# Understanding the RF response of the MADMAX experiment

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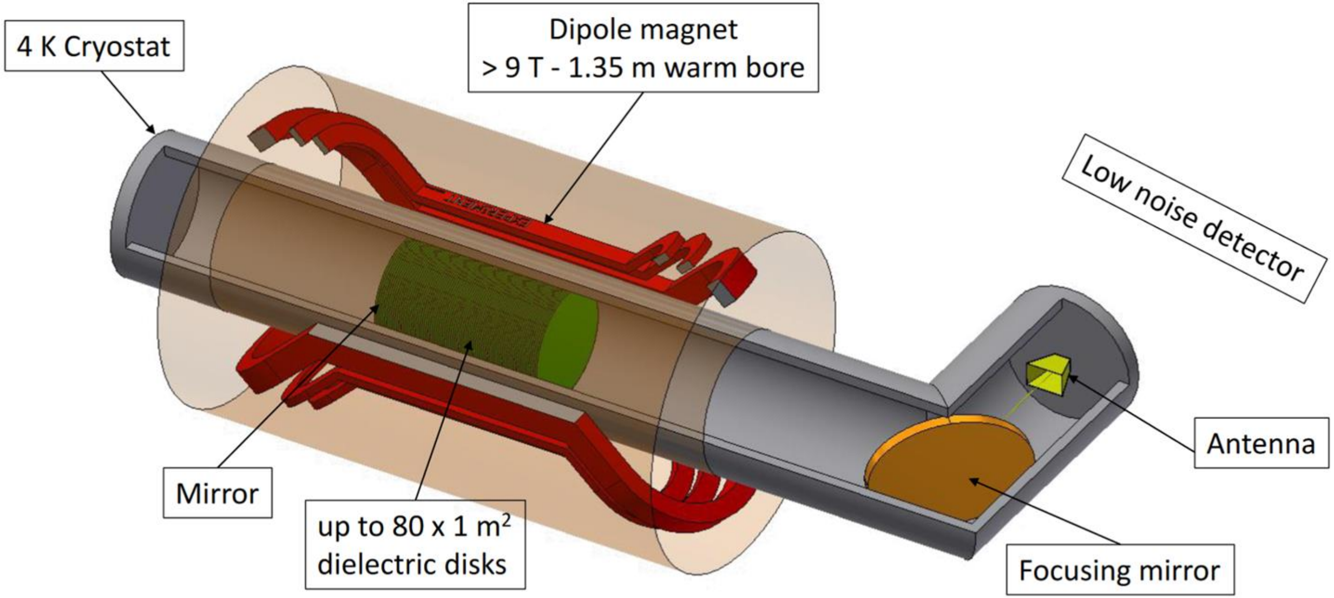
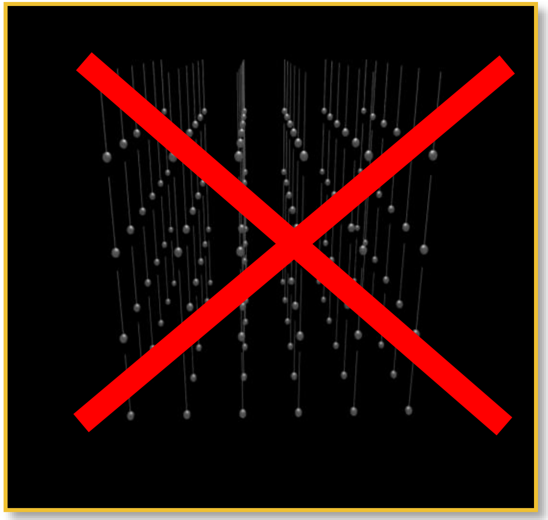
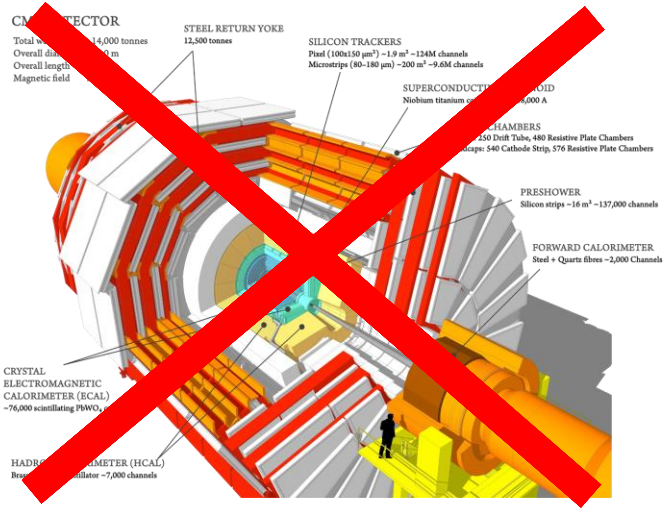
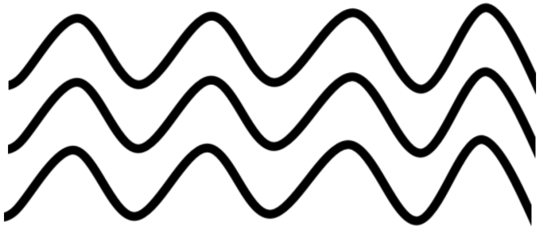
# What is MADMAX ?



