Institute for Theoretical and Mathematical Physics MSU

The Echo Method for Axion Dark Matter Detection

Pierre Sikivie (UF)
Ariel Arza (ITMP-MSU)

ITMP Moscow, January 2020

The QCD axion

Strong CP Problem

Peccei and Quinn proposal:

(Peccei and Quinn; 1977)

New Symmetry $U_{PQ}(1)$ broken at the energy scale f_a

Axion: Nambu-Goldstone boson that emerges from symmetry breaking

(Weinberg, Wilczek; 1978)

$$m_a = 6\times10^{-6}\,\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

By non-perturbative effects

Dark Matter Axions

Axions could solve the Dark Matter problem if they were produced in the early universe by a non-thermal mechanism

(Preskill, Wise and Wilczek; Abbott and Sikivie; Dine and Fischler 1983)

$$f_a \sim 10^{12}\text{GeV} \quad \Rightarrow \quad m_a \sim 10^{-5}\text{eV}$$

Axion Like Particles (ALPs):

(Svrcek and Witten 2006)

Motivated by extensions of the Standard Model, they also are cold dark matter candidates

(Arias et al. 2012)

Axion Experiments

$$L_{a\gamma\gamma} = -\, g a \overrightarrow{E} \cdot \overrightarrow{B} \qquad\qquad g = g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a}$$

$g_\gamma = -\,0.97$ **KSVZ model** (Kim 1979; Shifman et al. 1980)

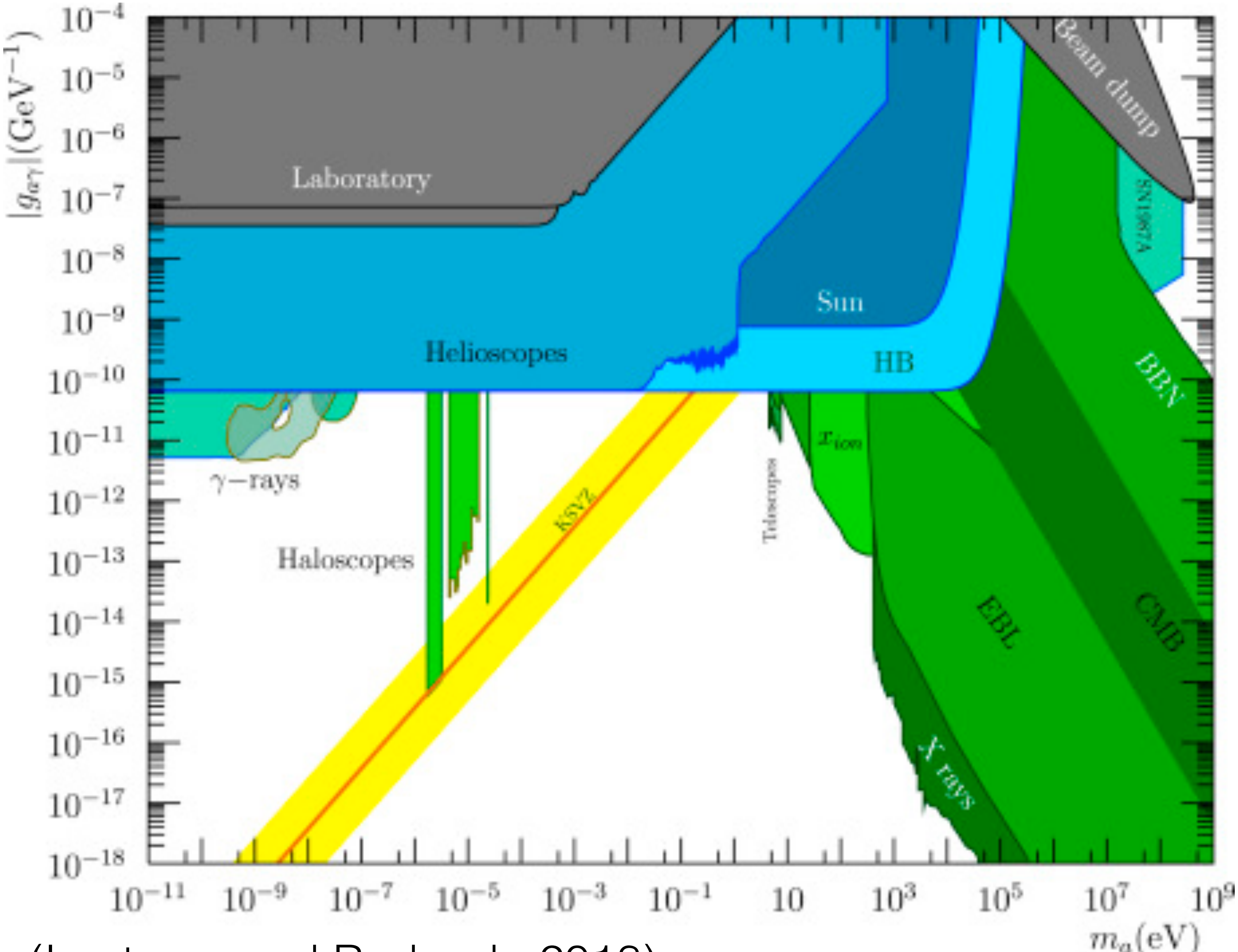
$g_\gamma = 0.36$ **DFSZ model** (Zhitnitskii 1980; Dine et al. 1981)

