

# Solar paraphotons

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I revisit the question of production of paraphotons, or hidden photons, in the Sun and suggest that a simultaneous observations of solar flares by conventional instruments and by axion helioscopes may provide a discovery channel for paraphotons.

## 1 Introduction

Hidden sectors, which interact very weakly with the observable world, are a usual ingredient of theories extending the Standard Model and aimed at the explanation of its parameters and their hierarchies. Commonly, the interaction between the observable and hidden sectors is mediated by a very heavy particle and appears in the effective lagrangian, which describes the physics at the experimentally testable energies, through non-renormalizable terms with couplings suppressed by inverse powers of the mediator mass. It has been understood long ago, however, that there generally exist renormalizable interactions between two sectors, so-called portals, whose strength is not suppressed by the mediator mass. Unless protected by some symmetries, these interactions may be strong enough to allow tests of the hidden sector even for the mediator masses of order the Planck scale. The Standard Model fields allow for three kinds of such interactions: (i) the quartic coupling of the Higgs scalar with some hidden scalar field (so-called Higgs portal), (ii) the Yukawa coupling with neutrino, Higgs and a hidden fermion, and (iii) the kinetic mixing term between the Standard-Model and hidden  $U(1)$  gauge fields. Here, we concentrate on the latter case, first discussed in Ref. [1] where the gauge boson of the additional  $U(1)$  group was called a paraphoton. The kinetic mixing term, which mixes the field strength of a hidden  $U(1)$  gauge field with that of the electromagnetic (or hypercharge)  $U(1)$ , is allowed by Lorenz and gauge invariance and is renormalizable. Even if absent at the tree level, it should be therefore generated by loop corrections unless a particular symmetry prohibits it [2]. There is no lack of theoretical models which have sufficient freedom to justify observable paraphotons with almost arbitrary parameters allowed by experimental constraints. Some part of the paraphoton parameter space (which for our purposes consists of the paraphoton mass  $m$  and the kinetic-mixing coupling  $\chi$  but in general includes also the gauge coupling of the hidden  $U(1)$ ), however, have special phenomenological importance because these values have been invoked for models explaining either experimental anomalies or the origin of the Standard-Model parameters. We emphasize three particularly interesting regions.

(1) Mimicking extra neutrinos in the CMB. Recent cosmological results suggest that the effective number  $N_{\text{eff}}$  of light neutrino species is larger than three: the WMAP7 data [3] gives  $N_{\text{eff}} = 4.34_{-0.88}^{+0.86}$ , in agreement with somewhat less precise SDSS Data Release 7 [4] and Atacama

Cosmology Project [5]. It has been suggested that paraphotons with mass  $m$  in the range  $(10^{-5} \div 10^{-2})$  eV may mimic extra neutrino species, the change in  $N_{\text{eff}}$  determined [6] by the mixing  $\chi$ . For the WMAP7 values quoted above,  $\chi = (1.1 \div 2.4) \times 10^{-6}$ .

(2) String compactifications with TeV-scale gravity. Some of popular approaches to the gauge hierarchy problem in the Standard Model imply lowering the fundamental gravitational scale down to the values of order electroweak scale or slightly higher. This is usually achieved in models with extra space dimensions, in particular, in string models. Paraphotons are generic by-product in these compactification models. In a certain class of the latter, the fundamental string scale is related [7] to the kinetic-mixing parameter  $\chi$ . The string scale is bounded from below by the early LHC results to be larger than a few TeV; its values within  $(5 \div 1000)$  TeV would correspond to  $\chi \sim (10^{-12} \div 10^{-10})$  for a wide range of possible paraphoton masses.

(3) “Unified” or “secluded” dark matter and hidden SM Higgs. These approaches attempt to explain the anomalies observed by DAMA, PAMELA and INTEGRAL, as well as possible non-observation of a light ( $\sim 100$  GeV) Higgs boson with unusual decay channels. Though quite different, all these scenarios point to  $\chi \sim (10^{-4} \div 10^{-3})$  and paraphoton mass in the GeV range.

For different values of the parameters  $m$  and  $\chi$ , various experimental techniques have been implemented to search for a potential signal of paraphotons. None was found, resulting in severe limits on the parameter space, see e.g. Ref. [8] for a review.

In the Sun, paraphotons may be produced from solar thermal photons by means of the kinetic mixing, see e.g. Refs. [9, 10, 11, 12]. The oscillation probability for the most general case will be presented elsewhere [12]; here we will be interested in two limiting cases important for the Sun, namely the case of optically thick emission region (the solar interior) and that of transparent emission region (solar outer atmosphere and solar flares).

## 2 Contribution of the optically thick Sun

The Sun has a rather sharp boundary where the density, and hence the transparency, changes by many orders of magnitude. It has been shown (see, e.g., Ref. [10]) that for paraphotons of keV energies, the contribution of the optically thick interior dominates. The total flux of paraphotons in this case is given by [10]

$$\frac{d\Phi}{d\omega} = \frac{3 \times 10^{24}}{\text{cm}^2 \cdot \text{s} \cdot \text{eV}} \left( \frac{\chi}{10^{-5}} \right)^2 \left( \frac{m}{\text{eV}} \right)^4 f_1(\omega, m),$$

where

$$f_1(\omega, m) = 1 \text{ eV} \times \omega^2 \int_0^1 d\xi \xi^2 \frac{\Gamma(\xi R_\odot)}{e^{\omega/T(\xi R_\odot)} - 1} \frac{1}{(\omega_p^2(\xi R_\odot) - m^2)^2 + \omega^2 \Gamma(\xi R_\odot)^2}.$$

