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MADMAX

Towards a Dielectric Axion Haloscope

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On behalf of the MADMAX Collaboration

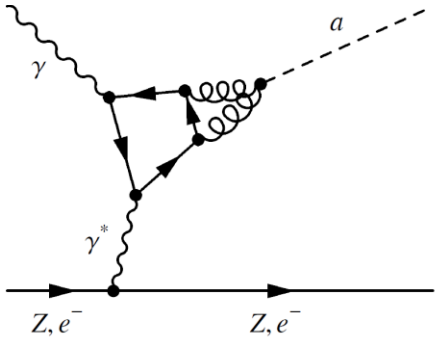
18th June 2021

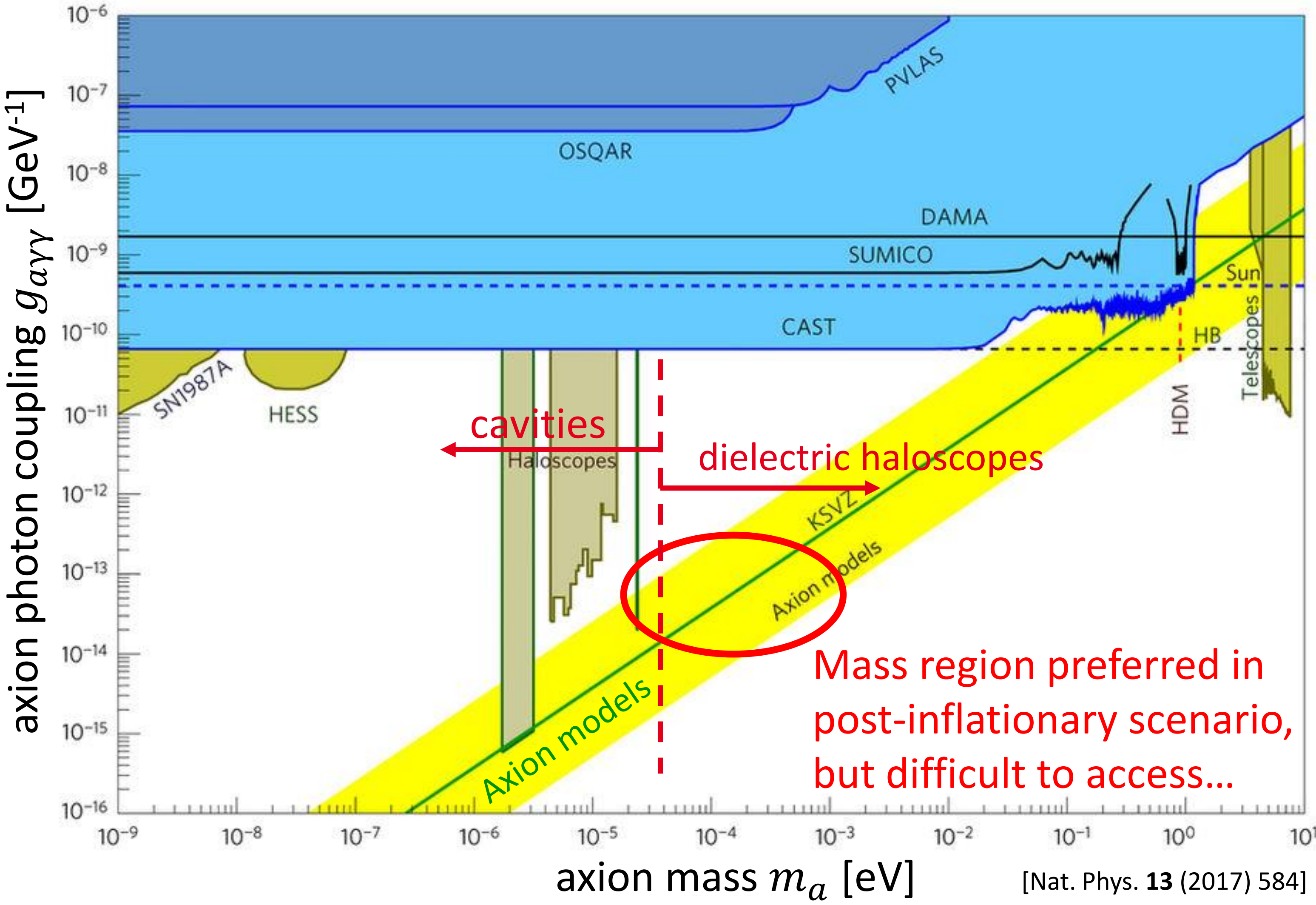
16th Patras Workshop on Axions, WIMPs and WISPs

Trieste/Virtual

Axion Parameter Space

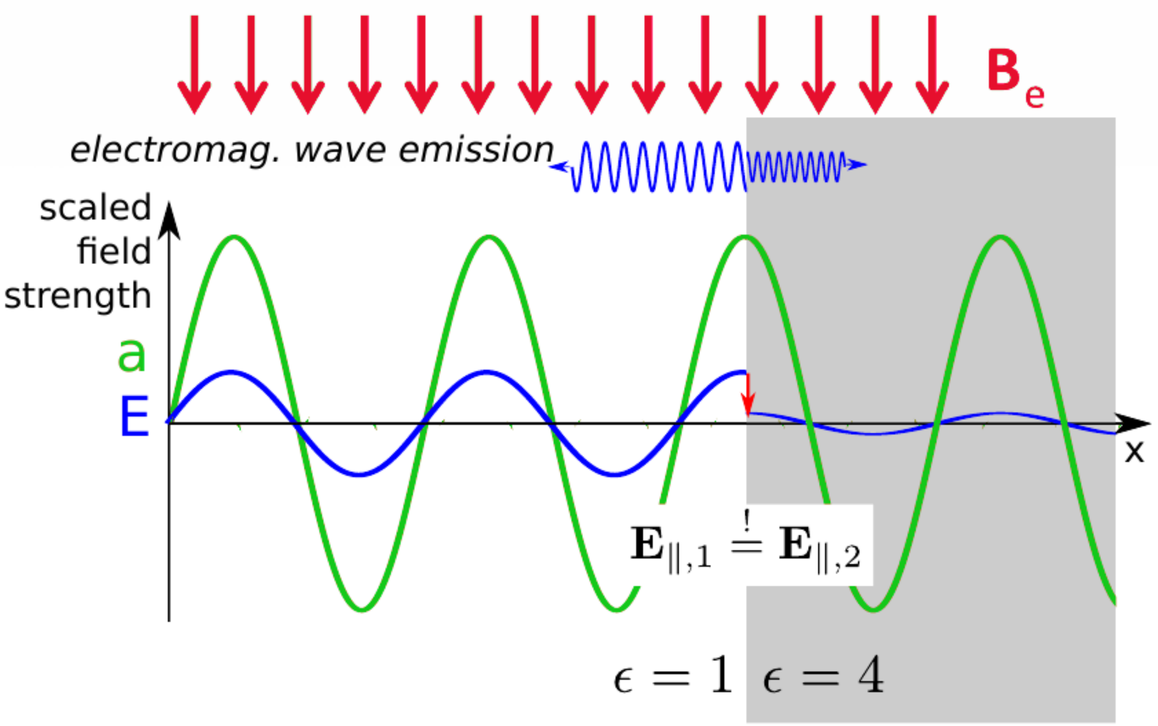
The Axion:
- Pseudo Nambu-Goldstone boson
- Small mass and small couplings
- Connected to solution of the strong CP problem
- Primakoff effect: Photon-Axion conversion in strong EM fields
- **Axion** can explain (part of) **Cold Dark Matter**





[Nat. Phys. **13** (2017) 584]

