THE COSMOLOGICAL CONSTANT AND HIGGS MASS WITH EMERGENT GAUGE SYMMETRIES*

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We discuss the Higgs mass and cosmological constant in the context of an emergent Standard Model, where the gauge symmetries "dissolve" in the extreme ultraviolet. In this scenario, the cosmological constant scale is suppressed by power of the large scale of emergence and expected to be of similar size to neutrino masses. Cosmology constraints then give an anthropic upper bound on the Higgs mass.

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1. Introduction

The Standard Model provides an excellent description of all particle physics experiments so far, from the LHC energies to low-energy precision measurements. The interactions of Standard Model particles are determined by gauge symmetries. Their masses come from coupling to the scalar Higgs field with the non-vanishing vacuum expectation value, v.e.v. Additional mass is generated in QCD from the non-perturbative confinement physics with dynamical chiral symmetry breaking, with about 99% of the mass of the hydrogen atom coming from the QCD confinement potential. The Higgs and QCD condensates fill all space, with values independent of the point in free space.

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Open puzzles include the origin of the gauge symmetries which determine particle dynamics and the hierarchies of scales in particle physics. The Higgs mass is very much less than the Planck scale despite a quadratically divergent counterterm which naively pushes its value towards the highest scales. The cosmological constant or vacuum energy density which drives the accelerating expansion of the Universe is characterized by a scale 0.002 eV [1], very much smaller than the QCD, Higgs mass and Planck scales.

Here, we argue that the tiny value of the cosmological constant may be telling us about the deeper origin of gauge symmetries in particle physics — they may be emergent in the infrared, "dissolving" in the ultraviolet close to the Planck scale (instead of extra unification) [2]. Given the incredible success of the Standard Model with no new particles or interactions seen so far in our experiments, perhaps the symmetries of the Standard Model are more special than previously anticipated. The Standard Model with measured parameters works as a consistent theory up to the Planck scale with a Higgs vacuum that sits very close to the border of stable and metastable. With an emergent Standard Model, new global symmetry violations would occur in higher dimensional operators, suppressed by powers of the large scale of emergence [3, 4]. Connected to space-time translational invariance, the cosmological constant scale comes out similar to the size of neutrino masses, suppressed by power of the large emergence scale.

The plan of this paper is as follows. Next, we explain the concept of emergence in particle physics. Then in Section 3, we discuss the scale hierarchies associated with renormalization: the Higgs mass and zero-point energies of the quantum field theory. Section 4 concerns the full Standard Model and the role of running masses and couplings in understanding the particle physics scale hierarchies. In Section 5, we discuss the cosmological constant, where particle physics combines with gravity. With an emergent Standard Model, the tiny value of the cosmological constant puts an anthropic upper bound on the size of the Higgs mass. Conclusions are given in Section 6.

2. Emergence

Emergence in physics occurs when a many-body system exhibits collective behaviour in the infrared that is qualitatively different from that of its more primordial constituents as probed in the ultraviolet [5, 6]. As an everyday example of emergent symmetry, consider a carpet which looks flat and translational invariant when looked at from a distance. Up close, *e.g.* as perceived by an ant crawling on it, the carpet has structure and this translational invariance is lost. The symmetry perceived in the infrared, *e.g.* by someone looking at it from a distance, "dissolves" in the ultraviolet when the carpet is observed close up.

For emergent particle physics, the key idea is that for a critical statistical system deep in the ultraviolet, close to the Planck scale, the only long-range correlations — light-mass particles — that might exist in the infrared self-organize into multiplets just as they do in the Standard Model [3]. The vector modes would be the gauge bosons of U(1), SU(2) and SU(3). In the self-organization process, small gauge groups will most likely be preferred. Gauge invariance would be exact (modulo spontaneous symmetry breaking) in the energy domain of the infrared effective theory. Going above the scale of emergence, nature would be described by (very possibly) completely different physics with different degrees of freedom. Possible emergent gauge symmetries in particle physics were discussed in early works by Bjorken [7], Jegerlehner [3, 8], and Nielsen and collaborators [9]. Recent discussion is given in [4, 10–13]. Emergent gauge symmetries, where we make symmetry instead of breaking it, are observed in many-body quantum systems beyond the underlying QED symmetry and atomic interactions [14–16].

