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VERY LIGHT GRAVITINO DARK MATTER* **

Gilbert Moultaka

Laboratoire de Physique Théorique et Astroparticules
UMR5207-CNRS, Université Montpellier II
Place E. Bataillon, 34095 Montpellier Cedex 5, France

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We address the question of dark matter in the context of gauge mediated supersymmetry breaking models. In contrast with mSUGRA scenarios, the messenger of the susy breaking to the visible sector can play an important role allowing a relic gravitino in the $\sim$ keV to 10MeV mass range to account for the cold dark matter in the Universe.

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1. Introduction: neutralino *versus* gravitino dark matter

It is certainly very attractive that two longstanding open questions — the origin of electroweak symmetry breaking and the nature of the non-baryonic dark matter in the Universe — seem to be on the verge of being answered simultaneously and presumably in a unified framework. LHC will give us the opportunity to start scratching the surface of this issue and, if we are lucky enough, to hint more clearly at the correct unified framework. Direct and indirect searches for dark matter will also bring in a very interesting complementarity with the LHC and Tevatron searches. On the theoretical side, several avenues for physics beyond the Standard Model offer particle candidates for non baryonic dark matter. Among these candidates, the (lightest) neutralino in the minimal supergravity (mSUGRA) scenario has been so extensively studied that it deserves the status of "benchmark scenario" [1]. It should be clear, though, that this scenario is just a possibility among other equally compelling ones. Actually, one of its main advantages is its relative model-independence regarding early Universe issues, making such a scenario "simpler" to study (not more "natural"!) for that matter.

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Let us recall briefly these early Universe issues, as they will be important for the subsequent discussion: *(i)* the particle content of the Universe at the end of inflation is assumed to be described by the MSSM plus the graviton and the gravitino. That is, the hidden sector responsible for supersymmetry breaking [and/or its communication to the MSSM] is essentially heavier than the reheat temperature, is not produced early on and has no bearing on the later evolution of the Universe. *(ii)* all the MSSM particles are initially in thermal equilibrium. *(iii)* the gravitino may or may not be in thermal equilibrium, and in the former case its number density depends strongly on the reheat temperature. Point *(i)* is valid typically in gravity mediated susy breaking models of which mSUGRA is an example, where the hidden sector lies somewhere between the GUT and the Planck scales. Point *(ii)* is a simplifying working assumption [which cannot be addressed further without a more concrete model for the production of the light particles (inflaton couplings to these particles, decay, *etc.*)]. Points *(i)*, *(ii)* validate in the mSUGRA-neutralino-LSP (and similar) scenarios a routine relic density calculation for *thermally produced* dark matter. The "naturalness" of the scenario is then inherited from the fact that any thermally produced weakly interacting stable particle having a weak scale mass gives in general the right order of magnitude of the relic density. Then detailed calculations delineate the regions of the parameter space consistent with WMAP as well as with particle physics constraints, yielding a plausible answer to the dark matter problem. However, point *(iii)* which typically leads to a gravitino problem remains completely non-tackled in this class of scenarios. This is so even in variations of the above scenario where a very heavy gravitino is supposed to produce the bulk of the dark matter non-thermally through its decay, (such as in the anomaly mediated susy breaking scenario), or when the gravitino is the lightest susy particle (LSP) but is produced dominantly non-thermally through the decay of the next to lightest susy particle (NLSP). In particular, in the latter scenario one needs to assume arbitrarily a sufficiently low reheat temperature to keep the thermal production subleading!

Having all this in mind, there is yet another important question for the high energy colliders, namely unravelling the origin of supersymmetry breaking. It is then quite natural to ask what happens to the dark matter issue if the gravitational interaction plays only a minor role in this breaking (and its mediation to the MSSM), thus invalidating the above scenarios. We will address this question hereafter in the context of a representative class of gauge mediated susy breaking (GMSB) models [2, 3] which can be probed at the LHC. Some features of points *(i)* to *(iii)* are modified in this context and we will argue that these modifications can allow for a very light (but still cold) gravitino dark matter freed in the same time from a gravitino problem.