Dielectric Haloscope



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

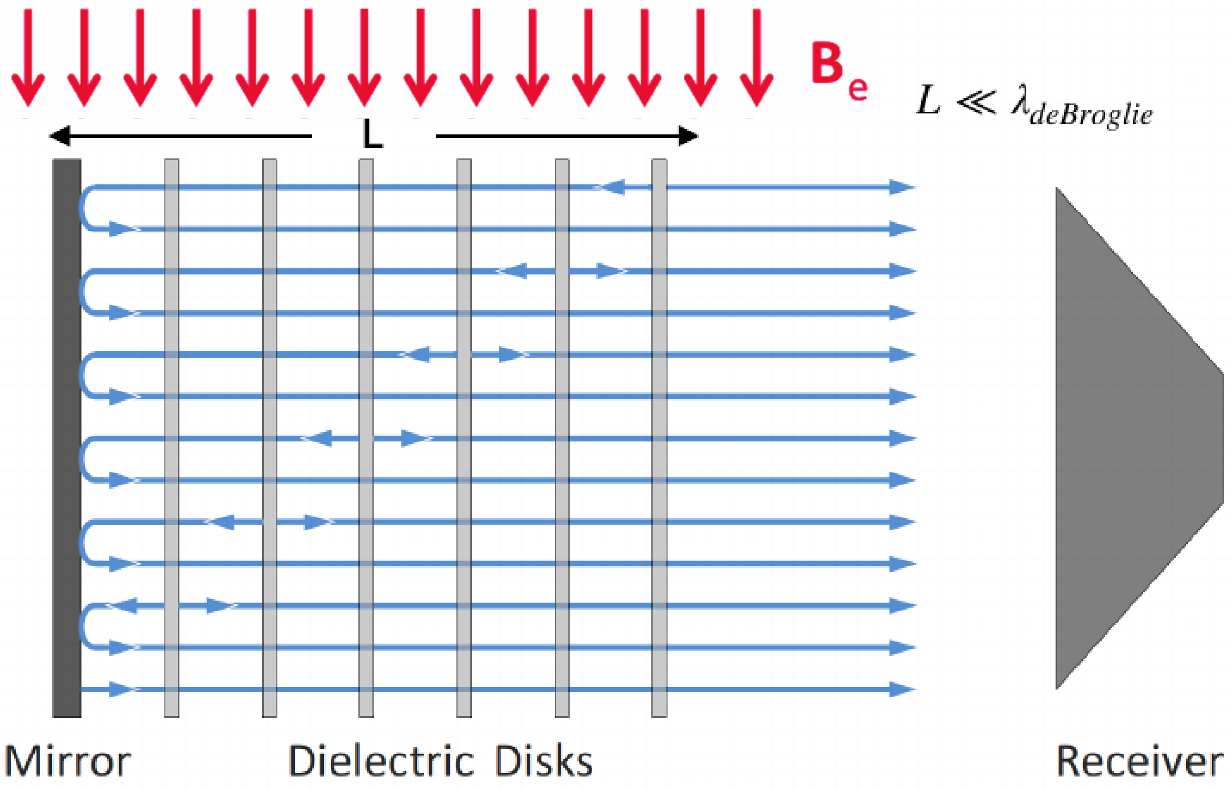
$\boldsymbol{E_a}$ is different in materials with different ε

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:

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

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

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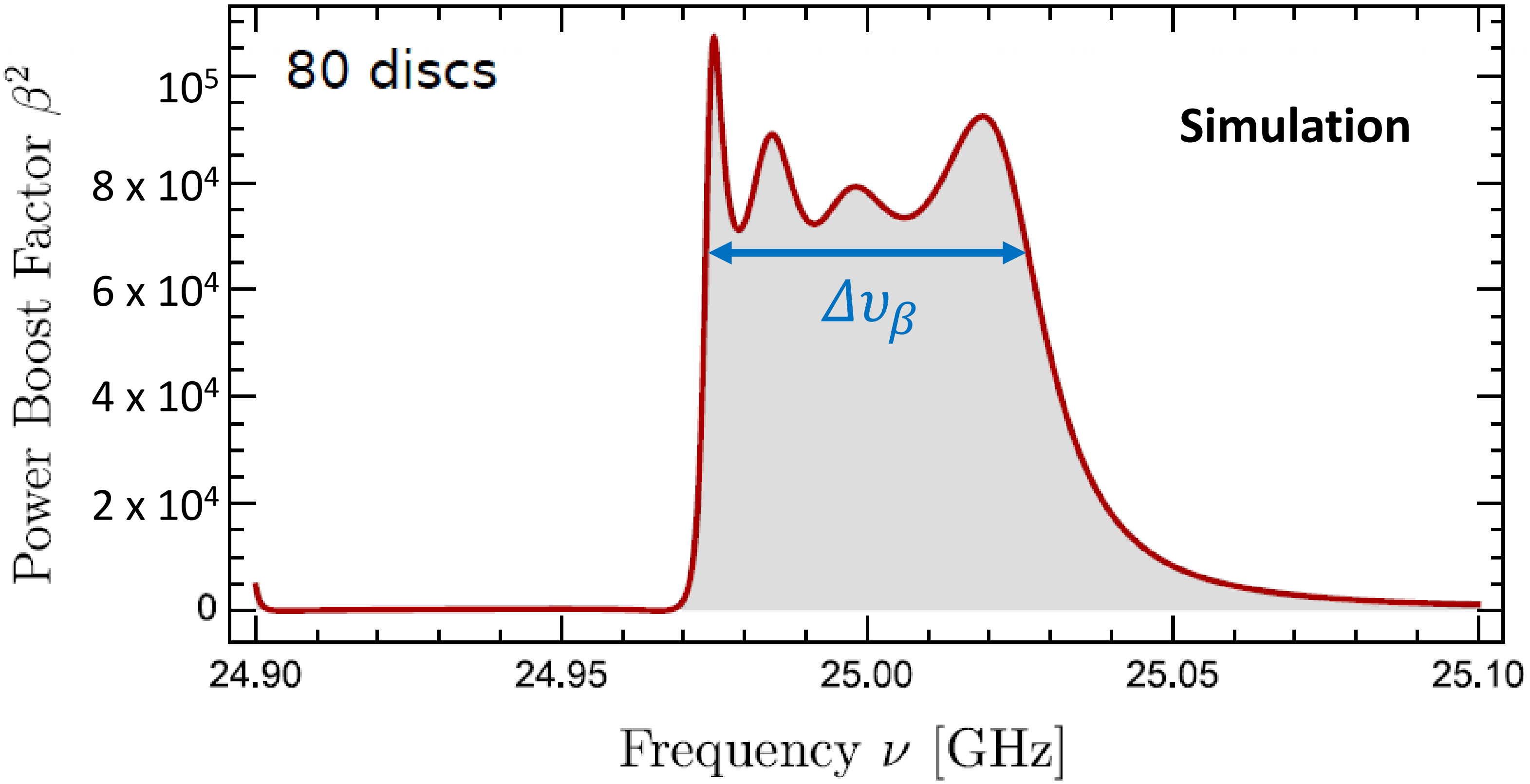
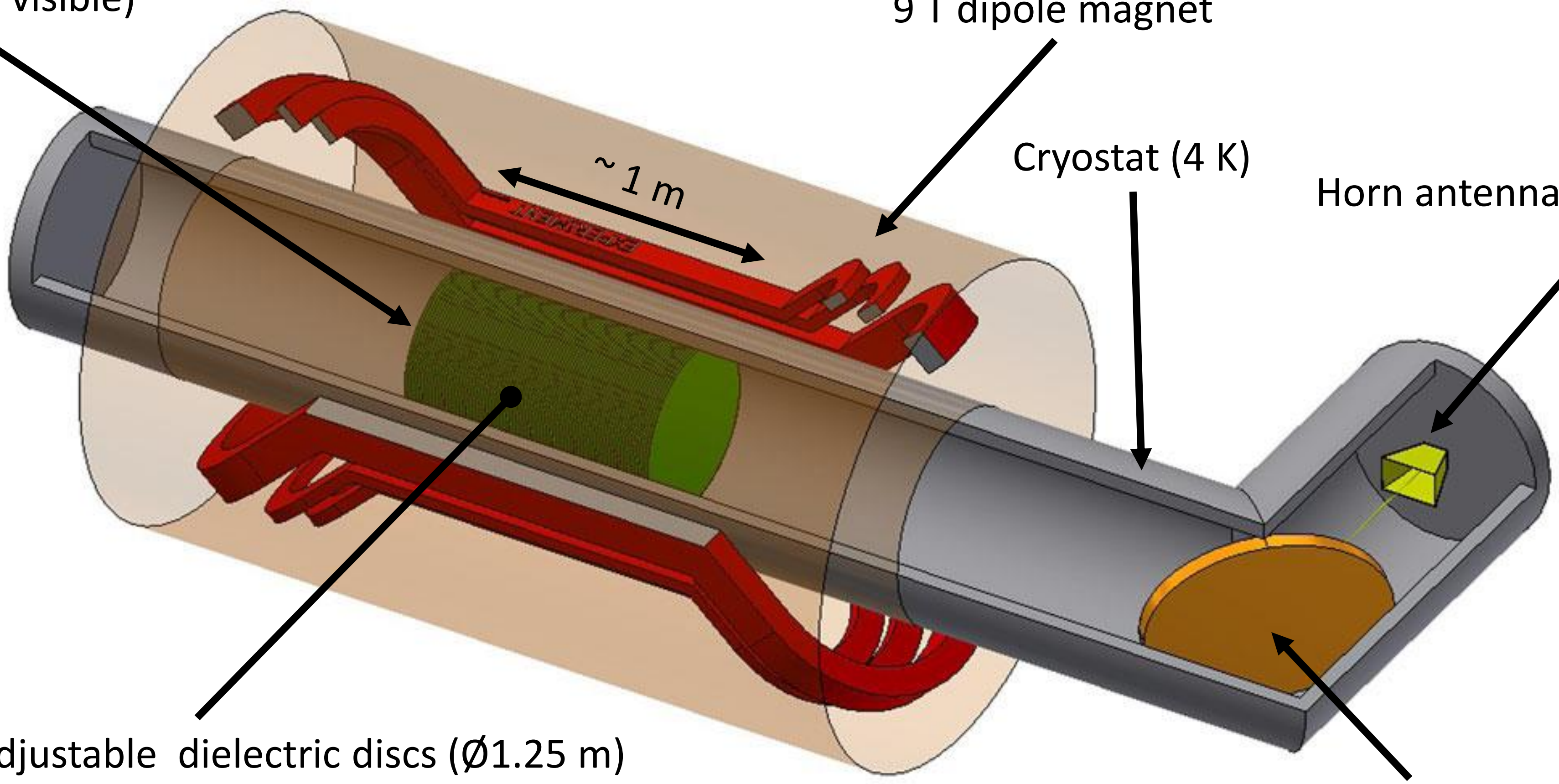
Dielectric Haloscope

