My Publications: Introduction and Conclusions

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1 Introduction

Particle physics, as a field dedicated to unraveling the fundamental constituents of matter and their interactions, inherently operates across a broad range of scales. At the core of this endeavor is the concept of length scale, which dictates the physical regimes where distinct phenomena dominate and provides a framework for bridging theoretical predictions with experimental observations. From the subatomic scales probed by high-energy colliders to the cosmological distances optically traversed by astronomical observatories, length scale provides an organizational scheme for the physics and the corresponding experiments that can probe it.

At the smallest length scales, on the order of the Planck length ($\approx 10^{-35}$ m), gravity is conjectured to play an important role in quantum processes [22]. At this scale, it has been theorized that spacetime itself may exhibit discrete or fluctuating properties. While the Planck scale remains far beyond current experimental reach, it underpins interesting theoretical frameworks like string theory and loop quantum gravity, which seek to unify quantum mechanics with general relativity. The electroweak scale ($\approx 10^{-18}$ m), however, is accessible through experiments like those at the Large Hadron Collider (LHC), where the Higgs boson and the process of electroweak symmetry breaking come into focus. At slightly larger length scales, the strong interaction, governed by quantum chromodynamics (QCD), operates at approximately 10^{-15} m, where confinement and the structure of hadrons emerge.

Together, the electroweak gauge group, $SU(2) \times U(1)$, and the strong gauge group, $SU(3)$, form the full gauge symmetry of the standard model. One class of standard model extensions are grand unified theories (GUTs), which seek to embed the standard model gauge group into a larger group in such a way that representations of the larger group illuminate the charge assignments of standard model fermions after symmetry breaking. The scale associated with GUTs ($\approx 10^{-31}$ m) is motivated by the similar magnitudes of the standard model gauge couplings under their renormalization group running at this scale. While the original $SU(5)$ grand unified theory due to Howard Georgi and Sheldon Glashow in 1974 has been ruled out due to its predictions of proton decay, variations of this model as well as others based on groups like $SO(10)$ or E_6, for example, remain consistent with experimental bounds [15].

The success of quantum field theory (QFT) in modern high energy physics is unparalleled and has, so far, been able to accommodate all of the particles found at length-scales probed by modern experimentation ($\approx 10^{-20}$ m [1]). These particles are organized according to their properties in the standard model of elementary particle physics and this model will serve as a foundation on which most of my work is built. Besides directly probing short-distance physics through collider experiments, precision tests of standard model predictions look to indirectly explore these scales through loop contributions to measurable parameters. In recent years, measurements of the anomalous magnetic moment of the muon have raised significant interest through an observed deviation from theoretical prediction [3, 4]. Tests at the opposite end of the length-scale spectrum include astronomical observations, spanning scales of 10^{26} m, which utilize cosmology to link particle physics to the early universe. Here, inflationary dynamics and relic particle abundances reflect processes at subatomic distances. In this framework, phenomena at the smallest scales imprint signatures on the largest.

Within the confines of known physics, scales have emerged at which the standard model is expected to break down. As was mentioned earlier, the Planck scale, characteristic of quantum gravity, and the GUT scale, of grand unification, are two such scales, while the scale of the Landau pole in the running of the standard model hypercharge gauge coupling ($\approx 10^{-57}$ m) is another example. Thus, the popular interpretation of the standard model is as an effective theory which is thought to hold up to an energy scale where "new physics" will become important [11]. Effective field theories exploit the separation of scales to describe low-energy phenomena without requiring a complete understanding of higher-energy dynamics. For instance, the Fermi theory of weak interactions successfully describes beta decay at scales much larger than the W boson's Compton wavelength [26], while QCD's chiral perturbation theory captures pion interactions at low energies [8]. This hierarchical approach hinges on a clear delineation of length scales, allowing physicists to focus on the relevant degrees of freedom.

Modern research in high-energy theory postulates new physics to solve problems in the standard model, which many believe is a low-energy effective theory. In my publications, physics at the smallest distance scales will be explored through extensions of the standard model. Firstly, the focus will be on the existence or non-existence of arbitrarily small length scales in spacetime and how they impact quantum field theories defined on it. To clarify, one possibility is that arbitrarily short distance scales exist and, hence, theories should be able to be validly extrapolated to all of them. Alternatively, there may exist a shortest length scale, for example in a theory where spacetime is discrete. The focus will then turn to related issues with short-distance physics regarding fine tuning. Where possible, the models will include a dark matter candidate whose phenomenology will be examined with regard to experimental constraints. The following sections of this introduction will delve deeper into each of these topics and briefly describe how they are included in each of my publications.

