Abstract

We review our recent results on dark matter from Starobinsky supergravity. In this context, a natural candidate for Cold Dark Matter is the gravitino. On the other hand, assuming the supersymmetry broken at scales much higher than the electroweak scale, gravitinos are super heavy particles. In this case, they may be non-thermally produced during inflation, in turn originated by the scalaron field with Starobinsky’s potential. Assuming gravitinos as Lightest supersymmetric particles (LSSP), the non-thermal production naturally accounts for the right amount of cold dark matter. Metastability of the gravitino LSSP leads to observable effects of their decay, putting constraints on the corresponding Unstable or Decaying Dark Matters scenarios. In this model, the gravitino mass is controlled by the inflaton field and it runs with it. This implies that a continuous spectrum of superheavy gravitinos is produced during the slow-roll epoch. Implications in phenomenology, model building in GUT scenarios, intersecting D-branes models and instantons in string theories are discussed.

1 Introduction

Direct searches for Weakly Interacting Massive Particles supersymmetric Dark Matter candidates do not give positive results as well as TeV-scale supersymmetry was not found at the LHC. It may move the supersymmetry scale to much higher energies. On the other hand, the Starobinsky $R + \zeta R^2$ model \cite{1} shows a substantially good agreement with Recent Planck data \cite{2}. In particular, Starobinsky’s model is conformally equivalent to a scalar-tensor theory and the scalar field is a slow-rolling inflaton. This may motivate a supergravity reformulation of the old Starobinsky model, assuming supersymmetry spontaneously broken at very high scales.

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A consistent embedding of the old Starobinsky model in supergravity is not so easy as naively expectable. For instance, it was realized the the first Starobinsky supergravity model proposed in Refs. [3, 4] entails a tachyonic instability of the Goldstino field for large values of the inflaton field. Recently, these issues were revisited in Refs. [5, 6] and in Refs. [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]: Starobinsky supergravity was reformulated in frameworks of non-linear Volkov-Akulov supersymmetry and no-scale invariance. This new class of models allows to reformulate a consistent $R + \zeta R^2$ supergravity without any pathologically unstable moduli fields. Recently, the consistency of Starobinsky supergravity with Null and Weak energy conditions was also discussed in Ref. [25]. In Ref. [25], we have also demonstrated that the Strong Energy condition is violated in a large region of parameter spaces, compatible with inflation.

However, new Starobinsky supergravity models do not only consistently contain old Starobinsky inflation but they may provide a new candidate of dark matter. In particular, these models must predict the presence of gravitinos, which, if in turn assumed as the lightest supersymmetric particle, may provide a natural candidate for cold dark matter. Of course, gravitino mass is highly dependent by supersymmetry breaking scale. So that Recent LHC constraints on TeV-ish SUSY may motivate the analysis of superheavy gravitinos. On the other hand, this opens new issues regarding the production of gravitons: may they account for the right amount of cold dark matter? In Ref. [24], we have provided the analysis regarding this issue.

Here we will review our recent results obtained in Ref. [24]. We have studied $R + \zeta R^2$ supergravity with local supersymmetry broken at scales higher than the inflaton reheating. We will show how super-heavy gravitinos are non-thermally produced during Starobinsky’s inflation. In this mechanism, the right Cold Dark Matter abundance, without any WIMP-like thermal miracle. On the other hand, assuming the gravitino mass heavier than then the inflaton mass, the suppression of the gravitino thermal production was shown in Ref. [46].

2 Gravitino mass in Starobinsky supergravity

The formulation of the Starobinsky supergravity is based on the following Lagrangian [14, 15, 16, 17, 20]:

$$L = -[\mathcal{L}_R + L\Phi(z, \bar{z})]_D + \zeta |\mathcal{W}_\alpha(\mathcal{V}_R)|\mathcal{W}^\alpha(\mathcal{V}_R)$$ (1)
\[ \mathcal{V}_R = \log \frac{L}{\mathcal{S}} \]

where the standard Einstein-Hilbert action is recovered by the first term, the higher derivative term \( R^2 \) term is originated from the kinetic term of the (real) superfield \( \mathcal{V}_R, \mathcal{S} \) is the so dubbed compensator field of minimal supergravity, \( \Phi(z, \bar{z}) \) is the Kähler potential of the \( z, \bar{z} \) fields and \( L \) is the linear multiplet.

