Bounds on Light Dark Matter

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In this talk we review the existing cosmological and astrophysical bounds on the light (with the mass in keV – MeV) range and super-weakly interacting dark matter candidates. A particular attention is paid to the sterile neutrino DM candidate.

The nature of Dark Matter (DM) is one of the most intriguing questions of particle astrophysics. Its resolution would have a profound impact on the development of particle physics beyond its Standard Model (SM). Although the possibility of having massive compact halo objects (MACHOs) as a dominant form of DM is still under debates (see recent discussion in [1] and references therein), it is widely believed that DM is made of non-baryonic particles. Yet the SM of elementary particles does not contain a viable DM particle candidate – massive, neutral and long-lived particle. Active neutrinos, which are both neutral and stable, form structures in a top-down fashion [2], and thus cannot produce observed large scale structure. Therefore, the DM particle hypothesis implies the extension of the SM. Thus, constraining properties of the DM, helps to distinguish between various DM candidates and may help to differentiate among different beyond the SM models (BSM). *What is known about the properties of DM particles?*

A lower bound on the mass of DM particle. The DM particle candidates have very different masses (for reviews see e.g. [3]). Quite a robust and model-independent *lower bound* on the mass of DM particles was suggested in [4]. The idea was based on the fact that for any fermionic DM the average phase-space density (in a given DM-dominated, gravitationally bound object) cannot exceed the phase-space density of the degenerate Fermi gas. This argument, applied to the most DM-dominated dwarf spheroidal satellites (dSph's) of the Milky Ways leads to the bound $m_{\rm DM} > 0.41$ keV [5].

For particular DM models (with the known primordial velocity dispersion) and under certain assumptions about the evolution of the system which led to the observed final state, this limit can be strengthened. This idea was developed in a number of works (see e.g. refs. in [5]).

Decaying DM. For any DM candidate there should exist a mechanism of its production in the early Universe. Although it is possible that the DM is produced through interactions with the non-SM particles only (e.g. from the inflaton decay) and is inert with respect to all SM interactions, many viable DM candidates are produced via interaction with the SM sector. According to this interaction the DM candidates can be subdivided into *annihilating* and

decaying ones. The annihilating DM candidates – WIMPs [6] – are well studied. A decaying DM candidate should be *superweakly* interacting (i.e. weaker than electroweak), otherwise it cannot have a cosmologically long lifetime. There are many examples of *super-WIMP* DM models: sterile neutrinos [7], gravitino in theories with broken R-parity [8], light volume modulus [9], Majoron [10]. All these candidate posses a 2-body decay channel: DM $\to \gamma + \nu, \gamma + \gamma$. Therefore, searching for a monochromatic decay line in the spectra of DM-dominated objects provides a way of *indirect detection* of the DM or helps to *constrain* its interaction strength with the SM particles.

The astrophysical search for *decaying* DM is in fact more promising. Moreover, the positive result would be much more conclusive, than in the case of annihilating DM. Indeed, the decay signal is proportional to the *column density*: $\int \rho_{\mathrm{DM}}(r) dr$ along the line of sight and not to the $\int \rho_{\mathrm{DM}}^2(r) dr$ (as it is the case of the annihilating DM). As a result *(i)* a vast variety of astrophysical objects of different nature would produce roughly the same decay signal [11, 12]; *(ii)* this gives a freedom of choosing the observational targets, allowing to avoid the complicated astrophysical backgrounds (e.g. one does not need to look at the Galactic center, expecting a comparable signal from dark outskirts of galaxies and clusters and dark dSph's); *(iii)* if a candidate line is found, its surface brightness profile may be measured (as it does not decay quickly away from the centers of the objects), distinguished from astrophysical lines (which usually decay in outskirts) and compared among several objects with the same expected signal. This makes astrophysical search for decaying DM *another type of a direct detection experiment*.

A search of the DM decay signal was conducted both in the keV – MeV range [11, 13] and in GeV range [12]. The aggregate constraints on the decaying DM lifetime (towards the radiative decay) are shown on Fig. 1
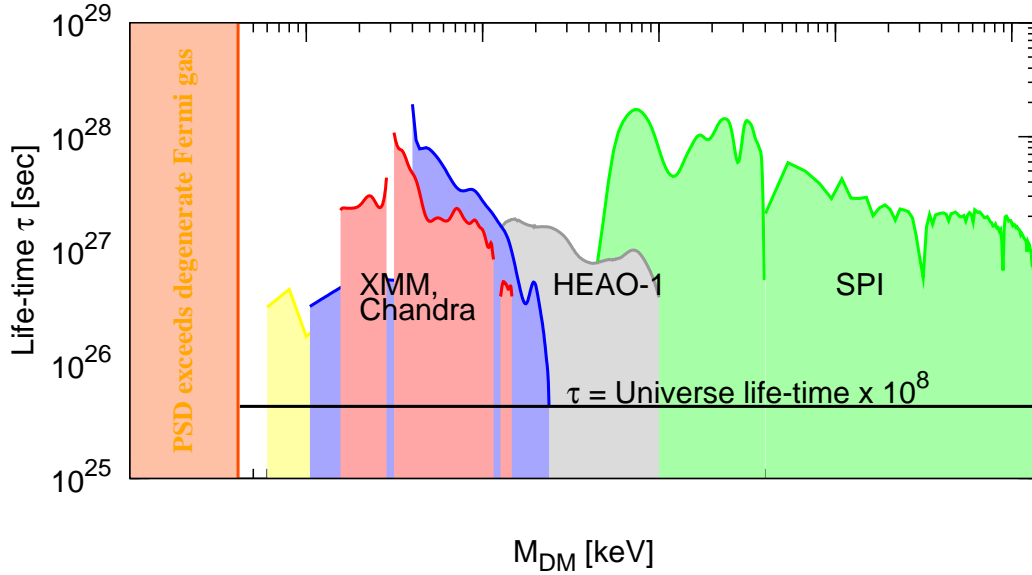

Figure 1: Restrictions on the lifetime of the radiatively decaying DM (based on [11, 13]). The lifetime exceeds the age of the Universe by at least 10^8.

