Mixed Sneutrino Dark Matter
and the Ratio $\Omega_b/\Omega_{dm}$.

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Abstract. It is known that the cosmological baryon density ($\Omega_b$) and dark matter density ($\Omega_{dm}$) have strikingly similar values. However, in most theories of the early Universe, each density is explained by separate dynamics and consequently there is no compelling reason for this observation. In this note, I briefly review a model in which the dark matter species possesses a particle-antiparticle asymmetry. This asymmetry determines both the baryon asymmetry and strongly affects the dark matter density, thus naturally linking $\Omega_b$ and $\Omega_{dm}$. In these models it is shown that sneutrinos can play the role of such dark matter.

INTRODUCTION

For some time it has been apparent that the inferred values of the cosmological baryon and dark matter densities are strikingly similar. The WMAP-determined range $^{2}$ for the dark matter density, $^3, 4$, $0.129 > \Omega_{dm} h^2 > 0.095$, is within a factor of a few of the combined WMAP and big-bang nucleosynthesis determined value of the baryon density $^3, 4$, $0.025 > \Omega_b h^2 > 0.012$.

In the vast majority of models of the early universe, the cosmological baryon and dark matter densities are independently determined. The surviving baryon density is set by a baryon asymmetry generated during baryogenesis, and thus depends upon unknown baryon-number violating dynamics and unknown CP-violating phases. In contrast, the dark matter density is set by the ‘freeze-out’ of the interactions that keep the dark matter in equilibrium, and is independent of the dynamics of baryogenesis. Consequently, there is no reason why we should expect $\Omega_b$ and $\Omega_{dm}$ to coincide.

One possible solution to this problem is to link the dynamics of baryogenesis with that of the origin of dark matter. In particular, it is natural to consider models where the dark matter and baryon sectors share a quantum number, either continuous or discrete, which provides a relation between their surviving number densities and thus energy densities.

Specifically, in $^1$, we proposed models of dark matter possessing a particle-antiparticle asymmetry, where this asymmetry strongly affects the dark matter density and through the electroweak (EW) anomaly, determines the baryon asymmetry, thus naturally linking $\Omega_b$ and $\Omega_{dm}$, (for an early attempt along these lines see $^5$.)

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$^1$ This note constitutes my contribution to the proceedings for the SUSY06 conference. It is based on a talk given at SUSY06 which presented the work in $^1$.

$^2$ This work does not include the most recent WMAP data $^2$. 
Assuming the particle-particle annihilation cross section is negligible, we are able to write down a simple relationship between $\Omega_{bh}h^2$ and $\Omega_{dm}h^2$ given by [1],

$$\Omega_{dm}h^2 = \Omega_{bh}h^2 \frac{A}{A_{\text{bary}}} \frac{m}{m_{\text{bary}}},$$

(1)

where $A$ and $A_{\text{bary}}$ are the particle-antiparticle asymmetries of the proposed dark matter relic and of baryons, defined by $A = (n - \pi)/n$. Here $m$ and $m_{\text{bary}}$ are the masses of our dark matter relic and of baryons (i.e. the proton mass). The ratio of $A$ to $A_{\text{bary}}$ is determined by the "chemical" equilibrium conditions between the two sectors just before the freeze-out of the relevant interactions.

If the particle-particle annihilation cross section for the relic is not negligible, Eq.(1) will not hold, although there will be a generic tendency for the density of the relic to move towards this value as a result of an asymmetry. For full details of how a matter-antimatter asymmetry affects the density of a thermal relic see [1] and references therein.

**THE MODEL: MIXED SNEUTRINO DARK MATTER**

In [1] it was shown that sneutrinos can play the role of such dark matter in a previously studied variant of the MSSM. In this model the light neutrino masses result from higher-dimensional supersymmetry-breaking terms [6, 7, 8]. This model preserves all the successes of the MSSM, while being, at least in part, testable at the LHC.

Within the context of the Minimal Supersymmetric Standard Model (MSSM), sneutrinos do not make a very appealing dark matter candidate. Sneutrinos tend to annihilate too efficiently, resulting in a relic density smaller than the observed dark matter density. Furthermore, their elastic scattering cross section is sufficiently large to be easily observed by direct dark matter experiments.

In the models of [6, 7, 8] the left-handed ‘active’ sneutrino, $\tilde{\nu}$, mixes, via large $A$-terms, with the right-handed ‘sterile’ sneutrino state, $\tilde{n}$, producing the light mass eigenstate given by $\tilde{\nu}_1 = -\tilde{\nu} \sin \theta + \tilde{n} \cos \theta$, where $\theta$ is a mixing angle. This mixing reduces the annihilation cross section, potentially providing the appropriate quantity of dark matter. In addition, since the coupling of the lighter sneutrino eigenstate, $\tilde{\nu}_1$, to the $Z$ is suppressed by $\sin \theta$, the direct LEP experimental constraints are weakened.

