MADMAX-Toward a dielectric haloscope

Novel detector for post-inflationary axion dark matter

Chang Lee on behalf of the MADMAX collaboration, Apr. 1st, 2023, UCLA DM

MAX PLANCK GESELLSCHAFT

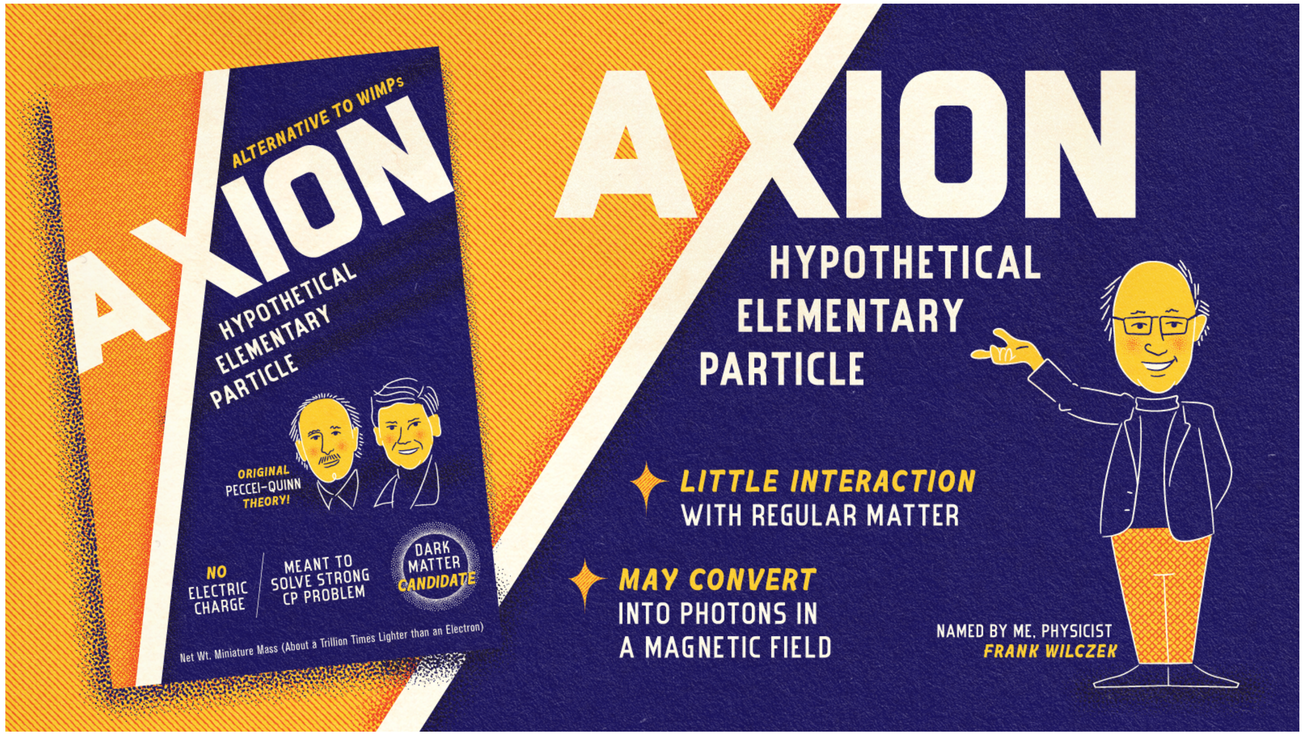
Motivation

QCD axion DM

- PQ symmetry to solve the strong CP problem
  - Spontaneous symmetry breaking @ f_A: axion
- well-motivated wave CDM candidate
  - Non-thermal: cold
  - Small interaction with SM particles.

$$\mathscr{L} = \frac{1}{f_A} J^\mu \partial_\mu \phi, \quad f_A \gg v_{\text{EW}}$$

  - Axion lifetime >> age of the universe.

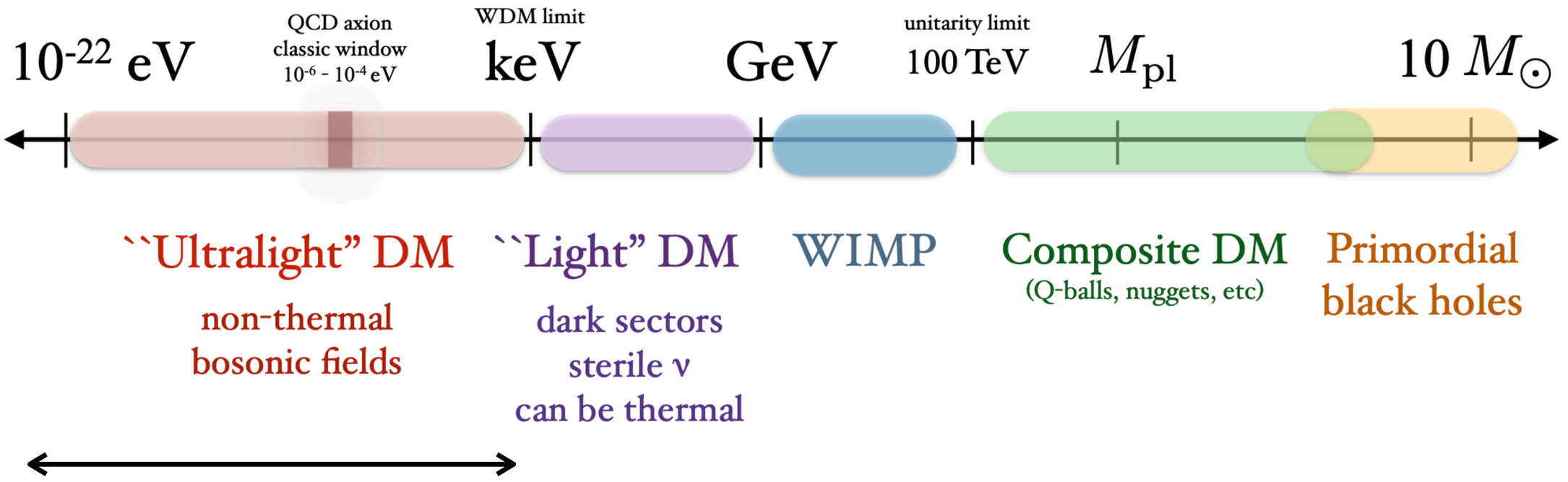


Symmetry magazine

Mass scale of dark matter

(not to scale)

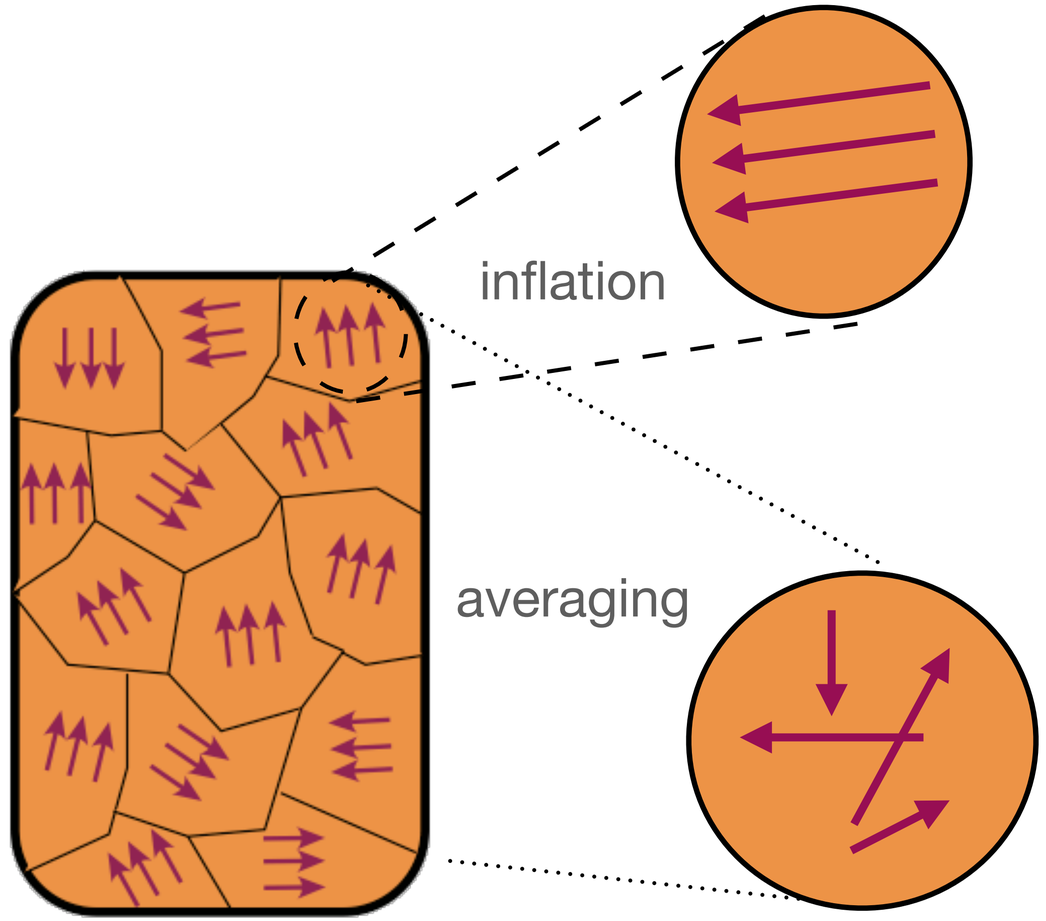
T. Lin 1904.07915



- Extremely large mass range: > 10^{20}!
- Where should we search first?

How heavy axion?

Post-inflationary axion DM mass



- Pre-inflationary scenarios allows much wider m_a.

- Post-inflationary production prefers

$m_a > 28\ \mu\text{eV}$

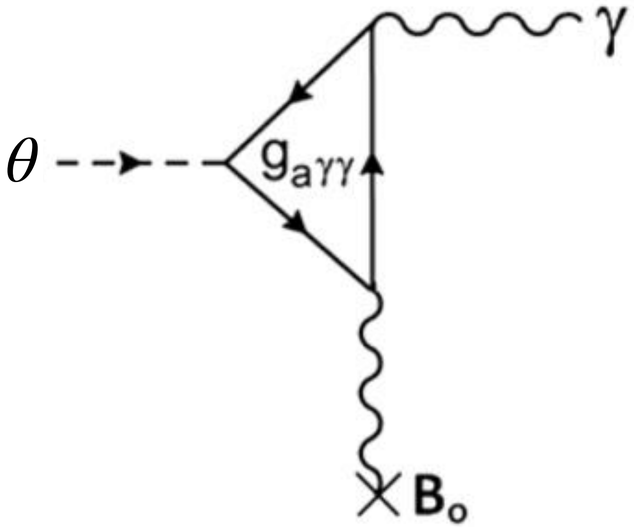
Borsanyi et al., Nature 539 (2016) 7627, 69-71

$m_a : 40 - 180\ \mu\text{eV}$.

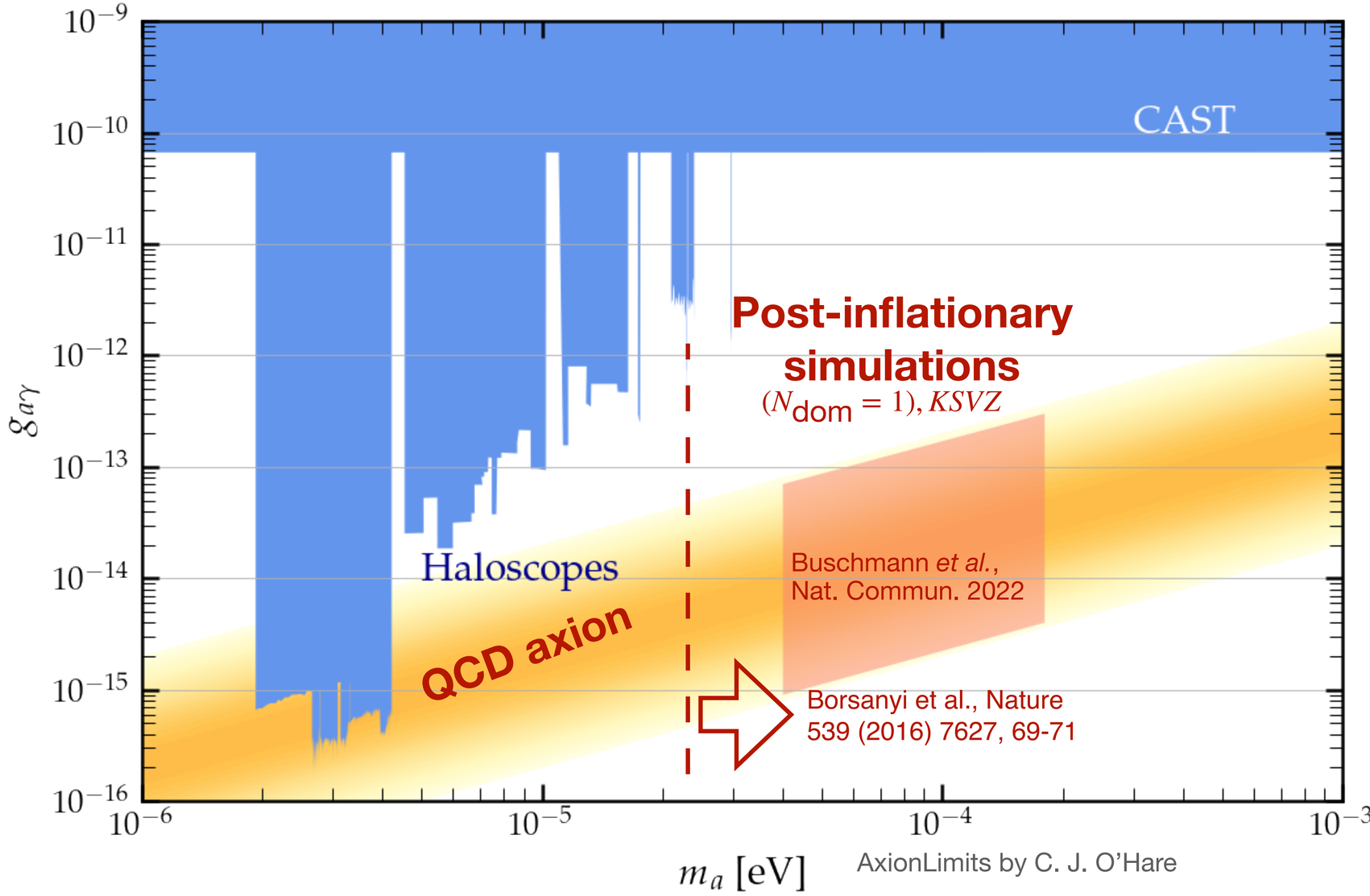
Buschmann *et al.*,
Nat. Commun. 2022

DM axion detection status

axion-photon coupling



- $m_a \sim 100\mu$eV, or $\gamma \sim 25$ GHz.



