# Searches for ultra-light dark matter with the Shuket experiment

VLDM 2021

September, 27th


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# Hidden photon dark matter

Assume new U(1) symmetry: new vector field $\phi^\mu$

Relevant part of lagrangian:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} - \frac{m^2}{2}\phi_\mu\phi^\mu - \boxed{\frac{\chi}{2}F_{\mu\nu}\phi^{\mu\nu}}$$

kinetic mixing with conventional photons
dimensionless parameter $\chi$

$\chi$ could be $10^{-12}$ / $10^{-3}$

K.R. Dienes *et al.*, Nucl Phys B 1997
M. Goodsell *et al.*, JHEP 2009
M. Goodsell *et al.*, JHEP 2012

# Relic density of hidden photons

- ⋆ Produced non-thermally via misalignment
- ⋆ Oscillations of the field
- ⋆ Frequency: $f = 2.4\ \mathrm{GHz} \times \dfrac{m}{10\ \mu\mathrm{eV}}$
- ⋆ In the Galaxy:

$$v = \frac{kc^2}{\omega} \quad , \qquad \omega = \frac{mc^2}{\hbar}\left(1 + \frac{v^2}{2c^2} + \mathcal{O}(\frac{v^2}{c^2})\right)$$

$v \sim 10^{-3}c$

# Hidden photons as dark matter

Phase space density is huge…

$$N_{\text{particles}} \simeq \frac{10^{12}\ \mathrm{M}_\odot}{m} \simeq 10^{83}\ \frac{10\ \mu\mathrm{eV/c^2}}{m}$$

$$N_{\text{cells}} \simeq \frac{\frac{4\pi}{3}p_{\max}^3 \times \frac{4\pi}{3}R^3}{(2\pi\hbar)^3} \simeq 2\times 10^{59} \times \left(\frac{m}{10\ \mu\mathrm{eV/c^2}}\right)^3$$

$$p_{\max} = m v_{\text{escape}} = m \times 550\ \mathrm{km/s}$$

$$R \sim 50\ \mathrm{kpc}$$

$$\frac{N_{\text{particles}}}{N_{\text{cells}}} \simeq 5\times 10^{23} \times \left(\frac{10\ \mu\mathrm{eV/c^2}}{m}\right)^4$$

# Mixing with the photon

Similarly to axion/photon mixing:

$$\left(\omega^2 - k^2 \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - m^2 \begin{pmatrix} \chi^2 & -\chi \\ -\chi & 1 \end{pmatrix}\right) \begin{pmatrix} \vec{A} \\ \vec{\phi} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

(with gauge fixing such that $\boldsymbol{\phi^0 = A^0 = 0}$)

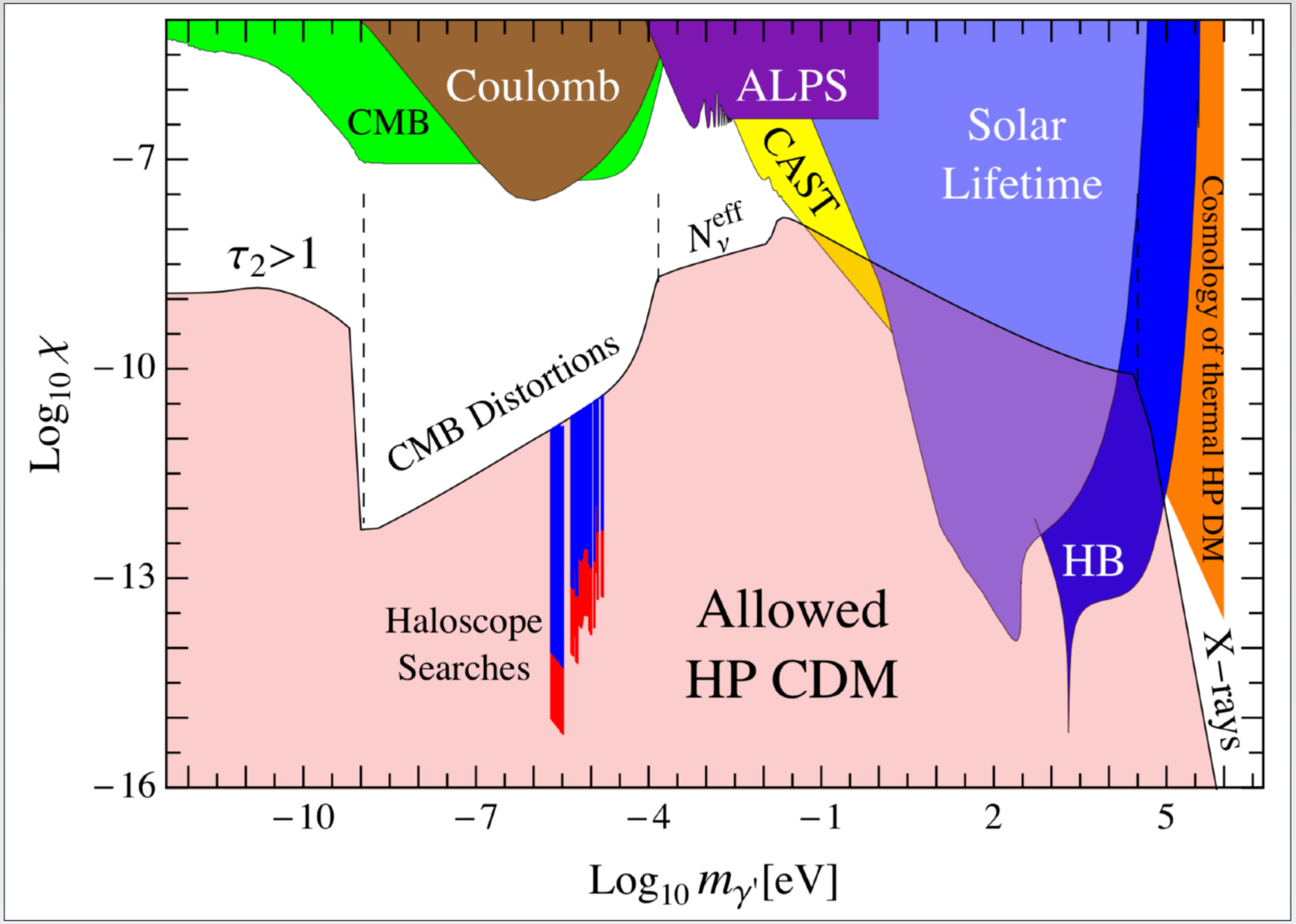
Where there is dark matter, there is a small electric field:

$$\begin{pmatrix} \vec{A} \\ \vec{\phi} \end{pmatrix}_{\mathrm{DM}} = \vec{\phi}_{\mathrm{DM}} \begin{pmatrix} -\chi \\ 1 \end{pmatrix} e^{-i\omega t}$$

$\langle \vec{\phi}^2_{\mathrm{DM}} \rangle$ given by DM density

$$\Rightarrow \quad \boxed{\vec{E}_{\mathrm{DM}} = -\partial_0 \vec{A} = \chi m \vec{\phi}_{\mathrm{DM}}}$$