Haloscopes **ADMX, HAYSTAC, MADMAX, ABRACADABRA**

Helioscopes **CAST, IAXO**

Light Shining Through a Wall **ALPS, OSQAR, ALPS II**

Current status of the axion search



(Irastorza and Redondo 2018)

Production and Detection of an Axion Dark Matter Echo

Ariel Arza and Pierre Sikivie
Department of Physics, University of Florida, Gainesville, Florida 32611, USA

(Received 4 February 2019; revised manuscript received 19 May 2019; published 27 September 2019)

Electromagnetic radiation with angular frequency equal to half the axion mass stimulates the decay of cold dark matter axions and produces an echo, i.e., faint electromagnetic radiation traveling in the opposite direction. We propose to search for axion dark matter by sending out to space a powerful beam of microwave radiation and listening for its echo. We estimate the sensitivity of this technique in the isothermal and caustic ring models of the Milky Way halo and find it to be a promising approach to axion, or axionlike, dark matter detection.

DOI: 10.1103/PhysRevLett.123.131804

The identity of dark matter remains one of the central questions in science today [1]. One of the leading candidates is the QCD axion. This hypothetical particle was originally postulated as a solution [2] to the strong CP problem of the standard model of particle physics, i.e., the puzzle why the strong interactions conserve P and CP. The

which Peccei-Quinn symmetry is spontaneously broken and other considerations, such axion production by topological defects, the precise temperature dependence of the axion mass, and the amount of entropy production associated with the QCD phase transition. In any case, the axions produced during the QCD phase transition are a

OUTLINE

Stimulated axion decay into two photons (The Echo)

The Echo in a cold flow

The Caustic Ring Halo Model

The Isothermal Halo Model

Backgrounds and Sensitivity of our proposal

Conclusions

Stimulated axion decay into two photons

$$\tau_a^0 = \frac{64\pi}{m^3 g^2}$$ **axion life-time for spontaneous decay**

$$m = 10^{-5}\text{eV}$$
$$g = 10^{-15}\text{GeV}^{-1}$$

$$\Rightarrow \quad \tau_a^0 \sim 10^{42}\text{yr}$$

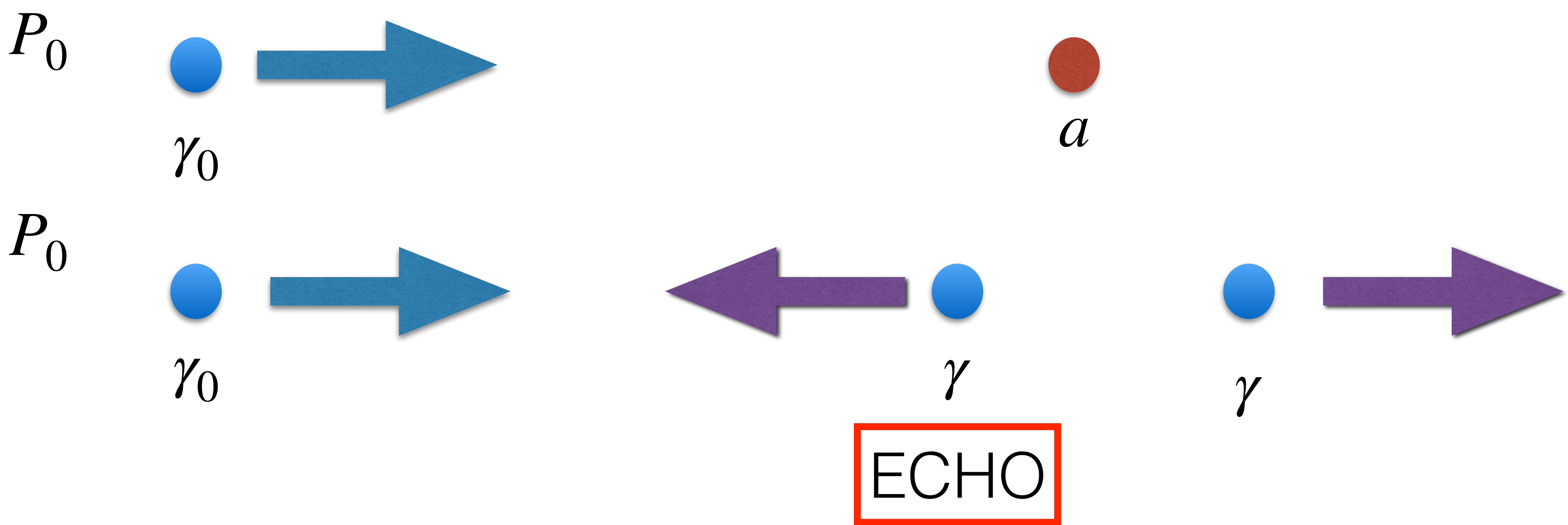
$$\tau_a = \frac{\tau_a^0}{1 + f_\gamma}$$ **Actual Axion Life-Time**

