

# Dark Matter Candidates: A Ten-Point Test

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An extraordinarily rich zoo of non-baryonic Dark Matter candidates has been proposed over the last three decades. Here we present a 10-point test that a new particle has to pass, in order to be considered a viable DM candidate: I.) Does it match the appropriate relic density? II.) Is it *cold*? III.) Is it neutral? IV.) Is it consistent with BBN? V.) Does it leave stellar evolution unchanged? VI.) Is it compatible with constraints on self-interactions? VII.) Is it consistent with *direct* DM searches? VIII.) Is it compatible with gamma-ray constraints? IX.) Is it compatible with other astrophysical bounds? X.) Can it be probed experimentally?

## INTRODUCTION

To identify the nature of Dark Matter is one of the most important open problems in modern cosmology. Although alternative explanations have been proposed in terms of modified gravity, the discrepancies observed in astrophysical systems ranging from galactic to cosmological scales appear to be better understood in terms of a dark, yet undiscovered, matter component, roughly 6 times more abundant than ordinary baryons in the Universe (see Refs. [1, 2] for recent reviews).

The possible connection of this exciting problem with New Physics beyond the Standard Model has prompted the proliferation of Dark Matter candidates, that are currently being searched for in an impressive array of accelerator, direct and indirect detection experiments. As our understanding of particle physics and astrophysics improves, we accumulate information that progressively reduces the allowed regions in the DM particles parameter space.

Here, we present a 10-point test that new particles have to pass in order to be considered good DM candidates. We will work under the assumption that a single DM species dominates the DM relic density, while contribution from other species is subdominant; it is straightforward to generalize the discussion to the case of multi-component DM. Furthermore, we will consider a standard  $\Lambda$ CDM cosmological model, although we discuss the consequences of more general models, allowing for instance a non-standard expansion history at the epoch of DM freeze-out.

Each of the following ten points, that represent *necessary* conditions for a particle to be considered a good DM candidate, will be discussed in a dedicated section, where we will review the literature on the subject and present the most recent results. In each section we will discuss how robust the constraints are, especially for those that heavily rely on astrophysical quantities such as the local DM density and velocity distribution, or the extrapolation of DM profiles at the center of galactic halos, often affected by large uncertainties.

A particle can be considered a good DM candidate only if a positive answer can be given to *all* the following points:

1. Does it match the appropriate relic density?
2. Is it cold?
3. Is it neutral?
4. Is it consistent with BBN?
5. Does it leave stellar evolution unchanged?
6. Is it compatible with constraints on self-interactions?
7. Is it consistent with direct DM searches?
8. Is it compatible with gamma-ray constraints?
9. Is it compatible with other astrophysical bounds?
10. Can it be probed experimentally?

The distinction between *gamma-ray constraints* and *other astrophysical bounds*, in points 8) and 9), is rather artificial, and it simply reflects the privileged role of photons in astrophysics, since they propagate along straight lines (unlike charged particles), and they can be detected with better sensitivity than, say, neutrinos. The fact of considering gamma-ray photons is then due to the fact that the decay or annihilation of some of the most common candidates falls in this energy range.

We also note that, strictly speaking, the last point is not really a *necessary* condition, as DM particles could well be beyond the reach of current and upcoming technology. However, measurable evidence is an essential step of the modern scientific method, and a candidate that cannot be probed, at least indirectly, would never be accepted as the solution to the DM puzzle.

## I. DOES IT MATCH THE APPROPRIATE RELIC DENSITY?

The analysis of the Cosmic Microwave Background (CMB) anisotropies is a powerful tool to test cosmological models, and to extract the corresponding cosmological parameters. For instance, the angular position of the peaks in the power spectrum of temperature anisotropies

is a sensitive probe of the curvature of the Universe (see e.g. [3, 4] for a review and a more extended discussion). The power spectrum of CMB anisotropies is fitted within the Standard Cosmological Model with a number of free parameters that depends onto the priors. The best fit of the three years WMAP data, with a 6 parameters flat  $\Lambda$ CDM model and a power-law spectrum of primordial fluctuations, gives [5]

$$\Omega_b h^2 = 0.0223_{-0.0009}^{+0.0007} \quad \Omega_M h^2 = 0.127_{-0.013}^{+0.007}$$

for the abundance of baryons and matter, respectively. The normalized abundance  $\Omega_i$  is defined as  $\Omega_i = \rho_i / \rho_c$ , where  $\rho_c$  is the critical density, and the scaled Hubble parameter  $h$  is defined as  $H_0 \equiv 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ . A joint-likelihood analysis on a larger data-sets including, besides WMAP3, also small scale CMB experiments (BOOMERang, ACBAR, CBI and VSA), Large-Scale Structures (SDSS, 2dFGRS) and SuperNova (HST/GOODS, SNLS), further strengthens the constraints to [6]

$$\Omega_b h^2 = 0.0220_{-0.0008}^{+0.0006} \quad \Omega_M h^2 = 0.131_{-0.010}^{+0.004}$$

Note that the baryonic density is consistent with the determination from big bang nucleosynthesis [7]

$$0.017 < \Omega_b h^2 < 0.024 \text{ (95 \% CL)}.$$

For a new particle to be considered a good DM candidate, a production mechanism that reproduce the appropriate value of the relic density must exist. Moreover, to guarantee its stability, its lifetime must exceed the present age of the Universe. Taking in account the estimates of the Hubble Space Telescope Key Project [8] and in agreement with the result derived by WMAP,  $H_0 = 72 \pm 3$  (statistical)  $\pm 7$  (systematic)  $\text{km s}^{-1} \text{ Mpc}^{-1}$ , we require a lifetime  $\tau \gtrsim 4.3 \times 10^{17}$  s.

In many proposed extensions of the Standard Model of particle physics, the stability of the DM particle is ensured by imposing a symmetry that forbids the decay of DM into Standard Model particles. For example, R-parity in Supersymmetry models (SUSY) [9, 10], K-parity in Universal Extra Dimensions Models (UED) [11], and T-parity in Little Higgs Models [12], prevent the lightest *new* particle in the respective theories from decay (see for example Ref.[13] for a detailed discussion on SUSY DM and Ref.[14] for a review on UED DM).

### Thermal relics

Among the best DM candidates, there is a class of particles called WIMPs (for weakly interacting massive particles), that are thermal relics and naturally achieve the appropriate relic density.

The scenario goes as follows: the WIMP is in thermodynamic equilibrium with the plasma in the early Universe, and it decouples when its interaction rate drops

below the expansion rate of the Universe. For a non-relativistic particle at decoupling, the number density over the entropy density remains frozen, i.e. the thermal relic *freezes-out*. The evolution of the number density of a generic species  $\chi$  in the Universe, is described by the following Boltzmann equation:

$$\dot{n}_{eq} + 3Hn = -\langle \sigma_{ann} v \rangle [n^2 - n_{eq}^2].$$

The second term in the l.h.s of the equation takes into account the dilution of the number density due to the expansion of the Universe.  $\langle \sigma_{ann} v \rangle$  is the thermal average of the annihilation cross section times velocity and it is parametrized with a non-relativistic expansion in powers of  $v^2$ , as:  $\langle \sigma_{ann} v \rangle = a + b\langle v^2 \rangle + \mathcal{O}(\langle v^4 \rangle) \simeq a + 6b/x$ , with  $x \equiv m/T$ .

$n_{eq}$  is the equilibrium density of WIMPs in the plasma at temperature  $T$  and for a non-relativistic specie is given by  $n_{eq} = g(\frac{mT}{2\pi})^{3/2} e^{-\frac{m_\chi}{T}}$ , where  $g$  denotes the number of degrees of freedom of  $\chi$  and  $m_\chi$  is the WIMP mass.

The Boltzmann equation can be solved integrating it in two extreme regions, long before and long after the WIMP freeze-out (e.g. WIMP decoupling), and matching then the solutions. Skipping the calculation details, that can be reviewed e.g. in [15], the relic density today for a generic WIMP  $\chi$  is [1]:

$$\begin{aligned} \Omega_\chi h^2 &\approx \frac{1.07 \times 10^9 \text{ GeV}^{-1}}{M_{Pl}} \frac{x_f}{\sqrt{g_{*f}}} \frac{1}{(a + 3b/x_f)} \\ &\approx \frac{3 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{ann} v \rangle}. \end{aligned} \quad (1)$$

where  $g_{*f}$  counts the relativistic degrees of freedom at the decoupling,  $M_{Pl}$  is the Planck mass and  $x_f \equiv m_\chi/T_f$  with  $T_f$  the freeze-out temperature. The last line is an order of magnitude estimate and it shows that the relic abundance of a non relativistic decoupled specie strictly depends on the annihilation cross section at freeze-out [13]. Furthermore, it has to be noticed that the annihilation cross section, for a particle of given mass, has a maximum, imposed by the partial wave unitarity of the S matrix,  $\langle \sigma_{ann} v \rangle_{max} \sim 1/m_\chi^2$  [35, 36]. Thus, with the use of Eq. 1, the requirement  $\Omega_M h^2 \lesssim 1$  implies the following constraint on the mass of the DM particle, also called "unitarity bound" [35]

$$m_{DM} \lesssim 340 \text{ TeV}.$$

Applying the more stringent constraint, obtained by WMAP, the upper bound on  $m_{DM}$  becomes:

$$m_{DM} \lesssim 120 \text{ TeV}.$$

However, this constraint was derived under the assumption that particles were in thermal equilibrium in the early universe, thus it applies only to thermal relics, and can be evaded by species which are non-thermally produced.

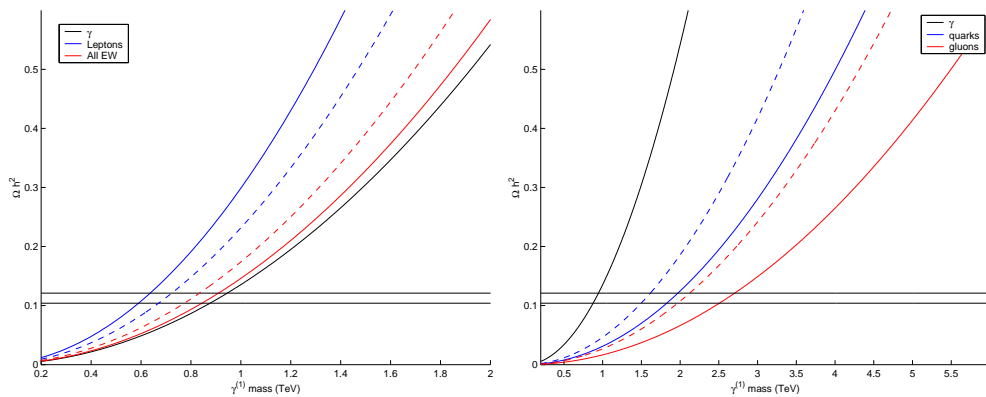


Figure 1: Left: Relic Abundance of  $B^{(1)}$  in the UED model as a function of its mass after including no coannihilation (black line), coannihilation with all leptons (blue) and all electroweak particles (red). For the cases with coannihilation, the solid and dashed lines are computed with a mass splitting  $\delta = 0.01$  and  $0.05$  respectively. Right: The same as in the left panel but accounting for coannihilation of  $B^{(1)}$  with all electroweak particles and quarks (blue line), and all level-one KK particles, including KK gluons (red line). Solid and dashed lines are for a mass splitting  $\delta = 0.01$  and  $0.05$  respectively. From Ref.[22].

The standard computation of the thermal relic abundance discussed above presents three important exceptions, as it has been shown, following previous ideas [16], by Griest and Seckel [17]. They take place for WIMPs lying near a mass threshold, for annihilations near to a pole in the cross section, or in presence of coannihilations. The last effect occur when a particle that shares a quantum number with the WIMP, is nearly degenerate in mass with it. If the mass gap is low enough (roughly  $\lesssim 10\%$ ) the coannihilation reactions, involving WIMP particles, can control the WIMP abundance and lower or enhance it.

Full relic density calculations, including all coannihilations, have been performed e.g. for the supersymmetric neutralino, for which numerical codes such as DarkSUSY [18] and micrOMEGAs [19] are publicly available. Coannihilations have a dramatic effect on the relic density, and they can lower it by a factor of up to several hundreds (see e.g. [20]).

Coannihilations are also important in UED models, where the relic density of the first excited state of the B, which may be the lightest Kaluza-Klein particle (LKP) and a viable DM candidate, may be enhanced or lowered depending on the coannihilation channel [21–23]. See Fig.1.

Deviations from Standard Cosmology can substantially change the picture. For example, due to the presence of scalar fields, the universe may undergo a period of much higher expansion rate and the relic abundance of a WIMP may result increased by several orders of magnitude [24, 25]. Furthermore, the production of entropy in the Universe after the WIMP decoupling may dilute its abundance, e.g. due to out-of-equilibrium decays of non-relativistic particles or to first-order phase transitions [26–29].

It is also possible that DM particles did not experience

the thermal history depicted above, and that they have inherited the appropriate relic density through the decay of a more massive species, that has earlier decoupled from the thermal bath. This is e.g. the case for Super-Weakly Interacting Massive Particles (SWIMP), such as the LSP gravitino in SUSY and the first excitation of the graviton in UED, which are produced by late decays of the next-to lightest particles (NLSP/NLKP) in the respective theories [30–33] and whose relic abundances are simply the rescaled thermal relic densities of the NLPs:

$$\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{NLP}}} \Omega_{\text{NLP}}.$$

Other production mechanisms may actually be concomitant for such candidates, such as the production at reheating after the end of the inflationary era (see e.g. [32, 34]. See also below for a brief discussion of gravitino production).

