Microwave Searches for Dark Matter

Axions, Shuket and all that …

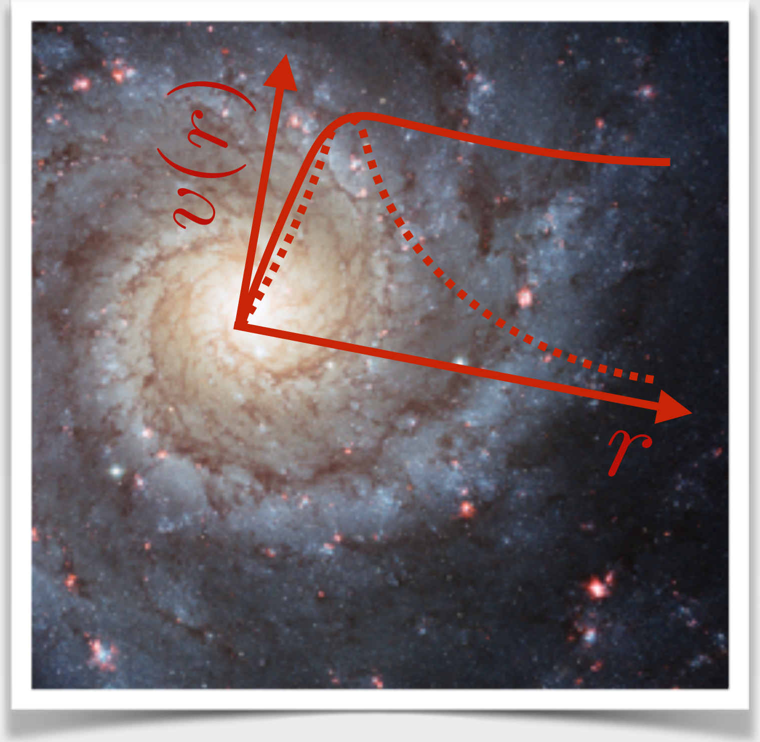
Tokyo-Paris seminars
September, 17th, 2021

Pierre Brun

Département de Physique des Particules
CEA Paris-Saclay

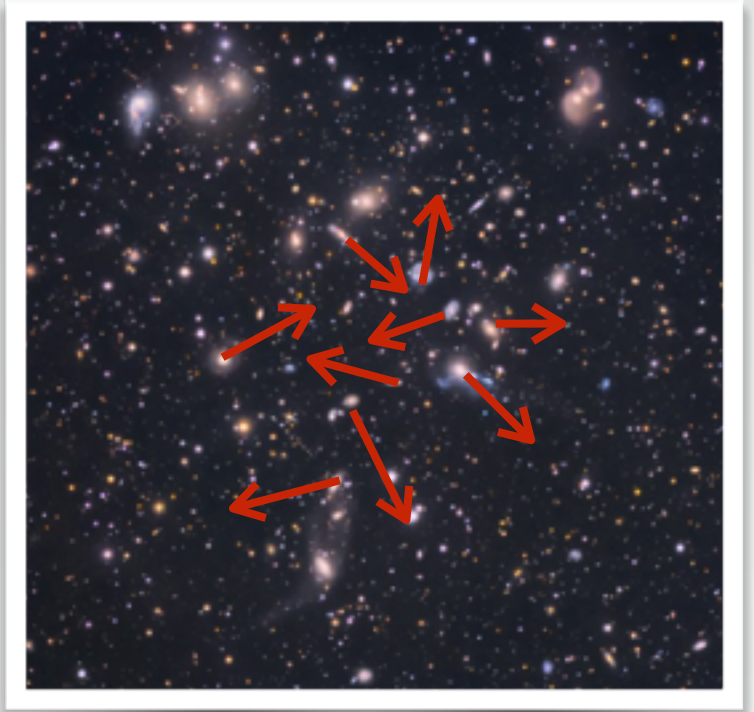
Dark matter at various scales

Galaxies



Rotation curves

Galaxy clusters



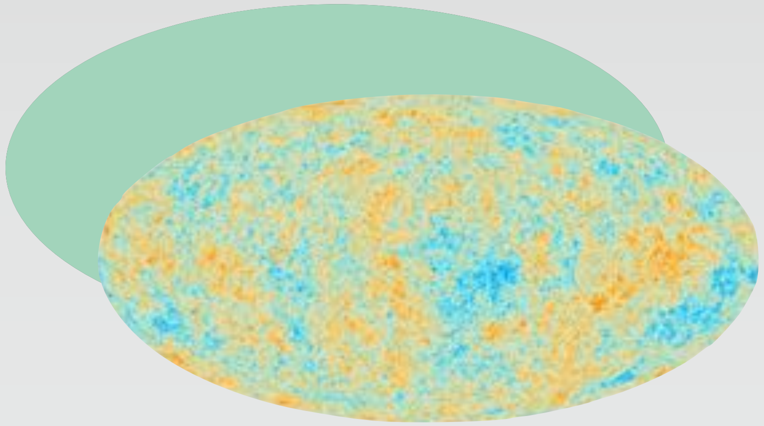
Velocity dispersion

Collision

New, dark component required

Dark matter at various scales

CMB emitted when first atoms formed

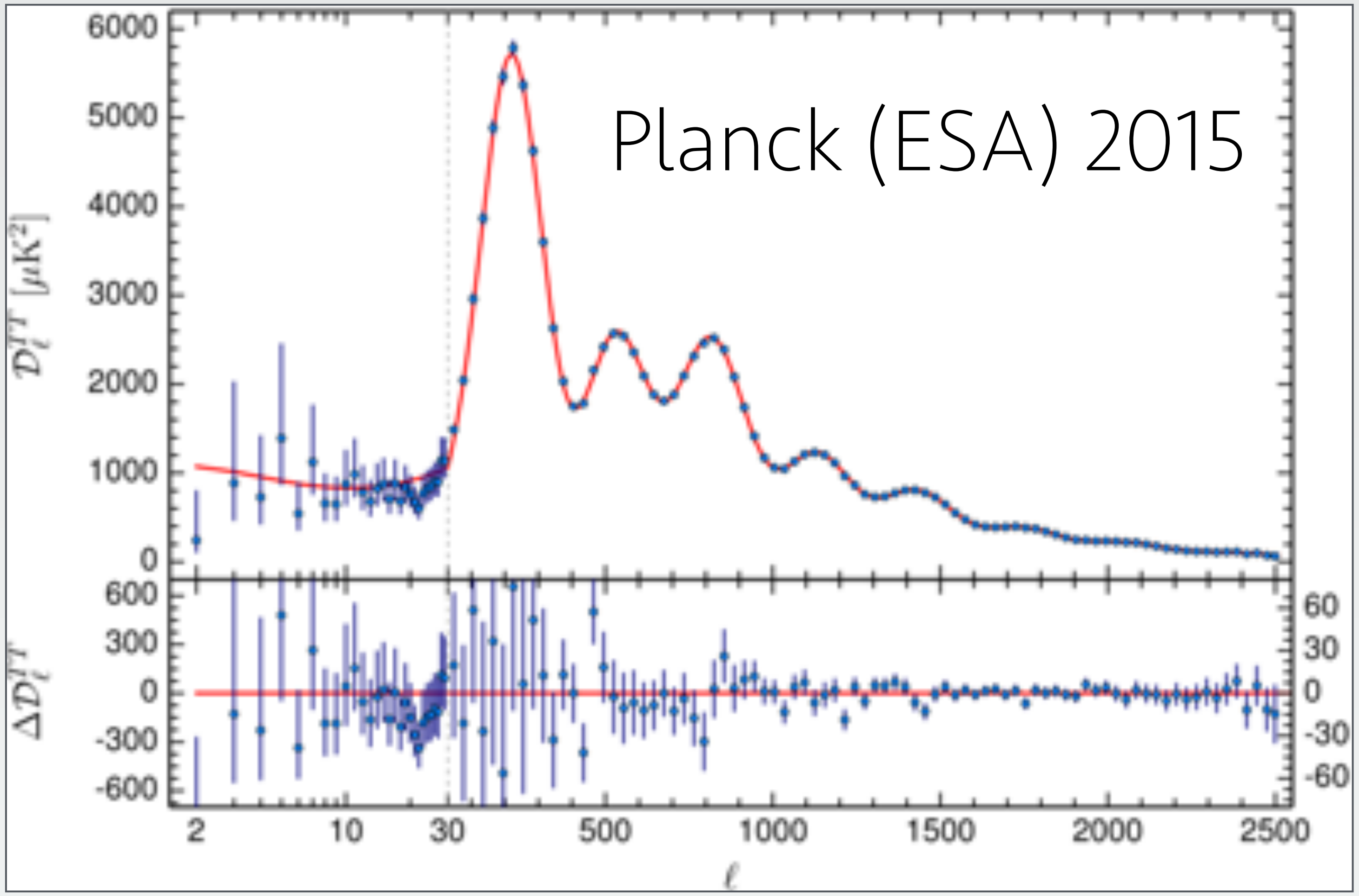


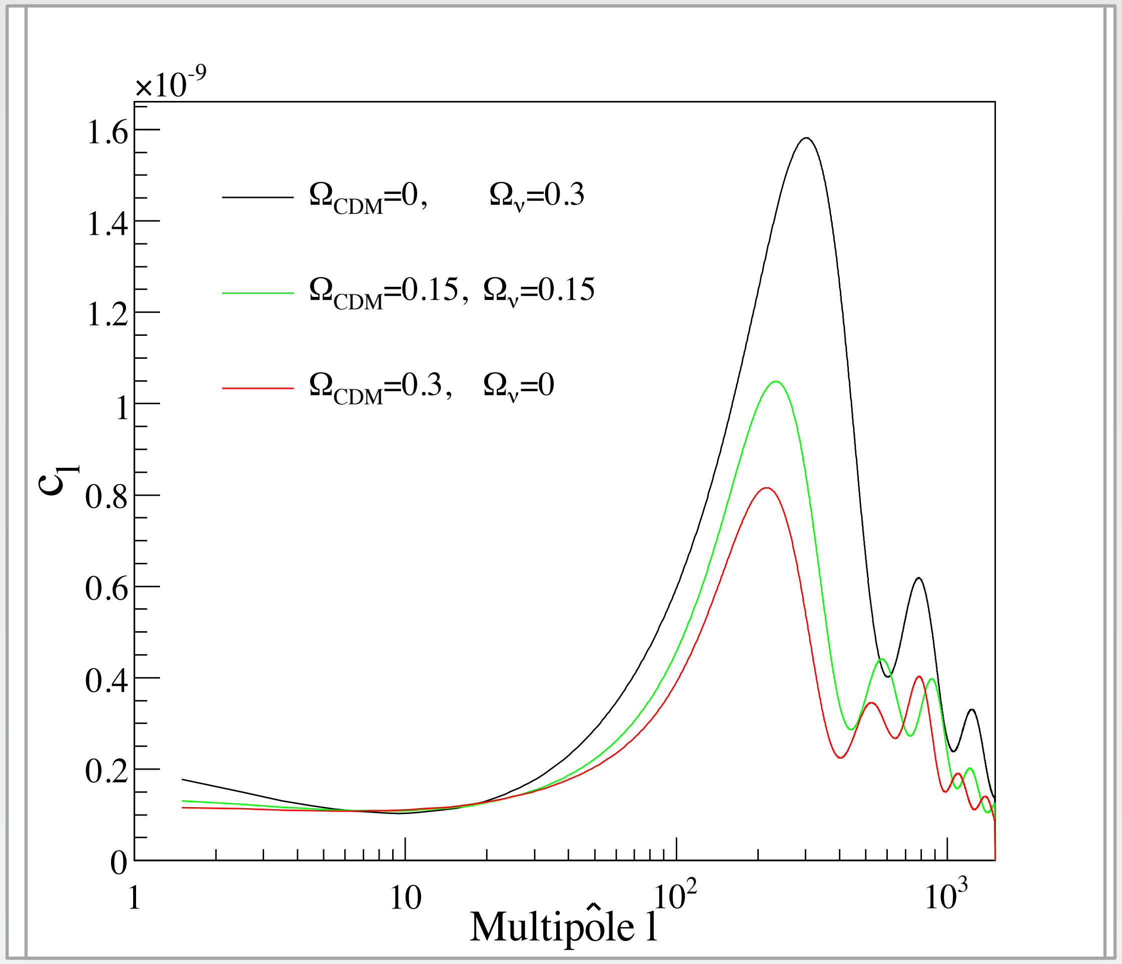
Very homogeneous
and isotropic

Density oscillations
before recombination

⇓

Temperature fluctuations

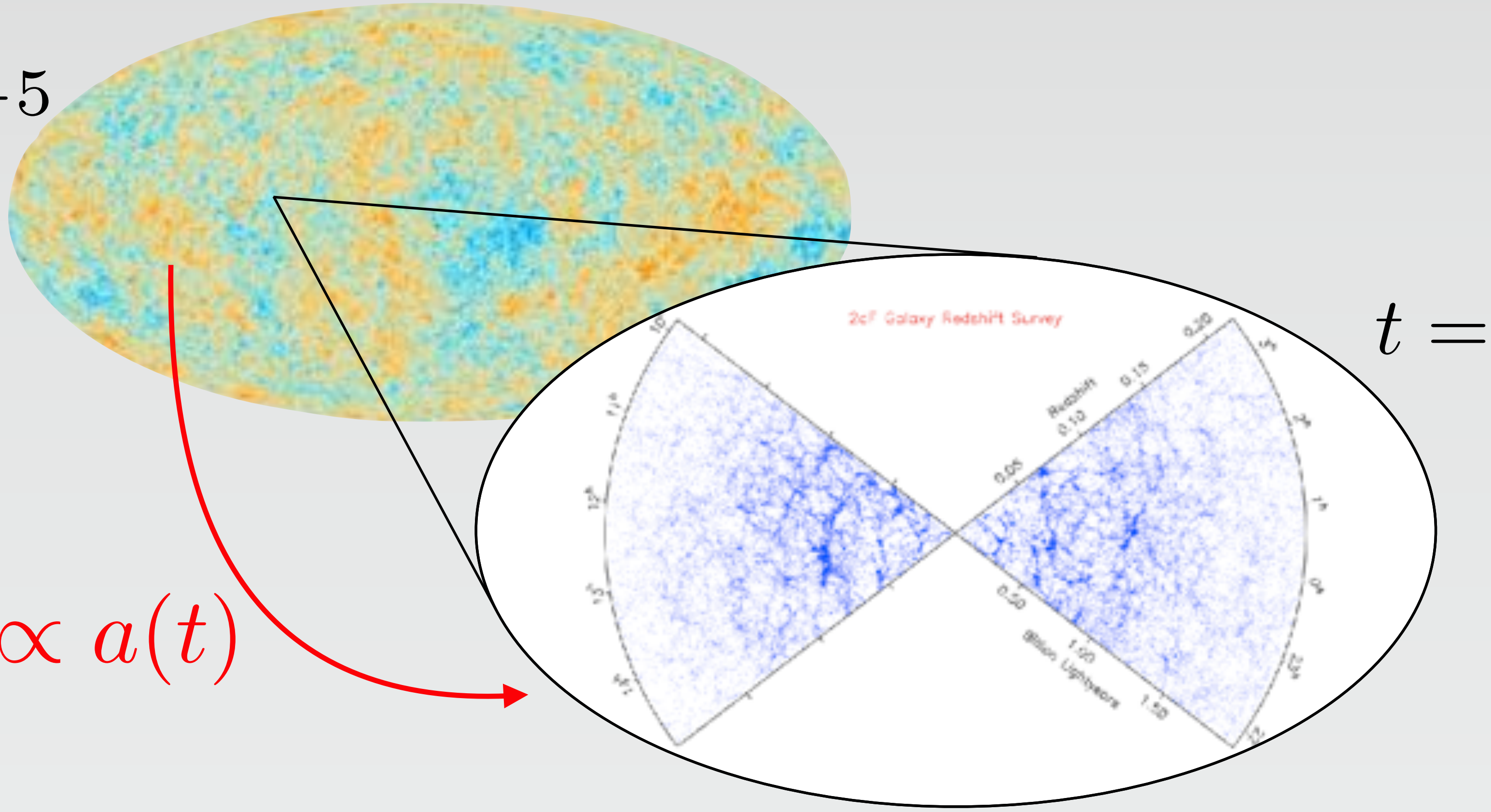

Planck (ESA) 2015



Dark matter at various scales

$t = 4 \times 10^5$ y, $a(t) \simeq 1/1000$

$\delta\rho/\rho \sim 10^{-5}$



$t = 10^{10}$ y, $\mathrm{a(t)} \simeq 1$

$\delta\rho/\rho \gg 1$

$\delta\rho/\rho \propto a(t)$

New type of matter required to explain growth of structures

Massive Weakly interacting Stable Cold

84 % of total mass

CP symmetry

- CP = Charge x Parity
- CP violation required for matter domination
- Weak interactions known to violate CP
- Strong interactions, electromagnetic interactions, gravitation known to conserve CP

The strong CP problem

- In general, QCD contains a term

$$\mathcal{L}_\theta = \frac{\theta}{32\pi^2}\mathrm{Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu})$$

$\theta \neq 0$ implies $\left\{ \begin{array}{l} \text{CP violation in strong sector} \\ \text{Non-vanishing neutron electric dipole} \end{array} \right.$

- Strong CP violation not observed

- Neutron electric dipole moment :

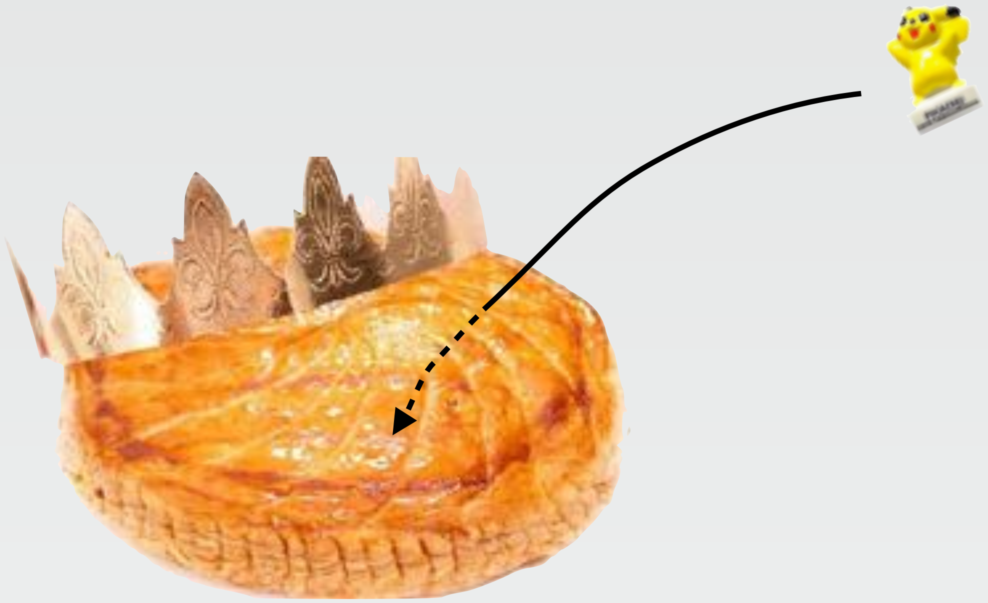
$$d_n \leq 2.9 \times 10^{-26}\ e.\mathrm{cm} \quad \Rightarrow \quad \underset{\substack{\uparrow \\ \boxed{\text{Fine tuning problem}}}}{\theta \leq 10^{-10}}$$

The strong θ parameter

- ⋆ θ is an angle
- ⋆ Why is θ=0 a problem?

The strong θ parameter

- ⋆ θ is an angle
- ⋆ Why is θ=0 a problem?



The strong θ parameter

- ⋆ θ is an angle
- ⋆ Why is θ=0 a problem?

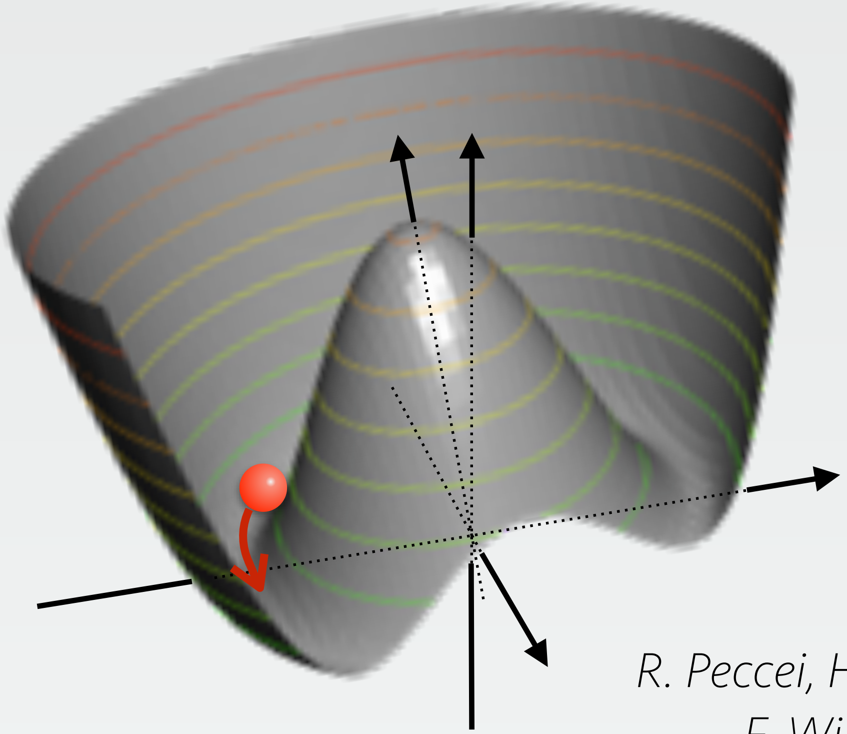
The strong $\boldsymbol{\theta}$ parameter

- ⋆ $\boldsymbol{\theta}$ is an angle
- ⋆ Why is $\boldsymbol{\theta}=0$ a problem?

An explanation is required: new force? new symmetry?