For a discussion of the gravitino mass from supergravity, it is convenient to consider the off-shell formulation of the minimal Starobinsky lagrangian during inflation. Its Kähler potential reads as

\[ K = -3 \log [T + \bar{T} - \Phi(z, \bar{z})], \quad \mathcal{W}_I \to 0. \quad (2) \]

The gravitino mass is directly controlled by the Kähler potential and the superpotential as

\[ m_{\tilde{G}} = e^{K/2} \frac{\mathcal{W}}{M_{Pl}^2} = e^{-\sqrt{2} \phi} \frac{\mathcal{W}}{M_{Pl}^2}. \quad (3) \]

Let us remark that Eq.(3) implies a direct connection among the gravitino mass and the inflaton field. In other words, gravitino mass is a functional of the inflaton field and it runs with it. This will turn out to imply important predictions in gravitino mass spectrum. Let us also note that

\[ \mathcal{W}_I = 0 \to m_{\tilde{G}} = 0. \]

Naturally, the gravitino is massless only in the supersymmetry and R-symmetry preserving phase. As a consequence, the fact that the gravitino mass depends on the inflaton field is not relevant in this case.

In our model, as mentioned above, we shall assume that supersymmetry is spontaneously broken at scales higher than the inflation reheating. This means that during inflation, the superpotential \( \mathcal{W} \) is a constant \( \mathcal{W}_0 > 0 \). So that, the relation among the gravitino mass and the inflaton field is not more trivial. We will see in the next sections that this will imply that a continuous spectrum of gravitinos will be produced during the inflation.

On the other hand, as mentioned above, the condition \( \mathcal{W}_I \to 0 \) during inflation provides a possible way-out to the moduli problems. In other words, the superpotential may roll down to zero before the inflation epoch, without causing any back-reactions to the slow-roll dynamics. As remarked above, \( \mathcal{W}_I = 0 \) corresponds to a vacuum state which is invariant under the R-symmetry and SUSY. So that, it seems that these
symmetries may act as a sort of projection from the full general case to the ones providing a successful inflation. However, the condition $W_I = 0$ cannot be compatible with our dark matter model, because implying massless gravitinos during inflation. So that, we suggest that $U_R(1)$ and SUSY are spontaneously broken before (or at least during) the slow-roll epoch. On the other hand, after the inflation epoch, the rapid rolling down of the superpotential is already assumed. Under these hypothesis, the superpotential may only be set to a constant non-zero value $→ W_0 = \text{const} \neq 0$. To show that this condition does not destabilize the model is straightforward. For instance, it will imply that the $G$-term will get an extra constant term:

$$\Delta G = \log W_0 + \log \bar{W}_0 = \text{const} \quad (4)$$

which in turns provides a constant term for the $V_{F,D}$-terms:

$$\Delta V_F = -3W_0\bar{W}_0$$

$$2\zeta \Delta V_D = -12.$$

So that, the spontaneous symmetry breaking of $U_R(1)$ and SUSY during inflation only implies that the inflaton potential is shifted by a constant, which may be reabsorbed in the cosmological term. But what is important is that this demonstrates that the spontaneous symmetry breaking of $U_R(1)$ and SUSY cannot destabilize the moduli fields, i.e. it does not contribute with new extra dangerous interactions term in $W_I$. For instance, the R-symmetry implemented in the action has fixed the structure of the potential under the condition on $W_I$. One can see that the only effect of a $W_0 = \text{const} \neq 0$ during the inflation is the shift of the Starobinsky’s potential of a constant factor and the $z_I$ fields remain stabilized.

3 Non-thermal production of Gravitinos during the slow-roll

In Ref. [24], we have calculated the the production rate of gravitinos during inflation.

One can estimate the energy density of the gravitinos produced during inflation as

$$\rho_G(\eta_e) = \langle m_G \rangle n_G(\eta_e) = \langle m_G \rangle H_e^3 \left( \frac{1}{a(\eta_e)} \right) \mathcal{P} \quad (6)$$

where $\eta$ is the time-like cosmological time variable, $n_G$ is the number density of gravitinos, $H_e$ is the Hubble rate at the end of the slow-roll epoch time $t_e$; where $\mathcal{P}$ is the power of emission of gravitinos from the expanding background which can be calculated
Figure 1: Gravitino mass function of Starobinsky inflaton. In the x-axis, the inflaton field is conveniently normalized in Planck units, while in the y-axis the gravitino mass function is normalized with respect of the average gravitinos mass \( \langle m_\tilde{G} \rangle \) (in \( \log_{10} \) scale in the y-axis). In particular, the oscillating epoch effectively starts at \( \phi/M_P \simeq 1 \). On the other hand, the slow-roll effectively starts at \( \phi/M_P \simeq 6 \). \( \Delta \phi/M_P \sim 1 \div 6 \) is the gravitino production epoch. So that, a continuous spectrum of super-heavy gravitinos is produced.

