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Heavy gravitino from dynamical generation of right-handed neutrino mass scale, and gravitational waves

Ryo Nagai [a], Fuminobu Takahashi [a,b,c], Norimi Yokozaki [a,*]

[a] Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan
[b] Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan
[c] Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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ABSTRACT

The absence of supersymmetric particles at the weak scale is a puzzle if supersymmetry solves the gauge hierarchy problem. We show that, if the right-handed neutrino masses arise from hidden gaugino condensation via GUT-suppressed operators, successful thermal leptogenesis leads to the lower bound on the gravitino mass, which may explain the little hierarchy problem. If domain walls associated with the gaugino condensation are formed after inflation, they annihilate when $H \sim m_{3/2}$. We address the possibility that observable gravitational wave signals might emerge from the domain wall annihilation.

1. Introduction

Supersymmetric extensions of the Standard Model (SUSY SM) has been one of the leading candidates for physics beyond the SM. It not only stabilizes the weak scale against radiative corrections, but also leads to successful gauge coupling unification at $M_{\rm GUT} \sim 2 \times 10^{16}$ GeV, hinting at the presence of a grand unified theory (GUT). However, no SUSY particles have been found at the LHC so far, pushing up the SUSY breaking scale to a few TeV or even heavier.

The discovery of the SM-like Higgs boson with a mass of 125 GeV [1,2] is also consistent with such a high-scale SUSY breaking scenario. For instance, if all the sfermion masses are of order the gravitino mass heavier than about 10 TeV [3–11], one can explain the SM-like Higgs boson mass thanks to the large stop radiative corrections [12–16]. The high-scale SUSY scenario greatly ameliorates the SUSY flavor and CP problems [17–22] as well as the gravitino/moduli problems [23–30].

One of the central issues in the high-scale SUSY scenario is the little hierarchy problem. Namely, the question why the SUSY breaking scale is much higher than the weak scale, if the SUSY is to solve the gauge hierarchy problem. In this paper, we show that thermal leptogenesis may play a key role in solving the little hierarchy problem.

Suppose that there is a hidden SUSY Yang-Mills (YM) sector that is coupled to right-handed neutrinos through nonrenormalizable operators. In the hidden SUSY YM sector, the fermionic partner of the hidden gauge boson, hidden gaugino, confines at low energy and forms a condensate. Then, the right-handed neutrinos acquire their masses through the interactions with the gaugino condensate, and so their mass scale is related to the dynamical scale of the gaugino condensation. The dynamical scale cannot be arbitrarily high, however, and its upper bound is related to the gravitino mass if we require the vanishingly small cosmological constant in the present vacuum. As we shall see, the gravitino mass is bounded below for a given right-handed neutrino mass scale. Interestingly, if we take the effective cut-off scale around the GUT scale, the typical mass scale of the right-handed neutrinos required for successful thermal leptogenesis [31] leads the heavy gravitino mass, $m_{3/2} \gtrsim 10$ TeV. Thus, the little hierarchy may be a result of successful thermal leptogenesis.

In our setup, the hidden strong dynamics not only generates the mass of right-handed neutrino but also predict interesting phenomena in the early Universe. To be concrete, let us consider a hidden SU(N) SUSY YM sector, where a $\mathrm{U}(1)_R$ symmetry is explicitly broken down to $Z_{2N\mathbf{R}}$ symmetry. At the dynamical scale, the discrete symmetry is further spontaneously broken to $Z_{2\mathbf{R}}$ by the gaugino condensation, leading to formation of the domain walls. If the gaugino condensate is formed after the inflation, the domain-wall network follows the scaling law. If the $Z_{2N\mathbf{R}}$ symmetry is also explicitly broken, it creates an energy bias between different vacua. When the pressure on the domain walls due to the energy bias becomes comparable to their tension, the domain walls start to annihilate, and the gaugino condensate decays into the right-handed neutrinos. The minimal explicit $Z_{2N\mathbf{R}}$ breaking comes from the

* Corresponding author.
E-mail address: n.yokozaki@gmail.com (N. Yokozaki).

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constant term in the superpotential, which determines the gravitino mass. If this is the main source of the energy bias, the domain walls decay at $H \simeq m_{3/2}$ [32]. In the course of violent annihilation processes, a large amount of gravitational waves can be emitted. The frequency and abundance of the gravitational waves we observe today are respectively determined by the gravitino mass and the dynamical scale. We will address a possibility to detect the gravitational waves by the forthcoming gravitational wave experiments such as Advanced LIGO [33], Einstein Telescope [34], and an experiment using Bose-Einstein condensation (BEC) [35].

Lastly let us mention related works in the past [36,37]. In Ref. [36], they proposed a scenario where both $U(1)_{B-L}$ and SUSY are dynamically broken at the same time, which relates the right-handed neutrino mass to the gravitino mass, and then derived a lower-bound on the gravitino mass, $m_{3/2} \gtrsim \mathcal{O}(1000)$ TeV, assuming non-thermal leptogenesis. In Ref. [37], they studied resonant leptogenesis [38–44] in a context of the right-handed sneutrino inflation [45], and found that the gravitino mass must be larger than $\mathcal{O}(100)$ TeV.

The rest of this paper is organized as follows. In Sec. 2, we give a model where the mass of the right-handed neutrino is generated by a hidden gaugino condensate. Then we show that the lower-bound on the gravitino mass is fixed by the requirement of the successful thermal leptogenesis. In Sec. 3, we discuss cosmological implications including predictions for the gravitational wave signals. Finally, Sec. 4 is devoted to conclusions.

