

PREPARED FOR SUBMISSION TO JHEP

Snowmass White Paper: String Theory and Particle Physics

Mirjam Cvetič,^{a,b,c} James Halverson,^{d,e} Gary Shiu,^f and Washington Taylor^g

^a*Department of Physics and Astronomy, and Department of Mathematics,
University of Pennsylvania, Philadelphia, PA 19104-6396, USA*

^b*Center for Applied Mathematics and Theoretical Physics, University of Maribor, Maribor, Slovenia*

^c*Theory Department, CERN, CH-1211, Switzerland*

^d*Department of Physics, Northeastern University, Boston, MA 02115*

^e*The NSF AI Institute for Artificial Intelligence and Fundamental Interactions*

^f*Department of Physics, University of Wisconsin-Madison,
1150 University Ave, Madison WI 53706, U.S.A.*

^g*Center for Theoretical Physics, Department of Physics, Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, MA 02139, USA*

E-mail: [cvetic at physics.upenn.edu](mailto:cvetic@physics.upenn.edu), [j.halverson at northeastern.edu](mailto:j.halverson@northeastern.edu),
[shiu at physics.wisc.edu](mailto:shiu@physics.wisc.edu), [wati at mit.edu](mailto:wati@mit.edu)

ABSTRACT: We review recent developments and outstanding questions regarding connecting the top-down UV complete physical framework of string theory with the observed physics of the Standard Model and beyond the standard model physics, emphasizing the global nonperturbative framework of F-theory and general lessons from UV physics. This paper, prepared for the TF01 conveners of the Snowmass 2022 process, provides a brief synopsis of this important area, focusing on ongoing developments and opportunities.

Contents

1	Introduction	1
2	Particle Physics from String Theory	3
2.1	Approaches to Standard Model-like constructions in string theory	3
2.2	Matter fields and the Standard Model	5
2.3	Particle Remnants of the String Landscape	7
2.4	SUSY breaking	8
2.5	Moduli Stabilization	9
2.6	UV lessons	11
3	Connections to other areas of research	13
3.1	Mathematics	13
3.2	Machine Learning and Computational Complexity	14
4	Outlook	17

1 Introduction

Ever since its formative years, string theory has been developed in close tandem with particle physics. Originally proposed as a theory of the strong interaction, string theory owes its roots to particle physics. While string theory was soon after elevated to a quantum theory of gravity thanks to the ubiquitous massless spin two particle that the theory predicts, its connection to particle physics has only grown stronger via the construction of increasingly realistic models and an understanding of typical features. The quest for unification of fundamental forces calls for an ultraviolet-complete theory that simultaneously incorporates both quantum gravity and chiral gauge theories. The need to develop a consistent framework to unify particle physics with gravity was the backdrop for the heterotic string [1] and Calabi-Yau compactifications [2]. The connection between string theory and particle physics has evolved a great deal in the past few decades. This invited white paper provides a synopsis of this important area, often referred to as “string phenomenology”, focusing on ongoing developments and opportunities.

Some of the central questions in this area of research are:

1) How precisely can we match observable particle physics with specific string vacuum constructions? This question has motivated constructions of string solutions for several decades, with a variety of different approaches leading to string models that capture the gauge group, matter content, and various other features of the observed Standard Model to varying degrees of precision, usually in the context of supersymmetric extensions. In recent

years more systematic approaches have given a more global picture of the set of possibilities and enormous classes of candidate (supersymmetric) Standard Model-like constructions, though there are still many challenges in constructing a set of vacua that contain all observed features of the Standard Model including Yukawa couplings, the Higgs field, supersymmetry breaking, the detailed structure of Standard Model parameters, and the observed cosmological constant.

2) What can be ruled out from string theory? While for some time there was an outlook in the community that “anything goes” in string theory, it is clear that UV consistency with quantum gravity imposes fairly stringent constraints on the set of allowed models of quantum field theory available from string theory. These constraints are clearest with more dimensions and supersymmetry, where for example in 6D and 10D the size and complexity of the gauge group and matter representations are already constrained by gravitational anomalies. These anomaly constraints can also be understood as manifestations of geometric constraints in the UV; similar constraints also hold in other dimensions although they are less well understood in 4D, and the study of other constraints from UV physics is a very active area of current research.

3) What features of string vacua are typical, and what are the consequences for particle physics? While the set of possible consistent string vacuum solutions is enormous, it is believed to be effectively finite. And within this large finite set some features occur overwhelmingly more often than others, at the level of naive counting of discrete sets (although a precise formulation of the measure across string vacua is still lacking). As our understanding of the global set of solutions of the theory increases we can make more informed observations of what kinds of features, beyond the Standard Model, such as hidden gauge and matter sectors, axion fields, etc., are typical in “most” string vacua. Other features, while realized in some string vacua, may be highly atypical and involve extensive fine-tuning, in a way that can be quantified in terms of numbers of continuous moduli or discrete parameters like fluxes that must take special values to realize these features. A crucial question for the next decade(s) is to identify more precisely what kinds of additional beyond the Standard Model structure are associated with typical realizations of Standard Model and Standard Model-like structure in string vacua, and what features are atypical or involve fine tuning.

Beyond these guiding questions, string theory has also more generally been a constant source of ideas for particle phenomenology. One of the deepest puzzles facing particle physics today is the electroweak hierarchy problem. Understanding the huge disparity between the weak scale and the Planck scale has been the driving force for particle theory in the past few decades. Given the ultraviolet sensitivity of this question, a theory valid all the way to the Planck scale is likely needed to make significant progress. As we review below, string theory has shown to be resourceful not only in realizing existing scenarios of physics beyond the Standard Model (such as supersymmetry, axions, etc.) but suggesting new ones, as well as offering new insights to the notion of naturalness. Only with a consistent quantum theory of gravity can we address other vexing naturalness problem involving gravity, such as the unreasonable smallness of the cosmological constant.

The subjects of particle physics and cosmology are deeply intertwined. We focus on

particle physics aspects in this contribution, leaving the connection between string theory and cosmology to a complementary white paper [3].

We should emphasize that the emphasis on topics in this contribution is influenced by the expertise and research interests of the authors; while we have made an effort to summarize the state of the field in the areas connecting string theory and particle physics that we believe are of most current significance and have greatest potential for developments in the coming years, we have not attempted to be comprehensive and some recent related developments are treated briefly or not at all.

2 Particle Physics from String Theory

Finding a realization of string theory solutions with the structure of the Standard Model gauge group and three generations of Standard Model chiral matter fields, as well as additional features such as the Higgs sector and proper Yukawa couplings, moduli stabilization, supersymmetry breaking and vanishingly small positive cosmological constant, etc. has been a major preoccupation of string theorists over the last three decades. For many years such constructions were developed on a somewhat ad hoc basis using a variety of available tools, primarily in the perturbative corners of string theory, such as algebraic geometry techniques in heterotic string theory and orbifold constructions in Type II string theory, and Standard Model-like constructions seemed somewhat rare. However, developments in recent years have given a better global picture of large parts of the landscape of string vacua. There is increasing evidence that there are huge classes of string vacua with Standard Model-like features, and, at least for vacuum solutions with supersymmetry there are increasingly powerful approaches to systematically identifying how such Standard Model-like vacua fit into the landscape, and how natural such solutions are. In particular, the approach of F-theory [4–6] provides a geometric framework in which the broadest class of supersymmetric string vacua yet identified are incorporated in an underlying connected moduli space (including most heterotic vacua as duals of a subset of F-theory vacua). While F-theory is intrinsically nonperturbative, the global lessons from this approach provide insight into the structure of the overall landscape and provide guidance for further work in narrowing down the nature of Standard Model-like solutions, computing more detailed features of these solutions, and identifying what physics beyond the Standard Model may naturally arise in tandem with it. The biggest challenges at this point to this approach are understanding supersymmetry breaking (§2.4) and the related questions of moduli stabilization and the small cosmological constant (§2.5); these latter issues are addressed more comprehensively in [3].

2.1 Approaches to Standard Model-like constructions in string theory

In the past few decades, enormous efforts have been undertaken to demonstrate explicit top-down string theory constructions of vacua with the gauge symmetry and particle spectrum of the Standard Model. This program originated in the studies of the $E_8 \times E_8$ heterotic string compactified on Calabi-Yau threefolds [2, 7–13]. Other efforts have involved Standard-like

Model constructions on heterotic orbifolds [14, 15] and free fermionic constructions [16, 17]. The first globally consistent construction with the exact matter spectrum of the Minimal Supersymmetric Standard Model (MSSM) heterotic was given in [9, 10], and more recently sophisticated computational and mathematical analyses of line bundle constructions have led to the construction of thousands of vacua with the Standard Model gauge group and three generations of Standard Model chiral matter fields based on the heterotic approach [12, 18]. With the advent of D-branes [19] these efforts were further advanced by studying D-branes at singularities (see [20–24] and references therein) and intersecting D-brane models in type II string theory [25–31] (for review see [32] and references therein), which led to the first globally consistent three-family Standard-like Model constructions [30, 31]. Both Heterotic and Type II constructions produced large classes of globally consistent models with Standard Model gauge sectors and three chiral families. One should, however, point out, that these constructions may be limited, in part, due to the perturbative values of the string coupling in these approaches. Furthermore, these models typically suffer from chiral and vector-like exotic matter, though by now there are large classes of constructions that are increasingly close to the MSSM. Another approach to string compactification is based on using special holonomy G_2 seven-manifolds to compactified M-theory to 4 dimensions. There has been substantial progress in this direction in recent years, as discussed further in §3.1; although a full description of a model with the Standard Model gauge group and chiral matter content in terms of a singular G_2 geometry is still some way in the future (for some initial developments in this direction, see [33]), this may in time be a promising approach for construction of a large class of semi-realistic string vacuum models.

While the above mentioned constructions concentrated on perturbative corners of string theory, the geometric approach of F-theory [34–36] gives a systematic and nonperturbative global picture of an even larger class of nonperturbative string vacua. In F-theory, the back-reactions of non-perturbative 7-branes onto the geometry of six compactified space dimensions are encoded in the geometry of an elliptically fibered Calabi-Yau fourfold. By studying this space of theories with well-established tools of algebraic geometry, a variety of top-down F-theory constructions have been realized where the gauge degrees of freedom are encoded in the singularity structure of the elliptically fibered Calabi-Yau fourfold. Following the initial intensive study of GUT F-theory models based on tuned $SU(5)$ GUT groups initiated by [37–40], a number of other classes of F-theory constructions with the Standard Model gauge group have been realized including directly realizing the Standard Model gauge group as a geometrically rigid symmetry [41], geometrically tuned Standard Model gauge groups [42–45], and Standard Model constructions from flux breaking of exceptional GUTs [46].

In F-theory, the matter spectrum is uniquely fixed by a background gauge configuration, which can be conveniently specified by the three-form gauge potential C_3 in the dual M-theory geometry. The chiral spectrum depends only on the field strength $G_4 = dC_3$, referred to as flux. By now, there exists an extensive toolbox for constructing and enumerating the G_4 flux configurations [43, 47–56]. The application of these tools has led to the construction of a variety of globally consistent chiral F-theory particle physics constructions [43, 55, 57, 58],

particularly in the class of tuned Standard Model gauge groups, which recently culminated in the largest explicit class of string vacua that realize the Standard Model gauge group along with the exact chiral spectrum and gauge coupling unification [59]. The construction of global Standard Model vacua from the $SU(5)$ GUT approach is complicated by the necessity for including hypercharge flux, which requires more complicated (non-toric) base manifolds [60, 61]. For a review of earlier efforts on constructions of (non-compact) $SU(5)$ GUTs, see reviews [62, 63], and for a comprehensive introduction to F-theory compactification [64].

The constructions just described begin to address the first question raised in the Introduction: How precisely can we match observable particle physics with specific string vacuum constructions? In the following subsections we address how much further these constructions can go beyond the gauge group and chiral matter content of the Standard Model. Related to the third question of the Introduction, however, there is also a question of typicality. As discussed further in §3.2, the number of complex threefold base geometries that support elliptically fibered Calabi-Yau fourfolds is enormous, likely on the order of 10^{3000} . One current area of active research is to understand which of the above constructions are most typical (involve the least fine tuning). While the (tuned) $SU(5)$ GUT models have been studied in the most detail, these models seem to be possible only on a small subset of the allowed F-theory bases and involve extensive tuning of moduli [65]. Similar issues hold for the constructions in which the Standard Model gauge group is directly tuned at special loci in the generic Weierstrass model over the base, as in the approach taken in [42, 43, 45, 59]. In terms of simple numerical counting, all but a handful of the enormous number of threefold bases that support F-theory constructions are populated by numerous geometric gauge factors associated with rigid divisors in the base; in 4D, these rigid gauge groups include the non-Abelian factors $E_8, E_7, E_6, F_4, G_2, SO(8), SO(7), SU(3), SU(2)$ but not e.g. $SU(5)$ or $SO(10)$ [66]. It is natural to expect that the most typical realizations of the MSSM in F-theory will arise through these rigid gauge groups, as explored in e.g. [46, 67]. While there are many challenges associated with making precise sense of the measure problem on the space of flux compactifications (see e.g. [68, 69]), the enormous numbers of vacua involved in geometric F-theory constructions suggest that some insight can be gained on questions of typicality of standard model constructions; further work in coming years should address how the more detailed physics of the different constructions described here differs and what physics beyond the Standard Model is more or less typical.

2.2 Matter fields and the Standard Model

As described above, we now have the technical facility to construct enormous classes of models with the Standard Model gauge group and chiral matter content. The next challenges are to understand more clearly the more detailed structure of these models. While F-theory provides a powerful nonperturbative framework for accessing the large scale picture of the set of vacua, explicit calculations of more detailed aspects of these vacua require technical tools not yet developed and which in some cases may be hard to access due to the fundamental nonperturbative nature of the physics in these solutions. Current work is focused on understanding

more detailed aspects of the vector-like part of the matter content, Higgs fields and Yukawa interactions.

