PROCEEDINGS OF SCIENCE

# Dark Matter candidates, light and heavy

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I very briefly mention the main candidates for Dark Matter, and their general properties.

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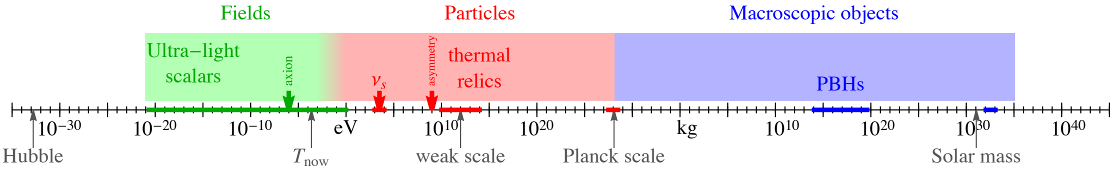

**Figure 1:** Possible range for the DM mass, and some notable candidates. The edges of the shaded areas correspond to the lower and upper bounds in eq. (1). Figure from [1].

## 1. Introduction

Dark Matter (DM) has been eluding the searches since many decades now. One of the reasons for this is that cosmological and astrophysical observations, while compelling on the evidence for its existence, are essentially silent on its properties, other than the basic ones (electrical neutrality, stability, coldness and being feebly interacting). Hence the candidates can span many orders of magnitude in any direction of the parameter space. One of these directions, which is convenient to use to organize the discussion, is the one of the DM mass.

The 'in-principle-viable' range of DM masses $M$ spans more than 90 orders of magnitude[1]

$$10^{-21}\ \text{eV} < M < 10^{37}\ \text{kg}. \tag{1}$$

The edges and the benchmarks in this range stem from the following considerations. First of all, the DM particle has to be heavier than $10^{-21}$ eV. This lower limit is determined by the request that the De Broglie wavelength $R = 2\pi/Mv$ of a DM particle fits within the small gravitationally bound dwarf galaxies (which typically have kpc size, velocity $v \sim 10$ km/s and mass $\sim 5 \times 10^5\ M_\odot$, where $M_\odot \simeq 2 \times 10^{30}$ kg is the solar mass). Second, an upper bound is provided by the fact that the DM mass must be somewhat smaller than the mass of a typical small dwarf galaxy: since these have masses of the order of few $10^5\ M_\odot$, one can conservatively impose $M \lesssim 10^4\ M_\odot$, to make sure that a sufficient number of DM 'particles' inhabit the dwarfs.[2]

This huge range can be conceptually split in three main qualitatively different regions, illustrated in fig.1: fields, particles and macroscopic objects. Fundamentally, particles and waves (fields) are the same objects, since Quantum Field Theory unifies them in a common description. From a practical point of view, however, descriptions using particles or waves are different enough to be useful in different regimes. As a rule of thumb, Dark Matter behaves as a classical field if $M \lesssim$ eV, and as a particle if $M \gtrsim$ eV. If it is a particle, DM can consist of a very large number of very light particles or, alternatively, of a much smaller number of much heavier particles, or anything in between, and these possibilities are compatible with all the observations. The allowed range of DM masses does depend, though, on whether the DM particle is a fermion or a boson. Fermionic DM is subject to the Pauli exclusion principle, which leads to a lower bound on DM mass, first derived by

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[1] One can similarly discuss the possible range for the strength of the interaction between DM and ordinary matter, which spans about 20 orders of magnitude from the minimal gravitational interaction $g \sim M/M_{\rm Pl}$ up to strong-interaction-like couplings $g \sim 4\pi$. See [2] for the graphical representation of this range.

[2] It is worth emphasizing that the absolute lower and upper limits of allowable DM mass $M$ arise from rather robust and model-independent considerations since they use just the basic properties of dwarf galaxies, the smallest astrophysical structures known to host Dark Matter.

