Relic abundance and detection prospects of neutralino dark matter in mirage mediation

Ken-ichi Okumura

Department of Physics, Kyushu University, Fukuoka 812-8581, Japan

Abstract. We analyze thermal relic abundance of neutralino dark matter and discuss future prospects of its direct and indirect detections in mirage mediation.

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INTRODUCTION

Supersymmetry (SUSY) is a promising candidate for physics beyond the standard model (SM) which provides an elegant solution of the gauge hierarchy problem and is also endowed with various phenomenological virtues, including renowned gauge coupling unification. SUSY with R parity naturally introduces the lightest supersymmetric particle (LSP) as a candidate for cold dark matter. If gravitino is heavy enough, the best candidate is LSP neutralino. On the other hand precision cosmology in these decades has pinned down its abundance in the universe. This enables us to select realistic SUSY models via the nature of LSP and calculation of its relic abundance under plausible assumption on the evolution of the universe. This is particularly interesting in view of making contact between new physics search in LHC and direct/indirect detection of cold dark matter.

Recently, a new class of SUSY breaking scenario called mirage mediation has been proposed \cite{2,3}, which is also known as the mixed modulus-anomaly mediation. It is a generic consequence of the KKLT-type moduli stabilization \cite{4} and its low energy SUSY spectrum is distinct from those of the conventional SUSY breaking scenarios such as minimal supergravity (mSUGRA), gauge mediation and anomaly mediation \cite{5,6}. Phenomenological and cosmological aspects of it have been investigated by several groups \cite{5,6,7,8}. In this paper, we summarize the results of our analysis on the thermal relic abundance of neutralino dark matter in mirage mediation and discuss prospects of its direct and indirect detections in ongoing and planned experiments.

MIRAGE MEDIATION

Here we briefly summarize the mirage mediation. More detailed explanations are found e.g. in \cite{5,1}. Mirage mediation is a natural consequence of the following two assump-

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1 okumura@higgs.phys.kyushu-u.ac.jp
2 This talk is based on the collaboration in \cite{1}.
tions on moduli stabilization and SUSY breaking:

- Gauge coupling modulus $T$ for visible gauge fields is stabilized by non-perturbative dynamics which does not break SUSY itself.
- SUSY is broken by a brane-localized source which is sequestered from visible sector.

Both of them are typically realized in KKLT moduli stabilization in type IIB string [4]. Small shift of the modulus vev by SUSY breaking uplifting leads to suppressed F-component relative to the gravitino mass [2],

$$M_0 \equiv F^T/(T + T^*) \approx m_{3/2}/\ln \left( M_{Pl}/m_{3/2} \right),$$

which gives mixed modulus-anomaly mediated patterns to the soft SUSY breaking terms at the unification scale, $M_{GUT}$,

$$\mathcal{L}_{\text{soft}} = -\frac{1}{2} M_a \lambda^a \lambda^a - \frac{1}{2} m_i^2 |\phi_i|^2 - \frac{1}{6} A_{ijk} \phi_i \phi_j \phi_k + \text{h.c.},$$

$$M_a = M_0 + M_a^{(3/2)}, \quad m_i^2 = \tilde{m}_i^2 + m_i^{2(3/2)} + \Delta m_i^2, \quad A_{ijk} = \tilde{A}_i + \tilde{A}_j + \tilde{A}_k + A_{ijk}^{(3/2)},$$

where $M_0$ and tilde indicate modulus mediation and superscript $(3/2)$ denotes anomaly mediation. $\Delta m_i^2$ represents their interference. Note $\ln \left( M_{Pl}/m_{3/2} \right) \approx 4\pi^2$ and the two contributions are comparable. We introduce the following dimensionless parameters,

$$\alpha \equiv m_{3/2}/M_0 \ln (M_{Pl}/m_{3/2}), \quad a_i \equiv \tilde{A}_i/M_0, \quad c_i \equiv \tilde{m}_i^2/M_0^2.$$  

$\alpha$ is dynamically set real due to shift symmetry of $T$ and R symmetry [3]. $a_i$ and $c_i$ are typically non-negative rational numbers, depending upon scaling property of the matter Kähler metric against $T + T^*$. In toroidal compactification, they are given by $a_i = c_i = 1 - n_i$ for matter fields with modular weight $n_i$. A unique feature of the mirage mediation is the fact that the addition of anomaly mediation is equivalent to effective shift of the modulus mediation scale from $M_{GUT}$ to the mirage messenger scale, $M_{\text{mir}} = M_{GUT}/(M_{Pl}/m_{3/2})^{\alpha/2}$ [5]. This is true not only for gaugino masses but also for trilinear couplings and soft scalar masses if relevant Yukawa couplings are negligible or only allowed for combination of $a_i + a_j + a_k = c_i + c_j + c_k = 1$. Note that the unification scale of the gauge couplings itself remains the same. This leads to rather degenerate low energy spectrum distinct from mSUGRA, gauge mediation or anomaly mediation and consequently its characteristic phenomenology.

