

Colliders as a simultaneous probe of supersymmetric dark matter and Terascale cosmology

Gabriela Barenboim

*Departament de Física Teòrica, Universitat de València
Carrer Dr. Moliner 50, E-46100 Burjassot (València), Spain
Email: gabriela.barenboim@uv.es*

Joseph D. Lykken

*Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510, U.S.A.
Email: lykken@fnal.gov*

ABSTRACT: Terascale supersymmetry has the potential to provide a natural explanation of the dominant dark matter component of the standard Λ CDM cosmology. However once we impose the constraints on minimal supersymmetry parameters from current particle physics data, a satisfactory dark matter abundance is no longer *prima facie* natural. This Neutralino Tuning Problem could be a hint of nonstandard cosmology during and/or after the Terascale era. To quantify this possibility, we introduce an alternative cosmological benchmark based upon a simple model of quintessential inflation. This benchmark has no free parameters, so for a given supersymmetry model it allows an unambiguous prediction of the dark matter relic density. As a example, we scan over the parameter space of the CMSSM, comparing the neutralino relic density predictions with the bounds from WMAP. We find that the WMAP–allowed regions of the CMSSM are an order of magnitude larger if we use the alternative cosmological benchmark, as opposed to Λ CDM. Initial results from the CERN Large Hadron Collider will distinguish between the two allowed regions.

KEYWORDS: Cosmology of Theories beyond the SM, Supersymmetry Phenomenology.

Contents

1. Introduction	1
2. The Neutralino Tuning Problem	4
3. A new cosmological benchmark	8
4. Results	10
5. Conclusion	11

1. Introduction

One of the most appealing features of Terascale supersymmetry [1] is the potential to provide a natural explanation of the dominant dark matter component of the standard Λ CDM cosmology. This explanation is driven by particle physics motivations from data which are completely unrelated to the astrophysical data that motivate Λ CDM. In most supersymmetry (SUSY) models the dark matter candidate is the neutralino, although there are other interesting possibilities. The mass and annihilation cross section of the neutralino are determined by the SUSY model parameters. Adapted to a Λ CDM cosmological history, the neutralino becomes a cold thermal relic, freezing out during a radiation-dominated era at a temperature equal to approximately 1/20th of its mass. SUSY model parameters thus determine the current neutralino abundance, which is usually expressed as a fraction, Ω_χ , of the critical density.

If we assume that neutralinos constitute nearly all of the non-baryonic matter at late times, then their abundance is quite constrained by astrophysical data. For example, combining the WMAP three year data with Sloan Digital Sky Survey data on large scale structure, one obtains [2] the (naive) 2-sigma limits:

$$0.095 < \Omega_\chi h^2 < 0.122 . \quad (1.1)$$

Thus the neutralino relic abundance is determined with $\sim 10\%$ accuracy.

Suppose for simplicity that we consider some subclass of Terascale SUSY models with the neutralino as the stable lightest supersymmetric partner (LSP). The most popular example is the CMSSM, inspired by minimal supergravity [3]–[5], where the SUSY parameter set is written m_0 , $m_{1/2}$, A , $\tan\beta$, and $\text{sign}(\mu)$. Imposing very rough considerations of naturalness, we can require m_0 , $m_{1/2}$ and $|A|$ to be less than, say, 3 TeV. If we assume Λ CDM cosmology we can scan over this parameter space, placing a mark at each point which would predict a relic density satisfying the “WMAP” constraints (1.1).

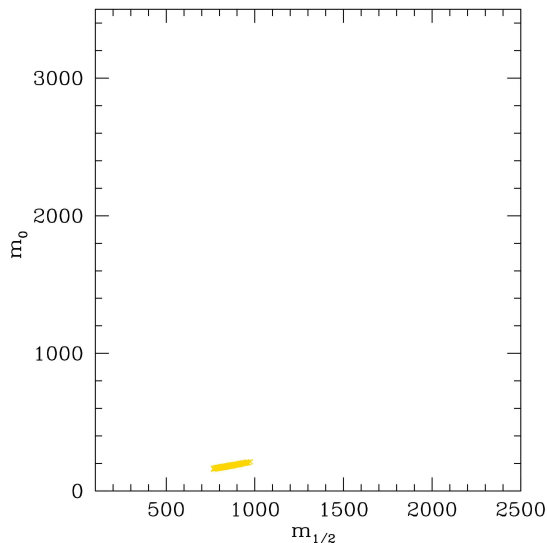


Figure 1: The WMAP–allowed points for the CMSSM, with $A = 0$, $\mu > 0$, and $\tan \beta = 5$. Points are shown only if the corresponding Higgs mass is ≥ 114 GeV. The scan was performed in 2 GeV increments.

The results look like figures 1 and 2, where we have chosen $A = 0$, $\mu > 0$, $\tan \beta = 5$ or 30, and we only plot points which also satisfy the existing experimental bounds on the superpartner particles and the Higgs. The “WMAP–allowed” regions are a very small fraction of the total parameter space. More significantly, once we impose experimental bounds the WMAP–allowed points are not generic; for a Bino-like neutralino generic points predict a relic density that is much too large, while for a Higgsino-like or Wino-like neutralino generic points predict a relic density that is much too small. Getting a WMAP–allowed relic density thus requires tuning to regions where various conspiracies take place, either enhancing the neutralino annihilation (or co-annihilation) cross section, or balancing the Bino-Higgsino-Wino content of the LSP. These conspiracies can be quantified by defining simple sensitivity measures of the predicted relic density to small variations in relevant SUSY parameters [6]. Since conspiracy is the opposite of naturalness, such an analysis [7]–[18] casts doubt upon the CMSSM, and perhaps Terascale SUSY in general, as a natural explanation of dark matter.

