Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

MADMAX

Towards a Dielectric Axion Haloscope

Christoph Krieger
Universität Hamburg

On behalf of the MADMAX Collaboration

19th July 2022

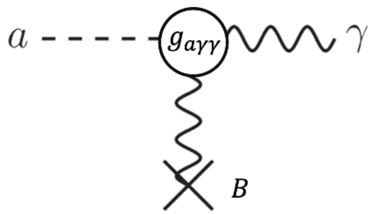
14th International Conference on Identification of Dark Matter

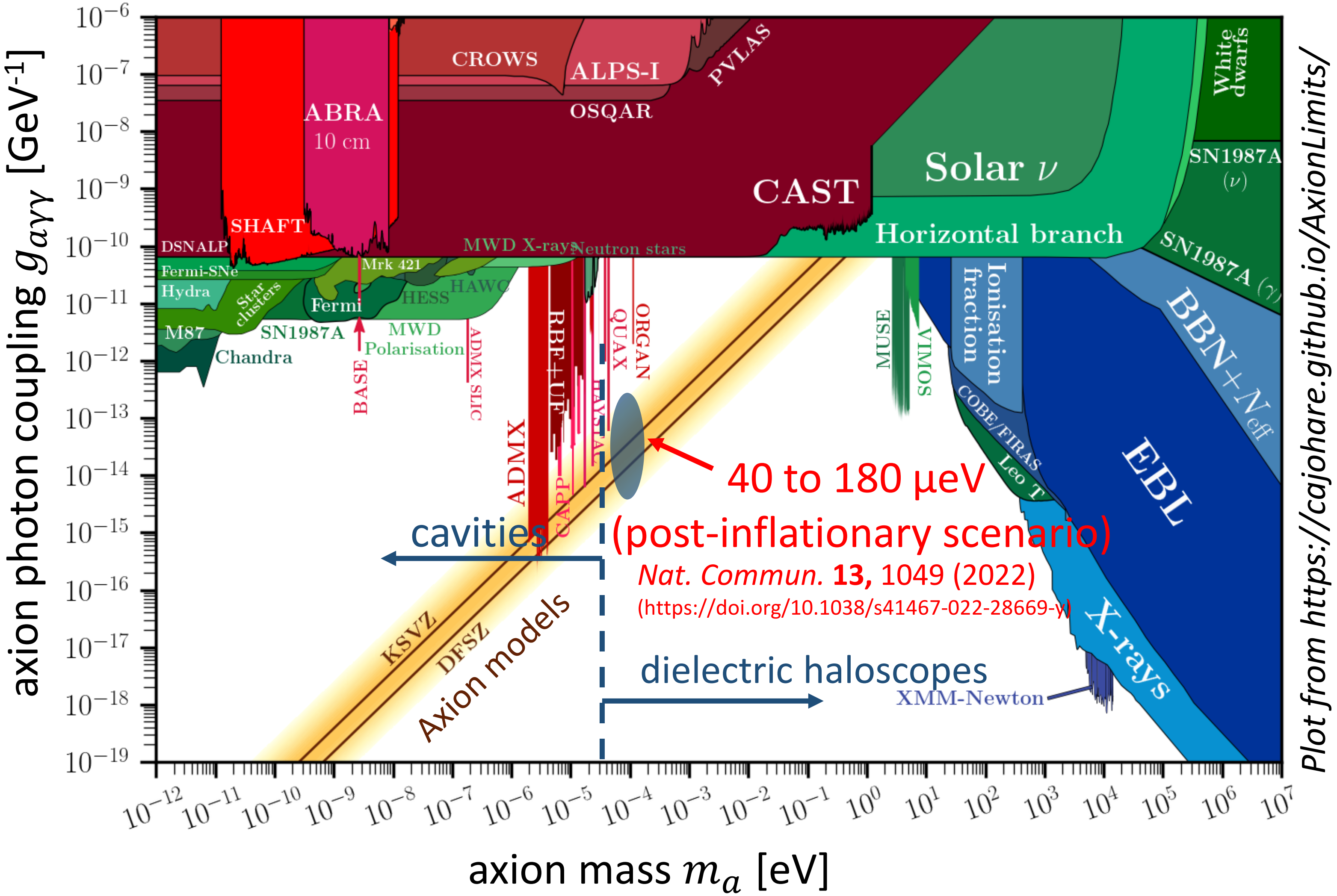
Vienna

Axion Parameter Space

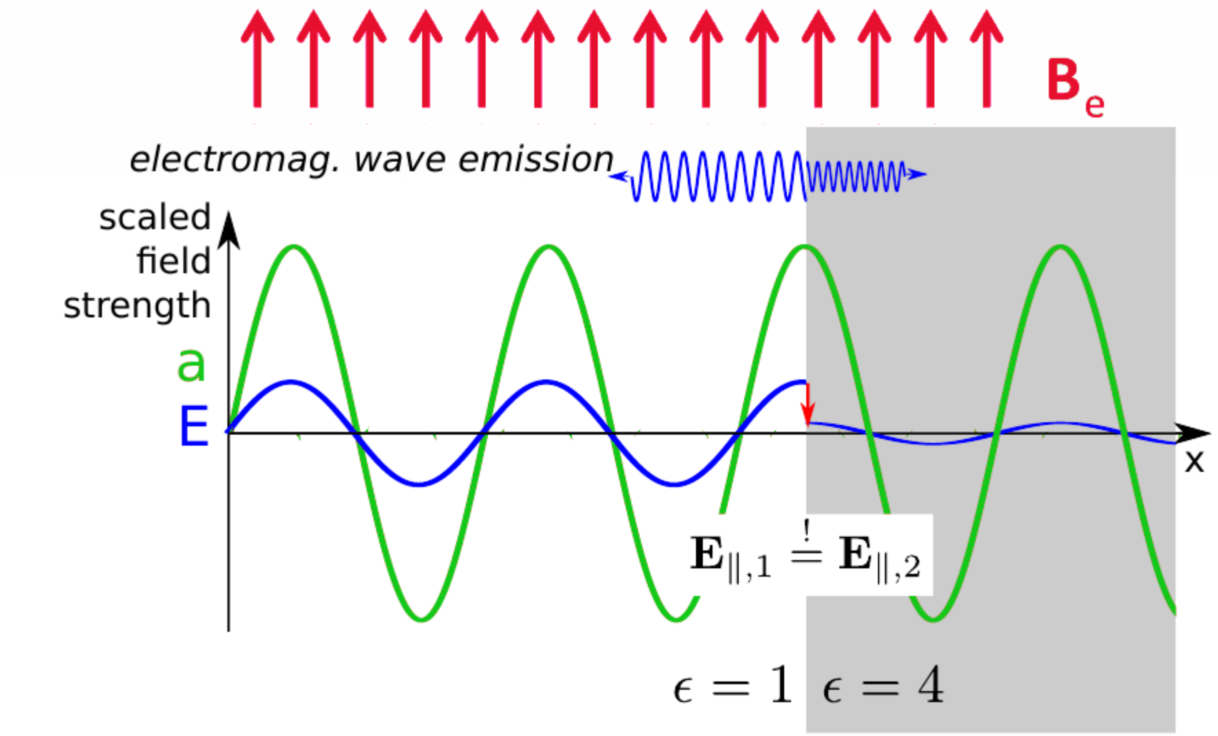
The Axion:

- 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**





Dielectric Haloscope



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

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

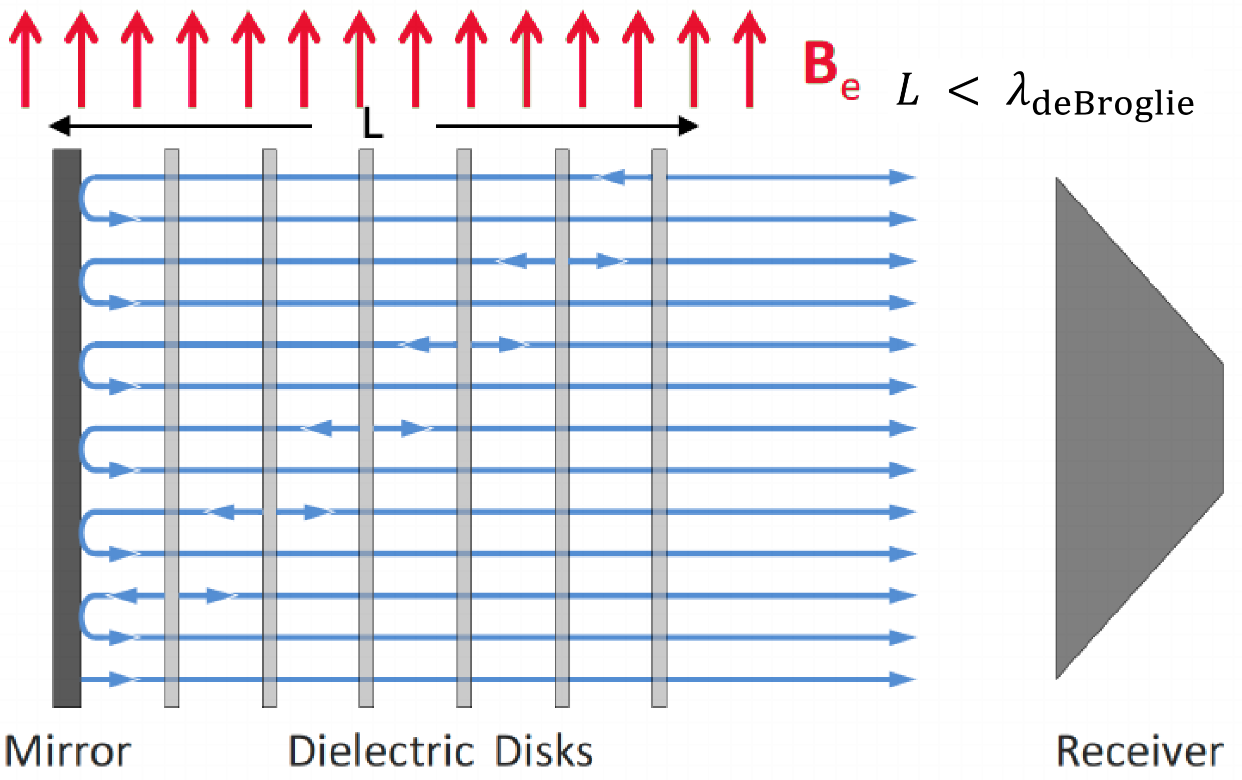
$\boldsymbol{E_a}$ is different in materials with different ε

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

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

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

Dielectric Haloscope



Boost emitted power through:

- coherent emission from multiple interfaces
- constructive interference effects

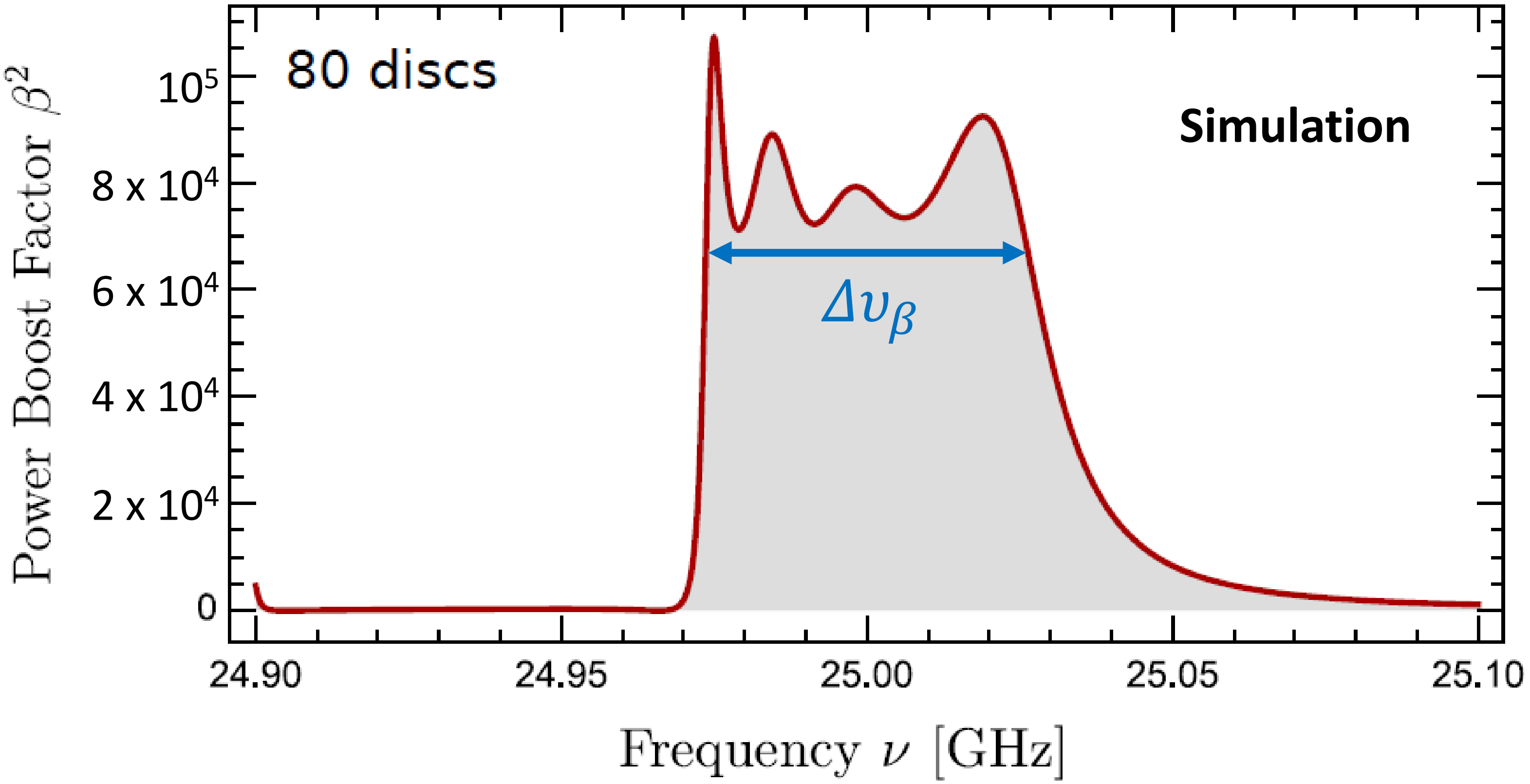
Power boost factor:

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

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

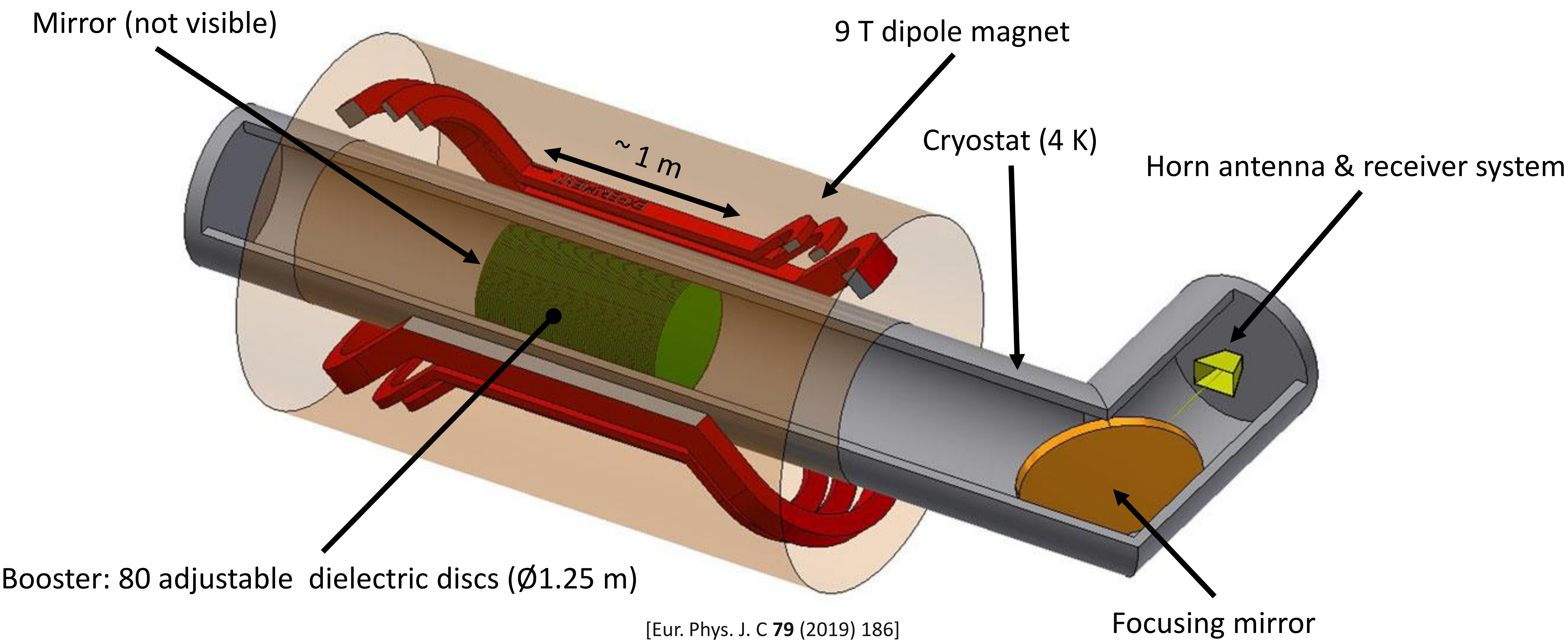
Dielectric Haloscope

- 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.