In particular, the methods described above are insufficient to determine the exact vector-like spectrum of the chiral zero modes, which depend not only on the flux G_4 , but also on the flat directions of the three-form potential C_3 . In [70, 71], methods for determining the exact vector-like spectra were put forward, and further advanced in the context of Standard Models in [72, 72]. Attaining a more detailed understanding of the vector-like spectrum and Higgs fields is a key goal of near-term research in this area.

Yukawa couplings in F-theory have been explicitly computed only in the ultra-local F-theory models [49, 73–75]. However, there has been recent progress on calculations of the holomorphic part of Yukawa couplings within a global $SU(5)$ GUT-like model [76]. The connection between F-theory and type II descriptions of Yukawa couplings has also been elucidated [77] via the role of D-instanton contributions [78–81]. (For review, see [82].) Furthermore the calculation of the Kähler potential, which determines the normalization of the kinetic energy terms and thus needed for the physical values of Yukawa couplings, remains an outstanding problem. Note that on the latter topic progress has been made in the heterotic [83, 84] and Type II context [85, 86]. The full determination of physical Yukawa couplings in globally consistent F-theory Standard Model constructions is an important goal of future research, and affects aspects such as the possibility of proton decay in these constructions.

Another class of questions relates to how typical the matter content of the Standard Model is among string vacua. While the light chiral matter content of the Standard Model, including 3 generations of quarks and leptons, appears somewhat arbitrary, and many string constructions that give the Standard Model gauge group also include various exotic matter fields, there are also strong constraints from anomaly cancellation conditions that limit the possible sets of matter fields. Naively, however, the matter that occurs in nature could live in arbitrarily complicated high-dimensional/high-charge representations of the non-Abelian and Abelian factors in the Standard Model gauge group $SU(3) \times SU(2) \times U(1)$ while still satisfying anomaly cancellation. There are some indications, however, that the set of possible matter representations realized in string theory is quite limited, so that only special simple representations like those of the Standard Model are realizable in a UV complete theory. The range of allowed representations for heterotic orbifold models was studied some time ago in [87]. More recently, analysis from the F-theory point of view seems to strongly limit the range of possible matter representations of non-Abelian groups that may arise from geometry [88–90], although there is more apparent flexibility for $U(1)$ charges [91–95]. Furthermore, the global structure of the gauge group affects the set of allowed matter fields; the observed Standard Model chiral matter spectrum is much more natural if the global structure of the group is $(SU(3) \times SU(2) \times U(1))/\mathbb{Z}_6$ (as occurs in most GUT models and many of the F-theory constructions delineated above) than the group without the quotient; in the F-theory context these issues have been studied recently in [44, 45, 96, 97]¹. Indeed, the “completeness

¹In F-theory the global structure of a gauge group is determined by the torsional part of the Mordell-Weil

hypothesis” (see e.g. [100]), recently proven in AdS space in [101], would indicate that if the gauge group lacks the quotient there must be massive exotics with nontrivial charge under the central \mathbb{Z}_6 . If string theory can be shown to strongly limit the set of possible matter fields that can appear in a low-energy vacuum with the gauge group of the Standard Model, it will help to fit observed physics into the landscape of “typical” theories, while otherwise there is another fine-tuning problem. Related issues are also discussed in §2.6.

Beyond the light chiral matter fields in the Standard Model, many string constructions contain a variety of further matter fields that may play roles as dark matter candidates; we explore these further in the following subsection.

2.3 Particle Remnants of the String Landscape

As mentioned above, string compactifications that give rise to the gauge group and chiral matter content of the Standard Model regularly exhibit new particles that are accidental consequences of the ultraviolet theory, i.e., they are not motivated by shortcomings of the Standard Models of particle physics or cosmology. Nevertheless, these particle remnants are potentially observable, providing both experimental constraints and opportunities. See [102] for a thorough account in lectures, including the topics discussed below: axions, dark gauge sectors, and vector-like exotics.

Axions. String theory contains higher-form gauge fields that regularly give rise to axions upon compactification [103]; in supersymmetric models, these axions are part of the same multiplet as scalar moduli fields (§2.5). The number of axions N is dictated by the topology of the extra dimensions. Generally, N is quite large; in the largest ensembles of supersymmetric type IIB or F-theory compactifications studied to date, N is in the hundreds [104] or thousands [105–108], respectively. This leads to the expectation that string theory gives rise not to one or a few axions, but an axiverse [109], with diverse set of implications for particle physics and cosmology; notably, these axions need not be the QCD axion. Furthermore, recent results demonstrate [110] that type IIB compactifications with large volume and weak coupling typically exhibit numerous very light axions, well below the eV scale. Possible implications of string theory for axions include for solving the strong CP problem [110], axion monodromy inflation [111–116] and reheating [117, 118], cosmological relaxation of the weak scale (aka the “relaxion” scenario) [119–121], fuzzy dark matter [122–124], black hole superradiance [125], gravitational waves [126–130], and couplings to axion-like particles [131, 132].

Dark Gauge Sectors. Consistency conditions such as Gauss’ law for higher-form gauge fields, generally associated with tadpole cancellation conditions, combined with geometric and topological features in the UV theory often require the presence of multiple gauge sectors, which may couple to the visible sector (if present) only via gravity and non-renormalizable interactions. For instance, visible sectors arise in one E_8 factor in the heterotic string, leaving the other E_8 as a potential dark matter sector [133], where some gauge factor may be forced

group of an elliptic fibration, addressed in non-Abelian cases in [98] and in the presence of Abelian factors in [96]. For review, see [99].

from a given distribution of instantons. More generally, as discussed above, F-theory compactifications typically give rise to dozens or hundreds of rigid gauge factors. These heterotic and F-theory mechanisms producing hidden sectors are related through duality [134]; duality with G_2 constructions suggests similar features there [135]. In many cases these extra sectors confine, giving rise to the possibility of dark glueball dark matter [136–138]. However, it is very easy to oversaturate the observed relic abundance [136], and more generally one might use cosmological observations to constrain F-theory, given the plethora of dark gauge sectors and axions that it exhibits. In addition, string theory also suggests new portals between the visible and dark gauge sectors e.g., through Stuckelberg couplings [139, 140].

Vector-like Exotics. Matter fields that are vector-like with respect to the Standard Model regularly arise in string compactifications and are experimentally allowed, provided that their mass is TeV-scale or above. Such new particles are the subject of many searches at LHC, and provide opportunities to explain existing data, such as WIMP dark matter [141, 142] and the B anomalies [143]. In string constructions a variant of vector-like exotics regularly arise, so-called quasi-chiral exotics [144–146], which are vector-like with respect to the Standard Model, but chiral with respect to another symmetry, which provides a mechanism to expect masses significantly below the string scale. In some other cases, these quasi-chiral exotics decouple from the low energy spectrum due to hidden sector strong dynamics and charge confinement [147, 148].

2.4 SUSY breaking

One of the greatest challenges in string phenomenology is the issue that the vacua that are best understood are those with at least some supersymmetry. Since low-scale supersymmetry (i.e. SUSY at the TeV scale or below) has not been observed at the LHC (or in astrophysical experiments), this presents a major challenge to connecting UV complete string constructions with observable physics. The most powerful approaches to understanding string vacua and computing physics in these backgrounds relies heavily on supersymmetry, in particular the nonperturbative approach of F-theory uses algebraic geometric methods in which the complex-analytic structure of the geometry is tied to space-time supersymmetry. Certainly, direct exploration of non-SUSY vacua and mechanisms of high-scale SUSY breaking in supersymmetric string vacua are significant priorities for this community. The problem of identifying non-supersymmetric de Sitter string vacua from conventional methods such as uplifted flux vacua is a major focus of current research, discussed slightly further in the following section and in more depth in [3].

At the same time, some lessons even from supersymmetric string vacua such as the presence of many scalar fields and axions, and gravitationally coupled hidden dark sectors from rigid gauge groups and associated matter uncharged under the Standard Model gauge group, seem to be present in the string landscape somewhat independently of the amount of supersymmetry involved. For example, virtually the same hidden sector rigid gauge group factors (e.g. $E_8, E_7, E_6, F_4, SO(8), G_2, SU(3), SU(2)$ but not $SU(5)$) arise in 6D supersymmetric F-

theory vacua with 8 supercharges as in 4D supersymmetric F-theory vacua with 4 supercharges [66, 149], and with similar frequencies [106–108], suggesting that some of these qualitative features of string vacua may persist even without SUSY or when SUSY is broken.

Another intriguing question is whether the geometries associated with supersymmetry are natural even if we drop the constraint of SUSY. In particular, there are few smooth compact manifolds known in the math literature that admit a Ricci flat global metric that are not essentially Calabi-Yau manifolds or closely related special holonomy manifolds [150]. (As a very simple example, in 2D the Gauss-Bonnet theorem shows that the only compact smooth 2D manifold admitting a Ricci flat metric is the torus.) Indeed, it was conjectured in [150] that any smooth manifold with a Ricci flat metric that lacks special holonomy leads to a “bubble of nothing” instability [151], and there is some recent evidence in support of this [152, 153]. This is a special case of the more general hypothesis that non-supersymmetric vacua may suffer from some form of instability. We will return to this in the next section when we discuss de Sitter vacua. Another approach to realizing non-supersymmetric vacua is to start with a hyperbolic compactification space and directly construct a solution with positive cosmological constant, as explored for example in [154] and references therein. The effort to directly construct explicit non-supersymmetric string vacua is a promising avenue for further research that might justify (or might disprove) the notion that features of supersymmetric string vacua are also natural for our non-supersymmetric world.

2.5 Moduli Stabilization

String theory has no free parameters; for example in type II string theory, the string coupling is encoded in the dynamical axiodilaton field. Upon compactification, the low-energy effective action of string theory constructions generically contains many parameters associated with vacuum expectation values (VEVs) of scalar fields, generalizing the type II axiodilaton field. Stabilizing these scalar fields (known as moduli) is thus important for drawing phenomenological predictions from string theory. Because no massless scalar fields are observed in nature, we expect that all these moduli are stabilized in a physically relevant vacuum of the theory. Fifth-force experiments and cosmological constraints typically put these moduli masses above $\mathcal{O}(10)$ TeV scale, though loopholes exist if one contemplates unconventional cosmological histories. Understanding precisely how moduli stabilization occurs is a major challenge for string theory. In some cases, the issue of moduli stabilization cannot be decoupled from particle physics considerations [155], though model-building can mitigate this tension [156–158]. In general, it is expected that any theory with broken supersymmetry will generically have mass terms for all the scalar fields. The question remains why the Higgs mass is significantly lighter than that of other moduli. This issue is akin to realizing inflation in string theory, which requires a hierarchy in masses between the inflaton and other moduli.

Mechanisms to stabilize moduli developed so far can be divided into two broad classes: power-law stabilization and non-perturbative stabilization. We refer the reader to [3] for their distinction and a more in-depth discussion. Here, we focus on the latter as they are more commonly used in particle physics model building from string theory. In general, even

constructions of supersymmetric string vacua incorporate mechanisms that stabilize most or all moduli fields. In $\mathcal{N} = 1$ solutions of type II string theory and F-theory, for example, fluxes generate a superpotential that stabilizes many of the (complex structure) moduli of the vacua directly (although there are questions about whether the number of fluxes, which is bounded by the D3-brane tadpole, is sufficient to stabilize a plurality of the complex structure moduli [159–162]); other effects such as gaugino condensation and nonperturbative instanton effects also arise that in general are expected to lift other moduli of the theory. See, e.g., [163] for a review². While this gives rise to a plethora of expected vacua with negative cosmological constants (including supersymmetric vacua), it is remarkably difficult to explicitly construct moduli-stabilized vacua with positive cosmological constant. There are a number of no-go theorems that demonstrate the impossibility of getting vacua with a positive cosmological constant (or even a slowly rolling vacuum with many e-folds of inflation) with simple (albeit limited) sets of ingredients from supergravity theory [166–169]. More involved setups that naively evade these no-go theorems were found to suffer from tachyonic instabilities [170–174] (an issue later revisited in e.g. [175–177]). It should be noted that the sources of potential considered in these no-go theorems are not general enough to exclude de Sitter vacua in string theory. It has been suggested that de Sitter vacua do not arise in regions of string theory that are within strict parametric control [178–180]. A lack of parametric control does not mean that no theoretical control is possible. However, in light of the Dine-Seiberg problem [181], one would have to carefully quantify that higher order terms which are ignored are indeed unimportant even though different order terms in the potential compete to give a minimum. In addition, the instability hypothesis mentioned in §2.4 (see [182] for a recent discussion regarding de Sitter instability) suggests that any proposed de Sitter vacuum should be subject to a more careful scrutiny. Another perspective on flux vacua without supersymmetry is given in [183]. These various considerations have reignited the interest in moduli stabilization in string theory, resulting in a number of technical advances. Recent work [184] has succeeded in constructing supersymmetric AdS vacua with exponentially small negative cosmological constant, a difficult task even with an optimized computer search [185]. Challenges remain in uplifting these solutions to de Sitter, all related one way or the other to the anti-D3-branes that break supersymmetry. Metastability of anti-D3-branes requires a large enough warped throat supported by a large quantity of D3-brane charge which may be in further tension with the tadpole constraints mentioned above, though detailed model building may mitigate this problem. It was argued that a large throat leads to a singular bulk problem [186]. The singularities of the internal metric may be resolved at the non-perturbative level [187], but theoretical control of the low energy effective theory remains to be shown. Furthermore, advances in lifting gaugino condensates to 10D have recently been made, including an improved understanding of the four-fermion couplings [188–191] and the generalized complex geometry [190, 192] needed to describe their backreaction to the internal

²Well-studied approaches to non-perturbative moduli stabilization include the KKLT scenario [164] and the Large Volume Scenario [165].

geometry. Such 10D lift allows us to quantify possible corrections to the stabilized vacua which is a result of an interplay of the classical flux energy, the non-perturbative instanton effects, and the anti-branes. Fleshing out these advances in full and constructing explicit vacua with all moduli stabilized, particularly with a small positive cosmological constant, remains a clear and precise challenge for the field in coming years.