This “Neutralino Tuning Problem” is similar to the much more famous “Little Hierarchy Problem” [19, 20] of the MSSM. While conceptually distinct, these problems are related by the fact that the superpartner and Higgs mass bounds from data eliminate what would otherwise be a generic WMAP–allowed region of the CMSSM known as the “bulk” region. The bulk region is generic because its only distinguishing feature is that the superpartners are light, as favored by naturalness applied to electroweak symmetry breaking. Thus at least in the CMSSM the two naturalness problems are coupled.

In this paper we revisit the important question of whether we can quantitatively evaluate the claim that Terascale supersymmetry provides a natural explanation of dark matter. This issue has not been fully resolved in the literature, due to a number of difficulties which

will we review in the next section. We will show that a physically meaningful approach to this question is to compare the robustness of the connection between SUSY and dark matter under alternative well-motivated cosmological scenarios.

There is ample motivation to vary our cosmological assumptions. Despite the dramatic success of the standard Λ CDM model in confronting a wide variety of astrophysical data, this same data is largely silent on the cosmological history of the universe before big bang nucleosynthesis (BBN), i.e., at temperatures above about 4 MeV. WMAP data is consistent with an epoch of primordial inflation, but we are very far from being able to flesh out these hints into a data-driven model which is sufficiently robust and detailed to make definitive statements about dark matter.

A difficulty in exploring cosmological alternatives is that, because Terascale cosmology¹ is almost a black box, it is easy to introduce new parameters which are relevant but unconstrained, modifying the neutralino relic density predictions by orders of magnitude. For example, we can dilute the neutralino density by adding entropy to the radiation bath some time after neutralino freeze-out but before BBN. Alternatively we can increase the predicted neutralino abundance by producing them non-thermally. Our solution is to look at alternative cosmological scenarios which are reasonably motivated, make definite predictions for dark matter, and are sufficiently simple and constrained that they have no relevant adjustable parameters. The dark matter predictions of Terascale SUSY can then be compared for these cosmological benchmark scenarios.

As a first alternative cosmological benchmark, we propose the Slinky model of quintessential inflation described in [21, 22]. This model has no adjustable parameters once we require that the current radiation and dark energy fractions take their WMAP-preferred values, and that the universe is overwhelming radiation-dominated during the time of BBN. Since the same inflaton is responsible for primordial inflation and for dark energy, it is not surprising that the universe is not completely radiation-dominated at the time that neutralinos freeze out. By making the minimal assumption that inflatons do not decay to neutralinos, we have a picture in which thermally produced neutralinos are diluted by a predictable amount, over and above the dilution of standard Λ CDM. This additional dilution of the neutralino abundance can be expressed (to an accuracy of a few percent) as a polynomial function of the square root of the neutralino freeze-out temperature.

Thus for any SUSY model we can compute the predicted neutralino relic abundance for two contrasting cosmological benchmarks, Λ CDM and Slinky. The ratio of the WMAP-allowed regions is a physically meaningful naturalness comparison. In our CMSSM scan, we find that this ratio is always small. For the Slinky benchmark the WMAP-allowed points are more generic, without balanced mixings, mass degeneracies, or resonance-inducing mass relations.

These results give a concrete measure of the Neutralino Tuning Problem in the CMSSM. At the same time, they define the beginnings of a straightforward program to probe Terascale cosmology at colliders.

¹In this phrase ‘Terascale’ refers to the physics responsible for the WIMP dark matter, not the freeze-out temperature.

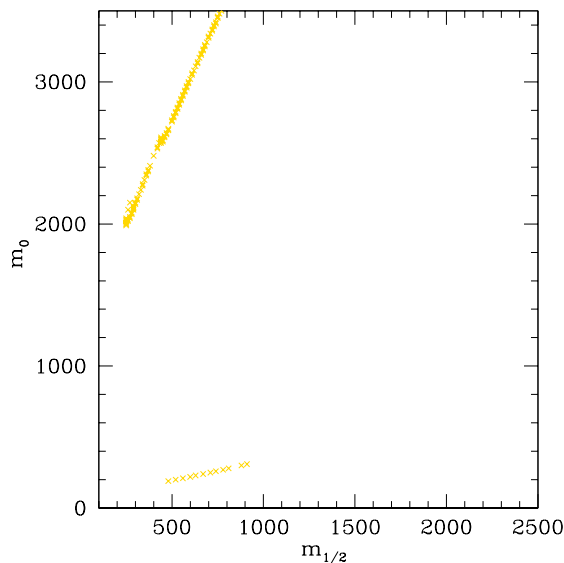


Figure 2: The WMAP–allowed points for the CMSSM, with $A = 0$, $\mu > 0$, and $\tan\beta = 30$. Points are shown only if the corresponding Higgs mass is ≥ 114 GeV. The scan was performed in 10 GeV increments, which misses a few of the highest mass points in the co-annihilation region (lower right).

2. The Neutralino Tuning Problem

This problem is most easily observed in (but not limited to) the CMSSM. We bound the parameter space by requiring m_0 , $m_{1/2}$ and $|A|$ to be less than, say, 3 TeV. We remove regions in which the lightest neutralino is not the LSP, or in which we do not get proper electroweak symmetry breaking. We also remove regions which are in direct conflict with experiment. For most of the MSSM parameter space, the most restrictive experimental constraint is the direct lower bound on the lightest Higgs mass from LEP. We will conservatively write this bound as $m_h \geq 114$ GeV. We fix the mass of the top quark to the 2005 combined Tevatron average [23] of 172.7 GeV; our results would differ only slightly using the newer combined average [24] of 171.4 GeV.