# Constraints on hidden photons

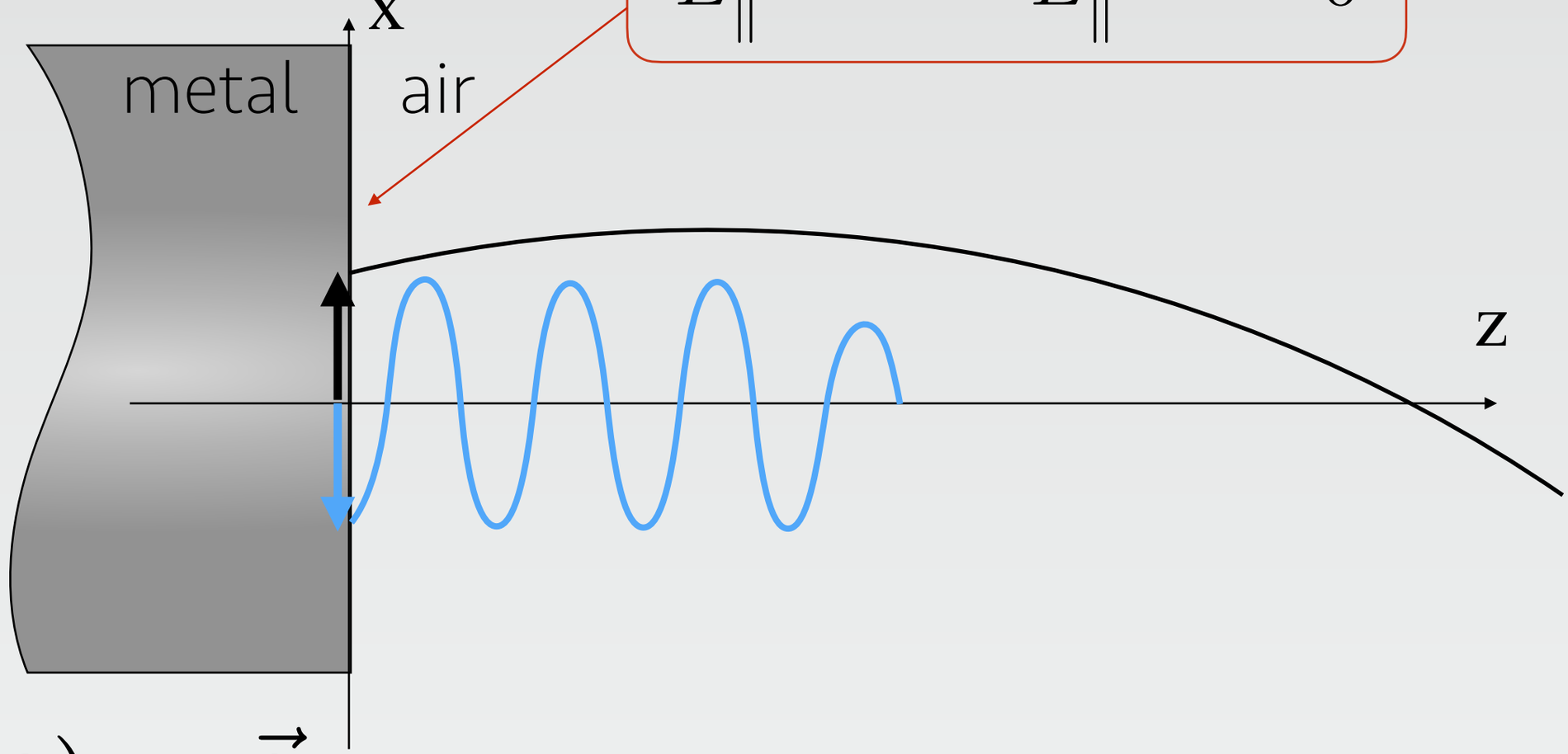



Interesting from model point of view, but no hint on the mass

# Imposing Boundary Conditions

$$\vec{E}_{\mathrm{DM}} = \chi m \vec{\phi}_{\mathrm{DM}} e^{-imt}$$

$$E_{\parallel}^{(metal)} - E_{\parallel}^{(air)} = 0$$

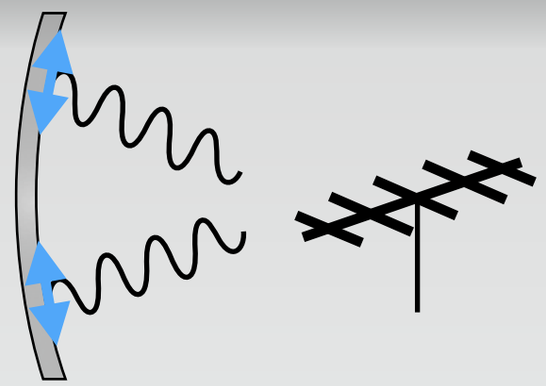



$$\vec{E}_{\parallel}(z=0) = \vec{0}$$

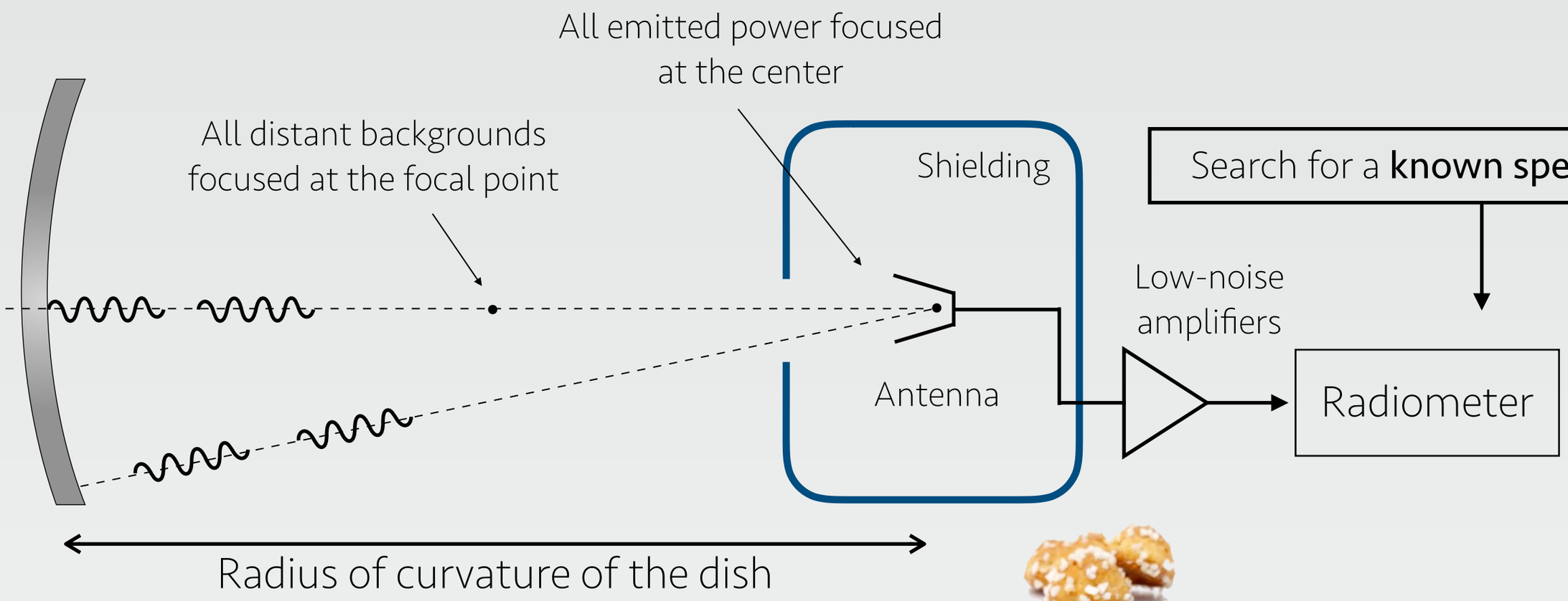
$$\vec{E}_{\mathrm{out}} = -\vec{E}_{\mathrm{DM},\parallel} e^{-i(mt-kz)}$$

# The SHUKET experiement

Dish antenna experiment



D. Horns et al. JCAP 2012
J. Jaeckel & J. Redondo, JCAP 2013
J. Jaeckel & S. Knirck, Patras 2016




SHUKET
=
SearcH for U(1) darK matter with an Electromagnetic Telescope

# Expected signal power

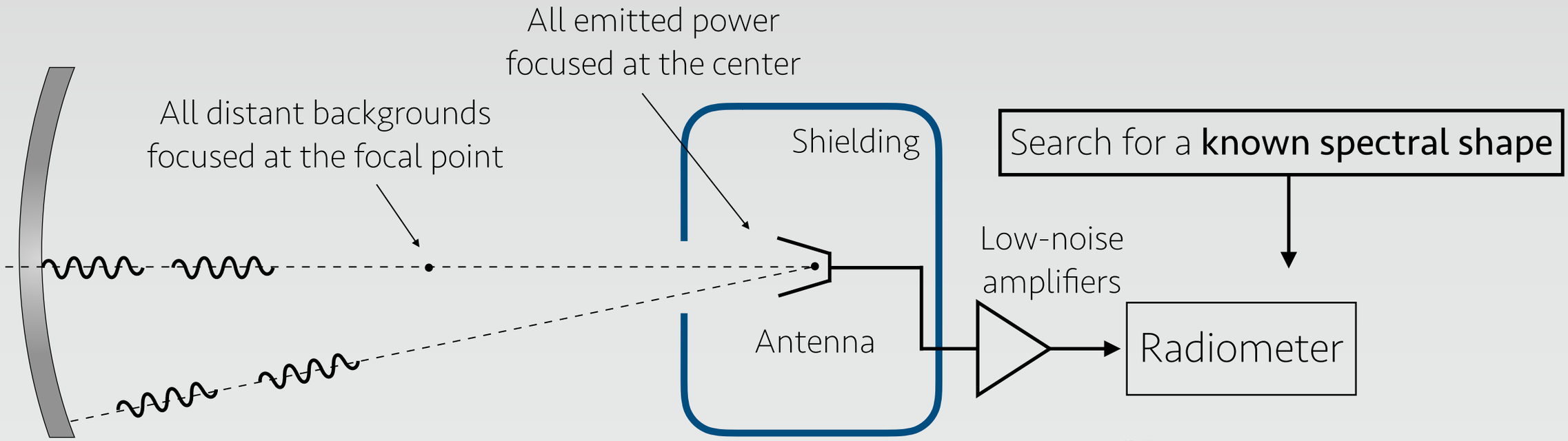
Power of out going wave depends  on

- dark matter density
- reflector area

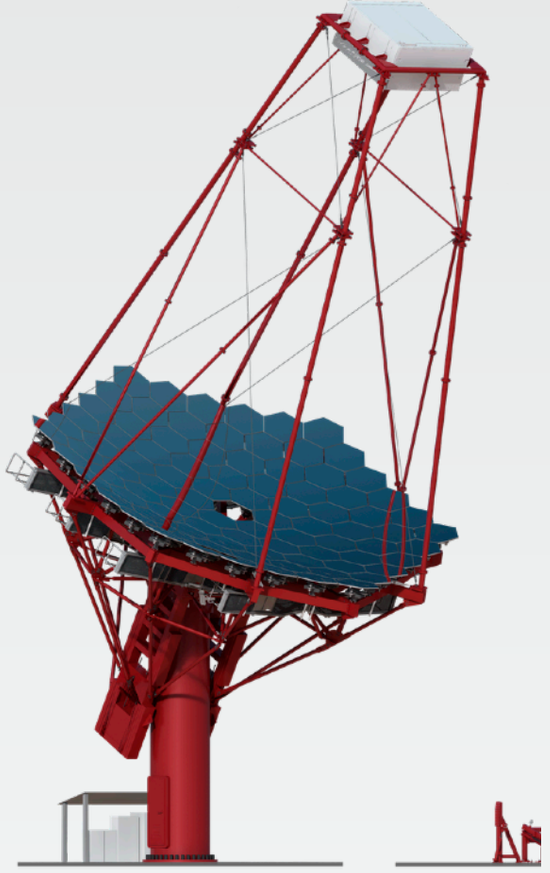
Reach on $\chi$ depends on detectable power $P_{det}$:

$$\chi = 4.5 \times 10^{-14} \left( \frac{P_{det}}{10^{-23}\ \mathrm{W}} \right)^{1/2} \left( \frac{0.3\ \mathrm{GeV/cm}^3}{\rho_\odot} \right)^{1/2} \left( \frac{1\ \mathrm{m}^2}{A_{dish}} \right)^{1/2} \left( \frac{\sqrt{2/3}}{\alpha} \right)$$

