Landscape Higgs and sparticle mass predictions from a logarithmic soft term distribution

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Abstract

Recent work on calculating string theory landscape statistical predictions for the Higgs and sparticle mass spectrum from an assumed power-law soft term distribution yields an expectation for $m_h \simeq 125$ GeV with sparticles (save light higgsinos) somewhat beyond reach of high-luminosity LHC. A recent examination of statistics of SUSY breaking in IIB string models with stabilized moduli suggests a power-law for models based on KKLT stabilization and uplifting while models based on large-volume scenario (LVS) instead yield an expected logarithmic soft term distribution. We evaluate statistical distributions for Higgs and sparticle masses from the landscape with a log soft term distribution and find the Higgs mass still peaks around $\sim 125$ GeV with sparticles beyond LHC reach, albeit with somewhat softer distributions than those arising from a power-law.

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1 Introduction

The cosmological constant problem—how can it be that the numerical value of $\Lambda_{cc}$ is more than 120 orders of magnitude less than its expected theoretical value [1]—finds a compelling resolution within the landscape of string vacua [2] coupled to anthropic reasoning [3]. The idea is that, with say $\sim 10^{500}$ string vacua states [4,5], each leading to different 4−d laws of physics and with a rather uniform distribution of $\Lambda_{cc}$ ranging from $m_P^2$ to values well below $10^{-120}m_P^2$, then it may not be surprising to find ourselves living within a pocket-universe (within the eternally-inflating multiverse) with such a small $\Lambda_{cc}$ since if its value was much larger, then the expansion rate would be so great that galaxy (structure) formation would not occur [6]. Such anthropic reasoning works if we posit in addition that our pocket universe is but one within a fertile/friendly patch wherein the Standard Model (SM) is the low energy effective field theory (EFT) and only one of a few fundamental parameters (such as $\Lambda_{cc}$) scans within the patch [7].

Possibly related to the cosmological constant problem is the riddle as to why—within the SM—the magnitude of the weak scale $m_{weak} \sim m_{W,Z,h} \sim 100$ GeV is so much lower than the Planck or GUT scale. Even if tree level SM parameters are dialed so that $m_{weak} \sim 100$ GeV, quadratically divergent quantum corrections to $m_h$ ought to drag its mass up to the highest energy scales admissible within the model. The latter situation is fixed [8, 9] by supersymmetrizing the SM into the softly broken Minimal Supersymmetric Standard Model or MSSM [10, 11]. While weak-scale SUSY stabilizes the weak scale, it still doesn’t explain its magnitude.

An explanation for the magnitude of the weak scale can also be found within the string landscape wherein something like the MSSM forms the low energy 4−d EFT. In this case, one again assumes a fertile patch of vacua wherein just the soft SUSY breaking terms scan between different pocket universes [12]. Then, the pocket-universe value for the weak scale is determined by the values of the soft SUSY breaking terms and the superpotential $\mu$ term. While the former are expected to scan, the latter value is presumably determined by whatever solution to the SUSY $\mu$ problem is invoked in nature [13]. Then, the pocket-universe value of the weak scale is given (in terms of the $Z$-mass) by

$$\frac{(m_{Z}^{PU})^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u) \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2 \approx -m_{H_u}^2 - \Sigma_u^u - \mu^2.$$  

Here, $m_{H_d}^2$ and $m_{H_d}^2$ are the Higgs field soft squared-masses and the $\Sigma_d^d$ and $\Sigma_u^u$ contain over 40 loop corrections to the weak scale (expressions can be found in the Appendix to Ref. [14]). Agrawal et al. [15,16] have calculated that if the pocket-universe (PU) value $m_{weak}^{PU}$ is much bigger or smaller than its measured value in our universe (OU), then complex nuclei and hence atoms as we know them would not form. The existence of atoms seems necessary for life as we know it; this is known as the atomic principle, in analogy with the structute principle used for anthropic reasoning in the case of the cosmological constant. Thus, a value of $m_{weak}^{PU}$ to within a factor of 2-5 of its value in our universe would form the anthropic requirement for life as we know it in a fertile patch of vacua with an MSSM-like low energy EFT.

Douglas has proposed a program for the statistical determination of the soft SUSY breaking terms, and hence the expected Higgs and sparticle mass spectrum, from sampling the array of soft terms expected within our fertile patch [17]. The distribution of 4−d supergravity
vacua with hidden sector SUSY breaking scale $m_{\text{hidden}}^2$ is expected to be a product of three distributions
\[
dN_{\text{vac}}(m_{\text{hidden}}^2, m_{\text{weak}}, \Lambda_{cc}) = f_{\text{SUSY}} \cdot f_{\text{EWSB}} \cdot f_{cc} \cdot dm_{\text{hidden}}^2
\]
where the hidden sector SUSY breaking scale $m_{\text{hidden}}^4 = \sum_i |F_i|^2 + \frac{1}{2} \sum_\alpha |D_\alpha|^2$ is a mass scale associated with the hidden sector (and usually in SUGRA-mediated models it is assumed $m_{\text{hidden}} \sim 10^{12}$ GeV such that the gravitino gets a mass $m_{3/2} \sim m_{\text{hidden}}^2/m_P$). Consequently, in gravity-mediation then the visible sector soft terms are of magnitude $m_{\text{soft}} \sim m_{3/2}$ [18–20].