$$f_\gamma = \frac{16\pi^2 \rho_\gamma}{m^3 \Delta\omega}$$ **stimulated axion decay** $\omega_\gamma = m/2$

Let's suppose a power of 1kWatt with a bandwidth of 1MHz during a time of 1 second in a volume of 1 meter cube

$$\Rightarrow \quad f_\gamma \sim 10^{25}$$

Stimulated axion decay into two photons (The Echo)



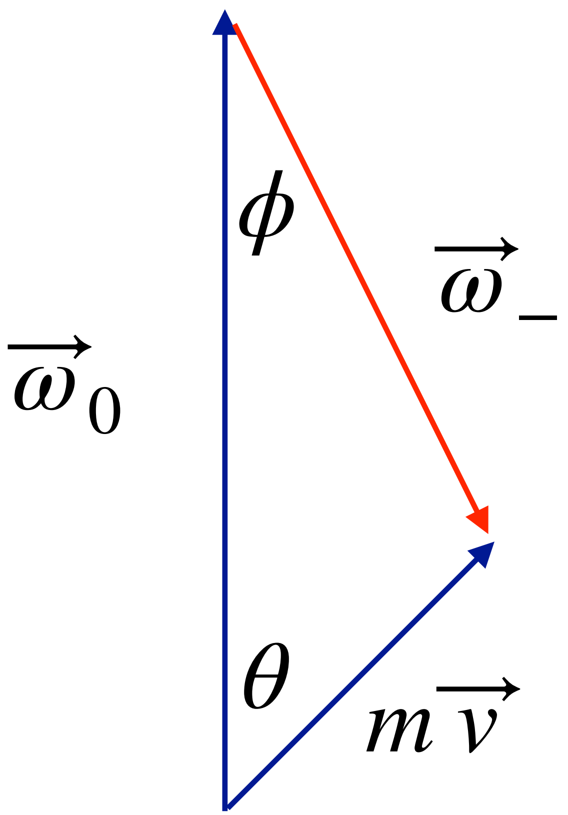
$$P_- = \frac{1}{16} g^2 \rho \frac{dP_0}{d\nu} t$$