With emergence, the Standard Model becomes an effective theory valid up to some large scale, the scale of emergence. The usual Standard Model action is described by terms of mass-dimension four or less. In addition, with emergence, one also finds an infinite tower of higher mass dimensional interaction terms with contributions suppressed by powers of a large ultraviolet scale M which characterizes the limit of the effective theory. If we truncate the theory to include only operator terms with mass dimension at most four, then the gauge-invariant renormalizable interactions strongly constrain the global symmetries of the theory which are then inbuilt. For example, electric charge is conserved and there is no term which violates lepton or baryon number conservation. The dimension-four action describes long-distance particle interactions. Going beyond mass-dimension four, one finds gauge-invariant but non-renormalizable terms where global symmetries are more relaxed and which are suppressed by powers of the large ultraviolet scale associated with emergence. Possible lepton number violation, also associated with Majorana neutrino masses, can enter at mass-dimension five, suppressed by a single power of the large emergence scale [17]. Baryon number violation can enter at dimension six, suppressed by the large emergence scale squared [17, 18]. Constraints from neutrino masses and proton decay searches suggest a scale of emergence in the region of 10^{15} to 10^{16} GeV [4].

With emergence, global symmetries would be restored with increasing large energy until we come close to the large energy scale M, where higher dimensional terms become important. Then the system becomes increasingly chaotic with new global symmetry breaking in the extreme ultraviolet. This scenario differs from the situation in unification models which exhibit maximum symmetry in the extreme ultraviolet.

3. Scale hierarchies in particle physics

Scale hierarchies arise from the size of QCD and Higgs condensates compared to the Planck scale as well as from renormalization effects involving the Higgs mass and zero-point energies associated with quantum fields.

The Higgs boson discovered at CERN in 2012 [19, 20] completes the particle spectrum of the Standard Model. In all experimental tests so far, it behaves very Standard Model like [21, 22] and provides masses to the Standard Model particles.

Theoretically, the renormalized Higgs mass squared comes with the divergent counterterm

$$m_{h\ \mathrm{bare}}^2 = m_{h\ \mathrm{ren}}^2 + \delta m_h^2 \,, \tag{1}$$

where

$$\delta m_h^2 = \frac{K^2}{16\pi^2}\frac{6}{v^2}\left(m_h^2 + m_Z^2 + 2m_W^2 - 4m_t^2\right) \tag{2}$$

relates the renormalized and bare Higgs mass, with the renormalized mass connected to the physical pole mass. Here, K is an ultraviolet scale characterizing the limit to where the Standard Model should work, v is the Higgs v.e.v., and the m_i are the Higgs, Z, W and top-quark masses. We neglect contributions from lighter-mass quarks. If K is taken as a physical scale, then why is the physical Higgs mass so small compared to the cut-off? This is the Higgs mass hierarchy puzzle. Boson and fermion contributions enter Eq. (2) with different signs. The renormalized and bare masses would coincide with no hierarchy puzzle if

$$2m_W^2 + m_Z^2 + m_h^2 = 4m_t^2 \,. \tag{3}$$

This equation is the Veltman condition [23]. It implies a collective cancellation between bosons and fermions. Taking the pole masses for the W, Z and top quark (80, 91 and 173 GeV) would require a Higgs mass of 314 GeV, much above the measured value[1].

Pauli [24] pointed out that a similar situation occurs with the zero-point energies, ZPEs, induced by quantization [25]. Along with condensates associated with spontaneous symmetry breaking, the ZPEs contribute to the vacuum energy in particle physics and, together with gravitational contributions, to the cosmological constant [26–28]. Zero-point energies come with ultraviolet divergence requiring regularization and renormalization. Working in flat space-time

$$\rho_{\mathrm{zpe}} = \frac{1}{2}\hbar \sum_{\mathrm{particles}} g_i \int_0^{k_{\max}} \frac{\mathrm{d}^3k}{(2\pi)^3}\sqrt{k^2+m^2} \,. \tag{4}$$

[1] Next-to-leading order corrections are suppressed by $1/(4\pi)^2$ and neglected here.