# Where are the particles?   What do we measure?



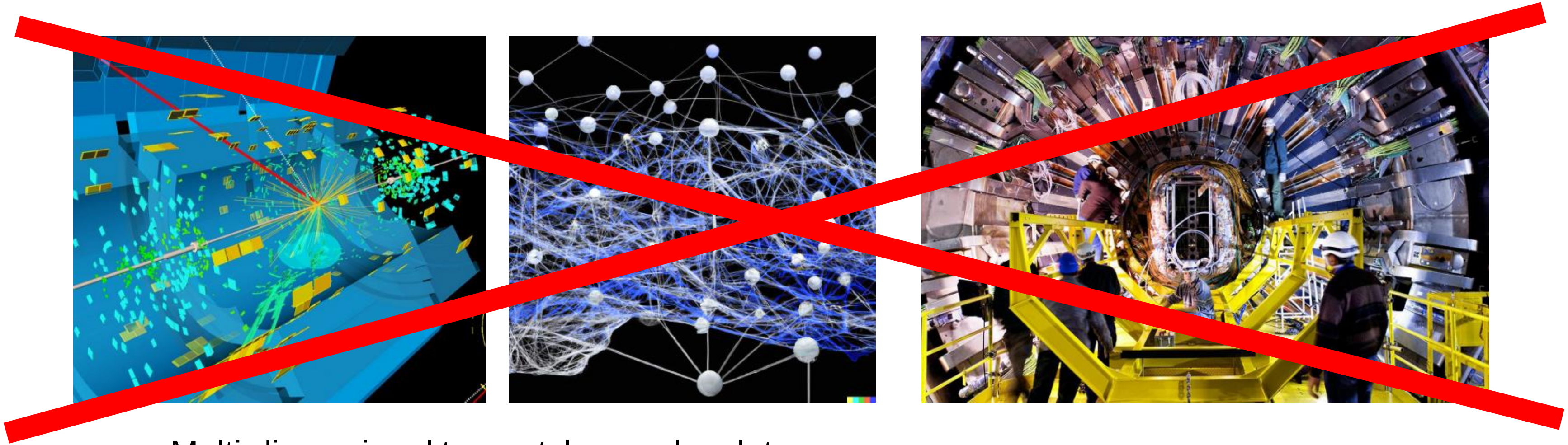


Everywhere!

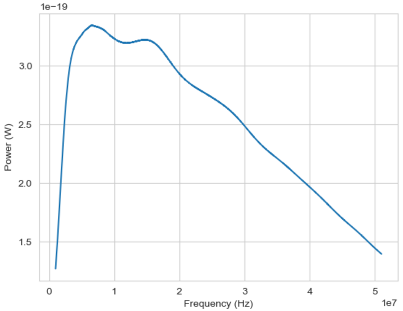

Power

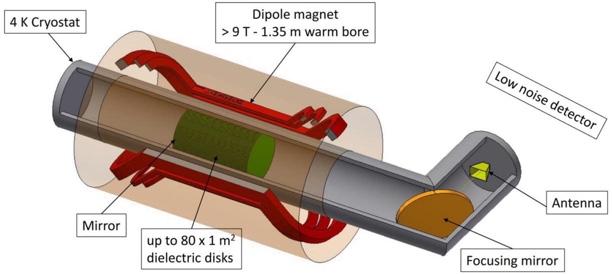
# How do we detect the particle?



Multi-dimensional top-notch complex data acquisition and analysis techniques

Multiple detectors with extremely high precision, sensitivity, and fast response



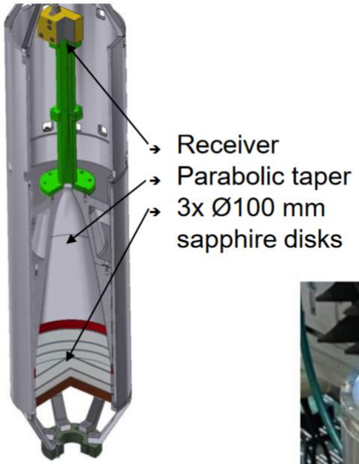



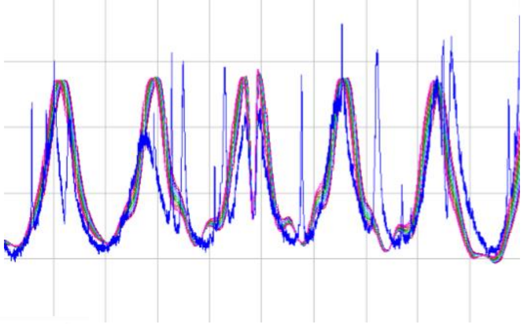

“Doable” data analysis and **outstanding calibration** of our detector!

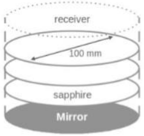
# How to calibrate it?

