GRAVITINO AND SUPERWIMPS IN COSMOLOGY*

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We will review models of Dark Matter, where the particle interacts much more weakly than weak, also called SuperWIMPs or E-WIMPs models. One particularly very well known candidate of this type is the gravitino, but also other well-motivated particles are the axino, a sterile neutrino or a particle of the hidden sector with GUT suppressed interaction with normal matter, *etc.* These candidates have a very different phenomenology than candidates of the weakly interacting type, *i.e.* WIMPs (Weakly-Interacting Massive Particles), but they can still be produced in cosmology in sufficient number to provide the measured Dark Matter density. Moreover, if they are connected to a larger sector of SM-charged new particles, like in the case of supersymmetric models, they can provide interesting alternative signatures at colliders.

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1. Introduction

While we have strong evidence of the presence of Dark Matter (DM) on many different scales, from galactic to cosmological, and from very different probes, all these observations are based on the DM gravitational effects and mostly just sensitive to its energy density[1]. In fact, from the cosmological perspective, Dark Matter is often modelled as a pressure-less fluid, with characteristics that are universal of most non-relativistic particle candidates, including also particle condensates like the axion. Structure formation is affected by the DM free-streaming and dissipation and thus excludes very light thermal relics as standard neutrinos, that constitute Hot Dark Matter, or particles which can cool down by emission. Nevertheless, also

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[1] For a review of particle Dark Matter see *e.g.* [1].

these constraints still leave the field open for many very different candidates and cannot give clear information on the particle properties of Dark Matter, like mass, spin or interactions. In fact, we do not know how strongly Dark Matter couples with itself or with normal matter. Some quite weak bounds exist on the self-interaction from the observation of the displacement between Dark Matter and gas like in the Bullet cluster [2, 3], or from the shape of Dark Matter halos [4, 5][2]. We have also upper bounds on the DM cross-section with nucleons, both from the direct detection experiments or from the non-observation of a neutrinos flux from the centre of the sun, as discussed by Tomer Volansky at this school, but we have no lower bound on the interaction strength down to gravity.

Of course, if Dark Matter has only gravitational interaction, it will be very difficult to identify it as a particle, but fortunately there is also the possibility that the DM couplings are stronger than gravitational and large enough to allow its efficient production in the early Universe. We will, therefore, concentrate here on supersymmetric DM candidates of this type, which have the advantage of being embedded in very well-defined models with a lot of particles (but often not the Dark Matter one ...) that could be observed at the LHC. Then, it becomes possible to identify DM indirectly from a combination of collider data and astrophysical observations.

2. Dark Matter SuperWIMP candidates

From the theoretical point of view, we can try to classify Dark Matter candidates depending on their mass and their strength of interaction with normal matter. This is quite a useful classification, since the mass allows us to translate the Dark Matter energy density into a number density and gives a hint of the Dark Matter production mechanism. In some cases, moreover, such production mechanism is also connected directly to the interaction of the Dark Matter particle with the SM particles in the primordial plasma.

Well-known candidate of this type are the WIMPs, for which indeed the production mechanism via freeze-out is directly related to the weak scale interaction cross-section of the DM particle with usual matter. A viable supersymmetric WIMP candidate is the neutralino, a linear combination of the superpartners of the EW gauge bosons and the Higgs (for a review of the WIMP mechanism in supersymmetry, see *e.g.* [7]). Note that also particles that interact very weakly decouple from the thermal bath through a freeze-out, but this happens while they are still relativistic and, therefore, their number density comparable to that of photons. It is, therefore, easy

[2] See also [6] for a very recent discussion including possible systematics affecting this type of constraints.

to compute the number density of a relativistic DM relic today as

$$\Omega_{\mathrm{DM,rel}}\, h^2 \sim 0.1 \left(\frac{m_{\mathrm{DM}}}{0.1\,\mathrm{keV}}\right) \left(\frac{g_*}{106.75}\right)^{-1}, \tag{1}$$

where m_{DM} is the Dark Matter mass and g_* is the effective number of degrees of freedom thermalized at the time of DM decoupling. We consider here the case, where DM has only two degrees of freedom and decouples at the time when the whole SM is thermalized and no subsequent entropy production dilutes the particle number[3].

Particle of this mass become unfortunately non-relativistic quite late in the cosmological history and retain some non-negligible velocity and free-streaming during the time of structure formation. In fact, very light relics of eV–keV masses constitute what is called Hot Dark Matter and are nowadays excluded as Dark Matter candidates since we observe density fluctuations at the galactic scales. Thermal relics above the keV mass range are instead called Warm Dark Matter and are not yet completely excluded as long as their free-streaming is sufficiently small. Determining exactly the mass boundary between excluded and allowed relics is not very simple, but for a thermal relic few groups found bounds around the few keV masses [8, 9]. We see, therefore, from the formula above that SuperWIMPs cannot usually be thermal relics and at the same time sufficiently cold for structure formation, apart in the case of a density dilution by a factor of the order of 100 after decoupling [10, 11].

