MADMAX

A Dielectric Haloscope Experiment

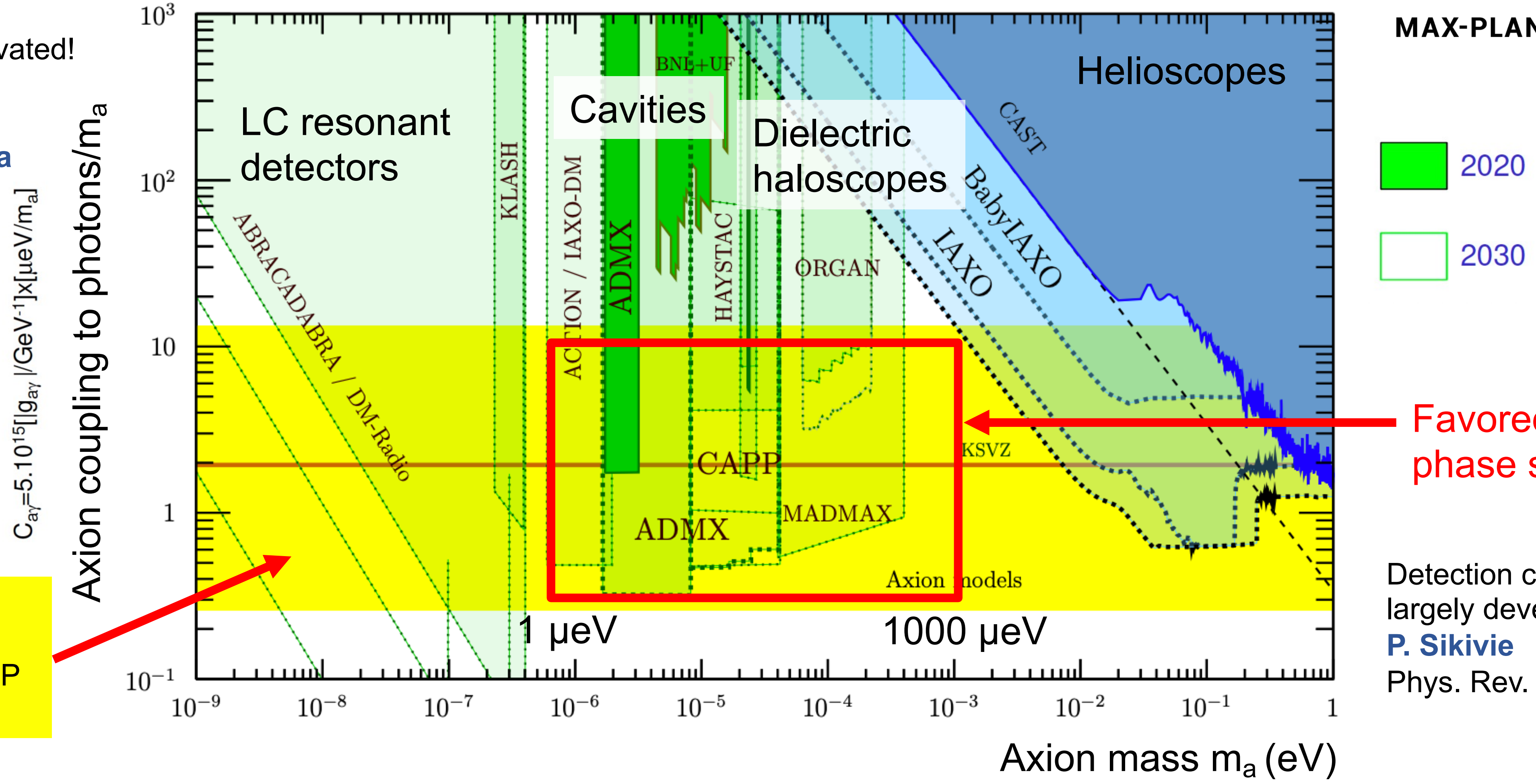
Derek A. Strom
Max Planck Institute for Physics, Munich, DE
On behalf of the MADMAX collaboration

Kashiwa Dark Matter Symposium, Kashiwa, Japan
December 2, 2022

- **Short Motivation**
- **Dielectric Haloscope Concept**
- **The MADMAX Experiment**
- **Recent progress in “closed booster” prototypes**

Motivation

Axions are well motivated!
See talks by:
Wen Yin
Kazunori Nakayama



Favored Axion DM phase space

Yellow band:
QCD axion
- Solving Strong CP problem

Detection concepts largely developed by **P. Sikivie**
Phys. Rev. Lett. **51**, 1415

- Limited region of Axion DM phase space explored by cavity experiments (e.g. ADMX)
- Higher mass region (i.e. 10 – 1000 µeV) still mostly unexplored
- Promising R&D in **dielectric haloscopes** for probing the high mass region (40-400 µeV)

Dielectric Haloscope Concept

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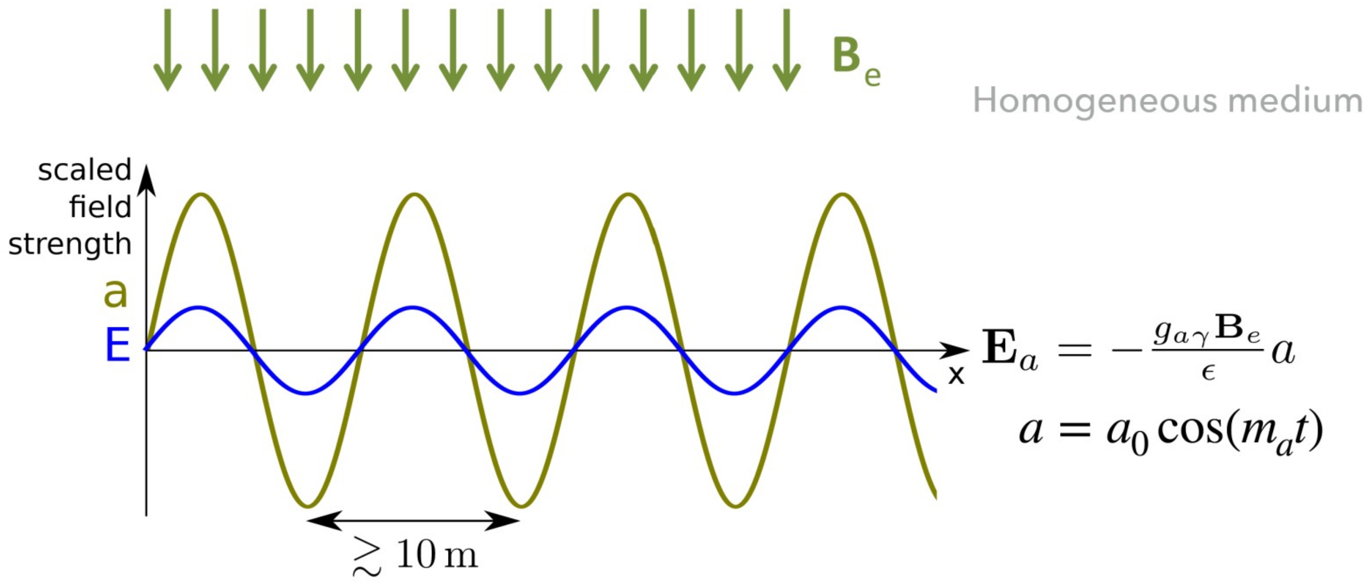
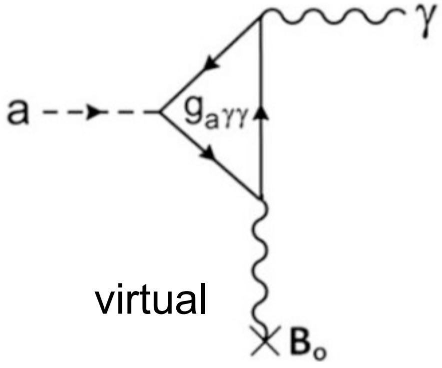


$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

$$a = a_0\cos(m_a t)$$

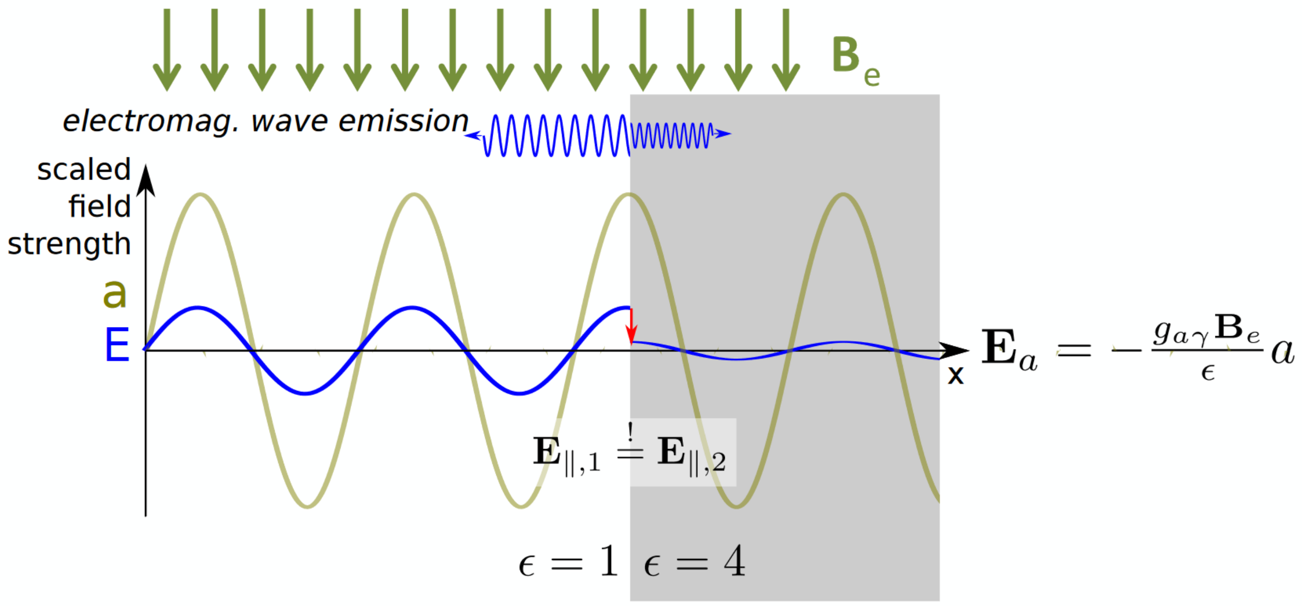
The axion field a(t) sources an oscillating electric field E_a in the presence of an external magnetic field B_e

Primakoff effect
Axion to photon conversion in presence of B-field



e.g. 100 μeV axion → 25 GHz photon

Dielectric Haloscope Concept



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

The axion field a(t) sources an oscillating electric field E_a in the presence of an external magnetic field B_e