2 Asymptotic Safety

Given the modern viewpoint of the standard model as an effective field theory which is a valid description of nature at the energy scales consistent with current collider experimentation, it is reasonable to ask what happens if one requires that this effective theory can be extrapolated to arbitrarily high energy scales. When this requirement can be met, the theory need no longer carry the label of "effective". In renormalized perturbation theory, ultraviolet divergences arising in loop diagrams are regulated and absorbed into counterterms order-by-order in perturbation theory according to a renormalization scheme, such as $\overline{MS}$, to maintain the renormalization conditions. The renormalization conditions define the physical couplings, while the counterterm describes the shift between the renormalized and bare couplings. This approach renders scattering amplitudes finite and independent of the regulator, yet the counterterm is dependent on the energy scale introduced by the regulator. While the bare coupling is independent of this scale, the renormalized coupling is not. Differentiating the renormalized coupling with respect to this scale eliminates the bare coupling and leaves behind a differential equation which describes how the renormalized coupling changes with respect to a change in energy scale so that the renormalization condition is consistently satisfied. This differential equation is called the renormalization group equation (RGE) for the coupling, and it can by calculated to any order in perturbation theory. Typically though, the contribution of higher-loop terms yields order of magnitude smaller corrections to the change in the size of the coupling and most numerical analyses don't include contributions past one- or two-loop order, however non-perturbative approaches to the renormalization group (RG) also exist [17]. Given each of the couplings in a theory, the full set of renormalization group equations determined to some order in perturbation theory comprises a system of coupled differential equations. Once a set of initial conditions is chosen for the couplings at an experimentally determined energy scale, the "running" of the couplings can be performed to find the value of the couplings either for higher energies (UV) or lower energies (IR). These values then determine the behavior of the quantum field theory at different length scales. Conventionally, the RGE for an arbitrary coupling, g_j, is denoted in the following way:

$$\frac{dg_j}{d\log\mu} = \beta(g_i). \tag{1}$$

Here, μ is the energy scale and $\beta(g_i)$ is called the β-function for the coupling, g_j, which generically depends on the other couplings in the theory, g_i, indexed by i. Qualitatively, these couplings can evolve in several different ways under the RG running into the UV. One scenario is when a coupling ceases to evolve under the RGE and, so, the coupling has reached a fixed-point under the renormalization group. This occurs when the β-function of the coupling vanishes. Quantum field theories in which all couplings approach UV fixed points are interesting since they become conformal in the UV limit. These fixed points are distinguished into two categories, zero and non-zero. The first of these is called a Gaussian fixed point and couplings which approach a fixed point of this type under the RG running are called asymptotically free, since at a high enough energy scale the particle interaction described by this coupling turns off. Hence, fixed points of this type are also called non-interacting UV fixed points. An example of this in the standard model is the strong gauge coupling [16]. The second type of fixed point is called a non-trivial (or interacting) UV fixed point. Couplings which approach a fixed point of this type are called asymptotically safe. In general, a quantum field theory in which at least one coupling flows towards a non-trivial fixed point while the rest flow towards Gaussian fixed points is called asymptotically safe, distinguishing it from a theory in which all couplings are asymptotically free.