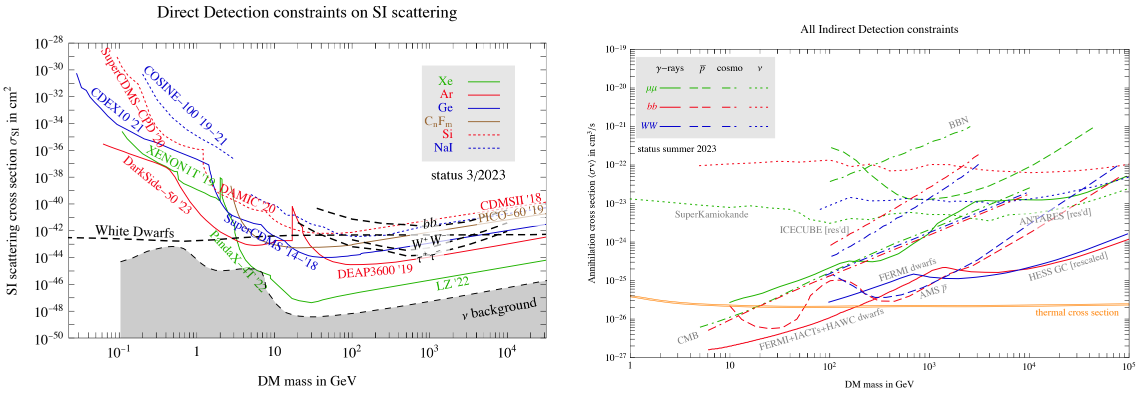

**Figure 2:** Status of the searches for WIMPs. Left: direct searches for Spin Independent scattering. Right: indirect detection searches. Figure from [1].

Gunn and Tremaine. A detailed study of dwarf spheroidal galaxies finds that fermionic DM must have $M > 0.1$ keV. DM can be heavier than the Planck mass, if it takes the form of a composite object. As the hypothetical mass increases, at some point black holes (BH) are the fundamental objects, hence DM could be made of BH.

Within this huge range, fall several candidates or classes of candidates. Their underlying motivations can be theoretical, phenomenological or just opportunistic. Still, till one of them is proven right or disproved, they are all legitimate choices. In the following, I will review some of these candidates, in a somewhat biased way.

## 2. Weak scale Dark Matter

Weakly Interacting Massive particles (WIMPs), i.e. with a mass around the weak scale ($\approx$ 100 GeV – 1 TeV) and interacting via the weak force (or, by extension, a weak-like force), are motivated by two disconnected theoretical reasons: i) the fact that they are produced in the right abundance via the thermal freeze-out mechanism in the Early Universe (a fact that is sometimes referred to as the *WIMP miracle*) and ii) the expectation that new physics would show up at the weak scale, to solve the hierarchy problem of the Standard Model, and, as a by product, WIMP DM particles are (were?) foreseen. It is important to stress that the two motivations are independent: even if new physics (e.g. in the form of supersymmetry) does not show up at the weak scale, the thermal production mechanism remains compelling. So, while true that WIMPs are not as popular as some decades ago, they do remain a well-motivated DM candidate.

Another ingredient of the huge success of WIMPs as DM candidates lies in the more opportunistic fact that they can be searched in a number of different ways. Except for searches at colliders, a summary of the current status of the limits from the main searches is presented in fig. 2: the so-called *direct detection searches* (left) rely on detecting the scattering of a DM particle in a nuclear recoil experiment and constrain the scattering cross-section as a function of the DM mass; the so-called *indirect detection searches* (right) hope to identify an excess in cosmic rays due to DM annihilations (or decays) in space and constrain the annihilation cross-section.

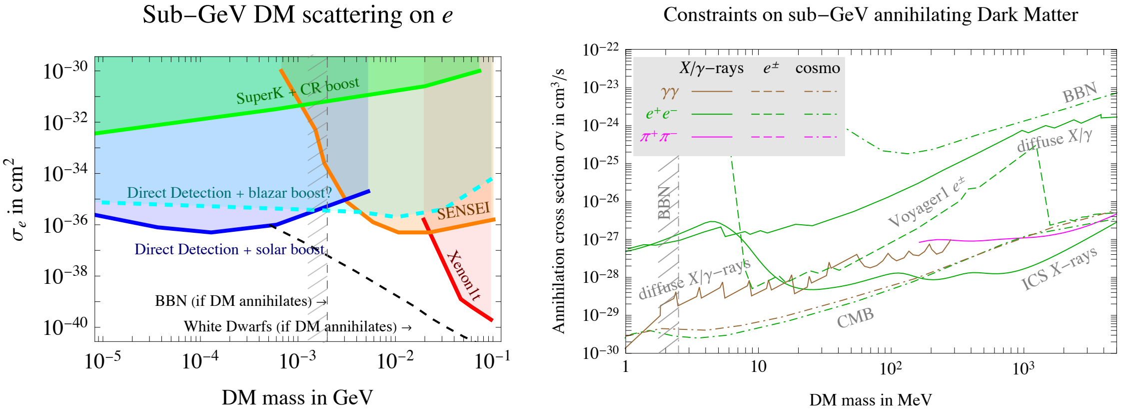

**Figure 3:** Status of the searches for sub-GeV Dark Matter. Left: direct searches for scattering on electrons. Right: indirect detection searches. Figure from [1].

