



# Reheating via R-Parity Violation in Galileogenesis Models

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## Abstract

In this paper we introduce an idea of lipogenesis scenario in higher derivative gravity induced DBI Galileo framework aka Galileogenesis in presence of one-loop R-parity violating couplings in the background of a low energy effective supergravity setup derived from higher dimensional string theory framework. We have studied extensively the detailed feature of reheating constraints and the cosmophenomenological consequences of thermal gravitino dark matter in light of PLANCK and PDG data. Finally, we have also established a direct Cosmo phenomenological connection among dark matter relic abundance, reheating temperature and tensor-to-scalar ratio in the context of DBI Galileo inflation.

The post Big Bang Universe passed through various phases in which reheating plays the crucial role in explaining production of different particle species from inflation. Particle cosmologists have a clear picture of this hot Big Bang phase because ordinary matter and radiation were driving it and also the physical processes that characterize it involve terrestrial physics. These particles interact with each other and eventually they come to a state of thermal equilibrium. This process completes when all the energy of the inflation transfer to the thermal energy of elementary particles. Amongst all particle's degrees of freedom, the production of thermal gravitinos during reheating [1–7] and its decay play a pivotal role in the context of lipogenesis [8–11] and dark

matter detection [12–15]. In a most general prescription usually two types of gravitinos are produced in this epoch—stable and unstable. Both of them stimulate the light element abundances during BBN [16–18] and directly affect the expansion rate of the universe. The gravitino enderg density is proportional to gravitino abundance which is obtained by considering gravitino production in the radiation dominated era following reheating [19–21]. In this paper we perform our complete phenomenological analysis

with a potential driven DBI Galileo framework in the background of  $N = 1$ ,  $D = 4$  supergravity [22–30] which can be obtained from the dimensional reduction from higher dimensional string theory setup [31–33]. The total phenomenological model is made up of the following crucial components:

- Higher order correction terms in the gravity sector are introduced in the effective action as a perturbative correction to the Einstein–Hilbert counterpart coming from the computation of Conformal Field Theory disk amplitude at the two-loop level [34–36].
- The matter sector encounters the effect of  $N = 1$ ,  $D = 4$  supergravity motivated DBI Galileo interaction which is embedded in the D3 brane.
- Additionally, we have considered the effect of R-parity violating interactions [37–40] in the matter sector which provide a convenient framework for quantifying quark and lepton-flavour violating effects

The low energy UV protective effective action for the proposed Cosmo phenomenological model is described by [31,32]:

$$S = \int d^4x \sqrt{-g} [K(\Phi, X) - G(\Phi, X) \square \Phi + B_1 R + (B_2 R^{\alpha\beta\gamma\delta} R_{\alpha\beta\gamma\delta} - 4B_3 R^{\alpha\beta} R_{\alpha\beta} + B_4 R^2) + B_5]$$

where the model dependent characteristic functions  $K(\Phi, X)$  and  $G(\Phi, X)$  are the implicit functions of Galileo and its kinetic counterpart is  $X = -1/2 g_{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi$ . Additionally,  $B_i$  are the self-coupling constants of graviton degrees of freedom appearing via dimensional reduction from higher dimensional string theory. Specifically,  $B_5$  be the effective four-dimensional cosmological constant. In general,  $B_2 = B_3 = B_4$  which implies that the quadratic curvature terms originated from two loop correction to the CFT disk amplitudes are not topologically invariant in 4D effective theory. In Eq. (1) for potential driven DBI Galileo model once we embed DBI theory in the Galileo background we can write,  $K(\Phi, X) = P(\Phi, X) - V(\Phi)$ , where the kinetic term of the effective action is given by:



$$P(\Phi, X) = -\frac{G_1}{f(\Phi)} \left[ \sqrt{1 - 2G_2 X f(\Phi)} - G_3 \right] - G_4 G(\Phi, X) - 2G_5 X$$