Originally, asymptotic safety was proposed in 1979 by Steven Weinberg in the context of quantum gravity [33]. The asymptotic safety paradigm says that the only physically sensible theories are those which can be extrapolated to arbitrarily high energies; however not every initial choice of coupling value at a particular energy scale in a theory must flow to a UV fixed point. In general, the set of couplings at a particular energy scale which do run to UV fixed points is a subset of the full parameter space with perhaps smaller dimensionality. This subspace is called the UV critical surface. While asymptotic safety can render a non-renormalizable theory predictive if the UV critical surface is of finite dimension, it can also increase the predictiveness of a renormalizable quantum field theory by reducing the dimensionality of the parameter space. This is of value in beyond-the-standard-model theories which often have many unconstrained couplings. The dimensionality of this critical surface can be found by examining the behavior of the couplings in the vicinity of a fixed point. Indeed, by considering the matrix consisting of first derivatives of the β-functions with respect to each of the couplings, the eigenvalues and eigendirections can provide information regarding the principal RG flow directions around the fixed point [25]. These directions are classified based on the sign of their eigenvalues. Negative eigenvalues correspond to directions which flow into the fixed point and so these eigendirections are called "relevant". Positive eigenvalues correspond to directions which flow away from the fixed point and so these eigendirections are called "irrelevant". Zero eigenvalues are called "marginal" since they could be either relevant or irrelevant and require a higher derivative analysis. Since we define the UV critical surface as the subspace consisting of all couplings which flow to a UV fixed point, the dimension of the UV critical surface is the number of relevant eigendirections plus the marginal eigendirections which flow into the fixed point.

In contrast to the situation of fixed point evolution for all of the couplings, the renormalization group can also indicate the perturbative breakdown of a theory at some energy scale. If a coupling diverges at a finite energy scale, the coupling is said to have encountered a Landau pole. This indicates that it is not possible to extrapolate the theory past this energy scale. In the standard model, the hypercharge gauge coupling encounters a Landau pole at a trans-Plankian energy scale. Of course, well below this scale quantum gravitational effects should become important, which are not included in the standard model. While a predictive quantum theory of gravitation has so far eluded theoretical physicists and mathematicians alike, its contribution to the RGEs of a theory can be quantified through a detailed functional renormalization group approach. It has been pointed out that the gravitational effects can be incorporated into an ordinary RGE analysis by including step function contributions to the beta functions [28]:

$$\Delta\beta_{grav}(g_i) = f\theta(\mu - M_{pl})g_i. \tag{2}$$

Here, M_{pl} is the Planck mass, $\theta(x)$ is the Heaviside theta function which "turns on" at the Planck scale, and f is treated as a phenomenological constant coefficient which, due to the universal coupling of gravity to matter, depends only on the type of coupling being evolved under the RGE *i.e.* gauge, Yukawa, or quartic.

If, according to Weinberg, gravity is described by an asymptotically safe quantum field theory, then all couplings involving the other quantum fields should be asymptotically safe as well. In both publications on asymptotic safety, we explore this possibility by requiring asymptotic safety to constrain the parameter space of a proposed gauged-baryon number extension of the standard model. Generically, these types of models allow for kinetic mixing between abelian gauge fields which is usually described by an unconstrained parameter in the theory. Since arbitrarily high energy scales are considered, gravitational effects will become important in the analysis. To account for this, we include approximations to gravitational corrections to the renormalization group equations which take effect above the Planck scale. We then identify several distinct scenarios which lead to an asymptotically safe model and constrain the kinetic mixing coupling. In the publication on asymptotically safe dark matter, this analysis is adjusted slightly to include a stable dark matter candidate in the model.

3 Dark Matter

While the physics at ever smaller length scales is dedicated to studying the fundamental interactions of particles, the physics describing bodies of increasingly large length scales has also provided powerful insight. The dominant force in the universe acting on bodies of these large scales is gravitation which has, so far, been best described by Einstein's 1917 theory of general relativity. While non-renormalizable as a quantum field theory, general relativity has withstood over a century of precision tests of its predictions [32]. However, if we assume that general relativity is a valid description of physics at large length scales in the universe and that the objects at this length scale are fully constituted by the particles of the standard model, then astronomical experimentation and observation stand in disagreement with theoretical prediction. An early example of this disagreement came from the study of galactic rotation curves [27]. The two possible remedies to this incongruency are either that general relativity is an incomplete description of gravitation at large scales or that there are undiscovered gravitationally interacting stable constituents to the matter content in the universe. The former is an active area of modern research given general relativity's lack of quantum formulation, however it is the less popular approach to this incongruency. For examples and discussions of modified gravity as a possible solution see Refs. [12, 24, 10]. The latter solution, called dark matter, has in recent decades been a dominating driver of research for extensions of the standard model. Besides galactic rotation curves, other experimental evidence for dark matter can be found in the historical account of Ref. [9]. These dark matter particles need to be massive, stable, and interact very weakly (if at all) with standard model particles. Popular solutions to the dark matter problem have been motivated by other problems in the standard model, however this assumes that various problems in the standard model ought to be intimately connected, which need not be the case. One example of this is the theoretical axion whose existence was postulated through the Pecci-Quinn mechanism to solve the strong CP problem [2]. Another example is the lightest supersymmetric particle (LSP) in supersymmetric theories, which are popular for solving the electroweak hierarchy problem [29].

