Summaries of the talks presented at the "1st Axion Strategy Meeting: brainstorming and discussion on future axion searches" held at CERN on Jan. 27th, 2009

This documents collects the short summaries provided by the speakers who have contributed to the success of the "1st Axion Strategy Meeting" organized by the CAST collaboration and held at CERN on January 27th, 2009. The purpose of the meeting was to provide a round table environment for the community of physicists, both theorists and experimentalists, working in axion, and more generally in WISP physics, to freely float ideas and informally discuss them with colleagues.
Each speaker kindly agreed to summarize his contribution in a short write-up to serve as a memory aid for future strategy meetings.

List of the material included

P. Brax (IPHT-CEA Saclay)	"Evading the CAST bound with chameleons"
G. Cantatore (Univ. and INFN Trieste)	"ALP detection via resonant regeneration at CAST"
S.N. Gninenko (INR Moscow)	"On search for eV hidden sector photons"
H.S. Hudson (SSL, UC Berkeley)	"Solar X-ray observations of solar axions"
A. Lindner (DESY Hamburg)	"Ultra-Light Particles beyond the Standard Model: laboratory experiments"
T. Papaevangelou (Saclay)	"New prospects for CAST from the new Microbulk performance"
J. Redondo (DESY Hamburg)	"A map of the low energy frontier: WISP opportunities beyond QCD axions"
S. Troitsky (INR Moscow)	"Astrophysical motivations for axion-like particles"

Motivated by the dark energy issue, i.e. the evidence in favour a period of acceleration in the recent past of the universe, I have presented quintessence models which do not have gravitational problems and might have consequences for Cast-type experiments, optical measurements of birefringence and the Casimir effect.

Quintessence models postulate the existence of a scalar field ϕ whose rolling along a runaway potential of the form

$$V(\phi) = \frac{M^{4+n}}{\phi^n} \tag{1}$$

would lead to the acceleration of the universe. These potentials have the property that there is an attractor behaviour which implies that the long time physics is independent of the initial conditions. The dynamics drive $\phi_{\text{now}} \sim m_{\text{Pl}}$ now which implies that M must be chosen in such a way that $V(\phi_{\text{now}}) = \Omega_\Lambda \rho_c$. Unfortunately the mass of the scalar field now is of order $m_\phi \sim H_0 \sim 10^{-33}$ eV. This is so small that a coupling of the scalar field to matter would lead to violations of Newton's law and the presence of a fifth force. Fortunately this can avoided if the scalar field couples to gravity in such a way that Newton's constant becomes

$$G_N(\phi) = e^{2\beta\phi/m_{\text{Pl}}} G_N \tag{2}$$

In this case, the dynamics of the scalar field are governed by an effective potential in the presence of matter

$$V_{\text{eff}}(\phi) = V(\phi) + e^{\beta\phi/m_{\text{Pl}}}\rho \tag{3}$$

where ρ is the matter density surrounding the scalar field. The effective potential has a density-dependent minimum where the mass of the scalar field becomes also density dependent. For this reason, the scalar field has been called a chameleon. The main advantage of this new coupling to gravity resides in the fact that in a dense environment, the mass is such that the range of the force mediated by the scalar field becomes smaller that 0.1 mm and is therefore undetectable. In a sparse environment with very dense matter bodies such as in the solar system, the chameleon interaction is screened due to another effect called the thin shell mechanism. All in all, chameleons evade the tight gravitational tests and can generate the acceleration of the universe.

Of course, it would be extremely interesting to predict laboratory effects for such particles. A host of laboratory consequences can be obtained if the scalar field couples to electromagnetism as

$$S_{\text{QED}} = \int d^4x \sqrt{-g} \frac{e^{\phi/M_\gamma}}{\alpha^2_{\text{QED}}} F_{\mu\nu} F^{\mu\nu} \tag{4}$$

Notice the similarity with the axion coupling although here we have a coupling to $E^2 - B^2$ and not $E.B$ in the Lagrangian. This coupling when $\phi \ll m_{\text{Pl}}$ leads to a triple interaction between one chameleon and two photons. This would lead to the creation of chameleons in the sun via the Primakoff effect and then the possibility of detecting them with the CAST experiment. This is particularly acute if $M_\gamma \leq 10^{11}$ GeV. Fortunately, even in this range, the chameleon is massive enough in the sun to avoid any production. Hence chameleons could have a low coupling scale M_γ. The negative results of the PVLAS experiment give us a bound on the coupling $M_\gamma \geq 10^6$ GeV. In the range between 10^6 and 10^{11} GeV, chameleon could lead to detectable effects for future measurements of the ellipcity in PVLAS-type experiments. We have performed this analysis and shown that, for $M_\gamma \leq 10^8$ GeV, the ellipticity could be detected by the BMV experiment.

In conclusion, chameleons could lead to the acceleration of the universe, evade gravitational tests and could be detectable by laboratory experiments.

ALP detection via resonant regeneration at CAST

G. Cantatore
University and INFN Trieste

Abstract

The introduction of the resonant regeneration idea brings into the realm of the possible for a laboratory based experiment to break the “CAST barrier”. An optical scheme to implement this concept is sketched, along with a possible implementation on CAST itself.

Summary

In the photon regeneration concept, axions (or Axion Like Particles - ALPs) are produced from a photon beam in a magnetic field zone, then propagate in a second magnetic field zone barred to the original photons, where they convert back to photons which are finally detected. This scheme leads to the crucial and dramatic experiment to prove the existence of ALPs: light shining through a wall (LSW).

The original concept, which was put to a first test in a pioneering experiment at Brookhaven by the BFRT collaboration, was later improved with the idea of introducing an optical resonator in the production section to enhance production probability. A rich panorama of experimental efforts has sprung up very recently along these lines and several groups, ALPS at DESY, BMV in France, GammeV and LIPSS in the US and OSQAR at CERN, have attempted, with different setups, to directly detect ALPs or, at least, to set meaningful bounds in the mass-coupling plane of ALPs. These bounds, however important as laboratory based tests, are still short by three orders of magnitude of the best experimental limit we now have on ALPs given by the CAST observations (or rather non-observations) on solar ALP emission (the “CAST barrier”).

The photon regeneration idea has recently been extended by proposing a second optical resonator, coherent with the first located in the production section, in the regeneration-detection section, thereby increasing production probability by a factor equal to the square of the finesse of the resonators (assumed to be identical) [see Sikivie et al., *“Resonantly Enhanced Axion-Photon Regeneration”*, Phys. Rev. Lett. (2007) vol. 98 (17) pp. 4)]. With present techniques finesses as large 10^5 can be easily achieved, enabling one to boost the overall ALP production probability of an LSW experiment by 10^{10} at least. There are several challenges to be met to achieve a successful resonant regeneration measurement. The main challenge is locking in frequency two geometrically aligned high-finesse Fabry-Perot resonators. Other issues are low background detectors, a high-power laser and accumulating sufficient statistics.

One possibility to meet the first challenge is to use a frequency-doubled Nd:YAG laser emitting two beams, at 1064 nm at 532 nm. The latter beam is generated from the first through a non-linear crystal and both beams are coherent. The second ingredient is setting up the Fabry-Perot resonators using “double-λ” mirrors, that is mirrors coated for high reflectivity in narrow bands (typically 10-30 nm) around the two emission wavelengths of the laser. In this way one of the two beams can be used to sense and lock the cavities, while the other, which will also resonate with the cavities once they are locked, to conduct the actual photon regeneration measurement. The principle of this technique is sketched in the Figure 1 below.