from a Bogoliubov transformation of creation and destruction operators associated to the gravitino field in the expanding FRW background; where \( \langle m_\tilde{G} \rangle \) is the average mass of gravitinos produced during the slow-roll, which is

\[
\langle m_\tilde{G} \rangle \simeq \langle e^{-\sqrt{3}\phi} \rangle \Delta N \frac{W_0}{M_{Pl}^2} \simeq 0.15 \frac{W_0}{M_{Pl}} \tag{7}
\]

considering the inflationary plateau has a width of \( \Delta \phi \simeq 5 M_{Pl} \), i.e \( \Delta N = \log a_f/a_i \simeq 60 \) e-folds. In first approximation, one may set in Eq.(7)

\[
\langle \phi \rangle \simeq \Delta \phi/2
\]

The mass spectrum is shown in Fig.1, as a function of the cosmological time.

One can estimate the relation among the gravitino energy density normalized over the radiation density. It reads as

\[
\frac{\rho_\tilde{G}(t_0)}{\rho_R(t_0)} = \frac{\rho_\tilde{G}(t_{Re})}{\rho_R(t_{Re})} \left( \frac{T_R}{T_e} \right) \tag{8}
\]

where \( \rho_\tilde{G}(t_{Re})/\rho_R(t_{Re}) \) is the after-Reheating epoch ratio among gravitinos and radiation and where \( t_0 \) is the present cosmological time.

\[
\rho_\tilde{G}(t_{Re})/\rho_R(t_{Re}) \text{ during the reheating epoch -inflaton decays to SM particles- is estimated as}
\]

\[
\frac{\rho_\tilde{G}(t_{Re})}{\rho_R(t_{Re})} \simeq \frac{8\pi}{3} \left( \frac{\rho_\tilde{G}(t_e)}{M_{Pl}^2 H^2(t_e)} \right) \tag{9}
\]
Let us remind that the inflaton mass sets the characteristic scale for the Hubble constant calculated in $t_e$: $H^2(t_e) \sim m_\phi^2$ and $\rho(t_e) \sim m_\phi^2 M_{Pl}^2$. This implies

$$\Omega_{\tilde{G}} h^2 \sim 10^{17} \left( \frac{T_{Rh}}{10^9 \text{GeV}} \right) \left( \frac{\rho_{\tilde{G}}(t_e)}{\rho_c(t_e)} \right)$$

(10)

where $\rho_c(t_e) = 3H(t_e)^2 M_{Pl}^2/8\pi$ is the critical energy density during $t_e$. Finally, Eq.(10) can be rewritten as

$$\Omega_{\tilde{G}} h^2 \sim \Omega_{Rh} h^2 \left( \frac{T_{Rh}}{T_0} \right) \frac{8\pi}{3} \left( \frac{\langle m_{\tilde{G}} \rangle}{M_{Pl}} \right) \frac{n_{\tilde{G}}(t_e)}{M_{Pl} H^2(t_e)}$$

(11)

Eq.(11) is very useful: it relates the gravitino abundance with the gravitino mass, the inflaton mass and the reheating temperature. The inflaton mass is of the order of $m_\phi \approx 10^{13}$ GeV or so. On the other hand, the reheating temperature is $T_{Rh}/T_0 \approx 4.2 \times 10^{14}$. These parameters are fixed for a successful inflation and reheating. So that, the correct abundance of dark matter is obtained for a gravitino mass of $\langle m_{\tilde{G}} \rangle \approx (10^{-2} \div 1) \times m_\phi \approx 10^{11} \div 10^{13}$ GeV, in turn constraining $W_0$ in Eq.(7). This means that the SUSY symmetry breaking scale is expected to be around the GUT scale $10^{15-16}$ GeV. This certainly leads to other indirect implications in particle physics beyond the standard model. In fact, if supersymmetry must be broken around the GUT scale, it does not be helpful for couplings unification in GUT scenarios like $SU(5)$ and $SO(10)$. As a consequence our model seems to motivate non-supersymmetric GUT scenarios in which the couplings unification is reobtained adding extra non-minimal multiplets (See for example Ref.[50] for a revival of non-supersymmetric $SO(10)$ models by introducing higher multiplets and considering RG corrections beyond the tree-level relations.). On the other hand, generically, these multiplets must be added in order to obtain a realistic spectrum of SM Yukawa and neutrino mass matrix [49]. An alternative paradigm to the unification is provided by intersecting D-branes models or quiver string theories. In this case, starting from $\mathcal{N} = 1$ supersymmetry, it can be broken at the GUT scale (here only taken as conventional) without destabilizing the construction, i.e. tachyons in D-brane worldsheets are avoided. This certainly seems to be a more promising class of models with respect to other attempts to construct intersecting D-brane models without supersymmetry, which in general are expected to be plagued by tachyons. Let us also note that in intersecting D-brane models, supersymmetry may be dynamically broken by the Euclidean D-brane instantons [51].
4 Phenomenology