Here, m is the particle mass; $g_i = (-1)^{2j}(2j+1)f$ is the degeneracy factor for a particle i of spin j, with $g_i > 0$ for bosons and $g_i < 0$ for fermions. The minus sign follows from the Pauli exclusion principle and the anti-commutator relations for fermions. The factor f is 1 for bosons, 2 for each charged lepton and 6 for each flavour of quark (2 charge factors for the quark and antiquark, each with 3 colours).

There is a subtle issue with how to handle ultraviolet divergences consistent with the fundamental symmetries in the problem. For example, imagine a two-dimensional world with circular symmetry. Then treating divergences involves a circle in momentum space extrapolated to infinity. If we instead sought to use a triangle in momentum space, the corners and edges would violate the underlying circular symmetry and might reasonably lead to wrong results when connecting to experiments the two-dimensional physicist might perform. A well-known example where two classical symmetries clash with quantum effects associated with ultraviolet momenta is the chiral anomaly. The vector vector axial-vector triangle diagram cannot be evaluated in a way that preserves gauge invariance (current conservation) at the vector vertices γ_α and γ_β, while preserving chiral symmetry at the axial-vector vertex $\gamma_\mu\gamma_5$. Gauge invariance wins with the correction in the axial-vector current leading to the correct decay rate for $\pi^0 \to 2\gamma$ in QED [29, 30] and the large η' mass in QCD [31].

For the ZPEs, it is important to choose a Lorentz covariant regularization procedure to ensure that the renormalized zero-point energy satisfies the correct vacuum equation of state. Dimensional regularization with minimal subtraction, $\overline{\text{MS}}$, is a good regularization. One finds

$$\rho_{\text{zpe}} = -p_{\text{zpe}} = -\hbar\, g_i\, \frac{m^4}{64\pi^2}\left[\frac{2}{\epsilon} + \frac{3}{2} - \gamma - \ln\left(\frac{m^2}{4\pi\mu^2}\right)\right] + \ldots \qquad (5)$$

from particles with mass m [32]. Here, p_{zpe} is the pressure, $D = 4 - \epsilon$ the number of dimensions, μ the renormalization scale, and γ is Euler's constant. If one instead uses a brute force cut-off on the divergent integral, the leading term in the ZPE proportional to k_{max}^4 obeys the radiation equation of state $\rho = p/3$. Equation (5) means that the ZPE vanishes for massless particles, *e.g.*, the photon. For the Standard Model particles, the ZPE is induced by the Higgs mechanism.

Bosons and fermions contribute to the net zero-point energy with different signs. This led Pauli to suggest a collective cancellation of the ZPE [24], much like the Veltman condition for the Higgs mass squared. If we wish to cancel the net ZPE, then the Pauli equivalent to the Veltman condition reads [24, 33]

$$\begin{aligned} 6m_W^4 + 3m_Z^4 + m_h^4 &= 12m_t^4\,, \\ 6m_W^4 \ln m_W^2 + 3m_Z^4 \ln m_Z^2 + m_h^4 \ln m_h^2 &= 12m_t^4 \ln m_t^2\,, \end{aligned} \tag{6}$$

where we again neglect the lighter mass quarks. For the Standard Model with the physical W, Z and top-quark masses, these two equations would need a Higgs mass of about 319 GeV and 311 GeV, respectively, close to the Veltman value of 314 GeV. With the Standard Model particle masses, the net ZPE is negative and fermions dominate.

If we want to cancel the Pauli constraints, we need some extra strength in the boson sector. A popular candidate for possible extra particles beyond the Standard Model are 2 Higgs Doublet Models, 2HDMs [34]. These are a simple extension of the Standard Model. One introduces a second Higgs doublet. There are 5 Higgs bosons, two neutral scalars h and H, one pseudoscalar A and two charged Higgs states $H^{\pm}$. Since the 125 GeV Higgs-like scalar discovered at CERN in 2012 [19, 20] has so far showed no departure from the Standard Model predictions, it must be assumed in any model with extra Higgs states that one of the neutral scalars h is a lot like the Standard Model Higgs.

Theoretical constraints on 2HDMs come from tree level unitarity, vacuum stability and requiring perturbative couplings. In addition, an extra Z_2 symmetry is imposed relating the two Higgs doublets to eliminate unwanted flavour changing neutral currents with Yukawa couplings. This Z_2 symmetry may be softly broken (through a mass mixing term).