A complementary approach to explicitly stabilizing moduli is to study what is possible, in principle, in regimes of the theory that may be controlled. For instance, for increasing topological complexity, control over the α' and g_s expansion in type IIB compactifications pushes the theory [110] to larger cycle volumes. This has numerous phenomenological implications; e.g., it correlates with increasingly light axions when their masses are generated non-perturbatively, and increasingly weak seven-brane gauge couplings. Applying such an analysis in the context of the 10^{15} F-theory compactifications with the gauge group and chiral spectrum of the Standard Model, it was found [193] that (for the bulk of the models) there is no part of the large volume moduli space that realizes the correct values of the Standard Model gauge couplings; they are far too weakly coupled. Avoiding this consequence requires either alternative moduli stabilization schemes that exist at small volume, focusing on models with lower topological complexity, or modifying the location of the Standard Model sector in the extra dimensions, which forces the existence of dark gauge sectors. Results such as these are demonstrative of a general principle in string compactification: there is no free lunch, and correlations from the UV theory often exist that defy expectations from an EFT point of view.

2.6 UV lessons

The electroweak hierarchy problem is arguably one of the main science drivers for particle physics beyond the Standard Model. In essence, it is a question of how an infrared (IR) scale can emerge from an ultraviolet (UV) scale without fine-tuning of UV parameters. In unifying particle physics with gravity, among the tunings in question is the huge disparity between the Higgs mass and the Planck scale. A notion of “naturalness” in accessing the degree of fine-tuning was succinctly articulated by ’t Hooft [194]: “at any energy scale μ , a physical parameter or set of parameters $\alpha_i(\mu)$ is allowed to be very small only if the replacement of $\alpha_i(\mu) = 0$ would increase the symmetry of the system.” There are reasons to expect that gravity may provide a break from this Wilsonian EFT reasoning. Heuristic arguments [100] as well as string theoretical reasonings [101, 195] suggest that quantum theories of gravity admit no global symmetries, making the above $\alpha_i(\mu) \rightarrow 0$ limit subtle. Another hint is the Bekenstein-Hawking entropy of a black hole, which links the classical IR solution of gravity with the degeneracy of highly massive states of the UV theory. This UV/IR mixing (a term coined in [196]) manifests in many forms in string theory. There have been attempts e.g. [197] to frame the Higgs mass computation in string theory in a way that respects this UV/IR duality. How this UV/IR mixing can concretely address the electroweak hierarchy problem remains to be explored. Meanwhile the vast but finite landscape of string vacua also suggests a notion of stringy naturalness [198] which measures the degree of tuning by the number of phenomenologically acceptable vacua leading to a given value of an observable. Similar

considerations of stringy naturalness may shed light on the scale of supersymmetry breaking [199–201] as well as other vexing hierarchy problems such as the smallness of the cosmological constant, though concrete realizations remain to be found.

The Swampland program [202] (see e.g. [203–207] for reviews) aims to make precise this UV/IR relation with an eye toward its phenomenological implications. Combining reasoning from such diverse areas as black hole physics, holography, scattering amplitudes, and the bootstrap, an interconnected web of swampland criteria has emerged. These criteria, if proven, may have interesting phenomenological implications. For example, milli-charged dark matter scenarios often considered in phenomenological studies are in tension with the absence of global symmetry in quantum gravity [208]. The Weak Gravity Conjecture (WGC) [209] has been used to put phenomenological constraints on axions [210–214] and dark photons [215]. Stronger versions of the WGC have been used to link the observed value of the cosmological constant with the neutrino masses (which for fixed Yukawa couplings, set the weak scale) [216, 217]. Ideas to stabilize the Higgs mass using the WGC in the presence of scalars have been explored [218, 219]. See the related Snowmass white papers [220, 221] for discussions of other phenomenological implications. While there is growing evidence for various swampland criteria, they are at present conjectural though continued serious attempts for proofs have been made [222–226].

Swampland considerations have also been utilized to constrain the gauge and matter content in consistent quantum theory of gravity. The Completeness Hypothesis [227] necessitates physical states with all possible gauge charges consistent with Dirac quantization. In the presence of higher form symmetries, these physical states include extended objects, such as strings and branes. A powerful general approach initiated in [228] makes use of brane probes to rule out infinite families of anomaly free gravitational theories. Subsequent works have found precise match of the allowed spectra with string constructions, sometimes involving fine details such as the global structure of the spacetime gauge group [229–236]. Investigations along this line, if successfully extended to lower dimensions, would suggest a notion of string universality [237] (or the string lamppost principle [230]) that all consistent supersymmetric theories of quantum gravity are realized in string theory. Six-dimensional supergravity theories and their string/F-theory realizations provide an excellent testbed for swampland ideas since the class of string constructions is fairly well understood and controlled, and known quantum consistency conditions also tightly bound the set of possible low-energy theories; these theories satisfy the completeness relation and some related conditions that may help to fully understand the role of quantum gravity constraints in this context [238, 239]. Improved understanding of quantum gravity constraints in more general contexts through the swampland together with continued advances in string compactifications would enable us to better understand the rigid pattern of particle spectra found in string theory.

3 Connections to other areas of research

3.1 Mathematics

Since the early days of string theory, there has been a constant flux of new ideas in both directions between physicists studying string theory and a wide range of branches of mathematics. This synergy between the fields has continued unabated, and perhaps even increased, in recent years. One particularly strong set of such connections relates to the use of geometry in string compactifications. In particular, in recent years there have been exciting developments generating new connections and insights for both math and physics related to special holonomy (“ G_2 ” manifolds) relevant for compactifications of 11-dimensional M-theory to 4D, and to the algebraic geometry of elliptically fibered Calabi-Yau threefolds and fourfolds, relevant for compactification of F-theory to 6D and 4D. These developments promise to provide powerful tools for better understanding F-theory and M-theory constructions of Standard Model-like string vacua.

In the context of F-theory, there has been significant progress in understanding many aspects of elliptically fibered Calabi-Yau threefolds and fourfolds. Evidence suggests that most known Calabi-Yau threefolds and fourfolds are in fact elliptically fibered [240–243]. New mathematical results on the finiteness of topological equivalence classes of Calabi-Yau fourfolds [244], expanding the earlier results on Calabi-Yau threefolds [245, 246], give insight into the global structure of string vacua, in general, and F-theory vacua, in particular. Progress has been made on generalizing the Kodaira classification of codimension one singularities in elliptic fibrations, which matches beautifully with the nonperturbative physics of non-Abelian gauge groups, by understanding higher-codimension singularities encoding matter and Yukawa couplings (for some examples see, e.g., [88, 247–249]). Difficult mathematical problems associated with the Mordell-Weil and Tate-Shafarevich/Weil-Châtelet groups of an elliptically fibered Calabi-Yau are connected with physics of continuous and discrete Abelian gauge symmetries in F-theory, and progress is being made in understanding these structures with mutual benefit to mathematicians and physicists. For a comprehensive review on these developments, see [99]. There are a number of open questions in these areas that are promising for progress in the coming years and will shed light on important questions both in physics and math.

M-theory compactifications on seven-manifolds with G_2 holonomy also give rise to large ensembles of $4d \mathcal{N} = 1$ vacua, where singularities at codimension 4, 6, and 7, encode the structure of gauge groups, non-chiral matter, and chiral matter, respectively; see [250] for an early review. More recently, constructions of so-called twisted connected sums [251] have given rise to millions of G_2 manifolds [252], which have been the subject of numerous physics studies in compact twisted connected sums [135, 253–259], and related Higgs bundle constructions [260–264]. For some recent progress on singular non-compact G_2 constructions and studies on gauge dynamics there, see [265, 266]. In general, though, much less is known about compact (singular) G_2 manifolds than Calabi-Yau compactifications. This is in part due to the fact

that there is no analog of Yau’s theorem, i.e., no simple topological check that guarantees the existence of a Ricci-flat metric with appropriate holonomy.

One set of questions that is common to the challenges of the G_2 special holonomy research and the elliptically fibered Calabi-Yau F-theory research is the challenge of understanding better how mathematical structures such as intersection theory operate in singular spaces. This is only partially understood by mathematicians and only in limited domains but is crucial to understanding the physics of string compactifications in both these areas. In particular, in G_2 holonomy manifolds and elliptically fibered Calabi-Yau varieties, singularities are essential for the physics of non-Abelian gauge theories, matter fields, Yukawa couplings and other important aspects of the theory. The primary approach taken to F-theory currently is to view it as a limit of a compactification of M-theory on a smooth Calabi-Yau, but a more intrinsic definition is given by IIB string theory, which is characterized by singular elliptic fibrations associated with 7-brane configurations. Finding a direct description of the physics of F-theory in terms of the singular geometries may be a crucial step to a better general class of tools for describing details of compactification; such a description, however, requires understanding intersection theory on singular spaces. Recent work [56, 267, 268] shows how some of these features must be properties of the singular spaces, providing examples of how a proper mathematical theory of these singularities should work; providing a systematic mathematically sound methodology for analyzing these spaces is an important challenge for the future.

A simple illustration demonstrates the importance of an appropriate homology and intersection theory on singular compactification spaces. Since gauge sectors arise at codimension 4 in G_2 compactifications, and two codimension 4 cycles do not intersect in a 7-manifold, one might conclude that distinct gauge sector loci cannot have jointly charged matter in G_2 compactifications. However, this directly contradicts the existence of uplifts of IIA models with intersecting D6-branes [269], and also local G_2 constructions of unfolding chiral matter [270]. The error is that the non-intersection of three-cycles holds in (smooth) 7-manifolds, but not in seven-dimension singular spaces. One way to correct this is to determine an appropriate homology and intersection theory in the presence of singularities, perhaps intersection homology [271] of Goresky and Macpherson, which corrects the failure of Poincaré duality on singular spaces.

3.2 Machine Learning and Computational Complexity

As our understanding of the theoretical framework for string compactifications increases, the problems in identifying the desired vacua and computing their characteristics become increasingly well-defined. Many of these problems are computationally challenging and involve non-perturbative physics or exponentially large search spaces, and will likely require sophisticated computational approaches, just as many of the detailed features of strongly coupled quantum field theories like QCD are currently best understood through lattice gauge computations. There have been efforts to use computational approaches to analyze a number of problems related to string compactifications, such as for the computation of exact metrics on Calabi-Yau compactification spaces, for which no analytic solution is known [272–277]. In this section we

focus on the use of modern methods of machine learning and associated methodologies for approaching some of the computational difficult challenges in string compactification.

The string landscape is vast, and our knowledge of it has grown significantly in the last decade. Evidence for exponentially large numbers of 4d string vacua was already given in 1987 [278], in the context of chiral heterotic models. However, the possibility received increased attention with work by Bousso and Polchinski [279], which provided a string theoretic mechanism for realizing Weinberg’s anthropic solution to the cosmological constant problem [280]. Famously, this led to an estimate of 10^{500} flux vacua in weakly coupled type IIB compactifications (reviewed in [69]), an estimate that recently ballooned to $10^{272,000}$ [105] by moving outside of the weakly coupled regime to F-theory. A more recent development is that the number of string geometries is also exponentially large. Though Kreuzer and Skarke’s classification relating four-dimensional reflexive polytopes and Calabi-Yau threefolds yields only a strict lower bound of $O(30,000)$ Calabi-Yau threefolds (from distinct Hodge numbers), this was always expected to be a significant undercount due to triangulated polytope combinatorics, and the number of Calabi-Yau fourfolds is dramatically larger, with a recently studied subset giving over 500 million distinct Hodge numbers for fourfolds [281]. A related setup in F-theory instead counts bases of elliptically fibered Calabi-Yau threefolds [282, 283] and fourfolds [106, 284, 285]. Compared to roughly 65,000 distinct toric bases for threefolds, this approach provides a strict lower bound of $O(10^{755})$ F-theory geometries for fourfold bases [107], which is also a vast undercount due to imposing a sufficient but not necessary condition; Monte Carlo estimates [108] suggest there are $O(10^{3000})$ geometries with the relaxed condition. Despite these large numbers of elliptically fibered Calabi-Yau fourfolds, a result appeared around the same time proving that the total number is finite [244]. However, the string landscape is not only vast, it is also unwieldy: computationally complex problems abound. For instance, the search for small cosmological constants in simplified idealized models is already NP-hard [286], although the success in finding explicit solutions with small cosmological constant in F-theory [184] suggests that the structure of the landscape may enable efficient solutions to this problem. Furthermore, [287] computing effective potentials often requires solving instances of NP-hard problems, and the search for local minima is itself (co)-NP-hard. Additionally, the appearance of both explicit diophantine equations in string theory (from both index theorems, e.g., and diophantine encodings of decision problems) brings *undecidability* into the game, by the negative solution to Hilbert’s tenth problem [288]. There are a number of potential mechanisms for avoiding complexity issues, however. For instance, landscape structure may aid in solving complex problems such as Diophantines [289]; fast-enough algorithms may exist for system sizes of interest [290]; some NP-hard problems have fully polynomial time approximation schemes, which allow for polynomial time solution if small errors are allowed; and complexity considerations can change by allowing for stochastic or quantum computers.

Taken together, the enormity and complexity of the landscape motivates the use of modern techniques from computer science. Much of the focus has been on machine learning, beginning with [291–294], which utilized supervised learning (both with and without neural networks)

and led to machine-assisted theorems via conjecture generation. Other notable areas include persistent homology, which can detect cycles and voids in the landscape [295, 296]; network science, which can be used to model tunneling transitions and dynamical measures [297]; fast SAT and SMT solvers [298, 299], which can solve string constraints by mapping them to famous problems in computer science, SAT and SMT; and genetic algorithms [161, 185, 292, 300–304], which use ideas from evolution to search for solutions, e.g., for string vacua satisfying various properties.