- $|\beta^2| > 10^4$ 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 Disc and Mirror Axion eXperiment



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

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The MADMAX Collaboration

Founded 18.10.2017
@ DESY/UHH

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

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Time Scale

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

Design Phase

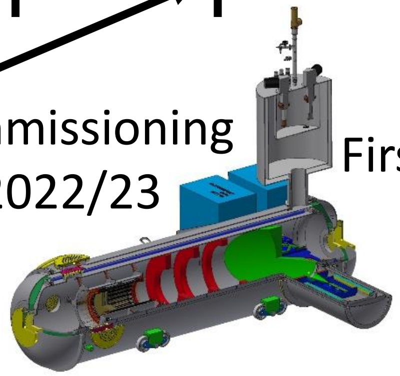
Prototyping Phase

Construction Phase

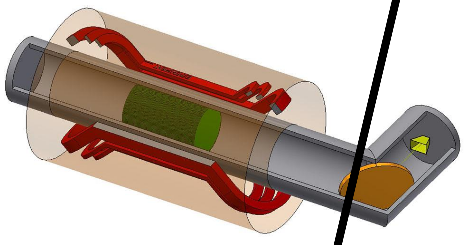
Foundation of MADMAX Collaboration

First endorsement by DESY PRC

Prototype commissioning to start in 2022/23



First physics data taking @ CERN



Full-size MADMAX magnet commissioning

Usage of MORPURGO magnet approved by CERN Research Board for 2021-2024

Designated Experimental Site

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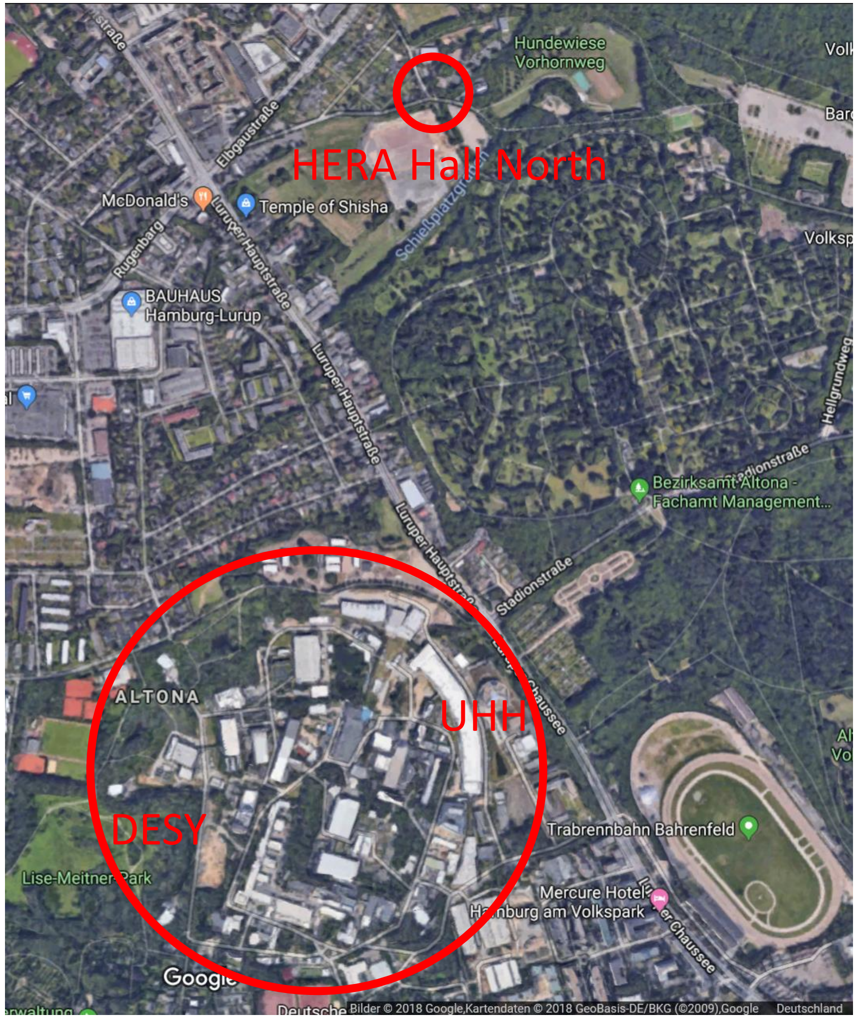
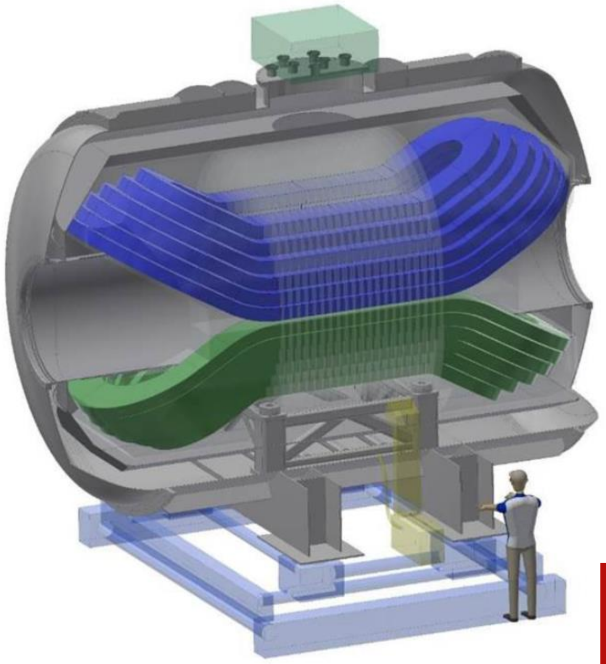


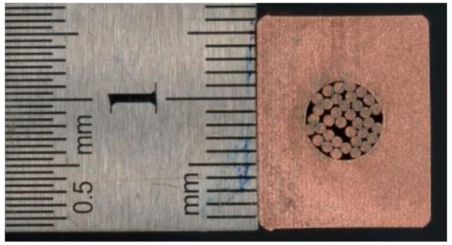
- MADMAX to be built at HERA Hall North
- Make use of DESY infrastructure
- Benefit: re-use H1 yoke as magnetic shielding to reduce fringe field

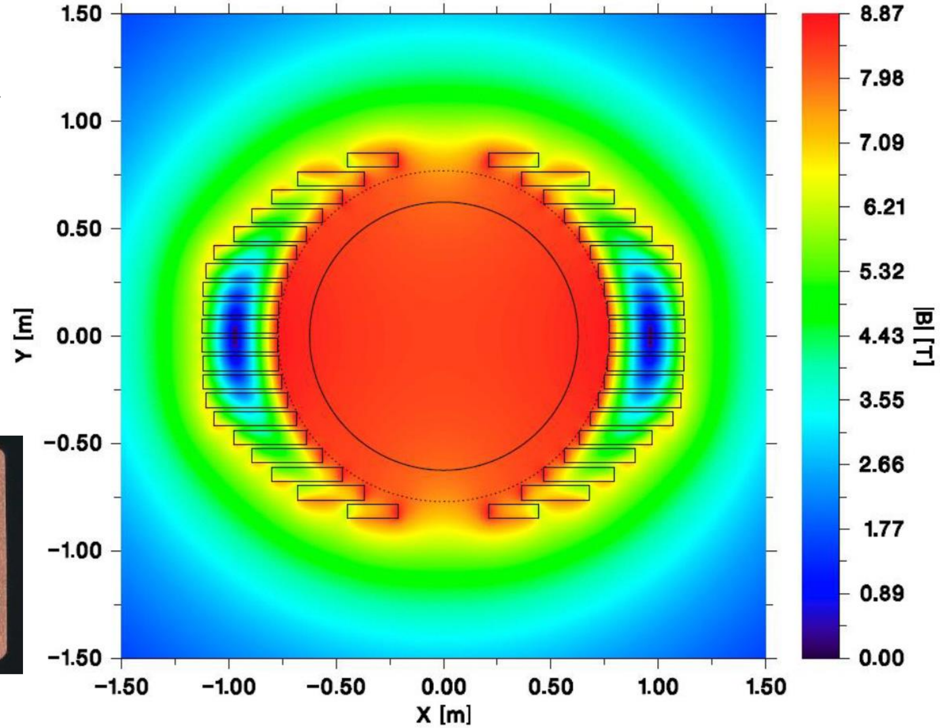
The Magnet



- Innovation Partnership with Bilfinger Noell and CEA Saclay
- Block Design with CICC superconducting cable: NbTi with Cu jacket

