

# Light gravitino dark matter for Hubble tension and LHC

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The recent measurements of the cosmological parameter  $H_0$  from the direct local observations and the inferred value from the Cosmic Microwave Background show  $\sim 4\sigma$  discrepancy. We demonstrate that a keV gravitino dark matter, which has a small fraction of non-thermal component (e.g. from the late decay of NLSP bino) may reconcile this tension. Furthermore, we discuss the implied collider signatures and point out that this scenario can be tested by searching for the dilepton plus missing energy events at the LHC in near future.

## INTRODUCTION

The  $\Lambda$ CDM model combining cold dark matter (CDM) with a cosmological constant  $\Lambda$  is remarkably successful in describing the results of cosmological observations. However, recently there is a growing tension in the determinations of Hubble constant, for example, the measurement from Cepheid-calibrated Type Ia Supernova  $H_0 = (74.03 \pm 1.42) \text{ km s}^{-1} \text{ Mpc}^{-1}$  [1] shows about  $4.4\sigma$  discrepancy with the inferred value  $H_0 = (67.36 \pm 0.54) \text{ km s}^{-1} \text{ Mpc}^{-1}$  [2] from the Cosmic Microwave Background (CMB). Due to the size of the discrepancy and the independence of the observations, a single systematic error in the data seems impossible to completely solve the discrepancy [3]. Therefore, the  $H_0$  tension may call for new physics beyond the standard  $\Lambda$ CDM (see e.g. [4–20] and reference therein).

As known, the cold dark matter can be an explanation for the formation of large-scale structure and galaxies. Despite of its success, the predictions made by the CDM deviate from the observational data in small-scale structure, such as *core-cusp* [21], *missing satellite* [22] and *too big to fail* [23] problems. One possible way of solving these problems is to introduce warm dark matter particles [24, 25]. The free-streaming motion of such warm DM particles reduce power on small scales, but keep the CDM predictions for the formation of large-scale structure. Besides, many models of dark matter in particle physics are not always consisting of the pure CDM. Thus, in conjunction with the Hubble tension, it seems timely to explore the possibilities of departures from the standard CDM model.

Also note that, as a compelling dark matter candidate, the Weakly Interacting Massive Particle (WIMP) [26] has been searched for in various (in)direct detections [27] and collider experiments [28]. However, the null results of detection have produced stringent bounds on such interac-

tions, which have motivated to explore the dark matter at lower masses and/or with different detection signatures (for recent reviews, see e.g. [29, 30]).

If DM particle is sufficiently light, it may affect the radiation energy density by mimicking an additional neutrino species in the early universe [31]. During the radiation era, the neutrino energy density  $\rho_\nu$  in flat geometry is related with the Hubble constant  $H(t)$  by

$$H^2(t) \simeq \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu). \quad (1)$$

where  $\rho_\gamma$  is the photon energy density. Any process that changes the abundance of neutrinos can alter the expansion rate of the universe. Interestingly, the Hubble constant and the effective number of neutrino species can have a positive correlation because the non-standard  $N_{\text{eff}}$  can affect the sound horizon, which in turn changes the angular position of the acoustic peaks. On the other hand, the combination of several observations from WMAP9 [32], Atacama Cosmology Telescope [33] and Hubble Space Telescope (HST) [34], have reported a larger value  $N_{\text{eff}} = 3.43 \pm 0.36$  [35] than the prediction  $N_{\text{eff}} = 3.046$  [36] from the Standard Model (SM) with three generations of fermions. So, increasing the effective neutrino species may also provide an avenue to ameliorate these results.

In this paper, we explore the possibility of explaining the Hubble tension by the light gravitino ( $\tilde{G}$ ), which is always predicted by locally supersymmetric extensions of the SM [37]. Depending on the supersymmetry-breaking mechanisms, the gravitino mass can range from eV scale up to the scale beyond the TeV region [38–51]. If the gravitino is the lightest supersymmetric particle (LSP), it can play the role of dark matter particle, which may or may not be in the thermal equilibrium with the hot primordial plasma. When the gravitino dark matter is light enough and non-thermally produced from the late

decay of the heavier next-to-LSP (NLSP), it can contribute to the radiation density by mimicking an extra neutrino species. Therefore, such a light gravitino dark matter may be a solution to the Hubble tension. We investigate this possibility by considering various astrophysical and cosmological constraints, and discuss the prospects of testing this scenario at the LHC.

