Direct search for dark matter axion with MADMAX

Fabrice Hubaut **(hubaut@in2p3.fr)**

CPPM/IN2P3 – Aix-Marseille Université

On Behalf of the MADMAX IN2P3 team

1- Scientific context
2- MADMAX: principles and prototyping phase
3- IN2P3 contributions and resources

Conseil scientifique IN2P3, 23 octobre 2023

(Very short) Theoretical motivations

- **CP violation in strong interaction**? (observed since 1964 in weak interactions)
  - CP-violating term in QCD Lagrangian (controlled by Θ) is allowed and **should exist**
  - … but $\mathbf{\Theta < 10^{-10}}$ from neutron electric dipole moment

➔ **Strong CP Problem = naturalness problem. Why is Θ so small ?**

(Very short) Theoretical motivations

- **CP violation in strong interaction**? (observed since 1964 in weak interactions)
  - CP-violating term in QCD Lagrangian (controlled by Θ) is allowed and **should exist**
  - … but **$\Theta < 10^{-10}$** from neutron electric dipole moment

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

- **Solution to Strong CP problem** **➔ Axion**
  - Mechanism: new global U(1) symmetry *(Peccei-Quinn, 1977)* spont. broken at scale f_a
    - ➔ Can occur before or after inflation → cosmological implications
  - Consequence: pseudo-Goldstone boson of the theory = **axion** *(Weinberg-Wilczek, 1978)*
    - ➔ Properties are all known given the scale of symmetry breaking f_a [$f_a >> f_{EW}$]
    - ➔ Tiny mass [$m_a \approx m_\pi f_\pi / f_a$ << eV], very weakly interacting [suppressed by f_a] and $\tau_{axion} > t_{Universe}$
  - Cold dark matter: non-thermal massive axion at $T \sim \Lambda_{QCD}$

➔ Axion = DM candidate motivated by particle physics since 40 years

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

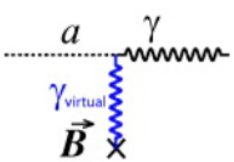
Axion/ALP direct searches

Lab experiments	Helioscopes	Haloscopes
Lab produced → fully controlled setup	Solar axions	Relic DM axions
Low axion flux	Medium axion flux	High axion flux
Model independent	Mildly model dependent	Model dependent
ALP	QCD axion / ALP	QCD axion DM [1-1000 μeV]
e.g. ALPS II	**e.g. (Baby)IAXO**	**e.g. MADMAX**

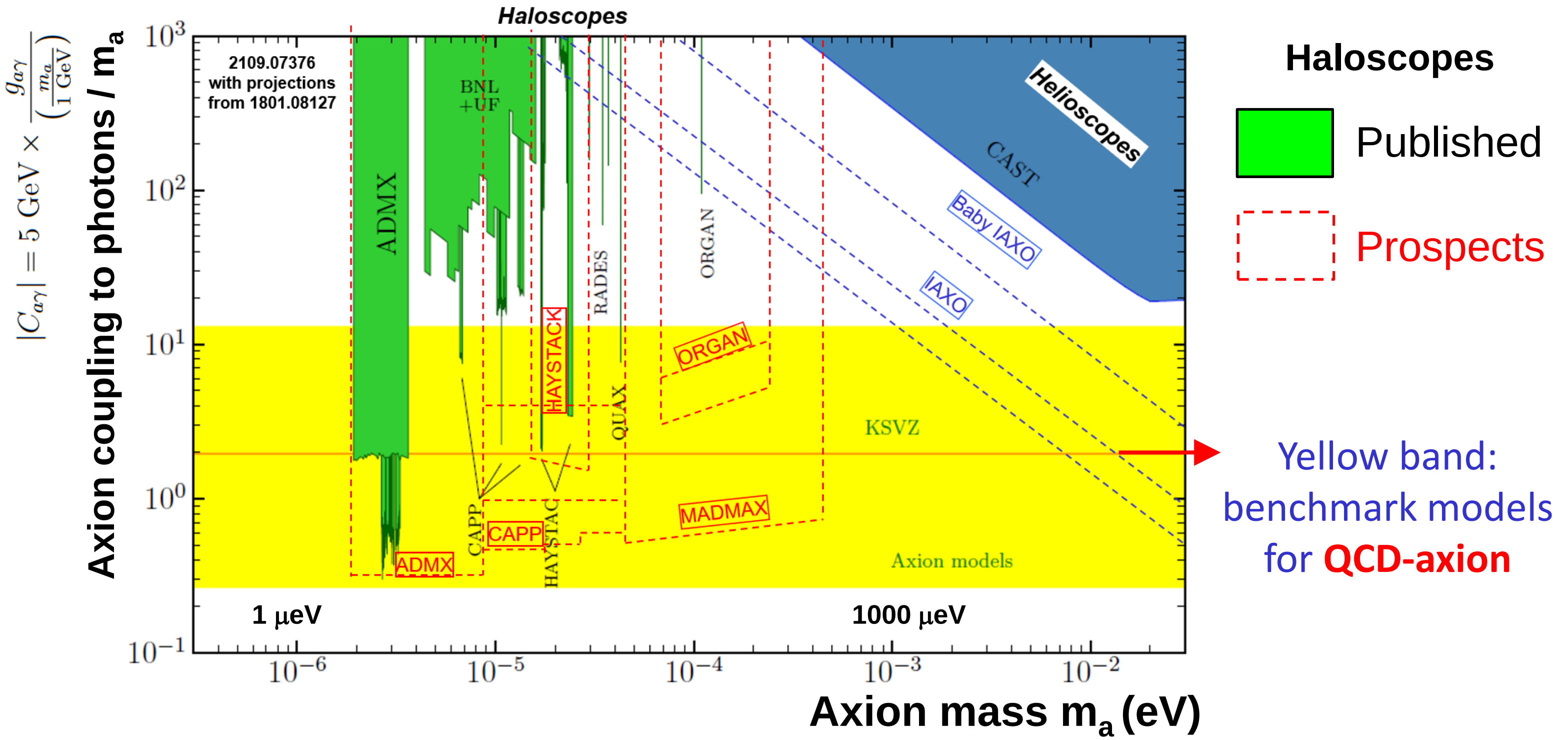
➔ Complementarity of 3 experimental approaches (e.g. DESY axion hub)

DM axion search: status / prospects

❑ Haloscopes = main way to search for Dark Matter axion



Primakoff effect aγ*→γ



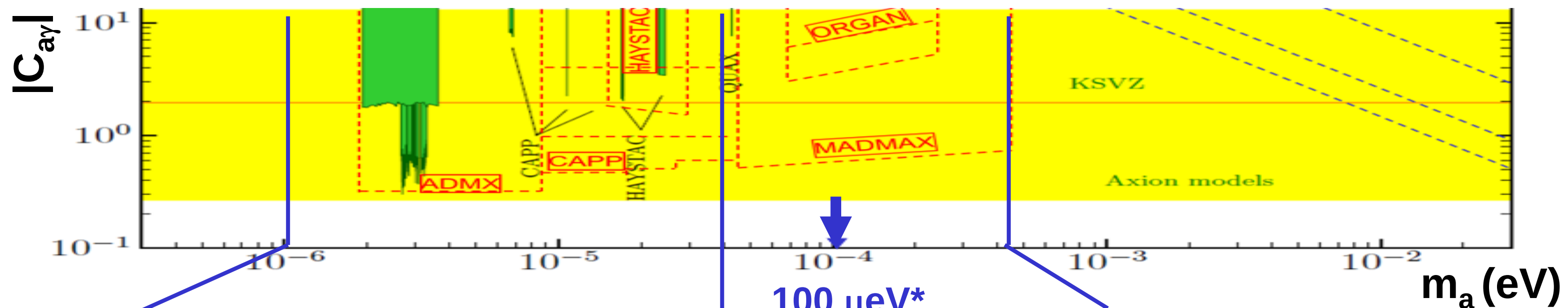
- Only very few experiments currently probe a (very small) part of the QCD axion phase space
- Vast R&D program to improve signal sensitivity and expand range of axion mass search

➔ Rising interest (techno improvements + LHC/WIMP results) **: next decade promising**

DM axion search: how?

