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Blueprints of the no-scale multiverse at the LHC

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We present a contemporary perspective on the String Landscape and the Multiverse of plausible string, M- and F-theory vacua. In contrast to traditional statistical classifications and capitulation to the anthropic principle, we seek only to demonstrate the existence of a nonzero probability for a universe matching our own observed physics within the solution ensemble. We argue for the importance of No-Scale Supergravity as an essential common underpinning for the spontaneous emergence of a cosmologically flat universe from the quantum ''nothingness.'' Concretely, we continue to probe the phenomenology of a specific model which is testable at the LHC and Tevatron. Dubbed No-Scale $\mathcal{F}$-$SU(5)$, it represents the intersection of the Flipped $SU(5)$ Grand Unified Theory (GUT) with extra TeV-Scale vectorlike multiplets derived out of F-theory, and the dynamics of No-Scale Supergravity, which in turn imply a very restricted set of high-energy boundary conditions. By secondarily minimizing the minimum of the scalar Higgs potential, we dynamically determine the ratio $\tan\beta \simeq 15$–20 of up- to down-type Higgs vacuum expectation values (VEVs), the universal gaugino boundary mass $M_{1/2} \simeq 450$ GeV, and, consequently, also the total magnitude of the GUT-scale Higgs VEVs, while constraining the low-energy standard model gauge couplings. In particular, this local *minimum minimorum* lies within the previously described ''golden strip,'' satisfying all current experimental constraints. We emphasize, however, that the overarching goal is not to establish why our own particular universe possesses any number of specific characteristics, but rather to tease out what generic principles might govern the superset of all possible universes.

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I. INTRODUCTION

The number of consistent, meta-stable vacua of string, M- or (predominantly) F-theory flux compactifications which exhibit broadly plausible phenomenology, including moduli stabilization and broken supersymmetry [1–6], is popularly estimated [7,8] to be of order 10^{500}. It is moreover currently in vogue to suggest that degeneracy of common features across these many ''universes'' might statistically isolate the physically realistic universe from the vast ''landscape,'' much as the entropy function coaxes the singular order of macroscopic thermodynamics from the chaotic duplicity of the entangled quantum microstate. We argue here though the counterpoint that we are not obliged *a priori* to live in the likeliest of all universes, but only in one which is possible. The existence merely of a nonzero probability for our existence is sufficient.

We indulge for this effort the fanciful imagination that the Multiverse of string vacua might exhibit some literal realization beyond our own physical sphere. A single electron may be said to wander all histories through interfering apertures, though its arrival is ultimately registered at a localized point on the target. The journey to that destination is steered by the full dynamics of the theory, although the isolated spontaneous solution reflects only faintly the richness of the solution ensemble. Whether the Multiverse be reverie or reality, the conceptual superset of our own physics which it embodies must certainly represent the interference of all navigable universal histories.

Surely, many times before has mankind's notion of the heavens expanded—the Earth dispatched from its central pedestal in our solar system and the Sun rendered one among some hundred billion stars of the Milky Way, itself reduced to one among some hundred billion galaxies. Finally, perhaps, we come to the completion of our odyssey, by realizing that our Universe is one of at least 10^{500} or so possible, thus rendering the anthropic view of our position in the Universe (environmental coincidences explained away by the availability of $10^{11} \times 10^{11}$ solar systems) functionally equivalent to the anthropic view of the origin of the Universe (coincidences in the form and content of physical laws explained away by the availability, through dynamical phase transitions, of 10^{500} universes). Nature's bounty has anyway invariably trumped our wildest anticipations, and though frugal and equanimous in law, Nature has spared no extravagance or whimsy in its manifestation.

Our perspective should not be misconstrued, however, as complacent retreat into the tautology of the weak anthropic principle. It is indeed an unassailable truism that an observed universe must afford and sustain the life of the observer, including requisite constraints, for example, on the cosmological constant [9] and gauge hierarchy. Our point of view, though, is sharply different; we should be able to resolve the cosmological constant and gauge hierarchy problems through investigation of the fundamental laws of our (or any single) Universe, its accidental and specific properties notwithstanding, without resorting to the existence of observers. In our view, the observer is the output of, not the *raison d'être* of, our Universe. Thus, our attention is an advance from this base camp of our own physics, as unlikely an appointment as it may be, to the summit goal of the master theory and symmetries which govern all possible universes. In so seeking, our first halting forage must be that of a concrete string model which can describe Nature locally.

II. THE ENSEMBLE MULTIVERSE

The greatest mystery of Nature is the origin of the Universe itself. Modern cosmology is relatively clear regarding the occurrence of a hot big bang, and subsequent Planck, grand unification, cosmic inflation, lepto- and baryogenesis, and electroweak epochs, followed by nucleosynthesis, radiation decoupling, and large scale structure formation. In particular, cosmic inflation can address the flatness and monopole problems, explain homogeneity, and generate the fractional anisotropy of the cosmic background radiation by quantum fluctuation of the inflaton field [10–14]. A key question though, is from whence the energy of the Universe arose. Interestingly, the gravitational field in an inflationary scenario can supply the required positive mass-kinetic energy, since its potential energy becomes negative without bound, allowing that the total energy could be exactly zero.

Perhaps the most striking revelation of the post-WMAP [15–17] era is the decisive determination that our Universe is indeed globally flat, i.e. with the net energy contributions from baryonic matter $\simeq 5\%$, dark matter $\simeq 23\%$, and the cosmological constant (dark energy) $\simeq 72\%$ finely balanced against the gravitational potential. Not long ago, it was possible to imagine the Universe, with all of its physics intact, hosting any arbitrary mass-energy density, such that "$k = +1$" would represent a supercritical cosmology of positive curvature, and "$k = -1$" the subcritical case of negative curvature. In hindsight, this may come to seem as naïve as the notion of an empty infinite Cartesian space. The observed energy balance is highly suggestive of a fundamental symmetry which protects the "$k = 0$" critical solution, such that the physical constants of our Universe may not be divorced from its net content.

This null energy condition licenses the speculative connection *ex nihilo* of our present universe back to the primordial quantum fluctuation of an external system. Indeed, there is nothing which quantum mechanics abhors more than nothingness. This being the case, an extra universe here or there might rightly be considered no extra trouble at all. Specifically, it has been suggested [10–12,18,19] that the fluctuations of a dynamically evolved expanding universe might spontaneously produce tunneling from a false vacuum into an adjacent (likely also false) meta-stable vacuum of lower energy, driving a local inflationary phase, much as a crystal of ice or a bubble of steam may nucleate and expand in a supercooled or superheated fluid during first-order transition. In this "eternal inflation" scenario, such patches of space will volumetrically dominate by virtue of their exponential expansion, recursively generating an infinite fractal array of causally disconnected "Russian doll" universes, nesting each within another, and each featuring its own unique physical parameters and physical laws.

From just the specific location on the solution "target" where our own Universe landed, it may be impossible to directly reconstruct the full theory. Fundamentally, it may be impossible even in principle to specify why our particular Universe is precisely as it is. However, superstring theory and its generalizations may yet present to us a loftier prize—the theory of the ensemble Multiverse.

