Observational tests for Beyond Standard Model Physics: CMB Photon oscillation into Hidden Sector and Axion like Particles ongoing project

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Ph.D. (c) in Theoretical Physics

CONICYT doctoral fellowship 21130928

Introduction

- **Historical remarks. Massive photons?**

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Limits on electrodynamics: paraphotons?

L. B. Okun'

Institute for Theoretical and Experimental Physics

(Submitted 8 April 1982)
Zh. Eksp. Teor. Fiz. **83**, 892–898 (September 1982)

The accuracy to which the electromagnetic interaction at large distances has been investigated is discussed. For a quantitative parametrization of possible deviations from electrodynamics a model with two paraphotons is used, the mass of one of them not being negligible.

PACS numbers: 03.50.Kk

Introduction

Photon oscillations and cosmic background radiation

Howard Georgi, Paul Ginsparg & S. L. Glashow

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

The possible existence of a second species of photon which is uncoupled to known forms of matter is considered here. Explicit mass terms in the lagrangian can give rise to photon masses and to oscillations of photon identity, without sacrificing the ability of the gauge theory to be renormalized. Current upper limits on the photon mass are $\sim 6\times10^{-16}$ eV c^{-2} (refs 1, 2). Photon oscillations corresponding to much smaller masses can significantly alter the spectral shape of the cosmic background radiation (CBR). Indeed, we show that the apparent discrepancy[3] between theoretical and observed CBR spectra can be resolved in terms of photon oscillations, and a mass parameter of 5×10^{-18} eV c^{-2}.

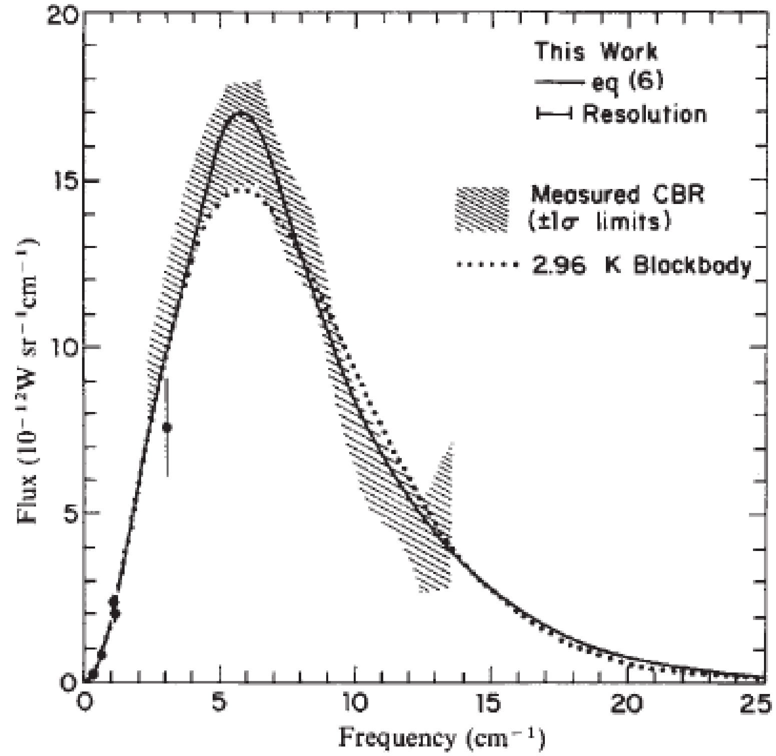
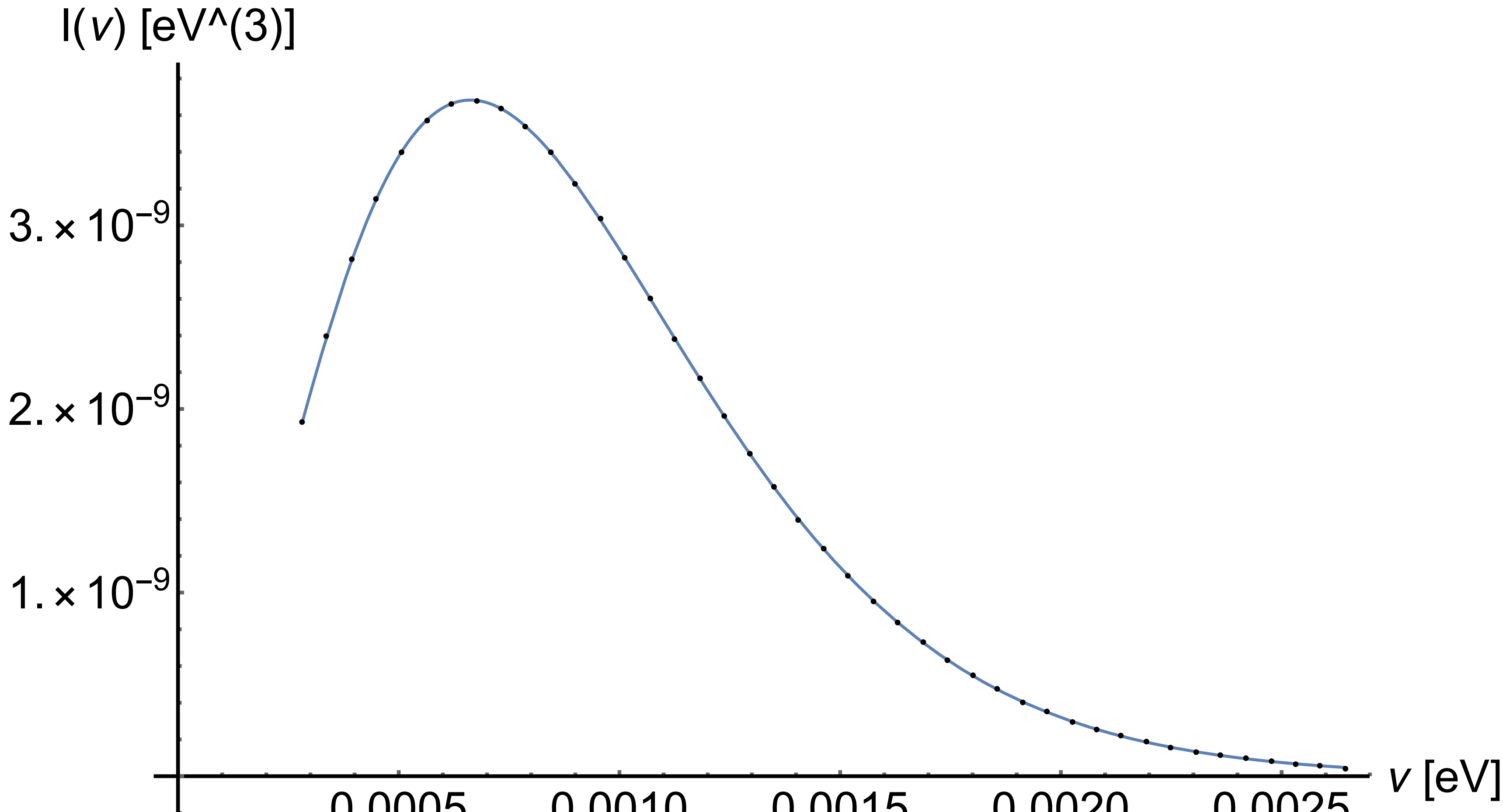