Assuming Λ CDM cosmology we can scan over the remaining CMSSM parameter space, placing a mark at each point where the computed neutralino relic density satisfies the WMAP constraints (1.1). Representative results are seen by fixing $A = 0$, $\mu > 0$, and choosing either $\tan\beta = 5$ (figure 1), $\tan\beta = 30$ (figure 2) or $\tan\beta = 50$ (figure 3). The figures are essentially identical to those in [25], except that our allowed regions are smaller; this is because we use the new WMAP 2-sigma bounds, while [25] uses the older WMAP 99% cl bounds, which are less constraining.

Once we impose experimental bounds the WMAP–allowed points of the CMSSM are not generic. For a Bino-like neutralino generic points predict a relic density which is much too large, while for a Higgsino-like or Wino-like neutralino generic points predict a relic density which is much too small. Getting a WMAP–allowed relic density thus requires tuning to regions where various conspiracies take place, either enhancing the neutralino

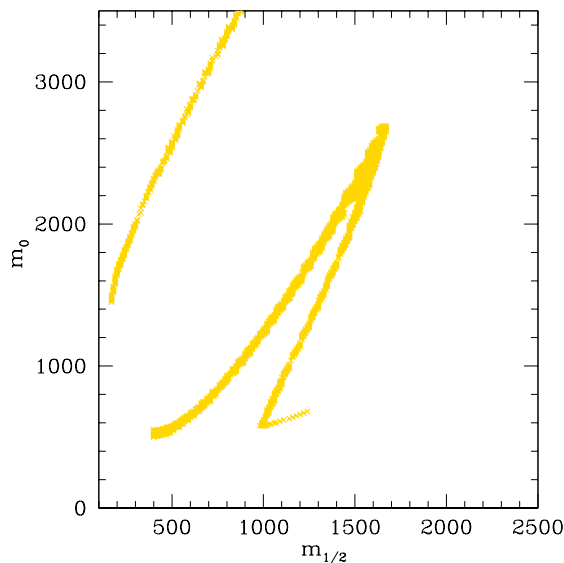


Figure 3: The WMAP–allowed points for the CMSSM, with $A = 0$, $\mu > 0$, and $\tan\beta = 50$. Points are shown only if the corresponding Higgs mass is ≥ 114 GeV. The scan was performed in 10 GeV increments.

annihilation (or co–annihilation) cross section, or balancing the Bino-Higgsino-Wino content of the LSP.

In figures 1 and 2, the lower slivers of WMAP–allowed points are made possible by tuning the lightest stau to be nearly degenerate with the lightest neutralino, producing co-annihilation at the time of freeze–out. The upper sliver in figure 2 is a “focus point” region [26], where we tune to give the LSP a significant Higgsino component. This allows neutralino pairs to annihilate more efficiently through t -channel chargino exchange into dibosons. The focus point region does not show up in figure 1 because it produces only points with $m_h < 114$ GeV. Apart from this, shifting $\tan\beta$ from 5 to 30 does not make a qualitative difference.

For a window of very large $\tan\beta$, which is itself a tuning, we obtain results as in figure 3. Here the focus point region has expanded, the co-annihilation sliver remains a sliver, and a new region, the “ A -funnel”, has opened up. In this region we are tuning $m_A \simeq 2m_{\text{LSP}}$, allowing neutralinos to annihilate efficiently through an s -channel resonance.

The Neutralino Tuning Problem of the MSSM has been known for some time, but this observation has not yet spawned anything like the febrile activity engendered by the Little Hierarchy Problem. Part of the reason is that it is not straightforward to address the Neutralino Tuning Problem in a physically meaningful and unambiguous fashion. This is most easily seen by attempting to quantify the problem.

The neutralino relic density, assuming a Λ CDM cosmological history, is a physical observable that is not conceptually different from, say, the selectron mass. Obviously in the limit that the WMAP errors shrink to zero, the allowed fraction of the CMSSM parameter space, or any other space of relevant parameters, will also shrink to zero. The “small” size of

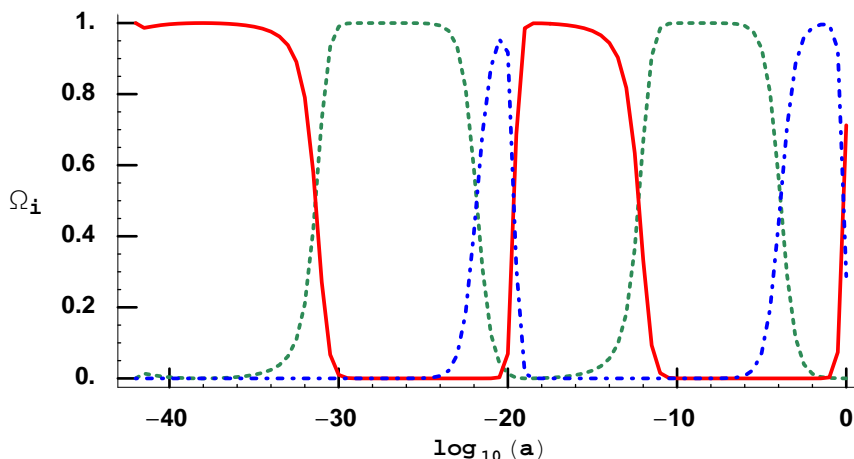


Figure 4: The cosmological history of Slinky. Shown are the relative energy density fractions in radiation (green/dashed), matter (blue/dot-dashed), and the noncanonical scalar (red/solid), as a function of the logarithm of the scale factor $a(t)$. The early period of (exotic) matter domination is illustrative and has no connection to neutralinos.

the WMAP-allowed region of the parameter space, in and of itself, therefore has no bearing on naturalness. It is simply a mapping from the parameter space to a particular physical observable with a small error bar. The same is true for more sophisticated statistical analyses [27]–[29].