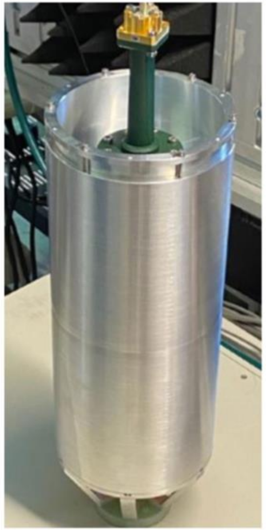
Simulations and **measurements**

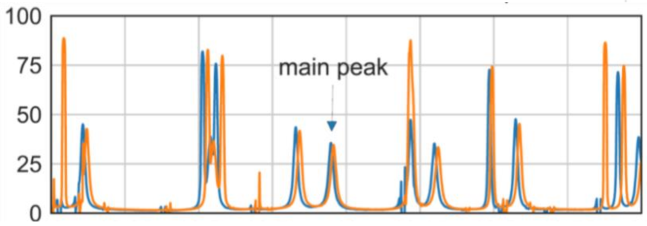
Reflectivity (2)
System temperature (7)



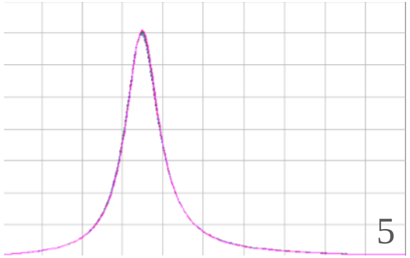





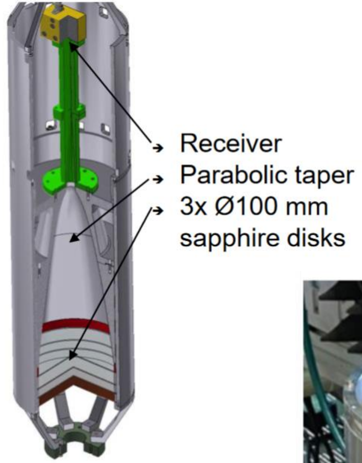



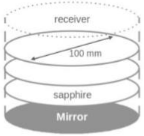


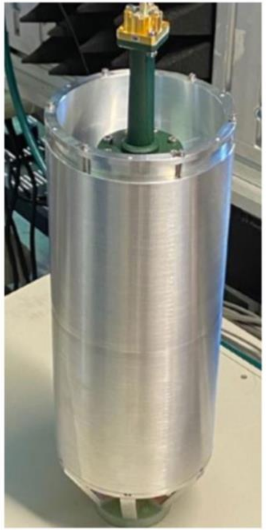

$\beta^2$ = something



# How to calibrate it?



Simulations and **measurements**

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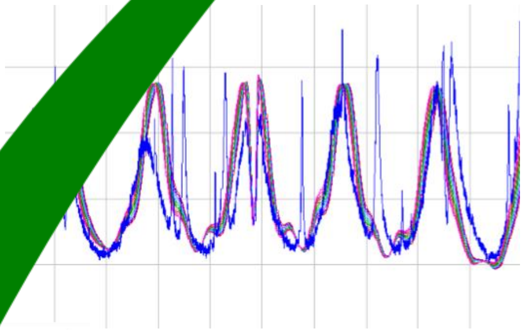
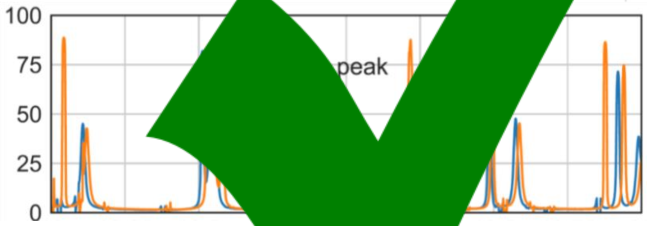
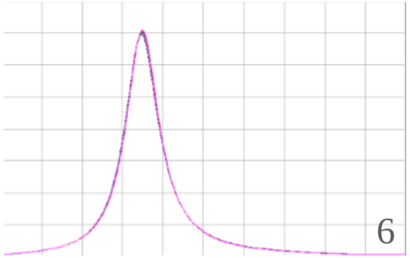
System temperature (7)






β^2 = something

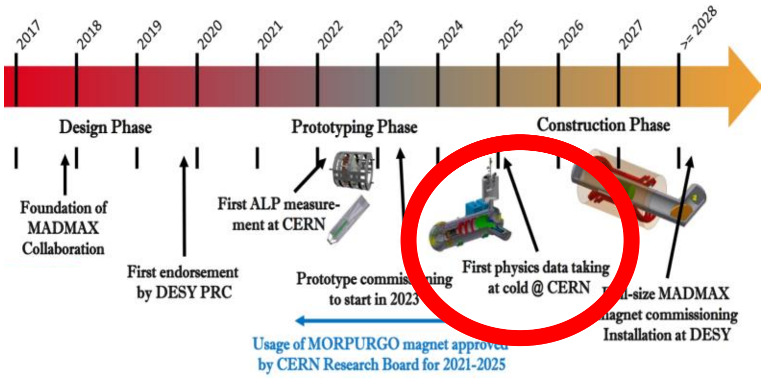


# Now at 4K

1. Insert the device in a cryostat and cool it down with liquid helium until it reaches thermal equilibrium (couple of days)
2. Measure the parameter of interest (15 minutes)
3. Extract the device and wait for it to warm up (couple of days)
4. Repeat for the other 8 measurements