Certainly, Superheavy gravitino dark matter cannot be searched by direct detection experiments or in TeV-scale collider physics. However, we will comment how superheavy gravitinos may be detected in very high energy indirect detection experiments, i.e. high energy cosmic rays observations.

The spontaneously symmetry breaking of the gauged $U_R(1)$ parity may allow to new effective operators destabilizing the gravitino and opening new decay channels to Standard Model particles. The new effective operators which may be generated are dependent by the details of the R-symmetry breaking. Of course, in realistic models, such operators must be very suppressed. Otherwise, the gravitino cannot be a good (meta)stable candidate for dark matter.

For example, $U(1)_R$ may be spontaneously broken by the a scalar singlet field $s$ contained in a supersymmetric chiral field $S$. Supposing that $R(S^n) = -R(L)$, being $R$ the charge operator of $U(1)_R$, one may introduce effective superpotentials like

$$W_{sHL} = \frac{1}{M^{n-1}} S^n HL$$

where $M$ is an effective suppression scale generated by UV completion of the model. This generates an effective operator

$$O_{sHL} = \frac{1}{M^{n-1}} \phi_S^n h_L$$

where $h$ is the Higgsino field -it mixes the Higgsino field with neutrinos. On the other hand, one can always introduce the operator

$$L_{\tilde{G}VV} = -i \frac{\langle \phi_S \rangle}{8 M_{Pl}} \psi\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu F_{\nu\rho}$$

(13)

coupling the gravitino with $W^\pm, Z, \gamma$. Neutral gauginos mix with higgsinos, and their mass eigenstates are neutralinos. So that, from (12) and (13), neutralinos mediate two-body decays $\tilde{G} \rightarrow \gamma\nu, Z\nu, V_R\nu$. In particular $\tilde{G} \rightarrow \gamma\nu$ is the particularly interesting since it may be constrained by very high energy gamma rays and neutrinos. A peaked 2-body decay distribution is predicted. The associated decay rate is

$$\Gamma^{(0)}_{\tilde{G} \rightarrow \gamma\nu} = \frac{\mu_0}{32\pi} \cos^2 \theta_W \frac{m_\nu m_G m_G^3}{m_\chi^2 M_{Pl}^2} \left( 1 - \frac{m_\nu^2}{m_G^2} \right)^3 \left( 1 + \frac{m_\nu^2}{3m_G^2} \right)$$

(14)

where $m_\nu$ is taken equal to heaviest neutrino, assumed to be $m_\nu \simeq 0.07$ eV;

$$\mu_0 \sim \frac{\langle \phi_S \rangle^{n-1}}{M^{n-1}}.$$
Let us note that in the case of \( n = 1 \), the gravitino is rapidly destabilized and the model should be easily ruled out. In high scale supersymmetry breaking, assuming \( m_\chi \simeq 10^{13} \text{GeV} \) and \( m_{\tilde{G}} \simeq 10^{11} \text{GeV} \), the decay rate is of only \( \Gamma^0 \simeq 10^{-20} \text{eV} \) corresponding to \( \tau^0 \simeq 10^5 \text{s} \). For a cosmologically stable gravitino the decay rate must be suppressed down to 1 Gyr or so, i.e. of \( 10^{-11}_{-12} \) orders.