❑ Experimental challenges for haloscopes

- 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** set-up or **large** area
- Scan over range of axion mass ➔ **tunable** set-up *[precision mechanics]*



100 μeV*

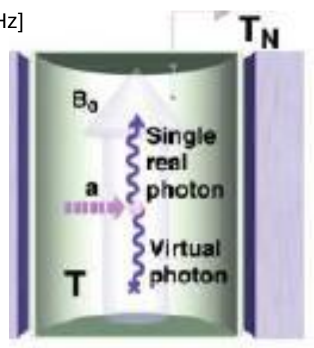
1 μeV [0.25 GHz]   **40 μeV** [10 GHz]   **400 μeV** [100 GHz] $[\nu_a = \nu_\gamma]$

→ RF / Microwave regime

Cavities

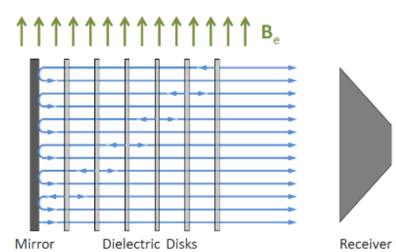
[baseline concept **1983**]

PRL51 (1983) 1415



- ➢ **Very high B**
- ➢ **Quantum noise limit**
- ➢ **Higher Q**
- ➢ **Multi-cavities**

Cavity too small + high noise



MADMAX

e.g. Dielectric haloscopes

[novel concept **2013**]

PRD88 (2013) 115002

➔ MADMAX can probe the favored post-inflationary range m_a ~ O(100) μeV*

**Nat. Com.* 13 (2022) 1, 1049 : 40 < m_a [μeV] <180

MADMAX (1/2)

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

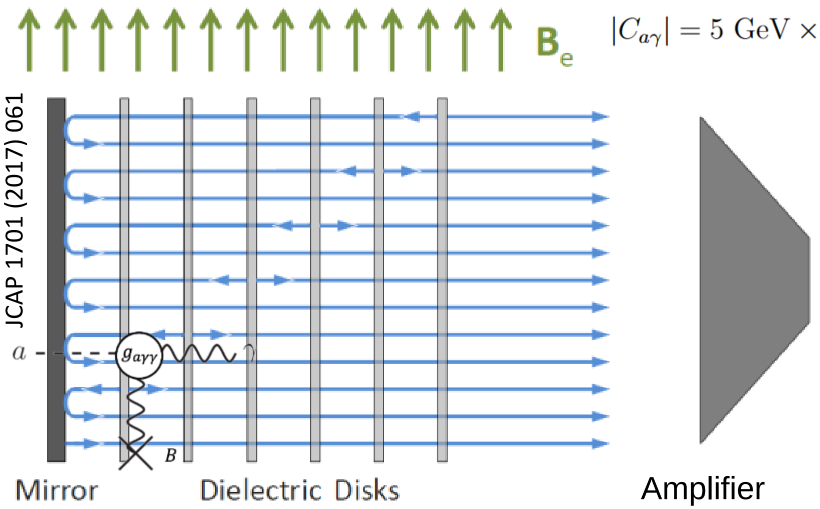
❑ A novel experimental concept: dielectric haloscope

- **Constructive interference** of coherent photon emissions at dielectric layer surfaces
  + **resonant** enhancement (~leaky resonant cavities) : boost (β^2) signal wrt mirror only

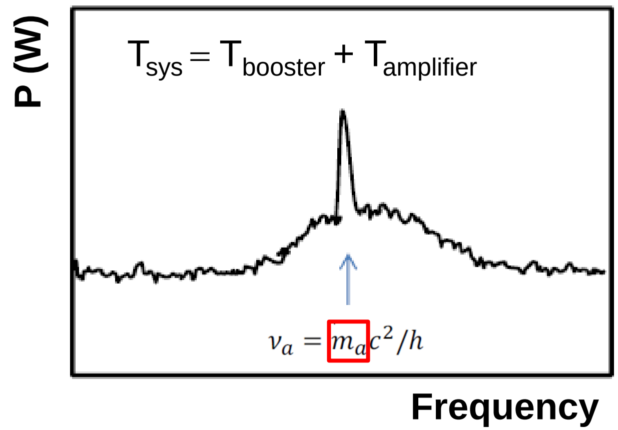
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

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

$$|C_{a\gamma}| = 5\ \mathrm{GeV} \times \frac{g_{a\gamma}}{\left(\frac{m_a}{1\ \mathrm{GeV}}\right)}$$



Thermal Noise



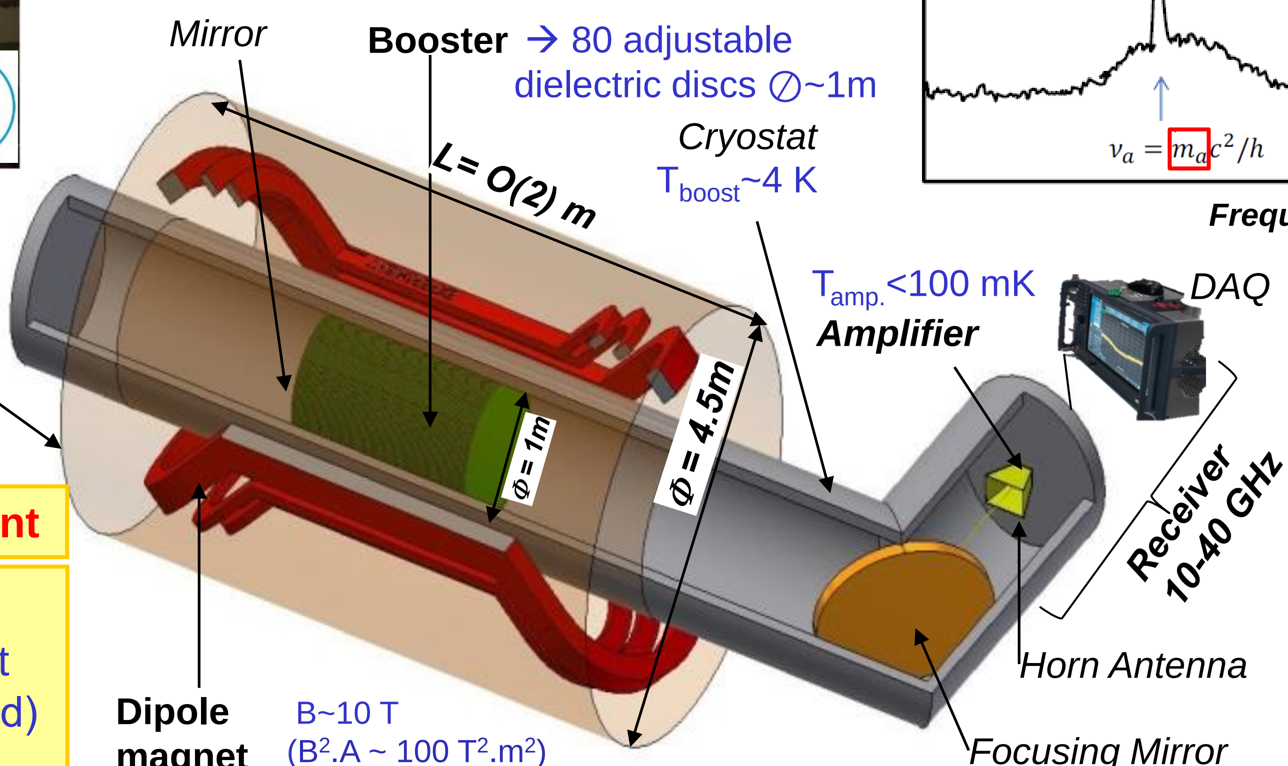
- **Axion mass scan** : move discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

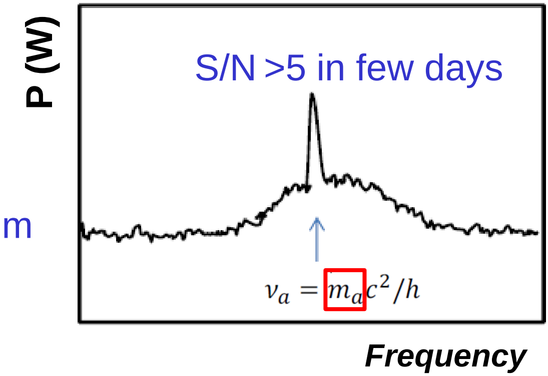
➔ MADMAX exploits a novel exp. approach to cover an uncharted phase space

MADMAX (2/2)

Formed in 2017. 10 institutes: French (2), German (6), Spanish (1) and US (1) → ~50 people

Experiment location: HERA in former H1 iron yoke





1st generation experiment

3 main challenges :

- High field dipole magnet
- Receiver (10's GHz, cold)
- Booster (cold, B field)

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

Prototyping phase strategy

❑ CERN lends us the world largest warm bore dipole magnet **[Morpurgo]**

- Usage by MADMAX during YETS approved by CERN RRB under CPPM impulse

❑ Address the two main challenges to develop booster concept

- Understand Radio Frequency (RF) response in O(10) GHz regime → Calibrate boost factor
- Move the disks at μm level precision at cold and under high B-field

Name	Goal	Type	Made of	Avail.	Test (Room Temp. / **Cold (10 K)**)
P200	Piezo-motor + mechanics	Open booster	1 moveable disk ϕ = 200 mm	2022	**2022**
CB100	RF studies + First physics	Closed booster	3 fixed disks ϕ = 100 mm	2021	2022, 23, **24**
CB200	RF studies + First physics	Closed booster	3 fixed disks ϕ = 200 mm	2023	24
OB300	Scan ALP around 80 μeV	Open booster	3-20 moveable disks ϕ = 300 mm	2024	**25, 26?**