A number of deep learning techniques have been utilized to study the string landscape and associated mathematical data. Due to the enormity of the landscape, we organize the discussion here according to the type of question under consideration, and the associated machine learning technique. *Prediction* is the domain of supervised learning, whereby a neural network or simpler algorithm is trained to predict outputs given inputs. String theoretic applications of supervised learning (e.g. [291–294, 305–311]), often predict physical features such as gauge group and Hodge numbers (which includes number of axions) given core geometric, D-brane, or flux data as input. Notably, conjectures may be generated by bringing the human into the loop: though supervised learning has intrinsic error, it can also learn correlations that can be understood by humans, especially when simpler techniques are used, that can lead to conjectures and even theorems [294, 312, 313]. Though supervised learning was the focus of early work, new directions quickly arose. *Search* for vacua with particular properties [314–317] may be carried out with deep Reinforcement Learning (RL), by which a trained neural network represents a learned policy function that chooses intelligent actions, given the state of the system; RL is the type of deep learning utilized by DeepMind in its famous works on Go and Chess [318]. For instance, the state could be an intermediate stage of constructing a string compactification with D-branes, where intelligent actions would push the system towards global consistency and interesting phenomenology. Genetic algorithms, an optimization technique that does not utilize a neural network, also regularly lead to good search results; see [319–321] for comparisons. Deep generative models are trained to sample from a desired probability distribution, and may be utilized to *simulate* SUSY EFT data [322] or string data [323]. Finally, a major recent and very notable development is in *self-generative learning*, where the neural network itself is trained to represent a function of interest, usually a solution to a PDE, such as a Calabi-Yau metric [324–326], which was recently extended to general Kreuzer-Skarke Calabi-Yau threefolds [327]; see also [328]. Interestingly, these closely resemble techniques used to learn ground states of quantum many-body systems [329]. For a recent review, see [330].

While it is not yet clear how far machine learning and related methodologies can go in addressing these difficult string vacuum questions, these developments lay the groundwork for a deepened understanding of the landscape that may be obtained via machine learning. Self-generative learning, including in the context of Calabi-Yau metrics, opens the door to the study of non-holomorphic data such as non-BPS charged particles and Kaluza-Klein modes that are difficult to study with traditional techniques. These same techniques can push the envelope in pure mathematics, for instance in studies of G_2 manifolds and singular spaces

with numerical metrics. Search, as offered by reinforcement learning and genetic algorithms, provides new opportunity to understand what is possible in string theory. Applications include the search for vacua with potential for realistic particle physics and cosmology, as well as other observables typical of those vacua. Specifically, these techniques could be utilized to efficiently search for vacua with small positive cosmological constants. Finally, generative models provide a means of sampling from desired distributions, which will be essential to making statistical predictions with some measures; see [323].

4 Outlook

As we have reviewed here, connecting the top-down framework of string theory with the bottom-up observational data of particle physics is an active and vibrant enterprise and is an important central component of completing our understanding of the Universe. In the last decade, substantial progress has been made in framing and beginning to address the questions listed in the introduction: How precisely can string theory match observed particle physics? What is ruled out from string theory? What are typical features of string vacuum solutions and what are the consequences for particle physics? The nonperturbative approach of F-theory and other developments in string compactification have given an increasingly global perspective on the set of string solutions from which these questions can be addressed. There are now substantial classes of top-down string constructions of vacua that contain the Standard Model gauge group and the three family chiral matter content, and some of these appear to involve fairly minimal fine tuning. Certain features, such as axions and strongly coupled hidden sectors arise ubiquitously in string vacuum constructions, and suggest natural dark matter candidates as well as potential avenues for applying cosmological constraints. Constraints on low-energy theories from string theory promise to shed insight on long-standing questions such as the hierarchy problem.

Many key questions, however, remain unanswered. The lack of experimental observation of low-energy supersymmetry sharpens the questions about the physics of SUSY breaking and the nature of non-supersymmetric solutions in string theory. The observed small positive cosmological constant sharpens the challenge of understanding de Sitter and non-supersymmetric string vacua. The landscape is large and while naive counting suggests that certain features may dominate, the measure problem is open, which is crucial for making any kind of precise statistical statement regarding string vacua.

This general research area, which aims at connections between UV-complete quantum gravity theories and the observed Standard Model of particle physics, promises to be a very exciting and dynamic area of activity in the coming decade, and brings together the research efforts of formal theorists with the large community of particle physicists working closer to experiment. Supporting this effort should be a crucial part of DOE high-energy priorities through the 2020s and 2030s.

Acknowledgements

The work of M.C. is supported by DOE Award DE-SC0013528Y, the Simons Foundation Collaboration grant #724069 on “Special Holonomy in Geometry, Analysis and Physics”, the Slovenian Research Agency No. P1-0306 and the Fay R. and Eugene L. Langberg Chair funds. The work of GS is supported in part by the DOE grant DE-SC0017647. The work of WT is supported in part by the DOE through grant DE-SC00012567. The work of J.H. is supported by NSF CAREER grant PHY-1848089.

References

- [1] D. J. Gross, J. A. Harvey, E. J. Martinec and R. Rohm, *The Heterotic String*, Phys. Rev. Lett. **54** (1985) 502–505.
- [2] P. Candelas, G. T. Horowitz, A. Strominger and E. Witten, *Vacuum Configurations for Superstrings*, Nucl. Phys. B **258** (1985) 46–74.
- [3] R. Flauger, V. Gorbenko, A. Joyce, L. McAllister, G. Shiu and E. Silverstein, *Snowmass White Paper: Cosmology at the Theory Frontier*, in *2022 Snowmass Summer Study*. 3, 2022. [2203.07629](#).
- [4] C. Vafa, *Evidence for F theory*, Nucl. Phys. **B469** (1996) 403–418 [[hep-th/9602022](#)].
- [5] D. R. Morrison and C. Vafa, *Compactifications of F theory on Calabi–Yau threefolds — I*, Nucl. Phys. **B473** (1996) 74–92 [[hep-th/9602114](#)].
- [6] D. R. Morrison and C. Vafa, *Compactifications of F theory on Calabi–Yau threefolds — II*, Nucl. Phys. **B476** (1996) 437–469 [[hep-th/9603161](#)].
- [7] B. R. Greene, K. H. Kirklin, P. J. Miron and G. G. Ross, *A Superstring Inspired Standard Model*, Phys. Lett. **B180** (1986) 69.
- [8] V. Braun, Y.-H. He, B. A. Ovrut and T. Pantev, *A Heterotic standard model*, Phys. Lett. B **618** (2005) 252–258 [[hep-th/0501070](#)].
- [9] V. Bouchard and R. Donagi, *An $SU(5)$ heterotic standard model*, Phys. Lett. **B633** (2006) 783–791 [[hep-th/0512149](#)].
- [10] V. Bouchard, M. Cvetič and R. Donagi, *Tri-linear couplings in an heterotic minimal supersymmetric standard model*, Nucl. Phys. B **745** (2006) 62–83 [[hep-th/0602096](#)].
- [11] L. B. Anderson, J. Gray, Y.-H. He and A. Lukas, *Exploring Positive Monad Bundles And A New Heterotic Standard Model*, JHEP **02** (2010) 054 [[0911.1569](#)].
- [12] L. B. Anderson, J. Gray, A. Lukas and E. Palti, *Two Hundred Heterotic Standard Models on Smooth Calabi–Yau Threefolds*, Phys. Rev. D **84** (2011) 106005 [[1106.4804](#)].
- [13] L. B. Anderson, J. Gray, A. Lukas and E. Palti, *Heterotic Line Bundle Standard Models*, JHEP **06** (2012) 113 [[1202.1757](#)].
- [14] O. Lebedev, H. P. Nilles, S. Raby, S. Ramos-Sanchez, M. Ratz, P. K. S. Vaudrevange and A. Wingerter, *The Heterotic Road to the MSSM with R parity*, Phys. Rev. D **77** (2008) 046013 [[0708.2691](#)].

- [15] O. Lebedev, H. P. Nilles, S. Raby, S. Ramos-Sanchez, M. Ratz, P. K. S. Vaudrevange and A. Wingerter, *A Mini-landscape of exact MSSM spectra in heterotic orbifolds*, Phys. Lett. B **645** (2007) 88–94 [[hep-th/0611095](#)].
- [16] A. E. Faraggi, D. V. Nanopoulos and K.-j. Yuan, *A Standard Like Model in the 4D Free Fermionic String Formulation*, Nucl. Phys. B **335** (1990) 347–362.
- [17] A. E. Faraggi, *A New standard - like model in the four-dimensional free fermionic string formulation*, Phys. Lett. B **278** (1992) 131–139.
- [18] L. B. Anderson, A. Constantin, J. Gray, A. Lukas and E. Palti, *A Comprehensive Scan for Heterotic SU(5) GUT models*, JHEP **01** (2014) 047 [[1307.4787](#)].
- [19] J. Polchinski, *Dirichlet Branes and Ramond-Ramond charges*, Phys. Rev. Lett. **75** (1995) 4724–4727 [[hep-th/9510017](#)].
- [20] G. Shiu and S. H. H. Tye, *TeV scale superstring and extra dimensions*, Phys. Rev. D **58** (1998) 106007 [[hep-th/9805157](#)].
- [21] G. Aldazabal, L. E. Ibanez, F. Quevedo and A. M. Uranga, *D-branes at singularities: A Bottom up approach to the string embedding of the standard model*, JHEP **08** (2000) 002 [[hep-th/0005067](#)].
- [22] M. Cvetič, A. M. Uranga and J. Wang, *Discrete Wilson lines in N=1 D = 4 type IIB orientifolds: A Systematic exploration for Z(6) orientifold*, Nucl. Phys. B **595** (2001) 63–92 [[hep-th/0010091](#)].
- [23] D. Berenstein, V. Jejjala and R. G. Leigh, *The Standard model on a D-brane*, Phys. Rev. Lett. **88** (2002) 071602 [[hep-ph/0105042](#)].
- [24] H. Verlinde and M. Wijnholt, *Building the standard model on a D3-brane*, JHEP **01** (2007) 106 [[hep-th/0508089](#)].
- [25] M. Berkooz, M. R. Douglas and R. G. Leigh, *Branes intersecting at angles*, Nucl. Phys. **B480** (1996) 265–278 [[hep-th/9606139](#)].
- [26] G. Aldazabal, S. Franco, L. E. Ibanez, R. Rabadan and A. M. Uranga, *D = 4 chiral string compactifications from intersecting branes*, J. Math. Phys. **42** (2001) 3103–3126 [[hep-th/0011073](#)].
- [27] G. Aldazabal, S. Franco, L. E. Ibanez, R. Rabadan and A. M. Uranga, *Intersecting brane worlds*, JHEP **02** (2001) 047 [[hep-ph/0011132](#)].
- [28] L. E. Ibanez, F. Marchesano and R. Rabadan, *Getting just the standard model at intersecting branes*, JHEP **11** (2001) 002 [[hep-th/0105155](#)].
- [29] R. Blumenhagen, B. Kors, D. Lüst and T. Ott, *The standard model from stable intersecting brane world orbifolds*, Nucl. Phys. **B616** (2001) 3–33 [[hep-th/0107138](#)].
- [30] M. Cvetič, G. Shiu and A. M. Uranga, *Three family supersymmetric standard - like models from intersecting brane worlds*, Phys. Rev. Lett. **87** (2001) 201801 [[hep-th/0107143](#)].
- [31] M. Cvetič, G. Shiu and A. M. Uranga, *Chiral four-dimensional N=1 supersymmetric type 2A orientifolds from intersecting D6 branes*, Nucl. Phys. **B615** (2001) 3–32 [[hep-th/0107166](#)].
- [32] R. Blumenhagen, M. Cvetič, P. Langacker and G. Shiu, *Toward realistic intersecting D-brane models*, Ann. Rev. Nucl. Part. Sci. **55** (2005) 71–139 [[hep-th/0502005](#)].

- [33] B. S. Acharya, K. Bobkov, G. L. Kane, J. Shao and P. Kumar, *The $G(2)$ -MSSM: An M Theory motivated model of Particle Physics*, Phys. Rev. D **78** (2008) 065038 [[0801.0478](#)].
- [34] C. Vafa, *Evidence for F theory*, Nucl. Phys. **B469** (1996) 403–418 [[hep-th/9602022](#)].
- [35] D. R. Morrison and C. Vafa, *Compactifications of F theory on Calabi-Yau threefolds. 1.*, Nucl.Phys. **B473** (1996) 74–92 [[hep-th/9602114](#)].
- [36] D. R. Morrison and C. Vafa, *Compactifications of F theory on Calabi-Yau threefolds. 2.*, Nucl.Phys. **B476** (1996) 437–469 [[hep-th/9603161](#)].
- [37] R. Donagi and M. Wijnholt, *Breaking GUT Groups in F -Theory*, Adv. Theor. Math. Phys. **15** (2011), no. 6, 1523–1603 [[0808.2223](#)].
- [38] C. Beasley, J. J. Heckman and C. Vafa, *GUTs and Exceptional Branes in F -theory - I*, JHEP **01** (2009) 058 [[0802.3391](#)].
- [39] C. Beasley, J. J. Heckman and C. Vafa, *GUTs and Exceptional Branes in F -theory - II: Experimental Predictions*, JHEP **01** (2009) 059 [[0806.0102](#)].
- [40] R. Donagi and M. Wijnholt, *Model Building with F -Theory*, Adv. Theor. Math. Phys. **15** (2011), no. 5, 1237–1317 [[0802.2969](#)].
- [41] A. Grassi, J. Halverson, J. Shaneson and W. Taylor, *Non-Higgsable QCD and the Standard Model Spectrum in F -theory*, JHEP **01** (2015) 086 [[1409.8295](#)].
- [42] D. Klevers, D. K. Mayorga Peña, P.-K. Oehlmann, H. Piragua and J. Reuter, *F -Theory on all Toric Hypersurface Fibrations and its Higgs Branches*, JHEP **01** (2015) 142 [[1408.4808](#)].
- [43] M. Cvetič, D. Klevers, D. K. M. Peña, P.-K. Oehlmann and J. Reuter, *Three-Family Particle Physics Models from Global F -theory Compactifications*, JHEP **08** (2015) 087 [[1503.02068](#)].
- [44] W. Taylor and A. P. Turner, *Generic Construction of the Standard Model Gauge Group and Matter Representations in F -theory*, Fortsch. Phys. **68** (2020), no. 5, 2000009 [[1906.11092](#)].
- [45] N. Raghuram, W. Taylor and A. P. Turner, *General F -theory models with tuned $(SU(3) \times SU(2) \times U(1))/\mathbb{Z}_6$ symmetry*, JHEP **04** (2020) 008 [[1912.10991](#)].
- [46] S. Y. Li and W. Taylor, *Natural F -theory constructions of Standard Model structure from E_7 flux breaking*, [2112.03947](#).
- [47] J. Marsano, N. Saulina and S. Schafer-Nameki, *A Note on G -Fluxes for F -theory Model Building*, JHEP **11** (2010) 088 [[1006.0483](#)].
- [48] A. P. Braun, A. Collinucci and R. Valandro, *G -flux in F -theory and algebraic cycles*, Nucl. Phys. **B856** (2012) 129–179 [[1107.5337](#)].
- [49] J. Marsano and S. Schafer-Nameki, *Yukawas, G -flux, and Spectral Covers from Resolved Calabi-Yau's*, JHEP **11** (2011) 098 [[1108.1794](#)].
- [50] T. W. Grimm and H. Hayashi, *F -theory fluxes, Chirality and Chern-Simons theories*, JHEP **1203** (2012) 027 [[1111.1232](#)].
- [51] S. Krause, C. Mayrhofer and T. Weigand, *Gauge Fluxes in F -theory and Type IIB Orientifolds*, JHEP **08** (2012) 119 [[1202.3138](#)].
- [52] V. Braun, T. W. Grimm and J. Keitel, *Geometric Engineering in Toric F -Theory and GUTs with $U(1)$ Gauge Factors*, JHEP **12** (2013) 069 [[1306.0577](#)].

