



Bringing axions to light : MADMAX

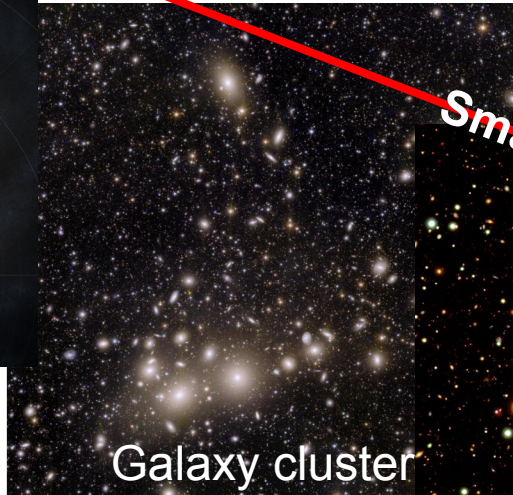
Workshop France-Ukraine

Thibaut Houdy
13th of October 2026

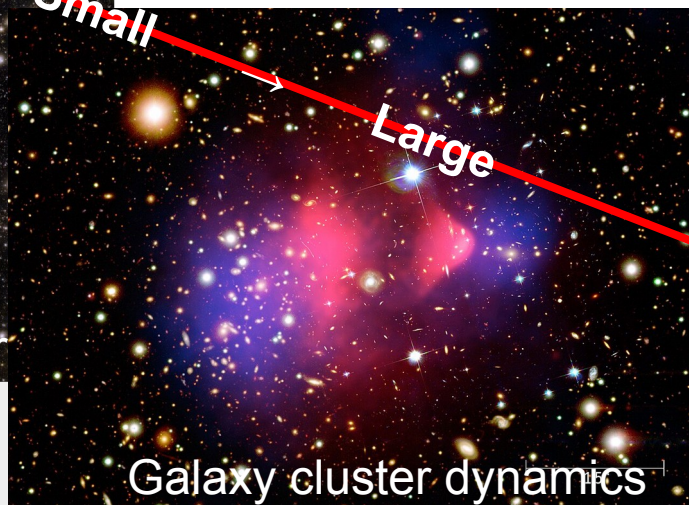
Dark matter



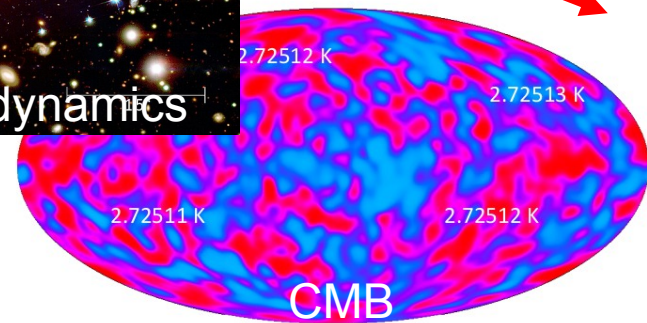
Galaxy



Galaxy cluster



Galaxy cluster dynamics

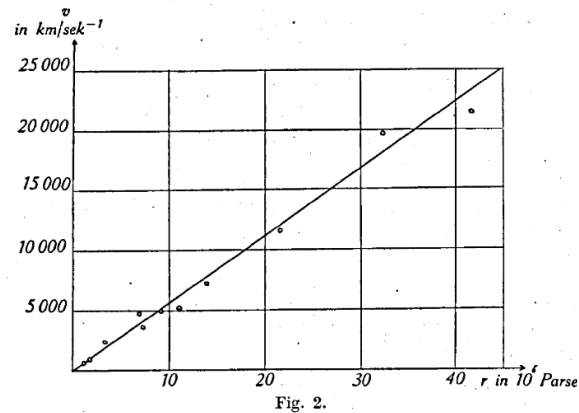
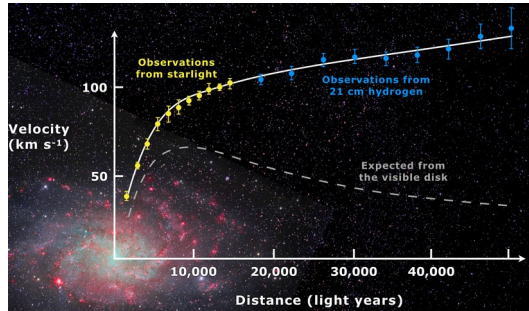


CMB

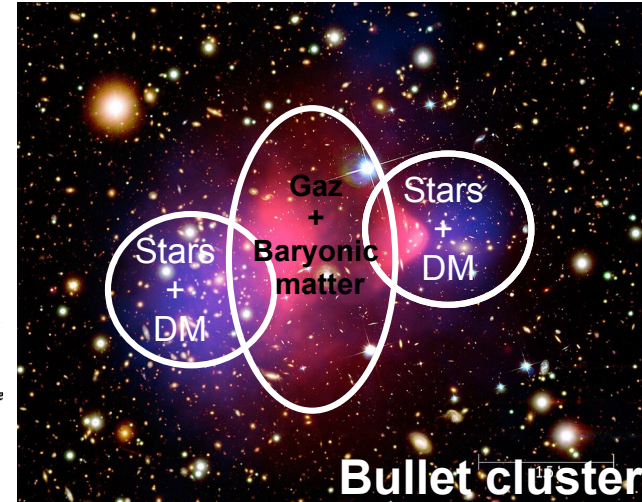
Why do we think DM exists?

- Rotation curve of spiral galaxies
- Velocities in Galaxy clusters (Virial theorem)
- Galaxy clusters dynamics (ex : Bullet Cluster)
- Power spectrum in the Cosmics Microwave Background
→ 85% of mass in the Universe is Dark Matter

Dark matter

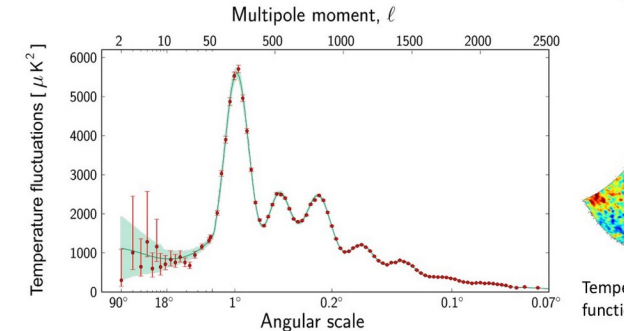


Die Rotverschiebung von extragalaktischen Nebeln
von F. Zwicky.

