DARK MATTER CANDIDATES: AXINO AND GRAVITINO

L. Covi
Institute for Theoretical Physics, Georg-August University Göttingen,
Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany

We review the scenarios of axino and gravitino Cold Dark Matter, highlighting recent theoretical developments and discussing possible signatures in the SUSY searches at the LHC and in indirect Dark Matter detection experiments.

1 Introduction

Axino and gravitino are particles that are found in models extending the Standard Model of particle physics to include supersymmetry and either the Peccei-Quinn (PQ) symmetry [1] or gravity. These extensions of the SM have a strong theoretical motivation for completely independent reasons compared to providing a DM candidate: Supersymmetry [2] solves the hierarchy problem connected to the Higgs mass and allows for gauge coupling unification. It is also the largest possible extension of the Poincaré symmetry. Gravity of course does not need any justification, since it is the first force observed in nature and should in any case be taken into account in any model discussing cosmology. The PQ symmetry instead has at the moment no phenomenological motivation, but is the most promising solution of the strong CP problem and offers also without supersymmetry another viable DM candidate, the axion [3]. So in both cases the additional particles are not introduced just to explain the Dark Matter conundrum, but arise from the assumed symmetries and their properties are determined by no or very few free parameters.

Moreover it is easy to see that axino and gravitino do indeed have the right characteristics to be Dark Matter [4]: they do not carry charge nor baryonic number, they are massive since supersymmetry has to be broken and can be sufficiently heavy to become cold DM. Moreover, if they are the lightest supersymmetric particle, they can be stable or sufficiently long-lived to be still present today.

They are Dark Matter candidates of the type called "SuperWIMPs" [5] or "E-WIMPs" [6], since their interactions with the SM and themselves are non-renormalizable and suppressed, in one case by the Planck mass and in the other by the Peccei-Quinn scale f_a. They are therefore usually non-thermal relics and not WIMPs. In fact if they did reach thermal equilibrium in the early universe, they decoupled when still relativistic with a large number density, such that they must have mass in the keV range and can only be Hot or Warm DM [7].

The fact that they interact so weakly means also that they are very elusive particles to study and measure at a collider. Only if they are DM and played a substantial role in the evolution of the Universe we may hope to gain information on their properties, like mass and couplings. While the SuperWIMPs scenario may seem therefore far away from collider phenomenology or even DM detection, we will see that this is not the case and that a "SuperWIMP connection" can arise, analogously as for the WIMP case, giving signals at LHC and, if R-parity is broken and the axino or gravitino DM is unstable, in indirect DM detection.

1.1 The axino

The Peccei-Quinn symmetry is an anomalous global $U(1)$ symmetry, broken at a high scale $f_a \sim 10^{11}$ GeV. After the breaking, the only surviving field in a non-supersymmetric model is the pseudo-goldstone boson of the symmetry, the axion. Due to the anomalous nature of the symmetry, the axion couples with the gluon field as [3]

$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a \; . \tag{1}$$

This coupling has the same form as the QCD θ term and therefore a non-vanishing θ can be reabsorbed into a and becomes a dynamical field. At the chiral QCD phase transition the axion acquires a mass and a potential via instanton effects and relaxes to the minimum with zero effective θ solving the strong CP problem. This is the PQ mechanism in a nutshell.

The axino is the superpartner of the axion [8] and its couplings can be obtained by supersymmetrising the axion ones as [9]

$$W_{PQ} = \frac{\alpha_s}{4\sqrt{2}\pi f_a} A W^\alpha W_\alpha \; . \tag{2}$$

where A is the axion chiral multiplet and W^α the vector multiplet containing the gluino λ^α and the gluon. In some models also couplings with the other SM gauge groups can arise and are of the same type. There are different axion models, depending on the PQ charges of the SM fields and on the presence of additional states: the KVSZ models [10] assume the existence of heavy colored states charged under the PQ symmetry, while the DFSZ models [11] mix the axion with the Higgs fields and give PQ charge also to SM fields. In the latter models also the superpotential couplings between the axino and Higgs/Higgsino can become important [12,13]. For a recent discussion on the axino couplings in all its subtleties, including momentum dependence, see [14,13].

