First physics results from MADMAX prototype experiments

Johannes Diehl for the MPP MADMAX group

MADMAX at the MPP

Thanks to everyone involved for making these results possible!

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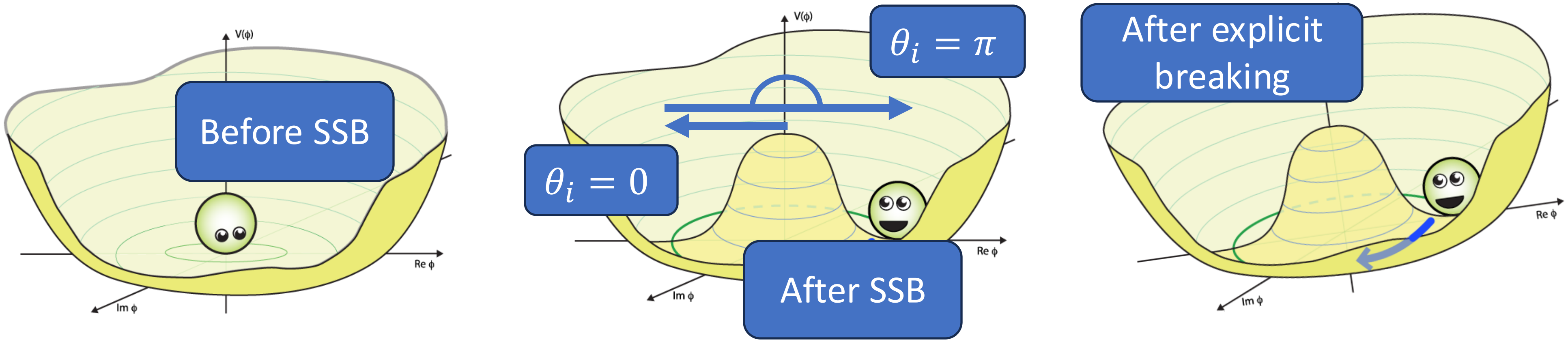
Help from Engineering department: David Kittlinger, Georg Obermüller, Alexander Sedlak

Special thanks to the MPP workshop & electronics department!

Setting the stage

Setting the stage: The Axion

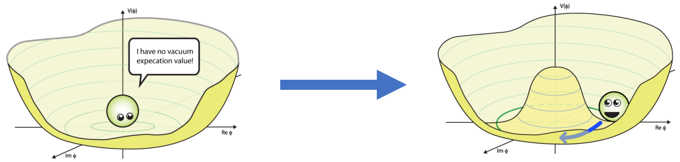
- Introduced to solve the CP problem of QCD
- New $U(1)_{PQ}$ ("Peccei-Quinn") symmetry is spontaneously broken at energy scale f_a, axion is pseudo Goldstone boson



- Misalignment production: relic oscillations around minimum produces axions as $\Omega_a^{mis} \propto f_a^{7/6} \theta_i^2$ Fox et al '04

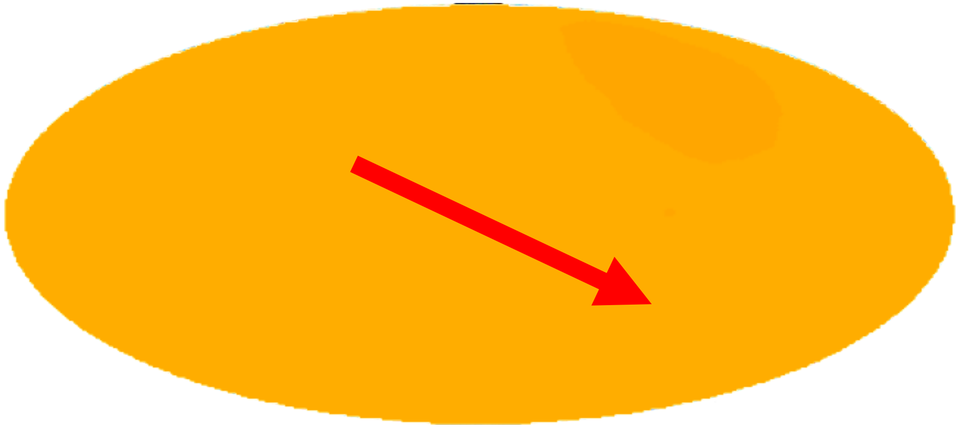
Image source: https://www.quantumdiaries.org/2012/02/14/

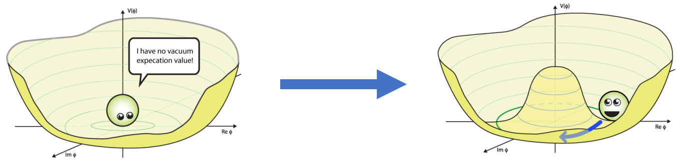
Setting the stage: Pre- and postinflationary scenarios



before inflation

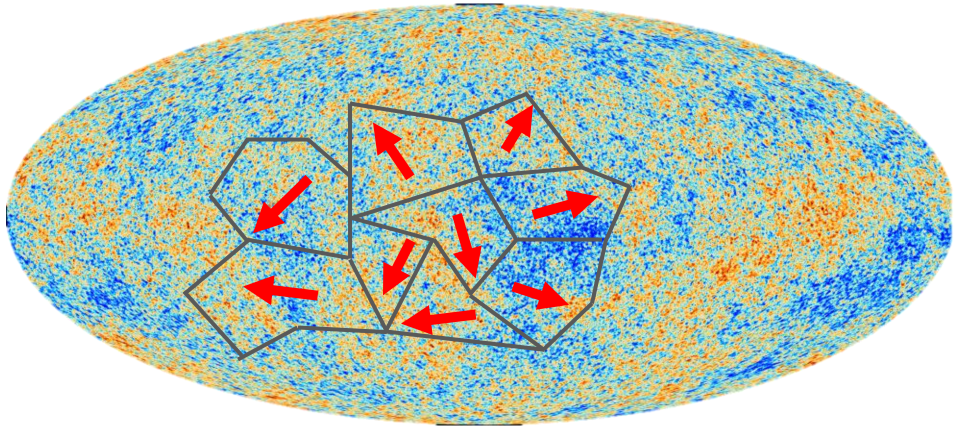
→ only one $0 < |\theta_i| < \pi$ in visible universe





After inflation

→ many small regions with different θ_i
→ use average of possible θ_i for misalignment production
→ topological defects may produce additional axions



Setting the stage: The Axion as CDM

- Very light: $\boldsymbol{m_a} \sim \mathbf{5.7\ \mu eV}\ \frac{10^{12}\mathrm{GeV}}{f_a}$
- Macroscopic wavelength: $\langle v_{\mathrm{DM}} \rangle \sim 10^{-3} c \rightarrow \boldsymbol{\lambda_{\mathrm{dB}}} \sim \mathbf{1\ km}\ \frac{\mu\mathrm{eV}/c^2}{m_a}$
- Large number density: $\rho_{DM} = 0.3\ \frac{\mathrm{GeV}/c^2}{\mathrm{cm}^3} \rightarrow \boldsymbol{N_a} \sim \frac{\mathbf{3 \times 10^{32}}}{\lambda_{dB}^3} \frac{\mu eV/c^2}{m_a}$

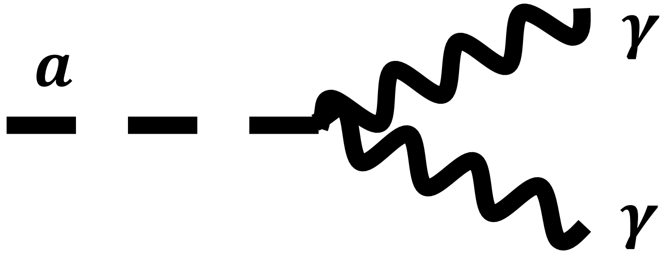
→ treat as classical wave with wavelength ≫ detector size

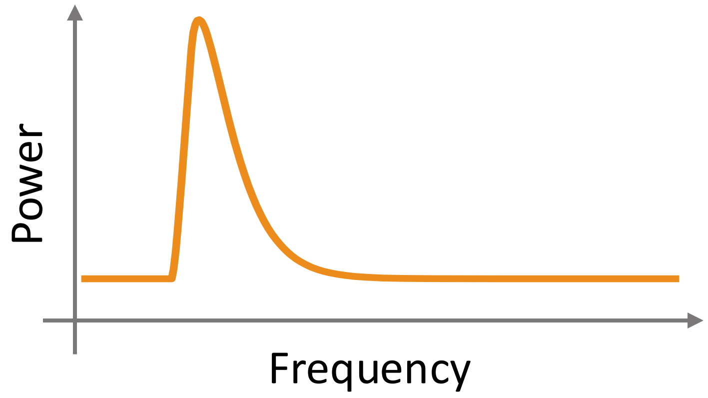
Setting the stage: Coupling to photons

- Axion has effective two photon vertex (Primakoff effect)
- Effective Lagrangian: $\mathcal{L}_{a\gamma} \propto g_{a\gamma} a\, \boldsymbol{E} \cdot \boldsymbol{B}$ with model dependent $g_{a\gamma} \propto f_a^{-1}$
- In practice use B-field to induce axion-photon conversion
- Axion signal in frequency spectrum: Localized ($\Delta\nu \sim 10^{-6}\nu_a$) peak at $\nu_a = \frac{m_a c^2}{h}$