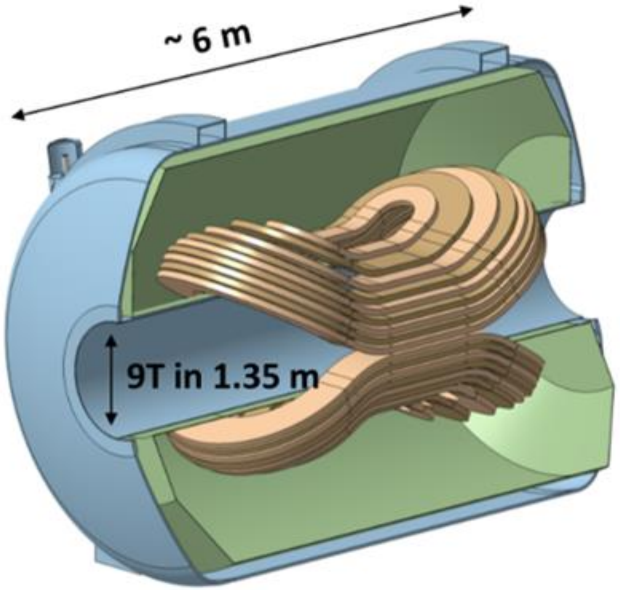
The MADMAX Experiment

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

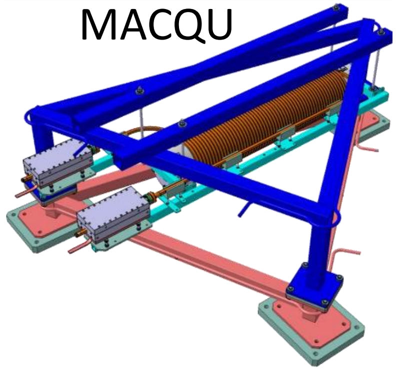


[Eur. Phys. J. C **79** (2019) 186]

MADMAX Magnet Update



- 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**



Development in innovation partnership

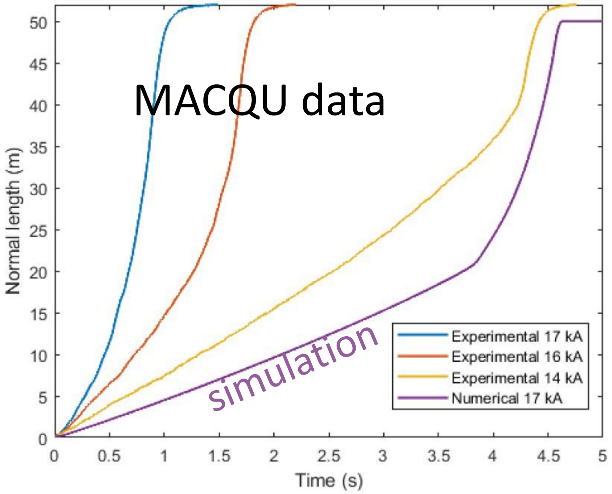
BILFINGER

BILFINGER NOELL GMBH

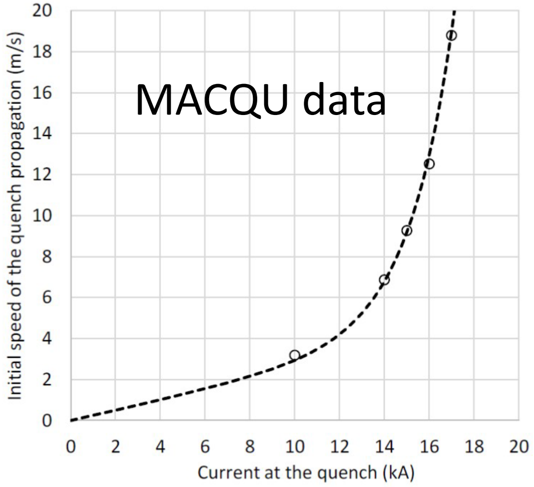
cea

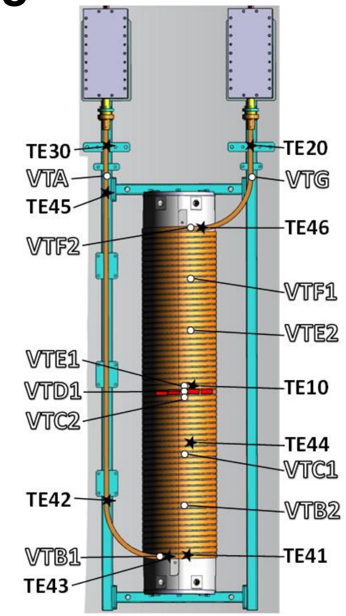
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

Quench propagation

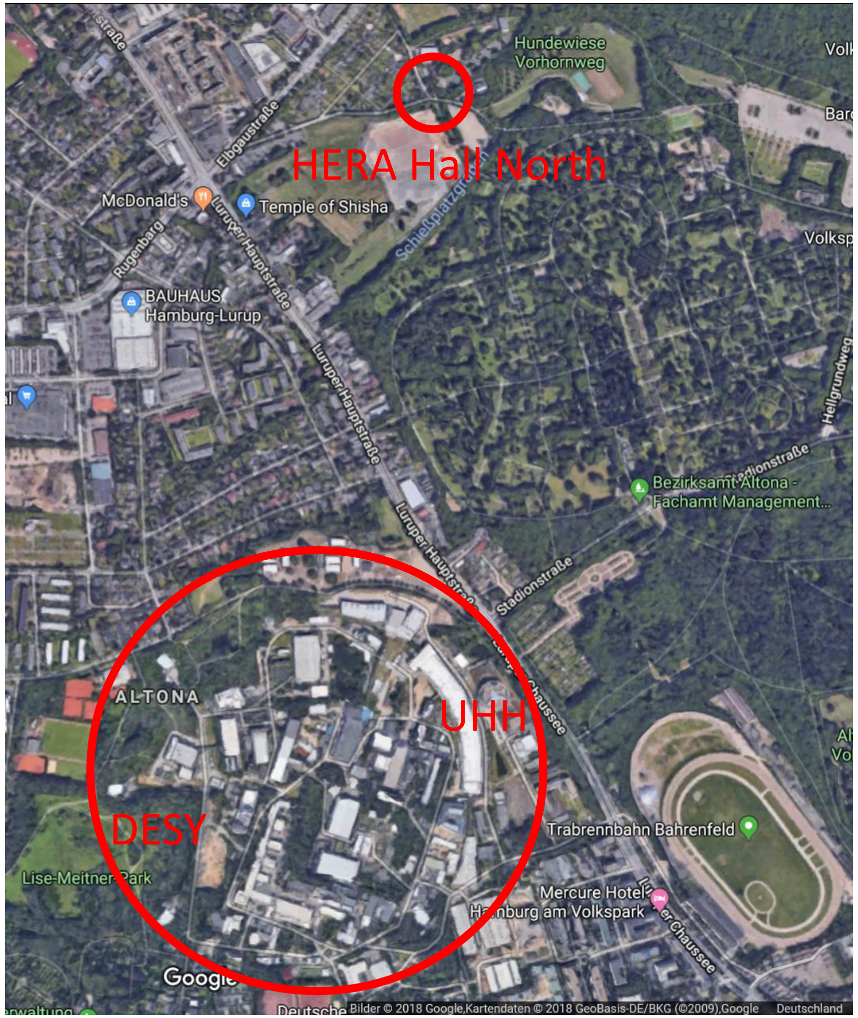


Quench velocity





Designated Experimental Site



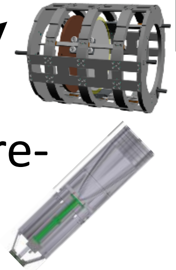
- MADMAX to be operated at HERA Hall North
- Make use of DESY infrastructure
- Benefit: re-use H1 yoke as magnetic shielding to reduce fringe field and increase B field

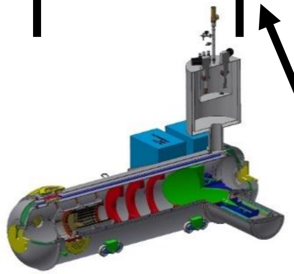
Time Scale

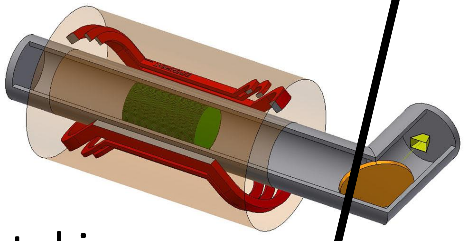
2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | >= 2028