- [53] M. Cvetič, A. Grassi, D. Klevers and H. Piragua, *Chiral Four-Dimensional F-Theory Compactifications With $SU(5)$ and Multiple $U(1)$ -Factors*, JHEP **04** (2014) 010 [[1306.3987](#)].
- [54] L. Lin, C. Mayrhofer, O. Till and T. Weigand, *Fluxes in F-theory Compactifications on Genus-One Fibrations*, JHEP **01** (2016) 098 [[1508.00162](#)].
- [55] L. Lin and T. Weigand, *G_4 -flux and standard model vacua in F-theory*, Nucl. Phys. **B913** (2016) 209–247 [[1604.04292](#)].
- [56] P. Jefferson, W. Taylor and A. P. Turner, *Chiral matter multiplicities and resolution-independent structure in 4D F-theory models*, [2108.07810](#).
- [57] S. Krause, C. Mayrhofer and T. Weigand, *G_4 flux, chiral matter and singularity resolution in F-theory compactifications*, Nucl. Phys. **B858** (2012) 1–47 [[1109.3454](#)].
- [58] M. Cvetič, L. Lin, M. Liu and P.-K. Oehlmann, *An F-theory Realization of the Chiral MSSM with \mathbb{Z}_2 -Parity*, JHEP **09** (2018) 089 [[1807.01320](#)].
- [59] M. Cvetič, J. Halverson, L. Lin, M. Liu and J. Tian, *Quadrillion F-Theory Compactifications with the Exact Chiral Spectrum of the Standard Model*, Phys. Rev. Lett. **123** (2019), no. 10, 101601 [[1903.00009](#)].
- [60] C. Mayrhofer, E. Palti and T. Weigand, *Hypercharge Flux in IIB and F-theory: Anomalies and Gauge Coupling Unification*, JHEP **09** (2013) 082 [[1303.3589](#)].
- [61] A. P. Braun, A. Collinucci and R. Valandro, *Hypercharge flux in F-theory and the stable Sen limit*, JHEP **07** (2014) 121 [[1402.4096](#)].
- [62] J. J. Heckman, *Particle Physics Implications of F-theory*, Ann. Rev. Nucl. Part. Sci. **60** (2010) 237–265 [[1001.0577](#)].
- [63] S. Schäfer-Nameki, *F-theory: From Geometry to Phenomenology*, Adv. Ser. Direct. High Energy Phys. **22** (2015) 245–275.
- [64] T. Weigand, *F-theory*, PoS **TASI2017** (2018) 016 [[1806.01854](#)].
- [65] A. P. Braun and T. Watari, *Distribution of the Number of Generations in Flux Compactifications*, Phys. Rev. **D90** (2014), no. 12, 121901 [[1408.6156](#)].
- [66] D. R. Morrison and W. Taylor, *Non-Higgsable clusters for 4D F-theory models*, JHEP **05** (2015) 080 [[1412.6112](#)].
- [67] J. Tian and Y.-N. Wang, *E-string and model building on a typical F-theory geometry*, [[1811.02837](#)].
- [68] F. Denef and M. R. Douglas, *Distributions of flux vacua*, JHEP **05** (2004) 072 [[hep-th/0404116](#)].
- [69] F. Denef, *Les Houches Lectures on Constructing String Vacua*, Les Houches **87** (2008) 483–610 [[0803.1194](#)].
- [70] M. Bies, C. Mayrhofer, C. Pehle and T. Weigand, *Chow groups, Deligne cohomology and massless matter in F-theory*, [1402.5144](#).
- [71] M. Bies, C. Mayrhofer and T. Weigand, *Gauge Backgrounds and Zero-Mode Counting in F-Theory*, JHEP **11** (2017) 081 [[1706.04616](#)].

- [72] M. Bies, M. Cvetič, R. Donagi, M. Liu and M. Ong, *Root bundles and towards exact matter spectra of F-theory MSSMs*, JHEP **09** (2021) 076 [[2102.10115](#)].
- [73] J. J. Heckman and C. Vafa, *Flavor Hierarchy From F-theory*, Nucl. Phys. B **837** (2010) 137–151 [[0811.2417](#)].
- [74] H. Hayashi, T. Kawano, R. Tatar and T. Watari, *Codimension-3 Singularities and Yukawa Couplings in F-theory*, Nucl. Phys. B **823** (2009) 47–115 [[0901.4941](#)].
- [75] S. Cecotti, M. C. N. Cheng, J. J. Heckman and C. Vafa, *Yukawa Couplings in F-theory and Non-Commutative Geometry*, [0910.0477](#).
- [76] M. Cvetič, L. Lin, M. Liu, H. Y. Zhang and G. Zoccarato, *Yukawa Hierarchies in Global F-theory Models*, JHEP **01** (2020) 037 [[1906.10119](#)].
- [77] A. Collinucci and I. n. García-Etxebarria, *E_6 Yukawa couplings in F-theory as D-brane instanton effects*, JHEP **03** (2017) 155 [[1612.06874](#)].
- [78] R. Blumenhagen, M. Cvetič and T. Weigand, *Spacetime instanton corrections in 4D string vacua: The Seesaw mechanism for D-Brane models*, Nucl. Phys. B **771** (2007) 113–142 [[hep-th/0609191](#)].
- [79] L. E. Ibanez and A. M. Uranga, *Neutrino Majorana Masses from String Theory Instanton Effects*, JHEP **03** (2007) 052 [[hep-th/0609213](#)].
- [80] B. Florea, S. Kachru, J. McGreevy and N. Saulina, *Stringy Instantons and Quiver Gauge Theories*, JHEP **05** (2007) 024 [[hep-th/0610003](#)].
- [81] R. Blumenhagen, M. Cvetič, D. Lust, R. Richter and T. Weigand, *Non-perturbative Yukawa Couplings from String Instantons*, Phys. Rev. Lett. **100** (2008) 061602 [[0707.1871](#)].
- [82] R. Blumenhagen, M. Cvetič, S. Kachru and T. Weigand, *D-Brane Instantons in Type II Orientifolds*, Ann. Rev. Nucl. Part. Sci. **59** (2009) 269–296 [[0902.3251](#)].
- [83] Z. Kakushadze, G. Shiu and S. H. H. Tye, *Couplings in asymmetric orbifolds and grand unified string models*, Nucl. Phys. B **501** (1997) 547–597 [[hep-th/9704113](#)].
- [84] V. Braun, T. Brelidze, M. R. Douglas and B. A. Ovrut, *Eigenvalues and Eigenfunctions of the Scalar Laplace Operator on Calabi-Yau Manifolds*, JHEP **07** (2008) 120 [[0805.3689](#)].
- [85] M. Cvetič and I. Papadimitriou, *Conformal field theory couplings for intersecting D-branes on orientifolds*, Phys. Rev. D **68** (2003) 046001 [[hep-th/0303083](#)], [Erratum: Phys.Rev.D 70, 029903 (2004)].
- [86] M. Cvetič, J. Halverson and R. Richter, *Realistic Yukawa structures from orientifold compactifications*, JHEP **12** (2009) 063 [[0905.3379](#)].
- [87] K. R. Dienes and J. March-Russell, *Realizing higher level gauge symmetries in string theory: New embeddings for string GUTs*, Nucl. Phys. B **479** (1996) 113–172 [[hep-th/9604112](#)].
- [88] D. Klevers, D. R. Morrison, N. Raghuram and W. Taylor, *Exotic matter on singular divisors in F-theory*, JHEP **11** (2017) 124 [[1706.08194](#)].
- [89] M. Cvetič, J. J. Heckman and L. Lin, *Towards Exotic Matter and Discrete Non-Abelian Symmetries in F-theory*, JHEP **11** (2018) 001 [[1806.10594](#)].

- [90] M. Esole and M. J. Kang, *Matter representations from geometry: under the spell of Dynkin*, [2012.13401](#).
- [91] W. Taylor and A. P. Turner, *An infinite swampland of $U(1)$ charge spectra in 6D supergravity theories*, JHEP **06** (2018) 010 [[1803.04447](#)].
- [92] N. Raghuram and W. Taylor, *Large $U(1)$ charges in F-theory*, JHEP **10** (2018) 182 [[1809.01666](#)].
- [93] F. M. Cianci, D. K. Mayorga Peña and R. Valandro, *High $U(1)$ charges in type IIB models and their F-theory lift*, JHEP **04** (2019) 012 [[1811.11777](#)].
- [94] A. Collinucci, M. Fazzi, D. R. Morrison and R. Valandro, *High electric charges in M-theory from quiver varieties*, JHEP **11** (2019) 111 [[1906.02202](#)].
- [95] N. Raghuram and A. P. Turner, *Orders of vanishing and $U(1)$ charges in F-theory*, JHEP **03** (2022) 051 [[2110.10159](#)].
- [96] M. Cvetič and L. Lin, *The Global Gauge Group Structure of F-theory Compactification with $U(1)$ s*, JHEP **01** (2018) 157 [[1706.08521](#)].
- [97] W. Taylor and A. P. Turner, *Generic matter representations in 6D supergravity theories*, JHEP **05** (2019) 081 [[1901.02012](#)].
- [98] C. Mayrhofer, D. R. Morrison, O. Till and T. Weigand, *Mordell-Weil Torsion and the Global Structure of Gauge Groups in F-theory*, JHEP **10** (2014) 016 [[1405.3656](#)].
- [99] M. Cvetič and L. Lin, *TASI Lectures on Abelian and Discrete Symmetries in F-theory*, PoS **TASI2017** (2018) 020 [[1809.00012](#)].
- [100] T. Banks and N. Seiberg, *Symmetries and Strings in Field Theory and Gravity*, Phys. Rev. D **83** (2011) 084019 [[1011.5120](#)].
- [101] D. Harlow and H. Ooguri, *Symmetries in quantum field theory and quantum gravity*, Commun. Math. Phys. **383** (2021), no. 3, 1669–1804 [[1810.05338](#)].
- [102] J. Halverson and P. Langacker, *TASI Lectures on Remnants from the String Landscape*, PoS **TASI2017** (2018) 019 [[1801.03503](#)].
- [103] P. Svrcek and E. Witten, *Axions In String Theory*, JHEP **06** (2006) 051 [[hep-th/0605206](#)].
- [104] M. Kreuzer and H. Skarke, *Complete classification of reflexive polyhedra in four-dimensions*, Adv. Theor. Math. Phys. **4** (2000) 1209–1230 [[hep-th/0002240](#)].
- [105] W. Taylor and Y.-N. Wang, *The F-theory geometry with most flux vacua*, JHEP **12** (2015) 164 [[1511.03209](#)].
- [106] W. Taylor and Y.-N. Wang, *A Monte Carlo exploration of threefold base geometries for 4d F-theory vacua*, JHEP **01** (2016) 137 [[1510.04978](#)].
- [107] J. Halverson, C. Long and B. Sung, *Algorithmic universality in F-theory compactifications*, Phys. Rev. D **96** (2017), no. 12, 126006 [[1706.02299](#)].
- [108] W. Taylor and Y.-N. Wang, *Scanning the skeleton of the 4D F-theory landscape*, JHEP **01** (2018) 111 [[1710.11235](#)].
- [109] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, *String Axiverse*, Phys. Rev. D **81** (2010) 123530 [[0905.4720](#)].

