WISPers from the Dark Side: Radio Probes of Axions and Hidden Photons

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Measurements in the radio regime embrace a number of effective approaches for WISP searches, often covering unique or highly complementary ranges of the parameter space compared to those explored in other research domains. These measurements can be used to search for electromagnetic tracers of the hidden photon and axion oscillations, extending down to $\sim 10^{-19}$ eV the range of the hidden photon mass probed, and closing the last gaps in the strongly favoured 1–5 μeV range for axion dark matter. This provides a strong impetus for several new initiatives in the field, including the WISP Dark Matter eXperiment (WISPDMX) and novel conceptual approaches for broad-band WISP searches in the 0.1–1000 μeV range.

1 WISP in the radio regime

The scope of experimental studies of dark matter (DM) has been expanding steadily towards low energies and to weakly interacting slim particles (WISP) [1, 2, 3] such as axions, axion-like particles (ALP) and hidden photons (HP). Best revealed by their coupling to standard model (SM) photons, the WISP may give rise to dark matter for a broad range of the particle mass and the photon coupling strength [4] as indicated by red lines in Fig. 1. At particle masses above $\sim$ 10^{-3} eV, the existing constraints effectively rule out WISP as DM particles, while there are very few measurements reaching sensible exclusion levels at lower energies. This domain corresponds to the radio regime at frequencies below 240 GHz where highly sensitive measurement techniques are developed for radioastronomical measurements, with typical detection levels of $\lesssim 10^{-22}$ W. Such sensitivity provides excellent opportunities for laboratory [5, 6, 7] and astrophysical [8] searches for WISP of both cosmological (dark matter) and astrophysical origin (photon-WISP conversion). The dependence of the latter signal in HP on the distance to the target object also offers a unique tool for reaching particle masses down to $\lesssim 10^{-18}$ eV [9] (see Fig. 1).

2 Astrophysical measurements

Astrophysical measurements in the radio can broaden substantially the range of parameter space probed for ALP and HP. Analysis of the WMAP CMB measurements in the radio domain at frequencies above 22 GHz has already provided excellent ALP and HP bounds down to masses
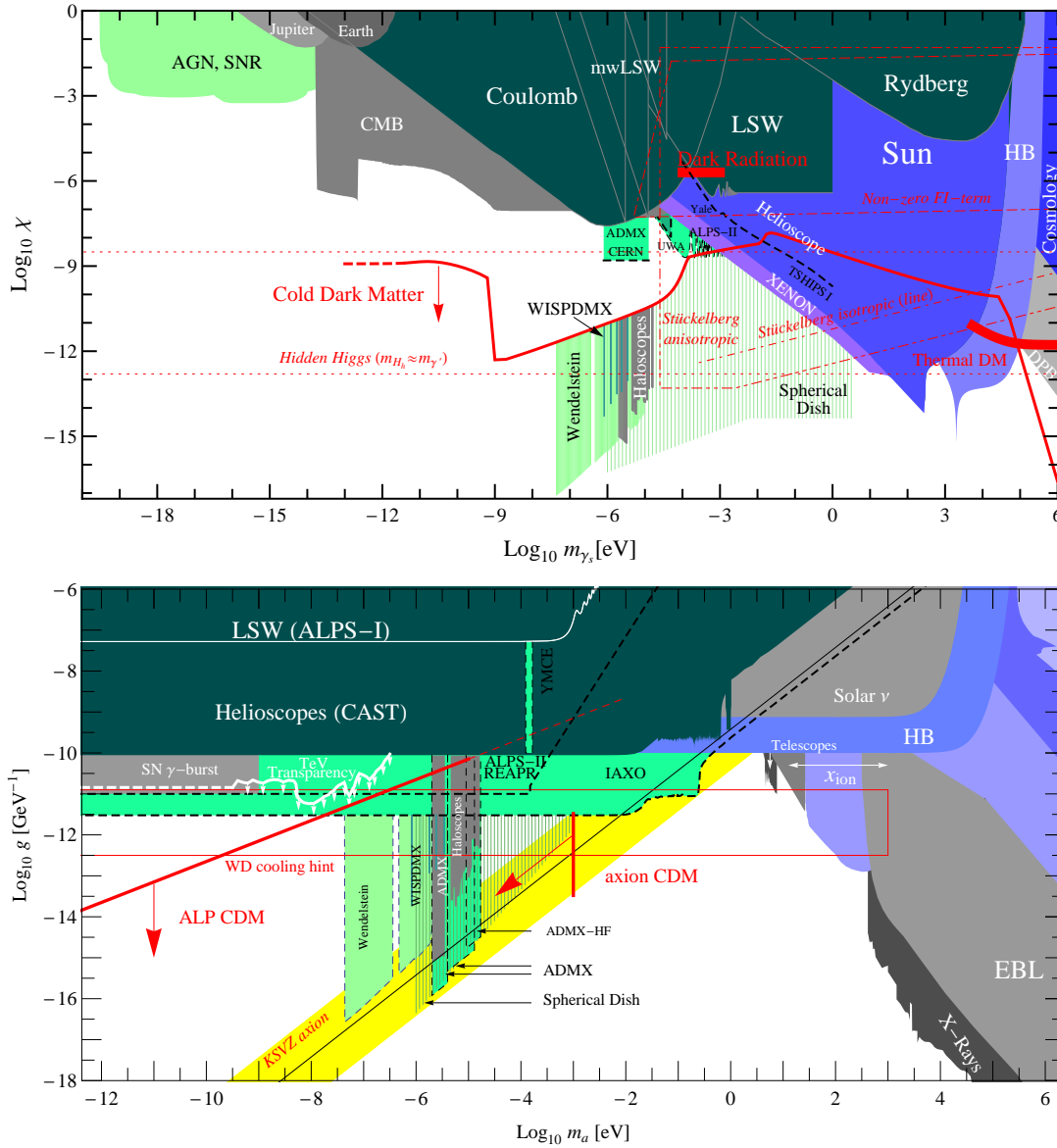
Figure 1: Exclusion limits for hidden photon (top) and ALP (bottom) couplings to SM photons. Existing measurements are indicated with gray/blue/dark green shades and white captions. Expected limits from future measurements are indicated with light green shades and black captions. The yellow band in the axion plot marks properties of the QCD axion. Red color indicates theoretical constrains for hidden photon and axion production and expectations for dark matter and dark radiation (for hidden photons) produced by hidden photons (figures adapted from [3]).