Design Phase — Prototyping Phase — Construction Phase

- Foundation of MADMAX Collaboration (2017/2018)
- First endorsement by DESY PRC (2019/2020)
- First ALP measure-ment at CERN (2022)
- Prototype commissioning to start in 2023
- First physics data taking at cold @ CERN (2025)
- Full-size MADMAX magnet commissioning (>= 2028)

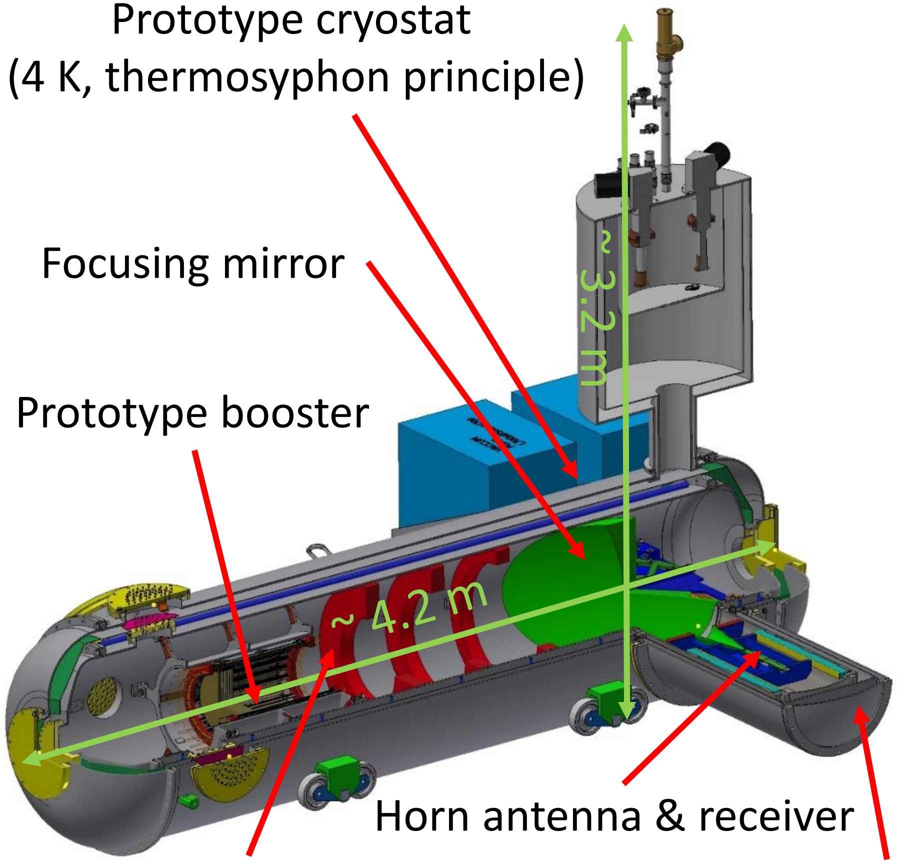






Usage of MORPURGO magnet approved by CERN Research Board for 2021-2025

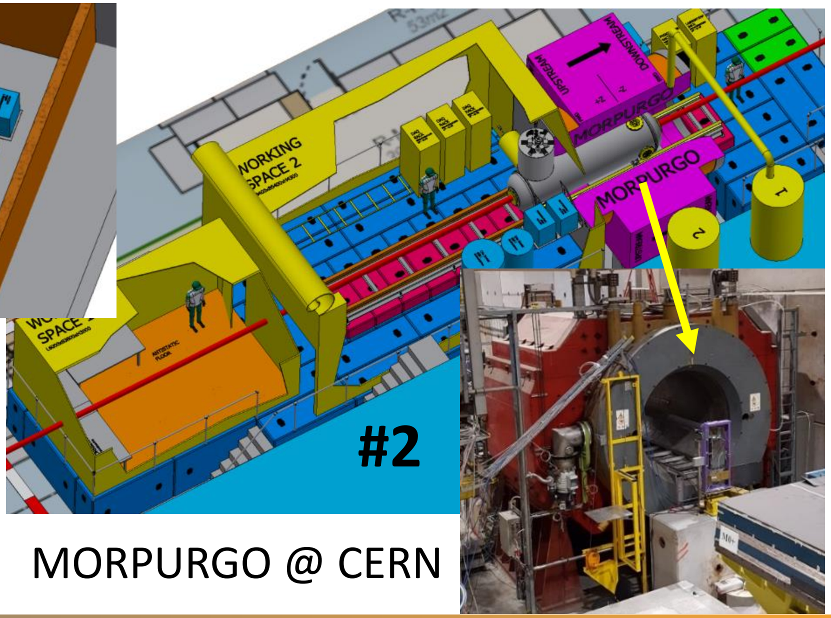
The MADMAX Prototype



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

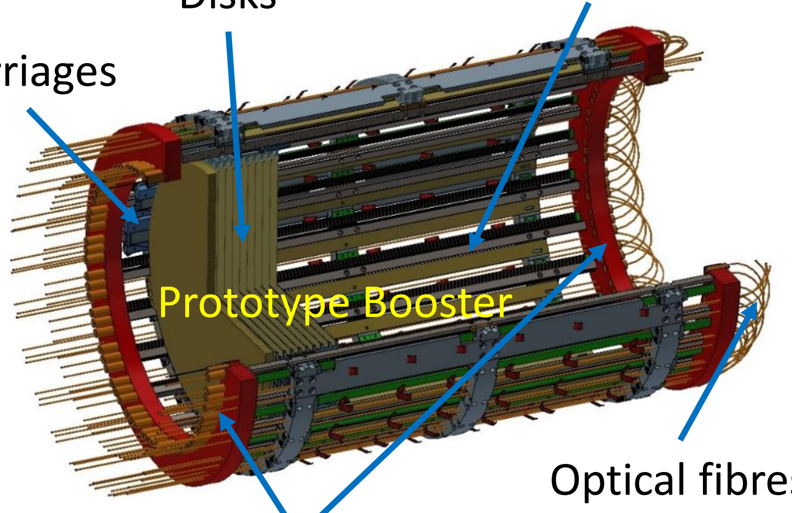
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

