Direct search for axion dark matter with MADMAX

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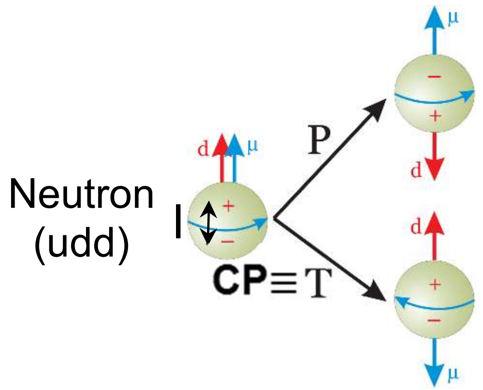
1- (Short) Theoretical motivations
2- Axion Dark matter searches
3- MADMAX experiment
4- Prototyping *(magnet, receiver, booster)* for first physics
5- French contributions, Timeline

CosPT Workshop – 12 may 2023

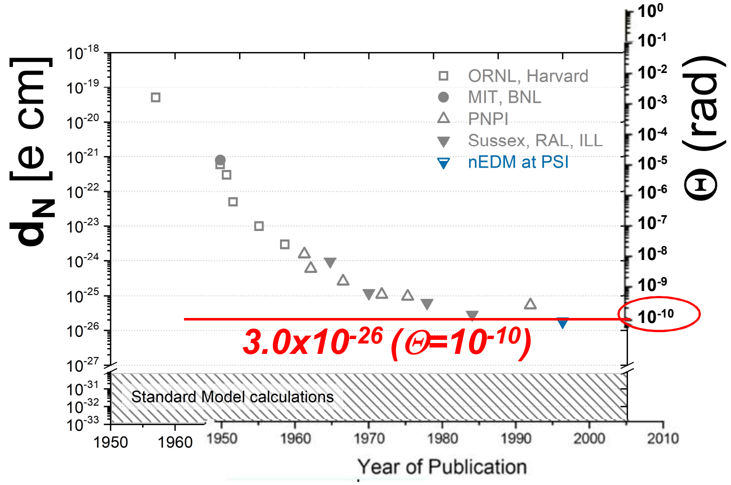
(Short) Theoretical motivations

❑ Sources of CP violation in the Standard Model *[one of the Sakharov conditions]*

- **CP violation exists in weak interaction**: observed in 1964 in kaon system
  - ✓ Associated phase in quark-mixing CKM matrix measured : δ_{13} **~ 1.2 rad**
  - ✓ Phase still to be measured in lepton sector (PMNS matrix) : T2K, DUNE, ORCA, …
- **CP violation in strong interaction ?**
  - ✓ CP-violating term in QCD Lagrangian (controlled by Θ) **is allowed and should exist**
  - ✓ … but **|Θ| < 10^{-10}** from neutron electric dipole moment



- Electric dipole moment: $d_N = e \cdot l$
- If strong CP : $d_N \sim \Theta \times 10^{-16}$ e·cm
- Experimental results today:
  → $d_N < 3\times10^{-26}$ e·cm → $|\Theta| < 10^{-10}$



→ Strong CP Problem = naturalness problem. Why is |Θ| so small ?

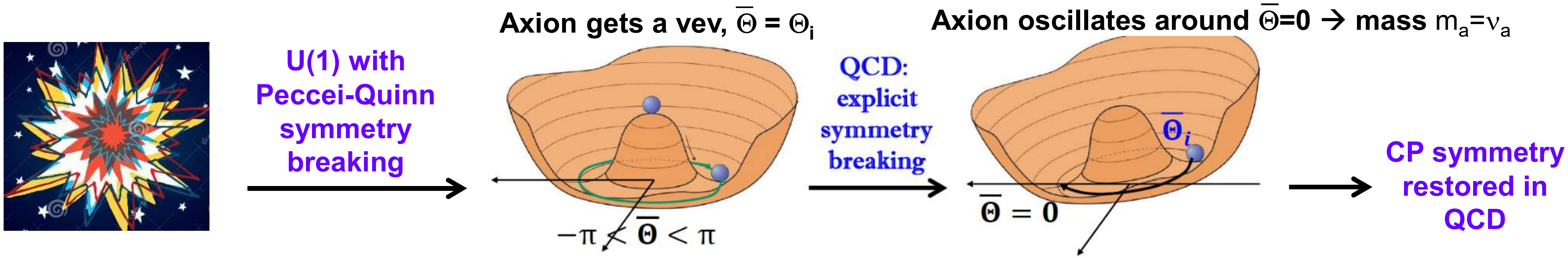
(Short) Theoretical motivations

❑ Solution to Strong CP problem ➔ Axion *[motivated by particle physics]*

- Mechanism: new global U(1) symmetry *(Peccei-Quinn, 1977)* spont. broken at scale $f_a >> f_{EW}$
  - ➔ Makes Θ a dynamical field ($\Theta = a/f_a$), with a = pseudo-scalar boson
  - ➔ Suppress CP-violating term in Lagrangian ($\Theta_{eff} \rightarrow \Theta - a/f_a$) : explains absence of CP strong

- Consequence: generation of a Goldstone boson = **axion** *(Weinberg-Wilczek, 1978)*
  - ➔ Properties are all known given the scale of symmetry breaking f_a [mass $\mathbf{m_a} \approx m_\pi f_\pi / \mathbf{f_a}$ << eV]
  - ➔ Very weak couplings to SM particles *(suppressed by f_a)* and $\tau_{axion} > t_{Universe}$

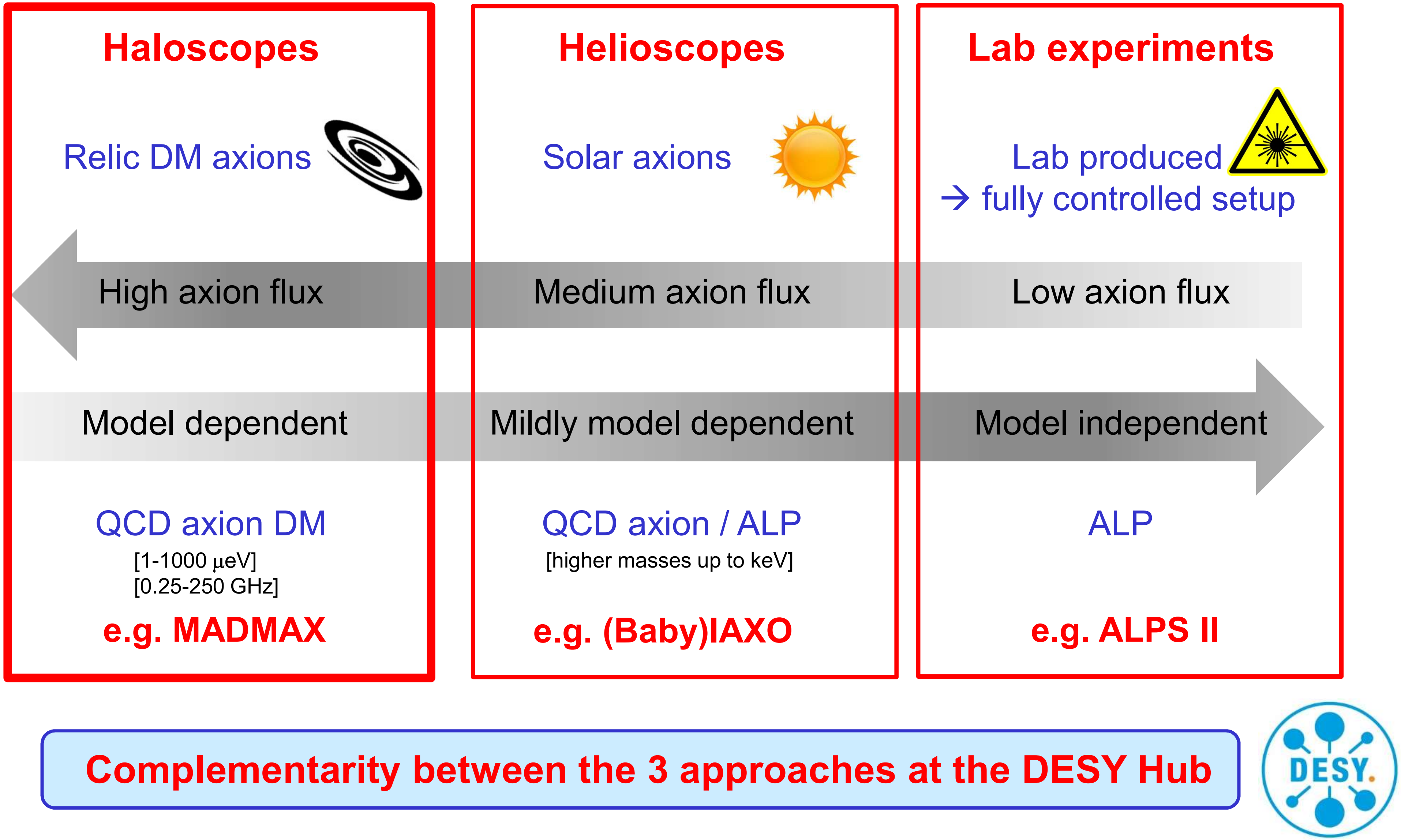
- Cosmology: Non-thermal axion production at $T \sim f_a$ *(can occur before or after inflation)*



➔ Axion = natural candidate for DM for $m_a = 1\text{-}10^3$ µeV *(i.e. $f_a = 10^{12}\text{-}10^{9}$ GeV >> f_{EW})*

Remark: ALP (Axion Like Particle) = scalar not solving strong CP problem but potential DM candidate

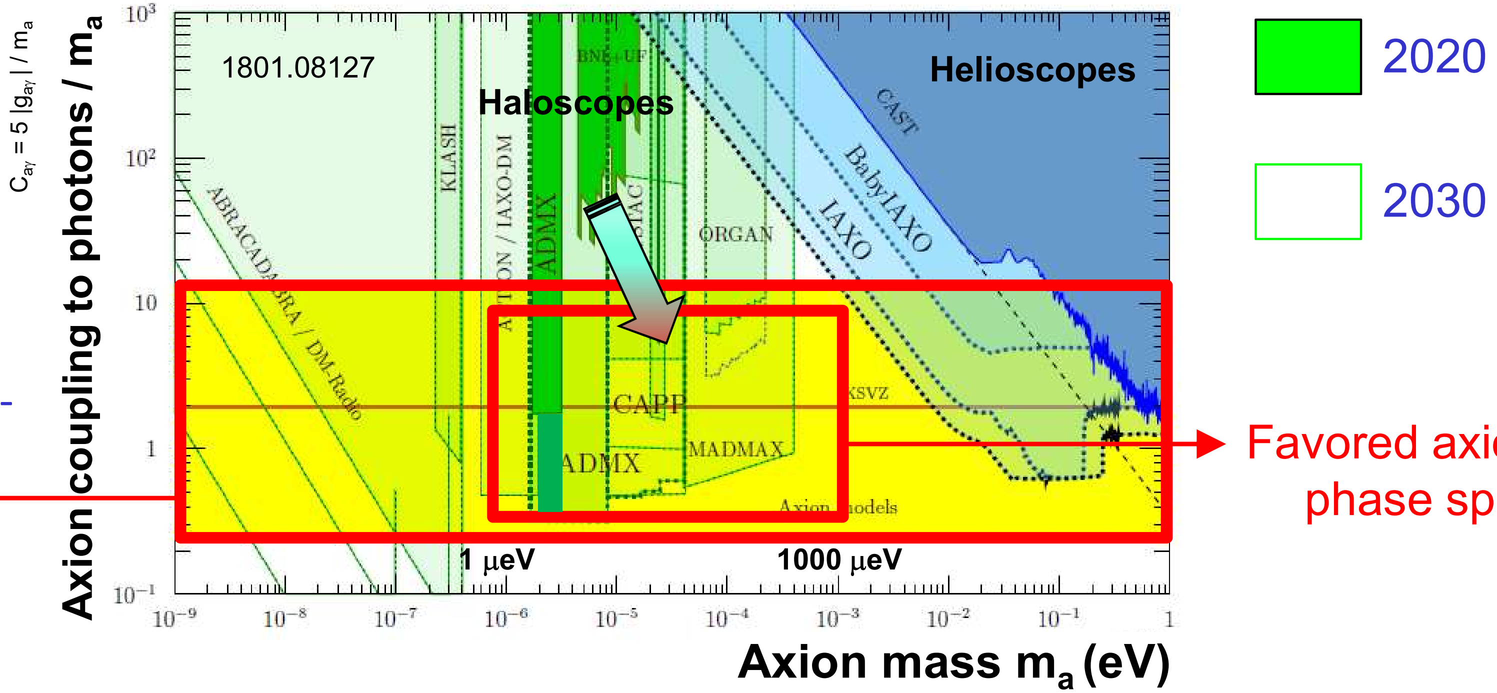
Axion/ALP searches



Axion Dark Matter searches (1/2)

❑ Extraordinary weak coupling of axions to photons …

Yellow band: QCD-axion, i.e. **solving strong CP pb**



Favored axion DM phase space

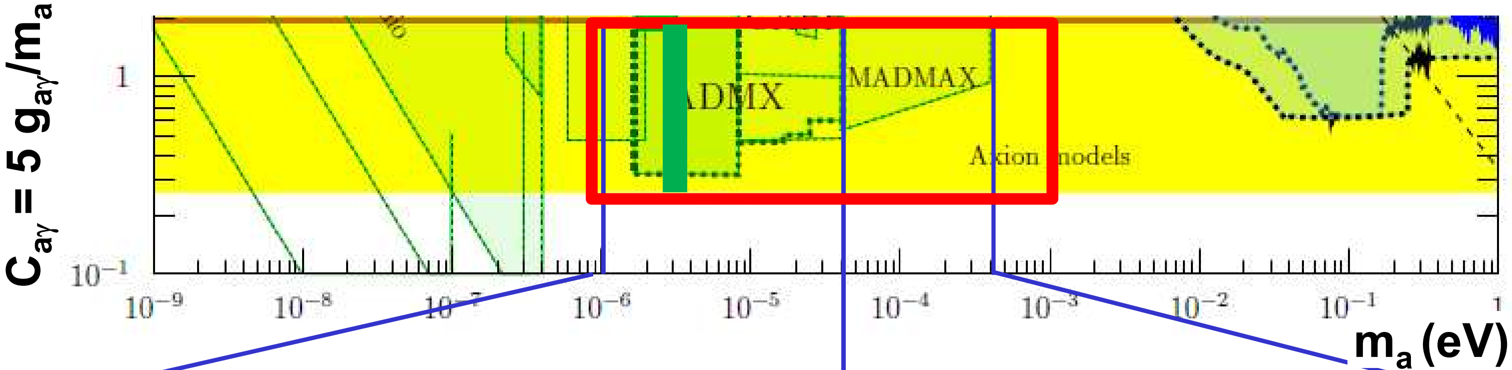
- Only 1 experiment (ADMX) currently probe a (very small) part of the favored phase space
- Vast R&D program to improve signal sensitivity and expand range of axion mass search *(post-inflationary scenarios suggests $m_a \sim 100\ \mu eV$)*

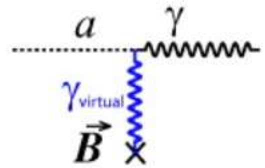
Next decade promising : axion DM most favorable region will be probed

Axion Dark Matter searches (2/2)