with an effective *Klebanov–Strassler* frame function

$$f(\Phi) = \left( \sum_{q=0}^2 f_{2q} \Phi^{2q} \right)^{-1}$$

which characterizes the throat geometry on the D3 brane. Here  $G_1$  and  $f_{2q}$  are originated from dimensional reduction. It is important to note that the functional  $G(\Phi, X)$  appearing in Eq. (1) and Eq. (2) are exactly same in the context of DBI Galileo theory. For more details on this issue see Refs. [31,32]. In the canonical limit when the contributions from the DBI Galileo sector is switched off then we get,  $K(\Phi, X) = X - V(\Phi)$ , for  $G_5 = -1/2$ . In such a case the S. Choudhury, A. Dasgupta / Nuclear Physics B 882 (2014) 195–204 197 contributions from the higher derivative terms are highly suppressed by the UV cut-off scale of the effective theory and finally we get back the usual results as obtained from Einstein gravity. But once the contribution of DBI Galileo is switched on, the complete analysis deviates from canonical behaviour and contribution from the higher derivative gravity sector plays crucial role to change the dynamical behaviour during inflation as well as reheating. Moreover, the one-loop effective Coleman–Weinberg potential is given by [31,32]:

$$V(\Phi) = \sum_{m=-2, m \neq -1}^2 \left[ \beta_{2m} + \delta_{2m} \ln \left( \frac{\Phi}{M} \right) \right] \left( \frac{\Phi}{M} \right)^{2m}$$

where  $\beta_{2m}$  and  $\delta_{2m}$  are the tree level constants and  $\delta_{2m}$  are originated from one-loop correction. In the present setup using Eq. (1) the Modified Friedman equation can be expressed as [31,32]:

$$H^4 = \frac{\rho}{3M_{Pl}^2 \theta}, \quad (5)$$

where the energy density can be written in terms of DBI Galileo degrees of freedom as:

$$\rho = 2K_X X - K - 2G_\Phi X - 2X(1 - \theta) + V(\Phi). \quad (6)$$

Here the subscripts represent the derivatives with respect to  $X$  and  $\Phi$ . Moreover,  $\theta$  be a constant which is appearing through dimensional reduction from higher dimensional stringy setup as:

$$\theta = \frac{\beta_1}{M_P^2} + \beta_2 - 4\beta_3 + \beta_4 + \frac{\beta_5}{M_P^4}, \quad (7)$$

In the present setup,  $M_P = 2.4 \times 10^{18}$  GeV be the reduced Planck mass. It is important to note that the Friedman equation obtained in the present context is completely different from the Friedman equation as appearing in the context of Einstein's General Relativity which will further modifies the

lipogenesis framework in the present context. To study this feature explicitly further we allow interaction of DBI Galileo scalar degrees of freedom with leptonic sector of the theory given by

$$\mathcal{L}_R^{int} = \sum_k [\mathcal{Y}_1^{ijk} v_i l_j \Phi + \mathcal{Y}_2^{ijk} v_i \bar{l}_j \Phi + h.c.]$$

where the generation indices are  $i, j, k = 1(e), 2(\mu), 3(\tau)$ . Here after summing over all the contributions of flavour indices the corresponding charged scalar field can be written as

$$\Phi = \frac{(\Phi_e \oplus \Phi_\mu \oplus \Phi_\tau)}{\sqrt{3}}.$$

This induces the decay of charged DBI Galileo ( $\Phi$  [ $\Phi^+$ ,  $\Phi^-$ ]) to the leptonic constituents through the phenomenological couplings (Dijk 1, Dijk 2). In this context these couplings violate a discrete symmetry called R-parity defined as,  $R_p \equiv (-1)^{3B+L+2S}$ , where  $B$ ,  $L$  and  $S$  are the baryon, lepton and spin angular momentum respectively. Such R-parity violating interactions in the LaGrange (8) can be identified with the lepton number violating (LNV) MSSM flat direction  $LL\bar{e}$  appearing in the super potential as [39,40]:

$$W_R^{MSSM} \supset \frac{1}{2} \epsilon_{ab} \lambda^{ijk} L_i^a L_j^b \bar{e}_k + h.c.$$

where  $a, m = 1, 2$  are weak isospin indices and flatness constraint requires  $I$

$$\Gamma(\Phi^+ \rightarrow v_i l_j^+) = \frac{m_\Phi}{16\pi^2} \tilde{F}_{ij},$$

$$\Gamma(\Phi^- \rightarrow v_i l_j^-) = \frac{m_\Phi}{16\pi^2} \tilde{B}_{ij}$$

where the bilinear functions  $\tilde{F}_{ij}$  and  $\tilde{B}_{ij}$ , can be expressed as:

$$m_\Phi \tilde{F}_{ij} = \frac{1}{3} \sum_k m_{\phi_k} F_{ijk},$$

$$m_\Phi \tilde{B}_{ij} = \frac{1}{3} \sum_k m_{\phi_k} B_{ijk}.$$

Here  $m_\Phi$  be the flavour independent inflation mass and  $k$  represents the  $k$ -th flavour dependent mass of the constituent  $\phi_k$ . Additionally, the expression for trilinear functions  $F_{ijk}$  and  $B_{ijk}$  are explicitly mentioned in Appendix A. To understand the thermal history of the universe from our model, it is convenient to express the decay width in terms of the Hubble parameter during the epoch of reheating as





$$\dot{\rho}_r + 4H\rho_r = \Gamma_\phi \rho_\phi, \quad (18)$$

where  $H \approx \sqrt{\frac{\rho_r + \rho_\phi}{3M_P^2}}$ . Here  $\rho_r$  and  $\rho_\phi$  represent the energy density of radiation and inflaton respectively. Assuming  $\Gamma_\phi \gg H$  from we get

$$\rho_\phi = \frac{\rho_{\phi_0}}{x^4} \exp[-\Gamma_\phi(t - t_{osc})] \quad (19)$$

where  $\rho_{\phi_0} = \beta_0$  (the energy scale of DBI Galileo inflation as appearing in Eq. (4)) and additionally we introduce a new parameter "x" defined as:

$$x := \frac{a}{a_{osc}} = [1 + H_{osc}(t - t_{osc})] \quad (20)$$

with  $H_{osc} = (\frac{\rho_{\phi_0}}{3M_P^2})^{1/4}$ . For  $t \leq t_{osc}^{-1}$  the exact solution of Eq. (18) can be written as

$$\rho_r = \frac{1}{x^4} \left[ \rho_{osc} - \rho_{\phi_0} \exp\left(-\frac{(x-1)\Gamma_\phi}{H_{osc}}\right) \right]. \quad (21)$$

Finally, we are interested in to compute the thermal dark matter gravitino relic abundance produced by the scattering of the inflaton decay products. To serve this purpose we start with the master equation of gravitino phenomenology as obtained from Boltzmann equation is given by [24]:

$$\left(\frac{d}{dt} + 3H\right)n_{3/2} = \langle \Sigma_{total} |v| \rangle n^2 - \frac{m_{3/2} n_{3/2}}{(E_{3/2})^3}, \quad (22)$$

where  $n = \zeta(3) T^3 / \pi^2$  is the number density of scatterers (bosons in thermal bath) with  $\zeta(3) = 1.20206$  .... Here Total is the total scattering cross section for thermal gravitino production,  $v$  is the relative velocity of the incoming particles with  $v = 1$  where  $\dots$  represents the thermal average. The factor  $m_{3/2} E_{3/2}$  represents the averaged Lorentz factor which comes from the decay of gravitinos can be neglected due to weak interaction. For the gauge group  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$  the thermal gravitino production rate is given by

$$\begin{aligned} \langle \Sigma_{total} |v| \rangle &= \frac{\tilde{a}}{M_P^2} \\ &= \frac{3\pi}{16\zeta(3)M_P^2} \sum_{i=1}^3 \left[ 1 + \frac{M_i^2}{3m_{3/2}^2} \right] C_i g_i^2 \ln\left(\frac{K_i}{g_i}\right), \end{aligned} \quad (23)$$

where  $i = 1, 2, 3$  stands for the three gauge groups  $U(1)_Y$ ,  $SU(2)_L$  and  $SU(3)_C$  respectively. Here  $M_i$  represent gaugino mass parameters and  $g_i(T)$  represents gaugino coupling constant at finite temperature (from MSSM RGE) [24,25]:

$$g_i(T) \simeq \frac{1}{\sqrt{\frac{1}{g_i^2(M_Z)} - \frac{b_i}{8\pi^2} \ln\left(\frac{T}{M_Z}\right)}} \quad (24)$$

with  $b_1 = 11$ ,  $b_2 = 1$ ,  $b_3 = -3$ . Here  $C_i$  and  $K_i$  represents the constant associated with the gauge groups  $U(1)_Y$ ,  $SU(2)_L$  and  $SU(3)_C$  with  $C_1 = 11$ ,  $C_2 = 27$ ,  $C_3 = 72$  and  $K_1 = 1.266$ ,  $K_2 = 1.312$ ,  $K_3 = 1.271$  [24,25].