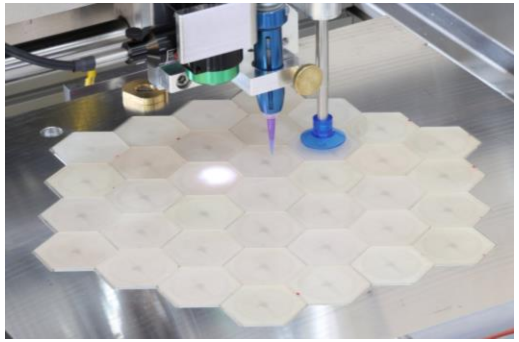
SHELL @Hamburg

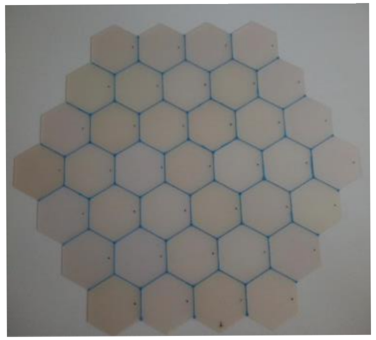


MORPURGO @ CERN

Prototyping the Booster



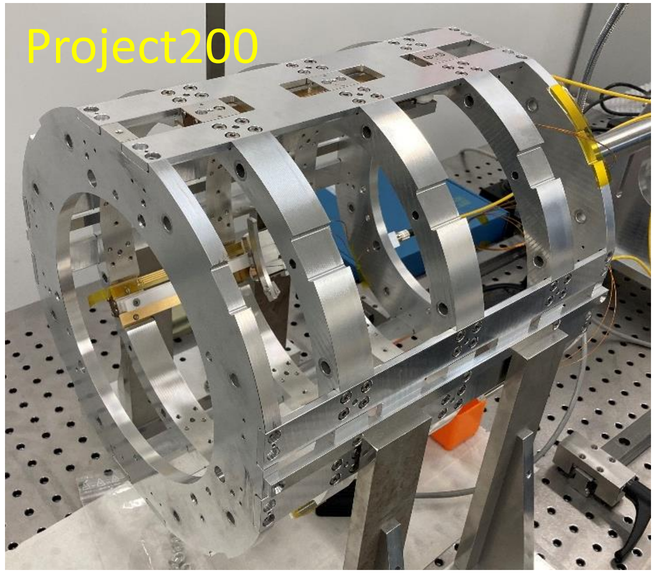


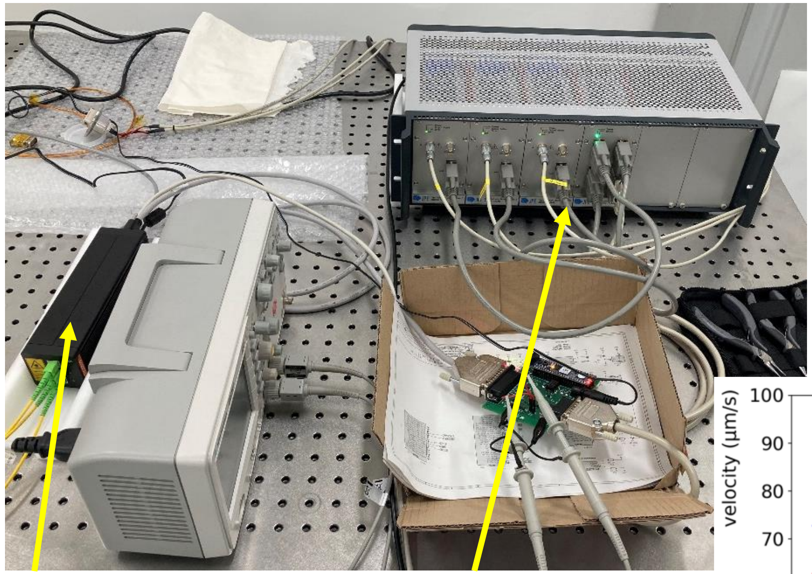


- Booster is the heart of MADMAX
- Need to manipulate many large area disks with precision < 10 µm
- Operating conditions:
  - Cryogenic temperatures: 4 K
  - High magnetic field: up to ~10 T
  - Vacuum or cold gehe exchange gas
- Long travel range
- Disk weight: 600 g for Ø300 mm
- ➢ **Piezo-driven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





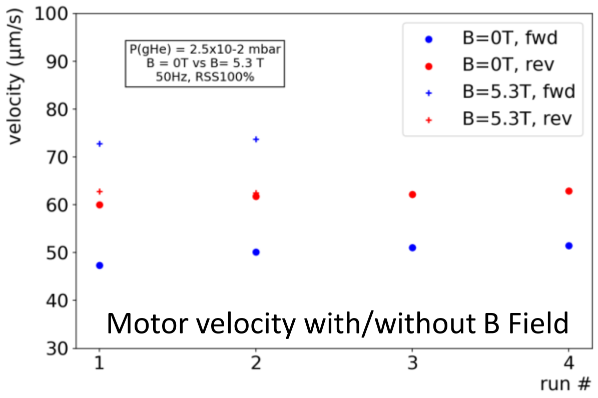
Laser interferometer   Piezo controllers

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

Single motor tests

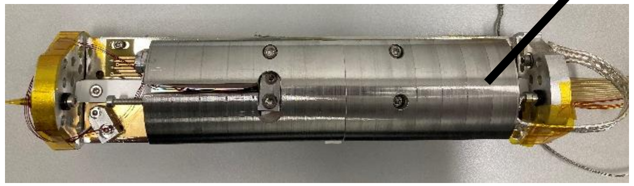
- Motor developed by company JPE
- Motor successfully tested at RT and 4 K
- Begin of 2022 test in ALPS II magnet

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



Motor velocity with/without B Field

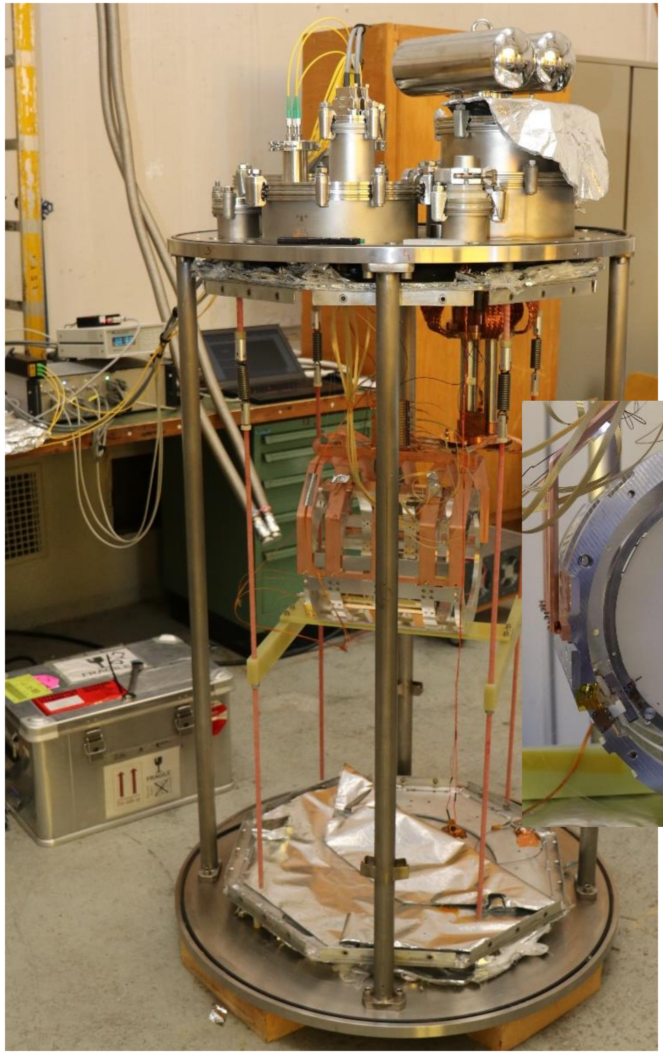
Single motor test rig

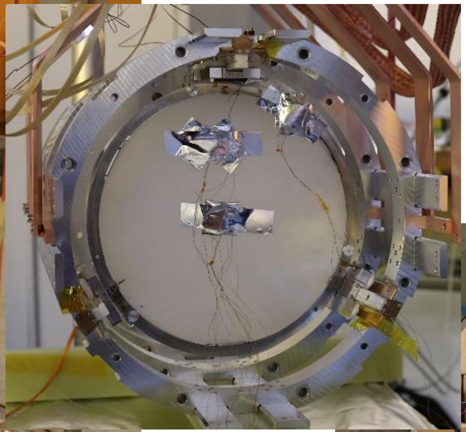


ALPS II magnet test stand

Testing the Disk Drive

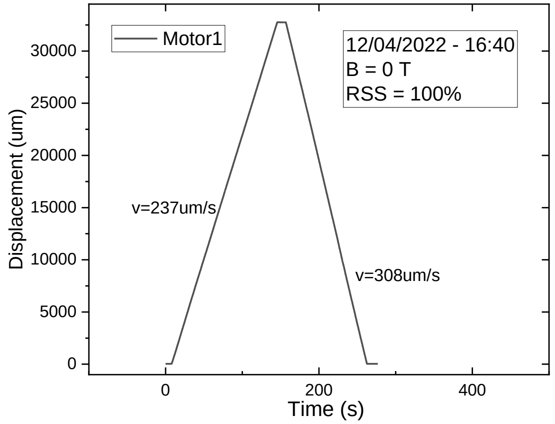
- Opportunity to test Project200 at CERN in spring 2022
- Project200 **successfully tested at CERN Cryolab and in CERN's Morpurgo magnet**
- All three **piezo motors work at cryogenic temperatures and in 1.6 T field** (at RT)
- Attocube laser interferometer works at cryogenic temperatures
- Project200 backbone structure **keeps optics alignment during cool-down**
- A **disk can be moved with three motors** using the laser interferometer feedback

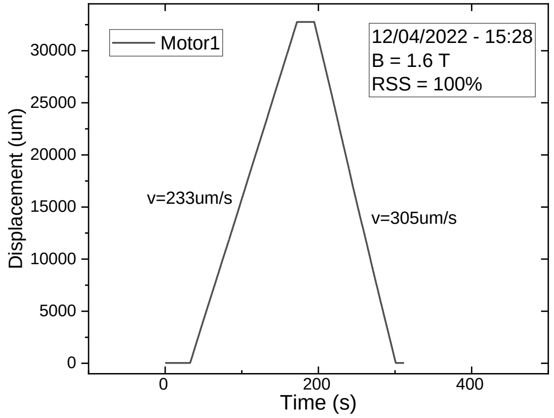




Project200 inside Morpurgo

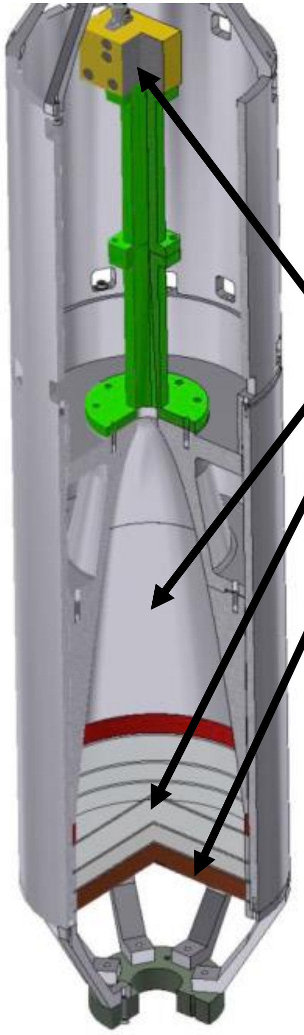
No difference in disk velocity with/without B field