2. Supersymmetry breaking through gauge mediation

If supersymmetry is realized in nature, not only would this give us confidence in our understanding of the large hierarchy stabilisation between the electroweak scale $G_{\rm F}^{-1/2}$ and the GUT or Planck scales, but also the hope that its dynamical breaking would 'explain' this hierarchy: one would expect typically $G_{\rm F}^{-1/2} \sim \langle F \rangle / M$ where M is the mass scale of some supersymmetric hidden sector and $\langle F \rangle^{1/2}$ the mass scale of its corresponding susy breaking communicated to the MSSM. Another relation coming from the supergravity sector and entailing a very small cosmological constant relates the gravitino mass $m_{3/2}$ to the total susy breaking mass scale $\langle F_{\rm tot} \rangle^{1/2}$ through $m_{3/2} \simeq \langle F_{\rm tot} \rangle / (\sqrt{3} m_{\rm Pl})$, where $m_{\rm Pl}$ is the (reduced) Planck mass and $\langle F \rangle \leq \langle F_{\rm tot} \rangle$. The resulting relation $G_{\rm F}^{-1/2} \lesssim m_{3/2} \, (m_{\rm Pl}/M)$ implies qualitatively that in gravity mediated susy breaking models ($M \simeq m_{\rm Pl}$), $m_{3/2}$ is of order the electroweak scale, while it becomes much smaller when the susy breaking is essentially mediated by a gauge sector ($M \ll m_{\rm Pl}$), the gravitino thus becoming the LSP. In the present study we will be interested in the range $m_{3/2} \sim \mathcal{O}(1)$keV – $\mathcal{O}(1)$GeV. Moreover, the considered GMSB models [2] have two separate sectors on top of the MSSM: a secluded sector where the dynamical susy breaking takes place with no direct couplings to the MSSM, and a messenger sector charged under the standard model gauge groups thus having gauge interactions with the MSSM particles. A spurion field couples directly to the messenger sector transferring to it part of the susy breaking effects, the latter being ultimately carried further to the MSSM via the gauge couplings of the messengers. In particular the gaugino and scalar soft susy breaking masses of the MSSM, $m^i_{1/2}$, m^s_0 are generated respectively to one and two loop orders in the form $\sim \left(\frac{\alpha_i}{4\pi}\right) \frac{\langle F_{\rm S} \rangle}{M_X}, \sqrt{\left(\frac{\alpha_i}{4\pi}\right)^2 \kappa^i_s} \frac{\langle F_{\rm S} \rangle}{M_X}$. Here i labels the three gauge couplings of the standard model, s the scalar quarks and leptons and Higgses, κ^i_s a numerical factor depending on the messenger number and representations, $\langle F_{\rm S} \rangle$ the partial susy breaking contribution transmitted by the spurion S to the visible sector, and M_X is the mass scale of the messenger sector. The ensuing universality of m^s_0 for each flavour sector at the messenger scale guarantees the absence of flavour changing neutral currents (FCNC). Furthermore, the low susy breaking scale in GMSB models may be favoured by the issue of the little fine-tuning problem [5].

3. Gravitino problem — messenger solution

Depending on the value of the reheat temperature $T_{\rm RH}$ subsequent to an initial inflationary phase of the Universe, the secluded and messenger sectors of GMSB may or may not be produced in the early Universe.