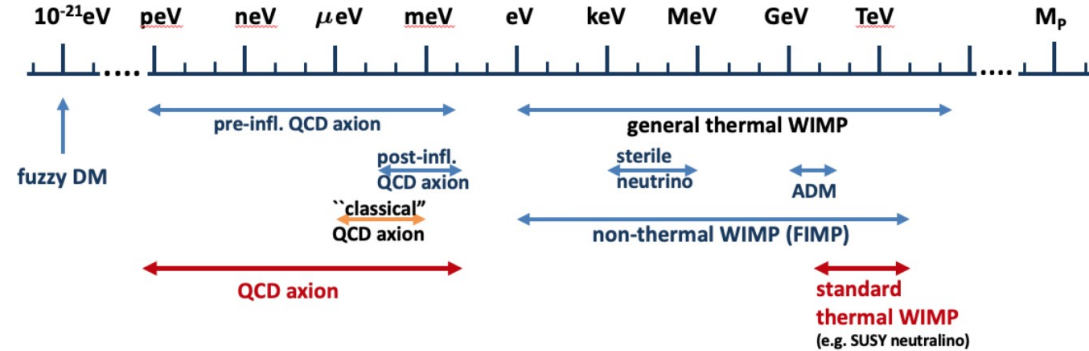
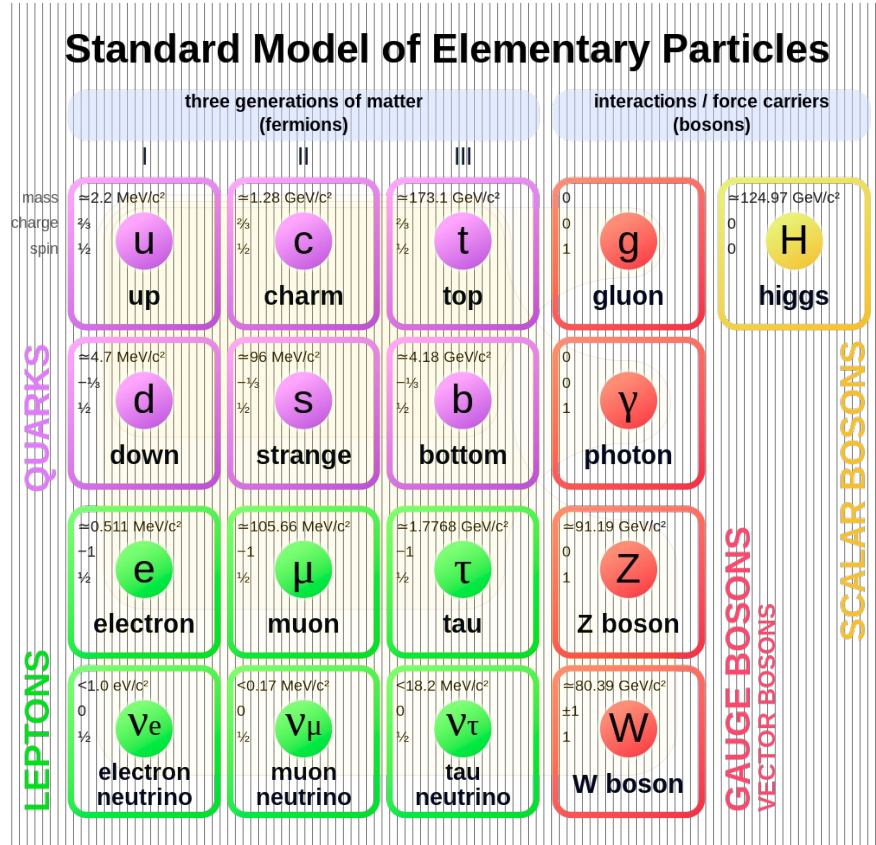


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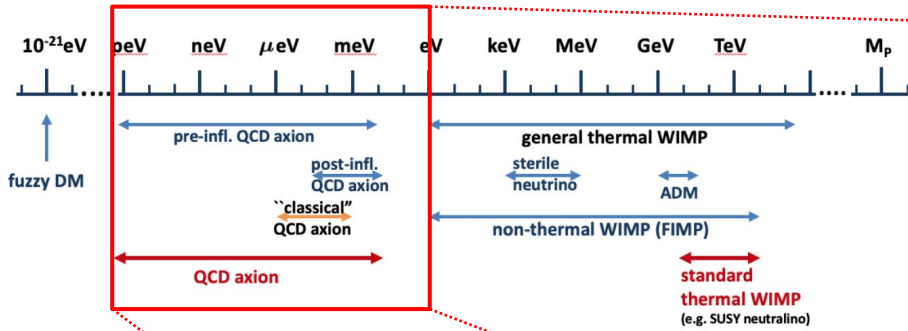


Dark matter



- No candidate in the standard model
- Must be abundant ($\sim 82\%$ of matter) and stable ($\tau_{\text{DM}} > 10^{17} \text{ s}$)
- Massive and neutral for EM and strong force
- Cold or not too warm
- Most favored candidates (so far) : WIMPs, sterile neutrinos (keV), axions

Dark matter

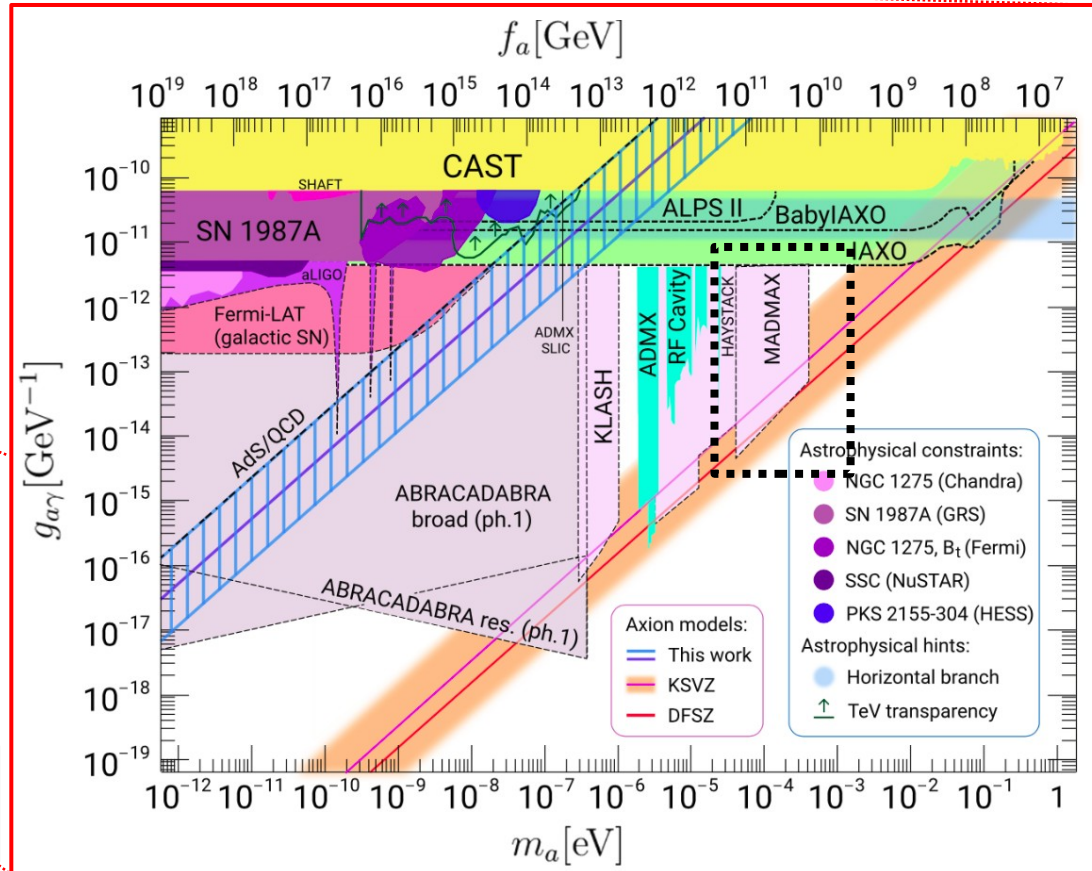


$$f_a m_a \approx m_\pi f_\pi$$

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

$$C_{a\gamma} = \left(\frac{E}{N} - 1.92\right) \approx 1$$

Axions are also a natural solution to the **strong CP problem** ($|\theta_{CP}| < 10^{-10}$)!