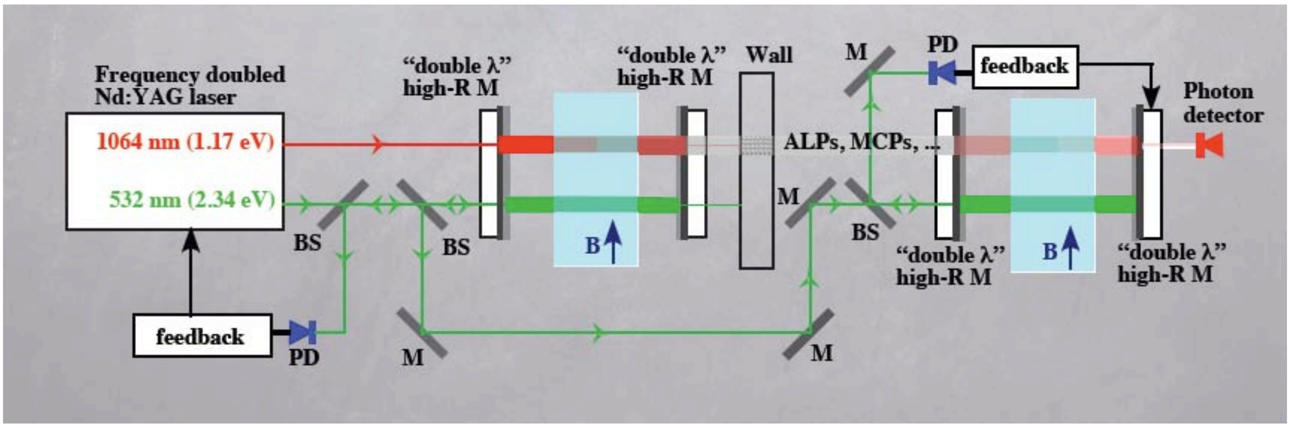

Figure 1 - Proposed scheme to frequency lock two geometrically aligned Fabry-Perot cavities made with "double-λ" mirrors using a frequency doubled Nd:YAG laser.

In this scheme the main laser frequency (at 1064 nm) is locked to the first (production) cavity using the Pound-Drever-Hall technique. This cavity becomes the effective instantaneous standard of frequency. The second (regeneration) cavity is locked to the production cavity by adjusting its length to follow the laser frequency.

The experimental environment at CAST might be suitable for a resonant regeneration experiment. It already offers a large magnet (10 T and 10 m long), a good laboratory environment and detector experience in the group. In a future development, one of the two available bores of the CAST magnet could be dedicated to a resonant regeneration experiment by implementing, for instance, the schematic setup illustrated in Figure 2. Here a single bore is split in two zones by an insert consisting of an opaque septum sandwiched between two mirrors, each belonging to a separate cavity. The frequency locking then follows the principle outlined in Figure 1. The proposed detector is a low background single photon counting Avalanche Photodiode (APD). The reach of such a setup in the mass-coupling plane of ALPs depends chiefly on the finesse that is achieved and to a lesser extent on the Dark Count Rate (DCR) of the detector and on the available laser power.

The graph of Figure 3 represents the bounds in the mass-inverse coupling plane of ALPs that could be reached with resonant regeneration at CAST in three different scenarios for the finesse (F), the detector DCR and the laser power (P). The current CAST bound (the "CAST barrier") is also given as a reference. Note that the photon regeneration limit, albeit hypothetical, and the "CAST barrier are methodologically different, since the first comes from a laboratory measurement and the second from an observatory-type experiment.

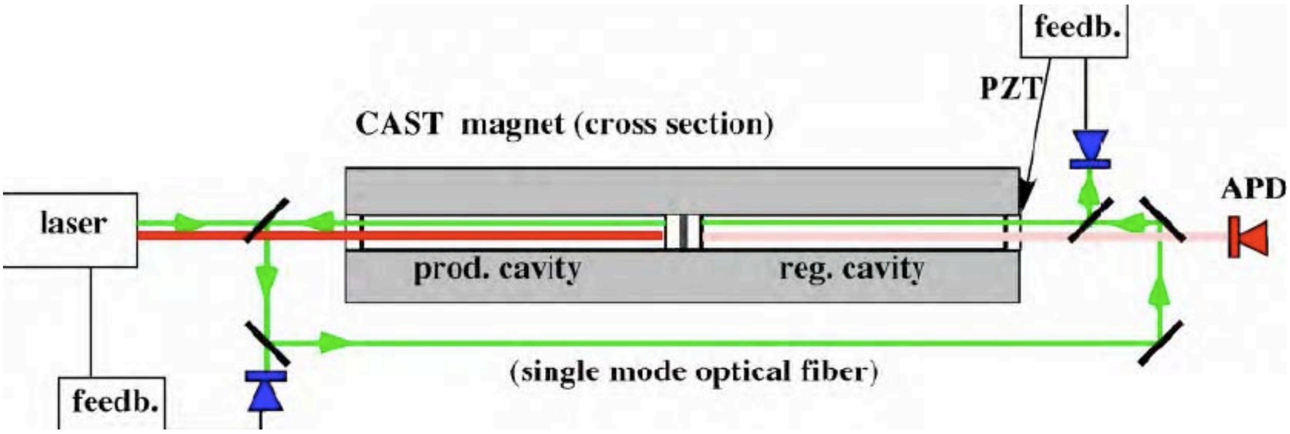

Figure 2 - Possible setup to implement a resonant regeneration experiment using the CAST magnet.