- [110] M. Demirtas, C. Long, L. McAllister and M. Stillman, *The Kreuzer-Skarke Axiverse*, JHEP **04** (2020) 138 [[1808.01282](#)].
- [111] L. McAllister, E. Silverstein and A. Westphal, *Gravity Waves and Linear Inflation from Axion Monodromy*, Phys. Rev. D **82** (2010) 046003 [[0808.0706](#)].
- [112] R. Flauger, L. McAllister, E. Pajer, A. Westphal and G. Xu, *Oscillations in the CMB from Axion Monodromy Inflation*, JCAP **06** (2010) 009 [[0907.2916](#)].
- [113] F. Marchesano, G. Shiu and A. M. Uranga, *F-term Axion Monodromy Inflation*, JHEP **09** (2014) 184 [[1404.3040](#)].
- [114] A. Hebecker, S. C. Kraus and L. T. Witkowski, *D7-Brane Chaotic Inflation*, Phys. Lett. B **737** (2014) 16–22 [[1404.3711](#)].
- [115] L. McAllister, E. Silverstein, A. Westphal and T. Wrase, *The Powers of Monodromy*, JHEP **09** (2014) 123 [[1405.3652](#)].
- [116] A. Hebecker, P. Mangat, F. Rompineve and L. T. Witkowski, *Tuning and Backreaction in F-term Axion Monodromy Inflation*, Nucl. Phys. B **894** (2015) 456–495 [[1411.2032](#)].
- [117] R. Blumenhagen and E. Plauschinn, *Towards Universal Axion Inflation and Reheating in String Theory*, Phys. Lett. B **736** (2014) 482–487 [[1404.3542](#)].
- [118] J. Halverson, C. Long, B. Nelson and G. Salinas, *Axion reheating in the string landscape*, Phys. Rev. D **99** (2019), no. 8, 086014 [[1903.04495](#)].
- [119] L. E. Ibanez, M. Montero, A. Uranga and I. Valenzuela, *Relaxion Monodromy and the Weak Gravity Conjecture*, JHEP **04** (2016) 020 [[1512.00025](#)].
- [120] J. Brown, W. Cottrell, G. Shiu and P. Soler, *Tunneling in Axion Monodromy*, JHEP **10** (2016) 025 [[1607.00037](#)].
- [121] L. McAllister, P. Schwaller, G. Servant, J. Stout and A. Westphal, *Runaway Relaxion Monodromy*, JHEP **02** (2018) 124 [[1610.05320](#)].
- [122] L. Hui, J. P. Ostriker, S. Tremaine and E. Witten, *Ultralight scalars as cosmological dark matter*, Phys. Rev. D **95** (2017), no. 4, 043541 [[1610.08297](#)].
- [123] J. Halverson, C. Long and P. Nath, *Ultralight axion in supersymmetry and strings and cosmology at small scales*, Phys. Rev. D **96** (2017), no. 5, 056025 [[1703.07779](#)].
- [124] M. Cicoli, V. Guidetti, N. Righi and A. Westphal, *Fuzzy Dark Matter Candidates from String Theory*, [2110.02964](#).
- [125] V. M. Mehta, M. Demirtas, C. Long, D. J. E. Marsh, L. McAllister and M. J. Stott, *Superradiance in string theory*, JCAP **07** (2021) 033 [[2103.06812](#)].
- [126] N. Kitajima, J. Soda and Y. Urakawa, *Gravitational wave forest from string axiverse*, JCAP **10** (2018) 008 [[1807.07037](#)].
- [127] N. Barnaby, J. Moxon, R. Namba, M. Peloso, G. Shiu and P. Zhou, *Gravity waves and non-Gaussian features from particle production in a sector gravitationally coupled to the inflaton*, Phys. Rev. D **86** (2012) 103508 [[1206.6117](#)].
- [128] S. Mukohyama, R. Namba, M. Peloso and G. Shiu, *Blue Tensor Spectrum from Particle Production during Inflation*, JCAP **08** (2014) 036 [[1405.0346](#)].

- [129] J. Liu, Z.-K. Guo, R.-G. Cai and G. Shiu, *Gravitational Waves from Oscillons with Cuspy Potentials*, Phys. Rev. Lett. **120** (2018), no. 3, 031301 [[1707.09841](#)].
- [130] J. Liu, Z.-K. Guo, R.-G. Cai and G. Shiu, *Gravitational wave production after inflation with cuspy potentials*, Phys. Rev. D **99** (2018), no. 10, 103506 [[1812.09235](#)].
- [131] J. Halverson, C. Long, B. Nelson and G. Salinas, *Towards string theory expectations for photon couplings to axionlike particles*, Phys. Rev. D **100** (2019), no. 10, 106010 [[1909.05257](#)].
- [132] M. Demirtas, N. Gendler, C. Long, L. McAllister and J. Moritz, *PQ Axiverse*, [2112.04503](#).
- [133] A. E. Faraggi and M. Pospelov, *Self-interacting dark matter from the hidden heterotic string sector*, Astropart. Phys. **16** (2002) 451–461 [[hep-ph/0008223](#)].
- [134] R. Friedman, J. Morgan and E. Witten, *Vector bundles and F theory*, Commun. Math. Phys. **187** (1997) 679–743 [[hep-th/9701162](#)].
- [135] A. P. Braun and S. Schäfer-Nameki, *Compact, Singular G_2 -Holonomy Manifolds and M/Heterotic/F-Theory Duality*, JHEP **04** (2018) 126 [[1708.07215](#)].
- [136] J. Halverson, B. D. Nelson and F. Ruehle, *String Theory and the Dark Glueball Problem*, Phys. Rev. D **95** (2017), no. 4, 043527 [[1609.02151](#)].
- [137] K. R. Dienes, F. Huang, S. Su and B. Thomas, *Dynamical Dark Matter from Strongly-Coupled Dark Sectors*, Phys. Rev. D **95** (2017), no. 4, 043526 [[1610.04112](#)].
- [138] B. S. Acharya, M. Fairbairn and E. Hardy, *Glueball dark matter in non-standard cosmologies*, JHEP **07** (2017) 100 [[1704.01804](#)].
- [139] W.-Z. Feng, G. Shiu, P. Soler and F. Ye, *Building a Stückelberg portal*, JHEP **05** (2014) 065 [[1401.5890](#)].
- [140] W.-Z. Feng, G. Shiu, P. Soler and F. Ye, *Probing Hidden Sectors with Stückelberg $U(1)$ Gauge Fields*, Phys. Rev. Lett. **113** (2014) 061802 [[1401.5880](#)].
- [141] M. Cirelli, N. Fornengo and A. Strumia, *Minimal dark matter*, Nucl. Phys. B **753** (2006) 178–194 [[hep-ph/0512090](#)].
- [142] J. Halverson, N. Orlofsky and A. Pierce, *Vectorlike Leptons as the Tip of the Dark Matter Iceberg*, Phys. Rev. D **90** (2014), no. 1, 015002 [[1403.1592](#)].
- [143] LHCb Collaboration, R. Aaij *et al.*, *Test of lepton universality in beauty-quark decays*, Nature Phys. **18** (2022), no. 3, 277–282 [[2103.11769](#)].
- [144] P. Anastasopoulos, T. P. T. Dijkstra, E. Kiritsis and A. N. Schellekens, *Orientifolds, hypercharge embeddings and the Standard Model*, Nucl. Phys. B **759** (2006) 83–146 [[hep-th/0605226](#)].
- [145] M. Cvetič, J. Halverson and P. Langacker, *Implications of String Constraints for Exotic Matter and Z' s Beyond the Standard Model*, JHEP **11** (2011) 058 [[1108.5187](#)].
- [146] J. Halverson, *Anomaly Nucleation Constrains $SU(2)$ Gauge Theories*, Phys. Rev. Lett. **111** (2013), no. 26, 261601 [[1310.1091](#)].
- [147] Z. Kakushadze, G. Shiu, S. H. H. Tye and Y. Vtorov-Karevsky, *A Review of three family grand unified string models*, Int. J. Mod. Phys. A **13** (1998) 2551–2598 [[hep-th/9710149](#)].

- [148] M. Cvetič, P. Langacker and G. Shiu, *Phenomenology of a three family standard like string model*, Phys. Rev. D **66** (2002) 066004 [[hep-ph/0205252](#)].
- [149] D. R. Morrison and W. Taylor, *Classifying bases for 6D F-theory models*, Central Eur. J. Phys. **10** (2012) 1072–1088 [[1201.1943](#)].
- [150] B. S. Acharya, *Supersymmetry, Ricci Flat Manifolds and the String Landscape*, JHEP **08** (2020) 128 [[1906.06886](#)].
- [151] E. Witten, *Instability of the Kaluza-Klein Vacuum*, Nucl. Phys. B **195** (1982) 481–492.
- [152] I. n. García Etxebarria, M. Montero, K. Sousa and I. Valenzuela, *Nothing is certain in string compactifications*, JHEP **12** (2020) 032 [[2005.06494](#)].
- [153] B. S. Acharya, G. Aldazabal, E. Andrés, A. Font, K. Narain and I. G. Zadeh, *Stringy Tachyonic Instabilities of Non-Supersymmetric Ricci Flat Backgrounds*, JHEP **04** (2021) 026 [[2010.02933](#)].
- [154] G. B. De Luca, E. Silverstein and G. Torroba, *Hyperbolic compactification of M-theory and de Sitter quantum gravity*, SciPost Phys. **12** (2022), no. 3, 083 [[2104.13380](#)].
- [155] R. Blumenhagen, S. Moster and E. Plauschinn, *Moduli Stabilisation versus Chirality for MSSM like Type IIB Orientifolds*, JHEP **01** (2008) 058 [[0711.3389](#)].
- [156] R. Blumenhagen, J. P. Conlon, S. Krippendorf, S. Moster and F. Quevedo, *SUSY Breaking in Local String/F-Theory Models*, JHEP **09** (2009) 007 [[0906.3297](#)].
- [157] T. W. Grimm, M. Kerstan, E. Palti and T. Weigand, *Massive Abelian Gauge Symmetries and Fluxes in F-theory*, JHEP **12** (2011) 004 [[1107.3842](#)].
- [158] M. Cicoli, S. Krippendorf, C. Mayrhofer, F. Quevedo and R. Valandro, *D-Branes at del Pezzo Singularities: Global Embedding and Moduli Stabilisation*, JHEP **09** (2012) 019 [[1206.5237](#)].
- [159] F. Carta, J. Moritz and A. Westphal, *Gaugino condensation and small uplifts in KKLT*, JHEP **08** (2019) 141 [[1902.01412](#)].
- [160] I. Bena, J. Blåbäck, M. Graña and S. Lüst, *The tadpole problem*, JHEP **11** (2021) 223 [[2010.10519](#)].
- [161] I. Bena, J. Blåbäck, M. Graña and S. Lüst, *Algorithmically Solving the Tadpole Problem*, Adv. Appl. Clifford Algebras **32** (2022), no. 1, 7 [[2103.03250](#)].
- [162] X. Gao, A. Hebecker, S. Schreyer and G. Venken, *The LVS Parametric Tadpole Constraint*, [2202.04087](#).
- [163] M. R. Douglas and S. Kachru, *Flux compactification*, Rev. Mod. Phys. **79** (2007) 733–796 [[hep-th/0610102](#)].
- [164] S. Kachru, R. Kallosh, A. D. Linde and S. P. Trivedi, *De Sitter vacua in string theory*, Phys. Rev. D **68** (2003) 046005 [[hep-th/0301240](#)].
- [165] V. Balasubramanian, P. Berglund, J. P. Conlon and F. Quevedo, *Systematics of moduli stabilisation in Calabi-Yau flux compactifications*, JHEP **03** (2005) 007 [[hep-th/0502058](#)].
- [166] J. M. Maldacena and C. Nunez, *Supergravity description of field theories on curved manifolds and a no go theorem*, Int. J. Mod. Phys. A **16** (2001) 822–855 [[hep-th/0007018](#)].

- [167] M. P. Hertzberg, S. Kachru, W. Taylor and M. Tegmark, *Inflationary Constraints on Type IIA String Theory*, JHEP **12** (2007) 095 [[0711.2512](#)].
- [168] U. H. Danielsson, S. S. Haque, G. Shiu and T. Van Riet, *Towards Classical de Sitter Solutions in String Theory*, JHEP **09** (2009) 114 [[0907.2041](#)].
- [169] T. Wrase and M. Zagermann, *On Classical de Sitter Vacua in String Theory*, Fortsch. Phys. **58** (2010) 906–910 [[1003.0029](#)].
- [170] U. H. Danielsson, S. S. Haque, P. Koerber, G. Shiu, T. Van Riet and T. Wrase, *De Sitter hunting in a classical landscape*, Fortsch. Phys. **59** (2011) 897–933 [[1103.4858](#)].
- [171] G. Shiu and Y. Sumitomo, *Stability Constraints on Classical de Sitter Vacua*, JHEP **09** (2011) 052 [[1107.2925](#)].
- [172] U. H. Danielsson, G. Shiu, T. Van Riet and T. Wrase, *A note on obstinate tachyons in classical dS solutions*, JHEP **03** (2013) 138 [[1212.5178](#)].
- [173] D. Junghans, *Tachyons in Classical de Sitter Vacua*, JHEP **06** (2016) 132 [[1603.08939](#)].
- [174] D. Junghans and M. Zagermann, *A Universal Tachyon in Nearly No-scale de Sitter Compactifications*, JHEP **07** (2018) 078 [[1612.06847](#)].
- [175] D. Andriot, *On the de Sitter swampland criterion*, Phys. Lett. B **785** (2018) 570–573 [[1806.10999](#)].
- [176] D. Andriot, *New constraints on classical de Sitter: flirting with the swampland*, Fortsch. Phys. **67** (2019), no. 1-2, 1800103 [[1807.09698](#)].
- [177] S. K. Garg and C. Krishnan, *Bounds on Slow Roll and the de Sitter Swampland*, JHEP **11** (2019) 075 [[1807.05193](#)].
- [178] U. H. Danielsson and T. Van Riet, *What if string theory has no de Sitter vacua?*, Int. J. Mod. Phys. D **27** (2018), no. 12, 1830007 [[1804.01120](#)].
- [179] G. Obied, H. Ooguri, L. Spodyneiko and C. Vafa, *De Sitter Space and the Swampland*, [1806.08362](#).
- [180] H. Ooguri, E. Palti, G. Shiu and C. Vafa, *Distance and de Sitter Conjectures on the Swampland*, Phys. Lett. B **788** (2019) 180–184 [[1810.05506](#)].
- [181] M. Dine and N. Seiberg, *Is the Superstring Weakly Coupled?*, Phys. Lett. B **162** (1985) 299–302.
- [182] B. Freivogel and M. Kleban, *Vacua Morphology*, [1610.04564](#).
- [183] S. Sethi, *Supersymmetry Breaking by Fluxes*, JHEP **10** (2018) 022 [[1709.03554](#)].
- [184] M. Demirtas, M. Kim, L. McAllister, J. Moritz and A. Rios-Tascon, *Small cosmological constants in string theory*, JHEP **12** (2021) 136 [[2107.09064](#)].
- [185] A. Cole, A. Schachner and G. Shiu, *Searching the Landscape of Flux Vacua with Genetic Algorithms*, JHEP **11** (2019) 045 [[1907.10072](#)].
- [186] X. Gao, A. Hebecker and D. Junghans, *Control issues of KKLT*, Fortsch. Phys. **68** (2020) 2000089 [[2009.03914](#)].
- [187] F. Carta and J. Moritz, *Resolving spacetime singularities in flux compactifications & KKLT*, JHEP **08** (2021) 093 [[2101.05281](#)].