E_a is different in materials with different ε

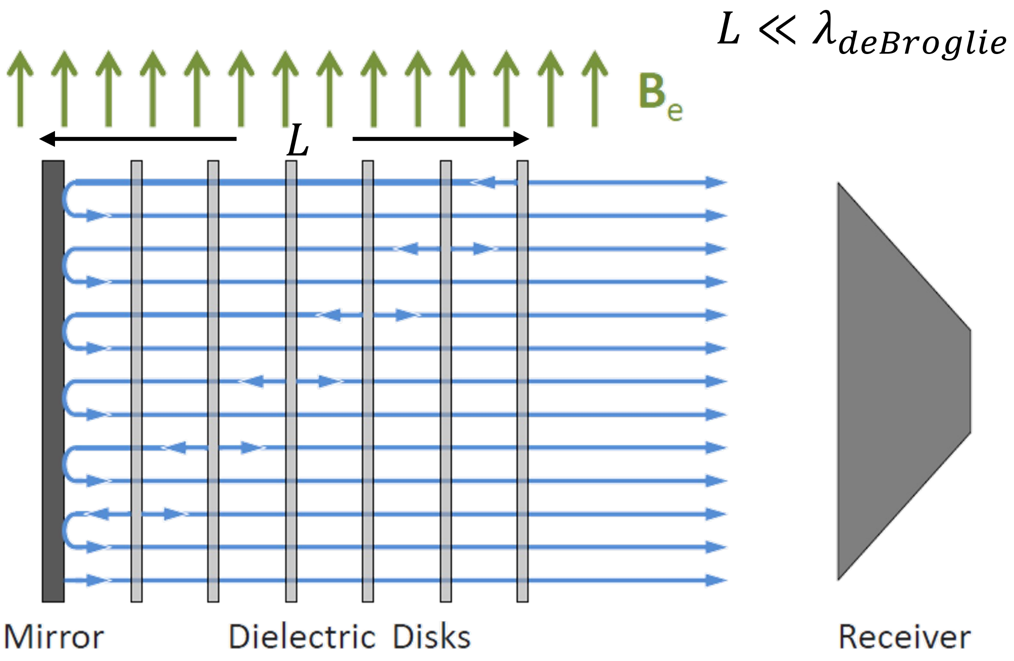
$E_{||}$ must be continuous at the surface

Discontinuity leads to emission of EM traveling waves

Power emitted at a vacuum-to-perfect-conductor interface:

$$P_{sig} = 2.2 \cdot 10^{-27}\mathrm{W}\left(\frac{A}{1\mathrm{m}^2}\right)\left(\frac{B_e}{10\mathrm{T}}\right)^2\left(\frac{g_{a\gamma}}{m_a}\right)^2 \qquad \mathcal{O}\left(\frac{g_{a\gamma}}{m_a}\right) = 1$$

Dielectric Booster Concept



Power enhancement comes from 2 sources:

- **Coherent emission** from multiple interfaces
- **Resonance** effects between interfaces

Power "Boost factor" β^2

$$\beta^2 = \frac{P_{\mathrm{booster}}}{P_{\mathrm{mirror\ only}}}$$

Output power P of a dielectric haloscope:

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

Search for: 40 – 400 μeV CDM axion
Signal: 10 – 100 GHz signal

$\beta^2 > 5 \cdot 10^4$ required to detect QCD axion

The MADMAX Experiment

- The **MA**gnetized **D**isc and **M**irror **A**xion *e****X****periment* (a novel Dielectric Haloscope)
- Search for **Axion dark matter** in the mass range **40 µeV – 400 µeV** (10 GHz – 100 GHz)
- Stack of adjustable, parallel **dielectric discs** (~1 m^2) in front of a highly reflective **mirror**
- Booster (discs + mirror) surrounded by a strong (~10 T) static **magnetic field**
- Constructive interference among different sources boost signal to detectable levels (10^{-23} -10^{-22} W)
- Power measured in a **heterodyne receiver** (i.e. frequency mixing and down-conversion)
- Current status: **extensive prototyping phase** in progress

The Proposed MADMAX Experiment

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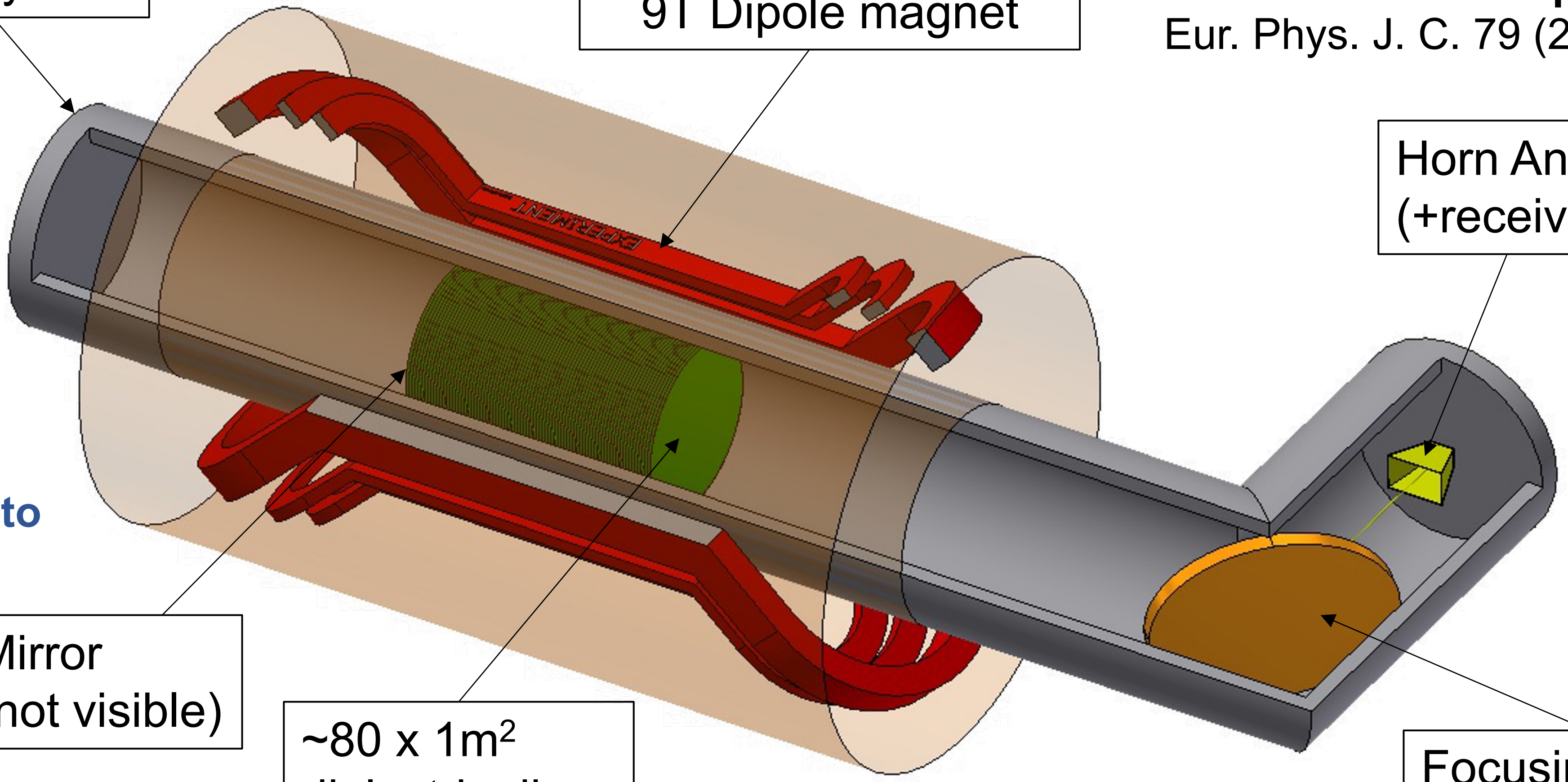
MADMAX White Paper
Eur. Phys. J. C. 79 (2019) 186

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

Start with prototypes to validate concepts



4 K Cryostat

9T Dipole magnet

Horn Antenna
(+receiver chain)

Mirror
(not visible)

~80 x $1m^2$
dielectric discs

Focusing mirror

The MADMAX Collaboration

MAX-PLANCK-INSTITUT
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~50 people
9 institutes

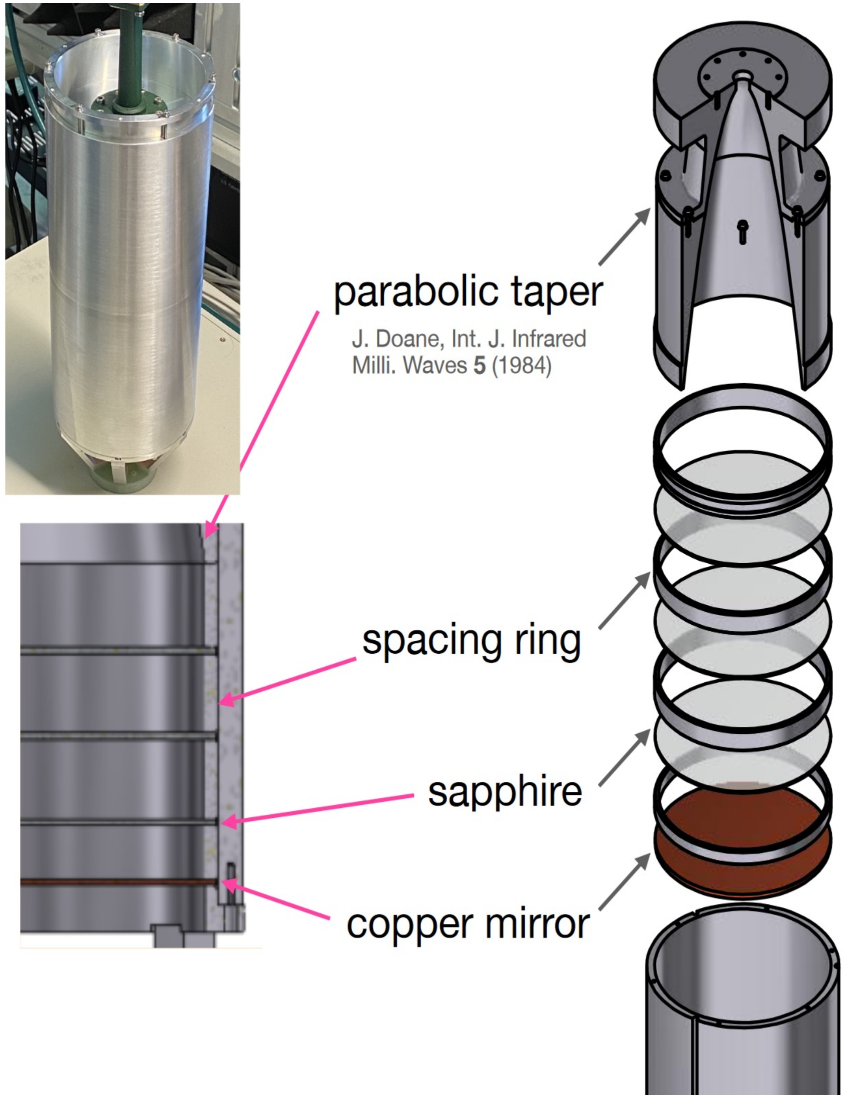
Est. October 18, 2017

RWTH AACHEN UNIVERSITY
NÉEL institut
DESY.
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
CPPM
MAX-PLANCK-INSTITUT FÜR PHYSIK
EBERHARD KARLS UNIVERSITÄT TÜBINGEN
Universidad Zaragoza