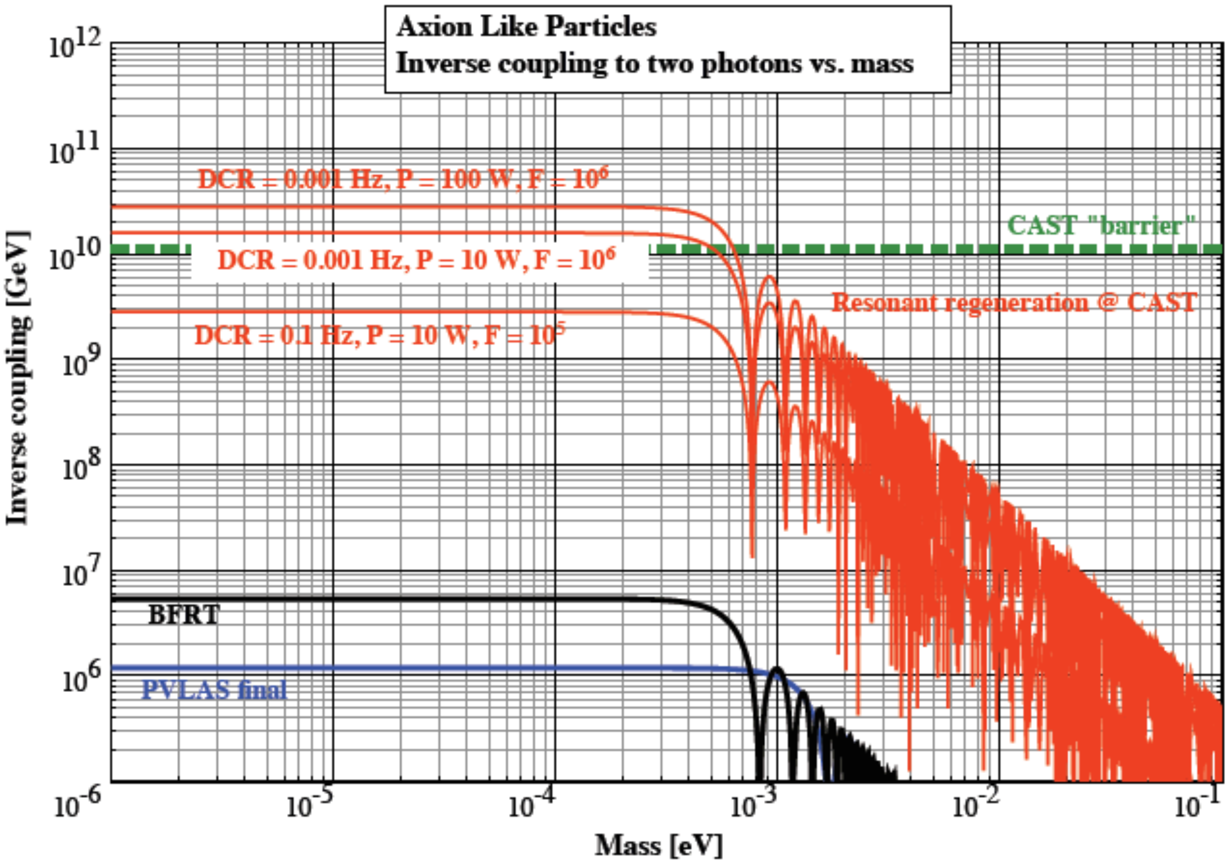

Figure 3 - Upper bounds in the ALP parameter space that could be set by a resonant regeneration experiment conducted at CAST. The three red curves represent three different choices of the relevant experimental parameters (Fabry-Perot finesse F, detector dark count rate DCR and laser power P). The green dashed line is the current bound given by CAST, while black and blue curves are the bounds derived from past polarization measurements by the BFRT and the PVLAS collaborations.

On search for eV hidden sector photons.

Sergei N. Gninenko
Institute for Nuclear Research, 117312 Moscow, Russia

Several interesting extensions of the Standard Model (SM) suggest the existence of 'hidden' sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. These sectors of particles do not interact with the ordinary matter directly and couple to it by gravity and possibly by other very weak forces. If the mass scale of a hidden sector is too high, it will be experimentally unobservable. However, there is a class of models with at least one additional $\mathrm{U_h}(1)$ gauge factor where the corresponding hidden gauge boson could be light. For example, Okun [1], see also [2], proposed a paraphoton model with a massive hidden photon (with a mass $m_{\gamma'}$) mixing with the ordinary photon resulting in photons oscillations, similarly to vacuum neutrino oscillations, with a vacuum mixing angle χ.

Since γ's can be produced through mixing with real photons, it is natural to consider the Sun as a source of low energy γ's [3]. To search for eV hidden photons one can upgrade the CAST experiment [4] with a simple helioscope detector schematically shown in Figure 1. Single photon detectors (SPDs), at both ends of a vacuum pipe, are looking for the single visible photons produced through oscillations of hidden photons inside the helioscope when it is pointing the Sun.

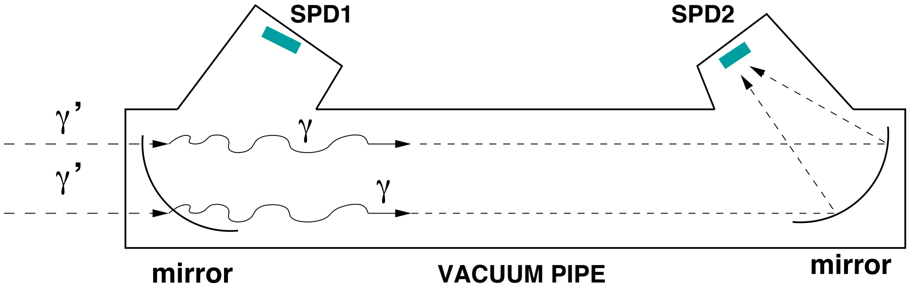

Fig. 1. *Schematic illustration of the direct search for solar γ'-flux in the CAST experiment. A vacuum pipe equipped from both sides by mirrors used to focus ordinary photons produced from $\gamma' \to \gamma$ oscillations on single photon detectors (SPDs). The manifestation of a signal would be an increase of the counting rate of the SPD that is 'illuminated' by the Sun compare to the other.*

We assume that the vacuum pipe has aperture with an effective diameter of $\simeq$ 50 cm and the length of 10 m. The whole helioscope detector could be mounted parallel to the LHC magnet on the CAST platform, allowing a movement of $\pm 8^o$ vertically and $\pm 40^o$ horizontally [4]. The manifestation of a signal would be an excess of events in the eV energy spectrum during the Sun tracking, compared to the background runs spectrum. For a high sensitivity of the proposed experiment to achieve a low background counting rate and a high efficiency for the single photon detection is crucial. Performing integration over solar hidden photon spectra [3] results in the hypothetical $\mathrm{CAST_{eV}}$ exclusion region shown in Figure 2. The details of calculations can be found in [3]. One can see that the proposed experiment improves the sensitivity at low masses due to the relatively large oscillation length. It surpasses the reach of already performed laser experiments and certainly of the CAST keV search, see [3]. The vacuum requirements are somehow crucial [3].

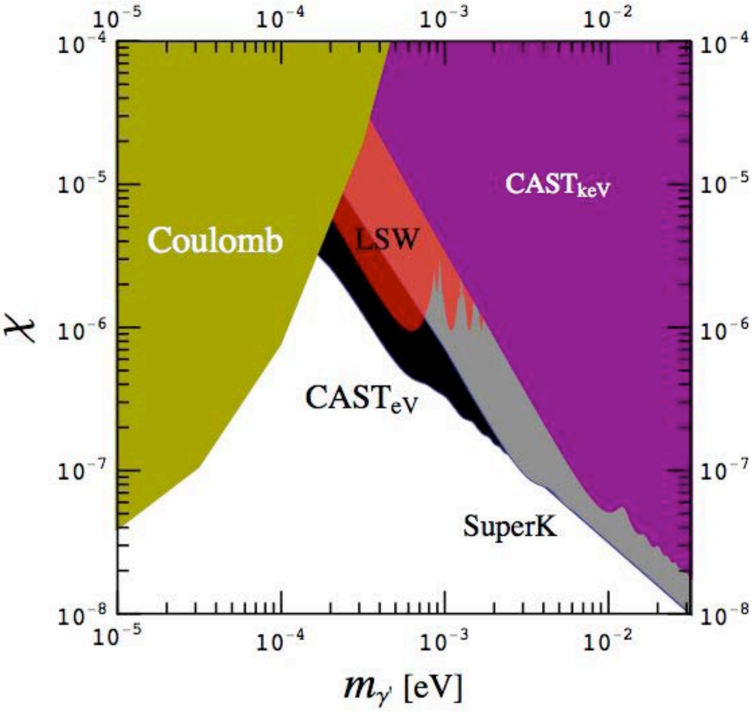

Fig. 2. *Regions in the* $(m_{\gamma'}, \chi)$ *plane which could be excluded by the proposed experiments: SuperK (gray region) and* $CAST_{eV}$ *(black). Also shown are the regions, with self explanatory labels, excluded by CAST in the keV range, by LSW experiments and by searches of deviations of Coulomb's law, see [3].*

References

[1] L.B. Okun, Sov. Phys. JETP 56 (1982) 502 [Zh. Eksp. Teor. Fiz. 83 (1982) 892].

[2] B. Holdom, Phys. Lett. B 166 (1986) 196.

[3] S.N. Gninenko and J. Redondo, Phys. Lett. B 664 (2008) 180.

[4] K. Zioutas et al.(CAST Collaboration), Phys. Rev. Lett. 94 (2005) 121301; K. Zioutas et al., Nucl. Instrum. Methods Phys. Res. A 425 (1999) 482.

Solar X-ray observations of solar axions

Hugh S. Hudson

Space Sciences Laboratory, University of California at Berkeley,
Berkeley, CA, 94720-7450, USA

E-mail: `hhhudson@ssl.berkeley.edu`

Abstract. Axions generated in the solar core can convert to X-ray photons in the magnetic field of the lower solar atmosphere. This note describes searches for these axions via the use of existing solar X-ray telescopes – specifically those on the satellites *Yohkoh* (1991-2001), RHESSI (2002-present), and *Hinode* (2006-present). These instruments were designed to study the solar corona, and an experiment optimized for an axion search could be more sensitive by orders of magnitude.

