

TF08 Snowmass Report: BSM Model Building

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Abstract

We summarize the state of Beyond the Standard Model (BSM) model building in particle physics for Snowmass 2021, focusing mainly on several whitepaper contributions to BSM model building (TF08) and closely related areas.

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1 Executive Summary

Despite its phenomenal successes, the Standard Model (SM) can only be considered a low-energy, effective field theory (EFT) description of particle physics which leaves many unanswered questions about the nature of reality at distance scales shorter than $\sim \text{TeV}^{-1}$. Among these so-far unanswered questions are the origin of the neutrino masses, an explanation for the quark and lepton flavor structures, the absence of measurable CP violation in QCD, and why the scales associated with gravity and weak interactions are so disparate. The SM also does not explain the observed asymmetry between matter and antimatter in the Universe. It is known that the cosmological dark matter cannot be composed of SM fields and the origin of the periods of accelerated expansion of the Universe are a mystery. Any explanation for these above mentioned puzzles must involve physics beyond the SM.

Using these clues, and others, the goal of beyond the Standard Model (BSM) model building is to uncover the next set of principles which determine how Nature behaves at the shortest distance scales and to build the “next” Standard Model that addresses one or more of these puzzles. At some level BSM model building can be thought of as turning “why?” questions into “how?” questions. While all BSM models follow the principle of *primum non nocere*, there are a plethora of creative, testable ideas that have been proposed that use a broad range of theoretical approaches. Some use concepts familiar from the SM while others introduce completely new ideas and techniques. Many lead to unique experimentally testable predictions, across experiments/observations that span a vast range of scales. Model building is an integral part of many other aspects of HEP, both taking inspiration from, and providing inspiration to, other areas [1–10]. Through BSM model building, theorists have also been instrumental in leading the case for new experimental programs, as well as motivating new search strategies at existing experiments [11]. The success of the theoretical efforts has been strongly advanced by the semi-automated event generation pipeline of FeynRules, the UFO file format, and event generators (for additional details see Sec. 2.8 of [12]).

Understanding the origin and stability of the electroweak scale has long been pursued by BSM model builders. The so-far null results of searches for new particles from LEP through to LHC have demonstrated that many elegant models are constrained, requiring some to substantial fine-tuning, or are simply not viable. This is not a failure – on the contrary, this demonstrates the remarkable success of the synergy between theory and experiment where ideas are proposed, models are built, particles are predicted, parameters are constrained, and then ideas/models are ultimately ruled out. Most BSM theories addressing the hierarchy problem are only midway through this shakeout process with experiment. Model-building remains an extremely active area to address a range of the puzzles of SM, and continues to push the envelope of new experimental probes to find or exclude the BSM ideas.

Flavor probes are highly sensitive to new physics, and the existing flavor constraints are very stringent, with a handful of hints of deviations beyond the SM. Many solutions to the hierarchy problem, such as composite Higgs models, models with extra dimensions, and models with low energy supersymmetry, all require a non-trivial flavor structure in order to avoid experimental bounds on BSM flavor-violation. The origin of such non-trivial

new physics flavor structure is an open question, as is the origin of the hierarchies in the spectrum of the SM quarks and leptons, the so-called SM flavor puzzle. An important aspect of flavor model building is to construct mechanisms that address such open issues, implement them in new physics models, and derive phenomenological consequences. The recent hint for BSM physics associated with flavor, from the muon anomalous magnetic moment and the B anomalies, could point to an exciting future ahead.

Cosmology and astrophysics have deep implications for BSM model building beyond providing evidence of dark matter and dark energy. The early universe may be considered as a “laboratory” equipped with a high-temperature bath. Its dynamics allows us to probe particle physics models in a way that is impossible at the present time. For example, particles that are too heavy and/or too feebly interacting to be abundantly produced today can be easily produced at much earlier times, potentially leading to observable signatures (e.g., dark radiation in many extensions to the SM) or constraints on new particle physics models. In addition to understanding the origin of the baryon asymmetry, the cosmos is also filled with exotic objects such as neutron stars and supernovæ that provide unique constraints on BSM models. Developments within observational cosmology play an increasingly important role in guiding model-building efforts, *e.g.* [8, 13–20]. With the impressive constraints from dark matter direct detection experiments, along with the apparent excess of photons from the Galactic center and the discrepancy between early and late measurements of the Hubble constant, the area of dark matter/dark sector model building has seen substantial growth in the last decade.

There has also been an ever increasing need to study the structure of models using methods beyond perturbative calculations. For example, a recurring theme in dark sector model building, and many other areas of BSM model building, is extended gauge sectors in which a new gauge group becomes strongly-coupled at scales relevant to the model. While effective field theory techniques and “scaled up QCD” can provide some insights, definitive results require dedicated lattice gauge theory simulations to study the non-perturbative dynamics. As detailed in [5], there is a strong synergy between effective field theory and lattice gauge theory that continues to inform and strengthen our understanding of gauge theory with applications to model-building beyond the SM. The list of applications is extensive: determining the properties of a QCD axion requires input from lattice QCD simulations; lattice simulations of the non-perturbative hadronic corrections to $(g - 2)_\mu$; lattice simulations of theories of strongly-coupled dark matter to determine the strength of the self-interactions as well as between dark matter and the SM.

Since the last Snowmass the landscape of experimental results has grown substantially *e.g.* many of the Higgs boson’s properties have been measured and confirmed to be SM like while there is no clear evidence for new particles at the LHC after Run 2, $(g - 2)_\mu$ appears to be discrepant from the SM prediction, there are numerous flavor anomalies involving b -quarks, and the search for direct detection of dark matter has tightly constrained dark matter’s properties. Alongside this evolution, the theory landscape has also substantially altered, which we outline in more details below, based upon contributions to TF08 [21–37].