## 3. Sub-GeV Dark Matter

The possibility that DM consists of a *light* particle has gained increasing attention recently (for definiteness we fix here the mass between a few MeV and about a GeV). While searches for DM have long been dominated by the paradigm of WIMPs, as mentioned above, the lack of convincing WIMP signals so far has turned the attention to lighter candidates.

In Direct Detection, most current experiments lose sensitivity for DM masses below $\sim 1$ GeV, because detecting the small amounts of energy deposited by DM via nuclear recoils becomes ineffective for DM much lighter than a typical nucleus. However, many significant efforts are underway to explore the sub-GeV regime. This includes extending the sensitivity of ‘traditional’ nuclear recoil detectors to ultra-low energy thresholds and exploiting the production of detectable signals via DM-electron scattering or the Migdal effect (the signal induced by the below-threshold shaking of a nucleus). In Indirect Detection, concerning charged particles the problem is that solar activity holds back sub-GeV charged cosmic rays and therefore we have no access to them. The only exception to this point is the use of data from the Voyager spacecraft, which is making measurements outside of the heliosphere, and produces relevant bounds. Concerning gamma-rays, the sensitivity of the most powerful of the recent telescopes has a gap (known as the ‘MeV gap’) in the relevant range for the search of this kind of DM, and therefore few constraints exist.

Another possibility for the ID of such light DM is to look for the Inverse Comptons X-rays produced by the energetic $e^{\pm}$ from DM over the ambient light (e.g. in the Galaxy). This technique turns out to produce some of the most stringent bounds. A summary of the searches is presented in fig. 3.

## 4. Primordial Black Holes

DM could be made of Massive Astrophysical Compact Halo Objects (MACHOs), i.e., ordinary astrophysical objects of macroscopic mass $M$, such as large planets, small dead stars or stray black holes. These objects do not emit light and therefore fulfill the definition of DM. The MACHOs that are composed of baryonic matter *and* were created in the late Universe, like all the other

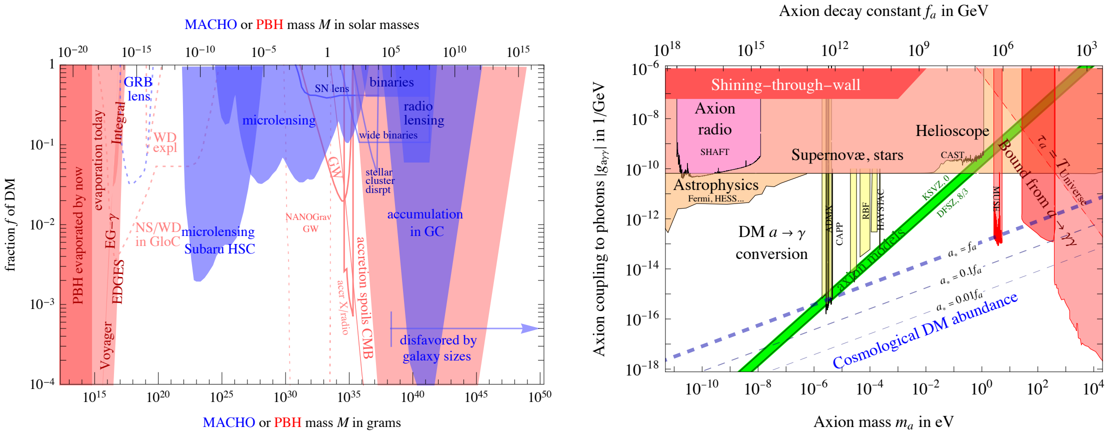

**Figure 4:** Left: limits on DM as primordial black holes and MACHOs. RIght: limits on DM as axions and axion-like particles. Figure from [1].

astrophysical objects (the most natural expectation), require a large baryonic abundance, which contradicts the bounds from BBN and CMB. DM made purely of baryonic MACHOs is thus ruled out. Astrophysical objects that consist of baryonic matter, but have somehow been created *before* BBN, are not subject to the cosmological constraints, since the material that makes them is subtracted from the baryonic budget early on, and can therefore constitute the DM. This is the case of *primordial* black holes (PBHs).