BILFINGER
BILFINGER NOELL GMBH
cea
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)



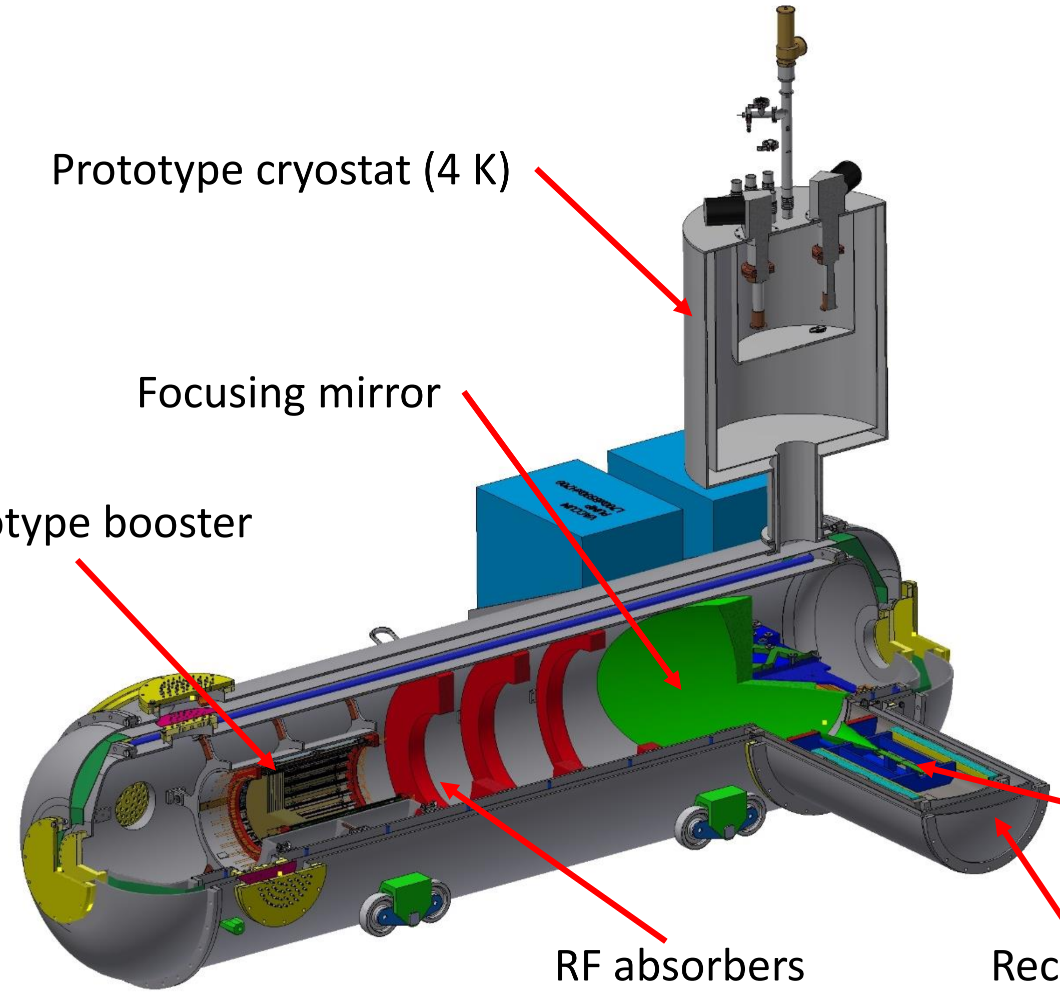


- Magnet design and construction drives the time scale of the project
- **Peak field 9 T**, homogeneity better than 20%
- Warm bore: **Ø 1.35 m**

First of a kind!

$\mathrm{FoM} = B^2 A = 100\ \mathrm{T}^2\ \mathrm{m}^2$

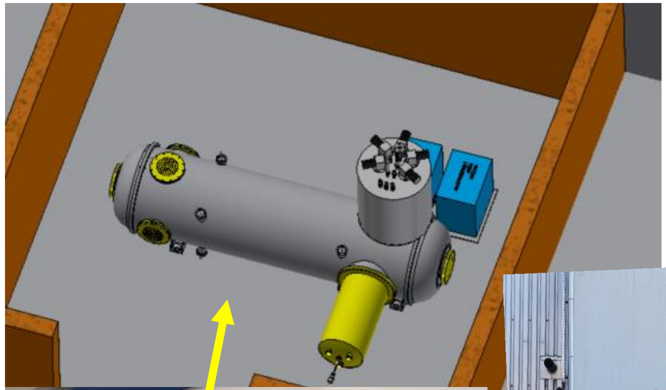
The MADMAX Prototype



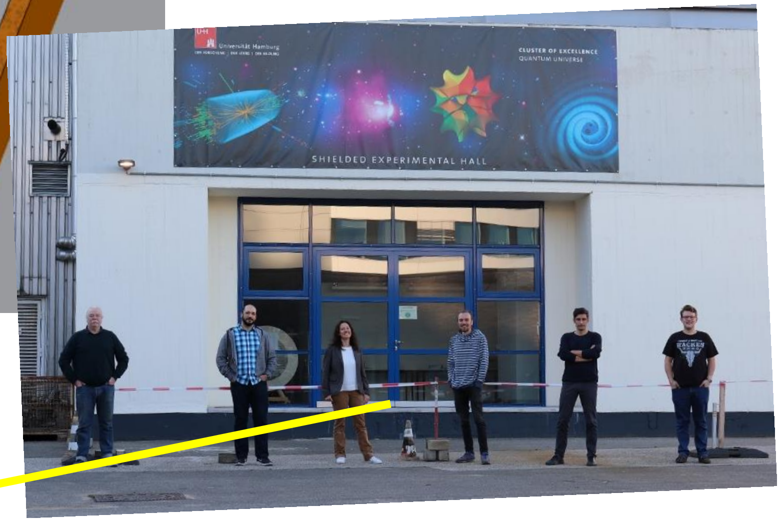
- Down-scaled down version of MADMAX:
  - 1/4 # dielectric disks
  - 1/16 disk area
  - 1/5 magnetic field
- Main goal #1: Demonstrating and prototyping key technologies for MADMAX
- Main goal #2: First axion search with a dielectric haloscope

The MADMAX Prototype

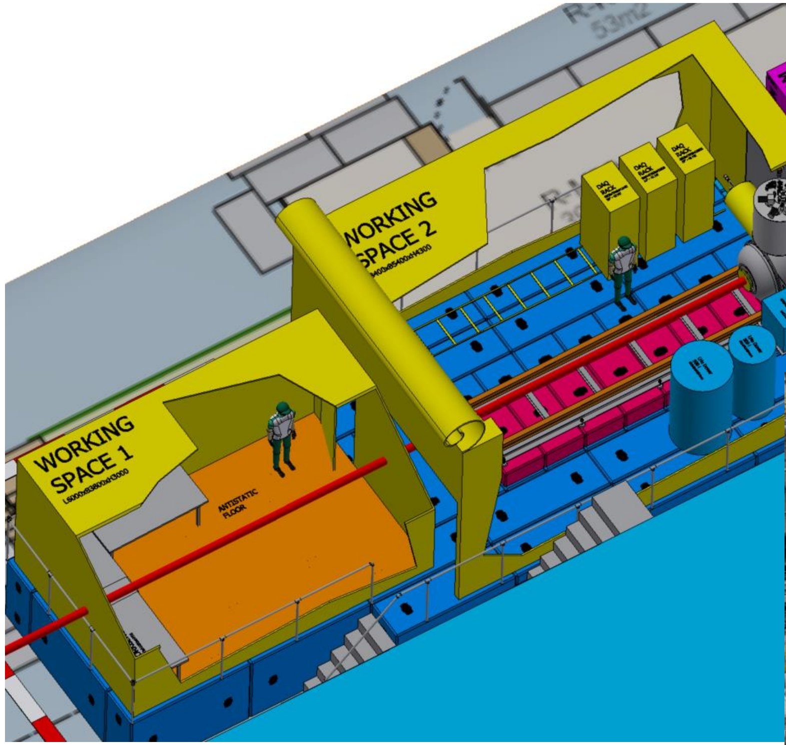
- Gain experience in operation and commissioning in SHELL @ UHH
- First physics measurements in MORPURGO magnet @ CERN

