Eur. Phys. J. C 52, 899–904 (2007)
DOI 10.1140/epjc/s10052-007-0414-4

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article – Experimental Physics

Searching for energetic cosmic axions in a laboratory experiment

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Received: 21 June 2007 / Revised version: 7 August 2007 /
Published online: 9 October 2007 –

Abstract. Astrophysical sources of energetic gamma rays provide the right conditions for maximal mixing between (pseudo)scalar (axion-like) particles and photons if their coupling is strong enough. This is independent of whether or not the axion interaction is standard at all energies or becomes suppressed in the extreme conditions of the stellar interior. The flux of such particles through the Earth could be observed using a metre long, Tesla strength superconducting solenoid. The rate of events in CAST caused by axions from the Crab pulsar is also estimated.

PACS. 14.80.Mz; 98.70.Rz; 95.85.Ry

Recently, the interest in axion-like particles has been reignited due to the PVLAS experiment reporting an observation of a rotation of the plane of polarization of a laser beam passing through a magnetic field [1] which was claimed to be compatible with the existence of a new (pseudo)scalar particle with a mass of $m \sim 10^{-3}$ eV and an inverse coupling to the photon of $M \sim 10^5$ GeV. This was unexpected since experiments such as CAST [2] have seemingly ruled out this region of parameter space. Attempts to explain this discrepancy resulted in alternative models for the pseudoscalar in which its effective coupling to photons is suppressed in the relatively extreme conditions of the stellar interior [3–12]. Alternative explanations of the effect by means of particles carrying very small electric charge [13, 14] were disfavoured [15] by preliminary PVLAS data and severely constrained by existing limits on the millicharged particles [16, 17]. Though the original results are not supported by further PVLAS studies [18] (see also early discussion in [19]), the theoretical work has demonstrated that an axion with such a strong coupling to the photon may be consistent with the CAST limits, provided the coupling is somehow suppressed at high temperature (such scenarios also depend on uncertainties in the model of the solar interior in parameters such as the magnetic field). More model-independent tests both in laboratory experiments [15, 20–22] and in gamma-ray astronomy [23–26] have been proposed. Here we suggest that if new axion-like particles exist which have a strong coupling to two photons, there should be a flux of these particles through the Earth coming from conversion of energetic gamma-rays emitted by astrophysical sources to axions in the magnetic fields of the sources themselves. Since the conditions (temperature, density and average momentum transfer) in such typical sources are much closer to those in the laboratory rather than the stellar interior, such a flux would be compatible with CAST limits and with bounds from stellar astrophysics. We argue that this flux can be detected in a laboratory experiment by using a superconducting solenoid surrounded by an electromagnetic calorimeter.

For definiteness, let us consider the Lagrangian density of the photon-pseudoscalar system,[1]

$$\mathcal{L} = \frac{1}{2}\left(\partial^\mu a \partial_\mu a - m^2 a^2\right) - \frac{1}{4}\frac{a}{M} F_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} ,$$

where $F_{\mu\nu}$ is the electromagnetic stress tensor and $\widetilde{F}_{\mu\nu} = \epsilon_{\mu\nu\rho\lambda} F_{\rho\lambda}$ its dual, a the pseudoscalar (axion) field, m the axion mass and M is its inverse coupling to the photon field. The coupling of the photon and pseudoscalar fields in this way means that a photon has a finite probability of mixing with its opposite polarisation and with the pseudoscalar in the presence of an external magnetic field [27–32]. The probability of the $a \to \gamma$ oscillation after traveling the distance L in the constant magnetic field with

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[1] The consideration and quantitative results for a scalar particle are similar, though other effects may be important in that case.

