Towards a medium-scale axion helioscope: the physics case and a proposal in Troitsk

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I discuss the physics case for a medium-scale axion helioscope with sensitivities in the axion-photon coupling a few times better than CAST. Search for an axion-like particle with these couplings is motivated by several persistent astrophysical anomalies. Then I report on the project of such a helioscope, TASTE, to be constructed in INR, Troitsk, Russia. On behalf of pre-collaboration, I discuss early conceptual design, existing infrastructure, projected sensitivity and timeline of this experiment.

1 Submission

Recent progress in astrophysics makes it possible to use observational data to search for axions and axion-like particles (ALPs), or to constrain their parameters. Detailed studies of stellar energy losses constrain $g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11}$ GeV^{-1} at the 68% confidence level, at the same time giving a weak indication in favour of the presence of an axion or ALP with $g_{a\gamma\gamma} \sim (2.9 \pm 1.8) \times 10^{-11}$ GeV^{-1} at the 68% confidence level, see Ref. [2] for references and a wider discussion. However, a much stronger evidence for the existence of an ALP with the photon coupling in this domain comes from the gamma-ray astronomy (for a brief review and more references, see Ref. [3]).

Indeed, the Universe is filled with background radiation, on which energetic gamma rays produce electron-positron pairs [4]. This process limits the mean free path of energetic photons to a small fraction of the Universe, strongly dependent on the photon energy. Analyses of ensembles of gamma-ray sources at distances corresponding to large optical depths indicate [5, 6] that the suppression is much weaker than expected. The statistical significance of this anomaly, 12.4 standard deviations [6], makes it a strong argument in favour of existence of unaccounted processes related to the gamma-ray propagation. Interestingly, all the studies which indicate the anomaly have been based on minimal models of the extragalactic background light (EBL), on the level of the sum of the light from observed galaxies [7], while the very recent dedicated observations making use of two different approaches [8, 9], indicate the EBL intensity twice higher. Proved to be true, these EBL values would make the gamma-ray propagation anomaly even more dramatic.

Potential astrophysical explanations in terms of secondary particles [10, 11] have troubles explaining the effect for most distant sources and, more importantly, are at odds with the ob-

*On behalf of the TASTE group of interest. Based on Ref. [1]

servations of strong variability of gamma-ray sources at large optical depths, e.g. [12]. One is forced to invoke new physics for the solution to the anomaly. The pair-production probability might be modified in the presence of a weak Lorentz-invariance violation; however, this violation would also result in non-observation of any TeV photons by Cerenkov atmospheric telescopes because the development of photon-induced air showers would also be suppressed, and is therefore excluded [13, 14].

The remaining viable explanation points to ALPs. Thanks to the interaction (**??**), photon and ALP mix in external magnetic fields [15, 16], while the ALP does not produce e^+e^- pairs. Depending on the parameters, this may result either in axion-photon oscillations in intergalactic magnetic fields, which would enlarge the mean free path of photons from distant sources [17, 18], or in a conversion of a part of emitted photons to ALPs in the magnetic field in the source or in its close environment, subsequent propagation of these ALPs through the Universe and reconversion back to photons in the Milky Way or its surroundings [19, 20]. Present upper limits on extragalactic magnetic fields together with constraints on ALP parameters from non-observation of gamma radiation from supernova SN1987A, persistence of the gamma-ray propagation anomaly up to high redshifts and some hints on the Galactic anisotropy in the anomaly manifestation make the second scenario more favourable [21], though the first one is not yet excluded. The second, Galactic-conversion, scenario may be realized for $g_{a\gamma\gamma} \sim \left(10^{-11} - 10^{-10}\right)$ GeV^{-1} and $m_a \sim \left(10^{-9} - 10^{-7}\right)$ eV. Experimental searches for a particle with parameters in this range is therefore strongly motivated.

Like other stars, our Sun contains a huge thermonuclear reactor in its center, and axions or ALPs, if exist, should be produced there. They can be detected on the Earth with an axion helioscope [15], a tube pointing to the Sun and filled with magnetic field allowing for ALP-photon conversion and subsequent photon detection. The CERN Axion Solar Telescope (CAST) is, up to day, the most powerful helioscope which has recently delivered the world-best upper limit on $g_{a\gamma\gamma}$ [22]. Amusingly, a weak excess of events was found in some runs, but it is not statistically significant. CAST has now finished its solar axion runs. An ambitious new project, the International Axion Observatory (IAXO), has been proposed a few years ago [23, 24] and is now at the research and design stage.