How do 2HDMs affect the Pauli and Veltman conditions? Possible extra Higgs states are looked for in direct searches [35, 36]. The parameter space is constrained with lower bounds on the masses from global electroweak fits [37] and rare B-decay processes [38, 39]. Different model scenarios depend on the fermion-to-Higgs couplings. The most constrained are type II models with 600 GeV $< m_{H^{\pm}}$, 530 GeV $< m_A$ and 400 GeV $< m_H$ [2]. Here, one doublet couples to up-type quarks and one to down-type quarks and leptons. Others are type I fermiophobic model where all fermions couple to just one doublet, lepton specific (one doublet to quarks and one to leptons) and flipped (the same as type II except leptons couple to the doublet with up-type quarks). There are also inert models where only one doublet acquires a v.e.v. and couples to fermions. These models are less constrained. For the Veltman condition extended to 2HDMs, a favoured benchmark point is quoted in type II model with $m_H \sim 830$ GeV and $m_A, m_{H^{\pm}} \sim 650$ GeV [42]. For

[2] Tighter constraints for type II models were claimed in [40], *viz.* 740 GeV $< m_{H^{\pm}}$, 750 GeV $< m_A$ and 700 GeV $< m_H$. These lower bounds are above the upper bounds from tree level unitarity assuming exact Z_2 symmetry (with no mass mixing soft symmetry breaking term), *viz.* $m_{H^{\pm}} \leq 616$ GeV, $m_A \leq 711$ GeV and $m_H \leq 609$ GeV with m_h taken to be 125 GeV as measured at the LHC [41].

the mass constraints quoted for type II models, we would need also extra fermions in the energy range of the LHC to cancel the Pauli condition if this scenario is manifest in nature.

4. Scale hierarchies with running masses and couplings

The Standard Model particle masses and couplings are related by

$$m_f = y_f \frac{v}{\sqrt{2}} \qquad (f = \text{quarks and charged leptons}) \,, \tag{7}$$

where y_f are the Yukawa couplings

$$m_W^2 = \frac{1}{4} g^2 v^2 \,, \qquad m_Z^2 = \frac{1}{4} \left(g^2 + g'^2\right) v^2 \tag{8}$$

with g and g' the SU(2) and U(1) electroweak couplings, and

$$m_h^2 = 2\lambda v^2 \,, \tag{9}$$

where λ is the Higgs self-coupling.

The SU(2) and QCD SU(3) couplings, g and g_s are asymptotically free, whereas the U(1) coupling g' is non-asymptotically free, rising in the ultraviolet. (The fine structure constant and its generalizations are defined by $\alpha_i = g_i^2/4\pi$.) Running of the Higgs self-coupling λ determines the stability of the electroweak vacuum. With the Standard Model parameters measured at the LHC, λ decreases with increasing resolution up to some very large scale. The sign of the β-function

$$\beta_\lambda = \mu^2 \frac{\mathrm{d}}{\mathrm{d}\mu^2} \lambda \left(\mu^2\right) \tag{10}$$

determines the scale evolution of λ with β_λ dominated by a large negative top-quark Yukawa coupling contribution (without which the sign of β_λ would be positive). QCD interactions of top quarks are also essential for keeping the β-function negative. Vacuum stability depends on whether λ crosses zero or not deep in the ultraviolet and involves a delicate balance of Standard Model parameters.

If we take just the Standard Model with no coupling to undiscovered new particles, then one finds that the electroweak vacuum sits very close to the border of stable and metastable suggesting possible new critical phenomena in the ultraviolet, within 1.3 standard deviations of being stable on relating the top-quark Monte Carlo and pole masses [43][3]. Taking the pole mass $m_t =$

[3] This 1.3σ difference is reduced if one includes the difference, about 600 MeV, in the top-quark and Monte Carlo and pole masses discussed in [44].

173 GeV, the 125 GeV Higgs mass is close to the minimum needed for vacuum stability. If the Standard Model parameters were just slightly different, the low-energy effective theory emerging from the extreme ultraviolet would be completely different from the Standard Model — see [4] and references therein. The Higgs and other particle masses might be linked to physics close to the Planck scale.