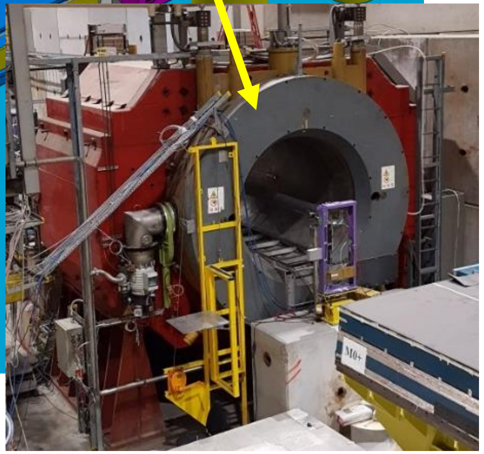


CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE



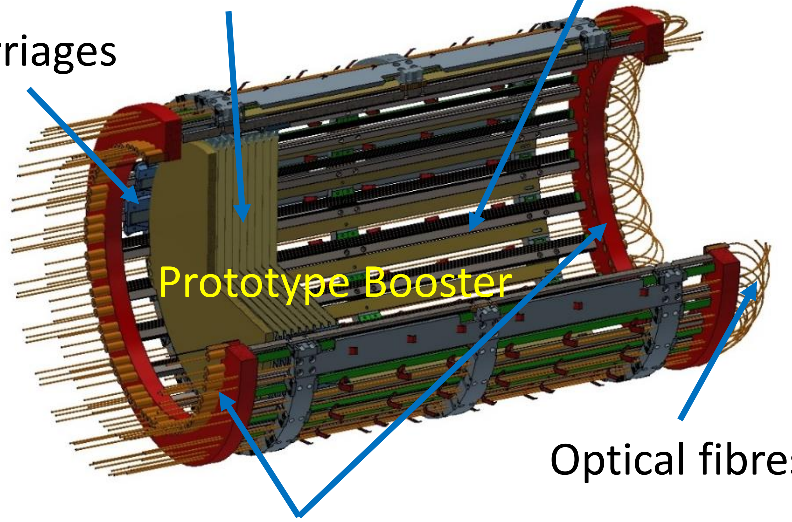
Shielded RF lab SHELL in Hamburg

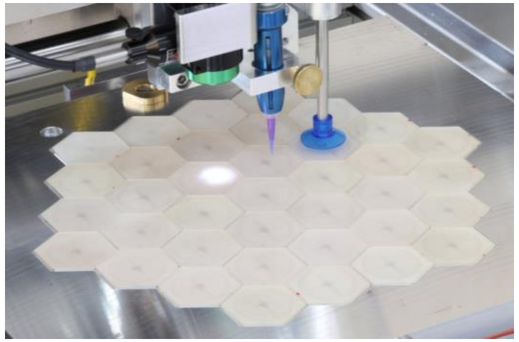


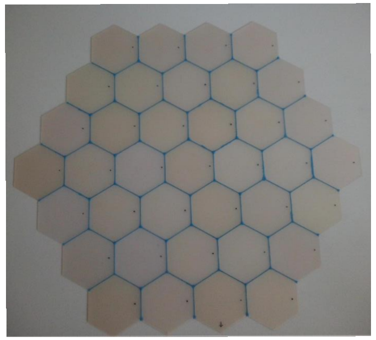


MORPURGO magnet @ CERN

Prototyping the Booster



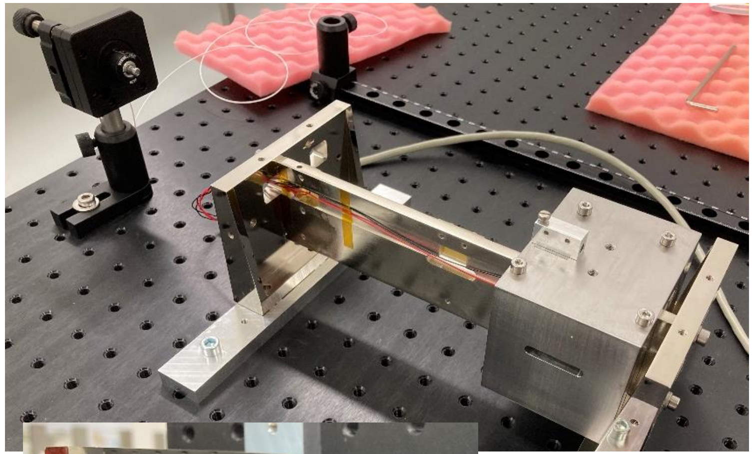


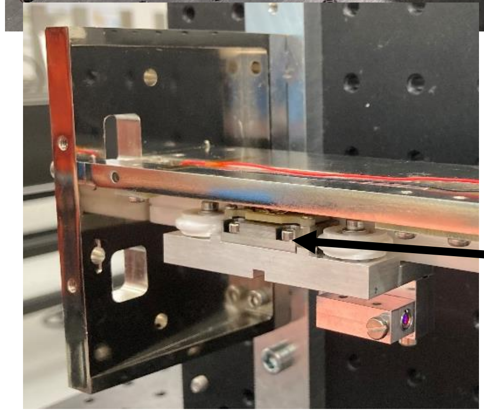


- Booster is the heart of MADMAX
- Need to manipulate many large area disks with precision < 10 µm
- Operating conditions:
  - Cryogenic temperatures: 4 K
  - High magnetic field: up to ~10 T
  - Vacuum
- Long travel range
- Disk weight: 600 g for Ø300 mm
- ➢ **Piezo-driven actuator system with feedback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

Prototype Disk Drive

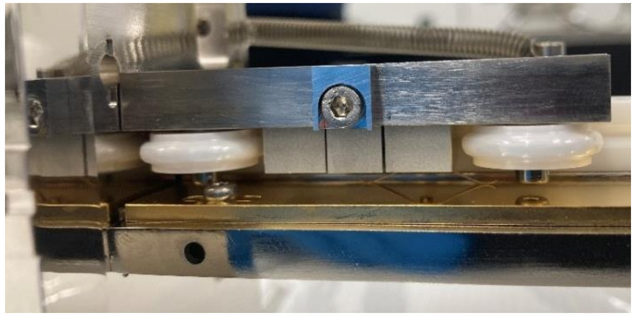


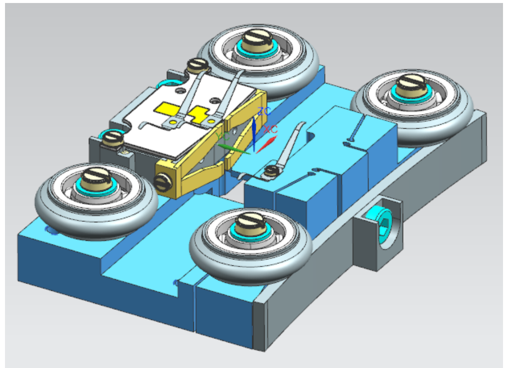


- Carriage on rail driven by piezo actuator (stick-slip principle)
- Successfully tested by manufacturer @ 12 K