### Other production mechanisms

Very heavy DM candidates, such as the so-called wimpzillas, have been proposed, with masses as large as  $10^{15}$  GeV, i.e. well above the unitarity limit (see e.g. [37] for a review). For mechanisms that produce these super-massive particles with  $\Omega_{DM} \sim 1$ , departure from thermal equilibrium is automatic [37], and the challenge is not to overproduce them. Several mechanisms have been proposed: for instance they could be created during reheating after inflation, with masses a factor  $10^3$  larger than the reheating temperature [38], or during a preheating stage, with masses up to the Grand Unification scale ( $10^{15}$  GeV) [39] or even to the Planck Scale [40], or again from bubble collisions if the inflation exit is realized by a first-order transition [41]. Another very interesting mechanism is of gravitational nature: wimpzillas may be

created by amplification of quantum fluctuations in the transition between the inflationary regime and the matter (radiation) dominated one, due to the nonadiabatic expansion of the spacetime [42, 43]. This scenario can produce particles with mass of the order of the inflaton mass and do not require couplings of wimpzillas with inflaton or other particles.

These particles can be accommodated in existing theoretical frameworks. For instance, stable or metastable bound states called cryptons arise in M-theory, and other possibilities are contemplated in string theories [44]. Furthermore, messenger bosons in soft supersymmetry breaking models may be very massive and in presence of accidental symmetries in the messengers sectors, might be stable [45].

Although wimpzillas have been invoked in top-down scenarios that seek to explain the origin of Ultra High Energy Cosmic Rays [43, 46, 47], this interpretation is today problematic because it predicts a large photon component in the UEHCRs spectrum, in disagreement with the recent results of the Auger experiment [48].

Several production mechanisms can act together to produce a given species, and its relic abundance receives contributions from each of them. The calculation depends on the details of the particle physics and cosmological models adopted. In the case of axions, i.e. light pseudoscalar particles introduced to solve the Strong CP Problem, the production mechanisms in the early Universe are scattering in the hot thermal plasma and possibly radiation by topological defects like axion-strings. Another relevant production mechanism is the so-called *misalignment*: the axion field rolls towards its minimum, near the QCD epoch, and it ends with coherent oscillations that produce a Cold Dark Matter condensate. A lower bound on the axion mass can be inferred requiring that they do not overclose the Universe, but the uncertainties in the calculation of their production make the constraint rather weak (for recent reviews of axions see [50, 51]).

As mentioned before, gravitinos can be copiously emitted by the decay of the NLP in SUSY but they can also be produced, during reheating, by inelastic  $2 \rightarrow 2$  scattering processes off particles in the thermal bath and in some scenarios they can act as Cold Dark Matter candidates (e.g. [52–57], see e.g. [58, 59] for more details and references on gravitino DM models). The efficiency of the production depends on the reheating temperature  $T_R$  so the bound on  $\Omega_{DM}$  translates into an upper limit on  $T_R$  [34, 55, 60]. In addition to thermal production and late decays of the NLSP, other non thermal and inflation model dependent contributions can arise and change considerably the predictions [61, 62].

Sterile neutrinos, which arise naturally in theoretical frameworks [63–66] or in the phenomenological  $\nu$ MSM [67], have been proposed as a solution of the LSND anomaly [68], as explanation of the high pulsar velocities [69] and as Dark Matter candidates. Recently, the

MiniBoone collaboration has reported its first results, excluding at 98% C.L. the two-neutrino appearance oscillation scheme obtained from LSND data [70]. The (3+1) scheme, involving one sterile neutrino specie, is excluded and also models with two or three sterile species are not viable because of the tension between appearance and disappearance data [71].

Sterile neutrinos may be produced in the early Universe from collision oscillation conversions of active thermal neutrinos. Their momentum distribution is significantly distorted with respect to a thermal spectrum due to the effects of quark-hadron transition, the modification of the neutrino thermal potential caused by the presence of thermal leptons and the heating of the coupled species (see e.g. [72] for precise computation of relic abundance). Moreover it has been proposed an enhanced resonant production, in presence of a lepton asymmetry in the early universe significantly higher than the baryonic one [73, 74].

## II. IS IT COLD?

The evolution of perturbations in the Universe depends on the microscopic properties of DM particles. The standard picture, widely accepted, is that after equality, when the Universe becomes Matter Dominated, the DM density perturbations begin to grow, and drive the oscillations of the photon-baryonic fluid around the DM gravitational potential wells. Soon after recombination, baryons kinematically decouple from photons and remain trapped in DM potential wells. Their density perturbations then grow to form the structures that we observe today in the Universe (see for more details [4, 15]).

### Hot Dark Matter

The imperfect coupling between baryons and photons at recombination leads to a damping of small scale anisotropies, also known as Silk damping [75]. A collisionless species, moving in the universe from higher to lower density regions, also tends to damp the fluctuations above its free-streaming scale. This a key property of Hot Dark Matter, which consists of species which are relativistic at the time of structures formation and therefore lead to large damping scales [76].

The prototype of HDM are Standard Model neutrinos: they were thermally produced in the early Universe and they termodinamically decoupled again relativistic at  $T \sim 1$  MeV, leading to a relic abundance today that depends on the sum of the flavor masses,  $m_\nu = \sum_{i=1}^3 m_{\nu_i}$ :

$$\Omega_\nu h^2 = \frac{m_\nu}{90 \text{ eV}}. \quad (2)$$

Their free-streaming length is [15]:

$$\lambda_{FS} \sim 20 \left( \frac{30 \text{ eV}}{m_\nu} \right) \text{ Mpc.}$$

Hot DM models are today disfavored (see e.g. [77] for a more complete discussion). For instance, the power spectrum of density perturbations should be suppressed beyond the free-streaming length of HDM particles, that for neutrino masses in the eV range corresponds roughly to the size of superclusters. Furthermore, HDM models predict a top-down hierarchy in the formation of structures, with small structures forming by fragmentation of larger ones, while observations show that galaxies are older than superclusters.

Small amounts of HDM can still be tolerated, provided that it is compatible with large scale structure and CMB data. Assuming an adiabatic, scale-invariant and Gaussian power spectrum of primordial fluctuations, WMAP data set an upper limit on the sum of light neutrino masses [5] (or equivalently, through Eq. 2, on  $\Omega_\nu$ )

$$\sum m_\nu < 2.11 \text{ eV (95 \% CL).}$$

The combination of data from WMAP, large scale structure and small-scale CMB experiments, further strengthens the constraint, but it also introduces potentially large systematic effects [78–81]. A significantly improved constraint can be obtained combining Ly- $\alpha$  forest, CMB, SuperNovae and Galaxy Clusters data [82, 83]:

$$\sum m_\nu < 0.17 \text{ eV (95 \% CL).}$$

These limits can be applied to a generic hot Dark Matter candidate, e.g. to thermal axions [51, 84, 85] or to hot sterile neutrinos [86].

### Cold Dark Matter

The standard theory of structure formation thus requires that Dark Matter is *cold*, i.e. it is made of particles that have become non-relativistic well before the matter domination era, and that can therefore clump on small scales. The prototype of cold DM candidates is the supersymmetric neutralino, whose free-streaming length is such that only fluctuations roughly below the Earth mass scale are suppressed [87, 88]. CDM candidates can be heavy thermal relics, such as the aforementioned neutralino, but also light species, non-thermally produced, like axions (see Sec. I for further comments and references).

N-body simulations of  $\Lambda$ CDM Universe are in agreement with a wide range of observations, such as the abundance of clusters at  $z \leq 1$  and the galaxy-galaxy correlation functions (see e.g. [89] for a review of CDM), making it a successful and widely accepted cosmological model.

However, the emergence of some discrepancies has lead some authors to question the CDM model and to propose alternative scenarios. For example, the number of satellite halos in Milky Way-sized galaxies, as predicted by simulations, exceeds the number of observed Dwarf galaxies [90, 91]. Furthermore, the rotation curves of low surface brightness (LSB) galaxies point to DM distributions with constant density cores rather than the cuspy profiles preferred by N-body simulations [92–95]. An additional problem arises when considering the angular momentum of dark matter halos: in simulations gas cools at early time into small mass halos, leading to massive low-angular momentum cores in conflict with the observed exponential disks [96].

Several astrophysical processes have been invoked in order to solve these problems, such as major mergers and astrophysical feedback[97]. The low efficiency of gas cooling and star formation may decrease the number of satellites in Milky Way-sized galaxies [98–100] and tidal stripping may have dramatically reduced the size of these substructures or disrupted a fraction of them [102, 103]. Furthermore, new ultra-faint dwarf galaxies have been recently detected, alleviating the discrepancy between CDM predictions and observations [101]. It has also been pointed out that the measurements of the LSB galaxies rotation curves may suffer of observational biases, for example due to the fact that DM halos are triaxials rather than spherically symmetric [104]. Moreover, small deviations of the primordial power spectrum from scale invariance, the presence of neutrinos [105] or astrophysical processes [106, 107] can sensibly affect the halo profiles. Anyway, the lack of convincing explanations of the problems discussed above leaves the door open to alternatives to the CDM scenario.

### Warm Dark Matter

To alleviate these problems, Dark Matter candidates with a strong elastic scattering cross section (SIDM) [108], or large annihilation cross sections [109] have been proposed. It has also been suggested that Dark Matter is *warm*, i.e. made of particles with velocity dispersion between that of HDM and CDM particles. The larger free-streaming length of WDM, with respect to CDM, reduces the power at small scales, suppressing the formation of small structures [110, 111]. For instance, a WDM particle with a mass of 1 keV and an abundance that matches the correct Dark Matter density, has a free-streaming length of order of galaxy scales  $\lambda_{FS} \sim 0.3 \text{ Mpc}$  [112]. Measurements of the growth of structures in galaxy clusters and Ly- $\alpha$  forest can then be used to set a lower bound on the mass of the WDM particle. Gravitinos in gauge-mediated supersymmetry breaking models might be warm DM candidates, if they decouple when the number of degrees of freedom was much larger than at the neutrino decoupling [113]. However, explicit computations show that such a light thermal gravitino cannot account for all the DM

[112].

Another WDM candidate is the sterile neutrino, produced in the early Universe by oscillation conversion of thermal active neutrinos, with a momentum distribution significantly suppressed and distorted from a thermal spectrum [67, 74, 114]. Its free-streaming scale is given by (see e.g. [27])

$$\lambda_{FS} \approx 840 \text{ Kpc h}^{-1} \left( \frac{1 \text{ KeV}}{m_s} \right) \left( \frac{\langle p/T \rangle}{3.15} \right),$$

where  $m_s$  is the mass state associated to the sterile flavor eigenstate.  $\langle p/T \rangle$  is the mean momentum over temperature of the neutrino distribution and the ratio  $\langle p/T \rangle / 3.15$  ranges from  $\approx 1$  for a thermal WDM particle to  $\approx 0.9$ , for a non-thermal sterile neutrinos distribution.

The suppression of the power spectrum by a thermal WDM of a given mass  $m_{WDM}$ , is identical to that produced by sterile neutrinos of mass  $m_s$  derived by [112, 115]:

$$m_s = 4.43 \text{ KeV} \left( \frac{m_{WDM}}{1 \text{ KeV}} \right)^{4/3} \left( \frac{0.25(0.7)^2}{\Omega_{WDM}} \right)^{1/3}.$$

This one-to-one correspondence allows to translate the bounds on sterile neutrinos to a generic thermal relic and viceversa.

A detailed analysis of the production of sterile neutrinos and of the evolution of their perturbations, as well as a comparison with the measured matter power spectrum, have been performed in Refs. [112, 116–119]). The resulting lower limits on the mass of the WDM particles strongly depend on the dataset used in the analysis. For example, in [116], a combination of the SDSS 3D power-spectrum and SDSS Ly- $\alpha$  forest allowed to constrain the sterile neutrino mass to

$$m_s \geq 1.7 \text{ KeV (95 \%CL)},$$

that translates in terms of a thermal WDM particle to

$$m_{WDM} \geq 0.50 \text{ KeV}.$$

The inclusion of high resolution Ly- $\alpha$  data makes the constraint even stronger, even if it has been pointed out that they may suffer of large systematic uncertainties [112, 116].

More recently, very stringent bounds on the mass of WDM particles have been obtained by different groups: [118]

$$m_s \geq 14 \text{ KeV (95 \% CL)} \quad (m_{WDM} \geq 2.5 \text{ KeV})$$

and [119]:

$$m_s \geq 28 \text{ KeV (} 2\sigma \text{)} \quad (m_{WDM} \geq 4 \text{ KeV}).$$

The delay of the reionization of the Universe also sets a constraint on the WDM mass [120–122]. In the case of sterile neutrinos, the X-rays produced by their decays can modify the picture, enhancing the production of molecular hydrogen and releasing heat in gas clouds [123–125].

### III. IS IT NEUTRAL?

Some extensions of the Standard Model of particle physics predict the existence of new, stable, electrically charged particles, such as the lightest messenger state in gauge-mediated supersymmetry breaking models [126] or even the LSP in the R-parity conserving Minimal Supersymmetric Standard Model (MSSM).

Massive charged particles, independently on the context they emerge, have been proposed as Dark Matter candidates by De Rújula *et al* and dubbed CHAMPs [127]. Evaluating their thermal relic abundance, with simple assumptions on the annihilation cross sections, the authors found a viable mass range of  $\sim 1 - 1000$  TeV. They also pointed out that a positively charged particle  $X^+$  can capture an electron to form a bound state chemically similar to an heavy hydrogen atom. An  $X^-$  can instead bind to an  $\alpha^{++}$  particle and an electron, resulting again in a heavy hydrogen-like atom, or alternatively it can capture a proton to produce a bound state called neutralCHAMP. The different behaviors of CHAMPs and neutralCHAMPs lead to different bounds on their abundance. Note also that De Rújula *et al.* concluded that  $X^-$  would emerge from Big Bang Nucleosynthesis preferentially in the form of neutralCHAMPs [127].