1.2 The gravitino

The gravitino is the superpartner of the graviton and belongs to the gravity multiplet in local supersymmetry (supergravity). Since the graviton has spin 2, the gravitino has spin 3/2 and its interactions are completely determined by the gravitational interaction and SUSY breaking [2]. In fact after SUSY breaking, thanks to the SuperHiggs mechanism, the gravitino absorbs the Goldstino state and becomes massive, similarly to what happens for the EW gauge fields with the Higgs Goldstone modes. If the gravitino is the lightest supersymmetric particle, the Goldstino component dominates the interactions and its couplings are just fixed by the Planck scale and the supersymmetry breaking masses. Singling out the Goldstino component as $\psi_\mu \sim i\sqrt{\frac{2}{3}}\frac{\partial_\mu \psi}{m_{\tilde{G}}}$ one obtaines the effective Goldstino lagrangian as [15]:

$$\mathcal{L}_{eff,\tilde{G}} = -\frac{m_\lambda}{4\sqrt{6} M_P m_{\tilde{G}}} \bar{\psi} \sigma^{\nu\rho} \lambda^a F^a_{\nu\rho} + i \frac{(m_\phi^2 - m_\chi^2)}{\sqrt{3} M_P m_{\tilde{G}}} \bar{\psi} P_R \chi \phi^* + h.c. \tag{3}$$

where M_P is the Planck mass, $m_{\tilde{G}}, m_\lambda, m_\phi, m_\chi$ are the gravitino, gaugino, scalar and chiral fermion masses respectively. Here $\lambda, F_{\nu\rho}$ belong to the same vector multiplet, while ϕ, χ are the scalar and fermion in a chiral multiplet.

We see from the above expression that the (light) gravitino couplings are completely fixed by the particle spectrum and the Planck scale. This is a consequence of the fact that the Goldstino couples to the supercurrent. Note that the lighter the gravitino is, the stronger it couples for the same superpartner masses. Since at the end all the SUSY breaking masses are proportional to the gravitino mass, the strength of the gravitino coupling is a signal of the SUSY breaking mediation model.

2 Thermal production and BBN constraints

Below the temperature at which the axino or gravitino are in thermal equilibrium, they are still produced by 2-to-2 body scatterings in the thermal bath. In considering these processes one can usually disregard back-reaction and obtains a thermal yield proportional to the highest temperature in the thermal bath, which we will call T_R. The interactions of axino and gravitino with the QCD gauge multiplet are very similar and the computations can be done with analogous techniques. One of the sources of uncertainties is the treatment of the IR divergence in the gluon t-channel, which has to be regulated by a gluon thermal mass. The gravitino abundance obtains substantial contributions from all SM gauge sectors, while on the other hand, the interaction with the EW and hypercharge groups is different and model-dependent for the axino case.

The gravitino yield reads [16]

$$\Omega_{\tilde{G}} h^2 = 0.3 \left(\frac{1 \text{ GeV}}{m_{\tilde{G}}} \right) \left(\frac{T_R}{10^{10} \text{ GeV}} \right) \sum_i c_i \left(\frac{m_{\lambda_i}}{100 \text{ GeV}} \right) \tag{4}$$

where m_{λ_i} are the 3 gaugino masses and $c_i \sim \mathcal{O}(1)$.

So in general there is always a bound on the reheat temperature and such temperature has to take a specific value in order to match the DM density. Note that the smaller $m_{\tilde{G}}$, the smaller the temperature has to be. Also given a specific temperature, the gaugino masses must satisfy an upper bound to avoid overclosure [17], so that one cannot push the whole SUSY spectrum to a high scale and still have gravitino DM.

The axino yield instead is given as [18]

$$\Omega_{\tilde{a}} h^2 \sim 0.3 \left(\frac{m_{\tilde{a}}}{0.01 \text{ GeV}} \right) \left(\frac{T_R}{10^4 \text{ GeV}} \right) \left(\frac{10^{11} \text{ GeV}}{f_a} \right)^2 \tag{5}$$

where $m_{\tilde{a}}$ is the axino mass. This computation has been recently revisited in [13], where also subleading terms in the gluon thermal mass have been included ending in a slightly larger yield than given in Eq. 5. In any case the axino DM case points at a pretty low reheat temperature [a].