### LIGHT GRAVITINO DARK MATTER

The gravitino is present in the gauge theory of local supersymmetry. It is the spin-3/2 superpartner of the graviton. The gravitino interactions are determined by supergravity and by the MSSM parameters and are suppressed by the Planck mass. The gravitino mass is obtained via the Super-Higgs mechanism [52] and strongly depends on the SUSY breaking schemes. In the gauge mediated supersymmetry-breaking (GMSB) models, the gravitino is usually the LSP and has a mass in the range of  $1 \text{ eV} \lesssim m_{3/2} \lesssim 1 \text{ GeV}$  [46]. However, this light gravitino dark matter may lead to some cosmological problems [53–59]. For example, if the gravitino was thermalized in the early universe, its mass  $m_{3/2}$  should be less than  $\sim 1 \text{ KeV}$  to avoid overclosing the universe. Otherwise, a low reheating temperature of inflation  $T_R$  is required to dilute the gravitino abundance and thus fails to explain the baryon asymmetry by the thermal leptogenesis.

On the other hand, the messenger particles are always predicted by the GMSB models, whose superpotential is usually given by

$$W = S\Phi_M\bar{\Phi}_M + \Delta W(S, Z_i), \quad (2)$$

where  $S$  and  $Z_i$  are respectively the spurion left chiral superfield and the secluded sector fields, and  $\Phi_M$  and  $\bar{\Phi}_M$  are the messenger left chiral superfields which are charged under the SM gauge group and transmit the SUSY breaking effect to the visible sector in terms of gauge interaction at the loop level. In the minimal version of the GMSB, the messenger number is conserved so that the lightest messenger particle would easily overclose the universe, unless it can be diluted to a very low abundance or has a tens of TeV mass. However, it should be noted that the lightest messenger can have interactions with the SM particles and sparticles by introducing additional messenger-matter interactions or gauge interaction [60–62]. Then, the late decay of the lightest messenger to visible sector particles can produce a substantial amount of entropy, and will dilute the light gravitino relic density to the observed value in the present universe. The dilution factor arising from the messenger decay can be parameterized by

$$D_m = \frac{4/3 M_m Y_m}{(90/g_*\pi^2)^{1/4} \sqrt{\Gamma_m M_P}}, \quad (3)$$

where  $Y_m$  is the yield of lightest messenger,  $M_m$  is the mass of messenger and  $\Gamma_m$  is the messenger decay width, and  $g_*$  denotes the number of relativistic degree of freedom at the temperature of the lightest messenger decay.

Given that the gravitino couplings are extremely weak, the pre-existing gravitino can be in or out of the thermal equilibrium in the early universe. The freeze-out temperature of the gravitino  $T_f^{3/2}$  is given by

$$T_f^{3/2} \approx 0.66 \text{ TeV} \left( \frac{g_*}{100} \right)^{1/2} \left( \frac{m_{3/2}}{10 \text{ keV}} \right)^2 \left( \frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^2, \quad (4)$$

where  $g^*$  is the effective degrees of freedom of relativistic particles at the gravitino freeze-out temperature and has the value in the range of 90–140 [63].  $m_{\tilde{g}}$  is the mass of gluino and should be heavier than 1 TeV according to the current LHC limits. From Eq. 4, it can be seen that a keV gravitino corresponds to a low freeze-out temperature  $T_f^{3/2} \sim 10 \text{ GeV}$ . On the other hand, thanks to the messenger dilution effect, the reheating temperature  $T_R$  can be as high as  $\sim 10^9 \text{ GeV}$  for the thermal leptogenesis. This indicates that such a light gravitino dark matter in the GMSB should be thermalized in the early universe, and its relic density can be calculated by

$$\Omega_{3/2}^{\text{TP}} h^2 = 1.14 \left( \frac{g_*}{100} \right)^{-1} \left( \frac{m_{3/2}}{\text{keV}} \right). \quad (5)$$

Note that the gravitino can also be non-thermally generated via the late decay of the NLSP, for example the radiative decay of bino,  $\tilde{B} \rightarrow \tilde{G}\gamma$  [64–66]. As stated above, such a non-thermal gravitino dark matter may be a solution to the Hubble constant problem. The non-thermal relic density of gravitino is given by

$$\begin{aligned} \Omega_{3/2}^{\text{NTP}} h^2 &= m_{3/2} Y_{\tilde{B}}(T_0) s(T_0) h^2 / \rho_c \\ &= \frac{m_{3/2}}{m_{\tilde{B}}} \Omega_{\tilde{B}} h^2, \end{aligned} \quad (6)$$

with

$$\begin{aligned} \Omega_{\tilde{B}} h^2 &= 0.0013 \left( \frac{m_{\tilde{\ell}_R}}{100 \text{ GeV}} \right)^2 \frac{(1+R)^4}{R(1+R^2)} \\ &\times \left( 1 + 0.07 \log \frac{\sqrt{R} \times 100 \text{ GeV}}{m_{\tilde{\ell}_R}} \right) \end{aligned} \quad (7)$$

