

Mirage in the Sky: Non-thermal Dark Matter, Gravitino Problem, and Cosmic Ray Anomalies

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arXiv:0904.3773 [hep-th]

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Recent PAMELA data: Positron excess in 10 – 100GeV range

We consider dark matter annihilation

Data prefers 3 properties of WIMP dark matter

- Fairly heavy
- Leptophilic
- Large annihilation cross section

Large cross section:

$$\Omega_{CDM} = 0.23 \left(\frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma v \rangle} \right)$$

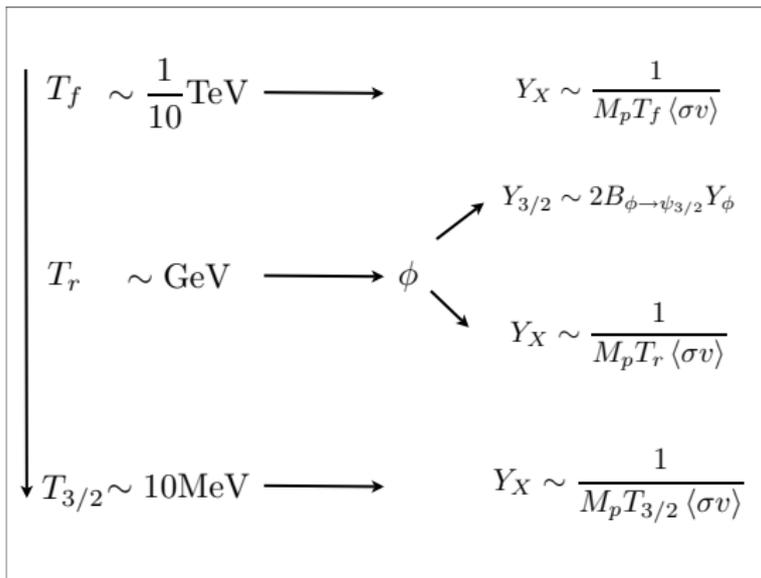
Model-independent analysis shows that the annihilation cross section required to explain the positron excess exceeds the canonical value ($\sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$) by at least an order of magnitude.

Consider non-standard thermal history: above equation is modified
Explore moduli and gravitino problems

Non-standard thermal history: well-motivated

Phase of matter or dark energy domination prior to BBN, the only way to connect to radiation (whose energy density decays faster than either) is through a reheating process

DM produced non-thermally at reheating: larger cross section needed for correct relic density.



Main thermal events in a scenario with a heavy moduli at 10^3 TeV, a gravitino mass at 10^2 TeV and a LSP at the TeV scale. Mass hierarchy obtained by mirage mediation to a supersymmetric $B - L$ model. We assume that there are no suppressed branching ratios. Enough LSP produced for self-annihilation to be important and the attractor solution for the abundance is reached at each phase transition. At each reheating phase, there is entropy production and the previous abundance of dark matter is diluted (by a factor roughly of $\left(\frac{T_{\text{new}}}{T_{\text{old}}}\right)^3$ between the two phases 'new' and 'old'). The final answer is given by the last decay $Y_X \sim \frac{1}{M_p T_{3/2} \langle\sigma v\rangle}$.

$$\Omega_X^{NT} = \Omega_X^T \frac{T_f}{T_r} = 0.23 \left(\frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \right) \frac{T_f}{T_r}$$

$$m_{3/2} = \kappa m_X .$$

Enhancement factor is given by

$$\frac{T_f}{T_{3/2}} = 6.14 \times 10^6 \left(\frac{\text{TeV}}{m_X} \right)^{1/2} \frac{1}{\kappa^{3/2} c_{3/2}^{1/2}} .$$

Non-thermal production of dark matter from the decay of the gravitino can give rise to the correct relic density if the cross-section is larger than the canonical value by a factor of $10^3 - 10^4$.

If the gravitino abundance is always very small, we can neglect its contribution to the dark matter relic density and instead look at cosmological moduli. By tuning the mass of this modulus one can get enhancement factor between $1 - 10^4$. In this case one must worry that the gravitino problem is not revived in this process by ensuring $B_{3/2}$ is small enough.

$$W = W_{\text{MSSM}} + (y_D)_{ij} H_u L_i N_j^c + \mu' H'_1 H'_2 + W_{\text{soft}}$$

