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# EVIDENCE FOR UBIQUITOUS LOW-ENERGY AXIONS?

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## Abstract

A few unexplained astrophysical observations could find a natural explanation by assuming the existence of electromagnetically decaying low-energy axions or other axion-like particles emitted from the Sun or other Sun-like stars. The decay photons would give rise to a 'self-illumination' of the Sun, providing the missing origin of the hot solar corona heating mechanism. Furthermore, in analogy with the terrestrial and other planetary atmospheres, the step-like temperature and density gradient in the transition region between the chromosphere and the corona, as yet not understood, can be naturally explained in terms of the absorption of these photons in this region of the solar atmosphere. We consider the observed soft-X-ray emission from the direction of the dark side of the Moon as a further signature of solar axion decays in flight, occurring between the Earth and the Moon. Surprisingly, later re-analyses of these X-rays tentatively consider their origin as being, against conventional reasoning, outside the Moon; their intensity is higher than the one expected from the interaction of the solar wind with the lunar surface by more than a factor of 10. With this scenario one could also explain the as yet missing origin of the diffuse (soft) X-ray background radiation. In all of these observations a temperature component of $\sim 10^6$ K is present. Under the assumption of isotropic decay, combined solar observations provide evidence for axion(-like) particles in the sub-keV range with a mean decay length of $\sim 0.05$ AU. To directly confirm this, we propose a search for two coincident photons below $\sim 400$ eV, but the 'window of opportunity' is below a few keV.

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# 1 INTRODUCTION

The direct detection of dark-matter particles has proved elusive since the first gravitational observation of a non-luminous matter in the Universe. So far, the outcome of the intense experimental and theoretical work in the field of dark matter during the last $\sim 20$ years was the birth of the new discipline of astroparticle physics.

In this work, a rather old question re-arises as to whether certain as yet unexplained astrophysical observations occur because of the involvement of novel very weakly interacting particles or additional as yet unknown properties of existing particles. For example, in order to explain the widespread ionization of the interstellar medium in the Galaxy, speculations included the electromagnetic decay of real or hypothetical exotic particles [1], more specifically massive dark-matter neutrinos providing the emission of the required ionizing photon [2]. Considerations based on axions apply as well, invoking either its $2\gamma$ decay mode or its coherent conversion to a photon within astrophysical electric/magnetic fields via the Primakoff effect.1) It is also worth noting an additional suggestion which fits the reasoning of this work. In order to explain the as yet unknown underlying mechanism(s) of the Gamma Ray Bursts, massive axions with properties far beyond the widely accepted theoretical axion concepts have been considered, providing a built-in dissipationless energy transfer mechanism from the hypothetical energy generating core to the outside layers some $100-1000$ km away [5]. Even though none of such intriguing ideas has been established so far [6], an additional electromagnetic energy source in the cosmos seems to be required.

In this work, we argue that the photon decay of some hypothetical particles, we call them more generally 'axion-like' (not to say a long-lived $\pi^0$-like particle), must be involved in certain unexplained astrophysical observations. An extensive astrophysical literature search has been undertaken, which includes also some 10–50 year old observations. In this work we focus mainly on:

a) the solar corona problem;
b) the observed X-rays from the direction of the dark side of the Moon; and last but not least,
c) the cosmic soft-X-ray background radiation.

Following the reasoning of this work along with the mentioned observations, we also suggest performing a *specific* axion search in a new type of experiment either on the surface (and in space) or underground, aiming to directly detect the $2\gamma$ decay mode. In addition, following this axion scenario, some astrophysical measurements could be reconsidered or re-analysed. A slightly modified design in future X-ray space detectors could allow them to operate also as sensitive orbiting axion telescopes.

# 2 OBSERVATIONAL EVIDENCE

In this section we present a few not yet understood astrophysical phenomena or experimental results, which can be explained in a combined way assuming an axion-like scenario. We also refer to quite recent publications in order to show that a conventional explanation of the observed phenomenon is still missing.

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1) a) The absence of a monochromatic axion line from the night sky expected from the $a \rightarrow \gamma\gamma$ decay of relic axions in the visible [3] almost excluded an axion rest mass in the $\sim$ 1–10 eV range. b) The X-ray spectrum from the quiet Sun: a *conventionally* expected thermal X-ray spectrum from solar axions converted inside the solar magnetic fields with mean energy of $\sim 4.4$ keV cannot be disentangled from the measured solar X-ray spectrum (e.g. Ref. [4]).