Closed Booster 100mm (CB100)

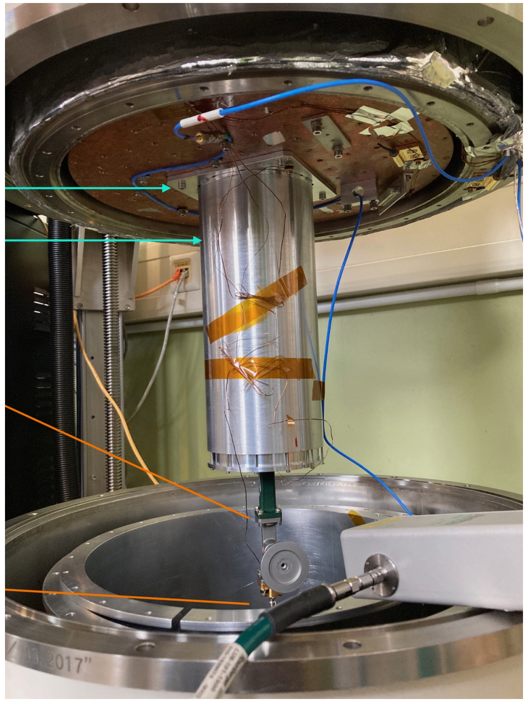
- Closed Booster prototype (developed at MPI)
  - To understand RF behavior @ RT, cold (4K), and in 1.6 T magnetic field
  - Measure reflectivity (∝ β^2)
  - Cu mirror + 3 sapphire discs Ø=100 mm
  - Fixed disc spacings

  optimized @ ~19 GHz



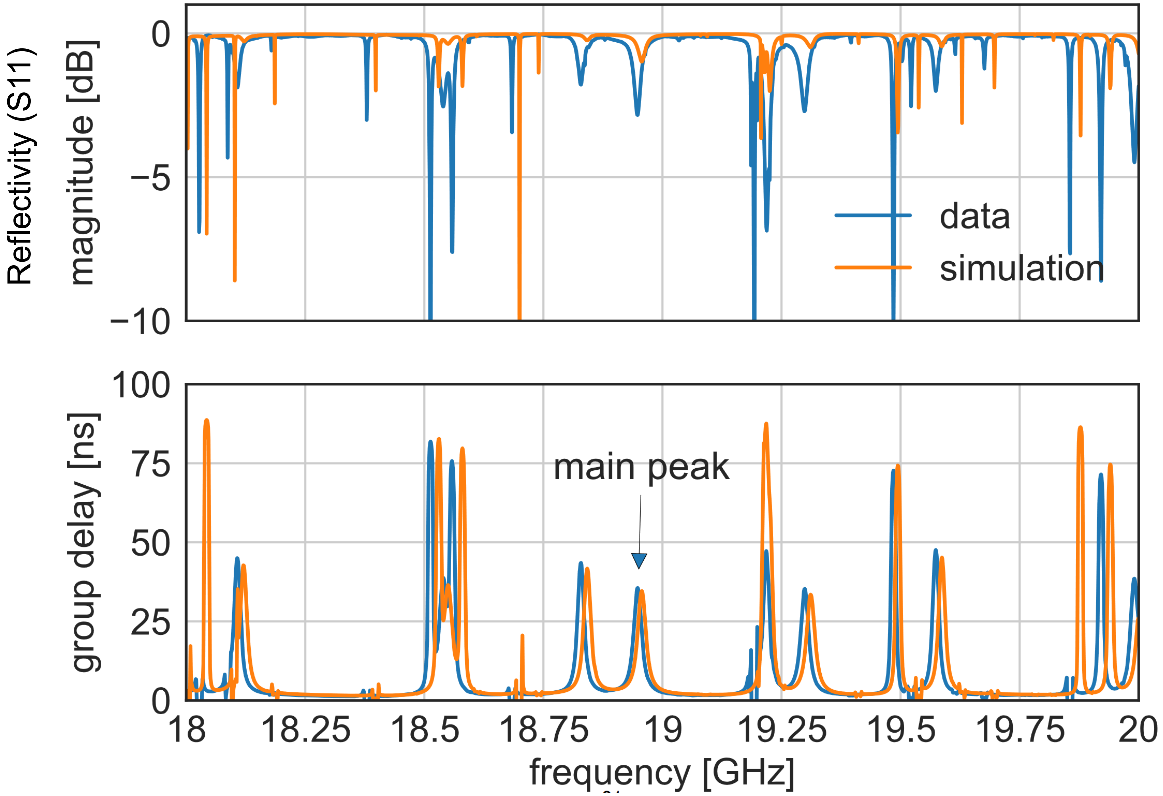
J. Doane, Int. J. Infrared Milli. Waves **5** (1984)

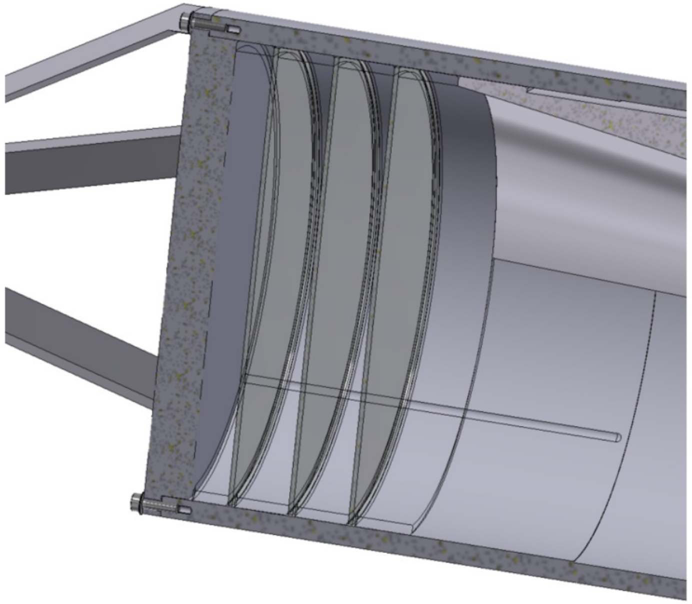
In 4K cryostat



CB100 RT Measurements

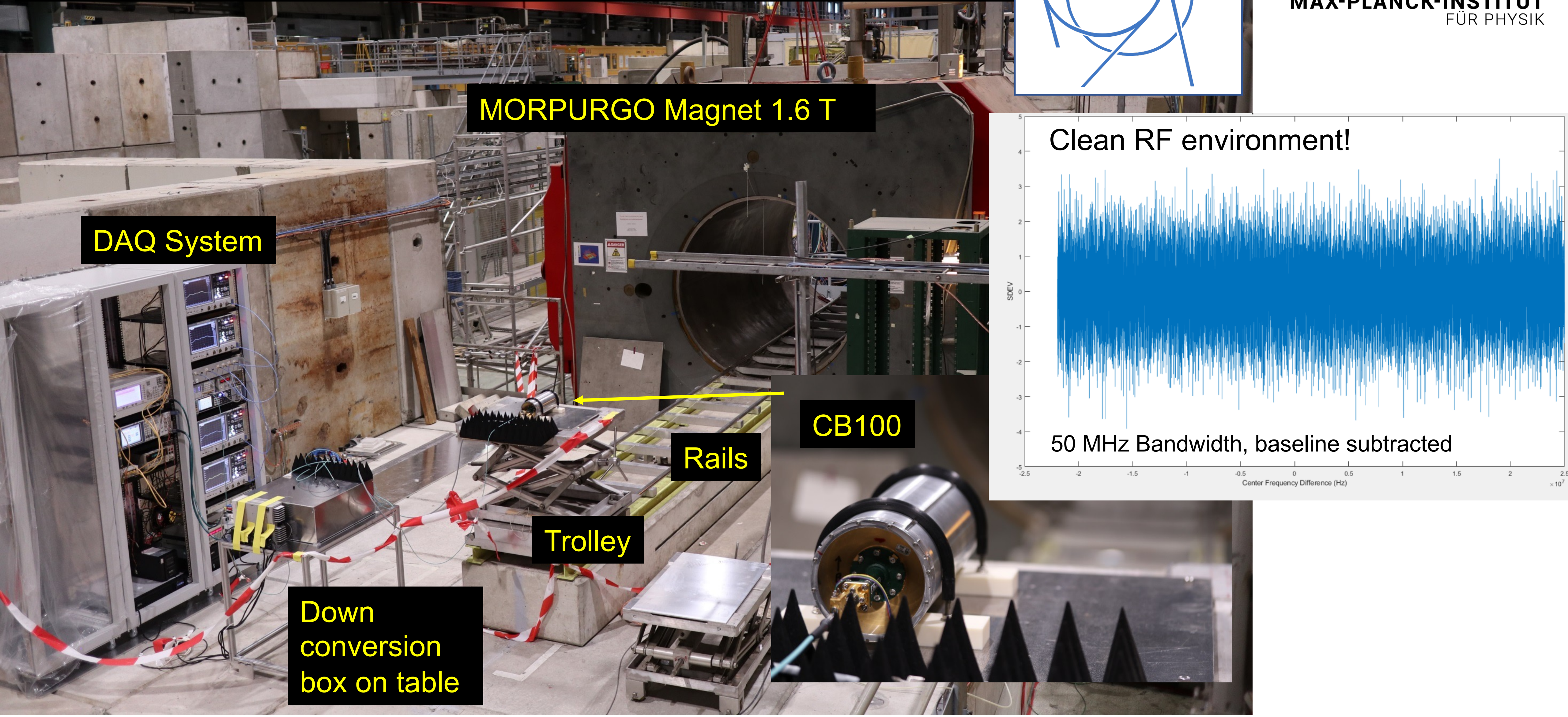
- Agreement between simulation and reality is good, given the mechanical uncertainties.
- Boost peak loss is slightly higher because of remaining transverse radiation (current) at rim of sapphire discs (solved in a newer version of the setup).