Ly-α constraints. The fable strength of interaction of light super-WIMP particles often means that they were produced in the early Universe in a non-thermal way and decoupled deep into the radiation dominated (RD) epoch, while still being relativistic. This makes these particles *warm DM* candidates (WDM) (see e.g. [14]).

An important way to distinguish between WDM and CDM models is the analysis of the Lyman-α (Ly-α) forest data (for an introduction see e.g. [15]). Although very promising, the Ly-α method is very complicated and indirect. As at redshifts, probed by Ly-α, the evolution of structure already enters a non-linear stage, to relate measured power spectrum with the parameters of each cosmological model, one would have to perform prohibitively large number of numerical simulations. Therefore, various simplifying approximations have to be realized (see e.g. [16]). Apart from computational difficulties, the physics, entering the Ly-α analysis is not fully understood, as it is complicated and can be significantly influenced by DM particles [18]. Bayesian approach, used to fit the cosmological data, should also be applied with caution to put bounds on the particle physics parameters [17].

In many super-weakly interacting DM models, due to the non-thermal primordial velocity distribution, the linear powerspectrum (PS) (used as initial conditions in Ly-α analysis) has complicated non-universal form. The analysis of [26] assumed PS with a cut-off at small scales, defined by the particle's velocities. These results are not applicable for many models of decaying DM. For example, in a number of models (sterile neutrinos, gravitino) the primordial velocity distribution is a mixture of colder and warmer components and the PS develops a plateau at small scales. This makes much smaller masses compatible with Ly-α bounds. For these smaller masses it is important to take into account explicitly the primordial velocities of the particles (and not only their effect on the PS). See detailed analysis [17].

Sterile neutrino DM. Although known as a DM candidate for some 15 years [7], the sterile neutrino DM recently attracted a lot of attention. It was shown [19] that if one adds three right-handed (sterile) neutrinos to the SM, it is possible to explain simultaneously the data on neutrino oscillations, the DM in the Universe and generate the correct baryon asymmetry of the Universe without introducing any new physics *above electro-weak scale*. The lightest (DM) sterile neutrino can have mass in keV-MeV range and be coupled to the rest of the matter weakly enough to provide a viable (*cold* or *warm)* DM candidate. This model, explaining the three observed BSM phenomena within one consistent framework, is called *the νMSM* [19, 20].

There are several mechanisms of production of DM sterile neutrino in the early Universe: non-resonant active-sterile neutrino oscillations (**NRP**) [7, 21], resonant oscillations in the presence of lepton asymmetry (**RP**) [22, 23], decay of the gauge-singlet scalar field [24] (see also [25]). The Ly-α analysis was performed so far only for NRP scenario, and the results were claimed to be in the range $5 - 15$ keV (see also [17]). Phase-space density bounds, applied to the NRP scenario lead to the $m_{\mathrm{NRP}} > 1.77 - 4$ keV.

Combining various constraints we see that there is a tension between the NRP scenario and the data (X-ray bounds and phase-space density arguments). For the RP mechanism a large window of allowed parameters remain open. These results are summarized on Fig. 2

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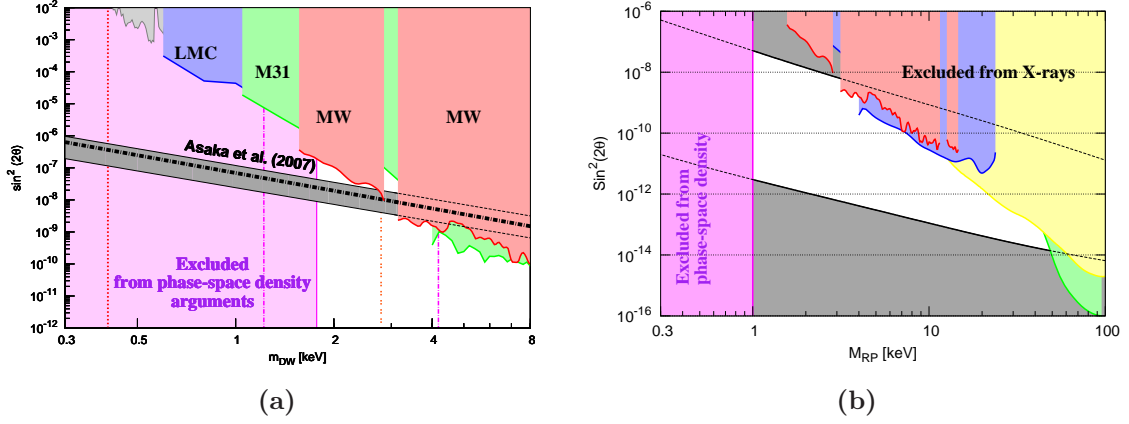[2] Y. B. Zel'dovich, A&A **5**, 84 (1970).

Figure 2: Restrictions on sterile neutrino DM in NRP (left) and RP (right) scenarios.

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