perpendicular component B is

$$P = \frac{4\Delta_M^2}{(\Delta_p - \Delta_m)^2 + 4\Delta_M^2} \sin^2\left(\frac{1}{2} L \Delta_{\rm osc}\right) ,$$

where

$$\Delta_M = \frac{B}{2M} = 7\times 10^{-7} \left(\frac{B}{4\,{\rm T}}\right)\left(\frac{10^5\,{\rm GeV}}{M}\right)\,{\rm cm}^{-1} ,$$
$$\Delta_m = \frac{m^2}{2\omega} = 2.5\times 10^{-11}\left(\frac{m}{10^{-3}\,{\rm eV}}\right)^2\left(\frac{1\,{\rm GeV}}{\omega}\right)\,{\rm cm}^{-1} ,$$
$$\Delta_p = \frac{2\pi\alpha n_{\rm e}}{\omega m_{\rm e}} = 3.6\times 10^{-4}\left(\frac{n_{\rm e}}{10^{22}\,{\rm cm}^{-3}}\right)\left(\frac{1\,{\rm GeV}}{\omega}\right)\,{\rm cm}^{-1} ,$$
$$\Delta_{\rm osc}^2 = (\Delta_p - \Delta_m)^2 + 4\Delta_M^2 ,$$

$n_{\rm e}$ is the electron density, $m_{\rm e}$ is the electron mass, α is the fine-structure constant and ω is the photon (axion) energy.

The discussion of [25], based upon the Hillas plot presented there, suggests that for the parameters $M \sim 10^5$ GeV and $m \sim 10^{-3}$ eV, the maximal mixing between photons and axions takes place inside the source for most of the astrophysical objects which emit gamma rays. This fact does not depend on details of the emission mechanism and on the models of the source; it is based entirely on the information about the geometrical size of the objects and the magnetic fields in their outer regions, obtained from astronomical observations. This maximal mixing means that if the flux F_γ of gamma rays is detected from the source, it should be inevitably accompanied by a flux $F_{\rm a} = F_\gamma/2$ of axions of the same energy, if such strongly coupled axions exist (the factor 1/2 is due to complete mixing between two photon and one axion polarizations).

Let us concentrate first on the gamma rays with energies $E \gtrsim 10$ keV and estimate the contribution of various astrophysical sources to the axion flux. The signal at these energies would be dominated by pulsars and gamma-ray bursts since other sources, e.g. active galactic nuclei, contribute only at high energies ($E \gtrsim 10$ MeV) where fluxes are too low to be detected in a realistic experiment of the type we discuss.

Pulsars. For a typical magnetosphere of a neutron star we assume the magnetic field $B \sim 10^{13}$ G at lengths $L \sim 10$ km. Due to such extreme magnetic fields, the conditions for maximal mixing would be fulfilled at energies as low as $E \gtrsim 10^{-4}$ eV. To estimate the fluxes of axion like particles at $E \gtrsim 100$ MeV, we use EGRET data [33]; there are five pulsars detected which emit such hard gamma rays (see Table 1). The spectral index α is determined as

$$\frac{{\rm d}N}{{\rm d}E} \propto E^{-\alpha} ,$$

where ${\rm d}N/{\rm d}E$ is the flux and $100\,{\rm MeV} \le E \le 10\,{\rm GeV}$ is the photon energy.

The fluxes of these five objects at lower energies were extrapolated from 100 MeV down using the spectrum of the Crab pulsar (see e.g. Fig. 5 of [34] from which we find $\alpha \approx 2.35$ for $100\,{\rm keV} \le E \le 100\,{\rm MeV}$).

Table 1. Five EGRET pulsars

Name	Flux at $E > 100$ MeV, 10^{-8} photons/cm^2/s	Spectral index α
Crab	226	2.19
Vela	834	1.69
Geminga	353	1.66
1055-52	33	1.94
1706-44	112	1.86

The contribution of other pulsars, important at soft gamma-ray energies only, was estimated with the help of the INTEGRAL reference catalog [35]. In that reference, the sources' spectra are classified in different ways. The three relevant spectral models are the following:

WP ("wabs powerlaw"):

$$S(E) = w(E) A \left(\frac{E}{E_0}\right)^\Gamma ,$$

for $\Gamma = 2$.

WHP ("wabs highcut powerlaw"):

$$S(E) = w(E) A \left(\frac{E}{E_0}\right)^\Gamma \begin{cases} \exp\left(\frac{E_{\rm cut} - E}{E_{\rm fold}}\right), & E > E_{\rm cut} ; \\ 1, & E < E_{\rm cut} , \end{cases}$$

for $\Gamma = 1$, $E_{\rm cut} = 10$ keV, $E_{\rm fold} = 15$ keV.