$\rightarrow g_{a\gamma} \propto m_a$

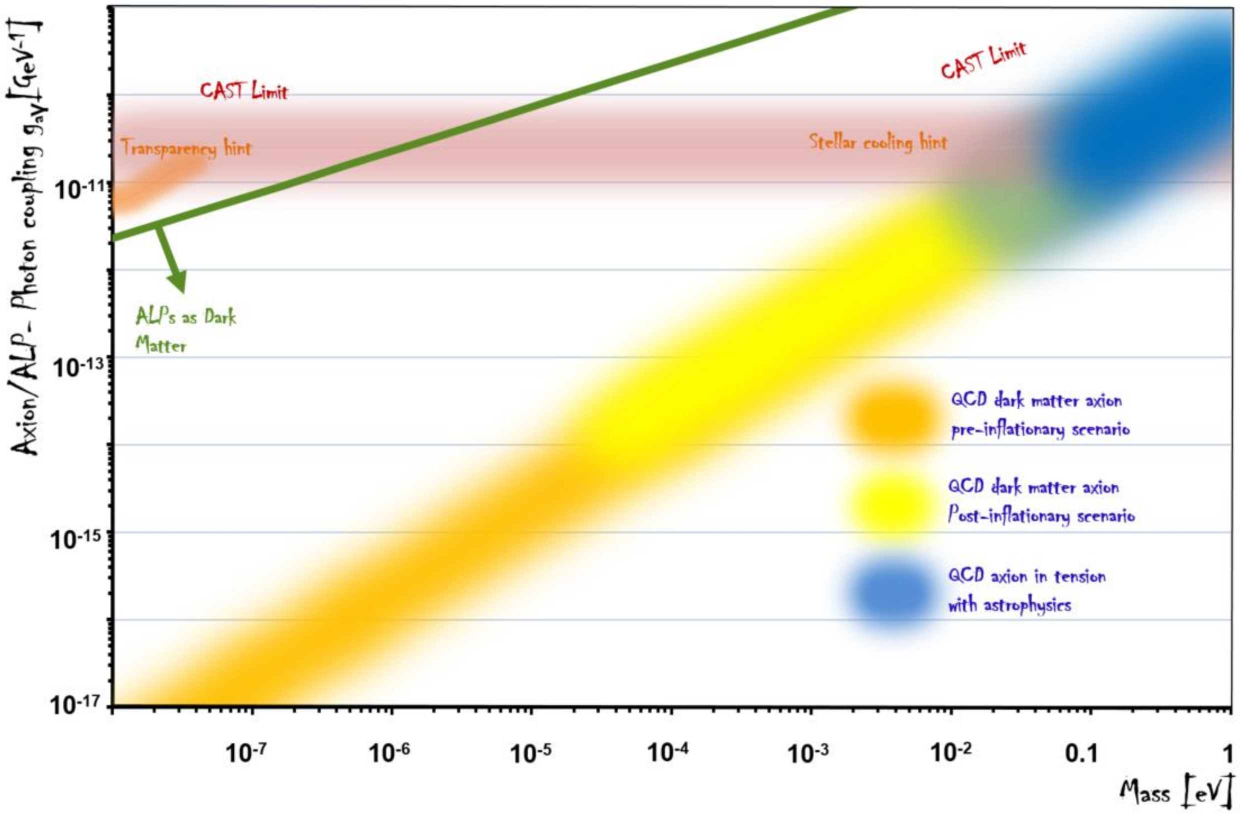
$\rightarrow$ long coherence time





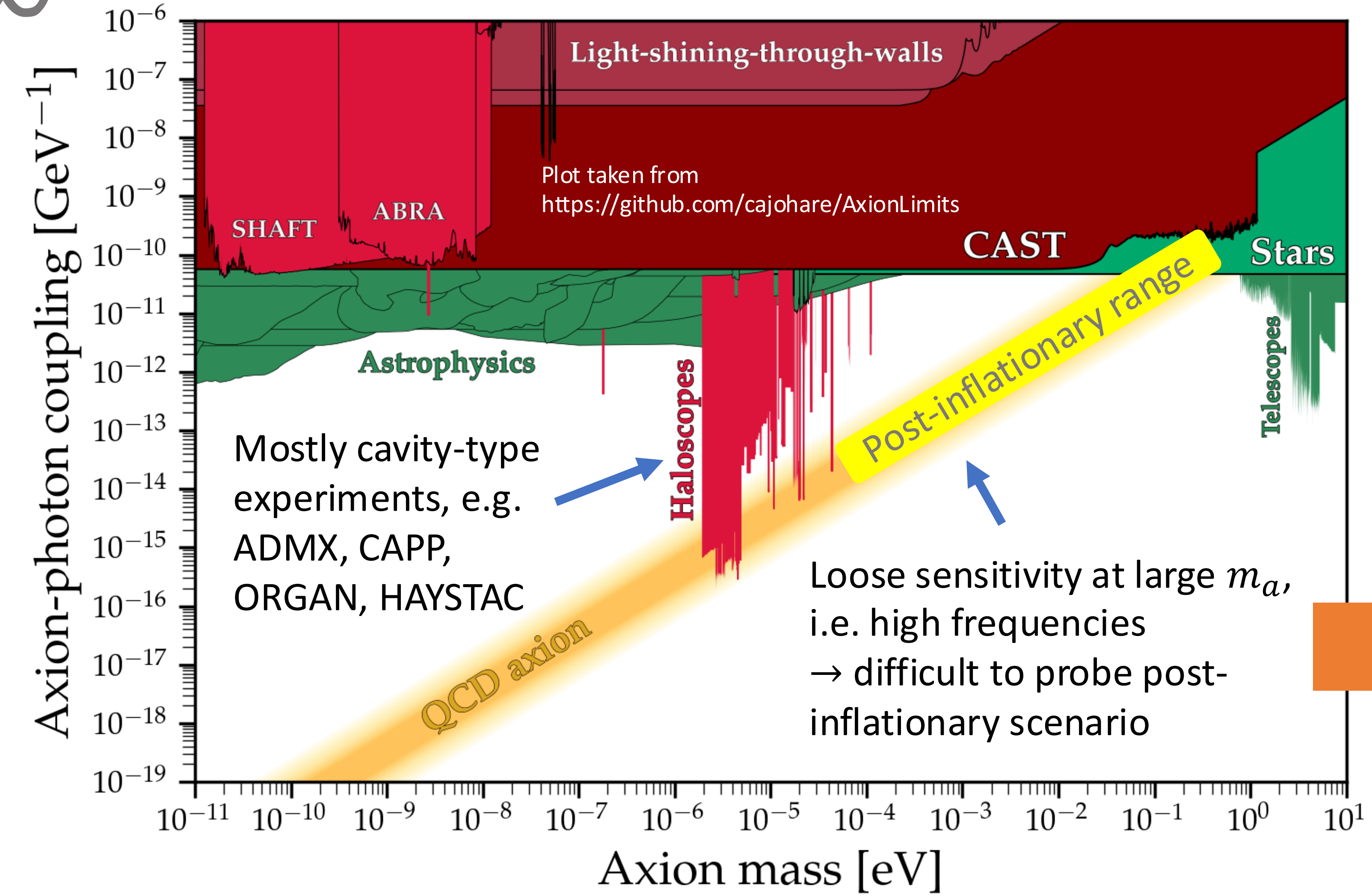
Setting the stage: Axion-Like Particles (ALPs)

- May not solve CP problem of QCD
- Light, pseudoscalar particles
- Main motivation: string compactifications leading to plethora of ALPs (“axiverse”)
- No relation between $g_{a\gamma}$ and m_a



The Magnetized Disk and Mirror Axion eXperiment

MADMAX: Motivation



Mostly cavity-type experiments, e.g. ADMX, CAPP, ORGAN, HAYSTAC

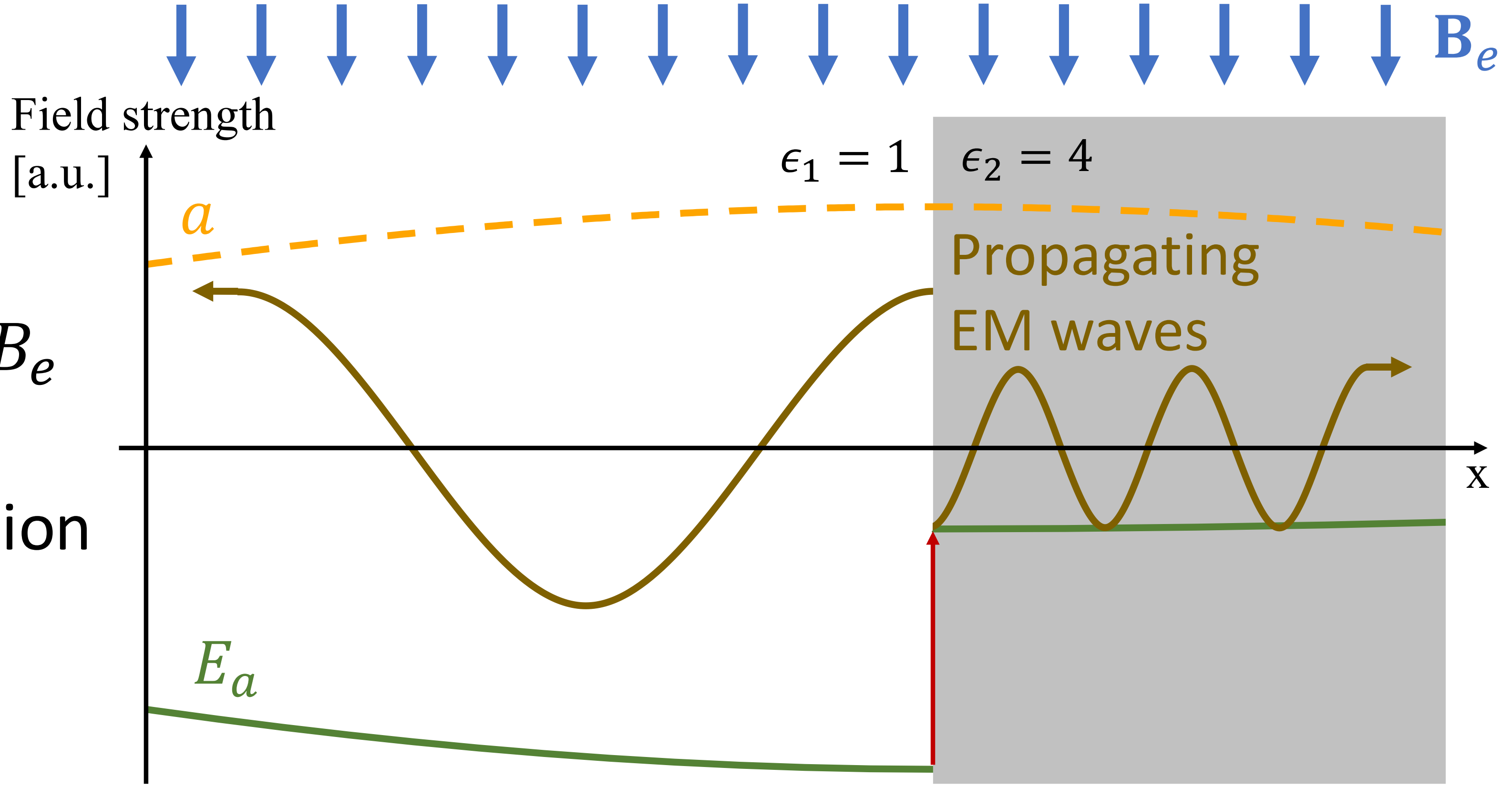
Loose sensitivity at large m_a, i.e. high frequencies → difficult to probe post-inflationary scenario

Magnetized Disk and Mirror Axion eXperiment

MADMAX: Working Principle

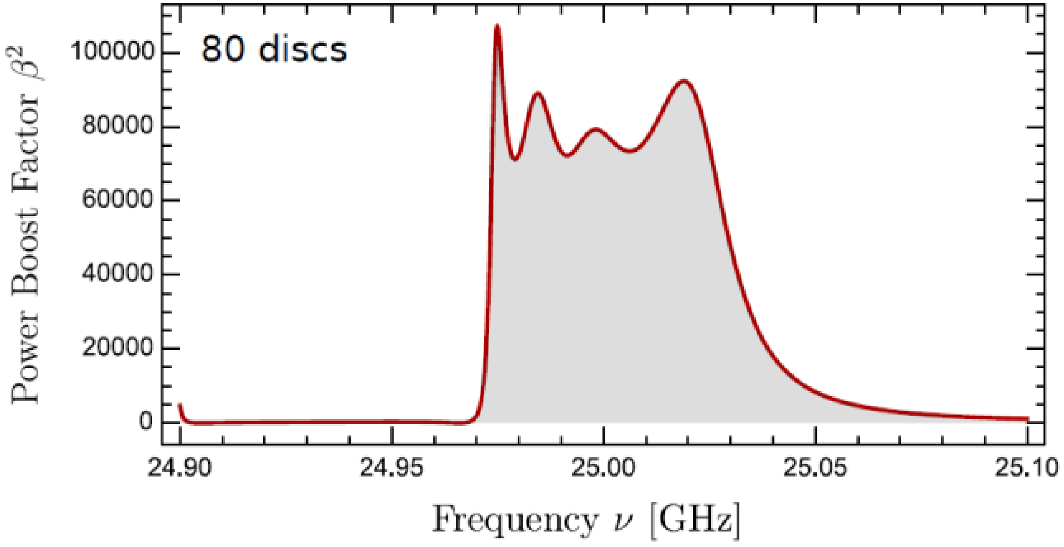
- Axion field a induces electric field E_a inside external magnetic field B_e
- Step in E_a at dielectric surface → photon emission
- Photon emission from single mirror ($\epsilon_2 = \infty$):

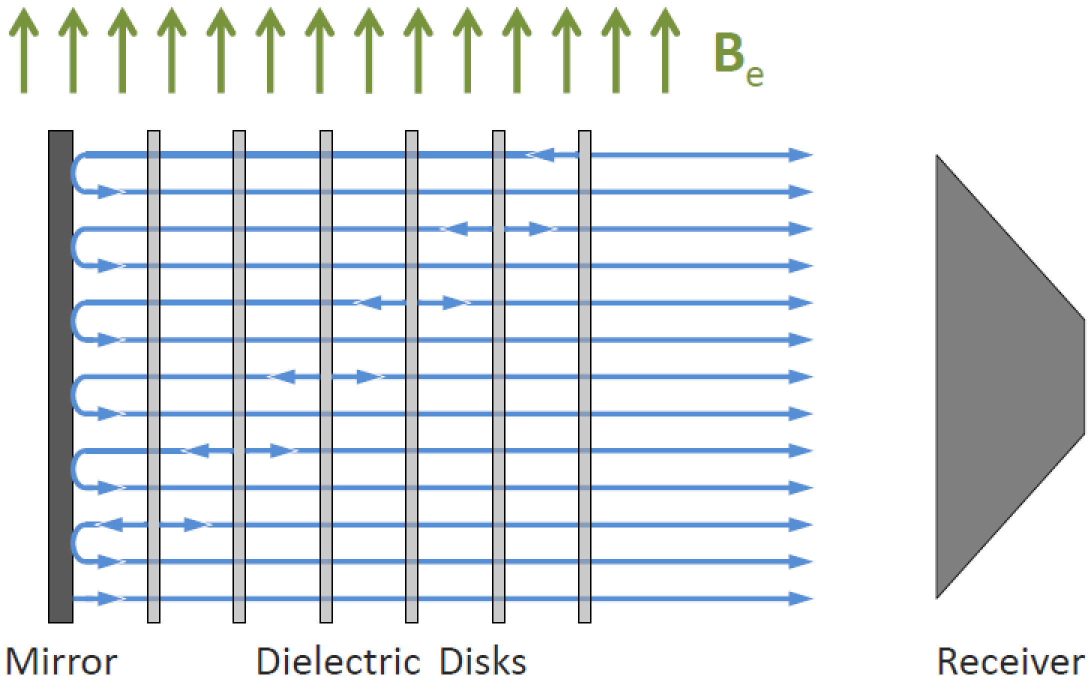
$$\frac{P_{\mathrm{mirror}}}{A} \sim 3 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\ \mathrm{T}}\right)^2 g_{a\gamma}^2 m_a^2$$



MADMAX: Boost Factor

- Place multiple surfaces, use constructive interference and slight resonance → power boost factor $\beta^2(\nu) = \frac{P_{\text{booster}}(\nu)}{P_{\text{mirror}}}$
- "Dielectric haloscope"

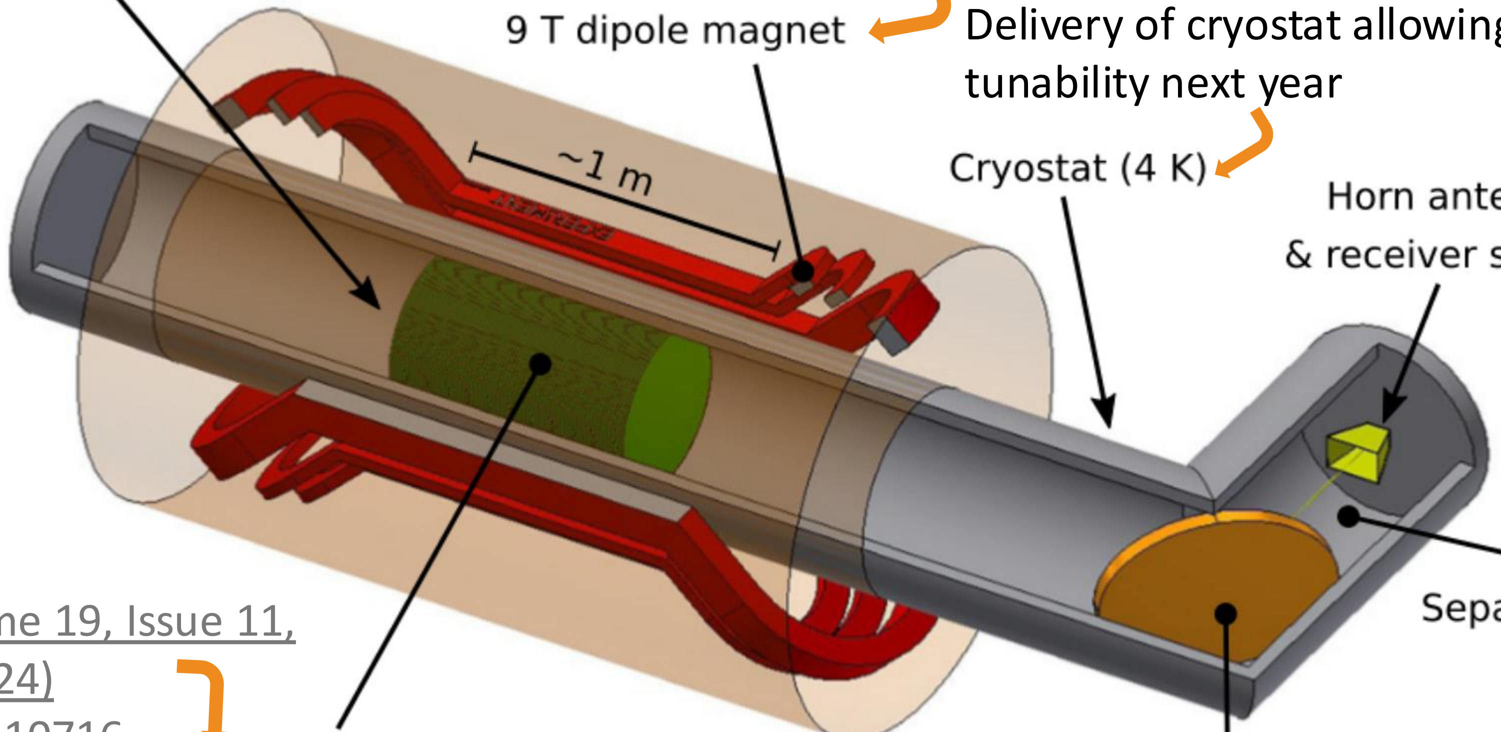




MADMAX: Design Goals

Special IEEE issue (Vol. 33, is. 7) on MADMAX magnet by CEA

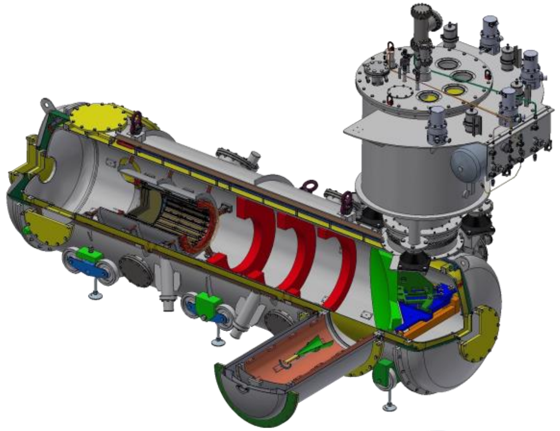
Delivery of cryostat allowing tunability next year