Given the inherently weakly interacting nature of dark matter, experimental probes of its properties are difficult. However, two questions that can be asked of it are "how much of it is around in the universe?" and, if it does interact with standard model particles, "how weak does that interaction need to be for physicists not to have found it yet?". To address the former first, the connection of particle physics to the large scale structure of the universe is studied in the Λ-CDM model of cosmology. For a brief review of this model see Ref. [13]. The Λ-CDM model includes dark energy to drive inflation, cold dark matter, and the usual matter content of the standard model. The application of this model to the plethora of early universe information that was obtained from the WMAP experiment to study the cosmic microwave background (CMB) highly constrained the parameter space and it was found that the relic density, Ωh^2, of dark matter at today's temperature of the universe is $\Omega h^2 = 0.1193 \pm 0.0009$ [35]. From a theoretical point of view, the relic density can be calculated by considering scattering amplitudes in quantum field theory and the statistical mechanics embedded in the Λ-CDM cosmology. The process described by this mechanics to leave a relic density of dark matter is called "freeze-out". To briefly describe this process, dark matter is thought to have existed in thermal equilibrium with ordinary matter at some early stage of the universe's evolution when the temperature was high enough. As the universe expanded and cooled, the momenta of the particles in it decreased and eventually the scattering processes that allowed the dark matter to communicate through whatever portal with visible matter became kinematically disallowed. Thus, the amount of dark matter was essentially frozen-out below a certain temperature. Propagating this amount of dark matter to present day temperatures allows one to find the relic density. For a review of this calculation, see Ref. [20]. For the latter question, this is simply answered by setting up a scattering experiment where either a dark matter particle is discovered, or upper bounds can be placed for the strength of the interaction. Typically, this is done by measuring the spin-independent cross section off of a nucleon in, for example, a Xenon atom [5]. This calculation can be done in quantum field theory for any given dark matter model and then compared with upper bounds placed by these experiments. Typically, these two experimental constraints for dark matter are used to restrict a theoretical model's parameter space in the dark sector.

In the publication on asymptotically safe dark matter, we build on the gauged baryon number extension of the standard model proposed in the earlier paper by including a stable TeV-scale dark matter candidate. Using the constraints imposed on the parameter space by asymptotic safety, we study whether this parameter space is compatible or not with measurements of the dark matter relic density and direct detection bounds. In the publication on tuning to edge of the abyss, we encounter dark matter in a different context, which we describe in the next the next section.

4 To Tune or Not to Tune

As the preceding sections have illuminated, the need for physics beyond the standard model seems inevitable at some energy scale beyond the current experimental limits. Assuming this to be true, it is interesting to ask what the impact of this scale of new physics on standard model quantities will be if the standard model is assumed to be a valid description of nature up to this scale. Physics in the Higgs sector of the standard model is one area that was found to be extremely susceptible to this scale of new physics [14]. The Higgs potential is given at tree level by:

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2. \tag{3}$$

The Higgs mass and quartic coupling, μ and λ, are input parameters in the standard model which are essential in setting the scale of electroweak symmetry breaking through the Higgs mechanism. For a review of the Higgs potential and its properties, see Ref. [30]. In 2012, the Large Hadron Collider (LHC) announced the discovery of a particle consistent with the theoretical properties of the Higgs boson and measured its mass to be 125 GeV [23]. While the discovery of the Higgs boson from its theoretical origins was an outstanding scientific success, the scale at which it was found reaffirmed the question posed at the beginning of this section. Indeed, no additional symmetry of the standard model is violated by the presence of the Higgs mass term and the Higgs is expected to interact with whatever physics is encountered at or above this new energy scale. Hence, the Higgs mass is unprotected from large (actually quadratically divergent) quantum corrections determined by the scale of this new physics. If this scale, Λ, were to be, say, the scale of grand unification, $M_{GUT} \approx 10^{16}$ GeV, or even the Planck scale for quantum gravity, $M_{pl} \approx 10^{19}$ GeV, then these corrections to the bare mass should push the physical Higgs mass close to one of these extremely high scales in comparison to the scales being probed by the LHC,