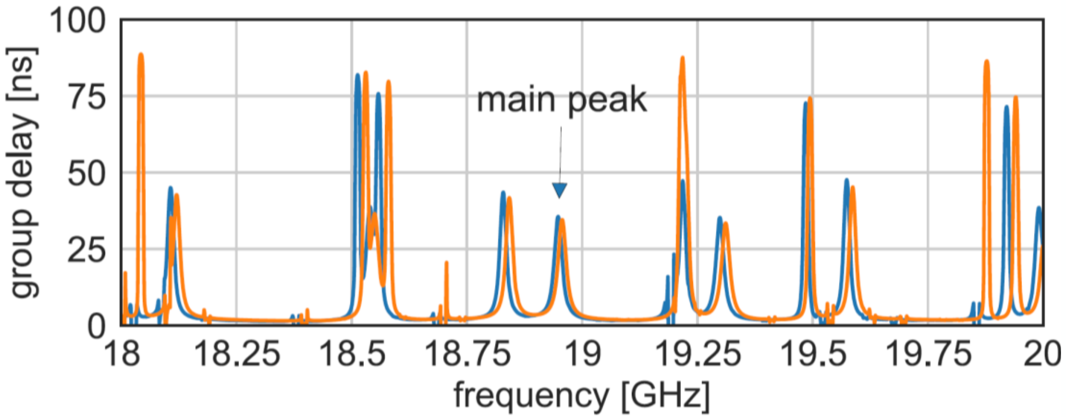
Closed Booster System

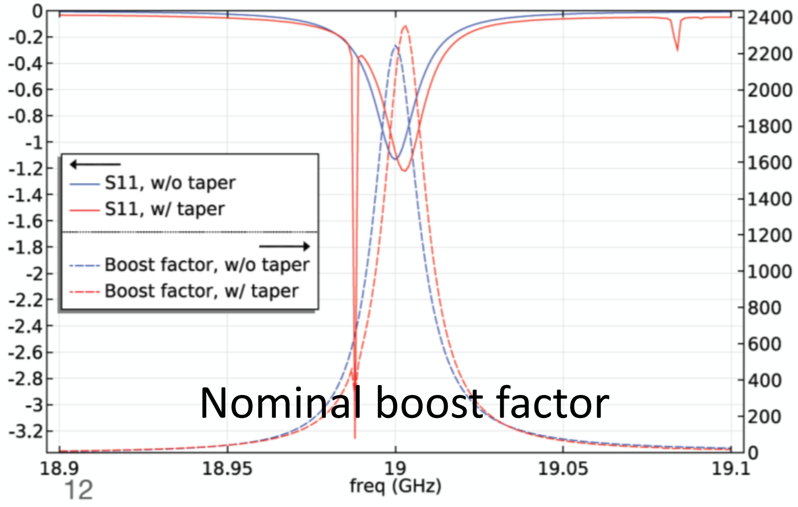
- Simple closed system to understand behaviour
- Can be operated at cryogenic temperatures
- Hidden Photon search and ALP search with Closed Booster 100



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

Simulated vs. measured RF response

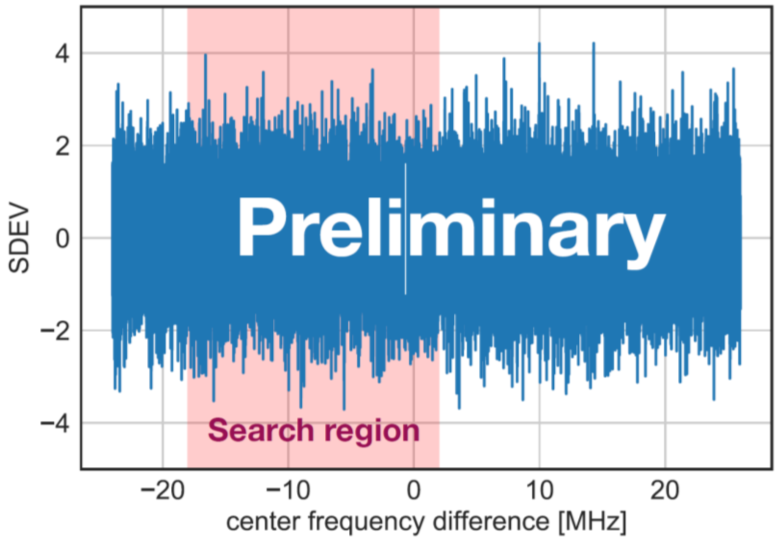




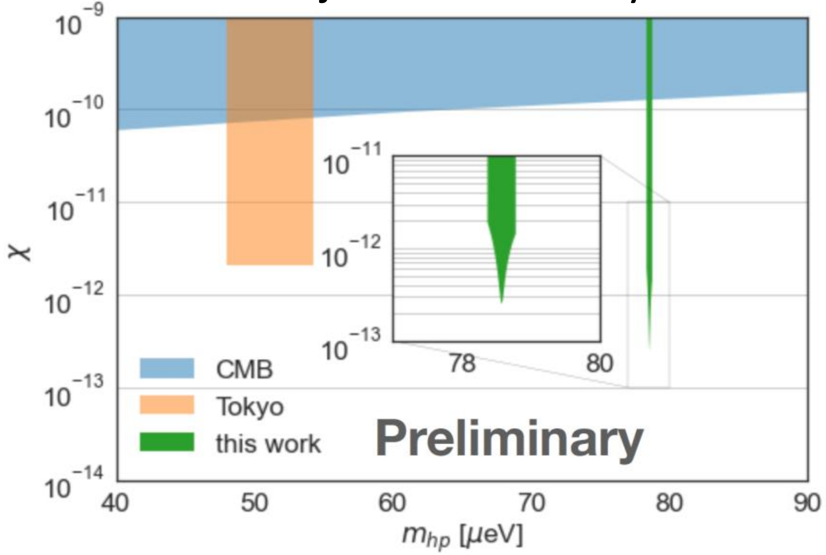
Nominal boost factor

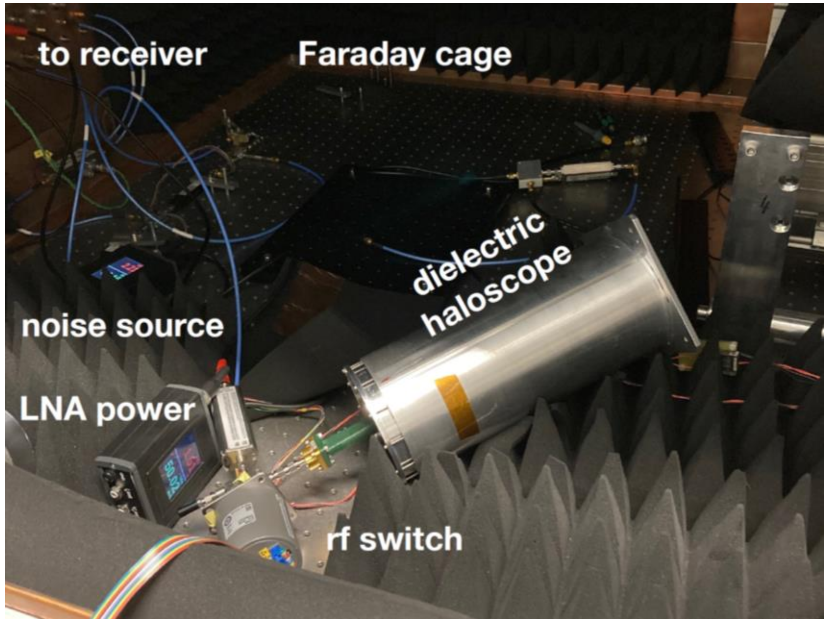
Hidden Photon Search

- Hidden Photon search performed at room temperature at MPP Munich
- Hidden Photon to microwave conversion without B field
- 32 days of data taking
- Noise temperature of ~200 K
- No excess observed in the data