Axions

$$\nabla \times \mathbf{B}_a - \dot{\mathbf{E}}_a = -g_{a\gamma\gamma} (\mathbf{E}_0 \times \nabla a - \dot{a} \mathbf{B}_0) ,$$

$$\nabla \times \mathbf{E}_a + \dot{\mathbf{B}}_a = 0 ,$$

$$\nabla \cdot \mathbf{B}_a = 0 ,$$

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+

Existence of an axionic field modifies
Maxwell equations proportionally to $g_{a\gamma\gamma}$

Axions

$$\nabla \times \mathbf{B}_a - \cancel{\dot{\mathbf{E}}_a} = -g_{a\gamma\gamma} (\mathbf{E}_0 \times \cancel{\nabla a} - \dot{a} \mathbf{B}_0),$$

MQS
approximation

$$\nabla \times \mathbf{E}_a + \dot{\mathbf{B}}_a = 0,$$

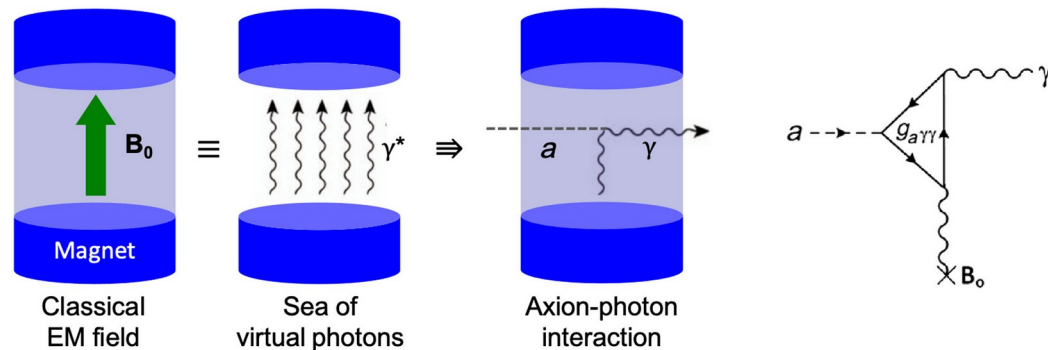
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Existence of an axionic field modifies
Maxwell equations proportionally to $g_{a\gamma\gamma}$

$$E_a(t) \propto -\frac{g_{a\gamma} B_0}{\epsilon} a(t)$$

Electric static field produced in an intense
magnetic field depending on the permittivity



Detecting axions

$$\nabla \times \mathbf{B}_a - \dot{\mathbf{E}}_a = -g_{a\gamma\gamma} (\mathbf{E}_0 \times \nabla a - \dot{a} \mathbf{B}_0),$$

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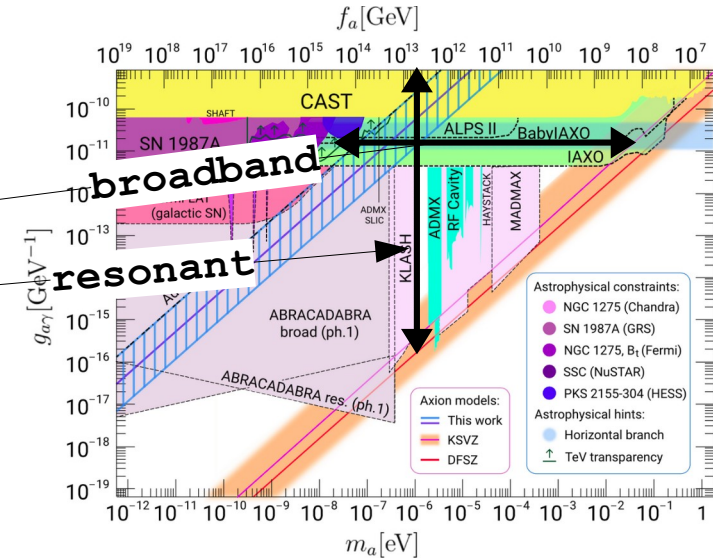
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Existence of an axionic field modifies
Maxwell equations proportionally to $g_{a\gamma\gamma}$

How to detect axions?

- producing axions in the lab : **anthropological axions**
- looking for solar axions : **axion helioscope**
- looking for galactic halo axions : **axion haloscope**



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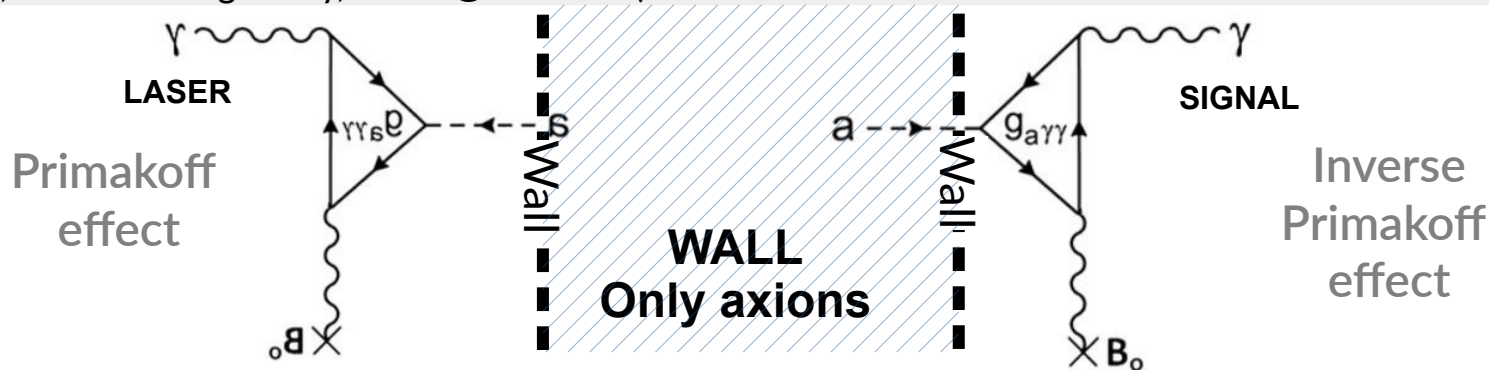
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Anthropological axions :

- Light shining through walls** : intense laser-beam in a B field $\rightarrow$ Primakoff effect, axion creation. Wall for bloquing the photons, axions are crossing. Second intense B-field for inverse Primakoff effect $\rightarrow$ ex : ALPS (DESY, 5,3 T, 2x122 m long cavity, 70 W @ 1064 nm)



Detecting axions

$$\nabla \times \mathbf{B}_a - \dot{\mathbf{E}}_a = -g_{a\gamma\gamma} (\mathbf{E}_0 \times \nabla a - \dot{a} \mathbf{B}_0) ,$$

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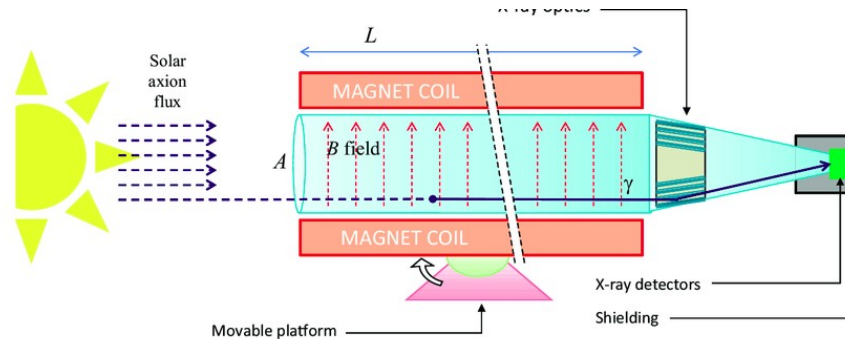
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Axion helioscope :

- Solar interior x-rays interact with strong B (Primakoff effect) to create axions (keV range, black body radiation of the Sun). Inverse Primakoff to detect x-rays in strong B. → ex : CAST, IAXO