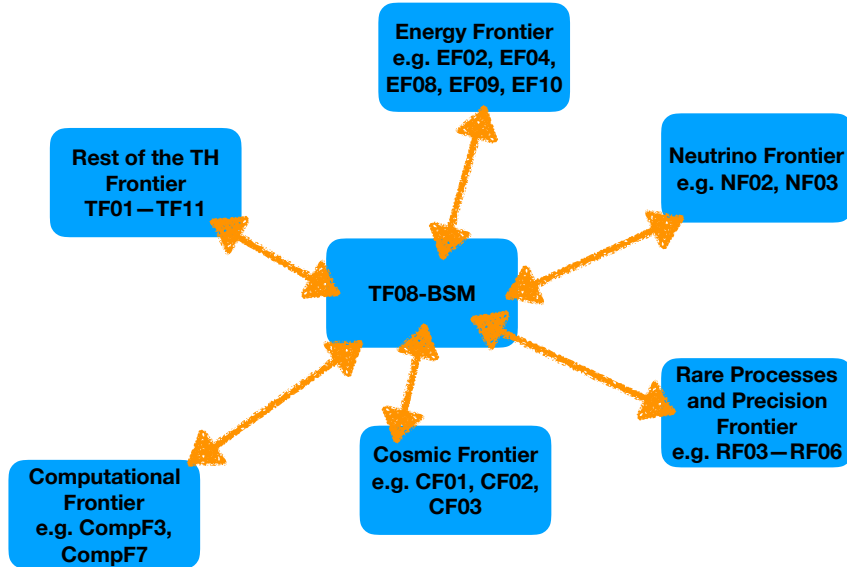


Figure 1: Model Building’s connections to other facets of the Snowmass process.

2 Naturalness

Naturalness has been one of the guiding principles in the development of Beyond the Standard Model (BSM) physics over the last several decades. Many of the naturalness puzzles of the Standard Model arise in trying to understand why a dimensionless number is small rather than $O(1)$, which might be viewed as the generic expectation. These include the famous electroweak hierarchy problem ($m_h^2/M_{\text{Pl}}^2 \ll 1$); the cosmological constant problem ($\rho_\Lambda/M_{\text{Pl}}^4 \ll 1$); the strong CP problem (effective $\theta \ll 1$); and the flavor problem ($y_f \ll 1$, or more broadly, the peculiar structure of fermion masses and mixings).

The scope of ideas to address the hierarchy puzzles has grown substantially. This includes such well-known scenarios as low-scale supersymmetry, composite Higgs, and extra dimensions as standard frameworks for BSM physics (for a recent review [34]). However, the lack of evidence for new states at the LHC has widened the playing field to new ideas, such as neutral naturalness, that may be able to address part of the hierarchy problem while avoiding the substantial constraints from experiment. These various proposals are discussed in turn below. Moreover, models that solve the naturalness problems of the Standard Model often have one or more dark matter candidates, having the potential to solve multiple problems within one framework. In this section, we focus on the naturalness, while in Sec. 3, we discuss dark matter models and mechanisms.

2.1 Supersymmetry

Supersymmetry is perhaps the best known solution to the electroweak hierarchy problem, and proceeds by making the mass of a scalar proportional to that of a fermion, which is itself protected by chiral symmetry. This symmetry must be softly broken in order to be consistent with the non-observation of degenerate superpartners. For excellent reviews, see e.g. [38,39]. One of the conceptual virtues of supersymmetry, beyond the fact that supersymmetry is the most general space-time symmetry allowed by Nature, is that it provides a very concrete theory in which quadratic divergences are absent. In supersymmetric extensions of the Standard Model, the quadratic divergences indeed vanish and are replaced by the mass splittings between Standard Model particles and their superpartners.

The status of weak scale supersymmetry, in light of LHC data, is still far from settled. At this point it is fair to say that supersymmetry has not yet appeared where the simplest implementations in a weak scale model would have led us to expect it. In its original incarnation, the MSSM now has to exist in moderately fine-tuned [40,41] regions of its parameter space; searches for Higgsinos are of particular importance as a way of gauging the level of tuning. That is not to say that supersymmetry could not appear above the TeV scale (e.g., see [22]), but this leaves a fair bit of daylight between Nature and naturalness expectations. It is also possible that the superpartners most easily accessible at the LHC are beyond reach, as can occur in variants of supersymmetry such as split-SUSY [42,43], or that the structure of weak scale supersymmetry is qualitatively different from the MSSM [44–47].

2.2 Warped Extra Dimensions and Composite Higgs Theories

Warped extra dimensions (reviewed in [35]) have provided a major driving force for many model building and phenomenological activities in high energy physics in the last few decades. The initial work in the late 90’s on Randall-Sundrum (RS) models, based on warped extra-dimensional geometry, was a new Beyond Standard Model (BSM) framework to maintain the EW hierarchy and as an added feature could naturally account for fermion hierarchies, making it one of the few of the electroweak theories to naturally account for both hierarchies with a single underlying mechanism. The experimental efforts to look for new physics in this framework, both by direct production, or by precision measurements, has been one of the drivers of our experimental programs—often in ways applicable to other BSM scenarios. In another work with the same broad motivation, ref. [48] constructed a 5D model where the KK states form a continuum beyond a certain scale—a qualitatively different spectrum of new physics states.

Models of electroweak symmetry breaking by a composite Higgs [49] with partial compositeness [50] in the top-quark sector give promising solutions to the hierarchy problem [51–55] of the Standard Model, extensively reviewed in [36]. At the effective field theory level, they can be described by specifying the pattern of symmetry breaking involved. Generically these models predict the existence of light scalars in addition to the Higgs boson, all emerging as pseudo Nambu-Goldstone bosons. Partial compositeness also implies the presence of vector-like quarks. This proliferation of new particles requires a systematic approach to

study this class of models and to facilitate a seamless transition between theory, data, and simulation codes.

There are many approaches to strongly-coupled electroweak symmetry breaking scenarios [52–55]. The most investigated ones include, e.g., 5D holographic theories [56] and multi-site deconstructed models like Little Higgs models [57]. There are also a class of composite Higgs models based on 4D asymptotically free (hypercolor) gauge theories. The assumption is that the hypercolor theory, after going through a near conformal running [58, 59], confines at the multi-TeV scale. To include top partial compositeness, its fundamental degrees of freedom contain fermionic matter in two inequivalent irreducible representations of hypercolor [60, 61], chosen in order to sequester the EW coset from the composite states carrying QCD color. There are two major types of experimental signatures in the low energy range. First, the pNGB nature of the Higgs boson implies modifications of its couplings with the other SM particles [62–66]. The other kind of signature involves additional particles beyond the SM, predicted by these models, for example, exotic electroweak pNGBs [67–70], colored pNGBs [69, 71], vector-like quarks [72–78] and other colored fermionic states in non-triplet irreps [79], vector resonances [80–84], and axion-like particles [85, 86].