Evolution of the Standard Model running couplings is shown in figure 1, where we evaluate the running couplings using the evolution code mr: Standard Model matching and running C++ package [45]. Corresponding to the running couplings in figure 1, in figure 2, we show the running top-quark, W, Z and Higgs boson masses and the Higgs v.e.v. v up to the scale, just above 10^{10} GeV, where λ becomes negative in this calculation with metastable vacuum. If here we reduce the PDG top mass to 171 GeV, then the vacuum stays stable up to the Planck scale.

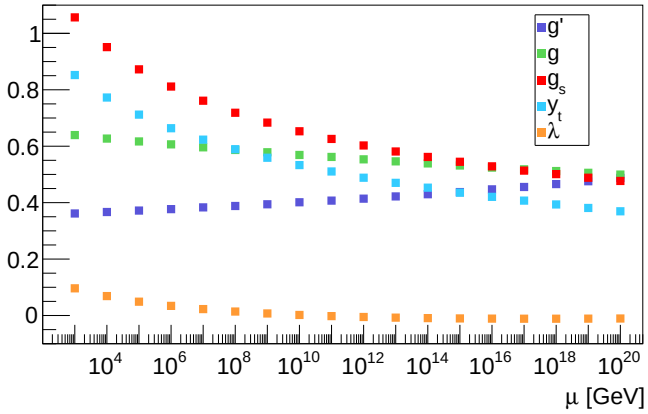


Fig. 1. Running of the Standard Model gauge couplings g, g, g_s for the electroweak SU(2) and U(1) and colour SU(3), the top-quark Yukawa coupling y_t and Higgs self-coupling λ. (From left, the points describe the evolution of g_s, y_t, g, g', λ in descending order.)

Both the Veltman and Pauli constraints are evaluated from loop diagrams so the masses which appear there are really renormalization group, RG, scale-dependent. Boson and fermion contributions enter with different signs and evolve differently under RG evolution which means they have a chance to cross zero deep in the ultraviolet.

Veltman crossing means that the renormalized and bare Higgs mass squared first coincide, with the scale hierarchy at lower energies then radiatively generated through evolution. The scale of Veltman crossing is calculation-dependent. With the Standard Model evolution code [45], crossing is found at the Planck scale with a Higgs mass about 150 GeV, and not

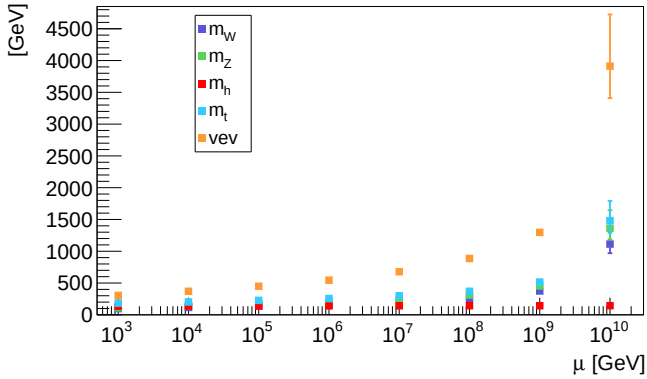


Fig. 2. Running $\overline{\text{MS}}$ masses and the Higgs v.e.v. in the Standard Model. For the relation to the PDG pole masses, see [45]. Uncertainties are calculated by varying all PDG values up and down by their respective uncertainties. (In the printed black and white version, the points from top describe the evolution of v, m_t, m_Z, m_W, m_h.)

below with the measured mass of 125 GeV — see figure 3 for input PDG masses of 125, 142 and 150 GeV. If we take input values $m_t = 171$ GeV and $m_h = 125$ GeV leading to a stable vacuum in this calculation, then Veltman crossing happens not below the Planck scale. In alternative calculations, Veltman crossing was reported at 10^{16} GeV with a stable vacuum [3], about 10^{20} GeV [46] and much above the Planck scale of 1.2×10^{19} GeV [47, 48] with a metastable vacuum.