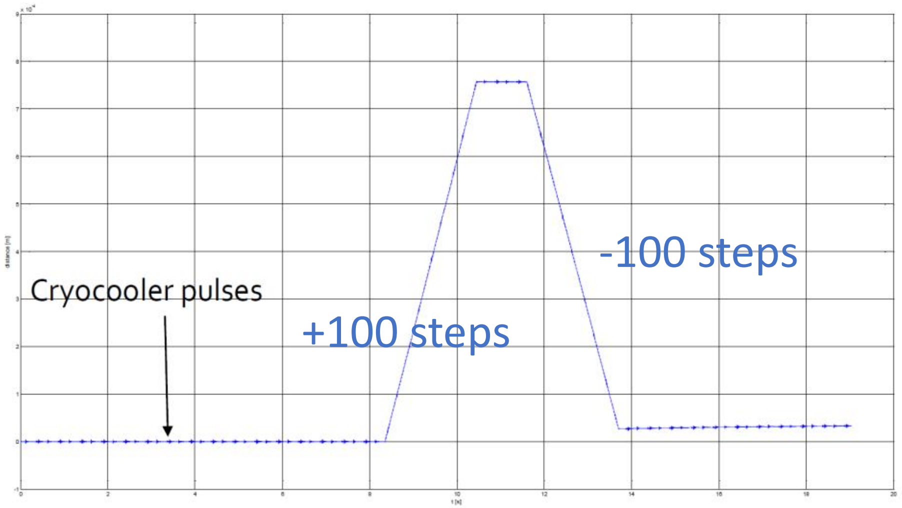
First disk drive unit developed by JPE

Driven by innovation





Disk drive movement @ 12 K

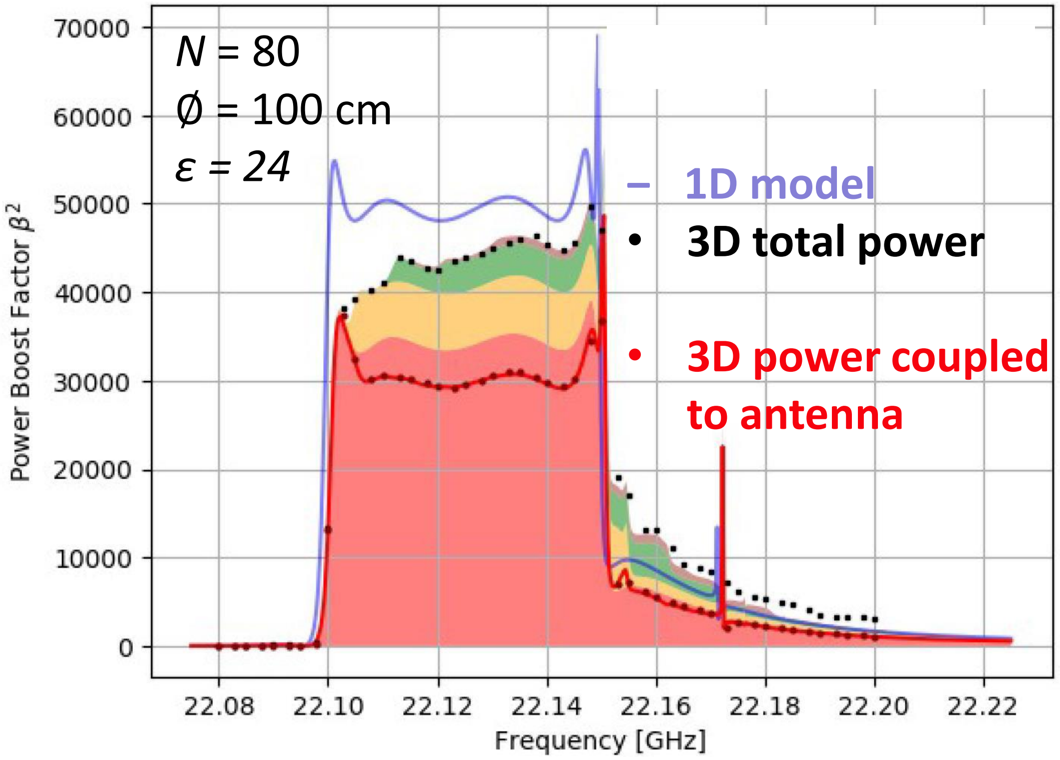


- Room temperature tests confirmed manufacturer results
- Cryogenic tests at MPP Munich currently in progress

System Design Studies

Detector feasibility study and design optimization using simulation of achievable boost factor

- **Geometry factor and coupling to antenna (beam shape)** → **~70 % compared to 1D**
- Dielectric losses → small losses for tan$\delta < 10^{-4}$
- Inaccuracy (position, roughness, tilt, thickness,…) → positioning precision < 10 µm
  roughness < 10 µm
  tilt < 0.1 mrad
  thickness measured to ± 5 µm
- DM velocity dispersion → no significant loss if $v < 10^{-2}$ c
- Tiling of disks



System Design Studies

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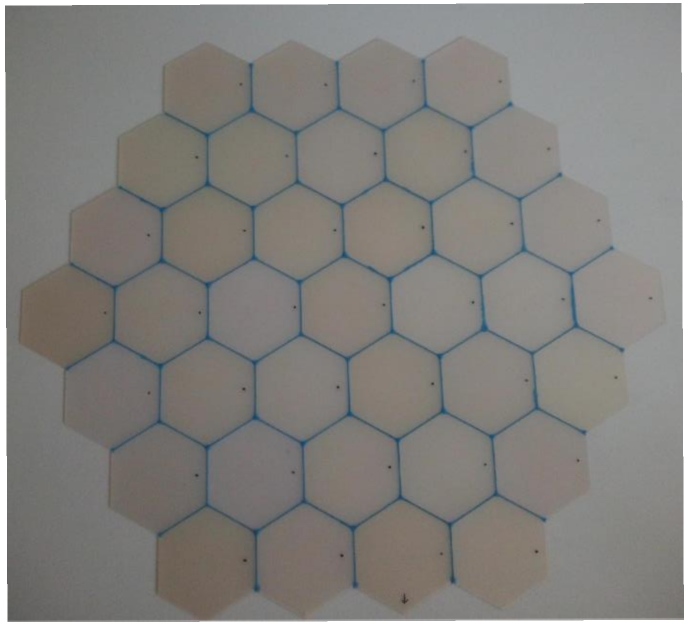
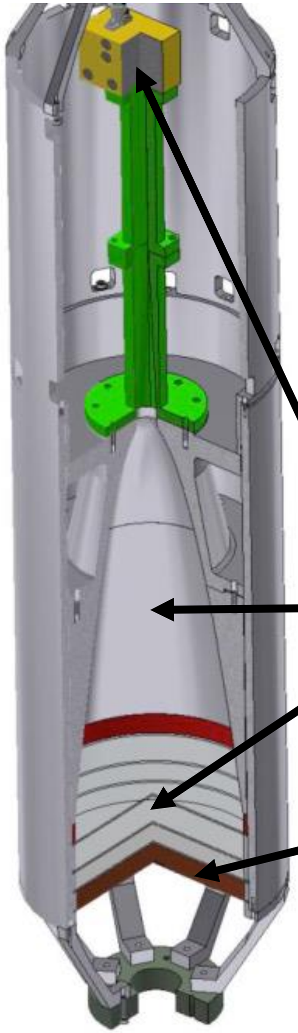
  thickness measured to ± 5 µm
- DM velocity dispersion → no significant loss if $v < 10^{-2}$ c
- **Tiling of discs** → **possibly large impact (very preliminary)**



Closed Booster System



- „Simpler“ closed system to understand behaviour and simulations
- Can be operated at cryogenic temperatures
- Planned operation at MORPURGO at CERN to understand influence of magnetic field on RF measurements

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

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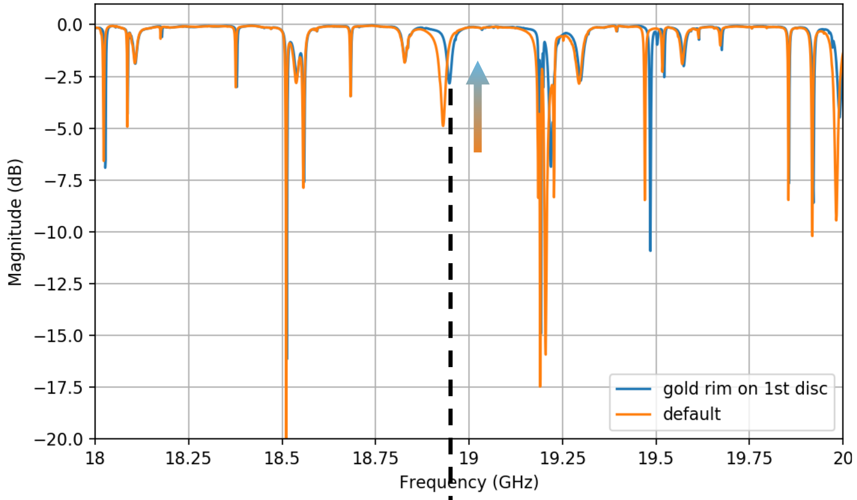
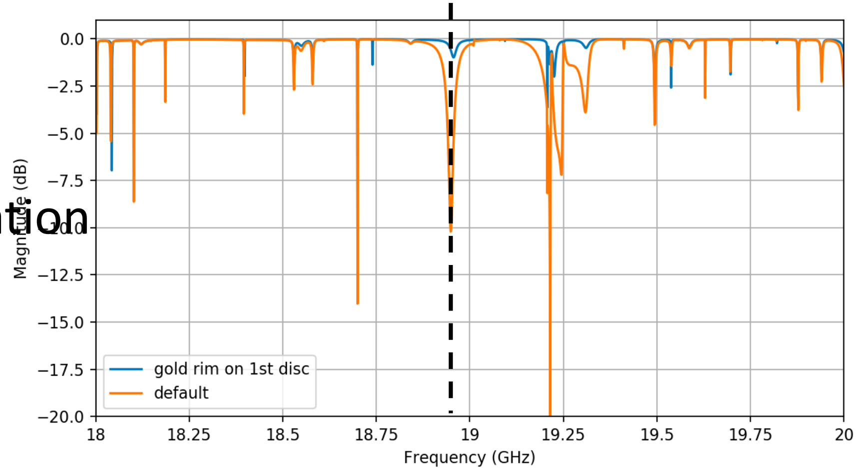
Closed Booster System