### 2.1 Solar corona

The existence of the solar corona has been known for more than 100 years. However, solar X-rays have been measured only over the last 50 years, providing an unexpectedly high temperature [7, 8]. The corona is the only atmospheric layer of the Sun that emits *thermally* in X-rays [9]. Quite recently, reconstructed X-ray energy spectra have been published, providing additional valuable information about our Sun, like temperature, solar cycle dynamics, etc. [4]. The average temperature of the quiet-Sun corona is $\sim 2 \cdot 10^6$ K, giving rise to the still enigmatic coronal heating problem [4, 7, 10, 11, 12]. The quiet-Sun X-ray luminosity ($L_x \approx 10^{26}$ ergs/sec [13, 14]) represents only a fraction of $\sim 10^{-7}$ of the total solar luminosity. Therefore, energy balance problems are irrelevant.[2)]

Thus, the main puzzles with the solar corona are the following:

a) In order to maintain the quiet Sun's high temperature corona, *nonthermally* supplied energy must be dissipated in the upper atmosphere [15].

b) The hot corona cannot be in thermodynamical equilibrium with the $\sim 300$ times cooler solar surface underneath, which emits an almost perfect blackbody radiation in the visible [16] (Fig. 1B).

c) One must explain the abrupt (within less than $\sim 100$ km) temperature increase (from $\sim 8 \cdot 10^3$ K to $\sim 5 \cdot 10^5$ K) in the chromosphere/corona transition region (Fig. 1A), against physical expectation [17, 18]. This is 'the solar corona problem'.[3)]

It is amazing that the mentioned step-like change of the corona temperature coincides in space with a similar (opposite) density gradient (Fig. 1A), thus suggesting a common origin. Qualitatively, this peculiar behaviour of the Sun's atmosphere is suggestive for some external irradiation (pressure), which can cause the 'compression' and heating of the intervening solar atmosphere. Depending on the energy, these photons — whatever their origin — are absorbed mainly at a certain depth (as seen from outside the Sun) due to the exponential increase of the density with decreasing height of the solar atmosphere (see Fig. 1A and Ref. [17]). One should keep in mind that the density at the place where both steps occur is $\sim 10^{-(12\pm1)}$ g/cm$^3$, i.e. an almost perfect vacuum, which actually does not facilitate a conventional explanation of this observation. However, the pressure (= column density) in the solar atmosphere at an altitude of $\sim 2000$ km is $\sim 10^{-5}$ g/cm$^2$. With hydrogen being the main constituent element, photons with $\sim 50$ to $\sim 100$ eV are absorbed efficiently [20], while higher energy ones will penetrate deeper, depositing less energy in the very thin atmosphere.

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[2)] In this work we refer for reasons of simplicity to quiet-Sun conditions only. The X-ray power of the active Sun is by a factor of $\sim 20$ higher compared to the quiet Sun, while the temperature reaches values of $\sim$ 8–20 MK [4, 14]. Within this work the study of the active Sun might be of interest as well.

[3)] Note that most of the solar light comes from the $\sim 100$ km visible photosphere ($\sim 5800$ K). Above that, there is the chromosphere which is astonishingly hot (up to 25 000 K), and above that, the corona (up to a few MK and locally much more [18]). Corona X-rays have been observed out to $\sim 1$ solar radius. The outer corona expands into the interplanetary space and slowly cools off. At $\sim$ 1–100 AU the temperature is still $\sim 10^5$ K [19] (see also R.F. Stein in Ref. [17]). If the corona is heated by thermal processes, it could not be hotter than the photosphere. Therefore, it must be heated by some non-thermal process(es) [17, 19]. One obvious explanation could be that only below a certain density is the energy input (whatever the required nonthermal energy transfer mechanism is in reality) sufficient to increase the temperature up to a certain value.

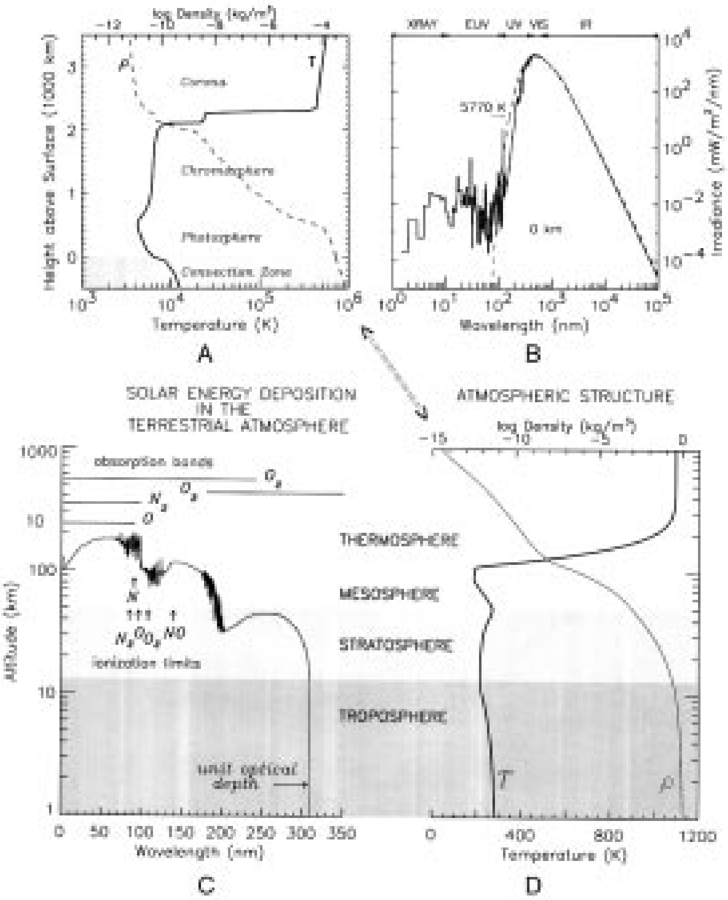

Figure 1: (**A**) The mean temperature ($T$) and density ($\rho$) profiles for the solar atmosphere; (**B**) solar irradiance spectrum (the dashed line is the Planck shape for a temperature $T = 5770$ K); (**C**) the altitude at which the Earth's atmosphere attenuates the incident solar radiation by a factor $1/e$; (**D**) temperature ($T$) and density ($\rho$) as functions of height in the Earth's atmosphere. (These figures are taken from Ref. [16].)