❑ … make axions extraordinary challenging to detect

- Convert axions into photons *[E field of O(10^{-12}. $\frac{B}{10\,T}$) V/m]* ➔ **high B_{field}** *[B >> 1T]*
- Boost E_{field} *[up to detectable P~10^{-22} W]* ➔ **resonant** cavities
- Scan over range of axion mass ➔ **tunable** set-up





1 μeV [0.25 GHz]

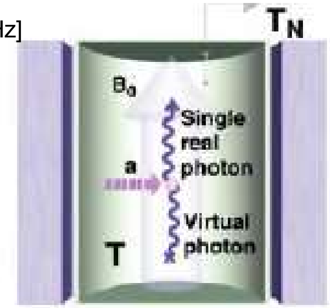
40 μeV [10 GHz]

400 μeV [100 GHz]

[$\nu_a=\nu_\gamma$]
→ Microwave regime

Cavities

PRL51 (1983) 1415

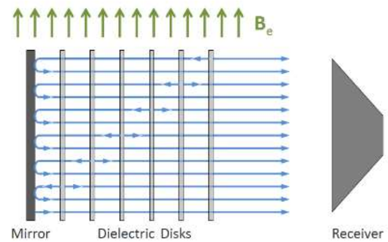


***ADMX**, HAYSTACK, CAPP*

Multicavities, Very High B

RADES, ADMX-SideCar, CAPP, GrAHal

Cavity size too small + high noise



MADMAX

Dielectric haloscopes

[novel concept 2013]
PRD88 (2013) 115002

➔ New ideas of last decade coming to maturity to scan favored mass range

MADMAX experiment (1/2)

White Paper [EPJC 79 (2019) 186, 1901.07401]

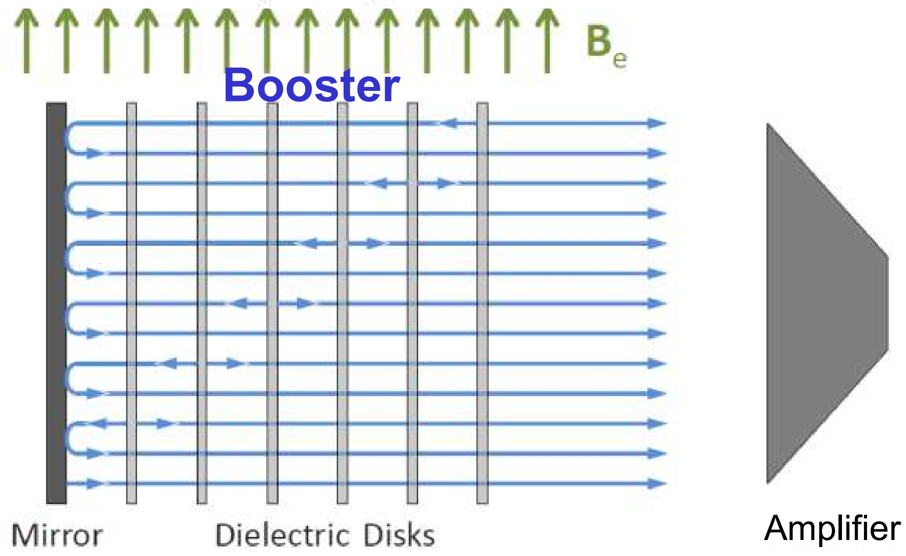
❑ Principles

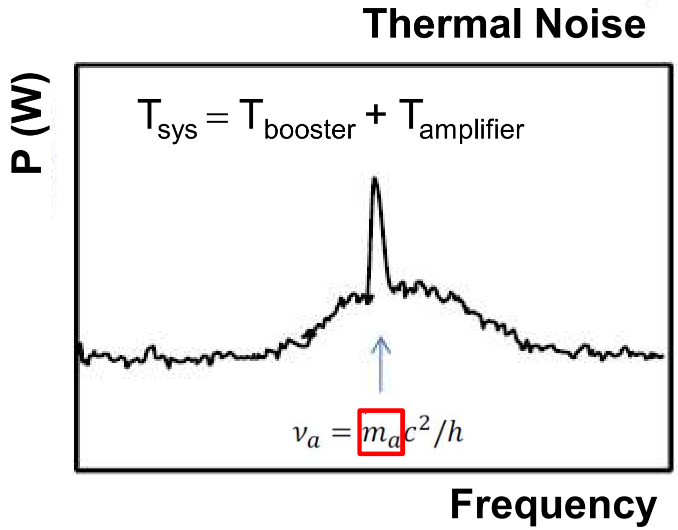
- **Constructive interference** of coherent photon emission at dielectric layers surface (~leaky resonators cavities): boost (β^2) wrt only mirror

$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

[ε, δ, N]

$$P_{sig} = 10^{-22}\mathrm{W} \times \left(\frac{SNR}{5}\right) \times \left(\frac{T_{sys}}{4\ \mathrm{K}}\right) \times \left(\frac{4\ \mathrm{days}}{t}\right)^{1/2}$$





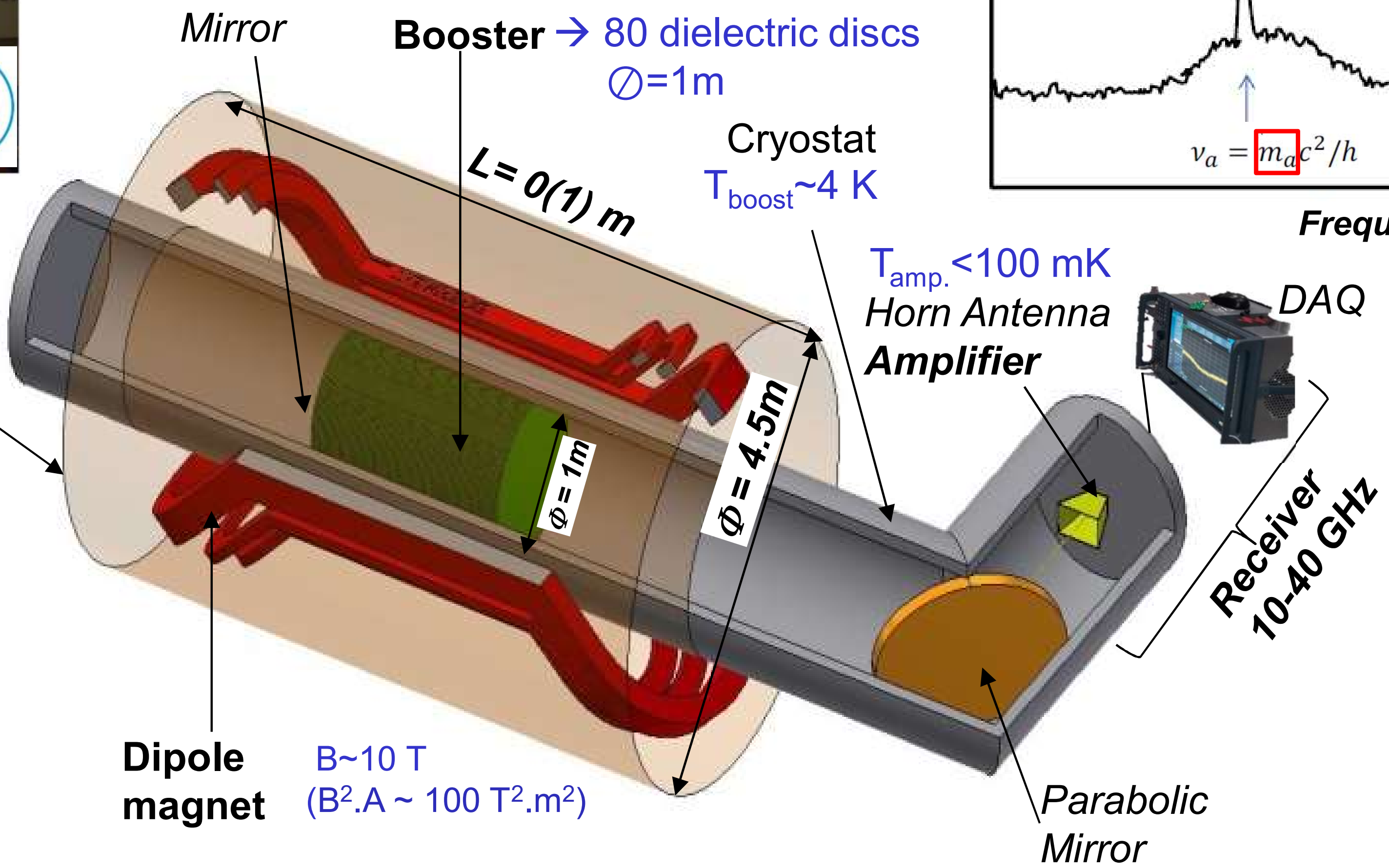
- **Axion mass scan** : by moving discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

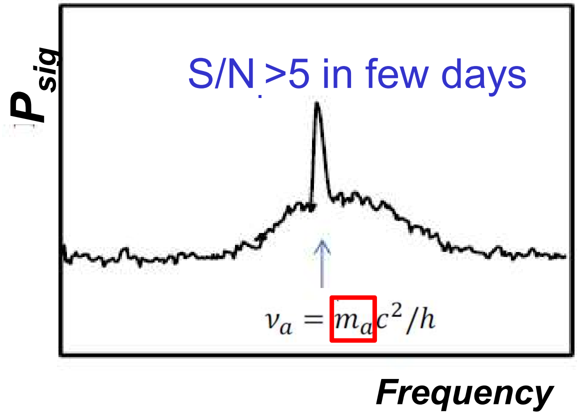
MADMAX exploits a new exp. approach to cover an uncharted phase space
[post-inflationary scenarios suggests m_a ~ 100 μeV]

MADMAX experiment (2/2)

~ 50 people, French (2), German (6) and Spanish (1) institutes

Experiment location: HERA in former H1 iron yoke





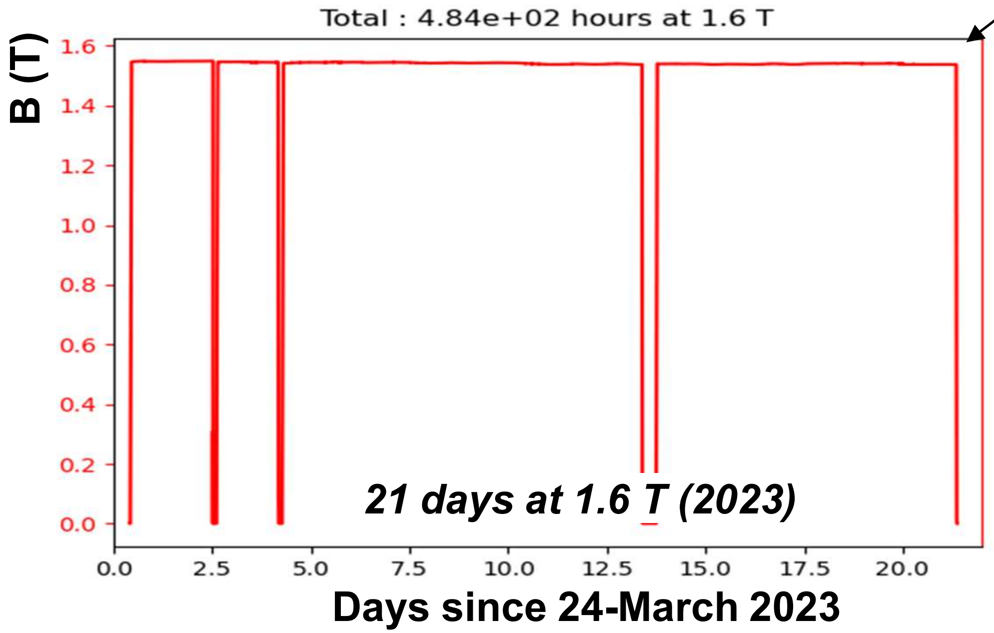
3 main challenges :
- Magnet
- Booster (cold, B field)
- Receiver (amp cold)

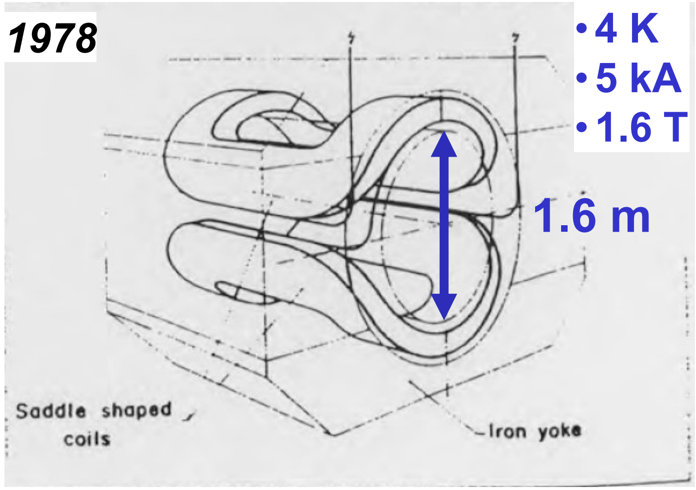
Start with prototyping phase to validate concept: cutting-edge R&D

Need a Magnet

❑ CERN borrows us the world largest warm bore dipole magnet

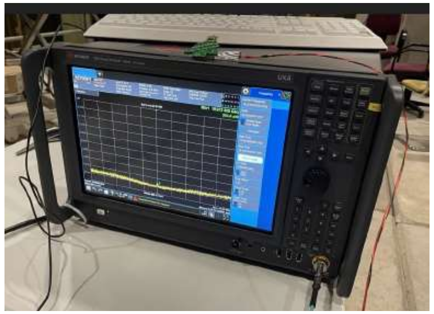
- **Jun 1978 :** Installation in the North Area at CERN
- **Sep 2020** : CERN RB approves usage by MadMax (YETS)
- **Mar 2021** : full refurbishing around magnet area
- **Mar 2022 : i**nstallation of new power converters
- **Apr 2022** : magnet recommissioning
- **Mar-Apr 2023:** MADMAX full user of the magnet

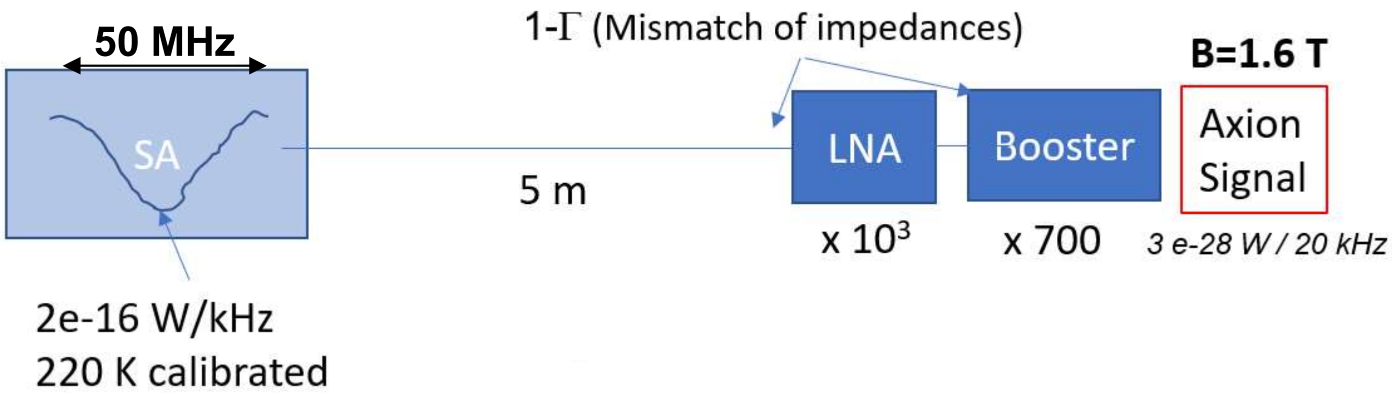




Need a Receiver System

- **Composed of**
  - **Low Noise Amplifier (LNA) ...**
    - ✓ "Classic" HEMT
  - **… connected to custom-made receiver**
    - ✓ Three mixing stages to down sample from 20 GHz to 50 MHz
    - ✓ Fast Fourier Transform in 4 samplers → 1% dead time
    - ✓ Tested at CERN in 2022 but saturation and time instability
  - **… connected to commercial spectrum analyzer (Keysight)**
    - ✓ Tested at CERN in 2023 : stable, no saturation but higher dead time*





* Improve dead time next year by adding data streaming

Develop the booster concept

❑ Address the two main challenges

- Move the disks at μm level precision at cold and under high B-field
- Understand RF behavior → Calibrate boost factor

➔ Ultimately do physics !