Dr. Xiaoyue Li (now at TRIUMF)
Dr. Chang Lee

EMC Tests with CB100 at CERN North Area, Prévessin
CB100 Measurements in Morpurgo (B=1.6T)

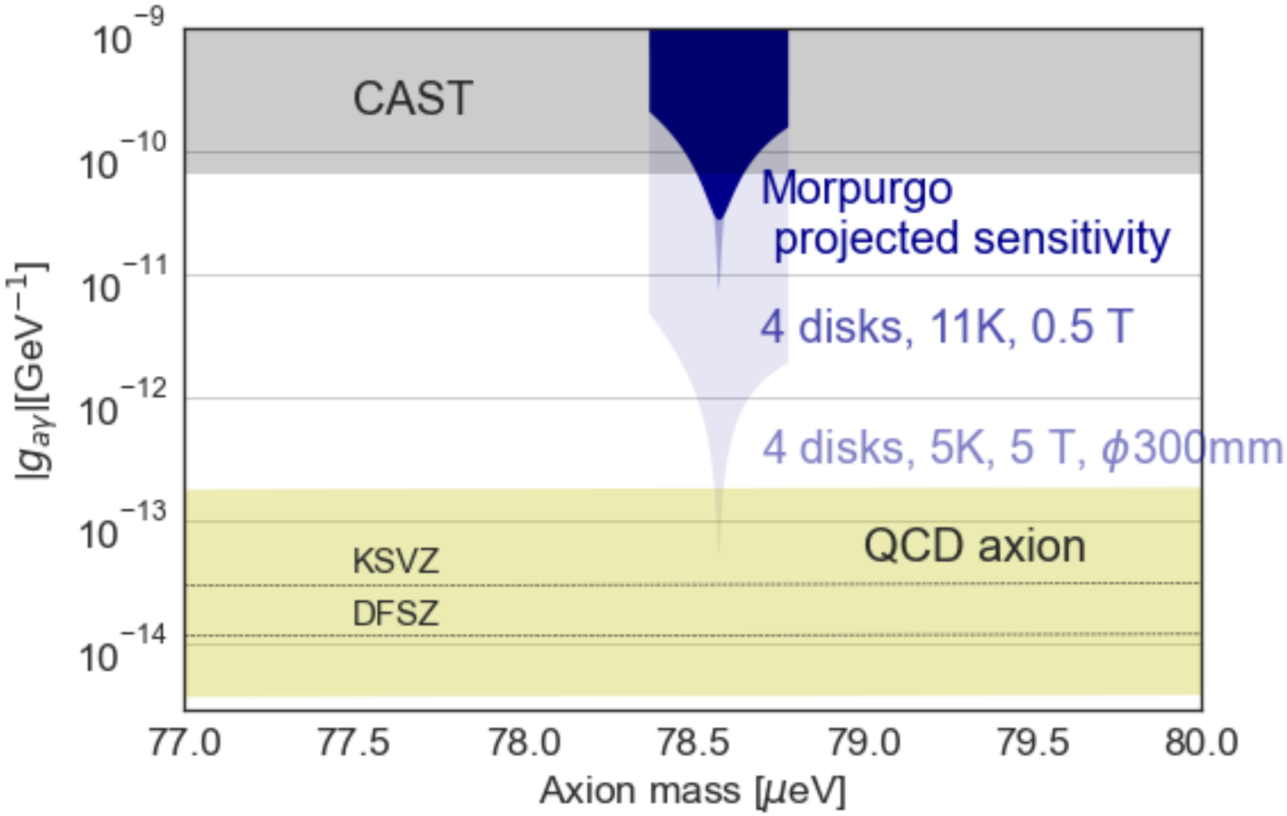


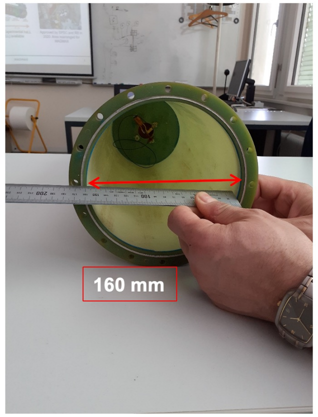
RT Booster Measurements @ 1.6 T

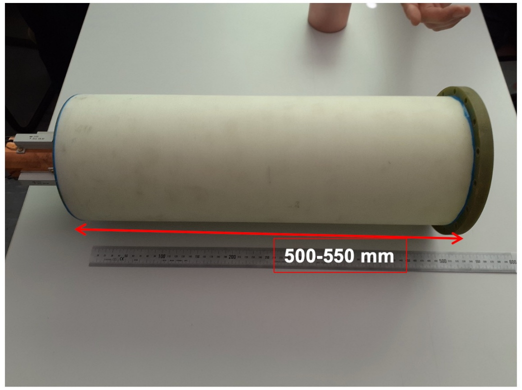
First measurements performed at RT at CERN's MORPURGO Magnet @ 1.6 T
Data analysis is ongoing

2022
CB100 → First measurements in April
P200 → First mechanics tests in a B-field
Piezoelectric motors tested successfully at 4.2 K and 5.6 T

2023
CB100/200 → Aim for 1st ALPs physics run
G10 cryostat test







G10 cryostat
Fast development
Inexpensive

Summary

- **MADMAX** is a novel dielectric haloscope aimed at discovering axion DM in the mass range 40-400 μeV
- **Active R&D and prototyping phase** is ongoing in several technologies
  - Progress in magnet, piezo motors, dielectrics, booster mechanics, and low-noise receiver
  - No time to cover everything in this talk – please see backup slides for more details
  - Several critical tests already performed in 2022
- **First Booster/RF measurements performed**
  - CB100 simulations and data agree well (within the mechanical uncertainties)
  - CB100 tests at 4.2 K are stable
  - Morpurgo environment is clean of RF interference in our setup
  - First measurement with CB100 in a 1.6 T B-field performed at CERN
- **Planned tests**
  - Scheduled test of CB100/CB200 in March 2023
  - Prototype cryostat to be delivered in 2023; Tests at CERN in 2025
- **First ALPs search beyond CAST with closed booster anticipated in 2023**

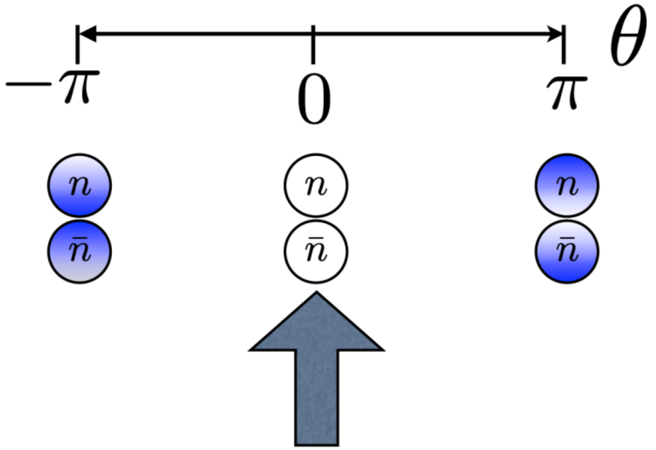
Backup

More Recent Developments

- Successful testing of custom piezo positioner motors in cryogenic temperature and in a 1.6 T B-field.
- A scaled-down 200 mm prototype (Project-200), was successfully tested in cryogentic environment and in a 1.6 T B-field.
- Exploring the use of low-noise quantum amplifiers (TWPAs).
- Development of a prototype cryostat is underway and funded by the German Research Foundation.

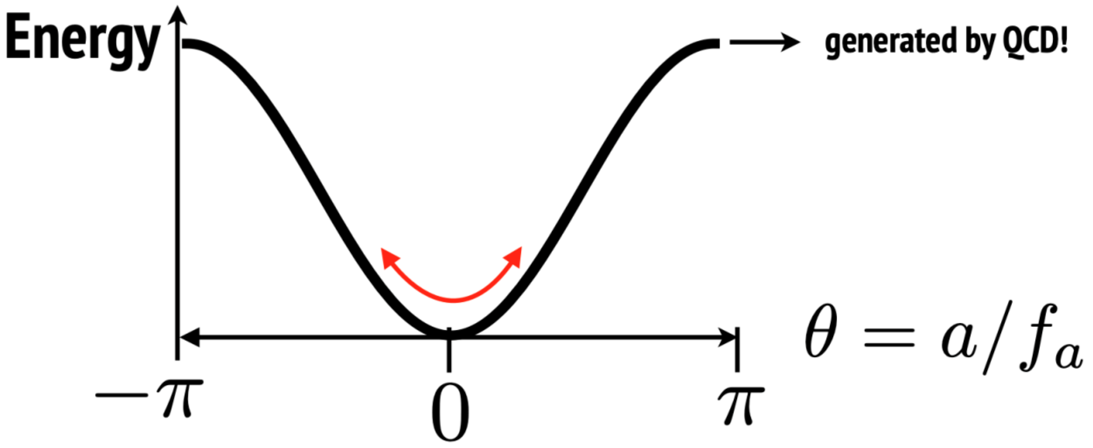
Motivation

- Sources of CP-violation in the Standard Model
    - CP-violation **observed in weak interactions** (neutral Kaon system, 1964)
        - CPV phase measured in the quark-mixing CKM matrix ($\delta_{13} \sim 1.2$ rad)
    - CP-violation **not observed in the strong interactions**
        - CPV θ-term in QCD Lagrangian is allowed and should exist
        - But **$|\theta| < 10^{-10}$** from neutron electron dipole moment measurements
- Lack of observed CP-violation in the strong interactions leads to the **Strong CP Problem**
    - **Why is θ so small?**
    - What if θ is not a fundamental constant?