All these findings and problems associated with the solar corona can be explained by assuming axion(-like) particles, which stream out of the interior of the Sun and undergo photon decay in flight, providing thus the necessary energy input which enables unexpected nonthermal phenomena to occur. In addition, from the $a \rightarrow \gamma\gamma$ decays, $\sim 50\%$ of the photons are emitted 'backward', i.e. towards the Sun, if the escaping axion-like particles are not relativistic. Thus, 'axions decaying in flight to photons outside the Sun can give rise to an external illumination of the solar atmosphere.' Obviously, the mean axion decay length should be comparable to or (much) greater than the solar radius. In the dense interior of the Sun they can only have a negligible impact due to energy considerations, thus avoiding any conflict, at least at first sight, with the generally accepted solar model(s). However, above some altitude, i.e. below a certain density, the thermodynamical equilibrium starts getting disturbed because of a relatively high external energy input, coming — ironically — from the Sun itself. Without taking into account this energy source, the temperature appears to increase to thermodynamically not allowed values.

The striking similarity of the temperature and density dependence on the altitude between the Earth and Sun atmospheres [16] strongly supports the conclusion reached above about an external source illuminating the Sun in the UV−X-ray region (compare Fig. 1A with Fig. 1D). The observation made in the atmosphere of Venus [21] seems to be relevant too: due to the solar irradiation, its nightside density ($\rho \approx 10^{-15}$ g/cm$^3$ at a height of 170–190 km) and temperature increase during local day time by a factor of 10 and 30%, respectively. The photoionization rate peaks at an altitude of $\sim$ 140 km [22]. Since the planetary absorption depth of the solar radiation reflects the energy of this radiation [16] (see Fig. 1C), we conclude that for the case of the solar atmosphere the photons emitted backwards near the Sun from the exotic particle decay must have an energy around $\sim$ 50 to $\sim$ 100 eV. The total axion(-like) energy is at least $\sim$ 100 to $\sim$ 200 eV, depending on its velocity. If the photon-emitting exotic candidate is some other heavy particle, then the kinematical/dynamical conclusions are not so straightforward.

### 2.2 X-rays from the direction of the dark side of the Moon

If axions escape from the Sun and are not highly relativistic, then the decay photons are emitted to a certain degree isotropically in space. This two-body decay kinematical effect magnifies (so to speak) the size of the X-ray emitting region of the Sun. If the solar axions escape isotropically, this magnification will be accordingly equal in all directions. Such a solar axion scenario should result in some (soft) X-rays coming obliquely from the Sun's near or far neighbourhood, depending on the axion mean decay length, and of course, on the detection sensitivity. However, a more or less isotropic $2\gamma$-emission will mimic scattering of solar X-rays by gas, plasma, dust, etc. [23], which is a well-known phenomenon in astrophysics. (Un)fortunately, the energy spectrum of the ubiquitous diffuse X-ray background radiation (XRB) overlaps with the solar one (Fig. 3), while its intensity is by no means negligible. Thus, reprocessing of solar X-rays by matter in outer solar space and the XRB must be taken into account, in order to correctly interpret existing data, or to design a new measurement following the reasoning of this work.

We reconsider here one experiment, which seems to be particularly relevant in favour of a solar axion-like scenario. The measurement we refer to was performed by the ROSAT [24] orbiting X-ray telescope in 1990, which provided an excellent X-ray 'photo' from the sunlit side of the moon [25]. In fact, with the X-ray telescope's field-of-view (FOV) aligned towards the Moon, this configuration eliminated (so to speak) the $\sim$ three times brighter diffuse XRB (see Fig. 4 in Ref. [25]). In addition, the excellent detector performance and its very low background level made such an observation possible. Unexpectedly, ROSAT has also observed rather intense X-ray emission coming from the optically dark side of the Moon (Fig. 2) : its *shadow* emits X-rays at a level as high as 1% and 30% compared to that of the bright side of the Moon and of the XRB radiation, respectively. It is interesting to note that all these three components are extracted from the same X-ray image, and they have a quite similar spectral shape (Fig. 3). The interaction of the solar wind with the dark surface of the Moon has been suggested as the source of these X-rays [25]. Such an explanation should actually be the natural one, but the estimated absolute intensity seemed not to be completely satisfactory. In fact, Ref. [26] reaches the tentative conclusion *that there was no emission from the Moon itself*, without excluding the opposite case, i.e. the original interpretation [25]. Moreover, eight years later, a preliminary re-analysis [27] of this apparently very clean experimental result from the dark Moon reaches the following tentative conclusions:[4)]

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[4)] The purpose was actually to propose a possible extra component of the soft XRB [27].

a) The dark side of the Moon is brighter than expected by a factor of more than 10.
b) This excess is consistent with the effect of an X-ray emitting region around the Earth.