A theoretical prediction: the axion

- ⋆ New symmetry is proposed
- ⋆ Strong CP is naturally suppressed
- ⋆ Cost: new particle



QCD CP violation
naturally cancelled

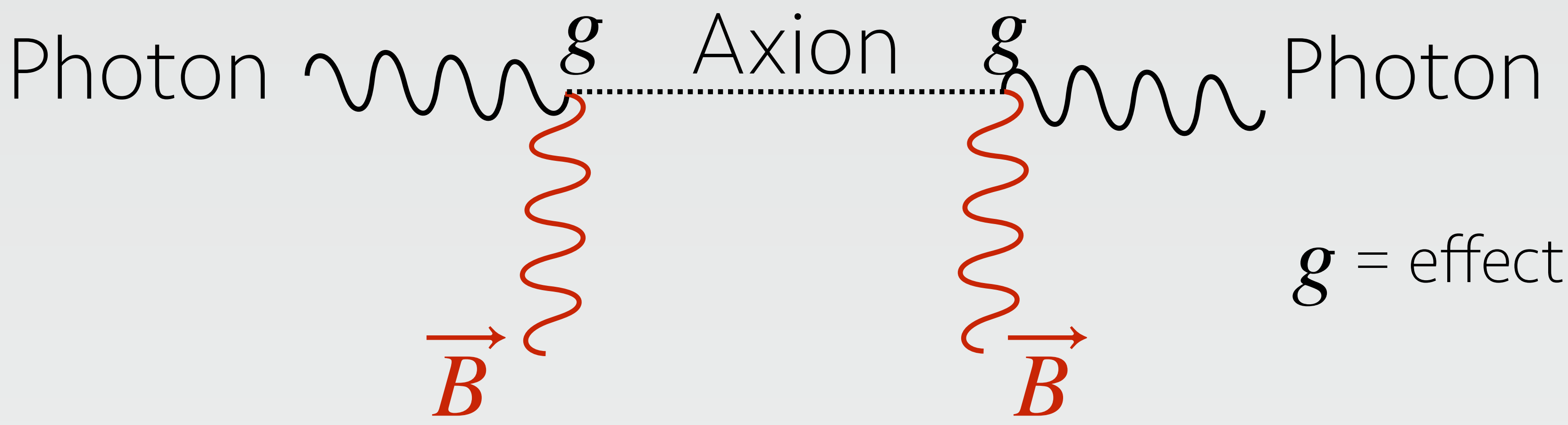
R. Peccei, H.R. Quinn (1977)
F. Wilczek (1978)

The Axion

Properties of the axion

- ★ Very light (< eV/c^2, electron 5×10^5 eV/c^2, proton 10^9 eV/c^2)

- ★ Axions couple to photons in a magnetic field



g = effective coupling (GeV^{-1}), very small

- ★ Could modify stellar lifetime

- ★ Can be the dark matter!

Axions and axion-like particles

- ⋆ Axion models : $\boldsymbol{\theta}$ is a dynamical field
  - Minimum of the potential for $\langle\theta\rangle = 0$

$$\mathcal{L} = \frac{C_\gamma}{32\pi^2}\frac{\theta}{f}\mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu}) \quad \propto \quad \theta\vec{E}\cdot\vec{B}$$

$$\boxed{m_\theta \propto 1/f}$$

Axions

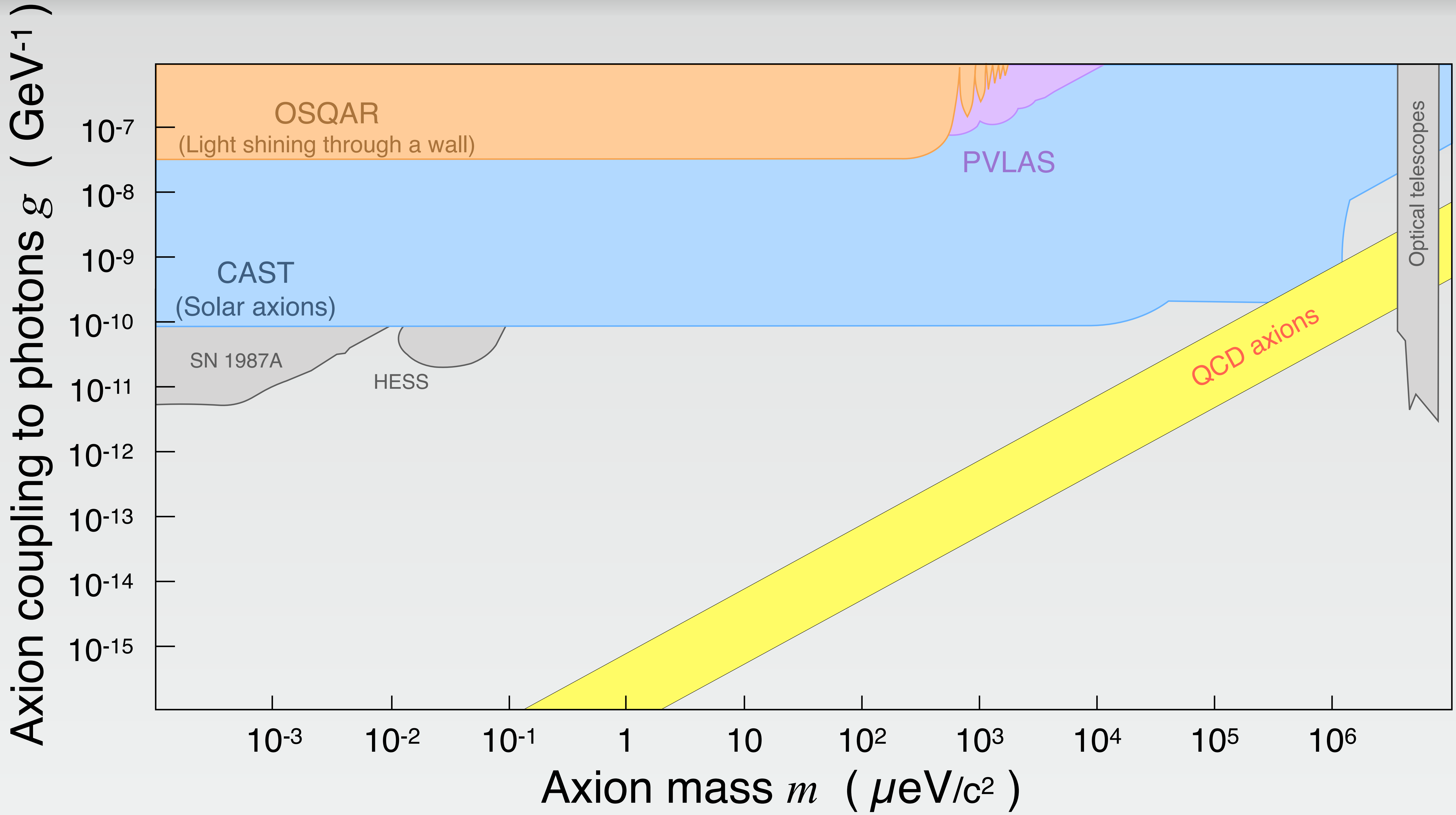
- ⋆ Similar class of particles $(\theta\vec{E}\cdot\vec{B})$
  - Extra dimensions
  - String theory, dilatons, etc.

$$\boxed{m_\theta \not\propto 1/f}$$

Axion-like particles

Axions are also natural dark matter candidate :
2 birds w/ 1 stone :
Strong CP and Dark Matter

Axion searches and constraints



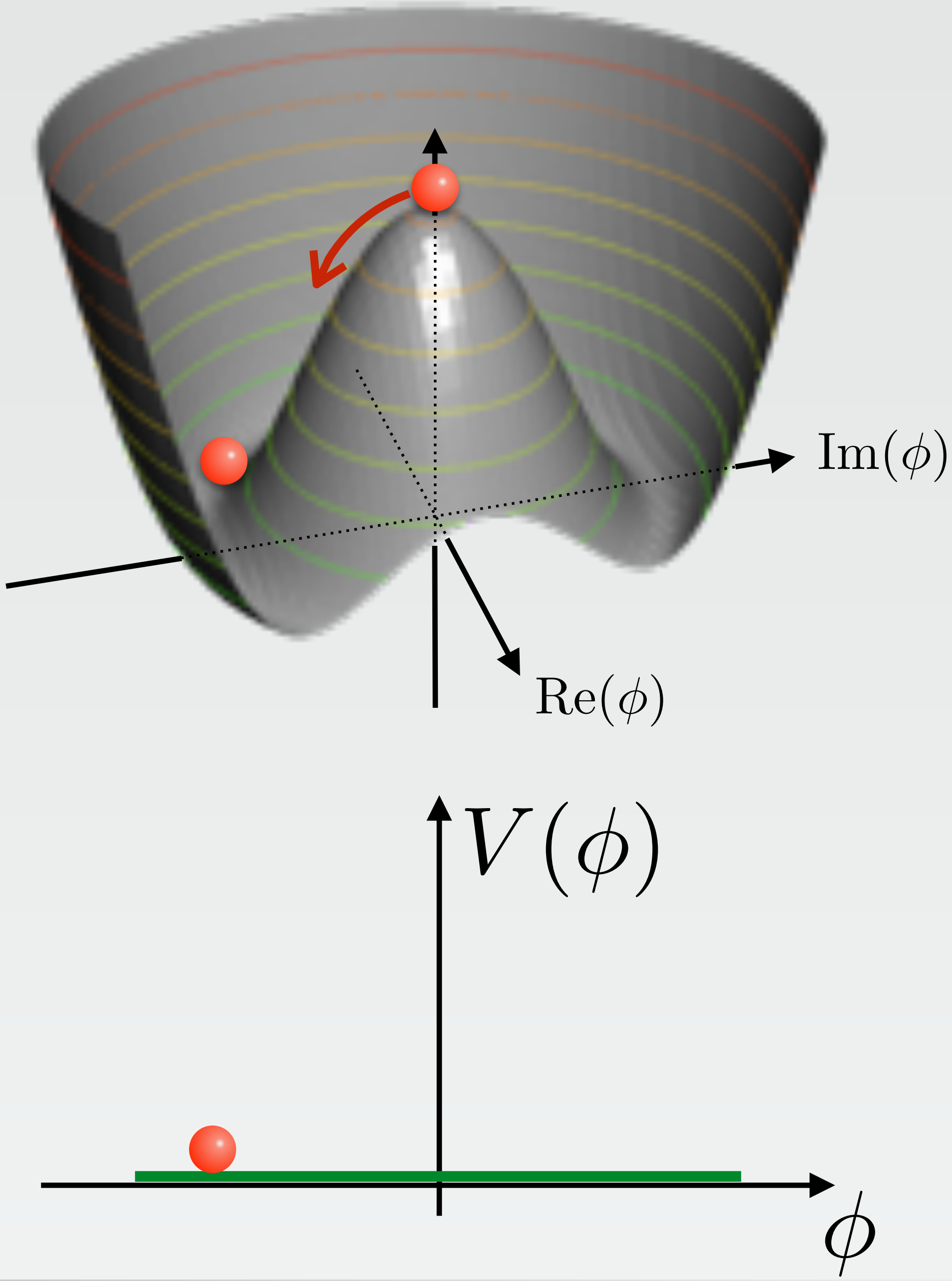
Axion Relic Density

- Thermal population irrelevant to CDM
- Different production mechanisms
  - Misalignment
  - Decay of topological defects if any
- 2 classes of scenarios :
  - PQ symmetry breaking before/after inflation

Cosmological Axions

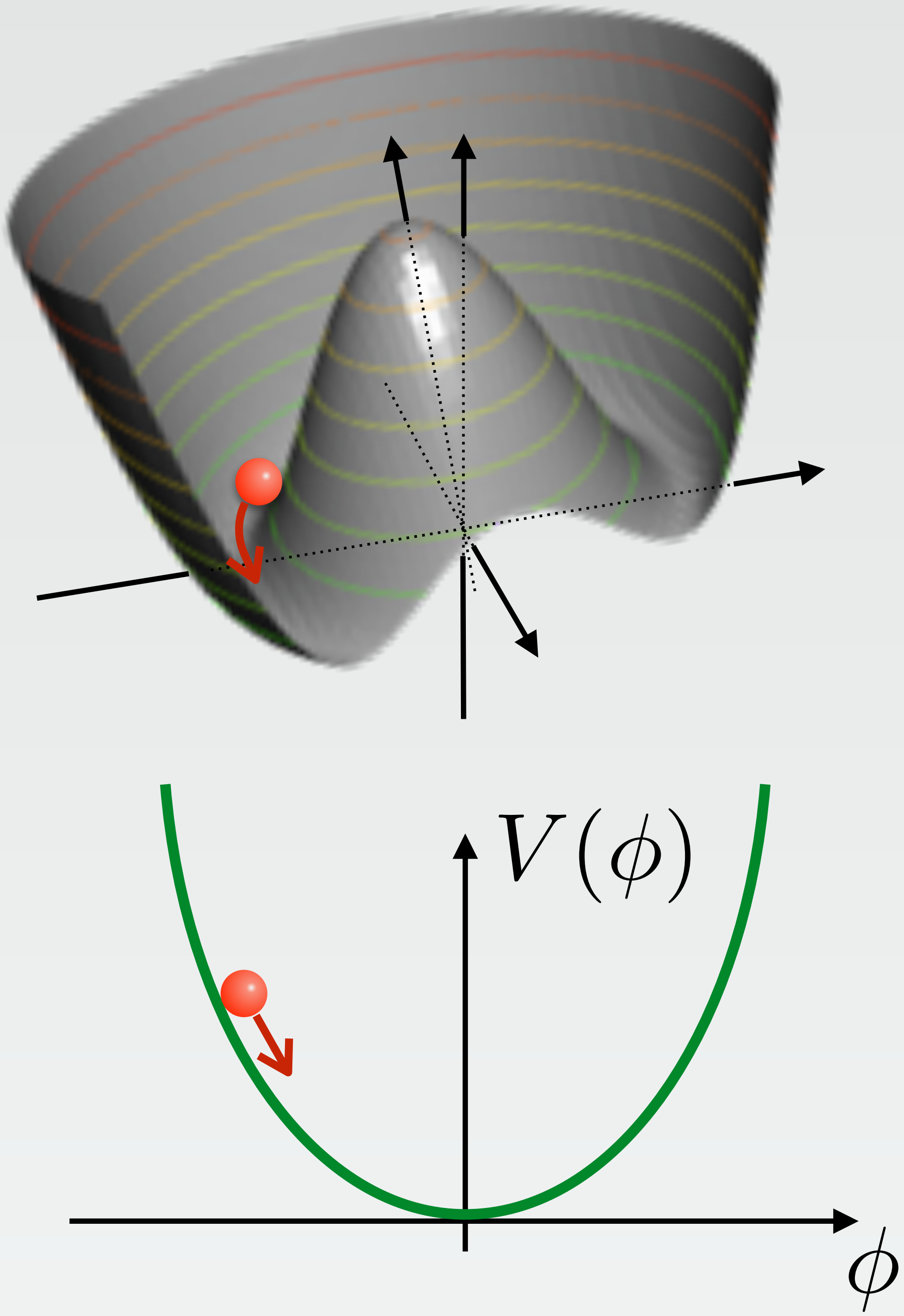
$$T = f_a \gg \Lambda_{QCD}$$

Breaking of Peccei-Quinn U(1)$_{PQ}$



$$T \sim \Lambda_{QCD}$$

QCD phase transition



Axion relic density

- ⋆ Occupation number is huge

- ⋆ Model as $\boldsymbol{k = 0}$ mode of a classical field:

$$\ddot{\phi} + 3H(t)\dot{\phi} + m^2\phi = (\text{terms with spatial derivatives}) = 0$$

- ⋆ Energy density: $\rho = \frac{1}{2}\dot{\phi}^2 + \frac{m^2}{2}\phi^2$

- ⋆ Pressure: $p = \frac{1}{2}\dot{\phi}^2 - \frac{m^2}{2}\phi^2$

- ⋆ Equipartition ⇒ $\frac{1}{2}\langle\dot{\phi}^2\rangle = \frac{m^2}{2}\langle\phi^2\rangle$

Axion relic density

- ⋆ Two regimes for $\ddot{\phi} + 3H(t)\dot{\phi} + m^2\phi = 0$

- ⋆ $m \ll 3H$ early times $t < t_1$ where $3H(t_1) = m$

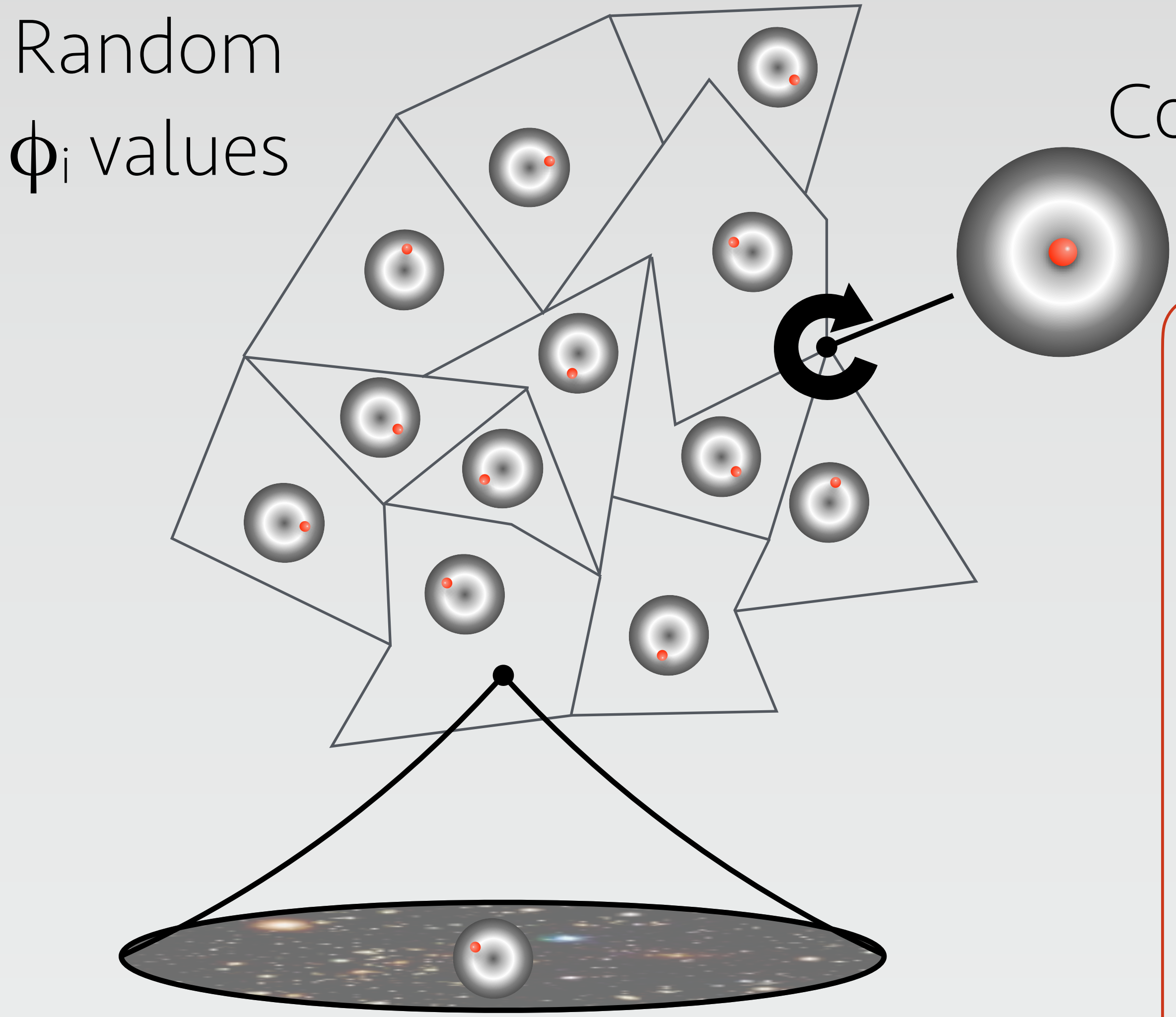
$$\phi = cte$$

- ⋆ $m \gg 3H$ late times $t > t_1$

$$\phi(t) = \phi_1 \sqrt{\frac{a_1^3}{a(t)^3}} \cos mt$$

$$\rho = \rho_i \left(\frac{a_{\rm osc}}{a}\right)^3$$ as expected for dark matter

Two Classes of Scenarios



Post-inflation PQ breaking

topological defects decay later

our Hubble volume

contains average over many ϕ_i

$$\Omega_\phi h^2 \sim 8 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} \times \left(\frac{g_{*,1}}{70}\right)^{-0.41} \left(\frac{\Lambda_{QCD}}{400\,\mathrm{MeV}}\right)$$

Pre-inflation PQ breaking

one ϕ_i singled out randomly

same initial conditions everywhere

$$\Omega_\phi h^2 = 0.11\,\phi_i^2 \left(\frac{10\,\mu\mathrm{eV}}{m}\right)^{1.184}$$