WC ("wabs cutoff"):

$$S(E) = w(E) A \left(\frac{E}{E_0}\right)^\Gamma e^{-E/E_{\rm cut}} ,$$

for $\Gamma = 1.7$, $E_{\rm cut} = 10$ keV.

For all models, $w(E)$ is the galactic absorption factor which is negligible at the level of approximations made in this paper and hence we set it equal to unity within our precision, $S(E)$ is the spectral energy distribution and A is given in Table 2, where these pulsars are listed, for $E_0 = 1$ keV.

Table 2. Pulsars from [35] except for those listed in Table 1 and one giving negligible contribution

Name	Model	A, photons/cm^2/keV
AX J0051-722	WHP	4.17×10^{-3}
RX J0052.1-7319	WHP	3.85×10^{-5}
SMC X-2	WHP	4.30×10^{-3}
AX J0058-720	WHP	1.69×10^{-4}
RX J0059.2-7138	WHP	2.58×10^{-2}
AX J0103-722	WHP	6.51×10^{-5}
AX J0105-722	WHP	1.60×10^{-4}
PSR B0628-28	WC	5.01×10^{-2}
PSR B0656+14	WP	1.59×10^{-3}
PSR B1509-58	WP	3.64×10^{-1}
AX J1740.2-2848	WHP	1.70×10^{-4}
PSR J1844-0258	WHP	1.60×10^{-3}
PSR B1951+32	WP	2.75×10^{-2}

Gamma-ray bursts. The magnetic field in a gamma-ray burst (GRB) is $B \sim 10^9$ G in a region of $L \sim 10^7$ m, so the resonant mixing happens for $E \gtrsim 1$ eV. As an approximation we suppose that all GRBs have the same spectra which differ only by the peak fluxes. A useful compilation of models for the GRB fluxes may be found in [36]. For the spectral energy distribution of a GRB, we use the band function [37]:

$$B(E) = \begin{cases} \bar{A}\left(\frac{E}{100\,\text{keV}}\right)^{\alpha} \exp\left[-(2+\alpha)\frac{E}{E_{\text{peak}}}\right], \\ \quad \text{if} \quad E < E_{\text{break}} \equiv \frac{\alpha-\beta}{2+\alpha} E_{\text{peak}}, \\ \bar{A}\left(\frac{E}{100\,\text{keV}}\right)^{\beta} e^{\beta-\alpha}\left[\frac{\alpha-\beta}{2+\alpha}\frac{E_{\text{peak}}}{100\,\text{keV}}\right]^{\alpha-\beta} \\ \quad \text{if} \quad E > E_{\text{break}} \end{cases} .$$

We use the mean values of parameters seen by BATSE as given in [38]:

$$\alpha = -1\,;$$
$$\beta = -2.25\,;$$
$$E_{\text{break}} = 250\,\text{keV}\,.$$

$\bar{A} \approx 0.01\,\text{keV}^{-1}$ normalizes the band function to one, $\int_{50\,\text{keV}}^{300\,\text{keV}} B(E)\,\mathrm{d}E = 1$.

To determine the dimensionful coefficient in front of the Band function, we need to sum up the intensities of all GRBs for a given period of time. We use the distribution of the peak count rates of BATSE bursts from [39]. The data used is for the energy band between 50 keV and 300 keV, that is why we took this band in the normalisation. We performed the integration of the histogram in Fig. 23 of [39] and obtained approximately 10^5 photons/cm^2/s/year for the sum of peak count rates of all BATSE-detected bursts. The peak count rate is 0.75 times the peak flux [39]. We have to correct also for the BATSE exposure (GRBs which happened when BATSE did not look at that part of the sky). According to [40], the exposure correction for 50–300 keV is 0.480.