On the basis of these arguments we consider the photons from the *direction* of the dark side of the Moon (Fig. 3B) as further evidence in favour of this solar axion decay scenario, with the axion total energy being at least twice that of Fig. 3B. It is interesting to note that the energy of the bulk of these single photons (Fig. 3B) from the dark Moon direction ($\sim$ 100 to $\sim$ 400 eV) is not much different from that derived from the assumed 'backward' emitted photons towards the solar corona of $\sim$ 50 to $\sim$ 100 eV. However, if this difference is real, it might reflect relativistic two-body kinematics or axion decay dynamics.

In conclusion, in our opinion 'conventional thinking fails to explain an (unexpected) X-ray observation in the $\sim$ sub-keV range, which fits best the solar axion-like scenario of this work.'

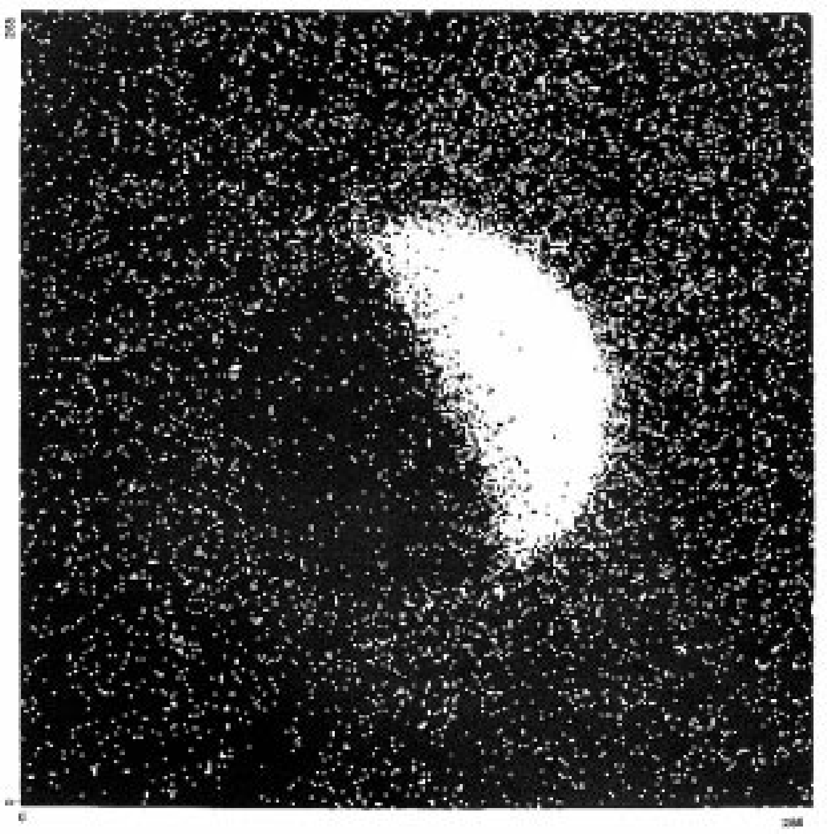

Figure 2: The X-ray photon image of the Moon as measured by ROSAT. The sunlit portion of the Moon is visible, as well as an X-ray shadow in the diffuse XRB radiation cast by the dark side of the Moon. Grey pixels denote one or two events, except in the brightest part of the crescent, corresponding to three or more counts.

