A 125 GeV Higgs Boson Mass and Gravitino Dark Matter in R-invariant Direct Gauge Mediation

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Abstract

We discuss the Standard Model-like Higgs boson mass in the Supersymmetric Standard Model in an R-invariant direct gauge mediation model with the gravitino mass in the $O(1)$ keV range. The gravitino dark matter scenario in this mass range is a good candidate for a slightly warm dark matter. We show that the Higgs boson mass around 125 GeV suggested by the ATLAS and CMS experiments can be easily achieved in R-invariant direct gauge mediation models with the gravitino mass in this range.
1 Introduction

The light gravitino is one of the most motivated candidate of dark matter in the supersymmetric theories, since the gravitino is the unique and the inevitable prediction of supergravity. If the gravitino were in the thermal bath in early universe the observed dark matter density, $\Omega_{\text{DM}} h^2 \sim 0.1$, requires the gravitino mass to be $m_{3/2} \simeq 100 \text{ eV}$. Unfortunately, however, such a very light gravitino decouples from the thermal bath when it is still relativistic, and the resultant free-streaming length is too long to be consistent with the successful galaxy formation [1].

If we had late time entropy production, on the other hand, the thermally produced gravitino dark matter scenario can be viable. That is, with late time entropy production, the dark matter density is diluted, and hence, the relic density of heavier gravitino dark matter can be consistent with the observed dark matter density. In particular, the gravitino dark matter with a mass in the keV range which has a free-streaming wavenumber around $k_{FS} \simeq 100 \ensuremath{-} 300 \text{ Mpc}^{-1} h$ is drawing attention as a solution to the seeming discrepancies between the observation and the simulated results of the galaxy formation based on the cold dark matter scenario [2].

In a collaboration with Yanagida and Yonekura [3], the authors showed that the required entropy production can be provided by decays of long lived particles in a supersymmetry breaking sector based on the R-invariant direct gauge mediation models developed in Refs. [4, 5]. Interestingly, the direct gauge mediation models tend to predict a hierarchical sparticle spectrum where the scalar fermions are much heavier than the gauginos [4, 5]. Especially, the model predicts the squark masses in the $\mathcal{O}(10 \ensuremath{-} 100) \text{ TeV}$ range for $m_{3/2} = \mathcal{O}(1 \ensuremath{-} 10) \text{ keV}$.

As is well studied, such a heavy squark leads to relatively heavy Standard Model (SM) like Higgs boson [12]. In this Letter, we show that the Standard Model-like Higgs boson with a mass around 125 GeV suggested by the ATLAS [13] and CMS [14] experiments can be easily achieved due to the heavy sfermions predicted in the R-symmetric direct gauge mediation models for $m_{3/2} = \mathcal{O}(1) \text{ keV}$, which predicts the free-streaming wavenumber

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1 See Refs. [6, 7] for other mechanisms for entropy production after the decoupling of gravitino.
2 For more recent generic discussions on the R-invariant direct mediation models, see Refs. [8, 9, 10, 11].
around $k_{FS} \simeq 100 - 300 \text{Mpc}^{-1} h$.

We also discuss how the electroweak symmetry breaking is achieved in the R-invariant gauge mediation model where the sfermion masses are of $O(10 - 100) \text{TeV}$. As we will show, it is rather difficult to achieve correct electroweak symmetry breaking in the minimal supersymmetric standard model (MSSM) with gauge mediated supersymmetry breaking for squark masses in $O(10-100) \text{TeV}$. We discuss possible extension of the supersymmetric standard model so that correct electroweak symmetry breaking is achieved.

The organization of the Letter is as follows. In section 2, we discuss the spectrum of the superparticles in the R-invariant direct gauge mediation for $m_{3/2} = 10 - 100 \text{keV}$. In section 3, we discuss the free-streaming length of gravitino dark matter. In section 4, we discuss the mass of the SM-like Higgs boson mass in the present model. In section 5, we discuss how the electroweak symmetry breaking is achieved in the R-invariant gauge mediation model for $m_{3/2} = O(1-10) \text{keV}$. The final section is devoted to our conclusions.

