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Dark-matter in gravity-mediated supersymmetry breaking

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In R parity conserving supersymmetric theories, the lightest superpartner (LSP) is stable. The LSPs may comprise a large fraction of the energy density of the current universe, which would lead to dramatic astrophysical consequences. In this talk, I will discuss some of the main points we have learned about supersymmetric models from relic abundance considerations of the LSP.

1. Introduction

Astrophysicists have long been telling us that the universe is mostly made up of dark matter. Modern analyses, which take into account the subtleties of large scale structure formation, big bang nucleosynthesis, and observations of how galaxies rotate, have largely condensed to one common conclusion: most of the dark matter is probably stable weakly interacting massive particles (WIMPs) [1].

While the astrophysics community was coming to grips with the properties of the dark matter, the supersymmetry community was working on its own problems. In the early 1980's it was first recognized that the proton would decay too quickly if all allowed gauge invariant renormalizable operators in the superpotential had order one strength. A discrete symmetry was postulated which eradicated these unwanted baryon and lepton violating interactions [2]. The postulated symmetry, R -parity, gave a positive charge to all standard model states, and negative charge to all superpartner states. The name " R -parity" is a somewhat unfortunate name since the symmetry is not intrinsically R -symmetric but rather an ordinary global discrete symmetry valid for the superfields (all matter fields are negatively charged, and all Higgs fields are positively charged). (A better name perhaps would have been "Matter parity", however *stare decisis* dictates that we continue using R -parity.)

It was soon realized that R -parity conservation

also implies that the lightest superpartner is stable. A short cognitive leap from this understanding is the realization that there might be many of these stable particles still hanging around the universe. In 1977 several authors demonstrated how to estimate the relic abundance of stable particles (stable neutral leptons were of primary interest then) which were in thermal equilibrium with the photon bath in the early universe [3]. The connection between that work and the existence of a stable neutral supersymmetric particle was quick. Weinberg [4] was one of the first (in print) to make the connection when he made the following ancillary comment in his gaugino masses paper: "... there is no clear conflict [of the photino's mass] with cosmology, and we have a hint that photinos may provide an important 'dark' contribution to the cosmic mass density." Soon after that Goldberg [5] presented his paper on neutralino relic abundance.

2. R -parity

Many useful papers have followed Goldberg's work, and many important points relating to neutralino dark matter have been discovered, refined and debated. One important debate is the origin of R -parity. R -parity is overkill since it banishes both baryon and lepton number violating operators, when in reality only one need be erased. (Proton decay, of course, proceeds via baryon and lepton number violation.) Therefore R parity is not unique in stabilizing the proton. Other discrete symmetries such as "baryon parity" can do the job as effectively [6]. Furthermore, the appli-

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cability of global symmetries has always been debated. Detractors have several arguments ranging from “why should global symmetries exist”, to the catalepsy inducing “worm holes violate global symmetries.” Of course no one would argue with accidental global symmetries which are based on particle content and *gauge* symmetries. Several authors have focused on the gauge symmetry part and have discovered that continuous gauge symmetries can spontaneously break down to a discrete gauge symmetry [7].

From the low energy perspective the only difference between a discrete gauge symmetry and a discrete global symmetry is the former must identically solve a set of discrete anomaly diophantine equations. It turns out that R -parity is the only Z_2 discrete symmetry which is anomaly free given the minimal supersymmetric particle spectrum [8]. Practitioners devoted to simplicity and the preëminence of gauge symmetries cannot help but be impressed with R -parity as the solution to the proton stability question. The work-horse continuous gauge symmetry which could give rise to R -parity is $U(1)_{B-L}$. Any group which contains $U(1)_{B-L}$ has the potential to spontaneously break down to the standard model plus R -parity as long as the order parameter is of the right congruency class [9]. Candidate groups include the well-motivated $SO(10)$, $SU(4)$, $SU(2)_L \times SU(2)_R$, and more. Nature could well give us R -parity conservation from these higher rank groups. More progress will surely come to light on how motivated R -parity is for the low energy theory. Without ever considering the positive ramifications of supersymmetric dark matter, R -parity still survives as a likely candidate symmetry to protect the proton from decaying too quickly.