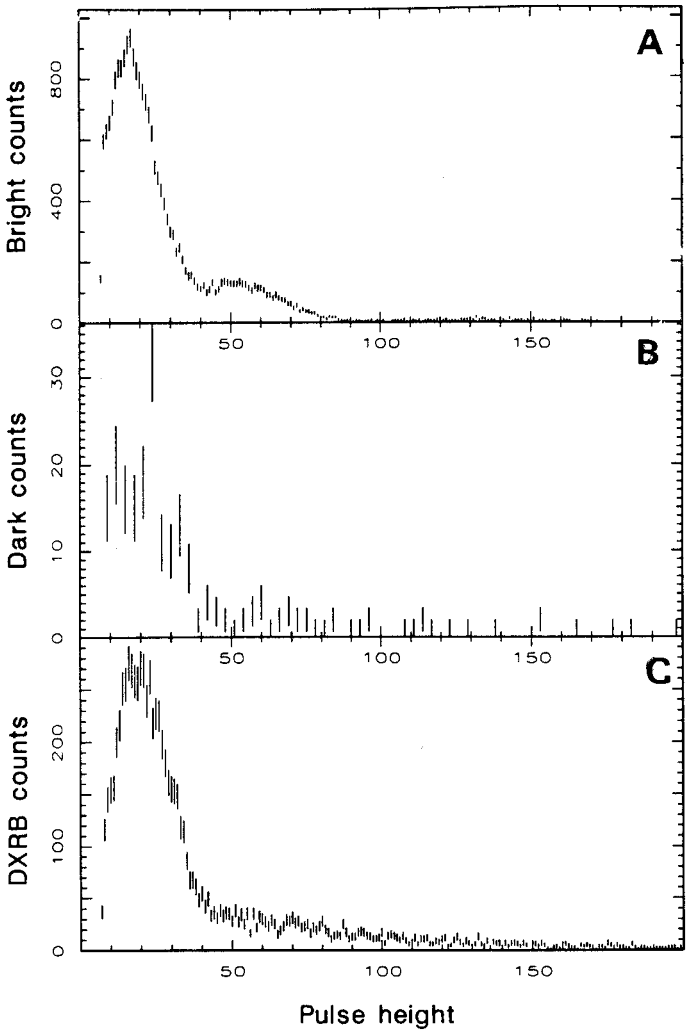

Figure 3: Measured raw pulse-height spectra from the observation in Fig. 2 (channel number multiplied by 10 gives the energy in eV): (**A**) X-rays from the sunlit side of the Moon; (**B**) X-rays from the dark side of the Moon; (**C**) cosmic X-ray background radiation. (Figures 2 and 3 are taken from Ref. [25]).

### 2.3 Cosmic soft X-ray background radiation (XRB)

The origin of the celebrated diffuse XRB radiation [28] remains a mystery [29] and is one of the key questions in astrophysics [30]. It was discovered accidentally [31] in 1962, predating the discovery of the cosmic microwave background radiation (CBR) by two years. Thus, from a wealth of data about its galactic component below 1 keV, the existence of a $\sim$ 100 pc extended optically thin local $\sim 10^6$ K ($\sim$ 0.1 keV) hot plasma has been invented, which fills the 'Local Hot Bubble' (LHB) [32]: a soft X-ray-emitting region around the Sun, whose origin is still unknown [32, 33]. The existence of a hot gas as a major constituent of the interstellar medium follows from the observed UV resonance absorption lines from highly ionized species such as O-VI [34]. However, for the extragalactic component above 1 keV [35], a similar scenario of a widespread optically thin and very hot uniform intergalactic medium (temperature $\sim$ 10–40 keV) has been ruled out experimentally [36, 37, 38, 39] by the measured Planck spectrum of the 2.7 K CBR by the FIRAS instrument on the COBE satellite. Such a spectrum should be distorted from Compton scattering with the very hot plasma electrons, requiring a large number of unresolved extragalactic faint sources [35].

Like our Sun, many other stars also have outer layers that are hotter than the underlying photosphere, giving rise to corona formation and X-ray emission. Observations suggest that the corona of the Sun and the stellar coronae have common heating mechanism(s) [7, 19, 40]. Therefore, the solar corona problem is not just a solar problem [7, 19, 40] and our conclusions based on solar observations become rather global. The $\sim 10^{11}$ stars per galaxy along with the $\sim 10^{11}$ galaxies in the Universe can obviously contribute to the observed galactic [42] and extragalactic diffuse XRB. A long mean decay length of the postulated axion-like particles, e.g. from $\sim 1$ AU to some pc's, will fit better the observed diffuse character of the XRB and that of the LHB (including the predicted axion-related X-rays from the dark Moon direction). Remarkably, the low energy XRB has also a temperature component of $\sim 10^6$ K [43], which is almost identical to that of the quiet-Sun corona [4, 15, 18, 48], the LHB [44, 45, 46] and the galactic diffuse X-ray emission beyond the LHB [42, 45, 46, 47]. Moreover, the pulse-height spectrum (below $\sim 1$ keV) of the XRB, and that from the direction of the dark side of the Moon (Fig. 3) are quite similar to each other [25], suggesting a common origin.

According to this scenario, it is reasonable to conclude that the low-energy diffuse XRB comes from escaping and decaying axions (or other photon-emitting exotica) in at least some of the $\sim 10^{22}$ Sun-like stars in the sky. Similarly, the XRB at higher energies could originate from hotter places in the sky, e.g. neutron stars.

## 3 DIRECT AXION DETECTION

Some 20 years ago [41], the first axion experiments searched for $\gamma\gamma$-coincidences, but far above the sub-keV range favoured by this work. It is not the purpose of this article to provide a complete design of all possible new solar axion telescopes. However, following the considerations of this work, the required conditions are rather obvious. In the following, we address a few possible configurations in orbit and on Earth.

a) **An orbiting X-ray telescope** could operate as a solar axion antenna, by searching for low-energy photons from regions at different heliocentric distances ($r_h$), with the Sun being outside its FOV. [5] Thus, a deviation from the $1/r_h^2$ law, due to the assumed axion decay, should be a clear signature. The above-mentioned dark Moon configuration [25] should be utilized again. In particular, when the Moon is completely inside the Earth's shadow, i.e. during a full lunar eclipse, this is most interesting, because of the almost eliminated solar X-ray background. Therefore, archived data should be re-analysed. Moreover, pointing the orbiting detector towards the *dark Earth* while it is in Earth's 'night' during each orbit around the Earth seems to be a very similar and attractive configuration repeating several times per day. In fact, for the purpose of this work, a wide detector FOV implies a better signal-to-noise ratio, or at least a higher sensitivity to detect (solar) axion decays inside the detector's FOV.