➔ Gradually build the final booster design + do physics

RF studies + First ALP Physics (1/2)

Name	Goal	Concept	Made of	Avail.	CERN test
CB100	RF studies + First physics	Closed booster	3 **fixed** disks ϕ = 100 mm	2021	2022, 2023

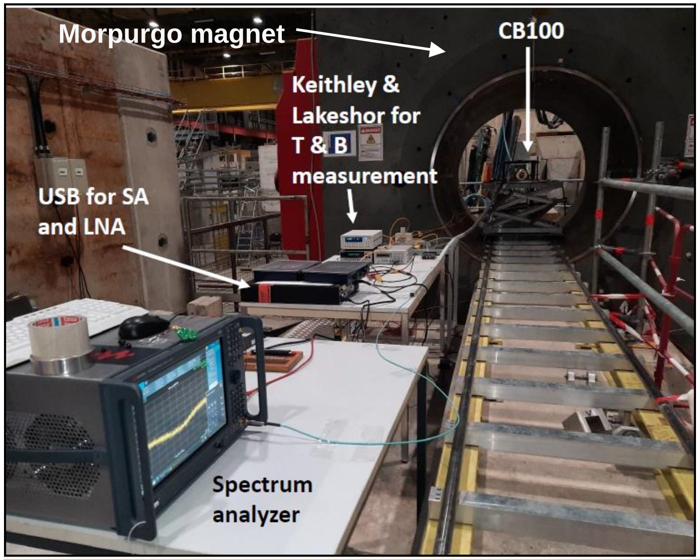
Booster

Mirror + 3 sapphire disks

Parabolic taper

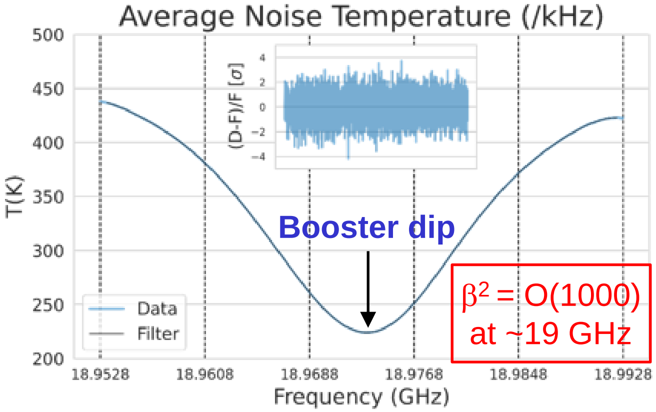
Cylindrical wave guide

Low Noise Amplifier (LNA)

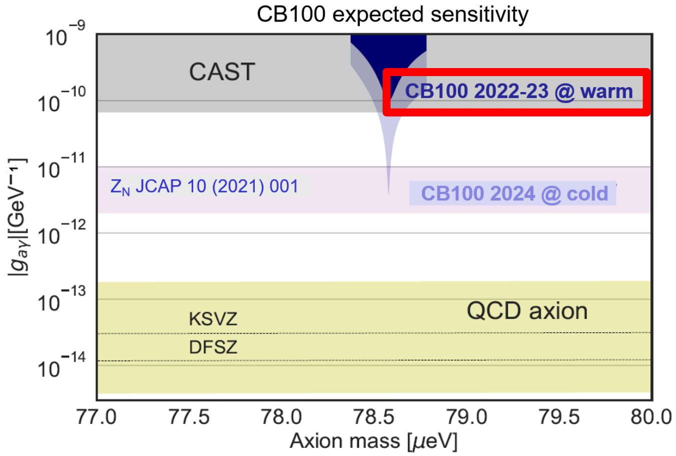


Good understanding of RF behavior + stability at CERN (21 days)

➔ **First ALP limit** [paper in preparation]



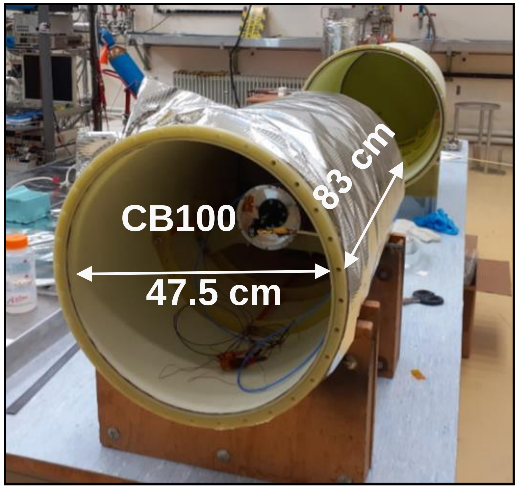
β^2 = O(1000) at ~19 GHz



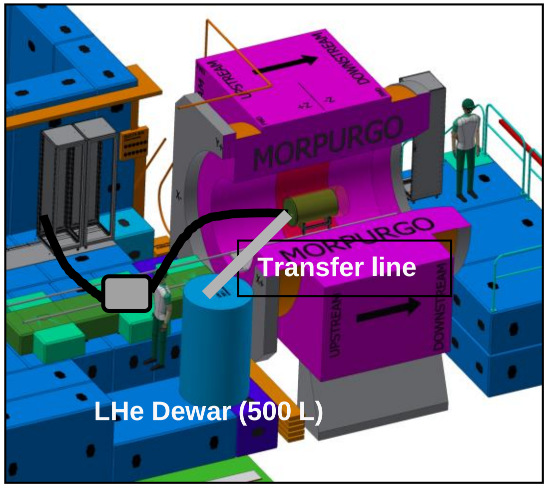
RF studies + First ALP Physics (2/2)

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

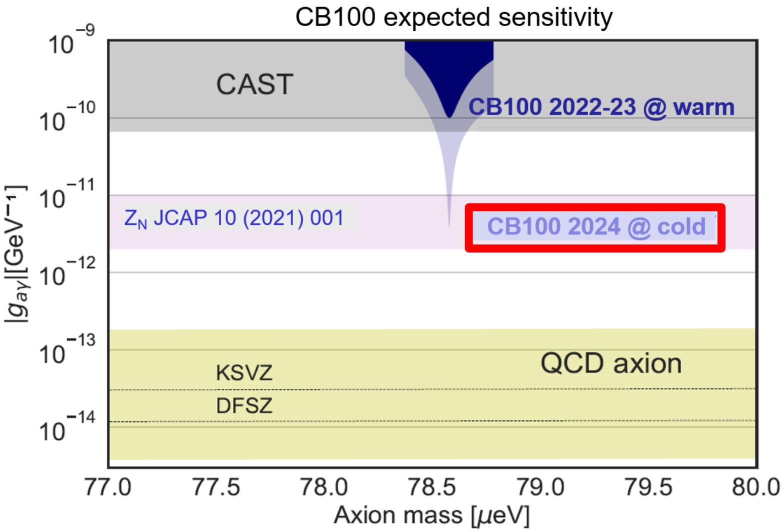
Develop a 'cheap' cryostat with CERN cryolab to cool the booster + LNA → Validated the principle in 2023