$$\omega_0 = \omega_- = \frac{m}{2}$$

$P_0 = 1\mathrm{kW}$ $\quad$ $t = 1000\mathrm{s}$

Isothermal dark matter model → $P_- \sim 10^{-21}\mathrm{W}$

The Echo in a cold flow



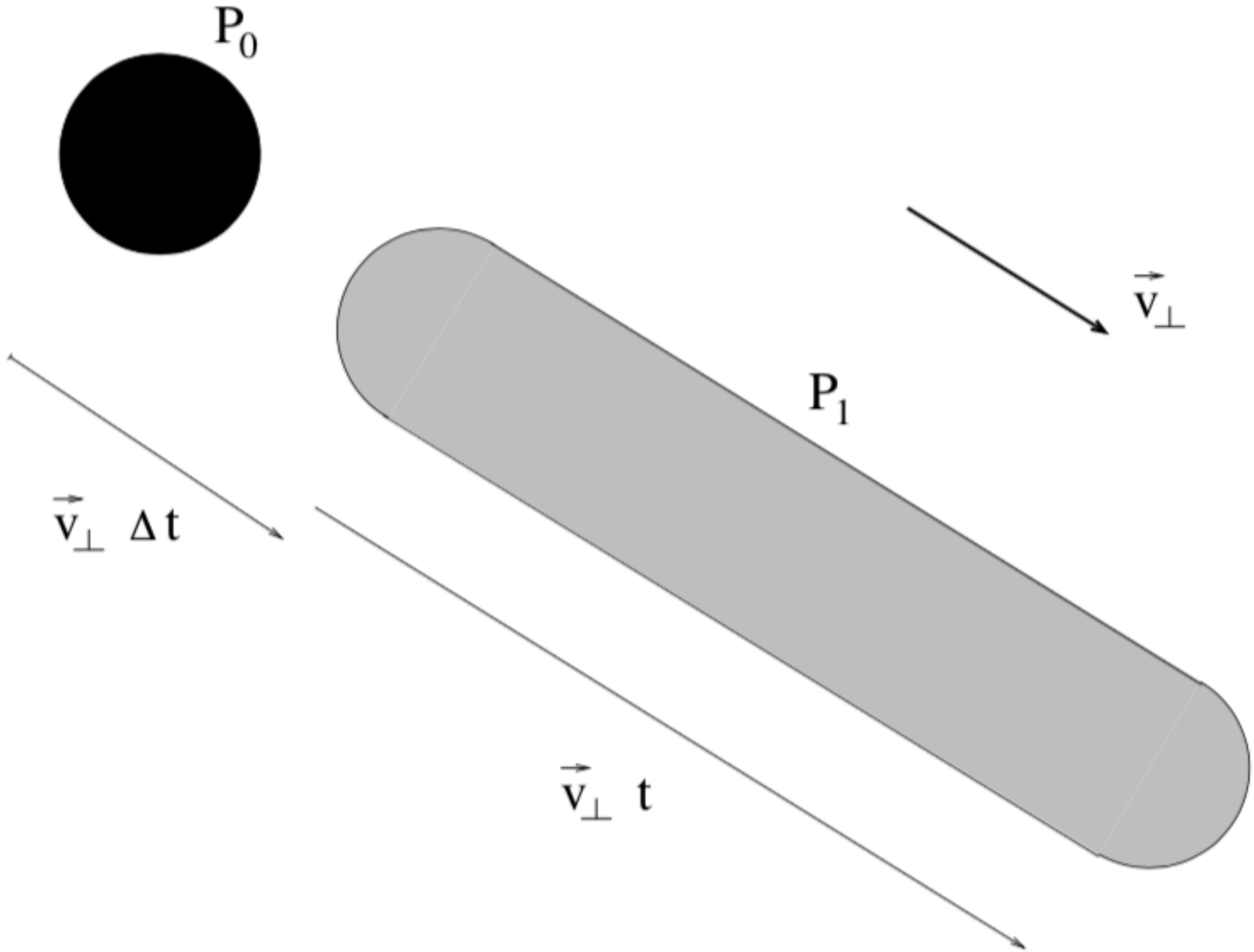
$$\omega_0 = \frac{m}{2}(1 + v_{\parallel}) + \mathcal{O}(v^2)$$

$$\omega_- = \frac{m}{2}(1 - v_{\parallel}) + \mathcal{O}(v^2)$$

$$\phi \simeq 2|v_{\perp}|$$

The echo is spread spatially and there is a maximum time during which the echo arrives to the detector