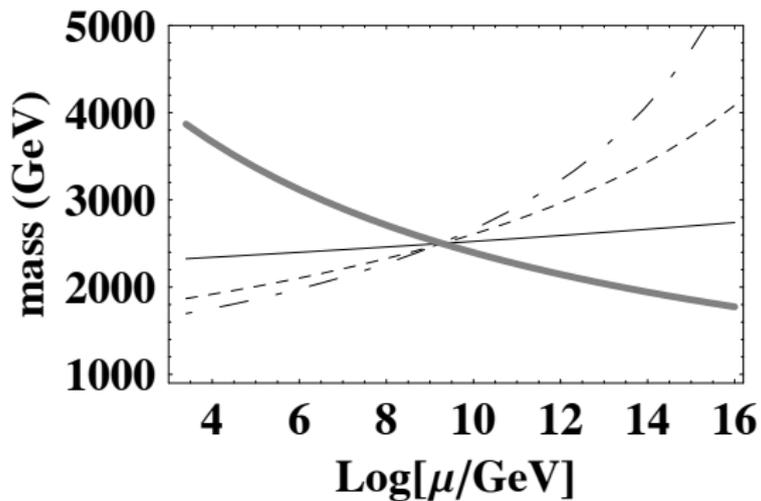
Fields	Q	Q^c	L	L^c	N	N^c	H'_1	H'_2
Q_{B-L}	1/6	-1/6	-1/2	1/2	-1/2	1/2	3/2	-3/2

Mirage mediation: either \tilde{Z}' or the right-handed sneutrino \tilde{N} is the LSP

Input parameters for RG running

$$M_0, \alpha, a_i, c_i, \tan\beta,$$

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

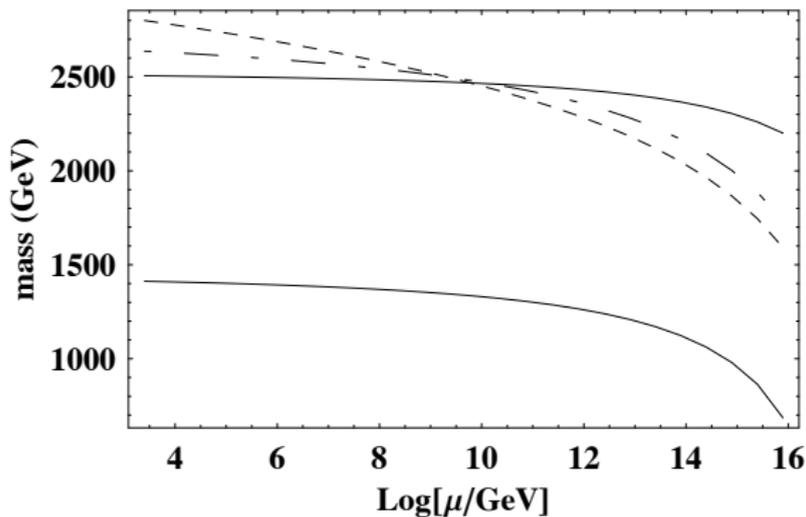


Running of gaugino masses in the $B - L$ model. The thick gray, solid, dotted, and dashed-dotted lines are the gluino, Wino, Bino, and \tilde{Z}' respectively. We have used $a_i=c_i=1$, $\tan \beta = 10$, $m_{3/2} = 77$ TeV, $M_0 = 2.5$ TeV ($\alpha = 1$)

If \tilde{Z}' gaugino is the LSP, then from the cosmology analysis we find a typical enhancement $\sim 10^4$ gives the correct relic density. This value of the enhancement follows from the fact that the gravitino mass and the LSP mass are typically correlated by a hierarchy $\kappa \sim \ln(M_{Pl}/m_{3/2}) \sim 4\pi^2$. One can lower the enhancement by raising M_0 , but in our case we cannot raise M_0 too much since we want the gaugino mass to be 1.5 – 2 TeV.

It is possible to generate such a large cross-section by having an annihilation funnel of $B - L$ gauginos into a pair of the ϕ , the lightest boson in the $B - L$ Higgs sector via the s -channel exchange of the ϕ , Φ (heavy Higgs).

A 1.5 TeV LSP has been fitted with PAMELA data for an enhancement 10^3 . Astrophysical uncertainties could provide a fit with enhancement 10^4



Running of right sneutrino (\tilde{N}), left selectron and right selectron masses in the $B - L$ model. From top, the solid, dotted, and dashed-dotted lines are the sneutrino, left selectron and right selectron masses, respectively. We have used $a_i=c_i=1$, $\tan \beta = 10$, $m_{3/2} = 77$ TeV, $M_0 = 2.5$ TeV ($\alpha = 1$). The solid line which does not go through the mirage point corresponds to \tilde{N} for $c_\nu=0.3$.