For both axino and gravitino, also the yield coming from the decay of superpartners instead of scatterings can be substantial and even dominate the production. On one hand, the decay of particles still in thermal equilibrium has recently attracted renewed attention [19] since it results in a yield independent on the reheat temperature, but so it corresponds to the DM abundance only for a particular value of the DM mass. On the other hand, the decay of the NLSP out of equilibrium [20,5] may also generate the correct DM number density independently of the temperature, but it can also endanger Big Bang Nucleosynthesis (BBN) predictions [21]. In fact the decays produce not only axino/gravitino but also energetic SM particles, that may change the abundance of light elements and spoil the agreement of BBN with the observations. The key parameter to check how dangerous the decay can be for BBN is the NLSP lifetime, which is very different for axino or gravitino LSP. For a Bino NLSP we have

$$\tau_{\tilde{B}} = 0.25 \, s \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}} \right)^{-3} \left(\frac{f_a}{10^{11} \text{ GeV}} \right)^2 \tag{6}$$

$$\tau_{\tilde{B}} = 5.7 \times 10^4 \, s \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}} \right)^{-5} \left(\frac{m_{\tilde{G}}}{1 \text{ GeV}} \right)^2 \tag{7}$$

[a] Note, though, that very recently [14] finds a suppressed yield for axion models with light PQ charged fermionic states.

for axino and gravitino LSP respectively. So we see immediately that the BBN constraints are much more stringent for gravitino DM than for the axino case, since for the axino case the NLSP often decays before BBN starts. For this reason, BBN constraints play an important role in the axino LSP scenario only for large values of f_a as obtained in [22 23].

Different mechanisms have been proposed to ease these troubles with Nucleosynthesis, e.g. NLSP dilution by entropy production [24], or tuning of the NLSP to have harmless decay channels, etc.. Here we will consider only two possibilities: reducing the NLSP number density by coannihilation with the gluino or shortening of the NLSP lifetime via R-parity breaking.

3 NLSP coannihilation and degenerate gaugino spectrum

Considering a light degenerate gaugino spectrum has two clear advantages: on one side it allows for larger T_R since the gravitino abundance is reduced by small gaugino masses [25] and on the other it allows to reduce substantially the NLSP number density at freeze-out via coannihilation [26]. We proposed this scenario in particular in order to reach reheat temperatures compatible with thermal leptogenesis [27]. We found that the most efficient coannihilation is between gluinos and Bino neutralinos and that it suppresses the Bino abundance up to four order of magnitude for a mass degeneracy below 5%. The coannihilation of Wino neutralino with the gluino is instead much less strong and does not improve much the situation; nevertheless, even without a degenerate gluino, the Wino neutralino coannihilates with the charginos and this effect allows to avoid the BBN constraints in a small window for light Wino around 100 GeV [28]. For Higgsino neutralino, the strong annihilation via Higgs resonance is more efficient in reducing the abundance than the coannihilation with the gluino.

We are therefore lead to a scenario with Bino-gluino coannihilation and in such case the BBN constraints can be evaded for light NLSP masses below 300 GeV and gravitino masses of the order of 1-10 GeV. The scalar supersymmetric spectrum was chosen heavy in our model, with sleptons above 600 GeV and squarks above 1 TeV.

3.1 Collider signatures and constraints

Such a low gluino and Bino mass may seem to be already excluded by colliders. Unfortunately (or fortunately for us) it is not, and this is due to the fact that the gluino decays mainly into Bino and gluon with a very soft jet, most of the cases with tranverse momentum below the experimental cuts. The signal from two light gluinos remains then only missing energy with very soft radiation and it is not easily triggered on.