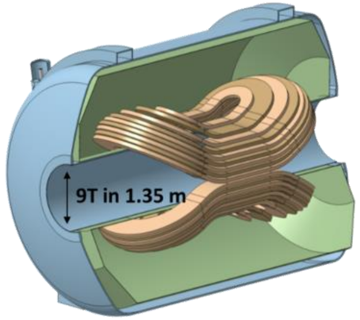


JINST, Volume 19, Issue 11, T11002 (2024)
arXiv: 2407.10716

To be located at DESY

Final magnet & setup expected after 2030



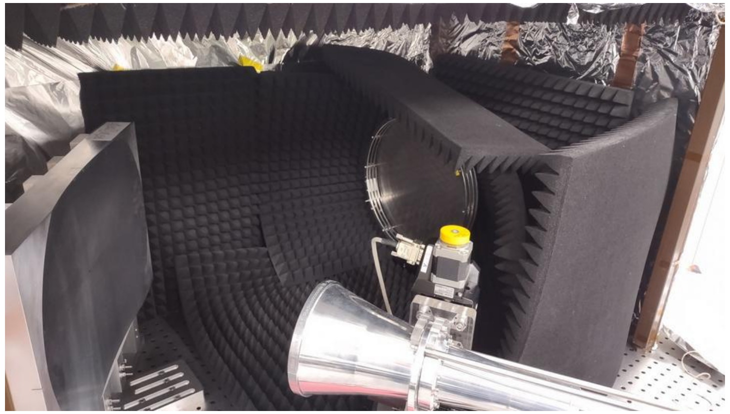


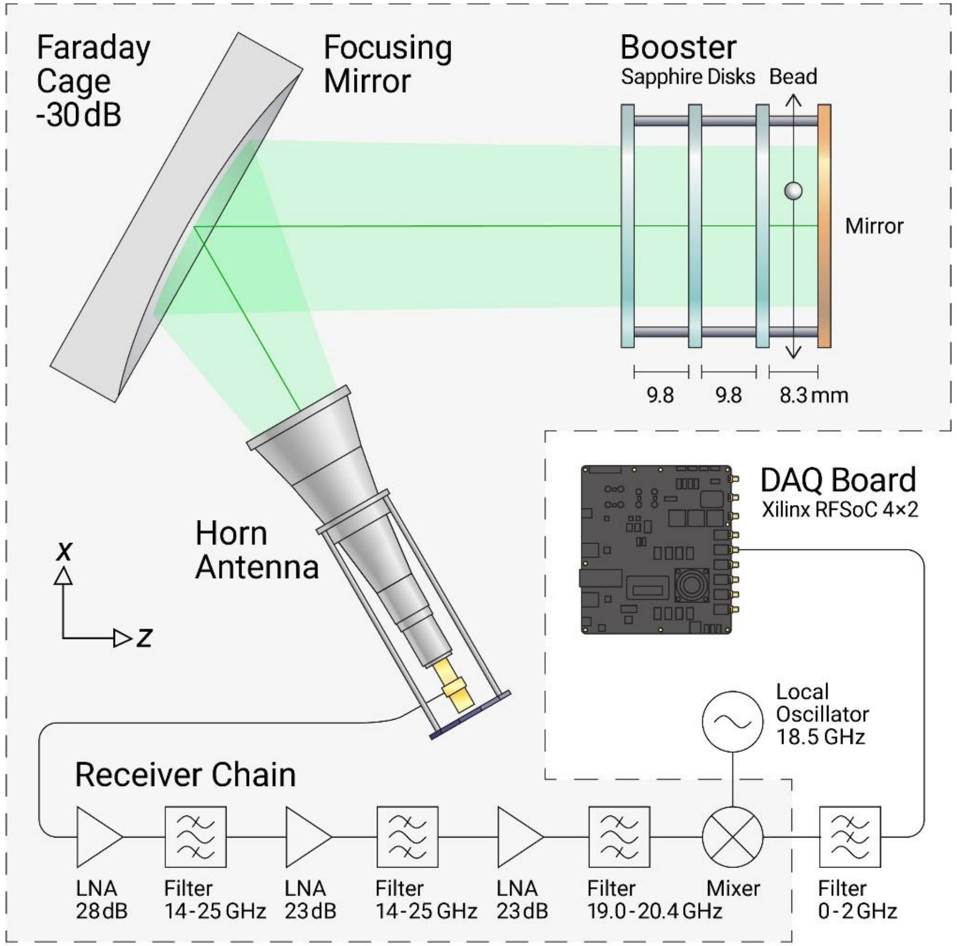
First Physics Results with MADMAX prototypes

First dark photon limit

arXiv:2408.02368

- 16.5 days data taking @ SHELL lab UHH
- Three disk open booster @ room temperature
- 30 cm sapphire disks at fixed distances





Collaboration effort

MPP contribution

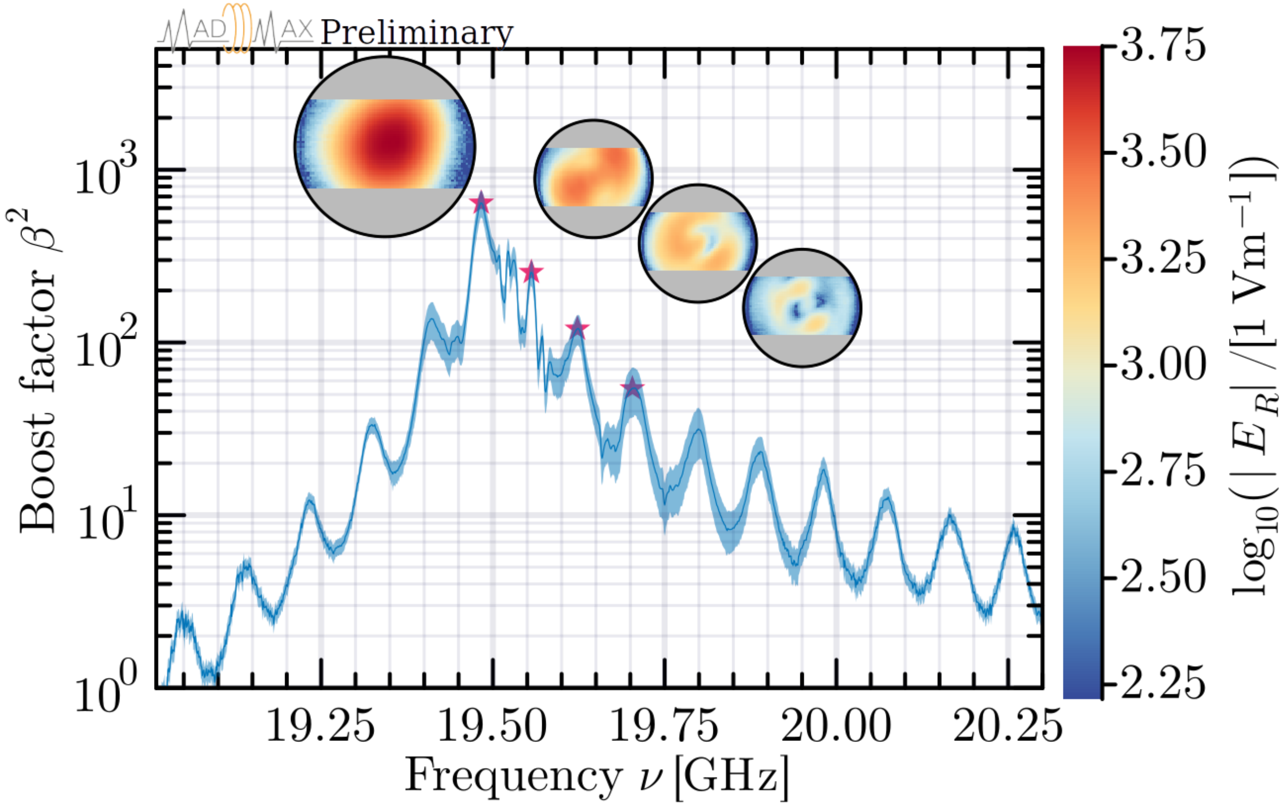
Theoretical groundwork → Build Booster → Measurements → Calibration → Statistical analysis

First dark photon limit

arXiv:2408.02368

Obtain boost factor via “bead pull” method:

- Measure E-fields in booster with small test bead
- Leverage reciprocity between E-field in reflection measurement and axion induced fields
- Less dependence on complicated RF simulations