# The reflector

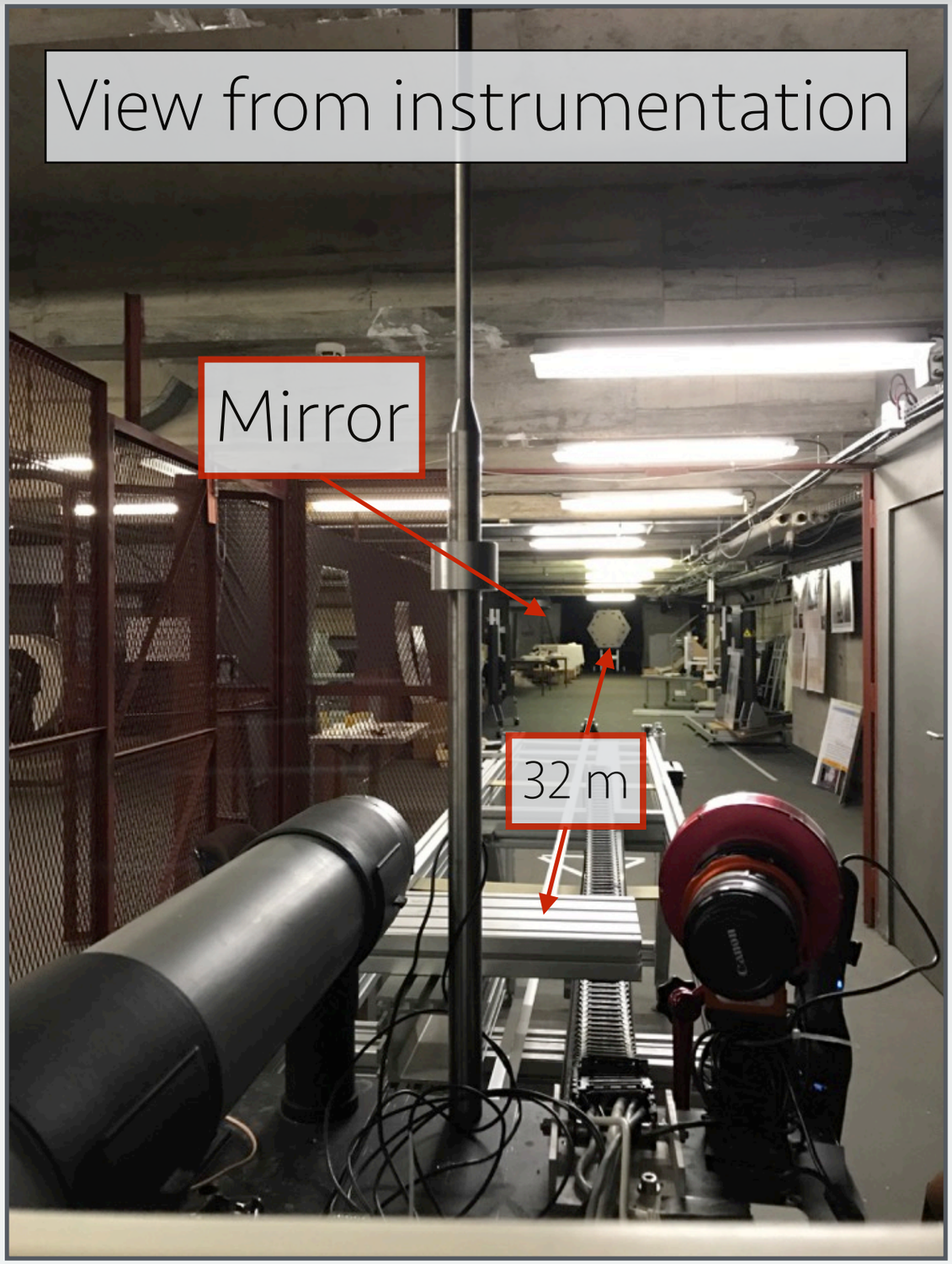


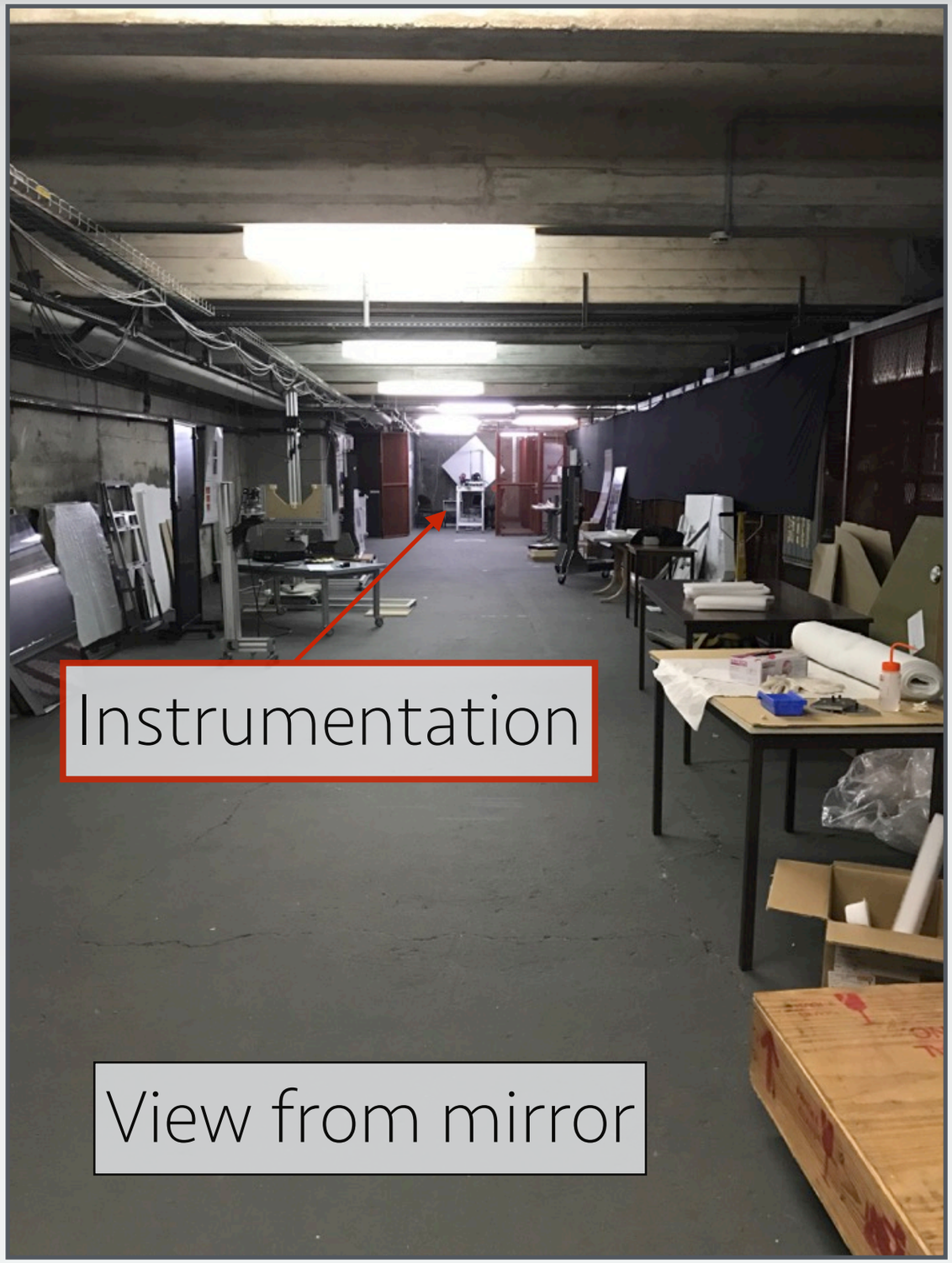

Mirror from a gamma-ray astronomy experiment (CTA)