In the case of neutralino dark matter, reduced gluino/bino mass ratio,

$$M_3 : M_2 : M_1 \simeq (1 - 0.3\alpha)g_1^2 : (1 + 0.1\alpha)g_2^2 : (1 + 0.66\alpha)g_1^2,$$

results in reduced higgsino and heavy Higgs boson masses relative to the bino mass through the RG running under constraint of radiative electroweak (EW) symmetry breaking. This enhances higgsino components in the lightest neutralino and also increases a chance for neutralino to annihilate via heavy Higgs boson resonance.

If SUSY breaking sector is sequestered by warped throat as in the KKLT moduli stabilization and gauge couplings are determined only by $T$, $\alpha = 1$ and $M_{\text{mir}} \sim 3 \times 10^9$. 

GeV are predicted. However, if we introduce dilaton-modulus mixing in gauge kinetic functions for visible gauge fields and/or non-perturbative dynamics of the modulus stabilization, the more varied value of $\alpha$ is available \[10\]. In the next section we first examine the minimal case $\alpha = 1$ and later extend it for general cases.

**RELIC ABUNDANCE AND DETECTION PROSPECTS**

In this section, we analyze the thermal relic abundance of the neutralino dark matter in mirage mediation and prospects of its direct and indirect detection. We assume that the universe undergoes standard thermal evolution during and after the decoupling of neutralino which occurs at a temperature, $T_X \sim m_\chi/20$ where $m_\chi$ is the lightest neutralino mass. For the numerical calculation of the abundance and various observables in direct/indirect detection, we extensively use the Dark SUSY 4.1 package \[11\].

The mirage mediation inherently involves a light modulus of $m_T \sim 4\pi^2 m_3/2$. After the inflation, it is known that if displaced such a modulus starts coherent oscillation and eventually dominates the energy density of the universe. Its subsequent decays to gravitino and other MSSM fields reheat the universe again. Recently, this process is examined in detail and non-thermal neutralino from the decay of the gravitino is found to overclose the universe \[8\]. We assume this non-thermal contribution is diluted before the universe reaches $T_X$. Such a dilution is possible by thermal inflation \[12\].

In figure 1, we present the thermal relic abundance of the neutralino in the minimal setup ($\alpha = 1$) as a function of $\tan \beta$. Left panel shows a case of universal modular weight $a_i = c_i = 1$ which corresponds to D7 matter fields in the KKLT setup \[4, 5\], while right panel shows alternative choice, $a_i = c_i = 1/2$. Within the magenta strip, the thermal abundance saturates the current WMAP bound, $0.085 < \Omega h^2 < 0.119$ (2$\sigma$) and below it (cyan region) non-thermal contribution is required to fill the bound but allowed as well. Green region is excluded due to stop LSP and gray region is excluded due to stau LSP. Brown region is disfavored by $b \to s, \gamma$ branching ratio. We also eliminate a region in which the lightest Higgs mass is below the current SM Higgs mass bound.

In $a_i = c_i = 1$ case, the lightest neutralino is almost bino whose annihilation cross section is known to be small. However, annihilation through heavy Higgs resonance ($\tan \beta \sim 22$) and coannihilation with stop (stau) near the boundary of stop (stau) LSP region reduce the relic abundance and a relatively heavy $M_0$ region satisfies the WMAP bound which evade the Higgs and $b \to s, \gamma$ bounds. On the other hand, in $a_i = c_i = 1/2$ case, stop LSP region disappears due to reduction of the RG contribution through the top Yukawa coupling. Reduction of the Higgs soft mass suppresses the heavy Higgs masses and removes the resonance away. Instead, it introduces non-negligible higgsino components in the lightest neutralino. This effect pushes up the WMAP region to $M_0 \approx 700$ GeV which is well above the Higgs and $b \to s, \gamma$ bounds.

In the upper half of figure 2, we show the spin-independent cross section of neutralino-proton scattering for the above two cases. The red points saturate the WMAP bound and the cyan points fall below it. Currently, CDMS experiment excludes the region above $\sim 10^{-6}$ pb and planned SuperCDMS is expected to reach sensitivity of $\sim 10^{-9}$ pb \[13\]. The spin-independent scattering proceeds through t-channel Higgs exchange and s-channel squark exchange. In many cases, the former dominates the process. In $a_i = c_i = 1$
case, this Higgs exchange is suppressed due to suppressed higgsino components. In the figure, all the allowed points are below the sensitivity of the planned direct detection experiment. On the other hand, in \( a_i = c_i = \frac{1}{2} \) case, all the WMAP allowed region (cyan) is above the SuperCDMS sensitivity due to the enhanced higgsino components.