These theories can also address the flavor structure of the SM, naturally explaining neutrino masses and large mixing angles in the lepton sector alongside small mixing angles in the quark sector. The scale of new physics need not be exceptionally high, for example in RS models this arises due a RS GIM mechanism [87–90]. Nevertheless, a multi-TeV (or higher) scale can pose challenges, but also in principle makes the framework more readily testable than many flavor models—although signals can still be challenging. More details on the flavor structure of the models is discussed in Sec. 5.

2.3 Neutral Naturalness

Higgs naturalness could arise by positing a new symmetry which relates the SM quarks to colorless partners, which has become known as neutral naturalness (reviewed in [23]). These are primarily bottom-up constructions that characterize the new partner particles and interactions only up to the few TeV scale and require completion at high energies, solving the so-called “little” hierarchy problem. Typically, these completions include new colored states with masses of order a few TeV, motivating future high-energy colliders to thoroughly test Higgs naturalness due to new symmetries.

Realizations of neutral naturalness typically include a hidden, dark, or secluded sector of particles that are related to at least some of the SM fields by a discrete symmetry. Because at least some of the hidden-sector particles are essential to explaining the mass of the Higgs boson, the Higgs is a robust link between the sectors. Signals of these connections can appear in deviations from the SM Higgs couplings and exotic Higgs decay modes that can be probed at future Higgs factories. Examining the Higgs for indications of these structures is highly motivated. The Higgs often acquires new, or exotic, decay modes. The strengths of these couplings and the mass of the twin fermions are both controlled by the ratio of the SM Higgs VEV to the twin Higgs VEV, v/f . This quantity is also directly proportional to the tuning of the model, making both Higgs coupling deviations and the invisible Higgs

width direct probes of naturalness.

While there are a variety of realizations of the idea of neutral naturalness, the twin Higgs framework has received extensive analysis. This pertains to higher-energy (UV) completions, collider phenomenology, dark matter candidates, cosmological and astrophysical signals, and intersections with neutrino and flavor physics. That this narrower focus has led to such a rich variety of signals and overlaps with other aspects of beyond the SM physics is impressive, but also points the way to further exploration through other neutral naturalness models. For example, the so-called fraternal model [91] makes \mathbb{Z}_2 breaking a main feature, only twinning the SM's third generation and allowing for modest deviations from the twin equality in some couplings. In effect, the model keeps only the minimal ingredients required for a twin-Higgs-like protection of the Higgs mass. In a similar vein, if the twin top quark is taken to be vector-like then even the third generation leptons can be removed without generating anomalies [92]. Rather than removing entire generations from the mirror twin model, simply allowing significant \mathbb{Z}_2 breaking between the fermion Yukawa couplings (other than the top quark) is enough to eliminate some cosmological concerns [93]. In weakly-coupled UV completions, a hard breaking of the \mathbb{Z}_2 in the quartic terms of the scalar potential can further reduce the need for fine-tuning [94].

Neutral naturalness models typically include a confining gauge group in the hidden sector. In the case of a mirror twin Higgs model, this includes states at or below the hidden confining scale, but this appears to be more the exception than the rule. Without light quarks, which can be pair produced to fragment tubes of confining color flux, states much heavier than the confinement scale evolve as though connected by a string of constant tension. These quirky bound states must shed energy until they reach low angular momentum configurations, after which they can decay efficiently. In addition to decays into SM vectors, the quirks or squirks have a significant branching fraction into hidden gluons. Thus, heavy quirks can produce showers of glueballs [95, 96]. Some fraction of these glueballs, the 0^{++} states, have displaced decays back into the SM, leading to striking signatures at current and upcoming colliders [97].

2.4 Cosmological Selection

The past decade has seen the emergence of several entirely new approaches, in some cases inspired by proposals for the strong CP and cosmological constant problems. Chief among these is relaxation of the weak scale. Aspects of these approaches can be found in several whitepapers, including [33, 34, 37].

The original incarnation is the *relaxion* [98], with a QCD axion-like particle ϕ coupled to the Standard Model with an additional inflationary sector whose properties are necessarily somewhat special. The scalar field ϕ must transit very large field values so it is a non-compact field. Below the QCD confinement scale, the coupling between ϕ and the gluon field strength gives rise to the familiar periodic axion potential with the height of the cosine potential typically $\Lambda^4 \sim f_\pi^2 m_\pi^2 \sim yv f_\pi^3$. The barrier height is linearly proportional to the Higgs VEV since m_π^2 changes linearly with the quark masses.

The idea is thus: starting at values of ϕ such that the total Higgs mass is large and positive, and assuming the slope of the ϕ potential causes it to evolve in a direction that lowers the Higgs mass, the ϕ potential will initially be completely dominated by the potential terms, until the point at which the total Higgs mass-squared goes from positive to negative and the Higgs acquires a vacuum expectation value. At this point the wiggles due to the quark masses grow linearly in the Higgs VEV, and generically ϕ will stop when the slope of the QCD-induced wiggles matches the slope of the potential of ϕ . This classical stopping point leads to a small electroweak scale relative to moderately large cutoff scale (perhaps 10^7 GeV or more).

There are challenges to protecting the shift symmetry of the relaxation over the vastly trans-Planckian excursions in field space required to explain the value of the weak scale, as enumerated by the Swampland program (see e.g. [28, 99]).

An alternative cosmological selection approach is to put many copies of the Standard Model in the same universe, but explain why one copy acquires the dominant energy density, called N -Naturalness [100]. N sectors, e.g., N copies of the Standard Model, are taken where from copy to copy, the Higgs mass parameters are distributed in some range from $-\Lambda_H^2$ to Λ_H^2 according to some probability distribution. For a wide range of distributions, the generic expectation is that some sectors have accidentally small Higgs masses, $m_H^2 \sim \Lambda_H^2/N$. In a universe with many sectors, the universe is populated by whatever sectors are abundant. It is necessary that the cosmological mechanism preferentially reheats sectors with smaller scales. The simplest way to accomplish this is to imagine an inflationary epoch, followed by reheating due to the decay of some reheaton.