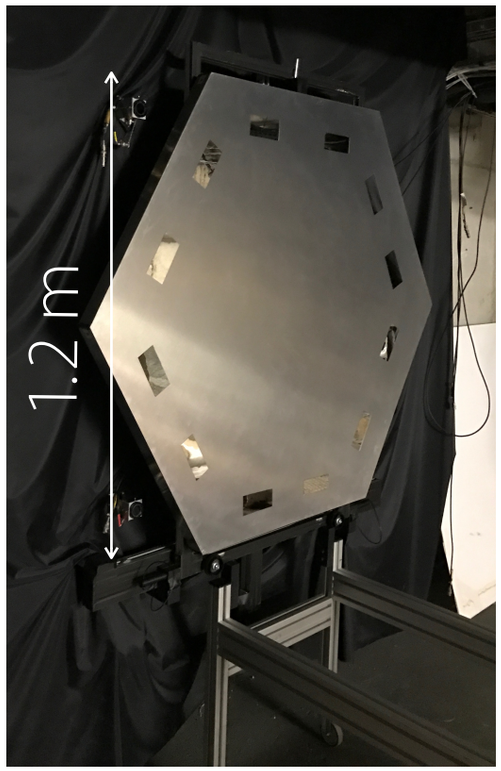
1.2 $m^2$
32 m radius

# Optical Test Bench at Saclay



# SHUKET setup

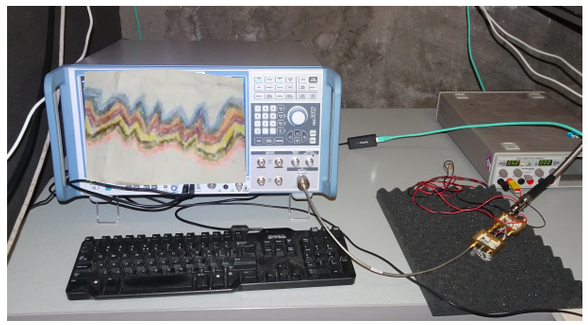



Mirror

32 m


Horn antenna + shielding

Amplifiers
+
Spectrum analyzer

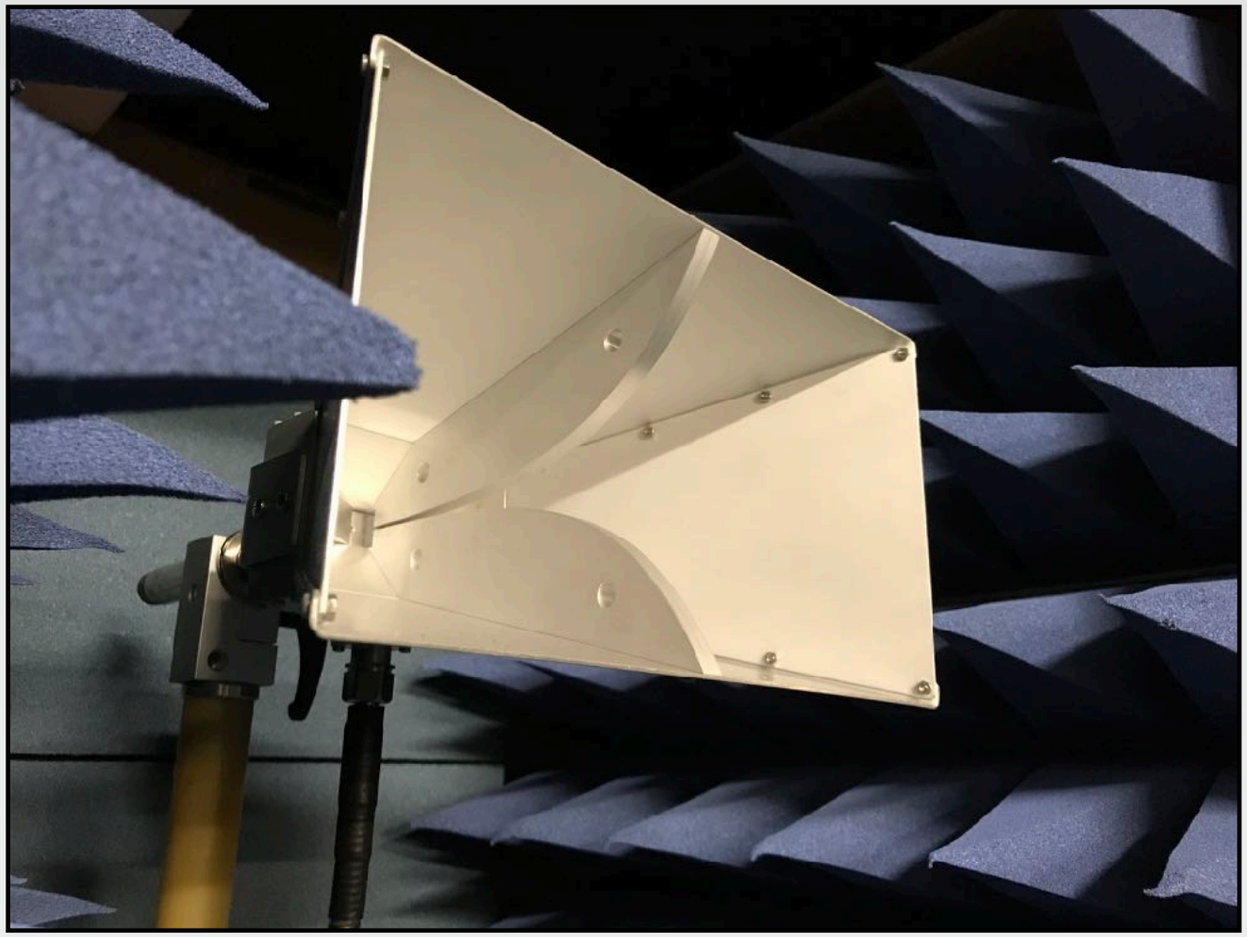


**Achieved $10^{-22}$ W/Hz sensitivity**

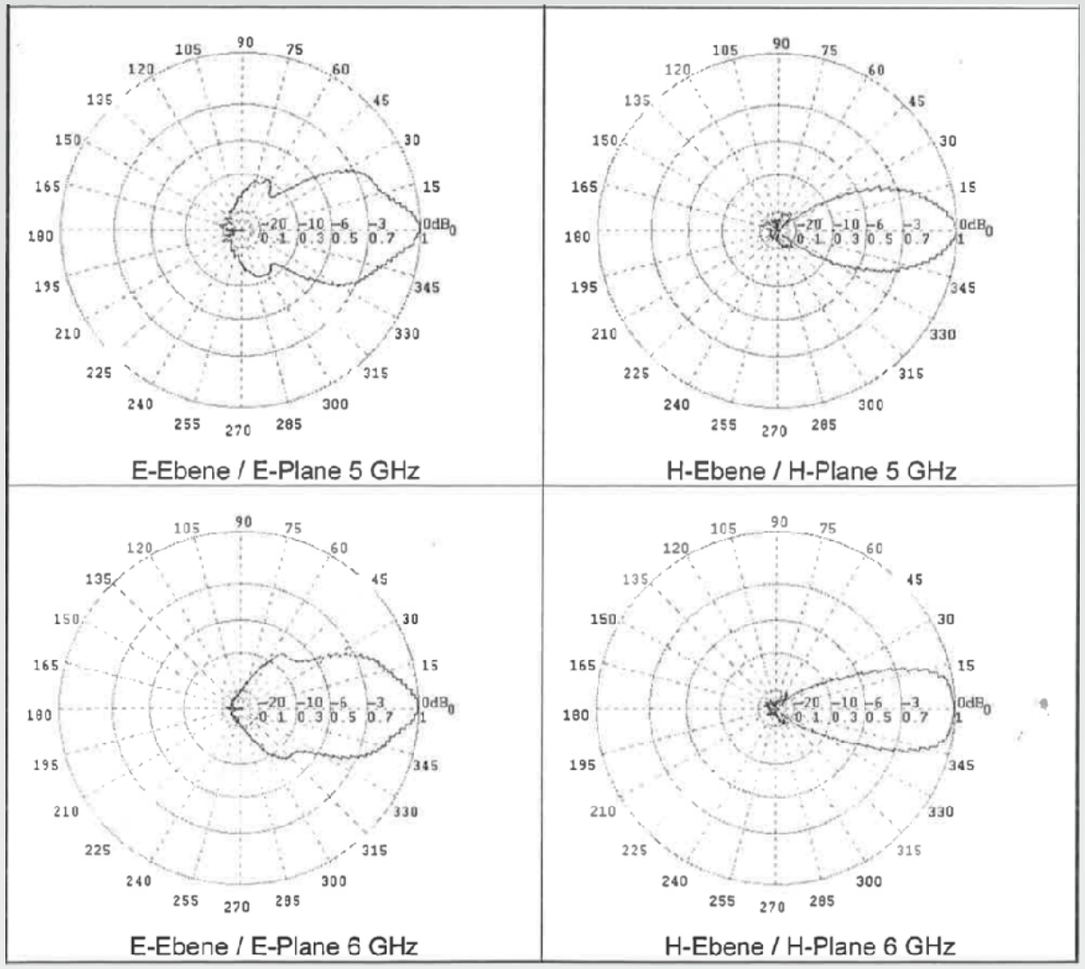
Constraints on hidden photons dark matter

# Horn Antenna

## Polarized horn antenna



## 1-18 GHz




- 2017 data taking : 5 GHz - 7 GHz
- Incoming spherical wave, tiny solid angle

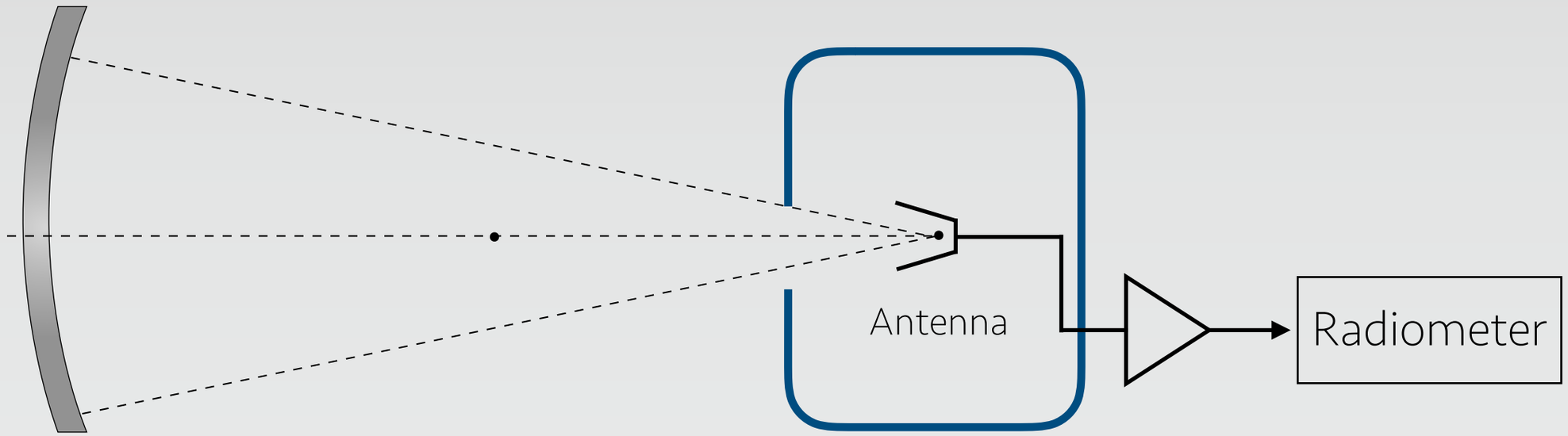
# Spectrum analyzer

- ⋆ Room-temperature LN amplifier ~30 dB
- ⋆ Loan from Rhodes & Schwarz
  - 3 GHz - 20 GHz FSP

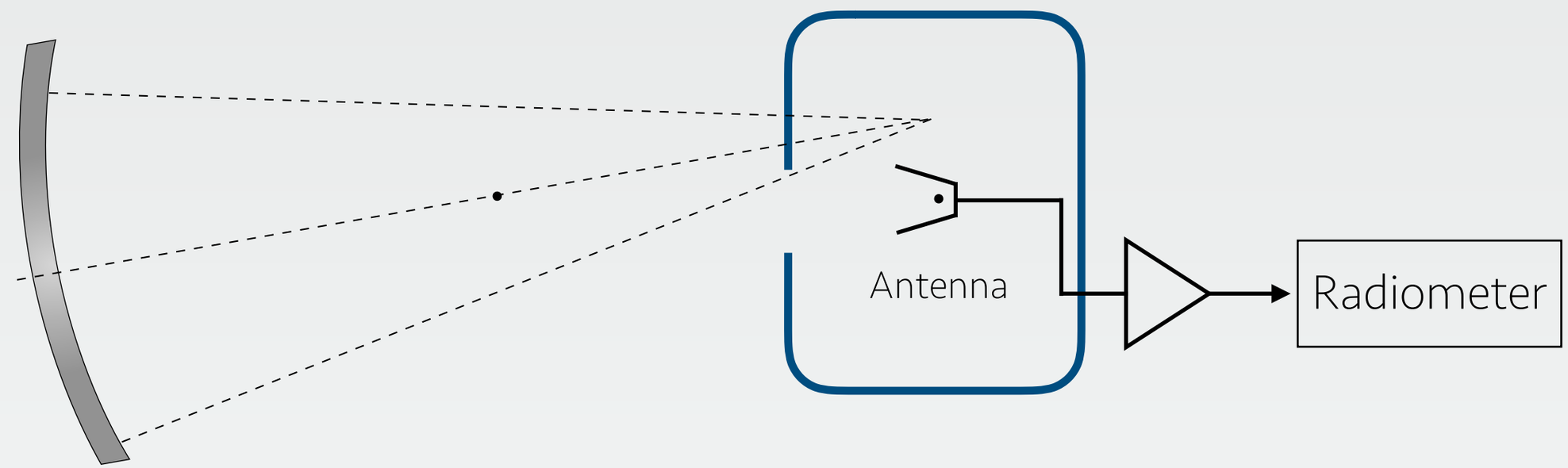
- ⋆ Performs FFT + power measurement in 1 Hz bins
- ⋆ 2 weeks : ~2 GHz bandwidth analyzed (5-7 GHz)

# ON and OFF runs

ON

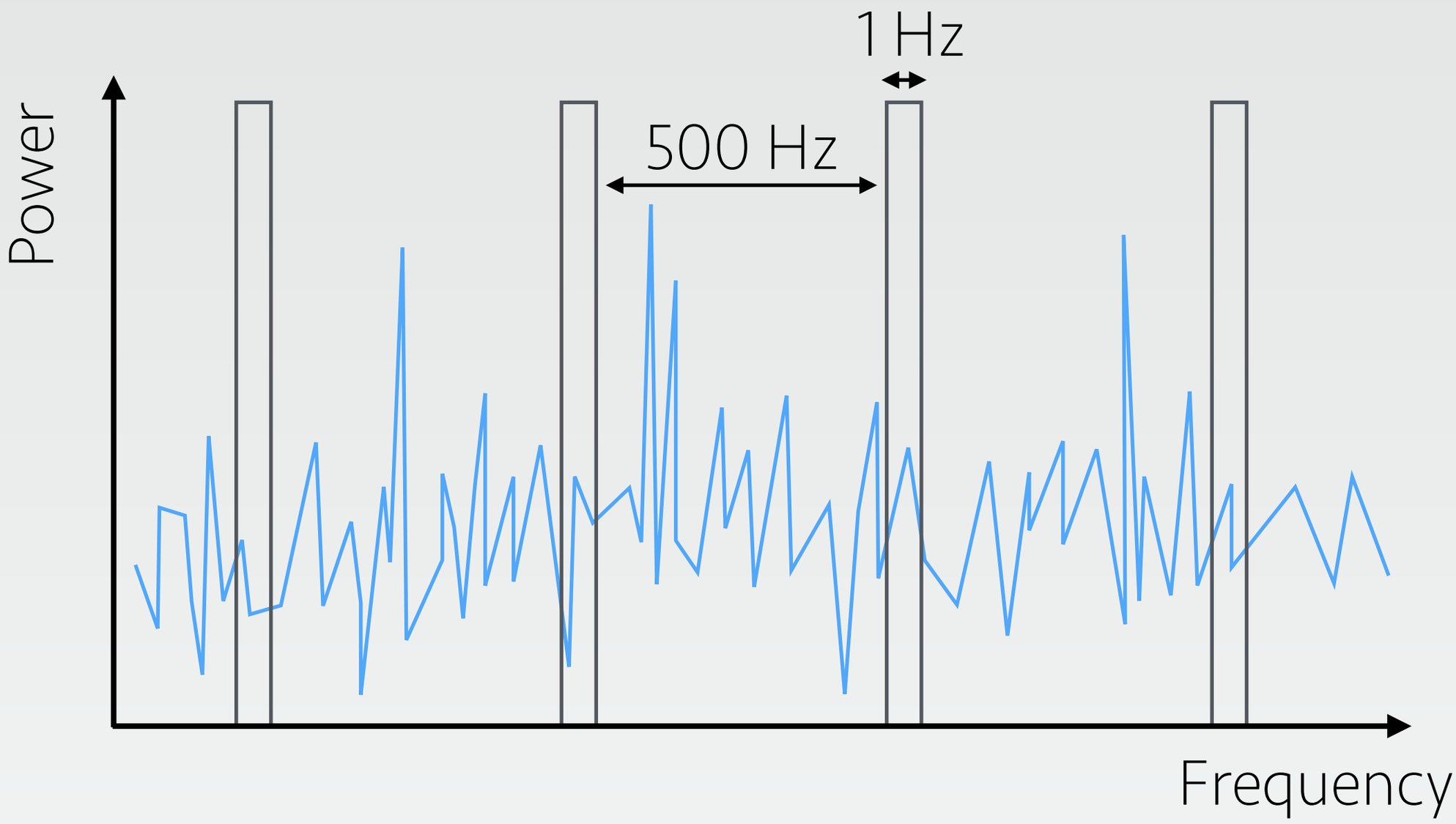



OFF



# Search optimization

- ⋆ Signal is constant, broad band (~5 kHz)
- ⋆ Most backgrounds removed by sampling