Fig. 1 Predicted spectrum of the cosmic background radiation (solid line) based on equation (6) with $T_A = 3.17$ K, $T_B = 2.0$ K, $\sin^2 2\phi = 0.4$, $\mu = 5\times10^{-18}$ eV c^{-2}, and bandwidth averaged as in ref. 3. The $\pm1\sigma$ flux limits (shaded area) of ref. 3 and other data points are taken from ref. 4. The spectrum of an ordinary 2.96 K blackbody (dotted line), which best fits the integrated flux of ref. 3, is also shown for comparison.

CMB today (1994 actually...)



COBE/FIRAS photon spectrum dataset of 43 measurements.

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ALPs interacts with photons also, only in the presence of electromagnetic fields.

Photon-HP Oscillations

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{\sin\chi_0}{2}B_{\mu\nu}F^{\mu\nu} + \frac{\cos{\chi_0}^2}{2}m_{\gamma'}^2 B_\mu B^\mu,$$

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Non Orthogonal Lagrangian!, proposed transformation:

$$\begin{aligned} A_R &= \cos\chi_0 A, \\ S &= B - \sin\chi_0 A, \end{aligned}$$

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New Lagrangian...

$$\mathcal{L}_{int} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}S_{\mu\nu}S^{\mu\nu} + \frac{1}{2}(A_\mu \; S_\mu)^{\mathbf{T}}\mathcal{M}^2(A_\mu \; S_\mu) \tag{1}$$

Photon-HP Oscillations

$$\mathcal{M}^2 = \begin{pmatrix} m^2_{\gamma'} \sin^2 \chi_0 & m^2_{\gamma'} \sin \chi_0 \cos \chi_0 \\ m^2_{\gamma'} \sin \chi_0 \cos \chi_0 & m^2_{\gamma'} \cos^2 \chi_0 \end{pmatrix}.$$

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this matrix can be diagonalized by a simple rotation

$$U = \begin{pmatrix} c_{\chi_0} & -s_{\chi_0} \\ s_{\chi_0} & c_{\chi_0} \end{pmatrix}$$

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$$\begin{pmatrix} \gamma_1 \\ \gamma_2 \end{pmatrix} = U \begin{pmatrix} \gamma \\ \gamma_s \end{pmatrix}$$

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$$\begin{pmatrix} \gamma_1 \\ \gamma_2 \end{pmatrix} = U \begin{pmatrix} \gamma \\ \gamma_s \end{pmatrix}$$

and the probability

$$P^{\mathsf{vac}}_{\gamma\to\gamma_s} = \sin^2 2\chi_0 \sin\left(\frac{m_{\gamma'}^2 l_{\mathsf{osc}}}{4\omega}\right)^2 \tag{3}$$

Photon-HP Oscillations in a medium

just add a “mass term” for the photon $\frac{1}{2}m_\gamma^2 A_\mu A^\mu$

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this implies

$$\mathcal{M}^2 = \begin{pmatrix} m_{\gamma'}^2 \sin^2\chi_0 + m_\gamma^2 & m_{\gamma'}^2 \sin\chi_0 \cos\chi_0 \\ m_{\gamma'}^2 \sin\chi_0 \cos\chi_0 & m_{\gamma'}^2 \cos^2\chi_0 \end{pmatrix}.$$

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this mass matrix is diagonalized now by

$$\sin 2\chi = \frac{\sin 2\chi_0}{\sqrt{\sin 2\chi_0{}^2 + (\cos 2\chi_0 - \xi)^2}}; \cos 2\chi = \frac{\cos 2\chi_0 - \xi}{\sqrt{\sin 2\chi_0{}^2 + (\cos 2\chi_0 - \xi)^2}} \quad (4)$$