Vacuum between Inner and Outer vessel



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

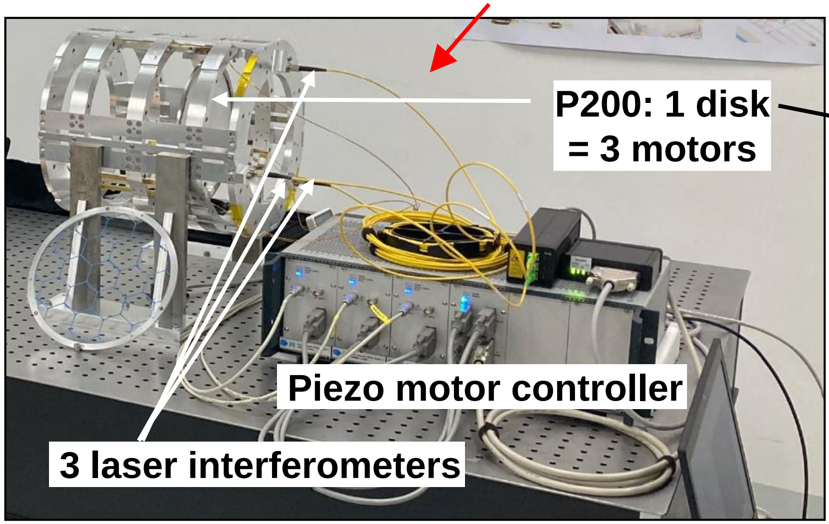


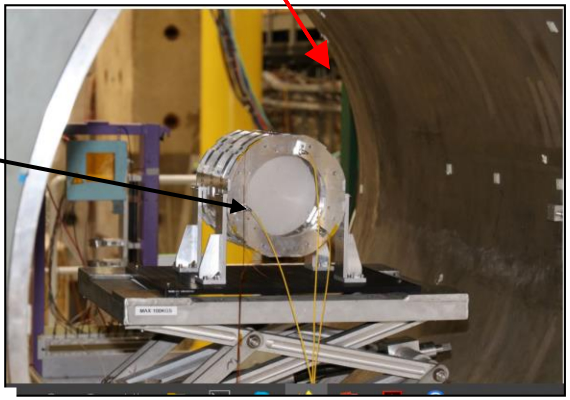
First short cold run in 2024

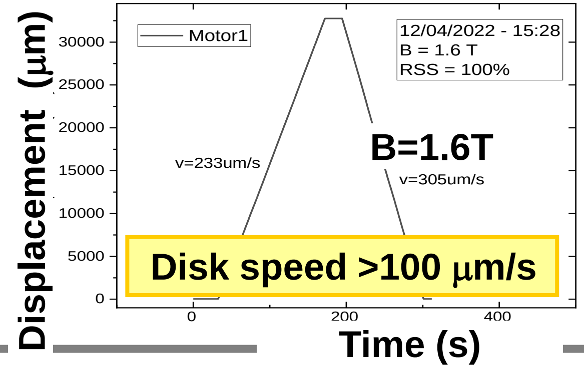
Tuneable setup: move the disk

Name	Goal	Concept	Made of	Avail.	CERN test
P200	Piezo-motor + mechanics	Open booster	1 **moveable** disk ϕ = 200 mm	2022	**2022**

- 2021: Successful test of 1 piezo motor at 5 K and 5.3 T (ALP magnet in DESY) [JINST 18 (2023) P08011]
- 2022: P200 proto tested in the lab, in a CERN cryostat (4 K) … and in 1.6 T at CERN







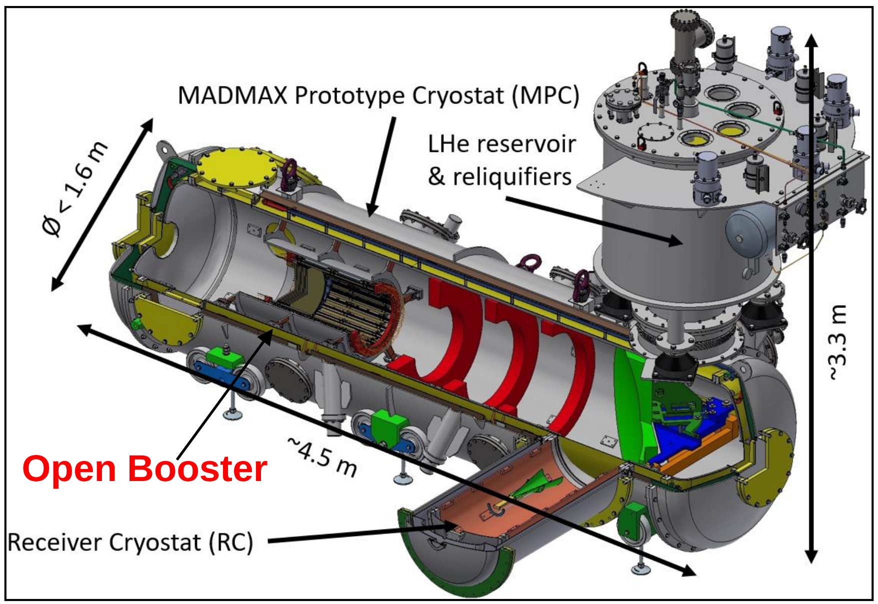
➔ Precisely move the disk at cold and in B-field

➔ Validate booster mechanics [paper in preparation]

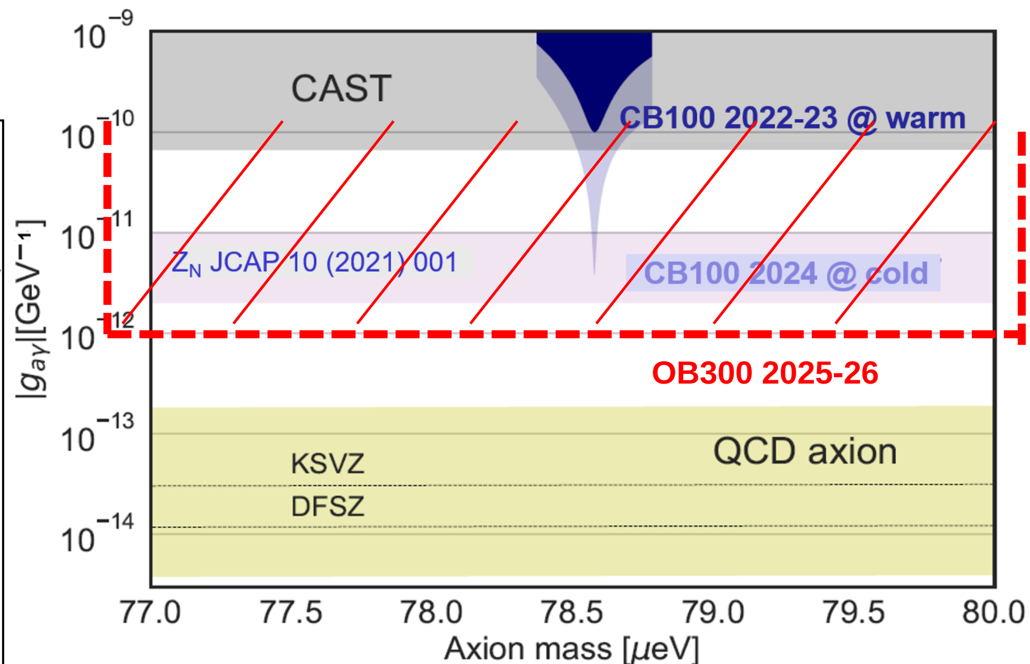
Final prototype (→ ALP physics)

Name	Goal	Concept	Made of	Avail.	CERN test
OB300	Scan ALP around 80 μeV	Open booster	3-20 **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



Long cold run + mass scan in 2025 (26?)

MADMAX timescale

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

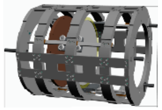
We are here !

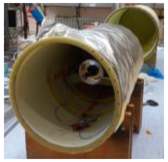
Design Phase

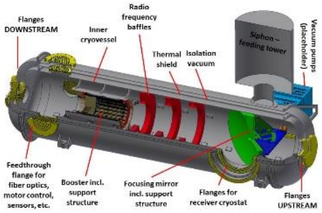
Prototyping Phase

Foundation of MADMAX Collaboration

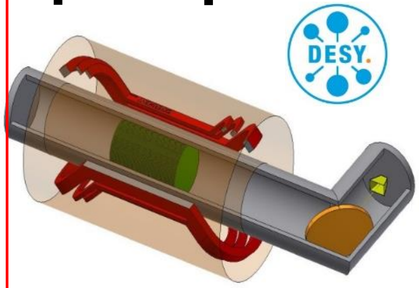
First endorsement by DESY PRC







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



Full-size MADMAX magnet commissioning

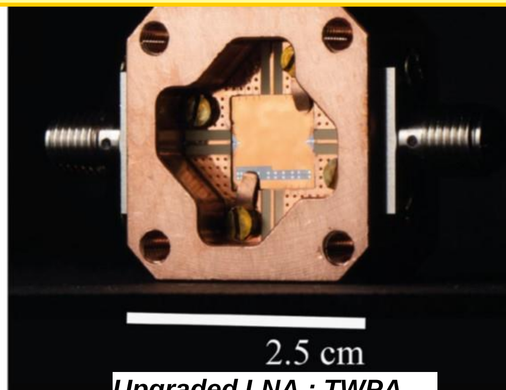
1000-10000 | 10 – 220 | 1.6 | 0.01-0.1 | ✔

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

MADMAX & France

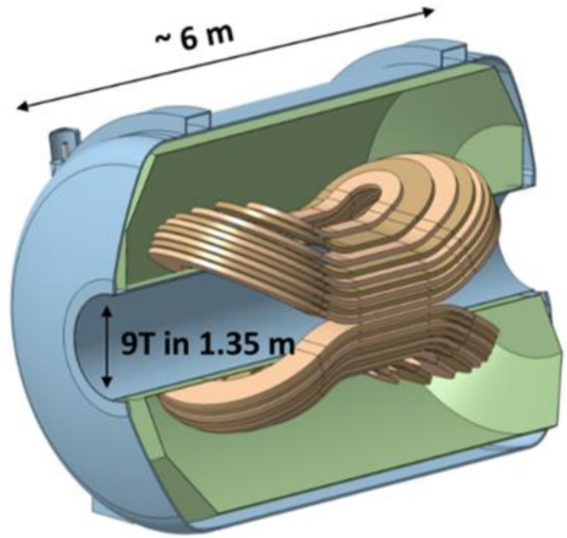
- **Outside IN2P3:** Institut Néel (INP, in MadMax) & CEA-IRFU (innovation partner)