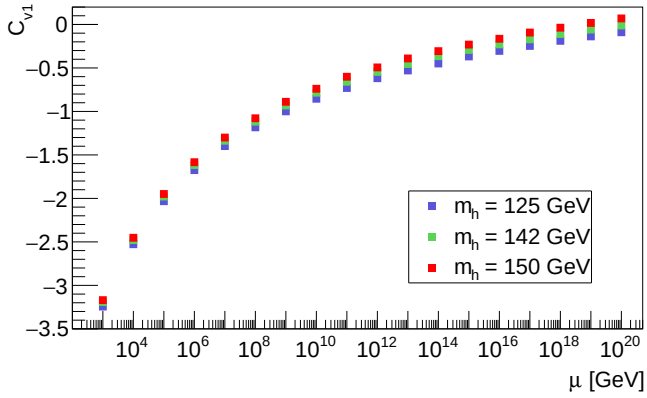


Fig. 3. Running of the Veltman coefficient for Standard Model particles. Here, $C_{\text{V1}} = \frac{3}{v^2}(m_h^2 + m_Z^2 + 2m_W^2 - 4m_t^2) = \frac{9}{4}g^4 + \frac{3}{4}g'^4 + 6\lambda - 6y_t^2$ evaluated using the running couplings in figure 1. The points are for Higgs masses m_h equal to 150, 142 and 125 GeV (top to below).

Figure 4 shows the evolution of the two Pauli constraints in Eq. (6), using again the evolution code in [45]. The first Pauli condition with terms $\propto m^4$ crosses zero above 10^{16} GeV corresponding to the net bosonic ZPE contribution outgrowing the fermionic top-quark contribution. The second Pauli condition is shown up to 10^{10} GeV, above which λ becomes negative. With negative λ, the combination $m_h^4 \ln m_h^2$ develops an imaginary part corresponding to vacuum instability; $[\ln(-\lambda) = \ln\lambda - i\pi$ for $\lambda > 0]$. For the stable vacuum case with inputs $m_t = 171$ GeV and $m_h = 125$ GeV, one finds that both Pauli curves cross zero between 10^{17} and 10^{18} GeV in this calculation. With a stable vacuum, λ remains positive definite so that v remains finite and the second Pauli condition develops no imaginary part.

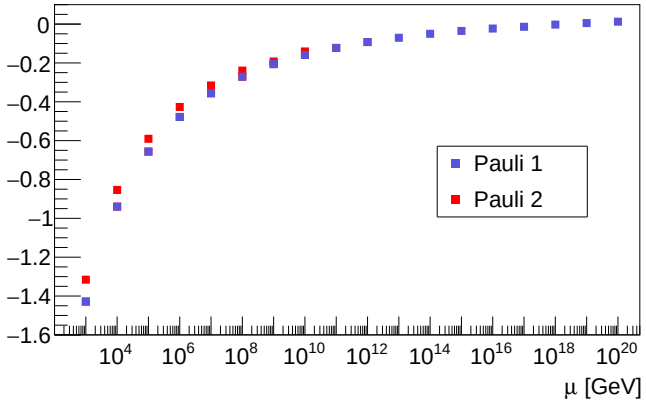


Fig. 4. Running values of the Pauli conditions in Eq. (6) for the Standard Model particles (bosons–fermions), *e.g.* Pauli 1 $\{6m_W^4 + 3m_Z^4 + m_h^4 - 12m_t^4\}$ and Pauli 2 $\{6m_W^4 \ln m_W^2 + 3m_Z^4 \ln m_Z^2 + m_h^4 \ln m_h^2 - 12m_t^4 \ln m_t^2\}$. The Pauli 1 (lower) points are normalized to v^4. The Pauli 2 (upper) points are normalized to $v^4 \ln v^2$ and plotted up to the scale so they develop an imaginary part when λ crosses zero just above $\mu = 10^{10}$ GeV signaling vacuum instability.

If the Standard Model is emergent below some large ultraviolet scale M, *e.g.* associated with vacuum stability and perhaps close to the scale where λ crosses zero, then the Standard Model will "dissolve" into more primordial degrees of freedom above this scale. With an emergent Standard Model, extrapolating perturbative evolution calculations above any scale of emergence corresponds to extrapolating into an unphysical region since the degrees of freedom there will be completely different.

5. Vacuum energy and the cosmological constant

Vacuum energy is measured through the cosmological constant Λ which appears in Einstein's equations of General Relativity. Before we couple to gravity, only energy differences have physical meaning, which allows us to cancel the ZPE through normal ordering.