Other ideas involve “trigger” operators [101] that play a privileged role in cosmological solutions to the hierarchy problem. Only three such operators are known and each leads to distinctive phenomenological predictions that are completely different compared to traditional solutions to the hierarchy problem. Triggers are therefore our best shot at discovering cosmological selection of the weak scale, either through axion-like signatures ($G\tilde{G}$) a new (quite special) Higgs doublet at HL-LHC [101] (H_1H_2) or new vector-like leptons at the HL-LHC [102].

2.5 Strong CP and Axions

The strong CP problem – why the effective $\theta \ll 1$ – remains one of the vexing naturalness puzzles in the SM. There are numerous approaches to solving the the strong CP problem. Perhaps the most famous solution posits a new pseudoscalar field, the QCD axion, that dynamically adjusts its vev to cancel the strong CP phase [103–110]. Other approaches to the strong CP problem are based on the observation that θ can violate certain discrete symmetries and the renormalization of θ in the Standard Model alone is minuscule [111–119].

Solutions to the strong CP problem involving axions have a wide range of phenomenological and cosmological applications [25, 31]. One of the most important axion interactions is its coupling to photons. Measuring this coupling could give us information about the far UV of the SM. A thriving experimental program is underway to detect axions, with a lot

of synergy between theory and experiment, and a number of new experimental proposals on the horizon [120–141]. The broad array of employed technologies, and their associated range of sensitivities in mass-coupling plane, has motivated a rejuvenation of axion model building where the axion’s properties are varied away from the naïve expectations [142–144].

Axions can also play a role in large-field inflation. The periodic shift symmetry $a \rightarrow a + 2\pi f_a$ naturally protects axions from Planck-suppressed operators, which generically spoil large-field inflationary models. Axions acquire a periodic potential from instantons of the form $V(a) = \Lambda^4 \sin(a/f_a)$, which for $f_a > M_{\text{Pl}}$ leads to a large-field model of inflation called natural inflation [145], which can be distinguished from other models of inflation by the spectral tilt and tensor-to-scalar ratio of the primordial power spectrum. However, quantum gravity appears to censor such natural inflation models. Within string theory, axion decay constants are constrained in all known examples to satisfy $f_a < M_{\text{Pl}}$ [146], and $f_a < M_{\text{Pl}}$ is a generic prediction of the axion version of the “Weak Gravity Conjecture” [147]. Models of natural inflation involving multiple axions [148–150] are similarly constrained by the Weak Gravity Conjecture [151–156]. Although loopholes to these constraints exist [152, 155, 157–159], it is unclear whether or not these loopholes can be successfully threaded in a UV complete theory of quantum gravity [160]. Indeed, surveys of axion landscapes in string theory have so far found them to be barren of large-field natural inflation [151, 161, 162].

For the axion to produce a sufficiently small effective value of θ , the Peccei-Quinn symmetry must be very nearly conserved, with no sources of explicit $U(1)_{\text{PQ}}$ violation other than QCD itself, otherwise the minimum of the axion potential shifts away from the desired value of $\theta(a) = 0$. This is the axion quality problem: the 10^{-10} fine tuning associated with θ has only been shifted into a different (and more severe) fine-tuning in the corrections to the axion potential. This requirement may be in tension with general expectations about quantum gravity since gravitational effects are not expected to respect global symmetries and thus provides an example of insights from high scale physics affecting BSM physics, more of this will be discussed in the next section. Several solutions have been proposed and recently there have been developments both in field- and string-theoretic model building. For instance, in “accidental” axion models the PQ-charged fields are also charged under some locally conserved symmetries, so that all gauge-invariant PQ-charged operators are necessarily higher-dimensional, and the PQ breaking $\sim (f_a/M_p)^n$ is suppressed by multiple powers of the Planck mass M_p . The local symmetry may be discrete [163–166] or continuous [167–172]. In composite axion models [173–178] the axion is a baryon-like particle, composed of quarks charged under a strongly coupled non-Abelian gauge group. In these models the confining dynamics often instigate the spontaneous breaking of $U(1)_{\text{PQ}}$, so that the scale f_a is generated dynamically.

2.6 Quantum Gravity Implications: Swampland

From the absence of global symmetries to the sub-extensive entropy of black holes, there is unambiguous evidence that the rules of effective field theory (EFT) consistency as currently understood are not enough to describe even the low energy regime of theories that admit a gravitational UV completion (reviewed in [28]). Quantum gravity provides us with powerful

reasons for seeking theories that are truly natural, in the sense that they explain small dimensionless numbers in terms of $O(1)$ inputs.

The expectation that there are no global symmetries in quantum gravity, and that at the UV cutoff scale there are not even *approximate* ones, provides a strong impetus, beyond simple aesthetic considerations, for the traditional model-building goal of explaining small numbers of the theory in terms of reasonable inputs. Technical naturalness can be a useful guiding principle for IR effective field theories, but a complete theory must go beyond it. This is not to say that a number cannot be small simply because of an accidental cancelation, although quantum gravity may also constrain how many such fine-tunings can occur [179]. It does mean that hierarchies that are not technically unnatural, like the flavor hierarchies, are important puzzles that could shed light on UV physics.

A general consequence of approximate global symmetries is a lowering of the cutoff scale as $\sim M_{\text{Pl}}/\sqrt{\log x^{-1}}$, with x some parameter such that the limit $x \rightarrow 0$ restores the corresponding symmetry. For example, $x = y_f$ for a fermion chiral symmetry, or $x = \mu^4/M_{\text{Pl}}^4$ for the shift-symmetry of an axion, with μ^4 the contribution to the axion potential. This conclusion seems a reasonable lower bound on the “cost” of realizing an approximate global symmetry, but it is not the whole story.