$$t_{max} = C\frac{R}{|v_{\perp}|}$$



P_0
$\vec{v}_\perp$
P_1
$\vec{v}_\perp \; \Delta t$
$\vec{v}_\perp \; t$

The Echo in a cold flow

$$\rho = \int d^3v \frac{d^3\rho}{dv^3}(\overrightarrow{v})$$

The echo is spread in frequency

$$\delta\omega_{-} = \frac{m}{2}\delta v_{\|}$$

$$P_c = \frac{1}{16} g^2 \rho \frac{dP_0}{d\nu} C \frac{R}{|v_{\perp}|}$$

The Caustic Ring Halo Model

The local dark matter distribution is dominated by a single flow

$v = 300\text{km/s}$ $\delta v = 70\text{m/s}$ $\rho = 1\text{GeV/cm}^3$

$B = 4 \times 10^{-8} m$

$\theta = 0.017$ → $v_\perp = 5\text{km/s}$

The Isothermal Halo Model

The velocity distribution is Gaussian

$v = 220\text{km/s}$ $\delta v = 270\text{km/s}$

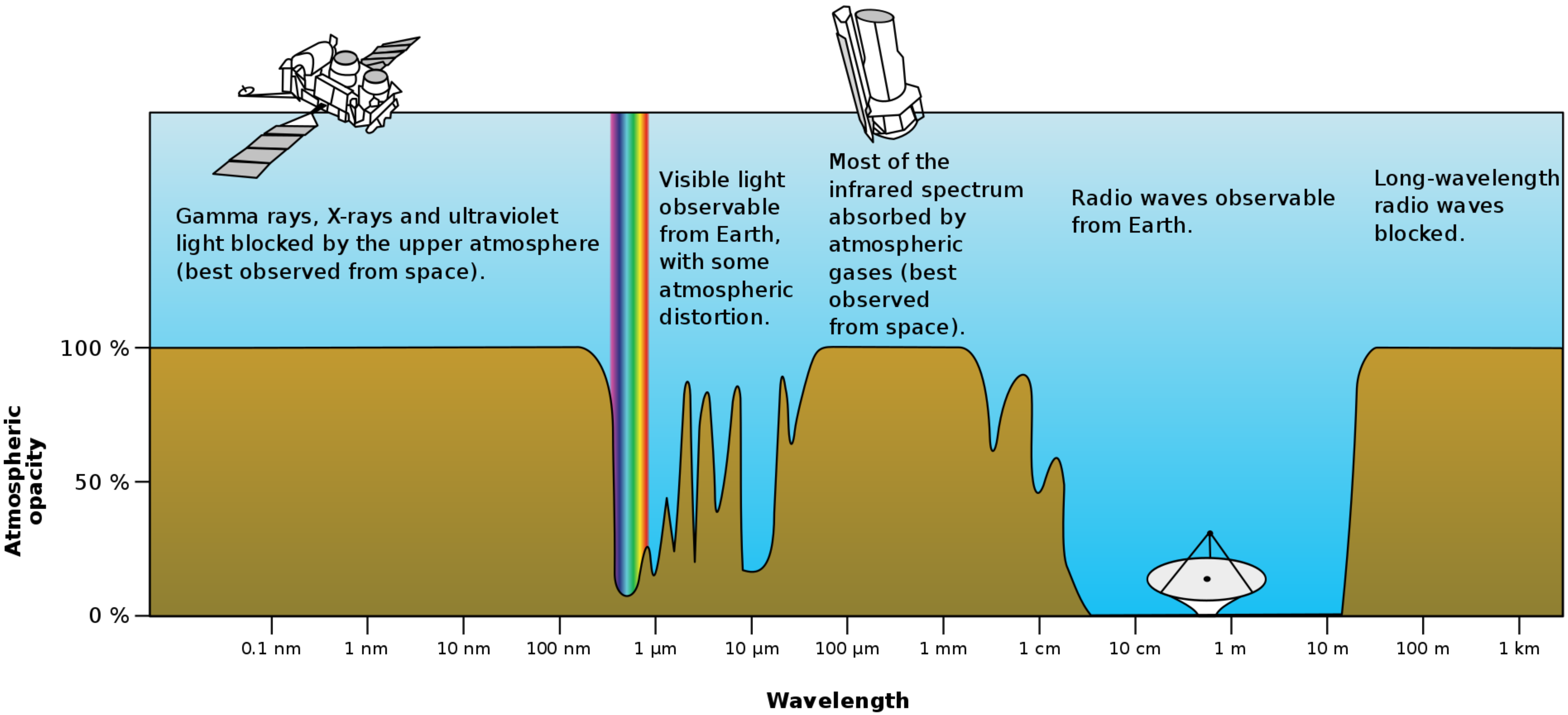
$\rho = 0.3\text{GeV/cm}^3$

The echo is spread in all directions

$$\left\langle \frac{1}{|v_\perp|} \right\rangle = \frac{1}{124\text{km/s}}$$

$B = 1.7 \times 10^{-4} m$

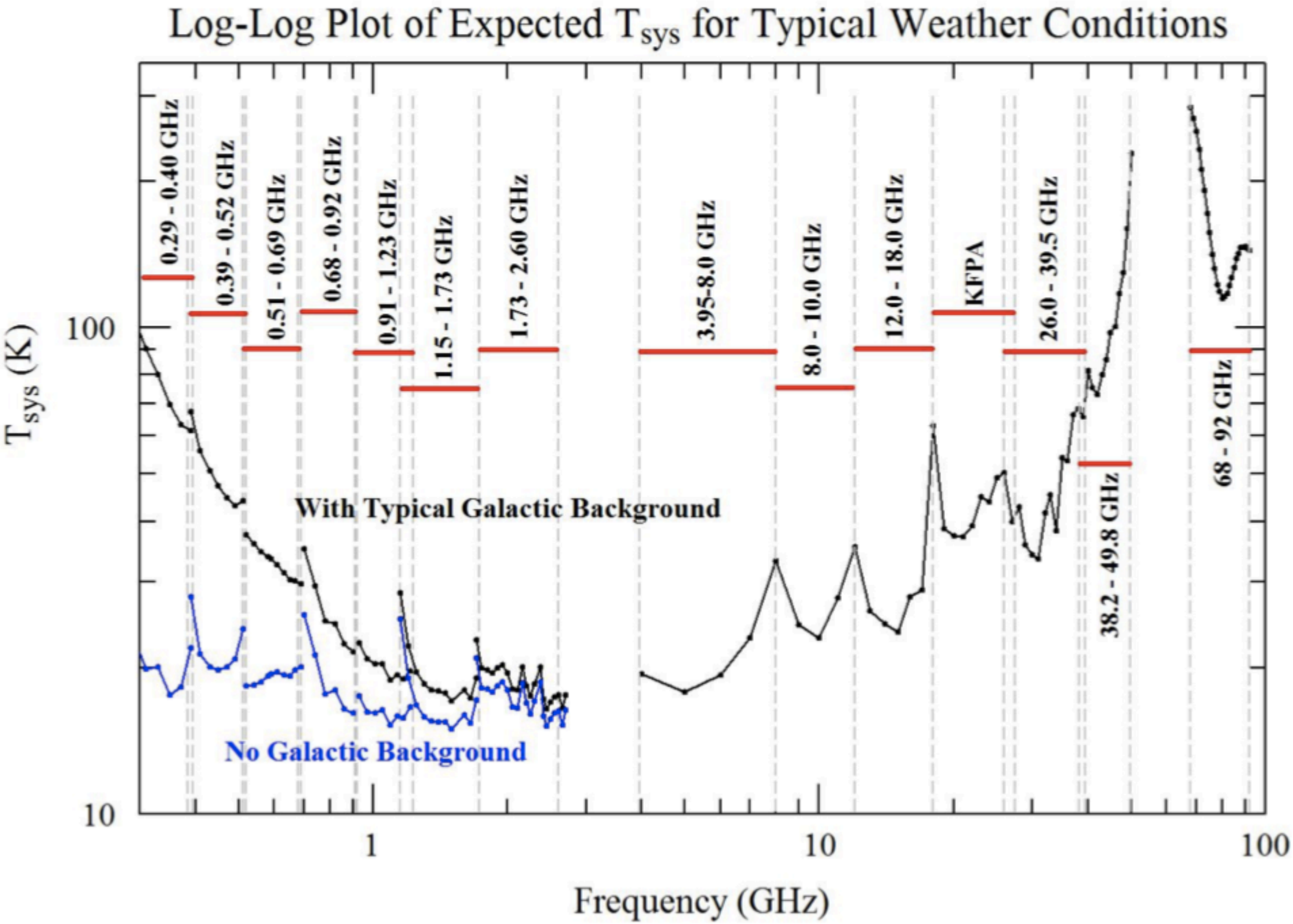
Sources of noise



$$s/n = \frac{P_c}{T_n}\sqrt{\frac{t_m}{B}}$$