As we stressed in the introduction this is in contrast with mSUGRA and leads to a modification of assumption *(i)*. Though the production of these sectors is *à priori* a complication it can also be a blessing. We will illustrate this aspect hereafter by considering the spurion and the messenger fields. The mass degeneracy within a supermultiplet of messenger fields is lifted by susy breaking leading to a lighter and a heavier scalar messengers with masses $M_\pm = M_X(1 \pm \langle F_{\rm S}\rangle / M_X^2)^{1/2}$ and a fermionic partner with mass M_X. Thus $\langle F_{\rm S}\rangle / M_X^2 < 1$. Moreover, one has to require $\langle F_{\rm S}\rangle / M_X \lesssim 10^5$GeV to ensure an MSSM spectrum $\lesssim \mathcal{O}(1)$TeV. One then expects typically $M_X \gtrsim 10^5$GeV. On the other hand taking for example a gravitino mass $m_{3/2} \simeq 1$MeV would imply typically an upper bound ($T_{\rm RH} \lesssim$)10^5GeV on the reheat temperature above which the thermally produced gravitino [via scattering of strongly interacting MSSM particles with a gluino mass $\sim$ 1TeV] would overclose the Universe [4]. This particular configuration illustrates qualitatively the possible interplay between the gravitino and the messengers: if $T_{\rm RH} \lesssim M_X$ only the MSSM is present and simultaneously the gravitino relic density is acceptably small. If $T_{\rm RH} \gtrsim M_X$ we have a gravitino problem, but since now the messenger sector is also (partly or wholly) produced it will on one hand contribute to the thermal gravitino production through scattering processes, and on the other hand will pause a cosmological problem on its own! Indeed in typical GMSB models the lightest messenger particle (LMP) with mass M_- is stable due to the conservation of a messenger quantum number. Its thermal relic density is calculable similarly to that of the mSUGRA neutralino LSP and is found to scale as $\Omega_{\rm M} h^2 \simeq 10^5 \left(M_-/(10^3{\rm TeV})\right)^2$, thus overclosing the Universe in most of the parameter space under consideration. A straightforward solution to this problem is to let the LMP decay into MSSM particles. An interesting scenario was proposed [6] where this LMP decay leads to a substantial increase of entropy thus solving *also* the gravitino problem by diluting its relic density to a level which can account for the dark matter in the Universe. For this scenario to work, though, a few necessary conditions are required which delineate the favourable parts of the parameter space: for instance, the LMP should dominate the Universe energy density before it decays, but it should decay after gravitino has freezed-out from the thermal bath. A typical configuration $T_{\rm d} < T_{\rm MD} < T_{3/2}^{\rm f}$ where $T_{\rm d}, T_{\rm DM}, T_{3/2}^{\rm f}$ denote, respectively, the LMP decay and matter domination temperatures, and the gravitino freeze-out temperature, is determined by the particle properties (annihilation cross-section and decay width of the LMP, *etc.* ...). The entropy release, diluting the initial gravitino density, is determined by the temperatures before and after LMP decay. But the final gravitino relic density can also receive substantial thermal and/or non-thermal contributions from LMP scattering or decay, depending on the detailed assumptions of the model which we briefly describe in the following sections.

4. Coupling to supergravity and GUT groups

Although (super)gravity plays no role in breaking supersymmetry in GMSB models, there are still a few reasons for considering its full coupling to the model: — the gravitational sector provides a natural framework for an unstable LMP — the complete couplings of the gravitino (and the graviton!) to the MSSM as well as to the spurion and messenger sectors are needed for a reliable estimate of the cosmological constraints, (not to mention the phenomenological need to reabsorb the goldstino degrees of freedom in the massive gravitino.) In the gauge sector the stability of the LMP is usually achieved by a discrete symmetry conserving the messenger number. Breaking explicitly this symmetry at low scales would ruin the natural suppression of FCNC in GMSB models (a crux of these models), unless the new couplings are unnaturally suppressed. In contrast, Planck scale physics arguably breaks discrete symmetries (at least when they are not residuals of broken continuous symmetries). Messenger number non-conserving effective operators are then expected, which will in most cases fall into two classes leading to slow decays of the LMP into MSSM particles with a suppression $\mathcal{O}(m_{3/2}^2)$ or $\mathcal{O}(m_{\rm Pl}^{-2})$ [7]. The proposal in [6] belongs to the first one of these two classes, however, as shown in [7] and illustrated in the next section, taking into account all the supergravity effects leads to modified results.

In order to preserve gauge coupling unification it is sufficient to assume that the messenger fields sit in complete GUT group representations [3]. In [7,8] we have studied somewhat in detail the impact of the usual assignments ($\mathbf{5}_{\rm M}+\overline{\mathbf{5}}_{\rm M}$ or $\mathbf{10}_{\rm M}+\overline{\mathbf{10}}_{\rm M}$ of SU(5) and $\mathbf{16}_{\rm M}+\overline{\mathbf{16}}_{\rm M}$ of SO(10)) on the gravitino DM scenario. A qualitative difference between SU(5) and SO(10) is that in the latter the LMP is an MSSM singlet. Its annihilation to standard model particles is one-loop suppressed [8], leading typically to much larger LMP relic density than in the SU(5) case for comparable LMP masses, whence a larger entropy production due to its decay and a smaller gravitino relic density.

