Expectations for SUSY from the landscape: a Snowmass 2021 TF01/TF08 Letter of Intent

Howard Baer[1], *Vernon Barger*[2], *Shadman Salam*[1] *and Dibyashree Sengupta*[1],
[1]Dept. of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA
[2] Dept. of Physics, University of Wisconsin, Madison, WI 53706, USA

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The tiny–seemingly fine-tuned– value of the cosmological constant emerges naturally near its measured value when considered from within the landscape of string vacua which gives rise to the multiverse. Similar reasoning applied to the SUSY breaking scale of a fertile patch of the landscape containing the MSSM favors large values of soft terms via a power-law distribution. The statistical draw to large soft terms must be balanced by keeping the calculated value of the weak scale in each pocket universe not too far from the measured value in our universe lest complex nuclei and hence atoms not arise (violation of the atomic principle). These results give rise to statistical predictions from the string landscape that favor $m_h \simeq 125$ GeV along with sparticles (other than higgsinos) beyond the projected reach of HL-LHC.

Perhaps the most plausible explanation for the tiny, yet non-zero, value of the cosmological constant (CC) Λ_{CC} comes from Weinberg's anthropic explanation, which finds a natural home within the context of the string landscape of flux vacua[1]. In such a setting, our (pocket) universe corresponds to but one of perhaps 10^{500} vacua, each with different 4-dimensional laws of physics which emerge from different compactification possibilities. In such a setting, for a vast set of vacua leading to the SM as the low energy effective field theory (EFT) but with varying CCs, it may not be surprising to find ourselves in a pocket universe with such a tiny Λ_{CC} since if it was too much bigger, then the expansion rate of the early universe would have been too great for galaxies, and hence structure, to form (the structure principle).

Similar reasoning may be applied to the the magnitude of the SUSY breaking scale. We restrict ourselves to a fertile patch of vacua with the MSSM as the low energy effective theory: a friendly, or predictive patch of the landscape of flux vacua. In such a setting, it is expected from string theory that multiple hidden sectors occur, and a variety of them may contribute to the overall scale of SUSY breaking. But there is nothing in the landscape that seems to prefer one set of SUSY breaking vevs F_X or D_X over any other. In this case, it is argued by Douglas[2], by Susskind[3] and by Arkani-Hamed *et al.*[4] that there should be a statistical draw to large values of the overall SUSY breaking scale m_{hidden} via a power-law: $dN_{vac} \sim (m^2_{hidden})^{2n_F+n_D-1}$ where n_F is the number of F-term breaking fields and n_D is the number of D-term breaking fields contributing to the overall SUSY breaking scale. The power law arises simply because the volume of the outer shells of SUSY breaking space is greater than inner shells, and the fact that F-terms are complex valued fields (giving the factor 2) while D-term fields are real valued (giving a factor 1). Note that the textbook case of SUSY breaking via a single F-term already gives rise to a statistical draw of $dN_{vac} \sim m^1_{soft}$ where $m_{soft} \sim m^2_{hidden}/m_P \sim m_{3/2}$. These deliberations have given rise in the past to debate as to whether nature prefers high-scale or low-scale SUSY breaking.

While dN_{vac} clearly favors high scale breaking (unless $n_F = 0$ and $n_D = 1$), the result must be tempered because in vacua which give rise to the MSSM as low energy EFT, then the soft SUSY breaking terms and superpotential μ parameter determine the magnitude of the weak scale. For most SUSY spectra calculations, the value of μ is artificially dialed to such a value as to ensure that the Z mass in our universe (OU) $m_Z^{OU} = 91.2$ GeV. But within our fertile patch of the multiverse, we must first of all make sure that EW symmetry is appropriately broken (no charge-or-color-breaking (CCB) minima) and even in that case, that EW symmetry is indeed broken). Once appropriate EW symmetry breaking is achieved, then the pocket-universe (PU) value of the Z mass is given by

$$\frac{(m_Z^{PU})^2}{2} = \frac{m^2_{H_d} + \Sigma^d_d - (m^2_{H_u} + \Sigma^u_u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \ . \qquad (1)$$

Here, Σ_u^u and Σ_d^d are the one-loop corrections arising from particles and sparticles that couple directly to the Higgs doublets. Over 40 contributions are listed in Ref. [5], of which the largest typically comes from the top-squarks $\Sigma_u^u(\tilde{t}_{1,2})$. Here, the overall weak scale is determined by m_Z^{PU} so that $m_{weak}^{PU} \sim m_{W,Z,h}^{PU}$. It has been shown by Agrawal *et al.*[6] that if the value of the weak scale $m_{weak}^{PU} >\sim (2-5)m_{weak}^{OU}$, then complex nuclei would not form and atoms as we know them would not exist. The necessity of atoms, and hence complex chemistry, for life as we know it is sometimes referred to as the *atomic principle*, in analogy to Weinberg's structure principle. Thus, we augment the distribution for viable vacua in the observer-friendly landscape to be

$$dN_{vac} \sim m_{soft}^n \cdot f_{EWSB} \cdot f_{CC} \tag{2}$$

where f_{EWSB} vetos inappropriate EW vacua and also requires $f_{EWSB} = \Theta(n_{ABDS} \cdot m_{weak}^{OU} - m_{weak}^{PU})$ and $n_{ABDS} \sim 2-5$ (in accord with Agrawal *et al.*) and $n = 2n_F + n_D - 1$. Also, Denef and Douglas have shown that CC selection acts independently of the SUSY scale selection with $f_{CC} \sim \Lambda_{CC}^4/m_{string}^4$.

It is argued in Ref. [7] that the various gaugino masses, A-terms and soft scalar masses should scan independently in the landscape due to their different dependences on the moduli fields. Then, under a statistical draw to large soft terms, one is pulled towards the edge of CCB or noEWSB vacua, or vacua with too large a value of m_{weak}^{PU} (termed *living dangerously* in the literature[4]). This also pulls the top-squarks to maximal mixing and hence a statistical preference for $m_h \sim 125$ GeV while the other sparticles, save the higgsinos, are pulled beyond the present reach of LHC[8, 9]: 1. $m_h \to 125$ GeV, 2. $m_{\tilde{g}} \sim 4 \pm 2$ TeV, 3. $m_{\tilde{t}_1} \sim 1.5 \pm 0.5$ TeV, $m_A \sim 3 \pm 2$ TeV, $\mu \sim 100 - 350$ GeV and $m_{\tilde{q},\tilde{\ell}} \sim 25 \pm 15$ TeV. Thus, sparticle masses are pulled to large values but not so large that they contribute too much to m_{weak}^{PU}. The anticipated non-degeneracy of the generations $m_0(i)$ for $i = 1-3$ turns out to be not a problem here in that first/second generation sfermions are pulled to a common upper bound which yields a mixed decoupling/quasi-degeneracy solution to the SUSY flavor and CP problems[10]. Under this *stringy naturalness*, a 3 TeV gluino is more natural than a 300 GeV gluino[11]!

Our goal for Snowmass 2021 is to engage in further explorations of this exciting predictive scenario for the string landscape. We hope especially to engage with other TF string theorists and model builders to explore the theoretical underpinnings of this predictive landscape scenario as to its theoretical viability and further implications. For instance, a recent work by Broeckel *et al.* explores the statistical draw of soft terms in the context of KKLT and Large Volume moduli-stabilization scenarios. They conclude KKLT does indeed give a power law selection while LVS gives instead a mild log draw to large soft terms.

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