III. THE INVARIANCE OF FLATNESS

More important than any differences between various possible vacua are the properties which might be invariant, protected by basic symmetries of the underlying mechanics. We suppose that one such basic property must be cosmological flatness, so that the seedling universe may transition dynamically across the boundary of its own creation, maintaining a zero balance of some suitably defined energy function. In practice, this implies that gravity must be ubiquitous, its negative potential energy allowing for positive mass and kinetic energy. Within such a universe, quantum fluctuations may not again cause isolated material objects to spring into existence, as their net energy must necessarily be positive. For the example of a particle with mass m on the surface of the Earth, the ratio of gravitational to mass energy is more than nine orders of magnitude too small

$$\left| -\frac{G_N M_E m}{R_E} \right| \div mc^2 \simeq 7 \times 10^{-10}, \tag{1}$$

where G_N is the gravitational constant, c is the speed of light, and M_E and R_E are the mass and radius of the Earth, respectively. Even in the limiting case of a Schwarzschild black hole of mass $M_{\rm BH}$, a particle of mass m at the horizon $R_S = 2G_N M_{\rm BH}/c^2$ has a gravitational potential which is only half of that required

$$\left| -\frac{G_N M_{\rm BH} m}{R_S} \right| = \tfrac{1}{2} mc^2. \tag{2}$$

It is important to note that while the energy density for the gravitational field is surely negative in Newtonian mechanics, the global gravitational field energy is not well defined in general relativity. Unique prescriptions for a stress-energy-momentum pseudotensor can be formulated though, notably that of Landau and Lifshitz. Any such stress-energy can, however, be made to vanish locally by general coordinate transformation, and it is not even entirely clear that the pseudotensor so applied is an appropriate general relativistic object. Given though that Newtonian gravity is the classical limit of general relativity, it is reasonable to suspect that the properly defined field energy density will be likewise also negative, and that inflation is indeed consistent with a correctly generalized notion of constant, zero total energy.

A universe would then be in this sense closed, an island unto itself, from the moment of its inception from the quantum froth; only a universe *in toto* might so originate, emerging as a critically bound structure possessing profound density and minute proportion, each as accorded against intrinsically defined scales (the analogous Newton and Planck parameters and the propagation speed of massless fields), and expanding or inflating henceforth and eternally.

IV. THE INVARIANCE OF NO-SCALE SUGRA

Inflation, driven by the scalar inflaton field is itself inherently a quantum field theoretic subject. However, there is tension between quantum mechanics and general relativity. Currently, superstring theory is the best candidate for quantum gravity. The five consistent 10-dimensional superstring theories, namely, heterotic $E_8 \times E_8$, heterotic $SO(32)$, Type I, Type IIA, Type IIB, can be unified by various duality transformations under an 11-dimensional M-theory [20], and the 12-dimensional F-theory can be considered as the strongly coupled formulation of the Type IIB string theory with a varying axion-dilaton field [21]. Self consistency of the string (or M-, F-) algebra implies a ten (or eleven, twelve) dimensional master space-time, some elements of which—six (or seven, eight) to match our observed four large dimensions—may be compactified on a manifold (typically Calabi-Yau manifolds or G_2 manifolds) which conserves a requisite portion of supersymmetric charges.

The structure of the curvature within the extra dimensions dictates in no small measure the particular phenomenology of the unfolded dimensions, secreting away the ‘‘closet space’’ to encode the symmetries of all gauged interactions. The physical volume of the internal spatial manifold is directly related to the effective Planck scale and basic gauge coupling strengths in the external space. The compactification is in turn described by fundamental moduli fields which must be stabilized, i.e. given suitable VEVs. The famous example of Kaluza and Klein prototypes the manner in which general covariance in five dimensions is transformed to gravity plus Maxwell theory in four dimensions when the transverse fifth dimension is cycled around a circle. The connection of geometry to particle physics is perhaps nowhere more intuitively clear than in the context of model building with $D6$-branes, where the gauge structure and family replication are related directly to the brane stacking and intersection multiplicities. The Yukawa couplings and Higgs structure are in like manners also specified, leading after radiative symmetry breaking of the chiral gauge sector to low-energy masses for the chiral fermions and broken gauge generators, each massless in the symmetric limit.

From a top-down view, Supergravity (SUGRA) is an ubiquitous infrared limit of string theory, and forms the starting point of any two-dimensional world sheet or D-dimensional target space action. The mandatory localization of the Supersymmetry (SUSY) algebra, and thus the momentum-energy (space-time translation) operators, leads to general coordinate invariance of the action and an Einstein field theory limit. Any available flavor of SUGRA will not, however, suffice. In general, extraneous fine-tuning is required to avoid a cosmological constant which scales like a dimensionally suitable power of the Planck mass. Neglecting even the question of whether such a universe might be permitted to appear spontaneously, it would then be doomed to curl upon itself and collapse within the order of the Planck time, for comparison, about 10^{-43} seconds in our Universe. Expansion and inflation appear to uniquely require properties which arise naturally only in the No-Scale SUGRA formulation [22–26].

SUSY is in this case broken while the vacuum energy density vanishes automatically at tree level due to a suitable choice of the Kähler potential, the function which specifies the metric on superspace. At the minimum of the null scalar potential, there are flat directions which leave the compactification moduli VEVs undetermined by the classical equations of motion. We thus receive without additional effort an answer to the deep question of how these moduli are stabilized; they have been transformed into dynamical variables which are to be determined by minimizing corrections to the scalar potential at loop order. In particular, the high-energy gravitino mass $M_{3/2}$, and also the proportionally equivalent universal gaugino mass $M_{1/2}$, will be established in this way. Subsequently, all gauge-mediated SUSY-breaking soft terms will be dynamically evolved down from this boundary under the renormalization group [27], establishing in large measure the low-energy phenomenology, and solving also the Flavor Changing Neutral Current (FCNC) problem. Since the moduli are fixed at a false local minimum, phase transitions by quantum tunneling will naturally occur between discrete vacua.

We conjecture, for the reasons given prior, that the No-Scale SUGRA construction could pervade all universes in the String Landscape with reasonable flux vacua. This being the case, intelligent creatures elsewhere in the Multiverse, though separated from us by a bridge too far, might reasonably so concur after parallel examination of their own physics. Moreover, they might leverage via this insight a deeper knowledge of the underlying Multiverse-invariant master theory, of which our known string, M-, and F-theories may compose some coherently overlapping patch of the garment edge. Perhaps we yet share appreciation, across the cords which bind our 13.7×10^9 years to their corresponding blink of history, for the common timeless principles under which we are but two isolated condensations upon two particular vacuum solutions among the physical ensemble.

V. AN ARCHETYPE MODEL UNIVERSE

Though we engage in this work lofty and speculative questions of natural philosophy, we balance abstraction against the measured material underpinnings of concrete phenomenological models with direct and specific connection to tested and testable particle physics. If the suggestion is correct that eternal inflation and No-Scale SUGRA models with string origins together describe what is in fact our Multiverse, then we must as a prerequisite settle the issue of whether our own phenomenology can be produced out of such a construction.

In the context of Type II intersecting D-brane models, we have indeed found one realistic Pati-Salam model which might describe Nature as we observe it [28–30]. If only the F-terms of three complex structure moduli are nonzero, we also automatically have vanishing vacuum energy, and obtain a generalized No-Scale SUGRA. It seems to us that the string derived Grand Unified Theories (GUTs), and particularly the Flipped $SU(5) \times U(1)_X$ models [31–33], are also candidate realistic string models with promising predictions that can be tested at the Large Hadron Collider (LHC), the Tevatron, and other future experiments.

In the latter case, the Flipped $SU(5) \times U(1)_X$ gauge symmetry can be broken down to the SM gauge symmetry by giving VEVs to one pair of the Higgs fields H and $\bar{H}$ with quantum numbers $(\mathbf{10}, \mathbf{1})$ and $(\overline{\mathbf{10}}, -\mathbf{1})$, respectively. The doublet-triplet splitting problem can be solved naturally via the missing partner mechanism [33]. Historically, Flipped $SU(5) \times U(1)_X$ models have been constructed systematically in the free fermionic string constructions at Kac-Moody level one [33–37]. To address the little hierarchy problem between the unification scale and the string scale, the Testable Flipped $SU(5) \times U(1)_X$ model class was proposed, which introduces extra TeV-scale vectorlike particles [38]. Models of this type have been constructed locally as examples of F-theory model building [39–44], and dubbed $\mathcal{F}$-$SU(5)$ [43,44] within that context.