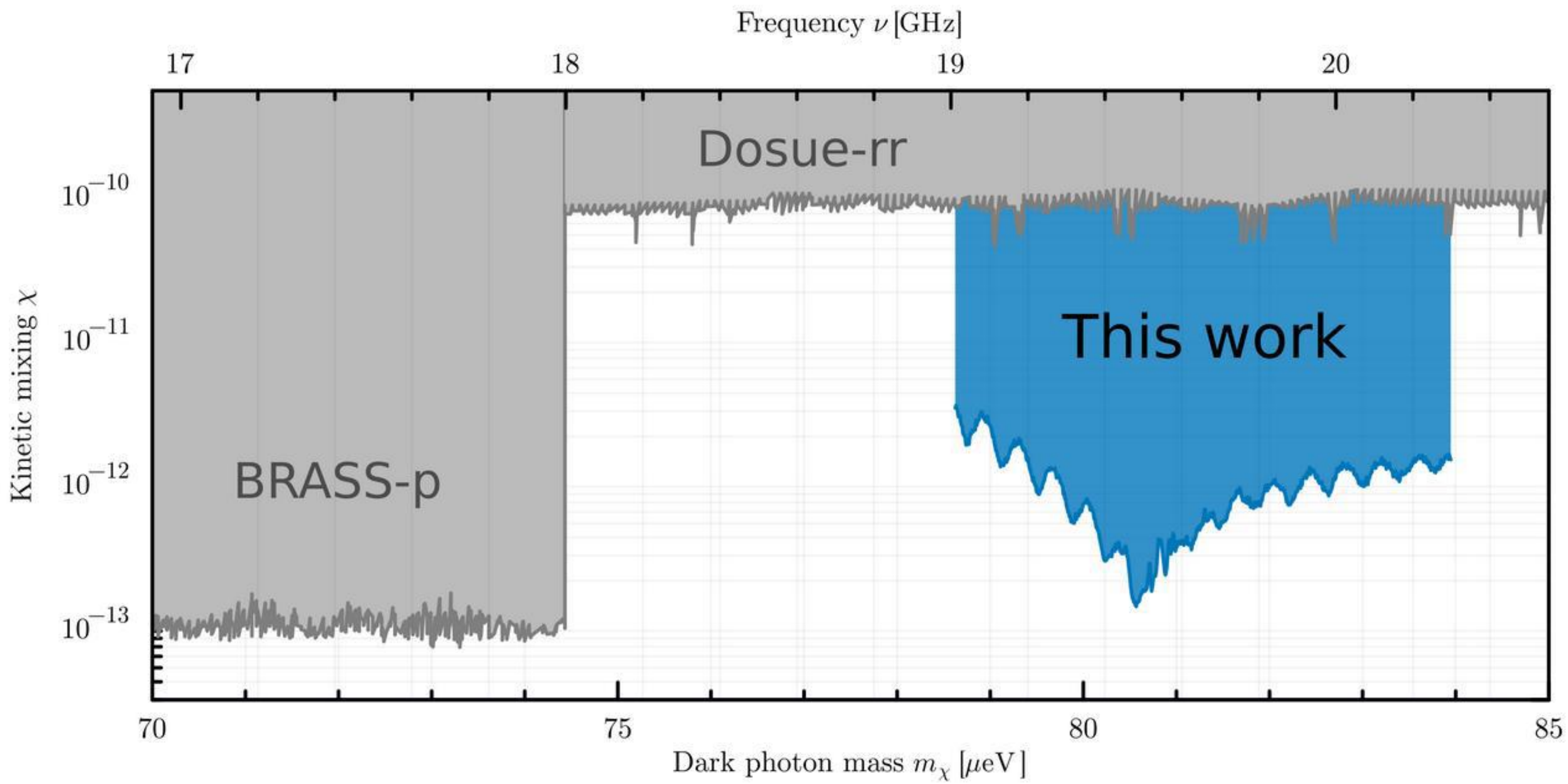


JCAP 04 (2024) 005, arXiv:2311.13359
JCAP 04 (2023) 064, arXiv:2211.11503

First dark photon limit

arXiv:2408.02368

- No potential signal found → set 95% CL exclusion limit



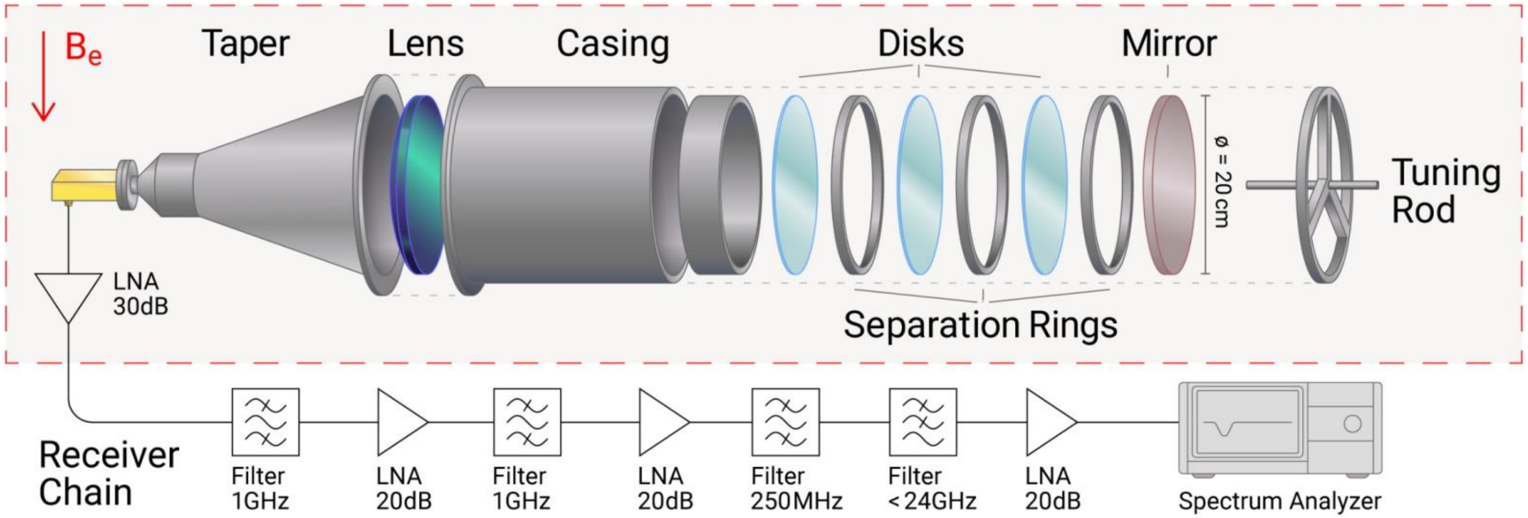
First ALP limits

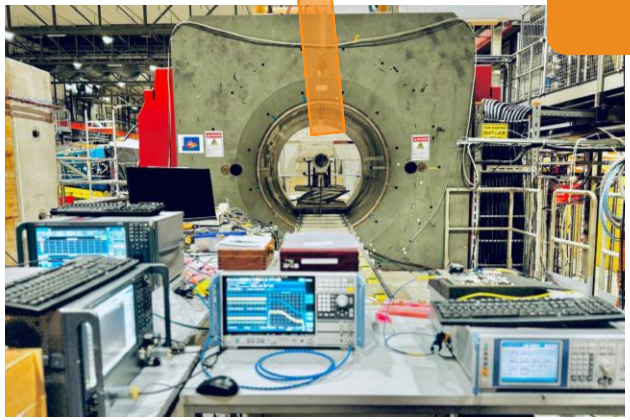
arXiv:2409.11777

- Primarily MPP
- MPP contribution

Build Booster → Prepare booster states → Measurements → Calibration → Statistical analysis

- 14.5 days data taking using 1.6 T MORPURGO magnet @ CERN
- Three disk closed booster @ room temperature
- 20 cm sapphire disks with replaceable spacers
  → small tunability





First ALP limits

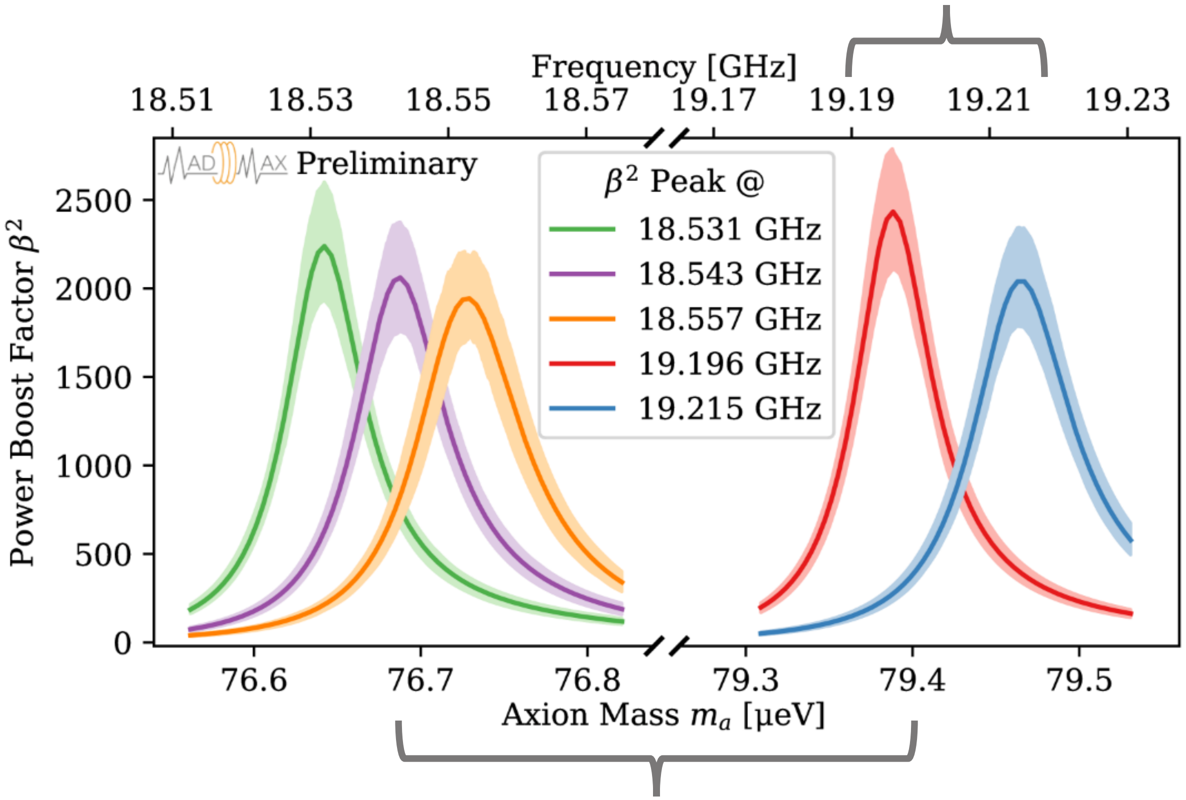
arXiv:2409.11777

Boost factor determination via simulations:

- Closed boundary conditions lead to finite set of modes in booster
- At frequency of boost peak one mode dominates → can use 1D model

Five datasets in two separate frequency ranges obtained

Vary pressure on mirror with tuning rod

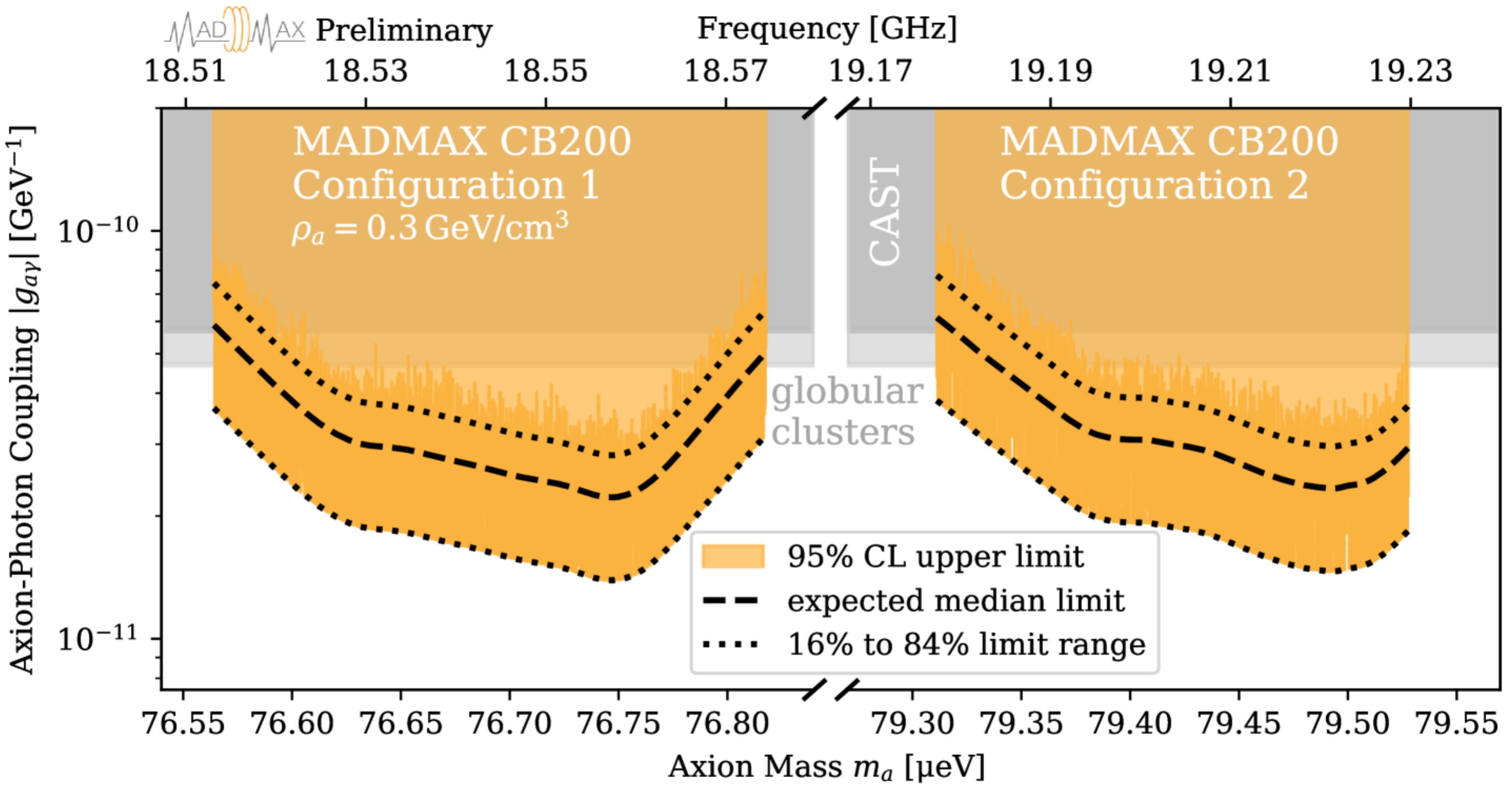


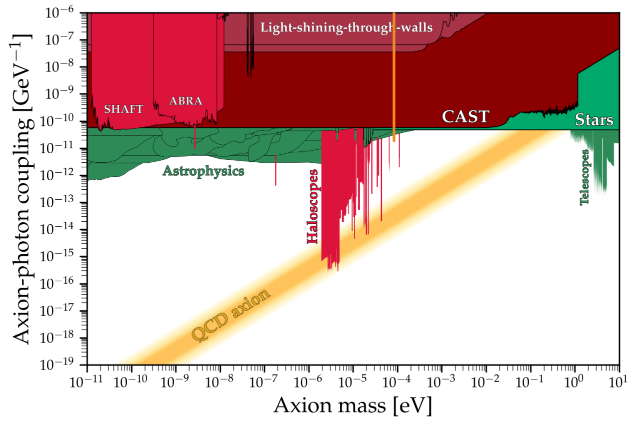
Different separation rings

First ALP limits

arXiv:2409.11777

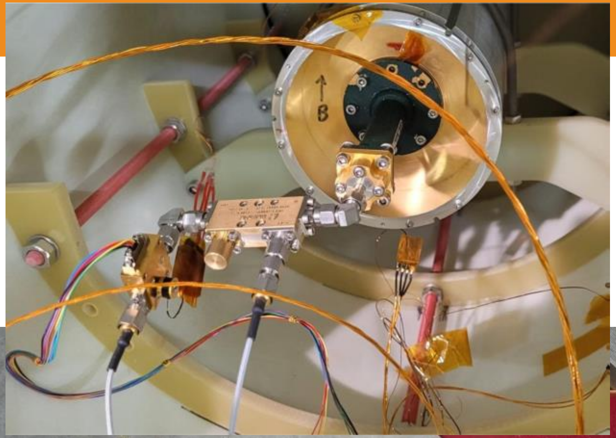
- No potential signal found → set 95% CL exclusion limit