Finally, we have to relate the peak count rate and the total energy of a GRB. To this end, we use the temporal development of the spectrum. A universal parametrisation for it reads [41, 42]:

$$I(t,E) = A \begin{cases} \exp\left[-\left(\frac{|t-t_0|}{\sigma_r(E)}\right)^{\nu}\right], & t \le t_0; \\ \exp\left[-\left(\frac{|t-t_0|}{\sigma_d(E)}\right)^{\nu}\right], & t > t_0, \end{cases}$$

where

$$\sigma_d(E) = 0.75(\ln 2)^{-1/\nu} W_0 \left(\frac{E}{20\,\text{keV}}\right)^{-0.4},$$

$$\sigma_d(E) = 0.25(\ln 2)^{-1/\nu} W_0 \left(\frac{E}{20\,\text{keV}}\right)^{-0.4},$$

and we use mean values of parameters: peakedness $\nu = 1.44$ and full width at half-maximum of the pulse $W_0 = 0.8$ s. The dimensionality of A is photons/cm^2/s. Note that the band function $B(E)$ gives the spectrum integrated over time, while at each moment, the flux per unit time per unit energy is $I(t,E)B_1(E)$, where $B_1(E)$ is the same Band function but with different parameters, $\alpha_1 = \alpha + 0.4$, $\beta_1 = \beta + 0.4$. The peak flux is given by

$$\text{Peak flux} = \int_{50\,\text{keV}}^{300\,\text{keV}} I(t,E)B_1(E)\,\mathrm{d}E\Bigg|_{t=t_0} = A\,.$$

To relate A to the coefficient in the integral spectrum, we integrate the flux over time (the dimensionality of the following equation is photons/cm^2/keV):

$$\int_0^{\infty} \mathrm{d}t I(t,E)B_1(E) = A_0 B(E)\,,$$

where

$$A_0 = A(\ln 2)^{-1/\nu} W_0 \left(\frac{100\,\text{keV}}{20\,\text{keV}}\right)^{-0.4} \int_0^{\infty} e^{-x^{\nu}}\,\mathrm{d}x\,.$$

We finally obtain the spectrum of our typical GRB with peak count rate P as

$$0.66 \frac{P}{\text{photons/cm}^2\text{/s}} B(E) \frac{\text{photons}}{\text{cm}^2\,\text{keV}}\,.$$

In our assumption that all GRBs have the same spectra up to P, the total flux is obtained by taking $P = 10^5$ photons/cm^2/s/year and dividing by the exposure factor, which results in the contribution of all GRBs of

$$4.4 \times 10^{-3} B(E) \frac{\text{photons}}{\text{cm}^2\,\text{s}\,\text{keV}}\,.$$

The total expected flux of astrophysical axions from pulsars and GRBs is plotted, as a function of energy, in Fig. 1.

Let us now consider possible ways in which these axion-like particles (a) could be detected in a laboratory experiment. One of the ideas of detection proposed a long time ago [43] for searching of solar axions is the following. If a is a long-lived particle, the flux of energetic a's would penetrate the Earth atmosphere without significant attenuation and would be observed in a detector via the inverse Primakoff effect, namely in the process of interaction of

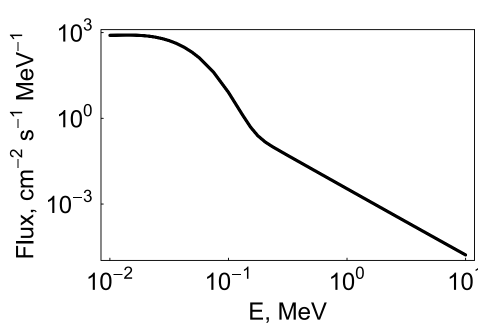

Fig. 1. Expected axion flux from all astrophysical sources versus energy

(pseudo)scalars with virtual photons from the static magnetic field of a superconducting magnet. An example of this kind of experiment on high-energy axion-photon conversion may be found in [44, 45].

The sketch of the experiment we propose is shown in Fig. 2. The main design feature of the detector is the presence of a volume V of a high ($\simeq 1$ T) magnetic field B with its internal surface covered with an electromagnetic calorimeter (ECAL) and surrounded by a VETO detector. The ECAL detects photons with energy $E_\gamma \gtrsim 10$ keV. The VETO serves for efficient suppression of environmental and cosmic backgrounds. The experimental signature of $a \to \gamma$ conversion is a single energetic photon detected in the ECAL (either through the photo electric effect or through Compton scattering) which will not be accompanied by any energy deposition in the VETO detector. Since the conversion happens due to the presence of the magnetic field, one could also search for it in the detector by comparing event rates in the ECAL taken with and without the magnetic field.

