RF technology in MADMAX

RF technology for fundamental physics

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The MADMAX collaboration:

Universität Hamburg — DER FORSCHUNG | DER LEHRE | DER BILDUNG
DESY.
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MAX-PLANCK-INSTITUT FÜR RADIOASTRONOMIE
IJCLab Irène Joliot-Curie — Laboratoire de Physique des 2 Infinis
RWTH AACHEN UNIVERSITY
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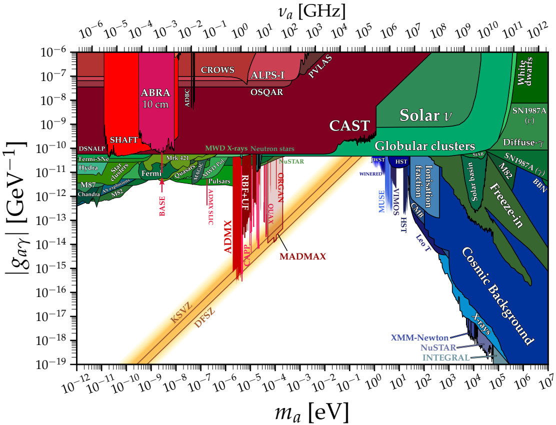
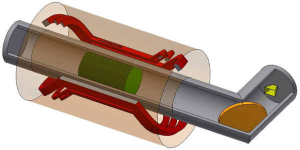
Axion dark matter

- Axion motivated by solution to strong CP problem
- Abundant production by vacuum realignment and topological defects
- Popular dark matter candidate
- Axions within a magnetic field induce an effective current: $\mathbf{J}_a = g_{a\gamma}\mathbf{B}\dot{a}$ (modified Maxwell)
- Equivalence between frequency and mass: well motivated mass range in RF band (0.3 GeV to 300 GeV)



Axion landscape with MADMAX projection
Yellow band: benchmark QCD axion models

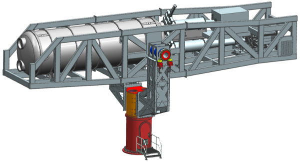
Experiment types



MADMAX

(Haloscopes)

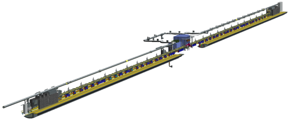
- Non-relativistic dark matter axions
- Usage of RF cavities



BabyIAXO

(Helioscopes)

- Relativistic solar axions
- X-Ray detector $\rightarrow$ no RF technology



ALPS II

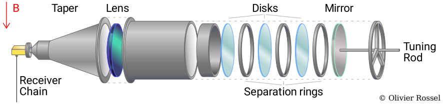
(Light-Shining-Through-Wall Experiments)

- Relativistic laboratory axions
- Laser technology
- RF signal after optical down conversion

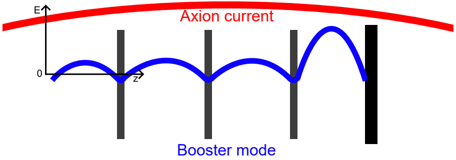
MADMAX

Booster principle

- Axion current J_a from coupling to magnetic field
- Couples to electric field within booster
- Signal power $P_{sig} \propto |\int_V dV \; J_a \cdot E|^2$
- Dielectrics allow to shape the booster mode
  $\rightarrow$ Booster enhances SNR!



MADMAX prototype booster system

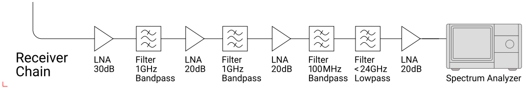


Schematic of electric field within booster

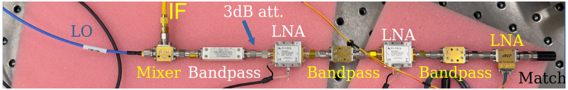
MADMAX

Receiver chain principle

- ADC noise floor at $\sim -120\,\text{dBm}$
- Signal at thermal noise level $\sim -170\,\text{dBm}$
  $\rightarrow$ Amplification of $> 50\,\text{dB}$ needed!
- Heterodyne system
- Amplification of signal *and* noise!