Further re-expressing Eq. (22) in terms of the parameter "x" and imposing the boundary condition  $T = 0$  at maximum energy density or ( $x = \text{mix}$ ) the thermal gravitino dark matter relic abundance is given by

Page | 79

$$\begin{aligned} \Omega_{3/2}(x) &= \frac{n_{3/2}(x)}{s(x)} \\ &= \frac{45}{2\pi^2 x^3 N_* T^3(x)} \left[ \frac{C_3}{4} \sqrt{\frac{C_2 + C_1(x-1)}{x^4}} \left\{ C_1(2-5x) - 2C_2 \right. \right. \\ &\quad + \frac{3C_1^2 x^2}{\sqrt{(C_1-C_2)(C_2+C_1(x-1))}} \tan^{-1} \left( \sqrt{\frac{C_2+C_1(x-1)}{C_1-C_2}} \right) \\ &\quad + \frac{1}{3x_{max}^2} \left\{ C_3(C_2+C_1(x_{max}-1)) \right\}^{\frac{3}{2}} \\ &\quad - \frac{C_3}{4} \sqrt{\frac{C_2+C_1(x_{max}-1)}{x_{max}^4}} \left\{ C_1(2-5x_{max}) - 2C_2 \right. \\ &\quad \left. \left. + \frac{3C_1^2 x_{max}^2}{\sqrt{(C_1-C_2)(C_2+C_1(x_{max}-1))}} \tan^{-1} \left( \sqrt{\frac{C_2+C_1(x_{max}-1)}{C_1-C_2}} \right) \right\} \right], \end{aligned} \quad (25)$$

where the entropy density is given by  $s(x) = \frac{2\pi^2}{45} N_* T^3(x)$ . Here the temperature can be expressed in terms of the tensor-to-scalar ratio and the parameter "x" as:

$$T(x) = \frac{1}{\sqrt{\pi}} \sqrt[4]{\frac{30}{N_* x^4} \left( \rho_{osc} - \rho_{\phi_0} \left\{ 1 - \frac{0.48(x-1)}{H_{osc}} \sqrt{\frac{N_* M_P^2}{\theta}} \right\} \right)} \quad (26)$$

and we also introduce new sets of parameters defined as:

$$\begin{aligned} C_1 &= \frac{\Gamma_\phi \rho_{\phi_0}}{H_{osc}}, \quad C_2 = \rho_{osc} - \rho_{\phi_0}, \\ C_3 &= \frac{30\sqrt{10}\alpha\zeta^2(3)}{H_{osc}\pi^7 M_P^2 N_*^{3/2}}, \quad x_{max} = \frac{4}{3} - \frac{4C_2}{9C_1 H_{osc}^2}. \end{aligned} \quad (27)$$

In this paper we introduce the lipogenesis scenario in presence of DBI Galileo which has the following remarkable phenomenological features: • In Fig. 1, the theoretically allowed region shows that the reheating temperature for DBI Galileo is high enough and lies around the GUT scale (1016 GeV). This is the first Observation we have made from our analysis in the context of DBI Galileo, which is remarkably different from the GR prescribed setup as using GR we can probe up to 1010 GeV. Such high values of the reheating temperature implies that the obtained value of the tensor-to-scalar ratio  $r$  from the DBI Galileo inflationary set up lies within a wide range:  $2.4 \times 10^{-3} < r < 0.12$ , at the pivot scale of momentum  $k \sim 0.002 \text{ Mpc}^{-1}$ , which confronts well the Planck data. If the signatures of the primordial gravity waves will be detected at present or in near future then the consistency between the high reheating temperature and gravity waves can be directly verified from our prescribed model using E1



