Improved limits on photon velocity oscillations

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Abstract

The mixing of the photon with a hypothetical sterile paraphotonic state would have consequences on the cosmological propagation of photons. The absence of distortions in the optical spectrum of distant Type Ia supernovæ allows to extend by two orders of magnitude the previous limit on the Lorentz-violating parameter \( \delta \) associated to the photon-paraphoton transition, extracted from the absence of distortions in the spectrum of the cosmic microwave background. The new limit is consistent with the interpretation of the dimming of distant Type Ia supernovæ as a consequence of a nonzero cosmological constant. Observations of gamma-rays from active galactic nuclei allow to further extend the limit on \( \delta \) by ten orders of magnitude.

Key words: Cosmology, Type Ia Supernovae, Paraphoton

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The existence of a second photon (paraphoton) mixing to the ordinary one was first postulated in [1] to explain a presumed anomaly in the spectrum of the Cosmic Microwave Background (CMB). In that model, the anomaly was attributed to a mass mixing of the two photons analogous to the oscillation of neutrinos. An ordinary photon oscillates with the time \( t \) in such a way that its probability to stay as such can be written as

\[
P(t) = 1 - \sin^2(2\phi) \sin^2 \left( \frac{\mu^2 t}{\omega} \right),
\]

where \( \omega \) is the frequency of the photon, \( \rho = c^2/4h^2 \), \( \phi \) is the mixing angle and \( \mu \) is the mass difference between the two mass eigenstates (i.e., the mass of the additional photon if the standard one is massless). Thus the oscillation
probability decreases with the increasing photon energy. The thermal nature of the CMB has then been established by COBE [2] and the anomaly has vanished; from the agreement of the CMB with the blackbody radiation, a second photon with mass $\mu \neq 0$ maximally mixing to the standard one has been excluded [3] at the level of

$$\mu < 10^{-18}\text{eV},$$

(2)

to be compared with the present limit of $m_\gamma < 2 \times 10^{-16}$ eV on the photon mass [4]. Eq. (1) shows that, in this kind of model, one achieves maximum sensitivity to the mixing by studying low-frequency radiation.

A different model [5] has been recently motivated by the possible existence of tiny departures from Lorentz invariance [6], which could explain the presence of cosmic rays beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff [7]. An additional photon state would experience Lorentz non-invariant mixing with the standard one, and the two eigenstates would propagate in any direction at slightly different velocities, say, $c$ and $(1 + \delta)c$. Velocity oscillations of photons could also result from violations of the equivalence principle in a Lorentz invariant theory [8], or from the mixing with photons in a “shadow” universe [9].

The paraphoton in [5] is sterile; photons emitted by ordinary matter evolve in such a way that the non-interacting component develops with time, and the probability for an ordinary photon to stay as such oscillates with time according to:

$$P(t) = 1 - b^2 \sin^2 (\delta \omega t/2)$$

(3)

with $\omega$ the frequency of the detected photon and $b^2 \equiv \sin^2 (2\phi)$, where $\phi$ is the mixing angle. We are concerned with the large mixing ($b \sim 1$) and small $\delta$ domain.

The extinction coefficient on light from a source at redshift $z$, due to velocity oscillations, can be written as a function of $z$ as:

$$P(z) = 1 - b^2 \sin^2(\delta \omega \hat{z}/2H_0),$$

(4)
where

\[ \hat{z} = H_0 \int_0^z (1 + \zeta) d\zeta \left(\frac{dt}{d\zeta}\right) \]  \hspace{1cm} (5)

\[ H_0 = h \times 100 \text{ km/s-Mpc}, \] and the redshift-time relation can be written:

\[ \frac{dy}{y} = -H(y) \, dt = -H_0 \left[ (1 - \Omega)y^2 + (\Omega - \Omega_\Lambda)y^3 + \Omega_\Lambda \right]^{1/2} \, dt \]

with \( y = (1 + \zeta) \), \( \Omega_\Lambda \) the cosmological constant and \( \Omega_M = \Omega - \Omega_\Lambda \). The function \( \hat{z}(z) \) is plotted in Figure 1 for \( \Omega = 1 \) and \( \Omega_\Lambda = 0 \); for \( \Omega = 1 \) and \( \Omega_\Lambda = 0.7 \); and for \( \Omega = 0.3 \) and \( \Omega_\Lambda = 0 \) respectively.

The analysis of Ref. [5] improves the previous limit [10] by ten orders of magnitude by studying the departures of the CMB from the thermal spectrum; a limit \( b\delta/h < 1.6 \times 10^{-32} \) is obtained, which corresponds to

\[ \delta < 1.1 \times 10^{-32} \]  \hspace{1cm} (6)

for \( h = 0.7 \) and \( b = 1 \).

By inspecting Eq. (3), one can see that, in this kind of model, one achieves maximum sensitivity to the mixing by studying high energy radiation.

The author of Ref. [5] observes that velocity oscillations might systematically distort the spectra of more distant sources and change their apparent magnitudes, complicating the determination of cosmological parameters via the measurements of redshifts and apparent magnitudes of distant Type Ia supernovae (SNe Ia) [11][12]. The effect could be such that data become consistent with a “standard” \( \Omega = 1 \) and \( \Omega_\Lambda = 0 \) universe.