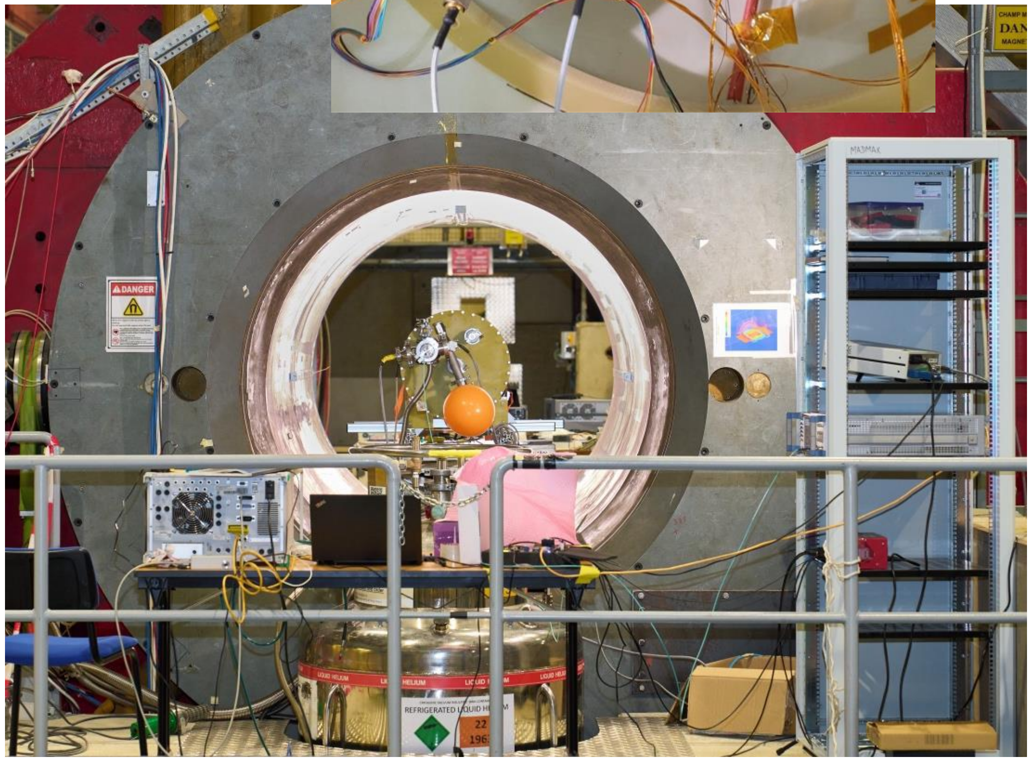


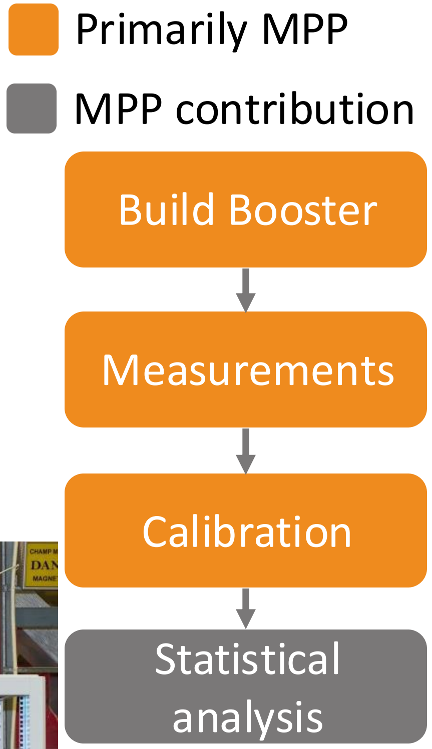


First cryogenic ALP search

- 1 day data taking using 1.6 T MORPURGO magnet @ CERN
- system temperature ∼14 K
- semi-automatic calibration → single thermal cycle
- Cryostat developed with CERN cryolab
- Analysis presently ongoing



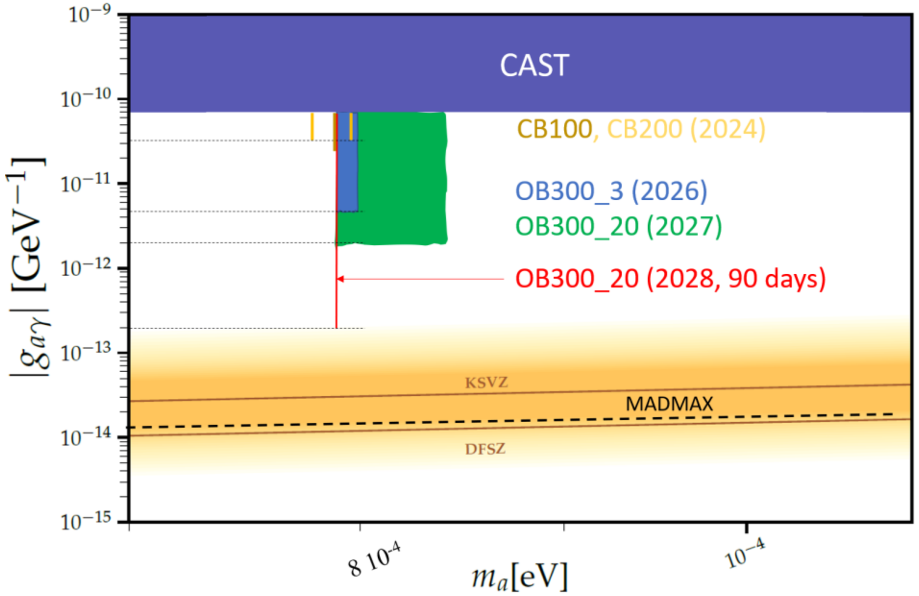




Outlook & Conclusion

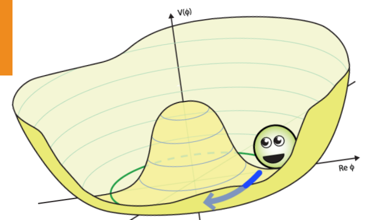
Next steps

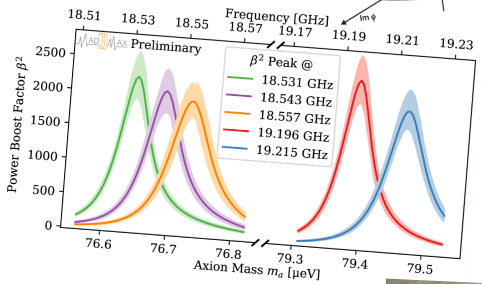
- To reach MADMAX design goals:
  - Number & radius of disks ↑
  - system temperature ↓
- Plans for next measurement campaigns:
  - 2025 FNAL, 9.4 T magnet, closed setup, diameter
  - 2026-2029 long CERN shutdown, open tuneable 30 cm setup at cold
- Investigate quantum limited & single photon detection to minimize system temperature
- Continuation of magnet project secured thanks to “MPG Vorhaben”

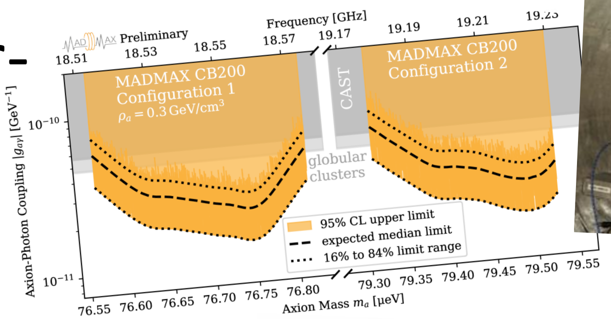


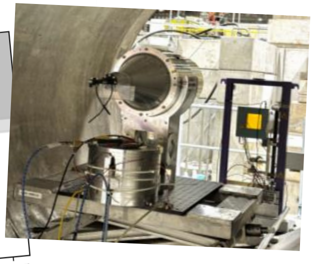
Conclusion

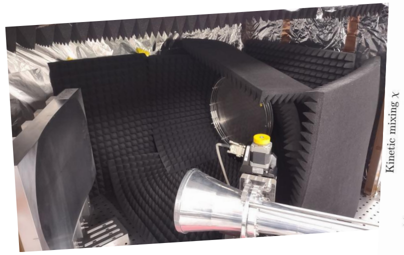
- Axions & ALPs are well-motivated DM candidates potentially also solving strong CP problem
- MADMAX first experiment proposed to search in post-inflationary mass range beyond 100 μeV
- Prototype setups demonstrate ability to deter-mine boost factor using different methods
- Competitive ALP and dark photon limits obtained
- Continue scaling of system using stronger FNAL magnet & longer run at CERN

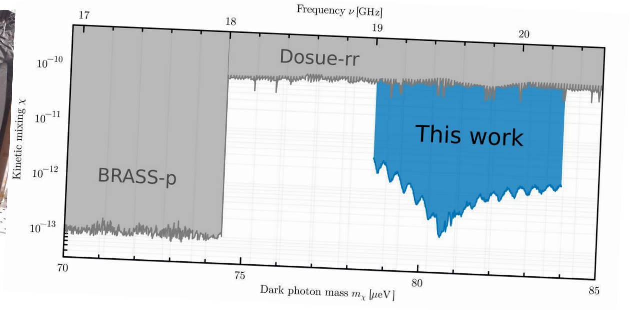








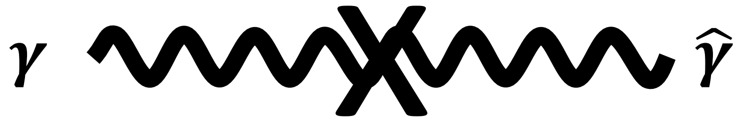




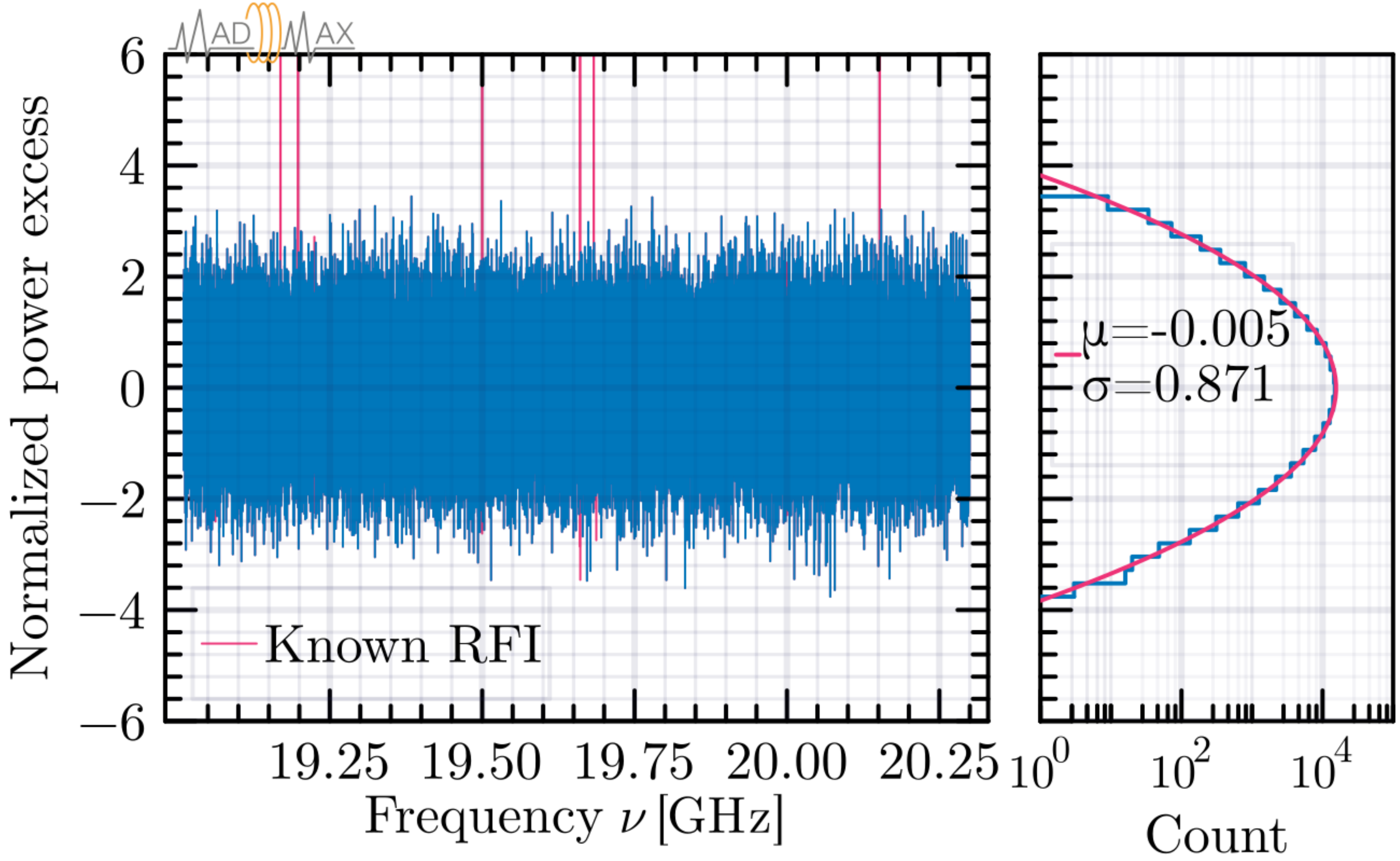
Backup

First dark photon limit – motivation

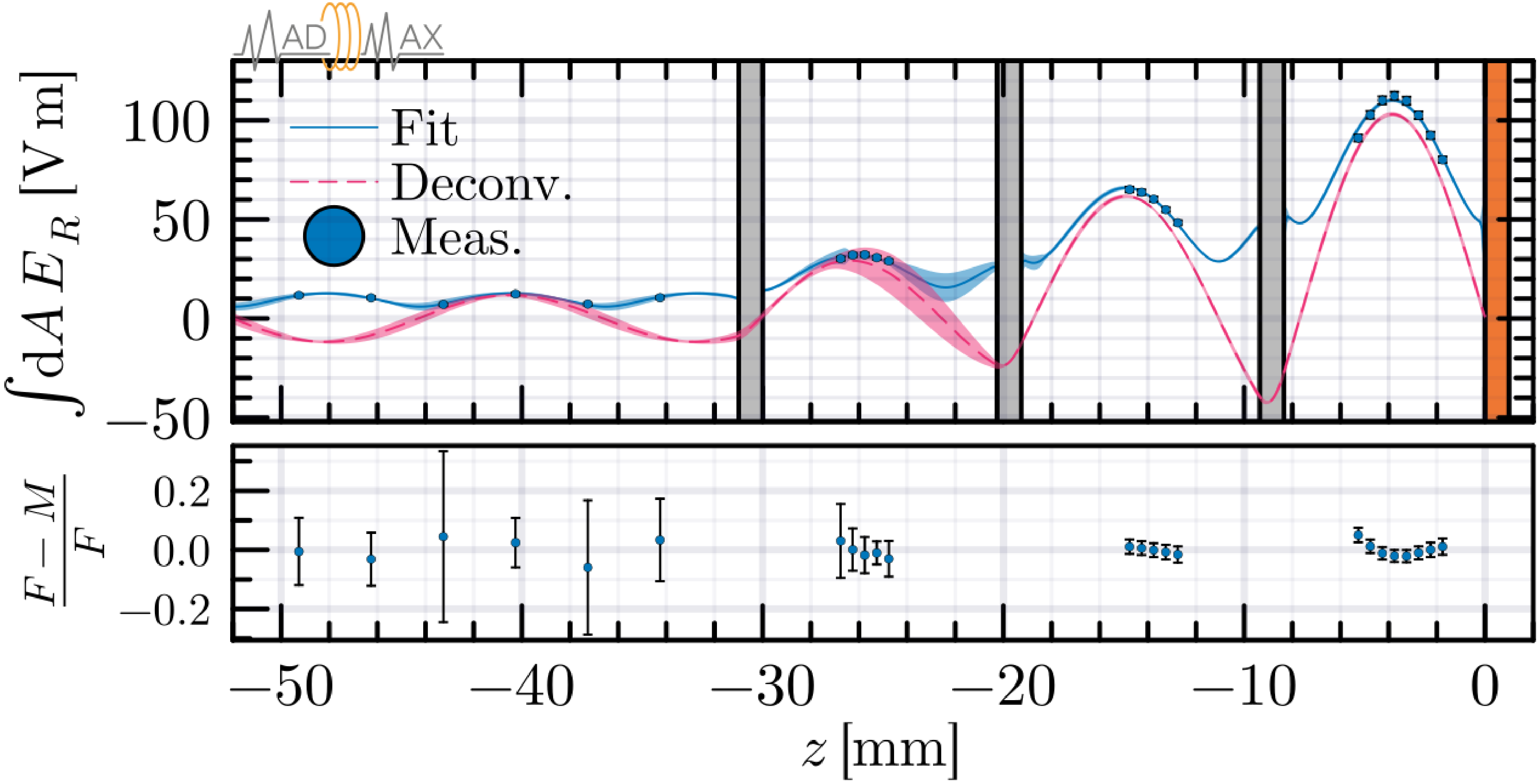
- New U(1) gauge symmetry, dark photon is corresponding gauge boson
- Kinetic mixing to normal photon, dimensionless mixing parameter χ
- Can be polarized or unpolarized
- Required experimental design very similar to ALPs, but no magnetic field required