The statistical limit on the sensitivity of the experiment searching for cosmic $a \to \gamma$ conversion scales roughly as $B^2 V$ [43]. Thus, to improve the sensitivity, large volume and strong magnetic field are required. Since the gamma-ray (and potential axion) spectra from the astrophysical objects are steep, see Fig. 1, the detection of low-energy recoil electrons in the ECAL is also crucial for the improvement of the sensitivity of the search. As an example, Fig. 3 presents the number of events per year as a function of the detection energy threshold in a detector of 1 m length and 1 m radius filled with 1 T magnetic field. The signal in such a detector will be optimised not for maximal mixing, as the mixing length in that situation will be much larger than the size of the detector. The presence of a non-zero electron density allow one to tune the mixing length so that the probability is increased, despite the fact that the mixing angle will be reduced. It is seen that at lower energies one expects thousands of events. Note that the majority of axions at these energies arrives from pulsars; as is seen from Tables 1 and 2, there are only a few strong sources among them, hence the background might be reduced if the gamma direction can be determined. In any case, such matters would have to be considered in detail if one had to choose the actual orientation of the detector.

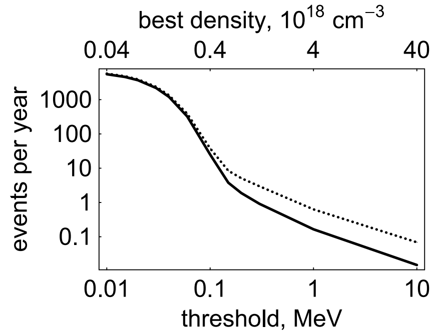

Fig. 3. Number of events per year versus energy threshold in a cylinder of 1 m length, 1 m radius permeated by a 1 T magnetic field. The *lower curve* assumes zero electron density inside the detector while the *upper curve* assumes an electron density chosen to bring the mixing length down to the size of the detector (shown above the plot)

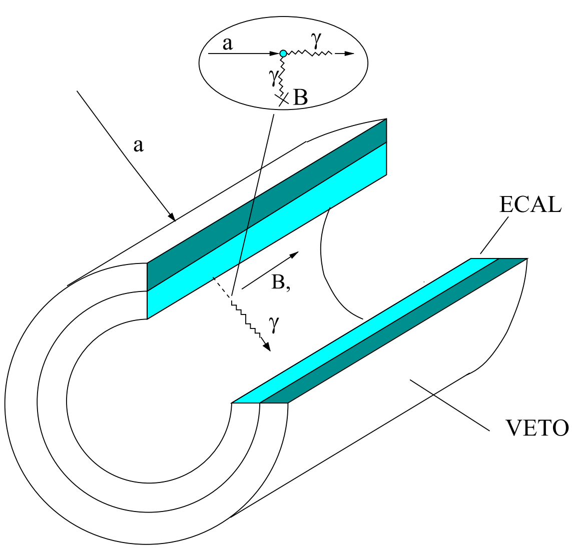

Fig. 2. Schematic layout of the high energy cosmic axion experiment. The main elements of the setup relevant for the axion search are illustrated

A possible approach which could satisfy the requirements discussed above is to use a massive liquid argon time projection chamber (TPC) as the ECAL. The external region of the chamber could also be used as the VETO. An example of such a detector is the one being developed in the framework of the ArDM project for the search of the Dark Matter [46, 47]. This experiment is designed to run with an effective target mass of almost 1 t and is capable of measuring energy depositions as low as 10 keV.

The first results from a liquid argon TPC in a magnetic field look quite promising [48]. A small liquid argon time projection chamber (LAr TPC) was operated for the first time in a magnetic field of 0.55 T. The imaging properties of the detector were not affected by the magnetic field. In a test run with cosmic rays, a sample of through going and stopping muons was collected. The chamber with the readout electronics and the experimental setup are described in [48], where examples of reconstructed and analyzed events are presented.