The solar atmosphere as an axion source: Axions emerging from the solar interior enter a medium (the chromosphere/corona) with complicated magnetic fields and a steeply decreasing plasma density. This medium cannot readily be represented by mean properties in view of the non-linear dependences embodied in the Primakoff process (see for example Raffelt, 1996). But if it could, an image of the solar core would appear at the center of the solar disk; the axion source would have a characteristic *spatial signature* as well as its *spectral signature*, which would be close to that of the blackbody distribution of the solar core, with a soft X-ray energy spectrum peaking at about 4 keV. The strongest magnetic fields occur in sunspots, and the sunspot regions unfortunately support many kinds of plasma activity (flares, jets, coronal mass ejections) that involve X-ray emission. However the "quiet" Sun, away from these active regions, also has strong magnetic fields in intense concentrations, and these fields spread out into the general corona with a horizontal component (the $\mathbf{B}_\perp$ needed for the Primakoff conversion) that may have an average value of order 3×10^{-3} T and dimension 10^5 m. Much larger values would be present in active regions.

If a solar axion signal were detected, its quantitative interpretation would be difficult because of the ill-understood complexities of the source. Current solar observations cannot determine the coronal magnetic field well, and the density distribution is limited by the restricted angular resolution and diagnostic power of the existing instrumentation.

The existing solar X-ray telescopes: The most sensitive searches for solar axions with existing data come from the three instruments summarized in Table 1. The X-ray telescopes on *Yohkoh* and *Hinode* are (were) classical grazing-incidence imagers, limited in response to energies well below the axion spectral peak. The RHESSI instrument

Table 1. Solar X-ray telescopes

Satellite	Dates	Spectral range	FOM
Yohkoh	1991-2001	<2 keV	*TBD*
RHESSI	2002-present	>3 keV	5×10^{-3}
Hinode	2006-present	<2 keV	*TBD*
Future mission	*TBD*	2-8 keV	7×10^{4}

is a rotating modulation collimator, sensitive in the right energy range but with a relatively high background counting rate. For each of these instruments, a time-sharing observational scheme is necessary. Suitable observations from RHESSI, for example, require offpointing the spacecraft from its normal Sun-center target; for *Hinode* the optimum axion observation requires continuous long exposures through thick integrating filters – note that the *Yohkoh* and *Hinode* X-ray telescopes read out image energies, rather than photon counts, because of the need for large image dynamic range.

Only the RHESSI data have been published thus far (Hannah et al., 2007). For a crude view of the relevance of these and the other solar X-ray observations, please see Figure 8 of Churazov et al. (2008), mentally adding an axion point at coordinates 3 keV, 3.6×10^{-10} erg (cm^2 sec keV)$^{-1}$ – this would be approximately the expectation for an axion/photon coupling constant $G_{a\gamma\gamma} = 10^{-10}$ GeV^{-1} (Carlson & Tseng, 1996). The limit obtained from solar observations refers to low axion masses.

Optimized future searches: A solar X-ray telescope optimized for axion detection would be quite different from the existing ones. It would have a large collecting area, a capability for continuous integration, and good efficiency in the 2-8 keV band. We define a "figure of merit" for the measurement (see Table 1) by $FOM = \sqrt{\epsilon A \Delta t / B \Delta E}$, where ϵ is the detection efficiency, A the detector area, Δt the integration time, B the spectral background counting rate of the detector, and ΔE the energy bandwidth. In Table 1 the FOM values are roughly normalized to that of CAST.

To miminize interference from the known solar X-ray sources, observation during sunspot minimum would be preferred. Although this is uncertain, the time range 2018-2020 seems optimum at the present time.

References

Carlson, E. D., and Tseng, L.-S. 1996, *Phys. Lett. B* **365**, 193.

Churazov, E., Sazonov, S., Syunyaev, R., and Revnivtsev, M. 2008, *Mon. Not. R. Astron. Soc.* **385**, 719

Hannah, I. G., Hurford, G. J., Hudson, H. S., Lin, R. P., and van Bibber, K. 2007, *ApJ* **659**, 77L

Raffelt, G. G. 1996, *Stars as Laboratories for Fundamental Physics* (University of Chicago Press)

Ultra-light Particles beyond the Standard Model: Laboratory Experiments

Axel Lindner, DESY

Abstract

Based on present day experience the future of laboratory experiment searching for Axion-Like Particles (ALPs) or other Weakly Interacting Sub-eV Particles (WISPs) is sketched.

Today's laboratory experiments

It is beyond the scope of this contribution to sketch a significant part of the landscape of the many different experimental approaches searching for new physics phenomena at the low energy frontier. Instead only "low energy photon" experiments are addressed. In these experiments the behavior of a freely propagating photon beam or "photon-photon" collisions are analyzed. In the first case one searches for oscillation phenomena like in the neutrino sector. In the second approach usually a high power laser beam is passed through a strong magnetic field. In these experiments either changes in the laser light polarization or "light-shining-through-a-wall" phenomena are searched for. Both approaches are used to look for WISPs which are frequently predicted in extension of the Standard Model[1]. A map of such physics is described in the contribution of J. Redondo to this workshop for example.

Present day "low-energy photon collider" experiments in the laboratory already reach an impressive sensitivity of couplings for axion-like particles (ALPs) to photons in the range of $10^{-7}\,\mathrm{GeV}^{-1}$ corresponding to new physics (if such WISPs exist) in the range of several 10 TeV. However, for ALPs this range is surpassed by limits derived from indirect (lifetimes of stars) or direct (searching for ALPs from the sun) astrophysics studies. Here couplings larger than $10^{-10}\,\mathrm{GeV}^{-1}$ are excluded. Please note that for a 1 meV QCD axion a coupling strength of about $10^{-13}\,\mathrm{GeV}^{-1}$ is to be probed.

The sensitivity of LSW-experiments is given by the strength of the laser beam ("photons on target" N_γ), the magnetic field strength and length ($\mathrm{B} \cdot \mathrm{l}$) and the detector sensitivity (ϵ). Some typical values are given in the Table 1. Please note that the reach for the coupling g of low mass ALPs to photons varies like $\mathrm{g} \propto (\epsilon/\mathrm{N}_\gamma)^{1/4} / \, (\mathrm{B} \cdot \mathrm{l})$.

---

[1] Laser light polarization experiments are also aiming at measuring nonlinear QED effects like the magnetic birefringence of the vacuum.

Experiment	N_γ	Laser properties	$B \cdot l$	ϵ
ALPS [1]	$5 \cdot 10^{24}$	532 nm, cw	22+22 Tm	40 mHz
BMV [2]	$6 \cdot 10^{23}$	1050 nm, 82 pulses	4.4+4.4 Tm	50 kHz, timing
GammeV [3]	$6 \cdot 10^{23}$	532 nm, 5 Hz pulses	15+15 Tm	130 Hz, timing
LIPSS [4]	$6 \cdot 10^{25}$	935 nm, cw	1.8+1.8 Tm	1 mHz
OSQAR [5]	–	488+514 nm, cw	136+136 Tm	–
Future Exp.	$1 \cdot 10^{29}$	1064-532 nm, cw	600+600 Tm	0.01 mHz

Tab. 1: Parameters characterizing existing or planned experiments searching for ALPs. The author estimated some of these numbers, if they are not given explicitly in available references. BMV and LIPSS apply timing gates to the detector read-outs to further suppress backgrounds. The values shown in the last row refer to possible future set-ups discussed below.