Galactogenesis models provide constraints on the Dark Matter interactions, in particular of CHAMPs. The energy loss timescale in this case is in fact dominated by Coulomb scattering off protons, and it must be longer than the dynamical timescale for galaxy formation. In Ref. [127], the authors concluded that only CHAMPs heavier than 20 TeV are able to remain suspended in the halo, and to be therefore rare on Earth. This estimate disagree with that obtained by Dimopoulos *et al* who found, for the same considerations, the limit  $M_X > 10^5$  TeV [128]. It has also been proposed that shock accelerations in supernovae could eject CHAMPs from the disk and reinject them back to the halo or out of the galaxy [128]. The latter possibility is energetically disfavored, while in the former case, it may lead to a dangerous heating of the disk.

One of the most stringent bounds on the CHAMPs abundance comes from searches of anomalous heavy water: CHAMPs, being chemically identical to heavy hydrogen, can be trapped in oceans and lakes in the form of HXO. If one assumes, as in Ref. [127], that CHAMPs heavier than 20 TeV remain suspended in the Galactic halo and they provide the Galactic DM, taking an accumulation time of  $3 \times 10^9$  yr, comparable with the age of oceans, the abundance of CHAMPs in sea water is predicted to be [129]:

$$\left( \frac{n_X}{n_H} \right)_{Earth} \sim 3 \times 10^{-5} \left( \frac{\text{GeV}}{m_X} \right) \Omega_X h^2.$$

If instead CHAMPs are present in the Galactic disk, taking in account the density and velocity of the interstellar gas, mostly hydrogen, the expected concentration

is [129]:

$$\left(\frac{n_X}{n_H}\right)_{Earth} \sim 6 \times 10^{-5} \left(\frac{\text{GeV}}{m_X}\right) \Omega_X h^2.$$

All the searches of anomalous hydrogen in sea water have failed so that the abundance of CHAMPs, for masses in the range 100 GeV-1000 GeV is constrained to be

$$\left(\frac{n_X}{n_H}\right)_{Earth} \sim 10^{-28} - 10^{-29},$$

while it raises to  $(n_X/n_H) < 10^{-20}$  for  $M_X \sim 10$  TeV (see [130] for a compilation of upper bounds of heavy hydrogen from sea water searches). As a result, CHAMPs as DM candidates are ruled out in the mass range  $M_X \sim 10 - 10^4$  GeV.

NeutralCHAMPs would preferentially bind on Earth to nuclei to form anomalous heavy isotopes. Null searches for these elements, covering a variety of nuclear species, constrain the NeutralCHAMPs abundance to be  $< 10^{-20} - 10^{-16}$  for  $M_X \sim 100 - 1000$  GeV [131] (for further details see [130] and references therein). The authors of Ref. [131], concluded that stable  $X^-$  Dark Matter in the mass range  $10^2 - 10^4$  GeV is thus to be considered unlikely.

CHAMPs are also constrained by balloon or satellites experiments for Cosmic Rays studies. Perl et al, taking in account data from different experiments [128, 133, 134], excluded CHAMPs as Galactic Dark Matter in the mass range  $2.4 \times 10^3 - 5.6 \times 10^7$  GeV and neutralCHAMPs for  $10^5 - 4 \times 10^7$  GeV [132]. The lower limit comes from the requirement that particles penetrate the solar wind and the energy deposition is above the experimental threshold. The upper bound is obtained comparing the maximum CHAMP flux at the top of the atmosphere allowed by the CR experiments, with the local DM flux, which is typically assumed to be  $\phi \sim 10^7 (\text{GeV}/M_X) \text{cm}^{-2}\text{s}^{-1}$ .

In the atmosphere, a proton in a neutralCHAMP gets replaced very quickly by a  $^{14}\text{N}$  atom, and the exchange is followed by a MeV  $\gamma$ -ray emission from the excited  $^{14}\text{N}X^-$  status. With the same argument explained above, the observational limits on  $\gamma$ -rays flux imply that neutralCHAMPs should be heavier than  $10^6$  GeV if they are to be the DM[128]. Further constraints on CHAMPs come from deep underground experiments. The responses of scintillators to monopoles and CHAMPs are expected to be similar, since they are both slowly moving, highly ionizing and penetrating. In Ref. [132], the authors applied the upper limit on monopole flux, obtained from MACRO experiment, to the CHAMP case, excluding the mass range  $10^8 - 10^{20}$  GeV.

Further constraints come from stellar evolution, in particular it has been shown that CHAMPs can disrupt a neutron star in a short timescale, falling into its center and producing a Black Hole. This argument excludes CHAMPs with masses  $10^2 - 10^{16}$  GeV [135]. In addition, the properties of diffuse interstellar clouds constrain the interactions of halo particles with atomic hydrogen:

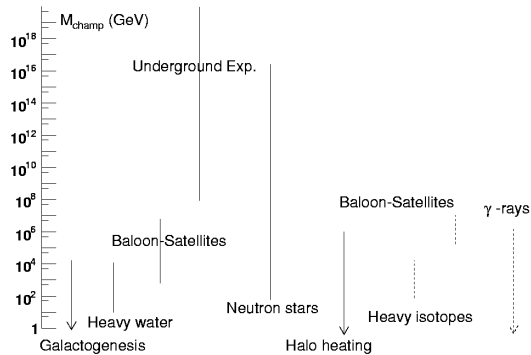


Figure 2: Exclusion plot for CHAMPs (solid lines) and NeutralCHAMPs (dotted lines). See text for more details.

the rate of energy deposition due to collisions must be smaller than the cooling rate, for clouds in equilibrium. It results that CHAMPs with masses below  $10^6$  GeV are ruled out because, for these particles, the expected cross section with hydrogen is higher than the maximum allowed value [136].

The various constraints on CHAMPs that we have discussed are summarized in Fig. 2. Even if the bounds are not completely model-independent, the combination of them basically rules out CHAMPs as DM.

The above limits apply to particles with integer electric charge, but theoretical frameworks have been proposed where particles with fractionary electric charge exist, also known as milli-charged particles [137–142]. For example, adding a new unbroken  $U(1)'$  gauge group, the photon and paraphoton can mix, and particles charged under  $U(1)'$  can have a small coupling with photons [137]. Moreover, realistic extensions of SM motivated by string theory exist, that naturally implement this mechanism [139].

Constraints on mass and charge of milli-charged particles come from a variety of observations, and in Fig. 3 we show the excluded regions in the parameter space  $(m_q, \epsilon)$ , with  $\epsilon = q/e$ , obtained by Davison et al. [143].

Milli-charged particles can also affect CMB anisotropies, and for this reason WMAP data can severely constrain their cosmological abundance, at least in some regions of the milli-charged particle parameter space [144].

Furthermore, searches of neutrino magnetic moment with reactor experiments exclude Dark Matter particles with  $q > 10^{-5}e$ , for masses  $m_q \lesssim 1$  keV [145].

The result of the PVLAS collaboration [146] have been tentatively interpreted in terms of milli-charged particles with masses  $m_q \sim 0.1$  eV and fractional electric charge  $\epsilon \sim 10^{-6}$  [139, 140, 148], but the experimental result was not confirmed after an upgrade of the PVLAS apparatus

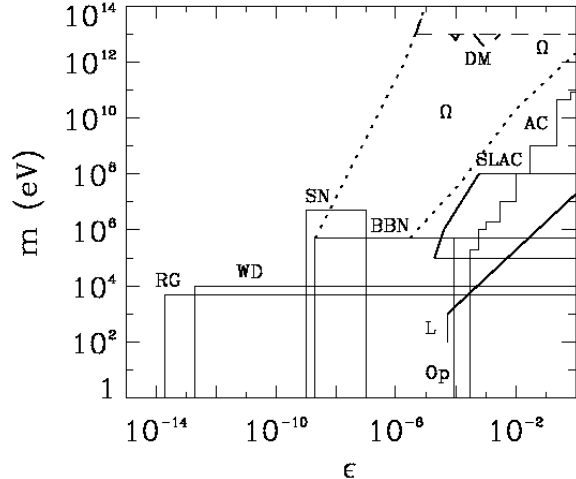


Figure 3: Excluded regions in the mass-charge plane for milli-charged particles. The constraints are relative to: RD plasmon decay in red giants; WD plasmon decay in white dwarfs; BBN big bang Nucleosynthesis; SN Supernova 1987A; AC accelerator experiments; SLAC SLAC millicharged particle search; L Lamb Shift; Op invisible decay of orthopositronium; DM Dark Matter searches. From Ref. [143].

[147].

Light milli-charged particles may largely affect sub eV Cosmology. In particular, processes such as  $\gamma\gamma \rightarrow q\bar{q}$  can distort the CMB energy spectrum, which has been measured with high sensitivity by FIRAS. A detailed analysis has been performed in Ref. [149] and the authors reported the conservative upper bound  $\epsilon \lesssim 10^{-7}$ , for  $m \lesssim 1$  eV, excluding in this way also the light milli-charged particles proposed in Ref. [139, 140, 148].

In principle, DM particles could have a  $SU(3)_c$  charge. For example, "colored" candidates are naturally predicted in SUSY models if the LSP is a squark [150] or a gluino [151, 152], or in gauge mediated SUSY breaking models, where messengers can be colored and stable [153], or in mirror models [154]. These "heavy partons", after the deconfinement temperature,  $T \sim 180$  MeV, are surrounded by a QCD cloud and confined inside hadrons forming a color neutral bound state [155]. These particles can be actively searched for by underground experiments, indirect detection experiments or through the search of rare anomalous isotopes.

Since the proposal that DM might interact strongly with ordinary matter (SIMP), regardless of the nature of the interaction [127, 128, 156], many candidates have been put forward, but also many constraints on the scattering cross section off nuclei,  $\sigma_{\chi N}$ .

For example, the SIMPs interactions with baryons may disrupt the disk of spiral galaxies [156, 157]. Moreover, they may dissociate the light elements produced during

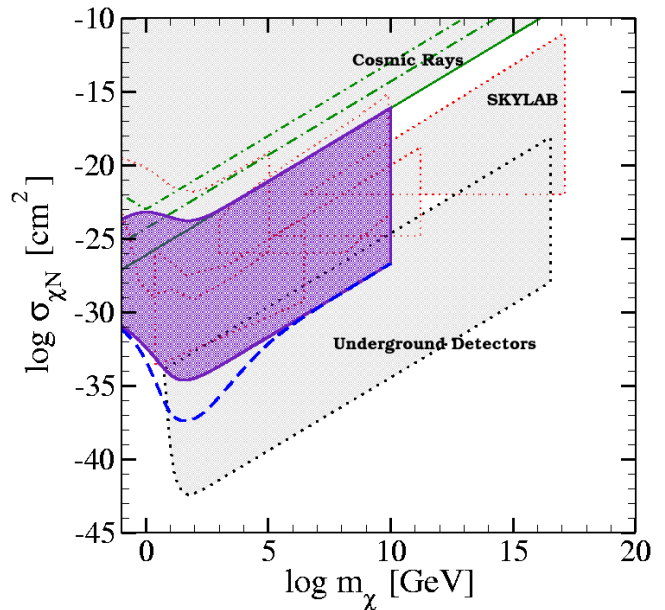


Figure 4: Excluded regions in the SIMP mass versus SIMP-nucleon cross section plane. The Violet area is excluded by the Earth's heat argument. See Ref.[165] and references therein.

Big Bang Nucleosynthesis, while SIMPs collisions with Cosmic Rays can produce an observable  $\gamma$ -ray flux [158]. The scattering of SIMPs off baryons also produces substantial distortion of CMB anisotropies and of the large scale structure power spectrum [159]. The SIMPs abundance for the mass range  $\sim 1 - 10^3$  GeV, is also constrained by searches in terrestrial samples of gold and iron [160].

Atmospheric and satellite experiments, originally intended for other purposes, have been used to investigate high DM cross sections with baryonic matter. In particular, the results of the X-ray Quantum Calorimeter experiment (XQC) allow to rule out a large portion of the SIMP parameter space ( $M_\chi, \sigma_{\chi N}$ ), as discussed in Refs. [161, 162] and (more recently and with substantial changes with respect to previous analyses) in Ref. [163].

Complementary constraints are obtained by underground experiments, which are sensitive to DM particles with small interactions. In fact, they are able to detect SIDM particles if their interactions with ordinary matter are high enough to trigger a nuclear recoil in the detector but at the same time low enough to allow the particles to penetrate the Earth crust to the detector [164]. Recently, Mack *et al.* have analyzed the effect of SIMP annihilations on Earth, showing that a substantial heating of the Earth's core may occur, if the capture rate is efficient [165]. This argument rules out the regions of the parameter space lying between astrophysical and underground detector constraints.

To summarize the constraints on the SIMP scenario, Fig. 4 shows the excluded areas in the SIMP parameter space. The bounds leave no room for SIMPs as Dark



Matter candidates in a very large mass range. Since the neutron-neutron scattering cross section is of order  $10^{-25} - 10^{-24} \text{ cm}^2$  and the expected value for colored Dark Matter candidates is not far from this range ( see e.g. [166]), DM particles are thus unlikely to bring color charge.