It should be noted that if gravitino lifetime is smaller than the age of the Universe, physics of the corresponding Unstable Dark Matter scenario should involve some additional stable particles - candidates to the modern dark matter. Moreover high energy neutrino and gamma background from gravitino decay lead to observable consequences \([53, 54]\) that may exclude this possibility. If the R-symmetry is spontaneously broken before inflation, \( \langle \phi_S \rangle \simeq 10^{15} \text{GeV} \), Assuming \( M \simeq M_{Pl} \), we must have \( (\langle \phi_s \rangle / M_{Pl})^{(n-1)} \simeq 10^{-11}_{-12} \). This may be obtained for \( n = 4 \). Operators with \( n < 4 \) are excluded, while operator with \( n > 4 \) seems to much suppressed to be phenomenologically interesting.

As a consequence, there is the interesting possibility of super-heavy gravitino decays \( \tilde{G} \rightarrow \gamma \nu \) with two photons and neutrino peaks of energy \( E_{CM} \simeq m_{\tilde{G}}/2 \simeq 10^8 \div 10^{13} \text{GeV} \). The observation of a so high energy neutrinos and photons could be a strong indirect evidence in favor of our scenario. In particular, these very high energy neutrinos can be observed by AUGER, Telescope Array, ANTARES and IceCube, and while eventually they could not be explained by any possible astrophysics sources.

5 New challenges for string phenomenology

The \( R + \zeta R^2 \) supergravity could be UV completed by string theory. Often in literature and in textbooks, one can find the following statement: in the limit of \( \alpha' = l_s^2 \rightarrow 0 \), \textit{superstrings reduce to supergravity models}. However, this is not completely corrected. For instance, non-perturbative stringy corrections can generate new effective superpotential terms, even if not allowed by abelian symmetries at perturbative level. As a consequence, non-perturbative stringy corrections may destabilize the gravitino. This may have dangerous or phenomenologically healthy implications (discussed above) for our model depending on the unknown global proprieties of the Calabi-Yau compactification.

It is conceivable that the initial \( U(1)_R \) gauge symmetry may be broken by Euclidean D-brane instantons of open superstring theories or worldsheet instantons in heterotic
superstring theory (See [47] for a review on this subject).

For example, a $\mu HL$ superpotential can be generated by $E2$-branes in intersecting D6-brane models was discussed in Refs. [34] (See also Refs. [26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37]). The term $\mu HL$ is phenomenologically dangerous. In fact, we must consider its interplaying with gravitino couplings with gauge bosons $W^\pm, Z, \gamma, V_R$ and their related gauginos, as mentioned above. As discussed in the previous section this should imply a very fast gravitino decay. So that, non-perturbative stringy instantons generating the $\mu HL$ superpotential must be suppressed in non-perturbative regime. If specific non-perturbative RR or NS-NS fluxes are wrapped by the instantonic Euclidean D-brane, such a suppression may be possible [48]. Calling $N_{N.P.}$ the non-pertubative suppression factor, this can screen the the bare decay rate as $\Gamma = N_{N.P.}\Gamma_0$. A suppres- 
sion factor $N_{N.P.} \approx 10^{-11}$ in order to get a gravitino cosmological life-time of at least 1 Gyr or so.

6 Conclusions

In this paper, we have reviewed Superheavy gravitino dark matter in Starobinsky supergravity with supersymmetry broken at high scales. We have reviewed how grav- itinos may be non-thermally produced during inflationary slow-roll. As a consequence parameters of the inflaton potential and of gravitino dark matter are interconnected. This model provides a new peculiar prediction: Super-Heavy Gravitinos are produced with a continuos mass spectrum, following the inflaton field\footnote{The parameters space of gravitinos mass may change if a consistent amount of Primordial Black Holes [52, 53, 54] were produced during the early Universe. We did not consider this other possible contribution.}.

We have commented about possible phenomenological implications of our scenario. In particular, our model suggests possible two-body decays $\tilde{G} \rightarrow \gamma \nu$ producing very high energy peaks of neutrinos and photons, of $E_{CM} \simeq 10^6 \div 10^{10}$ TeV. The detection of these very high energy neutrinos with a peak-like two-body decay distribution could provide a strong indirect hint in favor of our model.

Finally, we have commented on possible open issues regarding the UV completion of Starobinsky supergravity model in superstring theories. In particular, $U_R(1)$ is not enough to protect the gravitino by non-perturbative stringy instantons. The gravitino would be destabilized very fast if operators mixing the Higgsino with neutrino were generated by non-perturbative solutions. This seems to be another problem toward a
realistic UV embedding of our model in string theory in addition to the problem of string moduli stabilization during inflation.

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