where the mass ratio  $R \equiv (m_{\tilde{B}}/m_{m_{\tilde{\ell}_R}})^2$ . Given the strong LHC bounds on the squarks and gluinos, we only include the contributions of the right-handed sleptons to the relic abundance of bino NLSP in Eq. 7 [67]. For simplicity, we assume  $m_{\tilde{\ell}_R}$  as a common mass parameter of the three generation right-handed sleptons. It should be mentioned that only the first-two generation sleptons should be included in Eq. 7 when  $m_{\tilde{B}}$  is less than  $m_\tau$ .

Since the decay width of the lightest messenger is much smaller than the gravitino freeze-out temperature  $T_f^{3/2}$ , the messenger decay can dilute the thermally produced

gravitinos. Besides, the freeze-out temperature of the bino NLSP is usually  $\sim m_{\tilde{B}}/20$ . If the bino mass is around 1 GeV, it can still freeze out before the messenger decay and then be diluted by the entropy production. It should be noted that the non-thermally produced gravitinos from the bino late decay will not be further diluted as long as the bino decay is sufficiently delayed. Therefore, the final gravitino abundance can be calculated by

$$\Omega_{3/2}h^2 = \frac{1}{D_m}(\Omega_{3/2}^{\text{TP}}h^2 + \Omega_{3/2}^{\text{NTP}}h^2). \quad (8)$$

In our study, we require that the gravitinos solely compose the dark matter and satisfy the observed relic density within the  $3\sigma$  range,  $0.075 < \Omega_{3/2}h^2 < 0.126$  [68].

Another benefit of the messenger decay in our scenario is that the entropy production can cool down the velocity of the thermally produced gravitino dark matter. For example, when a particle with mass  $m$  freezes out from the primordial plasma relativistically, it has a present-day velocity  $\langle v_{3/2}^0 \rangle \approx 0.023 \text{ km s}^{-1} (g_*(T_{\text{dec}}/100)^{-1/3} (m/1 \text{ keV})^{-1}$ , which will be reduced to  $\sim \langle v_{3/2}^0 \rangle / D_m^{1/3}$ . Depending on the dilution factor, the thermally produced gravitino may become non-relativistic, even its mass is less than  $\sim 10$  keV. Whereas, the non-thermally produced gravitino that inherits the kinetic energy from the bino decay can be still relativistic. Due to the vague limits between hot, warm and cold dark matter, we identify the thermal gravitino dark matter as the CDM when  $\langle v_{3/2} \rangle < 0.1 \langle v_{3/2}^0 \rangle$  in the following calculations.

## CONSTRAINTS

The gravitino dark matter from the late decay of the bino can be nearly relativistic, and thus produce an extra radiation density  $\rho_R^{\text{extra}} = f \times \rho_{3/2} \times (\gamma_{3/2} - 1)$  in the early universe, where  $f = \Omega_{3/2}^{\text{NTP}}h^2 / (\Omega_{3/2}^{\text{TP}}h^2 + \Omega_{3/2}^{\text{NTP}}h^2)$  is the fraction of the non-thermal gravitino density in the total gravitino production and  $\gamma_{3/2}$  is the boost factor of the gravitino from the bino decay. At the matter-radiation equality, the energy density per neutrino species is approximately equal to 16% of the energy density of CDM. This implies that the non-thermal gravitino dark matter that has a kinetic energy equivalent to 1.16 can be regarded as an additional neutrino species. Therefore, the resulting effective neutrino species  $\Delta N_{\text{eff}}$  can be given by [31]

$$\Delta N_{\text{eff}} = f \times (\gamma_{3/2} - 1) / 0.16 \quad (9)$$

with

$$\gamma_{3/2}(a) = 1 + \left( \frac{a_\tau}{a} \right) \left( \frac{m_{\tilde{B}}}{2m_{3/2}} + \frac{m_{3/2}}{2m_{\tilde{B}}} - 1 \right) \quad (10)$$

where  $a_\tau$  is the scale factor at the time of bino decay. In Ref. [5], a comprehensive investigation of the CMB data

and direct measurements show that the Hubble tension shows that there is a positive correlation between  $N_{\text{eff}}$  and  $H_0$ . For example, when  $0.29 < \Delta N_{\text{eff}} < 0.85$ , the Hubble constant can reach  $H_0 = 74.03 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