Another quantitative approach comes from expanding the SUSY parameter space, and comparing the WMAP-allowed regions for the relic density with those obtained in the CMSSM. But this approach has serious drawbacks. If we expand our class of SUSY models by varying parameters which are irrelevant to the determination of the neutralino relic density, we have done nothing. If we expand our class of SUSY models by varying relevant parameters, we are also (in general) changing the measure on “theory space”, so a naive comparison of allowed regions is not meaningful. This makes it difficult, for example, to compare the CMSSM with the non-universal Higgs models defined in [30], where the focus point and A -funnel regions are complicated slices through a higher dimensional parameter space.

It may be possible to find a class of SUSY models which do significantly better than the CMSSM in an unambiguous, apples-to-apples comparison. However we would not learn much from this unless the new models had some theoretical or experimental motivation independent from our desire to explain dark matter.

Experimental motivation could come from the Large Hadron Collider (LHC). Initial physics runs may provide direct access to Terascale supersymmetry. This would certainly give a dramatic, but not complete, reduction of the SUSY parameter space compatible with particle physics data. It is possible that in a large fraction of this reduced parameter space the predicted neutralino relic density will satisfy the WMAP (or Planck) bounds. While this would not answer our original question of whether generic Terascale SUSY gives a natural explanation of dark matter, it would make this question somewhat moot. In such a case emphasis will naturally shift to trying to obtain precision comparable to

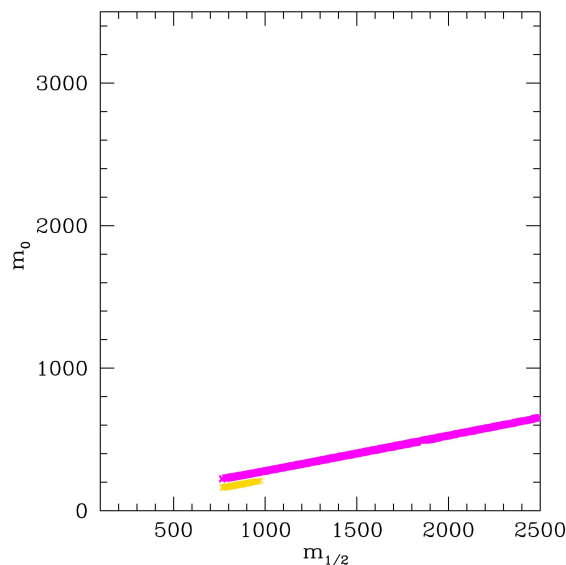


Figure 5: The WMAP-allowed points for the CMSSM, with $A = 0$, $\mu > 0$, and $\tan\beta = 5$. The scan was performed in 2 GeV increments.

the WMAP errors, and ultimately to assessing whether the neutralino constitutes the only major component of dark matter. It will not be possible to do this using only initial results from the LHC. Detailed studies [31] indicate that the International Linear Collider (ILC), combined with the LHC data as well as data from direct and indirect dark matter searches, will be required to provide adequate resolution of the relevant parameters.

In the meantime, it is prudent to assess our original assumptions about SUSY and about cosmology. Regarding SUSY it is certainly important to consider LSPs other than the neutralino. However as has been already noted by many authors [26], without simultaneously modifying our cosmological assumptions this tends to complicate the natural connection between SUSY and dark matter, rather than simplifying it.

Regarding cosmology, we have made two major assumptions. The first is that neutralinos are the overwhelming dominant component of dark matter. This is not very plausible, given that visible matter consists of several quite different stable components. On the other hand this assumption also has little impact on our analysis of the CMSSM, for the large part of the parameter space where the LSP is nearly 100% Bino. Here we generically predict far too much dark matter. Thus if we instead asked that the neutralino merely constitute a *significant* fraction of dark matter, our unhappiness with the CMSSM would be unchanged.

Our second major cosmological assumption was that we can naively extrapolate the Λ CDM picture back to the time of neutralino freeze-out, and that the neutralinos themselves are entirely thermal relics. This assumption is plausible but not yet directly supported by any data. The astrophysical data that supports the standard Λ CDM model is largely silent on the cosmological history of the universe before BBN. WMAP data is consistent with an epoch of primordial inflation, but we are very far from being able to

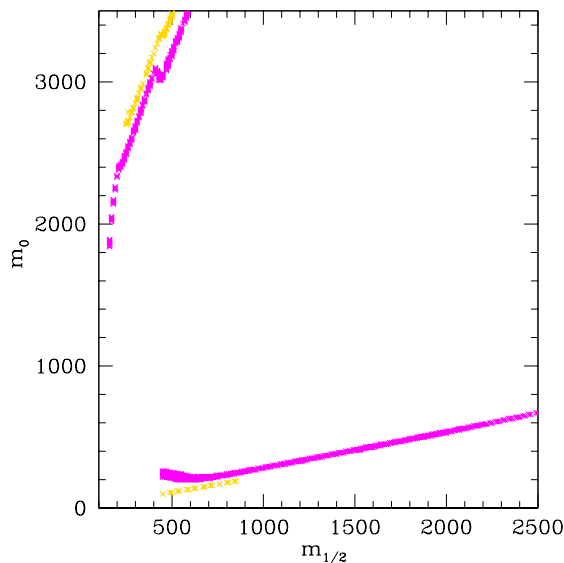


Figure 6: The WMAP-allowed points for the CMSSM, with $A = 0$, $\mu > 0$, and $\tan \beta = 10$. The scan was performed in 10 GeV increments.

connect these hints to definitive statements about dark matter.