As noted by Susskind [21] and Douglas [22], the scanning of the cosmological constant is effectively independent of the determination of the SUSY breaking scale so that $f_{cc} \sim \Lambda_{cc}/m_{\text{string}}^4$. Thus, the cosmological constant decouples from the statistical determination of the SUSY breaking scale.

One proposal for $f_{\text{SUSY}}$ arises from examining flux vacua in IIB string theory [17, 21, 23]. Since nothing in string theory prefers one SUSY breaking vev over another, then all values should be comparably probable. Then the SUSY breaking $F_i$ and $D_\alpha$ terms are likely to be uniformly distributed– in the former case as complex numbers while in the latter case as real numbers. Then one expects the following distribution of supersymmetry breaking scales
\[
f_{\text{SUSY}}(m_{\text{hidden}}^2) \sim (m_{\text{hidden}}^2)^{2n_F+n_D-1}
\]
where $n_F$ is the number of $F$-breaking fields and $n_D$ is the number of $D$-breaking fields in the hidden sector. Even for the case of just a single $F$-breaking term, then one expects a linear statistical draw towards large soft terms; $f_{\text{SUSY}} \sim m_{\text{soft}}^n$ where $n = 2n_F+n_D-1$ and in this case where $n_F = 1$ and $n_D = 0$ then $n = 1$. For SUSY breaking contributions from multiple hidden sectors, as typically expected in string theory, then $n$ can be much larger, with a consequent stronger pull towards large soft breaking terms.

An initial guess for $f_{\text{EWSB}}$, the (anthropic) electroweak symmetry breaking factor, was $m_{\text{weak}}^2/m_{\text{soft}}^2$ which would penalize soft terms which were much bigger than the weak scale. However, it was pointed out in Ref’s [24,25] that this ansatz fails in a variety of circumstances:

- If the trilinear soft breaking parameter $A_t$ gets too big, then the $m_{R_u}^2$ soft term can be driven negative resulting in charge or color breaking (CCB) vacua. Such vacua states would likely be hostile to life as we know it, and would have to be vetoed instead of merely penalized.

- If soft terms such as $m_{H_u}^2$ are too big, then they will not be driven negative at the weak scale and EW symmetry will not even break; such vacua should also be vetoed.

- For some soft terms, the larger their high scale value, then the smaller (more natural) is their associated contribution to the weak scale. This occurs for $m_{H_u}^2$, where if it is too small, it is driven deeply negative to (negative) multi-TeV squared values. Then one would expect $m_{\text{P}_{\text{L,R}}}$ to also be in the multi-TeV range absent any (improbable) fine-tuning. Also, the larger the $A_t$ parameter, then the smaller are the $\Sigma_u^u(i_{1,2})$ contributions to the weak scale (due to cancellations) [26,27]. And also, large first/second generation soft terms $m_0^2(1,2)$ in the tens of TeV range can drive $m_{\tilde{t}_{L,R}}^2$ to small weak scale values via 2-loop RG effects; this would also result in smaller $\Sigma_u^u(i_{1,2})$ contributions to the weak scale.
To ameliorate these issues, the form

$$f_{EWSB} = \Theta(30 - \Delta_{EW})$$

was adopted, which requires all contributions to the weak scale to be within a factor four of the measured value of the weak scale in our universe $m_{\text{weak}}^{\text{OU}}$. In addition, EW symmetry must be properly broken with no CCB minima.

The statistical calculation of generating soft terms according to $f_{\text{SUSY}}$ (as might be expected in a scan of our fertile patch of the landscape) along with the anthropic selection Eq. 4 that EWSB is properly broken with $m_{\text{weak}}^{\text{PU}} \lesssim 4m_{\text{weak}}^{\text{OU}}$, has led to some very compelling success. The statistical pull on soft SUSY breaking terms to large values pulls the sparticle mass predictions beyond present day limits from LHC: for instance, statistically we would expect for $n = 1$ or 2 that $m_{\tilde{g}} \sim 4 \pm 2$ TeV which explains why LHC hasn’t seen gluinos so far. But sparticles can’t be pulled so high that $m_{\text{weak}}^{\text{PU}}$ gets too big – lest we violate the atomic principle. The fact that $A_t$ gets pulled to large values (but stopping short of CCB vacua) leads to maximal mixing in the top-squark sector which also lifts $m_h$ to a statistical peak around $m_h \simeq 125$ GeV. Thus, from the string landscape with a power-law draw to large soft terms, we expect $m_h \simeq 125$ GeV while sparticles are typically beyond present LHC reach. This methodology has been applied to the two- and three-extra parameter non-universal Higgs gravity-mediation models [28–33] NUHM2 and NUHM3 in Ref. [25] and to mirage mediation in Ref. [34].

An alternative form for $f_{\text{SUSY}}$ is instead motivated by dynamical SUSY breaking (DSB) where instead of perturbative breaking, one expects SUSY breaking from non-perturbative effects [8]. These might include for instance SUSY breaking via gaugino condensation when some hidden sector gauge group becomes strongly interacting. In such a case, the hidden sector SUSY breaking scale is expected to be $m_{\text{hidden}}^2 \sim m_P^2 e^{-8\pi^2/b_0 g^2}$ where $g$ is the hidden sector gauge coupling and $b_0 \sim 1$ enters the hidden sector beta function. A strong motivation for DSB is that it provides some mechanism to generate an exponential hierarchy between the SUSY breaking scale and the fundamental scale $m_P$ in the theory. A plot of hidden sector SUSY breaking mass scale vs. $g_{\text{hidden}}^2$ is shown in Fig. 1. In the context of the landscape, if the hidden gauge coupling $g_{\text{hidden}}^2$ is uniformly distributed within various pocket universes [22], then the SUSY breaking scale will be logarithmically distributed across the decades of values. Then we might expect as well a slowly rising (log) distribution of soft terms. A log or log times a power law distribution of soft terms has been advanced by Dine et al. in a series of papers [35–38]. Such a log distribution may also be expected in non-perturbative SUSY breaking due to instanton effects [39].