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Axion haloscope :

- **Microwave cavities** : Axion halo couples to a tunable resonant cavity in the presence of an external magnetic field $\rightarrow$ excess power in the resonant cavity when TM_{010} frequency is close to halo energy ($Q \sim 200\,000$, bandwidth $\sim 1/Q$, scanning mass ranges) $\rightarrow$ ex: ADMX

Limitations : resonant frequency f as $V \sim f^3$, so too big for large $m_a \rightarrow$ skin effect that reduce Q

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- **Dish antenna** : mirror creates boundary conditions that forces EM wave to be emitted. Converge in the center of the spherical mirror $\rightarrow$ ex : BREAD
- Oscillating magnetic field in a toroid (10^{-22} T, SQUID techno), **low mass** $\rightarrow$ ABRACADABRA
- **Dielectrics cavity** : MadMax

Dielectric axions



$$\nabla \times \mathbf{B}_a - \dot{\mathbf{E}}_a = -g_{a\gamma\gamma} (\mathbf{E}_0 \times \nabla a - \dot{a} \mathbf{B}_0),$$

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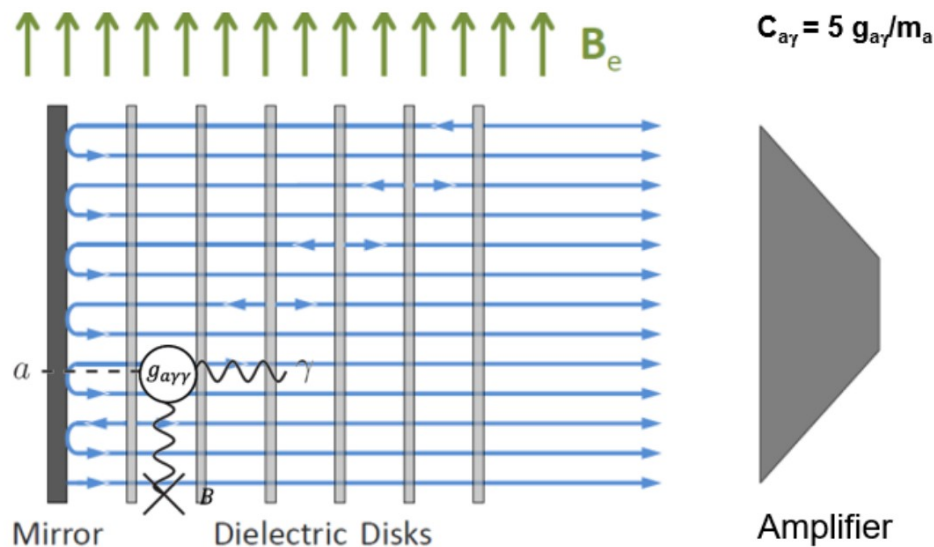
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Maxwell equations proportional to $g_{a\gamma\gamma}$

$$E_a(t) \propto -\frac{g_{a\gamma} B_0}{\epsilon} a(t)$$

Electric static field produced in an intense
magnetic field depending on the permittivity

$$\Delta \mathbf{E}_a(t) = -\left(\frac{1}{\epsilon_1} - \frac{1}{\epsilon_2}\right) g_{a\gamma} \mathbf{B}_e a_0 \exp\left(-i \frac{m_a c^2}{\hbar} t\right)$$

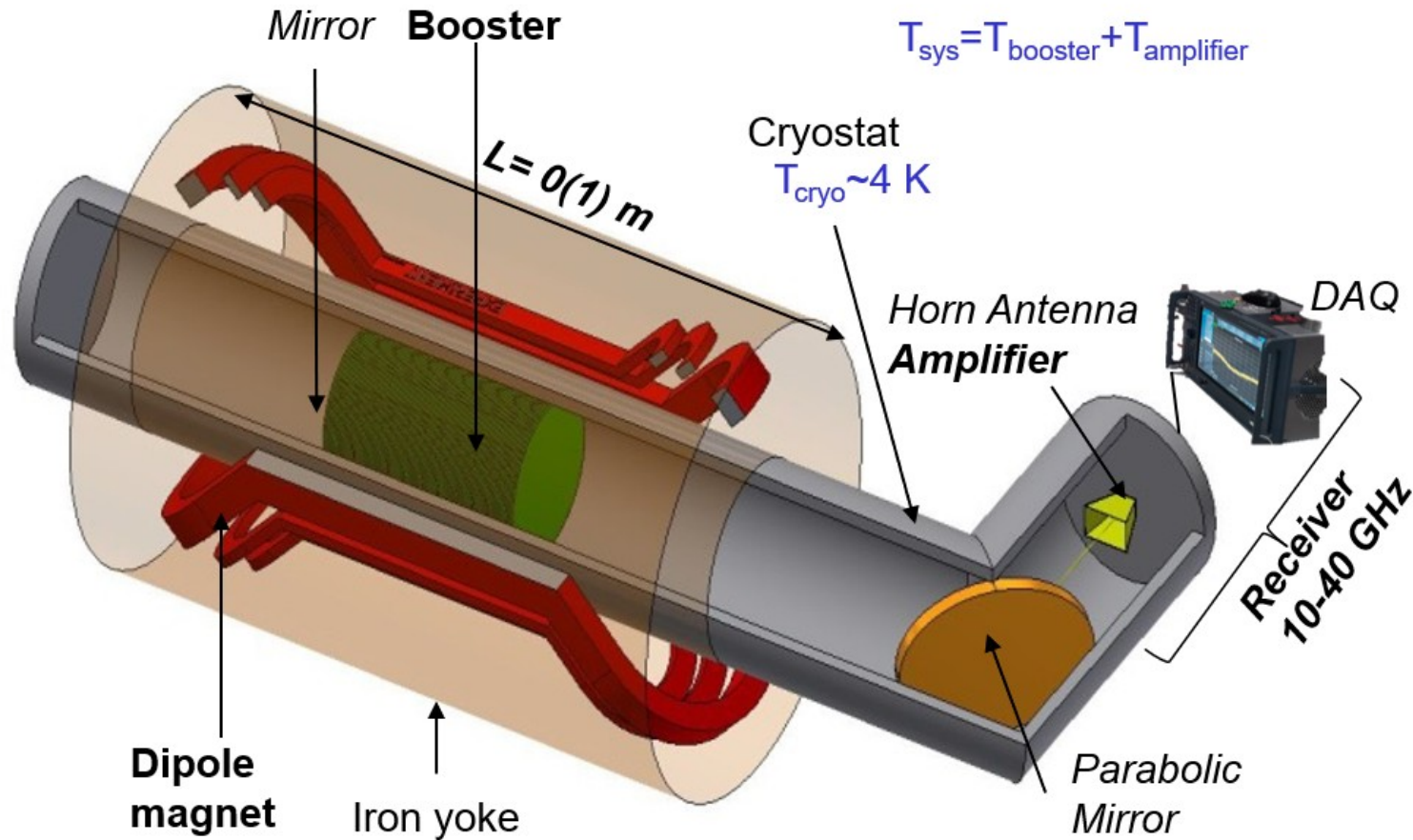
Continuity of E :
Emission of plane wave in the permittivity
gradient direction