The presence of “dark energy” has been recently independently confirmed [13,14] from a combination of measurements of the CMB and the distribution of galaxies on large scales. However, the uncertainties in measuring the cosmological parameters \( \Omega_M \) and \( \Omega_\Lambda \) do not allow to rule out the hypothesis that part of the dimming is due to photon mixing [15]. Given the current uncertainties of \( \pm 0.1 \) in the measurement of \( \Omega_M \) [14] and assuming that the Universe is flat with \( \Omega_M = 0.3 \), we can compute an upper limit for the contribution to the dimming of SNe Ia coming from photon-paraphoton oscillations.

The fractional loss of photons due to the oscillation into paraphotons is shown
in Figure 2 as a function of the wavelength in the optical region for different redshifts of the source. The curves were computed for $\delta = 10^{-32}$ (dotted lines) and $\delta = 10^{-33}$ (solid lines). A maximal mixing with $\delta = 10^{-32}$, of the order of the limit (6), would severely distort the optical spectrum for a redshift $z = 0.5$, and can thus be excluded. A value $\delta \sim 10^{-33}$ would fake a large part of the effect observed in [11][12]. The function $\hat{\varepsilon}(z)$ used in Figure 2 is calculated assuming $\Omega = 1$ and $\Omega_\Lambda = 0$; as seen in Figure 1, this is a conservative hypothesis compared to assuming, e.g., $\Omega = 1$ and $\Omega_\Lambda = 0.7$.

The improved sensitivity coming from the dimming of distant sources is made evident in Figure 3, where the fractional loss of photons emitted in the $B$-band due to the oscillation into paraphotons is displayed. We computed that the modulation would affect the observation of supernovae at $z = 0.5$ in the rest-frame $B$-band, while consistent with the current $\Omega_\Lambda$ value, for

$$\delta < 7 \times 10^{-34},$$

one order of magnitude smaller than the limit (6).

An independent limit can be obtained from the absence of distortions in the spectrum of SNe Ia between low-$z$ and high-$z$. The flux $F$ of SNe Ia is often also measured in a second band pass, usually the $V$-band, in order to address extinction effects. Using data of [11], and assuming the average extinction of distant and nearby SNe Ia is identical, we can compute the limit coming from the absence of distortions in the spectra from distant SNe spectra.

A limit of

$$\frac{(F(B)/F(V))_{z=0.5}}{(F(B)/F(V))_{z=0}} > 0.980 \ (95\% \ C.L.)$$

is obtained from the data of Ref. [11]; from this one obtains:

$$\delta < 2 \times 10^{-34}.$$  

More constraining limits could be reached if no distortions were observed in the spectrum of more distant supernovae.

The presence of the term $\omega$ in Eq. (4) is such that the sensitivity to $\delta$ improves further by making observations in the $\gamma$-ray region. In Figure 4 the fractional loss of photons due to the oscillation into paraphotons in the $\gamma$-ray region is

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1 The standard $B$-band goes from $\lambda = 380$ nm to $\lambda = 520$ nm (see [16]).

2 The standard $V$-band goes from $\lambda = 490$ nm to $\lambda = 680$ nm (see [16]).
averaged over the frequency between $E = 100$ MeV and $E = 10$ GeV, for a radiation with a power-law spectrum $E^{-2}$. The non-observation of distortions in the $\gamma$-ray spectrum at $z \sim 1$, in an energy region corresponding to the sensitivity of GLAST [17], can thus allow to set limits between $\delta < 10^{-41}$ and $\delta < 10^{-42}$.

A rule-of-thumb relation on the value of $\delta$ which could have sizable effects on the propagation from a given redshift $z$ of a photon of energy $E$ can be obtained by setting to unity the argument of the sine in Eq. (4):

$$\delta \sim \frac{3 \times 10^{-33}}{2(1 - 1/\sqrt{1 + z})} \left( \frac{1 \text{ eV}}{E} \right).$$  \hspace{1cm} (9)

The high-energy gamma data from Mkr 501 [18] at a redshift $z \simeq 0.034$, if interpreted as in agreement with models [19], allow to set a model-dependent limit

$$\delta < 10^{-44}$$  \hspace{1cm} (10)

from Eq. (9) assuming that there is no distortion at an energy $E \sim 10$ TeV.

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Fig. 1. The function $\hat{z}(z)$: for $\Omega = 1$ and $\Omega_\Lambda = 0$ (solid line); for $\Omega = 1$ and $\Omega_\Lambda = 0.7$ (dashed line); and for $\Omega = 0.3$ and $\Omega_\Lambda = 0$ (dotted line).
Fig. 2. Fractional loss of photons due to the oscillation into paraphotons as a function of the wavelength near the optical region. The curves for $\delta = 10^{-32}$ (dotted) and $\delta = 10^{-33}$ (solid) are shown.
Fig. 3. Fractional loss of photons emitted in the $B$-band (see text) due to the oscillation into paraphotons, as a function of the redshift $z$. The two curves correspond to $\delta = 2 \times 10^{-33}$ (upper curve) and $2 \times \delta = 10^{-34}$ (lower curve).
Fig. 4. Fractional loss of photons due to the oscillation into paraphotons in the $\gamma$-ray region, averaged over the frequency between $E = 100$ MeV and $E = 10$ GeV (assuming an energy spectrum proportional to $E^{-2}$), as a function of the redshift $z$. The two curves correspond to $\delta = 10^{-41}$ (upper curve) and $\delta = 10^{-42}$ (lower curve).