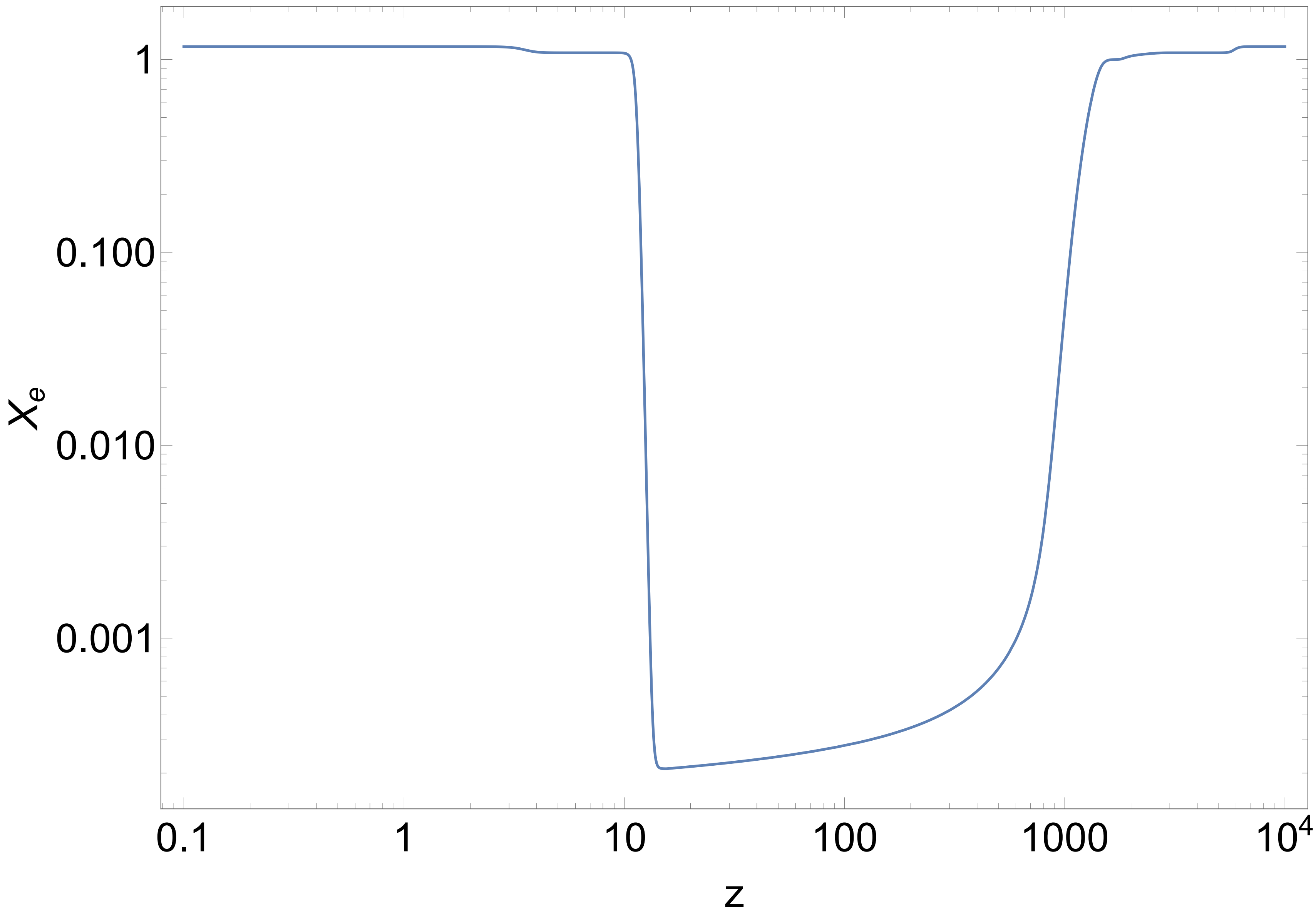
where

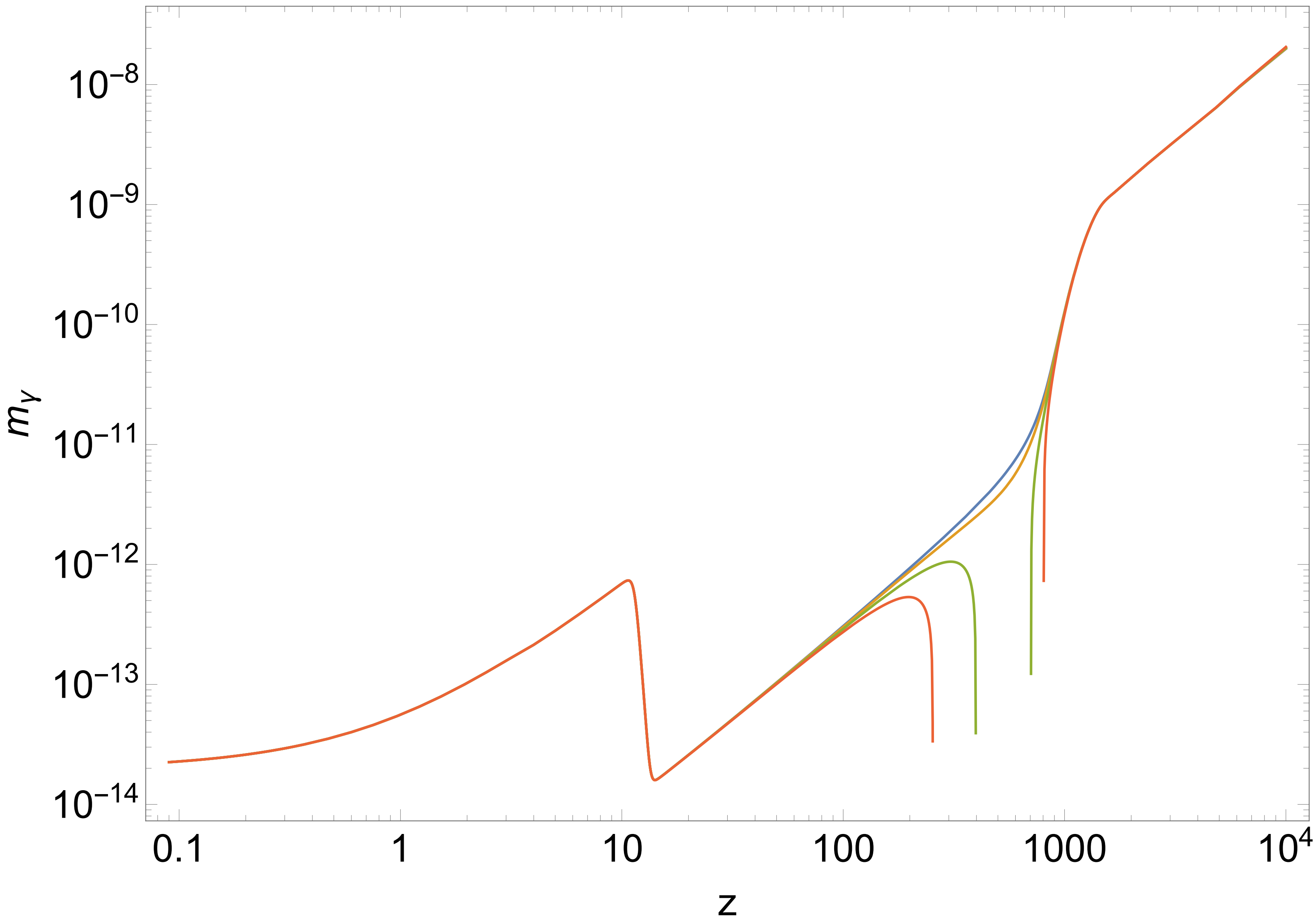
$$\xi = \frac{m_\gamma^2}{m_{\gamma'}^2}$$

Primordial plasma, m_γ

the "mass term" refers to a effective photon mass acquired in the travel of the photon trough the primordial universe

$$\left(\frac{m_\gamma}{\mathsf{eV}}\right)^2 \simeq \omega_{\mathsf{P}}^2 - 2\omega^2(n-1)_H$$
$$= 1{,}4\times 10^{-21}\left(X_e - 7{,}3\times 10^{-3}\left(\frac{\omega}{\mathsf{eV}}\right)^2(1-X_e)\right)\left(\frac{n_p}{\mathsf{cm}^{-3}}\right), \quad (5)$$


1
0.100
0.010
0.001
X_e
0.1
1
10
100
1000
10^4
z


10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
m_γ
0.1
1
10
100
1000
10^4
z

Then...

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where

$$P^{\text{res}}_{\gamma\to\gamma_s} = \frac{\pi m^2_{\gamma'}\chi_0^2}{\omega}\left|\frac{d\ \text{ln}\ m^2_\gamma(t)}{dt}\right|^{-1}_{t=t_{\text{res}}},$$