However, these constraints can be evaded by very massive composite dark matter candidates. For example macroscopically large nuggets of ordinary light quarks and/or antiquarks, with masses in the range  $m \sim 10^{20} - 10^{33} \text{ GeV}$ , can behave as collisionless cold dark matter, without contradicting observations [167].

#### IV. IS IT CONSISTENT WITH BBN?

Big Bang Nucleosynthesis (BBN) is one of the most impressive successes of the Big Bang Cosmology (See [7, 168] for reviews). It predicts the abundances of light elements produced in the first 3 minutes after the Big Bang, in agreement with the observations over a range spanning nine order of magnitudes.

The model is based on a set of coupled Boltzmann equations relating the number densities of protons, neutrons and light elements, through a network of nuclear chemical reactions. The weak interactions maintain the neutron-proton ratio to its equilibrium value until the freeze-out, that occurs at roughly 0.7 MeV. Later, nearly all neutrons are captured in the nuclei producing principally the most stable element  $^4\text{He}$ . Smaller amount of  $^2\text{H}$ ,  $^3\text{H}$ , and  $^7\text{Li}$  are synthesized but the production of heavier elements is suppressed by the large Coulomb barriers. Looking for astrophysical environments with low metallicity, it is possible to infer the primordial abundance of light elements in order to test the predictions of BBN.

In the framework of the Standard Model, BBN depends only on the baryon to photon ratio  $\eta$ , and observations of the abundance of different elements agree with predictions in the range [7]

$$4.7 \leq \eta \cdot 10^{10} \leq 6.5 \text{ (95\% CL)}.$$

The agreement between predictions and measurements is a powerful success of the model and it is remarkable that the inferred abundance of baryons quoted above is also consistent with the estimate of CMB experiments like WMAP [5]. BBN also provides a test of physics beyond the Standard Model, and it also constraints deviations from Standard Cosmology. In fact, the primordial abundance of  $^4\text{He}$  is proportional to the ratio  $n/p$  and its value is related to the freeze-out temperature of the weak interactions and it is therefore sensitive to the expansion rate at that time.

Since  $H \propto g_*^{1/2} T^2$ , an increase of the relativistic degrees of freedom  $g_*$  with respect to the SM value leads to a faster expansion rate, thus to an earlier freeze out of the neutron to proton ratio and consequently to a higher  $^4\text{He}$  abundance (and in general it also affects the abundance

of the other light elements). At  $T \sim 1 \text{ MeV}$ , the relativistic species in the Standard Model are photons, electrons and neutrinos so with  $N_\nu$  neutrino family  $g_* = 5.5 + \frac{7}{4}N_\nu$  and for  $N_\nu = 3$  this gives 43/4.

New relativistic particles can be accounted for through the introduction of an effective number of neutrinos:

$$\frac{7}{4}(N_\nu - 3) = \sum_{i=\text{extra b}} g_i \left(\frac{T_i}{T}\right)^4 + \frac{7}{8} \sum_{i=\text{extra f}} g_i \left(\frac{T_i}{T}\right)^4,$$

where  $T_i$  parametrizes the energy density of the relativistic species and b (f) stands for bosons (fermions).

A likelihood analysis, taking  $\eta$  and  $N_\nu$  as free parameters, and based on the abundance of  $^4\text{He}$  and  $^2\text{H}$ , constrains the effective number of neutrinos to be [169]:

$$1.8 < N_\nu < 4.5 \text{ (95\% CL)}.$$

Assuming the value of  $\eta$  inferred by CMB experiments, the limit is further strengthened to [169]:

$$2.2 < N_\nu < 4.4 \text{ (95\% CL)}.$$

These bounds on  $N_\nu$  can be applied to new species affecting the expansion rate during nucleosynthesis, such as gravitons [170], neutrinos with only right-handed interactions [169] or millicharged particles [143]. For a large class of supergravity models with a light gravitino, the requirement  $N_\nu < 4$  rules out gravitino masses below 1 eV [171]. However, particles coupled to photons or to neutrinos during BBN, with masses in MeV range, have a non trivial impact on BBN, that cannot be accounted for with an equivalent number of light neutrinos [172].

For instance, it has been suggested that MeV Dark Matter, with masses in the range 4-10 MeV and coupled with the electromagnetic plasma, can lower the helium and deuterium abundances, contrary to what one naively expects, and it can therefore improve the agreement between the predicted and measured  $^4\text{He}$  abundance [173].

In addition, the predictions of BBN can be dangerously modified by the decays of particles during or after BBN. For example, radiative decays induce electromagnetic showers and the subsequent photon-photon processes can destroy the light elements. In the early stages of BBN,  $t < 10^2 \text{ sec}$ , hadronic decays may modify the interconversion of protons and neutrons, increasing the  $n/p$  ratio and consequently enhancing the  $^4\text{He}$  and  $^2\text{H}$  abundance. The opposite effect occur for late hadronic decays,  $t > 10^2 \text{ sec}$ , when the energetic hadrons trigger the  $^4\text{He}$  dissociation.

Accurate calculations, with the use of BBN codes, restrict the primordial abundance of the decaying particle, depending on its lifetime, mass and hadronic branching ratio [174–178]. These results can be applied for instance to NLSP gravitinos: BBN requires an upper limit to the reheating temperature, which controls the primordial gravitino abundance, and in some cases the restrictions could lead troubles to thermal leptogenesis and inflation

models [175, 177]. The difficulties can be circumvented for example in the case of a heavy gravitino, which decays well before BBN [179, 180].

Alternatively, the gravitino could be stable and play the role of Dark Matter. In this case, the NLSP particle is typically long-lived, because of the extremely weak interactions of gravitino, and its late decays can affect BBN. Moreover, it has been pointed out that if the long-lived particles are charged, e.g the stau, they can form bound states with light elements, potentially overproducing  ${}^6\text{Li}$  and  ${}^7\text{Li}$  [181–185]. However, these elements can also be destroyed, alleviating the severe bounds on the CHAMPs abundance during BBN.

A neutralino NLSP is excluded [186–188], while sneutrino NLSP poorly affects BBN [189]. A stop NLSP is viable in some regions of the parameter space [190].

We note that these BBN bounds can be circumvented if the NLSP abundance is diluted due to a significant entropy production [191].

## V. DOES IT LEAVE STELLAR EVOLUTION UNCHANGED?

Stellar evolution provides a powerful tool to constrain particle physics, providing bounds that are often complementary to those arising from accelerator, direct and indirect Dark Matter searches.

If Weakly interacting particles are light, they may be produced in the hot plasma in the interior of stars, and if they escape without further interactions, they represent an energy loss channel for the star, possibly modifying the stellar evolution. Such particles may also be detected on Earth, as was the case for neutrinos from SN 1987A, or they can be indirectly searched for through their decay products. Here we describe the most important observational consequences (see Refs. [192, 193] for extensive reviews).

Stars as the Sun can be described as self-gravitating gas in hydrostatic equilibrium, such that the gas pressure equilibrates the gravitational force. A significant energy loss produces a contraction of the system and an increase of the burning rate of the stellar fuel, reducing the lifetime of the star and enhancing the neutrino flux. Moreover, exotic energy losses would modify the sound speed profile, which is accurately measured in the interior of the Sun by means of helioseismic measurements.

Globular Clusters are alternative interesting probes of stellar evolution models because they are gravitationally bound systems of up to a million stars, formed at the same time, with the same chemical composition and differing only for their masses. The ignition of helium in Red Giant stars is sensitive to the temperature and density of the helium core, and any energy loss channel inevitably tends to delay it, resulting in more massive cores and producing observational consequences, such as an enhancement of star brightness. Therefore, observations of Red Giants in Globular Clusters allow to derive an up-

per limit on the energy loss rate of the helium plasma,  $\epsilon$ , [192]:

$$\epsilon \lesssim 10 \text{ erg g}^{-1}\text{s}^{-1} \text{ at } T \approx 10^8 \text{ K}, \rho \approx 2 \times 10^5 \text{ g cm}^{-3},$$

where the value of temperature and density are appropriate for Red Giant cores. In Horizontal Branch stars, energy losses speed up the helium burning rate, decreasing their lifetimes, that can be measured by number counting in Globular Clusters. This argument provides another bound on  $\epsilon$  [192]:

$$\epsilon \lesssim 10 \text{ erg g}^{-1}\text{s}^{-1} \text{ at } T \approx 0.7 \times 10^8 \text{ K}, \rho \approx 0.6 \times 10^4 \text{ g cm}^{-3}.$$

In addition, the cooling rate of White Dwarfs, inferred by their luminosity functions, is in agreement with the predictions and therefore any new cooling channel has to be subdominant.

It is remarkable that the total number of neutrino detected from SN 1987A, their energy and their time distribution, is in agreement with expectations from the standard model which describes the core collapse of a star. Any further energy loss mechanism reduces the duration of the neutrino burst and can in principle spoil the success of the model, leading therefore to the following bound on  $\epsilon$  [192]:

$$\epsilon \lesssim 10^{19} \text{ erg g}^{-1}\text{s}^{-1} \text{ at } T = 30 \text{ MeV}, \rho = 3 \times 10^{14} \text{ g cm}^{-3}.$$

All the arguments listed above provide upper limits to any additional energy loss rate and can be applied to constrain, for instance, the neutrino properties, the graviton emission in theories with extra dimensions, as well as models with right-handed neutrinos, sterile neutrinos, milli-charged particles, axions and other pseudoscalar particles. For instance, updated limits on axions from stars are reviewed in Ref. [194] and the implications of light Dark Matter or sterile neutrino Dark Matter on Supernovae core collapse are discussed in Ref. [195, 196]. More details and references for other particle physics scenarios can be found in [192, 193].

As we have seen in Sec.III, the most restrictive bounds on the fractional charge of  $\sim \text{keV}$  milli-charged particles come from stellar physics, as it was shown in Fig.3.

The bounds discussed above apply to particles that are produced in the core of stars and that escape without losing energy, thanks to their weak interactions. However, if the particles interact strongly, they undergo multiple scattering, providing a mechanism for energy transport, in competition with photons, electrons or convection. This effect has been studied for keV-mass scalars produced in the Sun, Horizontal Branch stars and Red Giants, constraining the interactions of these particles [197, 198].

Moreover, the energy transport channel, provided by the WIMPs trapped in the Sun, may cool its interior and decrease the neutrino flux. This idea was proposed in the past as a solution of the solar neutrino problem and WIMPs with masses and cross sections suitable for this

purpose ( $m \sim 4 - 10 \text{ GeV}$   $\sigma \sim 10^{-36} \text{ cm}^2$ ) were called cosmions [199–201].

Stars in which the heat transport is dominated by core convection may be dramatically affected by WIMPs in the case of effective transport of energy. In fact, in this case, the convection is suppressed, and the core is not replenished with nuclear fuel from outer regions, leading to a reduced stellar lifetime and a modification of its evolution [202, 203]. As a consequence, main sequence stars would present an anomalous mass-to-luminosity relation and Horizontal Branch stars would develop thermal pulses [203–205]. However, taking in account the current limits on the WIMP-nucleon cross section inferred from direct searches, these effects seems to be hardly detectable for the Sun [206, 207].

Dark Matter annihilations may provide an important source of energy, which, for stars orbiting in high Dark Matter density regions, can even be comparable or overwhelm that originated by nuclear reactions. This scenario has been investigated, in the case of main sequence stars, in Ref.[208] and more recently, by means of numerical simulations, in Ref.[209, 210]. The most pronounced effects are on low-mass stars and the authors in Ref.[209, 210] have proposed that these "WIMP burners" could be found in regions where a recent star formation is inhibited, looking for populations of stars appearing oddly younger than higher mass ones. Although apparently young stars have been detected in the inner regions of Andromeda and of our own galaxy, it is difficult to interpret these observations in terms of WIMP burners. WIMP annihilations could also enhance the luminosity of White Dwarfs and neutron stars, as it has been observed in [211–213].

The effect of DM decays and annihilations on the formation of first structures have been investigated for light DM candidates [125, 214]. Recently, it has been pointed out that even standard DM candidates, such as the neutralino, may substantially modify the evolution of Population III stars, which may even be supported by DM annihilations rather than nuclear reactions, during part of their evolution [215].

## VI. IS IT COMPATIBLE WITH CONSTRAINTS ON SELF-INTERACTIONS?

The collisionless and cold nature of Dark Matter, has been questioned during the last decade, because of apparent discrepancies between the results of CDM simulations and observations. Two remarkable problems, as mentioned in Sec. II, are the conflict between the cuspy DM halos predicted by N-body simulations and the constant core profiles inferred by LSB and dwarfs [92, 93] and the excess of substructures in CDM halo with respect to the observed number of galaxy satellites [90, 91].

Although astrophysical explanations exist for the observed discrepancies, [98, 99, 104–107], many attempts have been made to modify the properties of DM parti-

cles in order to reproduce the appropriate astrophysical phenomenology. A possible solution is that DM is *warm* rather than *cold*, as mentioned before. Alternatively, DM might be self-interacting (SIDM), as proposed by Spergel and Steinhardt, with large scattering cross section (and small enough annihilations cross sections, in order to be consistent with the bounds from indirect detection) [108]. The net effect, under these assumptions, is that the central cusp reduces to an almost constant core. Moreover, subhalos can be destroyed by interactions with the surrounding halo particles, because they are excessively heated or because particles are scattered out of the them [108, 161]. Suitable SIDM candidates include Q-balls [108, 216], a quark-gluino bound state [161, 217] and scalar gauge singlets coupled with Higgs field [218].

