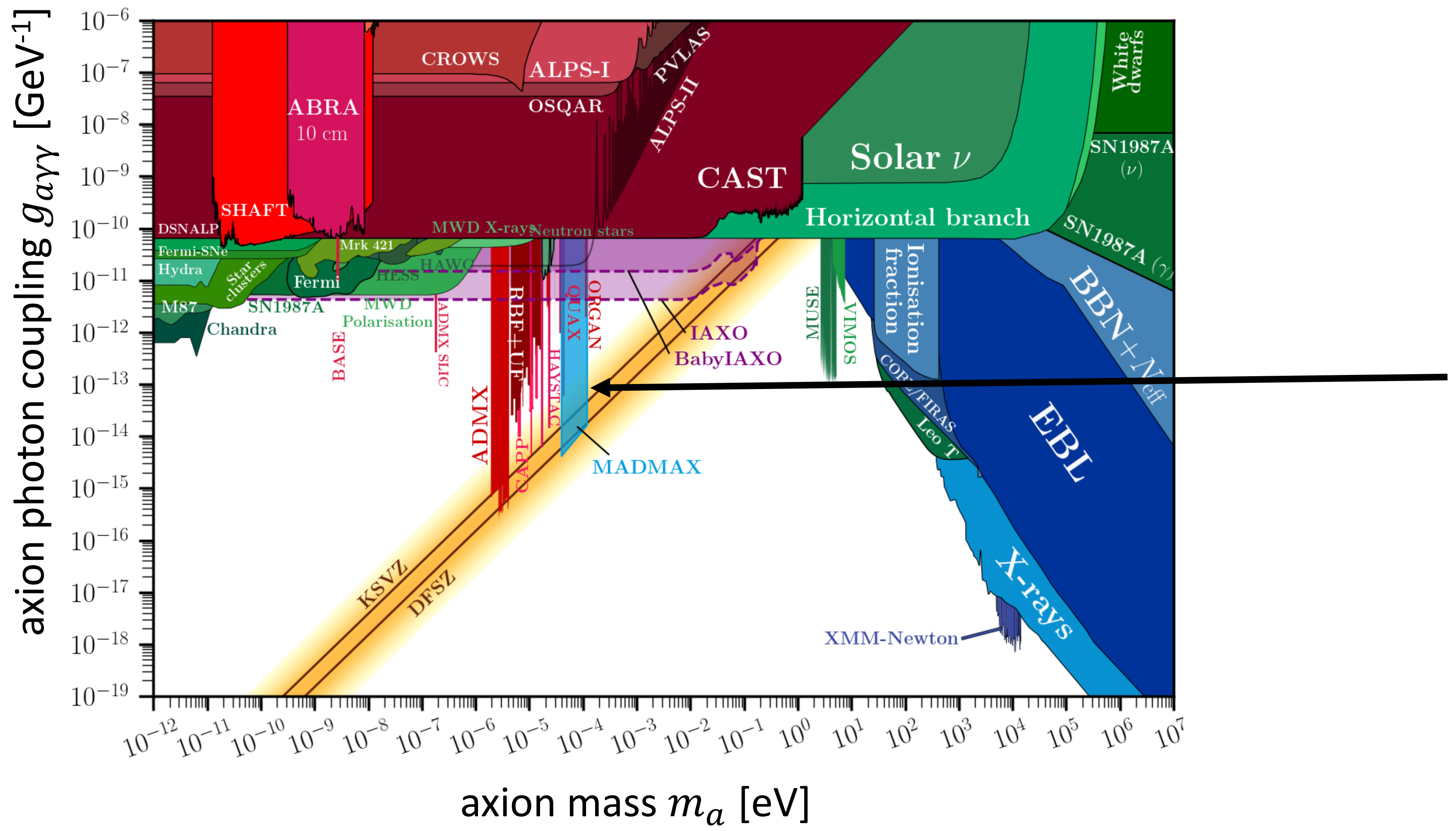
- Traveling wave parametric amplifier (TWPA)
- **First 10 GHz TWPA** produced (PRX 10, 021021)
- Added noise: 1 K above quantum limit
  (20 dB gain @ 10 GHz)
- Future development to 30 GHz





[Reversed Kerr TWPA arXiv:2101.05815]

MADMAX Sensitivity

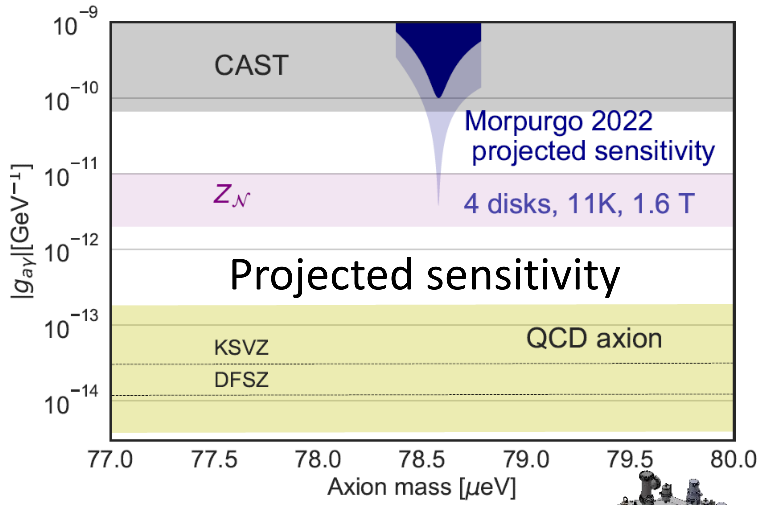


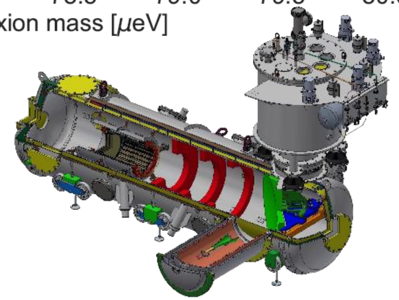
MADMAX:

$$N_{\text{disc}} = 80$$
$$A_{\text{disc}} = 1.2\ \text{m}^2$$
$$B_{\parallel} = 9\ \text{T}$$
$$T_{\text{sys}} = 8\ \text{K}$$

Summary & Outlook

- **MA**gnetized **D**isk and **M**irror **A**xion e**X**periment: dielectric haloscope to detect post-inflationary DM axions
- Continue work on analysis & calibration of Closed Booster 100
- Commissioning of full-size MADMAX at DESY in HERA Hall North starting (earliest) in 2028 with the huge magnet
- Commissioning of MADMAX Prototype to start in 2023
  → First operation at CERN during YETS 2024/25





MADMAX Collaboration Meeting
September 2022 @ Hamburg