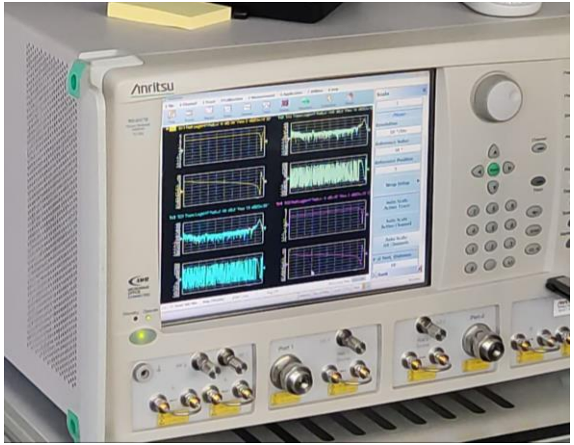
Total time required ~ 1 month

…. and if something went wrong?

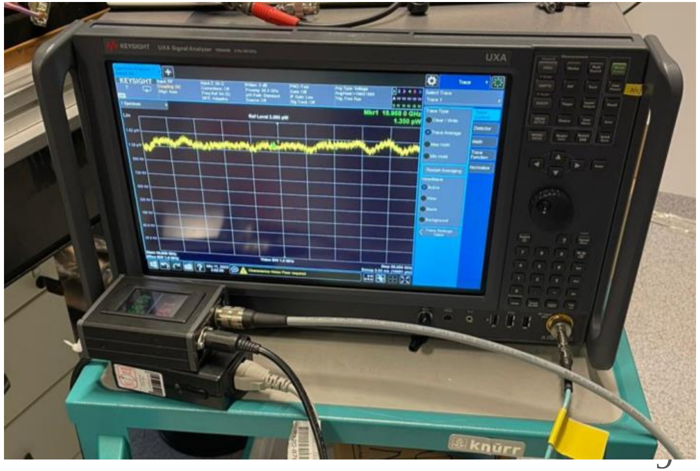


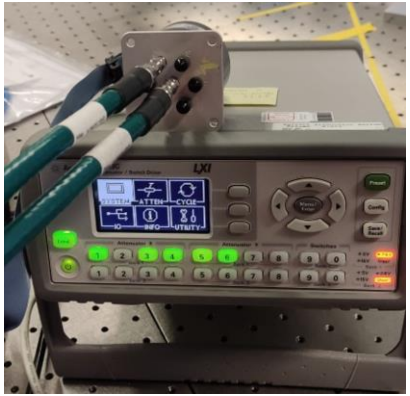

- Room temperature setup is different from the 4K setup
- Everything changes with temperature, and at these frequencies, you notice!
- Cables and calibration standards are not designed for 4K
- Few commercial cryogenic parts above 10GHz
- Temperature gradient of cables
- Calibration can degrade with time

