Direct search for dark matter axion with MADMAX

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CPPM/IN2P3 – Aix-Marseille Université

1- Scientific context
2- MADMAX: principles and prototyping phase
3- Technological developments (inc. IN2P3 participation)
4- Conclusion

Journées R&T IN2P3, 07 novembre 2023

How to see the axion ?

❑ **Convert it to photon in a magnetic field**

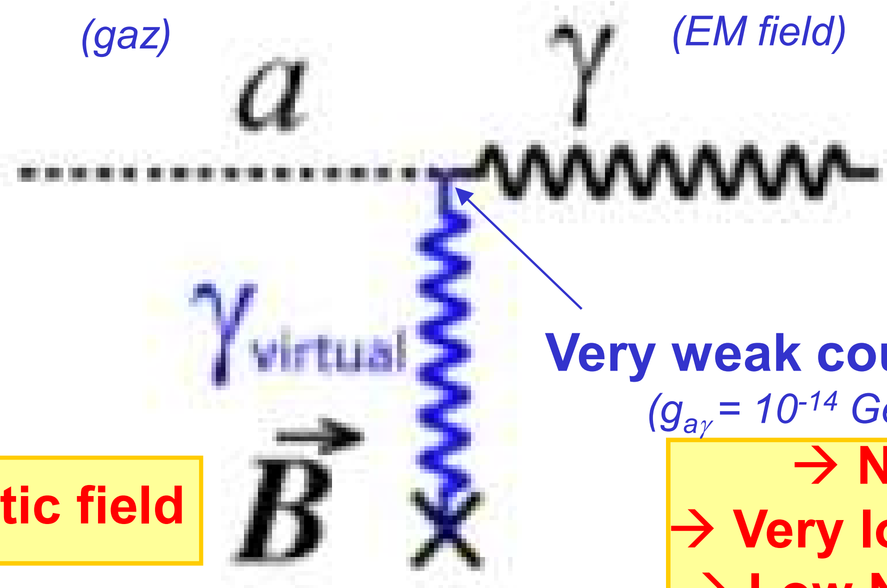
Exp. constraints

μeV ≈ 10^{-15} M(proton)
"Invisible" axion
(gaz)

↔

GHz
Photon
(EM field)

≈ RF, micro-wave



Very weak coupling: feeble signal
($g_{a\gamma} = 10^{-14}$ GeV^{-1} for $m_a = 100$ μeV)

High Magnetic field

→ Need boost
→ Very low temperature
→ Low Noise Amplifier

Axion search very rich in experimental challenges

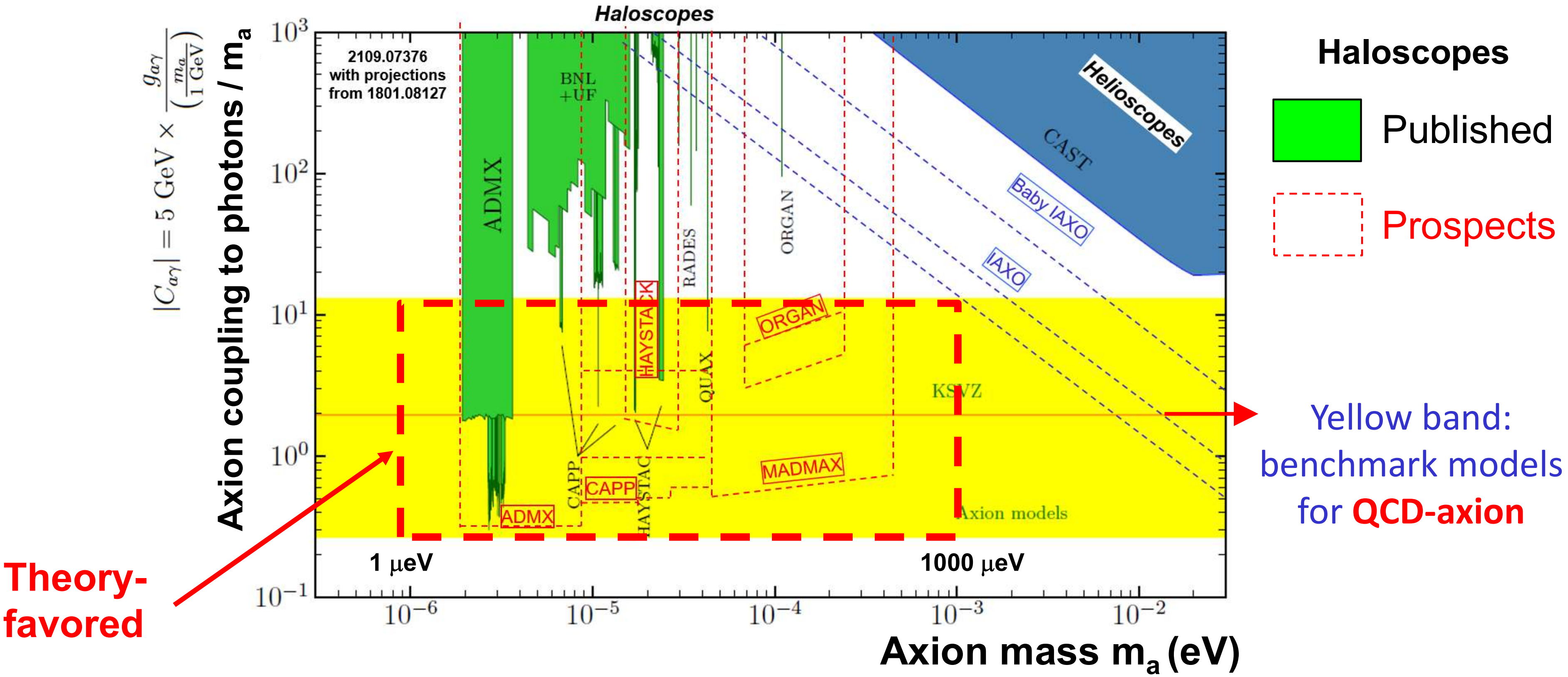
Axion/ALP direct searches

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**

Complementary experimental approaches *(all present in DESY axion hub)*

DM axion search: status / prospects

❑ **Haloscopes = main way to search for Dark Matter axion**



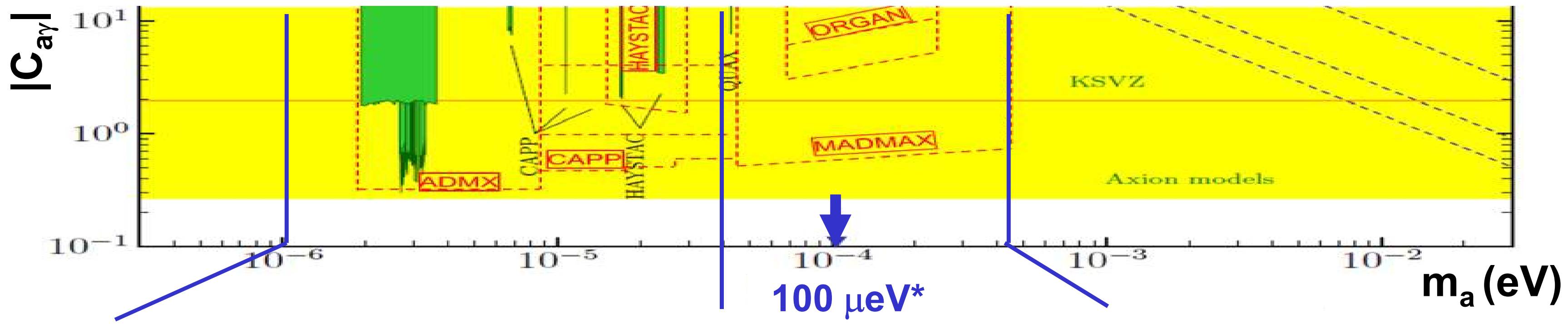
- Only very few experiments currently probe a (very small) part of the QCD axion phase space
- Vast R&D program to improve signal sensitivity and expand range of axion mass search

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

DM axion search: how?

Experimental challenges for haloscopes

- Convert axions into photons *[E field of O($10^{-12} \cdot \frac{B}{10\,T}$) 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]*



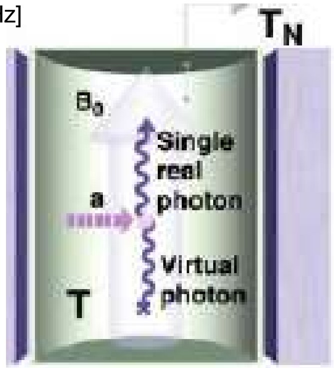
1 μeV [0.25 GHz] **40 μeV** [10 GHz] **400 μeV** [100 GHz] [$\nu_a = \nu_\gamma$]

→ RF / Microwave regime

Cavities

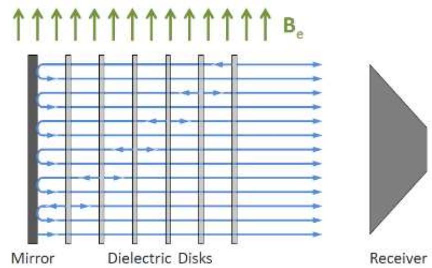
[baseline concept **1983**]

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 theory-favored 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]

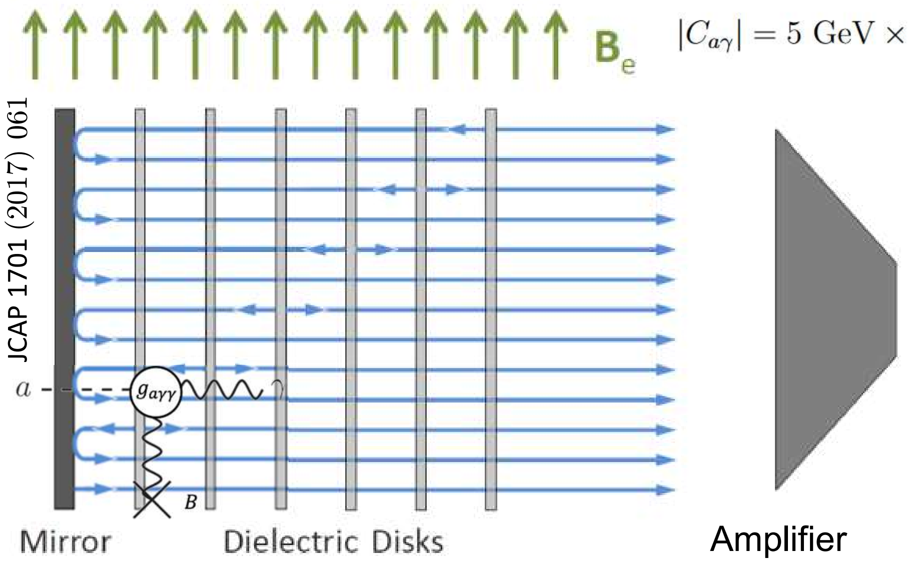
❑ A novel experimental concept: dielectric haloscope