On the other hand, if they are heavier than the keV-scale, SuperWIMPs can be sufficiently abundant to be Dark Matter even if they were not in thermal equilibrium in the primordial plasma. In that case though, one cannot rely on thermal equilibrium as initial condition and the exact particle number has to be computed by solving a Boltzmann equation starting from the particular initial conditions. A minimal assumption is that the number density of the SuperWIMPs was negligible at the time of reheating after inflation and that subsequently DM particles were produced in rare scatterings in the thermal plasma at and after reheating. Considering that the thermalization of SM particles is very fast, one can then use the instant reheating approximation and assume that all the particles with SM charges, including *e.g.* the SM superpartners, were in thermal equilibrium at the temperature T_{RH}, which is then used as initial temperature for the solution of the SuperWIMPs Boltzmann equation. The details of the Boltzmann equation depend, of course, on the couplings of the SuperWIMP particles and, therefore, on the particular model, but some general remarks are possible:

[3] Note that for the three Standard Model neutrinos, the decoupling takes place much later, so that the SM neutrino mass scale corresponding to $\Omega_\nu h^2 = 0.1$, assuming 3 degenerate neutrinos, is instead approximately 3 eV.

- non-renormalizable dimension 5 operators, in general, give particle production rates proportional to the temperature, so that the contribution at $T_{\rm RH}$ dominates over the subsequent epochs; in that case, the right DM density is directly related to the reheat temperature and can be fixed dynamically from $T_{\rm RH}$ and an upper bound on maximal reheat temperature is obtained in order to avoid overclosure of the Universe;
- the Boltzmann equation includes not only scatterings, but also decay contributions, which display a different temperature behaviour, *i.e.* they are independent of the temperature as long as the decay rate is short compared to the Hubble rate and they become effective only at the particular temperature corresponding to $\Gamma_{\rm D} = H(T)$. Depending on the interactions of the decaying particle, this effect can become important either when such particle is still in equilibrium or when it has already decoupled from the thermal bath. In both cases, the production mechanism is independent from $T_{\rm RH}$. Regarding the first case, the importance of including decays was realized for specific models in [12, 13] and the mechanism was first applied to Dirac neutrinos in [14]. It recently has been applied to a wider type of models and become popular under the name of "freeze-in" [15]. Of course, for the decay term to be dominant in the Boltzmann equation, it is necessary that the dimension 5 scattering are sufficiently suppressed or the reheat temperature not too high.
  In the second case instead, not only the DM density becomes independent of the reheat temperature, but it can be directly related to the density of the decaying particle at freeze-out and the WIMP mechanism can be translated into the "SuperWIMP mechanism" as [16–18]
$$\Omega_{\rm DM} h^2 = \frac{m_{\rm DM}}{m_{\rm WIMP}} \Omega_{\rm WIMP}\, h^2\,, \tag{2}$$
  where we assume that the decaying particle is of the WIMP type.

To become more precise, we will in the next sections concentrate on the specific cases of gravitino and axino as SuperWIMPs because for those candidates the couplings are mostly given by the symmetries of the models and the particles are introduced in the theory for reasons independent of the question of Dark Matter.

3. Gravitinos and axinos production mechanisms

Gravitinos are the supersymmetric partners of the graviton, characterized by spin 3/2 and couplings determined by supergravity [19]. They are, therefore, quite natural candidates for Dark Matter if they are the

Lightest Supersymmetric Particles (LSP) and, in fact, Pagels and Primack proposed them as relativistic thermal relics already in 1982 [20]. As discussed in the previous section, that type of gravitino DM would be today called HDM and is no more viable as dominant component. Axinos are instead the fermionic superpartners of the axion and share some interesting properties with the gravitinos. In fact, both particles interact via non-renormalizable interactions with matter, which are determined by the symmetry of the model, either gravity or the Peccei–Quinn symmetry. Also both particles acquire mass from supersymmetry breaking: the gravitino is the gauge fermion connected to supersymmetry and, therefore, acquires a mass via the SuperHiggs mechanisms and the axino remains mass-degenerate with the (nearly massless) axion as long as supersymmetry is unbroken. They can, therefore, be regarded as "naturally light" particles, even if the precise mass ordering between superpartners depends from the particular supersymmetry breaking model. In this paper, we will consider the two masses as free parameters and one candidate at a time, but interesting combinations have also been put forward, as *e.g.* the axino LSP with gravitino NLSP as a solution of the gravitino problem [21].