Future laboratory experiments searching for ALPs

The abovementioned parameters can be improved significantly in the near future. Here the most promising prospects are:

- An optical resonator is used to enhance the effective power of the laser beam in the magnet and rising N . This concept has been realized recently by the ALPS experiment [6]. It seems to be possible to achieve effective laser light powers beyond 10 kW in the magnet. From today's perspective this approach seems superior to the use of pulsed lasers (which allow for background suppression in detectors via timing).
- The most powerful magnets relatively easy available today are LHC dipoles. The OSQAR experiment at CERN envisages using two of such devices. It is straightforward to upgrade further to 4+4 magnets for example.
- A "transition edge sensor" (TES) measuring single photons via induced phase transition from a superconducting state [7, 8] would allow to increase the detector sensitivity to 0.01 mHz even for cw fluxes. Here the sensitivity is estimated conservatively from the cosmic ray flux and radioactivity in the surrounding as observed in the ALPS experiment.

With the "dream" numbers given in the last row of Table 1 the efficiency in the coupling of ALPs to photons could be improved by the factor $\approx 10^3$ compared to the (at present world-best) GammeV results. Such an outcome would bring laboratory set-ups already close to the sensitivity of astrophysics experiments.

An additional crucial step is the usage of an optical resonator also in the re-generation part of a LSW experiment[9, 10]. Such a cavity would increase the transition probability of WISPs to photons proportional to the finesse of the cavity, thereby raising the sensitivity in g by more than an order of magnitude. This would bring laboratory experiments well beyond the scope of astrophysics into an unexplored territory for ALPs on the way towards the QCD axion. However, quite a few challenges are to be solved to realize such a cavity. Different experimental groups have started to tackle these questions.

Future laboratory experiments searching for other WISPs

Here just a few remarks are given:

The laser and detector technologies developed for ALPs searches can be used to find hidden sector photons. Here only long straight vacuum sections, but no magnetic fields are necessary. In the mass regime around 1 meV (preferred by many extensions of the Standard Model) already present day experiments probe sensitivities not accessible in astrophysics.

Microwave cavities used in particle accelerators may also be applied to search for hidden sector photons or turn out to be factories of minicharged particles.

New light sources like free electron lasers (i.e. the XFEL under construction at DESY) will allow for new sensitive tests of QED with a corresponding discovery potential for WISPs.

Summary

The search for WISPs in the laboratory is necessary to complement astrophysics experiments. There is a wealth of laboratory experimental approaches, which - if not done so already today - will likely surpass the sensitivity of astrophysics. Finding the QCD axion will be the final goal, but this will remain a challenging target also in the mid-term future. The WISP community world-wide is increasing due to a growing understanding of the perspectives offered in the WISP sector. Partly this interest is strengthened by the fact that the scale of laboratory WISP searches matches perfectly to research centers like DESY. For such laboratories WISP experiments offers the possibility of particle physics experiments on site in the era of only one LHC at the high energy frontier.

References

[1] **ALPS** Collaboration, K. Ehret, `arXiv:0812.3495 [hep-ex]`.

[2] **BMV** Collaboration, M. Fouche *et al.*, *Phys. Rev.* **D78** (2008) 032013, `arXiv:0808.2800 [hep-ex]`.

[3] **GammeV** Collaboration, A. S. Chou *et al.*, *Phys. Rev. Lett.* **100** (2008) 080402, `arXiv:0710.3783 [hep-ex]`.

[4] **LIPSS** Collaboration, A. Afanasev *et al.*, *Phys. Rev. Lett.* **101** (2008) 120401, `arXiv:0806.2631 [hep-ex]`.

[5] **OSQAR** Collaboration, R. Ballou *et al.* CERN-SPSC-2007-039S; PSC-M-762, December, 2007.

[6] **ALPS** Collaboration, K. Ehret *et al.*, *publication in preparation* .

[7] B. Cabrera, *J Low Temp Phys.* **151** (2008) 82.

[8] D. Bagliani *et al.*, *J Low Temp Phys.* **151** (2008) 234.

[9] F. Hoogeveen and T. Ziegenhagen, *Nucl. Phys.* **B358** (1991) 3–26.

[10] P. Sikivie, D. B. Tanner, and K. van Bibber, *Phys. Rev. Lett.* **98** (2007) 172002, `arXiv:hep-ph/0701198`.

New prospects for CAST from the new Microbulk performance

Performance of the new Microbulk Micromegas in CAST

Two Micromegas detectors were build on August 2008, in order to replace the ones that were used during the first period of CAST ^{3}He phase. The new detectors were build according to the Microbulk technique, which allows to achieve better energy resolution and to minimize the materials that are used to only kapton, Copper and Plexiglas; thus, an improved background level was expect.

Both detectors were tested at CAST on the sunrise side during September and October 2009. They both detectors showed initially a background level less than 2cph in the range 1-7 keV, slightly improved compared to the previous situation. Surprisingly, this level was decreasing with time, to reach after two weeks an extraordinary level of the order of 0.05cph ($2\times10^{-7}s^{-1}keV^{-1}cm^{-2}$), Figure 1. The reason of this reduction appears to be the combination of the shielding quality with an enhanced particle discrimination efficiency and, currently, is under study.

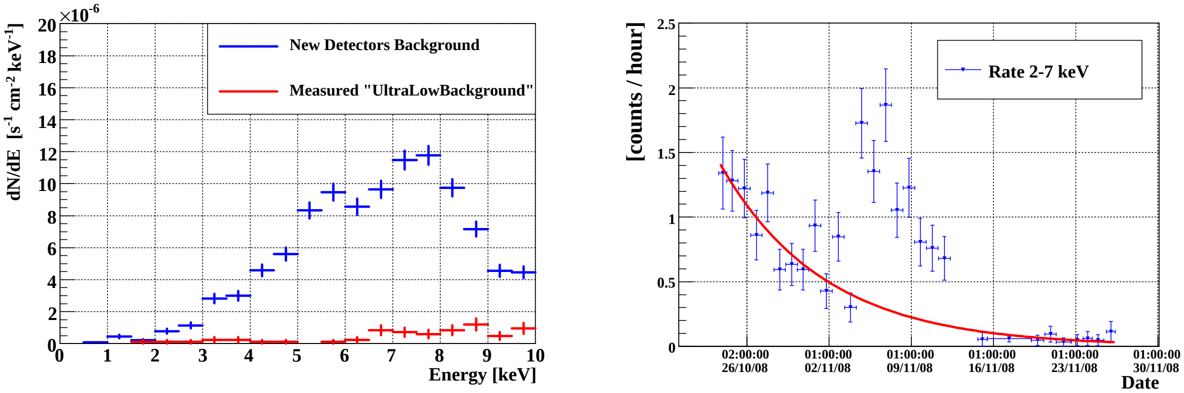

Figure 1. Left: The analogue spectra of the initial and final background of the new micromegas detector. Right: The background reduction with time; the sudden increase coincides with an interruption of the nitrogen flushing of the shielding interior. The performance of the detector (trigger rate, resolution, spatial homogeneity) was checked with ^{55}Fe calibration runs, which were performed at least daily, at random time of each day, and was stable.

Prospects for CAST

The new detectors replaced the CAST TPC detector and the old (unshielded) micromegas in order to improve the axion detection sensitivity during pressure scanning and counterbalance the losses due to reduced tracking time per pressure setting. However, the surprising performance of the new detectors brings up new prospects in improving the CAST Phase I result. Simulations show that an improvement is expected even for the “normal” background conditions, while if 3 "ultra-low-background" detectors were used the limit on $g_{a\gamma\gamma}$ would reach ~ 4.5×10^{-11} GeV^{-1}, (Figure 2).