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

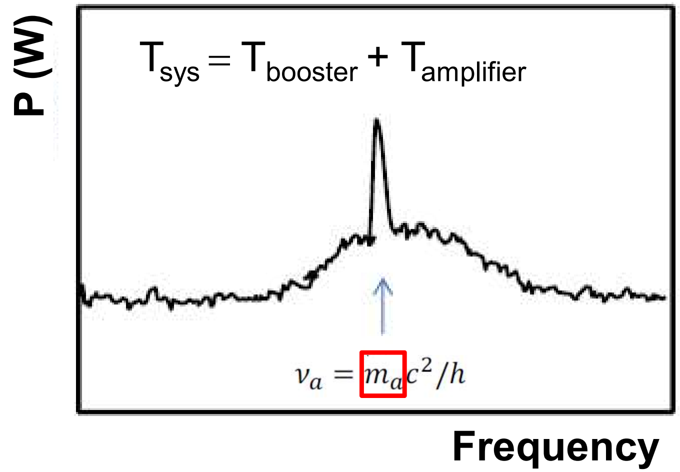
$$P_{sig} = 10^{-22}\ \mathrm{W} \times \left(\frac{\beta^2}{50000}\right) \times \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 \times \left(\frac{A}{1\ \mathrm{m}^2}\right) \times C_{a\gamma}^2$$

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

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



Thermal Noise



MADMAX (1/2)

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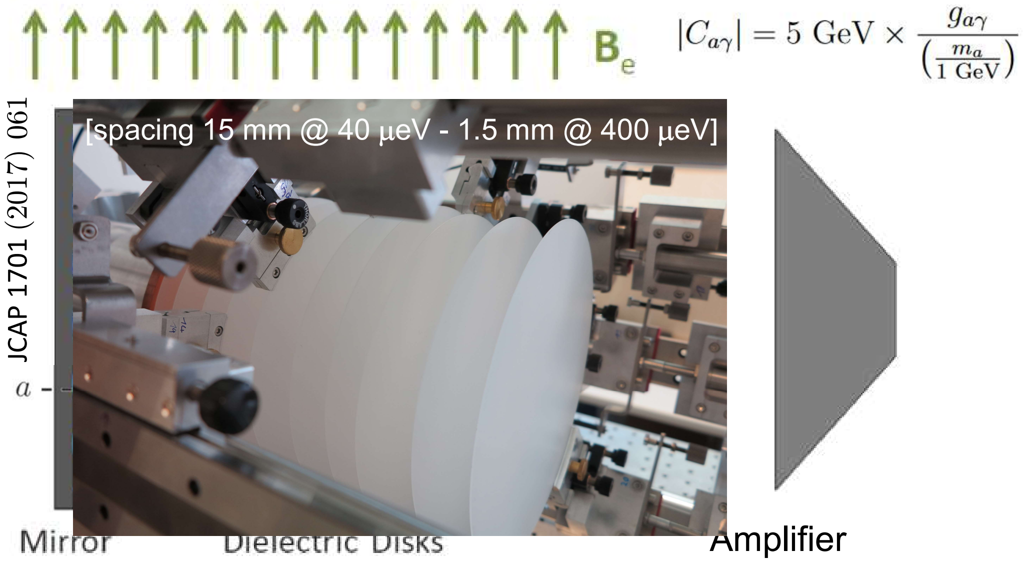

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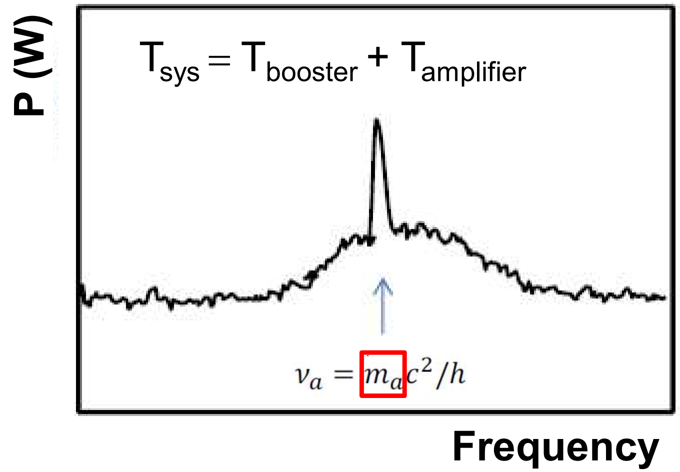


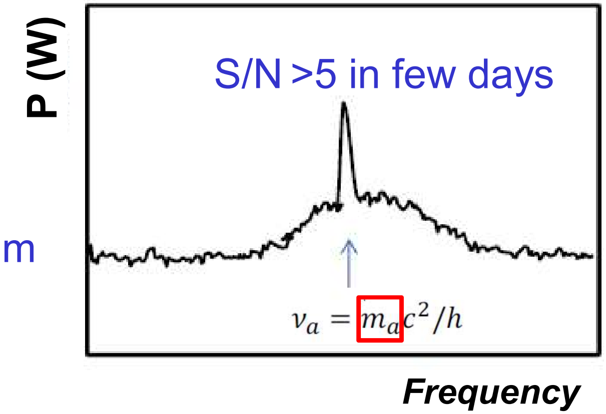
- **Axion mass scan**: move discs with piezo motors (μm prec.) at 4K under 10 T *(50 MHz step)*

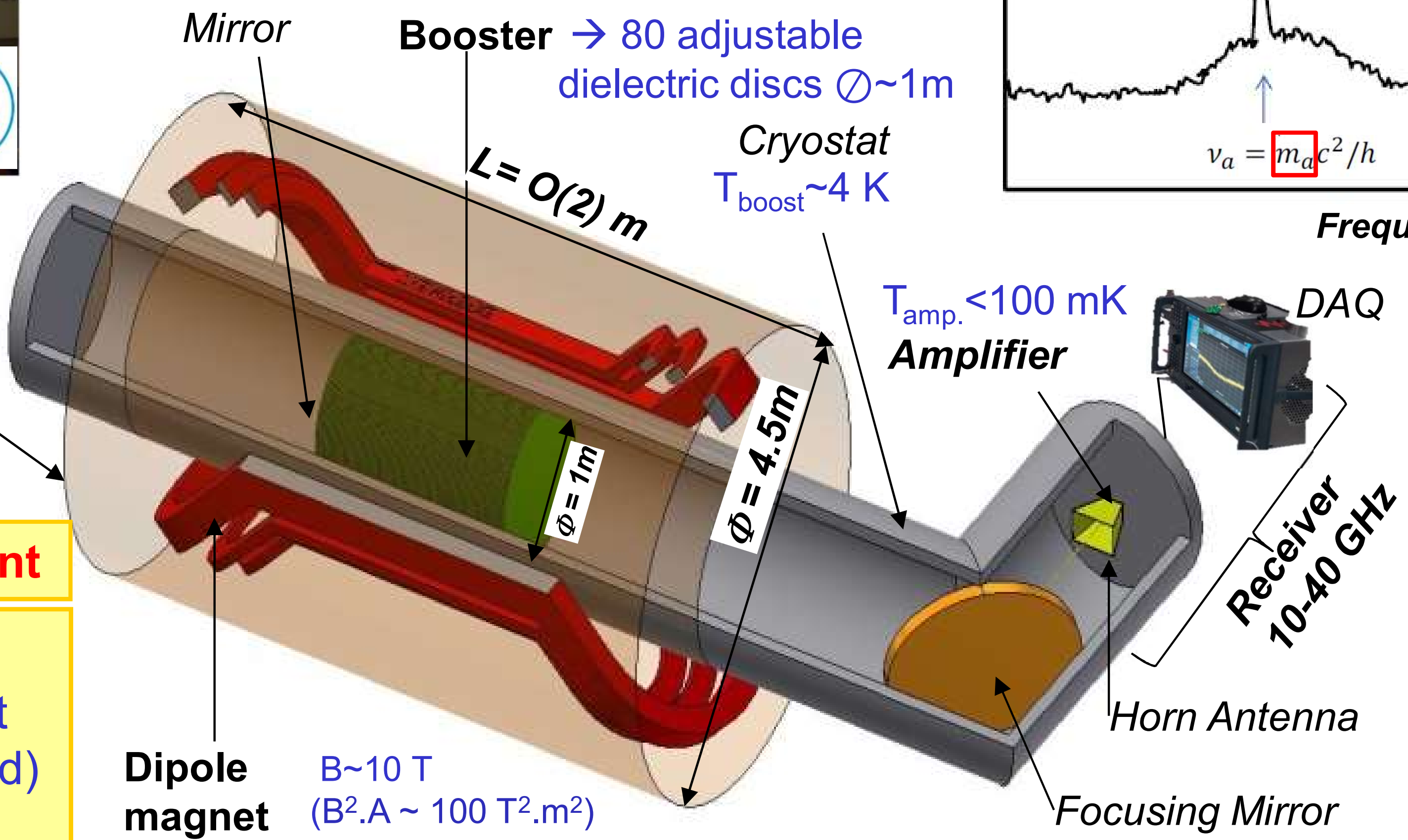
➔ MADMAX exploits a novel exp. approach to cover an uncharted phase space

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 booster concept: cutting-edge R&D

Prototyping phase strategy

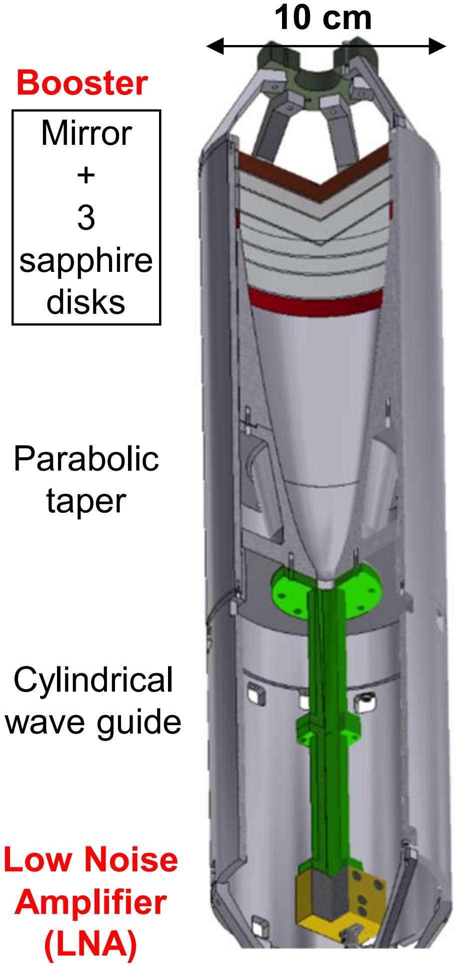
- **CERN lends us the world largest warm bore dipole magnet** **[Morpurgo]**
  - Usage by MADMAX during YETS approved by CERN RRB under CPPM impulse
- **Address the two main challenges to develop booster concept**
  - Understand Radio Frequency (RF) response in O(10) GHz regime → Calibrate boost factor
  - Move the disks at μm level precision at cold and under high B-field