Einstein's equations read

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu}\, R = -\frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu}\,. \tag{11}$$

Here, $R_{\mu\nu}$ is the Ricci tensor, R is the Ricci scalar and $T_{\mu\nu}$ is the energy-momentum tensor for excitations above the vacuum; G is Newton's constant and c is the speed of light. These equations determine the geodesics on which particles propagate in curved space-time. The cosmological constant measures the vacuum energy density

$$\rho_{\rm vac} = \Lambda/(8\pi G)\,. \tag{12}$$

It receives contributions from the ZPEs, any (dynamically generated) potential in the vacuum, *e.g.* induced by the QCD and Higgs condensates, and a renormalized version of the bare gravitational term ρ_Λ [49][4], *viz.*

$$\rho_{\rm vac} = \rho_{\rm zpe} + \rho_{\rm potential} + \rho_\Lambda\,. \tag{13}$$

Matter clumps together under normal gravitational attraction, whereas the cosmological constant is the same at all points in space-time and drives the accelerating expansion of the Universe. As an observable, the cosmological constant is renormalization scale-invariant. It is independent of how a theoretician might choose to calculate it[5]

$$\frac{\mathrm{d}}{\mathrm{d}\mu^2}\rho_{\rm vac} = 0\,. \tag{14}$$

On distance scales much larger than the galaxy, the Universe exhibits a large distance flat geometry. Observations based on supernovae type 1a, the large scale distribution of galaxies and the Cosmic Microwave Background [1, 50] point to a small positive value for the cosmological constant corresponding to

$$\rho_{\rm vac} = (0.002\ {\rm eV})^4 \tag{15}$$

and a present period of accelerating expansion that began about five billion years ago.

[4] Note that ρ_Λ corresponds to V_0 Eq. (3.8) of [26].

[5] Here, General Relativity is taken as a classical theory with Newton's constant RG scale-invariant.

Historically, Einstein introduced the cosmological constant in an attempt to give a static Universe [51]. Shortly afterwards, he expressed doubts describing Λ as "greatly detrimental to the formal beauty of the theory" [52]. The static Universe solution proved unstable to local inhomogeneities in the matter density. Einstein abandoned the cosmological constant, setting it equal to zero, following Hubble's observation of an expanding Universe [53]. Feynman in his lectures on gravitation also wrote that he believed Einstein's second guess and expected a zero cosmological constant [54]. It returned to physics with discovery of the accelerating expansion of the Universe.

Whereas the total $\rho_{\rm vac}$ is renormalization scale-invariant, individual contributions in Eq. (13) do carry scale dependence. For example, the ZPE contributions in Eq. (5) are scale-dependent both through explicit μ^2 dependence and through the running masses. The Higgs potential is RG-scale-dependent through the scale dependence of the Higgs mass and Higgs self-coupling, which determines the stability of the electroweak vacuum. This renormalization scale dependence cancels to give the scale-invariant $\rho_{\rm vac}$. The important question is whether there is anything left over. How big is the remaining $\rho_{\rm vac}$? How do we understand the measured tiny value in Eq. (15) with scale 0.002 eV when individual contributions involve the QCD and electroweak scales?

One finds a simple explanation with an emergent Standard Model. With a finite cosmological constant, Einstein's equations have no solution where $g_{\mu\nu}$ is the constant Minkowski metric [26]. That is, space-time translational invariance (a subgroup of the group of general co-ordinate transformations) is broken without extra fine tuning. The reason is that $\rho_{\rm vac}$ acts as a gravitational source which generates a dynamical space-time, with accelerating expansion for positive $\rho_{\rm vac}$. (For a Universe dominated by the cosmological constant, space-time is described by the de Sitter metric, $\mathrm{d}s^2 = \mathrm{d}t^2 - \mathrm{e}^{2H_\infty t}(\mathrm{d}r^2 + r^2\mathrm{d}\theta^2 + r^2\sin^2\theta\mathrm{d}\phi^2)$, where $H_\infty^2 = \frac{1}{3}c^2\Lambda$ is the Hubble constant in the infinite future.) A large net $\rho_{\rm vac}$ would challenge the successful phenomenology of Special Relativity and particle physics with flat space-time in our experiments.