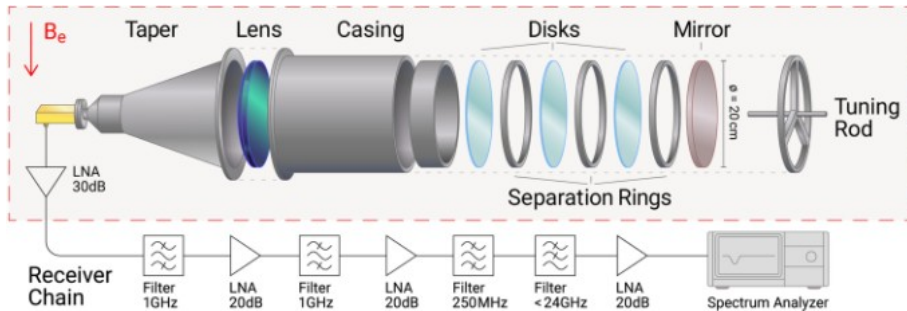
$$\left(\frac{P}{A}\right)_{\text{booster}} \approx 2 \cdot 10^{-27} \left(\frac{B_e}{10 \text{ T}}\right)^2 \beta^2 \frac{W}{m^2}$$

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

MADMAX goal



Closed Booster 200 mm (CB200) :



Design

- Came after CB100 (demonstrator at cold). Here not designed for being cooled down.
- 3 sapphire disks of 20 cm diameter and 1 mm thickness ($\epsilon=9$)
- Fixed boundary conditions simplifies number of allowed transmission modes (85% in TE₁₁)
- Tuning rod to vary the frequency of the booster by moving the mirror
- 250 MHz bandwidth with 9 Hz resolution (R&S FSW43 and LNAs)

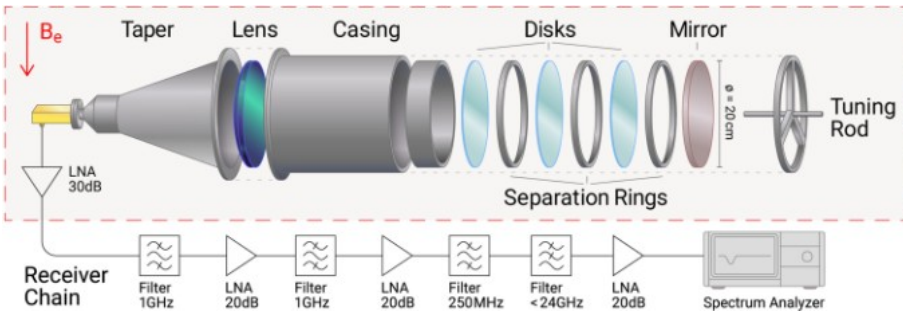
MADMAX proto

Closed Booster 200 mm (CB200) :

At room temperature

Design

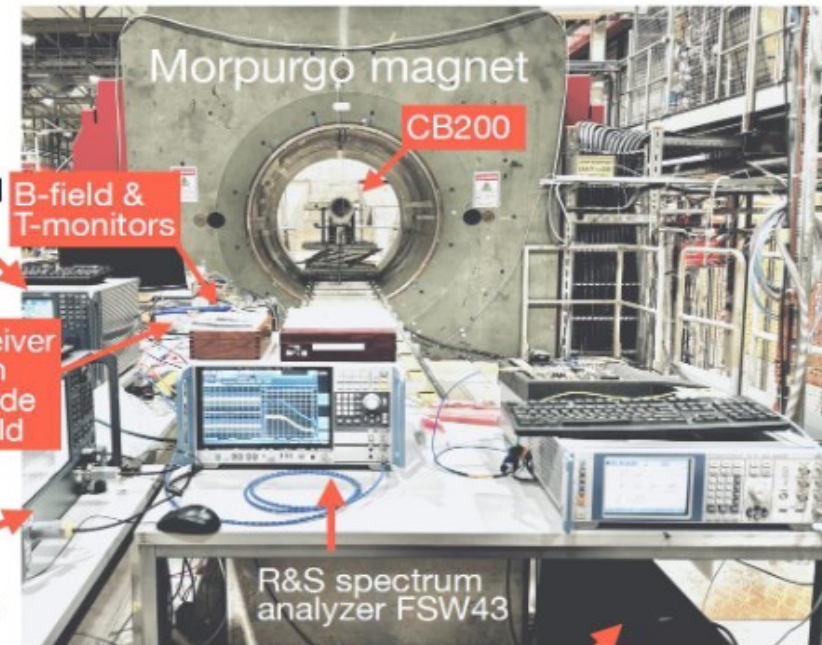
Set-up



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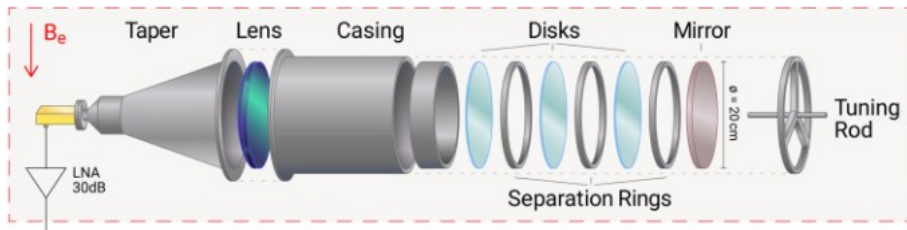
Spectrum analyzer for RFI measurement



From Béla Majorovits PATRAS 2025

MADMAX proto

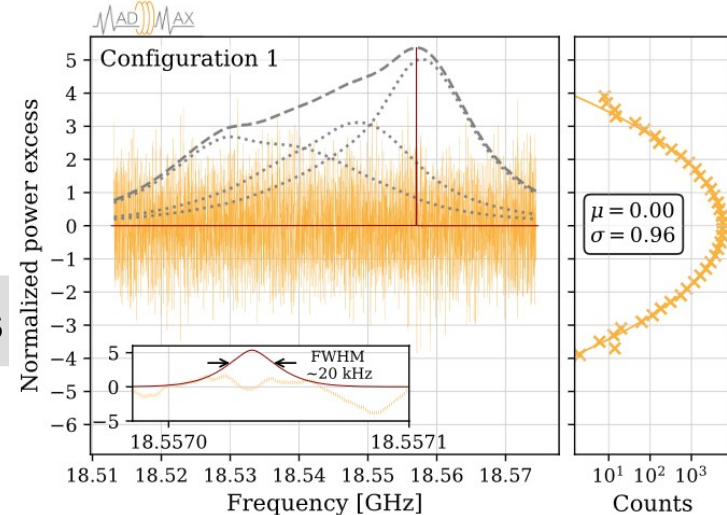
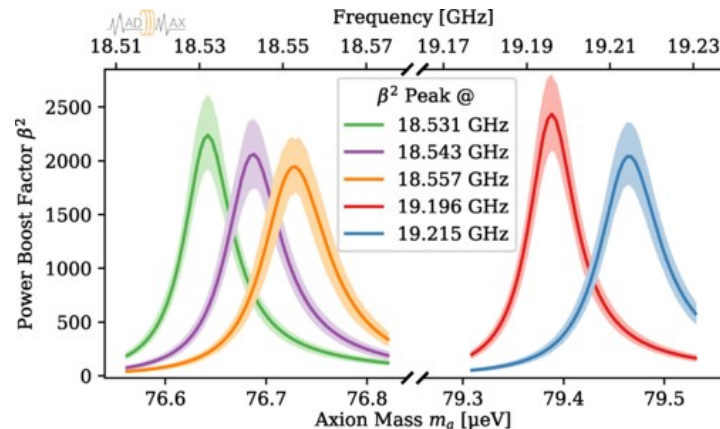
Closed Booster 200 mm (CB200) :



Design

Measurements

One of the main challenge of the experiment is the determination of the boost factor