$m$  and  $\omega$  are the paraphoton mass and energy,  $\omega_p$  is the usual plasma frequency,  $\chi$  is the mixing coupling,  $\xi$  is the radial coordinate measured in the units of the solar radius,  $R_\odot$ , while  $T$  and  $\Gamma$  determine the temperature and the inverse mean free path of a photon with energy  $\omega$ , calculated at a given point in the Sun, respectively. The plasma frequency in the Sun varies roughly from 0.1 eV to 300 eV and for  $m$  within this range, the integral is saturated by a contribution of a rather thin resonance slice, the paraphotosphere; otherwise, high-temperature inner parts dominate (see Fig. 1, left panel). The right panel of Fig. 1 gives approximate exclusion limits on

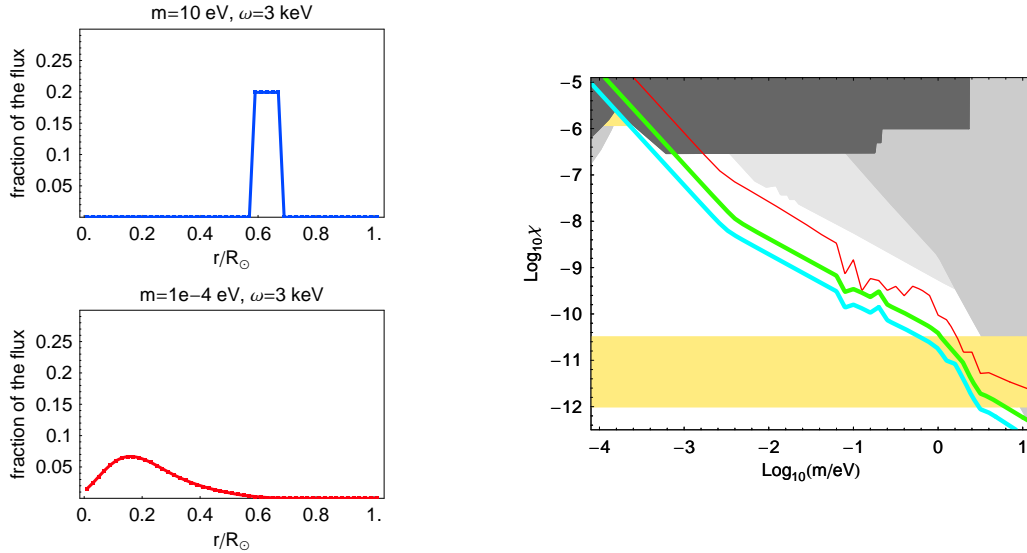


Figure 1: *Left*: Normalized contributions of various parts of the Sun to the total paraphoton flux. Upper panel: no resonance, the central part dominates. Lower panel: resonance, a thin slice dominates. *Right*: Paraphoton parameters. Dark gray: laboratory exclusion; light gray: astrophysical exclusion; very light gray: CAST exclusion from Ref. [10]. Very light gray (yellow online): theoretically favoured regions (see the Introduction). It is expected that future X-ray helioscopes will exclude the space above lines (top to bottom, the planned CAST upgrade and two options for the next-generation axion helioscope IAXO [13]).

the plane of paraphoton parameters (mass and coupling) expected for future X-ray helioscopes, together with current experimental bounds.

### 3 Solar flares

We assume that a flare happens in a small region with constant temperature and electron density and its emission is thermal. Then the ratio of the paraphoton flux from the flare to the photon flux at the same energy is approximately  $P/(1 - P)$ , where  $P$  is the probability of the conversion at the emission point. The duration of the flare is  $\sim 10^3$  s and normally, since  $P \ll 1$ , only a tiny number of paraphotons reach the detector during this time. The situation changes drastically if the density of plasma in the flare happens to be such that the resonance takes place. Then  $P \approx 1/2$  and a large number of photons were converted to paraphotons. It is easy to demonstrate that for a detector with area  $S$  and background noise  $n$ , the 95% CL exclusion limit on the mixing parameter  $\chi$  for one particular resonant mass may be determined by

$$\chi \gtrsim 8 \times 10^{-7} \left( \frac{F_{\text{obs}}}{10^5 \text{ cm}^{-2} \text{ s}^{-1} \text{ eV}^{-1}} \right)^{-1/2} \left( \frac{t}{1 \text{ s}} \right)^{-1/4} \left( \frac{n}{10^{-3} \text{ Hz}} \right)^{1/4} \left( \frac{S}{10 \text{ cm}^2} \right)^{-1/2} \left( \frac{\omega}{\text{keV}} \right)^{-1/2},$$

where  $F_{\text{obs}}$  is the flux of solar *photons* with energy  $\omega$  detected from the flare. In this formula,  $t$  is the period of time when the flare keeps resonant conditions, that is the plasma frequency does not change more than the resonance width. We note that while a flare looks as a rapid process at a particular wavelength, the change in appearance is related mostly to change in the temperature and not in the density (see e.g. discussion in Ref. [14] and particular numbers in Ref. [15]), so that  $t \gtrsim 1$  s is a typical value. However, in practice this approach can hardly be used to constrain  $\chi$  because one does not know the conditions in the flare with the required precision.

Instead, I suggest that the observation of flares with helioscopes may be a discovery channel for paraphotons. Indeed, the resonant conversion of photons to paraphotons in the flare manifests itself not only by appearance of paraphotons but also by a  $\sim 1/2$  drop in the regular *photon* flux. The study of light curves with excellent time resolution is possible with various instruments (e.g., SOXS, SPHINX etc.). One may search them for temporal coincidences between events in helioscopes and drops in the flare lightcurves; the background is almost zero and even a single coincident event may serve as a strong evidence for paraphotons.

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