Final ultra-low noise amplifier



Upgraded LNA : TWPA

Final magnet design



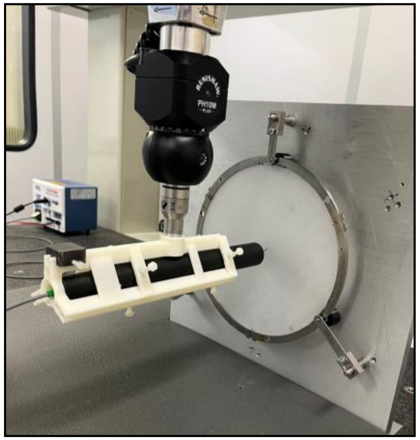
- **At IN2P3:**
  - **CPPM** joined MADMAX in 2020 (recommendations from CPPM scientific council)
  - **IJCLab**: will to join MADMAX soon. Internal discussions still ongoing → not further discussed
  - Remark: **CNRS IRL "*DMLab*" (with Helmholtz** centers**)** → MADMAX is a central project

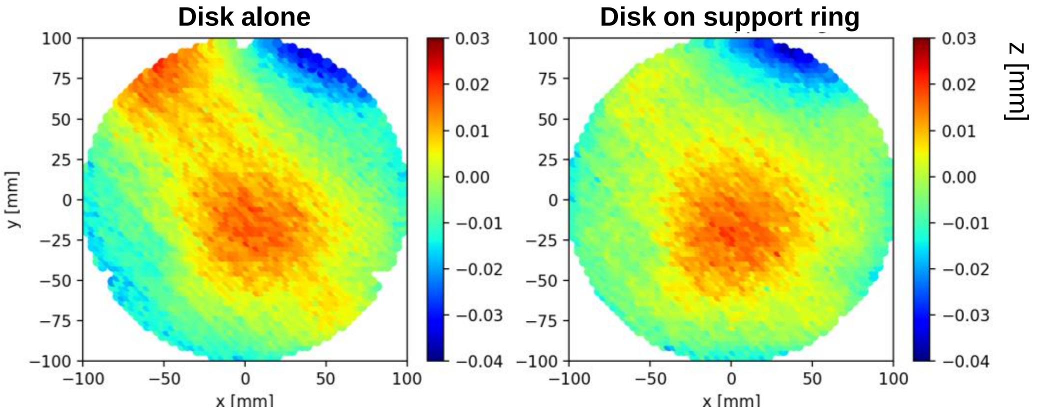
→ Pionering experimental work at IN2P3 on DM axion search

MADMAX & CPPM (1/3)

① Precision mechanics for the prototype boosters

- ➢ Precision 3D measurements O(μm) for geometry control of the prototype disks
  - CPPM expertise/infrastructure for precision measurements (e.g. ATLAS pixels)
- ➢ 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)



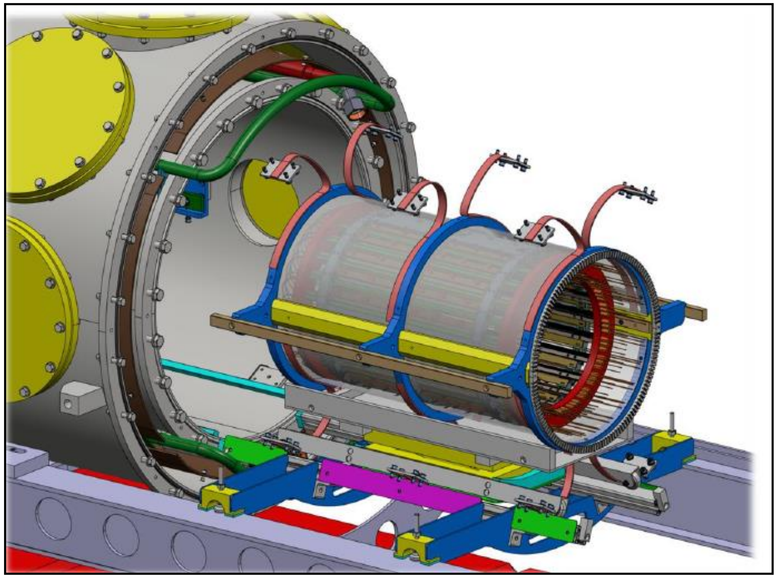


<10 μm RMS disk planarity alone/on the ring

MADMAX & CPPM (2/3)

② **Coordination of prototype tests at CERN in Morpurgo magnet**

- Impulsion for magnet choice → approved by CERN RRB in 2020
- Coordination of tests during YETS (~1 month/year, program 2021-2025 approved by SPSC)
- Conception, fabrication and installation of mechanical infrastructures around the magnet
  - Rails for electric racks, supports for prototypes, rails for big test cryostat, …
- Design and construction of mechanical structure to align OB300 booster in cryostat and of integration tools (at DESY and CERN)



MADMAX & CPPM (3/3)

③ **Simulation / data analysis**

- ➢ P200 and CB100 data analysis (2 publications soon)
- ➢ Simulations to optimize OB300 geometry (synergy with disk measurements)

➔ Responsabilities in all executive bodies of the MADMAX collaboration

- Member collaboration board
- Member executive board

- Member physics board
- CERN tests coordinator
- Member executive board

- Technical coordinator (2020, 2023-)
- Member executive board

+ IN2P3 master project coordinator

+ CPPM scientific coordinator

+ CPPM technical coordinator

IN2P3 human resources

- Current manpower → 7 scientists = 4 FTE [1 permanent physicist, 2 IT, 1 PhD]

International thesis 2022-2025 from CNRS/MITI AAP thanks to DMLab

	Nom des personnes	Statut	2021	2022	2023	2024
Physicists	**CPPM**		**100%**	**125%**	**200%**	**200%**
	Hubaut	DR	50%	50%	50%	50%
	Pralavorio	DR	50%	50%	50%	50%
	Dahbi	PhD		25%	100%	100%
	TOTAL (FTE)		**1,00**	**1,25**	**2,00**	**2,00**
Engineers	**CPPM**		**180%**	**200%**	**200%**	**210%**
	Beurhey	IR	10%	10%	10%	10%
	Karst	IR	50%	60%	80%	90%
	Gallo	IE	40%	40%	40%	30%
	Labat	IE	80%	90%		
	Roset	AI			70%	80%
	TOTAL (FTE)		**1,80**	**2,00**	**2,00**	**2,10**

+ IJCLab (2 physicists + 1 engineer): will to join MADMAX soon

Financial resources

- 2019-2022: CPPM proper resources to start activities [80 k€ in total]
- In parallel, answers to several project calls:

> - PHC Procope (2020-2021) → missions (9 k€/year)
> - IEA (2020-2021) → missions + small équipement (5.5 k€/year)
> - CNRS MITI PhD grant (2022-2025): international thesis in the framework of IRL DMLab
> - So far no success with ANR/DFG PRCI attempts (will resubmit this year).

- End 2022: IN2P3 agreed to start funding activities on MADMAX for the prototyping phase (2022-2025) → Fiche de projet

> - Received 7 k€ in 2022 and 23 k€ in 2023
> - Request O(50 k€) in 2024 and in 2025 → construction and tests of MADMAX protos

[+ DMLab IRL: PhD missions at DESY O(3) k€ per year]

Conclusions

- **Axion = DM candidate motivated by particle physics since 40 years**

- **DM axion direct search: rising interest, next decade promising**
  - Resonant cavity sensitivity starts to scratch the QCD axion phase space (~1 μeV)
  - Will be extended to most of the interesting mass range (1-1000 μeV) with novel experiments

- **MADMAX = novel exp. approach to cover theory-favored phase space**
  - Needs for precise (μm) instrumentation in extreme conditions (high B, 4 K, 10's GHz)
  - Prototyping phase at CERN 2021-2026 to validate concept → ALP competitive searches
  - CPPM in MadMax since 2020 → construction, simulation, test and data analysis of protos
  - Increase IN2P3 visibility in DM field, in complement with direct searches for WIMPs

Pionering experimental work at IN2P3 since 2020 in uprising field of DM axion direct searches

BACKUP

Collab Week at CPPM (Apr 2023)

Reviews

❑ Conseil scientifique IN2P3 (28 oct 2018)

http://old.in2p3.fr/actions/conseils_scientifiques/media/2018_octobre/Rapport-2018-10-final.pdf

➢ **Axions:** pas de participation expérimentale de l'IN2P3

Il faut noter que les axions sont un candidat générique à la matière noire, également physiquement motivé, et ce depuis plusieurs dizaines d'années. L'un des piliers des WIMPs étant mis à mal par l'absence de signe de nouvelle physique dans les résultats du LHC, cette alternative doit être gardée à l'esprit, en parallèle à l'élargissement du domaine de paramètres du candidat de type WIMP.