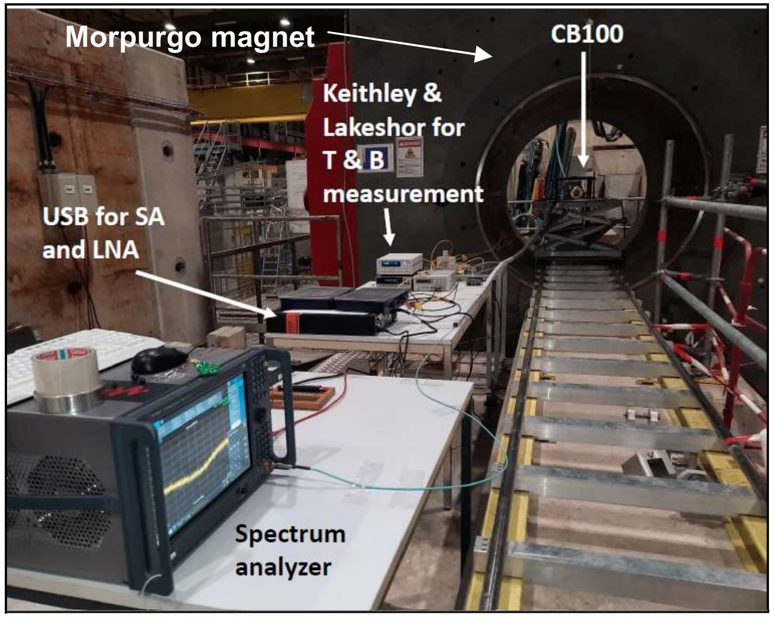
Name	Goal	Type	Made of	Avail.	Test: Room Temp.	Test: Cold (10 K)
P200	Piezo-motor + mechanics	Open booster	1 moveable disk ϕ = 200 mm	2022	**2022**	
CB100	RF studies + First physics	Closed booster	3 fixed disks ϕ = 100 mm	2021	2022, 23,	**24**
CB200	RF studies + First physics	Closed booster	3 fixed disks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

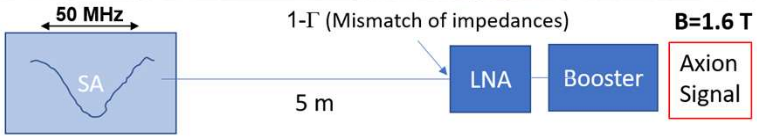
→ Gradually build the final booster design + do physics

RF studies + ALP Physics (1/2)

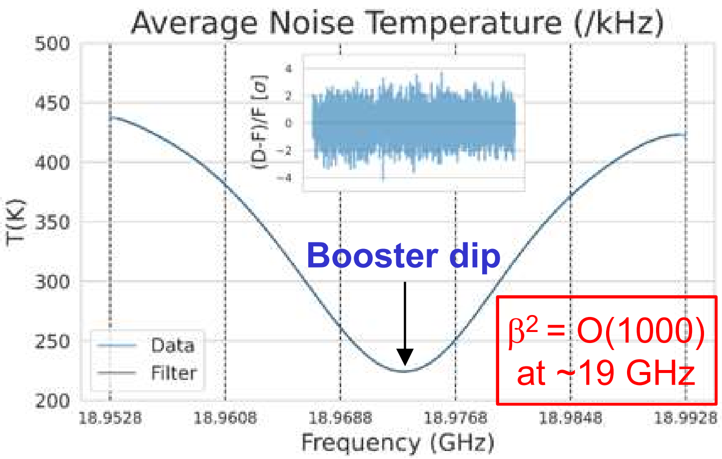
Name	Goal	Concept	Made of	Avail.	CERN test
CB100	RF studies + First physics	Closed booster	3 **fixed** disks ϕ = 100 mm	2021	2022, 2023 10 hr, 21 days

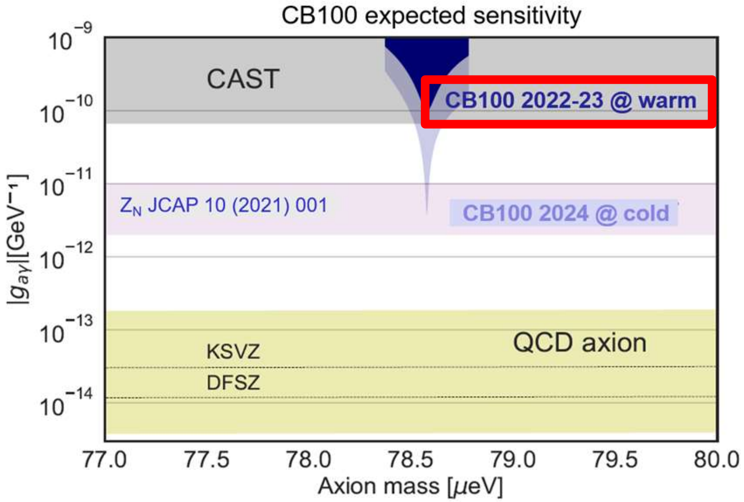






➔ **First ALP limit** [paper in preparation]

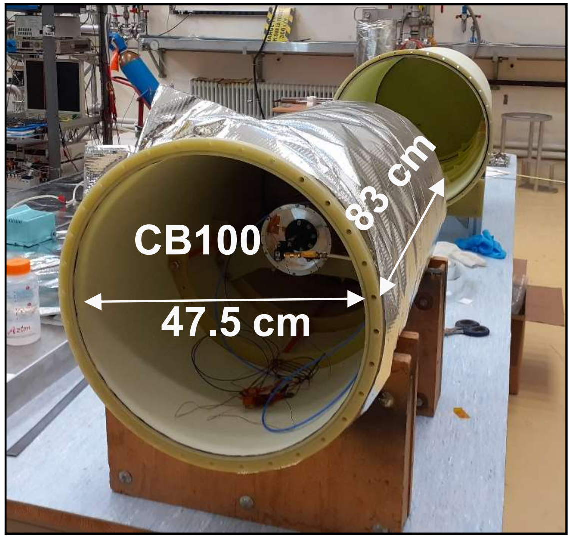




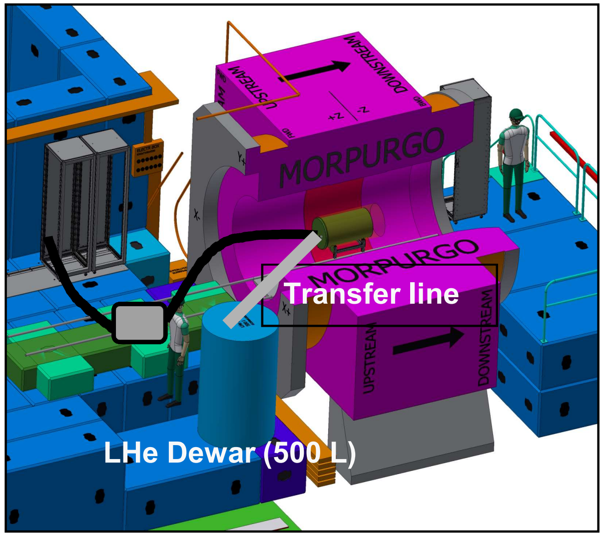
RF studies + ALP Physics (2/2)

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

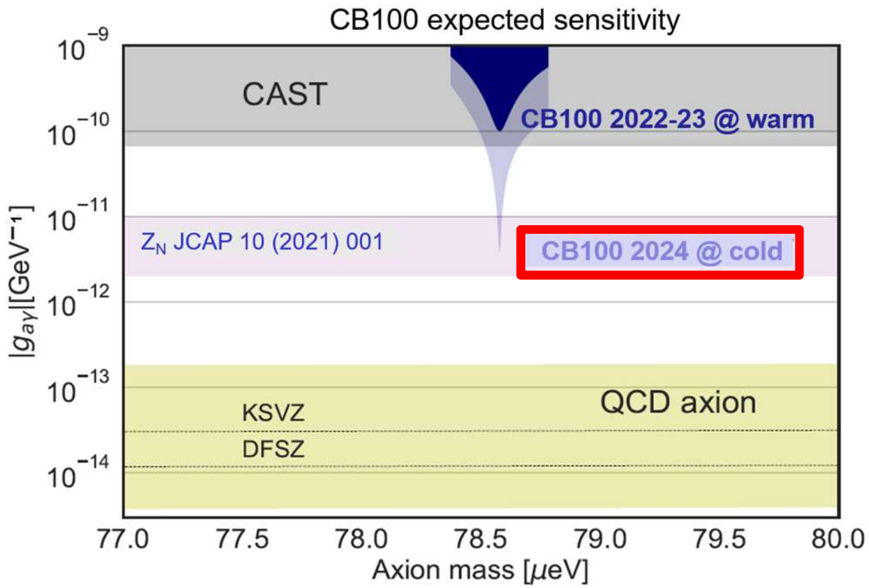
Develop a 'cheap' cryostat with CERN cryolab to cool the booster + LNA → Validated the principle in 2023



Vacuum between Inner and Outer vessel



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

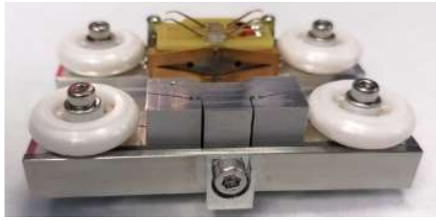


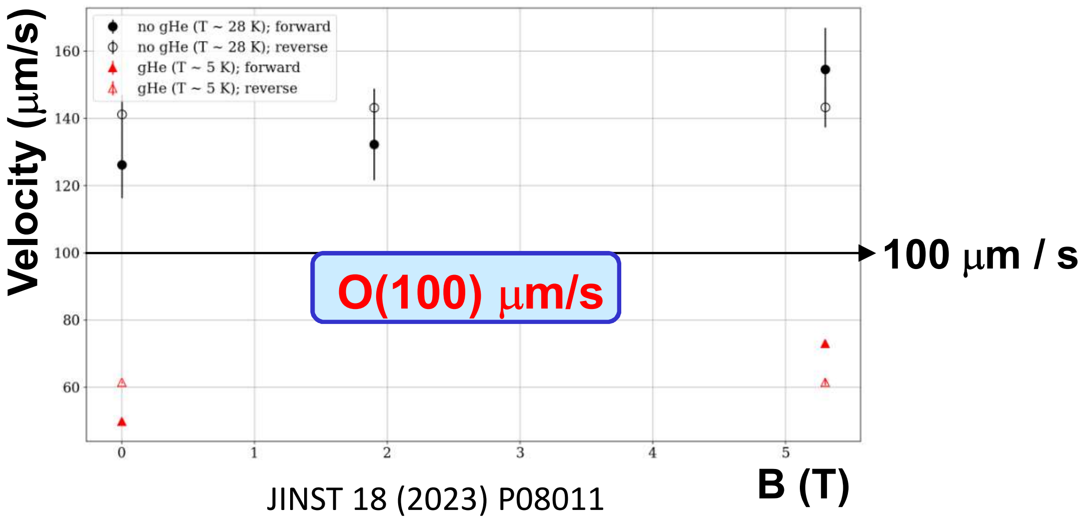
First short cold run in 2024

Set-up with moveable disk (1/2)