Simply put, a top-down approach of trying to fix pre-BBN cosmology sufficiently well to pin down the genesis of dark matter is likely to fail in the foreseeable future. More realistic is to combine a top-down approach with a bottom-up approach, which uses collider data and dark matter detection results. Thus, at the same time that we use data to determine the properties of dark matter, we are simultaneously using data (some of it the same data) to determine the cosmology of the Terascale epoch.

3. A new cosmological benchmark

With the assumption that neutralinos are thermal relics, their abundance $Y(X)$ can be computed as a function of $X = T/m_\chi$, the ratio of the temperature of the thermal bath divided by the mass of the LSP. The evolution equation for $Y(X)$ is [32, 33]:

$$\frac{dY}{dX} = \frac{m_\chi}{X^2} \sqrt{\frac{\pi g_*(m_\chi/X)}{45}} M_p \langle \sigma v \rangle (Y_{\text{eq}}(X)^2 - Y(X)^2) \quad (3.1)$$

where g_* is an effective number of degree of freedom, M_p is the Planck mass, $Y_{\text{eq}}(X)$ the thermal equilibrium abundance, and $\langle \sigma v \rangle$ is the relativistic thermally averaged annihilation cross section. The SUSY model determines the cross section, summing over the relevant annihilation and co-annihilation channels.

We have used `micrOMEGAs 2.0`, which solves (3.1) numerically [34, 35] and returns the predicted neutralino relic density as $\Omega_\chi h^2$. It also returns the freeze-out value of X , called X_F , which is roughly equal to 1/20. The program uses `SUSPECT 2.3` to compute the SUSY

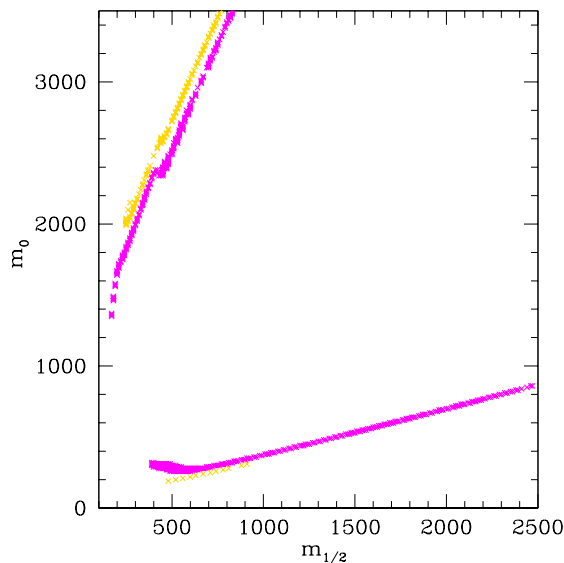


Figure 7: The WMAP–allowed points for the CMSSM, with $A = 0$, $\mu > 0$, and $\tan \beta = 30$. The scan was performed in 10 GeV increments.

spectrum from CMSSM input parameters [36]. As noted in the previous section we fix the top quark mass to be 172.7 GeV.

In the Slinky model of quintessential inflation, a single noncanonical inflaton is responsible for primordial inflation, one intermediate epoch of inflation and the present day accelerating expansion. The inflaton potential is an exponential of a periodic function, giving repeated epochs of progressively weaker accelerated expansion, alternating with epochs of radiation or matter domination. The qualitative form of the potential is chosen such that the time–varying equation of state of the inflaton has the simplest possible periodic behavior. The period is adjusted so that BBN occurs during a period of radiation domination. The remaining free parameter, which is the coefficient controlling the coupling of the inflaton to radiation (k_0), is always small, and is turned off at late times to avoid strong phenomenological constraints. This weak coupling is fixed by requiring that the present day ratio of radiation density to quintessence takes the WMAP–preferred value. The original Slinky allowed for the nonthermal production of dark matter via coupling to the inflaton; for the purposes of this paper we assume that this coupling is not present, and that dark matter is produced thermally entirely from neutralino freeze–out.

Thus Slinky is a simple well–motivated cosmological model with no adjustable parameters. Not surprisingly, at the time that neutralinos freeze out, the Hubble expansion rate H differs from what it would be in standard Λ CDM, since the universe is near the end of an epoch of accelerated expansion. Furthermore, between the time that the neutralinos freeze out and BBN, there is a significant entropy increase due to the inflaton coupling to radiation. The net effect is to dilute the neutralino relic density relative to what would be predicted with Λ CDM. Thus $\Omega_\chi(\text{Slinky}) = \Omega_\chi(\text{standard})/\gamma$, where γ is the Slinky dilution

factor. From a numerical analysis, we have found a heuristic formula for γ as a function of X_F :

$$\gamma = 0.6 + 0.5X_F^{-1/2} - 0.06X_F^{-1} + 0.01X_F^{-2} . \quad (3.2)$$

This formula is accurate to within a few percent. The exact solution can be obtained by calculating the entropy production through numerically solving the evolution equations for the inflaton, radiation and matter, i.e.

$$\begin{aligned} \dot{\rho}_\theta &= -3H(1+w)\rho_\theta - k_0H(1+w)\rho_\theta ; \\ \dot{\rho}_r &= -4H\rho_r + k_0H(1+w)\rho_\theta ; \\ \dot{\rho}_m &= -3H\rho_m ; \end{aligned} \quad (3.3)$$

where H is the Hubble rate, $w(t)$ is the inflaton equation of state parameter, and ρ_θ , ρ_r , ρ_m are the energy density of the inflaton, radiation and matter, respectively.