# Approaching the problem

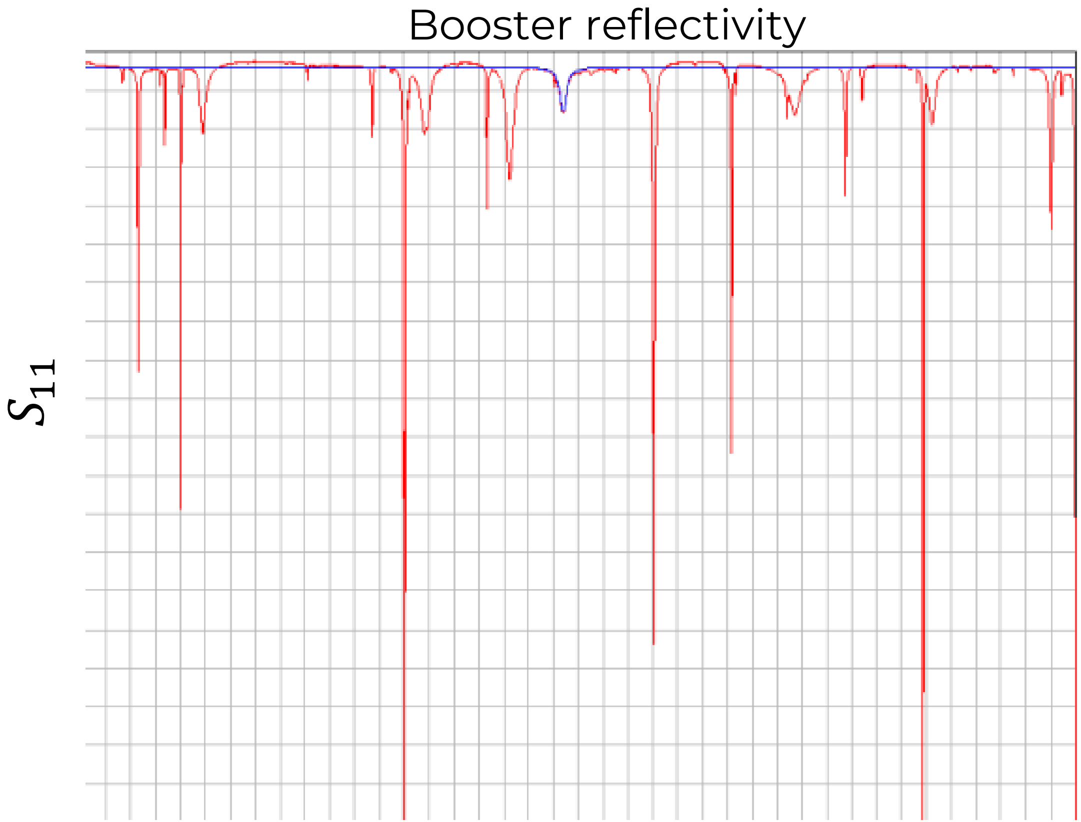



- Understanding how a VNA and a SA work
- Measurements at room temperature
- Effect of cooling down to 77K, 4K
- Study and maximize the stability of a switch at room temperature
- Evaluate **if and how** a switch could be introduced at 4K and obtain reproducible results



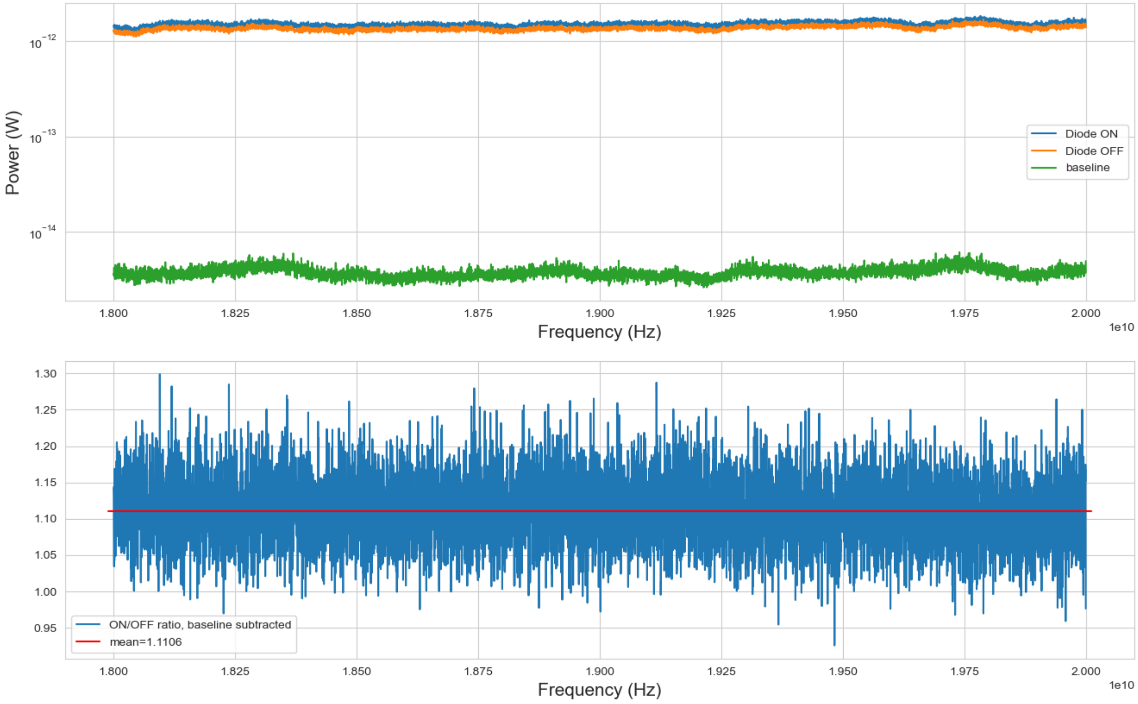
# Understanding and measuring with the VNA