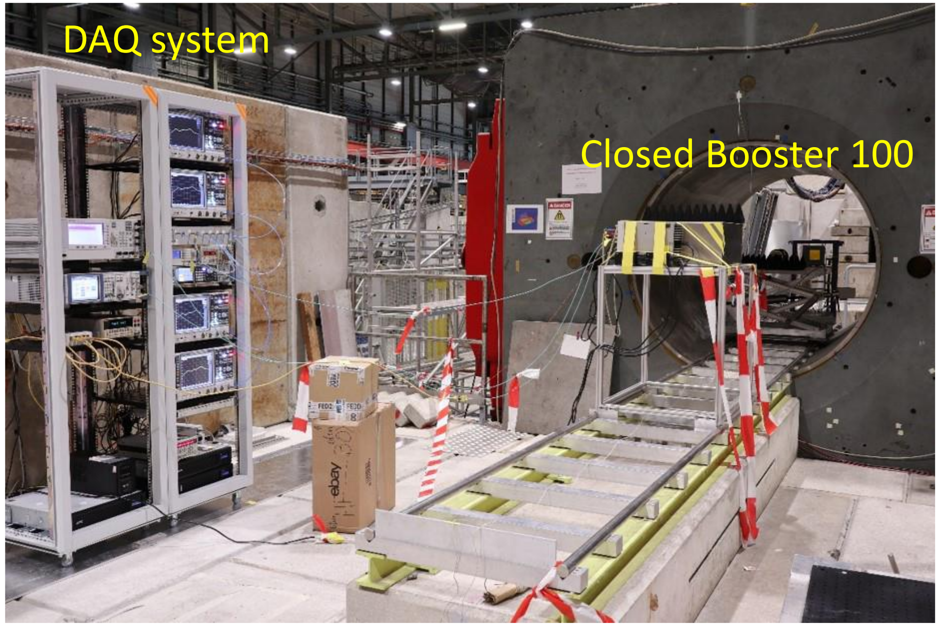
Projected sensitivity

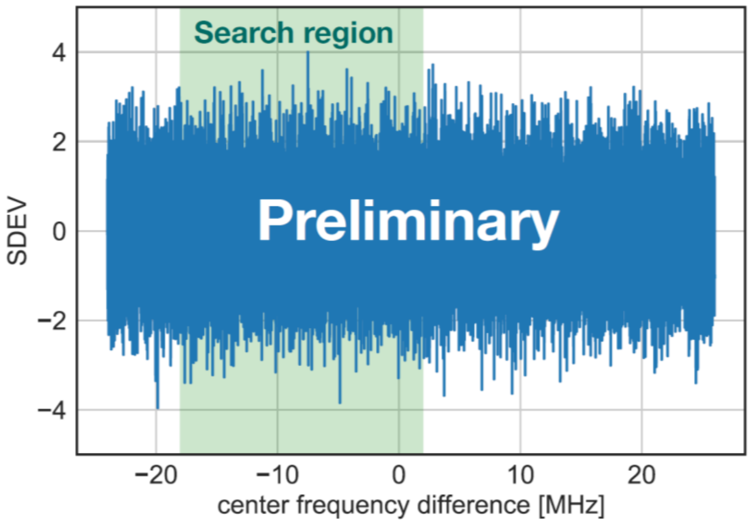




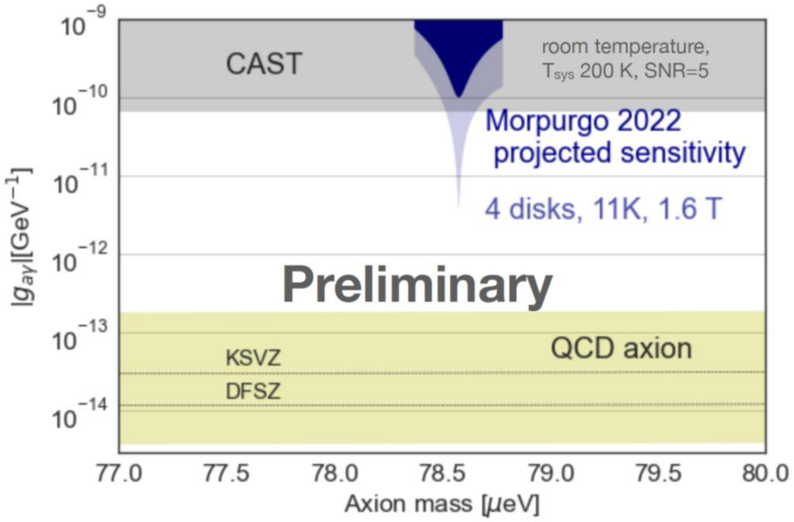
Axion Like Particle Search

- 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
- Possibilities for an upgrade allowing to cool the setup to < 10 K in Morpurgo currently under investigation



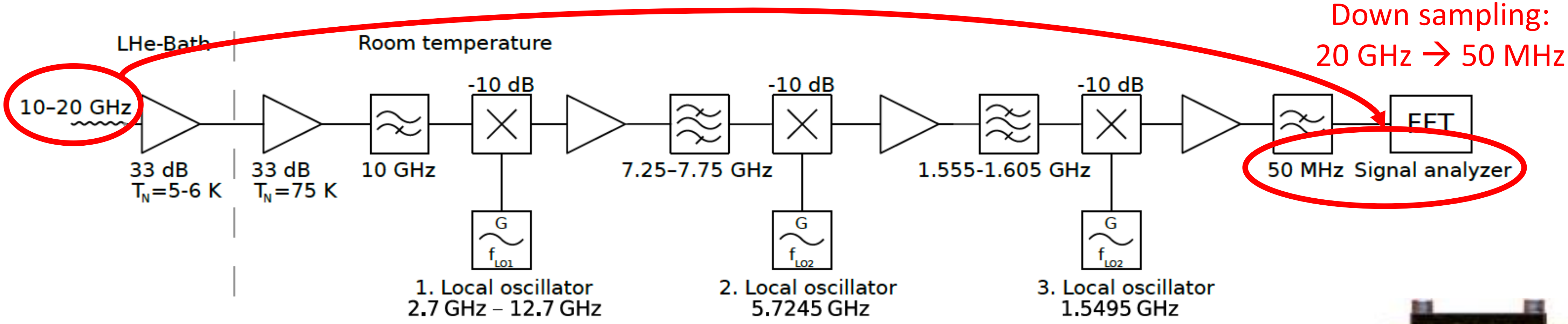


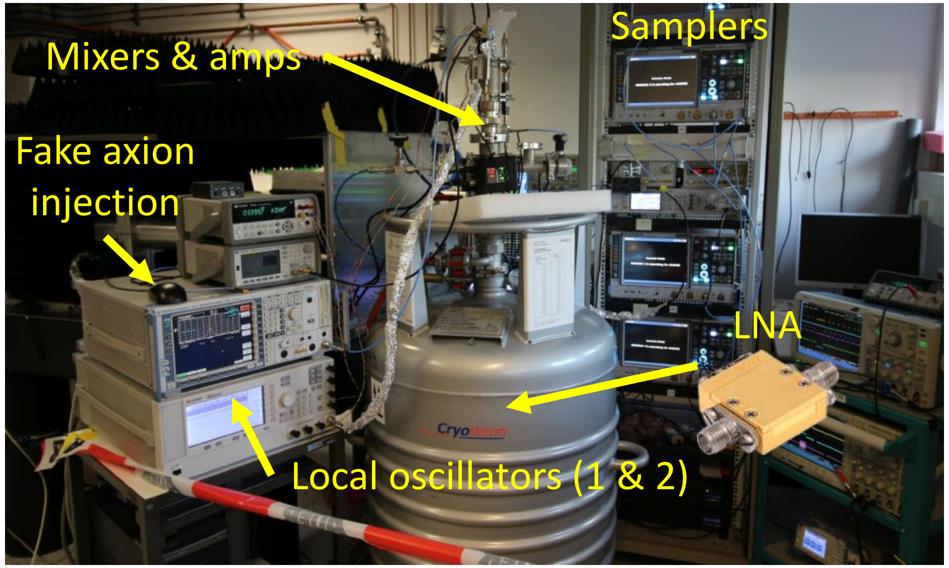
Projected sensitivity



CERN

Receiver Chain





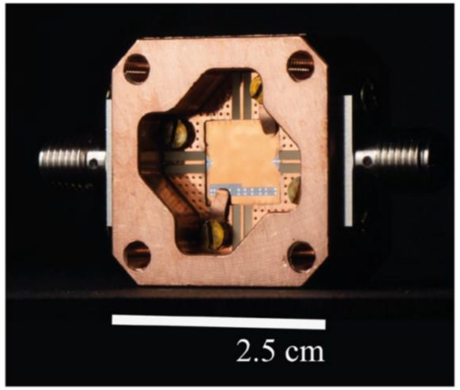
- Receiver chain with low-noise amplifier and three mixing stages
- Amplifiers for high frequencies still have to be developed, e.g. TWPAs for < 40 GHz