In reference [22], we described two variants of Slinky in which we change the discrete choice of the number of past inflationary epochs. In the variant with only a single period of primordial inflation, we would expect neutralino abundances very close to what is obtained using Λ CDM. In the variant with many inflationary periods, we would expect interesting results distinguishable from both Λ CDM and standard Slinky, however as discussed in [22] this variant is only marginally allowed by current data.

4. Results

The results of the CMSSM scans are shown in figures (5-8), for $A = 0$, $\mu > 0$, and various values of $\tan\beta$. We only show points for which the neutralino is the LSP, we obtain proper electroweak symmetry breaking, and we satisfy current experimental bounds including $m_h \geq 114$ GeV. The yellow points predict neutralino relic densities which satisfy the WMAP bounds (1.1). The magenta points predict neutralino relic densities which satisfy the WMAP bounds when combined with the Slinky dilution factor as given by (3.2). The value of the dilution factor varies between about 6 and 8 over the scans. These points are consistent with all accelerator bounds, and we have checked using `DarkSUSY 3.14` [37] that the resulting spin-independent LSP-nucleon cross sections are below the CDMS limits [38].

As seen in table 1, the WMAP-allowed region is an order of magnitude larger if we assume the modified Slinky cosmology rather than Λ CDM cosmology. In the large $\tan\beta \sim 50$ window this ratio is reduced to less than 3, but recall that this window is itself a (small) tuning. The large ratio for the case $\tan\beta = 5$ is enhanced by the lack of an allowed focus point region for the standard case. This comparison of allowed regions is only weakly dependent on the size of the WMAP error bars, or on the choice of metric in the “theory space”.

From a detailed comparison of the particle spectra, we find that the WMAP-allowed points in the Slinky case are more generic. This is not obvious from the figures, since except for the case of $\tan\beta = 50$ the magenta regions are fairly close to the yellow regions where stau co-annihilation or Bino-Higgsino mixing is occurring. Looking at the spectra, we find

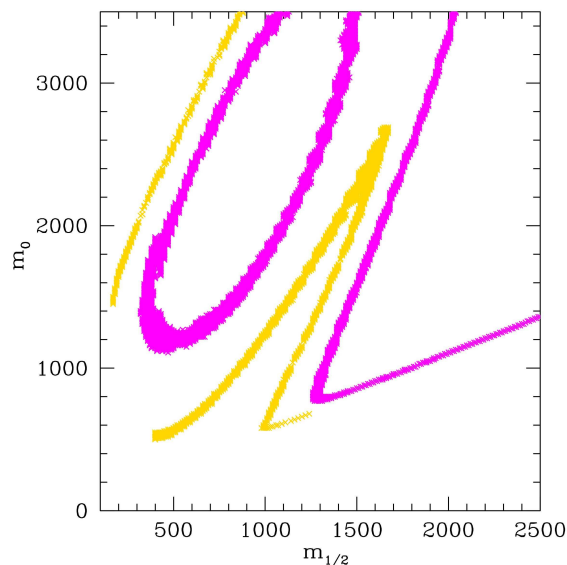


Figure 8: The WMAP-allowed points for the CMSSM, with $A = 0$, $\mu > 0$, and $\tan \beta = 50$. The scan was performed in 10 GeV increments.

$\tan \beta$	number of allowed standard points	number of allowed Slinky points
5	187	4812
10	68	435
30	108	434
50	1423	3578

Table 1: Results of CMSSM scans in the m_0 - $m_{1/2}$ plane, with $A = 0$, $\mu > 0$, and various values of $\tan \beta$. The scans were performed in 10 GeV increments, except for the case $\tan \beta = 5$, where the scan was in 2 GeV increments. The second column contains the points which give a WMAP-allowed neutralino relic density, as reported by micrOMEGAs 2.0. The third column shows the number of WMAP-allowed points when we include the additional dilution factor of the Slinky benchmark model.

that the lightest stau is at least 40 GeV heavier than the LSP in the lower magenta regions, while the Bino fraction in the upper magenta regions never dips below 0.88. The magenta regions do not involve the kind of balanced mixings, mass degeneracies, or resonance-inducing mass relations that characterize the yellow regions. Table 2 shows the particle spectra for some representative magenta points.

5. Conclusion

In this paper we have reviewed the Neutralino Tuning Problem of the CMSSM and MSSM. We have quantified this problem by an explicit comparison of the CMSSM for two different cosmological benchmark scenarios: standard Λ CDM and Slinky. The comparison shows that the standard case requires about an order of magnitude of extra tuning to successfully

m_0	$m_{1/2}$	$\tan\beta$	m_h	LSP	stau1	chargino1	gluino	LSP Bino fraction
240	810	5	114.2	341	382	642	1792	0.996
200	520	10	114.1	188	274	354	1065	0.990
1840	160	10	115.1	61	1822	109	492	0.906
1350	170	30	114	65	1239	113	500	0.887

Table 2: Superpartner and Higgs masses in GeV for selected CMSSM points which predict the correct amount of neutralino dark matter using the Slinky benchmark cosmology. All points have $A = 0$ and $\mu > 0$. The particle spectra are computed using `SUSPECT 2.3`.

account for dark matter. The WMAP-allowed regions for the Slinky case are still restricted to rather narrow strips, but this partly reflects the small ($\pm 10\%$) error bar on $\Omega_\chi h^2$ that we are trying to squeeze into.