3. What is the LSP?

I’ll assume R -parity conservation for the rest of the talk, and therefore the LSP is stable. What’s the LSP? This review is on gravity mediated theories, however it should be pointed out that if supersymmetry is broken at low scales then the gravitino could be the LSP [10]. Depending on its mass it too could be a dark matter candidate but

it is warm dark matter rather than the more preferred cold dark matter which cosmologists find so appealing. Nevertheless, in low-energy breaking supersymmetry theories cold dark matter candidates can be found such as the messengers in theories which communicate the supersymmetry breaking via gauge interactions [11]. I won’t discuss such theories further, and will only focus on the gravity mediated case. Part of what I am implying by “gravity mediated” is the assumption that the gravitino is heavy and irrelevant for our discussion and that no other states exist near the weak scale except MSSM states.

If we just write down the most general softly broken supersymmetric lagrangian with standard model gauge symmetries and R -parity conservation, we find that there are over one hundred free parameters corresponding to the masses, flavor mixing angles, and CP violating angles. Numerous simplifications are often imposed such as universality among scalar masses and among gaugino masses at the high scale, flavor angle alignment with the standard model CKM angles, and zero CP violating phases beyond the single phase in the CKM matrix. Not all of these restrictive assumptions are necessary simultaneously in many of the points that I will outline below. Unless otherwise stated, I will always assume that gaugino mass unification occurs at the high scale. In most cases it is straightforward to generalize results when the simplifying assumptions are abandoned.

The dark matter is probably not charged [12], so that leaves us with two possibilities for the dark matter: a sneutrino or the lightest neutralino. There are several problems with the sneutrino as a dark matter candidate. First, it interacts rather efficiently with ordinary matter, and if it constitutes much of the dark matter in our galactic halo then it should have already been detected up to the TeV mass range [13]. This covers a lot of ground in the sneutrino parameter space. More importantly, such high supersymmetry masses call into question the natural solution to electroweak symmetry breaking provided by supersymmetric theories. Second, renormalization group analyses demonstrate that there always exists at least one neutralino lighter

than the sneutrino if the sneutrino mass is above 80 GeV [14]. This statement is valid for any positive intrinsic soft supersymmetry breaking scalar masses at the high scale. At such low mass, the sneutrinos could not provide an interesting amount of dark matter (they annihilate very efficiently through the Z boson). Being $SU(2)$ partners with left-handed charged leptons, signatures at FNAL and LEP II should rule out the entire region below 80 GeV from slepton production and decay. Therefore, it is likely that sneutrinos are not the cold dark matter of the universe.

On the other hand, neutralinos provide a very nice dark matter candidate. For one, they usually come out the lightest particle given a survey over minimal model boundary conditions at the high scale [15]. Second, the composition is almost pure bino, which means that it doesn't couple at full $SU(2)$ strength to the Z boson. The bino is almost pure bino for several reasons. The renormalization group equations for gauginos dictate that the lightest gaugino at the weak scale be the bino. It is a factor of two lighter than the wino. The neutralino is a mixture of the bino, wino, and two higgsino states which scale roughly with the μ parameter. The μ parameter is a mass parameter in the Higgs potential that must be at precisely the correct value such that at the minimum of the potential $m_Z = 91.19$ GeV. The minimization conditions depend on the values of $\tan\beta$, $m_{H_u}^2$ and $m_{H_d}^2$. Usually, $m_{H_u}^2$ gets renormalized to rather large negative values scaling like the heavy top squark mass. To compensate for this large negative value, the μ^2 term in the potential must be large and positive, and it is typical that $|\mu|$ is substantially larger than the bino mass parameter. Therefore, a state which is mostly bino is the lightest neutralino. Of course, this is a conclusion based on the minimal model, but it has wide range of applicability in non-minimal models as well. I will briefly discuss later the implications of non-minimality.