## 2 R-invariant Direct Gauge Mediation Model

In this section, we briefly review the simplest R-invariant gauge mediation models developed in Refs. [4, 5]. We introduce two pairs of messenger fields $\Psi_i$ and $\tilde{\Psi}_i$ ($i = 1, 2$), which transform as $5$ and $5^*$ under the $SU(5)$ gauge group of the grand unified theory (GUT), respectively. We also introduce a supersymmetry breaking gauge singlet field $Z$ which
has non-vanishing expectation values of the $A$ and $F$ terms, such that,

$$\langle Z(x, \theta) \rangle = \langle Z \rangle + F \theta^2. \tag{1}$$

In the direct gauge mediation model, we assume this $F$ term is the dominant component of the supersymmetry breaking which leads to the gravitino mass,

$$m_{3/2} = \frac{F}{\sqrt{3}M_{Pl}}, \tag{2}$$

where $M_{Pl} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass. The superpotential of the messenger fields is assumed to be

$$W = \left( \tilde{\Psi}_1 \quad \tilde{\Psi}_2 \right) \left( \begin{array}{cc} kZ & m \\ m & 0 \end{array} \right) \left( \begin{array}{c} \Psi_1 \\ \Psi_2 \end{array} \right), \tag{3}$$

where $k$ denotes a coupling constant and $m$ the mass parameter. We can see the above superpotential is invariant under the R-symmetry with the charge assignment, $Z(2), \Psi_1(0), \tilde{\Psi}_1(0), \Psi_2(2), \tilde{\Psi}_2(2)$.

We split $\Psi_i$ and $\tilde{\Psi}_i$ into the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ representations, such as, $\Psi \rightarrow (\Psi_d, \Psi_\ell)$ and $\tilde{\Psi} \rightarrow (\tilde{\Psi}_d, \tilde{\Psi}_\ell)$. They transform as $(3_{-1/3}, 2_{1/2})$ and $(3_{1/3}, 2_{-1/2})$ under the SM gauge groups, respectively. We denote $\Psi_d$ and $\tilde{\Psi}_d$ as “down-type”, $\Psi_\ell$ and $\tilde{\Psi}_\ell$ as “lepton-type” messengers. We also distinguish the coupling constants and the mass parameters in Eq. (3) for each messenger by the subscripts such that $k_d$ and $k_\ell$, $m_d$ and $m_\ell$, respectively. In our analysis, we impose the following relations at the GUT scale:

$$k_d = k_\ell, \quad m_d = m_\ell, \tag{4}$$

which are eventually violated at the lower energy scale due to the renormalization group evolution.

The characteristic features of the mass spectrum are as follows:

- There is a hierarchy between gaugino masses and sfermion masses. Because the gaugino masses have no term $O(kF/m)$, the gaugino masses are much suppressed compared to the sfermion masses.
Due to the deviation from the GUT relation $k_d = k_\ell$ and $m_d = m_\ell$ at the messenger scale, the gaugino masses do not obey the so-called GUT relation. Namely, in this model, $M_1 : M_2 : M_3 \neq \alpha_1 : \alpha_2 : \alpha_3 \simeq 1 : 2 : 6$.

For detailed discussion on the spectrum, see Refs. [5, 3]. In Fig. 1, we show the superparticle mass spectrum in the present model for $m_{3/2} = 1$ keV and $m_{3/2} = 10$ keV. In Fig. 2, we also show the mass spectrum in the model with additional messenger pair. The figures show that the squark masses are in tens TeV range, while the gaugino masses are within a TeV range.