An alternative realization of an approximate global symmetry can be obtained by taking the weak coupling limit of a gauge theory. In this case, the obstruction to recovering an unbroken global symmetry is embodied by the Weak Gravity Conjecture (WGC) [147] (see e.g. [99] for a recent review). Loosely speaking, the WGC implies the presence of “super-extremal” degrees of freedom, whose charge-to-mass ratio is larger than that corresponding to an extremal black hole. Perhaps the most notable consequence of this statement is the existence of an upper bound on the cutoff scale of a $U(1)$ gauge theory given by $\Lambda \lesssim gM_{\text{Pl}}$, related to the presence of new dynamics linked to the existence of magnetic monopoles that satisfy the super-extremality bound [147]. A more sophisticated version of this statement, but that nevertheless seems to be satisfied in all known examples, suggests that a full *tower* of super-extremal states should be part of the theory [180–183]. In combination with the species bound (the expectation that gravity becomes strong at the scale $\Lambda_{\text{QG}} \sim M_{\text{Pl}}/\sqrt{N}$ [184, 185] in a theory with N degrees of freedom), this translates into $\Lambda_{\text{QG}} \sim g^{1/3}M_{\text{Pl}}$ [181, 186]. (Remarkably, the same $g^{1/3}$ scaling on the cutoff appears from an entirely different argument involving massive Stueckelberg gauge fields [187].) In other words, the cost of approaching a global symmetry by taking the $g \rightarrow 0$ limit of a gauge theory appears to be power-law rather than logarithmic. This is a much more severe cost, and a stronger constraint on model-building.

3 Dark Matter

The existence of DM is one of the most compelling pieces of evidence for physics beyond the SM. The most detailed understanding of DM arises from its gravitational imprints on cosmological observables, most notably from its effects on the acoustic peaks of the CMB angular anisotropies. Such observations have informed us of the abundance and general

characteristics of DM when the universe was only $O(10^5)$ years old. While its general particle physics description currently remains unknown, any DM candidate must be consistent with a plethora of terrestrial, astrophysical, and cosmological probes. At a minimum, any theory of DM must posit something that is non-relativistic, essentially collisionless, feebly-coupled to normal matter, and stable. Even with these restrictions, the theory space is incredibly vast. Over the past decade the broadening of theory priors has enlarged the exploration of this theoretical landscape. This is due in part to: 1) the null results at large underground direct detection experiments and high-energy colliders and 2) the realization that the strong empirical evidence for DM motivates an examination of viable models beyond just those tied to other top-down motivations of new physics.

Continued development of experimental technologies has also driven theoretical investigations into the nature of DM. For instance, low-threshold detectors sensitive to the sub-eV energy deposition of sub-MeV DM have fueled the exploration of cosmologically viable and detectable light DM candidates, while developments in precision sensors for ultralight bosonic DM across a wide range of mass scales have led to the identification of new cosmological targets within the larger parameter space [14–16].

3.1 Interaction Mechanisms

In classic *freeze-out*, the DM abundance is depleted through a two-to-two scattering process until its rate drops below the Hubble expansion rate, at which time its co-moving number density is (again) conserved. To get an abundance in agreement with observations requires a thermally-averaged annihilation cross-section, $\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/s$. For $O(1)$ coupling sizes, this famously points to a DM mass around 0.1-1 TeV. As described, the classic freeze-out scenario is highly predictive, though it can be significantly altered through various modifications to the framework above. There are a host of “exceptions” to thermal freezeout that began with the classic work from Griest and Seckel [188].

DM may not annihilate substantially with the visible sector; instead, it might annihilate or be converted into a secondary state (χ') which itself has interactions with the SM. The evolution of DM depends sensitively on the mass of the secondary state. If $m_\chi \gg m_{\chi'}$, dark matter is in the *secluded* regime [189], where the annihilations proceed as in classic freeze-out requiring $\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{sec}$ while the direct detection signal can be negligible.

If $m_\chi \simeq m_{\chi'}$, thermal freeze-out of both χ and χ' must be studied in parallel and the dynamics depend on whether χ' annihilates or decays to deplete its abundance. If χ' annihilates, and the DM annihilation cross-section is similar to classic freeze-out (though to dark states), the process is termed *coannihilation* [188]. Coannihilating DM can have direct detection and indirect detection rates comparable to that of classic freeze-out suppressed by a loop factor.

Forbidden DM [188, 190] is the same $2 \rightarrow 2$ process of classic freeze-out, but with the mass of the DM slightly below that of the outgoing SM state. This process, forbidden at zero temperature, has an exponentially suppressed rate proportional to $e^{-\Delta E/T}$, where ΔE is the energy threshold for the process.

DM densities can be substantially influenced by $3 \rightarrow 2$ or $4 \rightarrow 2$ interactions, also known as a phase of *cannibalism* [191]. The dynamics during a cannibal phase depend on whether DM is chemically coupled to the SM, kinetically coupled to the SM, or neither. If DM is both chemically and kinetically coupled, its bulk properties are unchanged over time. If it is only kinetically coupled, its number density drops, but its energy is transferred to the SM as is the case for SIMPs [192], co-SIMPs [193], and ELDERs [194].

The dark sector may be populated by the leakage of energy from the visible sector through sub-Hubble rate annihilations or decays of SM particles over time [195–197]. This production mechanism is known as *freeze-in* because in many respects it is the opposite of freeze-out; the DM is non-thermal. Many freeze-out processes can be time-reversed to provide a channel for freeze-in, and the relationship between couplings and DM abundances have opposite behaviors for freeze-out and freeze-in. Due to the smallness of coupling strengths relevant for freeze-in, the DM candidate in such models is sometimes called a *Feebly Interacting Massive Particle* (FIMP). The freeze-in parameter space is an extreme limiting case because it represents the smallest relevant coupling the DM can have with the SM plasma that affects early-universe observables in any meaningful way. Historically, some classic examples of DM candidates with freeze-in production mechanisms include sterile neutrinos [198–201], singlet scalars [202], and various particles in supersymmetric models including sneutrinos [203–206], axinos and neutralinos [207–210], gravitinos [211–216], goldstinos [217], and photinos [218].

Asymmetric dark matter posits a common origin for the baryon content of the Universe and DM (see Ref. [219] for an early suggestion in this direction). Since the former is set by an asymmetry, based on various direct and implicit empirical arguments, the DM abundance would also be taken to correspond to an asymmetry of DM over its antiparticle. A generic requirement of such models is the presence of sufficiently strong interactions that can lead to efficient elimination of the symmetric populations in both the visible and the dark sectors. For baryons, this is achieved by the presence of strong interactions in the low energy regime of QCD, while the requirement that the same occurs for asymmetric dark matter places restrictions on the new physics.