Axion Production from Cosmic Strings

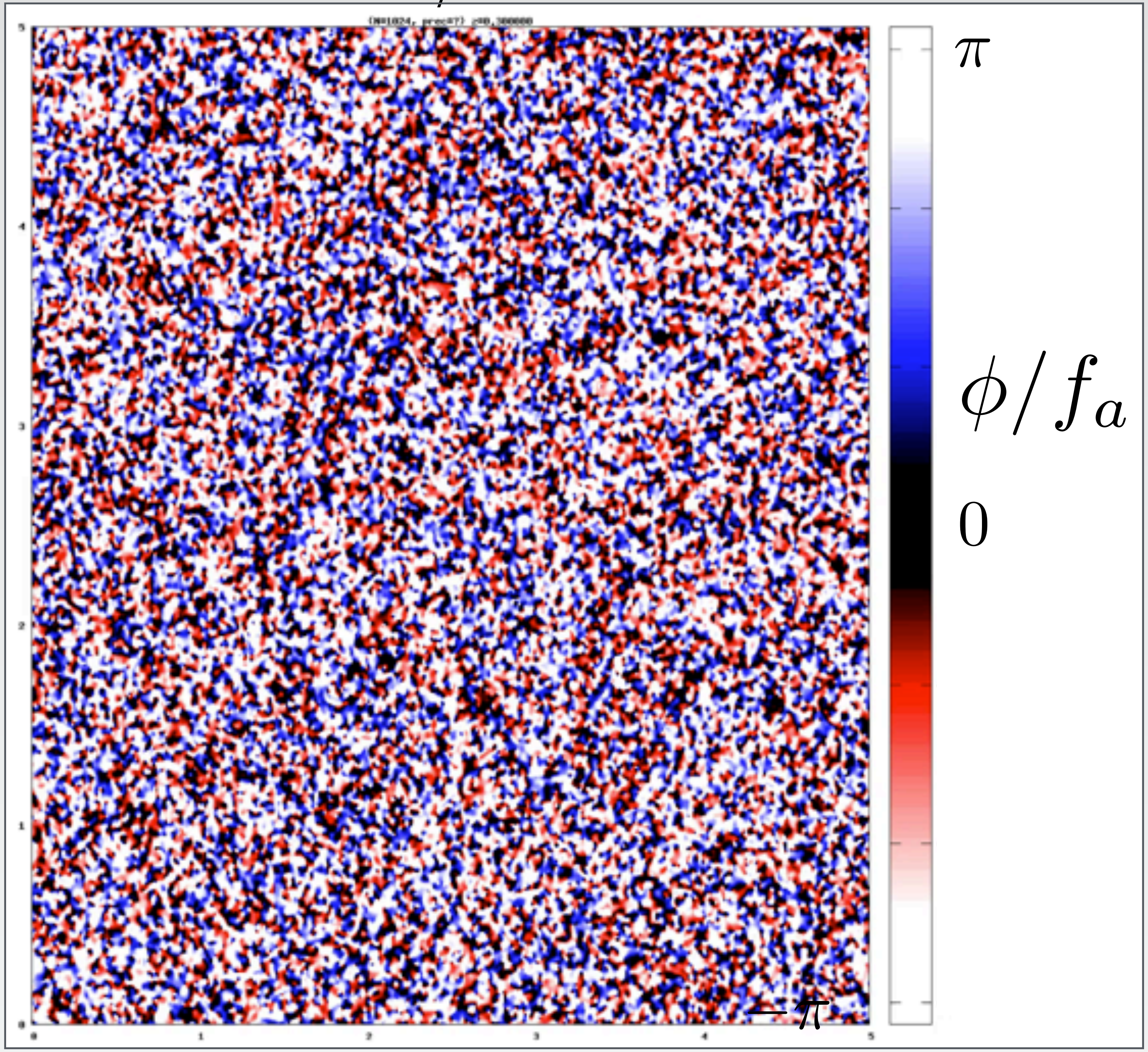
~ 10 comoving

solar systems

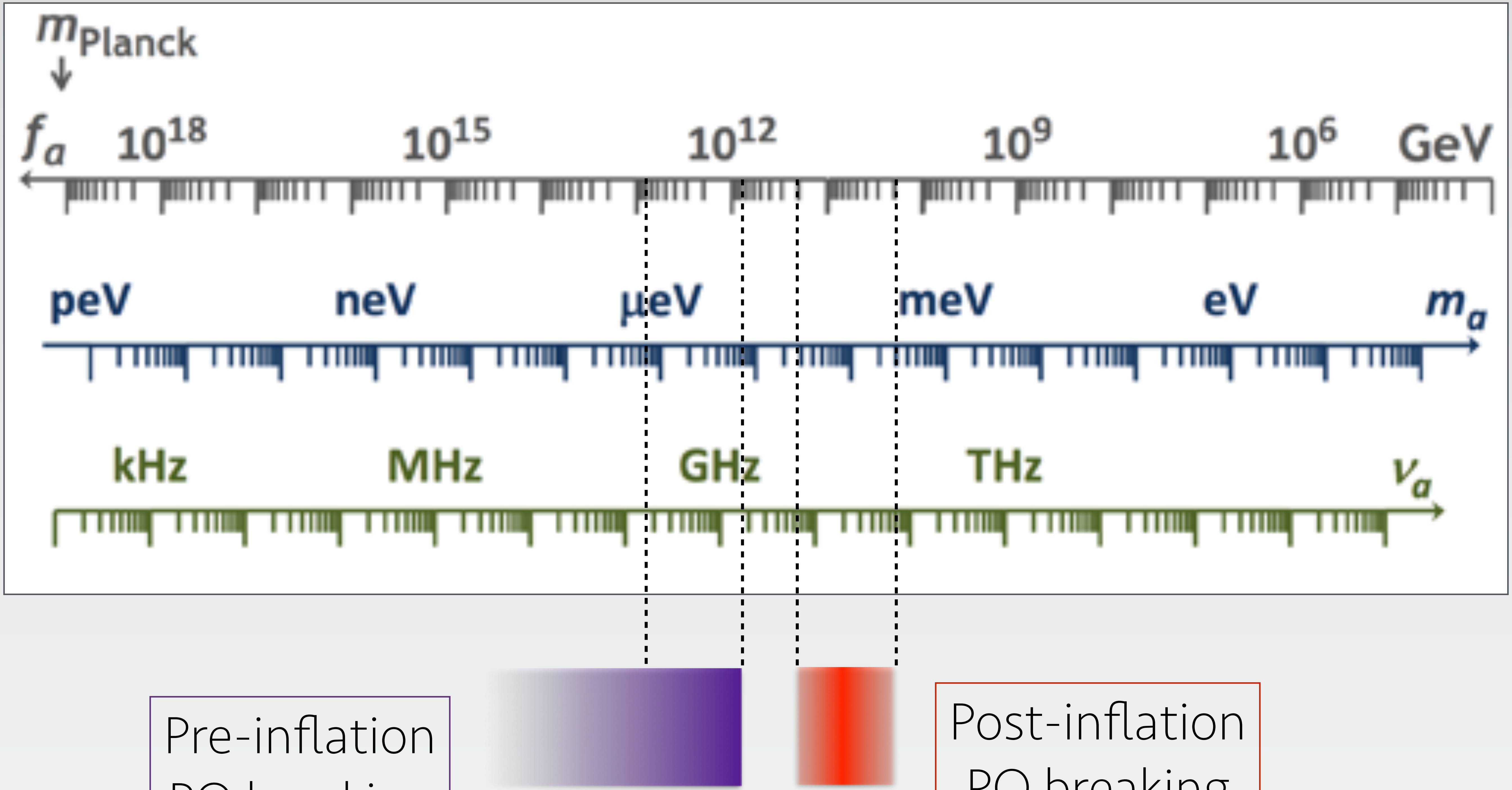
T_0 ~ 4 GeV

fraction of a second

courtesy J. Redondo



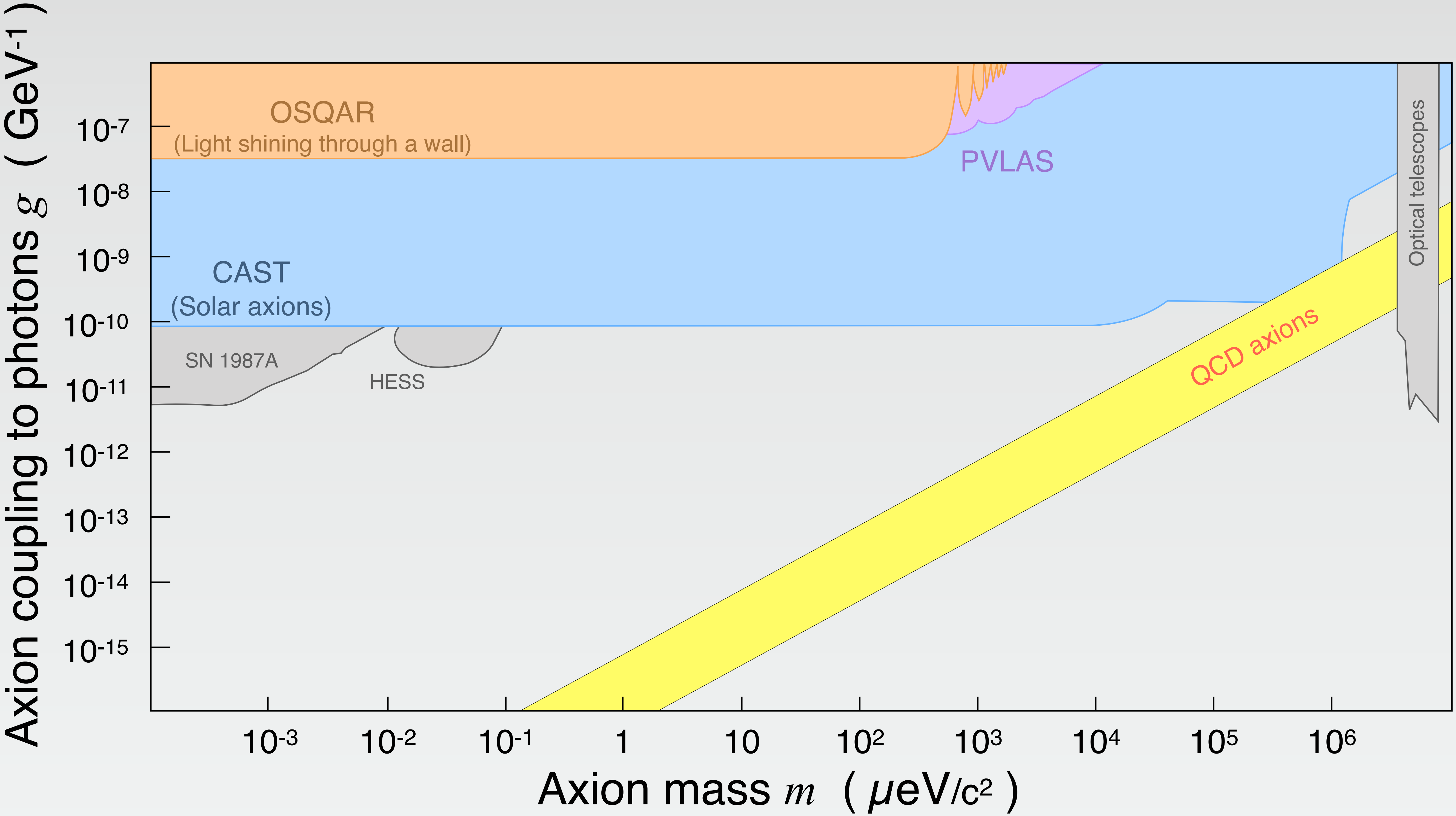
Relevant masses & frequencies



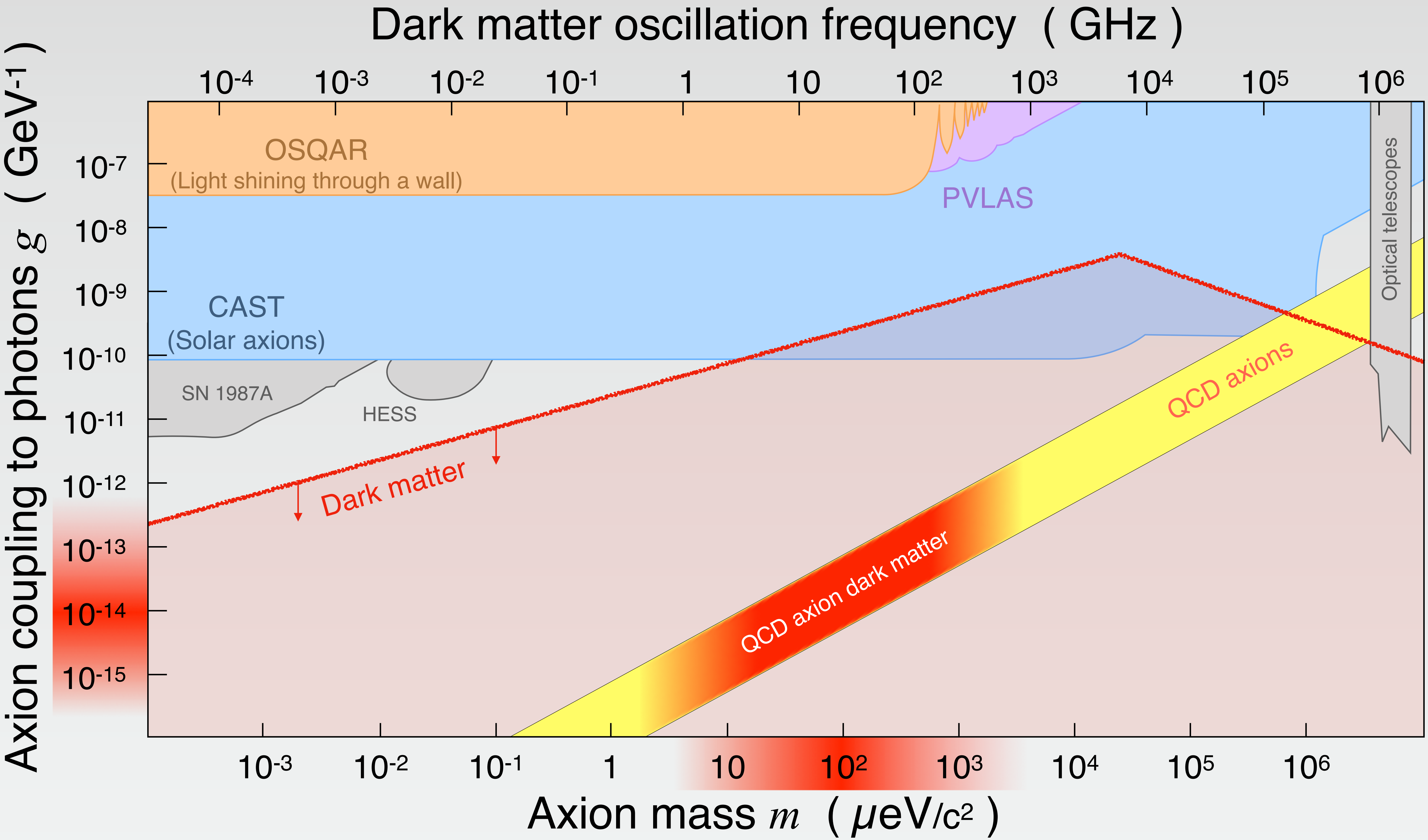
Pre-inflation
PQ breaking

Post-inflation
PQ breaking

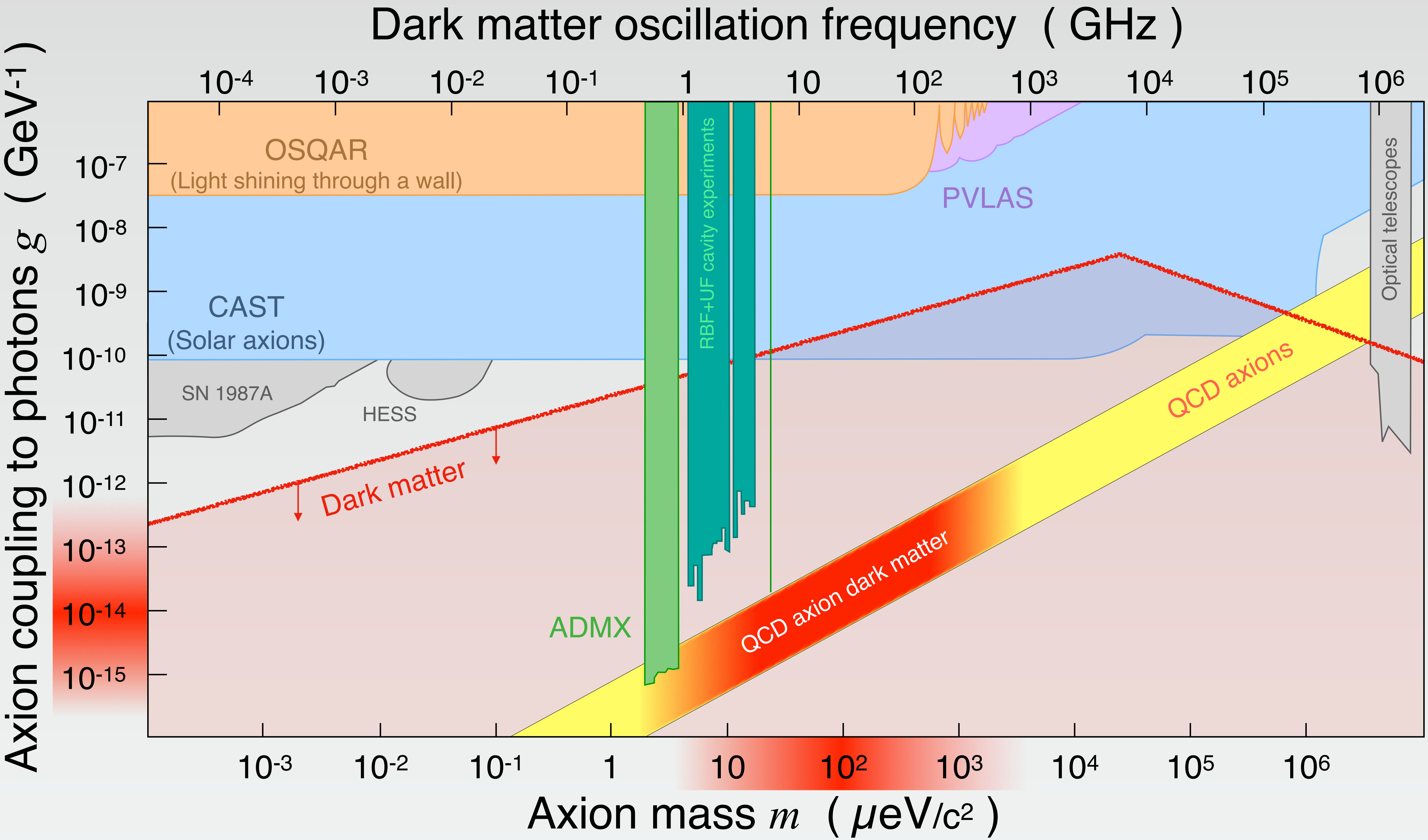
Axion searches and constraints



Axion searches and constraints



Axion searches and constraints



Axions as dark matter

Phase space density is huge…

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

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

$$\left\{\begin{aligned} &p_{\max} = m v_{\text{escape}} = m \times 550\ \text{km/s} \\ &R \sim 50\ \text{kpc} \end{aligned}\right.$$

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

Local Relic Axions

- ⋆ Axion field oscillates on scale > solar system
- ⋆ Velocity of the lab is < 300 km/s = 10^{-3} c

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

- ⋆ Oscillation frequency set by axion mass

$$k = 0 \ \Rightarrow \ \omega = \frac{mc^2}{\hbar} \qquad f = \frac{mc^2}{2\pi\hbar} \qquad \boxed{f = 2.4 \text{ GHz} \times \frac{m}{10 \ \mu\text{eV}}}$$

- ⋆ Known signal dispersion $\frac{\delta f}{f} = \frac{v^2}{2c^2} < 10^{-6}$

Classical description

$\mathscr{L}_{a\gamma} = g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} \propto g_{a\gamma} \vec{E} \cdot \vec{B}$ ⇒ modified Maxwell equations

$$\vec{\nabla} \cdot \vec{B} = \vec{0} \qquad \vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \boxed{- g_{a\gamma}\, c\, \vec{\nabla} \phi \cdot \vec{B}}$$

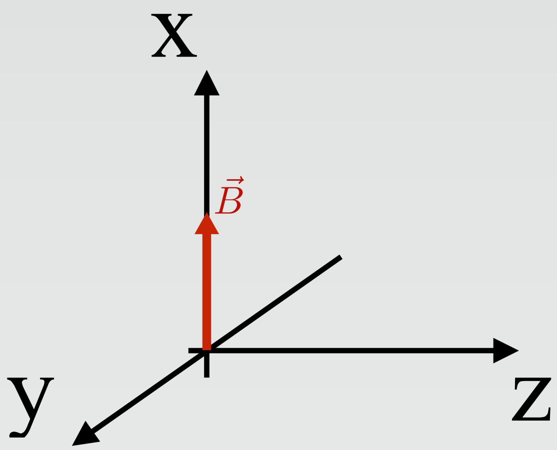
$$\vec{\nabla}_\wedge \vec{E} = - \dot{\vec{B}} \qquad \vec{\nabla}_\wedge \vec{B} = \mu_0 \vec{j} + \frac{1}{c^2} \dot{\vec{E}} \boxed{+ \frac{g_{a\gamma}}{c} \left(\vec{\nabla} \phi_\wedge \vec{E} + \overset{\Downarrow}{\boxed{\dot{\phi} \vec{B})}} \right)}$$

In an external magnetic field $\vec{B}_{\text{ext}}$ with $\phi(t)$ as for dark matter:

$$\vec{E}_{\text{DM}} = - \phi_0 g_{a\gamma}\, c\, \vec{B}_{\text{ext}} \cos\left(\frac{m_a c^2}{\hbar} t \right)$$

Equations of Motion

- ★ Consider a plane wave



$$\Psi = \begin{pmatrix} \vec{A}_{||} \\ \phi \end{pmatrix} \exp\left(-i(\omega t - kz)\right)$$

- ★ Leads to the equation of motion :

$$\left[(\omega^2 - k^2) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & -g|\vec{B}|\omega \\ -g|\vec{B}|\omega & m \end{pmatrix} \right] \begin{pmatrix} \vec{A}_{||} \\ \phi \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

Photon and axion mix, angle prop. to B field

G. Raffelt, L. Stodolsky, PRD 1988

Solutions of EoM

- ⋆ First line of EoM :

$$(\omega^2 - k^2)A_i + gB_i\omega\phi = 0$$

$$\Rightarrow \vec{A}_{DM} = -\phi_0 \frac{gB_x\omega}{\omega^2 - k^2} e^{-i(\omega t - kz)}\vec{e}_x$$

- ⋆ To ϕ is associated a small electric field :

$$\vec{E}_{DM} = -\partial_0 \vec{A}_{DM} = i\phi_0 g B_x e^{-i(\omega t - kz)}\vec{e}_x$$

Dark Matter Solution of EoM

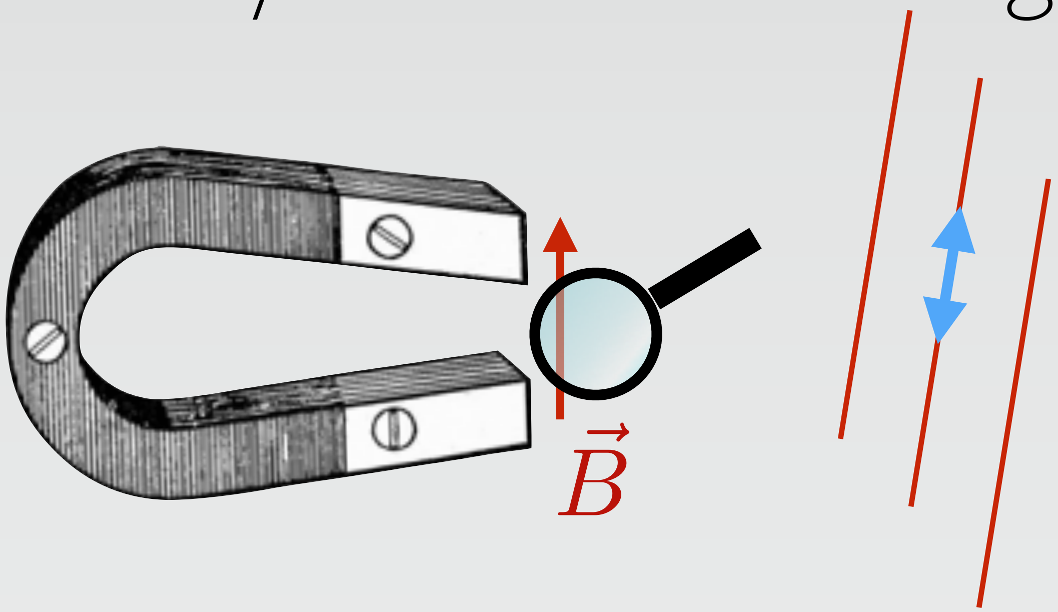
- ⋆ DM velocity is small $v = \dfrac{kc^2}{\omega} \ll c$
- ⋆ For $v = 10^{-3} c$, $\lambda_{DM} \simeq 30\ \mathrm{m}$
- ⋆ Practically a coherent oscillation :

$$\vec{E}_{DM} = i\phi_0\, g B_x\, e^{-i\omega t}\, \vec{e}_x$$

up to $o(10^{-3})$ terms

More Concretely...