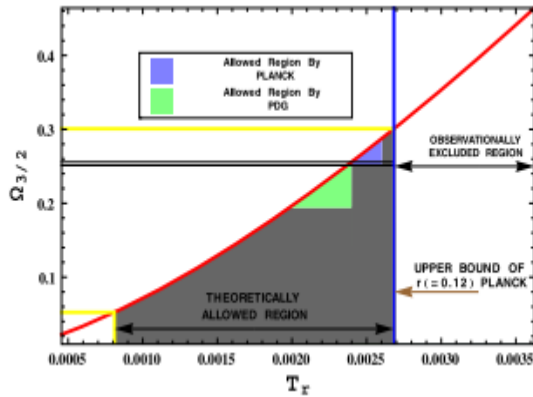


Fig. 2. Variation of gravitino dark matter relic density parameter ( $\Omega_{3/2}$ ) with respect to reheating temperature ( $T_r$ ). The dark grey shaded region shows the theoretically allowed region which lies within the upper bound of the tensor-to-scalar ratio ( $r = 0.12$ ) at the momentum pivot scale  $k = 0.002 \text{ Mpc}^{-1}$  represented by a blue vertical line in light of PLANCK data. We have explicitly shown the observationally allowed region of  $\Omega_{3/2}$  by imposing the constraints from the PLANCK data. Further we have also pointed the constraint parameter space obtained from the PDG catalog. Most importantly, the overlapping region within the range  $0.245 < \Omega_{3/2} < 0.250$  shown by the black strip satisfies both the constraints obtained from PLANCK and PDG data. For the numerical estimation in the present context we have used,  $G_1 = 1$ ,  $G_2 = 0.5$ ,  $G_3 = 2$ ,  $G_4 = 1$ ,  $G_5 = -0.5$  and  $B_1 = 2M_2 P$ ,  $B_2 = 2$ ,  $B_3 = 1$ ,  $B_4 = 3$ ,  $B_5 = 2M_4 P$ . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- In Fig. 2 we have explicitly shown the behaviour of gravitino relic abundance with respect to reheating temperature in light of PLANCK and PDG data. The overlapping region within the range  $0.245 < \Omega_{3/2} < 0.250$  satisfies both the dark matter constraints obtained from PLANCK and PDG data as given by [53,54]:

$$\begin{aligned} \Omega_{DM}^{PLANCK} &= 0.26 \pm 0.01 \\ \Omega_{DM}^{PDG} &= 0.22 \pm 0.03. \end{aligned} \quad (28)$$

In the present article we have studied cosmological consequences of reheating and dark matter phenomenology in the context of DBI Galileo on the background of low energy effective supergravity framework. We have engaged ourselves in investigating for the effect of perturbative reheating by imposing the constraints from primordial gravitational waves in light of the PLANCK data. Further we have established a cosmological connection between thermal gravitino dark matter relic abundance, reheating temperature and tensor-to-scalar ratio in the present

context. To this end we have explored the model dependent features of thermal relic gravitino abundance by imposing the dark matter constraint from PLANCK + PDG data, which is also consistent with the additional constraint associated with the upper bound of tensor-to-scalar ratio  $r = 0.002$  obtained from PLANCK data.

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## Appendix A

In Eqs. (11,13,15,17) the trilinear functions are given by:

$$\begin{aligned} F_{ijk} &= |\lambda_{ijk}|^2 \left[ 2 + \frac{9g^4}{4c_w^4} \left( \frac{1}{4} + 2s_w^4 - s_w^2 \right) I_1^2(m_{\phi_k}^2, 0, 0) \right] \\ B_{ijk} &= |\lambda_{ijk}|^2 \left[ 2 + \frac{9g^4}{4c_w^4} \left( \frac{1}{4} + 2s_w^4 + s_w^2 \right) I_1^2(m_{\phi_k}^2, 0, 0) \right] \end{aligned} \quad (29)$$

where the integral  $I_1(m_i^2, m_j^2, m_k^2)$  is defined as

$$I_1(m_i^2, m_j^2, m_k^2) = -i \int_0^1 \int_0^1 dx dy \left[ \gamma_E + \frac{1}{2} + \frac{N(x, y)}{2Q^2(x, y)} + \ln \left[ \frac{Q^2(x, y)}{4\pi\mu^2} \right] \right] \quad (30)$$

with

$$\begin{aligned} N(x, y) &= x(1-x)m_j^2 + y(1-y)m_i^2 + \frac{1}{2}[(1-x-y)(m_k^2 - m_i^2 - m_j^2)] \\ Q^2(x, y) &= x^2m_j^2 + y^2m_i^2 - xy(m_k^2 - m_i^2 - m_j^2) + (1-x-y)m_k^2. \end{aligned} \quad (31)$$

In Eq. (30)  $\gamma_E = 0.5772$  is the Euler-Mascheroni constant originating in the expansion of the gamma function. Here  $c_w = \cos\theta_w$ ,  $s_w = \sin\theta_w$  (where  $\theta_w$  = Weinberg angle) and  $m_Z$  be the mass of the Z boson.

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