First dark photon limit – grand spectrum

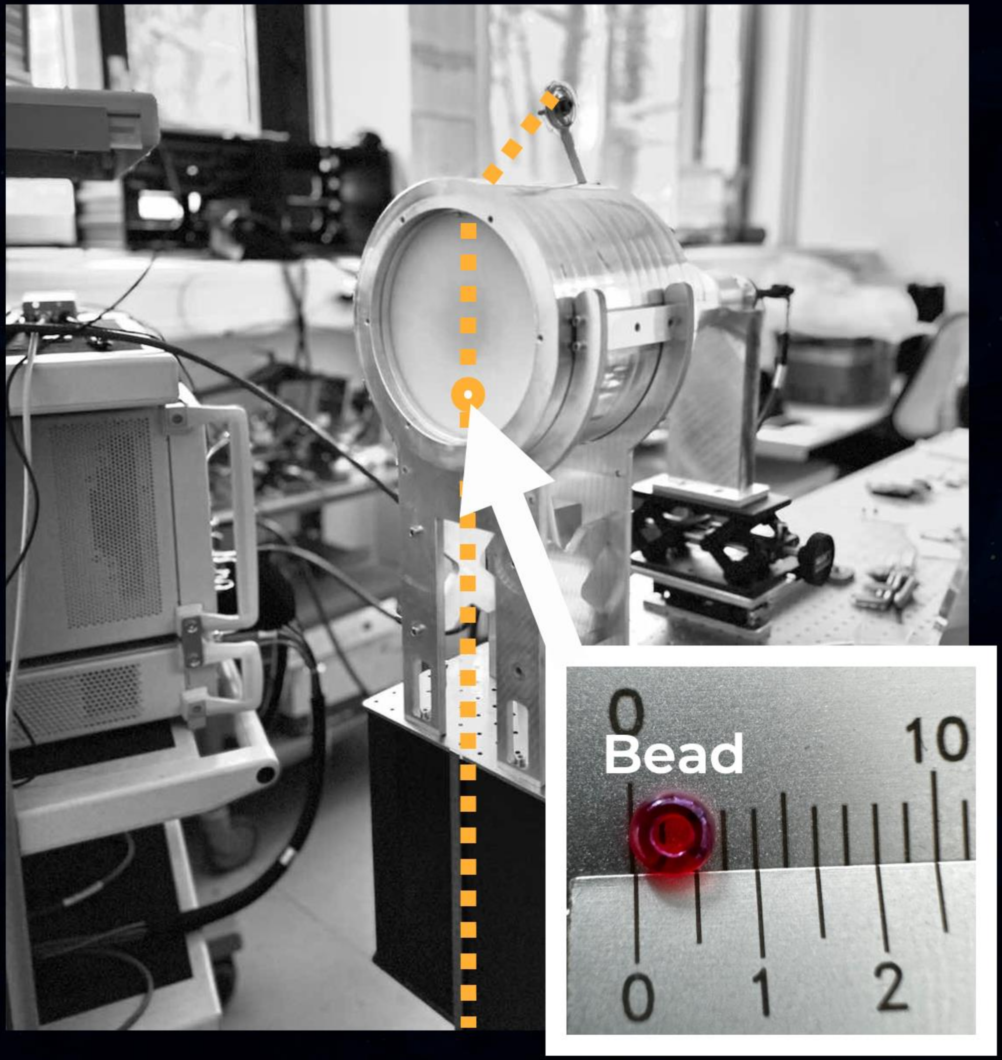


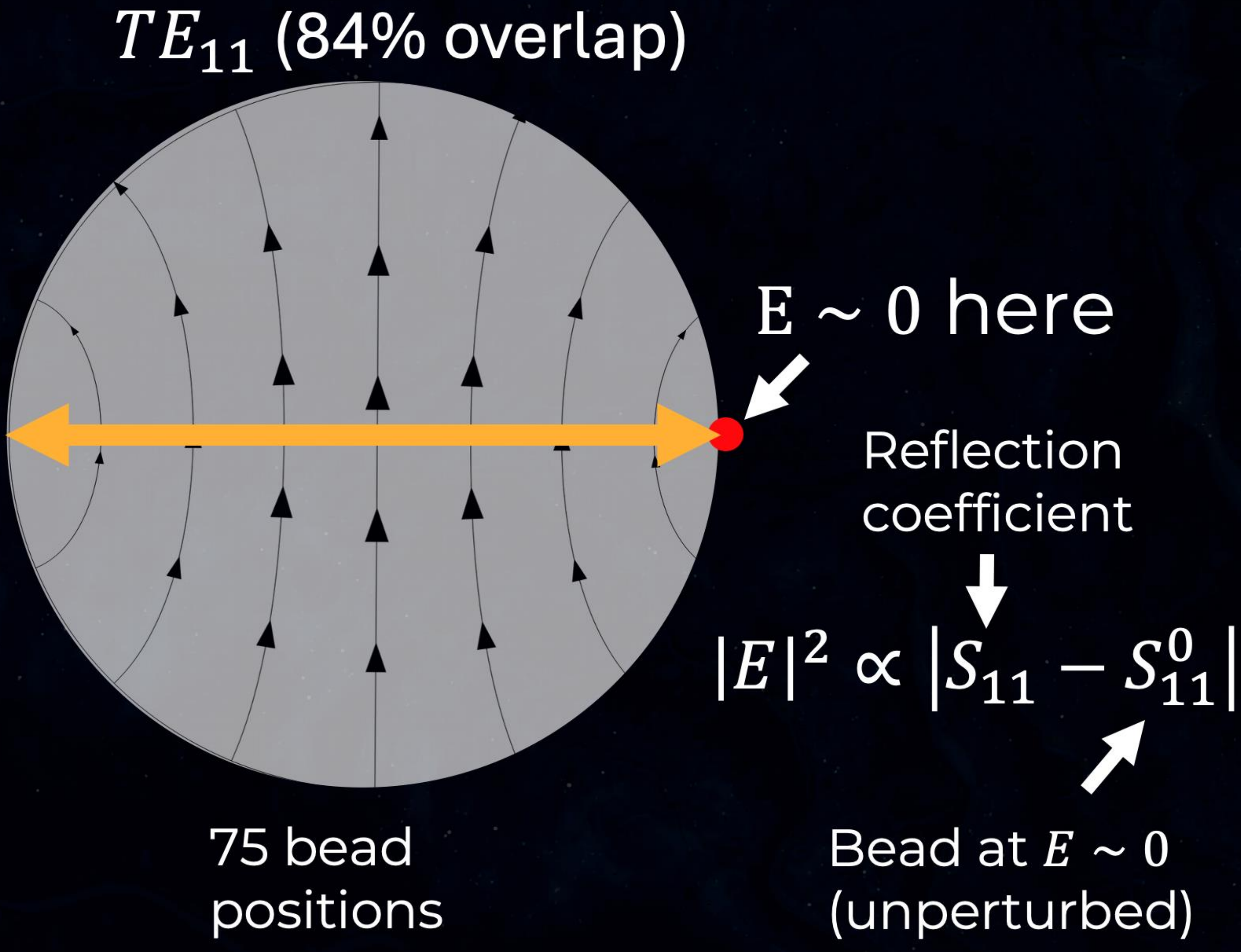
First dark photon limit – Field measurement