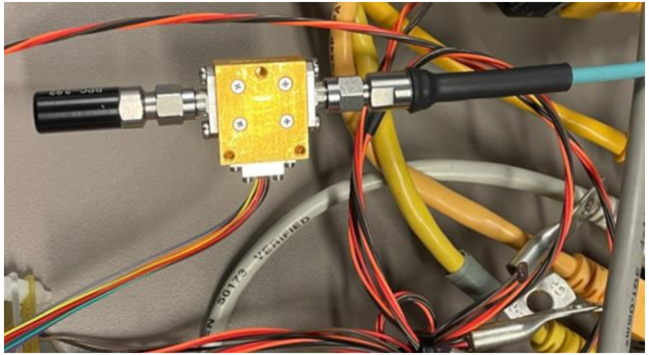

Credits: Olaf Reimann,

To be changed with my measurements this week

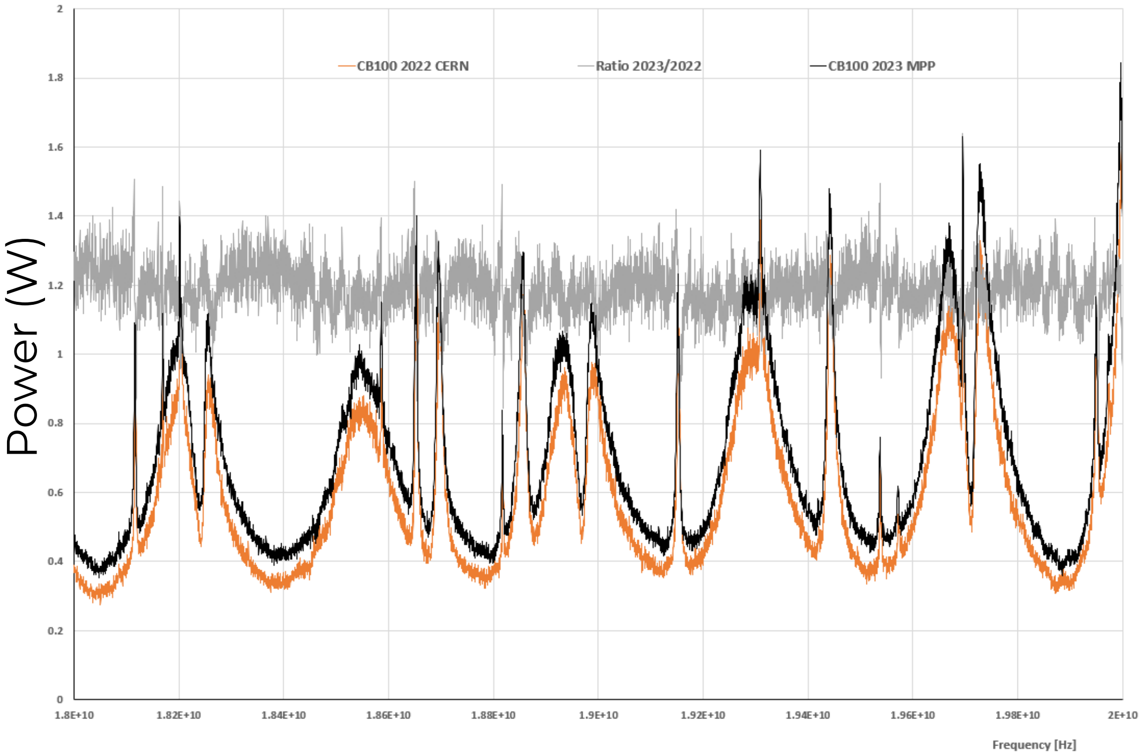
# Understanding and measuring with the SA



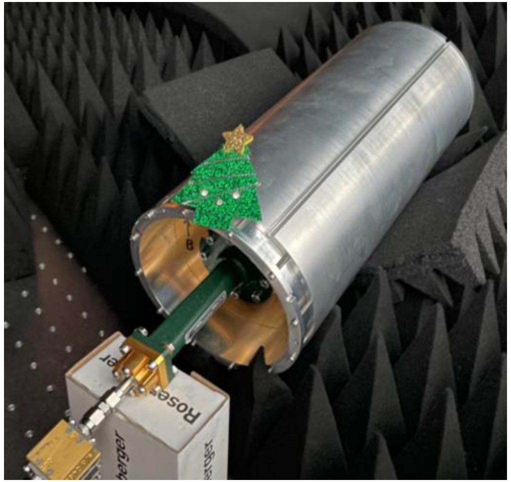

- What? Diode noise ON/OFF, load
- Why? Determination of noise temperature
- How?:



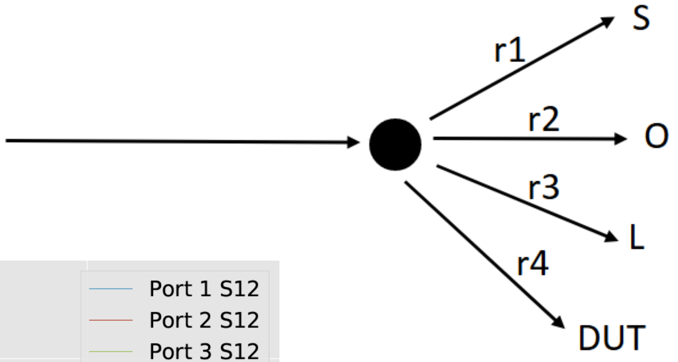
# Understanding and measuring with the SA