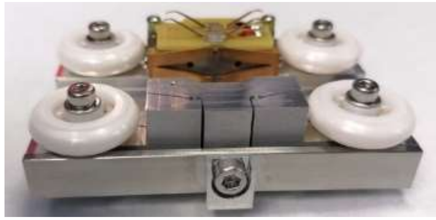
Name	Goal	Type	Made of	Avail.	Test (Room Temp. / **Cold (10 K)**)
P200	Piezo-motor + mechanics	Open Booster	1 moveable disk ϕ = 200 mm	2021	**2022**
CB100	RF studies + First physics	Closed booster	3 fixed disks ϕ = 100mm	2021	2022, 23, **24**
CB200	RF studies + First physics	Closed Booster	4 fixed disks ϕ = 200 mm	2022	24
Proto-3	Scan ALP around 100 μeV	Open Booster	3 moveable disks ϕ = 300 mm	2024	**25, 26?**

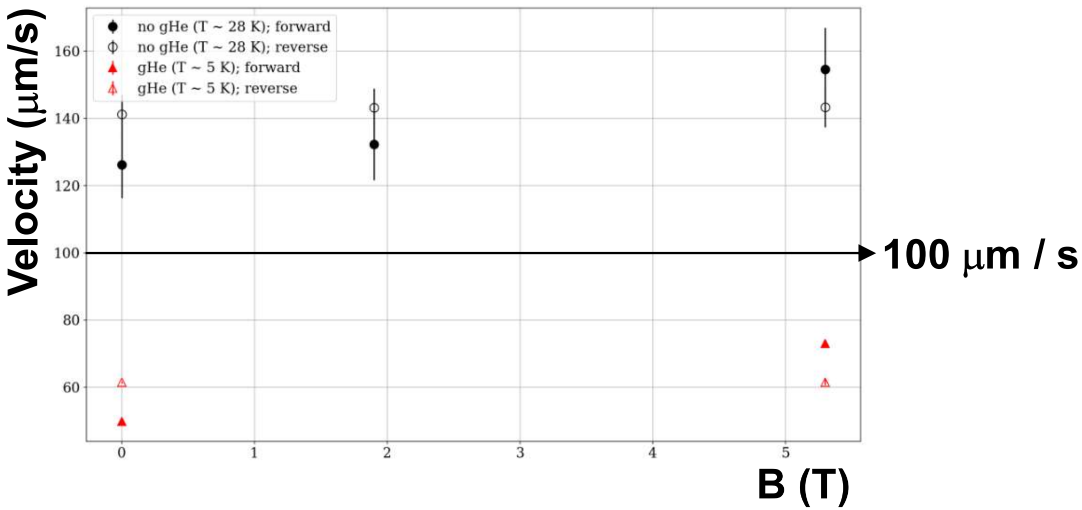
Gradually building the 'final' booster design

Testing the disk drive (1/2)

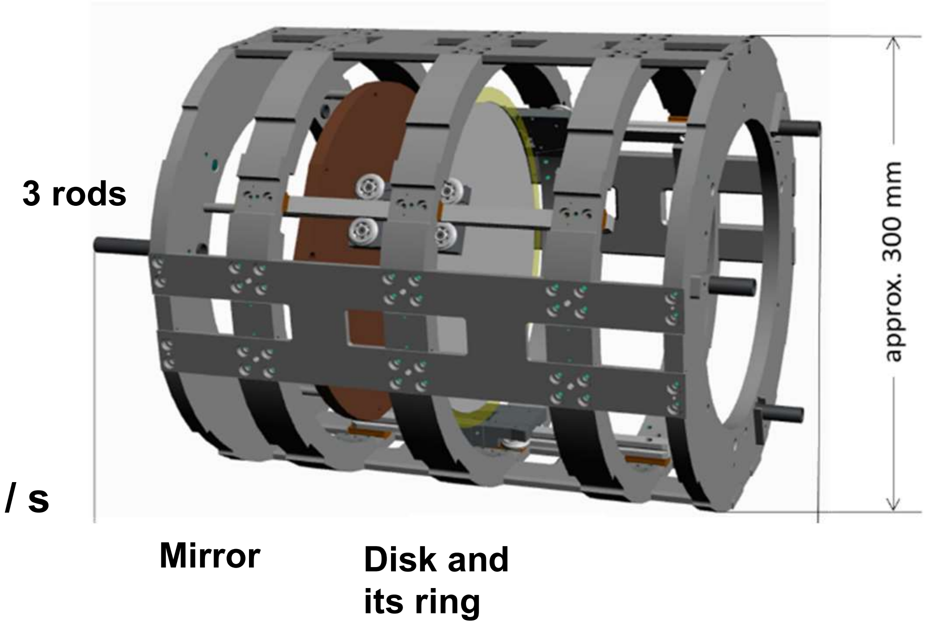
Name	Goal	Concept	Made of	Avail.	ALP Test
P200	Piezo-motor + mechanics	Open Booster	1 **moveable** disk ϕ = 200 mm	2021	2022

Test one commercial JPE piezo motor at 5 K and 5.3 T *(ALP magnet in DESY)*





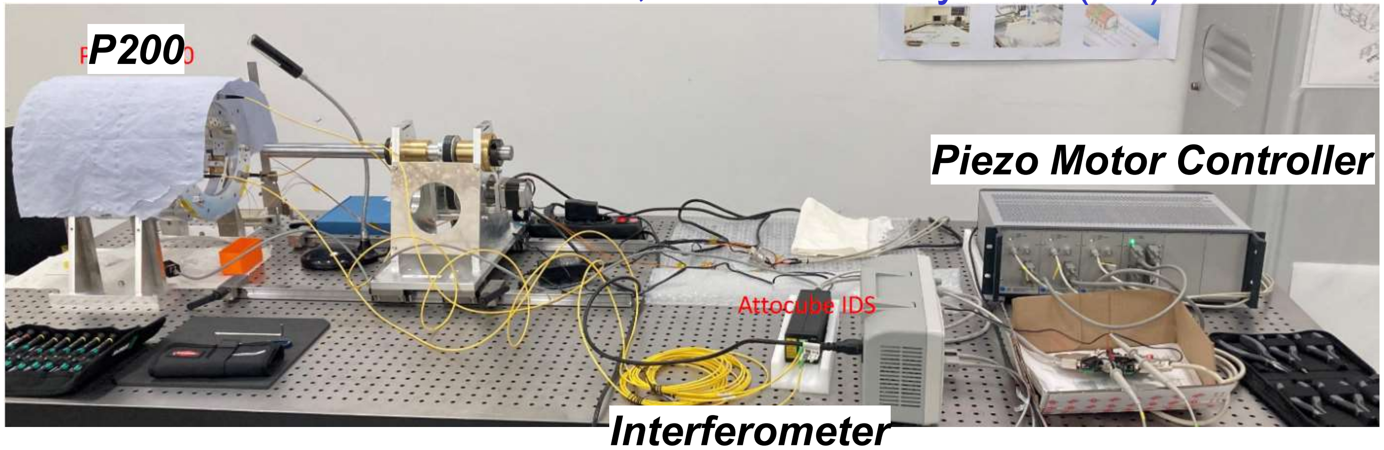
Build full mechanical structure of Open Booster and insert 1 mirror + 1 disk *(3 piezo motors)*



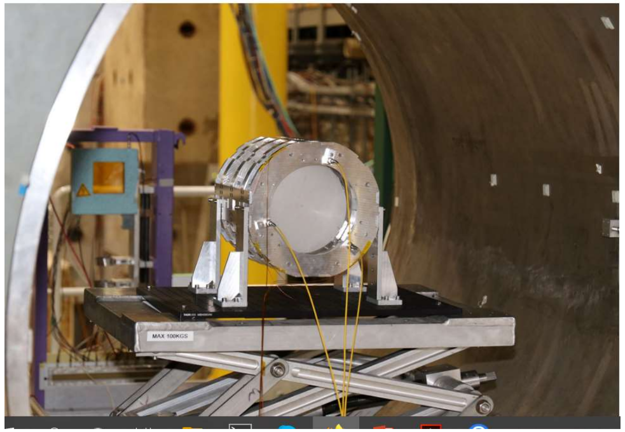
Testing the disk drive (2/2)

Name	Goal	Concept	Made of	Avail.	Morpurgo Test
P200	Piezo-motor + mechanics	Open Booster	1 moveable disk ϕ = 200 mm	2021	2022

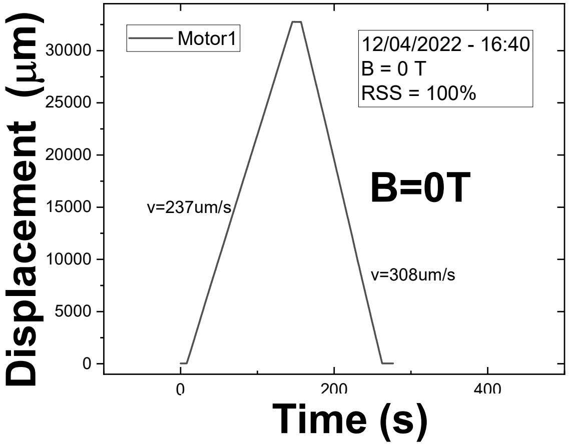
Tested in the lab, in a CERN cryostat (4K)

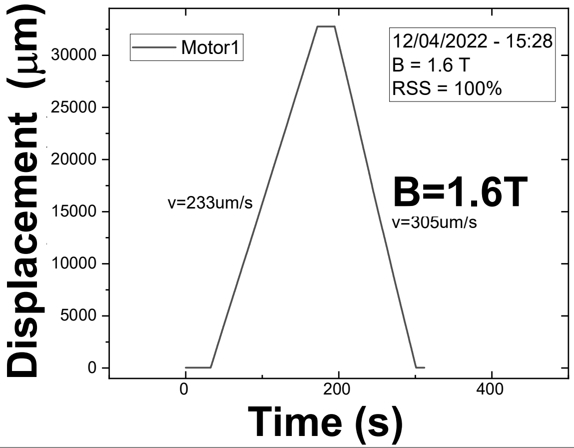


Tested under 1.6 T



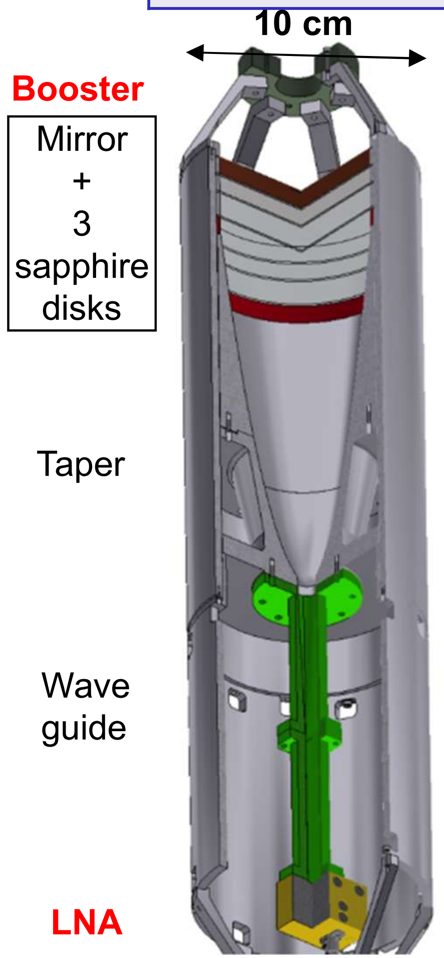
Validate piezo motors + booster mechanics



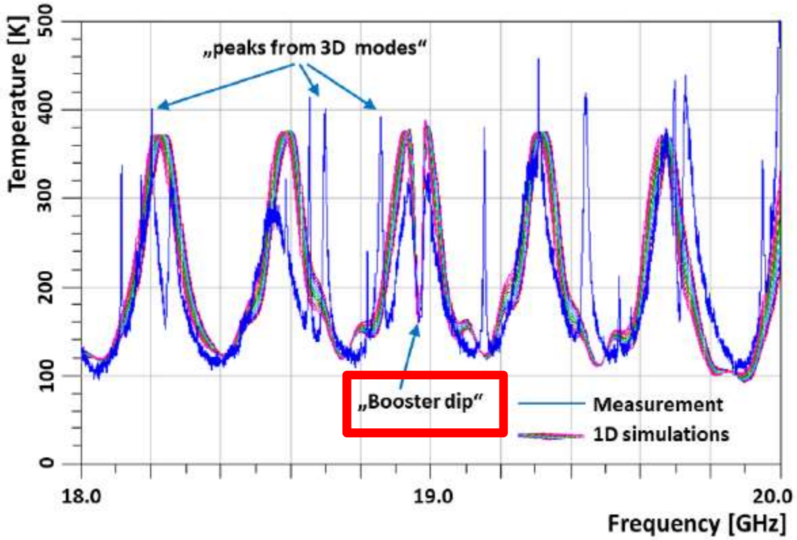


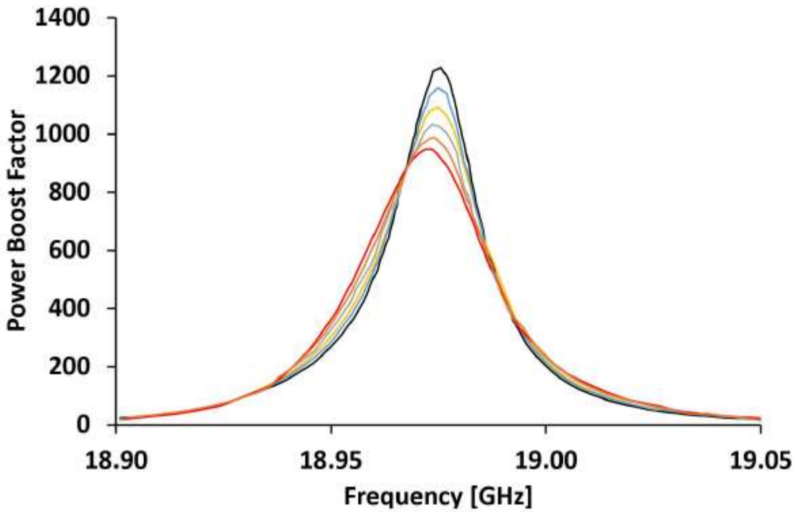
RF Studies (1/2)

Name	Goal	Concept	Made of	Avail.	Lab Test
CB100	RF studies	Closed booster	3 **fixed** disks ϕ = 100mm	2021	2022