CPPM : ouvre cette thématique avec contributions techniques (R&D innovante)

❑ APPEC committee

Rept. Prog. Phys., 85(5):056201, 2022, 2104.07634

Recommendation 6. European-led efforts should focus on axion and ALPs mass ranges that are complementary to the established cavity approach and this is where European teams have a unique opportunity to secure the pioneering role in achieving sensitivities in axion/ALP mass ranges not yet explored by experiments conducted elsewhere. In parallel, R&D efforts to improve experimental sensitivity and to extend the accessible mass ranges should be supported.

Reviews

Scientific reviews of the MADMAX project have already been conducted at DESY (PRC) and at CERN (SPSC). The CERN Research Board has endorsed the use of the Morpurgo magnet to test the prototypes. An excerpt of the recommendations from the DESY Physical Review Committee [25] is given below:

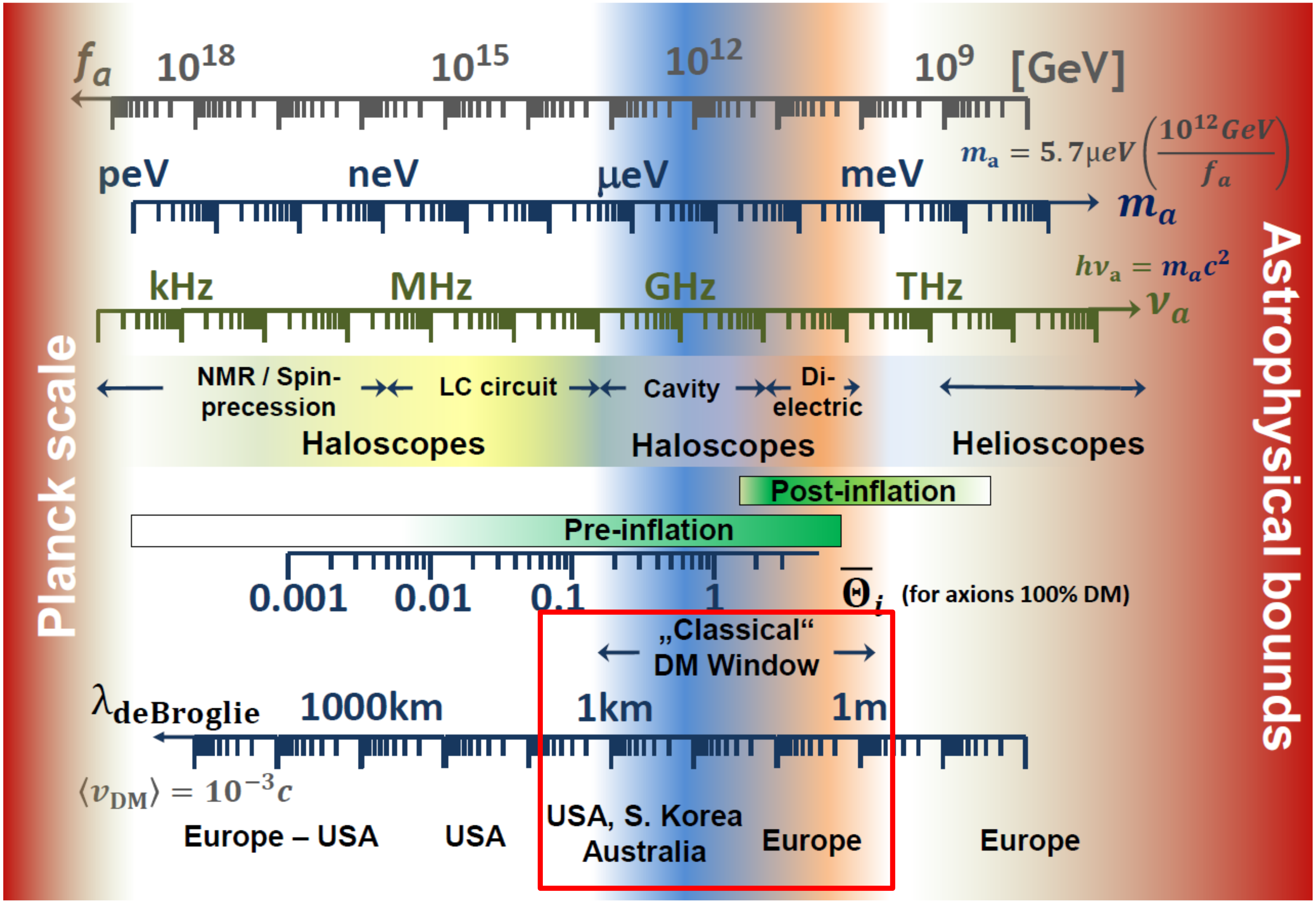
- Physics: "The committee enthusiastically endorses the physics goals of the MADMAX proposal, claiming ultimate sensitivity for a very large axion frequency range 10–100 GHz in two phases"; "there are several straightforward models of cosmology that lead to axions in the frequency range targeted by MADMAX to be the dominant contribution to dark matter";
- Technology: "The committee is impressed by the ingenuity of this new method to search for axions as dark matter particles in the frequency range of 10–40 GHz (40–160 μeV) in first phase and 40–100 GHz (160–400 μeV) in second phase"; "Despite being well-motivated the targeted mass range is very difficult to reach in other experiments. Therefore, this presents a unique window of opportunity where the MADMAX collaboration is at least several years ahead of potential competitors."
- Overall: "Therefore, the MADMAX experiment has significant discovery potential not only for a new particle, but also for discovering a main constituent of dark matter."; "The detection of axions will open the field of axion astrophysics and provide insight to the formation of galaxies, but also the strong interactions and it will most certainly secure a Nobel Prize for the experiment."

https://prc.desy.de/sites2009/site_prc/content/e38/e297184/e297225/infobox
Content297227/MADMAX_review_recommendations_12112019_final.pdf