In the lower half of figure 2 we show a prospect of indirect detection of neutralino dark matter through continuum gamma ray flux from the galactic center. Again, the red...
points saturate the WMAP bound and cyan points fall below it. Gamma ray flux from the galactic center depends not only on microscopic physics but also on poorly known galactic halo density profile. Its integrated effect on the gamma ray flux is parameterized by the quantity, $\bar{J}(\Delta \Omega)$ which measures cuspiness of the profile over a spherical region of solid angle $\Delta \Omega$. In this paper, we use a conservative model (isothermal halo density profile) which predicts $\bar{J}(\Delta \Omega) \sim 30$ with the detector angular resolution $\Delta \Omega = 10^{-3}$ sr and set $E_{\text{thr}} = 1$ GeV for gamma ray energy threshold. However, note that, for example, an extreme spiked halo model can predict $10^4$ times enhanced $\bar{J}(\Delta \Omega)$ and gamma ray flux [14]. In both $a_i = c_i = 1$ and $a_i = c_i = 1/2$ cases, the flux reaches $\sim 10^{-10} \text{cm}^{-2} \text{s}^{-1}$ which is similar to the expected reach of GLAST satellite. In $a_i = c_i = 1$ where the neutralino is bino like, the upper bound of the gamma ray flux similar to $a_i = c_i = 1/2$ is reached by enhanced annihilation via heavy Higgs resonance. If the density profile is described by the extreme model, most of the WMAP allowed region (cyan) is explored by the future indirect experiment.

Next we discuss the non-minimal case with $\alpha \neq 1$ which can be realized by dilaton-modulus mixing in gauge kinetic functions. In figure 3, we present thermal relic abundance as a function of $\alpha$ for universal modular weight $a_i = c_i = 1$ which is a benchmark scenario in the KKLT model (left panel) and alternative case ($a_M = c_M = 1/2$, $a_H = c_H = 0$) where the matter and Higgs modular weights take different values (right panel). The latter case is known to minimize fine-tuning in the EW symmetry breaking at $\alpha = 2$ [15]. The red region is excluded due to no EW symmetry breaking. The definition of allowed regions and other constraints are similar to those in figure 1.

In the benchmark case, two allowed regions are separated by a stop LSP region. In the left hand side, neutralino is bino like as discussed in previous section. Relic abundance is suppressed dominantly due to stop coannihilation for a particular choice of $\tan \beta (=10)$ in the figure. In the narrow window around $\alpha = 2$, the lightest neutralino is higgsino like and enhanced annihilation rate pushes up $M_0$ which saturates the WMAP result as heavy as 2.2 TeV. In the non-universal case, the stop LSP region disappears due to the reduced RG contribution through the top Yukawa coupling. The nature of LSP changes from pure bino to pure higgsino via bino-higgsino mixed region if we increase $\alpha$ from 0 to 2. The heavy Higgs resonance appears around $\alpha = 0.7$ for this particular choice of $\tan \beta$. It is clearly observed that enhanced higgsino components due to lowered mirage messenger scale expands the WMAP allowed region (cyan) relative to the conventional pure modulus mediation at the unification scale ($\alpha = 0$).

In the upper half of figure 4, we show the spin-independent cross section of neutralino-proton scattering for the non-minimal case. We scan $\alpha$ as in figure 3 for fixed $\tan \beta = 10$. In the benchmark case, we can clearly discriminate two separate regions corresponding to the bino like and higgsino like regions. Because the t-channel Higgs exchange is maximized in the mixed bino-higgsino region which is excluded due to stop LSP in this case, the upper bound of the cross section is below the expected reach of SuperCDMS. On the other hand, in the alternative case, the mixed bino-higgsino region is available and the upper bound of the cross section even exceeds the current CDMS bound.

In the lower half of figure 4, we present the continuum gamma ray flux from the galactic center for the non-minimal case. Parameters are scanned as the same as the upper half of the figure. In the benchmark case, the flux reaches $2 \times 10^{-11} \text{cm}^{-2} \text{s}^{-1}$ which barely touches the expected reach of H.E.S.S. experiment [16]. In the alternative
case, enhanced annihilation due to the mixed bino-higgsino region lifts the upper bound to $2 \times 10^{-10} \text{cm}^{-1} \text{s}^{-1}$ which is similar to the expected reach of GLAST. Note that these results are estimated using the conservative halo density profile and the extreme halo model can enhance the flux by $\sim 10^{-4}$. In such a case, these indirect detection experiments can explore almost entire WMAP allowed region.
CONCLUSION

In this paper, we briefly summarized the results of our analysis on thermal relic abundance and future prospects of direct and indirect detections of neutralino dark matter in mirage mediation. The abundance is reduced due to stop/stau coannihilation, heavy Higgs resonance and enhanced higgsino components. The WMAP bound can be satisfied in bulk of the parameter space. Future direct experiments can detect mixed bino-higgsino dark matter which appears in non-minimal modular weight cases. Indirect detection can explore the scenario if the galactic halo density has cuspy profile.

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