Simulate **LNA** (ADS) and **Booster+taper** system (3D COMSOL)
→ compare with measured system temperature in 18-20 GHz

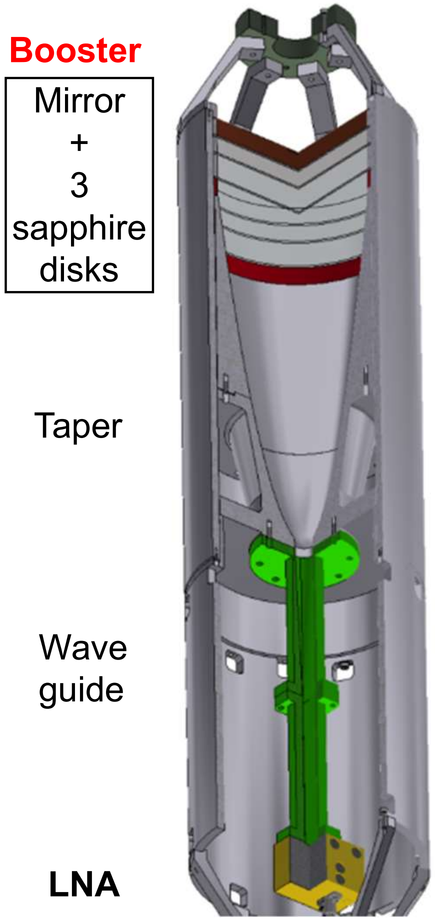


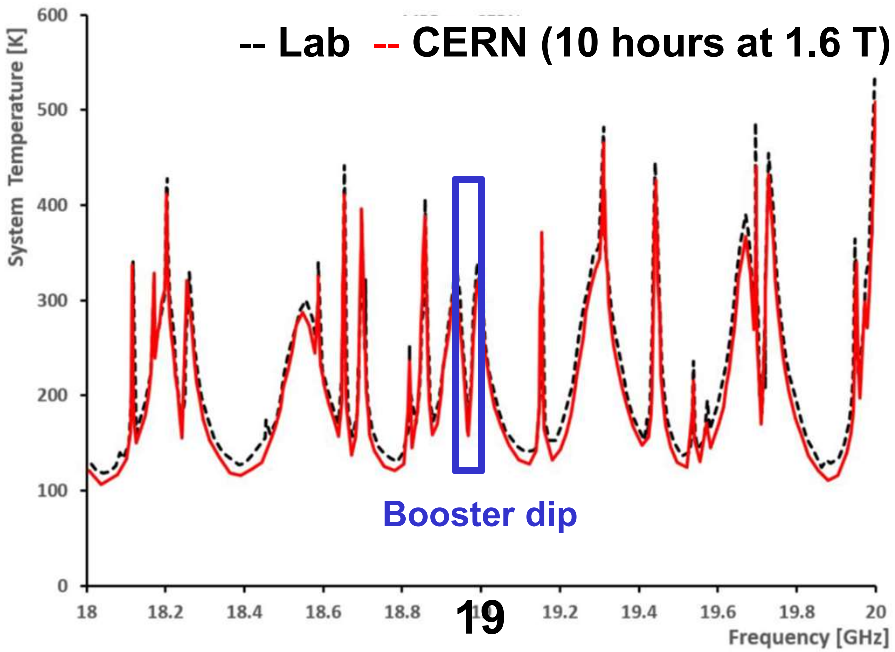


Simulation reproduces system temperature
→ β^2 **= O(1000) at 19 GHz** *(m_{ALP}=78.5 μeV)*

RF Studies (2/2)

Name	Goal	Concept	Made of	Avail.	Morpurgo Test
CB100	RF studies	Closed booster	3 fixed disks ϕ = 100mm	2021	2022



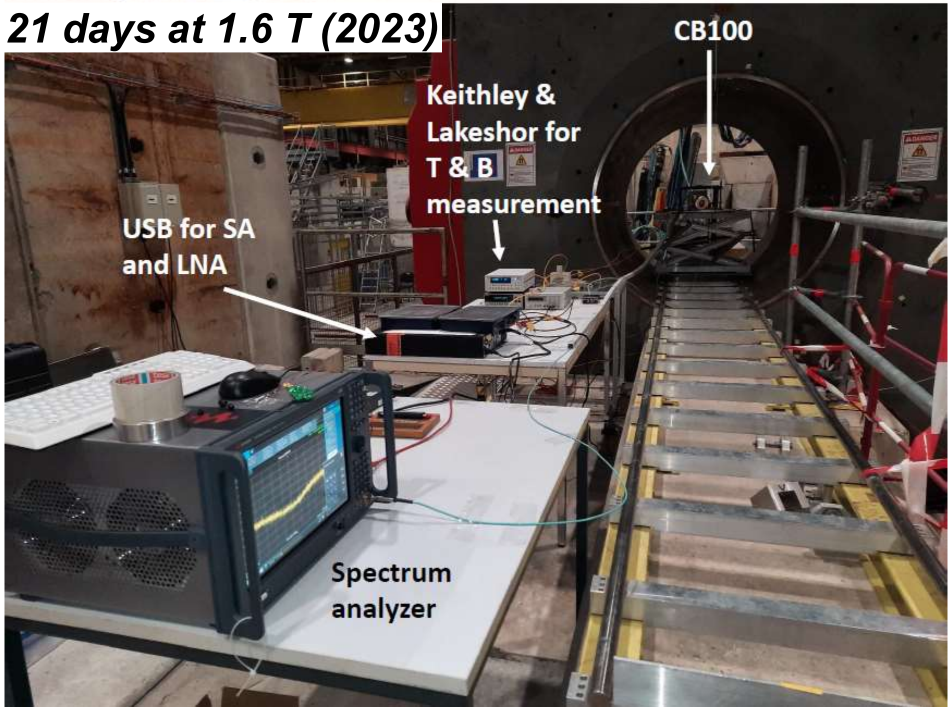


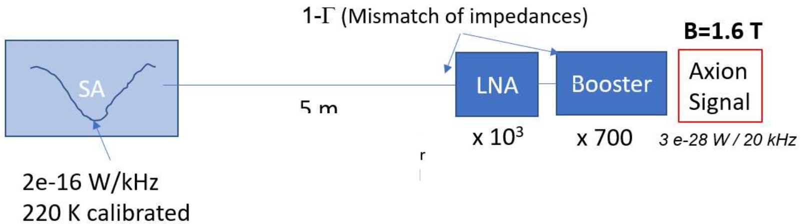
No impact from the CERN environment

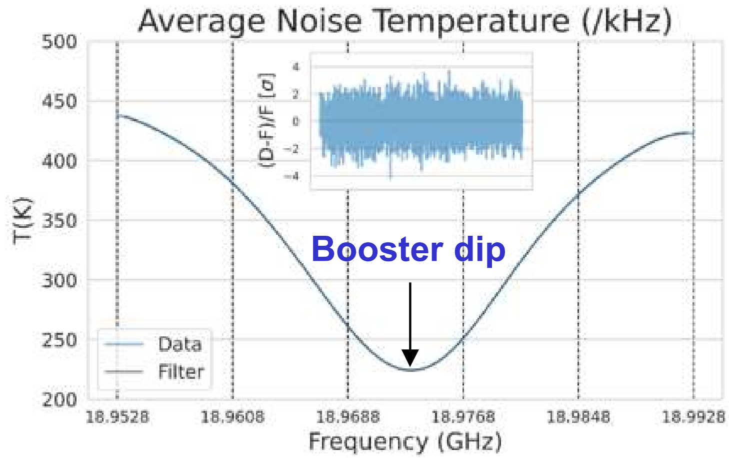
First Physics

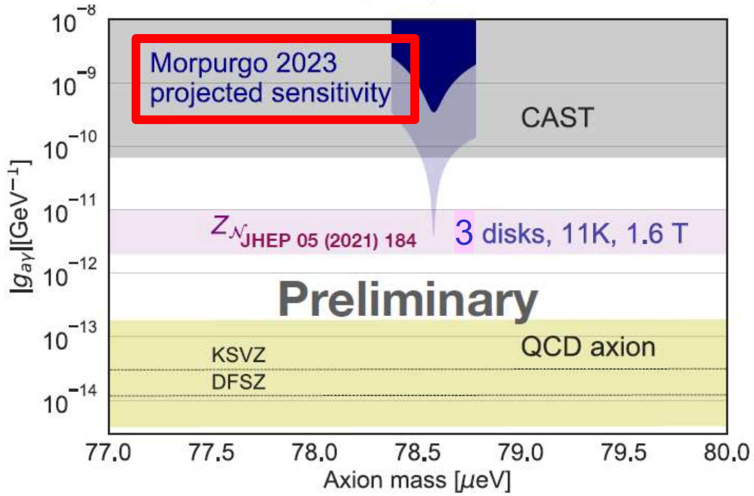
Name	Goal	Concept	Made of	Avail.	Morpurgo Test
CB100	First physics	Closed booster	3 fixed disks ϕ = 100mm	2021	2023

21 days at 1.6 T (2023)









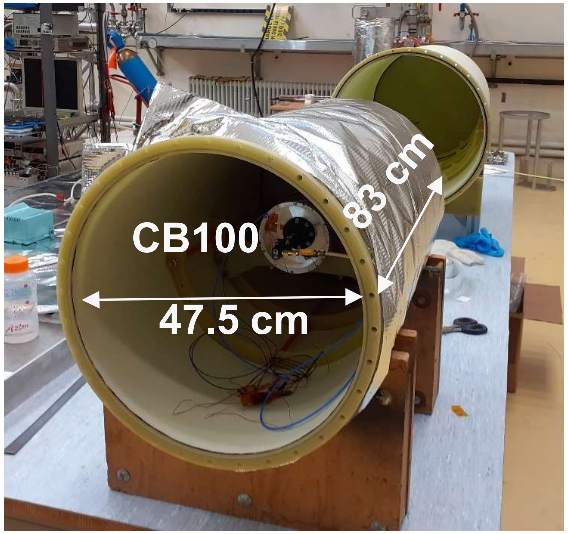
Very stable with time over 21 days → First physics

First ALP Physics

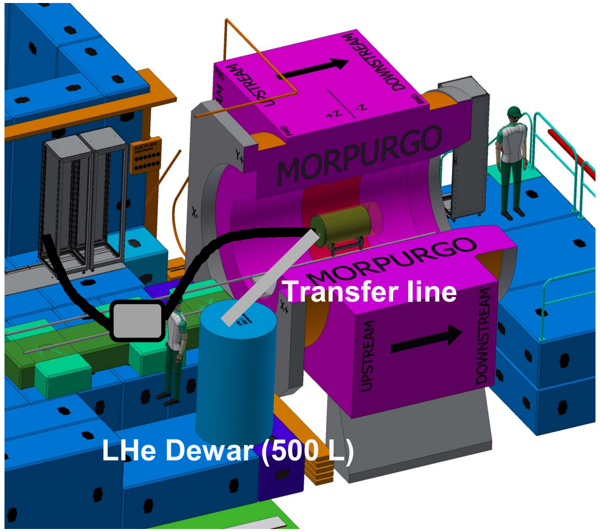
Name	Goal	Concept	Made of	Avail.	Morpurgo Test
CB100	RF studies + First physics	Closed booster	3 fixed disks ϕ = 100mm	2021	**2024**

Develop a 'cheap' cryostat with CERN cryolab to cool the booster + LNA → Validated the principle in 2023

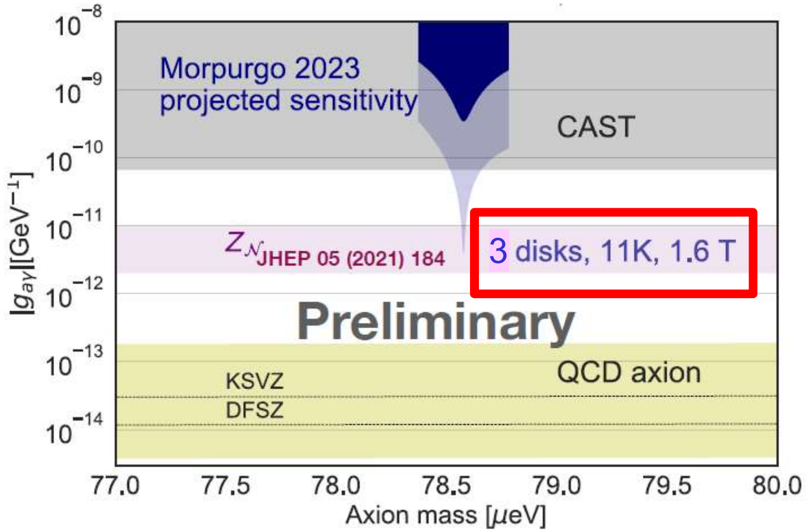
Provided we understand calibration at cold → Improve reach



Vacuum between Inner and Outer vessel



He flow from dewar to cryo
→ **cooling in ½ day**
→ **Stable <10K during >10 hours**

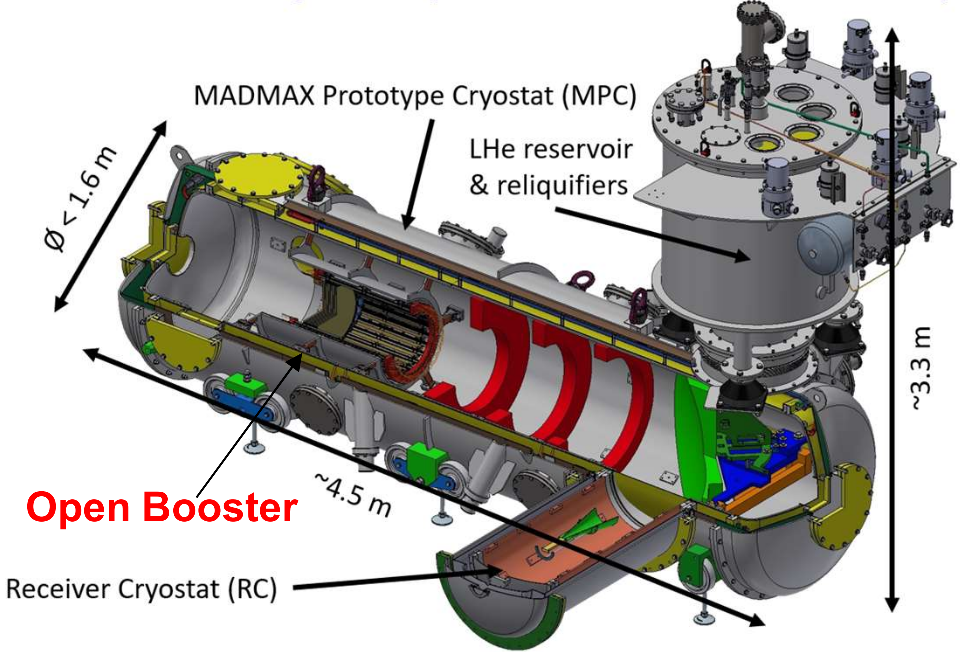


Short cold run

ALP Physics ++

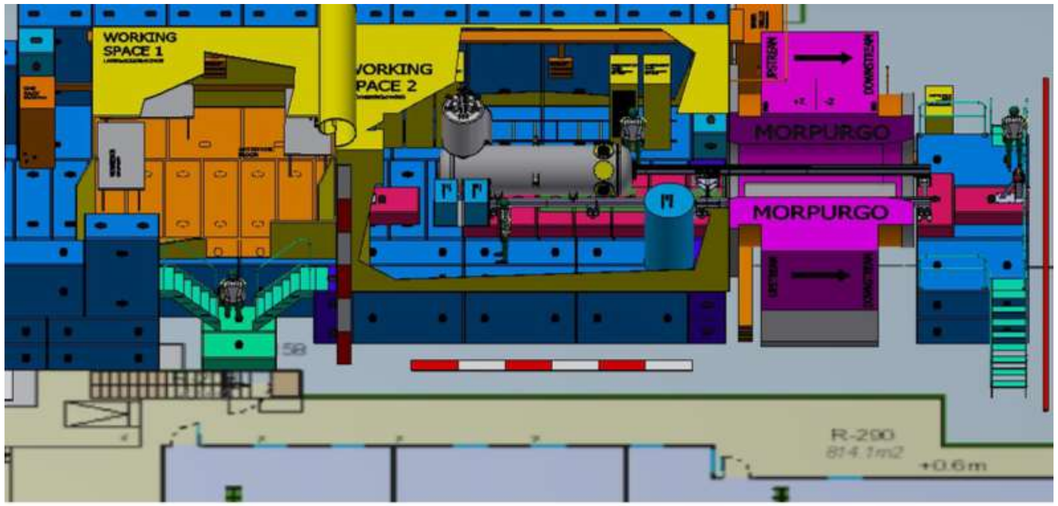
Name	Goal	Concept	Made of	Avail.	Morpurgo Test
Proto-3	Scan ALP around 100 μeV	Open Booster	3 moveable disks ϕ = 300 mm	2024	**2025, 26?**