The logarithmic landscape draw on soft terms has also emerged from considerations of Kähler moduli stabilization in Ref. [40]. In previous work, Kähler moduli effects were thought to be subleading, but in Ref. [40] the stabilization of Kähler moduli in KKLT [41], LVS [42] and perturbative moduli stabilization [43] (PS) schemes was examined. For these cases, it was found that KKLT and PS led to a power-law draw for soft terms whilst LVS stabilization led to a log draw. Given these motivations, in the present paper we calculate statistical distributions of Higgs and sparticle masses in the NUHM3 gravity-mediation model assuming a log draw on soft terms.
2 Results

In this Section, we will present the results of calculations of the string landscape probability distributions for Higgs and sparticle masses under the assumption of $f_{SUSY} = \log(m_{soft})$ along with Eq. 4 for $f_{EWSB}$. Our results will be presented within the gravity-mediated three extra parameter non-universal Higgs model NUHM3 with parameter space given by

$$m_0(1,2), m_0(3), m_{1/2}, A_0, \tan \beta, \mu, m_A \quad (NUHM3).$$

We adopt the Isajet [44] code for calculation of Higgs and superparticle mass spectrum [45] based on 2-loop RGE running [46] along with sparticle and Higgs masses calculated at the RG-improved 1-loop level [47].

To compare our results against similar calculations which were presented in Ref. [25] but using $f_{SUSY} = m_{soft}^n$, we will scan over the same parameter space

- $m_0(1,2) : 0.1 - 60$ TeV,
- $m_0(3) : 0.1 - 20$ TeV,
- $m_{1/2} : 0.5 - 10$ TeV,
- $A_0 : -50 - 0$ TeV,
- $m_A : 0.3 - 10$ TeV,
with \( \mu = 150 \text{ GeV} \) while \( \tan \beta : 3 - 60 \) is scanned uniformly. The goal here is to choose upper limits to our scan parameters which will lie beyond the upper limits imposed by the anthropic selection from \( f_{EWFT} \). Lower limits are motivated by current LHC search limits. Our final results will hardly depend on the chosen value of \( \mu \) so long as \( \mu \) is within an factor of a few of \( m_{W,Z,h} \sim 100 \text{ GeV} \).

Our first results are shown in Fig. 2, where we show probability distributions of input parameters. Our present \( f_{SUSY} = \log(m_{soft}) \) distributions are shown as shaded histograms. These are then compared to previous scans with \( f_{SUSY} = m_{soft}^n \) for \( n = 0 \) (typical uniform scan) and the simplest power-law scan with \( n = 1 \). In Fig. 2a), we show the distribution vs. first/second generation soft terms \( m_0(1,2) \). While the \( n = 0 \) result (green histogram) peaks at the few TeV range, and the \( n = 1 \) result (red histogram) peaks around 15-20 TeV, we see that the new log result is significantly harder than the uniform scan but slightly softer than \( n = 1 \). Here, the peak probability value for \( m_0(1,2) \) lies in the 10-20 TeV range with a tail extending to 40 TeV. Such large values of \( m_0(1,2) \) should still be enough to provide the mixed decoupling/quasi-degeneracy landscape solution to the SUSY flavor/CP problems as outlined in Ref. [48]. In frame b), we show the distribution vs. third generation soft mass \( m_0(3) \). Here, the log distribution peaks around 4 TeV which is again intermediate between the \( n = 0 \) and \( n = 1 \) histograms. For frame c), which shows the distribution in unified gaugino mass \( m_{1/2} \), we
see the log distribution peaks around 1 TeV with a tail extending to $\sim 2.5$ TeV. For comparison, the $n = 0$ scan peaks at very low $m_{1/2}$ while the $n = 1$ histogram peaks near $m_{1/2} \sim 1.5$ TeV. Finally, we show in frame $d$) the distribution in $-A_0$. While the uniform scan favors small $|A_0|$, leading to small stop mixing and lower $m_h$, the log scan is substantially harder with a double peak structure: one at small $|A_0|$ leading to small stop mixing, and another around $A_0 \sim -7$ TeV with large mixing. The large $-A_0$ bump occurs due to previously noted cancellations in the weak scale radiative corrections $\Sigma^\nu_0(\tilde{t}_{1,2})$ when $|A_0|$ becomes maximal just stopping short of inducing CCB minima in the scalar potential \cite{26,27}.