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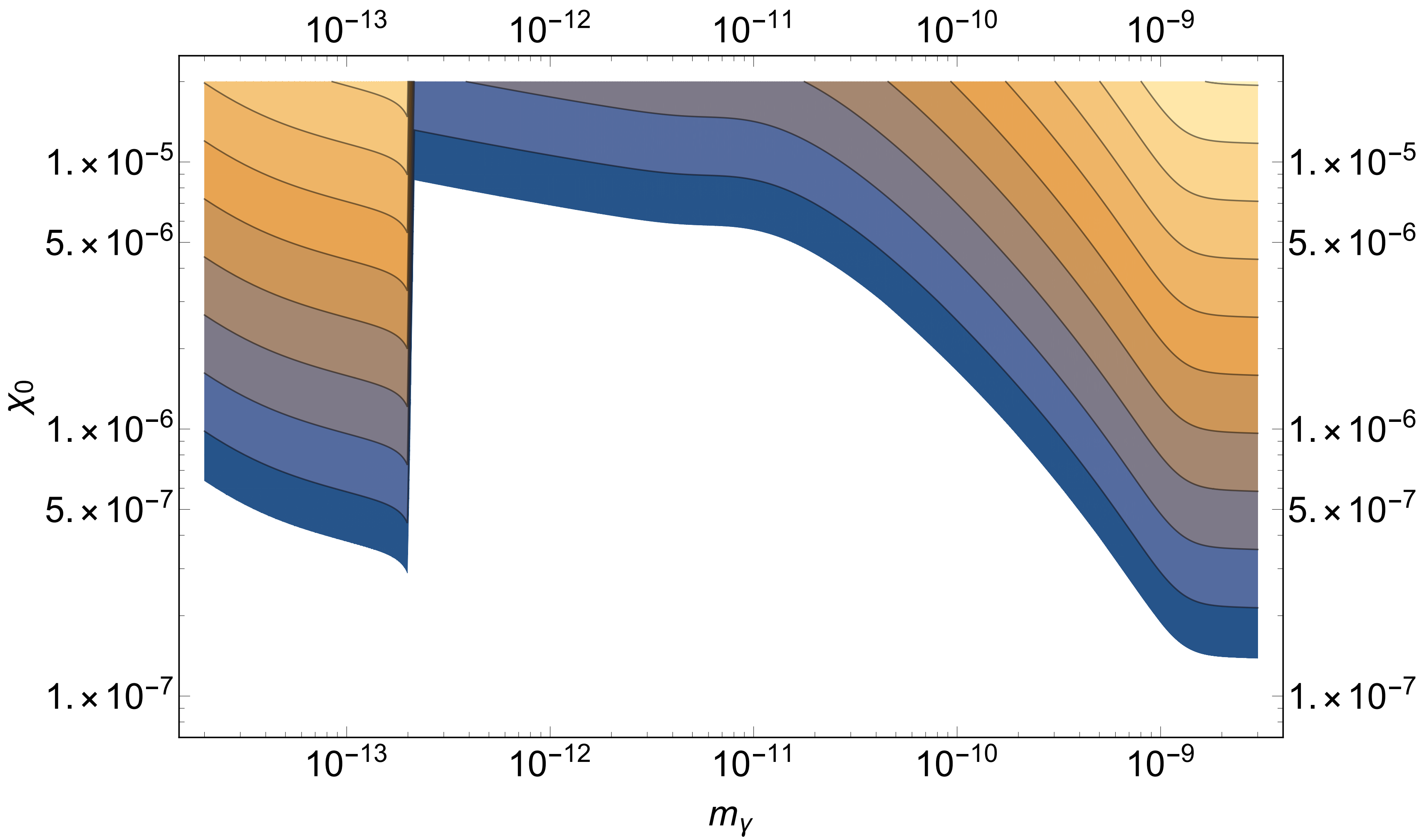
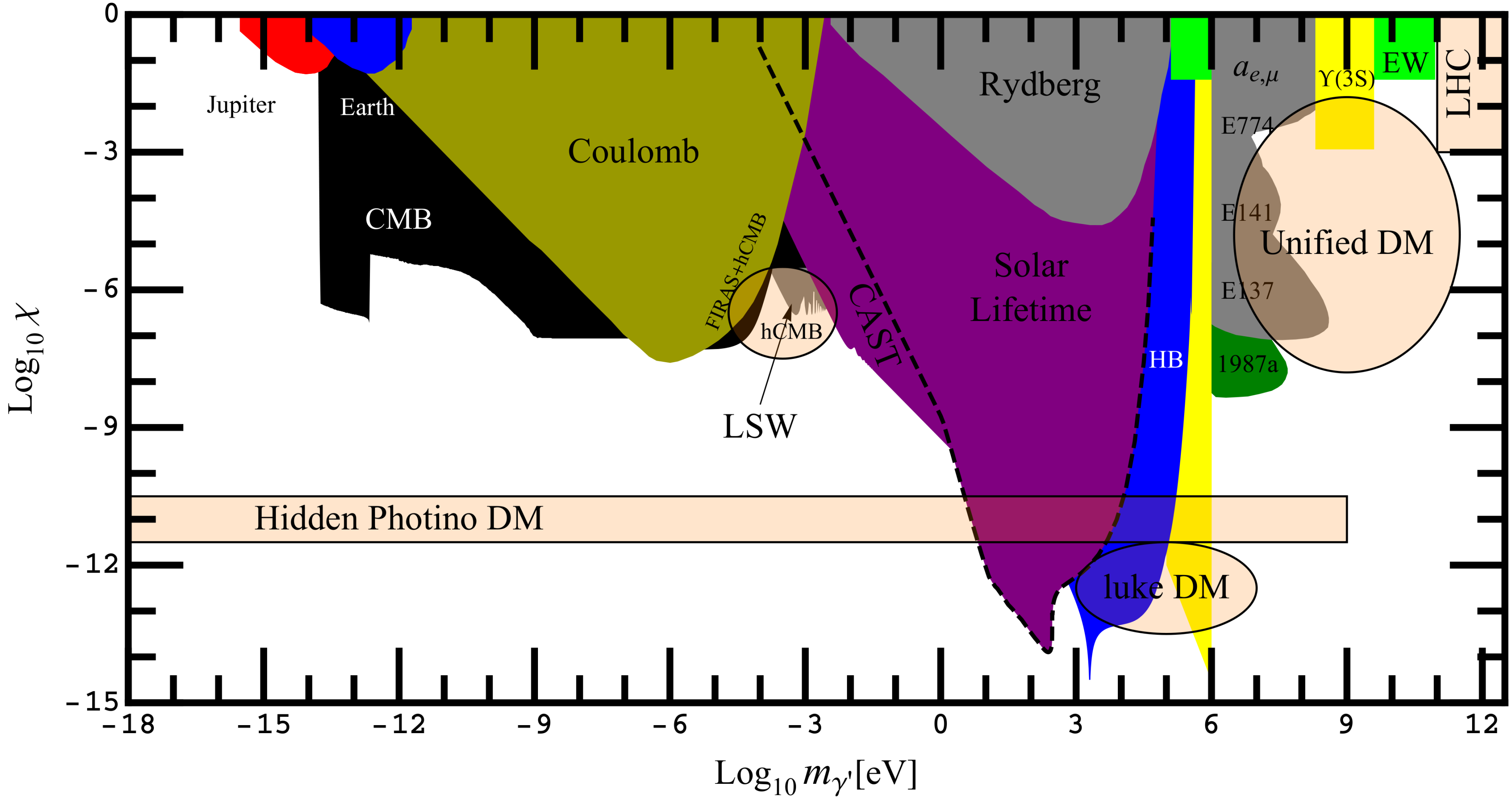
$$\chi^2 = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{I^{exp} - I(\chi_0, m_\gamma, z)}{\sigma_i^{exp}}\right)^2. \tag{6}$$



photon-HP exclusion plot with 99 % C.L.