- [188] Y. Hamada, A. Hebecker, G. Shiu and P. Soler, *On brane gaugino condensates in 10d*, JHEP **04** (2019) 008 [[1812.06097](#)].
- [189] Y. Hamada, A. Hebecker, G. Shiu and P. Soler, *Understanding KKLT from a 10d perspective*, JHEP **06** (2019) 019 [[1902.01410](#)].
- [190] S. Kachru, M. Kim, L. Mcallister and M. Zimet, *de Sitter vacua from ten dimensions*, JHEP **12** (2021) 111 [[1908.04788](#)].
- [191] Y. Hamada, A. Hebecker, G. Shiu and P. Soler, *Completing the D7-brane local gaugino action*, JHEP **11** (2021) 033 [[2105.11467](#)].
- [192] I. Bena, M. Graña, N. Kovensky and A. Retolaza, *Kähler moduli stabilization from ten dimensions*, JHEP **10** (2019) 200 [[1908.01785](#)].
- [193] M. Cvetič, J. Halverson, L. Lin and C. Long, *Constraints on Standard Model Constructions in F-theory*, Phys. Rev. D **102** (2020), no. 2, 026012 [[2004.00630](#)].
- [194] G. 't Hooft, *Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking*, NATO Sci. Ser. B **59** (1980) 135–157.
- [195] T. Banks and L. J. Dixon, *Constraints on String Vacua with Space-Time Supersymmetry*, Nucl. Phys. B **307** (1988) 93–108.
- [196] S. Minwalla, M. Van Raamsdonk and N. Seiberg, *Noncommutative perturbative dynamics*, JHEP **02** (2000) 020 [[hep-th/9912072](#)].
- [197] S. Abel and K. R. Dienes, *Calculating the Higgs mass in string theory*, Phys. Rev. D **104** (2021), no. 12, 126032 [[2106.04622](#)].
- [198] M. R. Douglas, *Basic results in vacuum statistics*, Comptes Rendus Physique **5** (2004) 965–977 [[hep-th/0409207](#)].
- [199] L. Susskind, *Supersymmetry breaking in the anthropic landscape*, in *From Fields to Strings: Circumnavigating Theoretical Physics: A Conference in Tribute to Ian Kogan*, pp. 1745–1749. 5, 2004. [hep-th/0405189](#).
- [200] M. R. Douglas, *Statistical analysis of the supersymmetry breaking scale*, [hep-th/0405279](#).
- [201] M. Dine, E. Gorbatov and S. D. Thomas, *Low energy supersymmetry from the landscape*, JHEP **08** (2008) 098 [[hep-th/0407043](#)].
- [202] C. Vafa, *The String landscape and the swampland*, [hep-th/0509212](#).
- [203] T. D. Brennan, F. Carta and C. Vafa, *The String Landscape, the Swampland, and the Missing Corner*, PoS **TASI2017** (2017) 015 [[1711.00864](#)].
- [204] E. Palti, *The Swampland: Introduction and Review*, Fortsch. Phys. **67** (2019), no. 6, 1900037 [[1903.06239](#)].
- [205] M. van Beest, J. Calderón-Infante, D. Mirfendereski and I. Valenzuela, *Lectures on the Swampland Program in String Compactifications*, [2102.01111](#).
- [206] M. Graña and A. Herráez, *The Swampland Conjectures: A Bridge from Quantum Gravity to Particle Physics*, Universe **7** (2021), no. 8, 273 [[2107.00087](#)].
- [207] D. Harlow, B. Heidenreich, M. Reece and T. Rudelius, *The Weak Gravity Conjecture: A Review*, [2201.08380](#).

- [208] G. Shiu, P. Soler and F. Ye, *Milli-Charged Dark Matter in Quantum Gravity and String Theory*, Phys. Rev. Lett. **110** (2013), no. 24, 241304 [[1302.5471](#)].
- [209] N. Arkani-Hamed, L. Motl, A. Nicolis and C. Vafa, *The String landscape, black holes and gravity as the weakest force*, JHEP **06** (2007) 060 [[hep-th/0601001](#)].
- [210] J. Brown, W. Cottrell, G. Shiu and P. Soler, *Fencing in the Swampland: Quantum Gravity Constraints on Large Field Inflation*, JHEP **10** (2015) 023 [[1503.04783](#)].
- [211] J. Brown, W. Cottrell, G. Shiu and P. Soler, *On Axionic Field Ranges, Loopholes and the Weak Gravity Conjecture*, JHEP **04** (2016) 017 [[1504.00659](#)].
- [212] M. Montero, A. M. Uranga and I. Valenzuela, *Transplanckian axions!?*, JHEP **08** (2015) 032 [[1503.03886](#)].
- [213] B. Heidenreich, M. Reece and T. Rudelius, *Weak Gravity Strongly Constrains Large-Field Axion Inflation*, JHEP **12** (2015) 108 [[1506.03447](#)].
- [214] A. Hebecker, T. Mikhail and P. Soler, *Euclidean wormholes, baby universes, and their impact on particle physics and cosmology*, Front. Astron. Space Sci. **5** (2018) 35 [[1807.00824](#)].
- [215] M. Reece, *Photon Masses in the Landscape and the Swampland*, JHEP **07** (2019) 181 [[1808.09966](#)].
- [216] L. E. Ibanez, V. Martin-Lozano and I. Valenzuela, *Constraining Neutrino Masses, the Cosmological Constant and BSM Physics from the Weak Gravity Conjecture*, JHEP **11** (2017) 066 [[1706.05392](#)].
- [217] Y. Hamada and G. Shiu, *Weak Gravity Conjecture, Multiple Point Principle and the Standard Model Landscape*, JHEP **11** (2017) 043 [[1707.06326](#)].
- [218] D. Lust and E. Palti, *Scalar Fields, Hierarchical UV/IR Mixing and The Weak Gravity Conjecture*, JHEP **02** (2018) 040 [[1709.01790](#)].
- [219] N. Craig, I. Garcia Garcia and S. Koren, *The Weak Scale from Weak Gravity*, JHEP **09** (2019) 081 [[1904.08426](#)].
- [220] P. Draper, I. G. Garcia and M. Reece, *Snowmass White Paper: Implications of Quantum Gravity for Particle Physics*, in *2022 Snowmass Summer Study*. 3, 2022. [2203.07624](#).
- [221] C. de Rham, S. Kundu, M. Reece, A. J. Tolley and S.-Y. Zhou, *Snowmass White Paper: UV Constraints on IR Physics*, in *2022 Snowmass Summer Study*. 3, 2022. [2203.06805](#).
- [222] C. Cheung, J. Liu and G. N. Remmen, *Proof of the Weak Gravity Conjecture from Black Hole Entropy*, JHEP **10** (2018) 004 [[1801.08546](#)].
- [223] Y. Hamada, T. Noumi and G. Shiu, *Weak Gravity Conjecture from Unitarity and Causality*, Phys. Rev. Lett. **123** (2019), no. 5, 051601 [[1810.03637](#)].
- [224] M. Montero, *A Holographic Derivation of the Weak Gravity Conjecture*, JHEP **03** (2019) 157 [[1812.03978](#)].
- [225] B. Bellazzini, M. Lewandowski and J. Serra, *Positivity of Amplitudes, Weak Gravity Conjecture, and Modified Gravity*, Phys. Rev. Lett. **123** (2019), no. 25, 251103 [[1902.03250](#)].
- [226] N. Arkani-Hamed, Y.-t. Huang, J.-Y. Liu and G. N. Remmen, *Causality, unitarity, and the weak gravity conjecture*, JHEP **03** (2022) 083 [[2109.13937](#)].

- [227] J. Polchinski, *Monopoles, duality, and string theory*, Int. J. Mod. Phys. A **19S1** (2004) 145–156 [[hep-th/0304042](#)].
- [228] H.-C. Kim, G. Shiu and C. Vafa, *Branes and the Swampland*, Phys. Rev. D **100** (2019), no. 6, 066006 [[1905.08261](#)].
- [229] M. Cvetič, M. Dierigl, L. Lin and H. Y. Zhang, *String Universality and Non-Simply-Connected Gauge Groups in 8d*, Phys. Rev. Lett. **125** (2020), no. 21, 211602 [[2008.10605](#)].
- [230] M. Montero and C. Vafa, *Cobordism Conjecture, Anomalies, and the String Lamppost Principle*, JHEP **01** (2021) 063 [[2008.11729](#)].
- [231] A. Font, B. Fraiman, M. Graña, C. A. Núñez and H. P. De Freitas, *Exploring the landscape of heterotic strings on T^d* , JHEP **10** (2020) 194 [[2007.10358](#)].
- [232] M. Cvetič, M. Dierigl, L. Lin and H. Y. Zhang, *Gauge group topology of 8D Chaudhuri-Hockney-Lykken vacua*, Phys. Rev. D **104** (2021), no. 8, 086018 [[2107.04031](#)].
- [233] A. Font, B. Fraiman, M. Graña, C. A. Núñez and H. Parra De Freitas, *Exploring the landscape of CHL strings on T^d* , JHEP **08** (2021) 095 [[2104.07131](#)].
- [234] M. Cvetič, M. Dierigl, L. Lin and H. Y. Zhang, *Higher-form symmetries and their anomalies in M-/F-theory duality*, Phys. Rev. D **104** (2021), no. 12, 126019 [[2106.07654](#)].
- [235] A. Bedroya, Y. Hamada, M. Montero and C. Vafa, *Compactness of brane moduli and the String Lamppost Principle in $d > 6$* , JHEP **02** (2022) 082 [[2110.10157](#)].
- [236] M. Cvetič, M. Dierigl, L. Lin and H. Y. Zhang, *One Loop to Rule Them All: Eight and Nine Dimensional String Vacua from Junctions*, [2203.03644](#).
- [237] A. Adams, O. DeWolfe and W. Taylor, *String universality in ten dimensions*, Phys. Rev. Lett. **105** (2010) 071601 [[1006.1352](#)].
- [238] D. R. Morrison and W. Taylor, *Charge completeness and the massless charge lattice in F-theory models of supergravity*, JHEP **12** (2021) 040 [[2108.02309](#)].
- [239] N. Raghuram, W. Taylor and A. P. Turner, *Automatic enhancement in 6D supergravity and F-theory models*, JHEP **07** (2021) 048 [[2012.01437](#)].
- [240] J. Gray, A. S. Haupt and A. Lukas, *Topological Invariants and Fibration Structure of Complete Intersection Calabi-Yau Four-Folds*, JHEP **09** (2014) 093 [[1405.2073](#)].
- [241] L. B. Anderson, X. Gao, J. Gray and S.-J. Lee, *Fibrations in CICY Threefolds*, JHEP **10** (2017) 077 [[1708.07907](#)].
- [242] Y.-C. Huang and W. Taylor, *On the prevalence of elliptic and genus one fibrations among toric hypersurface Calabi-Yau threefolds*, JHEP **03** (2019) 014 [[1809.05160](#)].
- [243] Y.-C. Huang and W. Taylor, *Fibration structure in toric hypersurface Calabi-Yau threefolds*, JHEP **03** (2020) 172 [[1907.09482](#)].
- [244] G. Di Cerbo and R. Svaldi, *Birational boundedness of low dimensional elliptic Calabi-Yau varieties with a section*, arXiv e-prints (Aug., 2016) arXiv:1608.02997 [[1608.02997](#)].
- [245] A. Grassi, *On minimal models of elliptic threefolds*, Math. Ann. **290** (1991) 287–301.
- [246] M. Gross, *A finiteness theorem for elliptic Calabi-Yau threefolds*, Duke Math. Jour. **74** (1994) 271.

- [247] S. H. Katz and C. Vafa, *Matter from geometry*, Nucl. Phys. B **497** (1997) 146–154 [[hep-th/9606086](#)].
- [248] P. Arras, A. Grassi and T. Weigand, *Terminal Singularities, Milnor Numbers, and Matter in F-theory*, J. Geom. Phys. **123** (2018) 71–97 [[1612.05646](#)].
- [249] M. Esole, P. Jefferson and M. J. Kang, *Euler Characteristics of Crepant Resolutions of Weierstrass Models*, Commun. Math. Phys. **371** (2019), no. 1, 99–144 [[1703.00905](#)].
- [250] B. S. Acharya and S. Gukov, *M theory and singularities of exceptional holonomy manifolds*, Phys. Rept. **392** (2004) 121–189 [[hep-th/0409191](#)].
- [251] A. Kovalev, *Twisted connected sums and special Riemannian holonomy*, [math/0012189](#).
- [252] A. Corti, M. Haskins, J. Nordström and T. Pacini, *G_2 -manifolds and associative submanifolds via semi-Fano 3-folds*, Duke Math. J. **164** (2015), no. 10, 1971–2092 [[1207.4470](#)].
- [253] J. Halverson and D. R. Morrison, *The landscape of M-theory compactifications on seven-manifolds with G_2 holonomy*, JHEP **04** (2015) 047 [[1412.4123](#)].
- [254] J. Halverson and D. R. Morrison, *On gauge enhancement and singular limits in G_2 compactifications of M-theory*, JHEP **04** (2016) 100 [[1507.05965](#)].
- [255] A. P. Braun, *Tops as building blocks for G_2 manifolds*, JHEP **10** (2017) 083 [[1602.03521](#)].
- [256] T. C. da C. Guio, H. Jockers, A. Klemm and H.-Y. Yeh, *Effective Action from M-Theory on Twisted Connected Sum G_2 -Manifolds*, Commun. Math. Phys. **359** (2018), no. 2, 535–601 [[1702.05435](#)].
- [257] A. P. Braun and M. Del Zotto, *Mirror Symmetry for G_2 -Manifolds: Twisted Connected Sums and Dual Tops*, JHEP **05** (2017) 080 [[1701.05202](#)].
- [258] A. P. Braun and M. Del Zotto, *Towards Generalized Mirror Symmetry for Twisted Connected Sum G_2 Manifolds*, JHEP **03** (2018) 082 [[1712.06571](#)].
- [259] A. P. Braun, M. Del Zotto, J. Halverson, M. Larfors, D. R. Morrison and S. Schäfer-Nameki, *Infinitely many M2-instanton corrections to M-theory on G_2 -manifolds*, JHEP **09** (2018) 077 [[1803.02343](#)].
- [260] T. Pantev and M. Wijnholt, *Hitchin’s Equations and M-Theory Phenomenology*, J. Geom. Phys. **61** (2011) 1223–1247 [[0905.1968](#)].
- [261] A. P. Braun, S. Cizel, M. Hübner and S. Schäfer-Nameki, *Higgs bundles for M-theory on G_2 -manifolds*, JHEP **03** (2019) 199 [[1812.06072](#)].
- [262] R. Barbosa, M. Cvetič, J. J. Heckman, C. Lawrie, E. Torres and G. Zoccarato, *T-branes and G_2 backgrounds*, Phys. Rev. D **101** (2020), no. 2, 026015 [[1906.02212](#)].
- [263] M. Hubner, *Local G_2 -manifolds, Higgs bundles and a colored quantum mechanics*, JHEP **05** (2021) 002 [[2009.07136](#)].
- [264] M. Cvetič, J. J. Heckman, T. B. Rochais, E. Torres and G. Zoccarato, *Geometric unification of Higgs bundle vacua*, Phys. Rev. D **102** (2020), no. 10, 106012 [[2003.13682](#)].
- [265] B. S. Acharya, L. Foscolo, M. Najjar and E. E. Svanes, *New G_2 -conifolds in M-theory and their field theory interpretation*, JHEP **05** (2021) 250 [[2011.06998](#)].