AxionLimits by C. J. O'Hare

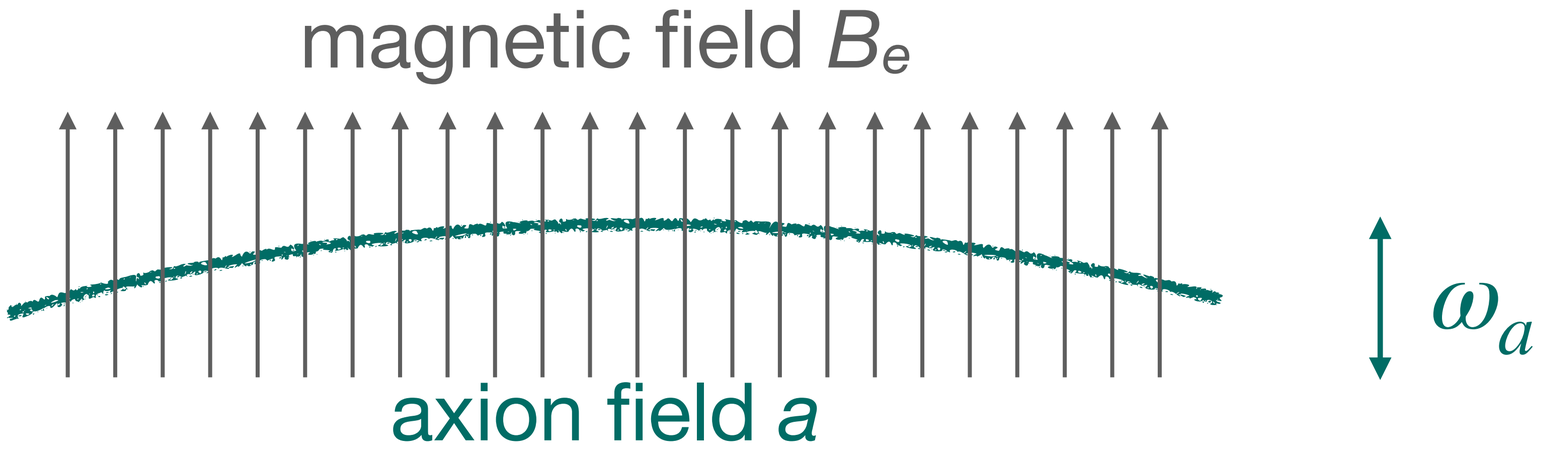
Principle

Principle

Axion-induced E-field

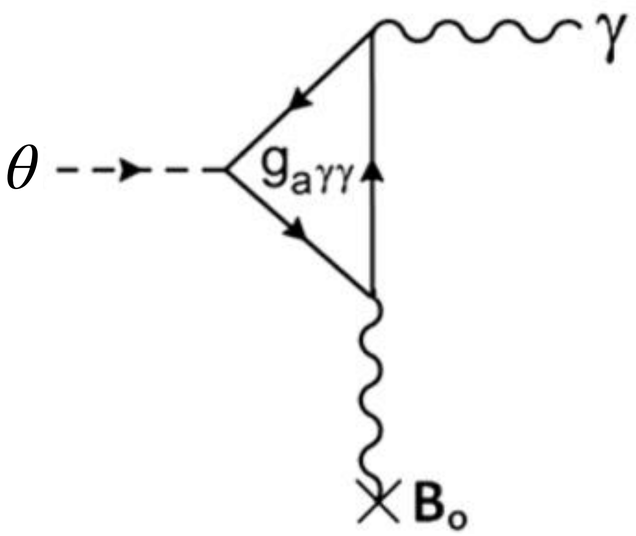
Principle

Axion-induced E-field

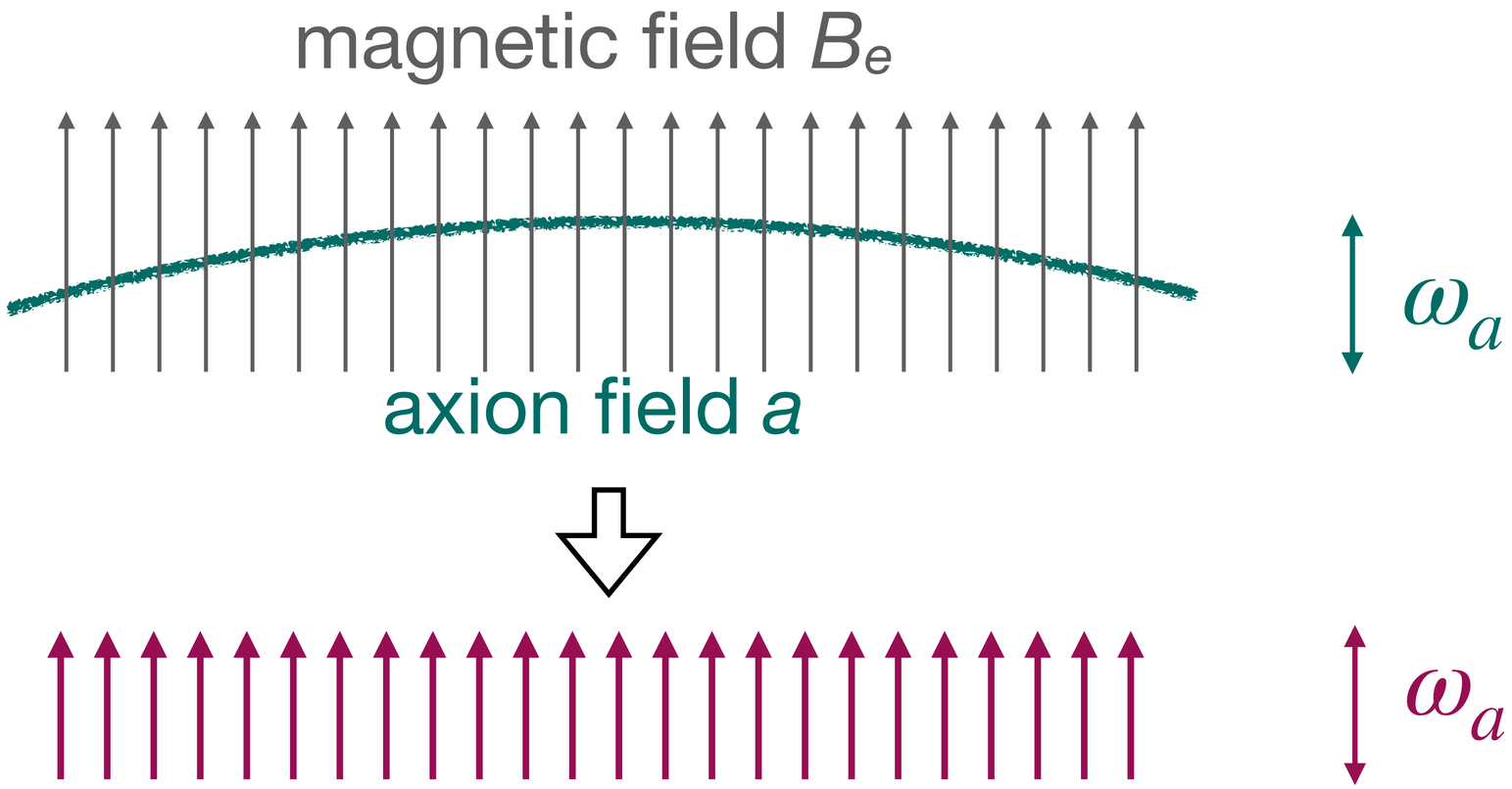


Principle

Axion-induced E-field



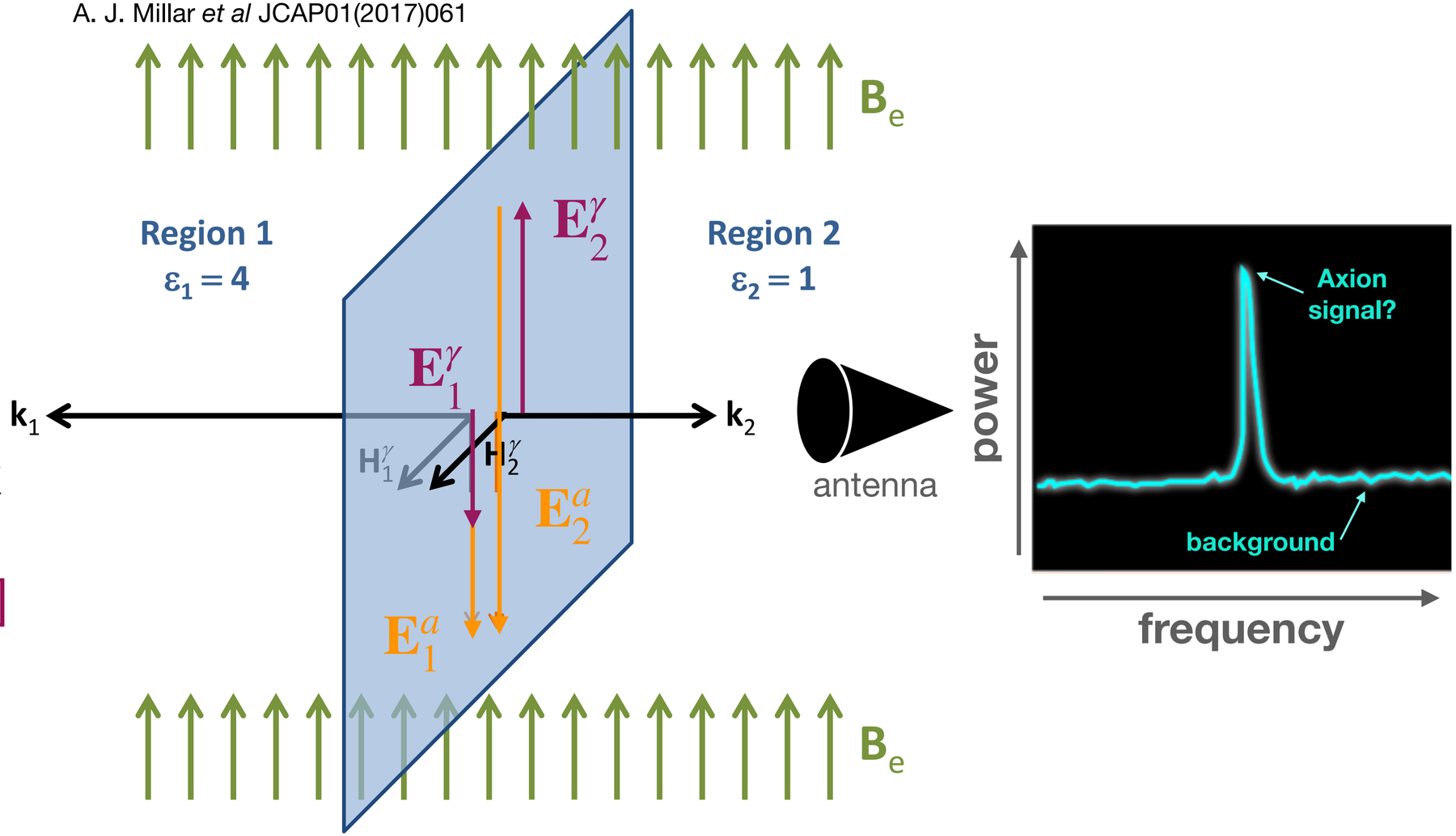
$$E^{\alpha} = -\frac{g_{a\gamma} B_e}{\varepsilon} a$$



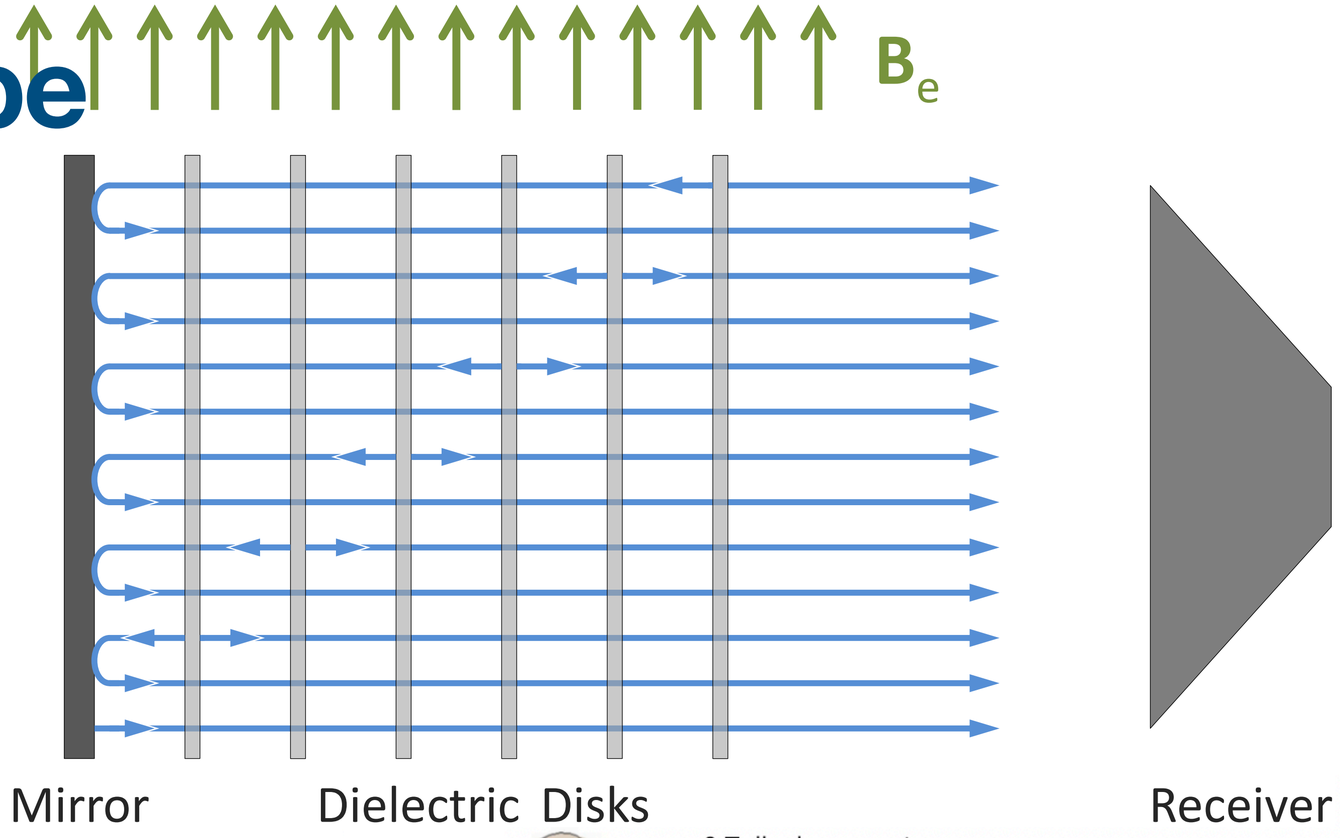
Traveling wave from dielectrics

- At the **boundaries**, different ε produce different E^{α}, and traveling waves are emitted.
- Problem: very weak signal.
  $E^{\alpha} \sim 10^{-13}$ [V/m/T]
  or $P^{\alpha} < 10^{-26}$ W.
  (assuming 1m², 10 T, 20 GHz)