$$m^2_{H,phys} = m^2_{H,0} + \mathcal{O}(\frac{\Lambda^2}{16\pi^2}). \tag{4}$$

This puzzle in high energy physics is called the electroweak hierarchy problem and it has motivated extraordinary amounts of model building to extend the standard model and find a solution. Now, the hierarchy problem wouldn't be an issue if the scale of new physics was fairly close to the electroweak scale. This idea served historically as the theoretical motivation for a lot of experimental collider research and push the beam energy to higher scales. However, so far, this scale of new physics has eluded experimentalists in what has been called the "desert" or even "nightmare" scenario for particle physics. Thus, the separation of this new scale from the electroweak scale does appear to be large and, hence, the hierarchy problem emerges. Of course, one solution to this problem is to simply have a large Higgs bare mass, $m^2_{H,0}$, almost exactly cancel the $\mathcal{O}(\Lambda^2)$ quantum corrections leaving behind the far smaller physical Higgs mass. Not only does this approach introduce a large scale into the framework, this kind of fine-tuning also is believed by many to be unlikely in nature and it is a commonly held belief amongst physicists that such tunings ought to have a physical explanation. Popular solutions to the hierarchy problem which are not fine-tuned include supersymmetry [21], extra spacetime dimensions [6, 7, 19], and a variety of other models which extend the Higgs sector and have no need for a Higgs mass term (see, for example, the original technicolor works presented in Refs. [34, 31] and the litany of further literature they inspired). Unfortunately, probes of fundamental physics at the LHC have yielded no experimental evidence for extra spacetime dimensions or supersymmetry if it is broken at the TeV scale. This has led some to propose that certain types of tuning might be favored in nature, and to explore their consequences in model building and phenomenology.

At the heart of the hierarchy problem is a large separation of scales. In 2024, a tuning paradigm was proposed by Howard Georgi in Ref. [18] which was successful at generating large physical scales in a scalar potential without introducing large parameters in the Lagrangian. For the scalar potential of a renormalizable field theory, the positivity domain is defined to be the set of all dimensionless couplings such that the scalar potential is bounded from below. This is an open subspace of the full parameter space whose closure yields the positivity domain together with its boundary. The tuning proposed by Georgi states that physical theories favor points in parameter space which live very close to this boundary. The way in which this tuning generates a large separation in scales is through a cubic term in the scalar potential. The tuning effectively eliminates the influence of the quartic terms in the potential, so that the cubic term dominates. Thus, the coupling of this term effectively picks the degree of "tilt" in the potential and generates the vacuum expectation value (vev). In the work of Ref. [18], this tuning was illustrated by considering the potential for the adjoint **24** of scalars in the minimal $SU(5)$ grand unified theory without the conventional mass term to generate a high GUT scale. Due to the shallowness of the potential with this type of tuning, quantum corrections are significant. However, if one picks a renormalization scale such that the tree-level vev remains fixed, the quantum corrections appeared, at least in Georgi's minimal $SU(5)$ analysis, to further stabilize the potential about the vev.

While Georgi demonstrated the power of his tuning paradigm by generating a large GUT scale without including any large couplings in the scalar sector of his model, we look to generate a large separation between a light dark scale and a heavier electroweak scale. In the publication on tuning to edge of the abyss, we utilize an extension of the standard model with a dark sector that includes a strongly coupled gauge group. The Higgs sector is also extended, but the traditional mass terms are assumed to be negligible. A linear term arises in the potential after condensation occurs amongst the strongly charged dark fermions. By applying the tuning paradigm proposed by Georgi to the quartic couplings in the scalar sector, we study the resulting scale separation, scalar boson mass spectrum, and how these predictions are impacted by quantum effects. We also show how a natural stable dark matter candidate arises after condensation occurs. Working within the parameter space that is restricted by the tuning paradigm, we look to identify a set of parameters which generates the electroweak scale while also agreeing with the observed dark matter relic density and remaining consistent with bounds on direct detection.

5 Conclusions

In these publications, we studied how physics at the shortest distance scales in nature effects quantum field theories across a broad range of scales and proposed extensions of the standard model to address the challenges faced by these theories at high energies.