On the other hand, we should note that the non-thermal gravitino will affect the growth of the structure due to its large free-streaming length. The free-streaming starts at the bino decay time and finishes at matter-radiation equality, which is given by

$$\begin{aligned} \lambda_{\text{FS}} &= \int_\tau^{t_{\text{eq}}} \frac{v_{3/2}(t)}{a(t)} dt \\ &\simeq 0.6 \text{ Mpc} \times \left( \frac{m_{\tilde{B}}}{10m_{3/2}} \right) \left( \frac{\tau}{10^4 \text{ sec}} \right)^{1/2} \\ &\times \left[ 1 + 0.1 \log \left( \frac{10m_{3/2}}{m_{\tilde{B}}} \left( \frac{10^4 \text{ sec}}{\tau} \right)^{1/2} \right) \right]. \end{aligned} \quad (11)$$

If the free-streaming distance that the gravitino propagates is larger than  $\sim \text{Mpc}$  set by the Lyman-alpha forest [69], it roughly cannot form the observed large-scale structure which in turn put a constraint on the non-thermal gravitino dark matter. By fitting the CMB data [2, 70], the large-scale structure observations [69] and cosmological simulations [71], it is found that the fraction of the non-thermal gravitino dark matter has to be very small. In order to suppress such a contribution, one can require the distortion on the linear matter power spectra  $\exp(-4.9f) > 0.95$  [72, 73], which corresponds to  $f < 0.01$ .

Besides, the late decay of bino via the process  $\tilde{B} \rightarrow \tilde{G}\gamma$  may affect the big-bang nucleosynthesis (BBN) [74], whose life-time in the limit of  $m_{\tilde{B}} \gg m_{\tilde{G}}$  is approximately given by

$$\tau_{\tilde{B}} \simeq \frac{48\pi M_P^2}{\cos^2 \theta_W} \left( \frac{m_{3/2}^2}{m_{\tilde{B}}^5} \right). \quad (12)$$

The photons from the bino decay may induce electromagnetic showers through their scattering off the background photons and electrons [75, 76]. The energetic photon in the shower can destroy the light elements such as D and  $^4\text{He}$ . The photodissociation of  $^4\text{He}$  happens at the cosmic time of  $\gtrsim 10^6 \text{ s}$ , while photodissociation of D will be important at higher temperature because of the smallness of its binding energy, which corresponds to a long-lived particle with a lifetime longer than  $10^4 \text{ s}$  [77, 78]. Thus, we require the life-time of our late decaying bino is shorter than  $10^4 \text{ s}$  to avoid the BBN constraints.

## NUMERICAL RESULTS AND DISCUSSIONS

In the numerical calculations, we adopt a bottom-up method to explore the parameter space for solving the Hubble tension. We consider the above constraints from

the DM relic density, the BBN and the large-scale structure observations. There are only four relevant input parameters in our scenario:  $m_{\tilde{B}}$ ,  $m_{\tilde{G}}$ ,  $m_{\tilde{L}_R}$  and  $D_m$ .

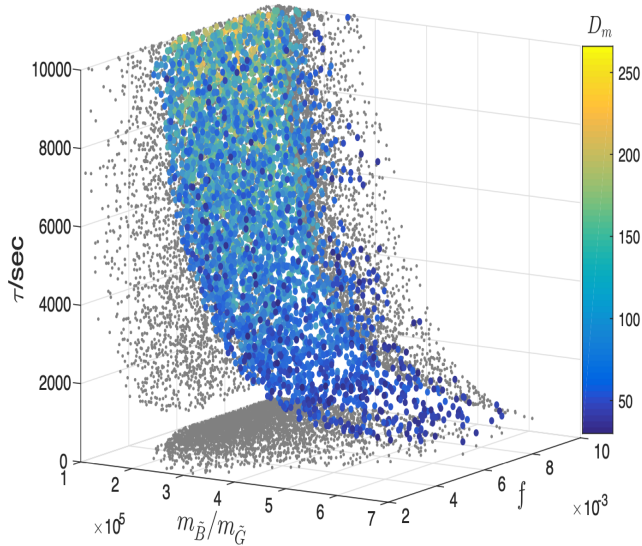


Figure 1. Samples for  $72.61 < H_0 < 75.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$  ( $1\sigma$  range of the measured value in [1]) allowed by the constraints of DM relic density, BBN and large-scale structure observations.