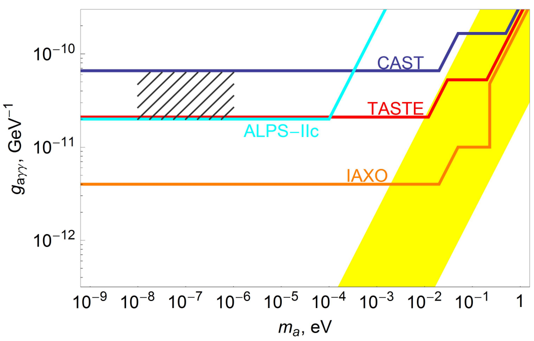

Figure 1: A sketch of comparison of sensitivities of proposed experiments to ALP parameters with the CAST limits. The yellow band is favoured by QCD axion models, the hatched area is favoured by the Galactic ALP conversion scenario explaining the anomalous transparency of the Universe.

In Fig. 1, we compare the projected sensitivity of our helioscope (Troitsk Axion Solar Telescope Experiment, TASTE) with those of two other projects aimed to explore the axion-photon coupling beyond the CAST limits, IAXO and ALPS-IIc.

Both projected experiments plan to cover the range of the parameter space motivated by the gamma-ray transparency of the Universe. However, there are significant differences with our proposal, which make all three projects complementary.

Indeed, ALPS-IIc, a light-shining-through-wall experiment, will be based on the resonantregeneration technique, which has not been demonstrated at work yet. If it works as planned, the first scientific runs are expected in 2020. Compared to helioscopes, this experiment will not cover the region of higher-mass ALPs and therefore will not explore the standard QCD axion scenario.

IAXO is a huge next-generation axion helioscopes with expected sensitivity superceding other projects. Given its scale and cost, the start of the full-scale experiment is planned beyond 2022. TASTE may be considered as a pathfinder for IAXO, aimed to scan physically interesting ALP and axion parameter space at much shorter timescale and at much lower cost.

Since the incoming solar-ALP flux is the same for all devices, it is customary to determine the sensitivity of a new helioscope to $g_{a\gamma\gamma}$ through the CAST sensitivity. Our goal is to have the sensitivity to $g_{a\gamma\gamma}$ three times better than CAST, and this determines technical requirements for the experiment.

The principal benefit of the new device with respect to CAST will be in the cross section of the conversion zone. Indeed, CAST used a decommissioned magnet from the Large Hadron Collider (LHC). For TASTE, we will construct a dedicated magnet so we are free to enlarge the cross-section area. However, the limitation comes from the X-ray telescope: the largest available ones have the diameter of ~ 60 cm. We therefore keep this diameter fixed in our proposal. On the other hand, we plan to use available superconducting cable, whose parameters and amount determine the working magnetic field value $B \sim 3.5$ T and the magnet length $L \sim 12$ m. Our goal is to have the tracking time fraction $\epsilon_t \sim 0.5$. For the X-ray optics, we use parameters of the SODART telescope. The area of the image in the focal plane $a = 0.5$ cm^2 is determined from Eq. (3.8) of Ref. [24]. For the detector efficiency and background, we take the best available presently values. These parameters result in the rough estimate of sensitivity 3 times better than CAST, that is down to $g_{a\gamma\gamma} \sim 2 \times 10^{-11}$ GeV^{-1}.

Two principal complications drive our preliminary magnet design. Firstly, the magnetic field should be perpendicular to the tube axis. Secondly, the entire system should be installed on a moving mount and hence its weight should be minimized. We therefore select a dipole-like magnet with active (iron-free) shielding, inspired in particular by some of proposals for the detector magnets of the Future Circular Collider (FCC), see Ref. [1] for details and references. Active shielding implies the use of additional external coils to close magnetic flux lines and to suppress stray fields. The magnet, in our preliminary conceptual design, consists of three identical sections, each of ~ 4 m length. The bore diameter is 60 cm, as dictated by the X-ray telescope part. The bore will be kept cold in order to possibly host equipment for dark-matter axion searches at certain stages of the project. The coil configuration and the magnetic-field map for one section are presented in Ref. [1].

Our plan is to construct one section first and to test it without the moving mount and the X-ray telescope; we call this stage of the experiment "LabTASTE" because the 4-meter magnet with a cold bore may be used as a laboratory to test various approaches to axion searches. It will be sufficient to perform dark-matter experiments. In parallel, depending on the availability of funds, two other magnet sections will be manufactured and RnD works for the X-ray part, as well as to the technical design of the moving platform, will be finalized.