# Expected sensitivity

System noise temperature:

$$T_{\mathbf{sys}} = 554\ \mathrm{K}$$

- 290 K environment
- 214 K Low noise amplifier
- 50 K spectrum analyser

Estimate of the noise fluctuation level:

$$P = kT_{\mathbf{sys}}\sqrt{\frac{\Delta_f}{\tau}}$$

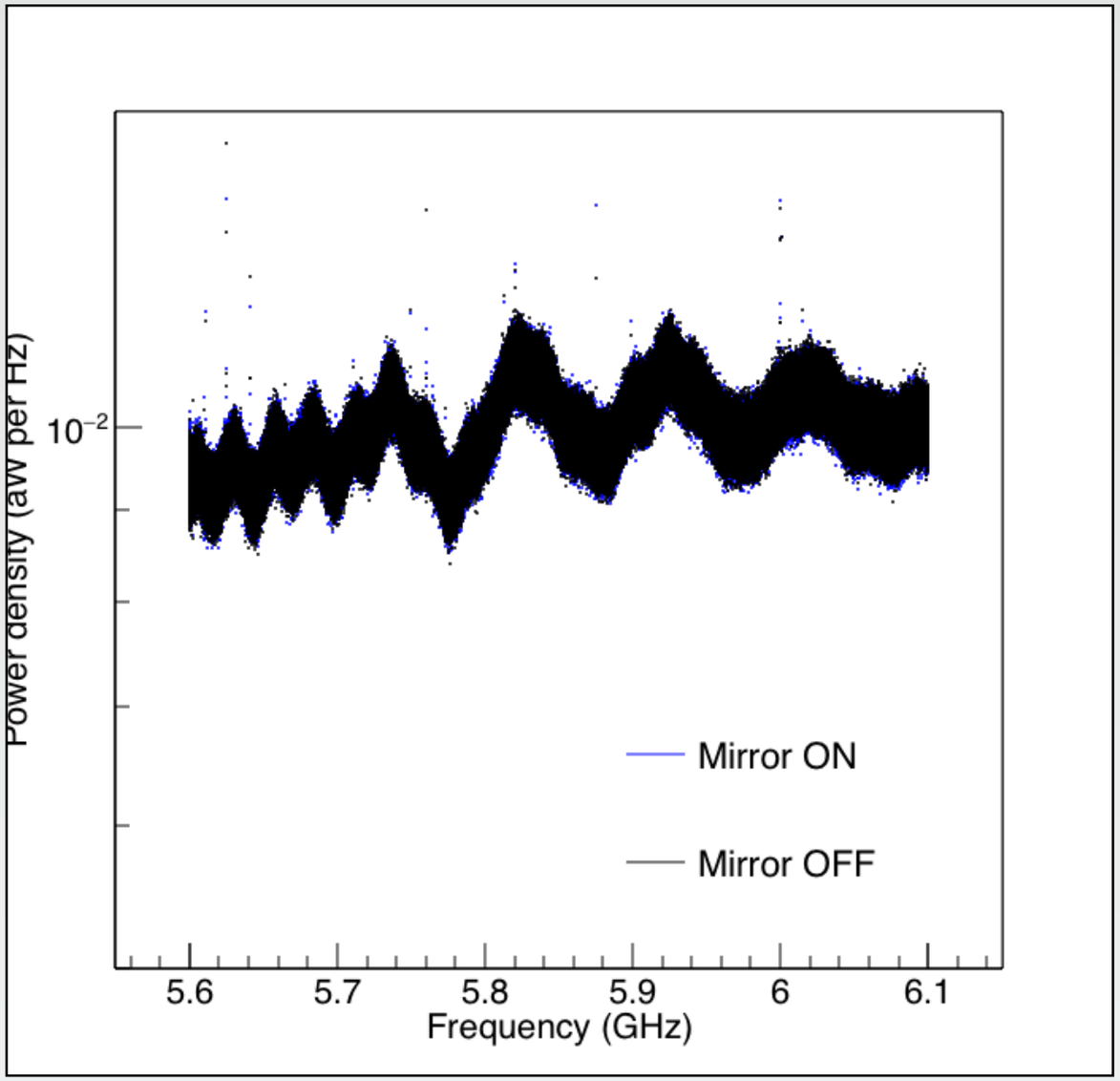
$\boldsymbol{\Delta_f}$: filter width (1 Hz)

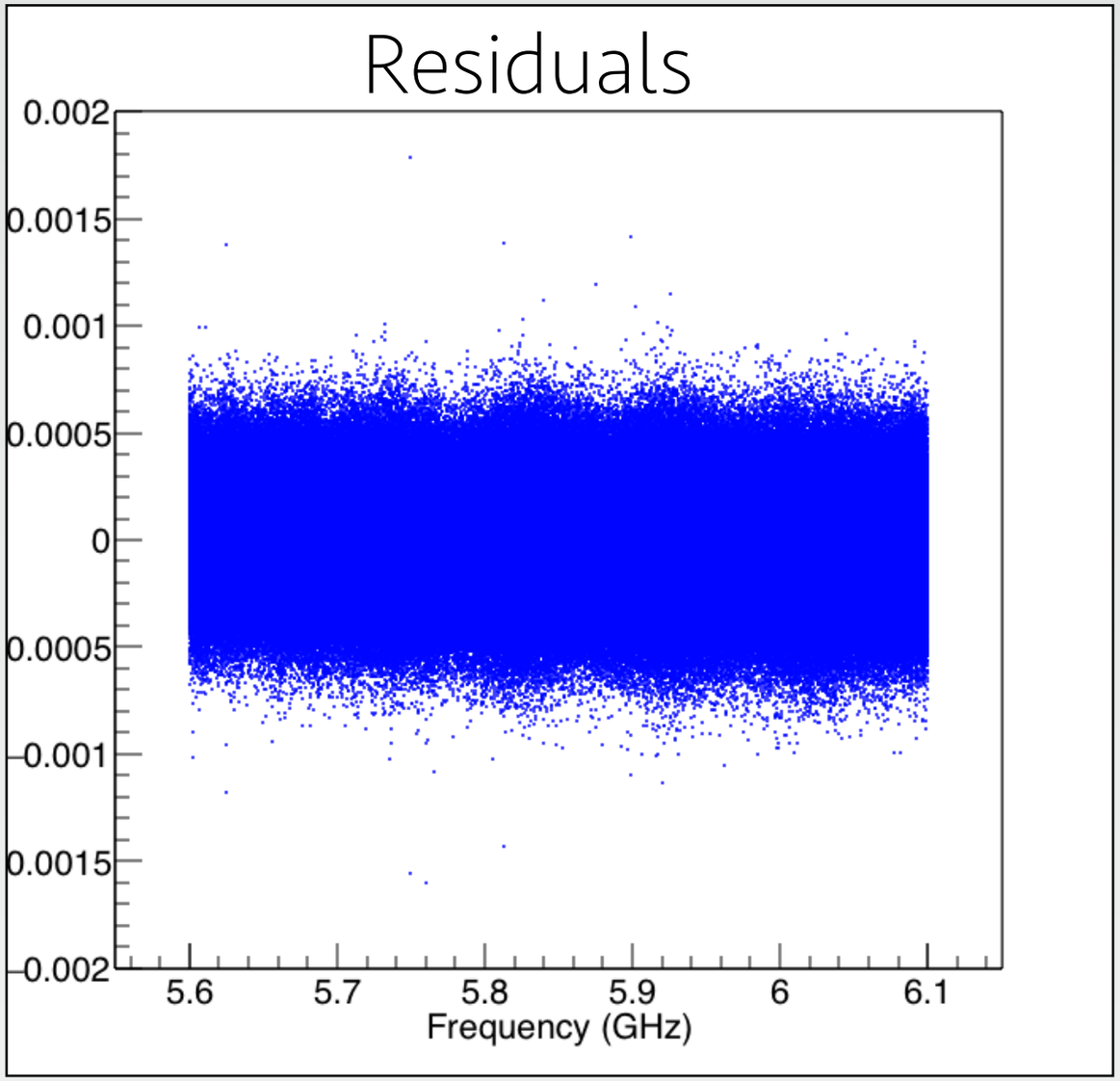
$\boldsymbol{\tau}$ : measurement time (8000 s)