3 Slightly Warm Gravitino Dark Matter

In this section, we briefly review the property of the gravitino dark matter. We assume that late time entropy production dilutes the gravitino relic abundance [3]. In this case, the resultant gravitino relic density is given by

$$\Omega_{3/2}h^2 \simeq 0.1 \left( \frac{100}{g_*(T_D)} \right) \left( \frac{m_{3/2}}{100 \text{ eV}} \right) \Delta^{-1}, \quad (5)$$

Here, $\Delta$ is the dilution factor due to the late time entropy production, and $g_*(T_D) \simeq 100$ denotes the effective massless degree of freedom in the thermal bath at the decoupling temperature $T_D$. To achieve the observed dark matter density, $\Omega_{DM}h^2 \simeq 0.1$ [16], the

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3 The gluino mass for the model with $m_{3/2} = 1$ keV (the left panel of Fig. 1) is almost excluded by the missing transverse momentum with jets by the ATLAS experiment [15].
required dilution factor is given by

\[ \Delta \simeq \left( \frac{100}{g_*(T_D)} \right) \left( \frac{m_{3/2}}{100 \text{ eV}} \right) \left( \frac{0.1}{\Omega_{3/2} h^2} \right) . \]  

(6)

In Refs. [3], we showed that the required dilution factor \( \Delta \) can be provided by the decay of long lived heavy particles in the supersymmetry breaking sector which generates \( \langle S(x, \theta) \rangle \) dynamically based on the dynamical supersymmetry breaking sector developed in Ref. [17, 18].

The “warmness” of a warm dark matter can be measured by the free streaming length \( \lambda_{FS} \) [19]. The density perturbation of the scale smaller than \( \lambda_{FS} \) is suppressed. The free-streaming wavenumber of the gravitino is roughly given by

\[ k_{FS} = \frac{2\pi}{\lambda_{FS}} \simeq 15 \text{ Mpc}^{-1}h \left( \frac{m_{3/2}}{1 \text{ keV}} \right) \left( \frac{g_*(T_D)}{100} \right)^{1/3} \Delta^{1/3} . \]  

(8)

By using Eqs. (6) and (8), we obtain

\[ k_{FS} \simeq 33 \text{ Mpc}^{-1}h \left( \frac{m_{3/2}}{1 \text{ keV}} \right)^{4/3} \left( \frac{\Omega_{3/2} h^2}{0.1} \right)^{-1/3} . \]  

(9)

The warm dark matter with the free-streaming wave number in this range is drawing attention as a solution for the small scale crisis in the conventional cold dark matter (ΛCDM) model [5]. Despite its success in reproducing the large scale structure of the universe, several intriguing discrepancies have been reported between the simulations of structure formation and observations at the small scales in the ΛCDM model. The observed number of galactic satellites in the inner region of the halo is an order of magnitude smaller than the predictions of the ΛCDM model by the N-body simulations [21, 22]. The ΛCDM model also predicts a cuspy dark matter density profile in the central region of the

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4 Here, we defined the free-streaming wavenumber [20]

\[ k_{FS} = \left( \frac{3a^2 H_0^2 \Omega_{DM}}{2 \langle v^2 \rangle} \right)^{1/2} , \]  

(7)

at the matter-radiation equality time.

5 In the present scenario, the gravitino warm dark matter has a Fermi-Dirac momentum distribution rescaled by the dilution factor. At this time, however, the detailed shape of the momentum distributions is not relevant to discuss the small scale crisis due to the limited resolutions of the N-body simulations and the observations. (See also model independent treatment of the warm dark matter in Ref. [23].)
halo while the observations indicate nearly uniform density cored profile [24]. The warm dark matter with the free-streaming wave number of \( k_{FS} = O(10) \text{ Mpc}^{-1} h \) is expected to resolve these issues since it can smear out the density fluctuation in small scale [2]. It should be noted that such a smeared small-scale structure might be probed in future experiments by, for example, using strong gravitational lensing [25], or by observing the 21 cm fluctuations in high red-shift region [26].

4 The Lightest Higgs Boson Mass

In this section, we calculate the SM-like Higgs boson mass in the R-invariant gauge mediation model for \( m_{3/2} = 1 - 100 \text{ keV} \) where the sfermions are in the tens TeV range. With such heavy sfermion masses, the renormalization group improved calculation is required for the precise calculation of the Higgs mass, with which we calculate the quartic coupling of the potential of the SM Higgs doublet at the electroweak scale,

\[
V = \frac{\lambda}{2} (|H|^2 - v^2)^2,
\]

where \( v = \langle H \rangle \sim 174 \text{ GeV} \).