HP constraints obtained from arXiv:1002.0329. Summary of astrophysical, cosmological and laboratory observations.

Axion-Photon Oscillation

$$\mathcal{L}_{pseudoscalar} = -\frac{1}{4} g_- F_{\mu\nu} \tilde{F}^{\mu\nu} \phi = g_- \vec{B} \cdot \vec{E} \phi$$

$$\mathcal{L}_{scalar} = \frac{1}{4} g_+ F_{\mu\nu} F^{\mu\nu} \phi = \frac{1}{2} g_+ (B^2 - E^2) \phi$$

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$$\Rightarrow \mathcal{L}_{pseudoscalar} = g_- B_T \omega A_{||} \phi$$

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$$\sin 2\theta = \frac{2gB\omega}{\sqrt{m_\phi^4 + (2gB\omega)^2}}; \quad \cos 2\theta = \frac{m_\phi^2}{\sqrt{m_\phi^4 + (2gB\omega)^2}}$$

ALPs bounds in medium

$$\sin 2\tilde{\theta} = \frac{\sin 2\theta}{\sqrt{\sin 2\theta^2 + (\cos 2\theta - \xi)^2}}; \quad \cos 2\tilde{\theta} = \frac{\cos 2\theta - \xi}{\sqrt{\sin 2\theta^2 + (\cos 2\theta - \xi)^2}}$$

where $\xi = \cos 2\theta \left(\frac{m_\gamma}{m_\phi}\right)^2$

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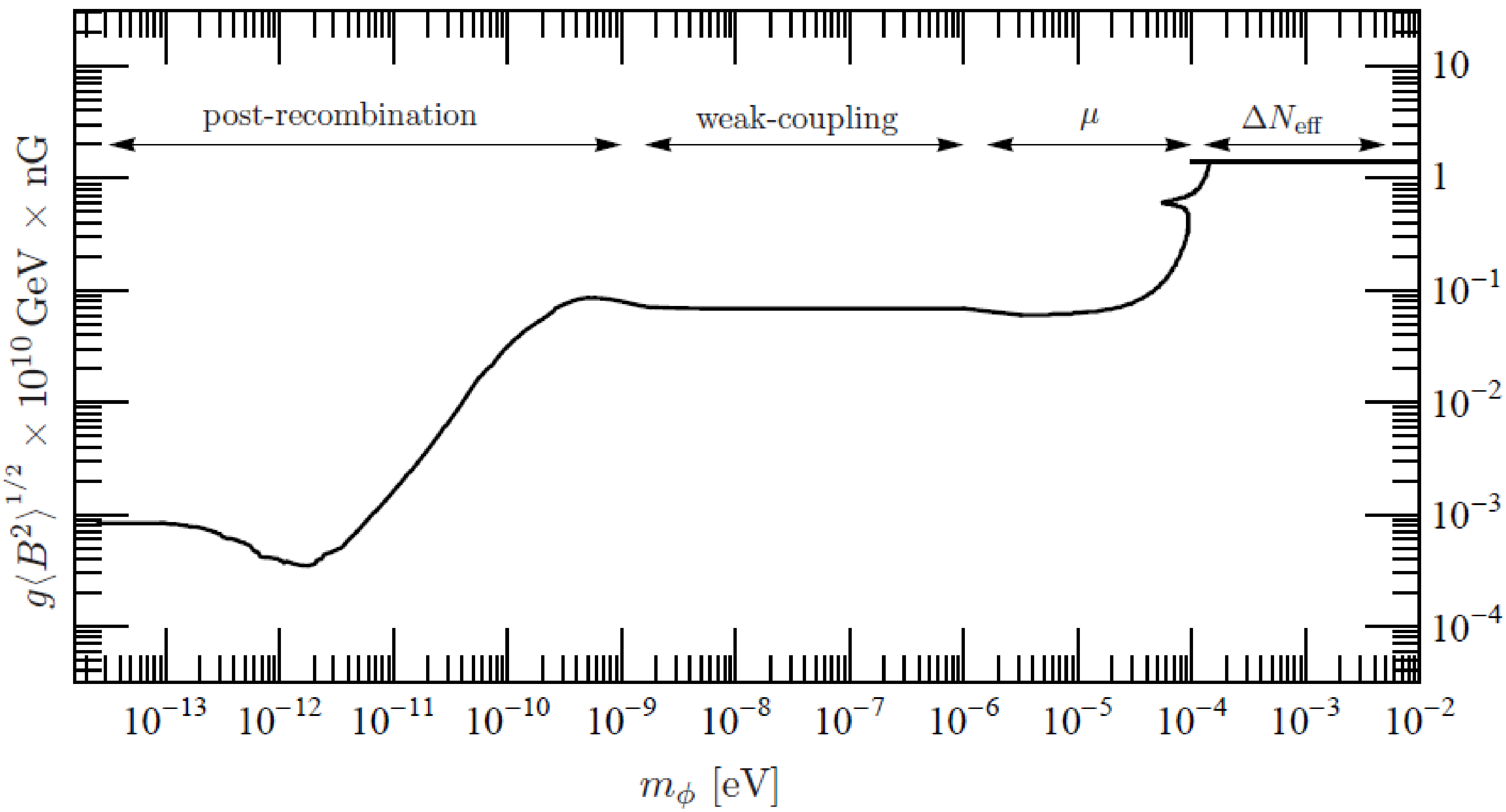
where $\xi = \cos 2\theta \left(\frac{m_\gamma}{m_\phi}\right)^2$

$$P^{\mathrm{res}}_{\gamma\to\phi} = \frac{\pi g^2 \omega}{m_\phi^2}\frac{1}{3}\left\langle B^2\right\rangle \left|\frac{d\ \ln\ m_\gamma^2(t)}{dt}\right|^{-1}_{t=t_{\mathrm{res}}}$$



ALPs-photon exclusion plot with 99 % C.L.

