

AXION-LIKE PARTICLES AND e-ASTROGAM

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Axion-like particles (ALPs) are neutral and very light pseudo-scalar particles a . They are a generic prediction of many extensions of the Standard Model, especially of those based on superstrings (in a broad sense). They are similar to the axion apart from two features. First, ALPs couple almost only to two photons through $g_{a\gamma} a \mathbf{B} \cdot \mathbf{E}$ (very small couplings to fermions are allowed but here they are discarded because they do not give rise to any interesting effect). Second, the two-photon coupling $g_{a\gamma}$ is totally unrelated to the ALP mass m . Hence, ALPs are described by the Lagrangian

$$\mathcal{L}_{\text{ALP}} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} m^2 a^2 + g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}, \quad (1)$$

where \mathbf{E} and \mathbf{B} denote the electric and magnetic components of the field strength $F^{\mu\nu}$. So, for ALPs the only new thing with respect to the Standard Model is shown in Figure 1.

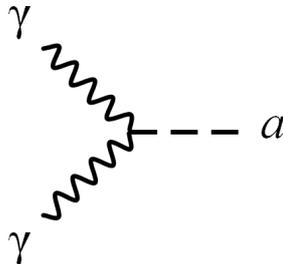


FIG. 1: Photon-photon-ALP vertex.

In spite of the fact that ALPs couple to two-photons, their interaction with both matter and radiation is negligibly small. To see this, consider the Feynman diagram in Figure 2, where f is a generic fermion. Since the cross-section is $\sigma \sim \alpha g_{a\gamma}^2$ we indeed get $\sigma < 10^{-50} \text{ cm}^2$. Moreover, let us address $a\gamma \rightarrow a\gamma$ scattering depicted in Figure 3. Then the cross-section is $\sigma \sim s g_{a\gamma}^4$, and so we find

$$\sigma < 7 \cdot 10^{-69} \left(\frac{s}{\text{GeV}^2} \right) \text{ cm}^2. \quad (2)$$

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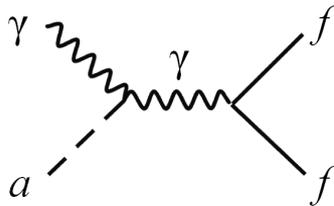


FIG. 2: This Feynman diagram represents the $a\gamma \rightarrow f\bar{f}$ scattering in the s -channel and the $af \rightarrow \gamma f$ scattering in the u -channel.

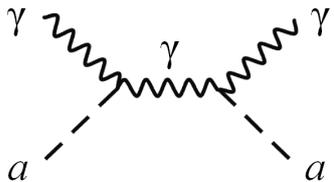


FIG. 3: Feynman diagram for the $a\gamma \rightarrow a\gamma$ scattering.

I. CONVERSION OF PHOTONS INTO AXIONS THROUGH COSMIC PROPAGATION

We will henceforth consider a monochromatic photon beam and assume that an external magnetic field \mathbf{B} is present (in stars the rôle of \mathbf{E} and \mathbf{B} is interchanged, but we shall not be interested in this situation). Hence in $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$ the term \mathbf{E} is the electric field of a beam photon while \mathbf{B} is the external magnetic field. So the mass matrix in the photon-ALP sector is non-diagonal, which implies that $\gamma \rightarrow a$ conversions occur, like the one shown in Figure 4.

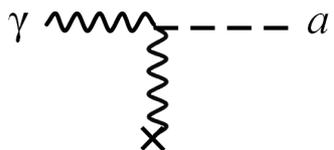


FIG. 4: $\gamma \rightarrow a$ conversion in the external magnetic field \mathbf{B} (in stars the rôle of \mathbf{E} and \mathbf{B} is interchanged).

Of course, also the inverse process $a \rightarrow \gamma$ takes place, and so as the beam propagates several $\gamma \rightarrow a$ and $a \rightarrow \gamma$ transitions occur, like in Figure 5, where a is real. Thus, in the presence of an external \mathbf{B} field photon-ALP *oscillations* $\gamma \leftrightarrow a$ can occur much in the same way as it happens for massive neutrinos of different flavor, apart from the need of an external field in order to compensate for the spin mismatch.