Motivation

- An elegant solution to the Strong CP Problem
  - **Peccei-Quinn Theory** (1977) introduces a new global U(1) symmetry
    - Spontaneously broken symmetry at a high energy scale $f_a >> f_{EW}$
    - **θ becomes a dynamic field** ($\theta = a/f_a$), where **a** is a new light, neutral pseudoscalar boson
  - Leads to oscillations around the minimum, i.e. the **Axion** (Weinberg-Wilczek, 1978)
    - **Very weakly coupled to SM particles**
- Axion is a natural **candidate for Dark Matter**

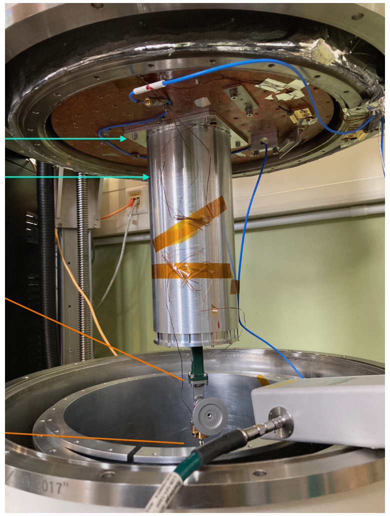


Prototype Boosters

- Develop and test smaller prototypes:
  - Room Temperature
  - Cold (4K)
  - B-field (1.6 T)

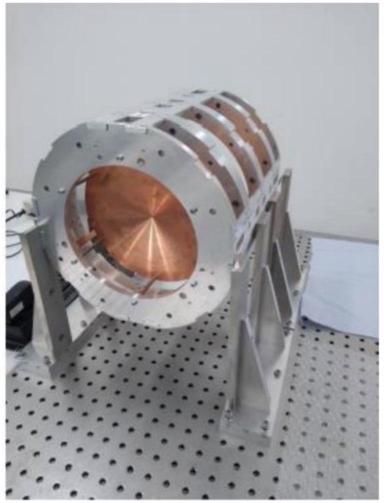
Name	acronym	disc diameter [mm]	Nr. of discs	Availability	Lab of tests (warm, cold, B-field)
Closed booster 100	CB100	100	3	2021	MPI, CERN
Closed booster 200	CB200	200	≥ 3	2022	
Project 200	P200	200	1	2021	UHH, DESY, CERN
Reduced booster	r-booster	300	≥ 3	2023	UHH, CERN
Prototype booster	P-booster	300	20	2024	

CB100 @ MPI



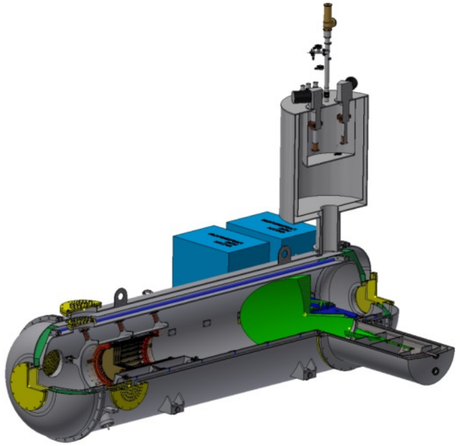
Tested at RT, 4K, 1.6T (RT) (2021-2022)

P200 @ UHH



Tests in Morpurgo magnet (2022-2023)

r/P-Boosters @ UHH

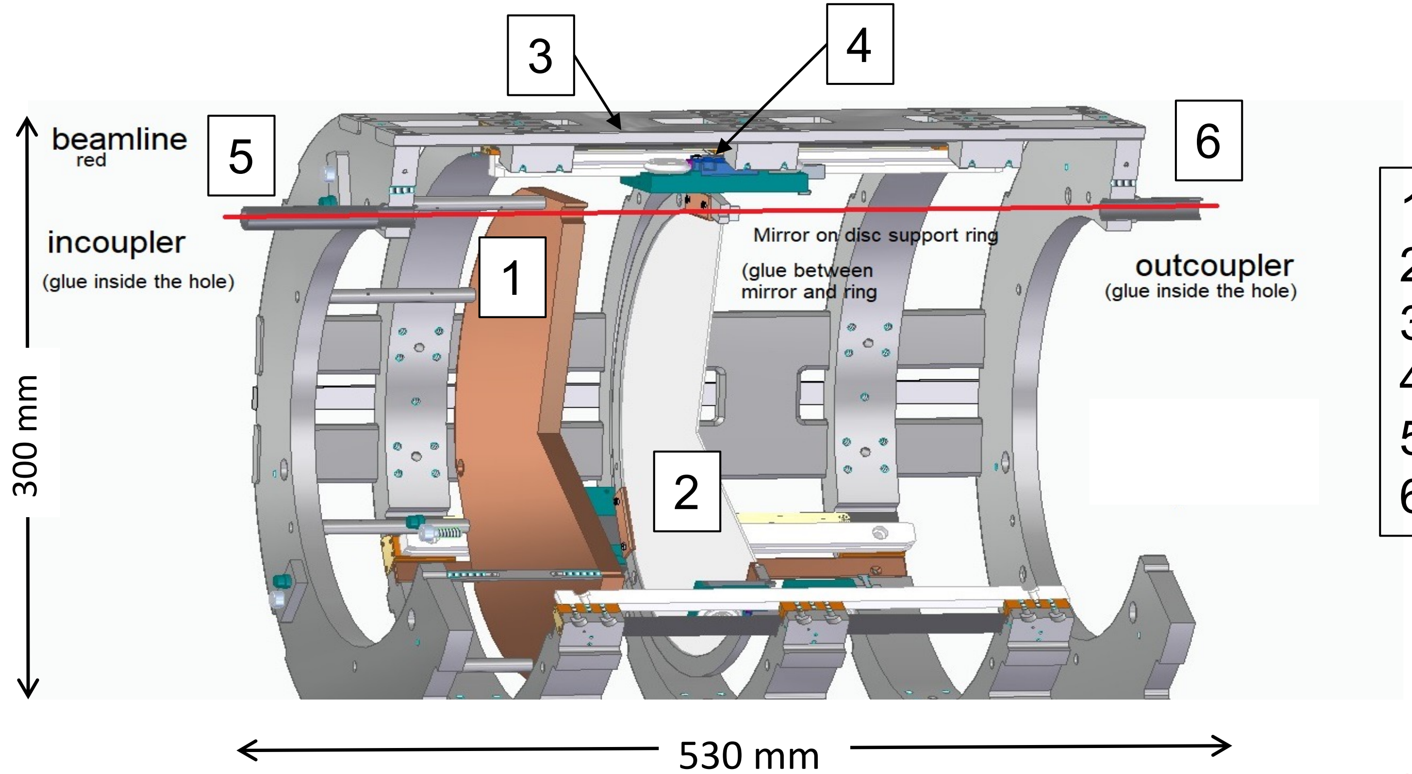


SHielded Exp. haLL (SHELL) now available

All proto. to be tested in 1.6T MORPURGO magnet @ CERN

Approved by CERN in 2020
Area prepared for MADMAX
Testing began in March 2022

Mechanics Prototype: Project 200

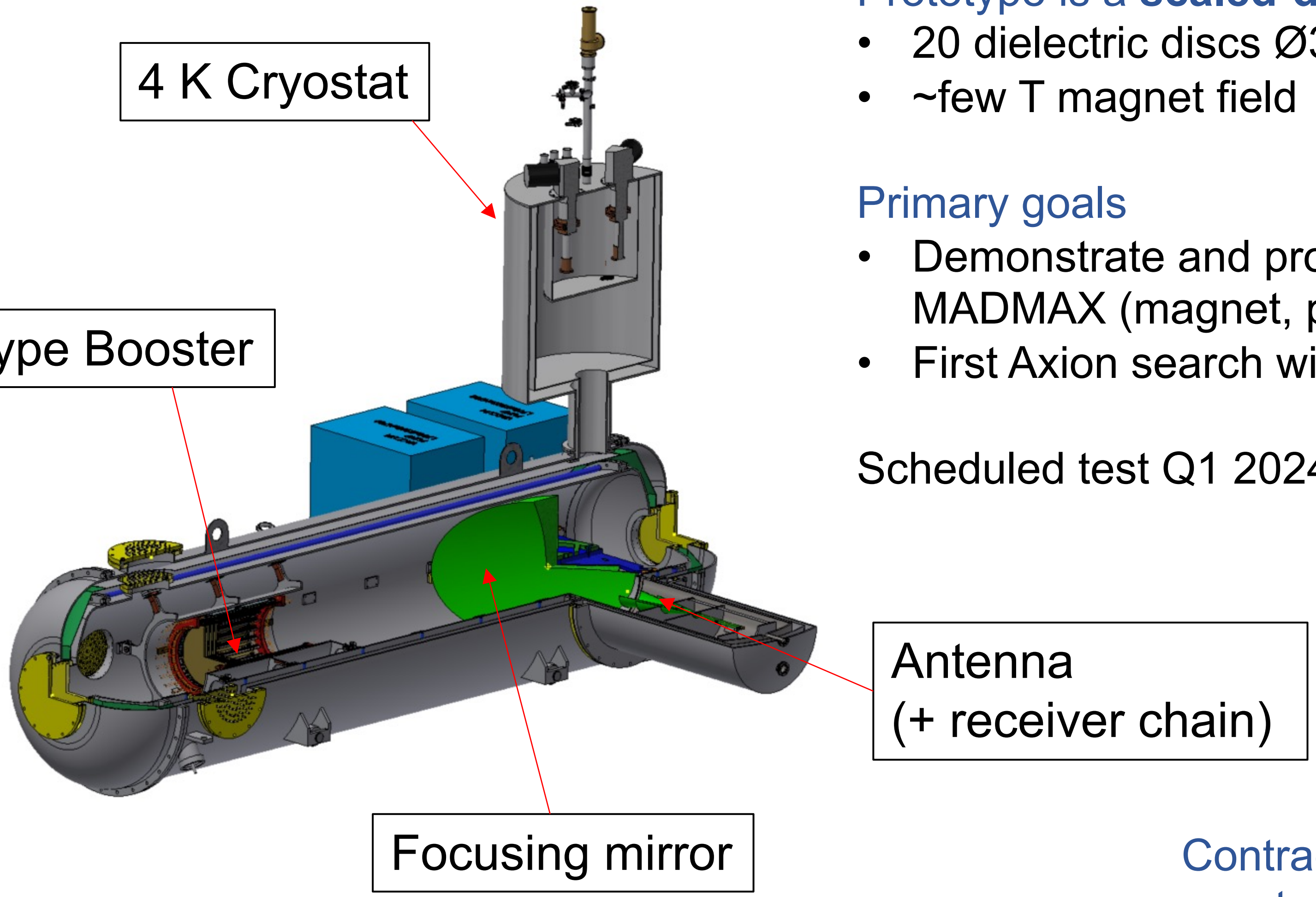


1- Cu mirror (fixed position)
2- Sapphire disc (adjustable positions)
3- P200 support structure
4- (3x) piezo motors
5- interferometer incoupler
6- interferometer outcoupler

Weight < 20 kg

P200 will validate the mechanics for the Prototype Booster

The MADMAX Prototype



Prototype is a **scaled-down version** of MADMAX

- 20 dielectric discs Ø30 cm
- ~few T magnet field

Primary goals

- Demonstrate and prototype key technologies for MADMAX (magnet, piezo motors, RF system, etc.)
- First Axion search with a dielectric haloscope

Scheduled test Q1 2024 (3 discs), Q1 2025 (20 discs)

Contract signed with Noell for cyrostat construction, to be delivered Q1 2023 @ UHH