In Fig. 3, we show the Higgs boson mass obtained by solving the renormalization group equations by matching the MSSM and the SM with gauginos with the boundary condition,

\[
\lambda = \frac{1}{4} \left( \frac{3}{5} g_1^2 + g_2^2 \right) \cos^2 2\beta,
\]

at the stop mass scale. We also match the renormalization group equations of the models with and without gauginos at the gaugino mass scales. The threshold corrections at the heavy scalar scale and at the weak scale are also taken into account, in accordance with Refs. [27, 28].

6 In this section, we have assumed the MSSM to obtain the lightest Higgs boson mass. As we will discuss in the next section, however, it is rather difficult to achieve correct electroweak symmetry breaking in the MSSM with gauge mediated supersymmetry breaking for squark masses in \( O(10-100) \text{ TeV} \). Correct electroweak symmetry breaking is, on the other hand, realized with an introduction of a singlet coupling to the Higgs doublet. Such interaction does not alter the following discussion based on the MSSM, since the required coupling between the singlet and the Higgs doublets is very small (see next section).

7 In our analysis, we also assumed that Higgsinos are as heavy as the sfermions. The effects of such a heavy Higgsinos to the quartic coupling constant of the Higgs doublet are discussed in Ref. [29].
In our calculation, we take $m_Z$ scale gauge coupling constants as $\alpha(m_Z)^{-1} = 128.944$ \cite{30} and $\alpha_s(m_Z) = 0.1184$ \cite{31}. We use a formula given in Ref. \cite{32} for the Weinberg angle $\sin^2 \theta_W(m_Z)$. The top Yukawa coupling constant $y_t$ is calculated by using top quark pole mass $m_t = 173.2$ GeV \cite{33} and weak scale threshold corrections given in Ref. \cite{34}.

The figure shows that the model leads to the lightest Higgs boson mass around 125 GeV which is suggested by recent ATLAS and CMS results for $m_{3/2} = 1 - 100$ keV for moderate values of the mixing angle of the two Higgs doublets, $\tan \beta$. We also show the for a given gravitino mass. As a result, we find that the both the Higgs boson mass around 125 GeV and the free-streaming wavenumber $k_{FS} \simeq 100 - 300 \text{Mpc}^{-1} h$ can be achieved simultaneously for $m_{3/2} = O(1) \text{keV}$.

5 The origins of $\mu/B\mu$

Finally, let us discuss the origins of the supersymmetric and the supersymmetry breaking Higgs mixing parameters, the so-called $\mu$ and $B$ parameters. As we have seen in section 2, the scalar boson masses are around 10 TeV. In such cases, the $\mu$ parameter is also required to be of $O(10)$ TeV for successful electroweak symmetry breaking.

The simplest way to provide the $\mu$ parameter is to assume that $\mu$ parameter is given by hand, i.e.,

$$W = \mu H_u H_d .$$

(12)

In this case, the $B$ parameter is mainly generated by the renormalization group effects,

$$\frac{dB}{d \ln \mu_R} = \frac{1}{16\pi^2} \left[ 6a_t y_t + 6a_b y_b + 6g_2^2 M_2 + \frac{6}{5} g_1^2 M_1 \right] \simeq \frac{1}{16\pi^2} \left[ 6g_2^2 M_2 + \frac{6}{5} g_1^2 M_1 \right].$$

(13)

Here, $\mu_R$ denotes the renormalization scale, $y_{t,b}$ the top and the bottom Yukawa coupling constants, and $a_{t,b}$ the $A$-terms of the top and the bottom squarks. In the final expression, we have neglected the $A$-term contributions to the beta function of $B$, since $A$-terms are generated at the two-loop order in the gauge mediation models. As a result, the radiatively generated $B$-term in this model is roughly given by

$$B \sim \frac{1}{16\pi^2} \left[ 6g_2^2 M_2 + \frac{6}{5} g_1^2 M_1 \right] \log \frac{M_{\text{mess}}}{m_{\text{squark}}} = O(0.1) \times M_2 ,$$