Dicke's radiometer equation

Sources of noise



Sources of noise

Back-Scattering of the outgoing beam

Rayleigh Scattering (molecules in the atmosphere)

$$T_n = 5.58 \times 10^{-2}\,\mathrm{K} \left(\frac{m}{10^{-5}\mathrm{eV}}\right)^3 \left(\frac{R}{50\mathrm{m}}\right) \left(\frac{300\mathrm{km/s}}{v}\right) \left(\frac{P_0}{\mathrm{GW}}\right)$$

For the near future

Back-scattering due to plasma effects in the ionosphere

Back-scattering due to fluctuations of the atmosphere refractive index (Troposcatter)

Deflection of the outgoing beam due to refractive index gradients

Sensitivity of our proposal

Caustic Ring Model

$$\frac{dE_0}{d\ln(m)} = 6.5\text{MWyear}\left(\frac{s/n}{5}\right)\left(\frac{10^{-4}\text{eV}}{m}\right)^{1/2}\left(\frac{0.36}{g_\gamma}\right)^{2}\left(\frac{T_n}{20\text{K}}\right)\left(\frac{\text{GeV/cm}^3}{\rho}\right)$$

$$\left(\frac{0.3}{C}\right)\left(\frac{t_m}{10^{-2}\text{s}}\right)^{1/2}\left(\frac{50\text{m}}{R}\right)\left(\frac{|v_\perp|}{5\text{km/s}}\right)$$