Reflectivity

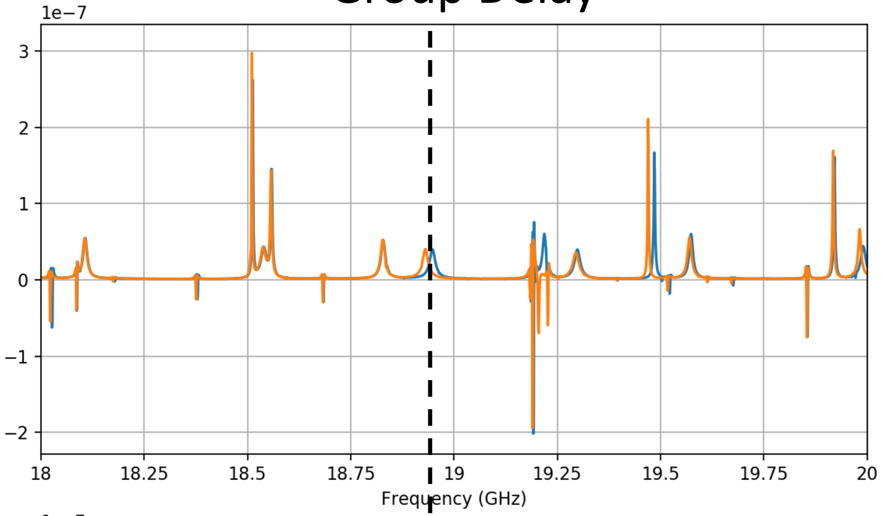
Data

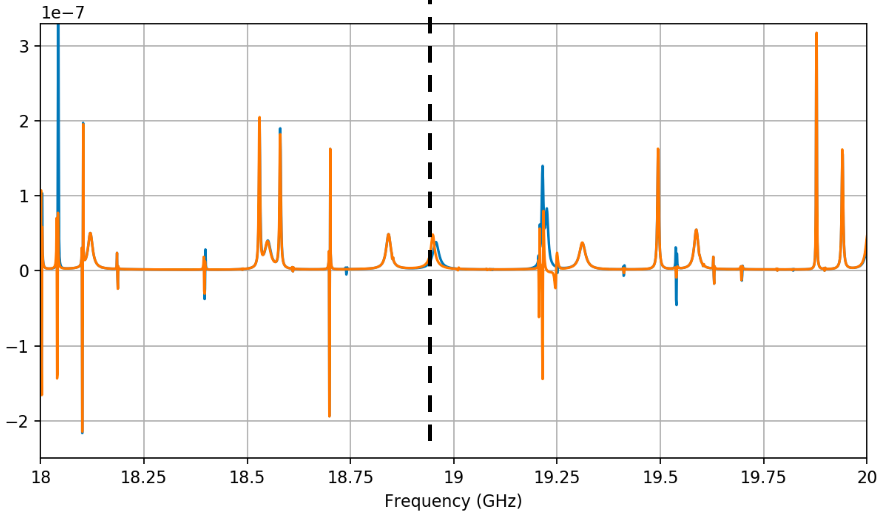


Simulation



Group Delay





Hunting losses:

- Sapphire disks
- Disk with gold coated rim

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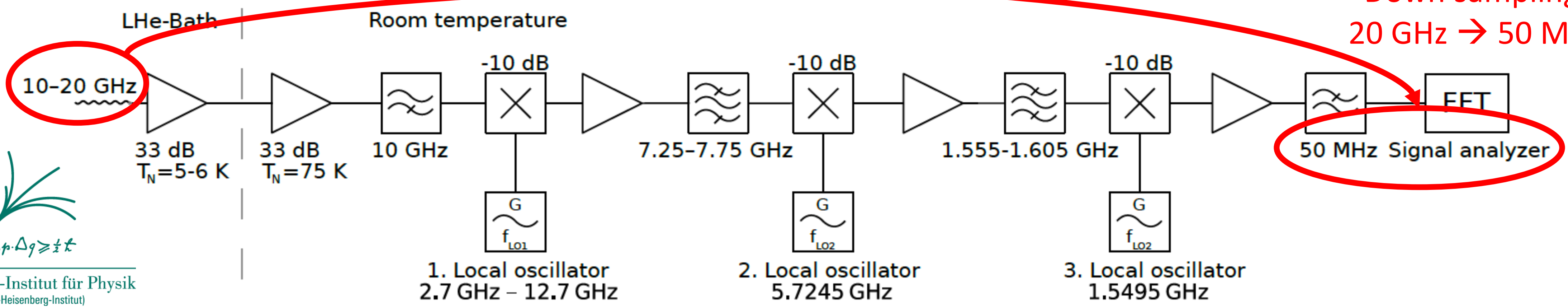
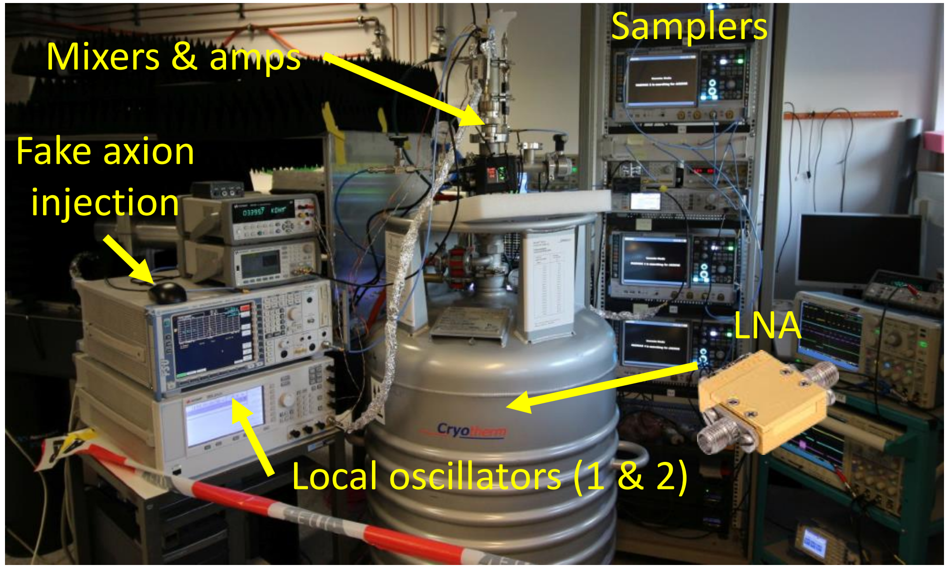
Receiver Chain



Down sampling:
20 GHz → 50 MHz



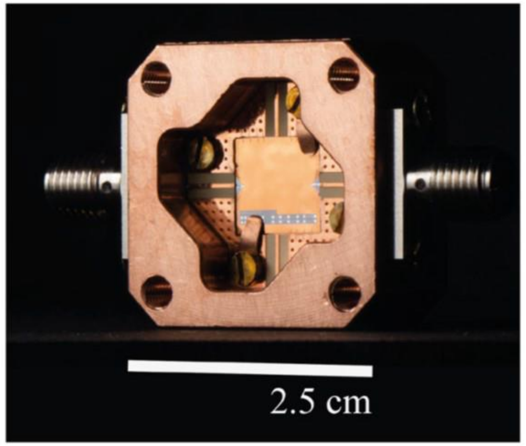
- Receiver chain with low-noise amplifier and three mixing stages
- Amplifiers for high frequencies (> 40 GHz) still have to be developed, e.g. TWPAs