Open Booster inserted in a Stainless Steel cryostat *(to be delivered in Mar 2024)*



Open Booster built with P200 and CB100 experience

Morpurgo CERN area refurbished to host the SS cryostat



Long cold run + mass scan

MADMAX and France (1/2)

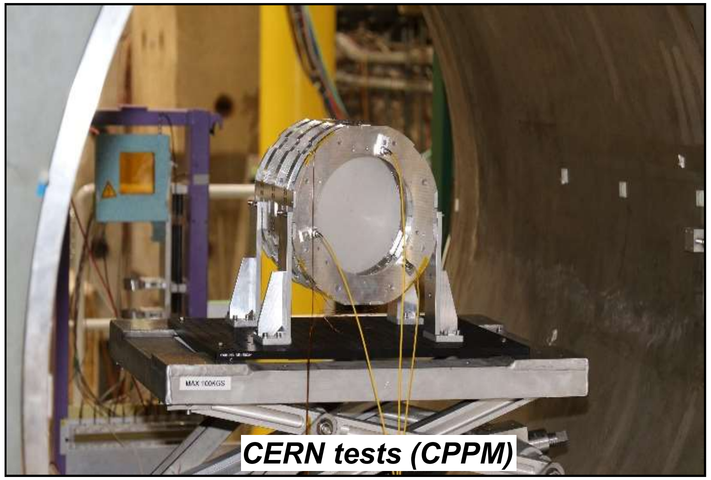
❑ **Two French institutes joined MADMAX in 2020**

- **CPPM** *(2 physicists, 3 engineers, 1 PhD)* **:** booster high precision mechanics, CERN infrastructure and coordination. Supported by IN2P3 for 4 years starting Jan 2023
- **Institut Neel :** ultra-low noise amplifier
- \+ **CEA-IRFU** : work for the final magnet
- \+ **IRL DMLab :** installed at DESY → MADMAX is one of the supported project

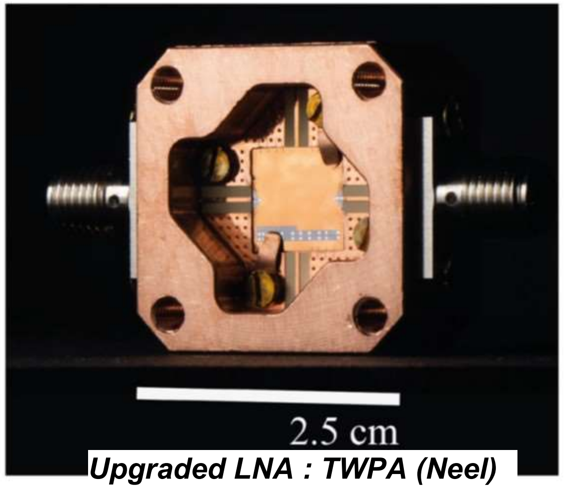
Disk planarity (CPPM)

Disk ring (CPPM)

(more in back-up)



CERN tests (CPPM)



Upgraded LNA : TWPA (Neel)

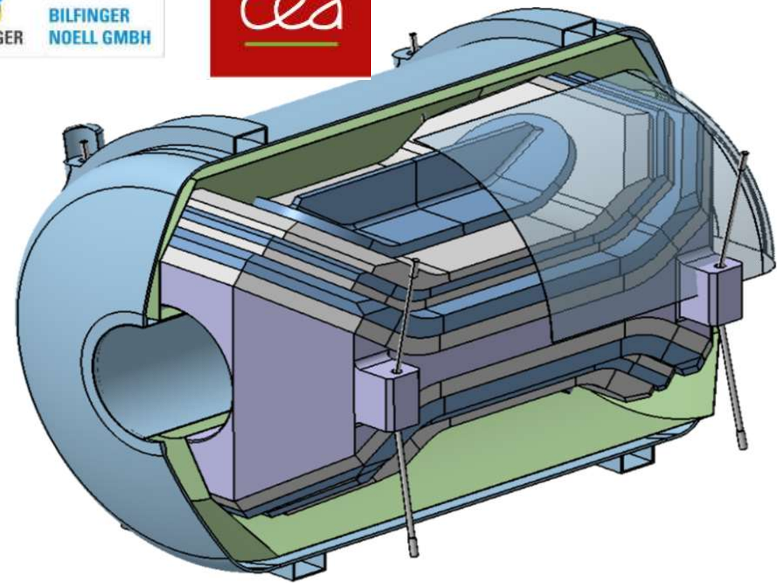
MADMAX looking for new (French) institutes to join !

MADMAX and France (2/2)

❑ Progresses on final magnet

- Design completed: 2x9 skateboard coils with novel copper CICC conductor

[NbTi with Cu jacket @ 1.8K]



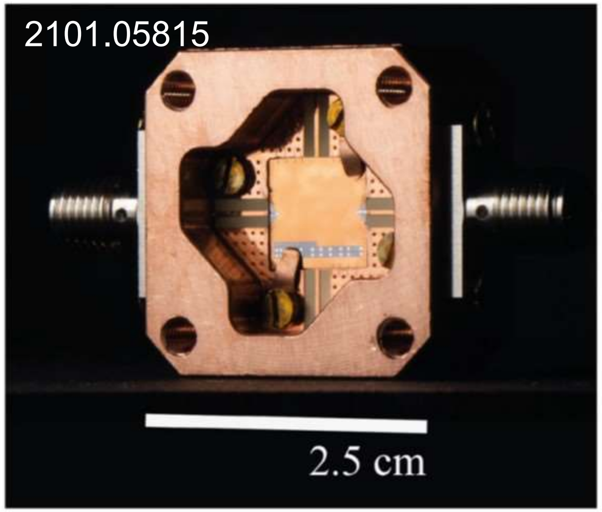
- Recently demonstrated that coils will be safe in terms of quench protection
- **Next** : Design, manufacture and test a small MADMAX coil (6T)

❑ Progresses on final receiver

- Very low noise pre-amplifier *[P_{sig}~T_{sys}]*

HEMT (G=33 dB, 4K added noise) below 40 GHz

- Josephson Junction being developed to further minimize noise *(quantum limit)*



TWPA prototype with G>20 dB and 1K added noise at 10 GHz

- **Next**: >40 GHz techno. to be developed

MADMAX timescale

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

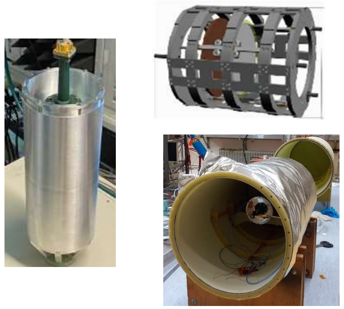
We are here !

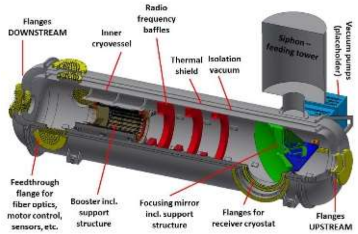
Design Phase

Prototyping Phase

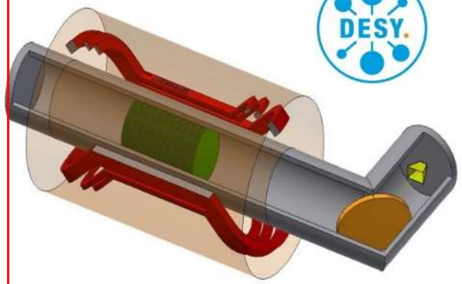
Foundation of MADMAX Collaboration

First endorsement by DESY PRC





Usage of **MORPURGO magnet (1.6T)** approved by **CERN** Research Board during beam shutdown



Full-size MADMAX magnet commissioning

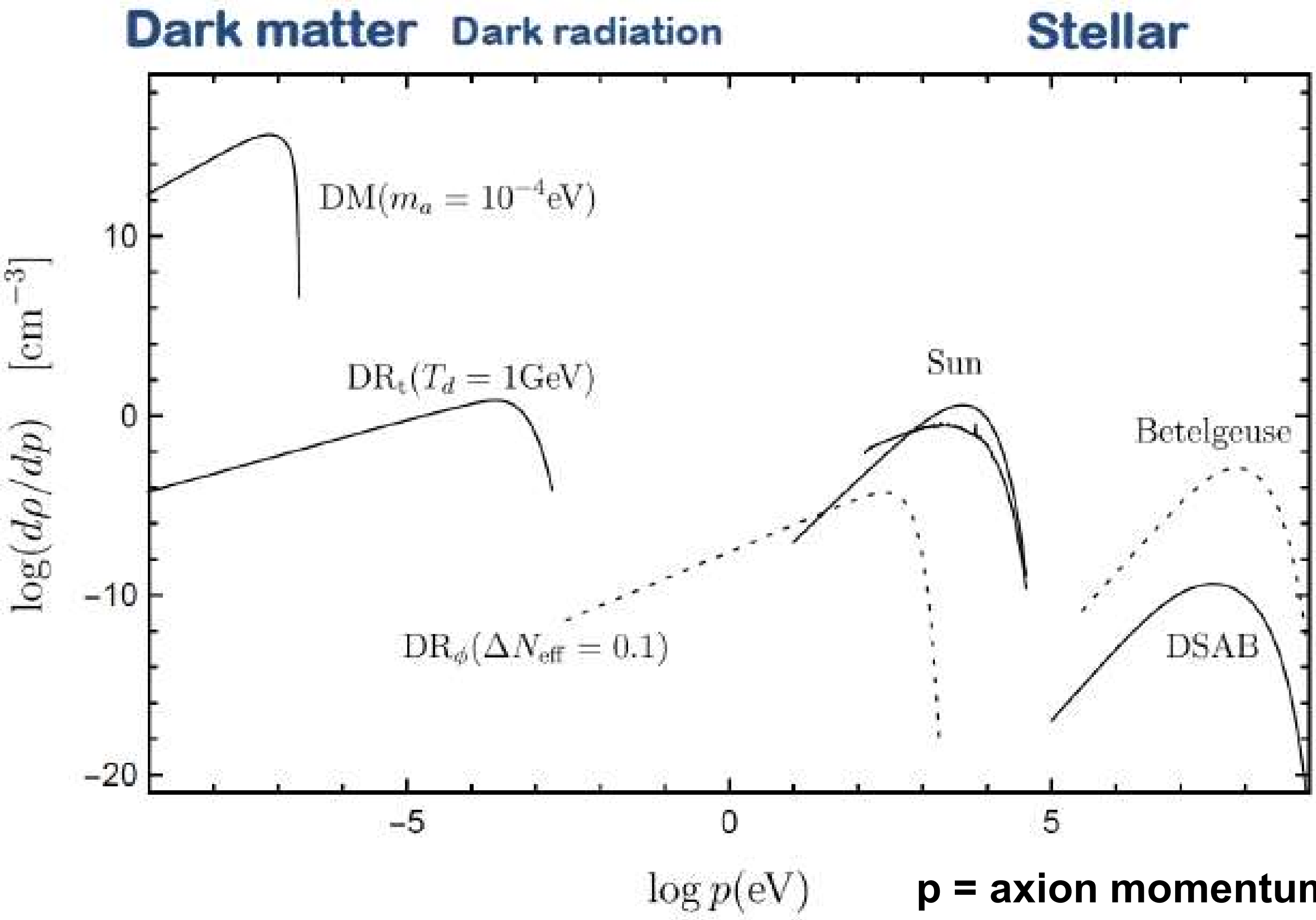
1000- 10000 | 10 – **220** | **1.6** | **0.01**-0.3

$$g_{a\gamma} \propto \left(\frac{50000}{\beta^2}\right)^{1/2} \times \left(\frac{T_{sys}}{4\,\mathrm{K}}\right)^{1/2} \times \left(\frac{10\,\mathrm{T}}{B_e}\right) \times \left(\frac{1\,\mathrm{m}^2}{A}\right)^{1/2} \times \left(\frac{4\,\mathrm{days}}{t}\right)^{1/4} \times \left(\frac{\mathrm{SNR}}{5}\right)^{1/2}$$