Semi-analytical calculations and N-body simulations have been developed to study the effect of SIDM interactions on halo structures, especially for what concerns the formation of flat cores. Different solutions are obtained, depending on the ratio between the mean free path of the Dark Matter particle ( $\lambda_{mfp} \propto (\rho \sigma/m)^{-1}$ , with  $n$  the number density and  $\sigma/m$  the scattering cross section per unit mass of the SIDM) and the virial radius of the halo. A cross section per unit mass in the range  $\sigma/m \sim 0.5 - 5 \text{ cm}^2 \text{ g}^{-1}$  was found to correctly reproduce the observed profile of galaxies [219–222]. More recently, Ahn and Shapiro have found a much higher value,  $\sigma/m \simeq 200 \text{ cm}^2 \text{ g}^{-1}$ , as the best fit to LSB rotation curves [223].

Several constraints exist on SIDM interactions. For instance, Gnedin and Ostriker have shown that, for  $0.3 \lesssim \sigma/m \lesssim 10^4 \text{ cm}^2 \text{ g}^{-1}$ , galactic halos in clusters would evaporate in a timescale shorter than an Hubble time [224]. Following the suggestion of Furlanetto and Loeb [225], Natarajan *et al.* compared the predicted truncation radii of SIDM halos with those of observed galactic halos in clusters, inferred by gravitational lensing, excluding  $\sigma/m > 42 \text{ cm}^2 \text{ g}^{-1}$  [226].

An upper limit of  $\sigma/m < 0.1 \text{ cm}^2 \text{ g}^{-1}$ , has been obtained by Arabadjis *et al.* comparing the results of simulations with the profile of the cluster MS 1358+62 [227]. Hennawi and Ostriker ruled out  $\sigma/m \gg 0.02 \text{ cm}^2 \text{ g}^{-1}$ , pointing out that the supermassive black holes at the center of galaxies would be more massive than observed [228]. The evidence of ellipticity in DM halos has been used to rule out  $\sigma/m > 0.02 \text{ cm}^2 \text{ g}^{-1}$  because self-interactions tend to produce more spherical halos [229]. The limits reported above rule out the range of cross sections required to explain the mass profiles of galaxies, although the underlying simplifying assumptions and incomplete statistics suggest to take them with a grain of salt (see e.g. [223, 231]).

More robust results are obtained from the analysis of the 1E 0657-56 cluster of galaxies [230], which actually consists of a bullet-like gas sub-cluster, exiting the core of the main cluster at high velocity,  $v \sim 4700 \text{ Km s}^{-1}$ . The combination of optical and X-ray images with the

weak lensing map, shows that the centroid of the collisionless subcluster galaxies is ahead of the subcluster gas distribution and coincident with that of the Dark Matter clump. This cluster not only provides a robust visual evidence for Dark Matter, but it is also provides a probe of its collisionless nature.

The subcluster DM halo would be dragged by the main halo in presence of DM self-interactions, leading to an offset between the galaxies centroid and the total mass peak inferred through weak lensing measurements. Moreover, the measured high merger velocity implies that eventual drag forces, due to DM collisions, are small. Finally, the mass to light ratio of the subcluster is in agreement with that observed in other clusters and in the main cluster, while SIDM would tend to scatter out the particles from the subcluster.

Markevitch *et al.* found that the latter argument provides the most restrictive limit to the self interaction cross section,  $\sigma/m < 1 \text{ cm}^2\text{g}^{-1}$  [231]. Making use of more recent observations and more accurate N-body simulations, this bound has been slightly improved,  $\sigma/m < 0.7 \text{ cm}^2\text{g}^{-1}$  [232]. Since this constraint assumes an identical mass-to light ratio of cluster and subcluster before the merger, a more robust limit is inferred by the absence of an offset between galaxies and total mass peaks, which implies  $\sigma/m < 1.25 \text{ cm}^2\text{g}^{-1}$  [232]. Almost the full range of cross sections needed to solve the discrepancies emerged in CDM models,  $\sigma/m \sim 0.5 - 5 \text{ cm}^2\text{g}^{-1}$ , is ruled out, thus disfavoring SIDM.

It has been suggested that the scattering cross section might be velocity dependent, thus smaller on average in clusters than in galaxies (e.g. [221, 224, 228, 233]). A possible functional form is

$$\sigma = \sigma_* \left( \frac{100 \text{ Km s}^{-1}}{v_{rel}} \right)^a.$$

In order to avoid a fast evaporation of the cluster or a core collapse, the parameters are restricted to be:  $\sigma_* = 0.5 - 1 \text{ cm}^2\text{g}^{-1}$  and  $a = 0.5 - 1$  [224, 228], and simulations have confirmed that in this range, predictions match the observed flat cores [221]. However, observations of the LSB galaxy NGC 5963 seem to require an effective cross section per unit mass  $\sigma/m < 0.2 \text{ cm}^2\text{g}^{-1}$ , in the low velocity regime  $\sim 150 \text{ km s}^{-1}$ , at odds with the quoted range [234].

In addition to the bounds presented above, that constrain the cross section per unit mass, additional limits come from the unitarity of the scattering matrix [35, 36]. This argument provides upper bounds on the total cross section and inelastic cross section. In the low energy regime, taking in account the range of SIDM elastic cross sections needed to reproduce the observed halo profile, the constraint on the total cross section can be turned into an upper bound on the SIDM mass:  $m < 12 \text{ GeV}$  [36]. Possible exceptions to unitarity bounds have been discussed in Refs. [35, 36].

Self-annihilating DM has also been proposed to solve the cold dark matter cusp crisis [109] This scenario is

however ruled out by the comparison of the neutrino flux from the Galactic center with the measured rate of (atmospheric) neutrinos, i.e. the least detectable among the final states produced in DM annihilations [235]. For the mass range  $10^{-1} - 10^5 \text{ GeV}$ ,  $\langle \sigma_{ann} v \rangle$  has to be less than roughly  $10^{-21} \text{ cm}^3\text{s}^{-1}$ .

## VII. IS IT CONSISTENT WITH DIRECT DM SEARCHES?

Direct DM searches aim at detecting DM particles through the measurement of nuclear recoils produced by DM scattering. Despite the large DM flux expected at Earth,  $\Phi \sim 10^5 (100 \text{ GeV}/m_{DM}) \text{ cm}^{-2}\text{s}^{-1}$  assuming a local density of  $\rho_0 \sim 0.3 \text{ GeVcm}^{-3}$  and mean velocity of  $\bar{v} \sim 220 \text{ km s}^{-1}$ , the weakness of WIMP interactions with nuclei makes direct detection challenging (see e.g. [236] for a review of direct searches).

The coupling between a WIMP and a nucleon receives contributions from both scalar (spin independent) and vector (spin dependent) interactions. The cross section for spin independent (SI) coupling with a nucleus (N) cross section is coherently enhanced with respect to the case of single nucleons:

$$\sigma_N^{SI} \simeq A^2 (M_{red}(N, M_\chi)/M_{red}(p, N_\chi))^2 \sigma_p^{SI}$$

where  $A$  is the atomic number and  $M_{red}$  is the reduced mass of the system WIMP ( $\chi$ ) - nucleus (proton) [237].

Although heavy nuclei are used in current DM direct detection experiments, the results are often given in terms of scattering cross section off protons in order to allow easy comparison between different experimental settings, involving different target materials. For spin dependent (SD) couplings, there is no coherent enhancement, and the cross section is determined by unpaired neutrons or protons in the target nucleus. For this reason, SI interactions usually dominate the cross section in current experiments, which exploit heavy nuclei. However, in region of parameter space where scalar coupling is suppressed, spin dependent couplings may represent the leading contribution to the direct detection event rate [238, 239].

The signature of DM elastic scattering off nuclei are nuclear recoils, characterised by an exponential recoil spectrum with typical energies of  $\mathcal{O}(10)$  keV or less, for WIMP masses between 1 and 100 GeV (see for more details e.g. [13]). In the case of inelastic scattering off nuclei or orbital electrons, the recoil is followed by a decay photon from the excited state [240, 241]. However, the natural radioactivity background makes the detection of this signal very problematic. Current experiments exploit a variety of detection techniques, focusing on signals such as scintillation, phonons, ionization or a combination of them, as well as a variety of targets, e.g. NaI, Ge, Si and Xe.

In order to discriminate a DM signal against the natural background, some experiments have been searching

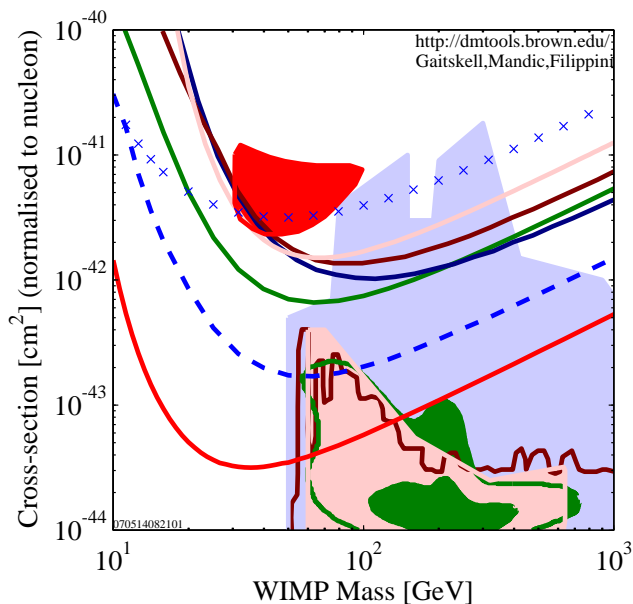


Figure 5: Upper limits on the spin independent WIMP-nucleon cross section, versus WIMP mass. The blue dashed (points) line is the Ge (Si) CDMS bound [250]. The dark red, pink, green and dark blue curves are the experimental limits respectively from EDELWEISS [253], CRESST 2004 [254], ZEPLIN II (Jan. 2007) [255] and WARP [256]. The lowest red solid line shows the first results from XENON 10 [251]. The red shaded region is the parameter space favored by DAMA experiment [247]. Supersymmetric models allow the filled regions colored: pink [257], green [258], dark red [259] and blue [260]. This figure has been obtained with the use of the interface at <http://dendera.berkeley.edu/plotter/entryform.html>.

for an annual modulation of the measured event rate [242]. In fact, the Earth rotation around the Sun is expected to produce a modulation of the relative velocity of DM particles given by

$$v_E = 220 \text{ Km/s} \{1.05 + 0.07 \cos[2\pi(t - t_m)]/1 \text{ year}\}$$

where  $t_m$  is approximatively the begin of June. The variation of the WIMP flux is actually small  $\approx 7\%$ , so that a large number of events has to be collected and therefore a large detector is needed.

In 1998, the DAMA collaboration obtained evidence for a modulation of the event rate, that was later confirmed with a confidence level of  $6.3 \sigma$  (see [243] for a recent discussion).

If interpreted in terms of a SI scattering of a WIMP off NaI, and further assuming an isothermal sphere DM halo, with a characteristic velocity of the Maxwell-Boltzmann distribution of  $v_0 = 270 \text{ Kms}^{-1}$ , with a local DM density of  $\rho = 0.3 \text{ GeV cm}^3$ , and with a slope  $\rho \propto r^{-2}$ , the DAMA result is compatible with the detection of a DM particle with a mass around 50 GeV and a WIMP-nucleons scattering cross section of order  $10^{-41} - 10^{-42} \text{ cm}^2$ .

Other experiments, such as CDMS and EDELWEISS,

have explored the region of parameter space allowed by the DAMA modulation signal, finding null results [244, 245]. The comparison between the DAMA annual modulation and the other mentioned experiments is however model-dependent. Taking into account astrophysical uncertainties, the DAMA allowed region is sensibly increased, with masses extending up to  $\sim 250 \text{ GeV}$  and spin independent WIMP-proton cross section down to  $10^{-43} \text{ cm}^2$  [246–248]. Nevertheless, null searches of recent experiments make the most naïve interpretation of the DAMA signal problematic [249–251].

It should be stressed, however, that the DAMA signal should not be dismissed without further investigation, especially in view of the fact that theoretical scenarios (despite exotic) exist where an interpretation in terms of DM appears not to be in conflict with other existing experiments [269] (see also references therein).

The upper bounds on the WIMP spin-independent coupling inferred by several experiments are summarized in Fig. 5. The most stringent result (as of November 2007) was obtained by the XENON collaboration. The limits on SD cross section are far weaker and the best constraints, plotted in Fig. 6, come from CDMS [239], NAIAD [262], Super-Kamiokande [266] and KIMS [267]. A better sensitivity to spin dependent couplings is expected for the COUPP experiment, a heavy liquid bubble chamber under development in the NuMI gallery at Fermilab [268].

In comparison, the theoretical predictions of neutralino elastic scattering off nucleons, for different SUSY scenarios, show that current direct searches have begun to explore a relevant portion of the parameter space, while improved sensitivities are needed to perform a complete scan [270, 271].

Direct detection constraints exclude the left-handed sneutrino in the MSSM as dominant Dark Matter component. However, the right-handed sneutrino, in extensions of the MSSM, is a viable Dark Matter candidate, compatible with direct searches [272, 273].

## VIII. IS IT COMPATIBLE WITH GAMMA-RAY CONSTRAINTS?

Aside from direct and accelerator searches, one may search for DM through the detection of its annihilation products, such as photons, anti-matter and neutrinos.