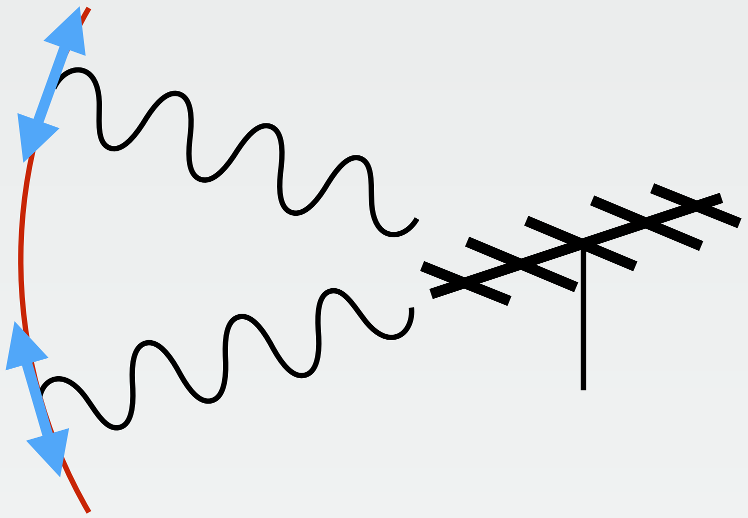
Everywhere in the background : $\phi = \phi_0 \exp(-i\omega t)$



$$g F_{\mu\nu} \tilde{F}^{\mu\nu} \phi \quad \propto \quad g\, \vec{E} \cdot \vec{B}\, \phi$$

small oscillating electric field along each B-field line

Possible lab experiment :
bend field lines,
detect EM radiation from this

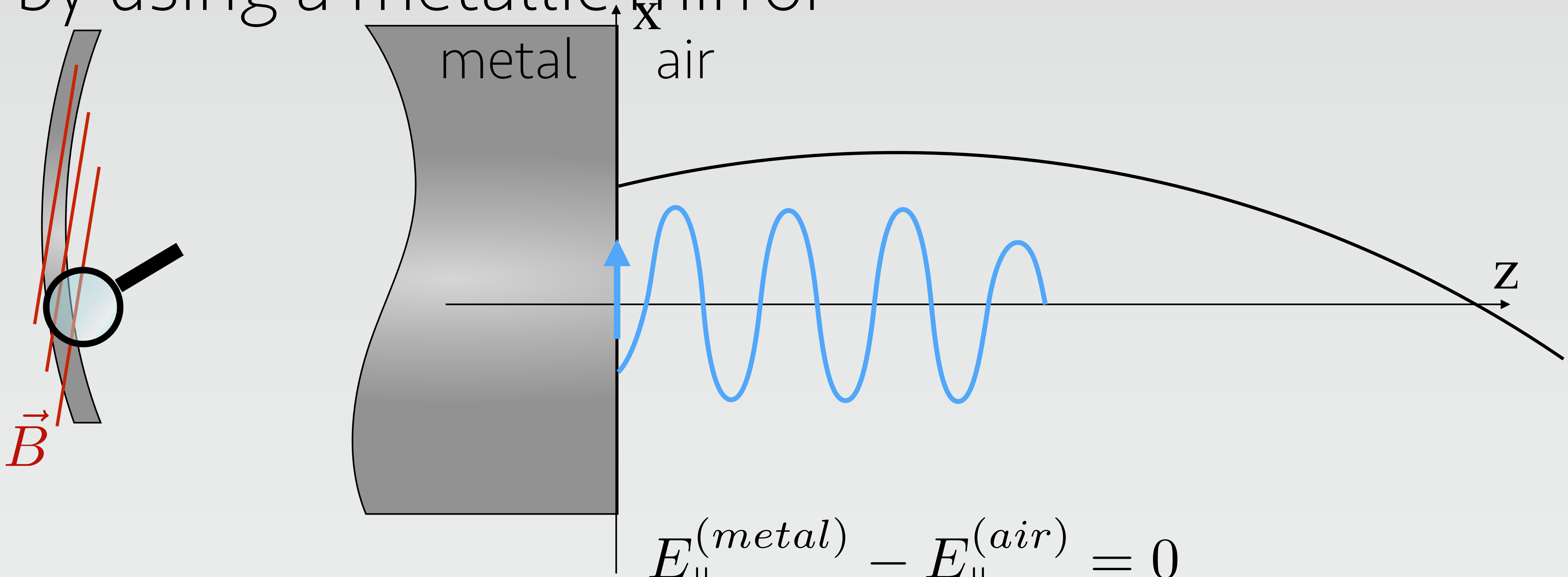


~10 GHz signal

Polarized

Imposing Boundary Conditions

.. by using a metallic mirror



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

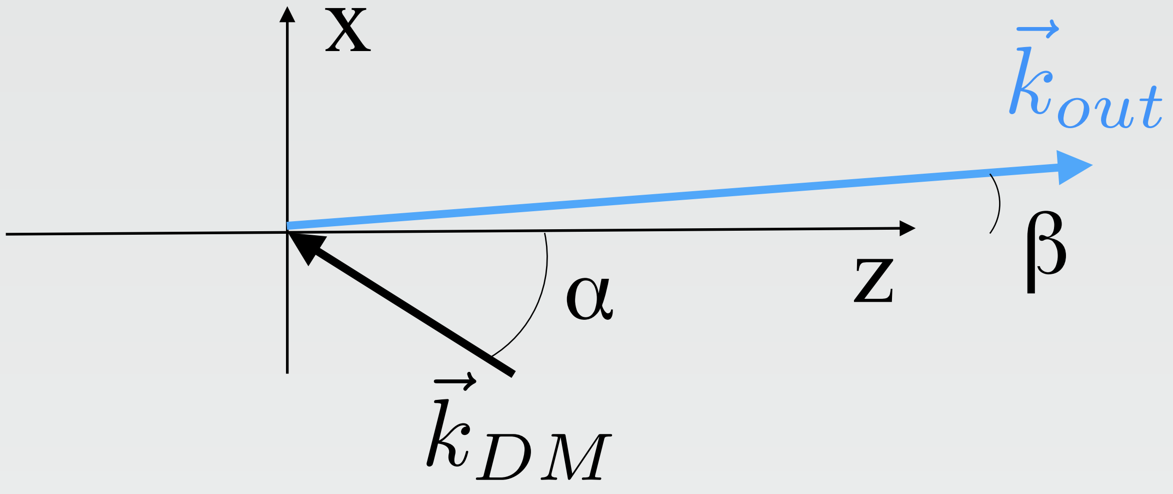
$$\vec{E}_{tot} = i\phi_0\, gB_x\, e^{-i(\omega t)}\ \vec{e}_x - i\phi_0\, gB_x\, e^{-i(\omega t - kz)}\ \vec{e}_x$$

$\vec{E}_{DM}$ $\vec{E}_{out}$

Experiment Principle

- ★ Radio emission is normal to the surface

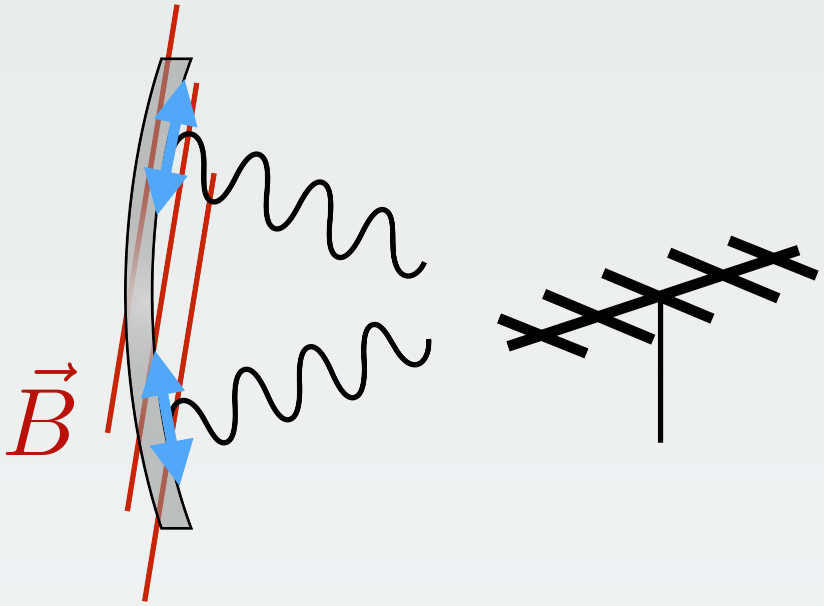
- ★ Another derivation show



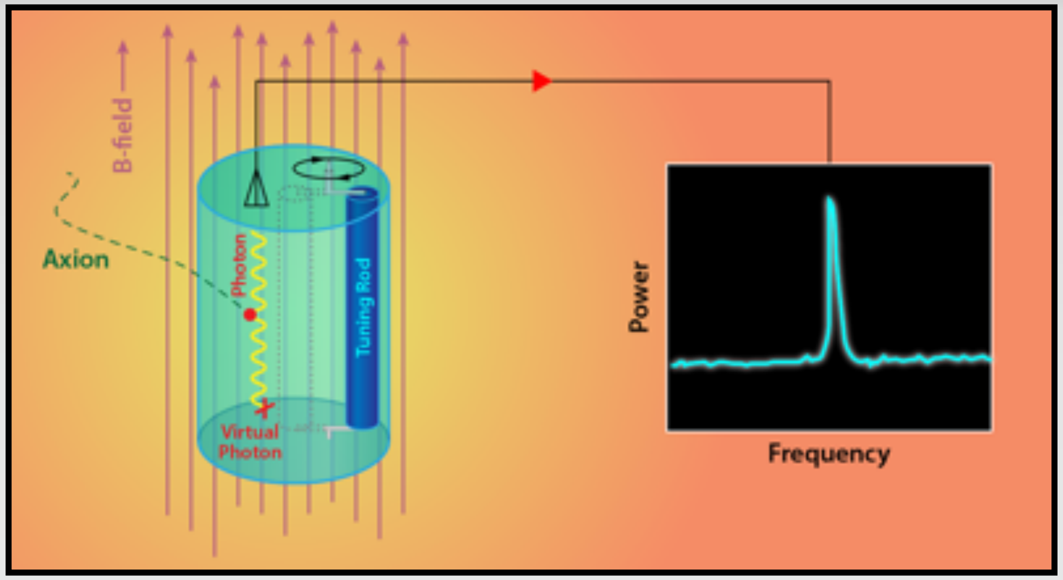
$$\sin(\beta) = \sin(\alpha)\frac{v}{c\sqrt{1-\left(\frac{v}{c}\right)^2}}$$

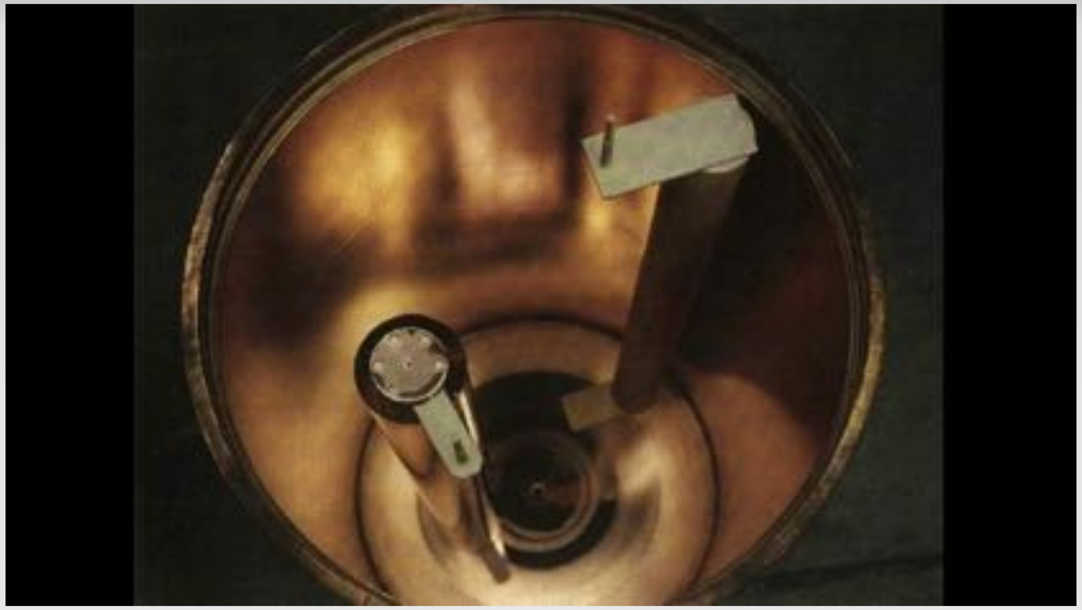
- ★ Proposed experiment

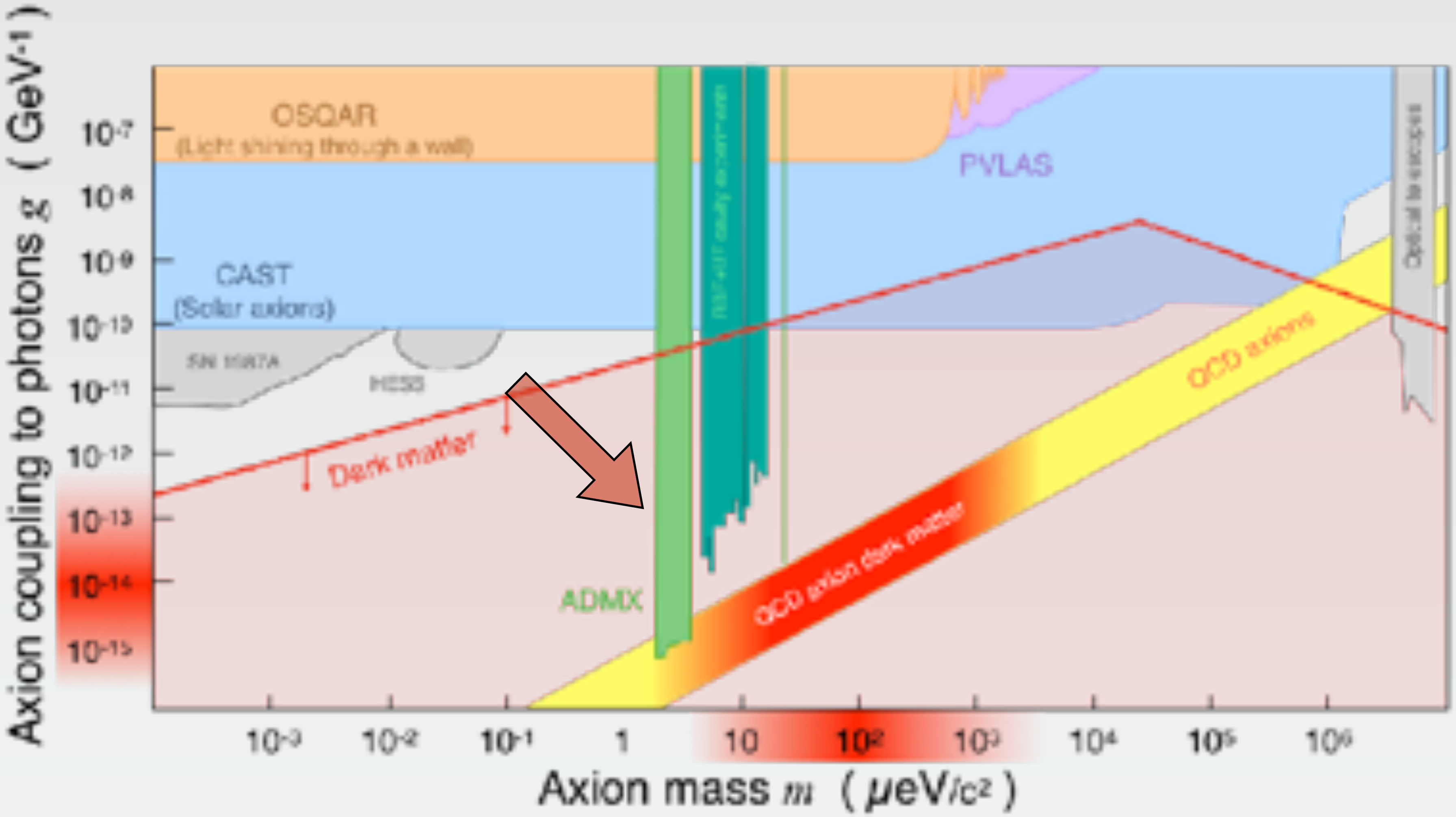
D. Horns et al. JCAP 2012
J. Jaeckel & J. Redondo, JCAP 2013
J. Jaeckel & S. Knirck, Patras 2016



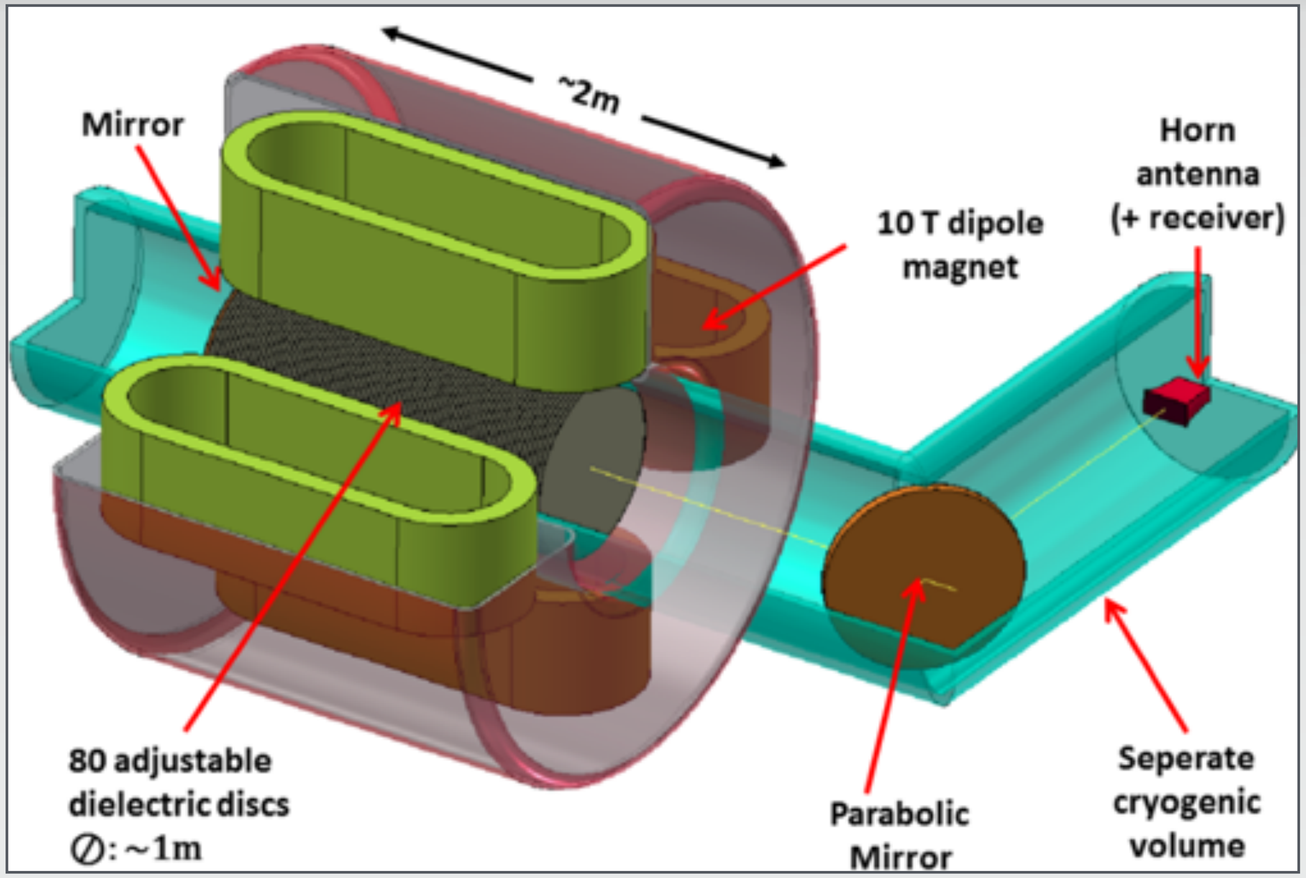
Narrowband experiments: ADMX



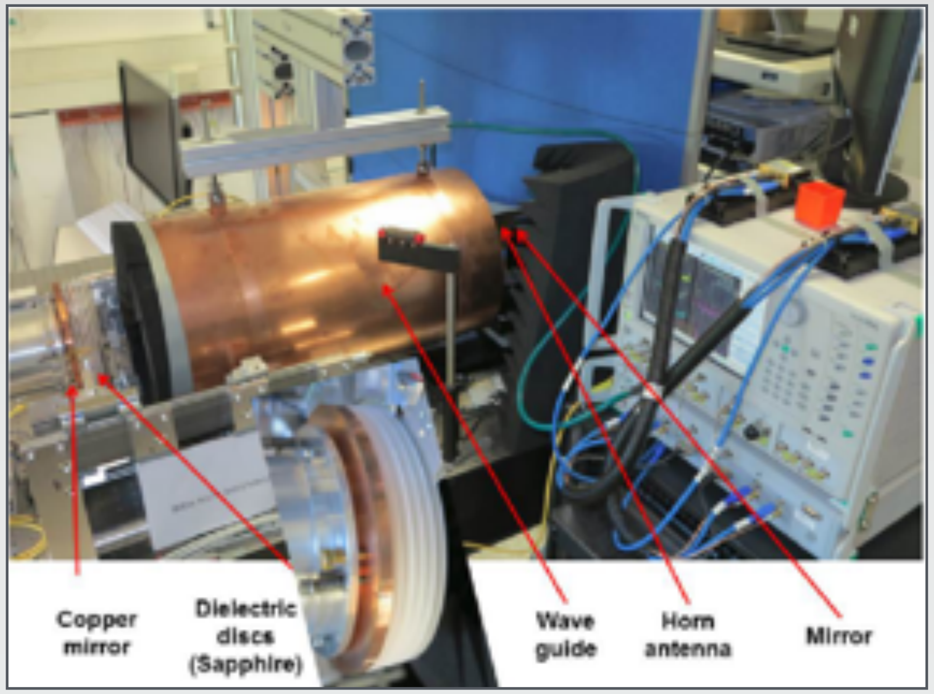




Narrowband experiments: MADMAX



Prototype at MPI Munich:



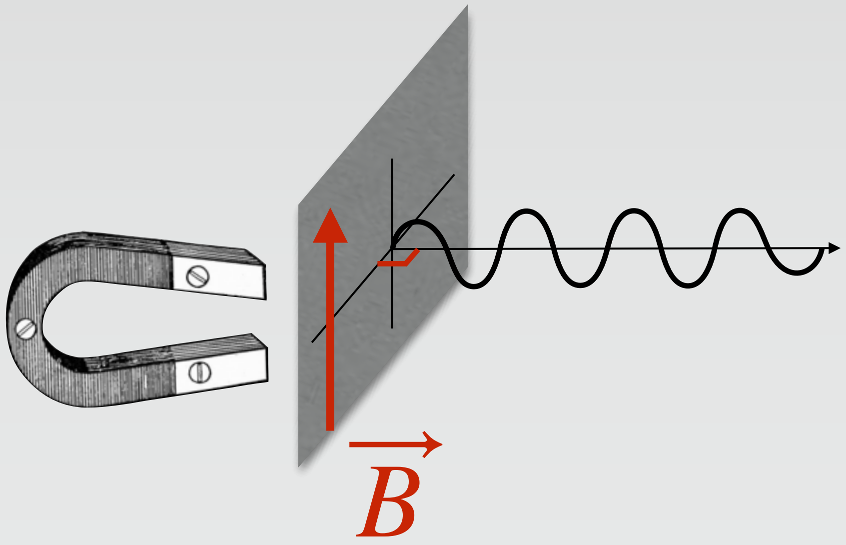
Very expensive magnet, long to produce
Challenging mechanics, requires lots of development

Do not work for $m_a > 200\ \mu\mathrm{eV}$ (i.e. $\nu > 50$ GHz)

Possible synergies in the detection strategies

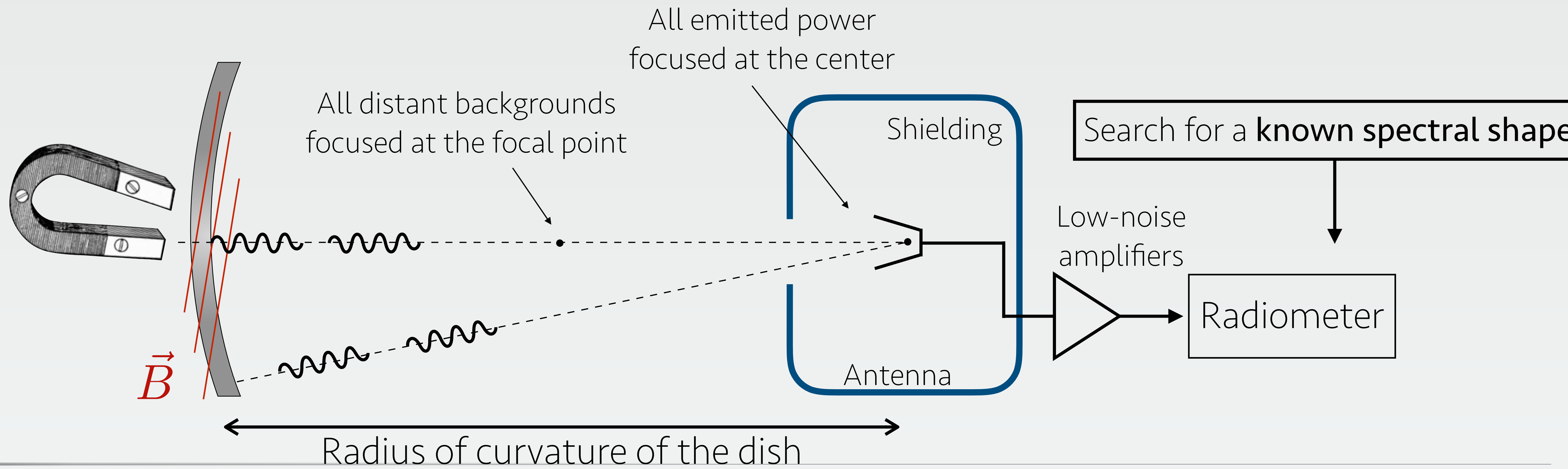
Proposed experiment: principle

Axion dark matter ⇒ magnetized conductor emits continuous microwaves



$$\boxed{f = 2.4\ \text{GHz} \times \frac{m\,c^2}{10\ \mu\text{eV}}} \qquad \boxed{\frac{\delta f}{f} = 10^{-6}}$$

Simplest possible experimental setup *(Horns et al., JCAP 2014)*:



All emitted power focused at the center

All distant backgrounds focused at the focal point

Shielding

Antenna

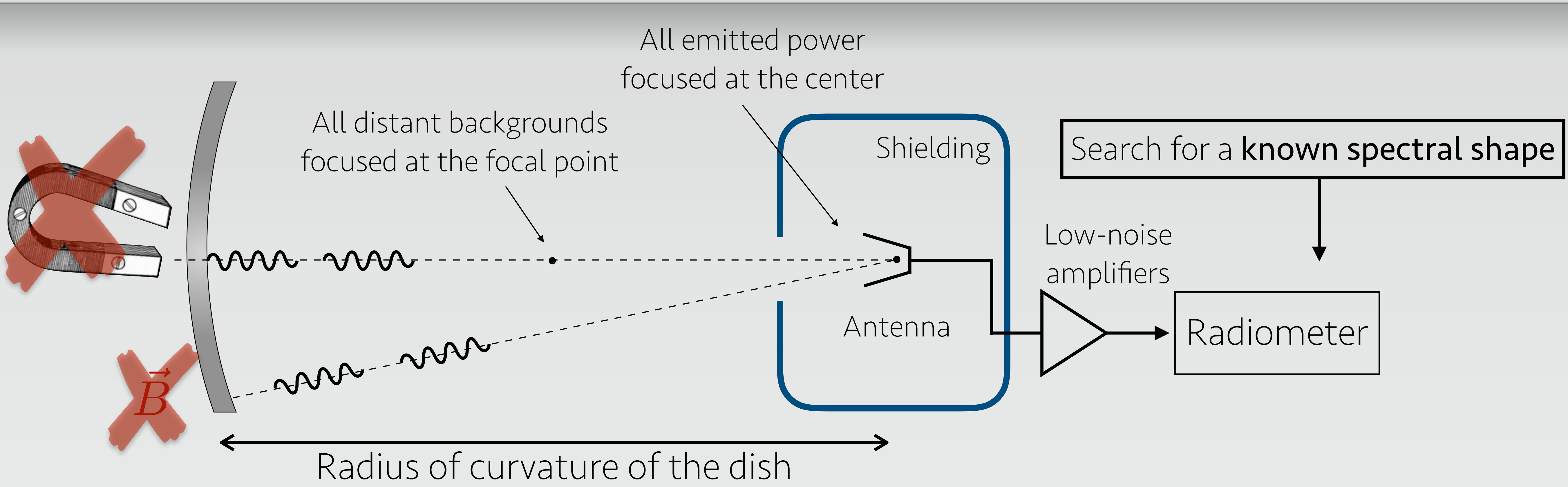
Search for a **known spectral shape**

Low-noise amplifiers

Radiometer

Radius of curvature of the dish

Pathfinder: SHUKET



All emitted power focused at the center

All distant backgrounds focused at the focal point

Shielding

Antenna

Search for a **known spectral shape**

Low-noise amplifiers

Radiometer

Radius of curvature of the dish

Poorman's experiment: no magnetic field

Sensitive to other type of dark matter: « dark photons »

SHUKET

=

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

Hidden photons

New vector field $\boldsymbol{\phi}$:

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

Relatable to axion coupling

$$-\frac{1}{4}gF_{\mu\nu}\tilde{F}^{\mu\nu}\phi \leftrightarrow -\frac{\chi}{2}F^{\mu\nu}X_{\mu\nu}$$

Same phenomenology (misalignment, oscillations, etc.) with

$$\vec{E}_{\mathrm{DM}} = \chi\omega\vec{\phi}$$

χ 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

Sensitivity to coupling parameters

- Axion-like particles

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\partial^\mu\phi + \frac{1}{2}m^2\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}gF_{\mu\nu}\tilde{F}^{\mu\nu}\phi$$

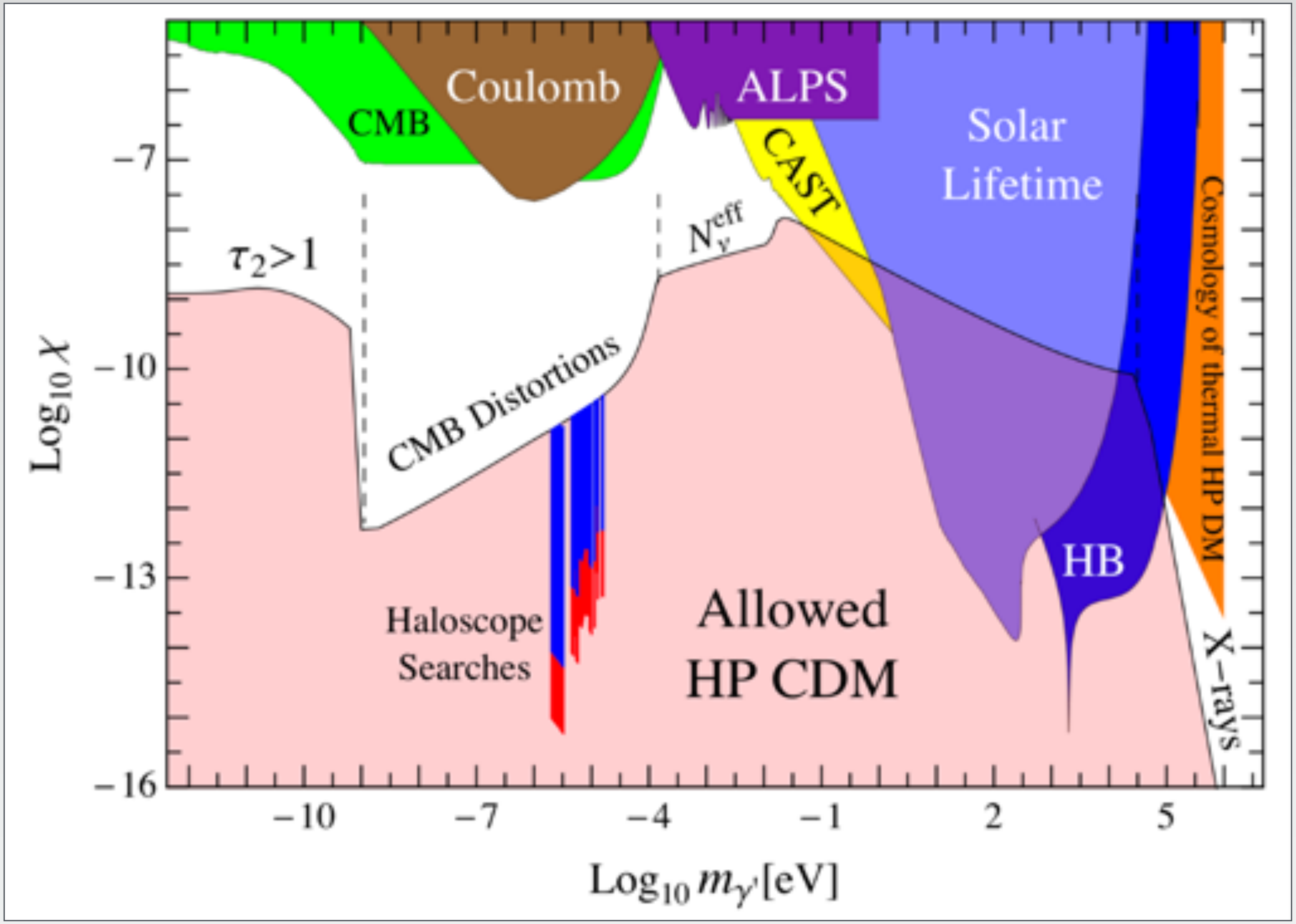
$$\boxed{g = \frac{3.6\times10^{-8}}{\mathrm{GeV}}\left(\frac{5\ \mathrm{T}}{B}\right)\left(\frac{P_{det}}{10^{-23}\ \mathrm{W}}\right)^{1/2}\left(\frac{m}{\mathrm{eV}}\right)\left(\frac{0.3\ \mathrm{GeV/cm}^{3}}{\rho_\odot}\right)^{1/2}\left(\frac{1\ \mathrm{m}^{2}}{A_{dish}}\right)^{1/2}}$$

- Hidden photons

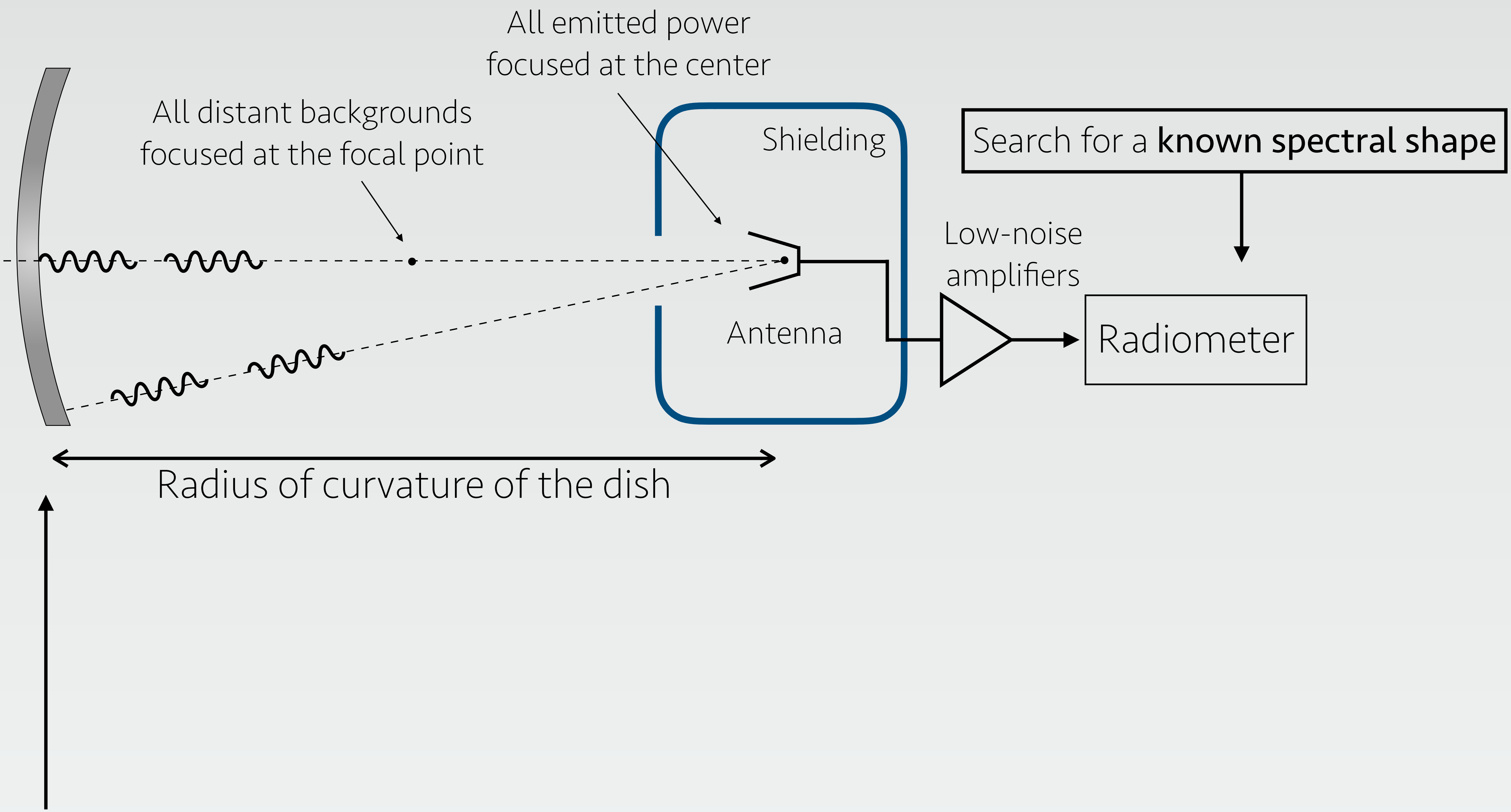
$$\mathcal{L} = -\frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{m^2}{2}\tilde{X}_\mu\tilde{X}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}\tilde{X}^{\mu\nu}$$

$$\boxed{\chi = 4.5\times10^{-14}\left(\frac{P_{det}}{10^{-23}\ \mathrm{W}}\right)^{1/2}\left(\frac{0.3\ \mathrm{GeV/cm}^{3}}{\rho_\odot}\right)^{1/2}\left(\frac{1\ \mathrm{m}^{2}}{A_{dish}}\right)^{1/2}\left(\frac{\sqrt{2/3}}{\alpha}\right)}$$