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

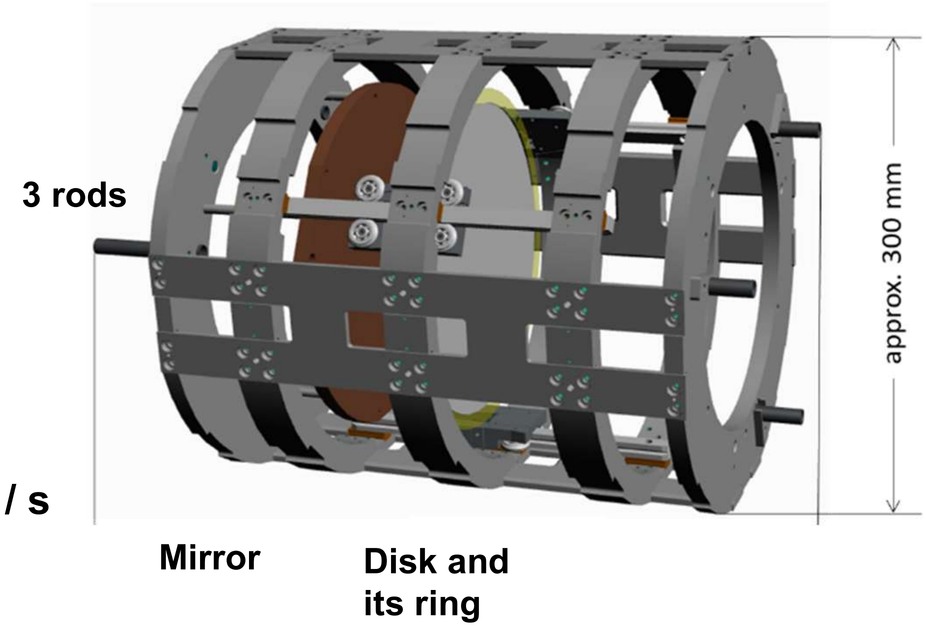
Successful test of JPE piezo motor at 5 K and 5.3 T *(ALP magnet in DESY)*





JINST 18 (2023) P08011

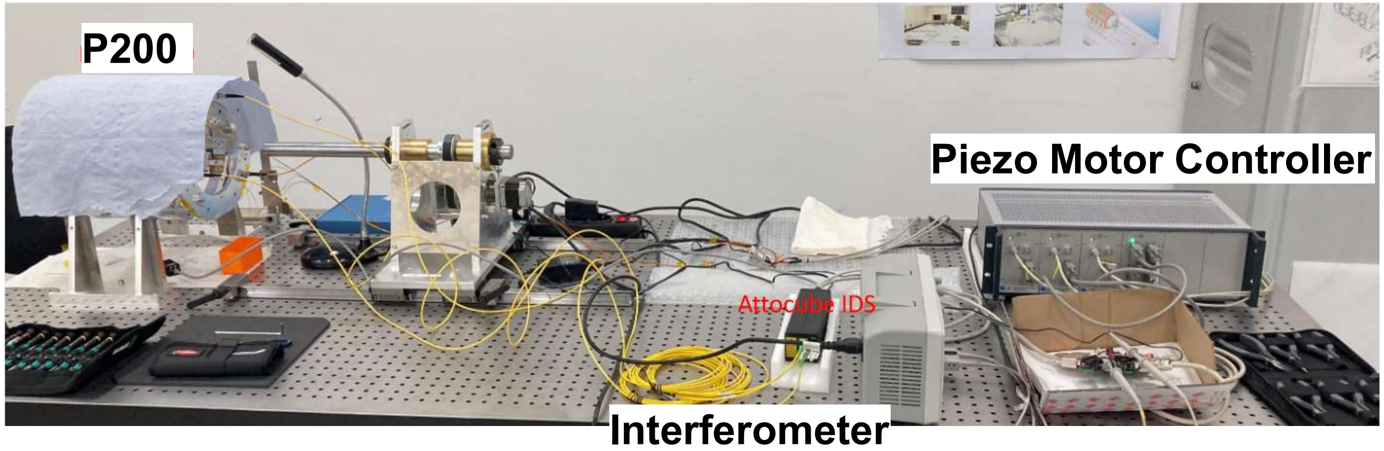
Build full mechanical structure of Open Booster and insert 1 mirror + 1 disk *(3 piezo motors)*

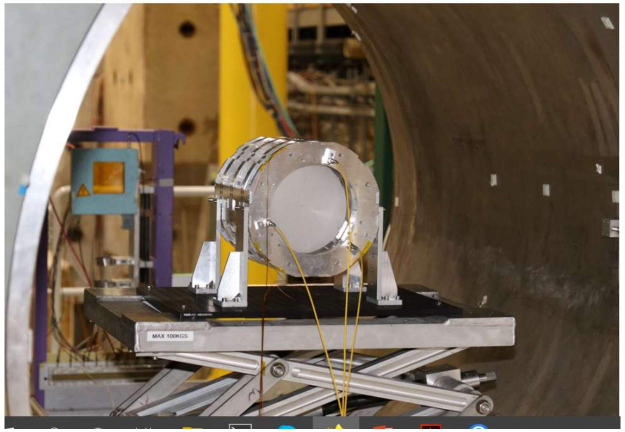


Set-up with moveable disk (2/2)

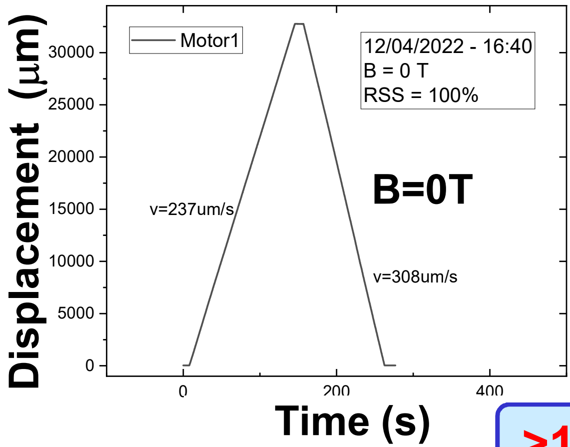
Name	Goal	Concept	Made of	Avail.	Morpurgo test
P200	Piezo-motor + mechanics	Open Booster	1 **moveable** disk ϕ = 200 mm	2021	2022

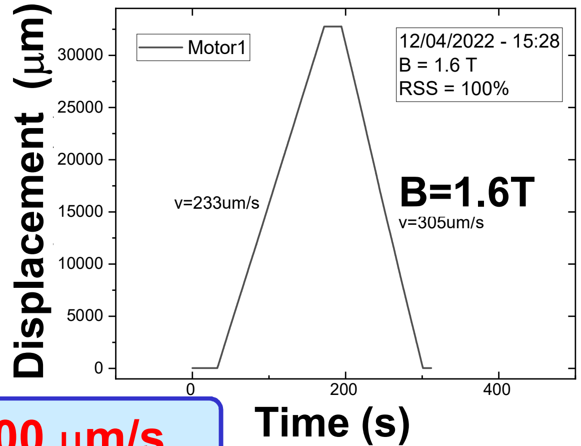
Tested in the lab, in a CERN cryostat (4K) … … and under 1.6 T