Slide by Juan Maldonado

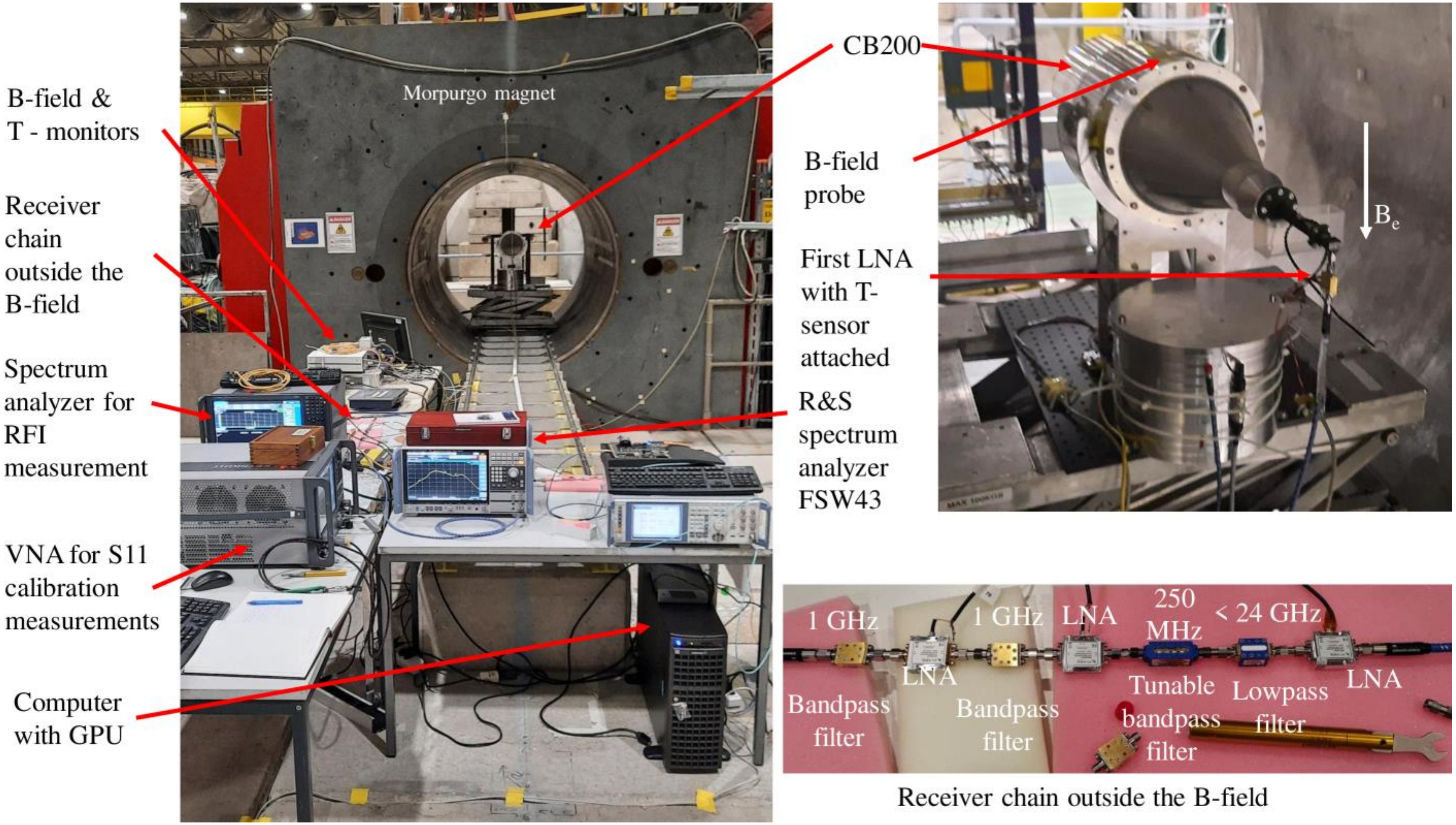
Field measurement setup



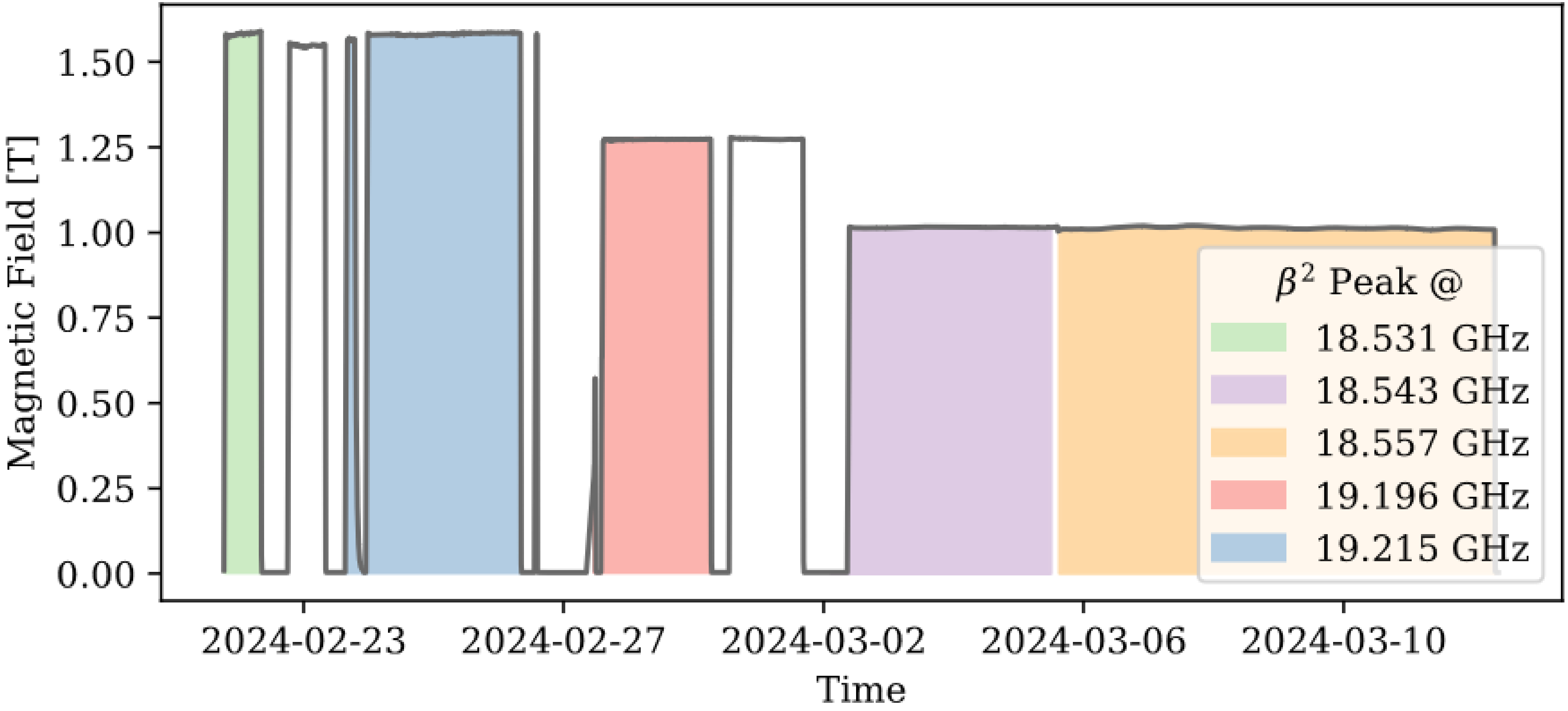


First ALP limits – setup

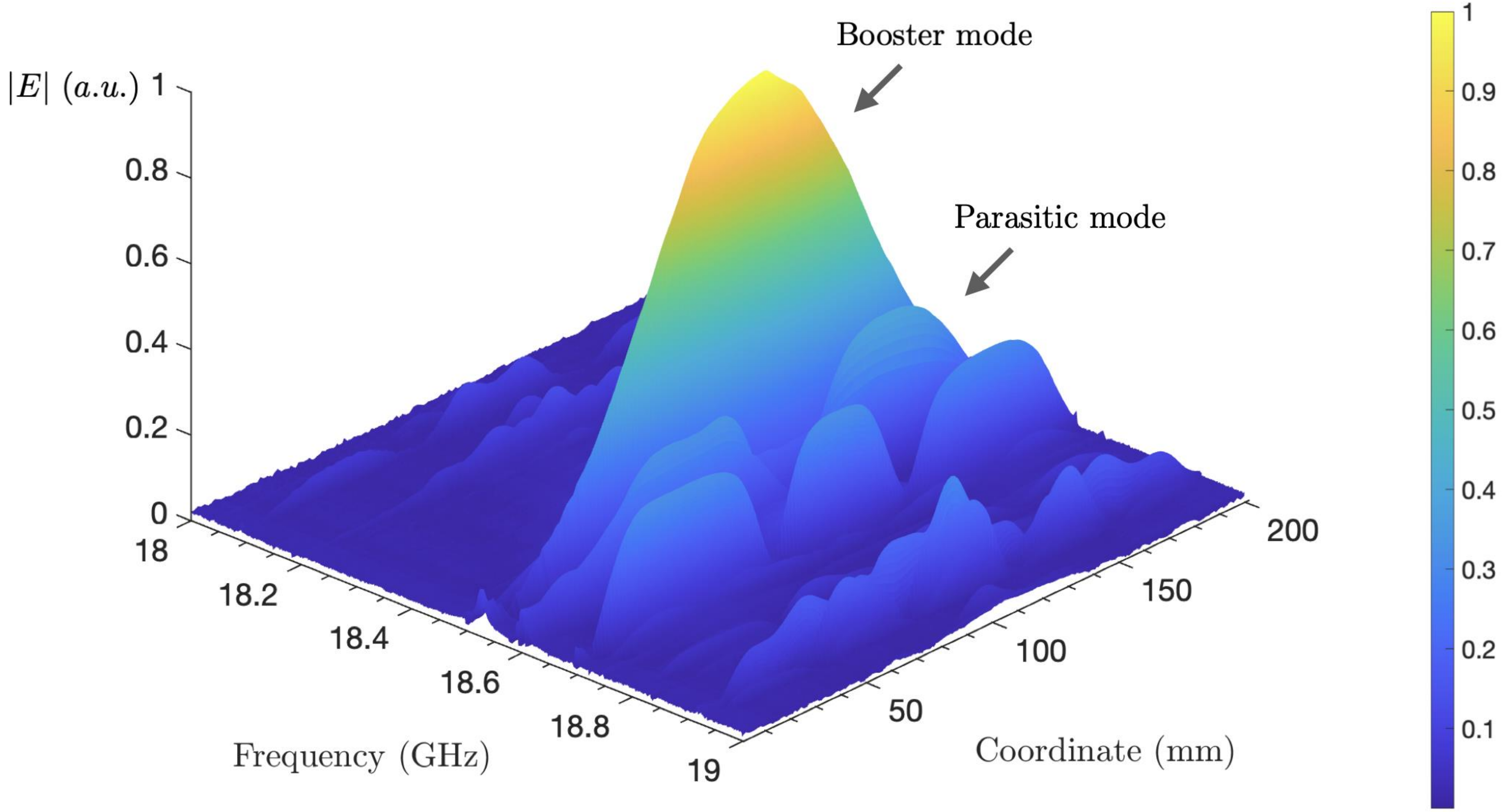
arXiv:2409.11777



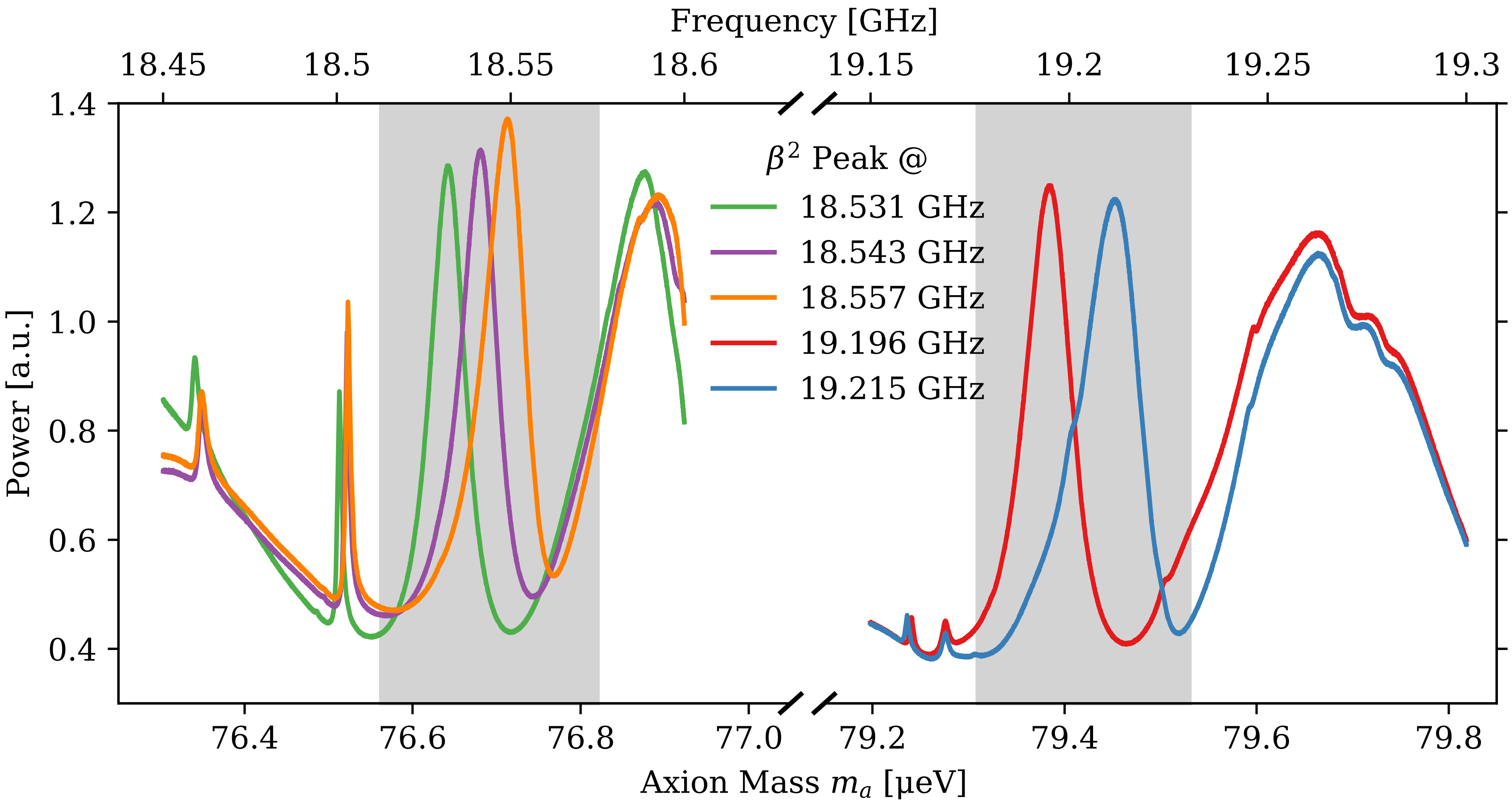
First ALP limits – B-field evolution



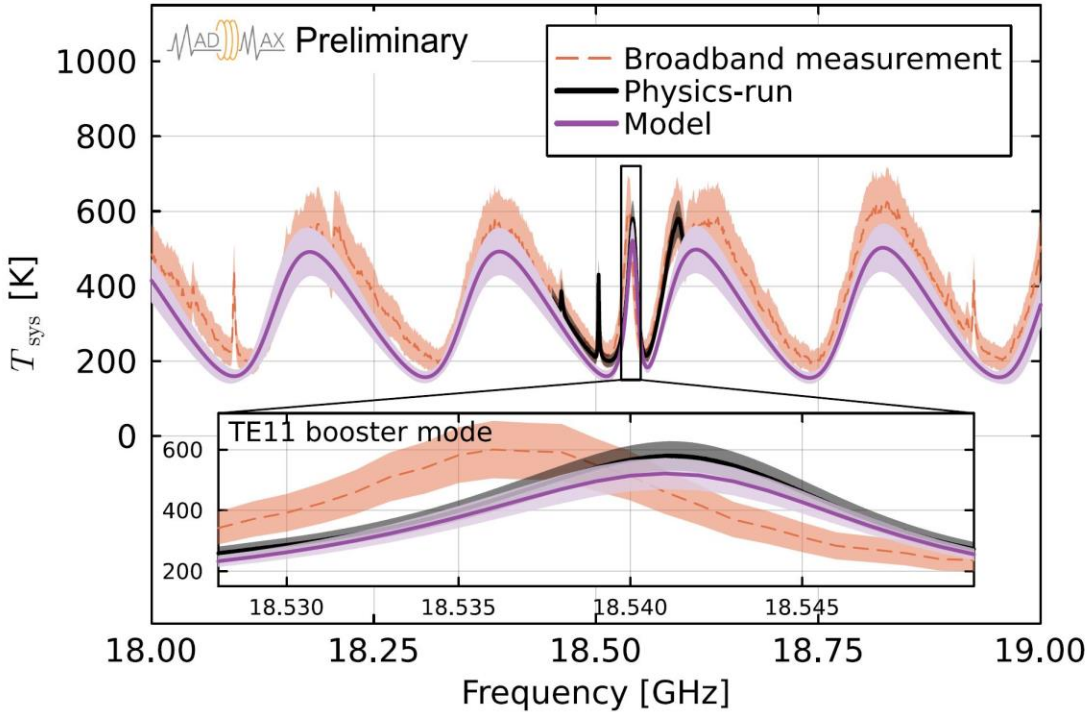
First ALP limits – fields in the system



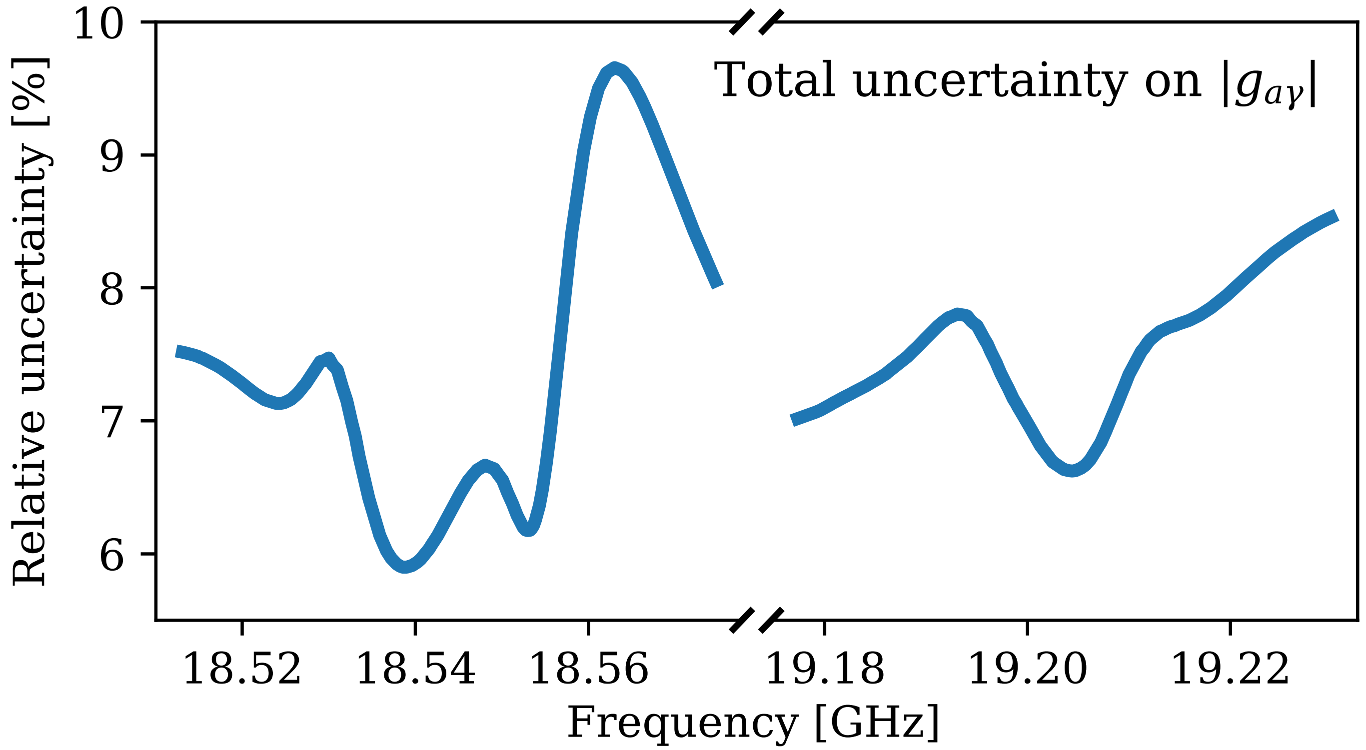
First ALP limits – raw data

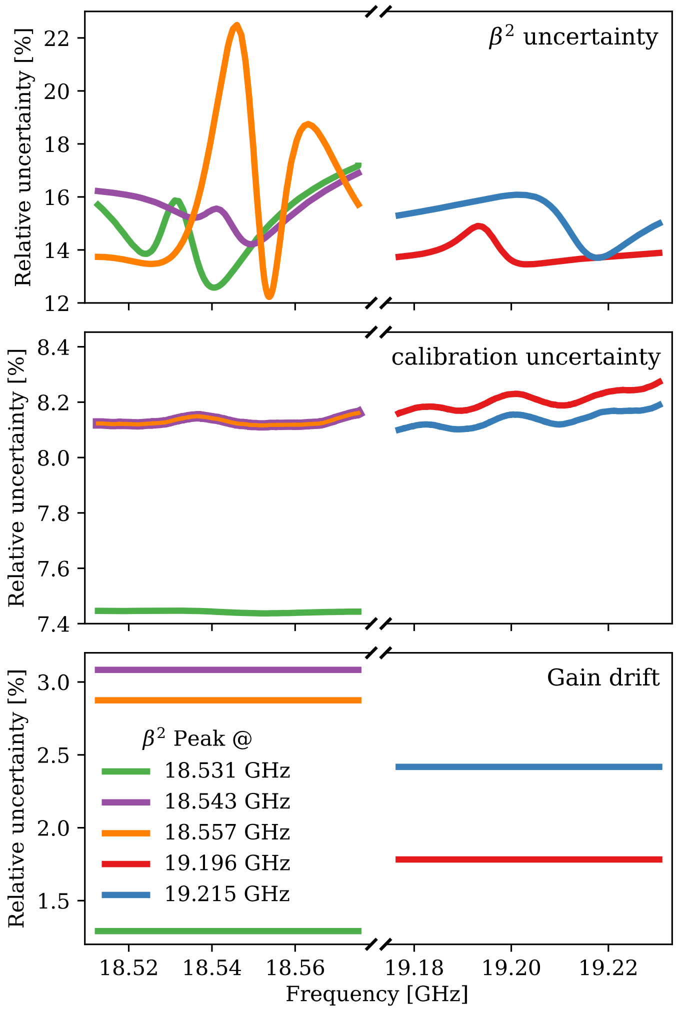


First ALP limits – calibration

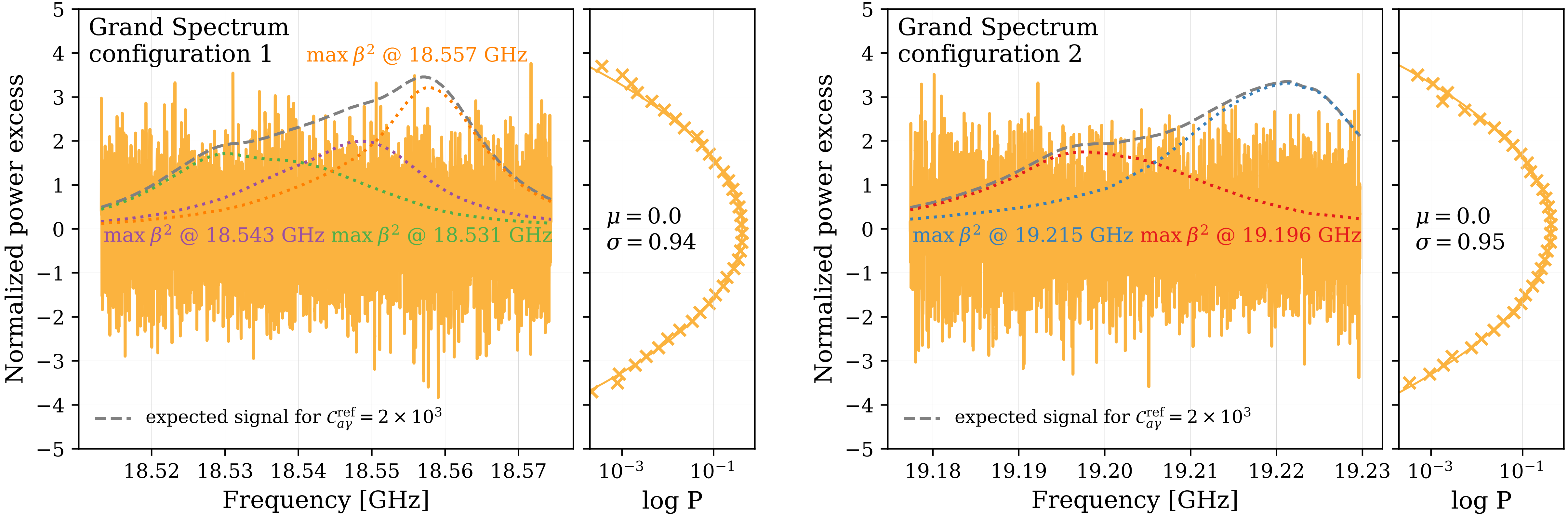


First ALP limits – uncertainties

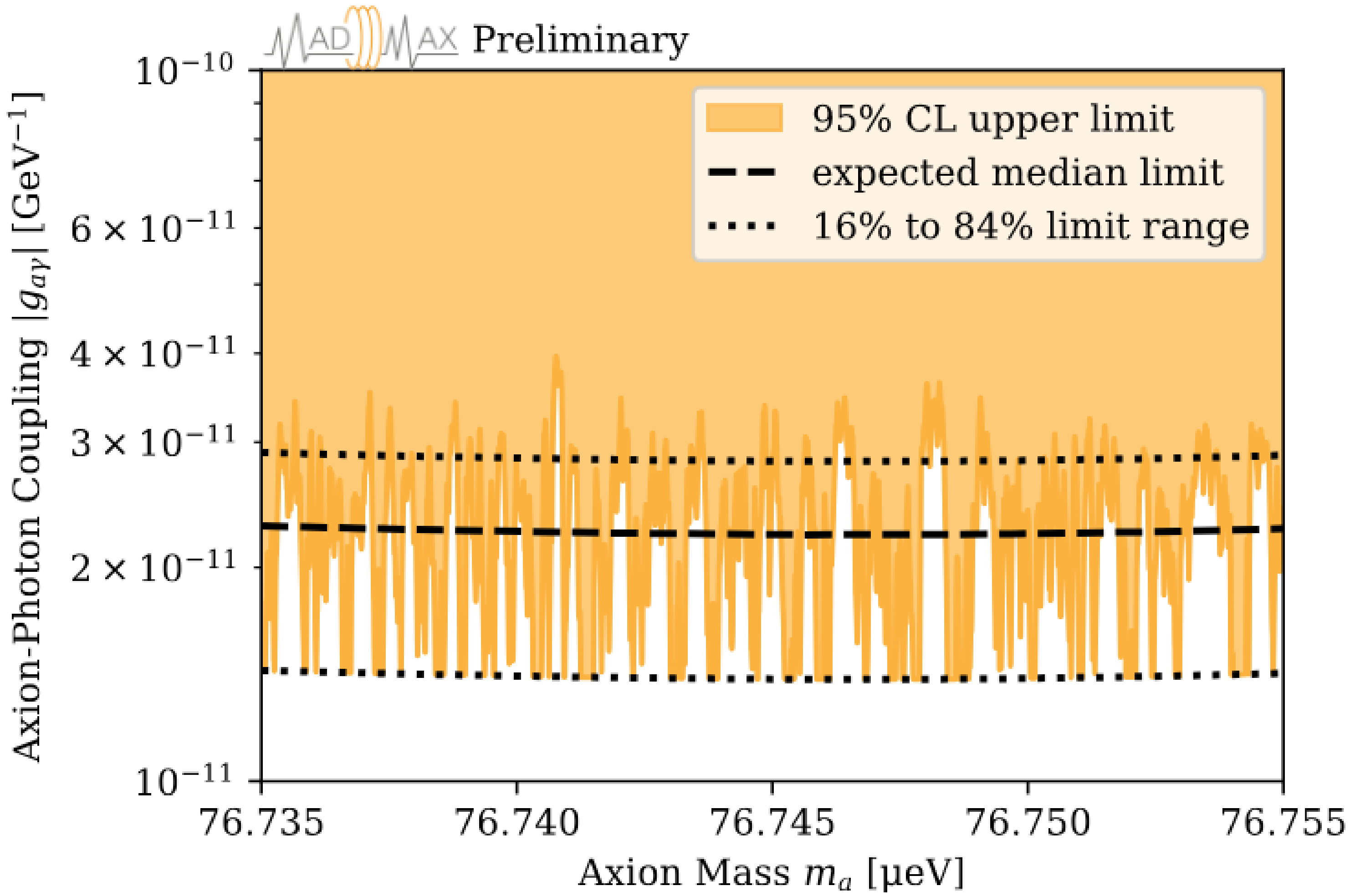




First ALP limits – grand spectra



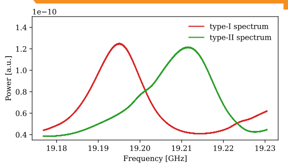
First ALP limits – limit zoom



Abstract Analysis Overview

Modelled after HAYSTAC '17

DATA (raw spectra)



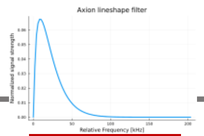
FILTER

Fit back-ground

Gaussian Random Samples

Combine to 1 spectrum

Gaussian Random Samples

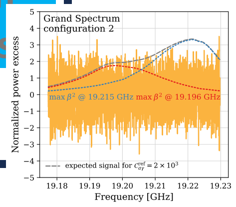


FILTER

Signal shape