In particular, since the energy scale of the annihilation photons is set by the DM mass, and since some of the most studied DM candidates, such as the supersymmetric neutralino and the LKP in UED models, are expected to lie in mass in GeV-TeV region, exotic gamma-ray sources are among the primary targets of indirect searches (see e.g. [274] for a review about DM searches though gamma-ray astrophysics). Significant emissions at other wavelengths is however predicted in most cases, due to the interactions of the annihilation products with ambient photons or magnetic fields, mak-

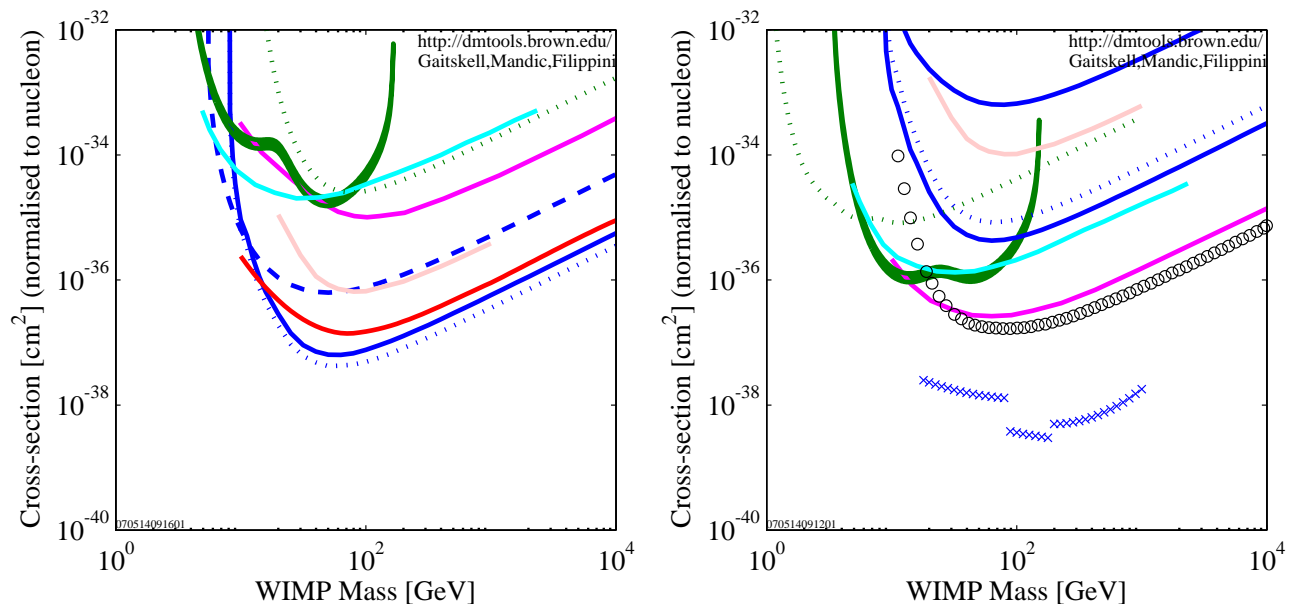


Figure 6: Upper limits on spin-dependent WIMP cross section as a function of the WIMP mass, in the case of a pure neutron (proton) and proton (left) coupling. The blue solid (dashed) line is the Ge (Si) CDMS bound [239]. The blue dotted line is the CDMS limit with an alternative form factor [239]. The light red, cyan, magenta and red curves are the experimental limits respectively from EDELWEISS [265], PICASSO [263], NAIAD 2005 [262] and ZEPLIN I [264]. The dark green shaded region shows the parameter space favored by DAMA experiments [261]. Finally the green points represent the CRESST results [261], the black crosses stand for Super-Kamiokande [266] and the black circles for KIMS 2007 [267]. The figures have been obtained with the use of the interface at <http://dendera.berkeley.edu/plotter/entryform.html>.

ing multi-wavelength searches possible. Emission at different energy scales has also been discussed in the context of other DM candidates, e.g. X-rays from the decay of sterile neutrinos (see Sec.IX).

The gamma-ray flux from WIMP annihilations in a DM halo depends on the particle physics parameters as well as on cosmological quantities, such as the profile of DM halos. More precisely, the gamma-ray flux at earth (if the WIMP is not its own antiparticle a factor 1/2 must be added) is given by

$$\phi(\psi, E_\gamma) = \frac{\langle \sigma_{ann} v \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{l.o.s.} ds \rho^2(r(s, \psi)),$$

where  $m_\chi$  and  $\langle \sigma_{ann} v \rangle$  are respectively the mass and the cross section annihilation times relative velocity of the DM particle. From Eq. 1 in Sec. I it follows that, to match the correct DM density, it is necessary for a cold thermal relic  $\sigma_{ann} v \sim 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ , although this value is just indicative because, for instance, coannihilations can substantially modify the picture, plus the cross section in the non relativistic limit may substantially differ from the one at decoupling (e.g. in the case of p-wave annihilations).  $\frac{dN_\gamma}{dE}$  is the photon spectrum from DM annihilations, that depends on the nature of DM candidate. Finally, the last term in the equation is the integration along the line of sight of the dark matter density squared. The quadratic dependence on  $\rho$ , suggests that ideal targets of indirect searches are regions where the DM den-

sity is strongly enhanced such as the Galactic center (e.g. [275–281, 299]), halo substructures (e.g. [282–287]) and the core of external galaxies (e.g. [288–291]). Prospects for detecting gamma-rays have been discussed also for overdensities in DM halos called caustics (e.g. [292–296]). Much steeper profiles, called *spikes*, may form due to adiabatic growth of black holes, for example around the Super Massive black hole at the Galactic center (see e.g. [297–299] for a discussion about the prospect for detecting DM annihilation gamma-rays in this scenario). Although in this case the spike is likely disrupted by astrophysical processes [297, 300, 301], a moderate enhancement, called *crest*, may form again due to gravitational interactions with the observed stellar cusp [302]. More promising targets may be mini-spikes around intermediate massive black holes, since they are not affected by dynamical processes that tend to lower the density enhancement [303, 304].

Although conclusive evidence for Dark Matter annihilations has not been obtained so far, gamma-ray experiments have nonetheless provided a wide range of observations that can be used as upper bounds of gamma-ray fluxes from DM annihilations, in order to constrain existing DM scenarios. In particular observations in the soft gamma-ray energy band, between roughly 50 keV and 1 MeV, have been performed by the Osse experiments [310] and more recently by INTEGRAL in the range 20–8000 keV (see [311, 312]). All-sky observations have been performed by COMPTEL in the energy range 3 MeV - 30

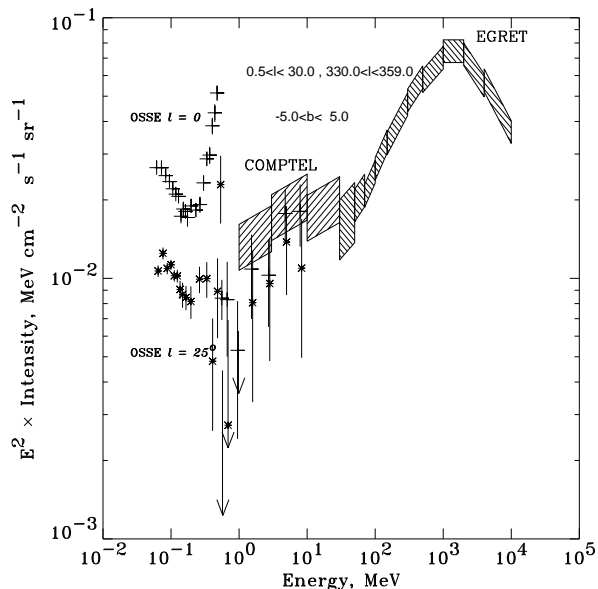


Figure 7: Spectrum of the inner Galactic plane for  $|b| < 5^\circ$  measured by different experiments for energies ranging from sub MeV up to tens of GeV. From Ref. [313]

MeV [313], and EGRET from 30 MeV to over 30 GeV [314]. In Fig.7 we show the spectrum of the inner Galactic plane as measured by these experiments.

Current Air Cherenkov Telescopes such as CANGAROO [305], HESS [306], MAGIC [307] and VERITAS [308] are collecting data at higher energies and the GLAST satellite [309], which is scheduled for launch in 2008, will allow much deeper observation in the energy range 20 MeV - 300 GeV.

As we have seen, there is no conclusive evidence of DM annihilations, but many claims of discovery, or hints of detection, have been put forward in recent years. For example the gamma-ray source been detected by EGRET in the direction of the Galactic center, has been interpreted in terms of DM annihilations (as discussed e.g. in [277, 278, 280, 281, 315]), although it was subsequently suggested that the source may be slightly offset with respect to the Galactic center [316].

The HESS experiment has recently discovered a very high energy source spatially coincident with Sgr A\*, the compact radio source at the Galactic center, and the spectrum has been subsequently confirmed by the MAGIC collaboration. Even in this case, however, the bulk of the signal can hardly be interpreted in terms of the annihilation of common DM candidates, since the shape of the energy spectrum is close to a perfect power-law over two decades in energy, a circumstance that rather points towards ordinary astrophysical sources [275, 279].

Hints of a DM signal may hide in the extragalactic gamma-ray background (EGB) which is inferred from

EGRET observations, after subtraction of the galactic component (see e.g. [323–328]). The existence of a bump in the EGB spectrum at few GeV [317, 318] has been tentatively interpreted in terms of DM annihilations [319–321]. This cannot be however considered as evidence for DM, since the freedom in the DM (cosmological and particle physics) parameters allow enough freedom to explain almost any excess observed in the GeV-TeV range (see the discussion in [322]). In order to obtain conclusive answers, a more robust evidence could be provided by the power spectrum of the EGB anisotropies as can be obtained e.g. by GLAST [329].

Another observation awaiting for a (not necessarily exotic) interpretation is the INTEGRAL detection of an intense 511 keV emission line, due to positron annihilations, towards the galactic center. Many astrophysical sources of positrons have been proposed, for example interactions of cosmic-rays with the interstellar medium [330], pulsars [331], gamma-ray bursts [333], microquasars [334] or radioactive nuclei expelled by stars such as supernovae, Wolf-Rayet and red-giants [332] (see [274, 311] and references therein). However, conventional astrophysical scenarios, can hardly explain the size and morphology of the emitting region, that coincides roughly with the Galactic bulge and that exhibits a fainter disk component [311, 312]. Other more exotic interpretations are again open, in particular the positron source may be provided by DM annihilations. DM candidates with masses close to the electroweak scale have been excluded because the concomitant photon emission would violate the gamma-ray bounds. However, this problem may be circumvented in models where the WIMP shares a quantum number with a specie nearly degenerate in mass, with a splitting in the MeV-range [335, 336].

It has been shown that a DM candidate in the MeV range may successfully explain the 511 keV line, while remaining compatible with other observational constraints [337]. A list of alternative candidates include axinos [316], sterile neutrinos [339], cosmic strings [340], moduli [341], Q-balls [342] and scalars coupled to leptons with gravitational strength [339].

Upper limits on the WIMP mass, in order to be consistent with the EGRET and COMPTEL bounds, can be derived by comparing the gamma-ray emission from internal bremsstrahlung processes and in-flight annihilations with existing gamma-ray data [343–345], that set an upper limit on the mass of the DM particle of about 3-7 MeV (but see also [346]). This would be in conflict with the lower bound on the MeV DM particle mass ( $\sim 10$  MeV) inferred by the cooling rate and neutrino emission of the SN 1987A [195], unless the coupling of these particles with neutrinos is suppressed.

Anyway, all the Dark Matter interpretations of the 511 keV line are today disfavored by recent observations of the emission [347].

It is thus important to search for clear, smoking-gun signatures of DM. The first, and maybe foremost, would be the detection of mono energetic gamma-ray lines,

produced e.g. by neutralino or LKP annihilations via loop-diagrams with  $\gamma\gamma$  or  $\gamma Z$  as final states (see e.g. [278, 323, 348–350]) or also in models with scalar dark matter [351, 352]. A number of alternative strategies have been proposed over the years, see e.g. Ref. [353] for a recent review.

## IX. IS IT COMPATIBLE WITH OTHER ASTROPHYSICAL BOUNDS?

### Neutrinos

Neutrinos can be produced in DM annihilations either directly or via the decay of other annihilation products, and may be detected with high-energy neutrino telescopes, that measure the Cherenkov light emitted by secondary muons propagating in water or ice.

The Sun and the Earth have been proposed as targets for indirect DM searches, since a large number of WIMPs could accumulate in their interior, releasing a large number of neutrinos. The neutrino flux depends on the capture rate of WIMPs in the Sun or in the Earth, thus on the elastic cross section of these particles.

The spin-dependent cross section is far less constrained than the spin-independent one (see Sec.VI) Since in the Earth the abundance of nuclei with odd atomic numbers is very small, the capture rate is dominated by the strongly constrained spin independent coupling, contrary to what happens in the Sun. The prospects for detecting neutrinos from the center of the Earth are therefore not particularly promising, at least for current and upcoming experiments [355]. The null searches of AMANDA have been used to derive an upper limit on neutrino flux from WIMP annihilations, for example in the framework of neutralino Dark Matter [356]. In the framework of MSSM, however, the most optimistic neutralino scenarios will be probed by kilometer size neutrino telescopes such as IceCube [357].

The prospects for detecting neutrinos from the annihilation of Kaluza-Klein Dark Matter in the Sun are more promising, because of its large axial coupling, and the annihilations of  $B^1$  particles to neutrino and tau leptons pairs, respectively forbidden and subdominant in the case of neutralino, dominate the neutrino spectrum, producing a large number of high energy neutrinos. The event rate in kilometer scale detectors is expected between 0.5 and 10 events per year [359].