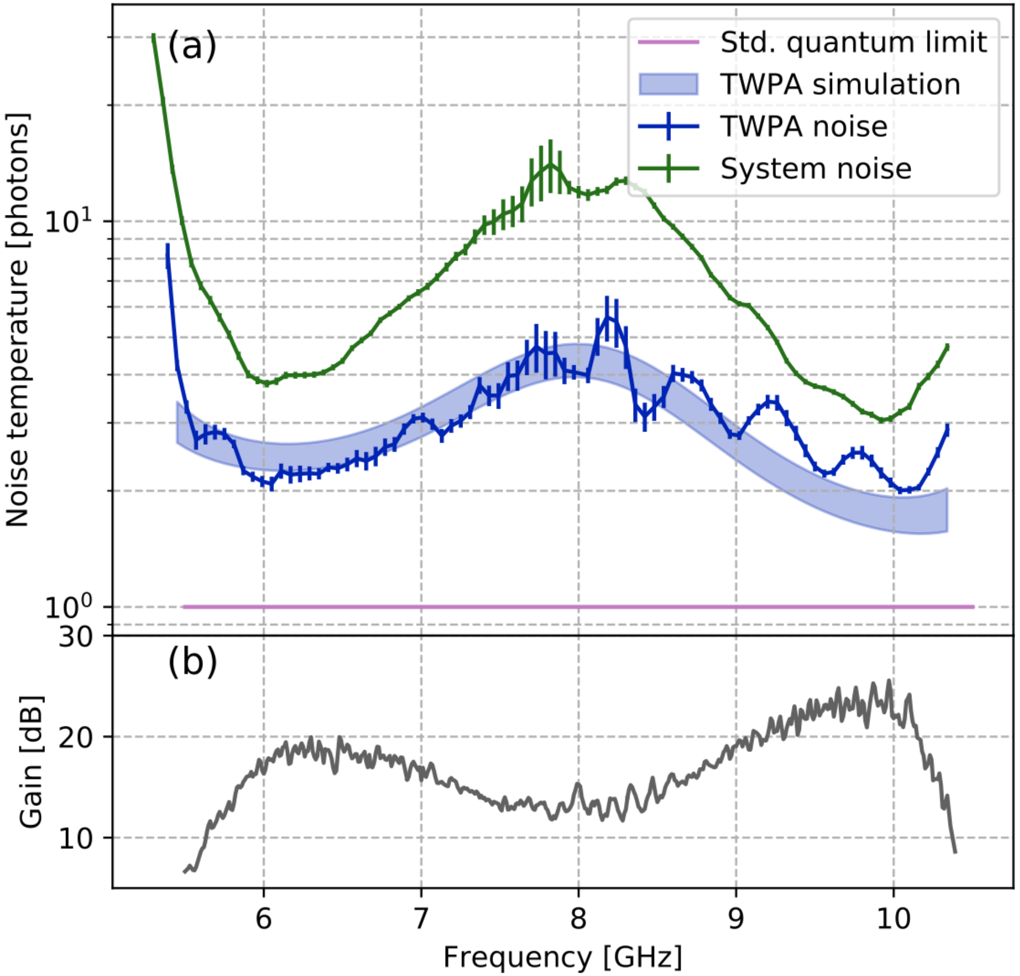
Test setup at MPP with 4 samplers and fake axion injection:
Detection of 1.2×10^{-22} W signal within few days

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

Quantum-limited Amplifier

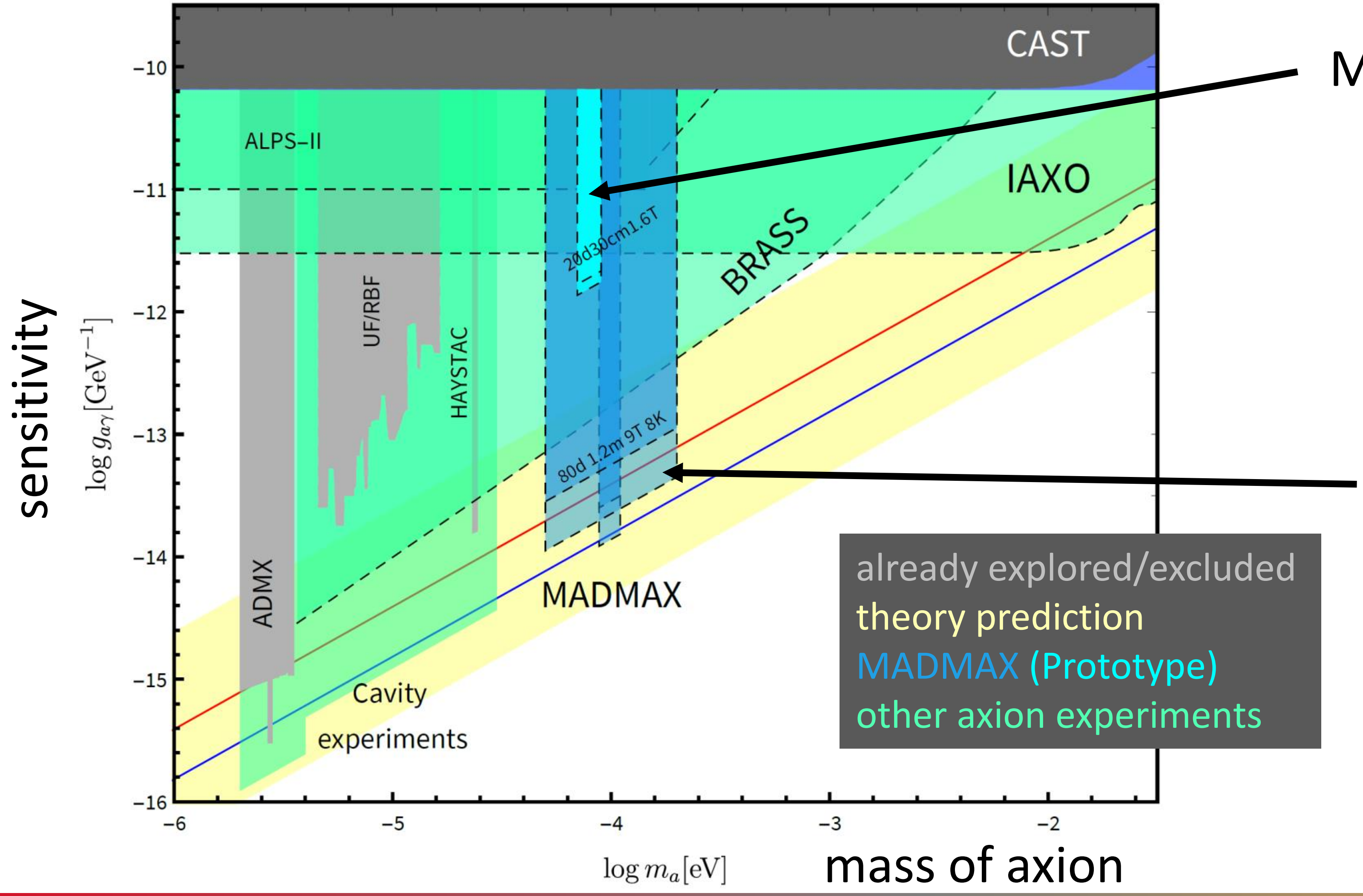
- Traveling wave parametric amplifier (TWPA)
- **First 10 GHz TWPA** produced (PRX 10, 021021)
- 1K noise temp, 20 dB gain @ 10 GHz
- Future development to 30 GHz





[Reversed Kerr TWPA arXiv:2101.05815]

MADMAX Sensitivity



MADMAX Prototype:

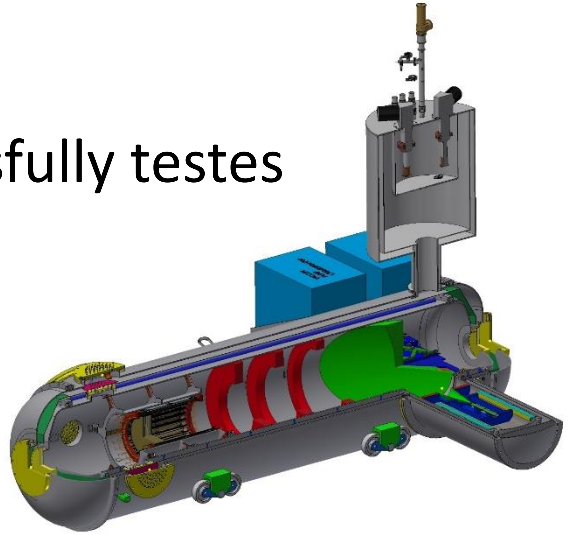
$N_{\text{disk}} = 20$
$A_{\text{disk}} = 0.07\ \text{m}^2$
$B_{\parallel} = 1.6\ \text{T}$
$T_{\text{sys}} = 8\ \text{K}$

MADMAX:

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

Summary & Outlook

- **MA**gnetized **D**isk and **M**irror **A**xion e**X**periment: a dielectric haloscope to detect post-inflationary dark matter axions
- MADMAX is now in the beginning of the prototyping phase
- Key progress so far:
  - Booster disk drive system: piezomotor and interferometer successfully testes
  - Gained understanding of the Closed Booster System
  - Magnet R&D ongoing: so far no show stoppers!



- Prototype to be commissioned in SHELL @ UHH in 2022/23
- First physics measurements with prototype at CERN (MORPURGO magnet)
- Commissioning of full-size MADMAX at DESY in HERA Hall North starting ≥ 2028