Another important feature of these models is that the light sneutrino states share a non-anomalous $(B - L)$-symmetry with the baryons which is only weakly broken by the Majorana neutrino masses. It is this approximately conserved symmetry which provides the link between the dark matter and baryon number densities.

Turning to the calculation of the relative asymmetry in the sneutrino and baryon sectors, the method is a simple adaptation of the standard "chemical" equilibration techniques applied to, for example, the calculation of the ratio $B/(B - L)$ in the MSSM [9] in the presence of anomaly-induced baryon number violating processes in the early universe.

In this analysis we assume that at a temperature $T$ (with $T > T_c$, where $T_c$ is the electroweak phase transition temperature) the MSSM susy spectrum, including $k$ rhd sneutrinos can be considered light ($m \lesssim T$).
FIGURE 1. Parameter space which provides the quantity of mixed sneutrino cold dark matter measured by WMAP, $0.129 > \Omega_{\text{dm}} h^2 > 0.095$. In the left frame, the standard calculation with no matter-antimatter asymmetry is used. In the center and right frames, a dark-matter matter-antimatter asymmetry with $A/A_{\text{bary}} \simeq 1/6$ and $A/A_{\text{bary}} \simeq 1/3$ respectively is included. In the shaded regions the observed $\Omega_b/\Omega_{\text{dm}}$ is reproduced. We use the parameters: $M_1=300$ GeV, $M_2=300$ GeV, $\mu=600$ GeV, $\tan \beta = 50$ and $m_h=115$ GeV. The region above the solid line in each frame is excluded by measurements of the invisible $Z$ decay width at LEP.

The resulting relative asymmetry in the sneutrino and baryon sectors is given by, $A/A_{\text{bary}} = k/3$ to $k/6$, where the variation depends upon the spectrum of sneutrino masses with respect to $T_c$. In what follows we specialize to the case in which $k = 1$.

An important point to note is that it does not matter what the dynamics are which generate the asymmetry at scales $E > T_c$ or indeed whether the asymmetry is generated in the baryon or neutrino or sneutrino sector. The $(B + L)$-anomaly-induced interactions together with EW gaugino and $A$-term interactions automatically distribute the asymmetry between the baryons and the dark matter states, with a predictable $A/A_{\text{bary}}$ ratio. The resonant leptogenesis mechanism discussed in Ref.[10] can do the job in the mixed sneutrino example. The result of the (B+L) violating "chemical" equilibration process is that we expect $1/3 \gtrsim A/A_{\text{bary}} \gtrsim 1/6$ independent of the source of the asymmetry.

RESULTS AND DISCUSSION

Our results are shown in figure[1]. The shaded regions of the parameter space predict a relic density within the range measured by WMAP, $(0.129 > \Omega_{\text{dm}} h^2 > 0.095)$. In the left frame, no asymmetry was included. In the center and right frames, an asymmetry of $A/A_{\text{bary}} \simeq 1/3$ and $A/A_{\text{bary}} \simeq 1/6$ respectively was included.

To further illustrate this effect, the result of this calculation across one value of $\sin \theta$ is plotted in figure[2] below. Below about 30 GeV, the asymmetry has little effect on the calculation and the solid and dot-dashed lines fall nearly on top of each other. In the range 30-70 GeV, however, the asymmetry pulls the relic density above the standard symmetric result into the range favored by WMAP. Above this range, sneutrino-antisneutrino annihilation decreases, leading to larger relic densities for the case with no asymmetry. The relic density for the asymmetric case, however, is largely determined by the sneutrino-sneutrino annihilation cross section and so does not increase as rapidly, resulting in a relic density much closer to the preferred value, even for $m_\tilde{\nu} > 70$ GeV.
SUMMARY

In the standard freeze-out calculation for a weakly interacting dark matter relic, there is little reason to expect a density of dark matter which is similar to the density of baryons. One possible solution is to introduce an asymmetry between dark matter particles and anti-particles which is related to the baryon-antibaryon asymmetry. This leads to a natural dark matter relic density of the same order of magnitude as the baryon density.

As an example, we considered a mixed sneutrino dark matter candidate which transfers its particle-antiparticle asymmetry to the baryons through the electroweak anomaly. The relic density calculation for such a candidate has extended and natural regions in the $\sin \theta$ and $m_{\tilde{\nu}}$ parameter space in which the observed $\Omega_b/\Omega_{DM}$ is reproduced.

ACKNOWLEDGMENTS

I thank my collaborators, John March-Russell and Dan Hooper.

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