Constraints on hidden photons



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



All emitted power focused at the center

All distant backgrounds focused at the focal point

Shielding

Search for a **known spectral shape**

Low-noise amplifiers

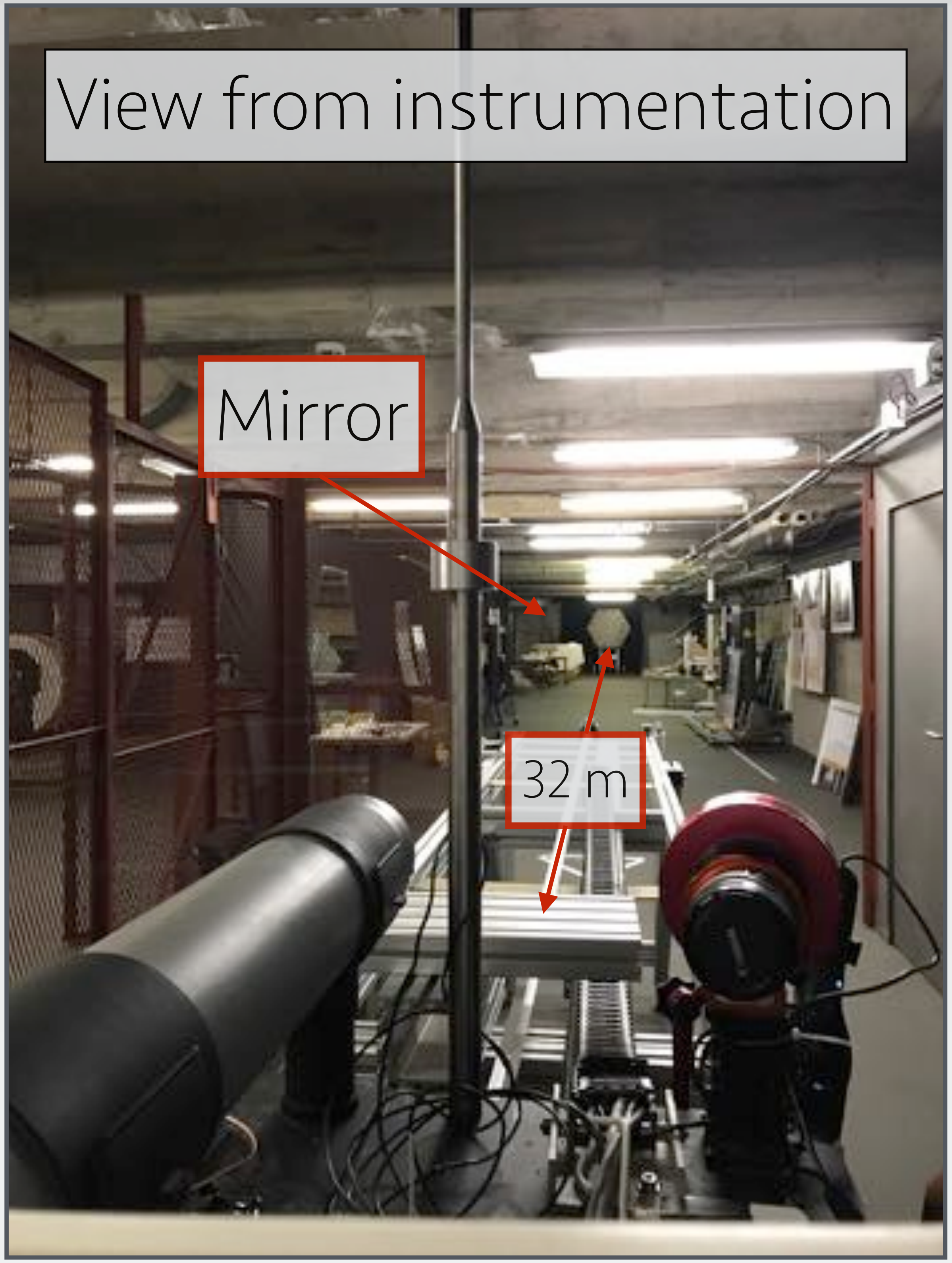
Antenna

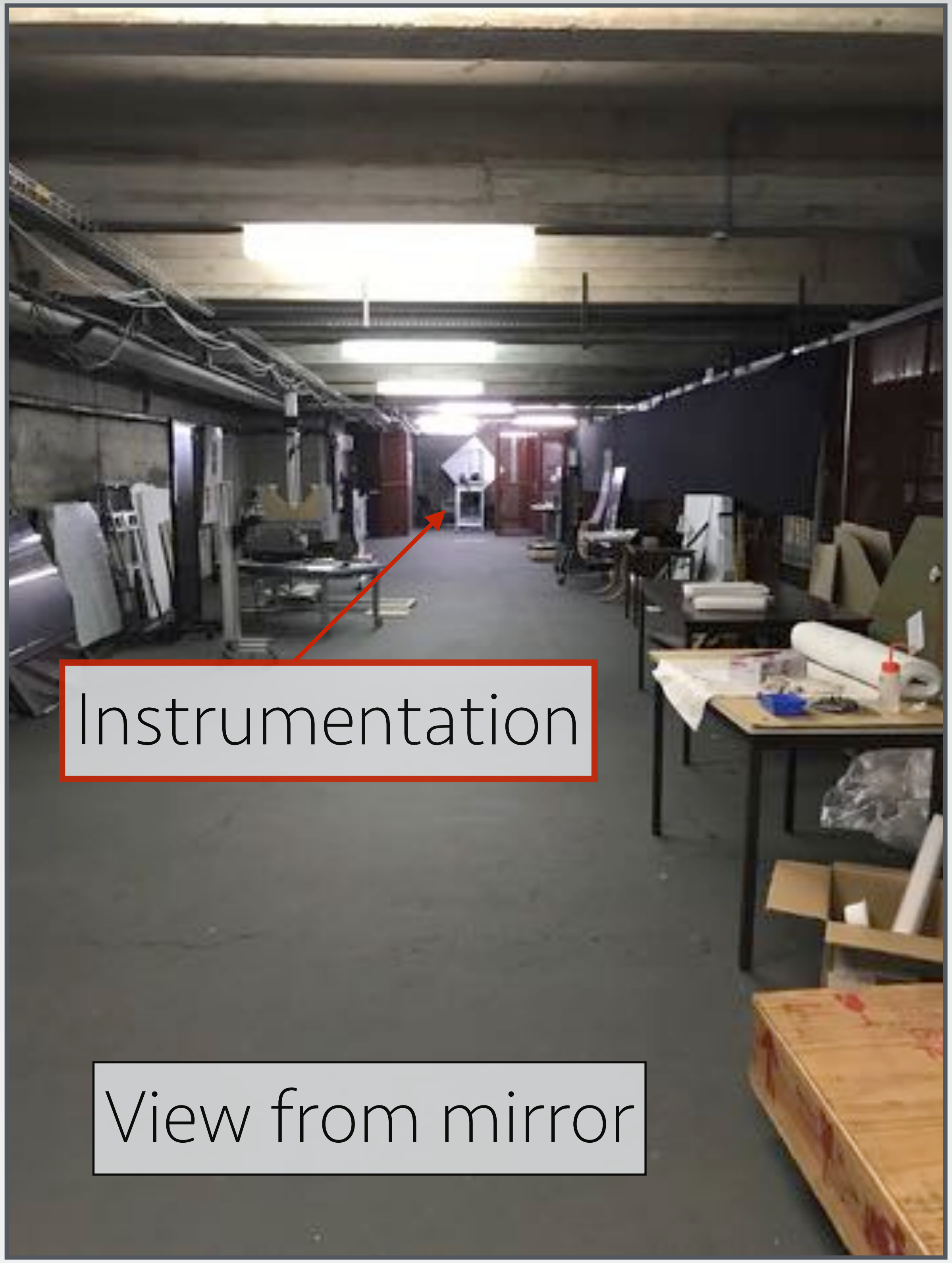
Radiometer

Radius of curvature of the dish

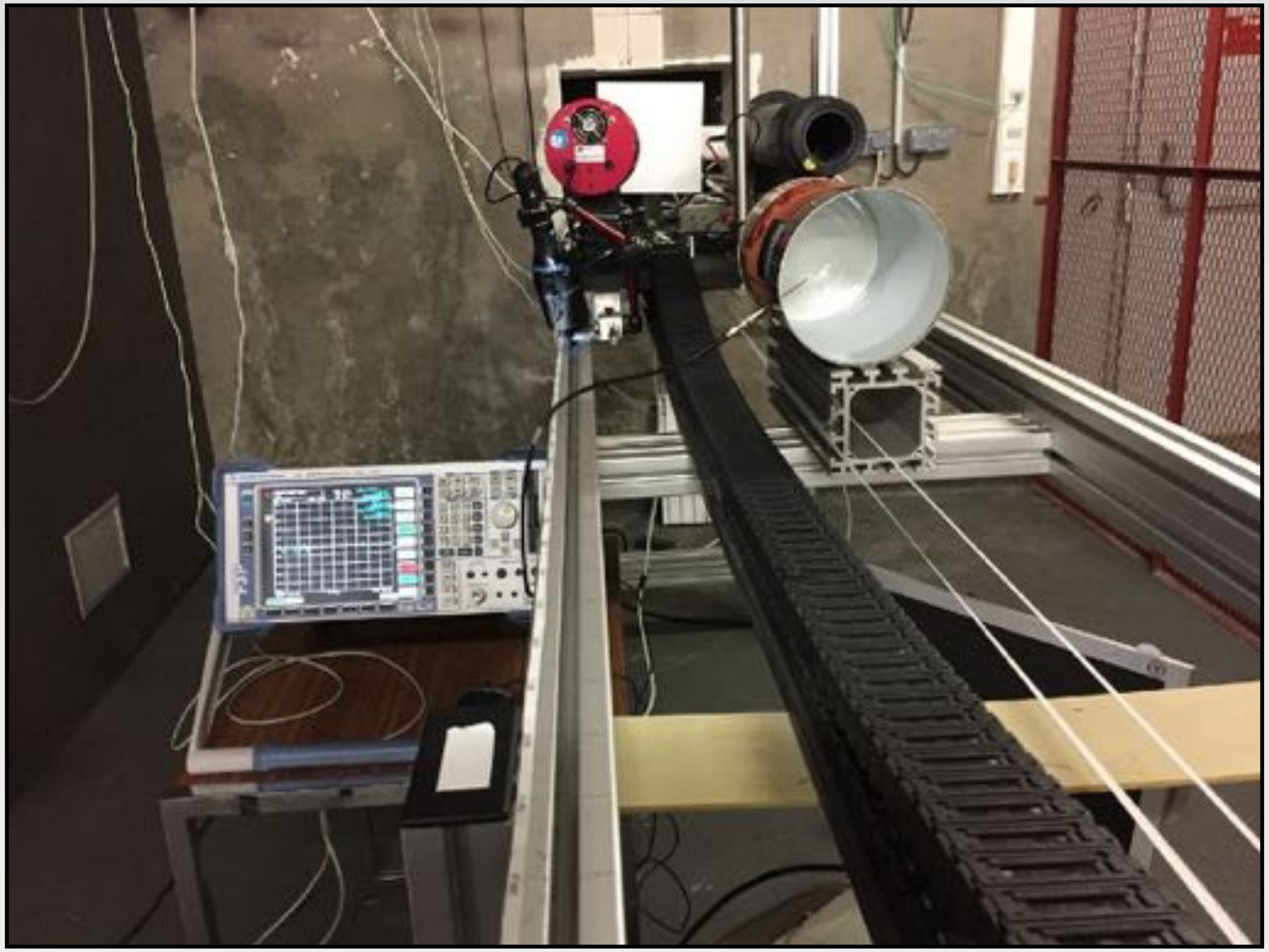
Mirror from a gamma-ray astronomy experiment (CTA)

Optical Test Bench at Saclay

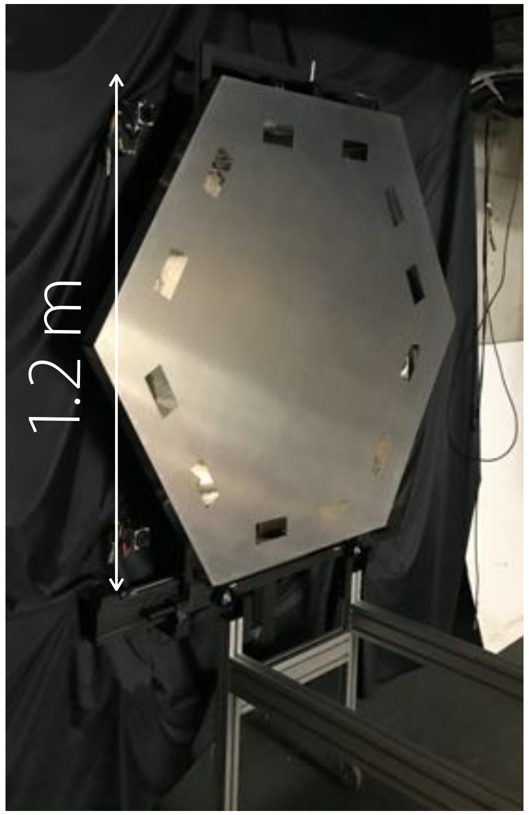




First setup



SHUKET improved setup



Mirror

32 m

Horn antenna + shielding

Amplifiers
+
Spectrum analyzer

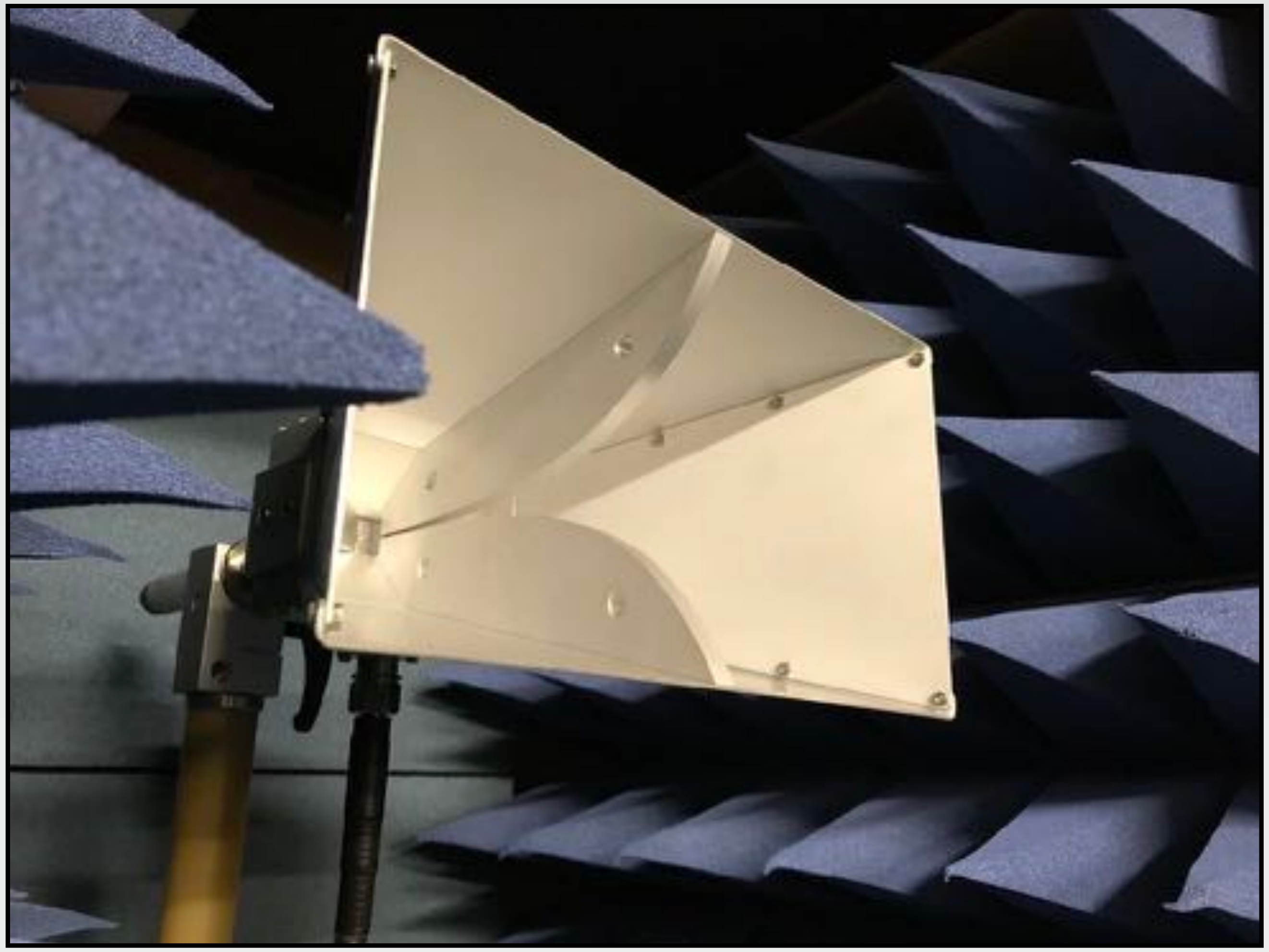
Achieved 10^{-22} W/Hz sensitivity

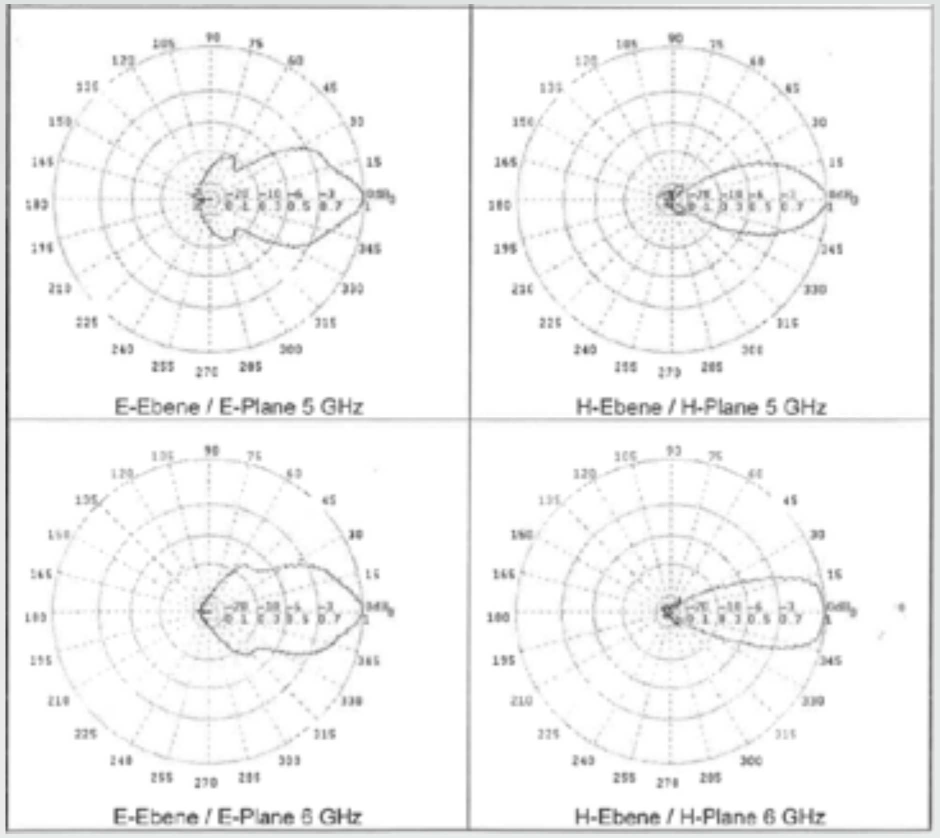
Constraints on hidden photons dark matter

Horn Antenna

Polarized horn antenna

1-18 GHz





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

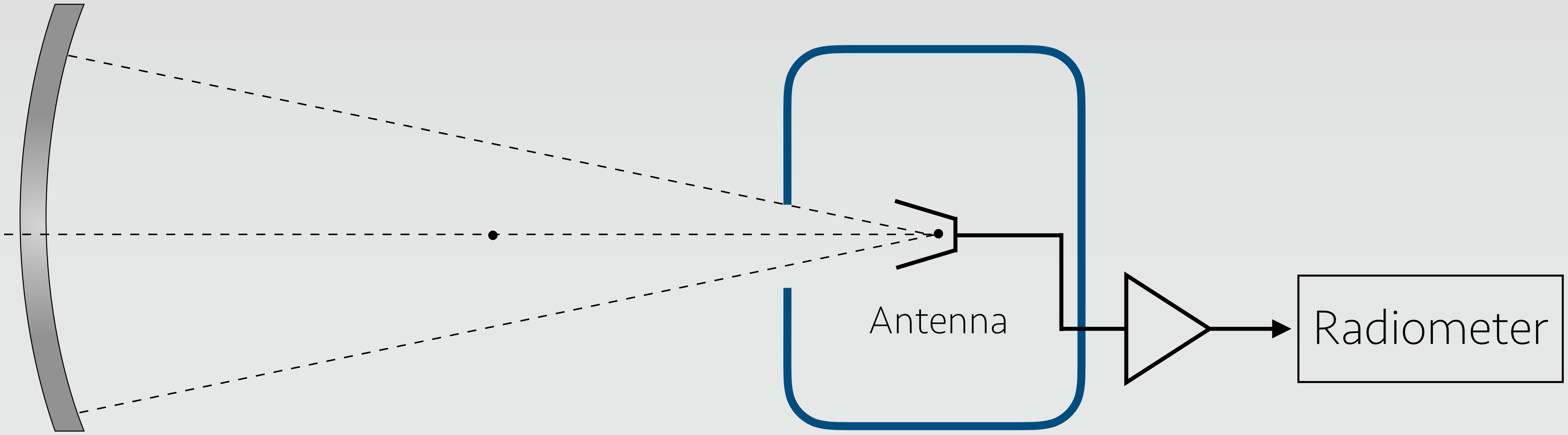
Spectrum analyzer

- ⋆ Room-temperature LN amplifier ~30 dB

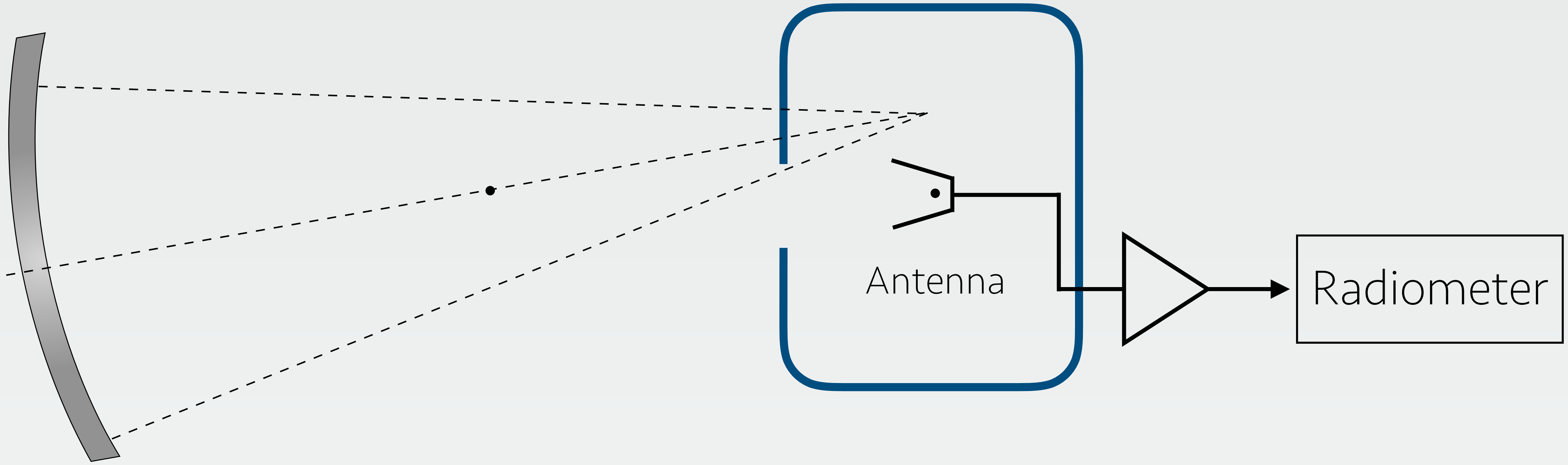
- ⋆ Loan from Rhodes & Schwarz
  - 3 GHz - 20 GHz FSP
- ⋆ Performs FFT + power measurement in 1 Hz bins
- ⋆ 2 weeks : ~2 GHz bandwidth analyzed (5-7 GHz)