More promising is instead the associate production of a squark and a gluino. Then an energetic jet arises from the much heavier squark decaying into gluino and quark and the resulting signal is a mono-jet and missing energy, similarly to what happens for WIMP DM with ISR [29] or graviton production in extra-dimensional models like ADD. The gluino-squark production rate depends strongly on the squark mass and we estimated last year that the first phase of LHC measurements, with 1 fb^{-1} of data, should be able to exclude a 300 GeV gluino NNLSP up to squark masses as large as 1.8 TeV. Preliminary results on the monojet signature have been presented in this conference [30] by the CMS collaboration for 36 pb^{-1}. Recently at the Europhysics Conference on High-Energy Physics 2011, new results were presented using 1 fb^{-1} of data by the ATLAS collaboration, which correspond to a model-independent constrain on the cross-section times acceptance for a monojet to lie below 0.11 pb at 95% CL [?]. While a detailed analysis of the acceptance for our scenario is missing, assuming it to be larger than 90%, this exclusion reaches approximately our expectation.

4 R-parity breaking

One easy way to avoid any clash with BBN predictions is to assume that the NLSP decays fast enough, i.e. with a lifetime below 0.1 s. This may happen for conserved R-parity if the gravitino is lighter than 0.01 GeV or so (see Eq. 7 for the dependence on the NLSP mass), but the decay is usually much faster if R-parity is violated, since it can proceed via a renormalisable interaction. In general the R-parity violating superpotential is given by

$$W_{R\!\!\!/ p} = \mu_i L_i H_u + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c \tag{8}$$

where capital letters denote MSSM chiral multiplets. The couplings μ_i, λ, λ' violate not only R-parity, but also lepton number conservation, while λ'' violates the baryon number conservation. If all these couplings are non-vanishing, the proton decays much too quickly, but for suppressing proton decay to acceptable level it is sufficient to require λ'' to be zero or very very small. The other couplings then can be large enough to allow for the decay of the NLSP directly to SM particles before BBN. Note that in this case there is no gravitino/axino in the final state and therefore no yield from NLSP decay.

The lifetime of a Bino NLSP can be estimated to be of the order

$$\tau_{\tilde{B}} \sim 10^{-10}\, s \left(\frac{|\zeta|}{10^{-7}}\right)^{-2} \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}}\right)^{-1} \tag{9}$$

where ζ denotes the dominant R-parity violating coupling $\sim \frac{\mu_i}{\mu}, \lambda, \lambda'$ and the superpartners are assumed to have $m \sim m_{\tilde{B}}$. It is clear therefore that even R-parity violating couplings as small as 10^{-12} can still lead to NLSP decay before Nucleosynthesis. On the other hand, the R-parity and lepton violating couplings do have to be sufficiently small to avoid wash-out of the baryon number via sphaleron processes and this gives an upper bound around 10^{-7}. We have then a window of couplings between $10^{-7} - 10^{-12}$ that gives consistency between cosmology and gravitino DM [32]. For the case of axino DM, we have seen that the BBN constraints are much weaker and R-parity violation is probably not necessary, but still possible [9].

4.1 *Axino and gravitino decay*

If R-parity is broken, then the LSP is not stable any more and we could be in danger of losing our DM candidate. We can see that this does not happen, since the decay rates are very small due to the non-renormalizable couplings and the smallness of the R-parity violation. The lifetimes for axino and gravitino for the case of bilinear R-parity violation read [33,9]

$$\begin{aligned} \tau_{\tilde{a}} &= 10^{27}\, s \left(\frac{|\zeta|}{10^{-10}}\right)^{-2} \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}}\right)^{2} \left(\frac{m_{\tilde{a}}}{10 \text{ GeV}}\right)^{-3} \left(\frac{f_a}{10^{11} \text{ GeV}}\right)^{2} & (10)\\ \tau_{\tilde{G}} &= 10^{27}\, s \left(\frac{|\zeta|}{10^{-7}}\right)^{-2} \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}}\right)^{2} \left(\frac{m_{\tilde{G}}}{10 \text{ GeV}}\right)^{-3} & (11)\end{aligned}$$

and can therefore be much longer than the age of the Universe. Similar lifetimes can be expected for trilinear R-parity violation, studied in the case of the gravitino in [34,35], but the decay channels are different. For gravitino masses just below the W/Z threshold 3-body decays are important though also for the case of bilinear R-parity breaking [36].