Several phenomenological constraints apply to PBHs as DM candidates, shown in fig. 4 (left). Being very conservative when taking into account the constraints for different ranges of PBH masses, one finds that the PBHs could constitute the whole of Dark Matter ($f = 1$) for

$$10^{-16}\, M_\odot \lesssim M \lesssim 3 \times 10^{-12}\, M_\odot. \tag{2}$$

Black holes at the low end of this range would have radii smaller than the size of an atom and mass comparable to a small asteroid or Mount Everest. On average, roughly one of these PBHs would be expected to be present in the solar system. They would be in the process of Hawking-evaporating right now and therefore can be searched for with cosmic rays.

## 5. Sterile neutrinos

Right-handed neutrinos $N$ with Majorana masses $M$ and Yukawa couplings $y\, NLH$ are one of the simplest extension of the SM. If $M \sim 10^{10}$ GeV, then with $y \sim 1$ one can reproduce the neutrino masses as $m_\nu = y^2 v^2/M$ (where $v$ is the higgs vev) and can generate baryogengesis via leptogenesis in its minimal implementation. Another interesting possibility is a right-handed neutrino with mass $M \approx$ keV, just above the Gunn-Tremaine bound discussed above, because it provides a decaying DM candidate. Indeed, in such a case the Yukawa couplings $y$ can be small enough to make the sterile neutrino stable on cosmological time-scales. Given that $M \ll v$, it is convenient to parameterize the effective theory in terms of the mixing angle(s) between the sterile neutrino and the active neutrinos, $\theta = yv/M \ll 1$. A one-loop decay then gives a detectable photon with rate

$$\Gamma(N \to \nu\gamma) = \frac{9\alpha_{\rm em} G_{\rm F}^2 M^5}{256\pi^4}\theta^2 \approx \frac{\theta^2}{4250\, T_{\rm U}}\left(\frac{M}{\rm keV}\right)^5, \tag{3}$$

where $G_F$ is the Fermi constant and $T_U = 13.7$ Gyr is the age of the Universe.

In 2014, two groups reported an independent detection of an $X$-ray line at $E_\gamma \simeq 3.55$ keV, using observations from XMM-NEWTON and CHANDRA of several galaxy clusters (notably, the flux from the Perseus cluster appeared to be anomalously high) and of the Andromeda galaxy M31. Subsequent works claimed the same signal, albeit with varying degrees of significance, in various other targets: the Galactic Center, patches of the Milky Way halo, other — but not all — clusters, some 'blank-sky' fields,. . . ; and with other telescopes: NUSTAR, SUZAKU. At the same time, other studies claimed no detection, again in various regions: in the GC, patches of the MW halo, dwarf galaxies including Draco, stacked galaxies, individual clusters, . . . .

If it is not of atomic origin, an issue which is highly debated, the 3.5 keV line can be produced by $M \approx 7.1$ keV DM particle decaying according to eq. (3), with a mixing angle $\theta \simeq 10^{-5}$.

## 6. Ultra-light Dark Matter

Provided that the cosmological history leads to a population of *non-relativistic* particles, DM could be a light or ultra-light bosonic field composed of DM particles with any of the allowed light DM masses, from $M \lesssim$ eV down to the minimum value $M \sim 10^{-21}$ eV. Being non-relativistic, these very light bosons dilute like matter during cosmological expansion: although the word 'matter' for such a system might appear bizarre, it has the property needed to be an acceptable DM candidate.

Within this extensive range, one can distinguish two broad classes. In the upper part of the mass range, the light bosons making up DM are known as the *Weakly Interacting Slim Particles (WISPs)*. Several DM candidates fall into this class, including *axions* (which are originally motivated by the solution of the strong CP problem) and *axion-like particles* (which are their extension). Historically, these have been searched for around $M \sim 10^{-6}$ eV, although higher and lower masses are possible. Indeed, more recent experiments are broadening the search, in particular trying to reach down to lighter masses. DM with mass around the lower allowable limit, $M \sim 10^{-21}$ eV, is known instead as *fuzzy DM*. Fig. 4 (right) summarizes the status of the parameter space, in terms of constraints on the effective coupling of these particles with photons.

## 7. Conclusions

The field of Dark Matter is in an *experiment driven* phase. Theory has proposed (and routinely proposes) many diverse candidates, a small fraction of which are discussed here. They are very useful benchmarks, with more or less solid motivations. However, the possible range of masses and interactions is so wide that virtually no list can be considered as exhaustive and searches should continue in all directions.

## References

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[2] M.R. Buckley and A.H.G. Peter, "Gravitational probes of dark matter physics," Phys. Rept. **761** (2018), 1-60 [arXiv:1712.06615 [astro-ph.CO]].