Most recently, we have studied No-Scale extensions of the prior in detail [45–47], emphasizing the essential role of the tripodal foundation formed by the $\mathcal{F}$-lipped $SU(5)$ GUT [31–33], two pairs of TeV-scale vectorlike multiplets with origins in $\mathcal{F}$-theory [38,43,44,48] model building, and the boundary conditions of No-Scale Supergravity [22–26]. It appears that the No-Scale scenario, particularly vanishing of the Higgs bilinear soft term B_μ, comes into its own only when applied at an elevated scale, approaching the Planck mass. $M_{\mathcal{F}} \simeq 7 \times 10^{17}$ GeV, the point of the second stage $SU(5) \times U(1)_X$ unification, emerges in turn as a suitable candidate scale only when substantially decoupled from the primary GUT-scale unification of $SU(3)_C \times SU(2)_L$ via the modification to the renormalization group equations (RGEs) from the extra $\mathcal{F}$-theory vector multiplets.

In particular, we have systematically established the hyper-surface within the $\tan\beta$, top quark mass m_t, gaugino mass $M_{1/2}$, and vectorlike particle mass M_V parameter volume which is compatible with the application of the simplest No-Scale SUGRA boundary conditions [22–26], particularly the vanishing of the Higgs bilinear soft term B_μ at the ultimate $\mathcal{F}$-$SU(5)$ unification scale [45,46]. We have demonstrated that simultaneous adherence to all current experimental constraints, most importantly contributions to the muon anomalous magnetic moment $(g-2)_\mu$ [49], the branching ratio limit on $(b \to s\gamma)$ [50,51], and the 7-year WMAP relic density measurement [15–17], dramatically reduces the allowed solutions to a highly nontrivial "golden strip" with $\tan\beta \simeq 15$, $m_t =$ 173.0–174.4 GeV, $M_{1/2} =$ 455–481 GeV, and $M_V =$ 691–1020 GeV, effectively eliminating all extraneously tunable model parameters, where the consonance of the theoretically viable m_t range with the experimentally established value [52] is an independently correlated "postdiction." Finally, taking a fixed Z-boson mass, we have dynamically determined the universal gaugino mass $M_{1/2}$ and fixed $\tan\beta$ via the "Super No-Scale" mechanism [47], that being the secondary minimization, or *minimum minimorum*, of the minimum $V_{\min}$ of the Higgs potential for the electroweak symmetry breaking (EWSB) vacuum.

These models are moreover quite interesting from a phenomenological point of view [43,44]. The predicted vectorlike particles can be observed at the Large Hadron Collider, and the partial lifetime for proton decay in the leading $(e|\mu)^+\pi^0$ channels falls around 5×10^{34} years, testable at the future Hyper-Kamiokande [53] and Deep Underground Science and Engineering Laboratory (DUSEL) [54] experiments [48,55]. The lightest CP-even Higgs boson mass can be increased [56], hybrid inflation can be naturally realized, and the correct cosmic primordial-density fluctuations can be generated [57].

VI. NO-SCALE FOUNDATIONS OF $\mathcal{F}$-$SU(5)$

In the traditional framework, supersymmetry is broken in the hidden sector, and then its breaking effects are mediated to the observable sector via gravity or gauge interactions. In GUTs with gravity-mediated supersymmetry breaking, also known as the minimal Supergravity (mSUGRA) model, the supersymmetry breaking soft terms can be parameterized by four universal parameters: the gaugino mass $M_{1/2}$, scalar mass M_0, trilinear soft term A, and the ratio of Higgs VEVs $\tan\beta$ at low energy, plus the sign of the Higgs bilinear mass term μ. The μ term and its bilinear soft term B_μ are determined by the Z-boson mass M_Z and $\tan\beta$ after the electroweak (EW) symmetry breaking.

To solve the cosmological constant problem, No-Scale Supergravity was proposed [22–26]. No-scale Supergravity is defined as the subset of Supergravity models which satisfy the following three constraints [22–26]: (i) the vacuum energy vanishes automatically due to the suitable Kähler potential; (ii) at the minimum of the scalar potential, there are flat directions which leave the gravitino mass $M_{3/2}$ undetermined; (iii) the supertrace quantity $\mathrm{Str}\mathcal{M}^2$ is zero at the minimum. Without this, the large one-loop corrections would force $M_{3/2}$ to be either zero or of Planck scale. A simple Kähler potential which satisfies the first two conditions is

$$K = -3\ln\left(T + \bar{T} - \sum_i \bar{\Phi}_i \Phi_i\right), \tag{3}$$

where T is a modulus field and Φ_i are matter fields. The third condition is model dependent and can always be satisfied in principle [58].

The scalar fields of Eq. (3) parameterize the coset space $SU(N_C+1,1)/(SU(N_C+1)\times U(1))$, where N_C is the number of matter fields. Analogous structures appear in the $N \geq 5$ extended Supergravity theories [59], for example, $N_C = 4$ for $N = 5$, which can be realized in the compactifications of string theory [60,61]. The noncompact structure of the symmetry implies that the potential is not only constant but actually identical to zero. For the simple example Kähler potential given above, one can readily check that the scalar potential is automatically positive semidefinite, and has a flat direction along the T field. Likewise, it may be verified that the simplest No-Scale boundary conditions $M_0 = A = B_\mu = 0$ emerge dynamically, while $M_{1/2}$ may be nonzero at the unification scale, allowing for low-energy SUSY breaking.

The specific Kähler potential of Eq. (3) has been independently derived in both weakly coupled heterotic string theory [60] and the leading order compactification of M-theory on S^1/Z_2 [61]. Note that in both cases, the Yang-Mills fields span a 10-dimensional space-time. It is not obtained directly out of F-theory, as represented, for example, by the strong coupling lift from Type IIB intersecting D-brane model building with $D7$- and $D3$-branes [39–42], where the Yang-Mills fields on the $D7$-branes occupy an eight-dimensional space-time. Nevertheless, it is certainly possible in principle to calculate a gauge kinetic function, Kahler potential and superpotential in the context of Type IIB interecting D-brane model building, and the F-theory could thus admit a more general definition of No-Scale Supergravity, as realized by a Kähler potential like

$$K = -\ln(S+\bar{S}) - \ln(T_1+\bar{T}_1) - \ln(T_2+\bar{T}_2) - \ln(T_3+\bar{T}_3), \tag{4}$$

where only three of the moduli fields S and T_i may yield nonzero F-terms.

In Ref. [2], No-Scale Supergravity was obtained in the Type IIB and F-theory compactifications at the leading order. Likewise, the subsequently introduced KKLT [3] constructions also manifest a No-Scale SUGRA structure at the classical level. Indeed, the No-Scale features are generically obtained at the tree-level in string-theory compactifications due to the presence of three complex extra dimensions. However, this classical level result is rather precariously balanced, and may be spoiled by quantum corrections to the superpotential including flux contributions, instanton effects, gaugino condensation, and the next order α' corrections. In this sense, we consider the KKLT type SUGRA models as a generalization or extension of the elemental No-Scale form.

The No-Scale $\mathcal{F}$-$SU(5)$ model under discussion has been constructed locally in F-theory [43,44], although the mass of the additional vectorlike multiplets, and even the fact of their existence, is not mandated by the F-theory, wherein it is also possible to realize models with only the traditional Flipped (or Standard) $SU(5)$ field content. We claim only an inherent consistency of their conceptual origin out of the F-theoretic construction, and take the manifest phenomenological benefits which accompany the natural elevation of the secondary GUT unification phase to $M_{\mathcal{F}} \simeq 7\times 10^{17}$ GeV as justification for the greater esteem which we hold for this particular model above other alternatives. There are, though, also delicate questions of compatibility between the local F-theoretic model building origins and the purely field-theoretic RGE running which we employ up to the presumed high scale. As one approaches the Planck mass M_{Pl}, consideration must be given to the role which will be played by Kaluza Klein (KK) and string mode excitations, and also to corrections of order α' from stabilization of the global volume of the six-dimensional internal space in association with the establishment of the string scale $M_{\mathrm{S}} \propto (M_{\mathrm{Pl}}/R^3_{\mathrm{global}})$.