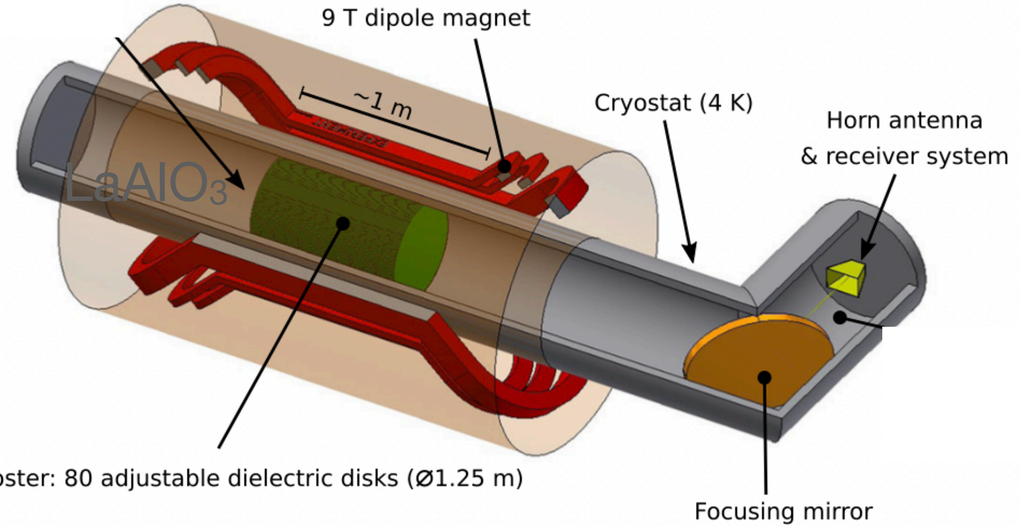
A. J. Millar *et al* JCAP01(2017)061



Dielectric haloscope



- Solution: constructive **interference** of signal from **multiple boundaries**
- Scale-up on transverse dimensions, sensitive to the QCD-axion
- Tuning by moving disks
  - Antenna couples only to the axion mode (ideally)

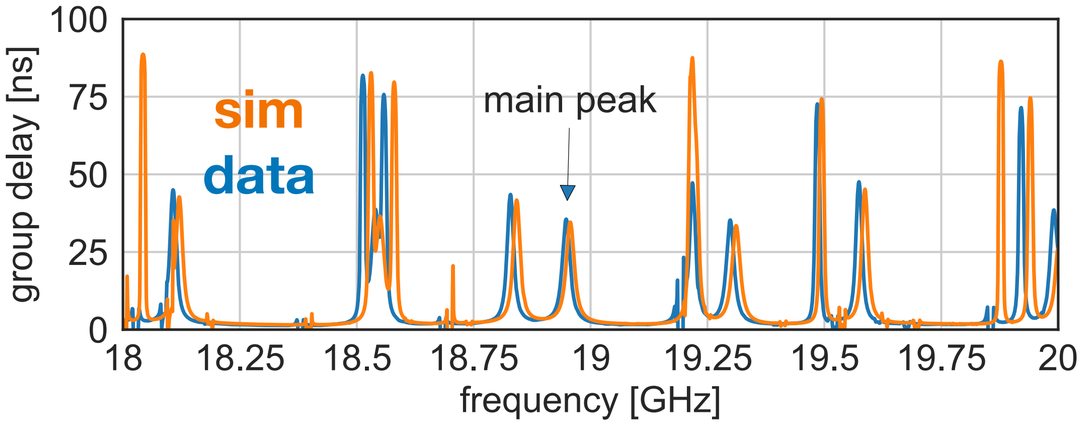


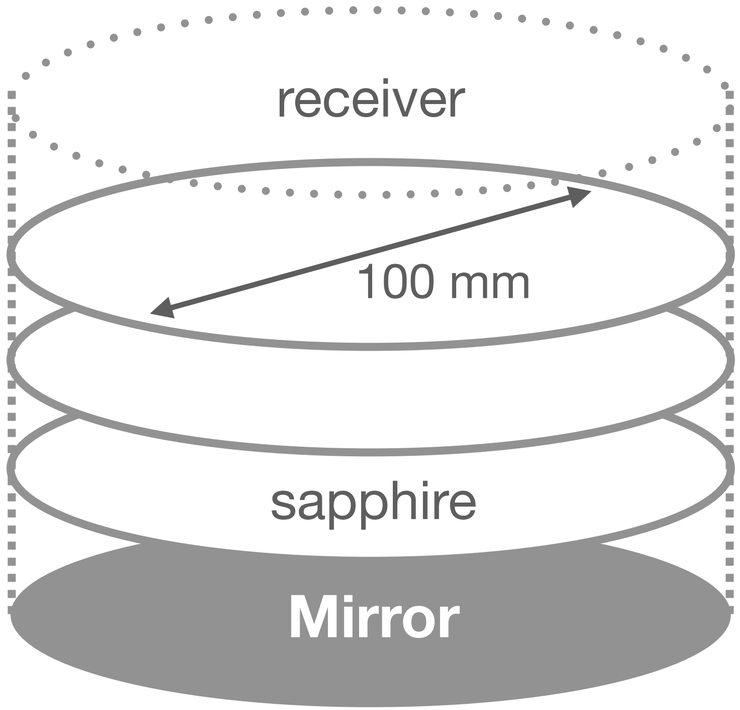
Closed booster

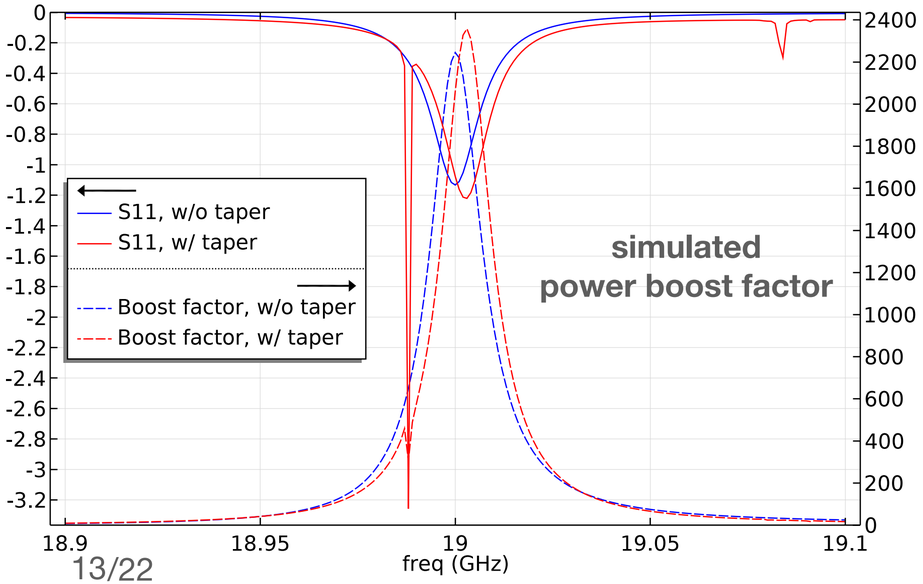
CB-100

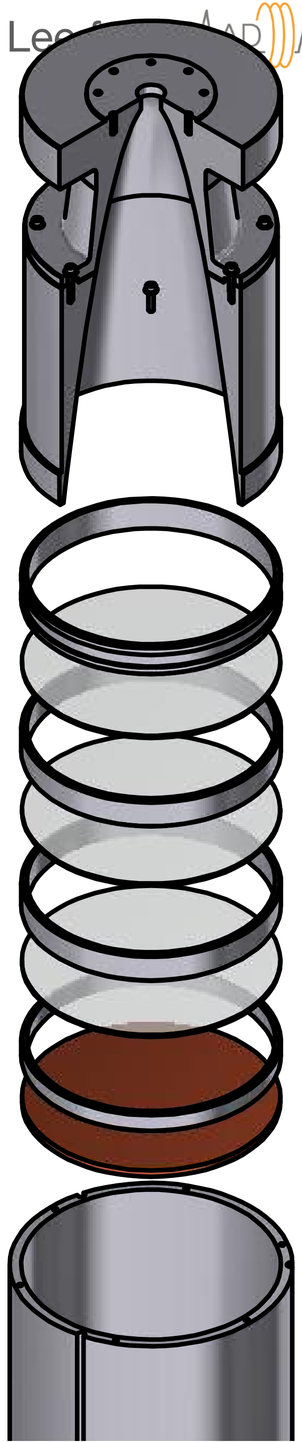
Construction

- A small & simple dielectric haloscope
  - “Closed”: conducting boundary
  - Understand the detector & its noise
  - First ALP DM search
- Measured reflectivity agrees with the simulation





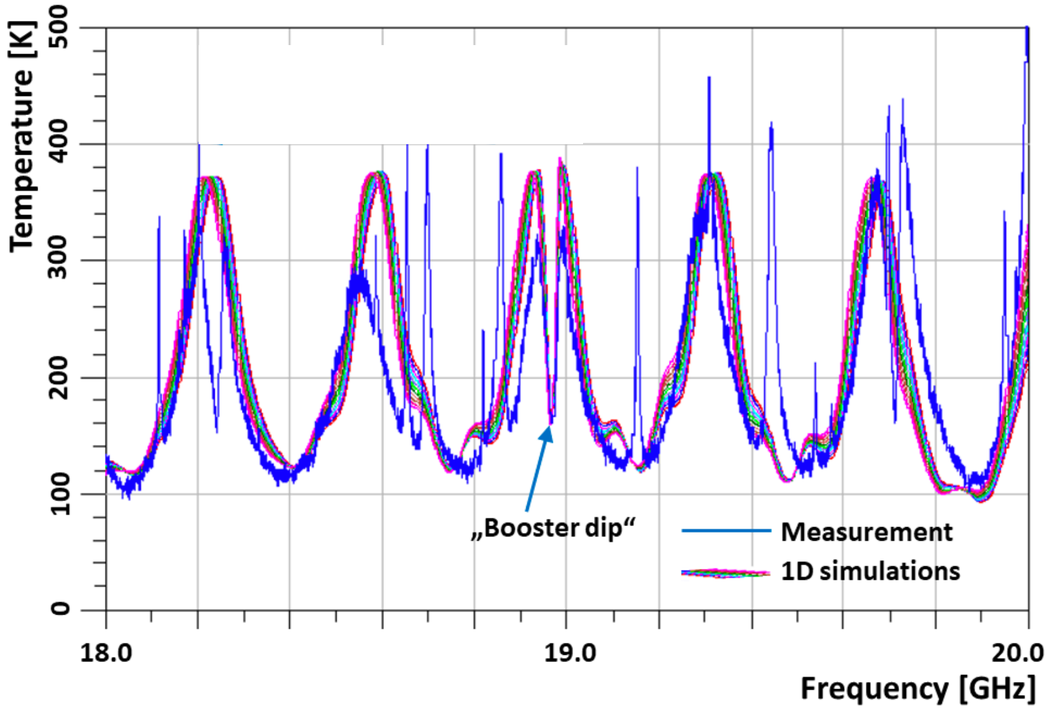


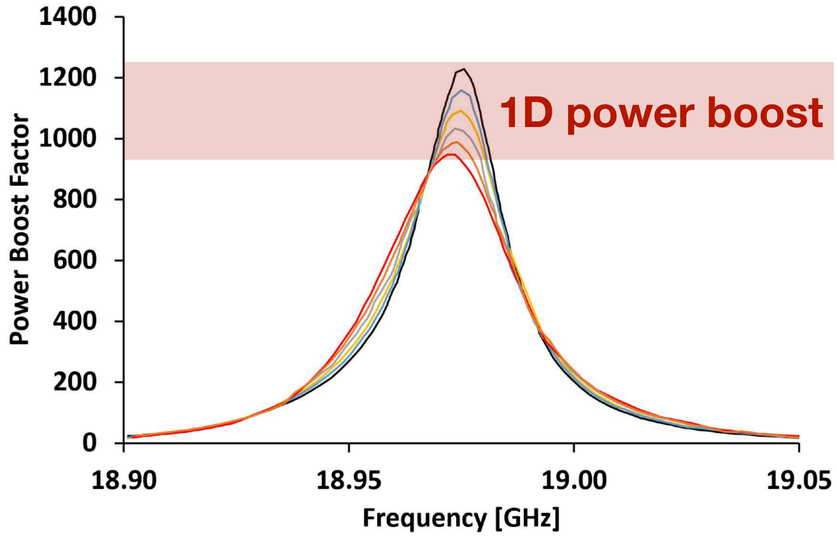


CB-100

Boost factor determination

- Milestone: boost factor determination developed.
  - The boost factor traces the thermal noise.
- Comparison of measurement with the noise model
  - “Oscillating T_{sys}”: noise wave reflects on the detector and interferes with itself.
  - T_{sys} ~ 200 K.
- ~700 power boost factor from the as-built 3D detector.
  (70% of the 1D model prediction)