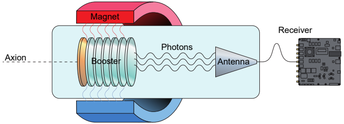


Closed booster receiver chain



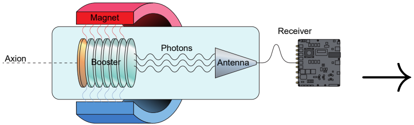
Open booster receiver chain

Simulated measurements

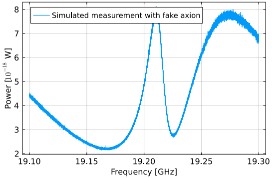


Experiment

Simulated measurements



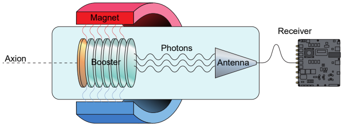
Experiment



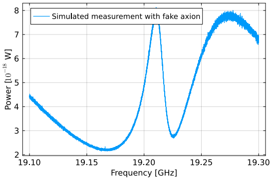
Simulated measurement
(with software-injected axion)

- Baseline shape subtracted using savitzky golay filter

Simulated measurements



Experiment



Simulated measurement
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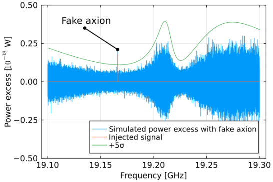
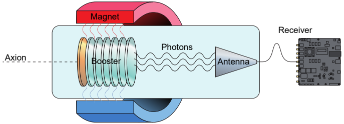


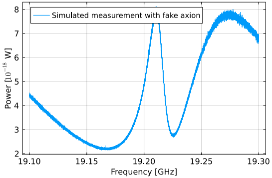
Residual power
(with software-injected axion)

- Baseline shape subtracted using savitzky golay filter
- Expected noise fluctuation $\sigma \propto \frac{P}{\sqrt{t_{int}}}$ known
  $\rightarrow$ Power excess can be translated to units of σ (with some extra steps)

Simulated measurements



Experiment



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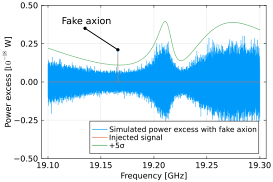
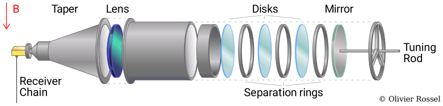


Residual power
(with software-injected axion)

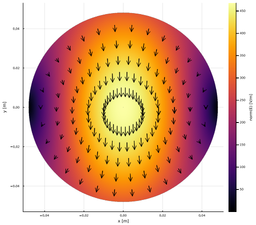
- Baseline shape subtracted using savitzky golay filter
- Expected noise fluctuation $\sigma \propto \frac{P}{\sqrt{t_{int}}}$ known
  $\rightarrow$ Power excess can be translated to units of σ (with some extra steps)
- Potential outcomes:
  1. $\geq 5\sigma$ excess found:
     $\rightarrow$ potential discovery, perform rescan
  2. No $\geq 5\sigma$ excess found, set bin-by-bin limit:
     $\rightarrow g_{a\gamma}$ that is ruled out by measurement with 95 % confidence (requires P_{sig}!)

Booster simulation

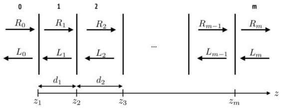


Booster system

- Closed booster is a circular waveguide
- Allowed modes depend on radius
- Focus on TE11 mode (fundamental mode)
- Transverse part given by theory
- Longitudinal part sum of all reflected waves



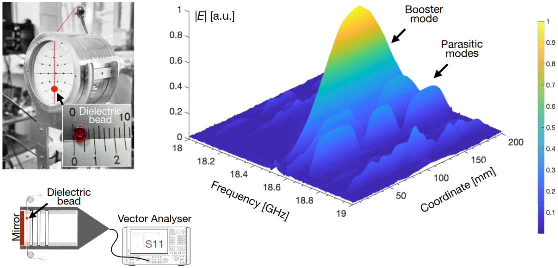
Transverse field of TE11 mode



Longitudinal part

Booster mode identification

- Frequency of TE11 mode resonance verified by bead pull measurement
- Alternative methods:
  - Press against mirror, see which feature moves on VNA
  - ”Poor persons beadpull”: glue absorber to different parts of the mirror