Axion scales

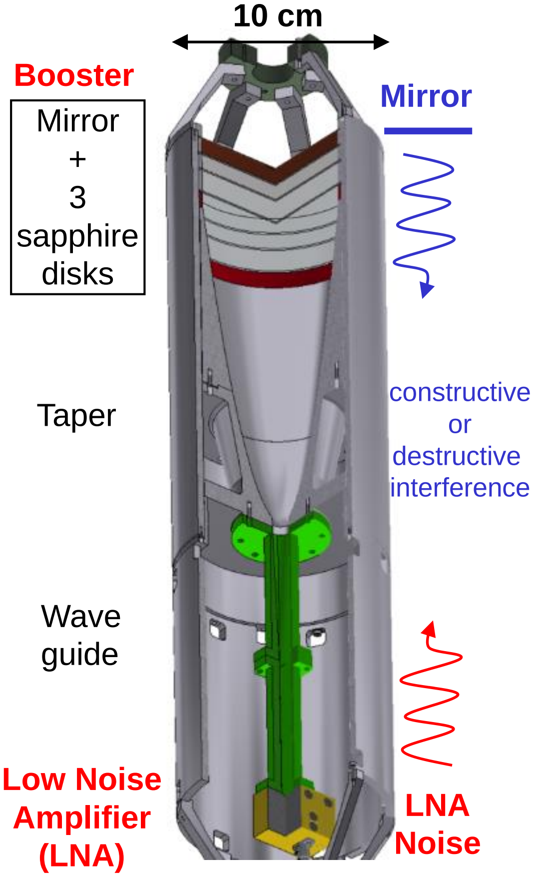
APPEC Committee Report

Rept. Prog. Phys., 85(5):056201, 2022, 2104.07634

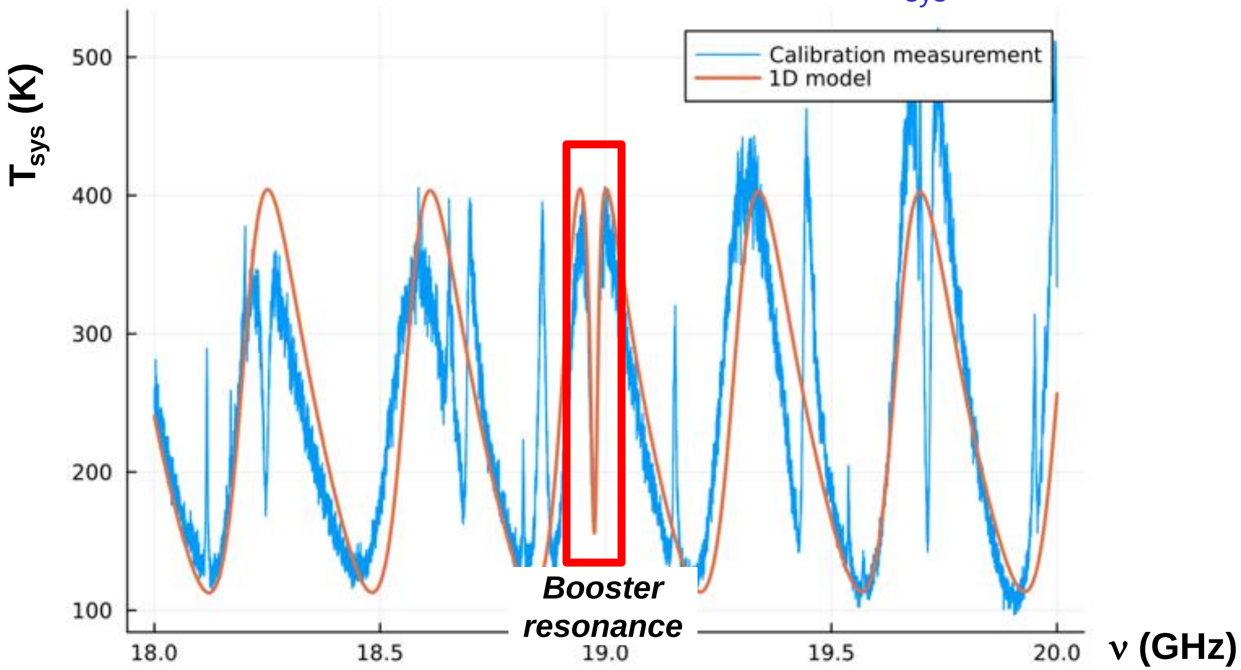


RF (1/3)

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



Simulate **LNA** (ADS) and **Booster+taper** system (COMSOL)
→ compare with measured system temperature (T_{sys}) in 18-20 GHz



Model the RF behavior *(esp. at the booster resonance)*

RF (2/3)

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

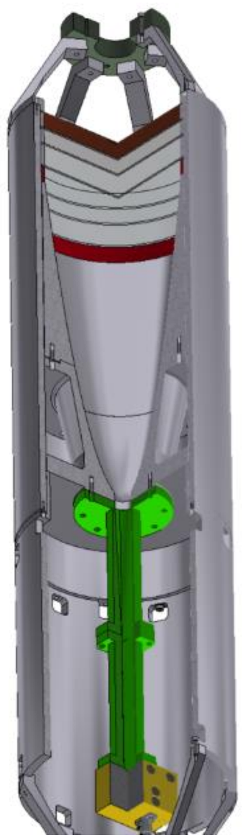
Booster

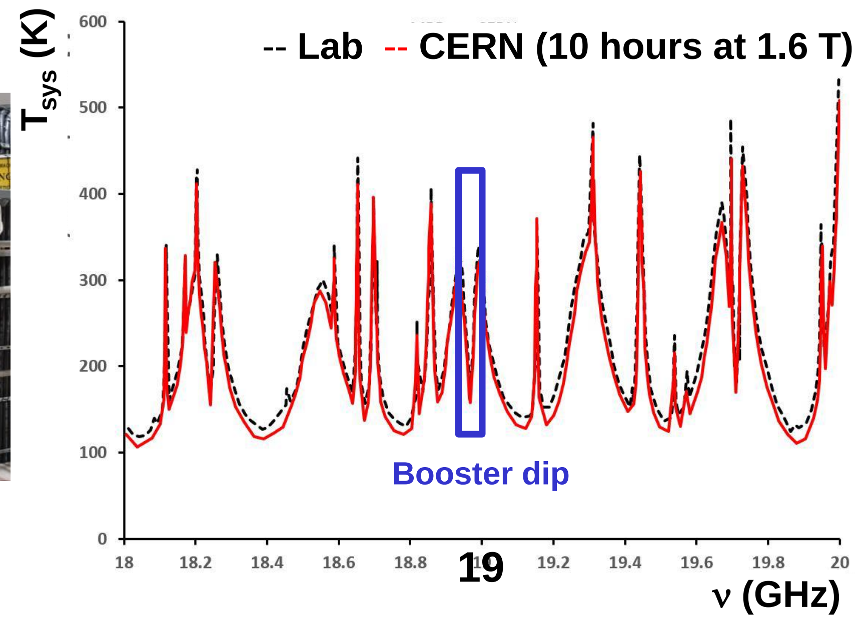
Mirror
+
3
sapphire
disks

Taper

Wave guide

LNA

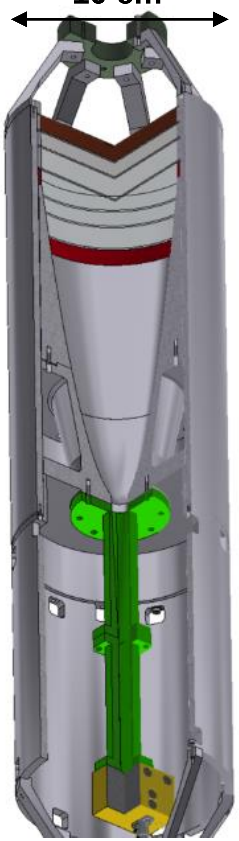




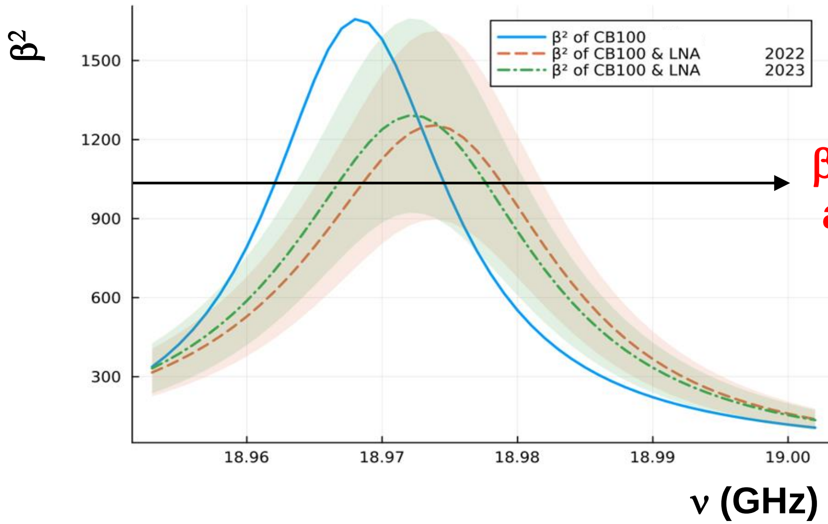
No impact from the CERN environment

RF (3/3)

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



Simulate **LNA** (ADS) and **Booster+taper** system (COMSOL)
→ Extract the boost factor shape