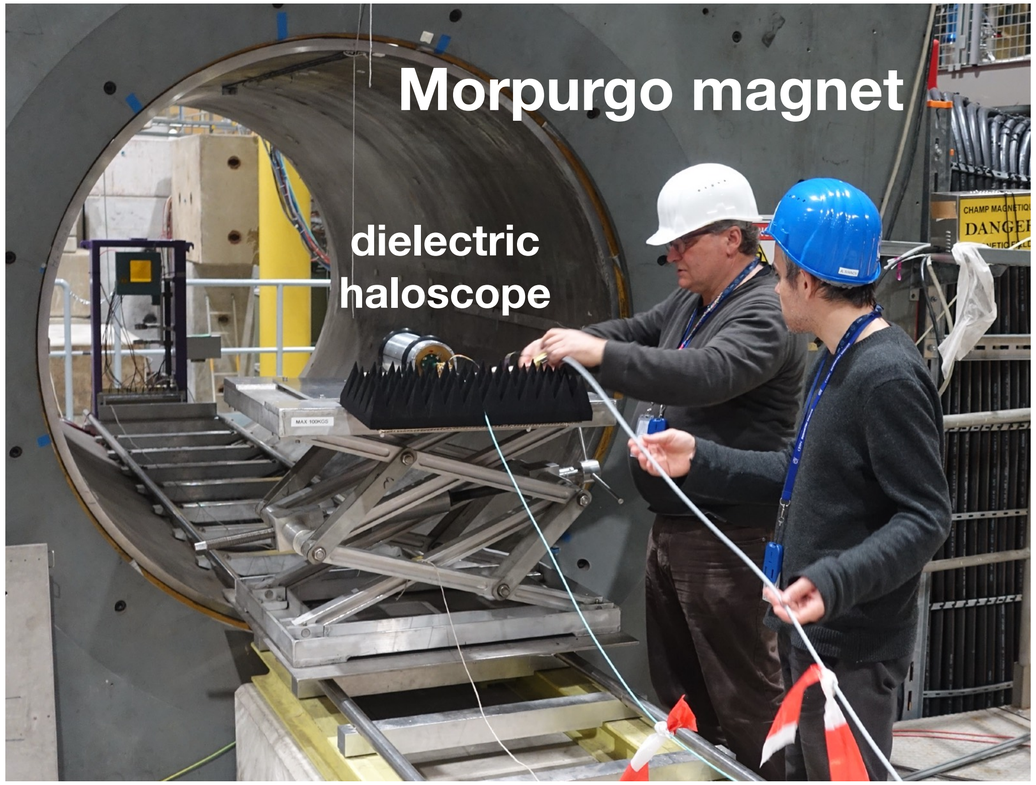


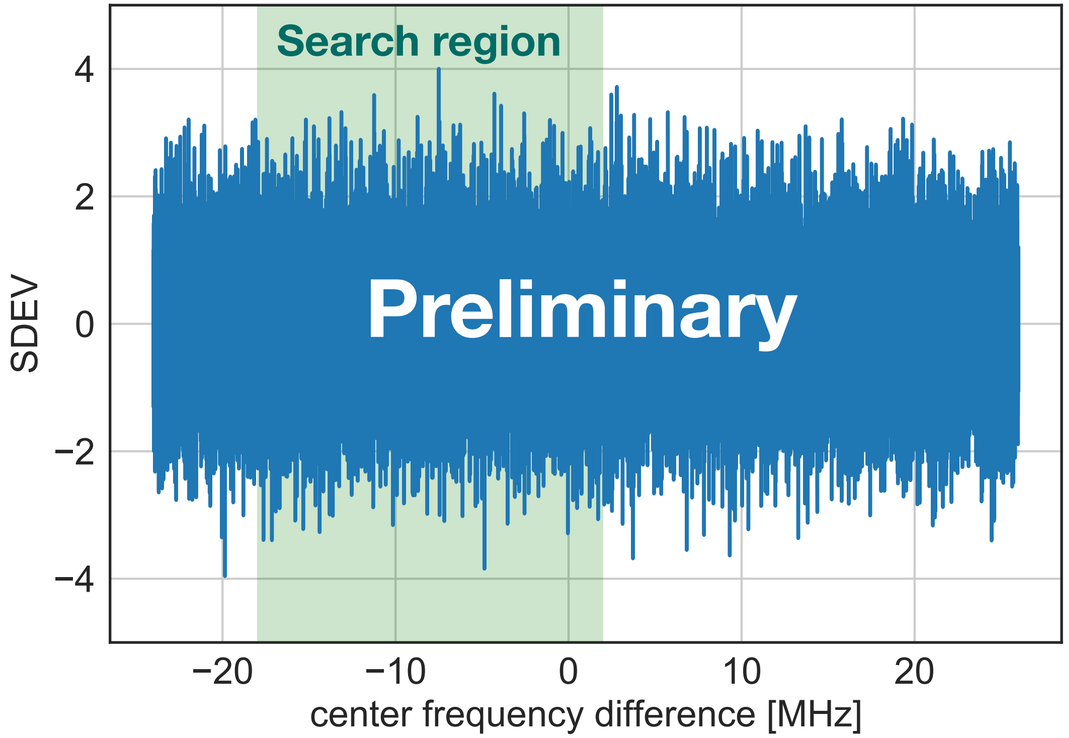


ALP search from CERN's Morpurgo magnet

- MADMAX traveled to CERN to use Morpurgo magnet for ALP search!
  We found no adversary EMI effects

- Planning upgrade with a 4K system.





ALP search from CERN's Morpurgo magnet

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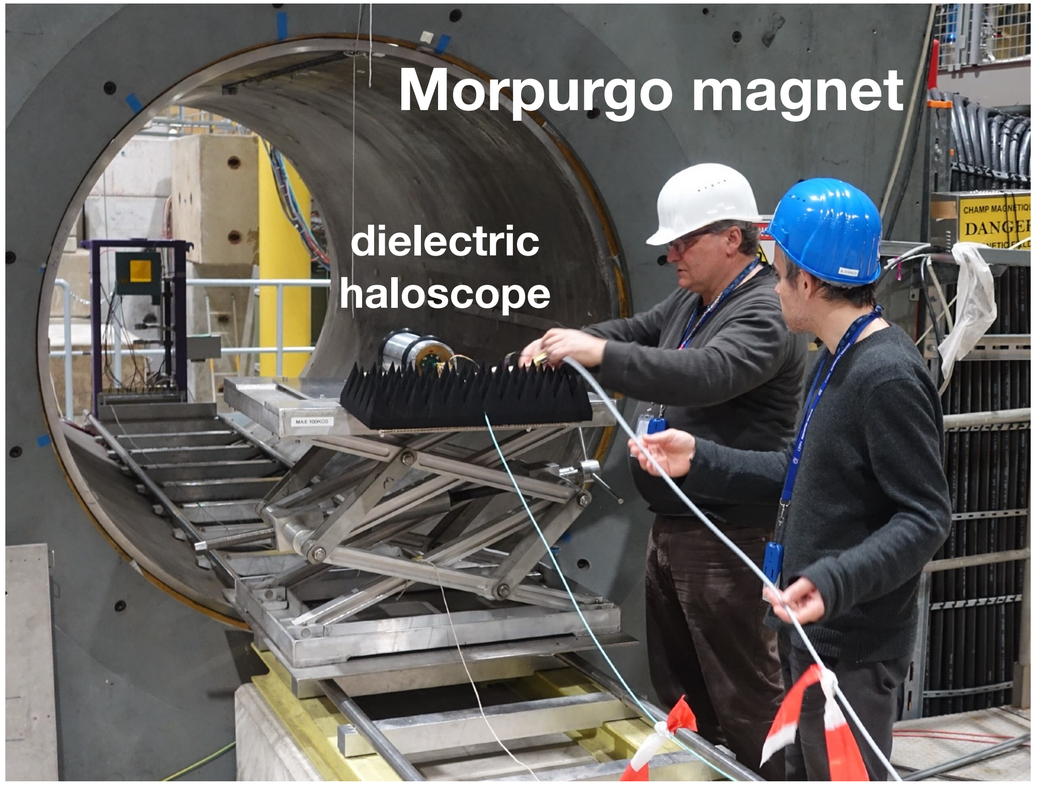
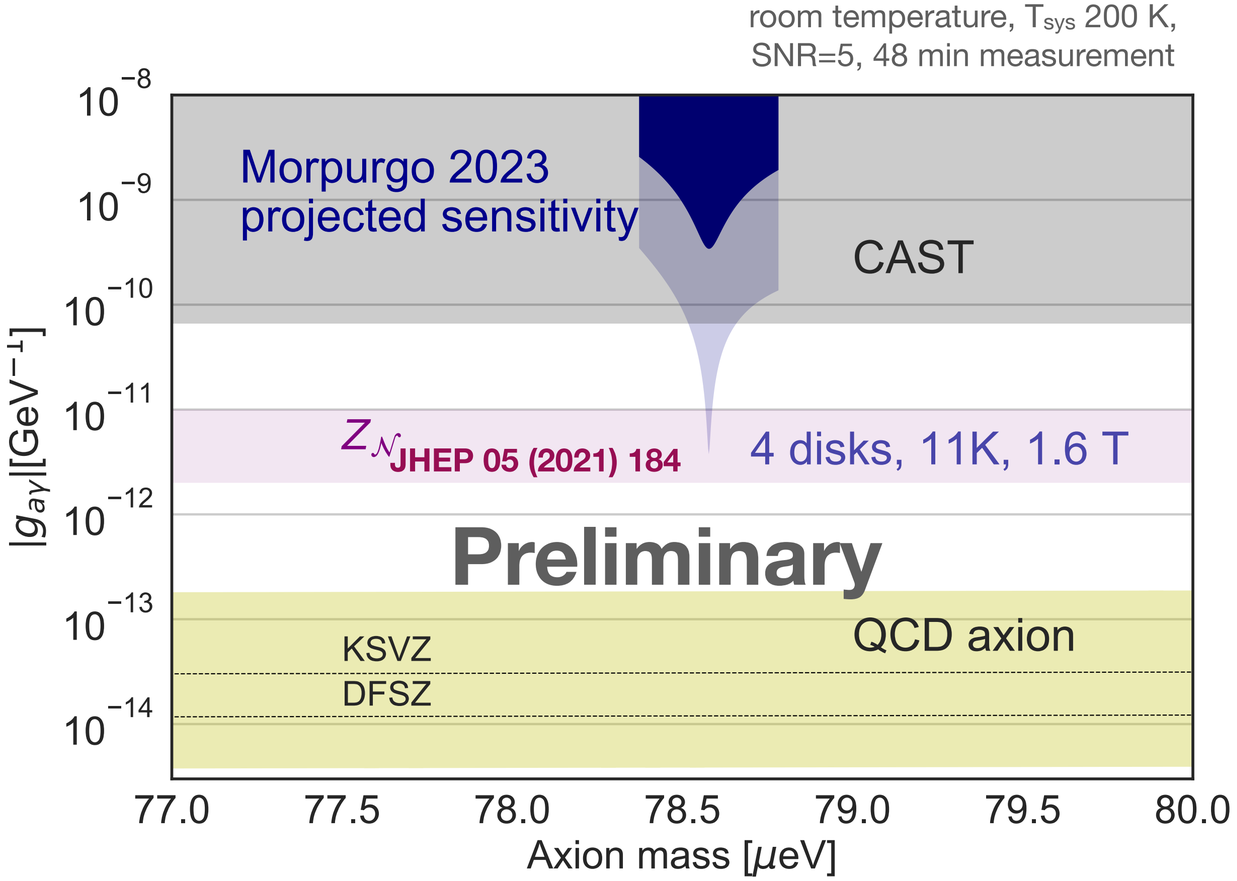
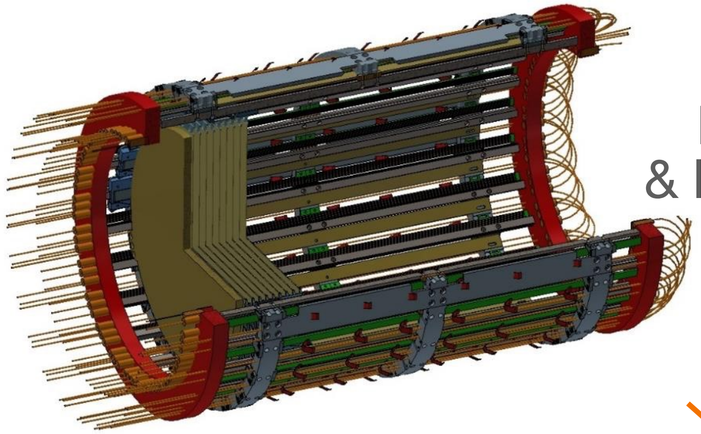
  We found no adversary EMI effects. Expect ~1 hr net @ 1.6 T.
- Planning upgrade with a 4K system.