ON and OFF runs

ON

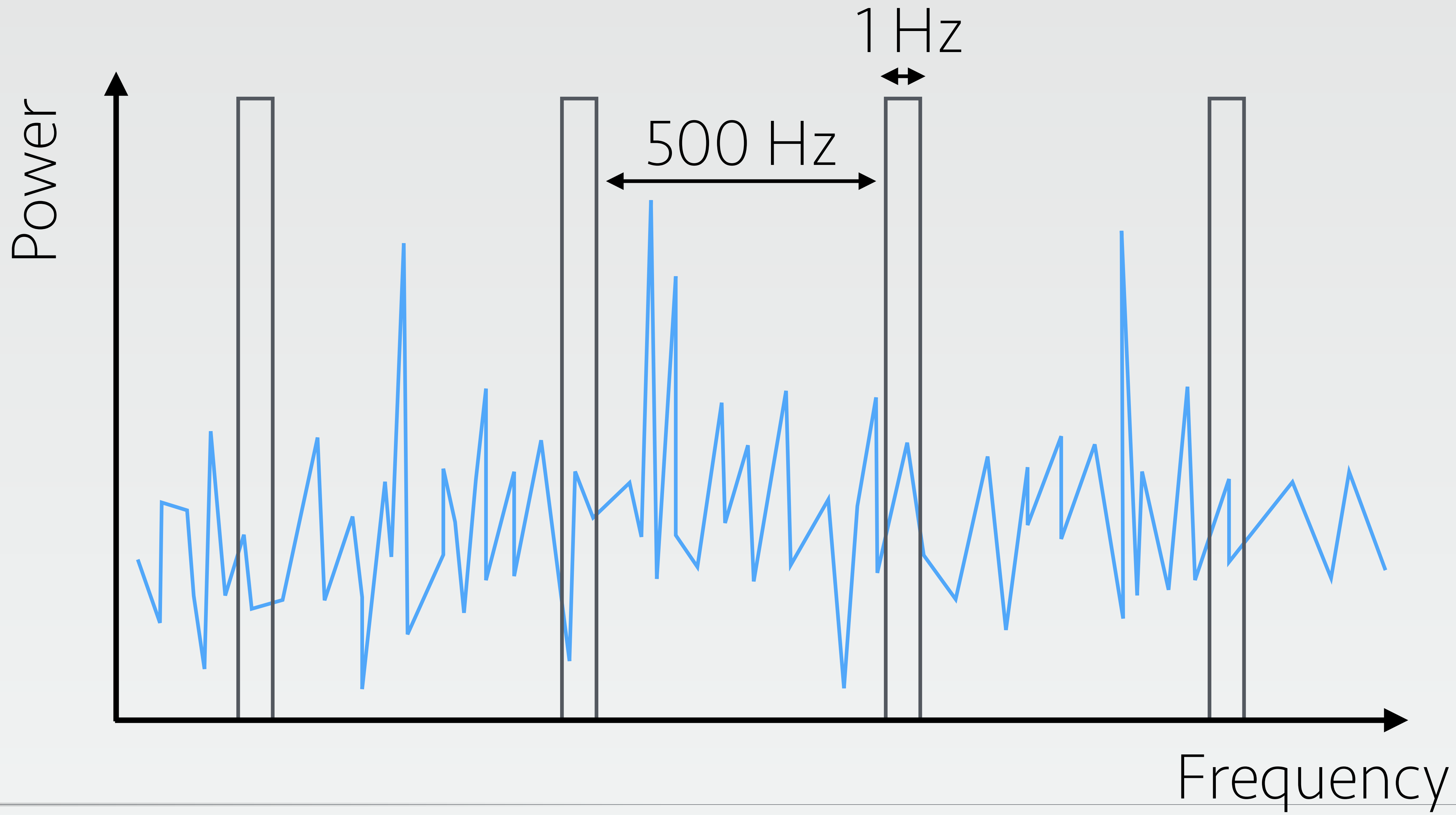


OFF



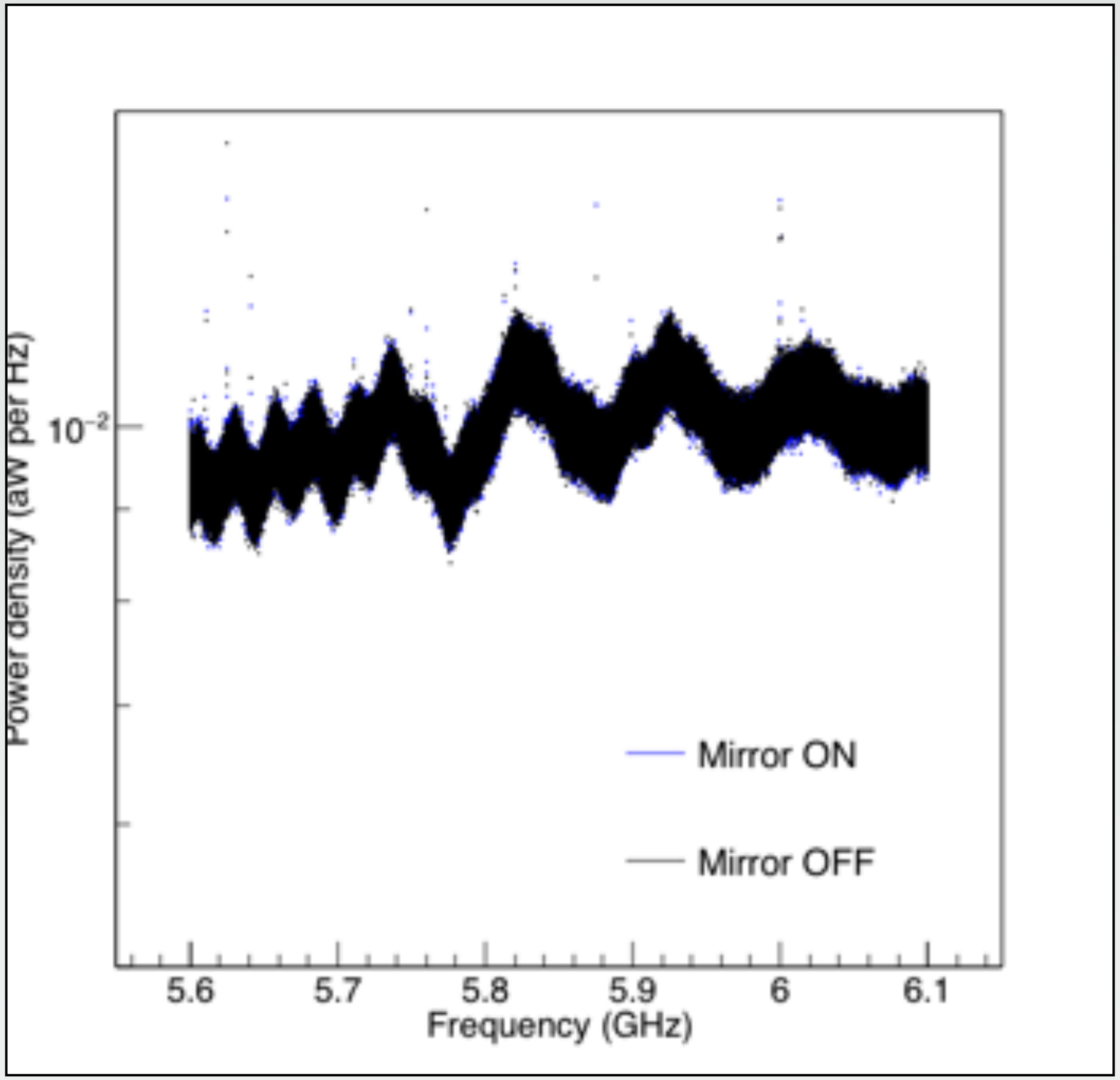
Search optimization

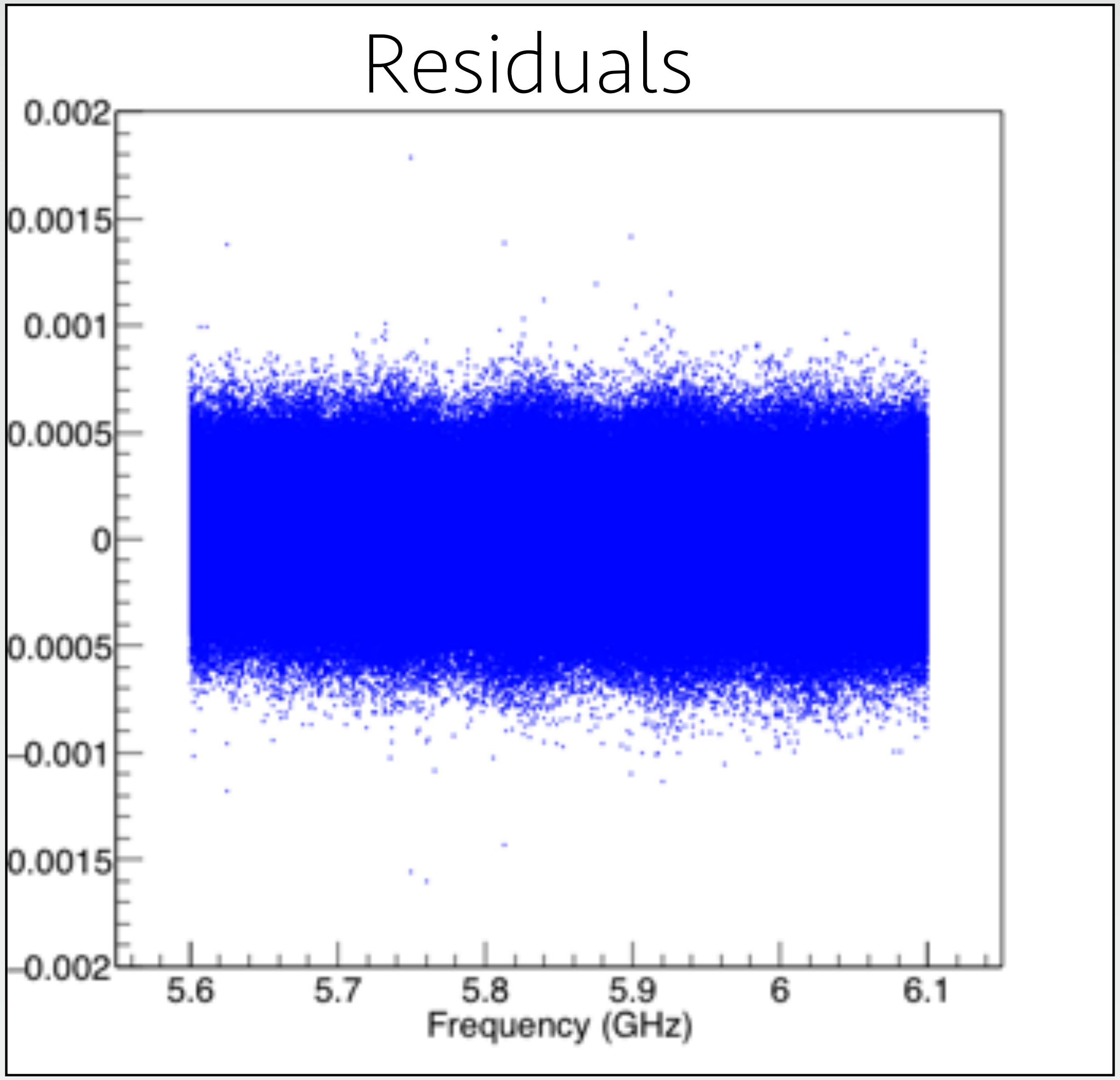
- ★ Signal is constant, broad band (~5 kHz)
- ★ Most backgrounds removed by sampling



Results

Power measurement w & w/o mirror



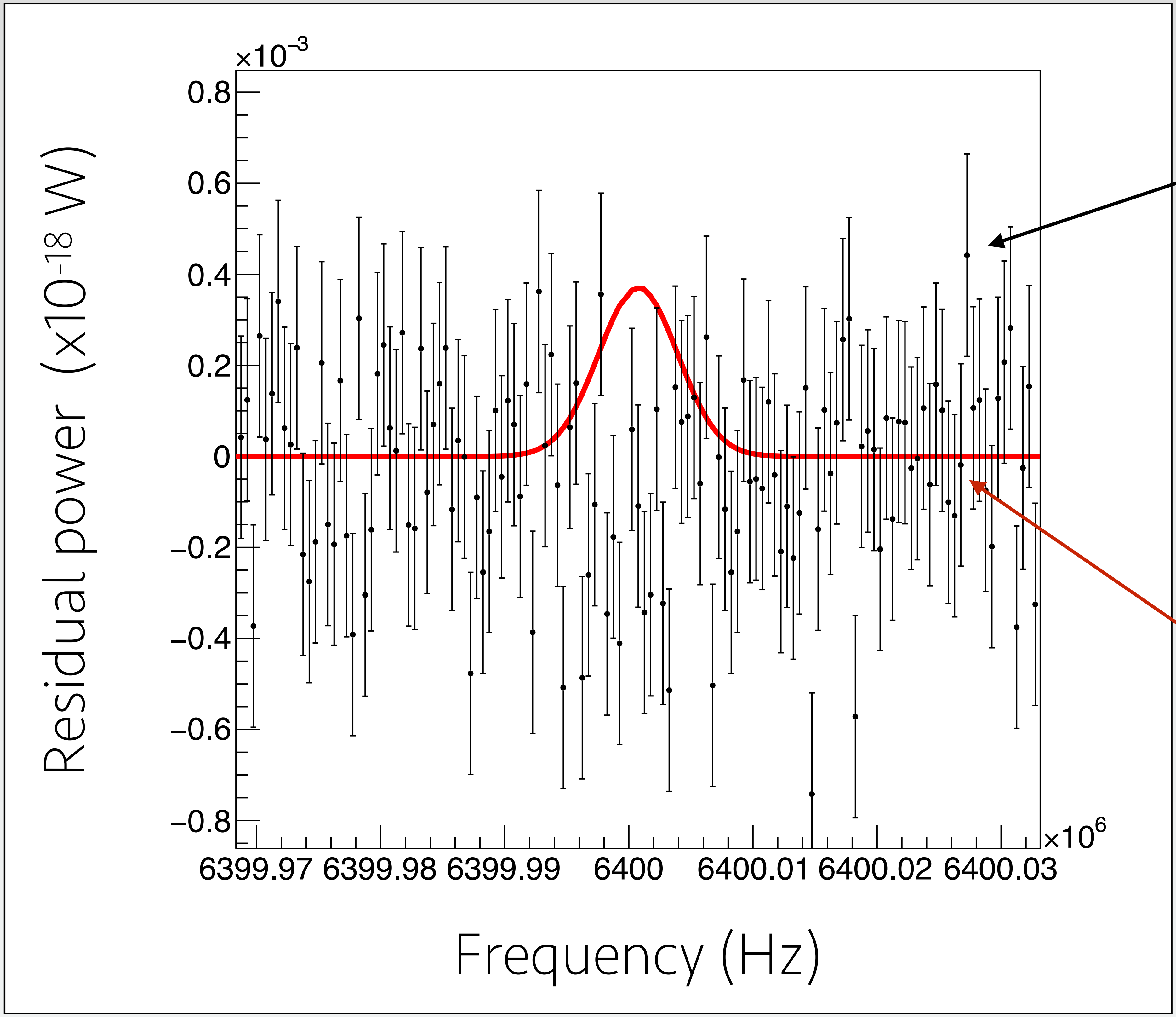


Expected sensitivity

System noise temperature :

290 K environment
214 K LNA
50 K spectrum analyser

Limits on potential signals

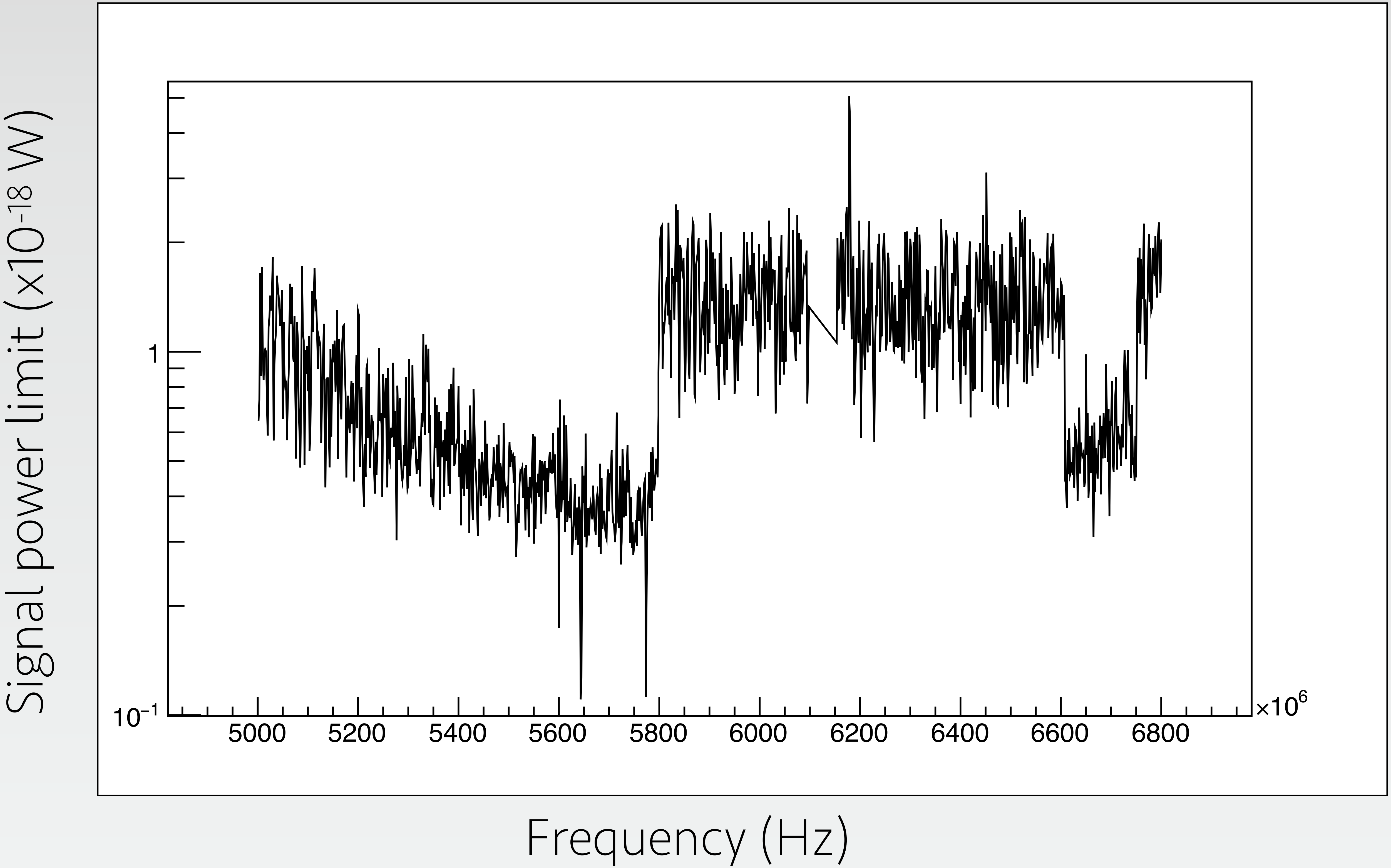


Measurements

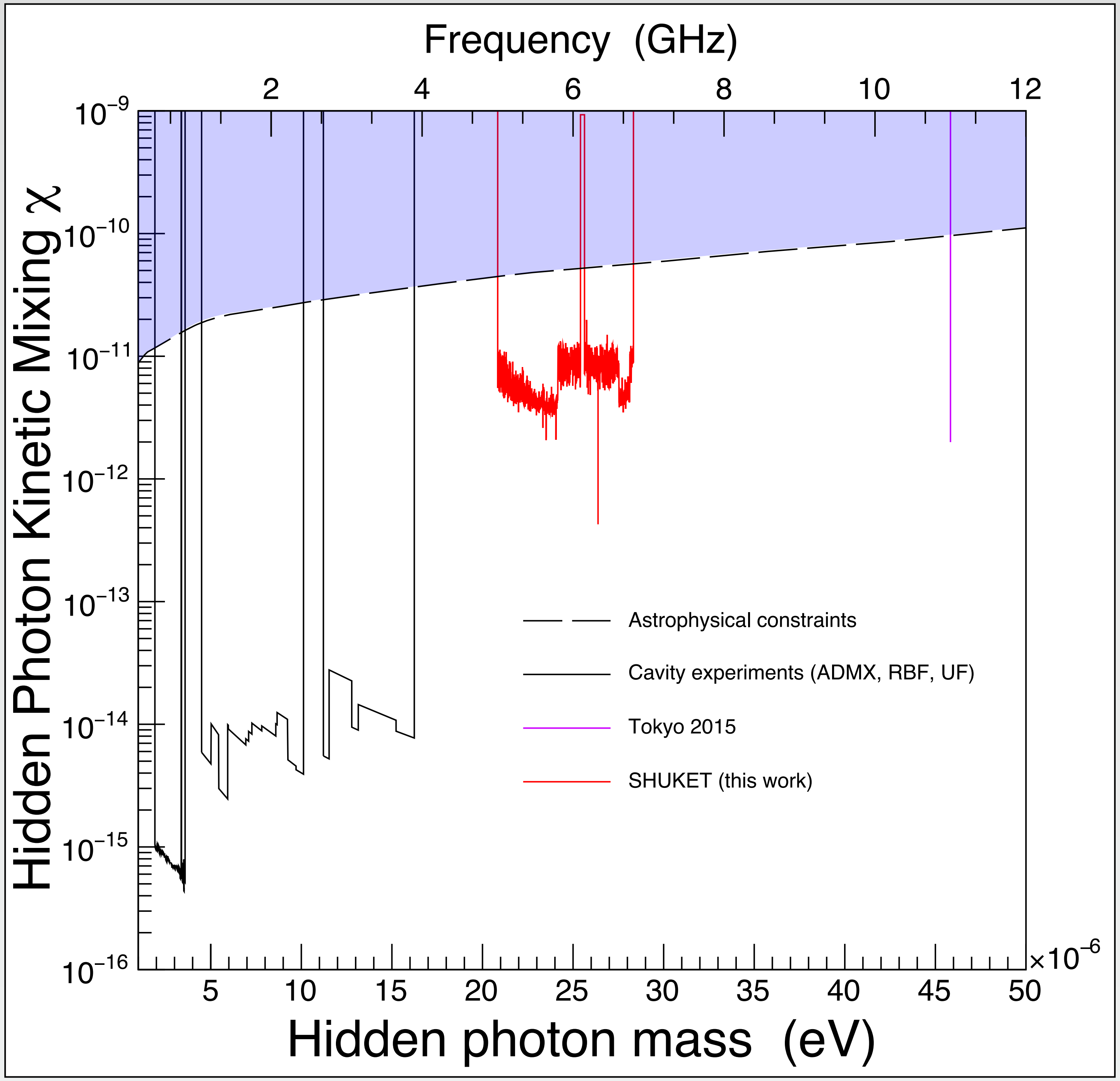
Dark matter fake signal

power = 7×10^{-19} W
(3 sigma excluded)