Magnet and Motor Prototyping

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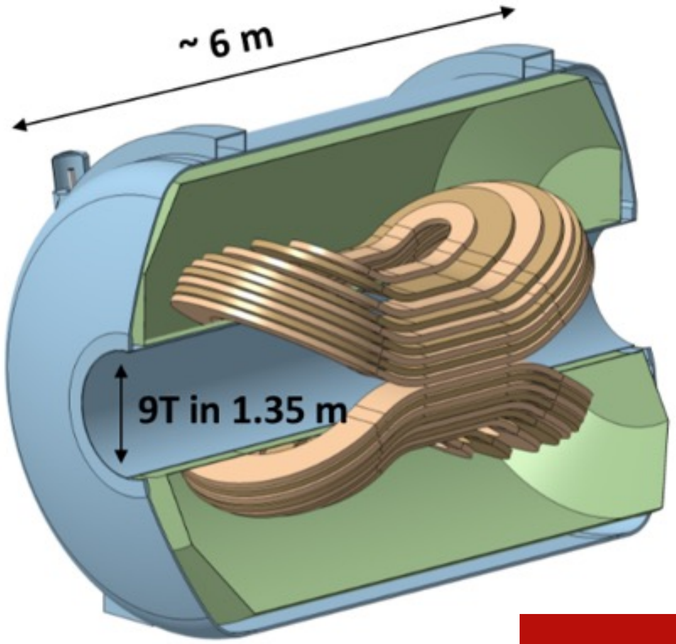
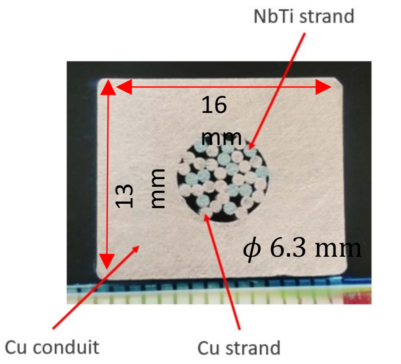
Magnet Design by CEA-Saclay & Bilfinger-Noell

- Dipole Magnet
- B > 9 T, Warm bore 1.35 m, I = 23.5 kA, stored energy ~500MJ
- FOM : 80-100 T^2m^2
- Status: Design and R&D phase in progress



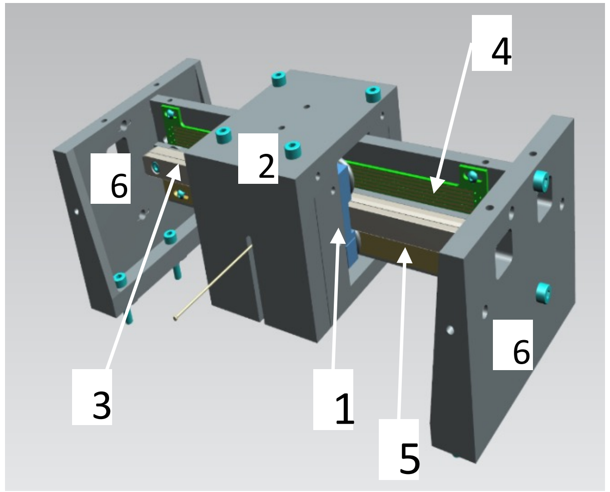
New conductor:
Cable-in-circuit conductor
with Cu profile

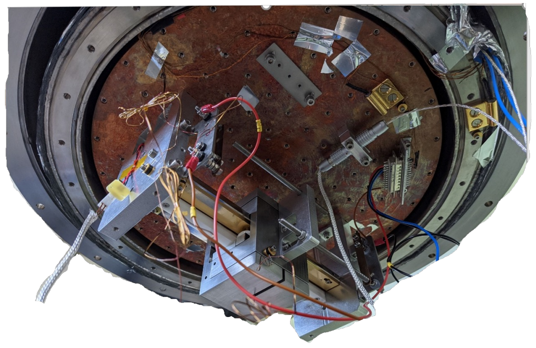


BILFINGER
BILFINGER NOELL GMBH

Piezo Motor Design by JPE Innovations

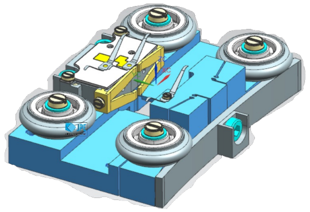
- Operation at cryogenic temperature and in strong B-field
- Reliable design (240 motors to move 80 discs)
- Durability, friction wear, lifetime
- Feasibility verified at 4.2 K and 5.6 T (Jan 2022)
- Status: Design and R&D phase in progress





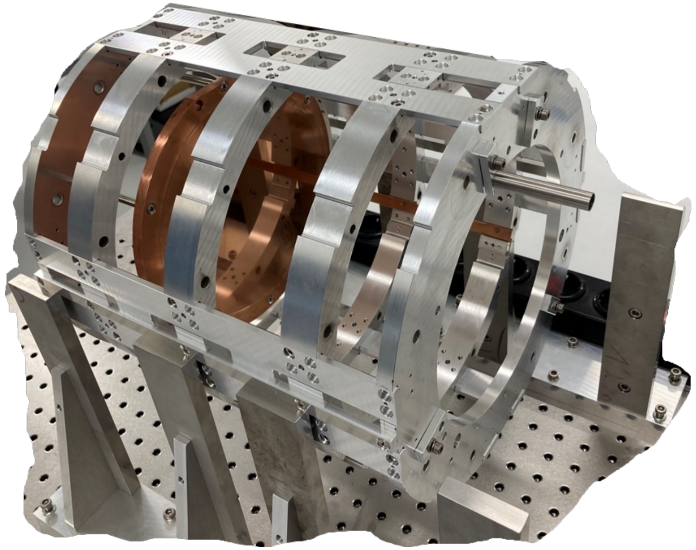
1 – motor carriage
2 – weight
3 – ceramic rail
4 – PCB
5 – cooling strip
6 – side plates

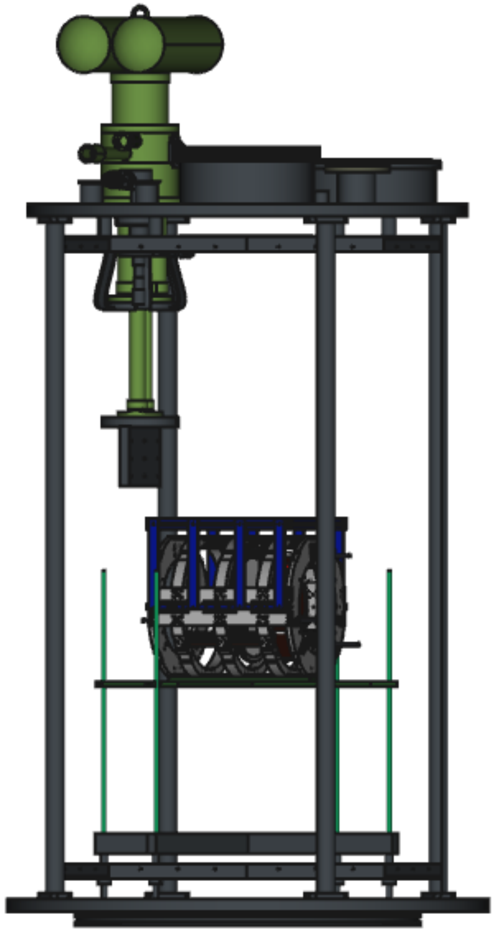
JPE
Driven by innovation



Project 200 in LHe @ CERN

Status:
- P200 assembled at UHH
- Tests at RT → Dec‘21/Jan’22
- Tests in CERN Cryostat:
  - 1st run → Feb, March 2022
  - 2nd run → Fall 2022





Tests at RT (in Hamburg)

Parameters checked:
- Stepsize
- Positioning accuracy (spec: +/- 10 mm)
- Tilt of the disc
- Reproducibility
- Drift (after 1s, 10 s, 10 min,…)

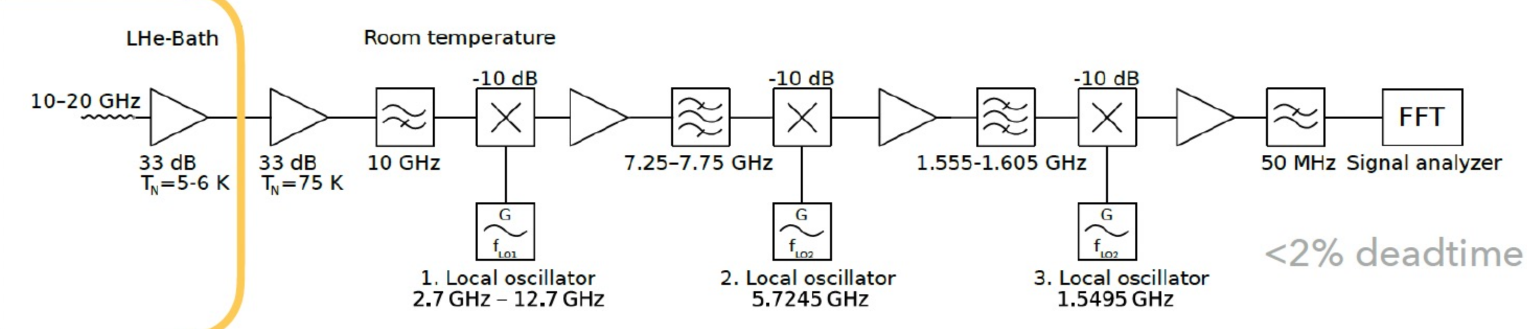
Tests at 4.2 K (CERN)