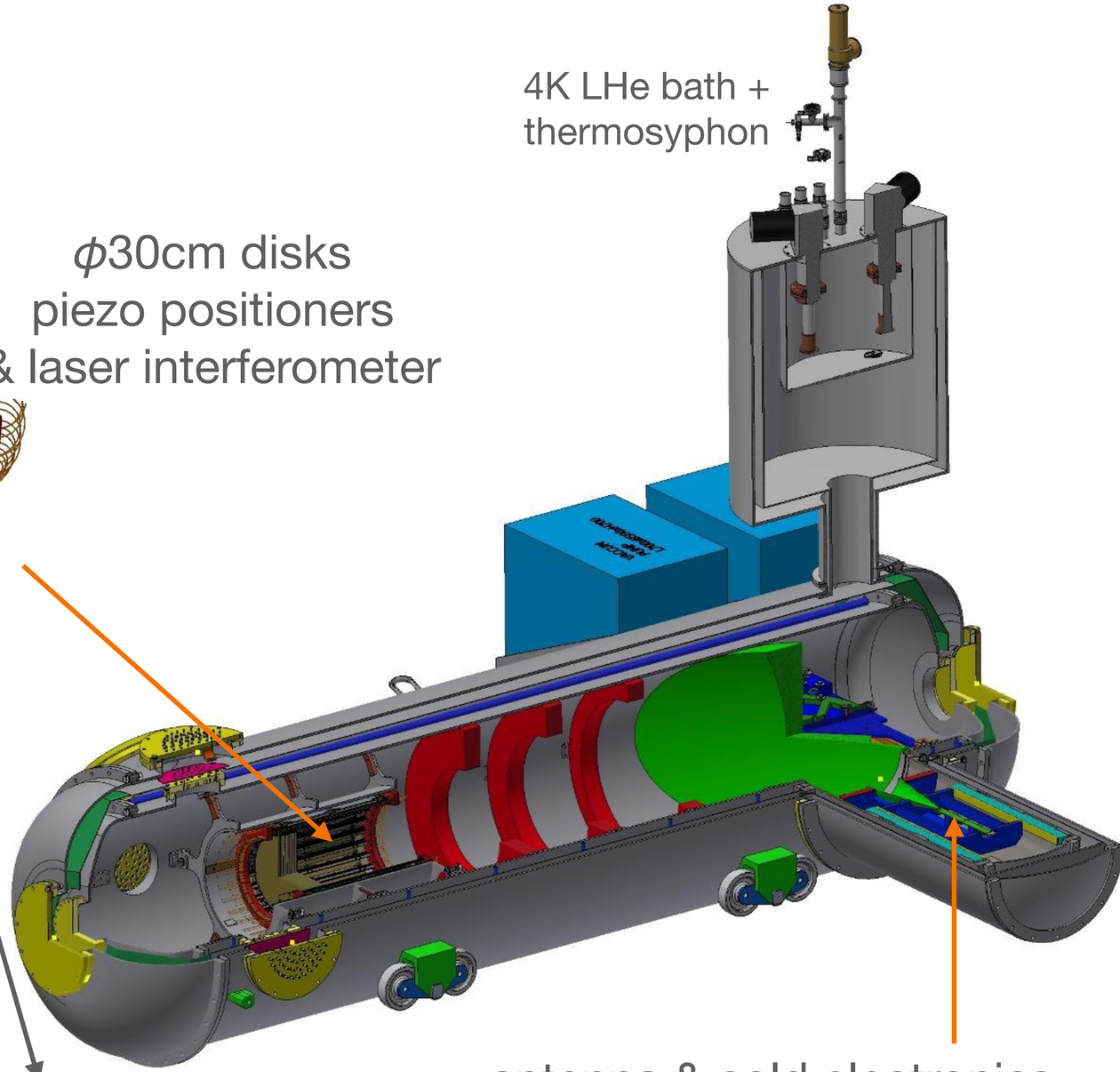
Future

MADMAX prototype



ϕ30cm disks
piezo positioners
& laser interferometer

4K LHe bath +
thermosyphon



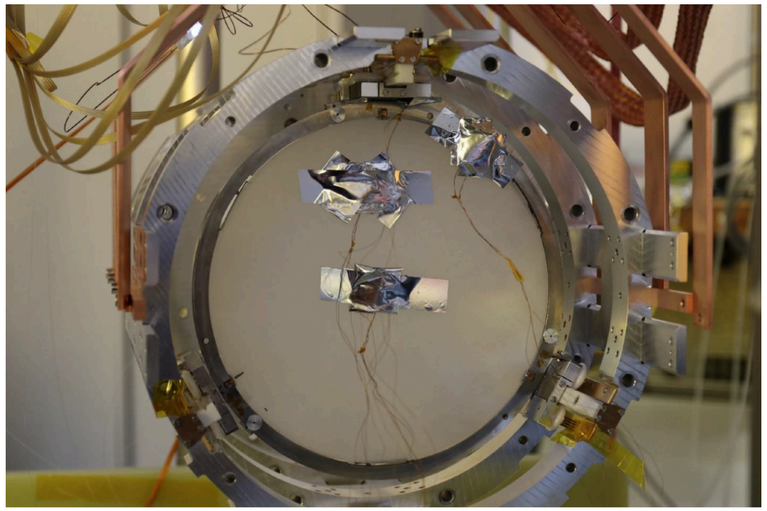
ϕ1.2 m

antenna & cold electronics

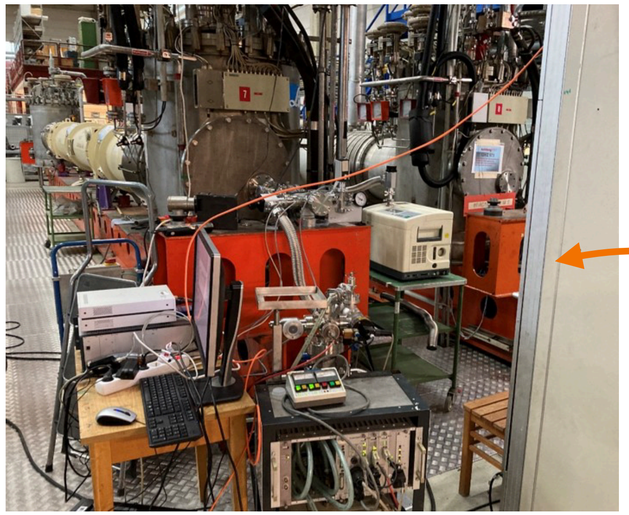
- Mechanical and rf feasibility tests.
- DFG funded! To be commissioned at UHH
- Foreseen operation in Morpurgo until 2025 during the beam SPS shutdown.

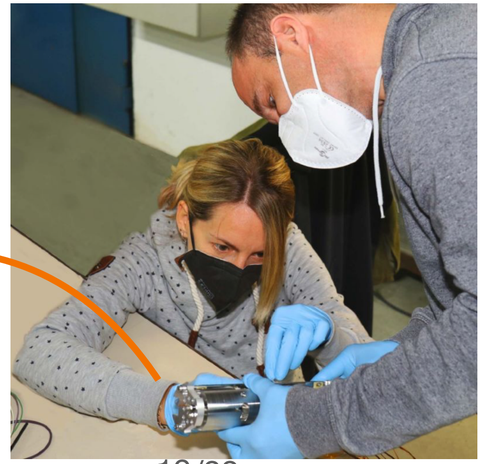
Mechanical feasibility R&D

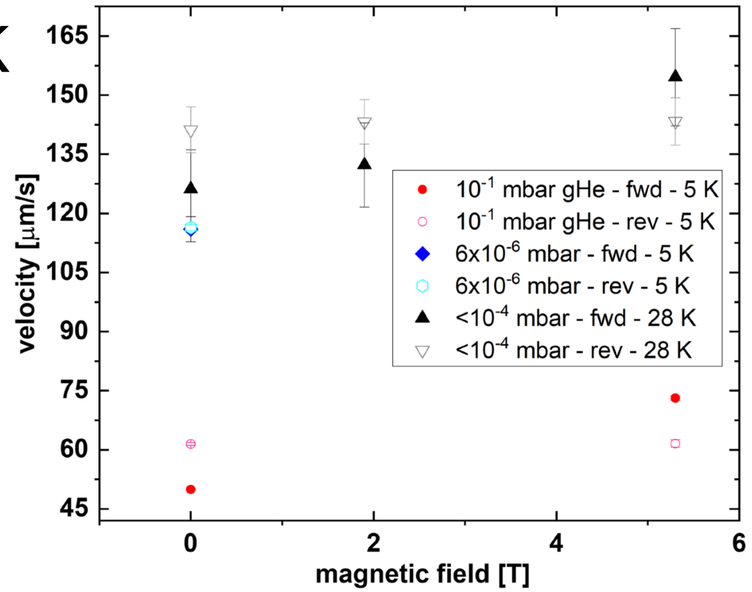
Milestones achieved!



- A dielectric haloscope can operate in high B and cryogenic temperatures.
- Project200 (ϕ200mm disks) successfully cooled at Cryolab @ CERN. CB-100 to be cooled this month.
- Piezo-motor operated inside the 5T ALPS II magnet, 4K

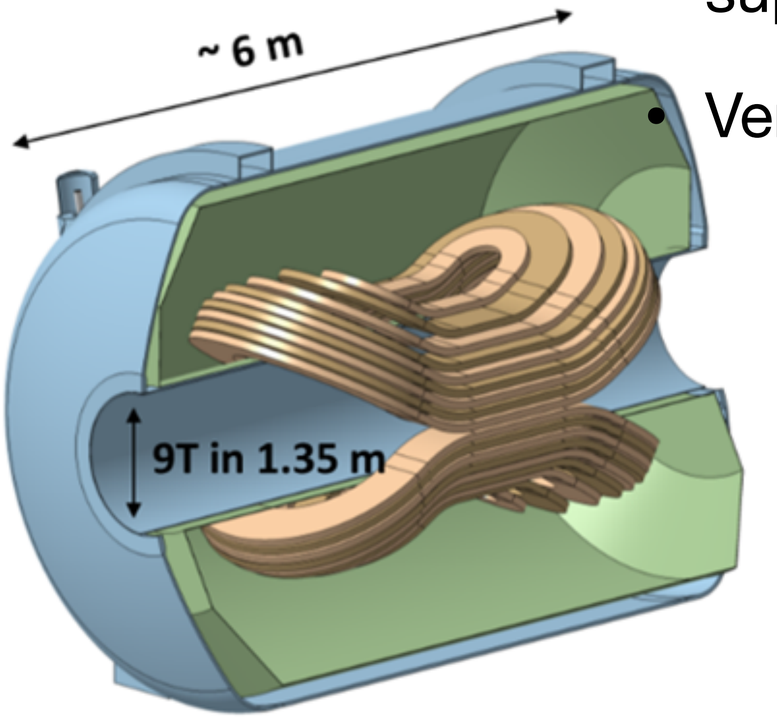


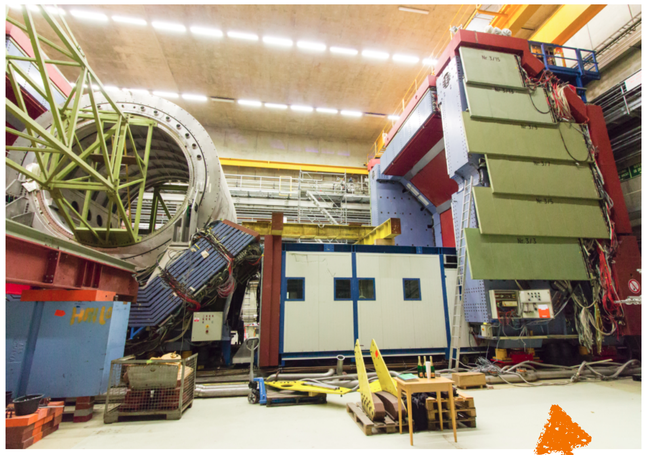


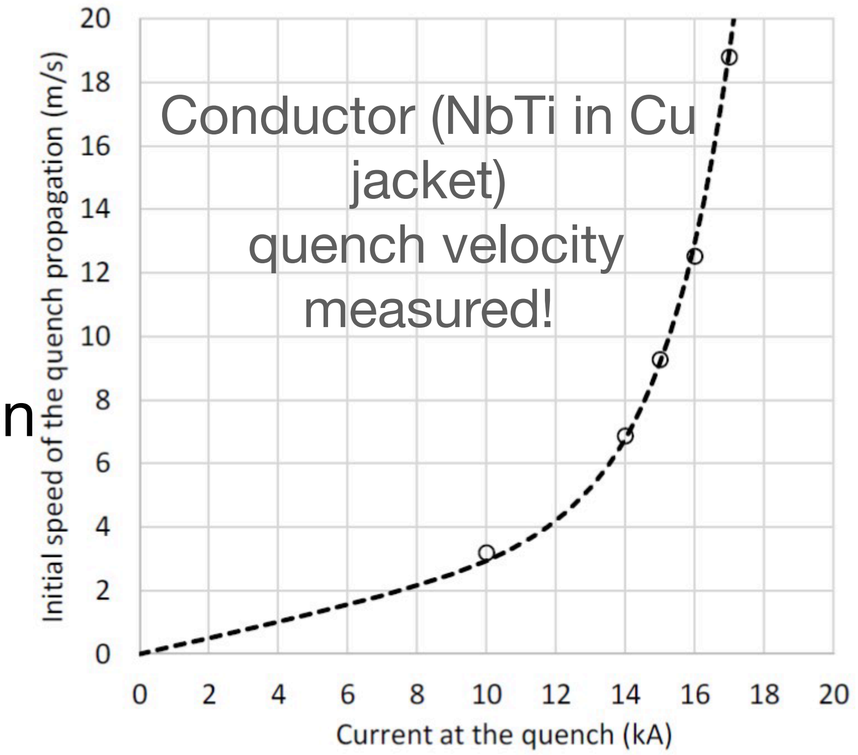


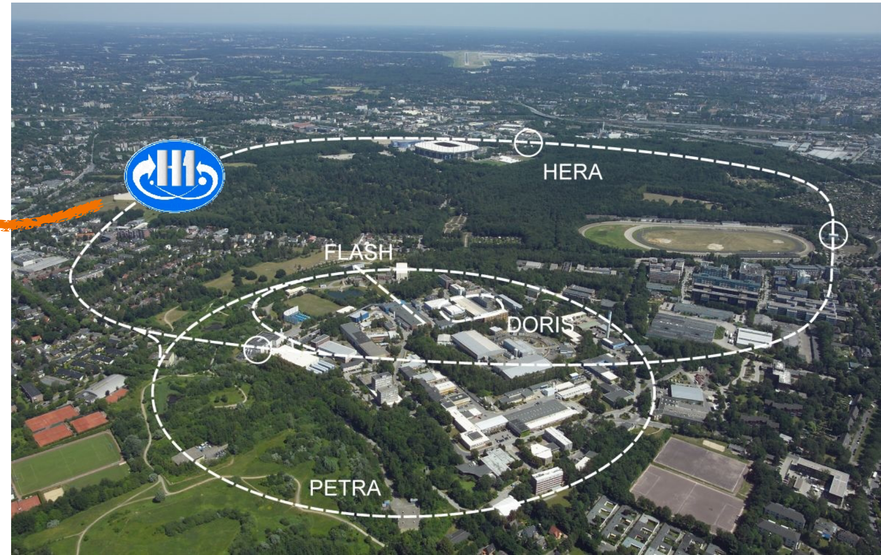
Full MADMAX Magnet

- Conductor design available, supply chain secured.
- Verified safe magnet operation