In the publication on asymptotic safety and gauged baryon number, the continuum perspective of spacetime was taken and asymptotic safety was imposed on a gauged baryon number extension of the standard model to ensure that the theory could be extrapolated to arbitrarily short distance scales. Integral to this analysis were approximate gravitational corrections to the renormalization group equations for each of the couplings in the theory. We studied the UV fixed point structure of the theory and identified several distinct scenarios. In each case, requiring that all couplings run to UV fixed points led to a restricted parameter space for the abelian gauge sector of the model, thus avoiding the Landau pole plaguing the hypercharge gauge coupling of the standard model and constraining the amount of kinetic mixing. Working within these constraints, we demonstrated the model's predictive power by briefly looking at the phenomenology of the Z' boson. Additionally, in the publication on asymptotically safe dark matter, we built on this model by including a stable TeV scale dark matter candidate. We then showed that the UV critical surface at the TeV scale was able to accommodate experimental measurements of the dark matter relic density and bounds on direct detection for certain mass ranges of the dark matter candidate.

In the publication on non-local spacetime defects, the perspective of discrete spacetime at the Planck scale was taken by utilizing the causal set theory framework. Through the propagator approach to field kinetics described by Steven Johnston, we sought to understand how non-local spacetime defects, which are characterized by a larger length scale than that of the discretization scale, impact the Feynman propagator of a real massive two-dimensional scalar quantum field. We proposed several models of spacetime defects and encoded them into Johnston's framework. We found numerically that in each case this led to a propagator with several distinct branches leading to multivaluedness in position space when plotted against the magnitude of the spacetime interval. Just as the usual propagator depends on initial and terminal points, the different branches in the propagator corresponded to propagation between different combinations of spacetime points and defects. By considering a low-energy effective description of the propagator, we averaged each of these curves together to gain a single valued, course-grained, effective propagator for the particle. This propagator was well-described by the standard form of the propagator for a real massive scalar field, but with a mass shift and a wavefunction renormalization. The source, however, for this was due to defects in the discretization of the free theory rather than from loop effects due to interactions.

In the publication on tuning to the edge of the abyss, we explored the implications of a paradigm in which a hierarchy between length scales arises through a particular type of fine tuning. Strong dynamics in the dark sector triggered condensation of the dark quarks and provided a linear term in the scalar potential. By applying a tuning paradigm proposed by Howard Georgi to the quartic couplings of this potential, so that the potential is very close to being unbounded from below, we generated a large separation between a light dark scale and a heavier electroweak scale. The stability of this separation was then verified by considering quantum corrections to the potential. The dark pions resulting from the condensation became natural stable dark matter candidates. We then showed that the restricted parameter space of this model from the tuning paradigm was able to accommodate experimental bounds on the dark matter direct detection, measurements of dark matter relic density, and satisfy the experimental bound on the Higgs mixing angle while still generating the electroweak scale.

While the work in these publications does not resolve the mysteries of physics at the shortest distance scales, it hopefully makes meaningful progress on a number of promising directions.

References

[1] M. Aaboud et al. Search for low-mass dijet resonances using trigger-level jets with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV. *Phys. Rev. Lett.*, 121(8):081801, 2018.

[2] C. B. Adams et al. Axion Dark Matter. In *Snowmass 2021*, 3 2022.

[3] D. P. Aguillard et al. Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm. *Phys. Rev. Lett.*, 131(16):161802, 2023.

[4] T. Aoyama et al. The anomalous magnetic moment of the muon in the Standard Model. *Phys. Rept.*, 887:1–166, 2020.

[5] E. Aprile et al. First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment. *Phys. Rev. Lett.*, 131(4):041003, 2023.

[6] Nima Arkani-Hamed, Savas Dimopoulos, and G. R. Dvali. The Hierarchy problem and new dimensions at a millimeter. *Phys. Lett. B*, 429:263–272, 1998.

[7] Masha Baryakhtar. Graviton Phenomenology of Linear Dilaton Geometries. *Phys. Rev. D*, 85:125019, 2012.

[8] Paulo F. Bedaque and Ubirajara van Kolck. Effective field theory for few nucleon systems. *Ann. Rev. Nucl. Part. Sci.*, 52:339–396, 2002.

[9] Gianfranco Bertone and Dan Hooper. History of dark matter. *Rev. Mod. Phys.*, 90(4):045002, 2018.

