Dark Matter – a light move

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This proceedings contribution reports from the workshop Dark Matter - a light move, held at DESY Hamburg in June 2013. Dark Matter particle candidates span a huge parameter range. In particular, well motivated candidates exist also in the sub-eV mass region, for example the axion. Whilst a plethora of setups searches for rather heavy Dark Matter particles, to this date only very few experiments aimed at direct detection of sub-eV Dark Matter exist. The aim of our workshop was to discuss if and how this could be changed in the near future.

1 Introduction and light Dark Matter theory

The standard model of particle physics (SM) has passed its last test with the recent discovery of the Higgs boson, but it is still incomplete as a full theory of nature. The most urgent claim of physics beyond the SM is the existence of non-baryonic dark matter (DM) in the Universe, most likely new particles whose nature we have failed to unveil so far. Extensions of the SM originally proposed to convert it in a more natural choice among conceivable theories, suggest a few DM candidates: weakly-interacting massive particles (WIMPs) or the axion, among the best motivated. To date, a major part of the community hopes for direct detection of DM in experiments aiming to record the recoil energy of nuclei after scattering with DM particles. This strategy is optimal for WIMPs with masses $\gtrsim 100$ GeV but leaves out very light DM candidates such as the axion, searched for by just one experiment (of a very different nature): ADMX. While there are great chances of discovering WIMPs in the near future, ADMX can only cover a part of all the viable axion DM parameter space. Moreover, axions are just an example of a broad class of particles, weakly-interacting slim particles (WISPs), that share most of their phenomenology [1]. In particular, WISPs are excellent DM candidates [2]. New experiments have been proposed to search for WISPy DM [3–7], sometimes sensitive to more than one type of DM candidate at a time, e.g. axion-like particles and hidden photons. These novel experiments can explore decades of pristine DM parameter space and pave the road to boost the sensitivity of ADMX-like experiments looking for axions in unexplored parameter regions.

The workshop 'Dark Matter – a light move' took place at DESY Hamburg at June 17th-18th [8] with the purpose of fostering new direct detection experiments looking for axions and other WISPs. The gathering was a blend of theorists and experimentalists expected to team up in selecting the most promising regions of parameter space and realistic set-ups that can cover them. The expertise of the audience was chosen to focus on exploiting the couplings of

WISPs to photons, which present several advantages. At the theoretical level, WISPs appear in well motivated field and string-theory extensions of the SM [9]. Axions and axion-like particles (ALPs) appear as pseudo-Nambu-Goldstone bosons of spontaneously broken global symmetries at high energy scales and as imaginary parts of moduli fields in string-theoretic theories or in general in theories where the sizes of gauge couplings are set by the vacuum expectation value of new fields. Their coupling to photons is of the well-known kind

$$\mathcal{L}_\phi = \frac{\phi}{2\pi f_\phi} F_{\mu\nu} F^{\mu\nu}, \tag{1}$$

where ϕ is the axion(ALP), f_ϕ a symmetry breaking energy scale and $F_{\mu\nu}$ the electromagnetic tensor. The mass of axions(ALPs) depends upon terms that explicitly break the global symmetries. For the axion we have $m_a = 6$ meV$(10^9$ GeV$/f_a)$ while for ALPs such a relation is much more model dependent. Hidden photons (HPs) appear also in field and string-theoretic extensions [10]. Their main interaction with photons is through kinetic mixing

$$\mathcal{L}_\chi = -\frac{\chi}{2} F_{\mu\nu} B^{\mu\nu}, \tag{2}$$

where $B^{\mu\nu}$ the HP field-strength and χ is the kinetic mixing, with typical values in the $10^{-12} \sim 10^{-3}$ range. WISPy cold dark matter can be produced in the early Universe by a variety of mechanisms. The most relevant are the misalignment mechanism and the decay of topological defects. The regions of mass-coupling parameter space where the full DM can be accounted for the different cases were summarized in the workshop and is shown in figs. 1 and 2. The most important constraints on WISPy DM come from: non-observation of WISP DM decay, absorption of WISP DM in the early universe plasma and indirect effects on stellar cooling (non-DM WISP emission), from refs. [10,11] which we have shadowed in black in the figures. A DM WISP background imprints generically isocurvature anisotropies (generated during inflation) in the cosmic microwave background which have not been observed, imposing strong constraints in WISP DM models and the parameters of inflation [12]. Finally, the WISPy DM paradigm could be particularly well tested because WISPs can form a Bose-Einstein condensate [13] and thus lead to the formation of peculiar caustics in galaxies [14], which could have already been observed [15].