$$P = 8.6 \times 10^{-23}\ \mathrm{W}$$

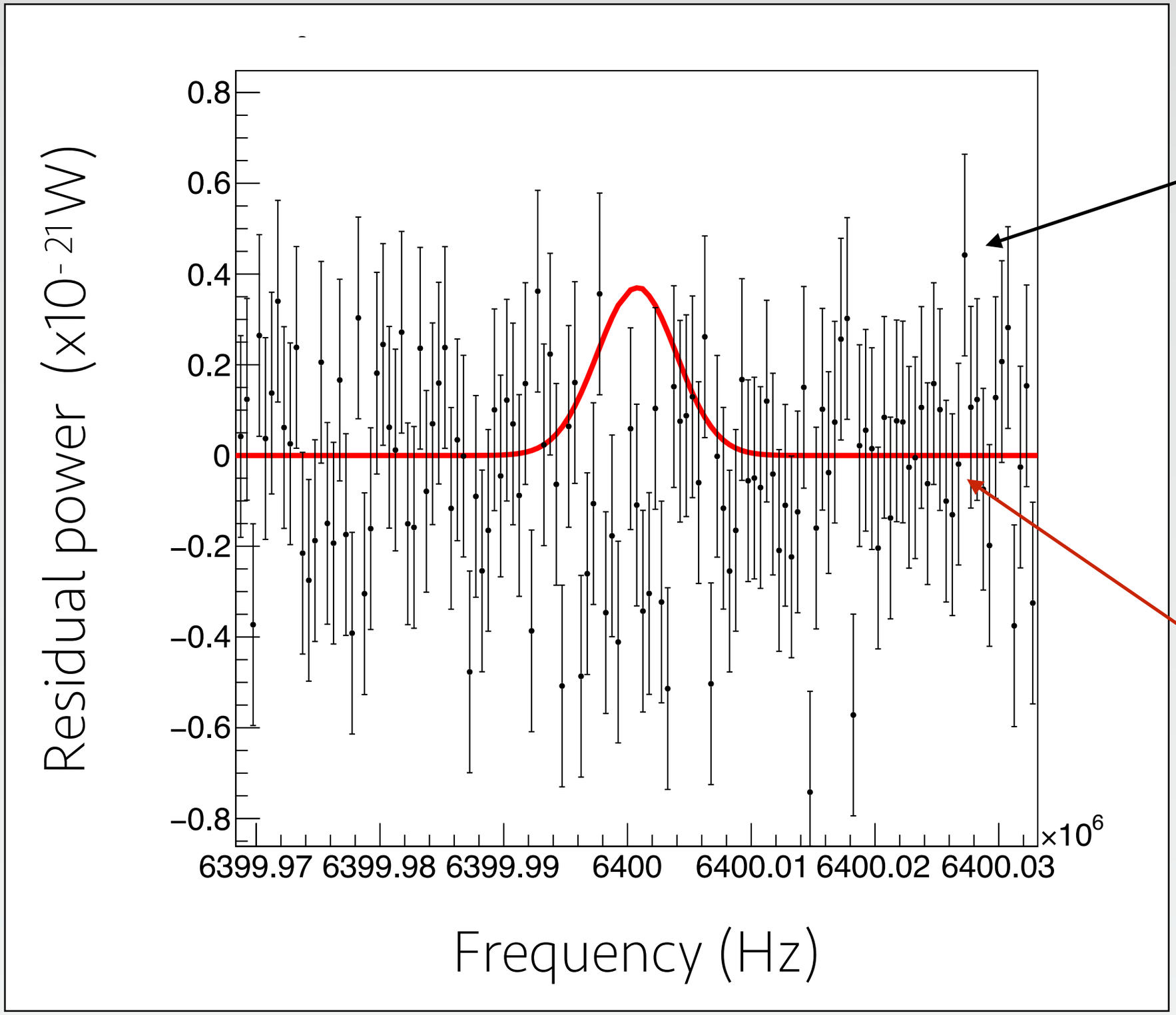
# Results

## Power measurement w & w/o mirror



# Limits on potential signals

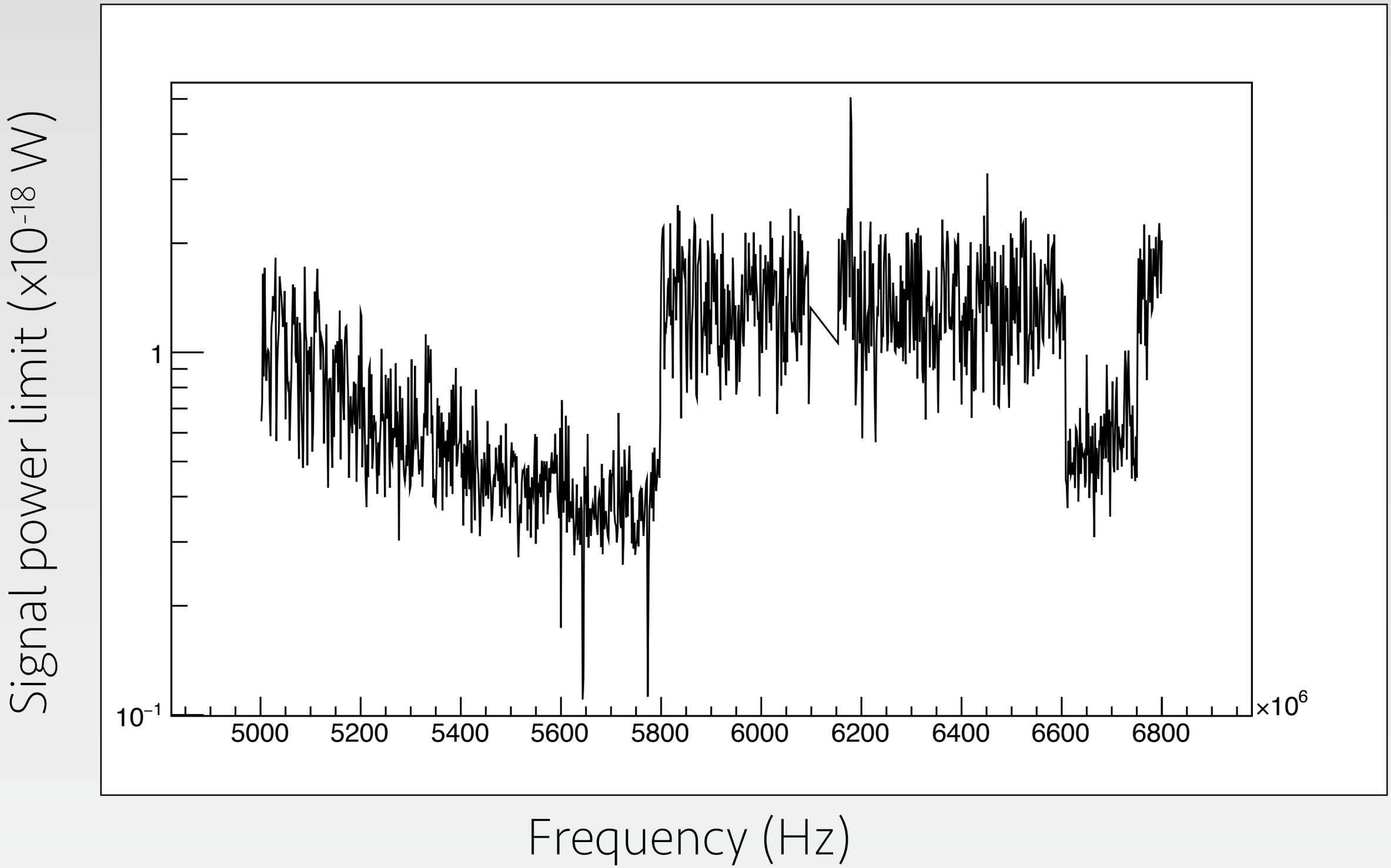



Measurements

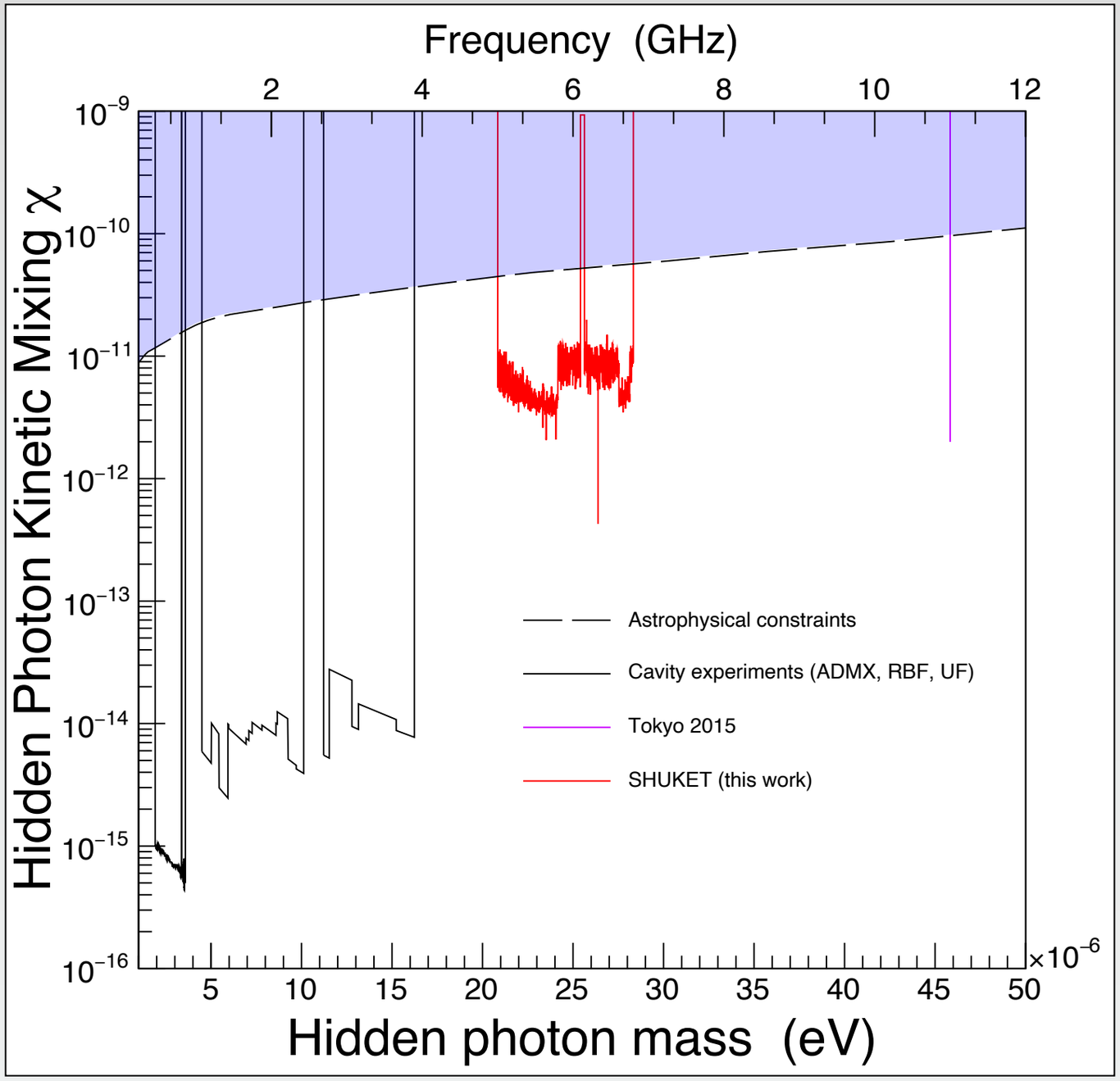
Dark matter fake signal

power = $7 \times 10^{-19}$ W
(3 sigma excluded)