Regarding the particle interactions, the gravitino couplings are particularly simple in the small gravitino mass limit, where the gravitino can be approximated with its spin $1/2$ component, the Goldstino, *i.e.* the Goldstone fermion of SUSY breaking, absorbed by the gravitino when it becomes massive to give the additional polarizations of a massive particle. Being a Goldstone particle, it couples derivatively to the supercurrent in a similar way as the Goldstone bosons of a broken symmetry couples to the corresponding current. The gravitino energy density from thermal scattering has been the study of detailed work in the recent years [22–24] and the result is given by

$$\Omega_{3/2}\, h^2 \sim 0.3 \left(\frac{m_{3/2}}{1\,\mathrm{GeV}}\right)^{-1} \left(\frac{T_{\mathrm{RH}}}{10^{10}\,\mathrm{GeV}}\right) \sum_i c_i \left(\frac{M_i}{100\,\mathrm{GeV}}\right)^2 , \tag{3}$$

where c_i are coefficients of the order of 1 and M_i denote the three gaugino masses at EW temperature (RGE effects to T_{RH} are included in the coefficients c_i).

The axino couplings are not surprisingly of a similar type, since even if it is not a Goldstone fermion itself, it is the superpartner of a pseudoGoldstone boson. All the couplings are, therefore, non-renormalizable and suppressed by the breaking scale of the global U(1) Peccei–Quinn symmetry, often denoted by f_a, like those of the axion[4]. There is, nevertheless, an important

[4] For a review of the axion's couplings see *e.g.* [25].

difference in the axino couplings, which depends on the Peccei–Quinn sector: if that sector contains very heavy particles, with masses much larger that the supersymmetry breaking scale or the temperature of the plasma, one can integrate them out in a supersymmetric manner and so obtain the coupling of the whole axion/axino multiplet as a supersymmetric term in the superpotential, as

$$W_{\rm PQ} = \sum_i \frac{C_{ai}\alpha_i}{8\sqrt{2}\pi f_a} A W^{i,\alpha} W^i_\alpha \,, \tag{4}$$

where α_i is the gauge coupling relative to the gauge group with vector supermultiplet W^i, C_{ai} are the corresponding axion couplings (often $C_{a3} = 1$ by the definition of f_a, while the couplings to the EW gauge multiplets is model dependent) and A is the axion chiral multiplet. This is often the case for the KSVZ type of axion models, where heavy chiral multiplets with masses at the Peccei–Quinn scale are introduced.

Within the dimension 5 interactions given above, usually the coupling to the QCD sector dominates and then axino number density has been computed by various groups [26–29] and it is given by

$$\Omega_{\tilde a}\, h^2 \sim 2.7 \left(\frac{m_{\tilde a}}{1\,{\rm GeV}}\right) \left(\frac{T_{\rm RH}}{10^4\,{\rm GeV}}\right) \left(\frac{f_a}{10^{11}\,{\rm GeV}}\right)^{-2} . \tag{5}$$

Recently, it has been realized in [30], that if the Peccei–Quinn sector is instead at a low mass scale, the dimension 5 axino couplings are suppressed at temperatures above that scale. This is mostly the case for the DFSZ type of axion models, where the Peccei–Quinn charged states are the SM particles and their superpartners. Then the direct coupling of the axion multiplet to the Higgs chiral multiplets, which gives rise to the μ term, is the strongest axino coupling and so the axino production can proceed via "freeze-in" through the decay of the Higgsinos in equilibrium [29–31].

In general, for the axino case, also more complex scenarios are possible, *e.g.* the Dark Matter can be also made for a substantial part by an axion condensate, depending on the value of f_a, as discussed recently in [32, 33].

4. BBN constraints on the NLSP

Apart for the population of DM particles produced by thermal processes, which have been discussed in the previous section, also the decay of the out of equilibrium NLSP produces LSPs, as long as R-parity is conserved. In that case though, due to the non-renormalizable couplings the decay of the NLSP happens quite late in cosmology and can cause a conflict with the predictions of Big Bang Nucleosynthesis. This is similar to the well-known gravitino problem [34–36], only that in this case the decaying particle is the NLSP instead of the gravitino. The most important parameter determining if the decay is dangerous is the NLSP lifetime, which is different depending if the LSP is a gravitino or an axino. In fact, for a Bino neutralino NLSP we have

$$\tau_{\tilde{B}} = \begin{cases} 0.57 \times 10^5\,\mathrm{s}\left(\frac{m_{\tilde{B}}}{100\,\mathrm{GeV}}\right)^{-5}\left(\frac{m_{3/2}}{1\mathrm{GeV}}\right)^2 & \text{gravitino LSP}\,, \\ 0.25\,\mathrm{s}\left(\frac{m_{\tilde{B}}}{100\,\mathrm{GeV}}\right)^{-3}\left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^2 & \text{axino LSP}\,, \end{cases} \tag{6}$$