There is a multitude of models of asymmetric dark matter (for reviews see Refs. [220–222]). There is no clear way to assign various asymmetric dark matter models to a few distinct classes. Nevertheless, there are some general features that broadly define different scenarios: (A) where a quantum number has an asymmetry that gets shared between the dark and visible sectors and (B) those that postulate a generalized “baryon number” that is preserved, with equal and opposite baryon and dark asymmetries.

Sommerfeld enhancement [223, 224] appears whenever the dark sector system is such that effectively long-range forces arise in the non-relativistic limit. Here, at non-relativistic velocities, a potential between the incoming DM particles leads to the formation of off-shell bound states, and significantly affects the interaction amplitude. This can lead to a strongly enhanced late-time annihilation signal and needs to be taken into account for the freeze-out calculation, as well as present-day indirect detection observables.

On-shell bound-state formation is a related process that has been investigated more

recently [225–227]. Its effect on the DM abundance [228, 229] and late-time signatures [230] become increasingly important with growing dark-sector coupling. A particularly interesting case is DM with EW charges. In particular for $SU(2)$ representations larger than 3, the effective coupling strength is large enough to support effective bound state formation [230, 231].

Inelastic dark matter (e.g., [232–242]) posits that the predominant interaction of dark matter with Standard Model particles is mediated by an interaction $X_1 X_2 \mathcal{O}$, where \mathcal{O} is an operator built from standard model field(s). There are numerous models of inelastic dark matter, where the inelastic interaction could be dimension-4, e.g., interacting with the Z or Higgs boson, or a higher dimensional interaction. The initial kinetic energy of the X_1 -nuclear system must be greater than the mass difference ($\delta \equiv m_{X_2} - m_{X_1}$) between X_1 and X_2 in order for scattering to take place. The fact that *only* DM with sufficiently large kinetic energy can scatter has important consequences. First, because inelastic dark matter must impinge with sufficiently large kinetic energy to scatter with a direct detection target nucleus, the available kinematic phase space for DM-nuclear scattering is reduced, and the effective DM-nuclear scattering rate is suppressed. The amount of suppression will depend on what fraction of dark matter in the Galactic halo has enough kinetic energy to overcome the inelastic scattering energy threshold. Next, the minimum required energy for inelastic DM-nuclear collisions implies a minimum recoil energy in the detector, E_R^{\min} . Traditional dark matter searches have optimized sensitivity to *elastic* DM-nuclei collisions by focusing on the limit $E_R^{\min} \rightarrow 0$, and pushing the observed recoil energy window as low as backgrounds and detector sensitivities allow. For inelastic dark matter with a sizable mass splitting, a low maximum recoil energy reduces detector sensitivity. At best, a low maximum recoil energy will be sub-optimal for detecting inelastic dark matter. At worst, if the dark matter’s *minimum* inelastic recoil energy lies above the window of recoil energies, considered in a direct detection analysis, the experiment is *insensitive* to inelastic dark matter.

3.2 Models

Supersymmetric dark matter appears in R-parity conserving weak scale supersymmetric theories, where the lightest superpartner is expected to be absolutely stable. The minimal content of a supersymmetric theory includes superpartners of all the SM particles, the Minimal Supersymmetric Standard Model (MSSM) (see for eg. Refs. [38, 243]). Further, unlike the SM, supersymmetry requires at least two Higgs doublets, one coupling to all the up-type fermions and the other to down-type fermions. Therefore, at a minimum, supersymmetry would include fermionic superpartners of these Higgs bosons and the SM gauge bosons. In the presence of non-minimal field content, there may be additional neutral fermionic states. A popular example is the Next-to-Minimal Supersymmetric SM (NMSSM) (see for e.g., Ref. [244]) which includes an additional singlet superfield coupling only to the Higgs superfields. Any one of the weakly charged, electrically neutral set of these *neutralinos* can be excellent thermal WIMP DM candidates. A key difference between a SUSY neutralino dark matter candidate and a “random stable fermion” is the expected presence of a set of correlated states in SUSY.

Since the couplings of the winos and Higgsinos are large and they are further accompanied by almost mass-degenerate charged states (the charginos), consistent relic density is obtained for DM masses of the order of the TeV scale [245–247]. However, weak scale bino or singlino DM candidates may realize an observationally consistent relic density without necessitating TeV scale winos and Higgsinos. An observationally consistent relic density for either binos or singlinos may be obtained by a wide variety of processes [248–250].

Dark matter in composite Higgs theories can be easily obtained in holographic composite Higgs scenarios by introducing a suitable discrete symmetry that makes some of the massive KK modes stable.* Two types of symmetries are often considered in the literature: discrete exchange symmetries that relate different copies of the bulk fields [251], and geometrical parity symmetries† connected to the S_1/Z_2 orbifold structure representing the extra spatial dimension (see for instance [253]).

Since all the fields propagating in the bulk of the extra dimension give rise to KK modes, there are different options for the DM candidate. A natural option is to identify the DM with a Z_2 -odd vector KK mode associated to a 5-dimensional gauge field. Gauge singlet candidates are easily obtained if the 5-dimensional gauge symmetry of the model (corresponding to the global symmetry of the composite sector) contains $U(1)$ subgroups. This happens, for instance in the minimal models with custodial symmetry, based on the coset $SO(5) \times U(1)_X / SO(4) \times U(1)_X$ [51]. Models featuring vector DM states have been constructed both on warped space [254, 255] and on flat space [251, 256].

Strong-coupled composite dark matter: It is also possible that the DM is a stable bound state of a confining dark sector. Depending on the details of the model, different symmetries can guarantee the stability of various DM candidates [257–261]. Given their rich dynamics, the confining dark sectors can give rise to many interesting observable phenomena. Below we review different DM candidates in such sectors and some intriguing dynamics that can happen therein, see Refs. [260, 262, 263] for recent reviews of such models.

Dark pions can become stable kinematically or through various symmetries, giving rise to dark meson DM candidates, see for instance Refs. [238, 259, 262, 264–273]. These dark mesons are composed of a dark quark and a dark anti-quark and are always bosons, regardless of the spin of dark quarks.

A more natural possibility, in direct analog with the SM, is that N dark quarks are charged under a dark confining $SU(N)$ form a color-neutral and stable baryon that can account for the observed DM abundance today, see for instance [257–259, 262, 266, 269, 274–278]. Depending on N , such baryons can be either fermions or bosons. Stability of such candidates can be guaranteed in many different ways, including by conservation of dark baryon number.