# Constraints on extra-power



# Constraints on hidden photons mixing




P. B., L. Chevalier, C. Flouzat, PRL 2019

# Re-analysis of Shuket

- ⋆ Based on the DAMNED experiment analysis

E. Savalle *et al.*, PRL 2021

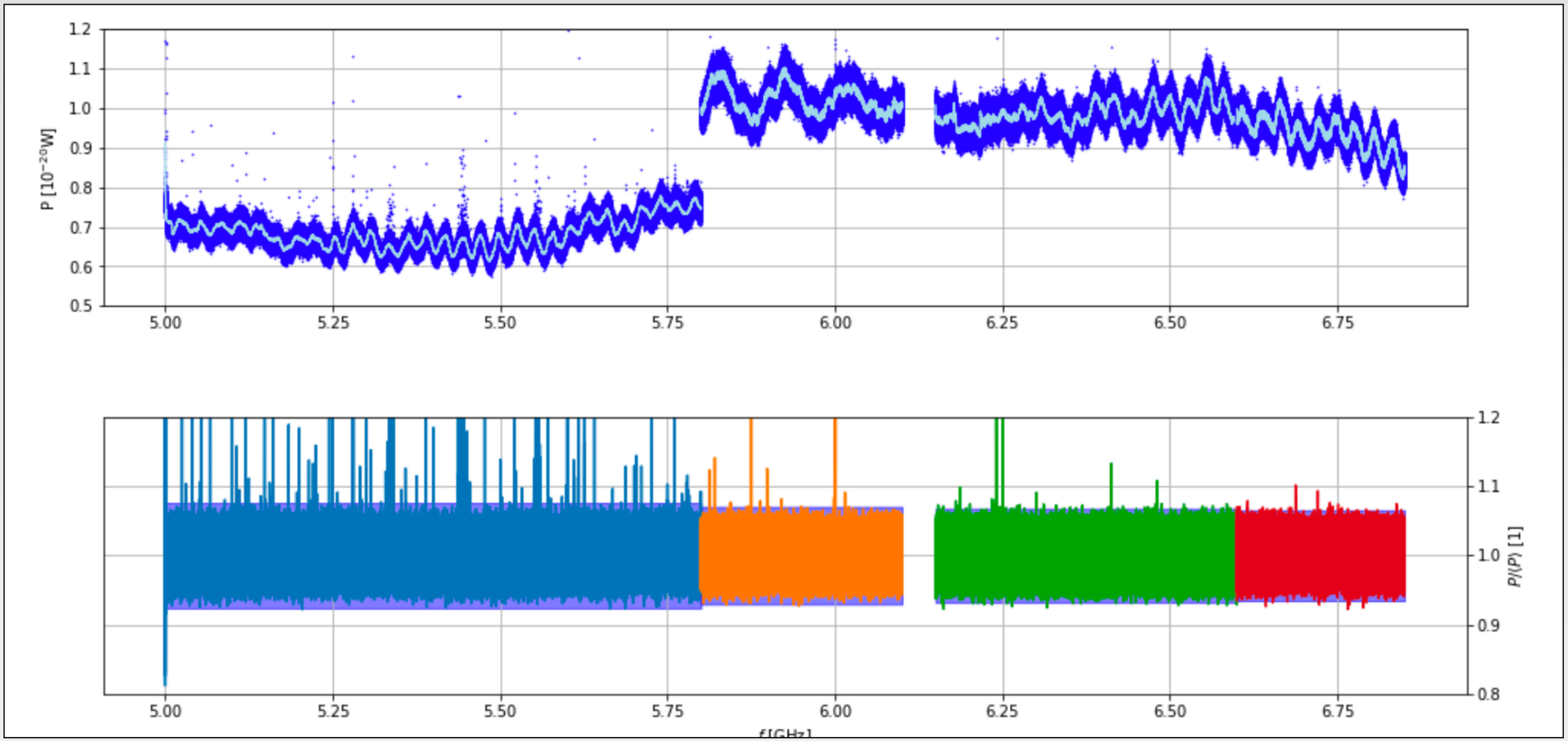
- ⋆ Use only ON data

- ⋆ Smooth-on data

- ⋆ Build a TS based on DM halo distribution as prior

- ⋆ $\chi$ is a built-in parameter

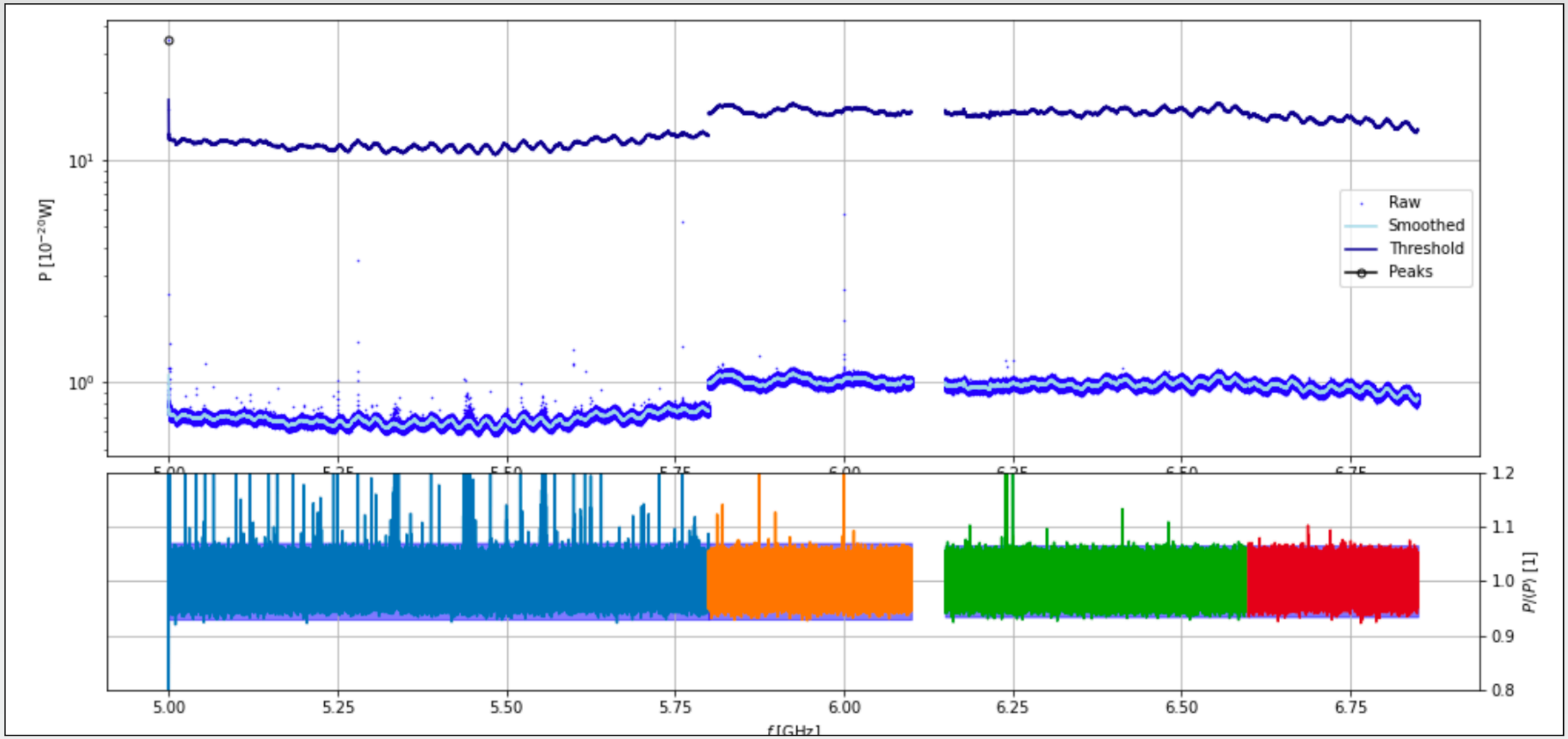
# Re-analysis of Shuket: smoothing




*A. HEES, E. SAVALLE, P. WOLF*

# Re-analysis of Shuket: thresholds

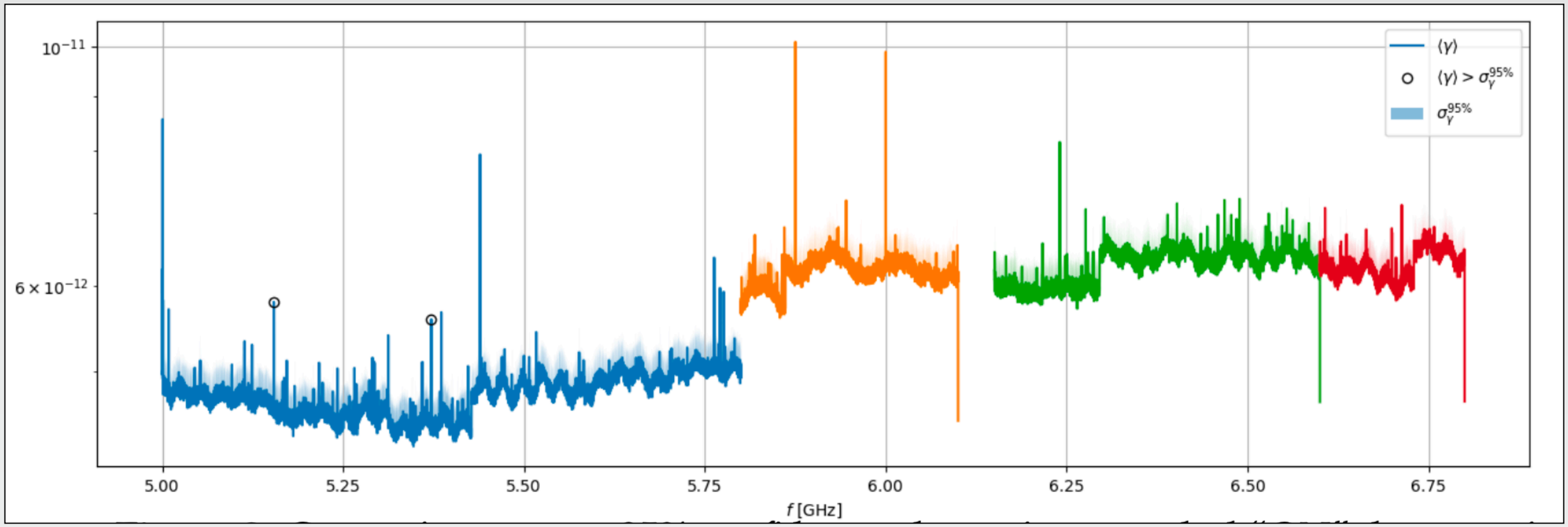
95% threshold




*A. HEES, E. SAVALLE, P. WOLF*

# Re-analysis of Shuket: exclusions

Exclusion lines on $\chi$