This lifetime may appear to be too large to give any observable signal, but note that it is smaller than the bounds on the proton lifetime. In fact the smallness of the decay rate is compensated by the number of DM particles in our halo and we can therefore predict signals from DM decay in all possible cosmic ray channels, i.e. gamma-rays [37], neutrinos [38] and gamma-rays and charged particles together[39]. For the case of bilinear parity violation, the most stringent bounds arise from the recent FERMI search for γ-lines [40], which can be translated into a bound on the decaying particle lifetime of the order of 6×10^{28} s [41,42]. This already excludes part of the interesting parameter space for gravitino Dark Matter [41,42], requiring $\zeta < 10^{-8}$, and is even stronger for the axino case, for which the R-parity violation couplings have already to be less than 10^{-11}.

4.2 Signals at colliders

Both in the case of R-parity conservation or not, the NLSP may appear stable at colliders and just escape with either missing energy for a neutralino NLSP or a charged track, for e.g. a stau NLSP. For the axino case, the NLSP can have a large range of lifetimes, but it always decays outside the detector, both for conserved R-parity, due to $f_a > 5 \times 10^9$ GeV, see Eq. 6, and for broken R-parity, due to the smallness of ζ, as discussed in the previous section. In this case, probably the most promising signal is a metastable stau NLSP leaving a highly ionizing track in the LHC detectors.

For gravitino LSP instead, different signals are possible, also depending on the NLSP. For the R-parity violation scenario with neutralino NLSP, the constraints from the FERMI Gamma-ray telescope push the decay length to be of order 100 m [42], but still a fraction of NLSPs could decay inside the detectors and be observed at the LHC [41]. In the same scenario with stau NLSP instead, the relation between the FERMI constraints and the stau decay length is more model-dependent [41] and also shorter decay lenghts may still be allowed.

Instead if R-parity is conserved, the NLSP decays inside the detectors only if the gravitino is light [43], with mass smaller than 1 MeV. Then even kinks in stau tracks may be observable [44]. For larger masses the NLSP will escape the detector as in the axino case and it will be difficult to distinguish between the different LSPs. In principle if the NLSP is charged and can be stopped, its decay may allow to disentangle the two cases [45].

5 Conclusions

The axino and the gravitino are good DM candidates, with similar properties. For both cases the reheat temperature in the Early Universe is bounded from above and Big Bang Nucleosynthesis gives constraints on the lifetime and density of the NLSP. These bounds are usually severe for the gravitino, but can be relaxed in specific scenarios. Here we have presented the case of a neutralino NLSP with a degenerate gaugino spectrum, which allows to avoid the constraints and gives quite special signatures at the LHC.

We have also shown that axino and gravitinos can survive as DM even for broken R-parity, but the breaking has to be suppressed. Indirect DM searches already set limits on the R-parity breaking couplings on the order 10^{-11} and 10^{-8} for the axino and the gravitino respectively. In the case of the axino LSP, R-parity breaking does not bring substantial advantages with respect to Nucleosynthesis constraints, apart for the case of very large f_a.

Different signals are expected at the LHC for axino or gravitino LSP compared to the usual supersymmetric scenarios with neutralino LSP: displaced vertices are still possible for the light gravitino case or for R-parity breaking parameters not far from the present bounds. Otherwise also just missing energy due to a long-lived neutralino NLSP or a metastable charged NLSP could appear as a signal. In the last case, it will be more difficult to identify the nature of the LSP.

Acknowledgments

It is a pleasure to thank G. Bertone, A. Brandenburg, W. Buchmüller, K.Y. Choi, , M. Grefe, J. Hasenkamp, K. Hamaguchi, A. Ibarra, H. B. Kim, J. E. Kim, M. Olechowski, S. Pokorski, J. Roberts, L. Roszkowski, F. D. Steffen, D. Tran, K. Turzynski, J. D. Wells and T. Yanagida for the fruitful collaborations. The author would like also to thank the organizers of Rencontres de Moriond EW 2011 for the chance to present this talk, the very lively and enjoyable atmosphere during the meeting and their patience in waiting for these Proceedings.

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