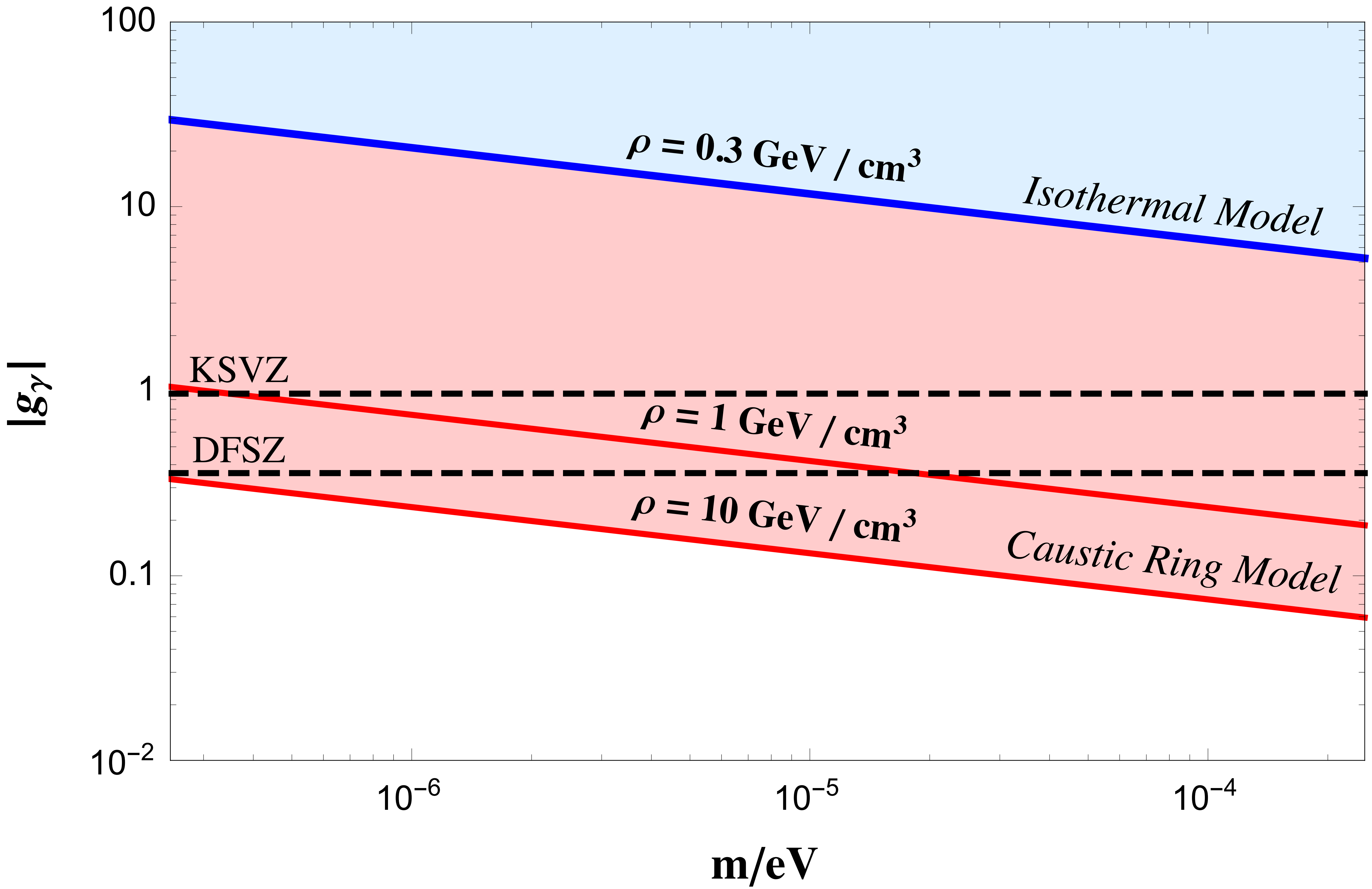
Isothermal Model

$$\frac{dE_0}{d\ln(m)} = 4.8\text{GWyear}\left(\frac{s/n}{5}\right)\left(\frac{10^{-4}\text{eV}}{m}\right)^{1/2}\left(\frac{0.36}{g_\gamma}\right)^{2}\left(\frac{T_n}{20\text{K}}\right)$$

$$\left(\frac{0.3}{C}\right)\left(\frac{t_m}{2\times10^{-4}\text{s}}\right)^{1/2}\left(\frac{50\text{m}}{R}\right)$$