(14)
Figure 3: The SM-like Higgs boson mass in one pair of messenger model (top) and two pairs of messenger model (bottom). In the filled region, the Higgs mass satisfies $124 \text{ GeV} \leq m_h \leq 126 \text{ GeV}$. We take $k_\ell F/m_\ell^2 = 0.95$ and $\langle Z \rangle/m_\ell = 1$. 
Table 1: A sample mass spectrum in the extended NMSSM is shown for $m_{3/2} \simeq 7 \text{keV}$. We introduce two pairs of messengers, and take $k\ell F/m_{\ell}^2 = 0.95$ and $\langle Z \rangle/m_{\ell} = 1$. In our analysis, we have set trilinear soft supersymmetry breaking terms are vanishing at the messenger scale, while the linear soft supersymmetry breaking term to be generated by the supergravity effects, i.e. $V_{\text{soft}} = -2m_{3/2}\xi_F S + h.c.$.

where we have used the messenger scale, $M_{\text{mess}} = O(10^{7}) \text{GeV}$, and $m_{\text{squark}} = O(10) \text{TeV}$. Unfortunately, however, the above generated $B$ term is too small to be viable since it leads to a too large Higgs mixing angle $\tan \beta$ via,

$$
\sin 2\beta = \frac{2B\mu}{m_{H_u}^2 + m_{H_d}^2 + 2\mu^2} \simeq O(10^{-2}) .
$$

Such a large $\tan \beta$ causes a Landau pole problem of the top Yukawa coupling below the GUT scale. Therefore, we need an alternative mechanism for the generations of the $\mu$ term and $B$ term for a successful model.

The next to the MSSM (NMSSM), on the other hand, provides the effective $\mu$ and $B$ parameters successfully. The superpotential of the Higgs sector in the (extended) NMSSM is given by

$$
W = \lambda_H S H_u H_d + \xi_F S + \frac{\kappa}{3} S^3 ,
$$

where $S$ is a gauge singlet Higgs field. We introduced dimensionless coupling constant $\lambda_H$ and $\kappa$, and also a dimensionful parameter $\xi_F$. It should be noted that this
superpotential is symmetric under a discrete $R$-symmetry, $Z_{4R}$, with the charge assignments $Q(S) = 2$, which can be consistent with $R$-symmetry of the messenger sector in the previous section. In the extended NMSSM, the effective $\mu$ and $B$ parameters are provided by the vacuum expectation values of $S$ and its $F$-component,

$$\mu_{\text{eff}} = \lambda_H \langle S \rangle \, , \quad (17)$$

$$B_{\text{eff}} = \langle F_S \rangle / \langle S \rangle = \kappa \langle S \rangle + \xi_F / \langle S \rangle \, . \quad (18)$$

Here, the vacuum expectation value of $S$ is obtained by the scalar potential of $S$,

$$V = m_S^2 |S|^2 + |\xi_F + \kappa S^2|^2 \, , \quad (19)$$

with the soft mass parameter $m_S^2$ leading to

$$\langle S \rangle \sim \sqrt{-m_S^2 - 2\kappa \xi_F} / \sqrt{2\kappa} \, . \quad (20)$$

In table[3] we show a sample spectrum of the model for $m_{3/2} \simeq 7 \text{ keV}$. To obtain the spectrum, we used NMSSMTool[36] modified for our purpose. In our analysis, we have further assumed that $m_S^2$ is generated by the interactions between $S$ and heavier fields such as extra quark multiplets [37]. To parametrize such effects, we simply introduced $m_S^2$ at the messenger scale. It should be noted that $m_S^2$ is expected to be one-loop suppressed compared with squark mass squared if $m_S^2$ is generated via the interactions to the extra quark multiplets. The table shows that the electroweak symmetry breaking is successfully obtained in the extended NMSSM even for such a suppressed $m_S^2$, i.e. $m_S^2 / m_{\text{squark}} = O(10^{-2})$.