In Fig. 1, we present the results of the life-time of bino ( $\tau$ ), the mass ratio  $m_{\tilde{B}}/m_{\tilde{G}}$ , the non-thermal gravitino DM fraction  $f$  and the dilution factor  $D_m$  for the samples allowed by the experimental constraints. It can be seen that there is a strong correlation between these quantities. The life-time of bino decreases as the mass ratio  $m_{\tilde{B}}/m_{\tilde{G}}$  becomes large, which can be much smaller than the BBN bound. The dilution factor is required to be in the range of  $29 < D_m < 266$ . The non-thermal gravitino DM fraction  $f$  can be suppressed to  $\mathcal{O}(10^{-3})$ . When  $m_{\tilde{B}}$  is fixed, a light gravitino will lead to a small thermal relic density of the gravitino DM, while a heavy gravitino will need a large dilution factor to reduce the thermal relic density. Both cases can result in a large value of  $f$ . On the other hand, for a given slepton mass, a heavy  $m_{\tilde{B}}$  will increase the relic density of non-thermal gravitino DM and thus enhance the value of  $f$ .

We comment on the possible realization of a large dilution factor  $D_m$  in Fig. 1. For example, in the general gauge mediation, the messenger sector is  $5 \oplus 5$  representation under  $SU(5)$ . They can annihilate into the SM particles through the gauge interactions as well as the goldstino via SUSY breaking effect. When  $M_m$  is about  $\mathcal{O}(10^8)$  GeV, the corresponding yield  $Y_m$  is around  $\mathcal{O}(10^{-9})$  and the decay width of the lightest messenger is about  $\mathcal{O}(10^{-22})$  GeV. Then, one can have a dilution factor of  $\mathcal{O}(10)$ - $\mathcal{O}(10^2)$ .

In Fig. 2, we show the above samples on the plane of  $m_{\tilde{B}}$  versus  $m_{\tilde{L}_R}$ . It should be noted that the effective

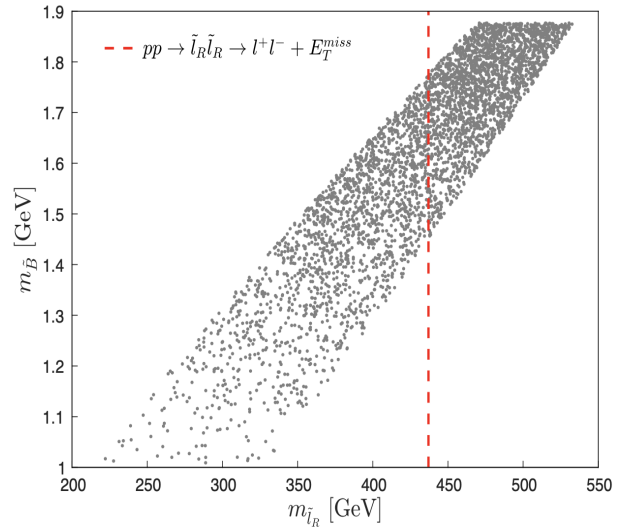


Figure 2. Same as Fig. 1, but projected on the plane of  $m_{\tilde{B}}$  versus  $m_{\tilde{L}_R}$ . The dashed line correspond to the 95% C.L. exclusion limits from the search for the slepton pair events at 13 TeV LHC with the luminosity of  $\mathcal{L} = 139 \text{ fb}^{-1}$  [79].

neutrino number  $\Delta N_{\text{eff}}$  needed for solving the Hubble tension and the large-scale observation produces a lower and upper limit on the fraction  $f$ , respectively. These lead to the bounds on the slepton mass, since the non-thermal gravitino DM relic density depends on the abundance of bino. From Fig. 2, we can see that the slepton mass  $m_{\tilde{L}}$  has to be less than about 520 GeV. Such a light slepton can be produced in pair through the Drell-Yan process  $pp \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$  at the LHC. Due to the small mass splitting between the bino and gravitino, the photon from the bino decay will be too soft to be observed by the detectors. Therefore, such slepton pair production process will give the dilepton plus missing energy signature at the LHC. In Fig. 2, we present the current LHC bounds of searching for selectron/smuon pair production, and find that the slepton with the mass lighter than about 440 GeV has been excluded. We can expect that the rest of parameter space can be fully probed by the HL-LHC.

## CONCLUSIONS

In this paper, we demonstrated that the keV gravitino dark matter with a small fraction of non-thermal relic density in the gauge mediation supersymmetry breaking may provide a solution to the Hubble tension between the CMB and distance ladder measurements. Since the non-thermal gravitino from the bino decay can mimic additional neutrino species, the expansion rate of the universe could be altered, and thus enhance the Hubble constant in the early universe. Thanks to the messenger decay, the gravitino abundance can be diluted to the observed value, and also make the thermally produced gravitino



still cold to satisfy the large-scale structure observations. Besides, we found that such a scenario can be tested by searching for slepton pair production at the LHC.

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