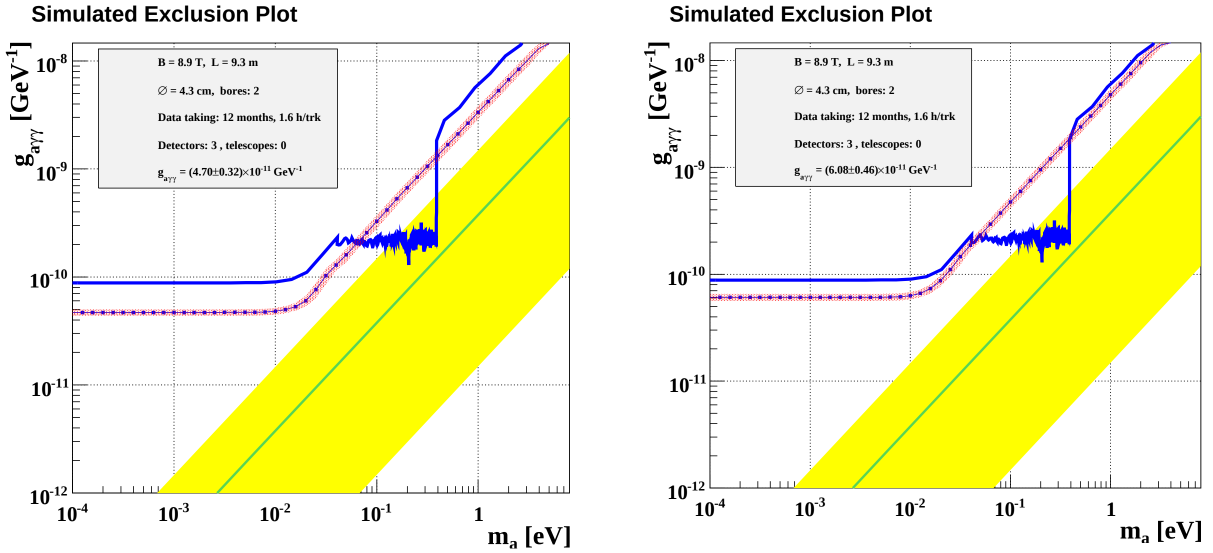

Figure 2. Left: the expected sensitivity for CAST Phase I conditions, with 3 "ultra-low-background" detectors. Right: the same for the "normal" conditions. The calculation is for 12 months data taking.

Towards the present limits of the helioscope technique

The result shown in Figure 2 can not be significantly improved with the existing CAST magnet, even by using x-ray optics for all detectors. In order to extend the sensitivity towards or below 10^{-11} GeV^{-1}, a new magnet is needed together with the high performance detectors. Two examples are shown in Figure 3.

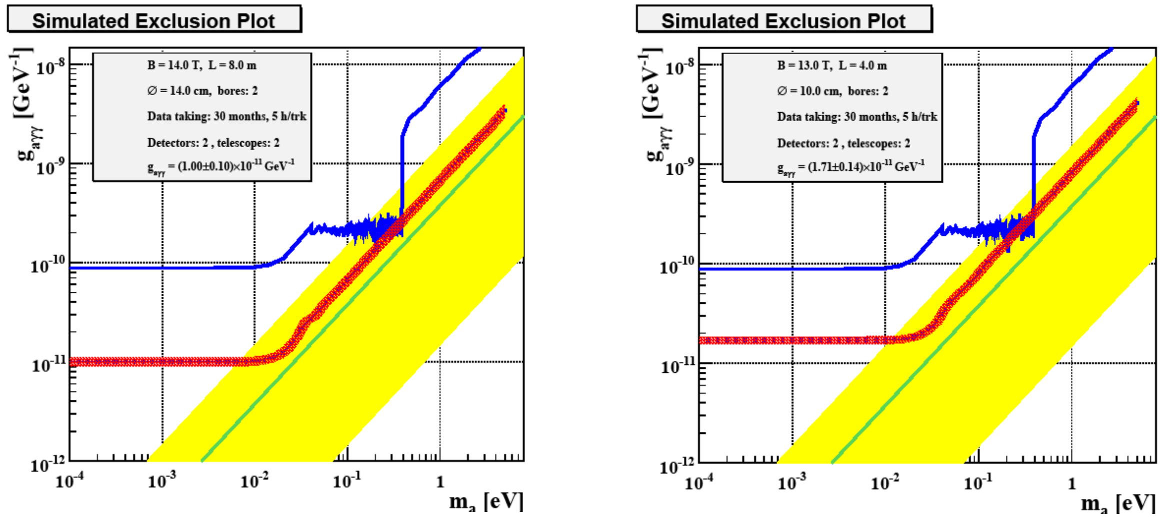

Figure 3. Left: the expected sensitivity for a magnet of B=13T and L=4m, with 3 "ultra-low-background" micromegas detectors. Right: the same for B=14T and L=8m. The magnet characteristic represent the expected CERN technology for the years 2013 and 2016.

A map of the low energy frontier:
– WISP opportunities beyond QCD axions –

Javier Redondo

Abstract

The case of weakly interacting sub-eV particles (WISPs) is reviewed with emphasis on the reach of experiments like CAST looking for WISPs emitted from the Sun.

Extensions of the standard model to cure its non-aesthetic features often include hidden sectors, i.e. sets of fields with no electro-weak or strong interactions. The paradigmatic example is string theory where the occurrence of new particles is overwhelming. Particles in these hidden sectors can always interact with the standard model (SM) particles through gravity but other options are theoretically and phenomenologically allowed. For instance super-weak interactions with SM particles can arise from radiative corrections (i.e. virtual processes) involving extremely heavy fields which have SM charges and also interact with the hidden sector particles. These heavy fields act as mediators of super-weak interactions and are also ubiquitous in extensions of the standard model like strings, grand unification or super-symmetric theories.

Particles living in these hidden sectors can have small masses, even below the eV, if these are protected by a symmetry from radiative corrections involving ultraviolet-completions of the theory. The only requirement thus for these particles to exist is therefore be associated with a mass-preserving symmetry and have small enough couplings to be phenomenologically allowed. The most stringent constraints for such weakly-interacting-sub-eV-particles (WISPs) often arise from indirect arguments involving stellar evolution but and in some particularly interesting cases from astrophysical observations like the CAST experiment looking for solar Axions.

We can list the possible inhabitants of hidden sectors according to the mass-preserving-symmetries we know. As the first and paradigmatic example we find axions and other Goldstone (GB) spin-0 bosons[1], the smallness of their mass being related with an underlying *global* symmetry, which is spontaneously broken at a very high scale f. These particles can develop a two-photon coupling like the one is searched for in CAST if the underlying global symmetry is anomalous in which case the two-photon coupling can be estimated as

$$g_{\gamma\gamma} = \alpha/f \simeq 7.3 \times 10^{-3}/f \tag{1}$$

GBs are massless unless there is a small contribution in their potentials that breaks explicitly their parent symmetry. With a explicitly breaking contribution of order Λ^4

and $\Lambda \ll f$ the mass of the now called pseudo-Goldstone Boson can be estimated as [2]

$$mf \simeq \Lambda^2 \ . \tag{2}$$

The latest data of CAST can probe $\Lambda \lesssim 10$ MeV, which starts to be very close to the QCD scale ~ 100 MeV for which the pGB would be the celebrated QCD axion.

A second example of hidden sector particles are hidden photons (HPs), gauge bosons of a hidden $\mathrm{U}(1)_{\mathrm{hid}}$ symmetry. These symmetries arise very frequently in string theory. Hidden photons can interact with SM photons via the so-called kinetic mixing term [3]

$$L_{\mathrm{kin.mix.}} = -\frac{1}{2}\chi F_{\mu\nu}B^{\mu\nu} \tag{3}$$

where $F_{\mu\nu}(B^{\mu\nu})$ are the photon(hidden photon) field strengths and χ the dimensionless mixing parameter whose magnitude has been found to range in the interval

$$10^{-16} < \chi < 10^{-2} \tag{4}$$

in a set of realistic string compactifications[4]. On the other hand their mass being protected by the gauge symmetry can be naturally very low, although we would like to have a motivation for non-zero values. Suggestive non-zero values arise in string-theories with large extra-dimensions which can be directly probed in the near future at the LHC. In such cases the masses of anomalous $U(1)$'s will fall in the attractive meV regime for a string scale around the TeV. Other possibility within string theory has emerged recently which considers relatively large volumes in the extra-dimensions as causing extremely small gauge couplings of the hidden sector[5]. In this case even a TeV mass scalar with hidden charge could produce sub-eV hidden photons by the Higgs mechanism.