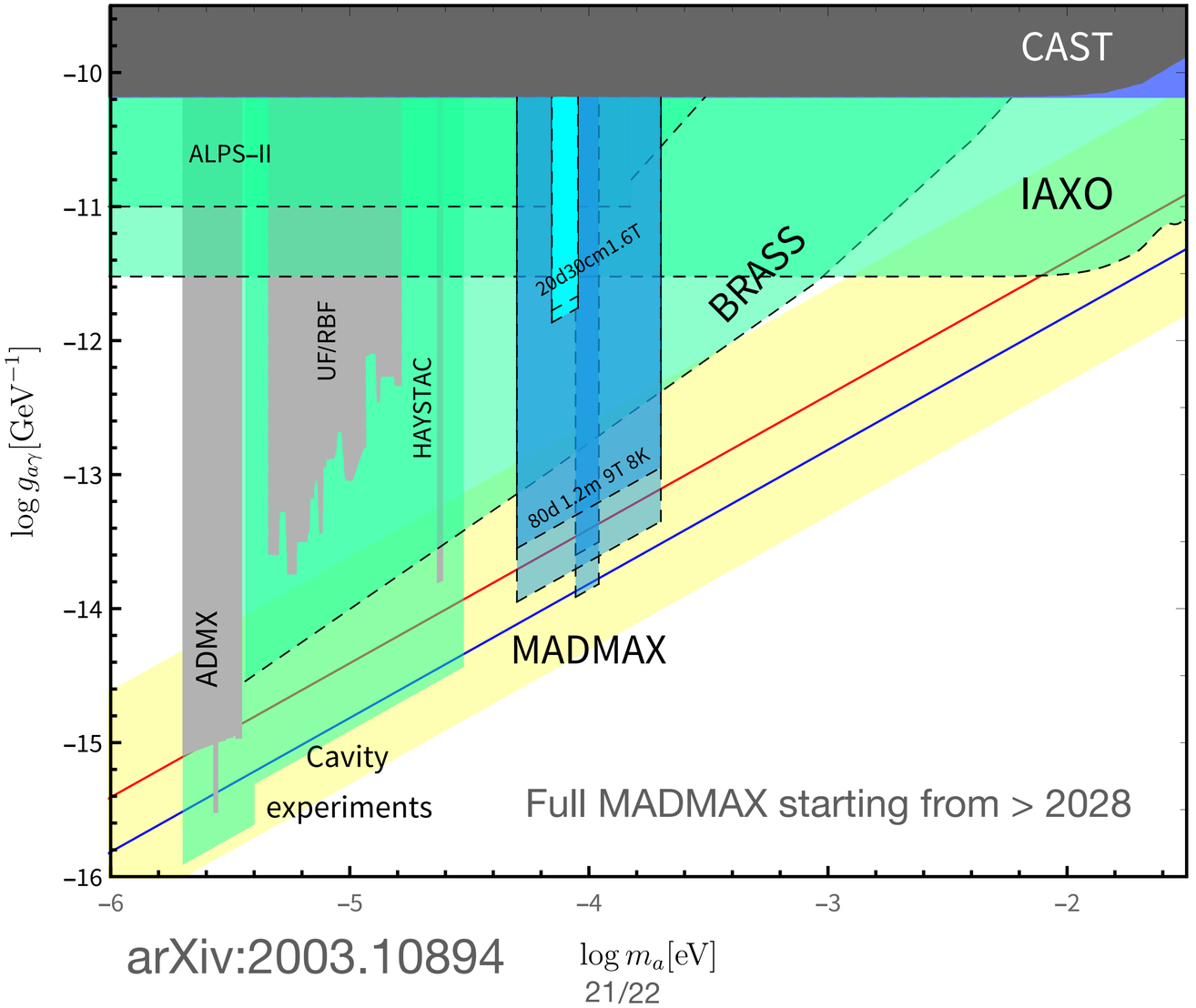




BILFINGER NOELL GMBH

MAX-PLANCK-INSTITUT FÜR PHYSIK

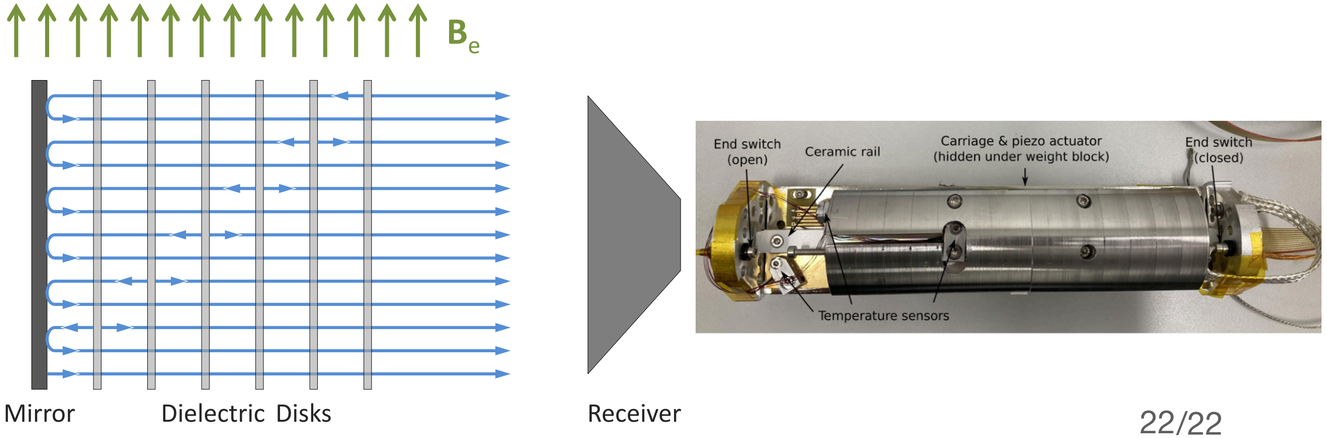
Projected sensitivity

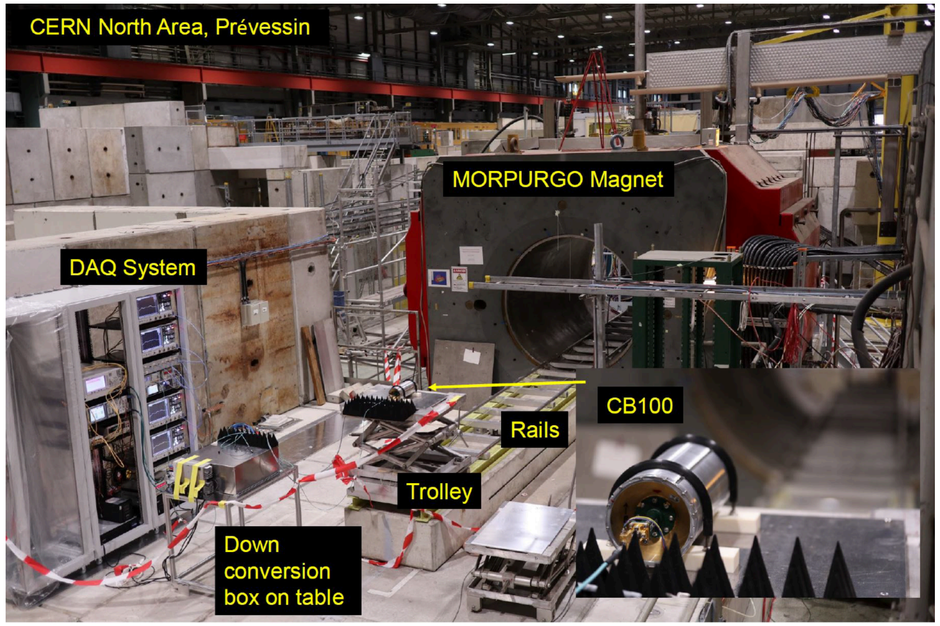


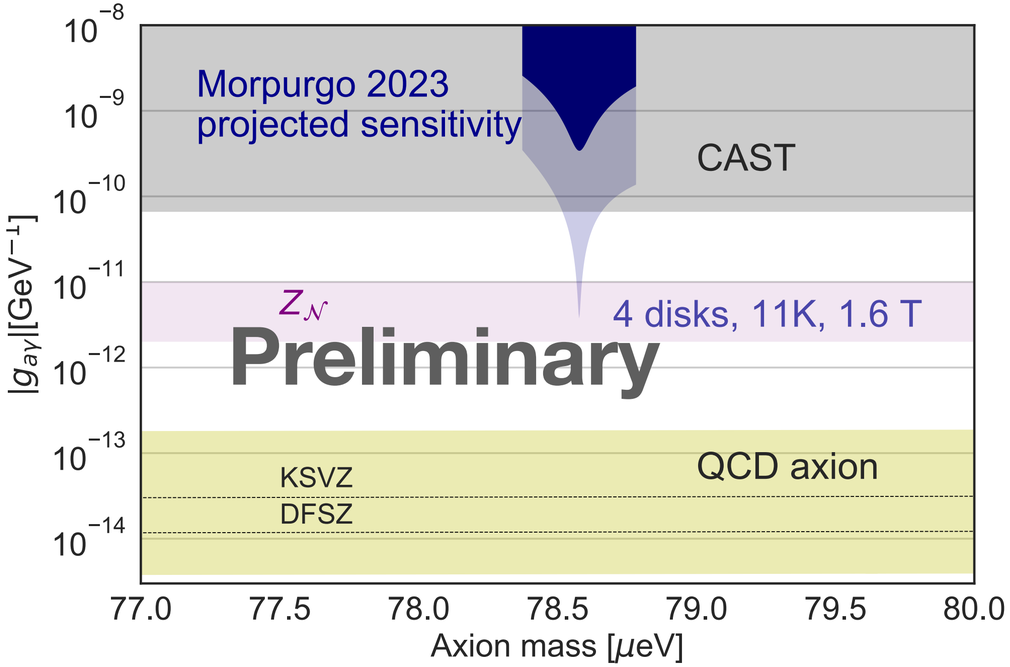
arXiv:2003.10894

Summary & Conclusion

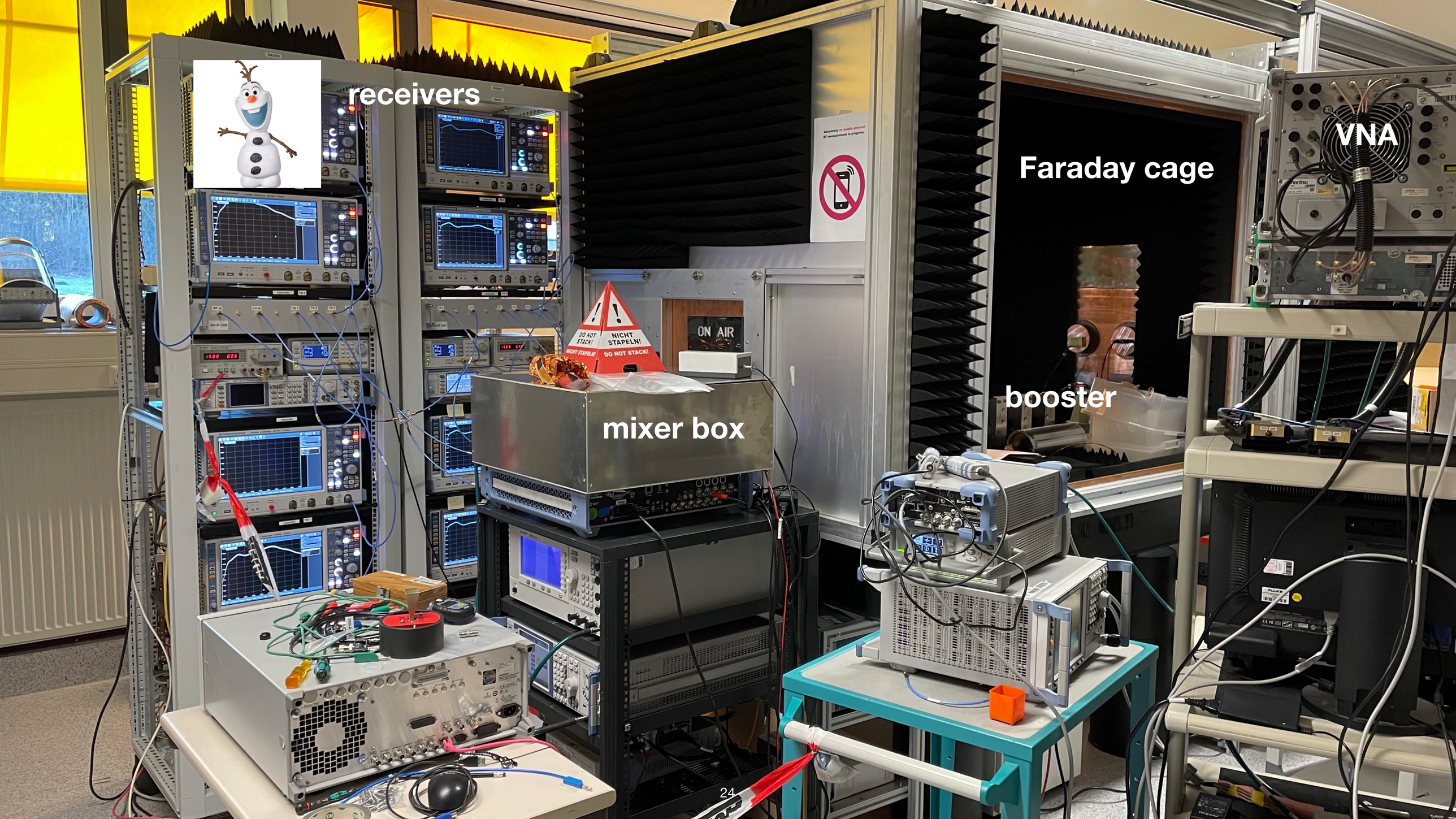
- Dielectric haloscope is a promising concept for detecting axions around $m_a \sim 100\,\mu\text{eV}$.
- Piezo motor and P200 successfully operated in high B-field and cryogenic temperatures.
- **First ALP DM search** using a small setup is ongoing at CERN.