These results do not mean that CMSSM+Slinsky is a fundamentally more natural theory than the CMSSM+ Λ CDM. To reach such a conclusion, one would have to overcome at least two obstacles. A mild obstacle is the usual problem that naturalness measures are ambiguous in the absence of a fundamental principle to fix the measure on the relevant parameter space. A more formidable obstacle is that CMSSM+Slinsky and CMSSM+ Λ CDM are theories not just of particle physics and dark matter production, but also of cosmology in general. No one has yet provided a criterion for evaluating naturalness in cosmology; e.g. which is more natural, a fine-tuned cosmological constant or a fine-tuned quintessence model? All we can claim about Slinky is that it has no free parameters once we specify a few qualitative features and tune two parameters to agree with cosmological data. Thus, whether or not Slinky is a natural cosmology, it is an attractive benchmark (the same is often said of the CMSSM as a theory of supersymmetry).

We expect that it should be possible to construct other interesting new cosmological benchmarks from examples already in the literature [39]–[44]. Note that a different cosmological benchmark with a larger dilution factor could look better than Slinky. Suppose for example that we fix m_0 , A , $\text{sign}(\mu)$ and $\tan\beta$, and look at

$$f(m_{1/2}) \equiv |d\Omega_\chi/dm_{1/2}|. \tag{5.1}$$

We can regard $f(m_{1/2})$ as a rough naturalness measure; larger $f(m_{1/2})$ in a region where we obtain WMAP-allowed points means that we will obtain a narrower strip of allowed points. Generically $f(m_{1/2})$ is largest at both small and large values of $m_{1/2}$, passing through zero at some intermediate value of $m_{1/2}$ where Ω_χ is maximized. Thus a cosmological benchmark with a larger dilution factor will pick up WMAP-allowed points in a region where $f(m_{1/2})$ is smaller. In addition, when we have a dilution factor γ , the obvious naturalness measure is not $f(m_{1/2})$ but rather $f(m_{1/2})/\gamma$, since it is the latter quantity which determines the width of the WMAP-allowed region in the approximation that γ is a slowly varying function of $m_{1/2}$.

The superpartner spectra in the standard and Slinky cases differ by at least tens of GeV. In addition, the Slinky spectra do not exhibit the mass degeneracies or resonance-inducing mass relations that occur in the standard case. Thus it should be possible to

discriminate between these spectra using initial data runs from the LHC. This opportunity deserves detailed study.

Suppose that experiments at the LHC do discover a spectrum of new particles consistent with the CMSSM, but not consistent with the WMAP upper bound as derived assuming a neutralino LSP and standard cosmology. Then we will face the interesting challenge of trying simultaneously to refine our knowledge of both the underlying Terascale physics and the underlying Terascale cosmology. Though both may be complicated, it seems prudent to develop a strategy that begins with simple benchmarks. The CMSSM+Slinky benchmark described here is a step in this direction.

Acknowledgments

We thank Marela Carena, Scott Dodelson and Will Kinney for useful discussions. JL acknowledges the support of the Aspen Center for Physics. GB is grateful for the hospitality of the Fermilab Theory Group and for the support from the Spanish MEC under Contract PR2006-0195 and FPA 2005/1678. Fermilab is operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the U.S. Department of Energy.

References

- [1] D.J.H. Chung et al., *The soft supersymmetry-breaking lagrangian: theory and applications*, *Phys. Rept.* **407** (2005) 1 [[hep-ph/0312378](#)].
- [2] D.N. Spergel et al., *Wilkinson microwave anisotropy probe (WMAP) three year results: implications for cosmology*, [astro-ph/0603449](#).
- [3] R. Barbieri, S. Ferrara and C.A. Savoy, *Gauge models with spontaneously broken local supersymmetry*, *Phys. Lett.* **B 119** (1982) 343.
- [4] L.J. Hall, J.D. Lykken and S. Weinberg, *Supergravity as the messenger of supersymmetry breaking*, *Phys. Rev.* **D 27** (1983) 2359.
- [5] P. Nath, R. Arnowitt and A.H. Chamseddine, *Gauge hierarchy in supergravity GUTs*, *Nucl. Phys.* **B 227** (1983) 121.
- [6] N. Arkani-Hamed, A. Delgado and G.F. Giudice, *The well-tempered neutralino*, *Nucl. Phys.* **B 741** (2006) 108 [[hep-ph/0601041](#)].
- [7] H. Baer et al., *Updated constraints on the minimal supergravity model*, *JHEP* **07** (2002) 050 [[hep-ph/0205325](#)].
- [8] J.R. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, *Supersymmetric dark matter in light of WMAP*, *Phys. Lett.* **B 565** (2003) 176 [[hep-ph/0303043](#)].
- [9] H. Baer and C. Balazs, *Chi² analysis of the minimal supergravity model including WMAP, $g(\mu)$ -2 and $b \rightarrow s\gamma$ constraints*, *JCAP* **05** (2003) 006 [[hep-ph/0303114](#)].
- [10] U. Chattopadhyay, A. Corsetti and P. Nath, *WMAP constraints, SUSY dark matter and implications for the direct detection of SUSY*, *Phys. Rev.* **D 68** (2003) 035005 [[hep-ph/0303201](#)].