where $m_{\tilde{B}}$ denotes the mass of the Bino. Since BBN starts at approximately one second, it is clear that the constraints are much more stringent for the gravitino than for the axino. For the latter the bounds are quite mild, as long as f_a is in the axion window $5 \times 10^9\,\mathrm{GeV} \leq f_a \leq 10^{12}\,\mathrm{GeV}$; the most stringent bounds are for the stau NLSP, whose decay rate takes place in the KVSZ models only at two loops and has been recently discussed in [37]. For the gravitino LSP case, the constraints are, instead, quite strong and exclude many NLSPs, apart if they are sufficiently heavy, possibly beyond the present LHC reach (note that the decay rate goes as the mass to the fifth power !) or if the gravitino is sufficiently light. Another way to relax the bounds is to reduce the NLSP density at decay, but this is quite difficult to achieve both in the CMSSM [38, 39] and for a general neutralino [40, 41], apart when efficient coannihilation with the gluino for a very compressed gaugino spectrum reduces the neutralino density by orders of magnitude [42].

Note that the BBN constraints are easily satisfied if the NLSP decays early into SM particles via R-parity breaking couplings; already couplings of the order of 10^{-10}–10^{12} are sufficient to open such decay channels. In that case, the gravitino or the axino can still remain as Dark Matter candidates since their decay time is much longer than the age of the Universe [43–45]. If the couplings are large enough such a decay could be observable in indirect detection observations [46–52].

At the moment, the FERMI data set a lower bound on the DM lifetime in photons of the order of 5×10^{28} s, already excluding part of the R-parity breaking parameter space [53, 54].

5. SuperWIMPs at the LHC

While the DM particles, we discussed, are too weakly interacting to be produced at colliders, even in cascade decays, the rest of the supersymmetric partners are charged under the SM gauge groups and should appear at the LHC if the available energy allows it. Therefore, the phenomenology at the LHC of this scenario is not very different from the usual SUSY WIMP scenario, apart for the fact the NLSP takes the role of the LSP in cascade decays and can be any particle of the supersymmetric spectrum, not only the neutralino. If the NLSP is charged, like a stau or a stop, and stable on collider's timescale, then the signature will be really distinctive and will immediately point to the SuperWIMP scenario. The LHC is already looking for such heavy long-lived particles, so far without any signal [55]. Still, even once a signal will be observed, it will not be so easy to disentangle the particular SuperWIMP particle. Probably the decay of the NLSP will have to be observed to give any hint [56].

Of course, also the possibility of observing the NLSP decay at the LHC is still open, either if the gravitino is very light, below the MeV scale [57–59], or if R-parity is violated. In the latter case, a possible signal at collider may be directly correlated to an indirect detection signal, especially for a neutralino NLSP [52, 54, 60]. For the case of stau NLSP, it will be in any case very important to measure the displaced vertices and determine the decay products to distinguish between model with or without R-parity [61–63].

Note that also model-independent search channels like the monojet or monophoton channels [64, 65] can be used to observe the NLSP and cover for example the case of compressed spectra [66]. Unfortunately, so far no signal of supersymmetry has been observed at the LHC.

6. Conclusion

SuperWIMPs are an alternative to WIMPs as CDM candidates and can be realized in many different scenarios. In the context of minimal supersymmetric models, in particular, there are already two promising SuperWIMP candidates, the gravitino or the axino LSP. Both can be produced in sufficient numbers even out of equilibrium and be so Cold Dark Matter. Due to the suppressed couplings, Big Bang Nucleosynthesis sets strong constraints on the lifetime and density of the NLSP if R-parity is conserved and may point, especially in the case of the gravitino LSP, to a strongly compressed spectrum or to large NLSP masses, even beyond the reach of the LHC. On the other hand, SuperWIMPs gravitino or axino can be DM even for broken R-parity, if the breaking is sufficiently suppressed and the DM lifetime is longer than $\sim 5 \times 10^{28}$ s; present indirect detection DM searches are already setting limits on these scenarios, but a decaying NLSP within the LHC detectors is still possible.

So far, unfortunately, no evidence of SuperWIMPs has been seen at colliders or in indirect DM detection, but more data are expected in the near future and a signal could appear anytime. Note indeed that the favored SuperWIMPs supersymmetric scenarios discussed here, like heavy superpartners, a compressed spectrum or R-parity violation, do not offer the classic

WIMP SUSY signals like jets and missing energy. Nevertheless, more channels are recently started to be analyzed by the LHC experiments and will be investigated more in detail in the next years.

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