The significance of the a-particles discovery with the proposed detector scales as [49, 50]:

$$S = 2(\sqrt{n_\mathrm{s} + n_\mathrm{b}} - \sqrt{n_\mathrm{b}}) \simeq n_\mathrm{s}/\sqrt{n_\mathrm{b}}\,,$$

where n_s and n_b are the number of detected signal and background events, respectively. Thus, assuming the value $M \sim 10^5$ GeV for the axion-photon coupling, requiring that $S \gtrsim 3$ and assuming $n_\mathrm{s} \simeq 10^2$ at the ECAL energy threshold $\simeq 0.1$ MeV (see Fig. 3) a background level of $n_\mathrm{b} \lesssim 3$ event/day has to be achieved, which seems to be quite realistic [46, 47].

One of the main sources of the background to $a \to \gamma$ events in the proposed experiment is expected from the neutrino processes with a significant electromagnetic component in the final state and with no significant energy deposition in the VETO. The expected amount of neutrino background events can be evaluated using Monte Carlo simulations. Assuming a total mass of the active part of the detector to be $\simeq 1\,\mathrm{t}$, the neutrino background is estimated to be $n_\mathrm{b} \lesssim 1$ event/day. Note that the above considerations give the correct order of magnitude for the sensitivity of the proposed experiment and may be strengthened and extended to the low recoil energy $E \gtrsim 10\,\mathrm{keV}$ by more accurate and detailed Monte Carlo simulations.

Let us turn now to the lower energies. As it has been pointed out above, pulsars provide necessary conditions for maximal axion-photon mixing at $E \gtrsim 1\,\mathrm{eV}$. We note that, assuming the above mentioned mass and couplings, keV-energy axions should be detected by CAST if it is pointed to the Crab pulsar. Such pointing was indeed performed [51] but the study has not yet been published. Given the Crab pulsar flux of about $2\,\mathrm{photons/cm^2/s}$ in the energy interval $1\,\mathrm{keV} \lesssim E \lesssim 14\,\mathrm{keV}$ [34], one expects (for these choices of M and m) ~ 0.05 events per 24 h of observation by CAST (to be compared with ~ 7 events expected – and not observed – from the Sun for the *minimal* axion model with $M \sim 10^{10}$ GeV). This flux can be tested by the experiment on the time scale of a year, given 3 h of pointing per day. Other pulsars have much lower fluxes and give negligible contributions.

To summarize, the presence of an axion-like particle with strong coupling to photons, no matter what kind of interactions it has in the extreme conditions (e.g. inside the Sun), can be tested with dedicated experiments using particle-physics detectors of meter-scale size and Tesla-scale magnetic fields. At $E \gtrsim 100\,\mathrm{keV}$, several dosen events per year are expected in a $\sim 1\,\mathrm{m}^3$, $\sim 1\,\mathrm{T}$ detector. At the energies of a few keV, CAST (properly pointed) may detect about one event from the Crab pulsar per ~ 480 h observational time.

Acknowledgements. We are grateful for discussions with V. Kuzmin, S. Popov, V. Rubakov, S. Sibiryakov, B. Stern, I. Tkachev and K. Zioutas. This work was supported in part by the Swedish Research Council (Vetenskapsrå det) and the Perimeter Institute (MF), by the Marie Curie Incoming International Fellowship of the EC, RFBR grant 04-02-16386 and the RAS Program "Solar activity" (TR), by the Russian Science Support Foundation fellowship, grants INTAS 03-51-5112, RFBR 07-02-00820 and NS-7293.2006.2 (ST), by the RFBR grant 07-02-00256 (NK). SG and ST thank ETH and CERN, respectively, for hospitality and support at the initial stages of the work.