4. Mass limits from relic abundance

A mostly bino LSP is highly desirable [16], since, as noted above, it doesn't interact well with the Z boson. Therefore, annihilations of two bi-

nos into the Z boson are not efficient and the binos fall out of equilibrium faster, having a rather large relic number density. It is of course general for any WIMP; if it annihilates efficiently then there are few leftover today. A non-relativistic particle's number density falls rapidly if it continues to stay in equilibrium with the photons. However, once it freezes out of equilibrium (interactions can't keep up with the expansion of the universe) then it no longer tracks the equilibrium number density all the way to zero. In fact, the relic density scales inversely proportional to its annihilation rate. Since by dimensional analysis the annihilation rate must scale as $1/m_{susy}^2$, and therefore the relic abundance scales as m_{susy}^2 . It should be no surprise then that as the supersymmetry breaking masses go higher and higher then the relic abundance gets too large. (That is the mass density calculation is incompatible with the Hubble constant and current age of the universe.) Therefore, there must be an upper limit to m_{susy} .

This upper limit can be illustrated nicely in the case of a pure bino. For this case we assume, somewhat realistically, that the only other relevant light particles in the spectrum are the right-handed sleptons. In this case, m_{susy} of the previous paragraph becomes a complicated function of the slepton mass and the bino mass. Drees and Nojiri [17] showed that in this model the lightest neutralino and right handed sleptons had to be below 200 GeV in order to not become incongruous with cosmological data. This remarkable result places an upper limit on two superpartner masses from physical principles alone. In other words, no insubstantial finetuning criteria need be placed on the electroweak symmetry breaking equations to obtain upper limits on the superpartner masses.

It is probably not realistic to assume that nature agrees with a pure bino LSP model. More detailed model analyses which solve the electroweak symmetry breaking equations and all the renormalization group equations of the minimal model (perhaps also not realistic) maintain the general result that superpartner masses are cutoff by relic abundance requirements. In Fig. 6 of ref. [15] one can see the effect of the relic abundance constraint on the superpartner spectrum. The effect is most

easily visualized by fixing the gaugino masses to a particular value and then increasing the scalar masses to higher and higher values. Since the (mostly) bino of the minimal model does not couple well with the Z , its main interactions are by t -channel slepton and squark exchange. As these scalar masses get higher the annihilation rate decreases and the relic abundance increases. At sufficiently high scalar mass the relic abundance becomes unacceptably large, indicating a cutoff in how the scalar masses can go. On the other hand, if the scalar masses are fixed in value, and the gaugino masses are raised, other catastrophic problems arise. For example, the LSP might become charged (usually the right-handed slepton), or the electroweak symmetry breaking equations have no correct solution. In any event, there is a cutoff in the superpartner masses. The fact that cosmological arguments such as the above can yield upper limits to the superpartner spectrum is one of the most important things we have learned.

There are many ways to study how non-minimality affects dark matter viability, or how dark matter viability affects non-minimal models. Certainly it is important to study how non-universal scalar masses interplay with dark matter. This is done by Arnowitz in these proceedings [18]. Other ideas include playing around with the neutralino mass matrix to see if other equally attractive dark matter particles come out. A theme permeating all these types of analyses is the requirement that the lightest neutralino not interact with the Z . Both the photino and the bino, long-studied dark matter candidates, satisfy this requirement. Other possibilities include the zino [19], sterile neutralino [20] and the symmetric higgsino [21,22]. By sterile neutralino I mean an additional degree of freedom in the neutralino mass matrix (such as the superpartner to a new Z' gauge boson or singlet Higgs).