In Fig. 4 we show various probability distributions for quantities associated with the Higgs/higgsino sector, including the light Higgs mass $dP/dm_h$ in frame $a$). From the frame, we see that with a log distribution of soft terms, the distribution in $m_h$ has a two-peak structure: a dominant peak around $m_h \sim 125$ GeV and a sub-dominant peak around $m_h \sim 120$ GeV. The dominant large $m_h$ peak coincides with the large $|A_0|$ peak of Fig. 2$d$ which leads to large stop mixing. As is well known, large stop mixing leads to large radiative corrections to $m_h$ \cite{49,51} and lifts $m_h$ up into the $\sim 125$ GeV range. This is shown in a scatter plot of events with appropriate EWSB and $m_{Z}^{PU} < 4m_{Z}^{OU}$ in the $m_h$ vs. $A_0$ plane in Fig. 3. There we see explicitly that large $-A_0$ events correlate with large $m_h \simeq 125$ GeV while lower values of $-A_0$ correspond to too low a value of $m_h$. 

Figure 3: Scatter plot of models with appropriate EWSB and $m_{Z}^{PU} < 4m_{Z}^{OU}$ in the $m_h$ vs. $A_0$ plane with $\mu = 150$ GeV.
Figure 4: Probability distributions for NUHM3 masses and parameters a) $m_h$, b) $m_A$, c) $\tan \beta$ and d) $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ from a log distribution of soft terms in the string landscape with $\mu = 150$ GeV. For comparison, we also show probability distributions for $n = 0$ and 1.

This is a testable prediction of the string landscape picture: a value of $m_h \sim 125$ GeV is reflective of large stop mixing which can be untangled for instance at an $e^+e^-$ collider operating with $\sqrt{s} > 2m_{\tilde{t}_1}$ \cite{52}. Other stringy scenarios– such as G2MSSM \cite{53} or mini-split SUSY \cite{54, 55} – obtain $m_h \sim 125$ GeV via very heavy (unnatural) top squarks but with rather small stop mixing. The low $m_h \sim 120$ GeV bump comes from small stop mixing, with $-A_0 \lesssim 1$ TeV.

In Fig. 4b), the distribution in $dP/dm_A$ peaks around $m_A \sim 1.5 - 2$ TeV with a long tail extending as high as 8 TeV. The upper limit on $m_A$ arises from the $m_{H_u}^2/\tan^2 \beta$ contribution to the weak scale in Eq. 1. For $\tan \beta \sim 10$, then $m_A \lesssim 3$ TeV but for larger values of $\tan \beta$, then $m_A \sim m_{H_d}$ can become much bigger: see the $\tan \beta$ vs. $m_A$ scatter plot of solutions in Fig. 5. Such large values of $m_A \gg m_h$ (and consequently $m_H$ and $m_{H^\pm}$) predict that the Higgs sector looks decoupled, with $h$ behaving largely as a SM-like Higgs boson. Thus, the landscape SUSY prediction is that precision Higgs measurements at HL-LHC or an $e^+e^-$ Higgs factory will see at best only small deviations from SM Higgs properties.

In frame c), we see the distribution in $\tan \beta$, which is scanned uniformly since it is not a soft term. The expected value is for $\tan \beta \sim 10$ with a falling tail towards larger values. Large $\tan \beta$ yields large bottom-squark $\Sigma_{u}^u(\tilde{b}_{1,2})$ and tau-lepton contributions to the weak scale and so is disfavored.

In frame d), we show the light Higgsino mass gap $\Delta m^0 \equiv m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$. This quantity is relevant to light higgsino pair production at LHC via the soft-opposite-sign-dilepton plus jet...
Figure 5: Scatter plot of models with appropriate EWSB and $m_{PU}^{Z} < 4m_{OU}^{Z}$ in the $\tan \beta$ vs. $m_A$ plane with $\mu = 150$ GeV. The orange dots have $m_h < 123$ GeV.

plus MET channel [56–63]. The prediction here is for a mass gap $\Delta m^0 \sim 8 - 12$ GeV but with a tail extending to $15 - 20$ GeV. However, the large $\Delta m^0 > 14$ GeV tail corresponds to models with $m_h < 123$ GeV and $m_{\tilde{g}} \lesssim 2.25$ TeV as can be seen from the scatter plot of $\Delta m^0$ vs. $m_h$ in Fig. 6.

Figure 6: Scatter plot of models with appropriate EWSB and $m_{PU}^{Z} < 4m_{OU}^{Z}$ in the $\Delta m^0$ vs. $m_h$ plane with $\mu = 150$ GeV. The orange dots have $m_h < 123$ GeV.
In comparison, the $n = 0$ draw predicts much larger mass gaps while $n = 1$ or 2 predicts gaps typically below 10 GeV. Such mass gaps can be easily measured to high precision at an $e^+e^-$ collider operating with $\sqrt{s} > 2m(higgsino)$ [64,65].

In Fig. 7, we show the predicted probability distributions for various strongly interacting sparticles which are relevant for LHC SUSY searches. In frame a), we show the distribution $dP/dm_{\tilde{g}}$. The log distribution has a peak at $m_{\tilde{g}} \sim 2.5 - 3$ TeV, somewhat beyond present LHC limits which require $m_{\tilde{g}} \gtrsim 2.2$ TeV. Only a small portion of log parameter space is excluded by the present LHC gluino mass limit, so from the landscape point of view, it is not surprising that LHC has not discovered SUSY. The distributions tails off to values of $m_{\tilde{g}} \sim 5 - 6$ TeV– such high values of $m_{\tilde{g}}$ would require at least an energy doubling upgrade of LHC for detection [66,67].