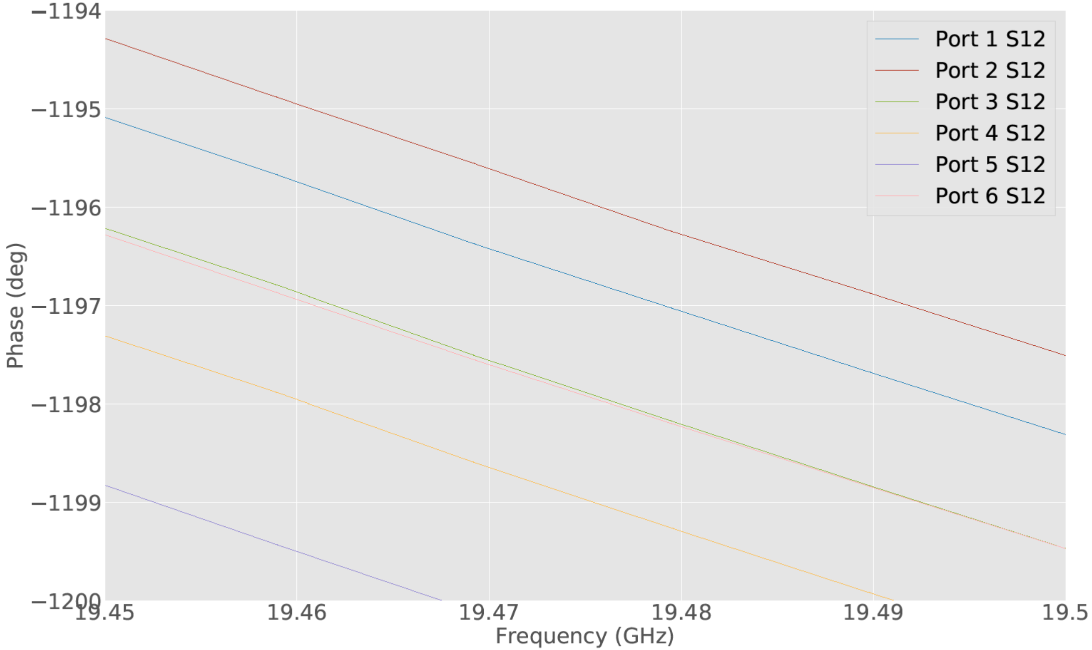



- What? Booster noise temperature
- Why? Understand power emission
- How?:



# Switch at room temperature



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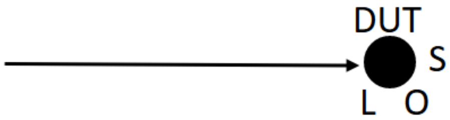
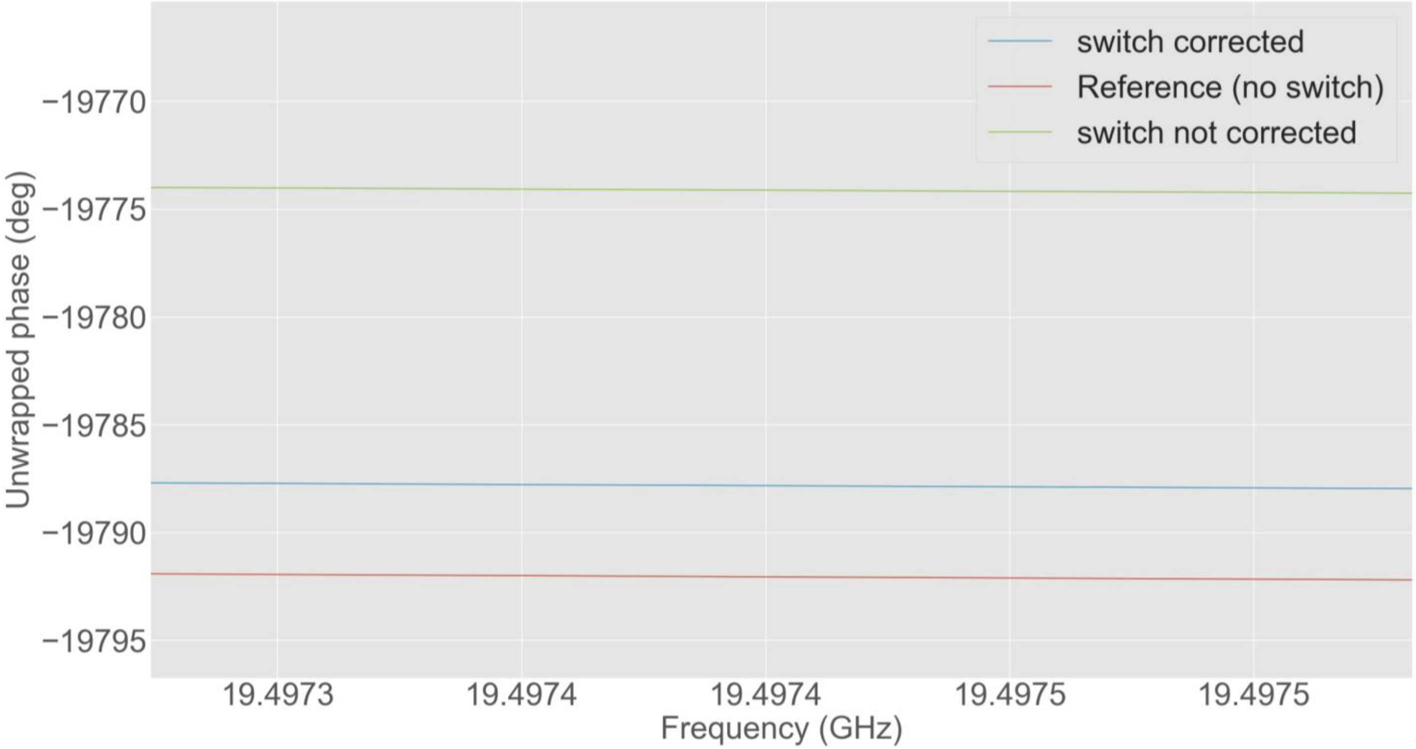
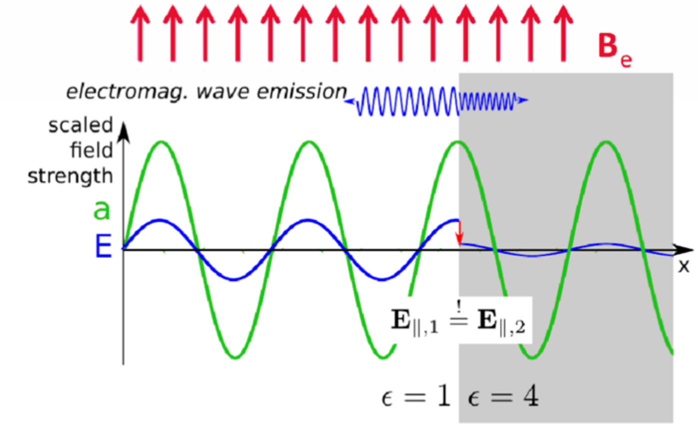