of 2×10^{-14} eV [10, 11]. Dedicated radio astronomical measurements at frequencies below 22 GHz should extend axion searches to masses below 10^{-9} eV and probe coupling constants down to 10^{-14} GeV^{-1} [12]. Signals from relic DM axions can be detected in the spectra of isolated neutron stars [8] and possibly also in pulsars.

2.1 Hidden photon signals in compact radio sources

For hidden photons (γ_s), radio observations at frequencies below 22 GHz offer an excellent (if not unique) tool for placing bounds on the mixing angle χ for m_{γ_s} down to $\approx 10^{-18}$ eV [9]. Existing data are sufficiently accurate for detection of kinetic mixing angles χ down to ~ 0.01, yielding presently a weak hint for a possible oscillatory signal with $\chi \approx 0.02$ in the 2–5 $\times 10^{-16}$ eV energy range. As adverse systematic effects mimicking the signal cannot be presently excluded, this indication should be verified. Placing better bounds on χ down to $\lesssim 10^{-3}$ can be made by using the expanded capabilities of the next generation radio astronomical facilities [9].

3 Laboratory experiments

Laboratory experiments using resonant microwave cavities at frequencies between 0.5 and 34 GHz have yielded the best sensitivity achieved for HP and ALP dark matter at masses below 10^{-3} eV [13]. While capable of reaching the fundamental sensitivity levels, these experiments are slow in scanning over large ranges of mass. Novel and fast broadband measurement techniques are critically needed here.

3.1 Microwave cavity experiments

Building on the success of the ADMX axion DM searches [5, 6, 13] covering the 2-5 μeV energy range, a WISP Dark Matter eXperiment has been initiated at DESY and the University of Hamburg, aiming at covering the 0.8-2 μeV energy range. The experiment utilizes a 208-MHz resonant cavity used at the DESY HERA accelerator and plans to make use of the H1 solenoid magnet. The cavity has a volume of 460 liters and a resonant amplification factor $Q = 46000$ at the ground TM$_{010}$ mode. The H1 magnet provides $B = 1.15$ T in a volume of 7.2 m^3. The signal is amplified by a broad-band 0.2–1 GHz amplifier with a system temperature of 100 K. Broad-band digitization and FFT analysis of the signal are performed using a commercial 12-bit spectral analyzer, enabling measuring at several resonant modes simultaneously.

Since the bandwidth of a single measurement is $\propto Q^{-1}$, the resonant modes of the cavity must be tuned in order to enable scanning over a sizable range of particle mass. The tuning will be done with a plunger assembly providing a ~ 2 MHz tuning range at the ground mode. The expected exclusion limits are shown in Fig. 1.

3.2 Experimental concepts for broad-band searches

The exceptional sensitivity of microwave cavity experiments comes at the expense of rather low scanning speeds (~ 10 MHz/year for WISPDMX), which makes it difficult to implement this kind of measurements for scanning over large ranges of particle mass. To overcome this difficulty, new experimental concepts are being developed that could relax the necessity of using the resonant enhancement and working in a radiometer mode with an effective $Q = 1$.

The measurement bandwidth of radiometry experiments is limited only by the detector technology, with modern detectors employed in radio astronomy routinely providing bandwidths in excess of 1 GHz and spectral resolutions of better than 10^6.

One possibility for a radiometer experiment is to employ a spherical dish reflector that provides a signal enhancement proportional to the area of the reflector [7]. Another possibility is to use the combination of large chamber volume and strong magnetic field provided by superconducting TOKAMAKs or stellarators such as the Wendelstein 7-X stellarator in Greifswald (providing $B = 3\,T$ in a $30\,\mathrm{m}^3$ volume). The exclusion limits expected to be achievable with the spherical reflector and stellarator experiments are shown in Fig. 1.

Deriving from the stellarator approach, a large chamber can be designed specifically for the radiometer searches, with the inner walls of the chamber covered by fractal antenna elements providing a broad-band receiving response and also enabling directional sensitivity to the incoming photons (through high time resolution enabling phase difference measurements between individual elements).

Further exploration of these approaches should ultimately enable performing definitive searches for hidden photon and axion/ALP dark matter in the 10^{-7}–10^{-3} eV mass range.

Acknowledgments

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