Constraints on extra-power



Constraints on hidden photons mixing

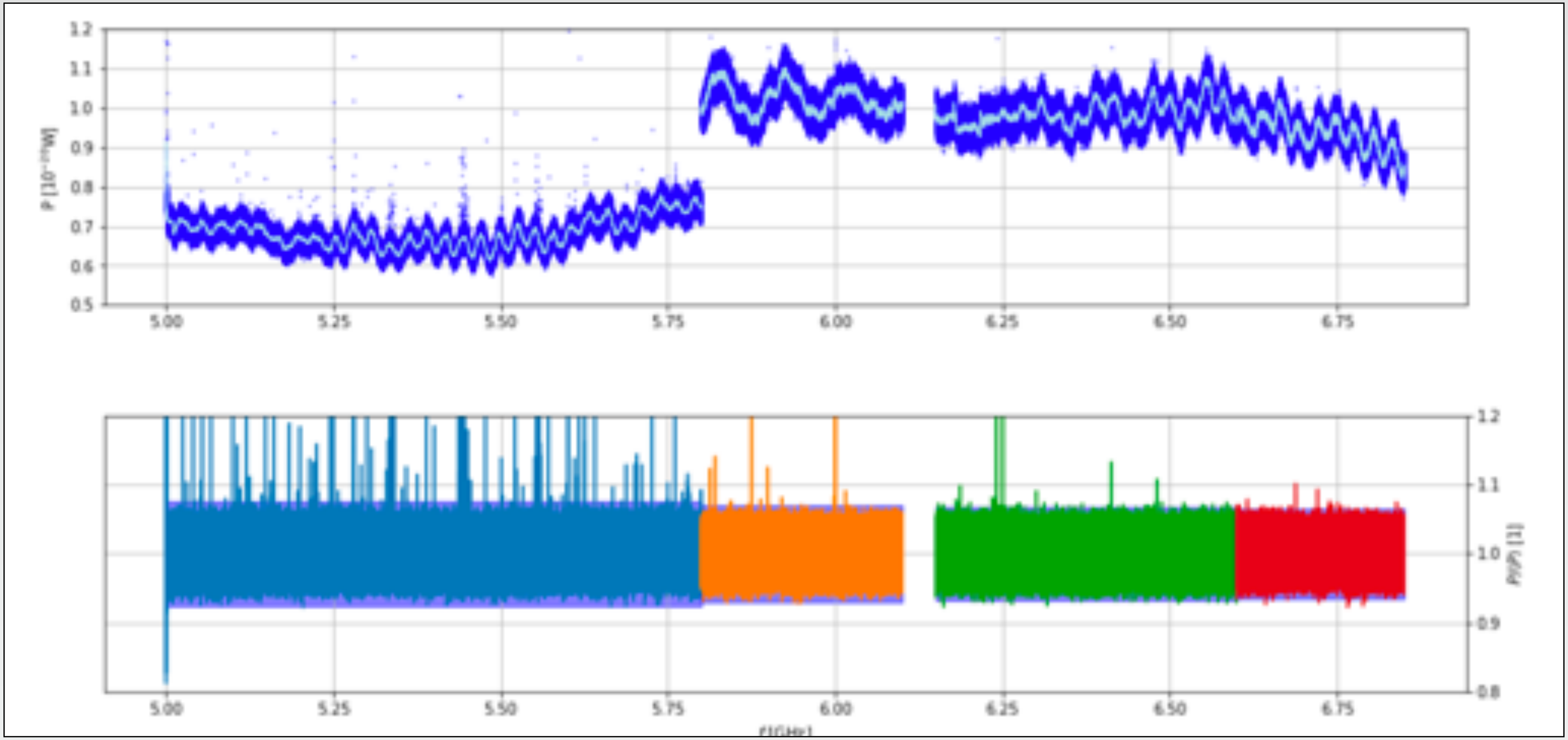


P. Brun, L. Chevalier, C. Flouzat, ***Phys. Rev. Lett.*** *122, 201801 (2019)*

SYRTE re-analysis of Shuket

- ⋆ Use only ON data
- ⋆ Smooth-on data
- ⋆ Build a TS based on DM halo distribution as prior
- ⋆ χ is a built-in parameter

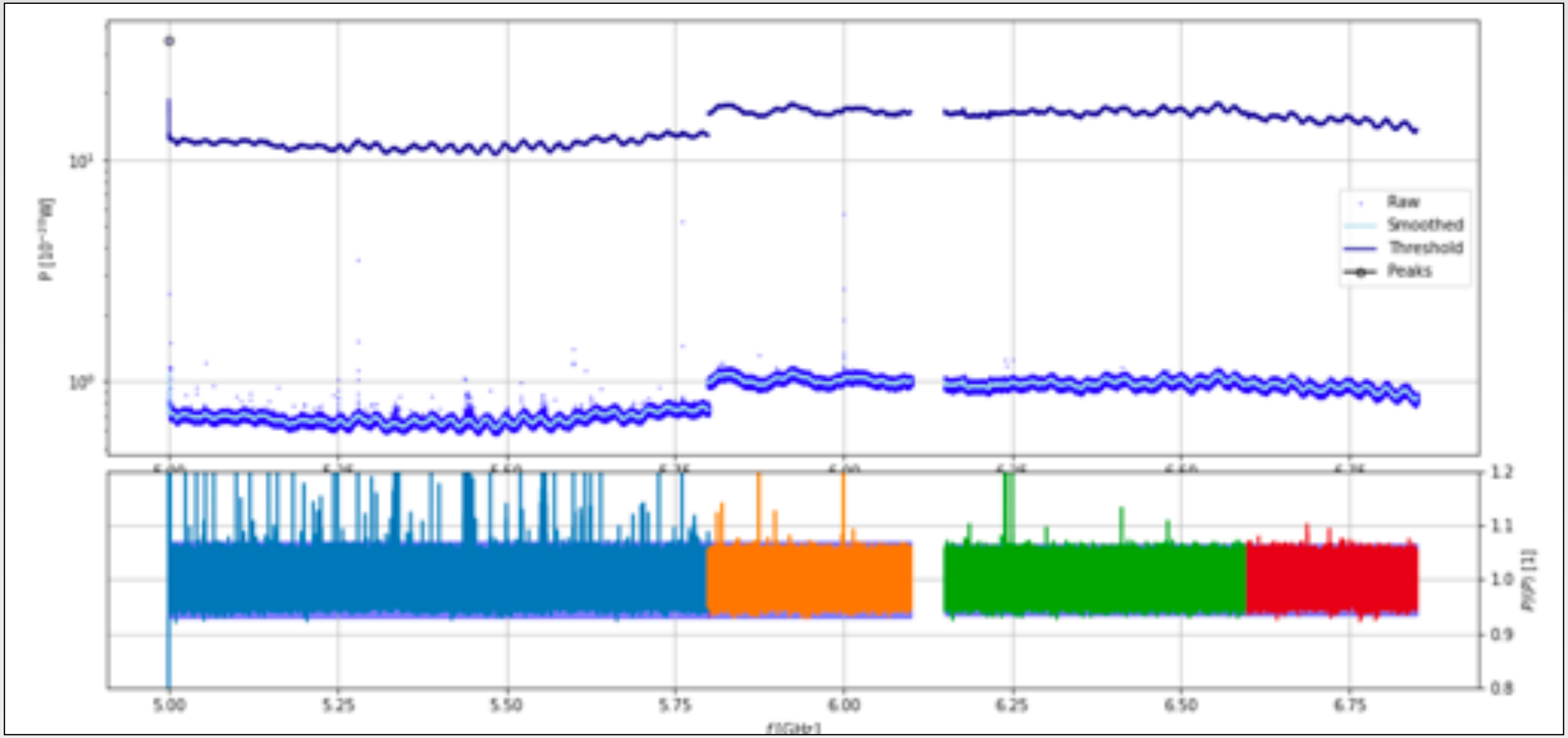
SYRTE re-analysis of Shuket



A. HEES, E. SAVALLE, P. WOLF

SYRTE re-analysis of Shuket

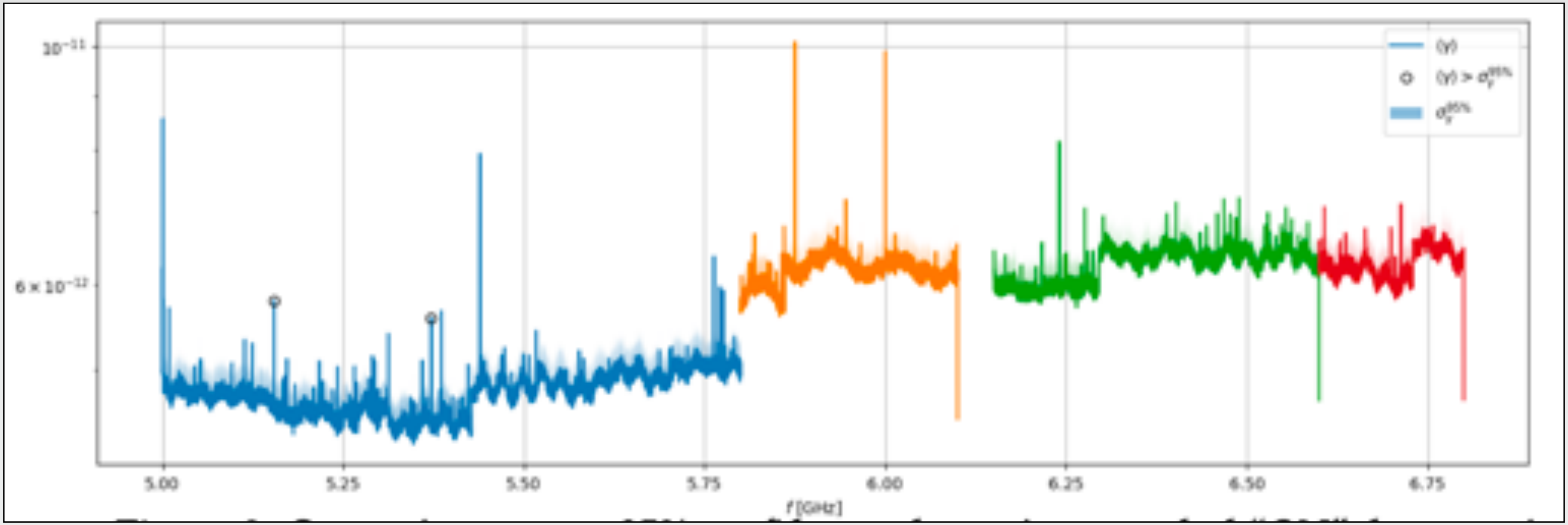
95% threshold



A. HEES, E. SAVALLE, P. WOLF

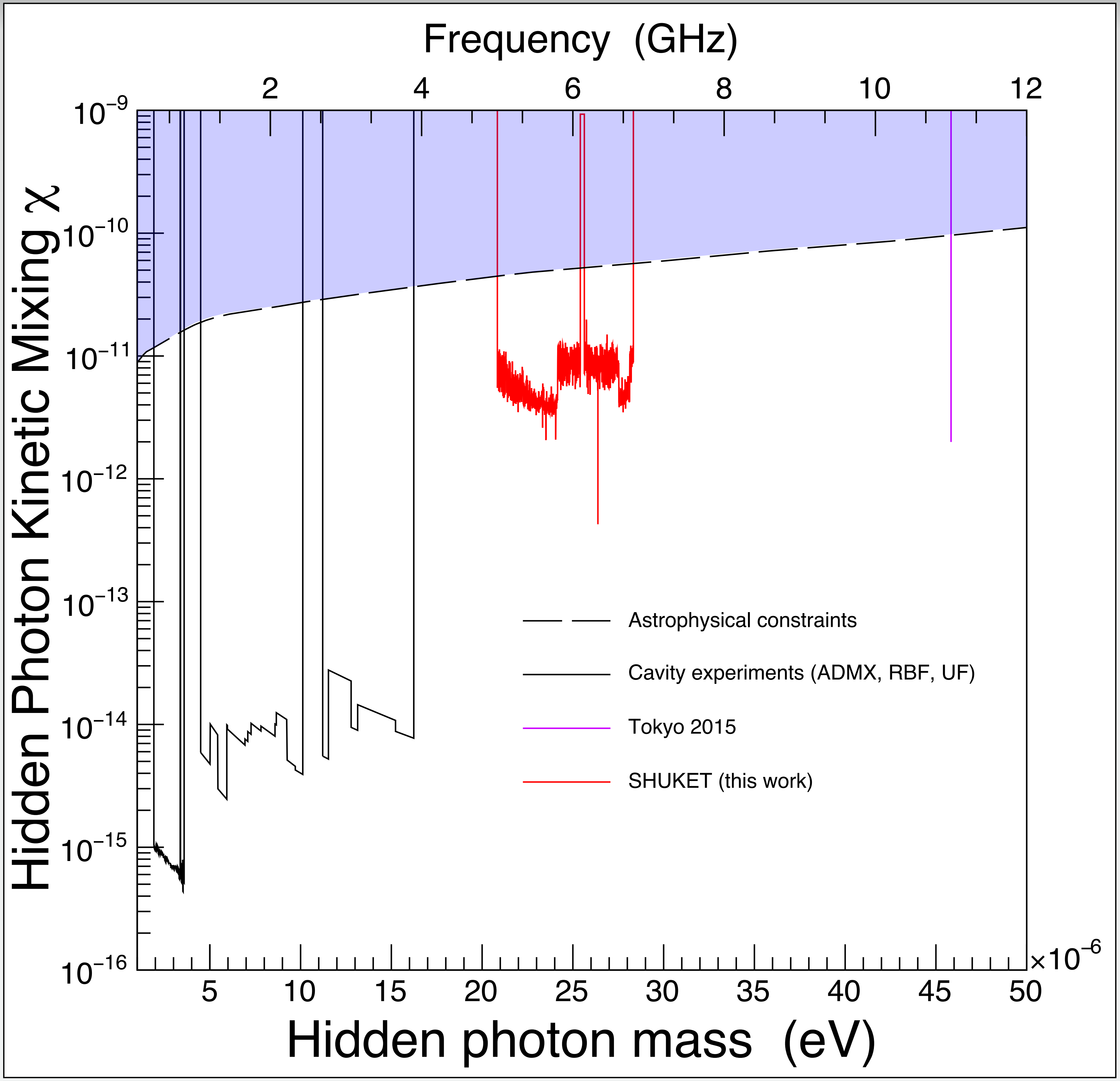
SYRTE re-analysis of Shuket

Exclusion lines on χ

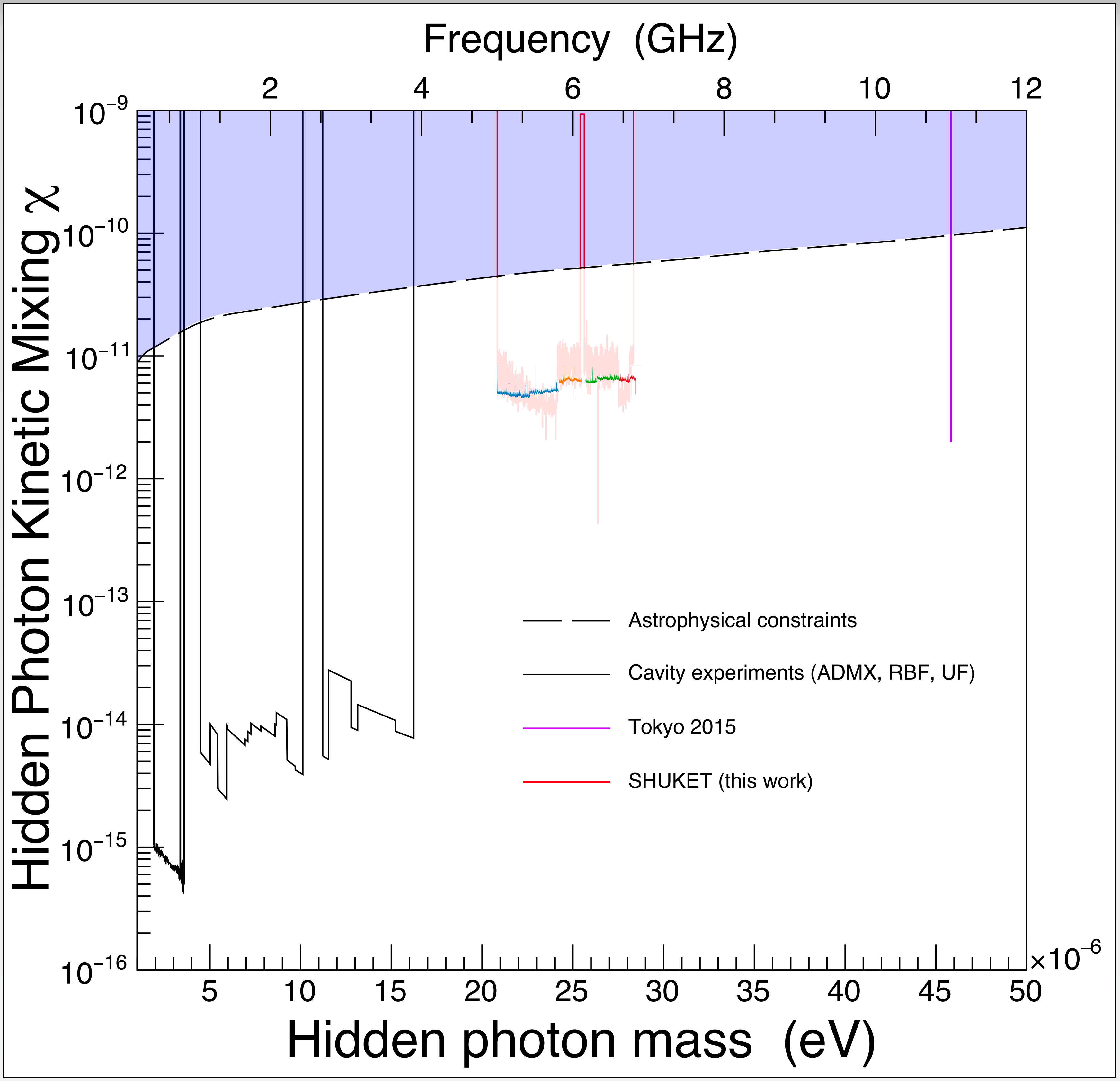


A. HEES, E. SAVALLE, P. WOLF

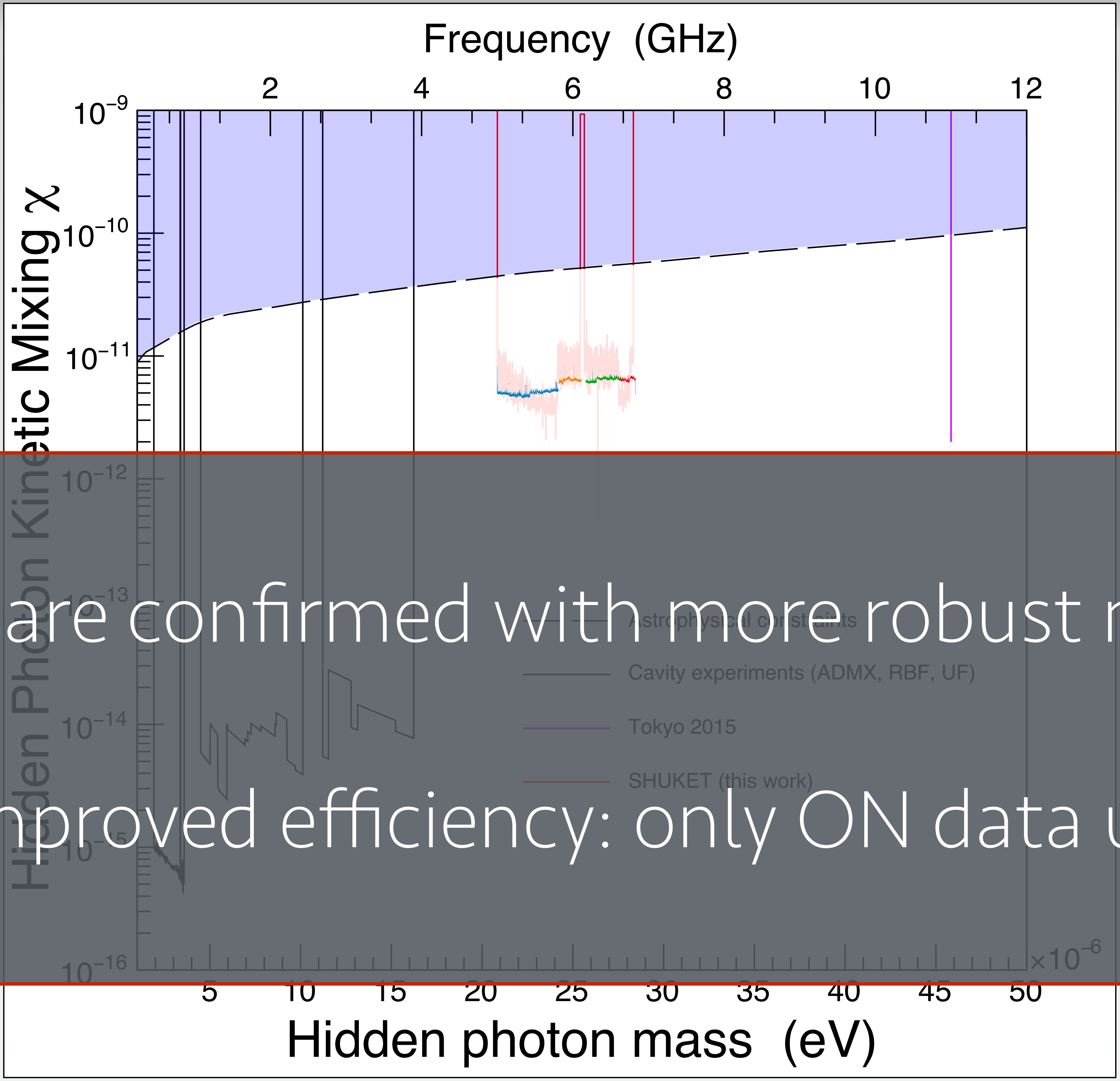
Constraints comparison



Constraints comparison



Constraints comparison



Results are confirmed with more robust method

x2 improved efficiency: only ON data used

Future plans : Hidden photons

- ⋆ CEA/SYRTE collaboration
- ⋆ New Shuket runs 10 GHz - 20 GHz
- ⋆ New, cryogenic low-noise amplifiers
- ⋆ Data taking optimized for SYRTE-style analysis
- ⋆ New reflector (could be cold)
- ⋆ New antenna
- ⋆ New spectrum analyzer

LNF-LNC6_20C

FEATURES

- RF bandwidth: 6-20 GHz
- Noise Temperature: 4.7 K typical
- Noise Figure: 0.070 dB typical
- Gain: 32 dB
- DC-power: Vd=1.00 V, Id=22 mA
- One gate and one drain supply only
- RF-connectors: female SMA
- DC-connector: 9-pin female Nano-D

$T_{noise} < 5$ K

Future plans : axions

- ⋆ Build a magnetic experiment
- ⋆ Use all that was learnt on the detection part
- ⋆ Solve the strong CP problem
- ⋆ Find out what dark matter is