2. Right-handed neutrino mass and hidden gaugino condensate

The crucial ingredient of our model is that the heavy right-handed neutrinos acquire their mass from a spontaneous breaking of the $U(1)_R$ symmetry. In the seesaw mechanism [46–48], the right-handed neutrino mass term is usually allowed by symmetry, and so, it can be naturally of order 10^{14-15} GeV. Instead here we assume that the right-handed neutrino mass is forbidden by the $U(1)_R$ symmetry, and it is generated by the spontaneous breaking of the $U(1)_R$ symmetry such as gaugino condensation.

To be explicit, let us consider a hidden SU(N) SUSY Yang-Mills sector. The gauge interactions become strong at a dynamical scale Λ, and the hidden gaugino λ_H^A forms a condensate,

$$\langle \lambda_H^A \lambda_H^A \rangle = -32\pi^2 \Lambda^3 e^{2\pi i k/N}, \tag{1}$$

where $k = 1, \cdots N$ labels the N distinct vacua [49]. Below the dynamical scale Λ, the effective superpotential of the gaugino condensation is given by

$$W_{GC} = N\Lambda^3 e^{2\pi i k/N}. \tag{2}$$

Now let us assume that the hidden gauge sector is coupled to the right-handed neutrinos via GUT-suppressed operators,

$$W_{N_R} = \frac{1}{M_*^2} N\Lambda^3 e^{2\pi i k/N} \bar{N}_R \bar{N}_R \tag{3}$$

where $\bar{N}_R$ is a chiral superfield containing a right-handed neutrino, M_* denotes the effective cut-off scale for the interaction between the hidden sector and the right-handed neutrino. We assume that M_* is of order the GUT scale, $M_* \sim 10^{15}$–10^{16} GeV. Here and in what follows we suppress flavor indices for simplicity. Therefore, the right-handed neutrino obtains its Majorana mass from the coupling to the hidden gaugino condensate,

$$M_{N_R} = 2\frac{N\Lambda^3}{M_*^2}$$

$$\simeq 2 \times 10^{10}\,\text{GeV} \left(\frac{N\Lambda^3}{(10^{14}\,\text{GeV})^3} \right) \left(\frac{10^{16}\,\text{GeV}}{M_*} \right)^2, \tag{4}$$

up to a phase factor. One example of $U(1)_R$ charge assignment is given at the end of this section.

The scale of the gaugino condensation is bounded above, and its upper bound is related to the gravitino mass. To see this, we note that the superpotential contains a constant term, W_0, to cancel the positive contribution of the SUSY breaking to the cosmological constant,[1]

$$W_0 = N\Lambda^3 e^{2\pi i k/N} + w_0 \equiv m_{3/2} M_{\rm Pl}^2 e^{i\delta}, \tag{5}$$

where w_0 is the constant term, $m_{3/2}$ the gravitino mass, and $M_{\rm Pl} = 2.4 \times 10^{18}$ GeV the reduced Plank mass. Here the gravitino mass is defined as a real parameter, and we have introduced a complex phase factor, $e^{i\delta}$. Barring cancellation among various contributions to the constant term, we obtain

$$R \equiv \frac{N\Lambda^3}{m_{3/2} M_{\rm Pl}^2} \lesssim 1 \tag{6}$$

Combining Eqs. (2), (4), (5), and (6), we arrive at

$$m_{3/2} \gtrsim 8\,\text{TeV} \left(\frac{M_*}{10^{16}\,\text{GeV}} \right)^2 \left(\frac{M_{N_R}}{10^9\,\text{GeV}} \right). \tag{7}$$

Successful thermal leptogenesis requires $M_{N_R} \gtrsim 4 \times 10^8$ GeV, assuming thermal initial abundance [50]. Thus, successful thermal leptogenesis implies that the gravitino mass $m_{3/2}$ should be heavier than several TeV for the GUT-scale cut-off.

A few comments are in order. First, the assumption about the initial abundance is likely satisfied in a scenario to be discussed in the next section, where a large number of right-handed neutrinos (as well as gravitational waves) is produced by the domain wall annihilation. Secondly, if the right-handed neutrino masses are slightly degenerate, the resultant baryon asymmetry can be enhanced by the resonant leptogenesis [38–44]. Therefore, the lower bound on the gravitino mass can be relaxed in this case. Thirdly, the gravitino is known to cause the gravitino problem [23–25]: the gravitino is thermally produced in the early Universe, and it later decays into the visible particles during the big bang nucleosynthesis, modifying the light element abundances in contradiction with the observation. If the gravitino is the lightest SUSY particle (LSP), its abundance may exceed the dark matter abundance. The gravitino problem is relaxed significantly if the gravitino mass is heavier than $\mathcal{O}(10)$ TeV, as it decays before the big bang nucleosynthesis, or if there is another dark sector (e.g. dark photon and dark photino) which contains the LSP with a mass much lighter than the gravitino mass. One can also avoid the overproduction of the LSP produced from the gravitino decay by introducing a small R-parity violating operator [51,52].

Before closing this section, let us give a concrete R-charge assignment of the matter fields which forbids the right-handed neutrino mass. Here we adopt a $Z_{6\mathbf{R}}$ symmetry with the R-charge of $R(\bar{N}_R) = 3$. See Table 1 for the R-charges of the other SSM fields. The right-handed neutrino can couple to the SSM sector in the $Z_{6\mathbf{R}}$ symmetric manner as [2]

$$W = Q\bar{U}H_u + Q\bar{D}H_d + L\bar{E}H_d + L\bar{N}_R H_u, \tag{8}$$

[1] We have assumed $\langle K \rangle \ll M_P^2$, where K is a Kahler potential.

[2] Here we have suppressed $\mathcal{O}(1)$ coefficients of these terms.