The most important question is whether our model can in fact be embedded into a globally consistent framework. Without such, we do not know the concrete Kähler potential of the SM fermions and Higgs fields, and cannot by this means explicitly calculate the supersymmetry breaking scalar masses and trilinear soft terms. This construction remains elusive though, and is beyond the reach of the current work. Regardless, one may anticipate that in such a globally consistent model, a string scale of order 10^{17} GeV would indeed be realized, as in the weakly coupled heterotic string theory, tying in nicely with our naïvely projected value for $M_{\mathcal{F}}$. It seems, additionally, that a field-theoretic application of the No-Scale boundary conditions might prove to be validated in this case. Moreover, we would not necessarily require the presence of instanton effects or gaugino condensation for stabilization of the modulus T as in the KKLT mechanism. This is crucial, because such effects can have the negative side effect of destroying the leading No-Scale structure. In fact, we could have no gaugino condensation at all, or the superpotential from gaugino condensation might only depend on S, as again exemplified in the Type IIB intersecting D-brane models [62].

Such considerations, coupled with the demonstrated testability and phenomenological success of the first-order analysis in the simplest No-Scale SUGRA framework, argue for a continuing study of the generalized No-Scale SUGRA picture. It is important to note that there exist several such generalizations, including the previously mentioned Type II intersecting D-brane models [28–30], mirage mediation of flux compactifications [63,64], and the extraction of SUSY-breaking soft terms from the leading order compactification of M-theory on S^1/Z_2 [65–69]; in the latter case, we have previously obtained (in a different model context) a generalization employing modulus dominated SUSY breaking [69].

In this paper, however, we maintain a ''first steps first'' perspective, concentrating on the simplest No-Scale Supergravity and reserving any such extensions for the future. The potential for stringy modifications duly noted, we then essentially aim to study an F-theory *inspired* variety of low-energy SUSY phenomenology, remaining agnostic as to the details of the Kähler structure. Nevertheless, by studying the simplest No-Scale Supergravity, we may still expect to encapsulate the correct leading-order behavior. We likewise maintain the simplicity of a leading-order approximation by neglecting consideration of any stringy threshold corrections, the substantive onset of which is anyway expected to be deferred to $M_{\mathcal{F}}$, the true GUT scale of this model. It should be added that since the running of the gauge couplings is logarithmically dependent upon the mass scale, the contributions to the RGEs from the string and KK mode excitations are quite small.

VII. THE SUPER NO-SCALE MECHANISM

The single relevant modulus field in the simplest stringy No-Scale Supergravity is the Kähler modulus T, a characteristic of the Calabi-Yau manifold, the dilaton coupling being irrelevant. We consider the gaugino mass $M_{1/2}$ as a useful modulus related to the F-term of T, stipulating, in other words, that the gauge kinetic function must depend on T. This is realized, for example, in the Type IIB intersecting D-brane models [62], where gauge kinetic functions explicitly depend on both S and T_i, as in Eq. (4). Again, since the F-theory may be considered as a strongly coupled formulation of the Type IIB string theory, it is natural to believe that the gauge kinetic function under this lift depends on T as well. While the limit is quite suggestive, lacking still a concrete globally consistent embedding, we cannot definitively prove that the superpotential remains unperturbed by T.

Proceeding tentatively as such, the F-term of T generates the gravitino mass $M_{3/2}$, which is proportionally equivalent to $M_{1/2}$. Exploiting the simplest No-Scale boundary condition at $M_{\mathcal{F}}$ and running from high energy to low energy under the RGEs, there can be a secondary minimization, or *minimum minimorum*, of the minimum of the Higgs potential $V_{\min}$ for the EWSB vacuum. Since $V_{\min}$ depends on $M_{1/2}$, the gaugino mass $M_{1/2}$ is consequently dynamically determined by the equation $dV_{\min}/dM_{1/2} = 0$, aptly referred to as the ''Super No-Scale'' mechanism [47].

It could easily have been that in consideration of the above technique, there were: (A) too few undetermined parameters, with the $B_\mu = 0$ condition forming an incompatible over-constraint, and thus demonstrably false, or (B) so many undetermined parameters that the dynamic determination possessed many distinct solutions, or was so far separated from experiment that it could not possibly be demonstrated to be true. The actual state of affairs is much more propitious, being specifically as follows. The three parameters M_0, A, B_μ are once again identically zero at the boundary because of the defining Kähler potential, and are thus known at all other scales as well by the RGEs. The minimization of the Higgs scalar potential with respect to the neutral elements of both SUSY Higgs doublets gives two conditions, the first of which fixes the magnitude of μ. The second condition, which would traditionally be used to fix B_μ, instead here enforces a consistency relationship on the remaining parameters, being that B_μ is already constrained.

In general, the $B_\mu = 0$ condition gives a hyper-surface of solutions cut out from a very large parameter space. If we lock all but one parameter, it will give the final value. If we take a slice of two-dimensional space, as has been described, it will give a relation between two parameters for all others fixed. In a three-dimensional view with B_μ on the vertical axis, this curve is the ''flat direction'' line along the bottom of the trench of $B_\mu = 0$ solutions. In general, we must vary at least two parameters rather than just one in isolation, in order that their mutual compensation may transport the solution along this curve. The most natural first choice is in some sense the pair of prominent unknown inputs $M_{1/2}$ and $\tan\beta$, as was demonstrated in Ref. [47].

Having come to this point, it is by no means guaranteed that the potential will form a stable minimum. It must be emphasized that the $B_\mu = 0$ No-Scale boundary condition is the central agent affording this determination, as it is the extraction of the parameterized parabolic curve of solutions in the two compensating variables which allows for a localized, bound nadir point to be isolated by the Super

No-Scale condition, dynamically determining *both* parameters. The background surface of $V_{\min}$ for the full parameter space outside the viable $B_\mu = 0$ subset is, in contrast, a steadily inclined and uninteresting function. In our prior study, the local *minimum minimorum* of $V_{\min}$ for the choices $M_V = 1000$ GeV and $m_t = 173.1$ GeV dynamically established $M_{1/2} \simeq 450$ GeV, and $\tan\beta \simeq 15$–20. Although we have remarked that $M_{1/2}$ and $\tan\beta$ have no *directly* established experimental values, they are severely indirectly constrained by phenomenology in the context of this model [45,46]. It is highly nontrivial that there should be accord between the top-down and bottom-up perspectives, but this is indeed precisely what has been observed [47].

VIII. THE GUT HIGGS MODULUS

An alternate pair of parameters for which one may attempt to isolate a $B_\mu = 0$ curve, which we consider for the first time in this work, is that of $M_{1/2}$ and the GUT scale M_{32}, at which the $SU(3)_C$ and $SU(2)_L$ couplings initially meet. Fundamentally, the latter corresponds to the modulus which sets the total magnitude of the GUT Higgs field's VEVs. M_{32} could of course in some sense be considered a "known" quantity, taking the low-energy couplings as input. Indeed, starting from the measured SM gauge couplings and fermion Yukawa couplings at the standard 91.187 GeV electroweak scale, we may calculate both M_{32} and the final unification scale $M_{\mathcal{F}}$, and subsequently the unified gauge coupling and SM fermion Yukawa couplings at $M_{\mathcal{F}}$, via running of the RGEs. However, since the VEVs of the GUT Higgs fields H and $\bar{H}$ are considered here as free parameters, the GUT scale M_{32} must not be fixed either. As a consequence, the low-energy SM gauge couplings, and, in particular, the $SU(2)_L$ gauge coupling g_2, will also run freely via this feedback from M_{32}.