References

1. PVLAS Collaboration, E. Zavattini et al., Phys. Rev. Lett. **96**, 110 406 (2006)
2. CAST Collaboration, S. Andriamonje et al., JCAP **0702**, 010 (2007)
3. E. Masso, J. Redondo, JCAP **0509**, 015 (2005)
4. E. Masso, Phys. Rev. Lett. **97**, 151 802 (2006)
5. M. Chaichian, M.M. Sheikh-Jabbari, A. Tureanu, hep-ph/0511323
6. P. Jain, S. Mandal, Int. J. Mod. Phys. D **15**, 2095 (2006)
7. I. Antoniadis, A. Boyarsky, O. Ruchayskiy, hep-ph/0606306
8. R.N. Mohapatra, S. Nasri, Phys. Rev. Lett. **98**, 050 402 (2007)
9. J. Jaeckel, E. Masso, J. Redondo, A. Ringwald, F. Takahashi, Phys. Rev. D **75**, 013 004 (2007)
10. P. Jain, S. Stokes, arXiv:hep-ph/0611006
11. J.A. Beswick, C. Rizzo, arXiv:quant-ph/0702128
12. P. Brax, C. van de Bruck, A.C. Davis, arXiv:hep-ph/0703243
13. H. Gies, J. Jaeckel, A. Ringwald, Phys. Rev. Lett. **97**, 140 402 (2006)
14. S.A. Abel et al., arXiv:hep-ph/0608248
15. M. Ahlers, H. Gies, J. Jaeckel, A. Ringwald, Phys. Rev. D **75**, 035 011 (2007)
16. A. Melchiorri, A. Polosa, A. Strumia, arXiv:hep-ph/0703144
17. see also S.N. Gninenko, N.V. Krasnikov, A. Rubbia, Phys. Rev. D **75**, 075 014 (2007)
18. PVLAS Collaboration, E. Zavattini et al., arXiv:0706.3419 [hep-ex]
19. A.C. Melissinos, arXiv:hep-ph/0702135
20. R. Rabadan, A. Ringwald, K. Sigurdson, Phys. Rev. Lett. **96**, 110 407 (2006)
21. K. Ehret et al., arXiv:hep-ex/0702023
22. E. Gabrielli, M. Giovannini, arXiv:hep-ph/0702197
23. A. Dupays et al., Phys. Rev. Lett. **95**, 211 302 (2005)
24. H. Davoudiasl, P. Huber, Phys. Rev. Lett. **97**, 141 302 (2006)
25. M. Fairbairn, T. Rashba, S. Troitsky, Phys. Rev. Lett. **98**, 201 801 (2007)
26. A. Mirizzi, G.G. Raffelt, P.D. Serpico, arXiv:0704.3044 [astro-ph]
27. D.A. Dicus et al., Phys. Rev. D **18**, 1829 (1978)
28. P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983)
29. P. Sikivie, Phys. Rev. Lett. **52**, 695 (1984) [Erratum]
30. P. Sikivie, Phys. Rev. D **32**, 2988 (1985)
31. P. Sikivie, Phys. Rev. D **36**, 974 (1987) [Erratum]
32. G. Raffelt, L. Stodolsky, Phys. Rev. D **37**, 1237 (1988)
33. R.C. Hartman et al., Astrophys. J. Suppl. **123**, 79 (1999)
34. R. Campana et al., arXiv:astro-ph/0701253 (and references therein)
35. K. Ebisawa et al., Astron. Astrophys. **411**, L59 (2003)
36. http://glast.pi.infn.it/Nikola/GRB_Phen/GRB_Phen.html
37. D. Band et al., Astrophys. J. **413**, 281 (1993)
38. R.D. Preece et al., Astrophys. J. Suppl. **126**, 19 (2000)
39. B.E. Stern et al., Astrophys. J. **563**, 80 (2001)
40. W.S. Paciesas et al., Astrophys. J. Suppl. **122**, 465 (1999)
41. E.E. Fenimore et al., Astrophys. J. Lett. **448**, 101 (1995)
42. J.P. Norris et al., Astrophys. J. **459**, 393 (1996)
43. K. van Bibber, P.M. McIntyre, D.E. Morris, G.G. Raffelt, Phys. Rev. D **39**, 2089 (1989)
44. NOMAD Collaboration, P. Astier et al., Phys. Lett. B **479**, 371 (2000)
45. S.N. Gninenko, Nucl. Phys. Proc. Suppl. **87**, 105 (2000)
46. A. Rubbia, J. Phys.: Conf. Ser. **39**, 129 (2006)

47. L. Kaufmann, A. Rubbia, J. Phys.: Conf. Ser. **60**, 264 (2007)
48. A. Badertscher et al., Nucl. Instrum. Methods A **555**, 294 (2005)
49. S.I. Bityukov, N.V. Krasnikov, Mod. Phys. Lett. A **13**, 3235 (1998)
50. S.I. Bityukov, N.V. Krasnikov, arXiv:hep-ph/0204326
51. K. Zioutas, CAST FRC-D 2003-05