5. Gravitino relic density

Let us first list all the ingredients entering the gravitino relic density calculation:

- The MSSM, the spurion and the messenger sector are all produced at the end of inflation (*i.e.* sufficiently high $T_{\rm RH}$).

- The gravitino relic density breaks up into $\Omega_{3/2} = (\Omega_{\rm th} + \Omega_{\rm non-th}) \times \Delta^{-1}$ where $\Omega_{\rm th} = \Omega_{\rm scatt} + \Omega_{\rm dec}$ is the contribution from scattering and/or decays of particles in the thermal bath, $\Omega_{\rm non-th}$ is the contribution of (slowly) decaying particles such as NLSP or LMP into gravitinos *subsequent* to the decoupling of the latter from the thermal bath, and $\Delta(\gg 1)$ is a dilution factor due to the late decay of the LMP into MSSM particles as discussed in Section 3.
- The decay of the LMP is induced by Planck scale messenger number non-conserving operators present either in the Kähler potential or in the superpotential. An exhaustive study is carried out in [7]. Here we consider for illustration two such non-minimal contributions to the Kähler potential, $\delta K_1 = \mathbf{5}_{\rm M}\overline{\mathbf{5}}_{\rm F} + h.c.$ and $\delta K_2 = \mathbf{5}_{\rm M}\overline{\mathbf{5}}_{\rm F}\mathbf{24}_{\rm H}/m_{\rm Pl} + h.c.$, where $\mathbf{5}_{\rm M}, \mathbf{5}_{\rm F}, \mathbf{24}_{\rm H}$ are superfield SU(5) multiplets respectively of the messengers, the MSSM matter fields and the GUT Higgs fields.
- An important characteristic of δK_1 (δK_2) is that it induces, after supersymmetry (and GUT symmetry) breaking, $m_{3/2}$ ($m_{3/2}M_{\rm GUT}/m_{\rm Pl}$) suppressed effective couplings leading to LMP two-body decays into a lepton and a gaugino, a Higgs and a slepton, a Higgsino and a matter fermion, or three-body decays into a sneutrino and two gravitinos. Some of these decays can affect the light elements abundance as predicted by the standard Big-Bang Nucleosynthesis (BBN), others can inject a hot/warm gravitino dark matter component leading to interesting constraints.
- Finally one has also to consider the effect of the gravitationally induced LMP annihilation into a pair of gravitinos which involves graviton and spurion exchanges and depends on whether the spurion is much heavier or lighter than the LMP.

In Figs. 1 and 2 we show the results, respectively, for δK_1 and δK_2 operators, in the plane $m_{3/2} - M_X$ (the messenger mass scale) and assuming a reheat temperature $T_{\rm RH} = 10^{12}$ GeV, a 150 GeV neutralino NLSP and a 1 TeV gluino. Left (right) panels correspond to a spurion heavier (lighter) than the LMP. They correspond to quite different behaviour of the LMP annihilation into gravitinos as shown in the figures. The horizontal line shaded areas in the left upper corners are physically excluded [they would correspond to a total susy breaking smaller than the fraction communicated to the visible sector!]. The grey shaded and black areas indicate the regions where the gravitino relic density is cosmologically acceptable; the white area is where the gravitino overcloses the Universe. Note that without the GMSB messenger sector all the $m_{3/2}$ range would have been excluded [4] given the value of $T_{\rm RH}$. The very light grey shading in the r.h. panels corresponds to $\Omega_{3/2} < 0.01$ thus solving the gravitino problem but not the DM issue. The