We consider this conceptual release of a known quantity, in order to establish the nature of the model's dependence upon it, to be a valid and valuable technique, and have employed it previously with specific regards to "postdiction" of the top quark mass value [46]. Indeed, forcing the theoretical *output* of such a parameter is only possible in a model with highly constrained physics, and it may be expected to meet success only by intervention of either grand coincidence or grand conspiracy of Nature. Simultaneous to the recognition of the presence of a second dynamic modulus, we lock down the value of μ, which by contrast is a simple numerical parameter, and ought then to be treated in a manner consistent with the top quark and vectorlike mass parameters. For this study, we choose a vectorlike particle mass $M_V = 1000$ GeV, and use the experimental top quark mass input $m_t = 173.1$ GeV. We emphasize that the choice of $M_V = 1000$ GeV is not an arbitrary one, since a prior analysis [46] has shown that a 1 TeV vectorlike mass is in compliance with all current experimental data and the No-Scale $B_\mu = 0$ requirement.

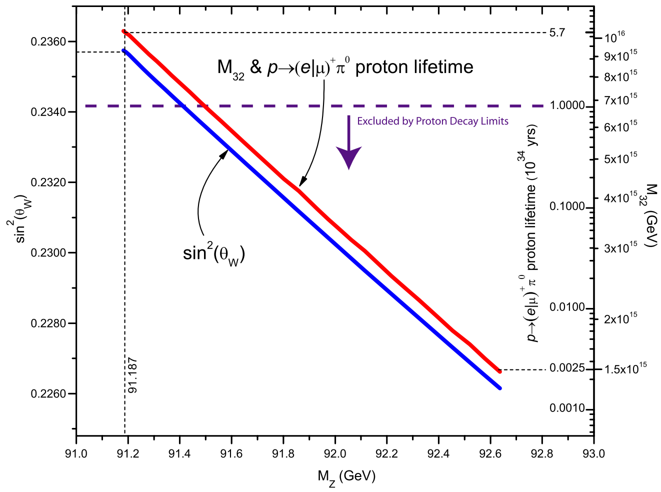

FIG. 1 (color online). The interrelated variation of $\sin^2(\theta_W)$, the GUT scale M_{32} (logarithmic axis), and the Z-boson mass M_Z is demonstrated for the parameter strips which preserve $B_\mu = 0$ and $\mu = 460$ GeV at $M_{\mathcal{F}}$. The variation in M_Z is linked dominantly to motion of the EW couplings via $\sin^2(\theta_W)$. Also shown is the corresponding predicted proton lifetime in the leading $(e|\mu)^+\pi^0$ channels, in units of 10^{34} years, with the current lower bound of 1.0×10^{34} years indicated by the dashed horizontal line.

The constant parameter μ is set consistent with its value prior to the variation of the GUT modulus.

In actual practice, the variation of M_{32} is achieved in the reverse by programmatic variation of the Weinberg angle, holding the strong and electromagnetic couplings at their physically measured values. Figure 1 demonstrates the scaling between $\sin^2(\theta_W)$, M_{32} (logarithmic axis), and the Z-boson mass. The variation of M_Z is attributed primarily to the motion of the electroweak couplings, the magnitude of the Higgs VEV being held essentially constant. We ensure also that the unified gauge coupling, SM fermion Yukawa couplings, and specifically also the Higgs bilinear term $\mu \simeq 460$ GeV, are each held stable at the scale $M_{\mathcal{F}}$ to correctly mimic the previously described procedure.

The parameter ranges for the variation depicted in Fig. 1 are $M_Z = 91.18$–92.64, $\sin^2(\theta_W) = 0.2262$–$0.2357$, and $M_{32} = 1.5 \times 10^{15} - 1.04 \times 10^{16}$ GeV, and likewise also the same for Figs. 2–8, which will feature subsequently. The *minimum minimorum* falls at the boundary of the prior list, dynamically fixing $M_{32} \simeq 1.0 \times 10^{16}$ GeV and placing $M_{1/2}$ again in the vicinity of 450 GeV. The low-energy SM gauge couplings are simultaneously constrained by means of the associated Weinberg angle, with $\sin^2(\theta_W) \simeq 0.236$, in excellent agreement with experiment. The corresponding range of predicted proton lifetimes in the leading $(e|\mu)^+\pi^0$ modes is $2.5 \times 10^{31} - 5.7 \times 10^{34}$ years [48]. If the GUT scale M_{32} becomes excessively light, below about 7×10^{15} GeV, then proton decay would be more rapid than allowed by the recently updated lower bound of 1.0×10^{34} years from Super-Kamiokande [70].

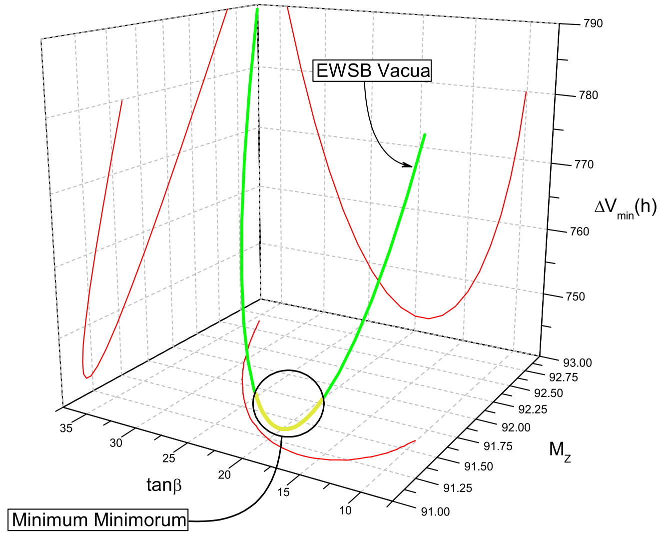

FIG. 2 (color online). Three-dimensional graph of (M_Z, tanβ, $\Delta V_{\rm min}(h)$) space. The projections onto the three mutually perpendicular planes are likewise shown. M_Z and $\Delta V_{\rm min}(h)$ are in units of GeV. The dynamically preferred region, allowing for plausible variation, is circled.

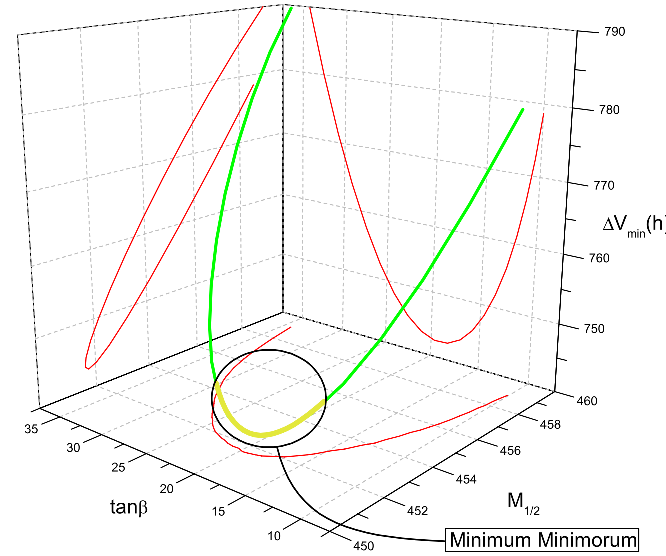

FIG. 4 (color online). Three-dimensional graph of ($M_{1/2}$, tanβ, $\Delta V_{\rm min}(h)$) space. The projections onto the three mutually perpendicular planes are likewise shown. $M_{1/2}$ and $\Delta V_{\rm min}(h)$ are in units of GeV. The dynamically preferred region, allowing for plausible variation, is circled.

We are cautious against making a claim in precisely the same vein for the dynamic determination of $M_Z \simeq 91.2$ GeV, since again the crucial electroweak Higgs VEV is not a substantial element of the variation. However, in *conjunction* with the radiative electroweak symmetry breaking [71,72] numerically implemented within the SUSPECT 2.34 code base [73], the fixing of the Higgs VEV and the determination of the electroweak scale may also plausibly be considered legitimate dynamic output, *if* one posits the M_F scale input to be available *a priori*.