The hierarchy between the gauginos and the gravitino remains $\sim 4\pi^2$, but for small values of c_ν in the mirage mediation input parameters, the sneutrino can be made much lighter than the gauginos. Thus, the hierarchy between the sneutrino LSP and the gravitino becomes $\kappa \sim 16\pi^2$ and a lower cosmological enhancement of 10^3

On the particle physics side, this cross-section can be obtained with and without the heavy Higgs annihilation funnel. The annihilation amplitude is proportional to the gauge boson mass which appears in the $\tilde{N}^*\tilde{N}\phi$ vertex.

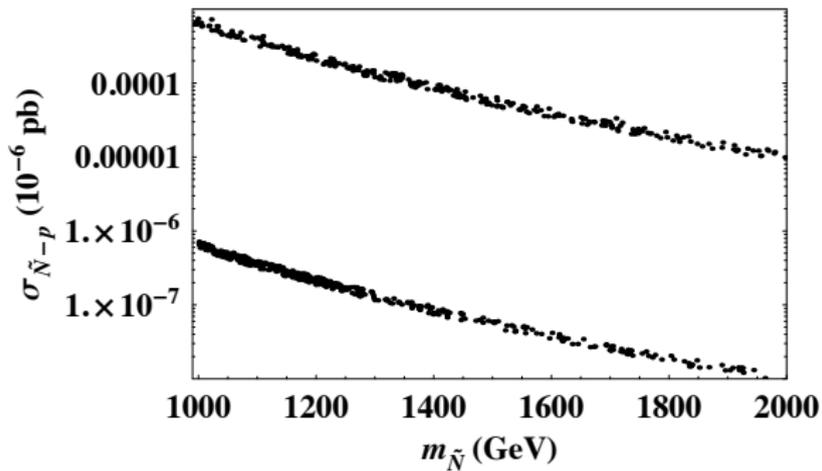
$\tilde{N}^* \tilde{N} \phi$ vertex arises from $V_D \supset \frac{1}{2} D_{B-L}^2$, where

$D_{B-L} = \frac{1}{2} g_{B-L} \left[Q_1 (|H'_1|^2 - |H'_2|^2) + \frac{1}{2} |\tilde{N}|^2 + \dots \right]$.. H'_i are new Higgs.

Dominant channel is $\tilde{N}^* \tilde{N} \rightarrow \phi \phi$ via the s -channel exchange of the ϕ , Φ , the t , u -channel exchange \tilde{N} , and the contact term $|\tilde{N}|^2 \phi^2$. The s -channel Z' exchange is subdominant because of the large Z' mass.

The sneutrino annihilation into $\nu \bar{\nu}$ final states is at least an order of magnitude below the $\phi \phi$ final states. Other fermion final states, through s -channel Z' exchange, have even smaller branching ratios (these fermion-anti-fermion final states are p-wave suppressed).

It is possible to distinguish between models of non-thermal dark matter and models with thermal dark matter that utilize Sommerfeld enhancement. The direct detection cross-section for sneutrino-nucleon scattering is mediated by Z' exchange and the cross-section can be quite large. To explain the PAMELA data in our model we need to use large Z' gauge boson mass and consequently the direct detection cross-section is reduced. If instead we use thermal dark matter with Sommerfeld enhancement in our model, a smaller Z' mass is needed to explain the dark matter content.



Sneutrino-nucleon scattering cross-section as a function of sneutrino mass. The top line corresponds to the thermal case where we need Sommerfeld enhancement to explain the PAMELA data. The bottom line corresponds to the non-thermal case as discussed in this work. The correct relic density is satisfied for both cases.

Conclusions

- Final decaying particle that non-thermally produces LSP may be either a cosmological modulus or the gravitino. Cosmological moduli typically produce gravitino, and the decay of either at a temperature above BBN tends to overproduce dark matter. A larger annihilation cross section for dark matter can naturally ease this overproduction problem.
- Possible to solve the moduli/gravitino problem in the $B - L$ model with mirage mediation. The natural hierarchy between LSP and gravitino/moduli in mirage mediation allows the gravitino to decay above BBN, while maintaining an LSP in the 1 – 2 TeV range. Moreover, a large enhancement of the annihilation cross section of 10^{3-4} is readily obtained in this model.
- The LSP can be either the new $B - L$ gaugino or the right-handed sneutrino. Both of these annihilate to the light Higgs of the new sector. This Higgs primarily decay into tau for $m_\phi > m(2\tau)$ due to the B-L charges. For the sneutrino LSP it is possible to distinguish between models of non-thermal dark matter and models with thermal dark matter that utilize Sommerfeld enhancement in certain regions of parameter space.