Finally...

3-particle Oscillations: ALPs-HP-photons

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$$
\begin{aligned}
\mathscr{L} \quad = \quad & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\sin\chi_0}{2}B_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g\phi B_{\mu\nu}\tilde{B}^{\mu\nu} \\
& + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \frac{\cos^2\chi_0}{2}m_\chi^2 B_\mu B^\mu + \frac{1}{2}m_\gamma^2 A_\mu A^\mu
\end{aligned}
$$

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3-particle Oscillations: ALPs-HP-photons

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$$\begin{aligned}\tilde{\mathscr{L}} &= -\frac{1}{4}F_{R\mu\nu}{F_R}^{\mu\nu} - \frac{1}{4}S_{\mu\nu}S^{\mu\nu} + \frac{1}{4}g\phi S_{\mu\nu}\tilde{S}^{\mu\nu} + \frac{1}{4}g\phi\sin^2\chi_0 F_{R\mu\nu}\tilde{F_R}^{\mu\nu} \\ &+\frac{1}{2}g\phi\sin\chi_0 S_{\mu\nu}\tilde{F_R}^{\mu\nu} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 + \frac{\cos^2\chi_0}{2}m_\chi^2 S_\mu S^\mu \\ &+\frac{\sin 2\chi_0}{2}m_\chi^2 S_\mu {A_R}^\mu + \frac{\sin^2\chi_0}{2}m_\chi^2 A_{R\mu}{A_R}^\mu + \frac{1}{2}\frac{m_\gamma^2}{\cos^2\chi_0}A_{R\mu}{A_R}^\mu\end{aligned}$$

3-Particle Mass Matrix

we can linearize the equations because the interactions between the particles are very weak and terms like $A_\gamma S$, ϕS and SS can be neglected, obtaining

$$-(\partial_t^2 - \vec{\nabla}^2)\vec{A} + g\sin^2\chi_0 \partial_t \phi \vec{B}_{\text{ext}} = \left(m_\chi^2 \sin^2\chi_0 + \frac{m_\gamma^2}{\cos^2\chi_0} \right) \vec{A} + \frac{m_\chi^2 \sin 2\chi_0}{2} \vec{S} \tag{7}$$

$$(\partial_t^2 - \vec{\nabla}^2)\vec{\phi} + m_\phi^2 \vec{\phi} = -g\sin\chi_0 \partial_t \vec{S} \cdot \vec{B}_{\text{ext}} - g\sin^2\chi_0 \partial_t \vec{A} \cdot \vec{B}_{\text{ext}} \tag{8}$$

$$-(\partial_t^2 - \vec{\nabla}^2)\vec{S} + g\sin\chi_0 \partial_t \phi \vec{B}_{\text{ext}} = m_\chi^2 \left(\cos^2\chi_0 \vec{S} + \frac{1}{2}\sin 2\chi_0 \vec{A} \right) \tag{9}$$

3-Particle Mass Matrix

With the equations decoupled, we use the next Ansatz for the fields

$$\vec{A}(y,t) = e^{i\omega t}\vec{A}(y)$$

$$\phi(y,t) = e^{i\omega t}\phi(y)$$

$$\vec{S}(y,t) = e^{i\omega t}\vec{S}(y)$$

and, with the relativistic approximation $(\omega^2 + \partial_y) \approx 2\omega(\omega - i\partial_y)$, the redefinitions $\vec{A} \to i\vec{A}$ and $\vec{S} \to i\vec{S}$, the system (7), (8) and (9) takes the form

$$[(\omega - i\partial_y)\mathbb{I}_{2\times 2} + \mathbf{M}_1] \begin{pmatrix} A_\perp \\ S_\perp \end{pmatrix} = 0 \qquad (10)$$

$$[(\omega - i\partial_y)\mathbb{I}_{3\times 3} + \mathbf{M}_2] \begin{pmatrix} A_\parallel \\ \phi \\ S_\parallel \end{pmatrix} = 0 \qquad (11)$$

3-Particle Mass Matrix

$$\mathbf{M}_1 = \begin{pmatrix} -\frac{1}{2\omega}\left(m_\chi^2 \sin^2\chi_0 + \frac{m_\gamma^2}{\cos^2\chi_0}\right) & -\frac{m_\chi^2 \sin 2\chi_0}{4\omega} \\ -\frac{m_\chi^2 \sin 2\chi_0}{4\omega} & -\frac{m_\chi^2 \cos^2\chi_0}{2\omega} \end{pmatrix} \tag{12}$$