In frame b), we show an example of first/second generation squark masses: in this case $m_{\tilde{u}_L}$. Here we see a peak value of $m_{\tilde{u}_L} \sim 15 - 20$ TeV with a tail extending to $\sim 40$ TeV. Such high first/second generation scalar masses are pulled upward until their two-loop RGE contributions to the top-squark sector cause those soft terms to run tachyonic resulting in CCB vacua.

Figure 7: Probability distributions for NUHM3 masses and parameters a) $m_{\tilde{g}}$, b) $m_{\tilde{u}_L}$, c) $m_{\tilde{t}_1}$ and d) $m_{\tilde{t}_2}$ from a log distribution of soft terms in the string landscape with $\mu = 150$ GeV. For comparison, we also show probability distributions for $m^{n}_{soft}$ with $n = 0$ and 1.

In frame c), we show $dP/dm_{\tilde{t}_1}$. For the log distribution, the peak is around $m_{\tilde{t}_1} \sim 1.5 - 2$ TeV. This compares to current LHC limits which require $m_{\tilde{t}_1} \gtrsim 1.1$ TeV. Thus, again we see that it is not surprising that top-squarks have not been detected at LHC from the string landscape point of view. In frame d), we show the distribution $dP/dm_{\tilde{t}_2}$. This distribution...
peaks at $m_{t_{\tilde{t}}} \sim 3$ TeV and would likely require at least an energy doubling of LHC in order to gain detection \cite{66,67}. The log distribution is again intermediate between the $n = 0$ and $n = 1$ scan results.

3 Conclusions

In this paper, we have been motivated by two major success stories for the string theory landscape: 1. its success in explaining the tiny value of the cosmological constant and 2. when applied to the statistics of SUSY breaking with a power-law draw to large soft terms and an anthropic bound on the pocket universe value of the weak scale $m_{\text{weak}}$, it predicts a value $m_h \simeq 125$ GeV with sparticles (other than hard-to-detect higgsinos) lifted beyond present LHC search limits. In this paper, we were motivated by an earlier suggestion by Dine based on DSB that soft terms would instead have a logarithmic statistical distribution. This case has also been recently advanced by Broeckel et al. \cite{40} where they consider the effects of Kähler moduli stabilization to derive a log distribution for soft terms from models of LVS stabilization. Alternatively, they find a power-law soft term statistical distribution for the KKLT and PS models.

The three scenarios are listed in Table 1 along with the expected form of soft terms: either from gravity mediation or mirage mediation. Higgs and sparticle mass distributions have previously been presented in Ref. \cite{25} for power-law draw and gravity mediation as expected in PS. In Ref. \cite{34}, the corresponding distributions have been presented for power-law draw but with mirage mediation. In this work, we complete the Table by presenting expected Higgs and sparticle statistical mass distributions for a log draw with gravity mediation, as may be expected from the LVS stabilization within the string landscape.

| model    | KKLT \cite{41} | LVS \cite{42} | PS \cite{43} |
|----------|----------------|---------------|--------------|
| soft terms | mirage       | grav        | grav         |
| soft dist. | $m_{\text{soft}}^n$ | log($m_{\text{soft}}$) | $m_{\text{soft}}^n$ |
| mass dist’ns | \cite{34} | this paper | \cite{25} |

Table 1: Three models of moduli stabilization along with expected form of soft terms, expected soft term distribution in string IIB landscape and reference for associated statistical distributions of Higgs and sparticle masses.

Our results from Fig. 4 show that the expectation for $m_h \simeq 125$ GeV still holds for a log draw, although the Higgs peak at 125 GeV is not as sharp as that found from $n = 1$ or 2 power-law draw. Also, sparticles (other than higgsinos) are still expected to lie beyond LHC search limits, but again not as sharply as in the power-law case. Of course, if experiment confirms SUSY particles within the ranges shown here, one will be able to distinguish mirage from gravity-mediation, for instance, by extracting running gaugino masses at an $e^+e^-$ collider and checking at which scale they might unify \cite{68}. But for the case of gravity mediation, based on just a single data point of SUSY spectra, there will be no way to distinguish between the different stabilization mechanisms LVS or PS.
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References

[1] S. Weinberg, The cosmological constant problem, Rev. Mod. Phys. 61 (1989) 1–23. doi:10.1103/RevModPhys.61.1 URL https://link.aps.org/doi/10.1103/RevModPhys.61.1

[2] L. Susskind, The Anthropic landscape of string theory (2003) 247–266 arXiv:hep-th/0302219. URL https://arxiv.org/abs/hep-th/0302219

[3] R. Bousso, J. Polchinski, Quantization of four form fluxes and dynamical neutralization of the cosmological constant, JHEP 06 (2000) 006. arXiv:hep-th/0004134 doi:10.1088/1126-6708/2000/06/006.

[4] F. Denef, M. R. Douglas, B. Florea, Building a better racetrack, JHEP 06 (2004) 034. arXiv:hep-th/0404257 doi:10.1088/1126-6708/2004/06/034.

[5] M. R. Douglas, S. Kachru, Flux compactification, Rev. Mod. Phys. 79 (2007) 733–796. arXiv:hep-th/0610102 doi:10.1103/RevModPhys.79.733.