Validate piezo motors + booster mechanics



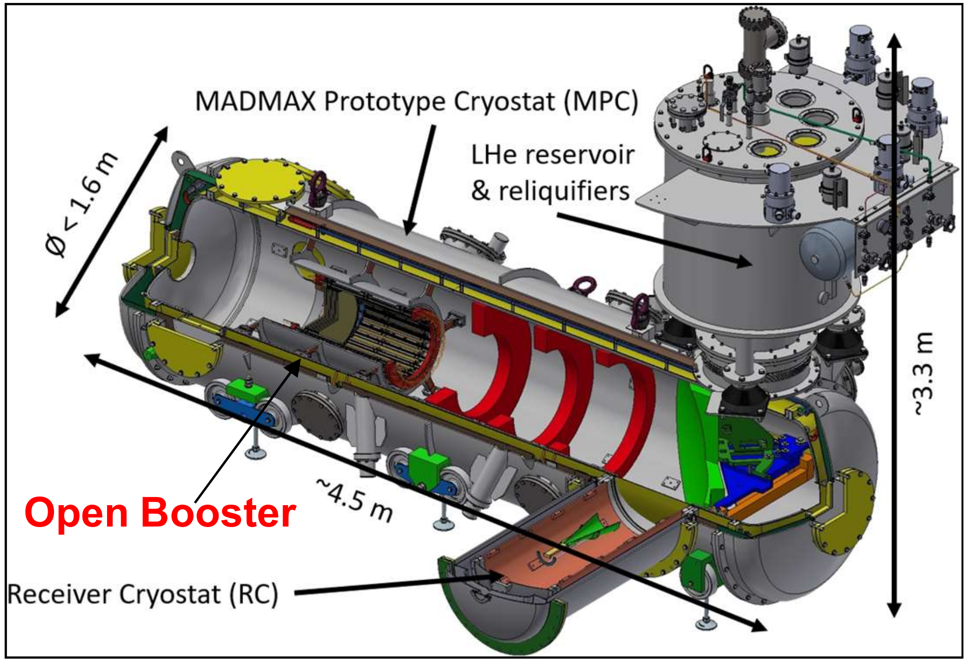


>100 µm/s

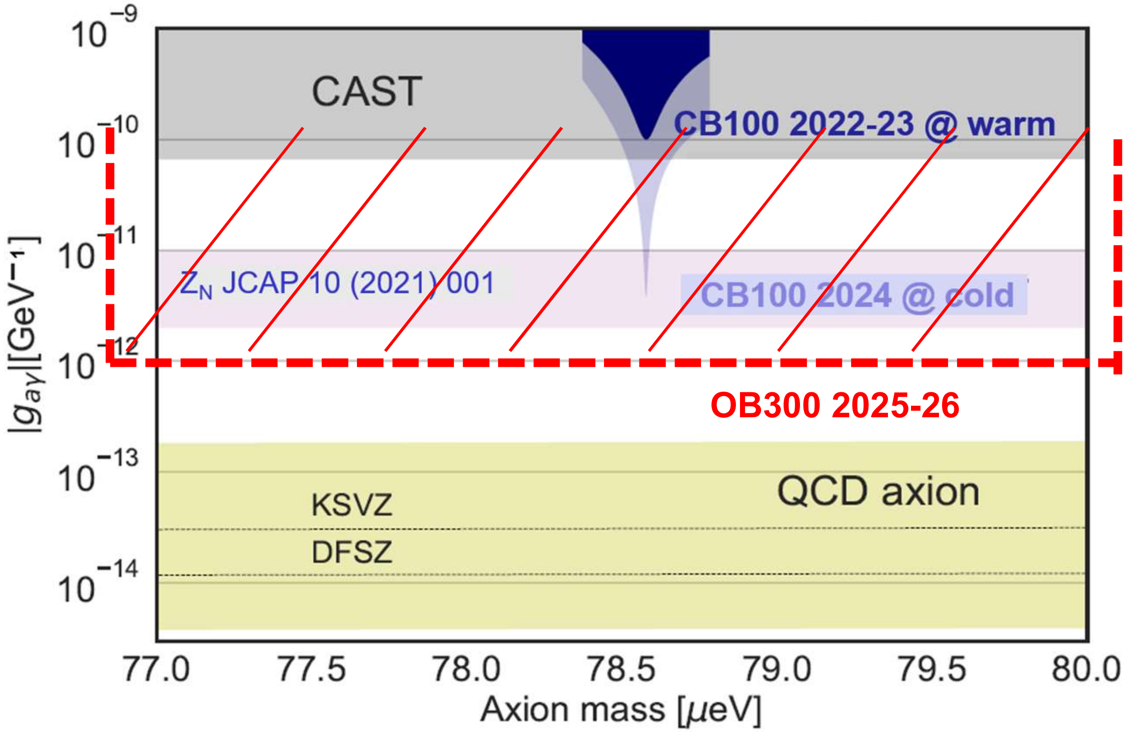
Final prototype + ALP physics

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

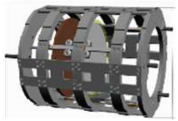
2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | >= 2028

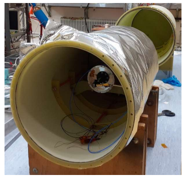
We are here !

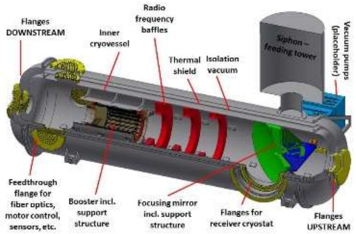
Design Phase ← Prototyping Phase →

Foundation of MADMAX Collaboration

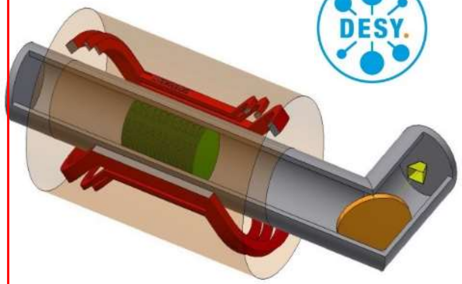
First endorsement by DESY PRC







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 & IN2P3

❑ Pionnering experimental work at IN2P3 on DM axion search

- **CPPM** joined MADMAX in 2020 *(2 physicists, 1 PhD, 4 IT → 4 FTE)*. **IJCLab**: will join in 2024
- **Master Project** at IN2P3 since 2023
- Presentation at IN2P3 Conseil Scientifique on Dark Matter (23-Oct 2023)
- Remark: **CNRS IRL "*DMLab*" (with Helmholtz** centers**)** → MADMAX is a central project

Responsabilities in all executive bodies of the MADMAX collaboration

- Member collaboration board
- Member executive board

+ IN2P3 master project coordinator

+ CPPM scientific coordinator

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

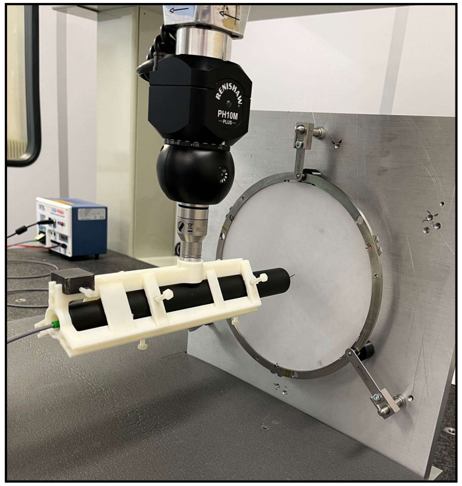
- Technical coordinator (2020, 2023-)
- Member executive board

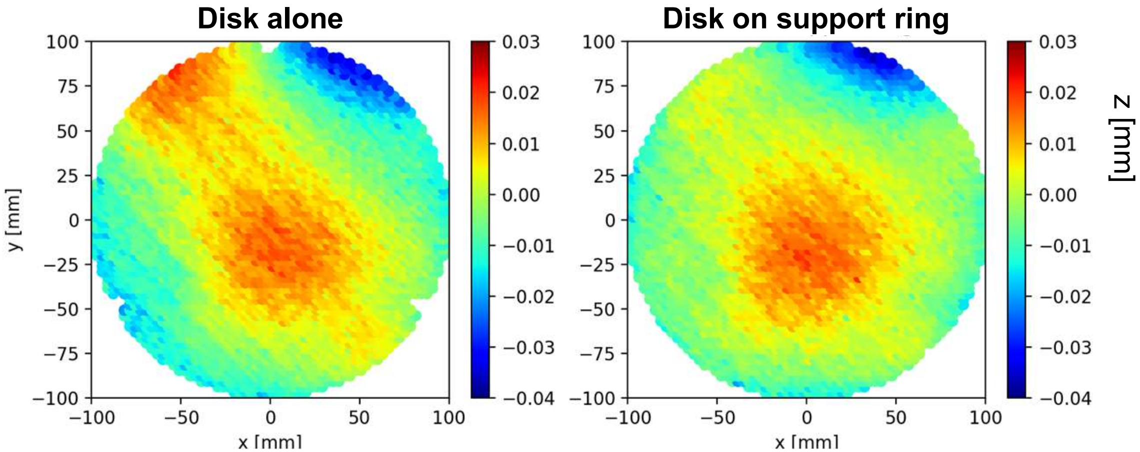
+ CPPM technical coordinator

MADMAX & CPPM (1/2)

❑ Precision mechanics for the prototype boosters

- Precision 3D measurements O(μm) for geometry control of the 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)



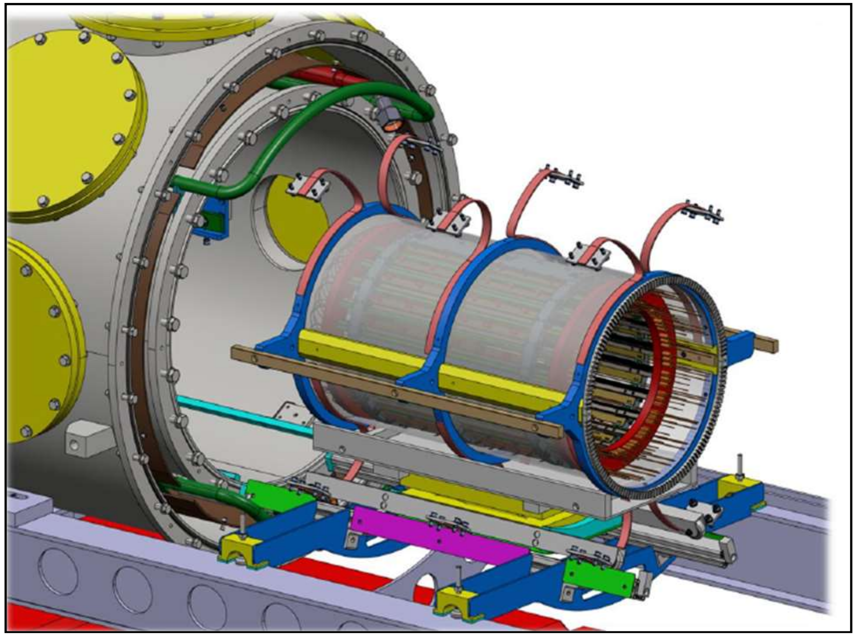


<10 μm RMS disk planarity alone/on the ring

MADMAX & CPPM (2/2)

❑ Coordination of prototype tests at CERN in Morpurgo magnet

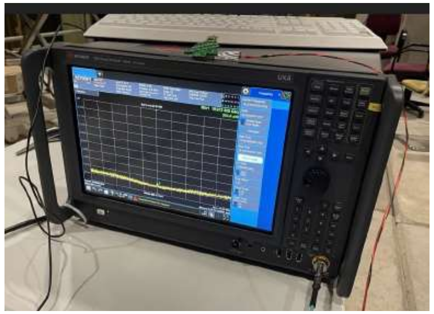
- Impulsion for magnet choice, approved by CERN RRB in 2020 for 2021-25 YETS *(~1 month/yr)*
- Conception, fabrication and installation of mechanical infrastructures around the magnet *(Rails for electric racks, supports for prototypes, rails for big test cryostat, …)*
- Design and construction of mechanical structure to align OB300 booster in cryostat and of integration tools (at DESY and CERN)
- Simulation and data analysis

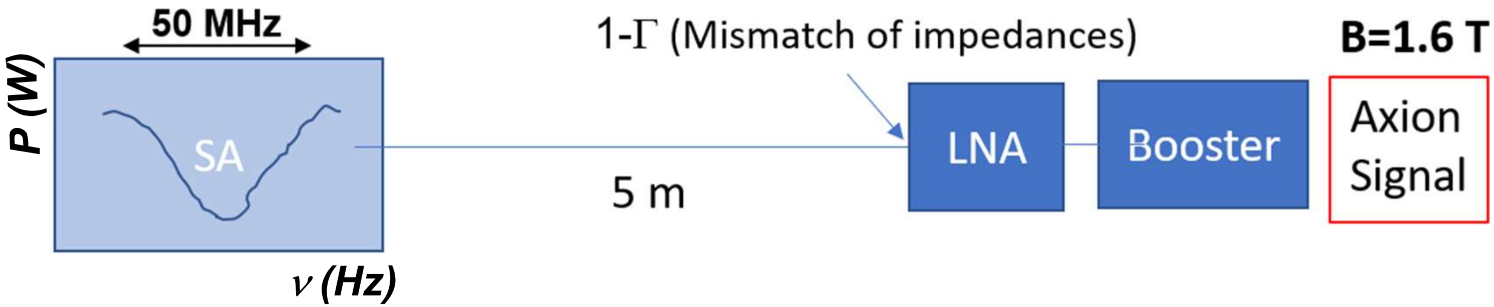


Receiver (1/2)