The key-point to detect ALPs with e-ASTROGAM is as follows. Suppose that a distant source emits a γ/a beam of energy E in the range $0.3 \text{ MeV} - 3 \text{ GeV}$ which propagates along the y direction reaching us. In the approximation $E \gg m$ – which is presently valid – the beam propagation equation becomes a Schrödinger-like equation in y , hence the beam is *formally* described as a *3-level quantum system*. Consider now the simplest possible case,

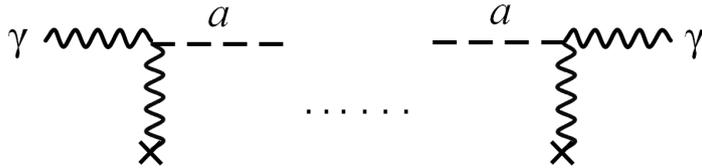


FIG. 5: Schematic view of a photon-ALP oscillation in the external magnetic field \mathbf{B} .

where no photon absorption takes place and \mathbf{B} is homogeneous. Taking \mathbf{B} along the z -axis, we have

$$P_{\gamma \rightarrow a}(E; 0, y) = \left(\frac{g_{a\gamma} B}{\Delta_{\text{osc}}} \right)^2 \sin^2 \left(\frac{\Delta_{\text{osc}} y}{2} \right), \quad \Delta_{\text{osc}} \equiv \left[\left(\frac{m^2 - \omega_{\text{pl}}^2}{2E} \right)^2 + (g_{a\gamma} B)^2 \right]^{1/2}, \quad (3)$$

where ω_{pl} is the plasma frequency of the medium. Defining next $E_* \equiv |m^2 - \omega_{\text{pl}}^2| / (2g_{a\gamma} B)$ it turns out that $P_{\gamma \rightarrow a}(E; 0, y) = 0$ for $E \ll E_*$, $P_{\gamma \rightarrow a}(E; 0, y)$ rapidly oscillates with E for $E \sim E_*$ – this is the *weak-mixing regime* – while $P_{\gamma \rightarrow a}(E; 0, y)$ is maximal and independent of m and E for $E \gg E_*$, which is the *strong-mixing regime*. Actually, the extragalactic magnetic field \mathbf{B} is currently modeled as a domain-like structure with $L_{\text{dom}} = (1 - 10)$ Mpc, $B = (0.1 - 1)$ nG in all domains, but the \mathbf{B} direction changes randomly in any domain: this \mathbf{B} structure is strongly motivated by galactic outflow models, and it turns out to enhance the oscillatory regime around E_* as shown in Figure 6.

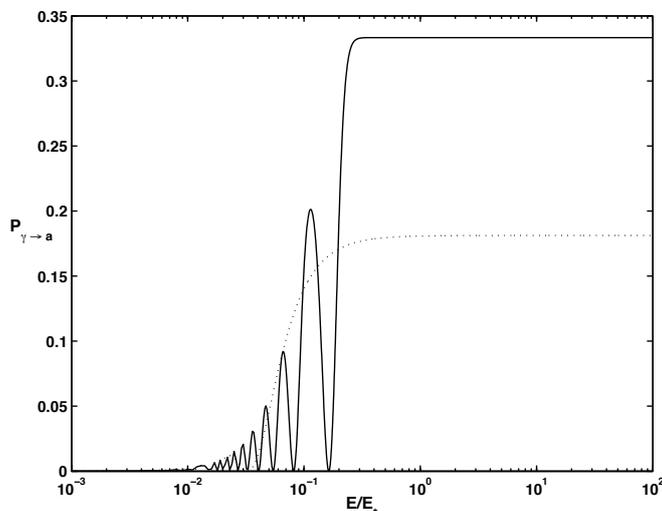


FIG. 6: Oscillatory behavior around E_* for $g_{a\gamma} = 0.33 \cdot 10^{-10} \text{ GeV}^{-1}$, 0.5 nG and $N = 200$ magnetic domains.

We stress that – on top of the above oscillatory behavior – we also have a slight dimming of the signal (De Angelis, Roncadelli and Mansutti 2008, Phys. Lett. B): because of energy conservation, the production of ALP implies a reduced photon flux. Actually, it can be shown that for $N \gg 1$ magnetic domains, the two photon polarization states and the single ALP state undergo equipartition, so that the signal becomes dimmer by a factor of 0.66.

In conclusion, the two features showing up in the energy spectrum due to an ALP are an *oscillatory behavior* and a *dimming of 0.66*.

Yet, this is not the end of the story, because e-ASTROGAM can perform also polarimetric measurements. This is because the coupling $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$ acts as a *polarizer*. It is indeed trivial to see that it entails that only the component \mathbf{B}_T orthogonal to the photon momentum \mathbf{k} matters, and that photons γ_{\perp} with linear polarization orthogonal to the plane defined by \mathbf{k} and \mathbf{B} do not mix with a , but only photons γ_{\parallel} with linear polarization parallel to that plane do (Maiani, Petronzio and Zavattini 1986, Phys. Lett. B). Specifically, two distinct phenomena come about: *birefringence*, namely the change of a linear polarization into an elliptical one with the major axis parallel to the initial polarization, and *dichrois*, namely a selective conversion $\gamma \rightarrow a$ which causes the ellipse's major axis to be misaligned with respect to the initial polarization. Thus, the measure of the polarization of radiation with known initial polarization provides additional information to discriminate an ALP from other possible effects. Very remarkably, we actually do *not need* to know the initial polarization by employing a simple trick. Because when one does not measure the polarization one has to sum over the two final photon polarizations – while when one does measure it no sum is performed – the signal has to be *twice as large* when the polarization is not measure as compared with the case in which the polarization is measured.