By extracting a constant μ slice of the $V_{\rm min}$ hypersurface, the secondary minimization condition on tanβ is effectively rotated, albeit quite moderately, relative to the procedure of Ref. [47]. The present minimization, referencing $M_{1/2}$, M_{32} and tanβ, is again dependent upon M_V and m_t, while the previously described [47] determination

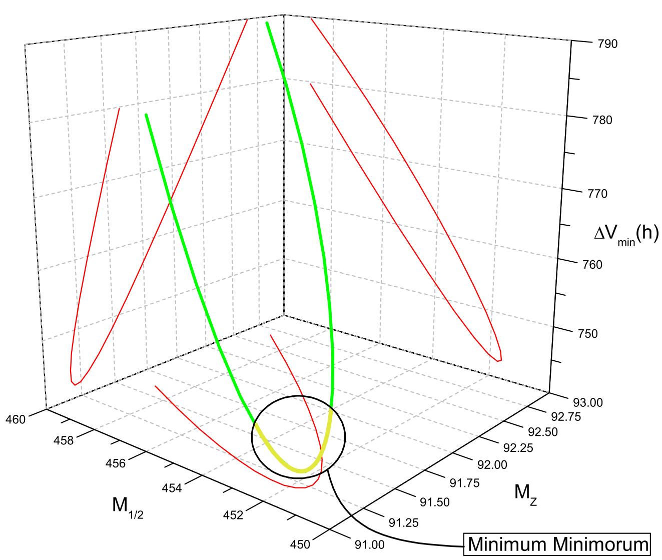

FIG. 3 (color online). Three-dimensional graph of (M_Z, $M_{1/2}$, $\Delta V_{\rm min}(h)$) space. The projections onto the three mutually perpendicular planes are likewise shown. M_Z, $M_{1/2}$, and $\Delta V_{\rm min}(h)$ are in units of GeV. The dynamically preferred region, allowing for plausible variation, is circled.

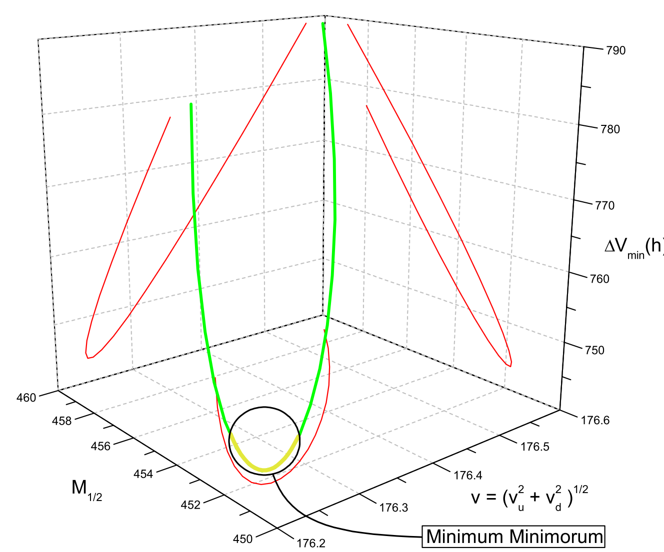

FIG. 5 (color online). Three-dimensional graph of (v, $M_{1/2}$, $\Delta V_{\rm min}(h)$) space. The projections onto the three mutually perpendicular planes are likewise shown. $M_{1/2}$, v, and $\Delta V_{\rm min}(h)$ are in units of GeV. The dynamically preferred region, allowing for plausible variation, is circled.

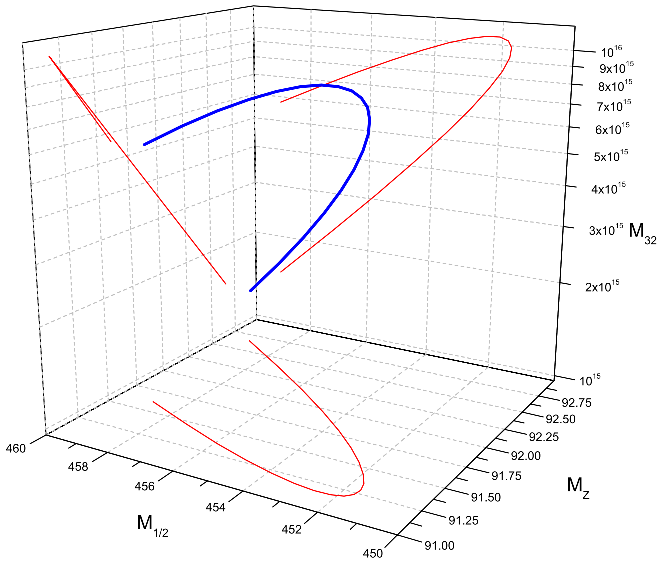

FIG. 6 (color online). Three-dimensional graph of $(M_Z, M_{1/2}, M_{32})$ space. The projections onto the three mutually perpendicular planes are likewise shown. M_Z, $M_{1/2}$, and M_{32} are in units of GeV.

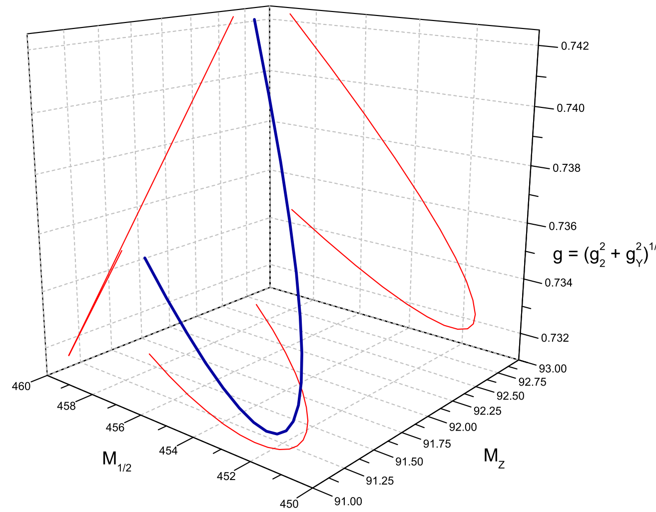

FIG. 8 (color online). Three-dimensional graph of $(M_Z, M_{1/2}, g)$ space. The projections onto the three mutually perpendicular planes are likewise shown. M_Z and $M_{1/2}$ are in units of GeV.

of $\tan\beta$ was, by contrast, M_V and m_t invariant. Recognizing that a minimization with all three parameters simultaneously active is required to declare all three parameters to have been simultaneously dynamically determined, we emphasize the mutual consistency of the results. We again stress that the new *minimum minimorum* is also consistent with the previously advertised golden strip, satisfying all presently known experimental constraints to our available resolution. Moreover, it also addresses the problems of the SUSY breaking scale and gauge hierarchy [47], insomuch as $M_{1/2}$ is determined dynamically.

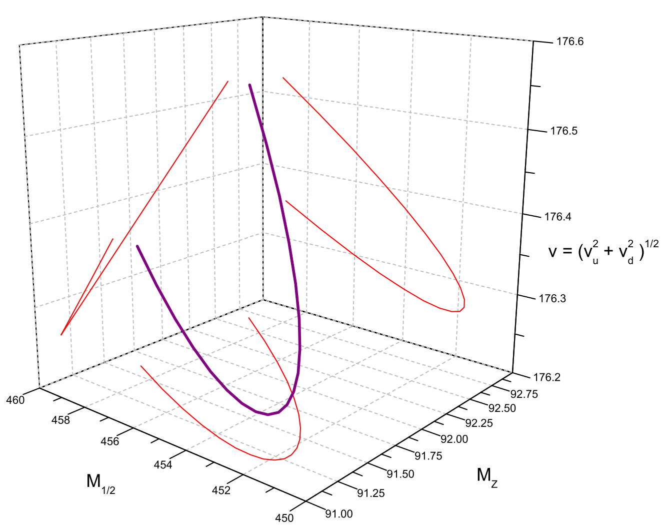

FIG. 7 (color online). Three-dimensional graph of $(M_Z, M_{1/2}, v)$ space. The projections onto the three mutually perpendicular planes are likewise shown. M_Z, $M_{1/2}$, and v are in units of GeV.