[6] S. Weinberg, Anthropic bound on the cosmological constant, Phys. Rev. Lett. 59 (1987) 2607–2610. doi:10.1103/PhysRevLett.59.2607 URL https://link.aps.org/doi/10.1103/PhysRevLett.59.2607

[7] S. Weinberg, Living in the multiverse, 2005, pp. 29–42. arXiv:hep-th/0511037

[8] E. Witten, Dynamical Breaking of Supersymmetry, Nucl. Phys. B 188 (1981) 513. doi:10.1016/0550-3213(81)90006-7

[9] R. K. Kaul, Gauge hierarchy in a supersymmetric model, Physics Letters B 109 (1) (1982) 19 – 24. doi:https://doi.org/10.1016/0370–2693(82)90453–1 URL http://www.sciencedirect.com/science/article/pii/0370269382904531

[10] S. Dimopoulos, H. Georgi, Softly Broken Supersymmetry and SU(5), Nucl. Phys. B 193 (1981) 150–162. doi:10.1016/0550–3213(81)90522–8

[11] H. Baer, X. Tata, Weak scale supersymmetry: From superfields to scattering events, Cambridge University Press, 2006.

[12] M. R. Douglas, The Statistics of string / M theory vacua, JHEP 05 (2003) 046. arXiv:hep-th/0303194 doi:10.1088/1126-6708/2003/05/046.
[13] K. J. Bae, H. Baer, V. Barger, D. Sengupta, Revisiting the susy mu problem and its solutions in the lhc era, Physical Review D 99 (11). doi:10.1103/PhysRevD.99.115027

[14] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev, X. Tata, Radiative natural supersymmetry: Reconciling electroweak fine-tuning and the higgs boson mass, Phys. Rev. D 87 (2013) 115028. doi:10.1103/PhysRevD.87.115028
URL https://link.aps.org/doi/10.1103/PhysRevD.87.115028

[15] V. Agrawal, S. M. Barr, J. F. Donoghue, D. Seckel, Viable range of the mass scale of the standard model, Physical Review D 57 (9) (1998) 5480–5492. doi:10.1103/physrevd.57.5480.
URL http://dx.doi.org/10.1103/PhysRevD.57.5480

[16] V. Agrawal, S. M. Barr, J. F. Donoghue, D. Seckel, Anthropic considerations in multiple-domain theories and the scale of electroweak symmetry breaking, Phys. Rev. Lett. 80 (1998) 1822–1825. doi:10.1103/PhysRevLett.80.1822.
URL https://link.aps.org/doi/10.1103/PhysRevLett.80.1822

[17] M. R. Douglas, Statistical analysis of the supersymmetry breaking scale arXiv:hep-th/0405279.

[18] S. K. Soni, H. Weldon, Analysis of the Supersymmetry Breaking Induced by N=1 Supergravity Theories, Phys. Lett. B 126 (1983) 215–219. doi:10.1016/0370-2693(83)90593-2

[19] V. S. Kaplunovsky, J. Louis, Model-independent analysis of soft terms in effective supergravity and in string theory, Physics Letters B 306 (3-4) (1993) 269–275. doi:10.1016/0370-2693(93)90078-v
URL http://dx.doi.org/10.1016/0370-2693(93)90078-v

[20] A. Brignole, Towards a theory of soft terms for the supersymmetric standard model, Nuclear Physics B 422 (1-2) (1994) 125–171. doi:10.1016/0550-3213(94)00068-9
URL http://dx.doi.org/10.1016/0550-3213(94)00068-9

[21] L. Susskind, Supersymmetry breaking in the anthropic landscape (2004) 1745–1749 arXiv:hep-th/0405189 doi:10.1142/9789812775344\_0040

[22] F. Denef, M. R. Douglas, Distributions of flux vacua, Journal of High Energy Physics 2004 (05) (2004) 072–072. doi:10.1088/1126-6708/2004/05/072
URL http://dx.doi.org/10.1088/1126-6708/2004/05/072

[23] N. Arkani-Hamed, S. Dimopoulos, S. Kachru, Predictive landscapes and new physics at a TeV arXiv:hep-th/0501082

[24] H. Baer, V. Barger, M. Savoy, H. Serce, The higgs mass and natural supersymmetric spectrum from the landscape, Physics Letters B 758 (2016) 113–117. doi:10.1016/j.physletb.2016.05.010
URL http://dx.doi.org/10.1016/j.physletb.2016.05.010
[25] H. Baer, V. Barger, H. Serce, K. Sinha, Higgs and superparticle mass predictions from the landscape, Journal of High Energy Physics 2018 (3). doi:10.1007/jhep03(2018)002 URL http://dx.doi.org/10.1007/JHEP03(2018)002

[26] H. Baer, V. Barger, P. Huang, A. Mustafayev, X. Tata, Radiative natural supersymmetry with a 125 gev higgs boson, Physical Review Letters 109 (16). doi:10.1103/physrevlett.109.161802 URL http://dx.doi.org/10.1103/PhysRevLett.109.161802

[27] H. Baer, V. Barger, S. Salam, Naturalness versus stringy naturalness (with implications for collider and dark matter searches), Physical Review Research 1 (2). doi:10.1103/physrevresearch.1.023001 URL http://dx.doi.org/10.1103/PhysRevResearch.1.023001

[28] D. Matalliotakis, H. Nilles, Implications of non-universality of soft terms in supersymmetric grand unified theories, Nuclear Physics B 435 (1-2) (1995) 115–128. doi:10.1016/0550-3213(94)00487-y URL http://dx.doi.org/10.1016/0550-3213(94)00487-Y