Finally, what is the mass range of the ALP that can be probed by e-ASTROGAM? It follows from the previous considerations that the answer is given by $E \sim E_*$. Neglecting ω_{pl} and recalling the second of Eqs. (3), such a condition becomes

$$E \sim \frac{m^2}{2g_{a\gamma} B}, \quad (4)$$

Owing on the energy range of e-ASTROGAM, from Eq. (4) we have

$$0.3 \text{ MeV} < \frac{m^2}{2g_{a\gamma} B} < 3 \text{ GeV}. \quad (5)$$

Taking e.g. $g_{a\gamma} = 0.33 \cdot 10^{-10} \text{ GeV}^{-1}$ and $B = 0.5 \text{ nG}$ the answer is

$$1.7 \cdot 10^{-13} \text{ eV} < m < 1.7 \cdot 10^{-11} \text{ eV}. \quad (6)$$

More generally, by employing the parametrizations $g_{a\gamma} = \alpha 10^{-10} \text{ GeV}^{-1}$ and $B = \beta \text{ nG}$, we get (independent of N)

$$1.1 \cdot 10^{-12} \alpha \beta \text{ eV} < m < 1.1 \cdot 10^{-10} \alpha \beta \text{ eV}. \quad (7)$$

II. AXION-LIKE PARTICLES FROM FROM SUPERNOVAE

ALPs are produced in the core of stars (like the Sun) through the Primakoff process in the Coulomb field \mathbf{E} of ionized matter, illustrated in Figure 4. The CAST experiment at CERN was looking at the Sun and found nothing, thereby deriving $g_{a\gamma} < 0.88 \cdot 10^{-10} \text{ GeV}^{-1}$. Recent analysis of globular clusters gives $g_{a\gamma} < 0.66 \cdot 10^{-10} \text{ GeV}^{-1}$ (PDG 2016). They can also be produced in at the centre of core-collapse (Type II) supernovae soon after the bounce (when also the neutrino burst is produced) by Primakoff effect and reconverted to photons of the same energy, during their travel or in the Milky Way. The arrival time of these photons would be the same as for neutrinos, providing a clear signature.

Integrated over the explosion time, which is of the order of 10 s, the Authors of (Meyer, Giannotti, Mirizzi, Conrad, Sanchez-Conde, Phys. Rev. Lett. 2017) find that the ALP spectrum can be parametrized by a power law with exponential cutoff,

$$\frac{dN_a}{dE} = C \left(\frac{g_{a\gamma}}{10^{-11} \text{GeV}^{-1}} \right)^2 \left(\frac{E}{E_0} \right)^\beta \exp \left(-\frac{(\beta+1)E}{E_0} \right) \quad (8)$$

with C , E_0 , and β given in Tab. I.

Progenitor mass	C [10^{50}MeV^{-1}]	E_0 [MeV]	β
$10 M_\odot$	5.32	94	2.12
$18 M_\odot$	9.31	102	2.25

TABLE I: Best fitting values for the parameters in Eq. (8).

The ALP energy spectrum (which corresponds to the photon energy spectrum after re-conversion to gamma-rays) is shown in Figure 7. The bulk is below ~ 100 MeV, which clearly shows the potential of e-ASTROGAM for a possible detection. e-ASTROGAM would have a sensitivity better than Fermi-LAT and access to much smaller mass/coupling values than dedicated laboratory experiments.

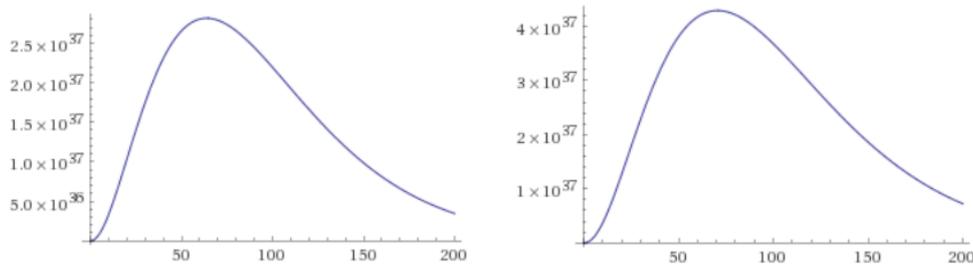


FIG. 7: The differential axion rate from the supernova, $dN_a/dE(\text{GeV}^{-1})$, for a SN of 10 (left) and 18 (right) solar masses. The abscissa is in MeV.