   We compare a wide-aperture X-ray detector orbiting at an altitude of 500 km and pointing towards the dark Earth with the ROSAT detector which measured X-rays from the dark Moon in a $\sim 0.5°$ narrow cone. The effective volume to detect (solar) axion decays is by a factor $\sim 447\ \mathrm{m}^3/37\ \mathrm{m}^3 = 12$ bigger for the dark

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[5] X-ray telescopes avoid having the Sun in their FOV, because of the $\sim 7 \cdot 10^9$ X-rays/cm$^2$·s·($\geq 60$ eV) arriving at the site of the Earth [49]. For example, ROSAT's FOV was pointing at 101° away from the Sun.

Earth configuration.[6] So far, to the best of our knowledge, the dark Earth has been observed with a narrow detector FOV [52], corresponding to a factor of only $\sim 10^{-3}$ (instead of 12), i.e. hopeless to have observed some signal in the past even unintentionally. Thus, the observed dark lunar emission rate of $\sim 0.15$/s ($E_\gamma \leq$ 1 keV) by ROSAT [25] translates into a rate $R$ for the dark Earth configuration of

$$R \approx 0.15 \times 12 \approx 1.8/\mathrm{s}, \tag{1}$$

assuming a 100 cm$^2$ orbiting X-ray detector at 500 km with $\sim 50°$ opening angle and $\sim 447$ m$^3$ *effective* fiducial volume within its FOV. This is actually a rather strong signal, which should be even stronger if photons from axion decay are preferentially emitted along the axion momentum. The axion decay rate $\mathrm{X}(\mathbf{r})$ at 1 AU from the Sun is then

$$\mathrm{X}(|\mathbf{r}| = 1\ \mathrm{AU}) \approx 4.5 \cdot 10^{-9}\ \text{axion decays/s} \cdot \mathrm{cm}^3. \tag{2}$$

b) **An X-ray detector** with $\sim 4\pi$ acceptance operating on Earth (or, better, underground) seems to be the most adequate experimental approach, since it allows reconstruction of axion decays inside its fiducial volume by observing $\gamma\gamma$-coincidences. Such a detector is actually blind to any solar X-rays. Again, assuming the axion scenario to explain the measured low-energy spectrum from the direction of the dark Moon [25] (Fig. 3B), and taking into account the rate derived above (see Eq. (1)), the expected coincidence rate $\mathrm{R}_{\gamma\gamma}$ should be measurable for a modest ($15 \times 15 \times 15$ cm$^3$) fiducial volume:

$$R_{\gamma\gamma} \approx 1.3\ \text{coincidences/d} \cdot (15\ \mathrm{cm})^3 \approx 385\ \text{coincidences/d} \cdot \mathrm{m}^3. \tag{3}$$

We are not aware of any experimental search of this type in the past. Because of the widely accepted extremely long lifetime of the 'standard' axions, such a measurement was obviously considered to be meaningless.

Background: Uncorrelated photons are distributed uniformly over the fiducial volume while the two photons from axion decay will convert at close distance from each other. To get an order of magnitude estimate of the background rate from uncorrelated two-prong events, we take the integral single-prong event rate ($R_{1\mathrm{prong}}$) as measured on the surface in a 1 keV window at 1 keV [54] using a Micromegas chamber [55] of dimensions $15 \times 15 \times 0.3$ cm$^3$:

$$R_{1\mathrm{prong}} \approx 1\ \text{event/s}\ . \tag{4}$$

At these energies, practically all photons entering the chamber sensitive volume interact in the gas, so this rate can be used to obtain the photon flux through the chamber in the same energy interval:

$$\Phi_\gamma = R_{1\mathrm{prong}}/(15\ \mathrm{cm})^2 \approx 0.004/\mathrm{s} \cdot \mathrm{cm}^2\ . \tag{5}$$

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[6] We consider a detector surface [51] $A = 100$ cm$^2$ with an opening angle of $\sim 50°$ orbiting at $\sim 500$ km. Assuming isotropic axion decay, the effective fiducial volume covered by the detector FOV is equal to $\int \frac{2}{4\pi r^2} \cdot A \cdot \cos\theta \mathrm{d}x\mathrm{d}y\mathrm{d}z = \frac{A}{2\pi} \int_0^{2\pi} \mathrm{d}\phi \int_0^{500\ \mathrm{km}} r^2 \cdot \frac{1}{r^2}\mathrm{d}r \cdot \int_{\cos 25°}^{\cos 0°} \cos\theta \cdot \mathrm{d}(\cos\theta)$, which is $\sim 447$ m$^3$ for a dark Earth observation [25] and $\sim 37$ m$^3$ for the dark Moon measurement by ROSAT. $\theta$ is the angle from the normal incidence on the detector surface and the factor of 2 comes from the two photons per axion decay.