The Galactic Center (GC), a well studied site for gamma-ray DM searches, offers instead poor prospects for detecting Dark Matter annihilations through neutrinos. An upper limit on neutrino flux from GC, in the case of neutralino Dark Matter, has been obtained by requiring that the associated gamma-ray emission would not exceed the flux measured by EGRET [360]. Unfortunately this bound is below the sensitivity of present and upcoming experiments, such as ANTARES, unless extreme scenarios are considered.

The prospects for detecting neutrinos from so-called *mini-spikes* around Intermediate Mass Black Holes (see the discussion in Sec. VIII) appear more promising. The strong enhancement of the DM density around these objects induces a substantial boost of the DM annihilation rate, leading to neutrino fluxes within the reach of ANTARES and IceCube [361].

A combination of data from different neutrino telescopes can already be used to set an upper bound on the total DM annihilation cross section in the non-relativistic limit, for WIMP masses between 100 MeV and  $10^5$  GeV, which is stronger than the unitarity bound. [235].

### Antimatter

Indirect searches of Dark Matter can be performed by looking at an exotic contribution in the spectra of positrons and antiprotons in cosmic-ray fluxes. These charged messengers, contrary to gamma-rays and neutrinos, do not provide information on the location of their source because of the interaction with the interstellar magnetic fields.

Positrons in cosmic-rays mostly originate from the decay of charged pions and kaons produced in cosmic-ray interactions with interstellar gas. Analytic treatments and numerical codes have been developed to describe the propagation of cosmic rays, and to compute the amount of secondary cosmic rays, including positrons, produced by collisions of primary particles with the interstellar medium (see e.g. [368] for a review about the cosmic-ray propagation in the Galaxy). The measurement of the positron fraction, i.e. the ratio of the positron flux over the sum of the positron and electron fluxes, provides an interesting tool to search for exotic positron sources in a region of a few Kpc from us.

In 1994, the HEAT experiment has observed an excess of the positron fraction, with respect to standard propagation models, at energies beyond 7 GeV [369]. This result has been subsequently confirmed by further measurements obtained by HEAT [370] and recently by re-analysis of the AMS-01 data [371, 372]. WIMP annihilations have been proposed to explain this enhancement, in particular in the framework of supersymmetry [373–380] and Kaluza-Klein Dark Matter [379, 381]. The spectral shape of the positron excess can be well reproduced by LSP annihilation models but a very high annihilation rate is necessary to match the correct normalization, requiring therefore unnaturally large amounts of local dark matter substructures [378]. Instead, a modest boost factor is needed for Kaluza-Klein Dark Matter, due to their large annihilation rate to charged leptons, that leads to a larger number, and harder spectrum, of positrons [379, 381].

The measurements of the positron fraction performed by several experiments, including AMS-01, CAPRICE and HEAT are in agreement with each other but the large uncertainties, as shown in Fig.8, do not allow to draw definitive conclusions on the nature of the GeV ex-



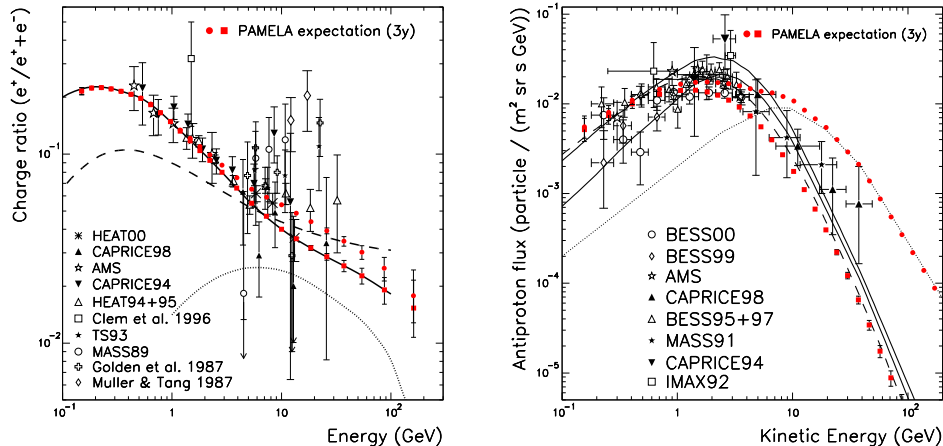


Figure 8: Left: Positron fraction as a function of energy. Shown are the theoretical calculations for pure secondary production (solid and dashed lines) and for pure primary production from neutralino ( $m_\chi=336$  GeV) annihilations (dotted line). Red circles (squares) show a projection of the Pamela measurements after three years of data taking with (without) a neutralino contribution. Right: Energy spectrum of anti-protons. Shown are the theoretical prediction for secondary (solid and dashed lines) and primary production from neutralino ( $m_\chi=964$  GeV) annihilations (dotted line). From Ref.[382].

cess. However, the situation may be clarified soon thanks the larger positron statistics that will be obtained by the PAMELA satellite [382], which was launched in June 2006, and the AMS-02 experiment [383], which should be launched in the near future.

Dark Matter annihilations in the galactic halo may produce antiprotons and the possible imprint on cosmic rays measurements, both at low and high energies, has been extensively studied [384–390]. However the data collected by several experiments, in particular BESS, CAPRICE and BESS-Polar, agree with the calculations of the positron production by cosmic rays, showing no evidence for primary antiprotons [391] (Fig.8 shows data from recent experiments and also theoretical calculations for pure secondary/primary antiproton production). Furthermore, these results cannot be easily translated into constraints on DM candidates, due to the large uncertainties on the antiproton flux induced by the propagation parameters [384, 385]. Much more data will soon be available thanks to Bess-Polar, PAMELA and AMS-02, in particular at high energies, where the contribution from DM annihilations might be dominant for heavy enough WIMPs [390].

Despite the uncertainties in the propagation models, the study of anti-matter fluxes can sometimes provide a useful diagnostic tool for specific DM scenarios. For instance, Bergström et al. have investigated the DM annihilation model of Ref.[392], proposed to explain the EGRET excess of the diffuse galactic gamma ray background, by computing the associated primary antiproton flux from WIMP annihilations. They were then able to rule out the scenario since the anti-proton flux was found to grossly exceed the measured anti-proton flux [393]. The model of Ref.[392] might still be made compatible

with observations allowing for an anisotropic diffusion of cosmic rays [394].

### Multi-wavelength approach and X-Rays emission

More in general, a multi-messenger, multi-wavelength analysis provides more robust results than the simpler *fit-the-bump* approach. For example, when interpreting the origin of a gamma-ray source, one may study the associated synchrotron, bremsstrahlung and Inverse Compton emission, produced by electrons and positrons inevitably produced along with gamma-rays in DM annihilations. These signals can in principle extend over a wide range of wavelengths, all the way from radio to gamma-rays. The limited field of view of radio and X-ray experiments makes it easier to perform multi-wavelength studies of a restricted number of candidate sources, such as the Galactic center [299, 395, 396] galaxy clusters [397, 398], and dwarf galaxies [399, 400]. Radio and X-ray observations are powerful techniques to search for WIMP annihilations and they can provide constraints even more restrictive than those inferred from gamma-rays [396, 400].

X-ray observations provide useful constraints also on DM candidates other than WIMPs. For example, sterile neutrinos (see Sec. II) can decay into active neutrinos  $\nu_\alpha$  and photons with energies in the X band:  $\nu_s \rightarrow \nu_\alpha + \gamma$ ,  $E_\gamma = m_s/2$ . Therefore, X-rays observations constrain the sterile neutrino mass  $m_s$  and their mixing angle with active neutrinos. Assuming then a production mechanism (see e.g. [72]), these limits can be turned into an upper bound on the particle mass. The observation of the cosmic X-ray background requires  $m_s < 8.9$  keV (95 % C.L.) [401], but more stringent constraints are obtained

from individual objects, such as galaxies or clusters of galaxies. For example the XMM-Newton observations of Virgo A impose  $m < 10.6$  keV (95 % C.L.) [402] and an analysis of the Virgo and Coma cluster data further restrict the bound to  $m < 6.3$  keV (95 % C.L.) [402, 403]. A significant improvement has been obtained from X-ray observations of the Andromeda Galaxy:  $m < 3.5$  keV (95 % C.L.) [404]. These results, combined with the lower limit on the sterile neutrino mass inferred by measurements of small scale clustering (see Sec. II), rule out sterile neutrinos in this scenario as the dominant Dark Matter component, constraining their fraction on the total Dark Matter amount to be  $f_s \lesssim 0.7$  at the  $2\sigma$  level [405].

However, sterile neutrinos remain viable for alternative production mechanisms, such as Higgs decays in models with an extended Higgs sector [406], or a resonant production in presence of a very large lepton asymmetry in the Universe,  $L \gg 10^{-10}$  [73, 74].

## X. CAN IT BE PROBED EXPERIMENTALLY?

The last requirement for a particle to be a good DM candidate, is that such particle can be probed experimentally, in the sense that it can be directly detected or that convincing evidence for it, or for the theoretical scenario it arises from, can be obtained with present or future experiments. The nature of this requirement is different from that of the nine other conditions discussed above, where we have essentially required that DM scenarios are not in conflict with existing experiments and observations. Here we add the requirement of "discoverability", that reflects our prejudice on what can be considered a *good* theory in science.

### A. Probing SuperWimps

DM particles may interact far less than weakly, and they could evade all conventional dark matter searches. For example, the supersymmetric gravitino, which only couples gravitationally, has been proposed as a well motivated Dark-Matter candidate. The LKP graviton in UED, axions and axinos are other examples of super-weakly interacting massive particles (or super-WIMPs), i.e. Dark Matter candidates that can be extremely difficult or impossible to observe in direct and indirect Dark Matter searches because of their very suppressed interactions [30, 410, 411].

However, the next to lightest supersymmetric particle (NLSP) could be long-lived, for example the stau NLSP lifetime is of order  $10^6$  sec, for gravitino masses of 10 GeV [412]. If the NLSP is a neutralino, this scenario may have an interesting collider signature, similar to the case of neutralino LSP, because the decays of the NLSP neutralino may occur outside the detector. In this case, the particle spectrum may allow the discrimination be-

tween gravitino and neutralino LSP through the analysis of selected decay channels [413], or spins [414], even if this programme may be challenging for the LHC.

A stau NSLP scenario, as possibly realized in supergravity models [413], offers a more promising opportunity to uncover gravitino Dark Matter models at colliders. The charged NLSP particle would have distinctive time-of-flight and energy-loss signatures that might enable to reconstruct its mass with high accuracy, at a level of per cent or even smaller [413, 415, 416]. A stau would be produced at the end of every supersymmetric cascade and being strongly ionizing, if it is sufficiently slow moving, it may be stopped inside the detector or in a surrounding water tank or calorimeter detector. In particular, it has been suggested that up to  $\mathcal{O}(10^3)$  and  $\mathcal{O}(10^4)$  charged NLSP can be trapped per year at LHC and ILC respectively, by placing a 10 Kton trap around the detector [412, 416, 417].

Collecting a large number of stau, it would be possible to measure the stau lifetime and kinematically determine the gravitino mass, from the dominant decay  $\tilde{\tau} \rightarrow \tau + \tilde{g}$ . The measurements of gravitino and stau masses would allow to compute the stau lifetime predicted by the supergravity model and if it matches the experimental value, one would obtain a strong evidence for supergravity and for gravitino LSP [412, 414, 417].

Detailed simulations have been performed to study the gravitino Dark Matter scenario at LHC and ILC (e.g. [413, 415, 418]). In particular, at ILC, with an integrated luminosity of  $200 \text{ fb}^{-1}$  at  $\sqrt{s} = 420$  GeV, thousands of stau will be stopped within the hadron calorimeter, allowing a reconstruction of the gravitino mass with an accuracy of few GeV and a determination of the Planck mass, for a test of supergravity predictions, at a level of 10 % [418].

As discussed in Sec.IV, for NLSP and gravitino masses in the GeV range, BBN bounds severely constrain the case of neutralino and stau NLSP, while a sneutrino NLSP is perfectly viable. In the latter case, the NLSP decay is invisible, but the predicted small sneutrino-stau mass splitting may produce interesting collider signatures, with soft jets or leptons in the final states [419]. Finally, models of gravitino DM with broken R-parity, may also be searched for in accelerators [420–422], but also through indirect detection [423, 424].

### Axinos

Axinos appear in supersymmetric models implementing the Peccei-Quinn mechanism for solving the strong CP problem, and correspond to the fermionic superpartner of the axion. Their mass ranges between the eV and the GeV scale, and they can be efficiently produced through thermal and non-thermal processes in the early Universe under the form of cold, warm or even hot Dark matter (see e.g. Refs. [410, 425–427] and references therein).

In particular, axinos cold Dark Matter is achieved for masses  $m \geq 100$  keV and for low reheating temperatures  $T_R \leq 10^6$  GeV, in contrast with gravitino CDM that can allow for higher values of  $T_R$ , such as  $T_R \sim 10^{10}$  GeV for  $m_{\tilde{g}} \sim 1$  TeV.

Axino couplings are suppressed by the inverse of the Peccei-Quinn breaking scale,  $f_a \geq 10^9$  GeV, and therefore these particles are extremely weakly interacting. As a consequence, similarly to the case of gravitino LSP, the lifetime of the NLSP can be long, and the strong bounds from Big Bang Nucleosynthesis avoided [427].

The direct production of axinos at colliders is strongly suppressed but they can be profusely produced by the decays of the NLSP particles. As in the case of gravitino, a large number of sleptons NLSP could be collected, in order to measure the NLSP lifetime and to reconstruct the axino mass and the Peccei-Quinn scale  $f_a$  (see [426] and references therein).