Before closing this section, let us comment on the effect of the interaction between $S$ to the Higgs doublets in Eq. (16) on the lightest Higgs boson mass,

$$\Delta m_{\text{higgs}}^2 = \lambda_H^2 v^2 \sin^2 2\beta \, . \quad (21)$$

This contribution is, however, highly suppressed for $\tan \beta = O(10)$ and $\lambda_H \ll O(1)$. Therefore, the additional contribution does not change the correlation between the Higgs boson mass and the free-streaming length of the gravitino in the previous section is not changed even if we assume the extended NMSSM.

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8Here, we have assumed that all the parameters are real valued.
6 Conclusions

In this Letter, we discussed the SM-like Higgs boson mass in the supersymmetric standard model in the R-invariant direct gauge mediation model with dark matter consisting of the gravitino with mass in the $\mathcal{O}(1)$ keV range. With such a gravitino mass, the model predicts rather heavy sfermion masses in $\mathcal{O}(10 - 100)$ TeV, which leads to a rather heavy lightest Higgs boson mass. As a result, we showed that the Higgs boson mass around 125 GeV can be easily achieved, which is suggested by the ATLAS and CMS experiments. Interestingly, gravitino dark matter with this mass range is an attractive candidate for warm dark matter to surmount some difficulties of the cold dark matter scenario at the small scale structure.

One of the distinctive features of the R-symmetric direct mediation model is that the model predicts a peculiar gaugino mass spectrum which violates the so-called GUT relation, in spite of the GUT invariant boundary condition. Thus, the measurement of the gaugino mass spectrum at the collider experiments provide a consistency test of the model. The null observation of the sfermions is also an important prediction of the present model. The warmness of dark matter will be more disclosed in future by the progress of the $N$-body simulation of the structure formation as well as the observation of the structure of the universe.

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References

[1] M. Viel, J. Lesgourgues, M. G. Haehnelt, S. Matarrese and A. Riotto, Phys. Rev. D 71, 063534 (2005) [astro-ph/0501562].

[2] For recent developments on the effects on the galaxy formation in the warm dark matter scenario, see, for example, H. J. de Vega, P. Salucci and N. G. Sanchez, New Astron. 17, 653 (2012) [arXiv:1004.1908 [astro-ph.CO]]; K. Markovic, S. Bridle, A. Slosar and J. Weller, JCAP 1101, 022 (2011) [arXiv:1009.0218 [astro-ph.CO]]; D. Boyanovsky, Phys. Rev. D 83, 103504 (2011) [arXiv:1011.2217 [astro-ph.CO]]; A. Kamada and N. Yoshida, in preparation, and references therein.

[3] M. Ibe, R. Sato, T. T. Yanagida and K. Yonekura, JHEP 1104, 077 (2011) [arXiv:1012.5466 [hep-ph]].

[4] K. I. Izawa, Y. Nomura, K. Tobe and T. Yanagida, Phys. Rev. D 56, 2886 (1997) [hep-ph/9705228].

[5] Y. Nomura and K. Tobe, Phys. Rev. D 58, 055002 (1998) [hep-ph/9810522].

[6] M. Fujii, M. Ibe and T. Yanagida, Phys. Rev. D 69, 015006 (2004) [hep-ph/0309064].

[7] J. Hasenkamp and J. Kersten, Phys. Rev. D 82, 115029 (2010) [arXiv:1008.1740 [hep-ph]].

[8] M. Ibe, K. Tobe and T. Yanagida, Phys. Lett. B 615, 120 (2005) [hep-ph/0503098].

[9] D. Shih, JHEP 0802, 091 (2008) [hep-th/0703196].

[10] Z. Komargodski and D. Shih, JHEP 0904, 093 (2009) [arXiv:0902.0030 [hep-th]].

[11] R. Sato and K. Yonekura, JHEP 1003, 017 (2010) [arXiv:0912.2802 [hep-ph]].

[12] Y. Okada, M. Yamaguchi and T. Yanagida, Phys. Lett. B 262, 54 (1991).

[13] G. Aad et al. [ATLAS Collaboration], arXiv:1202.1408 [hep-ex].