With the Standard Model as an effective theory emerging in the infrared, low-energy global symmetries can be broken through additional higher dimensional terms, suppressed by powers of the large emergence scale [10]. Suppose the vacuum including condensates with finite v.e.v.'s is translational invariant and flat space-time is consistent at dimension four, just as suggested by the successes of the Standard Model and Special Relativity. Then the RG-invariant scales $\Lambda_{\rm qcd}$ and electroweak $\Lambda_{\rm ew}$ might enter the cosmological constant with the scale of the leading term suppressed by $\Lambda_{\rm ew}/M$, where M is the scale of emergence (that is, $\rho_{\rm vac} \sim (\Lambda_{\rm ew}^2/M)^4$ with one factor of $\Lambda_{\rm ew}^2/M$ for each dimension of space-time). This scenario, if manifest in

nature, would explain why the cosmological constant scale 0.002 eV is similar to what we expect for the neutrino masses [55], which for Majorana neutrinos are themselves linked to a dimension-five operator with $m_\nu \sim \Lambda_{\rm ew}^2/M$ [17]. The cosmological constant would vanish at dimension four. In this sense, Einstein's second guess, also Feynman's guess, would be correct: the cosmological constant vanishes if we truncate the action to terms of mass dimension four or less. This vanishing cosmological constant is equivalent to a renormalization condition $\rho_{\rm vac} = 0$ at dimension four imposed by global space-time translational invariance, even in the presence of large QCD and Higgs condensates. The precision of global symmetries in our experiments, *e.g.* lepton and baryon number conservation, tells us that the scale of emergence should be deep in the ultraviolet, much above the Higgs and other Standard Model particle masses. Taking 0.002 eV $= \Lambda_{\rm ew}^2/M$ gives a value of M about 10^{16} GeV.

The tiny cosmological constant enters as a subleading term in the low-energy expansion of the action for an emergent Standard Model. Within this scenario, anthropic arguments place an upper bound on the value of $\Lambda_{\rm ew}$. It is interesting that the parameters of particle physics interactions are fine-tuned to our existence [56, 57]. Small changes in particle masses and couplings would lead to a very different Universe, assuming that the vacuum remained stable, with one example that small changes in the light-quark masses can prevent Big Bang nucleosynthesis. Accelerating expansion of the Universe takes over when the energy density associated with the cosmological constant exceeds the mean matter density (including dark matter contributions). Weinberg argued that if the cosmological constant were ten times larger, the present period of acceleration would have begun earlier enough that galaxies would have no time to form [58]. With $\rho_{\rm vac} \sim (\Lambda_{\rm ew}^2/M)^4$, this constraint corresponds to a factor of 1.33 on $\Lambda_{\rm ew}$ or upper bound on the Higgs mass, which is complementary to the lower bound, about 125 GeV, needed for electroweak vacuum (meta)stability with other PDG parameters held fixed.

6. Conclusions

With the great success of the Standard Model at the LHC and in low-energy precision experiments, it is worthwhile to re-evaluate our ideas about the origins of gauge symmetry in particle physics. Might the gauge symmetries be emergent? The (meta)stability of the electroweak vacuum suggests that the Standard Model parameters measured in experiments might be correlated with physics deep in the ultraviolet. Global space-time translational symmetry and the successful phenomenology of flat space-time in laboratory experiments and our everyday experience is consistent with emergent symmetry, with the cosmological constant scale suppressed by power of the

large scale of emergence. In this scenario, the cosmological constant scale would be similar to the size of Majorana neutrino masses. The tiny cosmological constant may be teaching us about the deeper origin of symmetry in particle physics. Future experiments will measure the dark energy equation of state with the EUCLID mission of ESA expected to be sensitive to variations from a time-independent cosmological constant of 10% or more [59]. (This experiment will measure the ratio of the pressure to energy density for dark energy, parametrized as $w = w_0 + (1 - a)w_1$ to accuracy 2% for w_0 and 10% for w_1, where a is the Universe scale factor (= 1 today) and $w = -1$ with $w_1 = 0$ for a time-independent cosmological constant.) Next generation neutrinoless double β-decay experiments [60, 61], *e.g.* the future LEGEND 1000 tonne experiment at Gran Sasso [62], will be sensitive to Majorana neutrinos with mass in the range of the scale of the cosmological constant scale, 0.002 eV.

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