The meV range of HP masses has recently attracted much attention. Because of the mixing term (3), vacuum photon↔HP oscillations occur like photon↔axion oscillations take place in a transverse magnetic field [6]. In a recent set of papers the emission of HPs from stellar and primordial plasmas has been computed and showed to led quite interesting effects [7, 8, 9]. The plasma density generally suppresses the effective photon-HP mixing, and the smaller the HP mass the larger the suppression. Thus unlike in the axion case, the astrophysical and cosmological bounds on hidden photons are systematically evaded for sufficiently small HP masses. The current bounds from the CAST non-observation of keV photons from the Sun and from searches of deviations of Coulomb's law leave an interesting region around meV masses, see Fig. 1. Hidden photons in this region can still play a cosmological role, since they are resonantly produced in the early universe (after BBN but before the CMB release) and immediately decoupled appearing during structure formation as additional invisible relativistic energy, like neutrinos. A slight preference for such energy component appears when combining cosmological data, which could signal to the existence of these HPs [8]. Interestingly enough, with meV masses the oscillation length of photon-HP transitions lies in the range of meters for frequencies in the visible. These oscillations have been searched in the laboratory by means of the "light-shining-through-walls" technique [10, 11, 12] and further experiments will

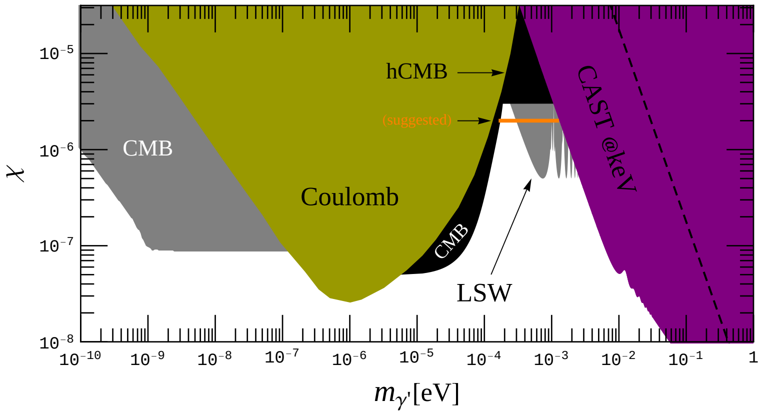

Fig. 1: Mass-Mixing parameter space for Hidden Photons. Shown are present laboratory, astrophysical and cosmological constraints. The orange line could be suggested by cosmology.

be performed in the near future [13]. Other purely laboratory experiments have been proposed to search for these particles [14, 15]. Of course, any positive signal will point to the possible use of these HPs for optical communications through dense matter, across the earth for example [16].

Hidden photons with meV masses would be also emitted from the Sun, but their production is suppressed in the high dense interior and therefore the expected spectrum it is substantially peaked at low energies, in the visible/infrared. A proposal to modify CAST in order to efficiently search for these particles has been raised by Gninenko [17] as was presented in this meeting. With different motivations, the CAST collaboration has recently started a program of these low-energy searches [18] which can produce nice results in the future. Another proposal has been raised by the Hamburger Sternwarte in collaboration with DESY: the *solar hidden photon search* SHIPS which it is currently under consideration.

As a final WISP candidate we should mention massless (or low mass) particles charged under a hidden U(1). These particles appear as mini-charged particles [3] since their electrical charge is proportional to the small kinetic mixing (4). As in the case of axions, astrophysics and cosmology impose the most severe constraints for these particles (except in complicated cases [19]) but so far no limits from the CAST data have been produced.

The list of WISPs presented here is by no means exhaustive but it should provide a flavor of the exciting candidates and phenomena that awaits us when exploring this *low energy frontier of fundamental physics*, a frontier that extends far beyond the well-known case of QCD axions. A complete physics case is under preparation and should be released before the “5th Patras meeting on Axions, WIMPs and WISPs” scheduled for July 2009.

References

[1] J. Goldstone, A. Salam, and S. Weinberg, *Phys. Rev.* **127** (1962) 965–970.

[2] S. Weinberg, *The quantum theory of fields. Vol. 2: Modern applications.* Cambridge, UK: Univ. Pr. (1996) 489 p.

[3] B. Holdom, *Phys. Lett.* **B166** (1986) 196.

[4] K. R. Dienes, C. F. Kolda, and J. March-Russell, *Nucl. Phys.* **B492** (1997) 104–118, `hep-ph/9610479`.

[5] C. P. Burgess *et al.*, *JHEP* **07** (2008) 073, `arXiv:0805.4037 [hep-th]`.

[6] L. B. Okun, *Sov. Phys. JETP* **56** (1982) 502.

[7] J. Redondo, *JCAP* **0807** (2008) 008, `arXiv:0801.1527 [hep-ph]`.

[8] J. Jaeckel, J. Redondo, and A. Ringwald, *Phys. Rev. Lett.* **101** (2008) 131801, `arXiv:0804.4157 [astro-ph]`.

[9] A. Mirizzi, J. Redondo, and G. Sigl, *JCAP* **0903** (2009) 026, `arXiv:0901.0014 [hep-ph]`.

[10] **BRFT** Collaboration, R. Cameron *et al.*, *Phys. Rev.* **D47** (1993) 3707–3725.

[11] **BMV** Collaboration, M. Fouche *et al.*, *Phys. Rev.* **D78** (2008) 032013, `arXiv:0808.2800 [hep-ex]`.

[12] **LIPSS** Collaboration, A. Afanasev *et al.*, `arXiv:0810.4189 [hep-ex]`.

[13] **ALPS** Collaboration, K. Ehret, `arXiv:0812.3495 [hep-ex]`.

[14] J. Jaeckel and A. Ringwald, *Phys. Lett.* **B659** (2008) 509–514, `arXiv:0707.2063 [hep-ph]`.

[15] J. Jaeckel and J. Redondo, *Europhys. Lett.* **84** (2008) 31002, `arXiv:0806.1115 [hep-ph]`.

[16] J. Jaeckel, J. Redondo, and A. Ringwald, `arXiv:0903.5300 [hep-ph]`.

[17] S. N. Gninenko and J. Redondo, *Phys. Lett.* **B664** (2008) 180–184, `arXiv:0804.3736 [hep-ex]`.

[18] **for the CAST** Collaboration, G. Cantatore *et al.*, `arXiv:0809.4581 [hep-ex]`.

[19] E. Masso and J. Redondo, *Phys. Rev. Lett.* **97** (2006) 151802, `hep-ph/0606163`.

Astrophysical motivations for axion-like particles

Sergey Troitsky
Institute for Nuclear Research, Moscow

Abstract: Mixing of photons with new light scalars and pseudoscalars (axion-like particles, ALP), which are predicted in several extensions of the particle-physics Standard Model, may simultaneously explain several astrophysical problems, in particular those related to long-distance propagation of energetic photons. Astrophysically motivated region of the ALP parameter space includes masses $m < 10^{-6}$ eV and ALP-photon couplings $1/M \sim (10^{-10}...10^{-11})\mathrm{GeV}^{-1}$.