Finally, yet another potential DM candidate from confining dark sectors are glueballs, see for instance Refs. [279–283]. The spectrum of glueballs in pure confining gauge groups

*From the 4-dimensional effective description perspective, this corresponds to identify the DM candidate with a heavy massive resonance coming from the composite dynamics.

†This type of symmetries are analogous to KK parity in universal extra dimension models (see for instance [252]).

has been studied extensively in the literature, see for instance Refs. [284, 285]. It is shown that many glueball states with different parity and charge-conjugation properties can exist in the spectrum of any confining gauge theory. Interactions of various glueball states within a pure Yang-Mills theory have been studied in Ref. [283].

Atomic/Mirror dark matter posits that DM could exist in atom-like bound states. Such dark atoms have a long history (see Refs. [286, 287]) and occur naturally in mirror twin Higgs models (see e.g. Refs [91, 93, 288–316]). In its simplest implementation, atomic DM [317–339] is made of two fermions of different masses oppositely charged under a dark $U(1)_D$ gauge symmetry [340, 341]. More complex scenarios in which one or both constituents of the dark atoms are themselves composite particles (such as dark nucleons) have also been considered. Similar to the visible sector, the presence of atomic DM generally requires a matter-antimatter asymmetry in the dark sector to set its relic abundance, although it is also possible for a symmetric component to survive [342], resulting in a mixture of darkly-charged DM [343–345] and dark atoms.

Light dark matter is an entire class of models in which dark matter has sub-GeV mass, and is invisible to ton-scale nuclear recoil detectors (reviewed in [346, 347]). As m_χ decreases, n_χ increases, so experiments with relatively small targets (gram-scale rather than ton-scale) can have comparable discovery prospects for the same thermally-motivated cross sections, if the energy threshold can be reduced. Furthermore, from the point of view of maximizing the DM signal, it is optimal to have systems with available excitations that match the low energies and momentum transfers associated with DM masses in the keV–GeV range. Since the DM mass is much lower than a nucleus mass in this regime, nuclear recoils are a poor kinematic match, but the wide range of available excitations in condensed matter systems offers a promising way forward.

There are several mechanisms that light dark matter can employ to get the correct relic abundance, see Sec. 3.1. The thermal histories for sub-GeV dark matter require, at a minimum, one additional ingredient: a new force which mediates the thermal contact between the dark matter and the SM. Indeed, dark matter cannot interact with the SM through the strong force (otherwise it would not be “dark” with respect to baryons), and neither can it be the weak force, which has too small of an annihilation cross section to generate the correct relic abundance of sub-GeV dark matter [348]. In principle, it could be the photon if dark matter had a small enough electric charge to be cosmologically “dark”, but the CMB excludes this possibility for freeze-out because such a small charge would not lead to sufficient annihilation and would yield an overabundance of DM unless other annihilation channels are introduced [349]. Hence, a benchmark model of such a new force is a *dark photon* [350, 351]. In this model, dark matter has a charge g_D under a “dark” version of electromagnetism, but unlike electromagnetism, the dark photon is massive, in many models comparable to the dark matter mass itself. The experimental and observational program to search for dark photons, motivated in part by developments in BSM model building, is one of the major developments over the past decade [352].

Axion and wave-like dark matter: The existence of dwarf galaxies means that Dark Matter whose mass is below \sim keV scale must be bosonic and furthermore that such dark matter must be heavier than 10^{-22} eV. Such ultra-light dark matter has a high number

density in our galaxy and is best understood in terms of classical waves. The (QCD) axion is the quintessential example, and there has been a resurgence in interest over the last decade as direct searches for particle dark matter become ever more constraining.

The non-thermal production of the axion is closely related to when and how the $U(1)_{PQ}$ symmetry is spontaneously broken in the early universe. If such breaking occurs after inflation, the radial mode is initially trapped at the origin and later rolls towards the potential minimum, spontaneously breaking the symmetry. At this time, the axion obtains random field values in different patches of the universe. There is an irreducible abundance from the misalignment mechanism [353–355] and the domain-wall network. Since the axion field is randomized, the axion field must have a spatial average of the misalignment angle. To explain the observed DM abundance, this misalignment contribution alone predicts an axion mass of order $m_a \simeq 30 \mu\text{eV}$ (or $f_a \simeq 2 \times 10^{11}\text{GeV}$) for the QCD axion and $m_a \simeq 600 \mu\text{eV} (10^{12}\text{GeV}/f_a)^4$ for ALPs. In addition to axion misalignment, topological defects [356, 357], such as axion strings and domain walls, will also form. The decay of the axion-string and domain-wall network radiates axions, which also contribute to the DM abundance. An accurate determination of the total axion abundance in this scenario requires lattice simulations because of the complex dynamics involved from the $U(1)$ symmetry breaking to the late-time oscillations. There have been extensive efforts dedicated to this numerical study [358–368]. In the case where the domain wall number is larger than unity, the domain walls are stable and will overclose the universe. This issue is avoided if explicit $U(1)$ breaking is introduced so that the domain walls decay and make an additional contribution to the axion abundance [359, 369–375], which allows for a smaller f_a to still explain DM.

If the symmetry is instead broken before or during inflation, the field values of both modes will be homogenized by inflation up to possible quantum fluctuations and the misalignment angle θ_i is a constant throughout the observable universe. The axion abundance, therefore, depends on the value of θ_i . The observed DM abundance is reproduced by $m_a \simeq 10 \mu\text{eV} \times \theta_i^{12/7}$ (or $f_a \simeq 6 \times 10^{11}\text{GeV}/\theta_i^{12/7}$) for the QCD axion and $m_a \simeq 7 \text{meV}/\theta_i^4 \times (10^{12} \text{GeV}/f_a)^4$ for ALPs. Thus, a large decay constant, as motivated by string theory or grand unification of the gauge and $U(1)$ symmetries [376, 377], needs a small θ_i to avoid overabundance. Similarly, a small decay constant calls for an angle very close to the hilltop of the cosine potential, $\theta_i \rightarrow \pi$, in order to exploit the inharmonicity. In the simplistic scenario, a very small/large θ_i has to come from a tuned initial condition. However, a small angle may also result from the early relaxation of the axion field during or after inflation (a large angle is similarly achieved with a further phase shift of π [378–380]) if the axion mass is larger in the early universe [381–384] or if inflation lasts a very long time [385–388].