# Summary

- **Understanding the RF response of MADMAX is fundamental** to maximize its sensitivity and axion detection capability
- CB-100 has been well understood **at room temperature**
- Vector calibration > 10 GHz, 4K **is an original challenge**. Active research is on going in quantum optics
- A **cryogenic** In-situ **calibration** is the **critical path issue** for all future MADMAX detectors.


Backup



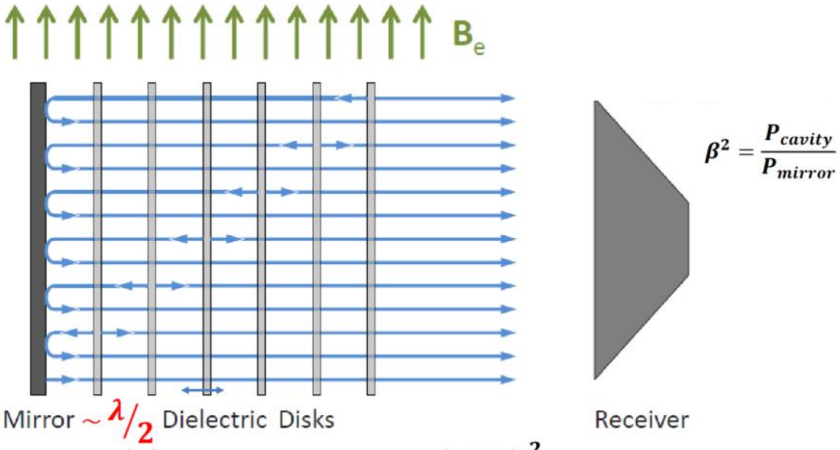

In an external magnetic field $B_e$ the axion field $a(t)$ sources an oscillating electric field $E_a$

$$E_a \cdot \epsilon \sim 10^{-12}\ \mathrm{V/m} \text{ for } B_e = 10\ \mathrm{T}$$

$E_a$ is different in materials with different $\varepsilon$

At the surface, $E_\parallel$ must be continuous
→ Emission of electromagnetic waves

Credits: The MADMAX Collaboration

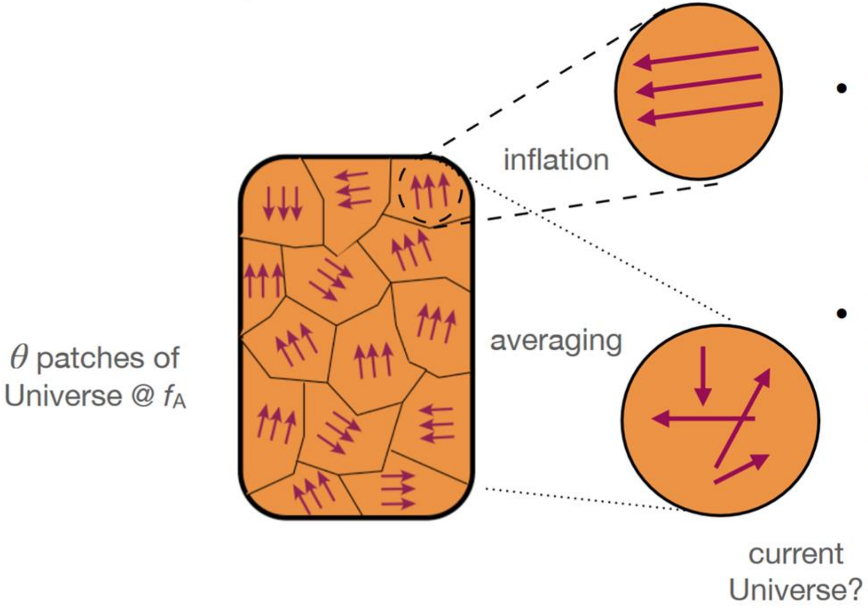



$$\left(\frac{P}{A}\right)_{cavity} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{\parallel}}{10\ T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2 \beta^2$$

# Why post-inflationary axions?

Credits: The MADMAX Collaboration

**Post-inflationary axion DM mass**




- Pre-inflationary scenarios allows much wider $m_a$.
- Post-inflationary production prefers $m_a$ : 40 – 180 $\mu$eV.

Buschmann *et al.*,
Nat. Commun. 2022

# Why are the axions treated as classical waves?

- CDM axions behave like a classical wave, e.g. $m_a$ = 100 μe\
  - 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

Credits: The MADMAX Collaboration