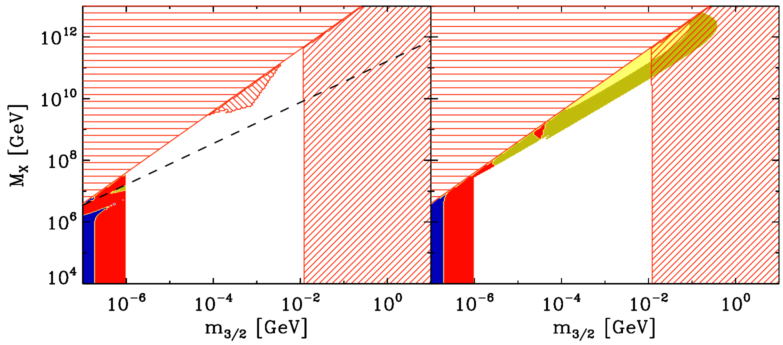

Fig. 1. The LMP decays through δK_1.

black and the two remaining increasingly light grey shadings correspond, respectively, to hot, warm and cold gravitinos accounting for the dark matter. As can be seen in the r.h. panels of the two figures, cold gravitino dark matter occurs for $10\,\mathrm{keV} \lesssim m_{3/2} \lesssim 1 - 10\,\mathrm{MeV}$ and a messenger scale $10^8\,\mathrm{GeV} \lesssim M_X \lesssim 10^{11}\,\mathrm{GeV}$. It is also interesting to note, in relation to structure formation issues, the possibility of mixed warm/cold DM in this range of parameters as can be seen in Fig. 1.

In the left-hand panels where the spurion is much heavier than the LMP, theoretical uncertainties occur above the black dashed line signalling a saturation of unitarity through multi-gravitino production. Moreover, a significant part of the potential DM solutions is excluded in this case by BBN constraints [*e.g.* in Fig. 2, the areas shaded by NE–SW oriented lines denote too slow NLSP (LMP) decays for large (small) $m_{3/2}$ and the NW–SE line shaded area corresponds to too energetic gravitinos].

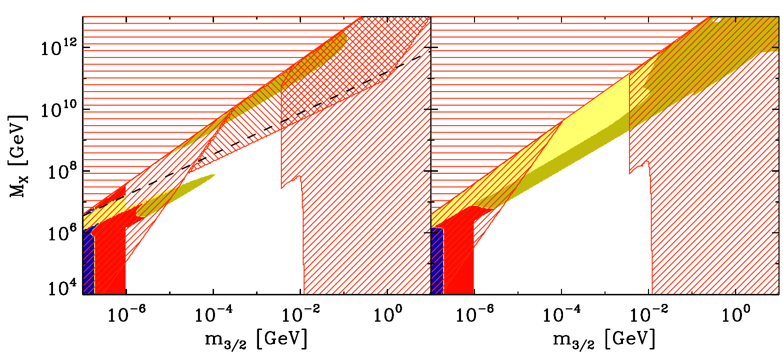

Fig. 2. The LMP decays through δK_2.

6. Signatures at the LHC

The coupling of a light gravitino to matter scales like $\langle F_{\rm tot}\rangle^{-1}$ through the goldstino component. This makes gravitino dark matter detection in direct and indirect dark matter searches deceptively hopeless in the mass range under consideration. The colliders become then a unique place to look for distinctive signatures. A favourable situation for the LHC would be a charged unstable slepton NLSP with $0.5\,\mathrm{m} \lesssim c\tau \lesssim 1\,\mathrm{km}$ [9], *e.g.* $c\tau \simeq 50$–$200\,\mathrm{m}$ for the lower part of the DM $m_{3/2}$ range considered in the previous section, taking $m_{\rm NLSP} = 150$–200 GeV. In the upper part of the allowed $m_{3/2}$ range [which can be even larger than in Figs. 1, 2, due to less restrictive BBN bounds] the slepton decays typically outside the detector but still yields a distinctive charged track. A neutralino NLSP would be a more difficult scenario with a $c\tau \gg \mathcal{O}(1)\mathrm{m}$, [10]. Distinguishing this case from a truly LSP neutralino would require indirect and more model-dependent information from other sectors of the MSSM (reconstruction of the would be neutralino relic density, signals from dark matter searches, ...).

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