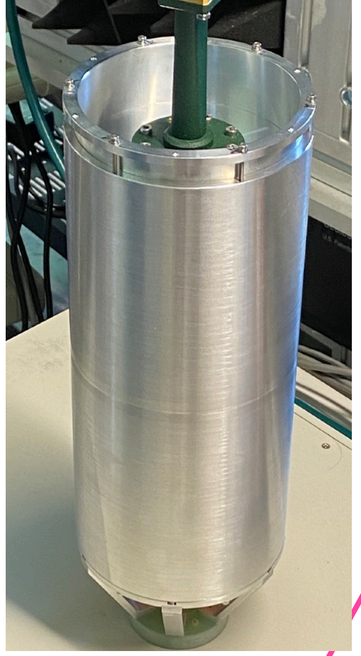


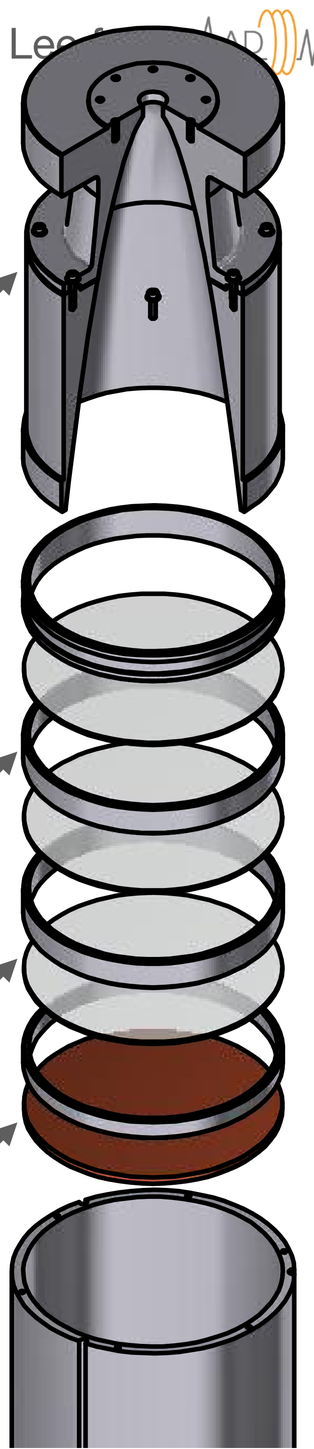


Back up slides

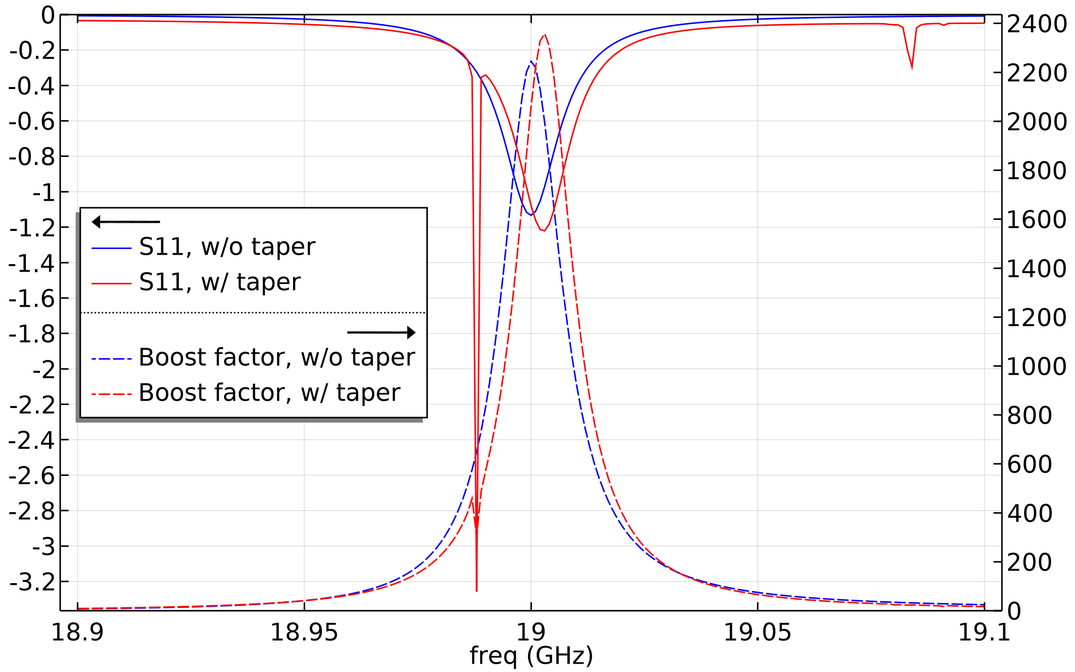

receivers
mixer box
Faraday cage
booster
VNA
ON AIR
DO NOT STACK!
NICHT STAPELN!
DO NOT STACK!
NICHT STAPELN!

Construction

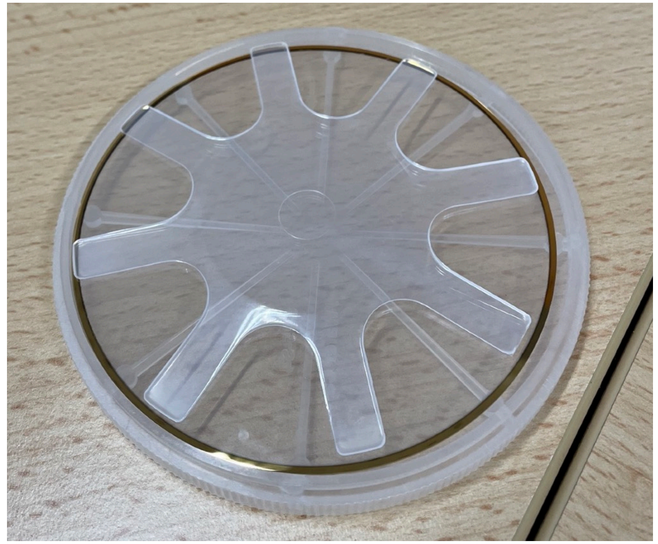


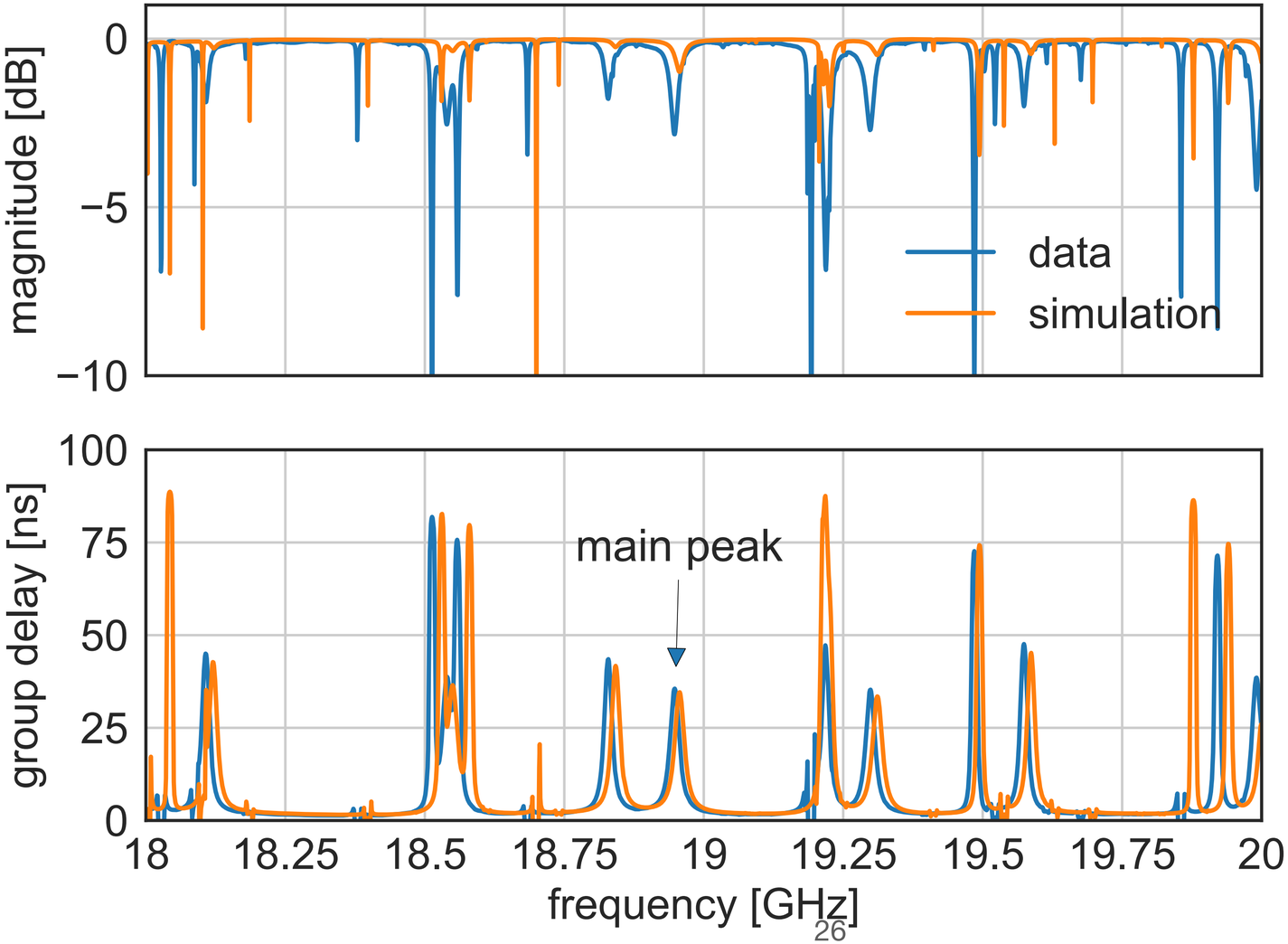


J. Doane, Int. J. Infrared Milli. Waves **5** (1984)



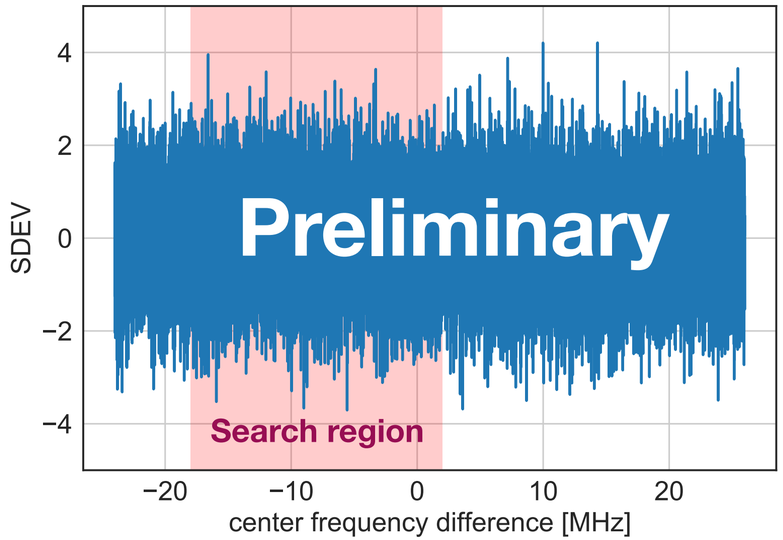
Room temp reflectivity

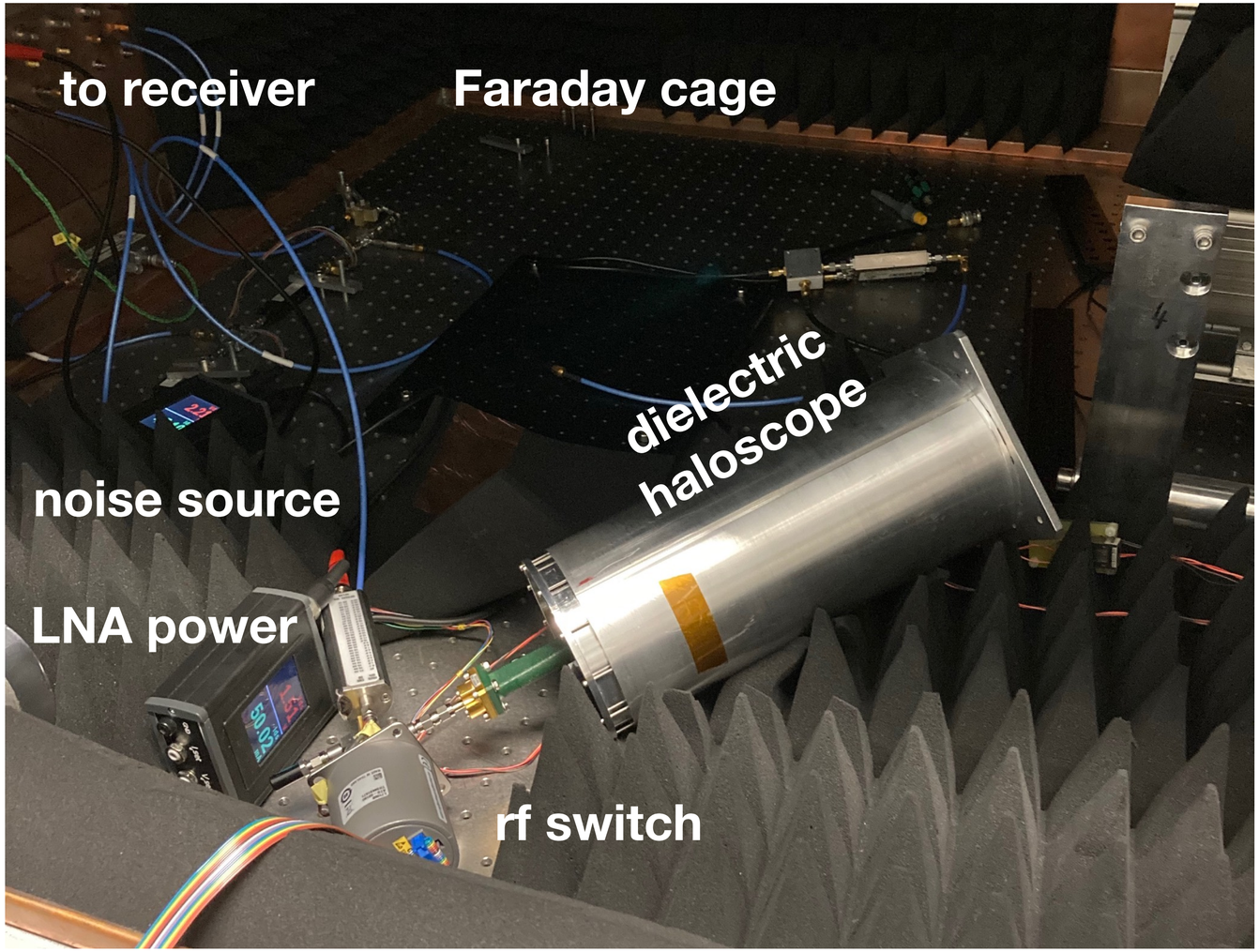




Hidden photon search @ MPP

- Hidden photon to microwave conversion w/o *B* field.
- 32 days, 200K effective T_{sys}
- No excess power observed