❑ Composed of

- **Low Noise Amplifier (LNA) ...**
  - ✓ “Classic” HEMT, G=33 dB, 4 K added noise
- **… connected to custom-made receiver**
  - ✓ Three mixing stages to down sample from 20 GHz to 50 MHz *(heterodyne mixing)*
  - ✓ Fast Fourier Transform in 4 samplers → 1% dead time
  - ✓ Tested at CERN in 2022 but difficult to move + some saturation & time instability
- **… connected to commercial spectrum analyzer (SA)**
  - ✓ Tested at CERN in 2023 : stable, no saturation but higher dead time*
  - ✓ Just bought a new SA with data streaming (~0 % dead time)

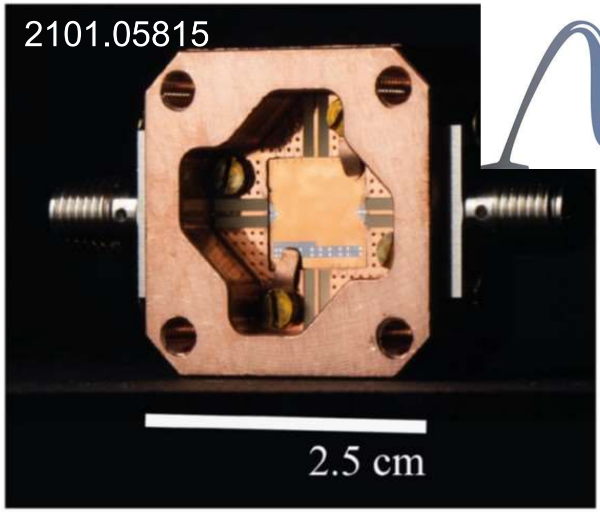




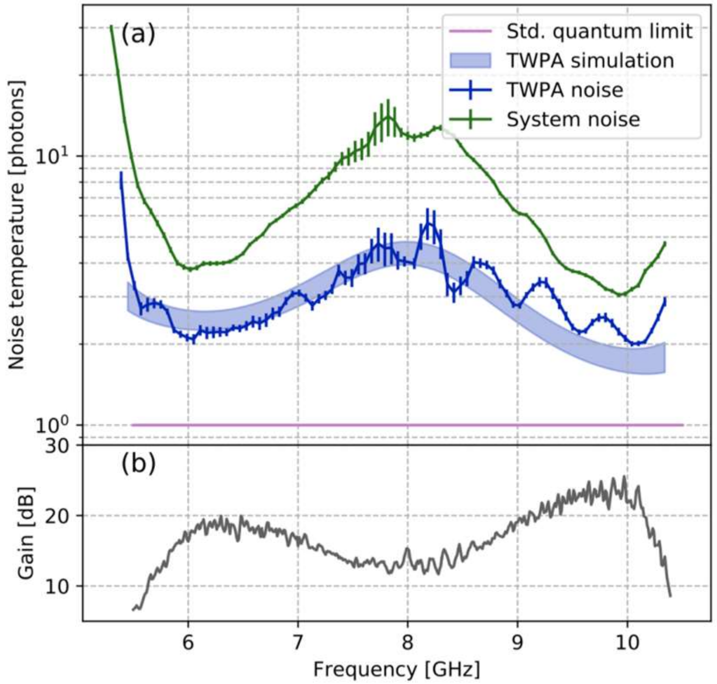
Receiver (2/2)

❑ Progresses on Low Noise amplifier

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



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



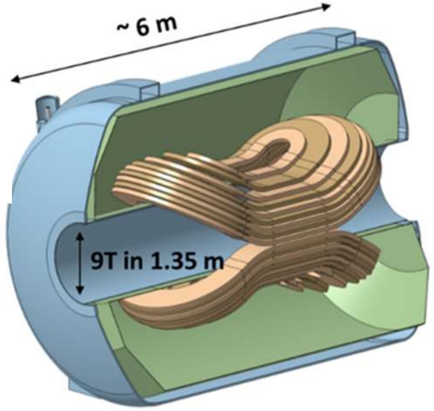
[Reversed Kerr TWPA arXiv:2101.05815]

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

Magnet

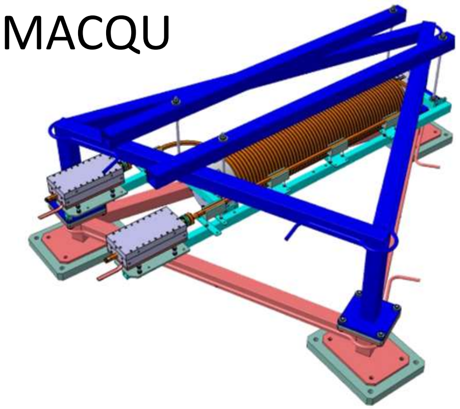
❑ Progresses on final magnet

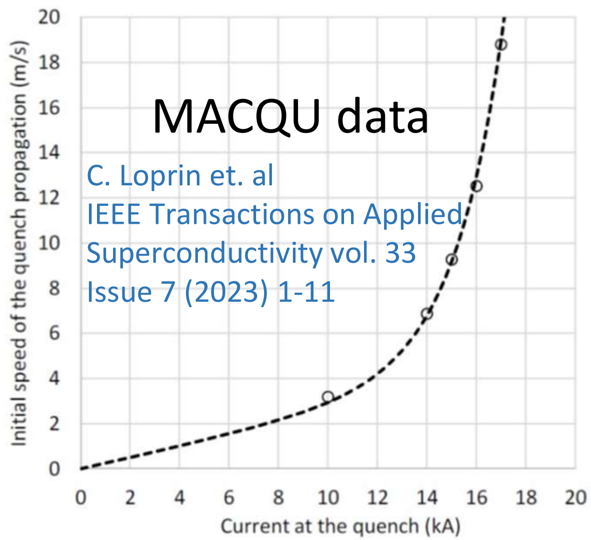
- Design completed: 2x9 skateboard coils with novel copper CICC conductor
  [NbTi with Cu jacket @ 1.8K]



- Recently demonstrated that coils will be safe in terms of quench protection (**MA**dmax **C**oil for **Q**uench **U**nderstanding)

MACQU





- **Next** : Design, manufacture and test a small coil (6T)

Conclusions

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

- **DM axion direct search: rising interest, next decades 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

Technological developments on mechanics (precision, piezo motors), magnet, low noise amplifier, cooling

BACKUP

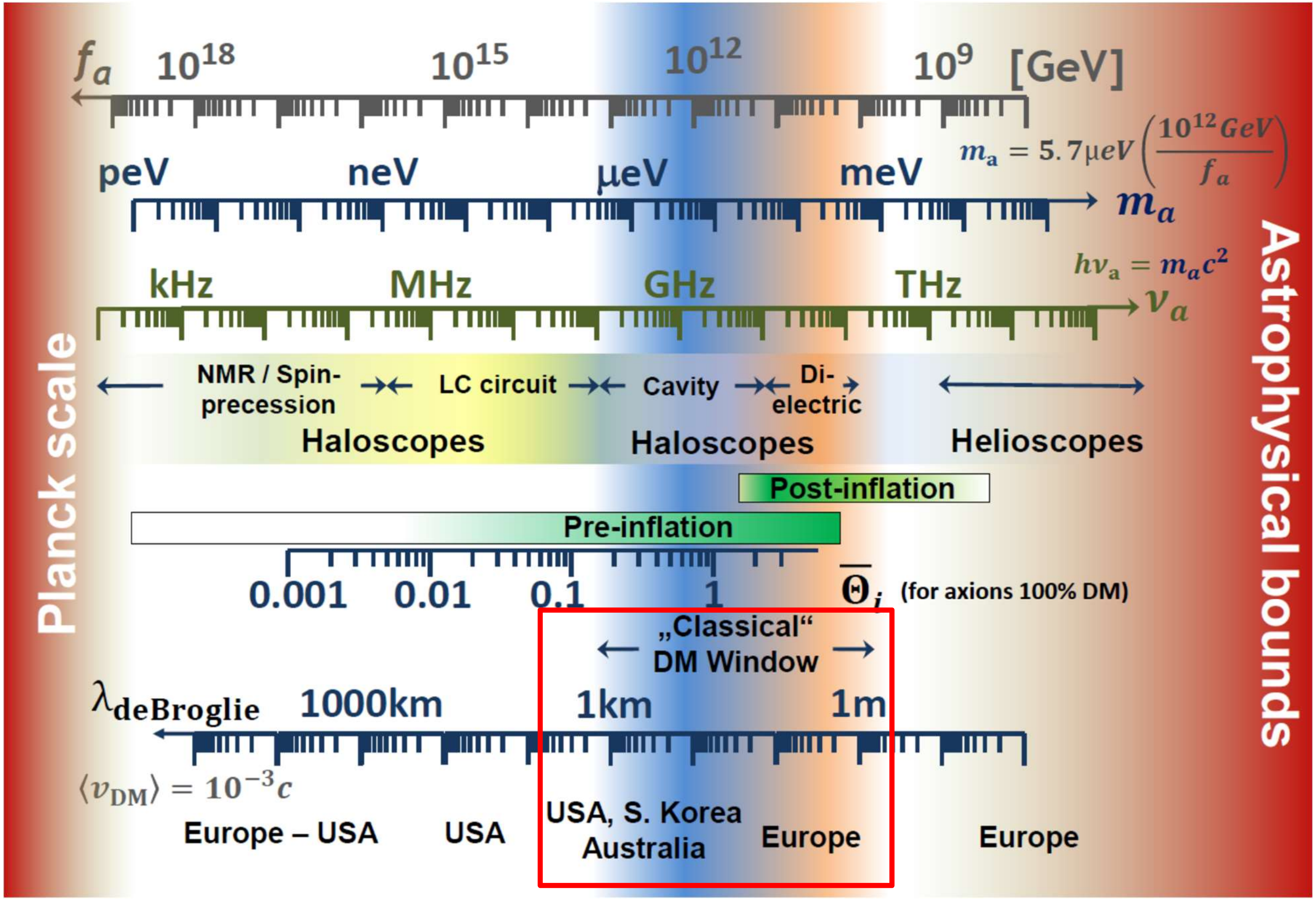

Collab Week at CPPM (Apr 2023)