IX. THE MINIMUM MINIMORUM OF THE ELECTROWEAK HIGGS POTENTIAL

In supersymmetric SMs, there is a pair of Higgs doublets H_u and H_d which give mass to the up-type quarks and down-type quarks/charged leptons, respectively. The one-loop effective Higgs potential in the 't Hooft-Landau gauge and in the $\overline{\rm DR}$ scheme is given by

$$V_{\rm eff} = V_0(H_u^0, H_d^0) + V_1(H_u^0, H_d^0), \quad (5)$$

where

$$V_0 = (\mu^2 + m_{H_u}^2)(H_u^0)^2 + (\mu^2 + m_{H_d}^2)(H_d^0)^2 - 2B_\mu \mu H_u^0 H_d^0 + \frac{g_2^2 + g_Y^2}{8}[(H_u^0)^2 - (H_d^0)^2]^2, \quad (6)$$

$$V_1 = \sum_i \frac{n_i}{64\pi^2} m_i^4(\phi)\left(\ln\frac{m_i^2(\phi)}{Q^2} - \frac{3}{2}\right), \quad (7)$$

where $m_{H_u}^2$ and $m_{H_d}^2$ are the supersymmetry breaking soft masses, g_2 and g_Y are, respectively, the gauge couplings of $SU(2)_L$ and $U(1)_Y$, n_i and $m_i^2(\phi)$ are, respectively, the degree of freedom and mass for ϕ_i, and Q is the renormalization scale. In our numerical results in the figures, we shall designate differences in the fourth-root of the effective Higgs potential as $\Delta V_{\rm min}(h) \equiv V_{\rm eff}^{1/4}$, measured in units of GeV relative to an arbitrary overall zero-offset.

We have revised the SUSPECT 2.34 code base [73] to incorporate our specialized No-Scale $\mathcal{F}$-$SU(5)$ with vectorlike mass algorithm, and, accordingly, employ two-loop RGE running for the SM gauge couplings, and one-loop RGE running for the SM fermion Yukawa couplings, μ term, and SUSY-breaking soft terms. For our choice of

$M_V = 1000$ GeV, $m_t = 173.1$ GeV, and $\mu(M_{\mathcal{F}}) \simeq 460$ GeV, we present the one-loop effective Higgs potential $\Delta V_{\rm min}(h)$ in terms of M_Z and $\tan\beta$ in Fig. 2, in terms of M_Z and $M_{1/2}$ in Fig. 3, in terms of $M_{1/2}$ and $\tan\beta$ in Fig. 4, and in terms of v and $M_{1/2}$ in Fig. 5, where $v = \sqrt{v_u^2 + v_d^2}$, $v_u = \langle H_u^0 \rangle$, and $v_d = \langle H_d^0 \rangle$. These figures clearly demonstrate the localization of the *minimum minimorum* of the Higgs potential, corroborating the dynamical determination of $\tan\beta \simeq 15$–20 and $M_{1/2} \simeq 450$ GeV in [47].

Additionally, we exhibit the $(M_Z, M_{1/2}, M_{32})$ space in Fig. 6, the $(M_Z, M_{1/2}, v)$ space in Fig. 7, and the $(M_Z, M_{1/2}, g)$ space in Fig. 8, where $g = \sqrt{g_2^2 + g_Y^2}$. Figure 6 demonstrates that $M_{32} \simeq 1.0 \times 10^{16}$ GeV at the *minimum minimorum*, which correlates to $M_Z \simeq 91.2$ GeV, or more directly, $\sin^2(\theta_{\rm W}) \simeq 0.236$. Together, the alternate perspectives of Figs. 6–8, complete the view given in Figs. 2–5 to visually tell the story of the dynamic interrelation between the M_Z, $M_{1/2}$, and M_{32} scales, as well as the electroweak gauge couplings, and the Higgs VEVs. The curves in each of these figures represent only those points that satisfy the $B_\mu = 0$ requirement, as dictated by No-Scale Supergravity, serving as a crucial constraint on the dynamically determined parameter space. Ultimately, it is the significance of the $B_\mu = 0$ requirement that separates the No-Scale $\mathcal{F}$-$SU(5)$ with vectorlike particles from the entire compilation of prospective string theory derived models. By means of the $B_\mu = 0$ vehicle, No-Scale $\mathcal{F}$-$SU(5)$ has surmounted the paramount challenge of phenomenology, that of dynamically determining the electroweak scale, the scale of fundamental prominence in particle physics.

We wish to note that recent progress has been made in incorporating more precise numerical calculations into our baseline algorithm for No-Scale $\mathcal{F}$-$SU(5)$ with vectorlike particles. Initially, when we commenced the task of fully developing the phenomenology of this model, the extreme complexity of properly numerically implementing No-Scale $\mathcal{F}$-$SU(5)$ with vectorlike particles compelled a gradual strategy for construction and persistent enhancement of the algorithm. Preliminary findings of a precision improved algorithm indicate that compliance with the 7-year WMAP relic density constraints requires a slight upward shift to $\tan\beta \simeq 19$–20 from the value computed in Ref. [45], suggesting a potential convergence to even finer resolution of the dynamical determination of $\tan\beta$ given by the Super No-Scale mechanism, and the value demanded by the experimental relic density measurements. We shall furnish a comprehensive analysis of the precision improved algorithm at a later date.

X. PROBING THE BLUEPRINTS OF THE NO-SCALE MULTIVERSE AT THE COLLIDERS

We offer in closing a brief summary of direct collider, detector, and telescope level tests which may probe the blueprints of the No-Scale Multiverse which we have laid out. As to the deep question of whether the ensemble be literal in manifestation, or merely the conceptual superset of unrealized possibilities of a single island Universe, we pretend no definitive answer. However, we have argued that the emergence *ex nihilo* of seedling universes which fuel an eternal chaotic inflation scenario is particularly plausible, and even natural, within No-Scale Supergravity, and our goal of probing the specific features of our own Universe which might implicate its origins in this construction are immediately realizable and practicable.

The unified gaugino $M_{1/2}$ at the unification scale $M_{\mathcal{F}}$ can be reconstructed from impending LHC events by determining the gauginos M_1, M_2, and M_3 at the electroweak scale, which will in turn require knowledge of the masses for the neutralinos, charginos, and the gluino. Likewise, $\tan\beta$ can be ascertained in principle from a distinctive experimental observable, as was accomplished for mSUGRA in [74]. We will not undertake a comprehensive analysis here of the reconstruction of $M_{1/2}$ and $\tan\beta$, but will offer for now a cursory examination of typical events expected at the LHC. We leave the detailed compilation of the experimental observables necessary for validation of the No-Scale $\mathcal{F}$-$SU(5)$ at the LHC for the future, and we especially encourage those specializing in such research to investigate the No-Scale $\mathcal{F}$-$SU(5)$.