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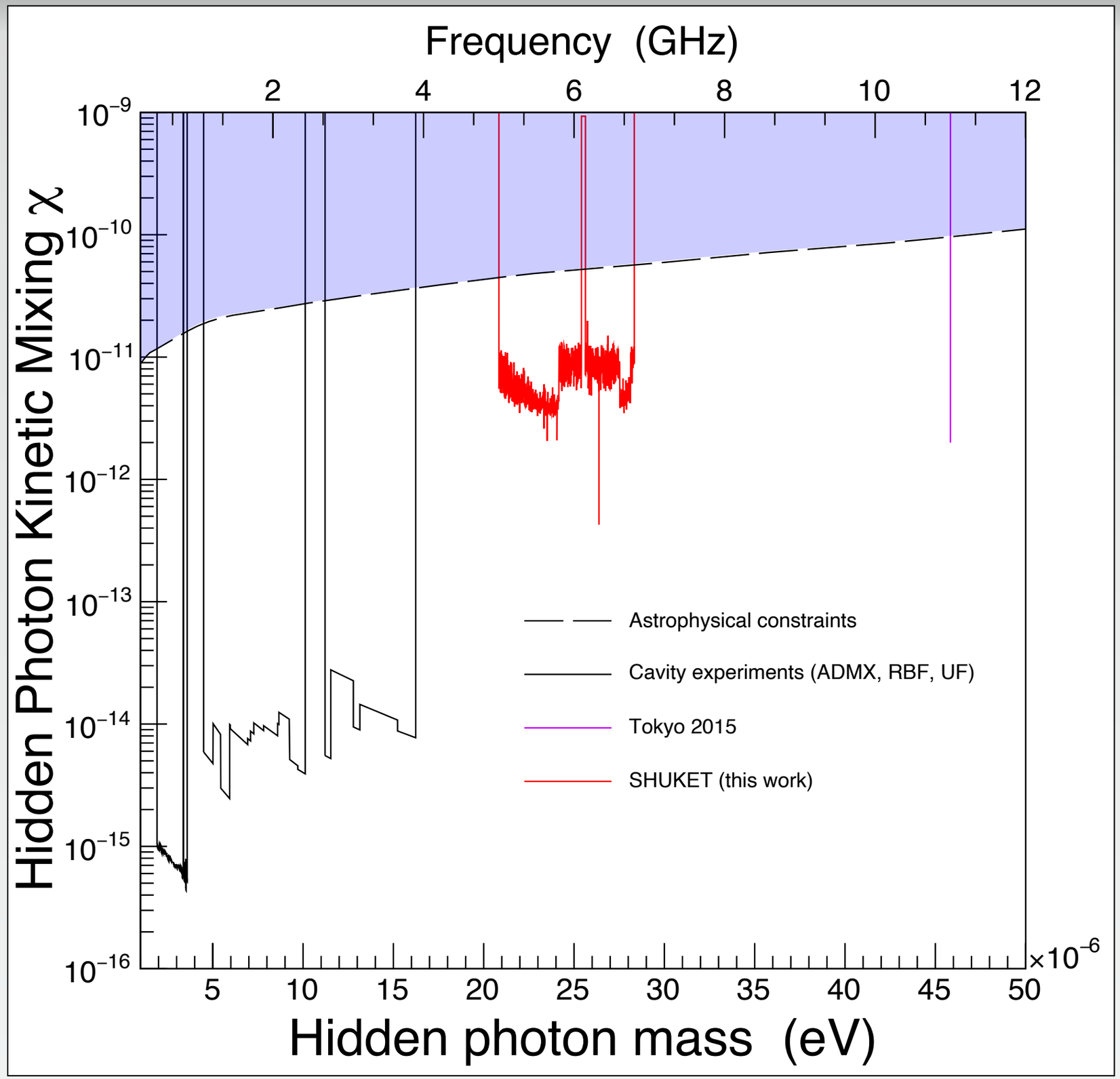
# Comparison of constraints



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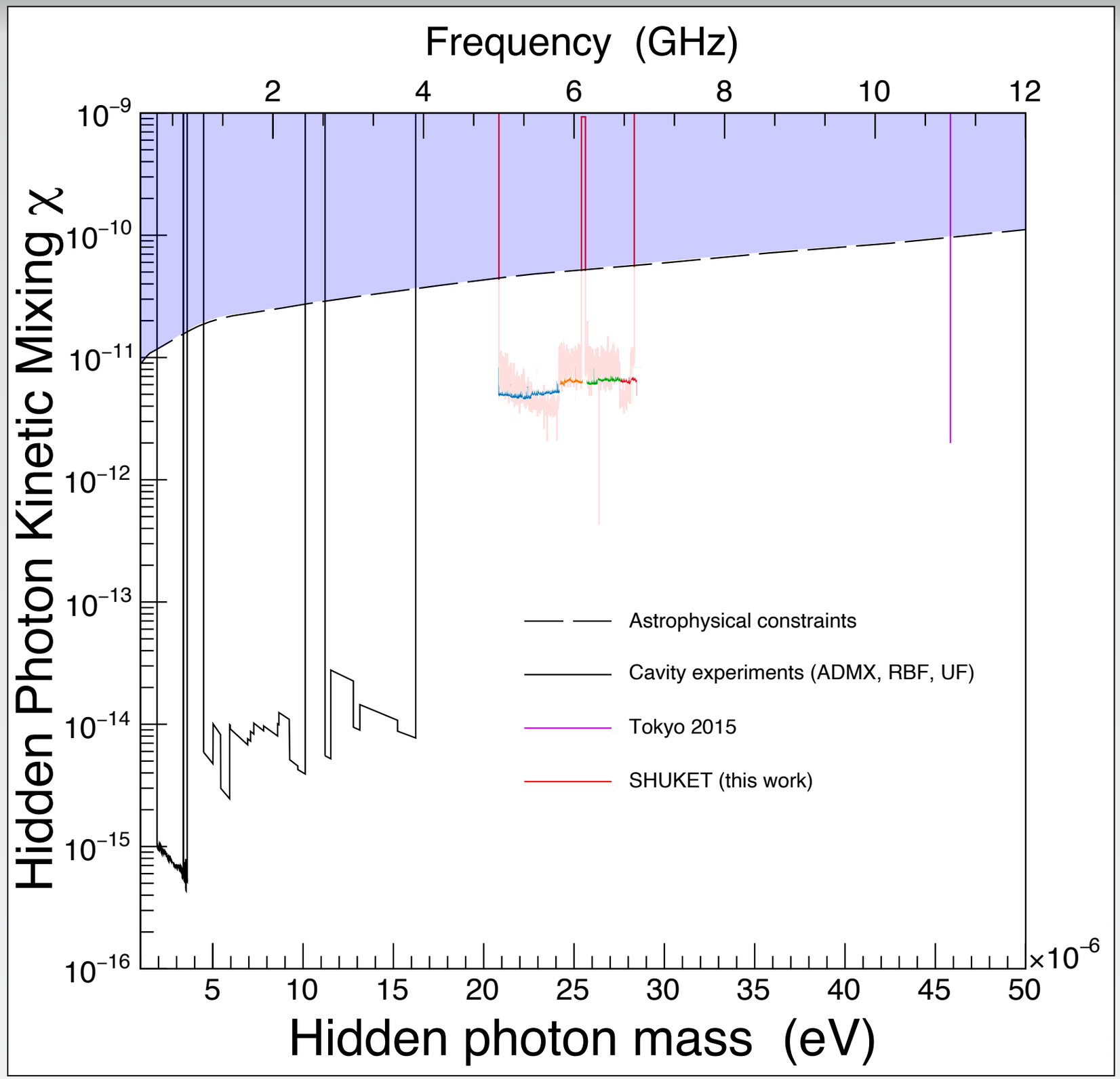

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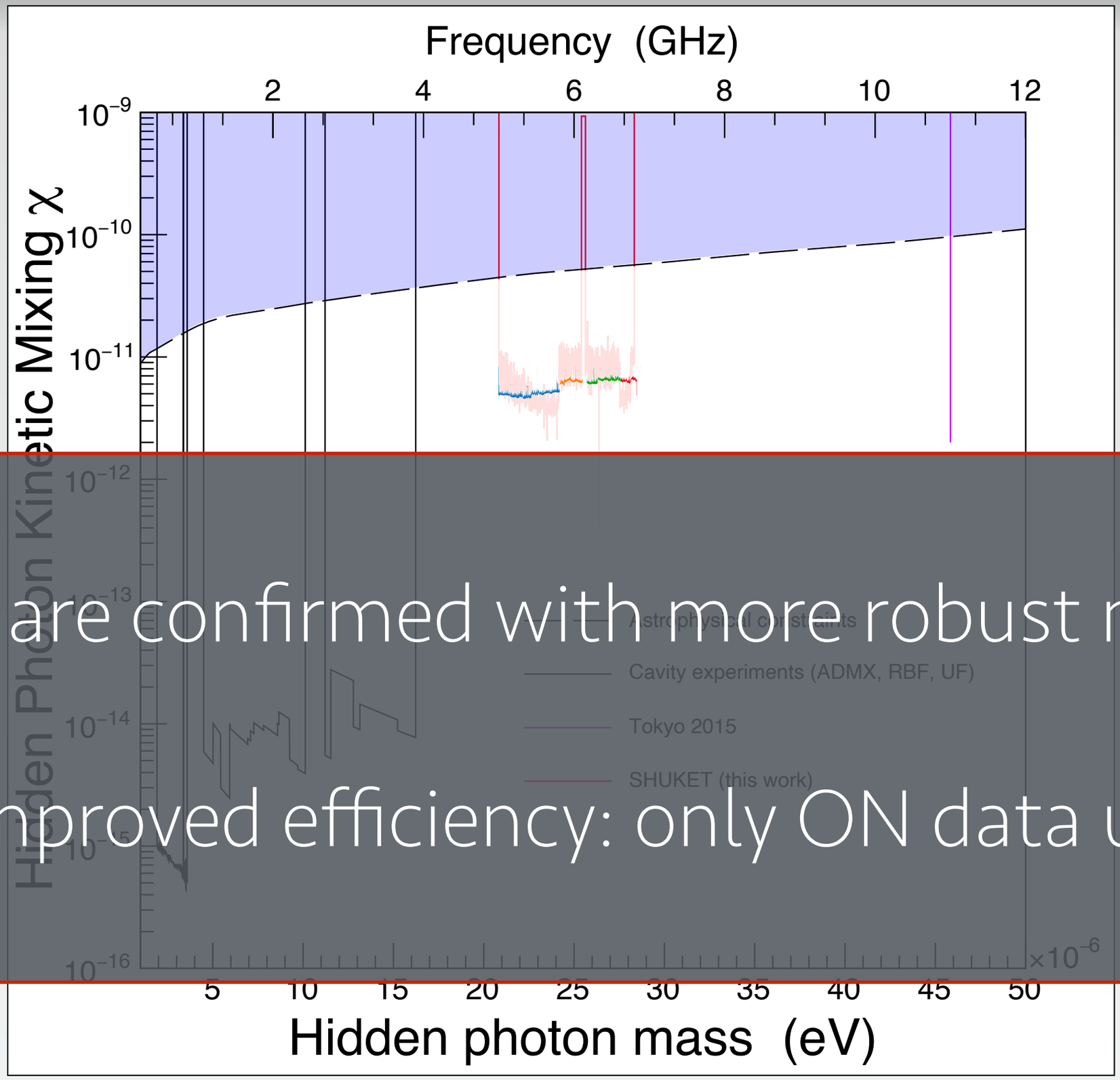


Results are confirmed with more robust method

x2 improved efficiency: only ON data used

# Future plans : Shuket 2

- ⋆ CEA/SYRTE collaboration
- ⋆ New Shuket runs 10 GHz - 20 GHz
- ⋆ New, cryogenic low-noise amplifiers


$T_{noise} < 5$ K

- ⋆ Data taking optimized for SYRTE-style analysis
- ⋆ New reflector (could be cold)
- ⋆ New antenna
- ⋆ New spectrum analyzer