Gaussian Random Samples

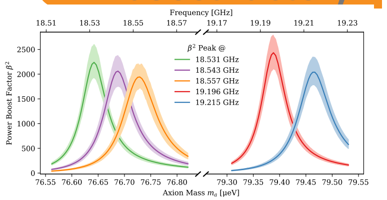
Grand Spectrum

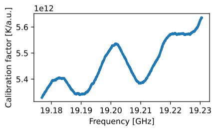


Optional, enhances sensitivity

Optional, combine using weights corresponding to signal strength

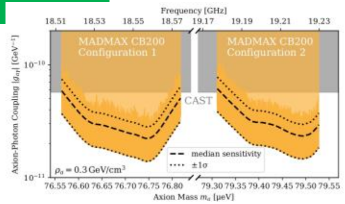
METADATA (power calibration, boost factor)





If a signal is there, how big would it be?

Exclusion Limit

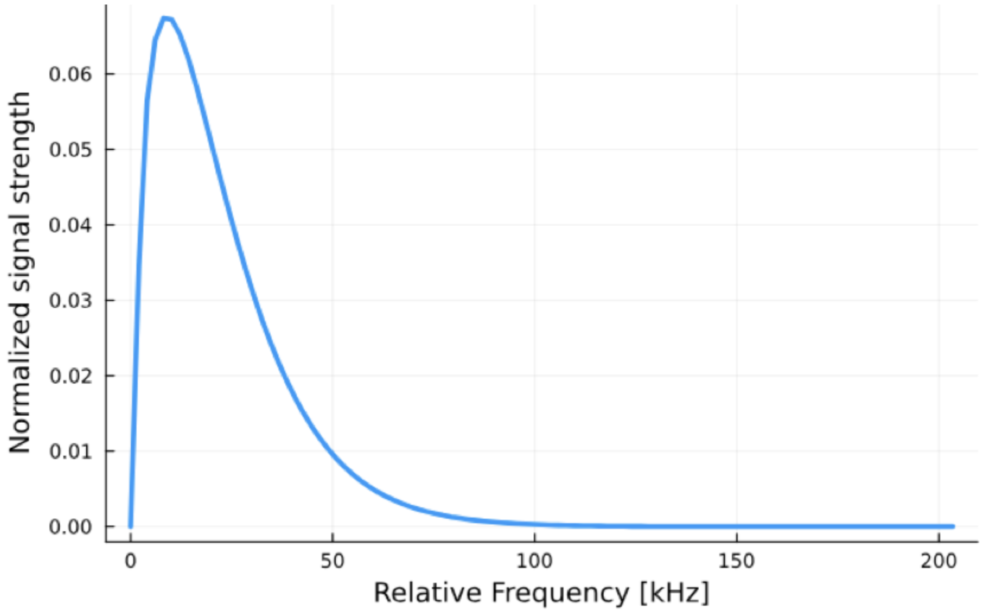


- Convert data to test statistic with known distribution
- Trace how to convert test statistic into signal parameter
- Hypothesis Test

MADMAX expected signal

$$\frac{dP}{d\omega} \propto \frac{\rho_a \; g_{a\gamma}^2(E/N)}{m_a^2} \cdot f(v_{DM})$$

- m_a axion mass
- ρ_a axion energy density
- $f(v_{DM})$ dark matter velocity distribution
- $g_{a\gamma}(E/N)$ axion-photon coupling (which depends on anomaly ratio E/N.



Frequentist Limits

1. Test statistic with known distribution
2. Decide on Hypothesis Test

   "measurement rules out a 5σ signal at 95% confidence level"
3. Trace how to convert test statistic into signal parameter