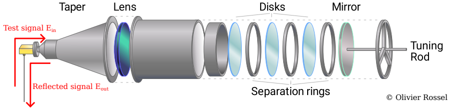


Electric field as measured by bead pull

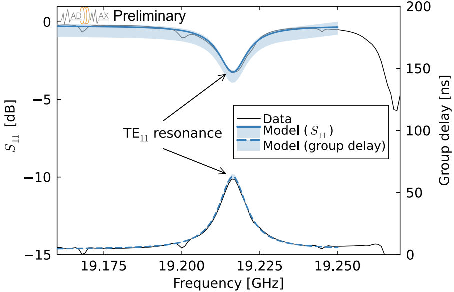
Booster simulation

Longitudinal part

- Lot's of free parameters:
  - Disk positions
  - Disk thicknesses
  - Losses
  - ...
- Extracted from reflectivity measurement
- Similar to cavity simulation (determining Q-factor and coupling)
- Allows to determine expected signal power P_{sig}

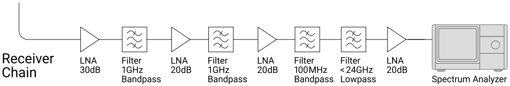


Reflectivity measurement



Reflectivity fit

Receiver chain calibration



Receiver chain

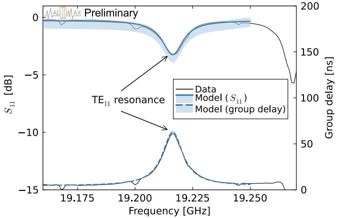
- Calibration using known *matched* noise source

- Best case:
  simple linear amplification by gain G
  $\rightarrow P_{meas} = GP_{sig}$
- Second best case:
  linear amplification G and added noise P_n:
  $\rightarrow P_{meas} = GP_{sig} + P_n$
- Third best case:
  linear amplification G, added noise P_n, added mismatch
  (receiver chain reflects Γ_r):
  $\rightarrow P_{meas} = G(1 - |\Gamma|^2)P_{sig} + P_n$

$\rightarrow P_{meas}$ given by affine function of P_{sig}

Receiver chain noise model

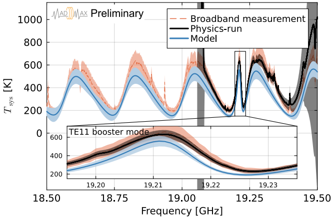
Why is it needed?



Reflectivity fit

→

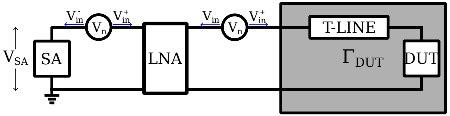
?



Noise measurement fit

- P_{sig} already given by booster simulation
- Receiver chain is only for measurement - shouldn't change a thing?
- Mismatched receiver: part of signal reflected back into booster
  $\rightarrow$ Receiver chain changes P_{sig}!
- Quantifying this requires knowledge of Γ_r as "seen" from booster
  $\rightarrow$ also requires knowledge of receiver chain position

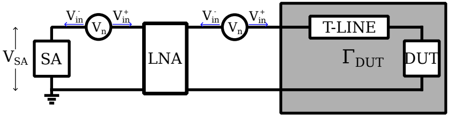
Receiver chain noise model



LNA noise as two voltage noise sources

- LNA noise modelled by correlated noise sources
- Connected device modelled by reflectivity
- Noise parameters determined by measuring known standards
- DUT emits noise of
  $P_n = k_B B T_{phys}(1 - |\Gamma_{DUT}|^2)$

Receiver chain noise model



LNA noise as two voltage noise sources

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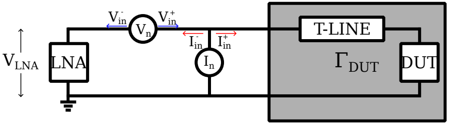
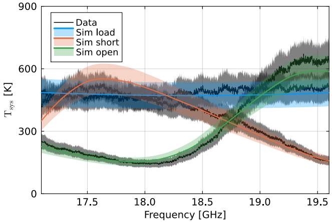