BACKUP

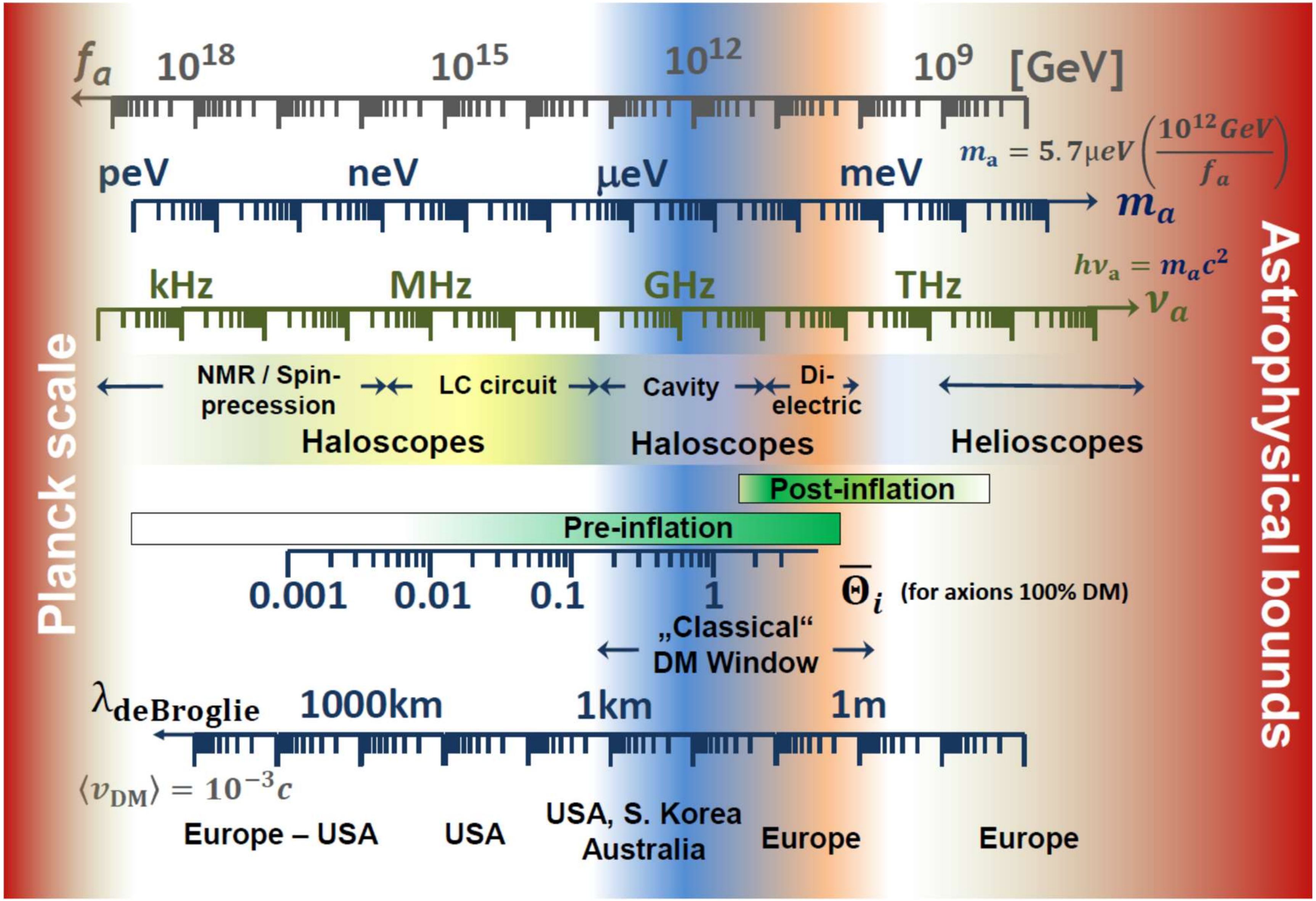
Collab Week at CPPM (Apr 2023)

Sources of axions



p = axion momentum

Axion scales

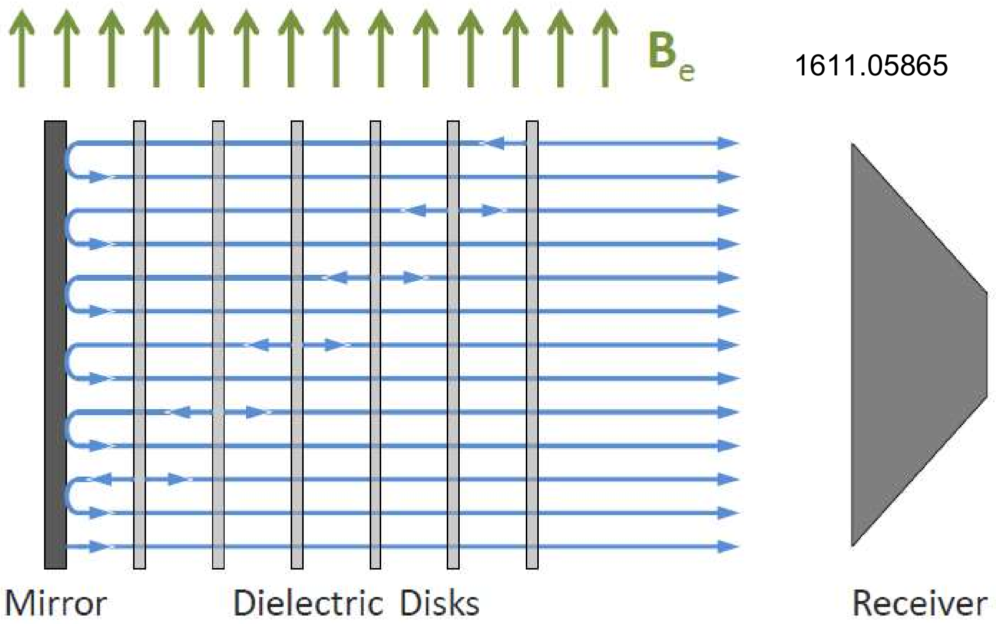


Dielectric haloscope

❑ Dielectric haloscope → MadMax experiment

- New experimental concept to alleviate cavity limitation at high m_a ($V \sim 1/m_a^3$)
- Discs + mirror in B_e → wave emission @ interfaces → constructive interferences + resonances

[if $\lambda_\gamma/2$ =distance between discs]



Lanthanide Aluminate ($LaAlO_3$)

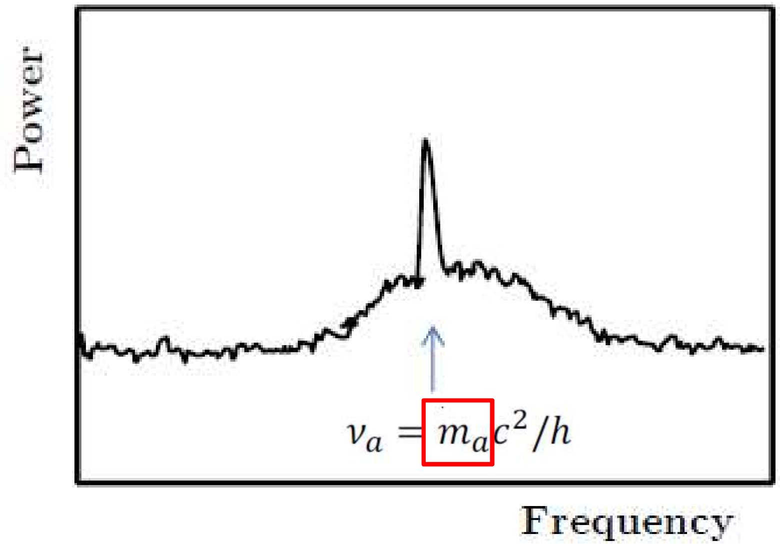
Sensitive to $P \sim 10^{-22}$ W in GHz regime (very low noise)

Power / Area

$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 C_{a\gamma}^{\ 2}\ \beta^2$$

Signal boost x10^5

→ $P \sim 10^{-22}$ W *($A = 1m^2$, $B = 10T$)*



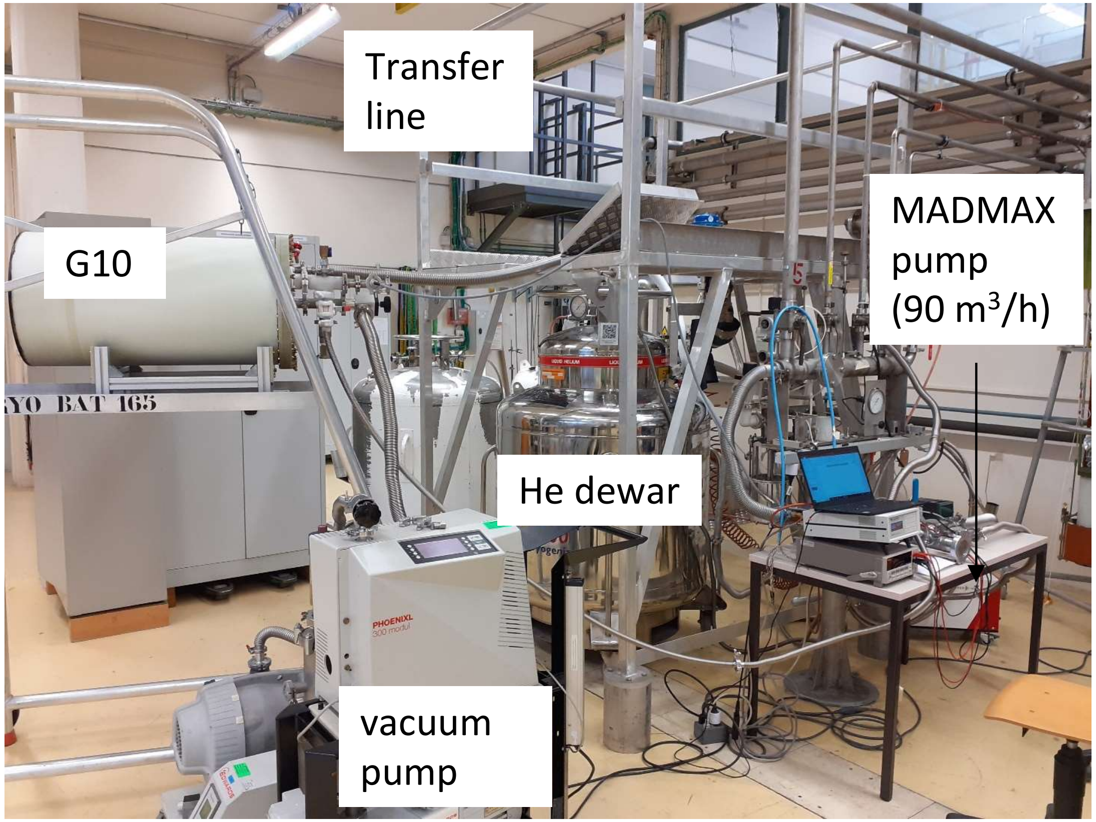
[$E = h\nu_a = m_a c^2 + 0.5 m_a v_a^2$, $v_a = 10^{-3}c$ → $h\nu_a = m_a c^2$]

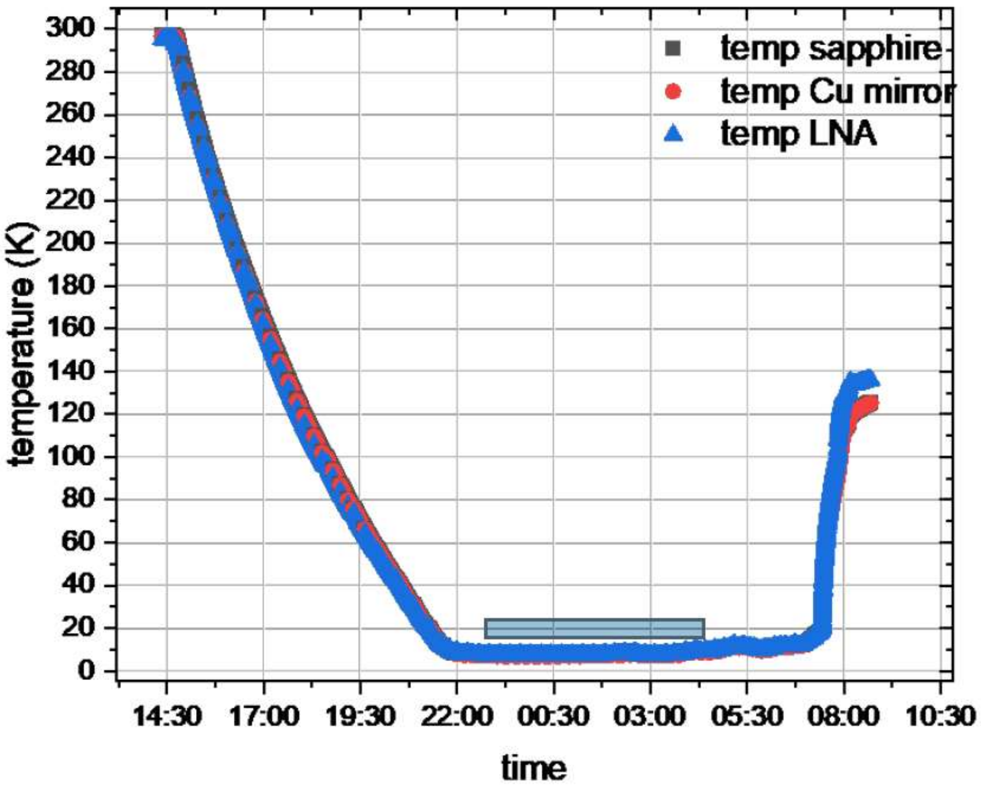
- Adjustable distance between discs → tune to scan m_a

  [spacing 15 mm for 40 μeV and 1.5 mm for 400 μeV]

→ MadMax only capable to explore m_a=40-400 μeV *(favored by post-inflation theory)*