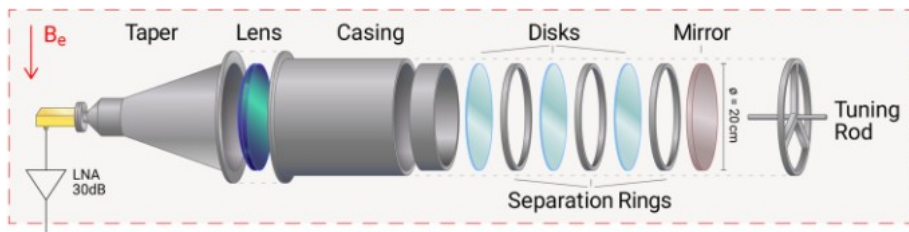


To do so :

- bead pull measurement in open booster
- reflectivity measurements
- complete simulations
- 5 frequencies scanned for 17 days with a $\beta \sim 2000$

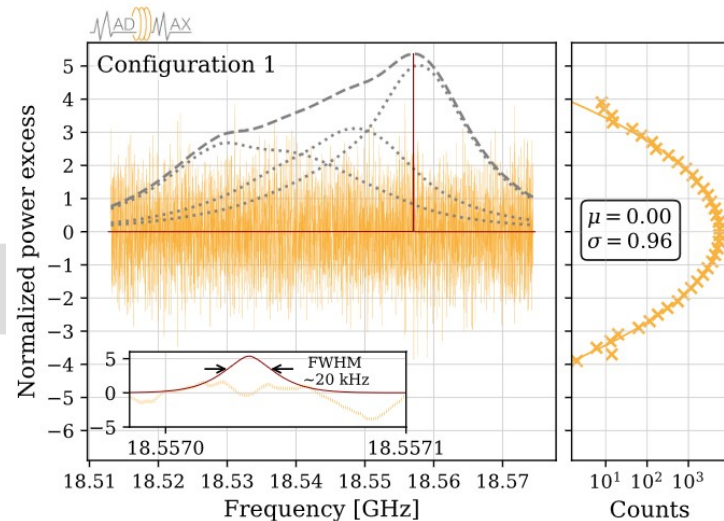
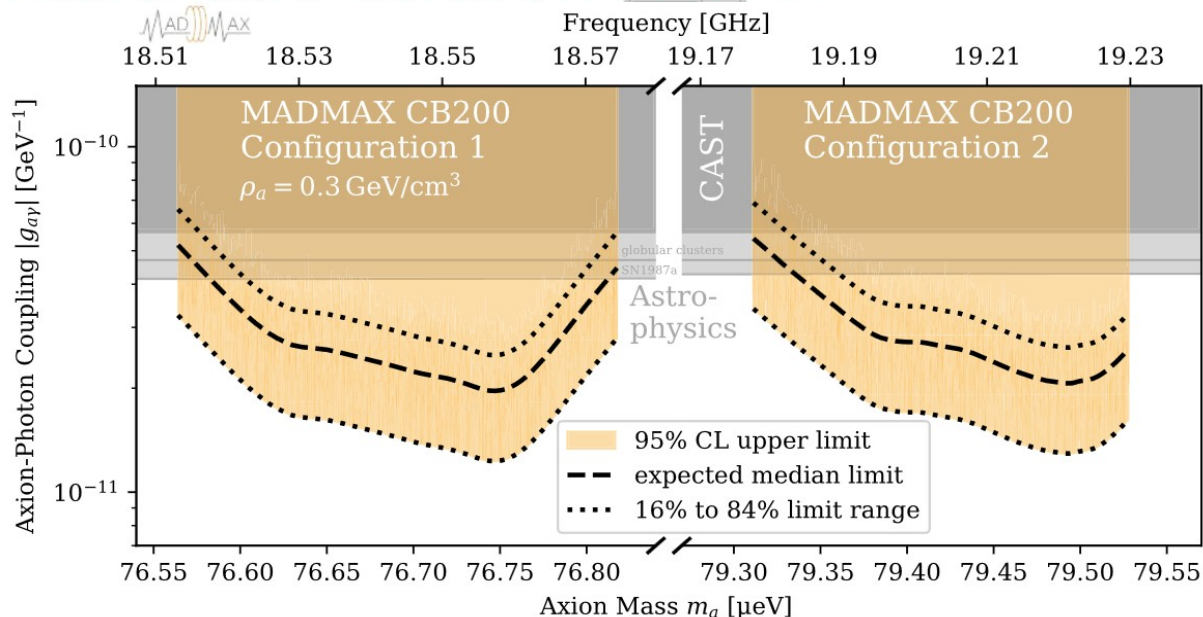
MADMAX proto

Closed Booster 200 mm (CB200) :



Design

Results

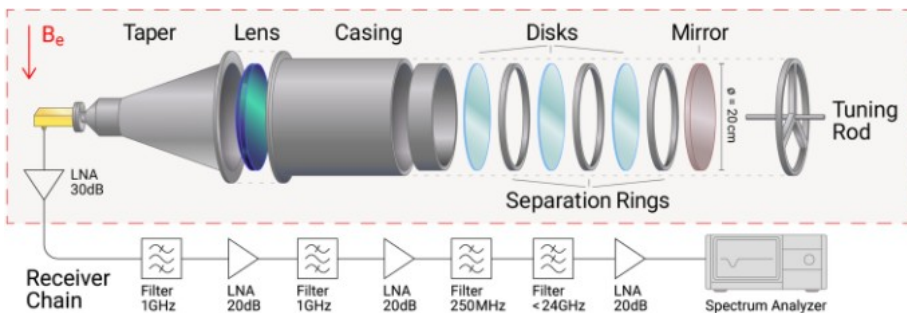


Exclusion

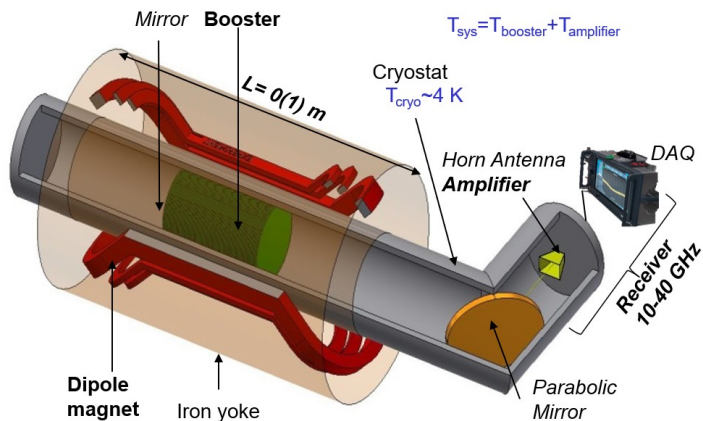
See PRL 135, 041001 (July, 2025)

MADMAX proof of concept

Closed Booster 200 mm (CB200) to Open Booster 300 mm (OB300)



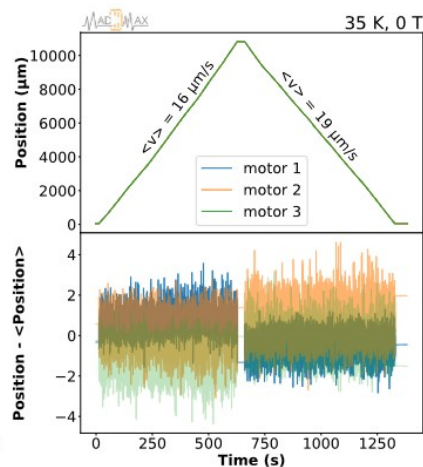
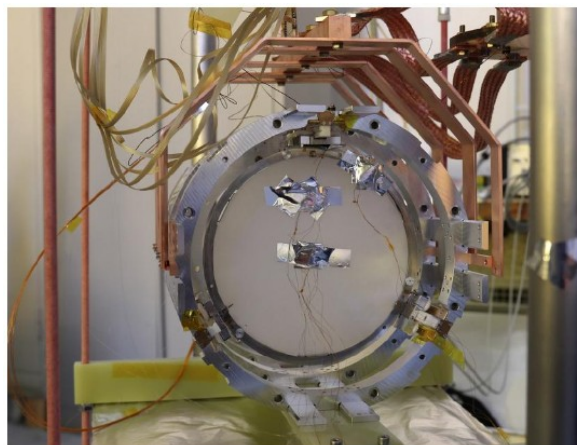
From proto to proof of concept



What is new/different?