New light particles which could mix with photons under certain conditions are predicted by many extensions of the Standard Model of particle physics. The best known one is the axion, a pseudoscalar particle which is a crucial ingredient of the most popular solution of the $U(1)$ problem in quantum chromodynamics [1]. The effective lagrangian of axion-photon interactions contains a term which gives rise to mixing in the external magnetic field. The coupling constant $1/M$ in front of this term is expressed through the axion mass m in a model-dependent way; numerically model-to-model variations are not so large. A particle with the similar interactions but with arbitrary values of m and M is called axion-like particle (ALP). Scalar particles with photon-mixing term are often also called ALPs. These scalar and pseudoscalar particles appear as a natural consequence of many models which motivate the hierarchy of Standard-Model constants and/or unify quantum field theory and gravitation (string theories – e.g. [2]; theories with extra dimensions – e.g. [3], models of supersymmetry breaking - e.g. [4]). Phenomenologically, it makes sense to consider two free parameters, m and M.

There exist a series of unsolved problems in the modern high-energy (1 keV - 100 TeV) and ultra-high-energy (10^{18} eV – 10^{20} eV) astrophysics which are related to emission and propagation of photons where sometimes the standard descriptions fail:

(1) observation of photons with energies in excess of 100 GeV from distant (up to redshift > 0.5 [5]) blazars (the so-called "infrared-TeV crisis", see e.g. [6, 7]): observed spectra fail to agree simultaneously with reasonable mechanisms of the gamma-ray emission in sources and with realistic estimates of intergalactic infrared background on which TeV photons experience intense scattering;

(2) indications to the existence of neutral particles with energies $> 10^{18}$ eV arriving from cosmologically distant sources - BL Lac type objects - in the data of the High Resolution Fly's Eye experiment [8, 9]: the mean free path of known neutral particles with these energies is many times smaller than the distance to these sources;

(3) luminosity function of active galaxies [10];

(4) luminosity function of white dwarfs [11];

(5) large-scale correlations in orientations of polarization planes of quasar emission [12];

(6) excess of the solar X-ray radiation as compared to theoretical models [13];

(7) pulsed emission at dosens GeV from the Crab pulsar [14] which is difficult to explain in classical models of pulsar radiation;

(8) extended sources of cosmic rays at 10^{15} eV [15];

(9) excess of X-ray radiation and the electron-positron annihilation line from the Galactic Center region.

For the problems (1)–(3), quantitative explanations have been suggested which invoke photon mixing with a light ALP (1, Ref. [16]; 2, Ref. [17]; 3, Ref. [10]). In all three cases, the required ALP parameters are similar: mass $m < 10^{-6}$ eV, inverse coupling constant $M \sim (10^{10} - 10^{11})$ GeV. For the problems (4)–(6), qualitative explanations with ALP mixing have been proposed, but the required ALP parameters were not determined (except for a particular scenario for the problem (5), Ref. [18]). ALP mixing may also help to solve the problems (7)–(9).

For the problem (2), the axion explanation has a number of consequences testable in cosmic-ray physics. First of all, they include the BL Lac correlation itself, which should be tested with independent data, and determination of the primary particles of correlated events which should be photons if the axion-mixing hypothesis is correct. Search of primary ultra-high-energy photons is a nontrivial task, and only recently considerable progress has been achieved, in particular by the efforts of the team members. One of the problems is related to the energy determination of the primary photons (see Ref. [19]). In particular, the largest modern experiment (the surface detector of the Pierre Auger observatory) underestimates photon energies by a factor of a few. This fact means in particular that the absence of BL Lac correlations in the preliminary data of this experiment [20] may be interpreted in favour of the photon hypothesis [21]. The most prospective way to test the correlation and to attempt the determination of the primary type of correlated events is to use the surface and fluorescent detectors of the Telescope Array experiment which started to work in 2008.

The astrophysically motivated part of the parameter space is not constrained by any of the experiments: the coupling constant is weaker than the best CAST limit and is several orders of magnitude weaker than the best laboratory limits (see Fig. 1). A large-scale experiment motivated by axion solutions of the astrophysical problems (1) and (2) of the above list has been suggested in 2009 [22]. Its concept includes a large array of scintillators sensitive, like CAST, to the solar axions. Another, purely laboratory experiment capable of studying this region of the parameter space, is discussed in the contribution by G. Cantatore to this meeting.

References

[1] Peccei, Quinn 1977, Phys.Rev.Lett.38:1440

[2] Svrcek, Witten 2006, JHEP 0606:051

[3] Rubakov 2001, Phys. Uspekhi 171:913

[4] Gorbunov, Dubovsky, Troitsky, 1999, Phys. Uspekhi 169:705

[5] MAGIC collaboration 2007, Science 320:1752

[6] Protheroe, Meyer 2000, Phys.Lett.B493:1

[7] Aharonian et al. 2006, Nature 440:1018

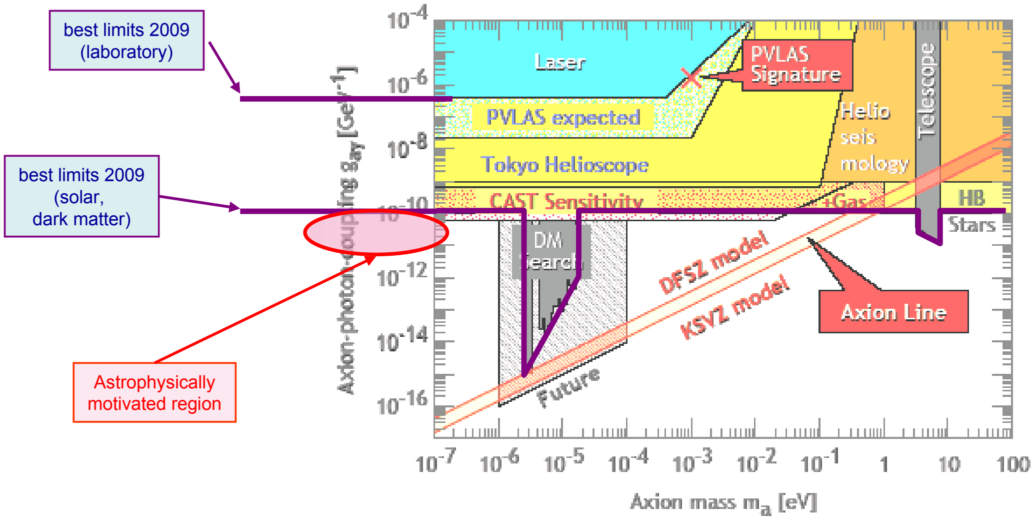

Figure 1: Parameter space of ALPs. The plot with constraints was taken from the webpage of G. Raffelt.

[8] Gorbunov et al. 2004, JETP Letters 80:167

[9] HiRes collaboration 2005, Astrophys.J.636:680

[10] Burrage, Davis, Show, 2009, arXiv:0902.2320

[11] Isern et al. 2008, arXiv:0812.3043

[12] Payez, Cudell, Hutsemekers 2008, arXiv:0805.3946

[13] Zioutas et al. 2009, arXiv:0903.1807

[14] MAGIC collaboration 2008, Science 322:1221

[15] MILAGRO collaboration 2008, Phys.Rev.Lett.101:221101

[16] Simet, Hooper, Serpico, 2008, Phys.Rev.D77:063001

[17] Fairbairn, Rashba, Troitsky, 2009, arXiv:0901.4085

[18] Piotrovich, Gnedin, Natsvlishvili 2008, arXiv:0805.3649

[19] Kalashev, Rubtsov, Troitsky 2008, arXiv:0812.1020

[20] Harari et al. 2007, arXiv:0706.1715

[21] Troitsky 2008, Mon. Not. Roy. Astron. Soc. 388:L79

[22] Avignone, Creswick, Nussinov, 2009, arXiv:0903.4451