If the mean photon absorption length is chosen to be $\sim 0.3$ cm, the $2\gamma$ signal events will occur within a small cell of volume $\Delta x\Delta y\Delta z \sim 1$ cm$^3$. In a chamber of the Micromegas type [55] $\Delta x$ and $\Delta y$ are measured directly by orthogonal electrodes while $\Delta z$ is measured from the time interval between the two signals. In a detector with a sensitive volume of 1 m$^3$ there are $10^6$ cells of volume 1 cm$^3$, hence the rate of two-prong accidental coincidences in such a detector is

$$R_{\mathrm{2prong}} = 10^6\ (\Phi_\gamma)^2 \cdot \Delta t \approx 3 \cdot 10^{-6} \text{ events/s} \approx 0.3 \text{ events/d}\ , \tag{6}$$

where $\Delta t = 0.2\ \mu$s is the drift time over 1 cm, assuming a standard drift velocity of 5 cm/$\mu$s. We note that photons of keV energies entering the chamber will predominantly interact at small distances from the chamber walls. Thus the background rate given by Eq. (6) can be further reduced by requiring that the events occur in a fiducial volume at some distance from the walls. In addition, for non-relativistic axions, the equal energies of the two $\gamma$'s will provide further background rejection. We note that this background varies as the third power of the photon absorption length which actually defines the cell size. It does not seem unrealistic, therefore, to reach an experimentally controllable background from two-prong events at a level well below that given by Eq. (3) for the axion signal.

In order to perform such a measurement, the main detector requirements are a) energy threshold as low as possible, e.g. $\sim$ 10–100 eV, in order not to miss a low-energy axion signal; and b) an adequate space and energy resolution, in order to distinguish the $2\gamma$ events from background, allowing also to implement constraints from the $a \rightarrow \gamma\gamma$ decay kinematics. Our preference is to photons in the sub-keV range, more precisely below $\sim$ 400 eV (see Fig. 3 of this work and the high statistics pulse-height spectra of the soft XRB in Fig. 4 of Refs. [26, 53]). Therefore, a low-density, low-Z X-ray detector should be used. A Micromegas chamber [55] working at low pressure and/or with low-Z gas, e.g. He, appears to be a promising detector for this purpose.

c) **The solar X-ray flux and solar axion density** should be correlated within the predicted axion scenario. The flux $\Phi_x$ of the solar X-rays[7)] and the corresponding axion decay rate X($\mathbf{r}$) are the two input parameters. In order to find this correlation, we choose a reference frame with the Earth at $\mathbf{r}$ = (0,0,0) and the Sun at $\mathbf{r}_\odot$ = (0,0,$d_\odot$), with $d_\odot$ = 1 AU. The density of solar axions in space is defined as

$$\rho_a(\mathbf{r}) = \rho_0 \frac{1}{|\mathbf{r} - \mathbf{r}_\odot|^2} e^{-|\mathbf{r}-\mathbf{r}_\odot|/\lambda} \text{ axions/cm}^3, \tag{7}$$

where $\mathbf{r} \equiv$ (x,y,z) and $\lambda$ is the mean axion decay length. Each space point outside the Sun is then a source of X-rays from axion decay and the production rate is given by

$$\mathrm{X}(\mathbf{r}) \ = \ \frac{2}{\tau} \cdot \rho_a(\mathbf{r}), \tag{8}$$

where $\tau$ is the axion mean lifetime and the factor of 2 comes from the decay $a \rightarrow \gamma\gamma$. Assuming isotropic decay, X($\mathbf{r}$) on Earth has the value given by Eq. (2). The flux $\Phi_x$ of X-rays from axion decays on Earth is then given by

$$\Phi_x = \int \mathrm{X}(\mathbf{r}) \frac{1}{4\pi r^2} \mathrm{d}x \mathrm{d}y \mathrm{d}z, \tag{9}$$

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[7)] The solar X-ray flux on Earth in the favourable energy range at $\sim$ 60–400 eV is $\Phi_x \approx 7 \cdot 10^9$/s·cm$^2$ [49].

where the integral is performed over the detector acceptance, which subtends an angle of $2\alpha = 0.5°$ given by the solar disc at 1 AU. Using polar coordinates and integrating over $\alpha$, it follows that

$$\Phi_x = 1.08 \times 10^{-5} \rho_0 \frac{1}{\tau} \int_0^{d_\odot - R_\odot} \frac{e^{-(d_\odot - r)}/\lambda}{(d_\odot - r)^2} \mathrm{d}r \ , \tag{10}$$

where $R_\odot = 6.96 \cdot 10^{10}$ cm is the solar radius. Finally, the number of $2\gamma$-coincidences from axion decays per second at the site of the Earth inside a detector of volume $V$ is given by

$$R_{\gamma\gamma}(|\mathbf{r}| = 1 \text{ AU}) = \frac{1}{\tau} \frac{\rho_0}{d_\odot^2} \cdot e^{-d_\odot/\lambda} \cdot V \ . \tag{11}$$

Combining Eq. (10) with Eq. (11) it follows that

$$R_{\gamma\gamma} = 9.25 \times 10^4 \cdot \frac{V}{d_\odot^2} \frac{e^{-d_\odot/\lambda}}{\int_0^{d_\odot - R_\odot} \frac{e^{-(d_\odot - r)}/\lambda}{(d_\odot - r)^2} \mathrm{d}r} \cdot \Phi_x \quad . \tag{12}$$

This equation establishes the relation between the flux of X-rays ($\Phi_x$) on Earth from solar axion decays in flight and the rate of $\gamma\gamma$-coincidences ($R_{\gamma\gamma}$) due to axion decays in a detector of volume $V$ on Earth. Figure 4 shows the $2\gamma$-coincidence rate as a function of the axion mean decay length $\lambda$. The rate derived above from the dark Moon direction (Eq. (3)) is consistent with an axion mean decay length of

$$\lambda \approx 0.05 \text{ AU} \ . \tag{13}$$

Such a decay length implies that only axions at the level $2 \cdot 10^{-9}$ survive the flight to the Earth.