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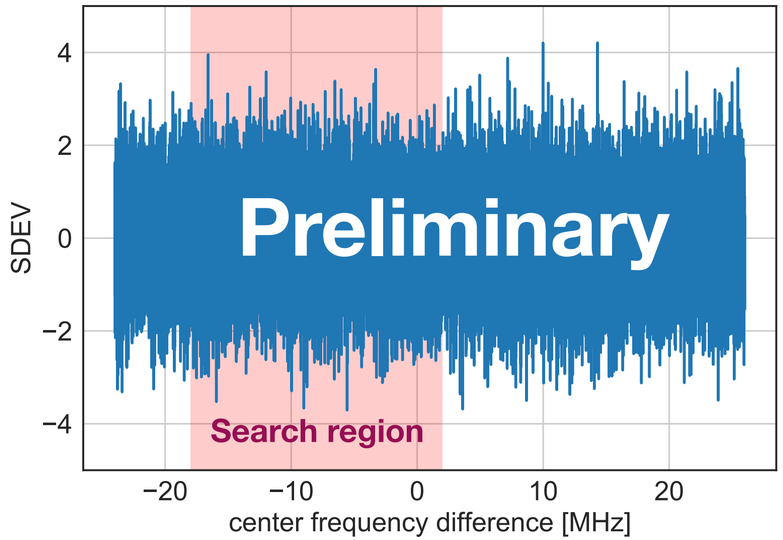
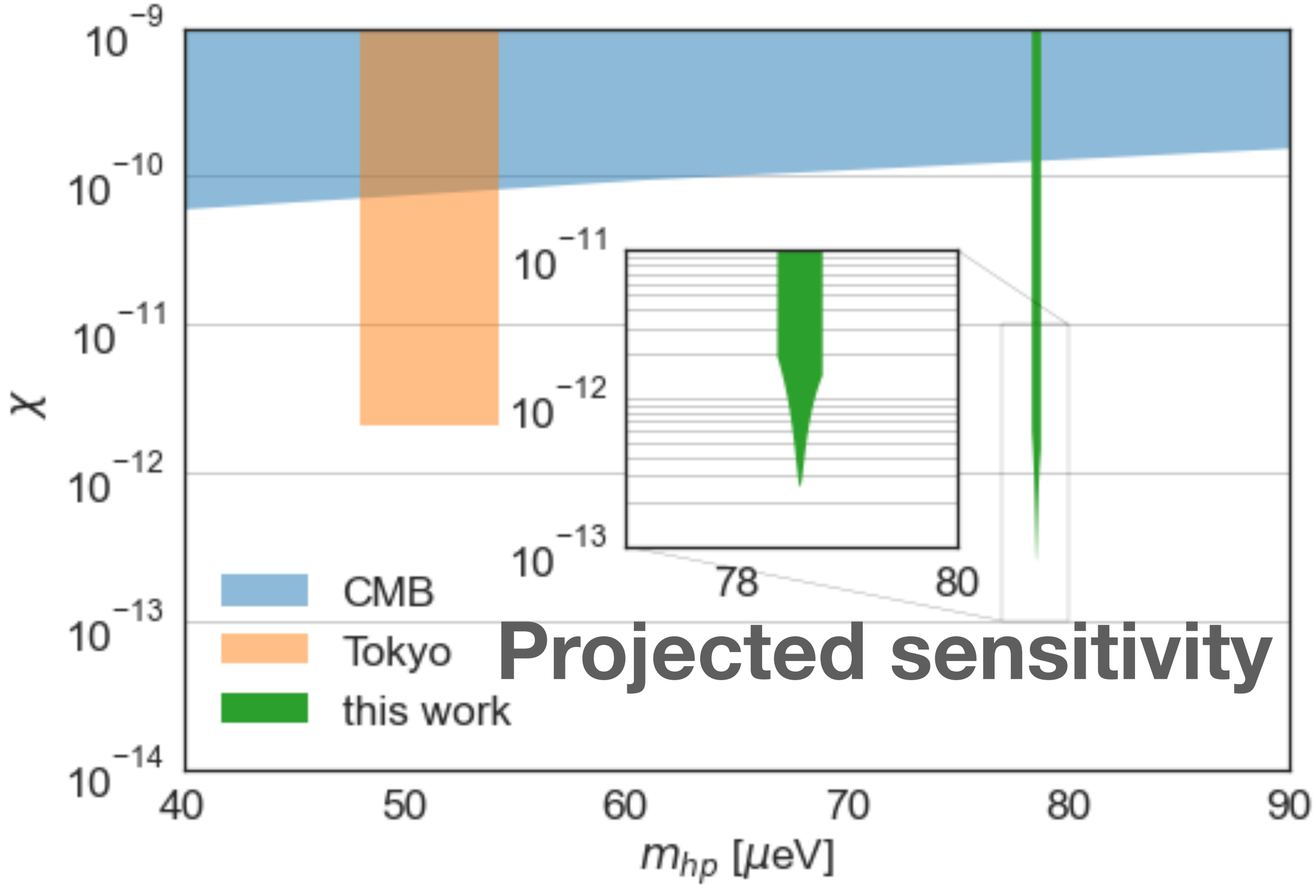
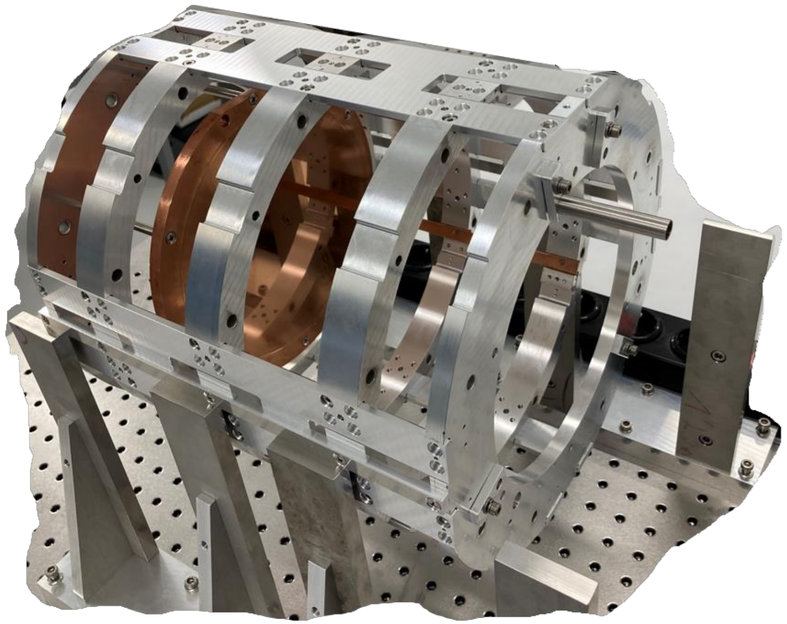
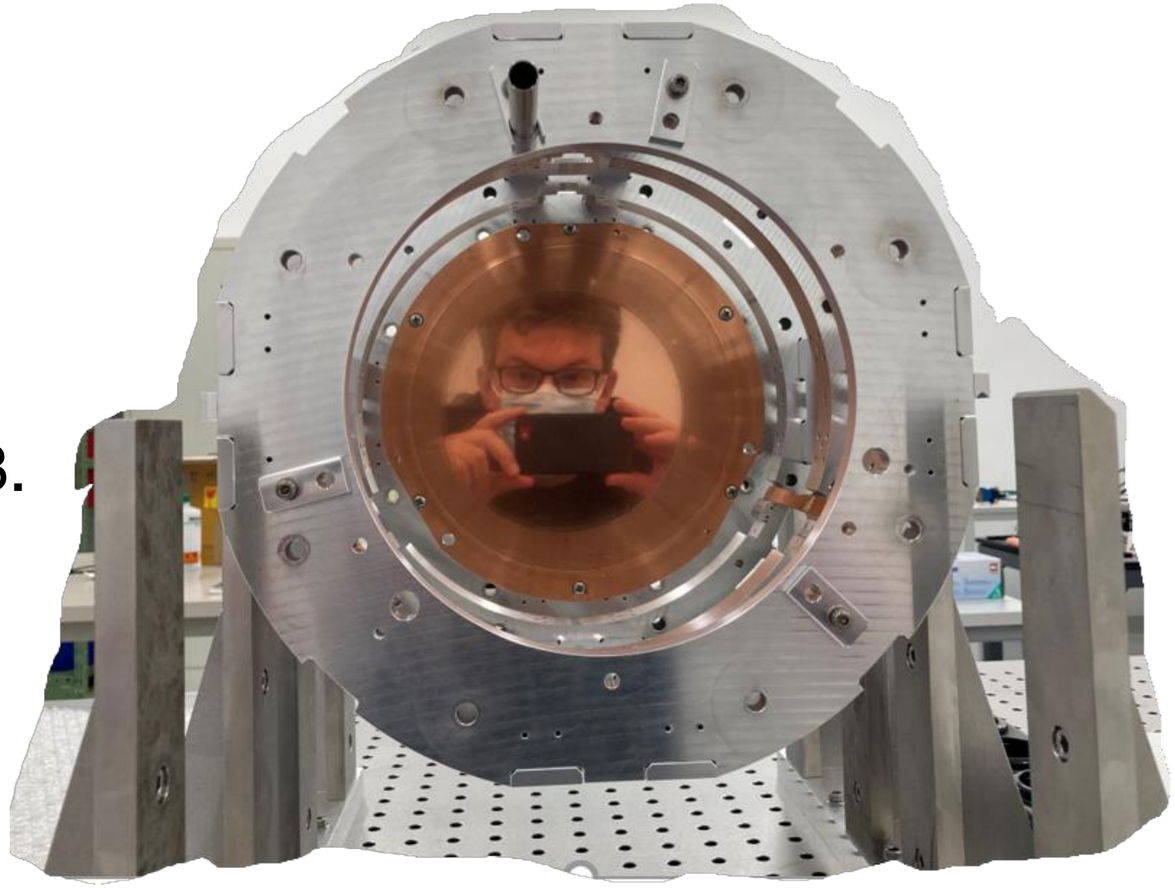




Project 200

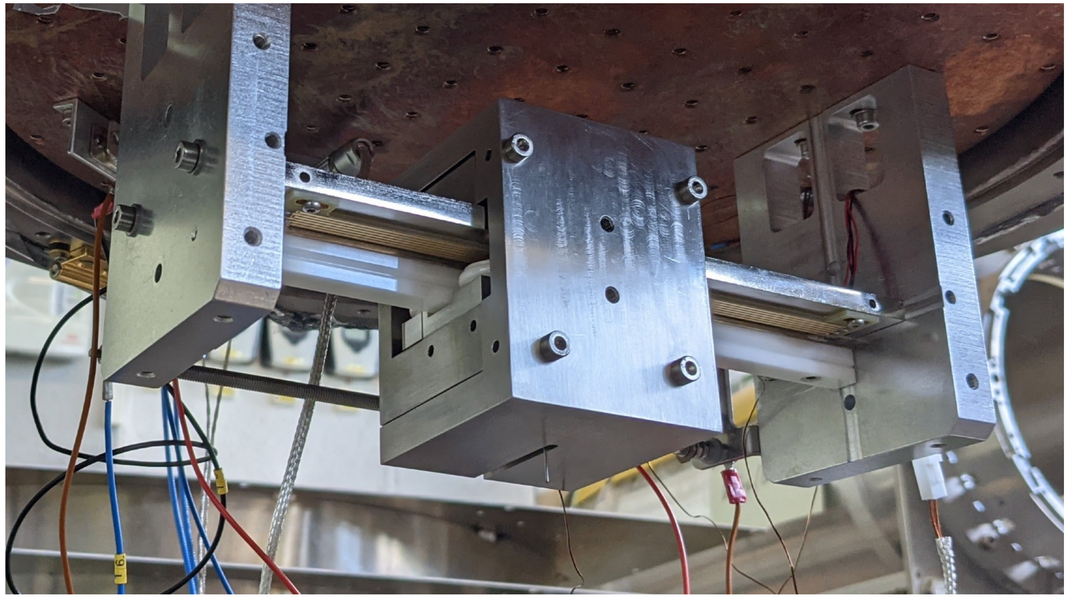
- Test piezo motor + laser interferometer @ cryogenic temp & high *B* field.
- CERN cryostat in 2022, Morpurgo in 2023.





Cryogenic piezo

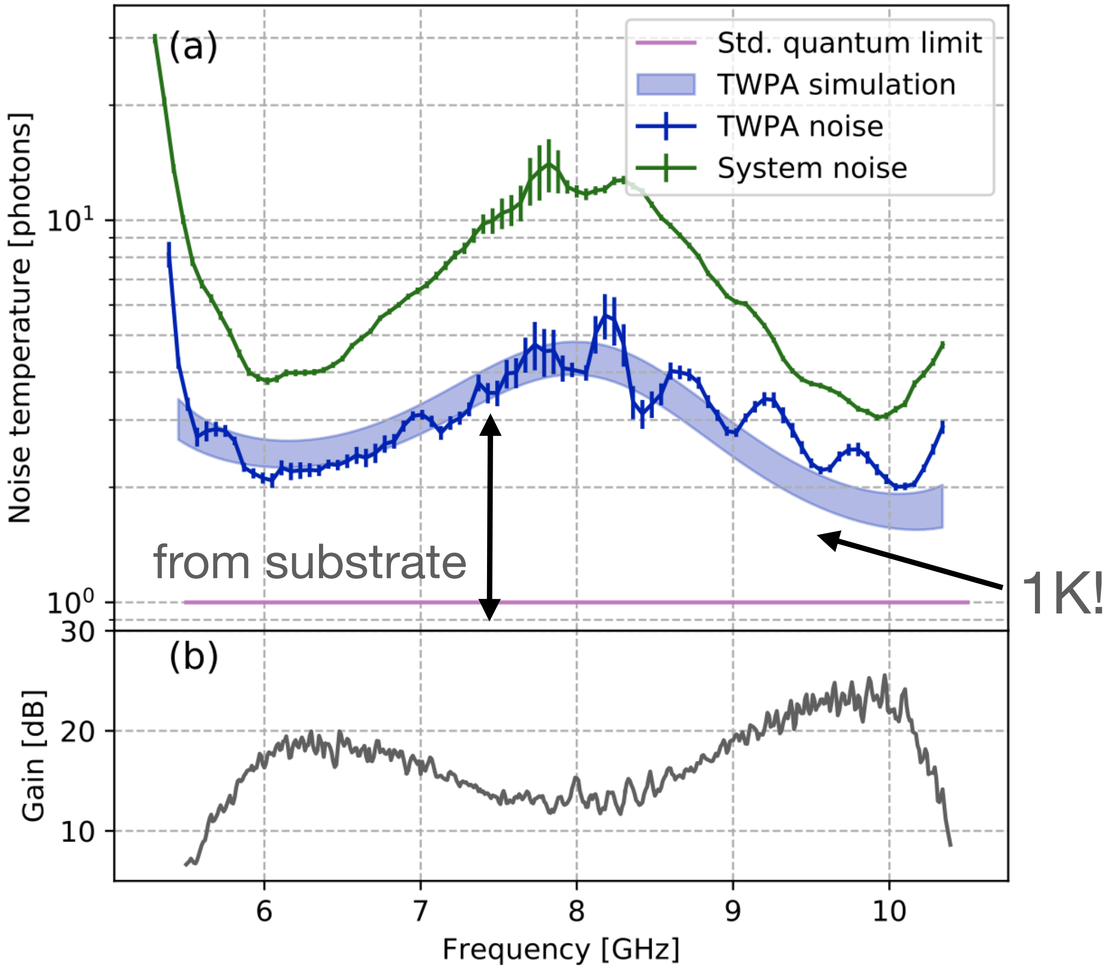
- Piezo positioner tested @ 4K
- Test @ 5T to follow



Quantum-limited amplifier

- Preamp: dominant source of background
  - Traveling wave parametric amp (TWPA)
  - > 10 GHz in design

$$\frac{\Delta\nu}{\Delta t} \propto \frac{Q^2 V^2 B_e^4}{T_{sys}^2}$$



Reversed Kerr TWPA [2101.05815]