- [266] M. Cvetič, J. J. Heckman, M. Hübner and E. Torres, *0-Form, 1-Form and 2-Group Symmetries via Cutting and Gluing of Orbifolds*, [2203.10102](#).
- [267] A. Grassi, J. Halverson, C. Long, J. L. Shaneson and J. Tian, *Non-simply-laced Symmetry Algebras in F-theory on Singular Spaces*, JHEP **09** (2018) 129 [[1805.06949](#)].
- [268] A. Grassi, J. Halverson, C. Long, J. L. Shaneson, B. Sung and J. Tian, *6D Anomaly-Free Matter Spectrum in F-theory on Singular Spaces*, [2110.06943](#).
- [269] M. Cvetič, G. Shiu and A. M. Uranga, *Chiral type II orientifold constructions as M theory on G(2) holonomy spaces*, in *9th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY01)*, pp. 317–326. 11, 2001. [hep-th/0111179](#).
- [270] B. S. Acharya and E. Witten, *Chiral fermions from manifolds of G(2) holonomy*, [hep-th/0109152](#).
- [271] M. Goresky and R. MacPherson, *Intersection homology theory*, Topology **19** (1980), no. 2, 135–162.
- [272] M. Headrick and T. Wiseman, *Numerical Ricci-flat metrics on K3*, Class. Quant. Grav. **22** (2005) 4931–4960 [[hep-th/0506129](#)].
- [273] S. K. Donaldson, *Some numerical results in complex differential geometry*, [math/0512625](#).
- [274] M. R. Douglas, R. L. Karp, S. Lukic and R. Reinbacher, *Numerical Calabi-Yau metrics*, J. Math. Phys. **49** (2008) 032302 [[hep-th/0612075](#)].
- [275] V. Braun, T. Brelidze, M. R. Douglas and B. A. Ovrut, *Calabi-Yau Metrics for Quotients and Complete Intersections*, JHEP **05** (2008) 080 [[0712.3563](#)].
- [276] L. B. Anderson, V. Braun, R. L. Karp and B. A. Ovrut, *Numerical Hermitian Yang-Mills Connections and Vector Bundle Stability in Heterotic Theories*, JHEP **06** (2010) 107 [[1004.4399](#)].
- [277] S. Kachru, A. Tripathy and M. Zimet, *K3 metrics*, [2006.02435](#).
- [278] W. Lerche, D. Lust and A. N. Schellekens, *Chiral Four-Dimensional Heterotic Strings from Selfdual Lattices*, Nucl. Phys. B **287** (1987) 477.
- [279] R. Bousso and J. Polchinski, *Quantization of four form fluxes and dynamical neutralization of the cosmological constant*, JHEP **06** (2000) 006 [[hep-th/0004134](#)].
- [280] S. Weinberg, *Anthropic Bound on the Cosmological Constant*, Phys. Rev. Lett. **59** (1987) 2607.
- [281] F. Schöller and H. Skarke, *All Weight Systems for Calabi–Yau Fourfolds from Reflexive Polyhedra*, Commun. Math. Phys. **372** (2019), no. 2, 657–678 [[1808.02422](#)].
- [282] D. R. Morrison and W. Taylor, *Toric bases for 6D F-theory models*, Fortsch. Phys. **60** (2012) 1187–1216 [[1204.0283](#)].
- [283] W. Taylor and Y.-N. Wang, *Non-toric bases for elliptic Calabi–Yau threefolds and 6D F-theory vacua*, Adv. Theor. Math. Phys. **21** (2017) 1063–1114 [[1504.07689](#)].
- [284] L. B. Anderson and W. Taylor, *Geometric constraints in dual F-theory and heterotic string compactifications*, JHEP **08** (2014) 025 [[1405.2074](#)].
- [285] J. Halverson and W. Taylor, *\mathbb{P}^1 -bundle bases and the prevalence of non-Higgsable structure in 4D F-theory models*, JHEP **09** (2015) 086 [[1506.03204](#)].

- [286] F. Denef and M. R. Douglas, *Computational complexity of the landscape. I.*, Annals Phys. **322** (2007) 1096–1142 [[hep-th/0602072](#)].
- [287] J. Halverson and F. Ruehle, *Computational Complexity of Vacua and Near-Vacua in Field and String Theory*, Phys. Rev. D **99** (2019), no. 4, 046015 [[1809.08279](#)].
- [288] M. Cvetič, I. Garcia-Etxebarria and J. Halverson, *On the computation of non-perturbative effective potentials in the string theory landscape: IIB/F-theory perspective*, Fortsch. Phys. **59** (2011) 243–283 [[1009.5386](#)].
- [289] J. Halverson, M. Plesser, F. Ruehle and J. Tian, *Kähler Moduli Stabilization and the Propagation of Decidability*, Phys. Rev. D **101** (2020), no. 4, 046010 [[1911.07835](#)].
- [290] N. Bao, R. Bousso, S. Jordan and B. Lackey, *Fast optimization algorithms and the cosmological constant*, Phys. Rev. D **96** (2017), no. 10, 103512 [[1706.08503](#)].
- [291] Y.-H. He, *Deep-Learning the Landscape*, [1706.02714](#).
- [292] F. Ruehle, *Evolving neural networks with genetic algorithms to study the String Landscape*, JHEP **08** (2017) 038 [[1706.07024](#)].
- [293] D. Krefl and R.-K. Seong, *Machine Learning of Calabi-Yau Volumes*, Phys. Rev. D **96** (2017), no. 6, 066014 [[1706.03346](#)].
- [294] J. Carifio, J. Halverson, D. Krioukov and B. D. Nelson, *Machine Learning in the String Landscape*, JHEP **09** (2017) 157 [[1707.00655](#)].
- [295] M. Cirafici, *Persistent homology and string vacua*, Journal of High Energy Physics **2016** (2016), no. 3, 1–34.
- [296] A. Cole and G. Shiu, *Topological Data Analysis for the String Landscape*, JHEP **03** (2019) 054 [[1812.06960](#)].
- [297] J. Carifio, W. J. Cunningham, J. Halverson, D. Krioukov, C. Long and B. D. Nelson, *Vacuum Selection from Cosmology on Networks of String Geometries*, Phys. Rev. Lett. **121** (2018), no. 10, 101602 [[1711.06685](#)].
- [298] A. E. Faraggi, B. Percival, S. Schewe and D. Wojtczak, *Satisfiability modulo theories and chiral heterotic string vacua with positive cosmological constant*, Phys. Lett. B **816** (2021) 136187 [[2101.03227](#)].
- [299] A. E. Faraggi, V. G. Matyas and B. Percival, *Towards Classification of $\mathcal{N} = 1$ and $\mathcal{N} = 0$ Flipped $SU(5)$ Asymmetric $\mathbb{Z}_2 \times \mathbb{Z}_2$ Heterotic String Orbifolds*, [2202.04507](#).
- [300] J. Blåbäck, U. Danielsson and G. Dibitetto, *Fully stable dS vacua from generalised fluxes*, JHEP **08** (2013) 054 [[1301.7073](#)].
- [301] J. Blåbäck, U. Danielsson and G. Dibitetto, *Accelerated Universes from type IIA Compactifications*, JCAP **03** (2014) 003 [[1310.8300](#)].
- [302] S. Abel and J. Rizos, *Genetic Algorithms and the Search for Viable String Vacua*, JHEP **08** (2014) 010 [[1404.7359](#)].
- [303] S. AbdusSalam, S. Abel, M. Cicoli, F. Quevedo and P. Shukla, *A systematic approach to Kähler moduli stabilisation*, JHEP **08** (2020), no. 08, 047 [[2005.11329](#)].
- [304] G. J. Loges and G. Shiu, *Breeding realistic D-brane models*, [2112.08391](#).

- [305] J. Liu, *Artificial Neural Network in Cosmic Landscape*, JHEP **12** (2017) 149 [[1707.02800](#)].
- [306] Y.-N. Wang and Z. Zhang, *Learning non-Higgsable gauge groups in 4D F-theory*, JHEP **08** (2018) 009 [[1804.07296](#)].
- [307] R. Altman, J. Carifio, J. Halverson and B. D. Nelson, *Estimating Calabi-Yau Hypersurface and Triangulation Counts with Equation Learners*, JHEP **03** (2019) 186 [[1811.06490](#)].
- [308] R. Jinno, *Machine learning for bounce calculation*, [1805.12153](#).
- [309] K. Bull, Y.-H. He, V. Jejjala and C. Mishra, *Machine Learning CICY Threefolds*, Phys. Lett. B **785** (2018) 65–72 [[1806.03121](#)].
- [310] T. Rudelius, *Learning to Inflate*, JCAP **02** (2019) 044 [[1810.05159](#)].
- [311] V. Jejjala, A. Kar and O. Parrikar, *Deep Learning the Hyperbolic Volume of a Knot*, Phys. Lett. B **799** (2019) 135033 [[1902.05547](#)].
- [312] C. R. Brodie, A. Constantin, R. Deen and A. Lukas, *Machine Learning Line Bundle Cohomology*, Fortsch. Phys. **68** (2020), no. 1, 1900087 [[1906.08730](#)].
- [313] M. Bies, M. Cvetič, R. Donagi, L. Lin, M. Liu and F. Ruehle, *Machine Learning and Algebraic Approaches towards Complete Matter Spectra in 4d F-theory*, JHEP **01** (2021) 196 [[2007.00009](#)].
- [314] J. Halverson, B. Nelson and F. Ruehle, *Branes with Brains: Exploring String Vacua with Deep Reinforcement Learning*, JHEP **06** (2019) 003 [[1903.11616](#)].
- [315] M. Larfors and R. Schneider, *Explore and Exploit with Heterotic Line Bundle Models*, Fortsch. Phys. **68** (2020), no. 5, 2000034 [[2003.04817](#)].
- [316] S. Krippendorf, R. Kroepsch and M. Syvaeri, *Revealing systematics in phenomenologically viable flux vacua with reinforcement learning*, [2107.04039](#).
- [317] A. Constantin, T. R. Harvey and A. Lukas, *Heterotic String Model Building with Monad Bundles and Reinforcement Learning*, [2108.07316](#).
- [318] D. Silver, J. Schrittwieser, K. Simonyan, I. Antonoglou, A. Huang, A. Guez, T. Hubert, L. Baker, M. Lai, A. Bolton, Y. Chen, T. Lillicrap, F. Hui, L. Sifre, G. van den Driessche, T. Graepel and D. Hassabis, *Mastering the game of Go without human knowledge*, Nature **550** (Oct, 2017) 354–359.
- [319] A. Cole, S. Krippendorf, A. Schachner and G. Shiu, *Probing the Structure of String Theory Vacua with Genetic Algorithms and Reinforcement Learning*, in *35th Conference on Neural Information Processing Systems*. 11, 2021. [2111.11466](#).
- [320] S. Abel, A. Constantin, T. R. Harvey and A. Lukas, *String Model Building, Reinforcement Learning and Genetic Algorithms*, in *Nankai Symposium on Mathematical Dialogues: In celebration of S.S.Chern's 110th anniversary*. 11, 2021. [2111.07333](#).
- [321] S. Abel, A. Constantin, T. R. Harvey and A. Lukas, *Evolving Heterotic Gauge Backgrounds: Genetic Algorithms versus Reinforcement Learning*, [2110.14029](#).
- [322] H. Erbin and S. Krippendorf, *GANs for generating EFT models*, Phys. Lett. B **810** (2020) 135798 [[1809.02612](#)].

- [323] J. Halverson and C. Long, *Statistical Predictions in String Theory and Deep Generative Models*, Fortsch. Phys. **68** (2020), no. 5, 2000005 [[2001.00555](#)].
- [324] L. B. Anderson, M. Gerdes, J. Gray, S. Krippendorf, N. Raghuram and F. Ruehle, *Moduli-dependent Calabi-Yau and $SU(3)$ -structure metrics from Machine Learning*, JHEP **05** (2021) 013 [[2012.04656](#)].
- [325] M. R. Douglas, S. Lakshminarasimhan and Y. Qi, *Numerical Calabi-Yau metrics from holomorphic networks*, [2012.04797](#).
- [326] V. Jejjala, D. K. Mayorga Pena and C. Mishra, *Neural Network Approximations for Calabi-Yau Metrics*, [2012.15821](#).
- [327] M. Larfors, A. Lukas, F. Ruehle and R. Schneider, *Learning Size and Shape of Calabi-Yau Spaces*, [2111.01436](#).
- [328] A. Ashmore, Y.-H. He and B. A. Ovrut, *Machine Learning Calabi-Yau Metrics*, Fortsch. Phys. **68** (2020), no. 9, 2000068 [[1910.08605](#)].
- [329] G. Carleo and M. Troyer, *Solving the quantum many-body problem with artificial neural networks*, Science **355** (Feb., 2017) 602–606 [[1606.02318](#)].
- [330] F. Ruehle, *Data science applications to string theory*, Physics Reports **839** (2020) 1–117 Data science applications to string theory.