[29] M. Olechowski, S. Pokorski, Electroweak symmetry breaking with non-universal scalar soft terms and large tan beta solutions, Physics Letters B 344 (1-4) (1995) 201–210. doi:10.1016/0370-2693(94)01571-s URL http://dx.doi.org/10.1016/0370-2693(94)01571-S

[30] P. Nath, R. Arnowitt, Non-universal soft susy breaking and dark matter, COSMO-97 doi:10.1142/9789814447263_0020 URL http://dx.doi.org/10.1142/9789814447263_0020

[31] J. Ellis, K. Olive, Y. Santoso, The mssm parameter space with non-universal higgs masses, Physics Letters B 539 (1-2) (2002) 107–118. doi:10.1016/s0370-2693(02)02071-3 URL http://dx.doi.org/10.1016/S0370-2693(02)02071-3

[32] J. Ellis, T. Falk, K. A. Olive, Y. Santoso, Exploration of the mssm with non-universal higgs masses, Nuclear Physics B 652 (2003) 259–347. doi:10.1016/s0550-3213(02)01144-6 URL http://dx.doi.org/10.1016/S0550-3213(02)01144-6

[33] H. Baer, A. Mustafayev, S. Profumo, A. Belyaev, X. Tata, Direct, indirect and collider detection of neutralino dark matter in SUSY models with non-universal Higgs masses, JHEP 07 (2005) 065. arXiv:hep-ph/0504001 doi:10.1088/1126-6708/2005/07/065

[34] H. Baer, V. Barger, D. Sengupta, Mirage mediation from the landscape, Physical Review Research 2 (1). doi:10.1103/physrevresearch.2.013346 URL http://dx.doi.org/10.1103/PhysRevResearch.2.013346

[35] M. Dine, E. Gorbatov, S. D. Thomas, Low energy supersymmetry from the landscape, JHEP 08 (2008) 098. arXiv:hep-th/0407043 doi:10.1088/1126-6708/2008/08/098
[36] M. Dine, Supersymmetry, naturalness and the landscape, in: 10th International Symposium on Particles, Strings and Cosmology (PASCOS 04 and Pran Nath Fest), 2004, pp. 249–263. arXiv:hep-th/0410201 doi:10.1142/9789812701756_0093.

[37] M. Dine, D. O’Neil, Z. Sun, Branches of the landscape, JHEP 07 (2005) 014. arXiv:hep-th/0501214 doi:10.1088/1126-6708/2005/07/014.

[38] M. Dine, The Intermediate scale branch of the landscape, JHEP 01 (2006) 162. arXiv:hep-th/0505202 doi:10.1088/1126-6708/2006/01/162.

[39] I. Affleck, M. Dine, N. Seiberg, Supersymmetry Breaking by Instantons, Phys. Rev. Lett. 51 (1983) 1026. doi:10.1103/PhysRevLett.51.1026.

[40] I. Broeckel, M. Cicoli, A. Maharana, K. Singh, K. Sinha, Moduli Stabilisation and the Statistics of SUSY Breaking in the Landscape arXiv:2007.04327.

[41] S. Kachru, R. Kallosh, A. Linde, S. P. Trivedi, de sitter vacua in string theory. Physical Review D 68 (4). doi:10.1103/physrevd.68.046005. URL http://dx.doi.org/10.1103/PhysRevD.68.046005.

[42] V. Balasubramanian, P. Berghlund, J. P. Conlon, F. Quevedo, Systematics of moduli stabilisation in calabi-yau flux compactifications. Journal of High Energy Physics 2005 (03) (2005) 007–007. doi:10.1088/1126-6708/2005/03/007. URL http://dx.doi.org/10.1088/1126-6708/2005/03/007.

[43] M. Berg, M. Haack, B. Kors, On volume stabilization by quantum corrections, Phys. Rev. Lett. 96 (2006) 021601. arXiv:hep-th/0508171 doi:10.1103/PhysRevLett.96.021601.

[44] F. E. Paige, S. D. Protopopescu, H. Baer, X. Tata, ISAJET 7.69: A Monte Carlo event generator for pp, anti-p p, and e+e- reactions arXiv:hep-ph/0312045.

[45] H. Baer, C.-H. Chen, R. B. Munroe, F. E. Paige, X. Tata, Multichannel search for minimal supergravity at pp and e+e- colliders. Phys. Rev. D 51 (1995) 1046–1050. arXiv:hep-ph/9408265 doi:10.1103/PhysRevD.51.1046.

[46] S. P. Martin, M. T. Vaughn, Two loop renormalization group equations for soft supersymmetry breaking couplings, Phys. Rev. D 50 (1994) 2282, [Erratum: Phys.Rev.D 78, 039903 (2008)]. arXiv:hep-ph/9311340 doi:10.1103/PhysRevD.50.2282.

[47] D. M. Pierce, J. A. Bagger, K. T. Matchev, R.-j. Zhang, Precision corrections in the minimal supersymmetric standard model. Nucl. Phys. B 491 (1997) 3–67. arXiv:hep-ph/9606211 doi:10.1016/S0550-3213(96)00683-9.