MADMAX
MAgnetized Disc and Mirror Axion eXperiment

Axion scales

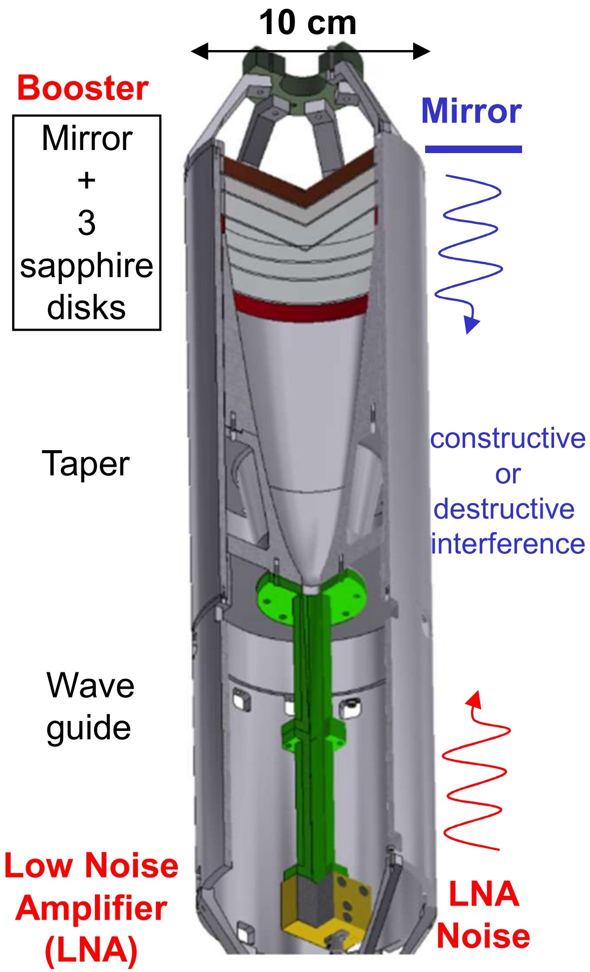
APPEC Committee Report

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

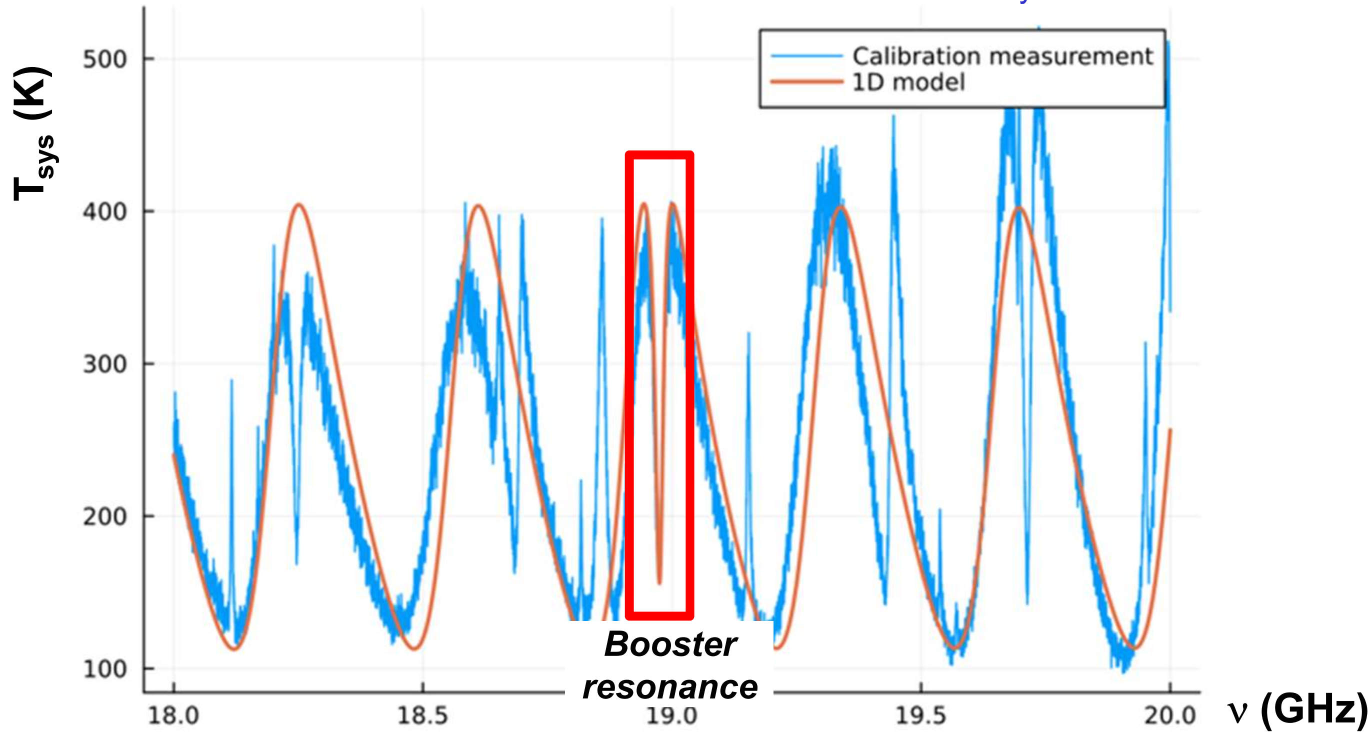


RF (1/3)

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



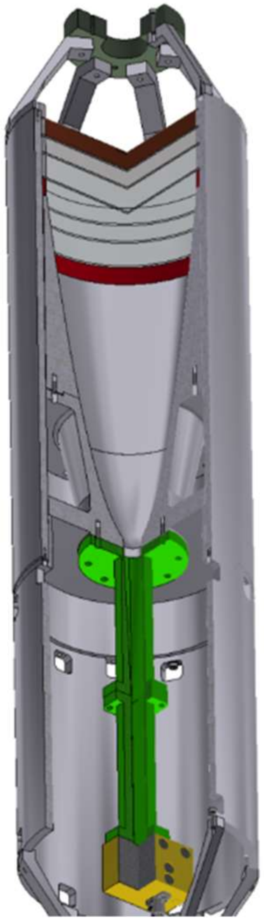
Simulate **LNA** (ADS) and **Booster+taper** system (COMSOL)
→ compare with measured system temperature (T_{sys}) in 18-20 GHz

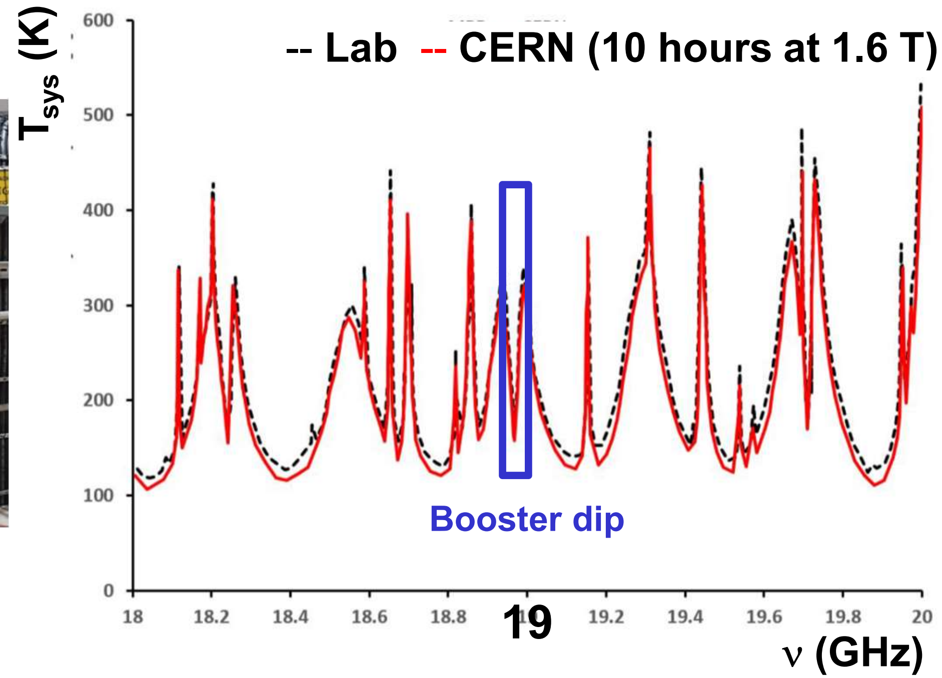


Model the RF behavior *(esp. at the booster resonance)*

RF (2/3)