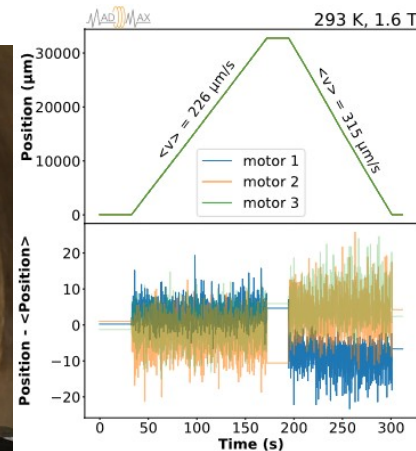
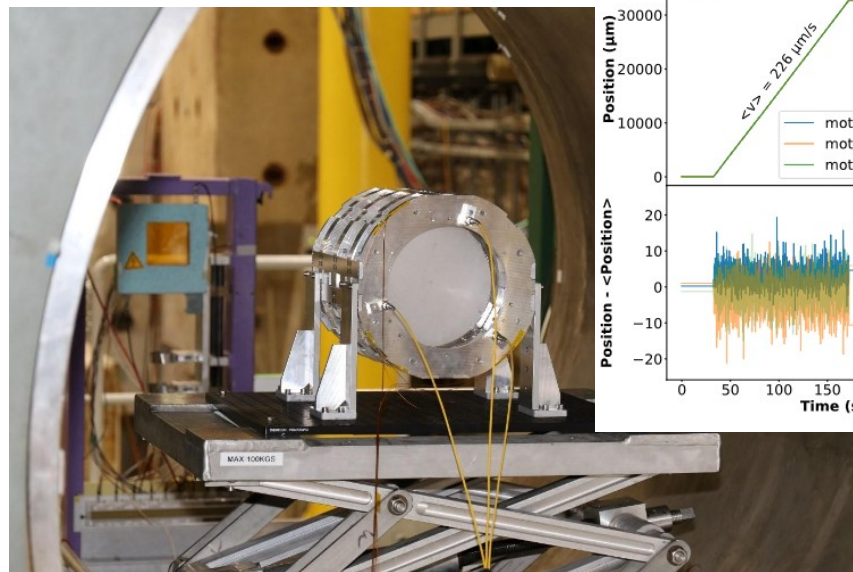
- Disks are bigger (20 cm to 30 cm) → need a new cryostat
- The structure of the signal pipe straight to bended → parabolic mirror
- Closed booster → open booster (challenge to couple with environment)
- Fixed disks → tunable moving disk (motors and positioning system available at cold)

Closed Booster 200 mm (CB200) to Open Booster 300 mm (OB300)



- Validation of the piezo motors in MORPURGO 1,6T magnet

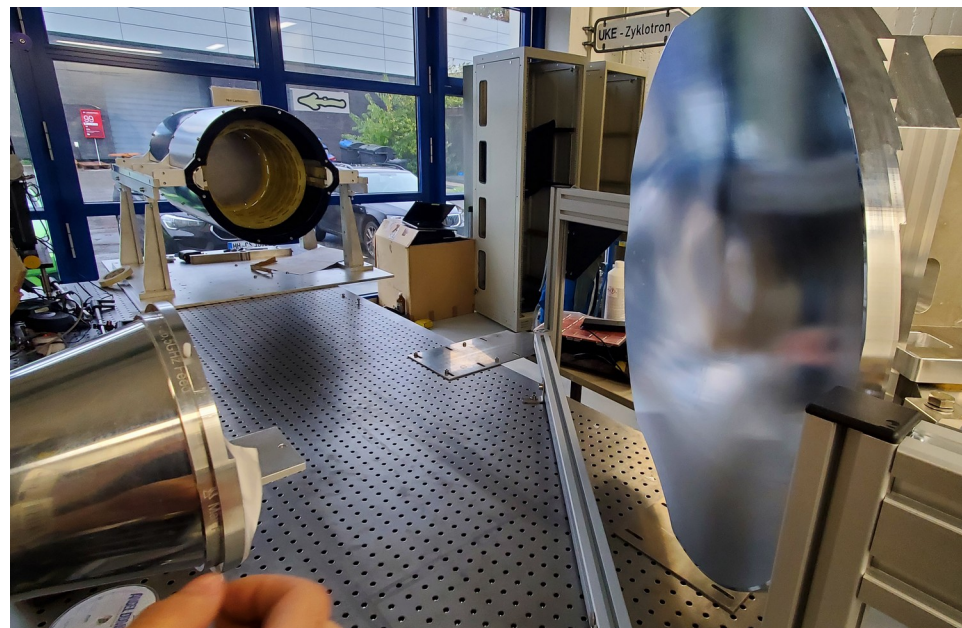
- Validation of the piezo motors at cold in a cryostat designed by CERN cryolab



Closed Booster 200 mm (CB200) to Open Booster 300 mm (OB300)