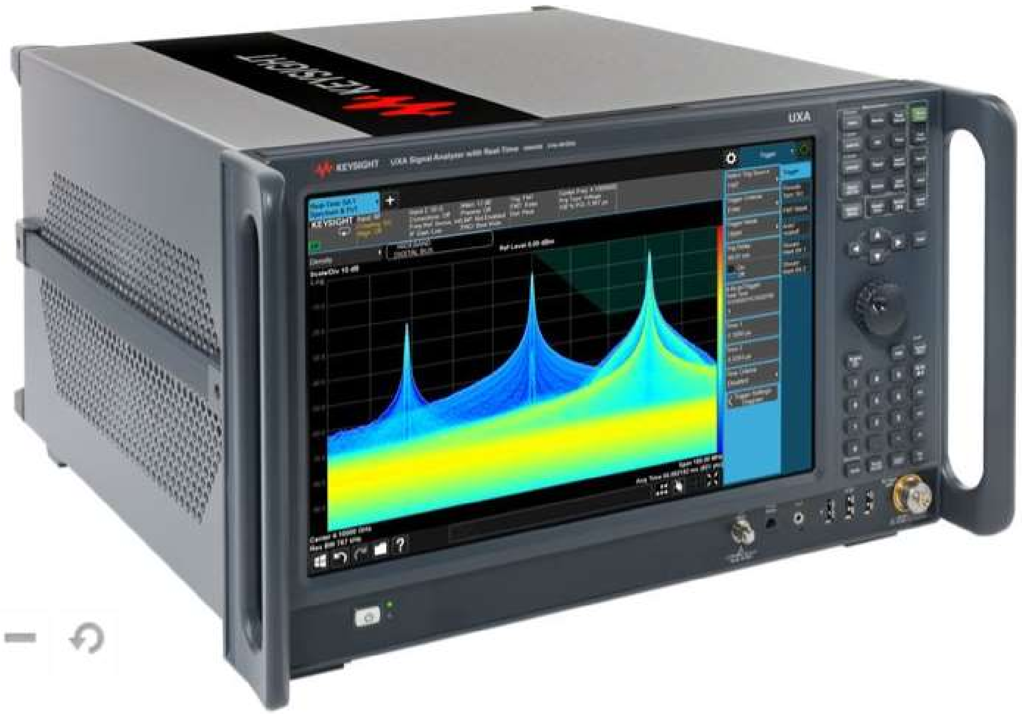
G10 cryostat





Spectrum Analyzer

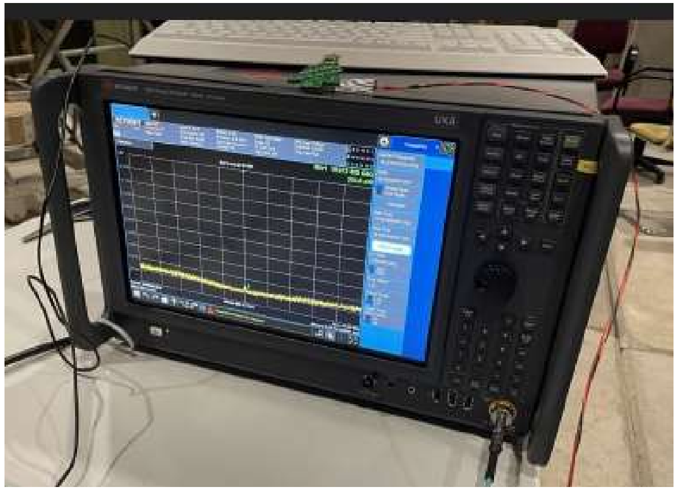
2023 → Keysigth : N9040B

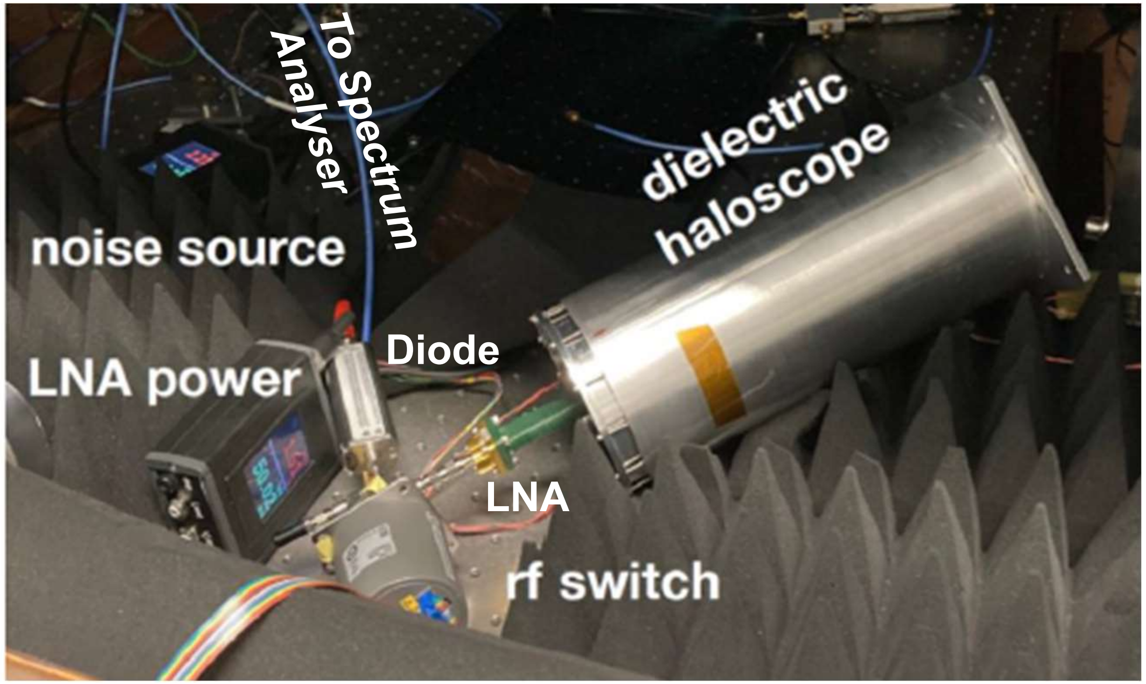


2024 → Rhode&Schwarz FSW26 with streaming option

System calibration (1/3)

Spectrum Analyser





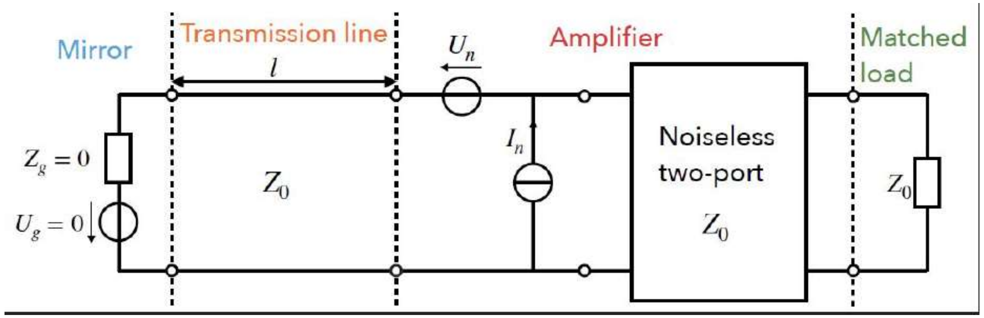
Diode

1- Power (W/kHz) to Thermal Noise Temp. (K) :

- Use a well calibrated diode with a 30 dB Attenuator
- T Diode On = Room Temperature + 50K = 345 K
- T Diode Off = Room Temperature = 295 K
- With P (Diode On), P (Diode Off), estimate reflections
- From P (LNA + Booster), P (Diode On), P (Diode Off) deduce **T (LNA + Booster)**

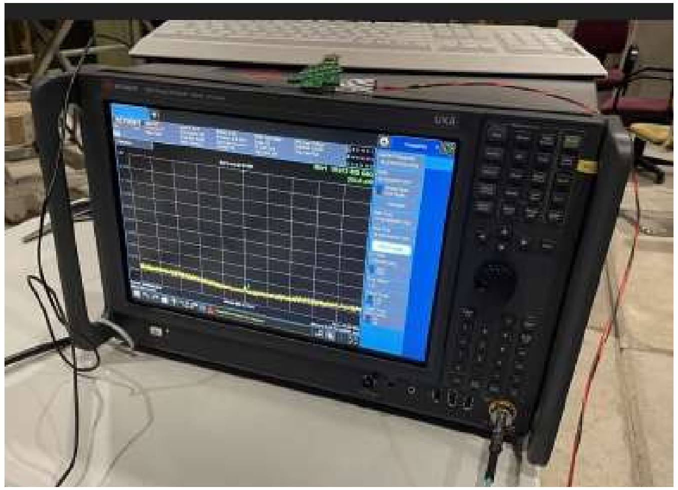
2- ADS model (I_n, U_n) for LNA Noise

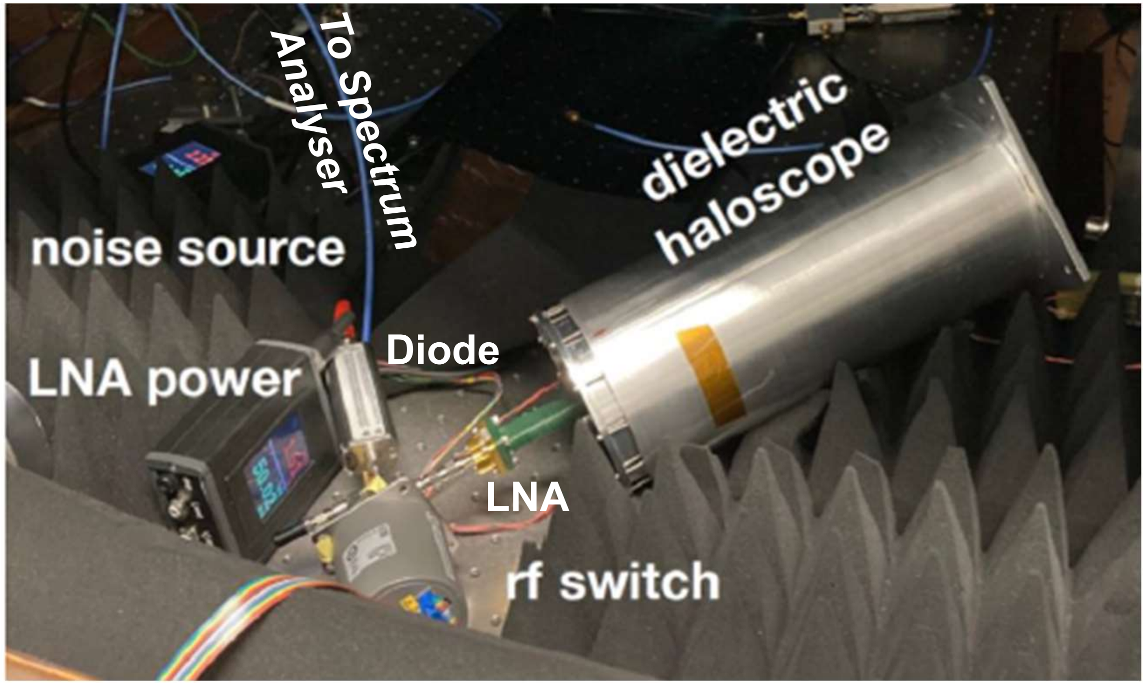
- Short / Open / Load with RF switch



System calibration (2/3)

Spectrum Analyser





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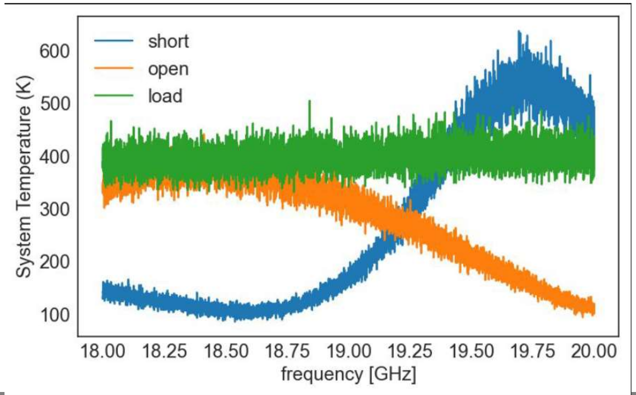
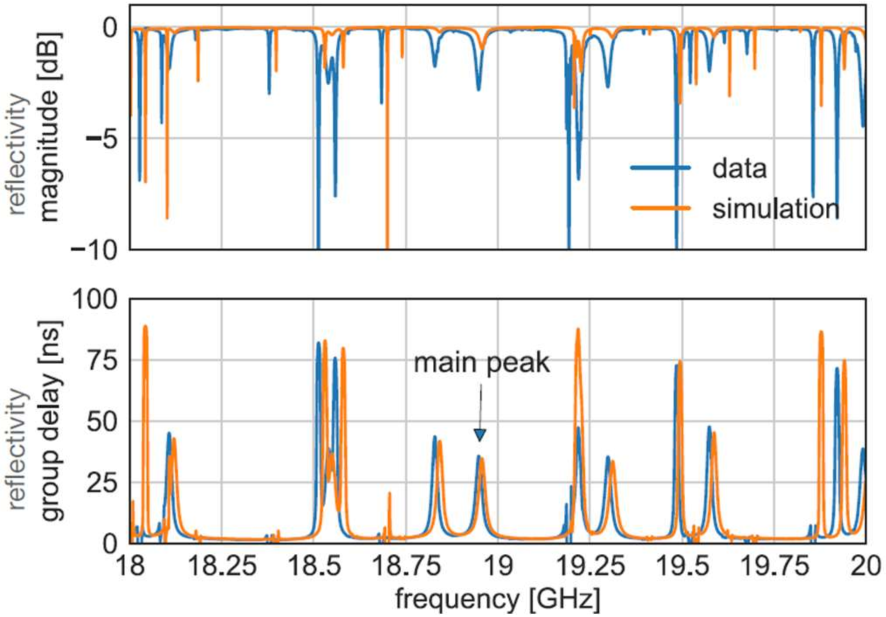
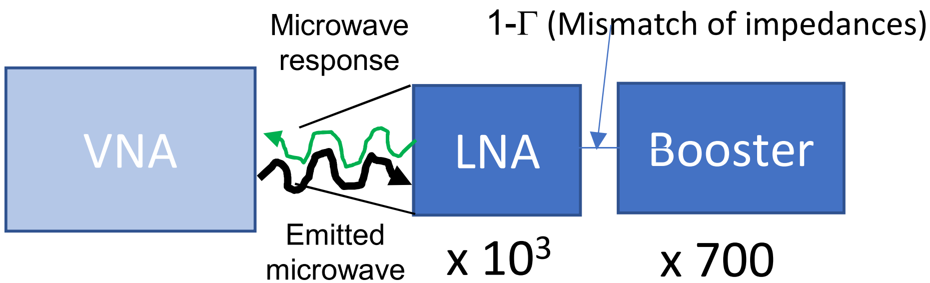


System calibration (3/3)

3- Reflectivity measurements with a VNA

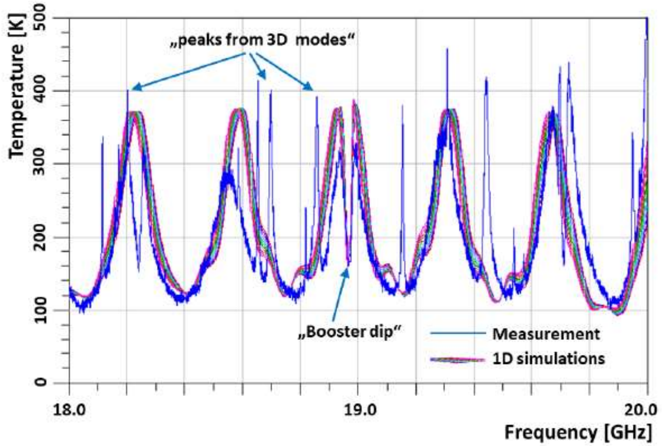
- Should match the 3D COMSOL simulation of the booster + taper





4- Merge ADS and COMSOL simulations to predict T (K)

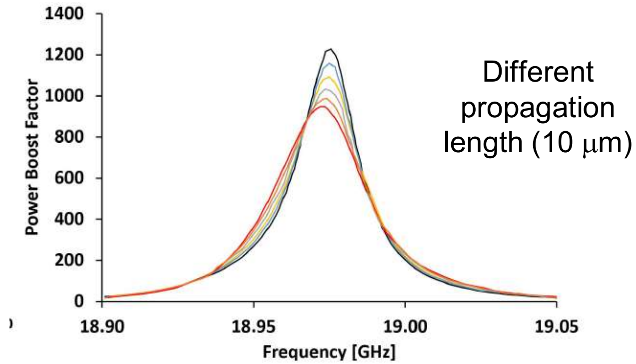
- Should match the measured T (SA)



- Wavy because of coherent and destructive interference (different propagation length) when injecting the LNA noise in the booster

5- Deduce the Booster factor from the model

- Including uncertainties



MadMax activities at CPPM

CPPM pioneer at IN2P3 in direct searches for axions, world rising activity and in particular in Germany (DESY "Axion Hub")

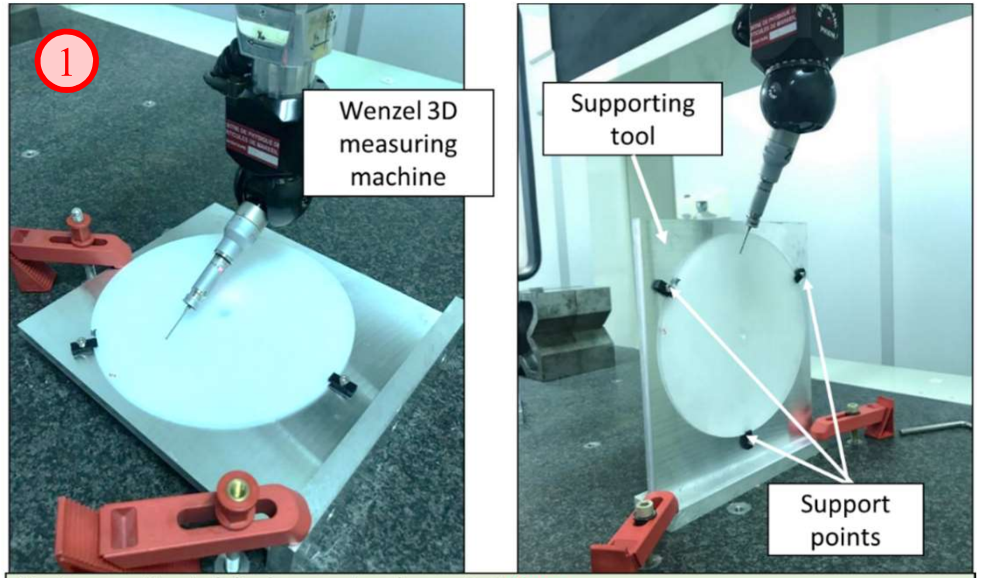
Precision mechanics at CPPM for the prototype boosters