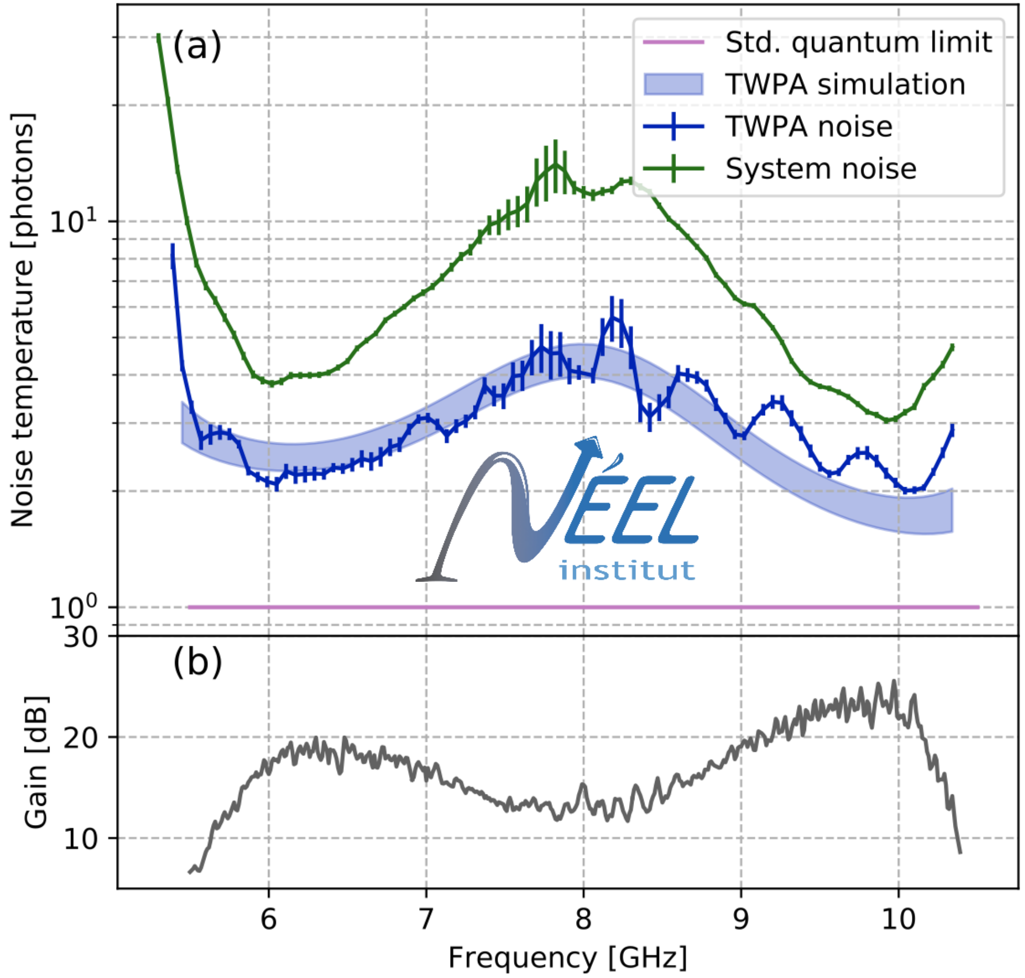
Test setup at MPP with 4 samplers and fake axion injection:
Detection of 1.2×10^{-22} W signal within few days

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

Quantum-limited Amplifier

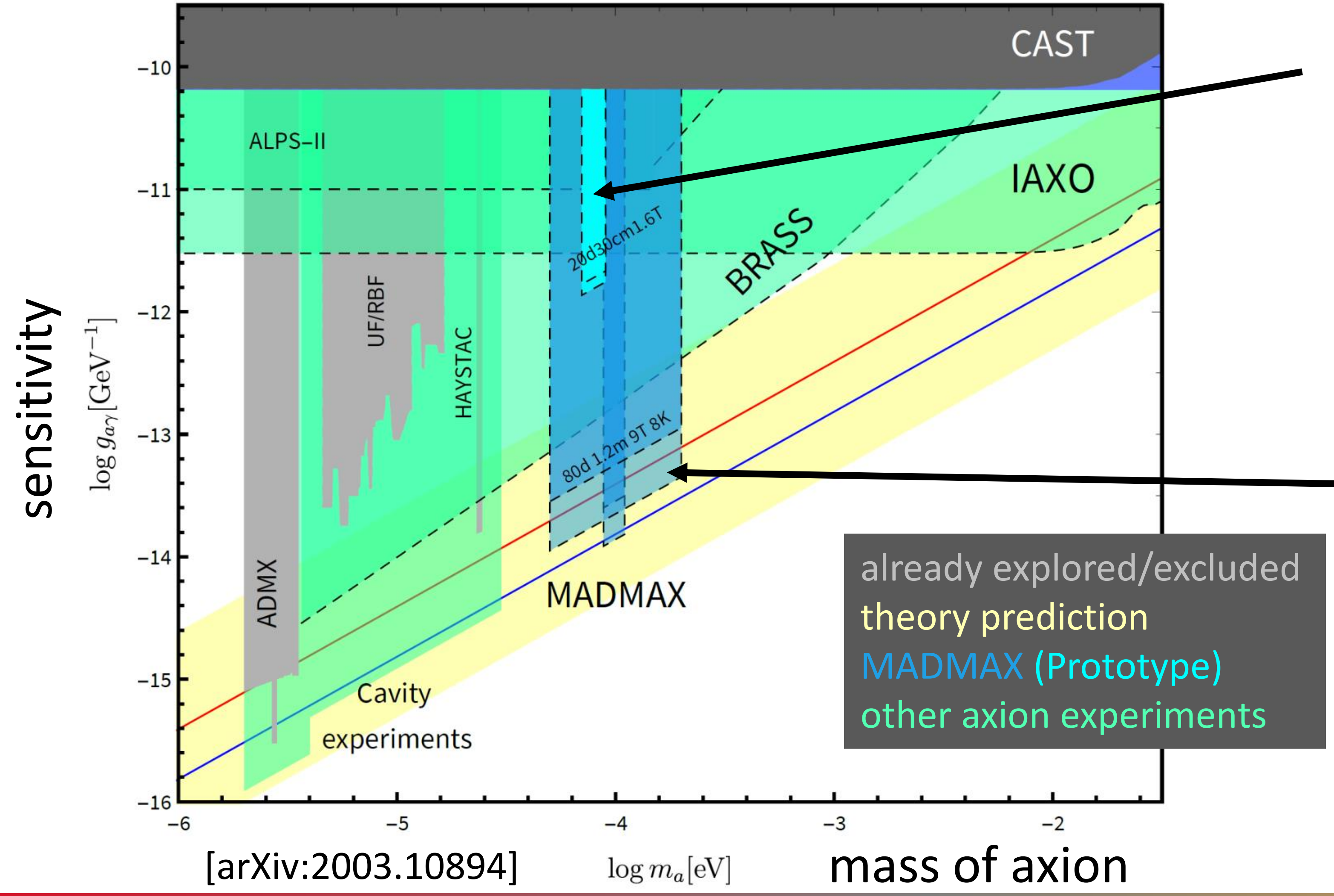
- Traveling wave parametric amplifier (TWPA)
- **First 10 GHz TWPA** produced (PRX 10, 021021)
- Added noise: 1 K above quantum limit
  (20 dB gain @ 10 GHz)
- Future development to 30 GHz





[Reversed Kerr TWPA arXiv:2101.05815]

MADMAX Sensitivity



[arXiv:2003.10894]

MADMAX Prototype:

$$N_{\text{disk}} = 20$$
$$A_{\text{disk}} = 0.07\ \text{m}^2$$
$$B_{\|} = 1.6\ \text{T}$$
$$T_{\text{sys}} = 8\ \text{K}$$

MADMAX:

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

Summary & Outlook

- **MA**gnetized **D**isk and **M**irror **A**xion e**X**periment: dielectric haloscope to detect post-inflationary DM axions
- Hidden Photon and ALP search performed with dielectric haloscope Closed Booster 100 (No excess observed)
- Derive observed limits on HPs and ALPs from Closed Booster 100 measurements
- Commissioning of MADMAX Prototype to start in 2023

Projected sensitivity