To make the magnet, we plan to use ~ 35 km of superconducting cable available at INR. It has been manufactured in 1990s for the MELC experiment [25] proposed to search for $\mu - e$ conversion in INR, Troitsk. This experiment has never been launched but the conductor is still kept in INR. Studies suggest that the conductor can be safely used in magnetic fields of ~ 5 T at the current of ~ 3.5 kA, which is implied by our design. We note that the magnet design presented here is very preliminary; parameters of the magnet should be optimized at the technical-design stage.

In our proposal, we aim at the maximal usage of available resources and plan to benefit from the cryogenic equipment of the Troitsk-nu-mass experiment [26] in INR. At the first stage of the project, LabTASTE, the system will be used in turns with Troitsk-nu-mass.

Though focusing of energetic X-ray photons is not an easy task, numerous X-ray telescopes have been developed for space-based astronomical instruments (a brief overview of their relevant parameters is given e.g. in Ref. [23]). In 1990s, the Soviet–Danish Roentgen Telescope (SODART) [27] has been developed and manufactured for the Spectrum-Roentgen-Gamma (SRG) space observatory which, however, has never been launched. The modern version of the SRG satellite, being considered for launch in 2018, will carry other scientific instruments. We propose to use one of two SODART X-ray mirrors in the TASTE project.

For the TASTE experiment, we plan to select the appropriate X-ray detector through additional RnD studies. Options to be considered include several solid-state detectors under development for astrophysics, high-energy physics and axion searches. The approaches followed by various groups participating in TASTE are described e.g. in Refs. [28, 29, 30]. One of the most challenging parameters of the detector is its low background. While present-day background rate values for astrophysical detectors are too high for our purposes, they are dominated by cosmic-ray contamination, which will be reduced by a combination of the passive shielding and a dedicated veto system. The detectors themselves will be tested and the shielding will be designed in the Low-background Measurement Laboratory in Baksan Neutrino Observatory of INR. Details of the detector design will be discussed elsewhere.

As discussed above, we preview two stages of the experiment, LabTASTE and the full TASTE. Subject to available funds, these projects may be realized in parallel, and this is the scenario we imply in the timeline presented in Fig. 2. A rough estimate of the budget, not including materials and equipment already available (the superconducting cable, the helium plant, the vacuum vessels and the X-ray telescope, as well as available infrastructure at the INR campus in Troitsk), gives ~ 5.5 MEuro, of which ~ 1.4 MEuro for LabTASTE.

To summarize, we propose a multi-purpose discovery experiment to search for axions and other hypothetical light particles, predicted by extensions of the Standard Model of particle physics and motivated by recent astrophysical observations. Our projected device, with its total cost on the scale of ~ 5 MEuro, would test, on the timescale of less than 5 years, several models of the anomalous transparency of the Universe, dark matter and even dark energy, as well as a particular part of the parameter space relevant for the axion solution of the strong CP problem.

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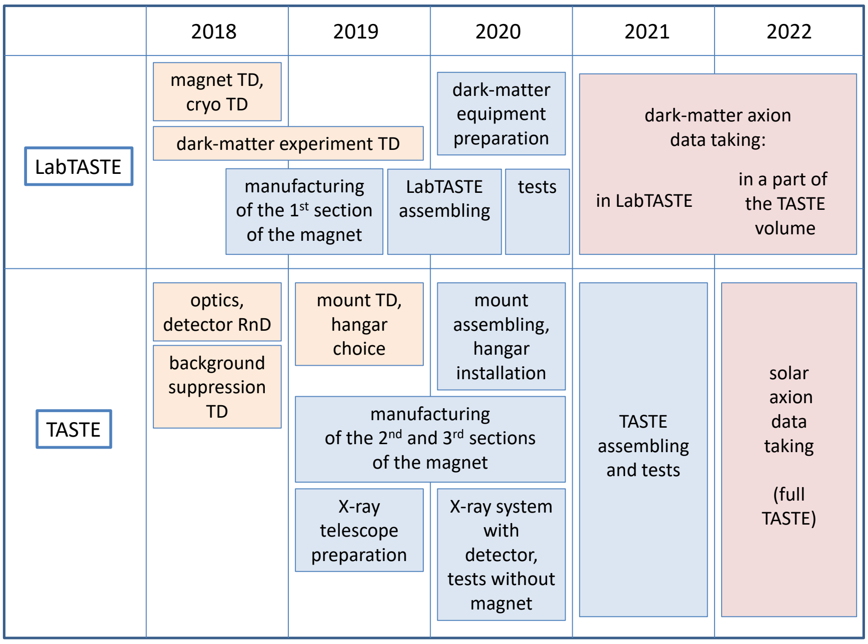

Figure 2: TASTE estimated timeline.

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