1. Precision 3D measurements O(µm) for geometry control of the prototype disks
   - CPPM expertise/infrastructure for precision measurements (e.g. ATLAS pixels)
2. Conception/fabrication of disk support rings
   - Interfaces between disks, piezo motors and interferometer system
   - Cutting edge and challenging R&D → Optimisation of fabrication process to obtain best planarity (<10µm)

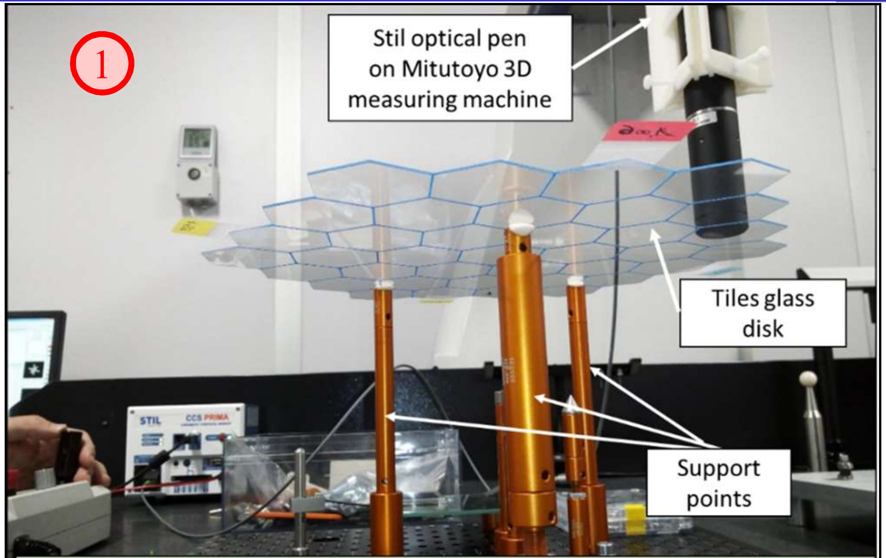
Infrastructures at CERN for protos tests protos in Morpurgo magnet

3. Conception, fabrication and installation of mecanical interfaces prototypes-Morpurgo
   - Rails for electric racks, supports for prototypes, rails for big test cryostat
4. Coordination of tests at CERN (programme 2021-2025 approved by SPSC) → tests prototypes CB100 (physics) and P200 (meca) in April 2022 in Morpurgo magnet 1.6T

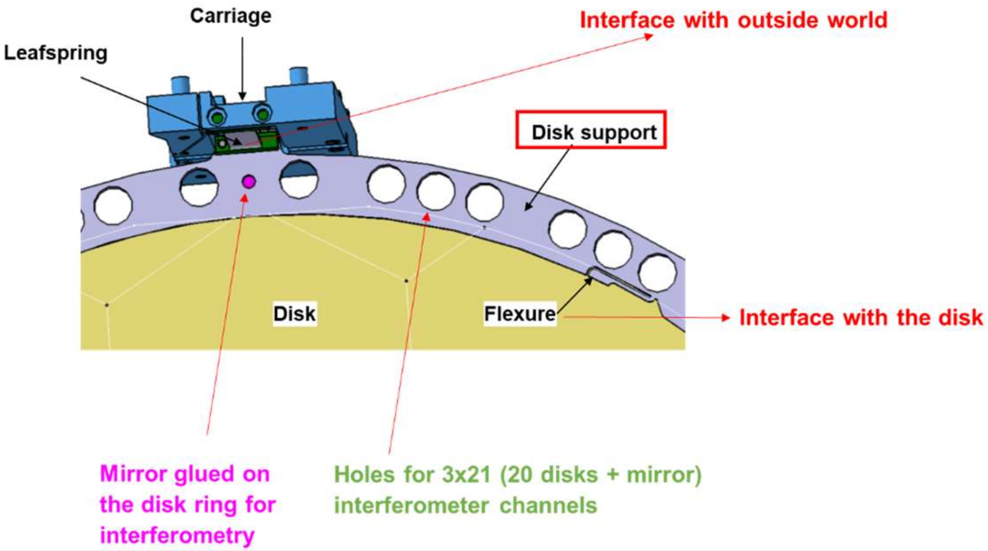
MadMax activities at CPPM

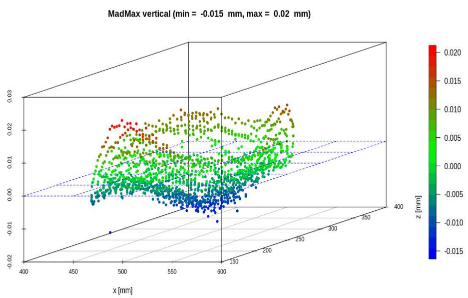


Maximum estimated displacement under contact 5 µm
Accuracy of the measurement < 5 µm
Measurement duration = 1 hour per disc (2 sides, 500 measurements per side)



Accuracy of the measurement < 2 µm in focal depth
Measurement duration = 3 hours per disc (2 sides, 2500 measurements per side)

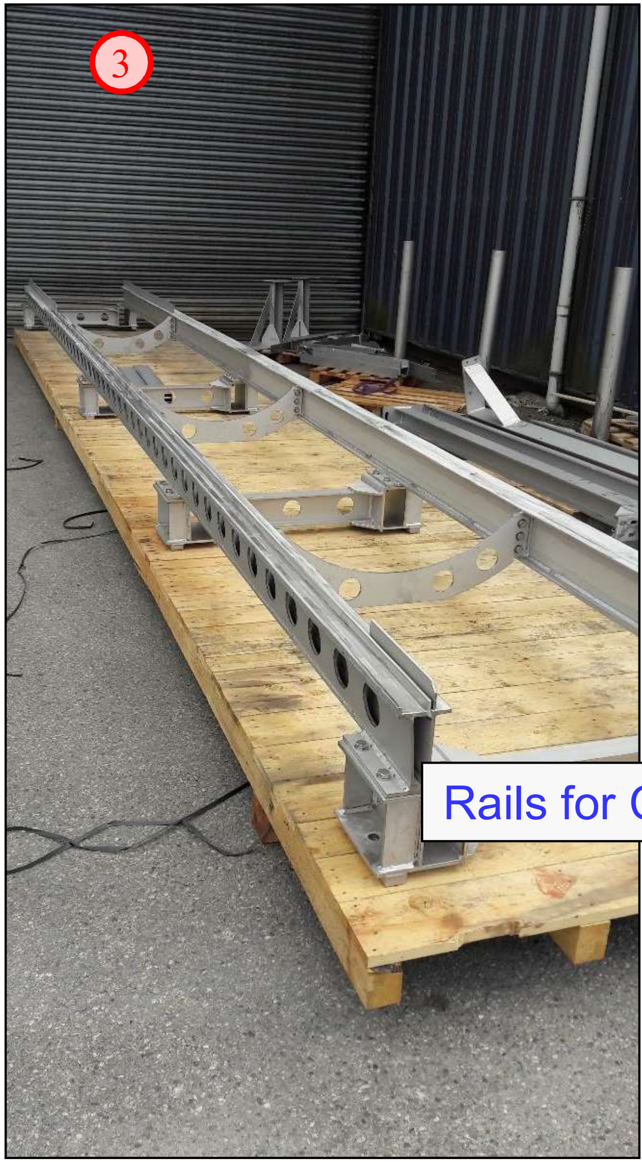


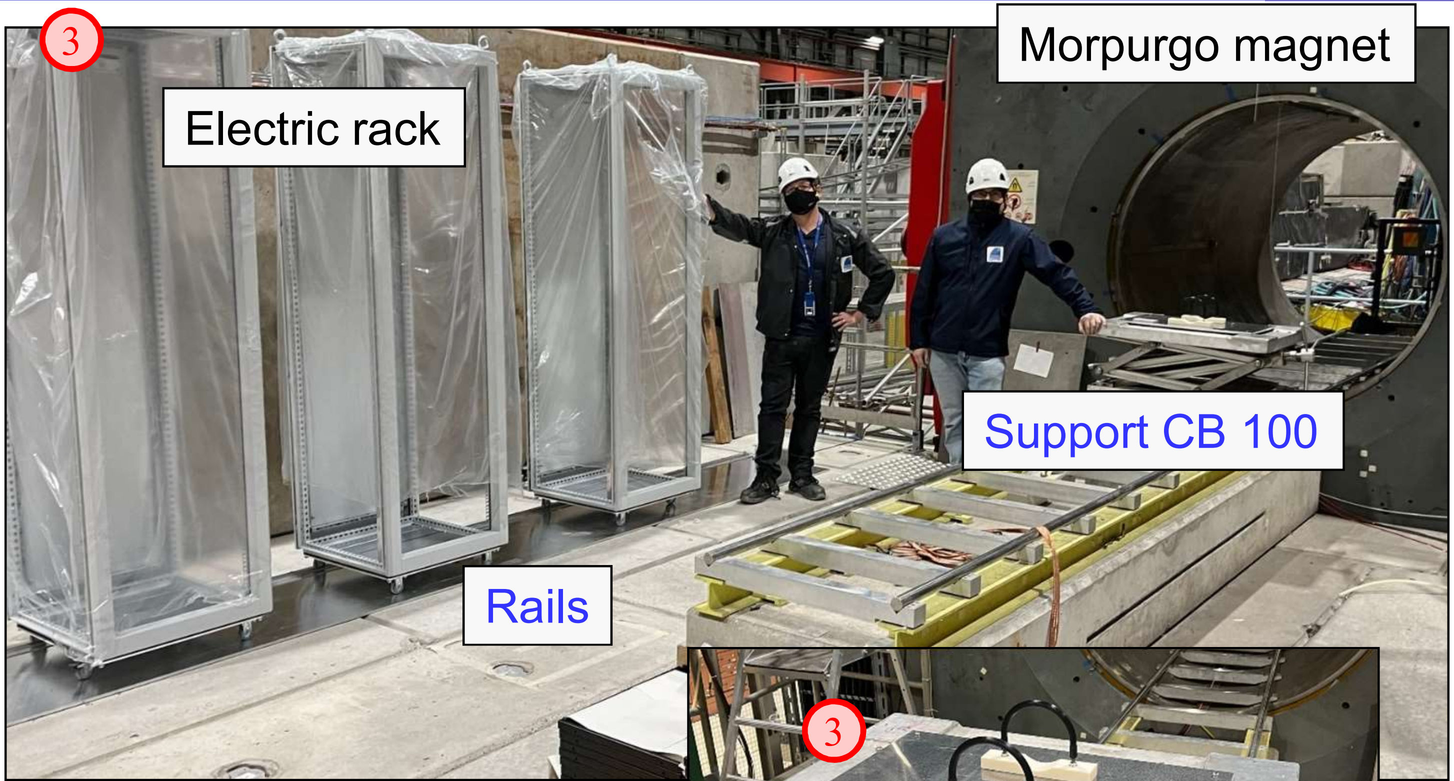


Min-max : 0.035 mm
RMS: 0.0067 mm

Disk planarity not modified by support

MadMax activities at CPPM

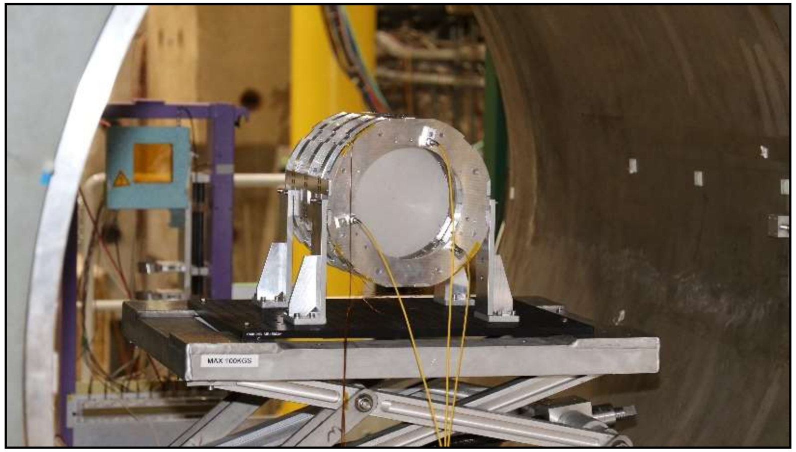


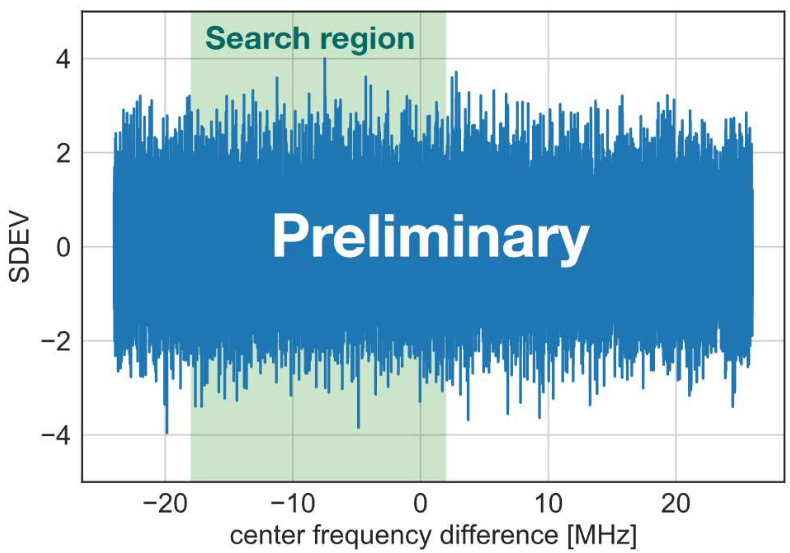


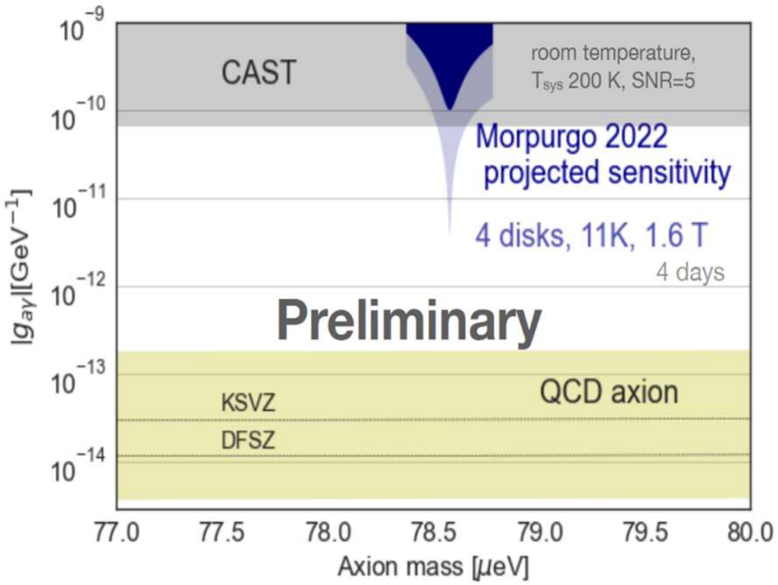
MadMax activities at CPPM

4

Tests of two first prototypes in April 2022 in Morpurgo (during SPS shutdowns)







➔ CPPM drives magnet @ CERN + participates to search for ALP @ ~80μeV