[48] H. Baer, V. Barger, D. Sengupta, Landscape solution to the susy flavor and cp problems. Physical Review Research 1 (3). doi:10.1103/physrevresearch.1.033179 URL http://dx.doi.org/10.1103/PhysRevResearch.1.033179.
[49] M. Carena, H. Haber, Higgs boson theory and phenomenology, Progress in Particle and Nuclear Physics 50 (1) (2003) 63–152. doi:10.1016/s0146-6410(02)00177-1
URL http://dx.doi.org/10.1016/S0146-6410(02)00177-1

[50] P. Draper, H. Rzehak, A review of higgs mass calculations in supersymmetric models, Physics Reports 619 (2016) 1–24. doi:10.1016/j.physrep.2016.01.001
URL http://dx.doi.org/10.1016/j.physrep.2016.01.001

[51] H. Baer, V. Barger, A. Mustafayev, Implications of a 125 gev higgs scalar for the lhc supersymmetry and neutralino dark matter searches, Physical Review D 85 (7). doi:10.1103/physrevd.85.075010
URL http://dx.doi.org/10.1103/PhysRevD.85.075010

[52] A. Arbey, et al., Physics at the e+ e- Linear Collider, Eur. Phys. J. C 75 (8) (2015) 371. arXiv:1504.01726 doi:10.1140/epjc/s10052-015-3511-9

[53] G. Kane, P. Kumar, R. Lu, B. Zheng, Higgs Mass Prediction for Realistic String/M Theory Vacua, Phys. Rev. D 85 (2012) 075026. arXiv:1112.1059 doi:10.1103/PhysRevD.85.075026

[54] A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro, Mini-split, Journal of High Energy Physics 2013 (2). doi:10.1007/jhep02(2013)126
URL http://dx.doi.org/10.1007/JHEP02(2013)126

[55] N. Arkani-Hamed, A. Gupta, D. E. Kaplan, N. Weiner, T. Zorawski, Simply Unnatural Supersymmetry arXiv:1212.6971

[56] H. Baer, V. Barger, P. Huang, Hidden susy at the lhc: the light higgsino-world scenario and the role of a lepton collider, Journal of High Energy Physics 2011 (11). doi:10.1007/jhep11(2011)031
URL http://dx.doi.org/10.1007/JHEP11(2011)031

[57] Z. Han, G. D. Kribs, A. Martin, A. Menon, Hunting quasidegenerate Higgsinos, Phys. Rev. D 89 (7) (2014) 075007. arXiv:1401.1235 doi:10.1103/PhysRevD.89.075007

[58] H. Baer, A. Mustafayev, X. Tata, Monojet plus soft dilepton signal from light higgsino pair production at lhc14, Physical Review D 90 (11). doi:10.1103/physrevd.90.115007
URL http://dx.doi.org/10.1103/PhysRevD.90.115007

[59] C. Han, D. Kim, S. Munir, M. Park, Accessing the core of naturalness, nearly degenerate higgsinos, at the LHC, JHEP 04 (2015) 132. arXiv:1502.03734 doi:10.1007/JHEP04(2015)132

[60] H. Baer, V. Barger, M. Savoy, X. Tata, Multichannel assault on natural supersymmetry at the high luminosity LHC, Phys. Rev. D 94 (3) (2016) 035025. arXiv:1604.07438 doi:10.1103/PhysRevD.94.035025
[61] H. Baer, V. Barger, S. Salam, D. Sengupta, X. Tata, The LHC higgsino discovery plane for present and future SUSY searches, Phys. Lett. B 810 (2020) 135777. arXiv:2007.09252, doi:10.1016/j.physletb.2020.135777.

[62] Search for new physics in the compressed mass spectra scenario using events with two soft opposite-sign leptons and missing momentum energy at 13 TeV.

[63] G. Aad, et al., Searches for electroweak production of supersymmetric particles with compressed mass spectra in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector, Phys. Rev. D 101 (5) (2020) 052005. arXiv:1911.12606, doi:10.1103/PhysRevD.101.052005.

[64] H. Baer, V. Barger, D. Mickelson, A. Mustafayev, X. Tata, Physics at a higgsino factory, Journal of High Energy Physics 2014 (6). doi:10.1007/jhep06(2014)172
URL http://dx.doi.org/10.1007/JHEP06(2014)172

[65] H. Baer, M. Berggren, K. Fujii, J. List, S.-L. Lehtinen, T. Tanabe, J. Yan, ILC as a natural SUSY discovery machine and precision microscope: From light Higgsinos to tests of unification, Phys. Rev. D 101 (9) (2020) 095026. arXiv:1912.06643, doi:10.1103/PhysRevD.101.095026.

[66] H. Baer, V. Barger, J. S. Gainer, H. Serce, X. Tata, Reach of the high-energy lhc for gluinos and top squarks in susy models with light higgsinos, Physical Review D 96 (11). doi:10.1103/PhysRevD.96.115008.
URL http://dx.doi.org/10.1103/PhysRevD.96.115008.

[67] H. Baer, V. Barger, J. S. Gainer, D. Sengupta, H. Serce, X. Tata, Lhc luminosity and energy upgrades confront natural supersymmetry models, Physical Review D 98 (7). doi:10.1103/physrevd.98.075010
URL http://dx.doi.org/10.1103/PhysRevD.98.075010.

[68] H. Baer, M. Berggren, K. Fujii, J. List, S.-L. Lehtinen, T. Tanabe, J. Yan, The ILC as a natural SUSY discovery machine and precision microscope: from light higgsinos to tests of unification, Phys. Rev. D 101 (9) (2020) 095026. arXiv:1912.06643, doi:10.1103/PhysRevD.101.095026.