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

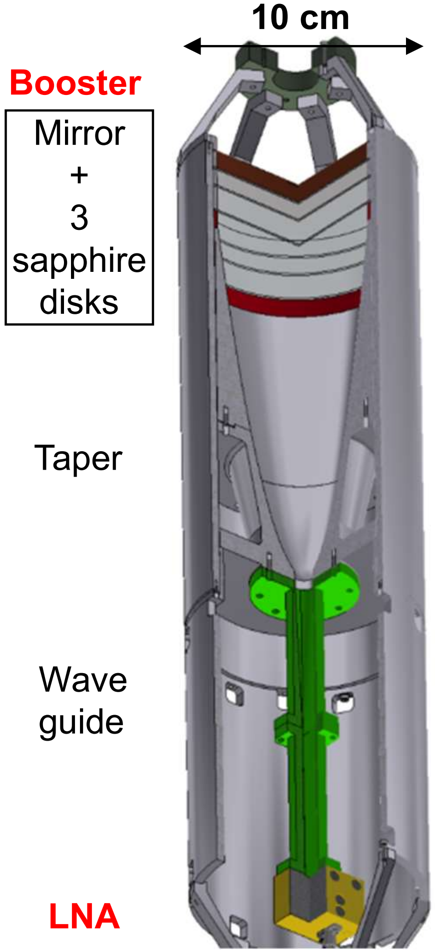




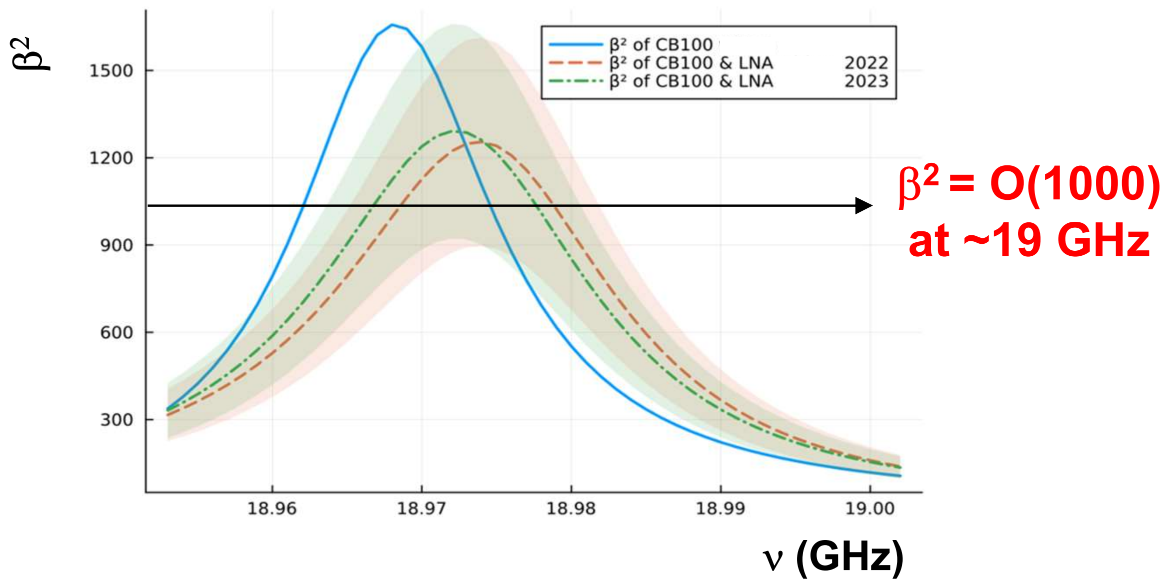
No impact from the CERN environment

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

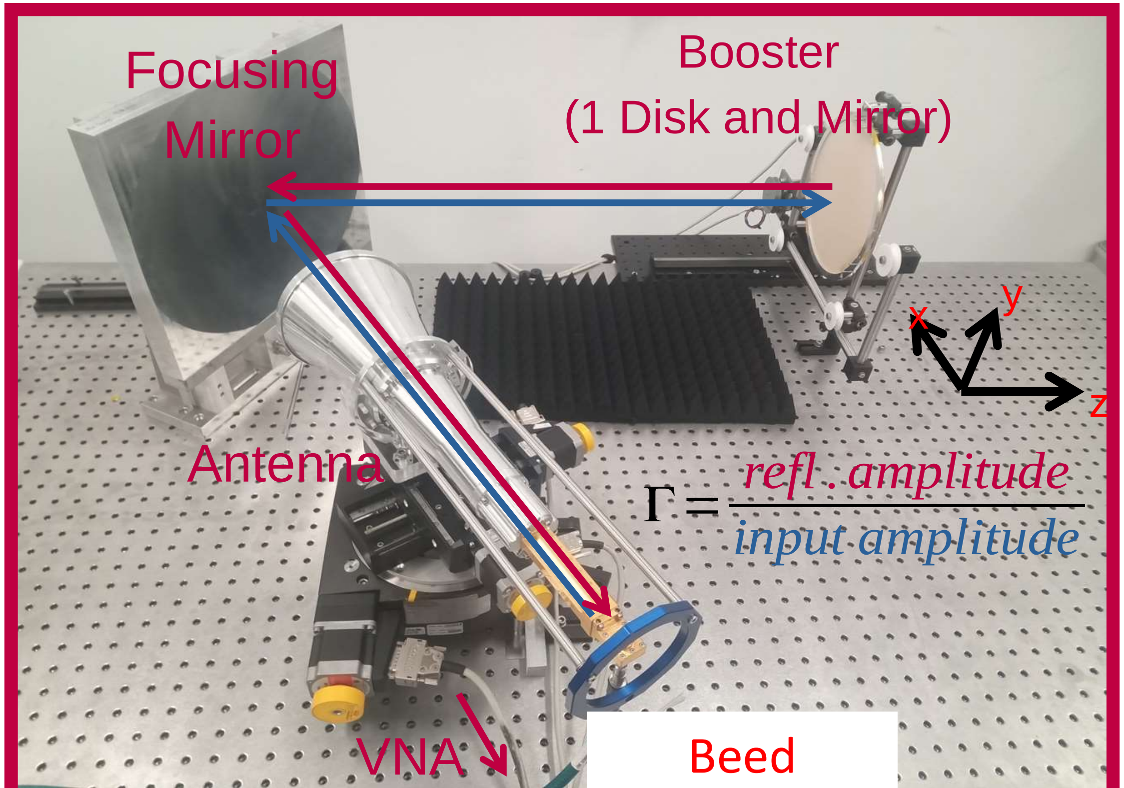


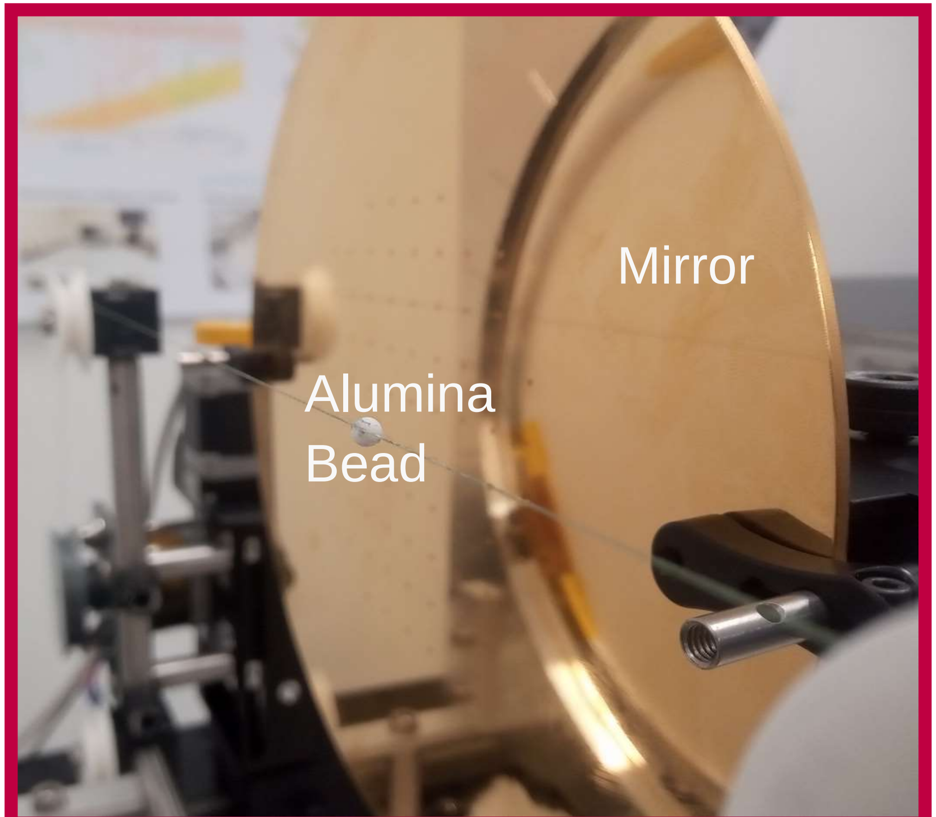
Model the boost factor shape with systematic uncertainties

[paper in preparation]

OB calibration (1/2)

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





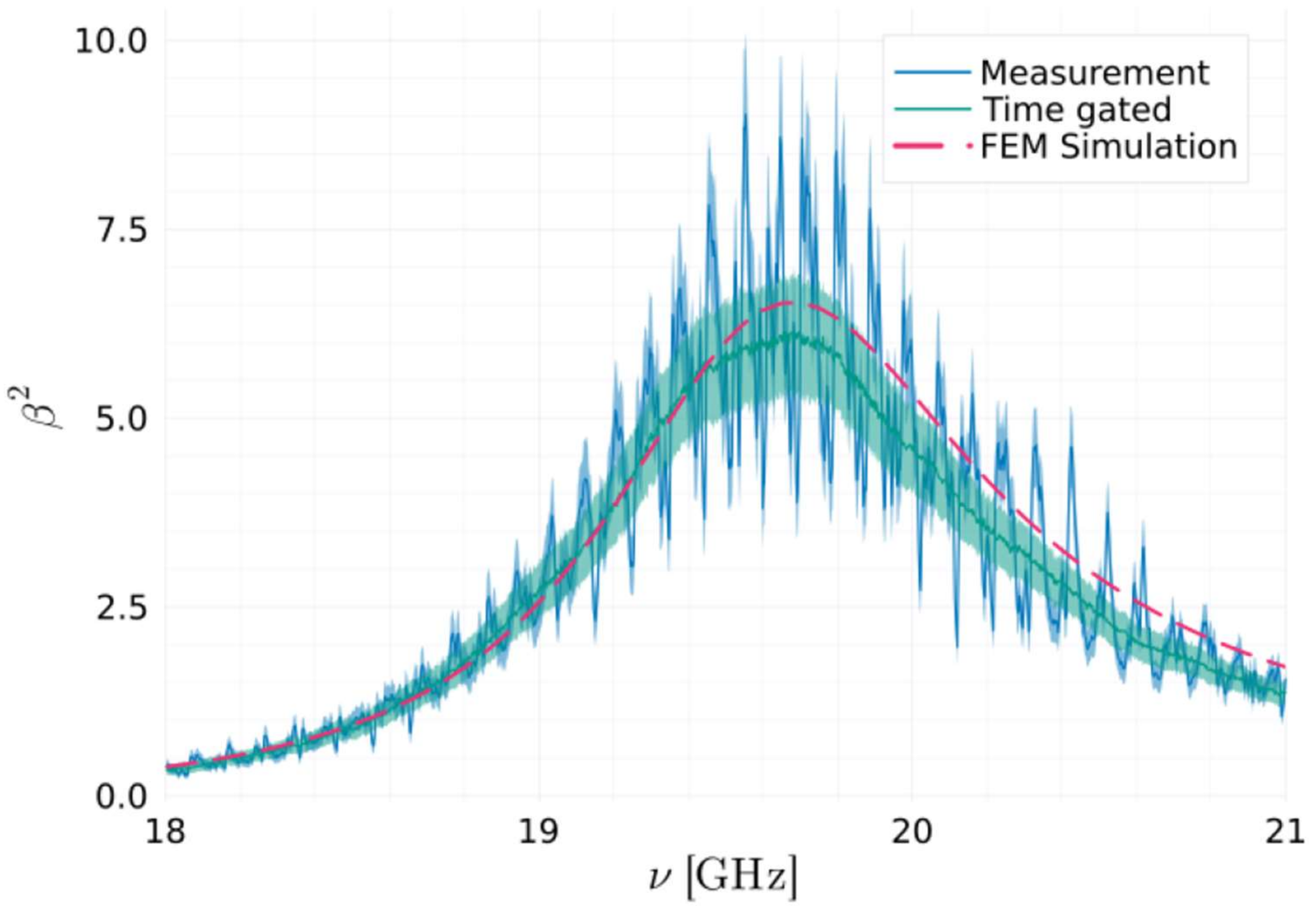
Beed properties

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

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

OB calibration (2/2)

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



Measure boost factor (+ systematics)

[paper in preparation]