LNA noise as voltage and current source

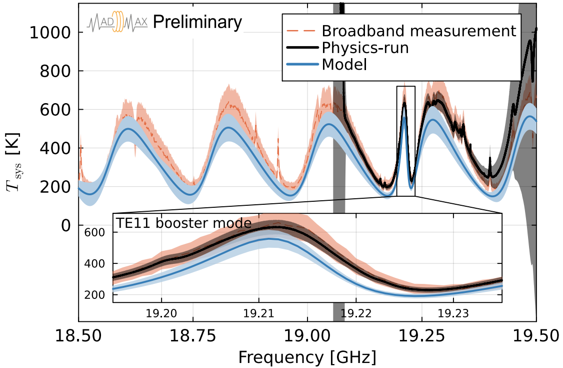
- LNA noise modelled by correlated noise sources
- Connected device modelled by reflectivity
- Noise parameters determined by measuring known standards
- DUT emits noise of
  $$P_n = k_B B T_{phys}(1 - |\Gamma_{DUT}|^2)$$



LNA connected to standards with simulation

Receiver chain + closed booster

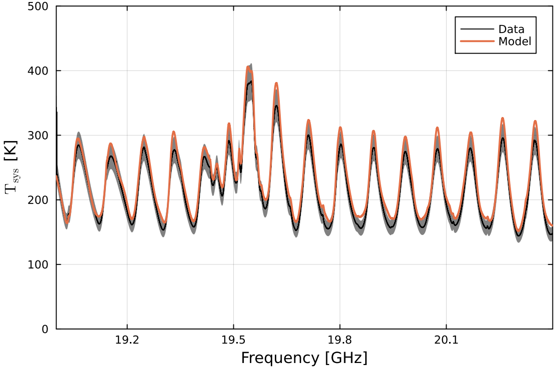
- LNA and booster parameters fixed
  $\rightarrow$ Full noise spectrum simulation possible
- Distance LNA $\leftrightarrow$ booster as fit parameter
- Allows to calculate change of P_{sig} due to receiver
- Now serves as additional calibration tool!



Noise measurement and model

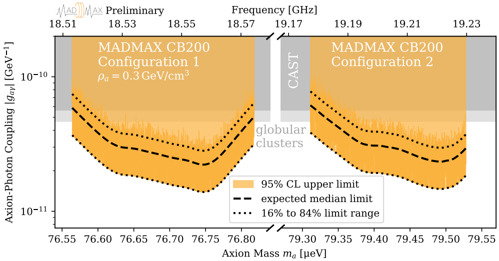
Receiver chain + open booster

- Open booster simulation more tricky
- Bead pull method used instead
- Noise model uses booster reflectivity measurement instead of model

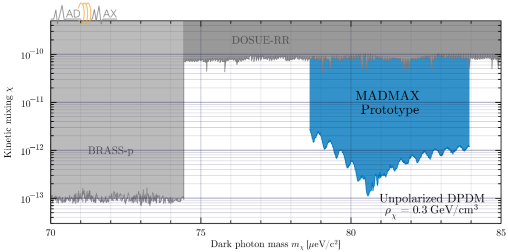


Noise model fit using reflectivity measurement

Final results



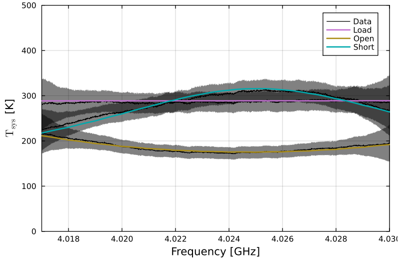
Axion limit using closed booster



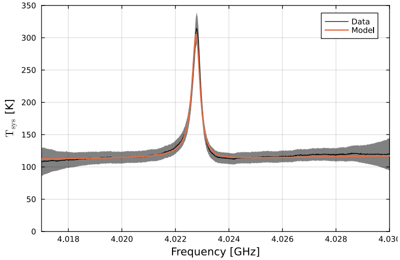
Dark photon limit using open booster

Receiver chain + cavity

- Model also applicable to cavities
- LNAs at lower frequencies usually better matched
- Still, effect non-negligible
- Circulators often used to bypass this effect



Lower frequency LNA model



Noise model for cavity

Summary

- Haloscope experiments are very sensitive microwave detectors
- MADMAX uses a combination of:
  - (Super) heterodyne receiver
  - Waveguides
  - Gaussian beam optics
  - Transmission line theory

  to build and simulate such a broadband detector
- Methods applicable to other haloscope experiments as well