We remind that all of these conclusions rely on the assumption of radiative isotropic decay of non-relativistic exotica.

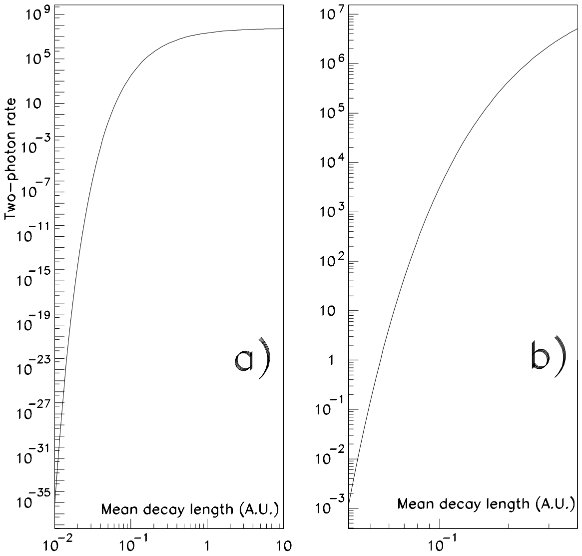

Figure 4: The dependence of the $\gamma\gamma$-coincidence rate per day, i.e. the solar axion decay rate, on the axion mean decay length $\lambda$ for a detector with a sensitive volume of $(15 \text{ cm})^3$ (see also Eqs. (7)–(12)): **a)** $0.01 \leq \lambda \leq 10$ AU, and **b)** $0.04 \leq \lambda \leq 0.4$ AU. From relation (3) it follows that $\lambda = 0.05$ AU.

## 4 WHERE ELSE?

In this section, we shortly mention some additional cases where solar or cosmic axions *could* be involved, in the hope of stimulating a feedback from the experts in the field.

1) The night-time ionization in terrestrial or celestial atmospheres. The measured ionization of the Earth's ionosphere at night is larger than predicted [57], thus requiring an extraterrestrial source of photons in the UV band.
2) Deviation from the heliocentric $1/R^2$ law for (quiet-) Sun X-rays, giving rise to an annual modulation. The direct or indirect observational signature could come from planets, interplanetary missions, comets, etc.
3) Underground experiments with threshold in the sub-keV range: The estimated rate in Eq. (1) translates to a rate of $\sim 1$ event/kg/day/keV. However, we would like to stress here that this rate could be (much) higher, if the photons are emitted in the forward direction.
4) The decay or the emission of radiation by escaping exotica outside the Sun resembles the well-known scattering of (solar) X-rays off electrons or dust particles in interplanetary space (see Fig. 5.1 in Ref. [23]). The same reasoning can apply to similar configurations in remote interstellar space [58] and to extended X-ray sources [50].
5) The huge soft X-ray excess from *Narrow* and *Broad Line Seyfert 1 Galaxies*, below 1 and 0.2 keV, respectively [56]. The remarkable X-ray luminosity is a few $10^{44}$ ergs/s, which is equivalent to $\sim 10^{17}$ solar X-ray luminosities. Also, the observed soft X-ray excess from the Virgo and Coma clusters is of interest [59].
6) Heating of the intergalactic medium, as its origin is not yet clear [60].
7) The X-rays from the centre of our own Galaxy.

## 5 DISCUSSION

In order to explain in a combined way a few important astrophysical observations of as yet unknown origin, we arrive at the conclusion that some new particle(s) must be involved in processes occurring inside and outside stars like our Sun. Among the many hypothetical particles considered so far in dark-matter searches, a not so 'standard' axion, or an axion-like particle with similar couplings, which escapes from the Sun (or other stars in the sky) and decays in outer space, is our first choice. It is worth mentioning that short-lived massive axions have already been discussed in the literature [5], including recent theories with extra dimensions [61], where the two-photon decay mode remains dominant. Such arguments provide theoretical support to our purely observationally/astrophysically motivated claim of celestial axion-like signatures in the $\sim$ sub-keV range, with exciting perspectives to enter a new land in physics.

Alternatively, a radiative decay of massive neutrinos or other hypothetical particles could, in principle, also explain the astrophysical observations considered here. Novel laboratory small-scale experiments, on the surface or underground, can clarify this issue too. We give a (theoretically) unbiased narrow parameter space where to directly search for such exotica. Fortunately, the axion decay to two photons allows to have a very high detection sensitivity, because of the much suppressed uncorrelated two-prong background events within a small distance and narrow time and energy windows. High-performance low-threshold detectors developed primarily for high-energy physics experiments can also be utilized for this kind of astro-particle physics.

Finally, we would like to note that a missing natural explanation of an observation is actually suggestive to search for an exotic approach. The framework of the celebrated dark-matter physics world is the next and natural new alternative source of possible exotic solutions. However, we would like to stress that this axion scenario is not supposed to replace previous related models, but it should be seen rather as complementary, providing a so far missing physics input.

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