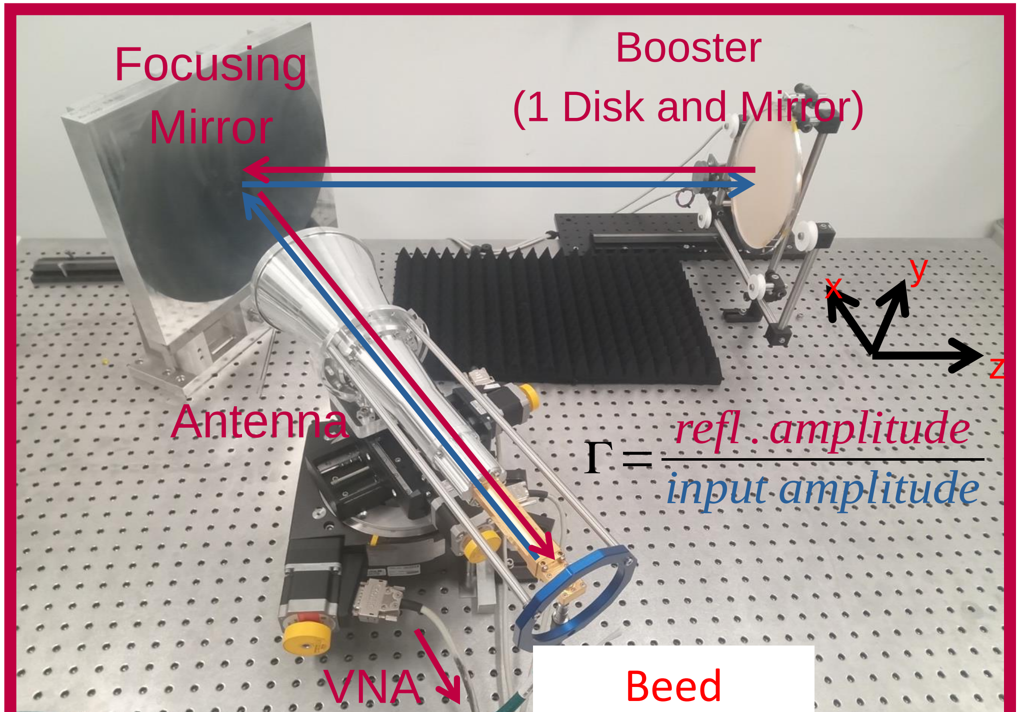


$\beta^2 = O(1000)$ at ~19 GHz

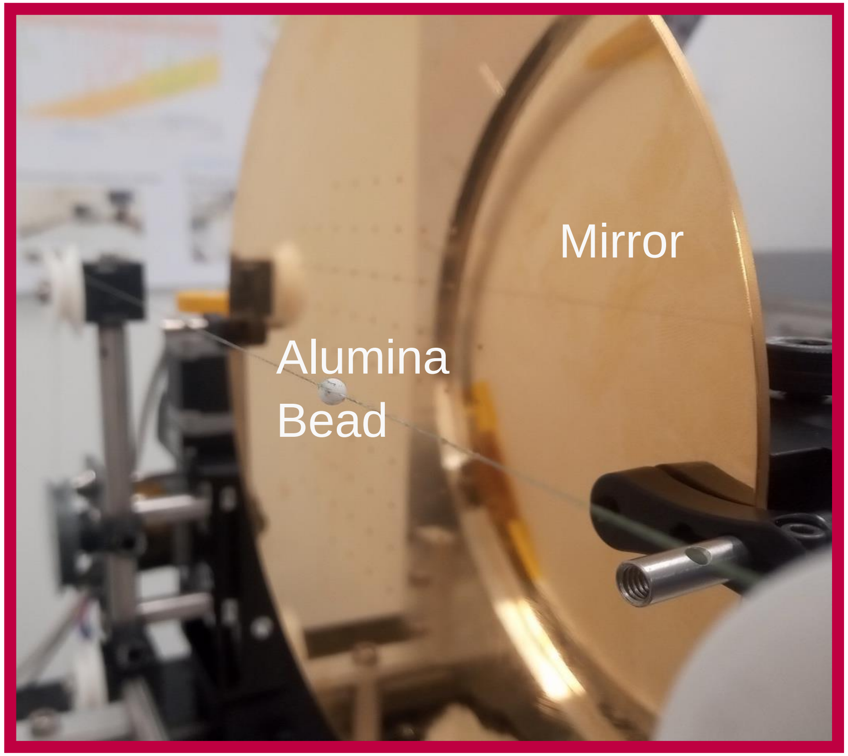
Model the boost factor shape with systematic uncertainties

OB calibration (1/2)

Boost factor determined using Bead Pull Method (non-resonant perturbation theory)
+ Lorentz reciprocity theorem   J. Egge, **JCAP 04 (2023) 064**



$$\Gamma = \frac{\text{refl. amplitude}}{\text{input amplitude}}$$



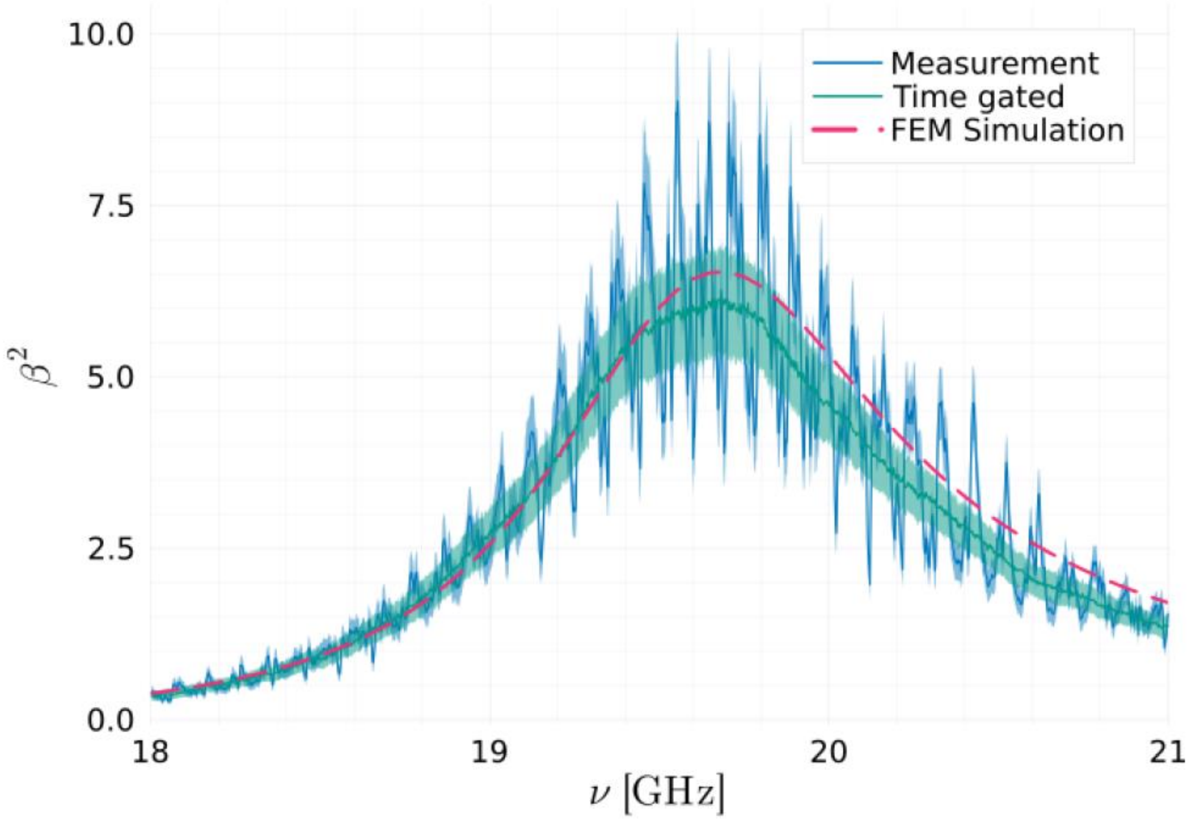
Beed properties

Change in reflection coefficient → $$\Delta\Gamma = \frac{\alpha_e \omega}{4P_{\text{in}}} \boldsymbol{E}_R^2$$ → E field

$$P_{\text{sig}} = \frac{g_{a\gamma}^2}{16 P_{\text{in}}} \left| \int_{V_a} \mathrm{d}V \, \boldsymbol{E}_R \cdot \dot{a} \boldsymbol{B}_e \right|^2 \Rightarrow \beta^2 = \frac{P_{\text{sig}}}{P_0}$$

OB calibration (2/2)

Test with a single disk + mirror (low boost factor)



Measure boost factor (+ systematics)

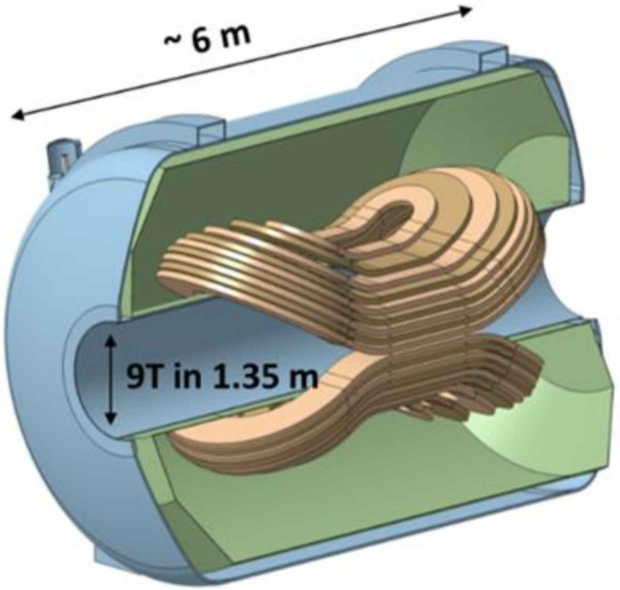
[paper in preparation]

Towards final magnet / receiver

❑ Progresses on final magnet

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

[NbTi with Cu jacket @ 1.8K]



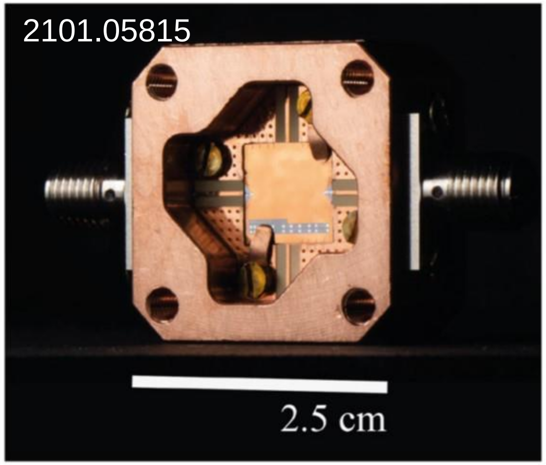
- Recently demonstrated that coils will be safe in terms of quench protection
- **Next** : Design, manufacture and test a small MADMAX coil (6T)

❑ Progresses on final receiver

- Very low noise pre-amplifier

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