Other models of dark matter: There are a plethora of other models of dark matter with intriguing properties and signals that we can only briefly mention due solely to space limitations of this summary report. This includes *sterile neutrino dark matter* (reviewed in [37]), *ultraheavy dark matter* (reviewed in [27]), *dynamical dark matter* (reviewed in [389]), and *hidden sectors and a multi-temperature universe* (reviewed in [21]).

4 Baryogenesis

There is more matter than antimatter in the Universe. This asymmetry, quantified as the ratio of baryon density to photon density, is measured at the time of Big Bang Nucleosynthesis (BBN) and the Cosmic Microwave Background (CMB) to be $(n_b - n_{\bar{b}})/n_\gamma = n_b/n_\gamma = (6.10 \pm 0.4) \times 10^{-10}$ [390]. Inflation dictates that such an asymmetry must be dynamically generated after reheating, necessitating a mechanism of *baryogenesis*.

In order to produce a matter–antimatter asymmetry, a model of particle physics must satisfy the so-called Sakharov conditions [391]. These are: (i) Baryon number (B) violation, (ii) C and CP violation, and (iii) departure from thermodynamic equilibrium. In the Standard Model (SM), (i) Baryon number is anomalously violated in the weak interactions of the SM. Although the rate of B -violating *sphaleron* processes is exponentially suppressed at zero temperature, sphalerons are very efficient at temperatures at which electroweak symmetry is restored, $T \gtrsim 130$ GeV [392, 393]. (ii) There is CP violation in the CKM matrix, and possibly in the PMNS matrix [394]. It has been argued that the CKM phase is not sufficient (in fact orders of magnitude too small) for producing the baryon asymmetry of the Universe. Within the SM there is no process to employ the CP violation in the PMNS matrix to produce the asymmetry. (iii) There are many ways a process could occur out of thermal equilibrium, such as particle decay at temperatures below its mass, or a first-order phase transition. There is no process in the SM that goes out of thermal equilibrium in the early Universe. These shortcomings of the SM are a clear sign of BSM physics. By the nature of the problem, these observations and the related new physics have strong implications for early Universe cosmology. Beyond-the-Standard Model models that seek to explain the baryon asymmetry invoke certain ingredients to satisfy the Sakharov conditions.

The question of generating the baryon asymmetry of the universe has been around for several decades. Leptogenesis is perhaps the best known model [395], where a lepton asymmetry is generated by right-handed neutrino decays and transferred to a baryon symmetry through electroweak sphalerons. Electroweak baryogenesis (reviewed in [396–400]) is also a well-known mechanism where the baryon asymmetry is generated during the electroweak phase transition. Nevertheless, there continue to be new ways to address this mystery, inspired by new theoretical ideas and observational opportunities. In the reviews [24, 37], numerous baryogenesis mechanisms have been discussed, with a focus on those developed in the last decade. A salient aspect of many of these contributions is experimental testability: while the vast majority of traditional baryogenesis models have involved high-scale physics and hence are difficult to probe experimentally, many new BSM models produce the baryon asymmetry at low scales and involve low-scale new physics, and are therefore experimentally observable. Many of these new models are expected to produce signals at multiple experiments, allowing for a multi-prong search for new physics (see [24] for details).

5 Flavor Model Building

Flavor violating processes, in particular those involving flavor changing neutral currents (FCNC) have exquisite sensitivity to new sources of flavor and CP violation beyond those of the SM [30]. This high sensitivity to new physics has its origin in the small amount of flavor breaking that is present in the SM. In the SM, the only sources of flavor violation are the hierarchical Yukawa couplings of the Higgs. The origin of the SM arrangement of the various quark and charged lepton masses, the hierarchical structure of the CKM matrix, and the absence of visible hierarchies in the PMNS matrix is often referred to as the SM flavor puzzle. Various classes of ideas exist to solve this puzzle: horizontal flavor symmetries [401], warped extra dimensions [402, 403], partial compositeness [50, 51, 56, 404], and radiative fermion masses [405]. In the SM, the quark FCNCs are suppressed by a loop factor and by small CKM matrix elements. As long as theoretical uncertainties in the SM predictions are under control, quark flavor violating processes can indirectly explore very high mass scales, in some cases far beyond the direct reach of collider experiments. In the lepton sector, SM predictions for FCNCs are suppressed by the tiny neutrino masses and below any imaginable experimental sensitivities. Electroweak contributions to electric dipole moments are also predicted to be strongly suppressed in the SM, several orders of magnitude below the current bounds. Charged lepton flavor violation and electric dipole moments are thus null tests of the SM. Any observation of such processes would be an unambiguous sign of new physics.

In the SM, the Yukawa couplings of the Higgs to the fermions are the only sources of flavor violation. Therefore, the Higgs might be the window into understanding flavor, with the precision Higgs program at the LHC, and in the future also at a Higgs factory, able to provide valuable inputs. In particular, Higgs decays involving tau, $h \rightarrow \tau\mu$ and $h \rightarrow \tau e$, are cases where the direct searches at the LHC are the most sensitive probes.

In addition to long-standing puzzles, in the last several years a number of “flavor anomalies” have created considerable excitement in the community. Discrepancies between SM predictions and experimental measurements are seen in B decays as well as in the anomalous magnetic moment of the muon. If the new physics origin for these experimental anomalies could be established, it would have a transformative impact on the field. First and foremost, such an indirect sign of new physics would establish a new mass scale in particle physics. This scale could become the next target for direct exploration at future high-energy colliders. With sufficient energy, discoveries would, at least in principle, be guaranteed. Second, the couplings of the new physics constitute new sources of flavor violation beyond the SM Yukawa couplings. Existing low energy constraints suggest that such new physics couplings have a hierarchical flavor structure. This provides a new perspective on the Standard Model flavor puzzle and invites the construction of flavor models that link the structure of the SM and BSM sources of flavor violation. At present, the global analyses point towards a small consistent set of dimension-6 effective operators (C_9 and/or C_{10}) to explain the B-physics anomalies. The leading candidate UV models generating these operators involve Z' (e.g. $L_\mu - L_\tau$) gauge bosons or leptoquarks.

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