2 Detecting WISPy DM

DM axions(ALPs) mix with photons in a background magnetic field (strength B) with an angle

$$\chi_\phi = \frac{g_{\phi\gamma} B}{m_\phi} \quad \text{(generic ALP)} \quad ; \quad \chi_a = \frac{g_{a\gamma} B}{m_a} \sim 10^{-15} \left(\frac{B}{10 \text{ T}} \right) C_{a\gamma} \quad \text{(axions);} \tag{3}$$

with $C_{a\gamma} \sim \mathcal{O}(1)$, while for HPs the angle is simply χ. The local density of DM, 0.3 GeV/cm^3 implies an electric field $|E| \sim 2.3 \times \chi$ kV/m and it holds for the DM mass m, and its frequency, $f = 240$MHz $\times (m/\mu\text{eV})$. The E-field carried by the DM WISP drives reflected waves from mirrors, emitted perpendicularly to the surface to a large degree due to the spatial coherence of DM waves [6]. The simplest experiment to concentrate this radiation is a spherical dish with a detector at its center, getting a radiated power per dish area $\sim \chi^2 |E|^2 = 1.4 \times 10^4 \chi^2$ W and $\sim 10^{-27}(B/10 \text{ T})^2 C_{a\gamma}^2$ W for axions (note that for axions and HPs, the radiated power is independent of the mass).

The emitted power can be amplified in a resonant cavity up to a factor of 10^6 (the width of the DM energy distribution) but since the WISP mass is unknown, one is forced to scan over frequencies in search for the tiny signal [16]. ADMX [17] is nowadays the only haloscope [18] of this kind. It employs a cylindrical cavity tunable with internal rods inside a 8T solenoid. Its dimensions (1 m long, 0.5 m diameter) set its lowest resonant frequency 0.48 GHz ($m = 2~\mu eV$). ADMX has already taken data in the $2 - 3.6\mu eV$ mass range with a low-noise SQUID amplifier reaching a system temperature $T_S \sim 3K$. Cooling with a dilution refrigerator is planed to achieve $T_S \sim 200\mu K$, which will be used to scan over masses with unprecedented sensitivity (ADMX-II). The first two cavity harmonics will be scanned in parallel, masses $2-9\mu eV$. R&D is taking place at Yale U. to produce haloscopes sensitive at higher masses (to cover the Scenario-I, see fig. 1 left hand panel) using superconducting hybrid cavities and Josephson parametric amplifiers working below the quantum limit (ADMX-HF). A first setup will take data in the 4-8 GHz range ($17 - 33\mu eV$) and new designs are being pushed with the ambition to cover up to 20 GHz. These prospects are shown in figs. 1 & 2 as green regions, IAXO is elaborated in the next section.
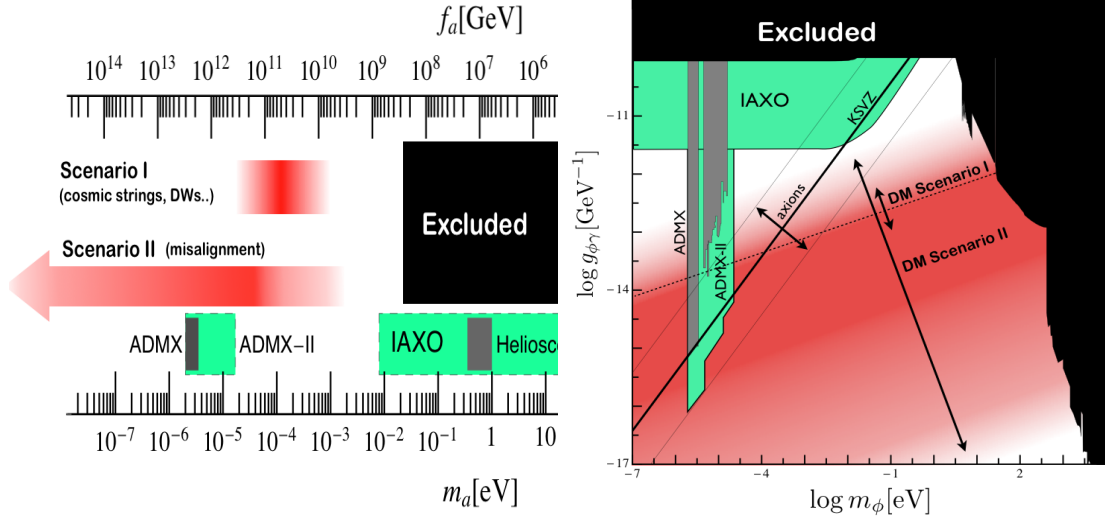

Figure 1: Parameter space for axions (left), ALPs (right) where they can account for the cold DM of the Universe together with excluded regions and the forecasts of ADMX and IAXO [19].