[10] Christian G. Boehmer, Tiberiu Harko, and Francisco S. N. Lobo. Dark matter as a geometric effect in f(R) gravity. *Astropart. Phys.*, 29:386–392, 2008.

[11] Ilaria Brivio and Michael Trott. The Standard Model as an Effective Field Theory. *Phys. Rept.*, 793:1–98, 2019.

[12] Salvatore Capozziello, V. F. Cardone, and A. Troisi. Dark energy and dark matter as curvature effects. *JCAP*, 08:001, 2006.

[13] J. J. Condon and A. M. Matthews. ΛCDM Cosmology for Astronomers. *Publ. Astron. Soc. Pac.*, 130(989):073001, 2018.

[14] Nathaniel Craig. Naturalness: past, present, and future. *Eur. Phys. J. C*, 83(9):825, 2023.

[15] Djuna Croon, Tomás E. Gonzalo, Lukas Graf, Nejc Košnik, and Graham White. GUT Physics in the era of the LHC. *Front. in Phys.*, 7:76, 2019.

[16] Alexandre Deur, Stanley J. Brodsky, and Guy F. de Teramond. The QCD Running Coupling. *Nucl. Phys.*, 90:1, 2016.

[17] N. Dupuis, L. Canet, A. Eichhorn, W. Metzner, J. M. Pawlowski, M. Tissier, and N. Wschebor. The nonperturbative functional renormalization group and its applications. *Phys. Rept.*, 910:1–114, 2021.

[18] Howard Georgi. Tuning to the edge of the abyss in SU(5). *Phys. Lett. B*, 853:138703, 2024.

[19] Gian F. Giudice and Matthew McCullough. A Clockwork Theory. *JHEP*, 02:036, 2017.

[20] E. Kolb and M. Turner. *The Early Universe*. Addison and Wesley, 1990.

[21] Stephen P. Martin. A Supersymmetry primer. *Adv. Ser. Direct. High Energy Phys.*, 18:1–98, 1998.

[22] C. Alden Mead. Possible Connection Between Gravitation and Fundamental Length. *Phys. Rev.*, 135:B849–B862, 1964.

[23] S. Navas et al. Review of Particle Physics. *Phys. Rev. D*, 110:030001, Aug 2024.

[24] Shin'ichi Nojiri and Sergei D. Odintsov. Dark energy, inflation and dark matter from modified F(R) gravity. *Tomsk State Pedagogical University Bulletin*, N8(110):7–19, 2011.

[25] Roberto Percacci. A Short introduction to asymptotic safety. In *Time and Matter*, pages 123–142, 10 2011.

[26] Antonio Pich. Effective field theory: Course, Les Houches Summer School in Theoretical Physics. *Session 68: Probing the Standard Model of Particle Interactions*, pages 949–1049, 6 1998.

[27] G. G. Raffelt. Dark matter: Motivation, candidates and searches. In *The 1997 European School of High-Energy Physics*, pages 235–278, 5 1997.

[28] M. Reuter. Nonperturbative evolution equation for quantum gravity. *Phys. Rev. D*, 57:971–985, 1998.

[29] Leszek Roszkowski, Enrico Maria Sessolo, and Sebastian Trojanowski. WIMP dark matter candidates and searches—current status and future prospects. *Rept. Prog. Phys.*, 81(6):066201, 2018.

[30] Marc Sher. Electroweak Higgs Potentials and Vacuum Stability. *Phys. Rept.*, 179:273–418, 1989.

[31] Leonard Susskind. Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory. *Phys. Rev. D*, 20:2619–2625, 1979.

[32] G. M. Tino, L. Cacciapuoti, S. Capozziello, G. Lambiase, and F. Sorrentino. Precision Gravity Tests and the Einstein Equivalence Principle. *Prog. Part. Nucl. Phys.*, 112:103772, 2020.

[33] S. Weinberg. *General Relativity: An Einstein centenary survey.* Cambridge University Press, 1979.

[34] Steven Weinberg. Implications of Dynamical Symmetry Breaking. *Phys. Rev. D*, 13:974–996, 1976. [Addendum: Phys.Rev.D 19, 1277–1280 (1979)].

[35] R. L. Workman et al. Review of Particle Physics. *PTEP*, 2022:083C01, 2022.