- [11] M. Battaglia et al., *Updated post-WMAP benchmarks for supersymmetry*, *Eur. Phys. J. C* **33** (2004) 273 [[hep-ph/0306219](#)].
- [12] R. Arnowitt, B. Dutta and B. Hu, *Dark matter, muon $g-2$ and other SUSY constraints*, [hep-ph/0310103](#).
- [13] H. Baer, A. Belyaev, T. Krupovnickas and X. Tata, *Linear collider capabilities for supersymmetry in dark matter allowed regions of the MSUGRA model*, *JHEP* **02** (2004) 007 [[hep-ph/0311351](#)].
- [14] M.E. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, *Sensitivity of supersymmetric dark matter to the b quark mass*, *Phys. Rev. D* **70** (2004) 035014 [[hep-ph/0404025](#)].
- [15] H. Baer, A. Belyaev, T. Krupovnickas and J. O’Farrill, *Indirect, direct and collider detection of neutralino dark matter*, *JCAP* **08** (2004) 005 [[hep-ph/0405210](#)].
- [16] J.R. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, *Prospects for sparticle discovery in variants of the MSSM*, *Phys. Lett. B* **603** (2004) 51 [[hep-ph/0408118](#)].
- [17] B.C. Allanach, G. Belanger, F. Boudjema and A. Pukhov, *Requirements on collider data to match the precision of WMAP on supersymmetric dark matter*, *JHEP* **12** (2004) 020 [[hep-ph/0410091](#)].
- [18] Y. Mambrini and E. Nezri, *Dark matter and colliders searches in the MSSM*, [hep-ph/0507263](#).
- [19] R. Barbieri and A. Strumia, *The ‘lep paradox’*, [hep-ph/0007265](#).
- [20] A. Birkedal, Z. Chacko and M.K. Gaillard, *Little supersymmetry and the supersymmetric little hierarchy problem*, *JHEP* **10** (2004) 036 [[hep-ph/0404197](#)].
- [21] G. Barenboim and J.D. Lykken, *Slinky inflation*, *Phys. Lett. B* **633** (2006) 453 [[astro-ph/0504090](#)].
- [22] G. Barenboim and J.D. Lykken, *Minimal noncanonical cosmologies*, *JHEP* **07** (2006) 016 [[astro-ph/0604528](#)].
- [23] CDF collaboration, *Combination of CDF and $D0$ results on the top-quark mass*, [hep-ex/0507091](#).
- [24] TEVATRON ELECTROWEAK WORKING GROUP collaboration, E. Brubaker et al., *Combination of CDF and $D0$ results on the mass of the top quark*, [hep-ex/0608032](#).
- [25] A. Djouadi, M. Drees and J.-L. Kneur, *Updated constraints on the minimal supergravity model*, *JHEP* **03** (2006) 033 [[hep-ph/0602001](#)].
- [26] J.L. Feng, *Supersymmetry and cosmology*, *Ann. Phys. (NY)* **315** (2005) 2.
- [27] J.R. Ellis, K.A. Olive, Y. Santoso and V.C. Spanos, *Likelihood analysis of the CMSSM parameter space*, *Phys. Rev. D* **69** (2004) 095004 [[hep-ph/0310356](#)].
- [28] B.C. Allanach and C.G. Lester, *Multi-dimensional mSUGRA likelihood maps*, *Phys. Rev. D* **73** (2006) 015013 [[hep-ph/0507283](#)].
- [29] B.C. Allanach, *Naturalness priors and fits to the constrained minimal supersymmetric standard model*, *Phys. Lett. B* **635** (2006) 123 [[hep-ph/0601089](#)].
- [30] H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, *Direct, indirect and collider detection of neutralino dark matter in SUSY models with non-universal Higgs masses*, *JHEP* **07** (2005) 065 [[hep-ph/0504001](#)].

- [31] E.A. Baltz, M. Battaglia, M.E. Peskin and T. Wizansky, *Determination of dark matter properties at high-energy colliders*, hep-ph/0602187.
- [32] G.B. Gelmini, P. Gondolo and E. Roulet, *Neutralino dark matter searches*, *Nucl. Phys. B* **351** (1991) 623.
- [33] J. Edsjo and P. Gondolo, *Neutralino relic density including coannihilations*, *Phys. Rev. D* **56** (1997) 1879 [hep-ph/9704361].
- [34] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *micrOMEGAs2.0: a program to calculate the relic density of dark matter in a generic model*, hep-ph/0607059.
- [35] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, *Micromegas: version 1.3*, *Comput. Phys. Commun.* **174** (2006) 577 [hep-ph/0405253].
- [36] A. Djouadi, J.-L. Kneur and G. Moultaka, *Suspect: a fortran code for the supersymmetric and Higgs particle spectrum in the MSSM*, hep-ph/0211331.
- [37] P. Gondolo et al., *DarkSUSY: computing supersymmetric dark matter properties numerically*, *JCAP* **07** (2004) 008 [astro-ph/0406204].
- [38] CDMS collaboration, D.S. Akerib et al., *First results from the cryogenic dark matter search in the soudan underground lab*, *Phys. Rev. Lett.* **93** (2004) 211301 [astro-ph/0405033].
- [39] G.F. Giudice, E.W. Kolb and A. Riotto, *Largest temperature of the radiation era and its cosmological implications*, *Phys. Rev. D* **64** (2001) 023508 [hep-ph/0005123].
- [40] T. Nihei, N. Okada and O. Seto, *Neutralino dark matter in brane world cosmology*, *Phys. Rev. D* **71** (2005) 063535 [hep-ph/0409219].
- [41] K. Kohri, M. Yamaguchi and J. Yokoyama, *Neutralino dark matter from heavy gravitino decay*, *Phys. Rev. D* **72** (2005) 083510 [hep-ph/0502211].
- [42] C. Pallis, *Quintessential kination and cold dark matter abundance*, *JCAP* **10** (2005) 015 [hep-ph/0503080].
- [43] C. Pallis, *Kination dominated reheating and cold dark matter abundance*, *Nucl. Phys. B* **751** (2006) 129 [hep-ph/0510234].
- [44] M. Drees, H. Imminiyaz and M. Kakizaki, *Abundance of cosmological relics in low-temperature scenarios*, *Phys. Rev. D* **73** (2006) 123502 [hep-ph/0603165].