3 New experiments

Listening at the workshop to the future plans of ADMX, it was quickly realized that rather than competing with ADMX in the 2-10 μeV mass range search for axions, the community would benefit of complementing it at different mass ranges and developing new approaches such as the dish-antenna experiment. First efforts in the first direction have started with WISPDMX [20], a cavity experiment [16] based on a HERA proton accelerator cavity. Two modes at 208 and 437.3 MHz (~ 0.9 and 1.8 μeV mass) will be recorded simultaneously with a tunning range $\sim 2\%$ provided by 5 plungers. A HP run is foreseen next year and magnet options for an

axion(ALP) search at DESY or CERN were discussed. At the latter facility, the considerable experience in microwave light-shining through a wall setups [21] could be used to boost the sensitivity and tuning range.

An exciting opportunity to look for WISP DM could also arise with IAXO, see [19]. IAXO's main purpose is detecting the solar axion flux, but the required toroidal magnet could host one or several long-cavity experiments or dish-antenna searches. The intense B-field (up to 5 T), the gigantic volume (8 cylindrical bores 20 m long and 0.6 m diameter) and the already implemented cryogenics are very desirable for DM searches. A long rectangular cavity (up to 20 m long and 0.42 m wide) can be fit into one bore and scan masses above 1.5 μeV in the spirit of ref. [3]. Tuning strategies are under discussion. As a pathfinder experiment, it was proposed to install such a wave-guide in the HERA dipole used by the ALPS experiment for its light-shining-through walls experiment[1], aiming at higher masses ($\sim 20 \mu$eV). Such an experiment is under discussion. Among the workshop participants, expertise in cavity construction, tuning, operation and signal detection was quickly put forward.

A good amendment to the cavity option could be a broadband dish search [6], see also the next section. A good deal of the workshop addressed the possible detector options for this undertaking.

4 A little workshop aftermath

In addition to WISPDMX at DESY, a small collaboration has formed from workshop participants to realize the first dish-antenna experiment searching for HP (and eventually ALP) DM. It will be a proof-of principle experiment: quick and cheap but having still an acceptable reach in the WISP Dark Matter parameter space. For this goal, we have successfully applied for additional support from the Helmholtz Alliance for Astroparticle Physics.

The most promising range for such a setup is the mm-wavelength regime (meV mass). The unexplored allowed parameter range for HP DM starts at rather large couplings $\chi \sim 10^{-9}$ whilst for the ALP DM, available detector sensitivities are promising to tackle viable parameter range. However, good detectors in the millimeter range are costly and less sensitive than in the optical regime. Due to this
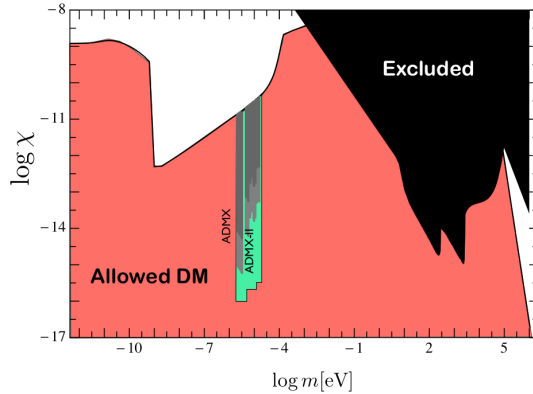

Figure 2: Parameter space for HPs where they can account for the cold DM of the Universe. Also shown are excluded regions and the forecasts of ADMX and IAXO.

fact, and due to the fact that the collaborators of this project are highly experienced in optical techniques, the dish/mirror Dark Matter search will be performed in the optical regime. With available equipment, eV photons down to $\chi \sim 10^{-12}$ should be accessible.

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[1]For the HERA magnet at the magnet test-bench, the cavity option would profit from the fact that the beam-pipe was straightened for the future second ALPS setup [22].

For the search for ALPs, the mirror setup will be embedded in a magnetic field. The unprobed parameter range for ALPs in the optical regime is even harder to tackle than for HPs. However, running the envisaged setup also in a magnet environment (superconducting solenoids with large bore are in principle available at DESY) will yield insight in the experimental complications arising from this demand and eventually pave the way for a dedicated ALP DM search in the mm-wavelength regime.

In summary, there are many experimental options available to check the sub-eV range for Dark Matter – we look forward to see more such options realized and to eventual findings that could solve the Dark Matter puzzle.

5   Acknowledgments

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