Parameters to be checked:
- Repeat RT measurements
- Temperature investigation

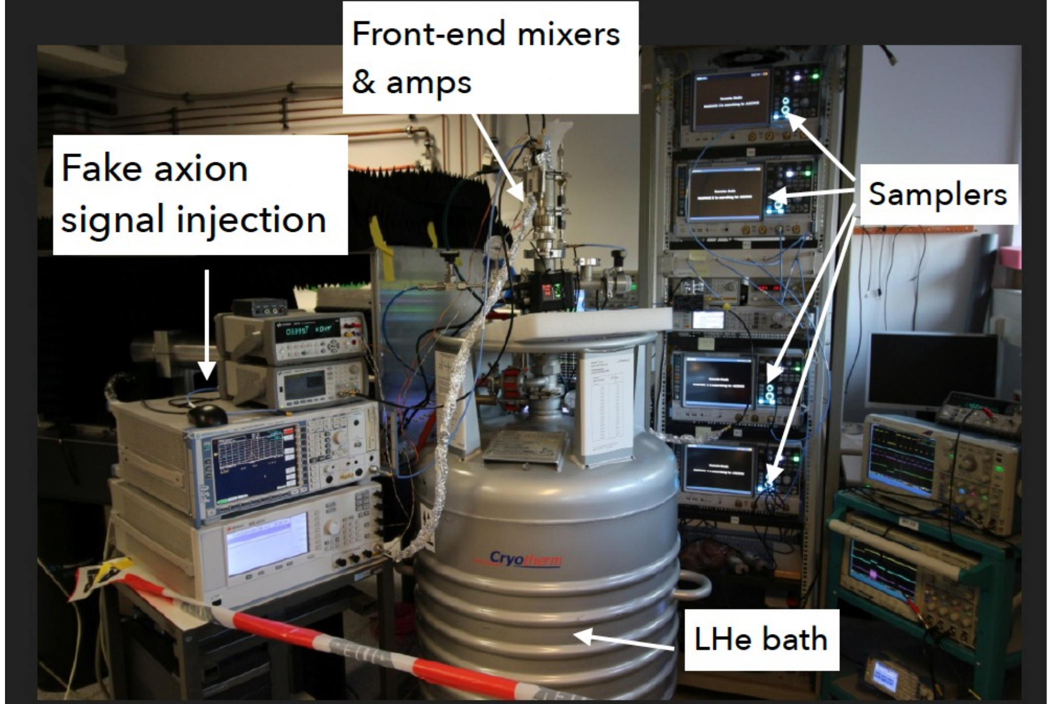
Receiver

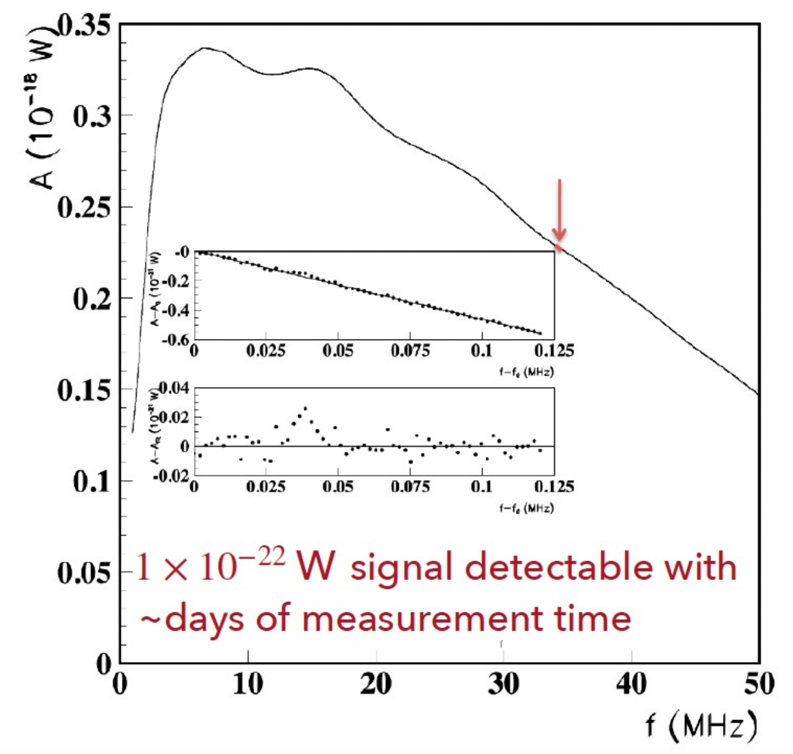
HEMT amplifier from Low Noise Factory

$T_{rec} = 5 - 6$ K



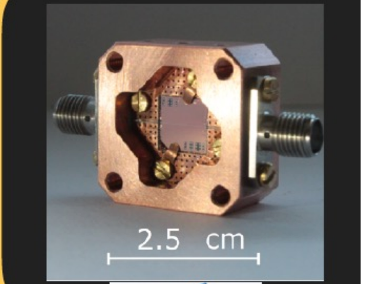
<2% deadtime

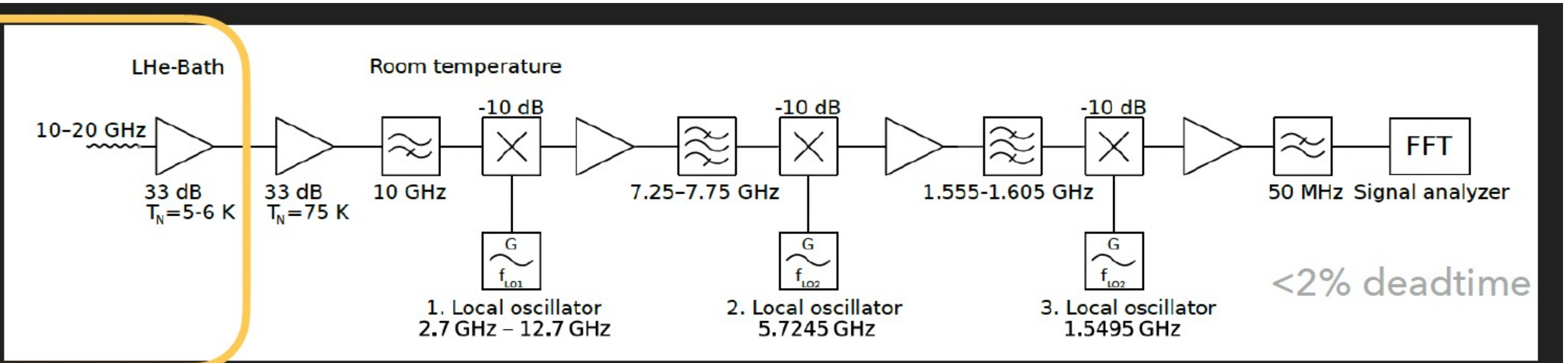




1×10^{-22} W signal detectable with ~days of measurement time

Low-noise Amplifier Developments





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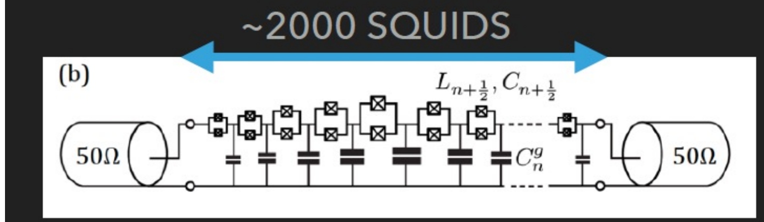
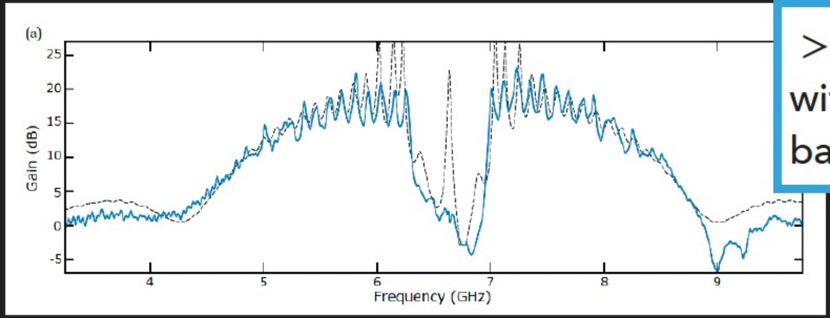
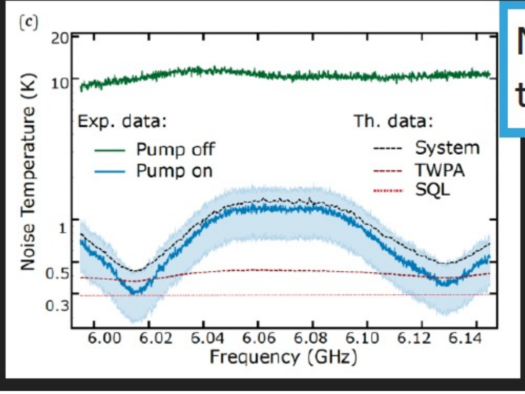


- The possibility of using a traveling wave parametric amplifier (TWPA) as the preamplifier is being investigated
  - Potentially halves the system noise temperature



> 15 dB gain with ~2 GHz bandwidth



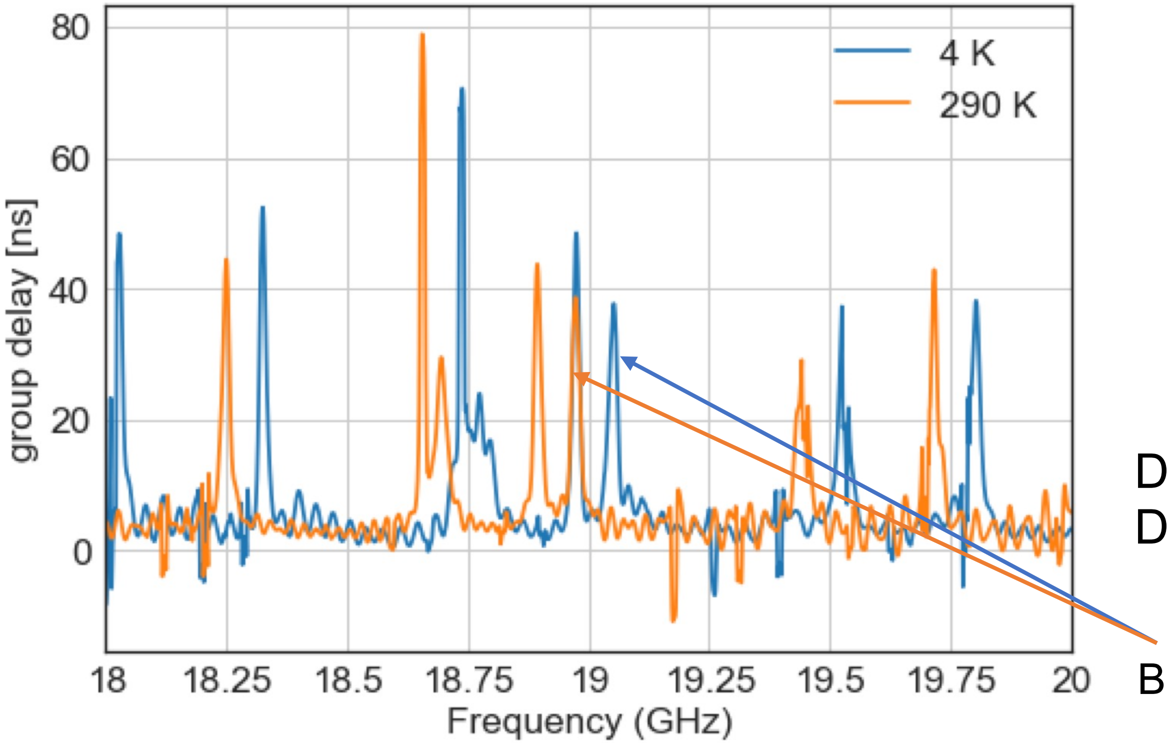
Noise temperature close to the quantum limit

L. Planat, *et. al. arXiv:1907.10158*

CB100 4K Measurements

- Observe Boost peak and mode crossings shift when going from RT to 4K (as expected).
- System stable at 4K and good for long term measurements.