For the benchmark SUSY spectrum presented in Table I, we have adopted the specific values $M_{1/2} = 453$, $\tan\beta = 15$ and $M_Z = 91.187$. We expect that higher order corrections will shift the precise location of the *minimum minimorum* a little bit, for example, within the encircled gold-tipped regions of the diagrams in the prior section. We have selected a ratio for $\tan\beta$ at the lower end of this range

TABLE I. Spectrum (in GeV) for the benchmark point. Here, $M_{1/2} = 453$ GeV, $M_V = 1000$ GeV, $m_t = 173.1$ GeV, $M_Z = 91.187$ GeV, $\mu(M_{\mathcal{F}}) = 460.3$ GeV, $\Delta V_{\rm min}(h) = 748$ GeV, $\Omega_\chi = 0.113$, $\sigma_{\rm SI} = 2 \times 10^{-10}$ pb, and $\langle \sigma v \rangle_{\gamma\gamma} = 1.8 \times 10^{-28}$ cm^3/s. The central prediction for the $p \to (e|\mu)^+ \pi^0$ proton lifetime is around 4.9×10^{34} years. The lightest neutralino is 99.8% Bino.

$\tilde{\chi}_1^0$	94	$\tilde{\chi}_1^\pm$	184	$\tilde{e}_R$	150	$\tilde{t}_1$	486	$\tilde{u}_R$	947	m_h	120.1
$\tilde{\chi}_2^0$	184	$\tilde{\chi}_2^\pm$	822	$\tilde{e}_L$	504	$\tilde{t}_2$	906	$\tilde{u}_L$	1032	$m_{A,H}$	916
$\tilde{\chi}_3^0$	817	$\tilde{\nu}_{e/\mu}$	498	$\tilde{\tau}_1$	104	$\tilde{b}_1$	855	$\tilde{d}_R$	988	$m_{H^\pm}$	921
$\tilde{\chi}_4^0$	821	$\tilde{\nu}_\tau$	491	$\tilde{\tau}_2$	499	$\tilde{b}_2$	963	$\tilde{d}_L$	1035	$\tilde{g}$	617

for consistency with our previous study [47], and to avoid stau dark matter.

At the benchmark point, we calculate $\Omega_\chi = 0.113$ for the cold dark matter relic density. The phenomenology is, moreover, consistent with the LEP limit on the lightest CP-even Higgs boson mass, $m_h \geq 114$ GeV [75,75], the CDMSII [76] and Xenon100 [77] upper limits on the spin-independent cross section σ_{SI}, and the Fermi-LAT space telescope constraints [78] on the photon-photon annihilation cross section $\langle \sigma v \rangle_{\gamma\gamma}$. The differential cross sections and branching ratios have been calculated with PGS4 [79] executing a call to PYTHIA 6.411 [80], using our specialized No-Scale algorithm integrated into the SUSPECT 2.34 code for initial computation of the sparticle masses.

The benchmark point resides in the region of the experimentally allowed parameter space that generates the relic density through stau-neutralino co-annihilation. Hence, the five lightest sparticles for this benchmark point are $\tilde{\chi}_1^0 < \tilde{\tau}_1^\pm < \tilde{e}_R < \tilde{\chi}_2^0 \sim \tilde{\chi}_1^\pm$. Here, the gluino is lighter than all the squarks with the exception of the lightest stop, so all squarks will predominantly decay to a gluino and hadronic jet, with a small percentage of squarks producing a jet and either a $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$. The gluinos will decay via virtual (off-shell) squarks to neutralinos or charginos plus quarks, which will further cascade in their decay. The result is a low-energy tau through the processes $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1^\mp \tau^\pm \rightarrow \tau^\mp \tau^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1^\pm \nu_\tau \rightarrow \tau^\pm \nu_\tau \tilde{\chi}_1^0$.

The LHC final states of low-energy tau in the $\mathcal{F}$-$SU(5)$ stau-neutralino co-annihilation region are similar to those same low-energy LHC final states in mSUGRA, however, in the stau-neutralino co-annihilation region of mSUGRA, the gluino is typically heavier than the squarks. The strong coupling effects from the additional vectorlike particles on the gaugino mass RGE running reduce the physical gluino mass below the squark masses in $\mathcal{F}$-$SU(5)$. As a consequence, the LHC final low-energy tau states in the stau-neutralino co-annihilation regions of $\mathcal{F}$-$SU(5)$ and mSUGRA will differ in that in $\mathcal{F}$-$SU(5)$, the low-energy tau states will result largely from neutralinos and charginos produced by gluinos, as opposed to the low-energy tau states in mSUGRA resulting primarily from neutralinos and charginos produced from squarks.

Also notably, the TeV-scale vectorlike multiplets are well targeted for observation by the LHC. We have argued [46] that the eminently feasible near-term detectability of these hypothetical fields in collider experiments, coupled with the distinctive flipped-charge assignments within the multiplet structure, represents a smoking gun signature for Flipped $SU(5)$, and have thus coined the term *flippons* to collectively describe them. Immediately, our curiosity is piqued by the recent announcement [81] of the DØ collaboration that vectorlike quarks have been excluded up to a bound of 693 GeV, corresponding to the immediate lower edge of our anticipated range for their discovery [46].

XI. CONCLUSION

The advancement of human scientific knowledge and technology is replete with instances of science fiction transitioning to scientific theory and eventually scientific fact. The conceptual notion of a Multiverse has long fascinated the human imagination, though this speculation has been largely devoid of a substantive underpinning in physical theory. The modern perspective presented here offers a tangible foundation upon which legitimate discussion and theoretical advancement of the Multiverse may commence, including the prescription of specific experimental tests which could either falsify or enhance the viability of our proposal. Our perspective diverges from the common appeals to statistics and the anthropic principle, suggesting instead that we may seek to establish the character of the master theory, of which our Universe is an isolated vacuum condensation, based on specific observed properties of our own physics which might be reasonably inferred to represent invariant common characteristics of all possible universes. We have focused on the discovery of a model universe consonant with our observable phenomenology, presenting it as confirmation of a nonzero probability of our own Universe transpiring within the larger String Landscape.

The archetype model universe which we advance in this work implicates No-Scale Supergravity as the ubiquitous supporting structure which pervades the vacua of the Multiverse, being the crucial ingredient in the emanation of a cosmologically flat universe from the quantum nothingness. In particular, the model dubbed No-Scale $\mathcal{F}$-$SU(5)$ has demonstrated remarkable consistency between parameters determined dynamically (the top-down approach) and parameters determined through the application of current experimental constraints (the bottom-up approach). This enticing convergence of theory with experiment elevates No-Scale $\mathcal{F}$-$SU(5)$, in our estimation, to a position as the current leading GUT candidate. The longer term viability of this suggestion is likely to be greatly clarified in the next few years, based upon the wealth of forthcoming experimental data.

Building on the results presented in prior works [45–47], we have presented a dynamic determination of the penultimate Flipped $SU(5)$ unification scale M_{32}, or more fundamentally, the GUT Higgs VEV moduli. We have demonstrated that the $B_\mu = 0$ No-Scale boundary condition is again vital in dynamically determining the model parameters. Procedurally, we have fixed the unified gauge coupling, SM fermion Yukawa couplings, and Higgs bilinear term $\mu \simeq 460$ GeV at the final unification scale $M_{\mathcal{F}}$, while concurrently allowing the VEVs of the GUT Higgs fields H and $\bar{H}$ to float freely, as driven by M_{32} and the low-energy SM gauge couplings, via variation of the Weinberg angle. Employing the "Super No-Scale" condition to secondarily minimize the effective Higgs potential, we have obtained $M_{32} \simeq 1.0 \times 10^{16}$ GeV, $\sin^2(\theta_W) \simeq 0.236$, and $\tan\beta \simeq 15$–20.

The blueprints which we have outlined here, integrating precision phenomenology with prevailing experimental data and a fresh interpretation of the Multiverse and the Landscape of String vacua, offer a logically connected point of view from which additional investigation may be mounted. As we anticipate the impending stream of new experimental data which is likely to be revealed in ensuing years, we look forward to serious discussion and investigation of the perspective presented in this work. Though the mind boggles to contemplate the implications of this speculation, so it must also reel at even the undisputed realities of the Universe, these acknowledged facts alone being manifestly sufficient to humble our provincial notions of longevity, extent, and largess.

ACKNOWLEDGMENTS

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