New cryostat at UHH dedicated to MADMAX

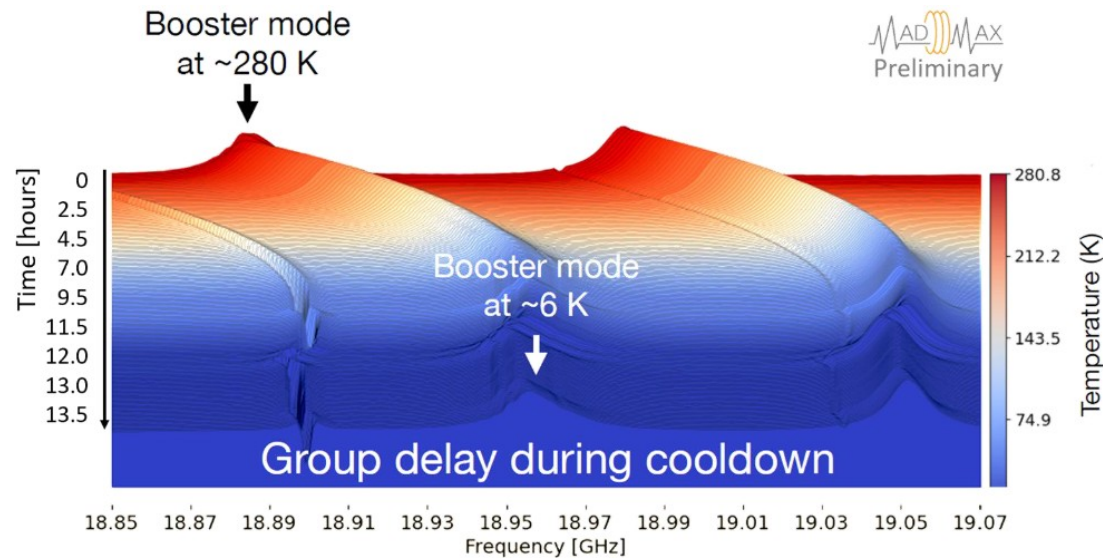


Open booster configuration tested and absorbers implemented

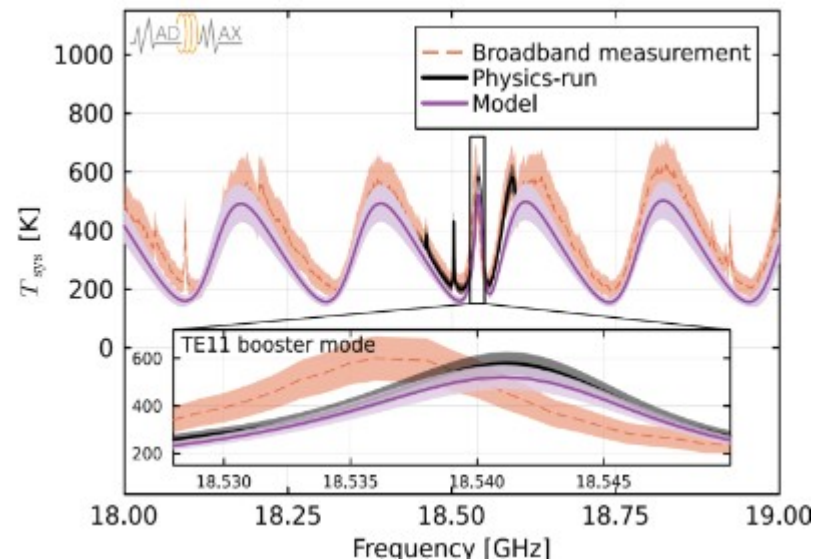
Conclusion

- MadMax collaboration : 20 researchers in France, Germany, US
- Local team : 3 permanent researchers (T.Houdy, Y. Kermaidic, A.Miyazaki)
- Joined the collaboration MADMAX in Dec 2023 with visible contributions on prototype data analysis and absorbers
- Collaboration is now assembling in Hamburg the OB300 for first cooling and dark photon run
- Next year we will dismount and remount at CERN for axion measurement in MORPURGO
- Challenge will be running at cold (motors, interferometers), characterisation of the boost factor at cold
- Next challenge will be to design a dedicated magnet and to increase the size of the disks

MADMAX booster

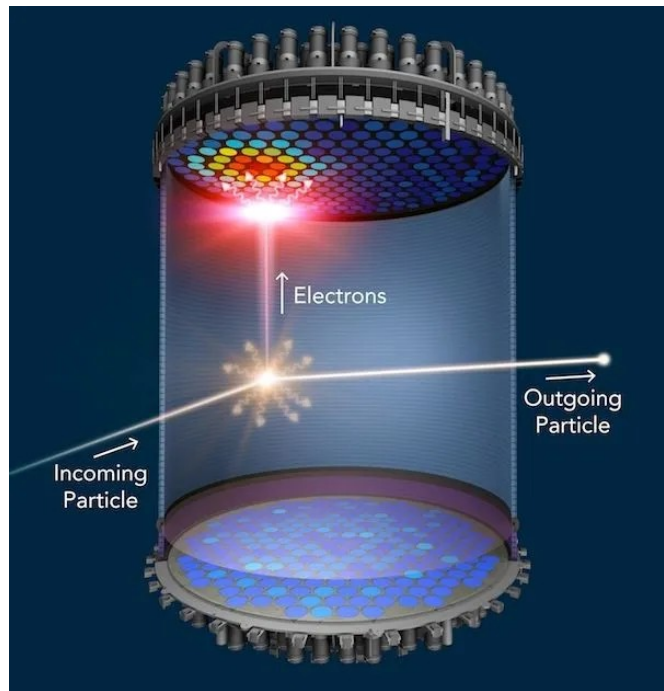


CB100 measurement during cooldown

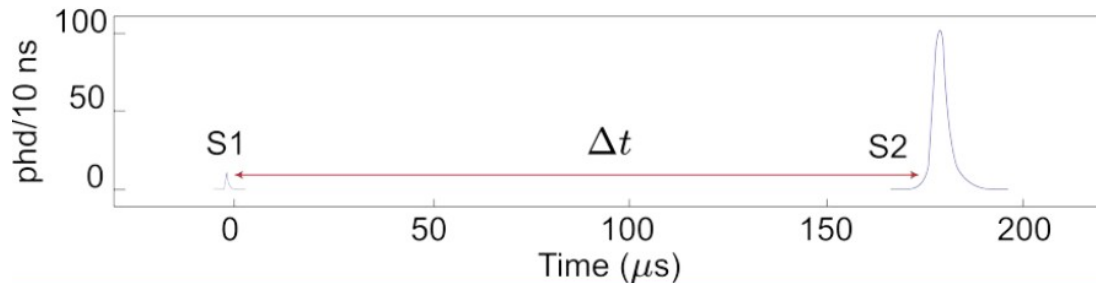
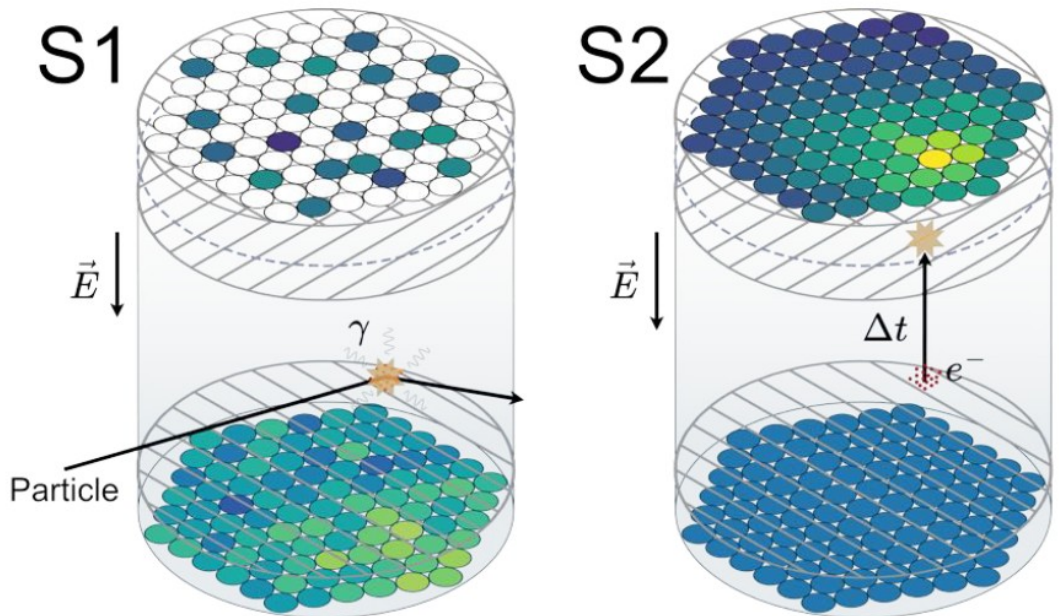


CB200 measurement at room temperature

First light in the dark?



- Collaboration LUX-Zeplin (LZ)
- TPC using 7 t of LXe
- Located at SURF, USA
- 2 signals (S1, S2) and external vetos



From S.Eriksen, TeVPA 2026

First light in the dark?

- A single event – LZ230616 occurred on 16th of June 2023, $248 \pm 23_{\text{stat}} \pm 23_{\text{syst}}$ keV compatible with elastic nuclear recoil of a WIMP
- 26.4 cm from cathode and 26.9 cm from TPC wall
- Unlikely to be neutrino or neutron. Accidental? But far from expected region
- <https://arxiv.org/abs/2609.02823>