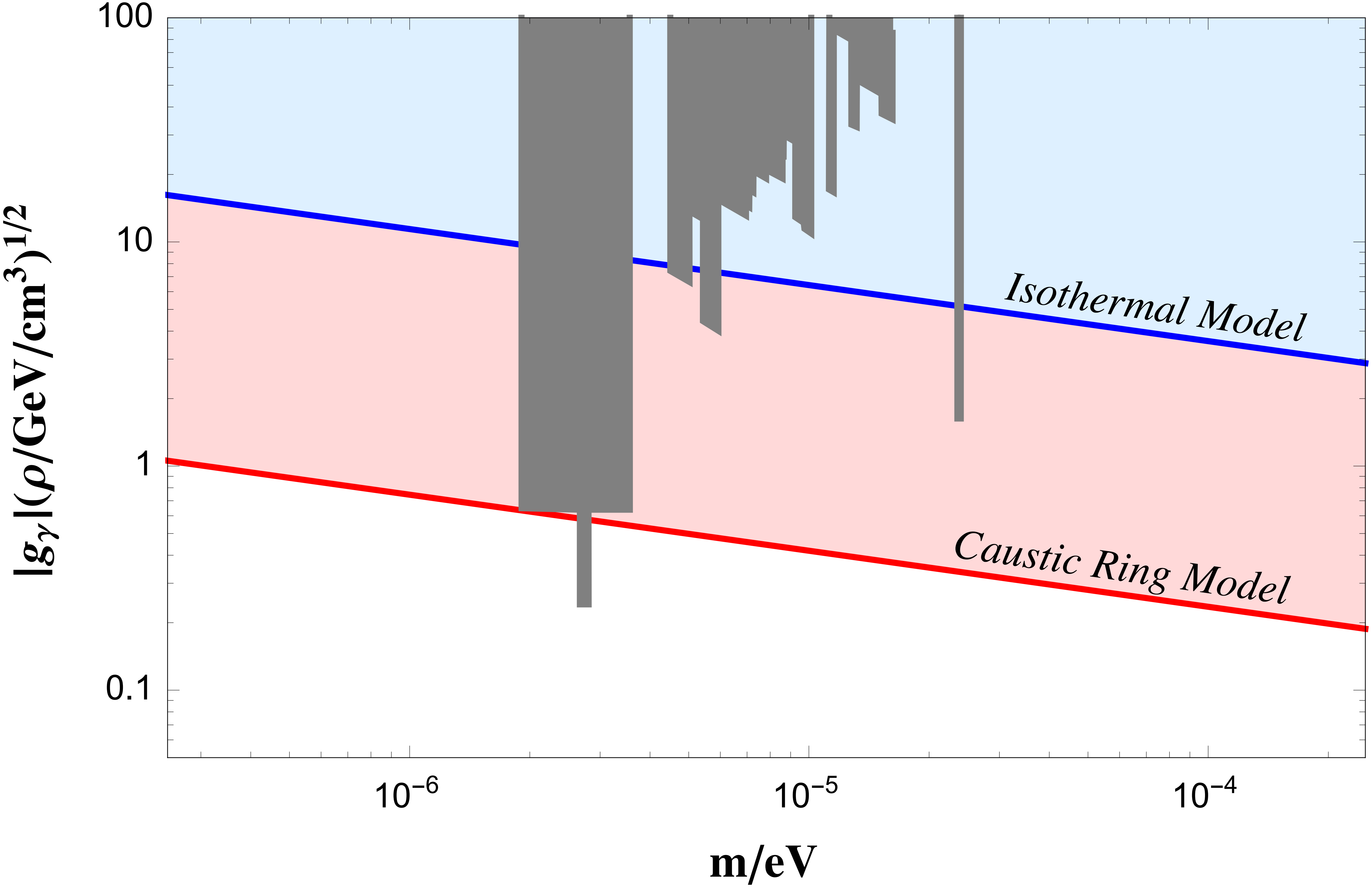
Sensitivity of our proposal

10 MWyear per factor 2



Sensitivity of our proposal

10 MWyear per factor 2



Conclusions

The echo method is attractive from the experimental point of view, specially for radio-astronomy technology

The echo method is applicable over a wide range of axion mass. Where the Earth's atmosphere is mostly transparent

$$2.5 \times 10^{-7}\text{eV} < m < 2.5 \times 10^{-4}\text{eV}$$

The echo method is much better in the Caustic Ring Model because the density is bigger, has less spread in frequency and less spread in physical space

What is Next?

Finding money

Finding or building a tunable power amplifier

Finding a radio telescope

Planning the best strategy to optimize resources

Control of leakages from the source

Spasibo!