However, the problem may arise of discriminating between axino and gravitino LSP models. For instance, a stau NLSP with a lifetime within the range 0.01 s - 10 h is predicted in both scenarios, while shorter or longer lifetime are possible only with a gravitino LSP. To solve this ambiguity, one may consider the three body decay  $\tilde{\tau} \rightarrow \tau + \gamma + \tilde{g}/\tilde{a}$ . For at least  $\mathcal{O}(10^4)$  observed stau decays, a clear distinction between the two models can be achieved through the angular distribution of the decay products and/or measuring its branching ratio [416, 428].

### Axion

Axions have been proposed as a viable CDM candidate and the suppression of their interactions by the Peccei-Quinn scale makes them very weakly interacting (see e.g. [50, 51] and references therein for more informations). Their relic abundance matches the Dark Matter cosmological density for masses around 10  $\mu$ eV but significant deviations from this value can occur because of the large uncertainties in the production mechanisms.

One of the most prominent phenomenological properties is the two photon interaction that allows axion-photon conversions in presence of an electromagnetic field:

$$\mathcal{L}_{a\gamma} = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a.$$

Here,  $\mathbf{E}$  and  $\mathbf{B}$  are respectively the electric and magnetic fields,  $a$  is the axion field and  $g_{a\gamma}$  is the coupling constant.

This coupling constant is linearly related to the mass of the axion and connected to measured properties of the pions and to details of the underlying particle physics model. However, in some cases this relation can be relaxed postulating the existence of axion-like particles with unconnected masses and couplings. The Primakoff process that converts axions into photons is at the basis of most axion searches (see e.g. [51, 429] for a discussion about axion searches).

For example, galactic Dark Matter axions could be resonantly converted into microwave photons in the magnetic field permeating a cavity. The signal would carry information on the mass as well as the axion distribution in the galactic halo. The ADMX experiment[430] has already started to explore the region of parameter space favored for Dark Matter axions, while a larger portion will be probed by the upgraded version of the same project and upcoming microwave cavity experiments.

Complementary searches are dedicated to axions produced by photon conversion in the electromagnetic field of the Sun, probing regions of the parameter space where axions are unlikely the dominant component of Dark Matter.

Solar axions can be searched for with axion helioscopes, through the reconversion to X-rays in external magnetic fields. The strongest bound is obtained by the null searches of the CAST experiment  $g_{a\gamma} < 8.8 \cdot 10^{-11}$  GeV $^{-1}$  for  $m_a \lesssim 0.02$  eV [431].

In addition, one may look for the axion Primakoff conversion into photons in the intense Coulomb field of nuclei in a crystal lattice. However the inferred limits are less restrictive with respect to the previous strategy.

Axions could also affect the polarization of a laser beam propagating through a magnetic field. If the light is linearly polarized with a non vanishing angle with the magnetic field direction, the polarization plane rotates because the polarization component parallel to the magnetic field is depleted by the photon-axion conversion processes whereas the perpendicular component does not. In addition to the rotation of the polarization plane (dichroism), an ellipticity is developed (birefringence) because of the different refractive indexes of the parallel and transverse polarization components. A positive signal of dichroism and birefringence was initially claimed by the PVLAS collaboration [146] and some models have been proposed to reconcile an axion-like interpretation with existing astrophysical bounds [140, 432–434]. However, recent observations, after an upgrade of the apparatus, appear to suggest that the signal was likely due to instrumental artefacts [147].

Axions can also be searched for with photon regeneration experiments, such as ALSP [435]. A laser beam propagates through a magnetic field where photons can be converted into axions. These particles, contrary to photons, can easily pass a opaque barrier wall and they can be subsequently reconverted in photons by the use of a second magnetic field. Finally, gamma-ray experiments could be sensitive to axion-like particles because the photon-axion conversions in the galactic magnetic field or in the photon production sites could induce detectable signatures in the spectra and fluxes of high-energy gamma ray sources [436–439].

## B. UED or SUSY?

We conclude this section with a comment on the discrimination between different DM scenarios. In fact, even in the case of the most well studied DM candidates, i.e. the supersymmetric neutralino and the LKP in UED, the experimental signatures may not easily allow an unambiguous identification. As we have seen, neutralinos could be pair-produced at LHC and escape the detector leading to an imbalance of measured momentum. The discovery reach depends on the rate of such missing energy events, that is strongly related to the squarks and gluino masses. The discovery potential of LHC and the ability to determine the SUSY parameters and masses for given supersymmetric models have been extensively studied [440–448] and for squarks and gluino lighter of 1 TeV the necessary integrated luminosity will be available at LHC already in the first year of operation [440]. In Fig. 9 we show the reach of LHC to TeV scale SUSY, for different channels.

An important role, in the discovery and understanding of SUSY, may be played by the planned positron-electron International Linear Collider (ILC) that should allow a more precise reconstruction of the supersymmetric parameters.

The interplay of LHC and ILC might be crucial for Dark Matter studies, because it would allow to measure the particle physics cross sections and sparticle masses with enough accuracy to infer the neutralino relic density and to test whether the LSP really constitutes the Dark Matter [449] (see also [450] for a broader discussion on the complementarity of LHC and ILC).

The prospects for discovery of Universal Extra Dimension at LHC are also promising. The most abundantly produced states are those strongly interacting, i.e. the first level quarks and gluons, with very large production cross sections for masses in the range of few hundreds GeV [451]. The first excitation of the hypercharge gauge boson,  $B^1$ , can be the LKP and, thanks to KK parity conservation, a good Dark Matter candidate. Similarly to R-parity conserving SUSY, the first level KK states have to be pair produced, and they subsequently decay into SM particles and into  $B^1$  LKP, with the latter escaping from the detector and leading to a missing energy signature. At LHC, the signature with the largest rate is  $E_T^{miss} + (N \geq 2)$  jets, but a more promising channel for UED discovery is that of multilepton final states, with the signature  $4l + E_T^{miss}$ . The LHC should then probe an inverse compactification radius of  $R^{-1} \simeq 1.5$  TeV [452].

However, if a signal of new physics will be detected at LHC, the problem will arise of discriminating between UED and SUSY [452]. In addition, also restricting to SUSY models, LHC will leave degeneracies in the parameter space as it has been shown in Ref. [453, 454]. Some specific features may simplify the task [455–458], also for a discrimination between SUSY and Little Higgs model [459].

For example, the spins of KK states are the same as

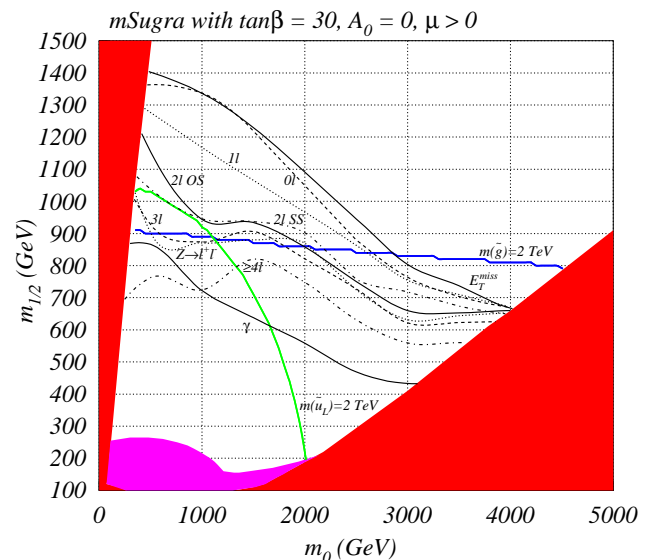


Figure 9: An example of the reach of LHC to TeV-SUSY for different channels in the plane  $m_0$  vs  $m_{1/2}$  in mSUGRA model. The channels taken in account are: zero leptons (0l), one lepton (1l), leptons with opposite charge (OS), leptons with same charge (SS), three leptons (3l), four or more leptons ( $\geq 4l$ ), any number of leptons plus one photon ( $\gamma$ ), at least 2 opposite sign leptons with the invariant mass within an optimized interval around the  $Z$  mass ( $Z \rightarrow l^+l^-$ ) and the inclusive missing transverse energy channel. The solid lines are the 2 TeV mass contours for squark and gluinos. The red region is excluded by theoretical arguments and the magenta region is excluded experimentally. An integrated luminosity of  $100 \text{ fb}^{-1}$  is assumed. From Ref. [441]

their SM partners while in SUSY they differ by  $1/2$ . The spin determination at LHC will be an extremely difficult task, but a charge asymmetry in the lepton-jet invariant mass distributions from particular cascade decays could be used to discriminate UED and SUSY. In particular, quasi-degenerate mass spectra, such as those expected in UED, tend to wash out the spin-correlations and therefore the prospect to exclude a UED pattern given a SUSY spectrum are much better than vice-versa [456–458].

Another difference between the two models is the structure of the Higgs sector: in the Minimal UED model the analogues of the heavy Higgs bosons in MSSM,  $H^0, A^0, H^\pm$  are absent. Even if the first level of Higgs boson has the same quantum numbers, it appears more similar to the higgsino, since it carries KK parity. However, this is not a robust criterium of discrimination at LHC because there are regions of the SUSY parameter space where only the SM higgs bosons can be detected, and therefore SUSY and UED could be confused [452].

A smoking gun signature of UED models is instead provided by the detection of second level particles. The  $\gamma^2$  and  $Z^2$  offer the best prospect for discovery and their resonances can be separately detected for  $R^{-1} \leq 1$  TeV [456]. However, this is not a probe of UED because

the resonance could be interpreted as an extra  $Z$  boson. A quasi-degenerate  $B^1$ - $Z^1$  double resonance is instead a more robust feature of UED, being an accidental mass degeneracy of extra- $Z$  bosons unmotivated. However, this double peak structure would be very difficult to observe at LHC (see Ref.[456] for more details).

In conclusion, it is likely that LHC alone will leave the door open to several models. Anyway, ILC, with  $\sqrt{s} = 3$  TeV, will provide a more adequate tool to effectively distinguish UED and SUSY. In particular the angular distribution of the events and the threshold shape in the KK muons/smuons pairs production are the most convincing evidences for UED/SUSY discrimination [455].

## XI. CONCLUSIONS

In conclusion, we have presented a set of requirements that a particle has to fulfil in order to be considered a viable DM candidate. The requirements are presented in the form of a ten-point test, and we have discussed each of them in a dedicated section that describes the nature of the requirement and guides the reader through the relevant literature.

The test performance of a small subset of DM candidates proposed over the years is shown in Tab.I. The  $\checkmark$  symbol is used when the candidates satisfy the corresponding requirement, and it is accompanied by a ! symbol, in the case that present and upcoming experiment will soon probe a significant portion of the candidate's parameter space. If the requirement can be satisfied only in less natural, or non-standard scenarios, or in the case of tension with observational data, the symbol  $\sim$  is used instead. Candidates with a  $\sim$  symbol in the last column, where the final result is shown, should still be considered viable. If one of the requirements is not satisfied, then the symbol  $\times$  is used, and since these requirements are *necessary* conditions, the presence of a single  $\times$  is sufficient to rule out the particle as a viable DM candidate.

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<i>DM candidate</i>	I. $\Omega h^2$	II. Cold	III. Neutral	IV. BBN	V. Stars	VI. Self	VII. Direct	VIII. $\gamma$ -rays	IX. Astro	X. Probed	Result
SM Neutrinos	×	×	✓	✓	✓	✓	✓	–	–	✓	×
<b>Sterile Neutrinos</b>	~	~	✓	✓	✓	✓	✓	✓	✓!	✓	~
<b>Neutralino</b>	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
<b>Gravitino</b>	✓	✓	✓	~	✓	✓	✓	✓	✓	✓	~
<b>Gravitino (broken R-parity)</b>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sneutrino $\tilde{\nu}_L$	~	✓	✓	✓	✓	✓	×	✓!	✓!	✓	×
<b>Sneutrino <math>\tilde{\nu}_R</math></b>	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
<b>Axino</b>	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
<b>SUSY Q-balls</b>	✓	✓	✓	✓	~	–	✓!	✓	✓	✓	~
<b><math>B^1</math> UED</b>	✓	✓	✓	✓	✓	✓	✓!	✓!	✓!	✓	✓
First level graviton UED	✓	✓	✓	✓	✓	✓	✓	×	×	✓	× <sup>a</sup>
<b>Axion</b>	✓	✓	✓	✓	✓	✓	✓!	✓	✓	✓	✓
<b>Heavy photon (Little Higgs)</b>	✓	✓	✓	✓	✓	✓	✓	✓!	✓!	✓	✓
<b>Inert Higgs model</b>	✓	✓	✓	✓	✓	✓	✓	✓!	–	✓	✓
Champs	✓	✓	×	✓	×	–	–	–	–	✓	×
<b>Wimpzillas</b>	✓	✓	✓	✓	✓	✓	✓	✓	✓	~	~

Table I: Test performance of selected DM candidates. The ✓ symbol is used when the candidates satisfy the corresponding requirement, and it is accompanied by a ! symbol, in the case that present and upcoming experiment will soon probe a significant portion of the candidate’s parameter space. If the requirement can be satisfied only in less natural, or non-standard scenarios, or in the case of tension with observational data, the symbol ~ is used instead. Candidates with a ~ symbol in the last column, where the final result is shown, should still be considered viable. If one of the requirements is not satisfied, then the symbol × is used, and since these requirements are *necessary* conditions, the presence of a single × is sufficient to rule out the particle as a viable DM candidate. Footnotes: <sup>a</sup> It is possible to reconcile a graviton LKP scenario with CMB and diffuse photon background measurements, if the minimal UED model is extended with right-handed neutrinos, Ref.[460].

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