5. Higgsino dark matter

Realization that a weak-scale higgsino could be a legitimate dark matter particle is a rather recent development. One way to obtain an higgsino as the lightest neutralino is to make $|\mu|$ much less

than the gaugino parameters in the neutralino mass matrix. A very low value of μ will create a roughly degenerate triplet of higgsinos. The charged higgsino and the neutral higgsinos can all coannihilate together with full $SU(2)$ strength, allowing the LSP to stay in thermal contact with the photons more effectively, thereby lowering the relic abundance of the higgsino LSP to an insignificant level. These coannihilation channels are often cited as the reason why higgsinos are not viable dark matter candidates. This claim is true in general, but there are two specific cases that I would like to summarize below that allow the higgsino to be a good dark matter candidate.

Drees *et al.* have pointed out that potentially large one-loop splittings among the higgsinos can render the coannihilations less relevant [22]. Under some conditions with light top squark masses, one-loop corrections to the neutralino mass matrix will split the otherwise degenerate higgsinos. If the mass difference can be more than about 5% of the LSP mass, then the LSP will decouple from the photons alone and not with its other higgsino partners, thereby increasing its relic abundance.

Another possibility [21] relating to a higgsino LSP is to set equal the bino and wino mass to approximately m_Z . Then set the $-\mu$ term to less than m_W . This non-universality among the gauginos and particular choice for the higgsino mass parameter, produces a light higgsino with mass approximately equal to μ , a photino with mass at about m_Z , and the rest of the neutralinos and both charginos with mass above m_W . There are no coannihilation channels to worry about with this higgsino dark matter candidate since it no other chargino or neutralino mass is near it. The value of $\tan\beta$ is also required to be near one so that the lightest neutralino is an almost pure symmetric combination of \tilde{H}_u and \tilde{H}_d higgsino states. The exactly symmetric combination does not couple to Z boson. The annihilation cross section near $\tan\beta \sim 1$ is proportional to $\cos^2 2\beta$. The relic abundance scales inversely proportional to this, and so the nearly symmetric higgsino in this case is a very good dark matter candidate. Note that there are no t -channel slepton or squark diagrams since higgsinos couple to squark proportional to the fermion mass. Because the higgsino

mass is below m_W , the top quark final state is kinematically inaccessible, and so the large top Yukawa cannot play a direct role in the higgsino annihilations.

This non-minimal higgsino dark matter candidate described in the previous paragraph was motivated by the $e^+e^-\gamma\gamma$ event reported by the CDF collaboration at Fermilab [23]. The non-minimal parameters which leads to a radiative decay of the second lightest neutralino (photino) into the lightest neutralino (symmetric higgsino) and photon also miraculously yield a model with a good higgsino dark matter candidate.

It should be noted that LEP II should be able to find the higgsino dark matter candidate. This is true because the higgsino mass must be below m_W in order to be a viable dark matter particle, and other charginos and neutralinos should have masses which hover around m_W . If its mass is higher than m_W then the W^+W^- annihilation channel opens up at full $SU(2)$ strength with no suppressions, leaving the density of relic higgsinos too small to be significant. (It is also possible that the higgsino could be in the multiple TeV region where it would start to again perhaps become a good dark matter candidate.) This is the reason that LEP II will be able to verify or rule out the light higgsino dark matter idea after it has taken data above 190 GeV.

6. Conclusion

Finally, there is still much to be done both experimentally and theoretically on the dark matter question. Experimentally, table top experiments, neutrino telescopes, cosmic ray detectors, etc., could all start becoming sensitive to supersymmetric neutralino relics in the next few years [24]. Currently, they typically fall a few orders of magnitude away from the expected signal. There is also more work to be done in the theoretical community. For example, demonstrating how R -parity can arise naturally from a string theory or from an elegant grand unified theory would be an interesting development which should predict ramifications for other phenomenological aspects of the model (extra Z' , or exotic D-term effects). High energy colliders in the near future might be

the first to detect the dark matter from decays of superpartners. However, to demonstrate that stable particles on detector time scales are real dark matter candidates that live at least as long as the age of the universe requires experiments specifically devoted to the task.

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