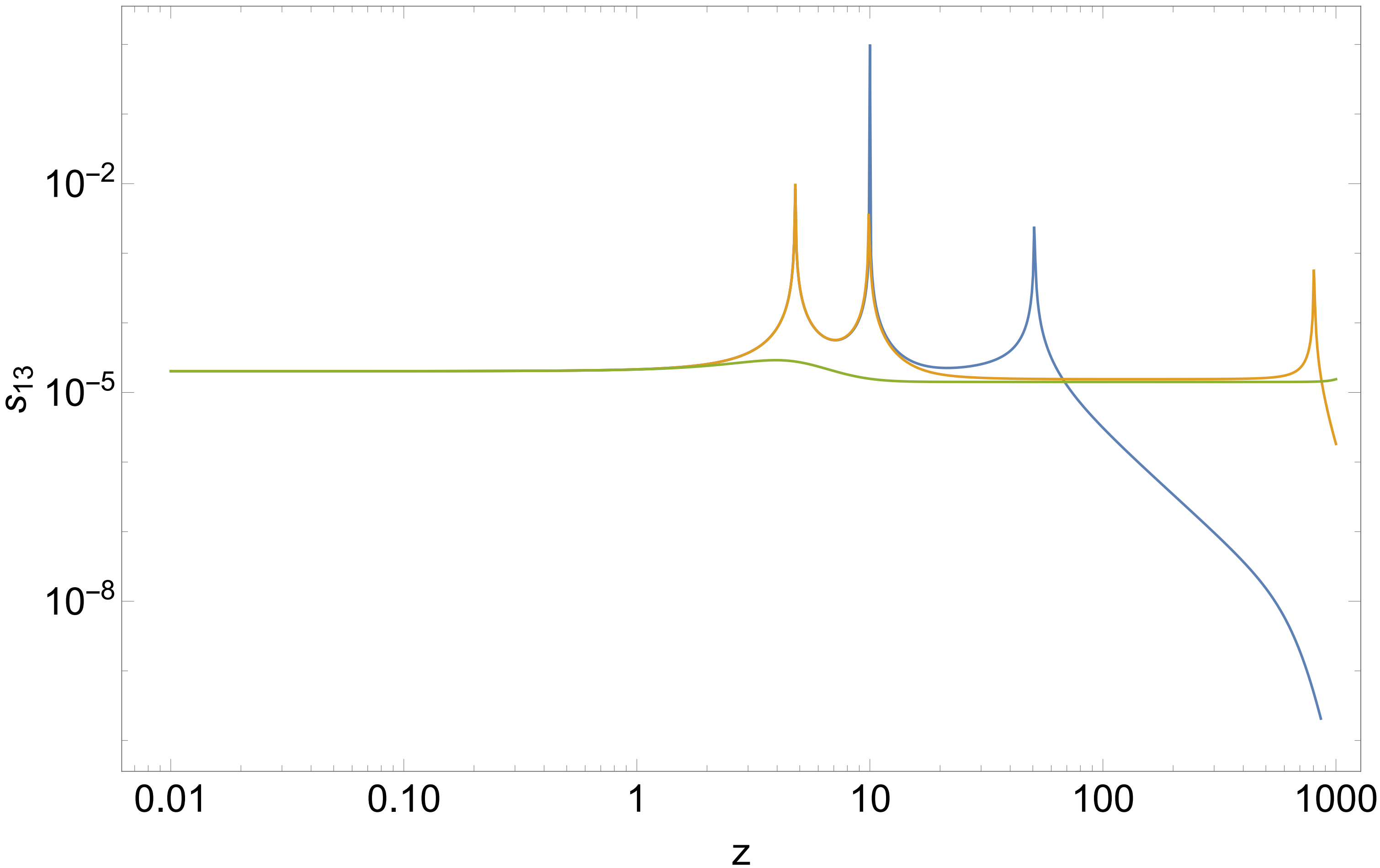
$$\mathbf{M}_2 = \begin{pmatrix} -\frac{1}{2\omega}\left(m_\chi^2 \sin^2\chi_0 + \frac{m_\gamma^2}{\cos^2\chi_0}\right) & -\frac{gB}{2}\tan^2\chi_0 & -\frac{m_\chi^2}{4\omega}\sin 2\chi_0 \\ -\frac{gB}{2}\tan^2\chi_0 & -\frac{m_\phi^2}{2\omega} & -\frac{gB}{2}\tan\chi_0 \\ -\frac{m_\chi^2}{4\omega}\sin 2\chi_0 & -\frac{gB}{2}\tan\chi_0 & -\frac{m_\chi^2}{2\omega}\cos^2\chi_0 \end{pmatrix} \tag{13}$$

Effective mixing in matter

When we deal with oscillations in matter, there is a effective mixing of the particles, related to the vacuum mixing. We have to compute this new mixing through the multiplication of our non-diagonal mass matrix (13) with 3 different rotation matrix, where each of one corresponds to a mixing coupling of the theory

$$\mathsf{U}_{\chi23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\chi23} & -s_{\chi23} \\ 0 & s_{\chi23} & c_{\chi23} \end{pmatrix},\ \mathsf{U}_{\chi13} = \begin{pmatrix} c_{\chi13} & 0 & s_{\chi13} \\ 0 & 1 & 0 \\ -s_{\chi13} & 0 & c_{\chi13} \end{pmatrix}$$
$$\text{and } \mathsf{U}_{\chi12} = \begin{pmatrix} c_{\chi12} & -s_{\chi12} & 0 \\ s_{\chi12} & c_{\chi12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

this is analogue to PMNS matrix for neutrino oscillations.



Blue line corresponds to $m_\phi = 0$, $g = 0$, orange for $m_\phi = 10^{-13}$, $g = 10^{-21}$ and green for $m_\phi = 10^{-13}$, $g = 10^{-19}$. χ_0 was fixed to 10^{-5} and $m_{\gamma'} = m_\gamma$