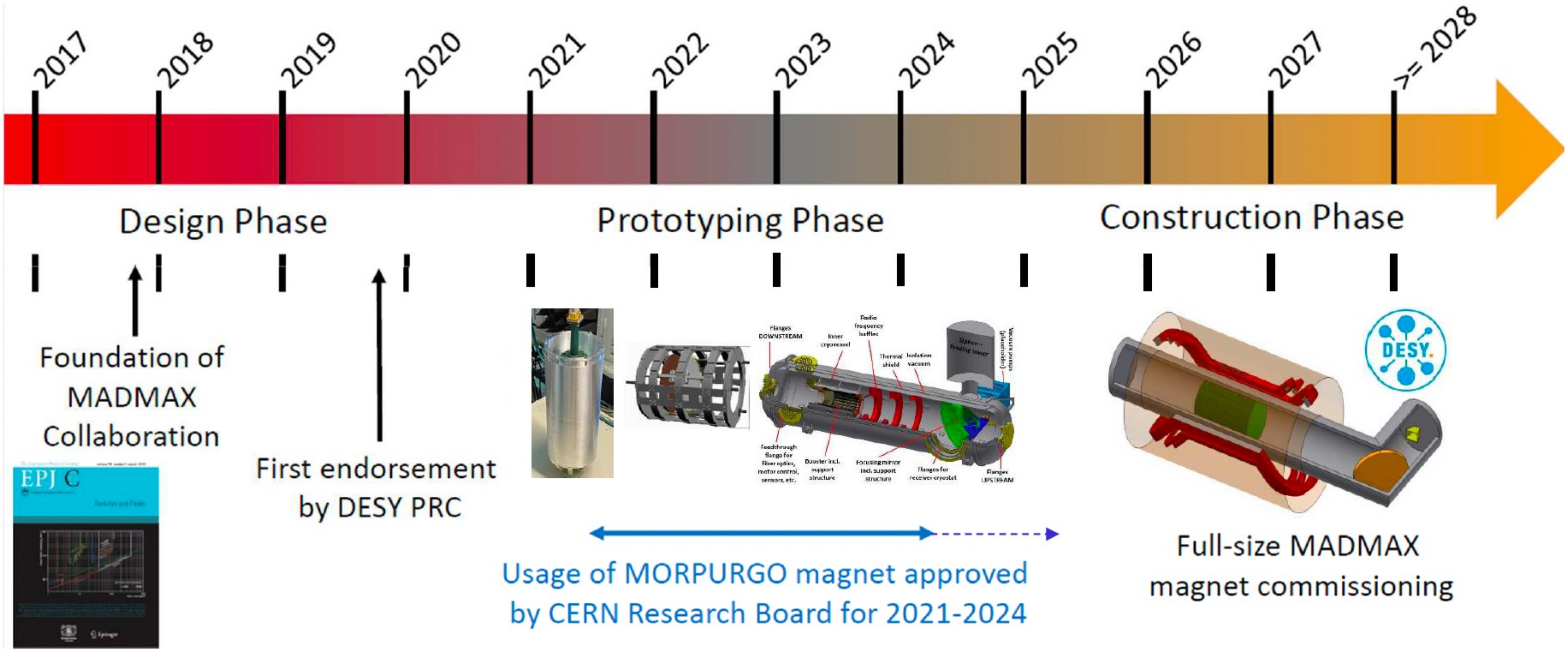
Group delay:
From RT (290K) to LHeT (4K)



Boost peak

Dr. Xiaoyue Li (now at TRIUMF)
Dr. Chang Lee

MADMAX Timeline



Design Phase

Prototyping Phase

Construction Phase

Foundation of MADMAX Collaboration

First endorsement by DESY PRC

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

Full-size MADMAX magnet commissioning

Modified Axion Maxwell Eqns

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a,$$

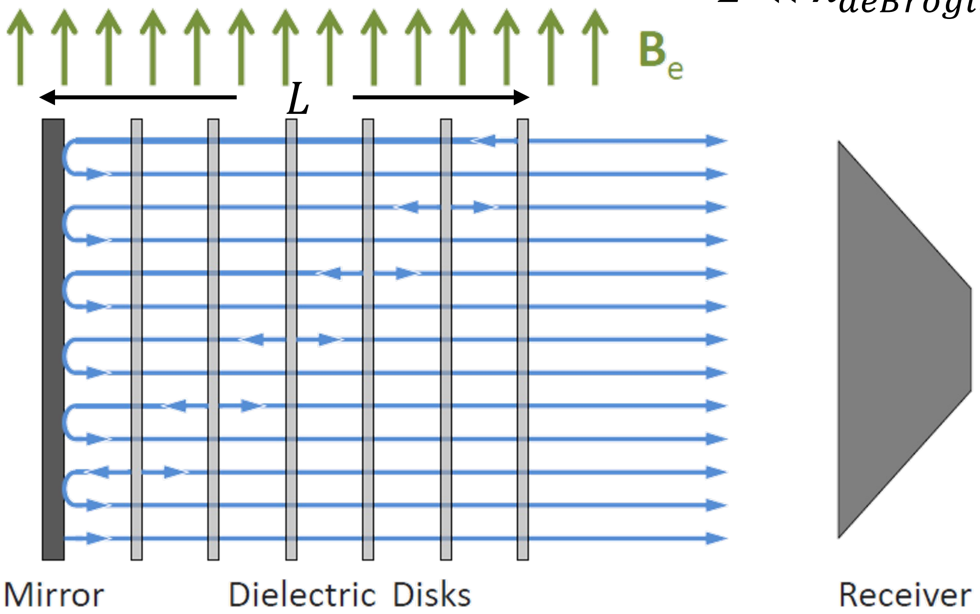
axion DM modifies maxwell equations:

- new equations:

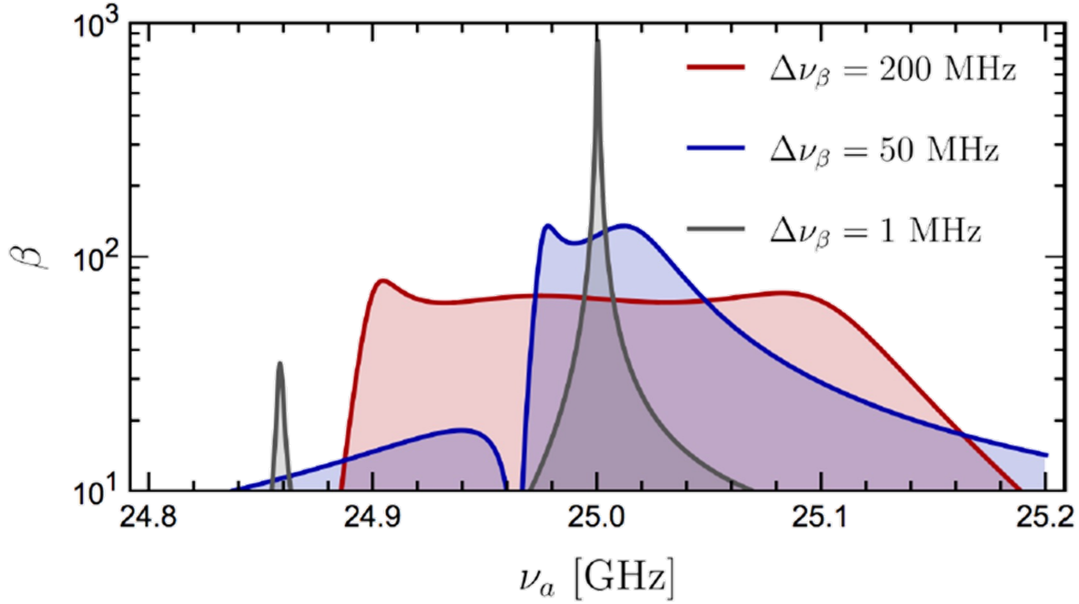
$$\begin{aligned}
\boldsymbol{\nabla}\cdot\mathbf{E} &= \rho - g_{a\gamma}\mathbf{B}\cdot\boldsymbol{\nabla}a\,,\\
\boldsymbol{\nabla}\times\mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma}\left(\mathbf{B}\,\dot{a} - \mathbf{E}\times\boldsymbol{\nabla}a\right)\\
\boldsymbol{\nabla}\cdot\mathbf{B} &= 0\,,\\
\boldsymbol{\nabla}\times\mathbf{E} + \dot{\mathbf{B}} &= 0\,,\\
\ddot{a} - \boldsymbol{\nabla}^2 a + m_a^2 a &= g_{a\gamma}\mathbf{E}\cdot\mathbf{B}\,.
\end{aligned}$$

MADMAX Booster Concept

$L \ll \lambda_{deBroglie}$



Boost of axion to photon conversion



Output power P of a dielectric haloscope:

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

- Possibility for narrow-band and broad-band measurements
- Scan axion mass by changing disc positions

The Axion Field

- Regardless of the initial conditions of the universe, the axion field will go to the minimum position. The amplitude will decrease with time, and we can always get a very small value of θ.
- Because the lifetime of the universe if finite, there will always be some oscillations of the axion field. These oscillations have some energy, which will be dark matter in nature.

$\theta(t,\mathbf{x}) = a(t,\mathbf{x})/f_a$

$m_a = 6\ \text{meV}\ (10^9\ \text{GeV}/f_a)$

$a(t,\mathbf{x})$ – axion field

f_a – energy scale

$\theta(t,\mathbf{x})$ – an angle $[-\pi, \pi]$

m_a – axion mass

How to detect the Axion

- Lagrangian interaction

$$\mathcal{L} = -C_{a\gamma}\frac{\alpha}{2\pi}\frac{a}{f_a}\vec{B}\cdot\vec{E}$$

- In a static magnetic field, the oscillating axion field generates EM-fields

$$\mathcal{L} = -C_{a\gamma}\frac{\alpha}{2\pi}\theta(t)\vec{B}_{EXT}\cdot\vec{E}$$

- Electric field amplitude independent of mass

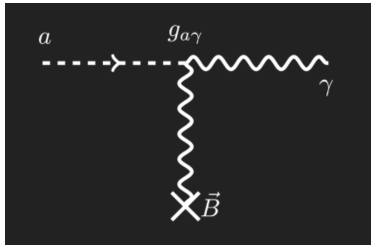
$$E_a = C_{a\gamma}\frac{\alpha B_{EXT}}{2\pi}\theta_0\cos(m_a t)$$

Oscillations at frequency

$$\omega \cong m_a$$

CDM Axion Direct Detection

- CDM axions behave like a classical wave, e.g. m_a = 100 µeV
  - Local galactic axion density: $\rho_a = 0.45\, GeV/cm^3$
  - Axion de Broglie wavelength: $\lambda_a = \frac{2\pi}{m_a v_a} \gtrsim 10\, m \;\; (v_a \approx 10^{-3} c)$
  - Axion phase-space occupancy: $\mathcal{N}_a \sim n_a \lambda_a^3 = \frac{\rho_a}{m_a} \lambda_a^3 \sim 10^{22}$
- Axion-photon interaction



$$\mathcal{L}_{a\gamma\gamma} = C_{a\gamma} \frac{\alpha}{2\pi f_a} a F^{\mu\nu} F_{\mu\nu}$$

$$g_{a\gamma} = C_{a\gamma} \frac{\alpha}{2\pi f_a}$$

m_a = 100 µeV
=> 25 GHz microwave photon

Axion parameter space

The Axion:

- A light, neutral pseudoscalar boson
- Small mass and couplings
- Solve the strong CP problem
  - Why does θ≈0?
- Primakoff effect: Axion to photon conversion in a strong B field