[14] S. Chatrchyan et al. [CMS Collaboration], arXiv:1202.1488 [hep-ex].

[15] ATLAS report, ATLAS-CONF-2012-033

[16] E. Komatsu et al. [WMAP Collaboration], Astrophys. J. Suppl. 192, 18 (2011) [arXiv:1001.4538 [astro-ph.CO]].
[17] K. -I. Izawa and T. Yanagida, Prog. Theor. Phys. 95, 829 (1996) [hep-th/9602180].
[18] K. A. Intriligator and S. D. Thomas, Nucl. Phys. B 473, 121 (1996) [hep-th/9603158].
[19] J. R. Bond, G. Efstathiou and J. Silk, Phys. Rev. Lett. 45, 1980 (1980).
[20] Private communication with A. Kamada.
[21] A. A. Klypin, A. V. Kravtsov, O. Valenzuela and F. Prada, Astrophys. J. 522, 82 (1999) [astro-ph/9901240]; B. Moore, S. Ghigna, F. Governato, G. Lake, T. R. Quinn, J. Stadel and P. Tozzi, Astrophys. J. 524, L19 (1999) [astro-ph/9907411].
[22] L. E. Strigari, J. S. Bullock, M. Kaplinghat, J. Diemand, M. Kuhlen and P. Madau, Astrophys. J. 669, 676 (2007) [arXiv:0704.1817 [astro-ph]].
[23] H. J. de Vega and N. G. Sanchez, Mon. Not. Roy. Astron. Soc. 404, 885 (2010) [arXiv:0901.0922 [astro-ph.CO]].
[24] See New Astron. 17, 653 (2012) in Ref. [2].
[25] N. Dalal and C. S. Kochanek, [astro-ph/0202290].
[26] A. Loeb and M. Zaldarriaga, Phys. Rev. Lett. 92, 211301 (2004) [astro-ph/0312134].
[27] N. Bernal, A. Djouadi and P. Slavich, JHEP 0707, 016 (2007) [arXiv:0705.1496 [hep-ph]].
[28] G. F. Giudice and A. Strumia, Nucl. Phys. B 858, 63 (2012) [arXiv:1108.6077 [hep-ph]].
[29] M. Ibe and T. T. Yanagida, Phys. Lett. B 709, 374 (2012) [arXiv:1112.2462 [hep-ph]]; M. Ibe, S. Matsumoto and T. T. Yanagida, [arXiv:1202.2253 [hep-ph]].
[30] K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, J. Phys. G G 38, 085003 (2011) [arXiv:1105.3149 [hep-ph]].
[31] S. Bethke, Eur. Phys. J. C 64, 689 (2009) [arXiv:0908.1135 [hep-ph]].
[32] P. H. Chankowski, Z. Pluciennik and S. Pokorski, Nucl. Phys. B 439, 23 (1995) [hep-ph/9411233].
[33] [Tevatron Electroweak Working Group and for the CDF and D0 Collaborations], [arXiv:1107.5253 [hep-ex]].
[34] K. G. Chetyrkin and M. Steinhauser, Nucl. Phys. B 573, 617 (2000) [hep-ph/9911434].

[35] For more detailed discussion on the NMSSM in the gauge mediation models, see, for example, D. E. Morrissey and A. Pierce, Phys. Rev. D 78, 075029 (2008) arXiv:0807.2259 [hep-ph]; U. Ellwanger, C. -C. Jean-Louis and A. M. Teixeira, JHEP 0805, 044 (2008) [arXiv:0803.2962 [hep-ph]], and references therein.

[36] U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP 0502, 066 (2005) [hep-ph/0406215]; U. Ellwanger and C. Hugonie, Comput. Phys. Commun. 175, 290 (2006) [hep-ph/0508022]. see also http://www.th.u-psud.fr/NMHDECAY/nmssmtools.html

[37] A. de Gouvea, A. Friedland and H. Murayama, Phys. Rev. D 57, 5676 (1998) [hep-ph/9711264]; M. Ibe, R. Kitano and H. Murayama, Phys. Rev. D 71, 075003 (2005) [hep-ph/0412200].